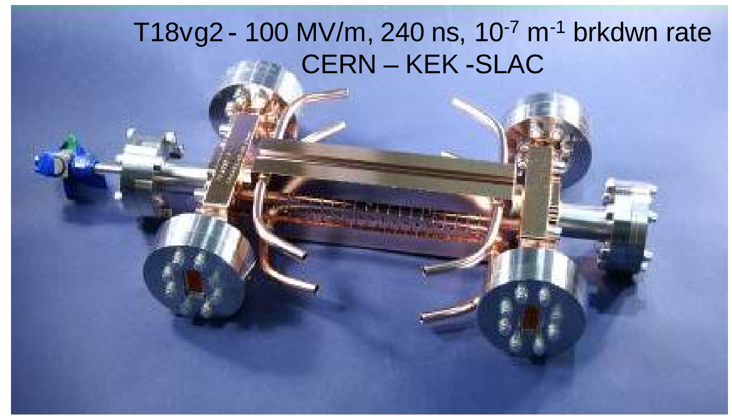
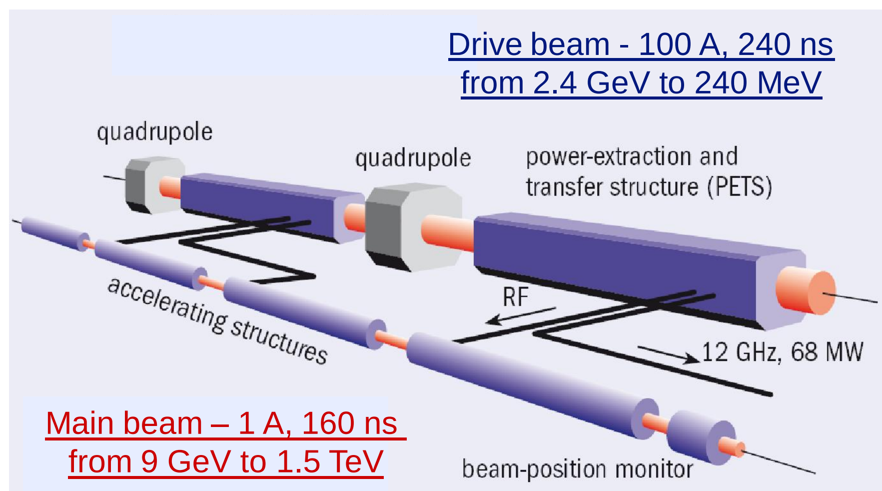
The CLIC way to a multi-TeV linear collider - Basic features

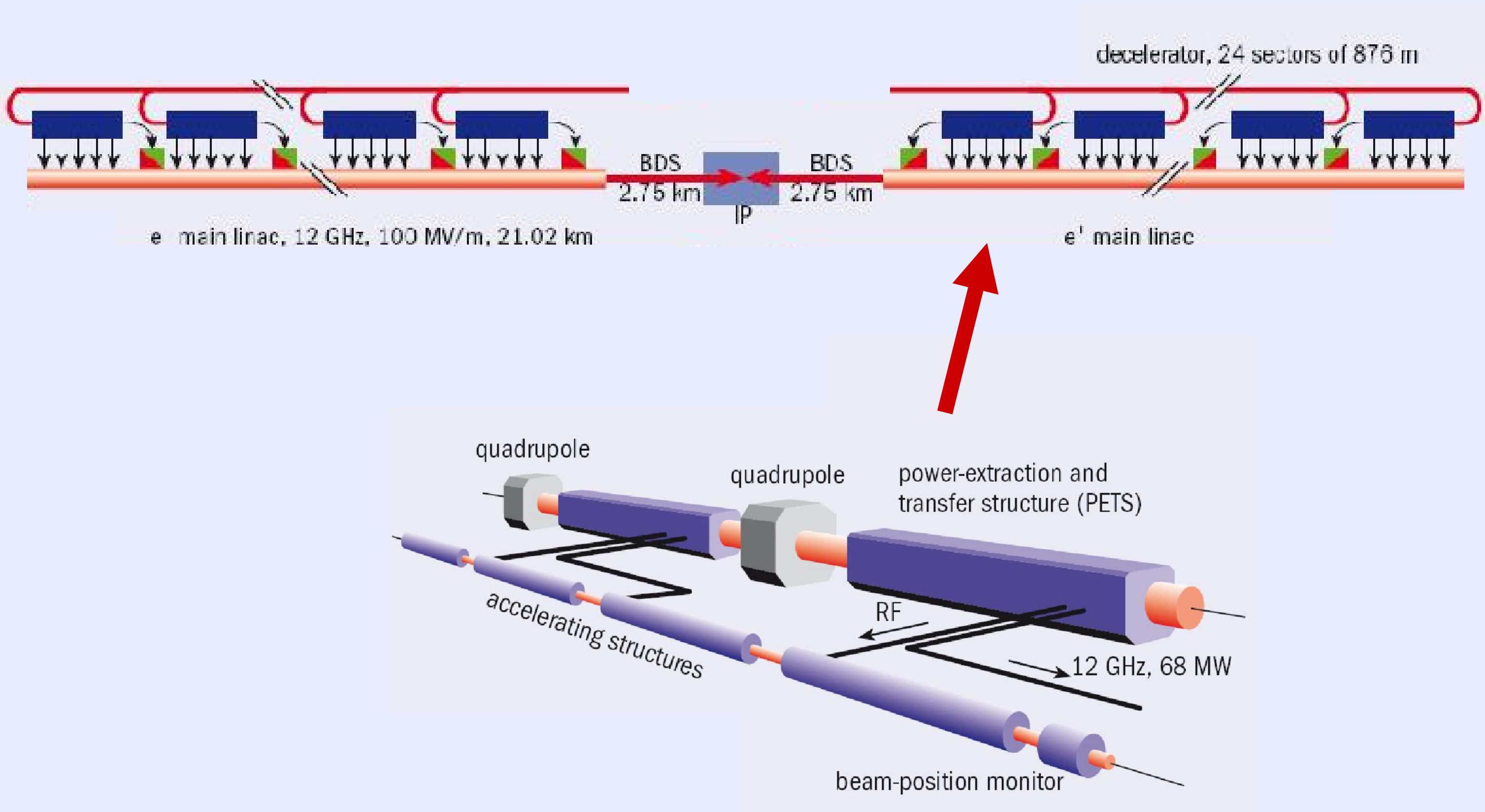
- High acceleration gradient (100 MV/m)
  - ✓ "Compact" collider - overall length @ 3 TeV < 50 km
  - ✓ Normal conducting accelerating structures
  - ✓ High acceleration frequency (12 GHz)

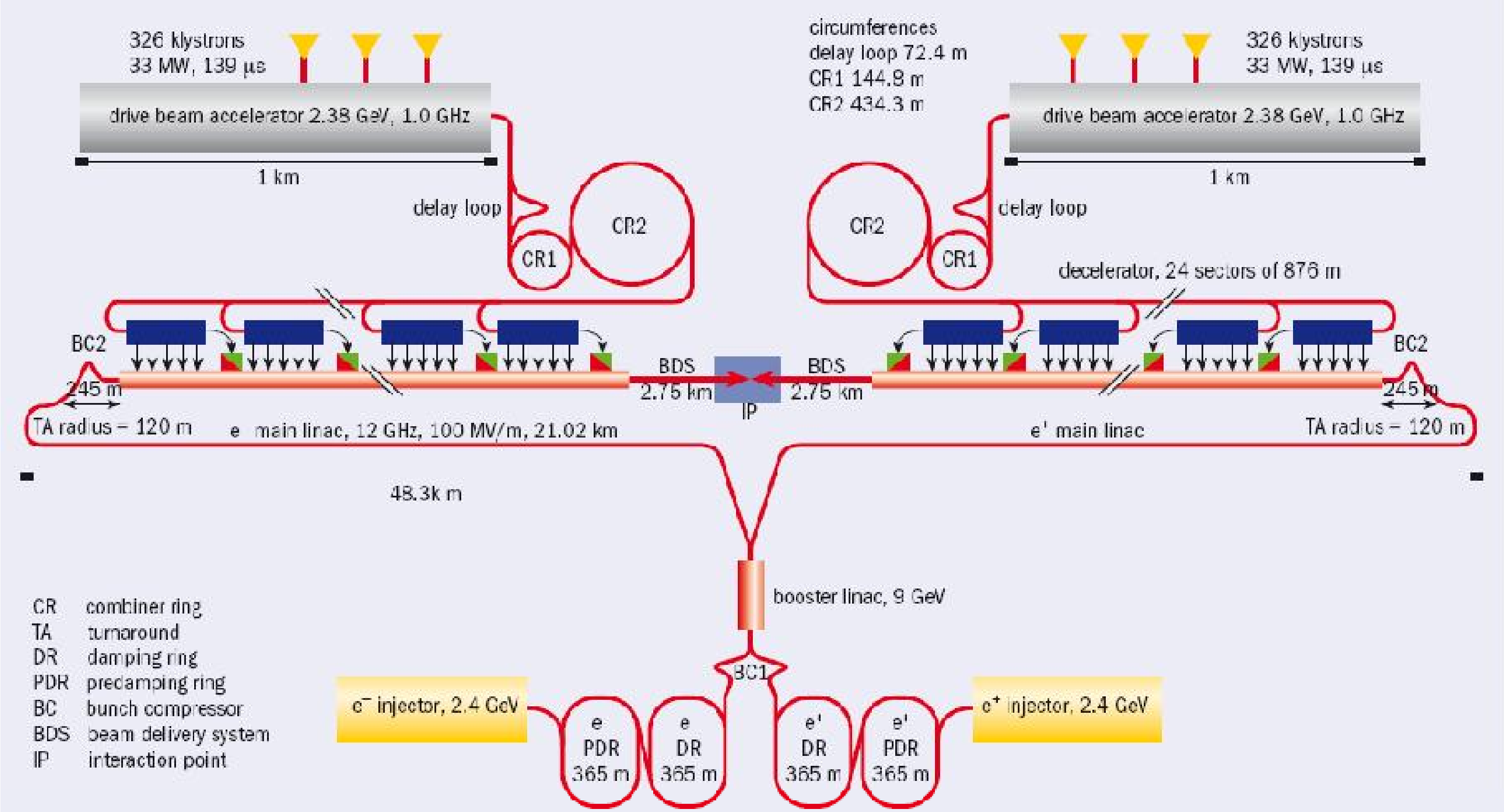


- Two-Beam Acceleration Scheme
  - ✓ Cost effective, reliable, efficient
  - ✓ Simple tunnel, no active elements
  - ✓ Modular, easy energy upgrade in stages

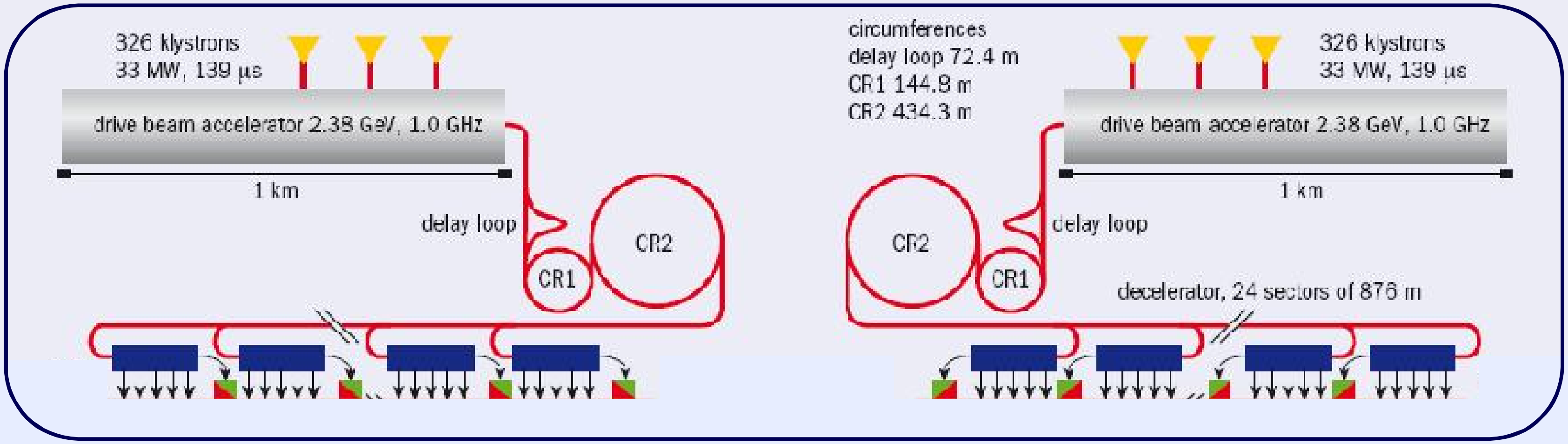


The CLIC Two-Beam Accelerator





CLIC schematic layout @ 3 TeV



CLIC RF power source

CLIC schematic layout @ 3 TeV

The CLIC scheme - What does the RF Power Source do ?

