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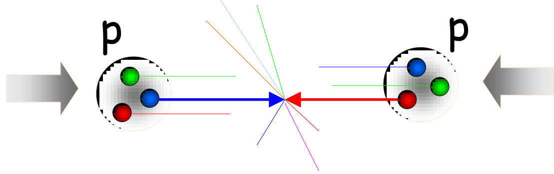
CLIC
Towards a Future Linear Collider

Roger Ruber

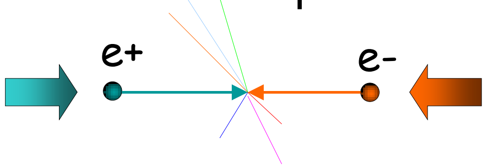
Uppsala University

Collider History

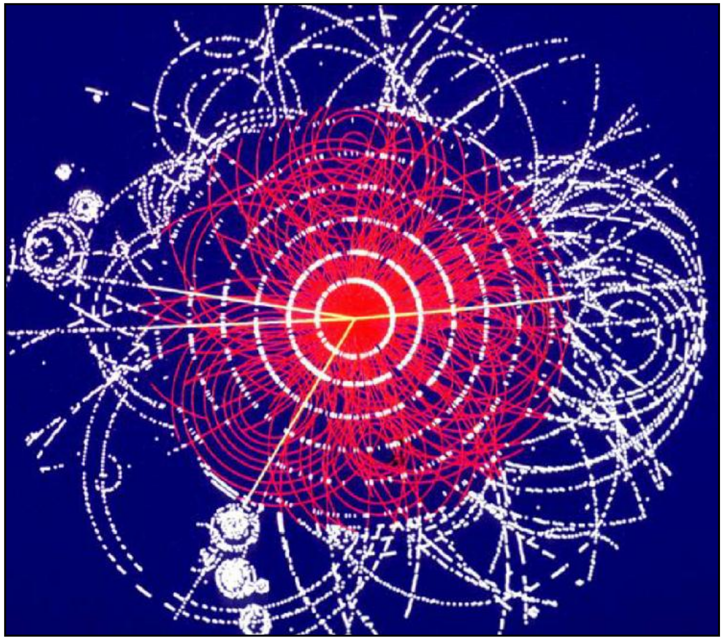
- hadron collider at the frontier of physics

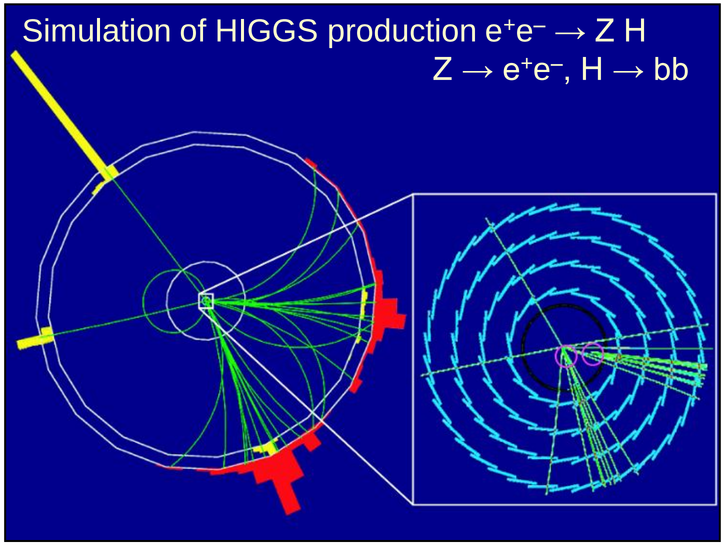


  - huge QCD background
  - not all nucleon energy available in collision
- lepton collider for precision physics



  - well defined CM energy
  - polarization possible
- next machine after LHC = lepton collider
  - energy determined by LHC discoveries consensus E_{cm} ≥0.5 TeV





Circular versus Linear Collider

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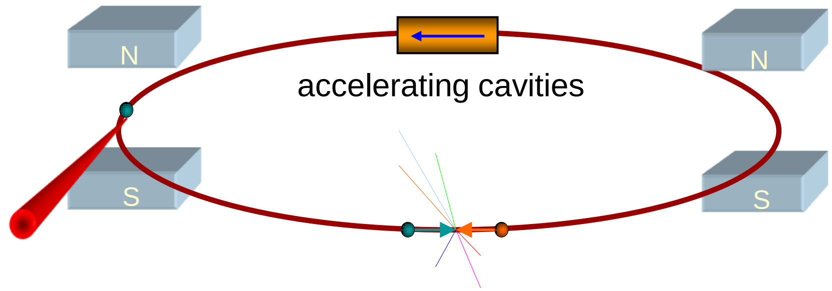
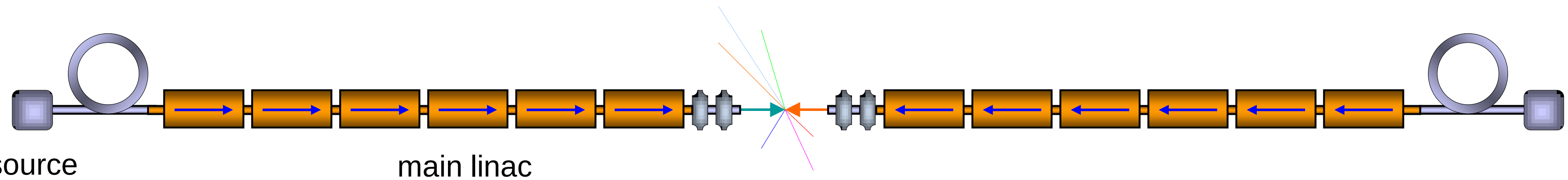


Circular Collider

many magnets, few cavities, stored beam

higher energy → stronger magnetic field

→ higher synchrotron radiation losses ($\propto E^4/R$)



Linear Collider

few magnets, many cavities, single pass beam

higher energy → higher accelerating gradient

higher luminosity → higher beam power (high bunch repetition)

Cost of Circular & Linear Accelerators

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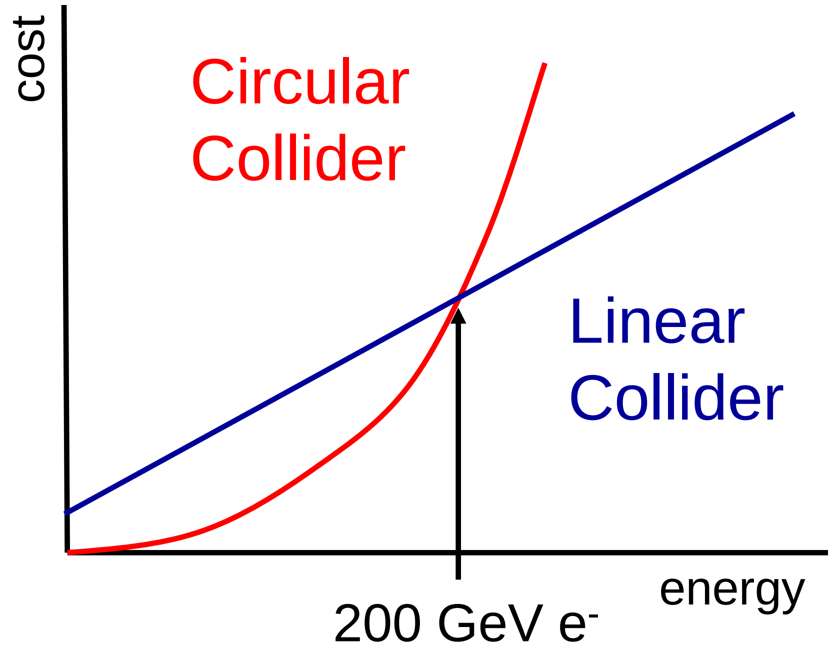


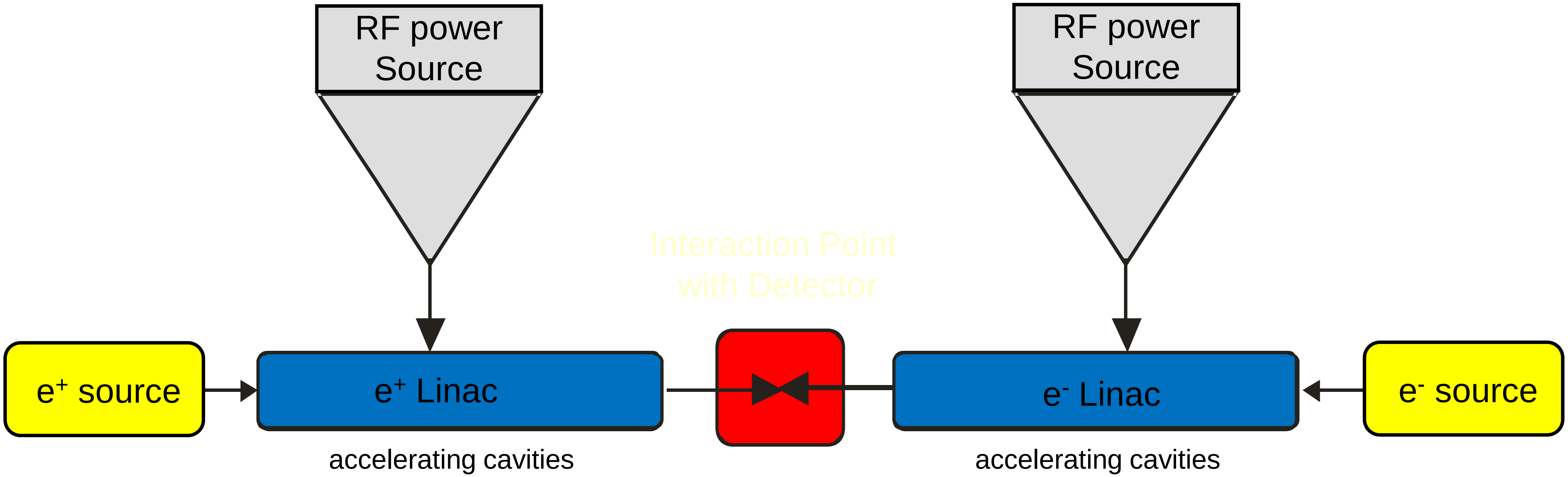
Circular Collider

- $\Delta E \sim (E^4/m^4R)$
- cost ~ aR + b ΔE
- optimization: $R \sim E^2 \rightarrow$ cost ~ cE^2

Linear Collider

- E ~ L
- cost ~ aL

Linear Collider R&D



1. high energy → high accelerating gradient
2. high luminosity → high current & small beam size
3. efficient power production
4. feasibility demonstration

The ILC and CLIC

ILC

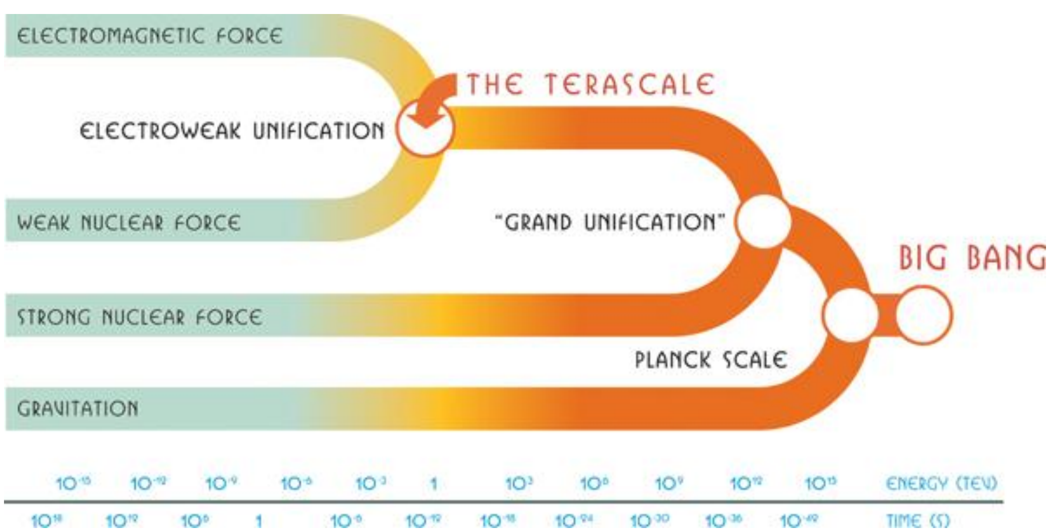
International Linear Collider

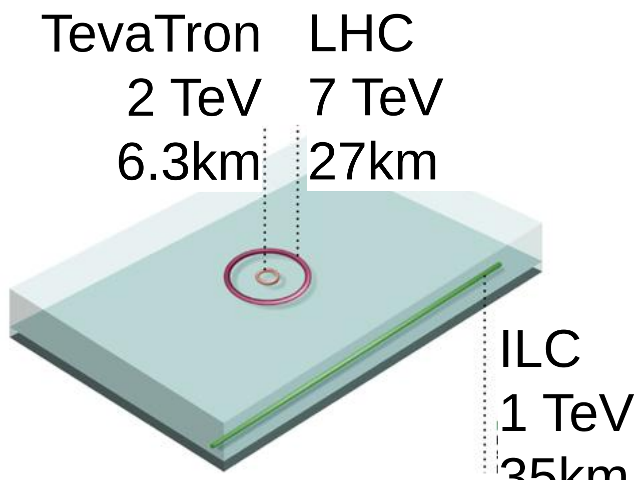
- superconducting technology
- E_{acc} = 31.5 MV/m at 1.3 GHz
- E_{CMS} = 0.5~1 TeV
- length ~31 km

