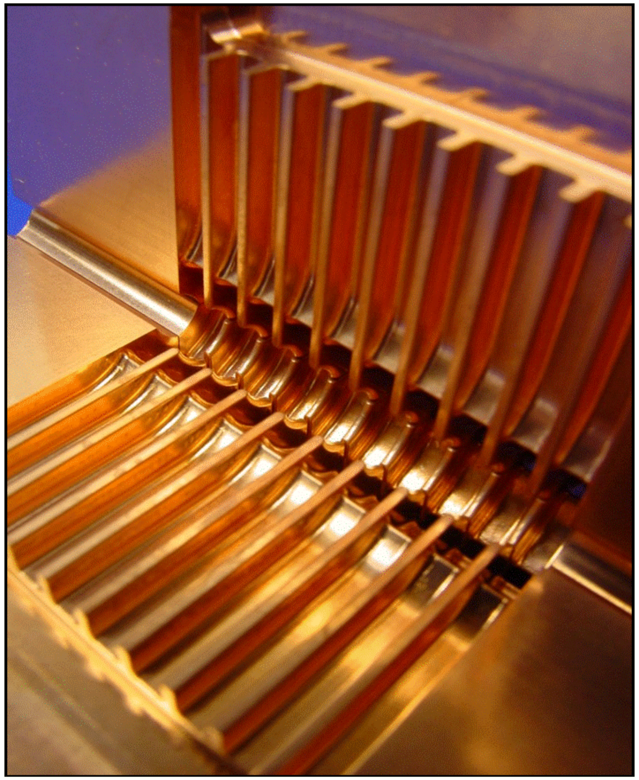
CLIC *(and room temperature RF)*

Frank Tecker – CERN

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

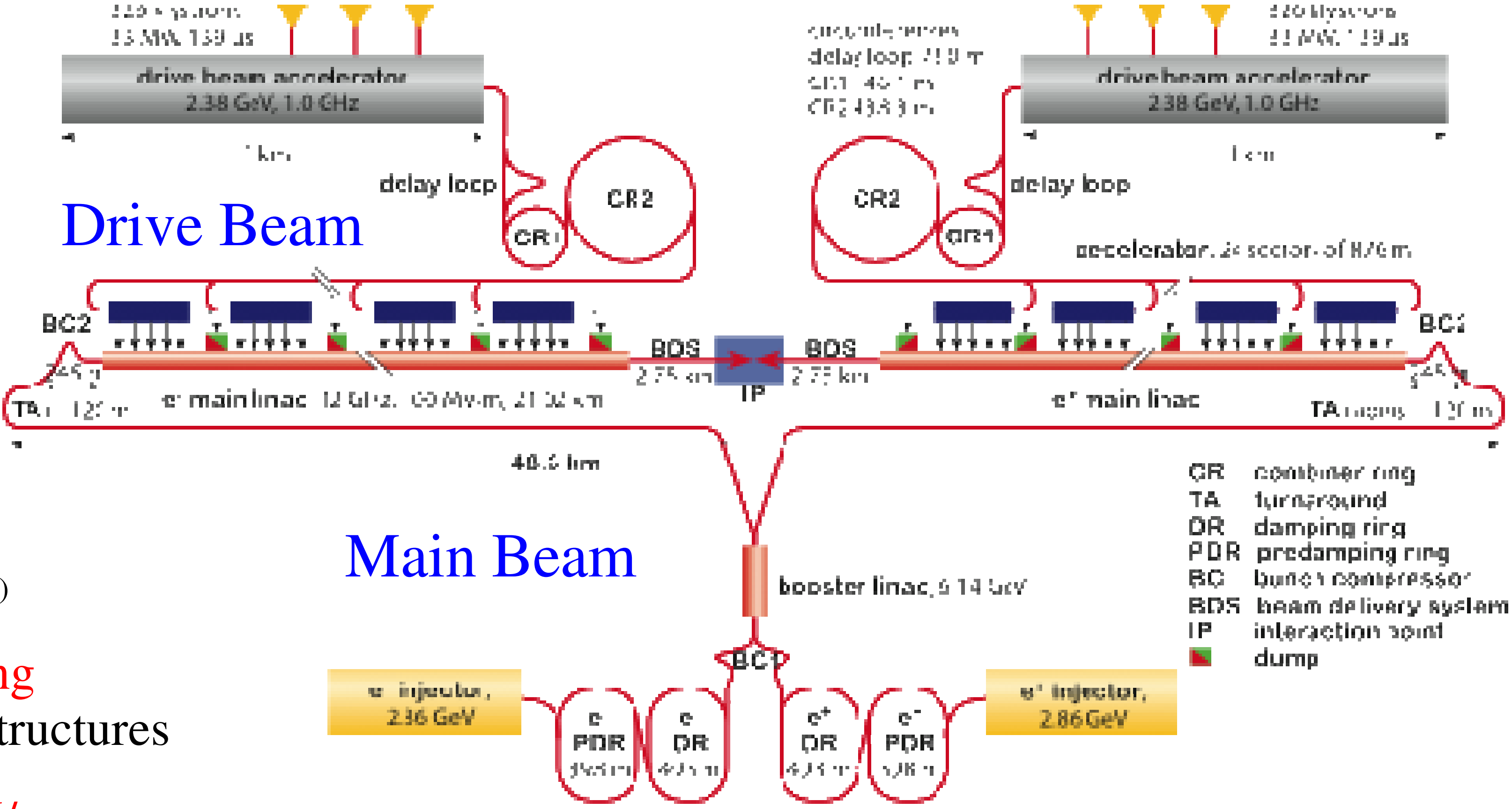


Preface

- Complex topic
- 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
  $6 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (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

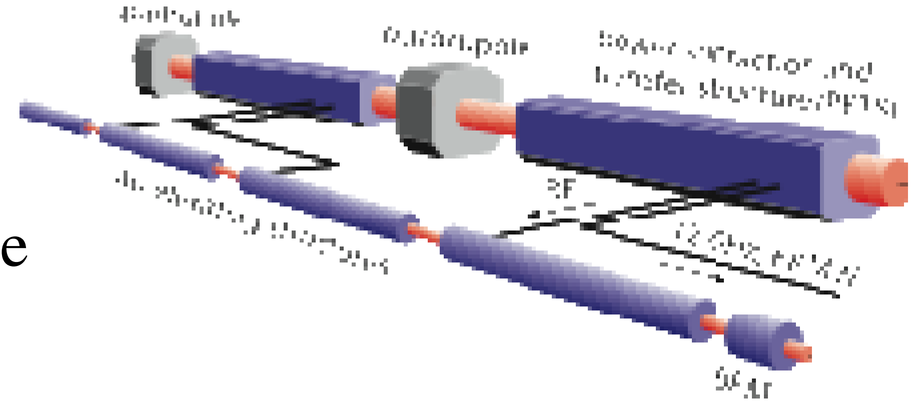


Part 1

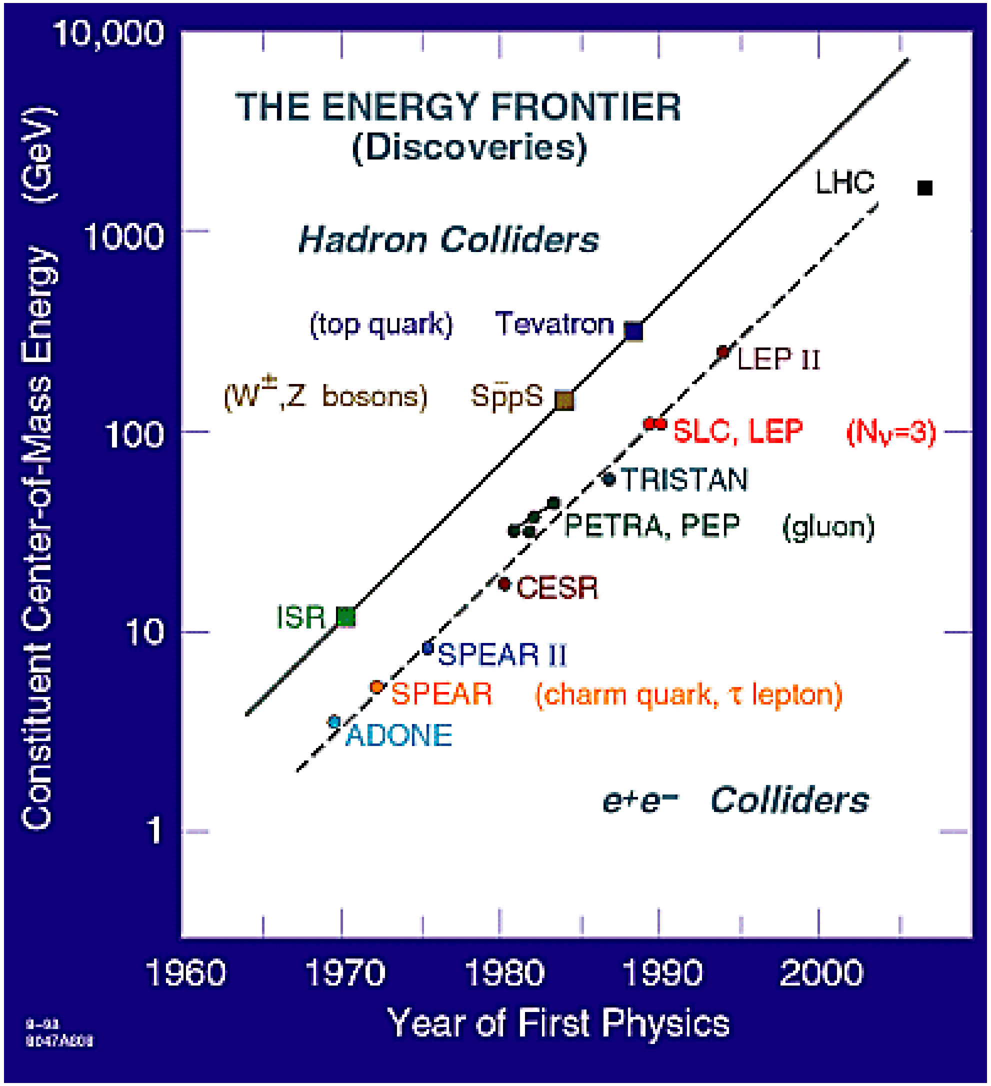
- ‘warm’ RF technology basics:
  - A linear collider at higher energy
  - Normal conducting RF structures
    - Gradient limits
    - Pulsed surface heating and Fatigue
    - Breakdown mechanism and phenomenology
  - Frequency choice
  - Wakefields and damping
  - Pulse train formats
  - Differences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



- History:
  - Energy constantly increasing with time
  - Hadron Collider at the energy frontier
  - Lepton Collider for precision physics
- LHC coming online now
- 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
  - Tevatron/LHC should discover Higgs (or something else)
  - 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!
- "Physics at the CLIC Multi-TeV Linear Collider" CERN-2004-005
- "ILC Reference Design Report – Vol.2 – Physics at the ILC" www.linearcollider.org/rdr

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

Reference Design Report
Physics at the ILC

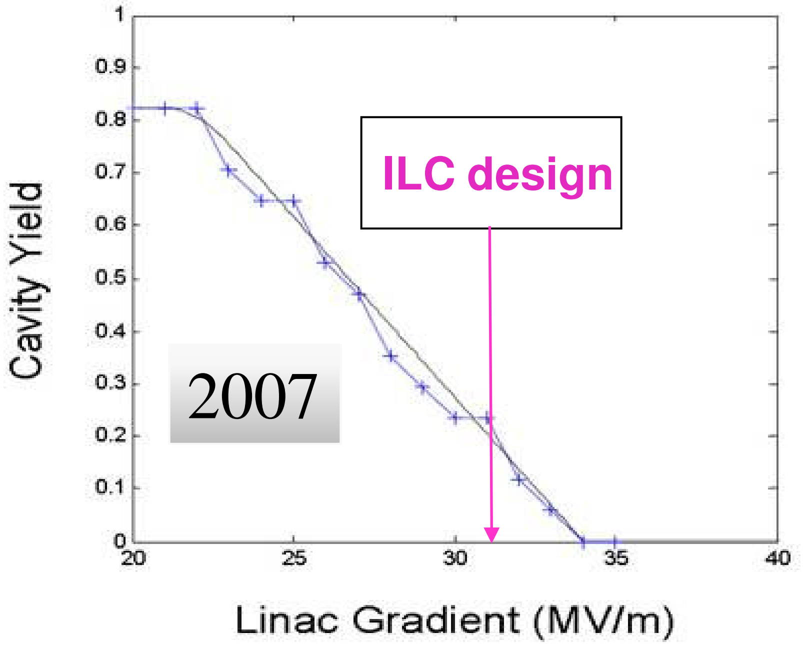
Linear Colliders - Energy

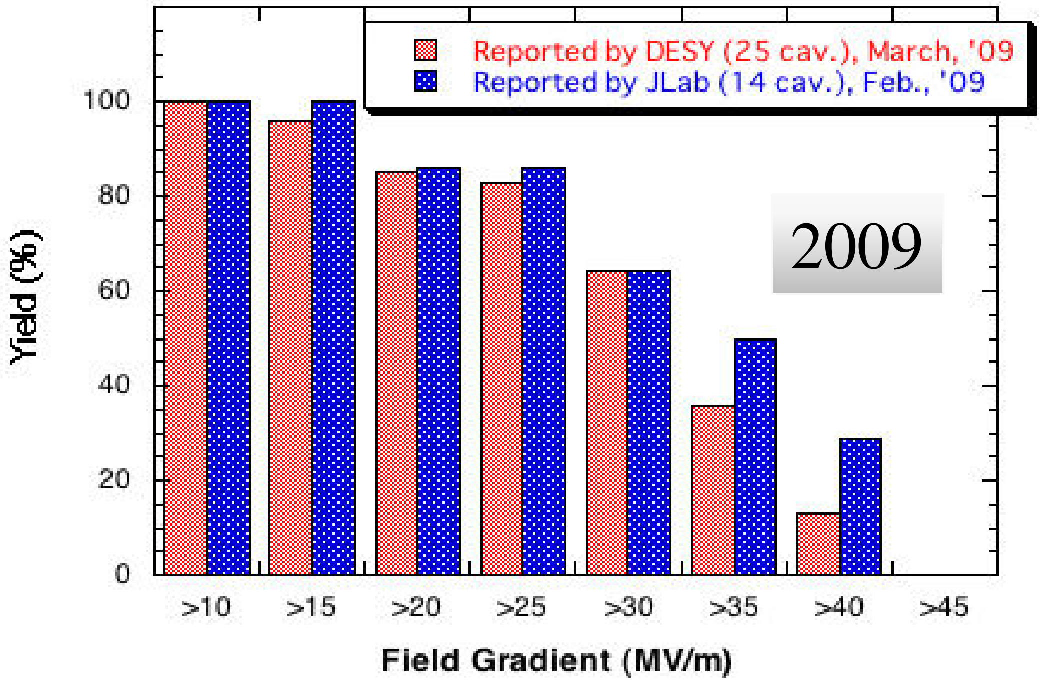
- Historical background: 2004 – ILC-TRC review
  - Evaluation of linear collider (LC) projects (NLC/JLC, TESLA and CLIC)
  - Decision for Superconducting Accelerator Technology for LC with $E_{cm} = 0.5\text{-}1$ TeV
- Consequences:
  - End of competition between normal conducting and SC schemes
  - 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 >100MV/m needed for $E_{cm} = 5$ 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

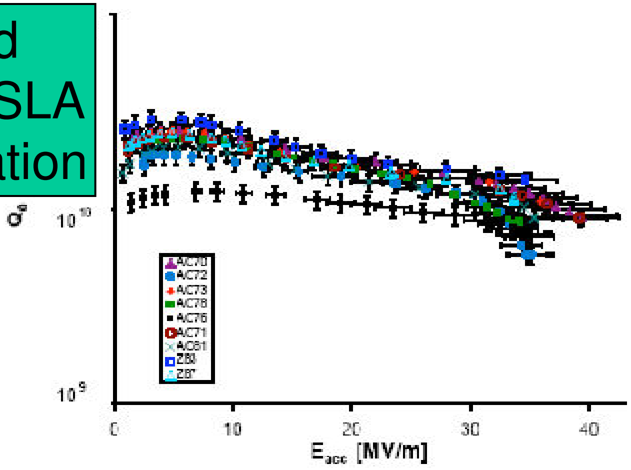
- Recent progress by R&D programme to systematically understand and set procedures for the production process
- goal to reach a 50% yield at 35 MV/m by the end of 2010
- already approaching that goal
- 90% yield foreseen later





R&D of SC RF cavities

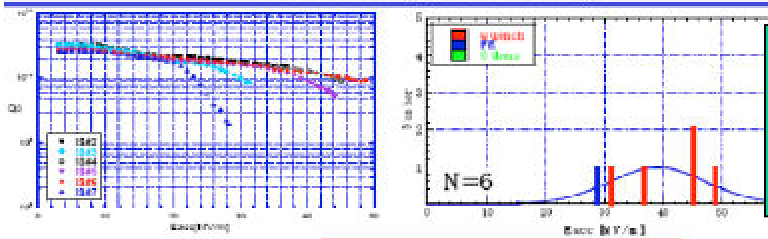
TESLA Nine-Cells: (Proof-of-Principle)
Best tests of 9 best Cavities (Vertical Test Results)



Derived From TESLA Collaboration

(A) CBP+CP+Anneal+EP(80μm)
+HPR+Baking(120C*48hrs)

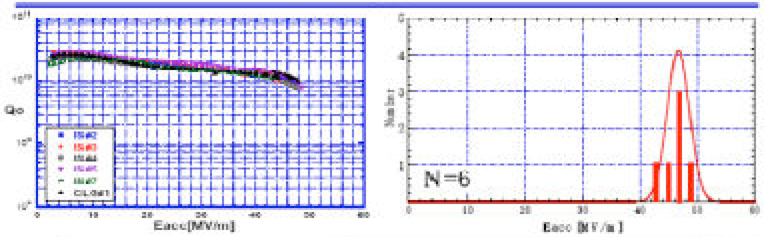
K. Saito et al.



New preparation techniques

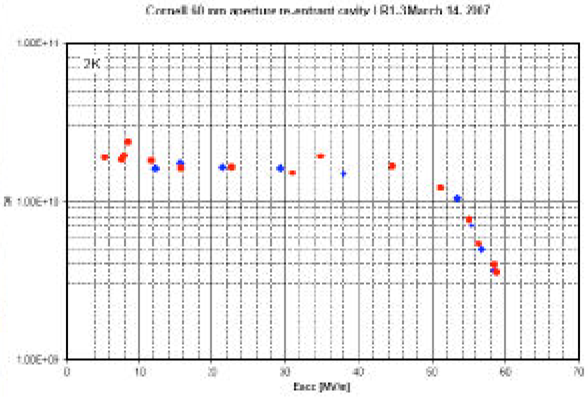
(D) +EP(20μm)+EP(3μm, fresh, closed) +HF+
+HPR+Baking (120C*48hrs)

K. Saito et al.



60mm-Aperture Re-Entrant Cavity, 58 MV/m!

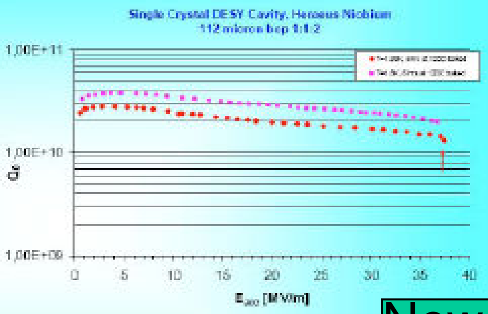
KEK/Cornell Collaboration



New cavity shapes

DESY single crystal cavity 1AC8 build from Heraeus disc by rolling at RWTH, deep drawing and EB welding at ACCEL

XFEL



Q(Eacc) curve after only 112 μ
and in situ baking 120°C for

Preparation and RF tests
P.Kneisel, JLab

W. Singer. Single Crystal Nb Technology Workshop, CBMM, Brazil, Oct. 30-Nov. 1, 20

New material
Large grains
Higher perf
Lower cost

Normal conducting structures

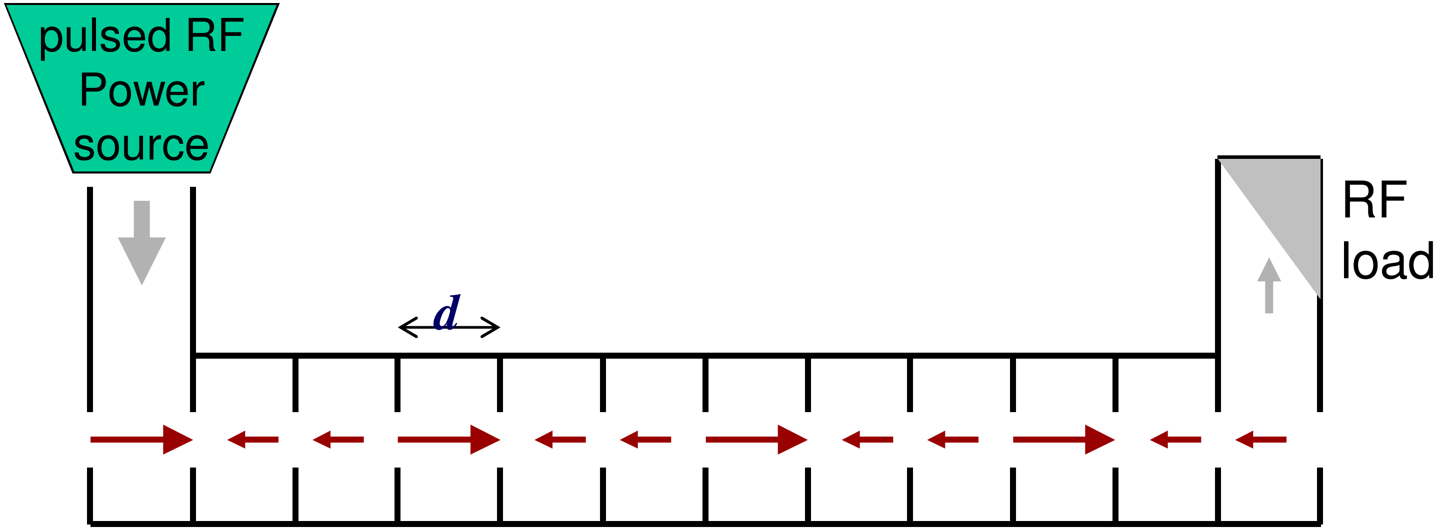
- Higher gradients (<50 MV/m) reachable with normal conducting accelerating structures

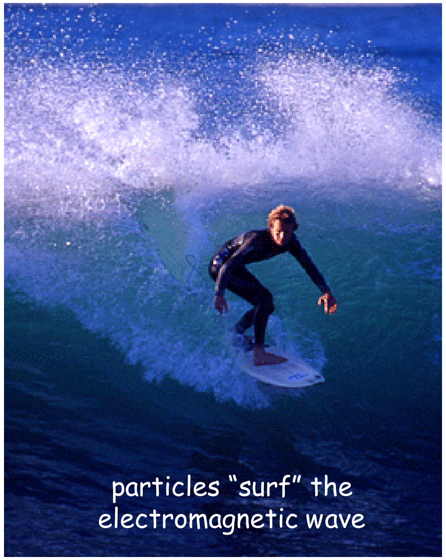
- But! Compare to advantages of SC RF cavities:
  - Very low losses due to tiny surface resistance
  - High efficiency
  - Long pulse trains possible
  - Favourable for feed-backs within the pulse train
  - Standing wave cavities with low peak power requirements
  - Lower frequency => Large dimensions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

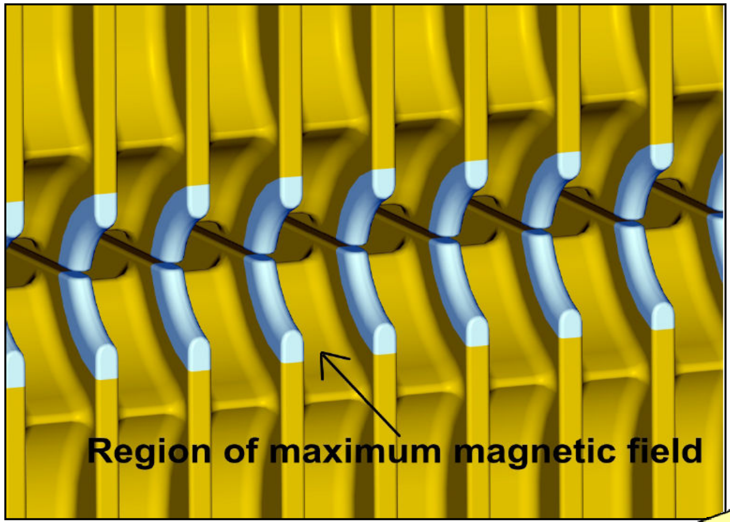
$$\eta_{RF\rightarrow beam} = \underbrace{\frac{P_{beam}}{P_{beam} + P_{loss} + P_{out}}}_{\approx 1 \text{ for SC SW cavities}} \frac{T_{beam}}{T_{fill} + T_{beam}}$$

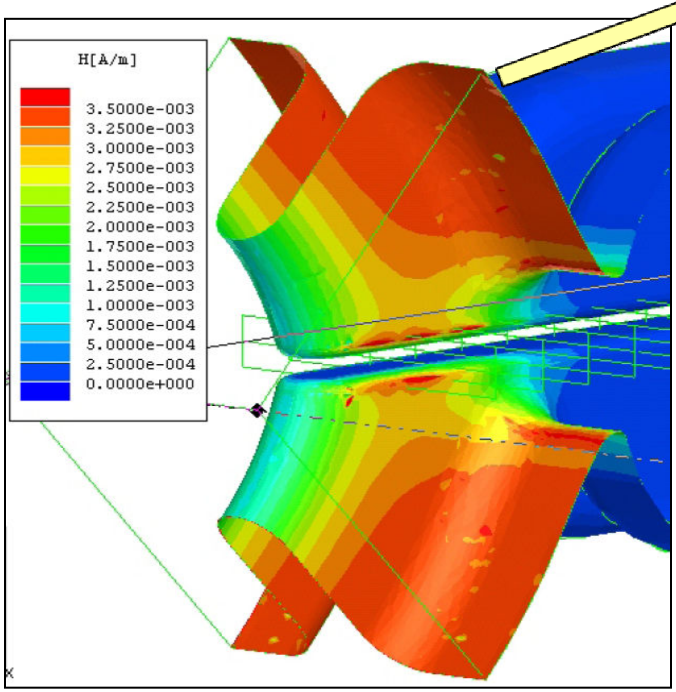
- => long pulse length favoured
- NC TW cavities have smaller filling time T_{fill}
  => Second term is higher for NC RF
- Typical values SC: $\eta = 0.6$
  NC: $\eta = 0.3$

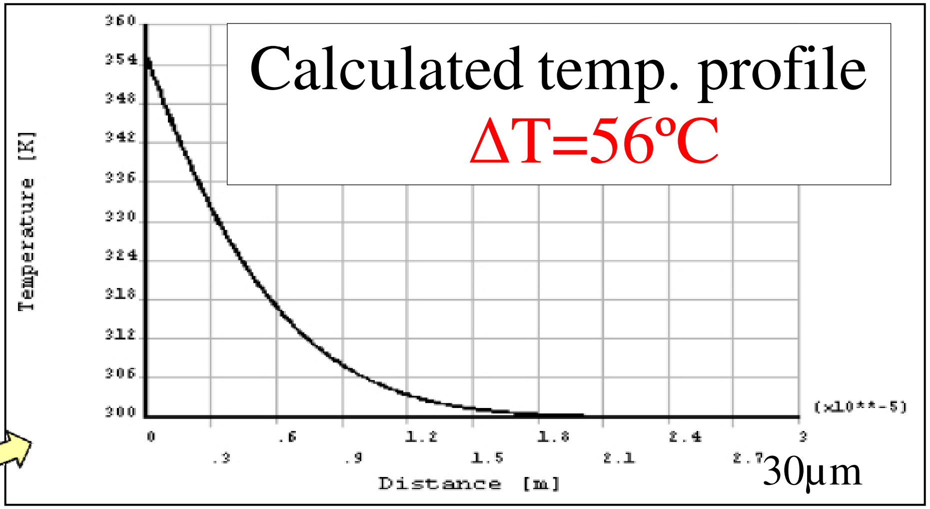
Limitations of Gradient E_{acc}

- 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





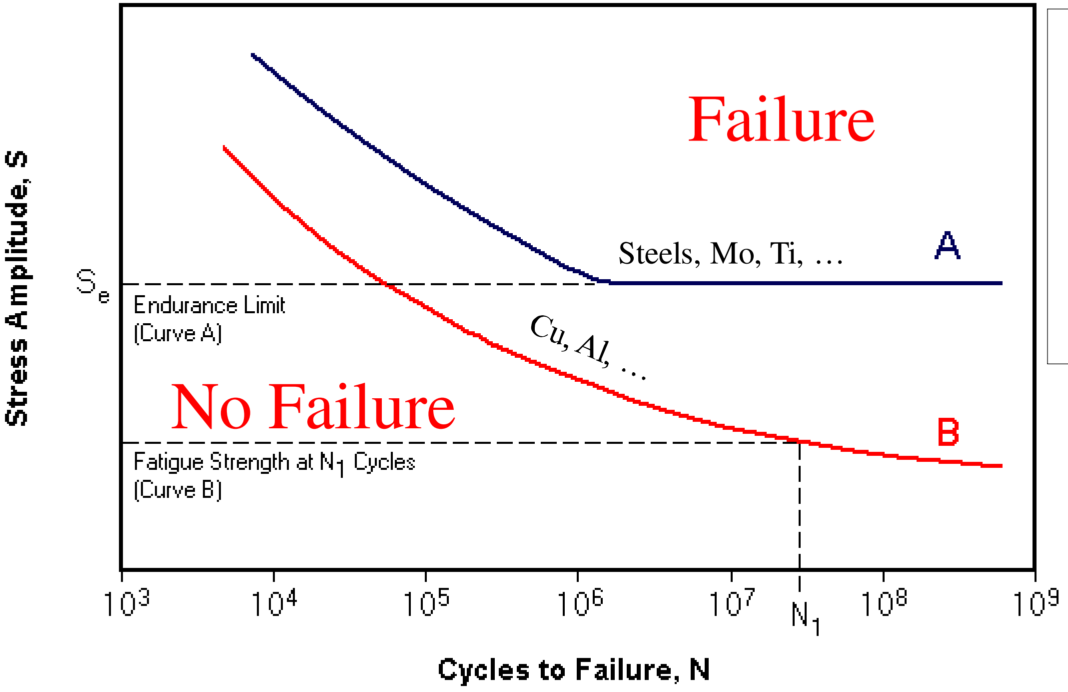

Calculated temp. profile

ΔT=56ºC


Cyclic compressive stresses

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

Fatigue curves



H_{peak}

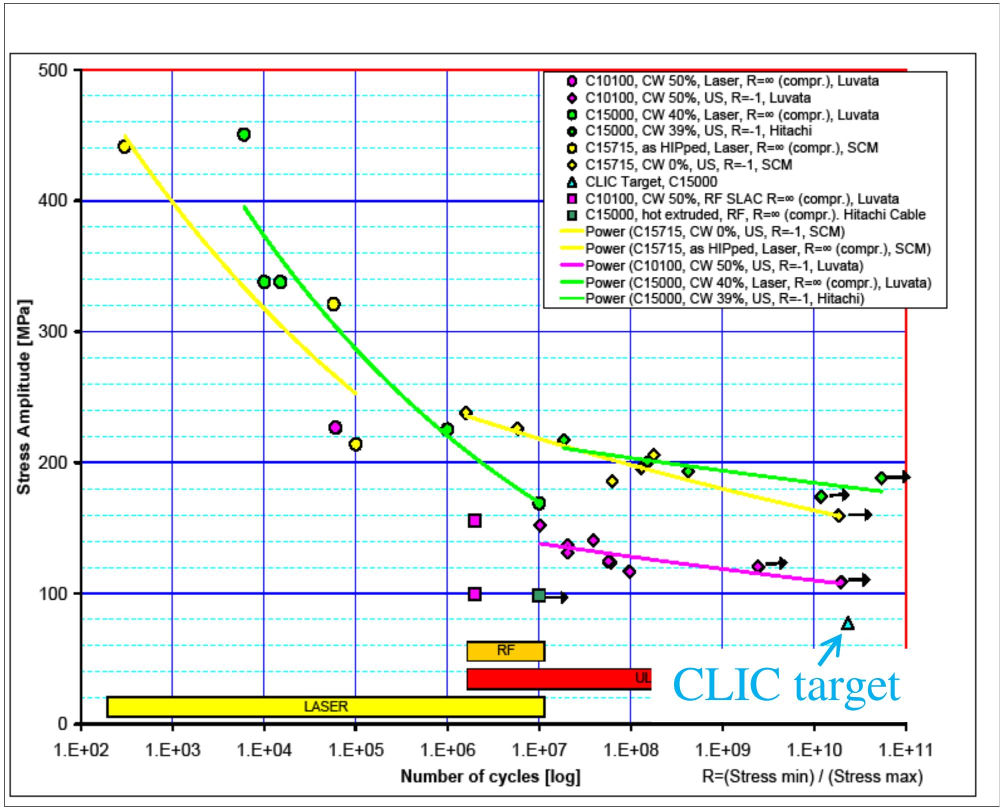
↕

ΔT

↕

σ

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 ΔT 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)

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

ΔT temperature rise, σ electric conductivity

λ heat conductivity, ρ 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

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

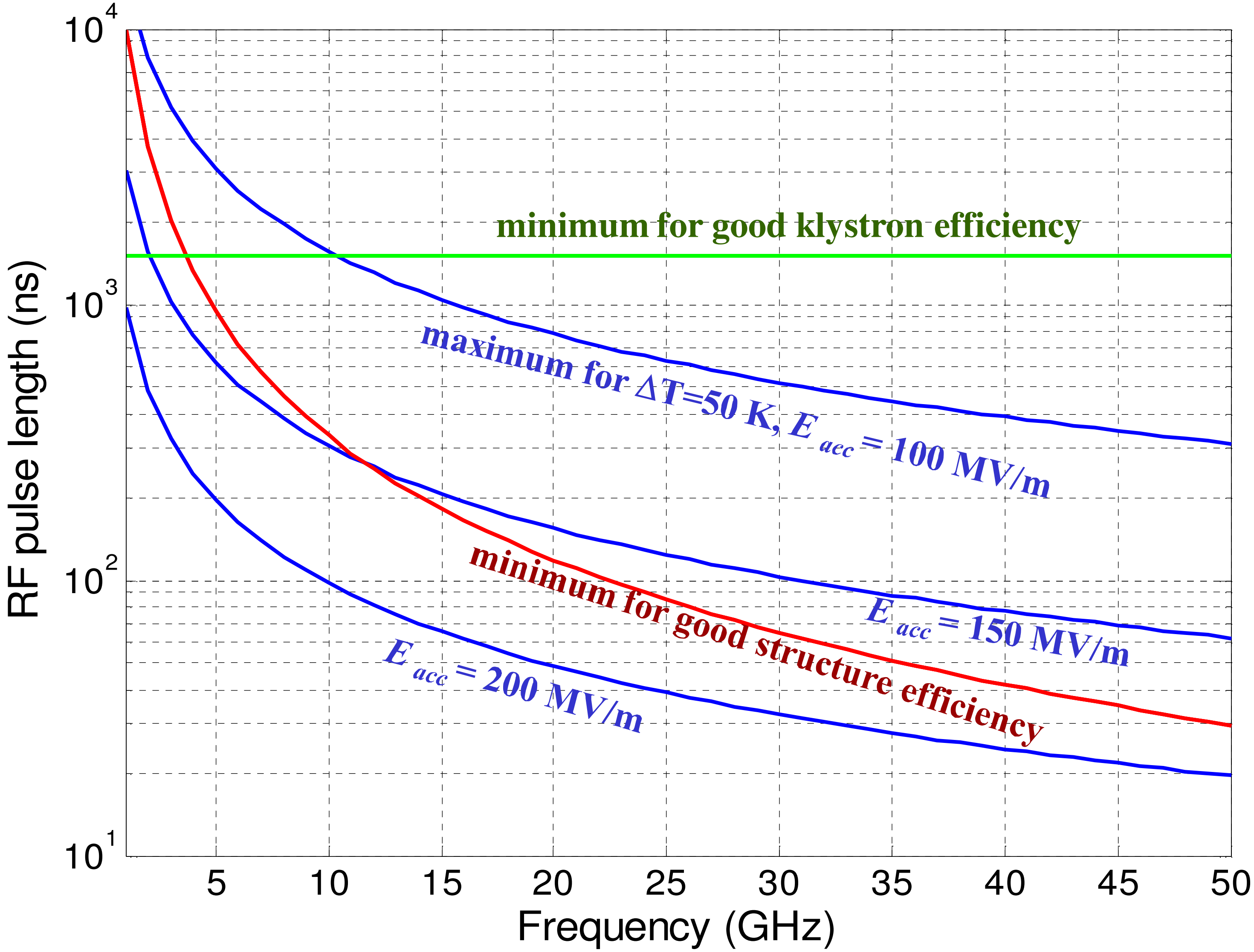
$$\Delta T_{\max} \approx 50\ \mathrm{K}$$

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

=> see homework

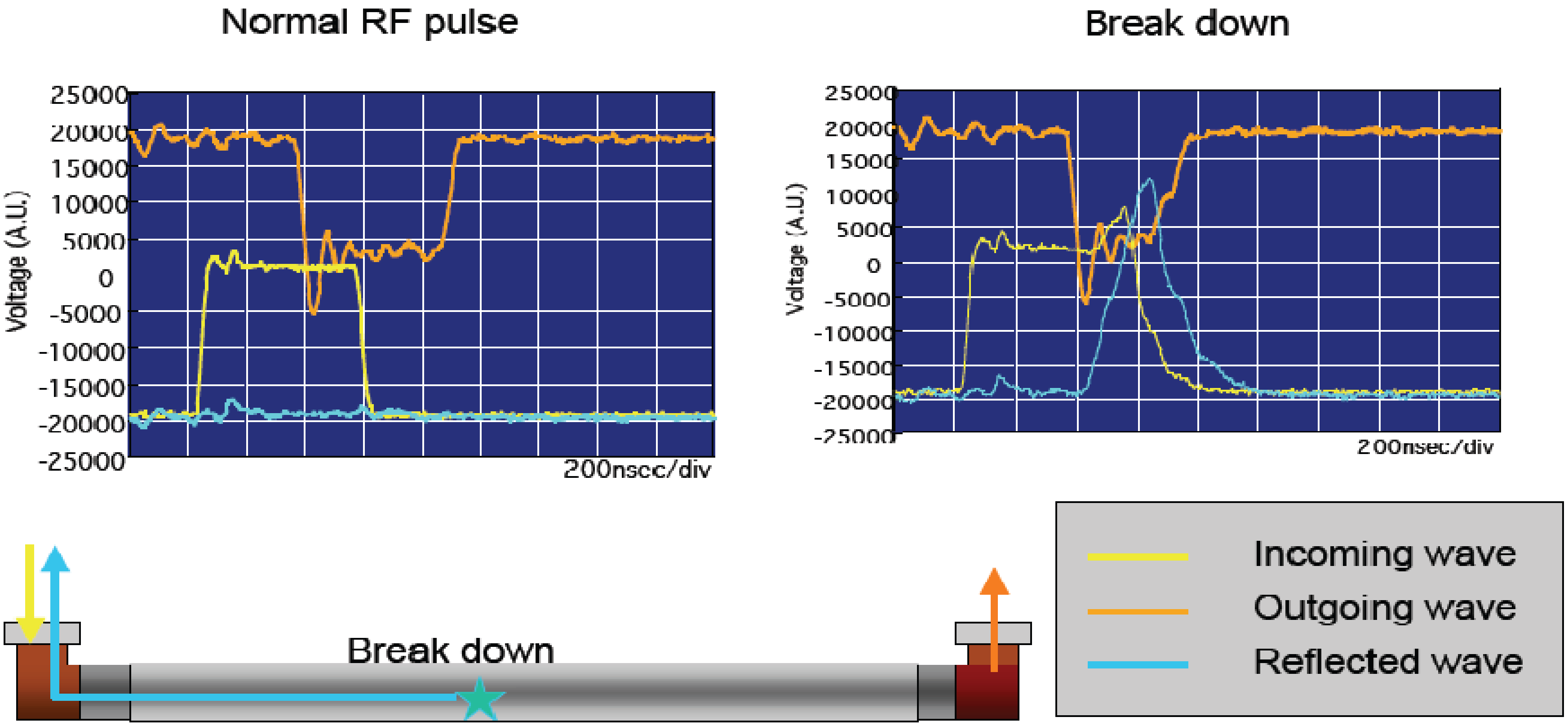
Frequency scaling of RF pulse length limits

(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

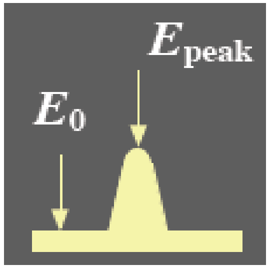
- Breakdown events characterised by
  - always
    - disappearance of transmitted power
    - reflection of incident power
    - emission of intense bursts of fast electrons (E_{Kin}~100 keV)
    - acoustic shock wave (can be detected with accelerometer)
    - build up time ~ 20 ns
  - often
    - fast 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

  β field enhancement factor

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

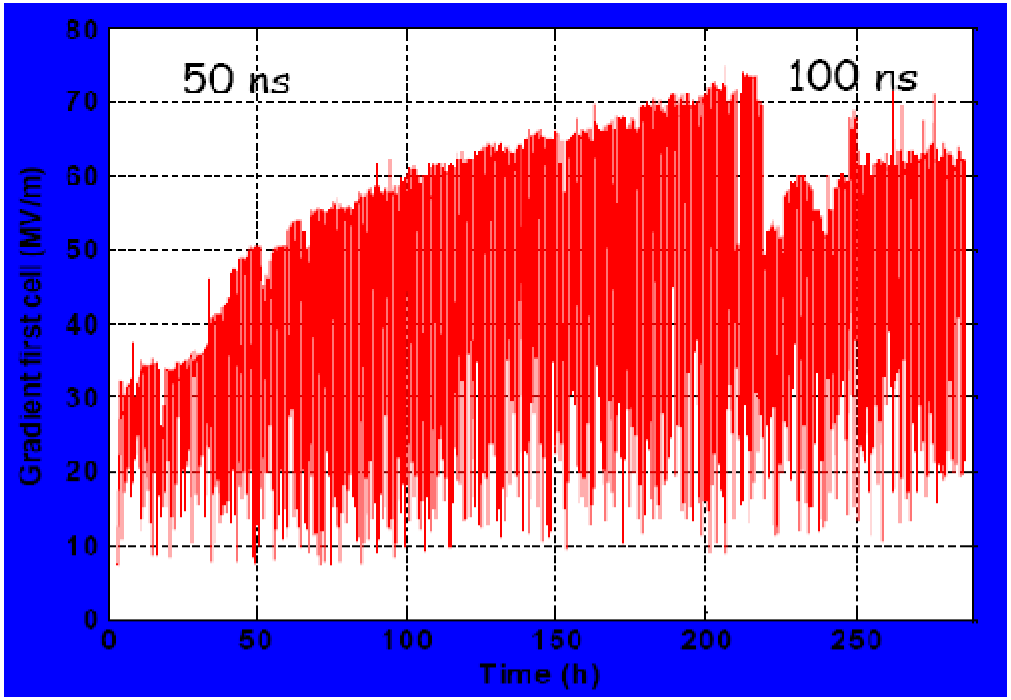


- Need conditioning to reach ultimate gradient

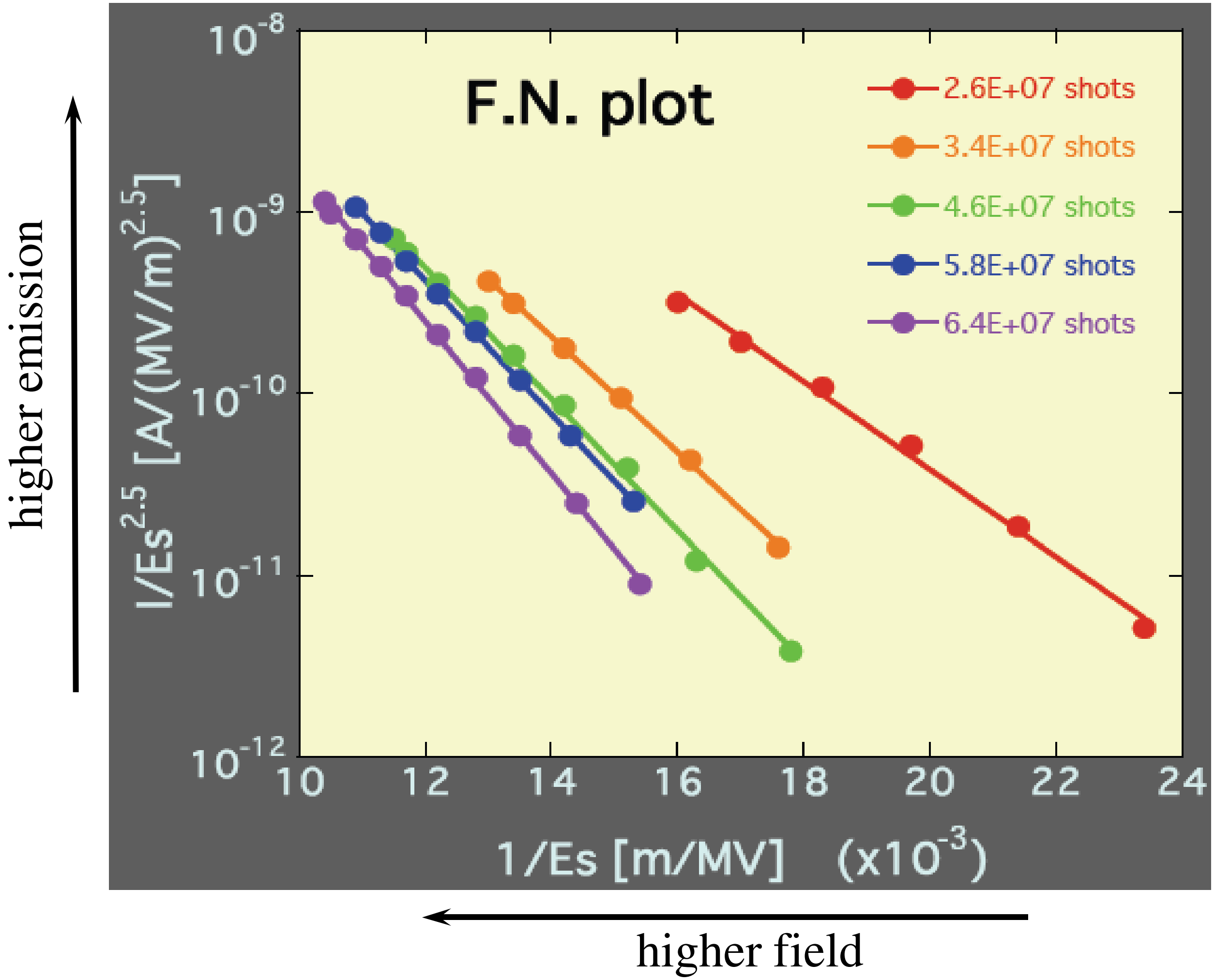
  RF power gradually increased with time
- RF processing can melt field emission points
  - Surface becomes smoother
  - field enhancement reduced
  - ⇒ higher fields

    less breakdowns

from S.Doebert



Improvement by conditioning



Fowler Nordheim law of field emission

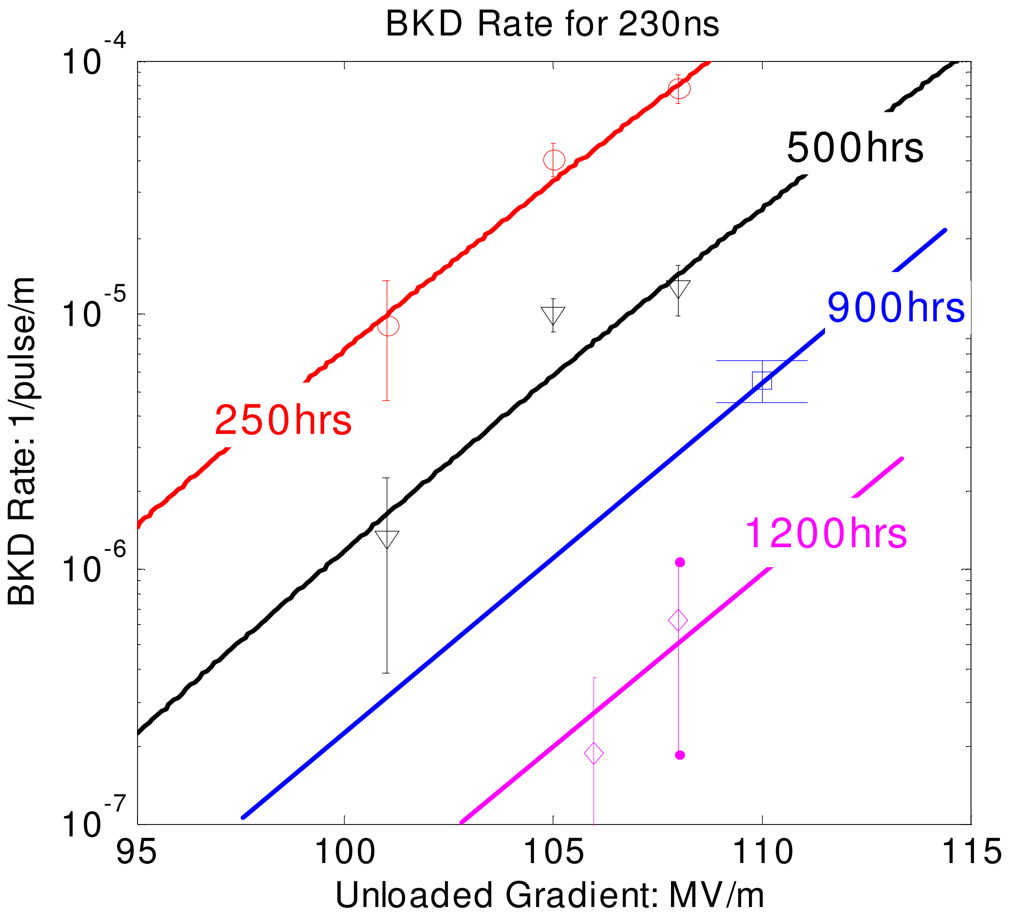
$$j_{FN} \propto \frac{E_{peak}^{\ 2}}{\phi} e^{\frac{-k\phi^{1.5}}{E_{peak}}}$$