The CLIC RF power source can be described as a “black box”, combining *very long RF pulses*, and transforming them in *many short pulses*, with *higher power* and with *higher frequency*

650 Klystrons

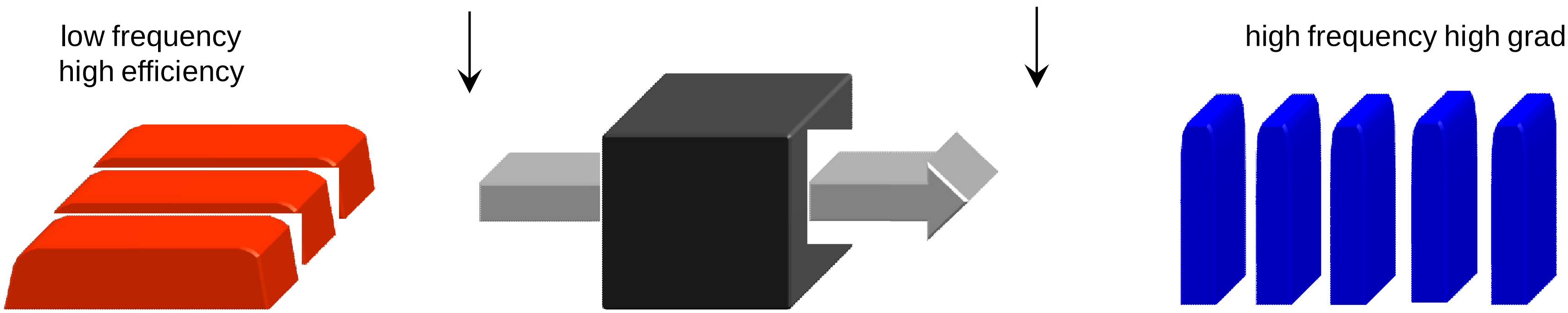
low frequency
high efficiency

Power stored in electron beam

Power extracted from beam in resonant structures

140000 Accelerating Structures

high frequency high gradient



Long RF Pulses

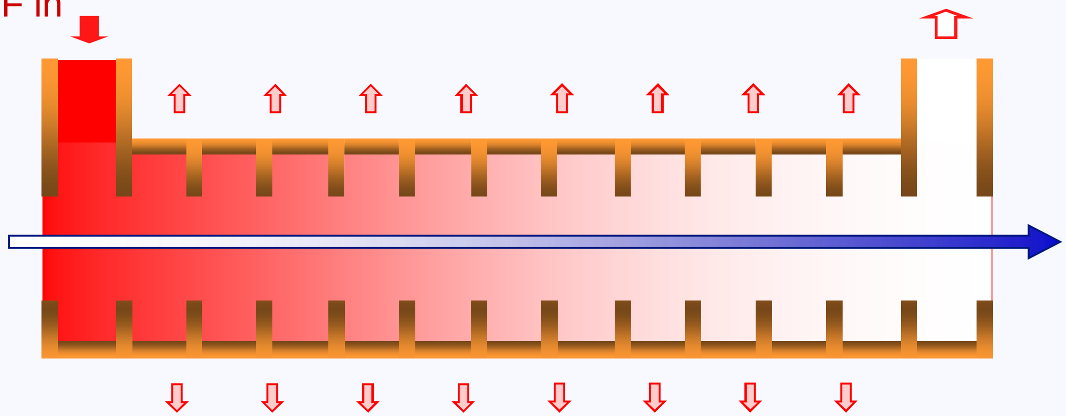
P_0 , n_0 , τ_0

Electron beam manipulation

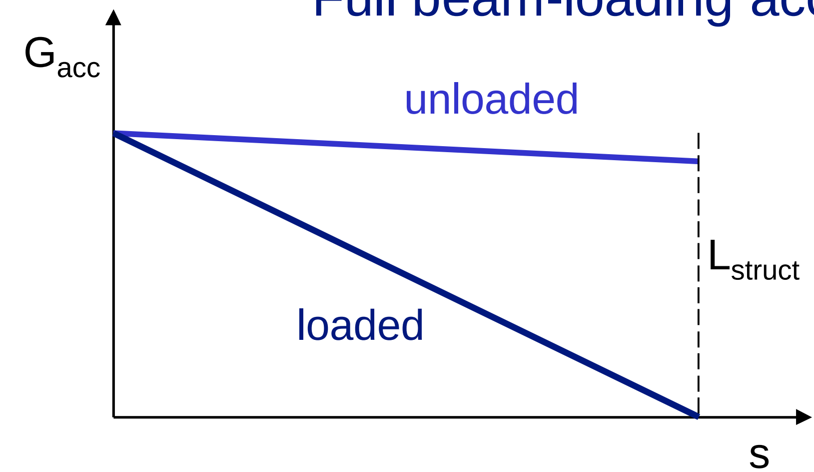
Short RF Pulses

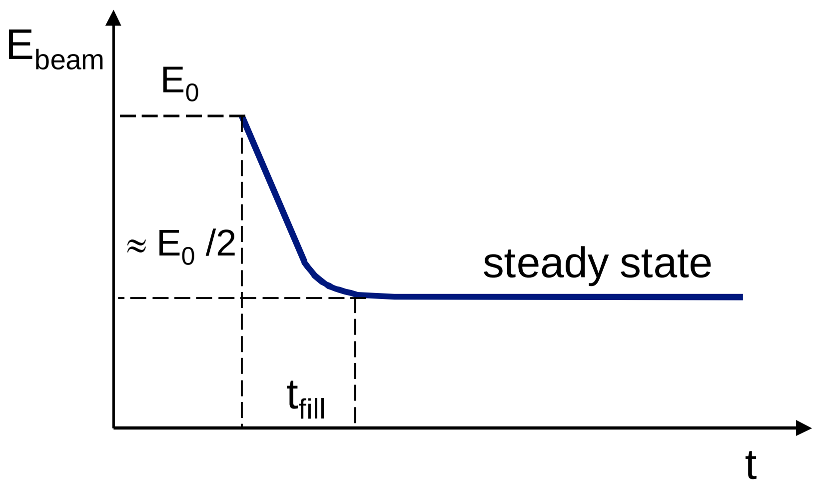
$$P_A = P_0 \times N_1$$
$$\tau_A = t_0 / N_2$$
$$\nu_A = \nu_0 \times N_3$$

Full beam-loading acceleration in TW sections

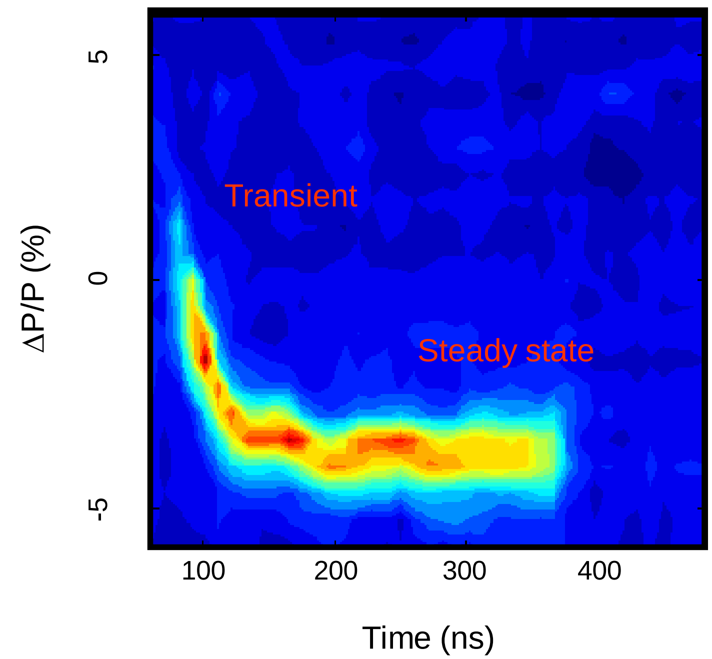


Full beam-loading acceleration in TW sections

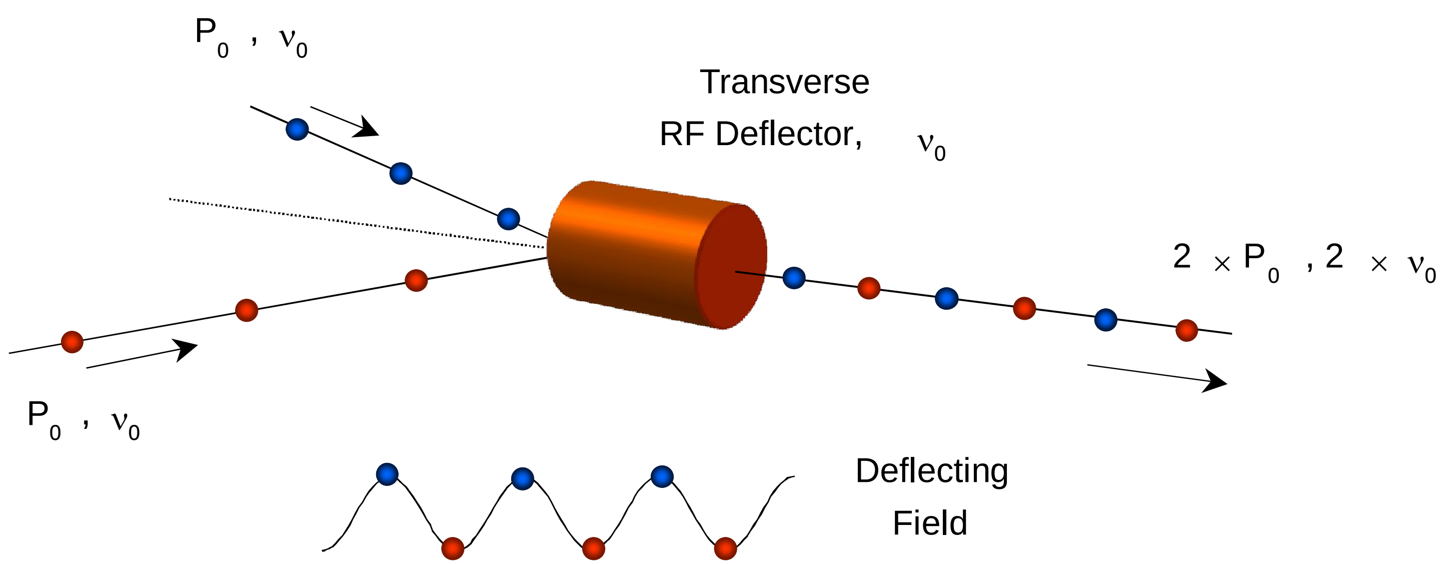




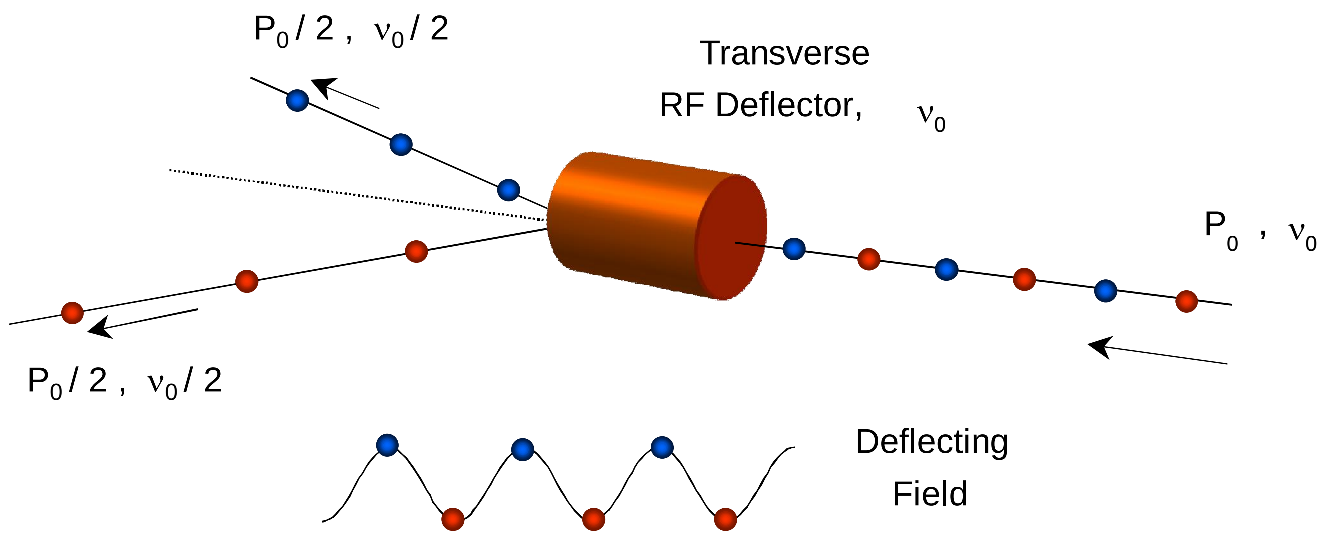
Time resolved beam energy spectrum measurement in CTF3



Beam combination/separation by transverse RF deflectors



Beam combination/separation by transverse RF deflectors

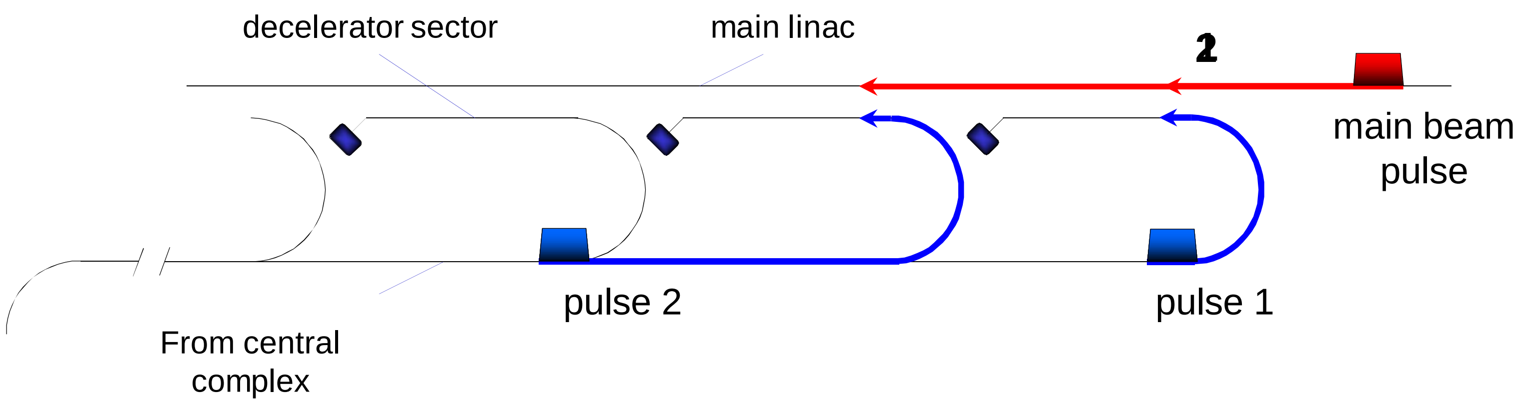


Counter flow distribution

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.

