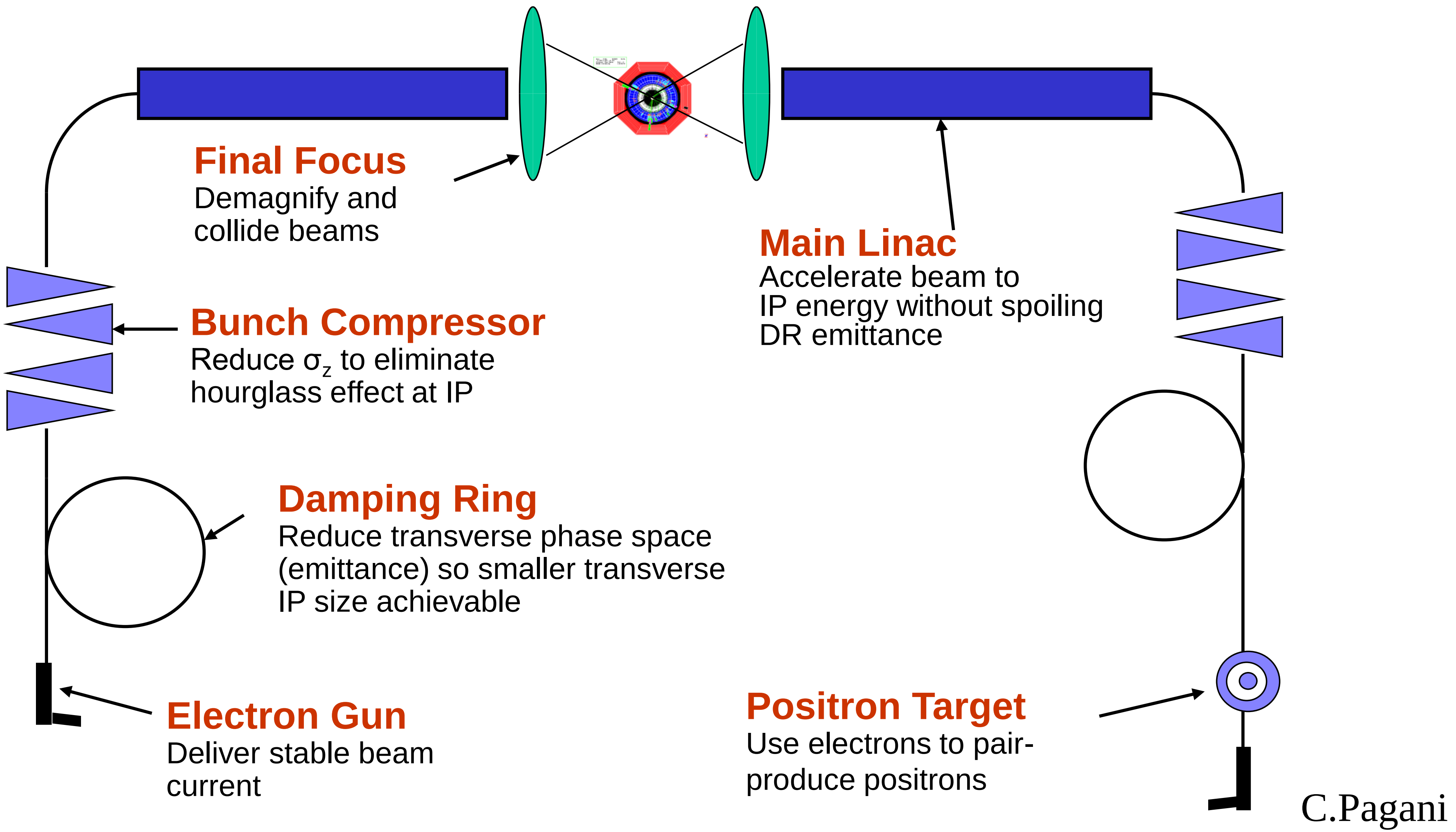
Linear Colliders Lecture 4

Frank Tecker – CERN

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

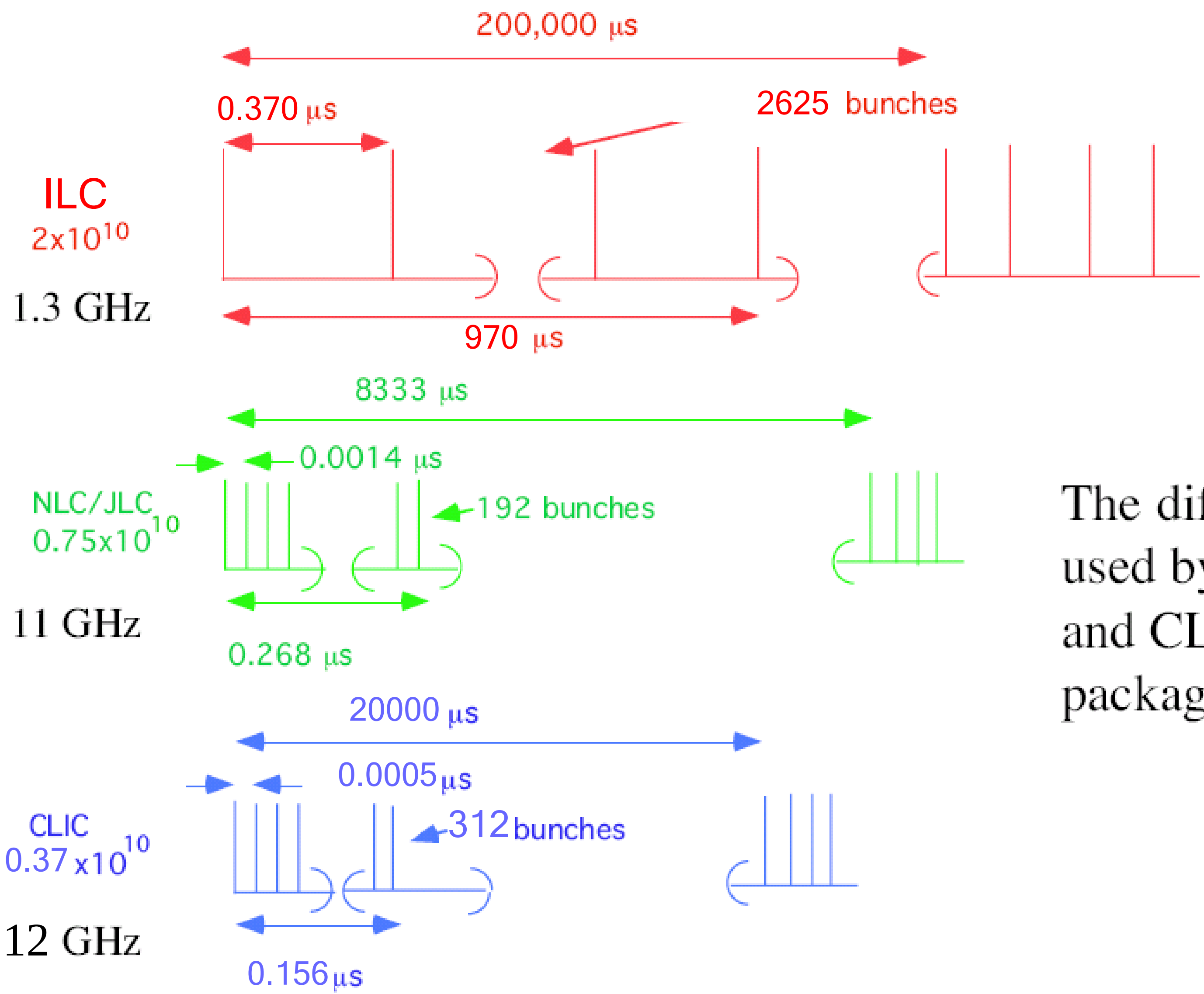
Generic Linear Collider



- We have seen the different sub-systems in the previous lectures
- Now let’s look at some differences in the real designs…

Bunch structure

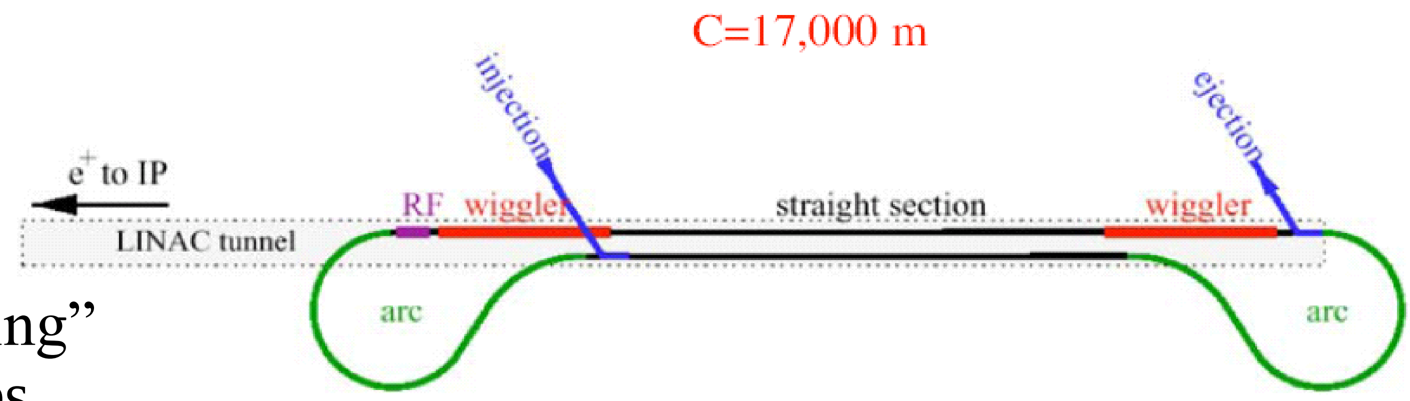
- SC allows long pulse, NC needs short pulse with smaller bunch charge

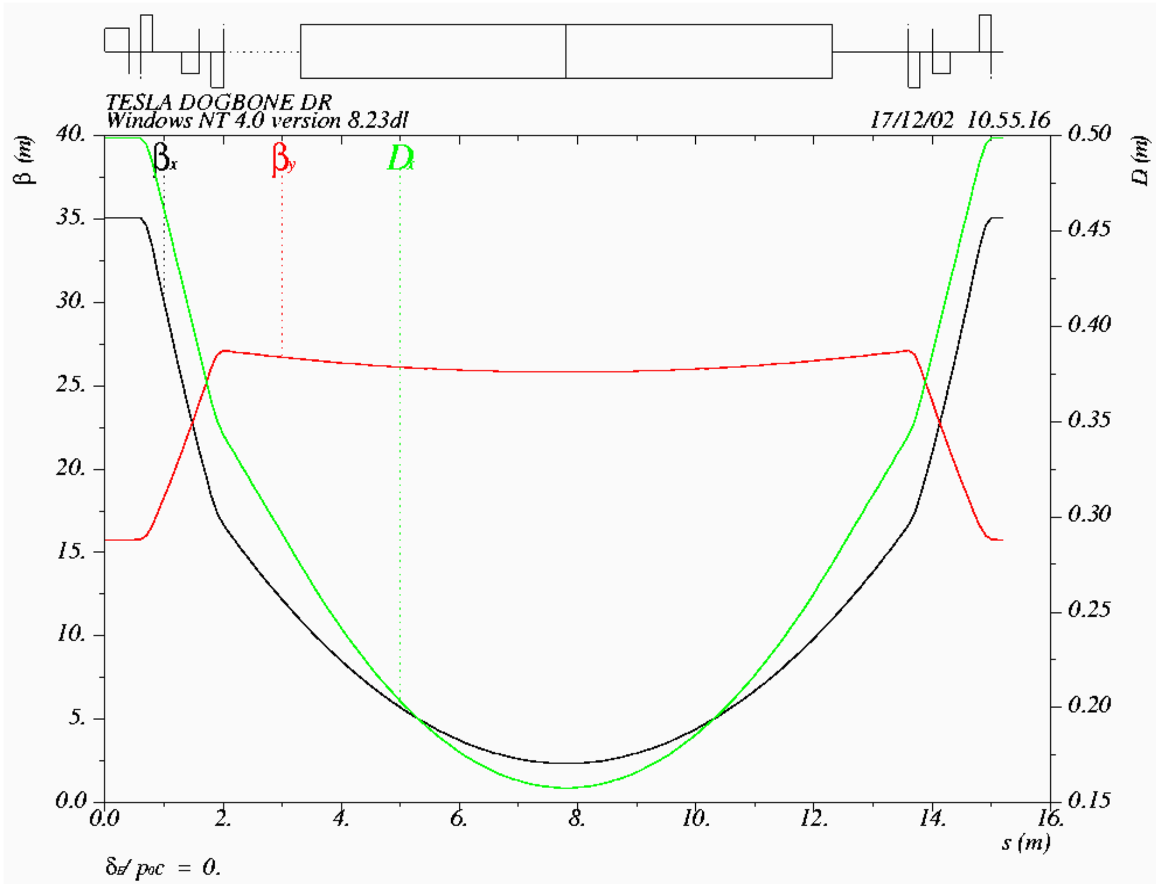


The different RF technologies used by ILC , NLC/JLC and CLIC require different packaging for the beam power