ϕ work function

from S.Yamaguchi

- Higher fields reachable
- Lower emission current at a given field

BD Rate at Different Conditioning Time

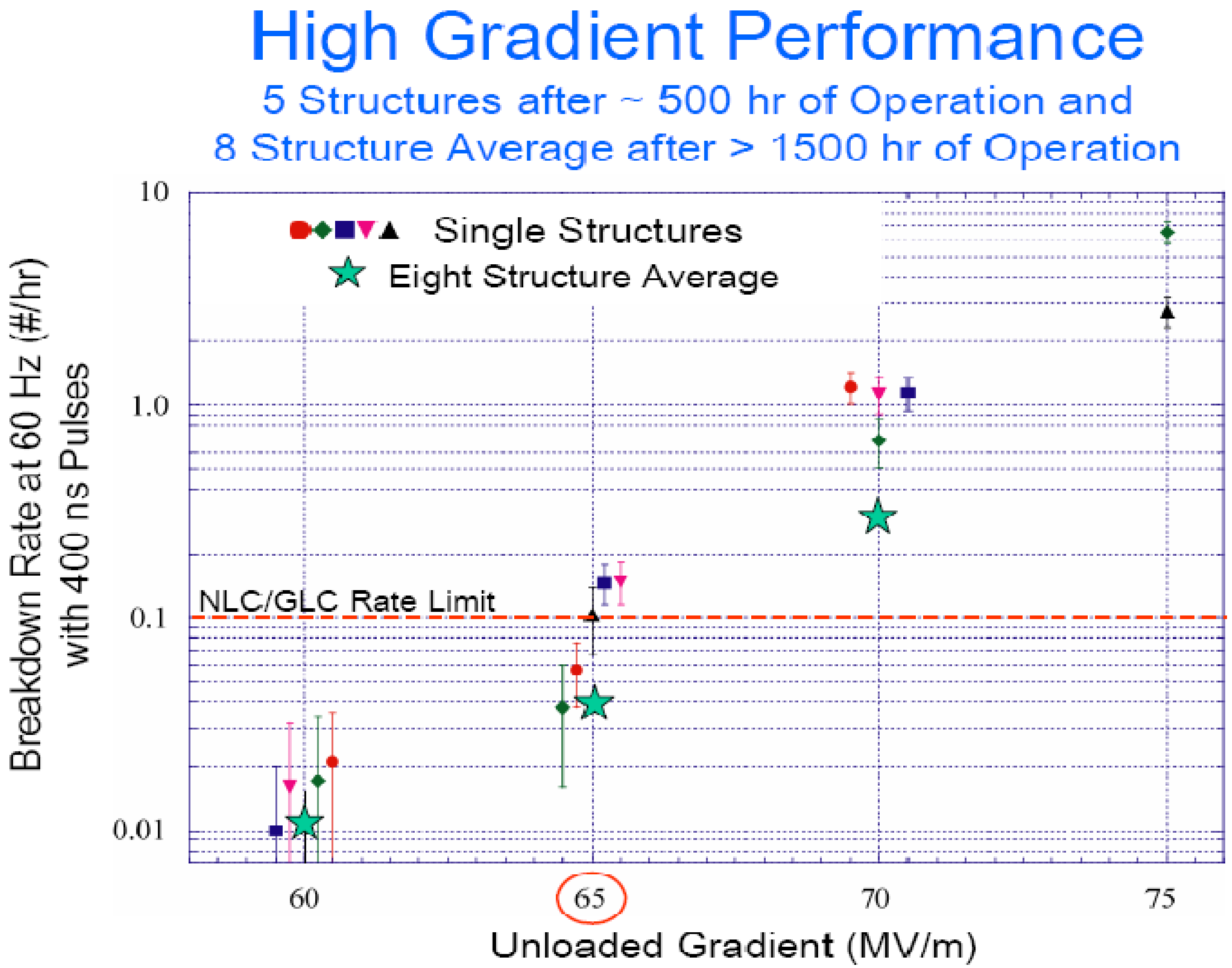


- After conditioning:
  - Higher fields reachable for constant BDR
  - Lower breakdown rate at a given field

Faya Wang

Breakdown-rate vs gradient

- Higher breakdown rate for higher gradient



High Gradient Performance

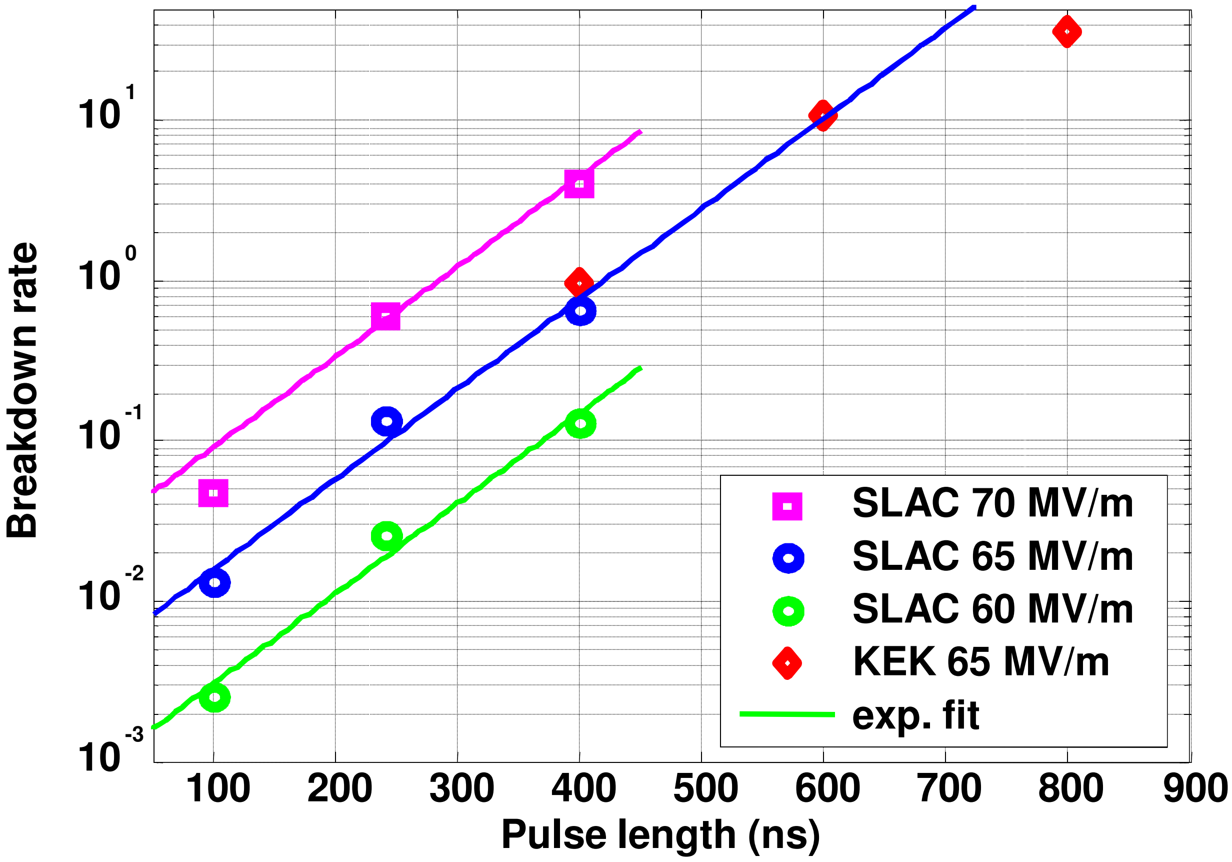
5 Structures after ~ 500 hr of Operation and

8 Structure Average after > 1500 hr of Operation

C. Adolphsen /SLAC

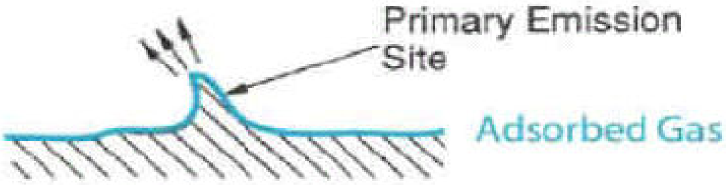
Breakdown-rate vs pulse length

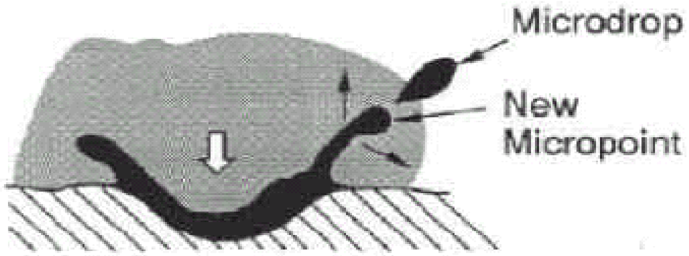
- Higher breakdown rate for longer pulses



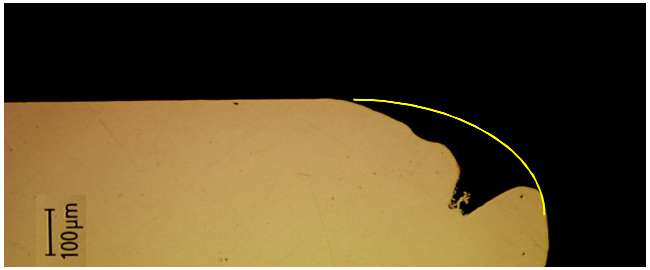
- Summary: breakdown rate limits pulse length and gradient

Conditioning limits

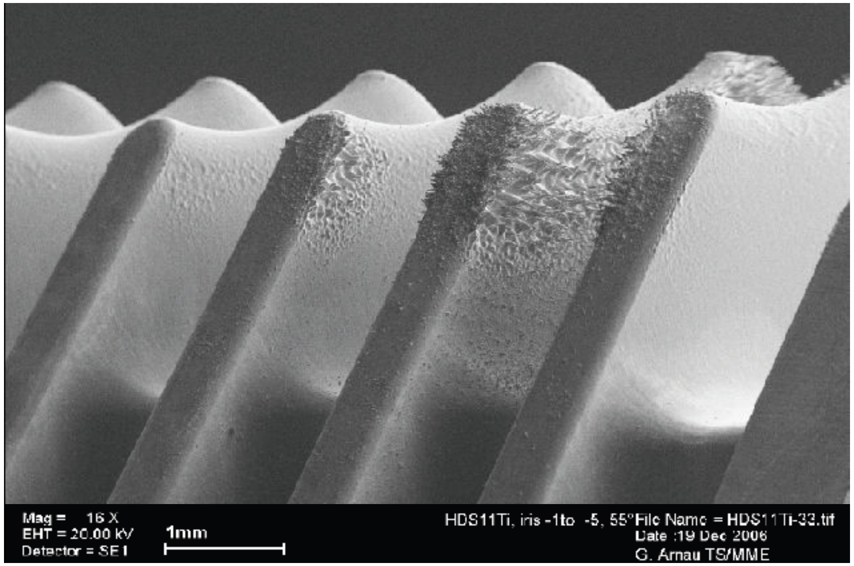




- More energy: electrons generate plasma and melt surface
- Molten surface splatters and generates new field emission points!
  ⇒ limits the achievable field
- Excessive fields can also damage the structures
- Design structures with low E_{surf}/E_{acc}
- Study new materials (Mo, W)



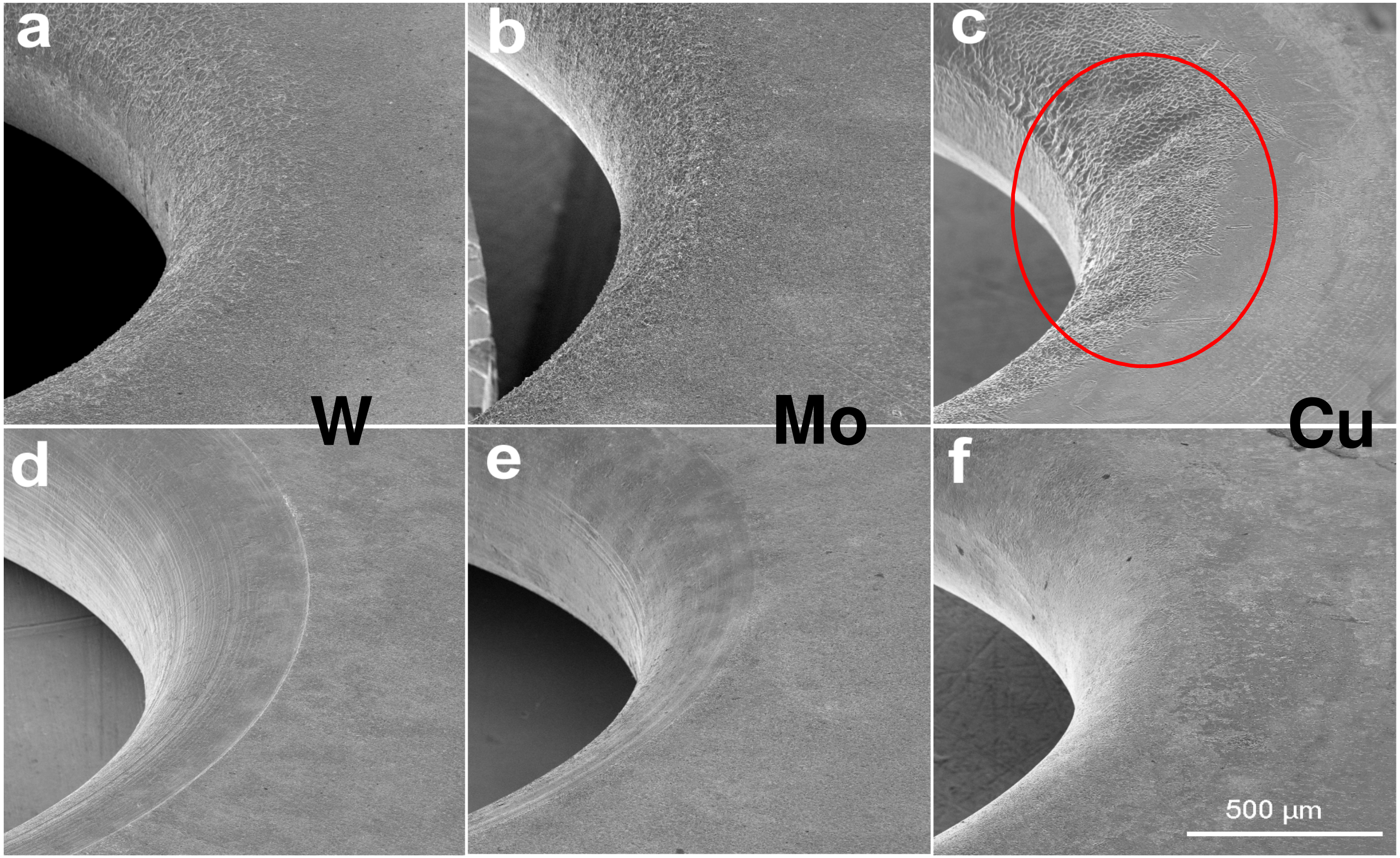
Damaged CLIC structure iris



Iris material tests in CTF2

First iris (highest field)

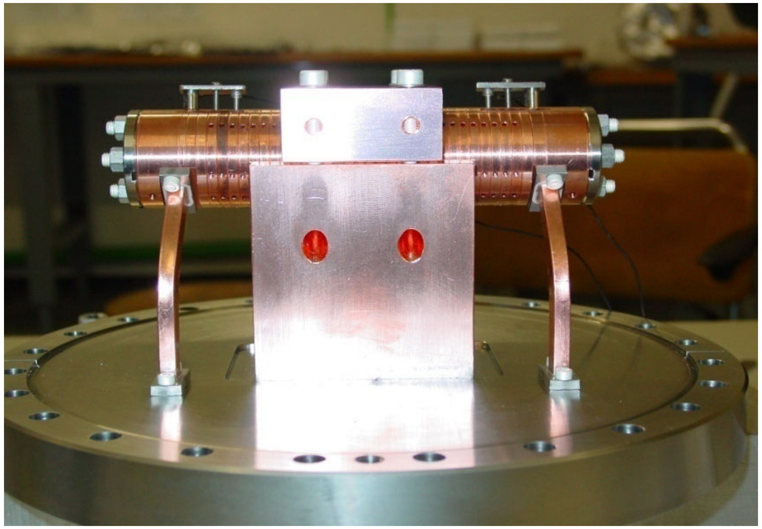
downstream iris



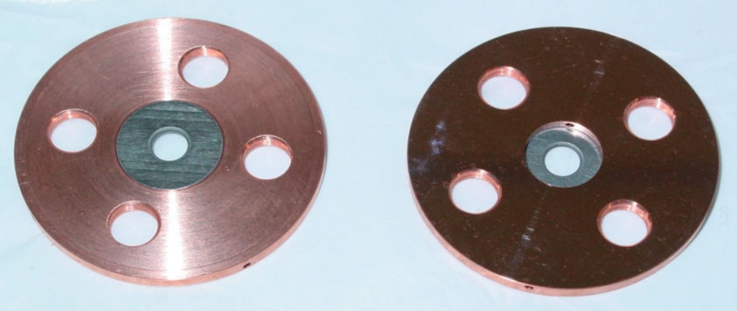
Damage on iris after runs of the 30-cell clamped structures tested in CTFII.
First (a, b and c) and generic irises (d, e and f) of W ,Mo and Cu structures respectively.

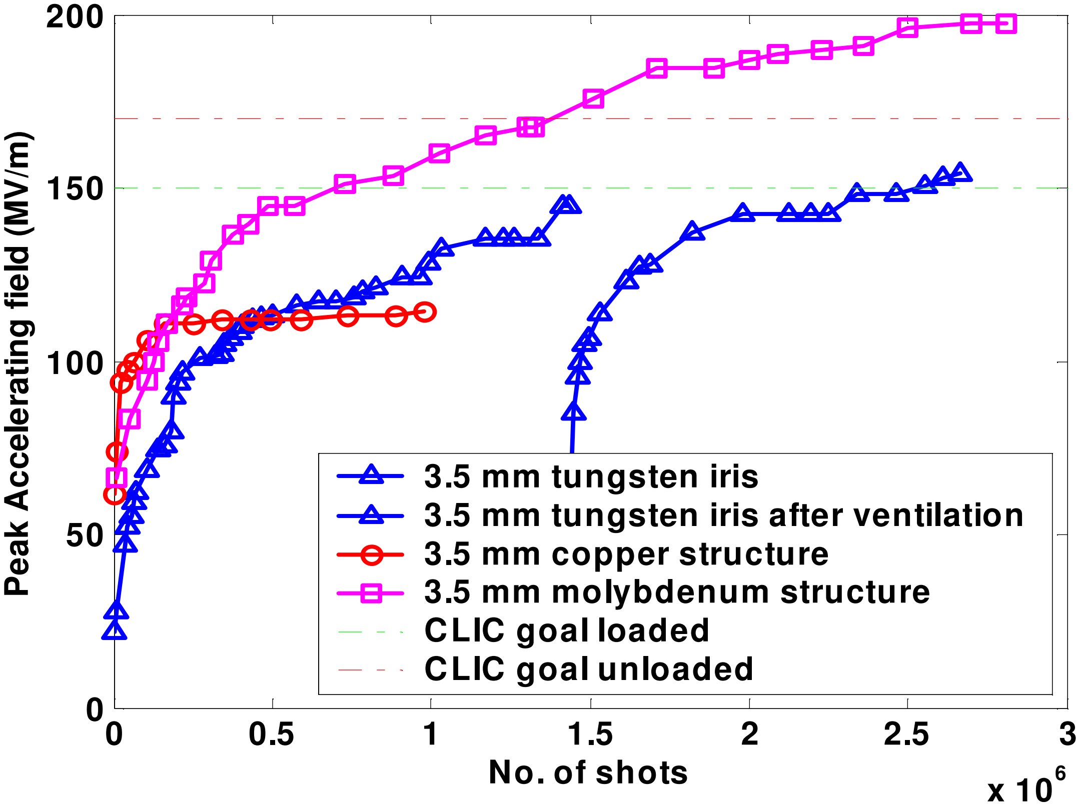
Achieved accelerating fields in CTF2

High gradient tests of new structures with molybdenum irises reached 190 MV/m peak accelerating gradient without any damage well above the nominal CLIC accelerating field of 150 MV/m but with RF pulse length of 16 ns only (nominal 160 ns)



30 cell clamped tungsten-iris structure





A world record !!!

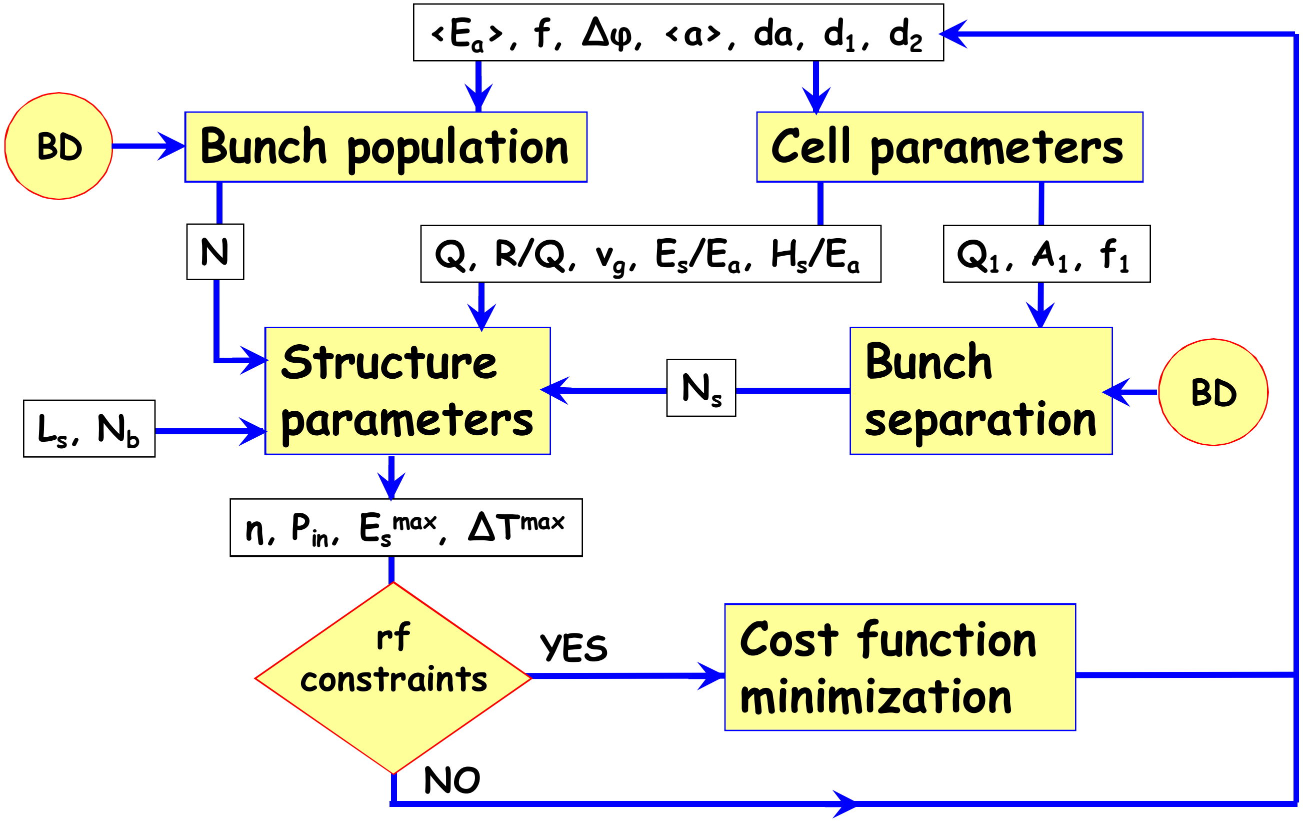
Frequency choice for NC RF

- 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

η, P_{in}, E_s^{max}, ΔT^{max}

rf constraints

YES

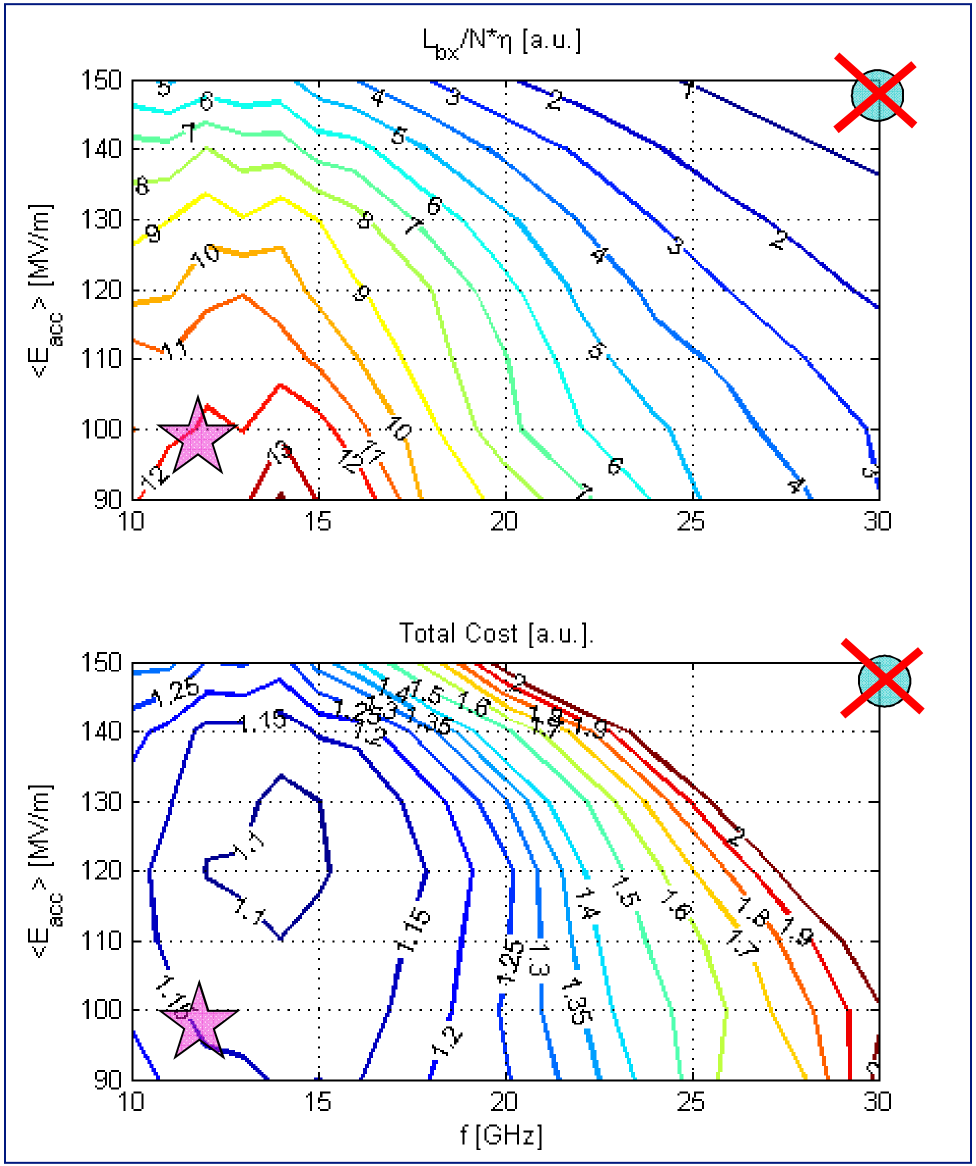
Cost function minimization

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 (ΔT<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

- Accelerating field:
  (transit time, field geometry)

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

- Stored e.m. energy:

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

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

- Peak power:
  (neglecting beam power)

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

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

- Example:

=> see homework

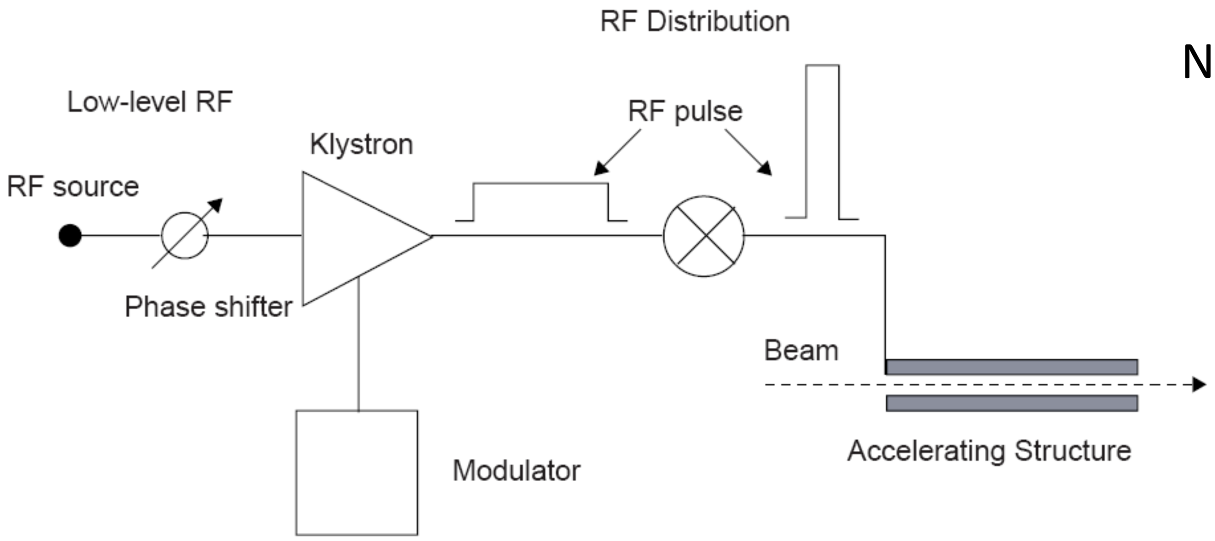
V = 1 TeV E = 50 MV/m L = 20 km f = 3 GHz

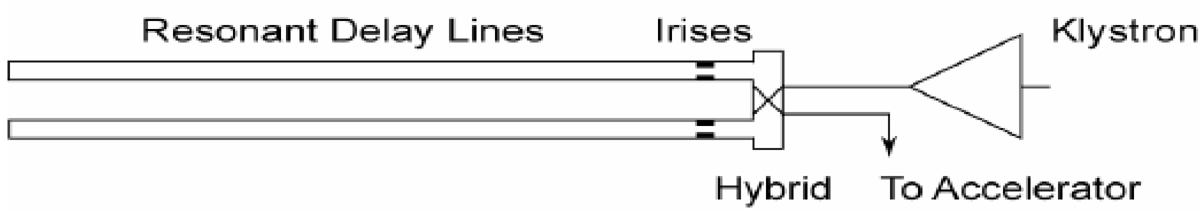
=> W = 0.8 MJ P = 1.2 TW P' = 60 MW/m

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

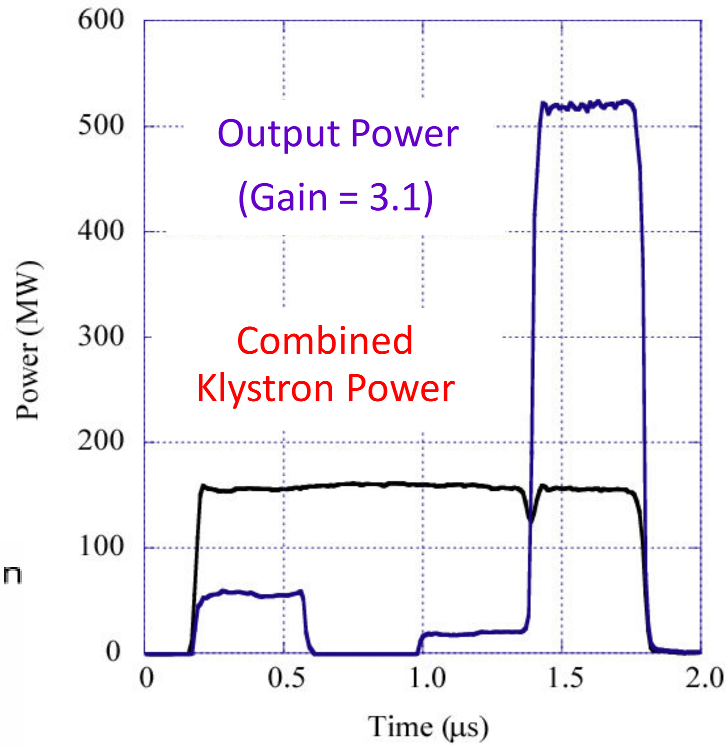
RF pulse compression

- 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



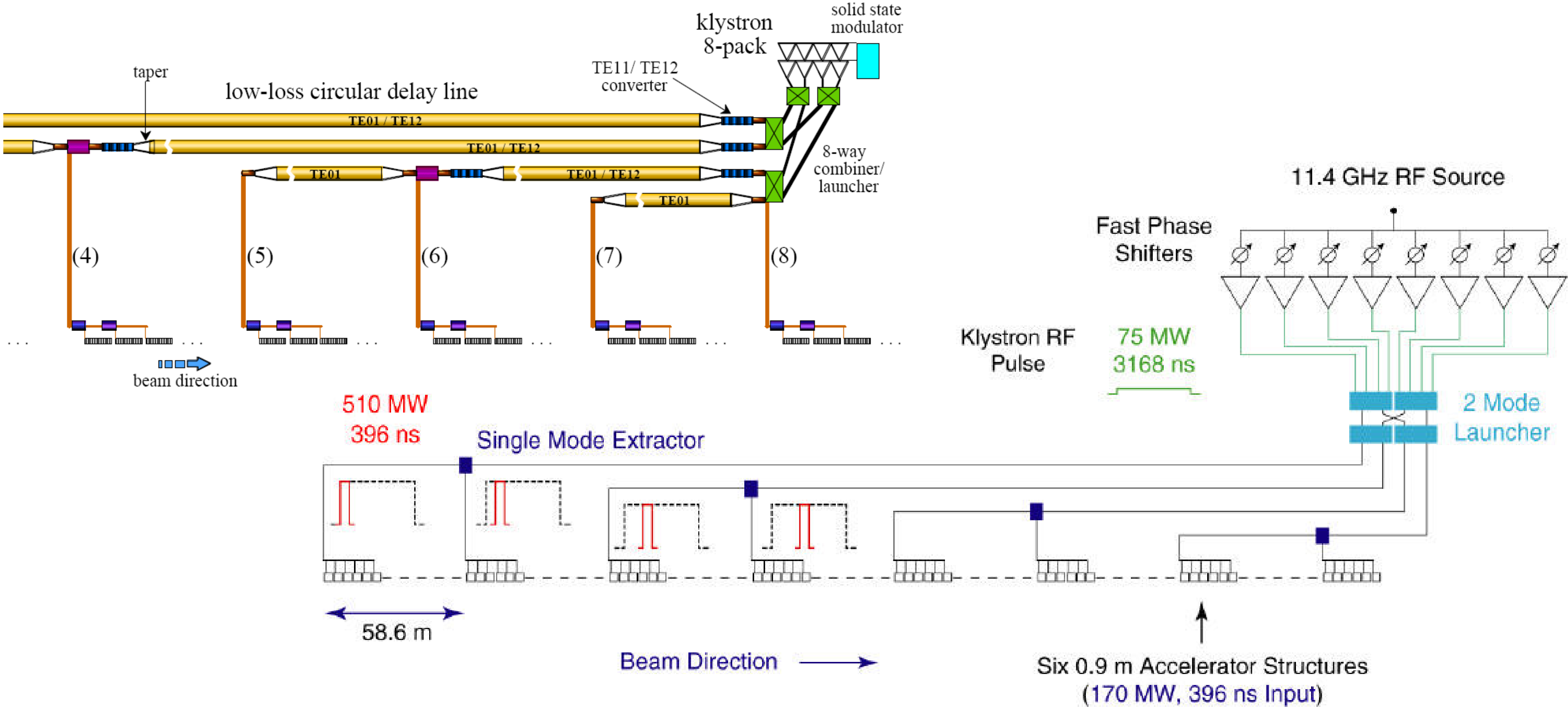


NLCTA pulse compressor: up to 500 MW

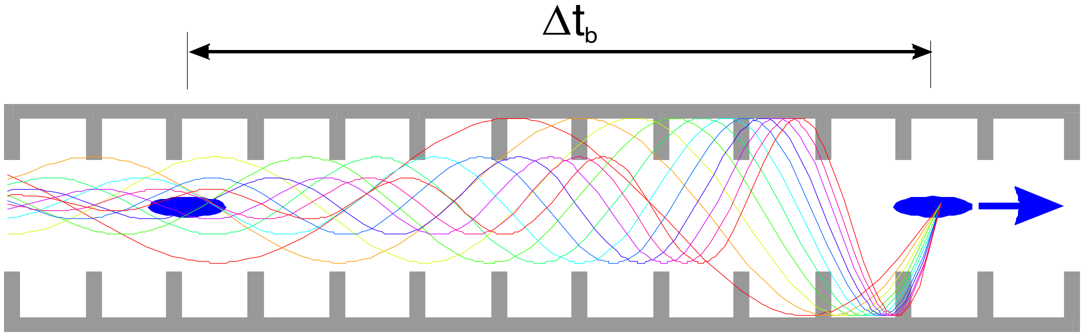


NLC Linac RF Unit

- 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



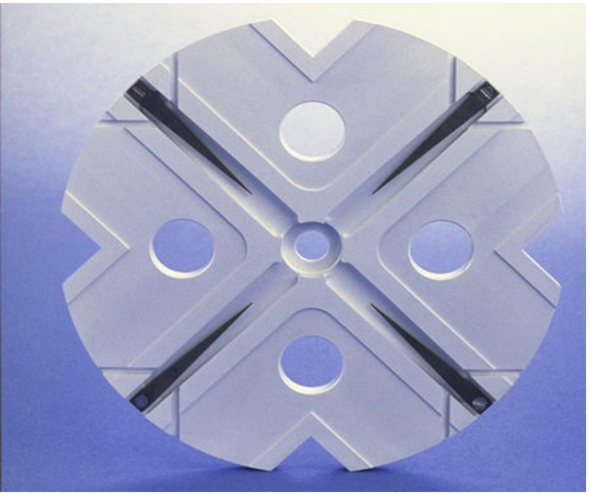
RF structures: transverse wakefields

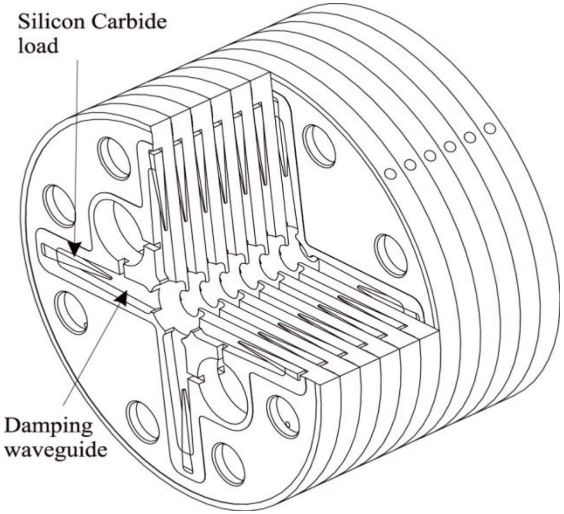


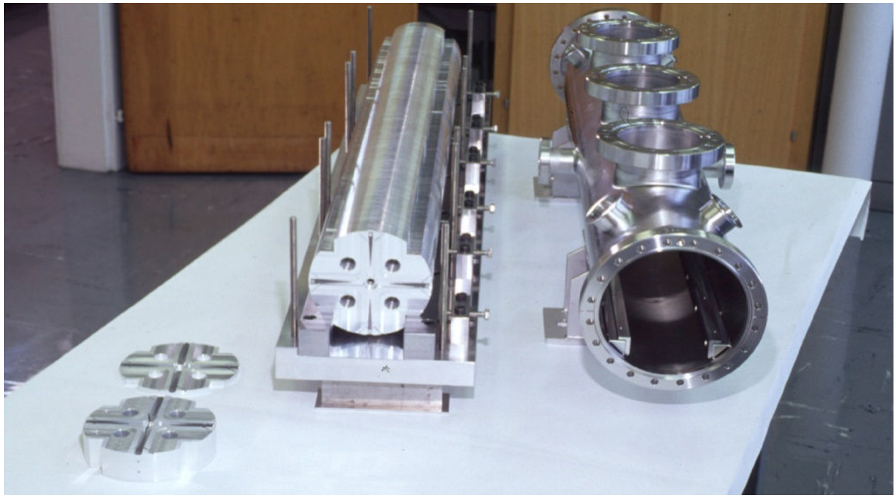
- Bunches induce wakefields in the accelerating cavities
- Later bunches are perturbed by these fields
- Can lead to emittance growth and instabilities!!!