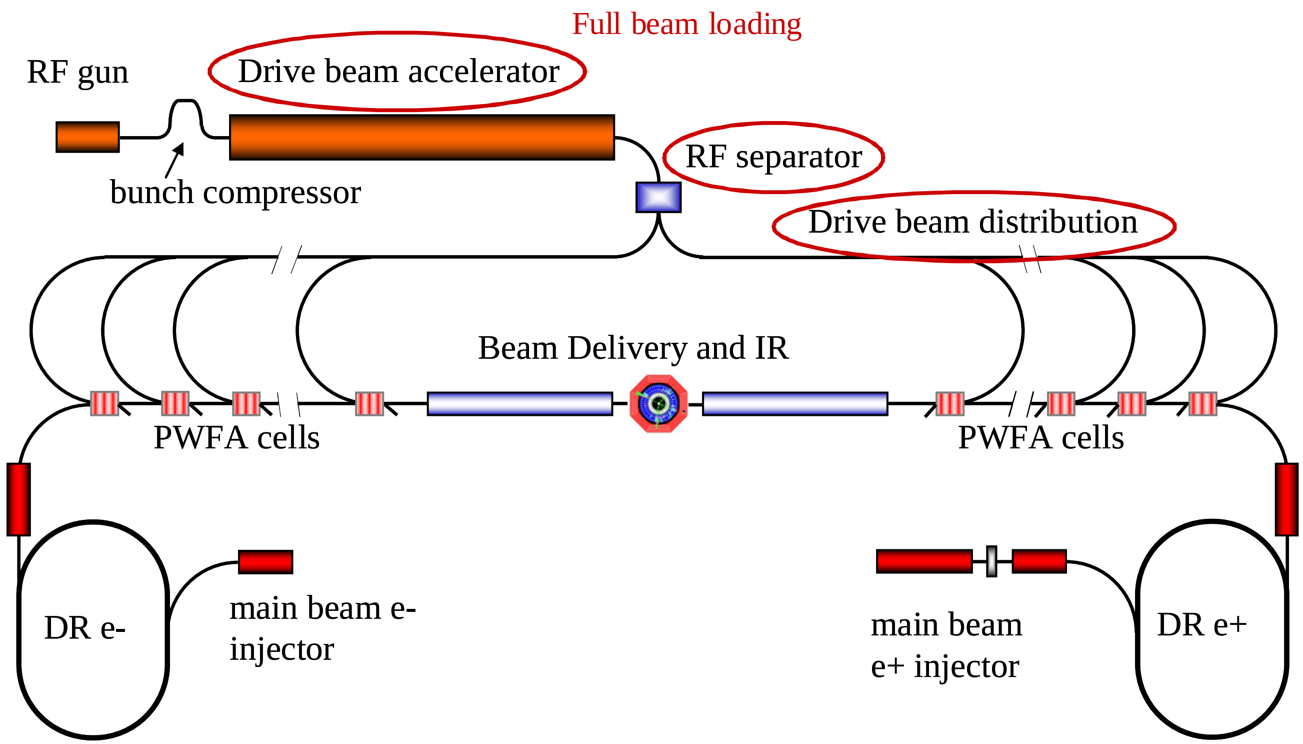
Each one feed a 900 m long sector of TBA.



(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 μs/c.

Use of CLIC-like drive beam in Plasma Wakefield Accelerator

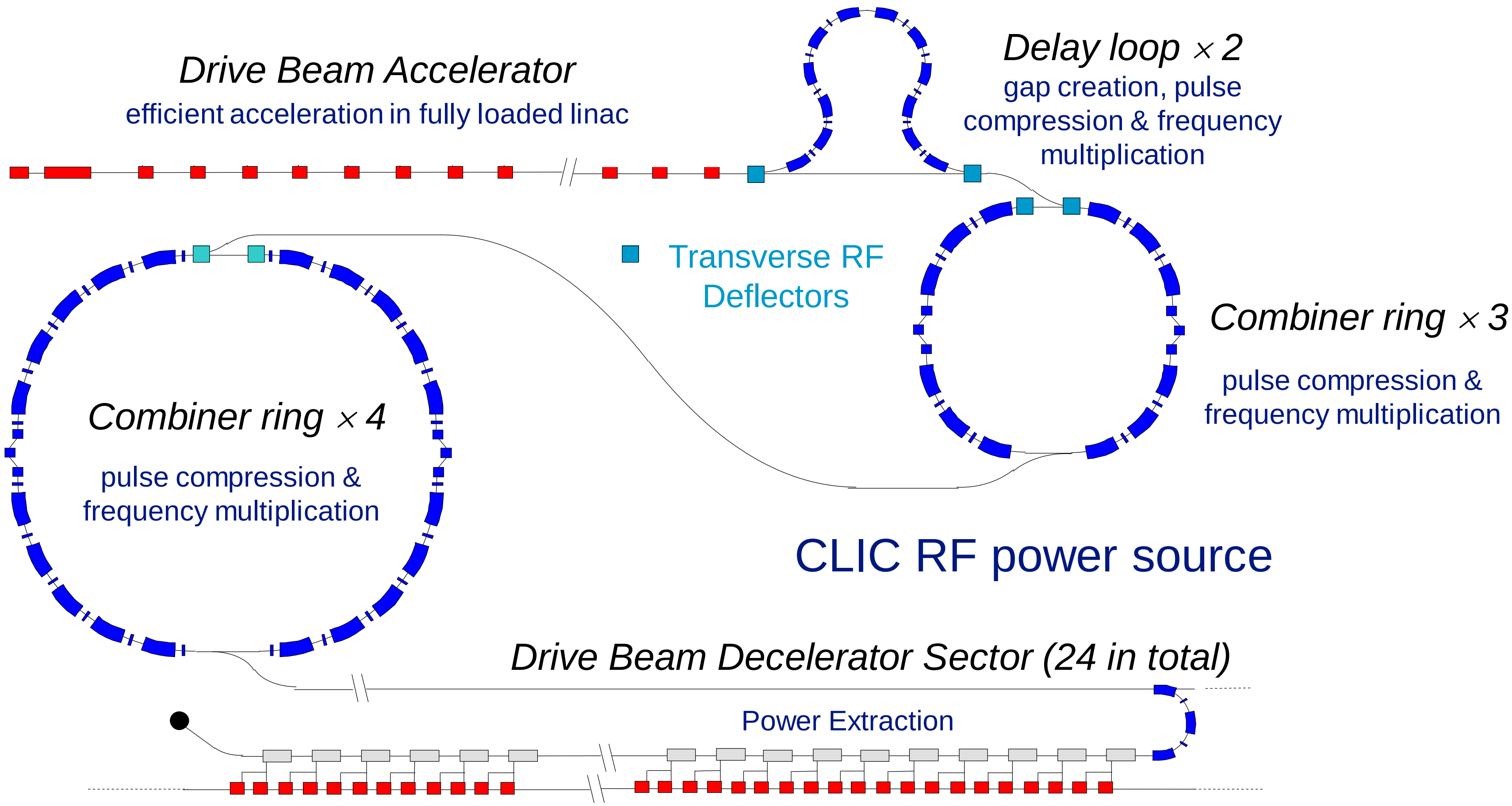


Concept for multi-stage PWFA Linear Collider

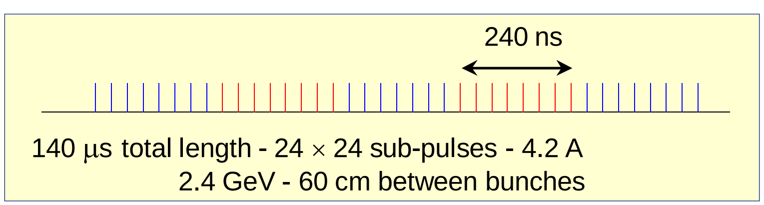
(collinear two-beam accelerator)

A. Seryi – PAC 09

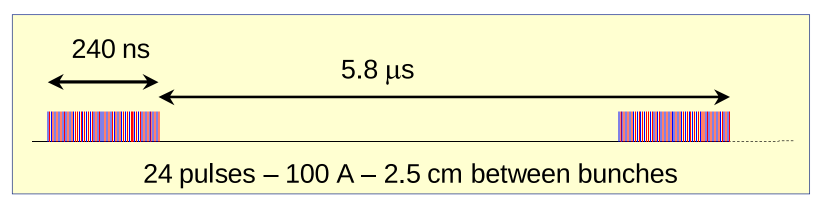
CTF3, Drive Beam Efficiency and use in PWFA-LC



Drive beam time structure - initial

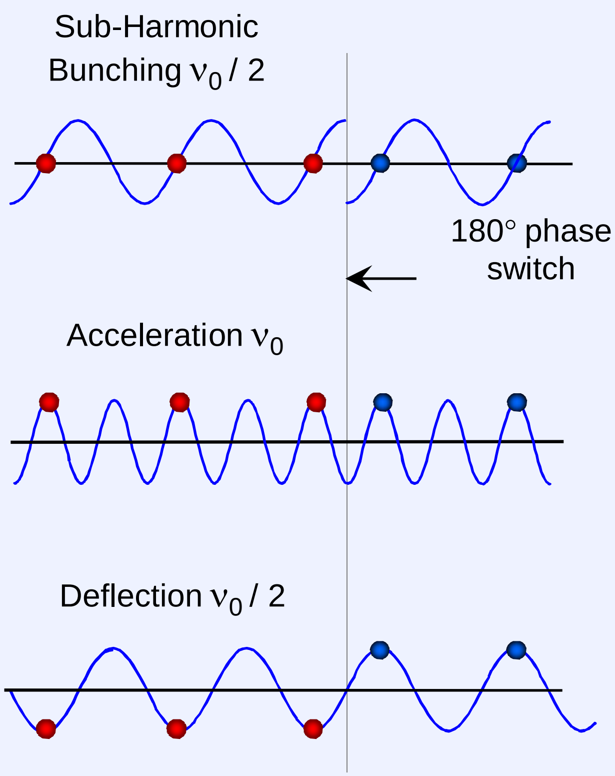


Drive beam time structure - final



Phase coding

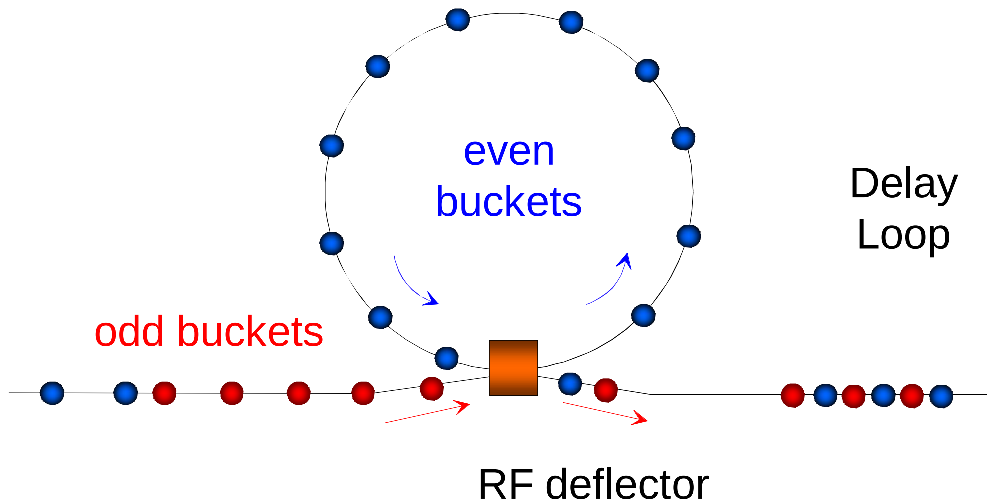
How to “code” the sub-pulses



Gap creation & first multiplication × 2

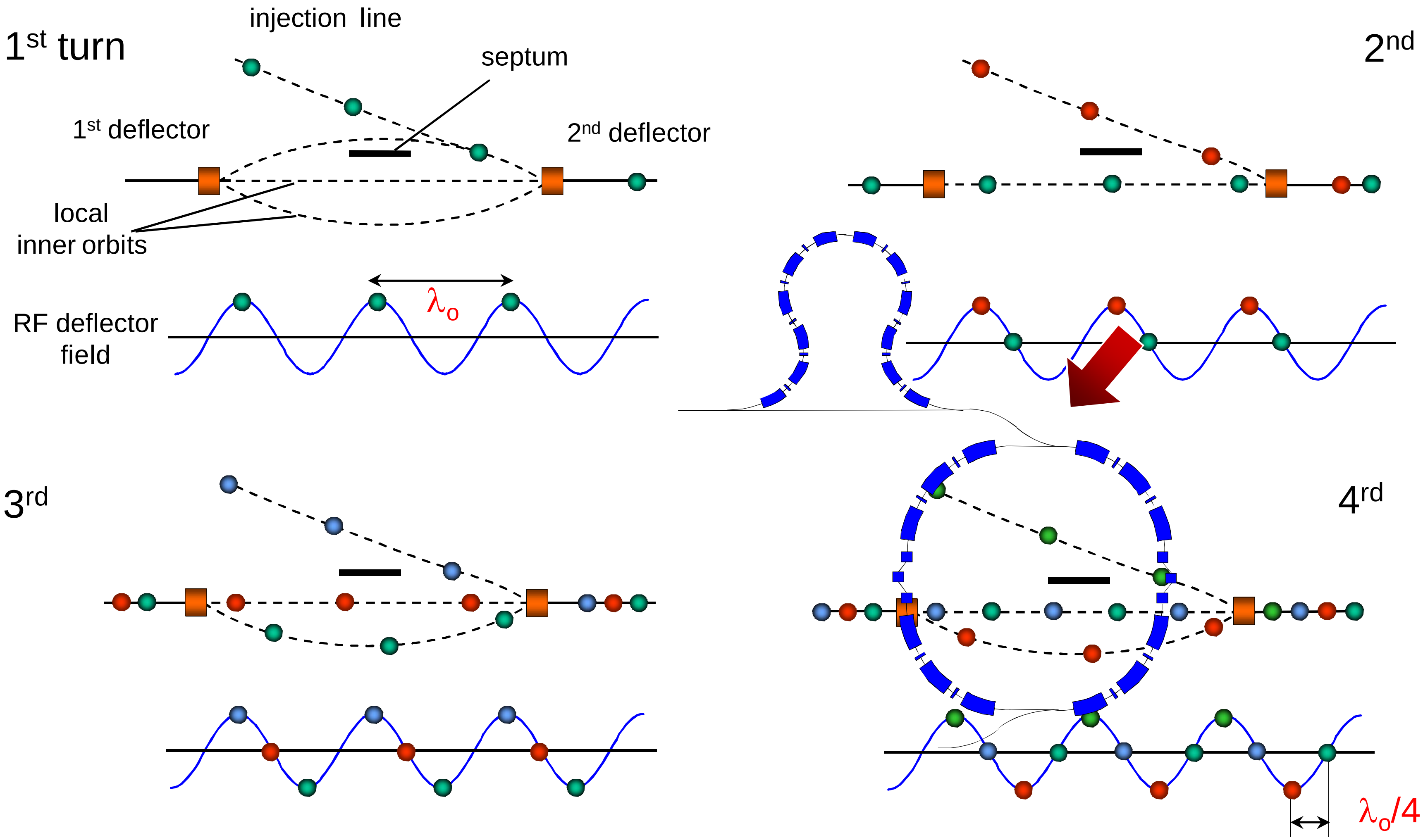
$$L_{delay} = n\ \lambda_0 = c\ T_{sub\text{-}pulse}$$