CLIC

Compact Linear Collider

- normal conducting technology
- E_{acc} = 100 MV/m at 12 GHz
- E_{CMS} = 1~3 TeV
- length ~48 km





Courtesy Sandbox Studio / interactions.org


LINEAR COLLIDER
INCLUDES PAINT SET
LINEAR COLLIDER

Basic Layout of a Linear Collider

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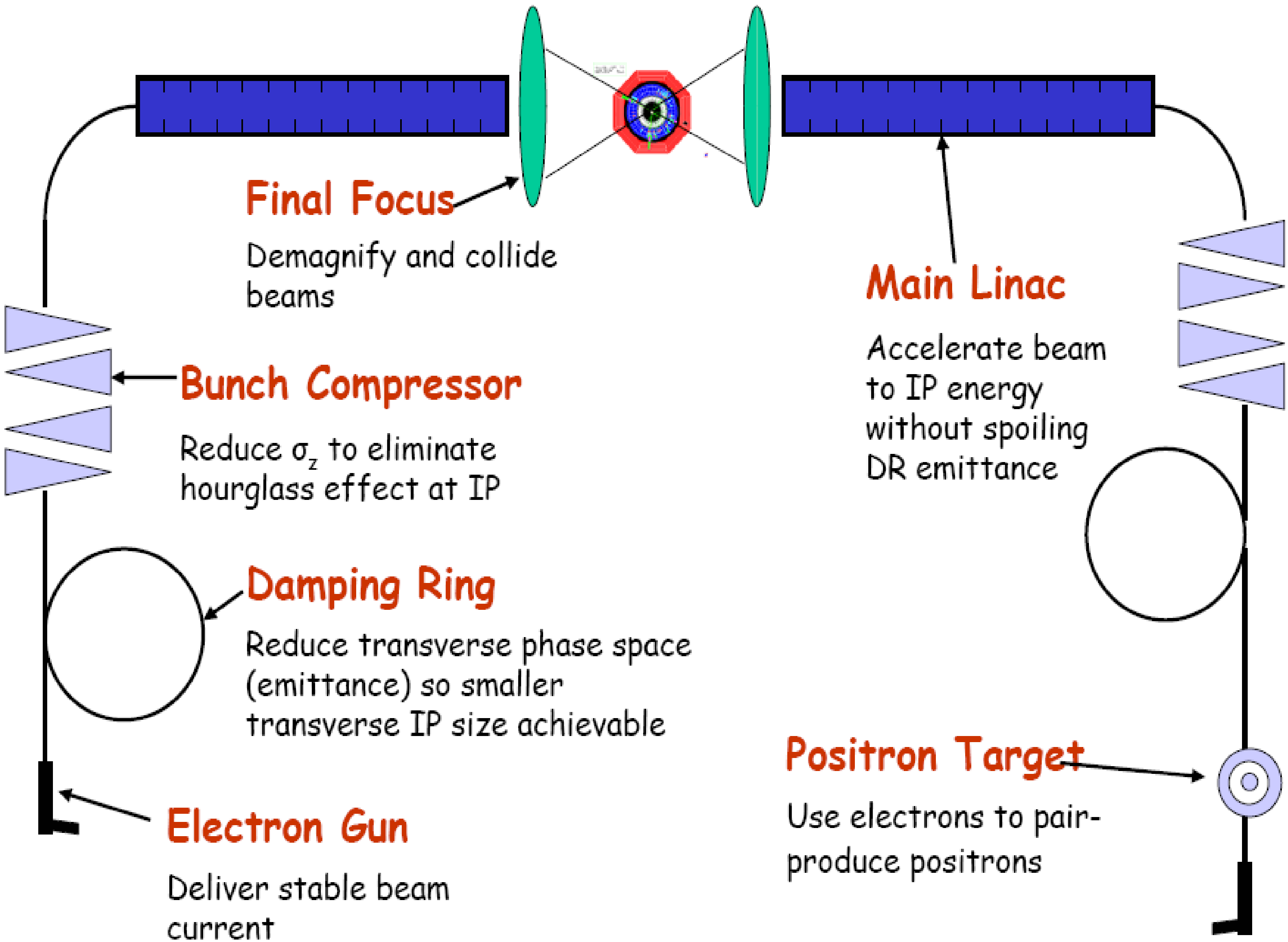

CLIC: Compact Linear Collider

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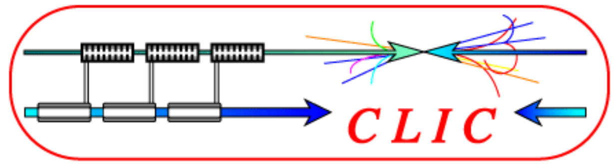
Baseline:

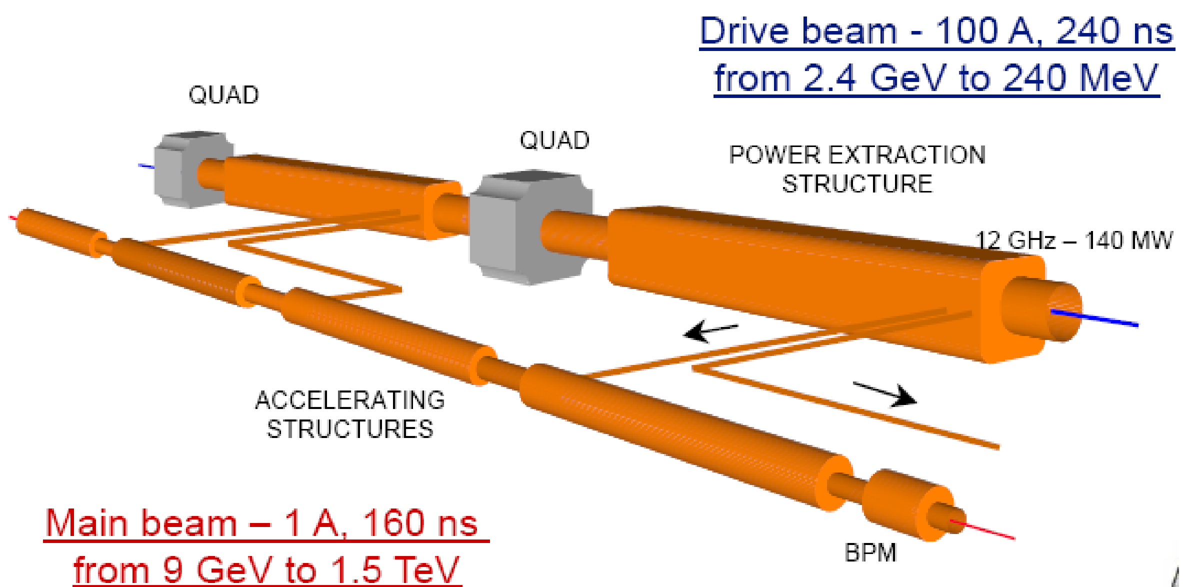
- 2 x 1.5 TeV
- 2×10^{34} $cm^{-2}s^{-1}$

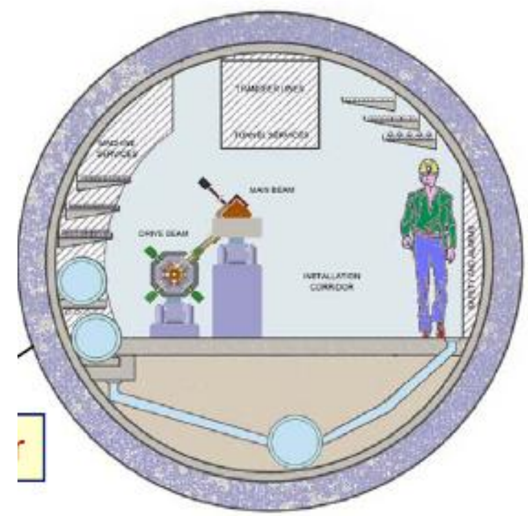


How to:

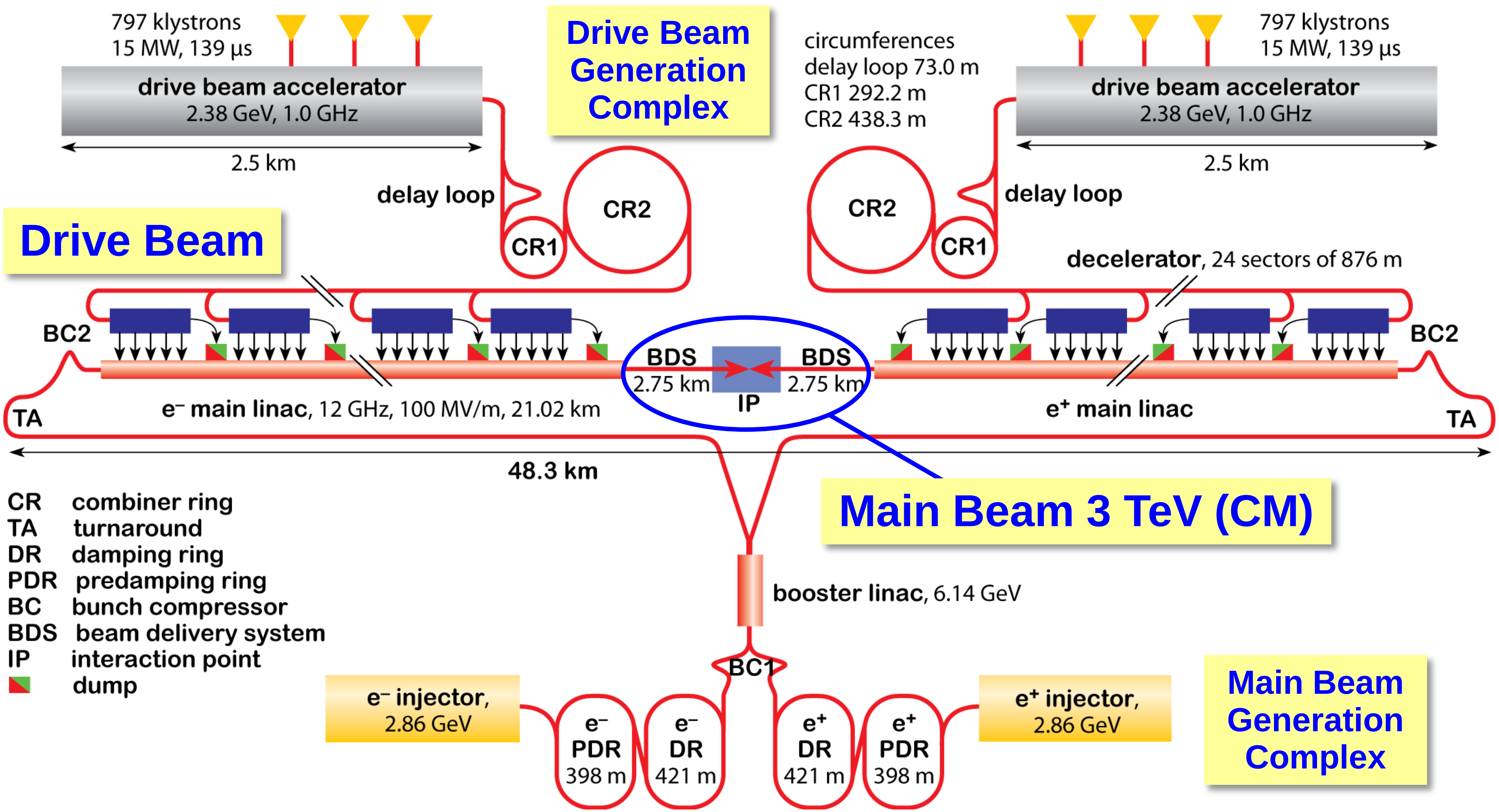
- NC linac plus ”drive beam” replacing klystrons
- short pulse (<200ns), high rep-rate (100Hz)
- achieve luminosity by very small beam size (1x100nm)