- Effect depends on *a/λ* (*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

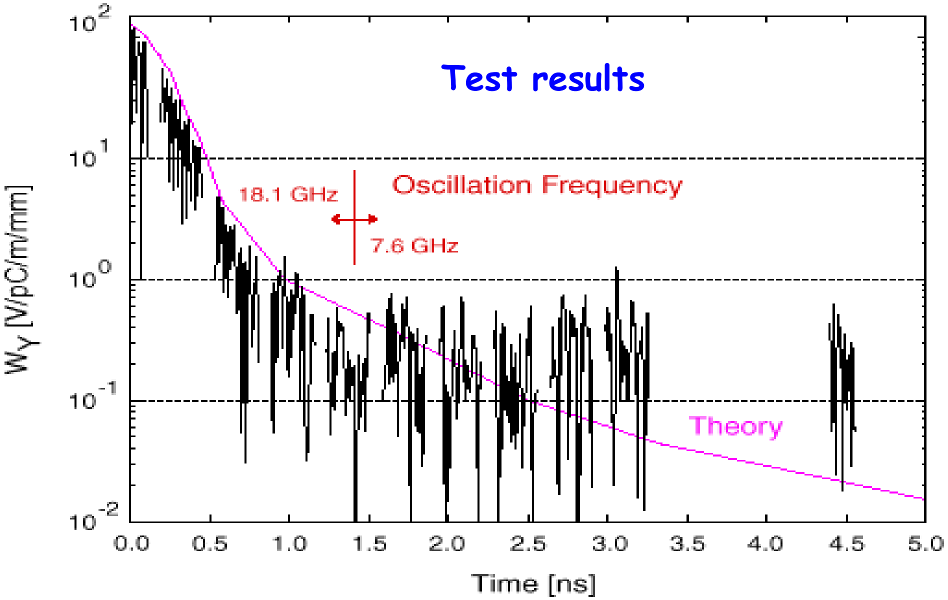
Accelerating structure developments





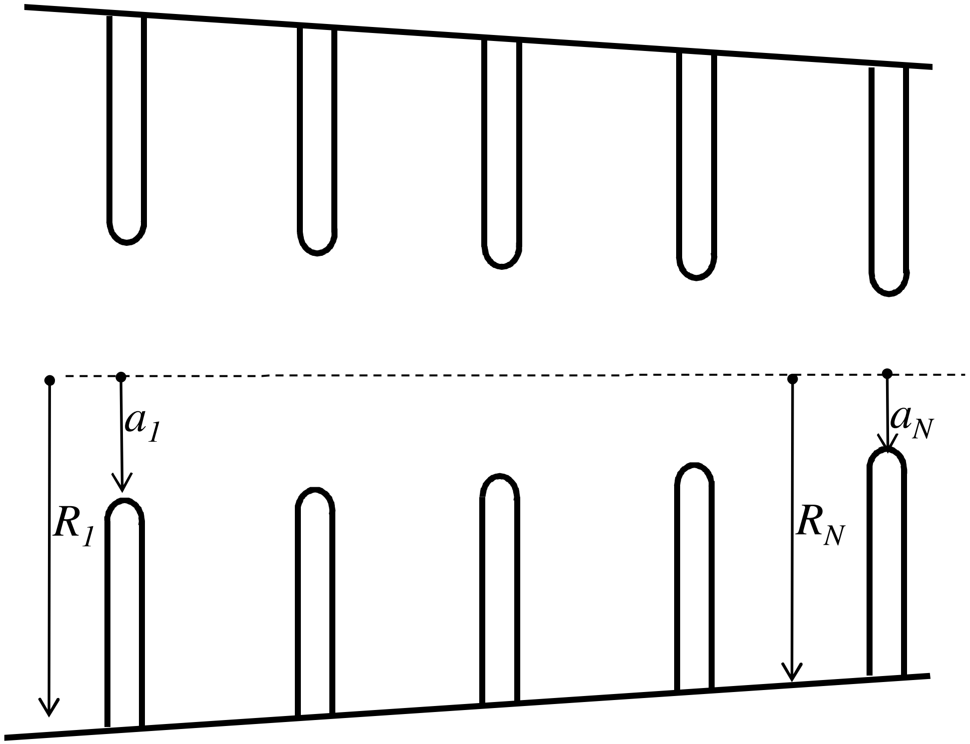


- Structures built from discs
- Each cell damped by 4 radial WGs
- terminated by SiC RF loads
- Higher order modes (HOM) enter WG
- Long-range wakefields efficiently damped

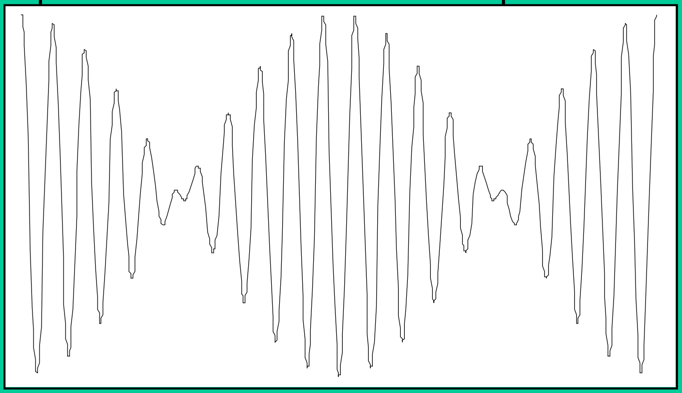


Dipole mode detuning

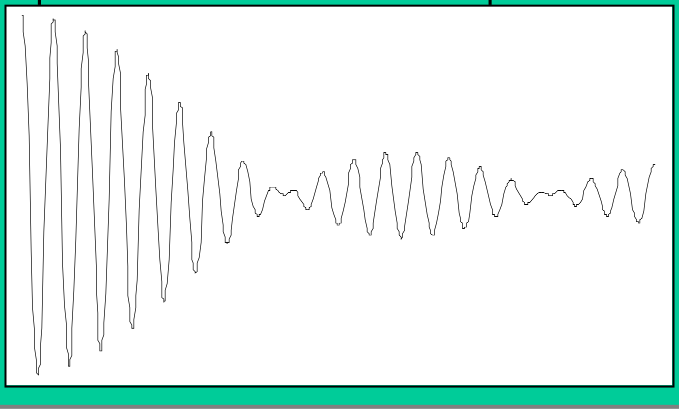
Structure parameters can be varied along structure keeping synchronous frequency for accelerating mode constant but varying synchronous frequencies of dipole modes



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



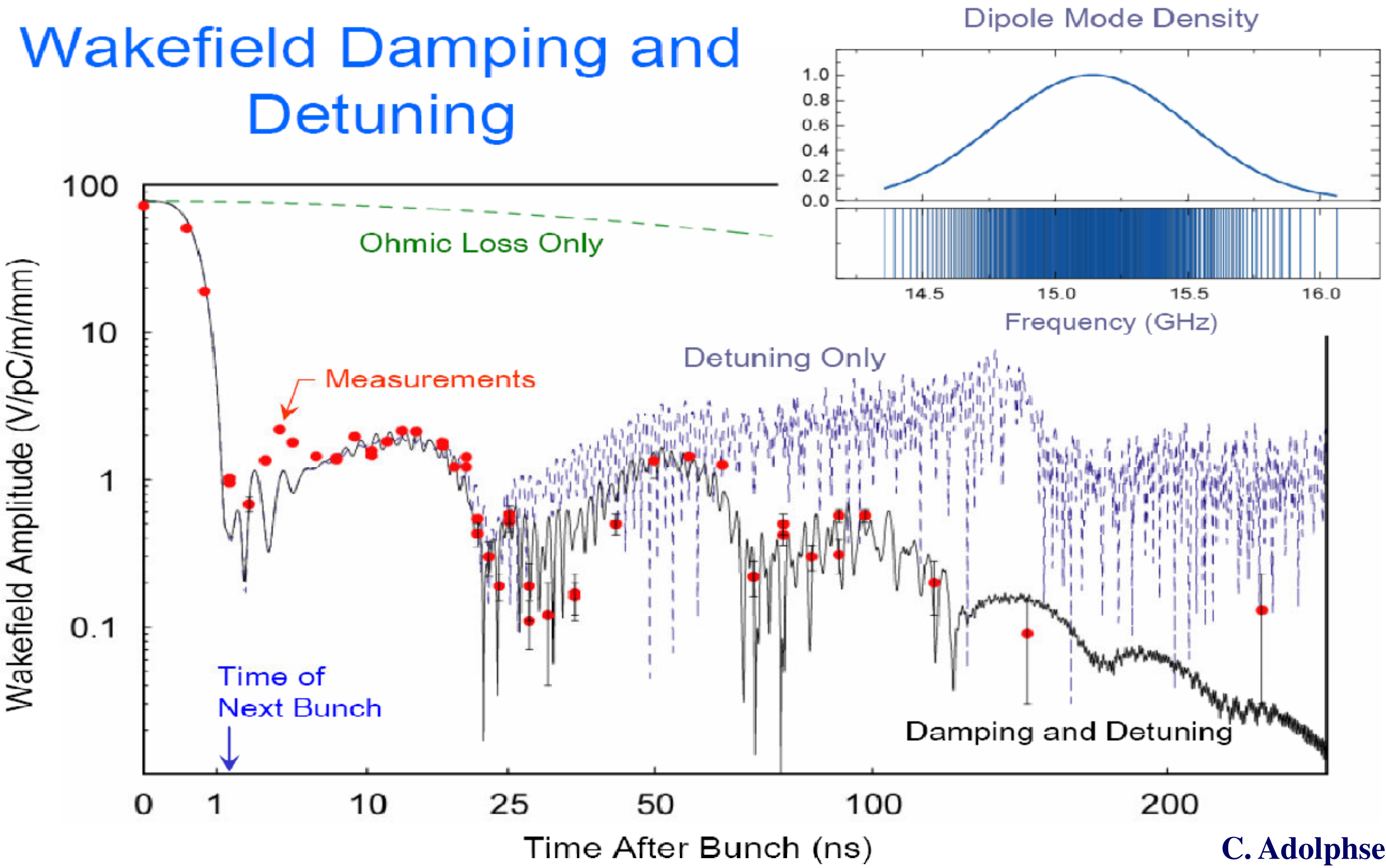
Long range wake of a dipole mode spread over **six** different frequencies



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

Damping and detuning

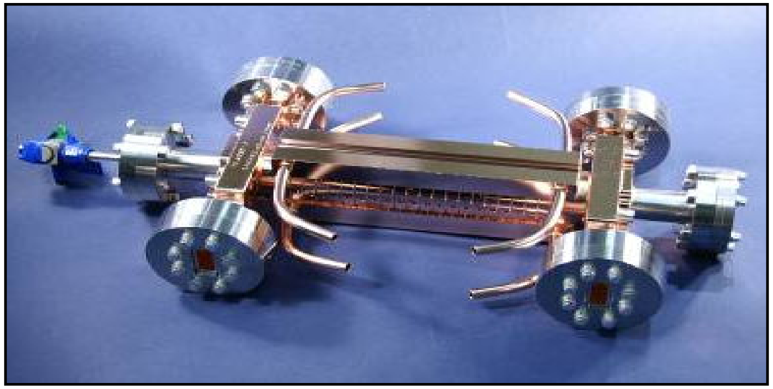
- Slight random detuning between cells makes HOMs decohere quickly
- Will recohere later: need to be damped (HOM dampers)



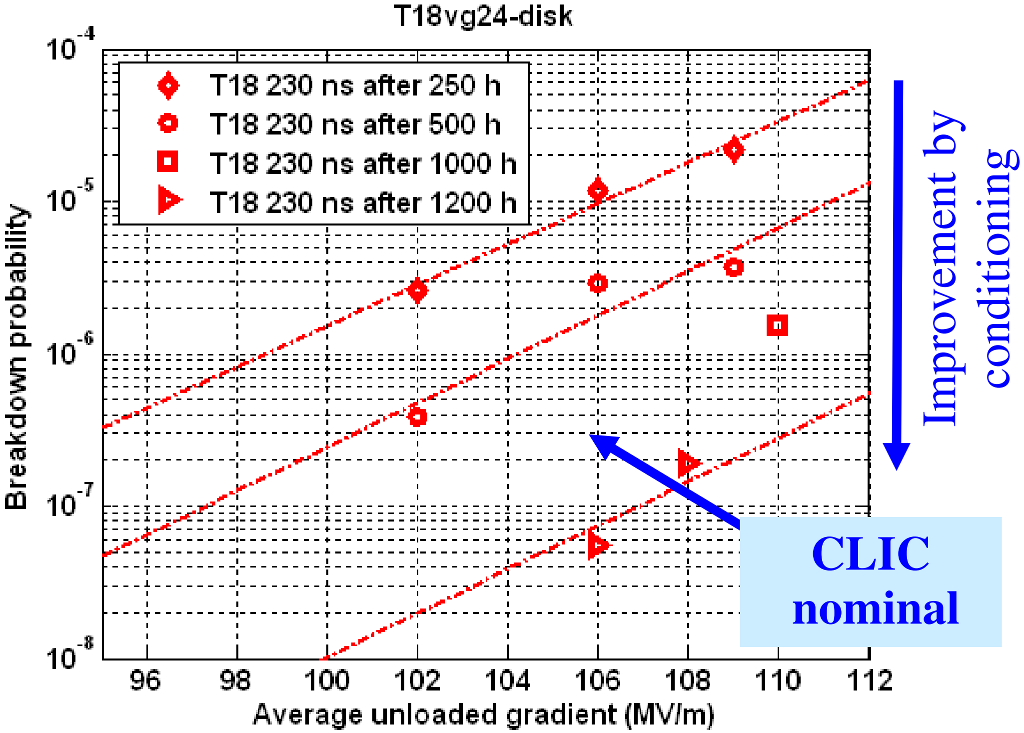
C. Adolphsen / SLAC

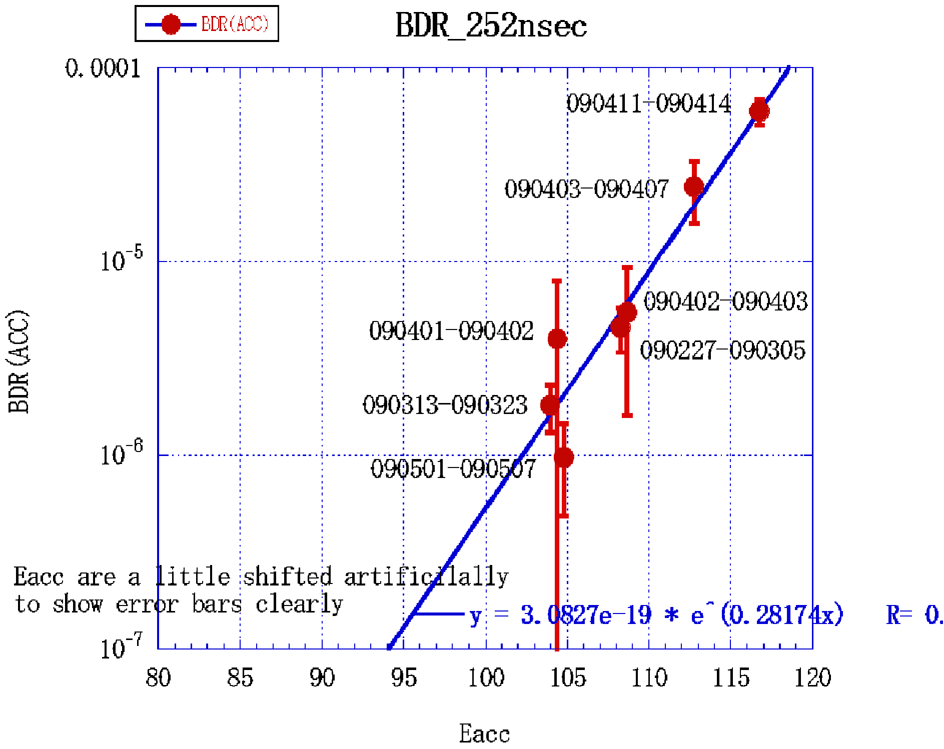
Present best structure performance

- 2 structures ***T18_VG2.4_disk (no damping)***
- tested at SLAC and KEK
- Exceeded 100 MV/m at nominal CLIC breakdown rate

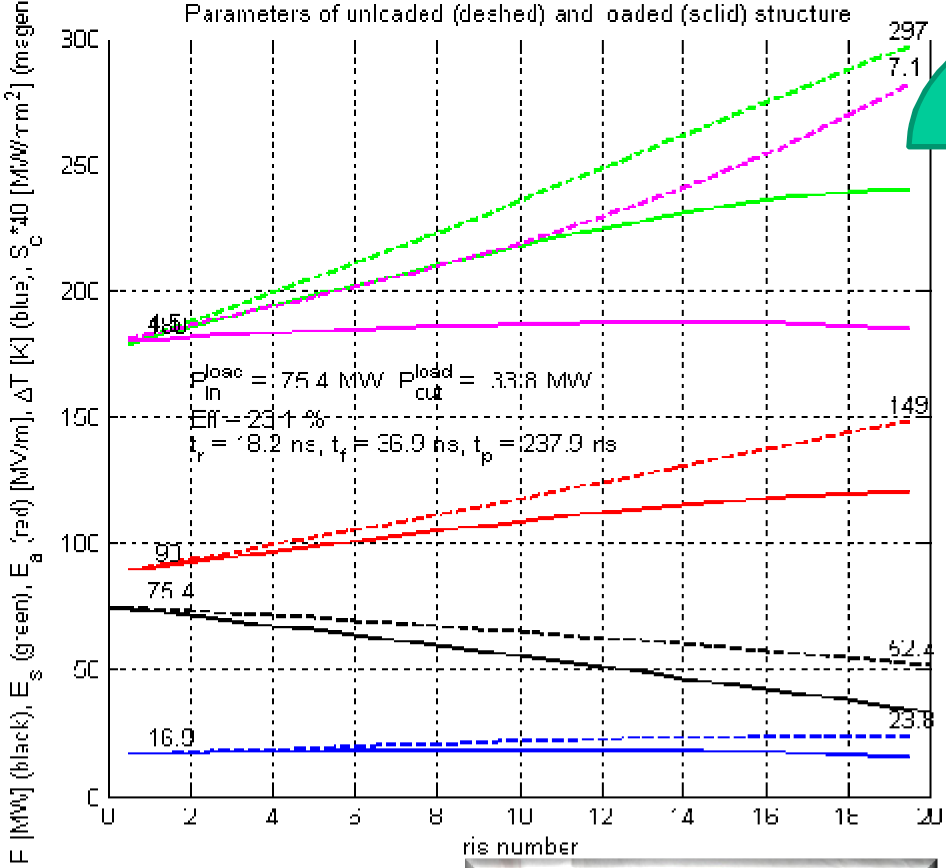


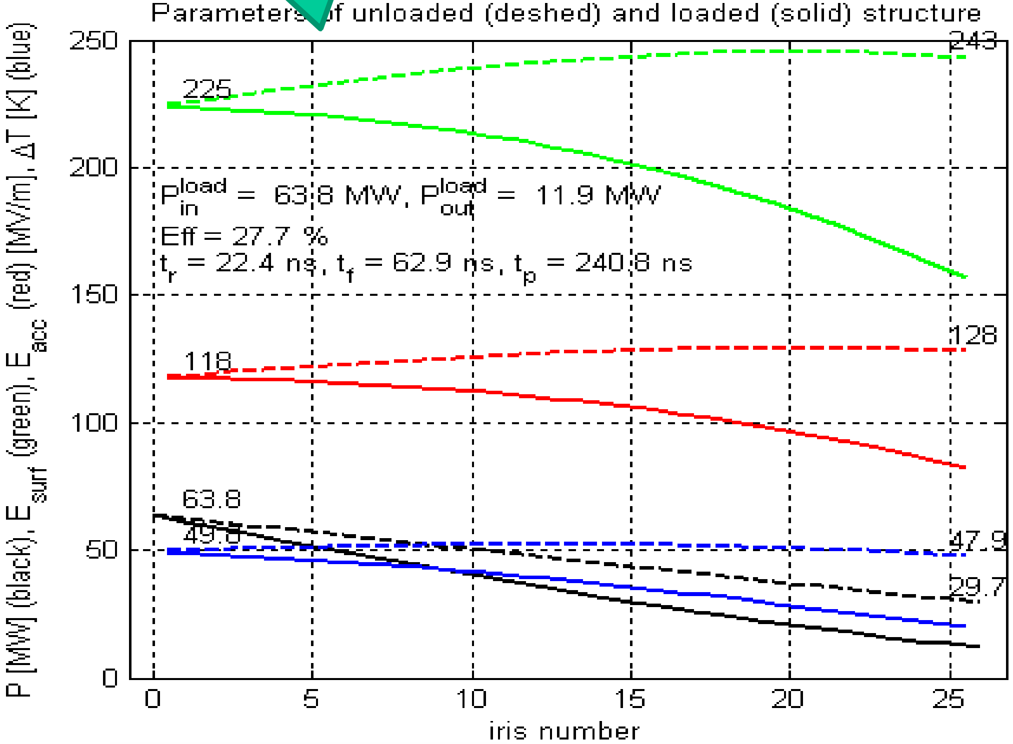
Frequency:	**11.424 GHz**
Cells:	**18+2 matching cells**
Filling Time:	**36 ns**
Length: active acceleration	**18 cm**
Iris Dia. a/λ	**0.155~0.10**
Group Velocity: vg/c	**2.6-1.0 %**
Phase Advace Per Cell	**2π/3**
Power for <Ea>=100MV/m	**55.5 MW**
Unloaded Ea(out)/Ea(in)	**1.55**
Es/Ea	**2**

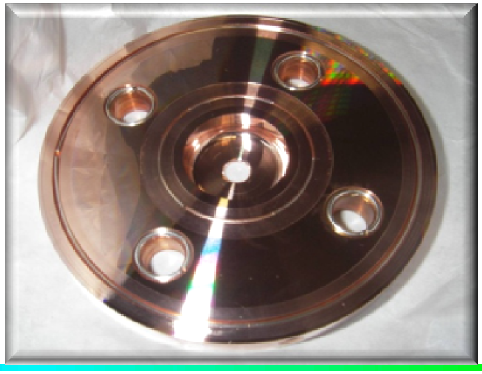




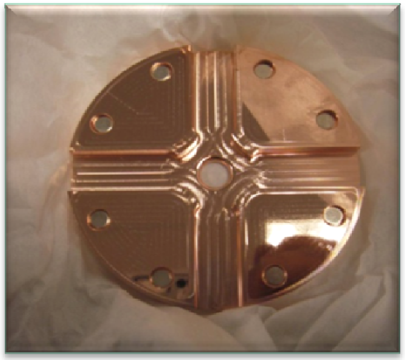
Achieved results to prototype CLIC structure







T18 test structure



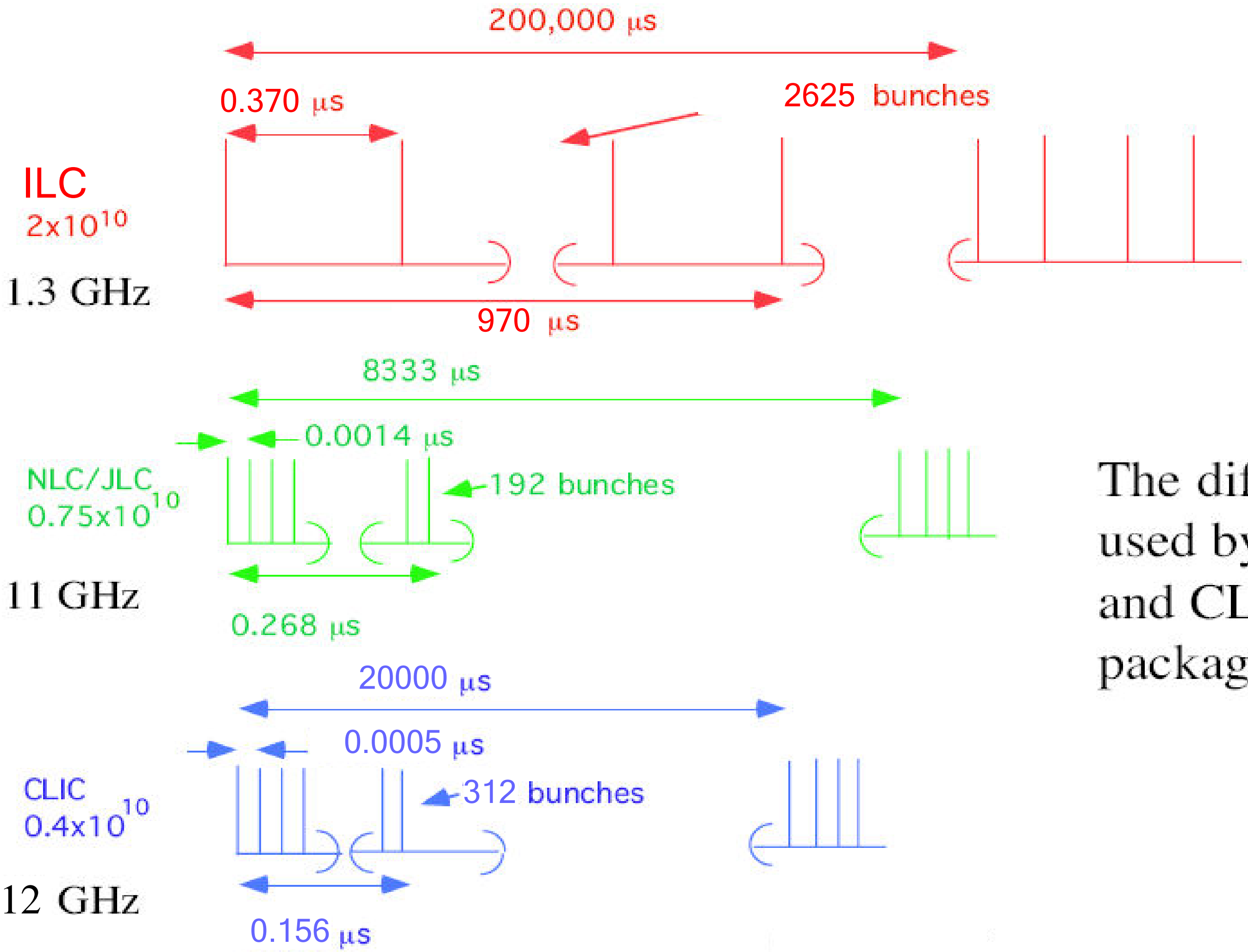
CLIC prototype

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

Bunch structure

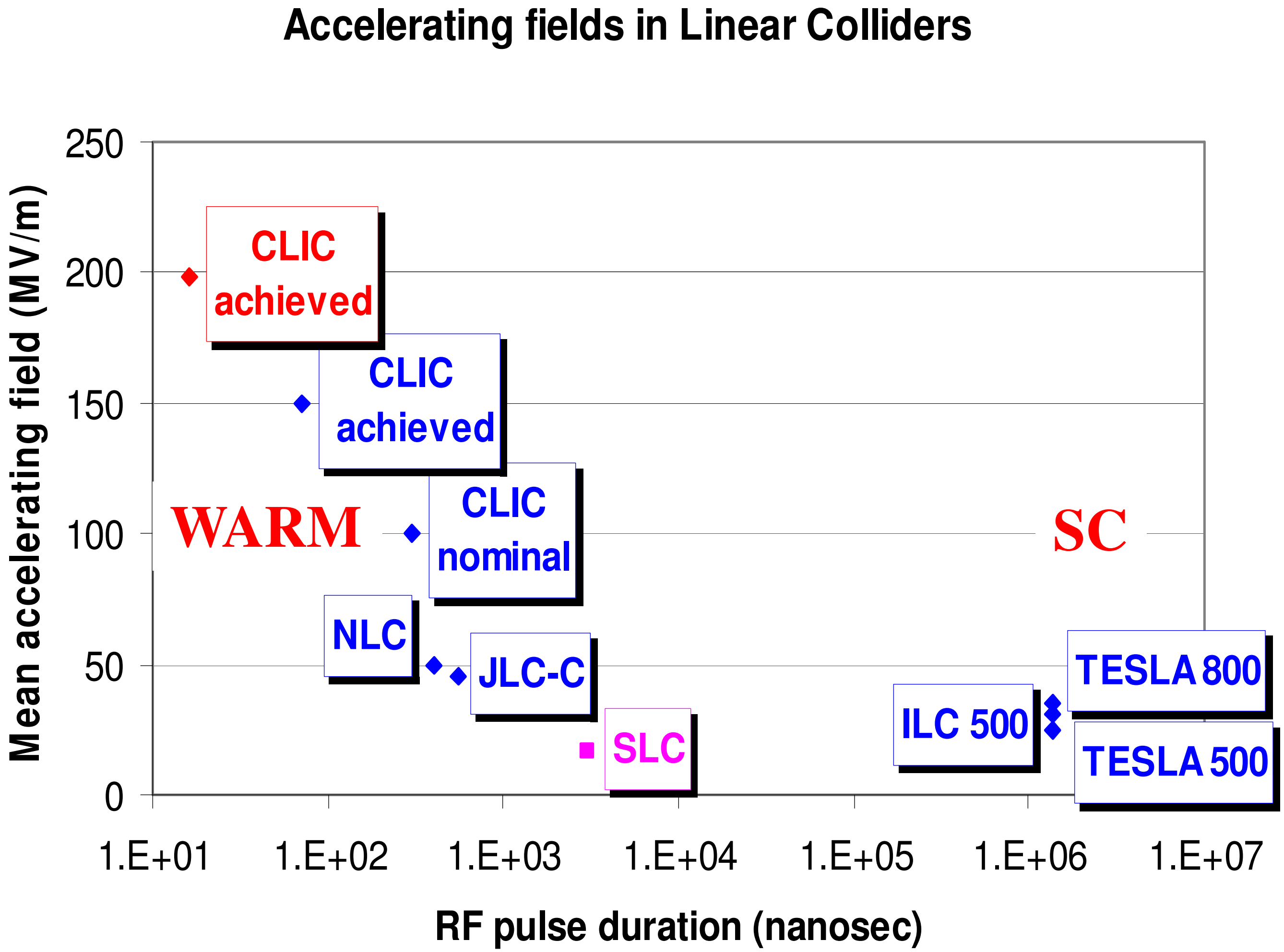
- SC allows long pulse, NC needs short pulse with smaller bunch charge



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

Accelerating gradient

- Superconducting cavities have lower gradient (fundamental limit) with long RF pulse
- Normal conducting cavities have higher gradient with shorter RF pulse length



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 (ε_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 forces detectors to integrate over several bunch crossings
Bunch train length	µs	970	0.156	One CLIC pulse fits easily in small damping ring, simple single turn extraction from DR. 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 (less linac movement between pulses)
$\gamma \varepsilon_x , \gamma \varepsilon_y$	nm	10000, 40	660, 20	Because of smaller beam size CLIC has more stringent requirements for DR equilibrium emittance and emittance preservation (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	129
Bunch length σ_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 β_y^* [mm]	~1.5	0.4	0.4	0.11	0.1
Vert. beam size σ_y^* [nm]	650	5	5.7	3	2.3

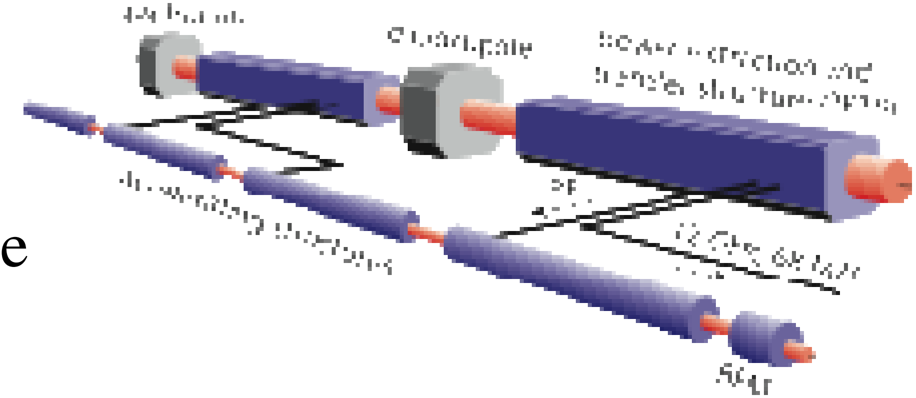
Parameters (except SLC) at 500 GeV

Part 1 - Summary

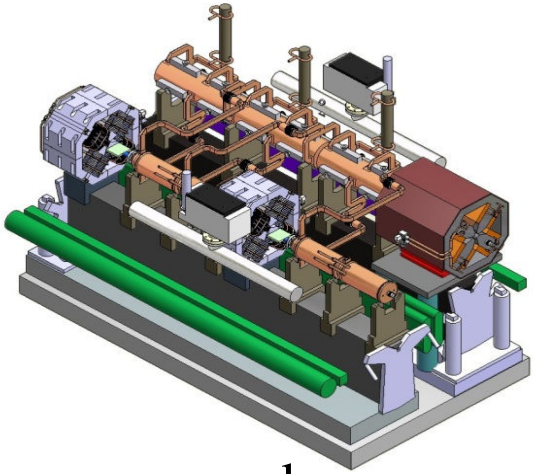
- Normal Conducting traveling wave structures for higher gradients
  - High peak power RF pulses needed
  - Limited by
    - Pulsed surface heating
    - RF breakdowns
    - Structure damage
  - Short RF pulses ~few 100ns (still as long as possible - for efficiency)
  - Klystrons not optimal for high 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 $\Rightarrow E_{cm} = 0.5 - 3$ 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 goal: Demonstrate all key feasibility issues and document in a CDR by 2010 (possibly TDR by 2015)

World-wide CLIC&CTF3 Collaboration

33 Institutes involving
21 funding agencies and 18 countries

Aarhus University (Denmark)
Ankara University (Turkey)
Argonne National Laboratory (USA)
Athens University (Greece)
BINP (Russia)
CERN
CIEMAT (Spain)
Cockcroft Institute (UK)
Gazi Universities (Turkey)

Helsinki Institute of Physics (Finland)
IAP (Russia)
IAP NASU (Ukraine)
INFN / LNF (Italy)
Instituto de Fisica Corpuscular (Spain)
IRFU / Saclay (France)
Jefferson Lab (USA)
John Adams Institute (UK)

JINR (Russia)
Karlsruhe University (Germany)
KEK (Japan)
LAL / Orsay (France)
LAPP / ESIA (France)
NCP (Pakistan)
North-West. Univ. Illinois (USA)
Oslo University (Norway)

Patras University (Greece)
Polytech. University of Catalonia (Spain)
PSI (Switzerland)
RAL (UK)
RRCAT / Indore (India)
SLAC (USA)
Thrace University (Greece)
Uppsala University (Sweden)

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	42.2 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	48.4 km
Total power consumption	390 MW

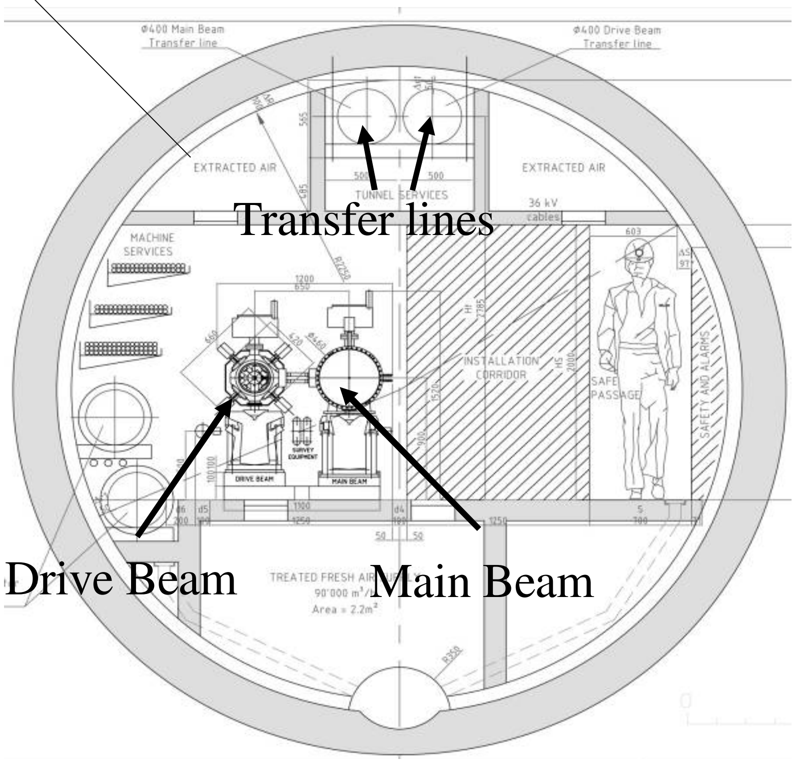
CLIC – basic features

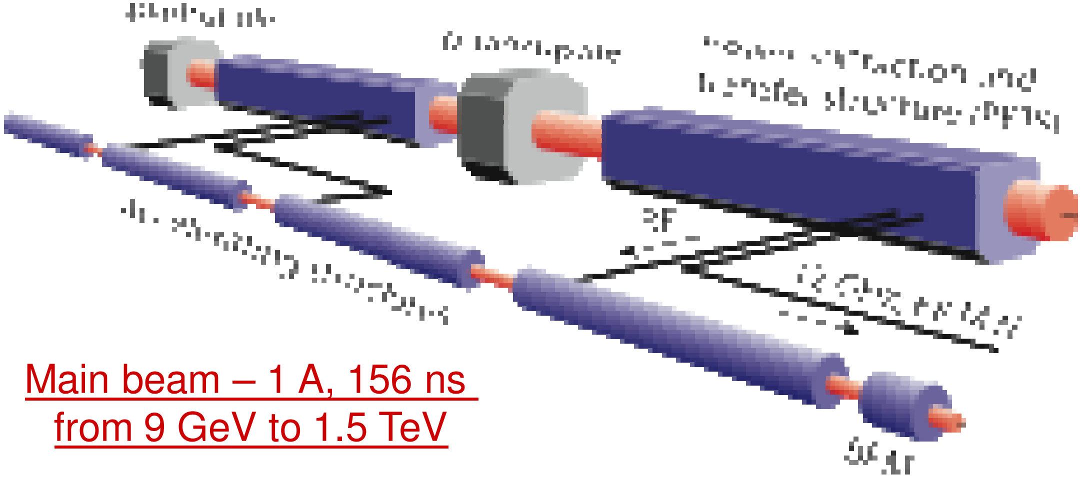
- High acceleration gradient
  - "Compact" collider – total length < 50 km
  - Normal conducting acceleration structures
  - High acceleration frequency (12 GHz)

- 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

CLIC TUNNEL CROSS-SECTION

4.5 m diameter





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

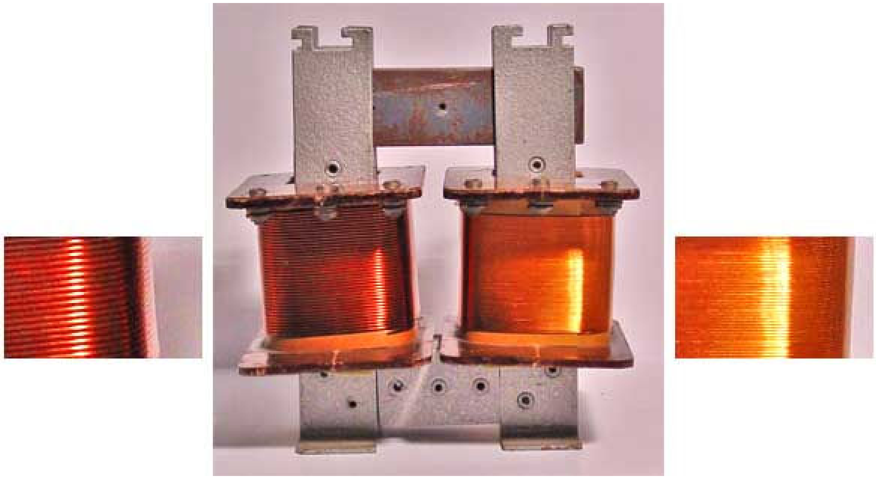
Drive beam - 101 A, 240 ns
from 2.4 GeV to 240 MeV

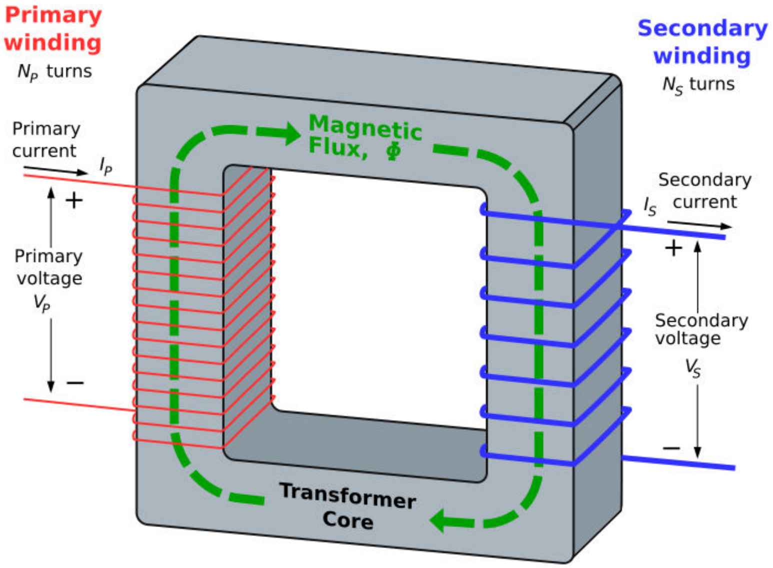
CLIC - a big transformer

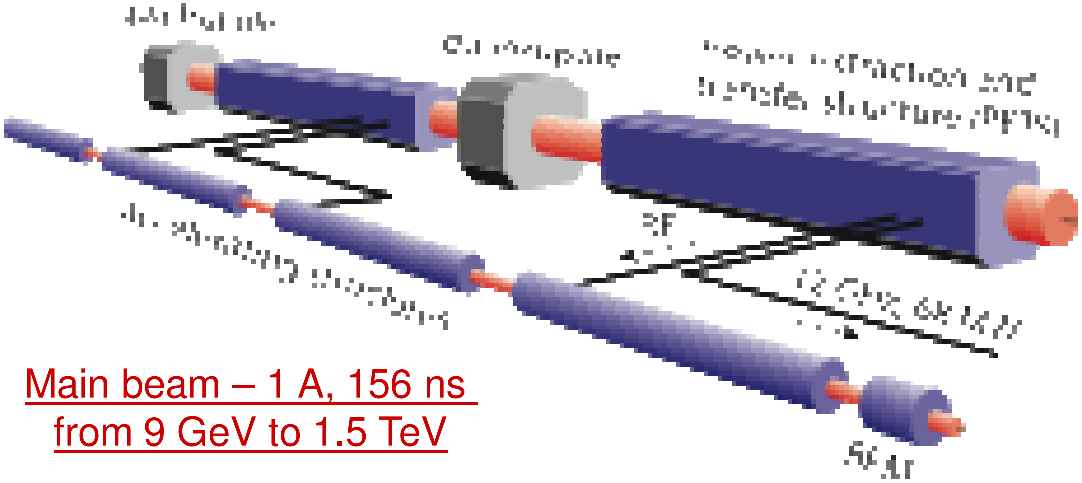
- Like a HV transformer:
  input: low voltage – high current
  output: high voltage – low current

- Here:
  input (‘Drive Beam’):
  low energy (GeV) – high current
  output (‘Main Beam’):
  high energy (TeV) – low current

- Transformer ‘core’:
  waveguides with RF waves





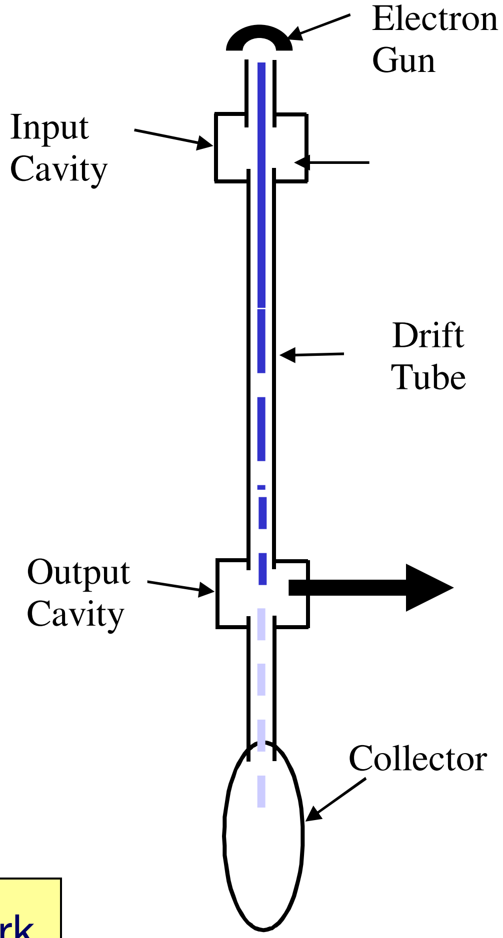


Main beam – 1 A, 156 ns
from 9 GeV to 1.5 TeV

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



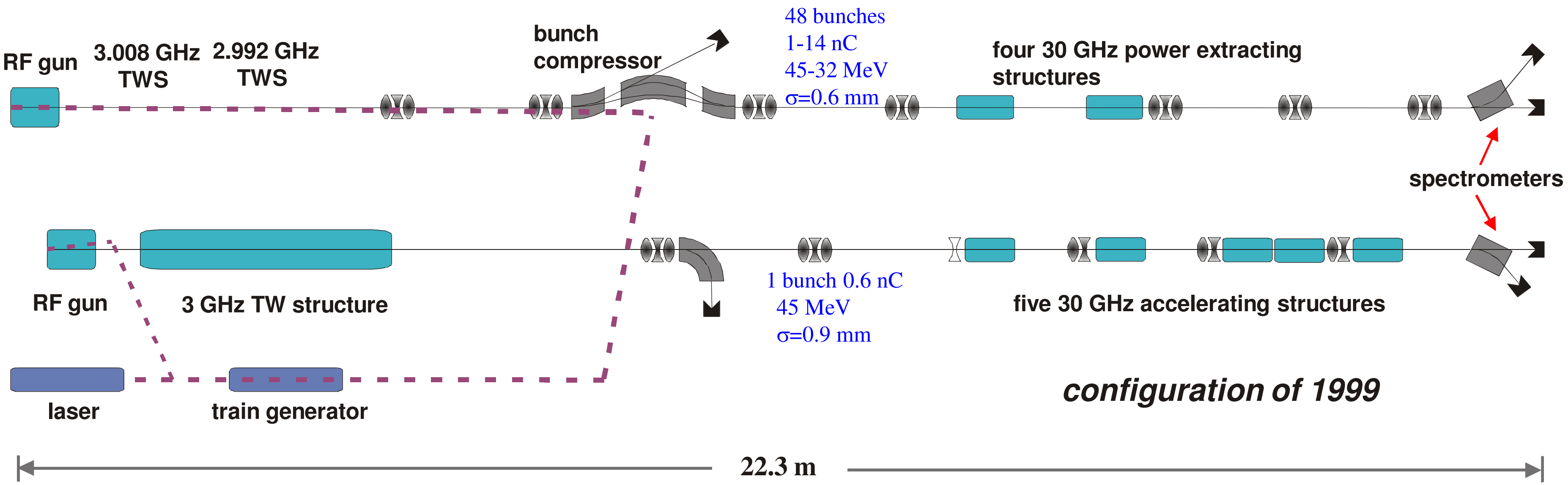
- We need: - high power for high fields
  - short pulses (remember: break-downs, surface heating)
- Many klystrons
  - ILC: 560 10 MW, 1.6 ms
  - NLC: 4000 75 MW, 1.6 μs
  - CLIC: would need many more ☹ $£€¥ ☹

