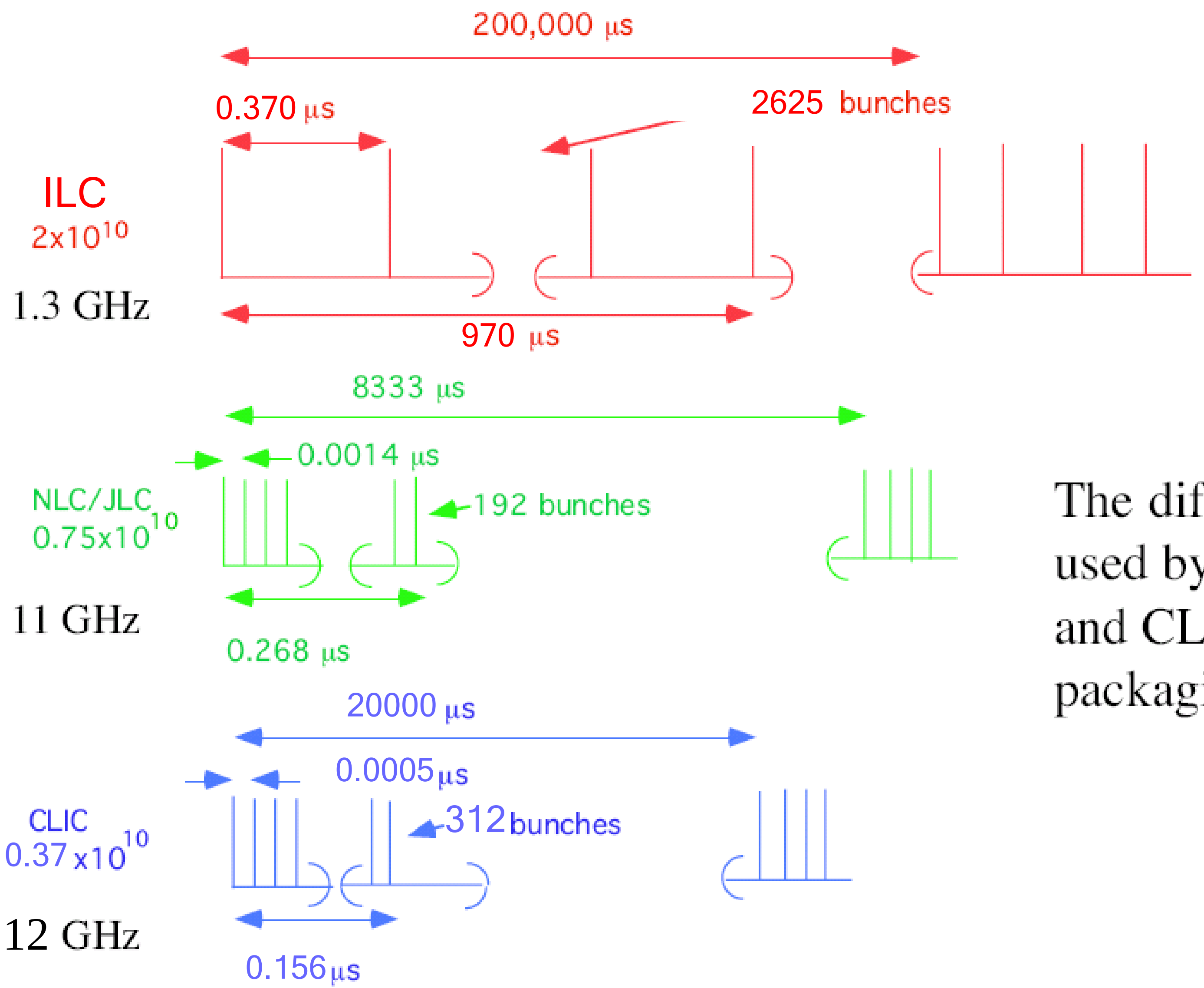
Linear Colliders
Lecture 4

Frank Tecker – CERN

- Damping rings
- NC/SC driven differences
- CLIC two beam scheme
- Drive Beam generation
- CLIC test facility CTF3

Bunch structure

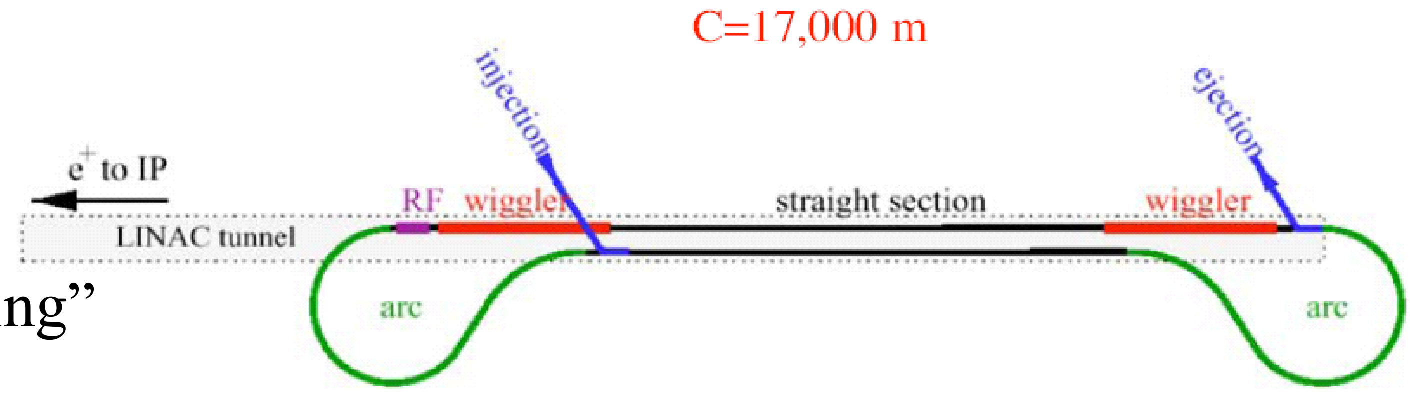
- SC allows long pulse, NC needs short pulse with smaller bunch charge

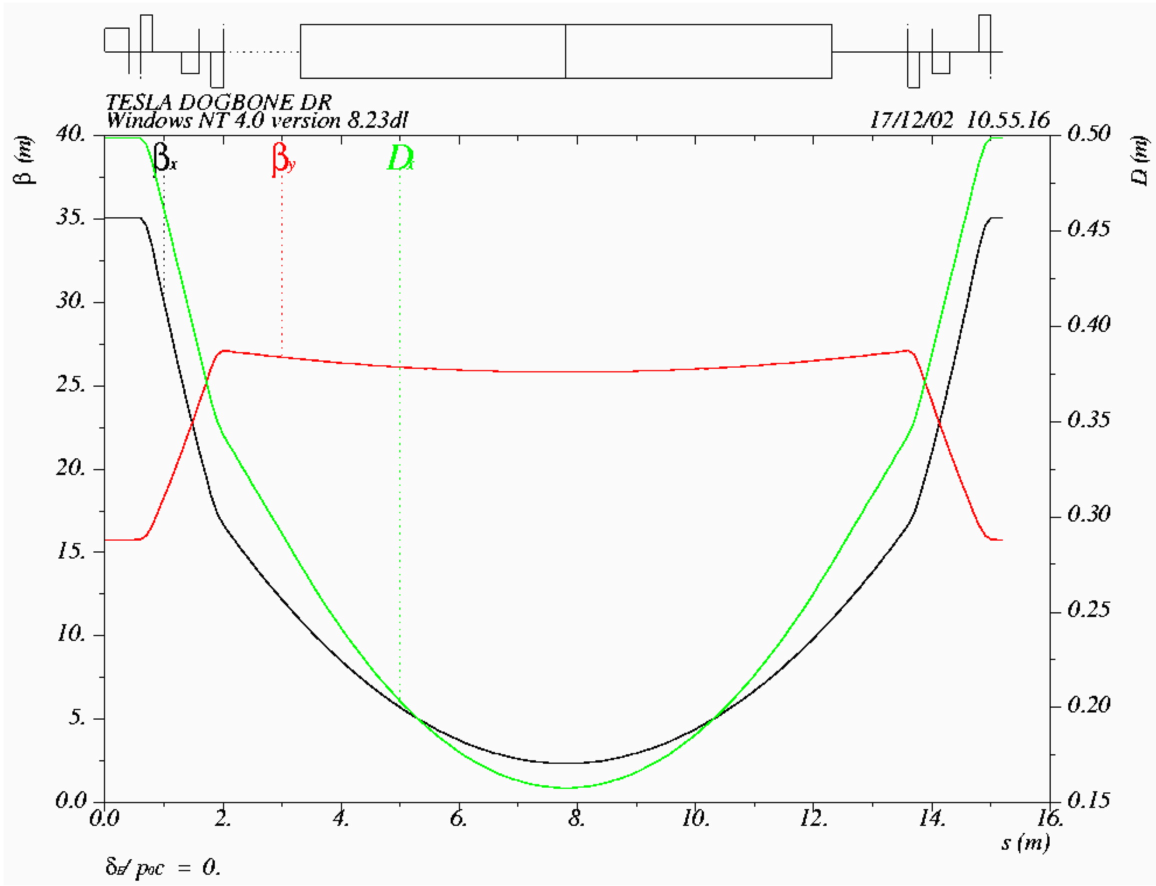


The different RF technologies used by ILC, NLC/JLC and CLIC require different packaging for the beam power

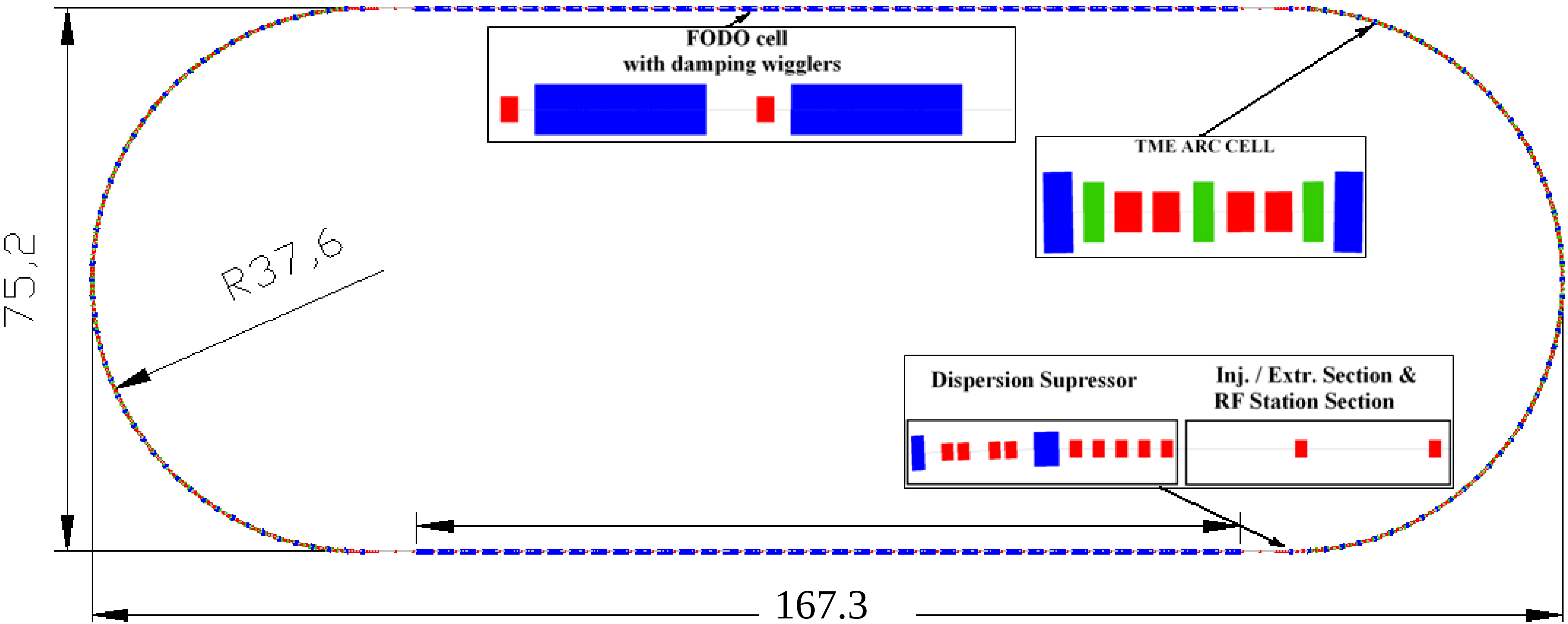
TESLA/ILC damping ring

- Long pulse:
  950µs * *c* = 285 km!!
- Compress bunch train into 17 km (or less) “ring”
- kick individual bunches
- Min. circumference by ejection/injection kicker speed (≈20 ns)
- “Dog bone” ring with ≈ 400m of 1.67 T wigglers
- 3.2 km circular rings in the baseline ILC design
- Very demanding kicker rise + fall time < 6 ns





