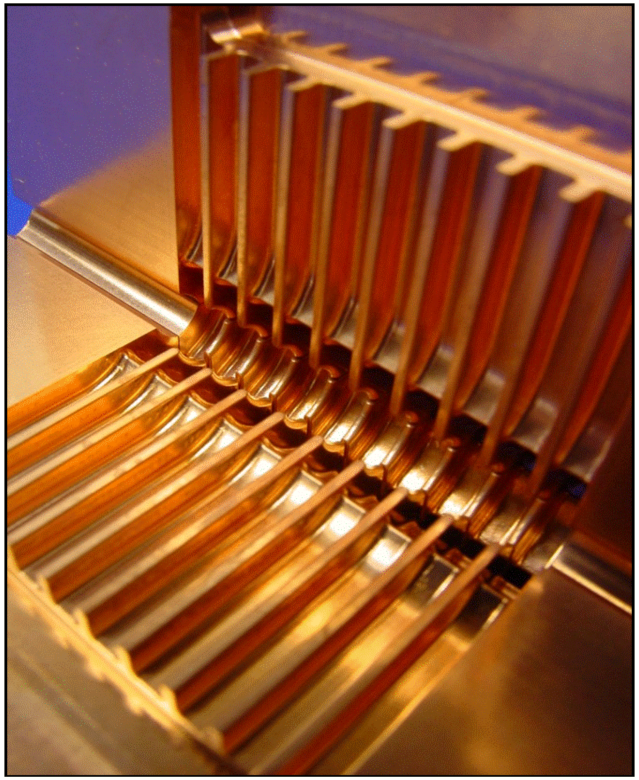
Room temperature RF and CLIC (Part II)

Frank Tecker – CERN

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



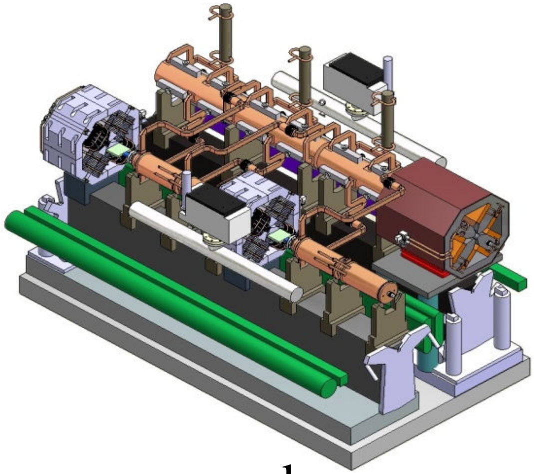
Lecture 1 - Summary

- 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

Lecture 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 goal: Demonstrate all key feasibility issues and document in a CDR by 2010 (possibly TDR by 2015)

World-wide CLIC / CTF3 collaboration

- 24 members representing 27 institutes involving 17 funding agencies of 16 countries

27 collaborating institutes

Ankara University (Turkey)
Berlin Tech. Univ. (Germany)
BINP (Russia)
CERN
CIEMAT (Spain)
Finnish Industry (Finland)
Gazi Universities (Turkey)

IRFU/Saclay (France)
Helsinki Institute of Physics (Finland)
IAP (Russia)
IAP NASU (Ukraine)
Instituto de Fisica Corpuscular
(Spain)
INFN / LNF (Italy)
J.Adams Institute, (UK)

JASRI (Japan)
JINR (Russia)
JLAB (USA)
KEK (Japan)
LAL/Orsay (France)
LAPP/ESIA (France)
LLBL/LBL (USA)
NCP (Pakistan)
North-West. Univ. Illinois (USA)

Oslo University (Norway)
PSI (Switzerland),
Polytech. University of Catalonia (Spain)
RAL (UK)
RRCAT-Indore (India)
Royal Holloway, Univ. London, (UK)
SLAC (USA)
Svedberg Laboratory (Sweden)
Uppsala University (Sweden)

New CLIC main parameters

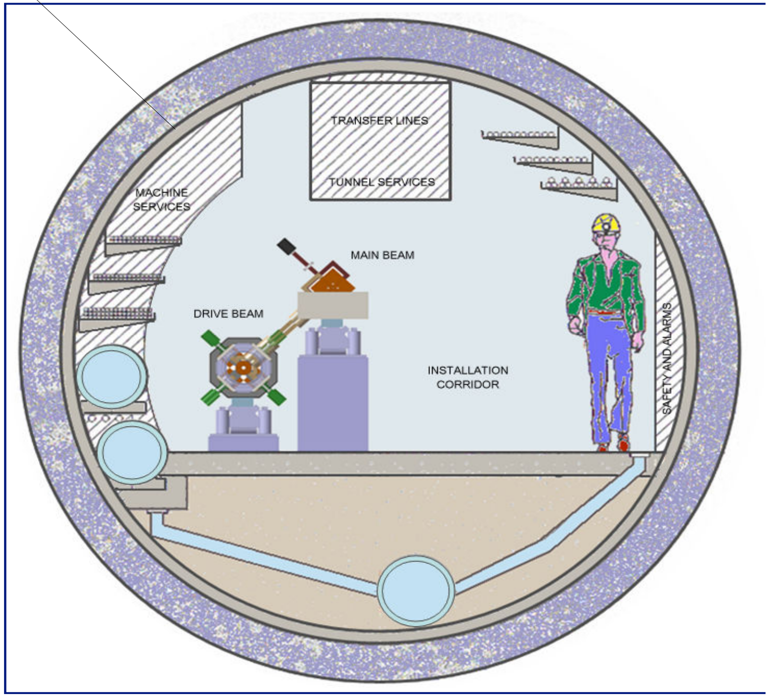
Center-of-mass energy	3 TeV
Peak Luminosity	$6 \cdot 10^{34}$ cm^{-2} s^{-1}
Peak luminosity (in 1% of energy)	$2 \cdot 10^{34}$ cm^{-2} s^{-1}
Repetition rate	50 Hz
Loaded accelerating gradient	100 MV/m
Main linac RF frequency	12 GHz
Overall two-linac length	42.2 km
Bunch charge	$3.7 \cdot 10^{9}$
Beam 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

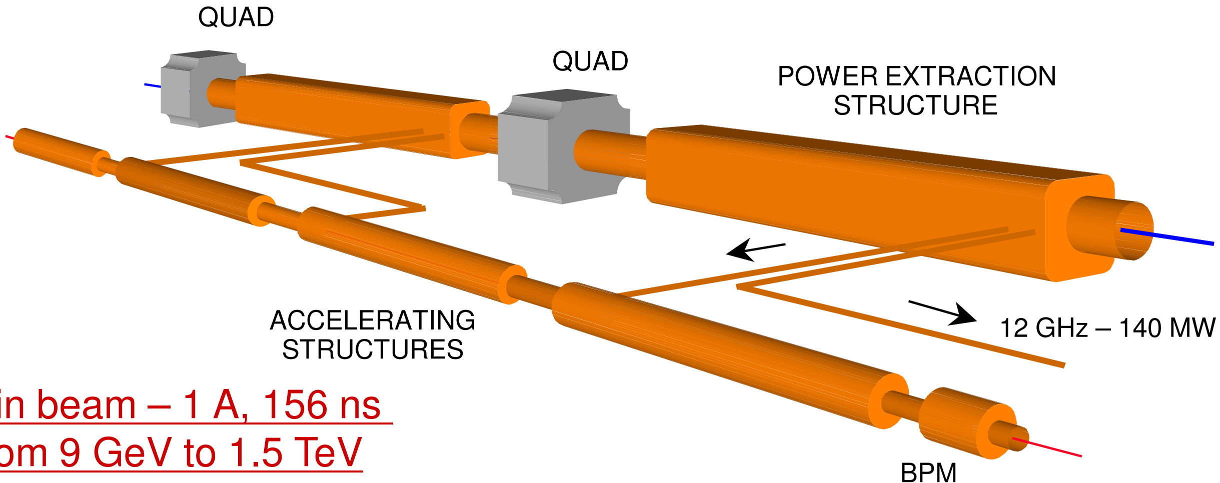
CLIC – basic features

- 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





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

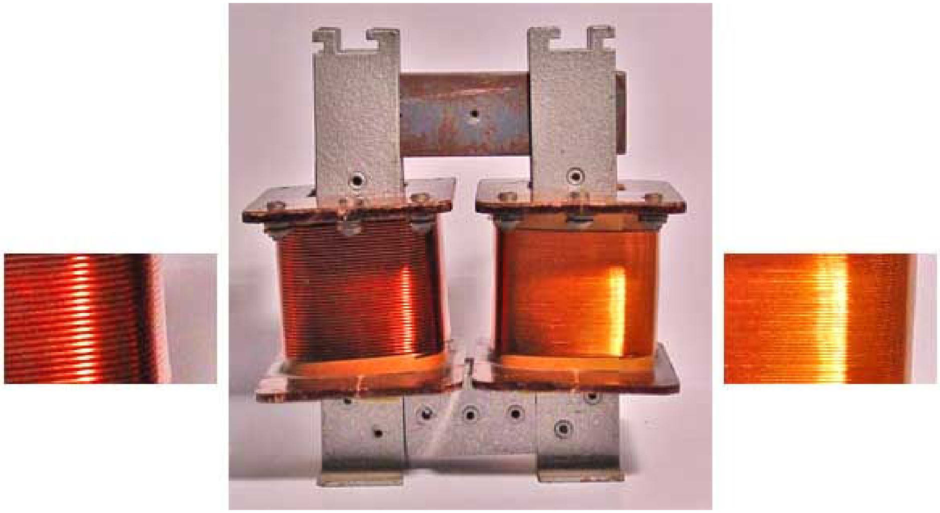
Main beam – 1 A, 156 ns
from 9 GeV to 1.5 TeV

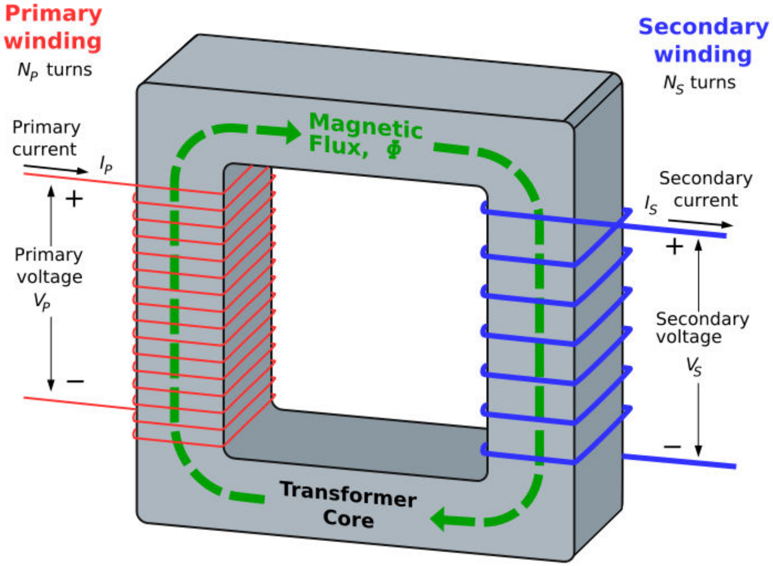
CLIC - a big transformer

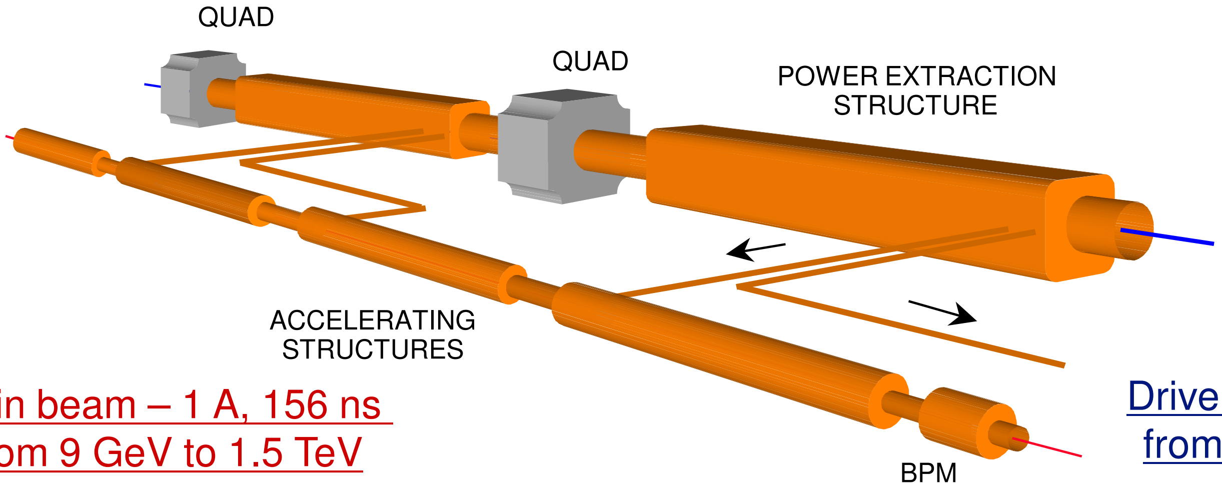
- Like a HV transformer:
  input: low voltage – high current
  output: high voltage – low current

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

- Transformer ‘core’:
  waveguides with RF waves





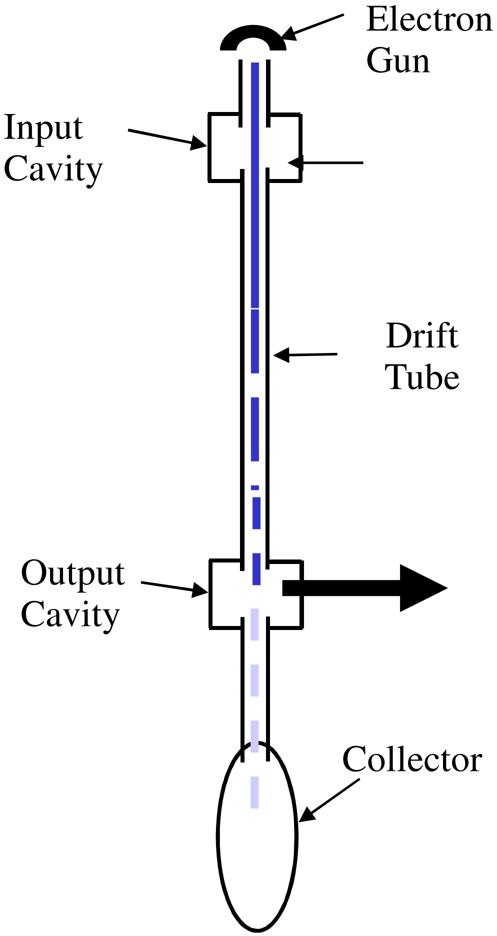


Main beam – 1 A, 156 ns
from 9 GeV to 1.5 TeV

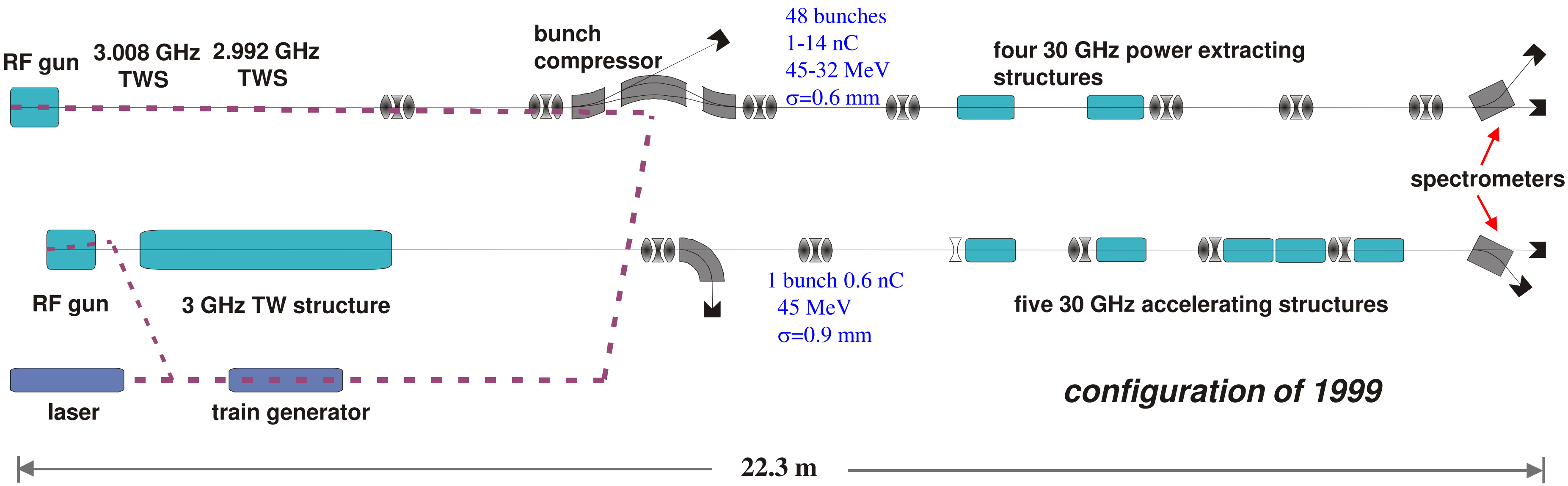
Drive beam - 101 A, 240 ns
from 2.4 GeV to 240 MeV

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



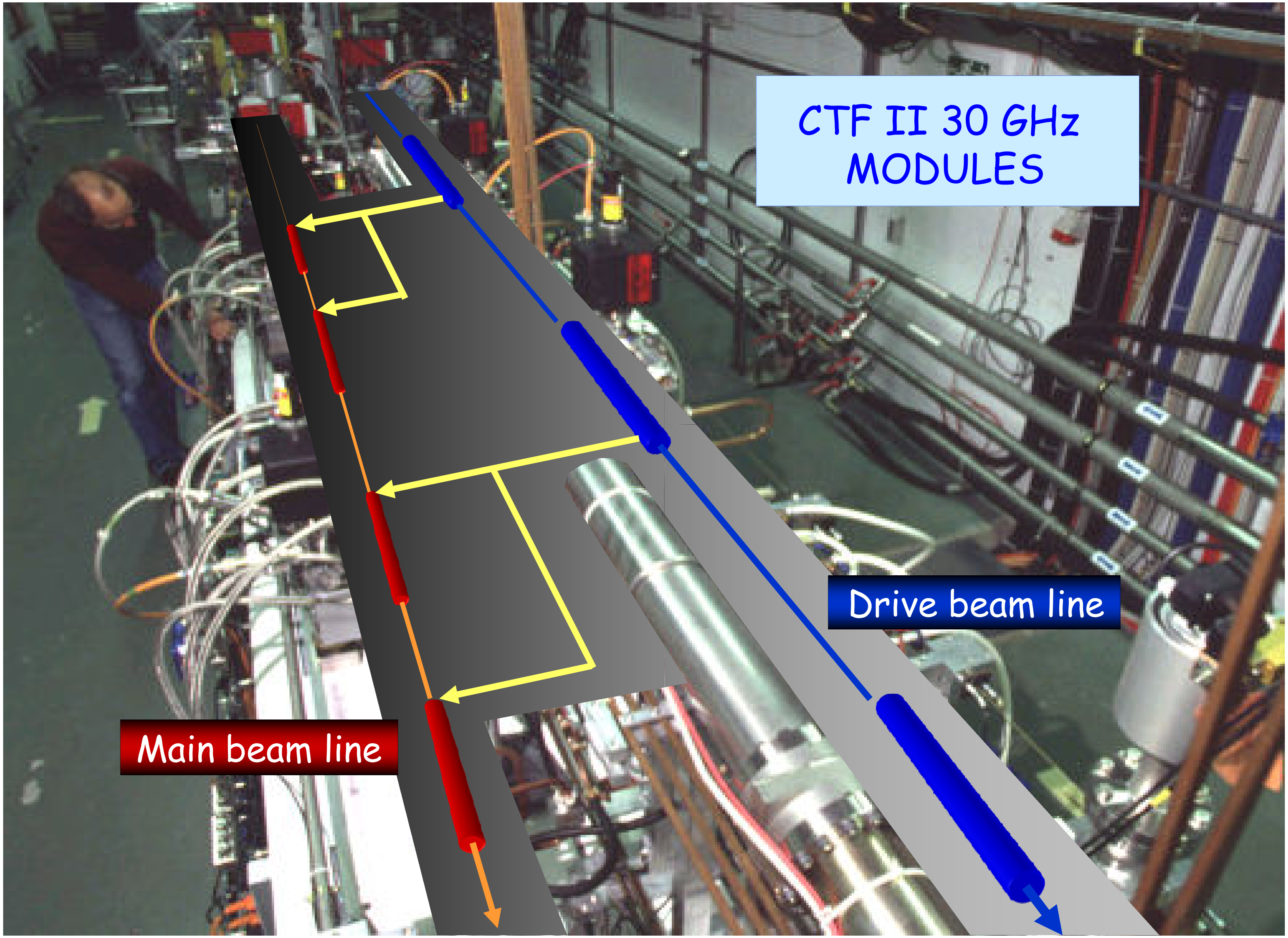
CLIC Test Facility CTF II



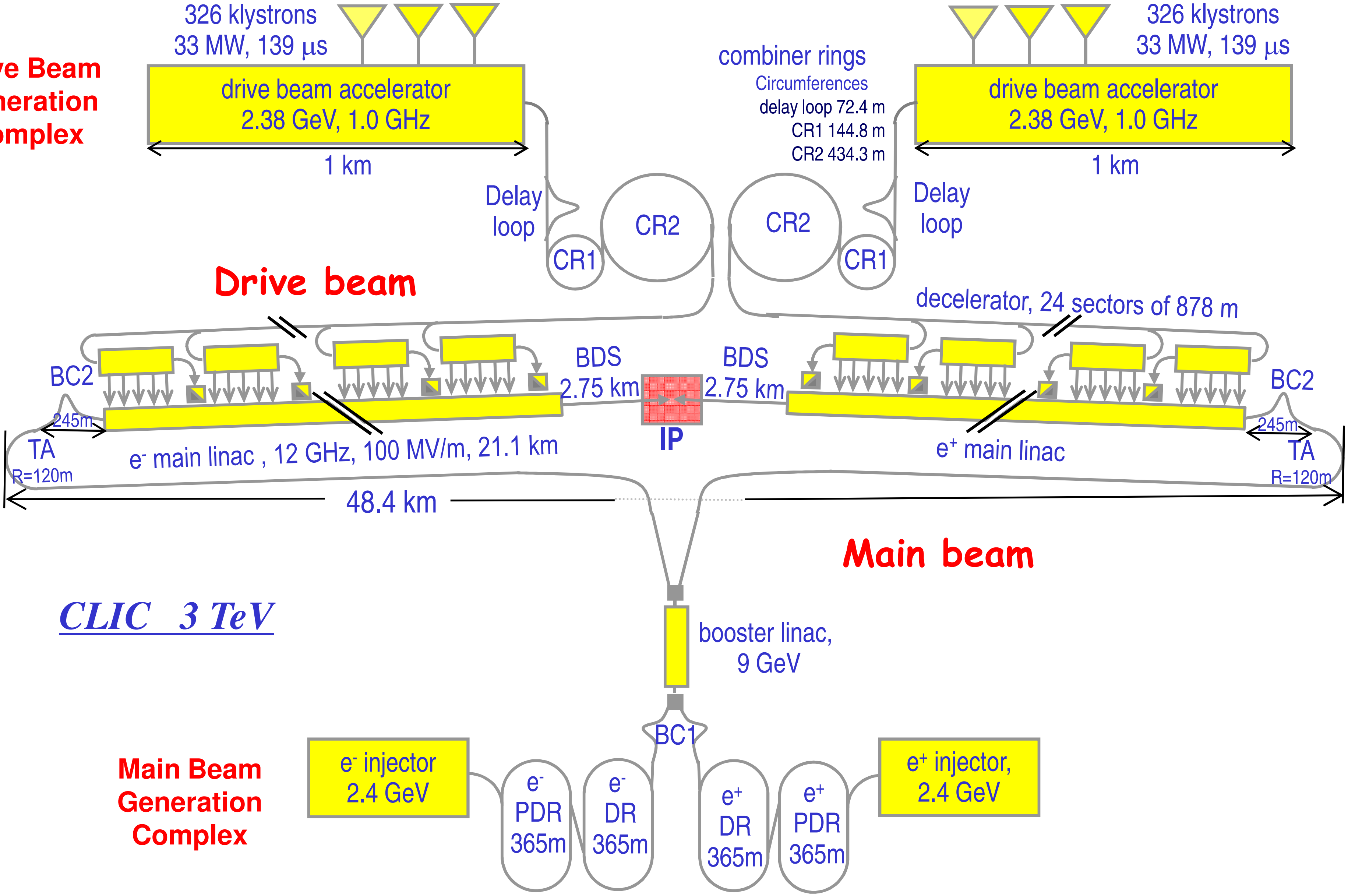
Dismantled in 2002, after having achieved its goals :

- 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



Drive Beam Generation Complex

326 klystrons
33 MW, 139 μs

drive beam accelerator
2.38 GeV, 1.0 GHz

1 km

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combiner rings
Circumferences
delay loop 72.4 m
CR1 144.8 m
CR2 434.3 m