Main Linac	
C.M. Energy	3 TeV
Peak luminosity	2×10^{34} $cm^{-2}s^{-1}$
Beam Rep. rate	50 Hz
Pulse time duration	156 ns
Average gradient	100 MV/m
# cavities	2 x 71,548





CLIC Layout



797 klystrons
15 MW, 139 μs
drive beam accelerator
2.38 GeV, 1.0 GHz
2.5 km
Drive Beam Generation Complex
circumferences
delay loop 73.0 m
CR1 292.2 m
CR2 438.3 m
797 klystrons
15 MW, 139 μs
drive beam accelerator
2.38 GeV, 1.0 GHz
2.5 km
delay loop
CR2
CR1
Drive Beam
CR2
CR1
delay loop
decelerator, 24 sectors of 876 m
BC2
BDS
2.75 km
IP
BDS
2.75 km
BC2
TA
e⁻ main linac, 12 GHz, 100 MV/m, 21.02 km
e⁺ main linac
TA
48.3 km
Main Beam 3 TeV (CM)
CR combiner ring
TA turnaround
DR damping ring
PDR predamping ring
BC bunch compressor
BDS beam delivery system
IP interaction point
dump
booster linac, 6.14 GeV
BC1
e⁻ injector, 2.86 GeV
e⁻ PDR 398 m
e⁻ DR 421 m
e⁺ DR 421 m
e⁺ PDR 398 m
e⁺ injector, 2.86 GeV
Main Beam Generation Complex

CLIC Two-beam Acceleration Scheme

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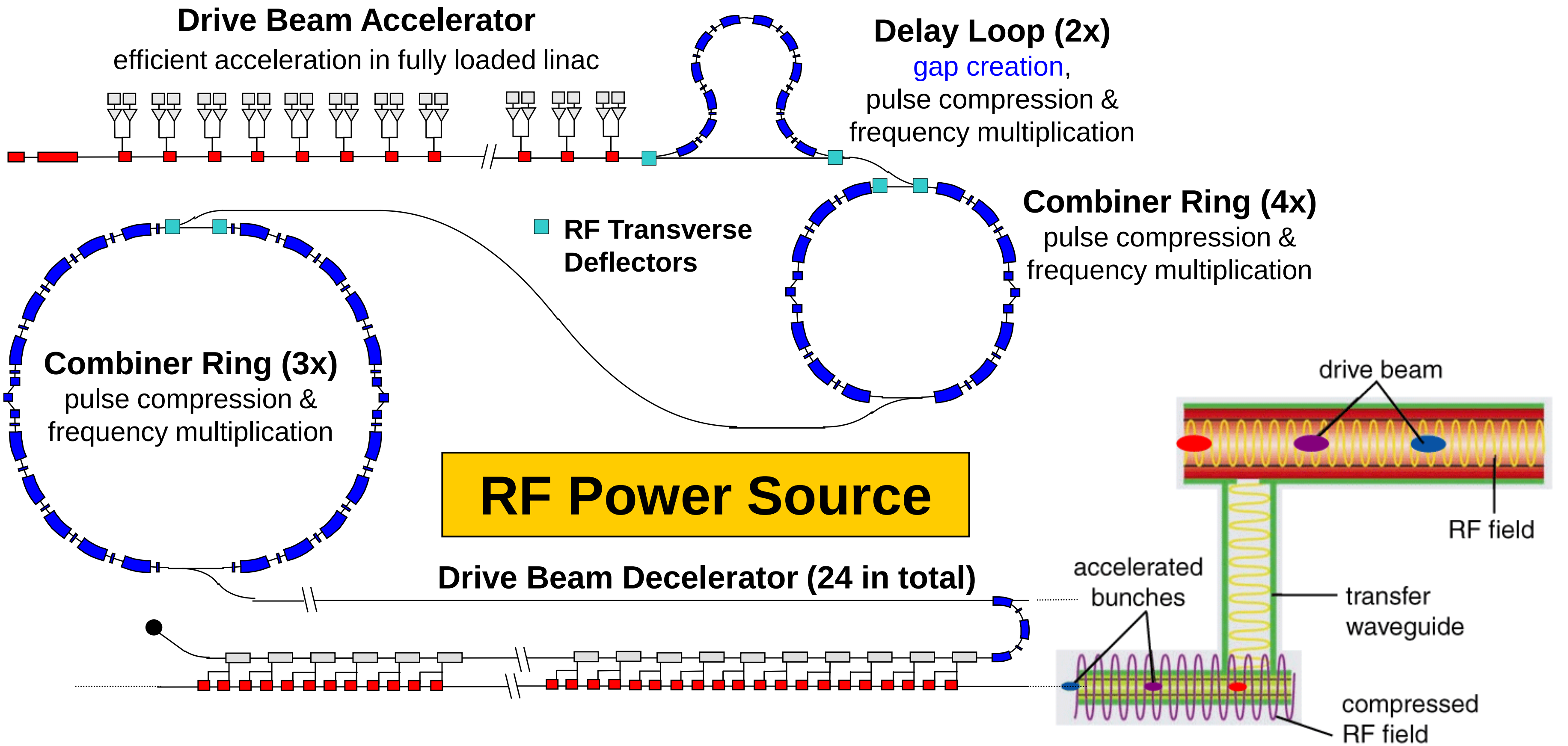
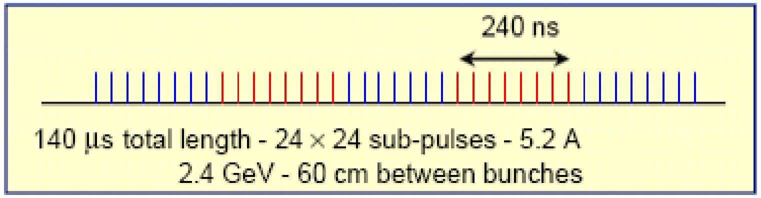
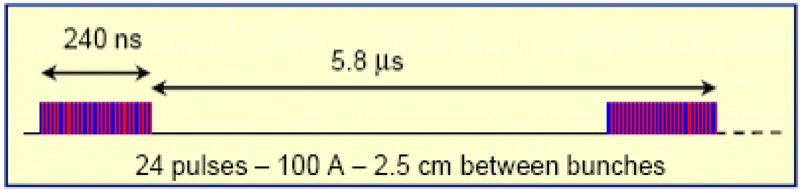


