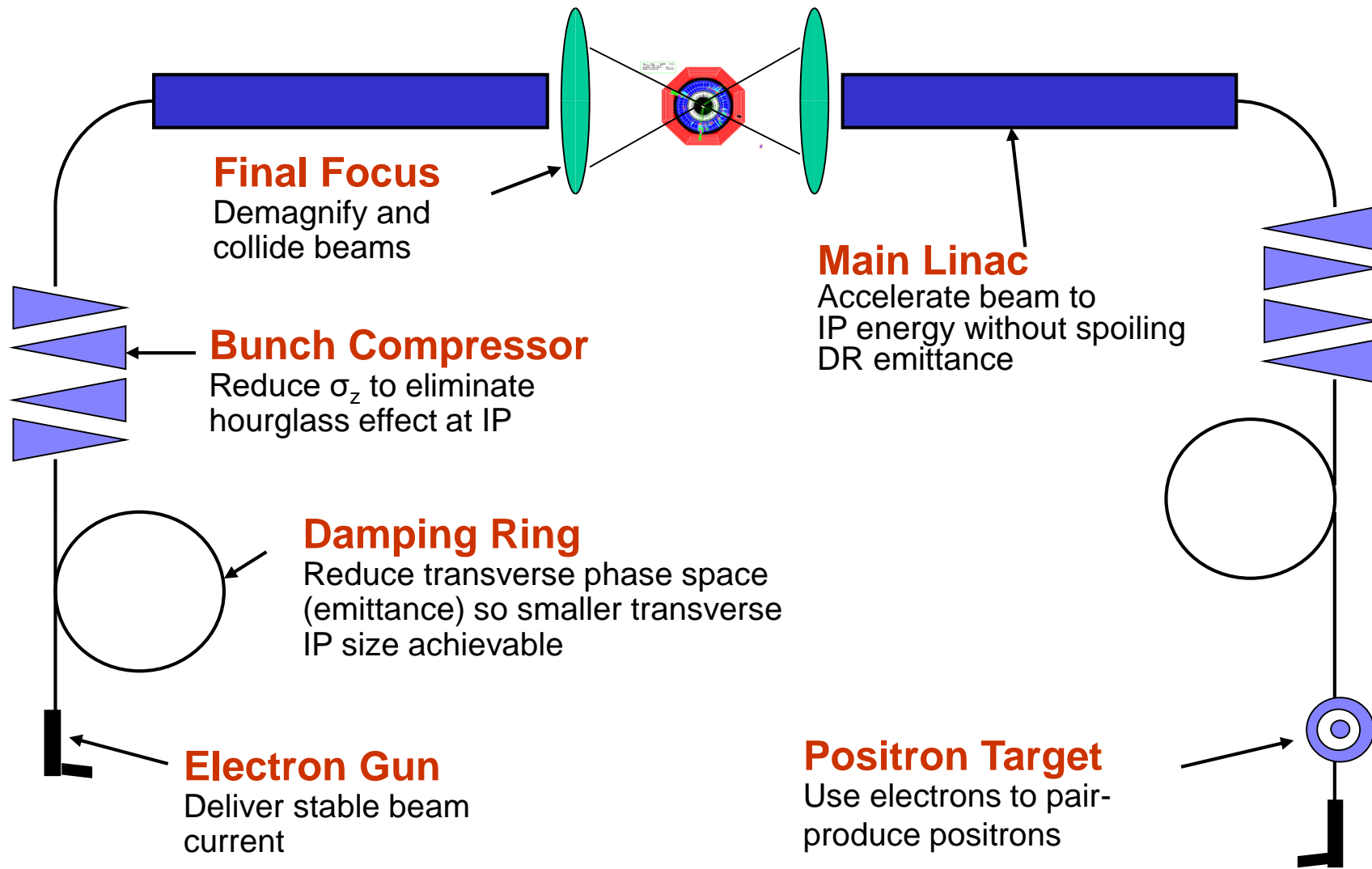# Linear Colliders Lecture 4

Frank Tecker – CERN

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

Generic Linear Collider

Final Focus
Demagnify and collide beams

Bunch Compressor
Reduce σ_z to eliminate hourglass effect at IP

Main Linac
Accelerate beam to IP energy without spoiling DR emittance

Damping Ring
Reduce transverse phase space (emittance) so smaller transverse IP size achievable

Electron Gun
Deliver stable beam current

Positron Target
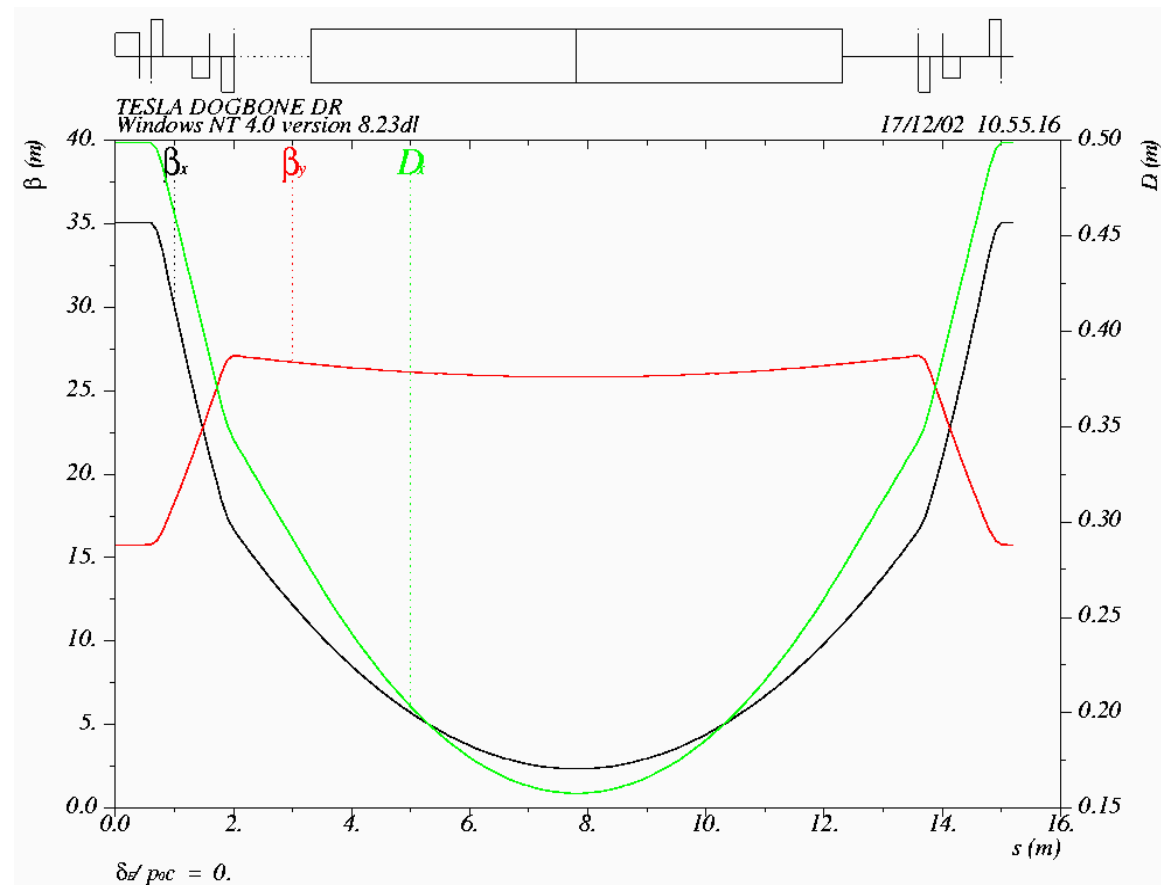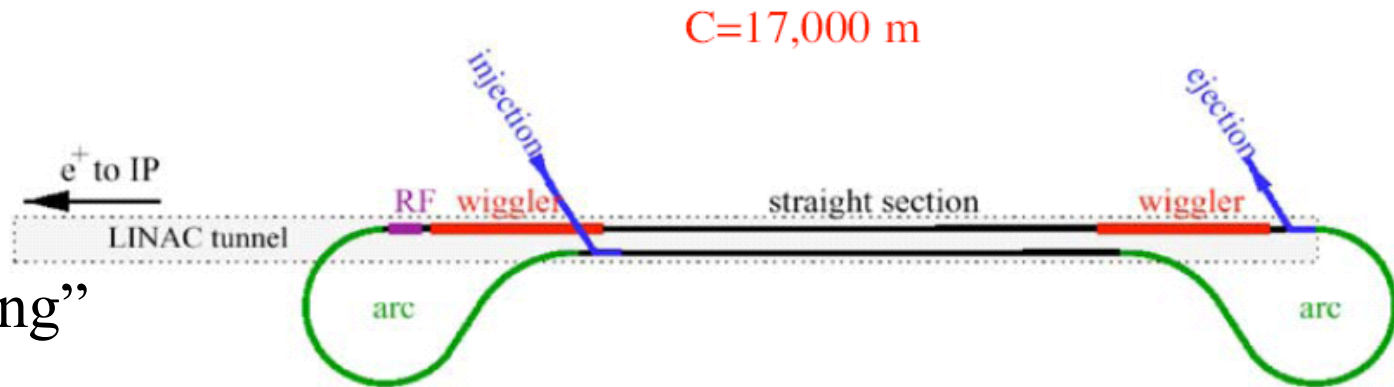Use electrons to pair-produce positrons

C.Pagani

- We have seen the different sub-systems in the previous lectures

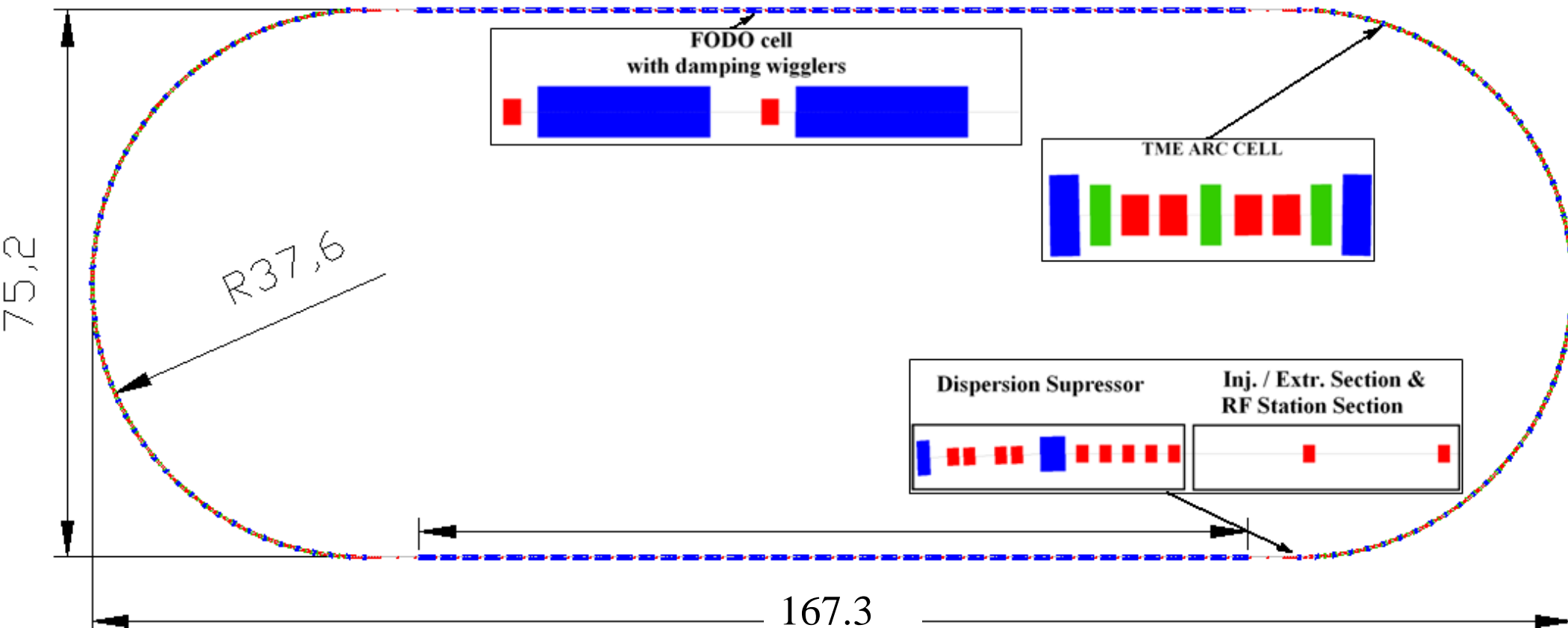- Now let's look at some differences in the real designs…