=> see homework

- Can reduce number by RF pulse compression schemes

- Drive beam like beam of gigantic klystron

CLIC Test Facility CTF II

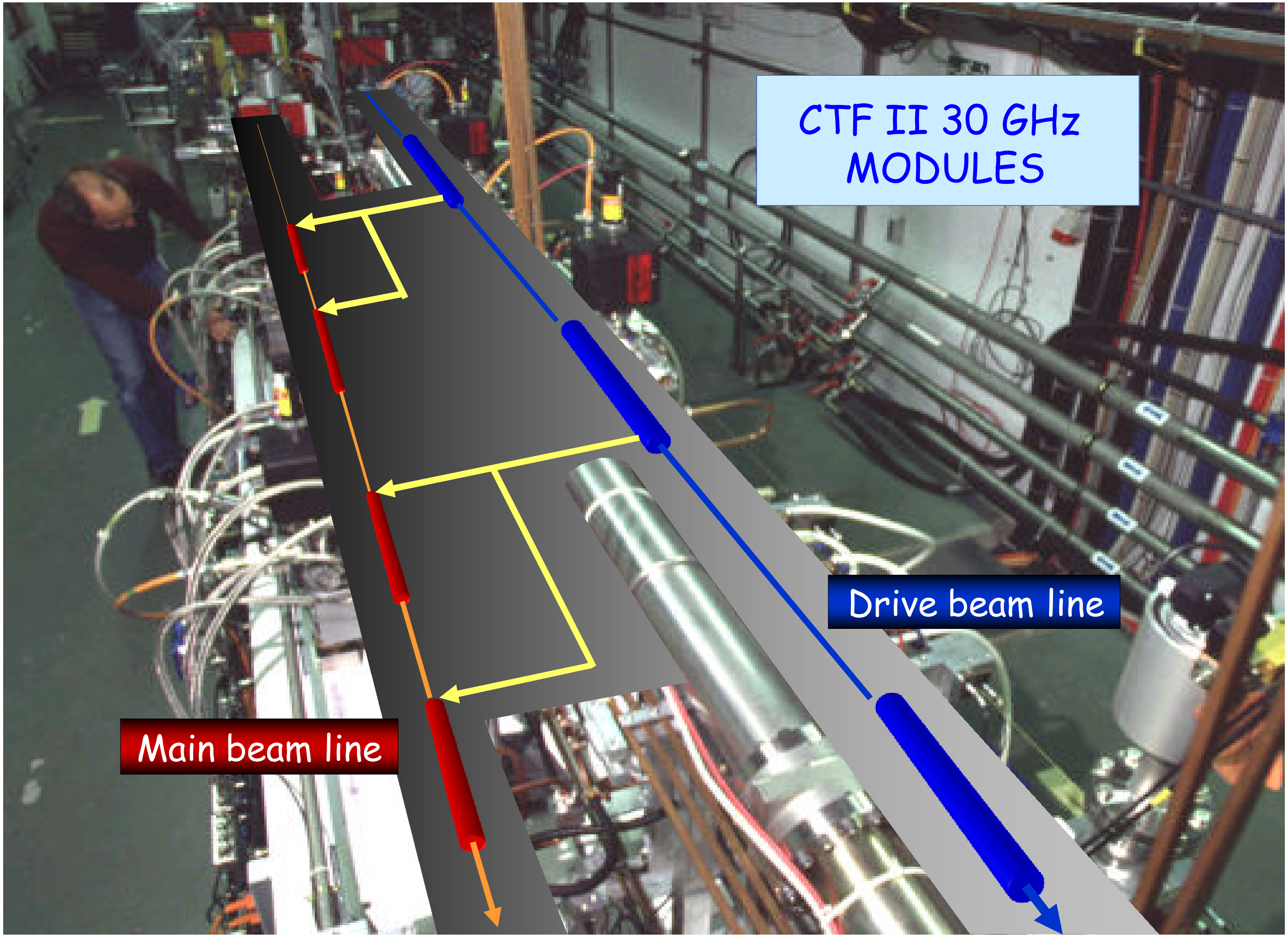


configuration of 1999

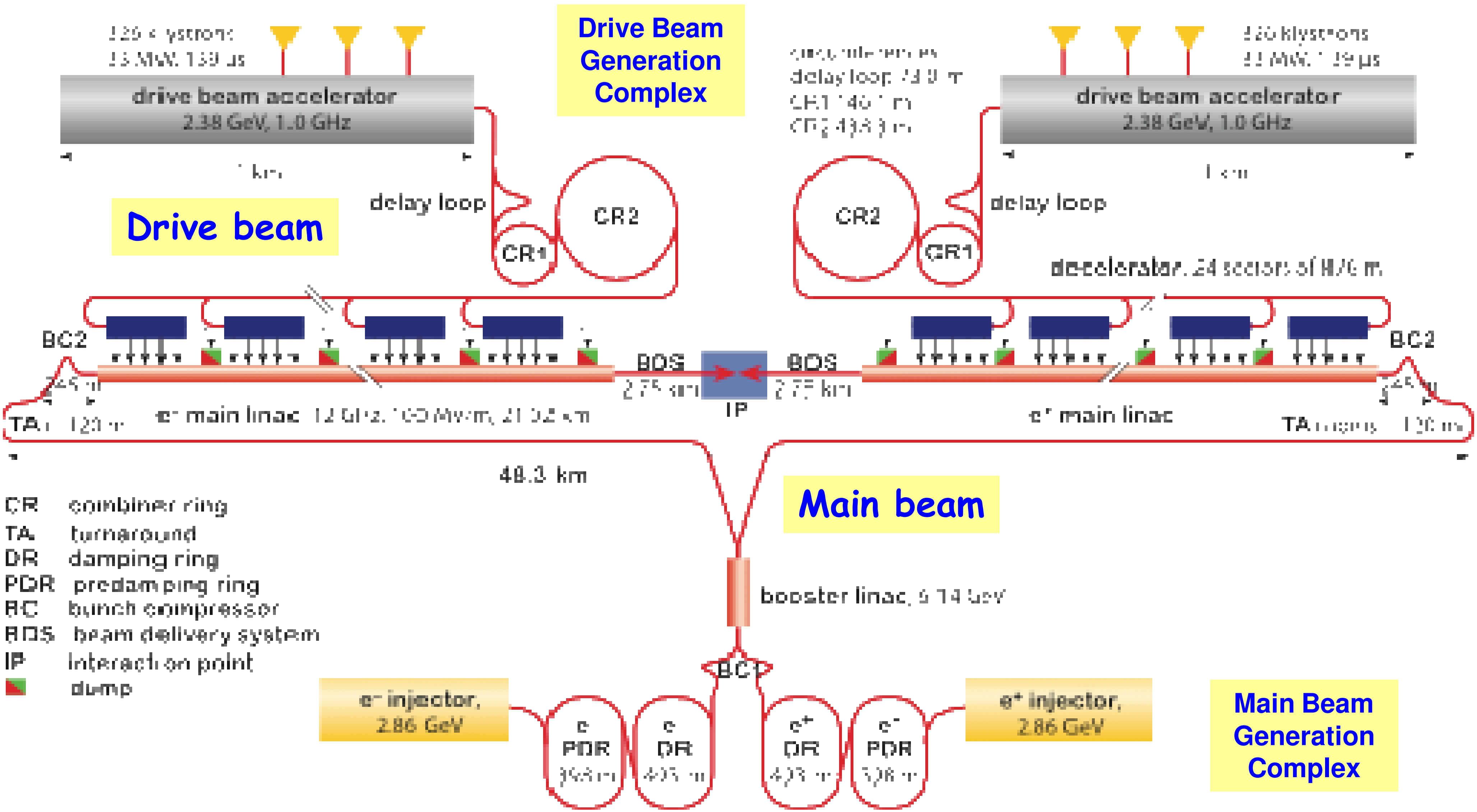
Dismantled in 2002, after having achieved its goals :

- 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



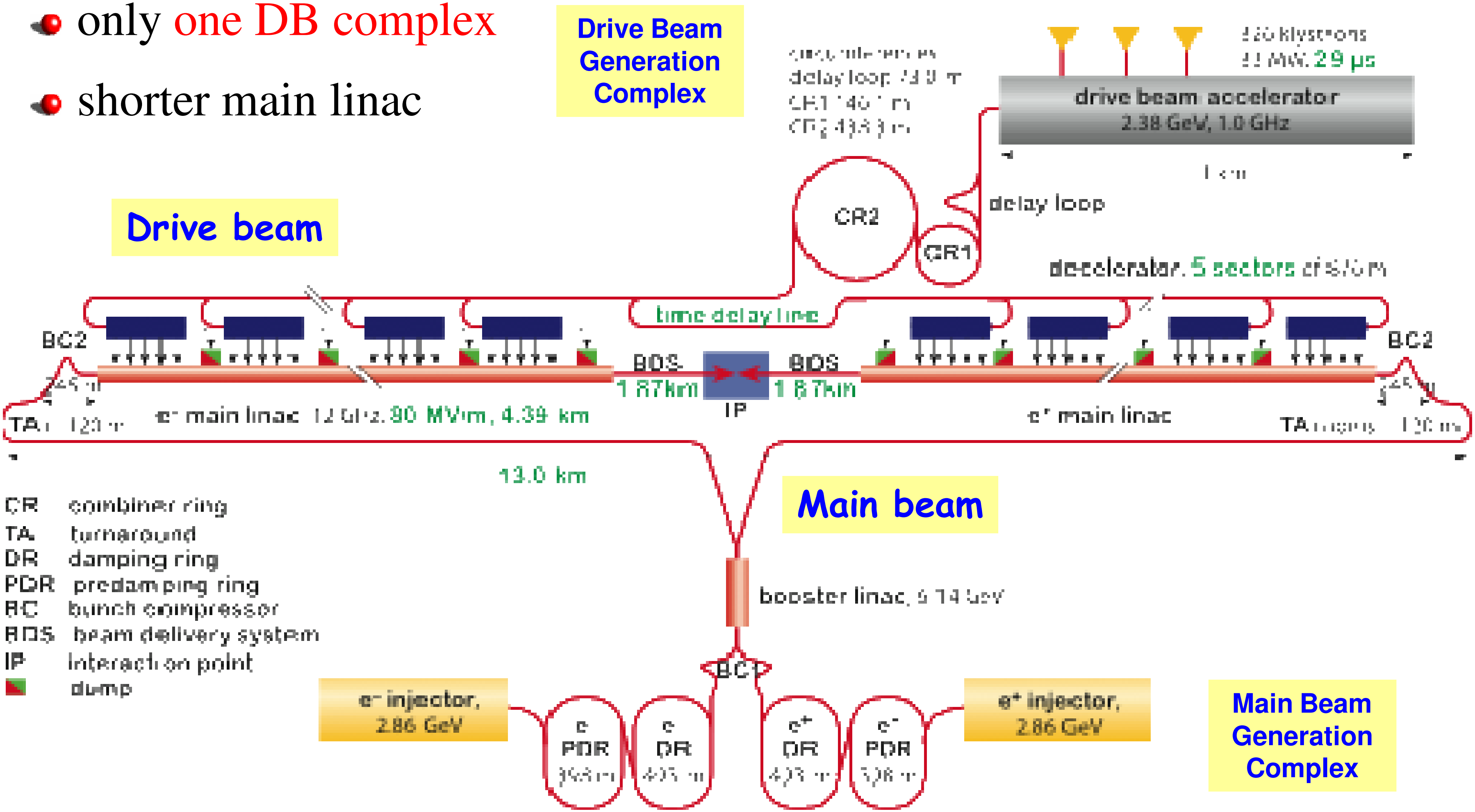
CLIC – overall layout – 3 TeV



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

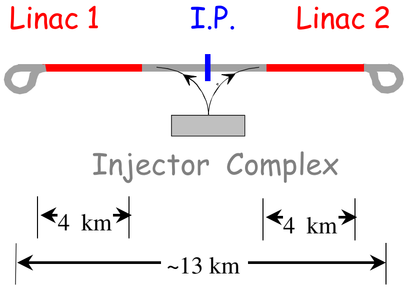
- only one DB complex
- shorter main linac



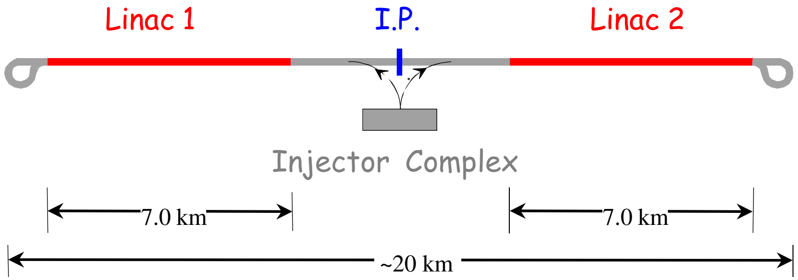
CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
🟥	dump

CLIC Layout at various energies

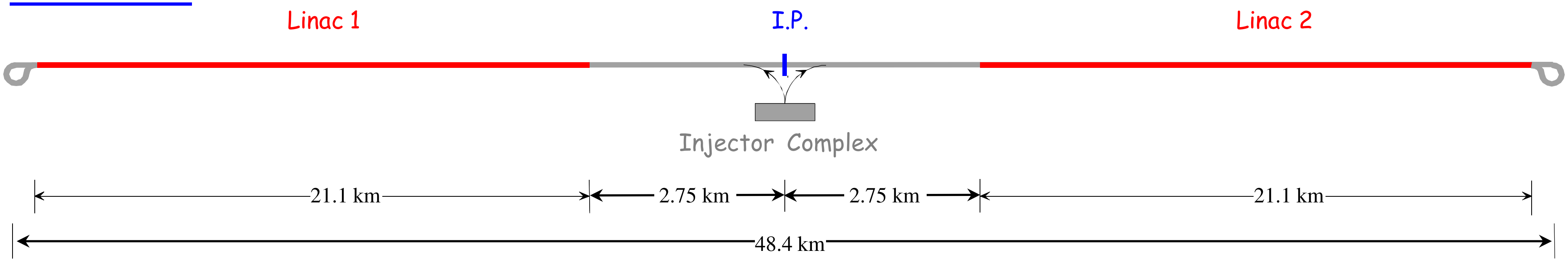
0.5 TeV Stage



1 TeV Stage

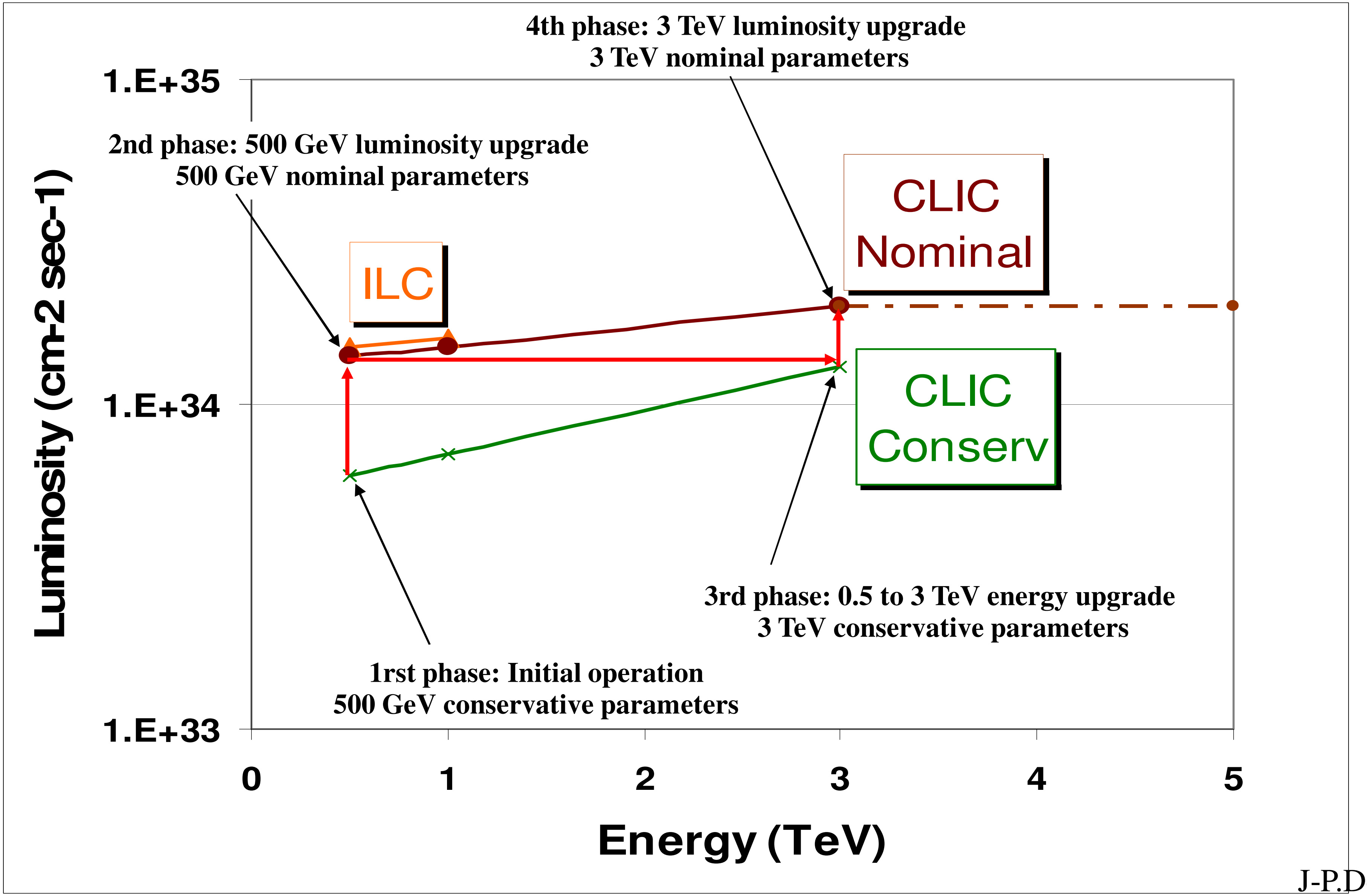


3 TeV Stage



CLIC Parameters and upgrade scenario

http://cdsweb.cern.ch/record/1132079/files/CERN-OPEN-2008-021.pdf



J-P.Delahaye

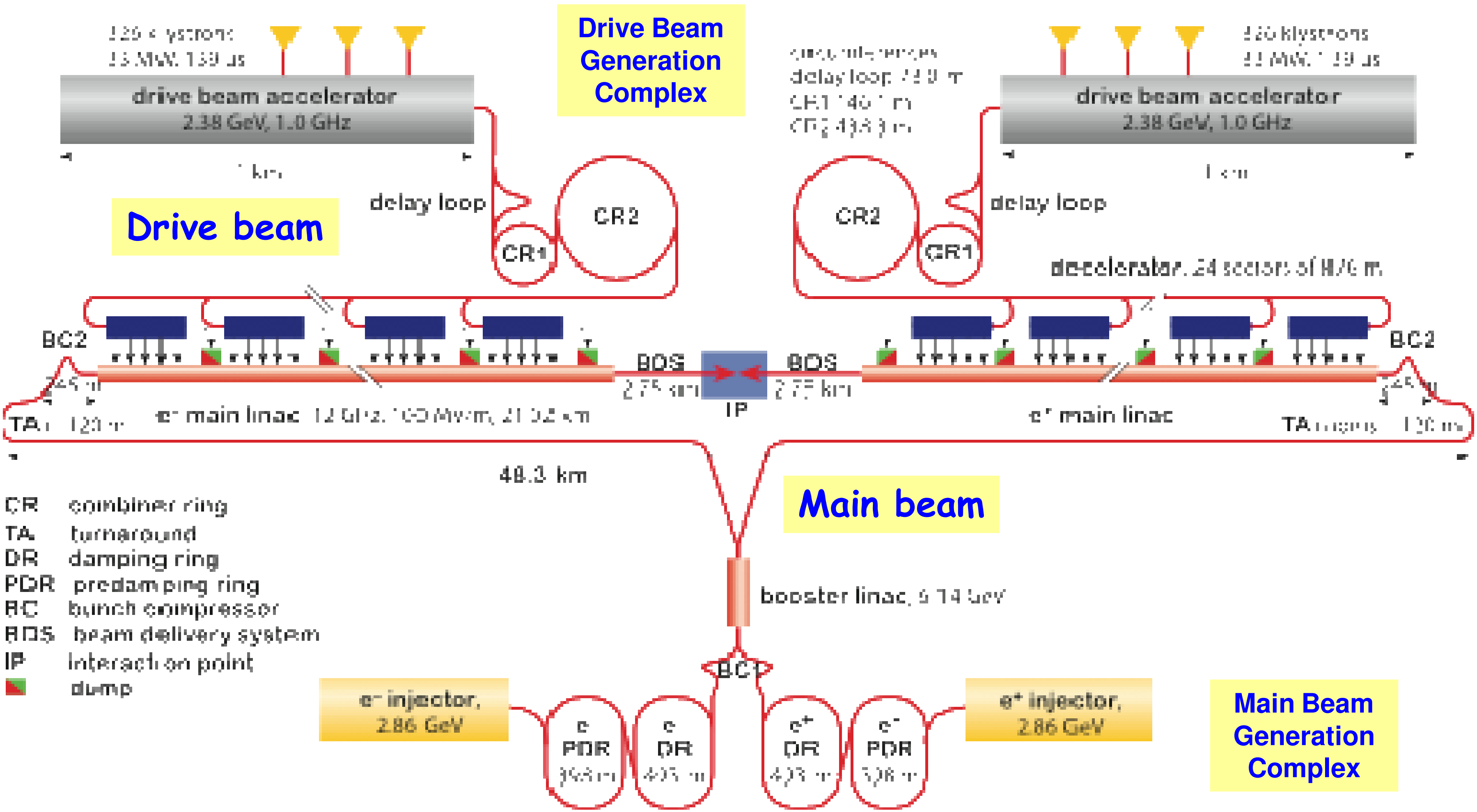
CLIC main parameters

Center-of-mass energy	CLIC 500 G		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 charge10^9	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 G Conservative	CLIC 500 G Nominal
Total (Peak 1%) luminosity	2.0 (1.3)·10^{34}	2.0 (1.5)·10^{34}	0.9 (0.6)·10^{34}	2.3 (1.4)·10^{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 charge10^9	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



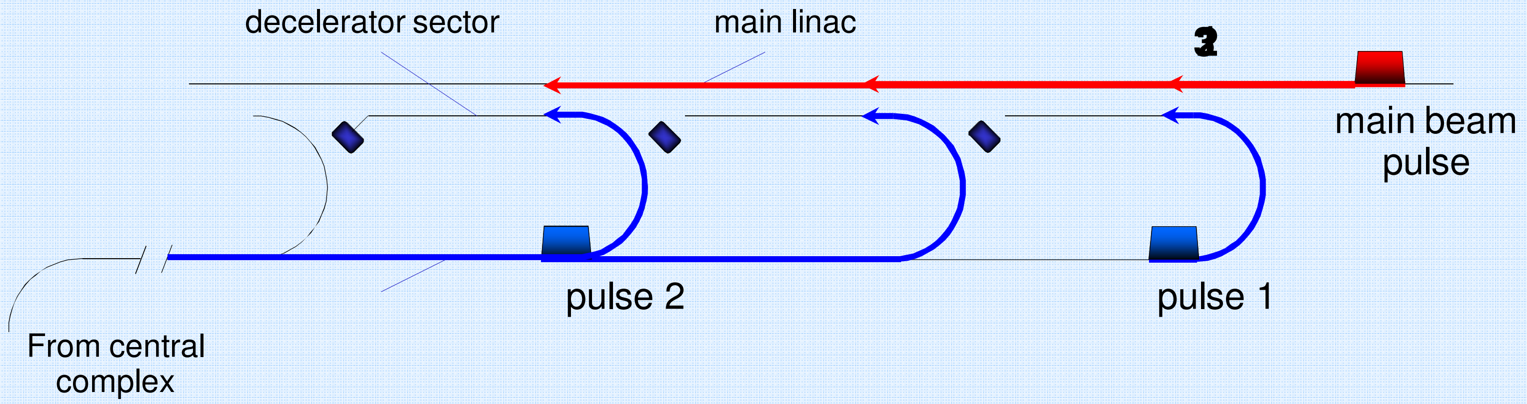
CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
🟥	dump

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

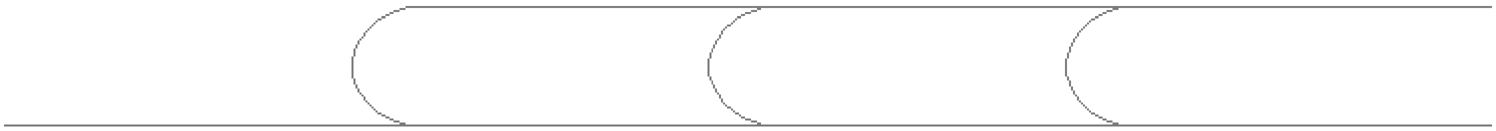
The distance between the pulses is 2 L_s = 2 L_{main}/N_S (L_{main}= single side linac length)

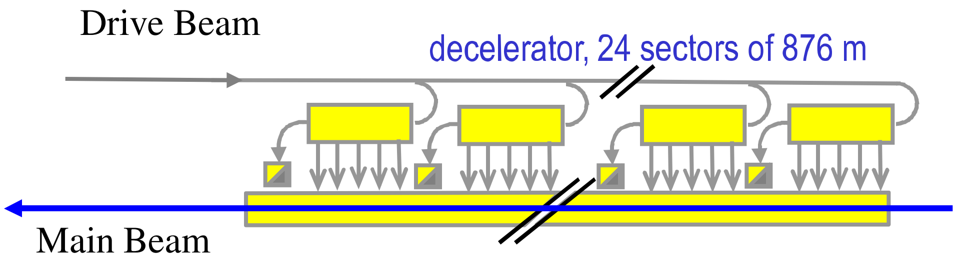
The initial drive beam pulse length t_{DB} is given by twice the time of flight through one single linac

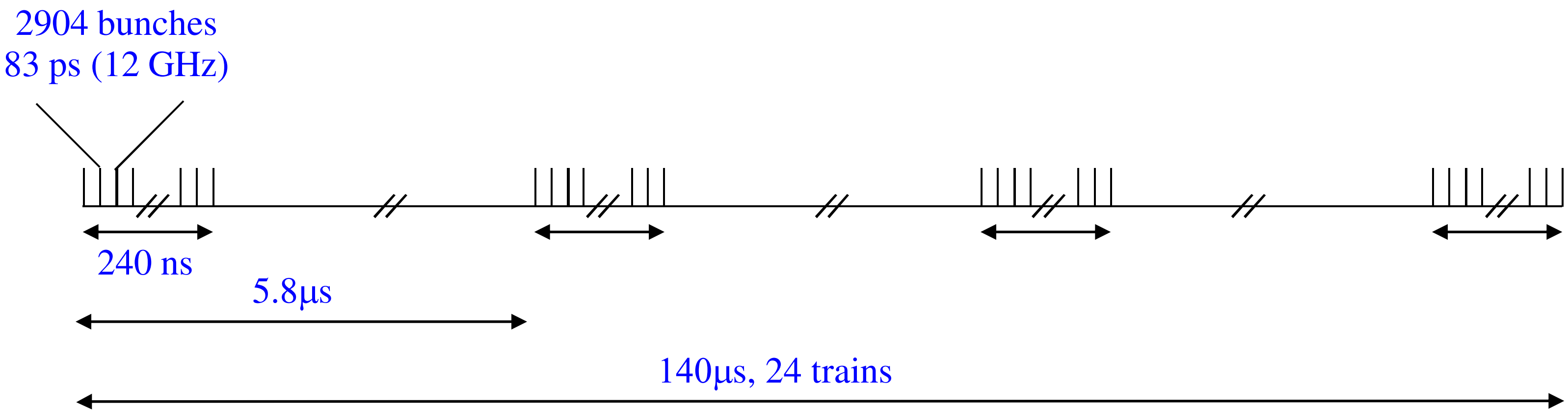
so $t_{DB} = 2 L_{main} / c$, 140 μs for the 3 TeV CLIC

R.Corsini

Drive beam time structure





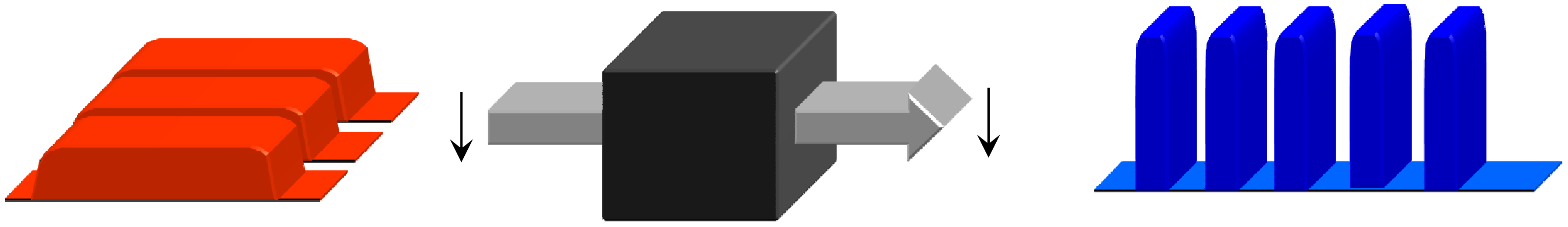


Bunch charge: 8.4 nC, Current in train: 100 A

G.Geschonke

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

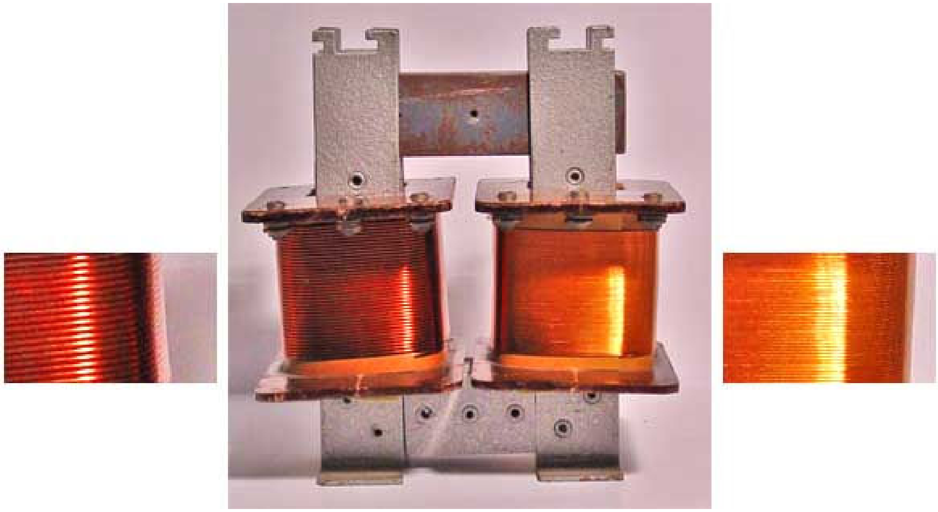
Long RF Pulses
P_0 , ν_0 , τ_0

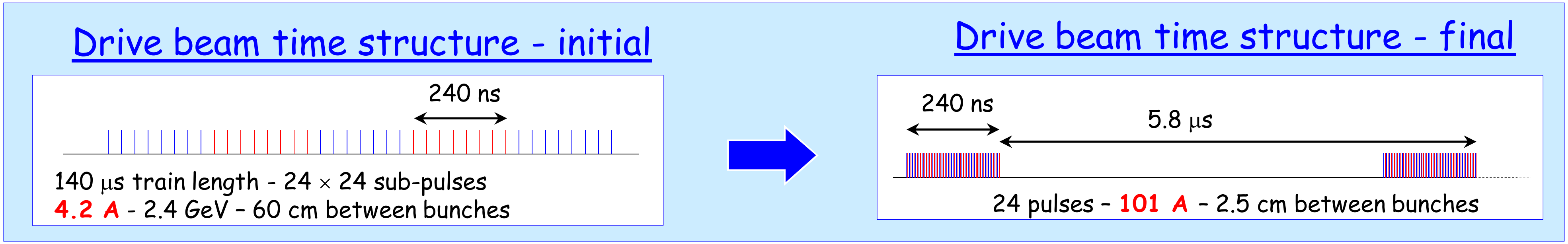
Electron beam manipulation
Power compression
Frequency multiplication

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



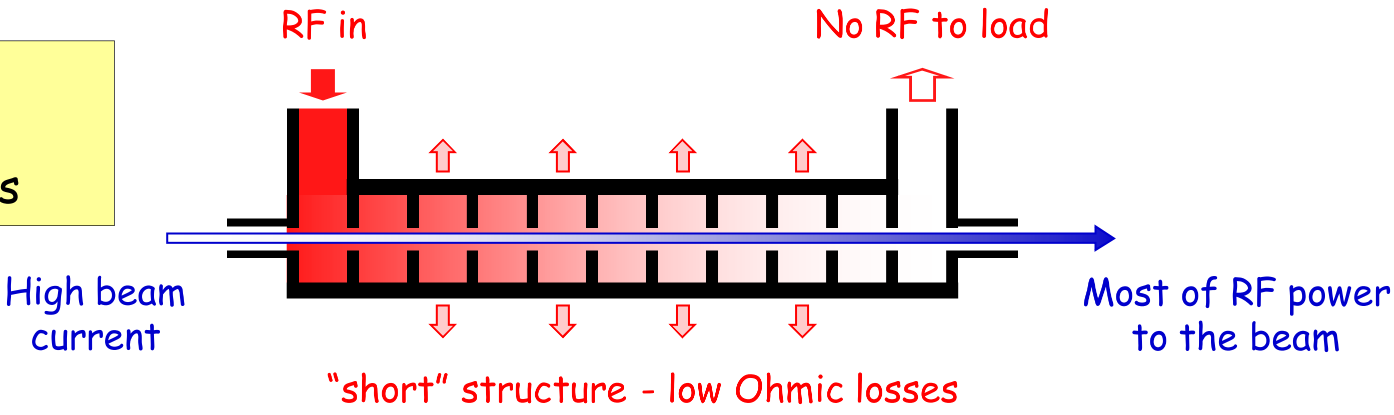

Drive beam time structure - initial

Drive beam time structure - final

Drive beam generation basics

- Efficient acceleration

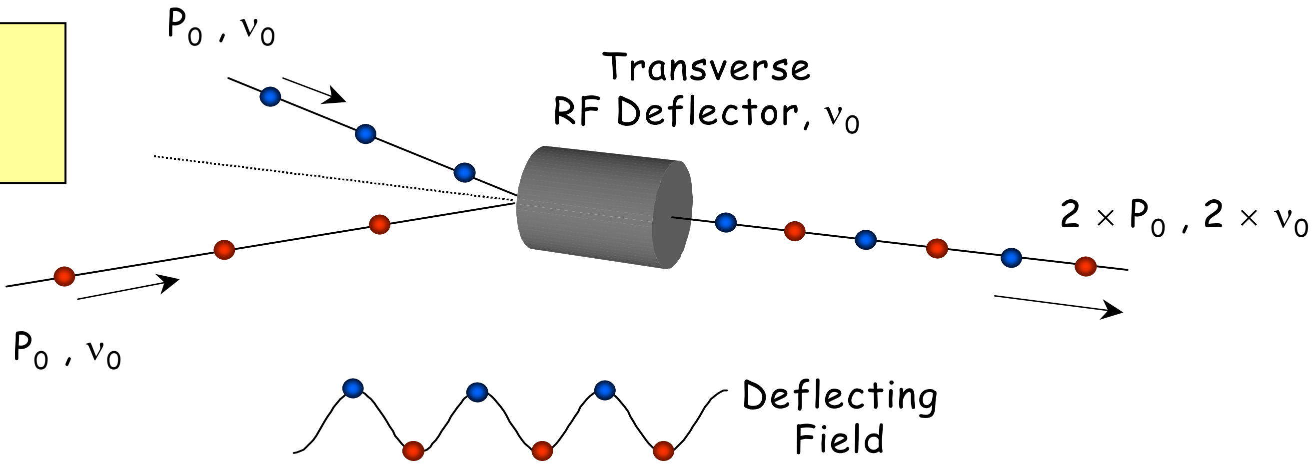
Full beam-loading
acceleration in
traveling wave sections



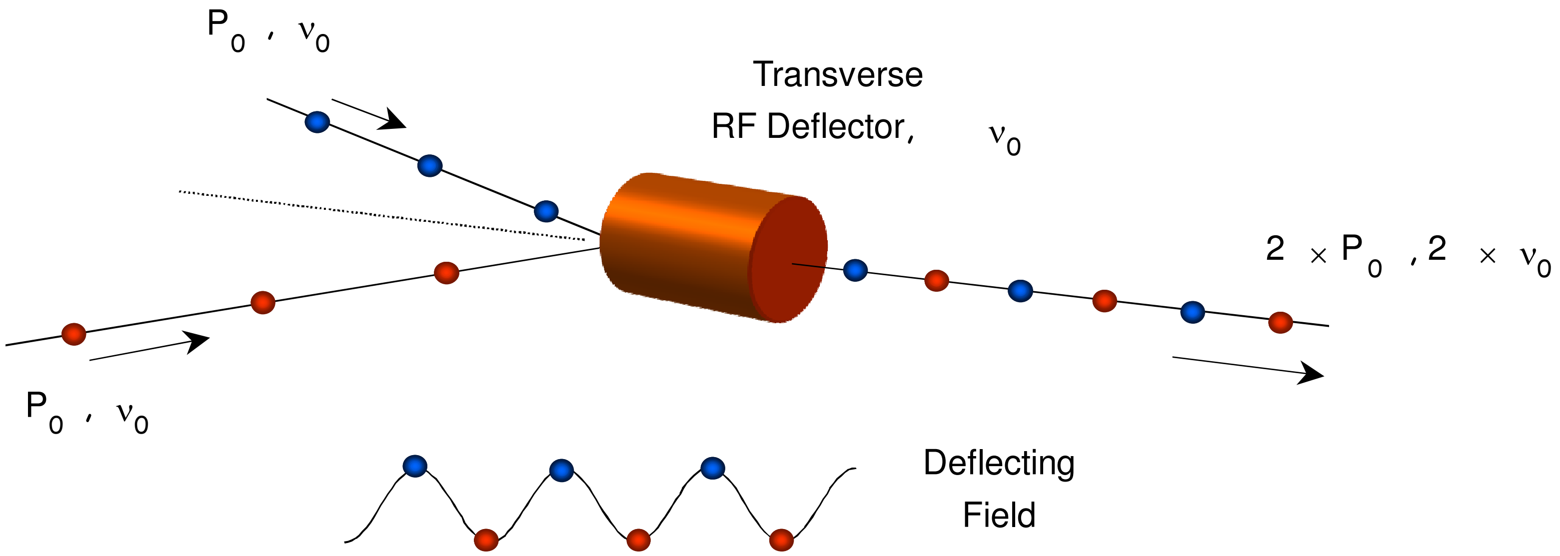
- Frequency multiplication

Beam combination/separation

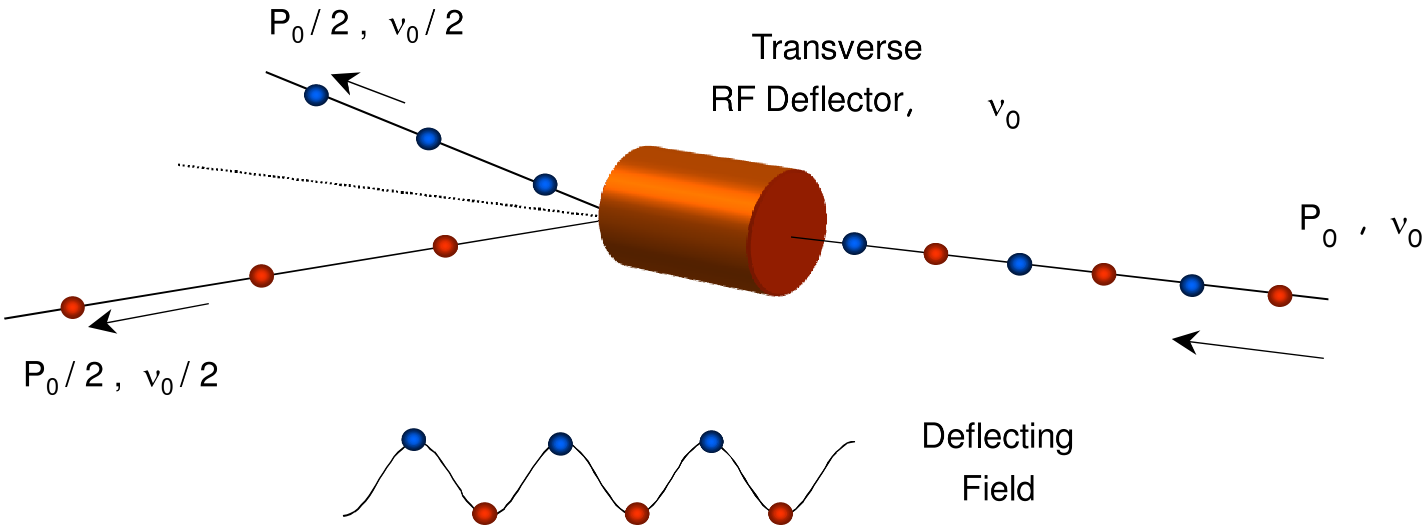
by transverse RF deflectors



Beam combination by RF deflectors

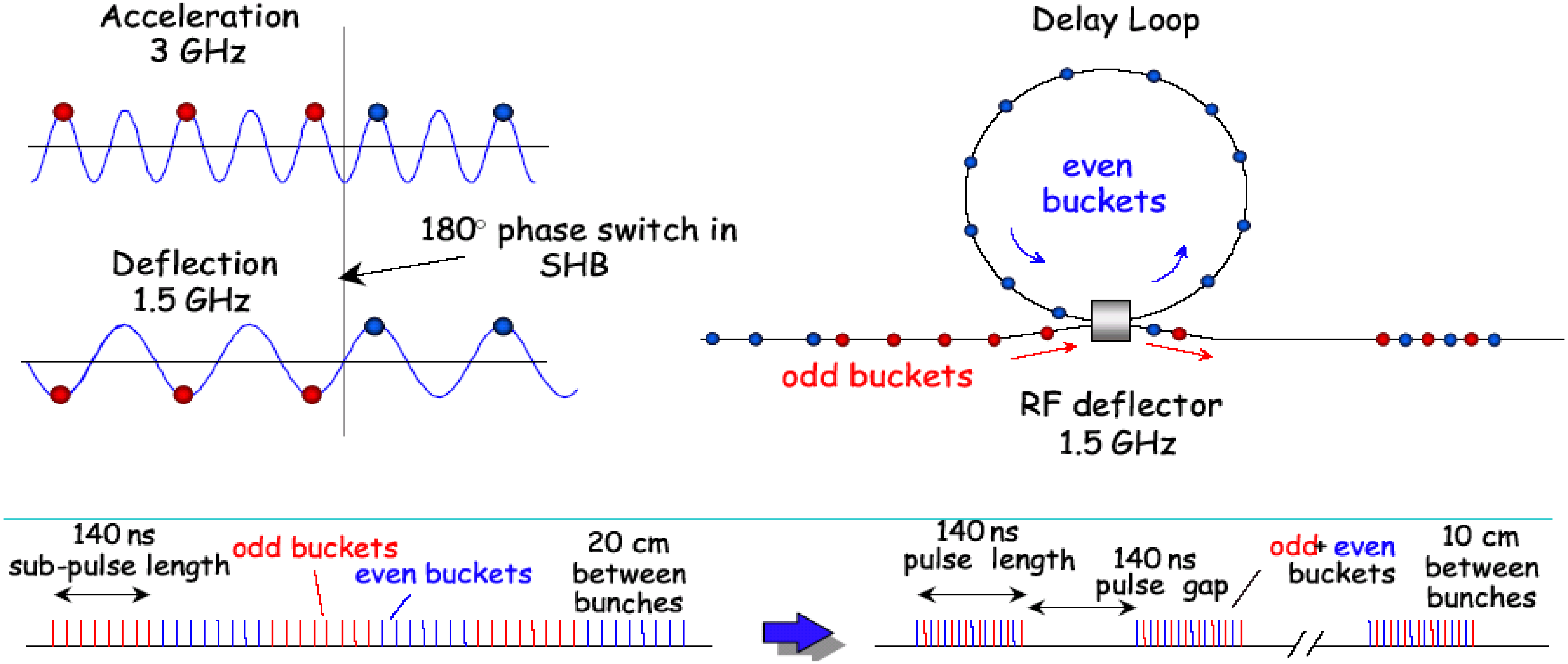


Beam separation by RF deflectors



Delay Loop Principle

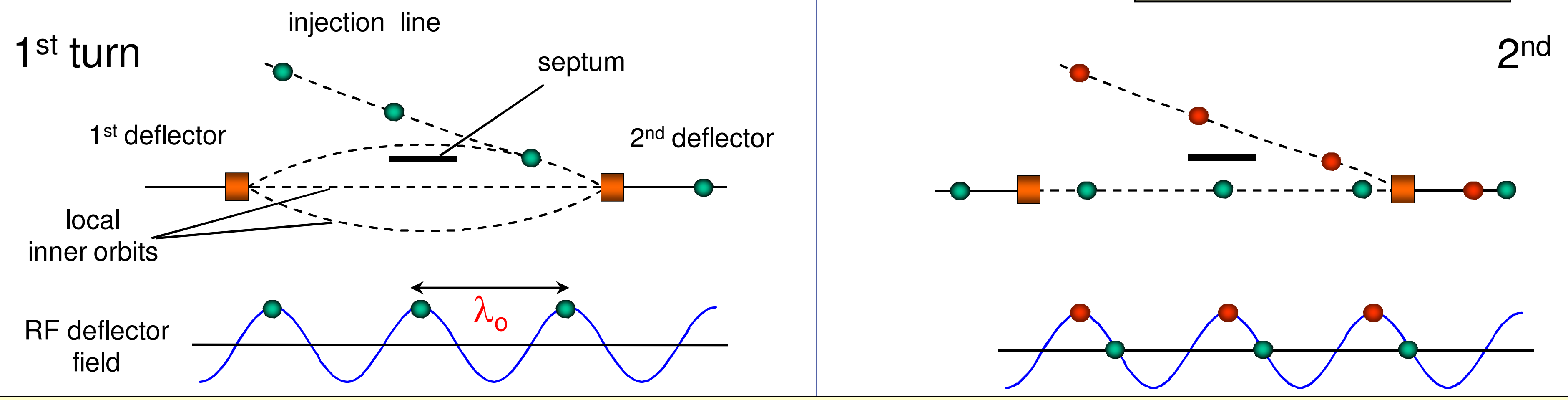
- **double repetition frequency and current**
- parts of bunch train delayed in loop
- RF deflector combines the bunches (f_{defl}=bunch rep. frequency)
- Path length corresponds to beam sub-pulse length



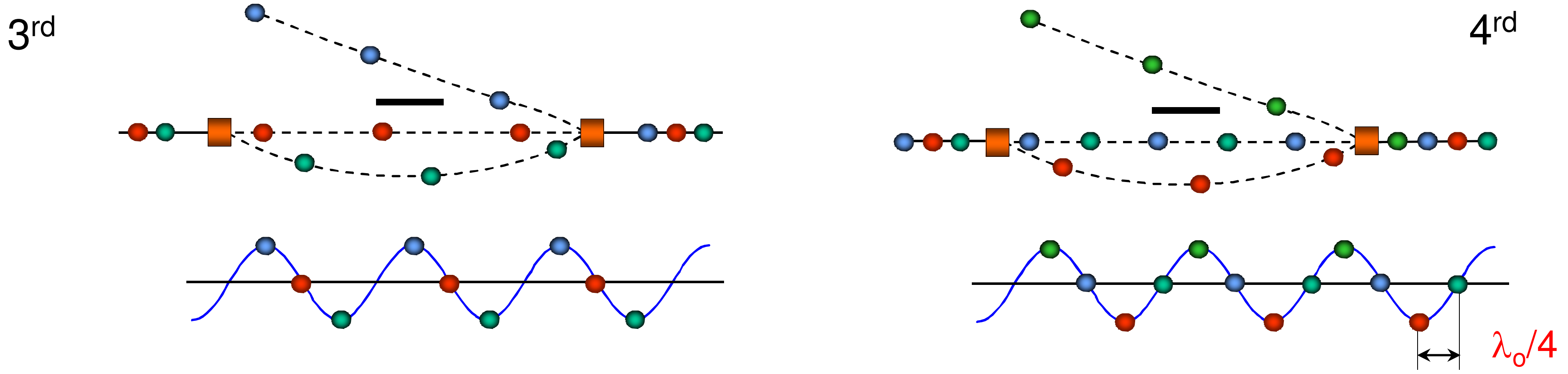
RF injection in combiner ring

- combination factors up to 5 reachable in a ring

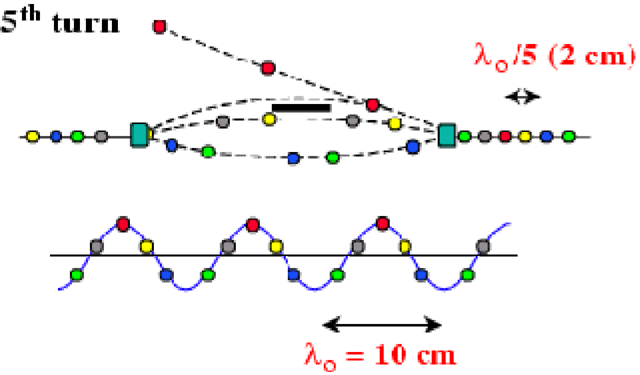
$$C_{ring} = (n + ¼)\ \lambda$$



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

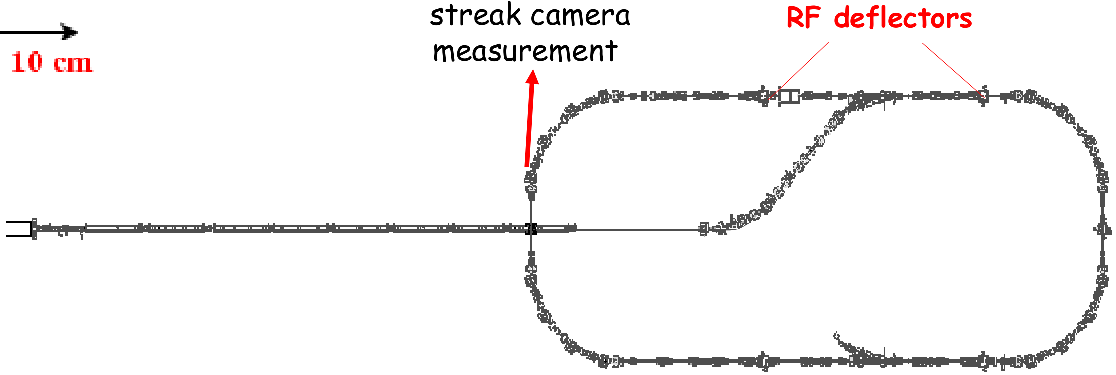


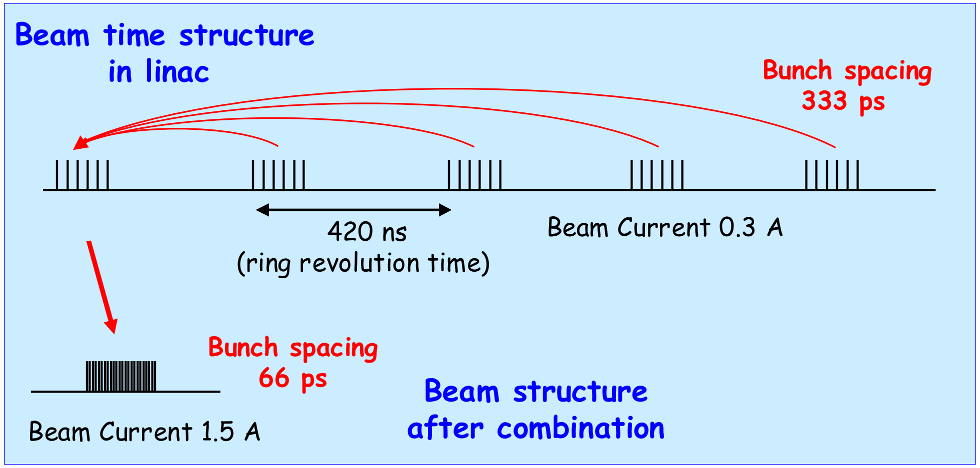
Demonstration of frequency multiplication