Combination scheme



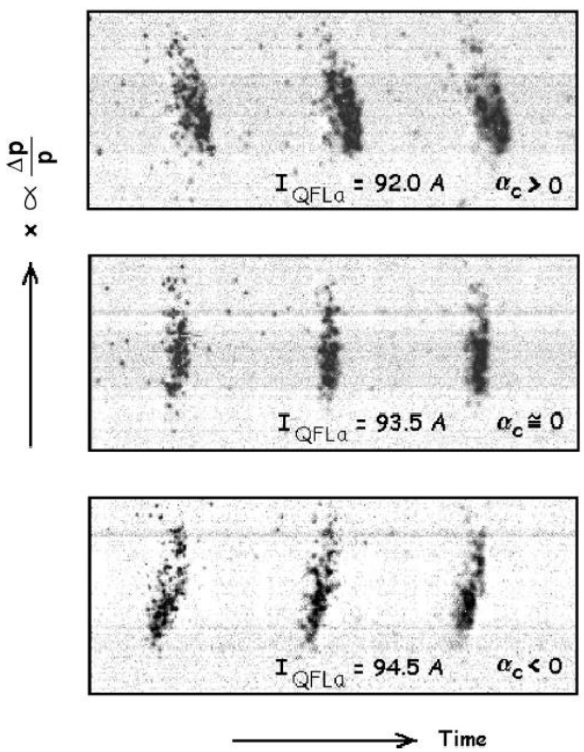
RF injection in combiner ring

$$C_{ring} = (n + ¼)\,\lambda$$

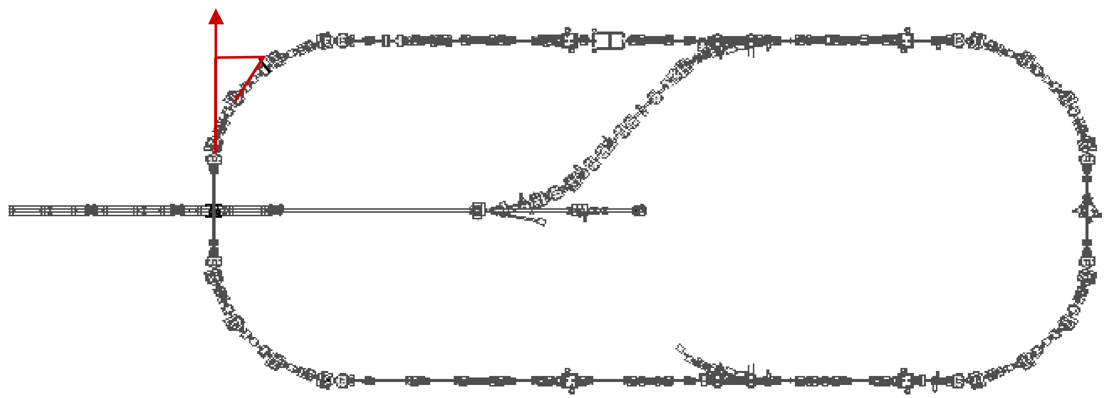


CTF3 preliminary phase (2001-2002)

Transition through zero momentum compaction optics - $\alpha \leq 10^{-4}$



streak camera measurement



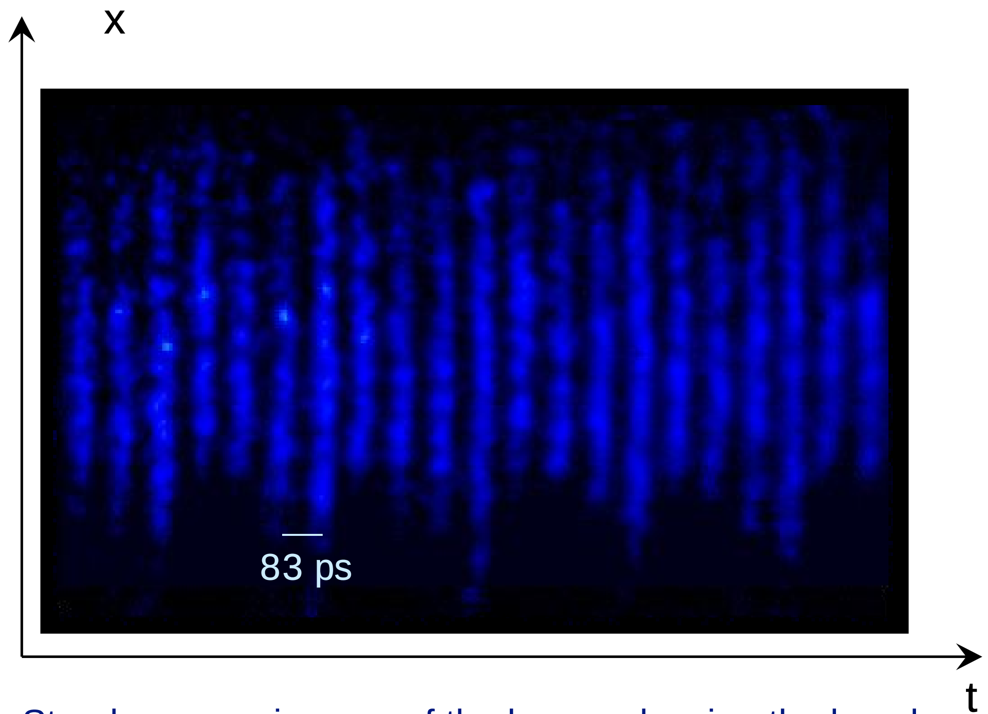
Beam structure after combination (factor 4)

Bunch spacing
83 ps

Pulse Length 6.6 ns
Beam Peak Current 1.2 A

...st was performed in 2002, *at low current and short pulse*,
...sitron Accumulator (EPA), properly modified

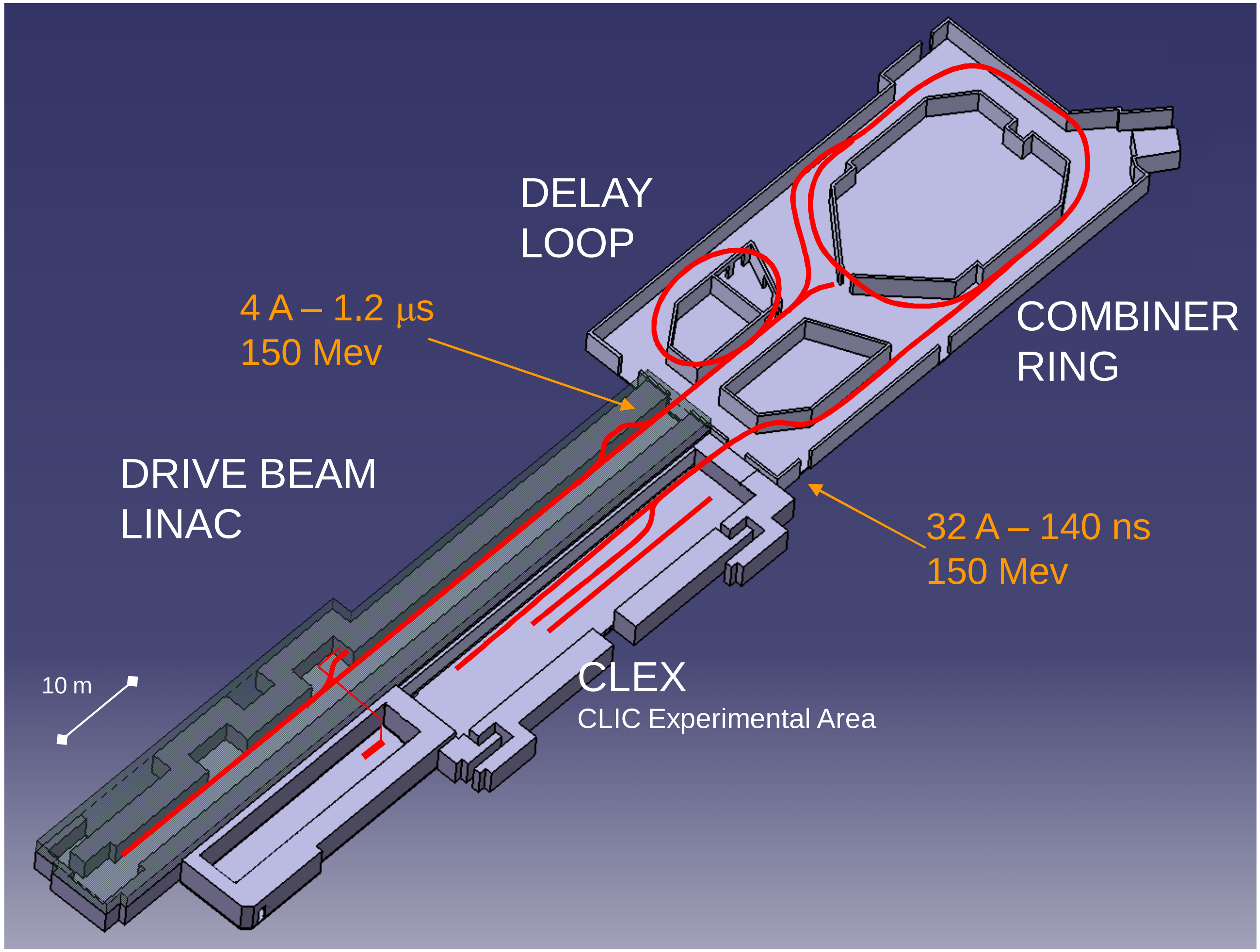
RF injection in combiner ring in CTF3 preliminary phase (2001-2002)



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

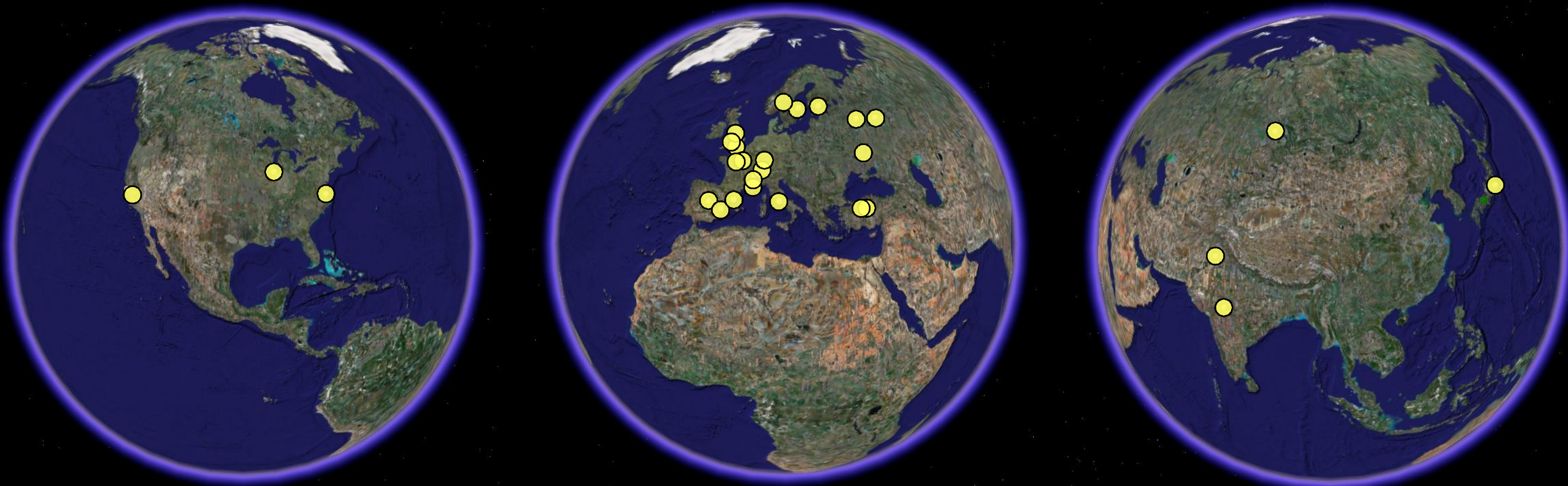
The CLIC Test Facility CTF3

is a small scale version of the CLIC drive beam complex



The CTF3 – CLIC world wide collaboration

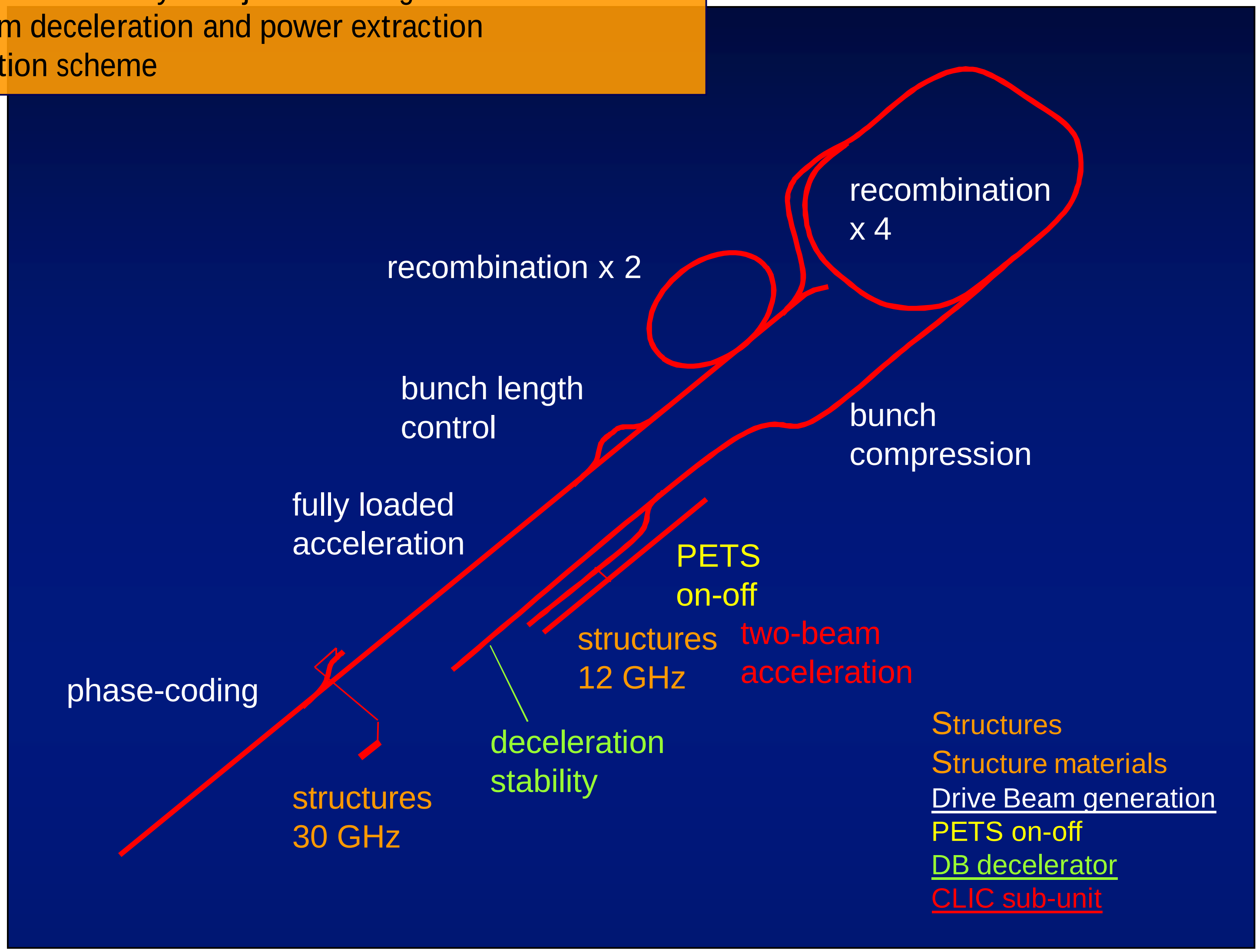
28 institutes involving 18 funding agencies from 16 countries