Delay loop

CR1

CR2

CR2

CR1

Delay loop

Drive beam

decelerator, 24 sectors of 878 m

BC2

BDS
2.75 km

BDS
2.75 km

BC2

245m

245m

TA
R=120m

e^- main linac , 12 GHz, 100 MV/m, 21.1 km

IP

e^+ main linac

TA
R=120m

48.4 km

Main beam

CLIC 3 TeV

booster linac,
9 GeV

BC1

Main Beam Generation Complex

e^- injector
2.4 GeV

e^- PDR 365m

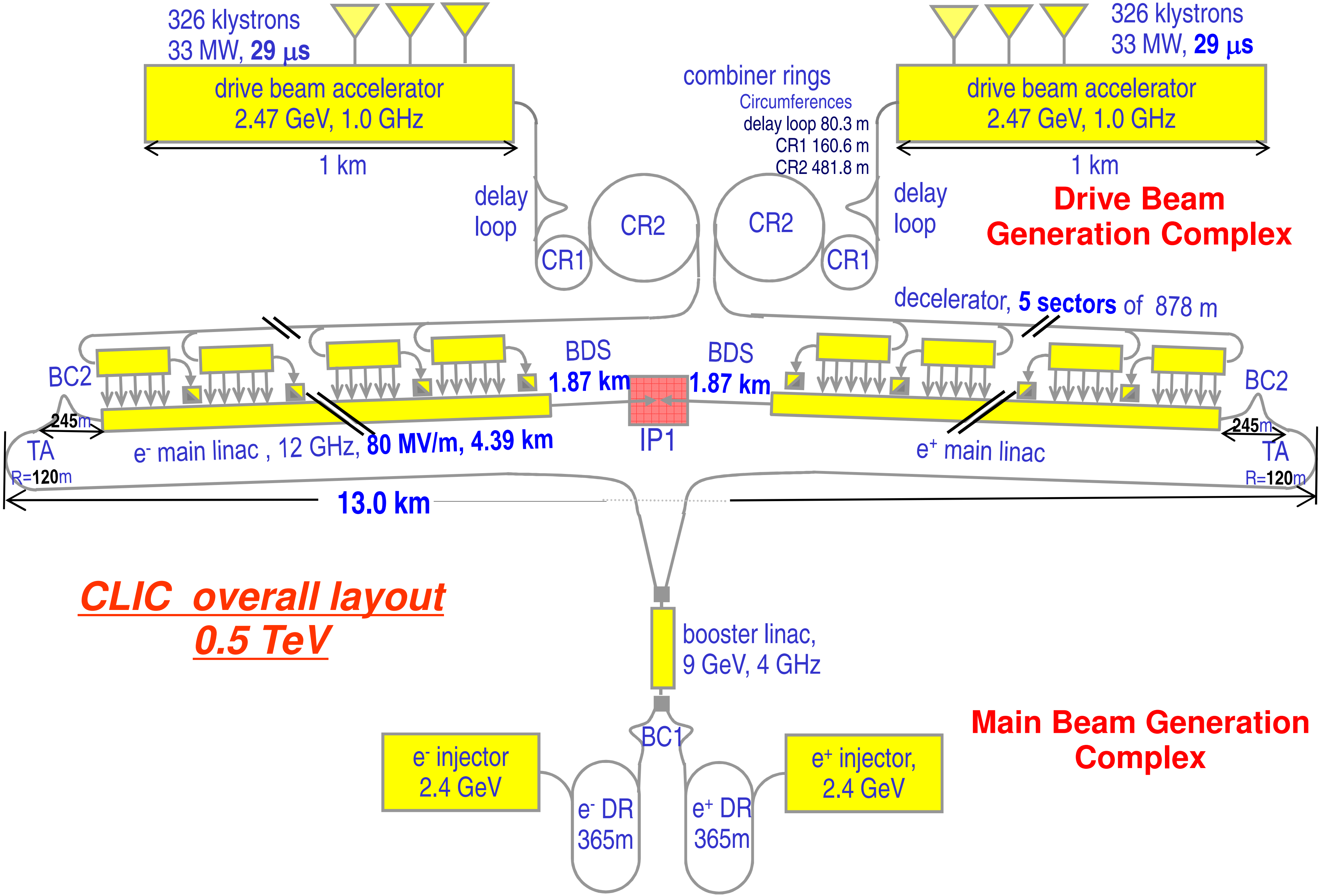
e^- DR 365m

e^+ DR 365m

e^+ PDR 365m

e^+ injector,
2.4 GeV

CLIC Layout for 0.5 TeV



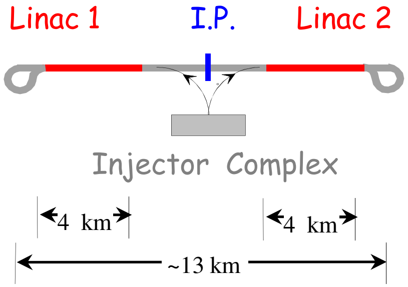
Drive Beam Generation Complex

CLIC overall layout 0.5 TeV

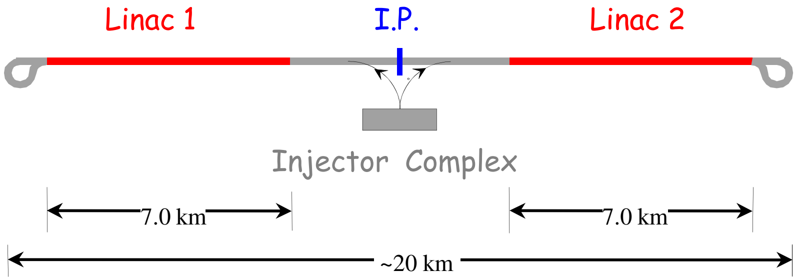
Main Beam Generation Complex

CLIC Layout at various energies

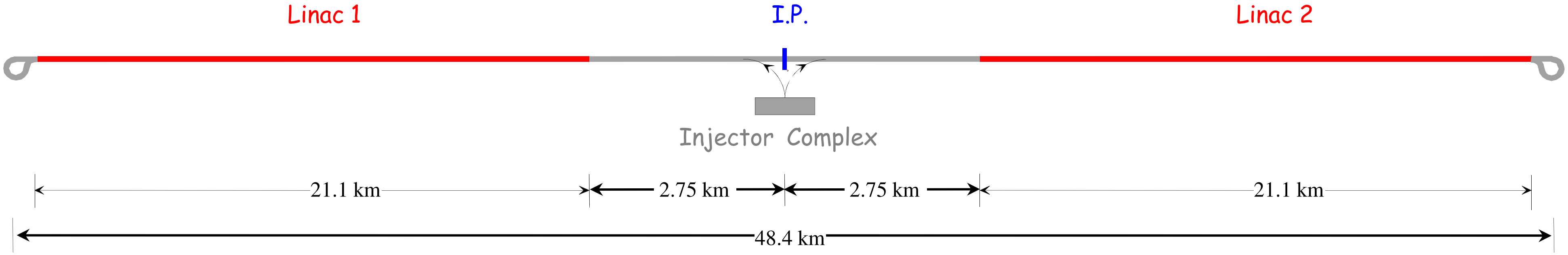
0.5 TeV Stage



1 TeV Stage

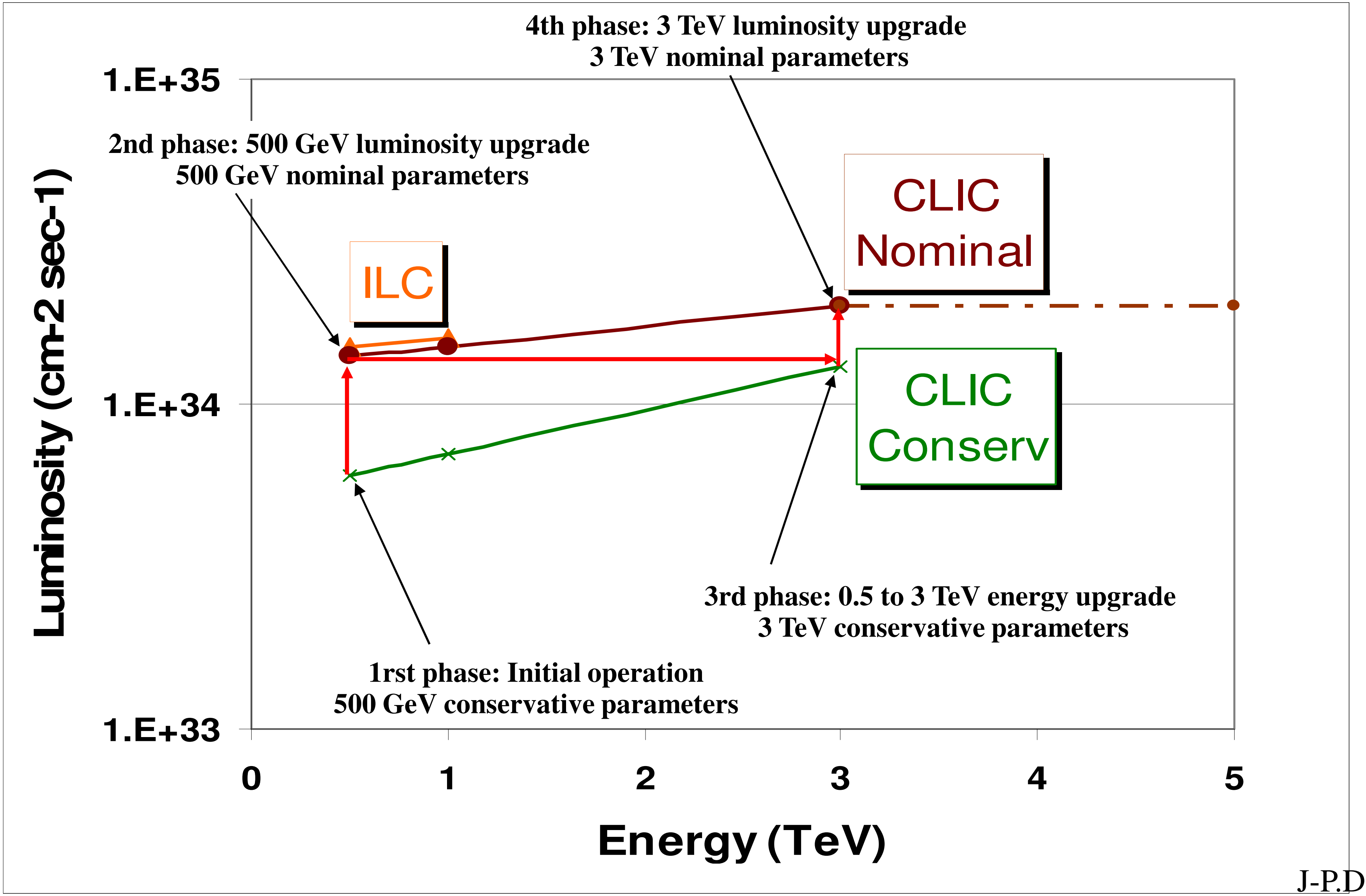


3 TeV Stage



CLIC Parameters and upgrade scenario

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



J-P.Delahaye

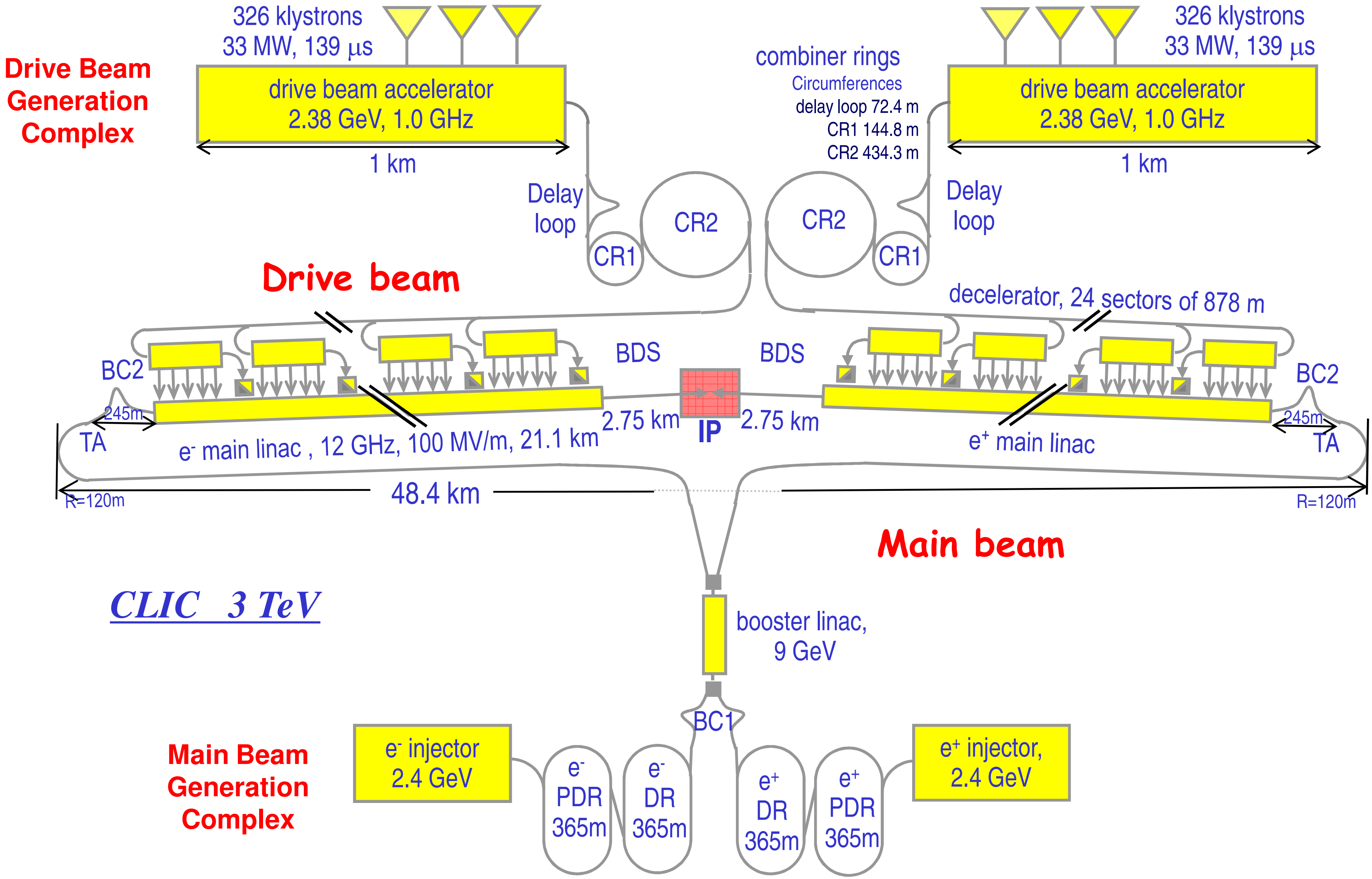
CLIC main parameters

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	$2.0\ (1.3)\cdot 10^{34}$	$2.0\ (1.5)\cdot 10^{34}$	$0.9\ (0.6)\cdot 10^{34}$	$2.3\ (1.4)\cdot 10^{34}$
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



Drive Beam Generation Complex

326 klystrons
33 MW, 139 μs

drive beam accelerator
2.38 GeV, 1.0 GHz

1 km

Delay loop

CR1

CR2

combiner rings
Circumferences
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Drive beam

decelerator, 24 sectors of 878 m

BC2

BDS

BDS

BC2

245m

TA

e^- main linac , 12 GHz, 100 MV/m, 21.1 km

2.75 km

IP

2.75 km

e^+ main linac

245m

TA

R=120m

48.4 km

R=120m

Main beam

CLIC 3 TeV

booster linac,
9 GeV

BC1

Main Beam Generation Complex

e^- injector
2.4 GeV

e^- PDR 365m

e^- DR 365m

e^+ DR 365m

e^+ PDR 365m

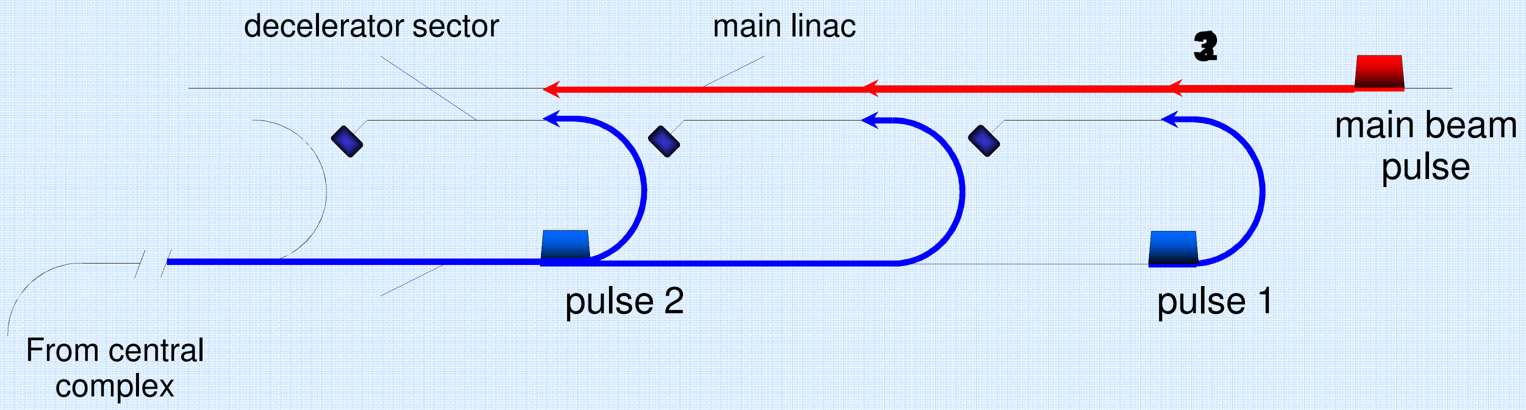
e^+ injector,
2.4 GeV

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 ones are used.

Each one feed a ~800 m long sector of TBA.

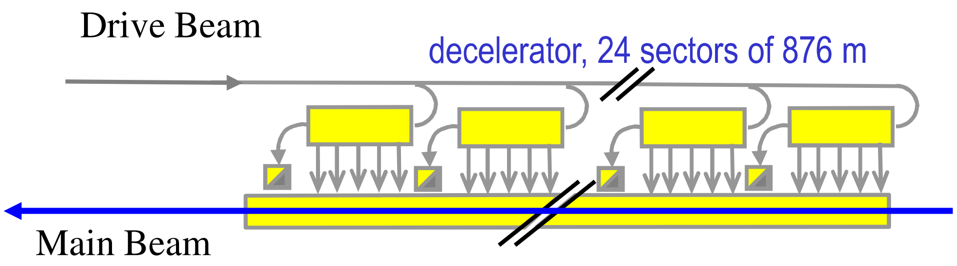


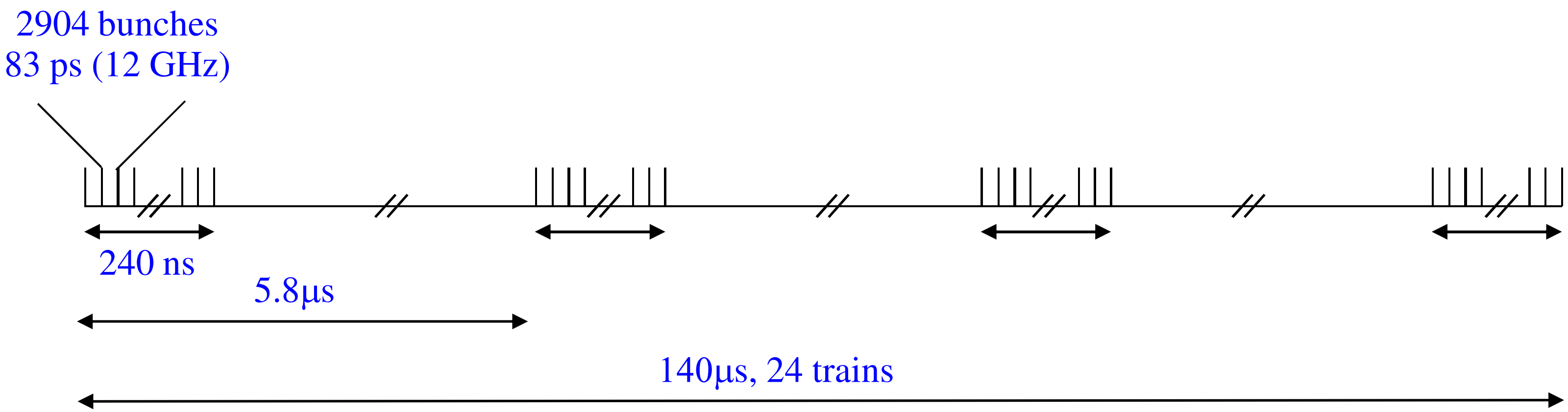
(DLDS-like system)

Counter-flow distribution allows to power different sectors of the main linac with different time bins of a single long electron pulse.
The distance between pulses is $2\ L_S = 2\ L_{main}/N_S$. The initial drive beam pulse length is equal to $2\ L_{main} = 140\ \mu s/c$.

R.Corsini

Drive beam time structure



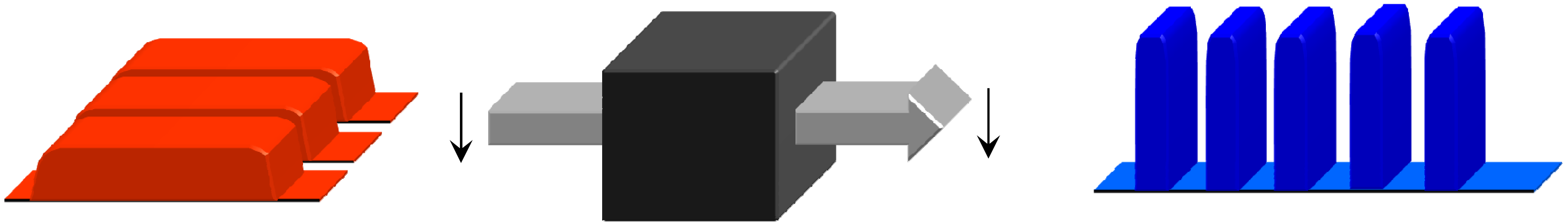


Bunch charge: 8.4 nC, Current in train: 100 A

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

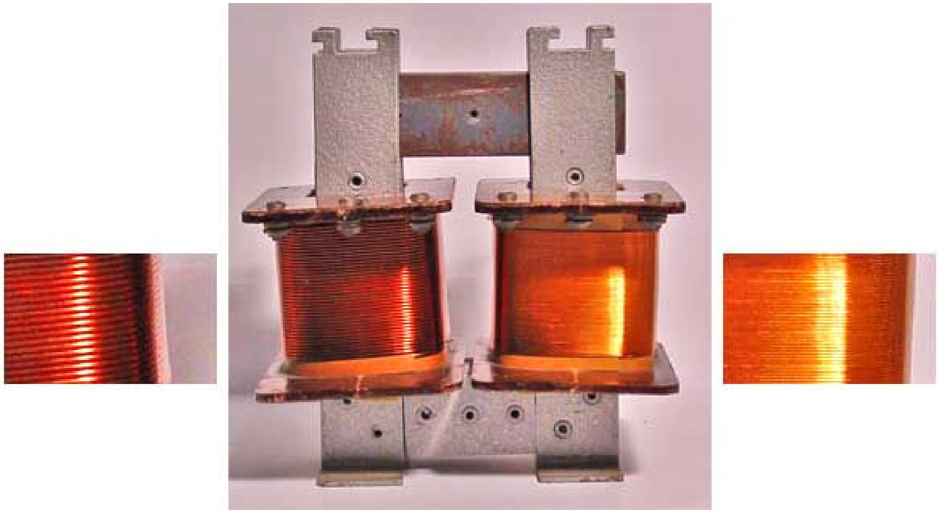
Long RF Pulses
P_0 , ν_0 , τ_0

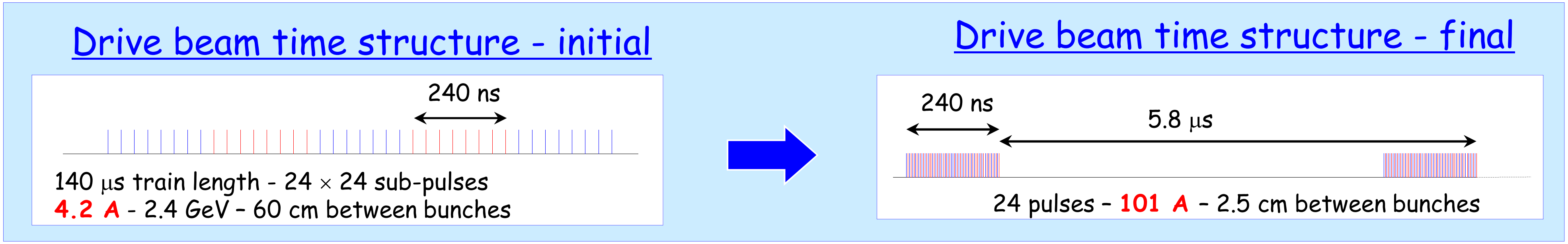
Electron beam manipulation
Power compression
Frequency multiplication

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

140 μs train length - 24 × 24 sub-pulses

4.2 A - 2.4 GeV – 60 cm between bunches

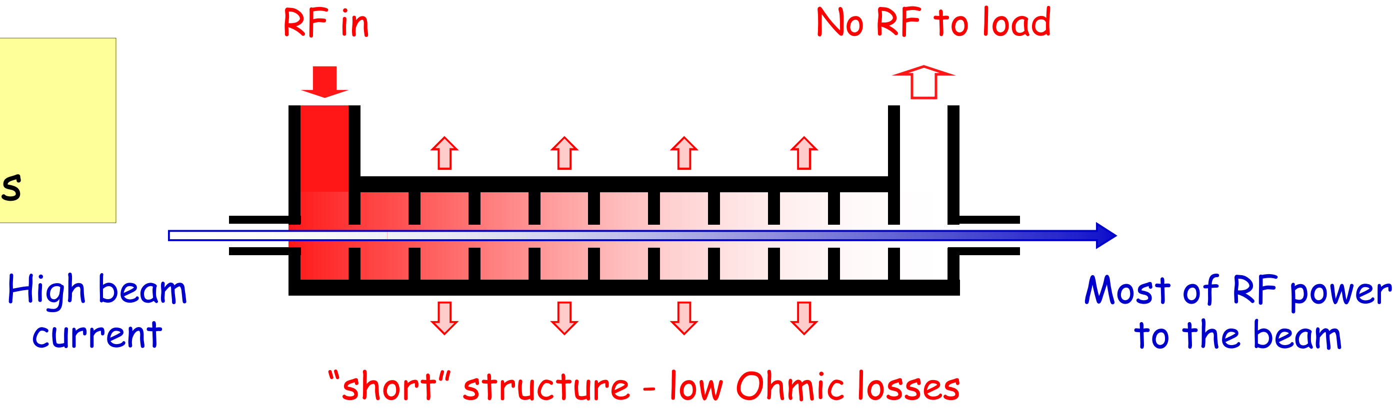
Drive beam time structure - final

24 pulses – 101 A – 2.5 cm between bunches

Drive beam generation basics

- Efficient acceleration

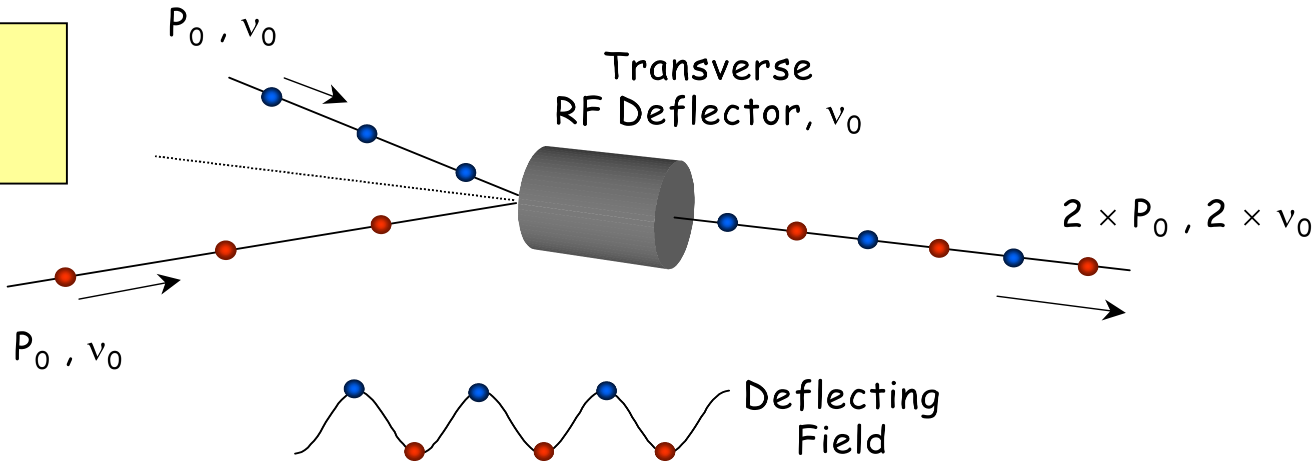
Full beam-loading
acceleration in
traveling wave sections



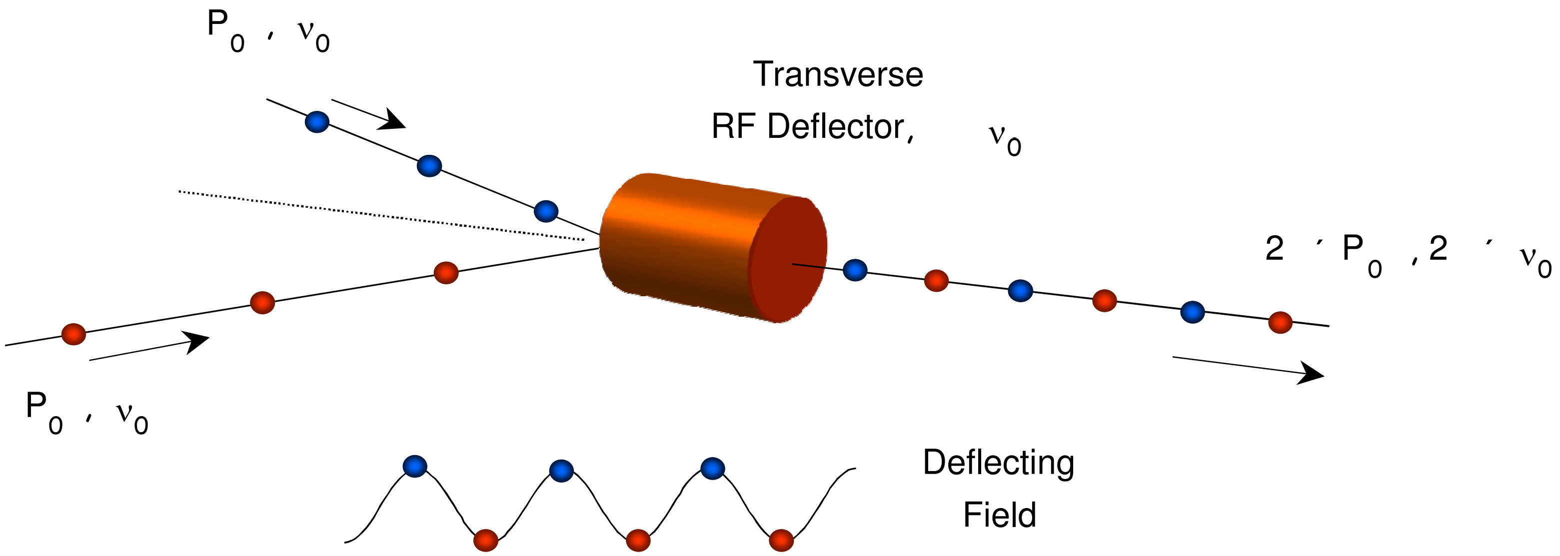
- Frequency multiplication

Beam combination/separation

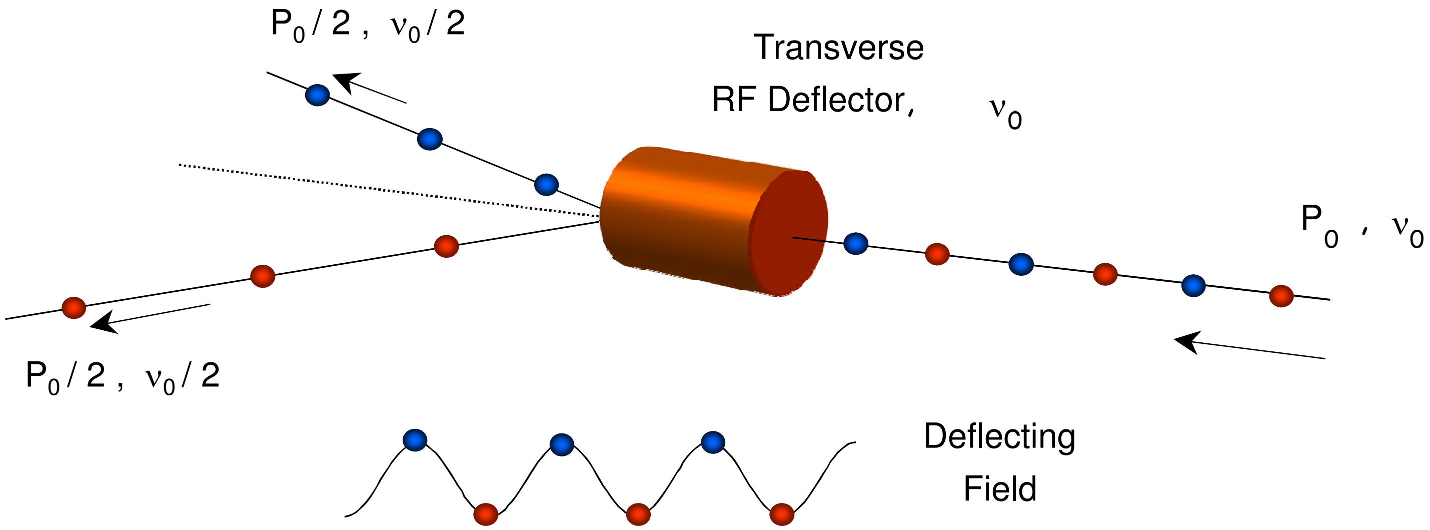
by transverse RF deflectors



Beam combination by RF deflectors

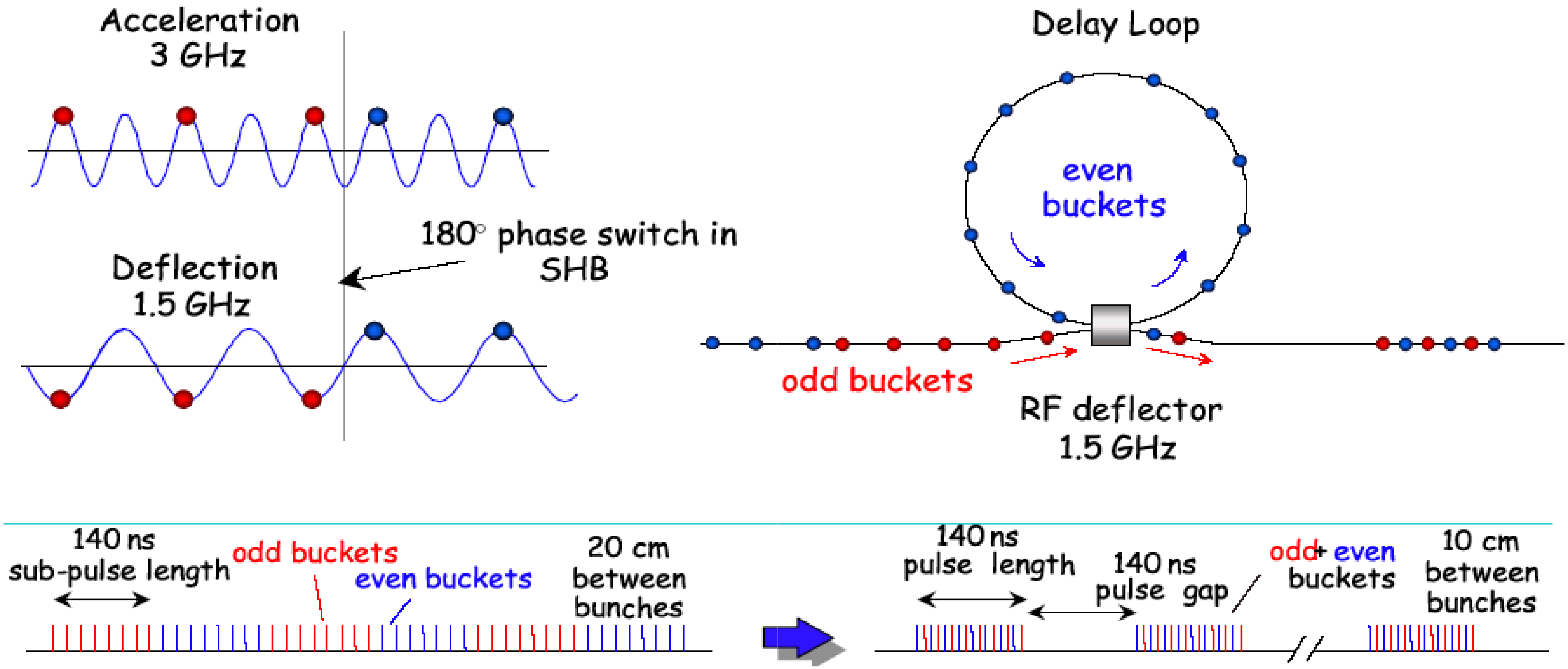


Beam separation by RF deflectors



Delay Loop Principle

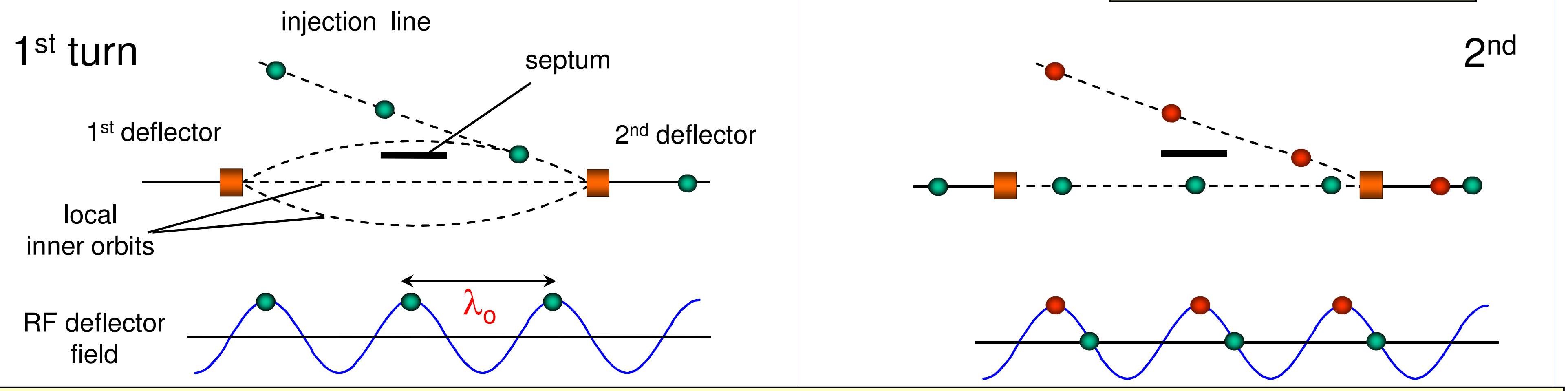
- **double repetition frequency and current**
- parts of bunch train delayed in loop
- RF deflector combines the bunches (f_{defl}=bunch rep. frequency)
- Path length corresponds to beam sub-pulse length



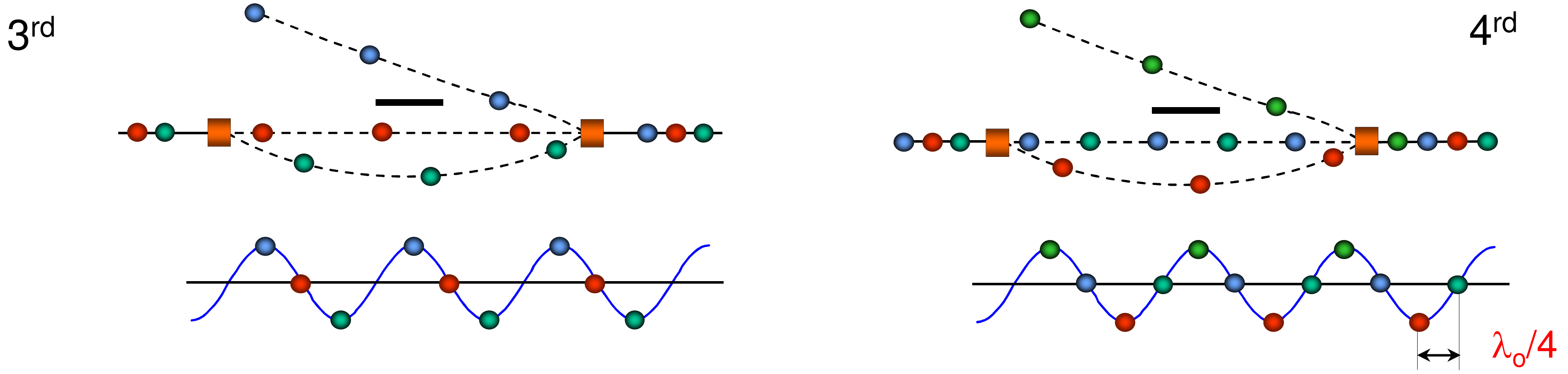
RF injection in combiner ring

- combination factors up to 5 reachable in a ring

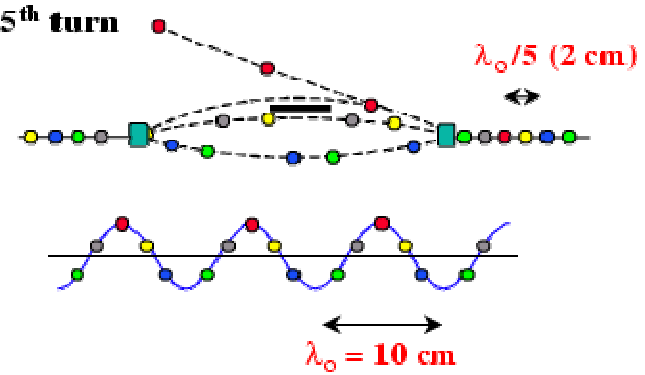
$$C_{ring} = (n + ¼)\,\lambda$$



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

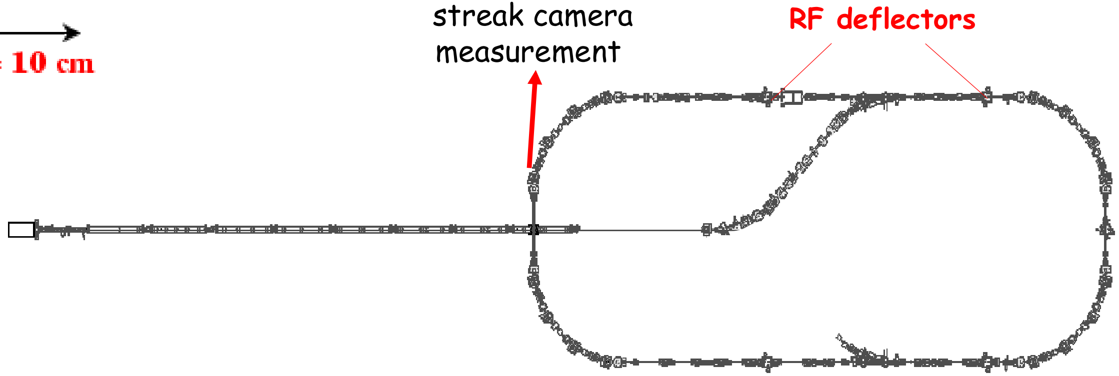


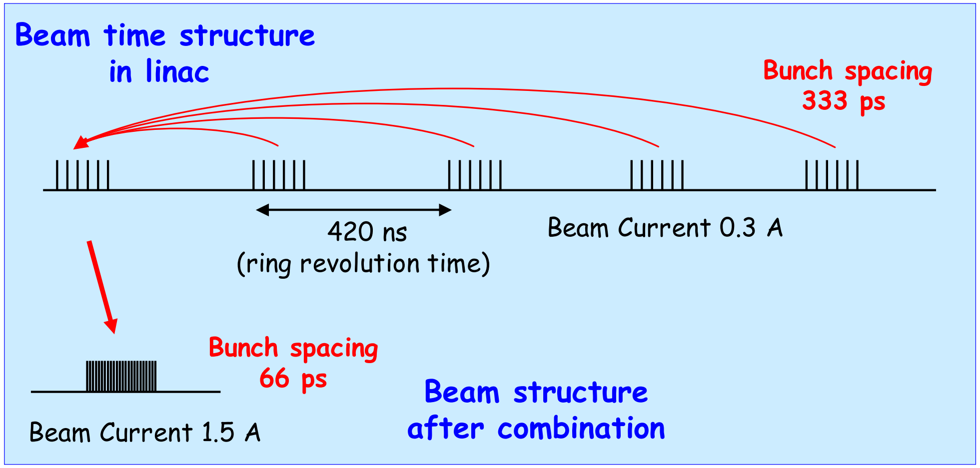
Demonstration of frequency multiplication