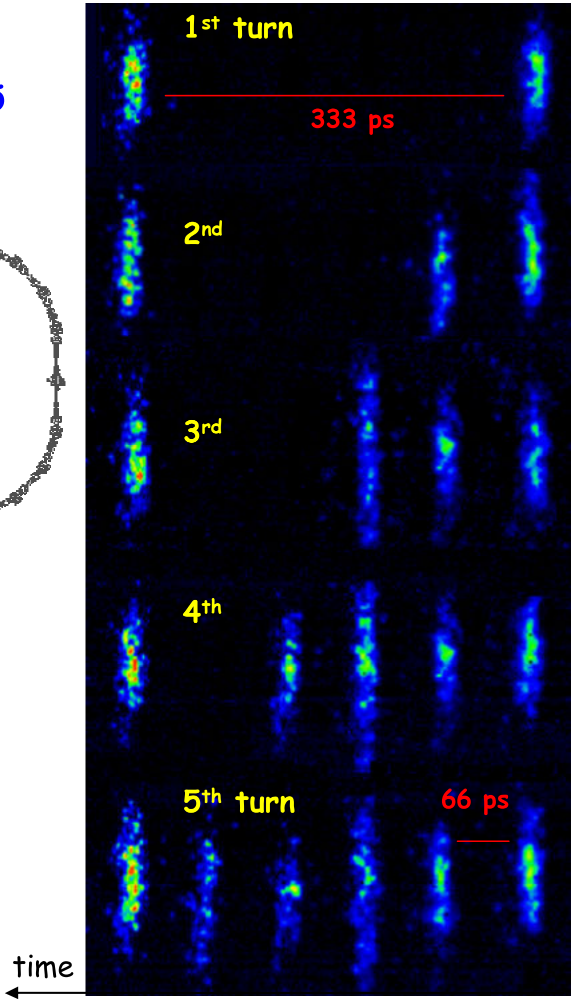
CTF3 - PRELIMINARY PHASE 2001/2002

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

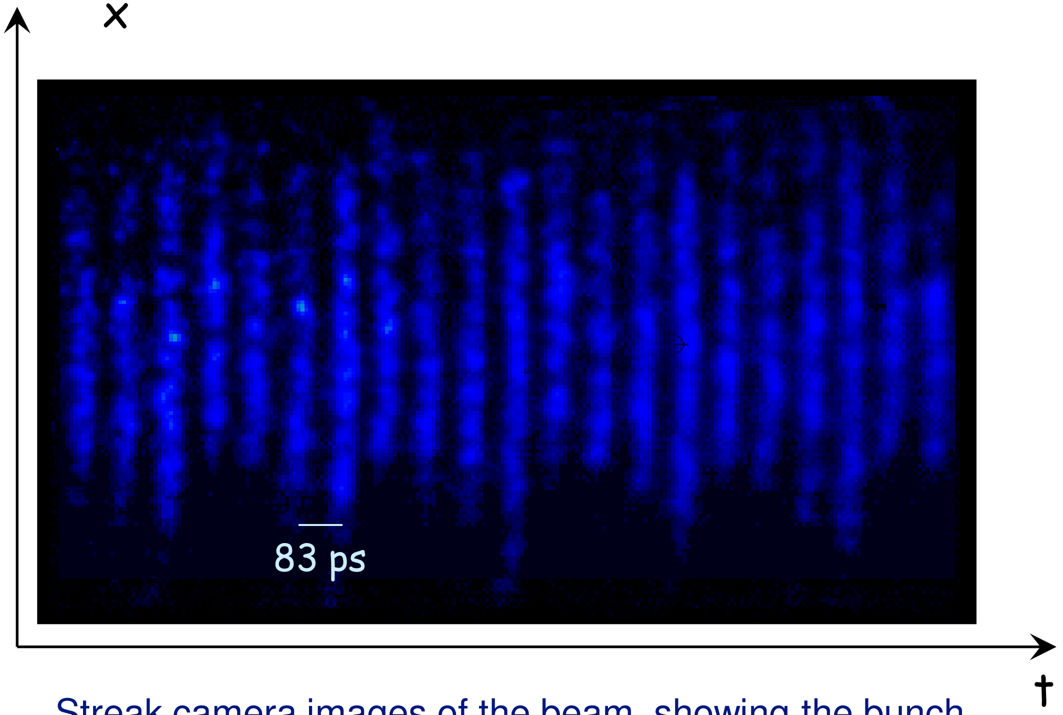




Streak camera image of beam time structure evolution



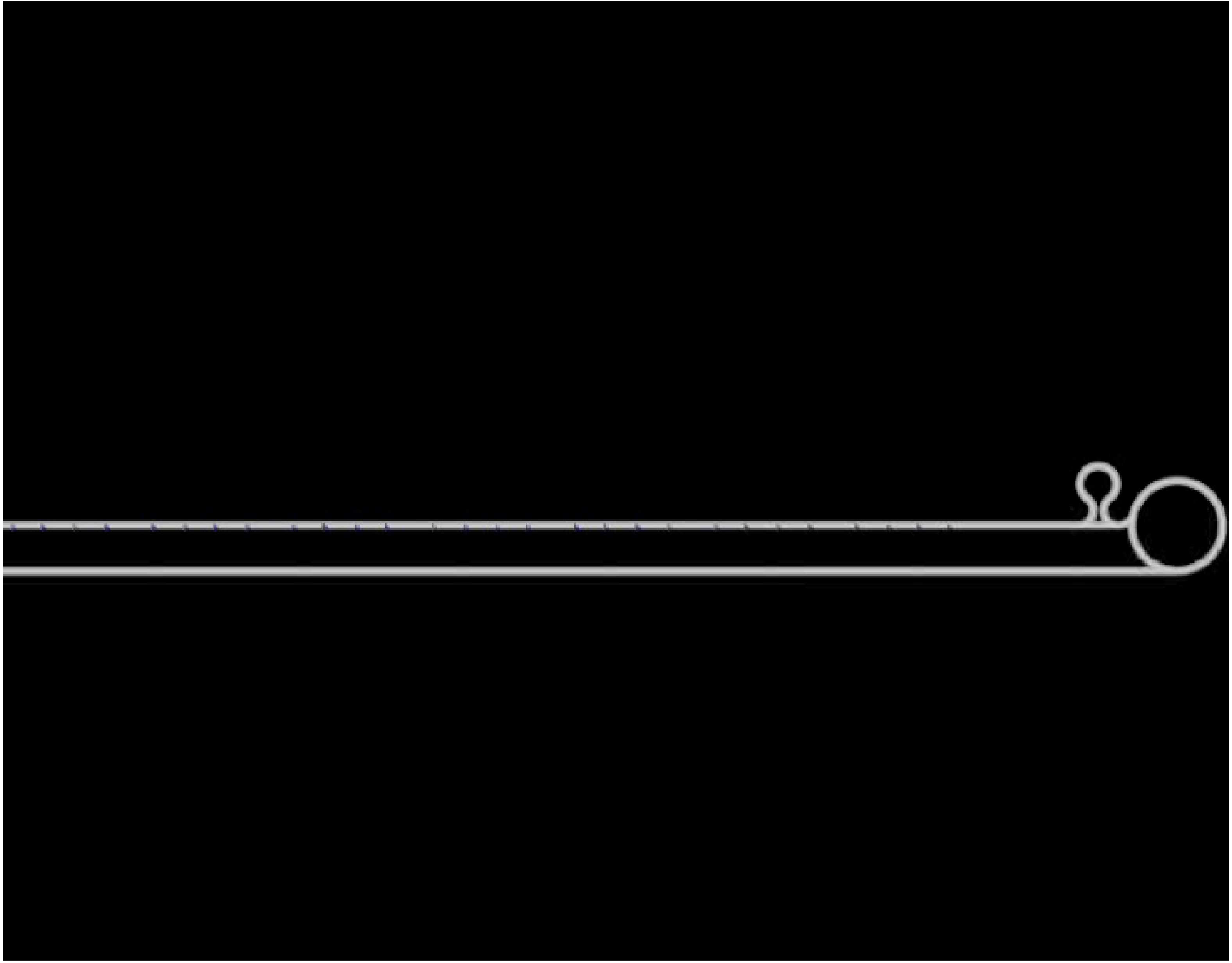
RF injection in combiner ring



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

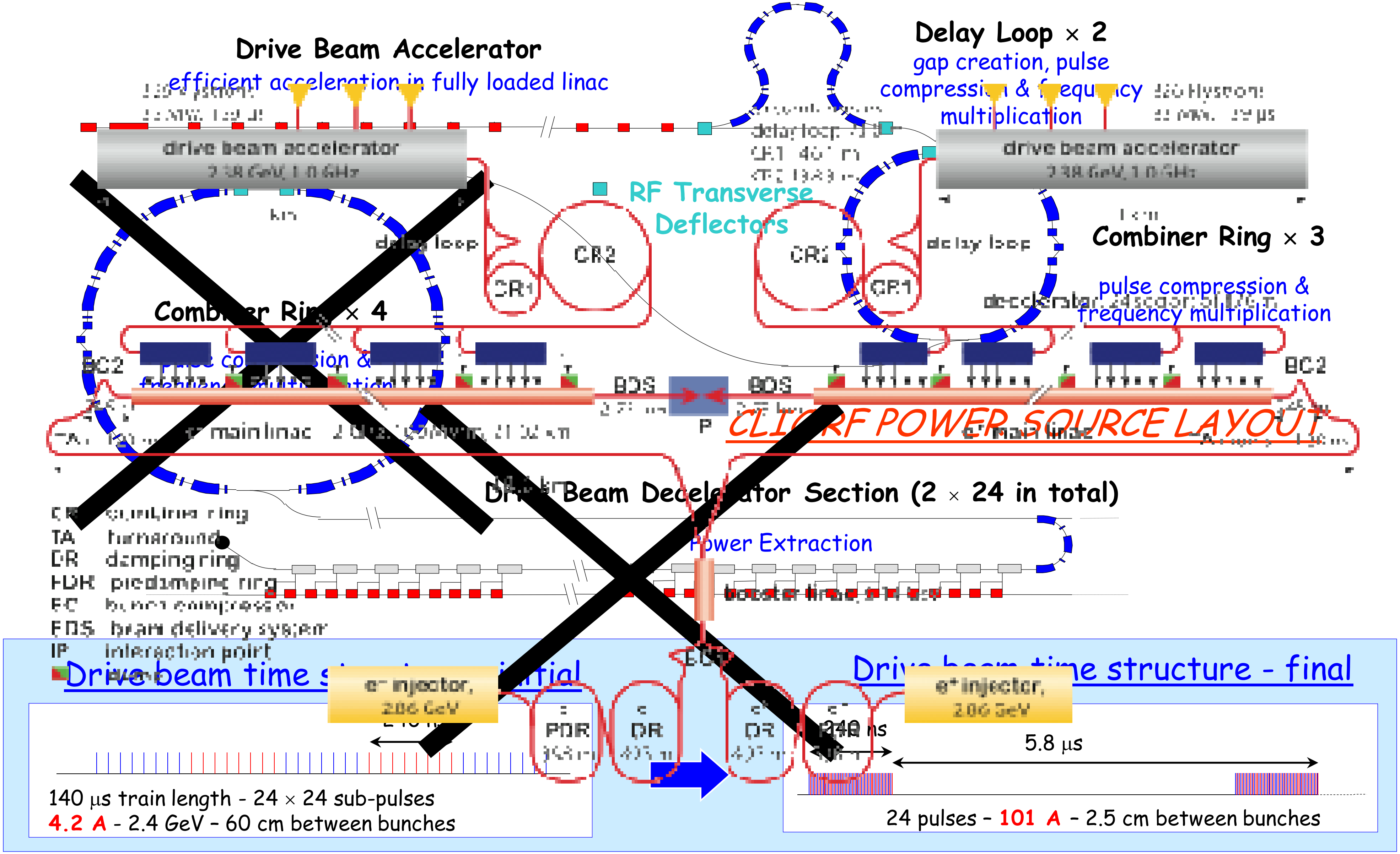
A first ring combination test was performed in 2002, *at low current and short pulse*, in the CERN Electron-Positron Accumulator (EPA), properly modified

Lemmings Drive Beam



Alexandra
Andersson

CLIC Drive Beam generation



Drive Beam Accelerator

efficient acceleration in fully loaded linac

Delay Loop × **2**

gap creation, pulse compression & frequency multiplication

RF Transverse Deflectors

Combiner Ring × **3**

pulse compression & frequency multiplication

Combiner Ring × **4**

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

Power Extraction

CLIC RF POWER SOURCE LAYOUT

Drive beam time s initial

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

Driv time structure - final

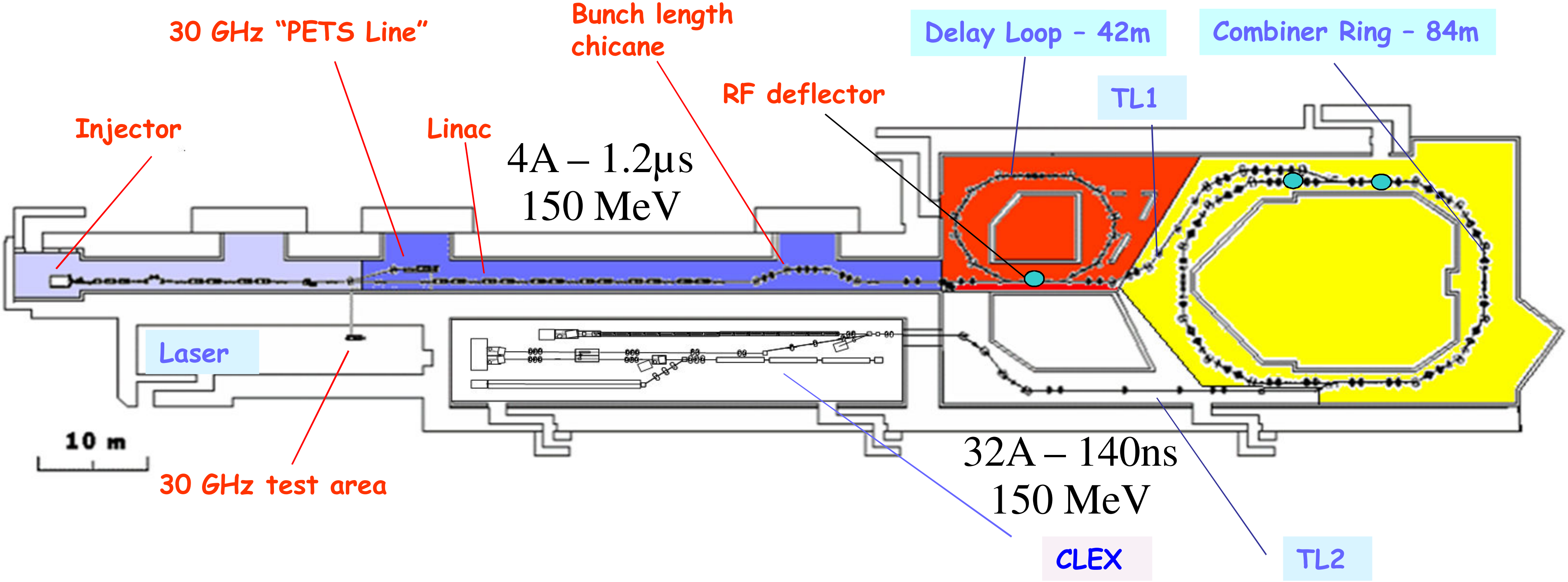
240 ns

5.8 µs

24 pulses – 101 A – 2.5 cm between bunches

CTF 3

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

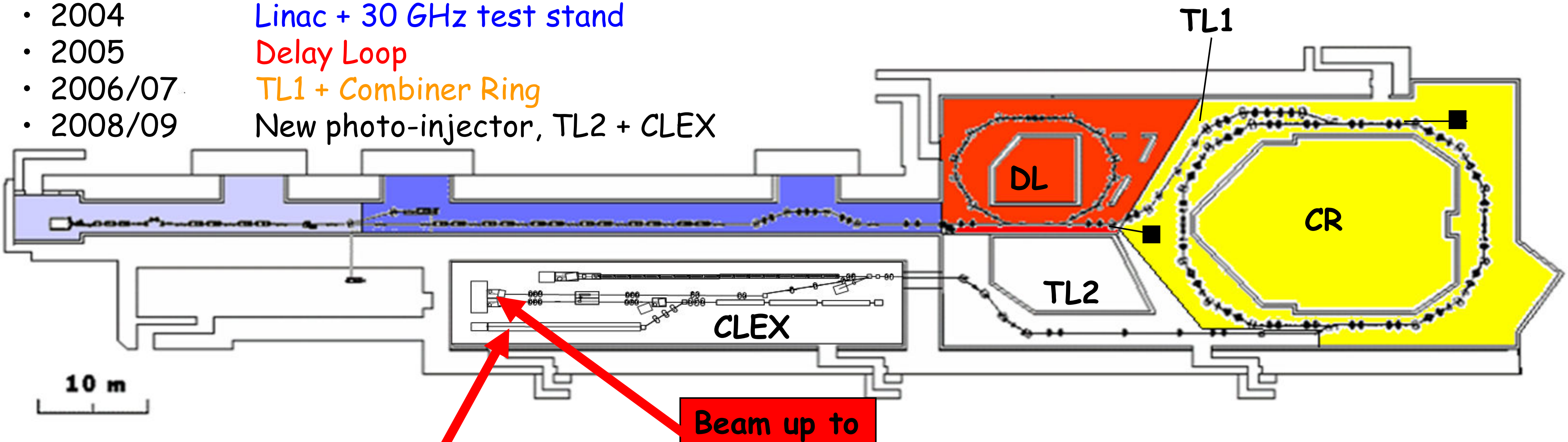


4A – 1.2μs
150 MeV

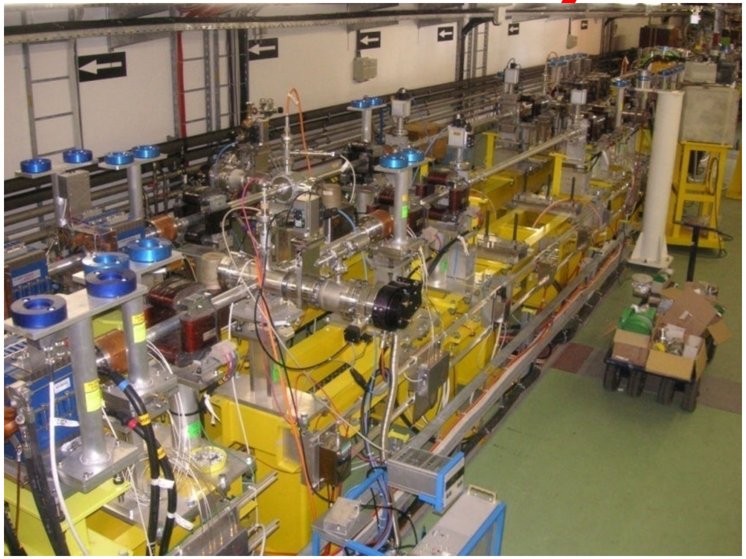
32A – 140ns
150 MeV

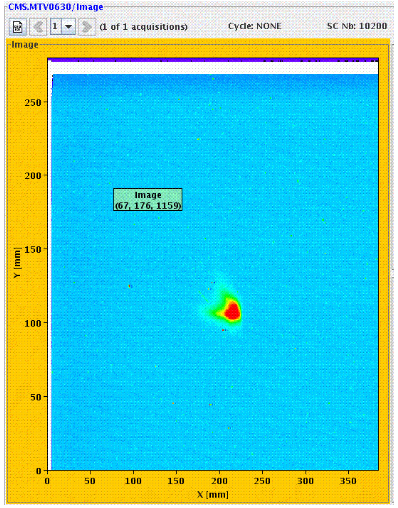
CTF3 Evolution

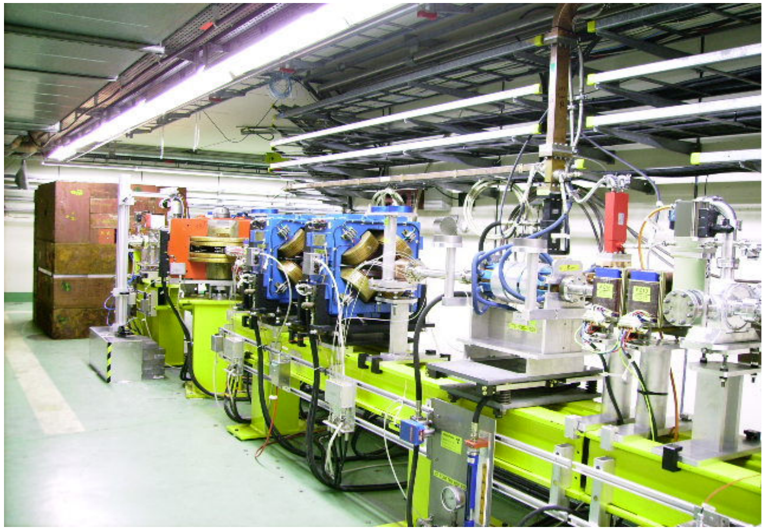
2003	Injector + part of linac
2004	Linac + 30 GHz test stand
2005	Delay Loop
2006/07	TL1 + Combiner Ring
2008/09	New photo-injector, TL2 + CLEX



Beam up to here





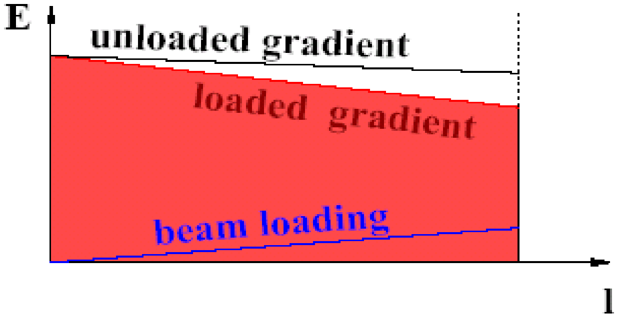


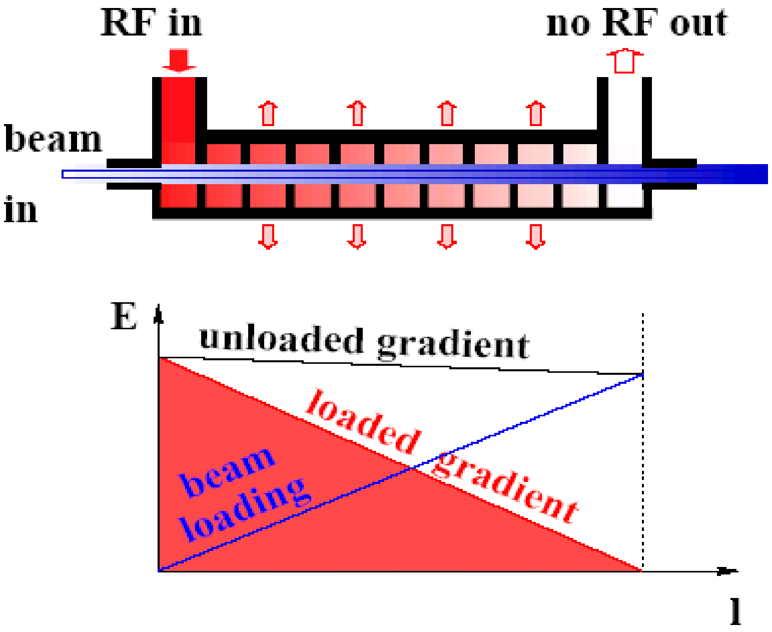
Fully loaded operation

- 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
- $V_{ACC} \approx 1/2\ V_{unloaded}$

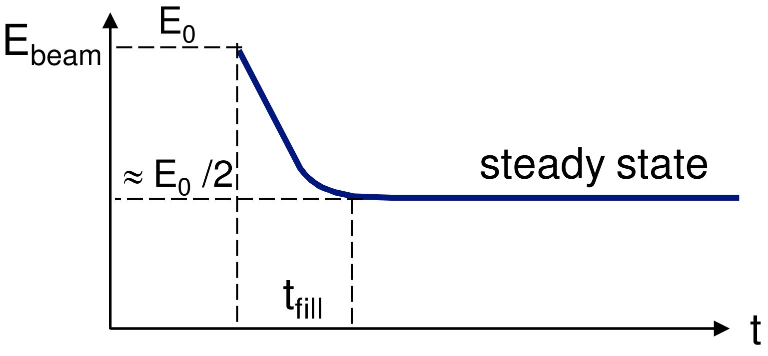
Fully loaded operation

- Disadvantage: any current variation changes energy gain

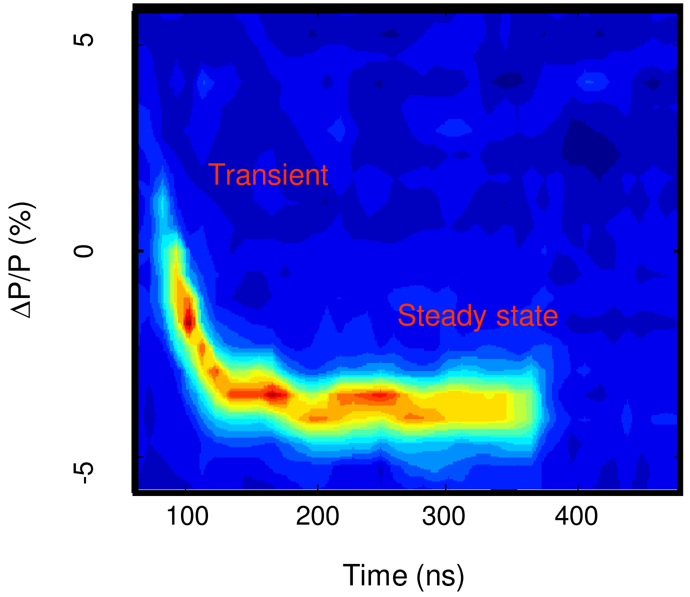
$$\frac{dV/V}{dI_{beam}/I_{beam}} = -\frac{I_{beam}}{I_{opt}}$$

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

- Requires high current stability
- Energy transient
  (first bunches see full field)

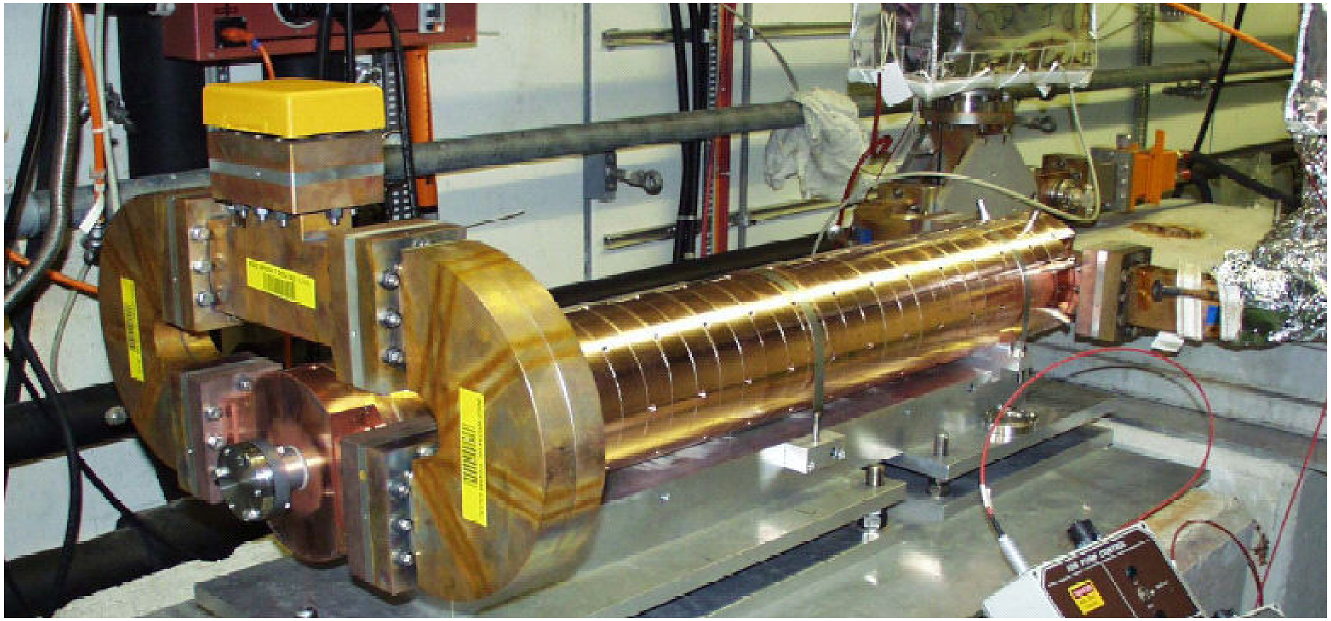


Time resolved beam energy spectrum measurement in CTF3

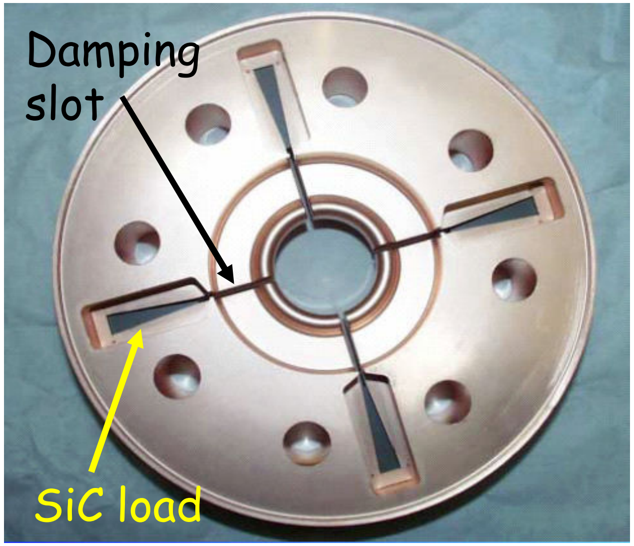


- Requires continuous bunch train

CTF3 linac acceleration structures

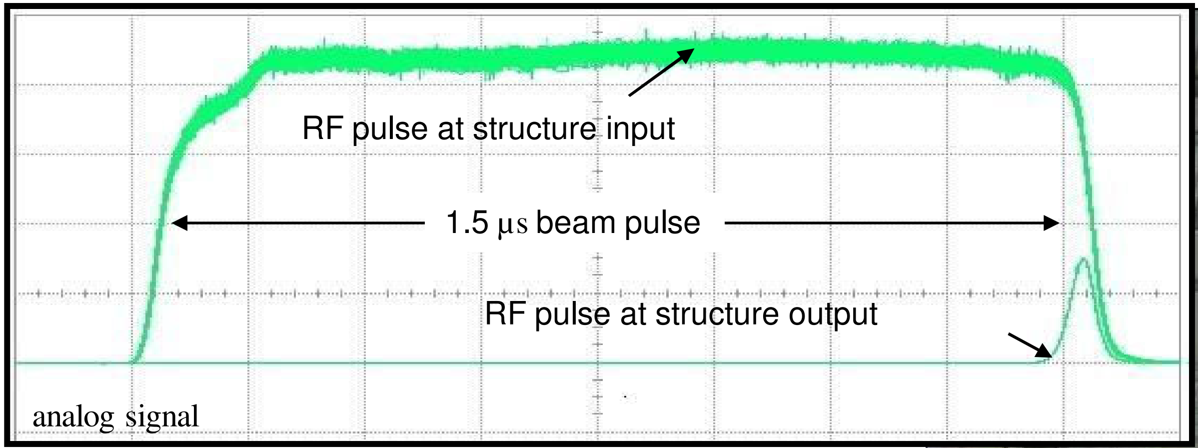


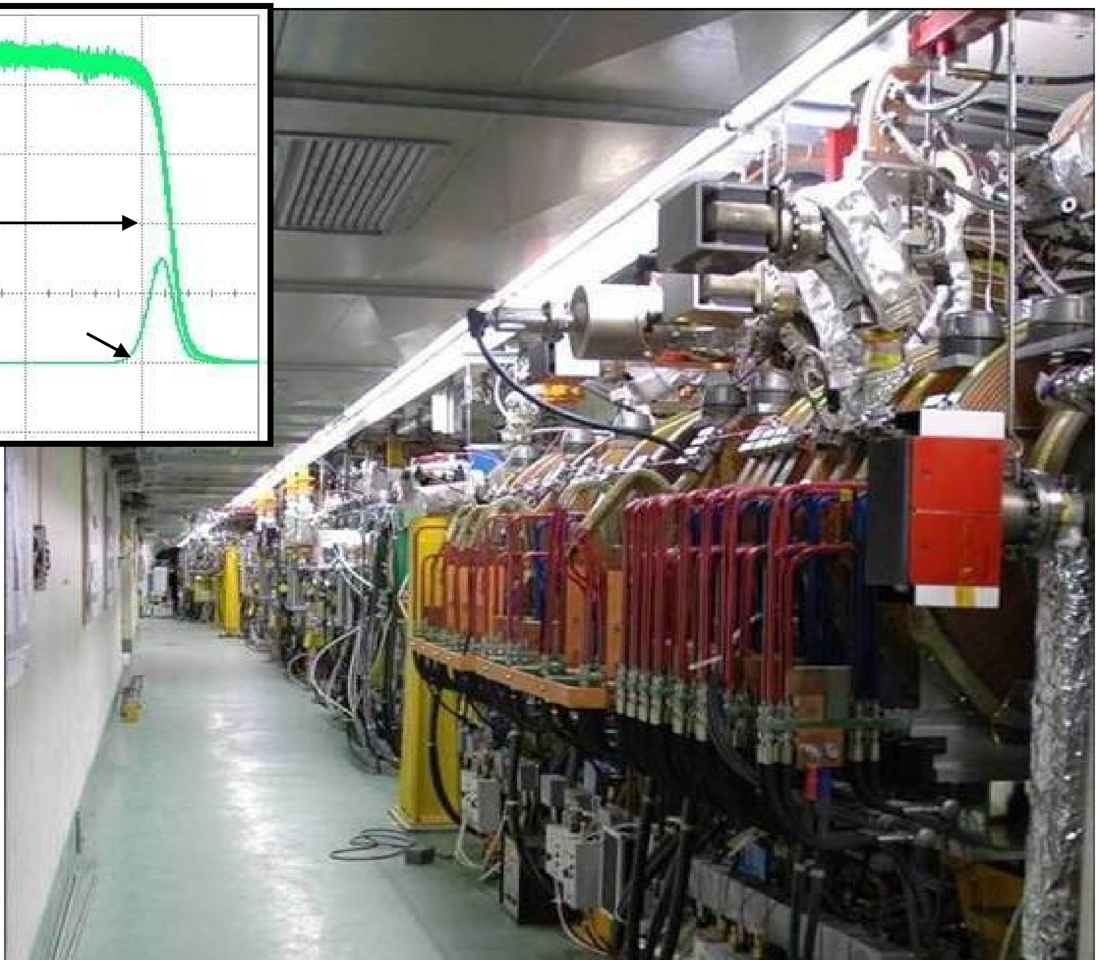
Dipole modes suppressed by slotted iris damping (first dipole's Q factor < 20) and HOM frequency detuning



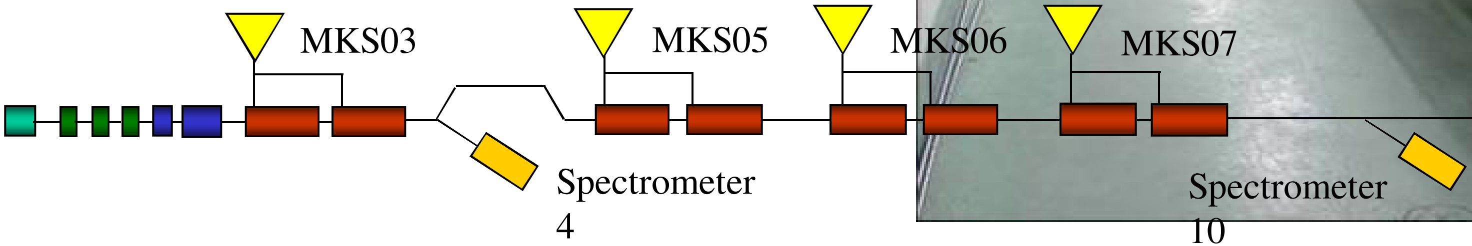
- 3 GHz 2π/3 traveling wave structure
- constant aperture
- slotted-iris damping + detuning with nose cones
- up to 4 A 1.4 μs beam pulse accelerated
  no sign of beam break-up

Full beam-loading acceleration in CTF3

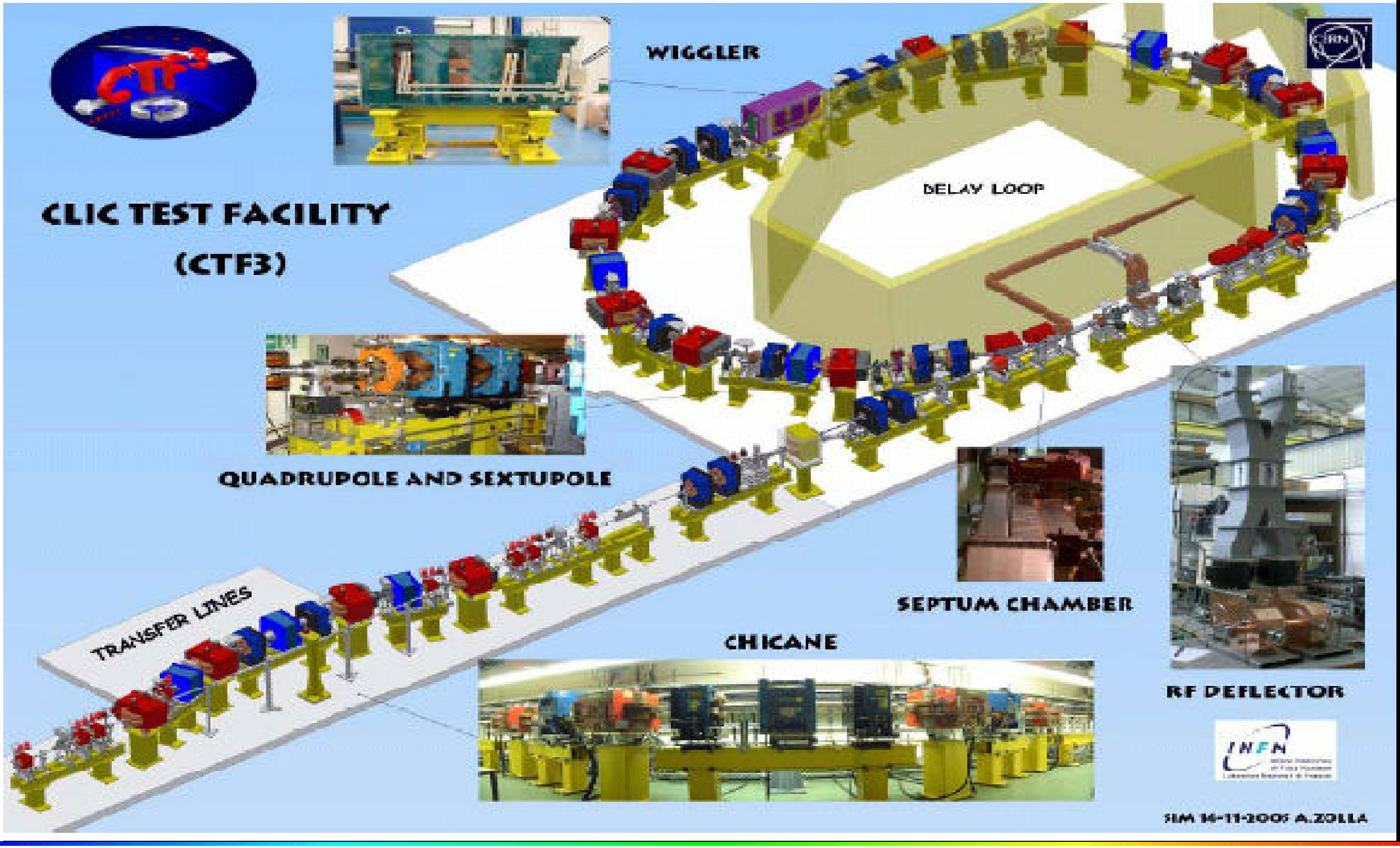




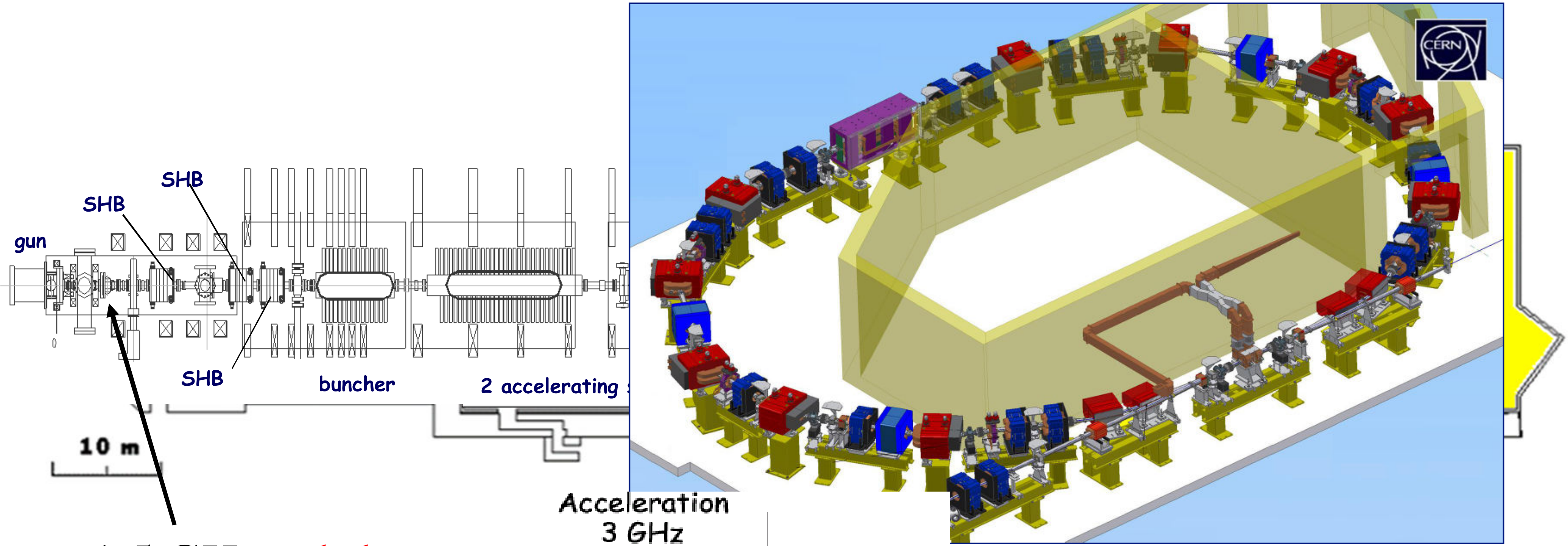
- Measured RF-to-beam efficiency 95.3%
- Theory 96%
  (~ 4 % ohmic losses)



