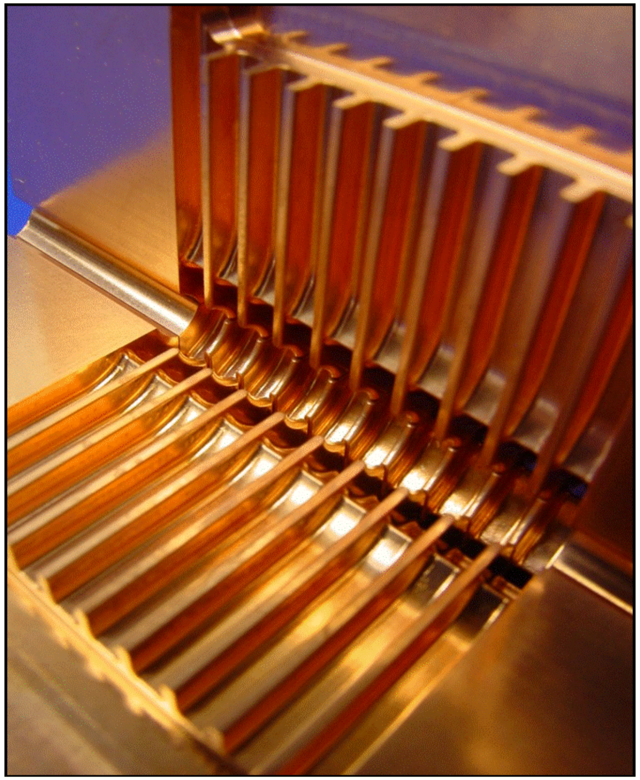
# CLIC (and room temperature RF)

Frank Tecker – CERN

- Introduction
- Room temperature RF cavities
- CLIC (Compact Linear Collider)
- CTF3 (CLIC Test Facility)

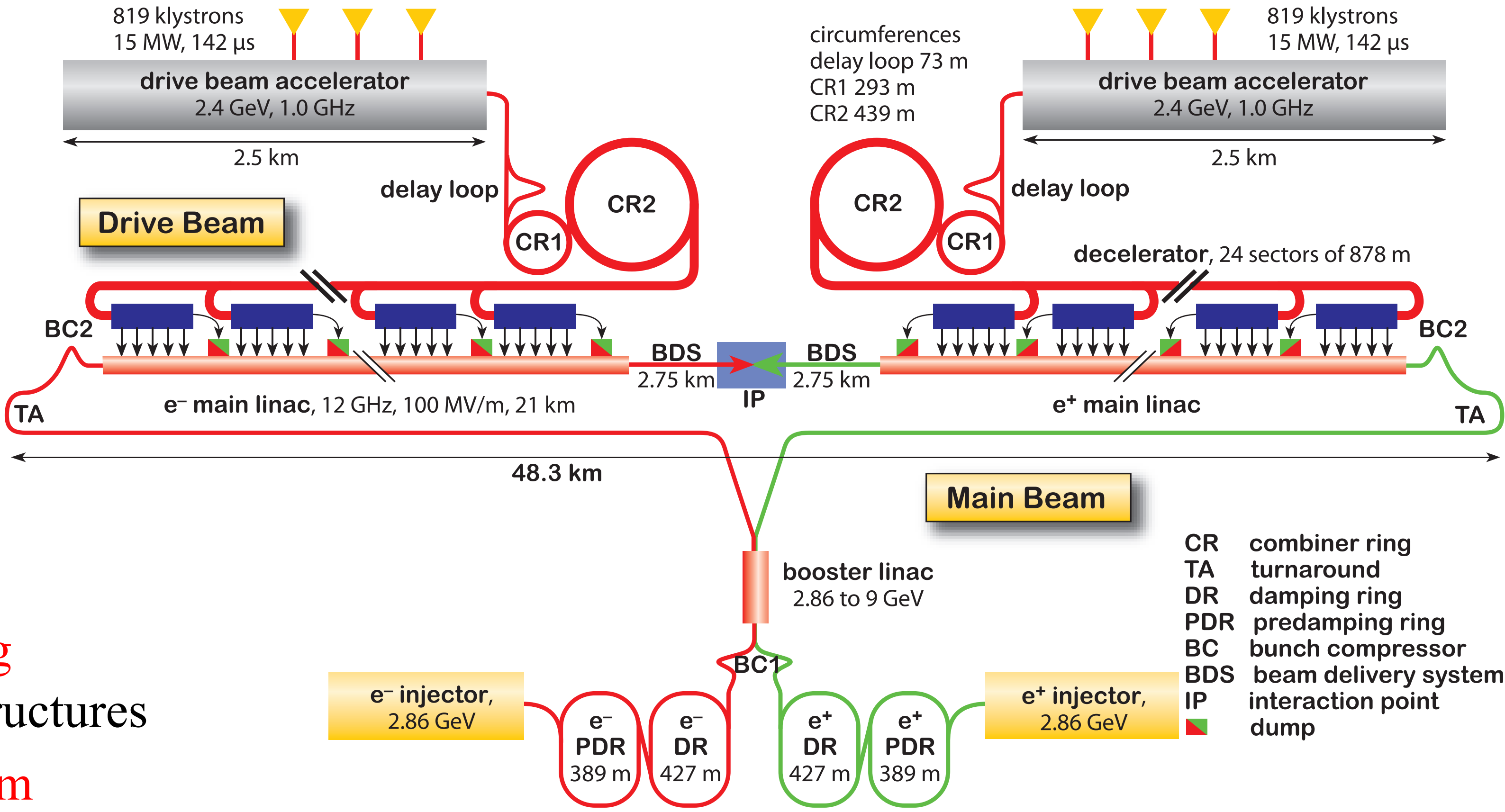


# Preface

- Complex topic - Don’t panic!
- Approach:
  - Explain the fundamental effects and principles that leads to differences between SuperConducting (SC) and normal conducting (NC) technology
  - I will not go much into technical details
  - Try to avoid formulae as much as possible
- Goal: You understand
  - Basic principles
  - The driving forces and limitations in NC linear collider design
  - The basic building blocks of CLIC
- Ask questions at any time! Any comment is useful! (e-mail: tecker@cern.ch)

# CLIC – in a nutshell

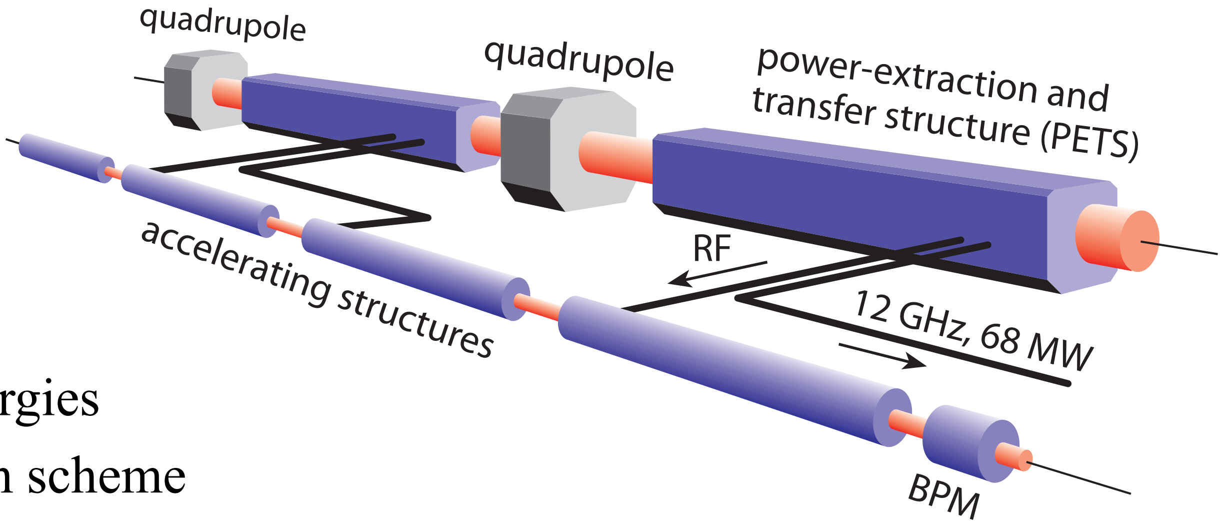
- Compact
  Linear
  Collider
- e+/e- collider
  for up to 3 TeV
- Luminosity
  $6\cdot10^{34}\text{cm}^{-2}\text{s}^{-1}$ (3 TeV)
- Normal conducting
  RF accelerating structures
- Gradient 100 MV/m
- RF frequency 12 GHz
- Two beam acceleration principle for cost minimisation and efficiency
- Many common points with ILC, similar elements, but different parameters



# Part 1

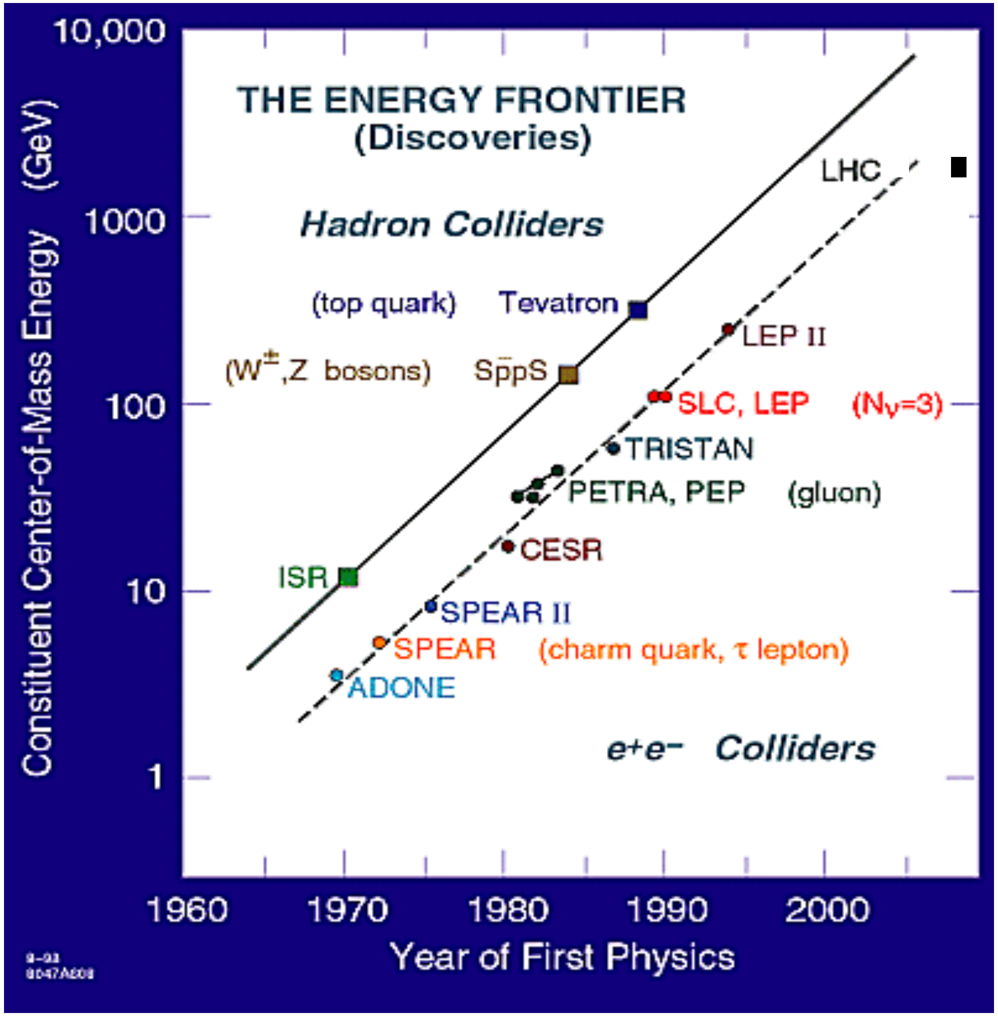
- ‘warm’ RF technology basics:
  - A linear collider at higher energy
  - Normal conducting RF structures
    - Gradient limits
    - Pulsed surface heating and Fatigue
    - Breakdown mechanism and phenomenology
  - Frequency choice
  - Wakefields and damping
  - Pulse train formats
  - Differences ‘warm’ and ‘SC’ RF collider

# Part 2



- CLIC scheme and CTF3:
  - CLIC layout at different energies
  - CLIC two-beam acceleration scheme
  - CLIC drive beam generation
    - Bunch train combination
    - Fully loaded acceleration
  - Demonstrations at the CLIC Test Facility CTF3
  - RF power production
  - CLIC main beam generation and dynamics
  - CLIC damping rings
  - CLIC alignment and stability

# Path to higher energy



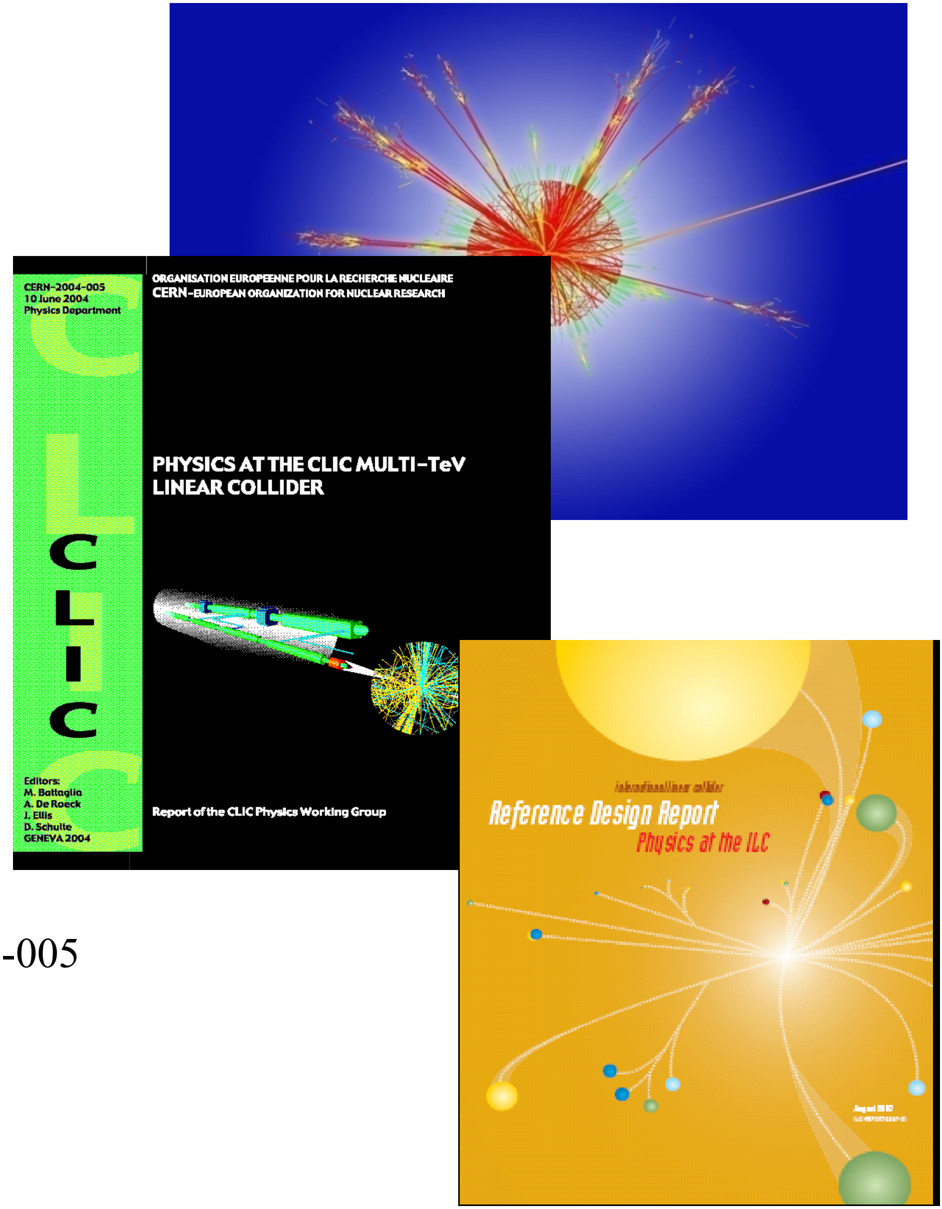
- Collider History:
  - Energy constantly increasing with time
  - Hadron Collider at the energy frontier
  - Lepton Collider for precision physics
- LHC online now
- e-/e+ storage ring excluded by synchrotron radiation
- Consensus to build Lin. Collider with $E_{cm} > 500$ GeV to complement LHC physics (*European strategy for particle physics* by CERN Council)

# TeV e+e- physics

- Higgs physics
  - LHC has discovered 'Higgs-like' particle
  - LC explore its properties in detail
- Supersymmetry
  - LC will complement the LHC particle spectrum
- Extra spatial dimensions
- New strong interactions
- . . .

=> a lot of new territory to discover beyond the standard model

- Energy can be crucial for discovery!



CERN-2004-005
10 June 2004
Physics Department

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
CERN–EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

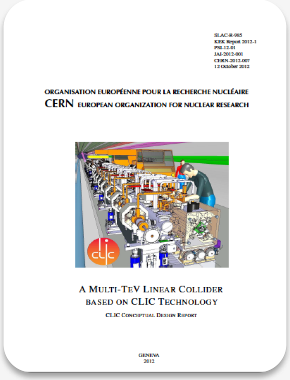
PHYSICS AT THE CLIC MULTI-TeV
LINEAR COLLIDER

Report of the CLIC Physics Working Group

Editors:
M. Battaglia
A. De Roeck
J. Ellis
D. Schulte
GENEVA 2004

- "Physics at the CLIC Multi-TeV Linear Collider" CERN-2004-005
  http://cdsweb.cern.ch/record/749219/files/CERN-2004-005.pdf
- "ILC Reference Design Report – Vol.2 – Physics at the ILC"
  www.linearcollider.org/rdr

# CLIC CDRs published



SLAC-R-985
KEK Report 2012-1
PSI-12-01
JAI-2012-001
CERN-2012-007
12 October 2012

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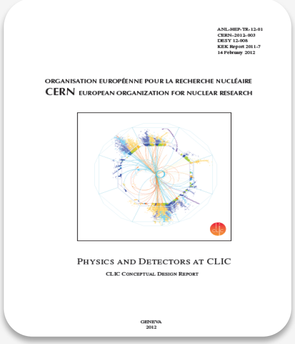
A Multi-TeV Linear Collider
based on CLIC Technology
CLIC Conceptual Design Report

GENEVA
2012

**Vol 1: The CLIC accelerator and site facilities** (H.Schmickler)

- CLIC concept with exploration over multi-TeV energy range up to 3 TeV
- Feasibility study of CLIC parameters optimized at 3 TeV (most demanding)
- Consider also 500 GeV, and intermediate energy range
- Complete, presented in SPC in March 2011, in print: https://edms.cern.ch/document/1234244/



ANL-HEP-TR-12-01
CERN–2012–003
DESY 12-008
KEK Report 2011-7
14 February 2012

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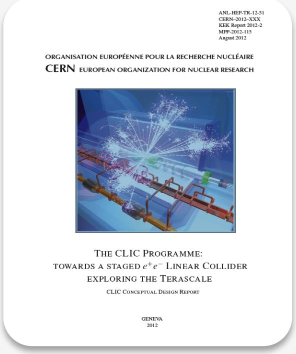
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Physics and Detectors at CLIC
CLIC Conceptual Design Report

GENEVA
2012

**Vol 2: Physics and detectors at CLIC** (L.Linssen)

- Physics at a multi-TeV CLIC machine can be measured with high precision, despite challenging background conditions
- External review procedure in October 2011
- Completed and printed, presented in SPC in December 2011 http://arxiv.org/pdf/1202.5940v1



ANL-HEP-TR-12-51
CERN–2012–XXX
KEK Report 2012-2
MPP-2012-115
August 2012

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The CLIC Programme:
towards a staged $e^+e^-$ Linear Collider
exploring the Terascale
CLIC Conceptual Design Report

GENEVA
2012

**Vol 3: "CLIC study summary"** (S.Stapnes)

- Summary and available for the European Strategy process, including possible implementation stages for a CLIC machine as well as costing and cost-drives
- Proposing objectives and work plan of post CDR phase (2012-16)
- Completed and printed, submitted for the European Strategy Open Meeting in September http://arxiv.org/pdf/1209.2543v1

In addition a shorter overview document was submitted as input to the European Strategy update, available at: http://arxiv.org/pdf/1208.1402v1

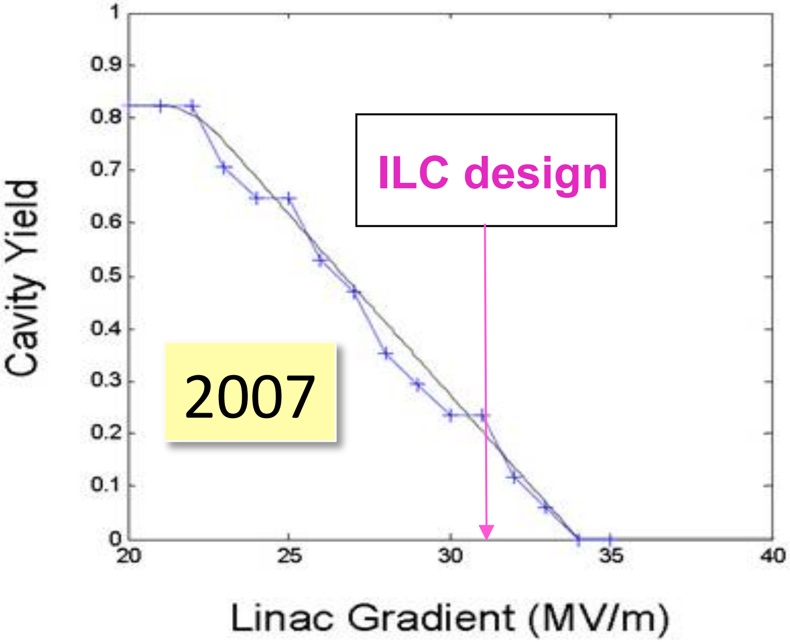
# Linear Colliders - Energy

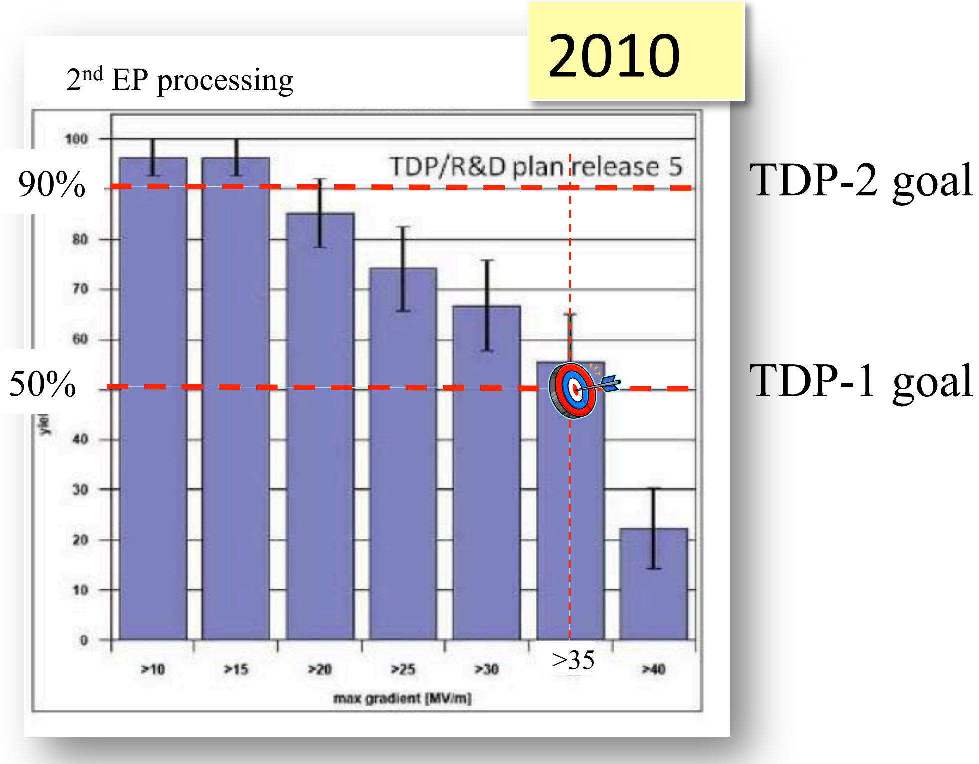
- Historical background: 2004 – ILC-TRC review
  - Evaluation of linear collider (LC) projects (NLC/JLC, TESLA and CLIC)
  - Decision for Superconducting Accelerator Technology for LC with $E_{cm} = 0.5\text{-}1$ TeV
- Consequences:
  - End of competition between normal conducting and SC schemes
  - Concentration of R&D on superconducting ILC scheme

- What about if interesting physics needs $E_{cm} >> 0.5\text{-}1$ TeV ???
  Tevatron + LHC results will determine the required energy!
  - LC size has to be kept reasonable (<50km?)
    gradient >100 MV/m needed for $E_{cm} = 3$ TeV
  - SC technology excluded, fundamental limit ~60 MV/m (excess of $H_{critical}$)
  - Normal conducting RF structures, but not trivial either!
  - => CLIC study for multi-TeV linear collider

# Achieved SC accelerating gradients

- Recent progress by R&D program to systematically understand and set procedures for the production process
- reached goal for a 50% yield at 35 MV/m by the end of 2010
- 90% yield foreseen later





Nick Walker

# Normal conducting structures

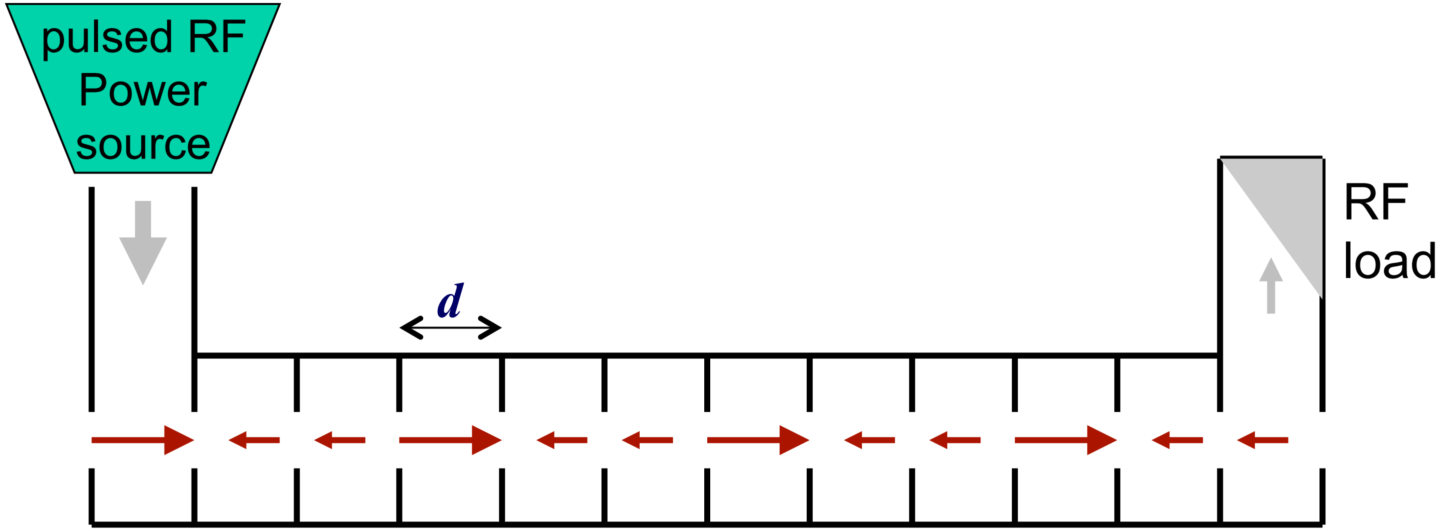
- Higher gradients (>50 MV/m) reachable with normal conducting accelerating structures

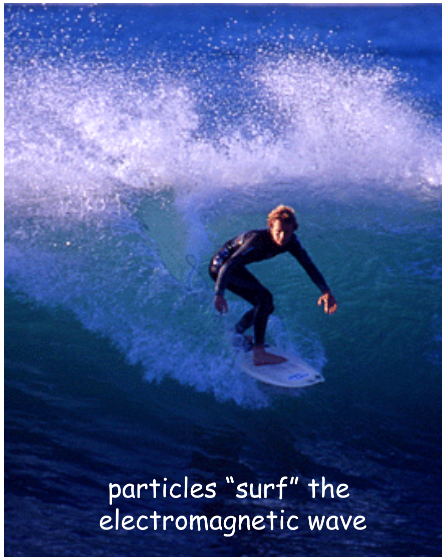
- But! Compare to advantages of SC RF cavities:
  - Very low losses due to tiny surface resistance
  - High efficiency
  - Long pulse trains possible
  - Favourable for feed-backs within the pulse train
  - Standing wave cavities with low peak power requirements
  - Lower frequency => Large dimensions and lower wakefields

- => Important implications for the design of the collider

# Traveling wave structures

- NC standing wave structures would have high Ohmic losses
- => traveling wave structures





- RF 'flows' with group velocity $v_G$ along the structure into a load at the structure exit
- Condition for acceleration: $\Delta\varphi = d \cdot \omega / c$ ($\Delta\varphi$ cell phase difference)
- Shorter fill time $T_{fill} = \int 1/v_G \, dz$ - order <100 ns compared to ~ms for SC RF

# RF efficiency: cavities

- Fields established after cavity filling time (not useful for beam)
- Steady state: power to
  beam, cavity losses, and (for TW) output coupler
- Efficiency: $$\eta_{RF \to beam} = \underbrace{\frac{P_{beam}}{P_{beam} + P_{loss} + P_{out}}}_{\approx 1 \text{ for SC SW cavities}} \frac{T_{beam}}{T_{fill} + T_{beam}}$$
- => long pulse length favoured
- NC TW cavities have smaller filling time $T_{fill}$
  => Second term is higher for NC RF
- Typical values SC: $\eta = 0.6$
  NC: $\eta = 0.3$

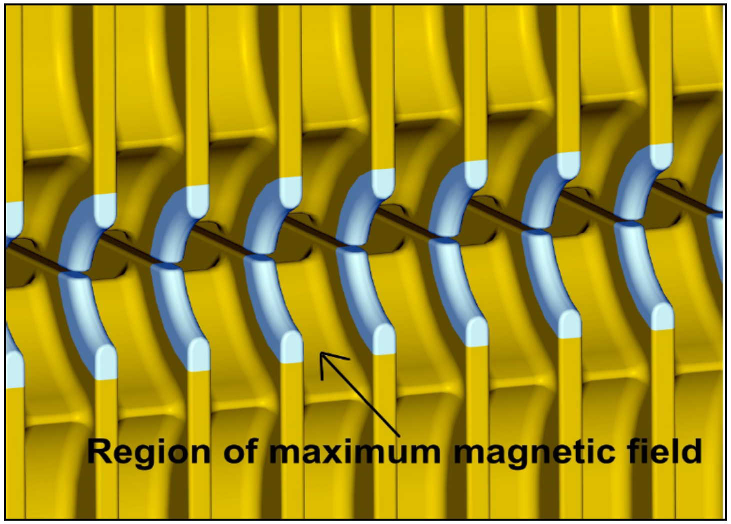
# Limitations of Gradient $E_{acc}$

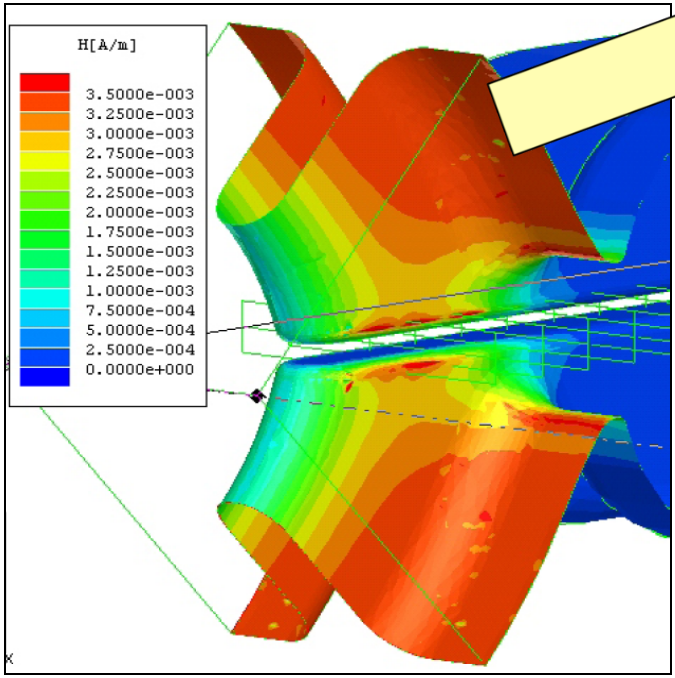
- Surface magnetic field
  - Pulsed surface heating => material fatigue => cracks

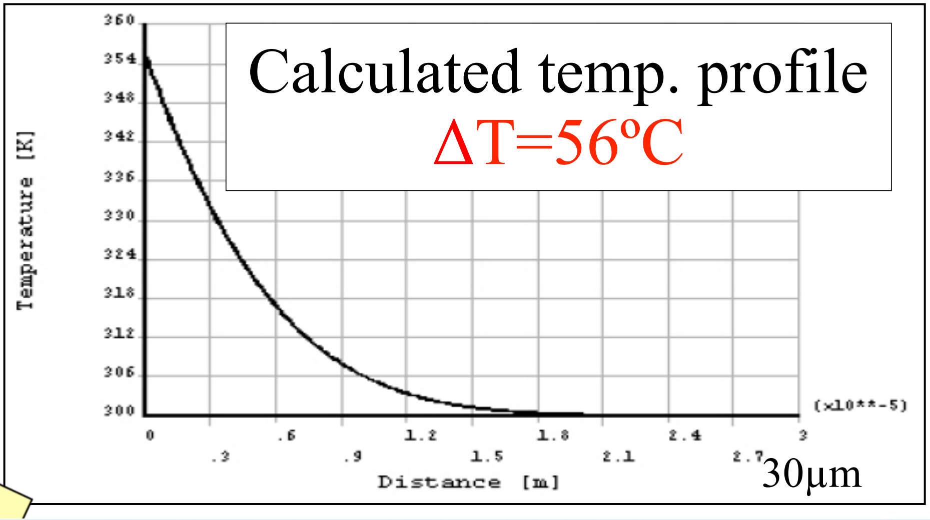
- Field emission due to surface electric field
  - RF break downs
  - Break down rate => Operation efficiency
  - Local plasma triggered by field emission => Erosion of surface
  - Dark current capture
    => Efficiency reduction, activation, detector backgrounds

- RF power flow
  - RF power flow and/or iris aperture apparently have a strong impact on achievable $E_{acc}$ and on surface erosion. Mechanism not fully understood

# Pulsed surface heating - Fatigue





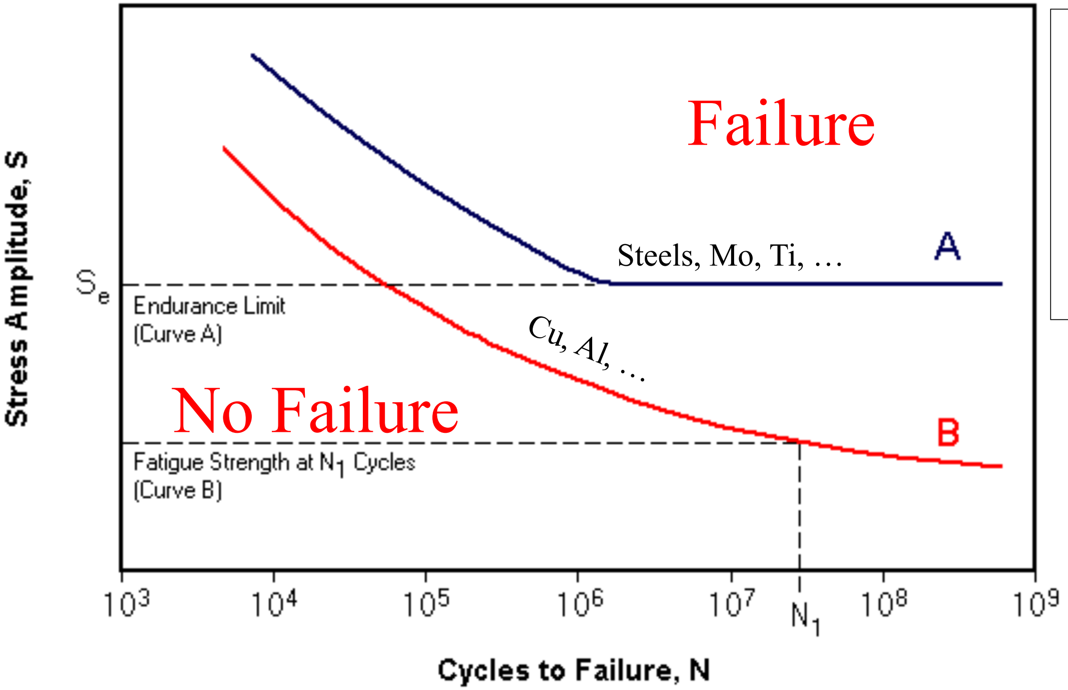


Calculated temp. profile
ΔT=56ºC

Cyclic compressive stresses

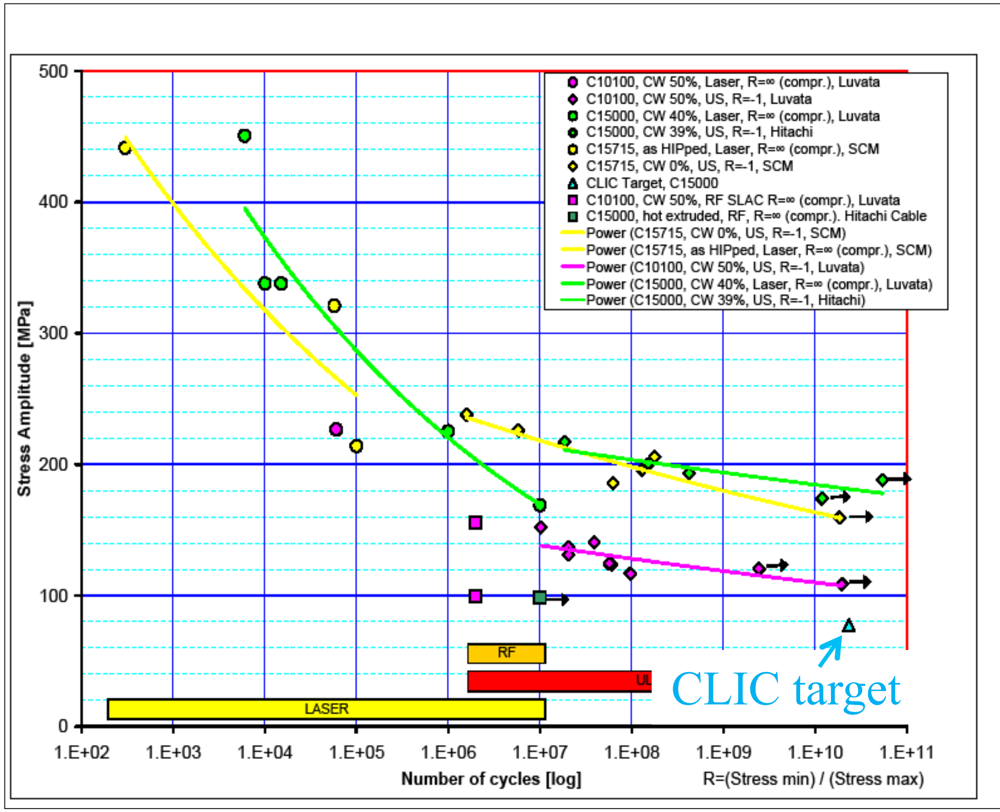
- Magnetic RF field heats up cavity wall
- Extension causes compressive stress
- Can lead to fatigue

# Fatigue curves



$H_{peak}$
↕
$\Delta T$
↕
$\sigma$

Candidates: Cu-OFE (C10100), CuZr (C15000), GlidCop Al-15



- High number of cycles limits to smaller stresses
- 20 years operation => ~$10^{10}$ cycles!
- Limits maximum $\Delta T$ and peak magnetic field

# Pulsed surface heating

- Pulsed surface heating proportional to
  - Square root of pulse length
  - Square of peak magnetic field
- Field reduced only by geometry, but high field needed for high gradient
- Limits the maximum pulse length => short pulses (~few 100ns)

$$\Delta T = \sqrt{\frac{\mu_0}{2\pi}\frac{\omega \boxed{t_P}}{\sigma\,\lambda\,\rho\,c_H}}\,\hat{H}^2$$

| | | | |
|---|---|---|---|
| $\Delta T$ | temperature rise, | $\sigma$ | electric conductivity |
| $\lambda$ | heat conductivity, | $\rho$ | mass density |
| $c_H$ | specific heat, | $t_P$ | pulse length |
| $\hat{H}$ | peak magnetic field | | |

$$\hat{H} = \frac{g_H}{377\,\Omega} E_{acc}$$

$g_H$ geometry factor of structure design

typical value $g_H \approx 1.2$

Numerical values for copper

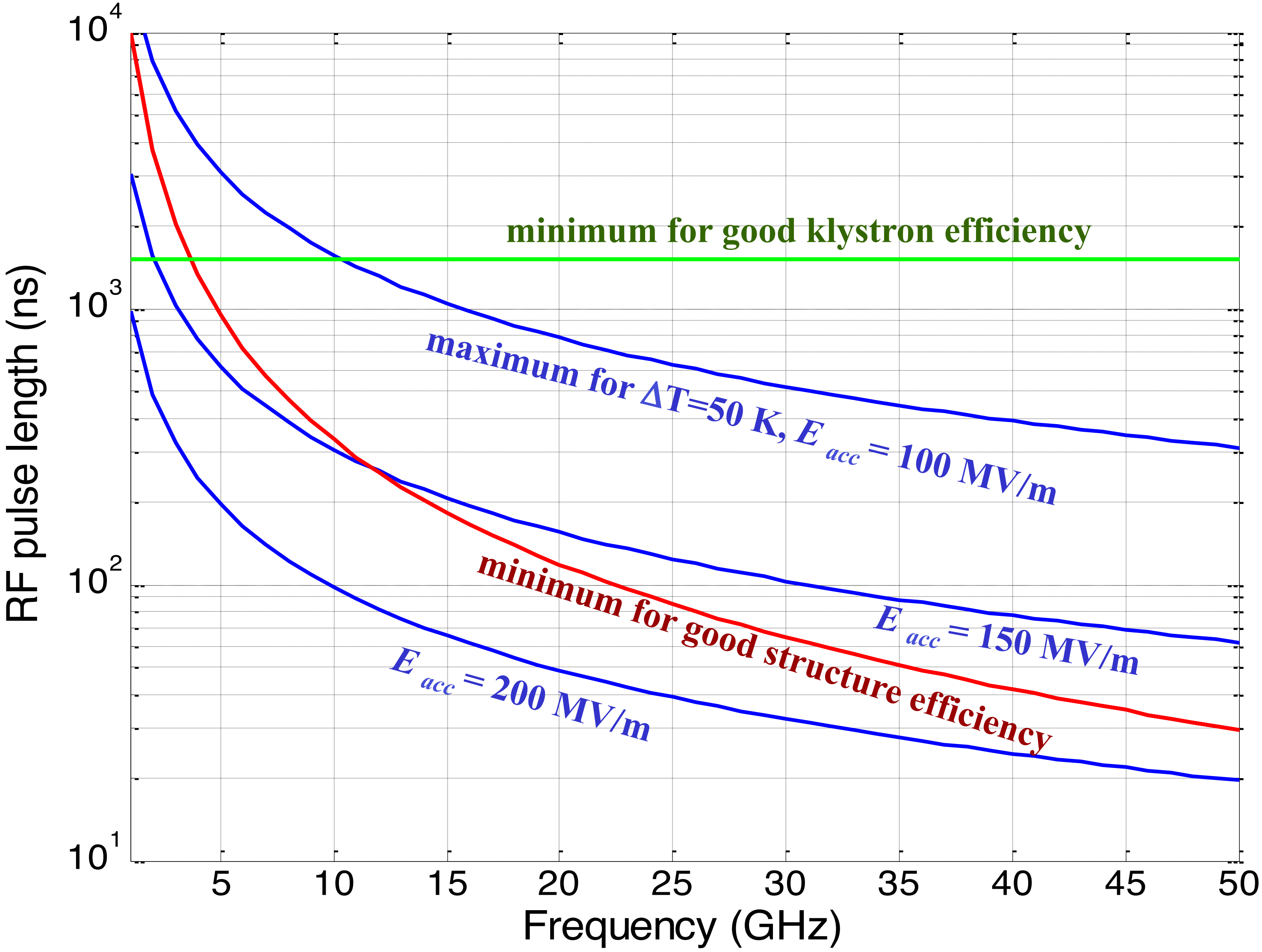
$$\Delta T \approx 4 \cdot 10^{-17} \left[\frac{\mathrm{K\,m}^2}{\mathrm{V}^2}\right] \sqrt{t_P\, f}\; E_{acc}^2$$

$$\Delta T_{\max} \approx 50\ \mathrm{K}$$

$$t_P < \left(\frac{\Delta T_{\max}}{4 \cdot 10^{-17}}\right)^2 \frac{1}{f\, E_{acc}^4}$$

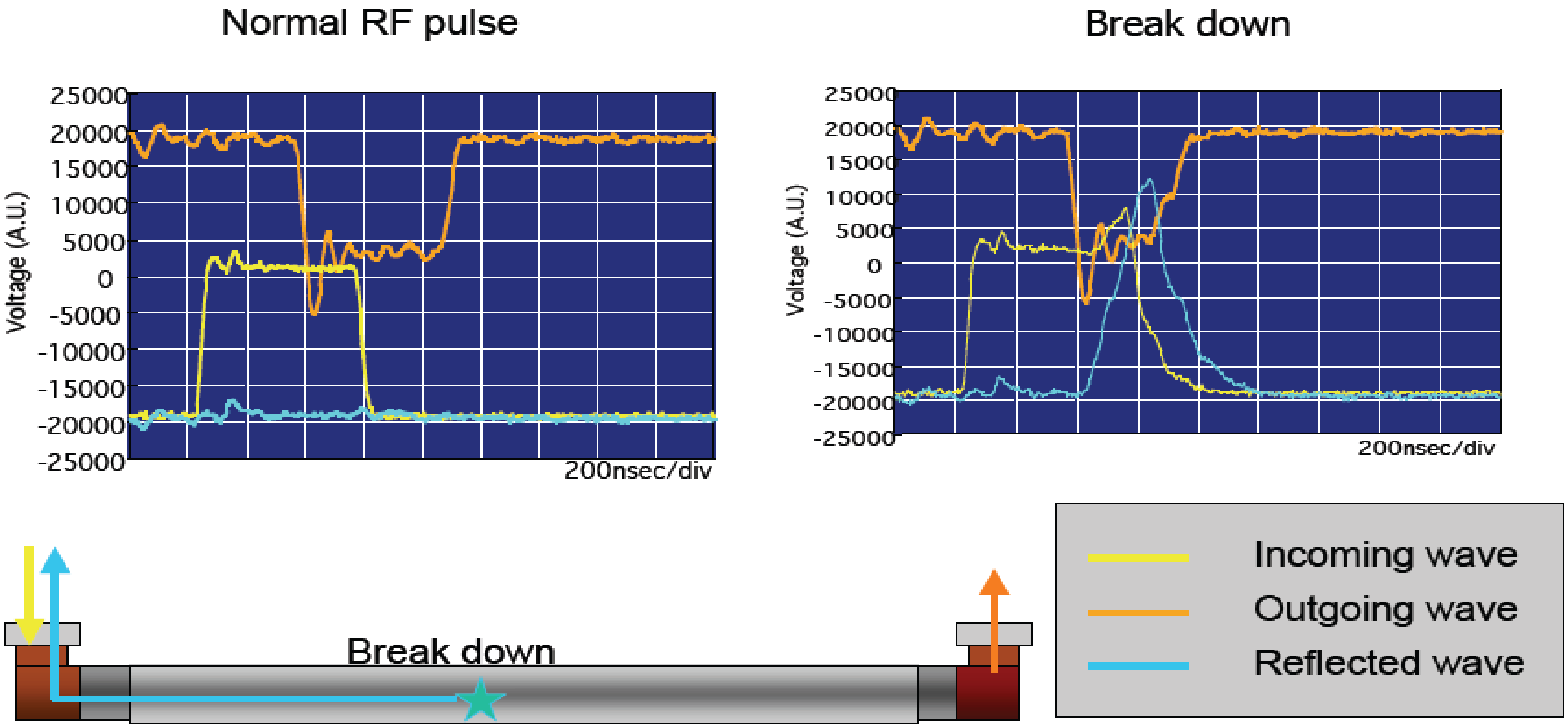
# Frequency scaling of RF pulse length limits

(for a typical accelerating structure geometry)



Hans Braun

# Breakdowns - RF wave form



from S.Fukuda/KEK

- Pulses with breakdowns not useful for acceleration
- Low breakdown rate needed

# Phenomenology of RF breakdowns

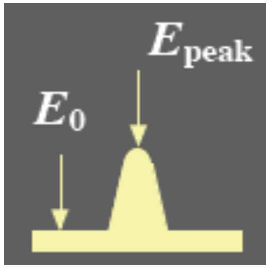
- Breakdown events characterised by
  - always
    - disappearance of transmitted power
    - reflection of incident power
    - emission of intense bursts of fast electrons ($E_{Kin}$~100 keV)
    - acoustic shock wave (can be detected with accelerometer)
    - build up time ~ 20 ns
  - often
    - fast rise of gas pressure
    - emission of visible and UV light,
      light pulse longer than incident RF pulse (~ few ms)
    - emission of positive ions ($E_{Kin}$~few 100 eV),
      pulse longer than incident RF pulse (~ few ms)
- usually no precursor signals !