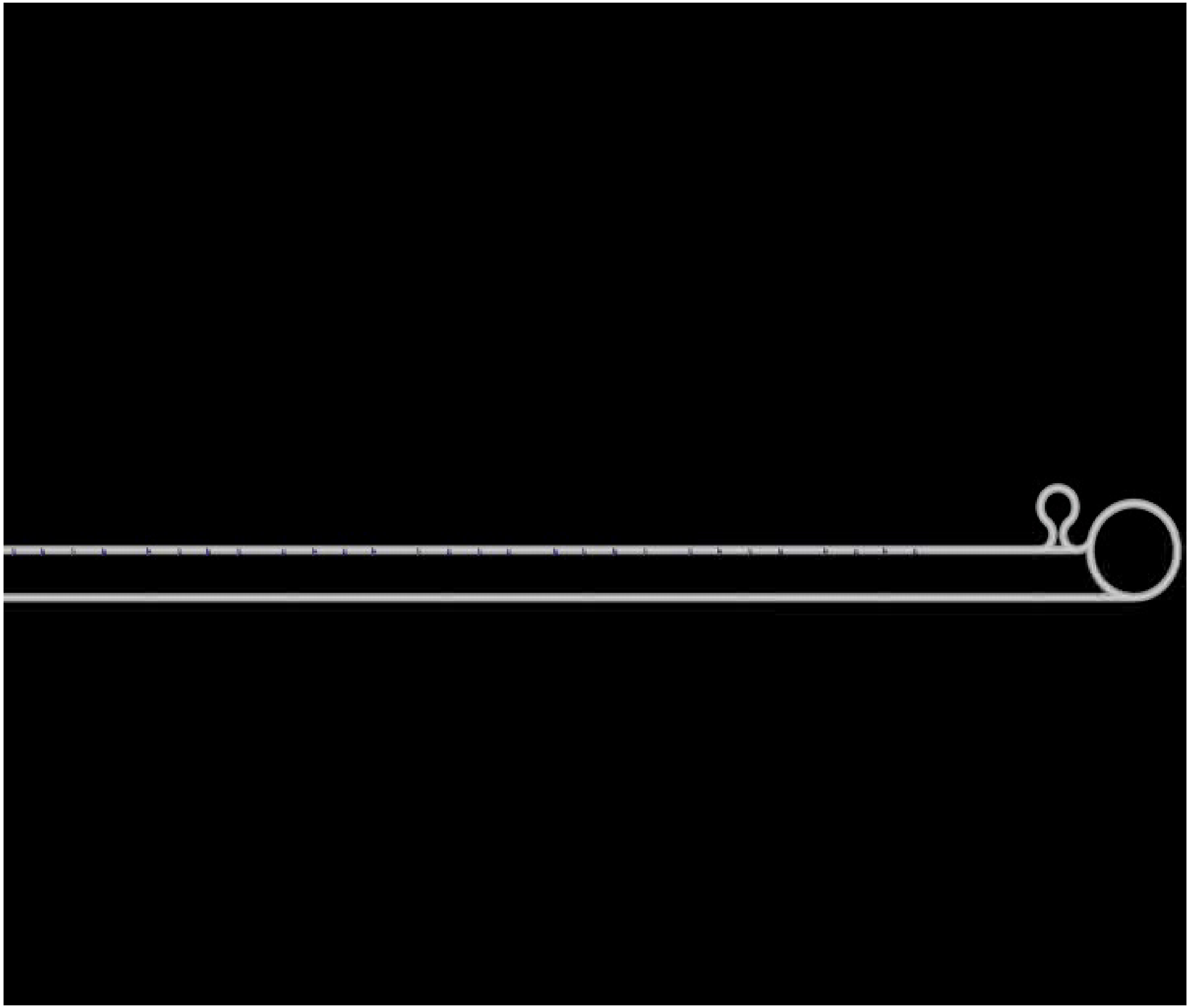
Drive beam time structure - initial



Drive beam time structure - final



Drive Beam Generation Scheme



Courtesy A. Andersson

The CTF3 Facility as CLIC Test Bench

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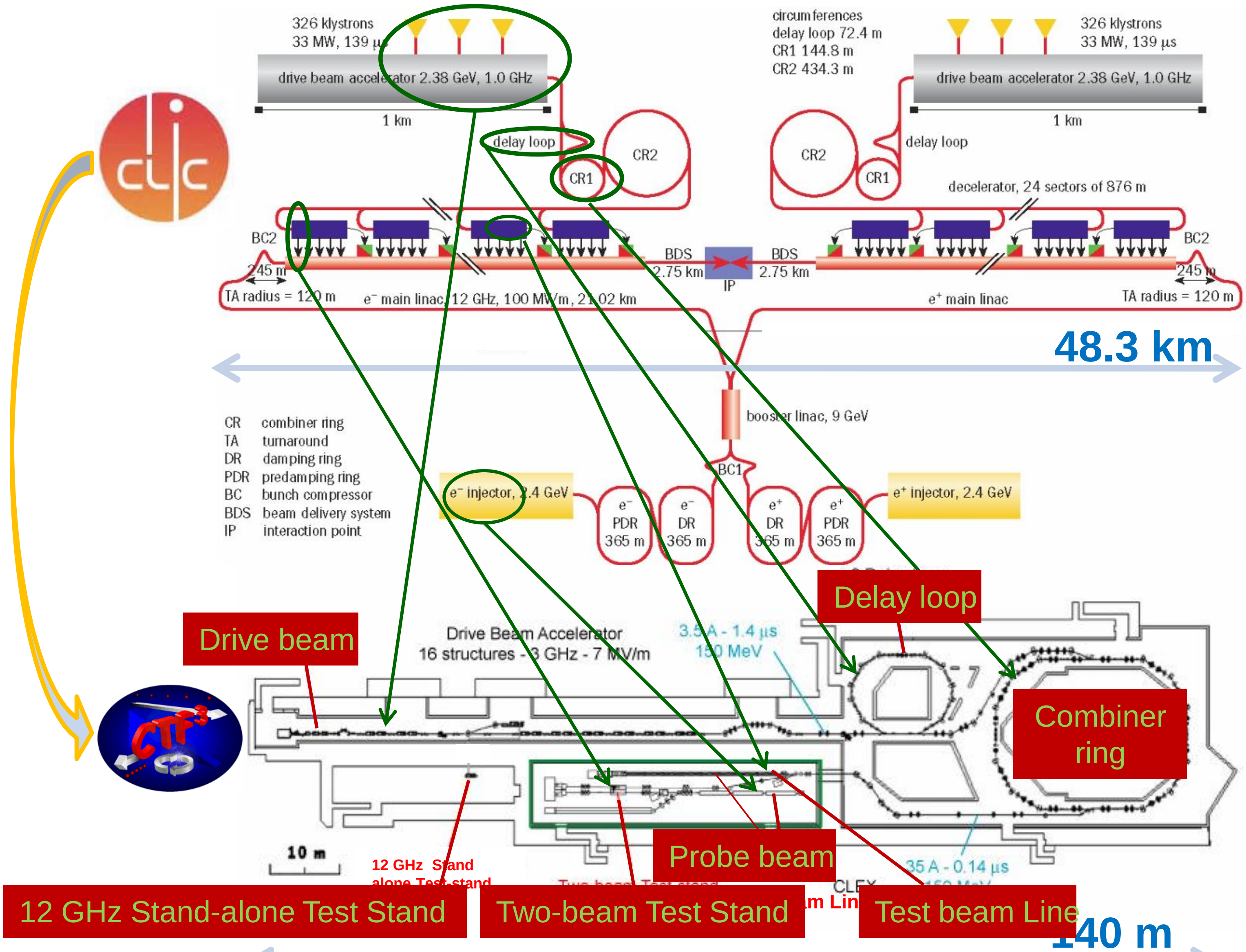
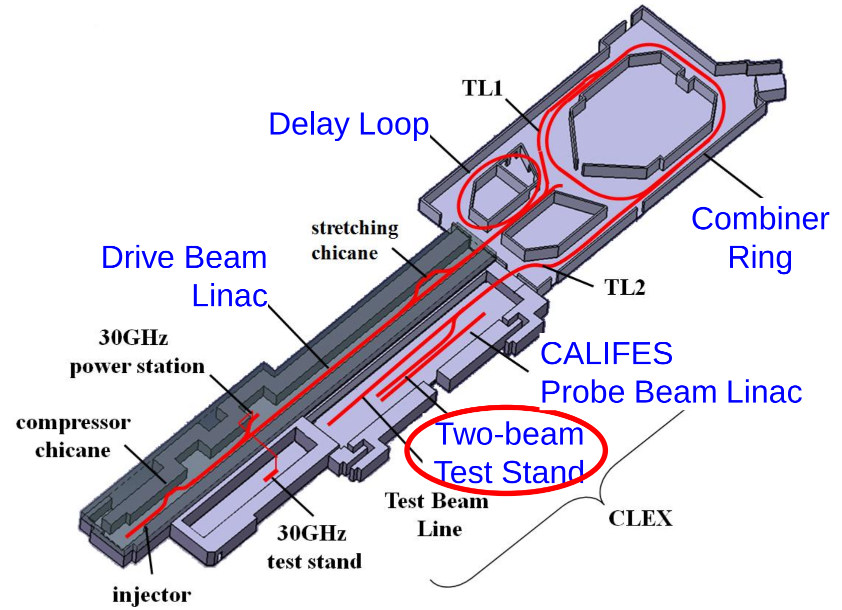


CTF3 Experimental Program

- Drive beam generation
  - appropriate time structure
  - fully loaded acceleration
- Drive beam deceleration
  - high power production
  - beam stability
- Two-beam acceleration
  - prototyping structures (PETS, ACS)
  - RF breakdown and beam kicks
- 12GHz klystron powered test stand
  - prototyping structures w/o beam
  - significantly higher repetition rate (50 Hz)
- Photoinjector
  - prototyping drive beam gun



TBTS is the only place available to investigate effects of RF breakdown on the beam

CTF3 Drive Beam

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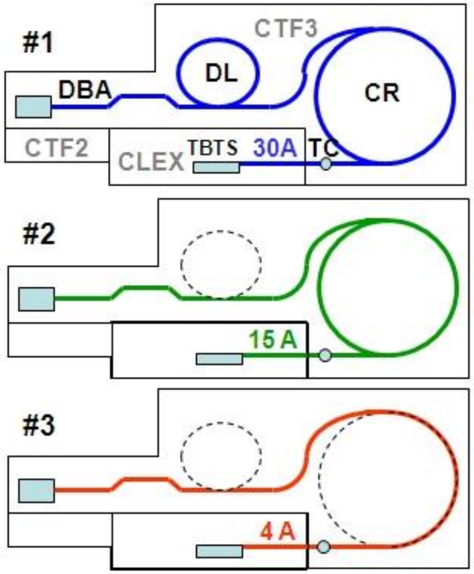
- Several operation modes possible,
- Tail clipper (TC) after the CR to adjust the pulse length,
- Upgrade possible to 150 MeV at 5 Hz repetition rate.



Mode	#1	#2	#3	
Energy	120			[MeV]
Energy spread	2			[%]
Current **(1)**	30	15	4	[A]
Pulse length **(2)**	140	240	1100	[ns]
DBA frequency	1.5	3	3	[GHz]
Bunch frequency	12	12	3	[GHz]
Repetition rate	0.8			[Hz]
PETS power	200	61	5	[MW]

Demonstration Fully Loaded Operation

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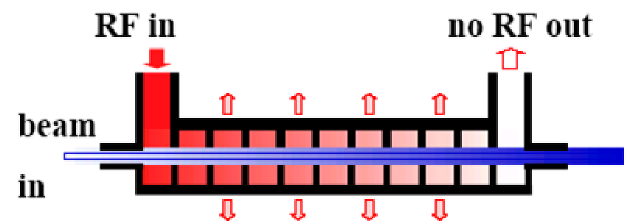
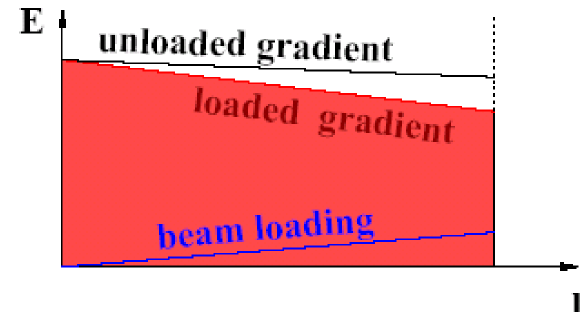
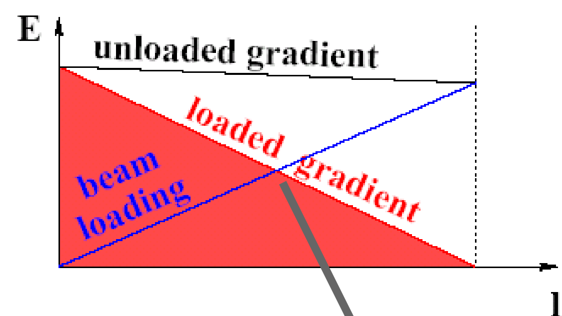
Efficient power transfer

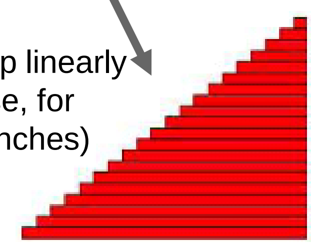
- **"Standard" situation:**
  - small beam loading
  - power at exit lost in load
- **"Efficient" situation:** $V_{ACC} \approx 1/2\ V_{unloaded}$
  - high beam loading
  - no power flows into load

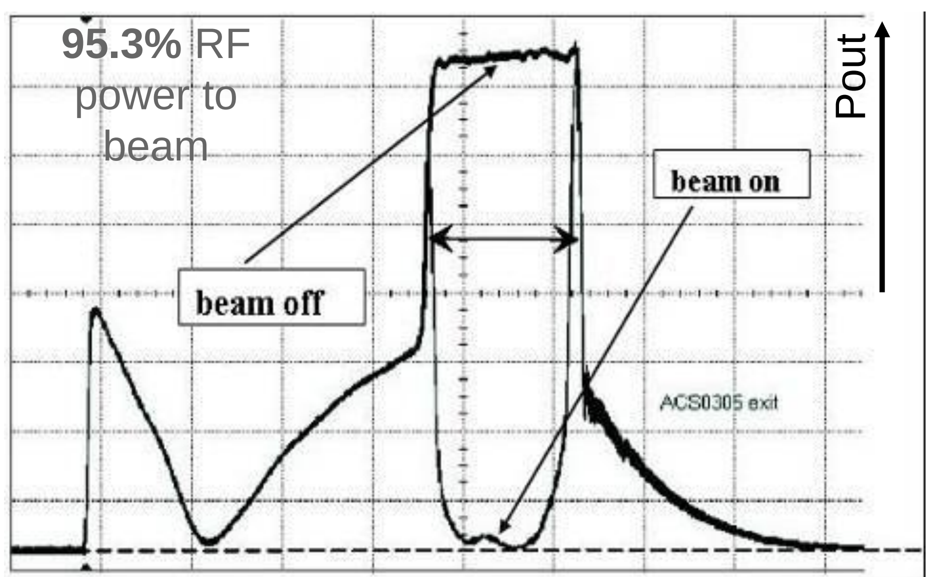






field builds up linearly (and stepwise, for point-like bunches)





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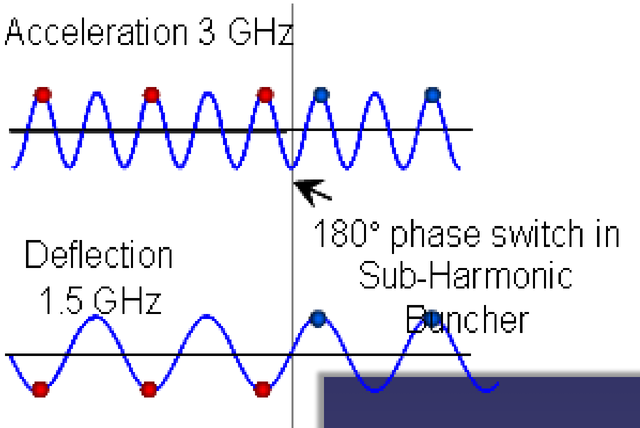
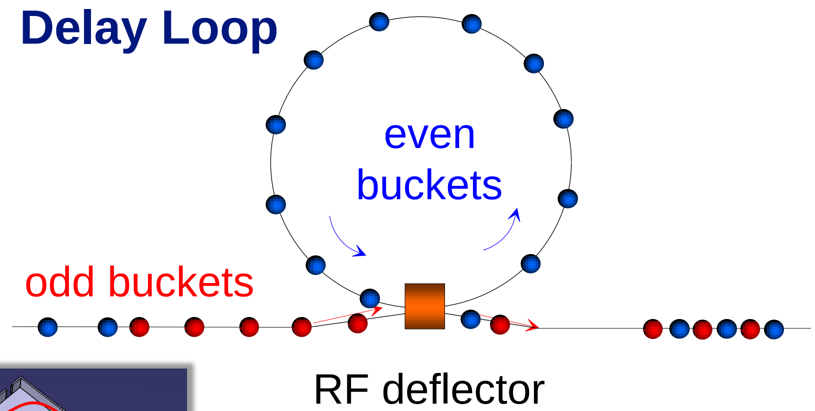
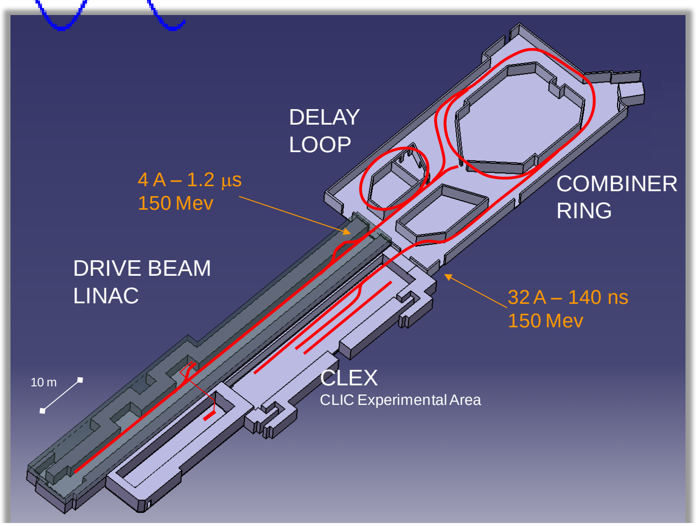
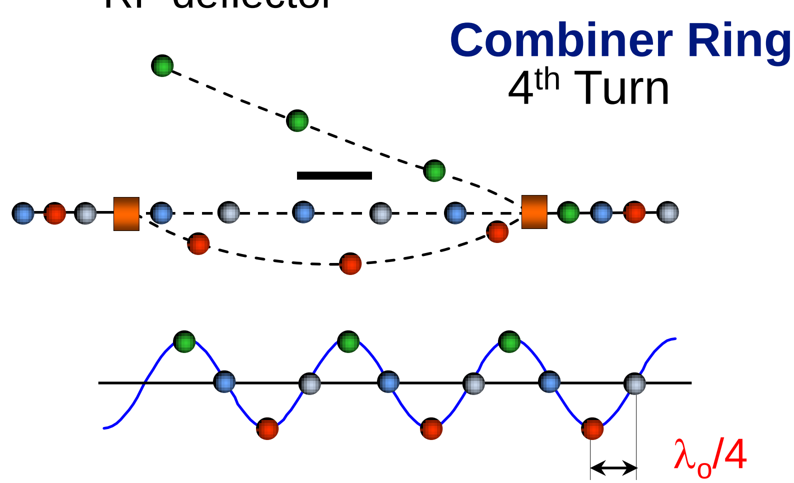
Recombination Principle