CLIC damping ring layout



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

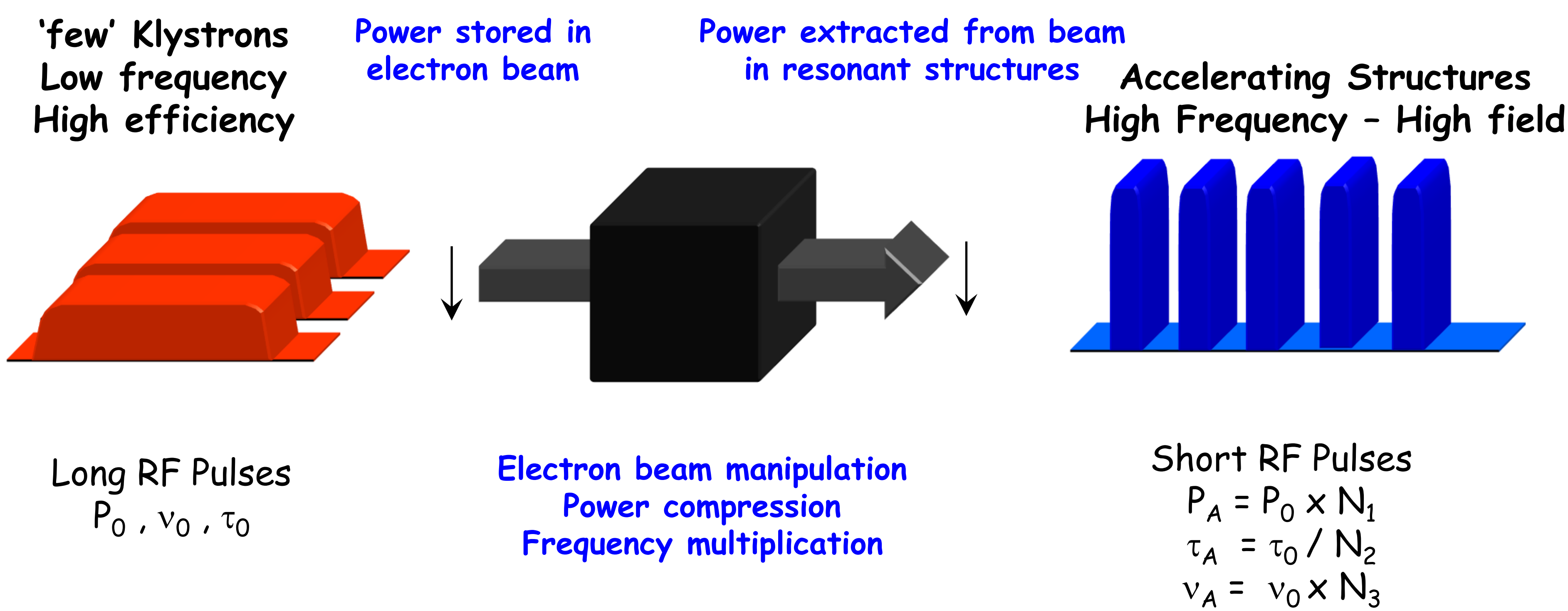
Warm vs Cold RF Collider

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

- ## 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 (Σ_y dilution) ☹
- Large number of e+ per pulse ☹
- very large DR ☹

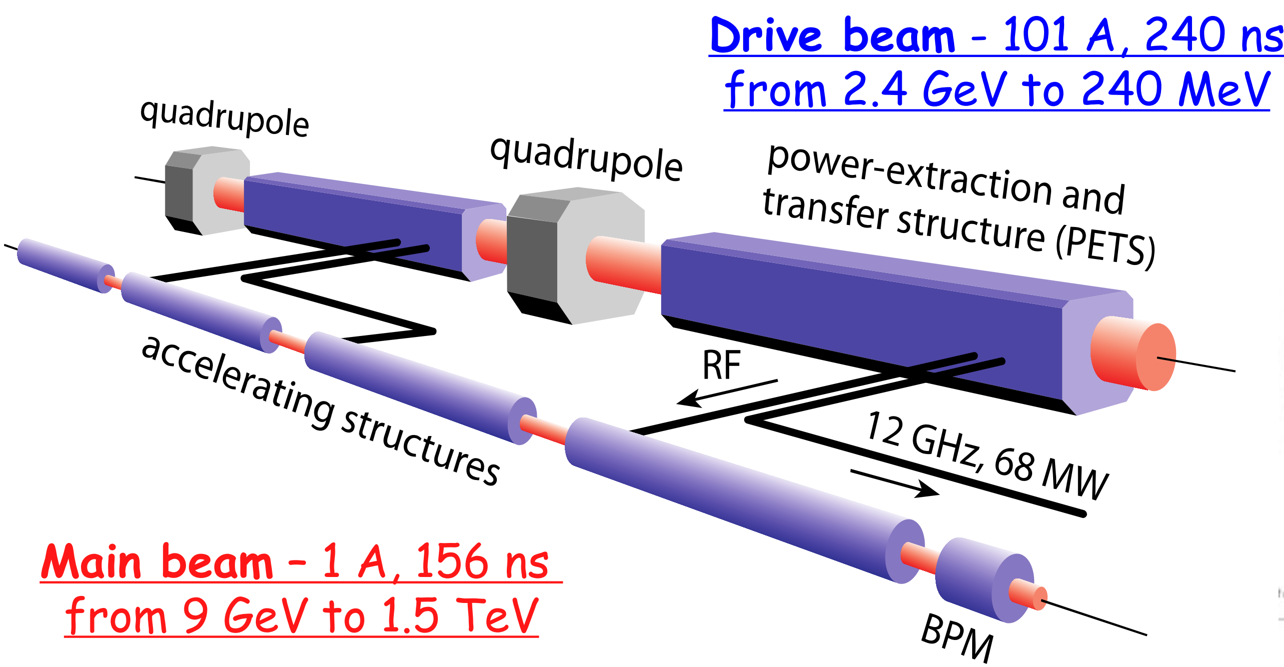
CLIC scheme

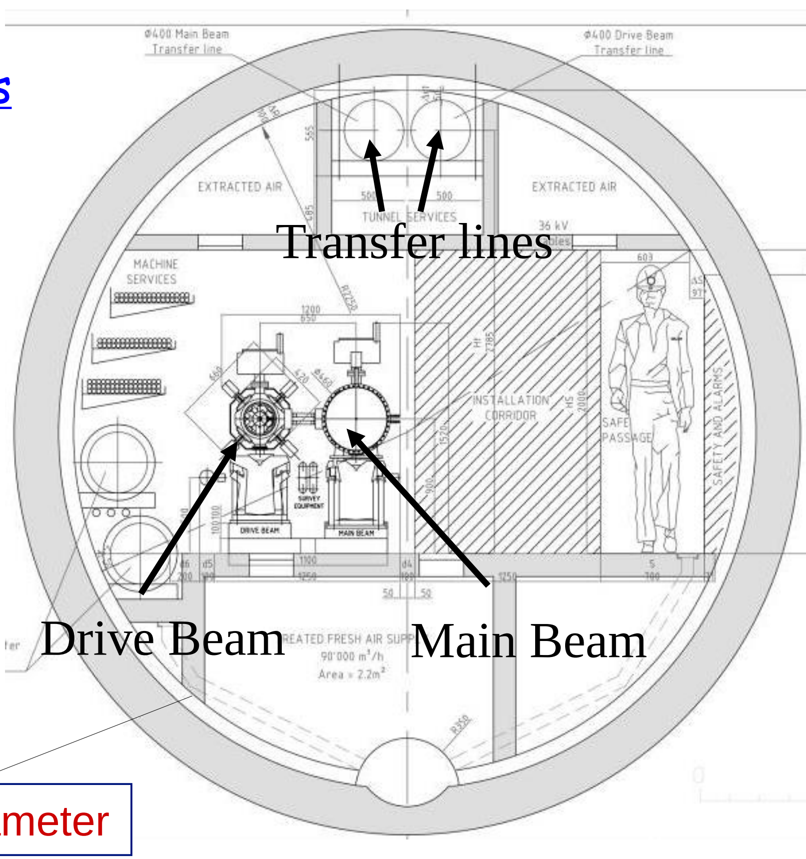
- Very high gradients (>100 MV/m) possible with NC accelerating structures at high RF frequencies (30 GHz → 12 GHz)
- Extract required high RF power from an intense e- “drive beam”
- Generate efficiently long pulse and compress it (in power + frequency)



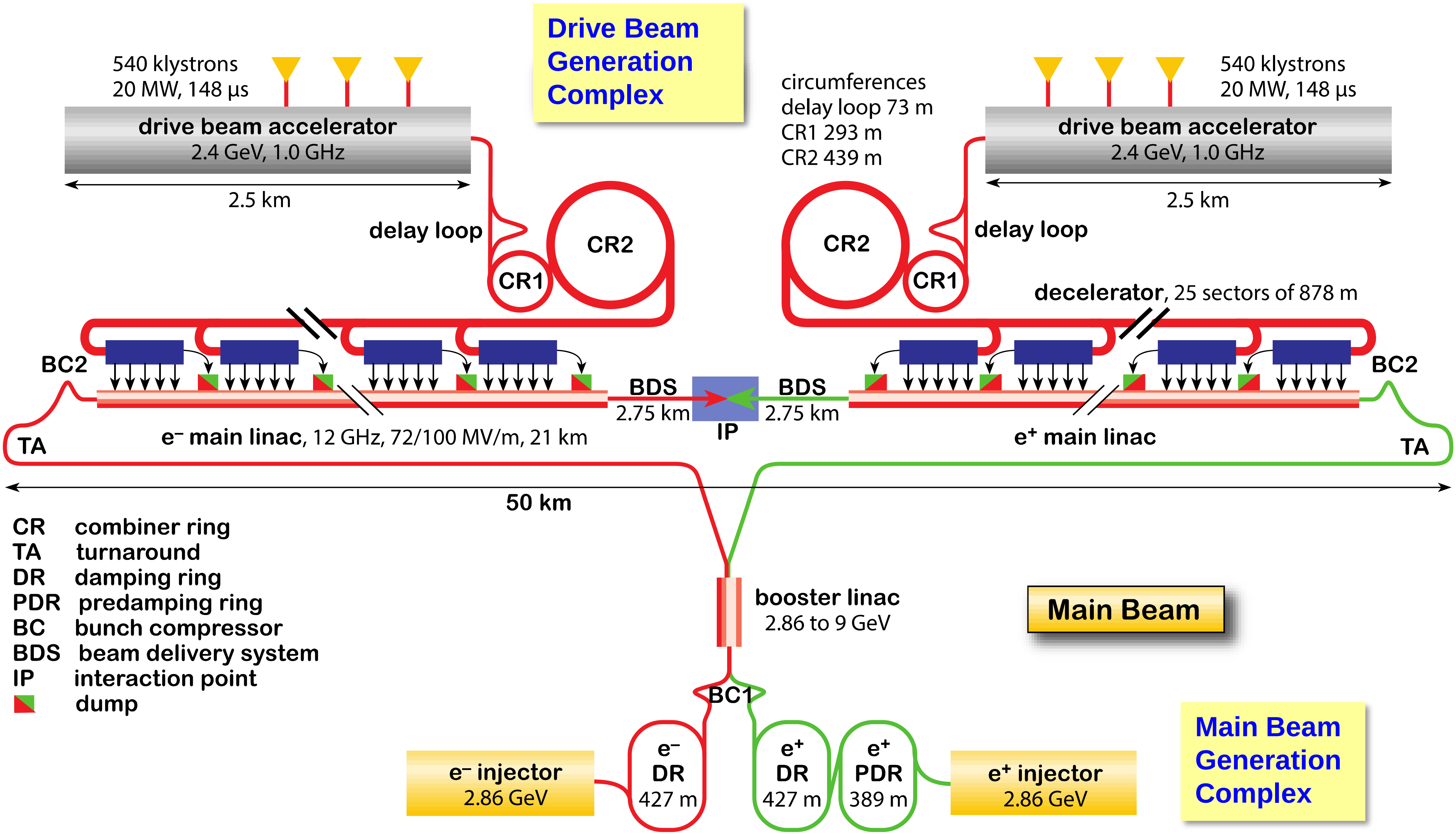
CLIC two beam scheme

- High charge Drive Beam (low energy)
- Low charge Main Beam (high collision energy)
- => Simple tunnel, no active elements
- => Modular, easy energy upgrade in stages

