



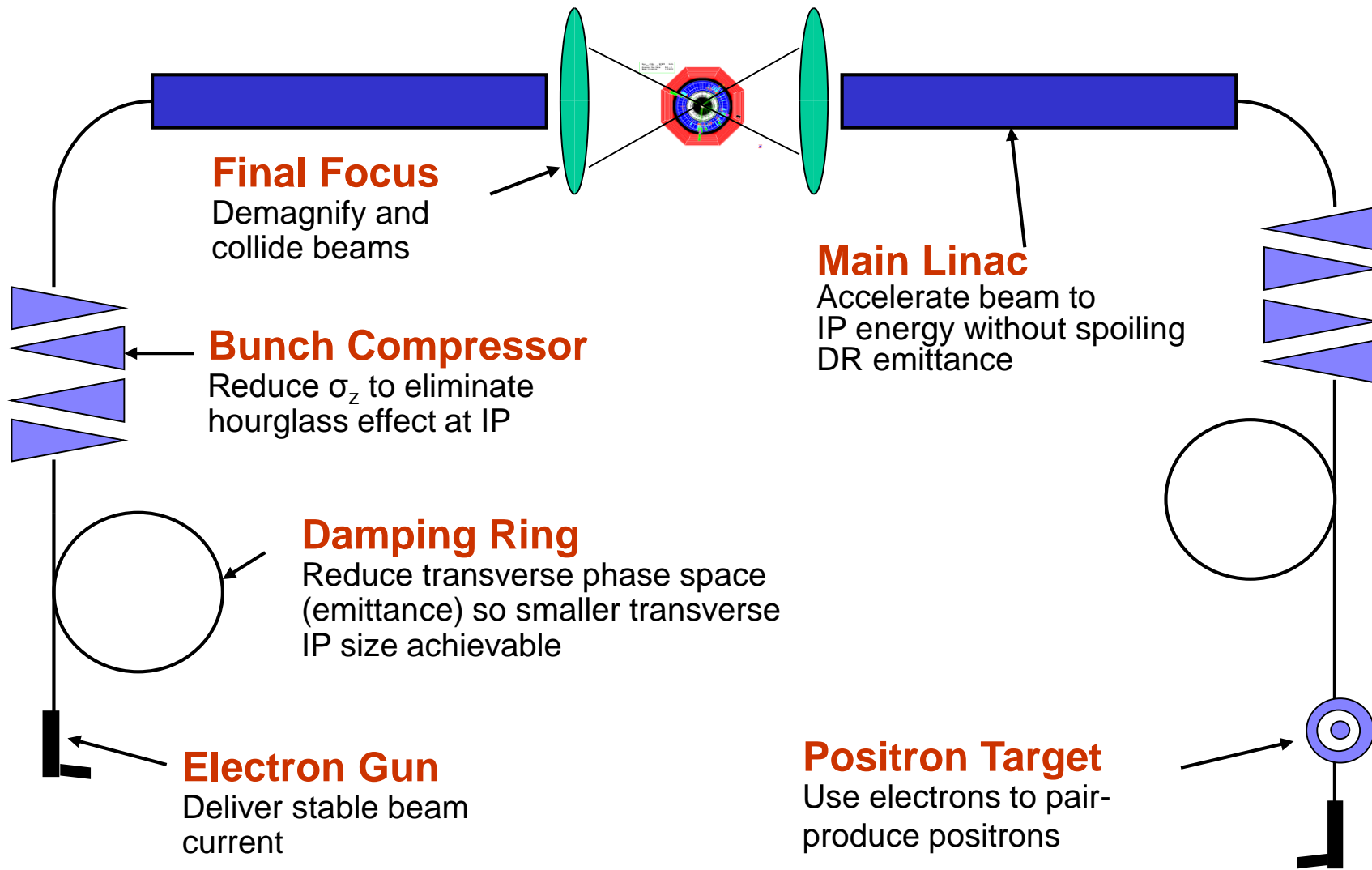
Linear Colliders

Lecture 4



Frank Tecker – CERN

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



C.Pagani

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

- Collimation:

- Beam halo will create background in detector
- Collimation section to eliminate off-energy and off-orbit particle
- Material and wakefield issues

- Crossing angle:

- NC small bunch spacing requires crossing angle at IP to avoid parasitic beam-beam deflections
- Luminosity loss ($\approx 10\%$ when $\ell = \ell_x / \ell_z$)

- Crab cavities

- Introduce additional time dependent transverse kick to improve collision

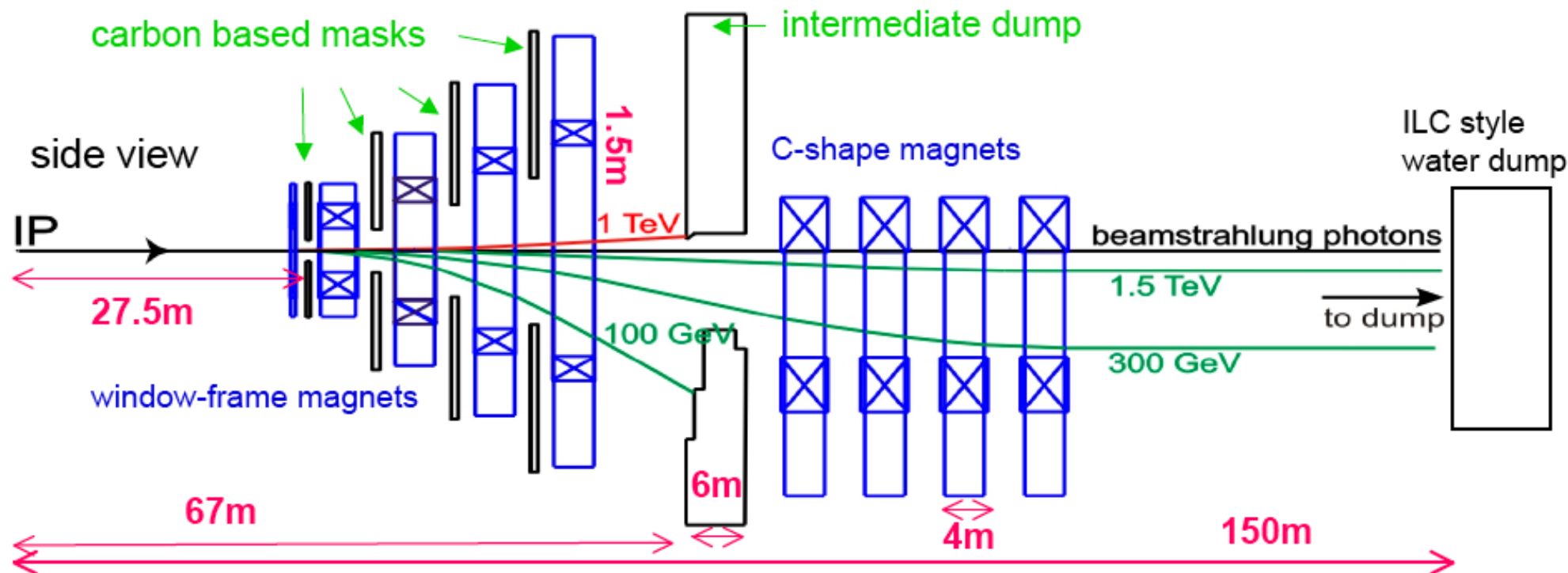
- Spent beam

- Large energy spread after collision
- Design for spent beam line not easy

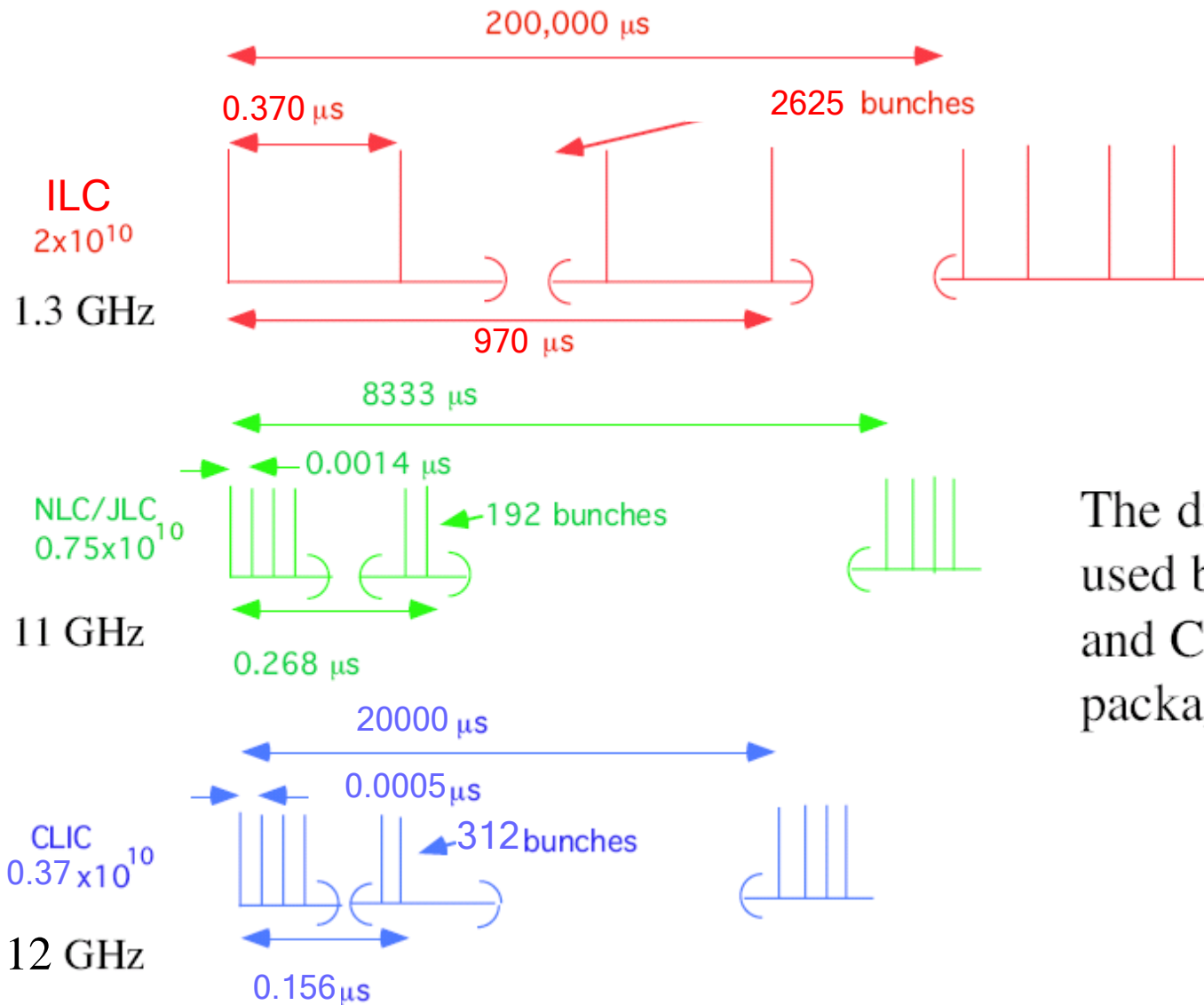
R.B. Appleby, A. Ferrari, M.D. Salt and V. Ziemann, Phys. Rev. ST Accel. Beams 12 (2009) 021001.