CTF3 - PRELIMINARY PHASE 2001/2002

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





Beam time structure in linac

Bunch spacing 333 ps

420 ns (ring revolution time)

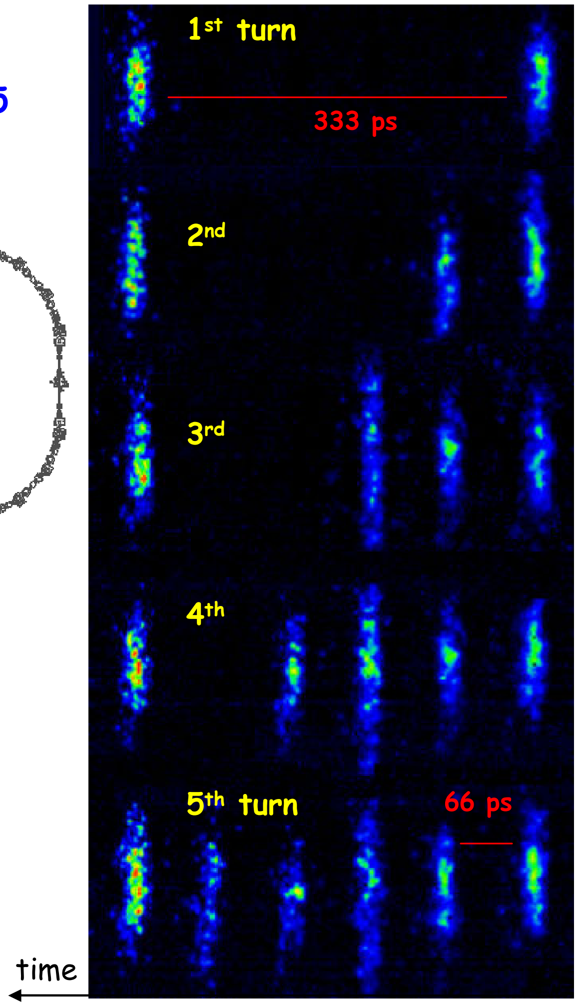
Beam Current 0.3 A

Bunch spacing 66 ps

Beam Current 1.5 A

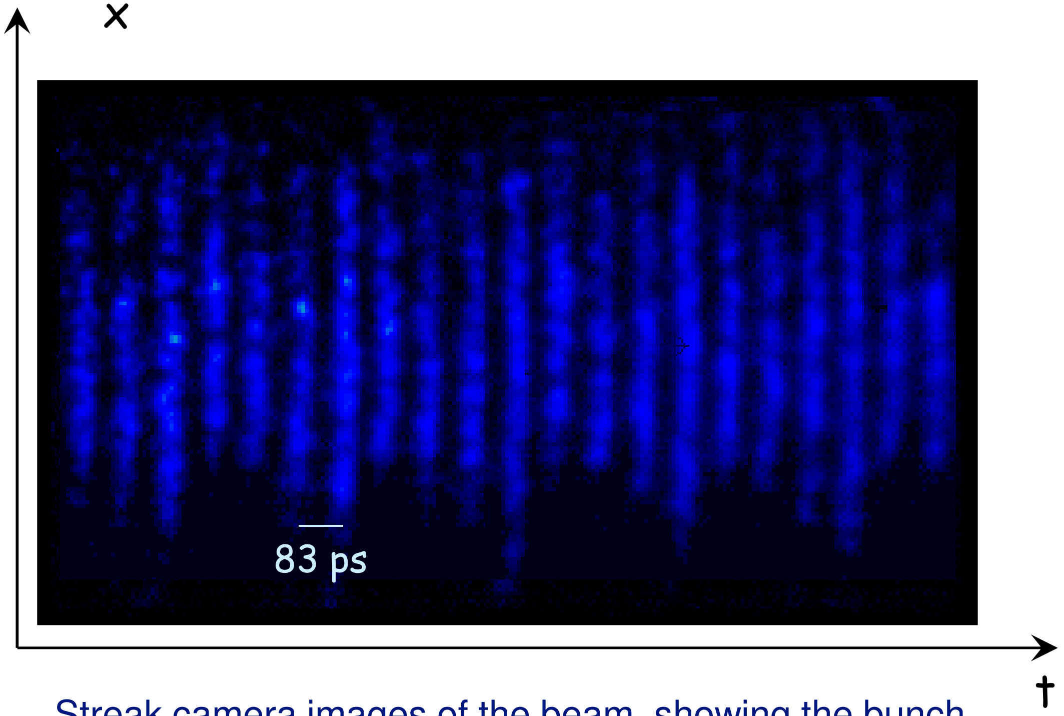
Beam structure after combination

Streak camera image of beam time structure evolution



CTF3 preliminary phase (2001-2002)

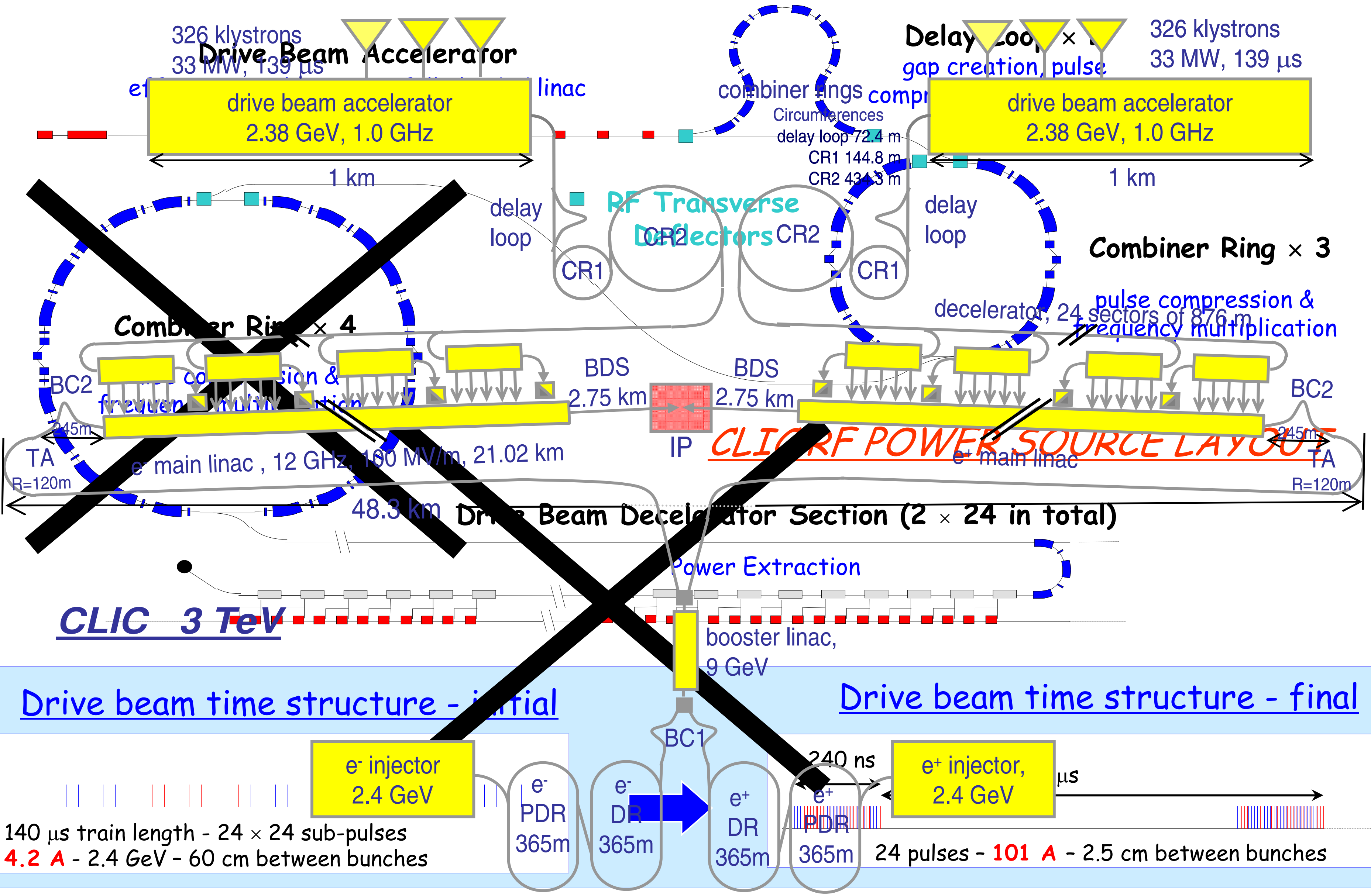
RF injection in combiner ring



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

CLIC Drive Beam generation



Drive beam time structure - initial

140 μs train length - 24 × 24 sub-pulses

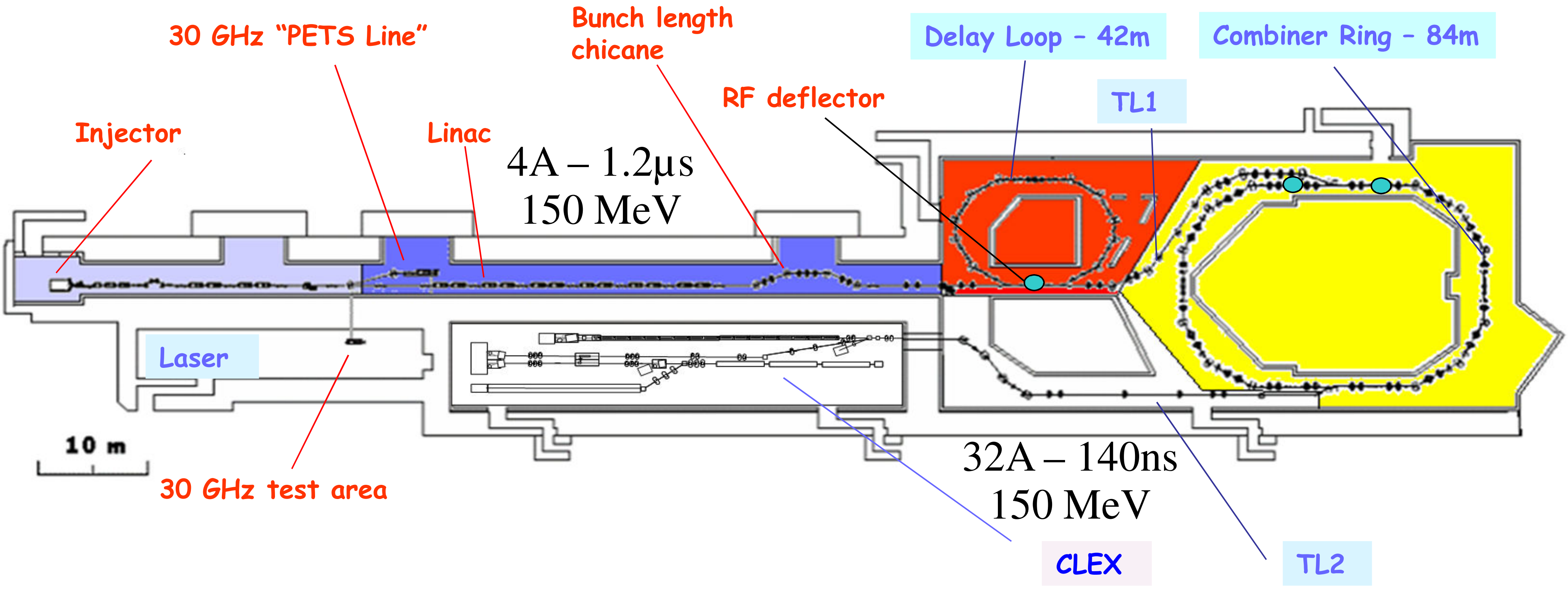
4.2 A - 2.4 GeV – 60 cm between bunches

Drive beam time structure - final

24 pulses – 101 A – 2.5 cm between bunches

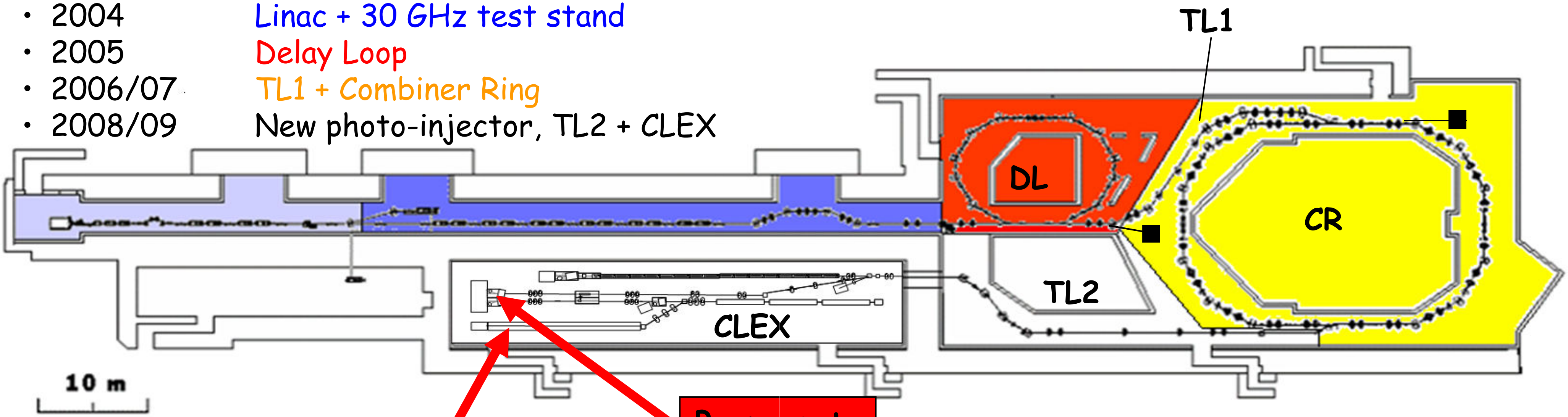
CTF 3

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

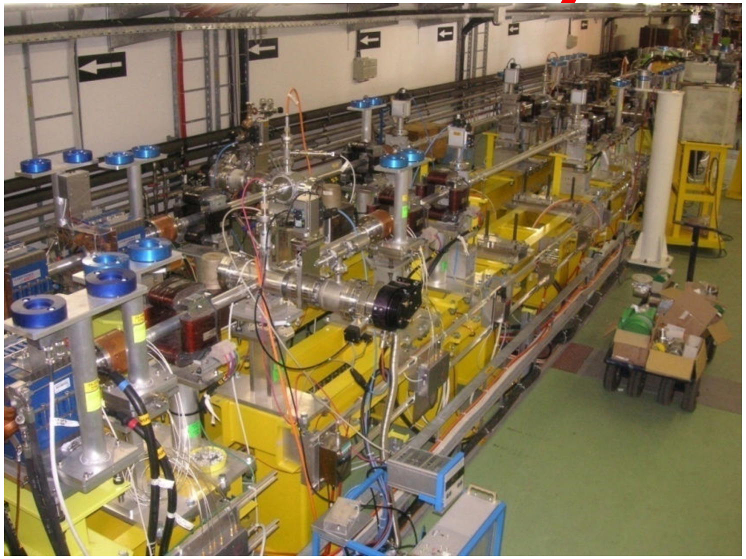


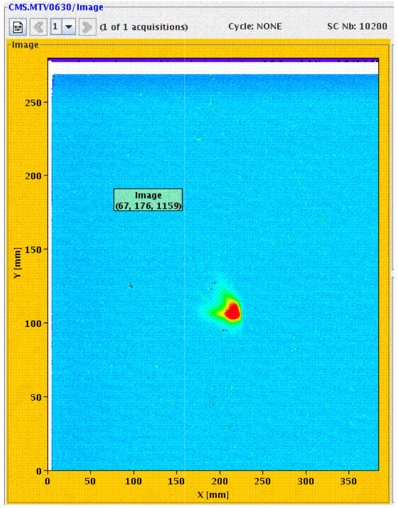
CTF3 Evolution

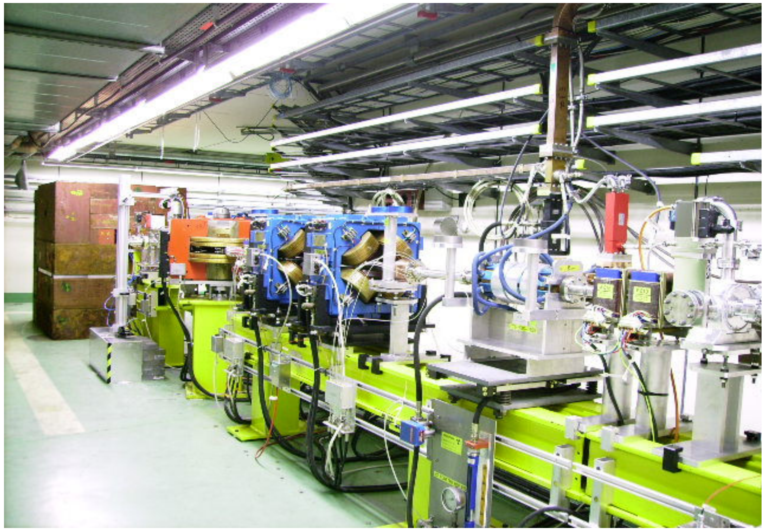
2003	Injector + part of linac
2004	Linac + 30 GHz test stand
2005	Delay Loop
2006/07	TL1 + Combiner Ring
2008/09	New photo-injector, TL2 + CLEX



Beam up to here





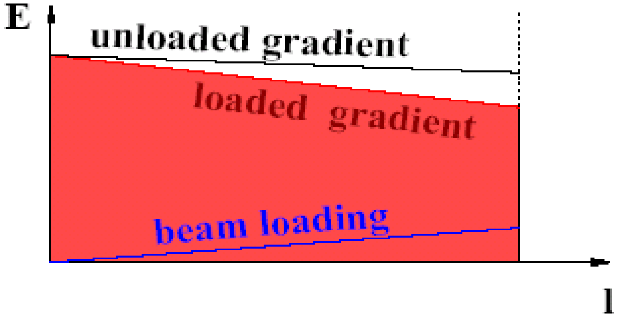


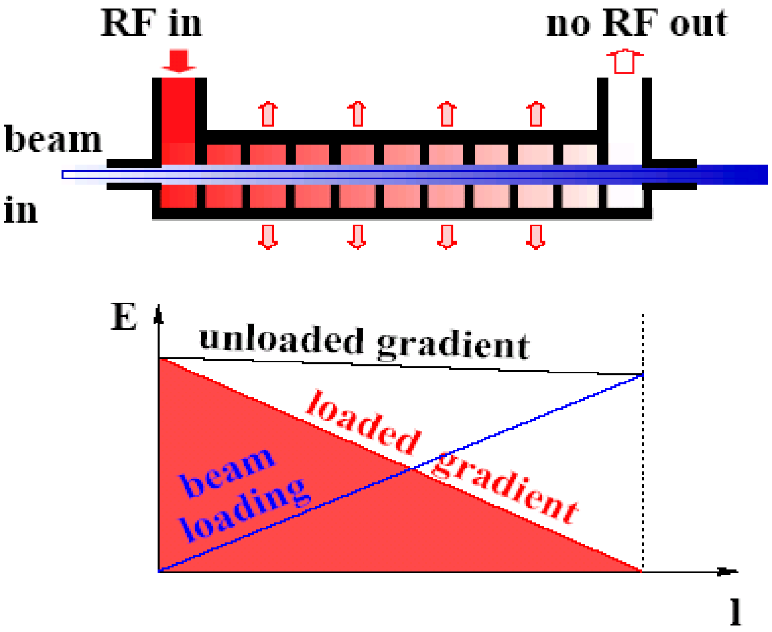
Fully loaded operation

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

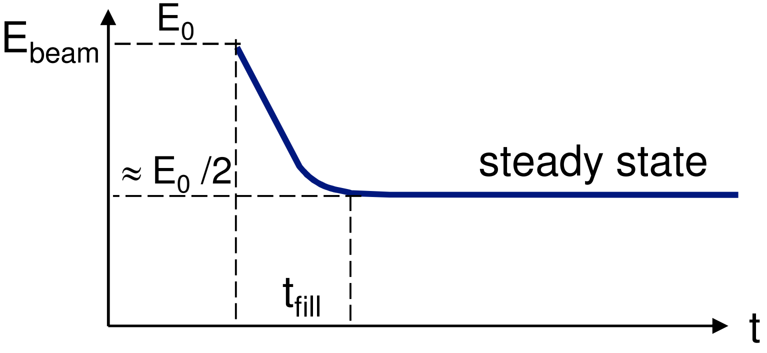
Fully loaded operation

- Disadvantage: any current variation changes energy gain

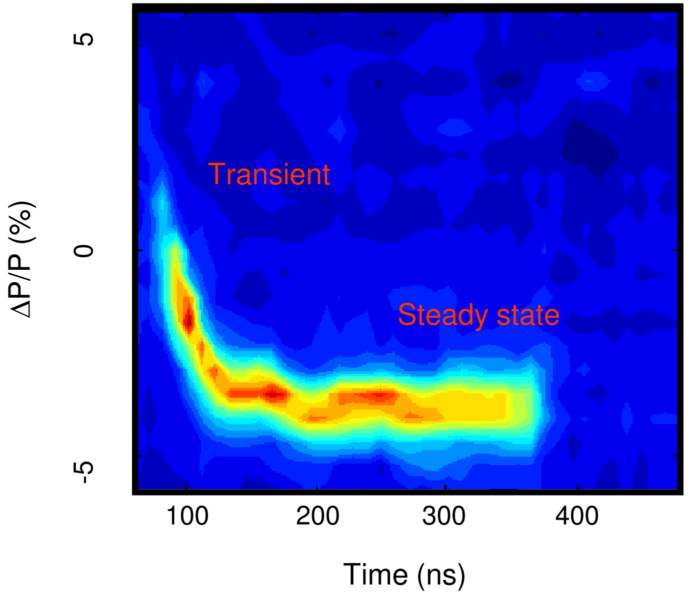
$$\frac{dV/V}{dI_{beam}/I_{beam}} = -\frac{I_{beam}}{I_{opt}}$$

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

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

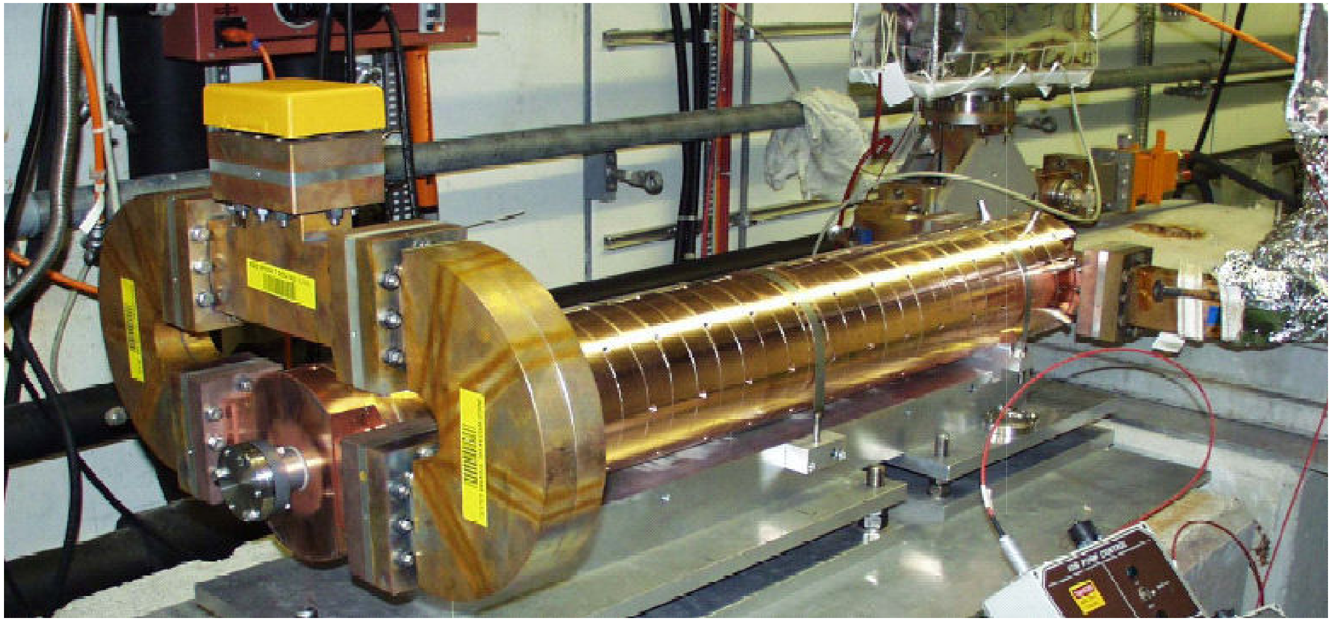


Time resolved beam energy spectrum measurement in CTF3

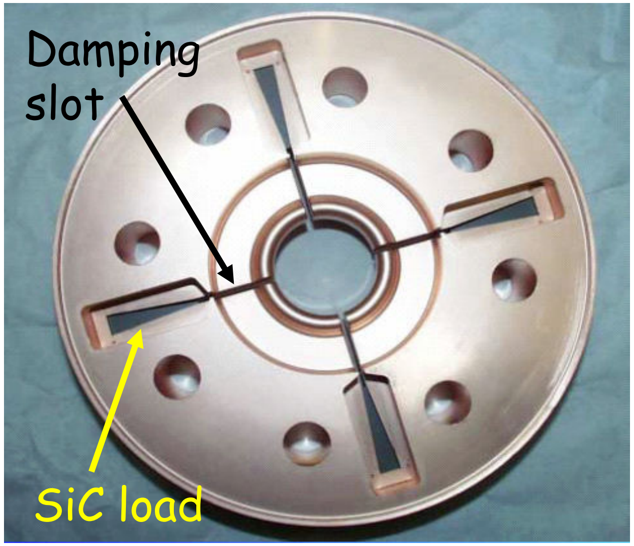


- Requires continuous bunch train

CTF3 linac acceleration structures

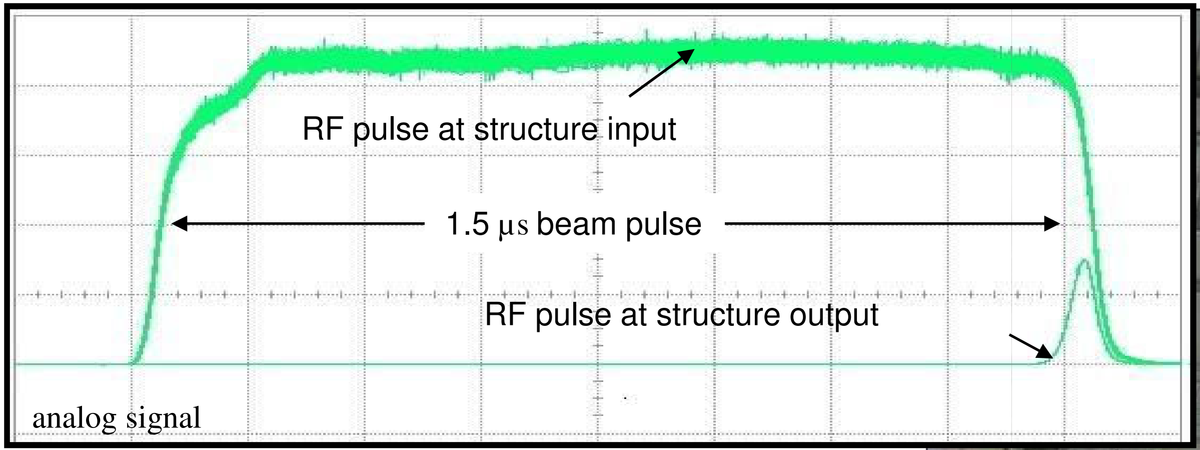


Dipole modes suppressed by slotted iris damping (first dipole's Q factor < 20) and HOM frequency detuning

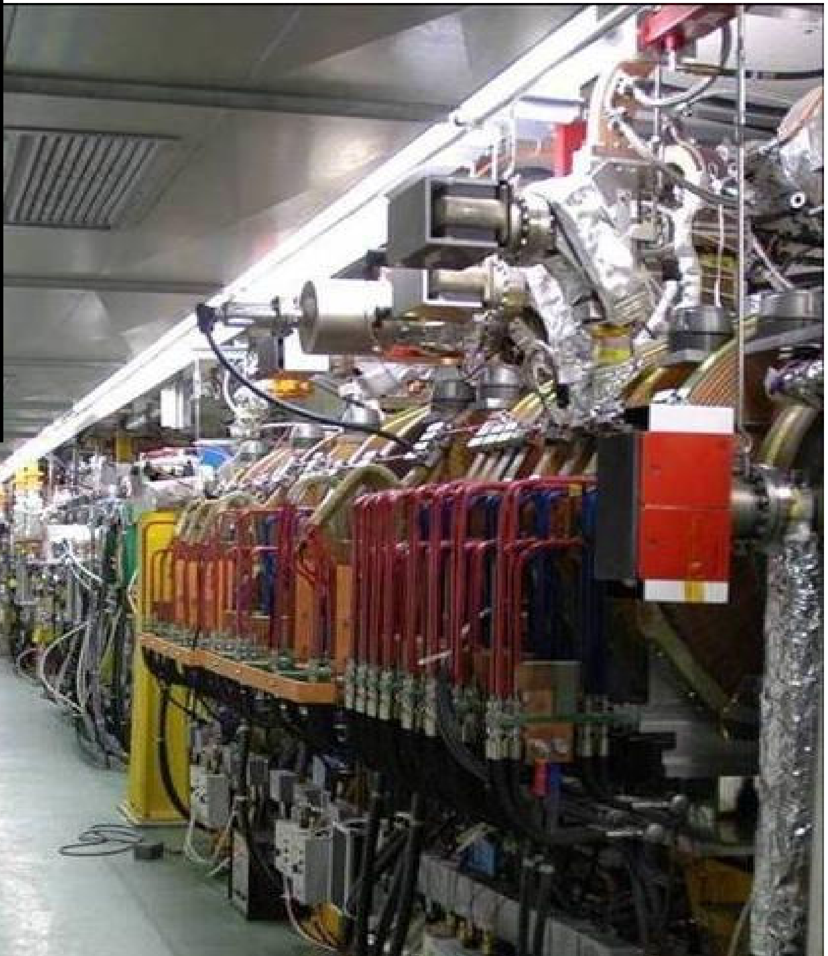


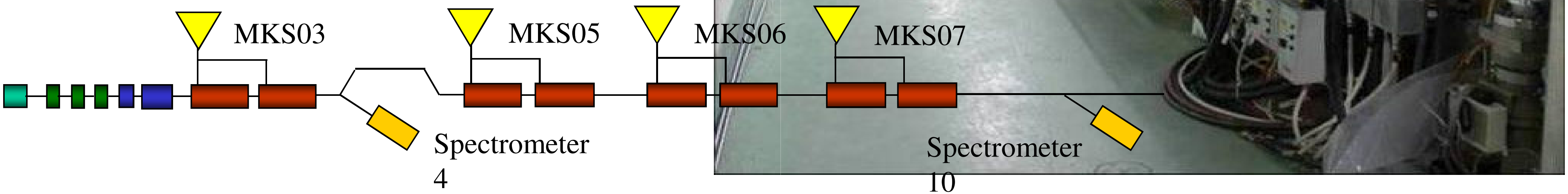
- 3 GHz 2π/3 traveling wave structure
- constant aperture
- slotted-iris damping + detuning with nose cones
- up to 4 A 1.4 µs beam pulse accelerated
  no sign of beam break-up