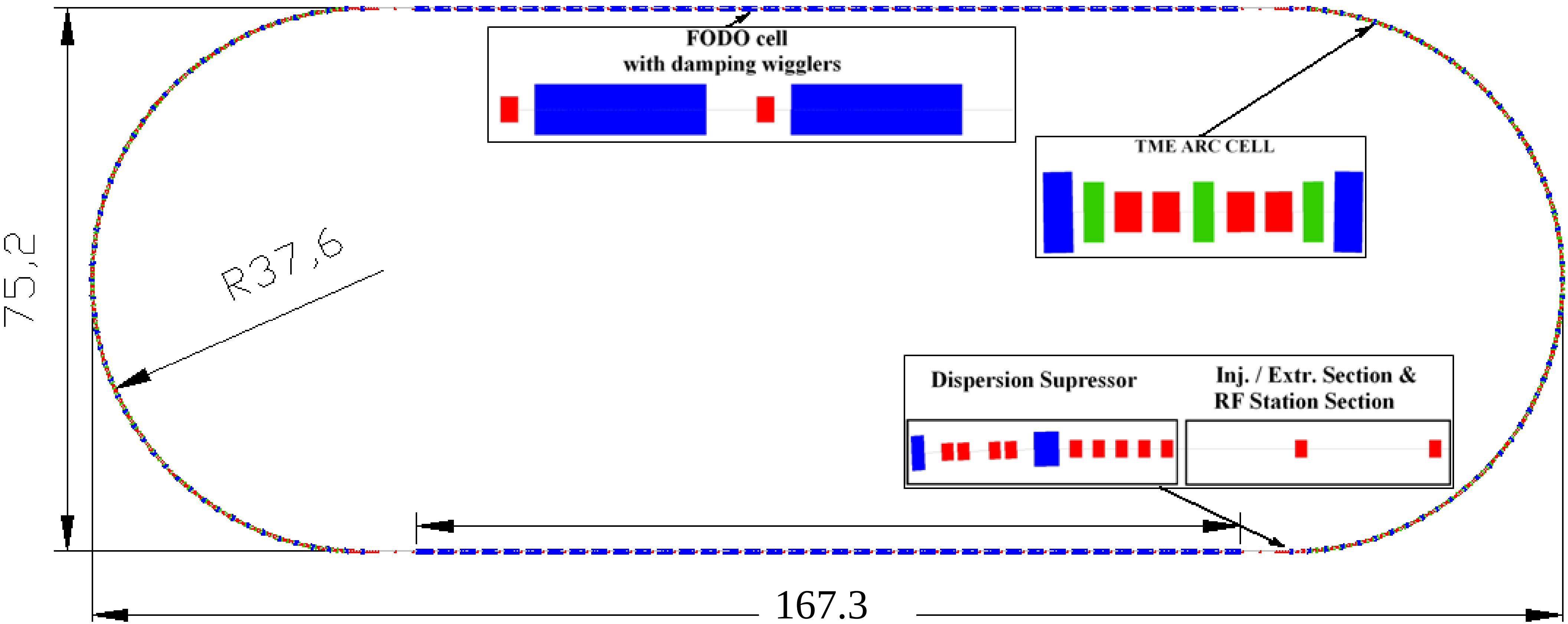
TESLA/ILC damping ring

- 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

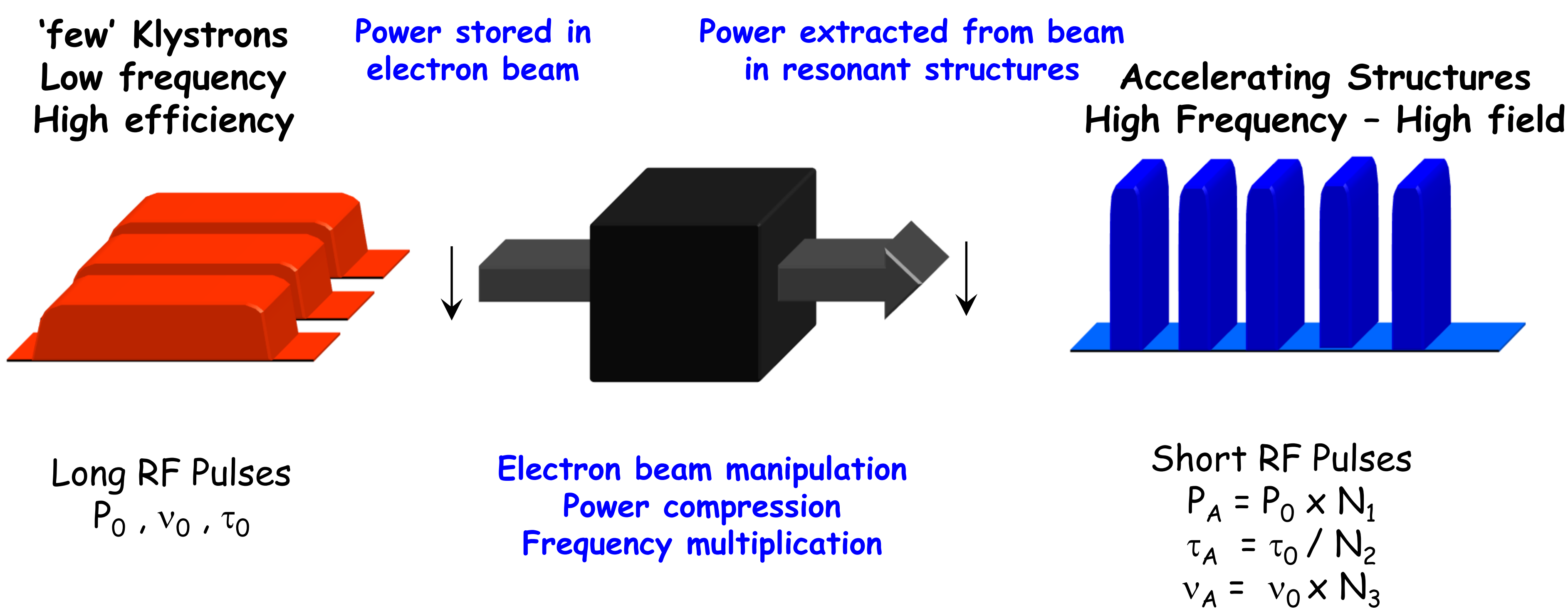
Warm vs Cold RF Collider

- 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 ☹

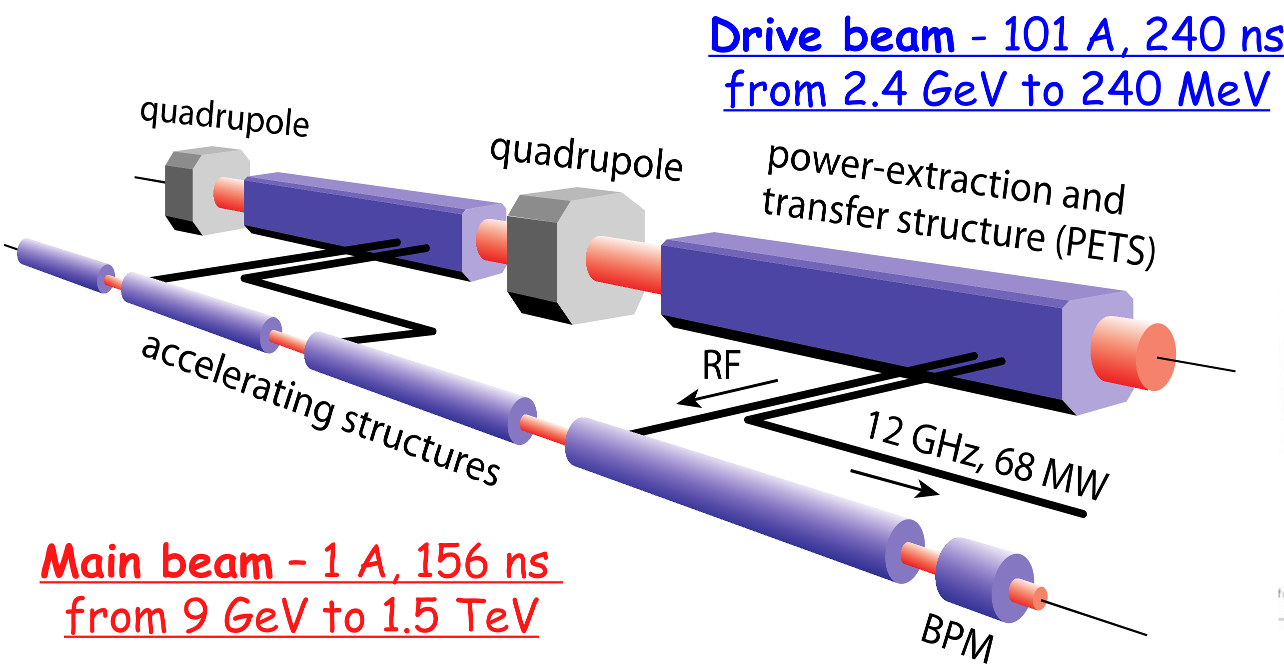
CLIC scheme

- 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)