Baseline: vertical chicane with 2x4 dipoles

1. Separation by dipole magnets of the disrupted beam, beamstrahlung photons and particles with opposite sign from coherent pairs, from low energy tails
 - Short line to prevent the transverse beam size from growing too much
 - Intermediate dumps and collimator systems
2. Back-bending region with dipoles to direct the beam onto the final dump
 - Long line allowing non-colliding beam to grow to acceptable size

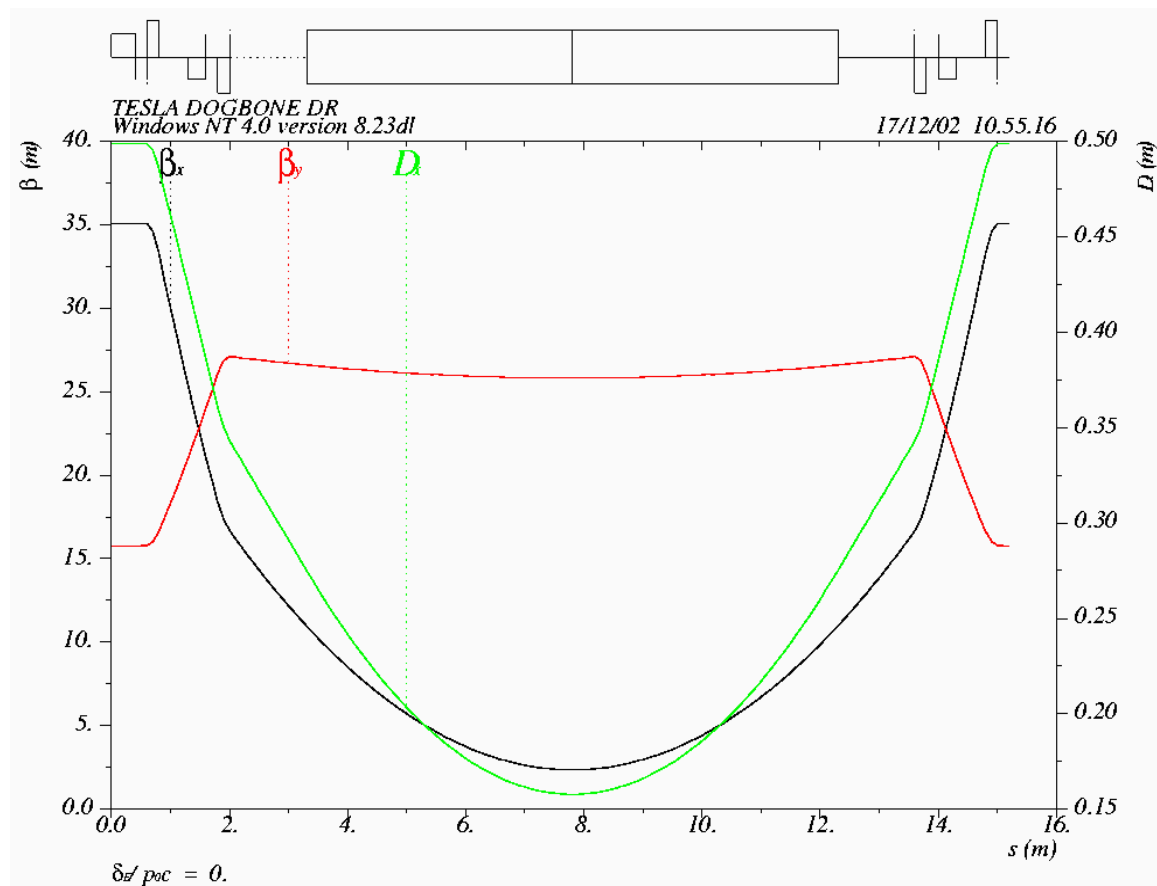
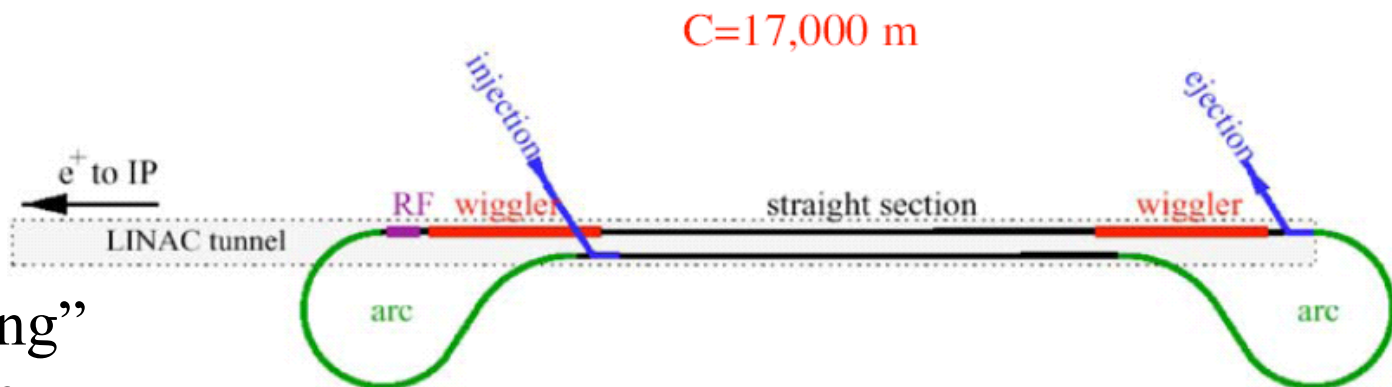


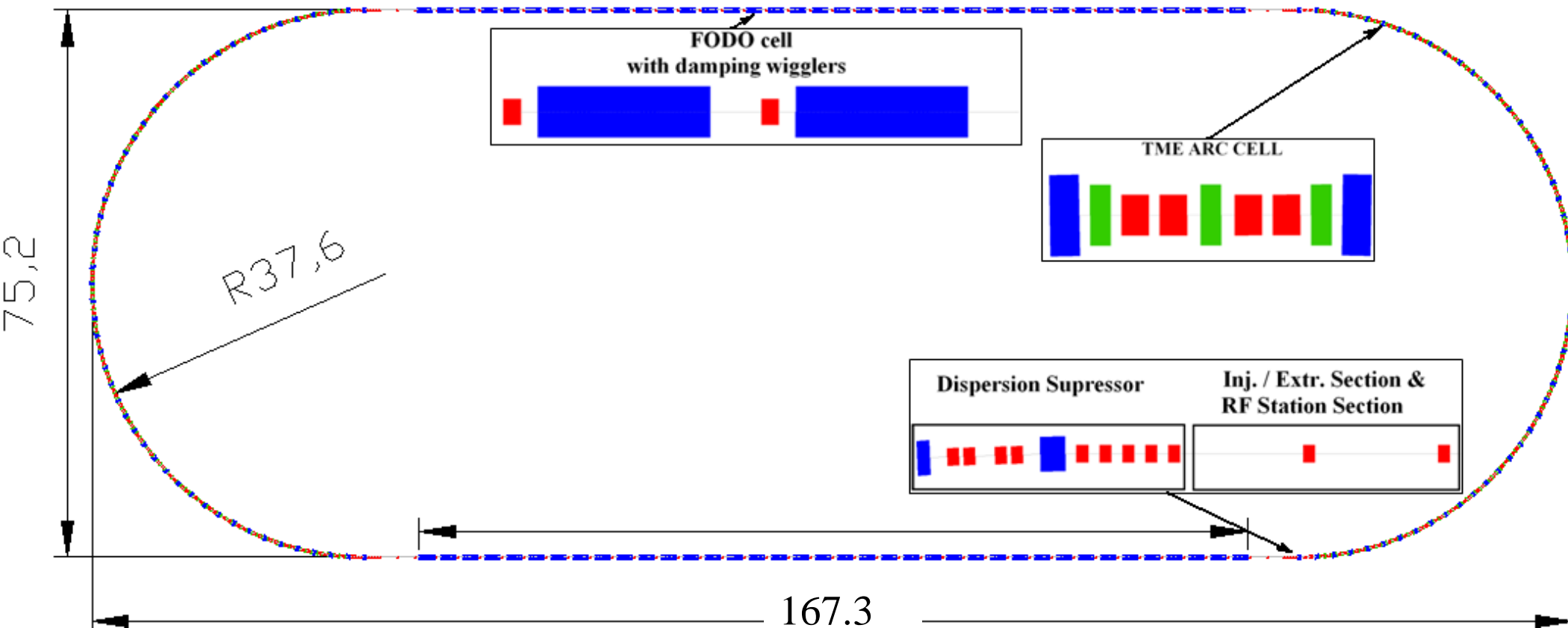
- **SC** allows long pulse, **NC** needs short pulse with smaller bunch charge



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

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





- 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

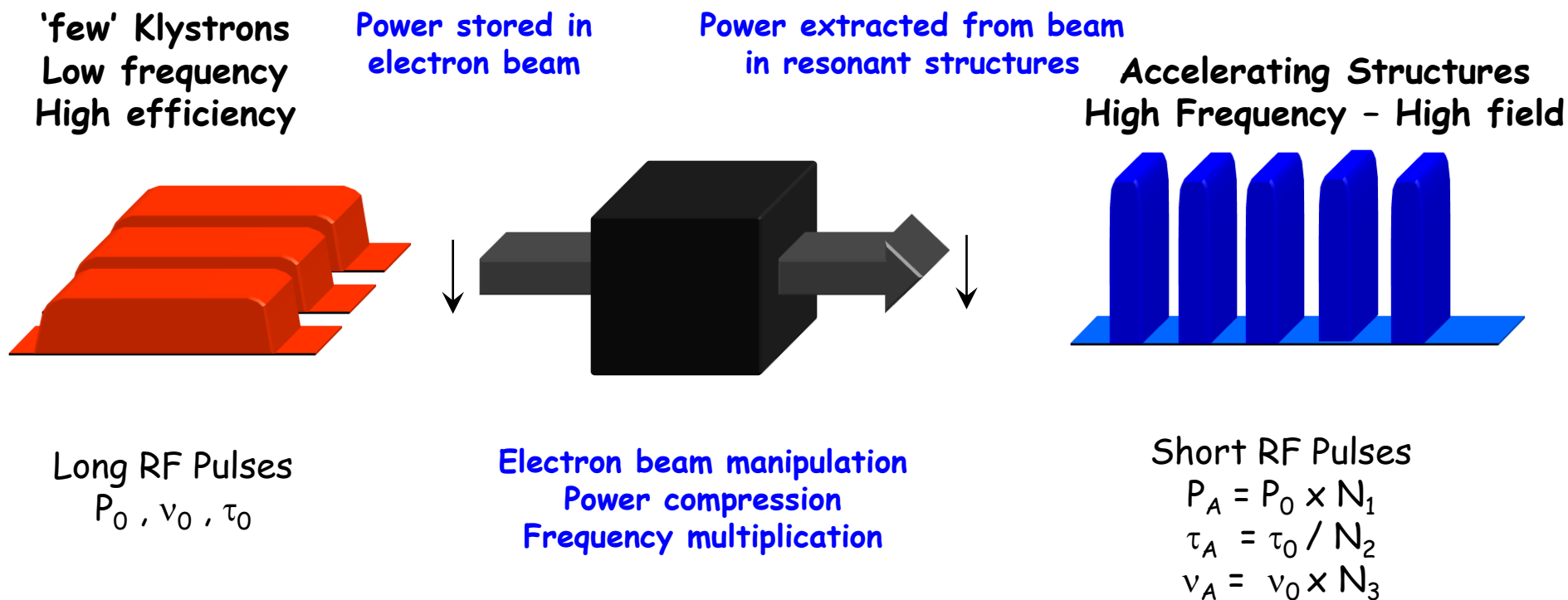
Normal Conducting

- High gradient \Rightarrow short linac 😊
- High rep. rate \Rightarrow ground motion suppression 😊
- Small structures \Rightarrow strong wakefields ☹️
- Generation of high peak RF power ☹️
- Small bunch distance ☹️

Superconducting

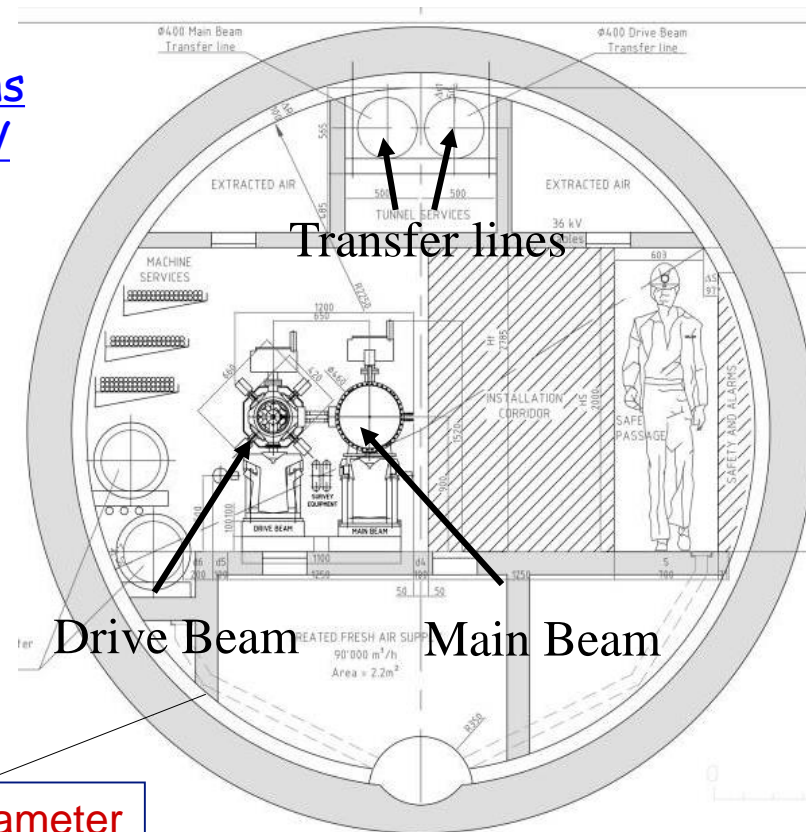
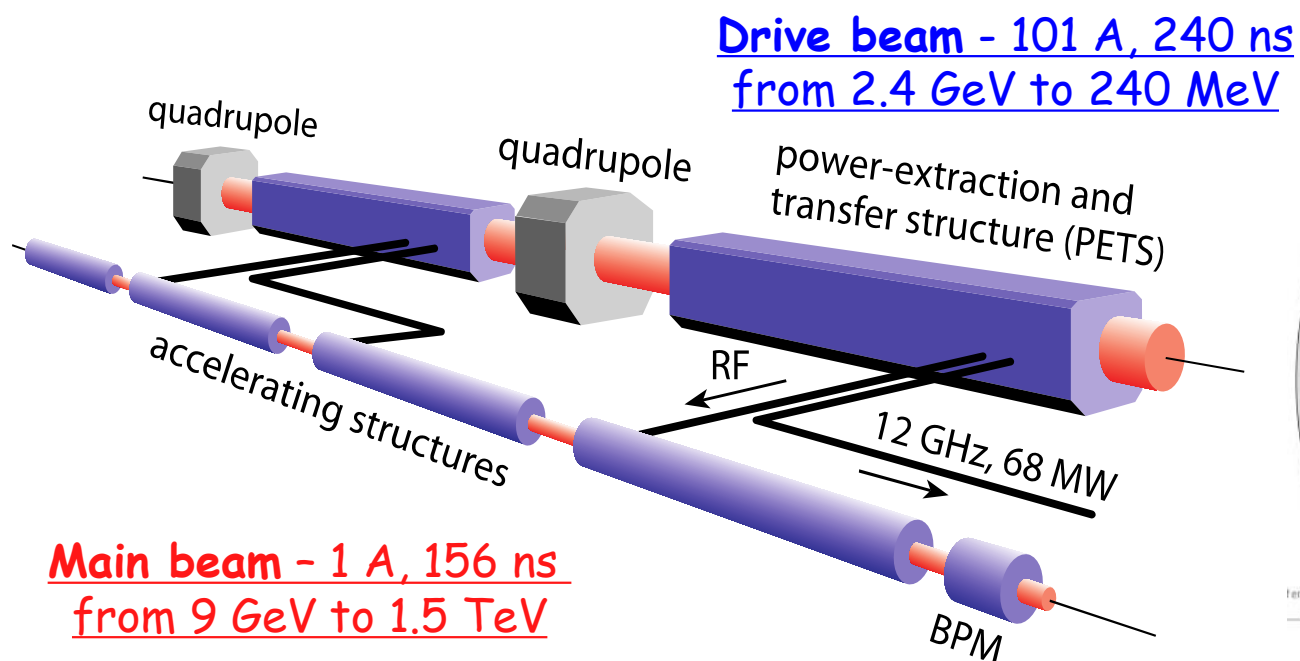
- long pulse \Rightarrow low peak power 😊
- large structure dimensions \Rightarrow low WF 😊
- very long pulse train \Rightarrow feedback within train 😊
- SC structures \Rightarrow high efficiency 😊
- Gradient limited <40 MV/m \Rightarrow longer linac ☹️
(SC material limit ~ 55 MV/m)
- low rep. rate \Rightarrow bad GM suppression
(Σ_y dilution) ☹️
- Large number of e+ per pulse ☹️
- very large DR ☹️

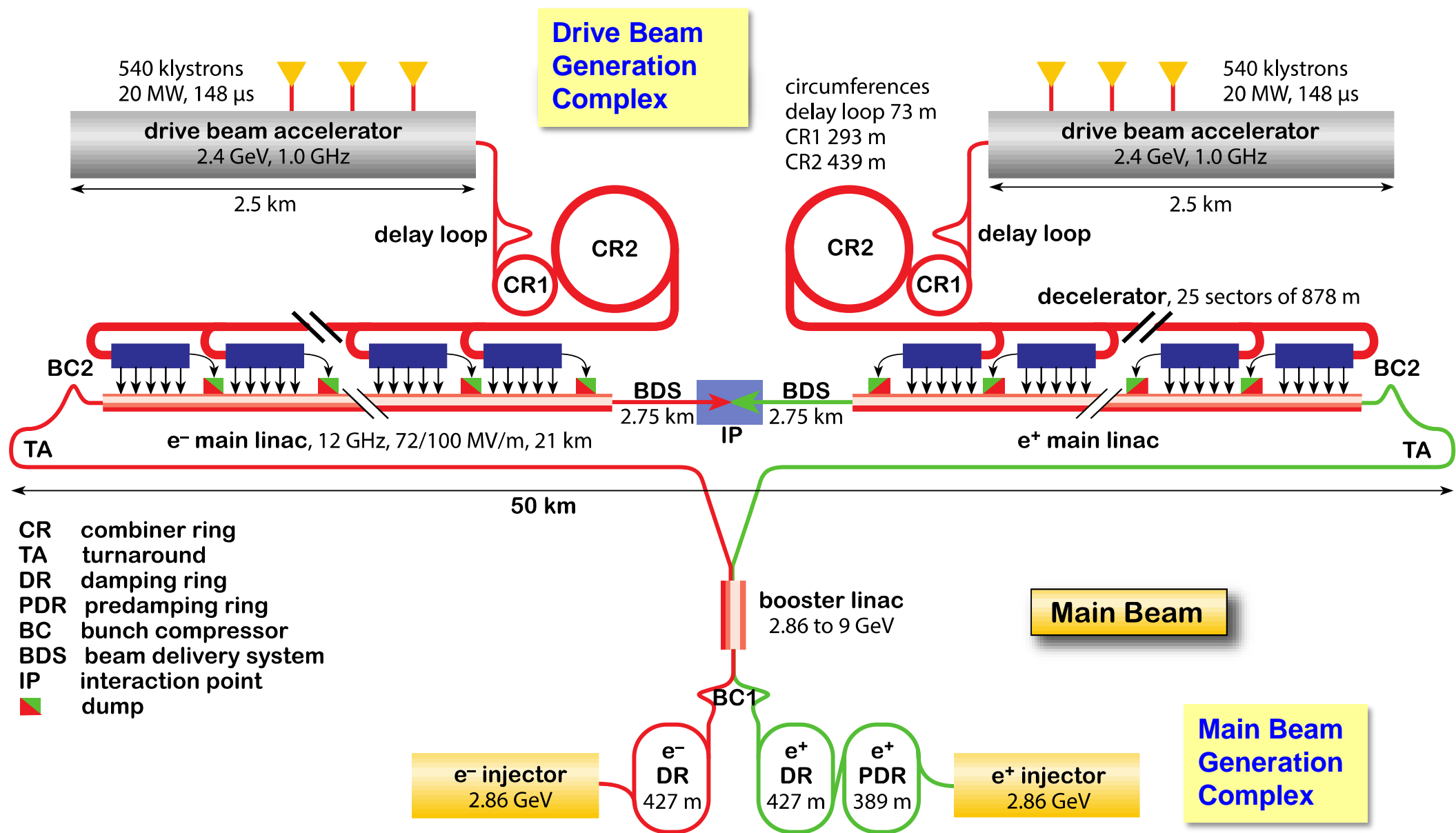
- Very high gradients (>100 MV/m) possible with NC accelerating structures at high RF frequencies (30 GHz \rightarrow 12 GHz)
- Extract required high RF power from an intense e- “drive beam”
- Generate efficiently long pulse and compress it (in power + frequency)



- 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

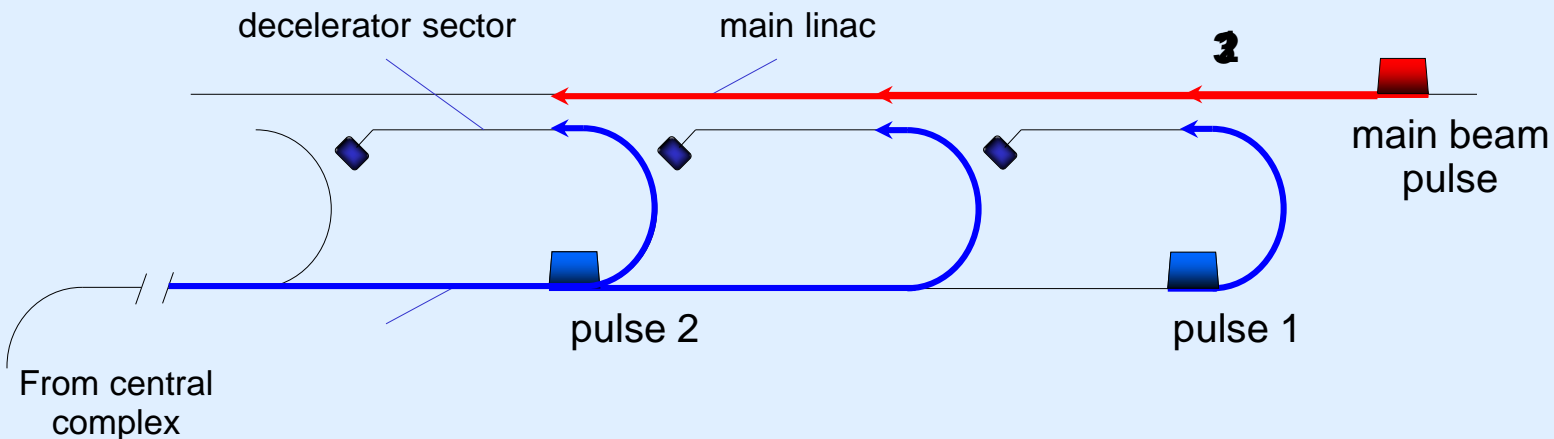




Counter propagation from central complex

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)

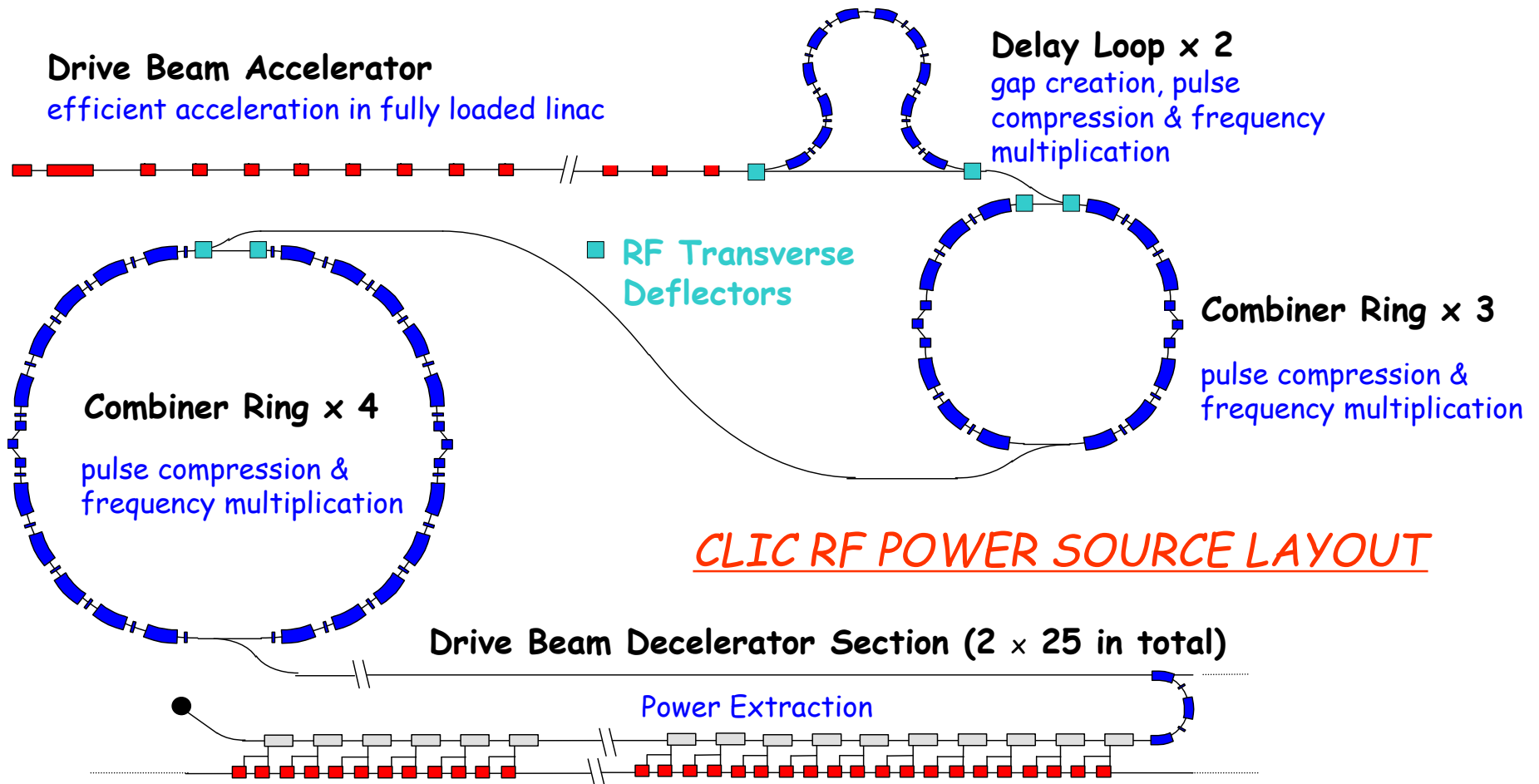


Counter flow distribution allows to power different sectors of the main linac with different time bins of a single long electron drive beam pulse

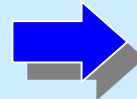
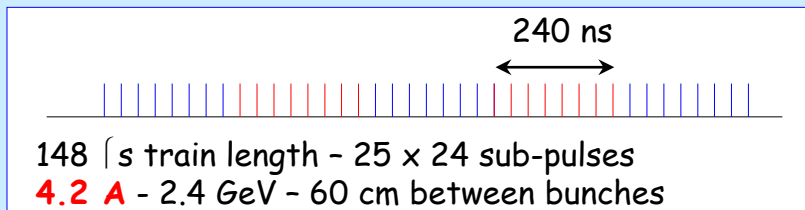
The distance between the pulses is $2 L_s = 2 L_{\text{main}} / N_S$ (L_{main} = single side linac length)

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

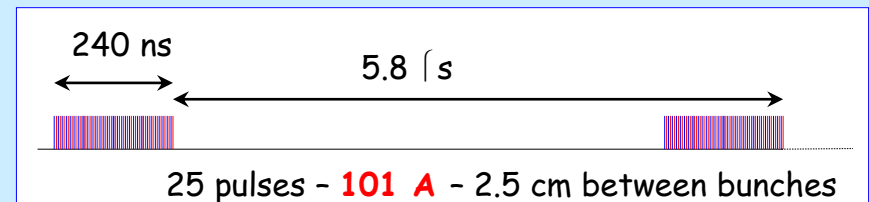
$$\text{so } t_{\text{DB}} = 2 L_{\text{main}} / c, \quad 148 \mu\text{s for the 3 TeV CLIC}$$

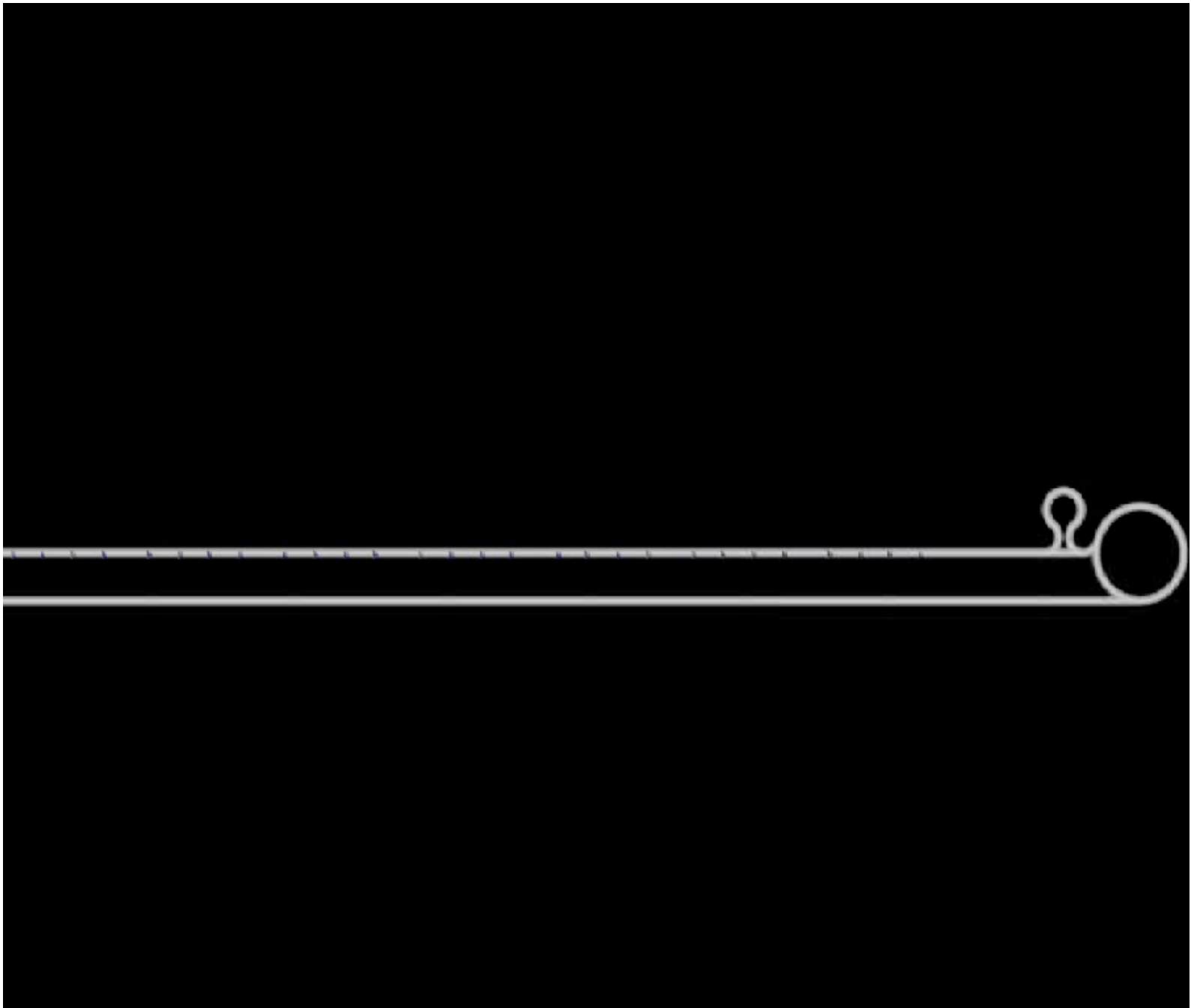


Drive beam time structure - initial



Drive beam time structure - final

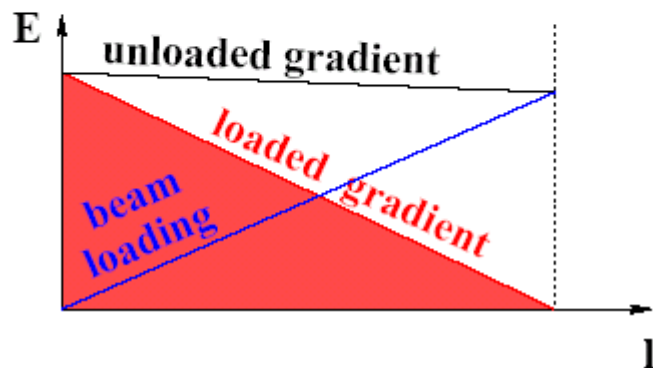
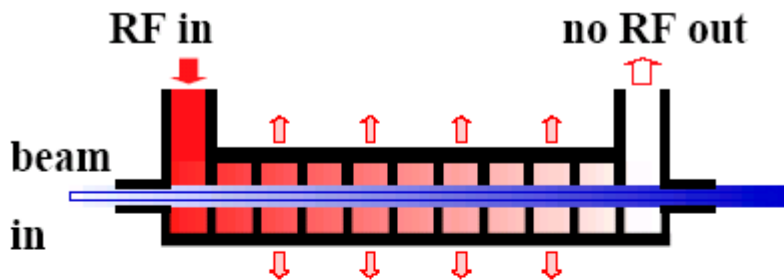
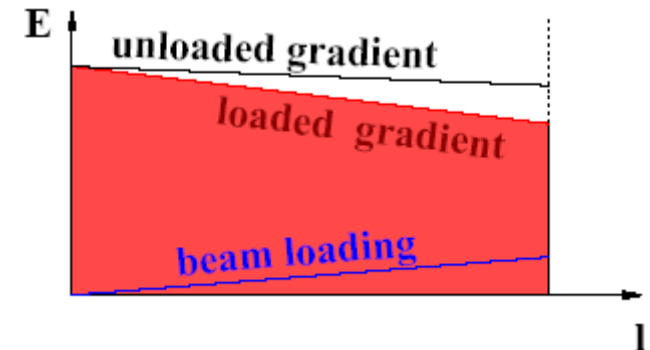




- **efficient** power transfer from RF to the beam needed

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

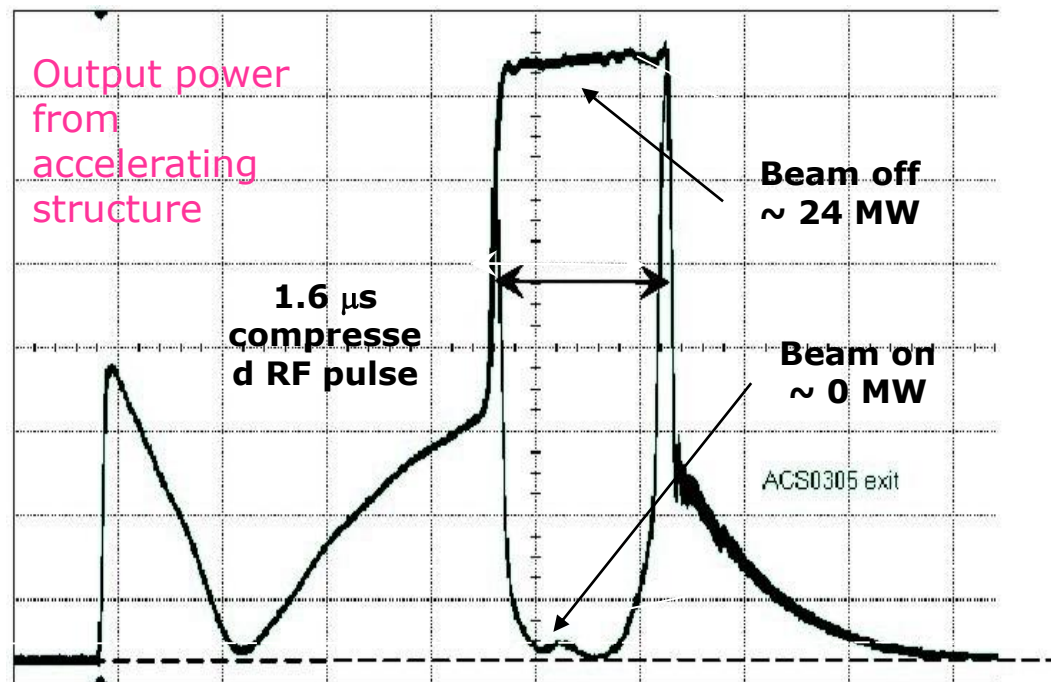
- Disadvantage: any current variation changes energy gain

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

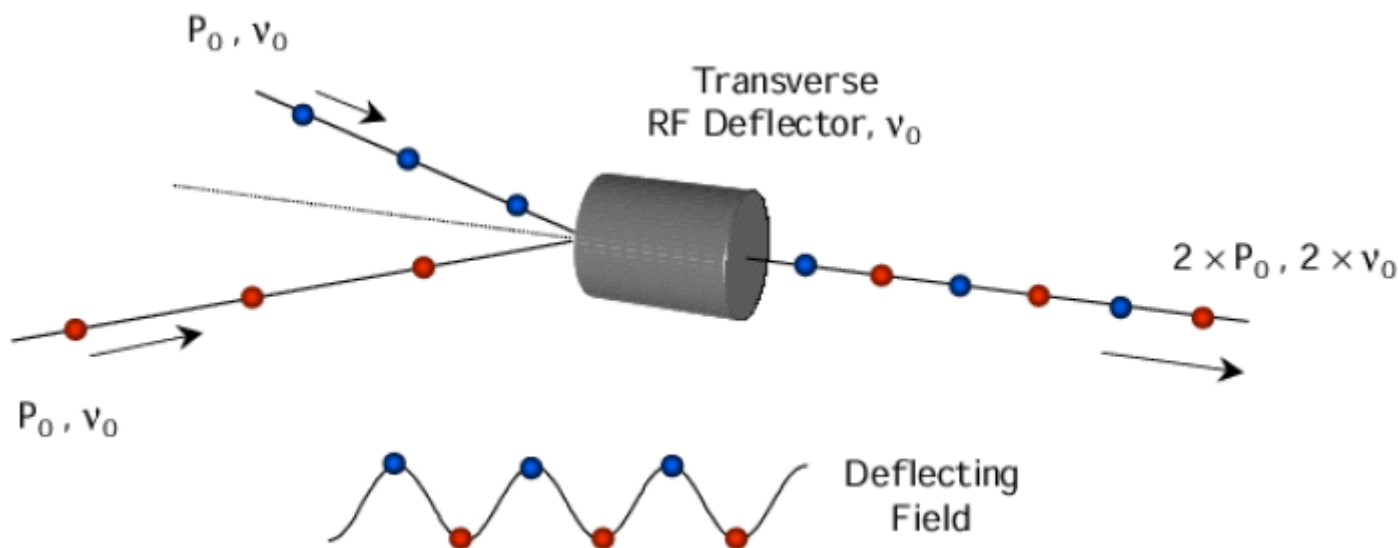
at full loading, 1% current variation = 1% voltage variation

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

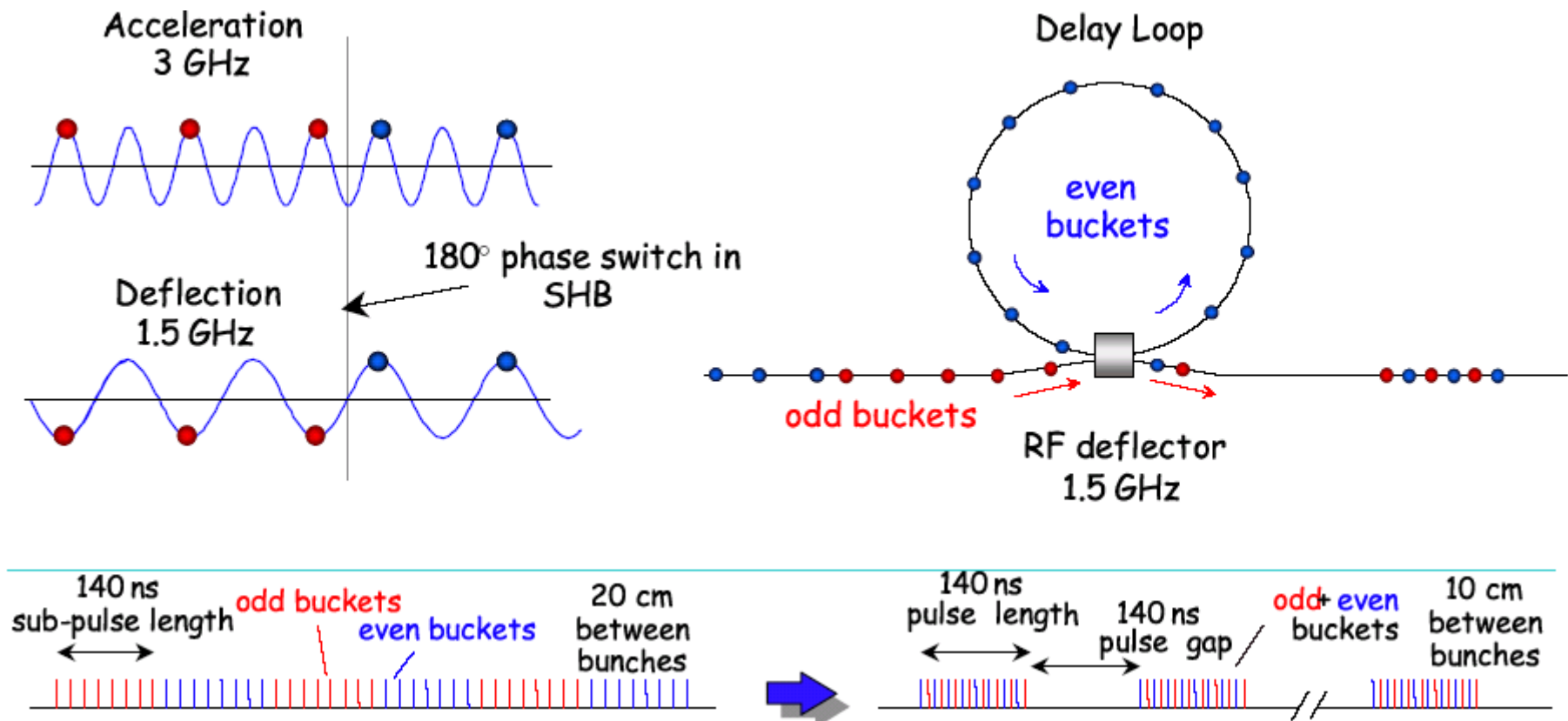
- Requires **high current stability**
- Stable beam successfully demonstrated in CTF3
- > 95% efficiency**



- 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

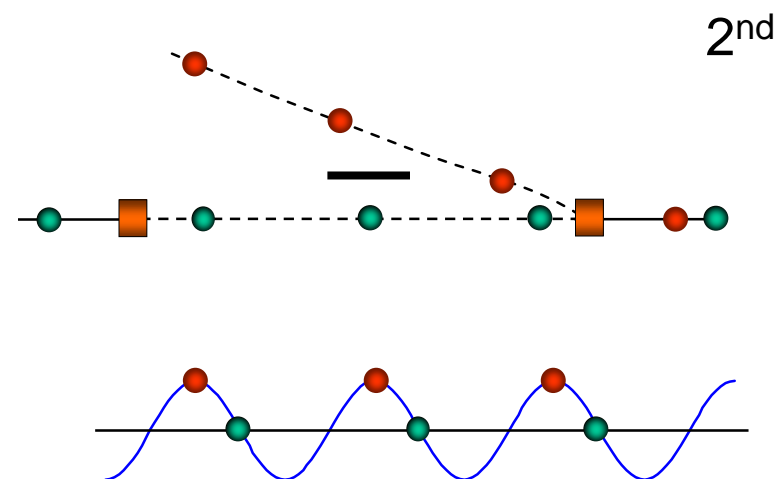
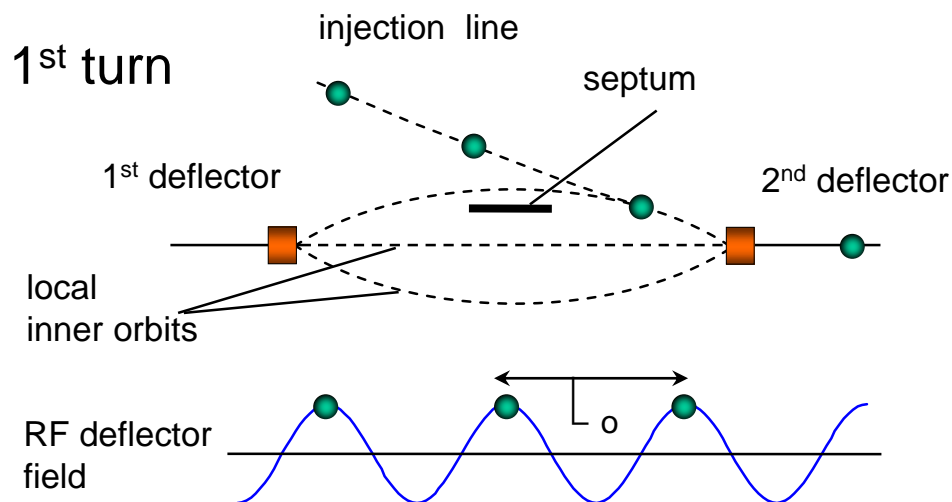


- double repetition frequency and current
- parts of bunch train delayed in loop
- RF deflector combines the bunches (f_{defl} = bunch rep. frequency)
- Path length corresponds to beam pulse length

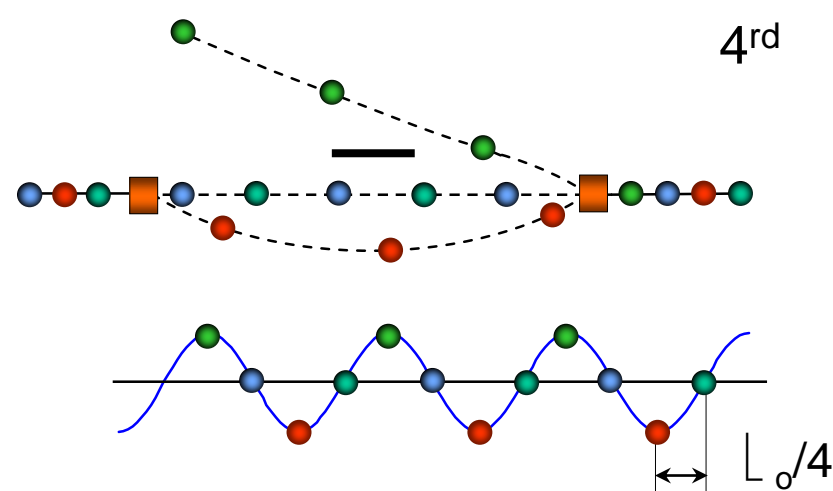
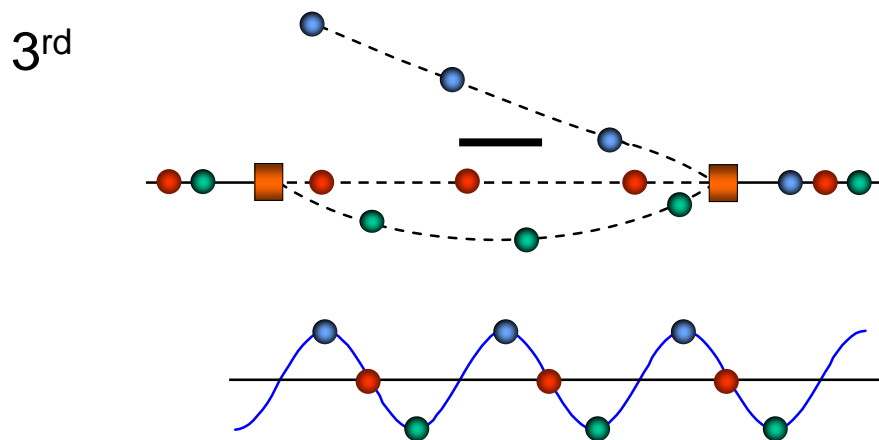


- combination **factors** up to 5 reachable in a ring

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



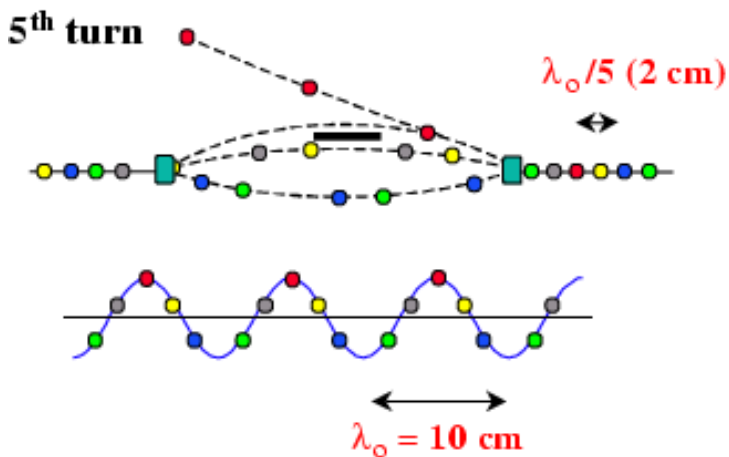
C_{ring} has to correspond to the distance of pulses from the previous combination stage!



Combination factor 5

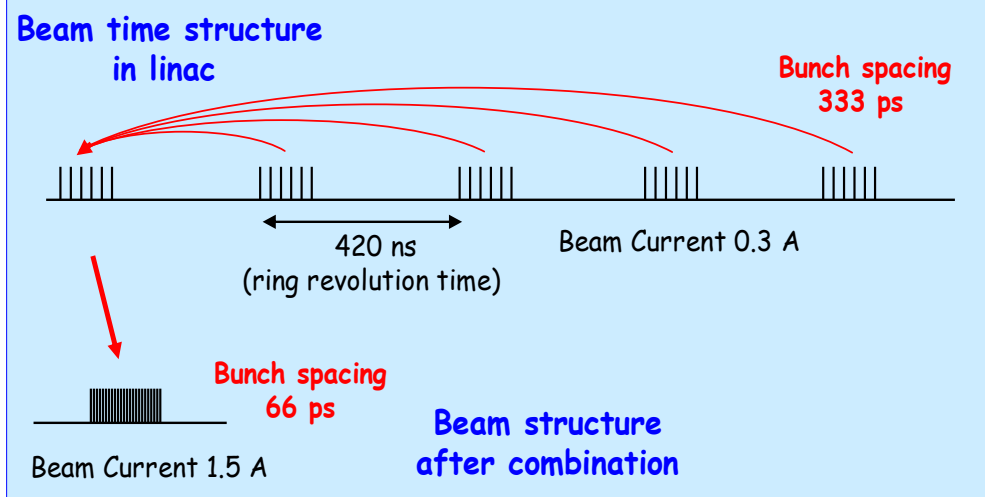
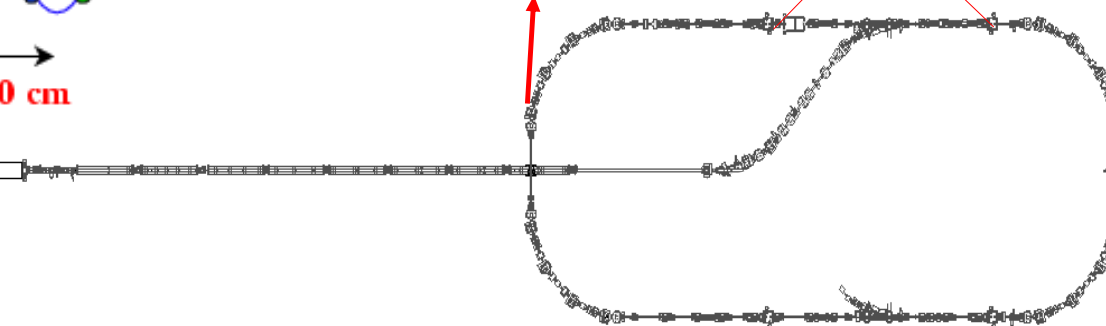
CTF3 - PRELIMINARY PHASE 2001/2002

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

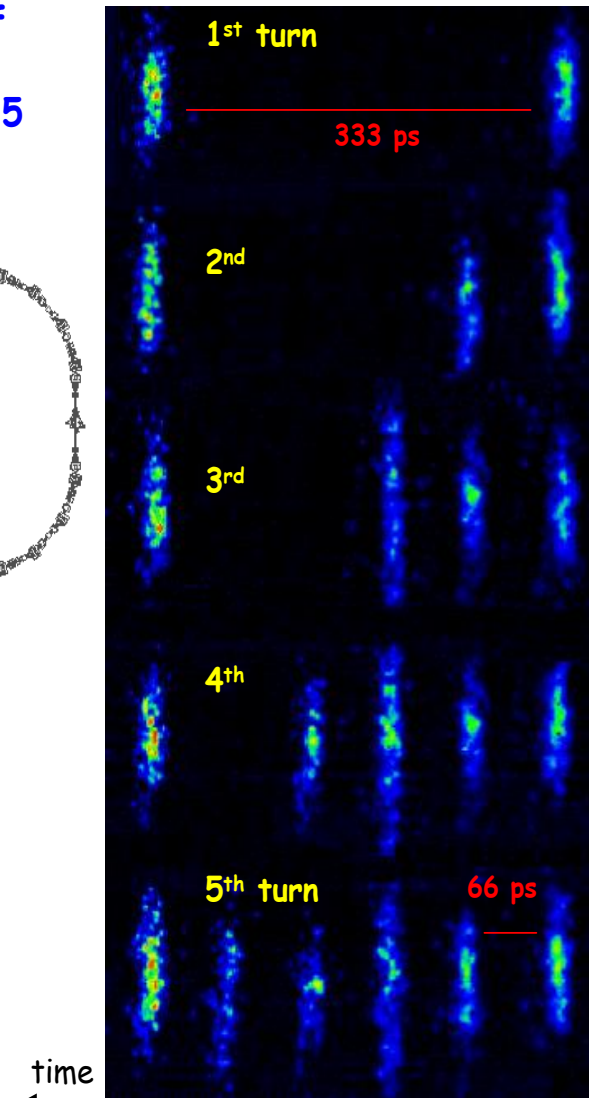


streak camera
measurement

RF deflectors

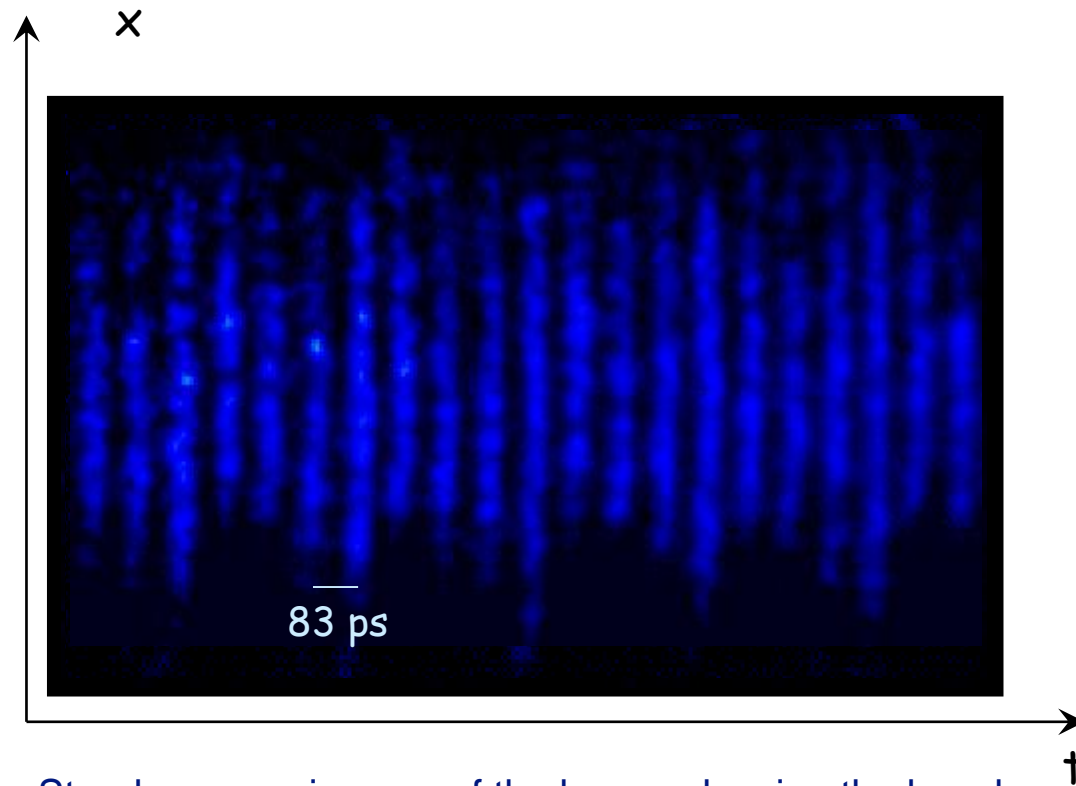


Streak camera image of
beam time structure evolution



RF injection in combiner ring

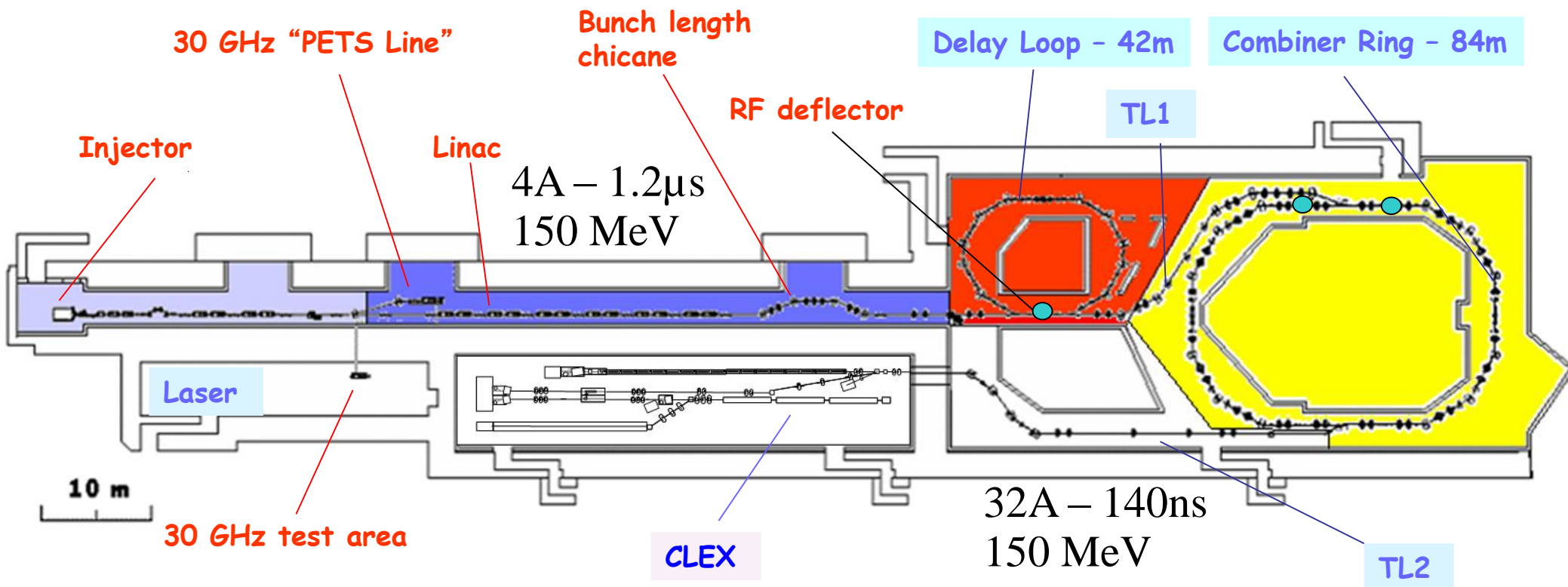
Combination factor 4



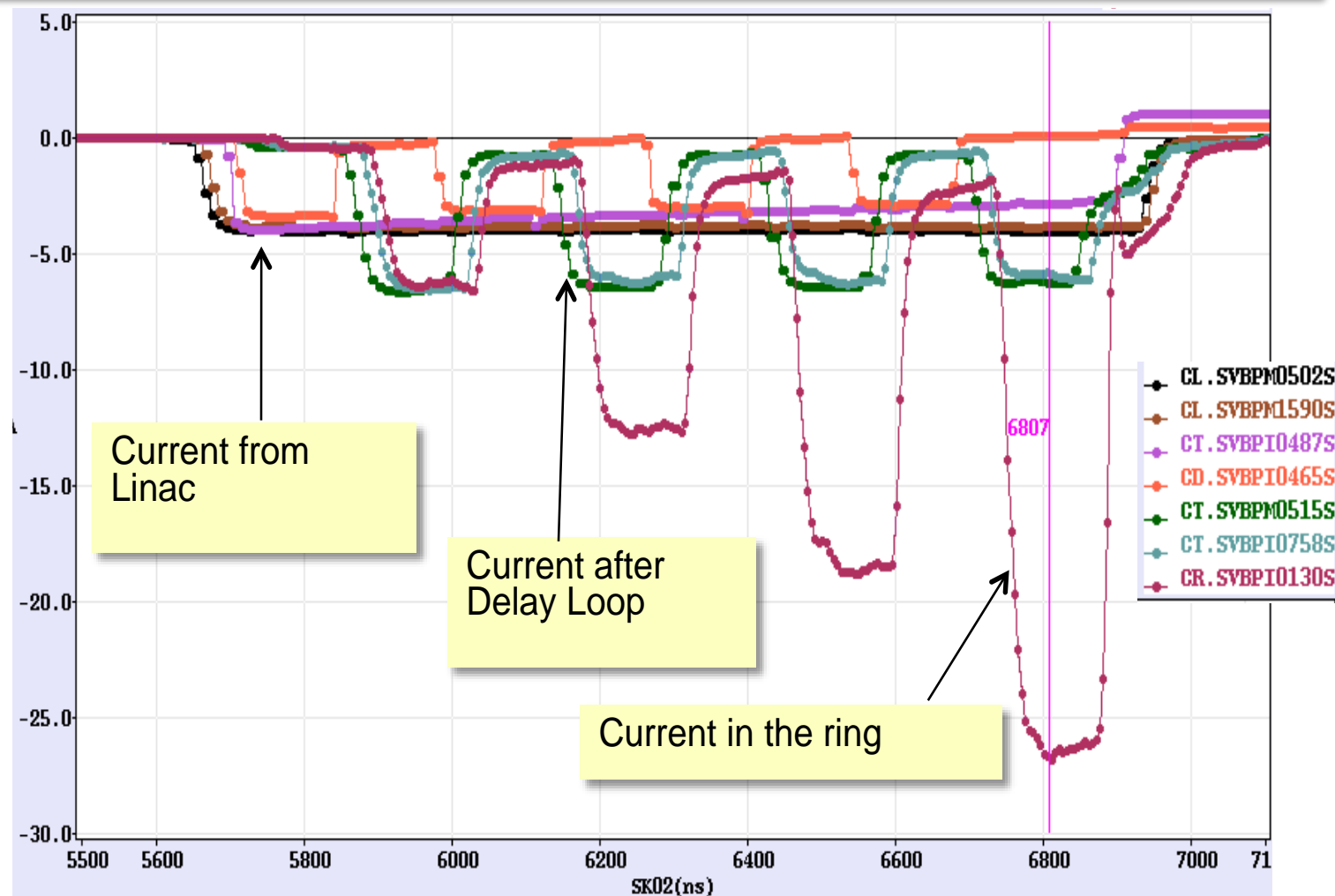
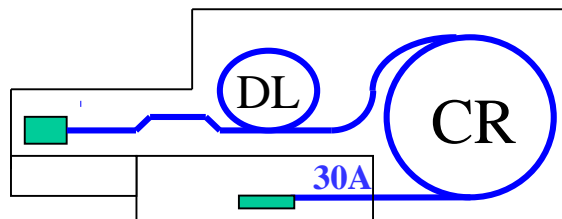
Streak camera images of the beam, showing the bunch combination process

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

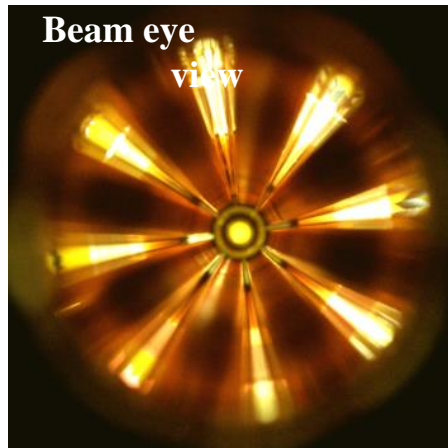
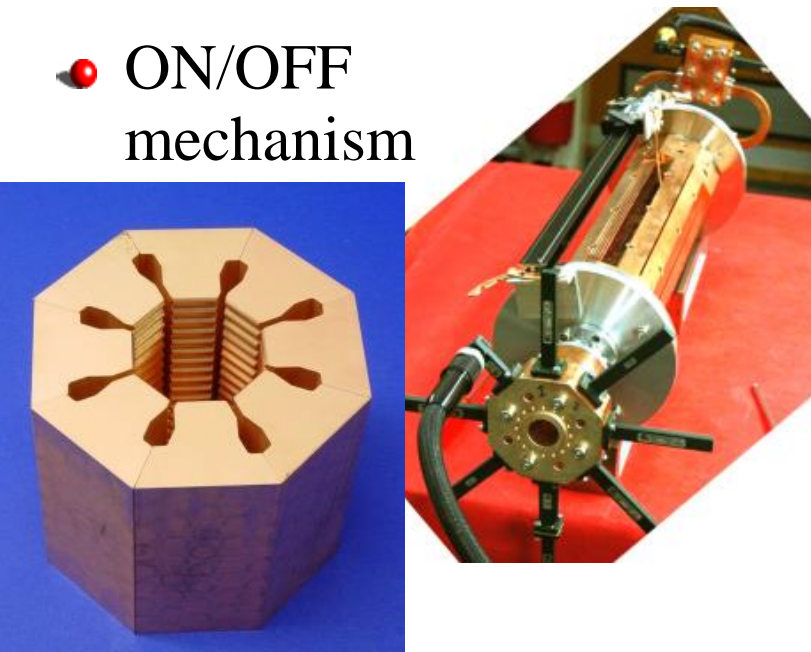
- demonstrate remaining CLIC feasibility issues, in particular:
 - Drive Beam generation (fully loaded acceleration, bunch frequency multiplication)
 - CLIC accelerating structures
 - CLIC power production structures (PETS)



- 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**



- 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:

$$P = I^2 L^2 F_b^2 W_0 \frac{\overset{\text{Design input parameters}}{\uparrow} \overset{\text{PETS design}}{\hat{R} / Q}}{4v_g}$$

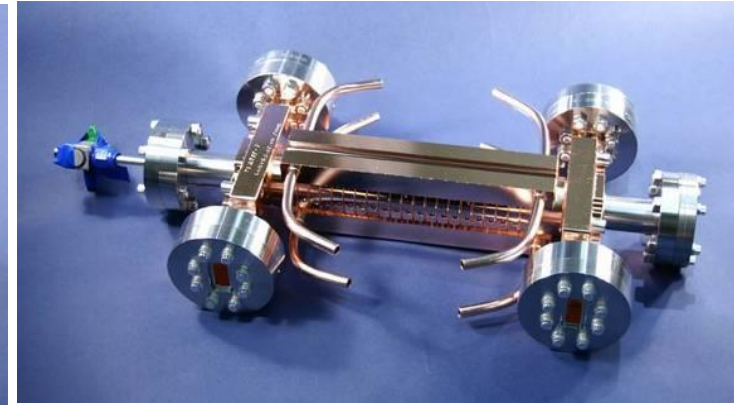
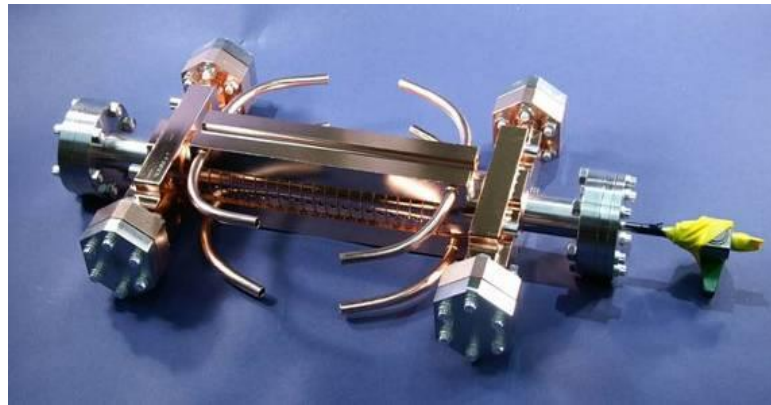
P - RF power, determined by the accelerating structure needs and the module layout.

I - Drive beam current

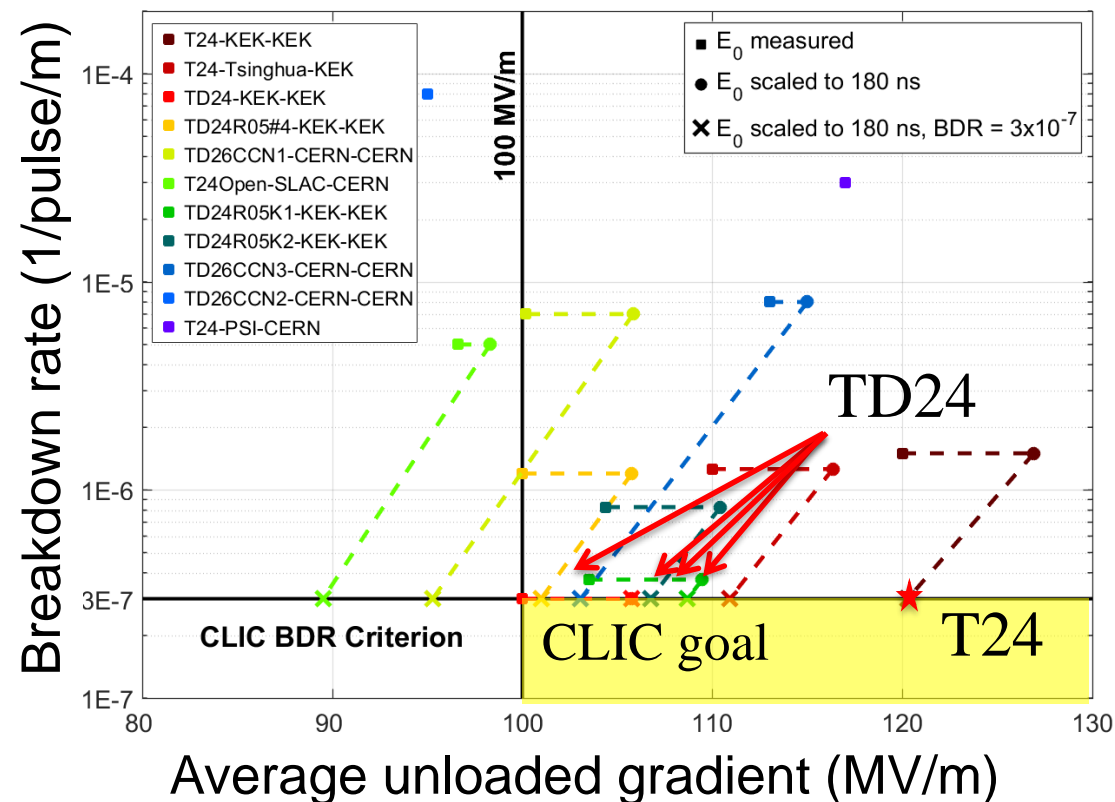
L - Active length of the PETS

F_b - single bunch form factor (≈ 1)

- RF breakdowns can occur
=> no acceleration and deflection



- Goal: $3 \cdot 10^{-7}/\text{m}$ 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

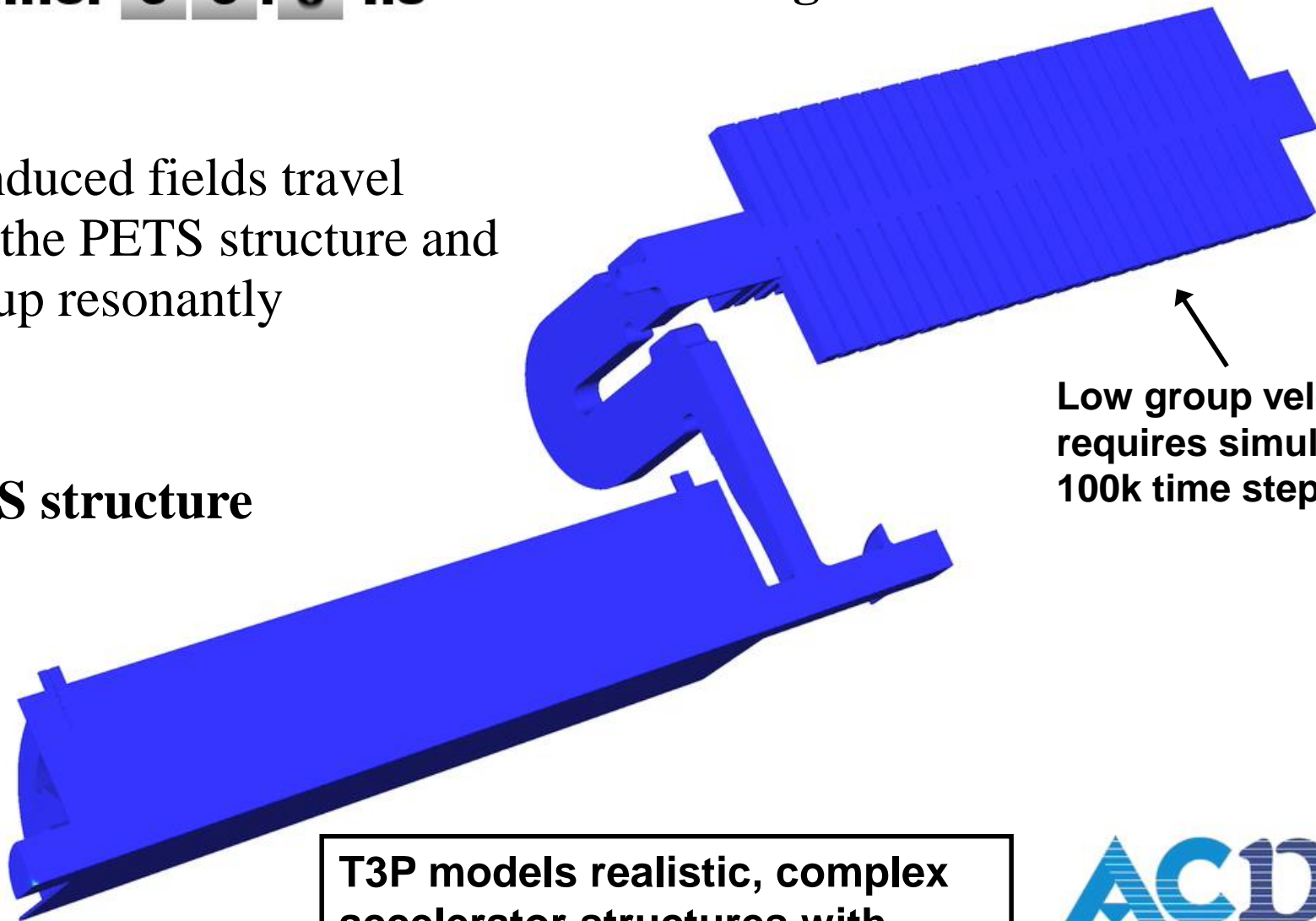


time: 0 0 . 0 ns

Accelerating structure

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

PETS structure



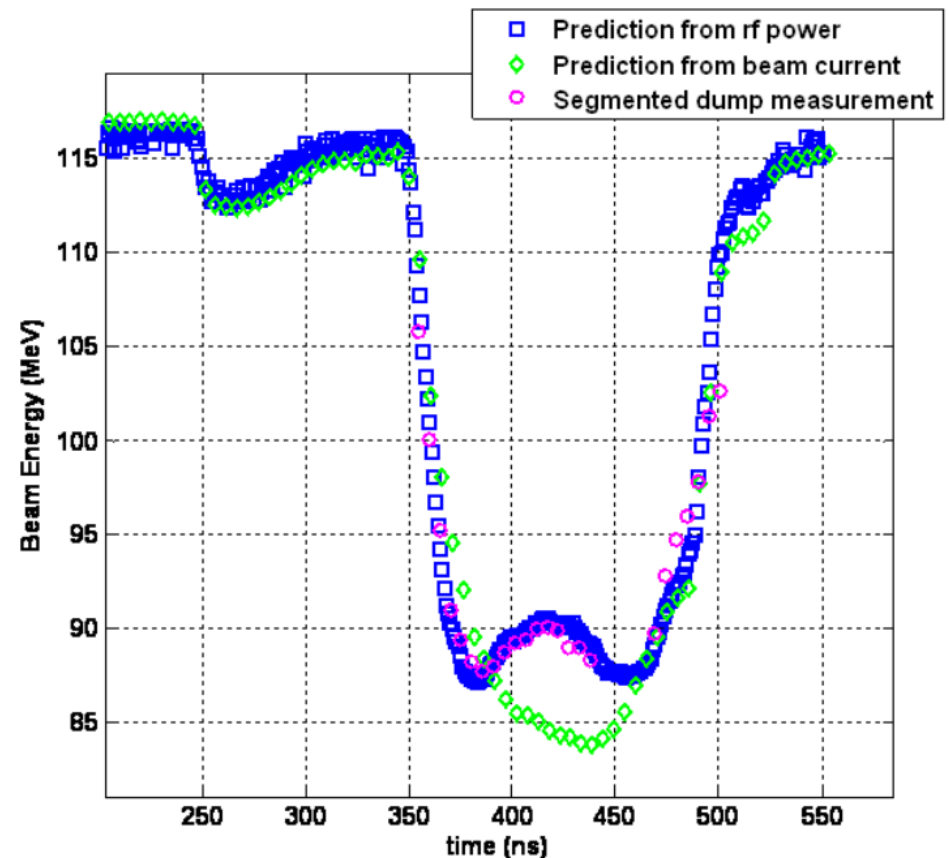
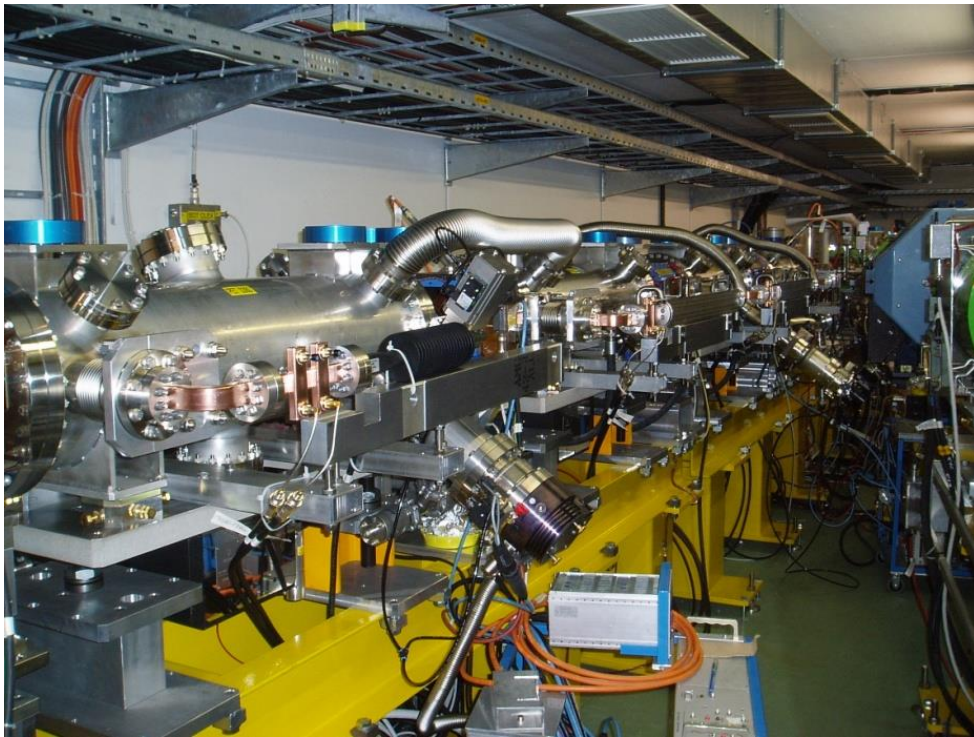
Low group velocity
requires simulations with
100k time steps

**T3P models realistic, complex
accelerator structures with
unprecedented accuracy**

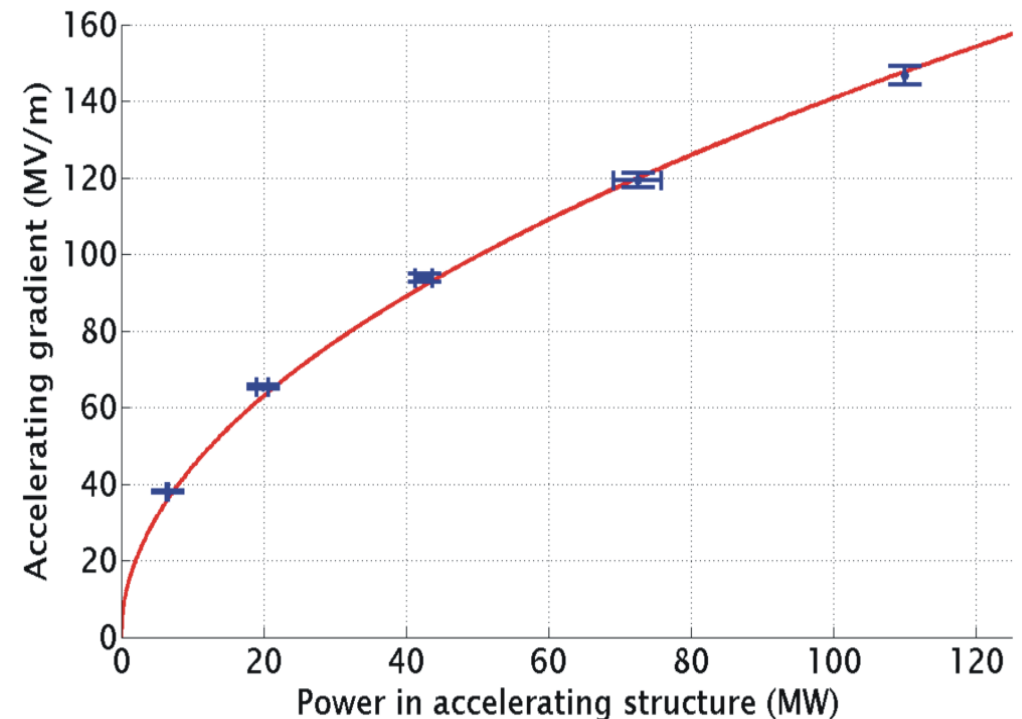
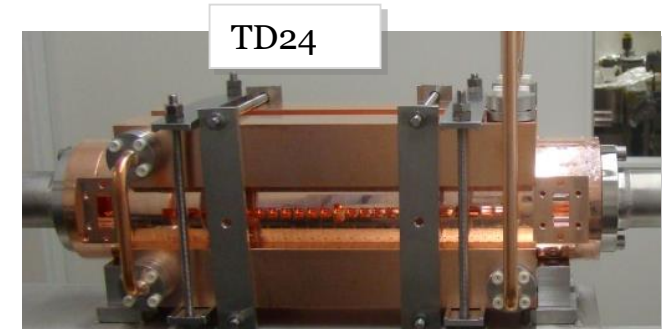
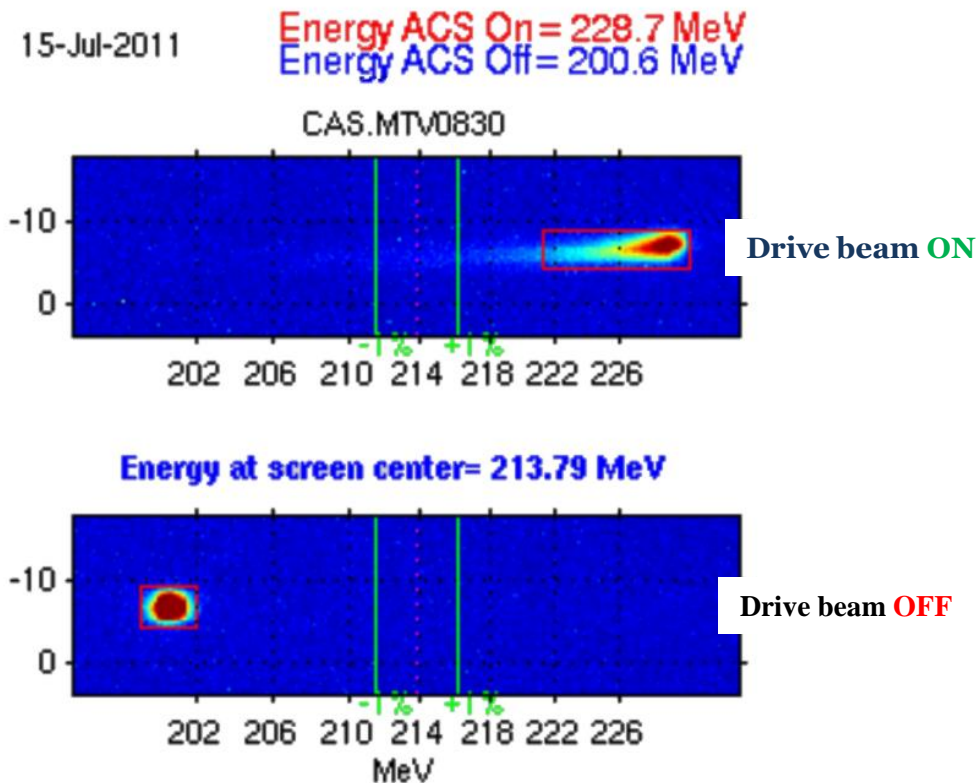


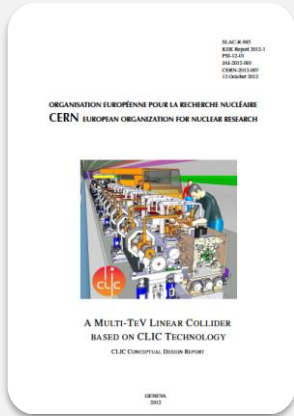
Arno Candel, SLAC

- 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



- Maximum probe beam acceleration measured: **31 MeV**
 \Rightarrow Corresponding to a gradient of **145 MV/m**

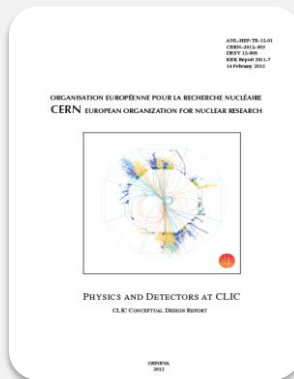




Vol 1: The CLIC accelerator and site facilities (H.Schmickler)

- 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/>

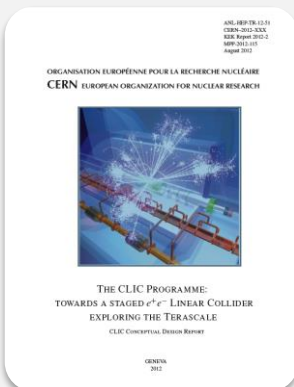
In addition a shorter overview document as input to the European Strategy update, available at:
<http://arxiv.org/pdf/1208.1402v1>



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

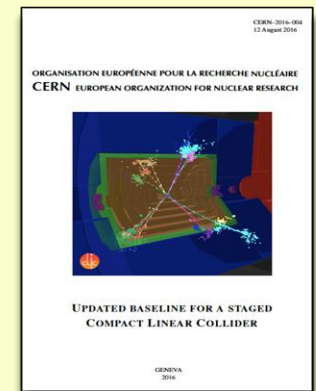
- Physics at a multi-TeV CLIC machine can be measured with high precision, despite challenging background conditions
- External review procedure in October 2011
- Completed and printed, presented in SPC in December 2011
<http://arxiv.org/pdf/1202.5940v1>

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



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>



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



Compact Linear Collider

- 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>