# Structure conditioning

- Material surface has some intrinsic roughness (from machining)
- Leads to field enhancement

  $\beta$ field enhancement factor

$$E_{\text{peak}} = \beta E_0$$

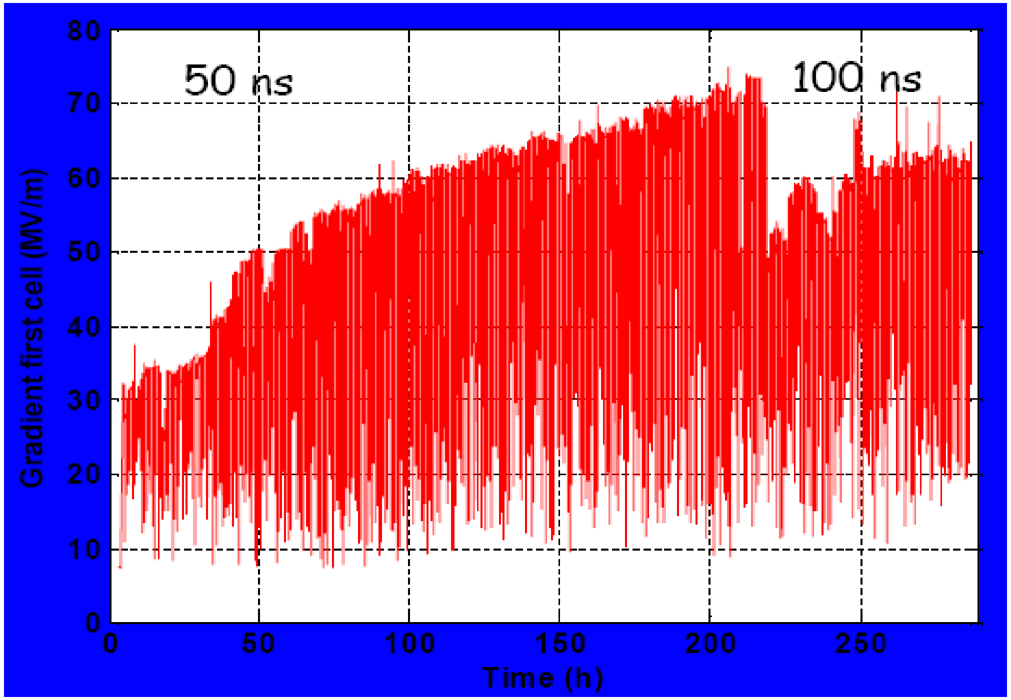


- Need conditioning to reach ultimate gradient

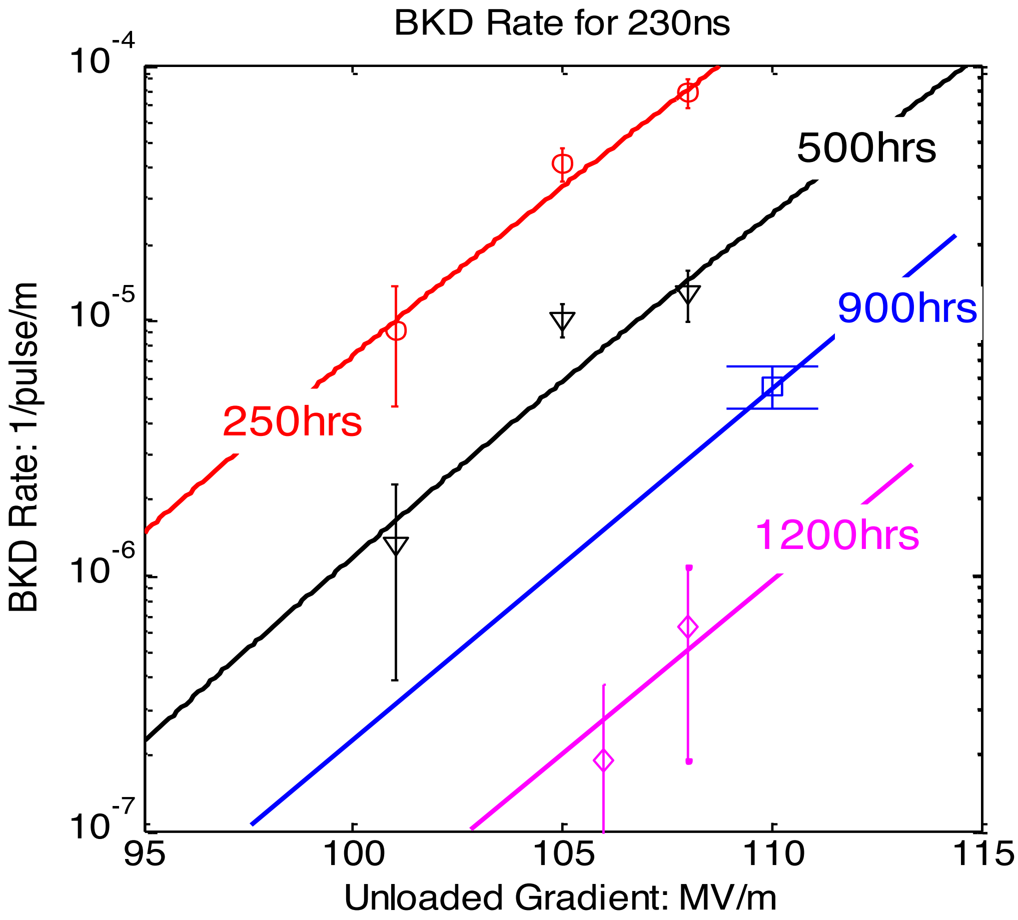
  RF power gradually increased with time
- RF processing can melt field emission points
  - Surface becomes smoother
  - field enhancement reduced
  - => higher fields

    less breakdowns

from S.Doebert



# BD Rate at Different Conditioning Time

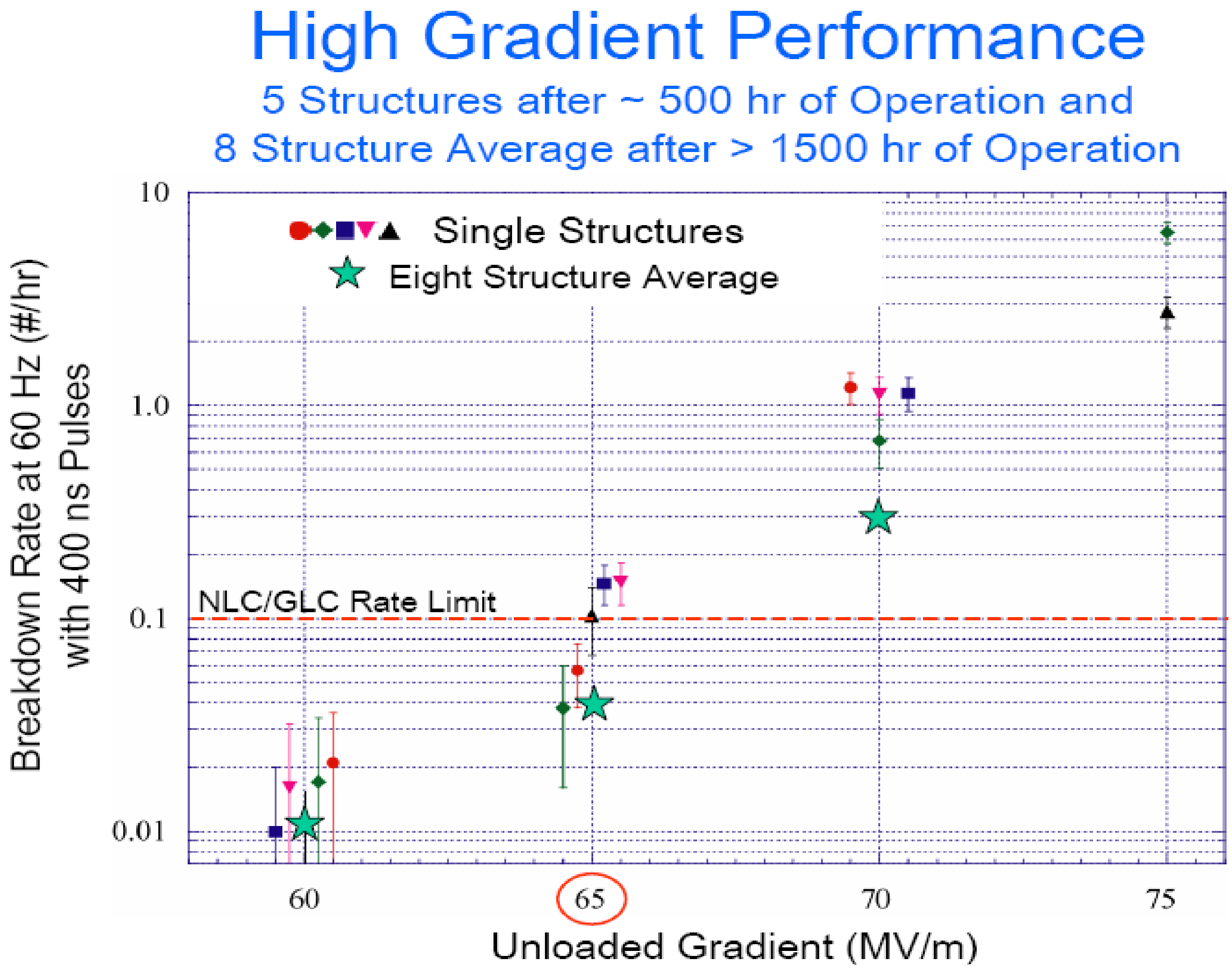


- After conditioning:
  - Higher fields reachable for constant BDR
  - Lower breakdown rate at a given field

Faya Wang

# Breakdown-rate vs gradient

- Higher breakdown rate for higher gradient



High Gradient Performance

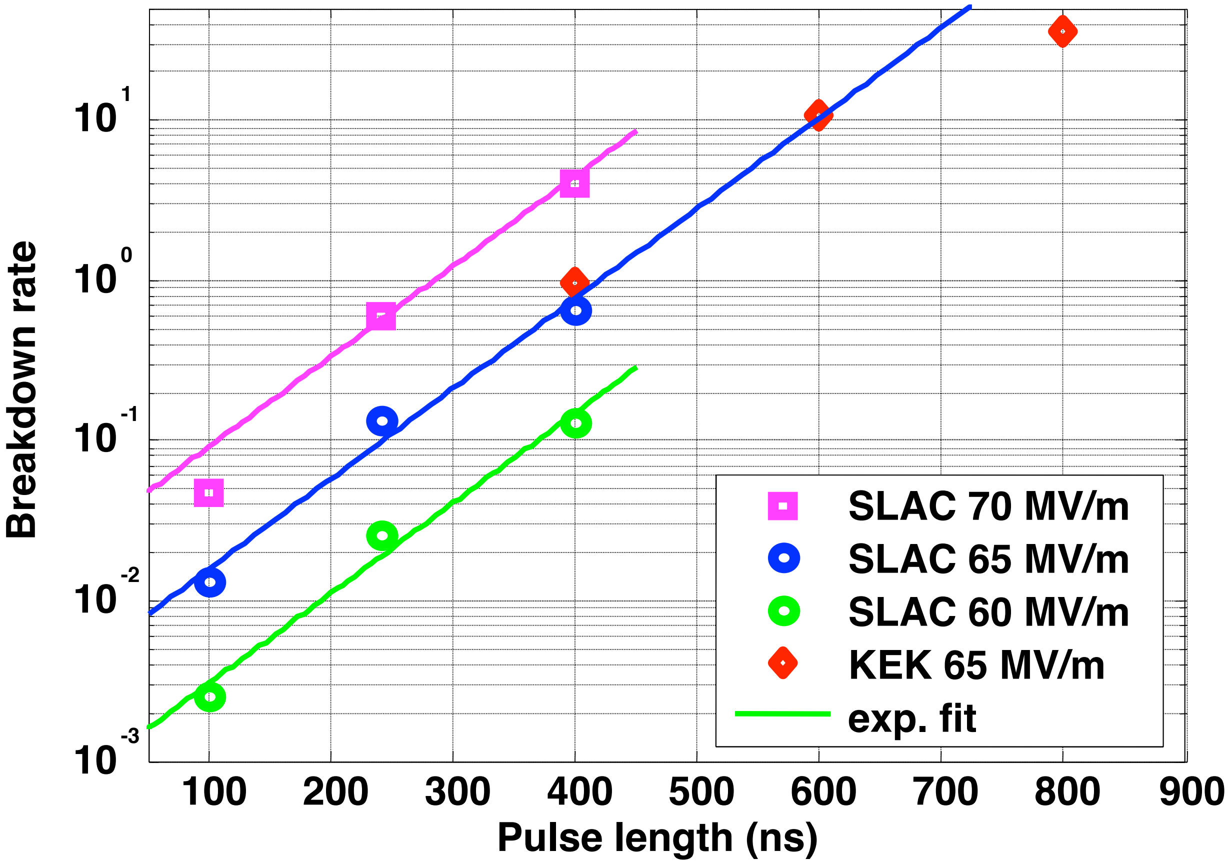
5 Structures after ~ 500 hr of Operation and

8 Structure Average after > 1500 hr of Operation

C. Adolphsen /SLAC

# Breakdown-rate vs pulse length

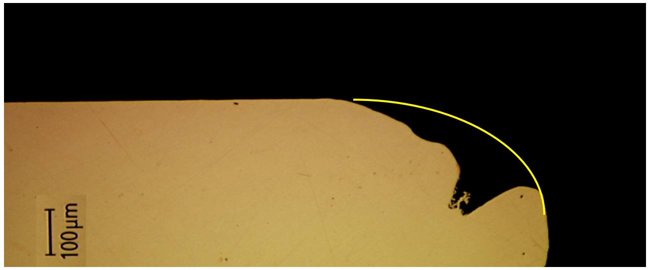
- Higher breakdown rate for longer RF pulses



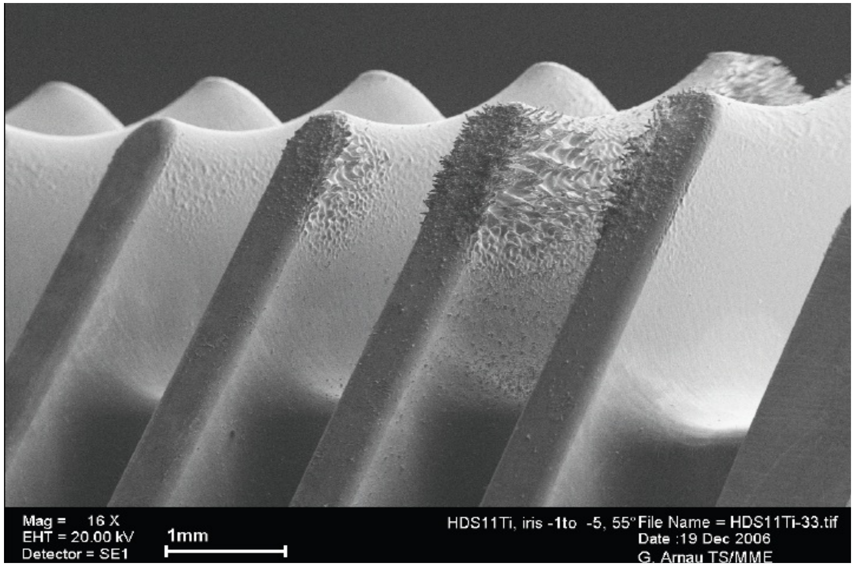
- Summary: breakdown rate limits pulse length and gradient

# Conditioning limits

- More energy: electrons generate plasma and melt surface
- Molten surface splatters and generates new field emission points!
  => limits the achievable field
- Excessive fields can also damage the structures
- Design structures with low $E_{surf}/E_{acc}$
- Study new materials (Mo, W)



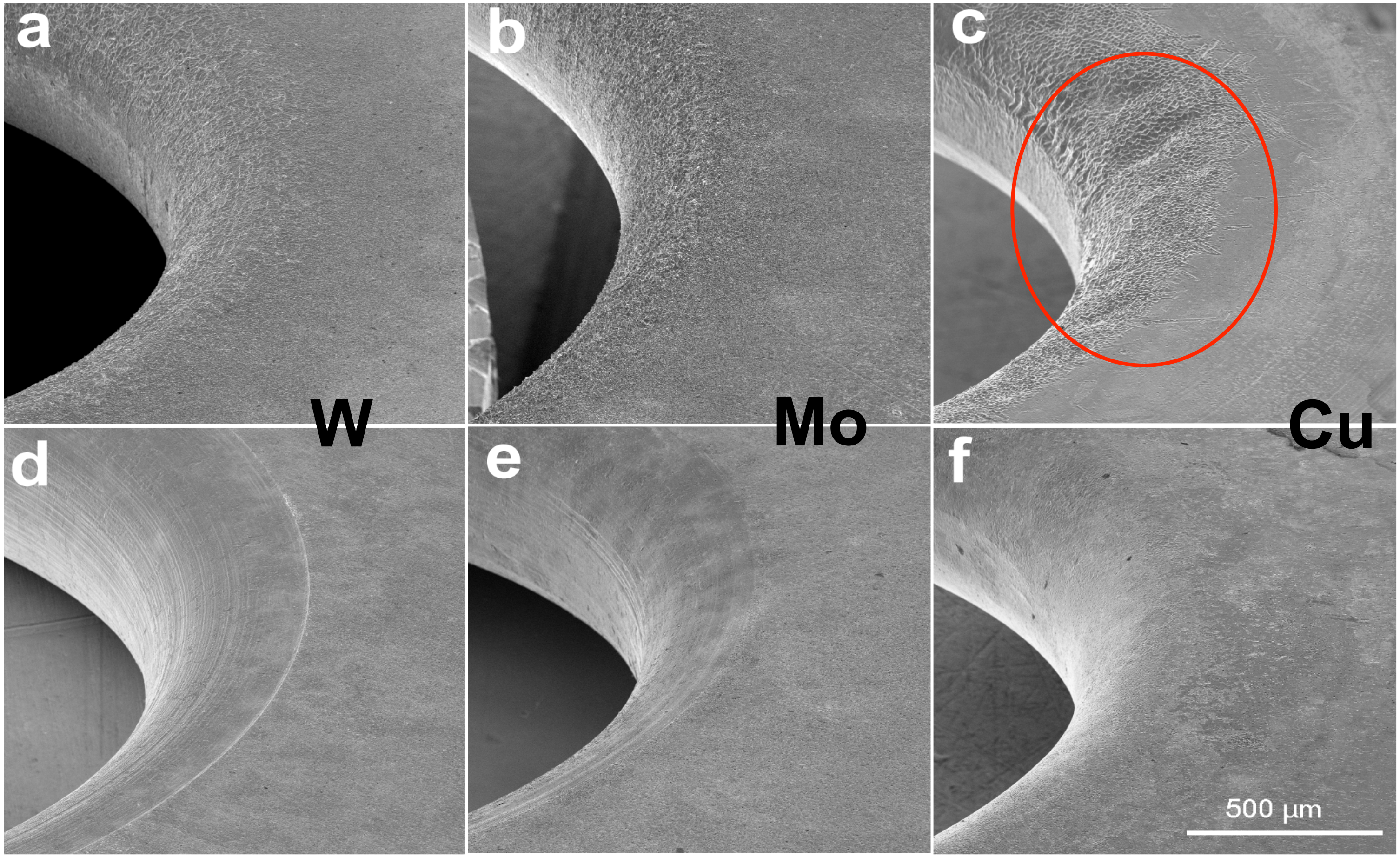
Damaged CLIC structure iris



# Iris material tests in CTF2

First iris
(highest
field)

downstream
iris



Damage on iris after runs of the 30-cell clamped structures tested in CTFII.
First (a, b and c) and generic irises (d, e and f) of W ,Mo and Cu structures respectively.

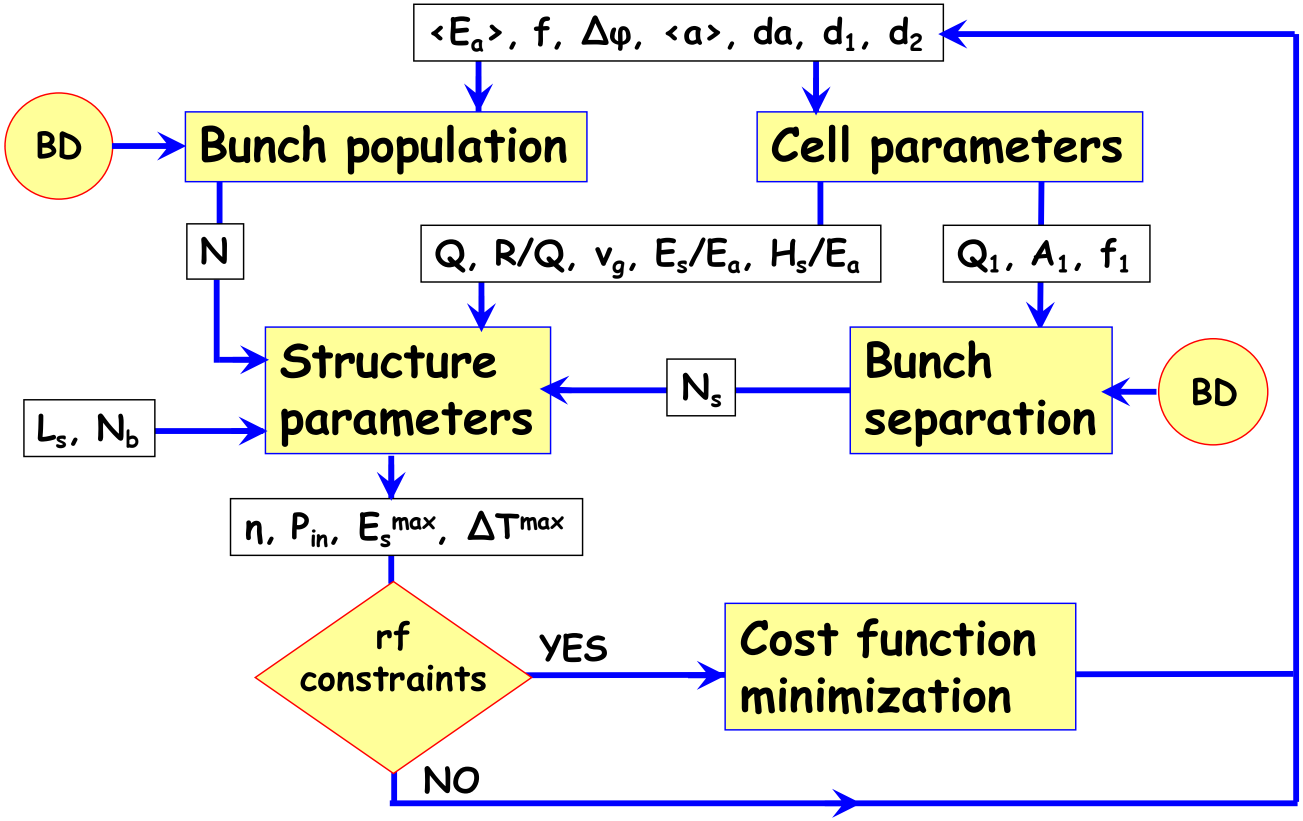
# Frequency choice for NC RF

- Shunt impedance $R_s \propto f^{1/2}$ (higher acceleration, as $R_s = V^2/P$)
- RF peak power $P_{rf} \propto 1/f^{1/2}$
- Stored energy $E \propto 1/f^2$
- Filling time $T_{fill} \propto 1/f^{3/2}$
- Structure dimensions $a \propto 1/f$
- Wakefields $W_\perp \propto f^3$

- The choice of frequency depends on the parameters above (cost issues!)
- Higher frequency is favourable for NC structures if you can manage the wakefield effects
- Actual frequency also depends on availability of RF power sources (high power klystrons up to ~17 GHz)

# A real life frequency choice

- Many more parameters in collider design
  - Take beam dynamics (BD) into account
  - Bunch charge and distance (wakes!), cell geometry, fields, efficiency,...



$\langle E_a \rangle$, $f$, $\Delta\varphi$, $\langle a \rangle$, $da$, $d_1$, $d_2$

BD

Bunch population

Cell parameters

N

$Q$, $R/Q$, $v_g$, $E_s/E_a$, $H_s/E_a$

$Q_1$, $A_1$, $f_1$

Structure parameters

$N_s$

Bunch separation

BD

$L_s$, $N_b$

$\eta$, $P_{in}$, $E_s^{max}$, $\Delta T^{max}$

rf constraints

YES

Cost function minimization

NO

# CLIC: Why 100 MV/m and 12 GHz ?

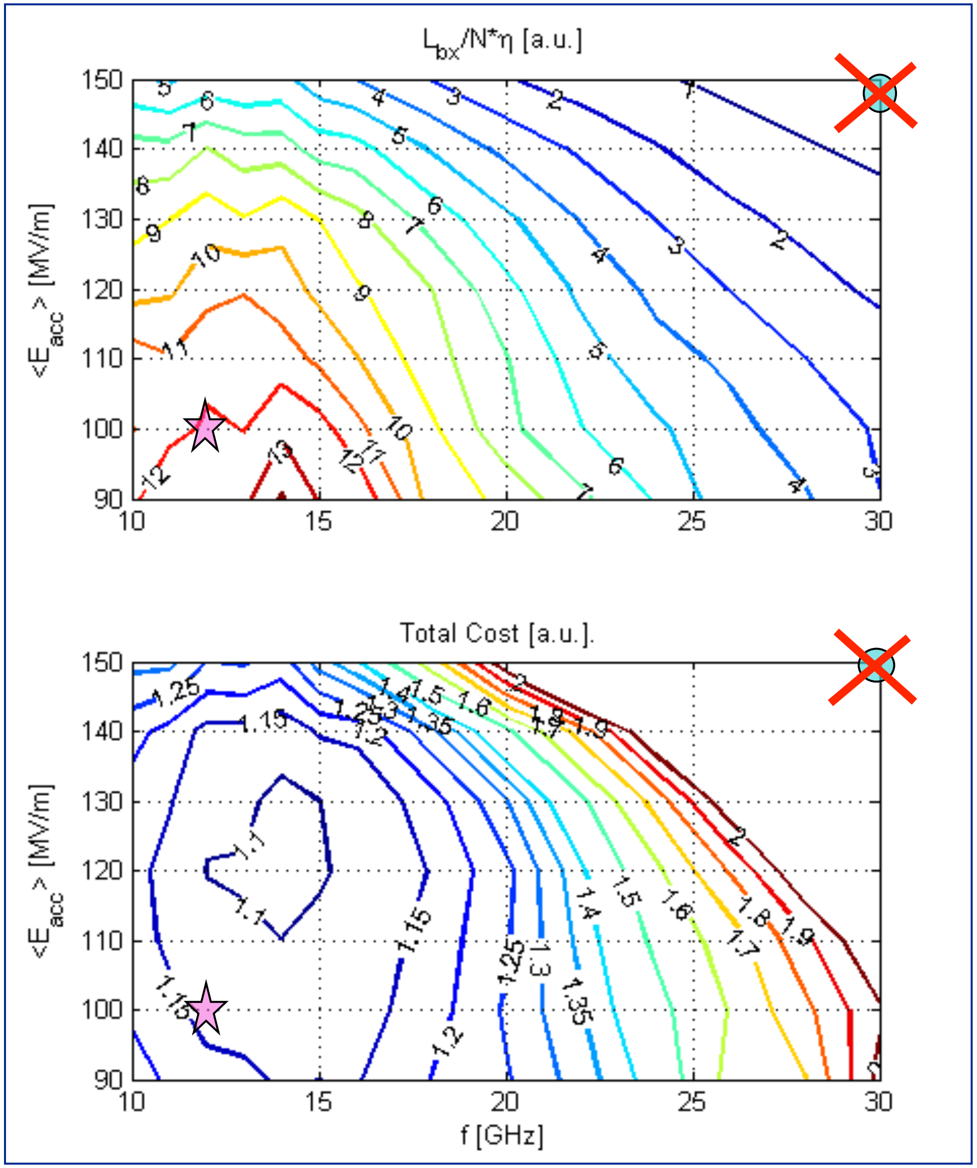
- Optimisation - figure of merit:
  - Luminosity per linac input power

- Structure limits:
  - RF breakdown – scaling ($E_{surf}$<260MV/m , $P/C\tau^{1/3}$ limited)
  - RF pulse heating ($\Delta T$<56°K)

- Beam dynamics:
  - emittance preservation – wake fields
  - Luminosity, bunch population, bunch spacing
  - efficiency – total power

- take into account cost model

**after > $60 * 10^6$ structures:**
**100 MV/m 12 GHz chosen,**
**previously 150 MV/m, 30 GHz**



A.Grudiev

# Power requirements – Klystron linac

- Accelerating field:
  (transit time, field geometry)

$$E_{acc} = g\,E_0, \quad \text{with} \quad g_{Typical} \approx 0.6$$

- Stored e.m. energy:

$$W_{Linac} \approx \tfrac{\pi}{2}\varepsilon_0\, L\, \frac{E_{acc}^2}{g^2}\left(2.405\,\tfrac{c}{\omega}\right)^2 J_1(2.405)^2$$

$$\approx 140000\left[\frac{\mathrm{J\,m}}{\mathrm{V^2 s^2}}\right]\frac{L\,E_{acc}^2}{f^2} \propto \frac{V\,E_{acc}}{\boxed{f^2}}$$

- Peak power:
  (neglecting beam power)

$$P = -\frac{\omega}{Q}W \quad \text{power lost,} \quad Q \approx \frac{7\cdot 10^8}{\sqrt{f}\,[\mathrm{s}^{1/2}]} \quad \text{(typical value for Cu)}$$

$$\approx \frac{2\pi f^{\frac{3}{2}}[\mathrm{s}^{1/2}]}{7\cdot 10^8}W \quad \approx 0.0013\left[\frac{\mathrm{J\,m}}{\mathrm{V^2 s^{3/2}}}\right]\frac{V\,E_{acc}}{\boxed{\sqrt{f}}}$$

- Example:

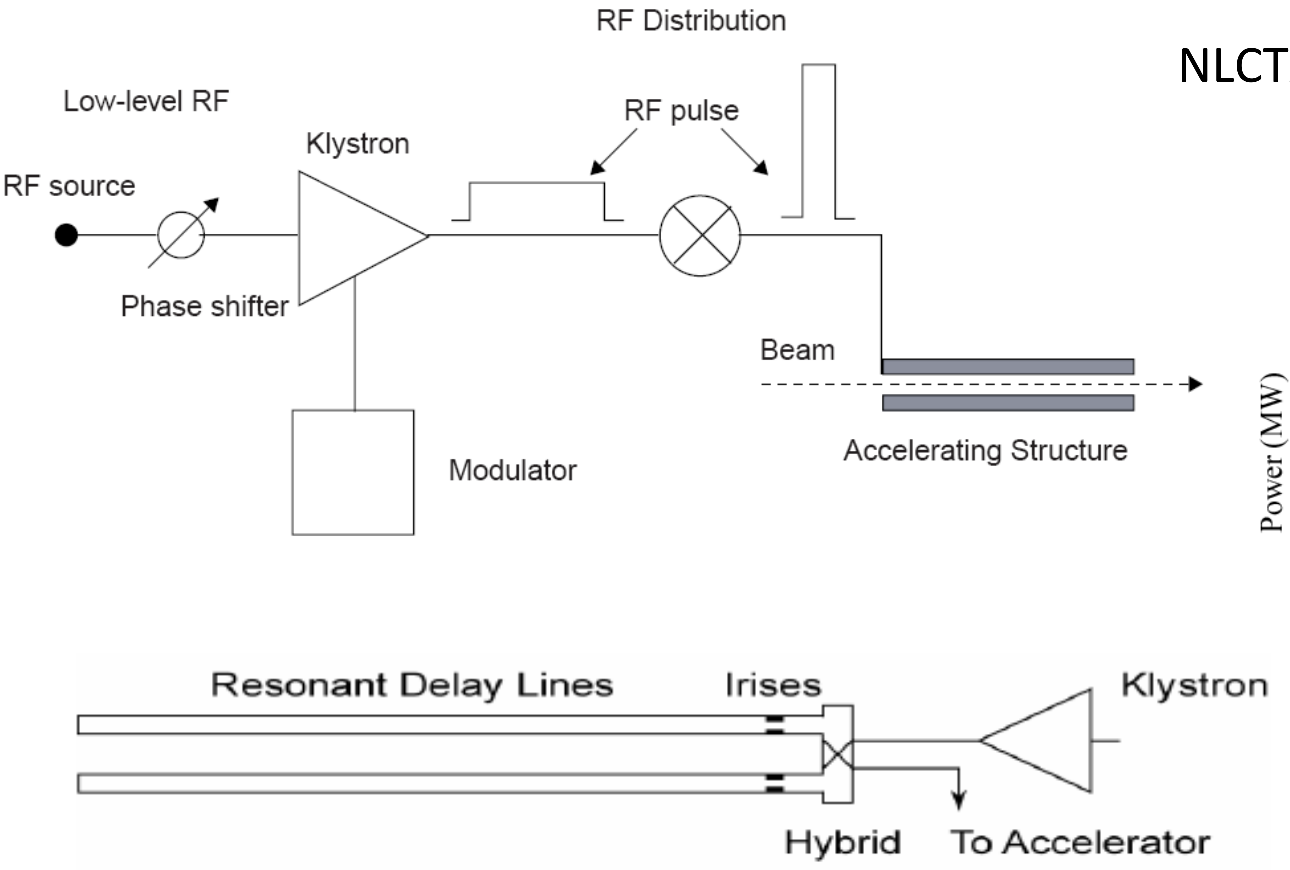
$V = 1$ TeV    $E = 50$ MV/m    $L = 20$ km    $f = 3$ GHz

=>    $W = 0.8$ MJ    $P = 1.2$ TW    $P' = 60$ MW/m

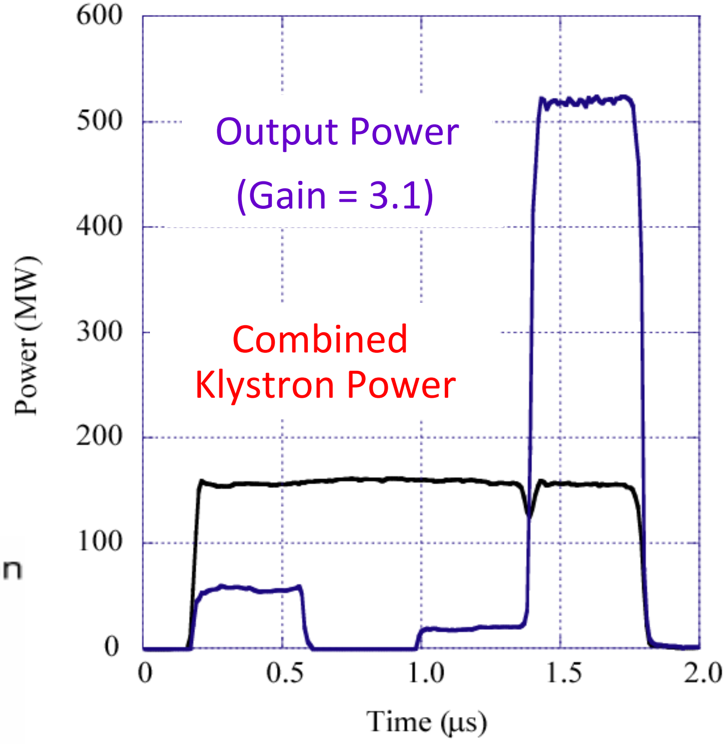
- Would need 20000 60 MW klystrons,  Not very practical!
  => higher frequency, pulse compression (NLC/JLC), drive beam (CLIC)

# RF pulse compression

- NC structures: short pulses of very high power needed
- Klystrons produce longer pulses and are power limited
- Way out: transform long RF pulses into shorter with higher power

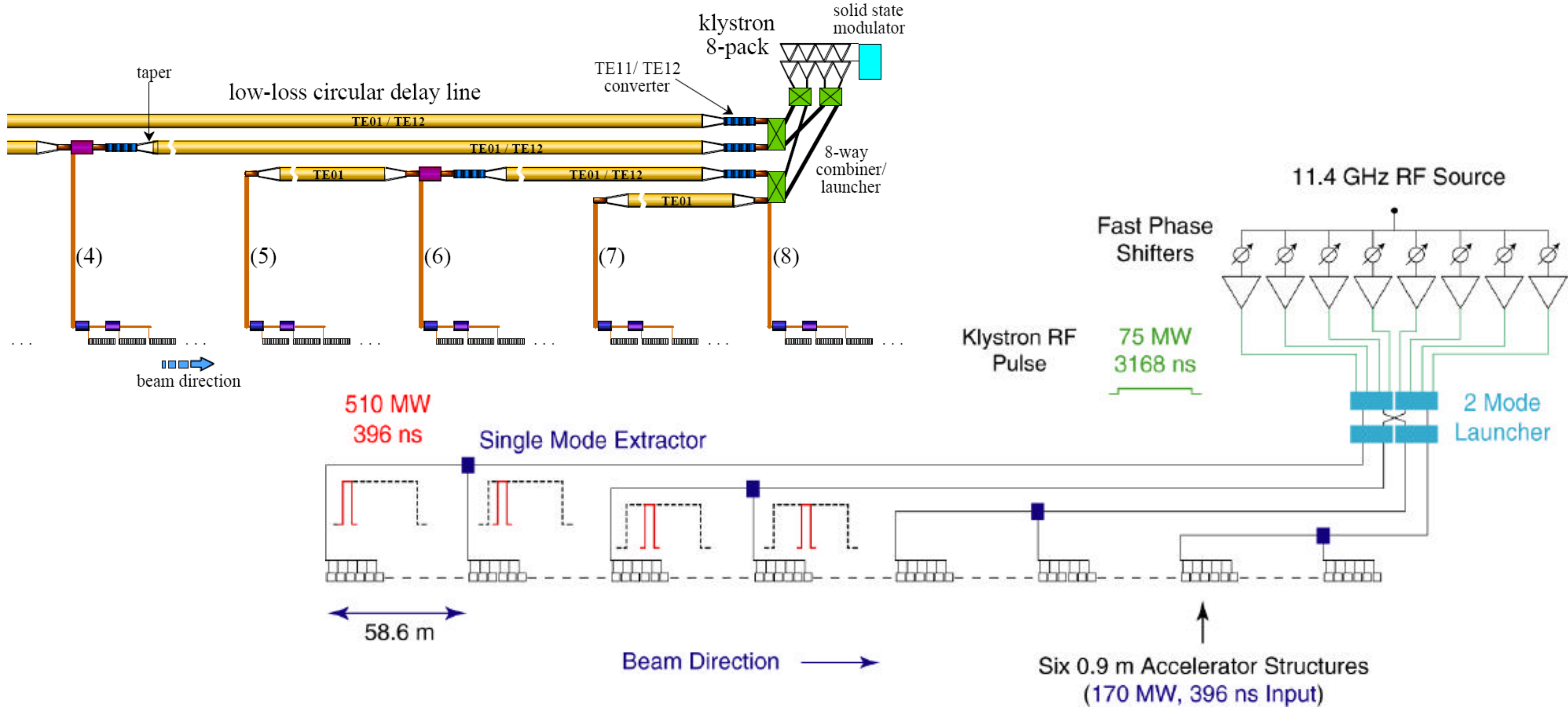


NLCTA pulse compressor: up to 500 MW

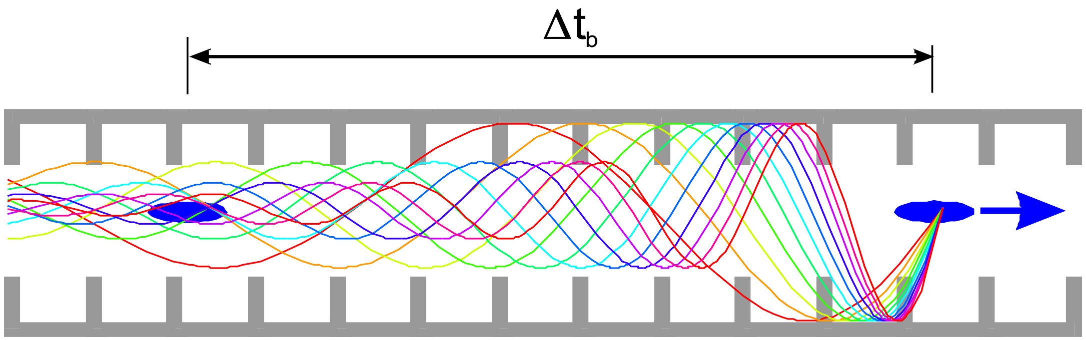


# NLC Linac RF Unit

- Output pulses of 8 klystrons phase modulated and combined
- Depending on phase combination, power takes a different path
- Long klystron pulses are converted into shorter pulses



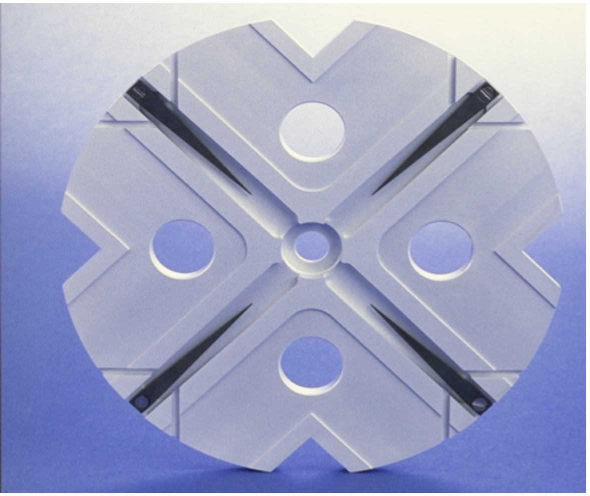
# RF structures: transverse wakefields

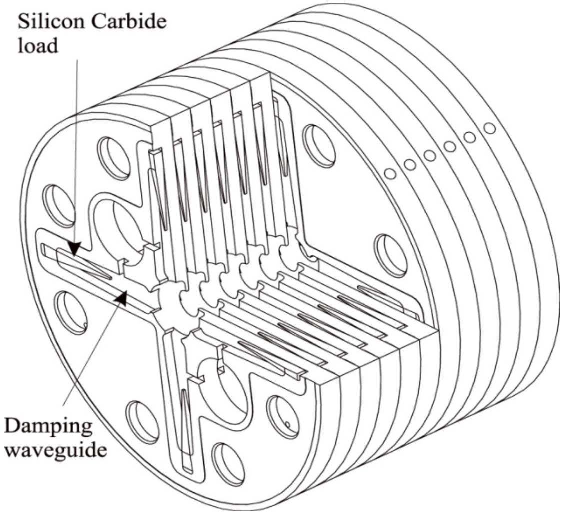


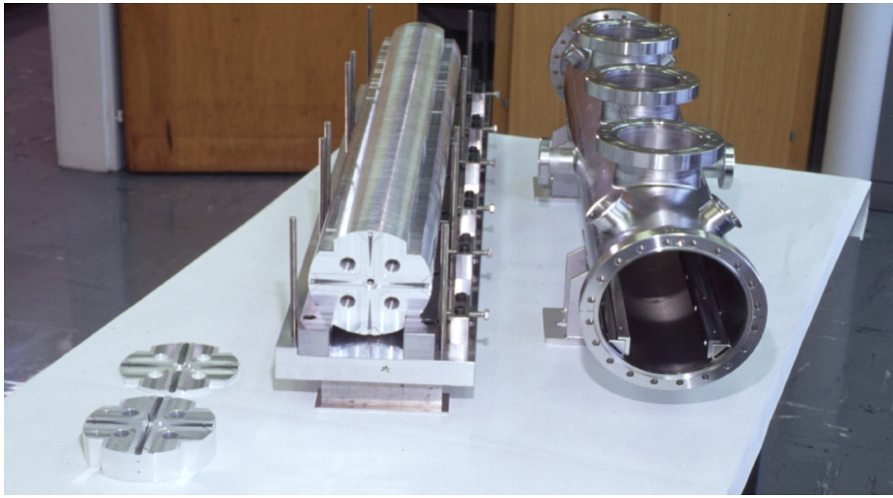
- Bunches induce wakefields in the accelerating cavities
- Later bunches are perturbed by these fields
- Can lead to emittance growth and instabilities!!!

- Effect depends on $a/\lambda$ ($a$ iris aperture) and structure design details
- transverse wakefields roughly scale as $W_\perp \propto f^3$
- less important for lower frequency:
  Super-Conducting (SW) cavities suffer less from wakefields
- Long-range minimised by structure design

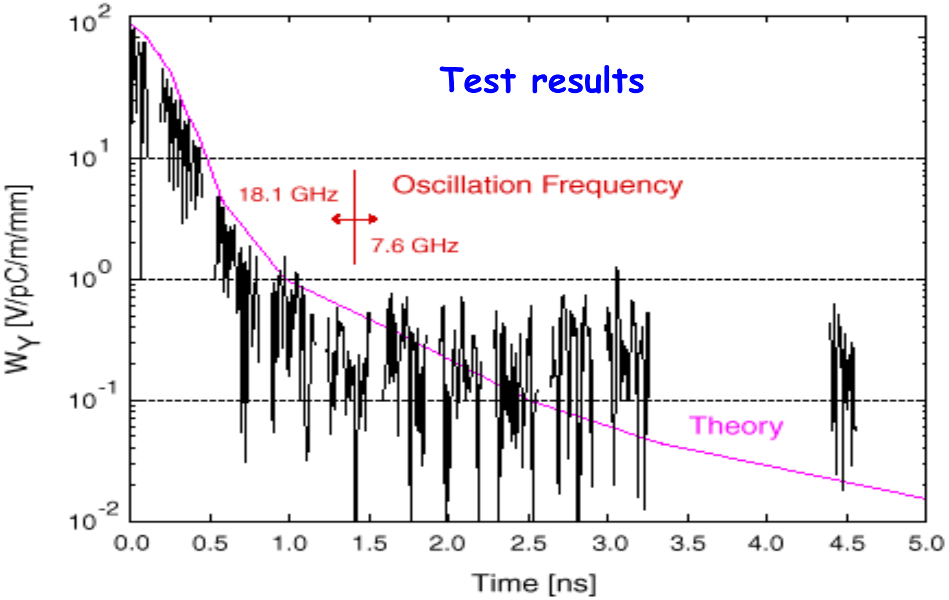
# Accelerating structure developments





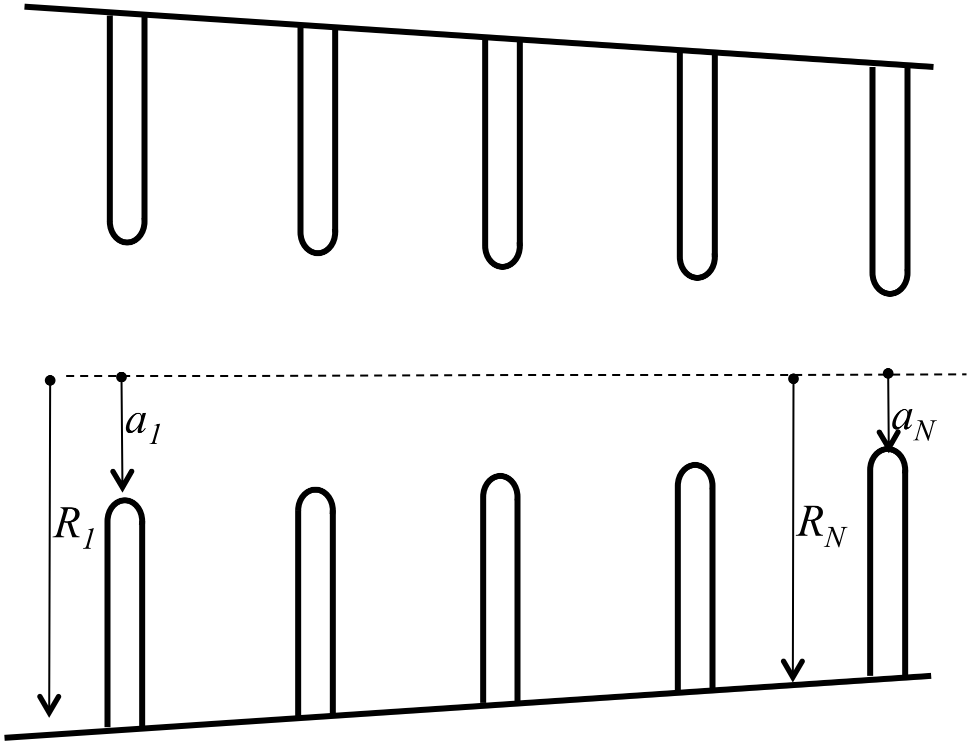


- Structures built from discs
- Each cell damped by 4 radial WGs
- terminated by SiC RF loads
- Higher order modes (HOM) enter WG
- Long-range wakefields efficiently damped

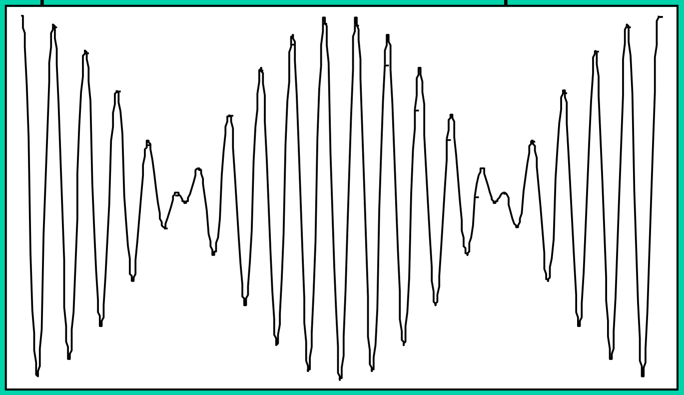


# Dipole mode detuning

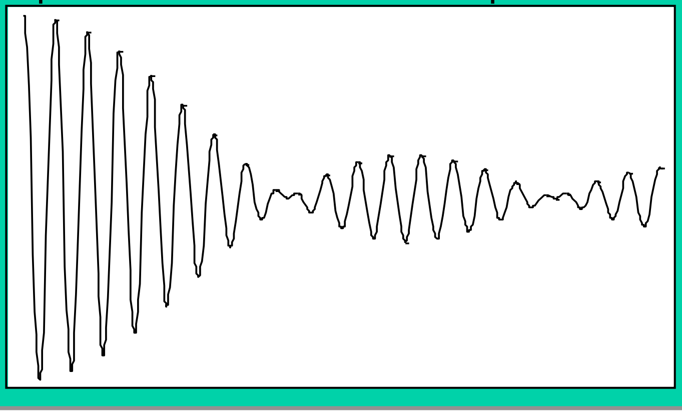
Structure parameters can be varied along structure keeping synchronous frequency for accelerating mode constant but varying synchronous frequencies of dipole modes



Long range wake of a dipole mode spread over **two** different frequencies



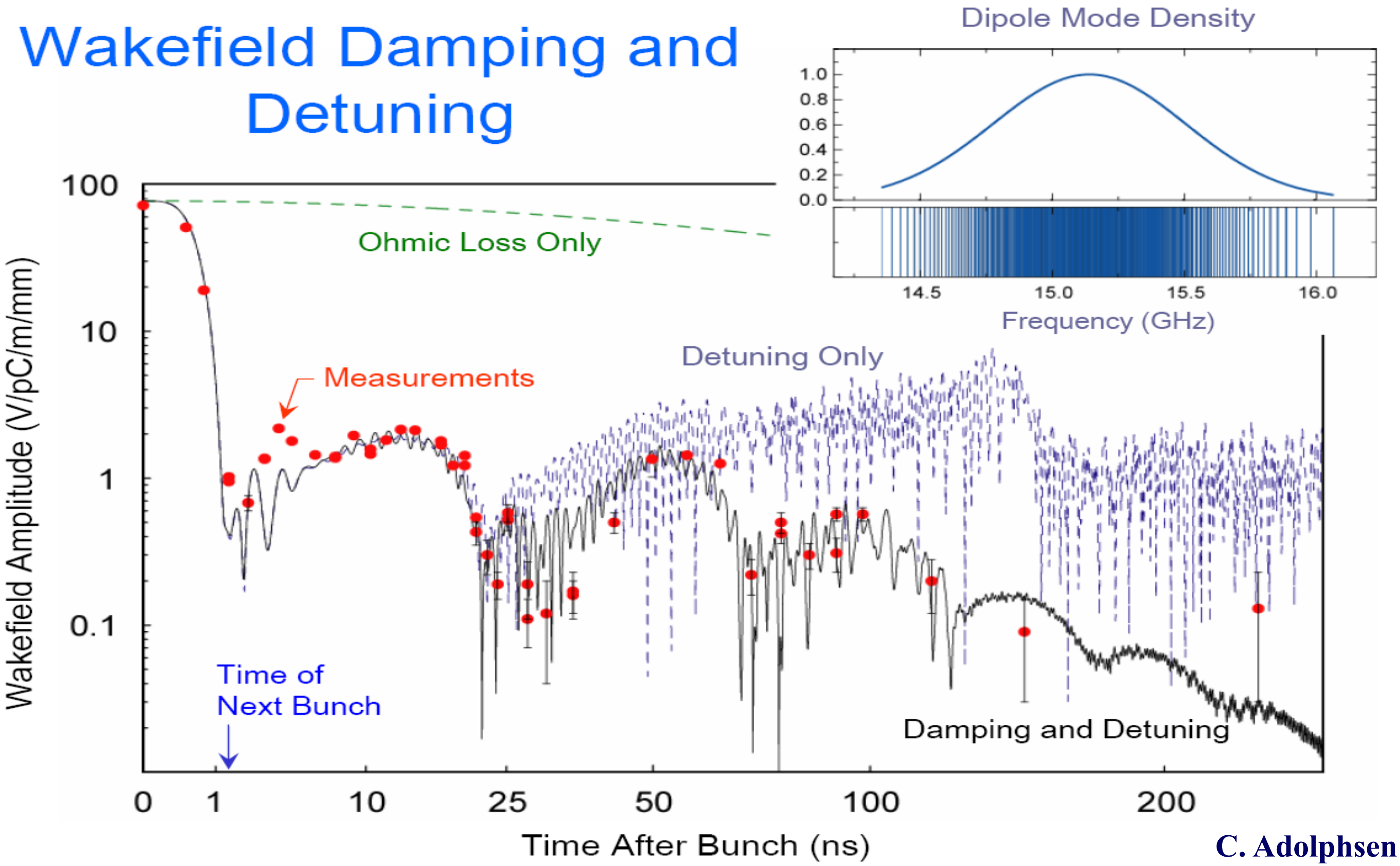
Long range wake of a dipole mode spread over **six** different frequencies



Ideal is a Gaussian weighting of frequency distribution, but finite number of cells leads always to re-coherence after some time !