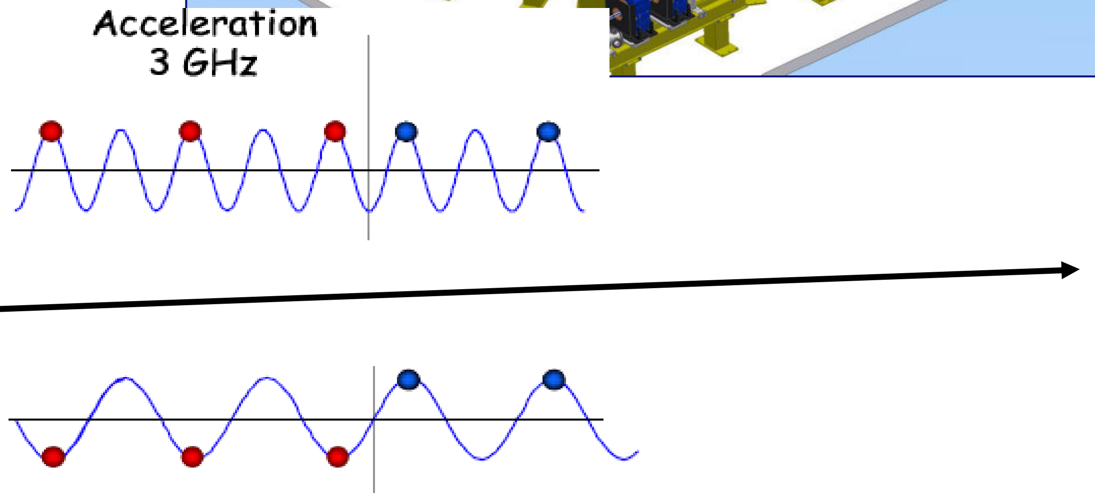
CTF3 Delay Loop



Delay Loop operation

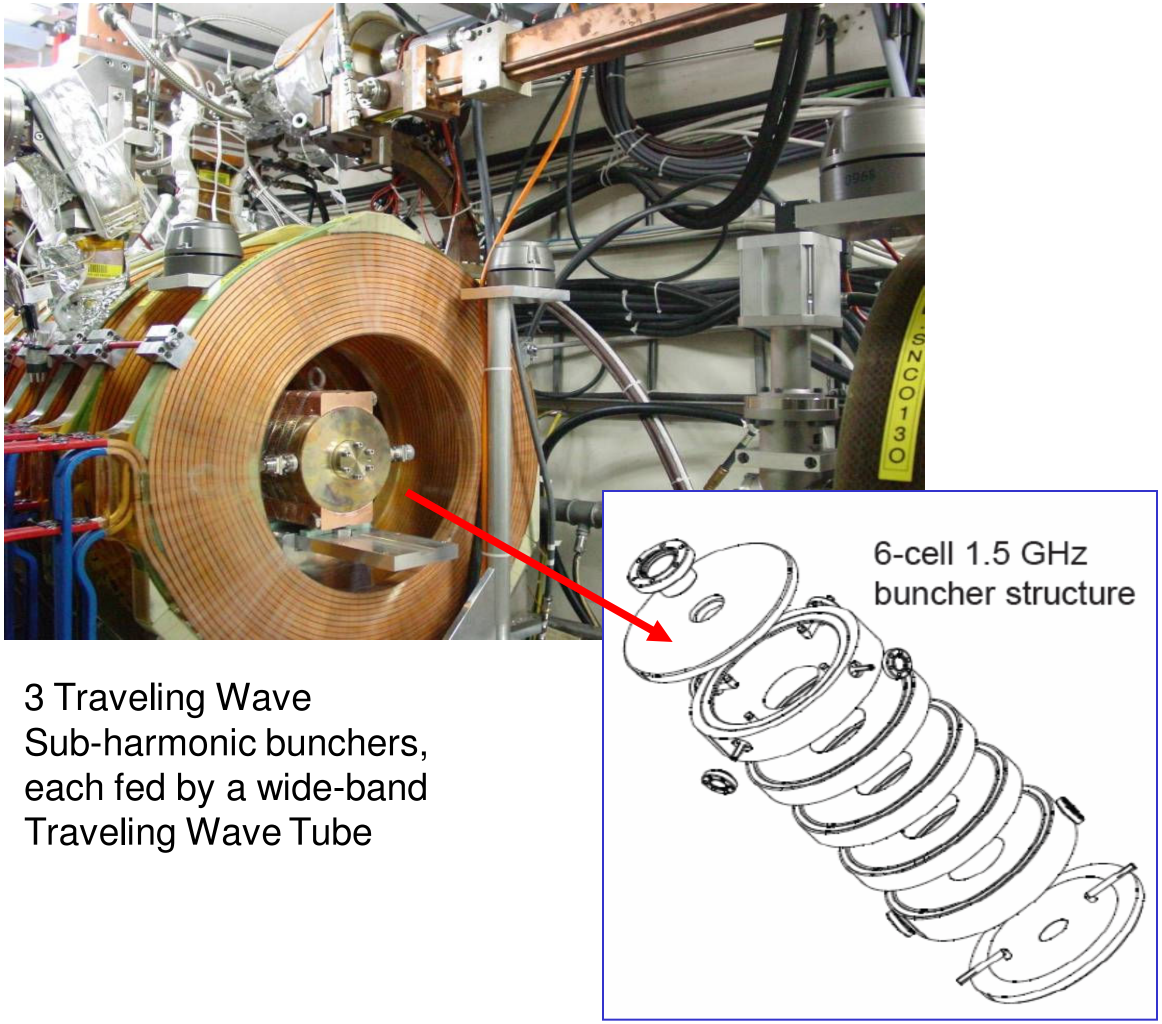


- 1.5 GHz sub-harm. bunching system
- 1.5 GHz RF deflector



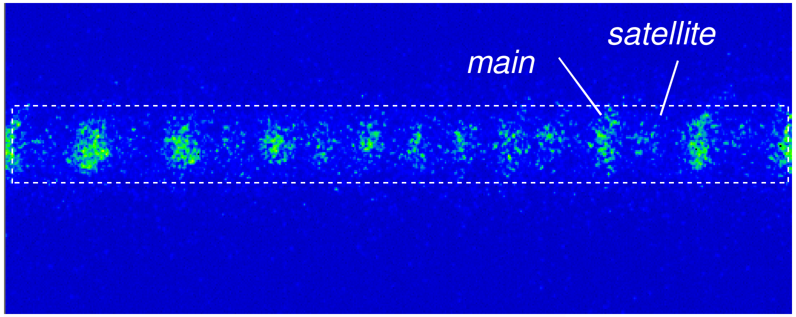
Sub-harmonic bunching system

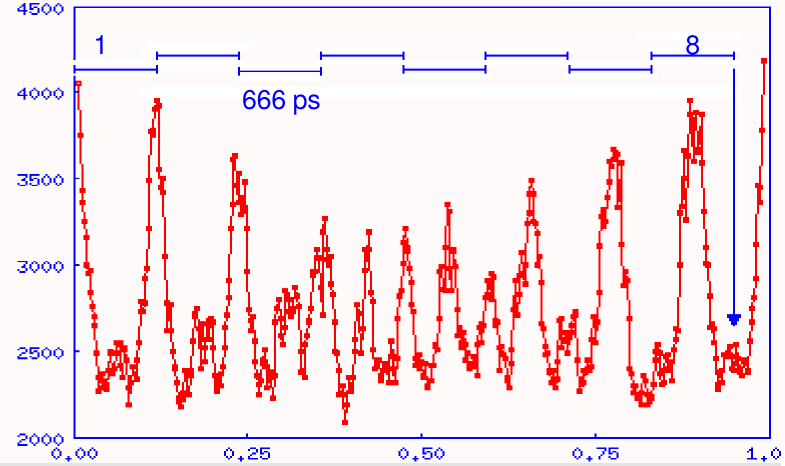
Fast phase switch from SHB system (CTF3)


6-cell 1.5 GHz buncher structure

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

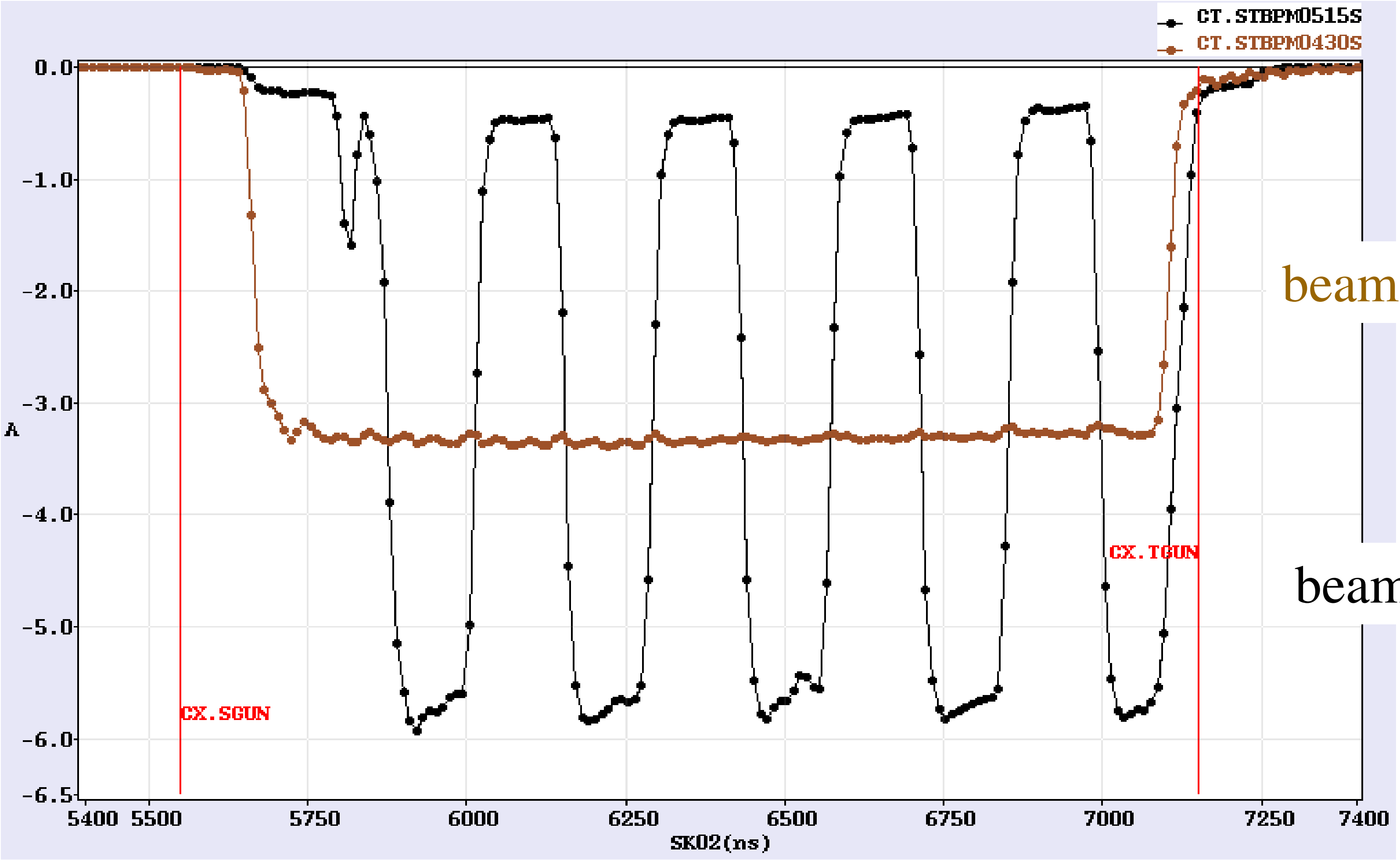
Streak camera image





$8.5 \cdot 666\ \text{ps} = 5.7\ \text{ns}$

Delay Loop – full recombination

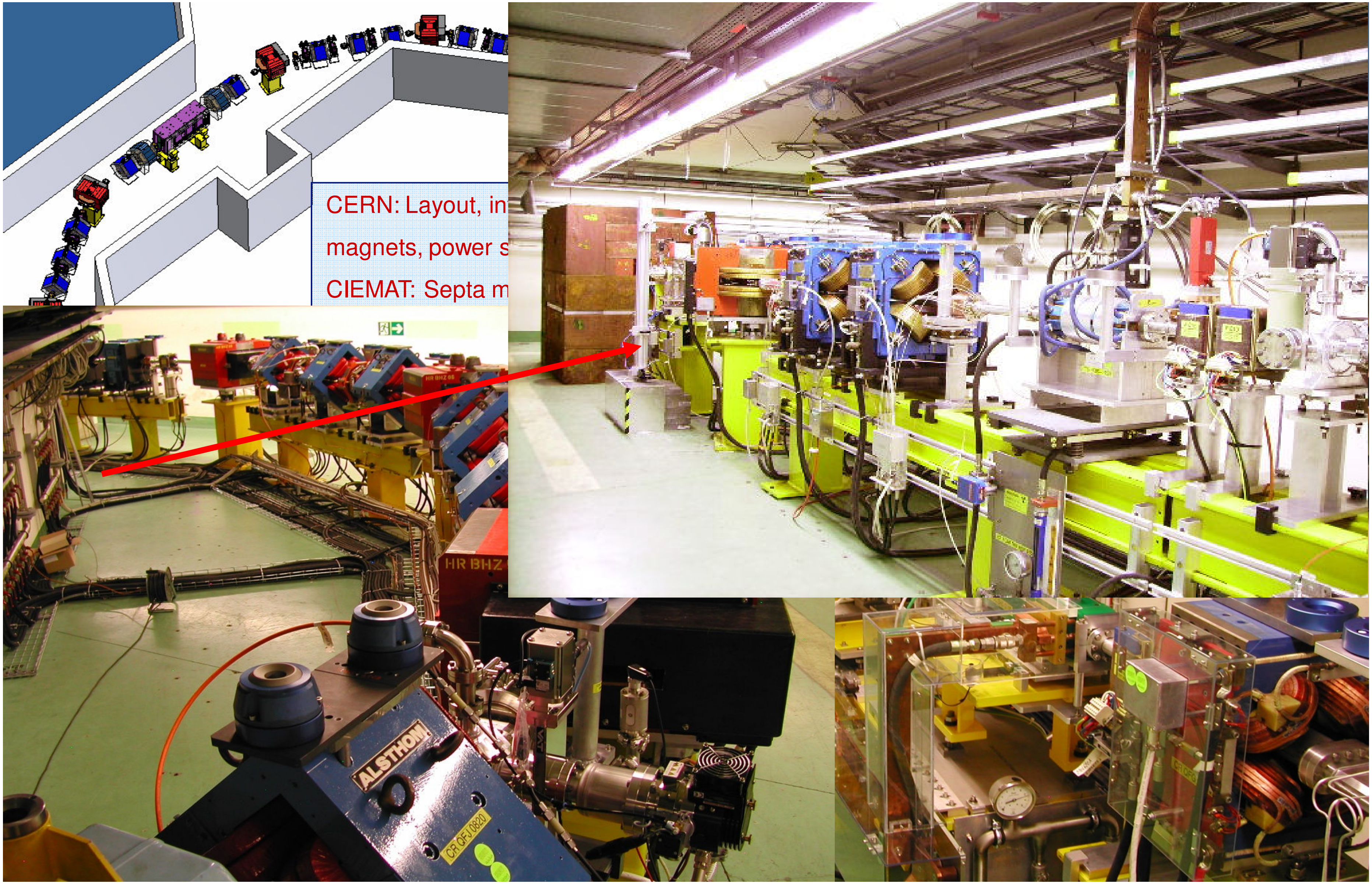


beam before the DL

beam after the DL

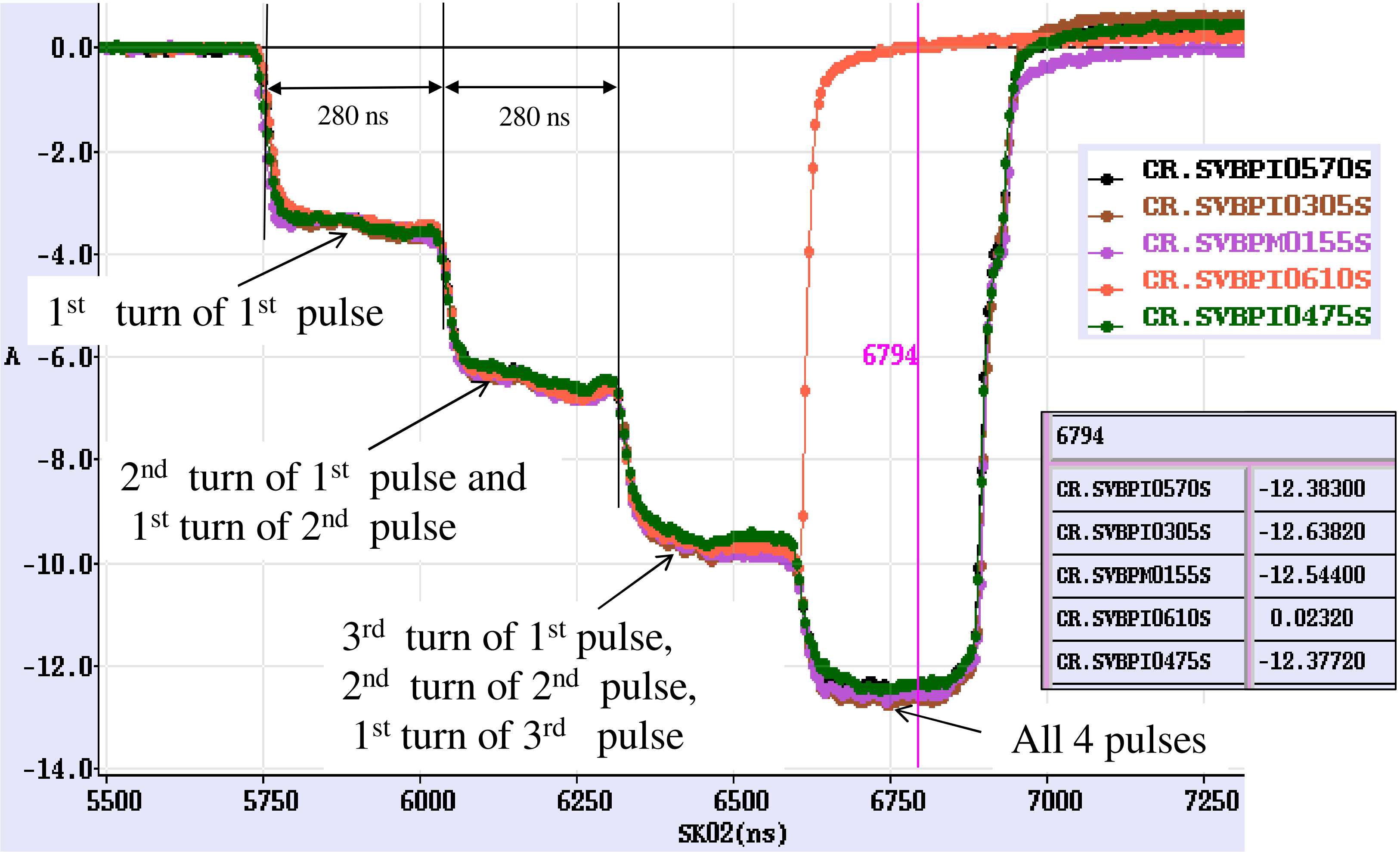
- 3.3 A after chicane => < 6 A after combination (satellites)

CTF3 combiner ring



Combiner ring - latest status

- factor 4 combination achieved with 13 A, 280 ns,



6794	
CR.SVBPI0570S	-12.38300
CR.SVBPI0305S	-12.63820
CR.SVBPM0155S	-12.54400
CR.SVBPI0610S	0.02320
CR.SVBPI0475S	-12.37720

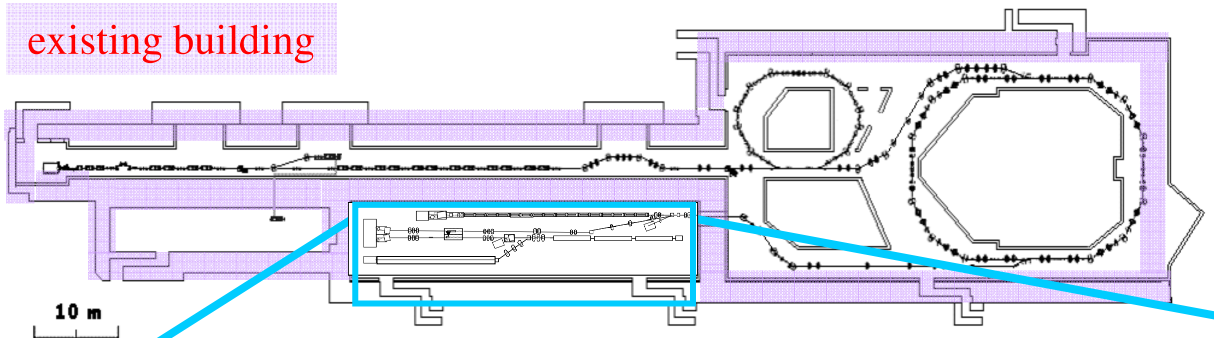
1st turn of 1st pulse

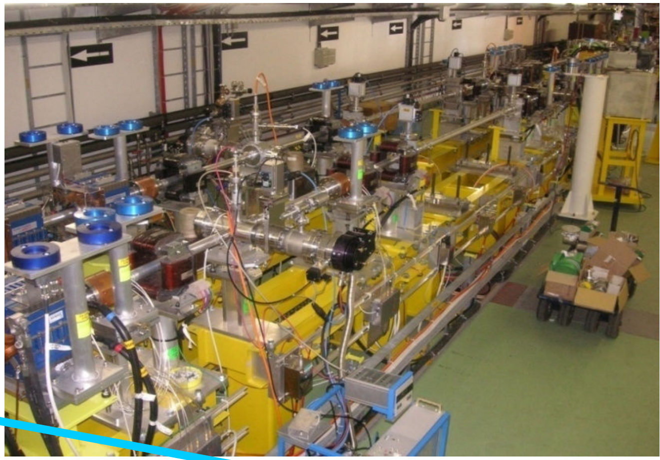
2nd turn of 1st pulse and
1st turn of 2nd pulse

3rd turn of 1st pulse,
2nd turn of 2nd pulse,
1st turn of 3rd pulse

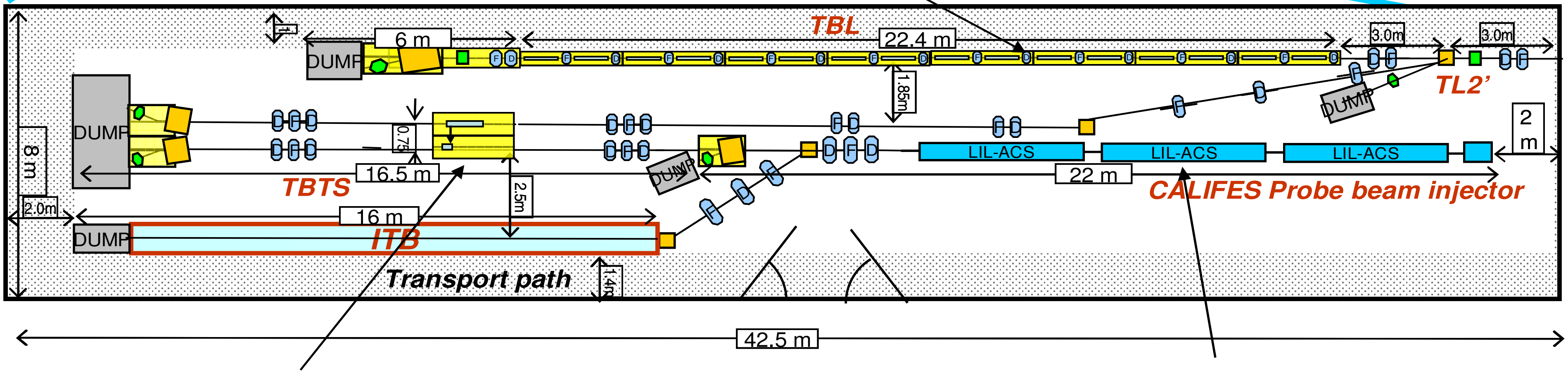
All 4 pulses

CLEX (CLIC Experimental Area)





Test Beam Line TBL



Two Beam Test Stand

Probe Beam

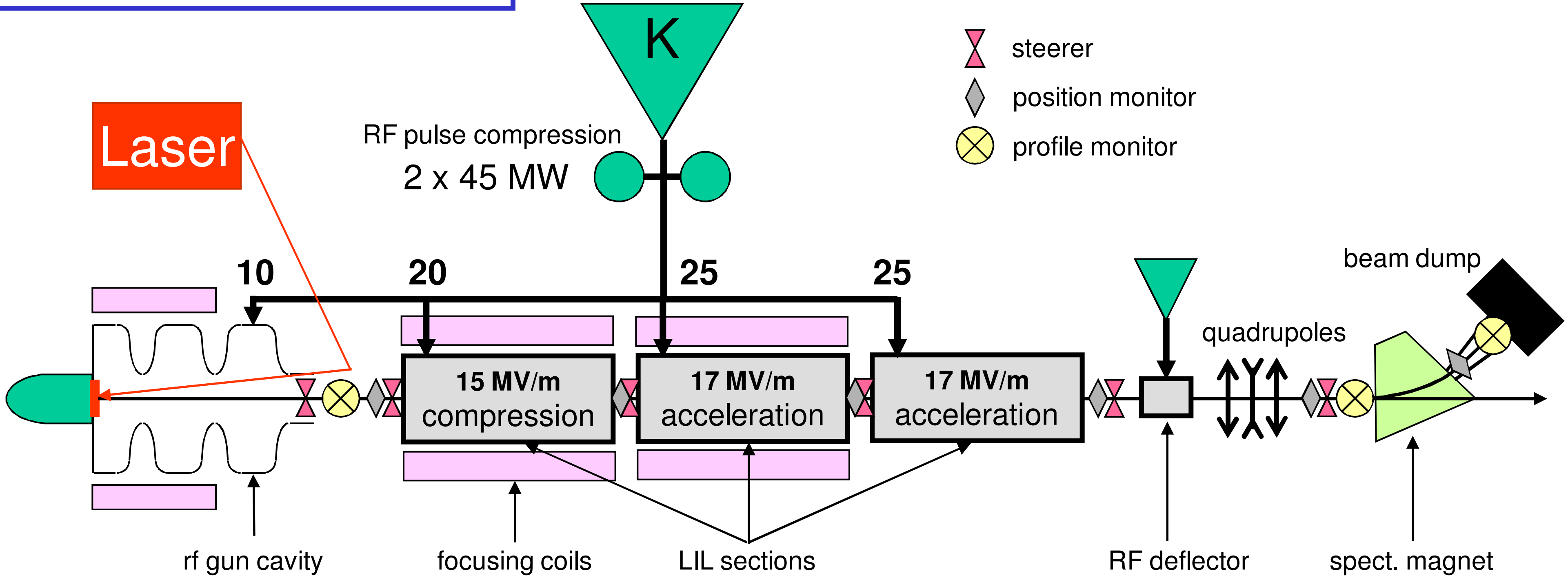
- Combined beam extracted to CLEX
- tests for power production, deceleration and two-beam studies

Probe Beam

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

200 MeV
bunch charge 0.5 nC
number of bunches 1 - 64

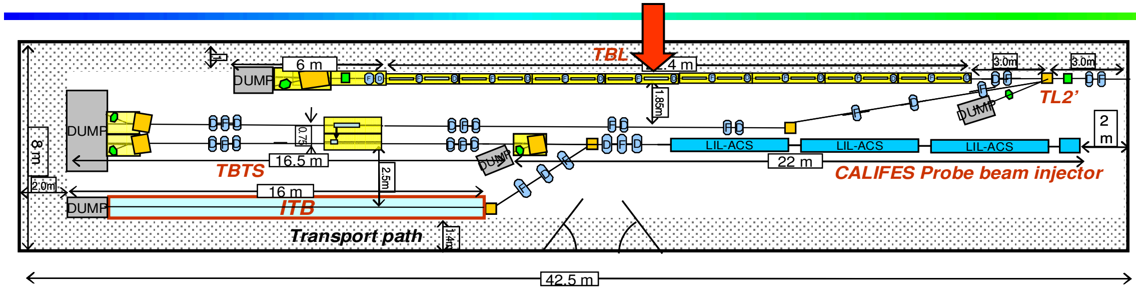
Status:
Installed, RF conditioning in Sept.
Laser under development



CALIFES

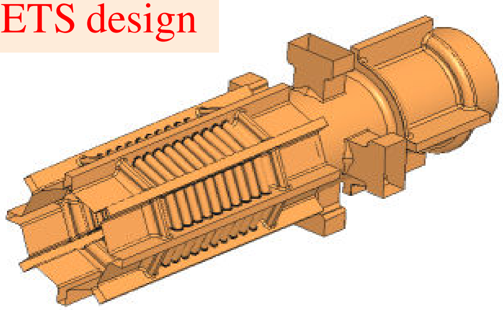
A. Mosnier, CEA Dapnia

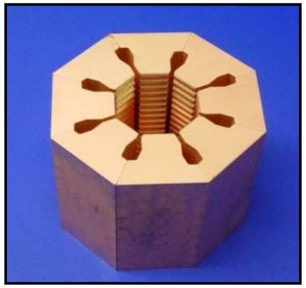
Test Beam Line TBL



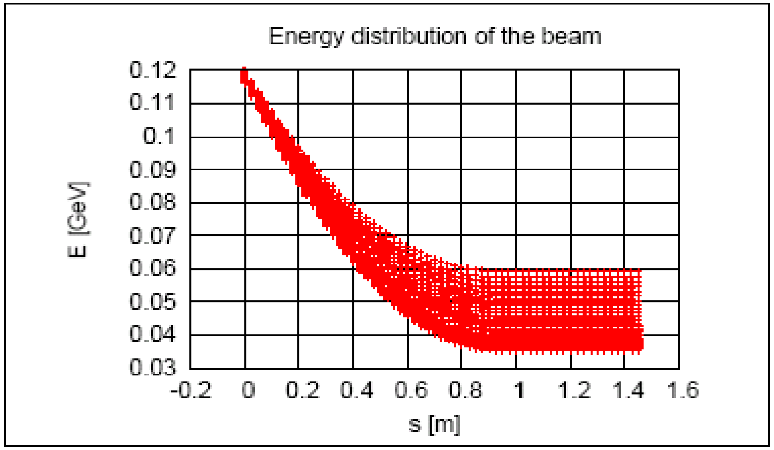
- High energy-spread beam transport decelerate to 50 % beam energy
- Drive Beam stability
- Stability of RF power extraction total power in 16 PETS: 2.5 GW
- Alignment procedures

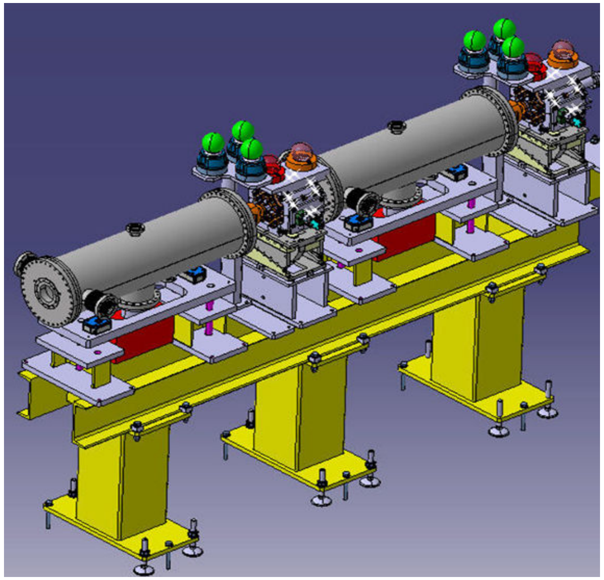
PETS design





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





2 standard cells,
16 total

PETS development: CIEMAT
BPM: IFIC Valencia
and UPC Barcelona

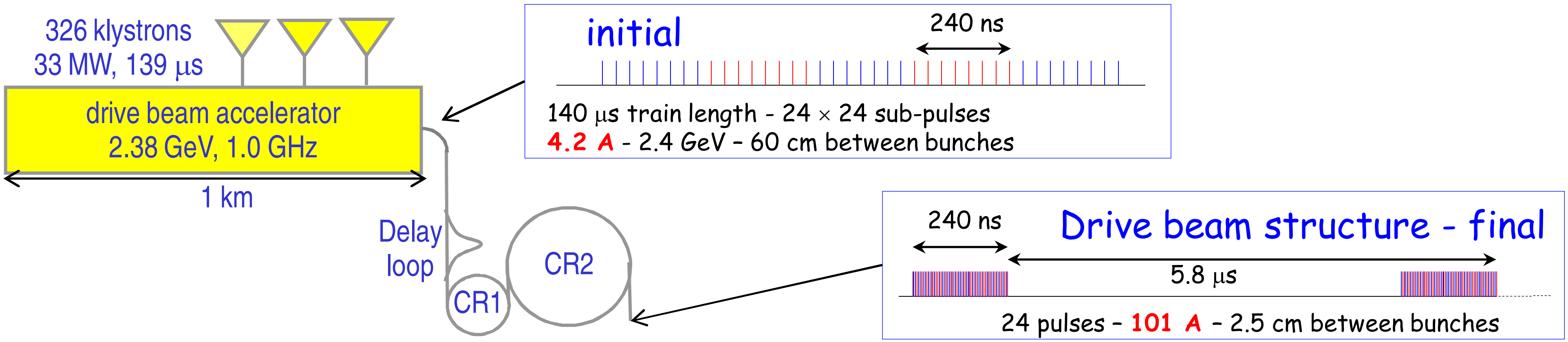
Comparison CLIC - CTF3

	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

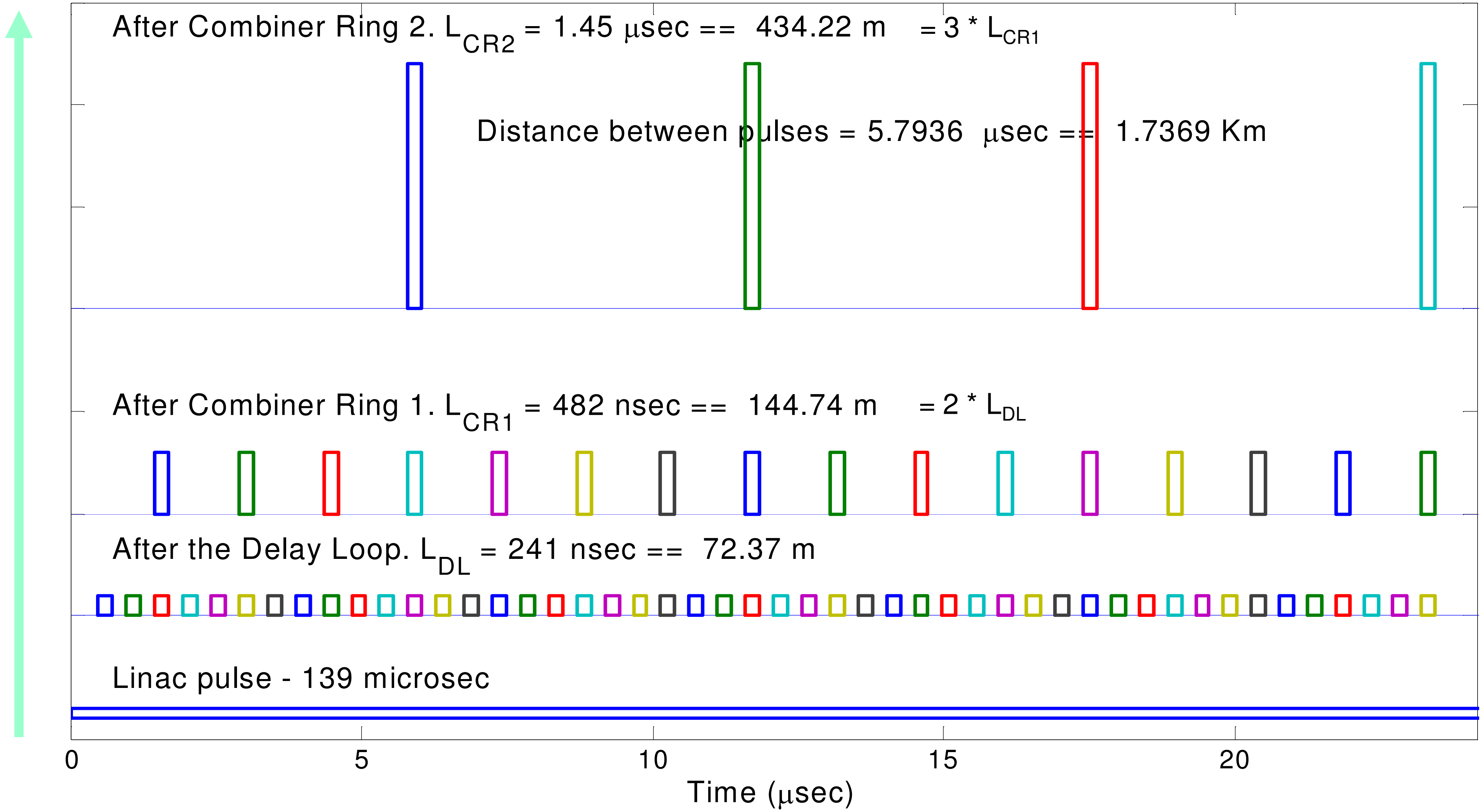
- Still considerable extrapolation to CLIC parameters
- Especially total beam power (loss management, machine protection)
- Good understanding of CTF3 and benchmarking needed

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

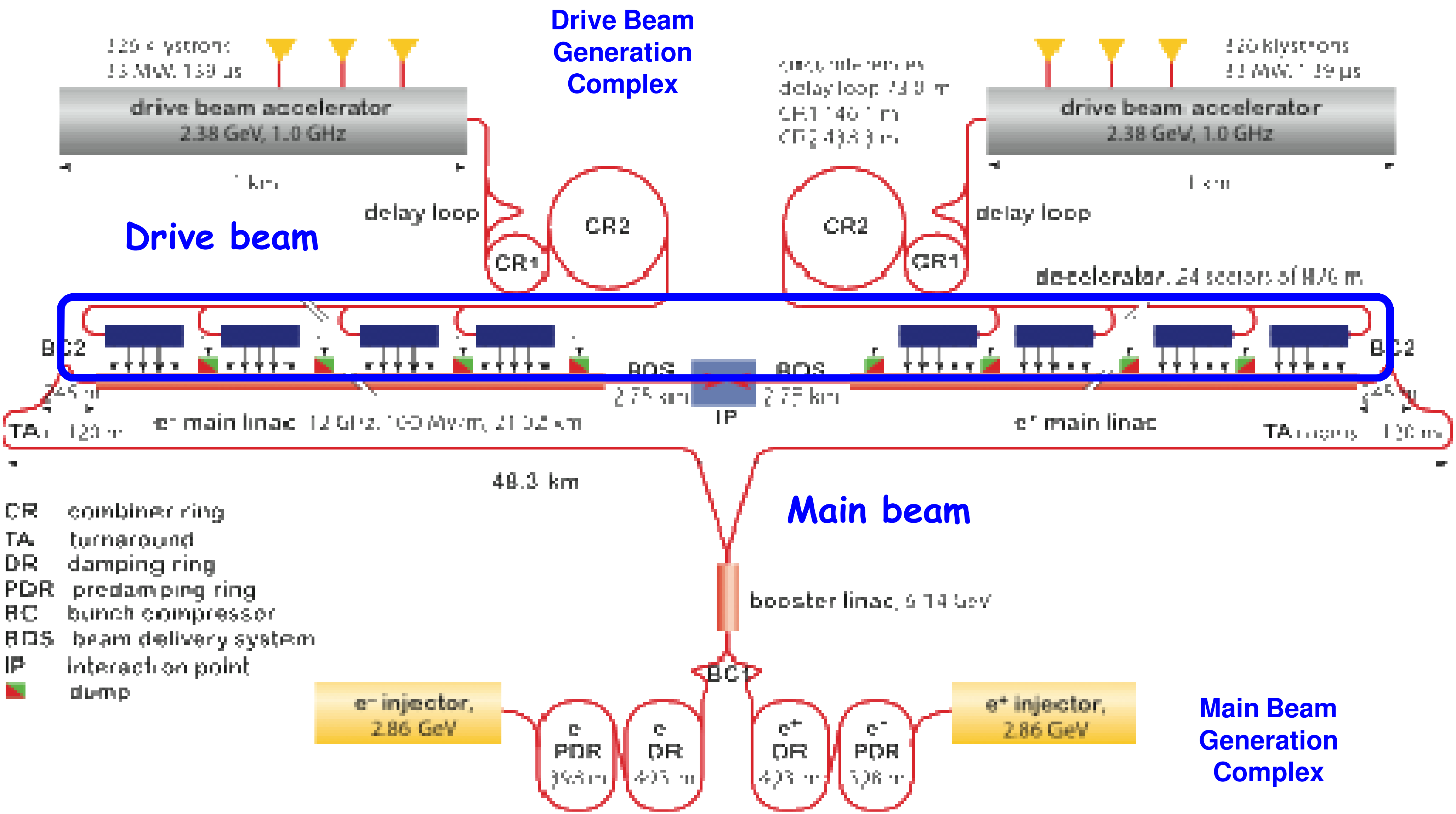


Drive Beam time structure



C.Biscari

CLIC – power generation



Drive Beam Generation Complex

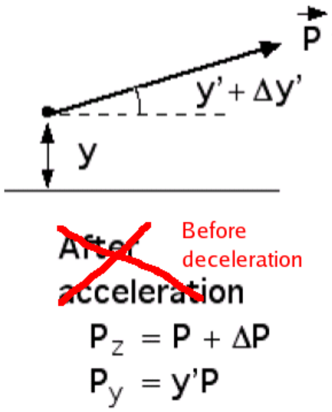
Drive beam

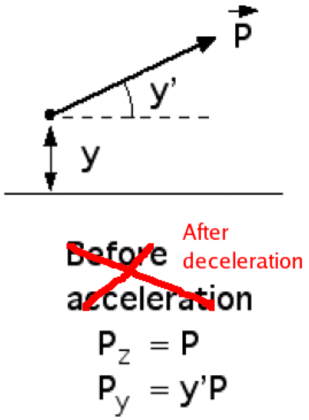
Main beam

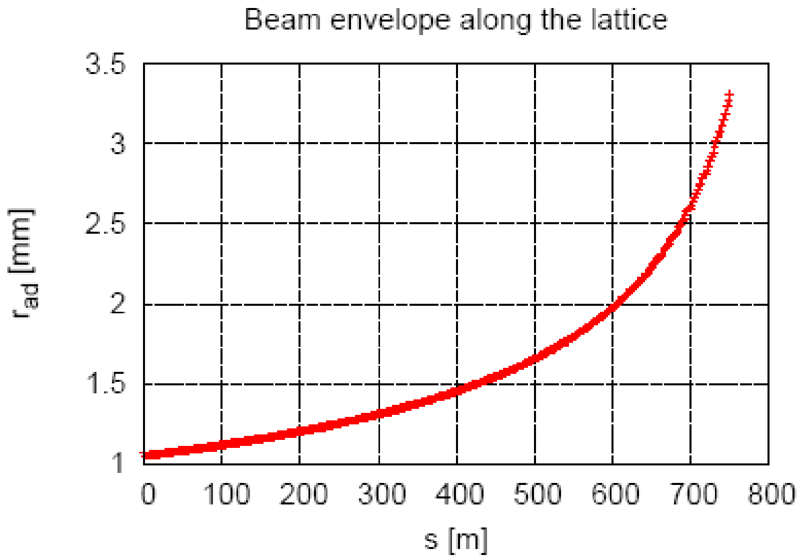
Main Beam Generation Complex

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%

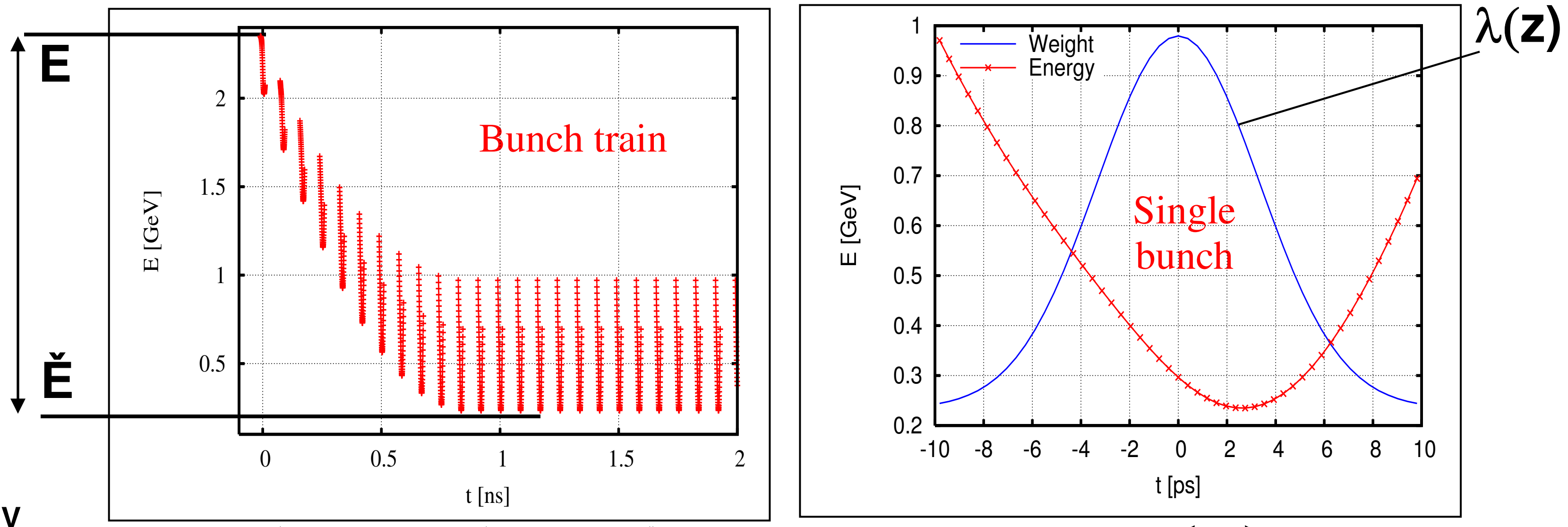
Deceleration and beam transport

- 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



$t_{fill} = (L_{PETS}/v_g)(1-\beta_g)_g = 1$ns **$t_b = 83$ps**

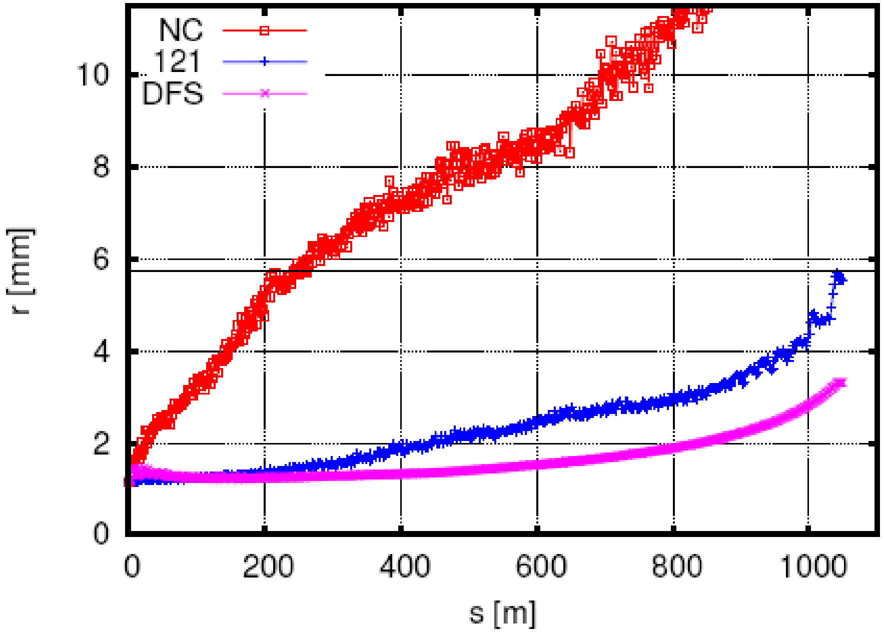
$t_z = 3$ps **$\sigma_z = 1$mm**

E.Adli

CLIC decelerator

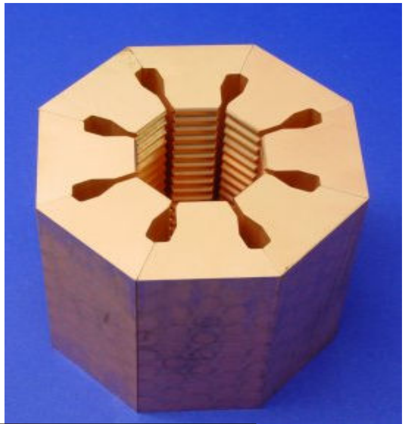
- Goal: transport particles of all energies through the decelerator sector: in the presence of huge energy spread (90%)
- Tight FODO focusing (large energy acceptance, low beta)
- Lowest energy particles ideally see constant FODO phase-advance μ≈90°, higher energy particles see phase-advance varying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

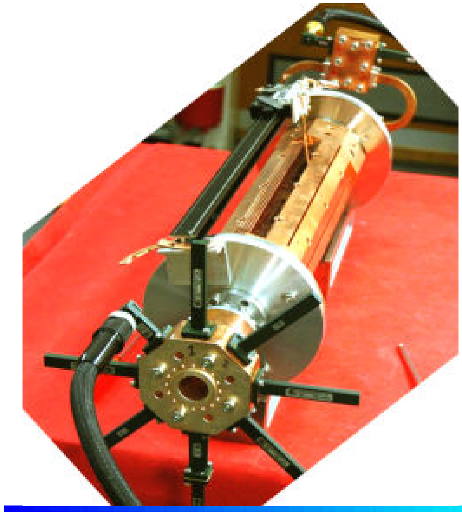
- Good quad alignment needed (20μm)
- Good BPM accuracy (20μm)
- Orbit correction essential
  - 1-to-1 steering to BPM centres
  - DFS (Dispersion Free Steering) gives almost ideal case

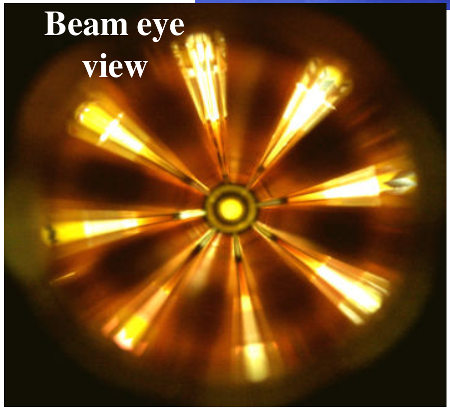


Power extraction structure PETS

- 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







The power produced by the bunched (ω_0) beam in a constant impedance structure:

Design input parameters

PETS design

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

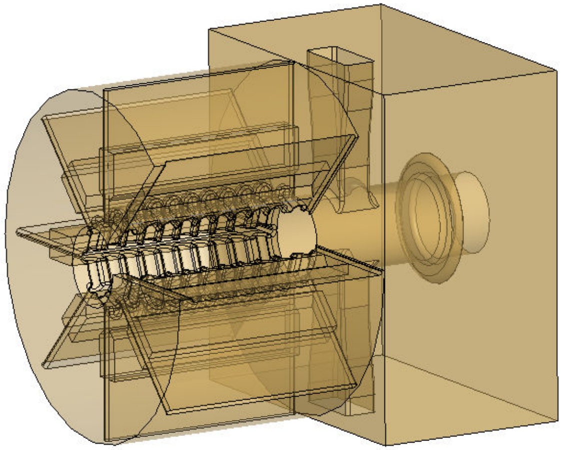
P – RF power, determined by the accelerating structure needs and the module layout.