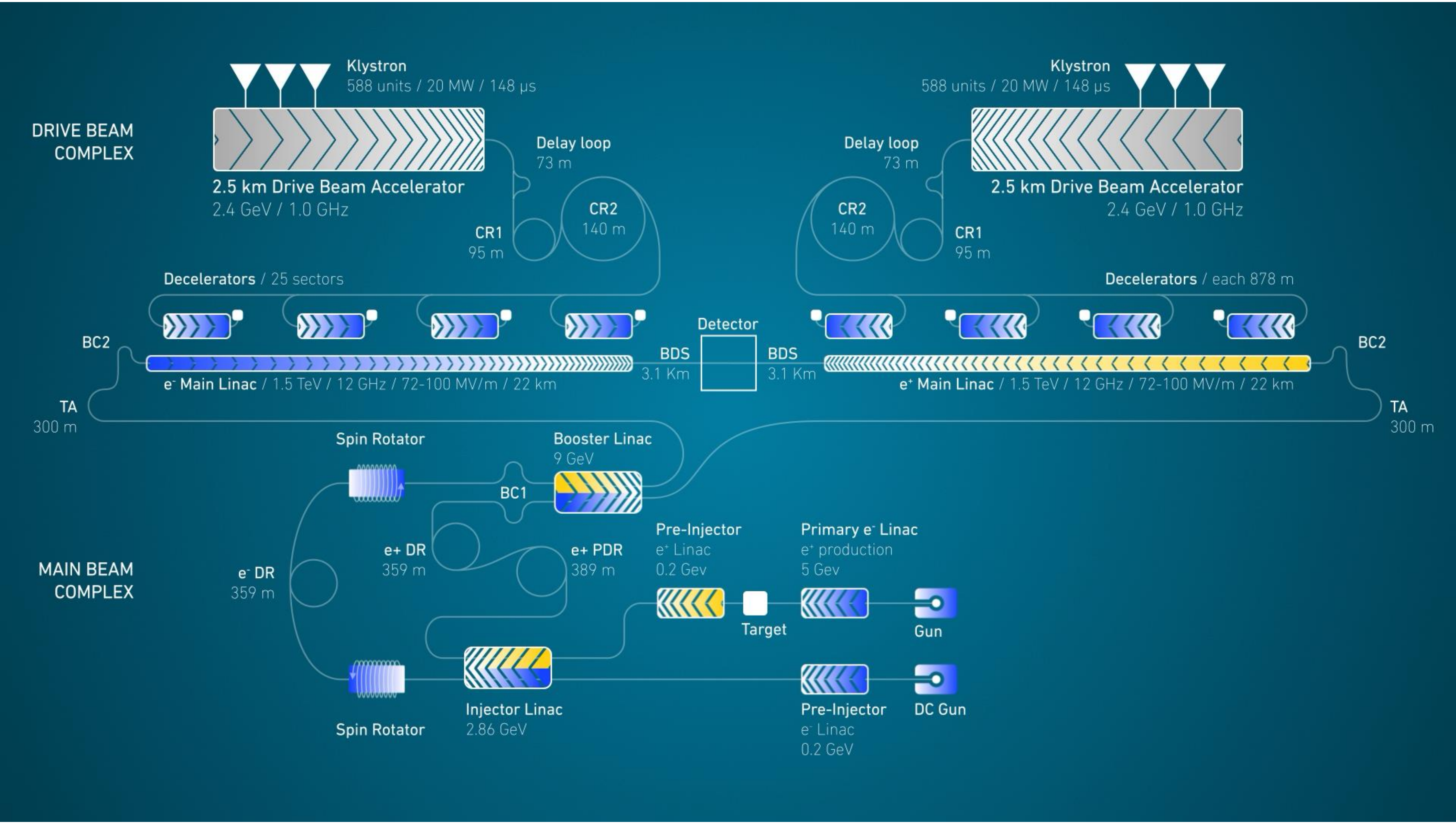




CLIC – overall layout – 3 TeV



CR combiner ring
TA turnaround
DR damping ring
PDR predamping ring
BC bunch compressor
BDS beam delivery system
IP interaction point
(red/green square) dump

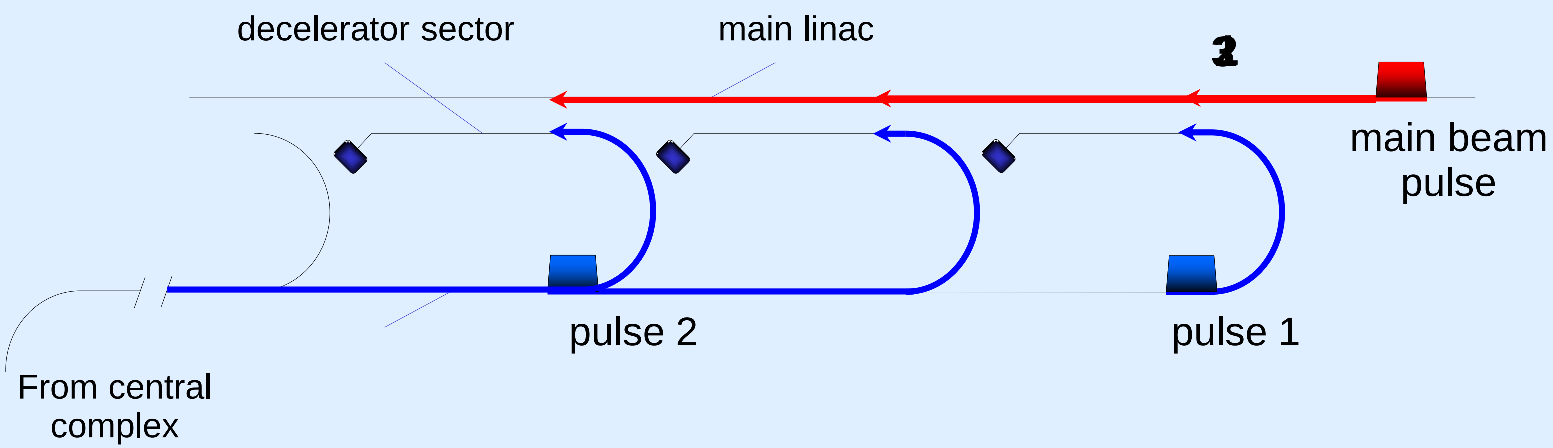

DRIVE BEAM COMPLEX
Klystron
588 units / 20 MW / 148 μs
2.5 km Drive Beam Accelerator
2.4 GeV / 1.0 GHz
Delay loop
73 m
CR1
95 m
CR2
140 m
Decelerators / 25 sectors
Decelerators / each 878 m
BC2
TA
300 m
e- Main Linac / 1.5 TeV / 12 GHz / 72-100 MV/m / 22 km
e+ Main Linac / 1.5 TeV / 12 GHz / 72-100 MV/m / 22 km
BDS
3.1 Km
Detector
MAIN BEAM COMPLEX
Spin Rotator
Booster Linac
9 GeV
BC1
e+ DR
359 m
e+ PDR
389 m
e- DR
359 m
Pre-Injector
e+ Linac
0.2 Gev
Primary e- Linac
e+ production
5 Gev
Target
Gun
Injector Linac
2.86 GeV
Pre-Injector
e- Linac
0.2 GeV
DC Gun

Two-beam acceleration

Counter propagation from central complex

Instead of using a single drive beam pulse for the whole main linac, several (N_S = 25) 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

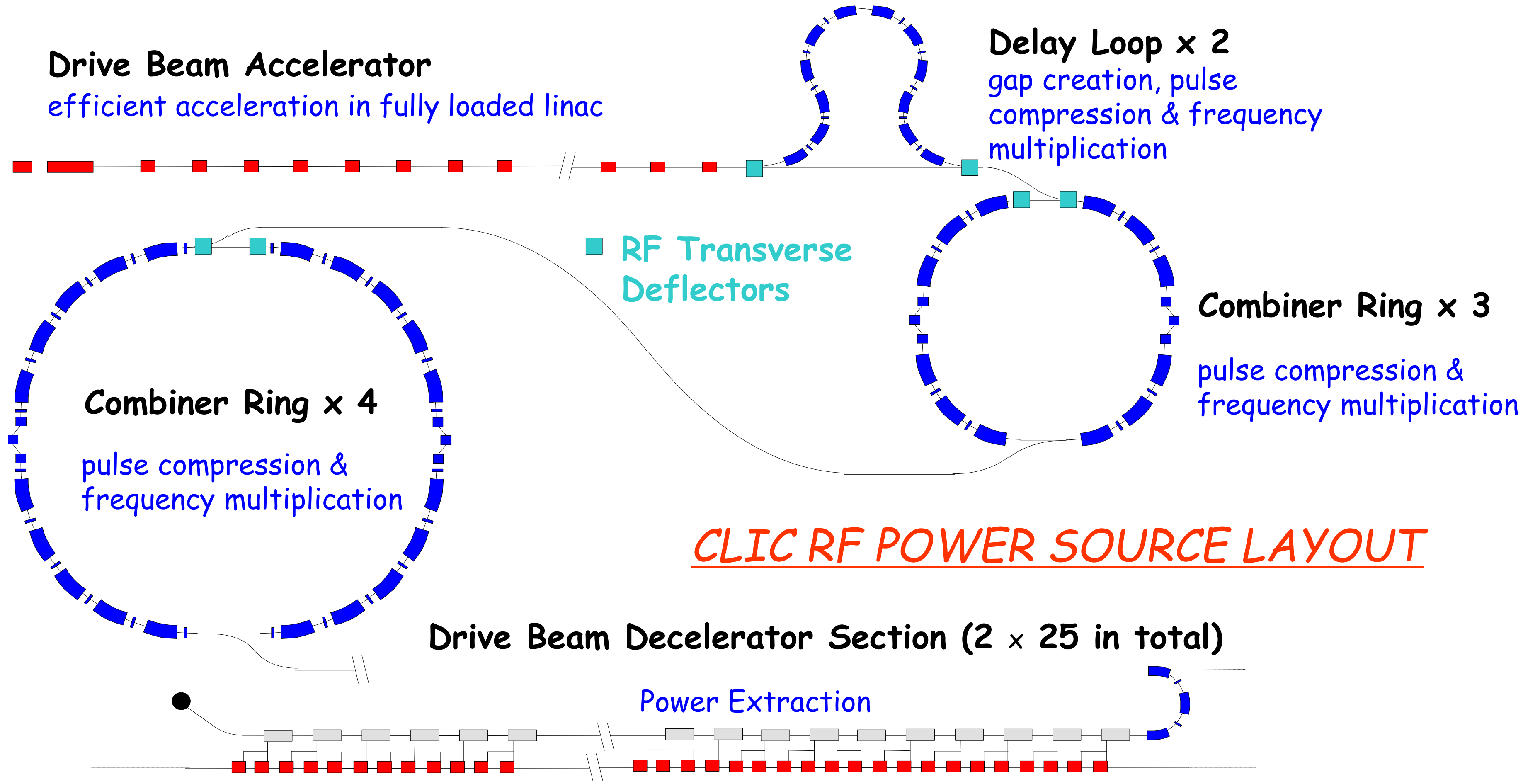
The distance between the pulses is 2 L_s = 2 L_{main}/N_S (L_{main}= single side linac length)

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

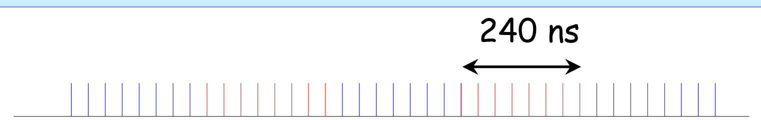
so t_{DB} = 2 L_{main} / c, 148 µs for the 3 TeV CLIC