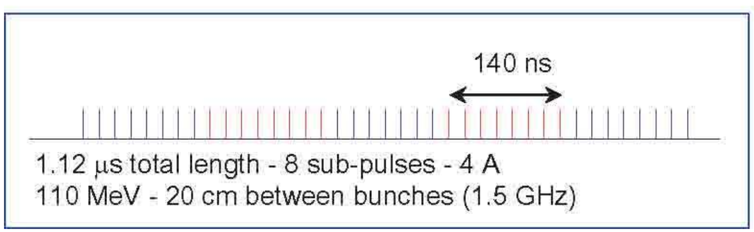




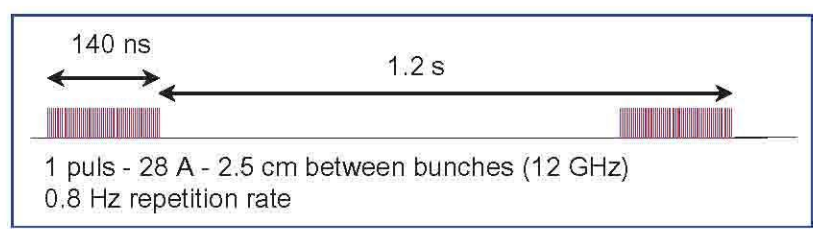




Initial time structure

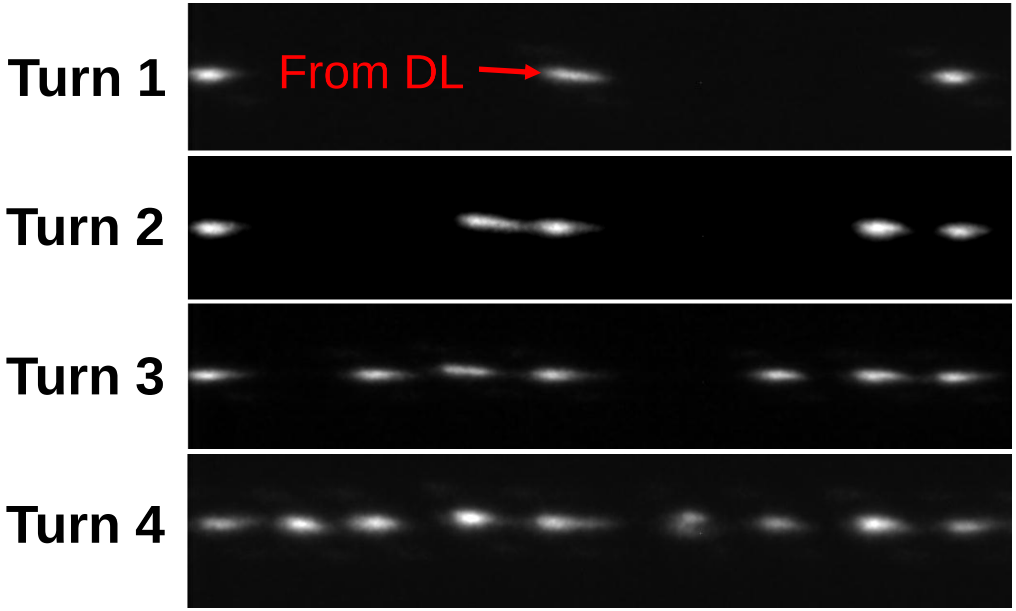


Final time structure

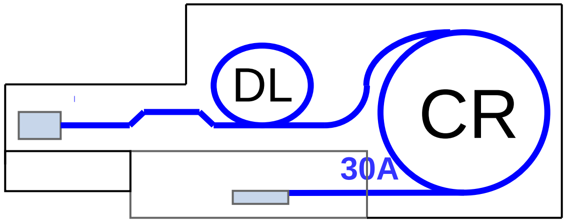


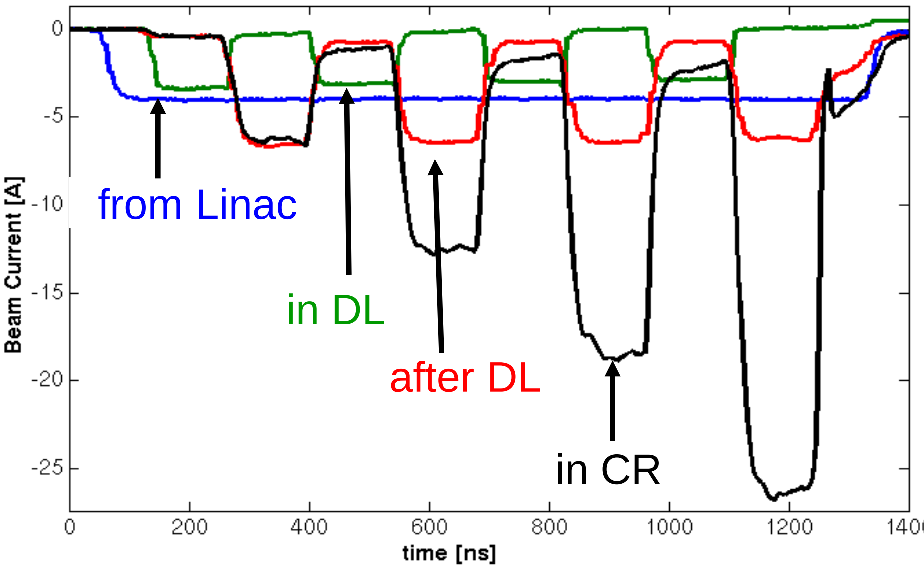
Bunch Re-combination DL + CR

- **Streak camera images from CR**
- bunch spacing:
  - 666 ps initial
  - 83 ps final
- circulation time correction by wiggler adjustment



- **Signal from BPMs**





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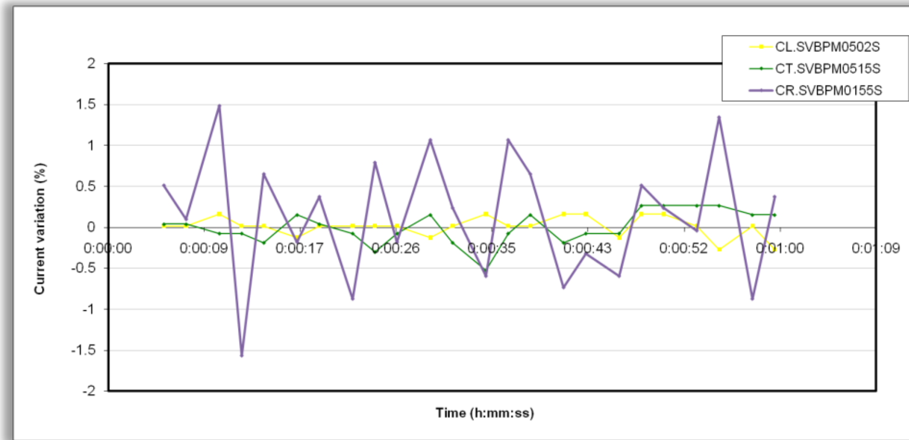
Ongoing Work

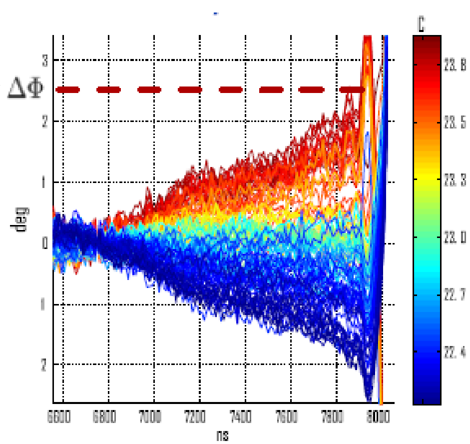
- **Beam current stabilization**
  - CLIC requires stability at 0.075% level
  - ok from linac and DL
    need improvement in CR

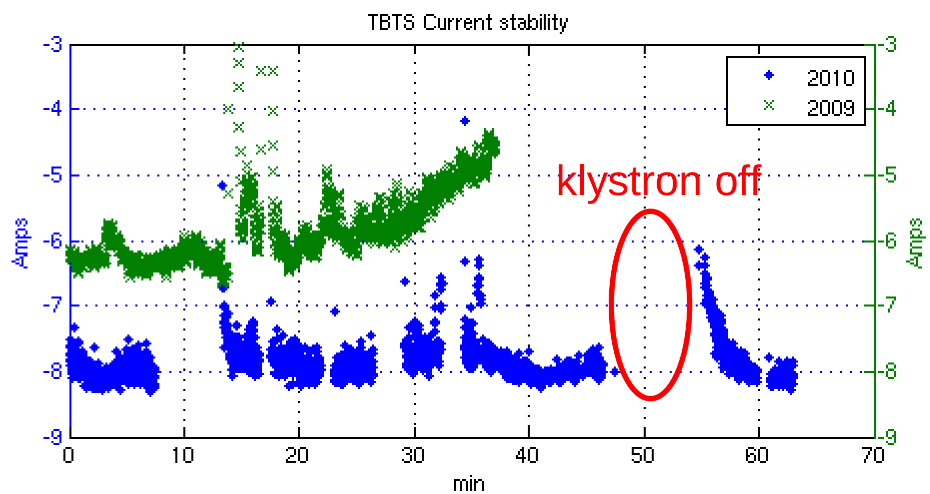
	LINAC	DL	CR
Variation	0.13%	0.20%	1.01%



- **Phase stabilization**
  - temperature stabilization
    pulse compressor cavity
- **Transfer line commissioning**
  - transport losses from CR to experiment hall

RF phase stability along pulse (for different ambient temperatures)





CALIFES Probe Beam

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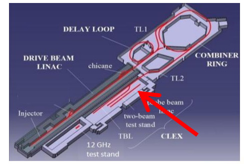
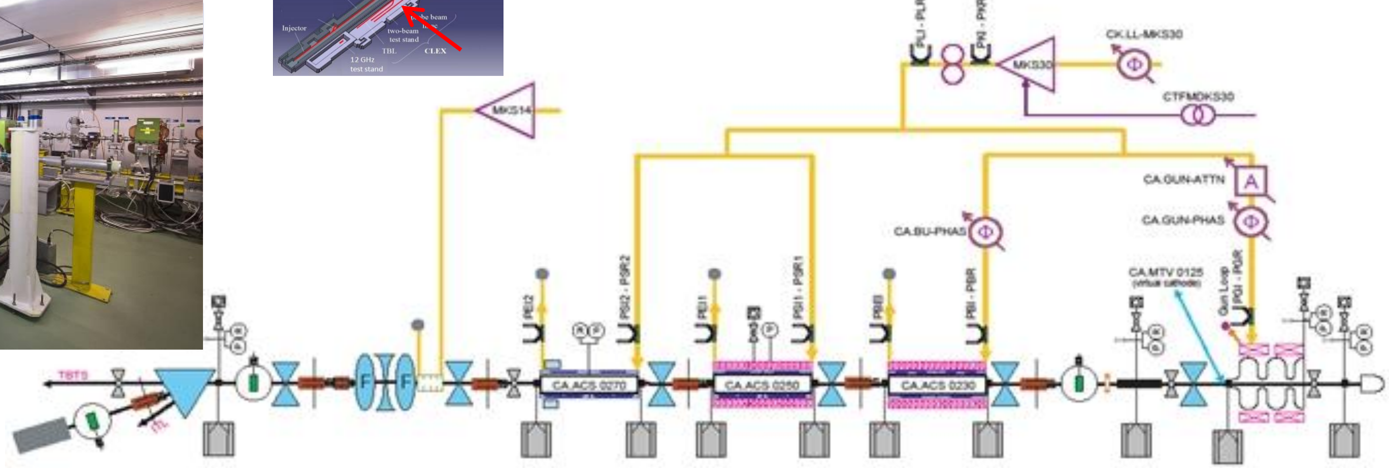
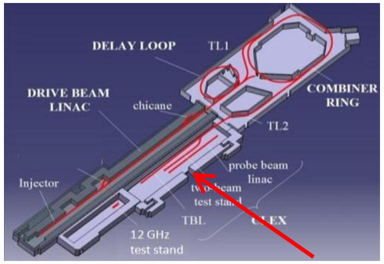