I – Drive beam current

L – Active length of the PETS

F_b – single bunch form factor (≈ 1)

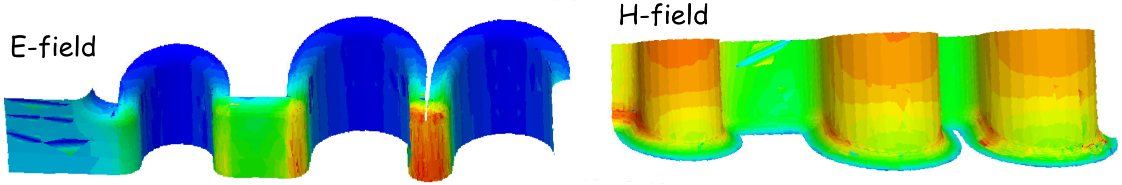
Power Extraction Structure (PETS)



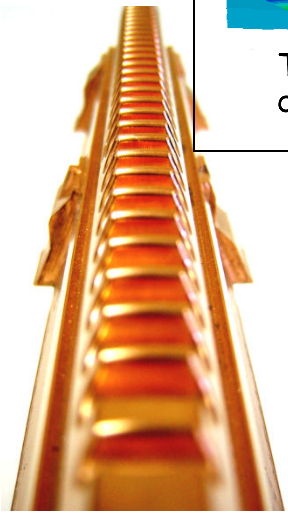
The PETS comprises eight octants separated by the damping slots. Each of the slots is equipped with HOM damping loads. This arrangement follows the need to provide strong damping of the transverse modes.

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
(ΔT max (240 ns, Cu) = 1.8 C^0)



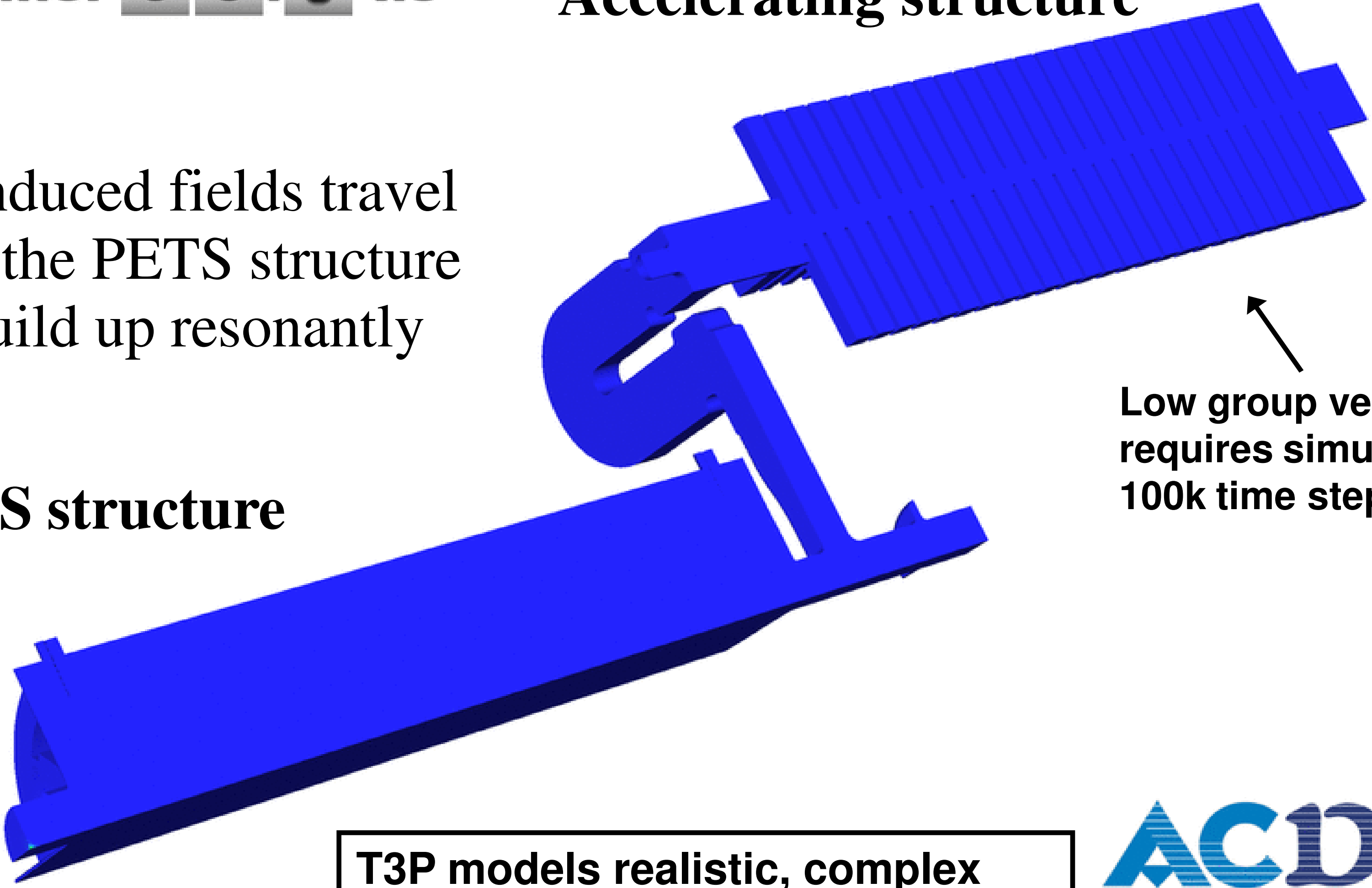
To reduce the surface field concentration in the presence of the damping slot, the special profiling of the iris was adopted.



I. Syratchev

Simulation of RF Power Transfer

time: 0 0 . 0 ns



Accelerating structure

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

PETS structure

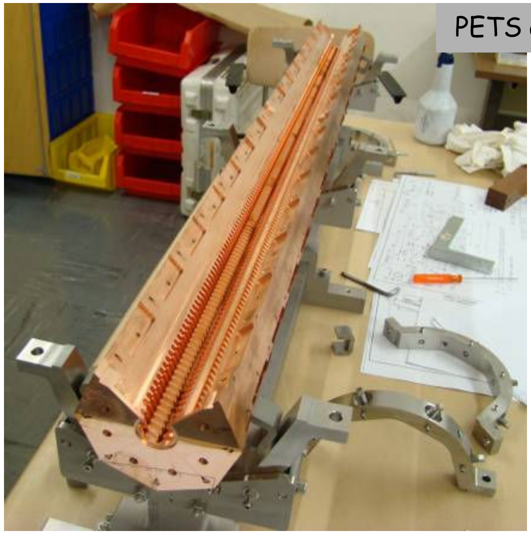
Low group velocity requires simulations with 100k time steps

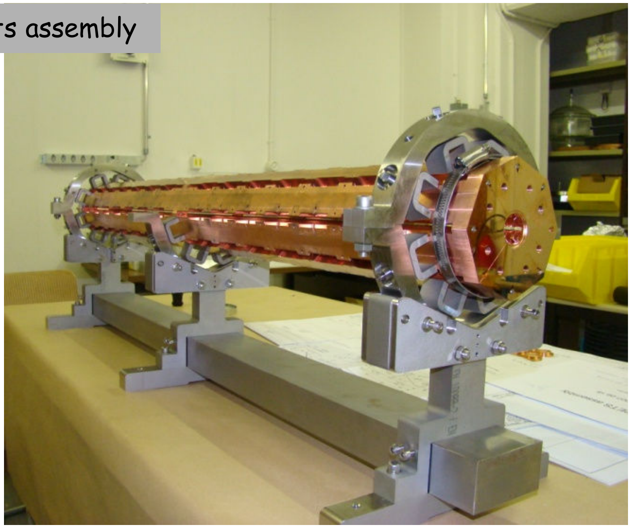
T3P models realistic, complex accelerator structures with unprecedented accuracy

12 GHz PETS test assembly

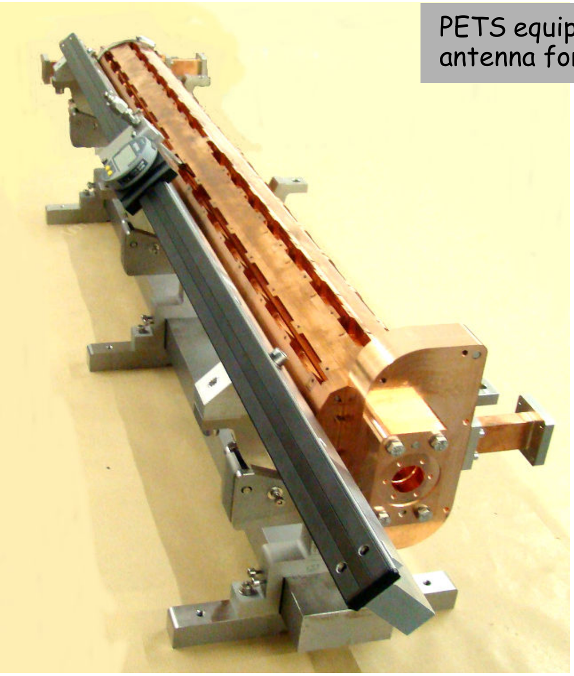
8 bars, as received from VDL

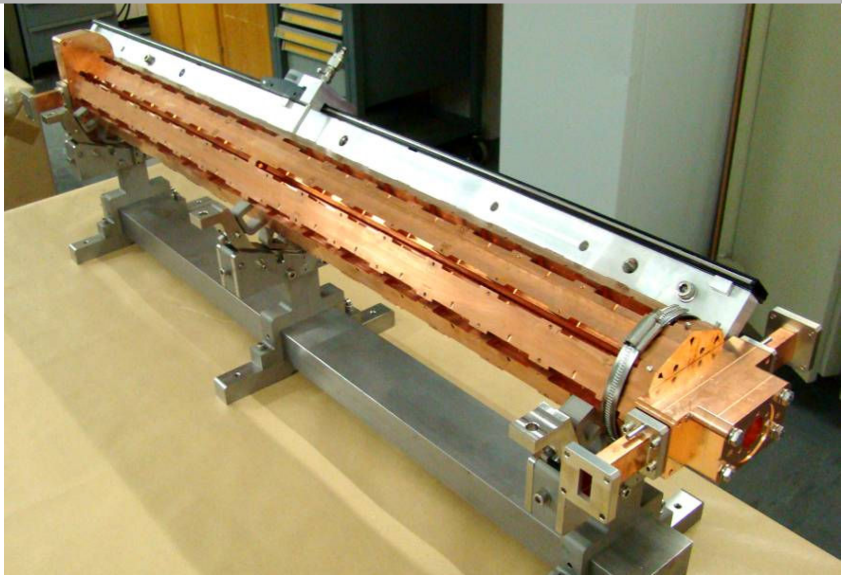
PETS octants assembly

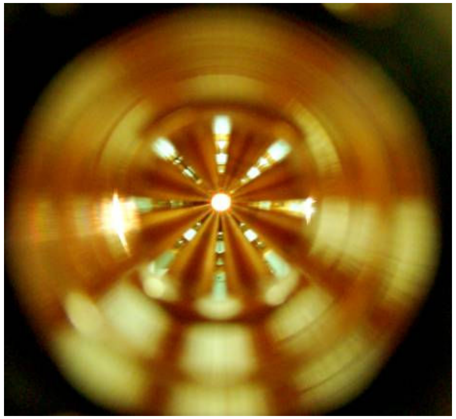




PETS equipped with the power couplers and electronic ruler with pick-up antenna for the phase advance measurements.

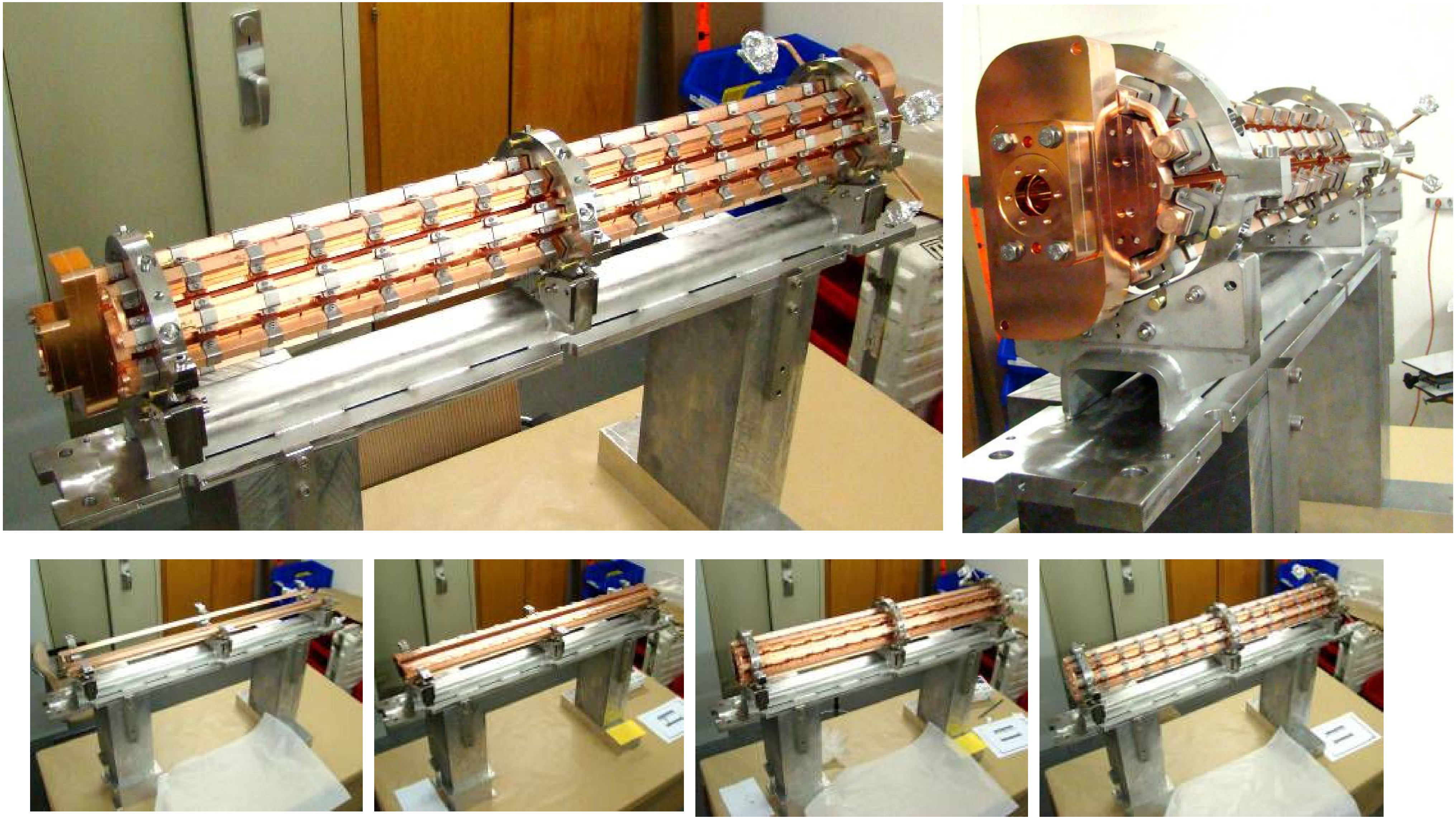






I. Syratchev

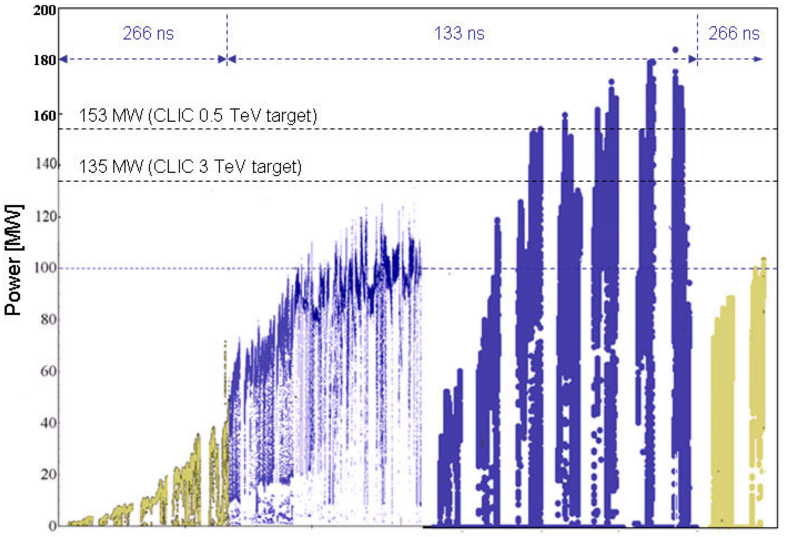
12 GHz TBTS PETS final assembly

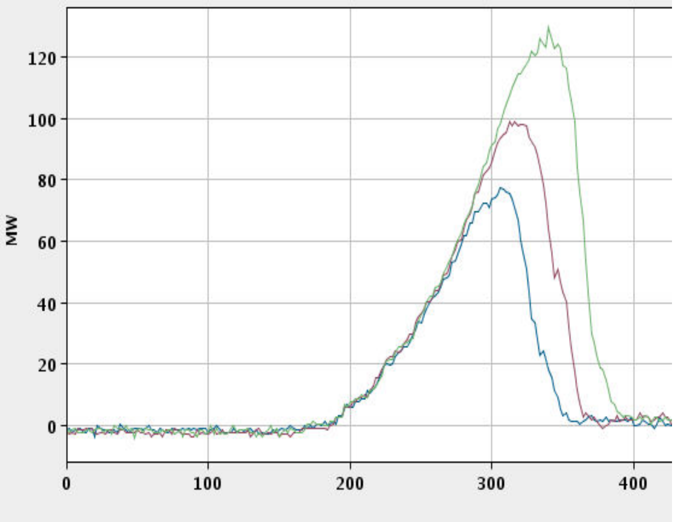


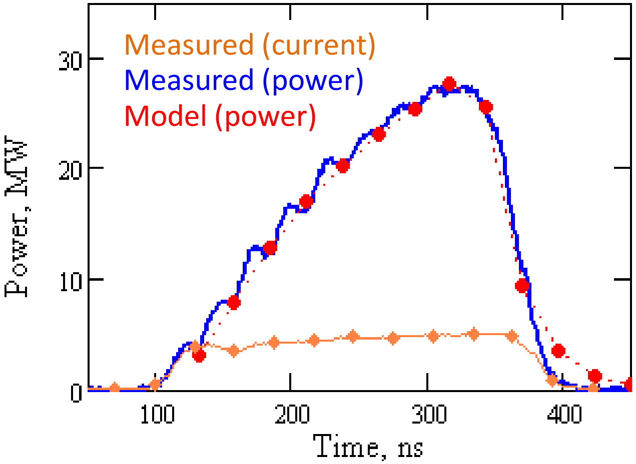
I. Syratchev

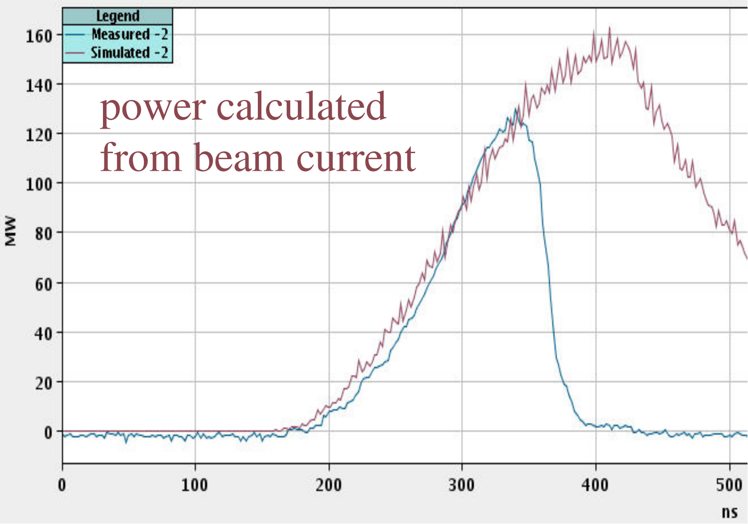
Present PETS status (12 GHz)

- achieved 125 MW @ 266ns in RF driven test at SLAC
- up to ~130 MW peak power beam driven at CTF3 (6A beam current, recirculation) (still breakdowns)
- model well understood





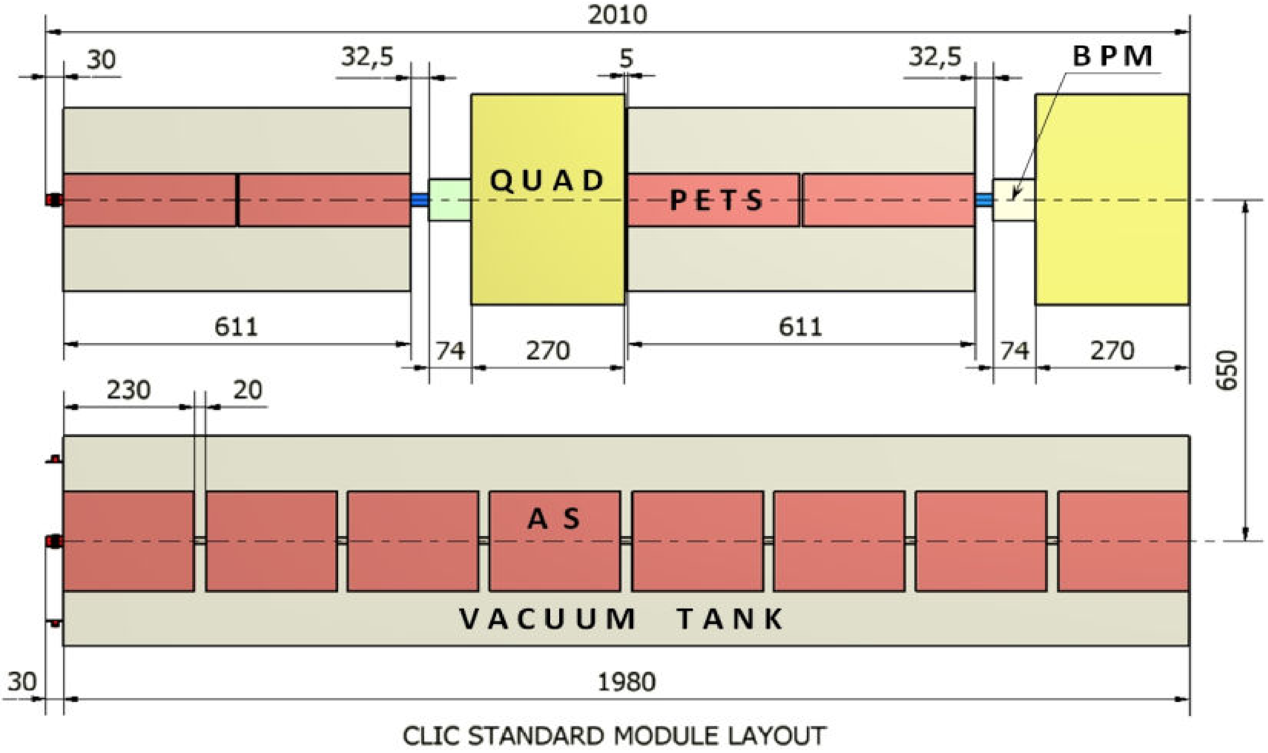




power calculated from beam current

CLIC two-beam Module layout

Standard module



Total per module
8 accelerating structures
8 wakefield monitors

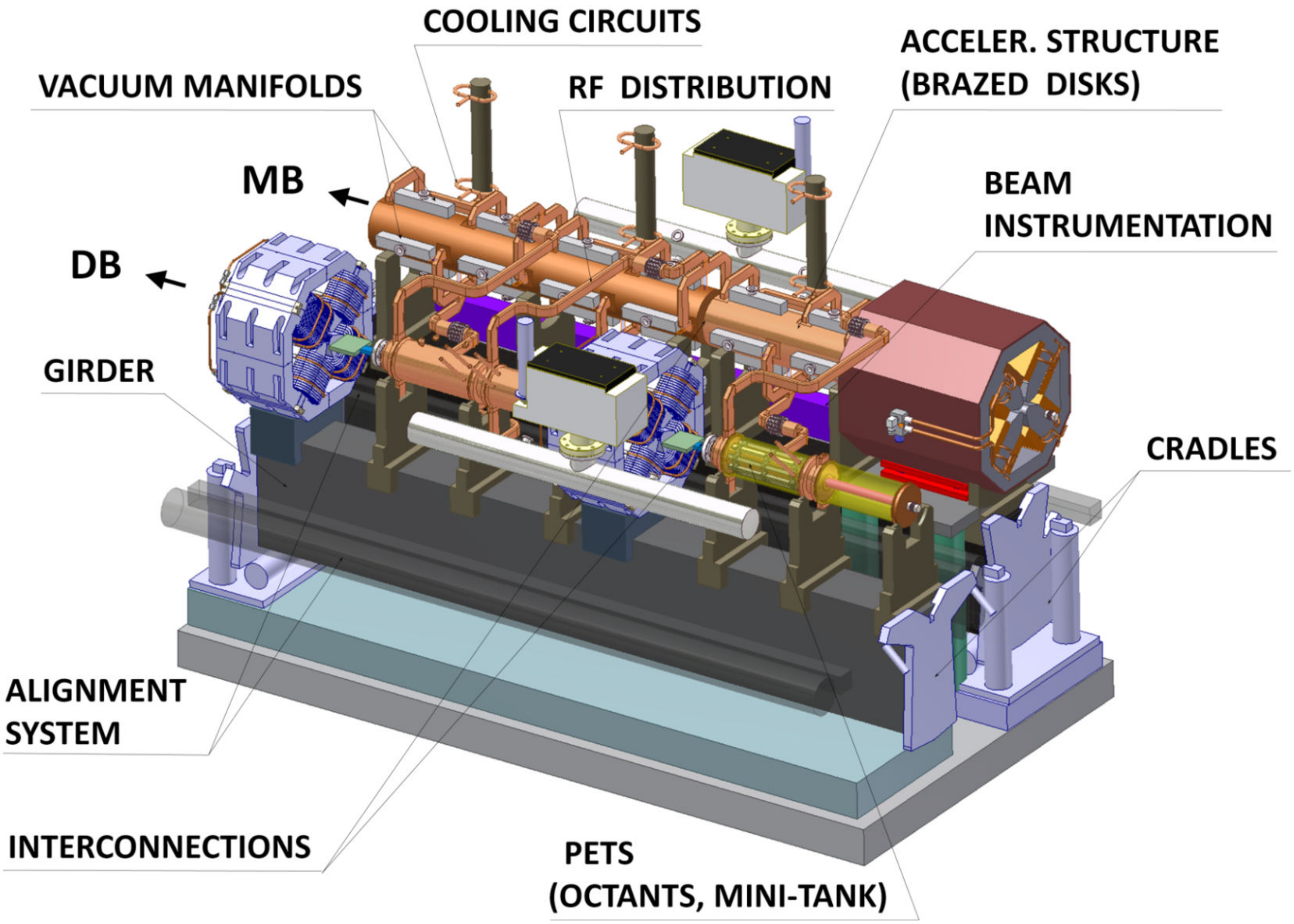
4 PETS
2 DB quadrupoles
2 DB BPM

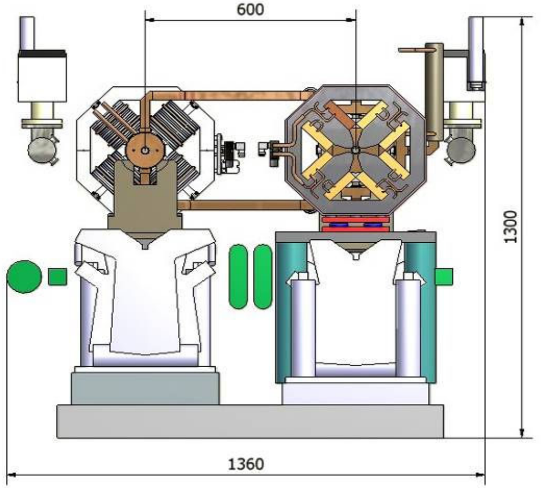
Total per linac
8374 standard modules

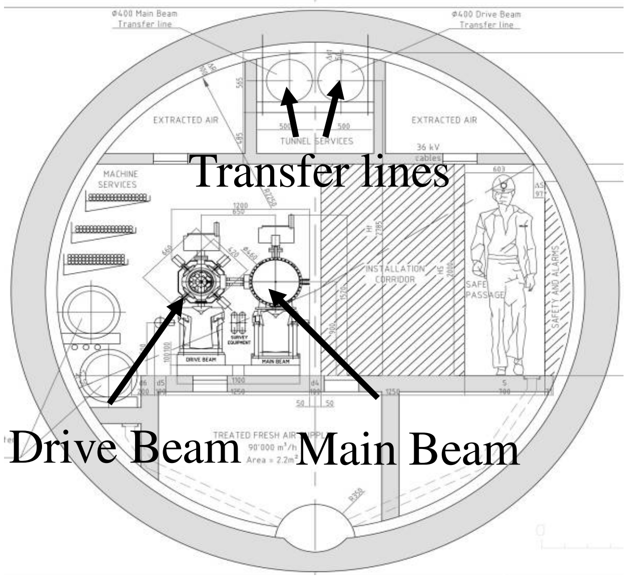
- Other modules have 2,4,6 or 8 acc.structures replaced by a quadrupole (depending on main beam optics)
- Total 10462 modules, 71406 acc. structures, 35703 PETS

G.Riddone

CLIC two-beam Module



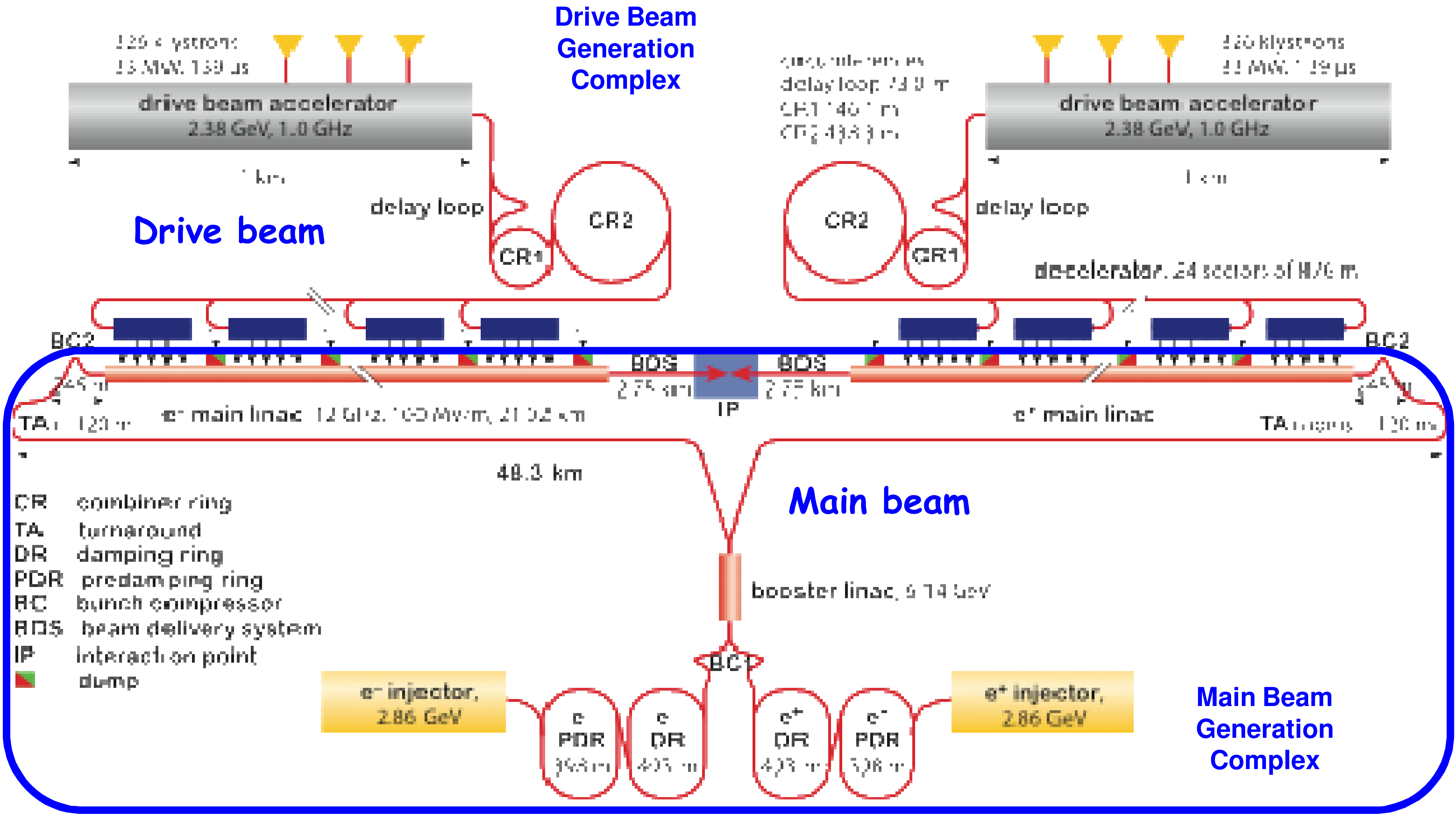




- Alignment system, beam instrumentation, cooling integrated in design

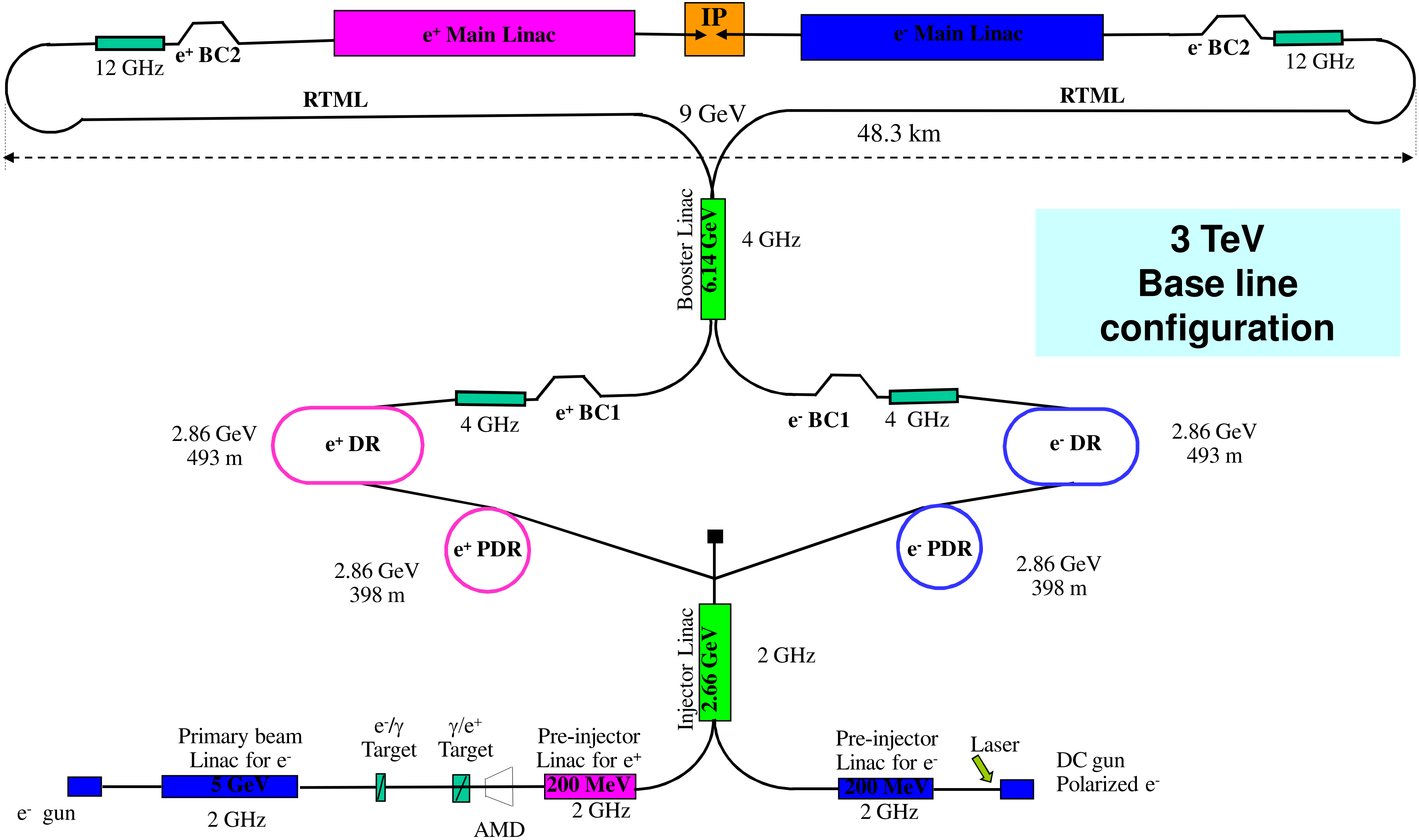
G.Riddone

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

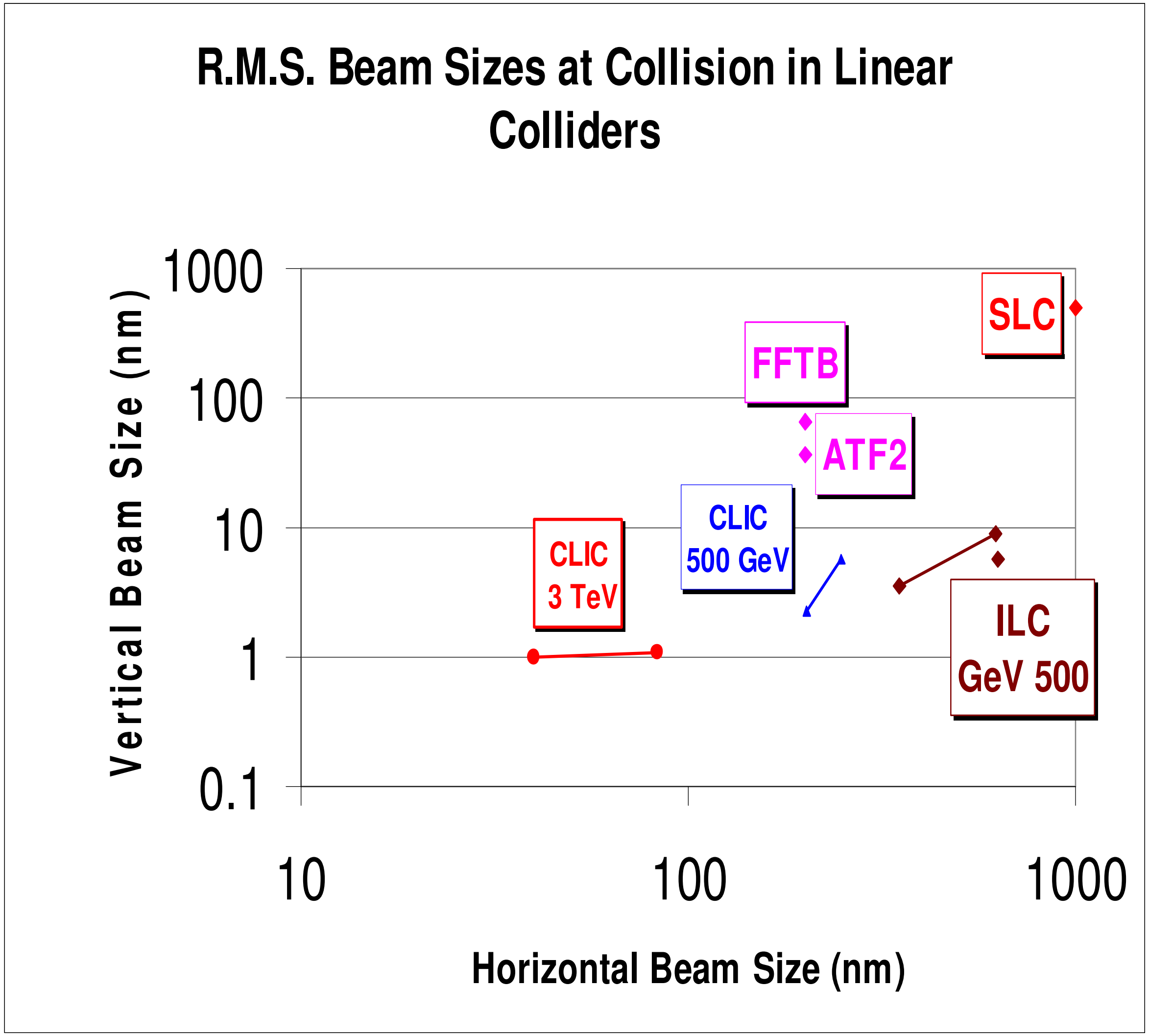
Main beam Injector Complex



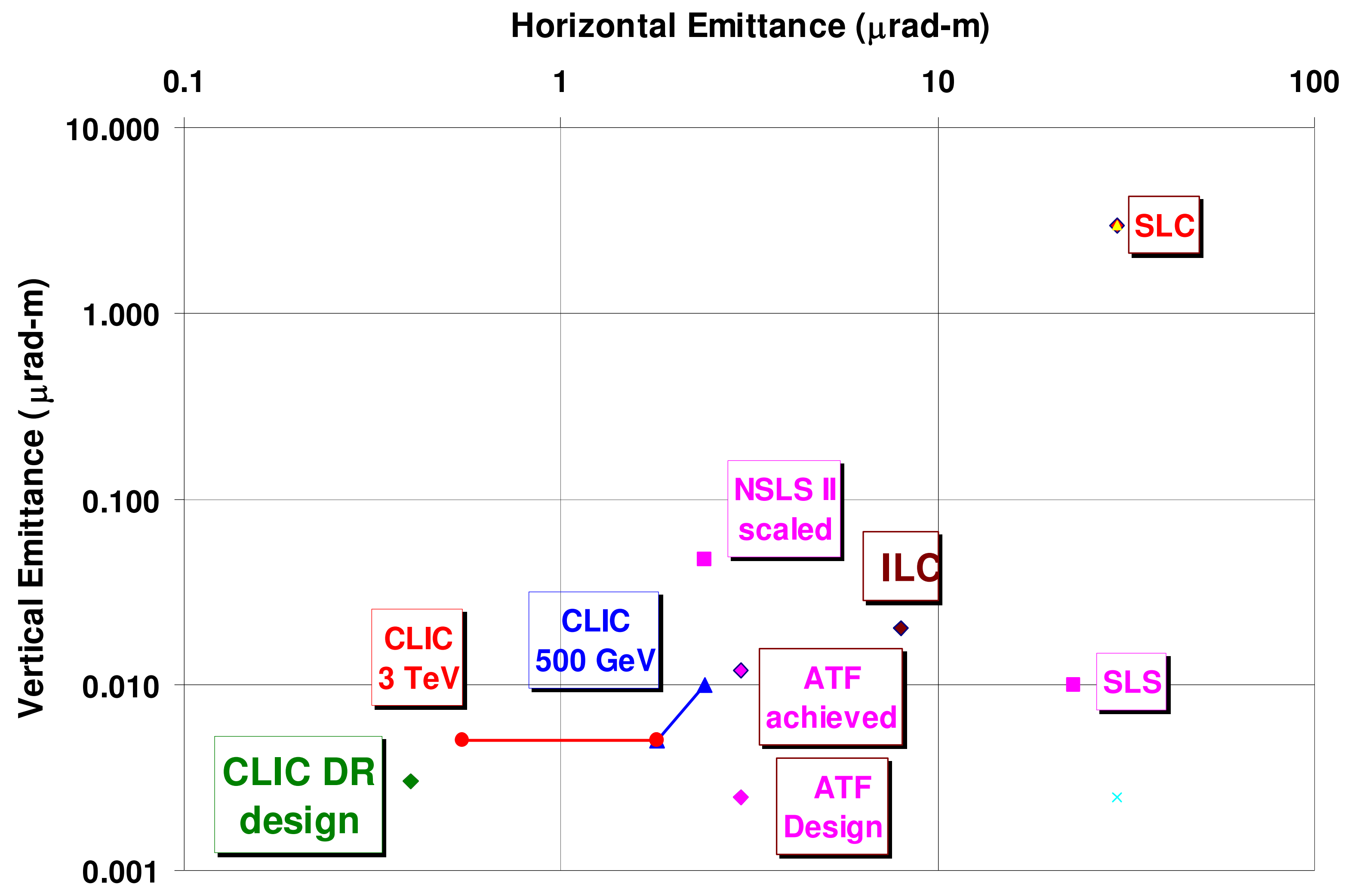
3 TeV
Base line
configuration

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 intrumentation
  - Beam based corrections and feed-backs



Damping Ring emittance



Damping Rings - Reminder

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: $\tau_D = \dfrac{2E}{P}$ $\qquad P = \dfrac{2}{3}\dfrac{r_e c}{(m_o c^2)^3}\dfrac{E^4}{r^2}$ $\qquad \boxed{\tau_D \propto \dfrac{\rho^2}{E^3}}$