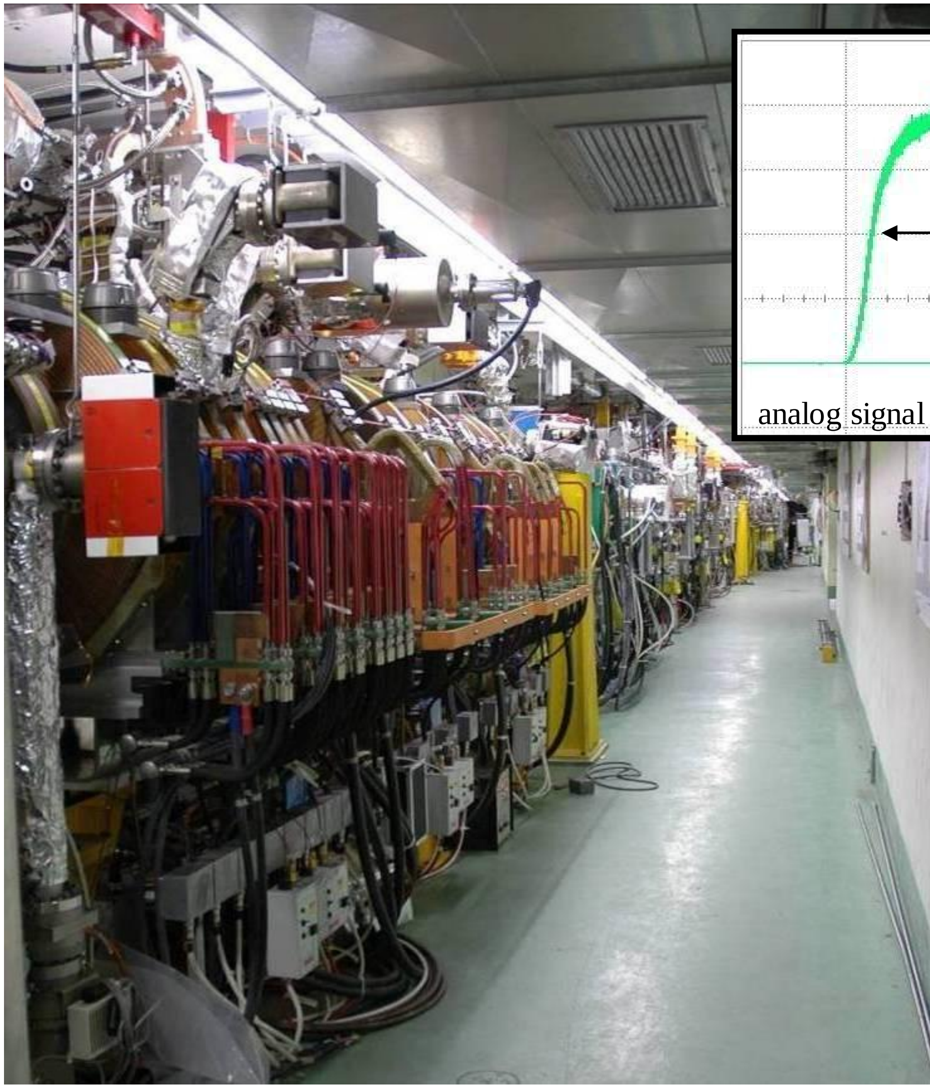
Ankara University (Turkey)	**Helsinki Institute of Physics (Finland)**	**JLAB (USA)**	**Oslo University (Norway)**
BINP (Russia)	**IAP (Russia)**	**Karlsruhe University (Germany)**	**PSI (Switzerland),**
CERN	**IAP NASU (Ukraine)**	**KEK (Japan)**	**Polytech. University of Catalonia (Spain)**
CIEMAT (Spain)	**Instituto de Fisica Corpuscular (Spain)**	**LAL/Orsay (France)**	**RRCAT-Indore (India)**
Cockcroft Institute (UK)	**INFN / LNF (Italy)**	**LAPP/ESIA (France)**	**Royal Holloway, Univ. London, (UK)**
Gazi Universities (Turkey)	**J.Adams Institute, (UK)**	**NCP (Pakistan)**	**SLAC (USA)**
IRFU/Saclay (France)	**JINR (Russia)**	**North-West. Univ. Illinois (USA)**	**Uppsala University (Sweden)**

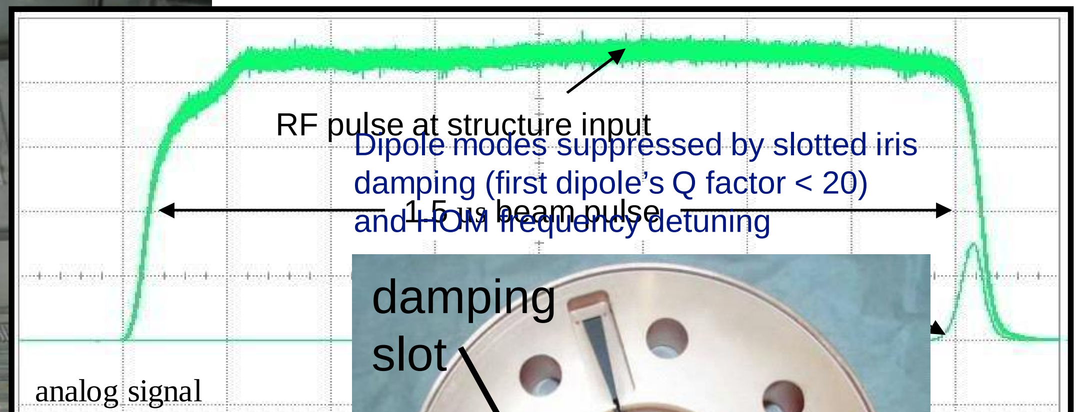
CTF3, Drive Beam Efficiency and use in PWFA-LC

- ✓ Provide RF power to test accelerating structures and components
- ✓ Full beam-loading accelerator operation
- ✓ Electron beam recombination by RF injection at high current
- ✓ Safe and stable beam deceleration and power extraction
- ✓ Two-beam acceleration scheme

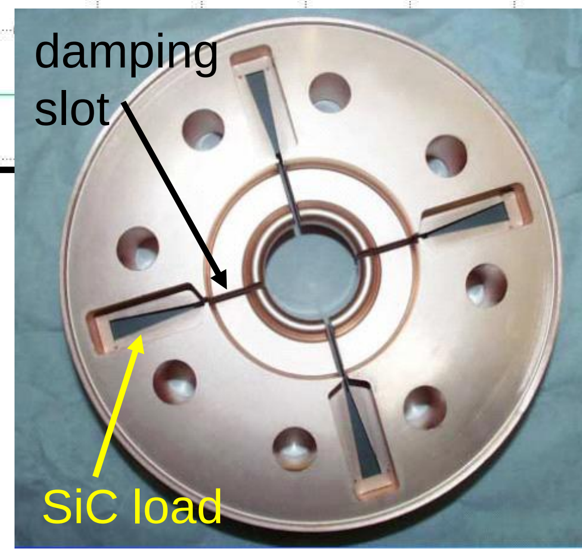


Drive Beam linac – high current, full beam loading operation





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

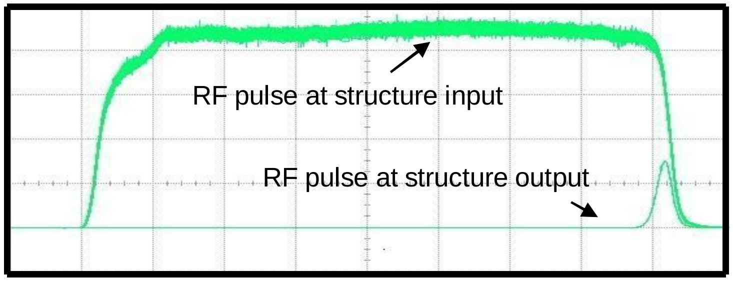


efficiency

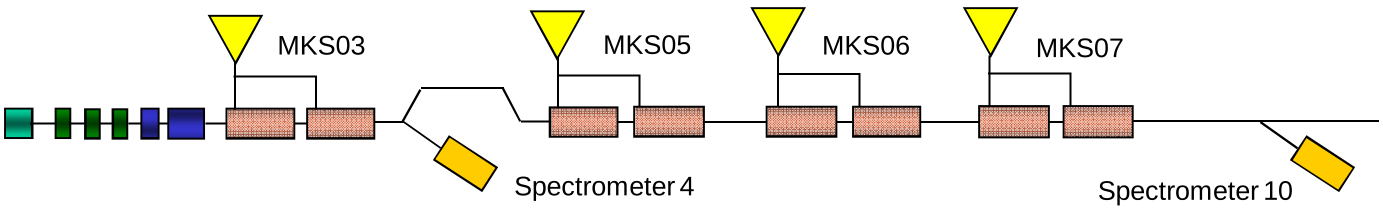
Direct measurement of efficiency at CTF3:

Setup: Adjust RF power and phase in all klystrons to beam current, such that fully loaded condition is fulfilled

1.5 µs beam pulse



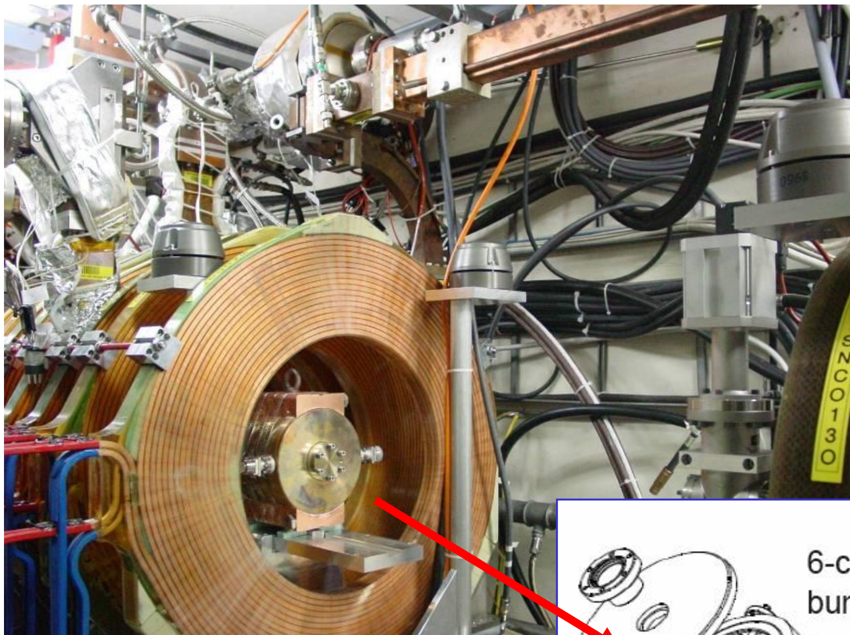
analog signal



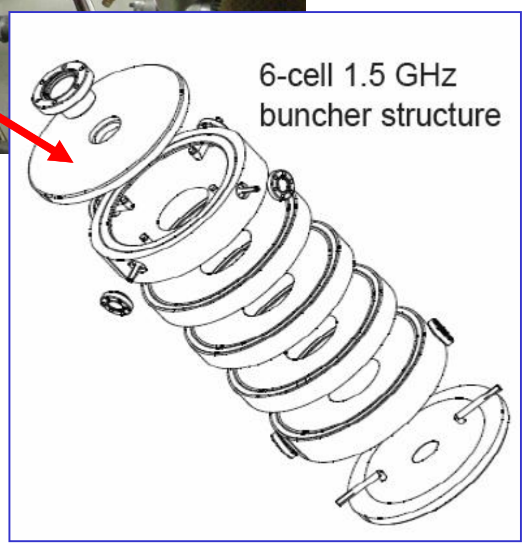
Method:
- Measure RF power, current and initial/final beam energy.
- Switch off one klystron at a time and measure relative energy in spectrometer 10.
- Check consistency and compare with calculations.