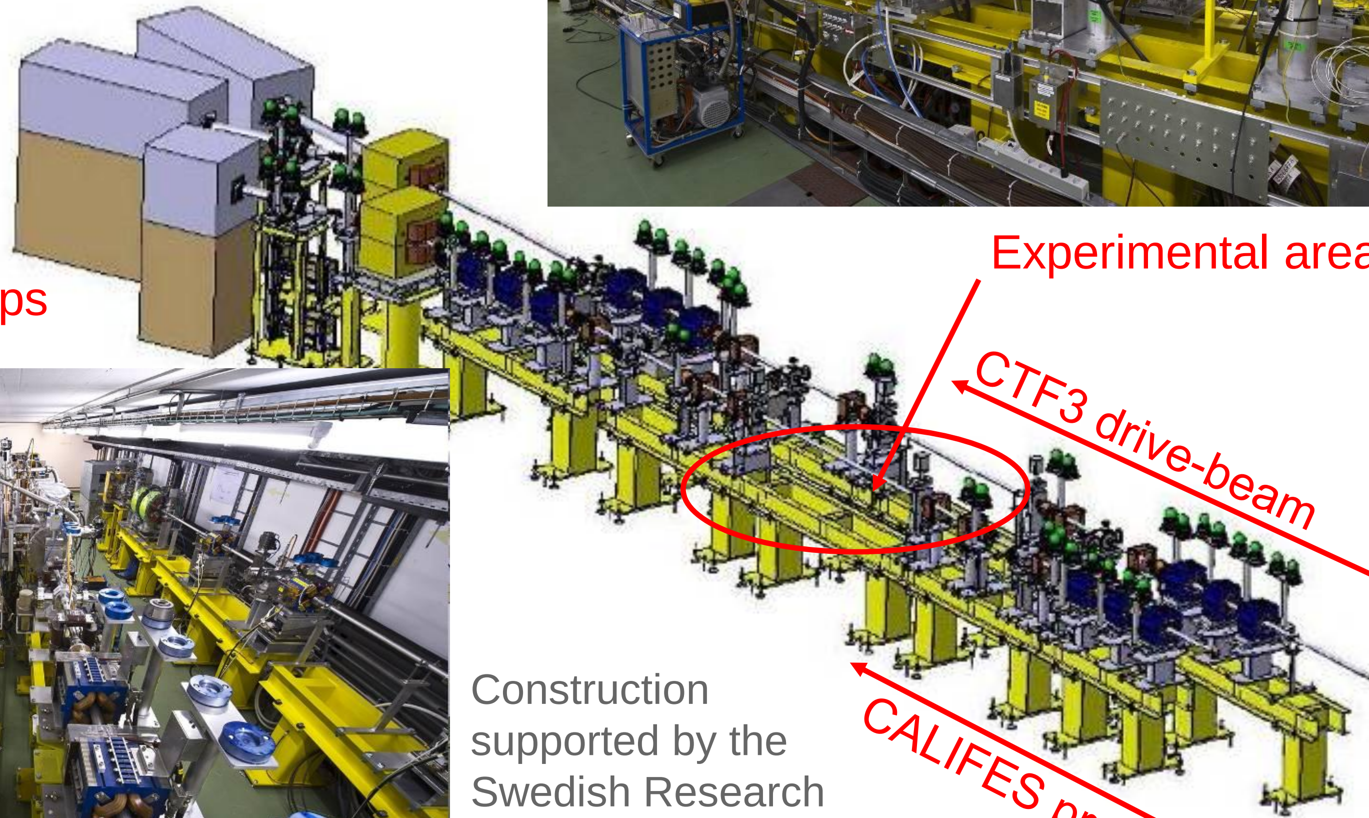
- A standing-wave photo-injector
- 3 travelling-wave structures, the first one used for velocity bunching
- A single klystron (45 MW – 5.5 ms) with pulse compression (120 MW – 1.3 ms)
- A RF network with splitters, phase shifters, attenuator, circulator and couplers

Energy	200 MeV
Energy spread	1% (FWHM)
Pulse length	0.6–150 ns
Bunch frequency	1.5 GHz
Bunch length	1.4 ps
Bunch charge	0.085–0.6 nC
Intensity	
- short pulse	1 A
- long pulse	0.13 A
Repetition rate	0.833 – 5 Hz

Two-beam Test Stand



Spectrometers and beam dumps



Construction supported by the Swedish Research Council and the Knut and Alice Wallenberg Foundation

Two-beam Test Stand Prospects

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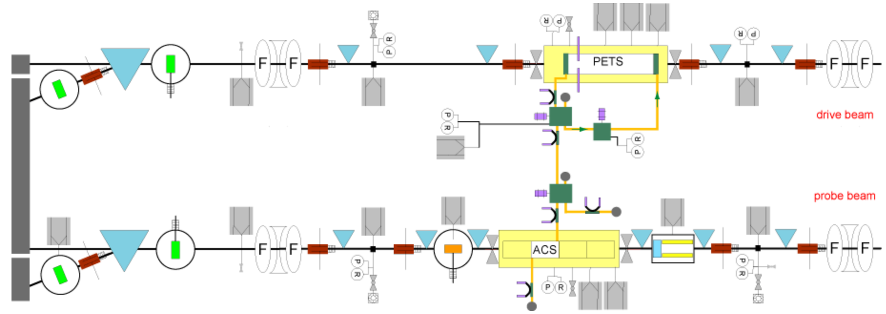
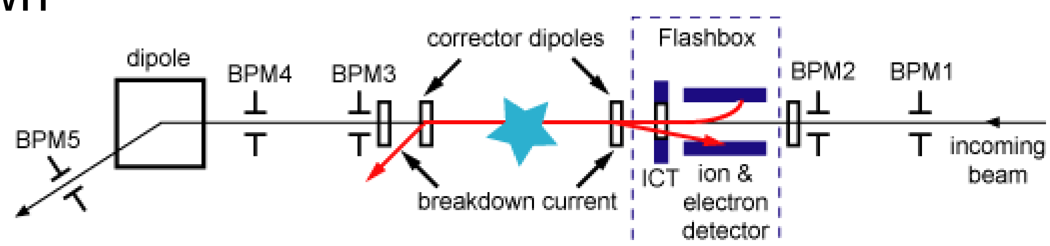
Versatile facility



- two-beam operation
  - 28A drive beam [100A at CLIC]
  - 1A probe beam [like CLIC]
- excellent beam diagnostics, long lever arms
- easy access & flexibility for future upgrades

Unique test possibilities

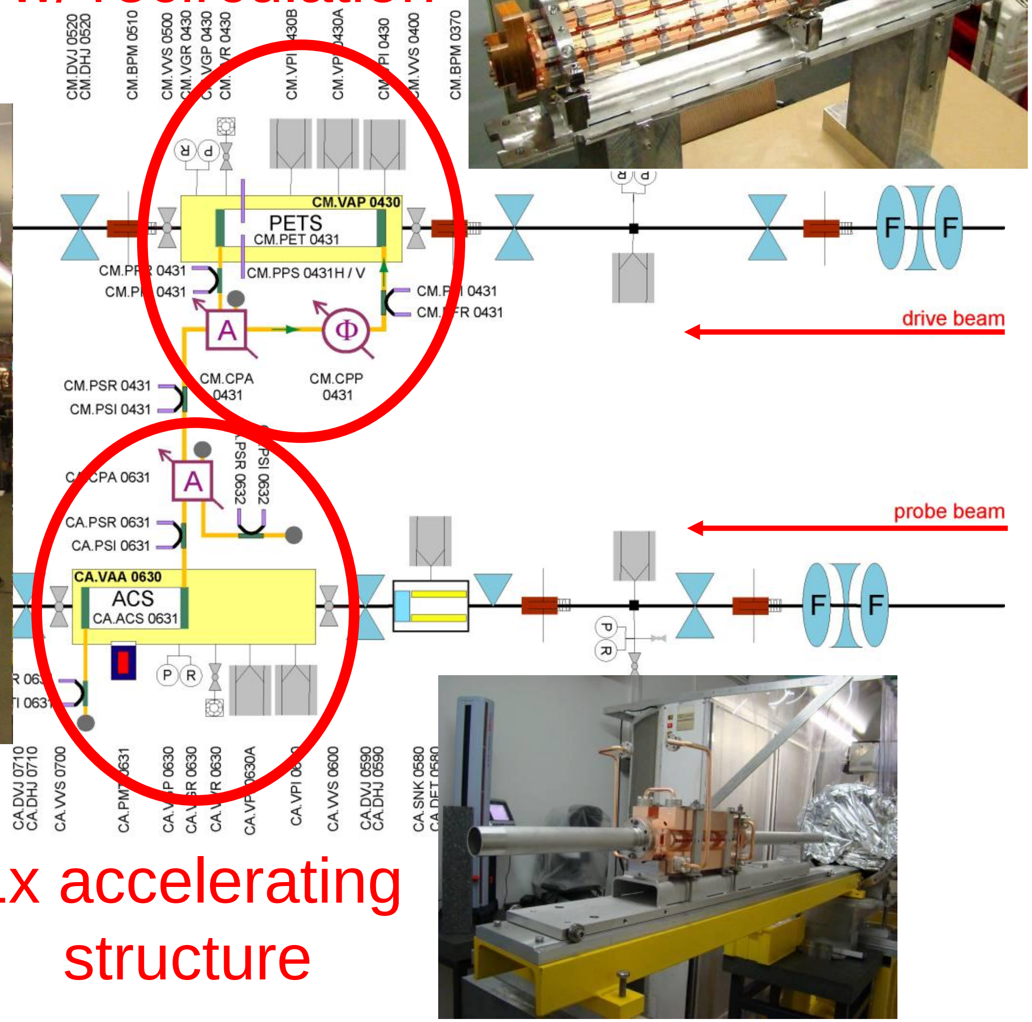
- power production in prototype CLIC PETS
- two-beam acceleration and full CLIC module
- studies of
  - beam kick & RF breakdown
  - beam dynamics effects
  - beam-based alignment