R.Corsini

CLIC Drive Beam generation

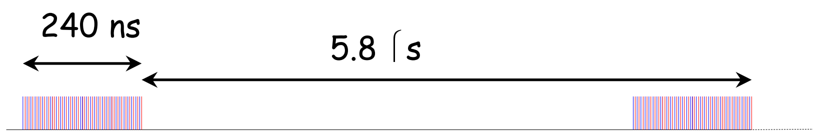


Drive beam time structure - initial



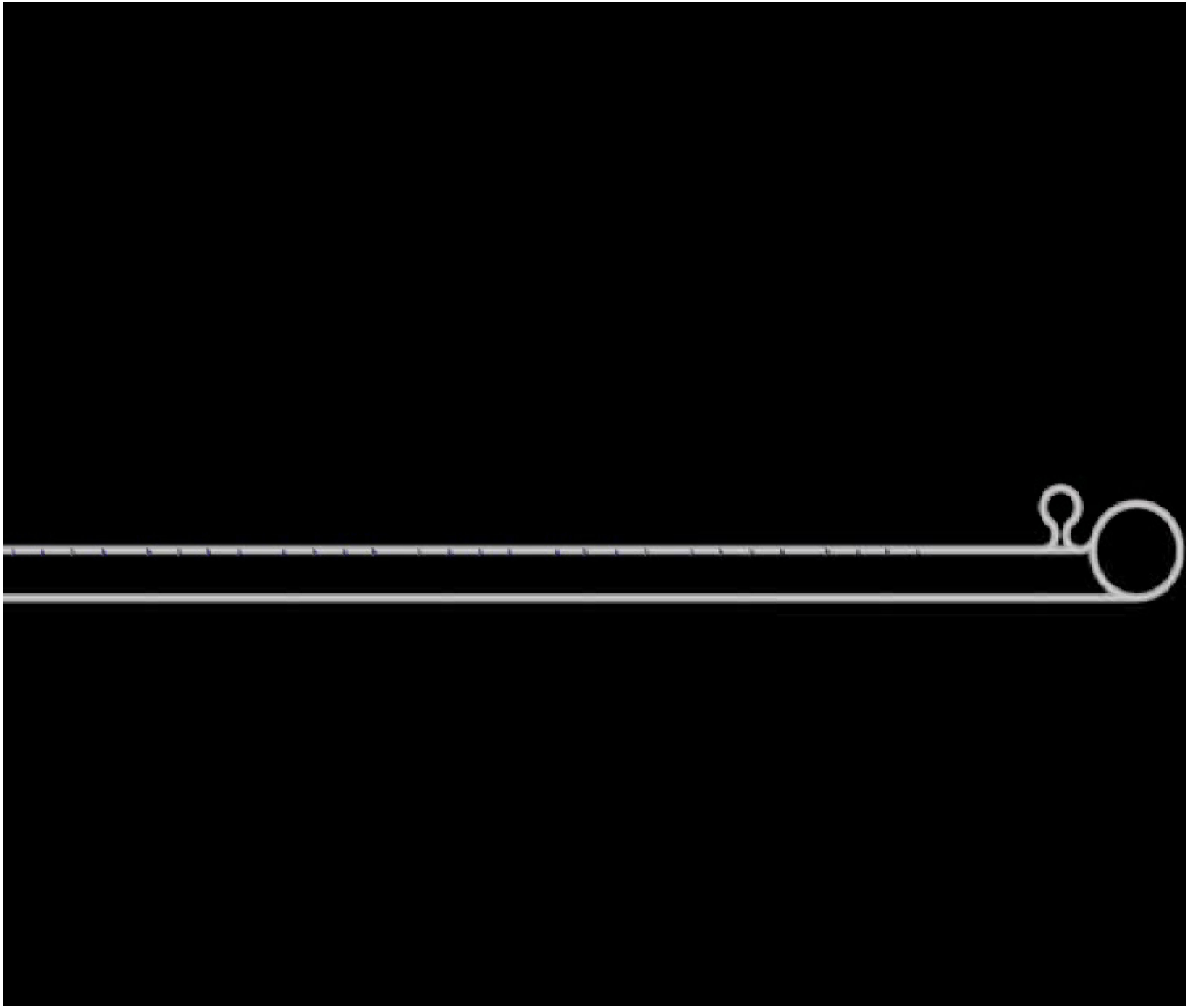
148 μs train length - 25 x 24 sub-pulses
4.2 A - 2.4 GeV – 60 cm between bunches

Drive beam time structure - final



25 pulses – **101 A** - 2.5 cm between bunches

Lemmings Drive Beam



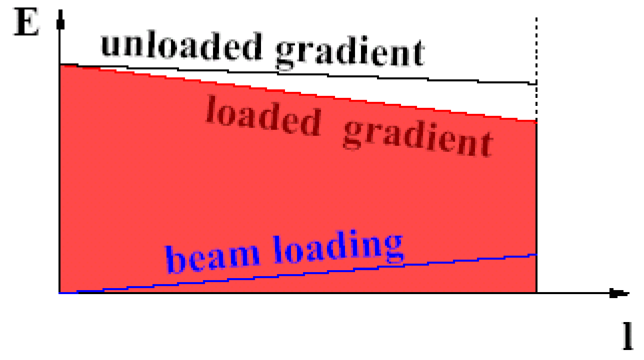
Alexandra Andersson

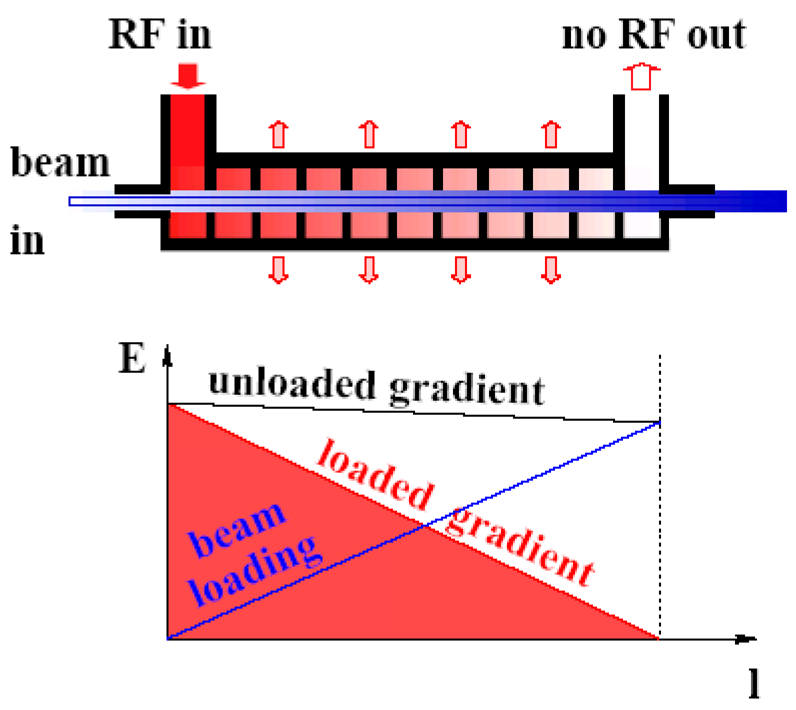
Fully loaded operation

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

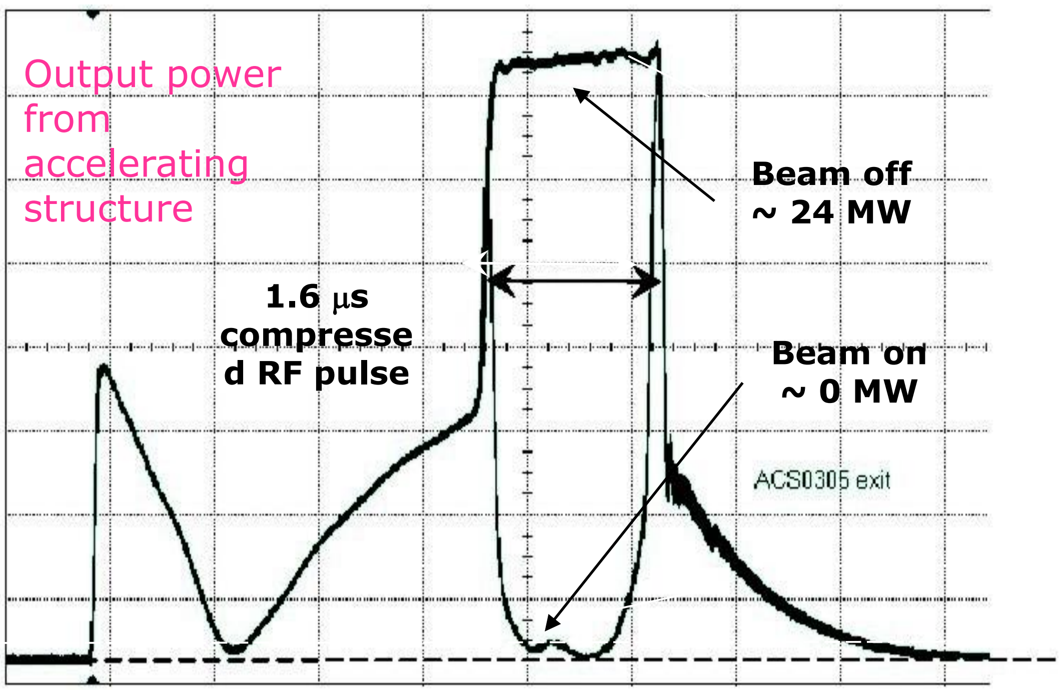
Fully loaded operation

- Disadvantage: any current variation changes energy gain

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

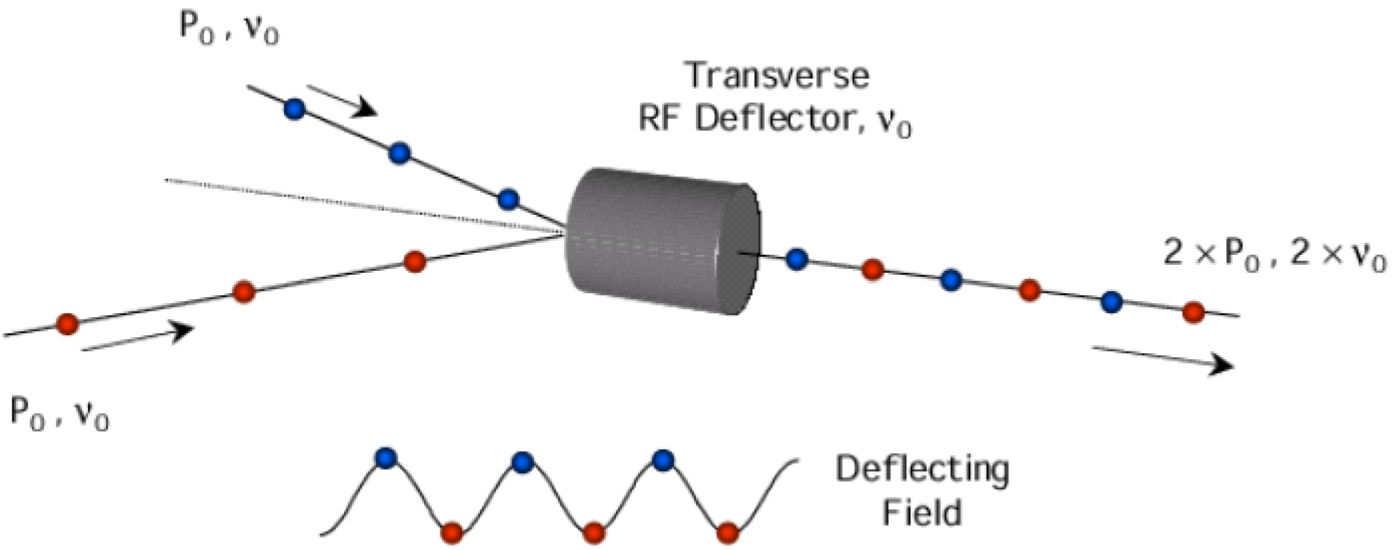
at full loading, 1% current variation = 1% voltage variation
at 20% loading, 1% current variation = 0.2% voltage variation

- Requires high current stability
- Stable beam successfully demonstrated in CTF3
- > 95% efficiency