- **SC** allows long pulse, **NC** needs short pulse with smaller bunch charge
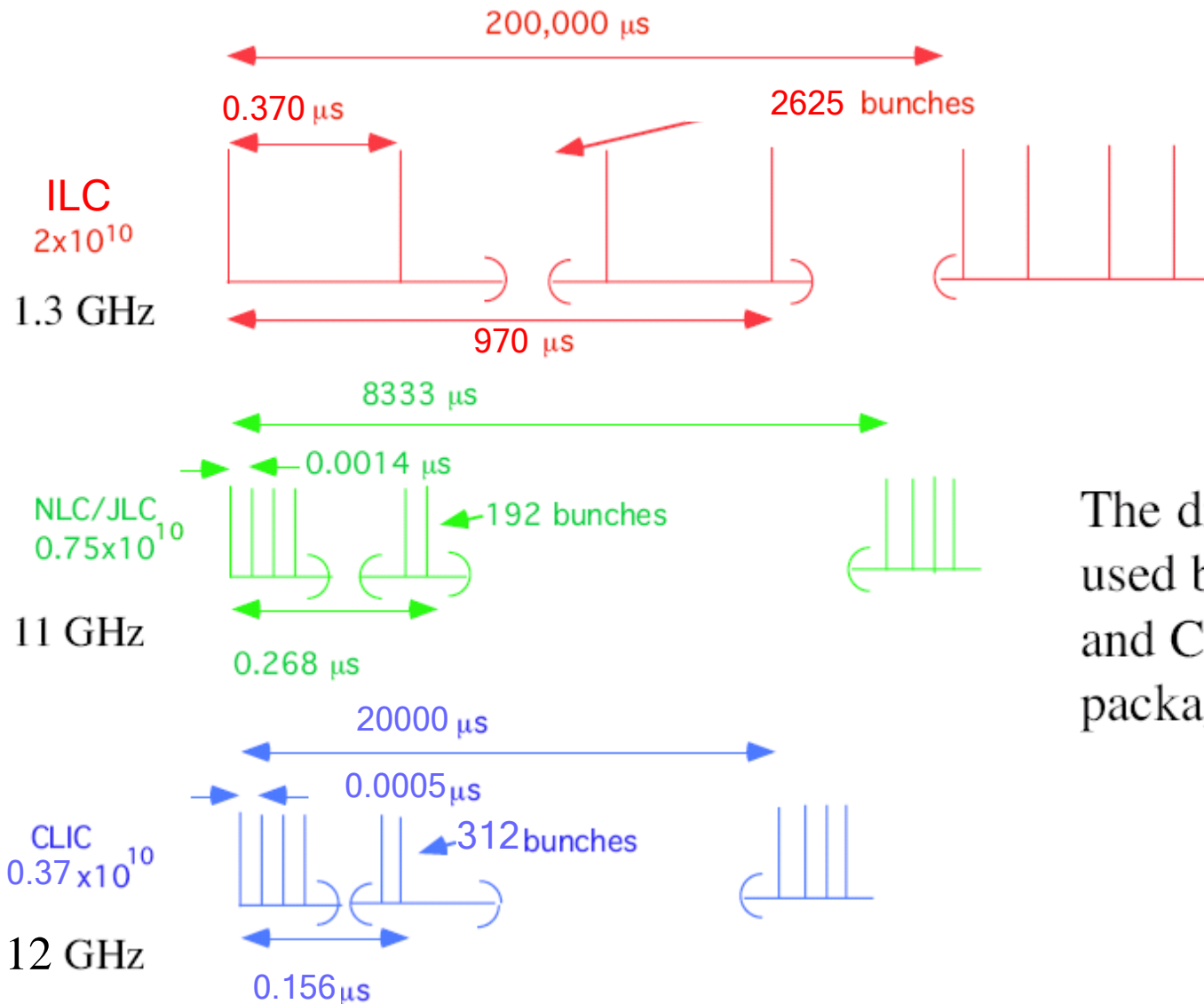
The different RF technologies used by ILC , NLC/JLC and CLIC require different packaging for the beam power

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

C=17,000 m

injection

e⁺ to IP

LINAC tunnel   RF wiggler   straight section   wiggler   ejection

arc   arc

TESLA DOGBONE DR
Windows NT 4.0 version 8.23dl   17/12/02 10.55.16

β (m) β_x β_y D_x D (m)

δ_z/p_0c = 0.

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)
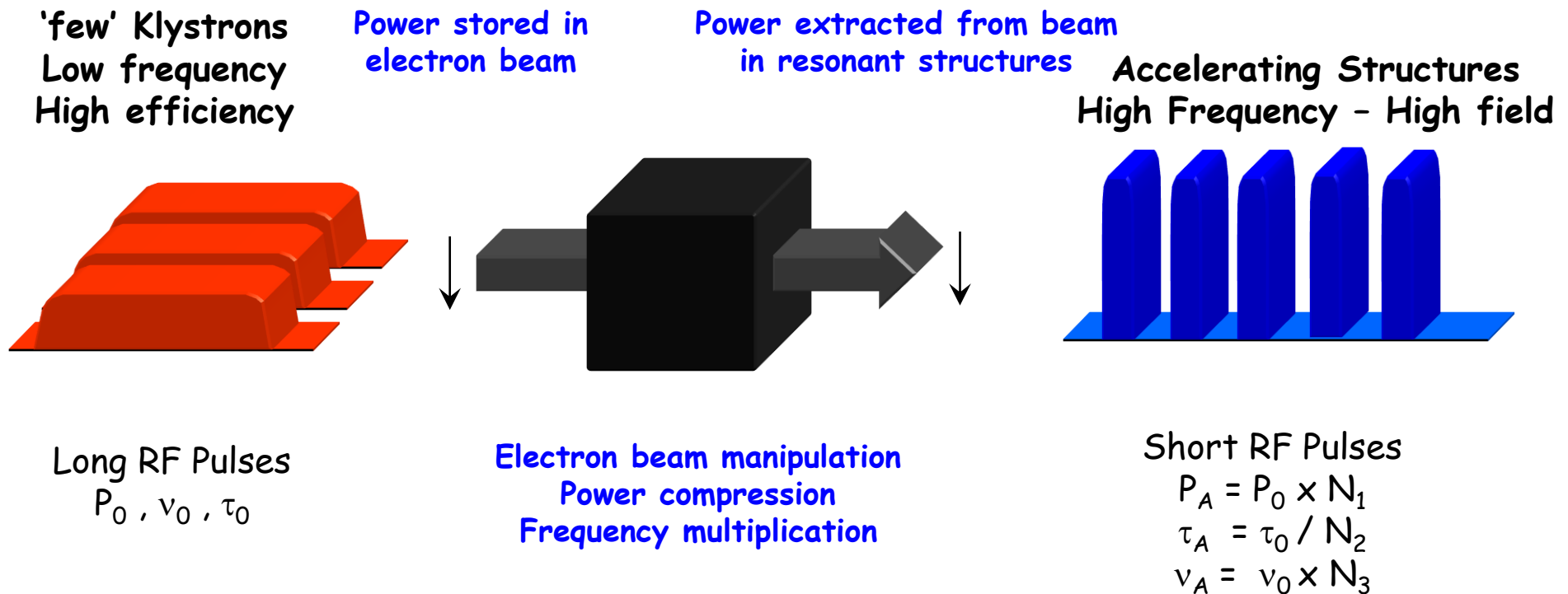   - 26 Damping wiggler FODO cells in the long straight sections