Full beam-loading acceleration in CTF3

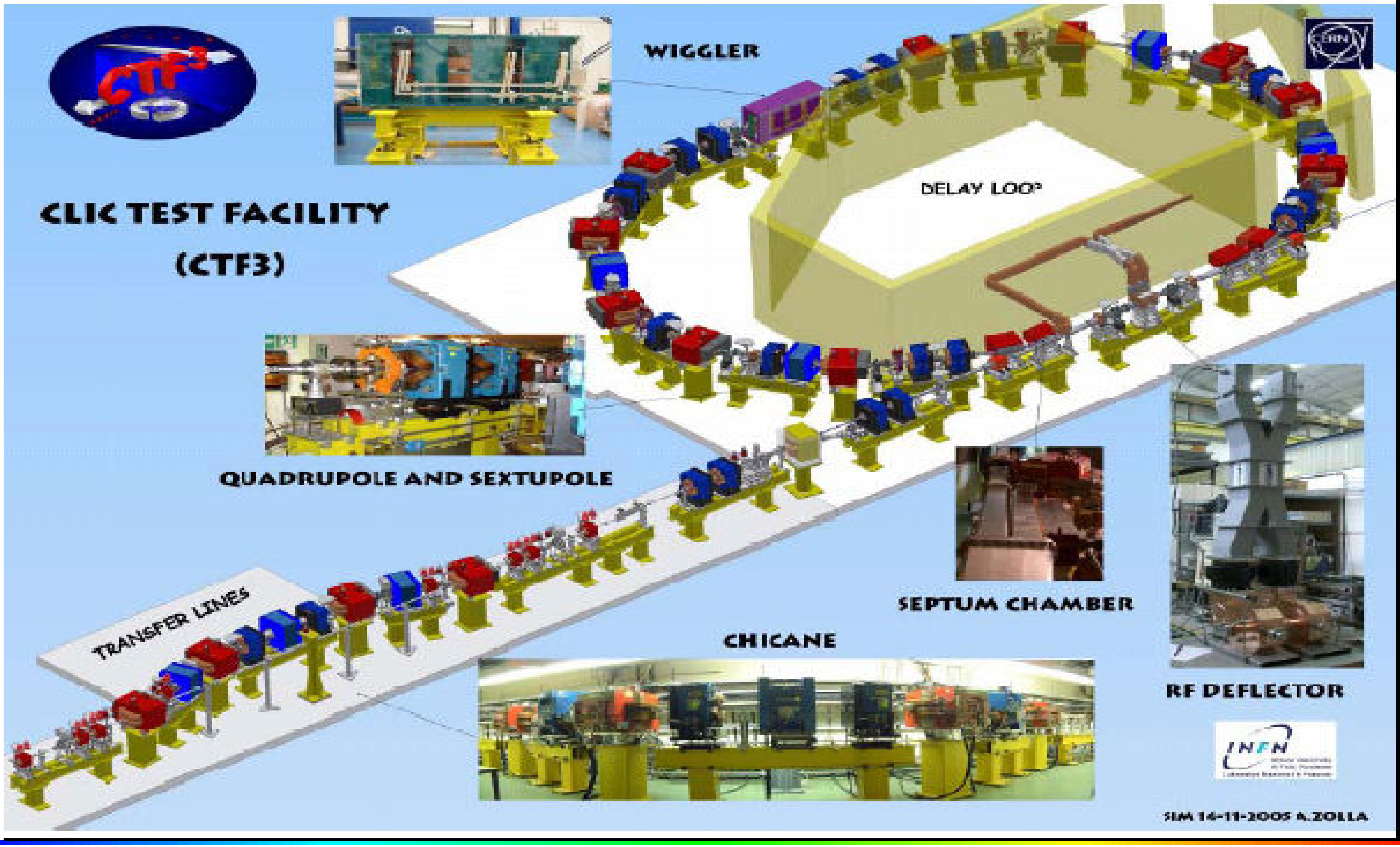


- Measured RF-to-beam efficiency 95.3%
- Theory 96%
(~ 4 % ohmic losses)

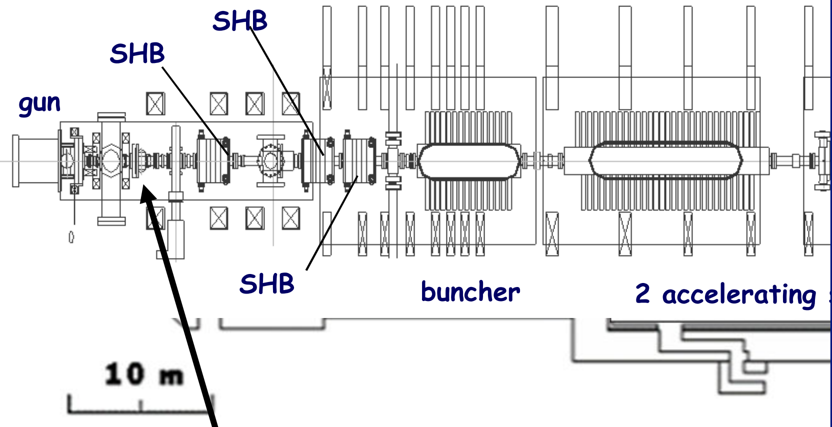


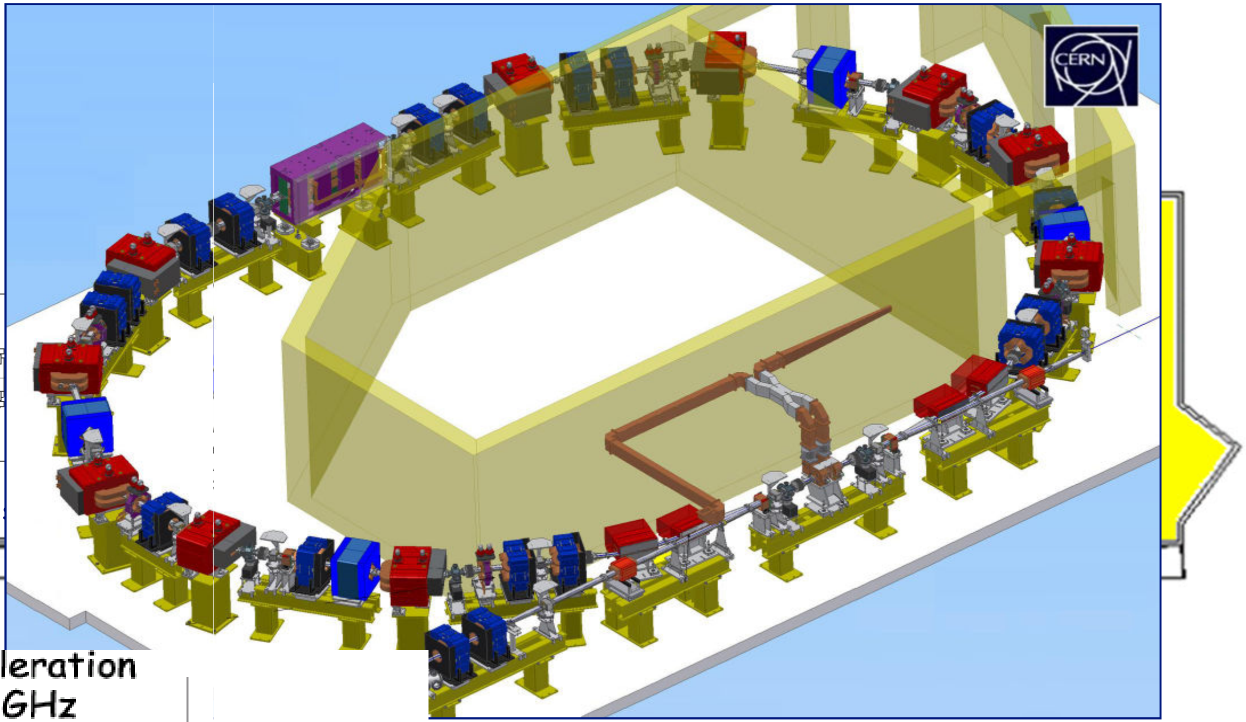


CTF3 Delay Loop

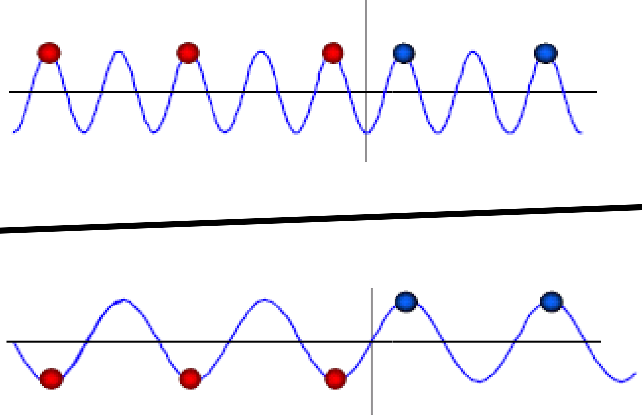


Delay Loop operation



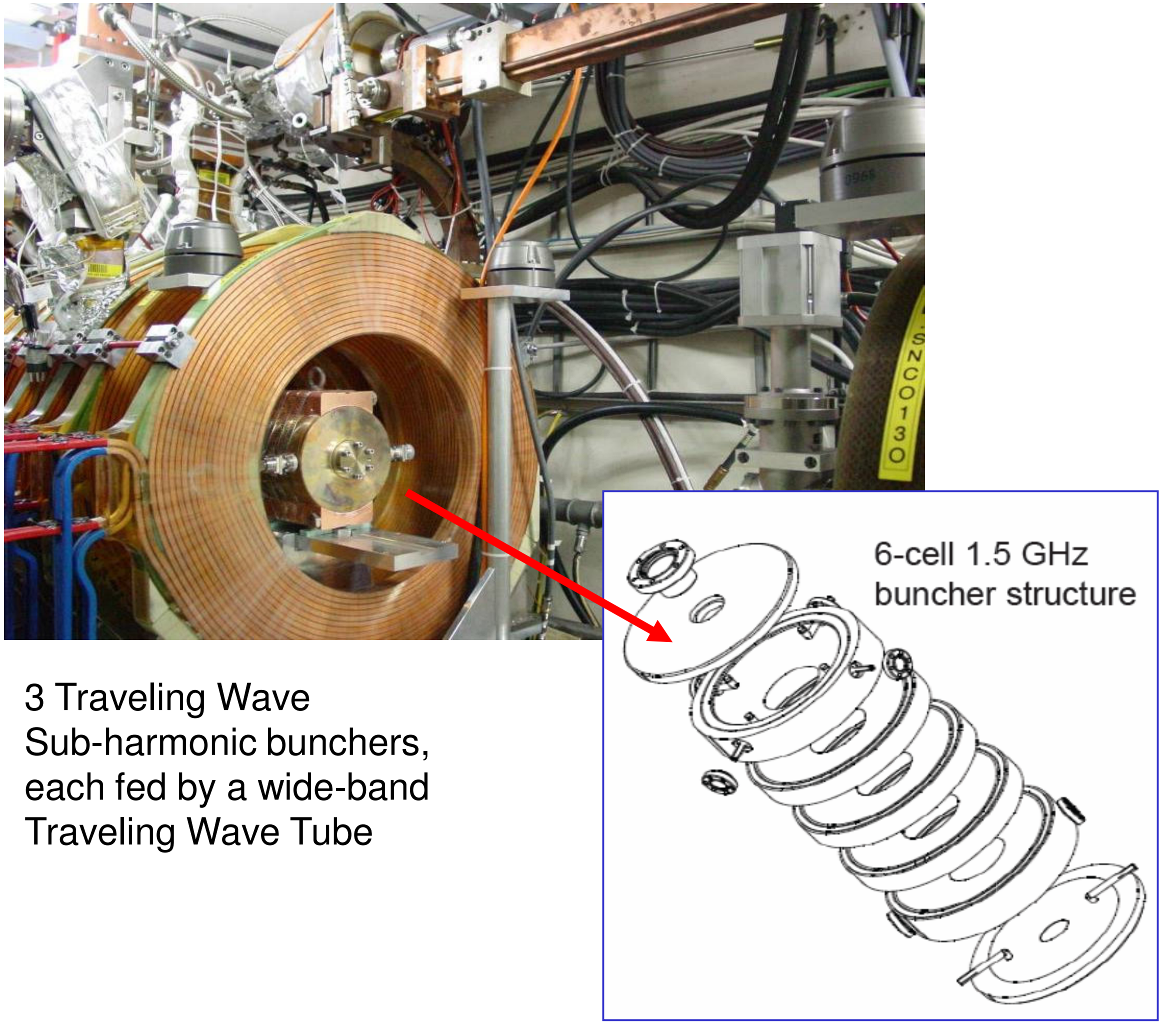


- 1.5 GHz sub-harm. bunching system
- 1.5 GHz RF deflector



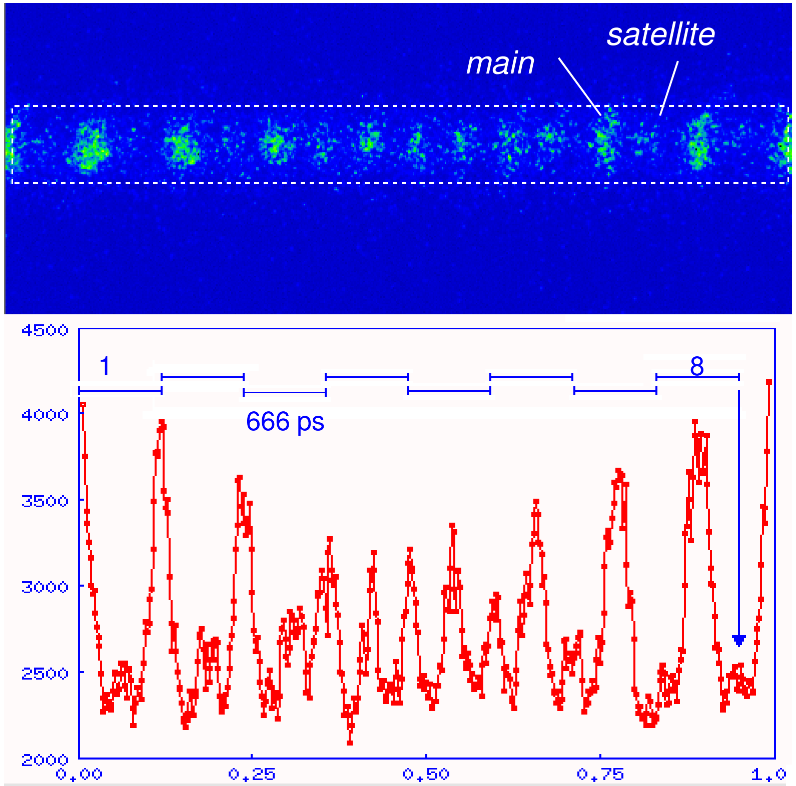
Sub-harmonic bunching system

Fast phase switch from SHB system (CTF3)



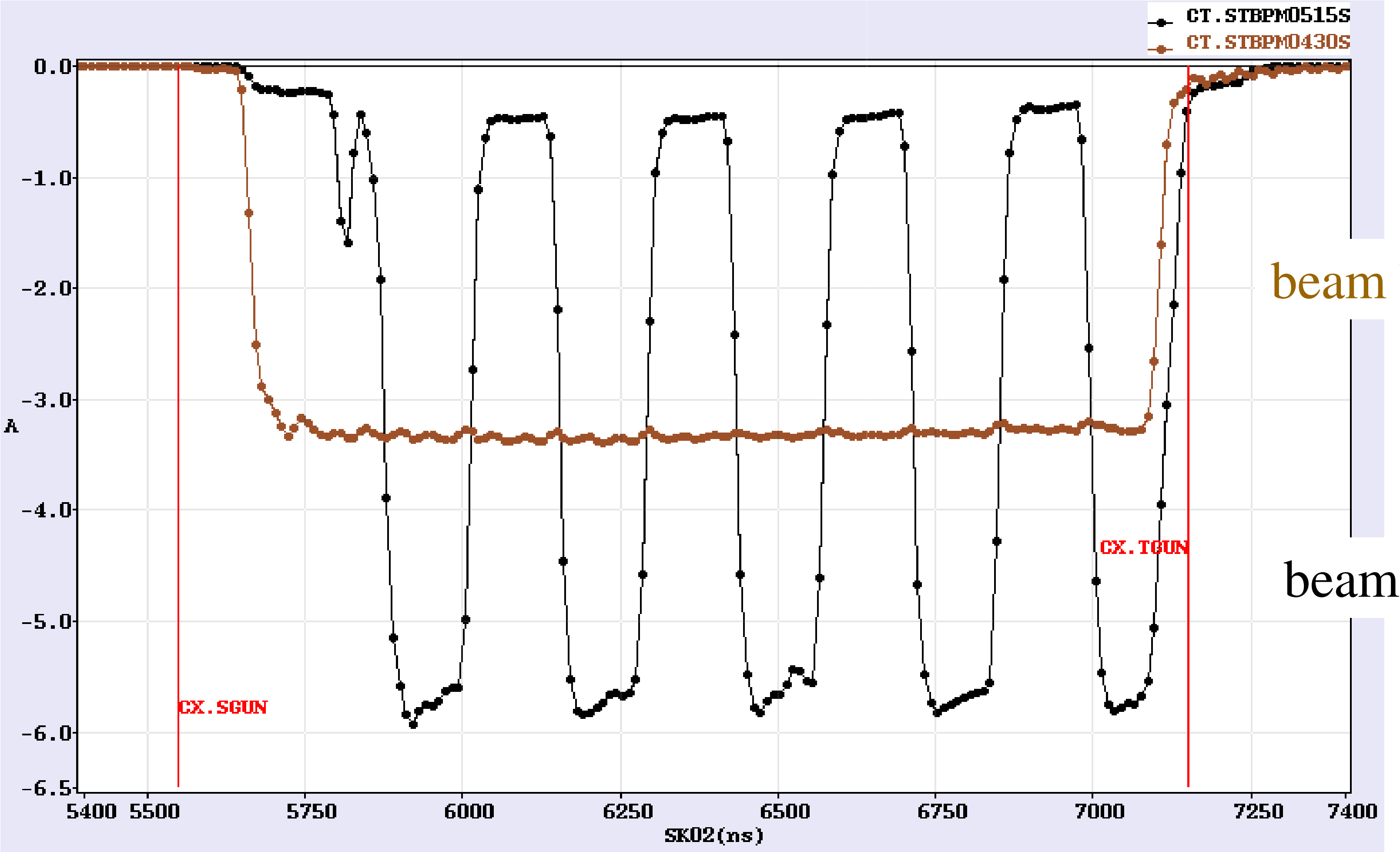
3 Traveling Wave Sub-harmonic bunchers, each fed by a wide-band Traveling Wave Tube

Streak camera image



$8.5 \cdot 666$ ps = 5.7 ns

Delay Loop – full recombination

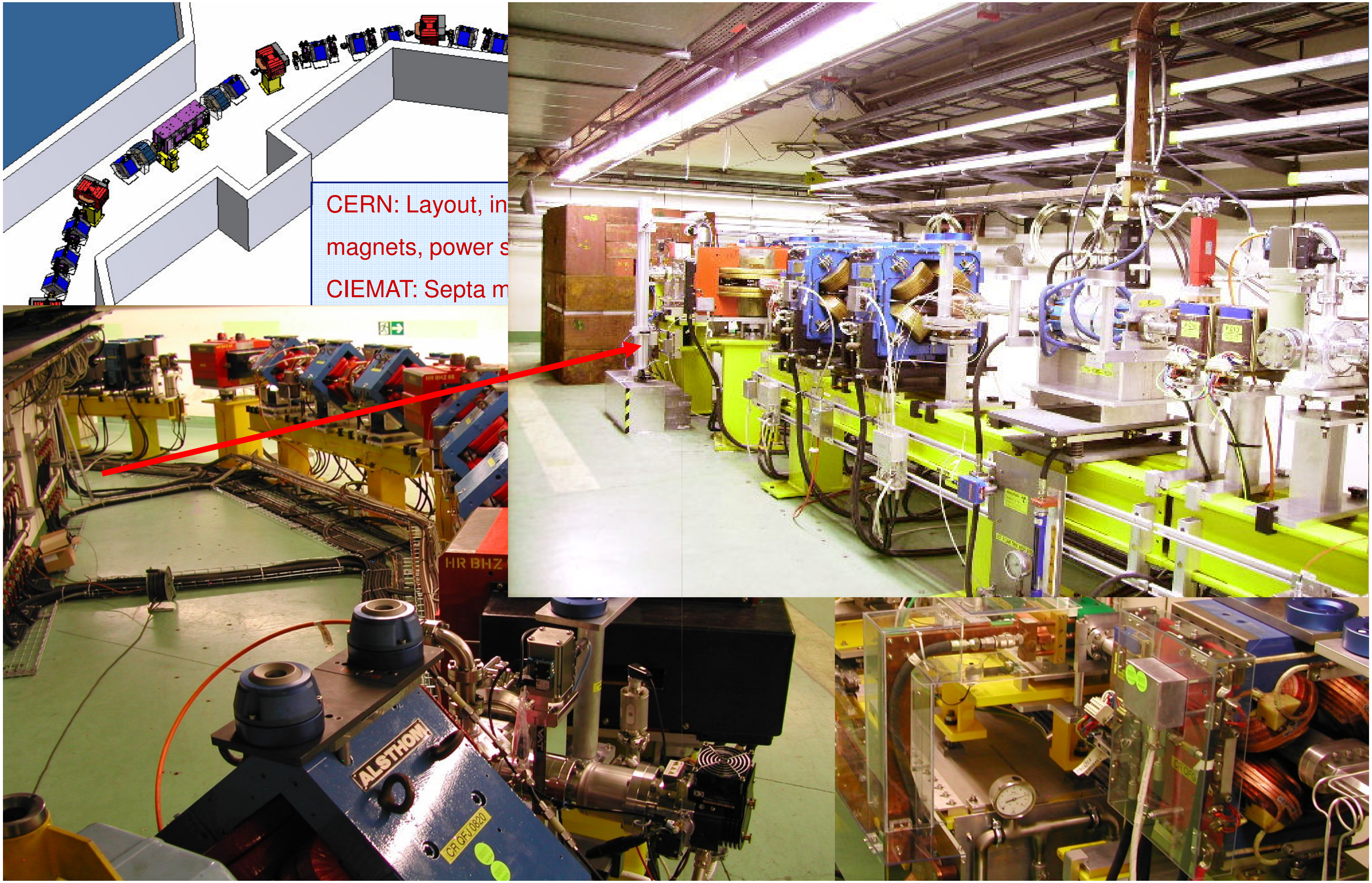


beam before the DL

beam after the DL

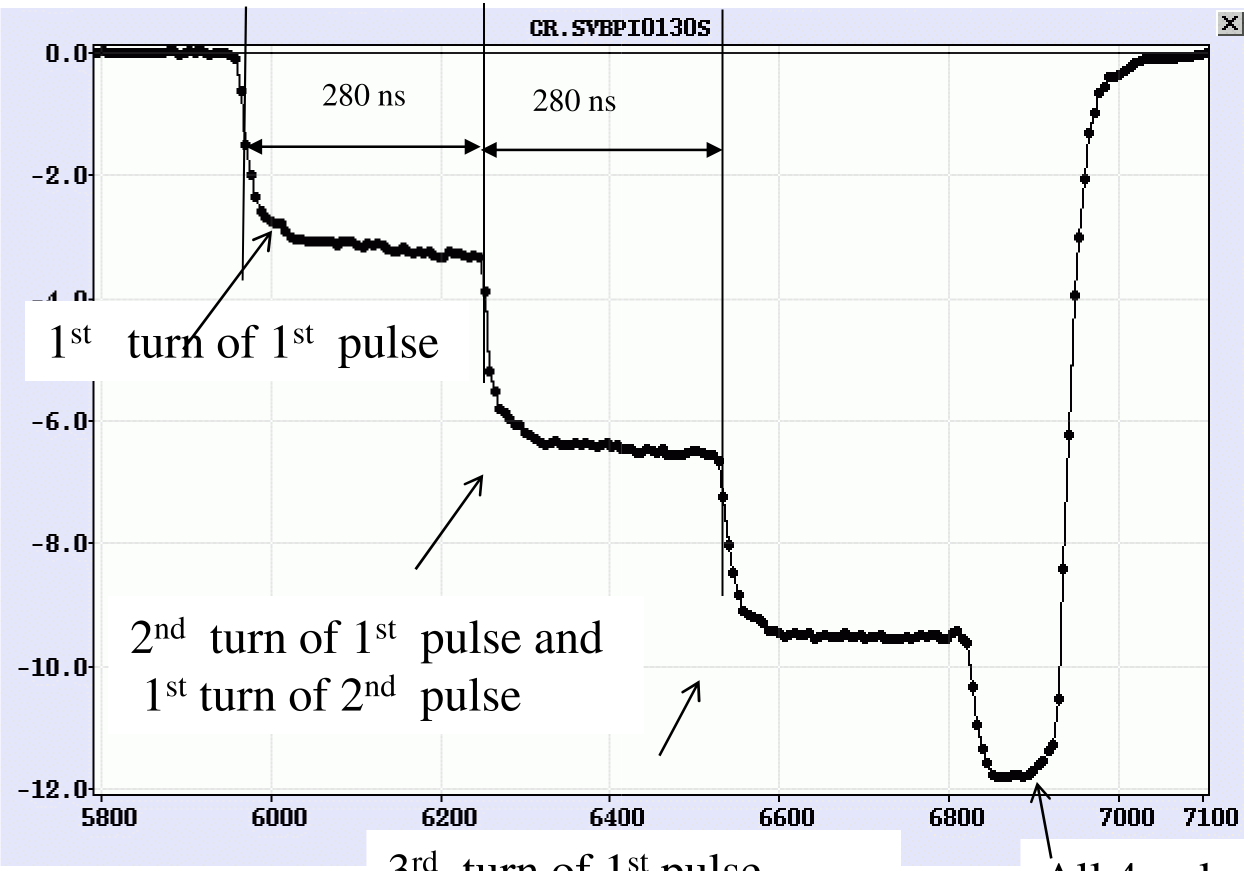
- 3.3 A after chicane => < 6 A after combination (satellites)

CTF3 combiner ring



CERN: Layout, in
magnets, power s
CIEMAT: Septa m

Combiner ring - latest status



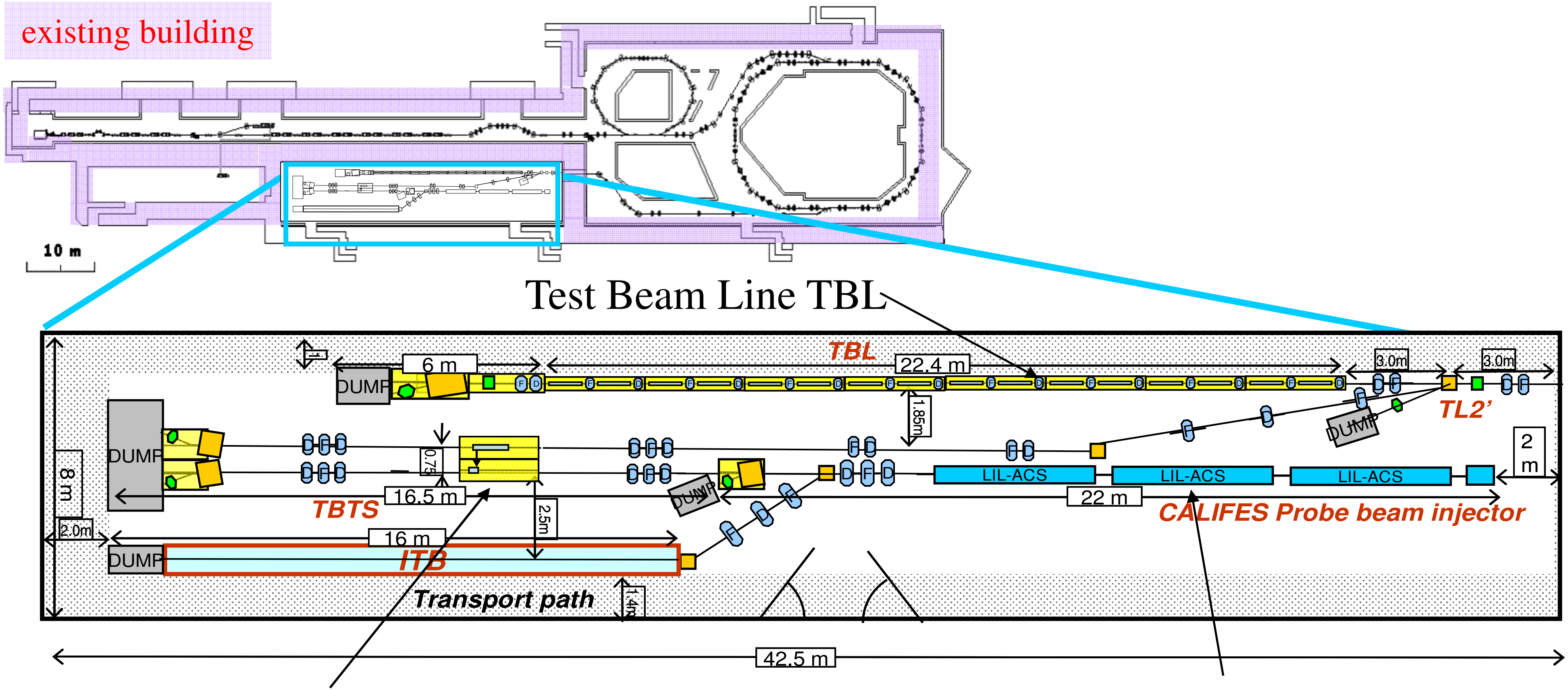
1st turn of 1st pulse

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

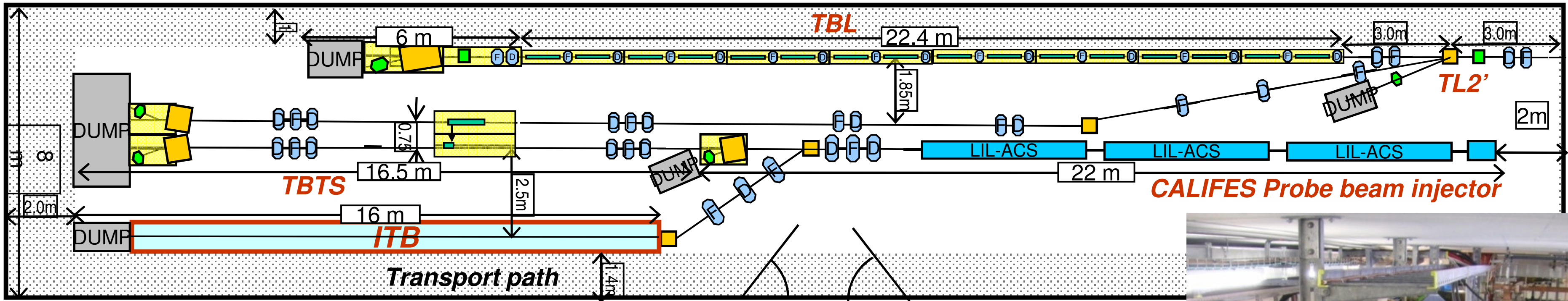
Two Beam Test Stand

Probe Beam

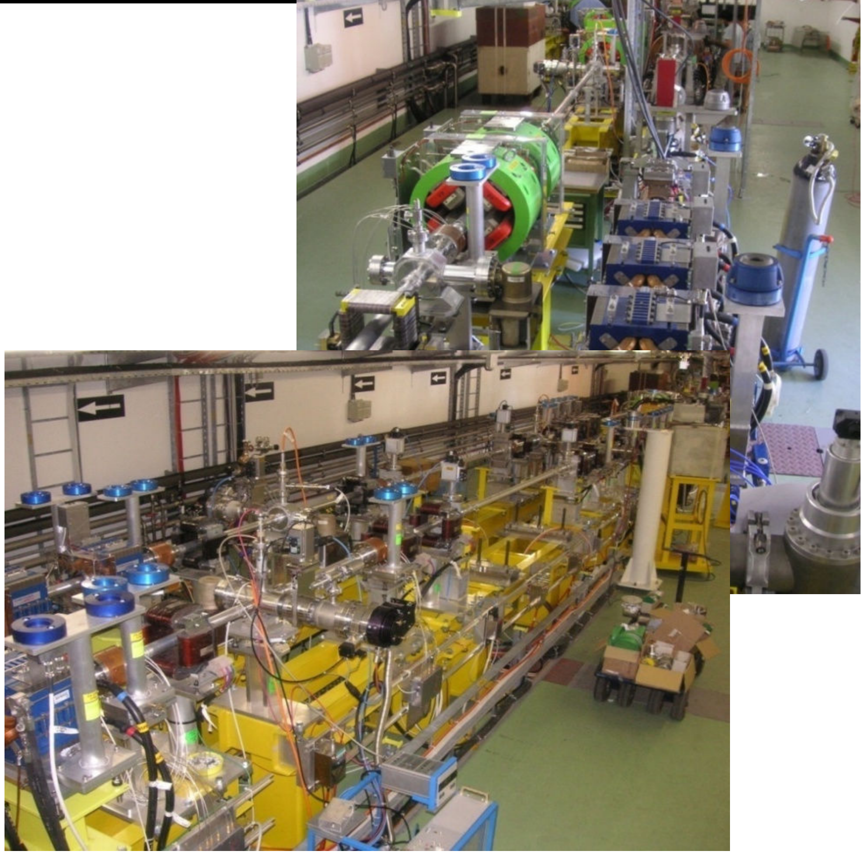
Construction during 2006/beg 2007
installation of equipment from 2007 - 2009

Beam in CLEX from
Aug 2008 onwards

CLEX – Installation status



- Beam lines TL2, TL2’, CALIFES, and TBTS installed
- Initial TBL ongoing
- CALIFES structures RF conditioning soon
- in October:
  - Probe beam RF gun bake out + RF conditioning
  - TBTS PETS installation
  - New CR RF deflectors
- Shutdown 08/09:
  - Tail Clipper in TL2
  - TBTS accelerating structure

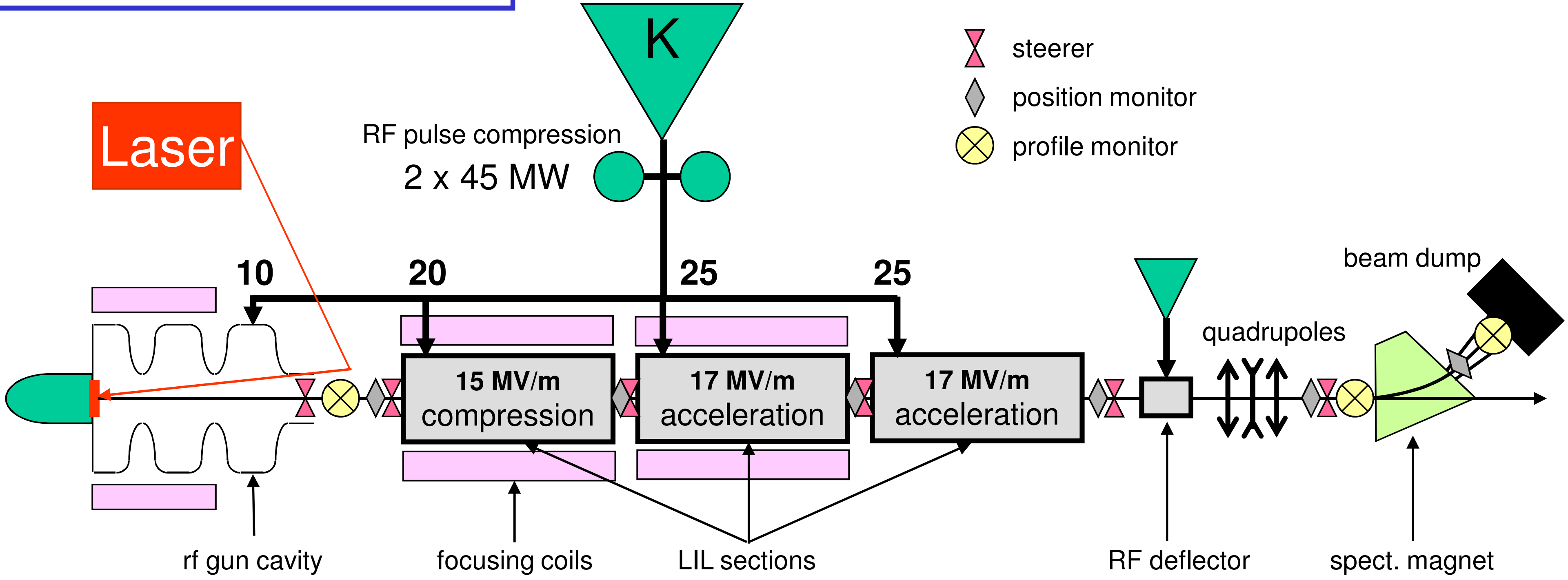


Probe Beam

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

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

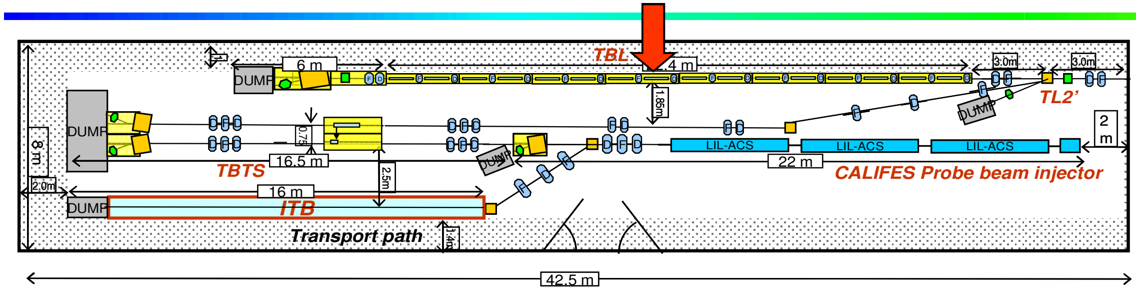
Status:
Installed, RF conditioning in Sept.
Laser under development



CALIFES

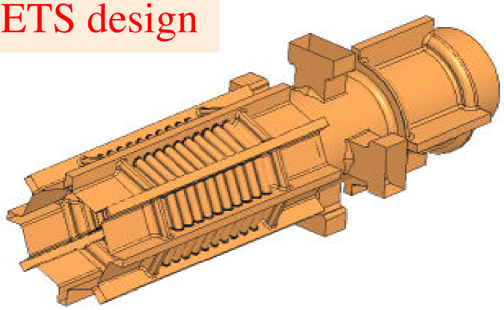
A. Mosnier, CEA Dapnia

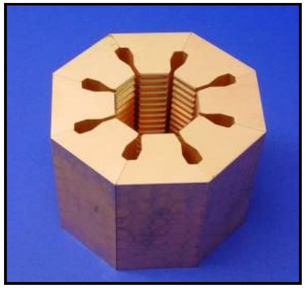
Test Beam Line TBL



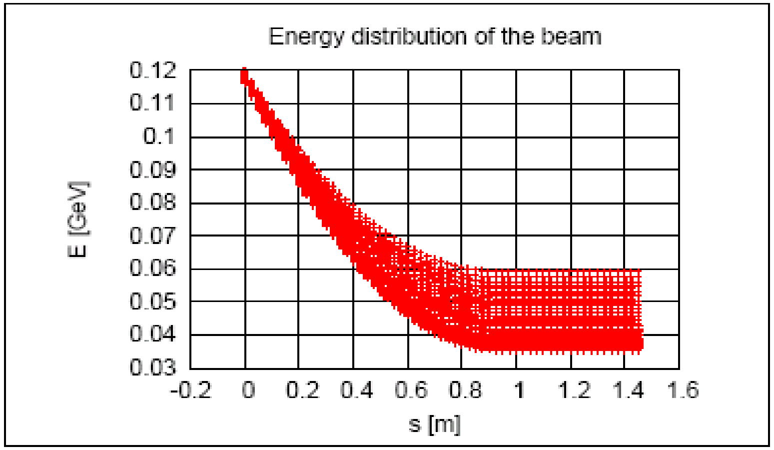
- High energy-spread beam transport
  decelerate to 50 % beam energy
- Drive Beam stability
- Stability of RF power extraction
  total power in 16 PETS: 2.5 GW
- Alignment procedures

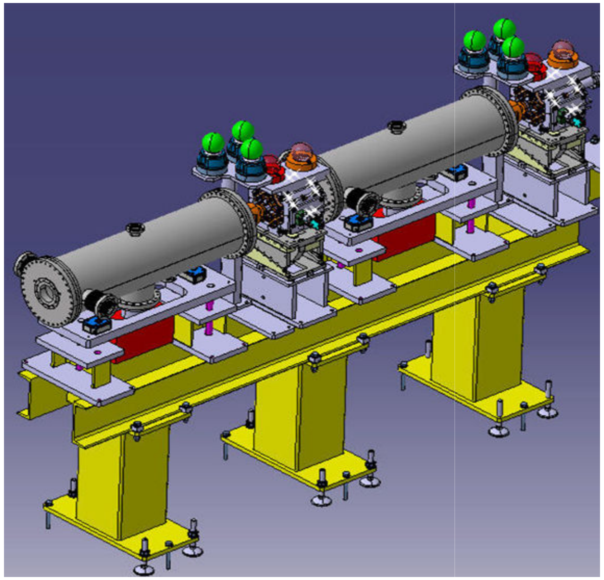
PETS design





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





2 standard cells,
16 total

PETS development: CIEMAT
BPM: IFIC Valencia
and UPC Barcelona

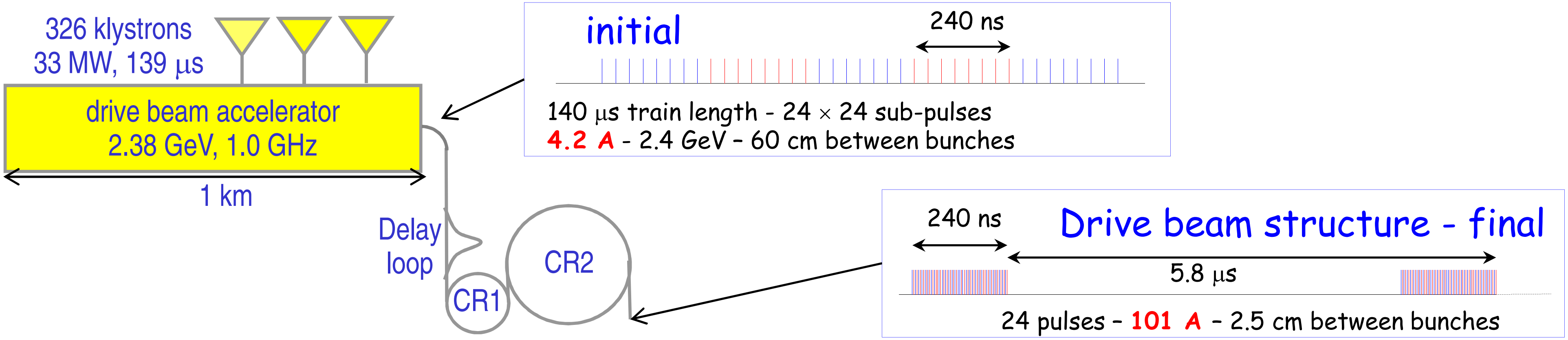
Comparison CLIC - CTF3

	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



326 klystrons
33 MW, 139 μs

drive beam accelerator
2.38 GeV, 1.0 GHz

1 km

Delay loop

CR1

CR2

initial

240 ns

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

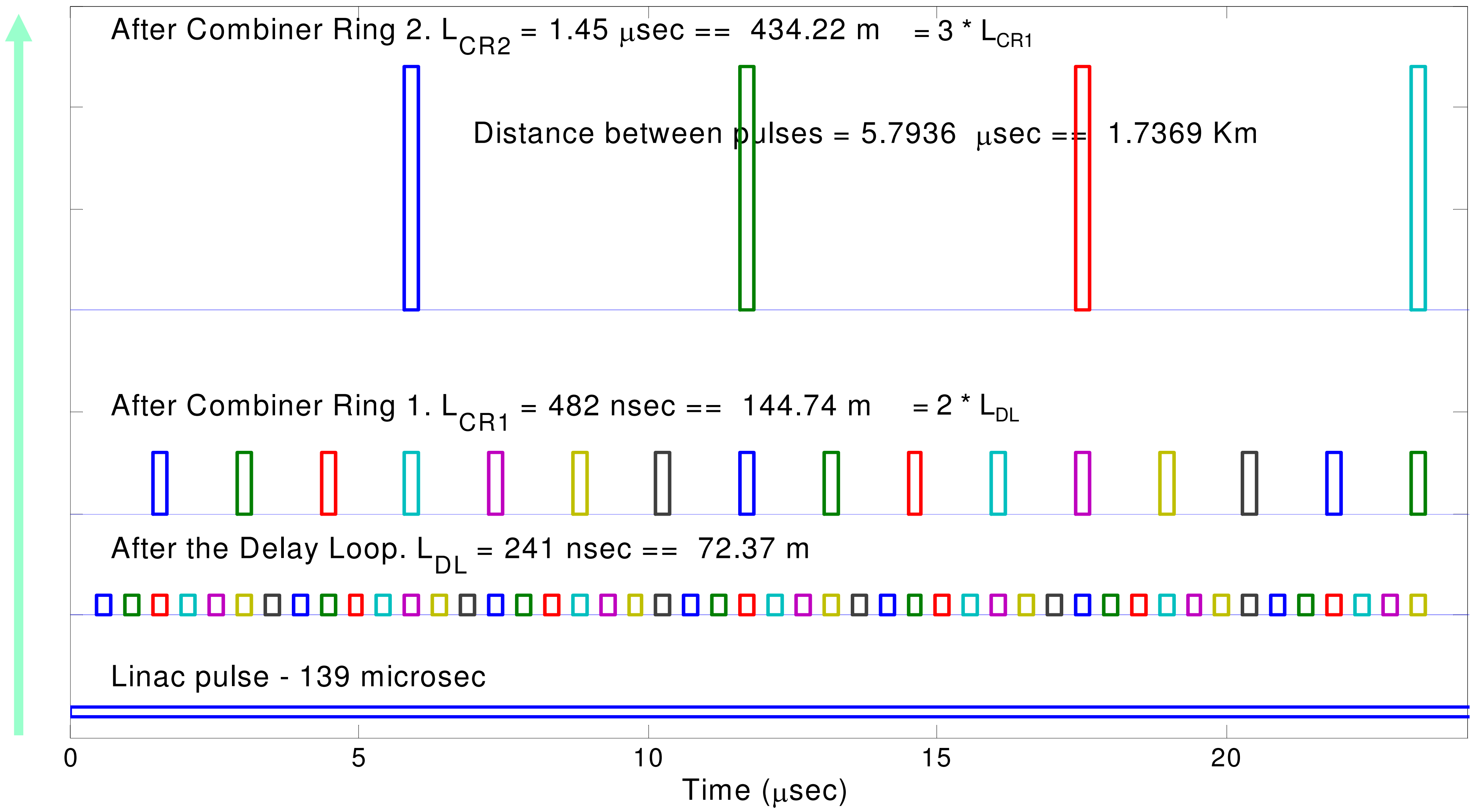
Drive beam structure - final

240 ns

5.8 μs

24 pulses – **101 A** – 2.5 cm between bunches

Drive Beam time structure



After Combiner Ring 2. L_{CR2} = 1.45 µsec == 434.22 m = 3 * L_{CR1}

Distance between pulses = 5.7936 µsec == 1.7369 Km

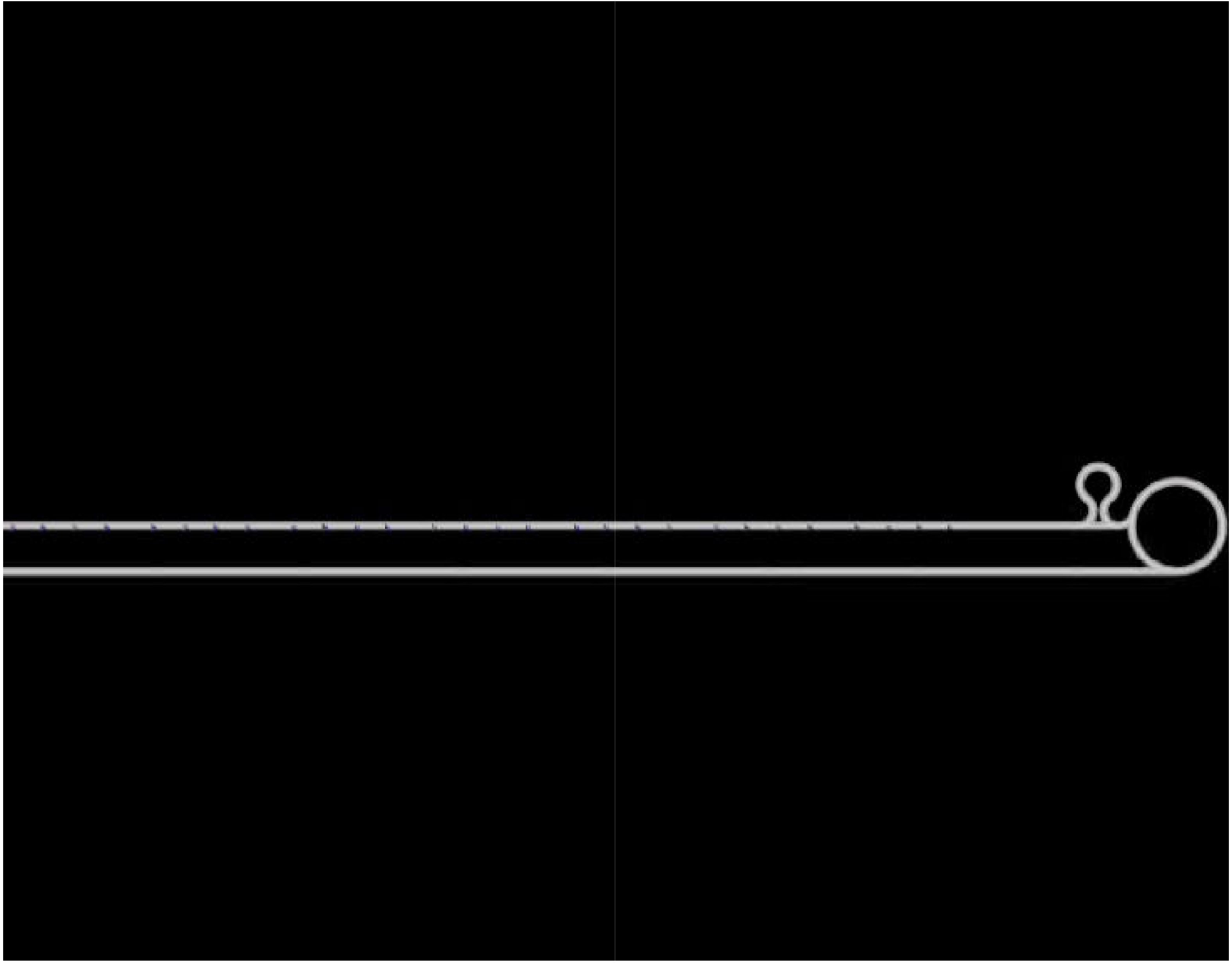
After Combiner Ring 1. L_{CR1} = 482 nsec == 144.74 m = 2 * L_{DL}

After the Delay Loop. L_{DL} = 241 nsec == 72.37 m

Linac pulse - 139 microsec

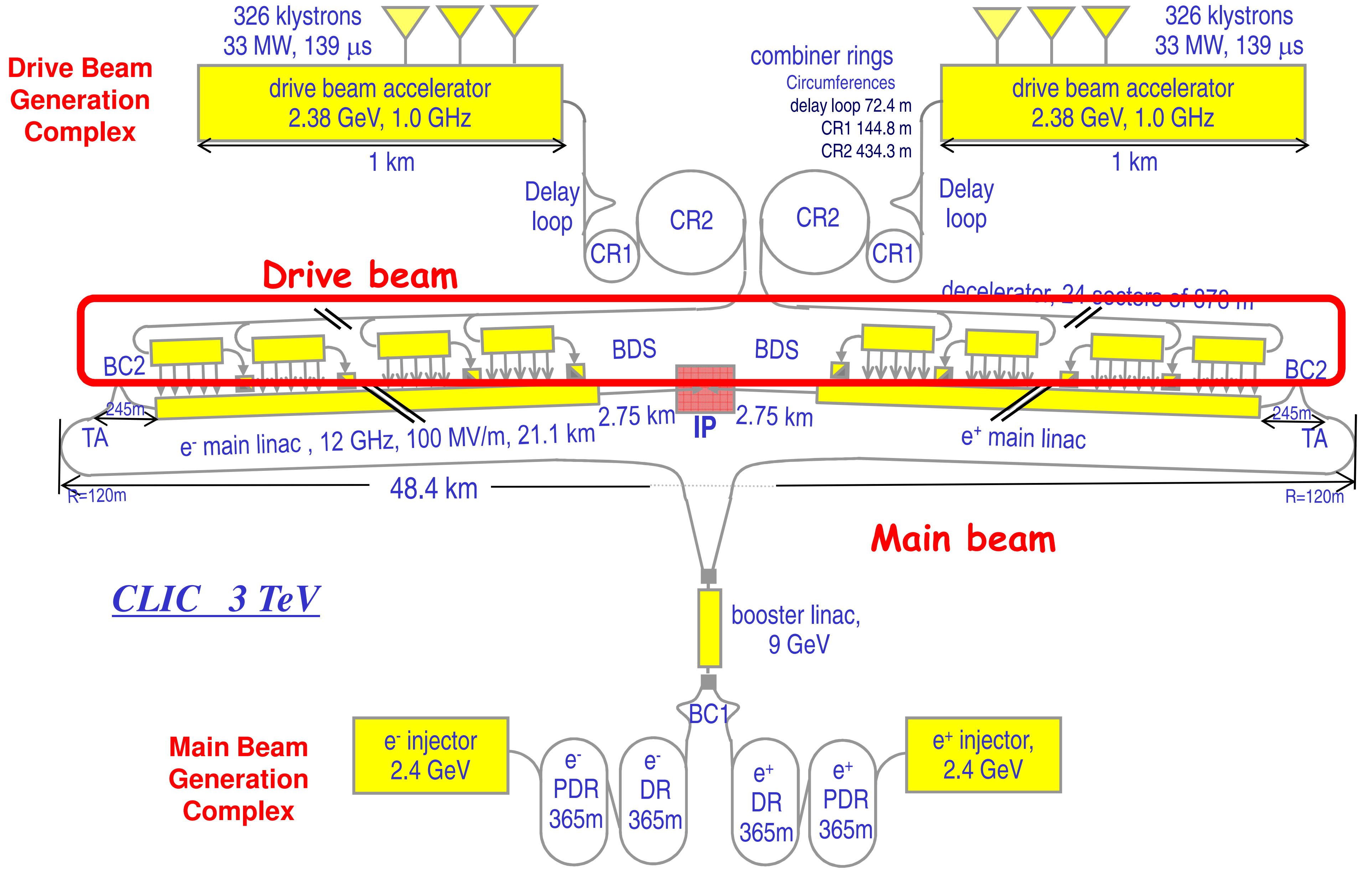
C.Biscari

Lemmings Drive Beam



Alexandra
Andersson

CLIC – power generation



Drive Beam Generation Complex

326 klystrons
33 MW, 139 μs

drive beam accelerator
2.38 GeV, 1.0 GHz

1 km

Delay loop

CR1

CR2

combiner rings
Circumferences
delay loop 72.4 m
CR1 144.8 m
CR2 434.3 m

326 klystrons
33 MW, 139 μs

drive beam accelerator
2.38 GeV, 1.0 GHz

1 km

Delay loop

CR2

CR1

Drive beam

decelerator, 24 sectors of 878 m

BC2

BDS

BDS

BC2

245m

TA

e^- main linac , 12 GHz, 100 MV/m, 21.1 km

2.75 km

IP

2.75 km

e^+ main linac

245m

TA

R=120m

48.4 km

R=120m

Main beam

CLIC 3 TeV

booster linac,
9 GeV

BC1

Main Beam Generation Complex

e^- injector
2.4 GeV

e^- PDR 365m

e^- DR 365m

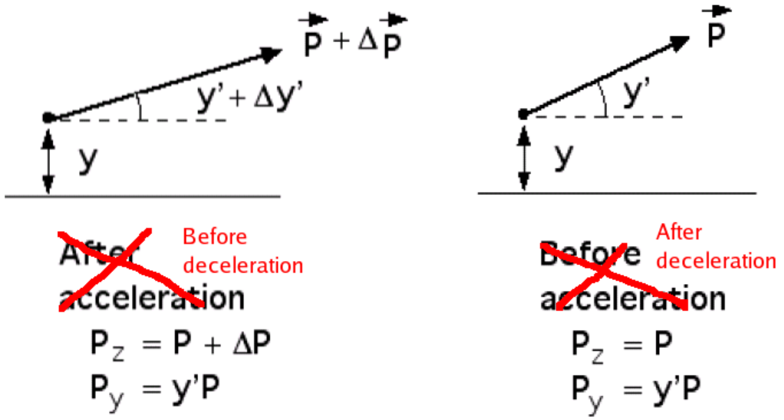
e^+ DR 365m

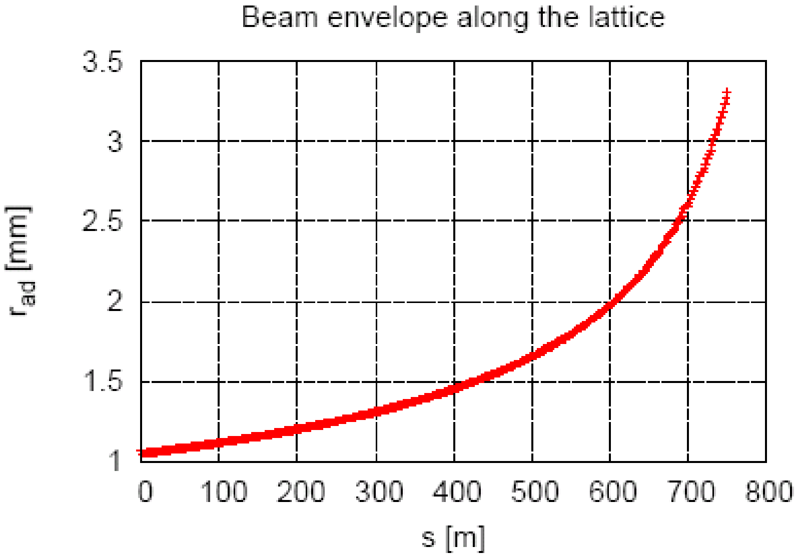
e^+ PDR 365m

e^+ injector,
2.4 GeV

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

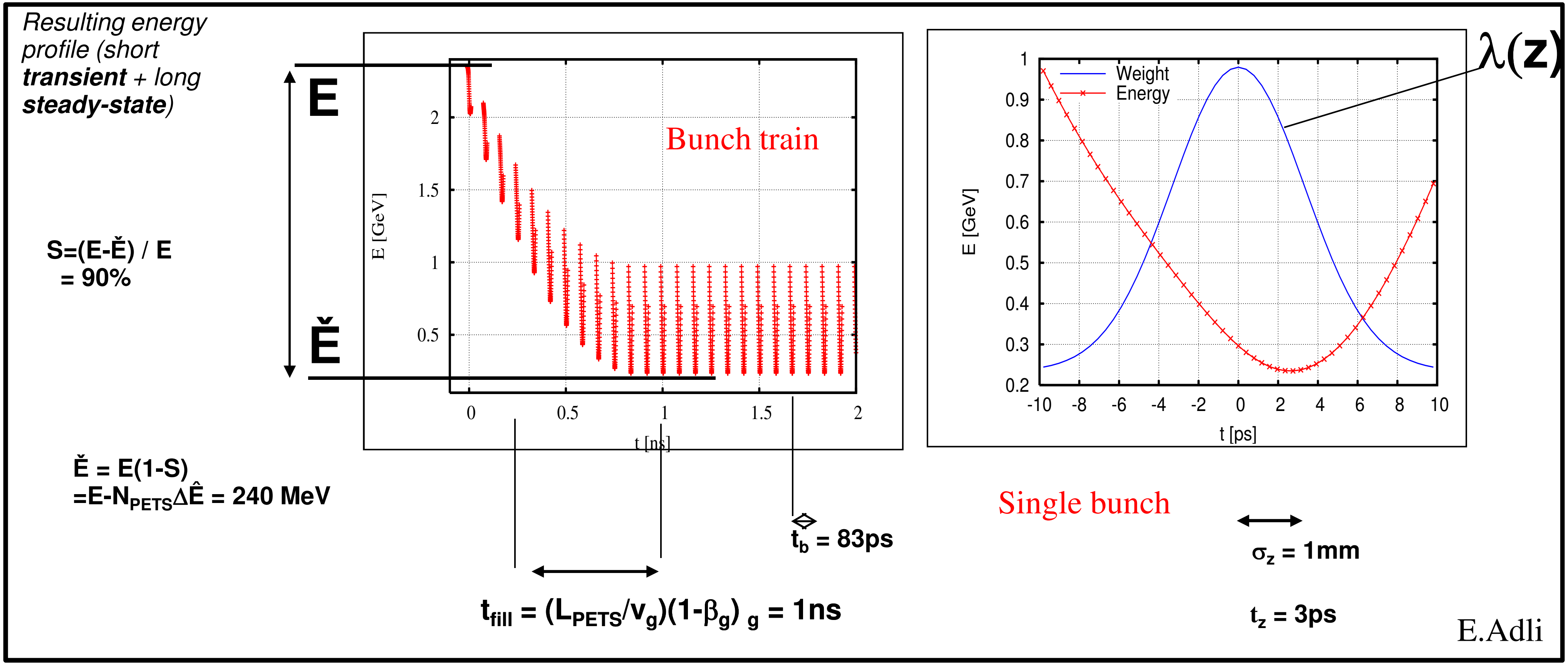



Beam envelope along the lattice

- 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%



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

Bunch train

S=(E-Ě) / E = 90%

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

t_b = 83ps

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

Single bunch

σ_z = 1mm

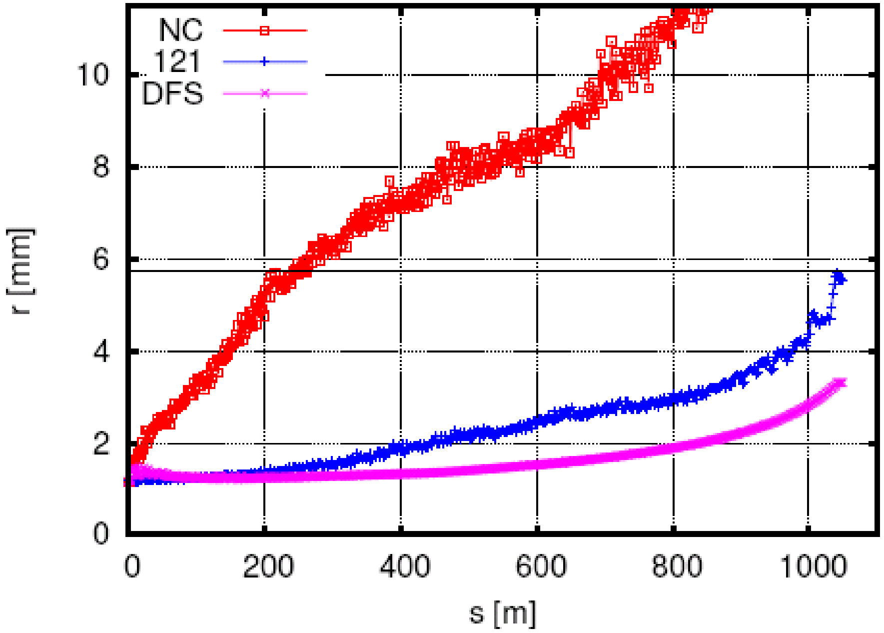
t_z = 3ps

E.Adli

CLIC decelerator

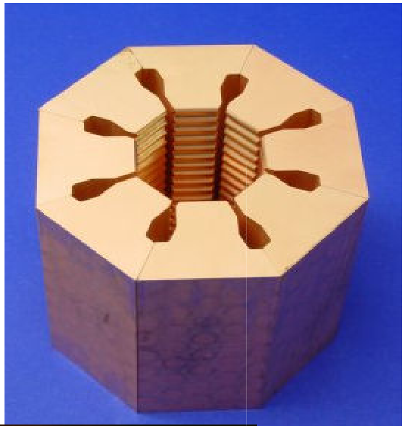
- Goal: transport particles of all energies through the decelerator sector: in the presence of huge energy spread (90%)
- Tight FODO focusing (large energy acceptance, low beta)
- Lowest energy particles ideally see constant FODO phase-advance μ≈90°, higher energy particles see phase-advance varying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

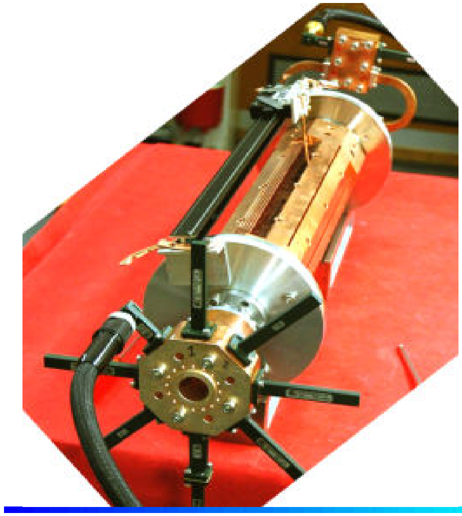
- Good quad alignment needed (20μm)
- Good BPM accuracy (20μm)
- Orbit correction essential
  - 1-to-1 steering to BPM centres
  - DFS (Dispersion Free Steering) gives almost ideal case

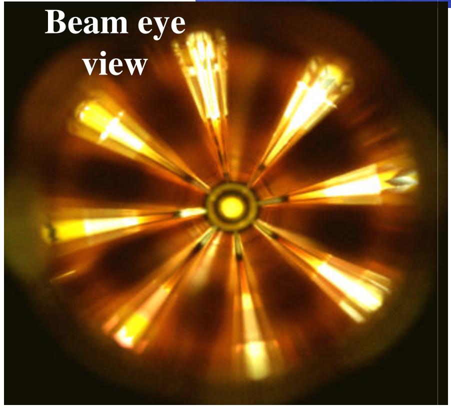


Power extraction structure PETS

- 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







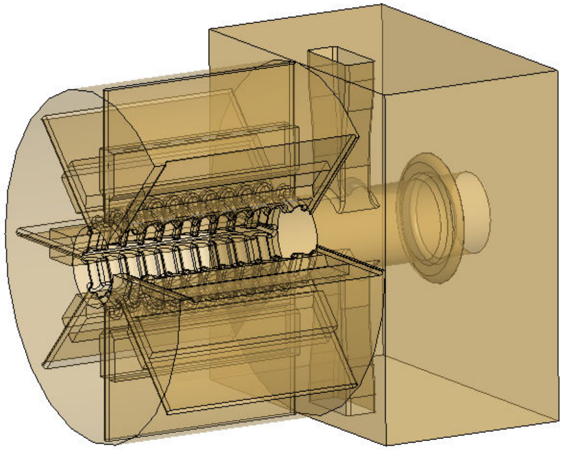
The power produced by the bunched (ω_0) beam in a constant impedance structure:

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)

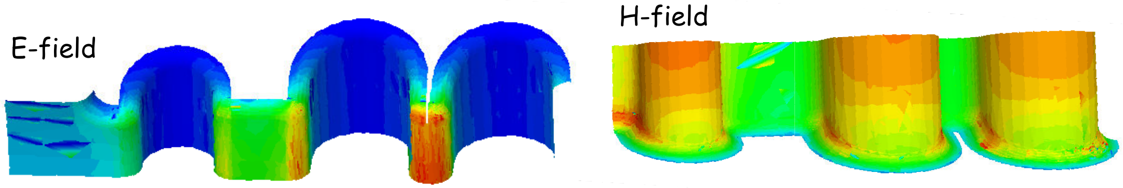
Power Extraction Structure (PETS)



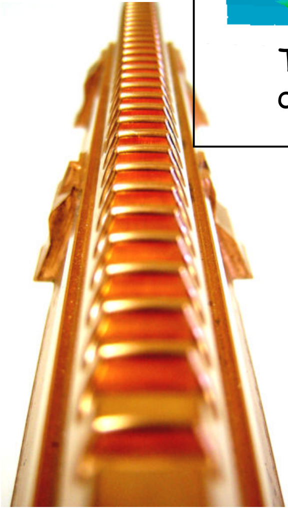
The PETS comprises eight octants separated by the damping slots. Each of the slots is equipped with HOM damping loads.
This arrangement follows the need to provide strong damping of the transverse modes.

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)



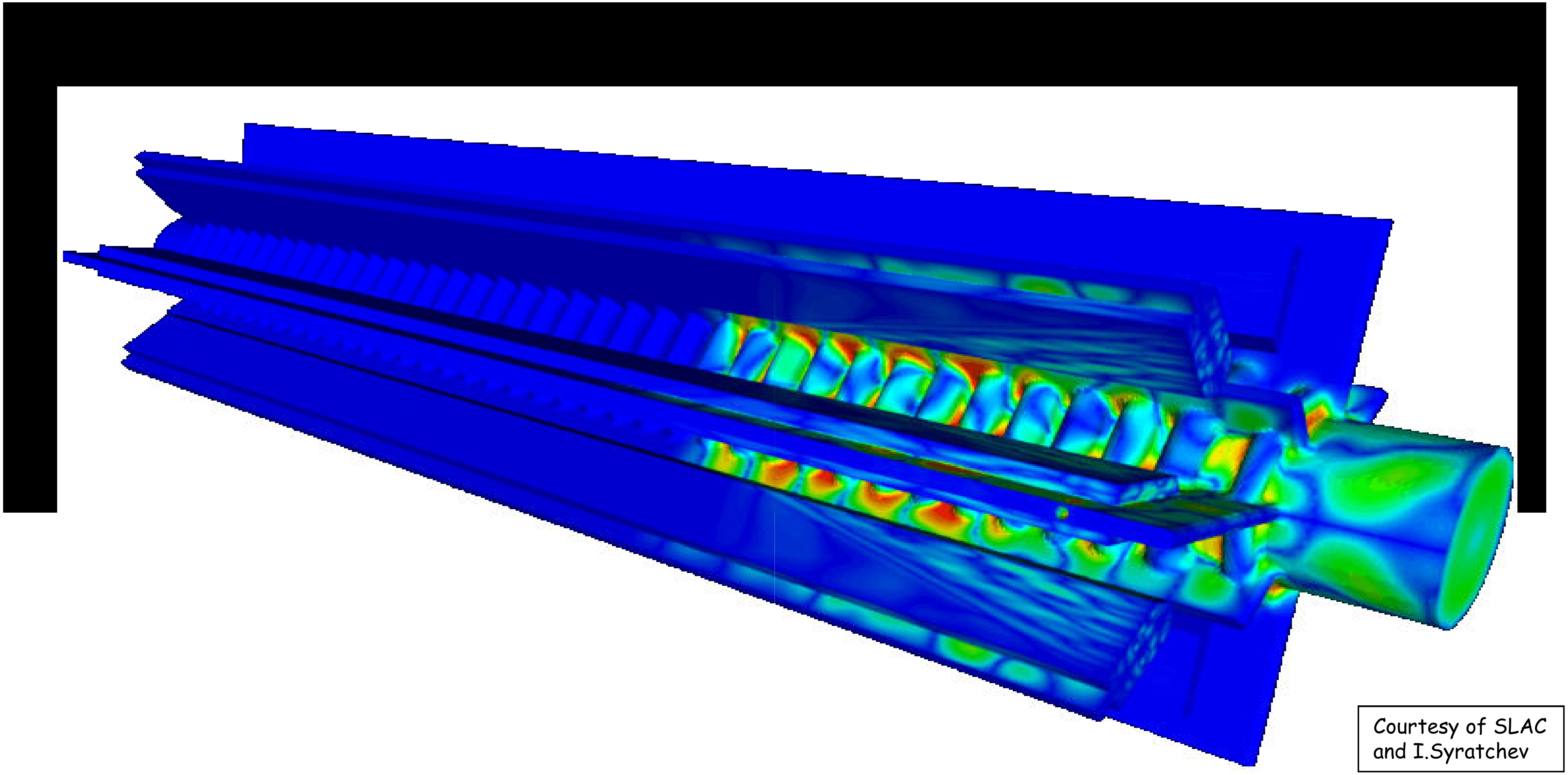
To reduce the surface field concentration in the presence of the damping slot, the special profiling of the iris was adopted.



I. Syratchev

Field development in a PETS

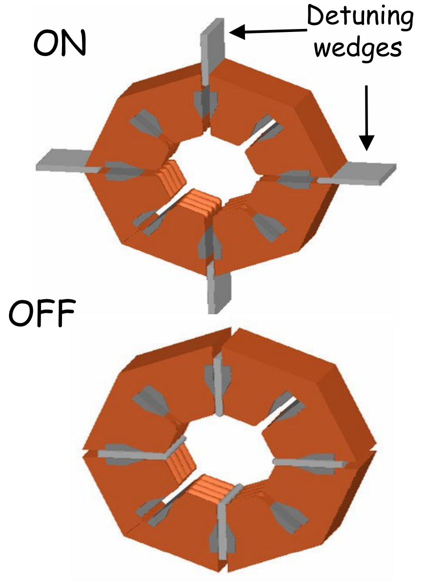
- The induced fields travel along the PETS structure and build up resonantly (here only dipole fields in animation)

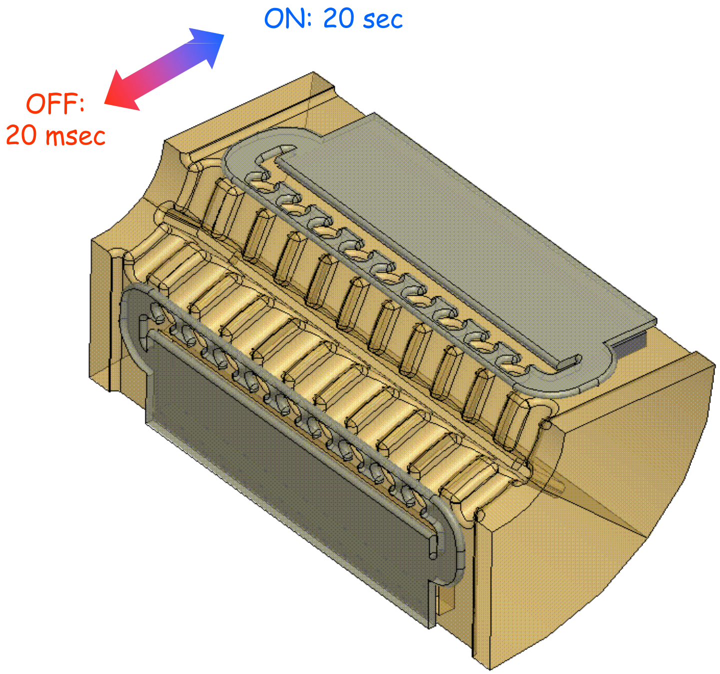


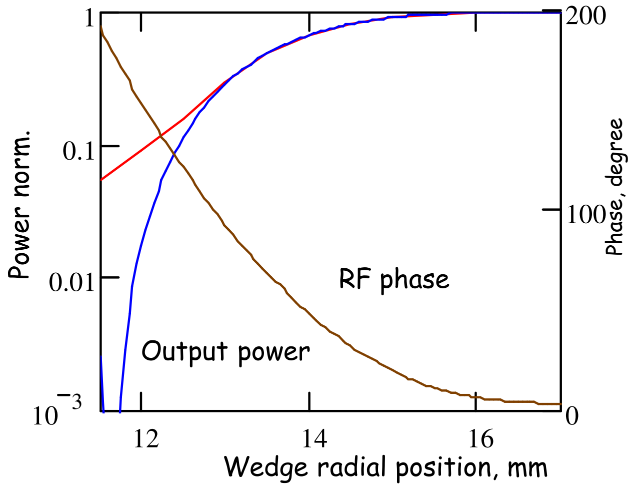
Courtesy of SLAC and I.Syratchev

PETS ON-OFF

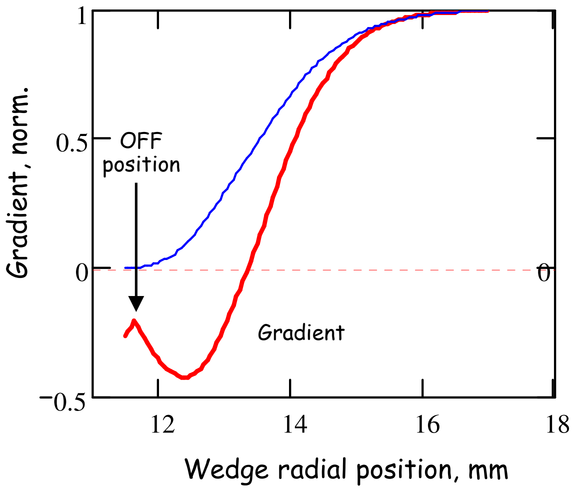
- RF breakdowns in accelerating structures and/or PETS
- might be necessary to switch the single PETS structure OFF but you can’t avoid beam in a single PETS
- Solution: introduce strong detuning by radial wedges
- for operation efficiency: switching OFF very fast between pulses (20 msec)





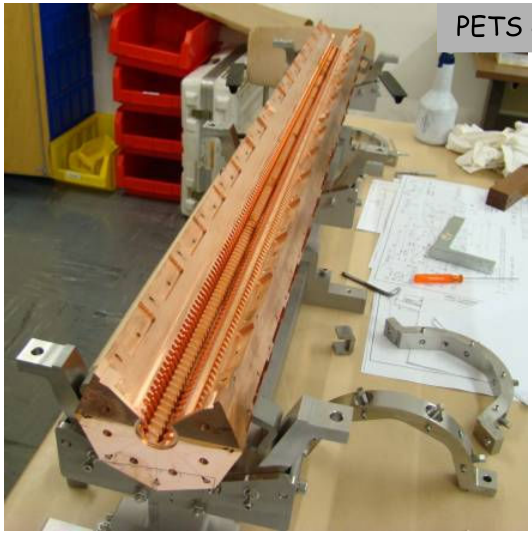
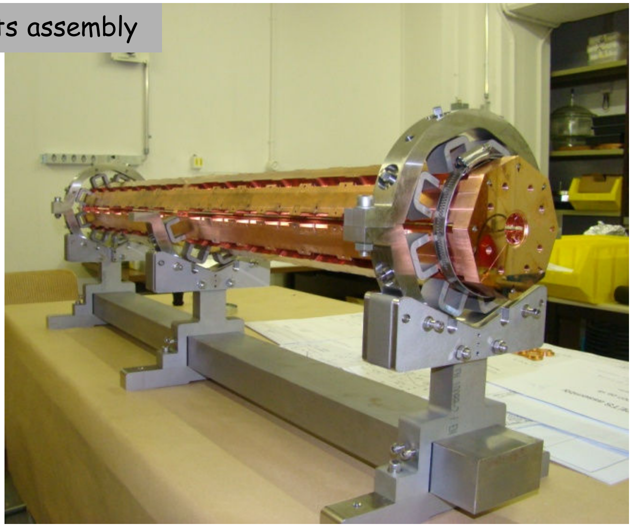


Main beam acceleration

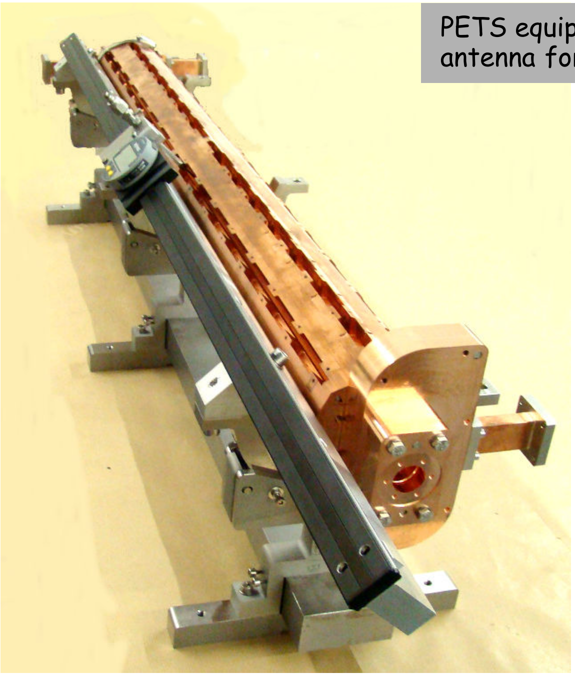
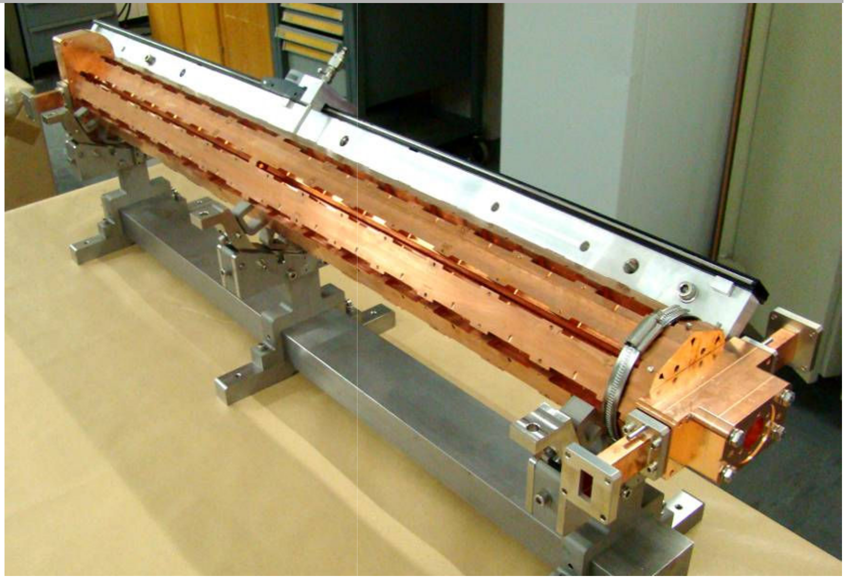
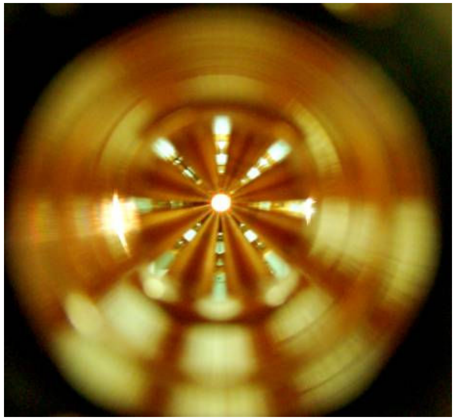


12 GHz PETS test assembly


8 bars, as received from VDL

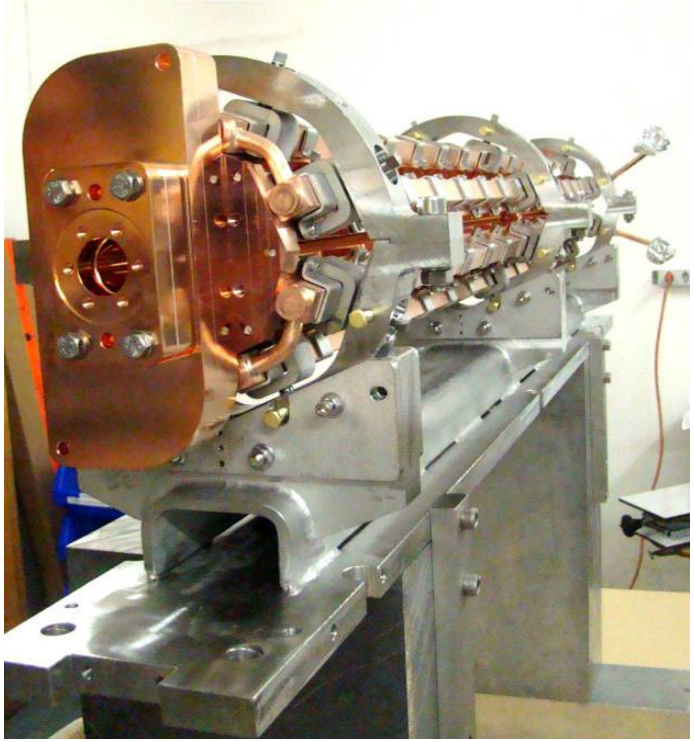


PETS octants assembly

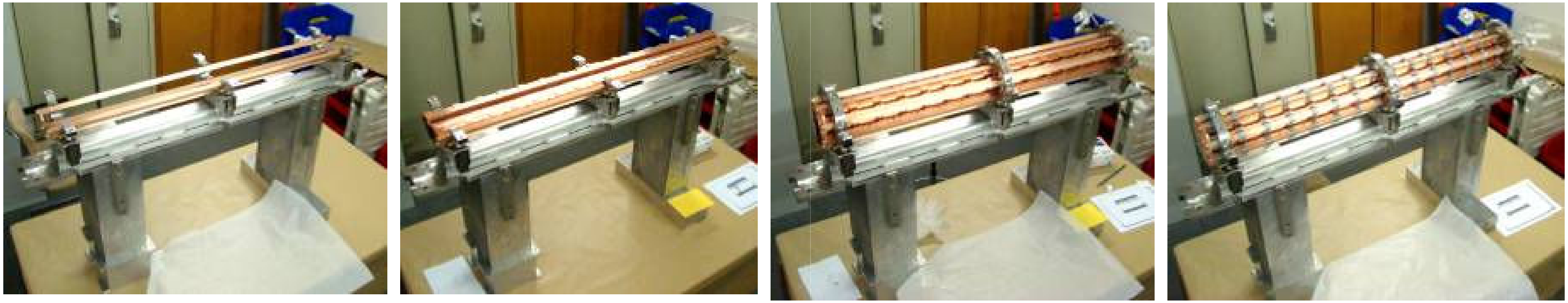
PETS equipped with the power couplers and electronic ruler with pick-up antenna for the phase advance measurements.

I. Syratchev

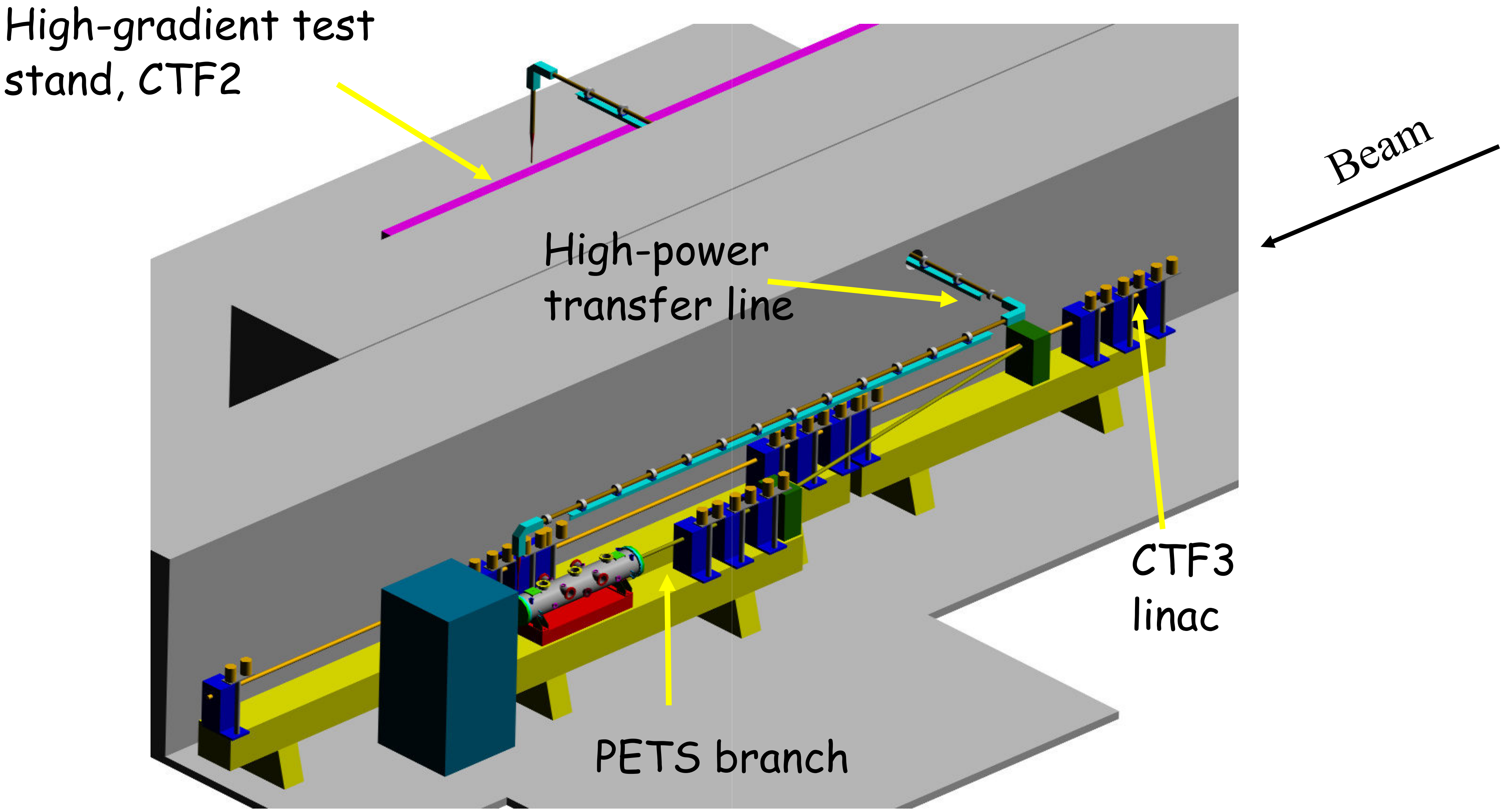
12 GHz TBTS PETS final assembly



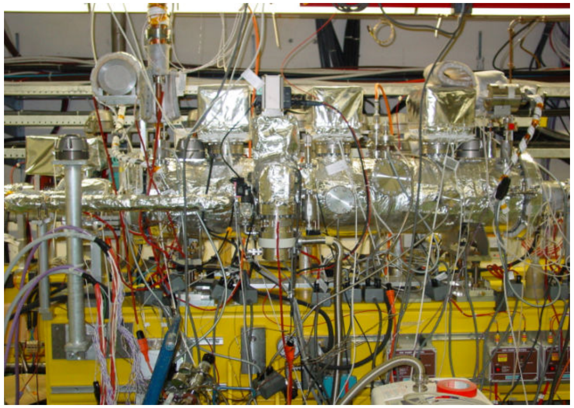


I. Syratchev

30 GHz test line in CTF3

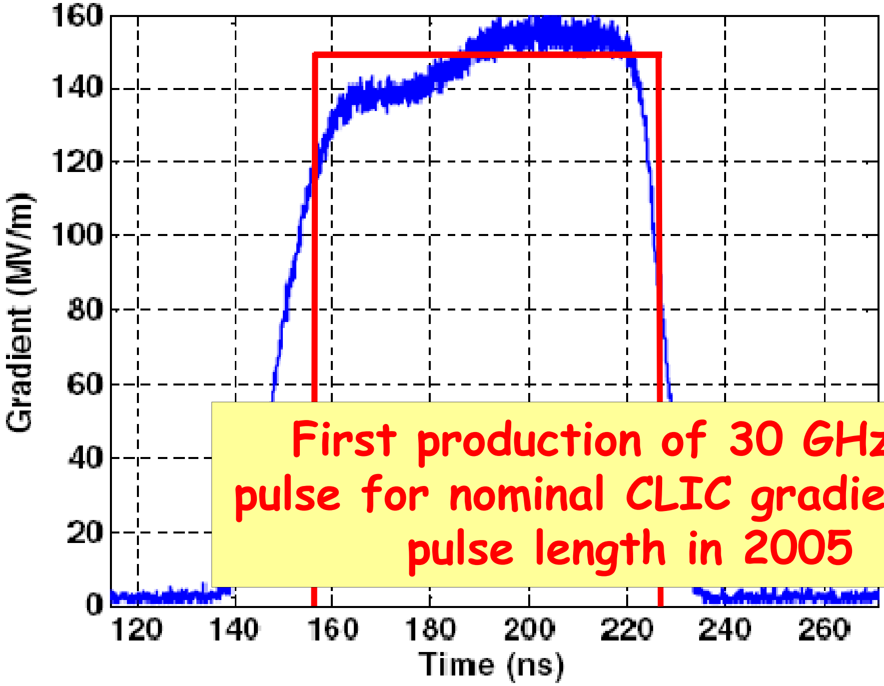


30 GHz power production (PETS)



vacuum tanks containing Power Extraction Transfer Structure

17m waveguide with 5 bends
but low-loss (85% transmission)
(Russian collaboration)

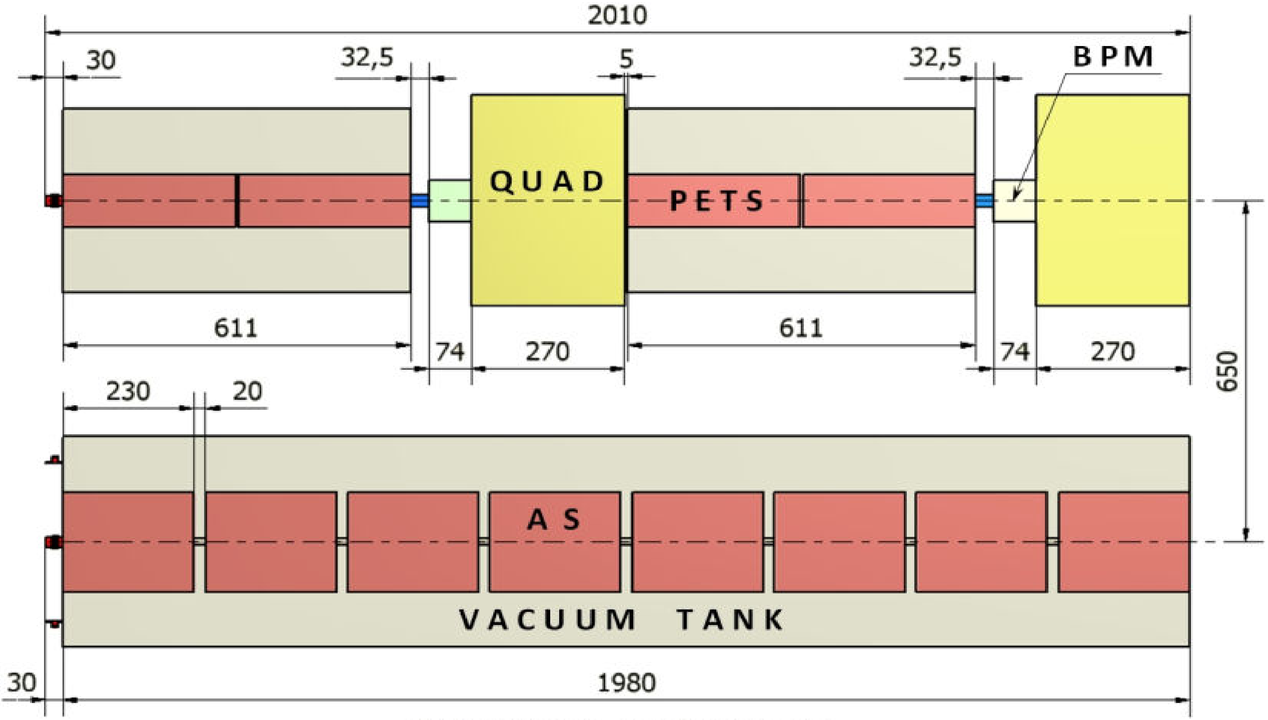


First production of 30 GHz RF pulse for nominal CLIC gradient and pulse length in 2005

high power load / accel. structure

CLIC two-beam Module layout

Standard module



CLIC STANDARD MODULE LAYOUT

Total per module
8 accelerating structures
8 wakefield monitors

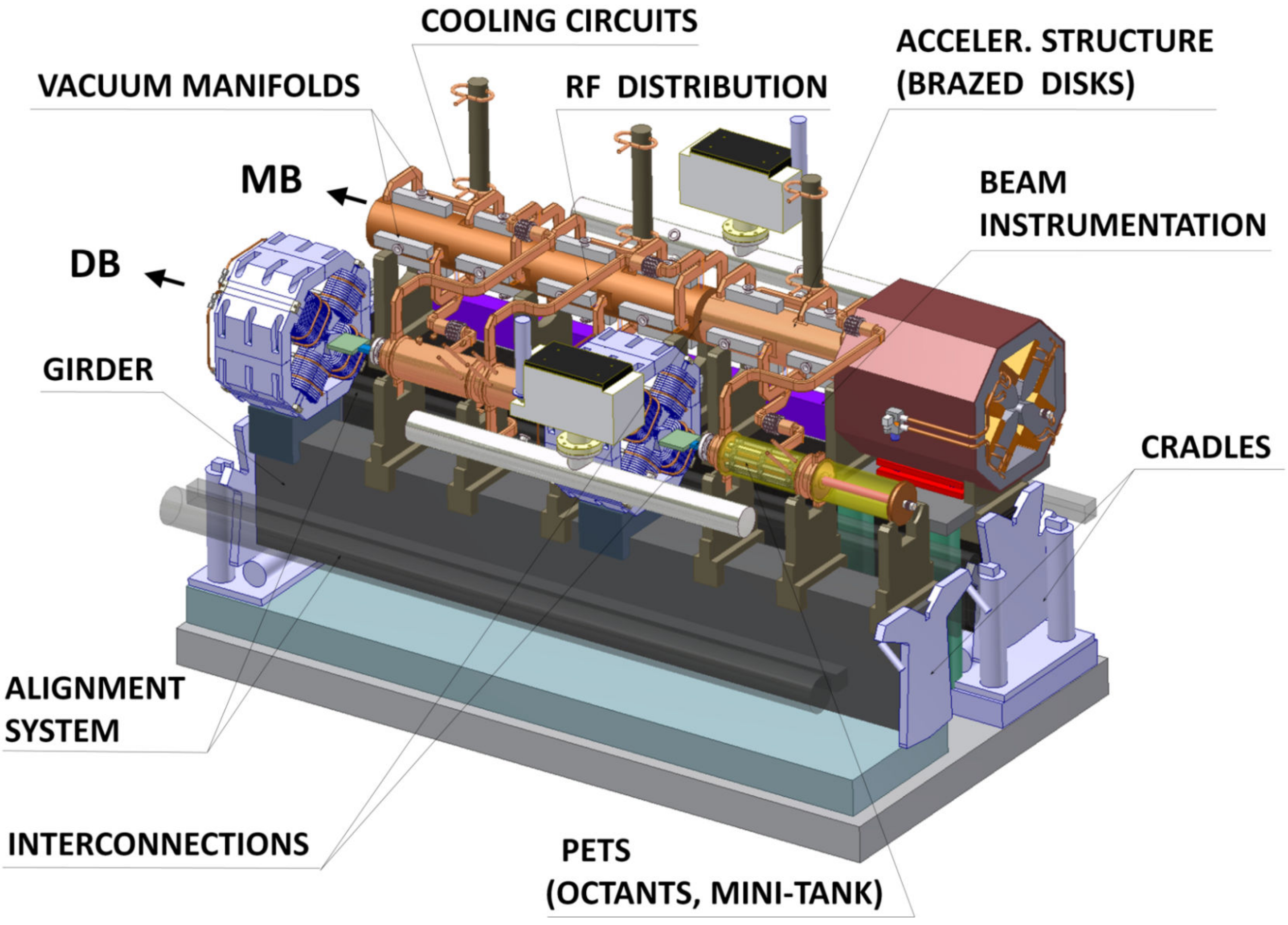
4 PETS
2 DB quadrupoles
2 DB BPM

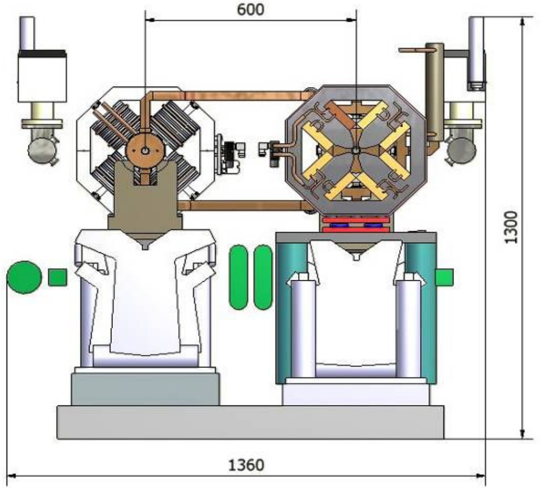
Total per linac
8374 standard modules

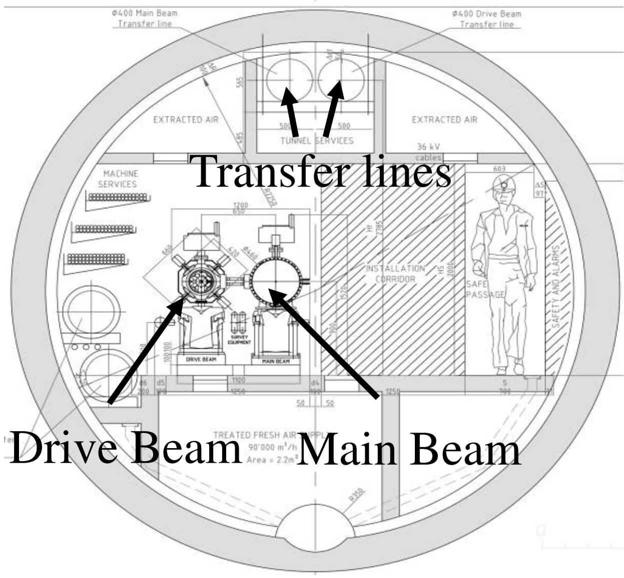
- Other modules have 2,4,6 or 8 acc.structures replaced by a quadrupole (depending on main beam optics)
- Total 10462 modules, 71406 acc. structures, 35703 PETS

G.Riddone

CLIC two-beam Module



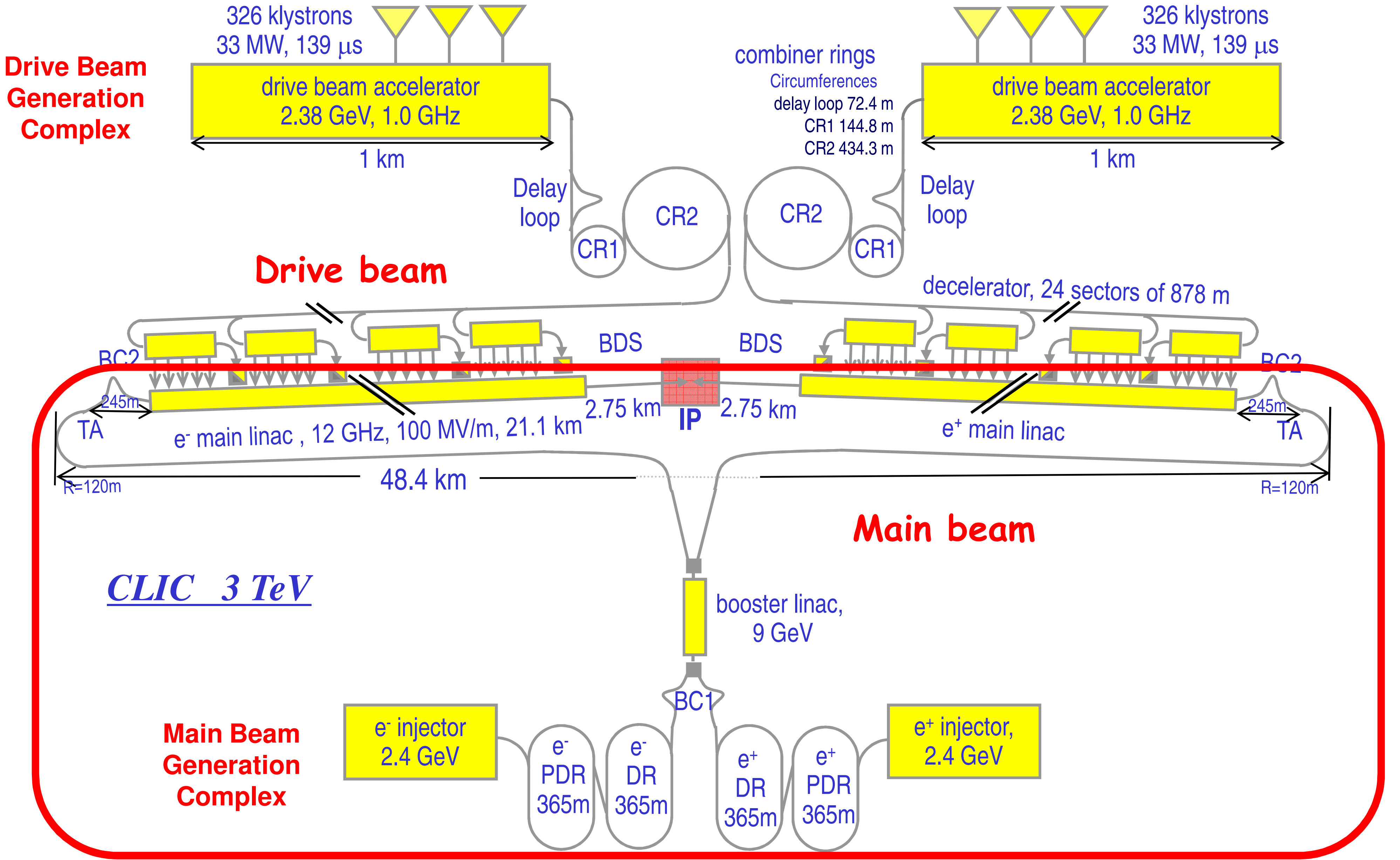




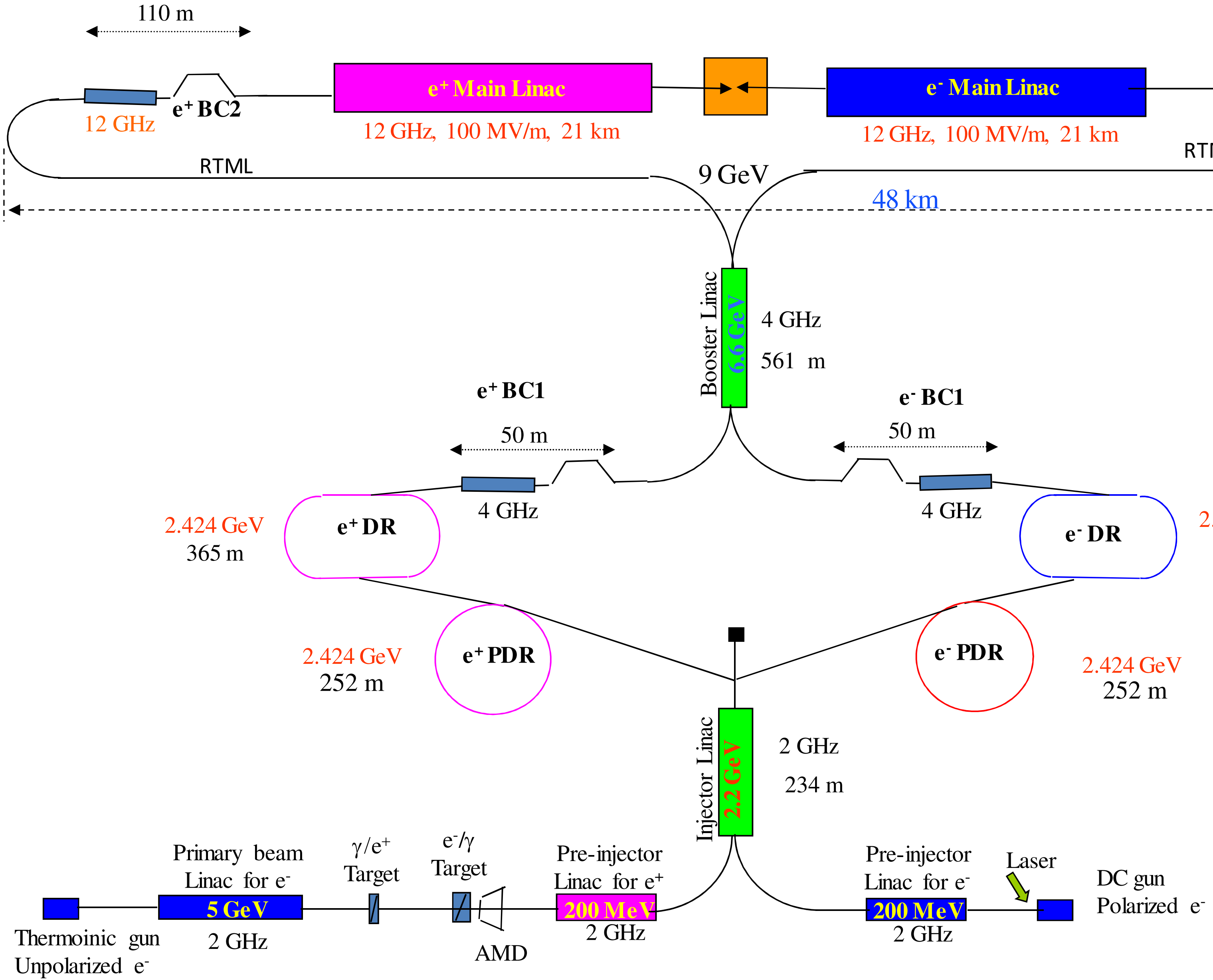
- Alignment system, beam instrumentation, cooling integrated in design

G.Riddone

CLIC – main beam generation

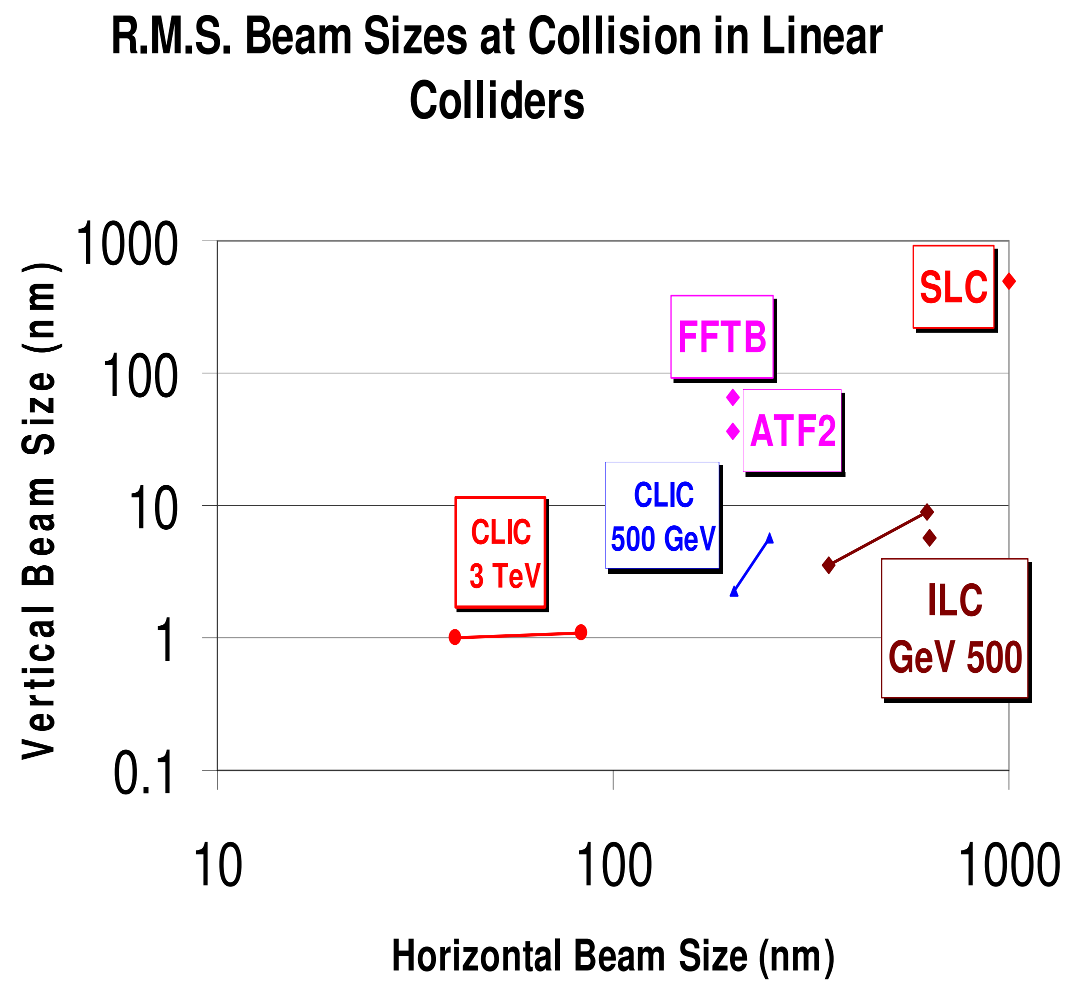


Main beam Injector Complex

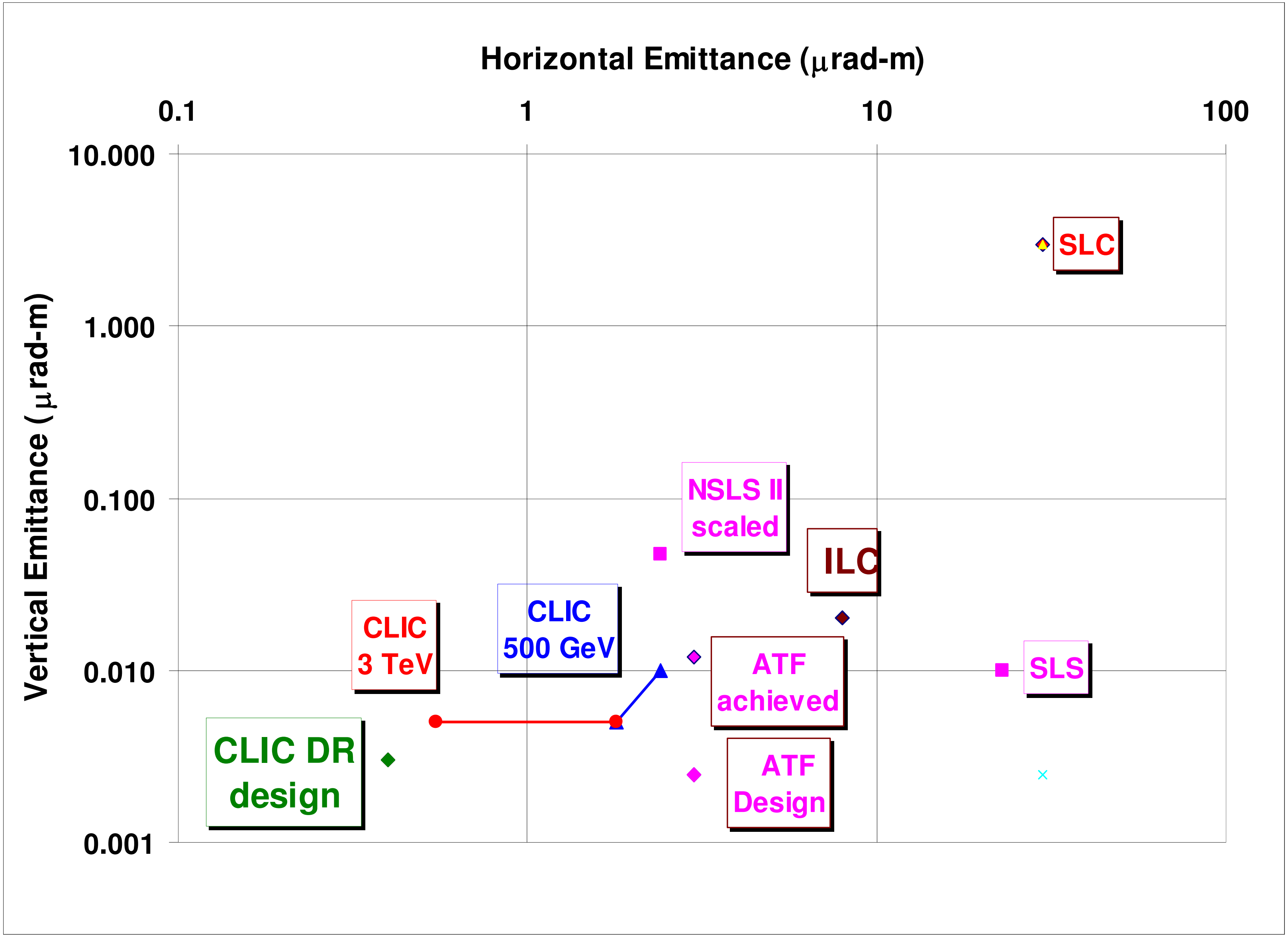


Crucial: Emittance

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

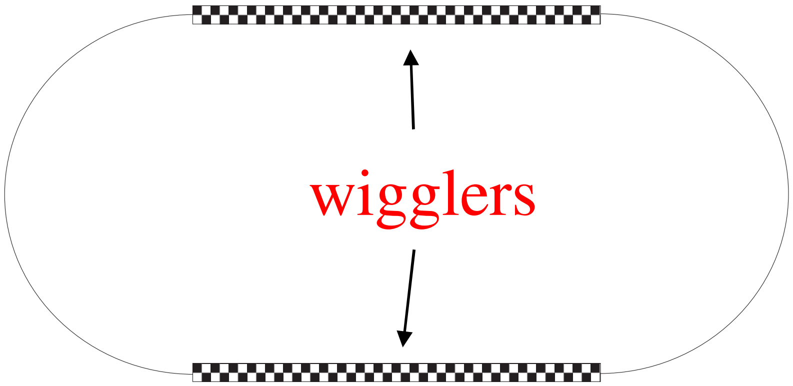
  $\mathcal{D} \approx 1$

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

Damping Rings - 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:

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

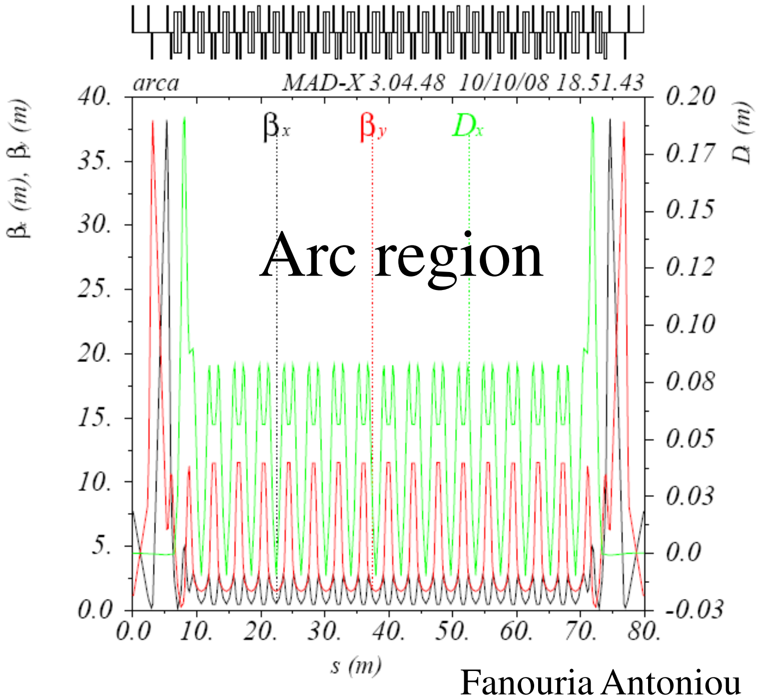
$\langle B^2 \rangle$ is the field square averaged over the wiggler length

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” linac e^- beam (no IBS) would need ~ 17ms to reach equilibrium in DR (very close to repetition time of 20ms – 50 Hz)
- 252 m long race-track PDRs with 80m of wigglers
  - Wiggler Parameters: B_w=1.7 T, L_w=2 m, λ_w=5 cm
  - 15 TME arc cells + 2 Disp.Suppr. + 2 matching sections per arc
  - 10 FODO cells in each straight section
  - Transverse damping time $\tau_{x,y}$=2.5 ms
  - e+ emittances reduced to $\gamma\varepsilon$ = 18 mm.mrad

Pre-Damping Ring input

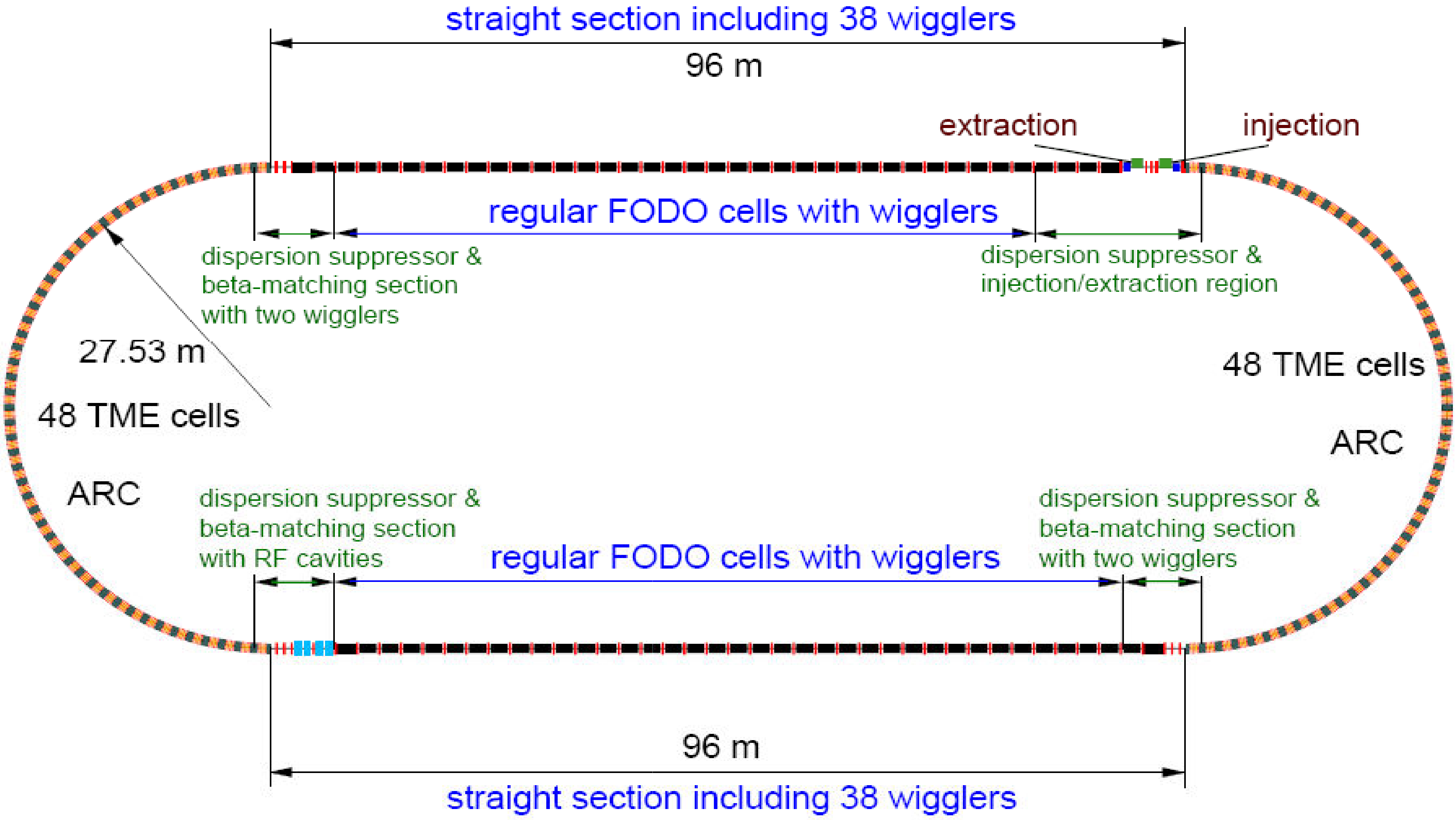
Parameter	Unit	e^-	e^+
Energy (E)	GeV	2.424	2.424
No. of particles/bunch (N)	10^9	4.4	6.4
Bunch length (rms) (σ_z)	mm	1	5
Energy Spread (rms) (σ_E)	%	0.1	2.7
Horizontal emittance ($\gamma\varepsilon_x$)	mm. mrad	100	9300
Vertical emittance ($\gamma\varepsilon_y$)	mm. mrad	100	9300



Fanouria Antoniou

CLIC damping ring layout

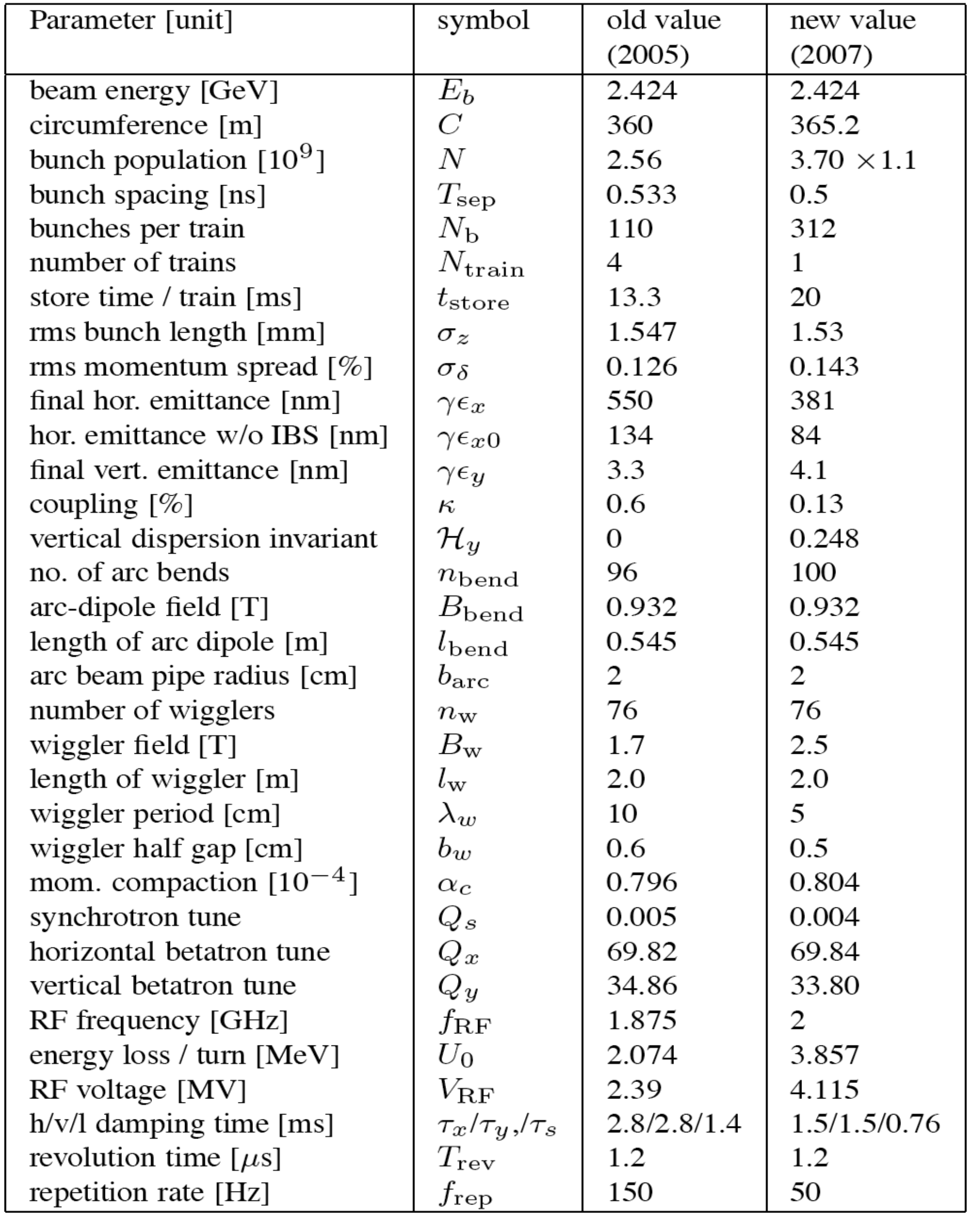
- Total length 365m (much smaller than ILC), beam pulse only 47m



M. Korostelev, PhD thesis, EPFL 2006

CLIC damping rings

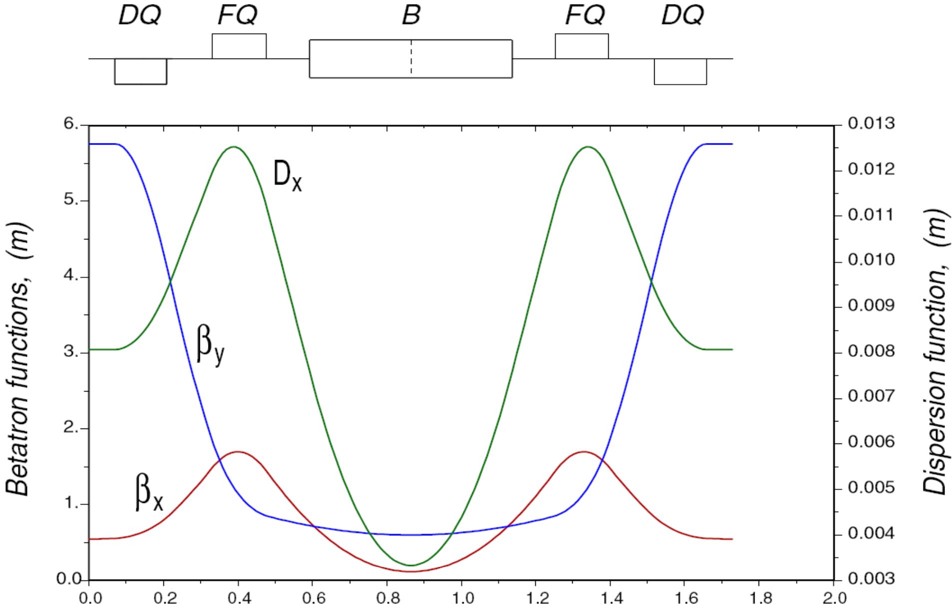
- Two rings of racetrack shape at energy of 2.424 GeV
- Arcs: 1.8m long TME cells straight sections: FODO cells with 2m-long superconducting damping wigglers (2.5T, 5cm period) total length of 365.2 m
- Phase advance per TME cell: 210° in the horizontal and 90° in the vertical plane
- The chromaticity is controlled by two sextupole families.
- Transverse damping time $\tau_{x,y}$=1.5 ms
- Final normalized emittance
- $\gamma\varepsilon_x$=381 nm.rad, $\gamma\varepsilon_y$=4.1 nm.rad

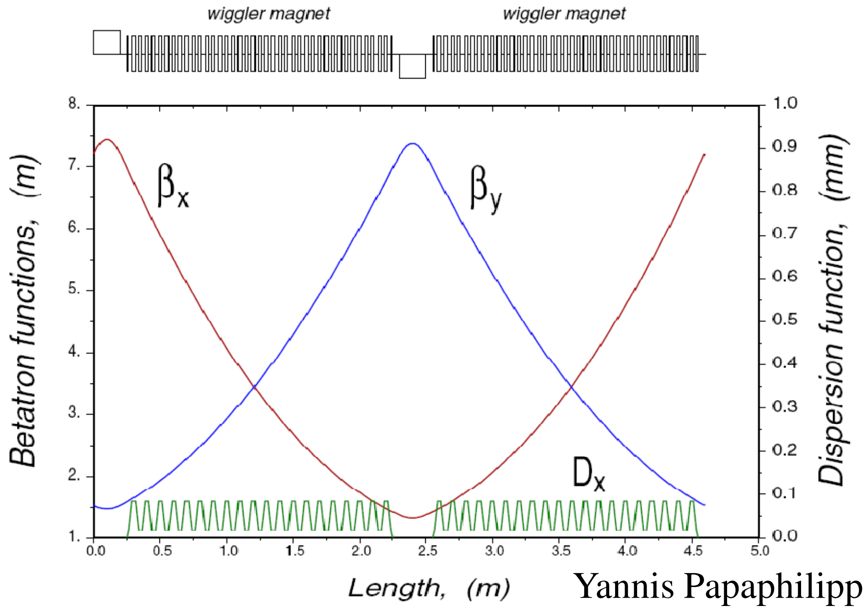


Parameter [unit]	symbol	old value (2005)	new value (2007)
beam energy [GeV]	E_b	2.424	2.424
circumference [m]	C	360	365.2
bunch population [10^9]	N	2.56	3.70 $\times$1.1
bunch spacing [ns]	T_{sep}	0.533	0.5
bunches per train	N_{b}	110	312
number of trains	N_{train}	4	1
store time / train [ms]	t_{store}	13.3	20
rms bunch length [mm]	σ_z	1.547	1.53
rms momentum spread [%]	σ_δ	0.126	0.143
final hor. emittance [nm]	$\gamma\epsilon_x$	550	381
hor. emittance w/o IBS [nm]	$\gamma\epsilon_{x0}$	134	84
final vert. emittance [nm]	$\gamma\epsilon_y$	3.3	4.1
coupling [%]	κ	0.6	0.13
vertical dispersion invariant	$\mathcal{H}_y$	0	0.248
no. of arc bends	n_{bend}	96	100
arc-dipole field [T]	B_{bend}	0.932	0.932
length of arc dipole [m]	l_{bend}	0.545	0.545
arc beam pipe radius [cm]	b_{arc}	2	2
number of wigglers	n_{w}	76	76
wiggler field [T]	B_{w}	1.7	2.5
length of wiggler [m]	l_{w}	2.0	2.0
wiggler period [cm]	λ_w	10	5
wiggler half gap [cm]	b_w	0.6	0.5
mom. compaction [10^{-4}]	α_c	0.796	0.804
synchrotron tune	Q_s	0.005	0.004
horizontal betatron tune	Q_x	69.82	69.84
vertical betatron tune	Q_y	34.86	33.80
RF frequency [GHz]	f_{RF}	1.875	2
energy loss / turn [MeV]	U_0	2.074	3.857
RF voltage [MV]	V_{RF}	2.39	4.115
h/v/l damping time [ms]	$\tau_x/\tau_y,/\tau_s$	2.8/2.8/1.4	1.5/1.5/0.76
revolution time [μs]	T_{rev}	1.2	1.2
repetition rate [Hz]	f_{rep}	150	50

Arc and wiggler cell

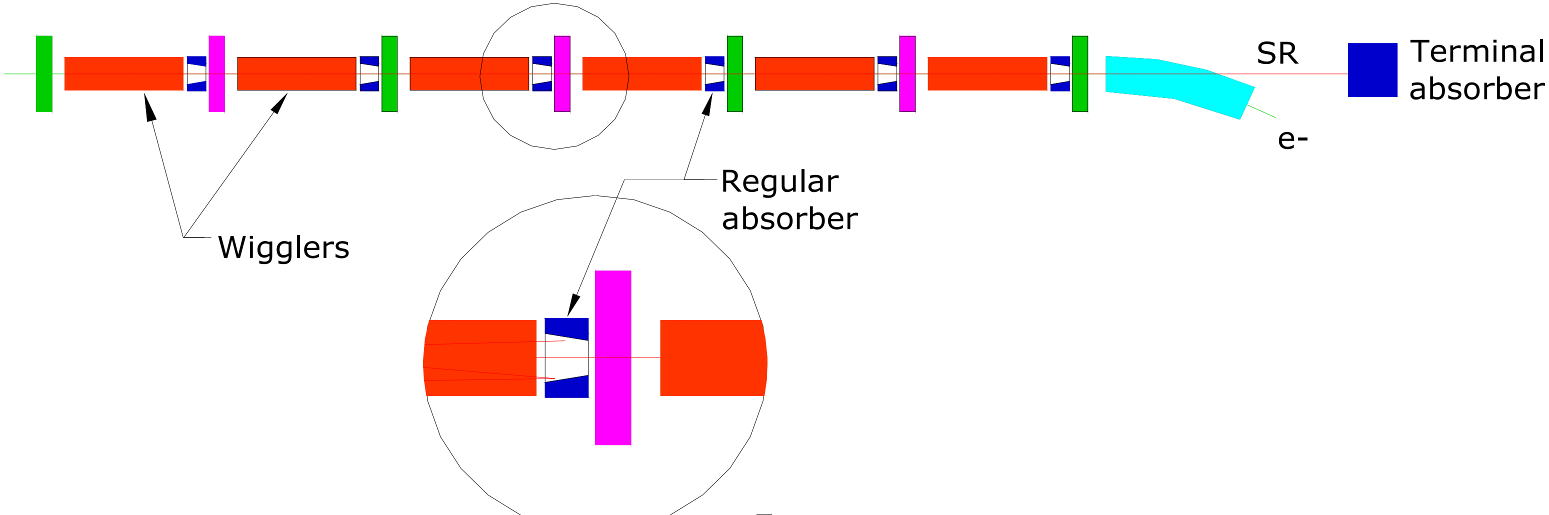
- TME arc cell chosen for compactness and efficient emittance minimisation over Multiple Bend Structures used in light sources
  - Large phase advance necessary to achieve optimum equilibrium emittance
  - Very low dispersion
  - Strong sextupoles needed to correct chromaticity
  - Impact in dynamic aperture
  - Very limited space
  - Extremely high quadrupole and sextupole strengths
- FODO wiggler cell with phase advances close to 90° giving
  - Average β's of ~4m and reasonable chromaticity
  - Quad strength adjusted to cancel wiggler induced tune-shift
  - Limited space for absorbers



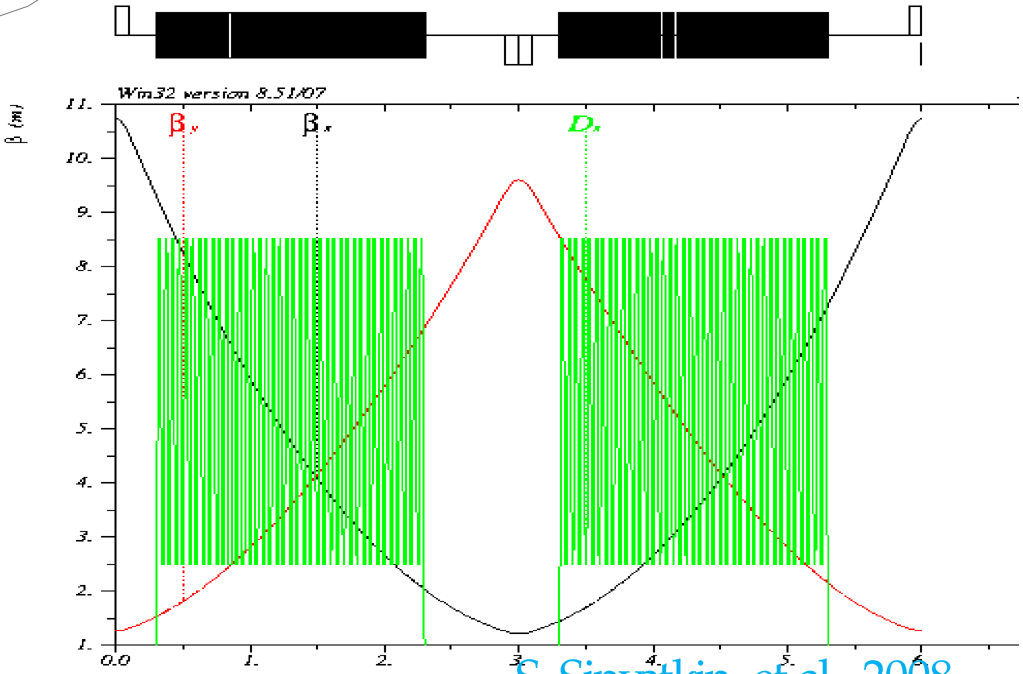


Yannis Papaphilippou

Wiggler cell including absorbers



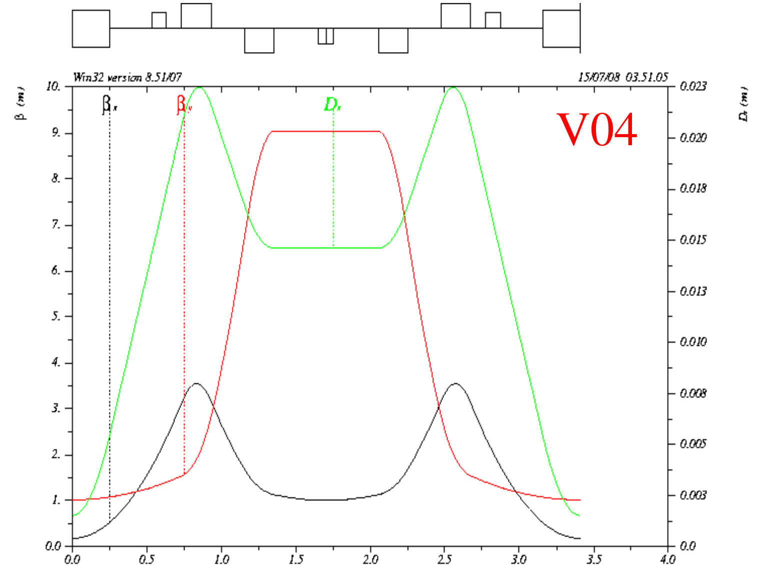
- Added space between wiggler and downstream quadrupoles for accommodating SR absorbers
- 30% increase of the wiggler section length
- Slight increase of beta maxima (and chromaticity)

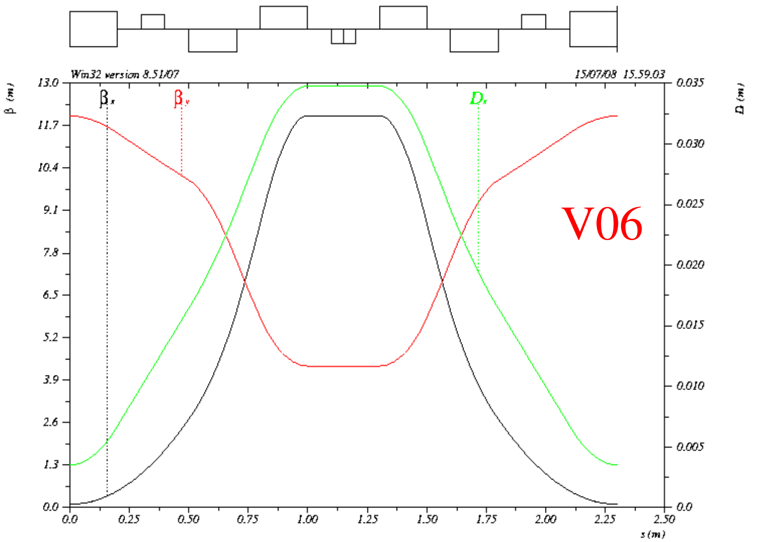


S. Sinyatkin, et al., 2008

New proposed arc cells

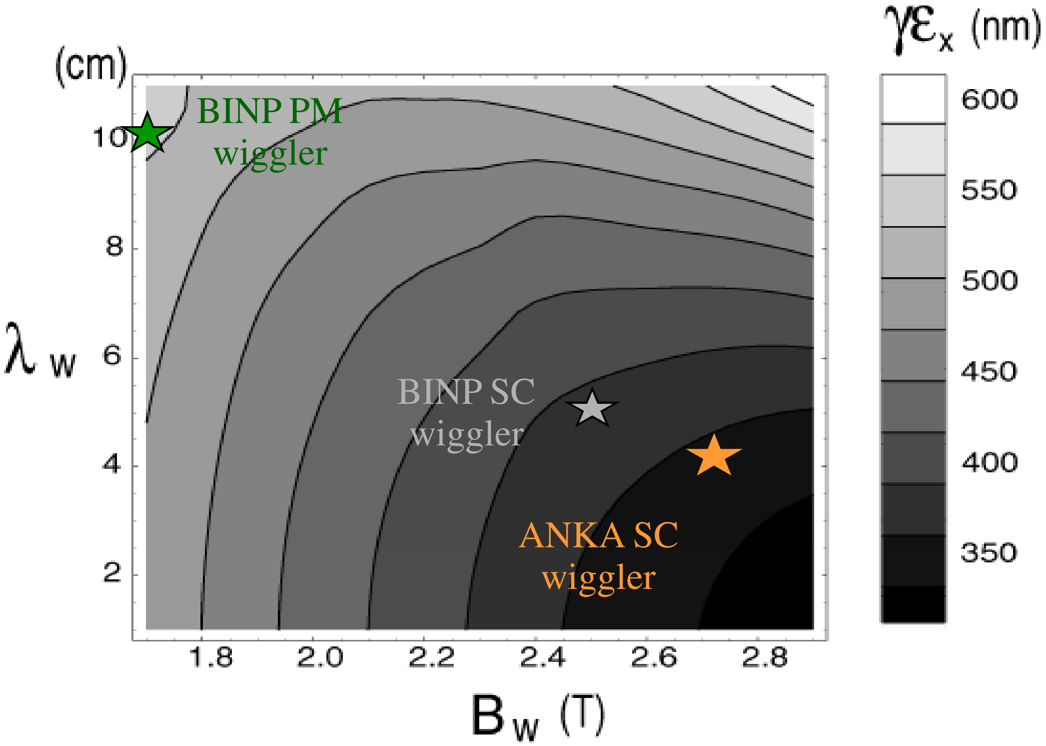
S. Sinyatkin, et al., 2008





Structure version	Original	V04	V06
Energy [GeV]	2.424		
Circumference [m]	365.21	**534**	493.05
Coupling	0.0006		
Losses per turn [MeV/turn]	3.8600	3.9828	3.9828
RF voltage [MV]	4.38	4.35	4.601
Natural chromaticity x / y	-103 / -136	**-186/ -118**	-148.8 / -79.0
Compaction factor	8.0213E-05	4.56E-05	6.4427E-05
Dumping time x / s [ms]	1.53 / 0.76	2.17 / 1.09	1.99 / 1.01
Dynamic aperture a/σ_{inj} x / y	±3.5 / 6	**±1.5 / 5**	**±12 / 50**
Number of arc cells	100		
Number of wigglers	76		
Cell length [m]	1.729	2.729	2.300
Dipole length [m]	0.544944	0.4	
Bend field [T]	0.93	1.27	
Bend gradient [1/m^2]	0	0	**-1.10**
Max. Quad gradient [T/m]	**220**	107.7	**60.3**
Sext. strength [T/m^2]*10^3	**80**	24.1	**-6.59**
Phase advance x / z	0.581 / 0.248	0.524 / 0.183	0.442 / 0.045
Bunch population, N*10^9	4.1		
IBS gain factor	5.1831	3.62	2.89
Normalized Emittance [nm*rad]	**449**	**439.26**	**428.4**
Bunch length [mm]	1.402	1.450	1.380
Longitudinal emmitance [eVm]	5339	5694	5188

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

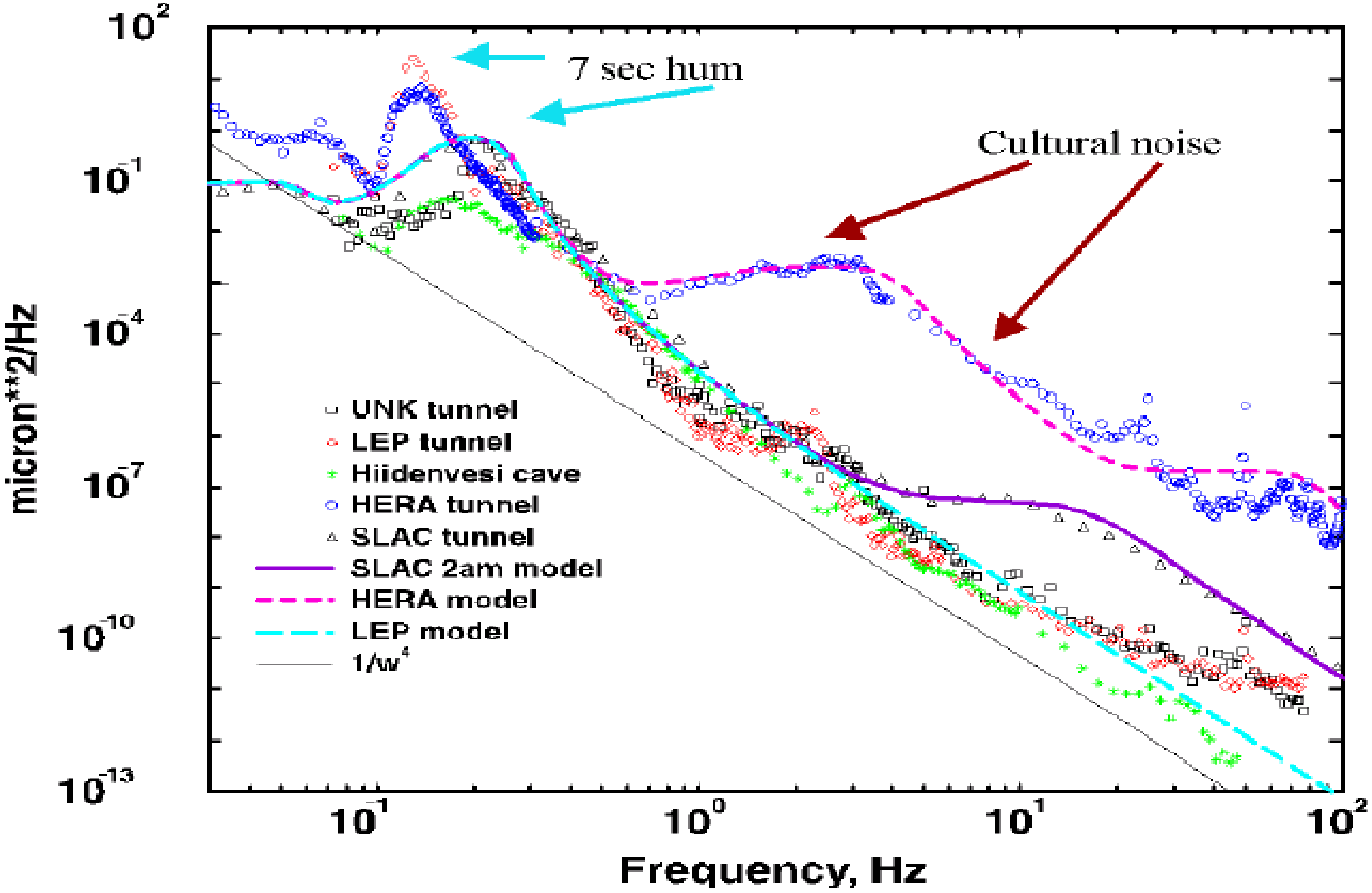
Alignment + Stabilisation

- 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

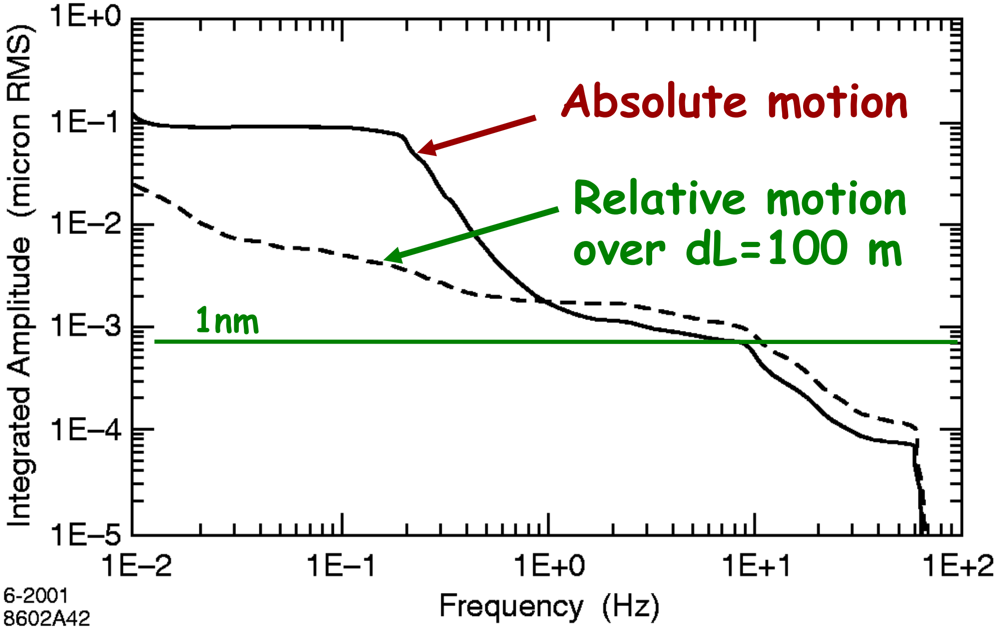
- Need to consider short and long term stability of the collider
- Ground motion model: ATL law

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

A site dependent constant
T time
L distance

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

- 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

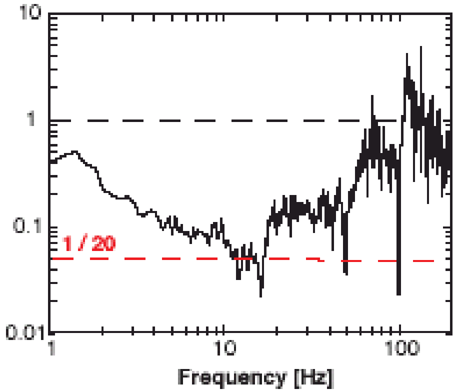
Need active damping of vibrations


CERN vibration test stand

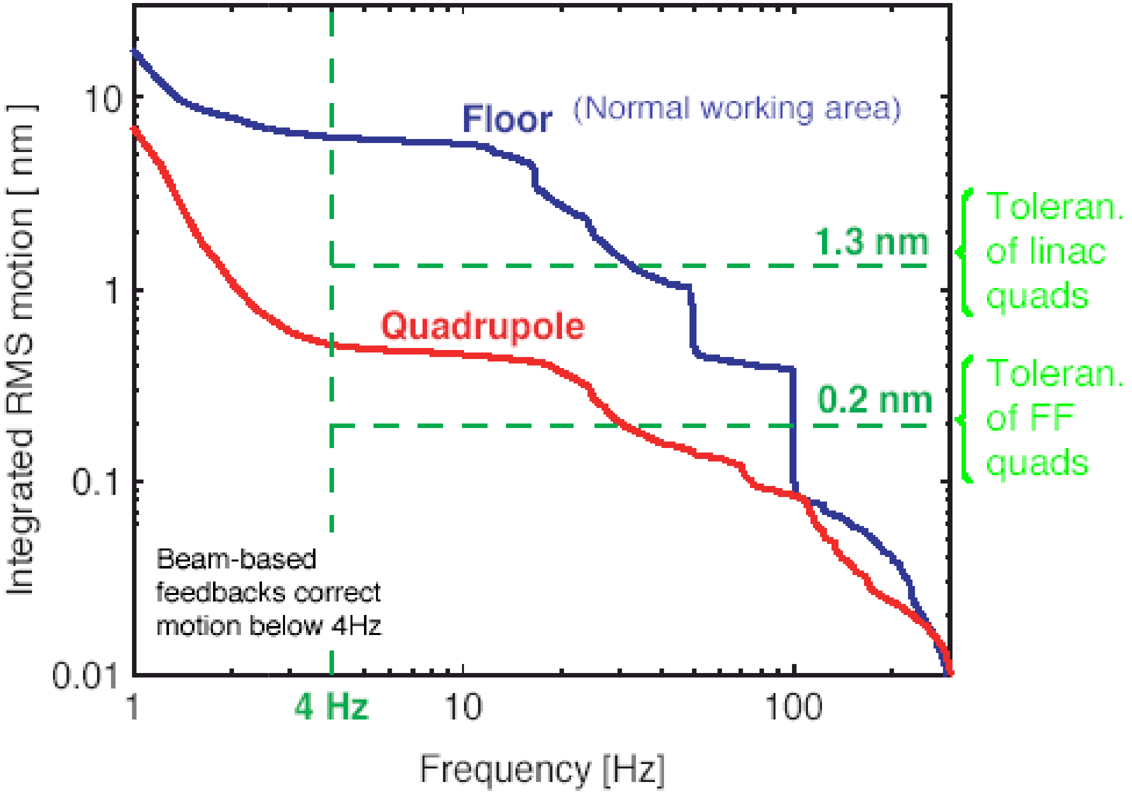
Ground motion

Vertical stabilization of a CLIC prototype quadrupole

Ground-to-table transmission



Integrated *vertical* RMS motion versus frequency



RMS vibrations above 4 Hz

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

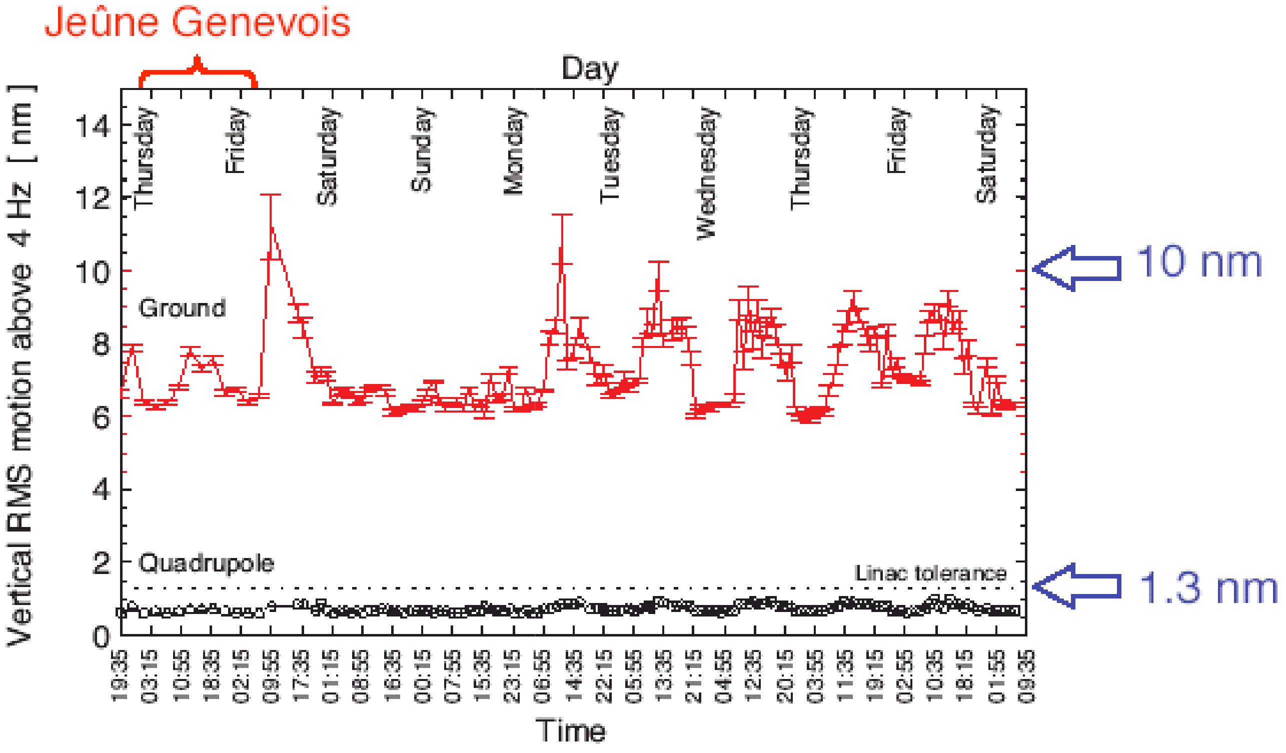
CLIC prototype magnets stabilized to the sub-nanometre level !!

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***?



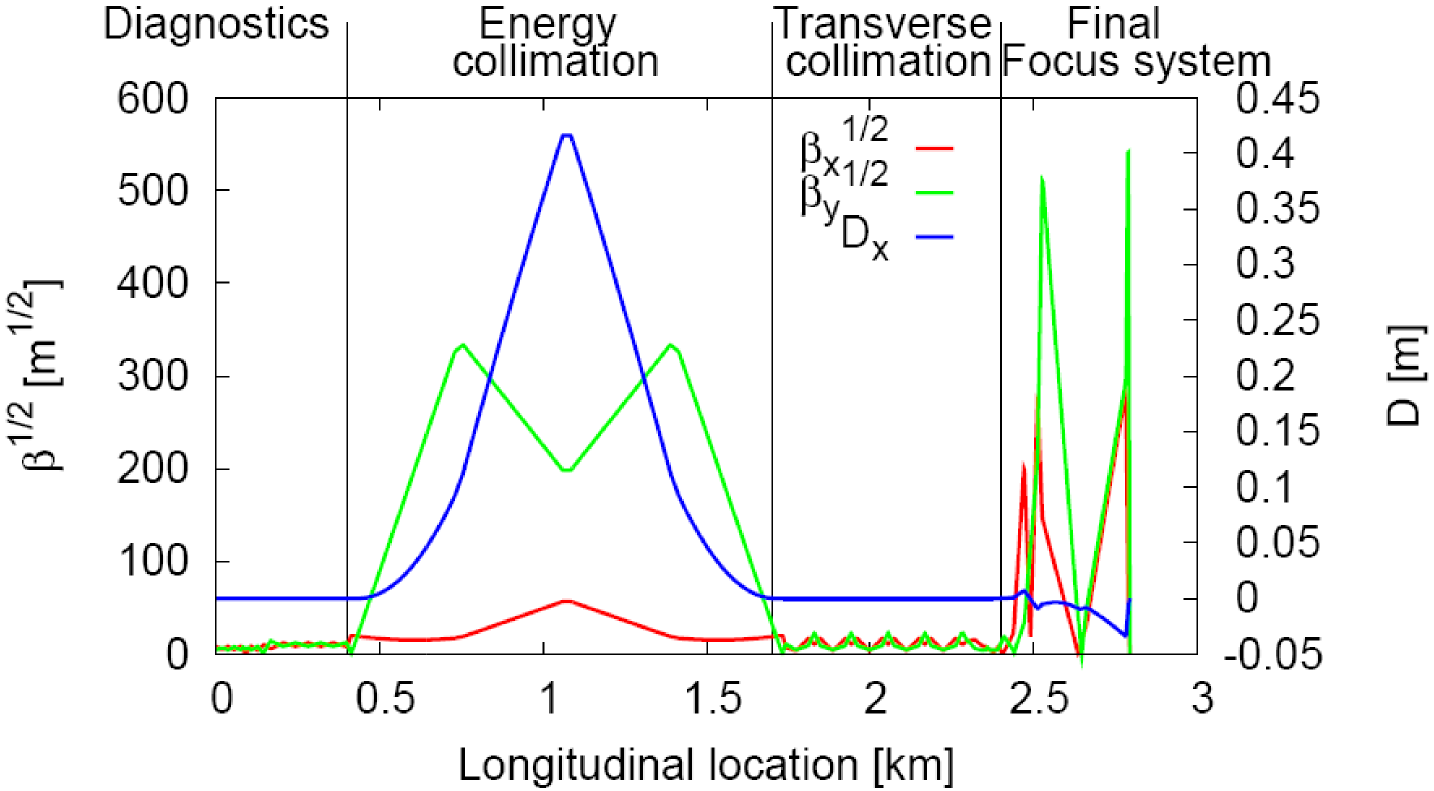
Quadrupole vibrations kept below the 1 nm level

over a period of 9 consecutive days!

Stefano Redaelli

Beam Delivery System

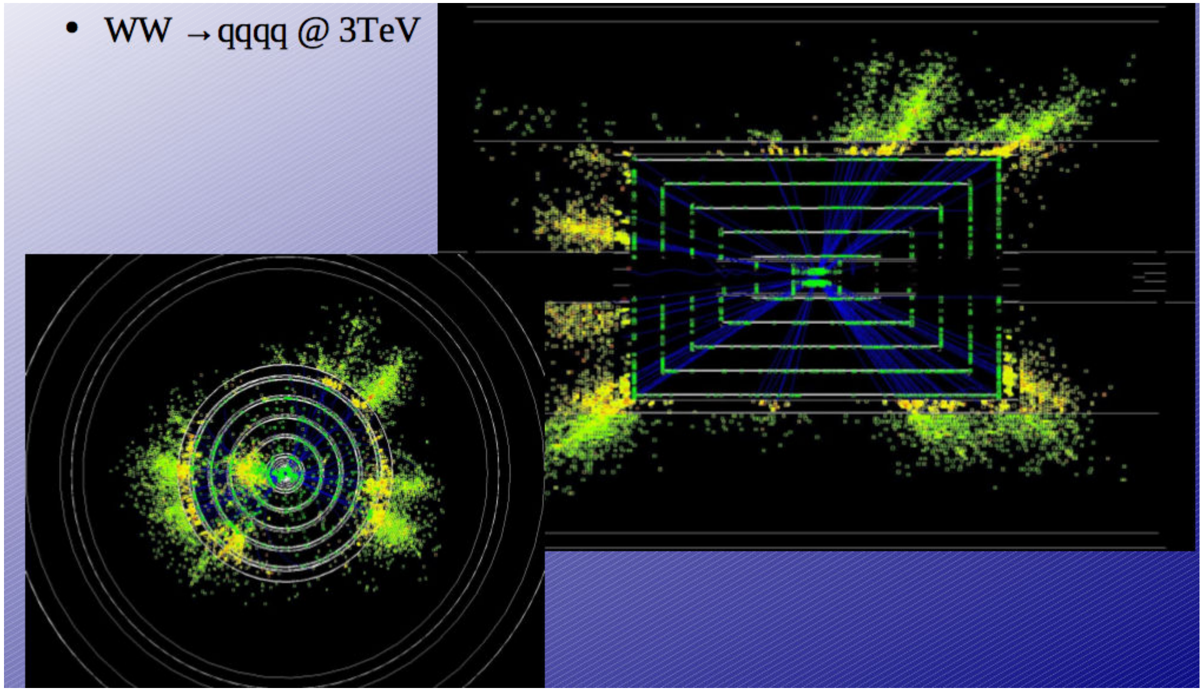
- many common issues as for ILC
- diagnostics, emittance measurement, energy measurement, …
- collimation, crab cavities, beam-beam feedback, beam extraction, beam dump



CLIC detectors

- Different time structure of the beam has to be taken into account
- 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

- Collaboration meeting with ILC Project managers and specific experts on 08/02/08 at CERN for collaboration on subjects with strong synergy between CLIC and ILC:

  1) Civil Engineering and Conventional Facilities
  2) Beam Delivery Systems & Machine Detector Interf.
  3) Detectors
  4) Cost & Schedule
  5) Beam dynamics & Beam Simulations

  Possible additional working groups on Positron Generation and Damping Rings

- Mandate and work plan by nominated conveners:

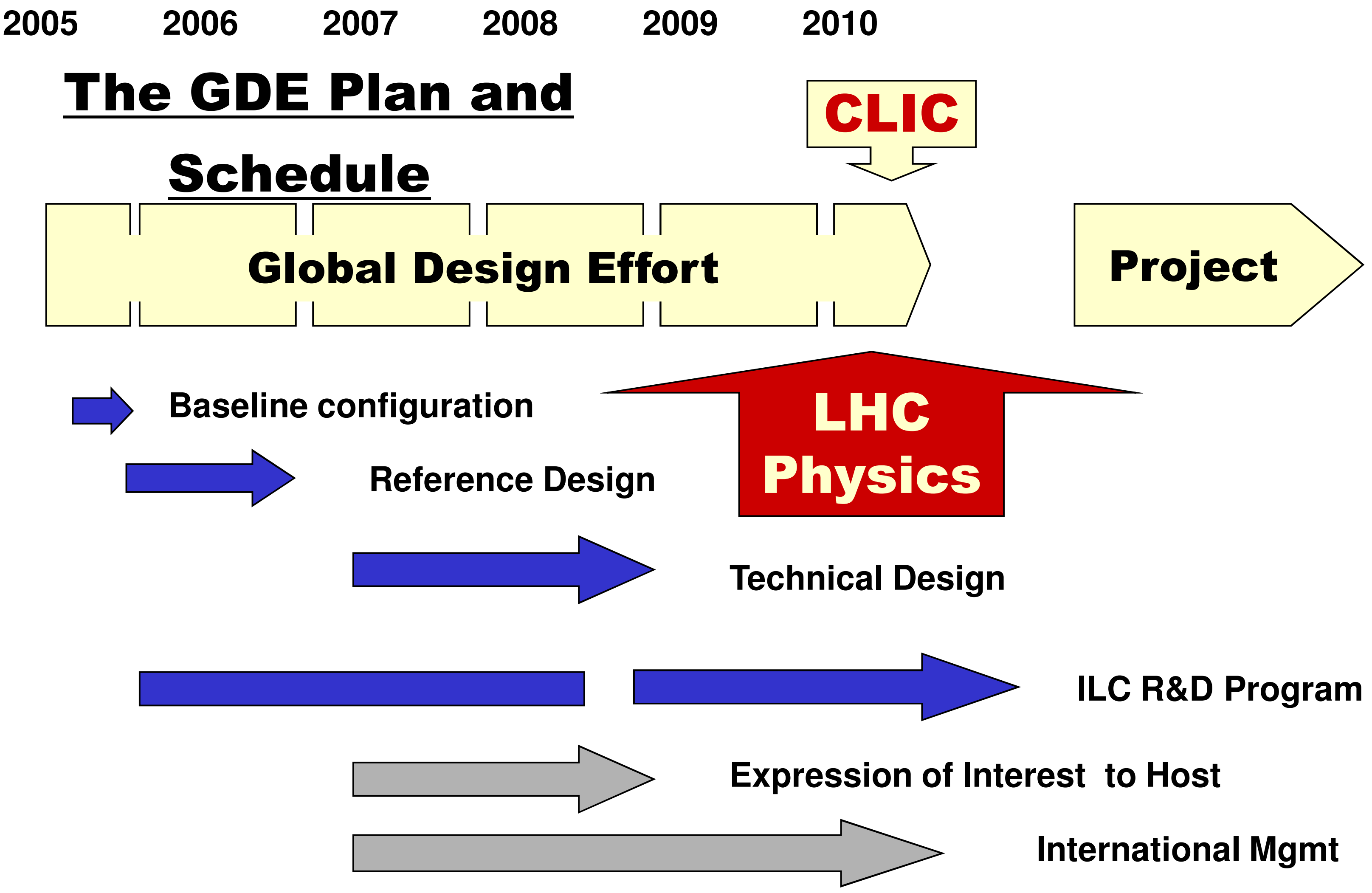
  http://indico.cern.ch/conferenceDisplay.py?confId=27435

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

- Report of progress in existing meetings

CLIC and ILC timeline

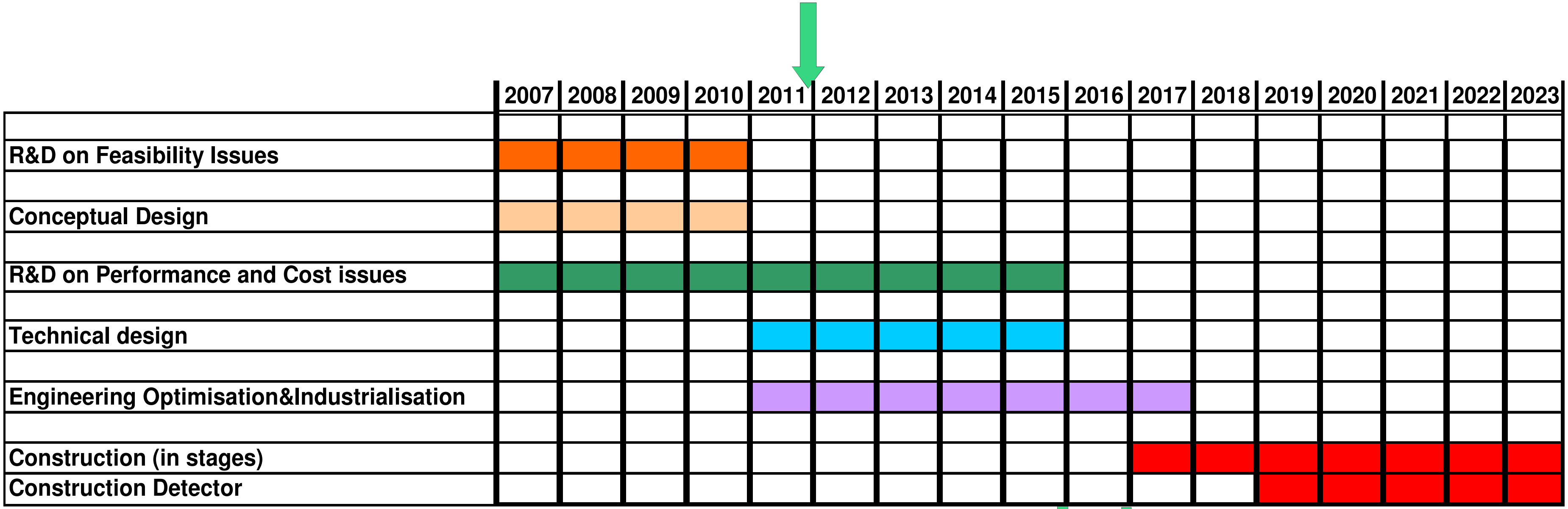
From B. Barish, ILC Global Design Effort director



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

Aim to provide the High Energy Physics community with the feasibility of CLIC technology for Linear Collider in due time, when physics needs will be fully determined following LHC results

Alternative to the SC technology in case sub-TeV energy range is not considered attractive enough for physics

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
- 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

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*