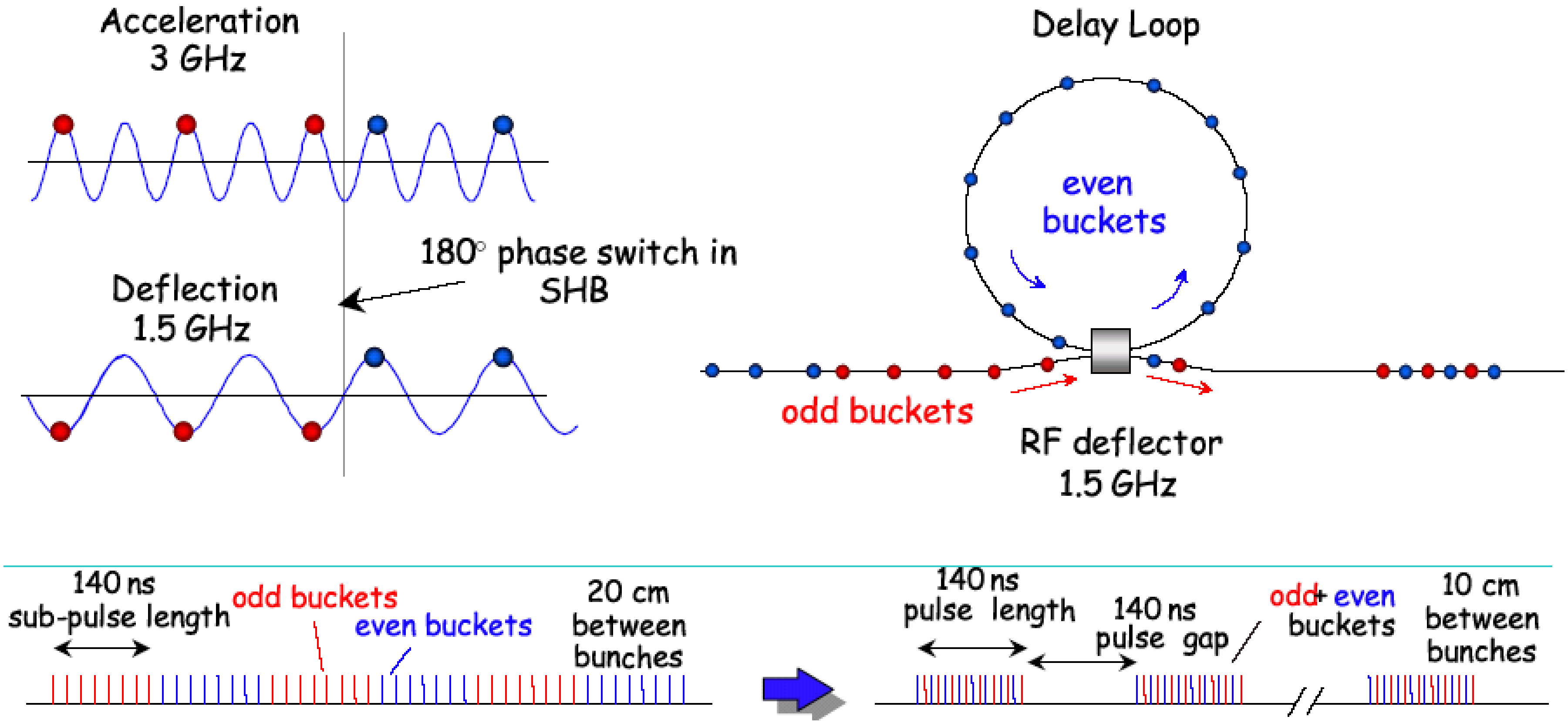
Frequency multiplication

- basic principle of drive beam generation
- transform very long pulses into short pulses with higher power and higher frequency
- use RF deflectors to interleave bunches
  - => double power
  - => double frequency



Delay Loop Principle

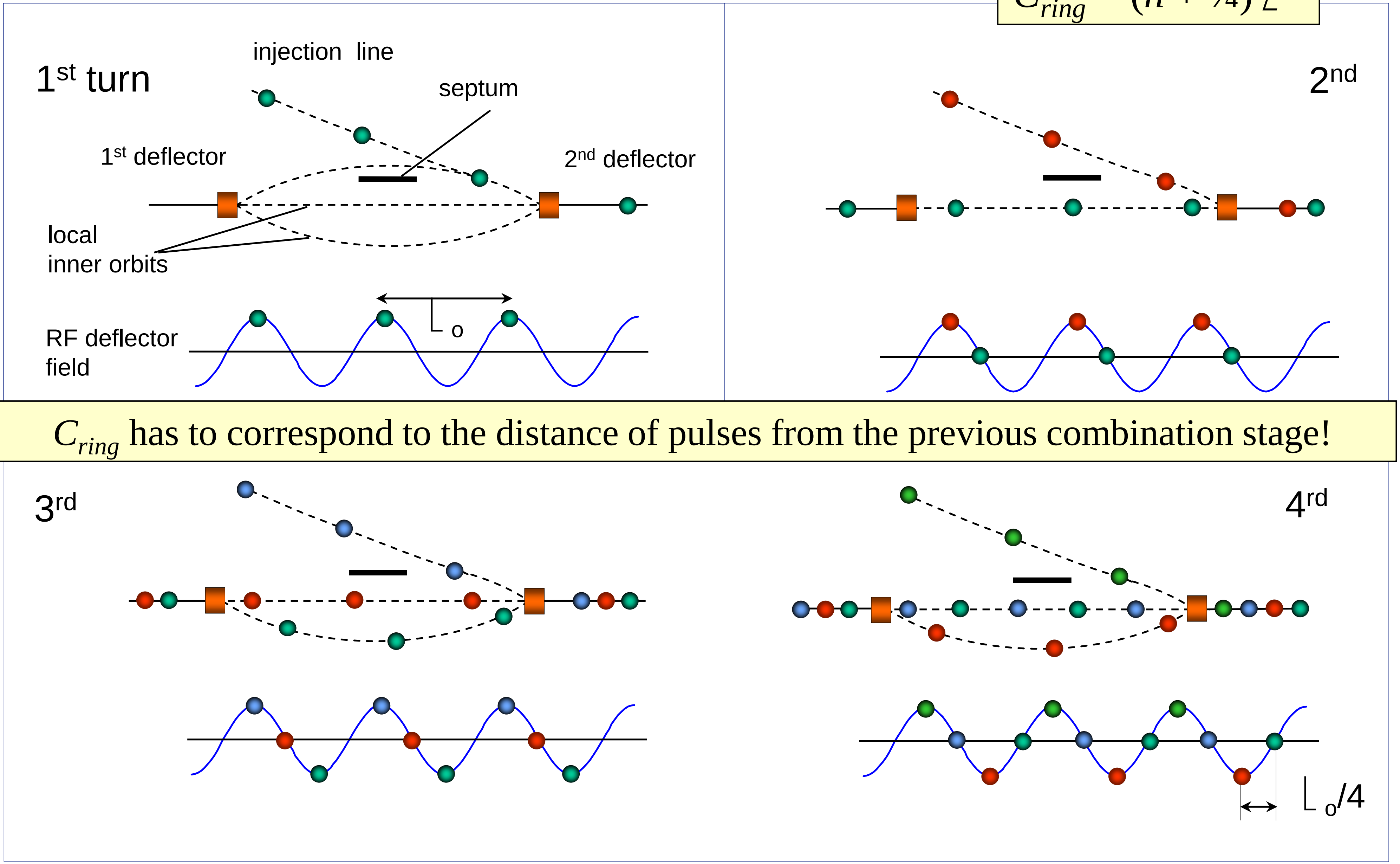
- **double repetition frequency and current**
- parts of bunch train delayed in loop
- RF deflector combines the bunches (f_{defl}=bunch rep. frequency)
- Path length corresponds to beam pulse length



RF injection in combiner ring (factor 4)

- combination factors up to 5 reachable in a ring

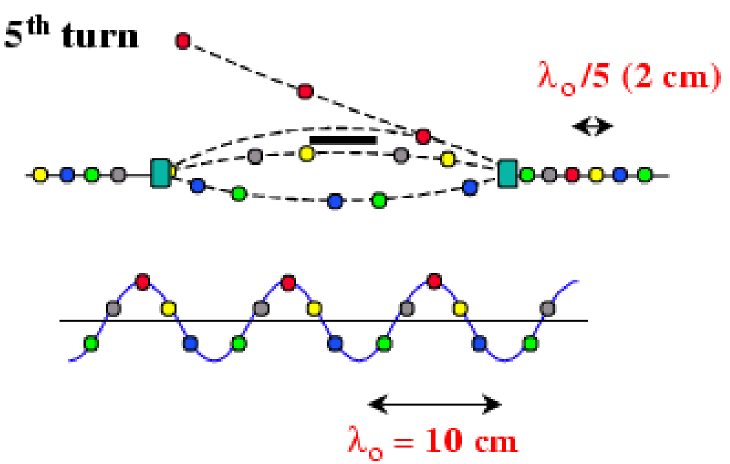
$C_{ring} = (n + 1/4)\,\lambda$



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

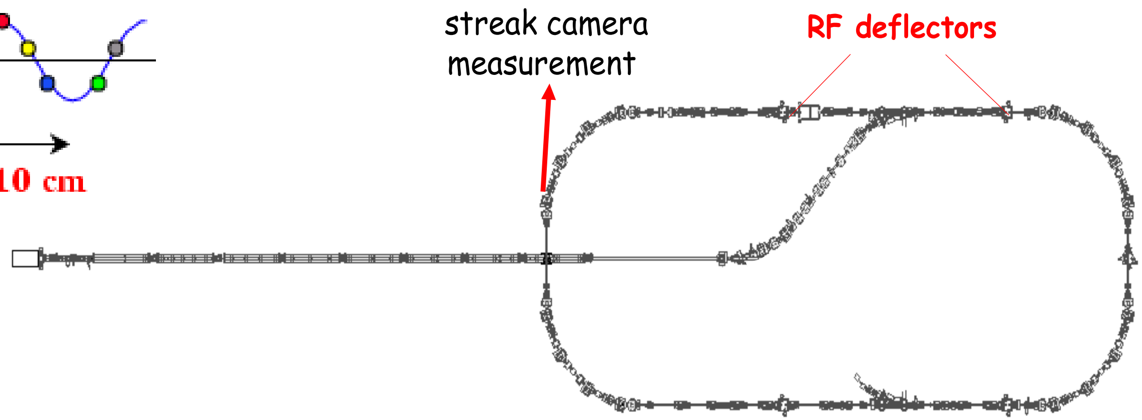
Demonstration of frequency multiplication