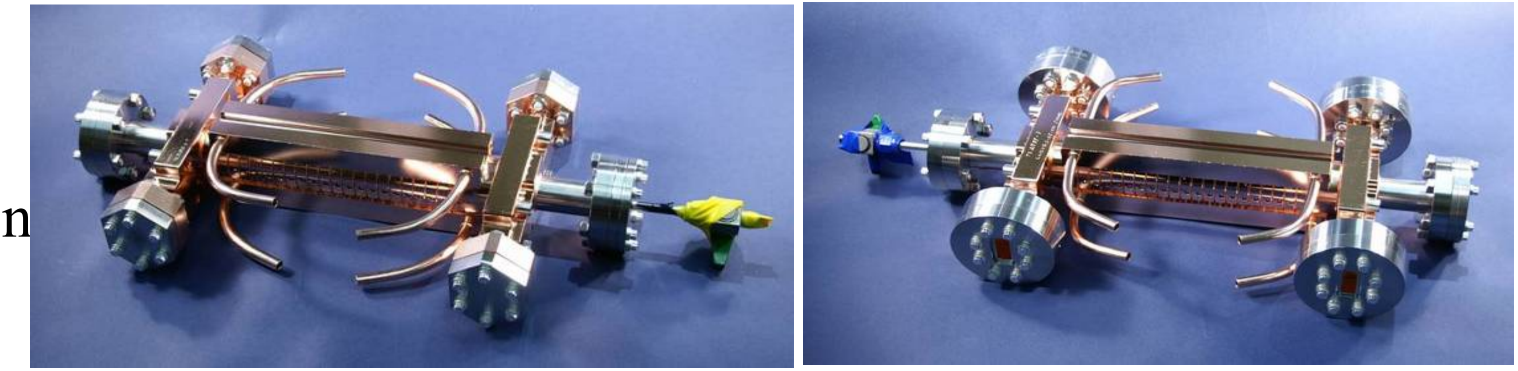
# Damping and detuning

- Slight random detuning between cells makes HOMs decohere quickly
- Will recohere later: need to be damped (HOM dampers)

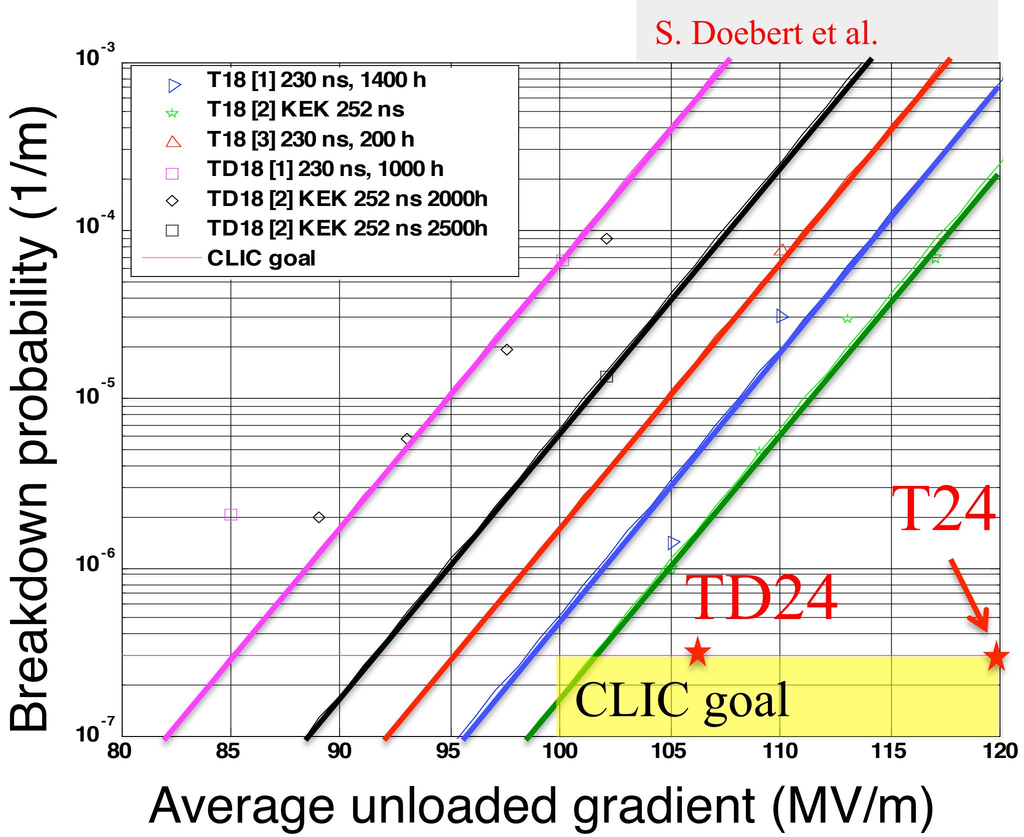


C. Adolphsen / SLAC

# Accelerating Structure Results



- RF breakdowns can occur
  => no acceleration and deflection
- Goal: $3\ 10^{-7}$/m breakdowns
  at 100 MV/m loaded gradient
  at 230 ns pulse length
- latest prototypes (T24 and TD24) tested (SLAC and KEK)
- => TD24 reached 106 MV/m at nominal CLIC breakdown rate
  (without damping material)
- Undamped T24 reaches 120MV/m



# NC RF structures - Summary

- Traveling wave structures
  - Short RF pulses ~few 100ns (still as long as possible - for efficiency)

- Higher frequency preferred (power reasons)
  - Smaller dimensions and higher wakefields
  - Careful cavity design (damping + detuning)
  - Sophisticated mechanical + beam-based alignment

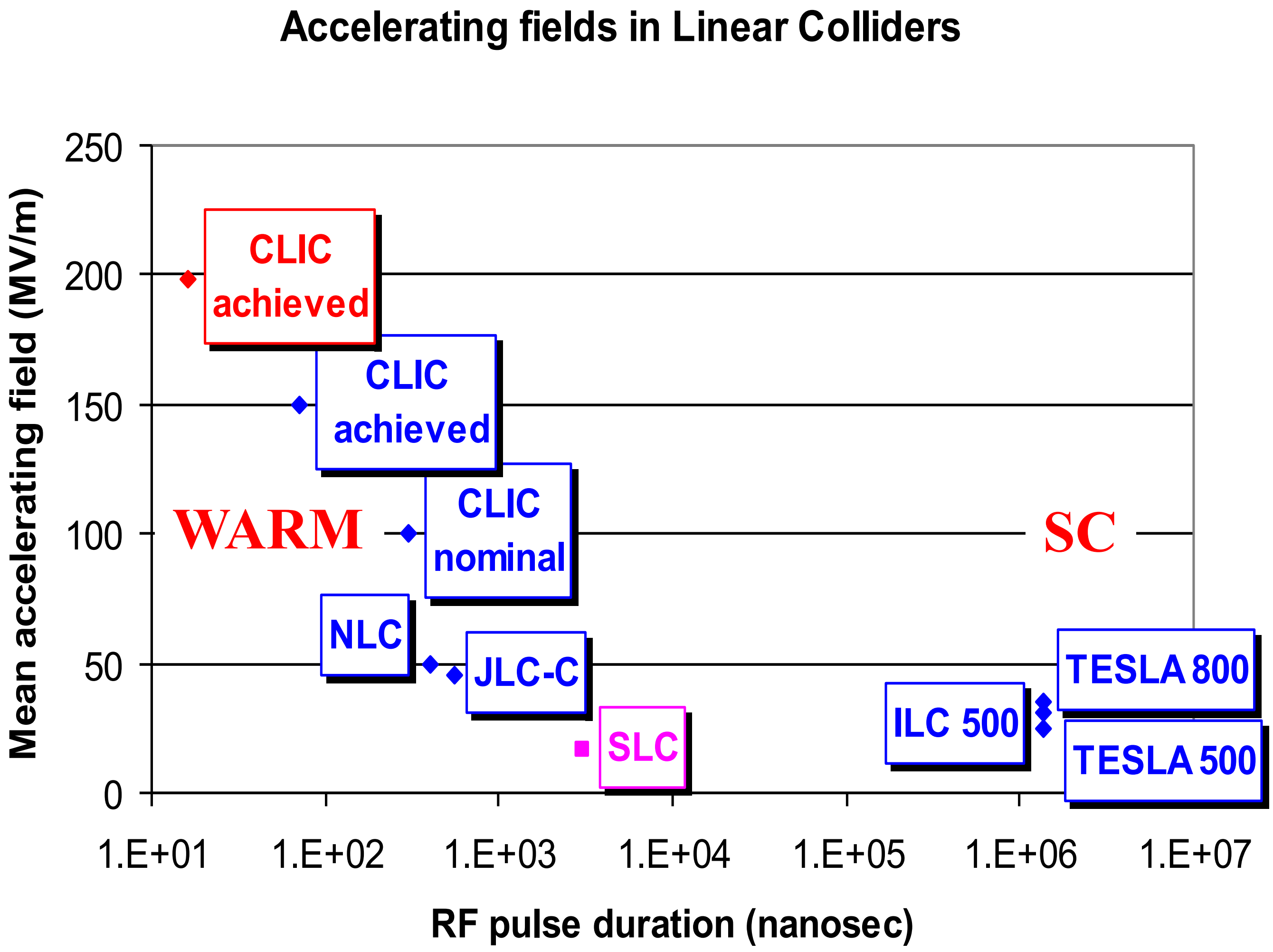
- Higher gradients achievable
  - Limited by
    - Pulsed surface heating
    - RF breakdowns
    - Structure damage

- Klystrons not optimal for high power short pulses
  => RF pulse compression and Drive Beam scheme

# Accelerating gradient

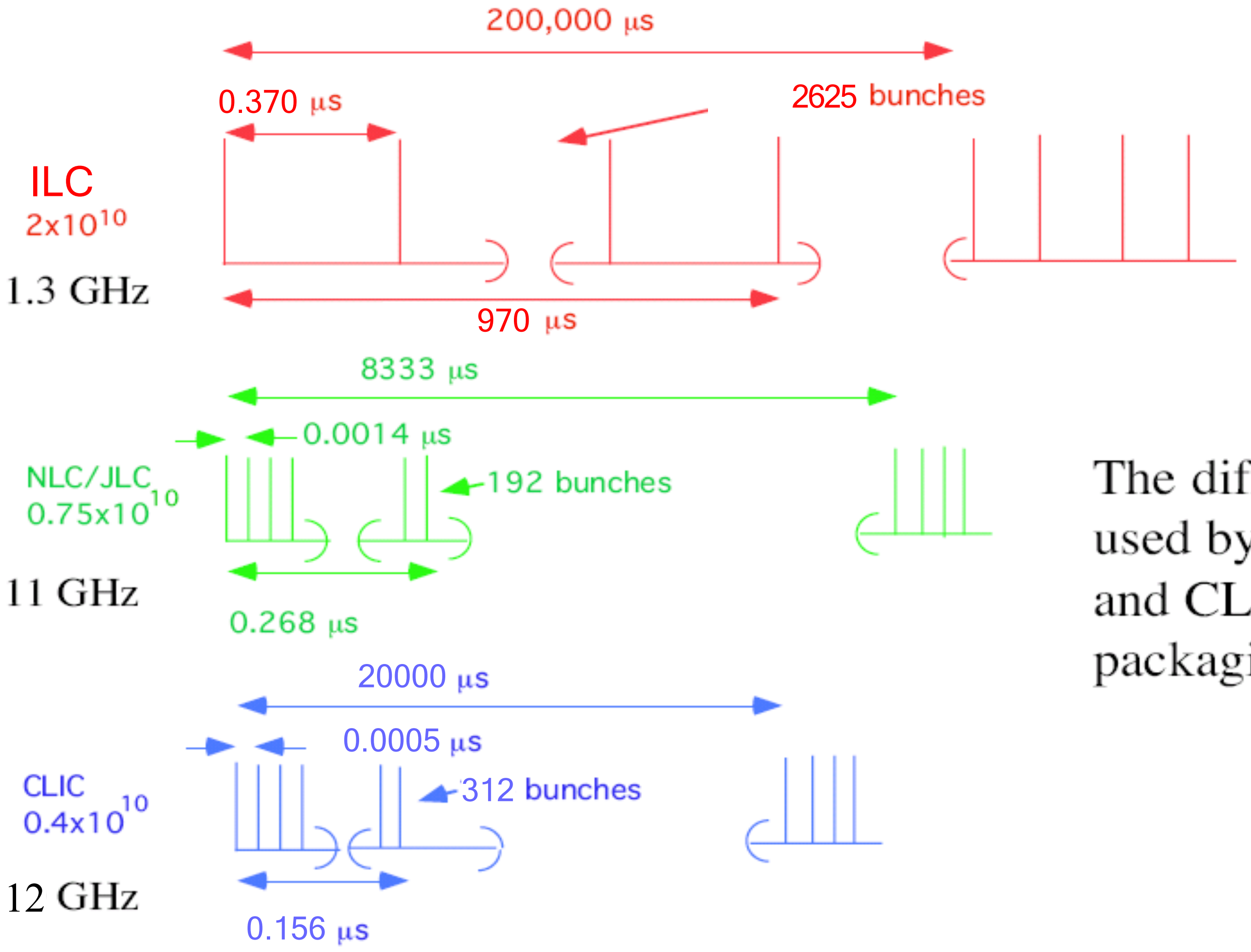
- Superconducting cavities have lower gradient (fundamental limit) with long RF pulse

- Normal conducting cavities have higher gradient with shorter RF pulse length



# Bunch structure

- SC allows long pulse, NC needs short pulse with smaller bunch charge



The different RF technologies used by ILC, NLC/JLC and CLIC require different packaging for the beam power

# Warm vs Cold RF Collider

- Normal Conducting
- High gradient => short linac ☺
- High rep. rate => ground motion suppression ☺
- Small structures => strong wakefields ☹
- Generation of high peak RF power ☹

- Superconducting
- long pulse => low peak power ☺
- large structure dimensions => low WF ☺
- very long pulse train => feedback within train ☺
- SC structures => high efficiency ☺
- Gradient limited <40 MV/m => longer linac ☹ (SC material limit ~ 55 MV/m)
- low rep. rate => bad GM suppression ($\varepsilon_y$ dilution) ☹
- Large number of e+ per pulse ☹
- very large DR ☹

# Comparison ILC - CLIC

| | | ILC | CLIC | remarks |
|---|---|---|---|---|
| No. of particles / bunch | $10^9$ | 20 | 3.7 | CLIC can't go higher because of short range wakefields |
| Bunch separation | ns | 370 | 0.5 | Short spacing essential for CLIC to get comparable RF to beam efficiency, but CLIC requirements on long range wakefield suppression much more stringent<br>forces detectors to integrate over several bunch crossings |
| Bunch train length | ∝s | 970 | 0.156 | One CLIC pulse fits easily in small damping ring, simple single turn extraction from DR.<br>But intra train feedback very difficult. |
| Charge per pulse | nC | 8400 | 185 | Positron source much easier for CLIC |
| Linac repetition rate | Hz | 5 | 50 | Pulse to pulse feedback more efficient for CLIC<br>(less linac movement between pulses) |
| $\gamma\ \epsilon_x$ , $\gamma\ \epsilon_y$ | nm | 10000, 40 | 660, 20 | Because of smaller beam size CLIC has more stringent requirements for DR equilibrium emittance and emittance preservation<br>(partly offset by lower bunch charge and smaller DR) |

# Parameter comparison

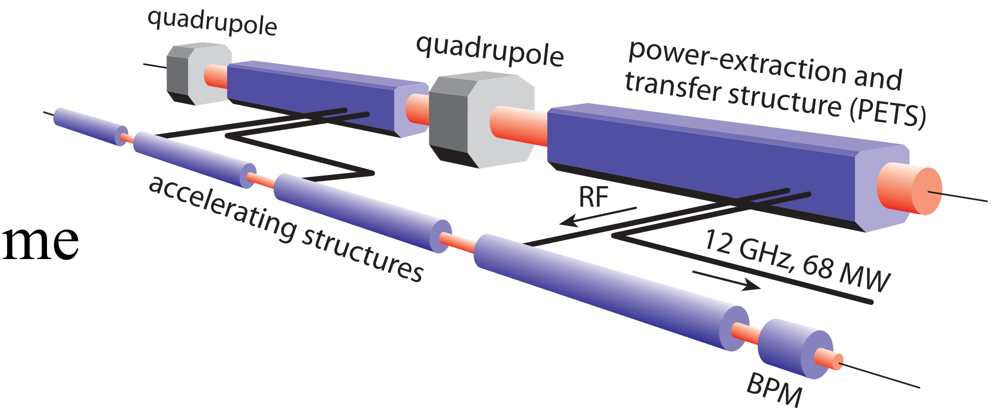
| | **SLC** | **TESLA** | **ILC** | **J/NLC** | **CLIC** |
|---|---|---|---|---|---|
| **Technology** | NC | Supercond. | Supercond. | NC | NC |
| **Gradient [MeV/m]** | 20 | 25 | 31.5 | 50 | 100 |
| **CMS Energy E [GeV]** | 92 | 500-800 | 500-1000 | 500-1000 | 500-3000 |
| **RF frequency $f$ [GHz]** | 2.8 | 1.3 | 1.3 | 11.4 | 12.0 |
| **Luminosity $L$ [$10^{33}$ cm$^{-2}$s$^{-1}$]** | 0.003 | 34 | 20 | 20 | 23 |
| **Beam power $P_{beam}$ [MW]** | 0.035 | 11.3 | 10.8 | 6.9 | 4.9 |
| **Grid power $P_{AC}$ [MW]** | | 140 | 230 | 195 | 270 |
| **Bunch length $\sigma_z^*$ [mm]** | ~1 | 0.3 | 0.3 | 0.11 | 0.07 |
| **Vert. emittance $\gamma\varepsilon_y$ [$10^{-8}$m]** | 300 | 3 | 4 | 4 | 2.5 |
| **Vert. beta function $\beta_y^*$ [mm]** | ~1.5 | 0.4 | 0.4 | 0.11 | 0.1 |
| **Vert. beam size $\sigma_y^*$ [nm]** | 650 | 5 | 5.7 | 3 | 2.3 |

Parameters (except SLC) at 500 GeV

# Part 1 - Summary

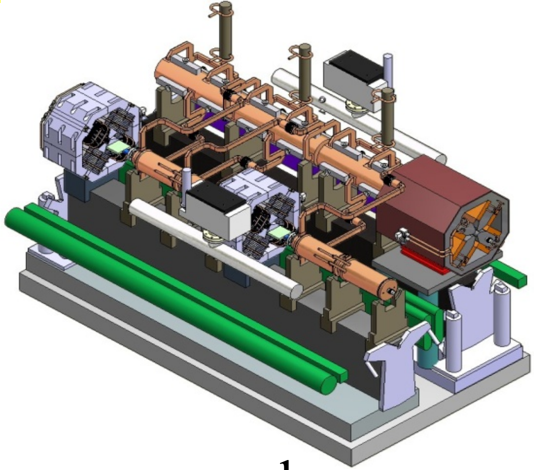
- Normal Conducting traveling wave structures for higher gradients
  - High peak power RF pulses needed
  - Limited by
    - Pulsed surface heating
    - RF breakdowns
    - Structure damage
  - Short RF pulses ~few 100ns (still as long as possible - for efficiency)
  - Klystrons not optimal for high power short pulses
    => RF pulse compression and Drive beam scheme
  - Higher frequency (X-band) preferred (power reasons)
    - Smaller dimensions and higher wakefields
    - Careful cavity design (damping + detuning)
    - Sophisticated mechanical + beam-based alignment
- Important implications on the design parameters of a linear collider

# Part 2 – now!



- CLIC scheme and CTF3:
  - CLIC layout at different energies
  - CLIC two-beam acceleration scheme
  - CLIC drive beam generation
    - Bunch train combination
    - Fully loaded acceleration
  - Demonstrations at the CLIC Test Facility CTF3
  - RF power production
  - CLIC main beam generation and dynamics
  - CLIC damping rings
  - CLIC alignment and stability

# Multi-TeV: the CLIC Study



- Develop technology for linear e+/e- collider with the requirements:
  - $E_{cm}$ should cover range from ILC to LHC maximum reach and beyond => $E_{cm} = 0.5 – 3$ TeV
  - Luminosity > few $10^{34}$ $cm^{-2}$ with acceptable background and energy spread
    - $E_{cm}$ and $L$ to be reviewed once LHC results are available
  - Design compatible with maximum length ~ 50 km
  - Affordable
  - Total power consumption < 500 MW

- Present status: Demonstrated the key feasibility issues and documented in a CDR (possibly TDR by 2016-20)

# Current CLIC&CTF3 Collaboration

## CLIC multi-lateral collaboration - 44 Institutes from 22 countries

ACAS (Australia)
Aarhus University (Denmark)
Ankara University (Turkey)
Argonne National Laboratory (USA)
Athens University (Greece)
BINP (Russia)
CERN
CIEMAT (Spain)
Cockcroft Institute (UK)
ETH Zurich (Switzerland)
FNAL (USA)
Gazi Universities (Turkey)
Helsinki Institute of Physics (Finland)
IAP (Russia)
IAP NASU (Ukraine)
IHEP (China)
INFN / LNF (Italy)
Instituto de Fisica Corpuscular (Spain)
IRFU / Saclay (France)
Jefferson Lab (USA)
John Adams Institute/Oxford (UK)
Joint Institute for Power and Nuclear Research SOSNY /Minsk (Belarus)
John Adams Institute/RHUL (UK)
JINR (Russia)
Karlsruhe University (Germany)
KEK (Japan)
LAL / Orsay (France)
LAPP / ESIA (France)
NIKHEF/Amsterdam (Netherland)
NCP (Pakistan)
North-West. Univ. Illinois (USA)
Patras University (Greece)
Polytech. Univ. of Catalonia (Spain)
PSI (Switzerland)
RAL (UK)
RRCAT / Indore (India)
SLAC (USA)
Sincrotrone Trieste/ELETTRA (Italy)
Thrace University (Greece)
Tsinghua University (China)
University of Oslo (Norway)
University of Vigo (Spain)
Uppsala University (Sweden)
UCSC SCIPP (USA)

# CLIC main parameters

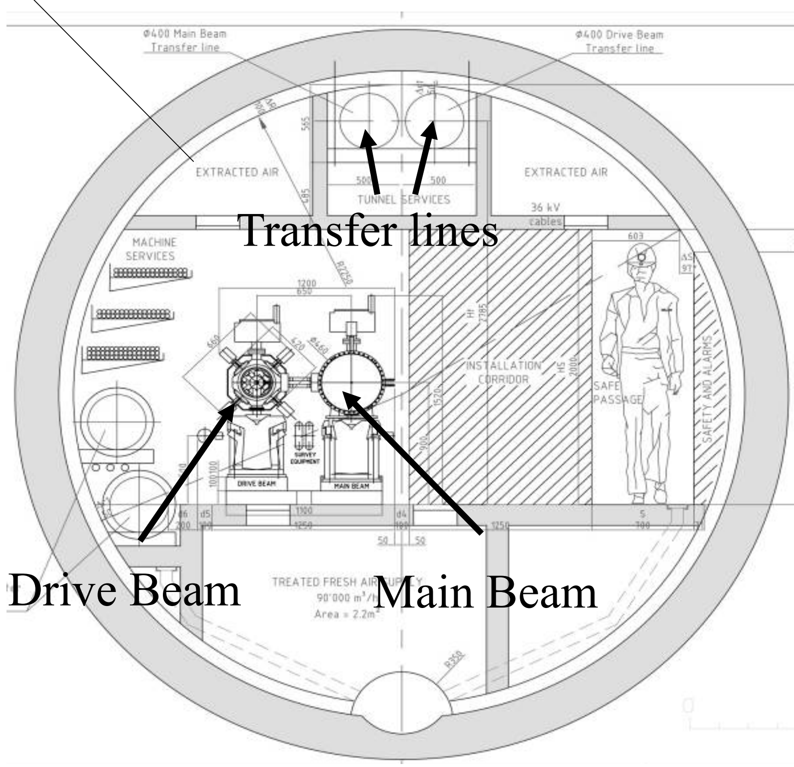
| | |
|---|---|
| Center-of-mass energy | 3 TeV |
| Peak Luminosity | $6 \cdot 10^{34}$ cm$^{-2}$ s$^{-1}$ |
| Peak luminosity (in 1% of energy) | $2 \cdot 10^{34}$ cm$^{-2}$ s$^{-1}$ |
| Repetition rate | 50 Hz |
| Loaded accelerating gradient | 100 MV/m |
| Main linac RF frequency | 12 GHz |
| Overall two-linac length | 42 km |
| Bunch charge | $3.7 \cdot 10^{9}$ |
| Beam pulse length | 156 ns |
| Average current in pulse | 1 A |
| Hor./vert. normalized emittance | 660 / 20 nm rad |
| Hor./vert. IP beam size before pinch | 45 / ~1 nm |
| Total site length | 48.3 km |
| Total power consumption | 589 MW |

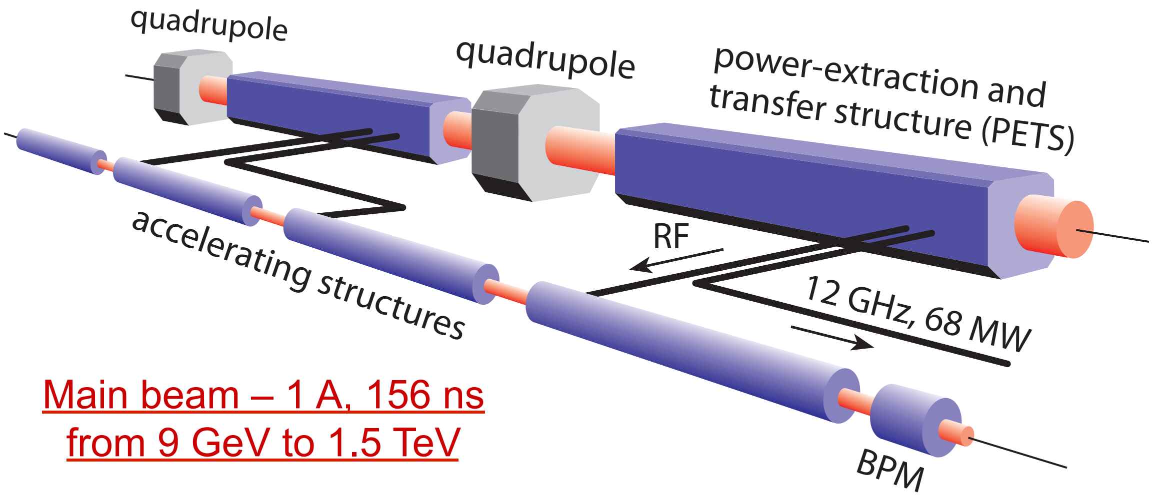
# CLIC – basic features

- High acceleration gradient
  - “Compact” collider – total length < 50 km
  - Normal conducting acceleration structures
  - High acceleration frequency (12 GHz)
- Two-Beam Acceleration Scheme
  - High charge Drive Beam (low energy)
  - Low charge Main Beam (high collision energy)
  - => Simple tunnel, no active elements
  - => Modular, easy energy upgrade in stages

5.6 m diameter

CLIC TUNNEL
CROSS-SECTION



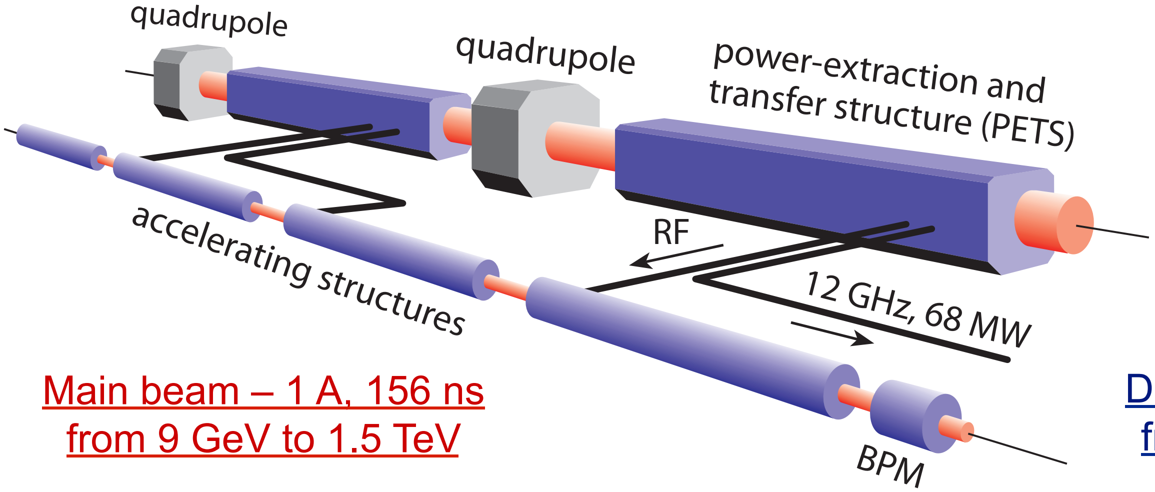


Drive beam - 101 A, 240 ns
from 2.4 GeV to 240 MeV

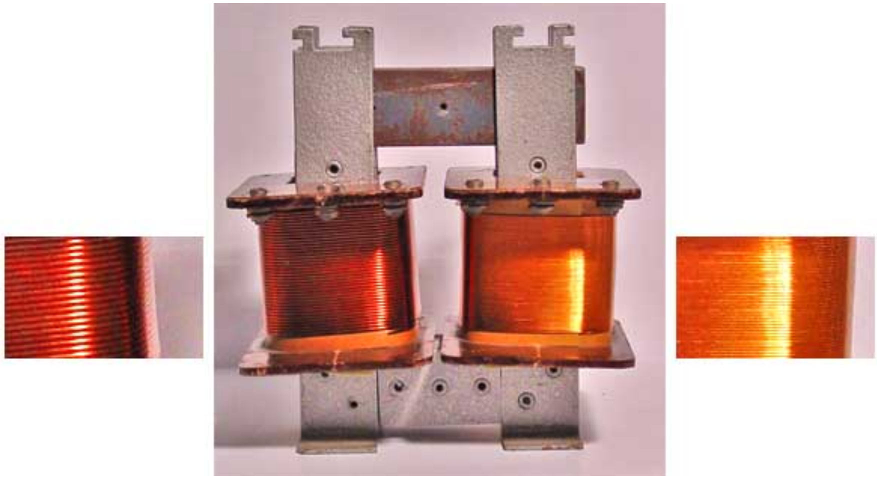
Main beam – 1 A, 156 ns
from 9 GeV to 1.5 TeV

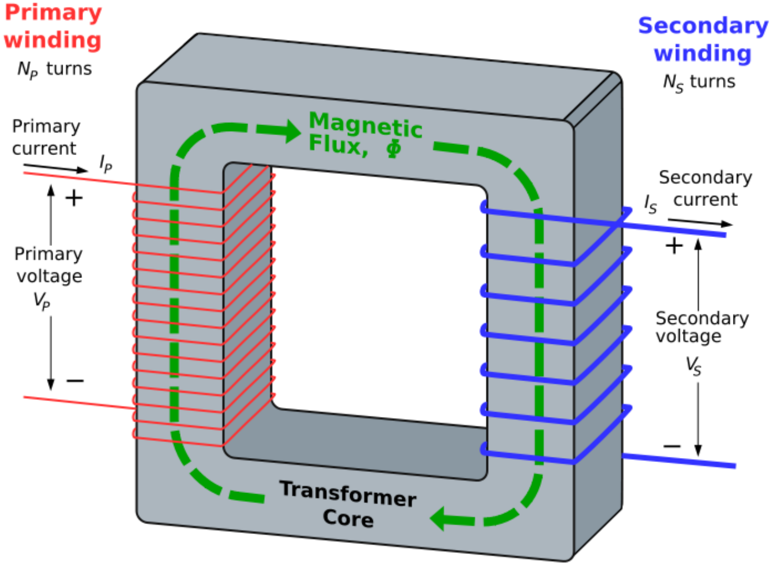
# CLIC - a big transformer

- Like a HV transformer:
  input: low voltage – high current
  output: high voltage – low current
- Here:
  input (‘Drive Beam’):
  low energy (GeV) – high current
  output (‘Main Beam’):
  high energy (TeV) – low current
- Transformer ‘core’:
  waveguides with RF waves



Main beam – 1 A, 156 ns
from 9 GeV to 1.5 TeV



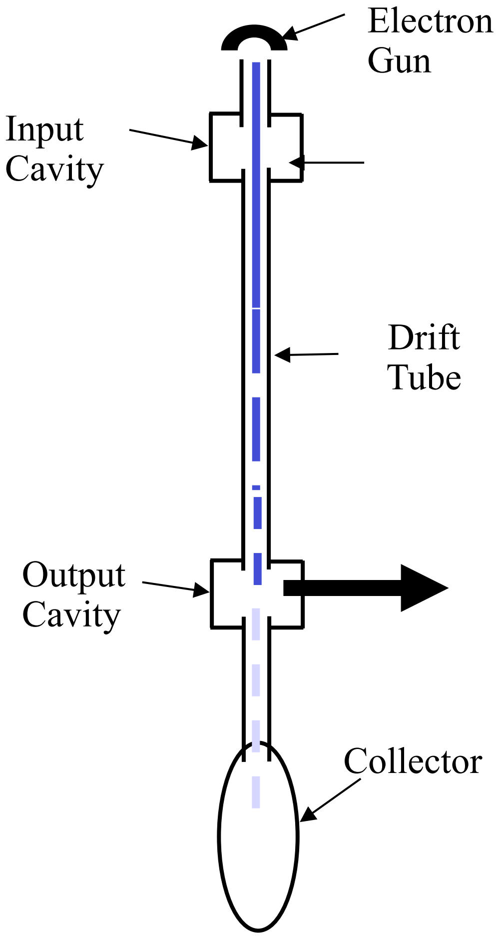


Drive beam - 101 A, 240 ns
from 2.4 GeV to 240 MeV

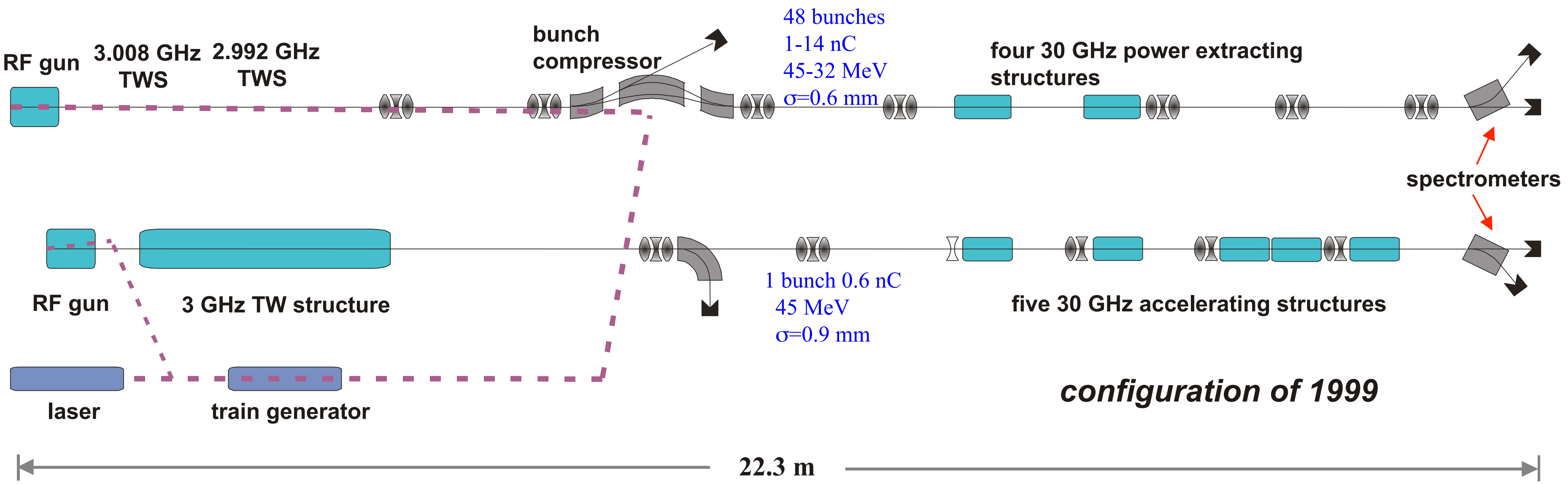
# Why not using klystrons?

- Reminder: Klystron
  - narrow-band vacuum-tube amplifier at microwave frequencies (an electron-beam device).
  - low-power signal at the design frequency excites input cavity
  - Velocity modulation becomes time modulation in the drift tube
  - Bunched beam excites output cavity
- We need: - high power for high fields
  - short pulses (remember: break-downs, surface heating)
- Many klystrons
  - ILC: 560 10 MW, 1.6 ms
  - NLC: 4000 75 MW, 1.6 μs
  - CLIC: would need many more ☹ $£€¥ ☹
- Can reduce number by RF pulse compression schemes

- **Drive beam like beam of gigantic klystron**



# CLIC Test Facility CTF II

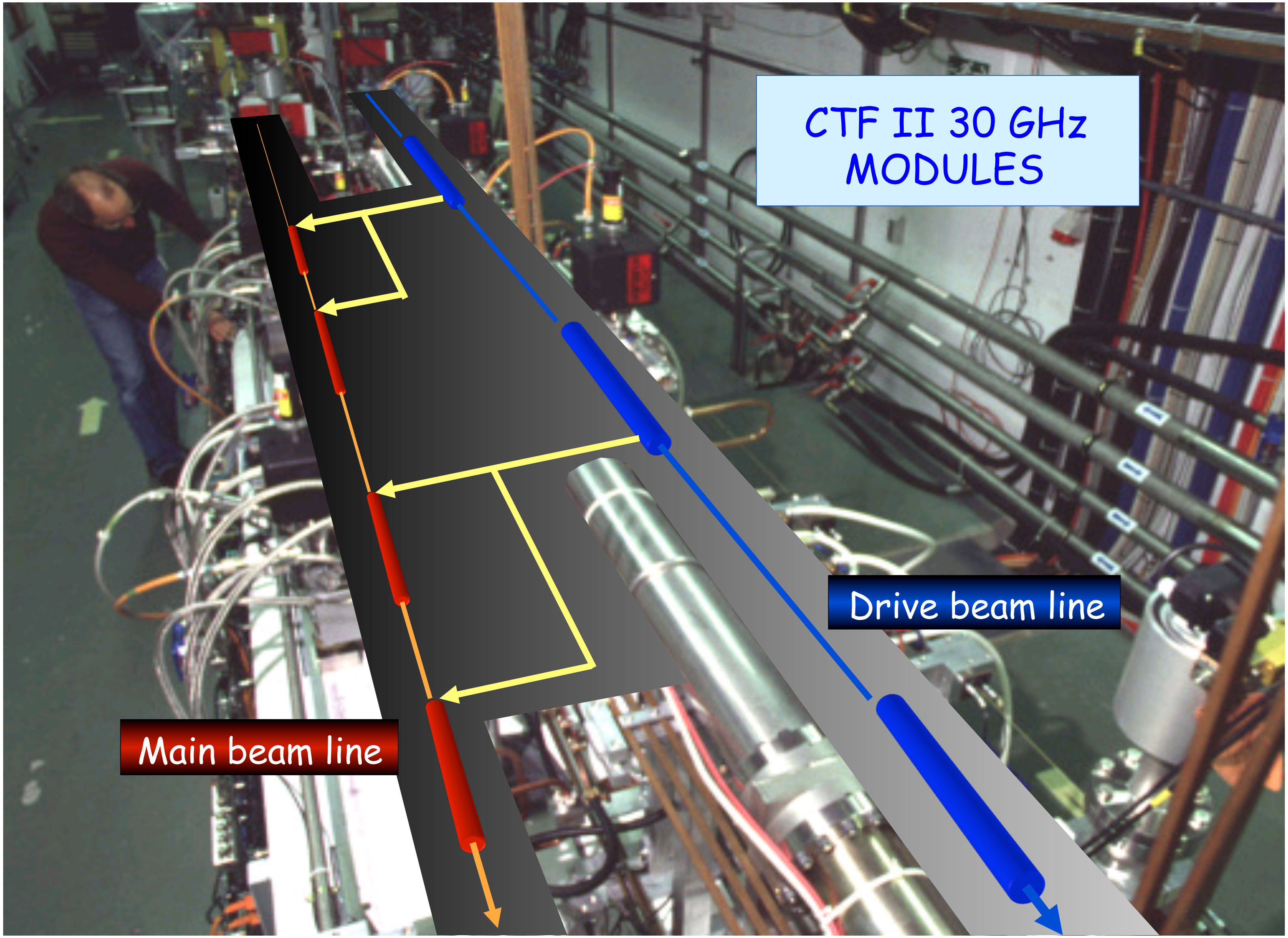


*configuration of 1999*

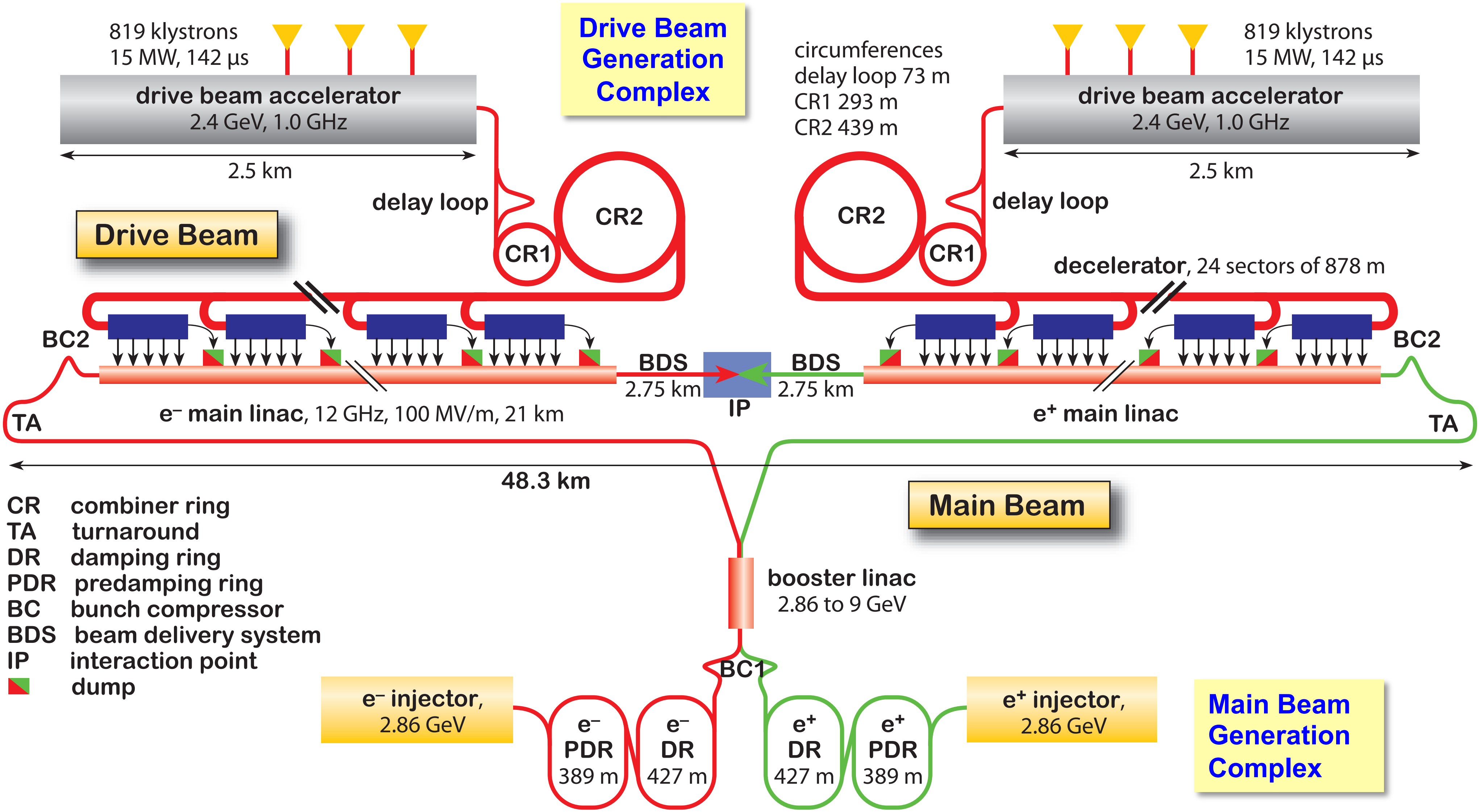
## Dismantled in 2002, after having achieved its goals :

- Demonstrate feasibility of a two-beam acceleration scheme
- Provide high power 30 GHz RF source for high gradient testing (280 MW, 16 ns pulses)
- Study generation of short, intense e-bunches using photocathode RF guns
- Demonstrate operability of μ-precision active-alignment system in accelerator environment
- Provide a test bed to develop and test accelerator diagnostic equipment

# CLIC Test Facility CTF II



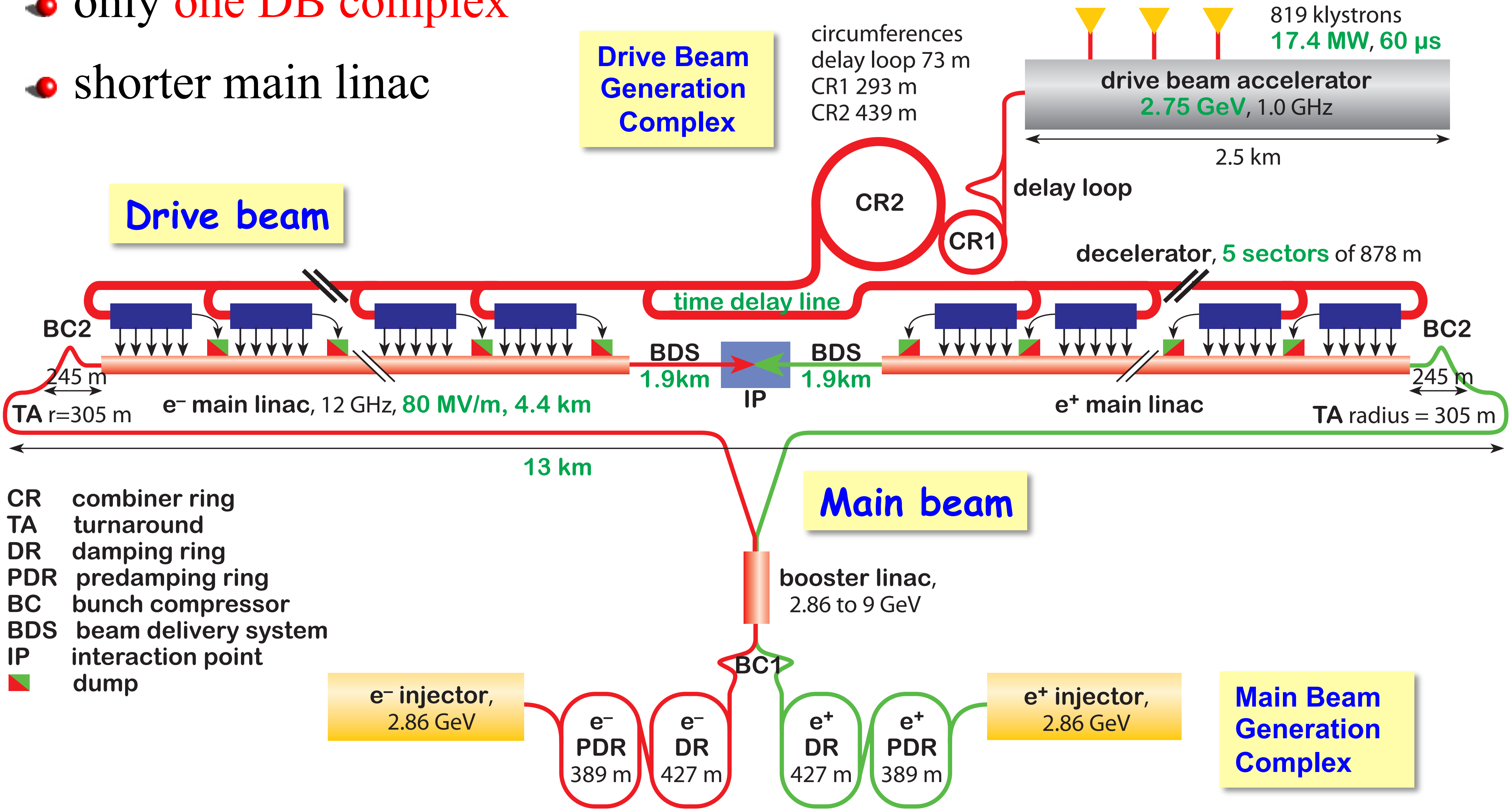
# CLIC – overall layout 3 TeV



| | |
|---|---|
| CR | combiner ring |
| TA | turnaround |
| DR | damping ring |
| PDR | predamping ring |
| BC | bunch compressor |
| BDS | beam delivery system |
| IP | interaction point |
| ◩ | dump |

# CLIC – layout for 500 GeV

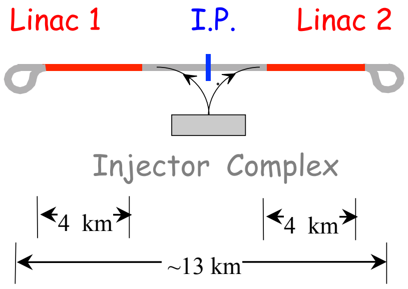
- only one DB complex
- shorter main linac



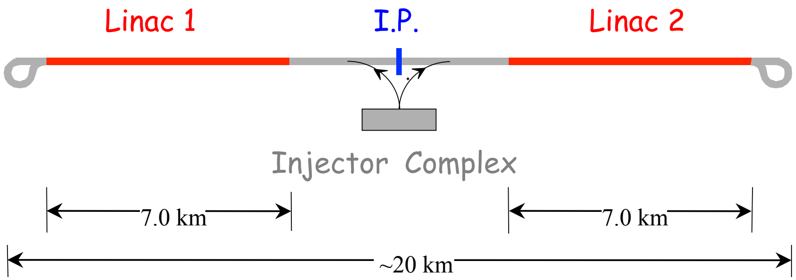
| | |
|---|---|
| CR | combiner ring |
| TA | turnaround |
| DR | damping ring |
| PDR | predamping ring |
| BC | bunch compressor |
| BDS | beam delivery system |
| IP | interaction point |
| ◩ | dump |