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 ☹
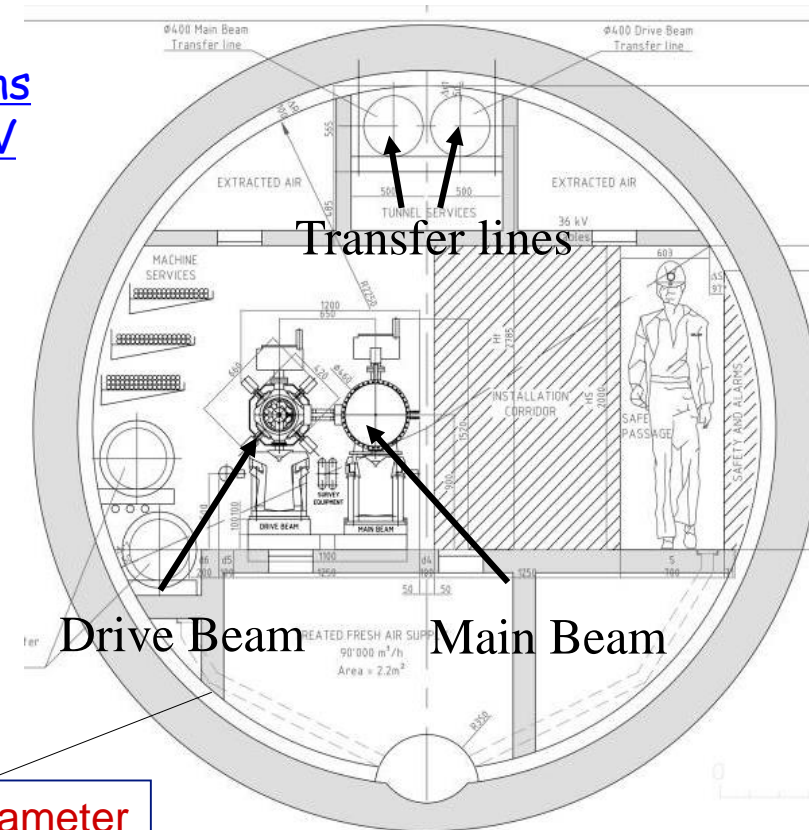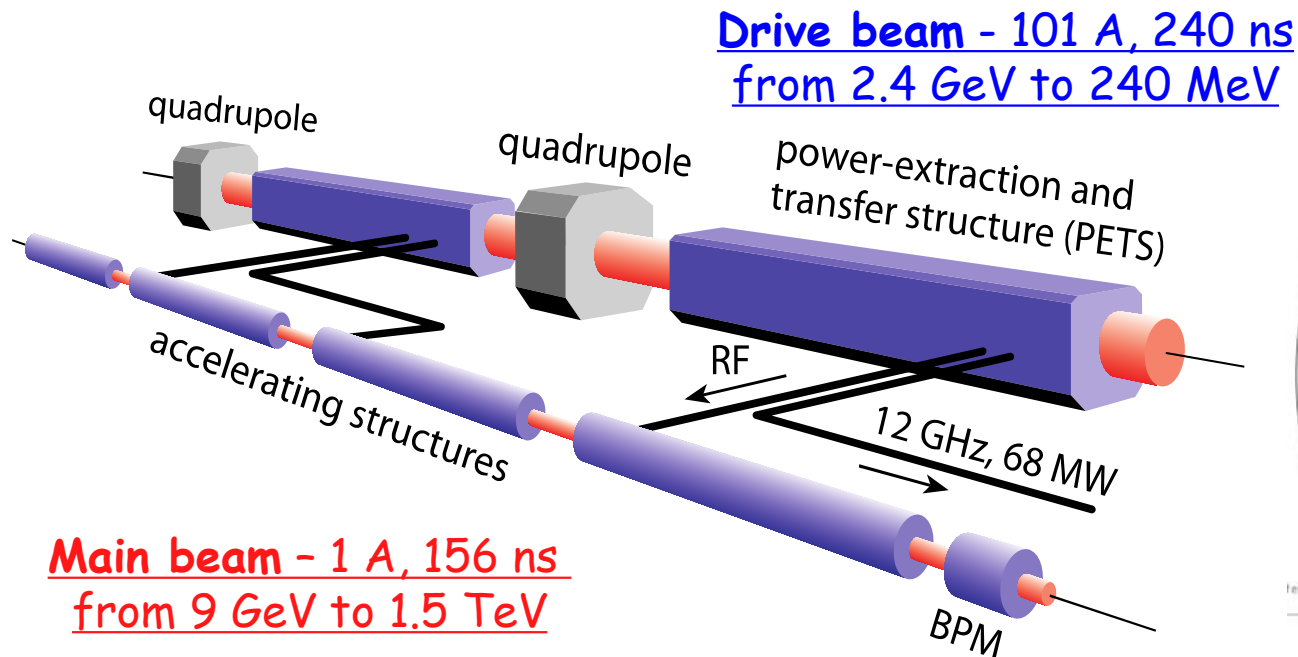
- Small bunch distance ☹

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 ($\sum_y$ dilution) ☹

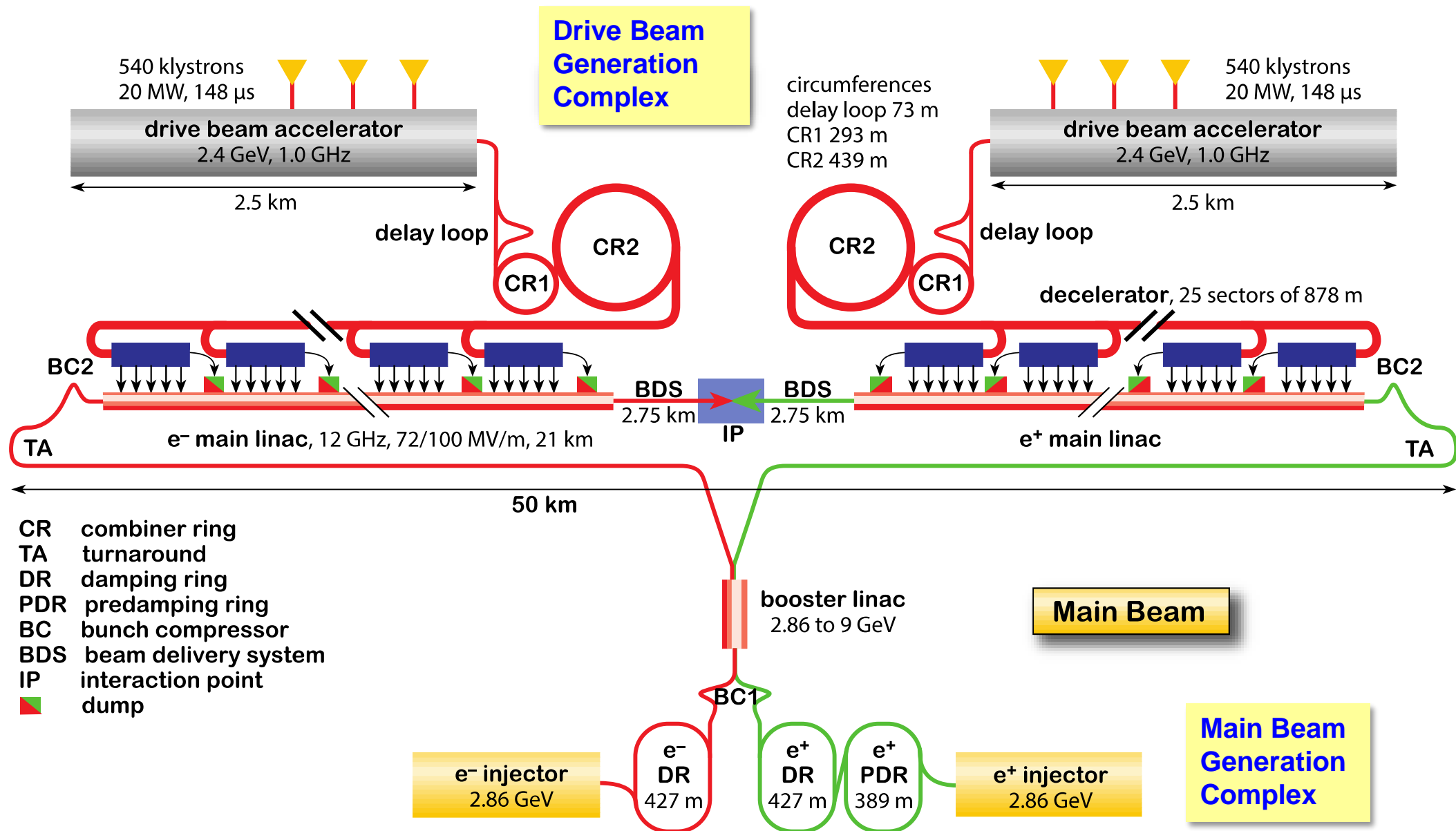- Large number of e+ per pulse ☹

- very large DR ☹

CLIC scheme

- **Very high gradients** (>100 MV/m) possible with NC accelerating structures at high RF frequencies (30 GHz $\rightarrow$ 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

Drive beam - 101 A, 240 ns from 2.4 GeV to 240 MeV

quadrupole

quadrupole

power-extraction and transfer structure (PETS)

accelerating structures

RF

12 GHz, 68 MW

Main beam – 1 A, 156 ns from 9 GeV to 1.5 TeV

BPM

Transfer lines

Drive Beam

Main Beam

5.6 m diameter

CLIC – overall layout – 3 TeV

Drive Beam Generation Complex

540 klystrons
20 MW, 148 µs

drive beam accelerator
2.4 GeV, 1.0 GHz

2.5 km

circumferences
delay loop 73 m
CR1 293 m
CR2 439 m

540 klystrons
20 MW, 148 µs

drive beam accelerator
2.4 GeV, 1.0 GHz

2.5 km

delay loop

CR2

CR1

CR2

CR1

delay loop

decelerator, 25 sectors of 878 m

BC2

BC2

BDS
2.75 km

BDS
2.75 km

IP

TA

TA

e⁻ main linac, 12 GHz, 72/100 MV/m, 21 km

e⁺ main linac

50 km

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

booster linac
2.86 to 9 GeV

Main Beam

BC1

Main Beam Generation Complex

e⁻ injector
2.86 GeV

e⁻
DR
427 m

e⁺
DR
427 m

e⁺
PDR
389 m

e⁺ injector
2.86 GeV

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)
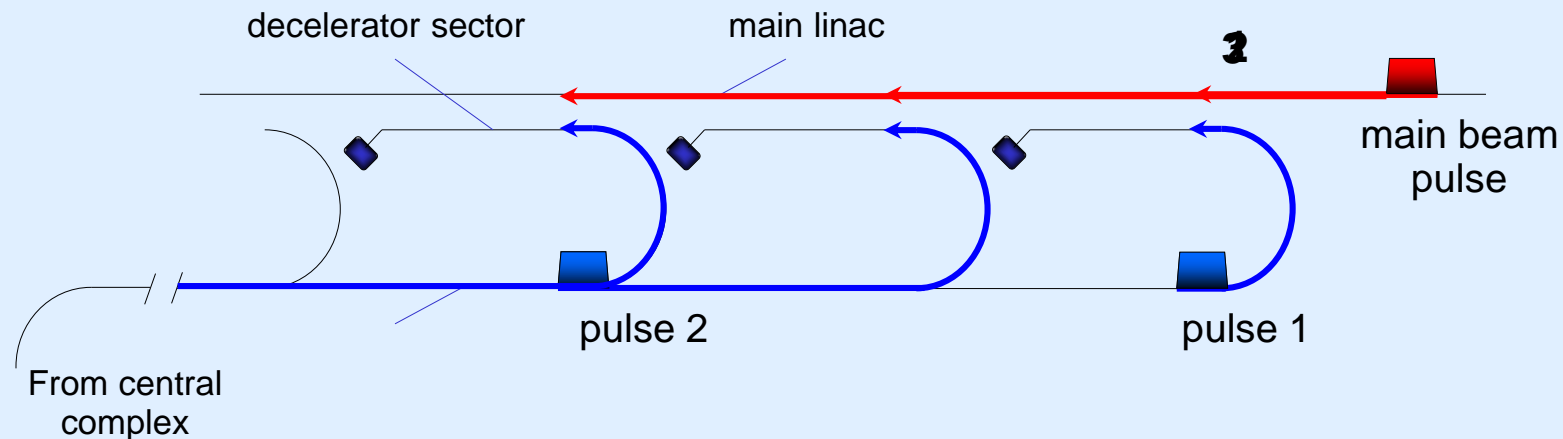
Counter flow distribution allows to power different sectors of the main linac with different time bins of a single long electron drive beam pulse
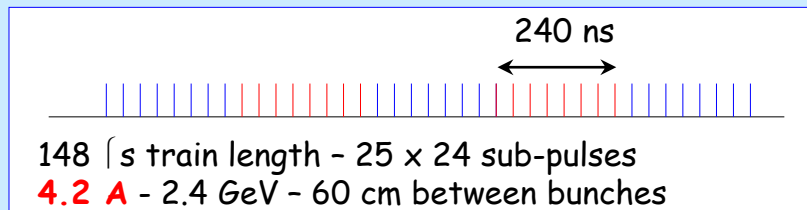
The distance between the pulses is 2 L_s = 2 L_{main}/N_S (L_{main}= single side linac length)

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 Accelerator
efficient acceleration in fully loaded linac