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

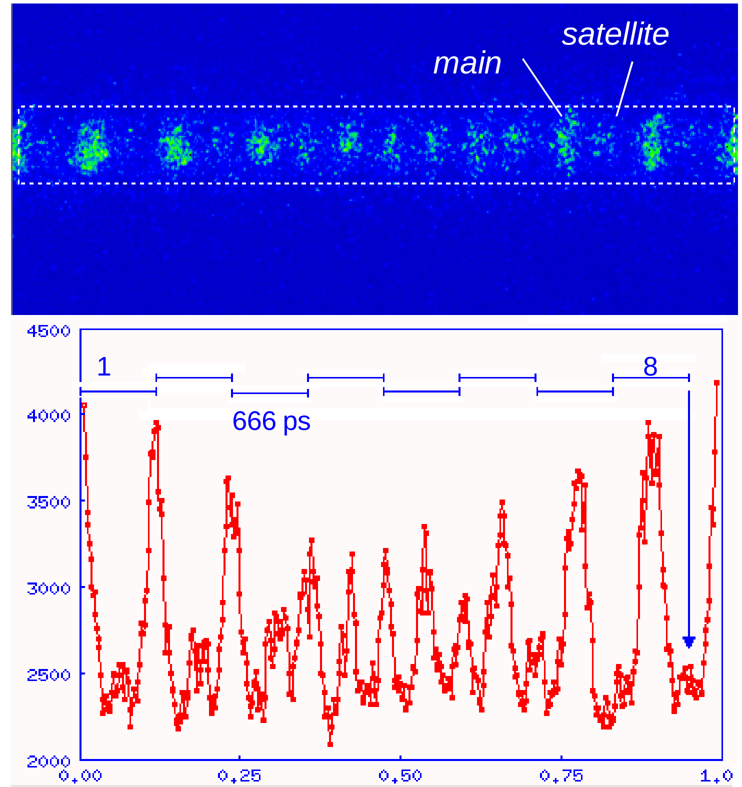
Fast phase switch from SHB system (CTF3)



3 TW Sub-harmonic bunchers, each fed by a wide-band TWT



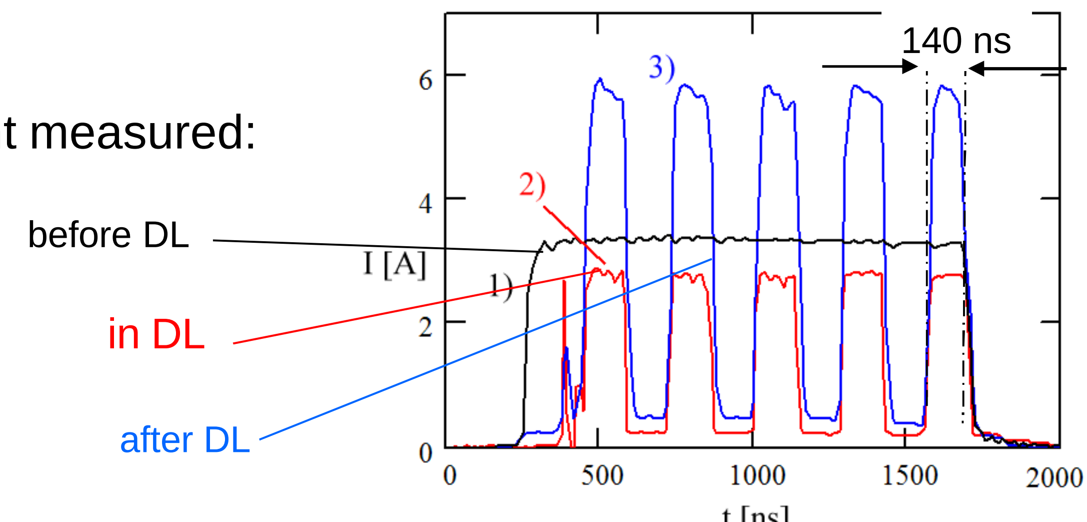
Streak camera image

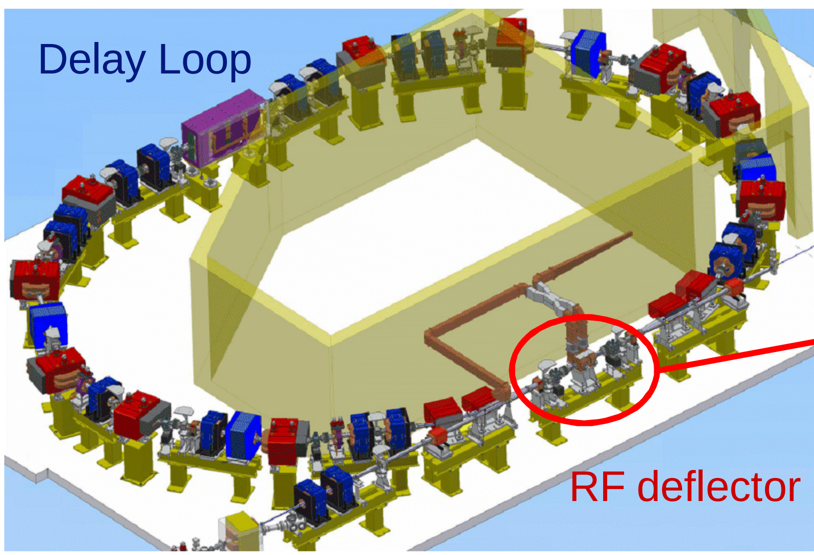


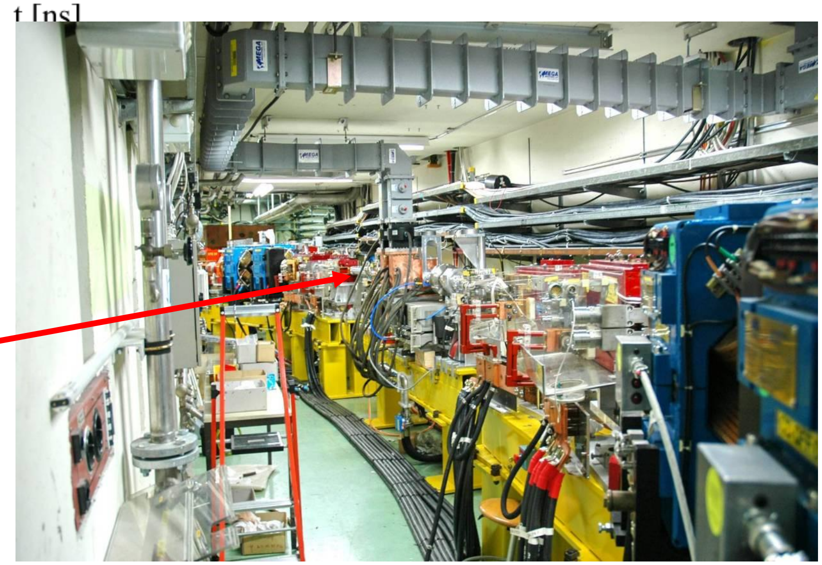
8.5 · 666 ps = 5.7 ns

Delay Loop – beam current multiplication x 2, hole creation

Beam current measured:

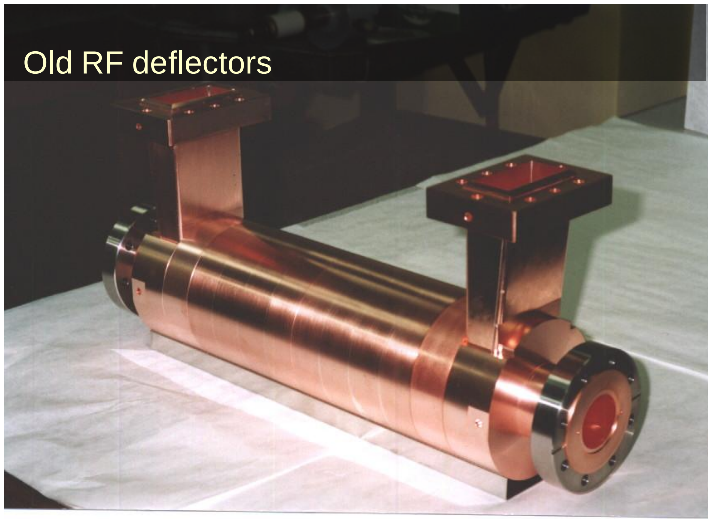


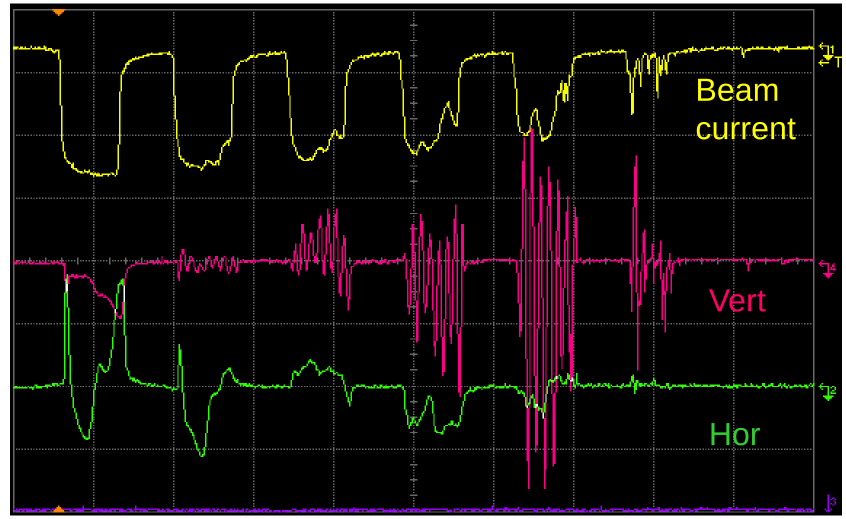


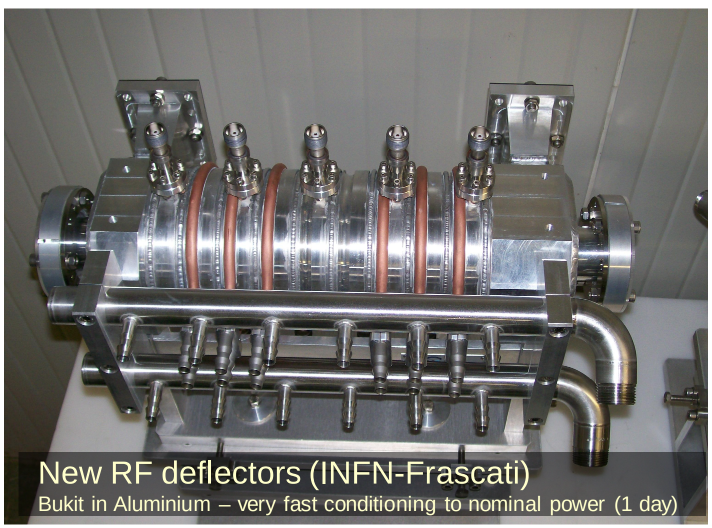


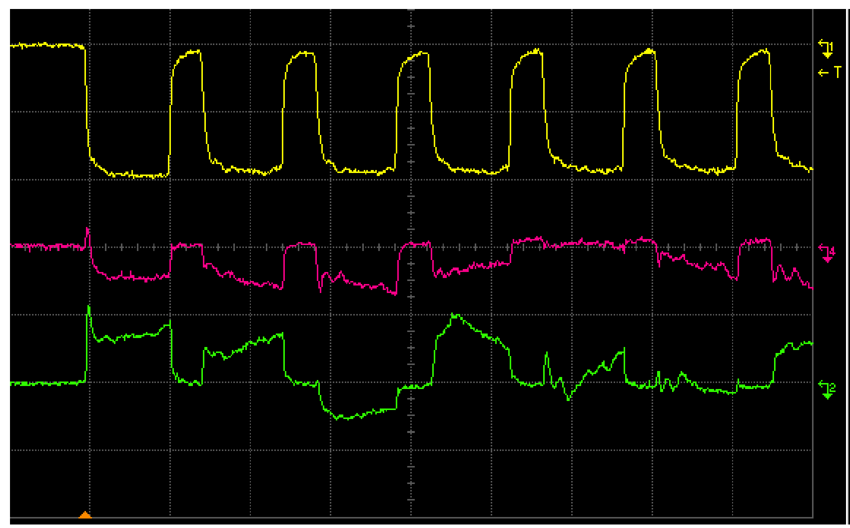
Combiner Ring

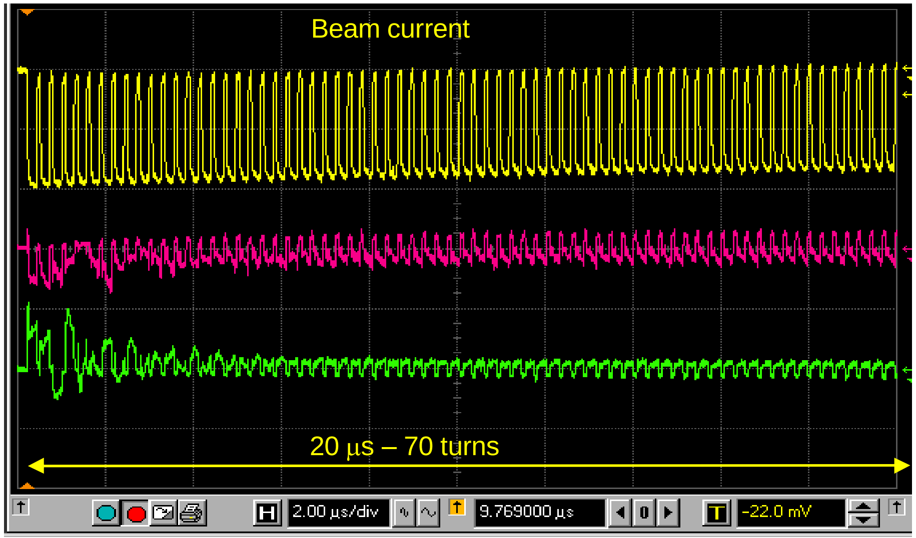
Fast vertical beam instability in CTF3 solved by new deflectors
with strong damping of the vertical deflecting mode and larger hor./vert. detuning


Old RF deflectors




New RF deflectors (INFN-Frascati)
Bukit in Aluminium – very fast conditioning to nominal power (1 day)



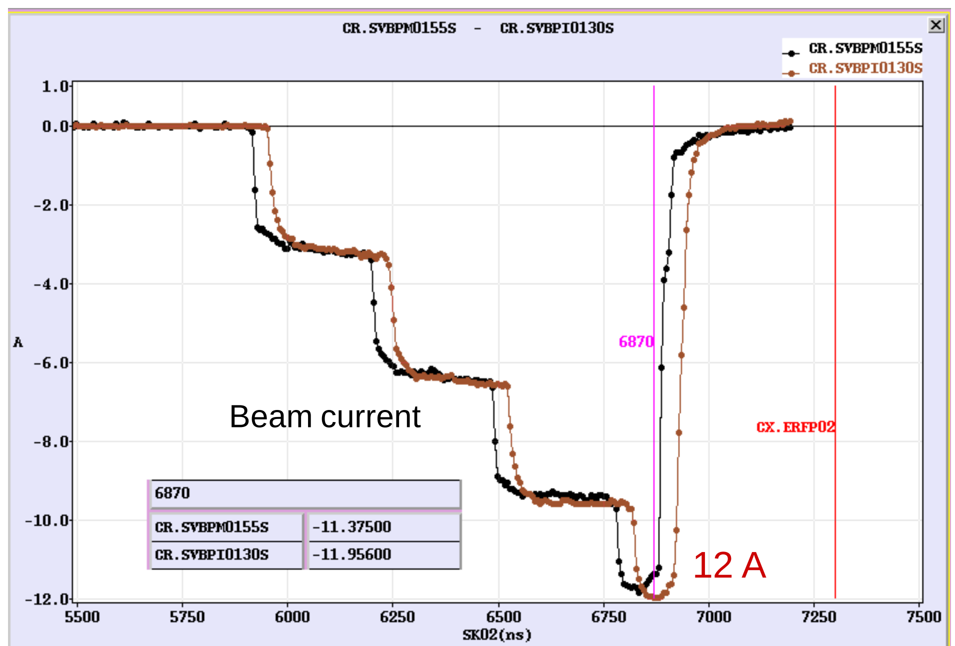


Without the losses from the fast vertical beam instability (plus improved optics control and tuning tools) it is now possible to circulate the 3 A beam with very small losses for hundreds of turns.