# CLIC Layout at various energies

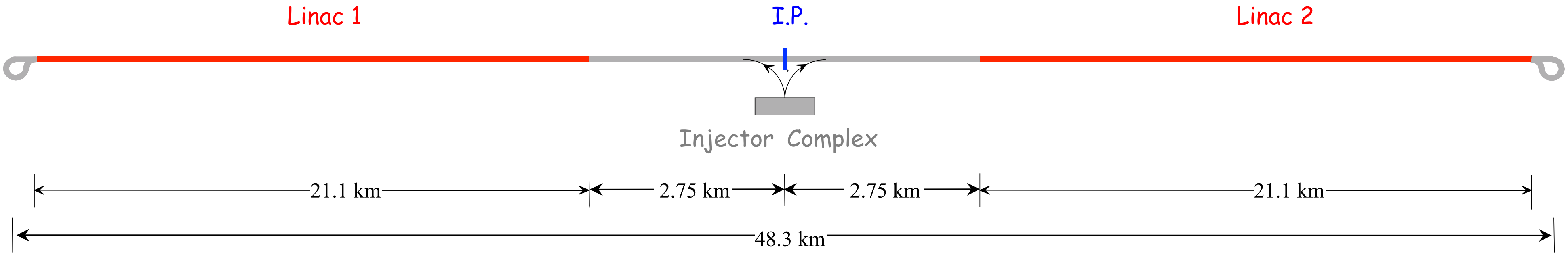
**0.5 TeV Stage**



**1 TeV Stage**



**3 TeV Stage**



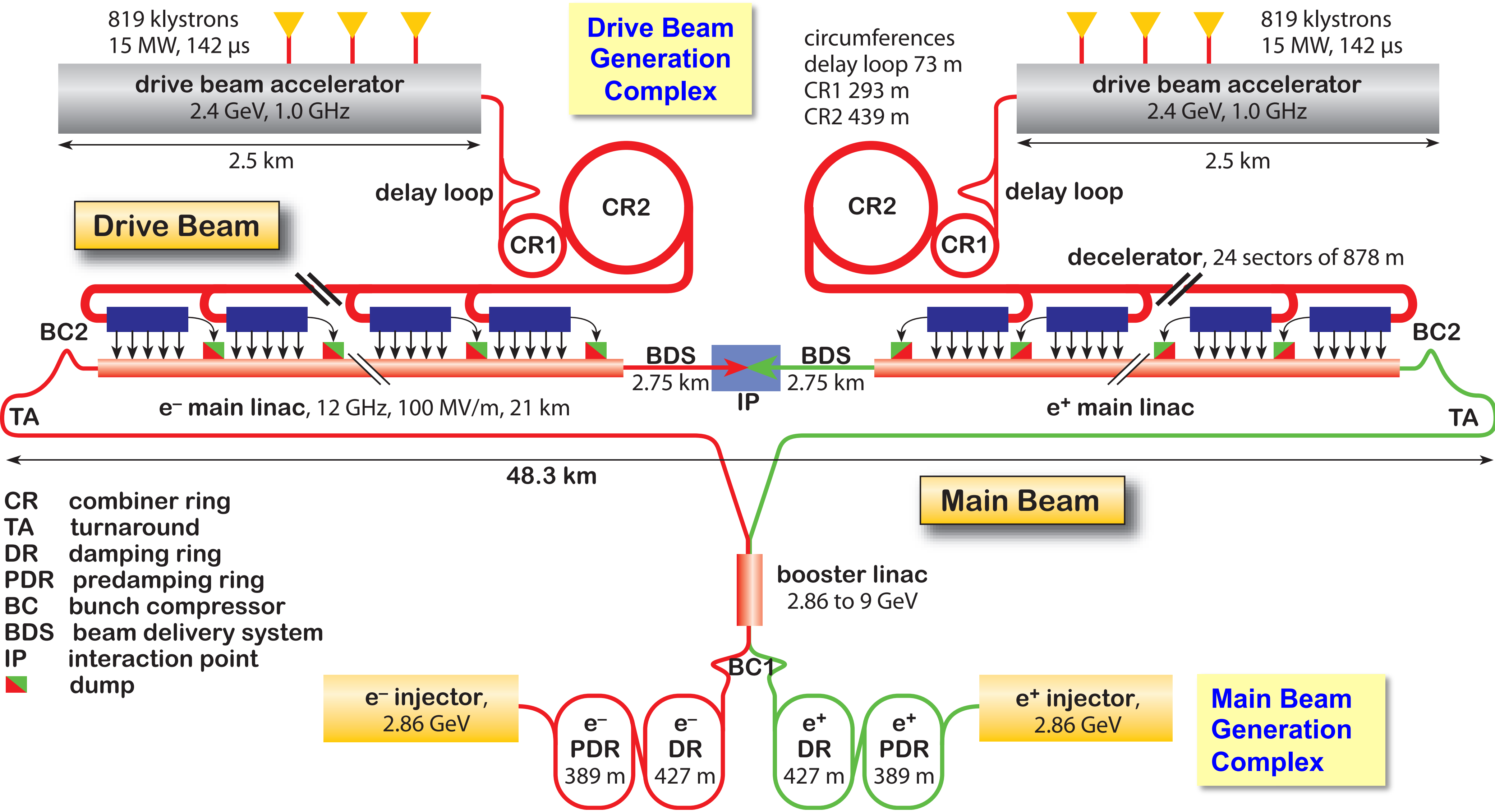
# CLIC main parameters

| Center-of-mass energy | CLIC 500 GeV | | CLIC 3 TeV | |
|---|---|---|---|---|
| Beam parameters | Conservative | Nominal | Conservative | Nominal |
| Accelerating structure | 502 | | G | |
| Total (Peak 1%) luminosity | 0.9 (0.6)·$10^{34}$ | 2.3 (1.4)·$10^{34}$ | 2.7 (1.3)·$10^{34}$ | 5.9 (2.0)·$10^{34}$ |
| Repetition rate (Hz) | 50 | | | |
| Loaded accel. gradient MV/m | 80 | | 100 | |
| Main linac RF frequency GHz | 12 | | | |
| Bunch charge$10^9$ | 6.8 | | 3.72 | |
| Bunch separation (ns) | 0.5 | | | |
| Beam pulse duration (ns) | 177 | | 156 | |
| Beam power/beam MWatts | 4.9 | | 14 | |
| Hor./vert. norm. emitt ($10^{-6}$/$10^{-9}$) | 3/40 | 2.4/25 | 2.4/20 | 0.66/20 |
| Hor/Vert FF focusing (mm) | 10/0.4 | 8 / 0.1 | | 4 / 0.1 |
| Hor./vert. IP beam size (nm) | 248 / 5.7 | 202 / 2.3 | 83 / 1.1 | 40 / 1 |
| Hadronic events/crossing at IP | 0.07 | 0.19 | 0.75 | 2.7 |
| Coherent pairs at IP | <<1 | <<1 | 500 | 3800 |
| BDS length (km) | 1.87 | | 2.75 | |
| Total site length km | 13.0 | | 48.3 | |
| Wall plug to beam transfert eff | 7.5% | | 6.8% | |
| Total power consumption MW | 129.4 | | 415 | |

# LC comparison at 500 GeV

| Center-of-mass energy | NLC 500 GeV | ILC 500 GeV | CLIC 500 GeV Conservative | CLIC 500 GeV Nominal |
|---|---|---|---|---|
| Total (Peak 1%) luminosity | $2.0\ (1.3)\cdot10^{34}$ | $2.0\ (1.5)\cdot10^{34}$ | $0.9\ (0.6)\cdot10^{34}$ | $2.3\ (1.4)\cdot10^{34}$ |
| Repetition rate (Hz) | 120 | 5 | 50 | |
| Loaded accel. gradient MV/m | 50 | 33.5 | 80 | |
| Main linac RF frequency GHz | 11.4 | 1.3 (SC) | 12 | |
| Bunch charge$10^9$ | 7.5 | 20 | 6.8 | |
| Bunch separation ns | 1.4 | 176 | 0.5 | |
| Beam pulse duration (ns) | 400 | 1000 | 177 | |
| Beam power/linac (MWatts) | 6.9 | 10.2 | 4.9 | |
| Hor./vert. norm. emitt ($10^{-6}/10^{-9}$) | 3.6/40 | 10/40 | 3 / 40 | 2.4 / 25 |
| Hor/Vert FF focusing (mm) | 8/0.11 | 20/0.4 | 10/0.4 | 8/0.1 |
| Hor./vert. IP beam size (nm) | 243/3 | 640/5.7 | 248 / 5.7 | 202/ 2.3 |
| Soft Hadronic event at IP | 0.10 | 0.12 | 0.07 | 0.19 |
| Coherent pairs/crossing at IP | <<1 | <<1 | <<1 | <<1 |
| BDS length (km) | 3.5 (1 TeV) | 2.23 (1 TeV) | 1.87 | |
| Total site length (km) | 18 | 31 | 13.0 | |
| Wall plug to beam transfer eff. | 7.1% | 9.4% | 7.5% | |
| Total power consumption MW | 195 | 216 | 129.4 | |

# CLIC – overall layout 3 TeV



| | |
|---|---|
| CR | combiner ring |
| TA | turnaround |
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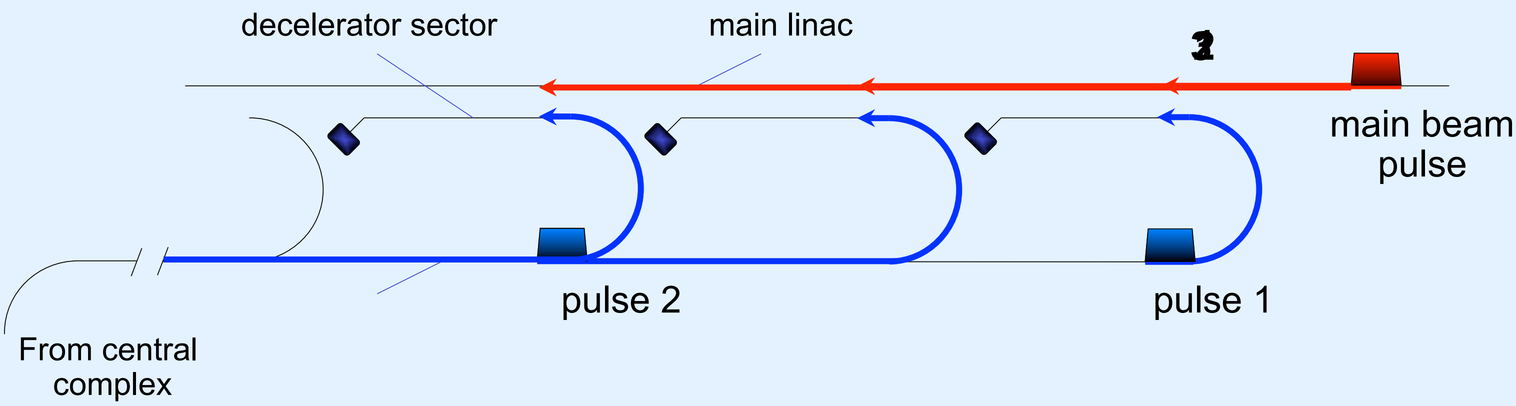
| PDR | predamping ring |
| BC | bunch compressor |
| BDS | beam delivery system |
| IP | interaction point |
| 🟥 | dump |

# Two-beam acceleration

*Counter propagation from central complex*

Instead of using a single drive beam pulse for the whole main linac, several ($N_S$ = 24) short drive beam pulses are used

Each one feed a ~880 m long sector of two-beam acceleration (TBA)



Counter flow distribution allows to power different sectors of the main linac with different time bins of a single long electron drive beam pulse

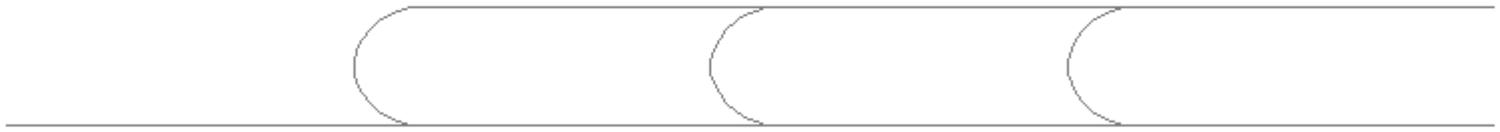
The distance between the pulses is 2 $L_s$ = 2 $L_{main}/N_S$ ($L_{main}$= single side linac length)

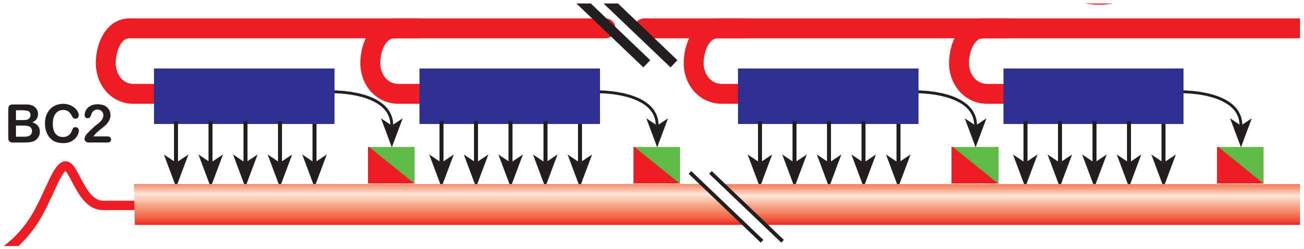
The initial drive beam pulse length $t_{DB}$ is given by twice the time of flight through one single linac

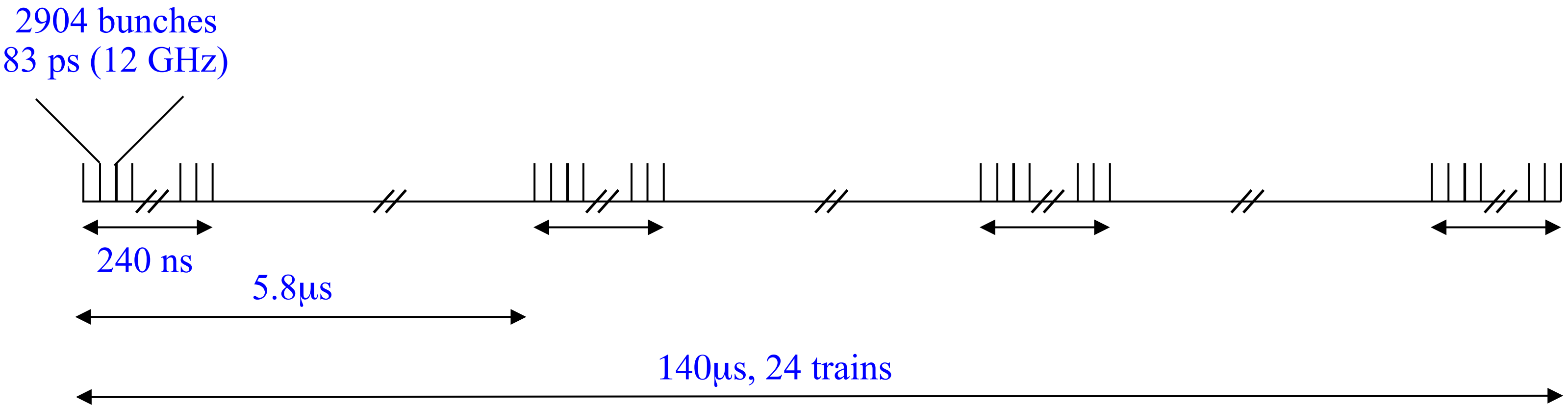
so $t_{DB} = 2 L_{main} / c$, 140 μs for the 3 TeV CLIC

R.Corsini

# Drive beam time structure







2904 bunches
83 ps (12 GHz)

240 ns

5.8μs

140μs, 24 trains

**Bunch charge: 8.4 nC, Current in train: 100 A**

# CLIC scheme

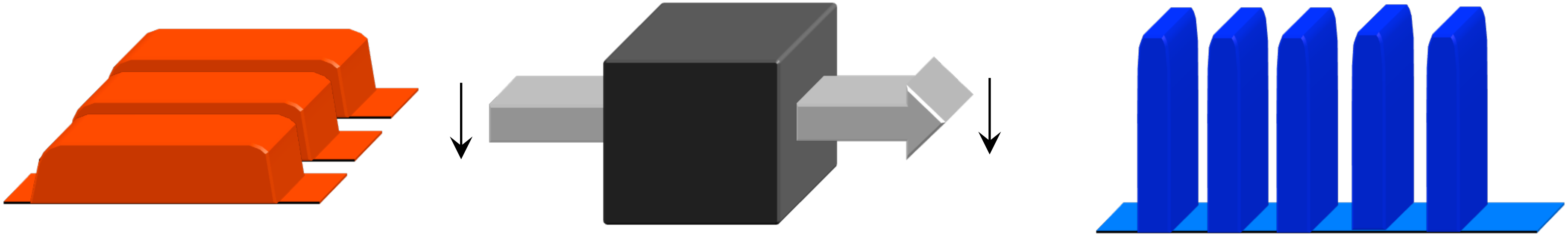
- Very high gradients possible with NC accelerating structures at high RF frequencies (30 GHz → 12 GHz)
- Extract required high RF power from an intense e- “drive beam”
- Generate efficiently long beam pulse and compress it (in power + frequency)

‘few’ Klystrons
Low frequency
High efficiency

Power stored in
electron beam

Power extracted from beam
in resonant structures

Accelerating Structures
High Frequency – High field



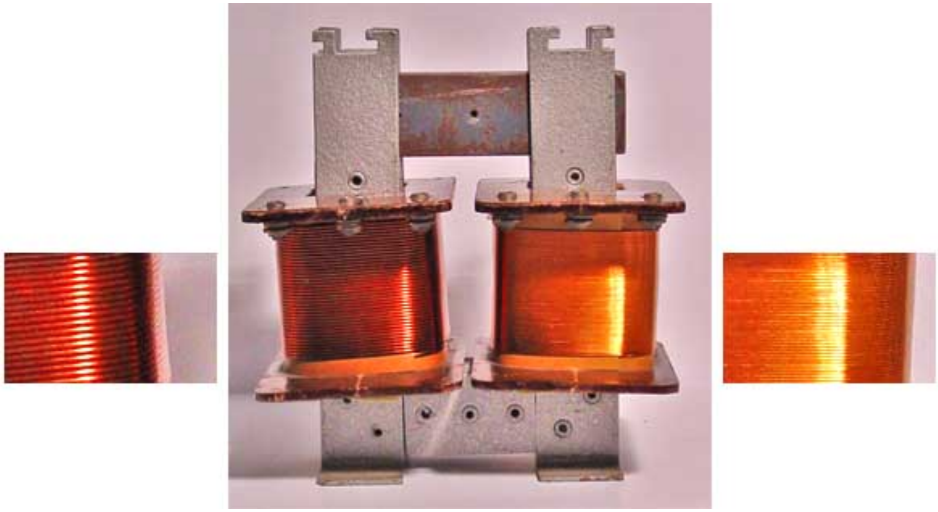
Long RF Pulses
$P_0$ , $\nu_0$ , $\tau_0$

Electron beam manipulation
Power compression
Frequency multiplication

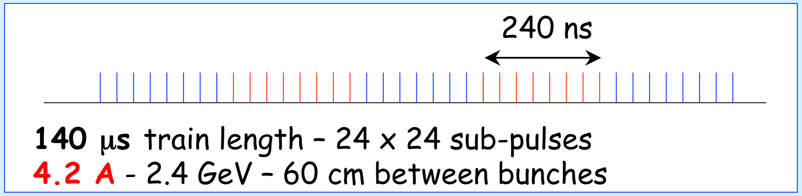
Short RF Pulses
$P_A = P_0 \times N_1$
$\tau_A = \tau_0 / N_2$
$\nu_A = \nu_0 \times N_3$

# Again a 'transformer'!

- But this one in time domain
- Input: Long beam pulse train
  low current
  low bunch frequency
- Output: Short beam pulse trains
  high current
  high bunch frequency
- => high beam power

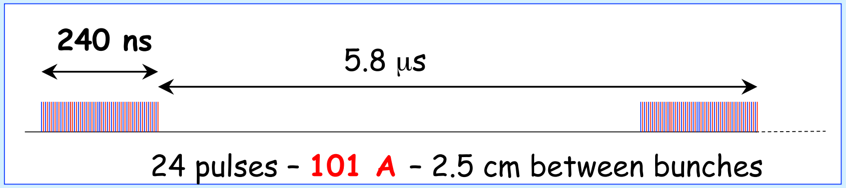


Drive beam time structure - initial



140 µs train length - 24 x 24 sub-pulses
4.2 A - 2.4 GeV - 60 cm between bunches

Drive beam time structure - final

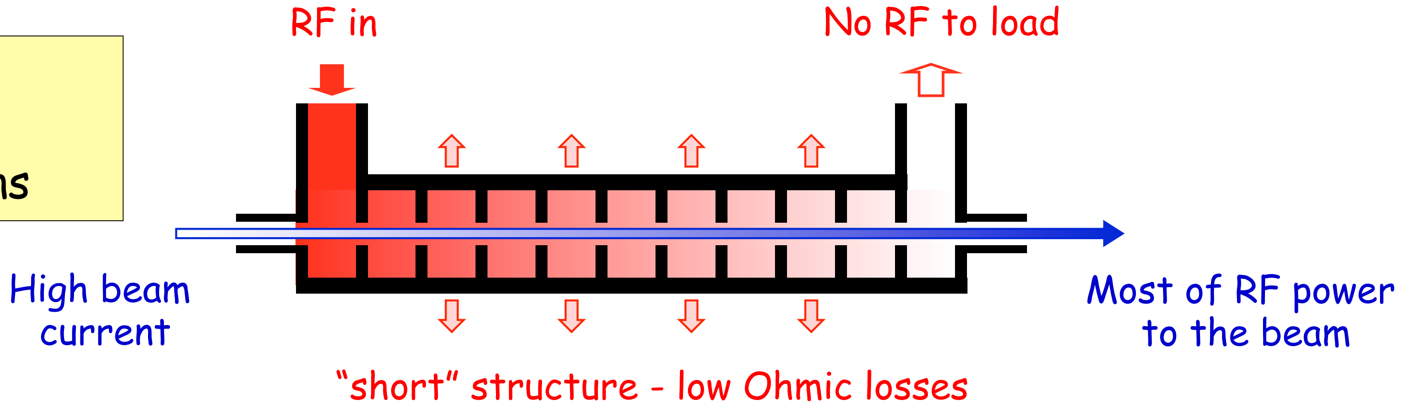


24 pulses - 101 A - 2.5 cm between bunches

# Drive beam generation basics

- Efficient acceleration

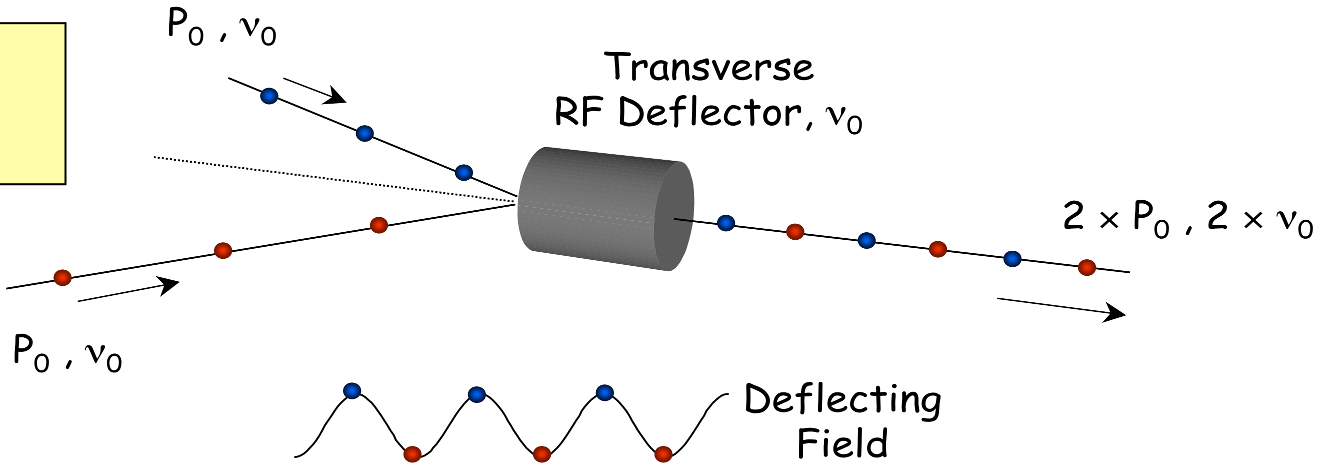
Full beam-loading
acceleration in
traveling wave sections



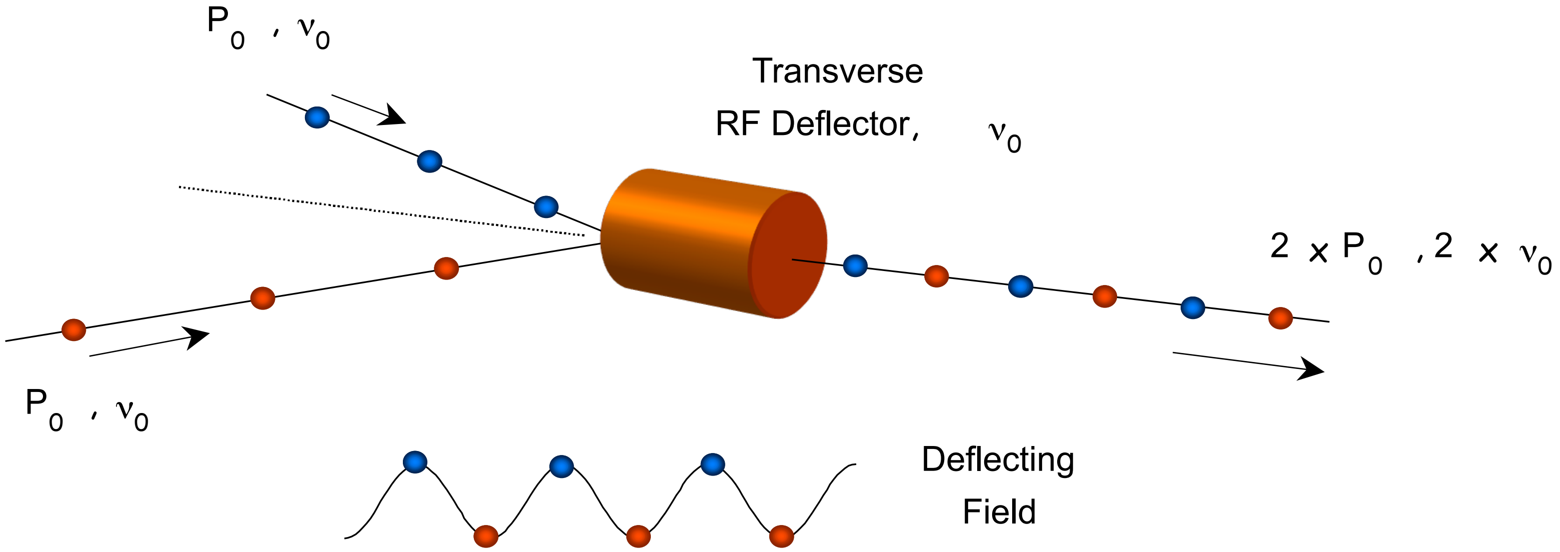
- Frequency multiplication

Beam combination/separation

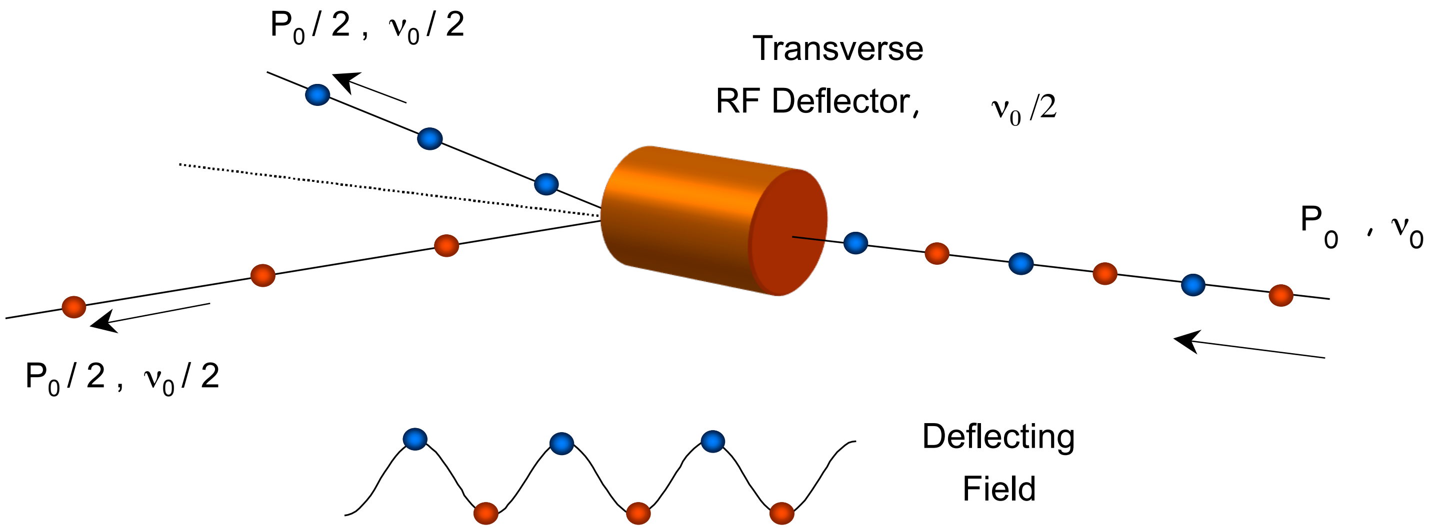
by transverse RF deflectors



# Beam combination by RF deflectors

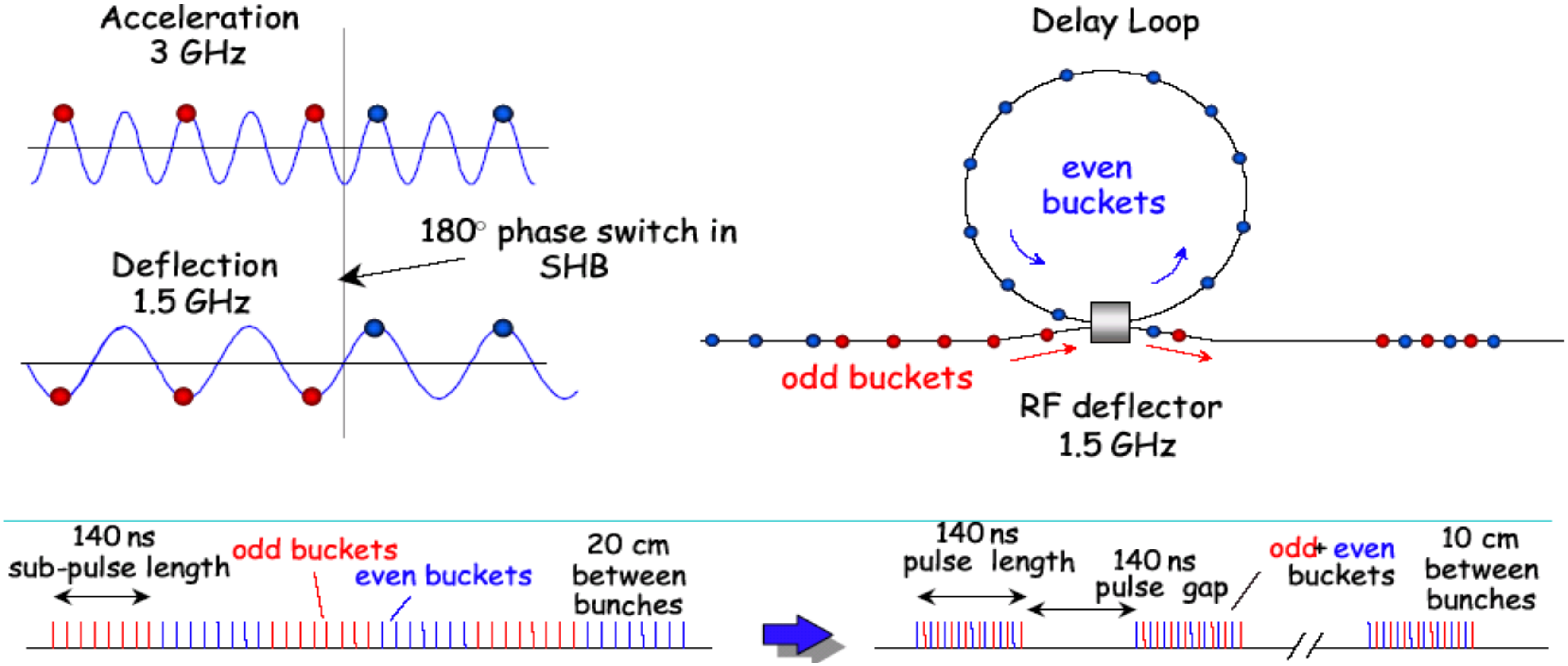


# Beam separation by RF deflectors



# Delay Loop Principle

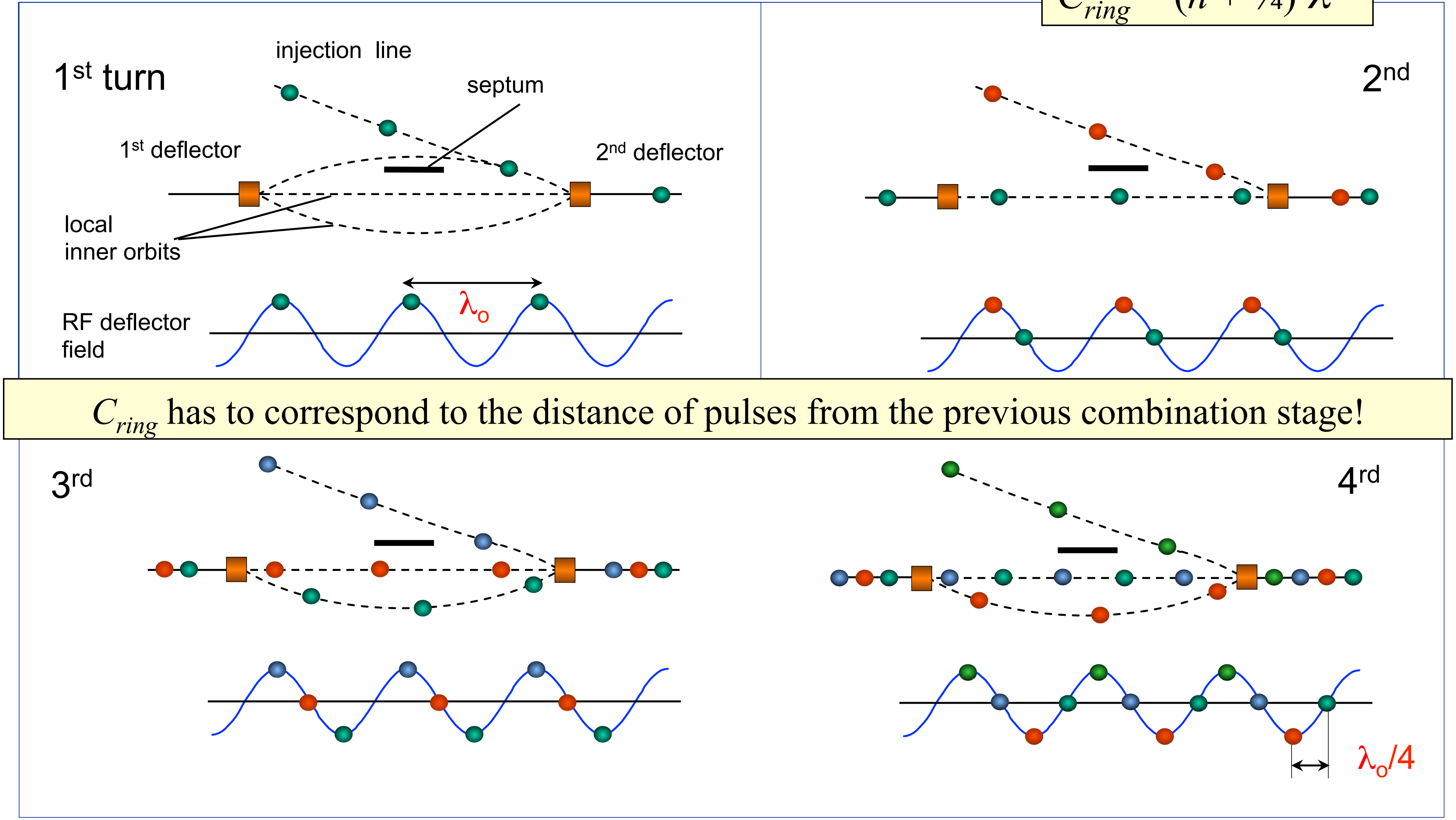
- **double repetition frequency and current**
- parts of bunch train delayed in loop
- RF deflector combines the bunches ($f_{defl}$=bunch rep. frequency)
- Path length corresponds to beam sub-pulse length



# RF injection in combiner ring (factor 4)

- combination factors up to 5 reachable in a ring

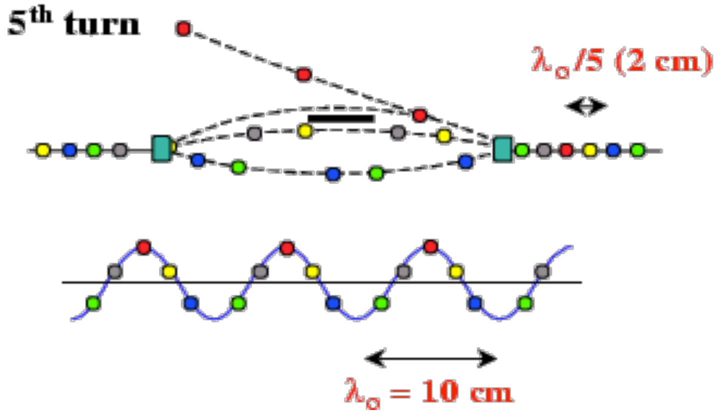
$C_{ring} = (n + \frac{1}{4})\,\lambda$



$C_{ring}$ has to correspond to the distance of pulses from the previous combination stage!

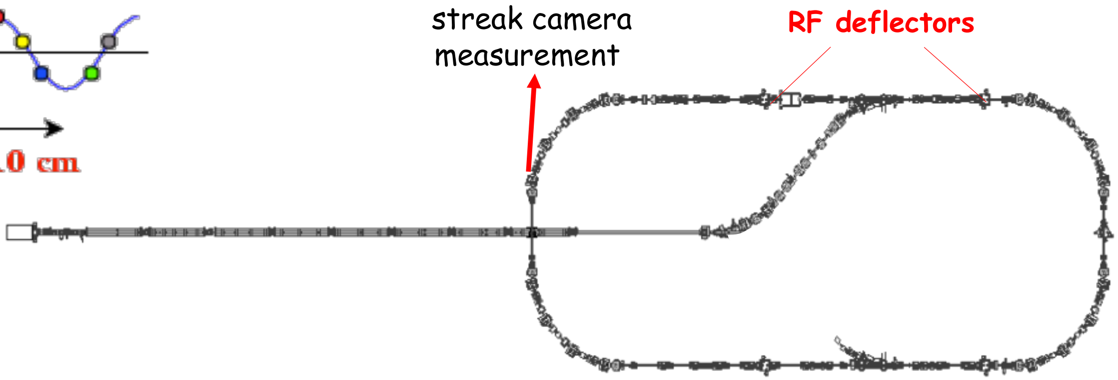
# Demonstration of frequency multiplication

## Combination factor 5

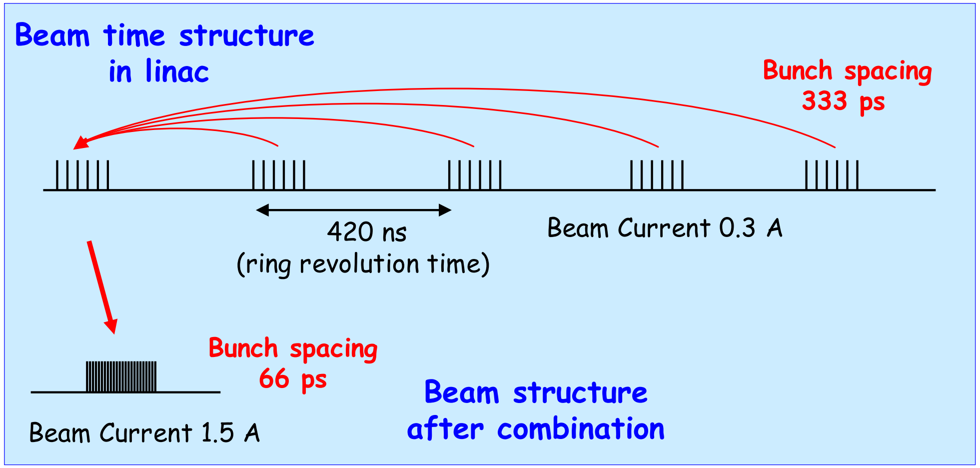


*CTF3 - PRELIMINARY PHASE 2001/2002*

**Successful low-charge demonstration of electron pulse combination and bunch frequency multiplication by up to factor 5**


streak camera measurement

RF deflectors


**Beam time structure in linac**

Bunch spacing 333 ps

420 ns (ring revolution time)

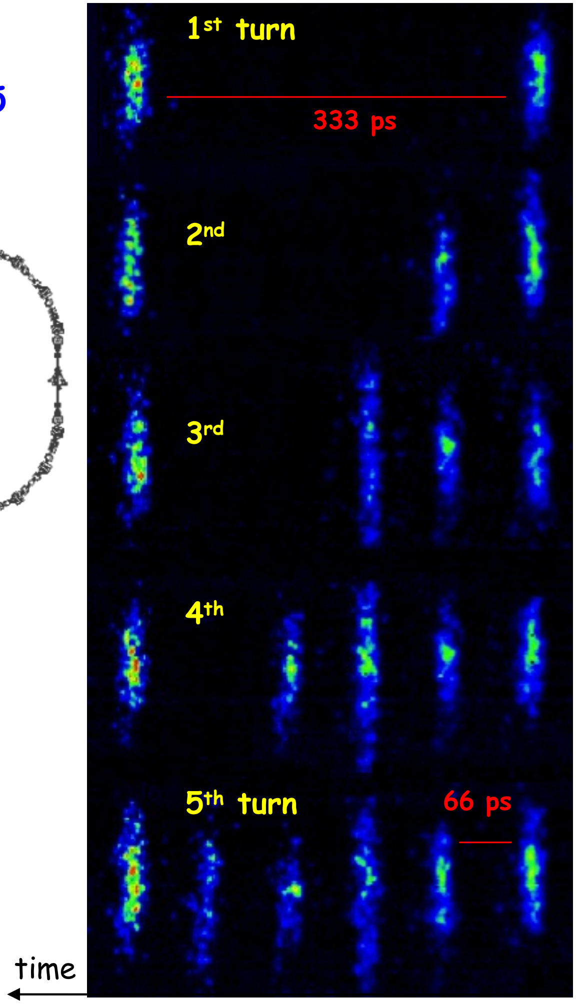
Beam Current 0.3 A

Bunch spacing 66 ps

Beam Current 1.5 A

**Beam structure after combination**

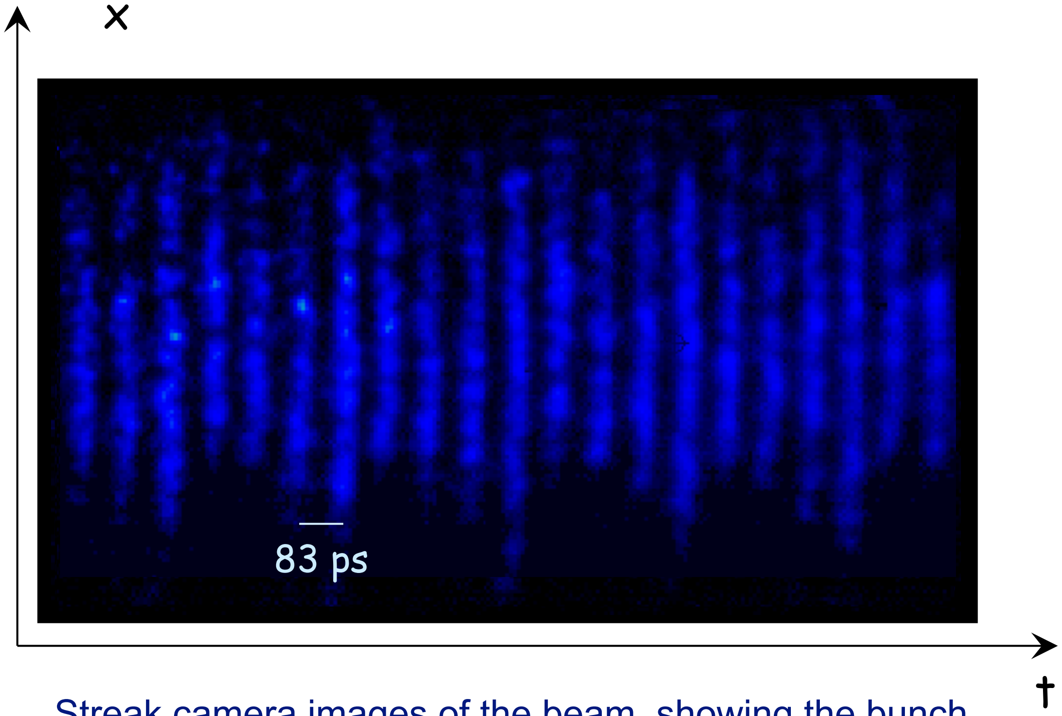
Streak camera image of beam time structure evolution



# CTF3 preliminary phase (2001-2002)

RF injection in combiner ring

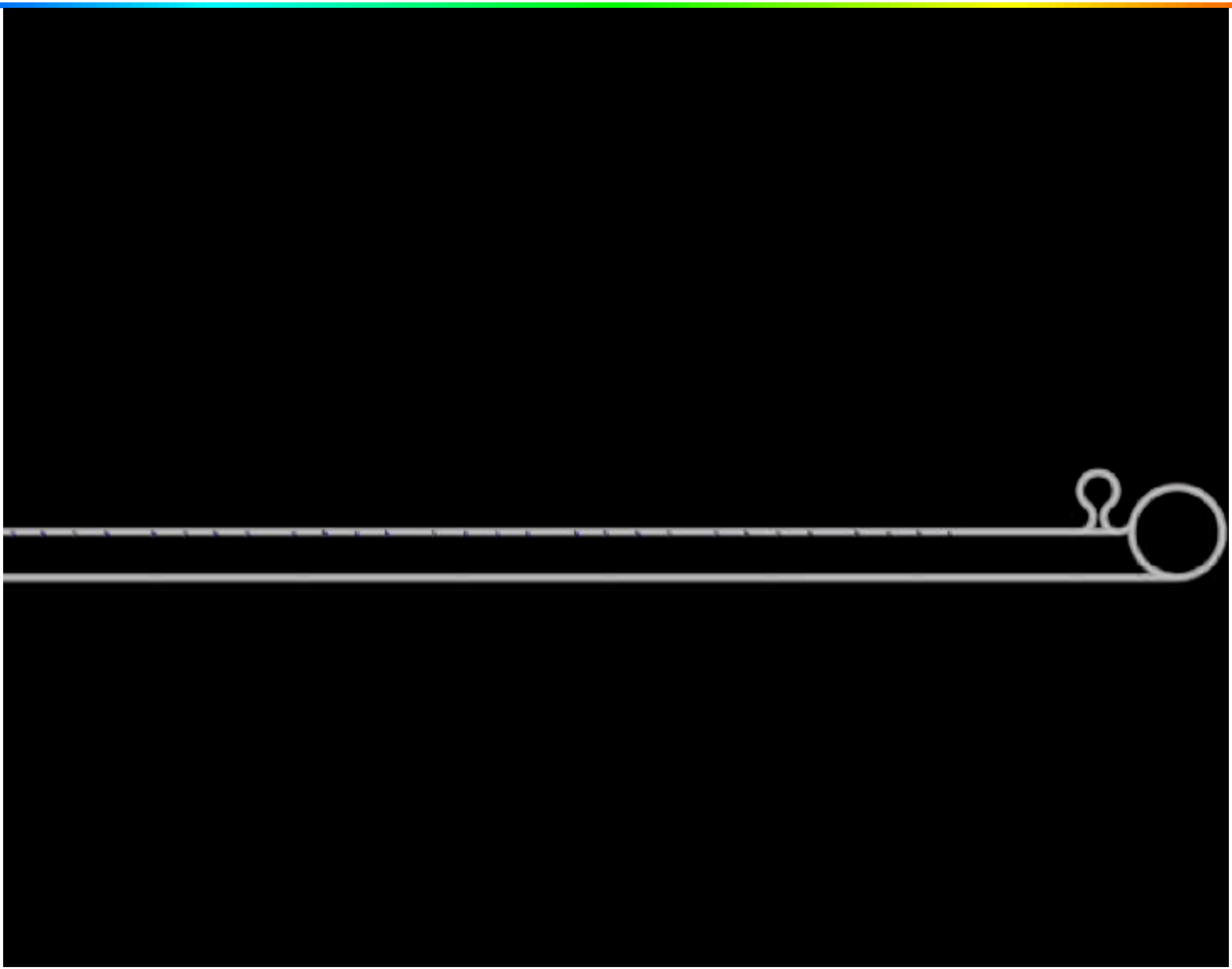
Combination factor 4



Streak camera images of the beam, showing the bunch combination process

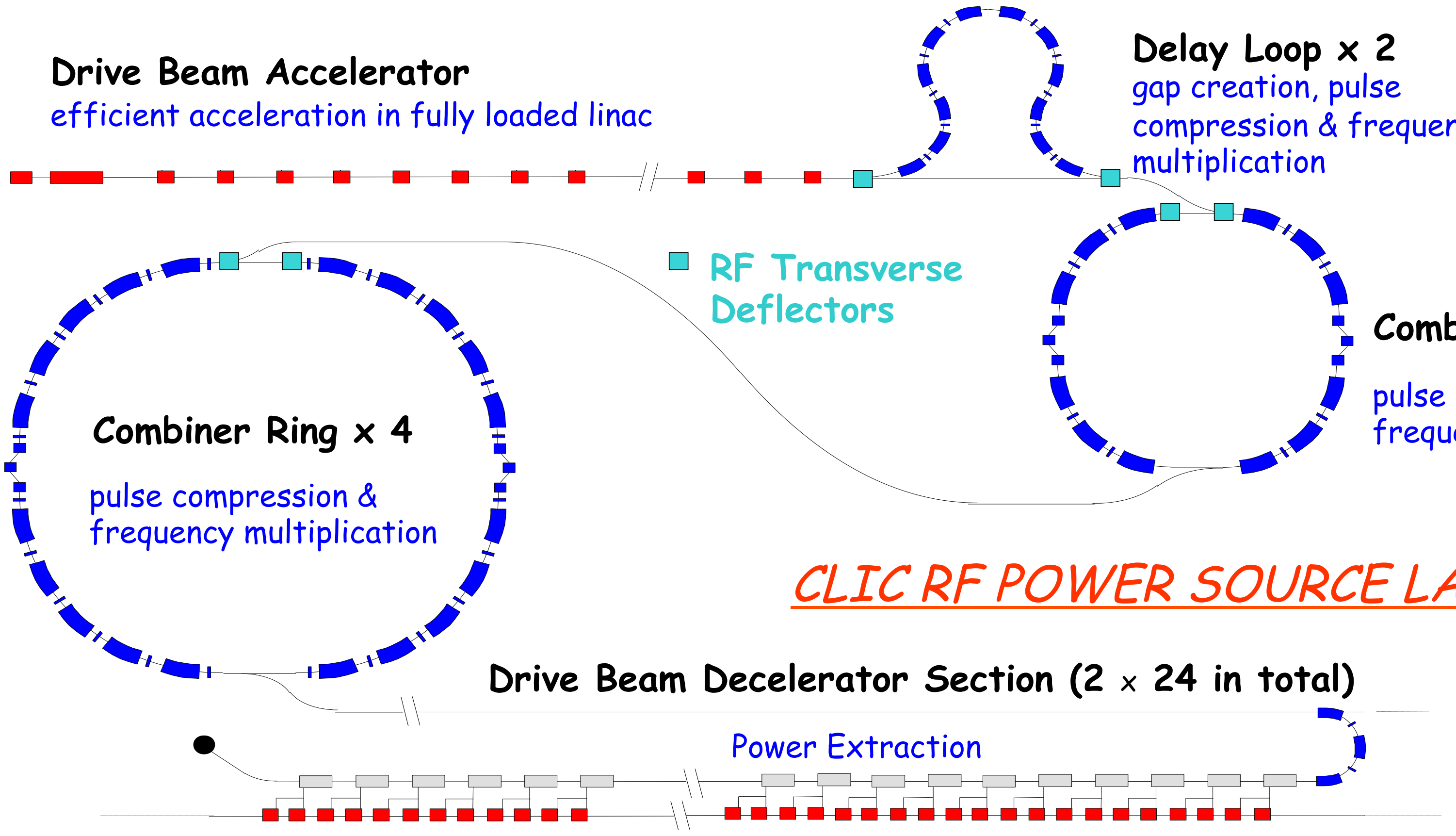
A first ring combination test was performed in 2002, *at low current and short pulse*, in the CERN Electron-Positron Accumulator (EPA), properly modified

# Lemmings Drive Beam



Alexandra
Andersson

# CLIC Drive Beam generation



**Drive Beam Accelerator**
efficient acceleration in fully loaded linac

**Delay Loop x 2**
gap creation, pulse compression & frequency multiplication

RF Transverse Deflectors

**Combiner Ring x 3**
pulse compression & frequency multiplication

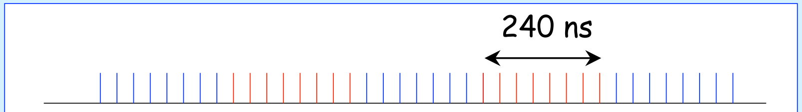
**Combiner Ring x 4**
pulse compression & frequency multiplication

*CLIC RF POWER SOURCE LAYOUT*

**Drive Beam Decelerator Section (2 x 24 in total)**

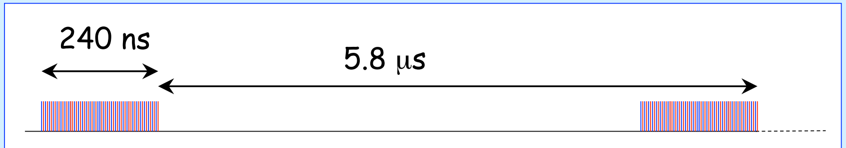
Power Extraction

## Drive beam time structure - initial



140 µs train length – 24 x 24 sub-pulses
4.2 A - 2.4 GeV – 60 cm between bunches

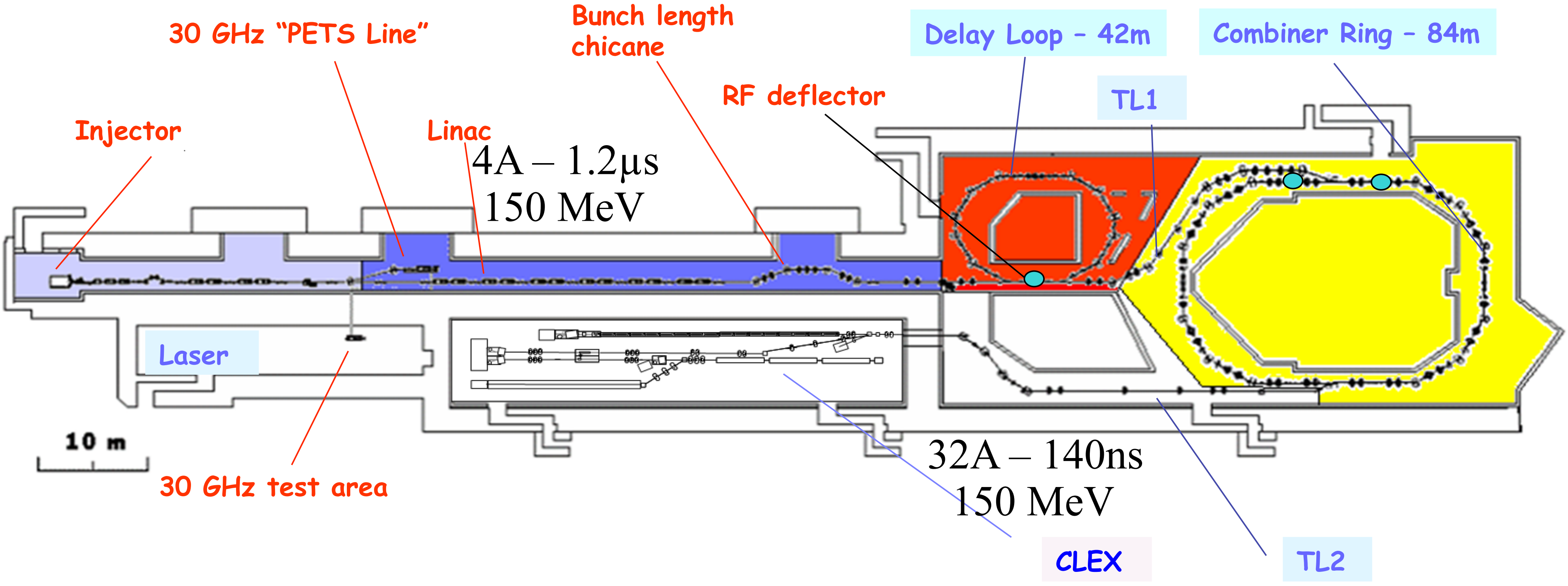
## Drive beam time structure - final



24 pulses – 101 A – 2.5 cm between bunches

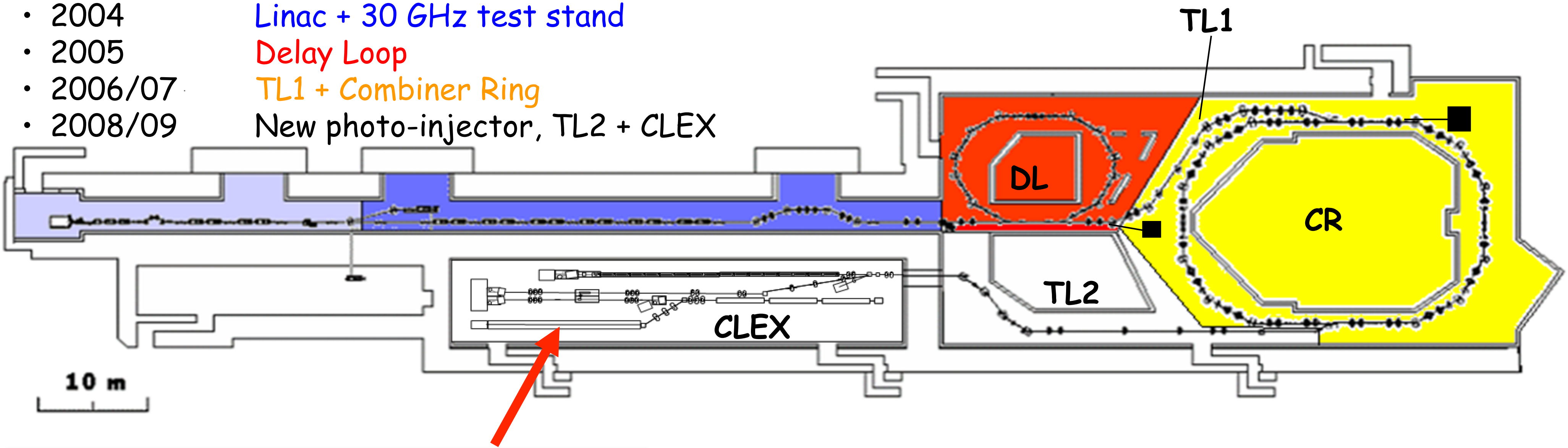
# CLIC Test Facility CTF 3

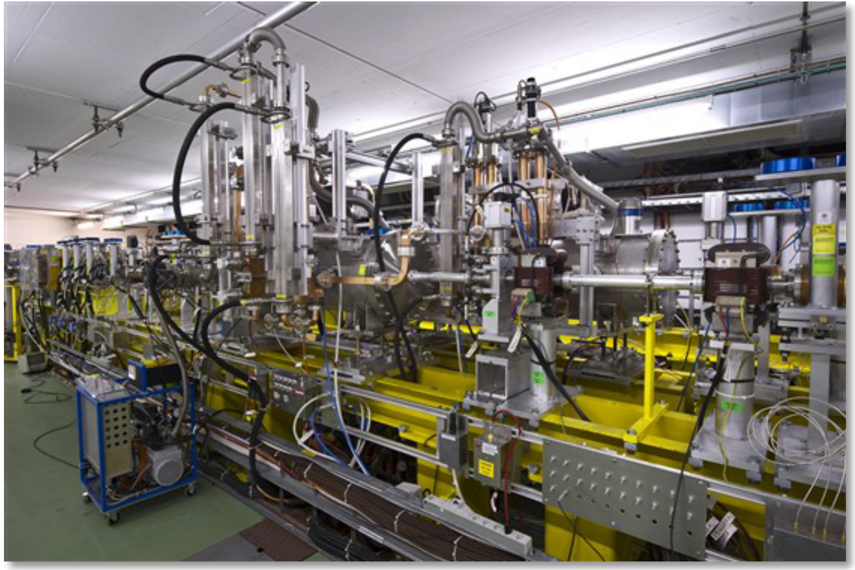
- demonstrate Drive Beam generation
  (fully loaded acceleration, bunch frequency multiplication 8x)
- Test CLIC accelerating structures
- Test power production structures (PETS)

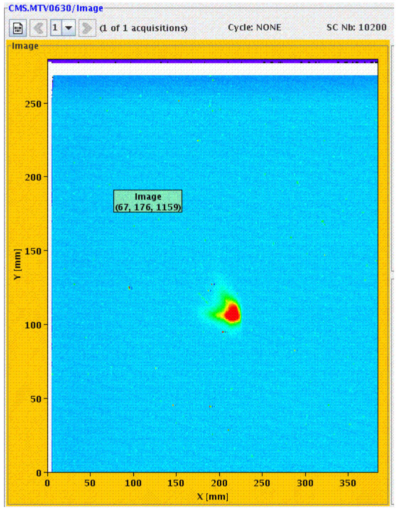


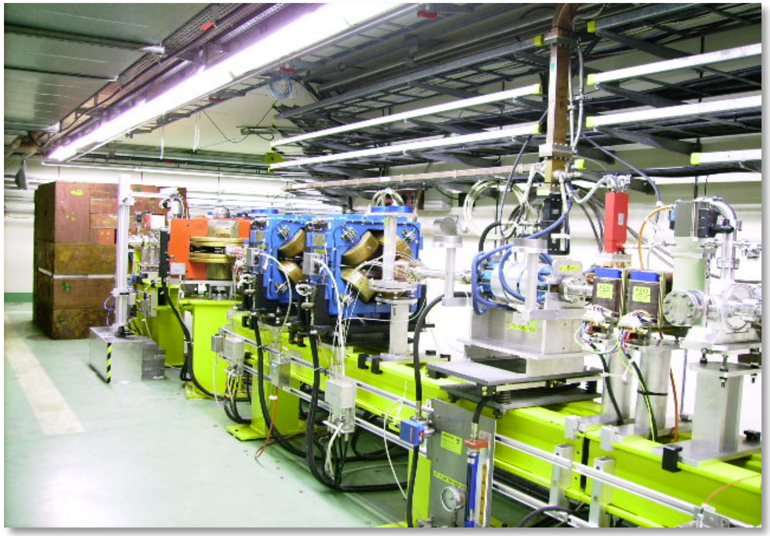
# CTF3 Evolution

| | |
|---|---|
| 2003 | Injector + part of linac |
| 2004 | Linac + 30 GHz test stand |
| 2005 | Delay Loop |
| 2006/07 | TL1 + Combiner Ring |
| 2008/09 | New photo-injector, TL2 + CLEX |







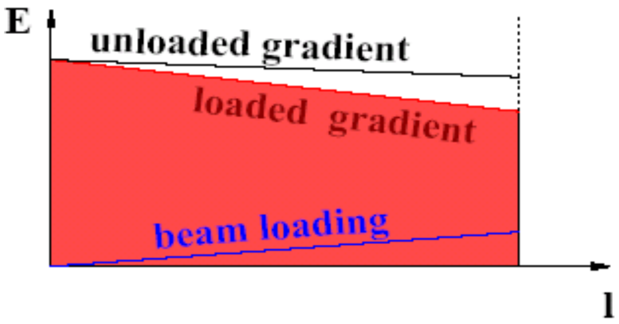


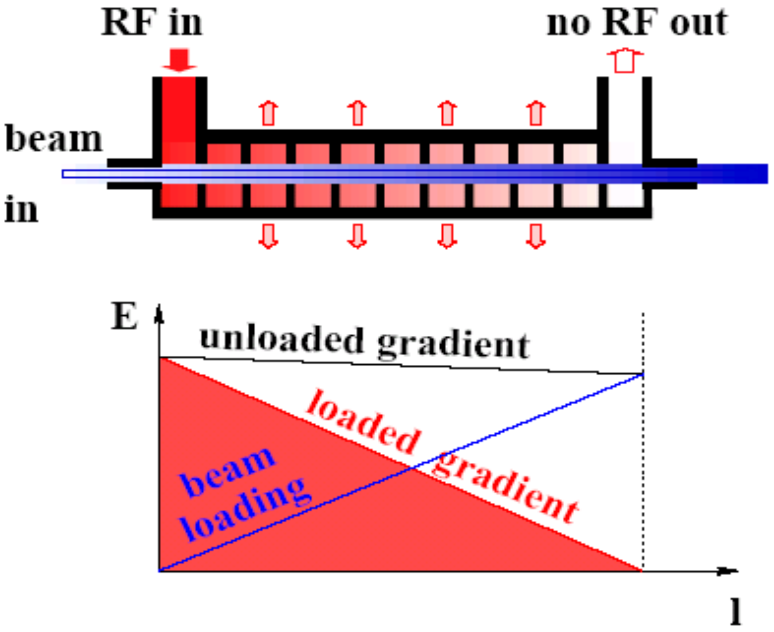
# Fully loaded operation

- efficient power transfer from RF to the beam needed

“Standard” situation:

  - small beam loading
  - power at structure exit lost in load





“Efficient” situation:

- high beam current
- high beam loading
- no power flows into load
- $V_{ACC} \approx 1/2\ V_{unloaded}$

# Fully loaded operation

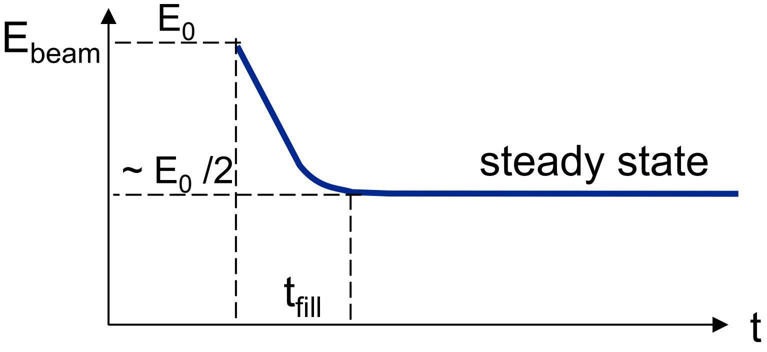
- Disadvantage: any current variation changes energy gain

$$\frac{dV/V}{dI_{beam}/I_{beam}} = -\frac{I_{beam}}{I_{opt}}$$

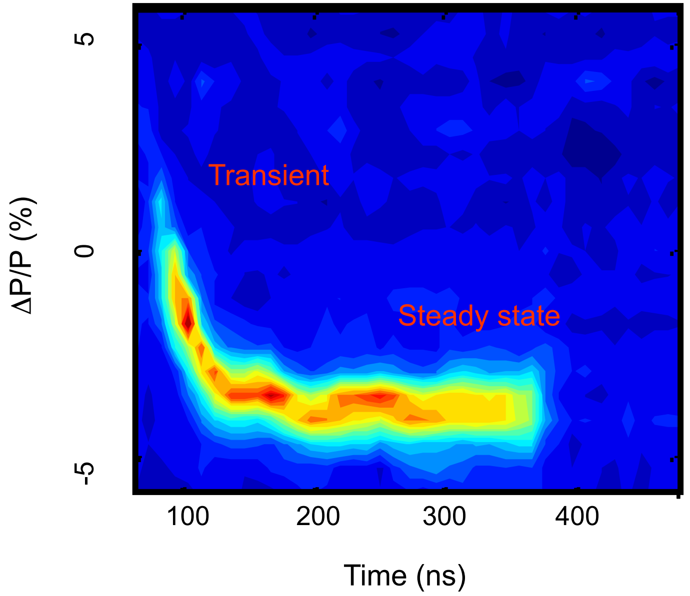
at full loading, 1% current variation = 1% voltage variation

- Requires high current stability
- Energy transient

  (first bunches see full field)

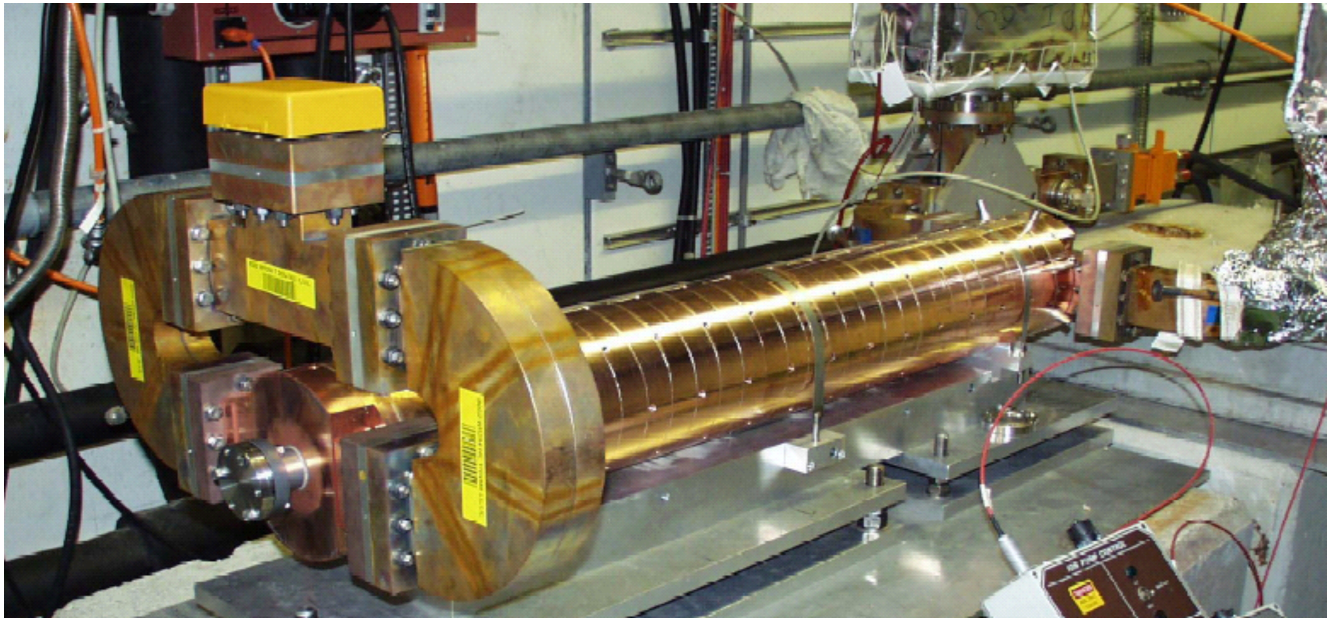


Time resolved beam energy spectrum measurement in CTF3

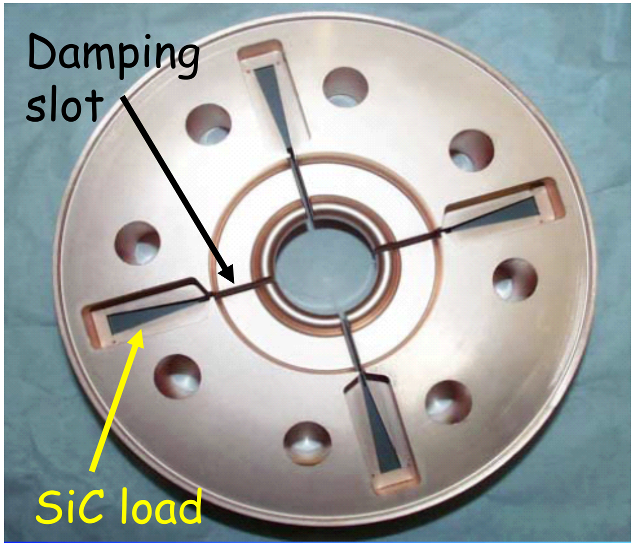


- Requires continuous bunch train

# CTF3 linac acceleration structures

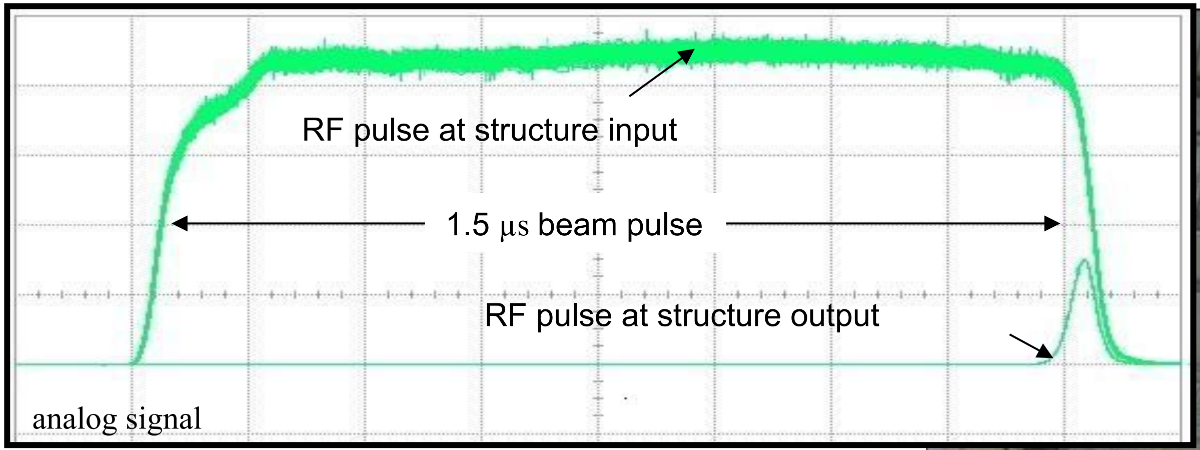


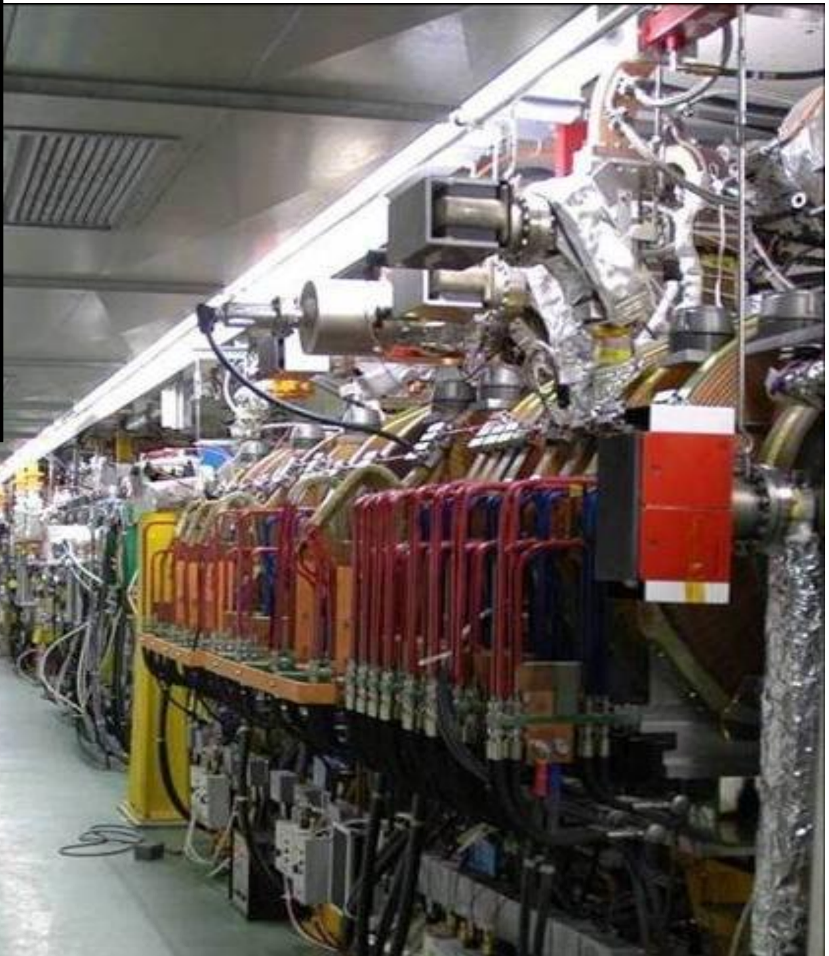
Dipole modes suppressed by slotted iris damping (first dipole's Q factor < 20) and HOM frequency detuning



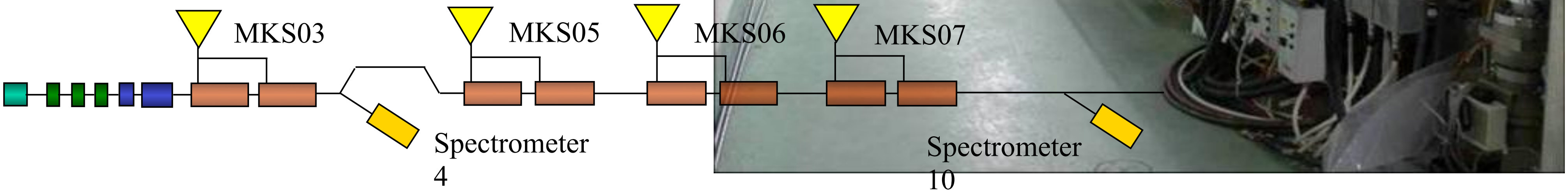
- 3 GHz $2\pi/3$ traveling wave structure
- constant aperture
- slotted-iris damping + detuning with nose cones
- up to 4 A 1.4 µs beam pulse accelerated
  no sign of beam break-up

# Full beam-loading acceleration in CTF3

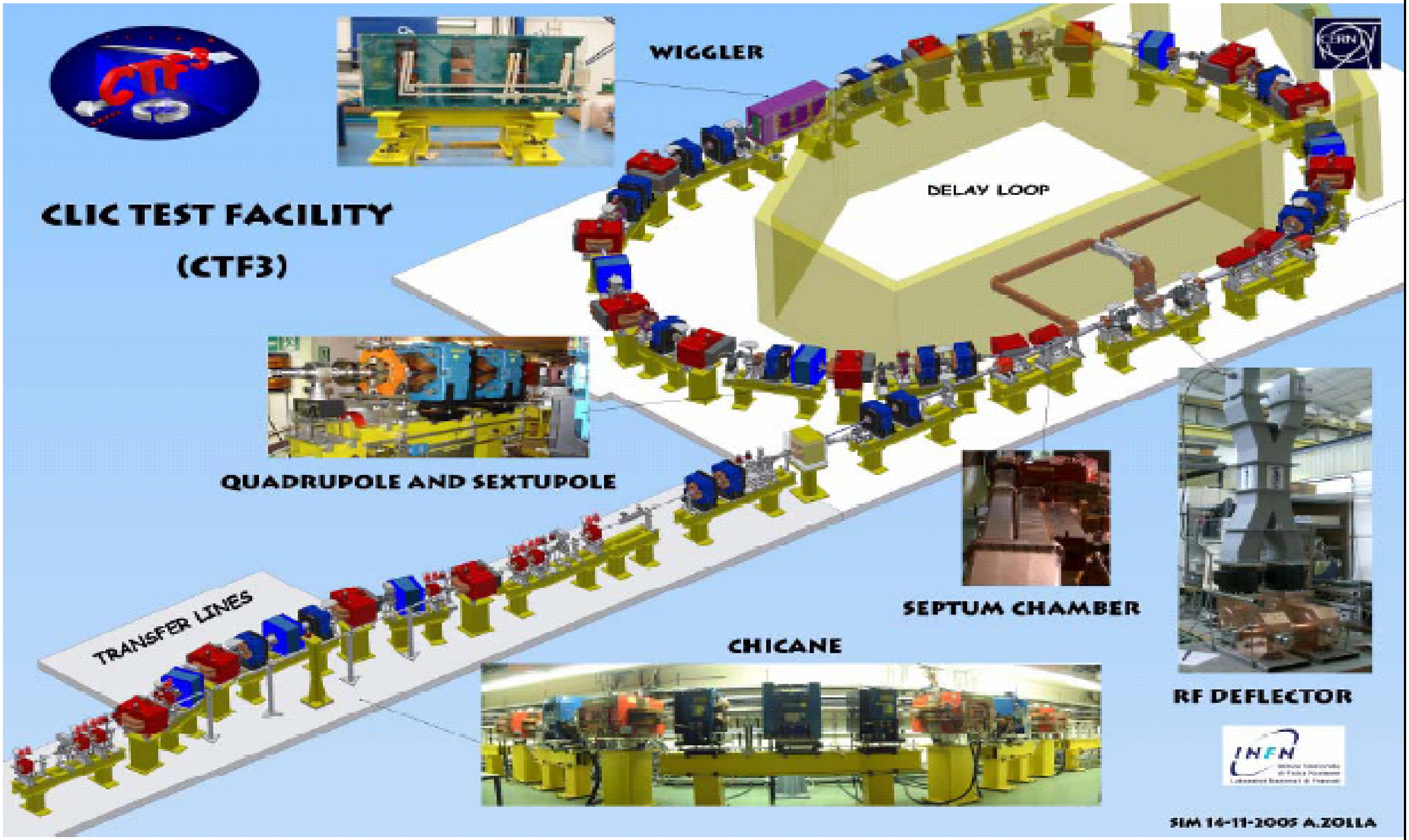




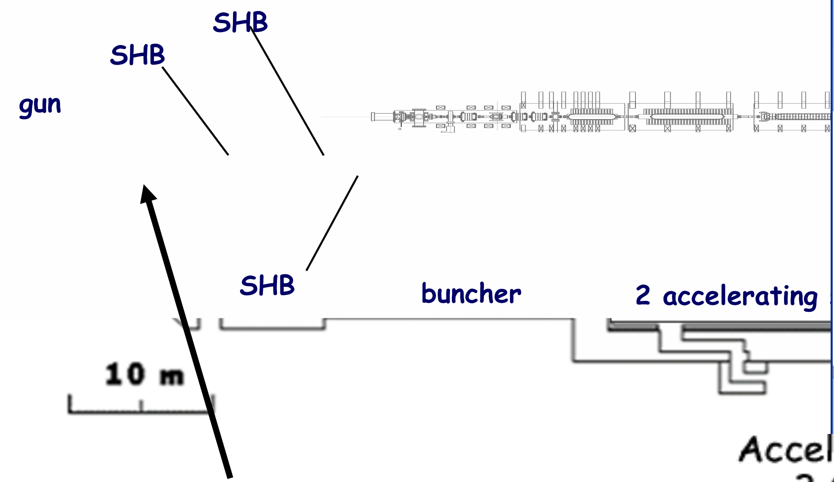
- Measured RF-to-beam efficiency 95.3%
- Theory 96%
  (~ 4 % ohmic losses)

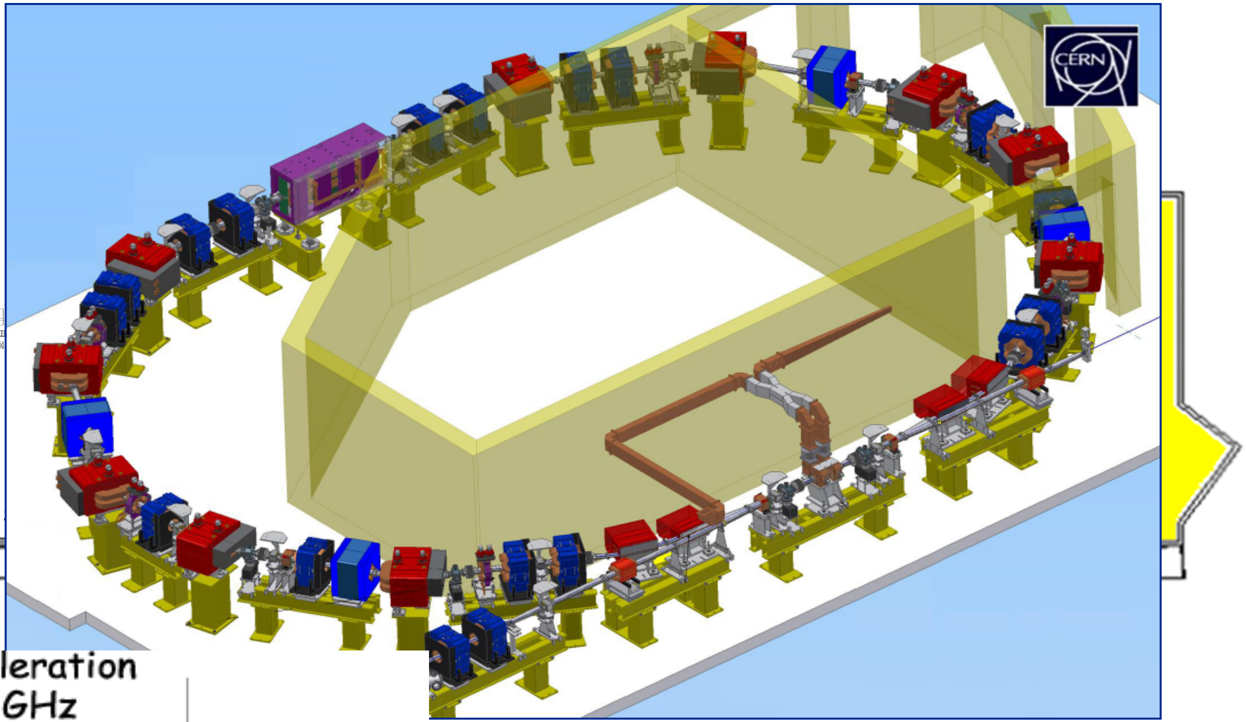


# CTF3 Delay Loop



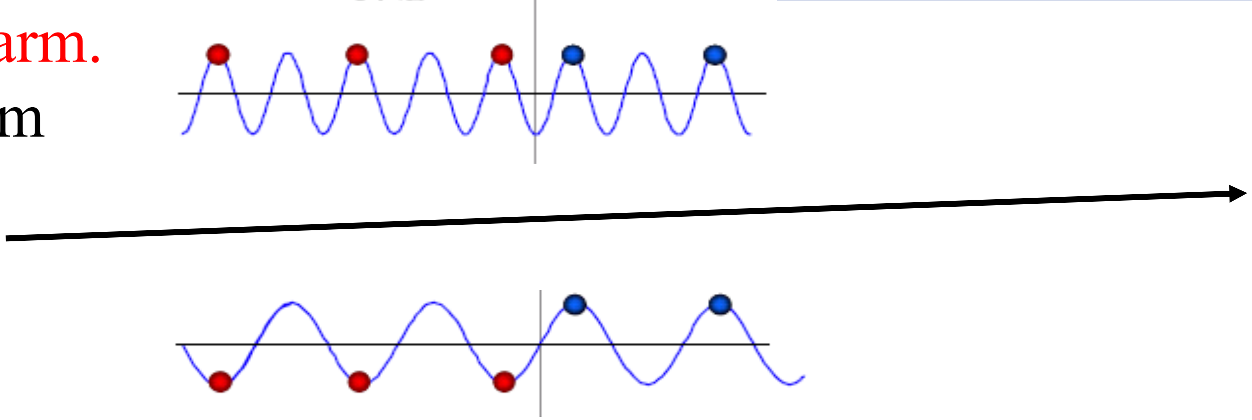
# Delay Loop operation





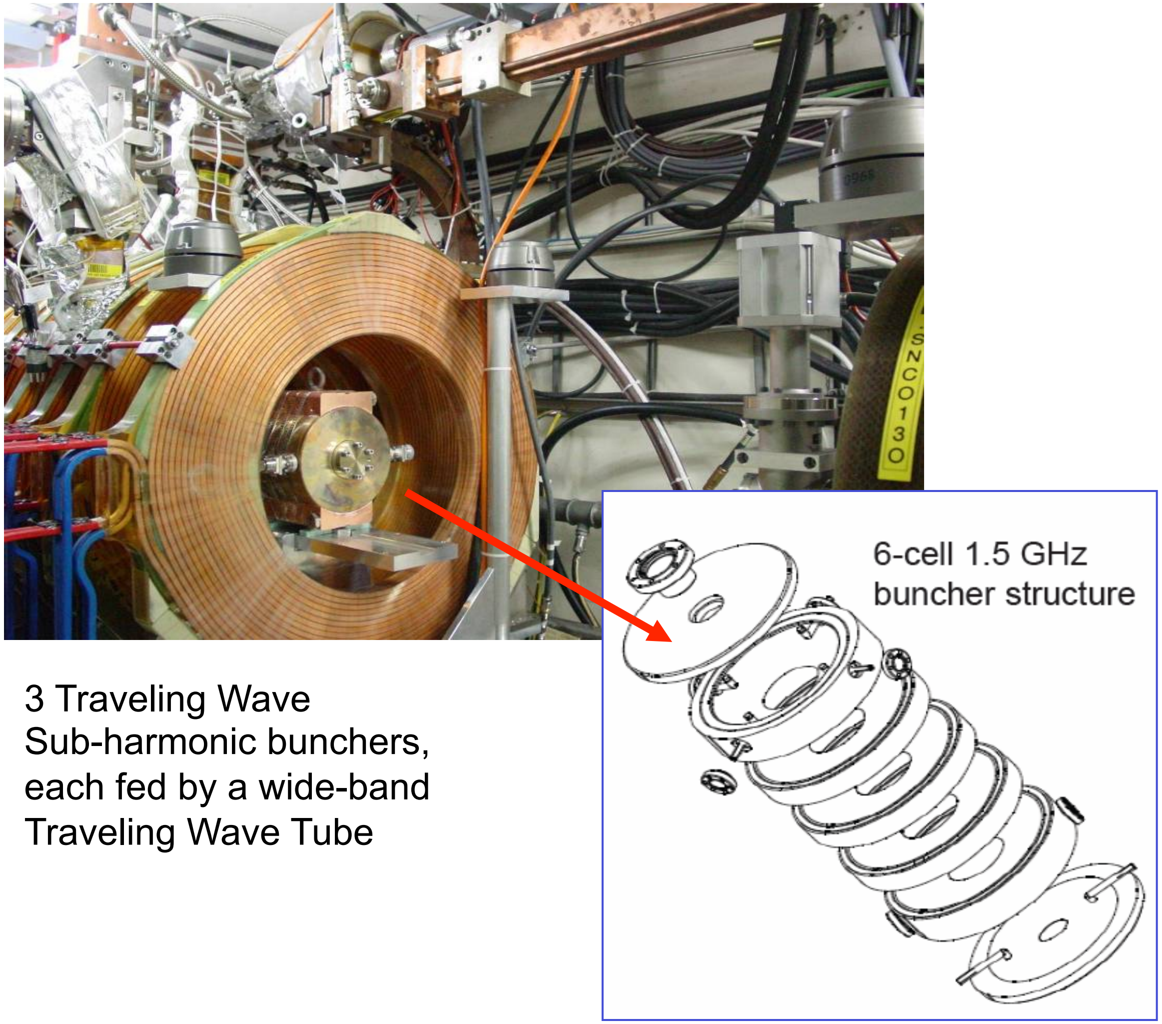
- 1.5 GHz sub-harm. bunching system
- 1.5 GHz RF deflector

Acceleration
3 GHz



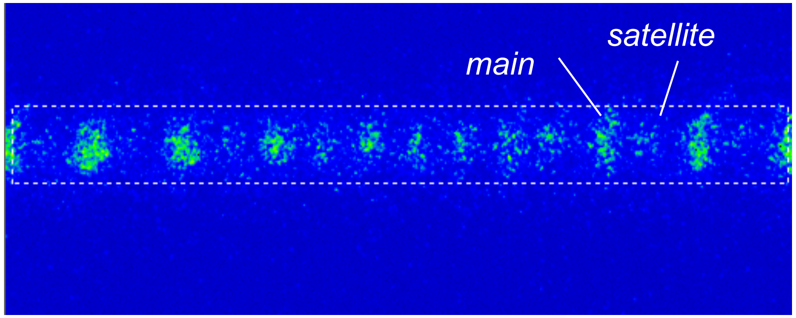
# Sub-harmonic bunching system

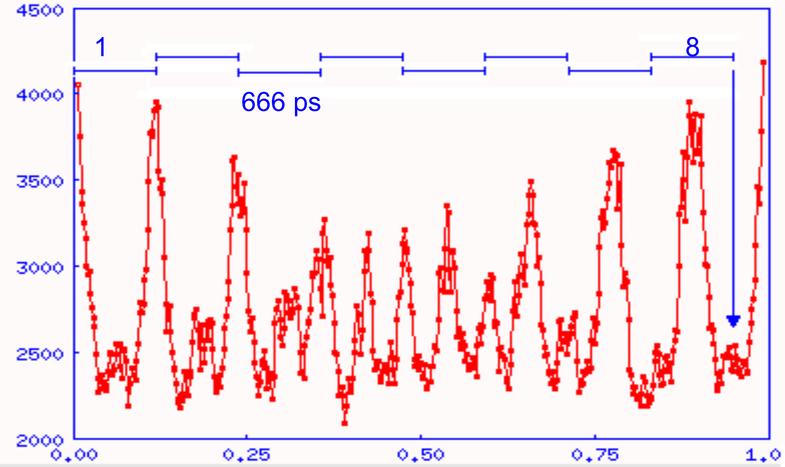
Fast phase switch from SHB system (CTF3)



3 Traveling Wave Sub-harmonic bunchers, each fed by a wide-band Traveling Wave Tube

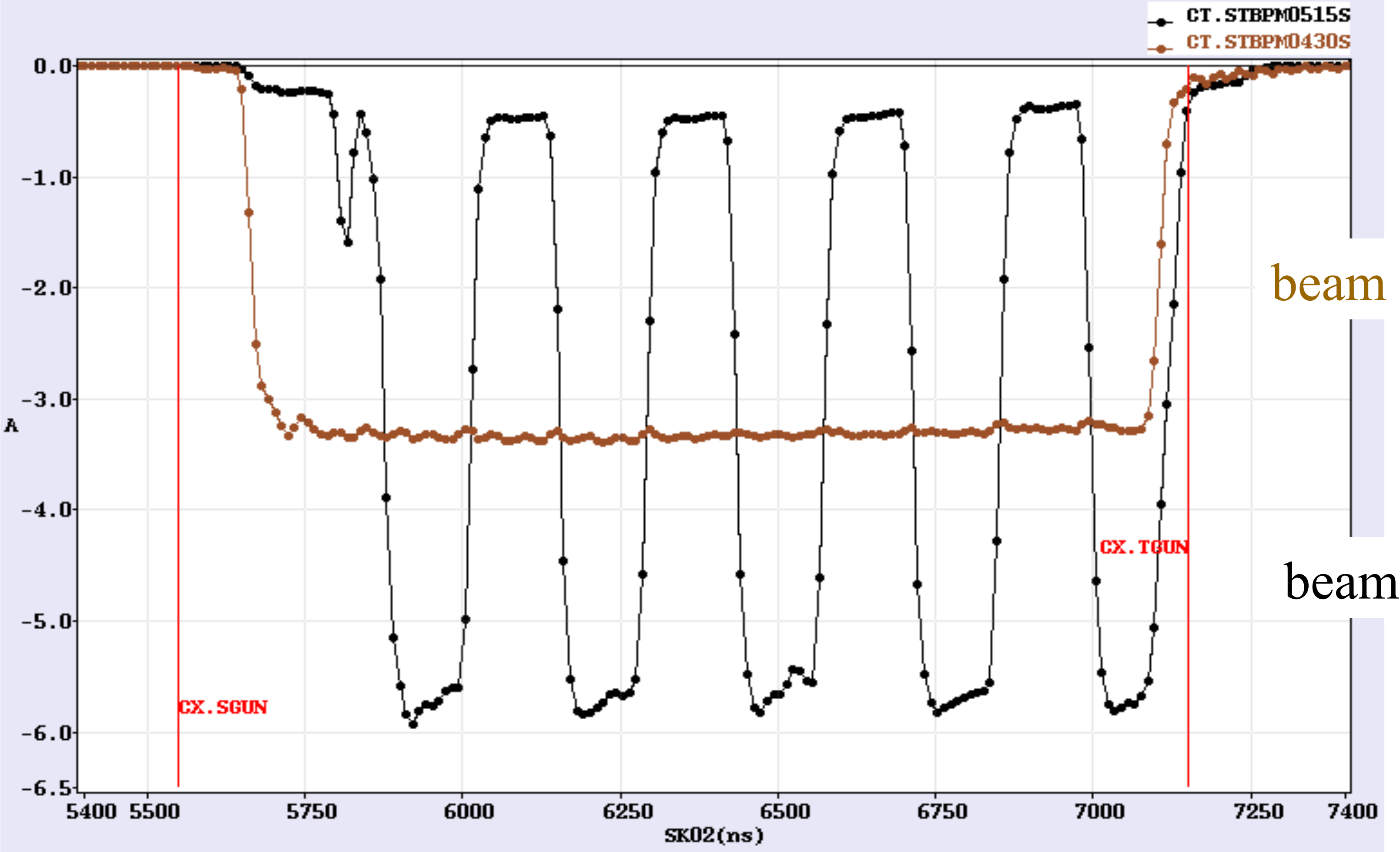
*Streak camera image*





$8.5 \cdot 666$ ps = 5.7 ns

# Delay Loop – full recombination

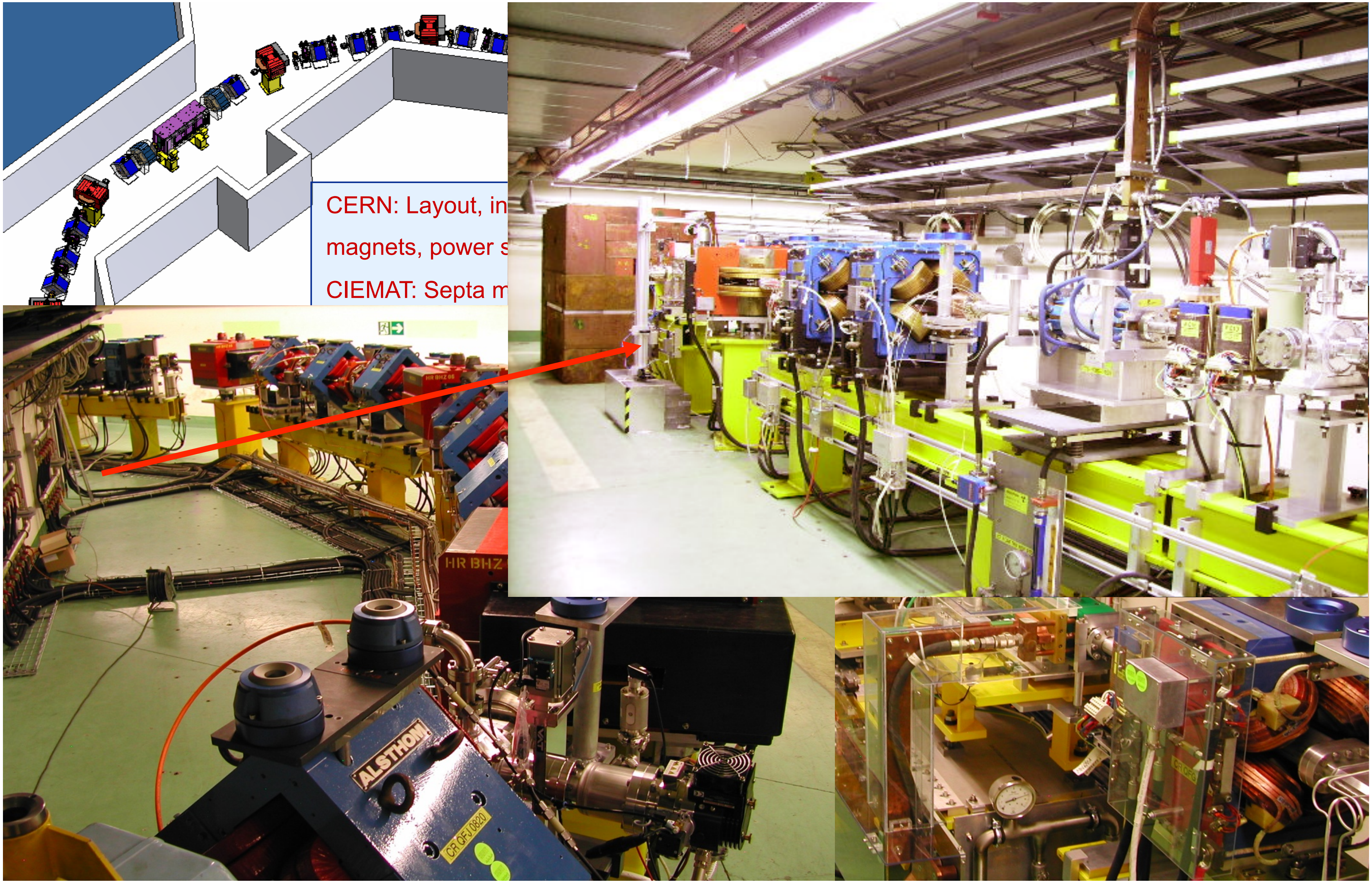


beam before the DL

beam after the DL

- 3.3 A after chicane => < 6 A after combination (satellites)

# CTF3 combiner ring



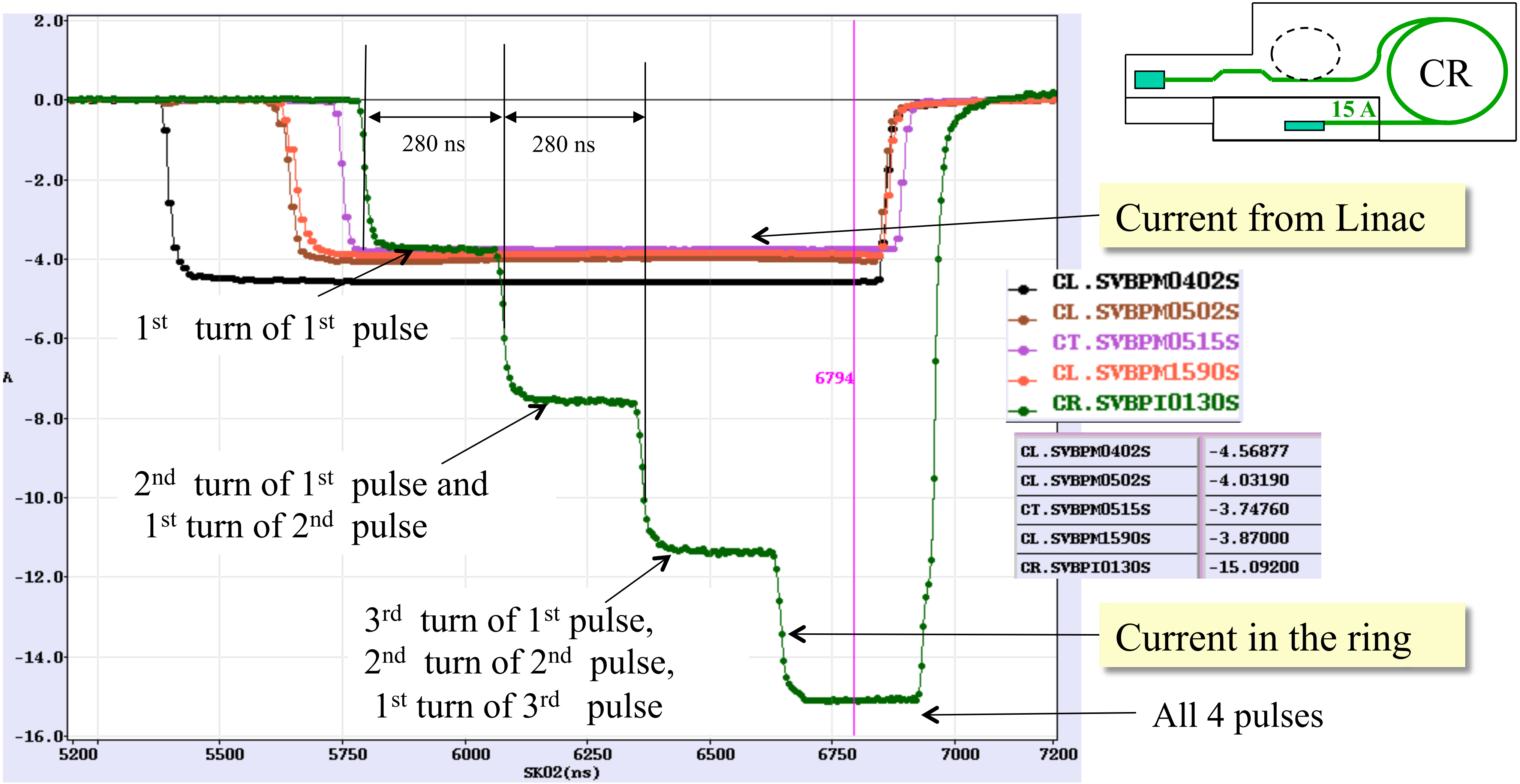
CERN: Layout, in

magnets, power s

CIEMAT: Septa m

# Combiner ring status

- factor 4 combination achieved with 15 A, 280 ns (without Delay Loop)



Current from Linac

$1^{st}$ turn of $1^{st}$ pulse

$2^{nd}$ turn of $1^{st}$ pulse and
$1^{st}$ turn of $2^{nd}$ pulse

$3^{rd}$ turn of $1^{st}$ pulse,
$2^{nd}$ turn of $2^{nd}$ pulse,
$1^{st}$ turn of $3^{rd}$ pulse

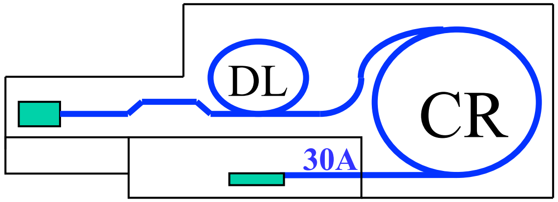
Current in the ring

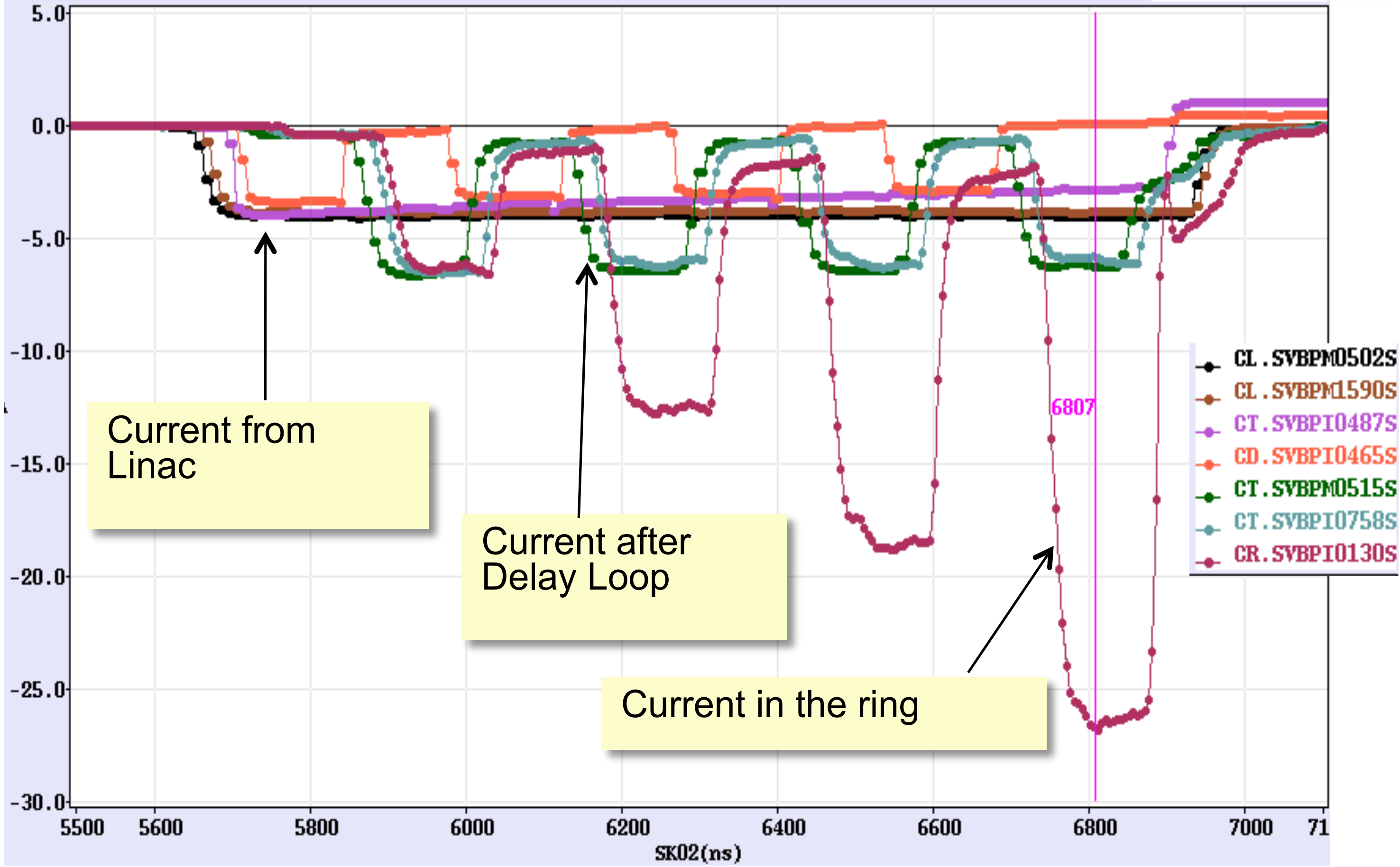
All 4 pulses

| | |
|---|---|
| CL.SVBPM0402S | -4.56877 |
| CL.SVBPM0502S | -4.03190 |
| CT.SVBPM0515S | -3.74760 |
| CL.SVBPM1590S | -3.87000 |
| CR.SVBPI0130S | -15.09200 |

# Drive beam generation achieved

- combined operation of Delay Loop and Combiner Ring (factor 8 combination)
- ~26 A combination reached, nominal 140 ns pulse length
- => **Full drive beam generation**, main goal of 2009, **achieved**





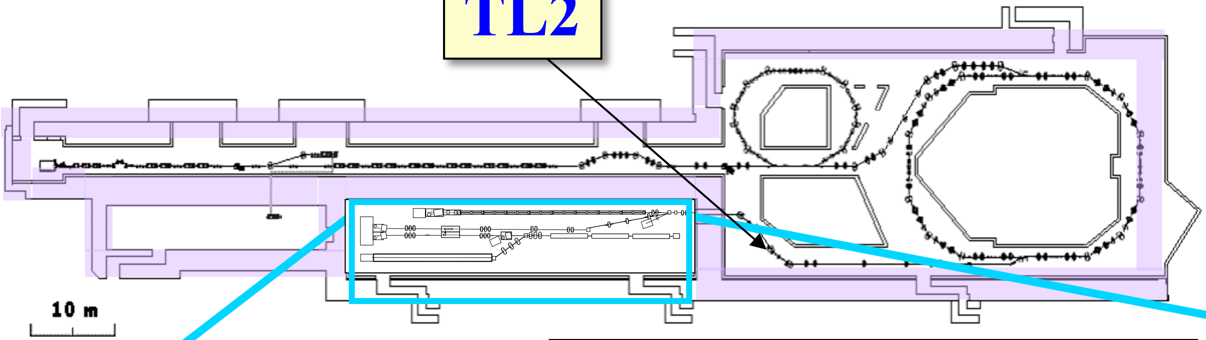
Current from Linac

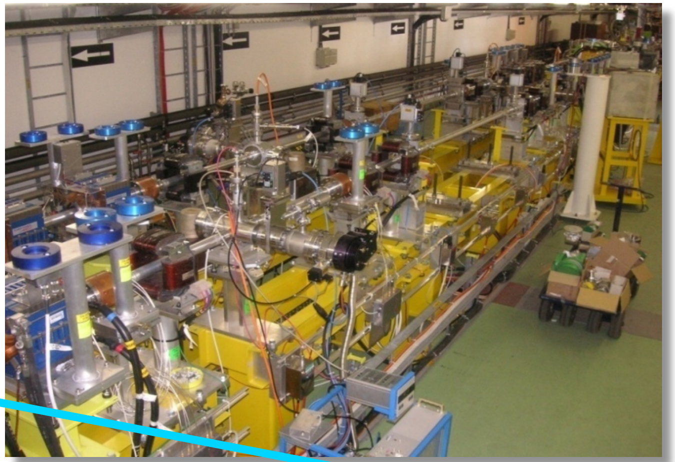
Current after Delay Loop

Current in the ring

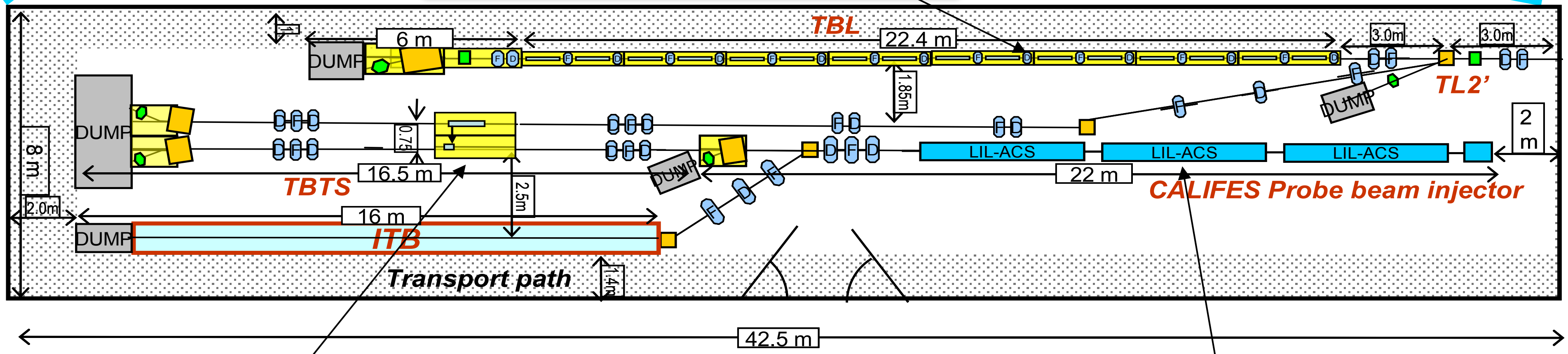
# CLEX (CLIC Experimental Area)

**TL2**





**Test Beam Line - TBL**

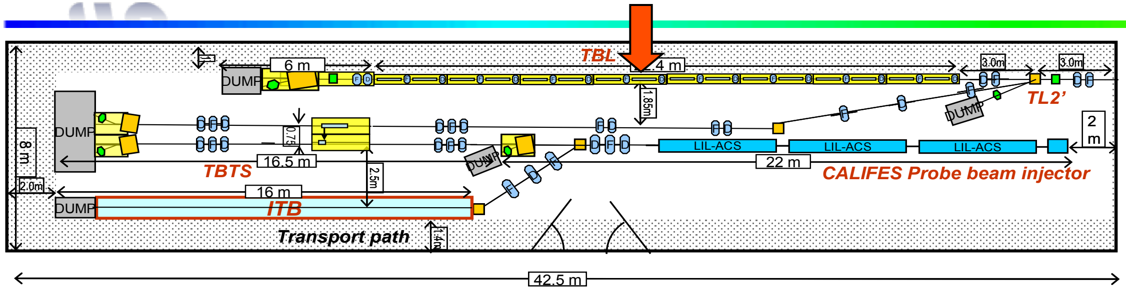


**Two Beam Test Stand - TBTS**

**Probe Beam - CALIFES**

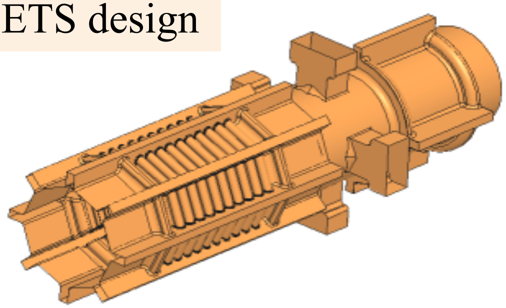
- tests for power production, deceleration and two-beam studies

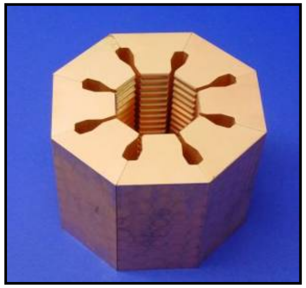
# Test Beam Line TBL



- High energy-spread beam transport
  decelerate to 50 % beam energy
- Drive Beam stability
- Stability of RF power extraction
  total power in 16 PETS: 2.5 GW
- Alignment procedures

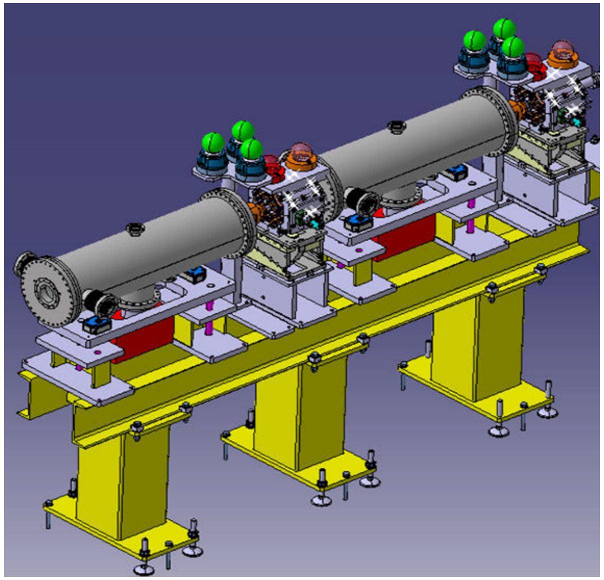
PETS design

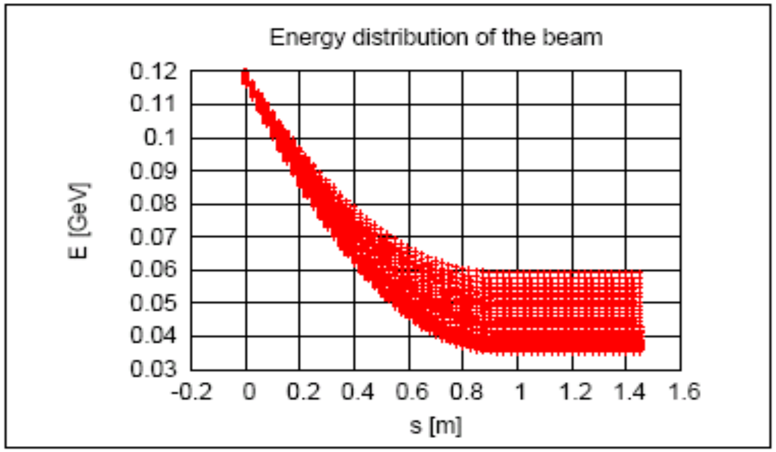




5 MV/m deceleration (35 A)
165 MV output Power

2 standard cells,
16 total



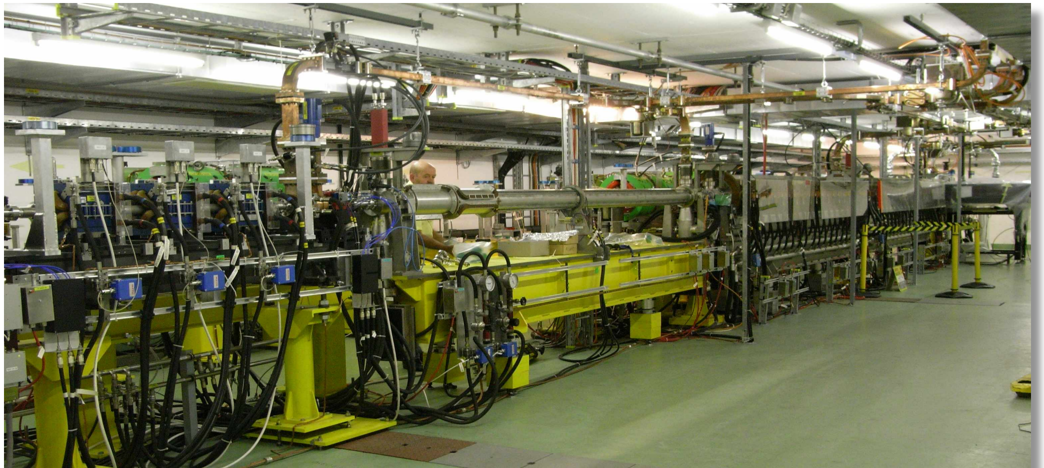


PETS development: CIEMAT
BPM: IFIC Valencia
and UPC Barcelona

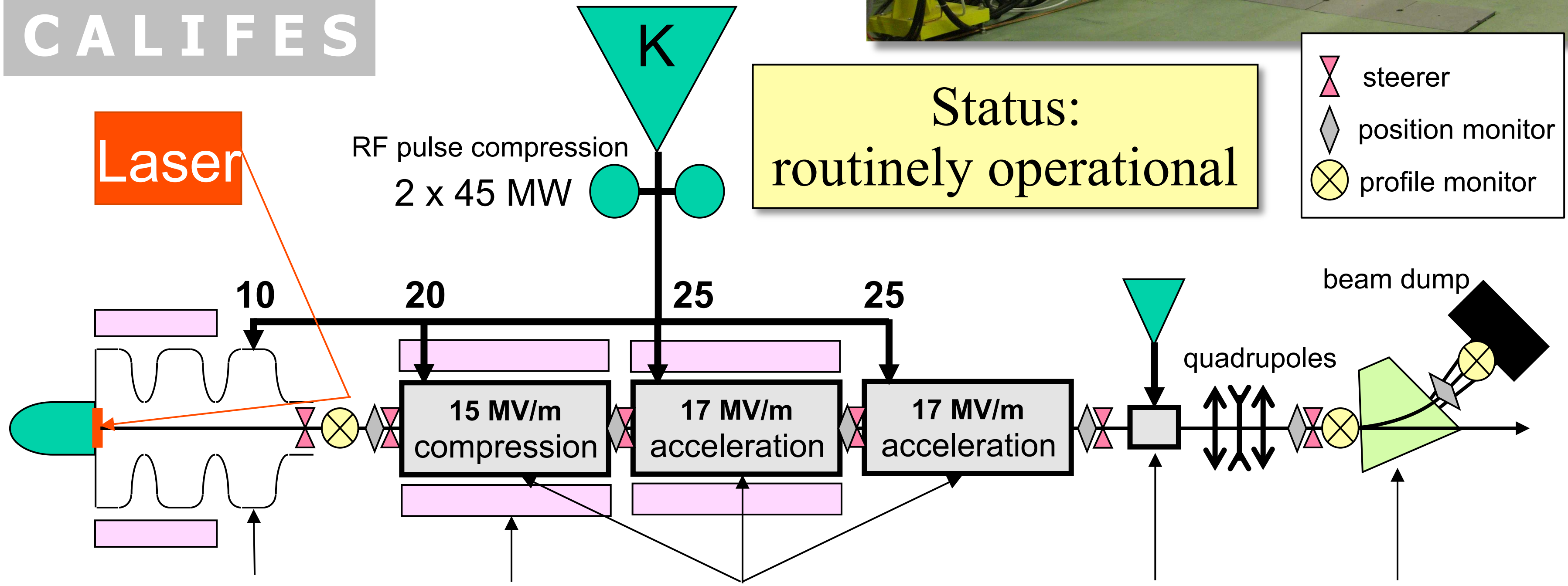
# Probe Beam Injector - CALIFES

**Responsibility of IRFU (DAPNIA)**
**CEA, Saclay, France**

180 MeV
bunch charge 0.6 nC
number of bunches 1 - 64



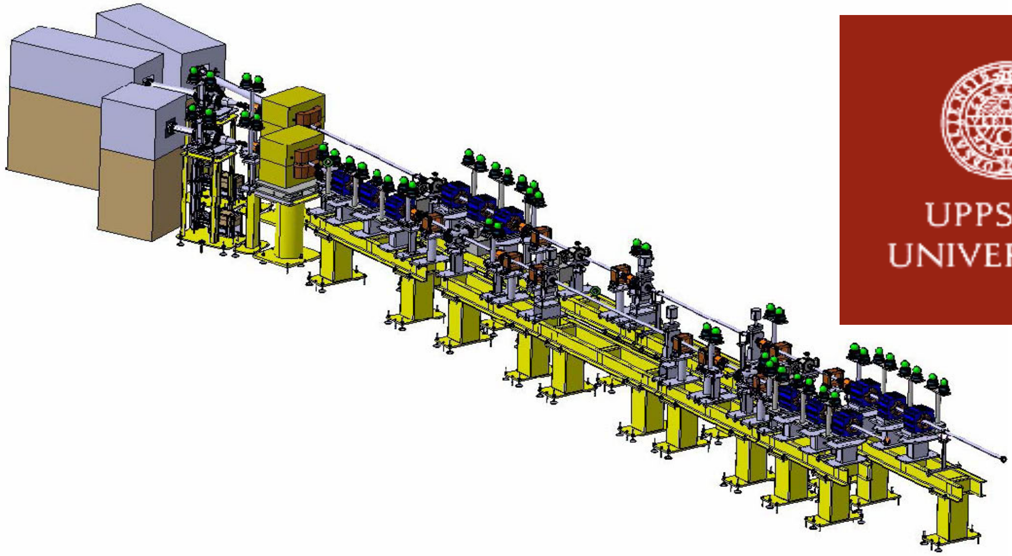
CALIFES



Status:
routinely operational

A. Mosnier

# Two-Beam Test Stand - TBTS



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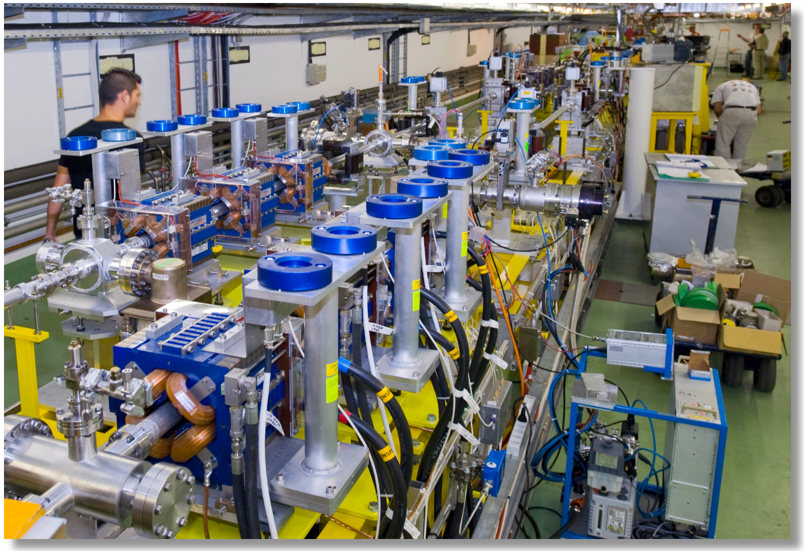
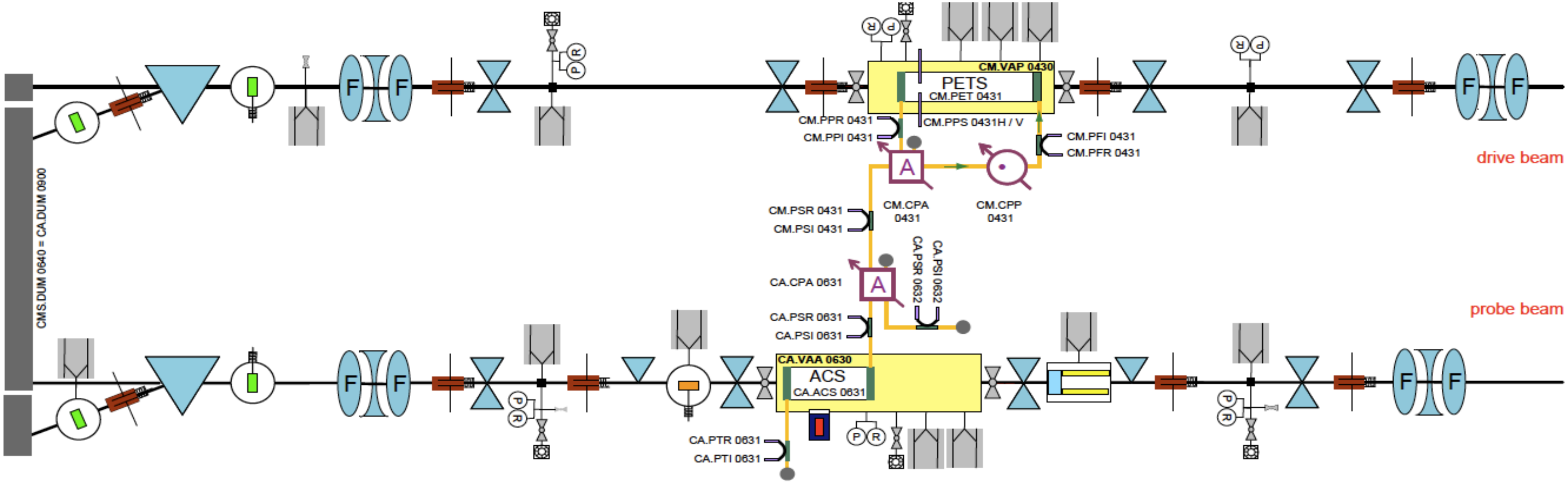
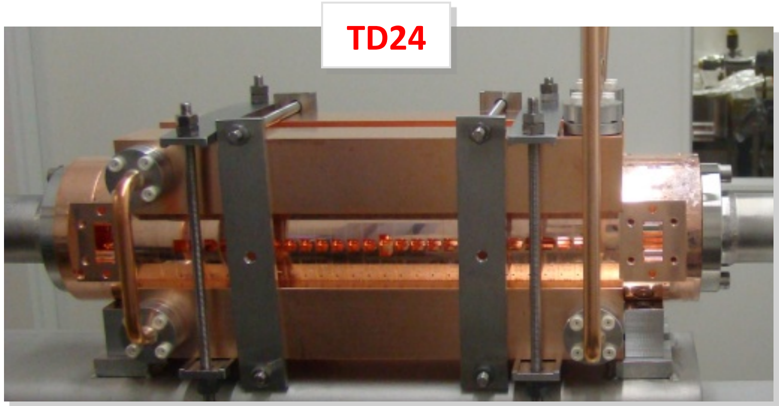
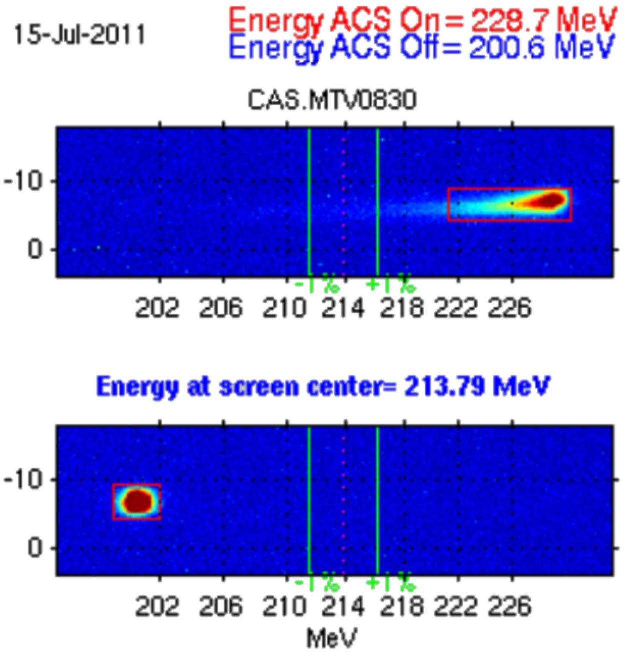




# Two-beam acceleration in CTF3

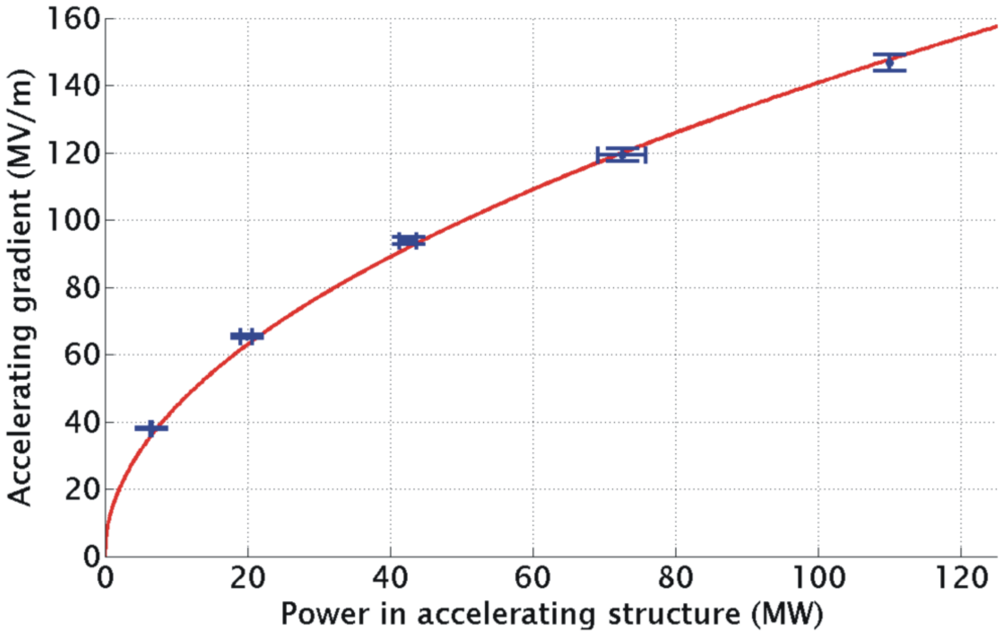
- maximum probe beam acceleration of 31 MeV measured
- => **gradient ~145 MV/m**





**Drive beam ON**

**Drive beam OFF**



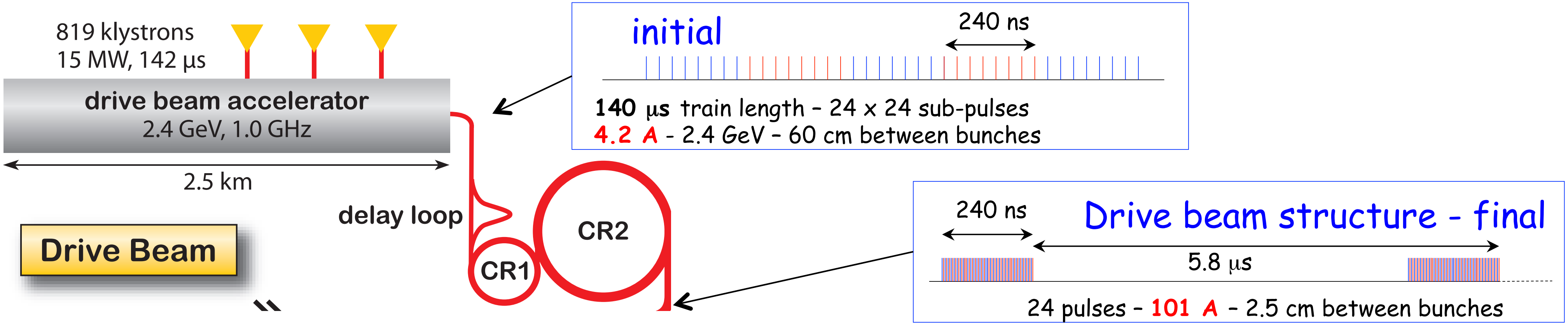
# Comparison CLIC - CTF3

| | **CTF3** | **CLIC** |
|---|---|---|
| Energy | 0.150 GeV | 2.4 GeV |
| Pulse length | 1.2 µs | 140 µs |
| Multiplication factor | 2 x 4 = 8 | 2 x 3 x 4 = 24 |
| Linac current | 3.75 A | 4.2 A |
| Final current | 30 A | 100 A |
| RF frequency | 3 GHz | 1 GHz |
| Deceleration | to ~50% energy | to 10% energy |
| Repetition rate | up to 5 Hz | 50 Hz |
| Energy per beam pulse | 0.7 kJ | 1400 kJ |
| Average beam power | 3.4 kW | 70 MW |

- Still considerable extrapolation to CLIC parameters
- Especially total beam power (loss management, machine protection)
- Good understanding of CTF3 and benchmarking needed

# Drive beam generation summary

- Conventionally generate a long beam pulse with the right bunch structure (fill every 2nd RF bucket and switch between even and odd buckets every time of flight $T_{DL}$ in the Delay Loop)
- Fully loaded acceleration: Efficiently accelerate long beam pulse
- Bunch interleaving: Delay parts of the pulse and interleave the bunches in a Delay Loop and Combiner Ring(s)
- => the long pulse (low frequency and low current) is transformed into shorter pulses of high current and high bunch repetition frequency



819 klystrons
15 MW, 142 μs

drive beam accelerator
2.4 GeV, 1.0 GHz

2.5 km

delay loop

CR1

CR2

Drive Beam

initial

240 ns

140 μs train length - 24 x 24 sub-pulses
4.2 A - 2.4 GeV - 60 cm between bunches

Drive beam structure - final

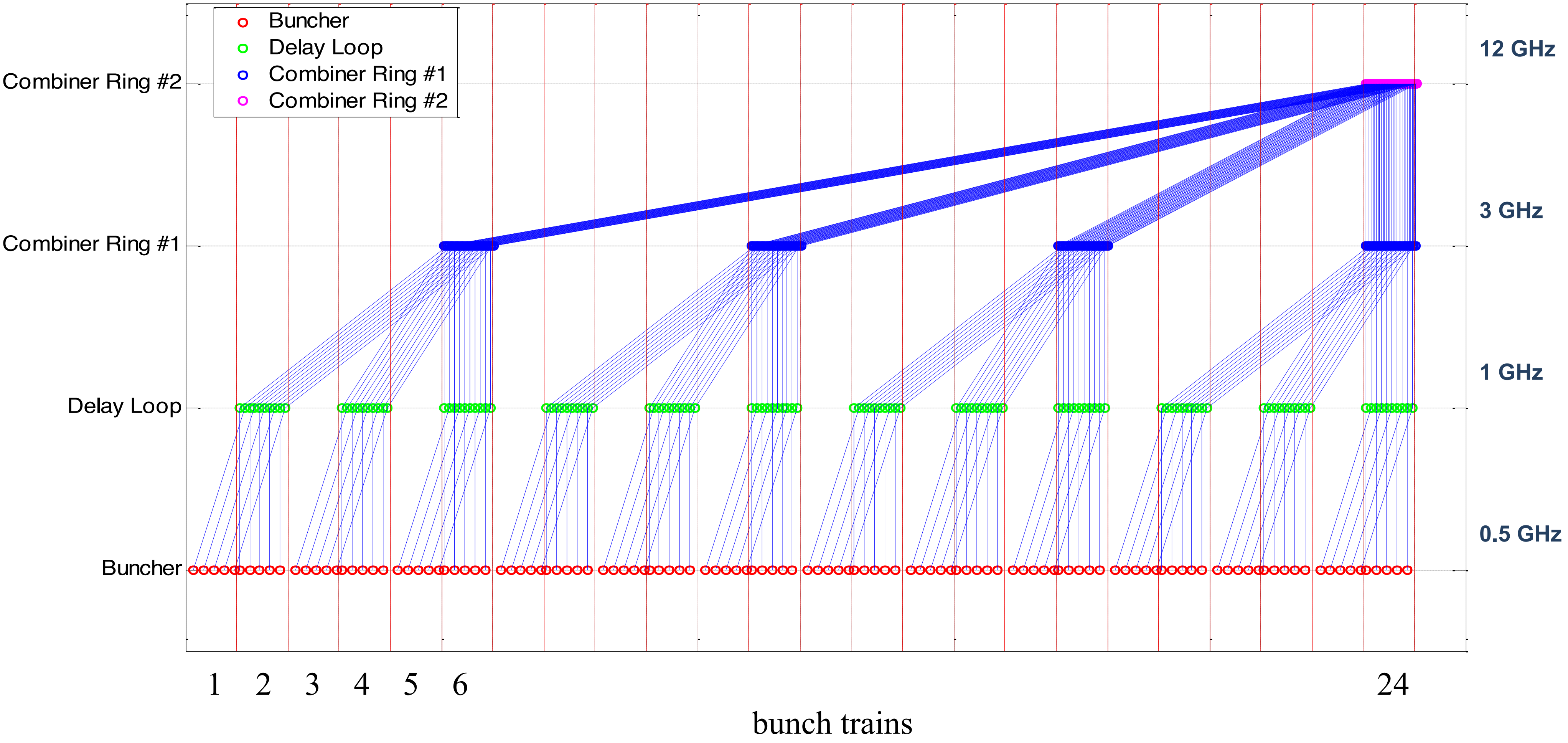
240 ns

5.8 μs

24 pulses – 101 A – 2.5 cm between bunches

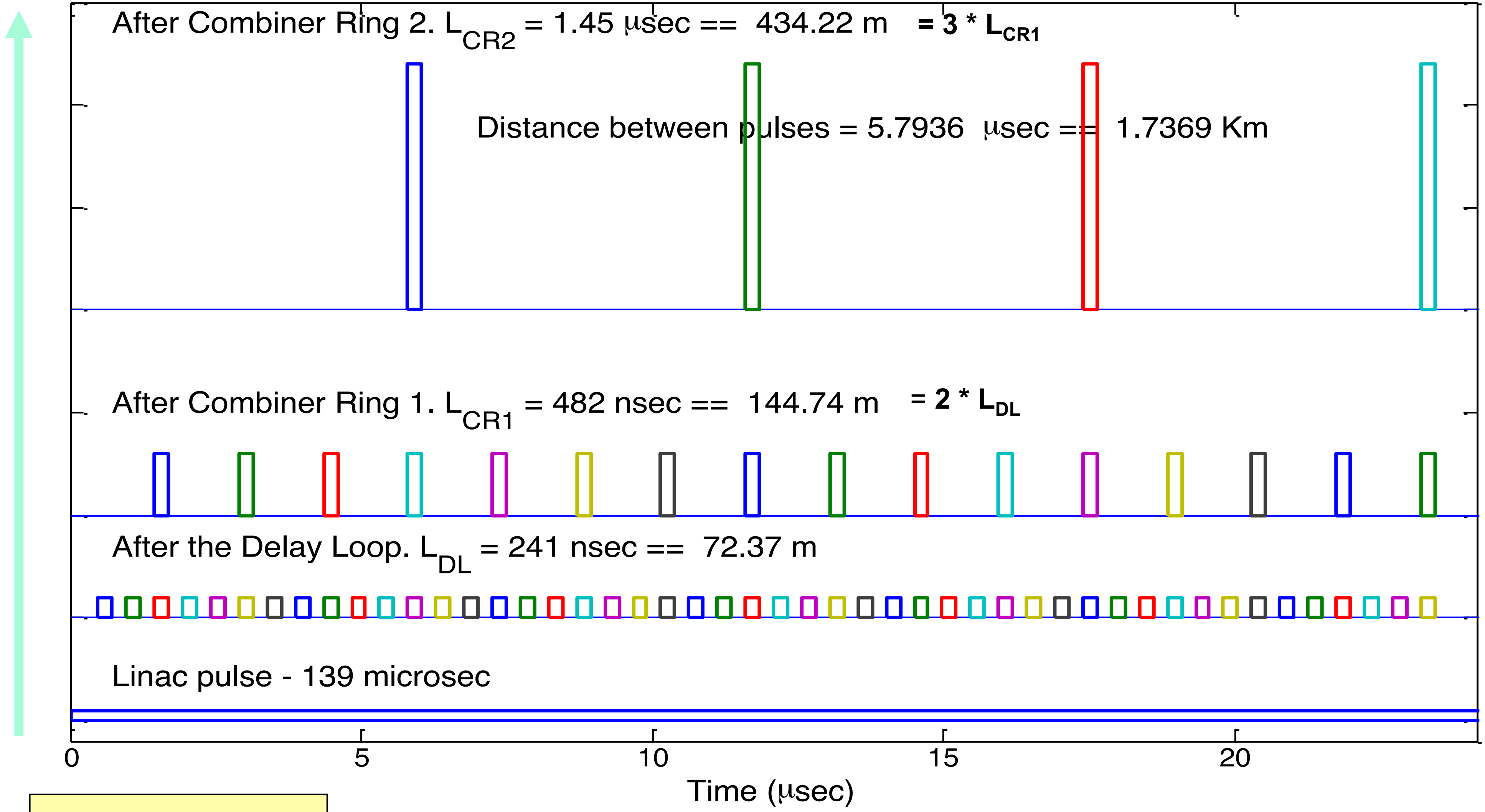
# Drive Beam Combination Steps

$f_{beam} = 4 * 3 * 2 * f_{initial}$



Oleksiy Kononenko

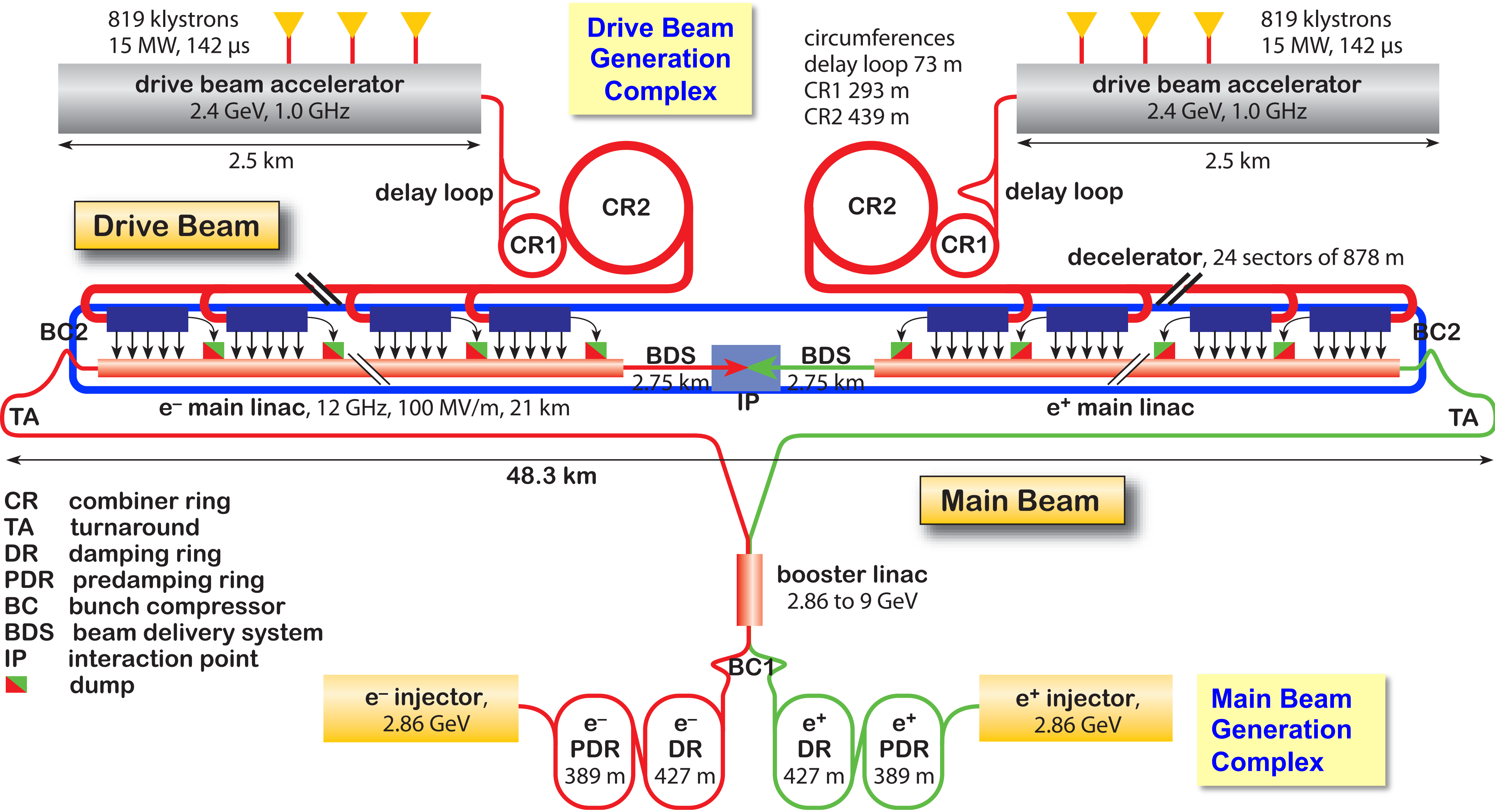
# Drive Beam time structure



=> see homework

C.Biscari

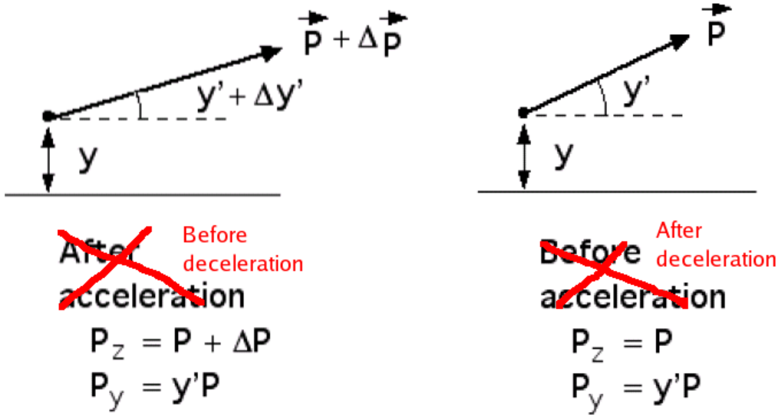
# CLIC – power generation

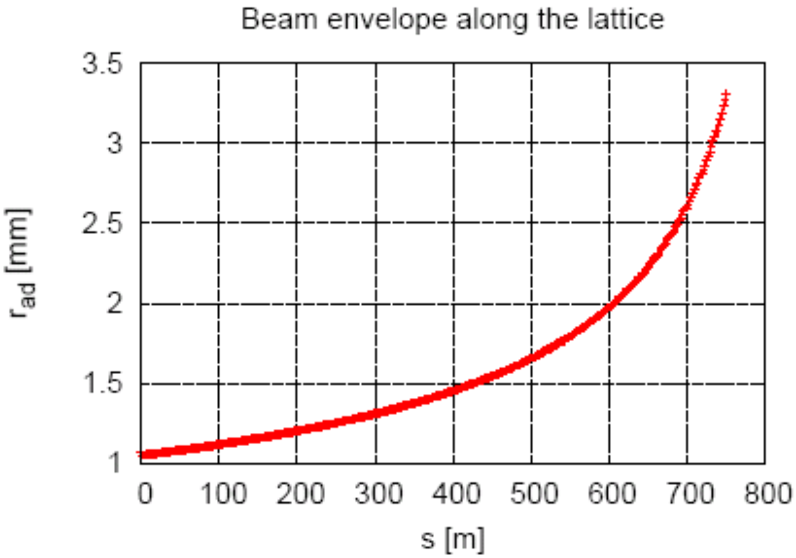


| | |
|---|---|
| **CR** | **combiner ring** |
| **TA** | **turnaround** |
| **DR** | **damping ring** |
| **PDR** | **predamping ring** |
| **BC** | **bunch compressor** |
| **BDS** | **beam delivery system** |
| **IP** | **interaction point** |
| ◩ | **dump** |

# CLIC decelerator

- High current drive beam induces RF fields in special structures
- Particles will be decelerated
- Adiabatic UN-damping increases transverse oscillations
  => emittance growth along the decelerator



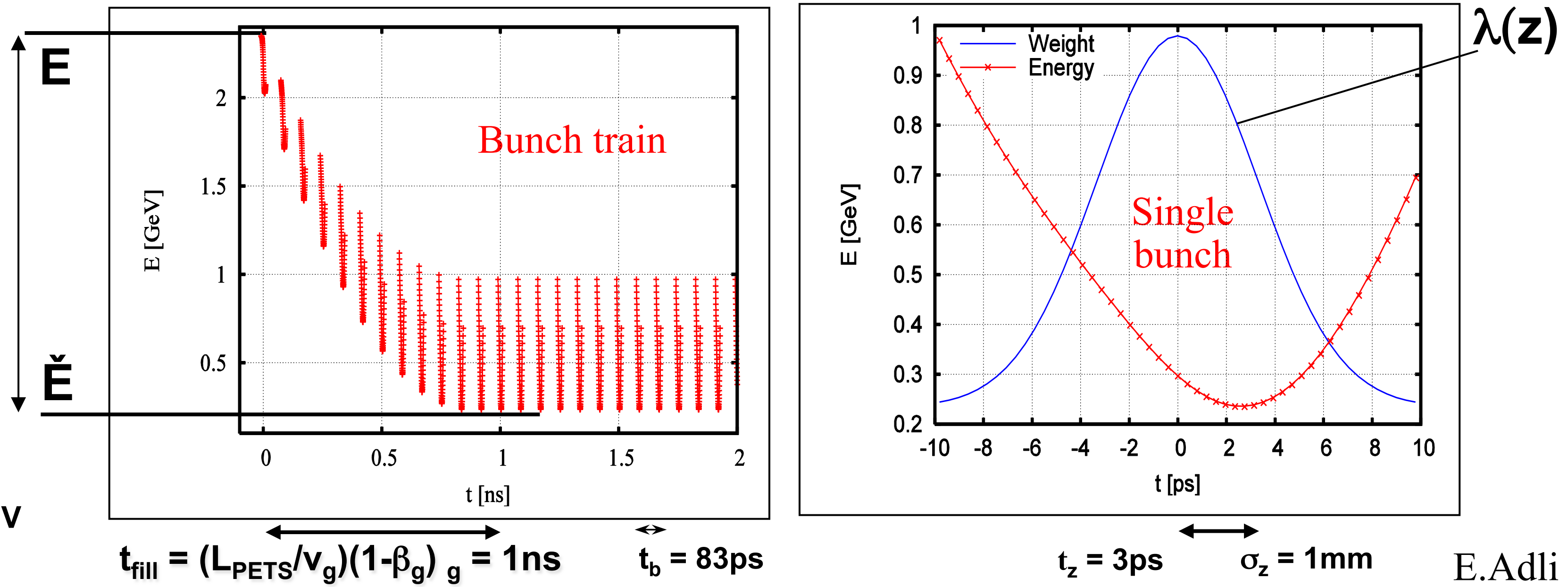


- Sector length trade-off from beam dynamics, efficiency, and cost
- CLIC values: decelerate from 2.37 GeV to 237 MeV => 10%