TBTS Test Area

CERN EDMS Id. 894313 (version 6.3)
Roger Ruber, 2010/03/03

1x PETS
w/ recirculation

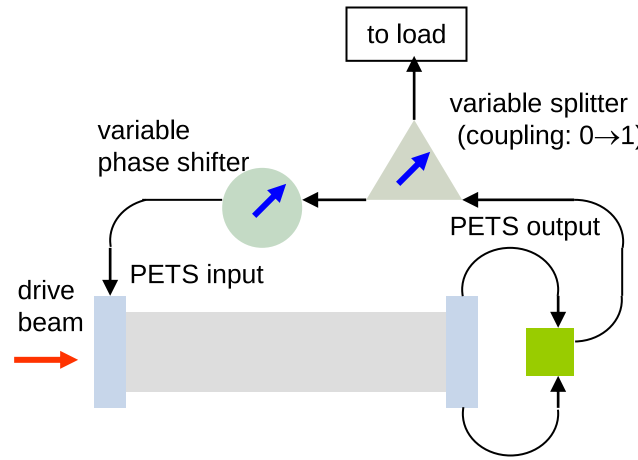


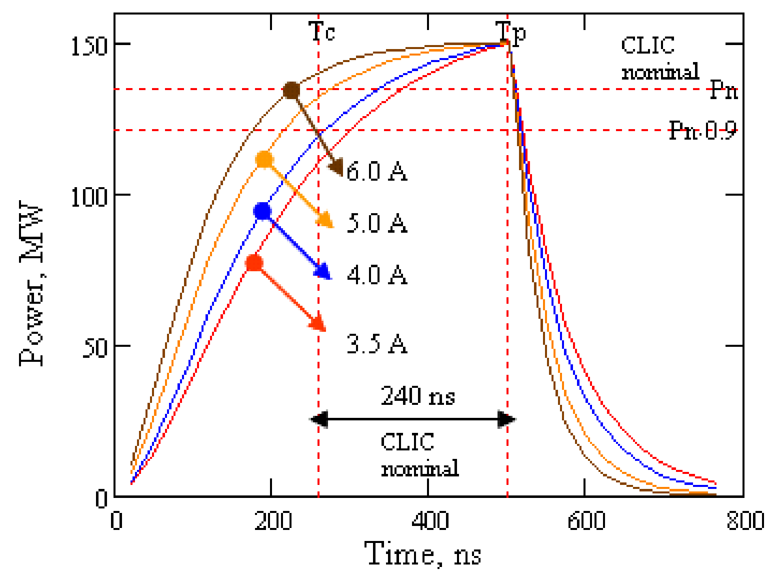
1x accelerating
structure

PETS Power Recirculation

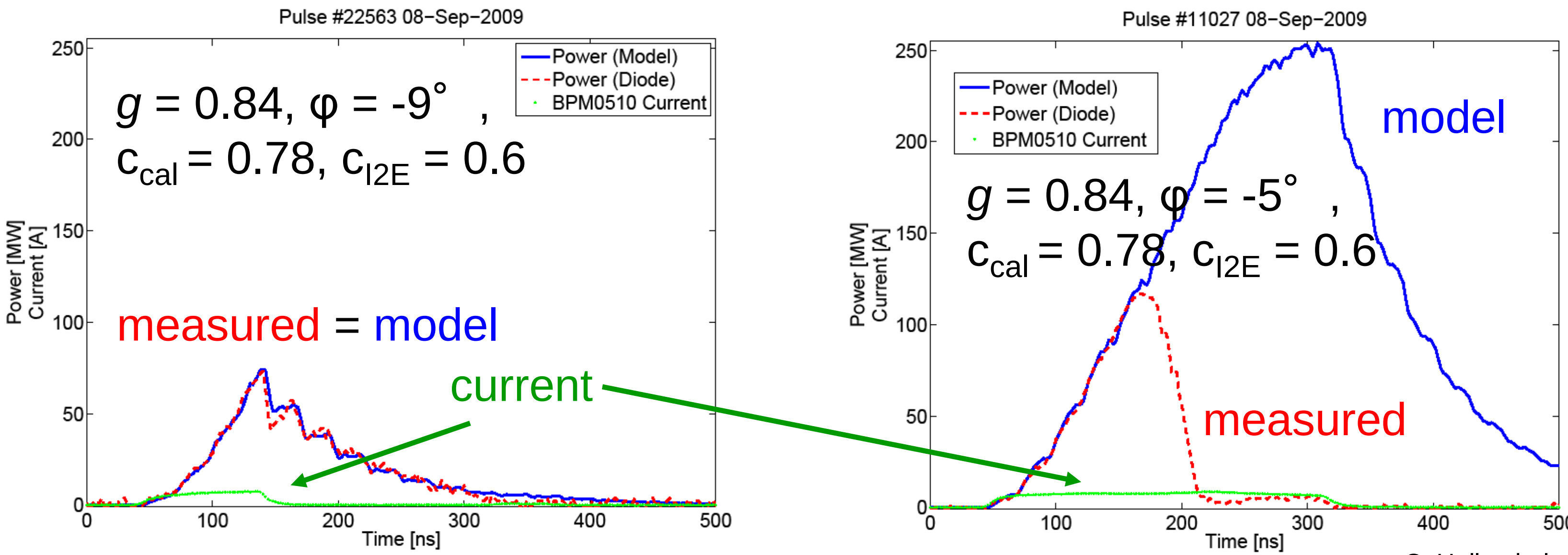
- PETS length 1m, to compensate for lower beam current compared to CLIC
- External recirculation loop
  - increase PETS power in long pulse, low current mode #3
- power recirculation through external feedback loop:
  - electron bunch generates field burst
  - field burst returns after roundtrip time $t_r = 26$ns

  PETS operates as amplifier (LASER like)
- phase shifter to adjust phase error in the loop





Power Reconstruction with Recirculation



C. Hellenthal,
CLIC Note 811 (2009)

- Parameters constant during normal operation
  → predicts PETS output power (CTF3 Note 092, 094, 096)
- Accurate parameter fit rising slope
  → gives recirculation loop loss factor and phase shift
- Energy difference (ε) measurement and model indicates ”pulse shortening” → breakdown indicator

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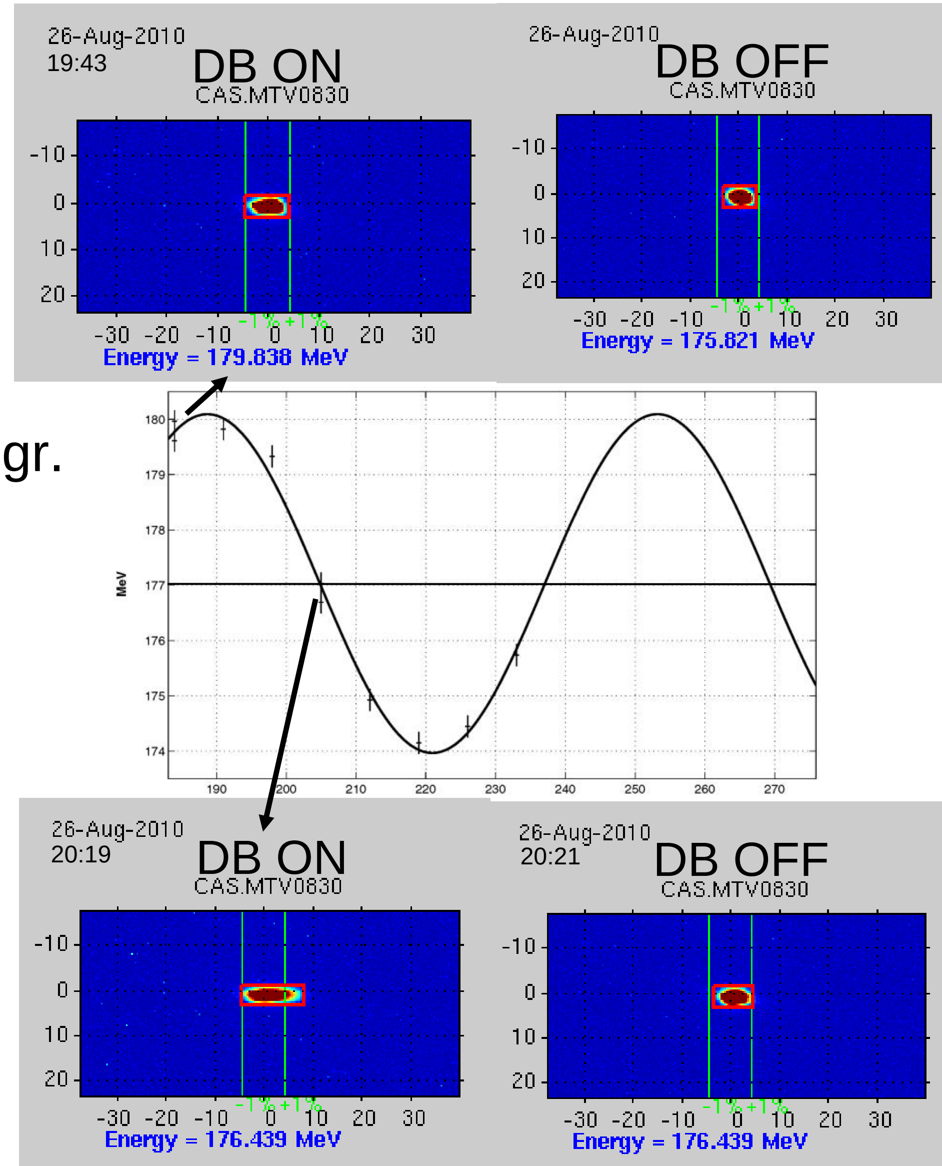
First Trial Probe Beam Acceleration

- Fine tuning DB↔PB timing
  - **3GHz phase scan klystron**
  - coherent with 1.5GHz laser timing signal
- **~6 MeV peak-to-peak**
  - zero crossing: 177 MeV, 205 degr.
  - phase scaling: 5.58 (expect 4x)
- optimize
  - PB energy spread & bunching
  - klystron pulse compression
  - coherency klystron and laser
  - low input power (ACS not conditioned)



Two-beam Acceleration Experiments

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- Probe beam repetition rate is twice the drive beam rep-rate,
- DB / PB relative timing and phase adjusted to maximize energy and minimize energy spread after ACS,
- PB pulse length 10 to 100 ns,
- DB pulse length 100 to 240 ns.