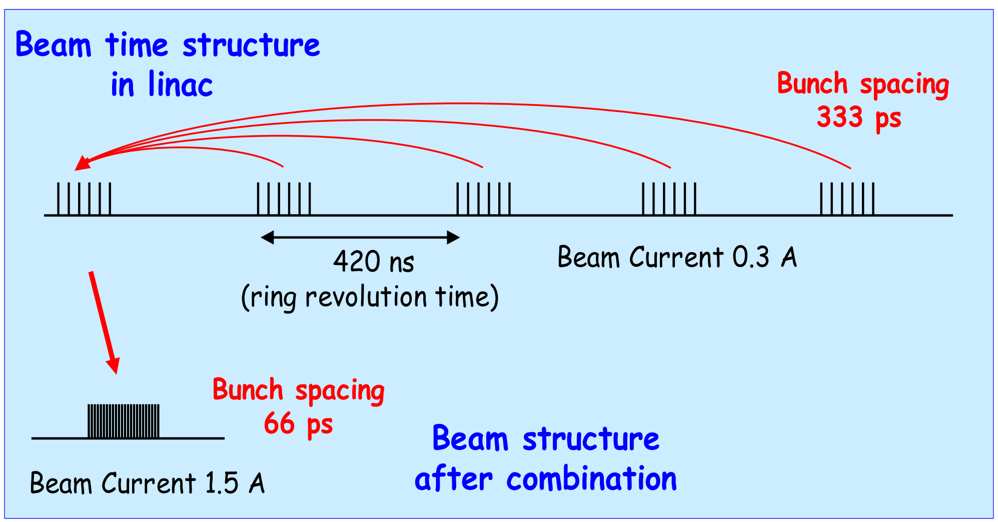
Combination factor 5



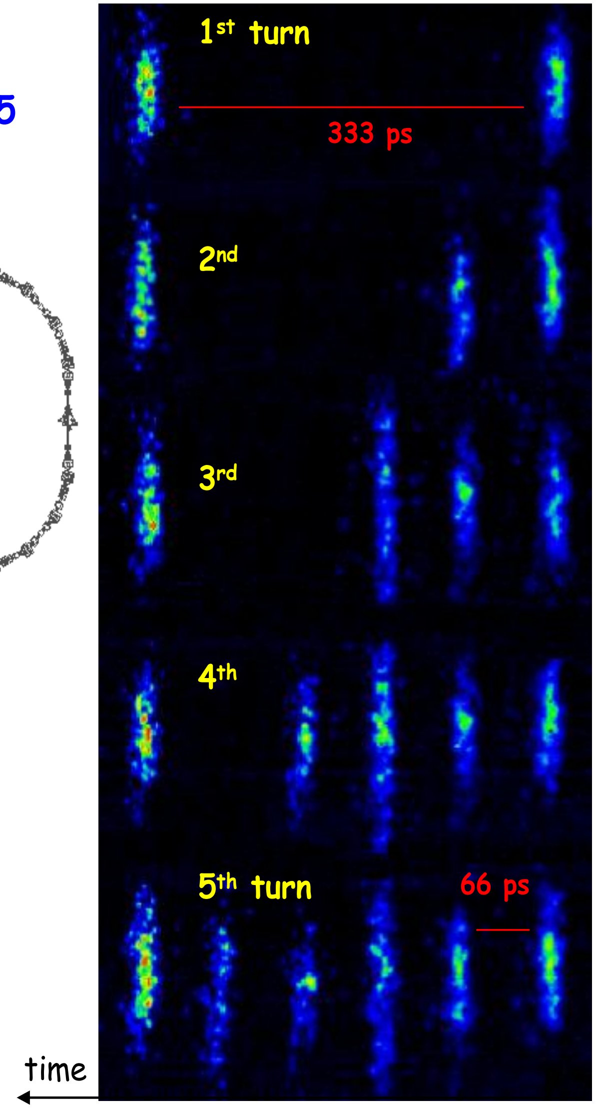
CTF3 - PRELIMINARY PHASE 2001/2002

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



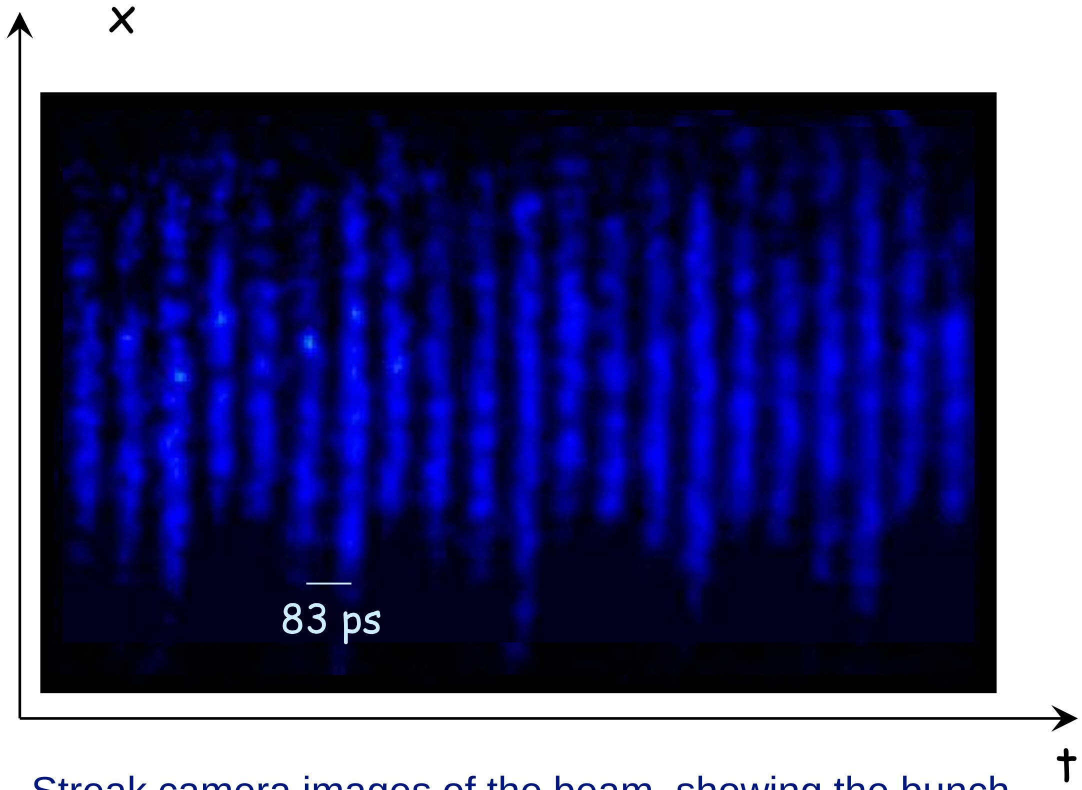


Streak camera image of beam time structure evolution



RF injection in combiner ring

Combination factor 4

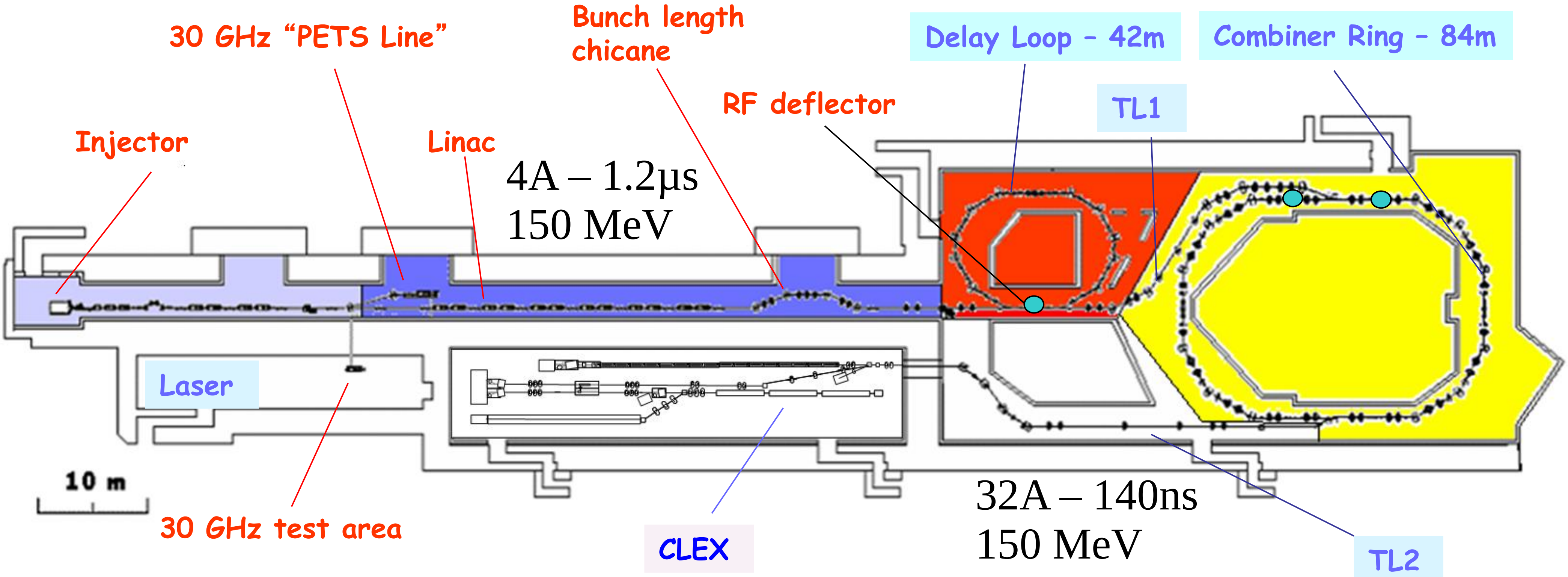


Streak camera images of the beam, showing the bunch combination process

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

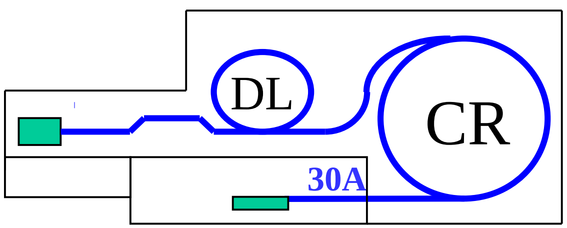
CTF 3

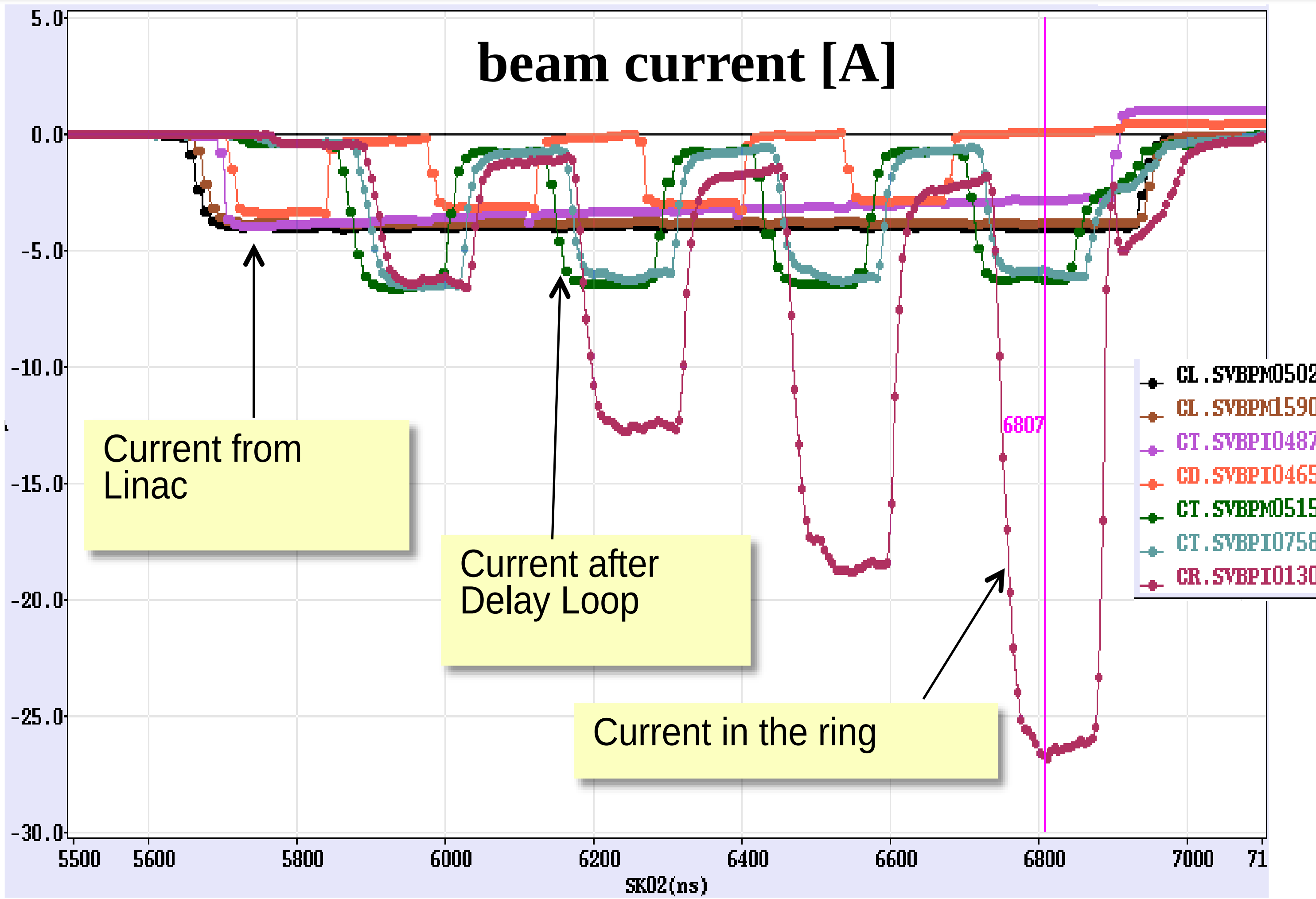
- demonstrate remaining CLIC feasibility issues, in particular:
  - Drive Beam generation (fully loaded acceleration, bunch frequency multiplication)
  - CLIC accelerating structures
  - CLIC power production structures (PETS)



Drive beam generation achieved

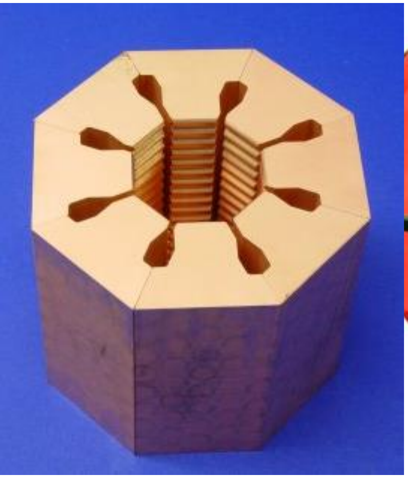
- combined operation of Delay Loop and Combiner Ring (factor 8 combination)
- ~26 A combination reached, nominal 140 ns pulse length
- => **Full drive beam generation**, main goal of 2009, **achieved**

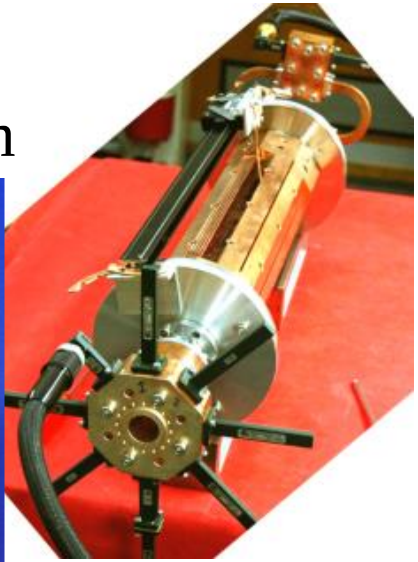


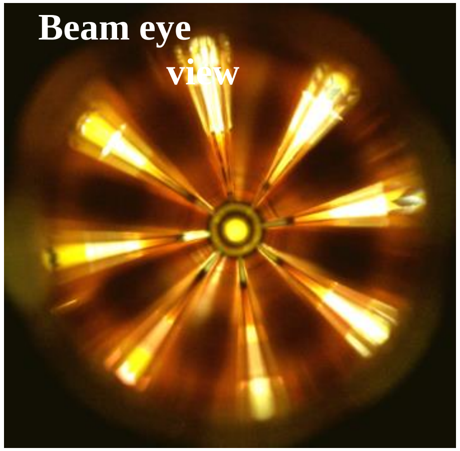


Power extraction structure PETS

- 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







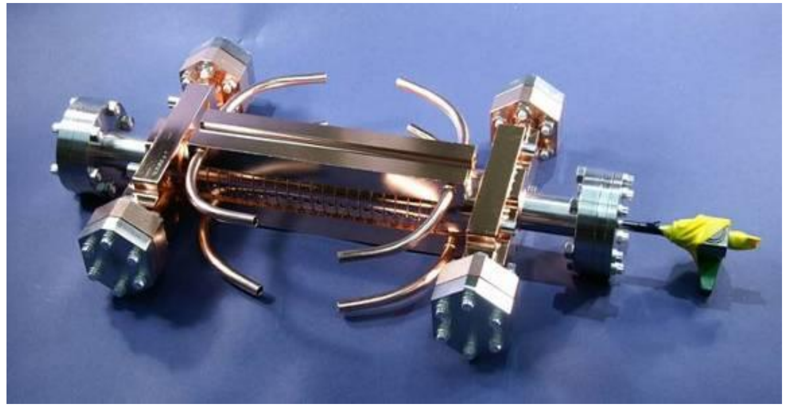
The power produced by the bunched (ω_0) beam in a constant impedance structure:

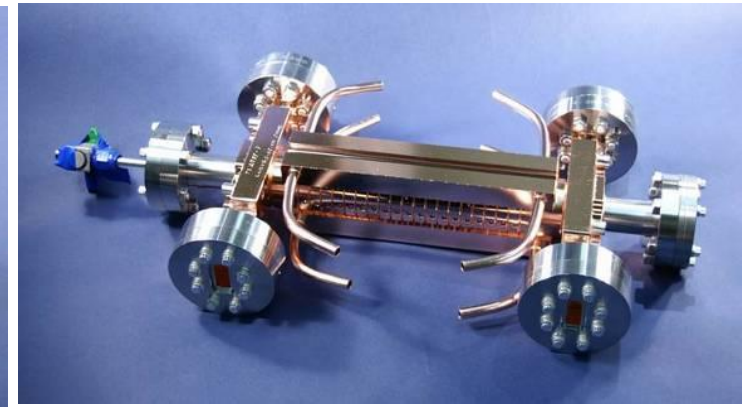
Design input parameters — PETS design

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

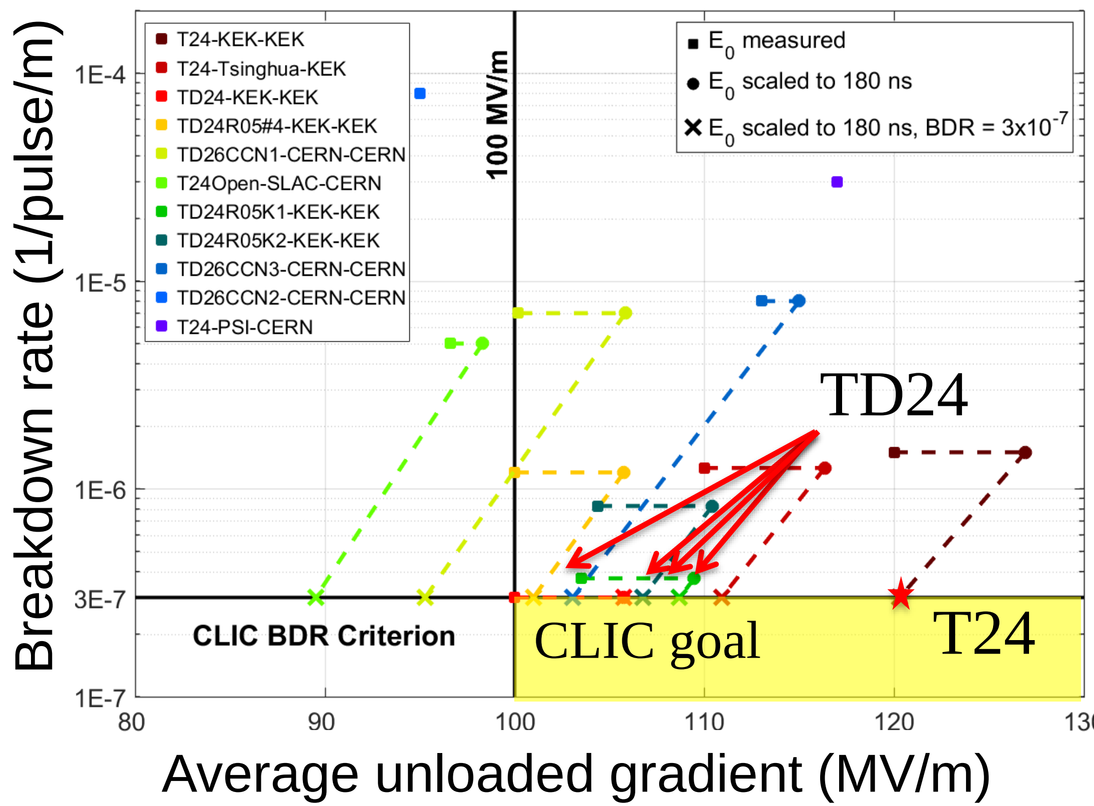
P – RF power, determined by the accelerating structure needs and the module layout.
I – Drive beam current
L – Active length of the PETS
F_b – single bunch form factor (≈ 1)

Accelerating Structure Results

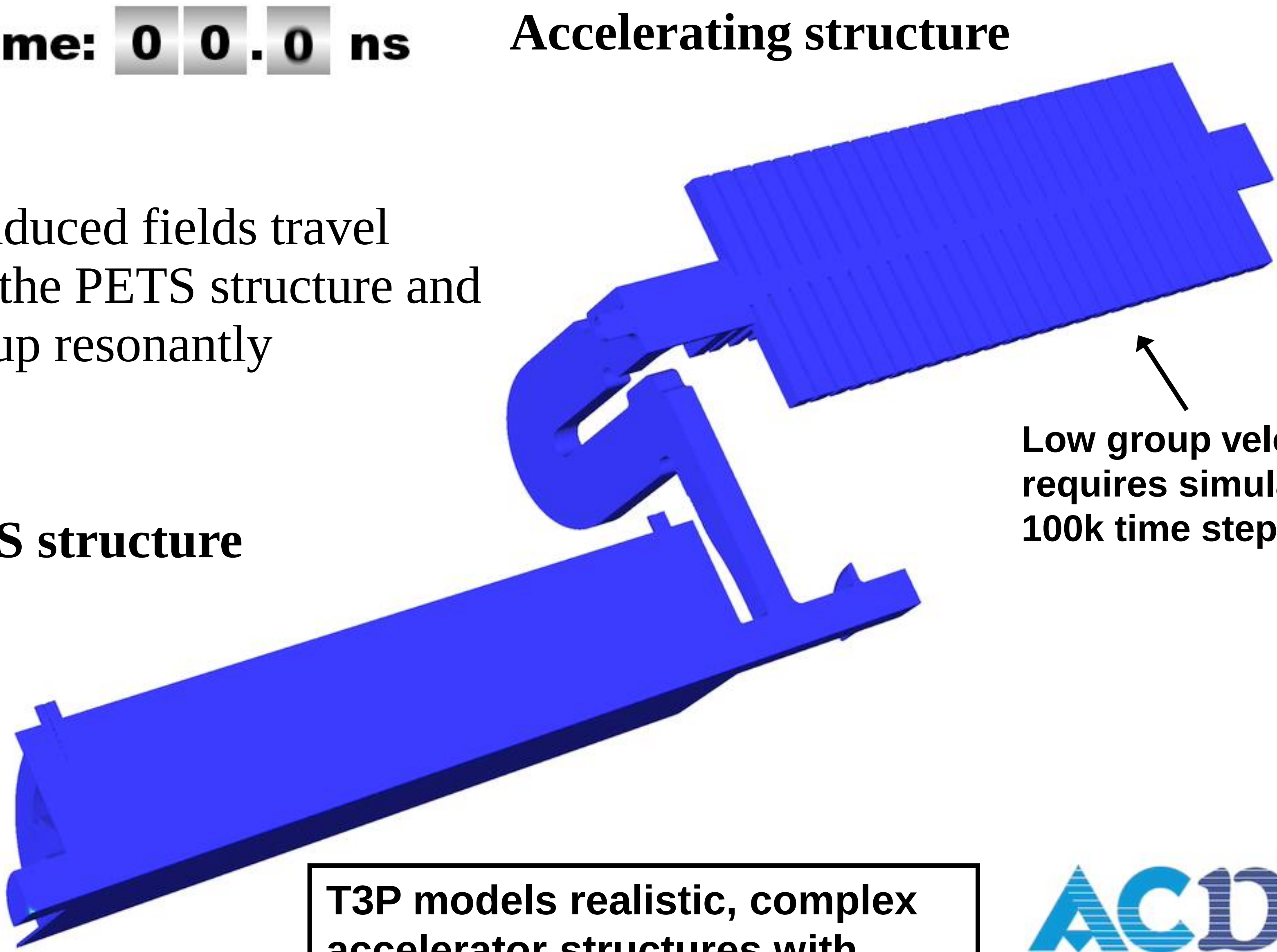




- RF breakdowns can occur => no acceleration and deflection
- Goal: 3 10^{-7}/m breakdowns at 100 MV/m loaded gradient at 230 ns pulse length
- latest prototypes (T24 and TD24) tested (SLAC and KEK)
- => TD24 reach up to 108 MV/m at nominal CLIC breakdown rate (without damping material)
- Undamped T24 reaches 120MV/m



time: 0 0 . 0 ns



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

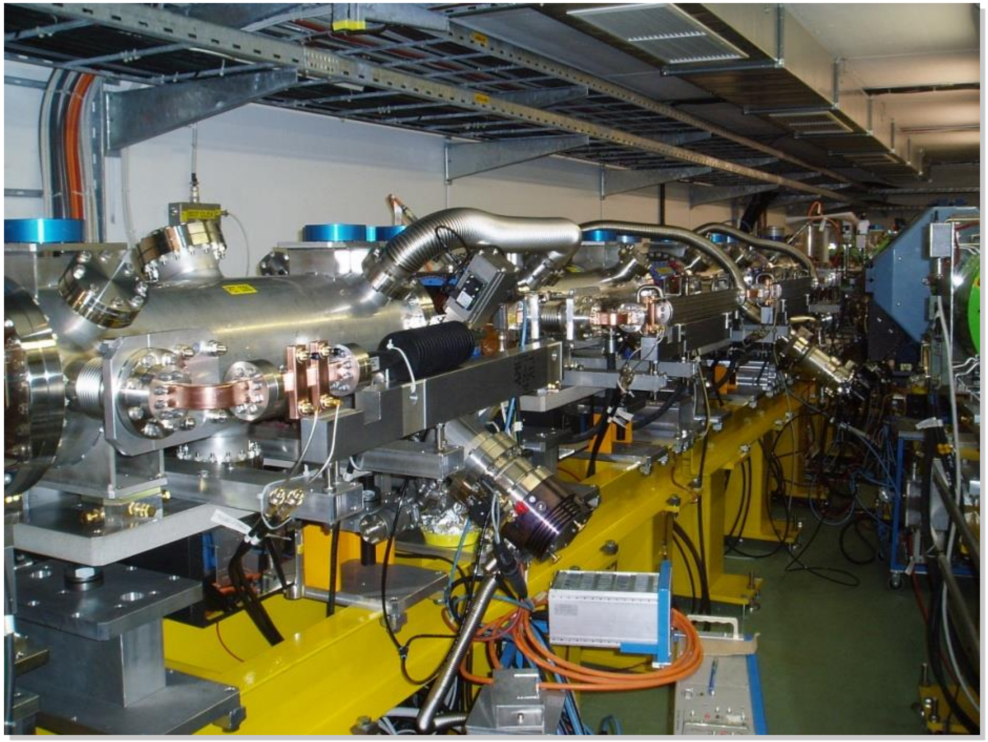
Low group velocity requires simulations with 100k time steps