Delay Loop x 2
gap creation, pulse compression & frequency multiplication

■ **RF Transverse Deflectors**

Combiner Ring x 3
pulse compression & frequency multiplication

Combiner Ring x 4
pulse compression & frequency multiplication

CLIC RF POWER SOURCE LAYOUT

Drive Beam Decelerator Section (2 × 25 in total)

Power Extraction

Drive beam time structure - initial

240 ns

148 ⌈s 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 ⌈s

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
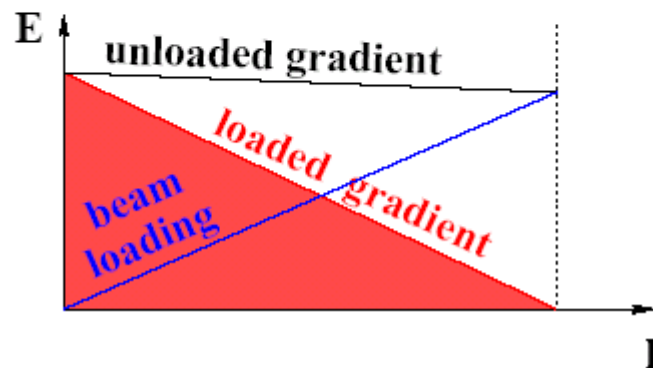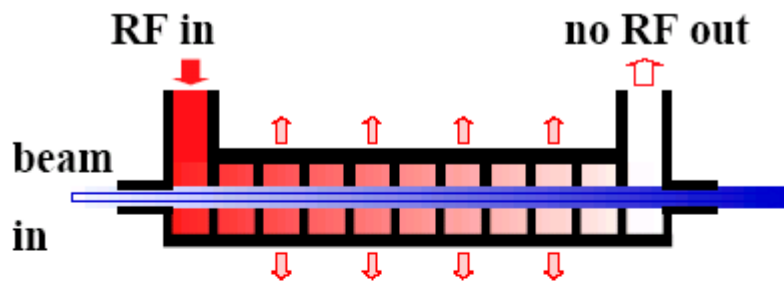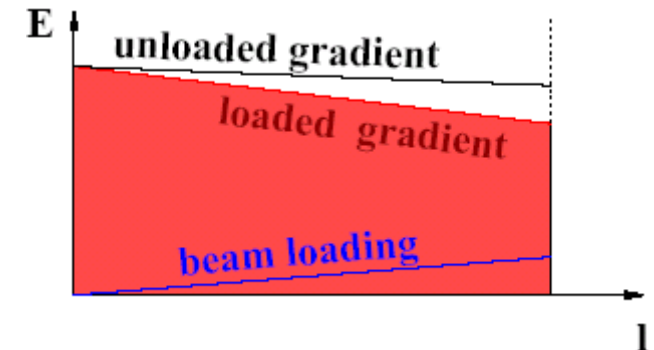
"Efficient" situation:

- 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

Output power from accelerating structure

1.6 µs compressed RF pulse

Beam off ~ 24 MW

Beam on ~ 0 MW

ACS0305 exit

Frequency multiplication
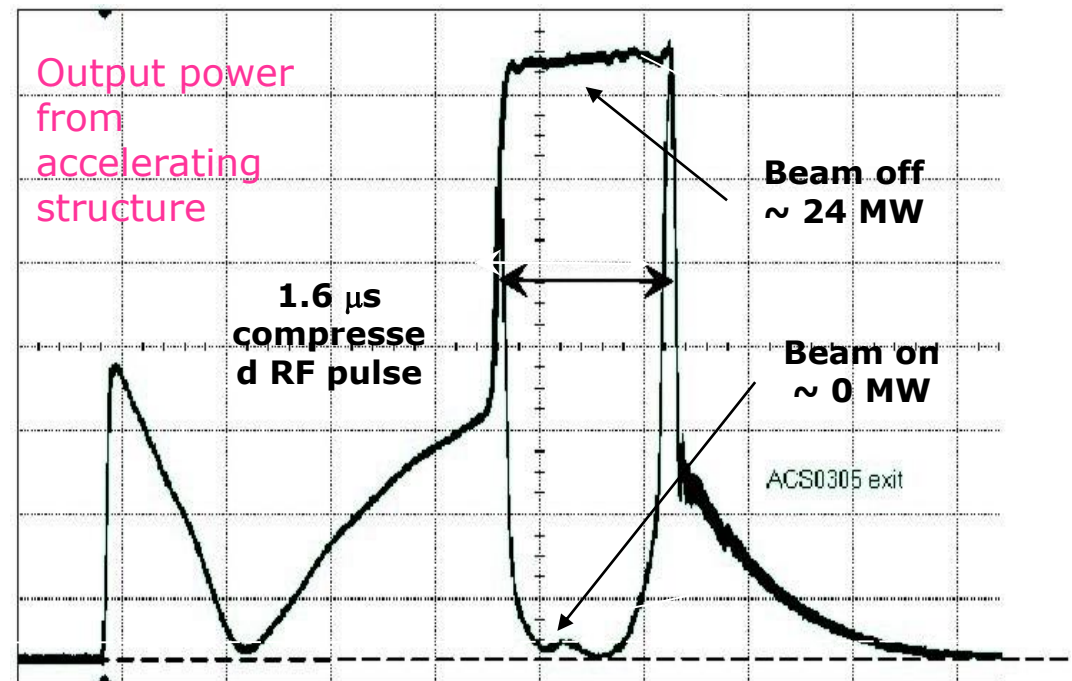
- basic principle of drive beam generation

- transform very long pulses into short pulses with higher power and higher frequency

- use RF deflectors to interleave bunches

  - => double power

  - => double frequency

P_0 , ν_0

Transverse
RF Deflector, ν_0

$2 \times P_0$, $2 \times \nu_0$

P_0 , ν_0

Deflecting
Field

Delay Loop Principle
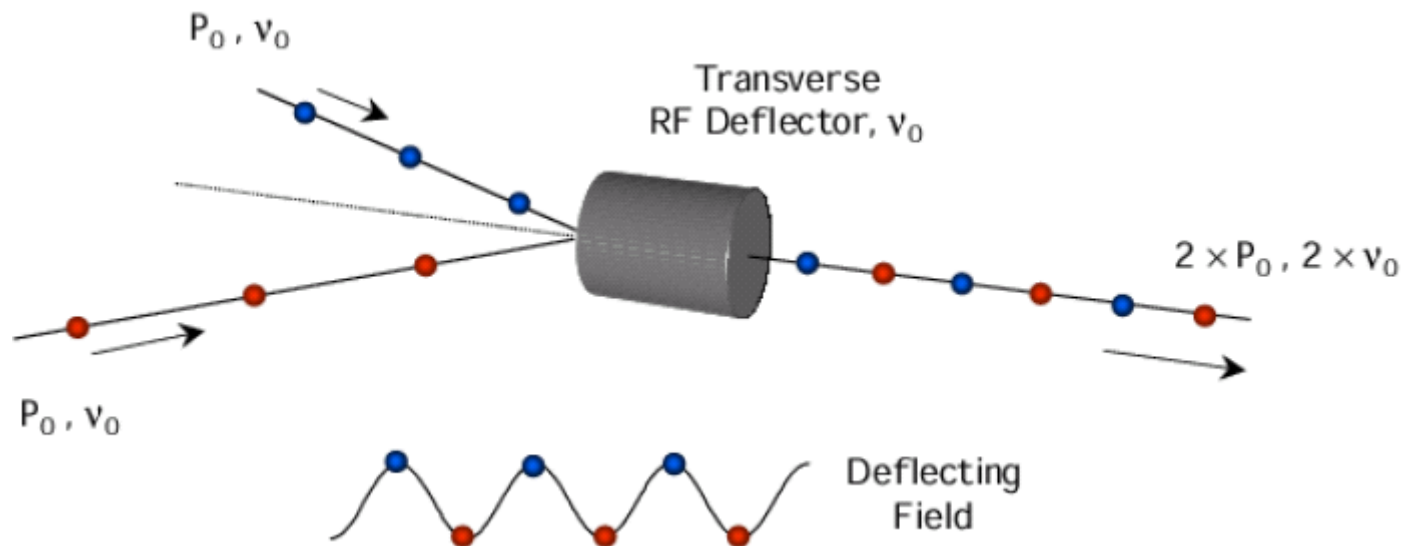
- **double repetition frequency and current**
- parts of bunch train delayed in loop
- RF deflector combines the bunches (f_{defl}=bunch rep. frequency)
- Path length corresponds to beam pulse length
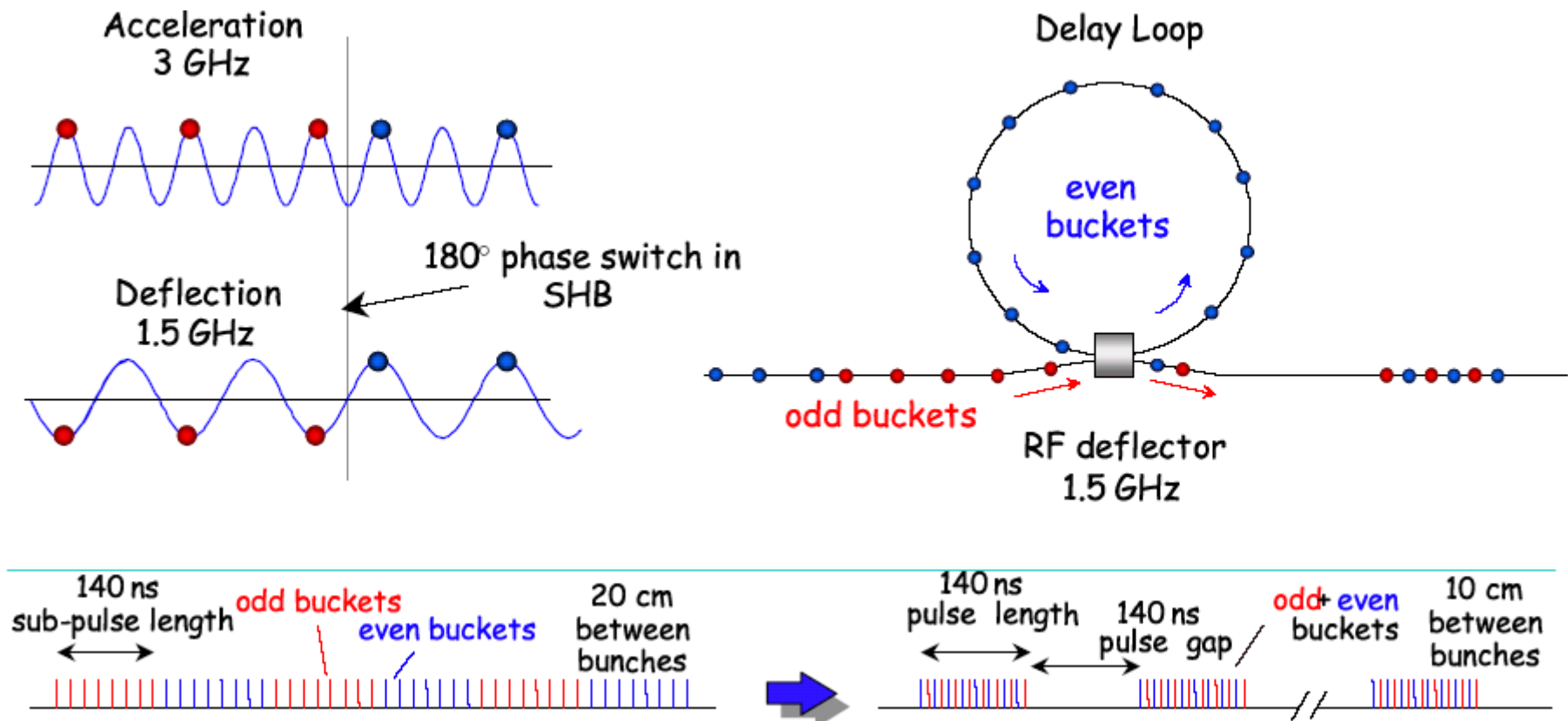
- combination factors up to 5 reachable in a ring