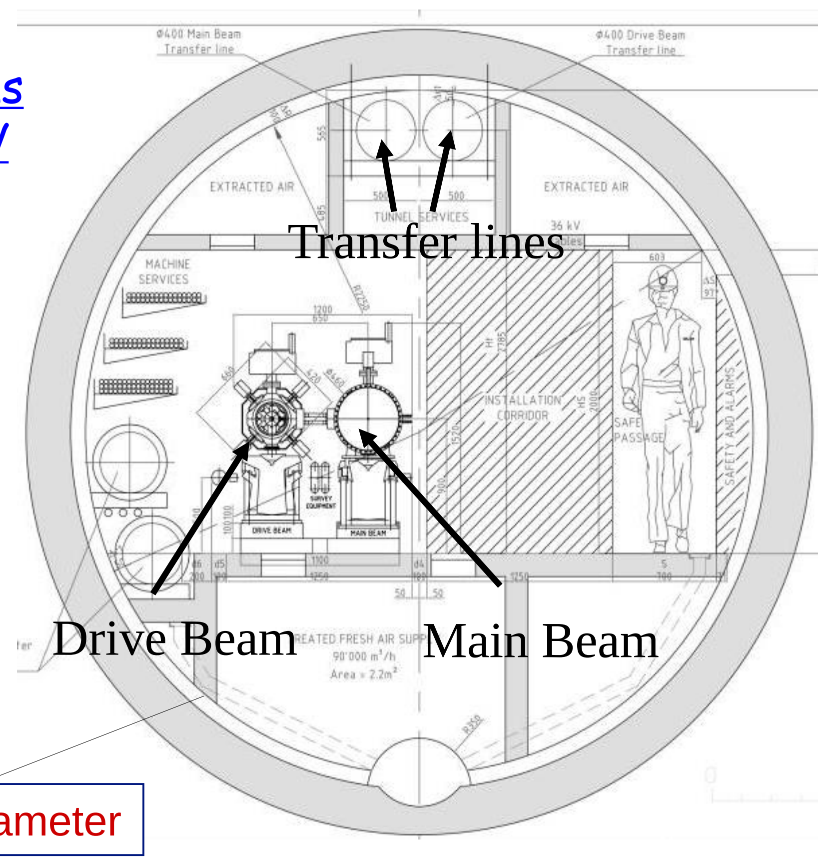


CLIC two beam scheme

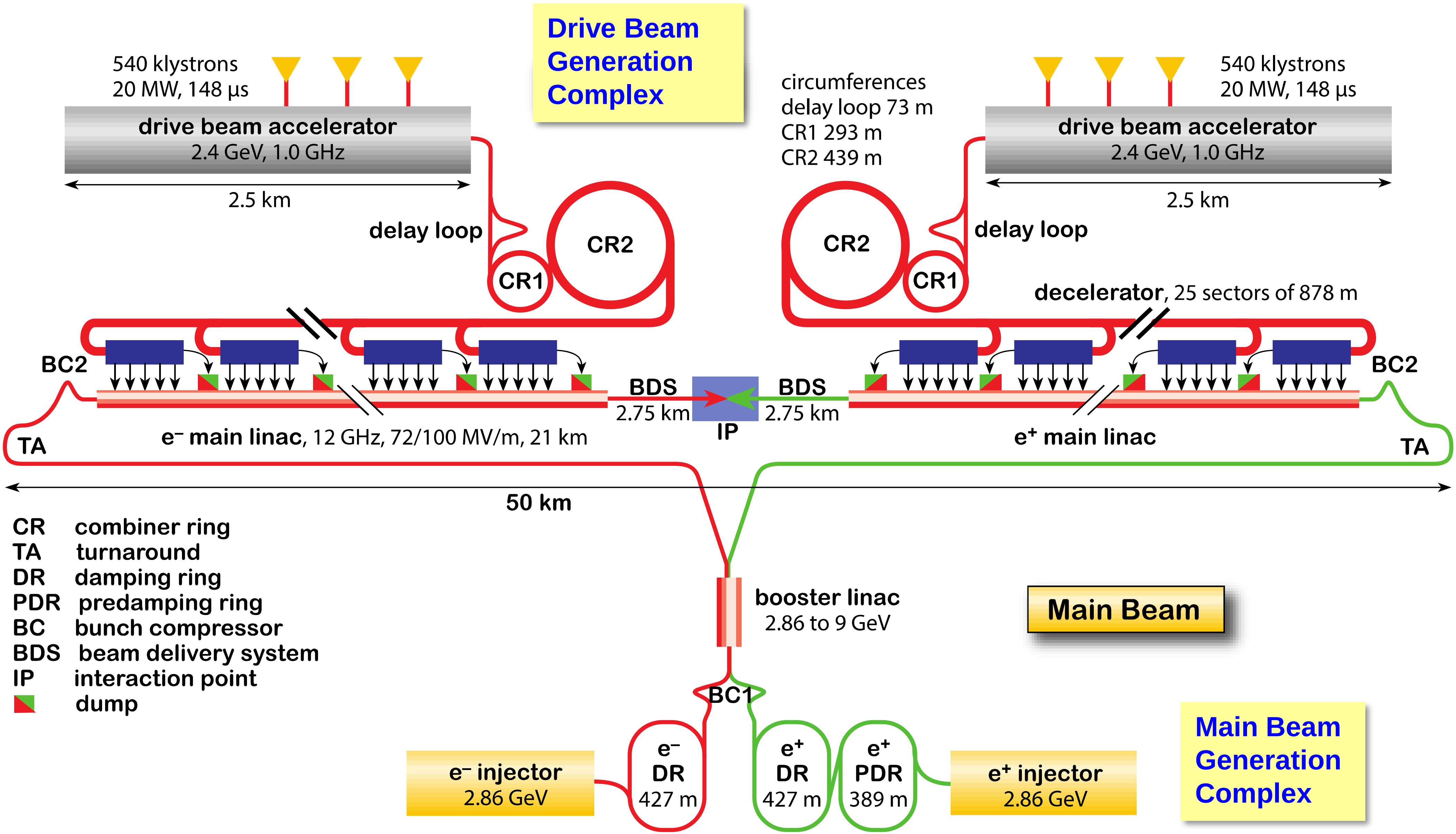
- High charge Drive Beam (low energy)
- Low charge Main Beam (high collision energy)
- => Simple tunnel, no active elements
- => Modular, easy energy upgrade in stages



CLIC TUNNEL CROSS-SECTION



CLIC – overall layout – 3 TeV



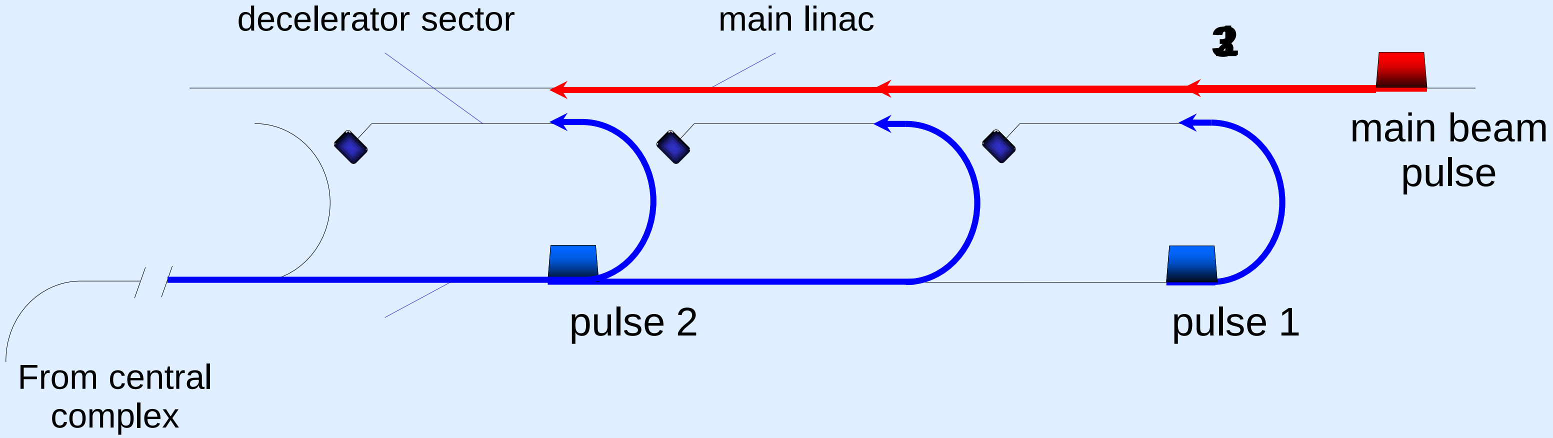
CR combiner ring
TA turnaround
DR damping ring
PDR predamping ring
BC bunch compressor
BDS beam delivery system
IP interaction point
dump

Two-beam acceleration

Counter propagation from central complex

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

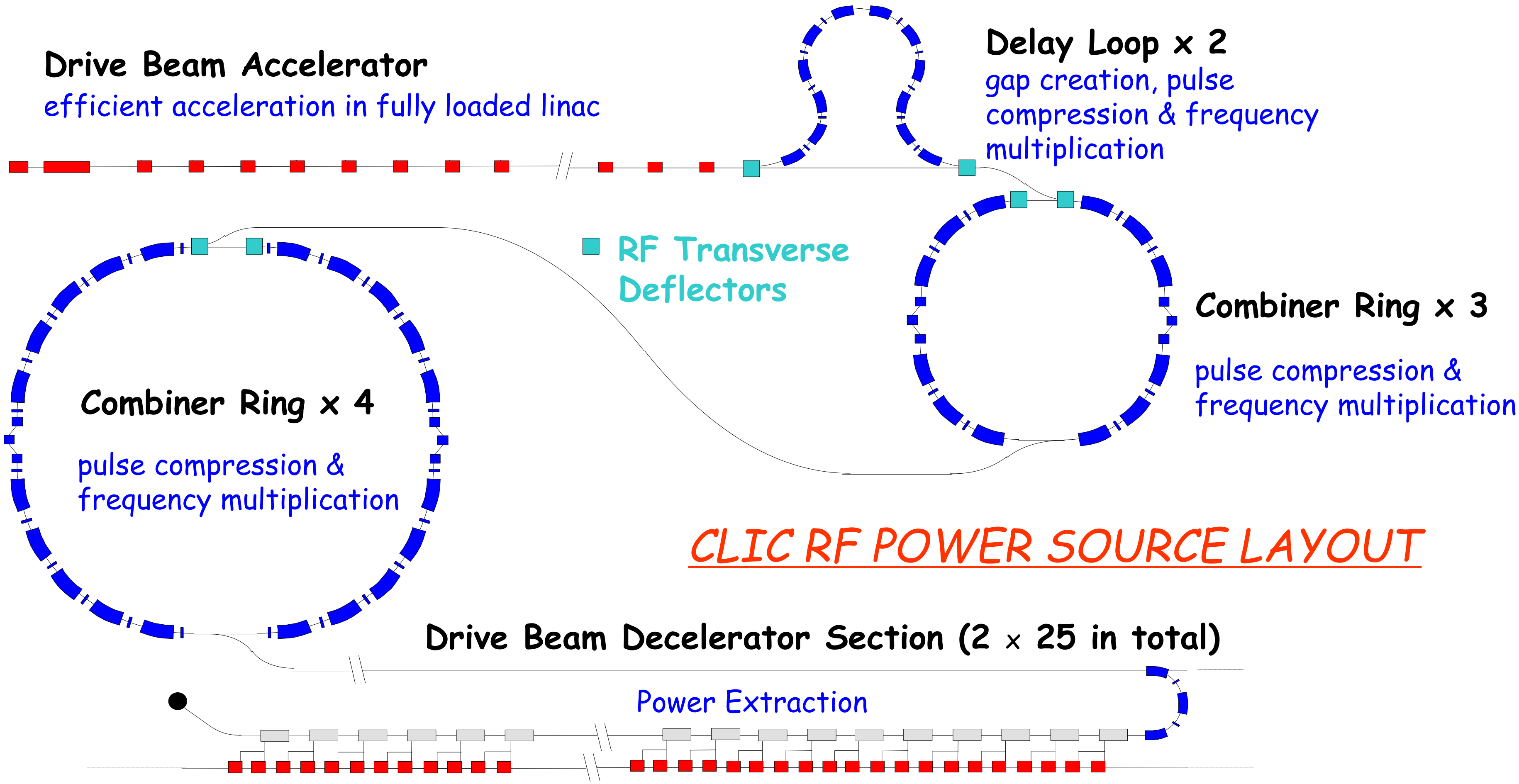
The distance between the pulses is $2 L_s = 2 L_{main}/N_S$ (L_{main}= single side linac length)

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

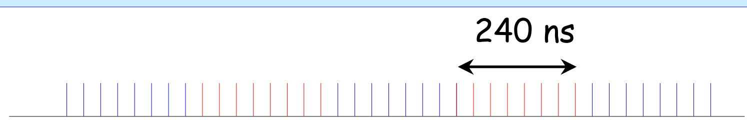
so $t_{DB} = 2 L_{main} / c$, 148 μs for the 3 TeV CLIC