  $\mathcal{D} \approx 1$

LEP: E ~ 90 GeV, P ~ 15000 GeV/s, τ_D ~ 12 ms

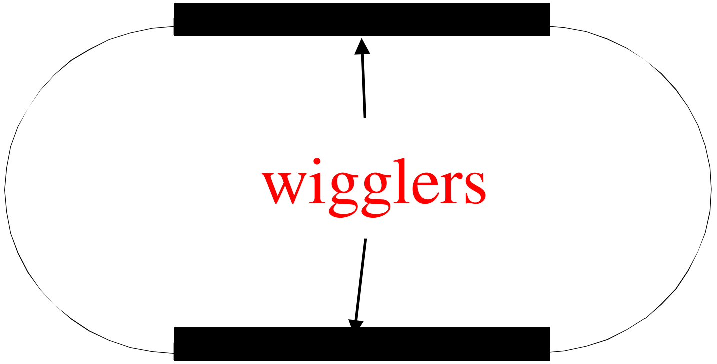
Damping rings

- $\tau_D \propto \frac{\rho^2}{E^3}$ 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 $E \approx 2$ GeV
  - $\rho \approx 50$ m
  - $P_\gamma = 27$ GeV/s [28 kV/turn]
  - hence $\tau_D \approx$ 150 ms - we need 7-8 τ_D !!! ⇒ store time too long !!!
- Increase damping and P using *wiggler magnets*

Damping Rings - Reminder

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

=> see homework



- 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
ΔE_{arcs}	energy loss in the arcs
L_{wiggler}	total length of wiggler

- Energy loss in wiggler:

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

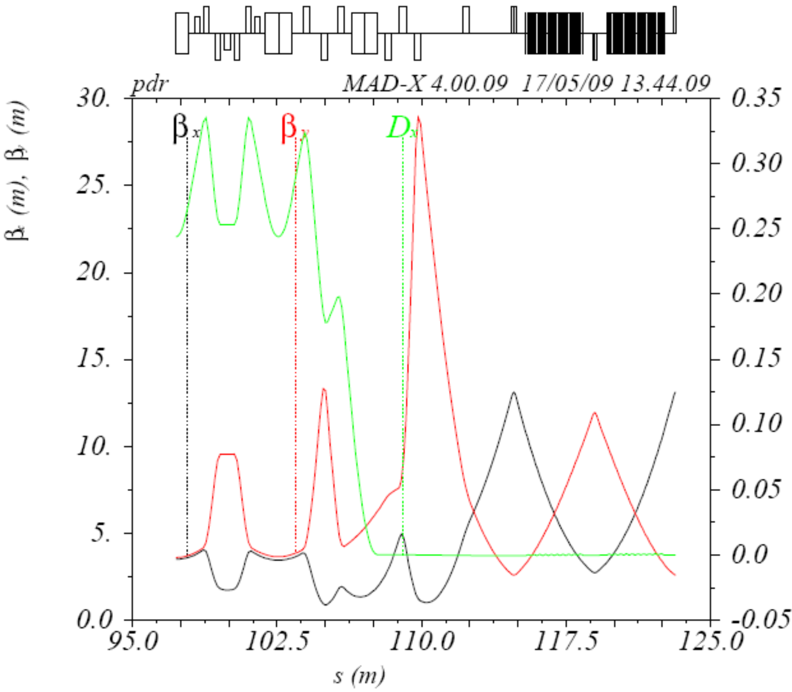
$<B^2>$ is the field square averaged over the wiggler length

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, λ_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

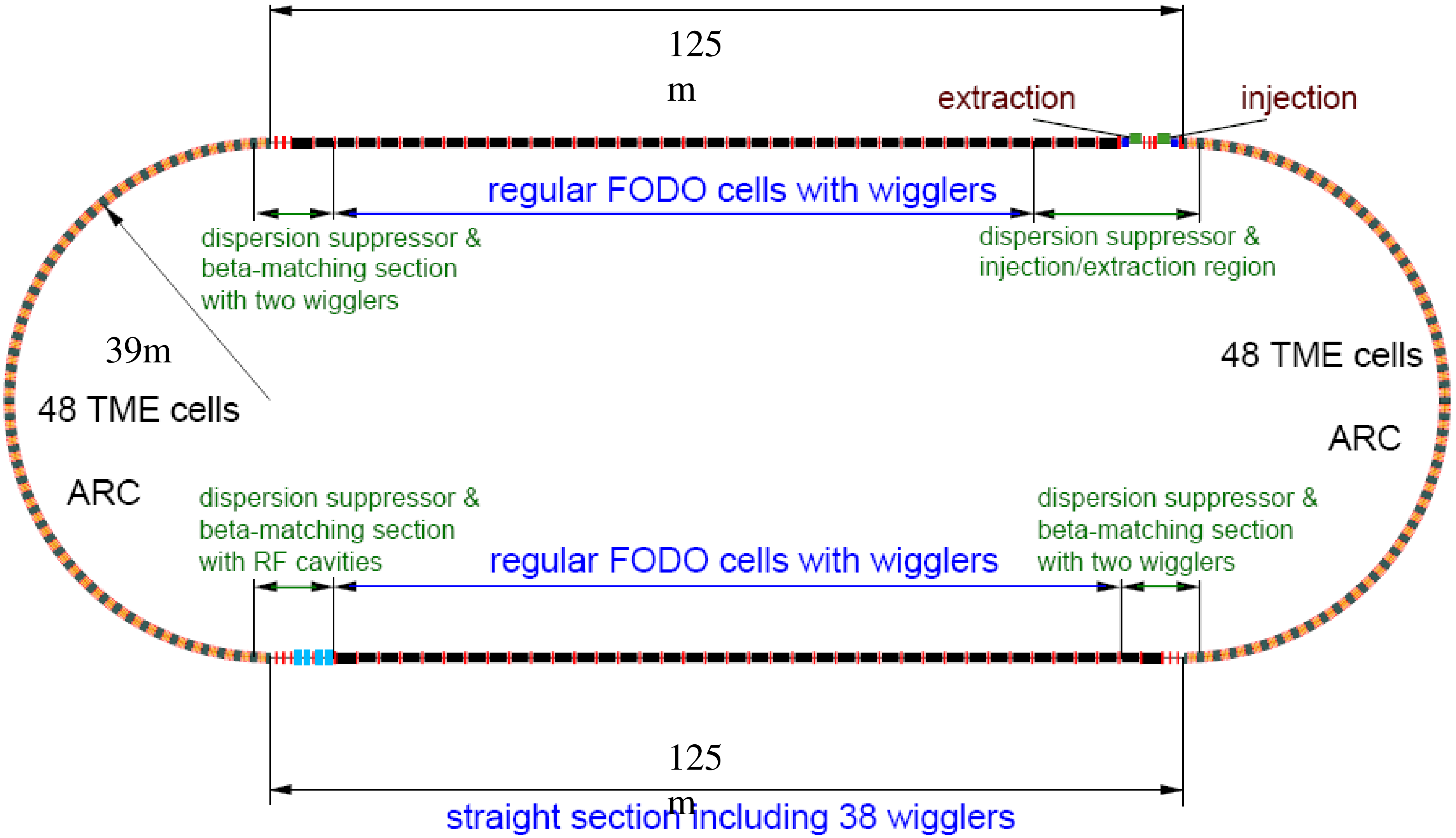
Parameter	Unit	e^-	e^+
Energy (E)	GeV	2.86	2.86
No. of particles/bunch (N)	10^9	4.4	6.4
Bunch length (rms) (σ_z)	mm	1	10
Energy Spread (rms) (σ_E)	%	0.1	8
Hor./vert. emittance ($\gamma\varepsilon_{x,y}$)	mm. mrad	100	7000



Fanouria Antoniou

CLIC damping ring layout

- Total length 493m (much smaller than ILC), beam pulse only 47m



CLIC damping rings

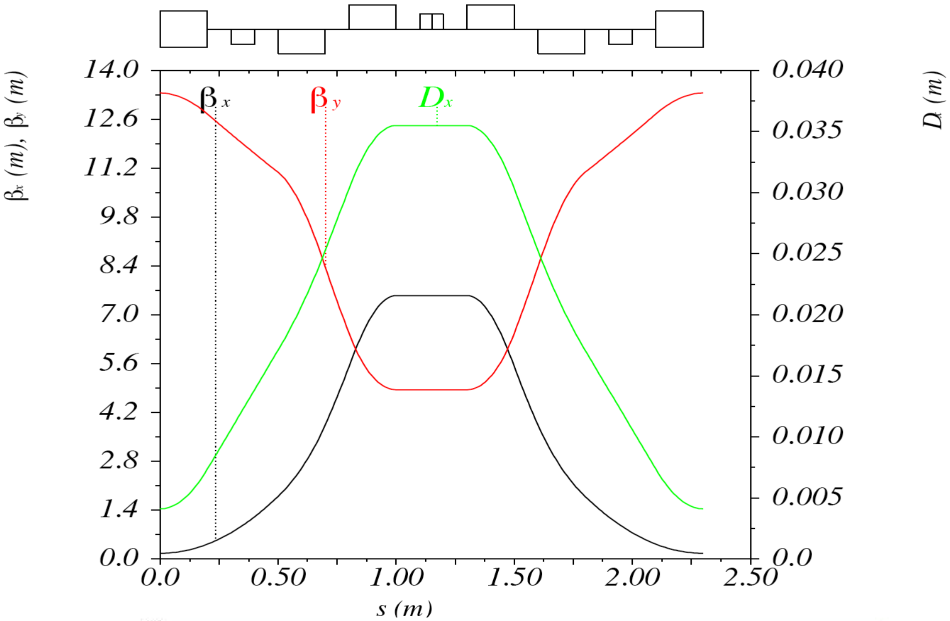
- Two rings of racetrack shape at energy of 2.86 GeV
- Arcs: 2.3 m long cells
  straight sections: FODO cells with 2m-long superconducting damping wigglers (2.5T, 5cm period)
  total length of 493 m
- Phase advance per arc cell:
  158° in the horizontal and
  18° in the vertical plane
- chromaticity is controlled by two sextupole families.
- Transverse damping time $\tau_{x,y}$=1.87 ms
- Final normalized emittance:

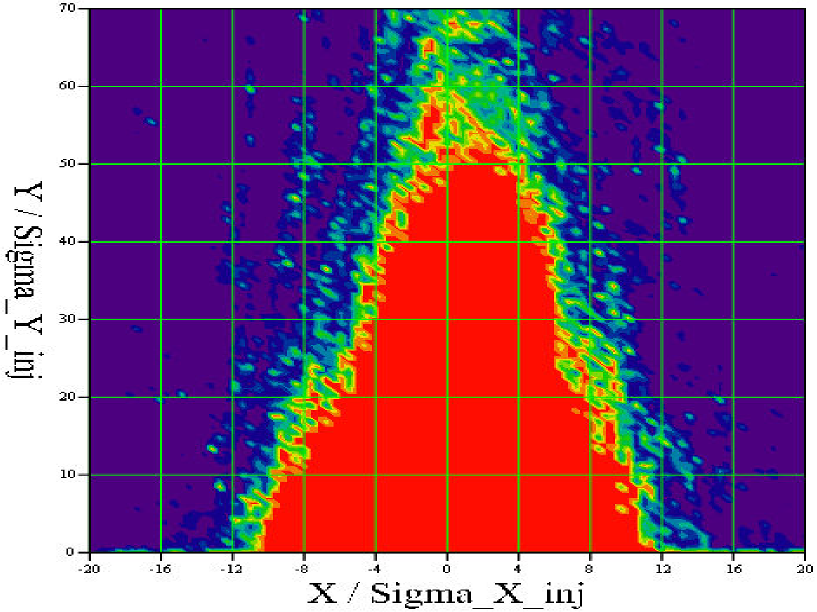
$\gamma\varepsilon_x$= 480 nm.rad, $\gamma\varepsilon_y$= 4.7 nm.rad

Lattice version	**Original**	**New**
Energy [GeV]	2.42	2.86
Circumference [m]	**365.21**	**493.05**
Coupling	0.0013	
Energy loss/turn [Me]	3.86	5.04
RF voltage [MV]	5.0	6.5
Natural chromaticity x / y	-103 / -136	-149 / -79
Compaction factor	8E-05	6e-5
Damping time x / s [ms]	1.53 / 0.76	1.87 / 0.94
Dynamic aperture x / y [σ_{inj}]	**±3.5 / 6**	**±12 / 50**
Number of arc cells	100	
Number of wigglers	76	
Cell /dipole length [m]	1.729/0.545	2.30 / 0.4
Bend field [T]	0.93	1.27
Bend gradient [1/m^2]	0	-1.10
Max. Quad. gradient [T/m]	**220**	**60.3**
Max. Sext. strength [T/m^2 10^3]	**80**	**6.6**
Phase advance x / z	0.58 / 0.25	0.44/0.05
Bunch population, [10^9]	4.1	
IBS growth factor	**5.4**	**2.0**
Hor. Norm. Emittance [nm.rad]	**470**	**480**
Ver. Norm. Emittance [nm.rad]	**4.3**	**4.7**
Bunch length [mm]	1.4	1.4
Longitudinal emittance [eVm]	3500	3700

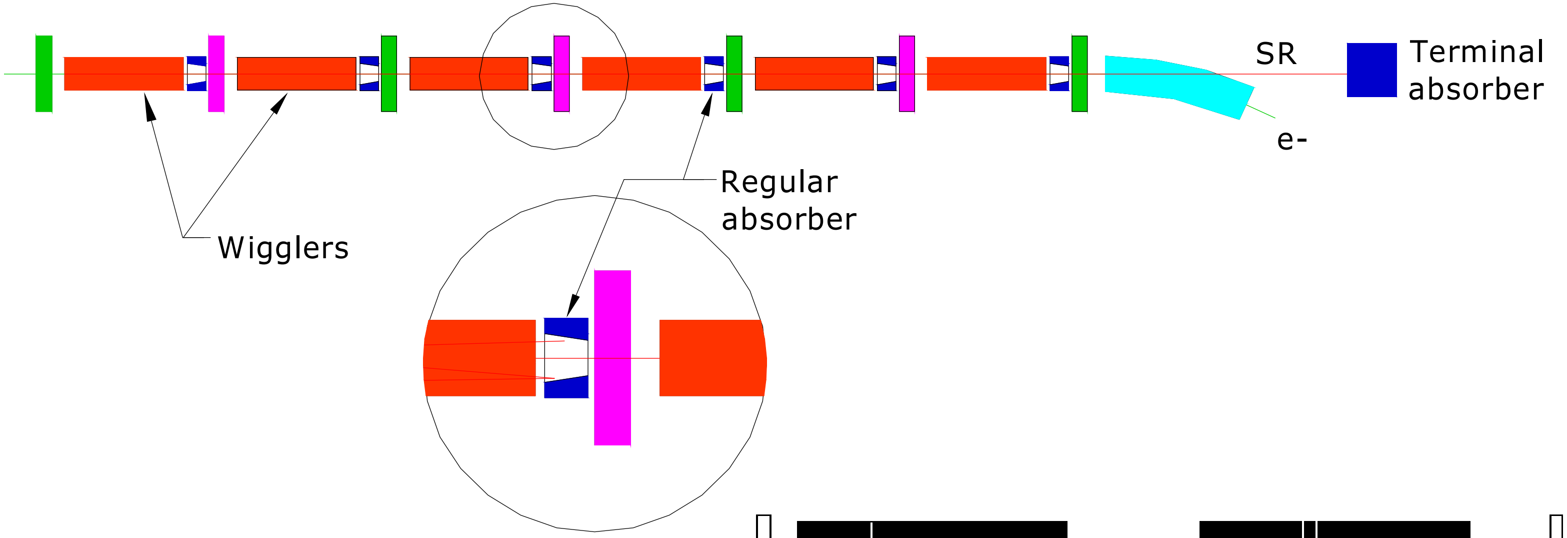
DR arc and dynamic aperture

- 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)

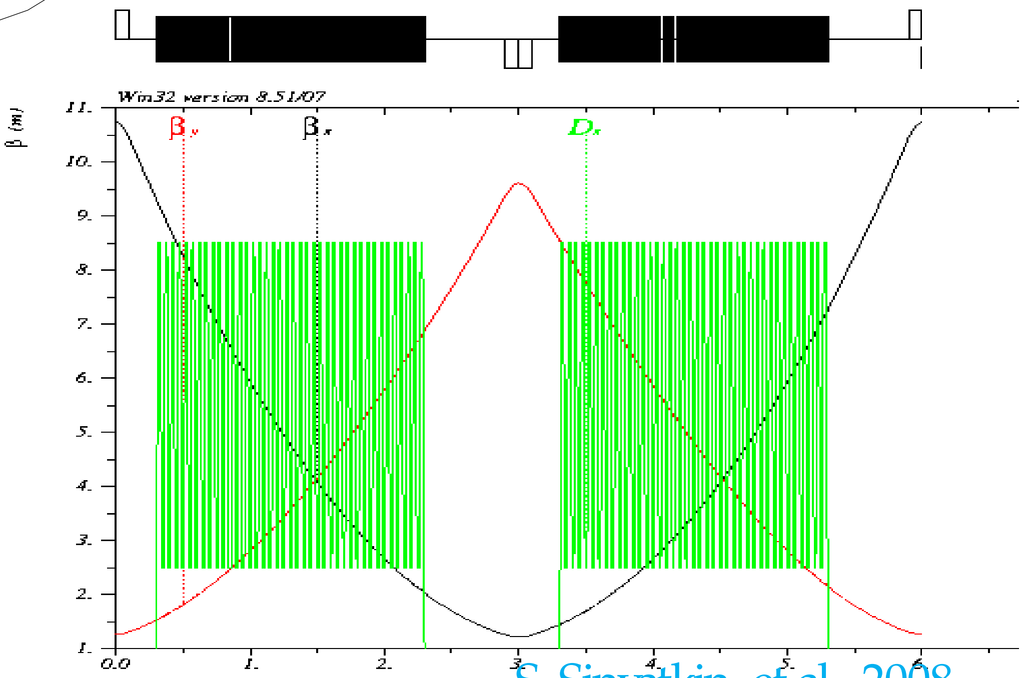




Wiggler cell including absorbers

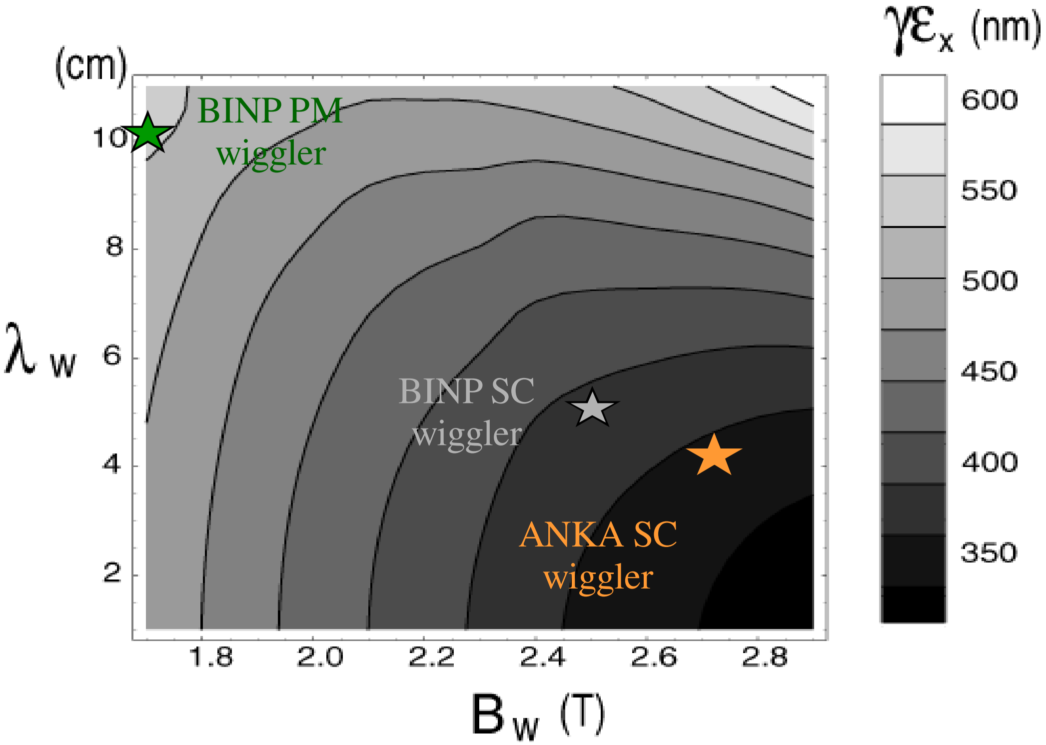


- Superconducting wigglers need to be shielded from synchrotron radiation (several kW/m)
- Space between wiggler and downstream quadrupoles for accommodating SR absorbers
- Horizontal phase advance optimised for lowering IBS, vertical phase advance optimised for aperture



S. Sinyatkin, et al., 2008

Wigglers' effect with IBS



- Super-conducting magnets have to be designed, built and tested
- Two wiggler prototypes
  - 2.5T, 5cm period, NbTi coil, built by BINP
  - 2.8T, 4cm period, Nb3Sncoil, built by CERN/ANKA
- Aperture fixed by radiation absorption scheme

- 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

Parameters	**BINP**	**ANKA/CERN**
B_{peak} [T]	2.5	2.8
λ_W [mm]	50	40
Beam aperture full gap [mm]	20*	24*
Conductor type	NbTi	$NbSn_3$
Operating temperature [K]	4.2	4.2

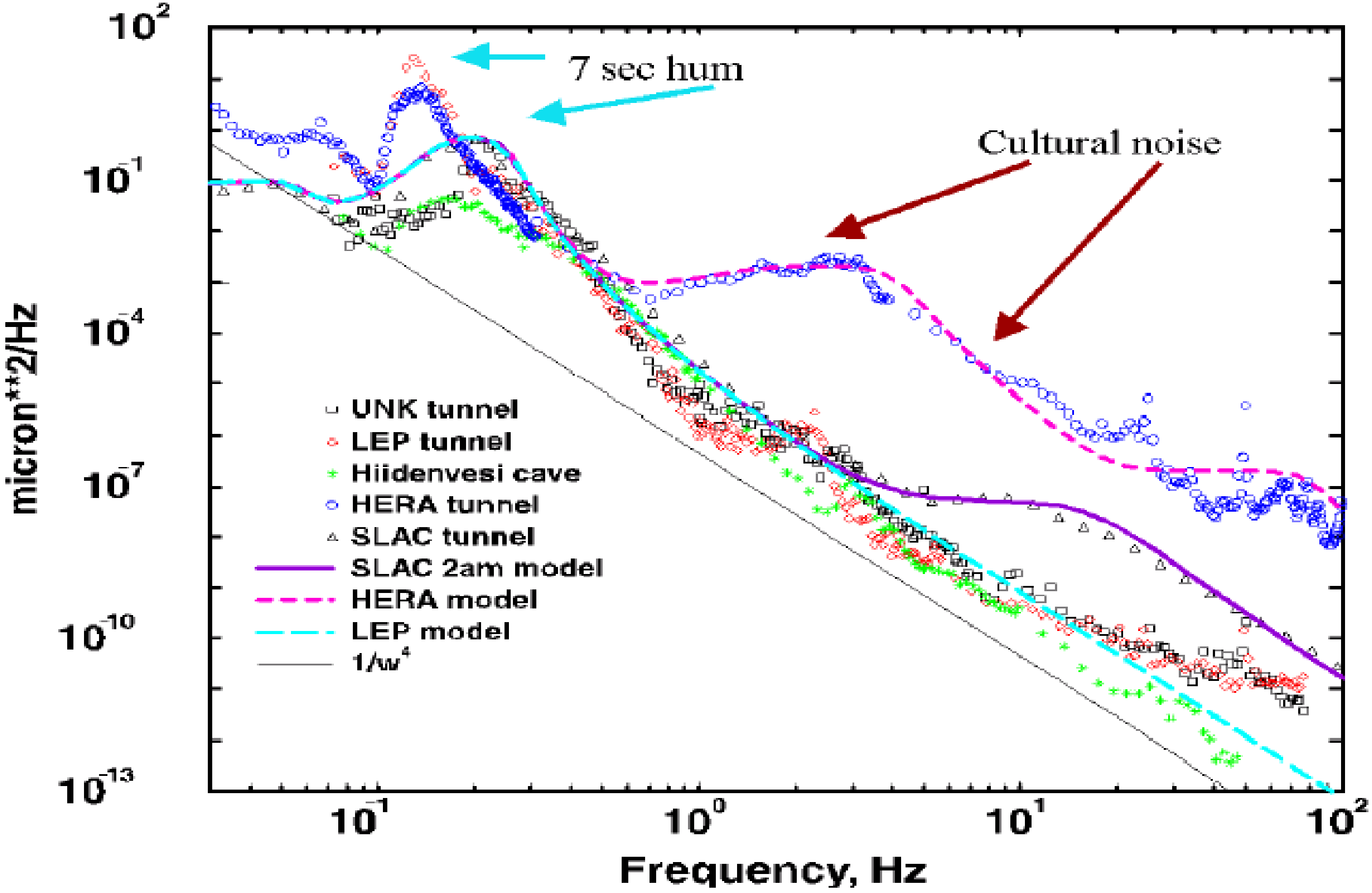
Alignment + Stabilisation

- 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

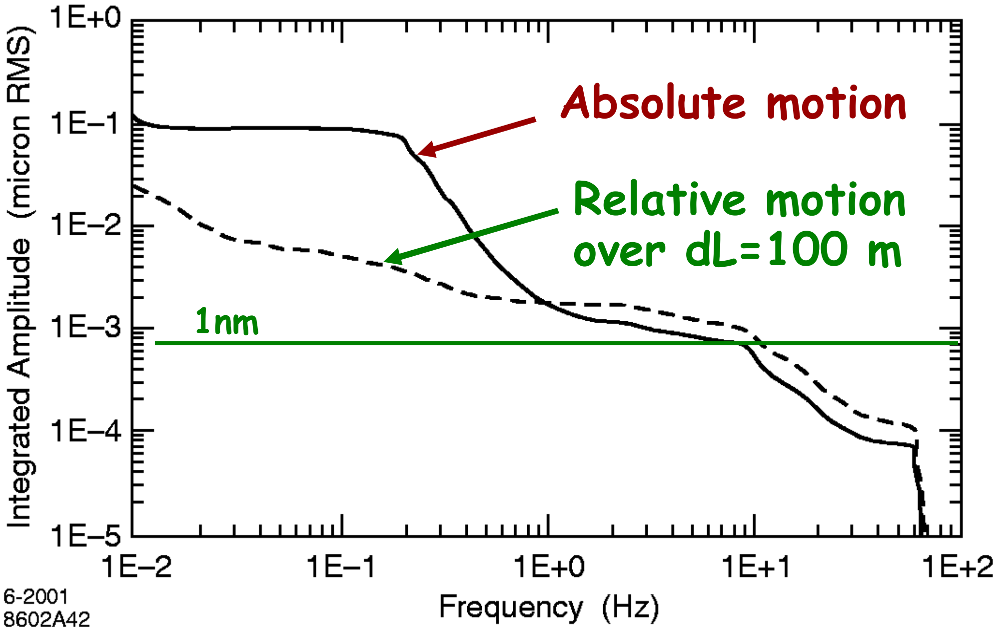
- Need to consider short and long term stability of the collider
- Ground motion model: ATL law

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

A site dependent constant
T time
L distance

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

- 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

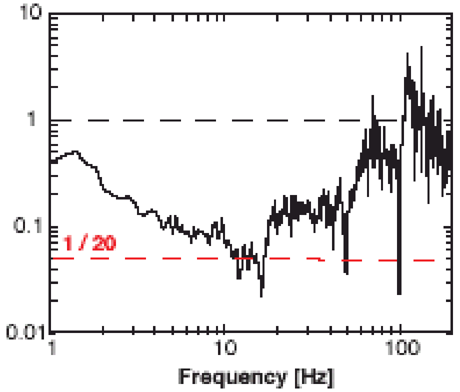
➡ Need active damping of vibrations

CERN vibration test stand

Ground motion

Vertical stabilization of a CLIC prototype quadrupole

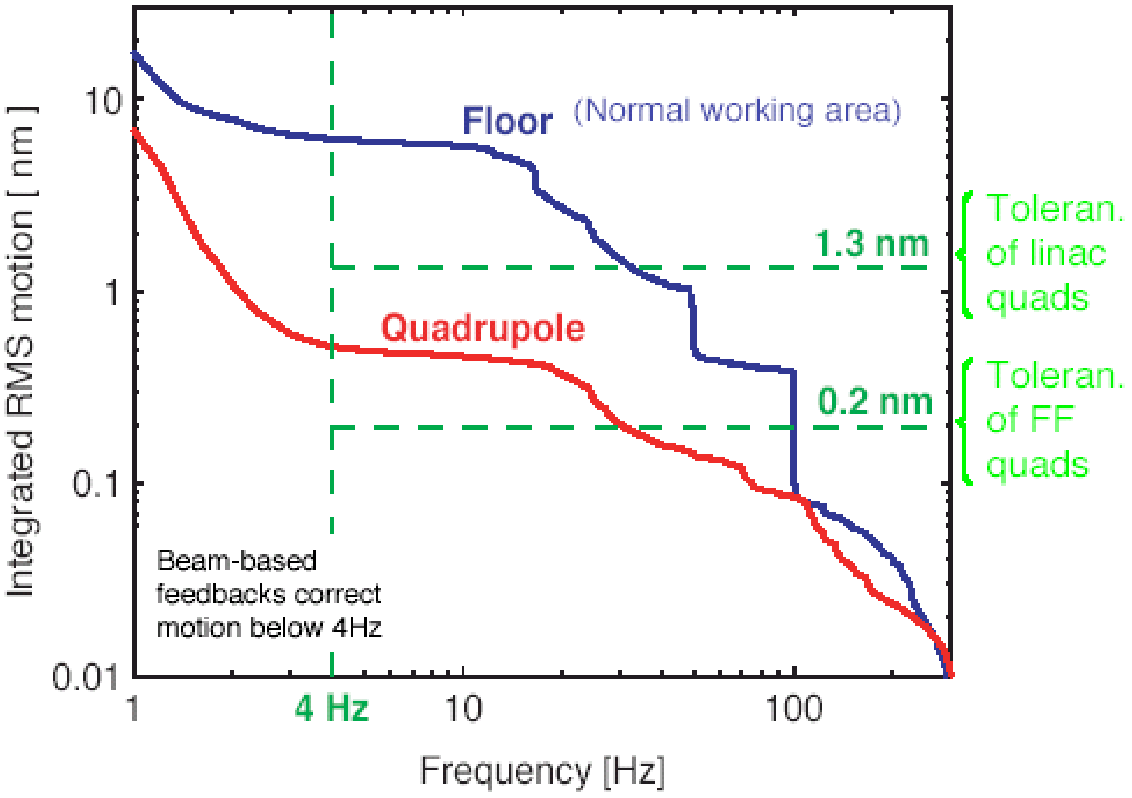
Ground-to-table transmission



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



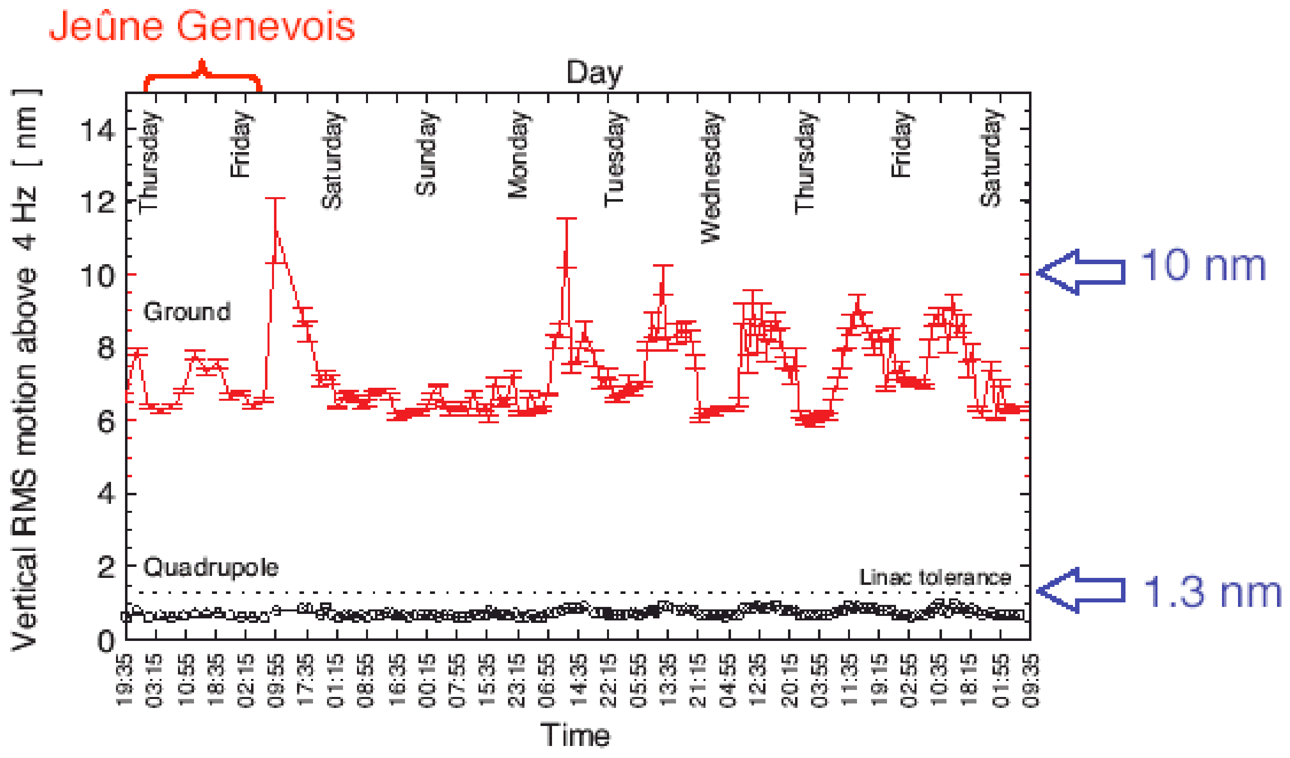
CLIC prototype magnets stabilized to the sub-nanometre level !!

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***?



Jeûne Genevois

10 nm

1.3 nm

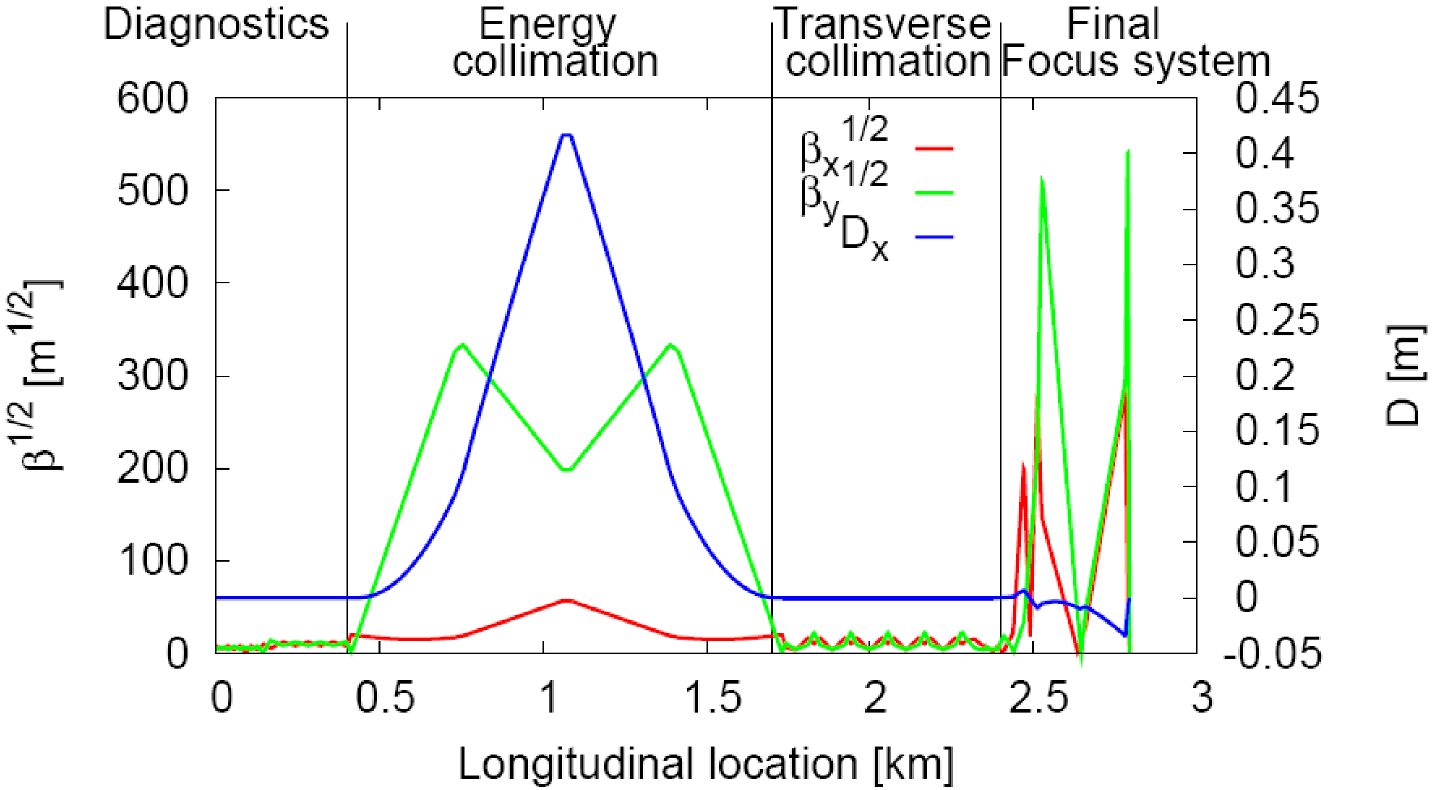
Quadrupole vibrations kept below the 1 nm level

over a period of 9 consecutive days!

Stefano Redaelli

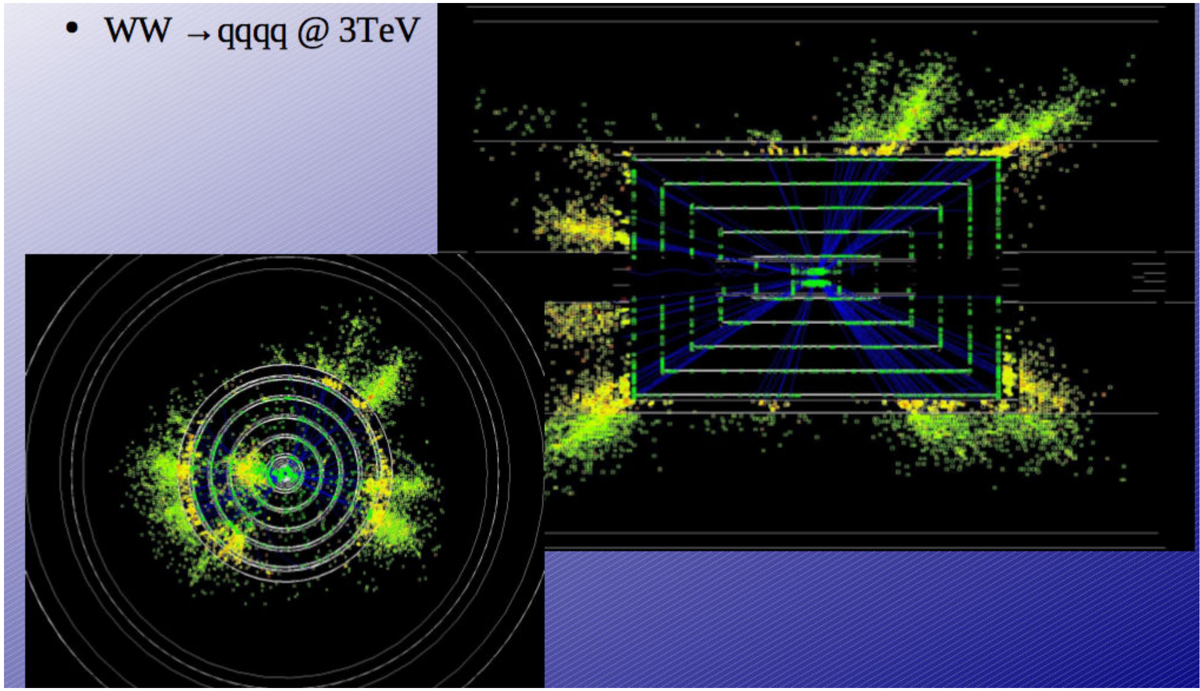
Beam Delivery System

- 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 (9λ),…)
- ILC/CLIC collaboration, profiting from ILC developments
- Start-up with studies with SiD-like (ILD) detectors



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

- Constructive exchange of view with B.Barish during his visit at CERN in Nov 07 http://www.linearcollider.org/cms/?pid=1000465

- Focusing on subjects with strong synergy between CLIC & ILC
  - making the best use of the available resources
  - adopting systems as similar as possible
  - identifying and understanding the differences due to technology and energy (technical, cost….)
  - 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

http://cern.ch/CLIC-Study/CLIC_ILC_Collab_Mtg/Index.htm

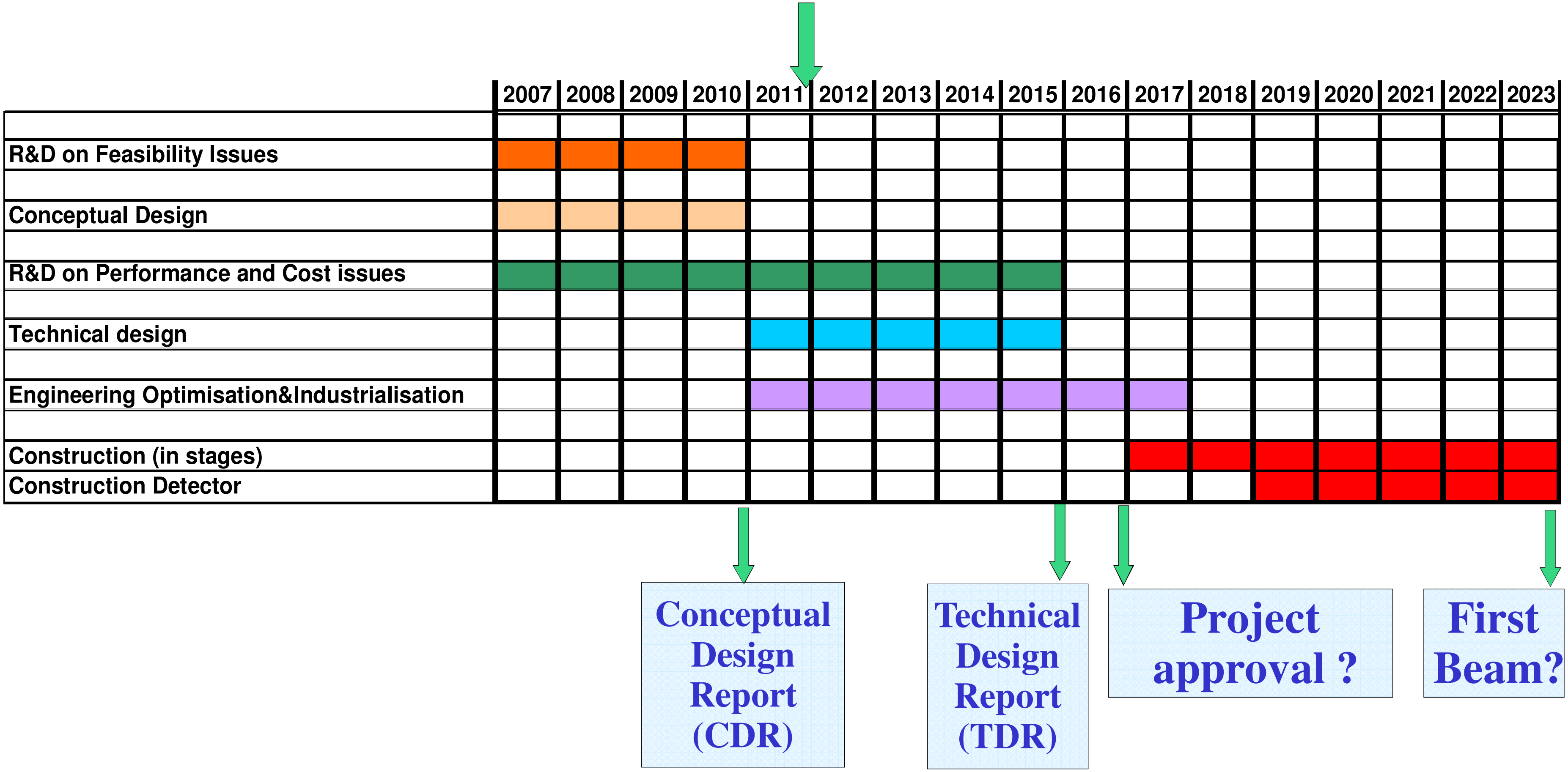
CLIC/ILC Collaboration

- 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 Rings
- Participation of CLIC experts to ILC meetings and ILC experts to CLIC meetings

Tentative CLIC schedule

- Shortest, Success-Oriented, Technically-Limited long-term Schedule

Technology evaluation and Physics assessment based on LHC results for a possible decision on Linear Collider with staged construction starting with the lowest energy required by Physics



	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
R&D on Feasibility Issues	🟧	🟧	🟧	🟧													
Conceptual Design	🟧	🟧	🟧	🟧													
R&D on Performance and Cost issues	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩								
Technical design					🟦	🟦	🟦	🟦	🟦								
Engineering Optimisation&Industrialisation					🟪	🟪	🟪	🟪	🟪	🟪	🟪						
Construction (in stages)											🟥	🟥	🟥	🟥	🟥	🟥	🟥
Construction Detector													🟥	🟥	🟥	🟥	🟥

Conceptual Design Report (CDR)

Technical Design Report (TDR)

Project approval ?

First Beam?

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 2010
- CLIC Conceptual Design Report planned for end 2010

- LHC (or Tevatron) physics discoveries (>2011) will tell which way to go …

Documentation

- General documentation about the CLIC study: http://cern.ch/CLIC-Study/
- CLIC scheme description:
  http://preprints.cern.ch/yellowrep/2000/2000-008/p1.pdf
- Recent Bulletin article:
  http://cdsweb.cern.ch/journal/article?issue=28/2009&name=CERNBulletin&category=News%20Articles&number=1&ln=en
- CLIC Physics http://clicphysics.web.cern.ch/CLICphysics/
- CLIC Test Facility: CTF3 http://ctf3.home.cern.ch/ctf3/CTFindex.htm
- CLIC technological challenges (CERN Academic Training)
  http://indico.cern.ch/conferenceDisplay.py?confId=a057972
- CLIC Workshop 2008 (most actual information) http://cern.ch/CLIC08
- EDMS http://edms.cern.ch/nav/CERN-0000060014
- CLIC ACE (advisory committee meeting)
  http://indico.cern.ch/conferenceDisplay.py?confId=58072
- CLIC meeting (parameter table) http://cern.ch/clic-meeting
- CLIC parameter note http://cern.ch/tecker/par2007.pdf
- CLIC notes http://cdsweb.cern.ch/collection/CLIC%20Notes

Acknowledgements

- First of all: THANK YOU!
  For being so brave to follow all this lecture (I hope!) ☺

- Thanks to everyone from whom I picked some material:

  Chris Adolphsen, Markus Aicheler, Alexandra Andersson, Fanouria Antoniou, Barry Barish, Caterina Biscari, Hans Braun, Roberto Corsini, Jean-Pierre Delahaye, Steffen Doebert, Brian Forster, S. Fukuda, Günther Geschonke, Alexey Grudiev, Samuli Heikkinen, Alban Mosnier, Yannis Papaphilipou, Stefano Redaelli, Germana Riddone, Louis Rinolfi, Daniel Schulte, Igor Syratchev, Helga Timkó, Rogelio Tomas, Faya Wang, Walter Wuensch, S.Yamaguchi
  + everyone I forgot