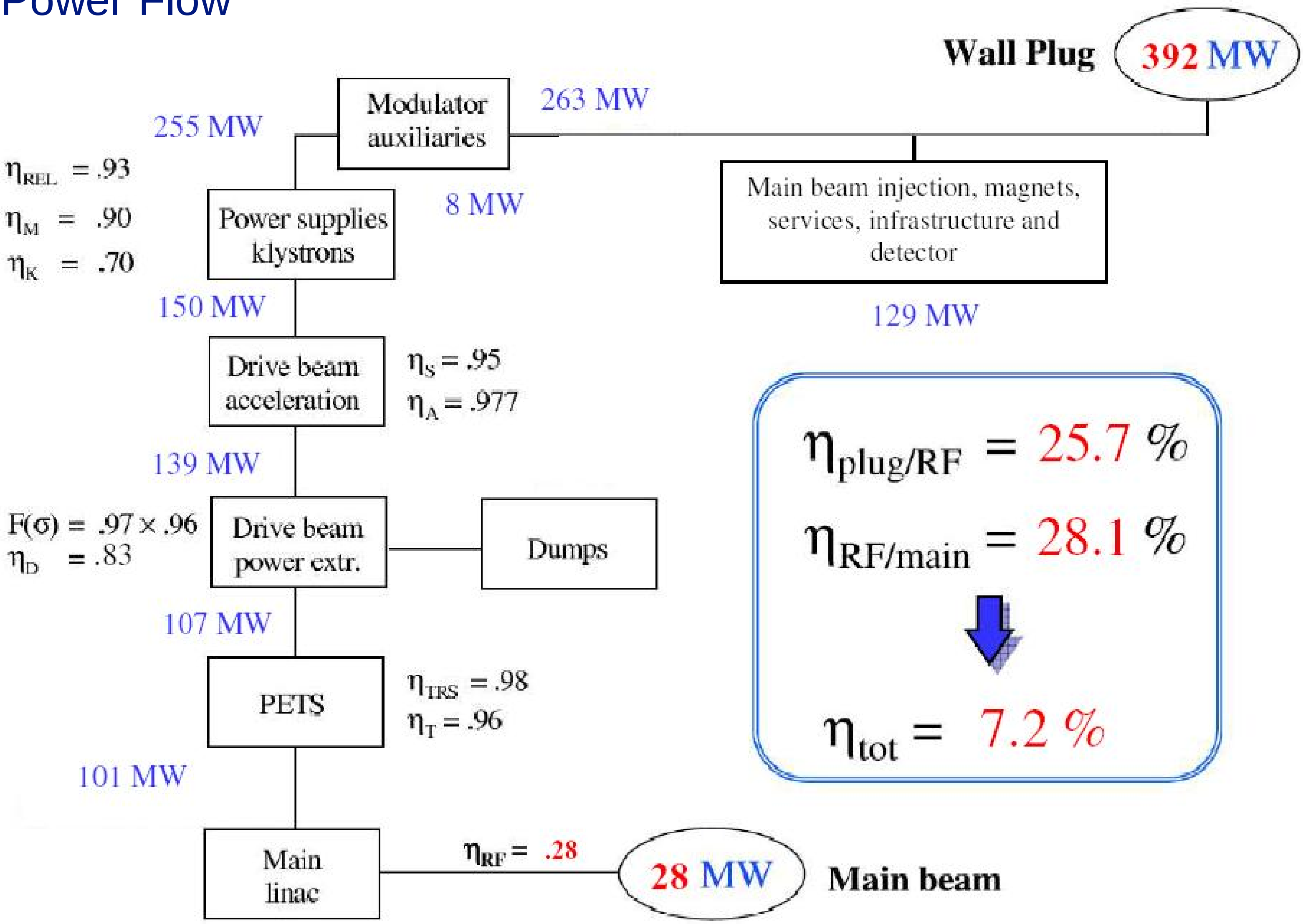
Combiner Ring

Bunch re-combination of a 3 A beam with factor four current increase had been demonstrated – 12 A reached.

(DL still by-passed, and limited by RF pulse length)



CLIC Power Flow



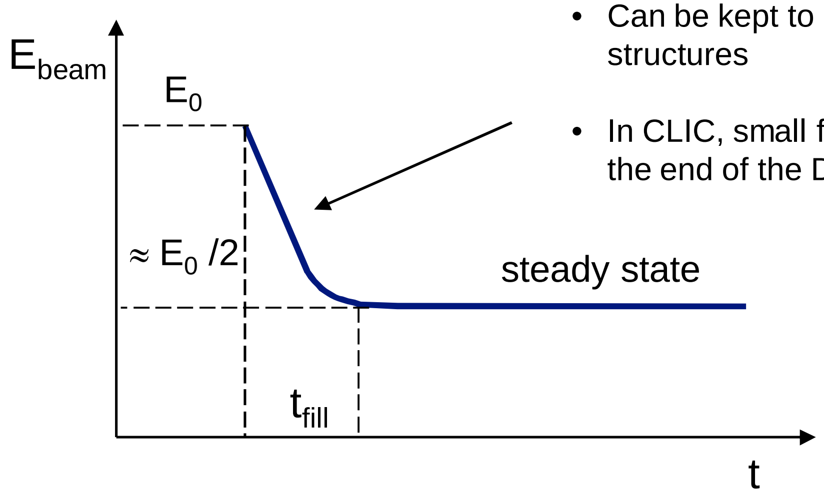
CLIC Power Consumption Breakdown

Main beam magnets	**Grid power [MW]**
Injector linacs	1.2
Positron pre-damping ring	0.8
Electron pre-damping ring	0.3
Damping rings warm magnets	2.2
Damping ring SC wigglers	0.5
Surface to tunnel transfer	2.1
Return lines	1.0
Turn arounds	2.2
Main linacs	8.4
Beam delivery system	3.0
Spent beam lines	4.1
Main beam magnets total	**25.8**
Main Beam Injector RF	
Positron production linac	0.5
Main beam linacs 2.4 and 9 GeV	1.8
Pre-damping rings	6.5
Damping rings	6.5
Main beam injector RF total	**15.2**

Drive beam magnets	**Grid power [MW]**
DB Accelerator	0.4
Delay loops	1.2
Combiner rings 1	1.3
Combiner rings 2	1.3
Surface to tunnel transfer	1.3
Return lines	0.3
Turn arounds	32.7
Decelerators	7.7
Beam dumps	0.5
Drive beam magnets total	**46.7**
Drive beam linac RF	
Modulator auxiliaries	7.8
RF power	255.5
Drive beam linac RF total	**263.3**
Beam, RF and alignment instrumentation	**5.0**
Detector	**15.0**
Water systems	**9.8**
Ventilation systems	**8.8**
Tunnel infrastructure	**2.5**
Grand total	**392.1**

Table 11: CLIC 3 TeV power consumption

Energy spread in full beam-loading regime

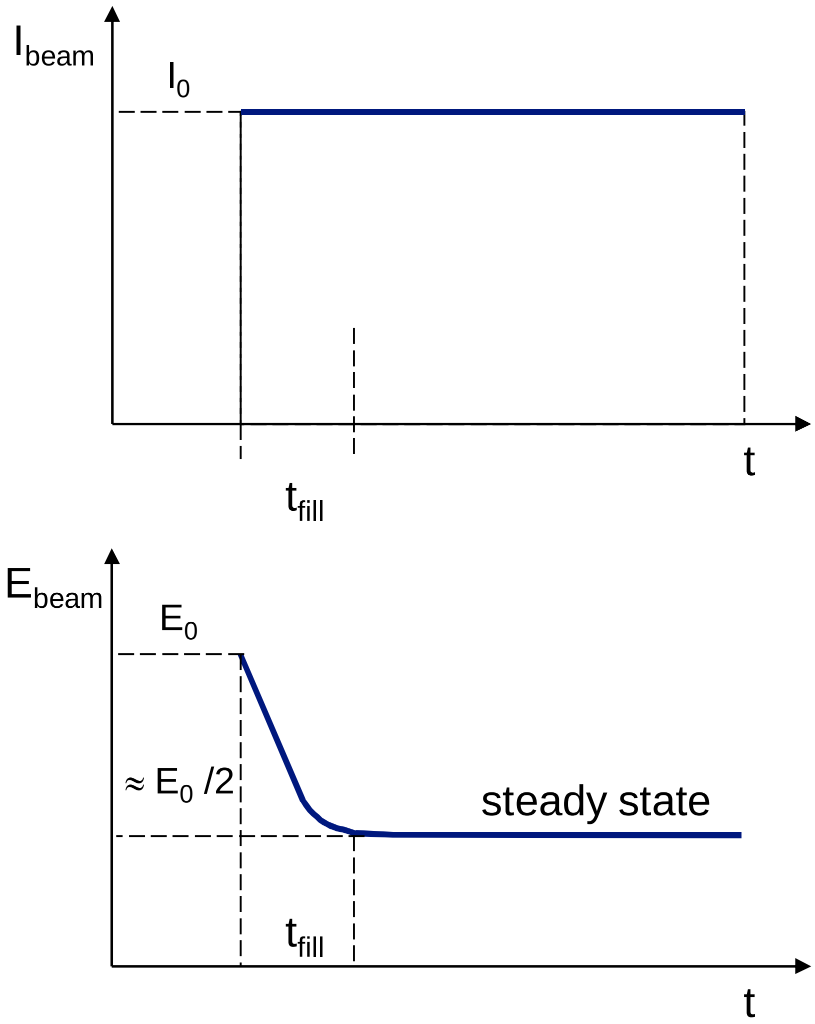


Initial transient

- Can be kept to a few percent level by RF delayed filling of DBA structures
- In CLIC, small fraction of the pulse – will be lost in a controlled way at the end of the DBA

- Any drive beam current variation will result in a corresponding variation in final drive beam energy
- That's why in CLIC we accelerate a long (140 μs) constant current drive beam pulse, and only split/recombine it after acceleration

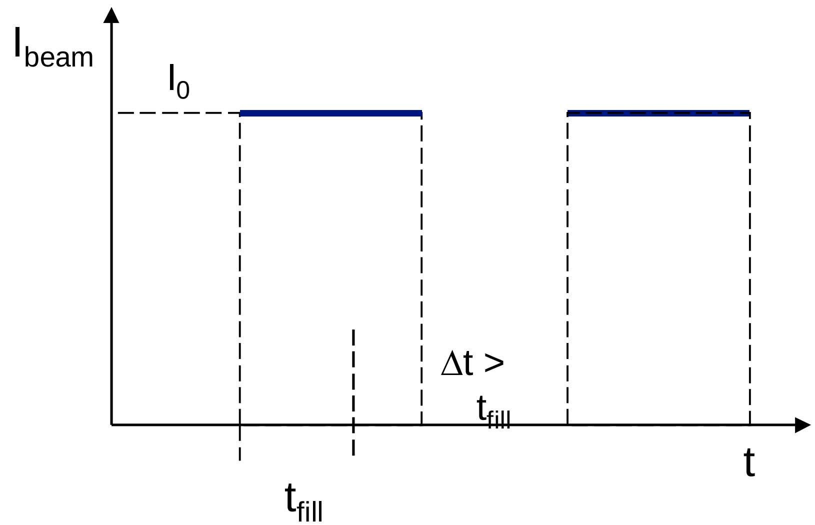
Energy spread in full beam-loading regime

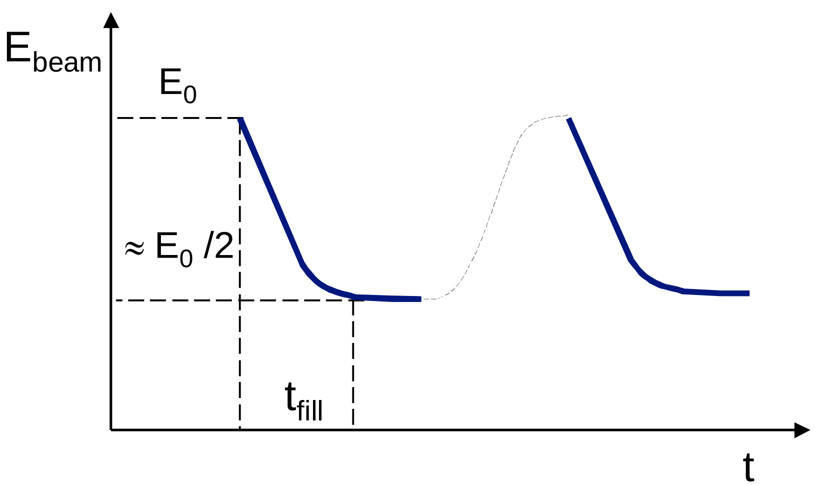


Constant current drive beam pulse with duration >> t_{fill}

Steady state after t_{fill}

Energy spread in full beam-loading regime

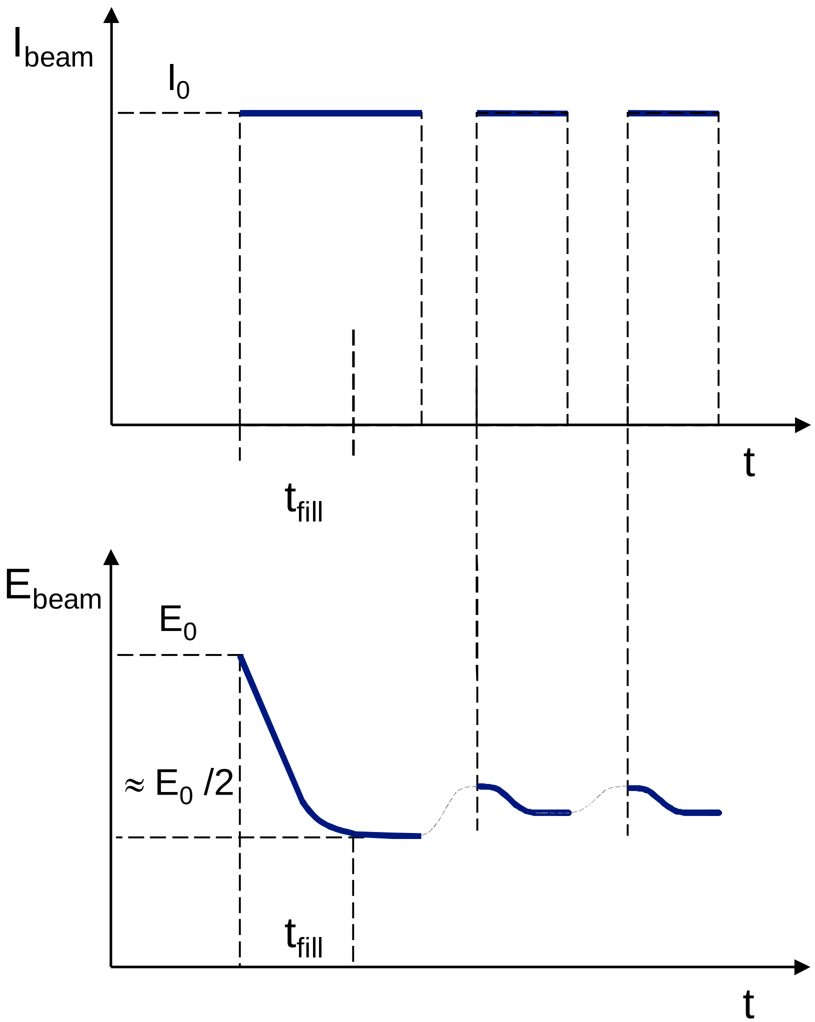




Drive beam pulses with duration > t_{fill}
spaced by $\Delta t > t_{fill}$

"Short" steady states

Energy spread in full beam-loading regime



Drive beam pulses with duration < t_{fill} spaced by Δt < t_{fill}

quasi steady-state ("filtering")