R.Corsini

CLIC Drive Beam generation

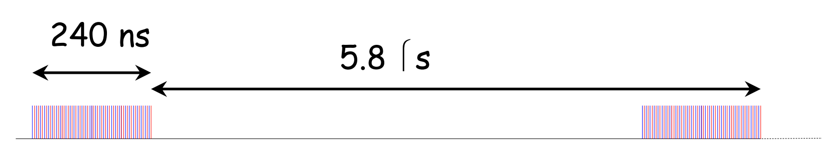


Drive beam time structure - initial



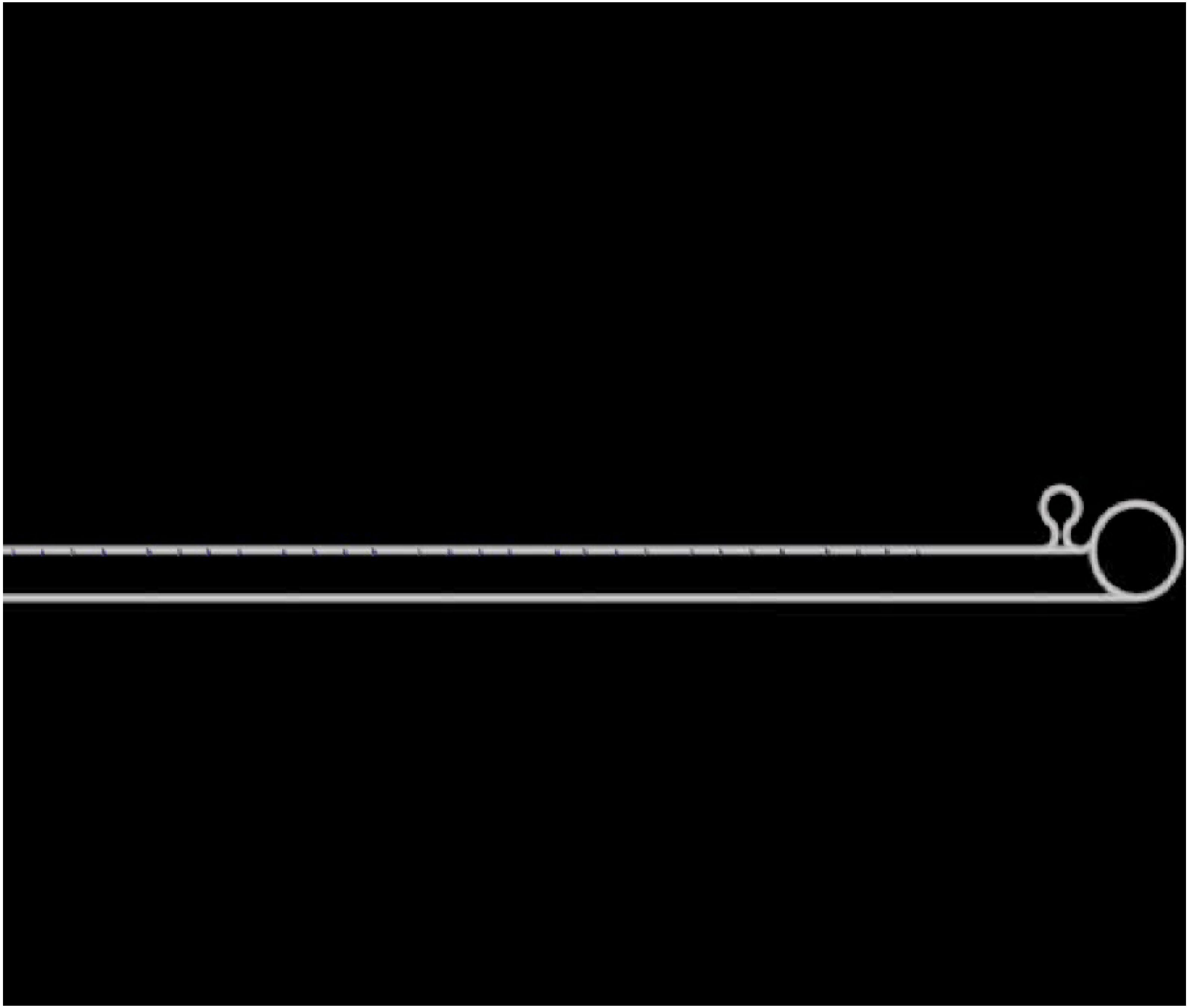
148 µs train length - 25 x 24 sub-pulses
4.2 A - 2.4 GeV - 60 cm between bunches

Drive beam time structure - final



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

Lemmings Drive Beam



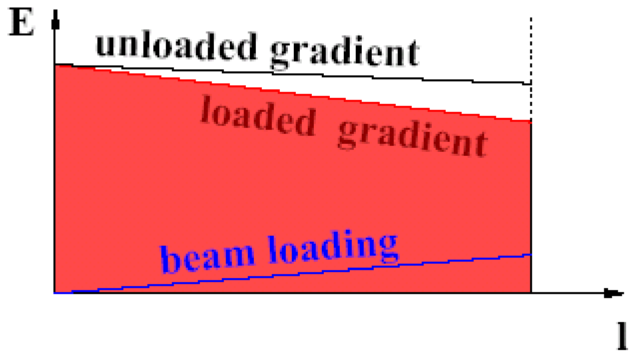
Alexandra Andersson

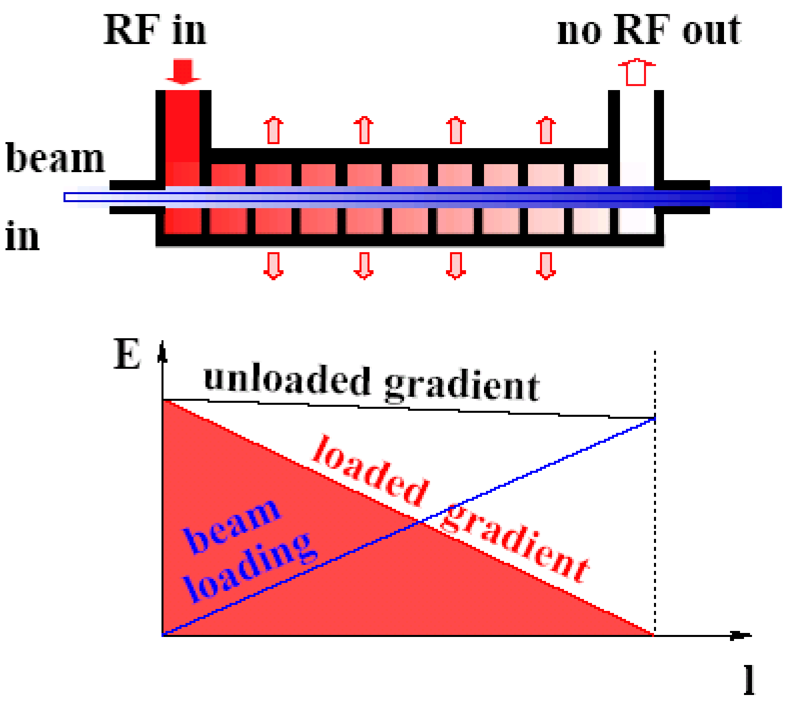
Fully loaded operation

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

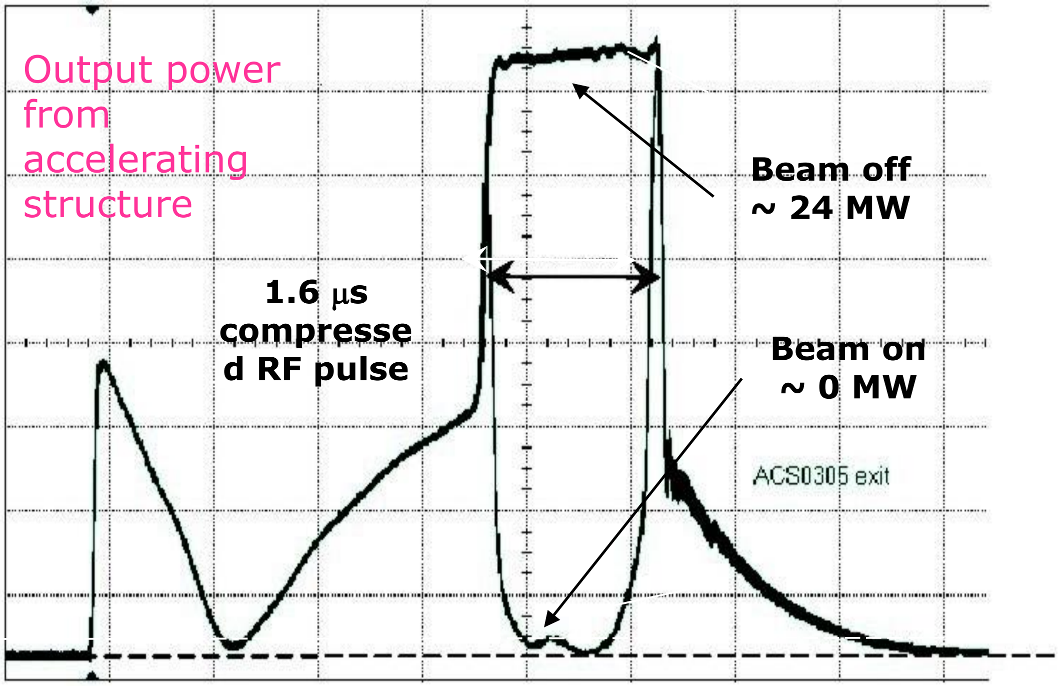
Fully loaded operation

- Disadvantage: any current variation changes energy gain

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

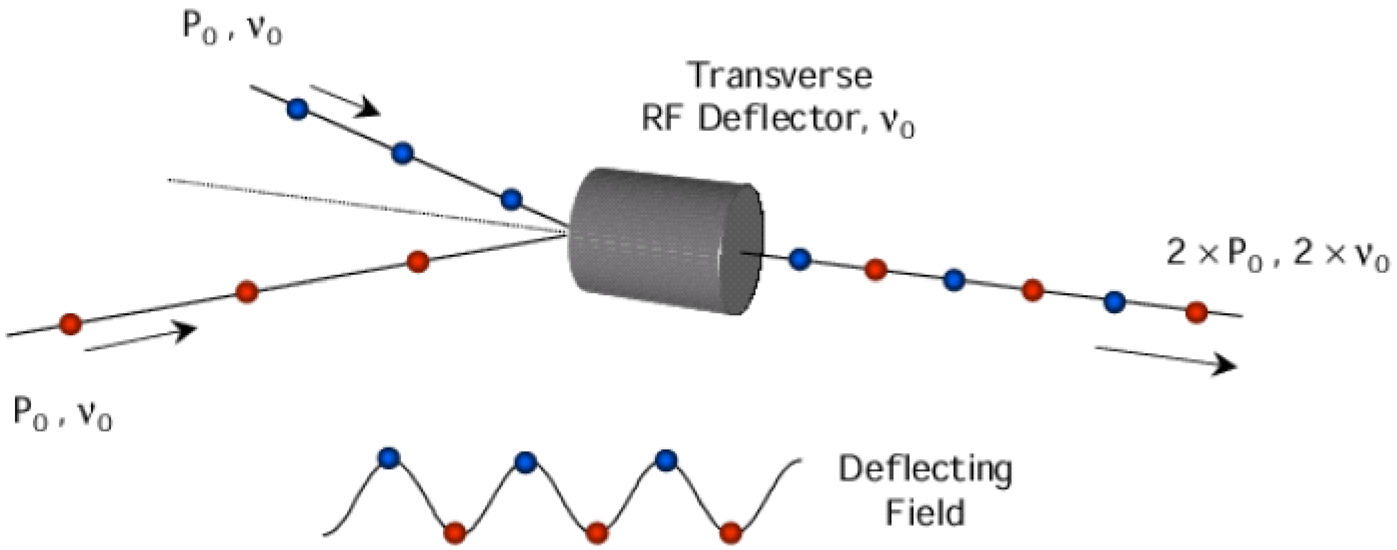
at full loading, 1% current variation = 1% voltage variation
at 20% loading, 1% current variation = 0.2% voltage variation