# Deceleration and beam transport

- 24 decelerator sectors per main linac
  - Each sector receives one drive beam pulse of 240 ns, per main beam pulse
  - Up to S=90% of the initial particle energy is extracted within each pulse leading to an energy extraction efficiency of about 84%
  - after short transient => steady state with large single bunch energy spread

*Resulting energy profile (short* ***transient*** *+ long* ***steady-state****)*



**$S=(E-\check{E})\,/\,E$**
**$= 90\%$**

**$\check{E} = E(1-S)$**
**$=E-N_{PETS}\Delta\hat{E}$ = 240 MeV**

**$t_{fill} = (L_{PETS}/v_g)(1-\beta_g)\ _g$ = 1ns**

**$t_b$ = 83ps**

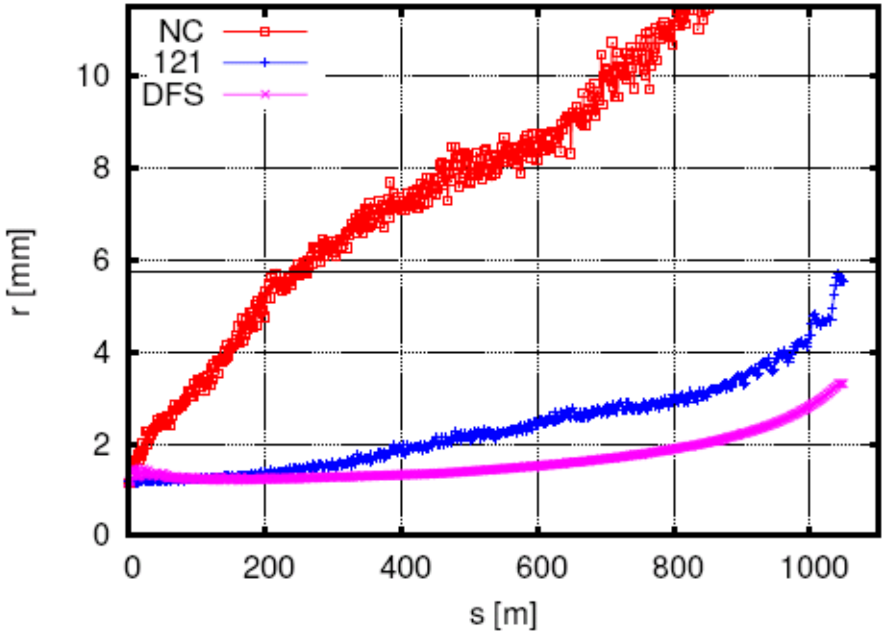
**$t_z$ = 3ps** **$\sigma_z$ = 1mm**

E.Adli

# CLIC decelerator

- Goal: transport particles of all energies through the decelerator sector: in the presence of huge energy spread (90%)
- Tight FODO focusing (large energy acceptance, low beta)
- Lowest energy particles ideally see constant FODO phase-advance μ~90º, higher energy particles see phase-advance varying from μ~90º to μ~10º

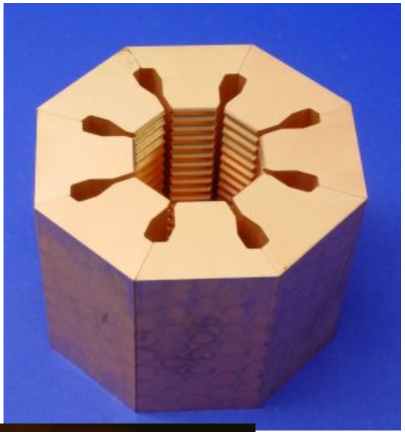
- Good quad alignment needed (20μm)
- Good BPM accuracy (20μm)
- Orbit correction essential
  - 1-to-1 steering to BPM centres
  - DFS (Dispersion Free Steering) gives almost ideal case

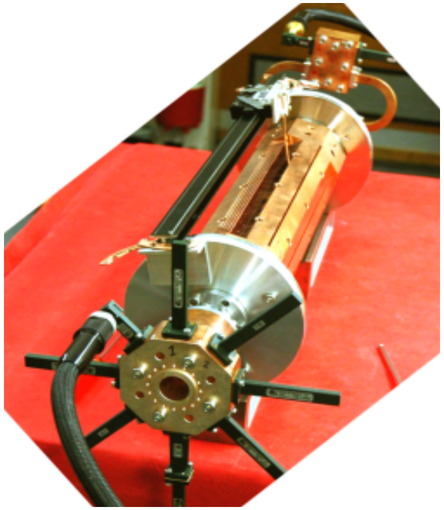


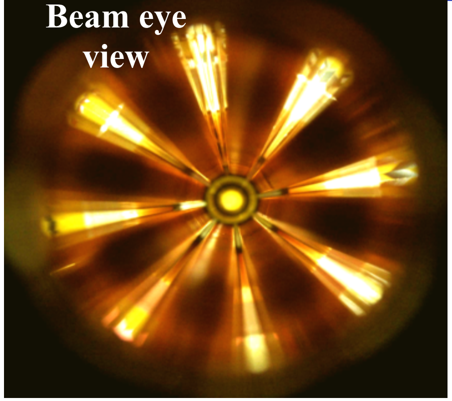
# Power extraction structure PETS

- must extract efficiently >100 MW power from high current drive beam
- passive microwave device in which bunches of the drive beam interact with the impedance of the periodically loaded waveguide and generate RF power
- periodically corrugated structure with low impedance (big a/λ)
- ON/OFF mechanism

=> see homework







The power produced by the bunched ($\omega_0$) beam in a constant impedance structure:

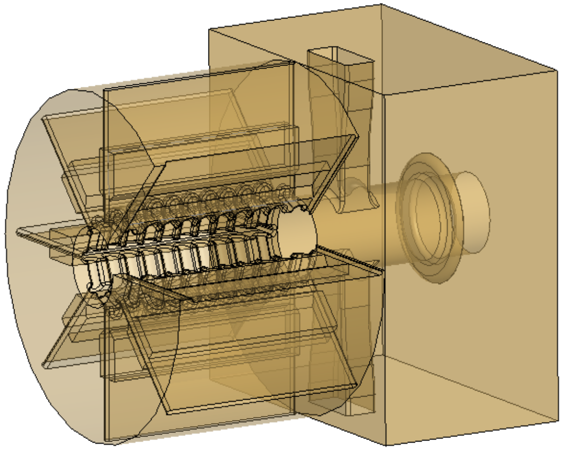
Design input parameters

PETS design

$$P = I^2 L^2 F_b^2 \omega_0 \frac{R/Q}{4 v_g}$$

P – RF power, determined by the accelerating structure needs and the module layout.
I – Drive beam current
L – Active length of the PETS
$F_b$ – single bunch form factor (≈ 1)

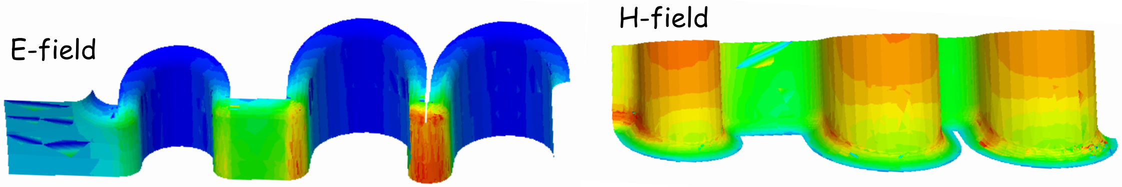
# Power Extraction Structure (PETS)



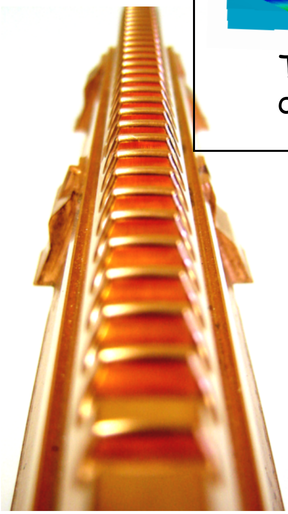
The PETS comprises eight octants separated by the damping slots. Each of the slots is equipped with HOM damping loads.
This arrangement follows the need to provide strong damping of the transverse modes.

PETS parameters:

- Aperture = 23 mm
- Period = 6.253 mm ($90^0$/cell)
- Iris thickness = 2 mm
- R/Q = 2258 Ω
- V group= 0.453
- Q = 7200
- P/C = 13.4
- E surf. (135 MW)= 56 MV/m
- H surf. (135 MW) = 0.08 MA/m
($\Delta$T max (240 ns, Cu) = 1.8 $C^0$)



To reduce the surface field concentration in the presence of the damping slot, the special profiling of the iris was adopted.

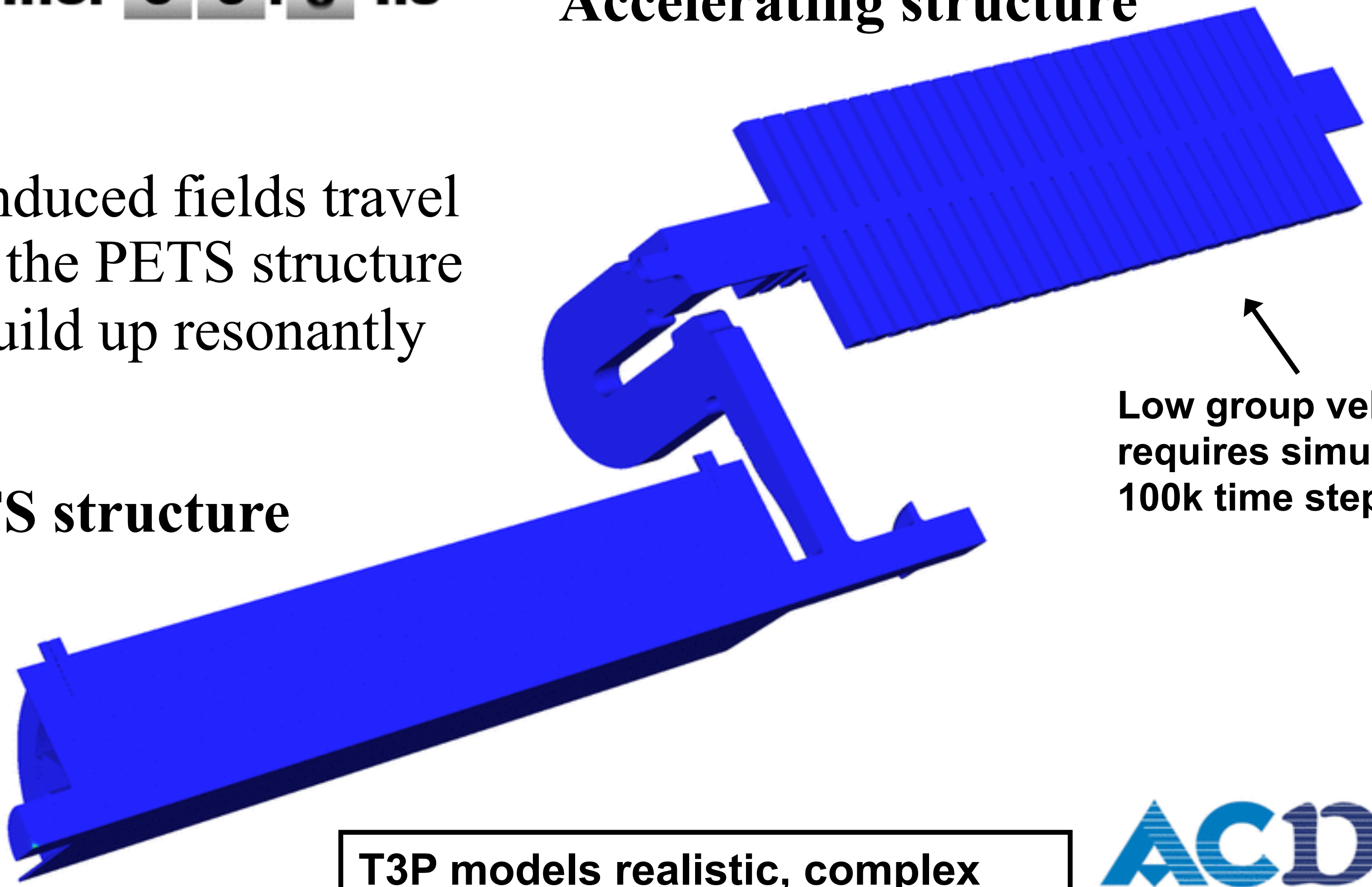


I. Syratchev

# Simulation of RF Power Transfer

**time: 0 0 . 0 ns**

- The induced fields travel along the PETS structure and build up resonantly



**Low group velocity requires simulations with 100k time steps**

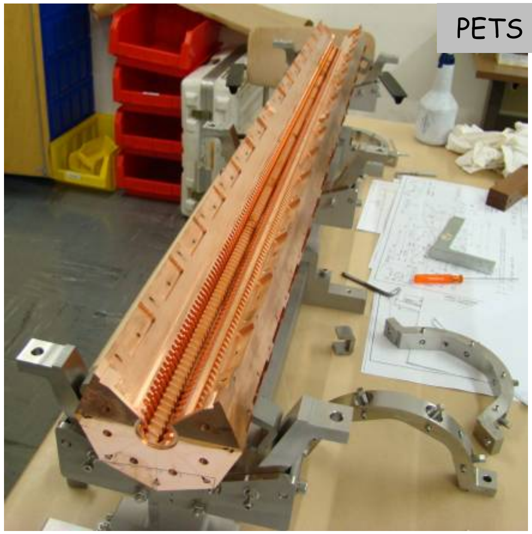
**T3P models realistic, complex accelerator structures with unprecedented accuracy**

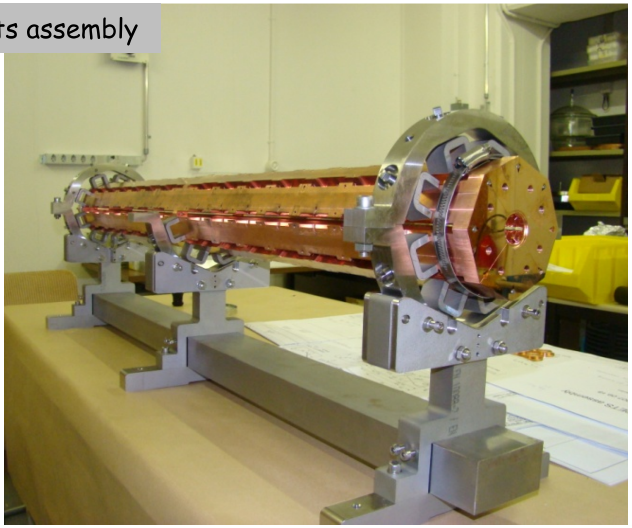
Arno Candel, SLAC

# 12 GHz PETS test assembly

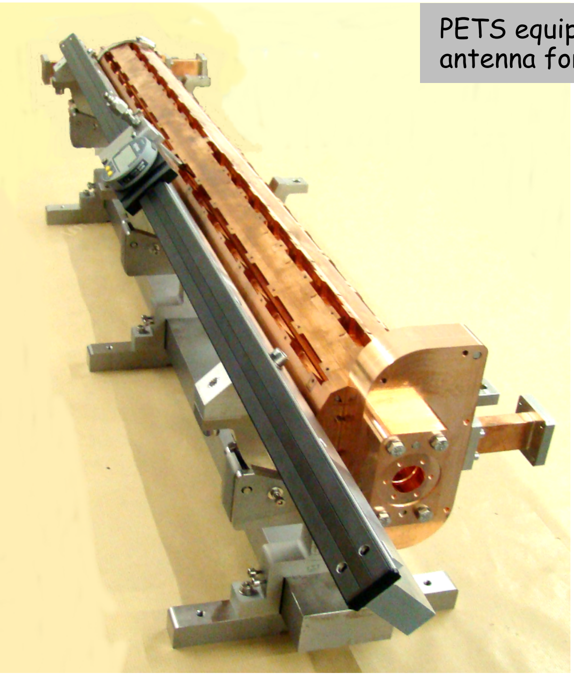

8 bars, as received from VDL

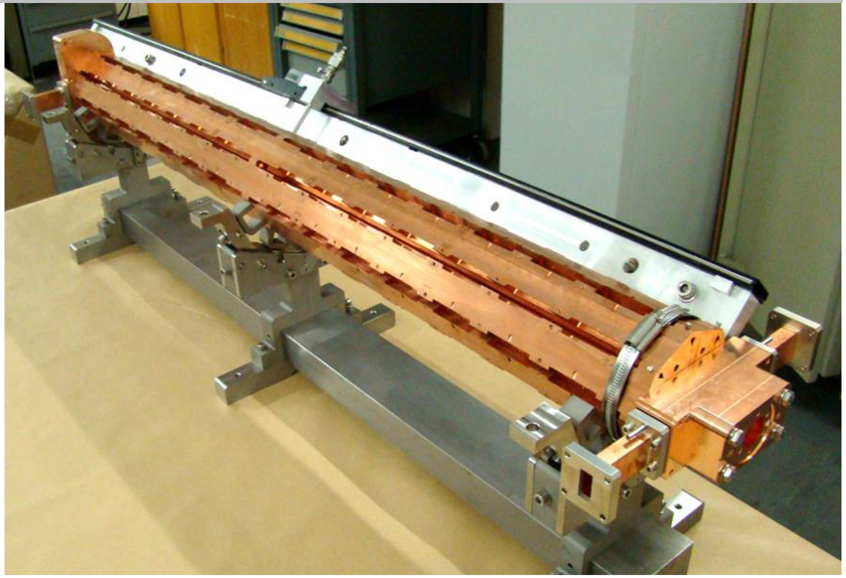
PETS octants assembly

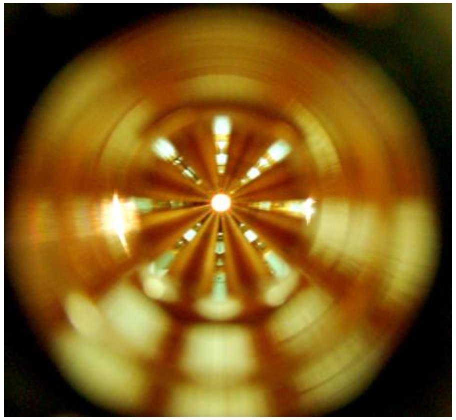




PETS equipped with the power couplers and electronic ruler with pick-up antenna for the phase advance measurements.

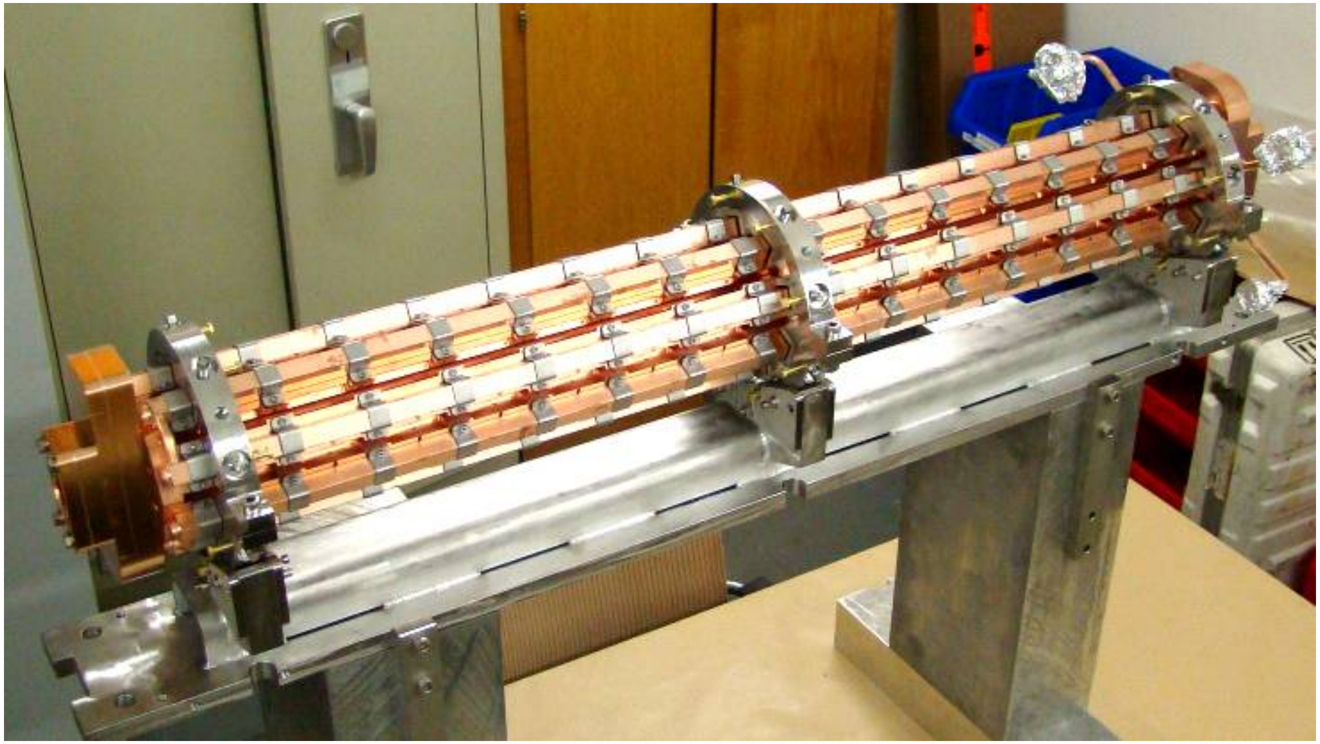


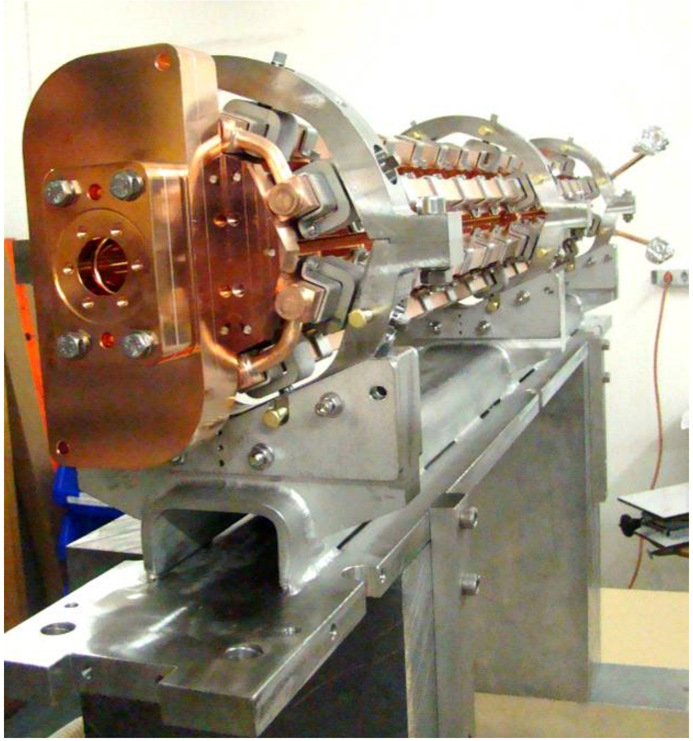


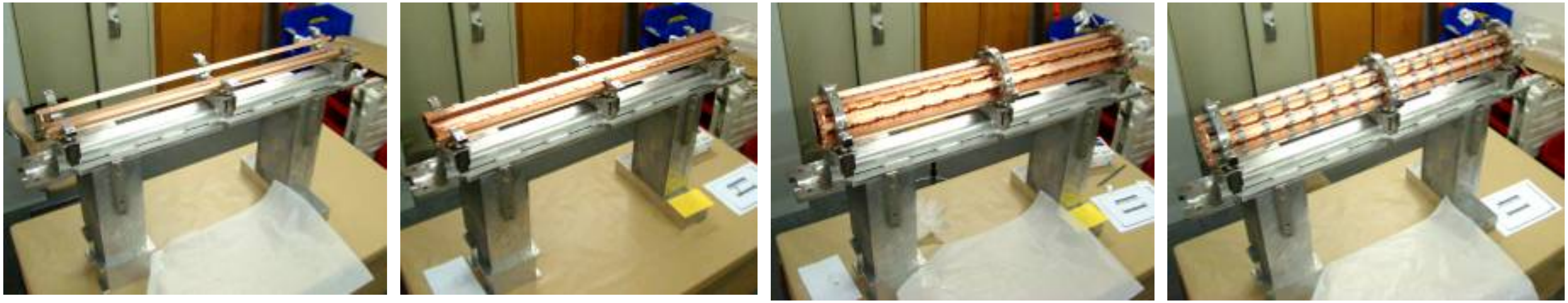


I. Syratchev

# 12 GHz TBTS PETS final assembly





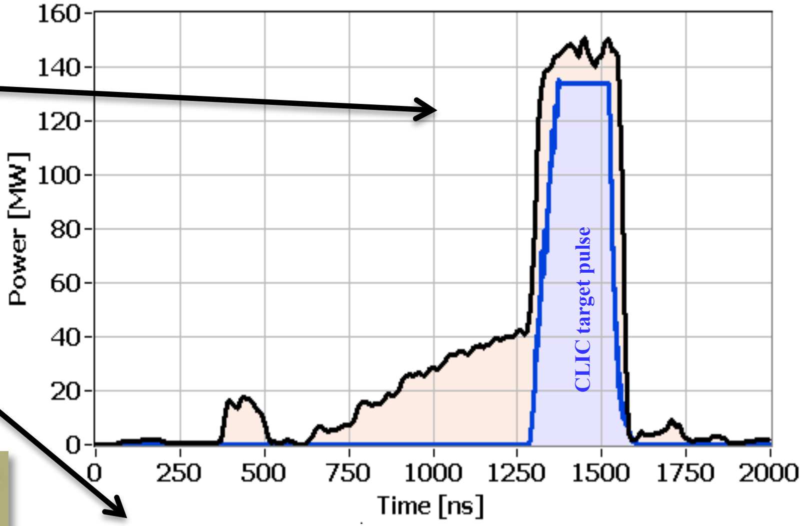


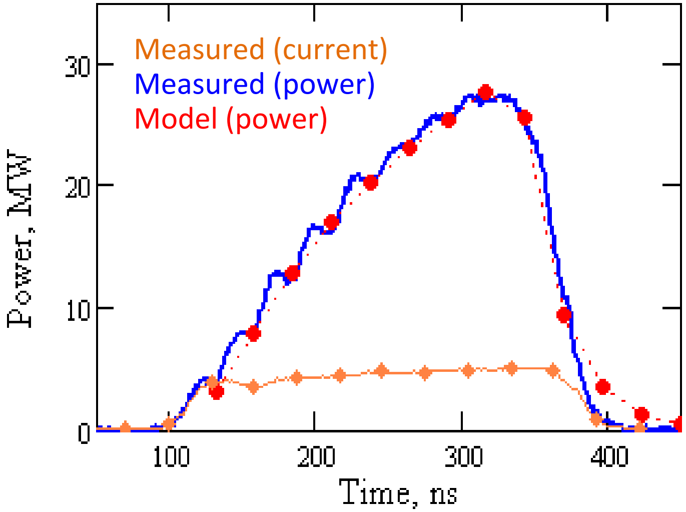
I. Syratchev

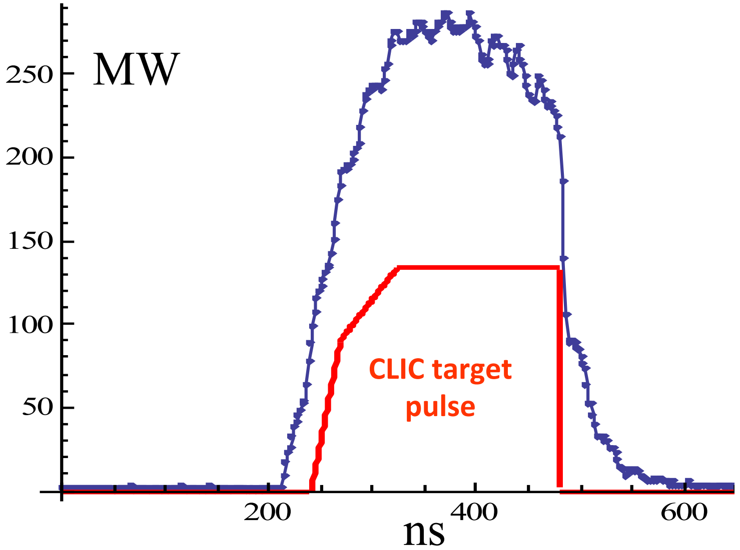
# Present PETS status (12 GHz)

- achieved 150 MW @ 266ns in RF driven test at SLAC
- up to >250 MW peak power beam driven at CTF3 (recirculation)
- model well understood

Typical RF pulse shape in ASTA during the last 125h of operation

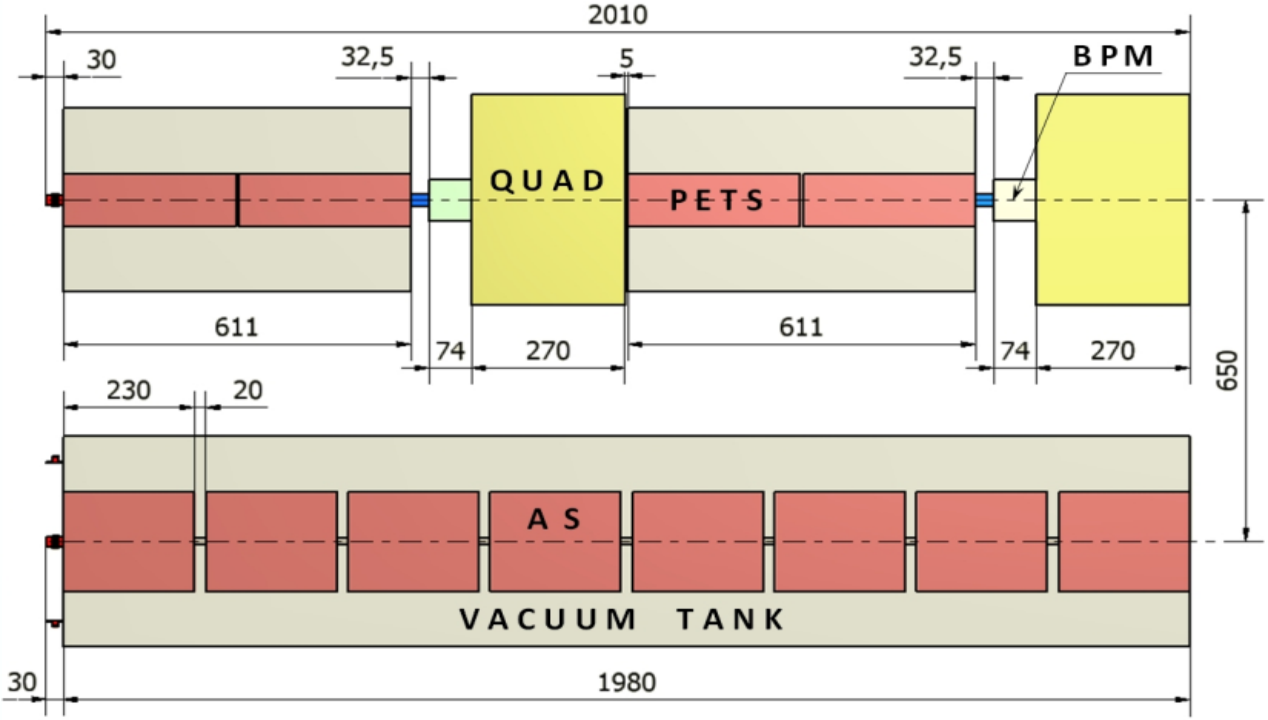






# CLIC two-beam Module layout

Standard module



CLIC STANDARD MODULE LAYOUT

**Total per module**
8 accelerating structures
8 wakefield monitors

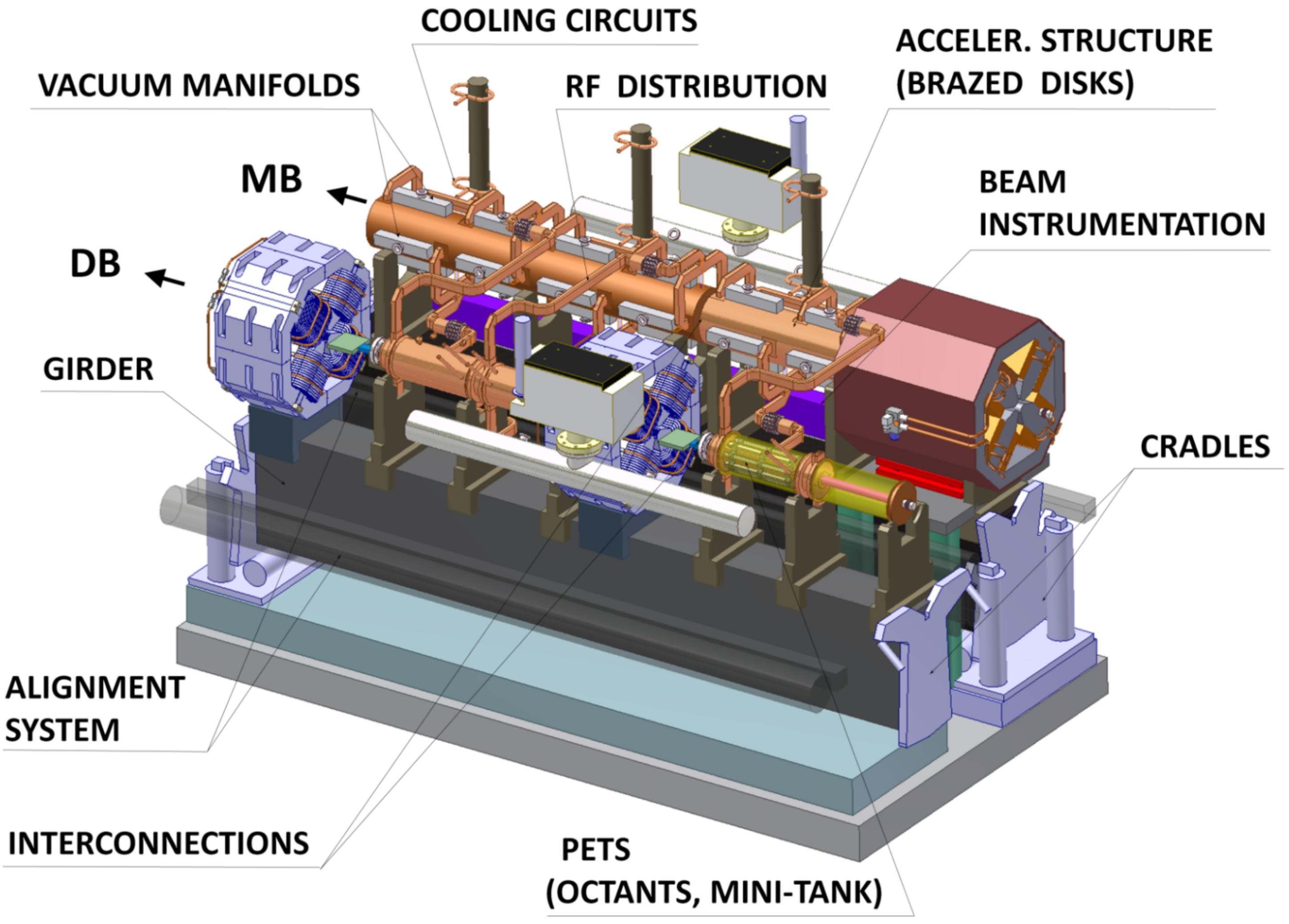
4 PETS
2 DB quadrupoles
2 DB BPM

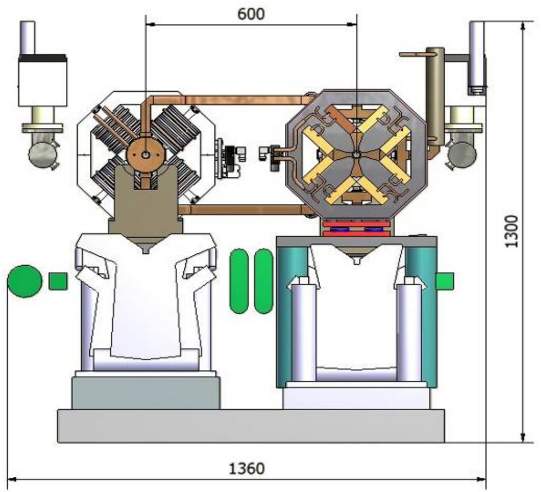
**Total per linac**
8374 standard modules

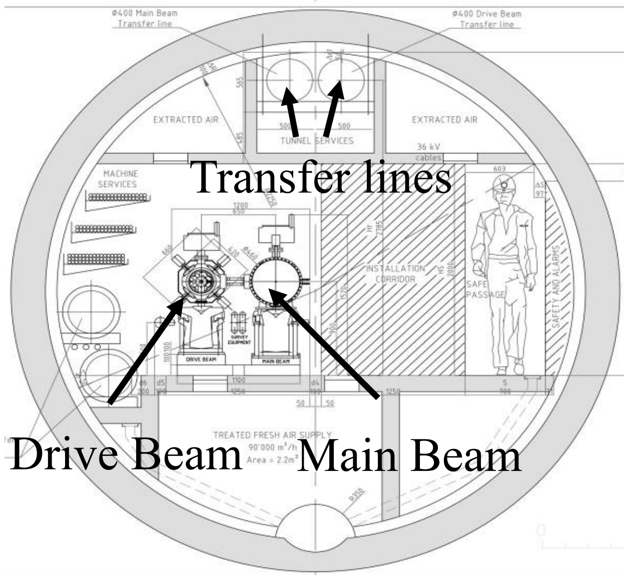
- Other modules have 2,4,6 or 8 acc.structures replaced by a quadrupole (depending on main beam optics)
- Total 10462 modules, 71406 acc. structures, 35703 PETS

G.Riddone

# CLIC two-beam Module



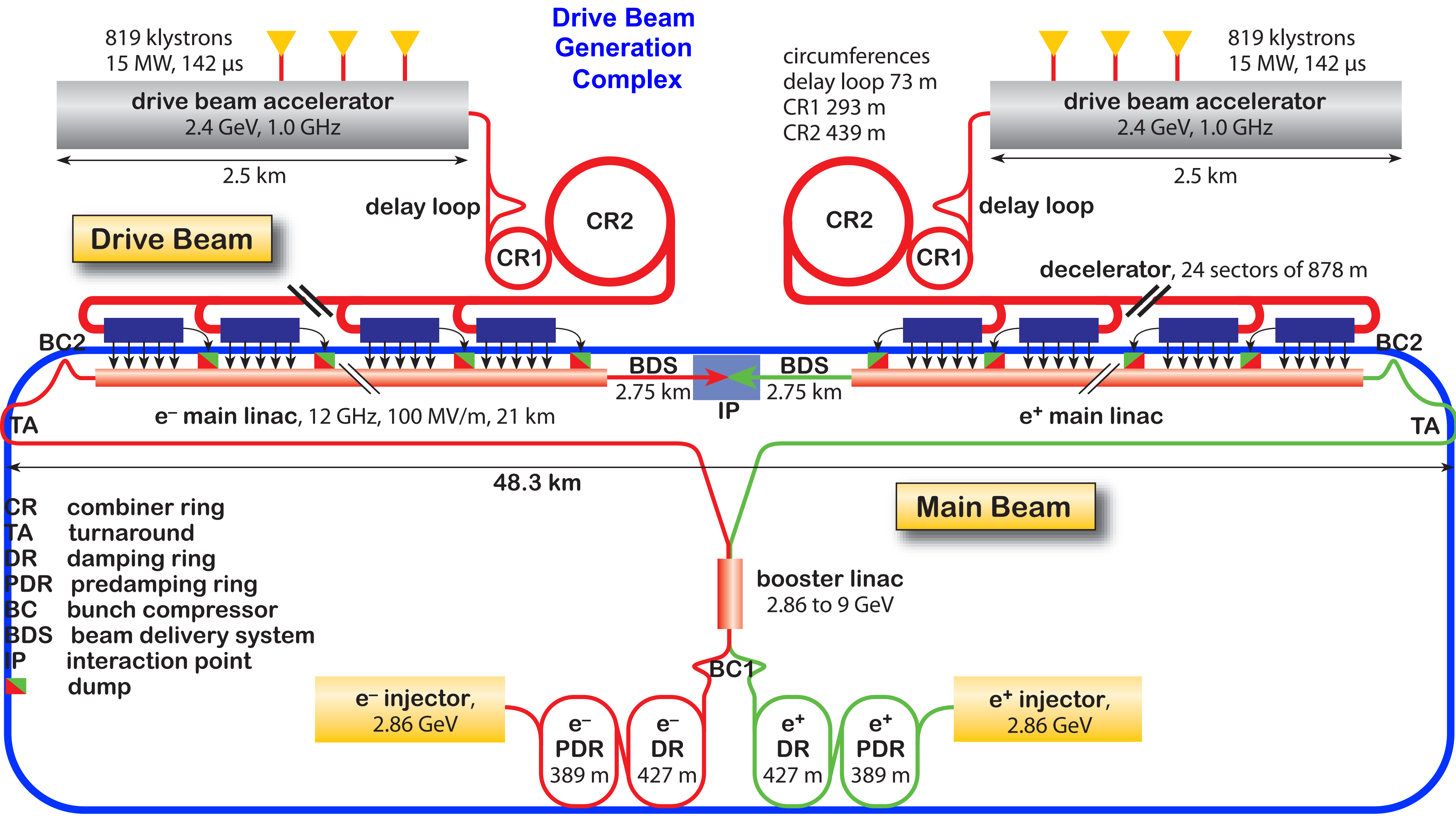




- Alignment system, beam instrumentation, cooling integrated in design

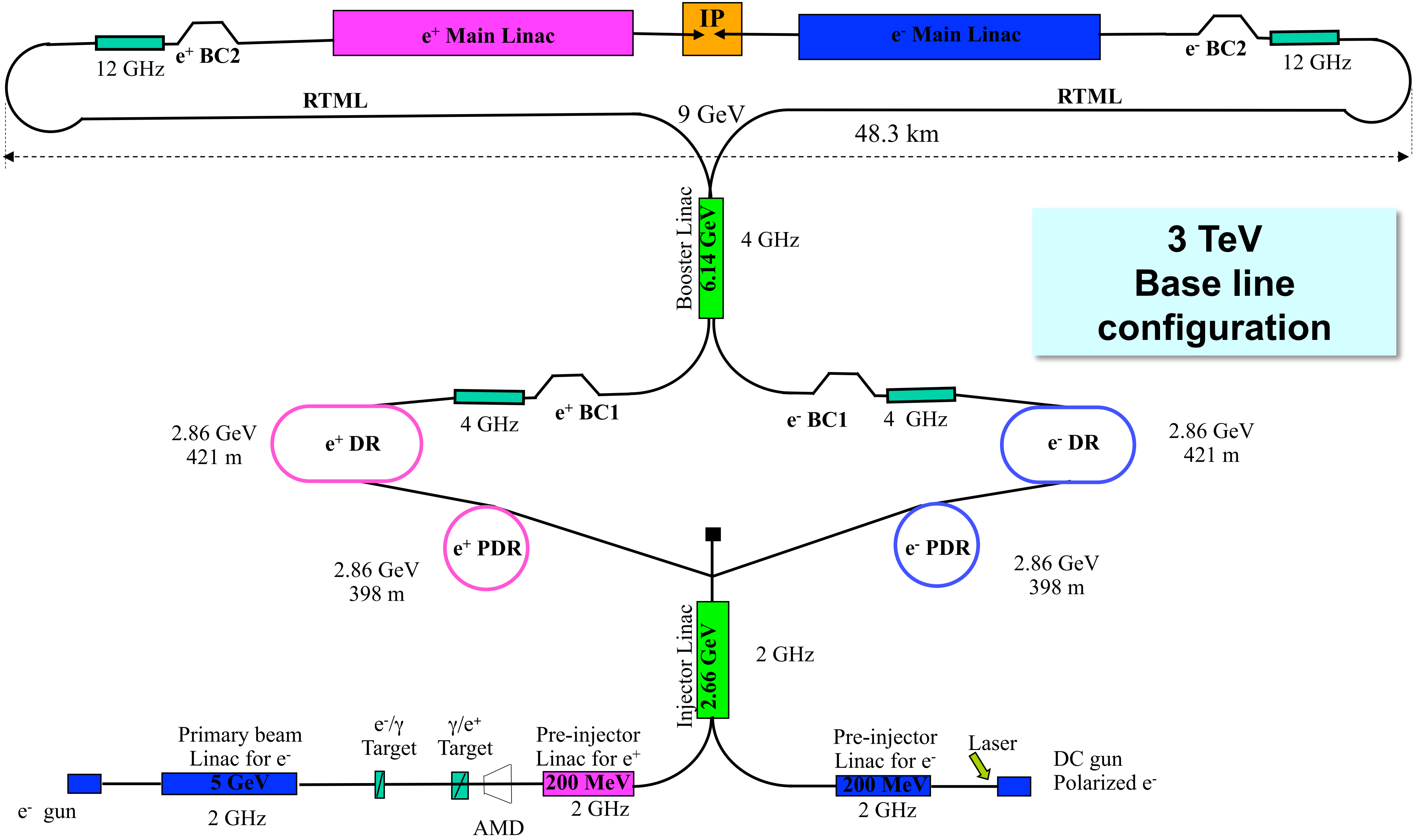
G.Riddone

# CLIC – main beam generation



| | |
|---|---|
| CR | combiner ring |
| TA | turnaround |
| DR | damping ring |
| PDR | predamping ring |
| BC | bunch compressor |
| BDS | beam delivery system |
| IP | interaction point |
| 🟥 | dump |

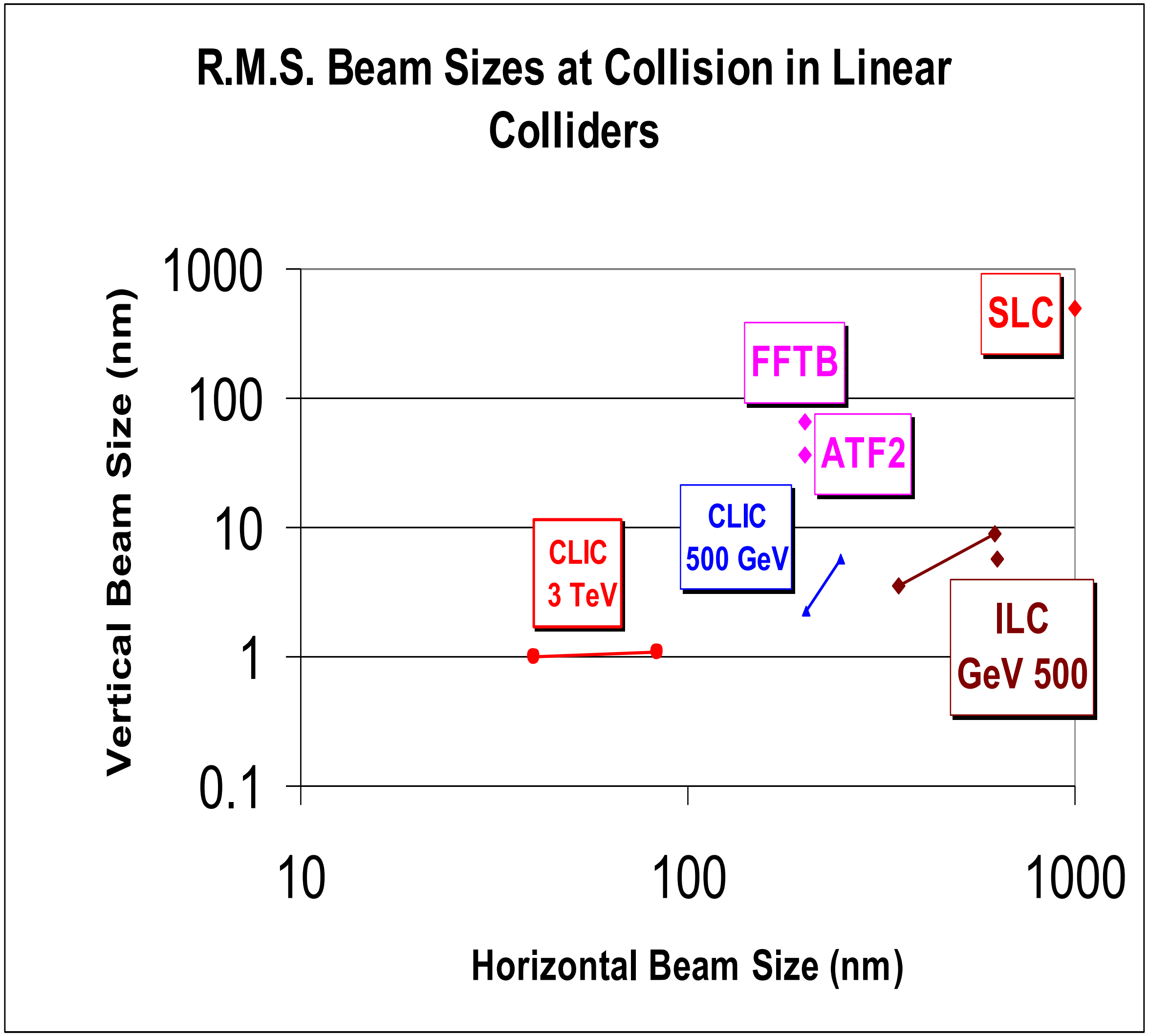
# Main beam Injector Complex



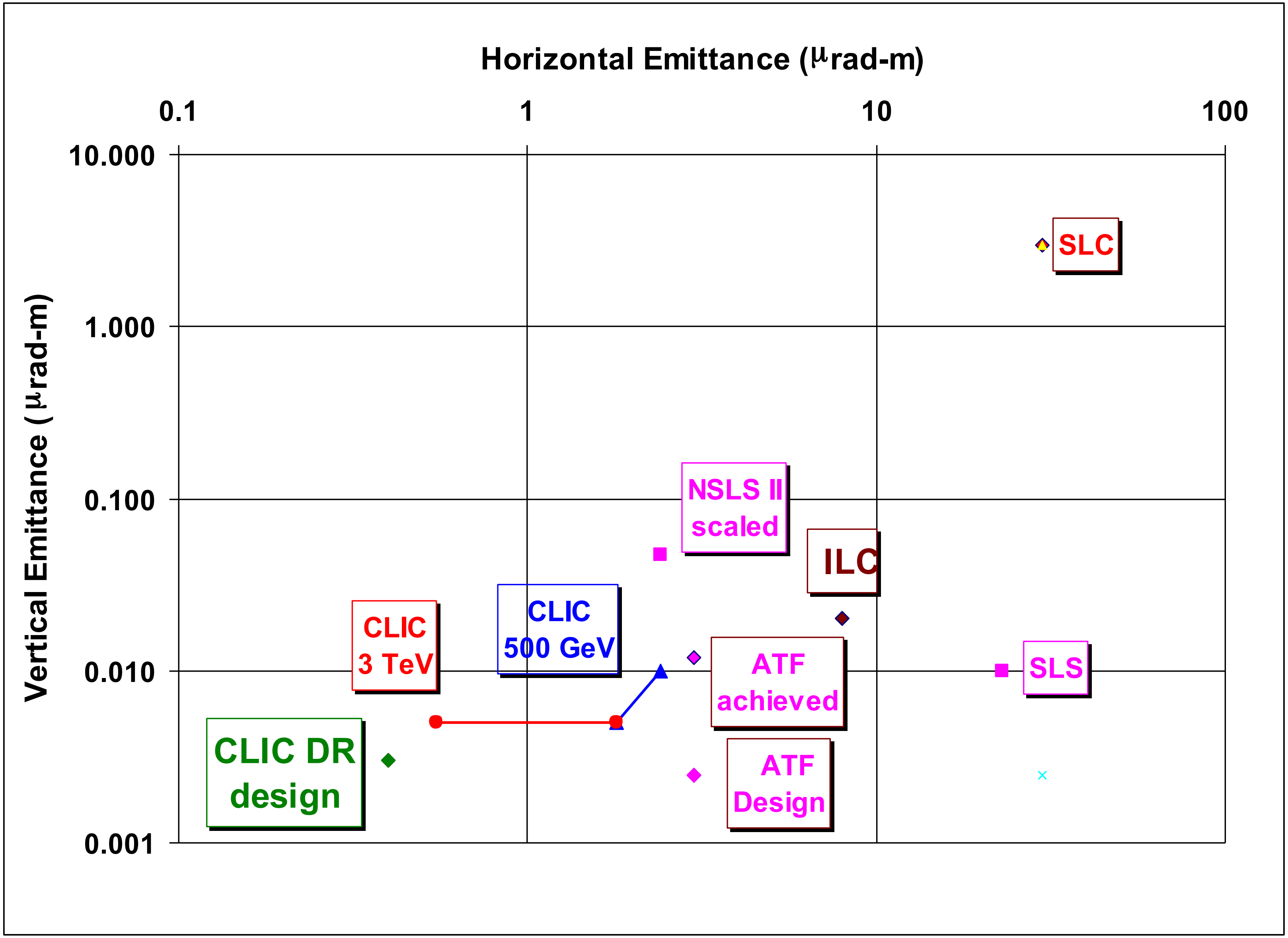
**3 TeV**
**Base line configuration**

# Crucial for luminosity: Emittance

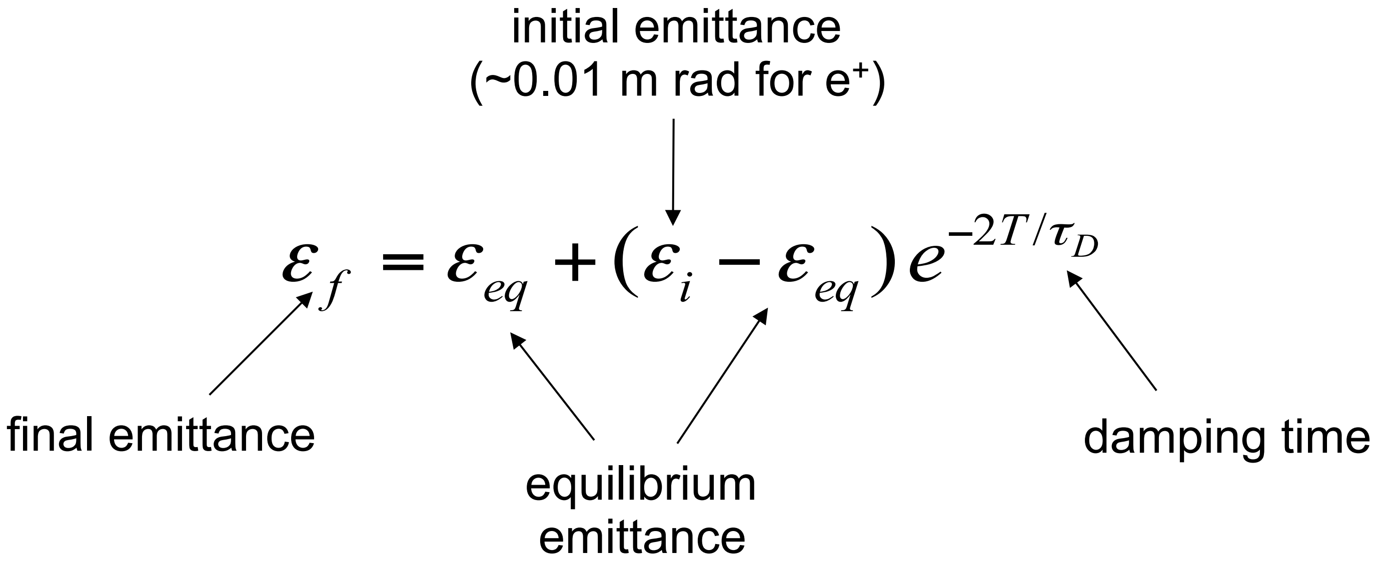
- CLIC aims at smaller beam size than other designs
- Implications:
  - Generate small emittance in the Damping Rings
  - Transport the beam to the IP without significant blow-up
  - Wakefield control
  - Very good alignment
  - Precise instrumentation
  - Beam based corrections and feed-backs



# Damping Ring emittance



# Damping Rings – damping time



initial emittance
(~0.01 m rad for e⁺)

$$\varepsilon_f = \varepsilon_{eq} + (\varepsilon_i - \varepsilon_{eq})\, e^{-2T/\tau_D}$$

final emittance

equilibrium
emittance

damping time

- for e+ we need transverse emittance reduction by few $10^5$
- ~7-8 damping times required
- transverse damping time: $\tau_D = \frac{2E}{P}$ $\qquad P = \frac{2}{3}\frac{r_e c}{(m_o c^2)^3}\frac{E^4}{r^2}$ $\qquad \boxed{\tau_D \propto \frac{\rho^2}{E^3}}$

  $\mathcal{D} \approx 1$

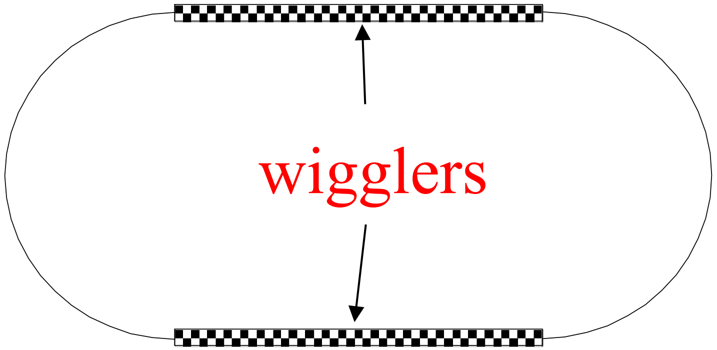
LEP: $E$ ~ 90 GeV, $P$ ~ 15000 GeV/s, $\tau_D$ ~ 12 ms

# Damping rings

- $\tau_D \propto \frac{\rho^2}{E^3}$ suggests high-energy for a small ring. But
  - required RF power: $P_{RF} \propto \frac{E^4}{\rho^2} \times n_b N$
  - equilibrium emittance: $\varepsilon_{n,x} \propto \frac{E^2}{\rho}$ limit E and ρ in practice
- DR example:
  - Take E ≈ 2 GeV
  - $\rho \approx 50$ m
  - P = 27 GeV/s [28 kV/turn]
  - hence $\tau_D \approx$ 150 ms - we need 7-8 $\tau_D$ !!! ⇒ store time too long !!!
- Increase damping and P using wiggler magnets

# Damping Rings

- Bare ring damping time too long
- Insert wigglers in straight sections in the damping ring



- Average power radiated per electron with wiggler straight section

$$P = c\frac{\Delta E_{\text{wiggler}} + \Delta E_{\text{arcs}}}{L_{\text{wiggler}} + 2\pi\rho_{\text{arcs}}}$$

$\Delta E_{\text{wiggler}}$ energy loss in wiggler
$\Delta E_{\text{arcs}}$ energy loss in the arcs
$L_{\text{wiggler}}$ total length of wiggler

- Energy loss in wiggler:

$$\Delta E_{\text{wiggler}} \approx \frac{K_\gamma}{2\pi} E^2 \left\langle B^2 \right\rangle L_{\text{wiggler}} \text{ with } K_\gamma \approx 8\cdot 10^{-6}\,\text{GeV}^{-1}\text{Tesla}^{-2}\text{m}^{-1}$$

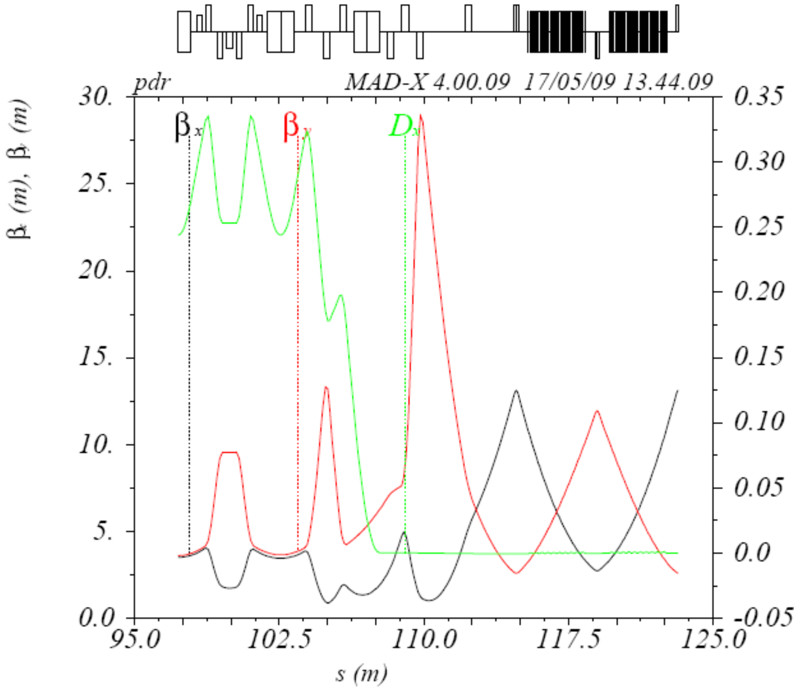
$\langle B^2 \rangle$ is the field square averaged over the wiggler length

# CLIC Pre-Damping Rings

- Most critical the e$^+$ PDR
  - Injected e$^+$ emittance ~ 2 orders of magnitude larger than for e$^-$
    i.e. aperture limited if injected directly into DR
- PDR for e$^-$ beam necessary as well
  - A "zero current" e$^-$ beam (no IBS) would need ~ 17ms to reach equilibrium in DR
    (very close to repetition time of 20ms – 50 Hz)
- 398m long race-track PDRs with 120m of wigglers
  - Target emittance reached with the help of conventional high-field wigglers (PETRA3)
  - Wiggler Parameters: $B_w$=1.7 T, $L_w$=3 m, $\lambda_w$=30 cm
  - 15 TME arc cells + 2 Disp.Suppr. + 2 matching sections per arc, 10 FODO cells in each straight section
  - Transverse damping time $\tau_{x,y}$=2.3 ms
  - e+ emittances reduced to $\gamma\varepsilon$ = 18 mm.mrad

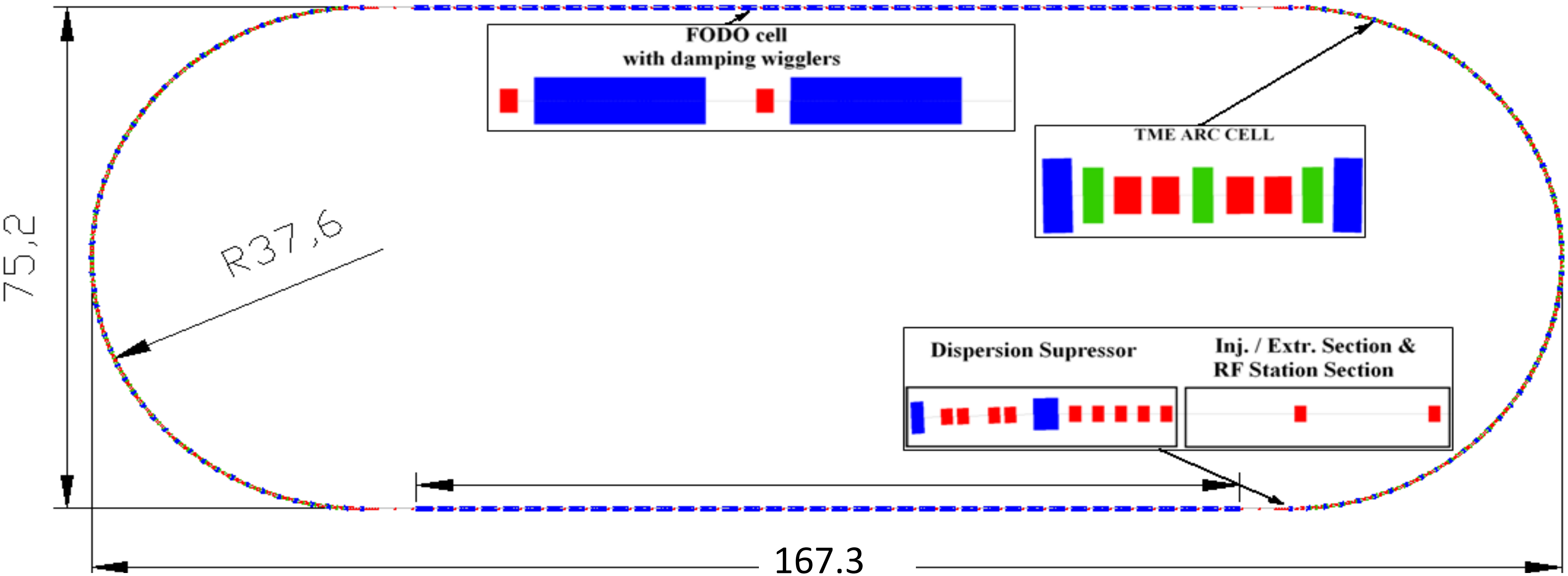
Pre-Damping Ring input

| Parameter | Unit | e$^-$ | e$^+$ |
|---|---|---|---|
| Energy (E) | GeV | 2.86 | 2.86 |
| No. of particles/bunch (N) | $10^9$ | 4.4 | 6.4 |
| Bunch length (rms) ($\sigma_z$) | mm | 1 | 10 |
| Energy Spread (rms) ($\sigma_E$) | % | 0.1 | 8 |
| Hor./vert. emittance ($\gamma\varepsilon_{x,y}$) | mm. mrad | 100 | 7000 |



Fanouria Antoniou

# CLIC damping ring layout



- Total length 421m (much smaller than ILC), beam pulse only 47m
- Racetrack shape with
  - 96 TME arc cells (4 half cells for dispersion suppression)
  - 26 Damping wiggler FODO cells in the long straight sections

# CLIC damping rings

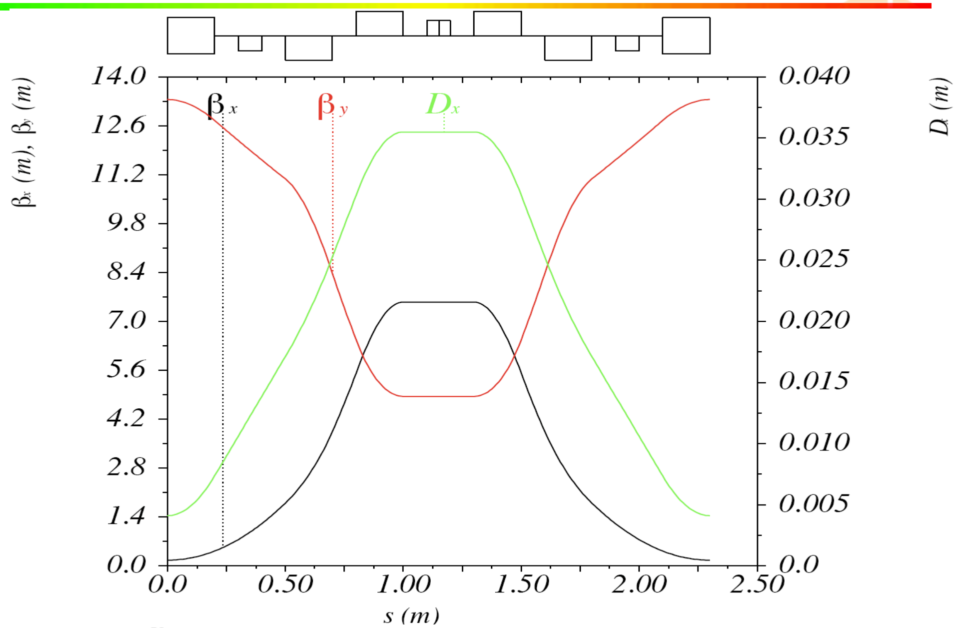
- Two rings of racetrack shape at energy of 2.86 GeV
- Arcs: 2.36 m long cells
  straight sections: FODO cells with 2m-long superconducting damping wigglers (2.5T, 5cm period)
  total length of 421 m
- chromaticity is controlled by two sextupole families.
- Transverse damping time $\tau_{x,y}$=1.88 ms
- Final normalized emittance:

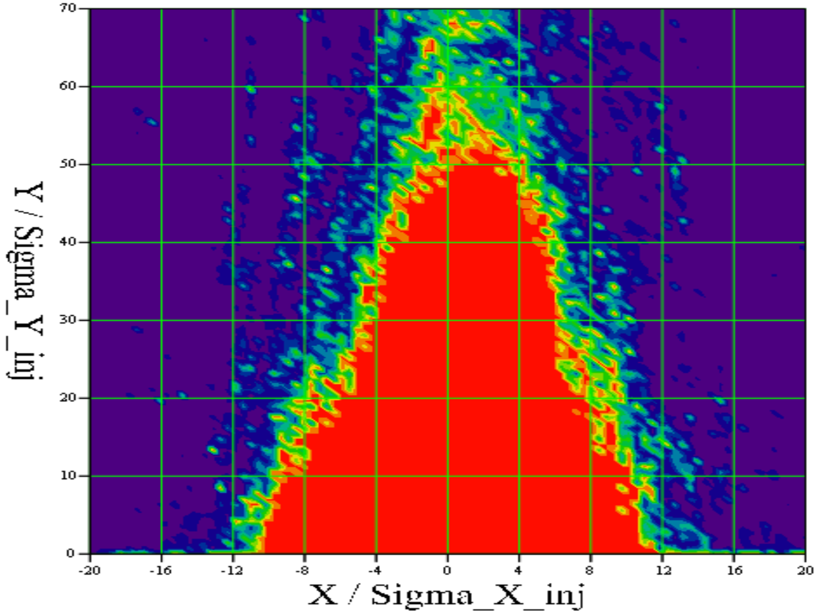
  $\gamma\varepsilon_x$= 400 nm.rad, $\gamma\varepsilon_y$= 4.5 nm.rad

| Parameters | Value |
|---|---|
| Energy [GeV] | 2.86 |
| Circumference [m] | 420.56 |
| Coupling | 0.0013 |
| Energy loss/turn [MeV] | 4.2 |
| RF voltage [MV] | 4.9 |
| Natural chromaticity x / y | -168/-60 |
| Momentum compaction factor | 8e-5 |
| Damping time x / s [ms] | 1.9/ 0.96 |
| Dynamic aperture x / y [$\sigma_{inj}$] | 30 / 120 |
| Number of dipoles/wigglers | 100/52 |
| Cell /dipole length [m] | 2.36 / 0.43 |
| Dipole/Wiggler field [T] | 1.4/2.5 |
| Bend gradient [$1/m^2$] | -1.10 |
| Max. Quad. gradient [T/m] | 73.4 |
| Max. Sext. strength [$kT/m^2$] | 6.6 |
| Phase advance x / z | 0.452/0.056 |
| Bunch population, [$10^9$] | 4.1 |
| IBS growth factor | 1.4 |
| Hor./ Ver Norm. Emittance [nm.rad] | 400 / 4.5 |
| Bunch length [mm] | 1.6 |
| Longitudinal emittance [keVm] | 5.5 |

# DR arc and dynamic aperture

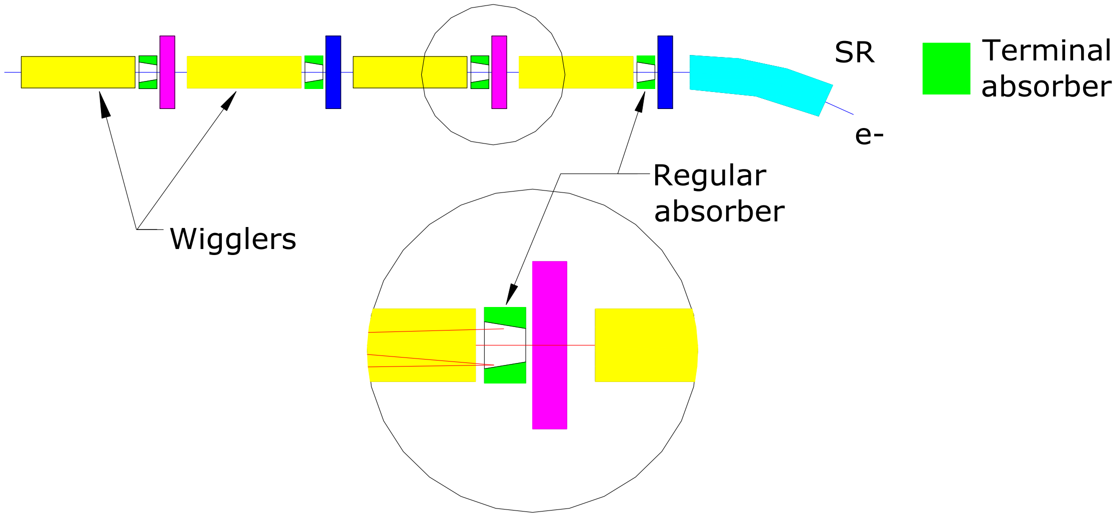
- Combined function bends with small gradient (as in NLC DR and ATF)
- Increasing space, reducing magnet strengths
- Reducing chromaticity, increasing dynamic aperture (we need to accommodate a high emittance beam at injection!)
- Intra-Beam-Scattering (IBS) becomes very important for tiny emittance and beam size
- other important effects:
  - electron cloud (special chamber coating)
  - fast ion instability (good vacuum)



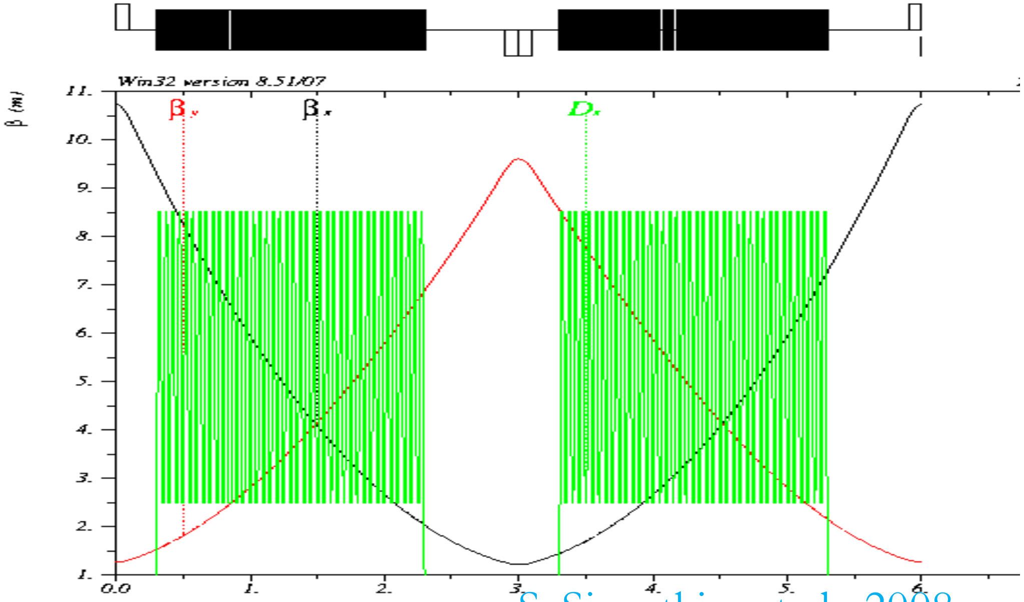


# Wiggler cell including absorbers

- Stronger wiggler fields and shorter wavelengths necessary to reach target emittance due to strong IBS
- With super-conducting wigglers, the achieved normalized horizontal emittance drops below 400nm



- Superconducting wigglers need to be shielded from synchrotron radiation (several kW/m)
- Space between wiggler and downstream quadrupoles for accommodating SR absorbers
- Horizontal phase advance optimised for lowering IBS, vertical phase advance optimised for aperture



S. Sinyatkin, et al., 2008

# Alignment + Stabilisation

- Acceptable wakefield levels from beam dynamics studies have been used already in the structure design stage
- Alignment procedure based on
  - Accurate pre-alignment of beam line components (O(10µm))

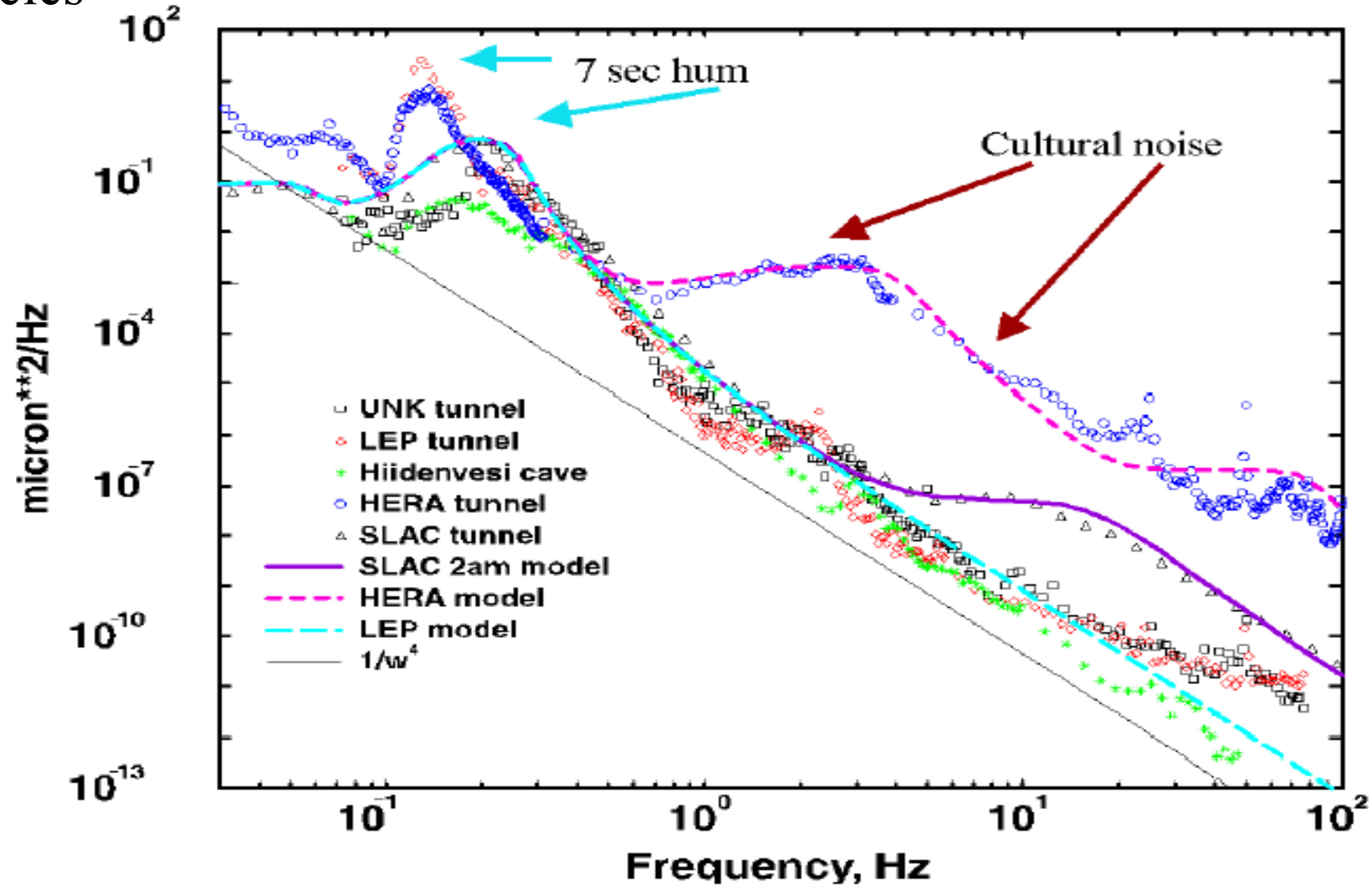
| | |
|---|---|
| accelerating structures | 14 µm (transverse tolerance at 1σ) |
| PETS structures | 30 µm |
| quadrupole | 17 µm |

  - Beam-based alignment using BPMs with good resolution (100nm)
  - Alignment of accelerating structures to the beam using wake-monitors (5µm accuracy)
  - Tuning knobs using luminosity/beam size measurement with resolution of 2%

- Quadrupole stabilisation (O(1nm) above 1Hz)
- Feedback using BPMs resolving 10% of beam size (i.e. 50nm resolution)

# Ground Motion

- Site dependent ground motion with decreasing amplitude for higher frequencies



# Ground motion: ATL law

- Need to consider short and long term stability of the collider
- Ground motion model: ATL law

$$\left\langle \Delta y^2 \right\rangle = ATL$$

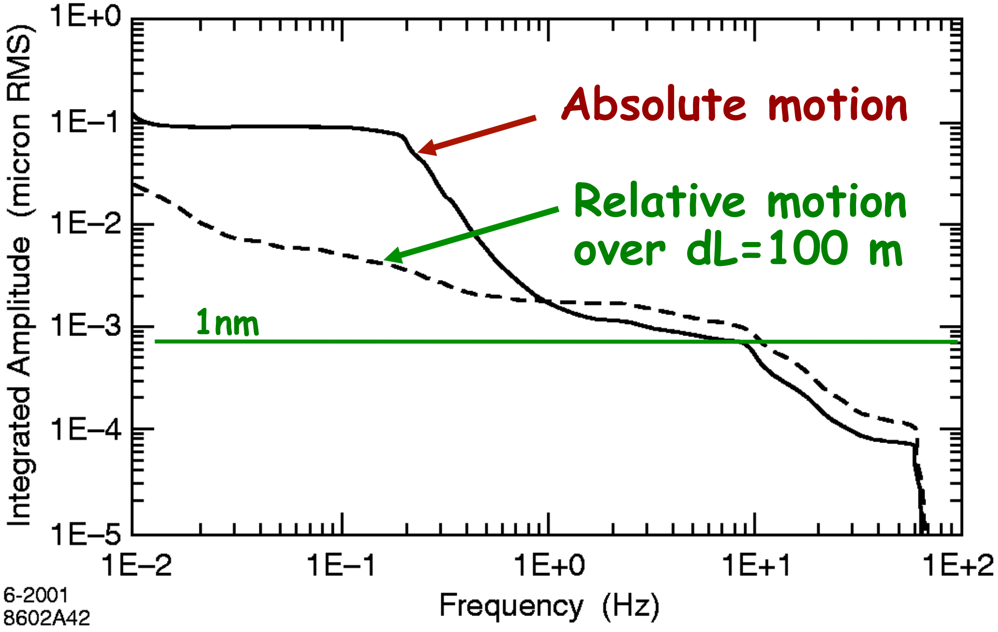
$A$ range $10^{-5}$ to $10^{-7}\,\mu\mathrm{m}^2/\mathrm{m/s}$

$A$ site dependent constant

$T$ time

$L$ distance

- This allows you to simulate ground motion effects
- Relative motion smaller
- Long range motion less disturbing



# Stability Studies

Vertical spot size at IP is ~ 1 nm *(10 x size of water molecule)*

Stability requirements (> 4 Hz) for a 2% loss in luminosity

| Magnet | horizontal | vertical |
|---|---|---|
| Linac (2600 quads) | 14 nm | 1.3 nm |
| Final Focus (2 quads) | 4 nm | 0.2 nm |

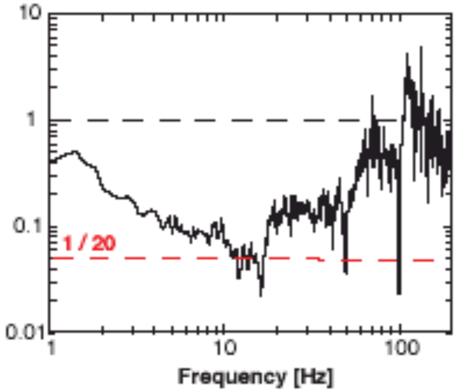
→ Need active damping of vibrations


CERN vibration test stand

# Ground motion

## Vertical stabilization of a CLIC prototype quadrupole

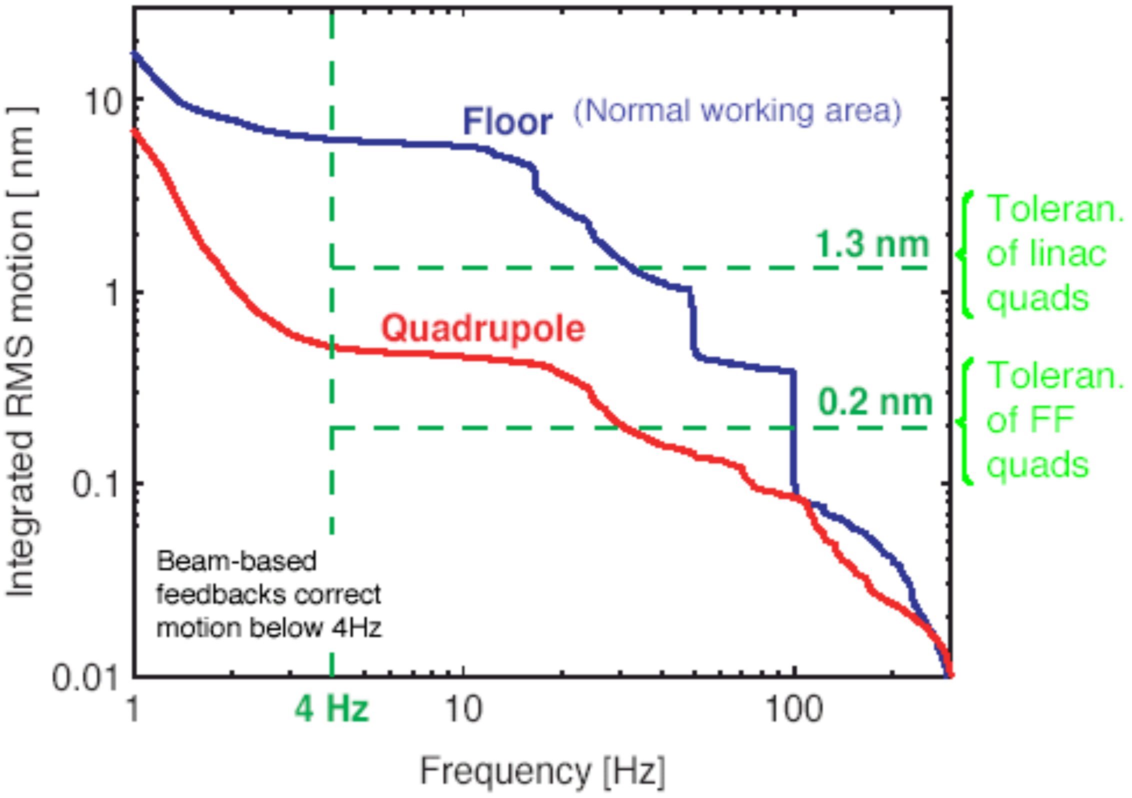
Ground-to-table transmission



**RMS vibrations above 4 Hz**

| | Quad [nm] | Ground [nm] |
|---|---|---|
| Vertical | **0.43** | **6.20** |
| Horizontal | **0.79** | **3.04** |
| Longitud. | 4.29 | 4.32 |

Integrated *vertical* RMS motion versus frequency



Beam-based feedbacks correct motion below 4Hz

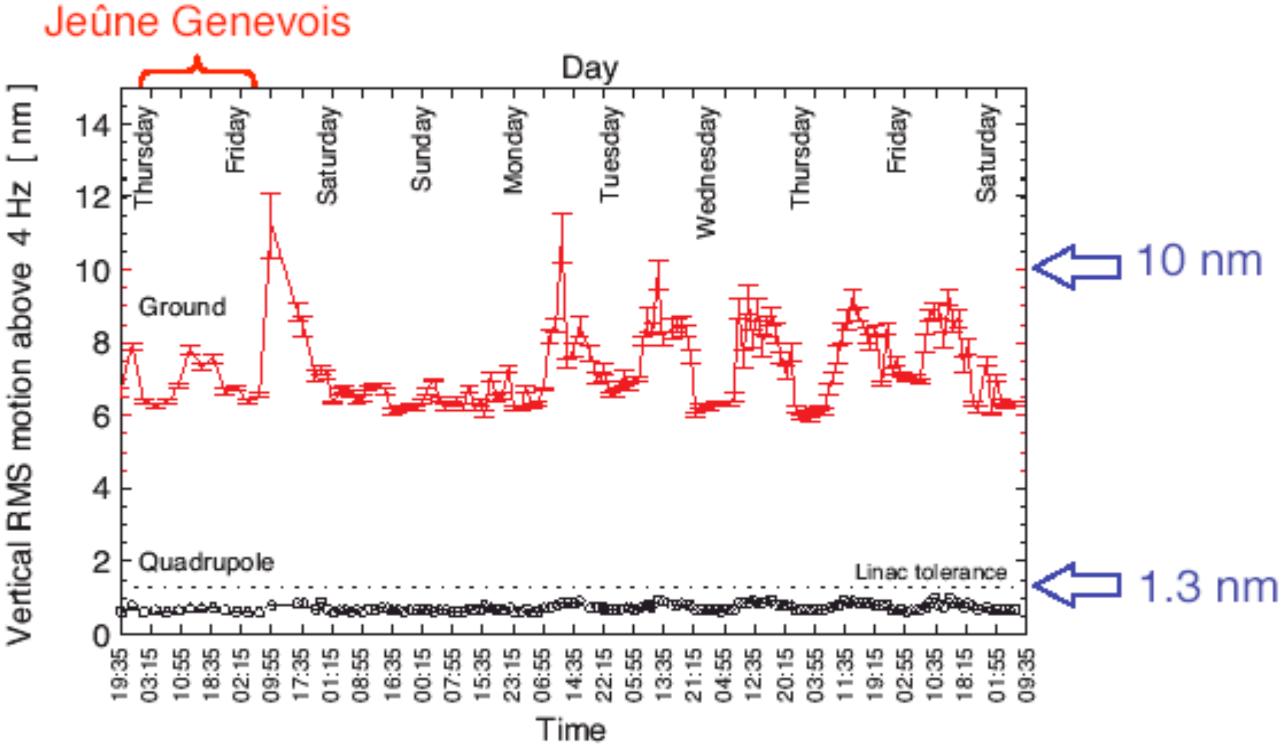
**CLIC prototype magnets stabilized to the sub-nanometre level !!**

***Above 4 Hz:*** **0.43 nm** on the quadrupole instead of **6.20 nm** on the ground.

*Stefano Redaelli*

*(World record in magnet stability)*

# Ok, this is good. But is it *stable*?



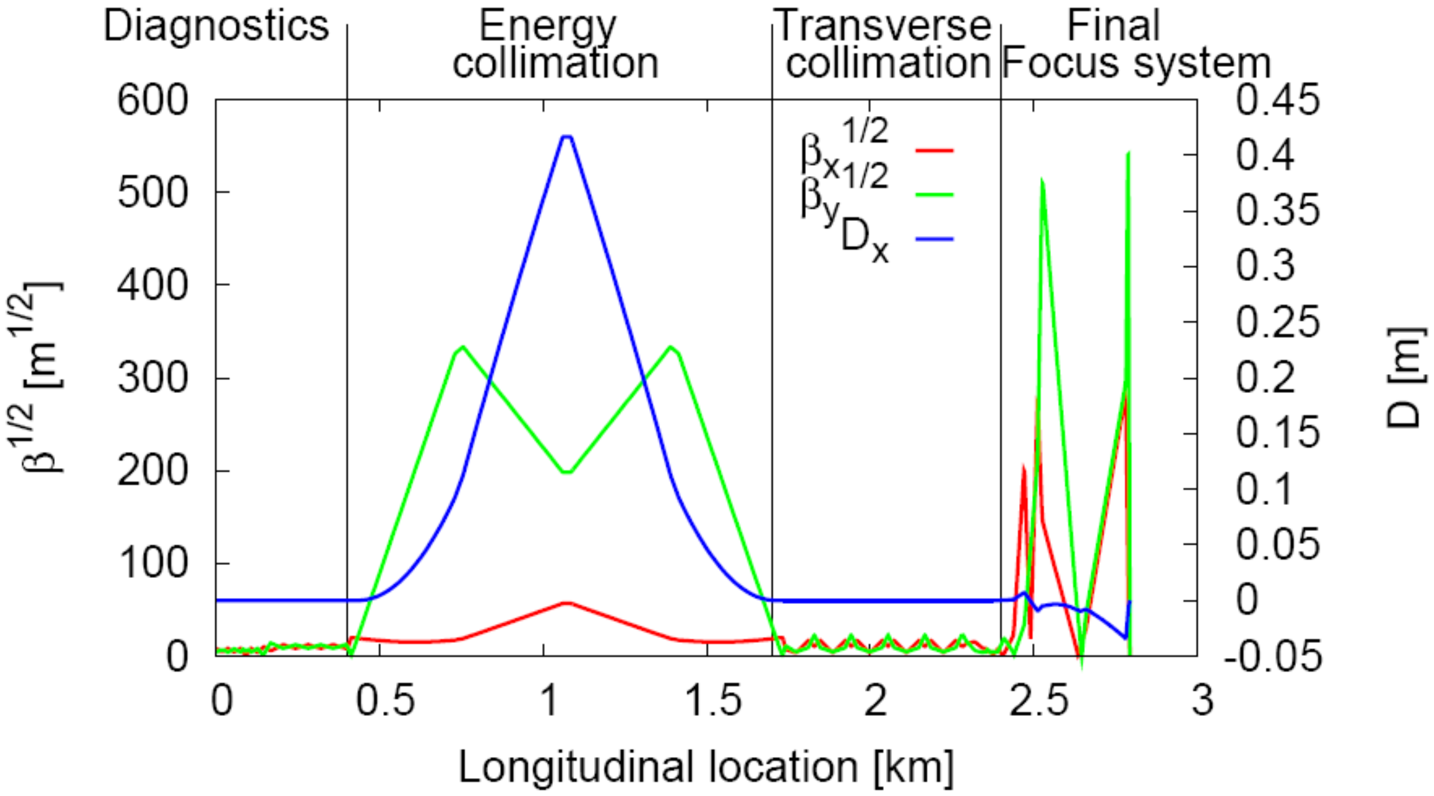
**Quadrupole vibrations kept below the 1 nm level**

over a period of 9 consecutive days!

*Stefano Redaelli*

# Beam Delivery System

- many common issues as for ILC
- diagnostics, emittance measurement, energy measurement, …
- collimation, crab cavities, beam-beam feedback, beam extraction, beam dump

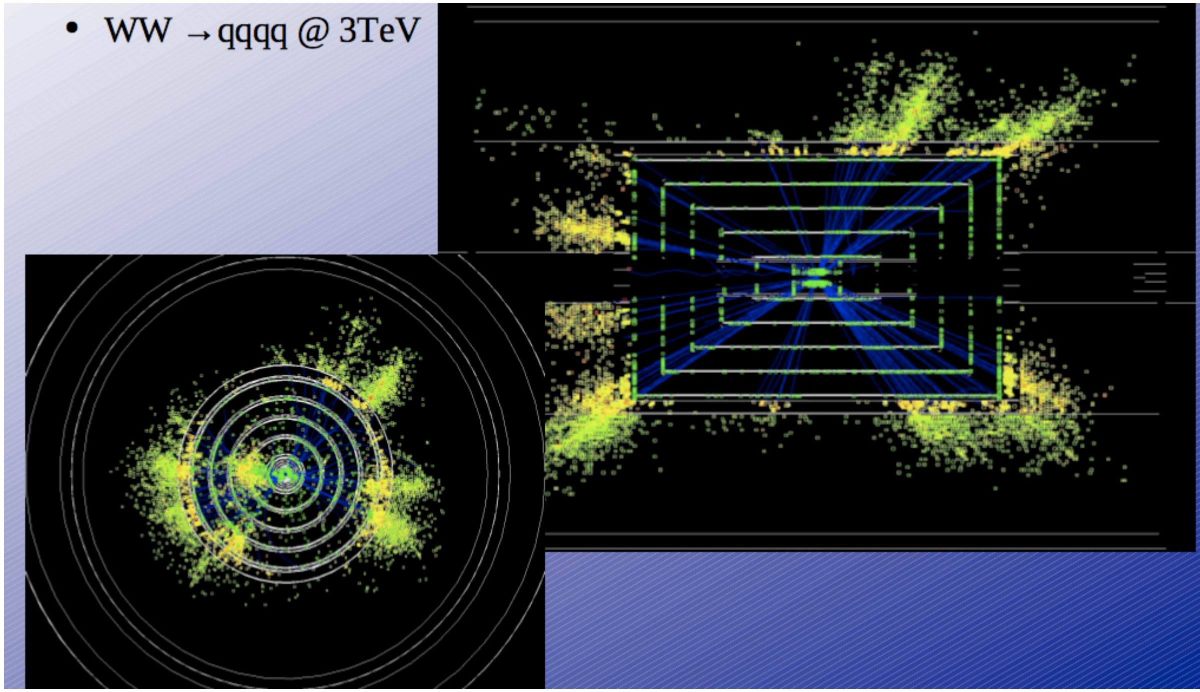


# CLIC detectors

- Different time structure of the beam has to be taken into account detectors have to integrate over several bunch crossings
- changes for multi-TeV collisions  
(first vertex layer moved out, calorimeter deeper ($9X_0$,…)

- ILC/CLIC collaboration, profiting from ILC developments
- SiD and ILD detector concepts have been adapted to CLIC
- Linear Collider Detector project at CERN focuses on physics and detector issues for both ILC and CLIC

http://cern.ch/lcd



# Other issues

- Many similar issues as ILC
  - Collimation
  - Final focus system
  - Beam-beam effects
  - Detector background
  - Extraction of post collision beams
  - Beam instrumentation
  - Feed-backs
  - Efficiency!
  - …

# CLIC/ILC Collaboration

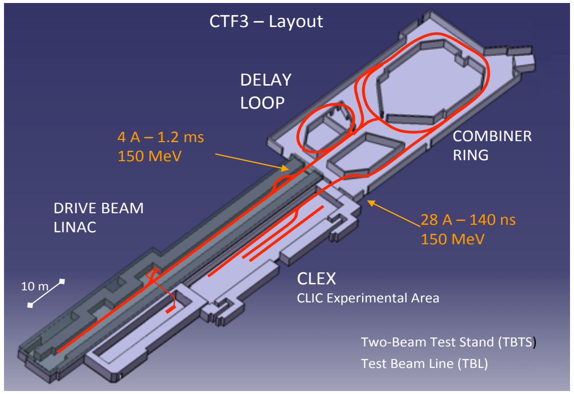
- Developing common knowledge of both designs and technologies on status, advantages, issues and prospects for the best use of future HEP
- Preparing together the future evaluation of the two technologies by the Linear Collider Community made up of CLIC & ILC experts

- Technology and parameters are quite different
- => Collaboration in working groups on subjects with strong synergy between CLIC and ILC:
  1) Civil Engineering and Conventional Facilities
  2) Beam Delivery Systems & Machine Detector Interface
  3) Detectors
  4) Cost & Schedule
  5) Beam dynamics & Beam Simulations
  6) Positron Generation
  7) Damping Ring
  8) General Issues
- Participation of CLIC experts to ILC meetings and ILC experts to CLIC meetings and several common workshops

# CLIC - Future Planning

## 2012-16 Development Phase

Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.



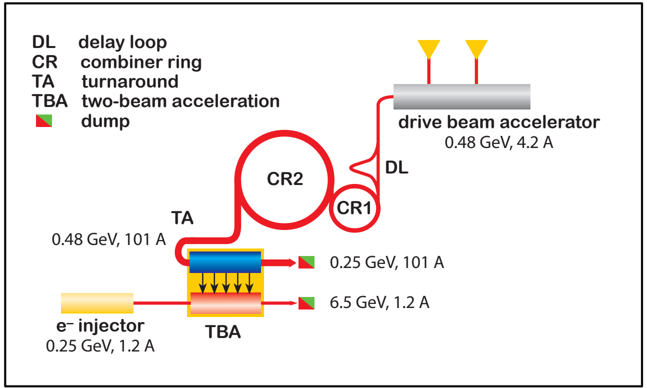
## 2016-17 Decisions

On the basis of LHC data and Project Plans (for CLIC and other potential projects), take decisions about next project(s) at the Energy Frontier.

## 2017-22 Preparation Phase

Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement.

Prepare detailed Technical Proposals for the detector-systems.



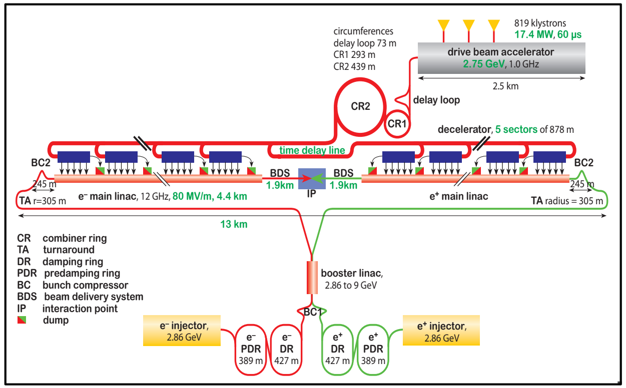
## 2022-23 Construction Start

Ready for full construction and main tunnel excavation.

## 2023-2030 Construction Phase

Stage 1 construction of a 500 GeV CLIC, in parallel with detector construction.

Preparation for implementation of further stages.



## 2030 Commissioning

From 2030, becoming ready for data-taking as the LHC programme reaches completion.

# CONCLUSION

- World-wide Consensus for a Lepton Linear Collider as the next HEP facility to complement LHC at the energy frontier
- Energy range < 1 TeV accessible by ILC
- CLIC technology based on
    - normal conducting RF structures at high frequency
    - two-beam scheme

only possible scheme to extend collider beam energy into Multi-TeV energy range

- Very promising results but technology not mature yet, requires challenging R&D
- CLIC-related key issues addressed in CTF3 by 2011
- CLIC Conceptual Design Report published

- LHC (or Tevatron) physics discoveries (>2012) will tell which way to go …

# Documentation

- General documentation about the CLIC study: http://CLIC-study.org
- CLIC on INDICO http://indico.cern.ch/categoryDisplay.py?categId=1068
- CLIC Physics + Detector http://cern.ch/LCD
- CLIC scheme description:
  http://preprints.cern.ch/yellowrep/2000/2000-008/p1.pdf
- CERN Bulletin article:
  http://cdsweb.cern.ch/journal/CERNBulletin/2012/47/News%20Articles/1493549
- CLIC Test Facility: CTF3 http://ctf3.home.cern.ch/ctf3/CTFindex.htm
- Int. Linear Collider Workshop 2012 (most actual information)
  http://www.uta.edu/physics/lcws12
- EDMS http://edms.cern.ch/nav/CERN-0000060014
- CLIC technological challenges (CERN Academic Training)
  http://indico.cern.ch/conferenceDisplay.py?confId=a057972
- CLIC ACE (advisory committee meeting)
  http://indico.cern.ch/conferenceDisplay.py?confId=58072
- CLIC meeting http://cern.ch/clic-meeting
- CLIC notes http://cdsweb.cern.ch/collection/CLIC%20Notes

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