Energy spread in full beam-loading regime

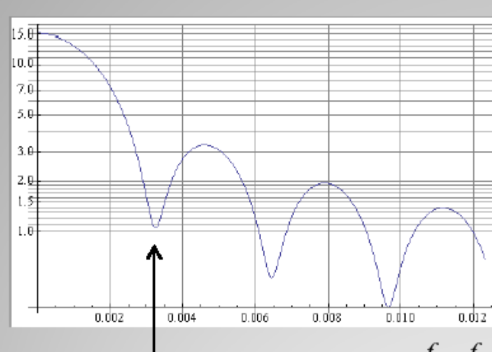
E. Jensen-D.Schulte, CLIC ACE May 2009

- Drive beam phase jitter leads to luminosity drop.
- $\Delta\varphi$ at 1 GHz causes 12 $\Delta\varphi$ at 12 GHz!
- Any R_{56} transforms drive beam energy jitter to phase jitter.
- With full beam loading, drive beam current error transforms to energy error (and then phase error).
- Requirement (order of magnitude):
  drive beam phase jitter <0.02° (3.5E-4, 50 fs)
  drive beam energy jitter <$\mathcal{O}$(1E-4)
  (With a feed-forward, this may be relaxed by a factor 10!)
- Accelerating structures and recombination scheme act as filters for the noise.

Filtering of drive beam current variations

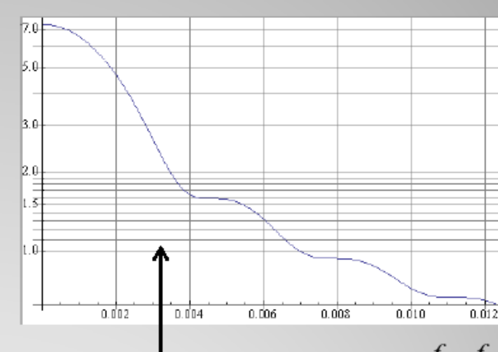
Filtering of klystron power variations

- filtering the klystron signal: $\left| \frac{V_{acc}}{\sqrt{P_{klystron}/(33\,\text{MW})}} \right|$



τ_{fill}^{-1} $\quad \frac{f - f_c}{\text{GHz}}$

- filtering the beam signal: $\left| \frac{V_{acc}}{I_{beam}/(4.21\,\text{A})} \right|$

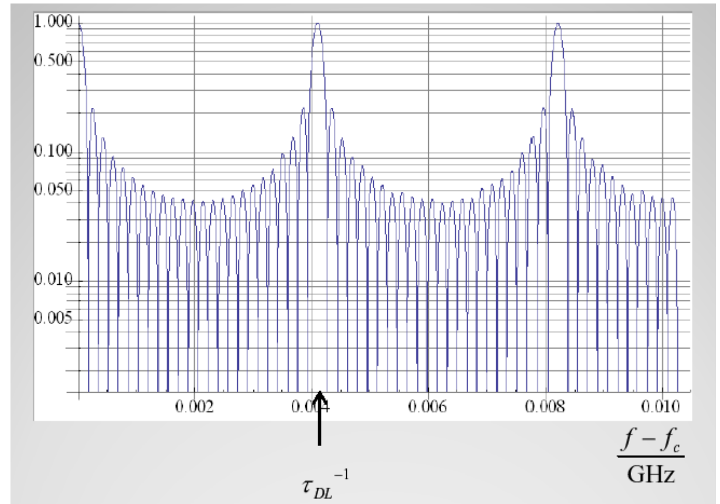


τ_{fill}^{-1} $\quad \frac{f - f_c}{\text{GHz}}$

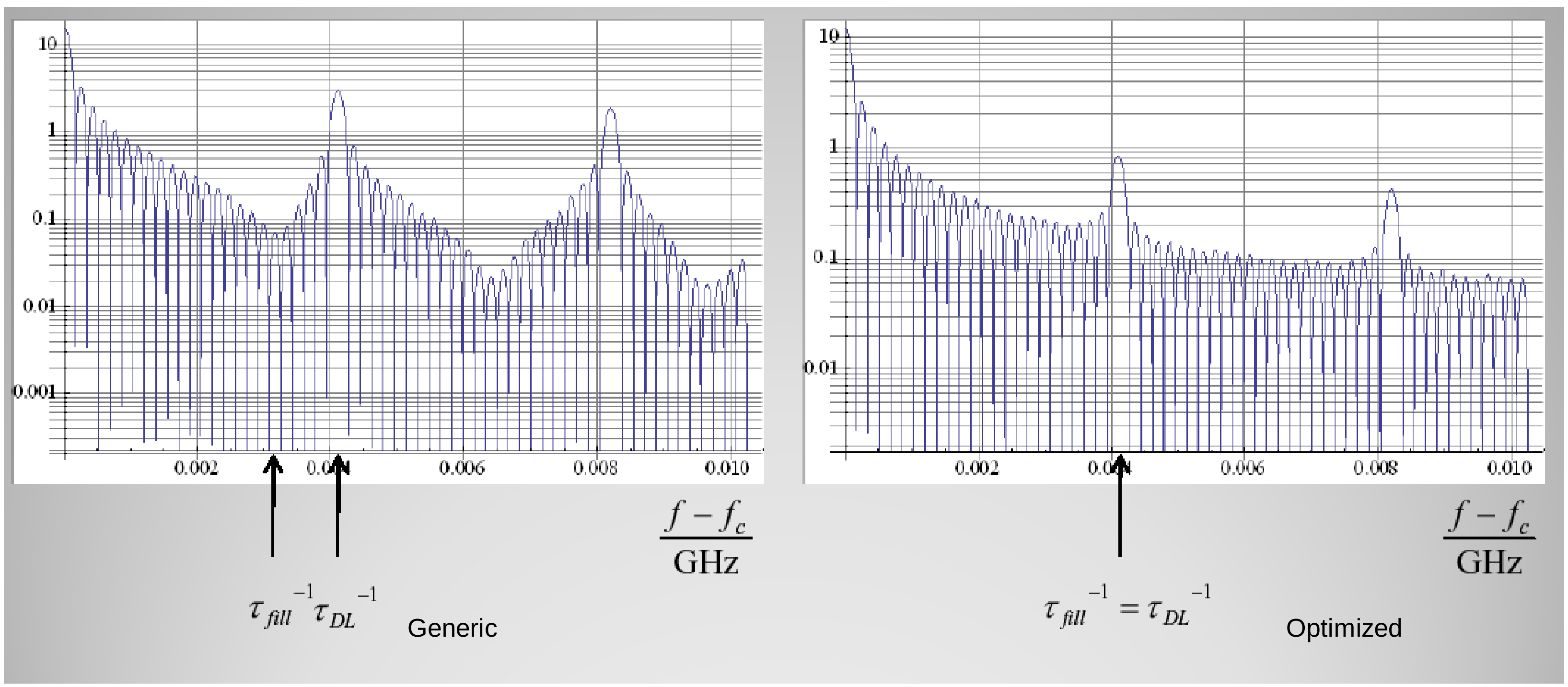
CTF3, Drive Beam Efficiency and use in PWFA-LC

If the beam is split/recombined like in the CLIC scheme, there is an additional filtering effect

Re-combination transfer function



Total transfer function



Some drive beam issues for multi-stage PWFA Linear Collider

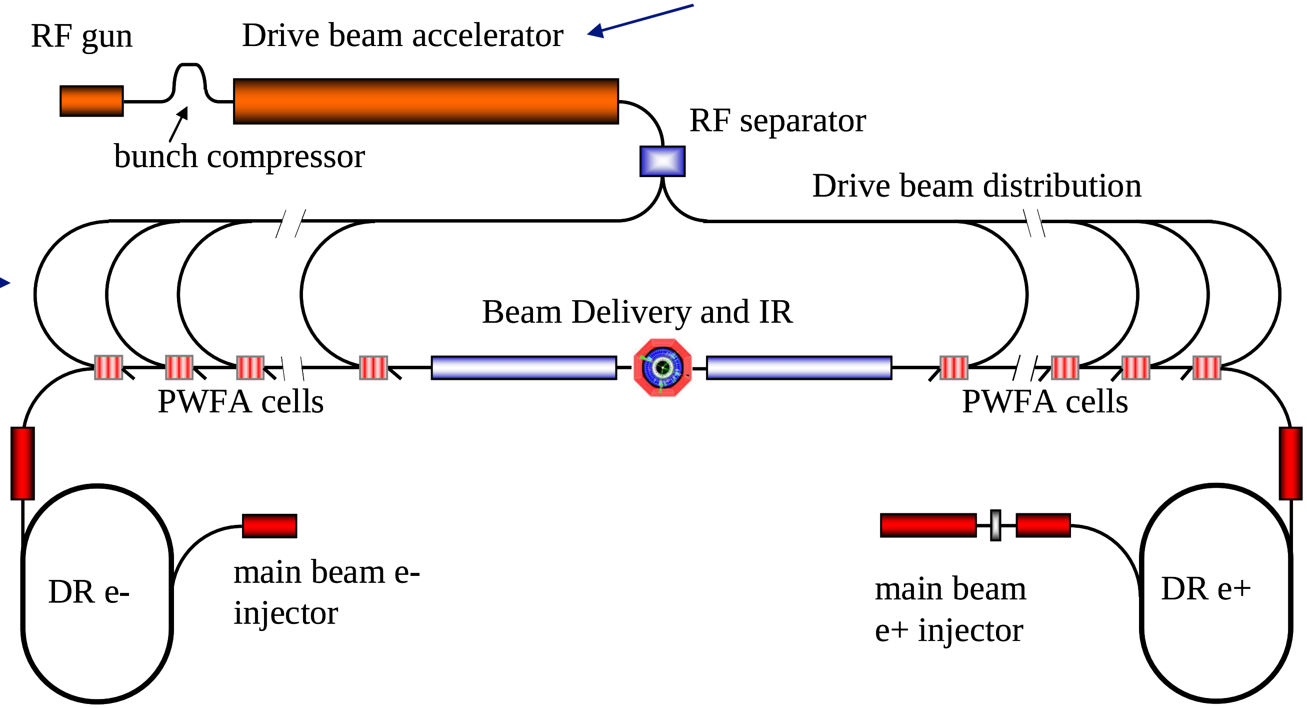
Power loss
by SR in arcs

Bunch
length/compression
SR & CSR

Phase stability

(Cost) optimum
for drive beam energy

Time structure – energy spread



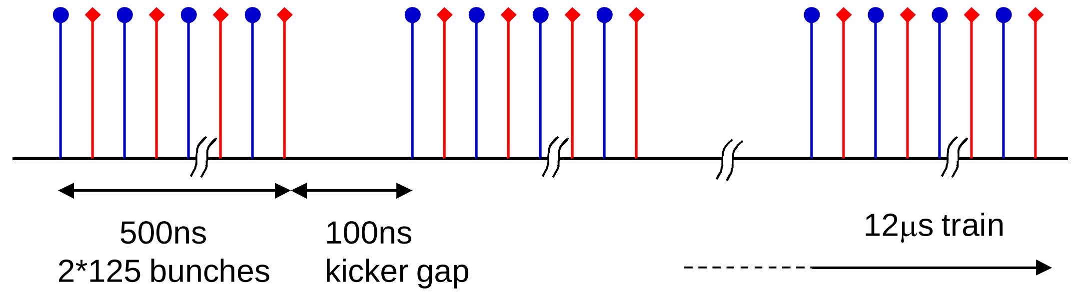
Control of drive beam losses

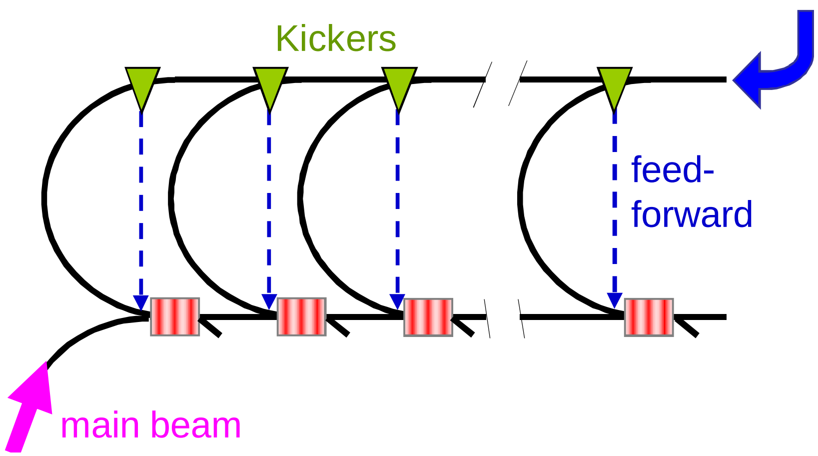
Machine protection system

CLIC-like drive beam as a PWFA collider driver – time structure

A. Seryi – CLIC Workshop 2008

Single train for e+ and e- sides
Separation by RF deflectors





Kickers with ~100 ns rise time
Possibility for feed-forward
Plasma cell spacing c*600 ns/2

NB: DBA fill time ~ 250 ns

animation of beam drive distribution: