Linear Colliders
Lecture 4

Frank Tecker – CERN

- CLIC two beam scheme
- Drive Beam generation
- CLIC test facility CTF3

CLIC scheme

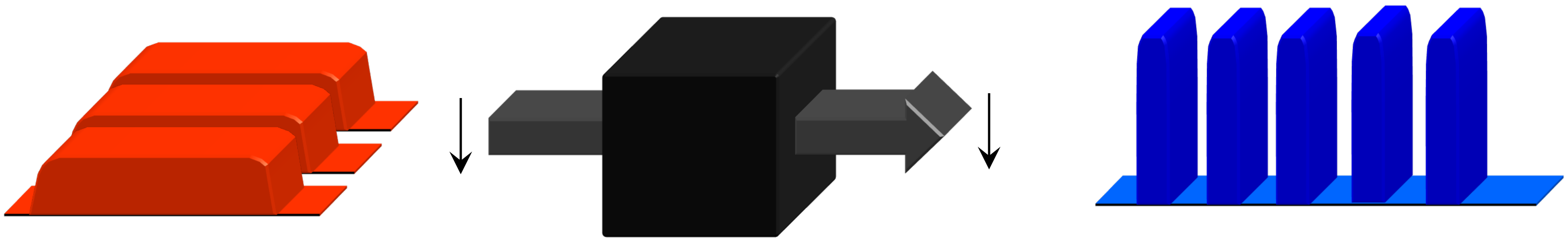
- Very high gradients (>100 MV/m) possible with NC accelerating structures at high RF frequencies (30 GHz → 12 GHz)
- Extract required high RF power from an intense e- "drive beam"
- Generate efficiently long pulse and compress it (in power + frequency)

'few' Klystrons
Low frequency
High efficiency

Power stored in
electron beam

Power extracted from beam
in resonant structures

Accelerating Structures
High Frequency – High field



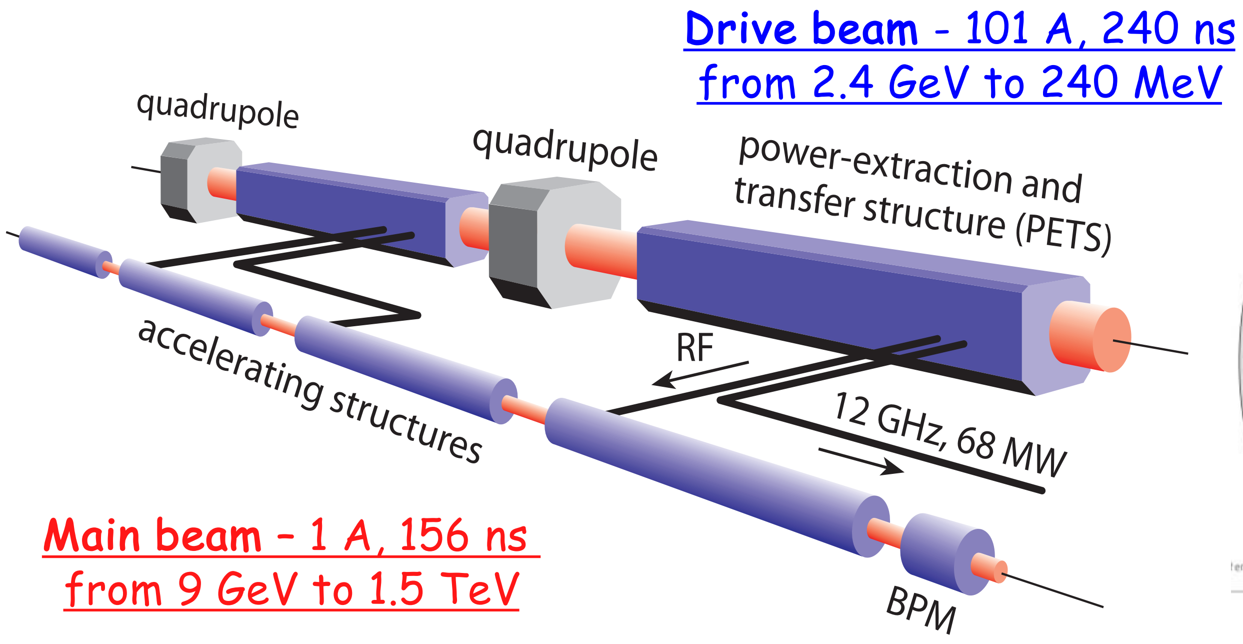
Long RF Pulses
P_0 , ν_0 , τ_0

Electron beam manipulation
Power compression
Frequency multiplication

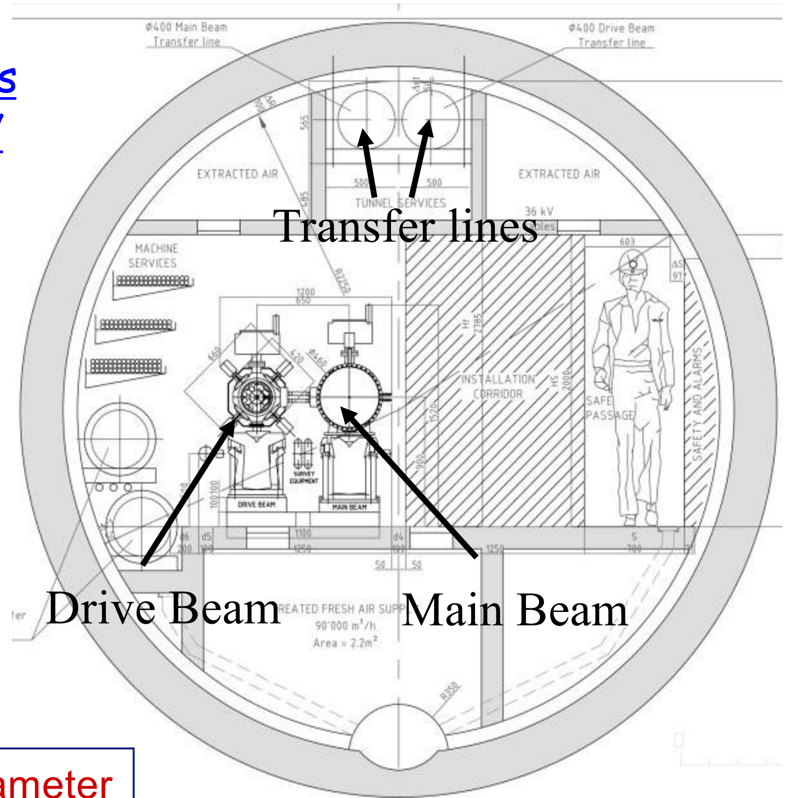
Short RF Pulses
$P_A = P_0 \times N_1$
$\tau_A = \tau_0 / N_2$
$\nu_A = \nu_0 \times N_3$

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

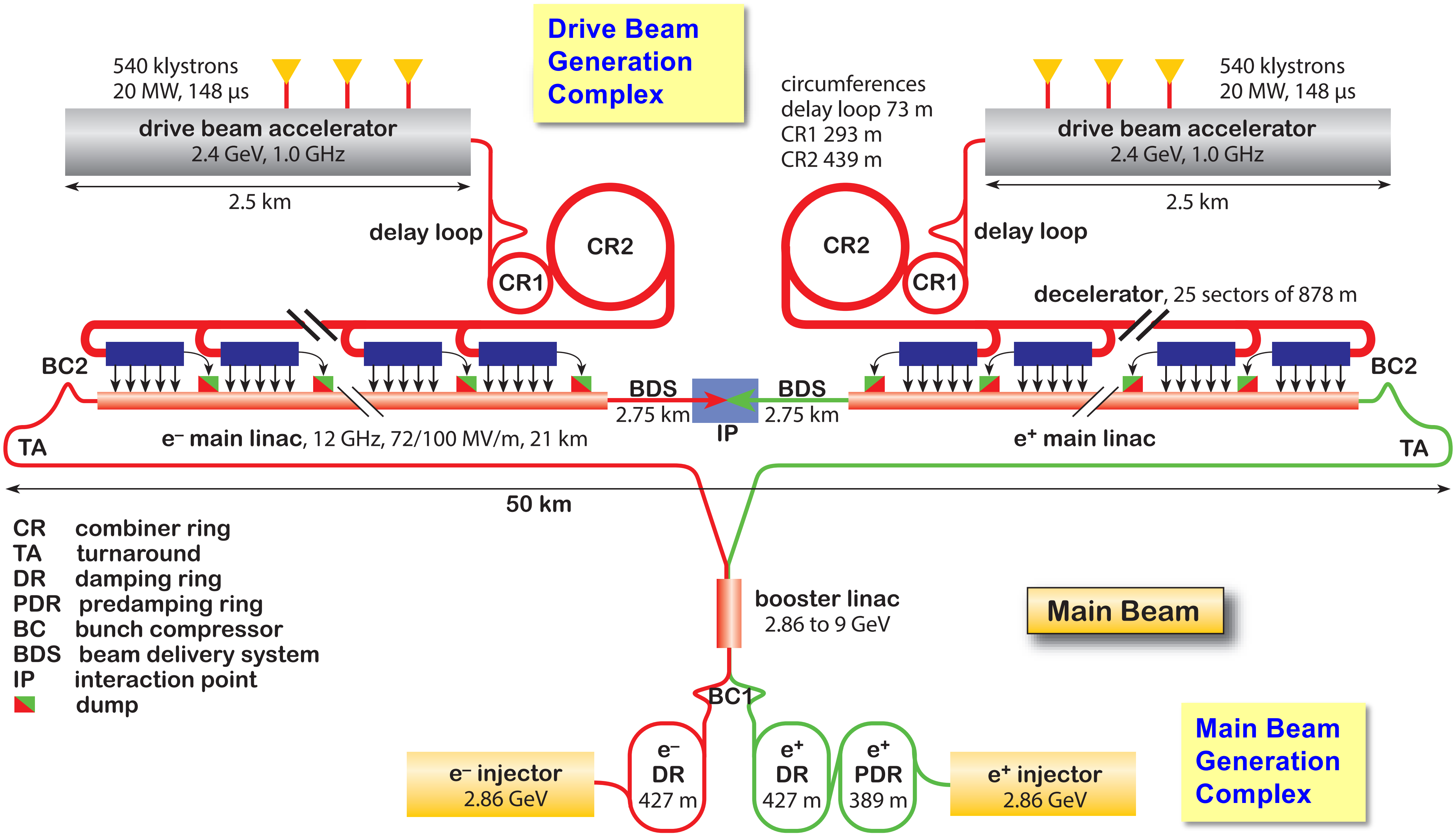


CLIC TUNNEL CROSS-SECTION

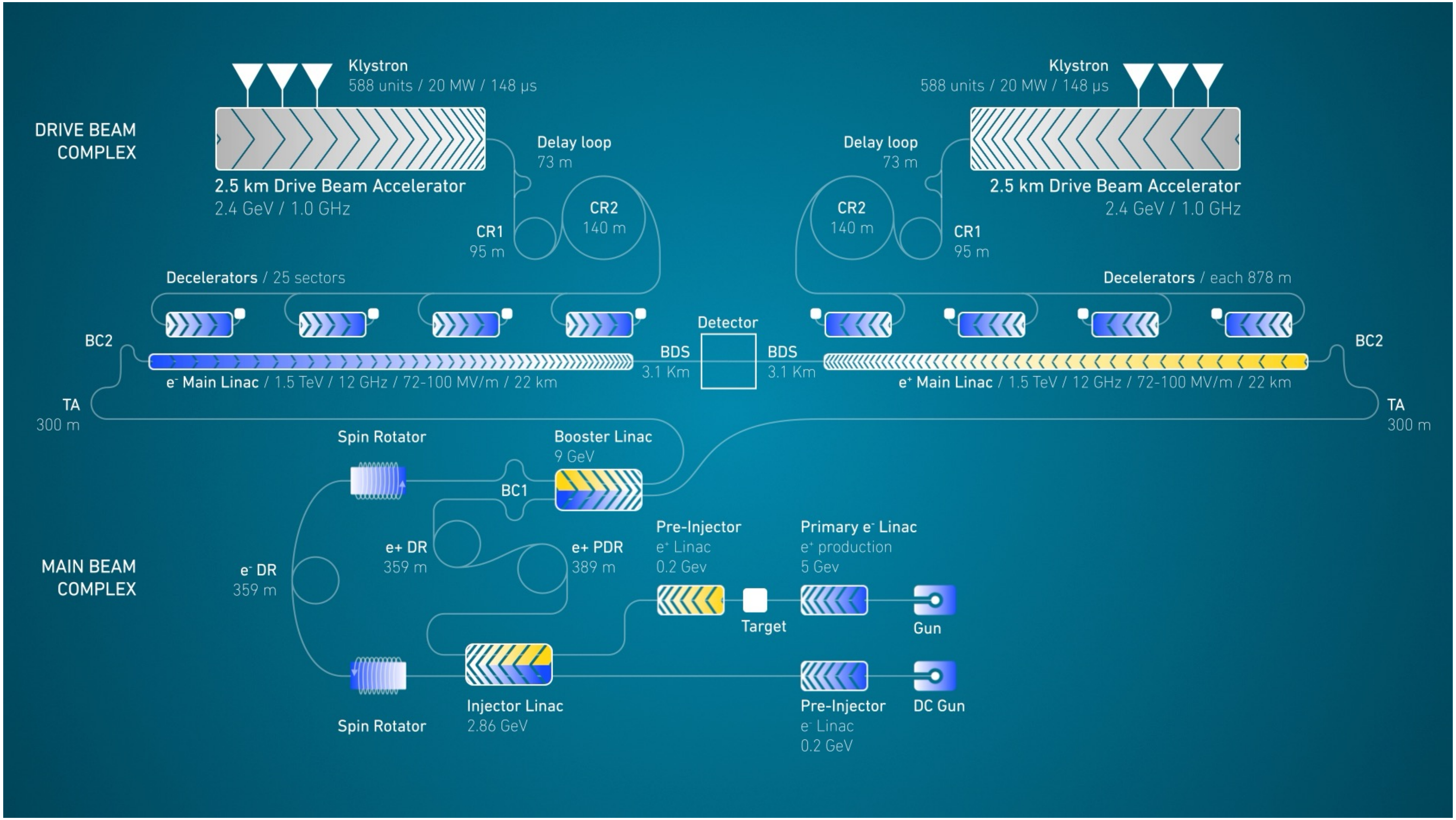


5.6 m diameter

CLIC – overall layout – 3 TeV



CLIC



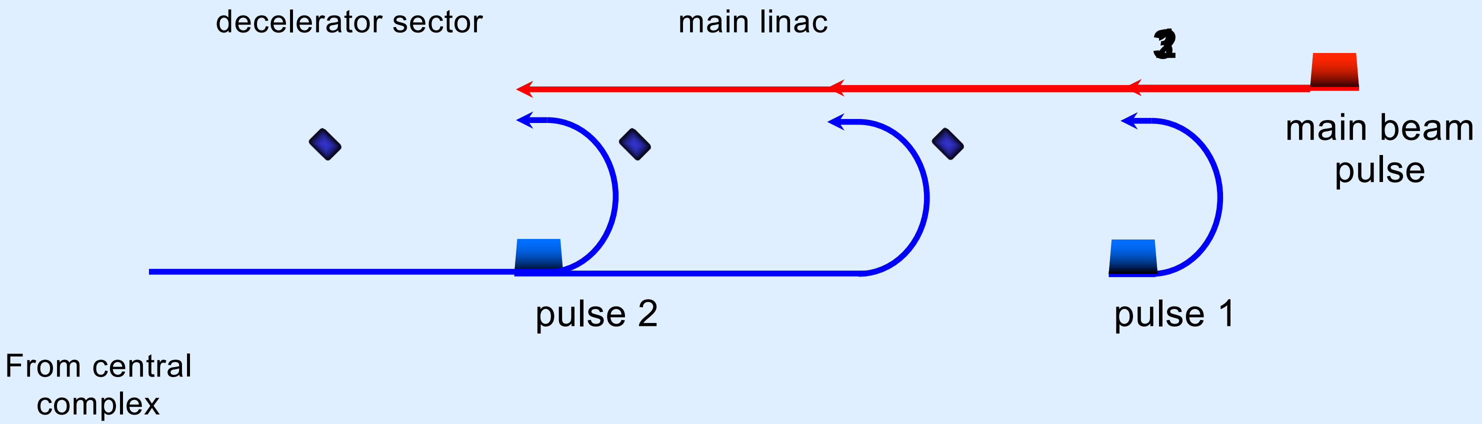
DRIVE BEAM COMPLEX
Klystron
588 units / 20 MW / 148 μs
2.5 km Drive Beam Accelerator
2.4 GeV / 1.0 GHz
Delay loop
73 m
CR1
95 m
CR2
140 m
Decelerators / 25 sectors
Decelerators / each 878 m
Detector
BDS
3.1 Km
BC2
TA
300 m
e- Main Linac / 1.5 TeV / 12 GHz / 72-100 MV/m / 22 km
e+ Main Linac / 1.5 TeV / 12 GHz / 72-100 MV/m / 22 km
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

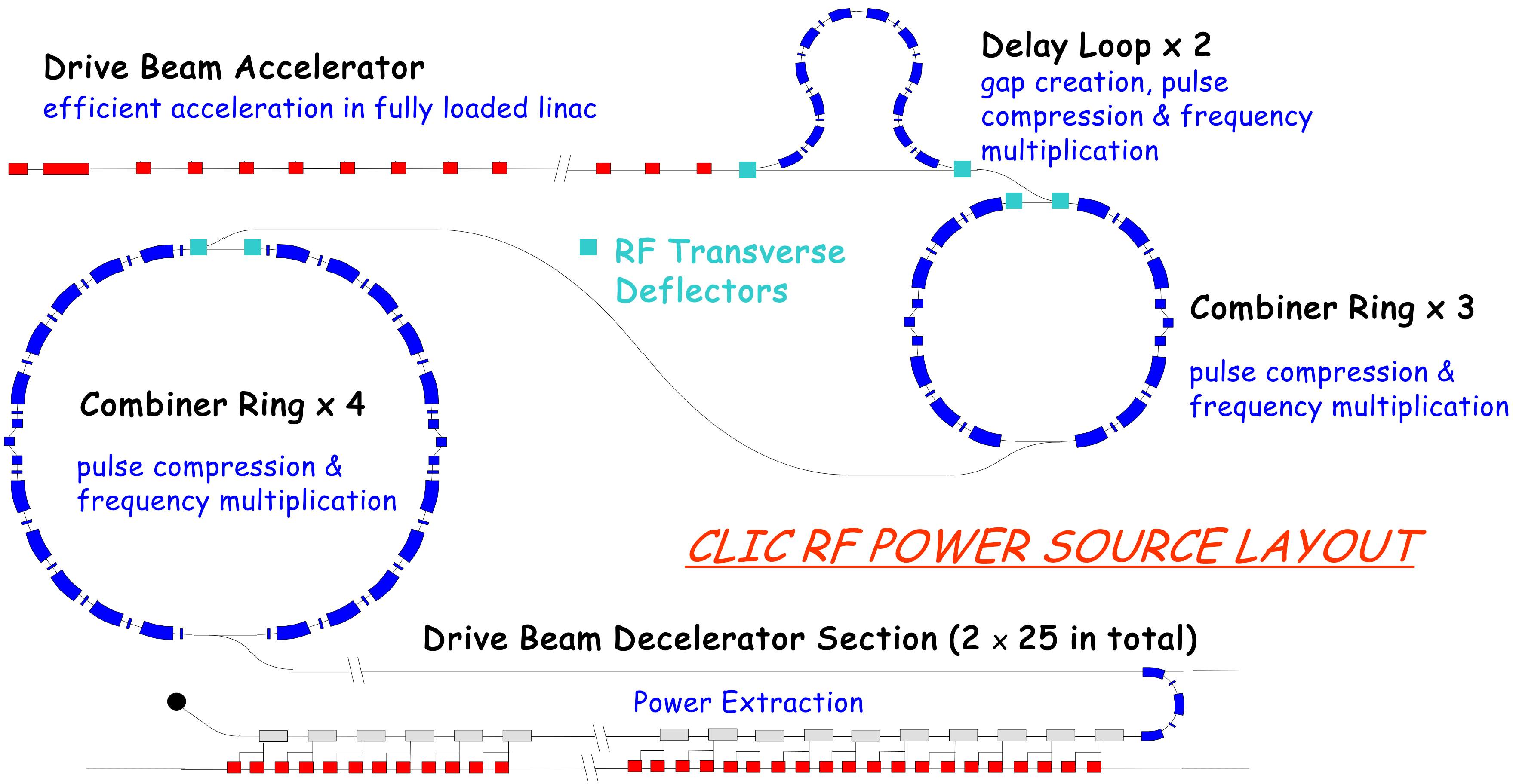
The distance between the pulses is $2\ L_s = 2\ L_{main}/N_S$ (L_{main}= single side linac length)

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

240 ns

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

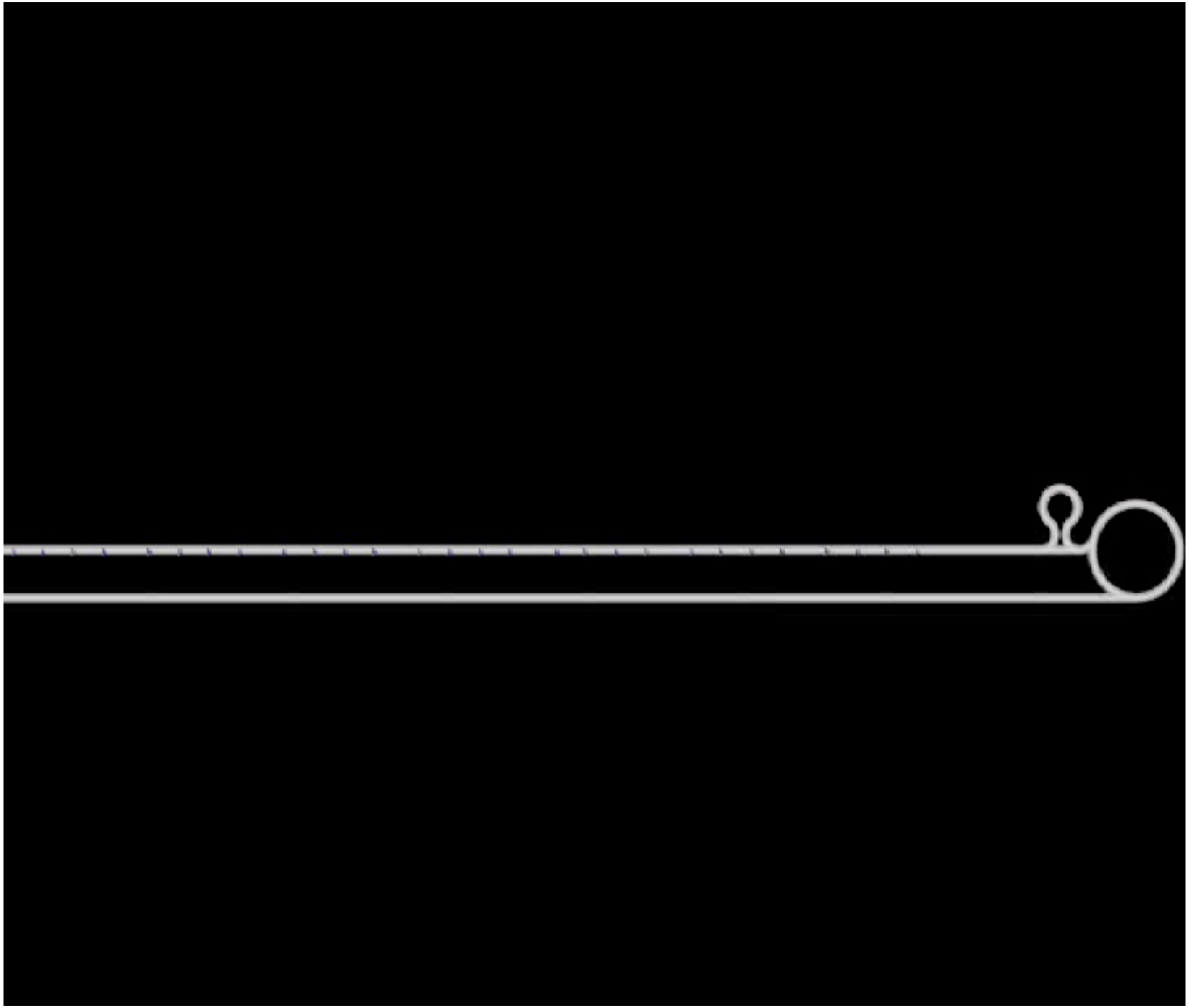
Drive beam time structure - final

240 ns

5.8 μs

25 pulses - 101 A - 2.5 cm between bunches

Lemmings Drive Beam



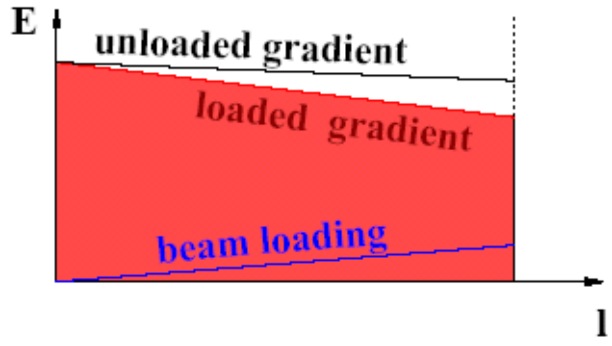
Alexandra Andersson

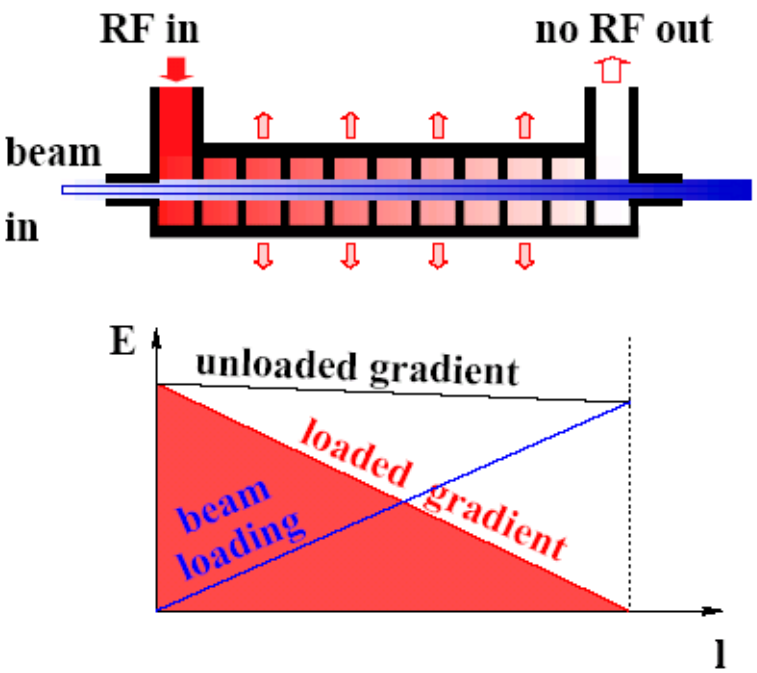
Fully loaded operation

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

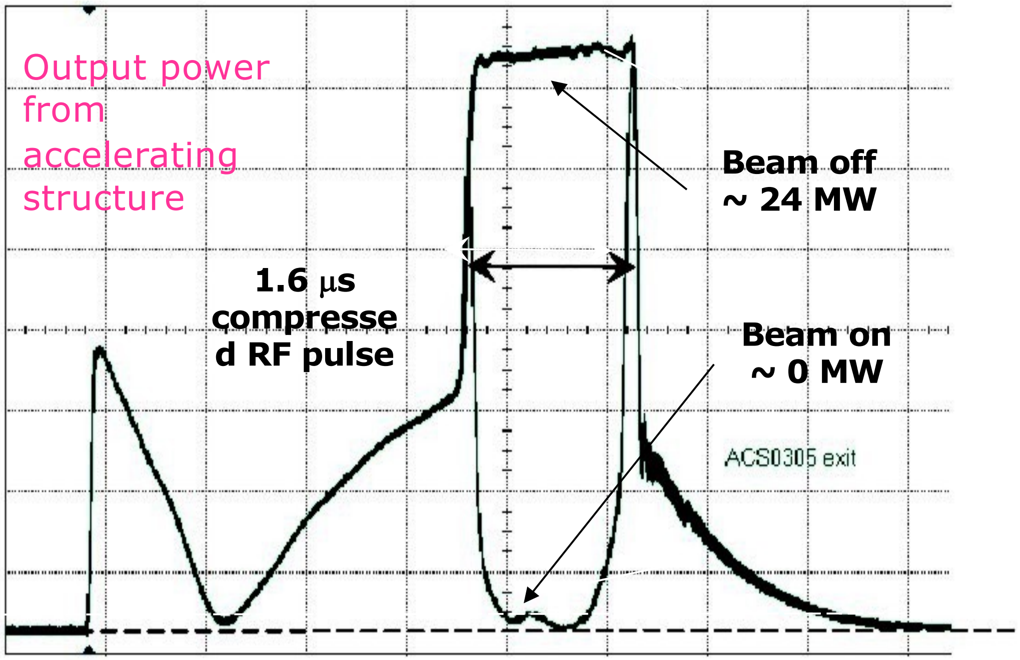
Fully loaded operation

- Disadvantage: any current variation changes energy gain

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

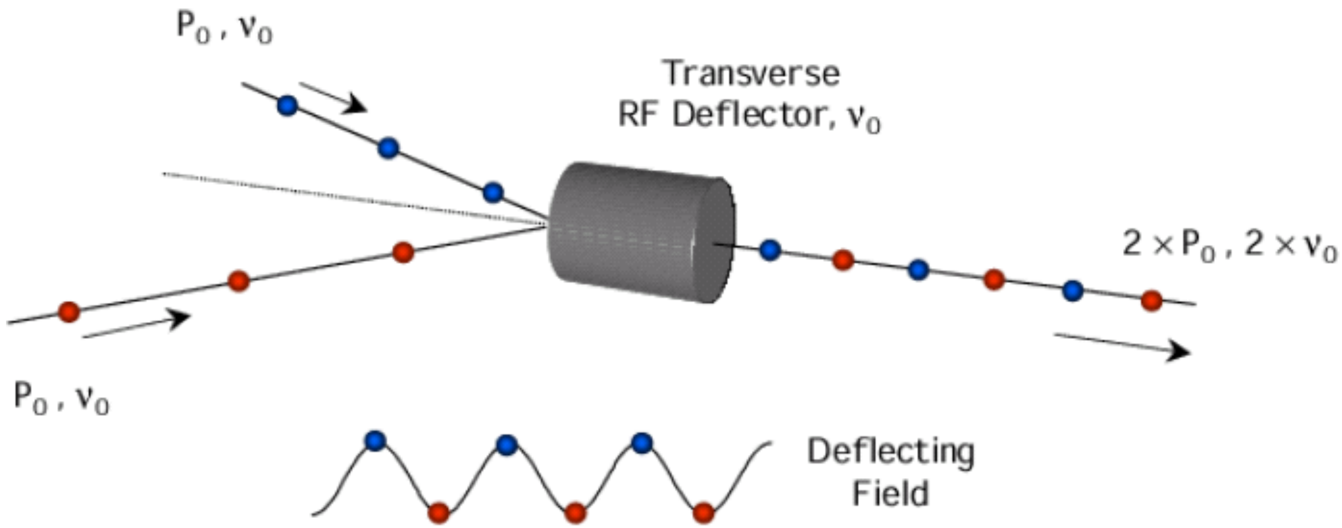
at full loading, 1% current variation = 1% voltage variation
at 20% loading, 1% current variation = 0.2% voltage variation

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



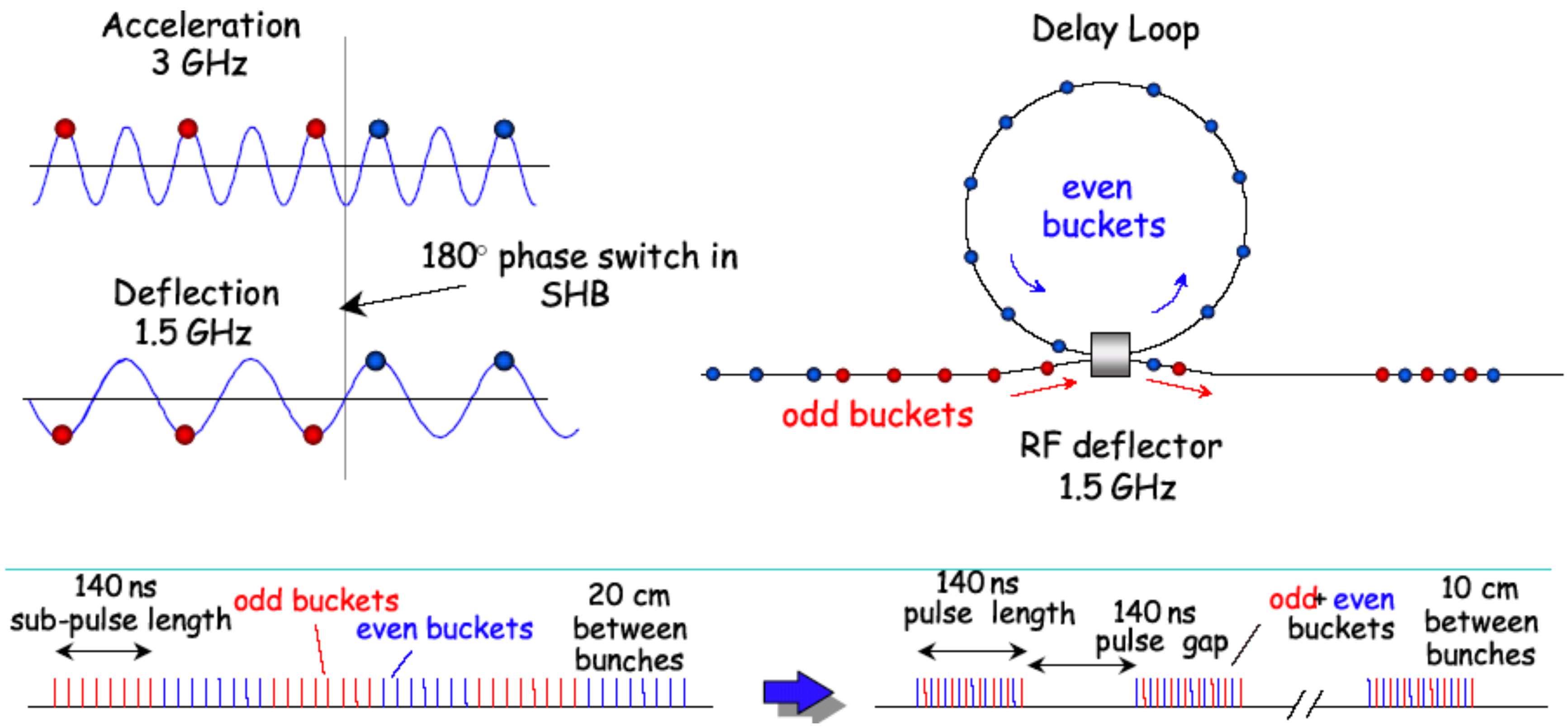
Frequency multiplication

- 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

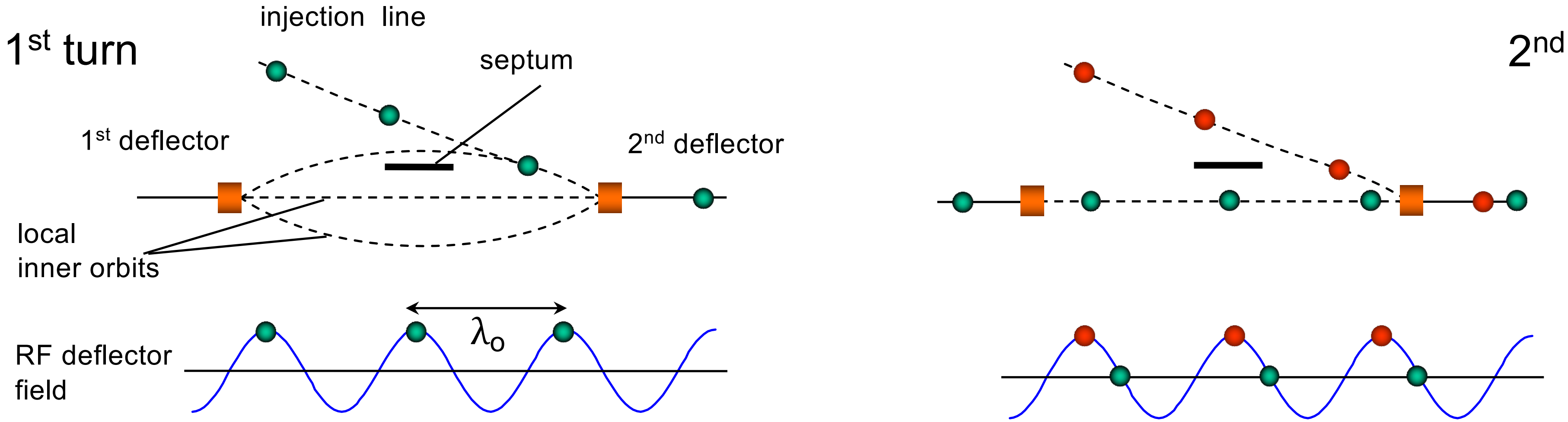
- **double repetition frequency and current**
- parts of bunch train delayed in loop
- RF deflector combines the bunches (f_{defl}=bunch rep. frequency)
- Path length corresponds to beam pulse length



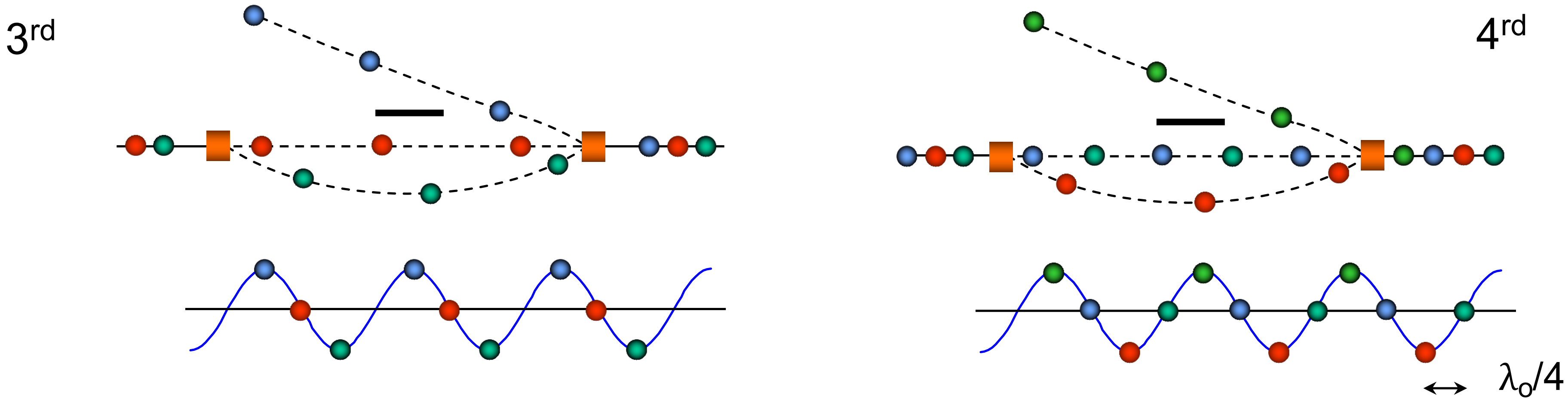
RF injection in combiner ring (factor 4)

- combination factors up to 5 reachable in a ring

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

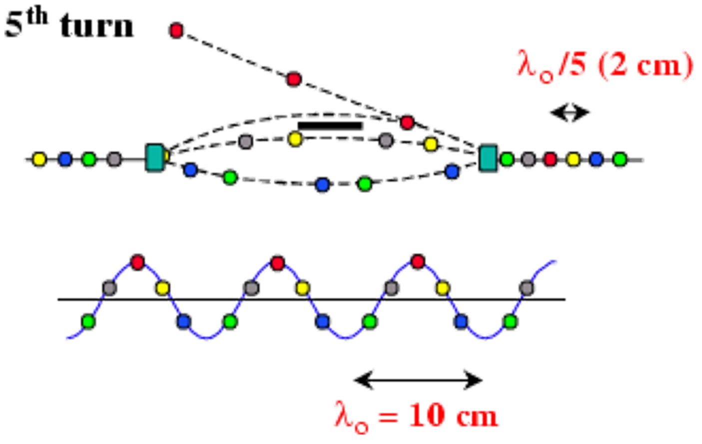


C_{ring} has to correspond to the distance of pulses from the previous combination stage!



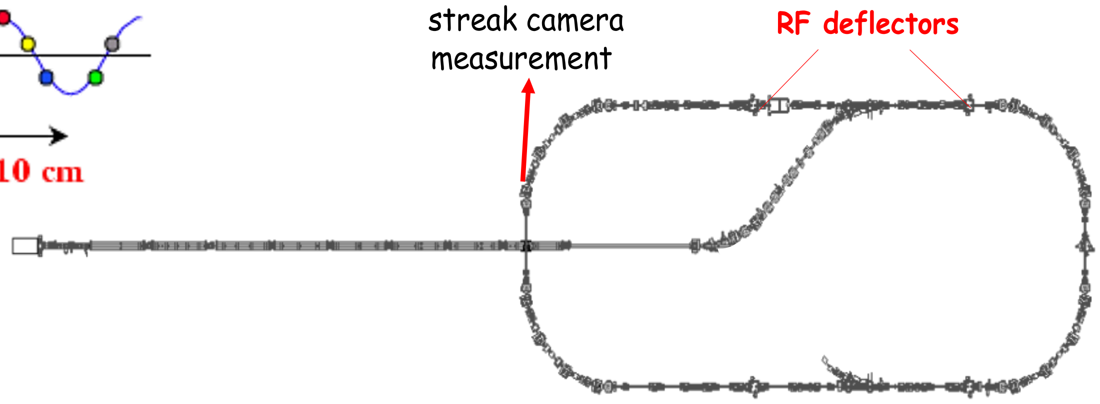
Demonstration of frequency multiplication

Combination factor 5

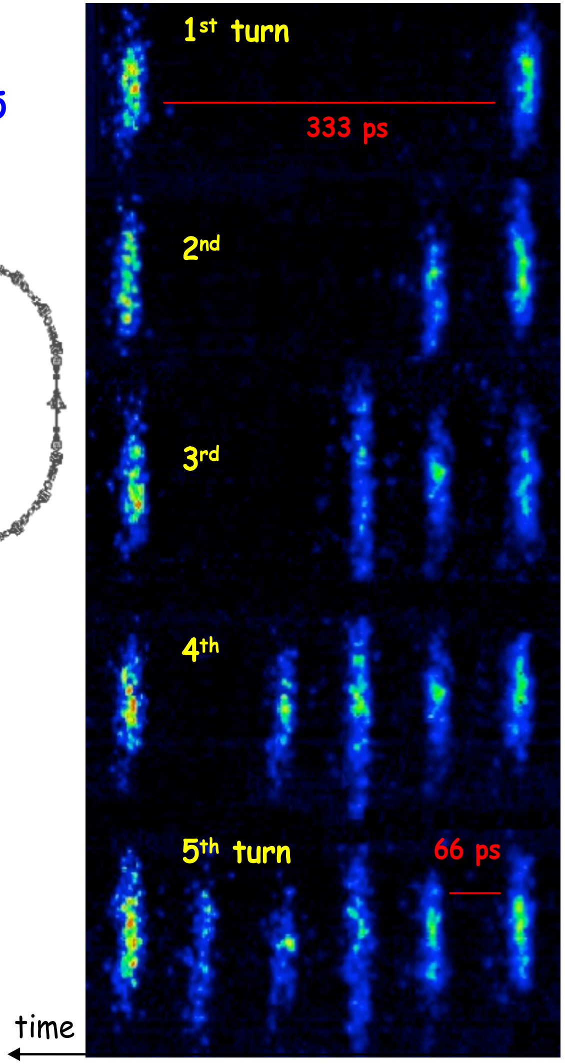


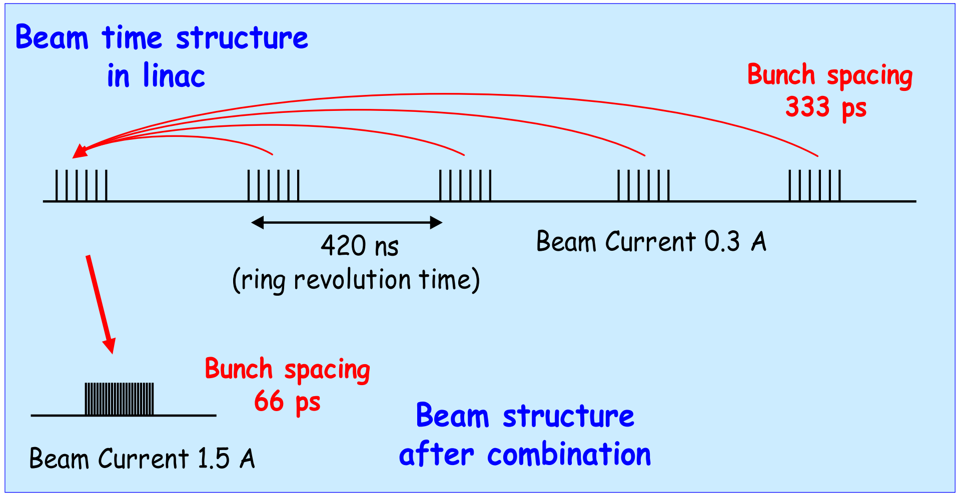
CTF3 - PRELIMINARY PHASE 2001/2002

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

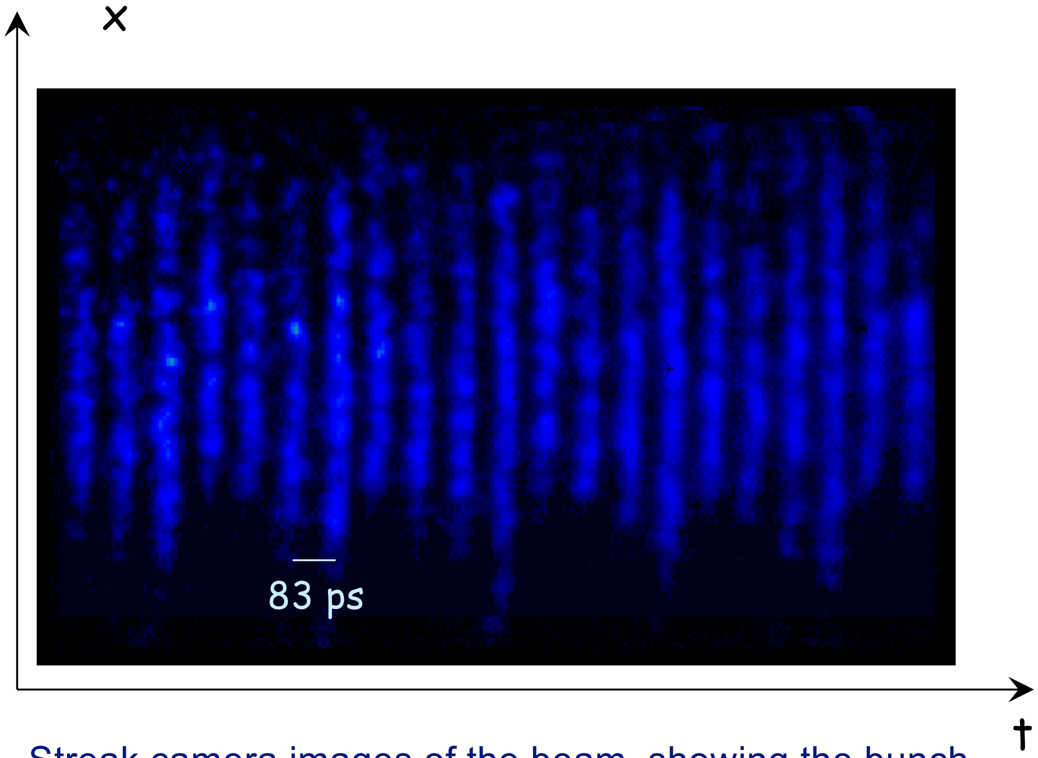




CTF3 preliminary phase (2001-2002)

RF injection in combiner ring

Combination factor 4

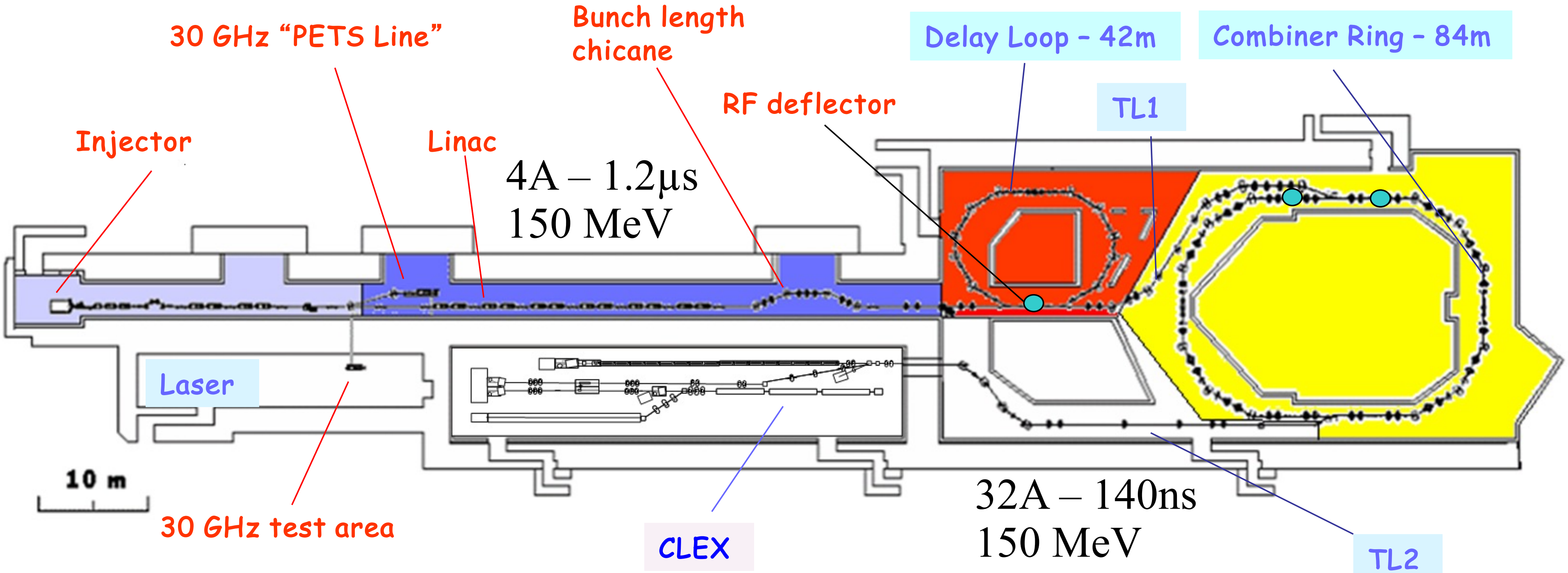


Streak camera images of the beam, showing the bunch combination process

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

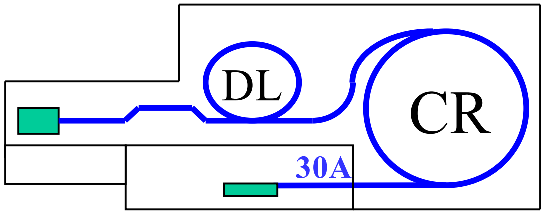
CTF 3

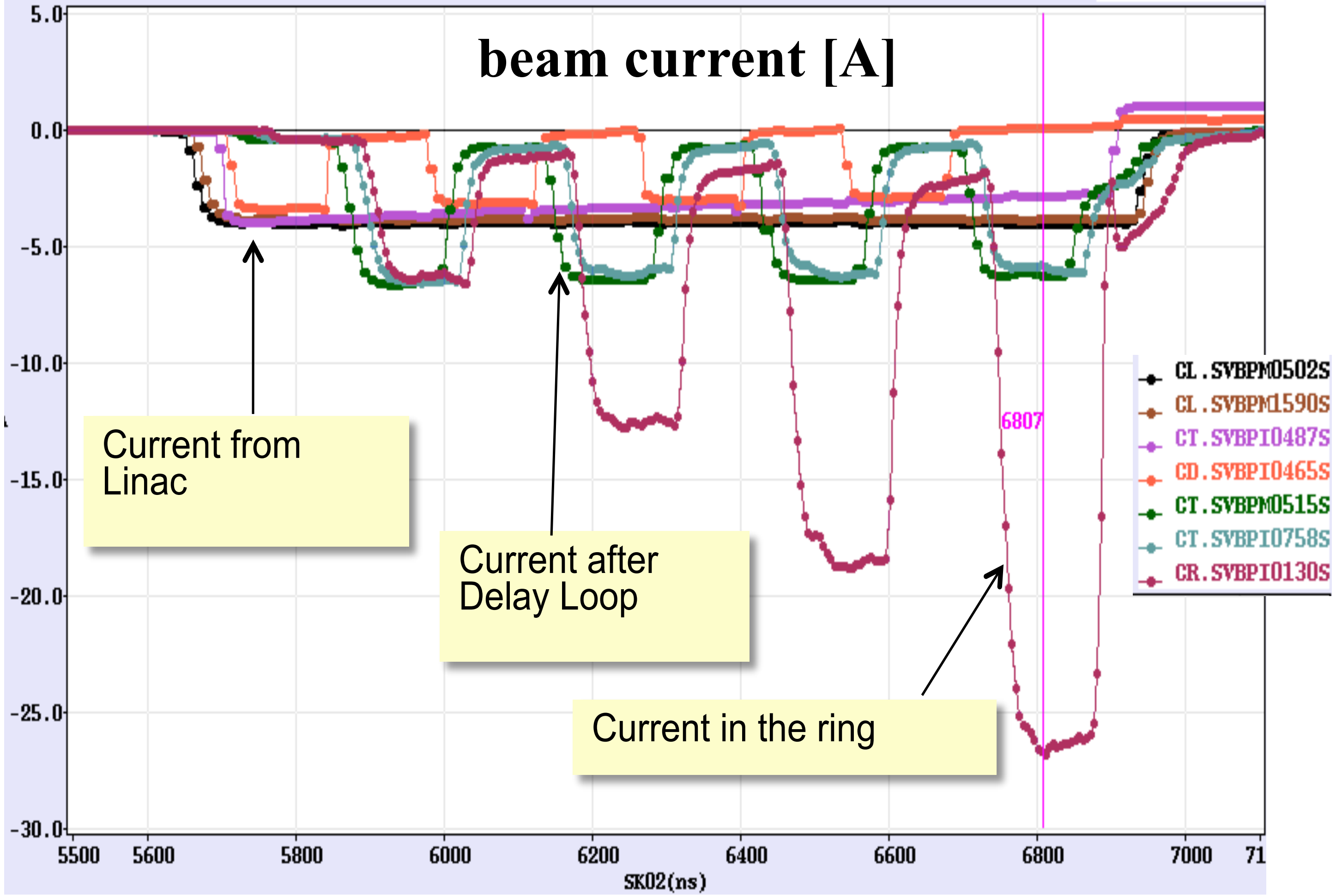
- demonstrate remaining CLIC feasibility issues, in particular:
  - Drive Beam generation (fully loaded acceleration, bunch frequency multiplication)
  - CLIC accelerating structures
  - CLIC power production structures (PETS)



Drive beam generation achieved

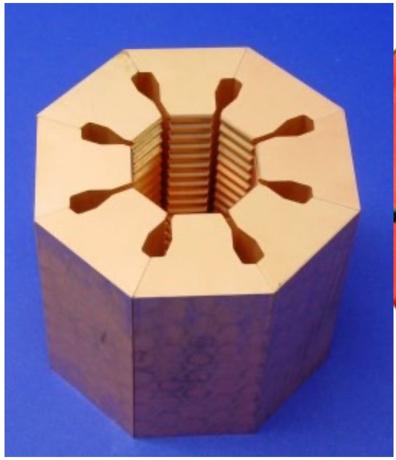
- combined operation of Delay Loop and Combiner Ring (factor 8 combination)
- ~26 A combination reached, nominal 140 ns pulse length
- => **Full drive beam generation**, main goal of 2009, **achieved**

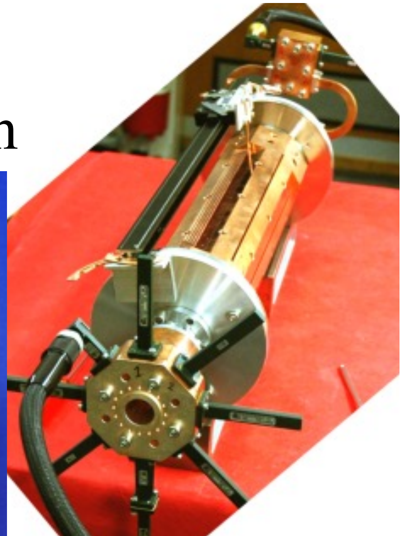


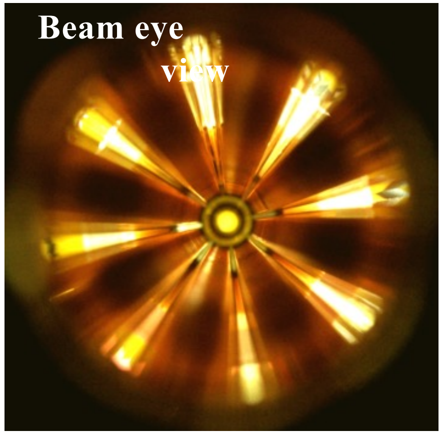


Power extraction structure PETS

- 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:

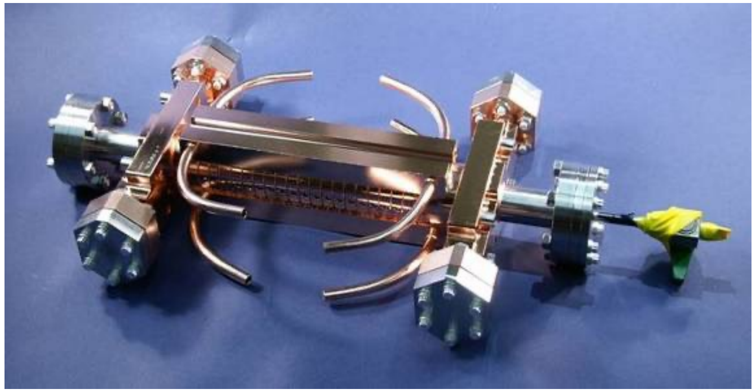
Design input parameters → $I^2 L^2 F_b^2 \omega_0$; PETS design → R/Q and v_g

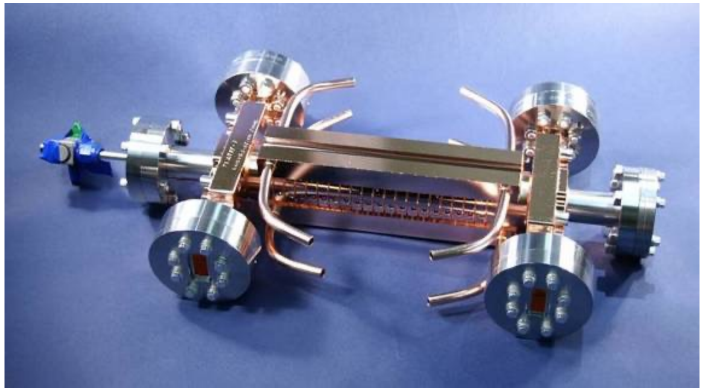
$$P = I^2 L^2 F_b^2 \omega_0 \frac{R/Q}{4 v_g}$$

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)

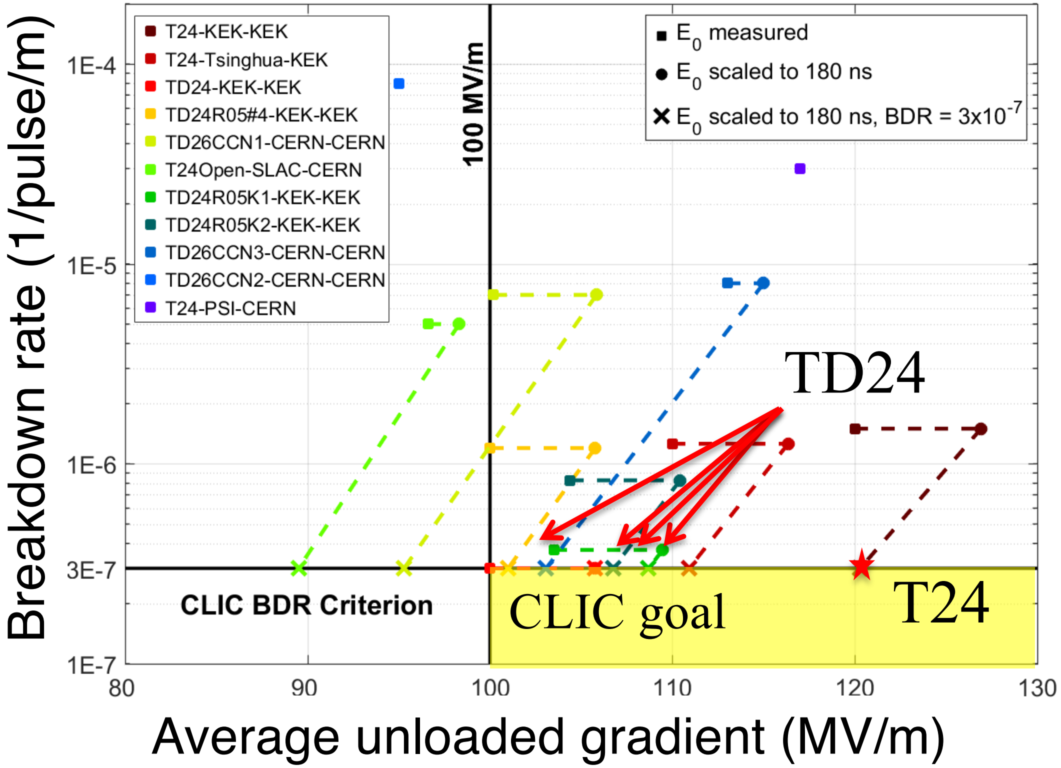
Accelerating Structure Results

- RF breakdowns
  can occur
  => no acceleration
  and deflection





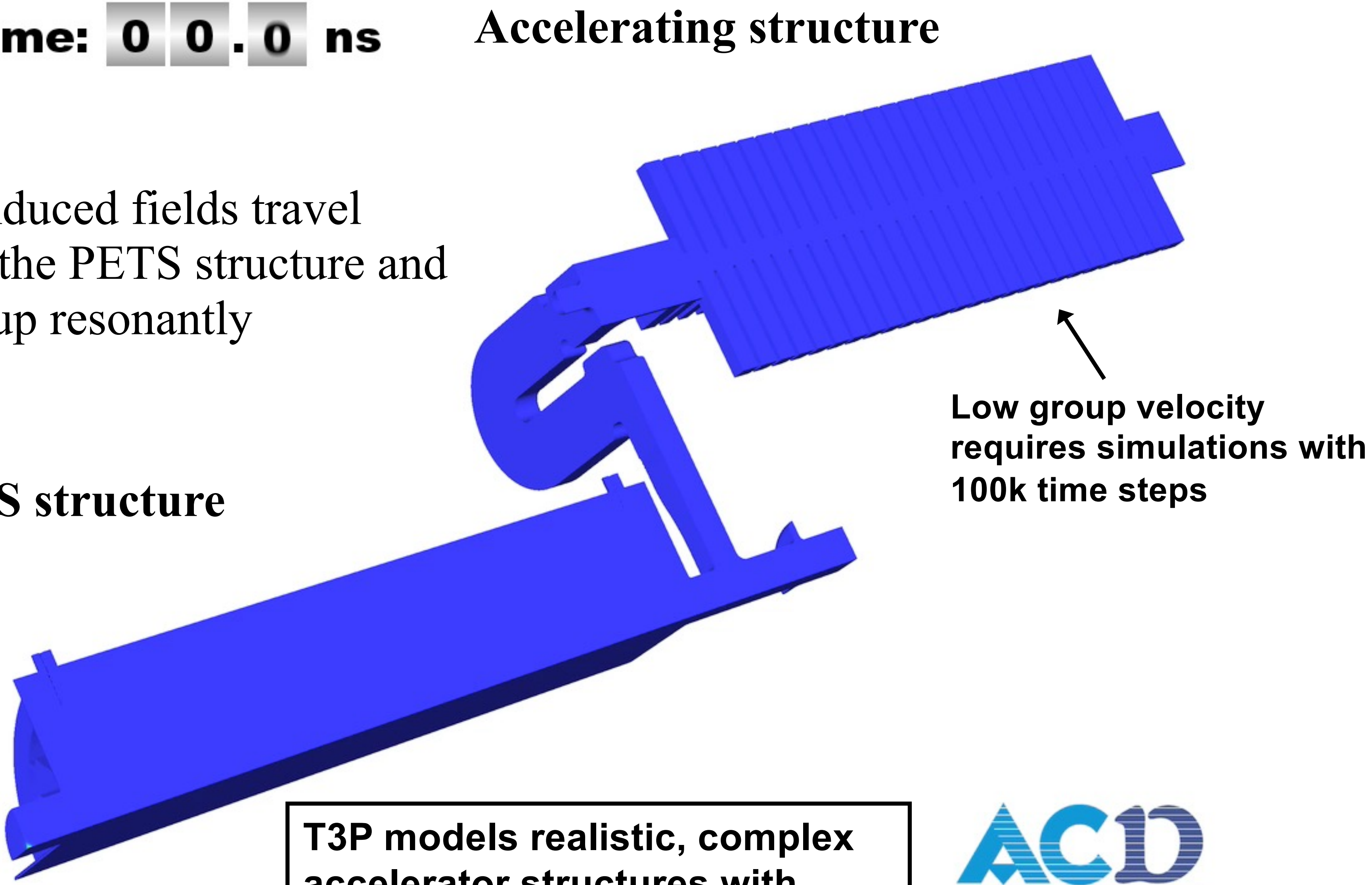
- Goal: 3 10^{-7}/m
  breakdowns
  at 100 MV/m loaded gradient
  at 230 ns pulse length
- latest prototypes (T24 and TD24) tested (SLAC and KEK)
- => TD24 reach up to 108 MV/m
  at nominal CLIC breakdown rate
  (without damping material)
- Undamped T24 reaches 120MV/m



Simulation of RF Power Transfer

time: 0 0 . 0 ns

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



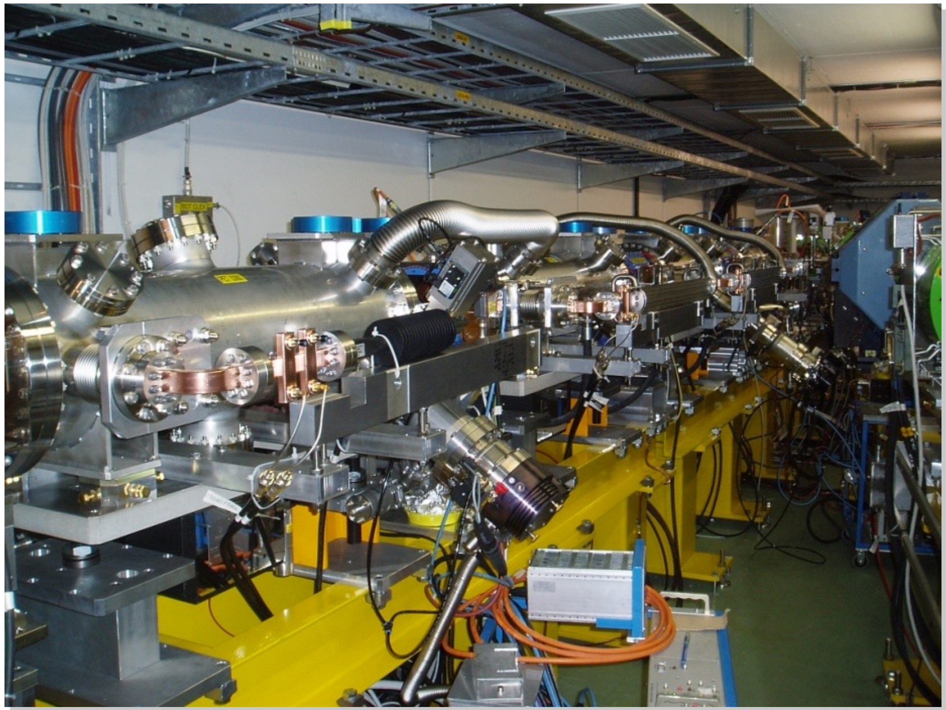
T3P models realistic, complex accelerator structures with unprecedented accuracy

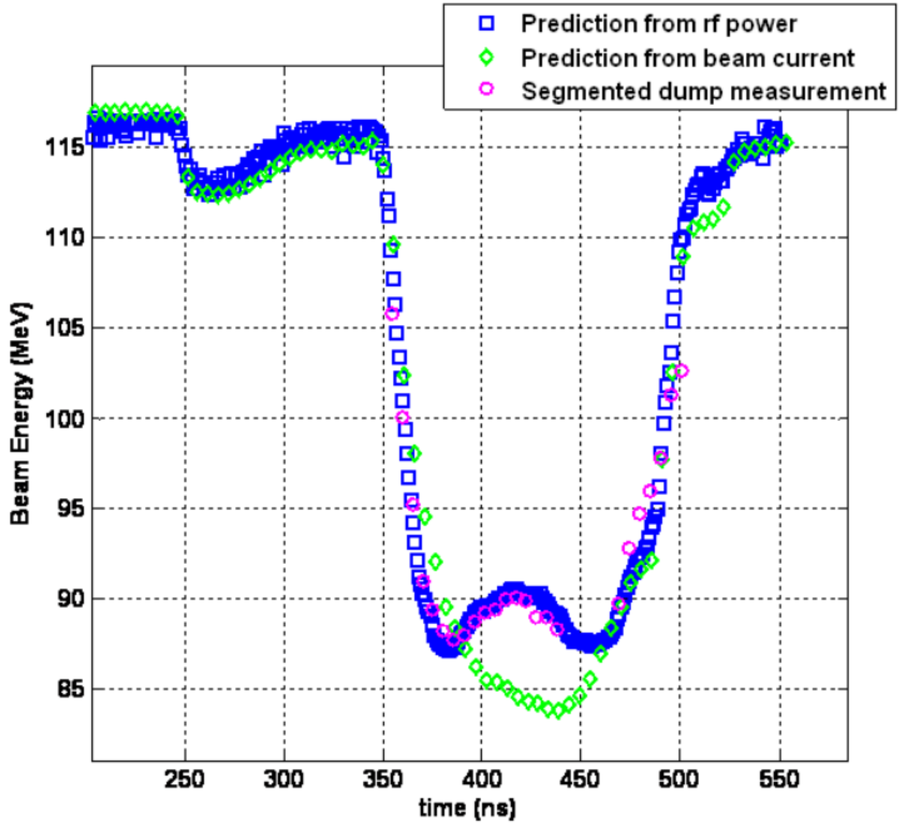
ADVANCED COMPUTATIONS

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

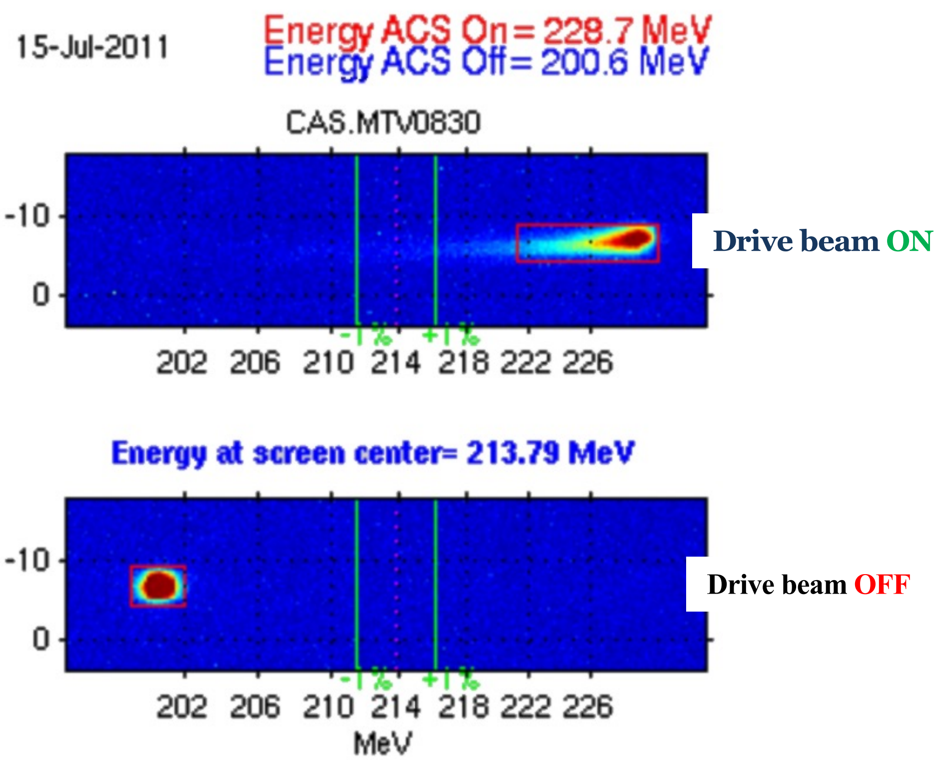


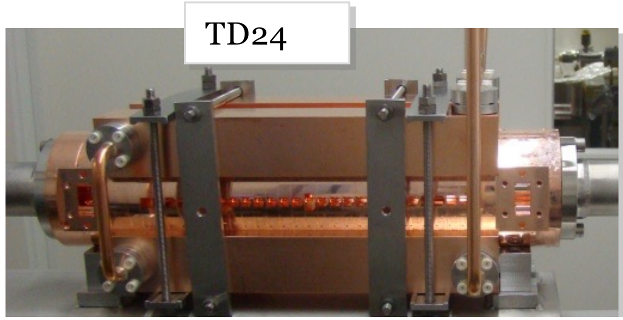


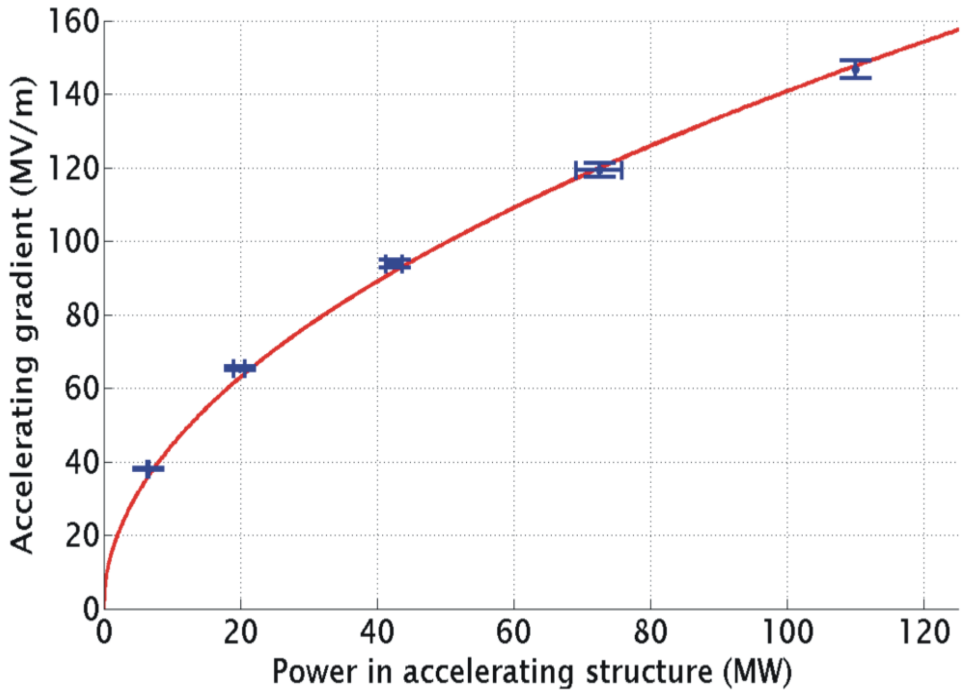
Achieved Two-Beam Acceleration

- Maximum probe beam acceleration measured: 31 MeV

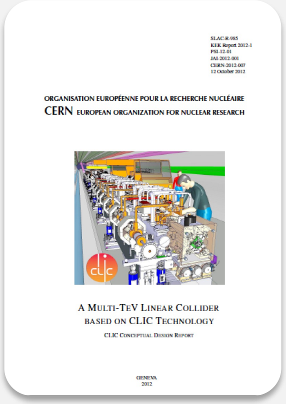
  => Corresponding to a gradient of 145 MV/m







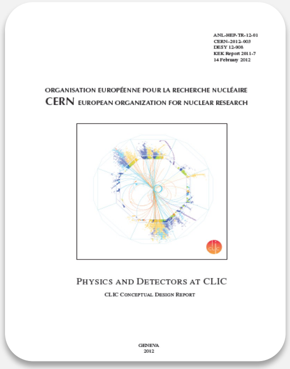
CLIC CDRs published 2012



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

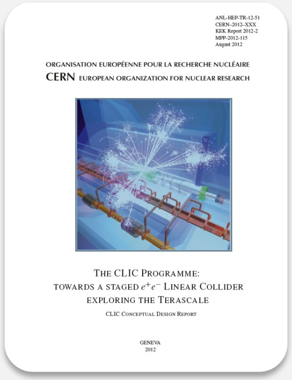
- CLIC concept with exploration over multi-TeV energy range up to 3 TeV
- Feasibility study of CLIC parameters optimized at 3 TeV (most demanding)
- Consider also 500 GeV, and intermediate energy range
- Complete, presented in SPC in March 2011, in print: https://edms.cern.ch/document/1234244/

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)

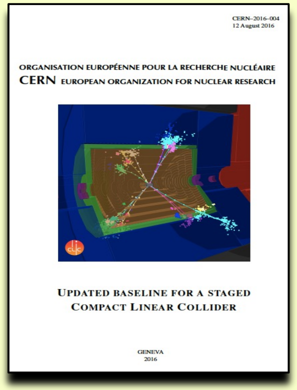
- Physics at a multi-TeV CLIC machine can be measured with high precision, despite challenging background conditions
- External review procedure in October 2011
- Completed and printed, presented in SPC in December 2011 http://arxiv.org/pdf/1202.5940v1



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

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)
- Snowmass white paper (March 22) : https://arxiv.org/abs/2203.09186

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 former ILC schools http://agenda.linearcollider.org/event/6906 or http://agenda.linearcollider.org/event/7333
- Some nice animations for CLIC on http://clic.cern

LCWS 2024
8–11 July 2024, Tokyo, Japan
https://agenda.linearcollider.org/event/10134/