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



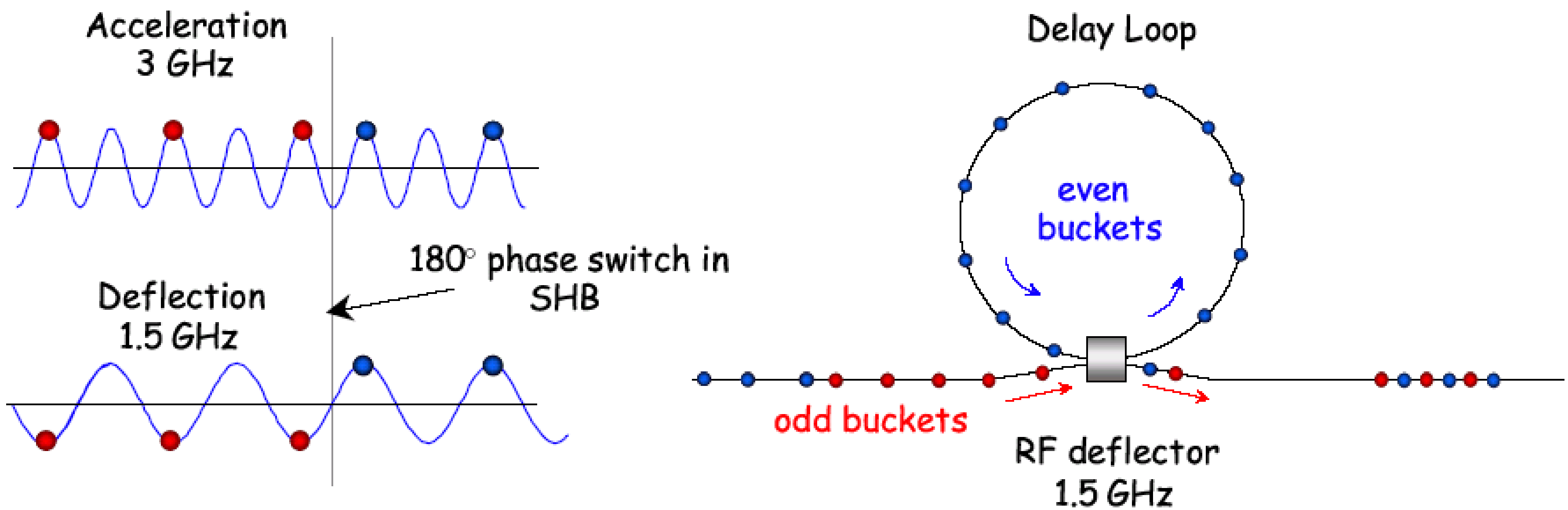
Frequency multiplication

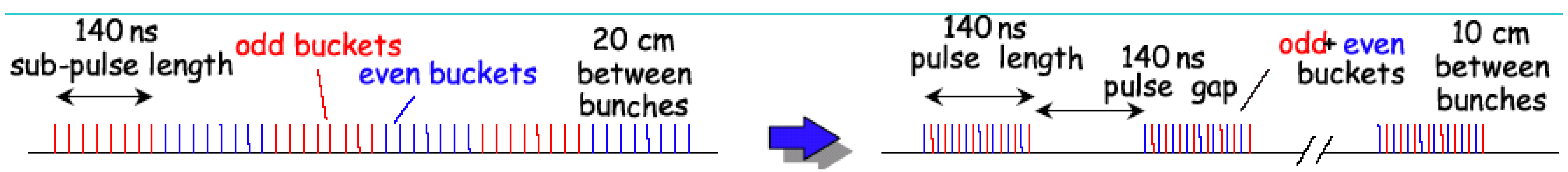
- basic principle of drive beam generation
- transform very long pulses into short pulses with higher power and higher frequency
- use RF deflectors to interleave bunches
  - => double power
  - => double frequency



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

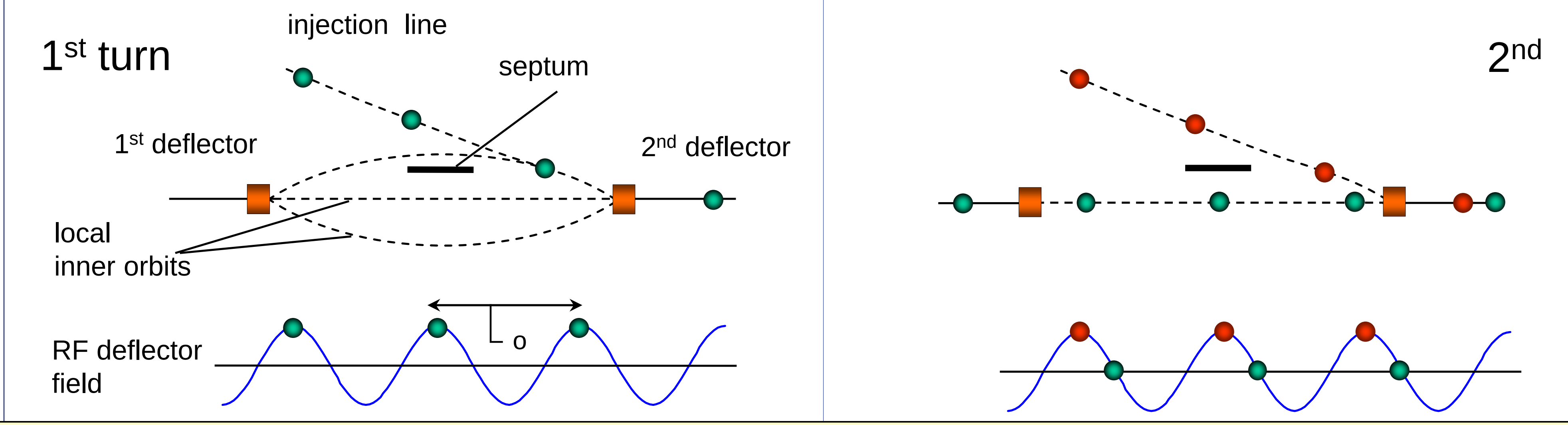




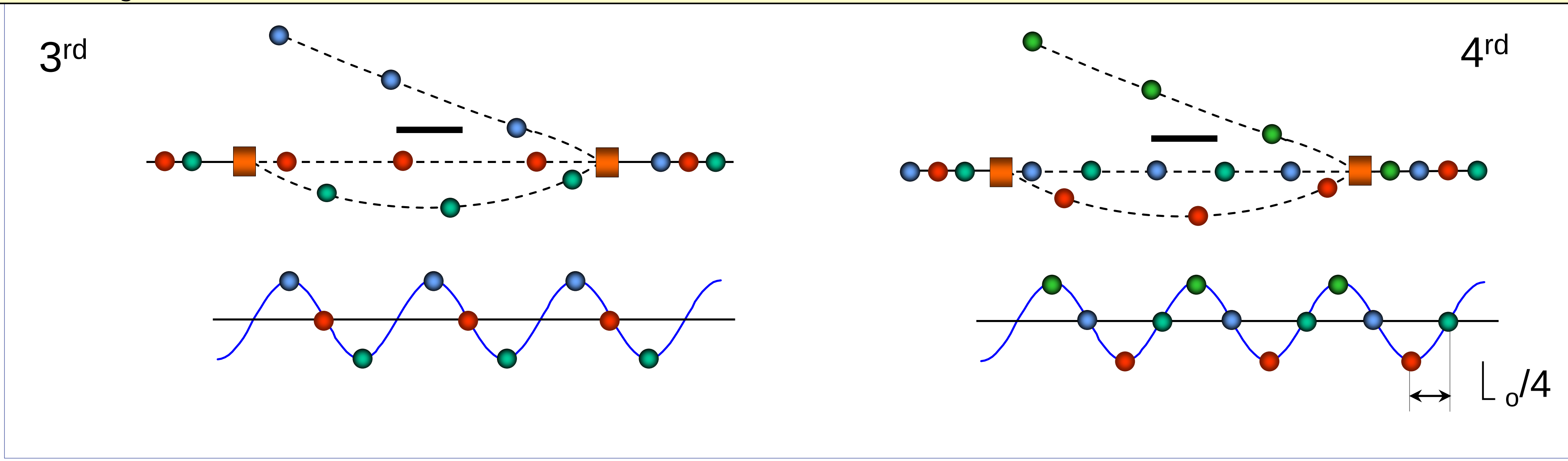
RF injection in combiner ring (factor 4)

- combination factors up to 5 reachable in a ring

$C_{ring} = (n + ¼)\,\lambda$

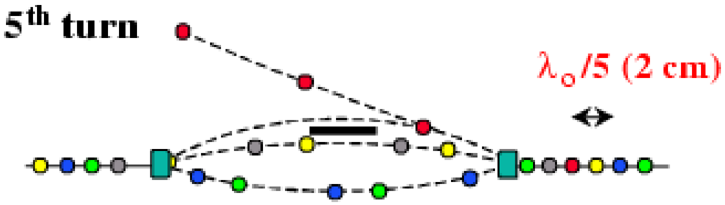


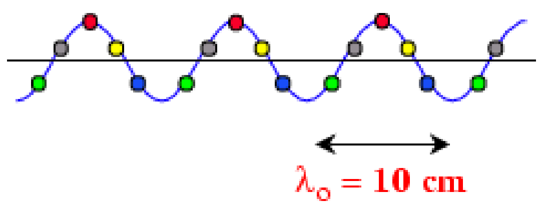
C_{ring} has to correspond to the distance of pulses from the previous combination stage!



Demonstration of frequency multiplication

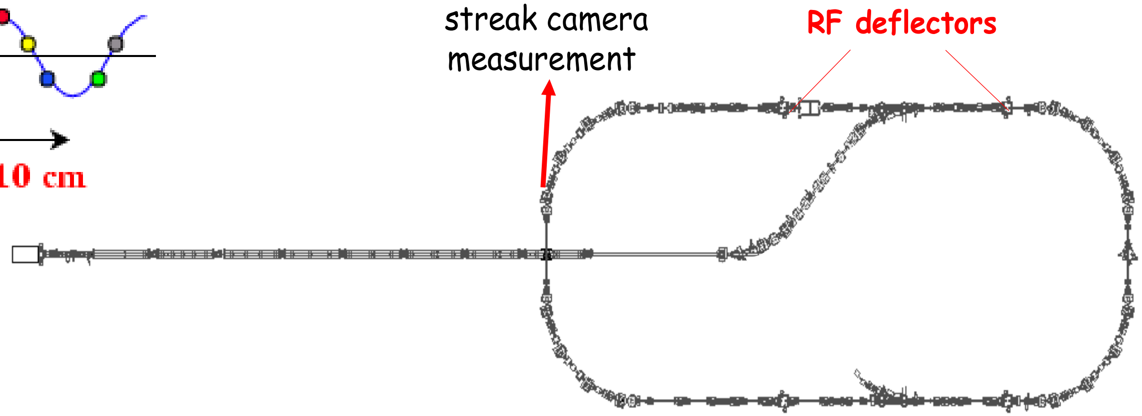
Combination factor 5

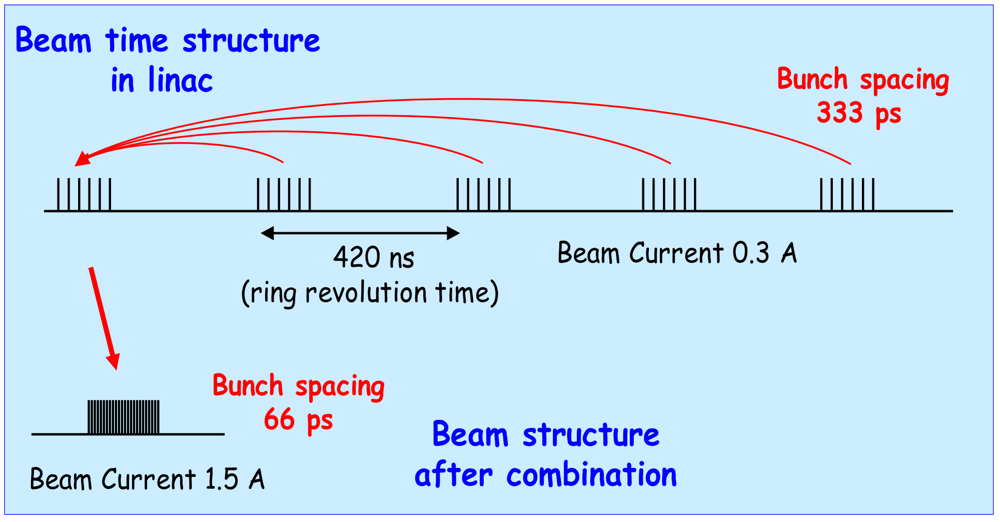




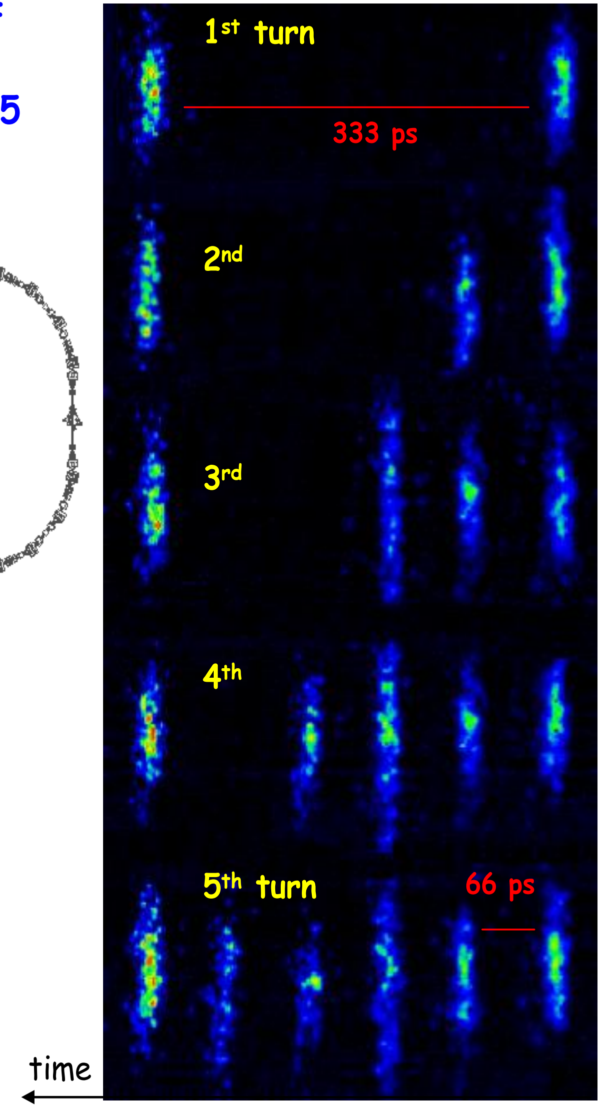
CTF3 - PRELIMINARY PHASE 2001/2002

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





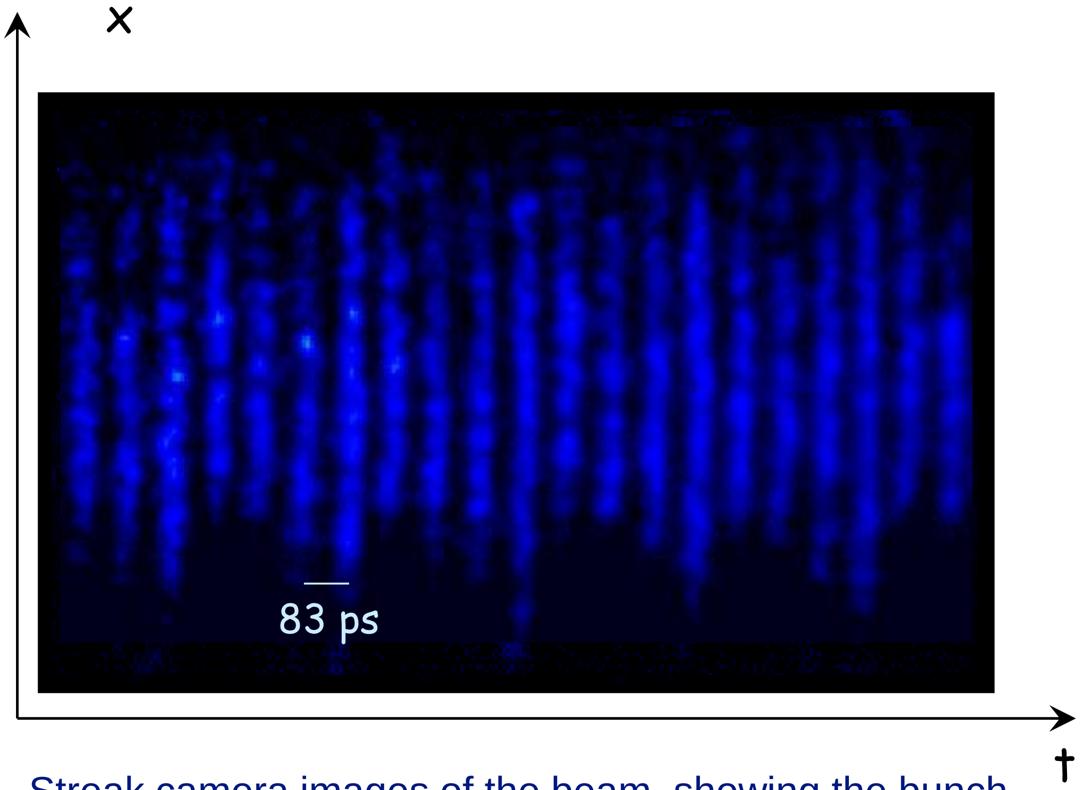
Streak camera image of beam time structure evolution



CTF3 preliminary phase (2001-2002)

RF injection in combiner ring

Combination factor 4

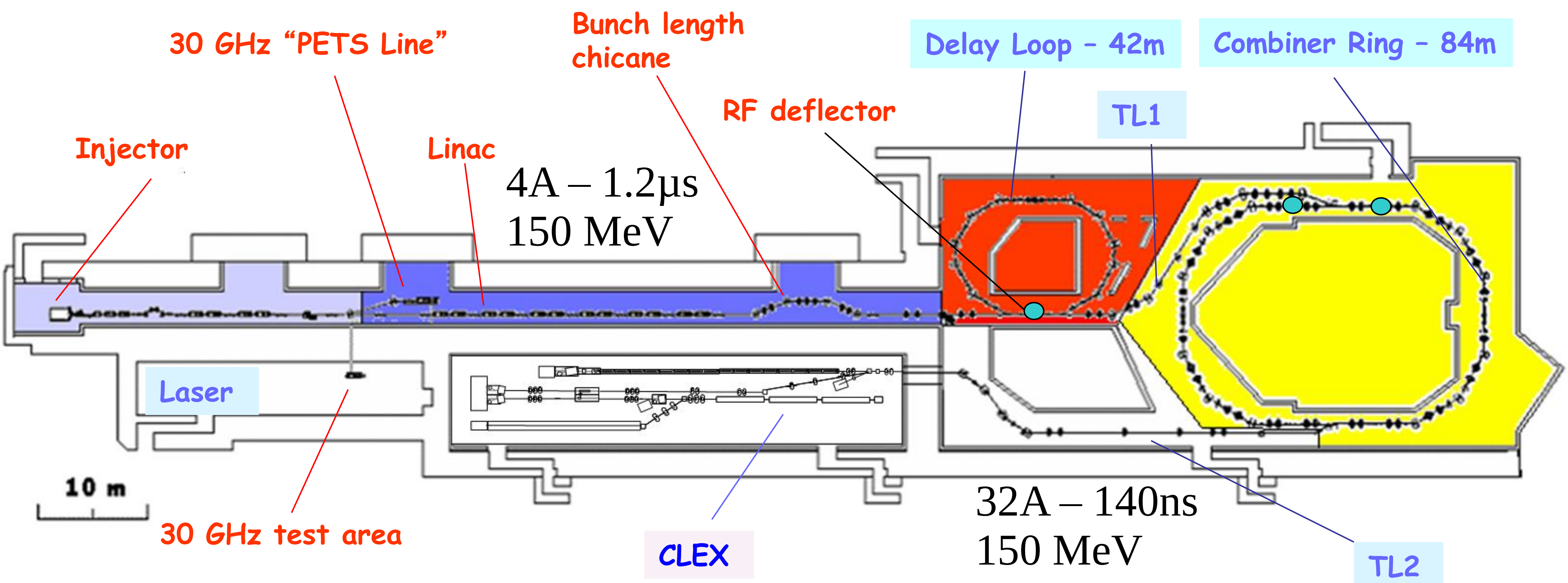


Streak camera images of the beam, showing the bunch combination process

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

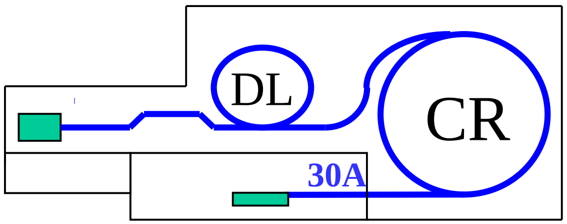
CTF 3

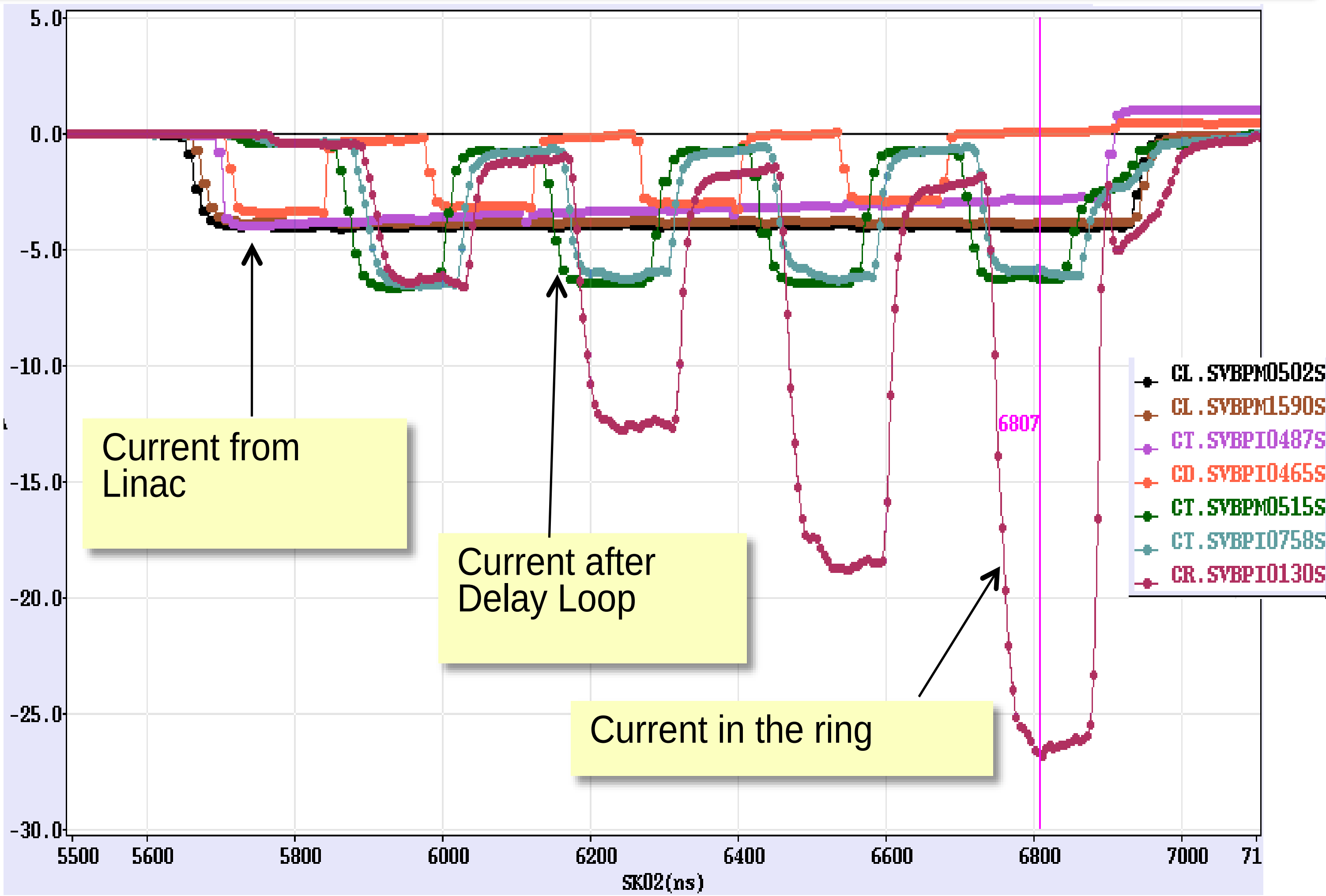
- demonstrate remaining CLIC feasibility issues, in particular:
  - Drive Beam generation (fully loaded acceleration, bunch frequency multiplication)
  - CLIC accelerating structures
  - CLIC power production structures (PETS)



Drive beam generation achieved

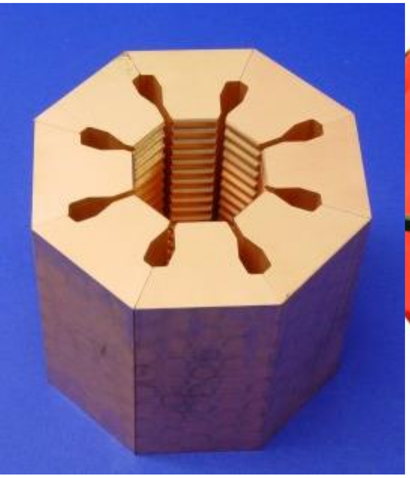
- combined operation of Delay Loop and Combiner Ring (factor 8 combination)
- ~26 A combination reached, nominal 140 ns pulse length
- => **Full drive beam generation**, main goal of 2009, **achieved**

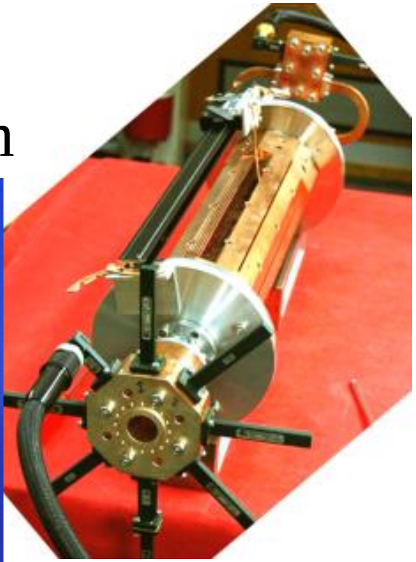


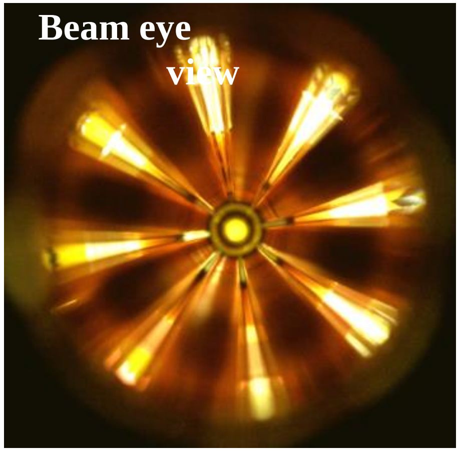


Power extraction structure PETS

- 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

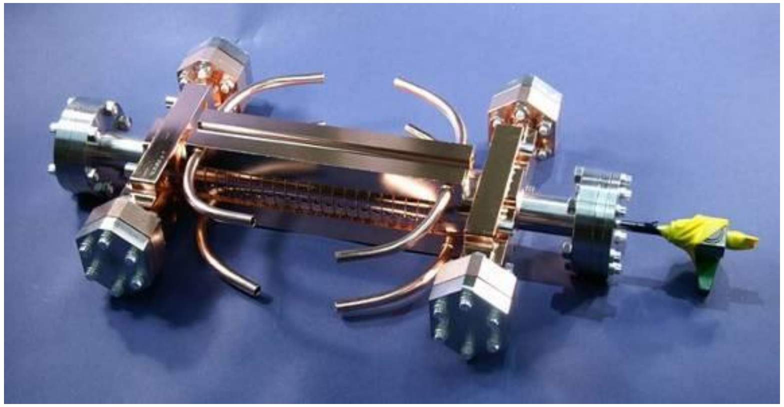
PETS design

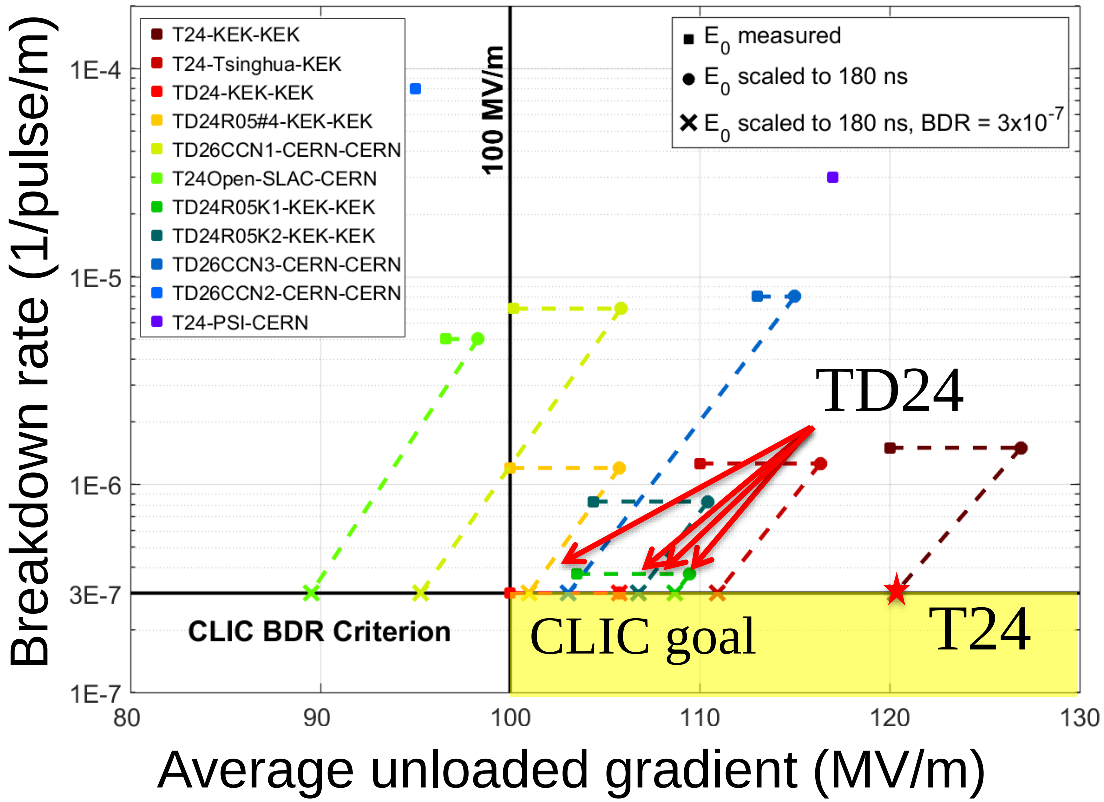
$$P = I^2 L^2 F_b^2 \omega_0 \frac{R/Q}{4 v_g}$$

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

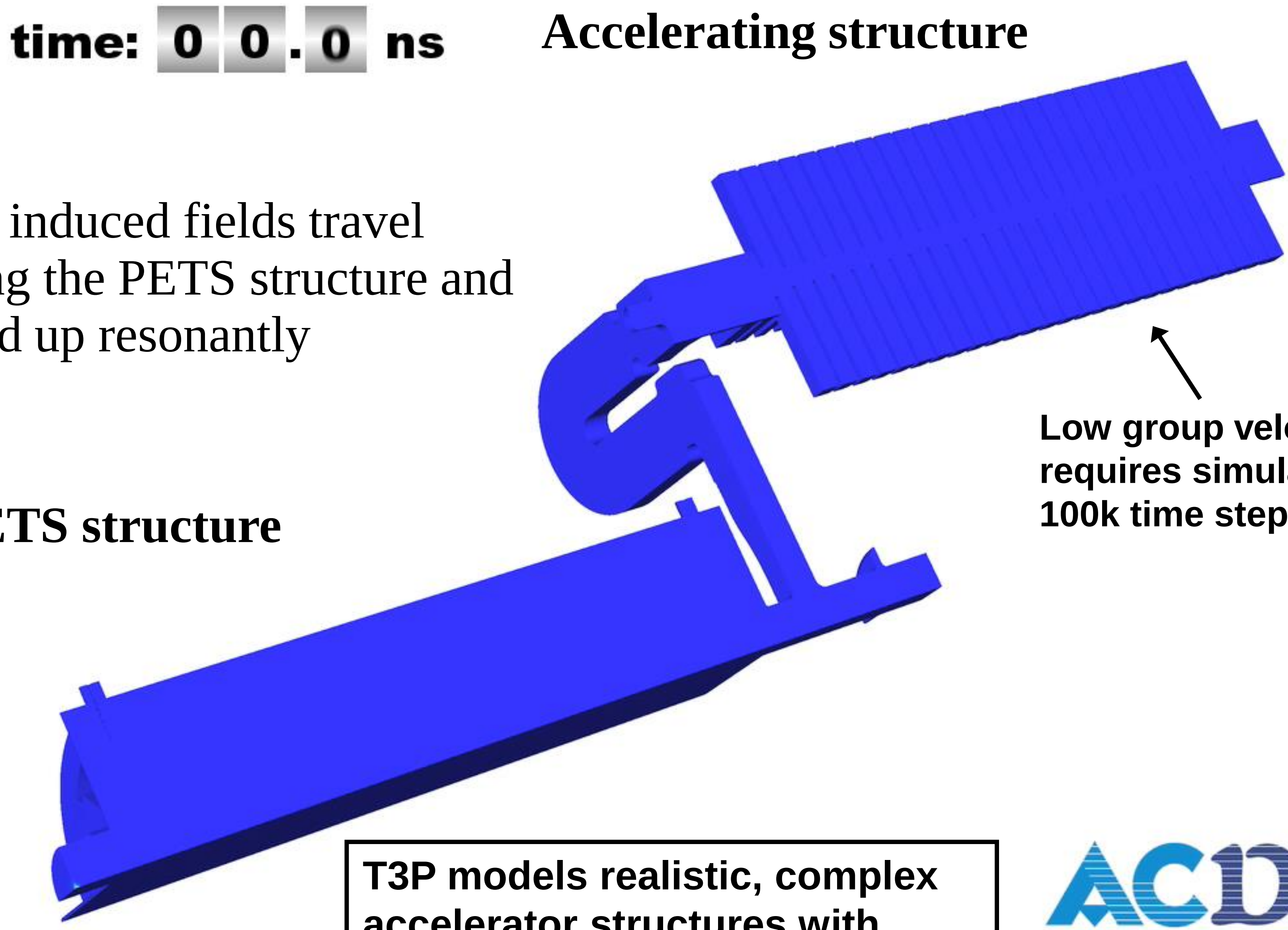
- RF breakdowns can occur
  => no acceleration and deflection
- Goal: 3 10^{-7}/m breakdowns
  at 100 MV/m loaded gradient
  at 230 ns pulse length
- latest prototypes (T24 and TD24) tested (SLAC and KEK)
- => TD24 reach up to 108 MV/m at nominal CLIC breakdown rate (without damping material)
- Undamped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





Simulation of RF Power Transfer

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

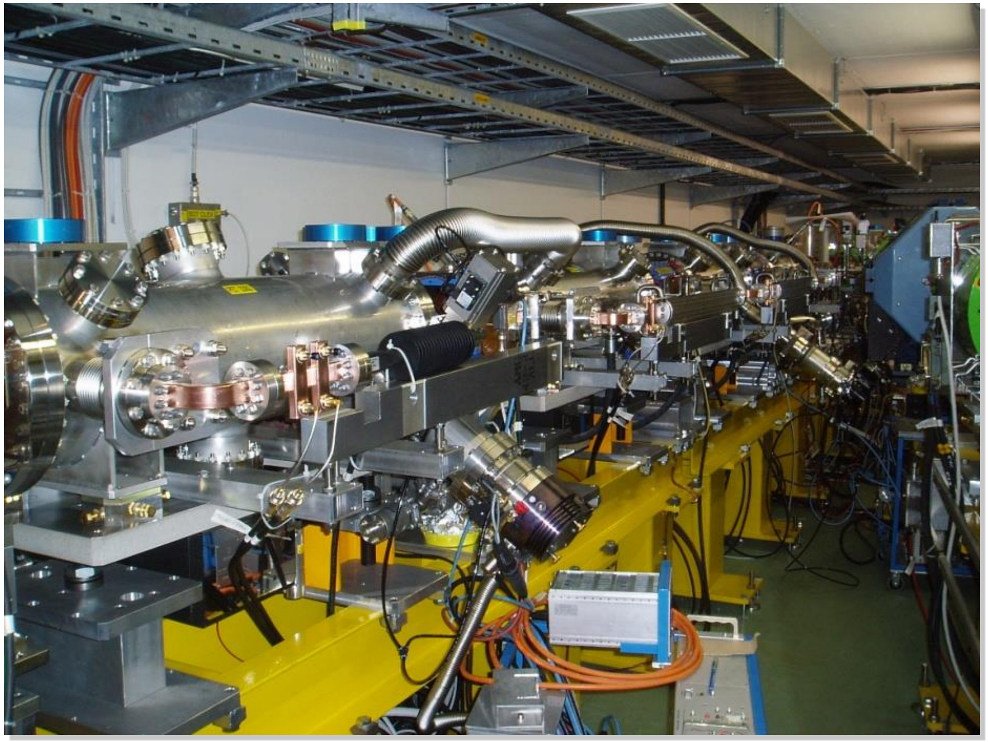


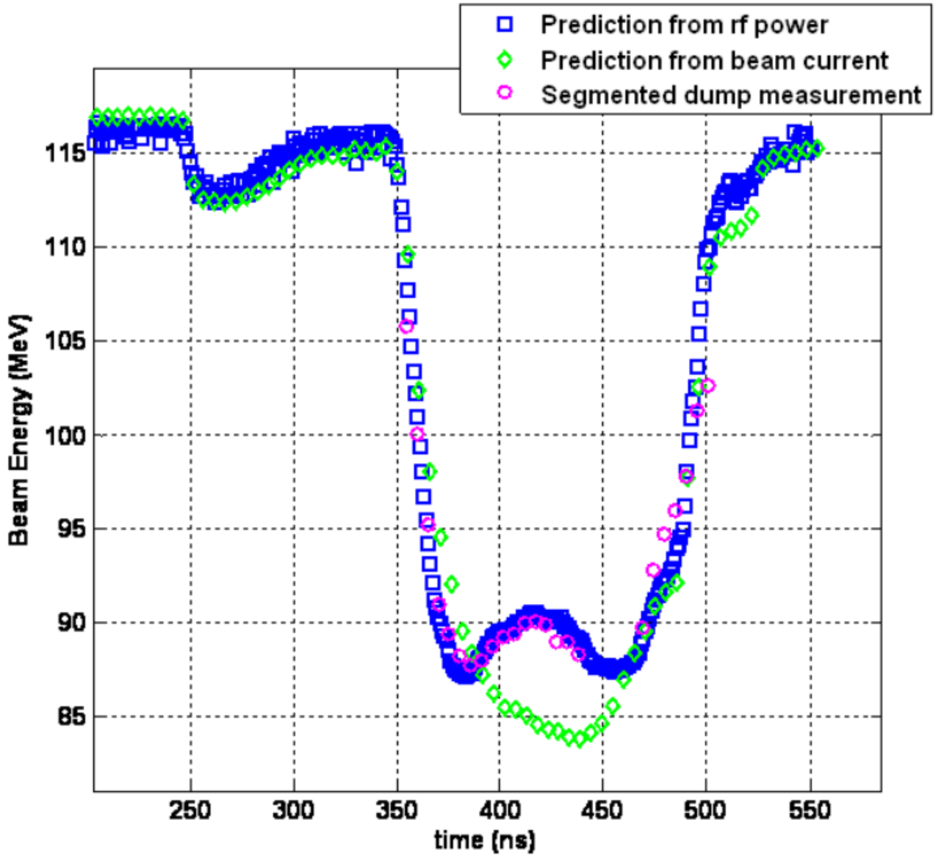
T3P models realistic, complex accelerator structures with unprecedented accuracy

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

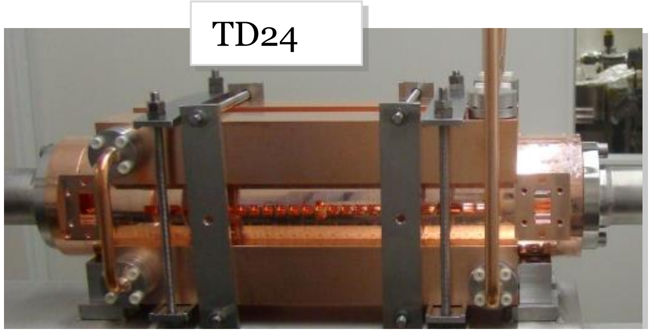


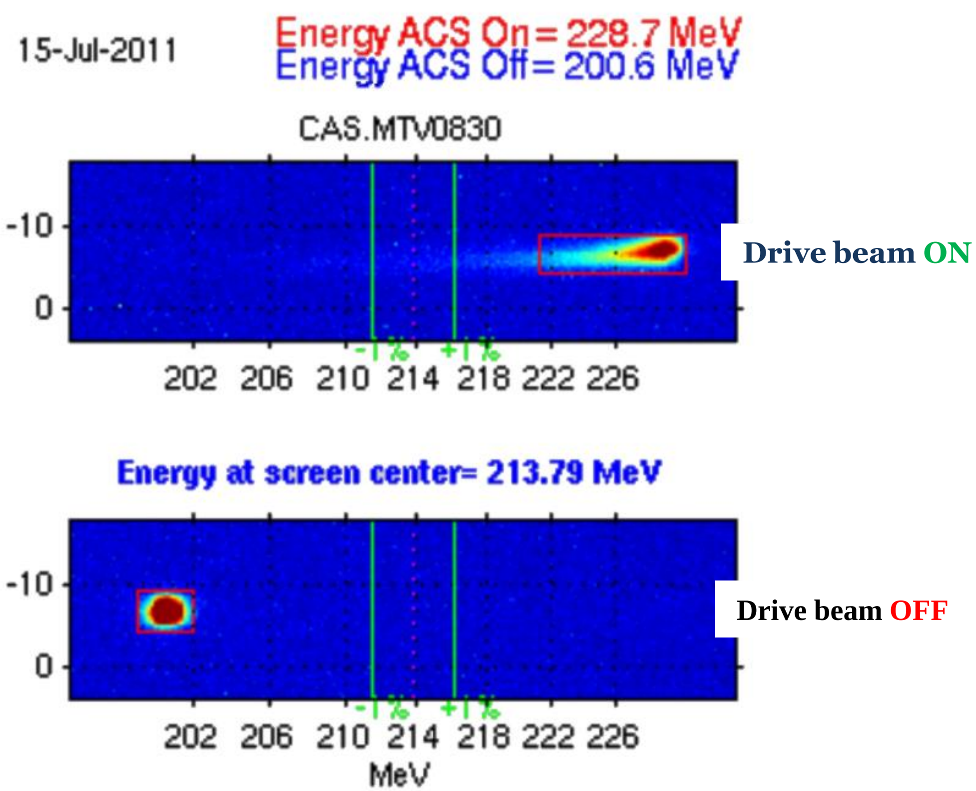


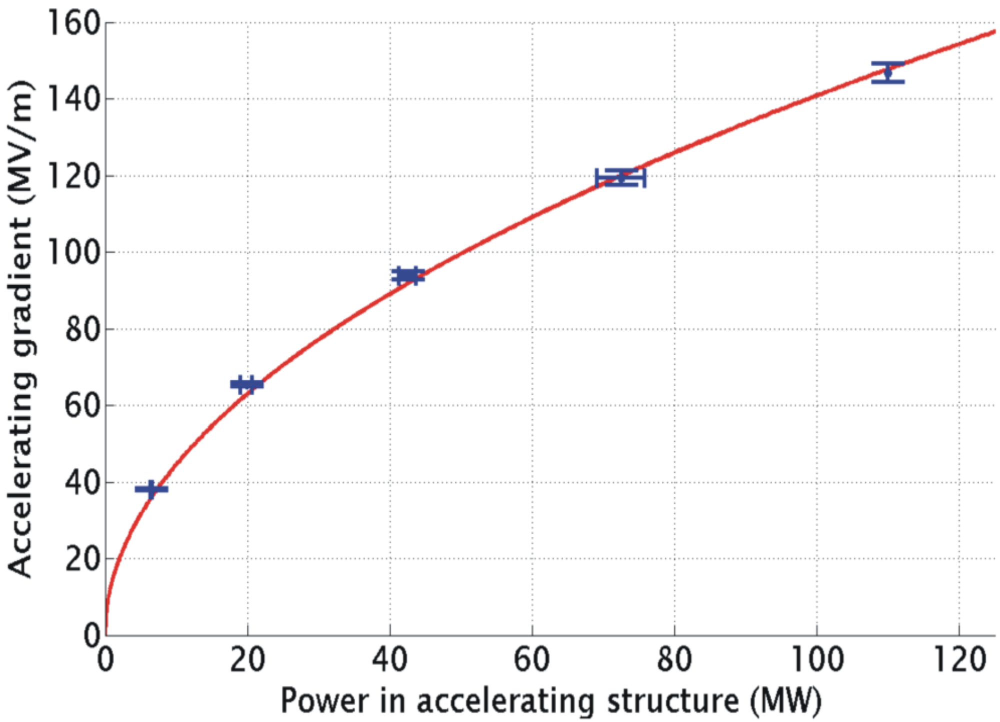
Achieved Two-Beam Acceleration

- Maximum probe beam acceleration measured: 31 MeV

  => Corresponding to a gradient of 145 MV/m







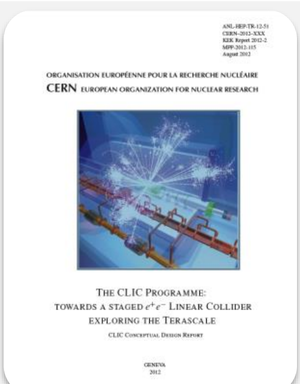
CLIC CDRs published 2012

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

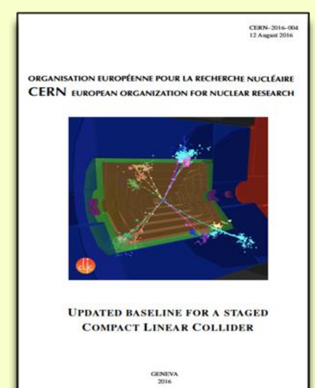


Vol 3: "CLIC study summary" (S.Stapnes)

- 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/



Latest 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, arXiv:1812.06018)
- **CLIC Project Implementation Plan** (CERN-2018-010-M)
- **The CLIC potential for new physics** (CERN-2018-009-M)
- **Detector technologies for CLIC** [In collaboration review]

Journal publications

- **Top-quark physics at the CLIC electron-positron linear collider** [In journal review] (arXiv:1807.02441)
- **Higgs physics at the CLIC electron-positron linear collider** (Journal, arXiv:1608.07538)
  - Projections based on the analyses from this paper scaled to the latest assumptions on integrated luminosities can be found here: CDS, arXiv.

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

2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions

Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

Ready for construction; start of excavations

2035 First Beams

Getting ready for data taking by the time the LHC programme reaches completion

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