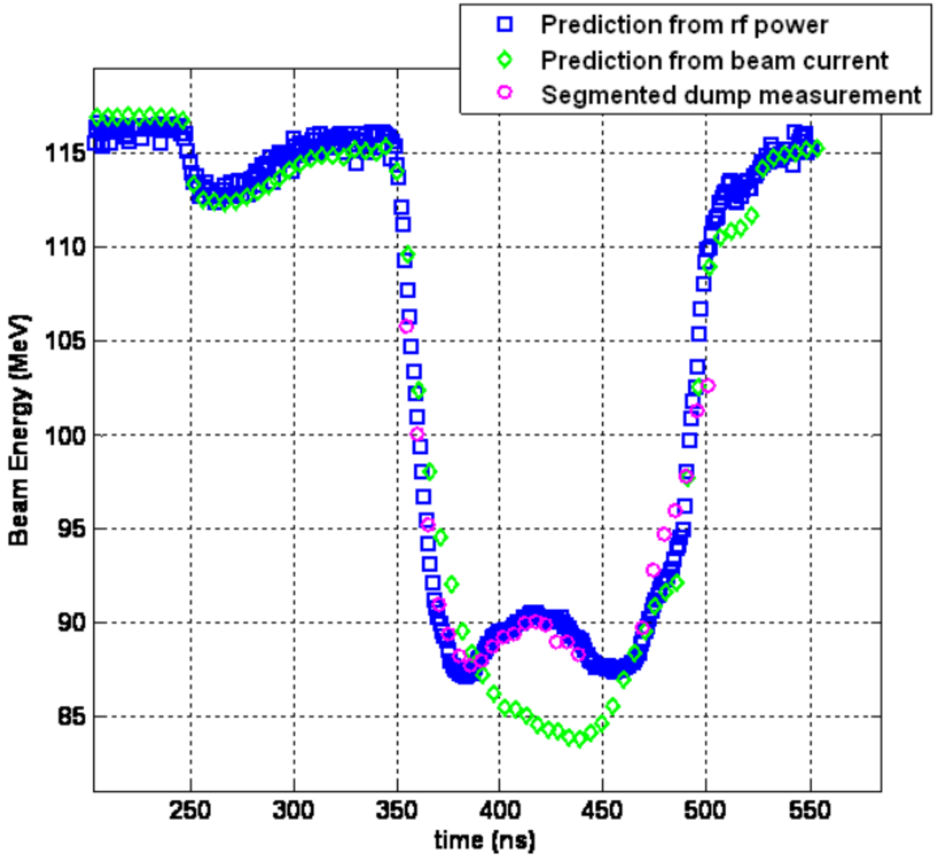
T3P models realistic, complex accelerator structures with unprecedented accuracy

Arno Candel, SLAC

Achieved Deceleration + RF power generation

- Drive beam has high current and high energy spread
- Stable transport in simulations verified experimentally with 13 PETS
- 24 A beam decelerated by ~51%, >1.3 GW power produced!
- Good agreement of power production, beam current and deceleration

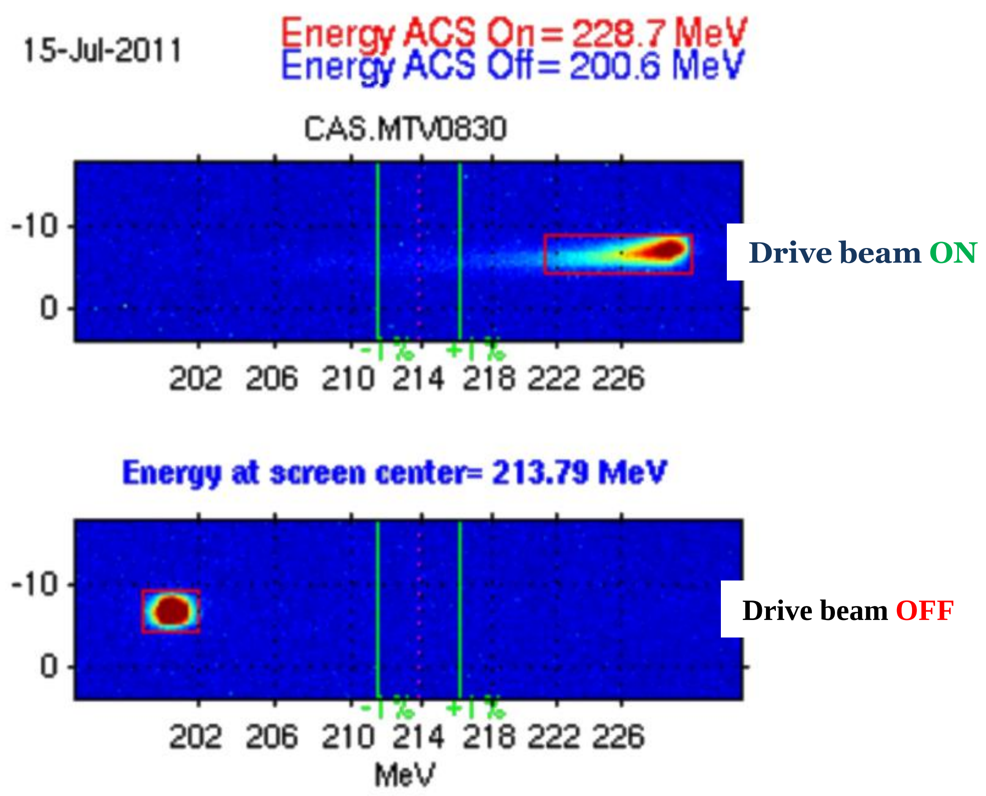


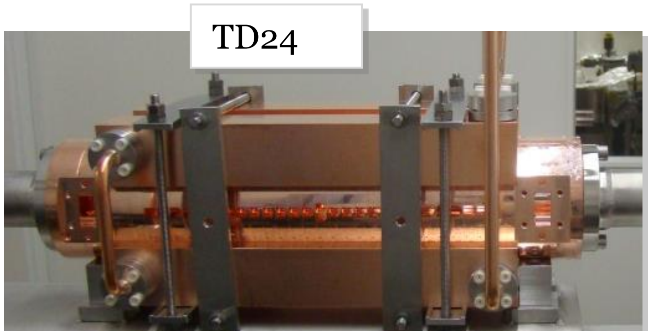


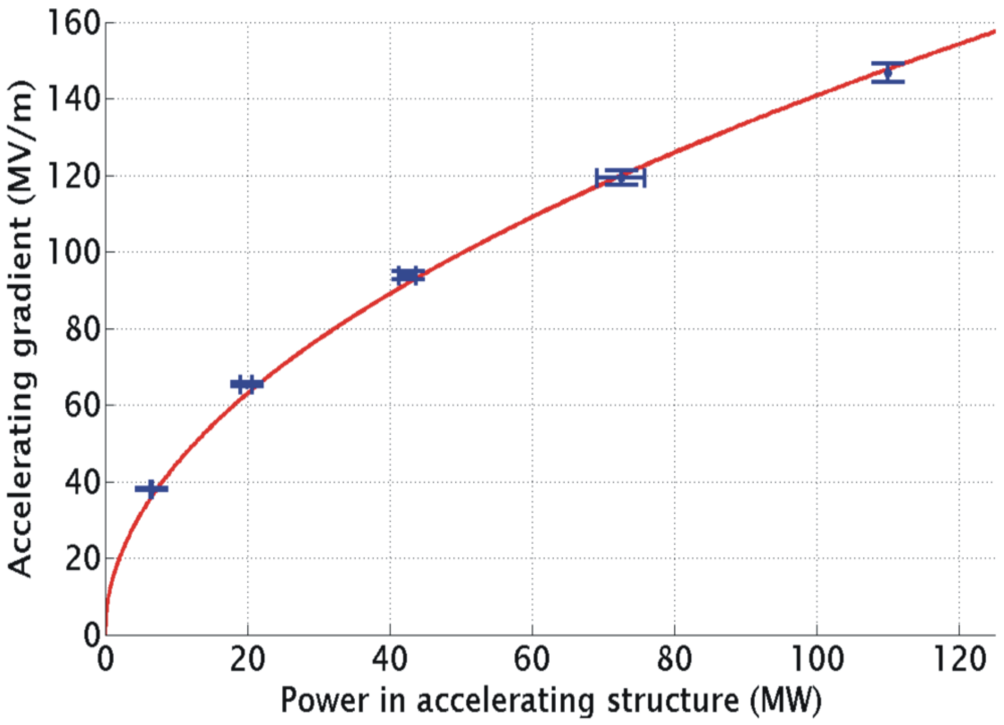
Achieved Two-Beam Acceleration

- Maximum probe beam acceleration measured: 31 MeV

  => Corresponding to a gradient of 145 MV/m







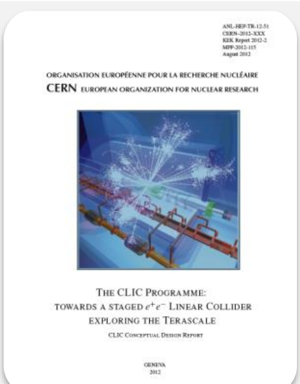
CLIC CDRs published 2012

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

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

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

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

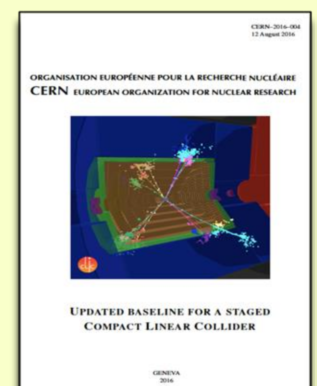


Vol 3: "CLIC study summary" (S.Stapnes)

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

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

2016:
CLIC Baseline update After Higgs discovery https://cds.cern.ch/record/2210892/



Recent CLIC information

CLIC input to the European Strategy for Particle Physics Update 2018-2020

Formal European Strategy submissions

- The Compact Linear e+e- Collider (CLIC): Accelerator and Detector (arXiv:1812.07987)
- The Compact Linear e+e- Collider (CLIC): Physics Potential (arXiv:1812.07986)

Yellow Reports

- CLIC 2018 Summary Report (CERN-2018-005-M)
- CLIC Project Implementation Plan (CERN-2018-010-M)
- The CLIC potential for new physics (CERN-2018-009-M)
- Detector technologies for CLIC (CERN-2019-001)

Journal publications

- Top-quark physics at the CLIC electron-positron linear collider (Journal, arXiv:1807.02441)
- Higgs physics at the CLIC electron-positron linear collider (Journal, arXiv:1608.07538)

CLICdp notes

- Updated CLIC luminosity staging baseline and Higgs coupling prospects (CERN Document Server,arXiv:1812.01644)
- CLICdet: The post-CDR CLIC detector model (CERN Document Server)
- A detector for CLIC: main parameters and performance (CERN Document Server, arXiv:1812.07337)

Link: http://clic.cern/european-strategy

Summary

- Linear e+/e- Collider the only realistic approach to highest energy
- Many challenges!!!
- Efficient acceleration
  - RF system
  - High gradient
- Extremely small beam sizes
  - Damping ring performance is crucial
  - Emittance preservation
  - Alignment and stabilisation
- Much interesting work left to do!!!
- Much more detailed lectures at recent ILC schools http://agenda.linearcollider.org/event/6906 or http://agenda.linearcollider.org/event/7333
- Some nice animations for CLIC on http://clic.cern
- CERN Accelerator School lecture video about ILC/CLIC latest status at https://indico.cern.ch/event/1018359/contributions/4312245