$$C_{ring} = (n + ¼) \angle$$

1st turn

injection line

septum

1st deflector

2nd deflector

local inner orbits

RF deflector field

L_o

2nd
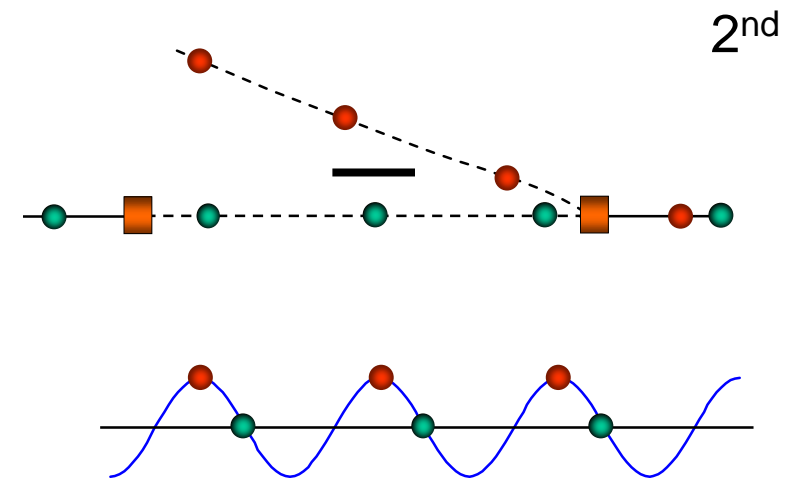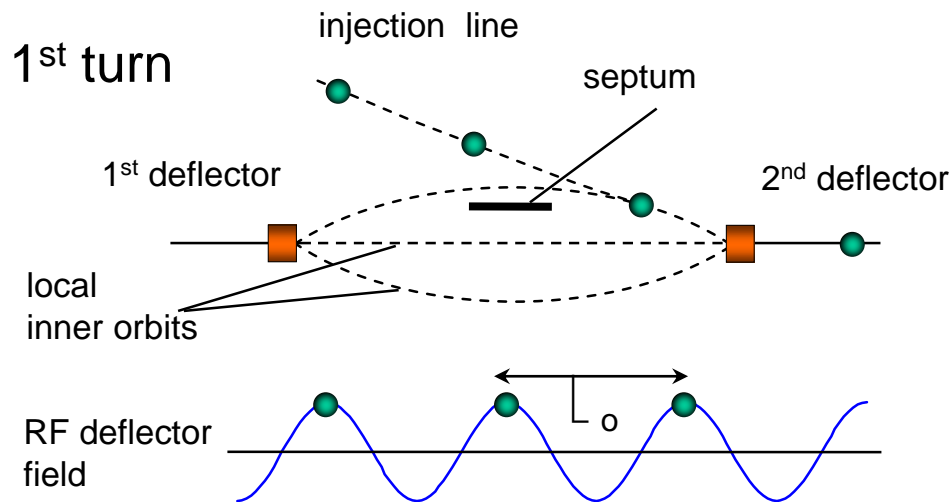
C_{ring} has to correspond to the distance of pulses from the previous combination stage!

3rd

4rd

$L_o/4$
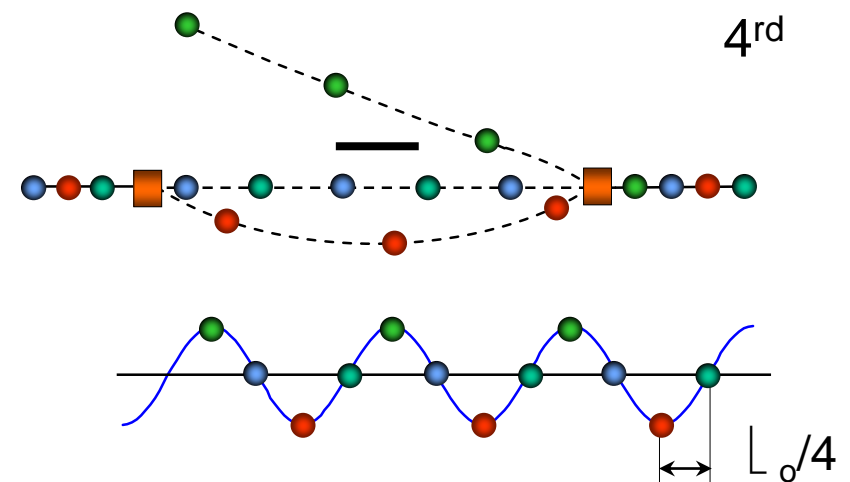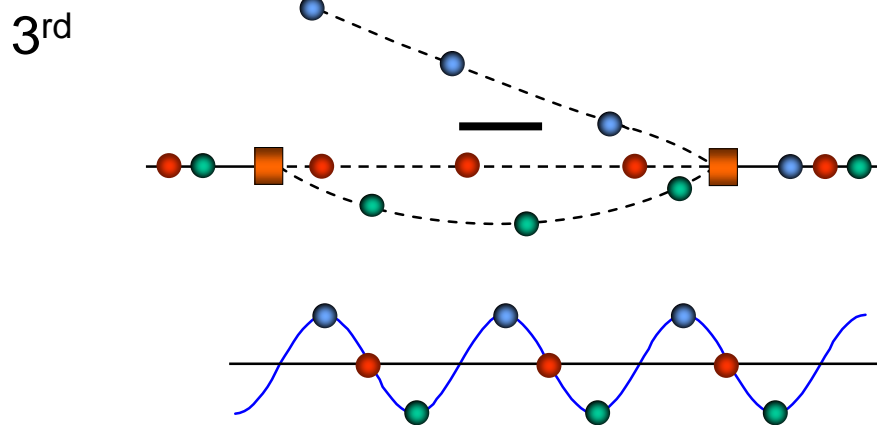
Combination factor 5

5th turn

$\lambda_o/5$ (2 cm)

$\lambda_o = 10$ cm

CTF3 - PRELIMINARY PHASE 2001/2002

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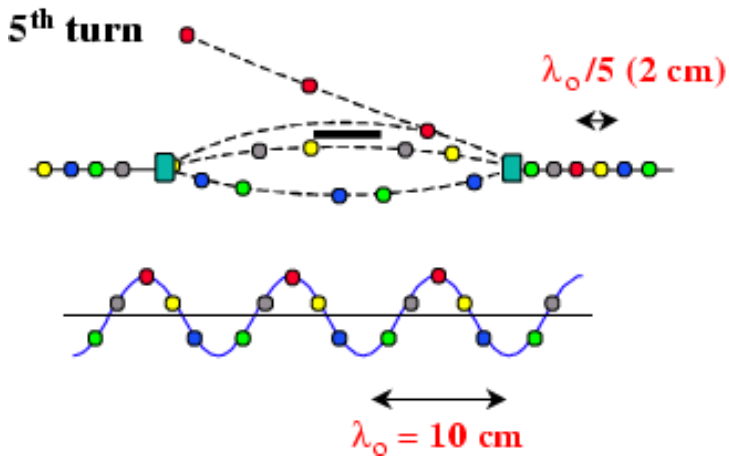
streak camera measurement

RF deflectors

Streak camera image of beam time structure evolution

1st turn

333 ps

2nd

3rd

4th

5th turn   66 ps
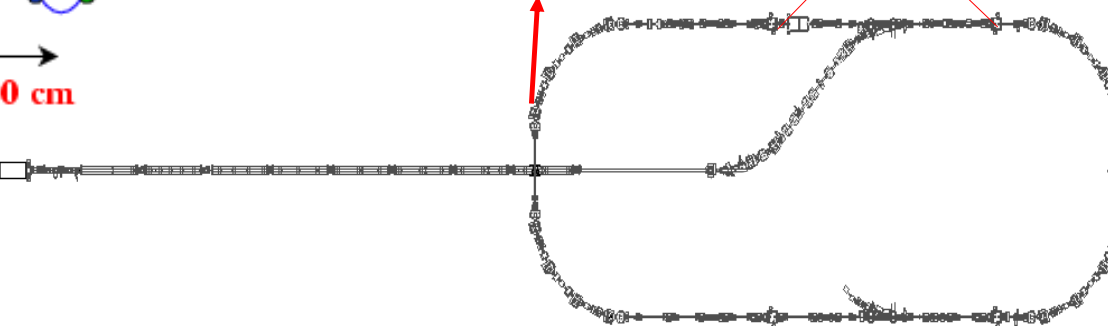
time

Beam time structure in linac

Bunch spacing 333 ps

420 ns
(ring revolution time)
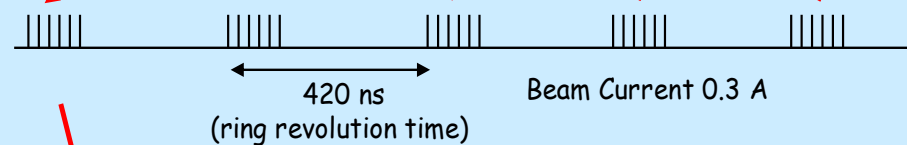
Beam Current 0.3 A

Bunch spacing 66 ps

Beam Current 1.5 A

Beam structure after combination
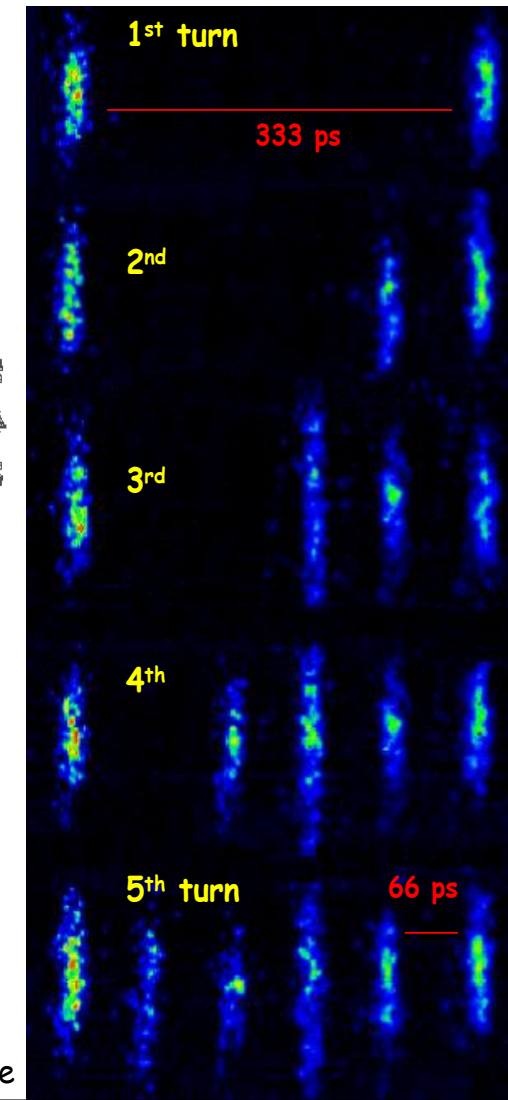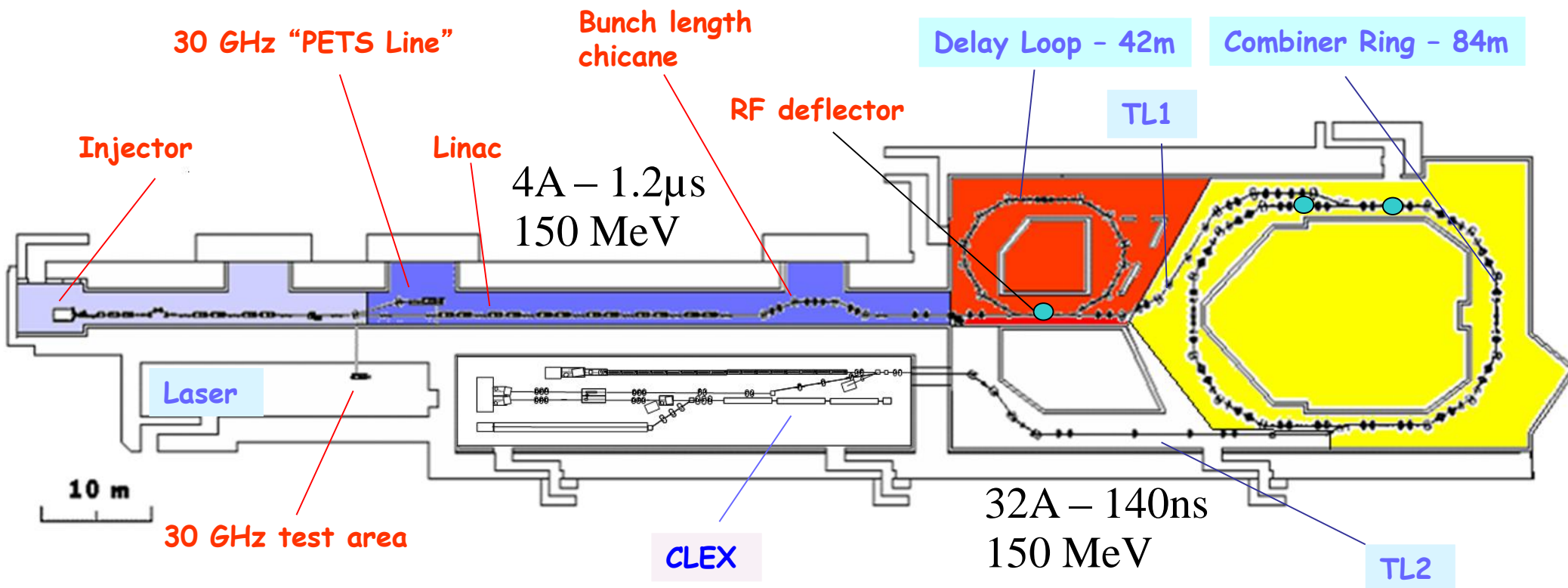
RF injection in combiner ring   Combination factor 4
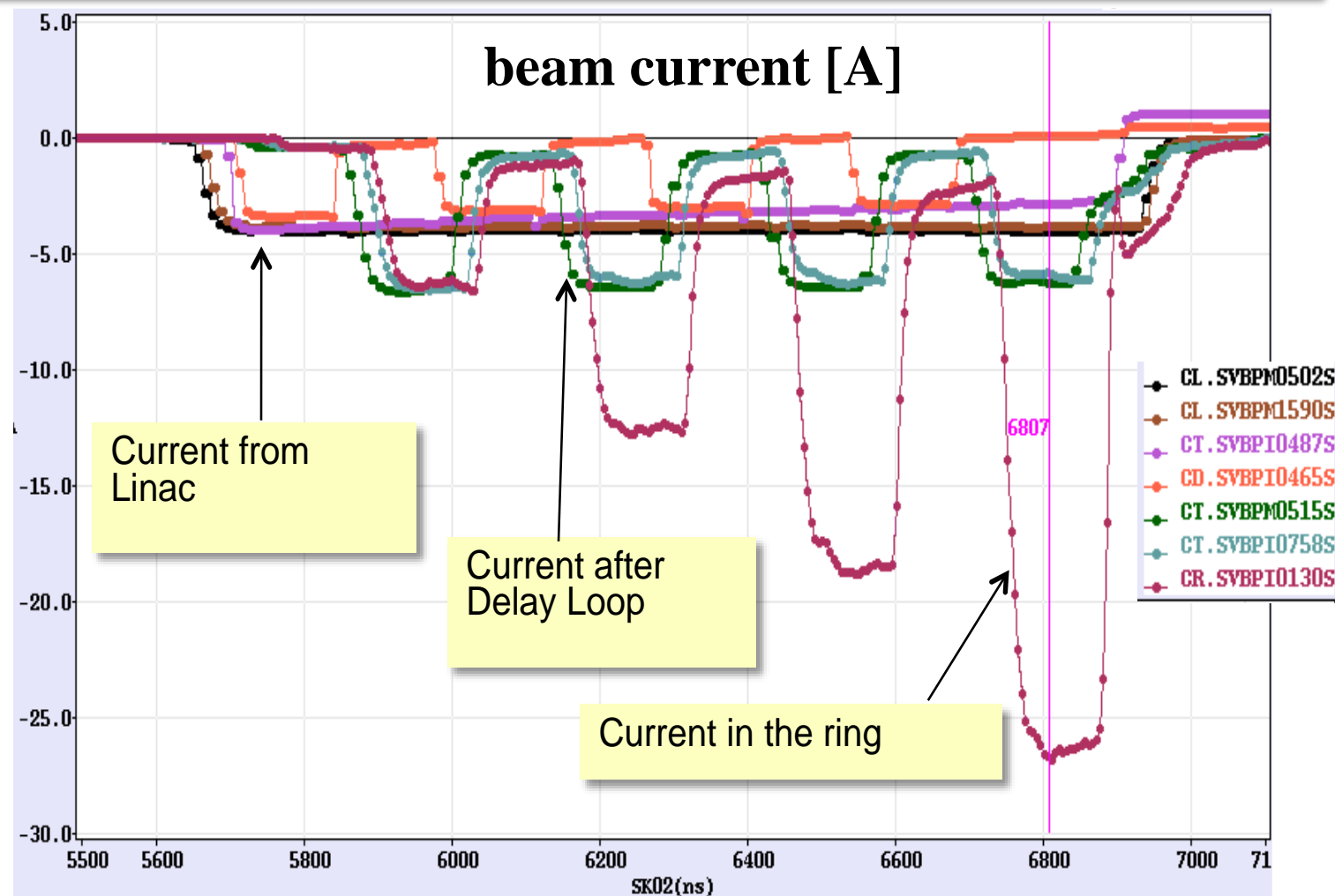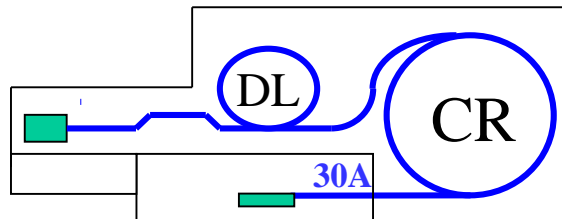

X

83 ps

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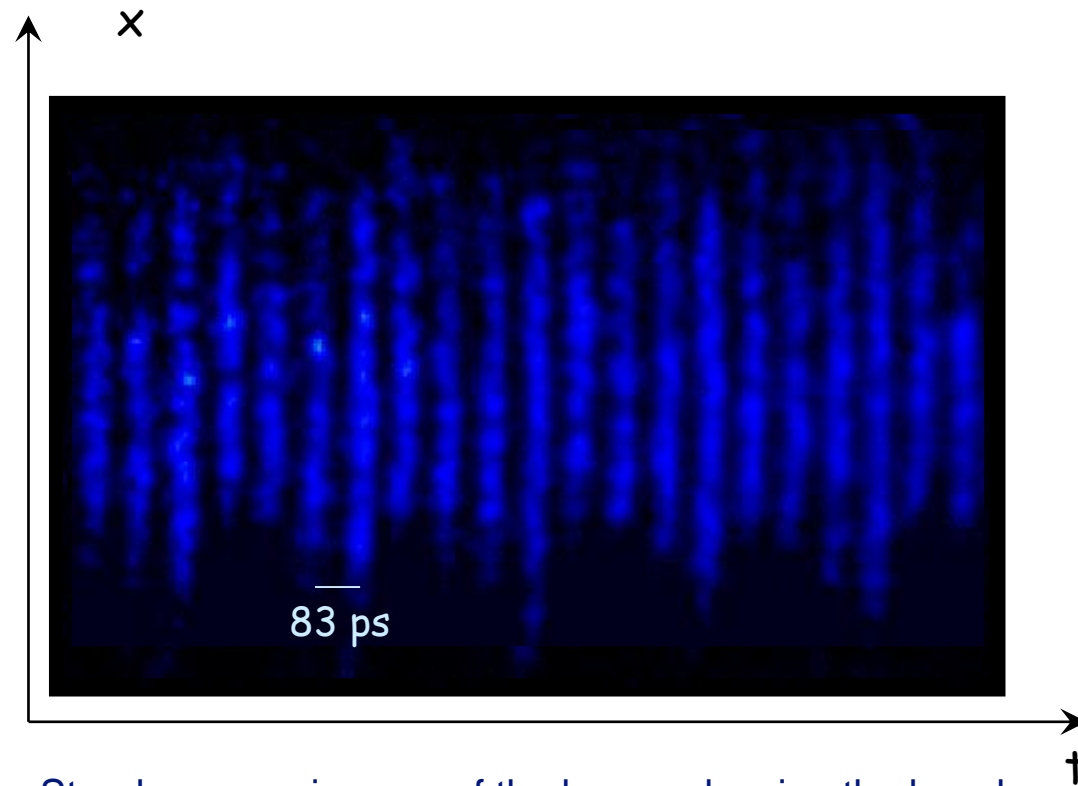
Streak camera images of the beam, showing the bunch combination process

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)

30 GHz "PETS Line"

Bunch length chicane

Delay Loop – 42m

Combiner Ring – 84m

RF deflector

TL1

Injector

Linac

4A – 1.2μs
150 MeV

Laser

10 m

30 GHz test area

CLEX

32A – 140ns
150 MeV

TL2

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**

beam current [A]

Current from Linac

Current after Delay Loop

Current in the ring

CL.SVBPM0502S
CL.SVBPM1590S
CT.SVBPI0487S
CD.SVBPI0465S
CT.SVBPM0515S
CT.SVBPI0758S
CR.SVBPI0130S

SK02(ns)

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

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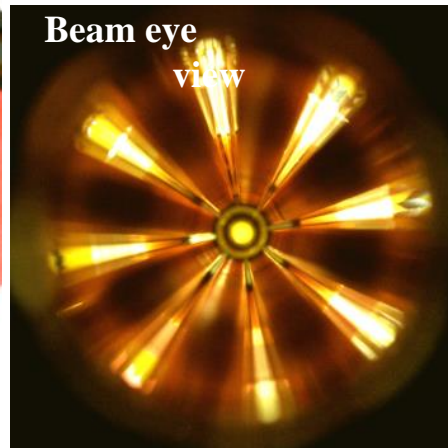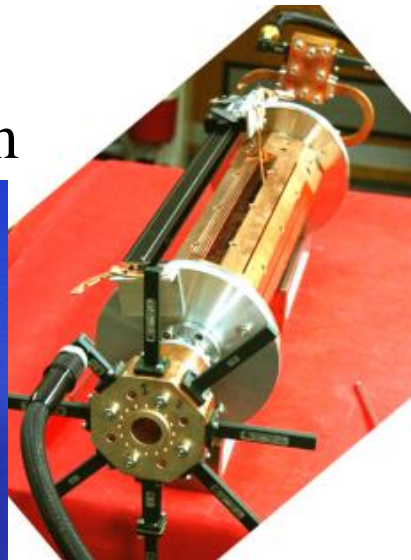
The power produced by the bunched (ω_0) beam in a constant impedance structure:

Design input parameters PETS design

$$P = I^2 L^2 F_b^2 W_0 \frac{R/Q}{4 v_g}$$

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
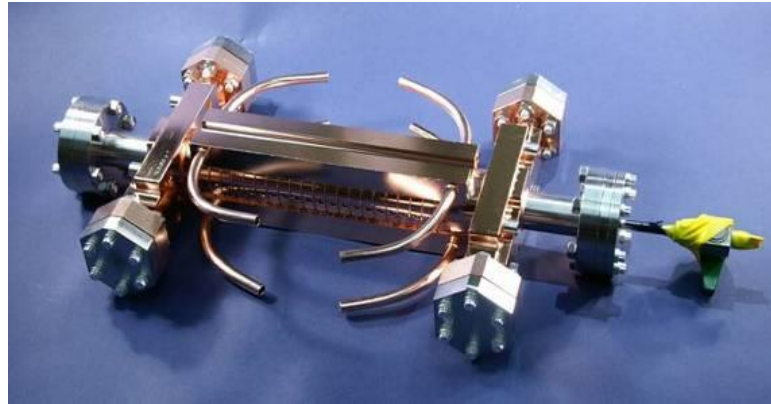
- Goal: 3×10^{-7}/m breakdowns at 100 MV/m loaded gradient at 230 ns pulse length

- latest prototypes (T24 and TD24) tested (SLAC and KEK)

- => TD24 reach up to 108 MV/m at nominal CLIC breakdown rate (without damping material)
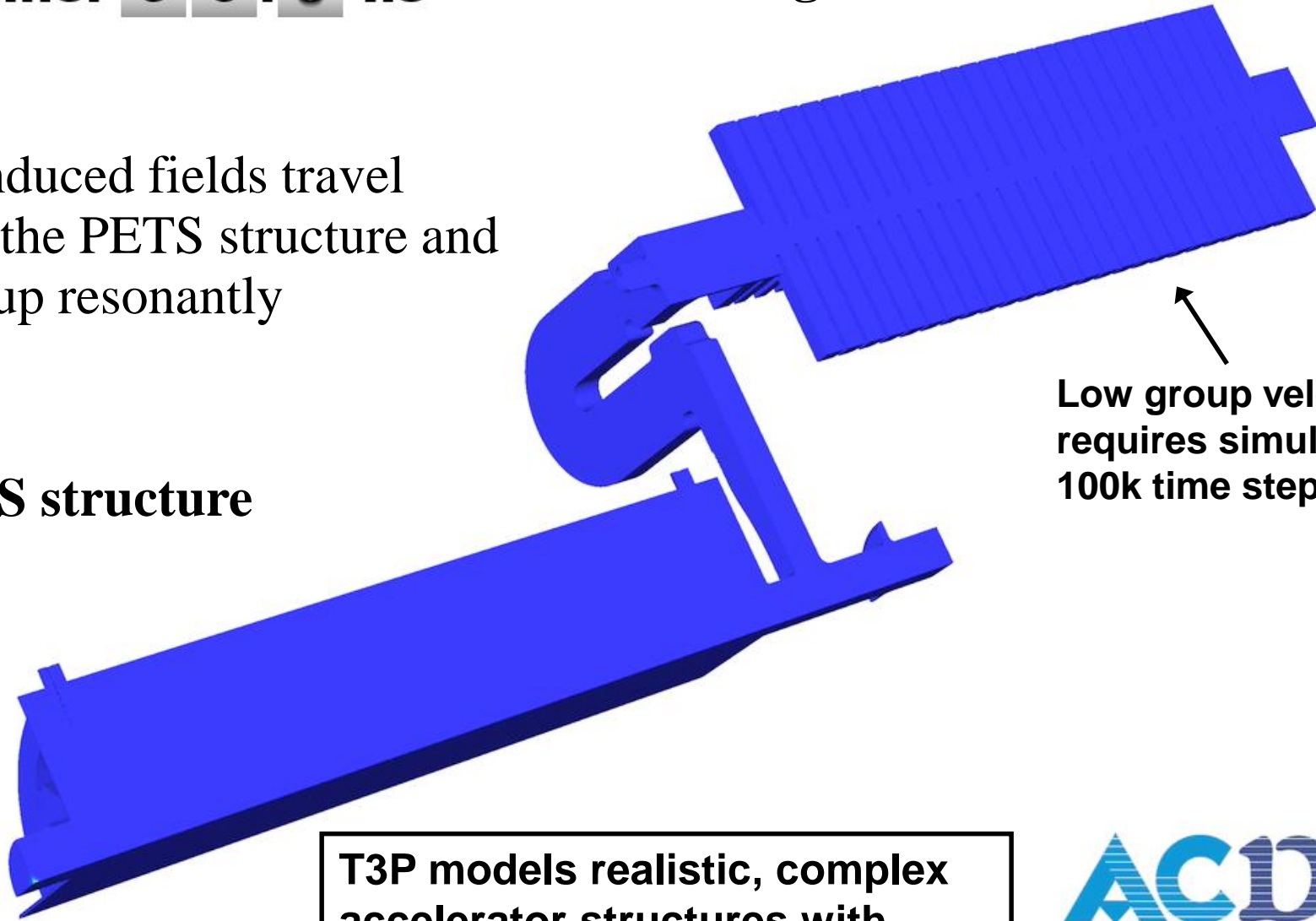
- Undamped T24 reaches 120MV/m

Simulation of RF Power Transfer
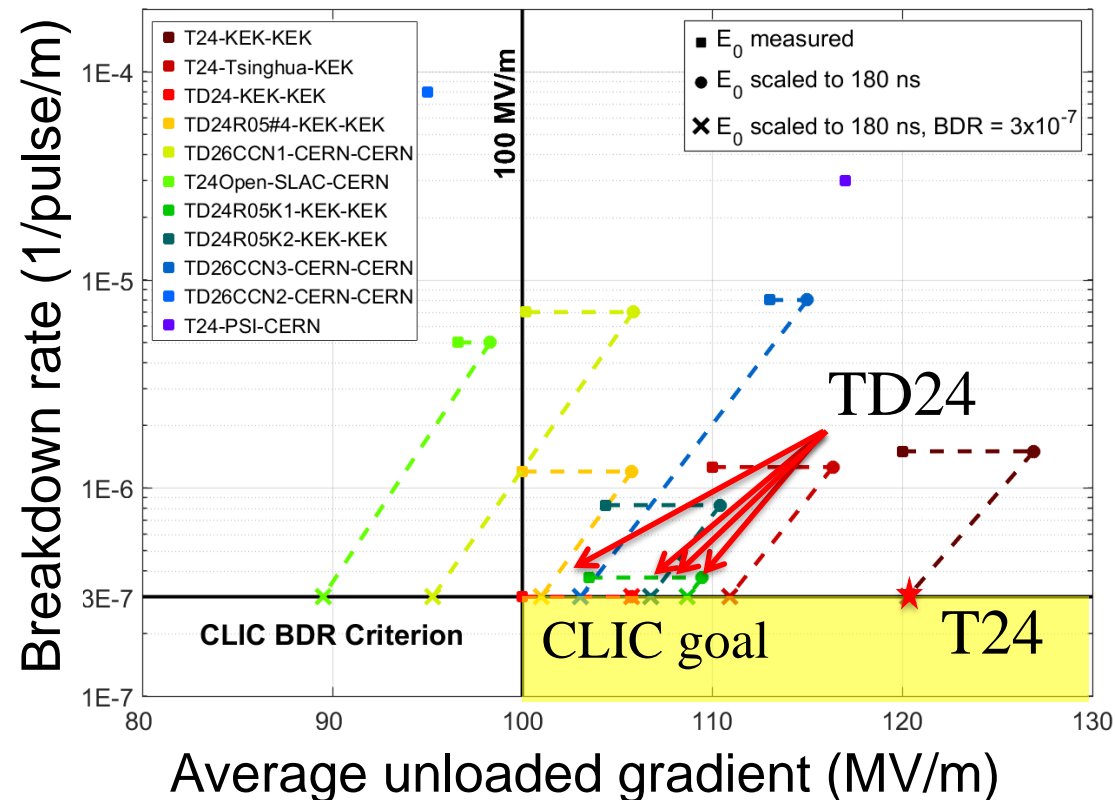
time: **0 0.0** ns

Accelerating structure

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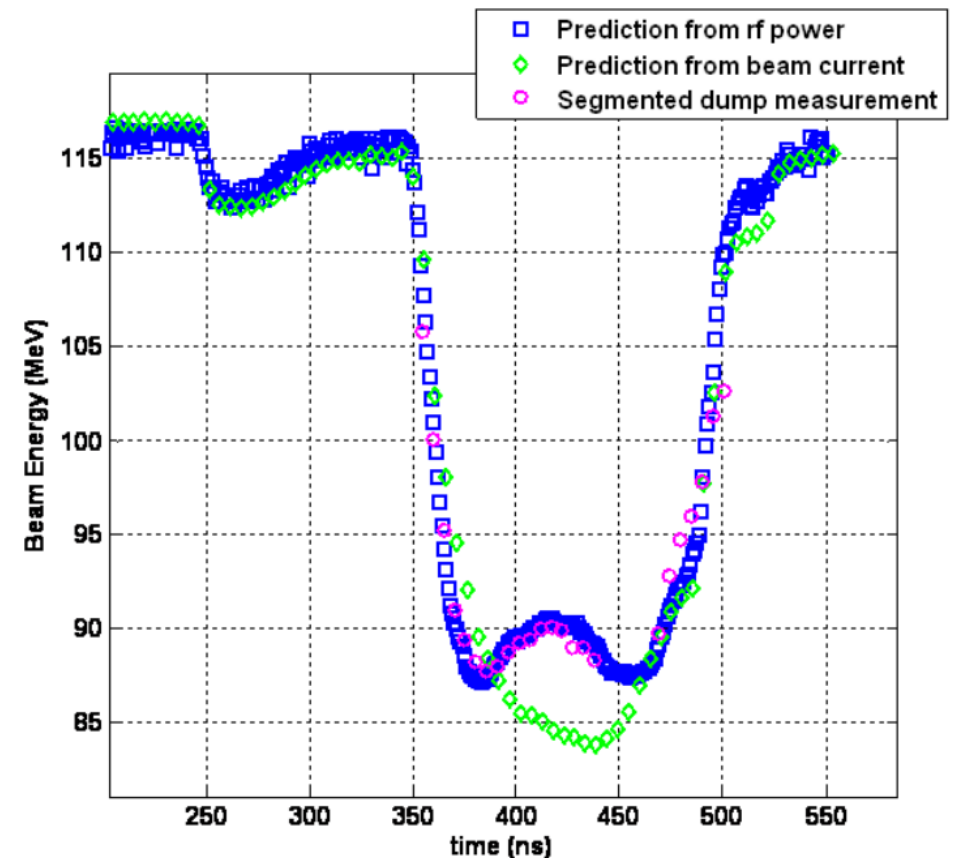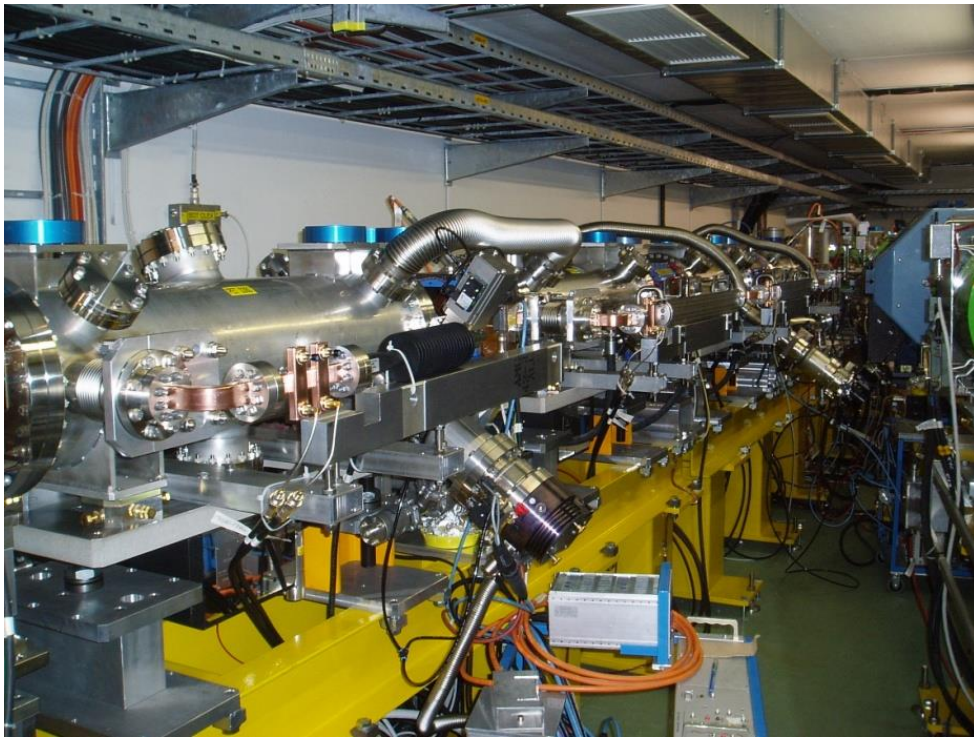
PETS structure

Low group velocity requires simulations with 100k time steps

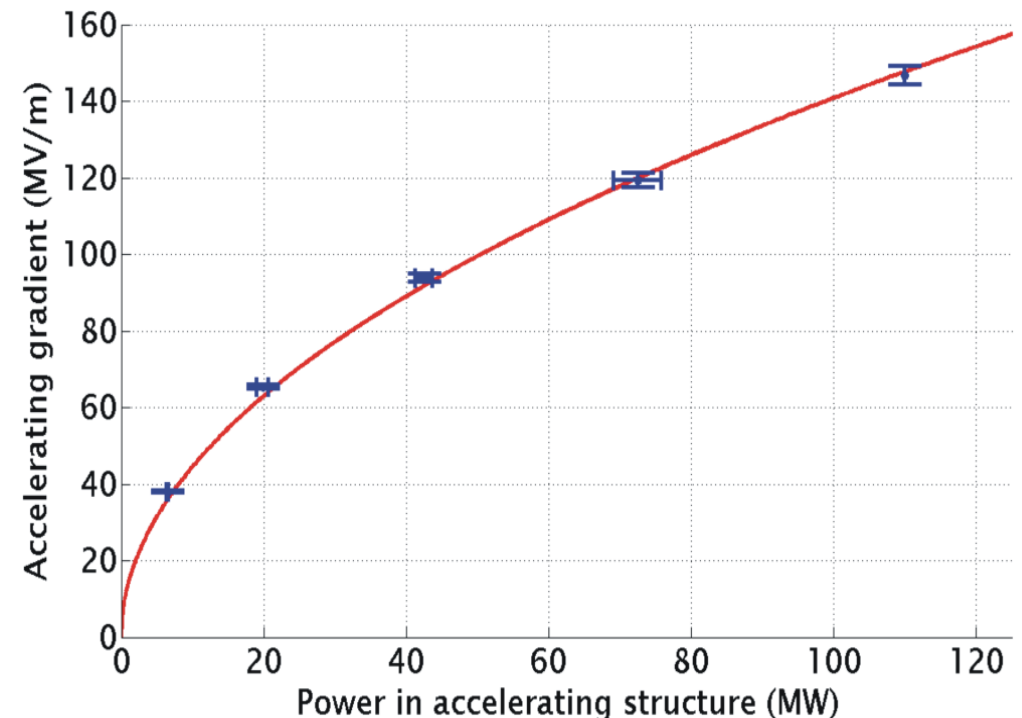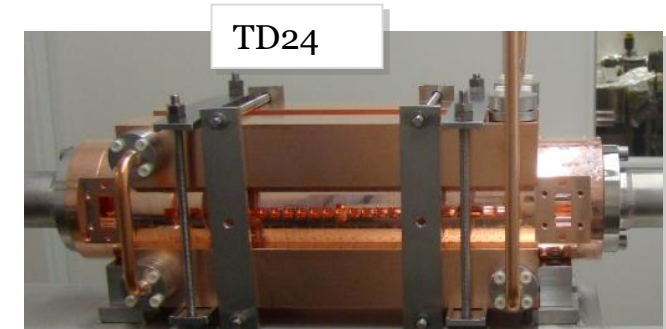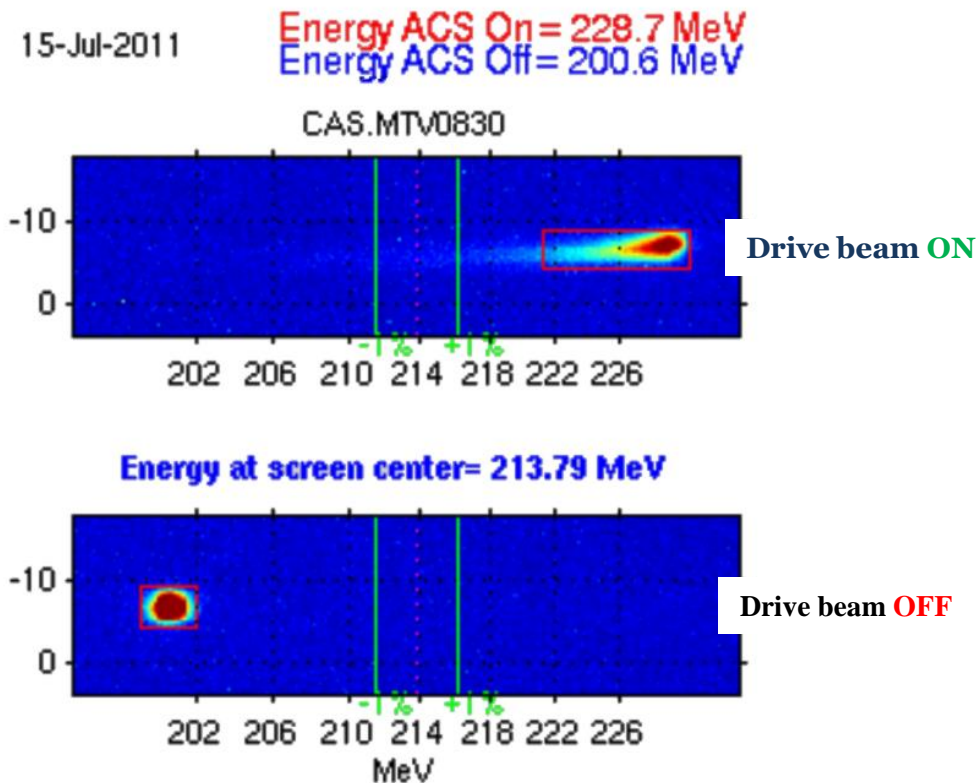T3P models realistic, complex accelerator structures with unprecedented accuracy
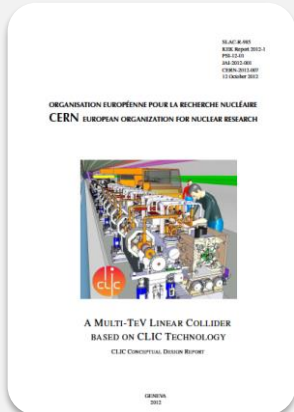
Arno Candel, SLAC

- 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

Achieved Two-Beam Acceleration

- Maximum probe beam acceleration measured: 31 MeV

  => Corresponding to a gradient of 145 MV/m

TD24

15-Jul-2011

Energy ACS On = 228.7 MeV
Energy ACS Off = 200.6 MeV

CAS.MTV0830

Drive beam ON

Energy at screen center= 213.79 MeV

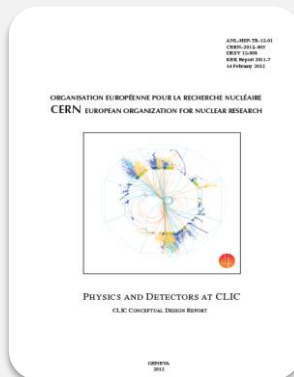Drive beam OFF

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

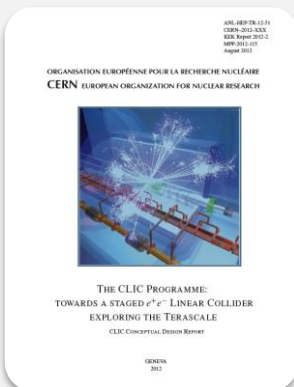- Complete, presented in SPC in March 2011, in print:
  https://edms.cern.ch/document/1234244/

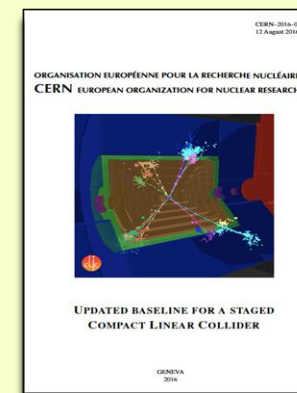## Vol 2: Physics and detectors at CLIC (L.Linssen)

- 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