Raw video of the spectrum line MTV screen

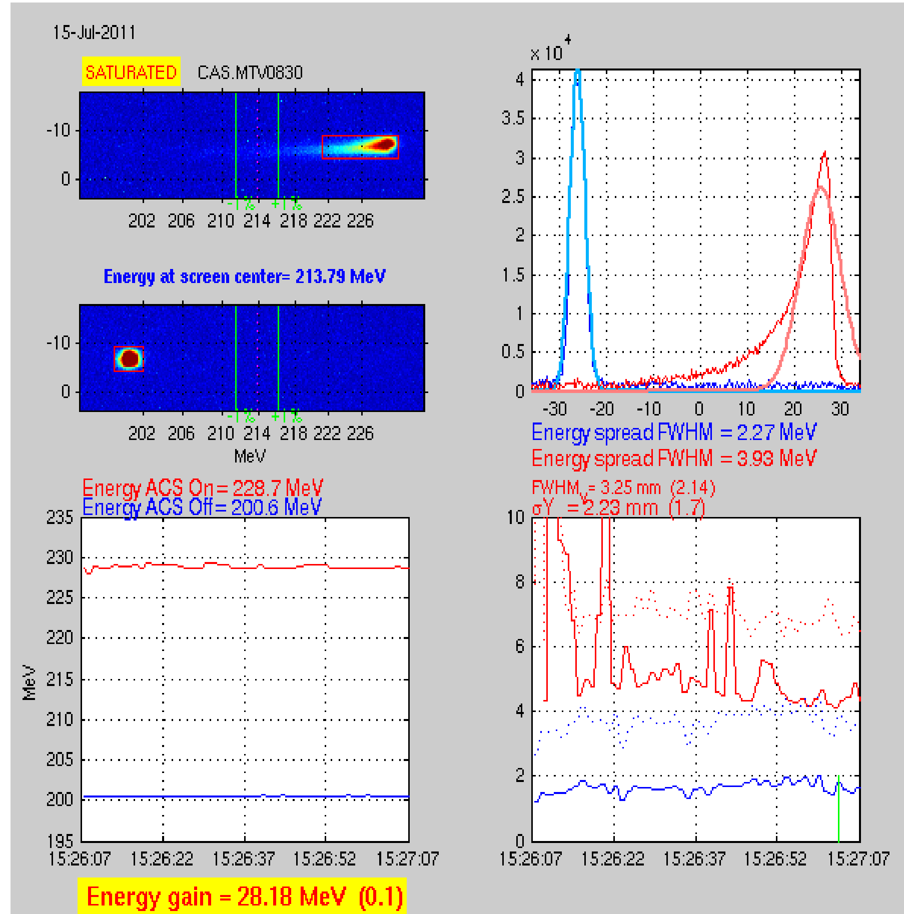

Image processing of the spectrum line MTV screen

Conditioning Process

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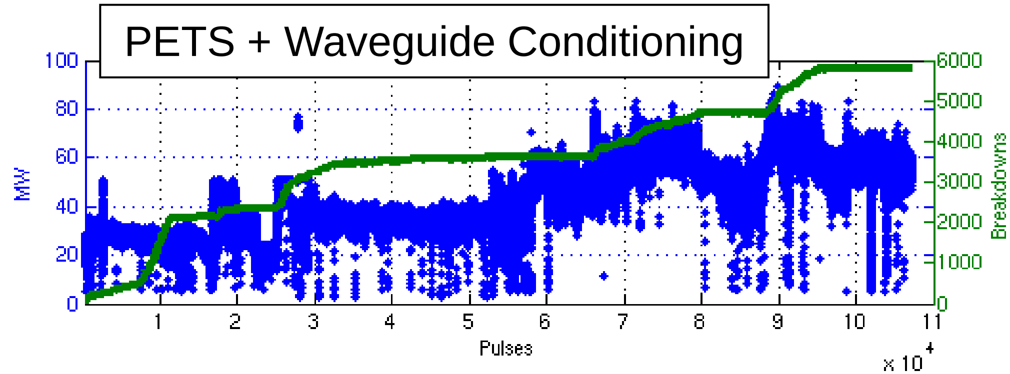
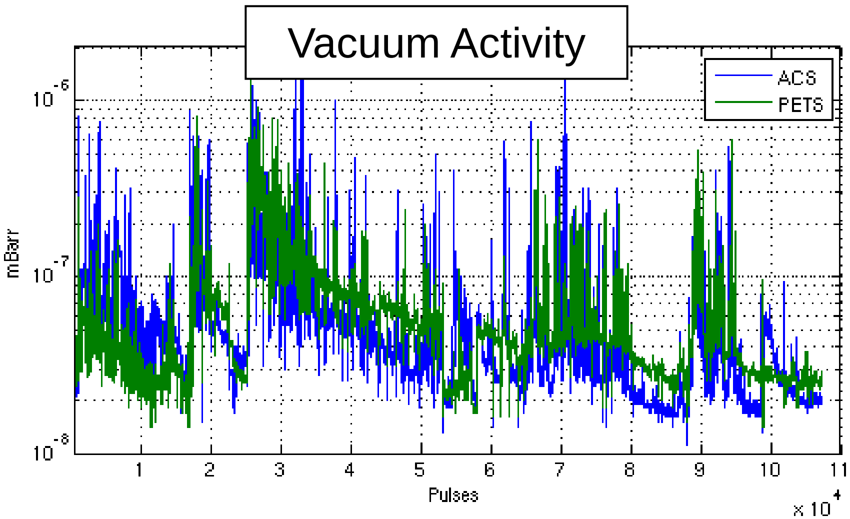
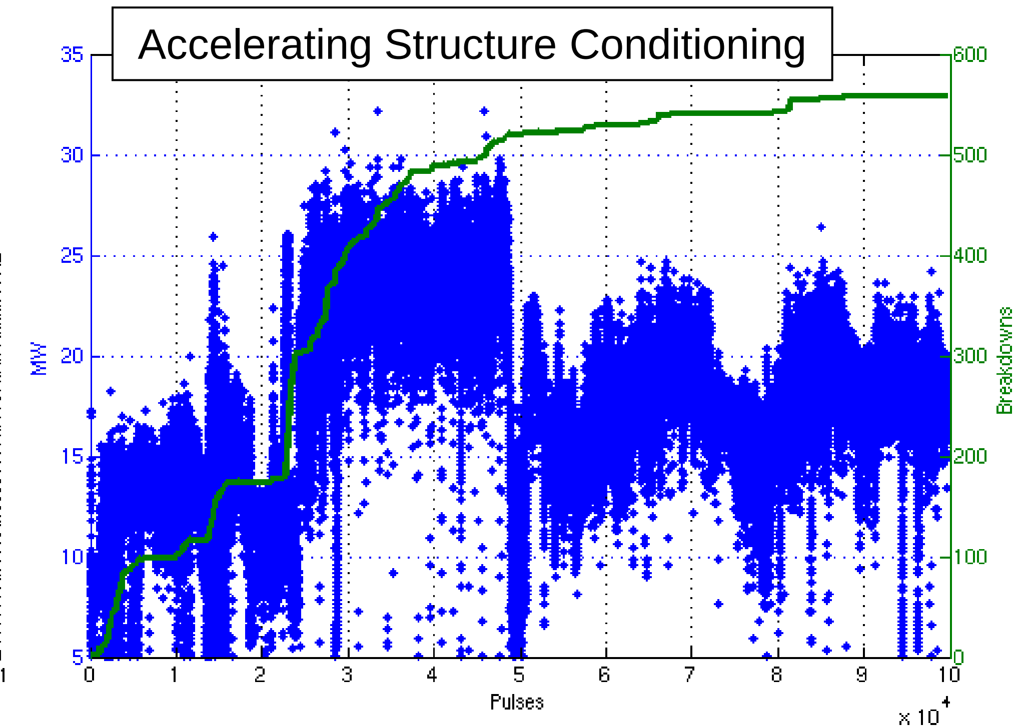
Present stable level:

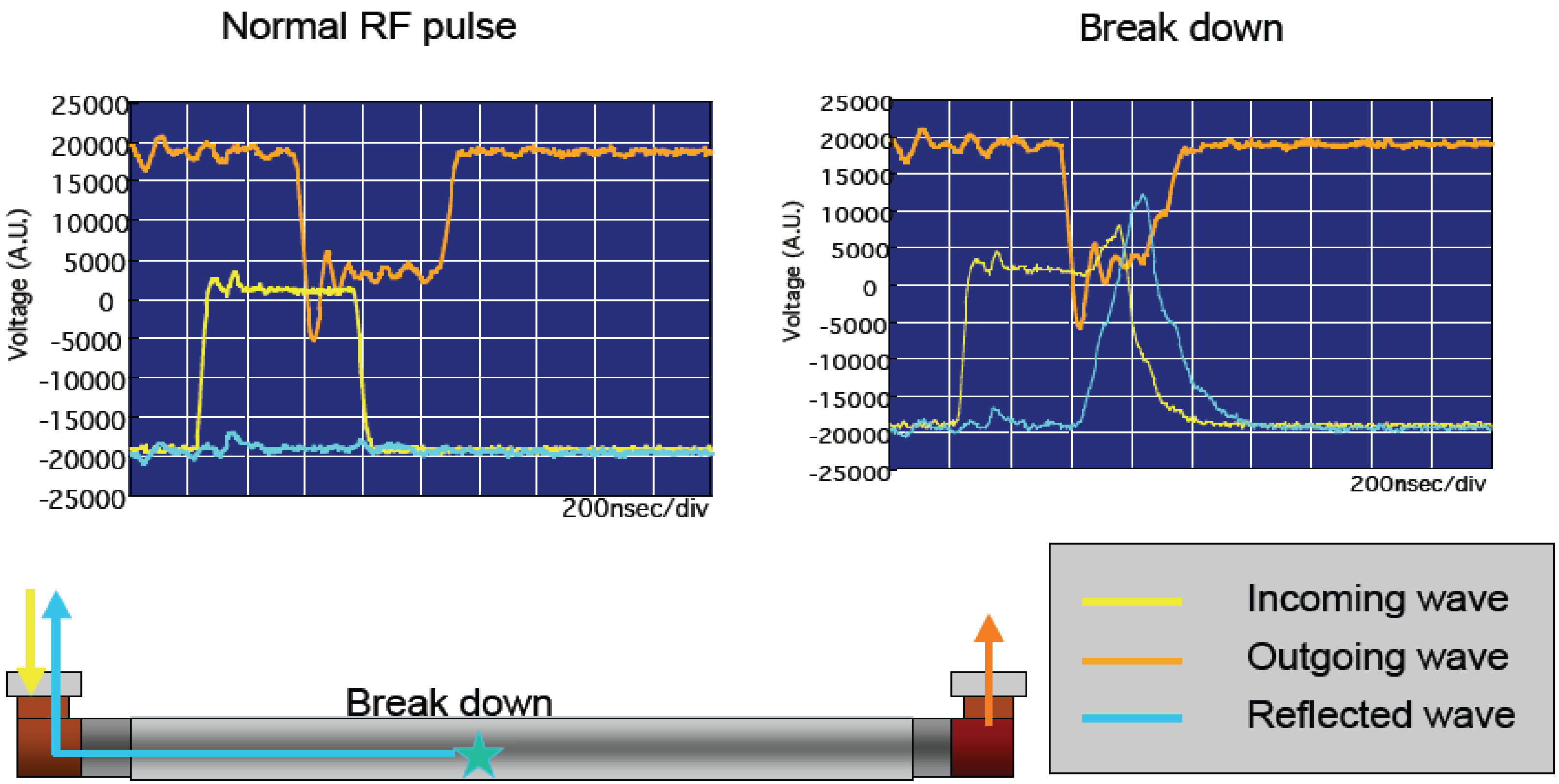
- PETS + recirculation loop
  - ~70 MW peak power,
  - ~200 ns pulse
- Accelerating structure
  - ~23 MW peak power







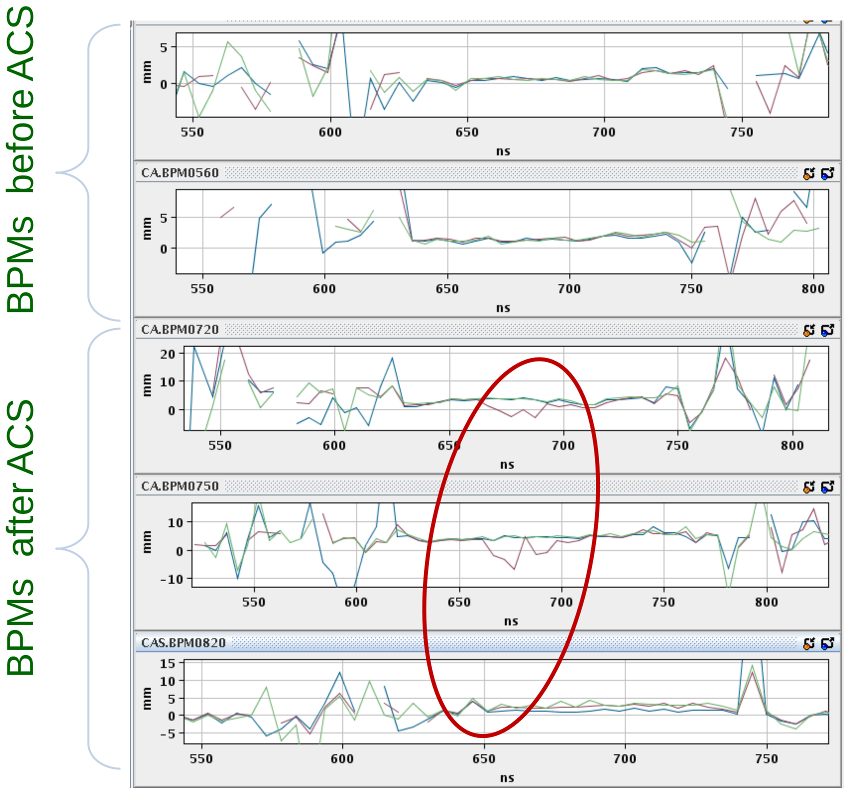
RF Waveform Distortion on Breakdown



from S.Fukuda/KEK

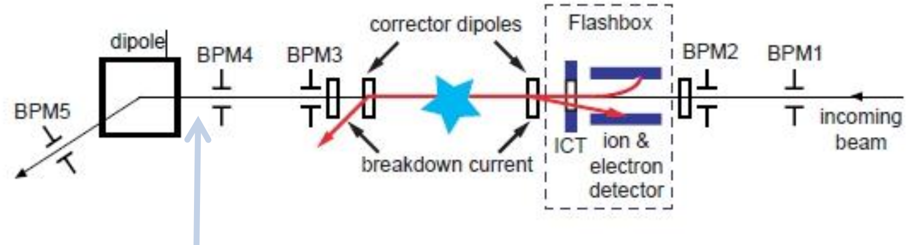
- Pulses with breakdowns not useful for acceleration (beam kick and instabilities)
- Low breakdown rate required (< 10^{-6}) for useful operation

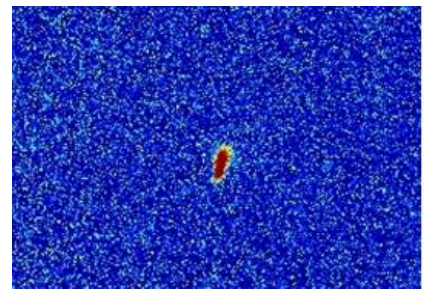
Breakdown Kick



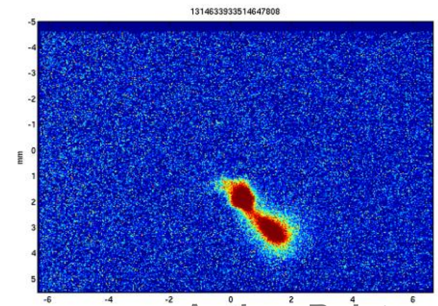
Volker Ziemann

Possible kick recorded during a breakdown



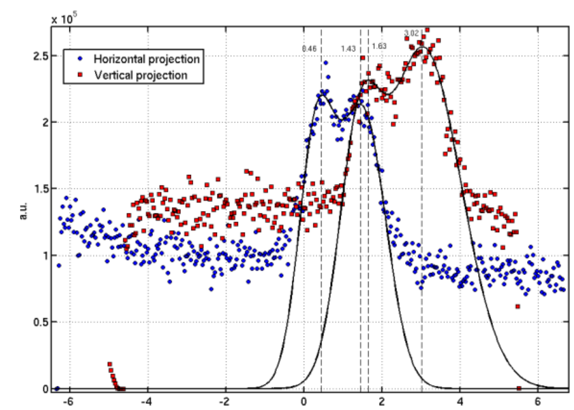


Beam without BD



Andrea Palaia

Beam with BD
Kick : 0.4 mrad



- Present BPM noise level too high,
- Measurements with MTV screen instead.

Beam Kick Measurements

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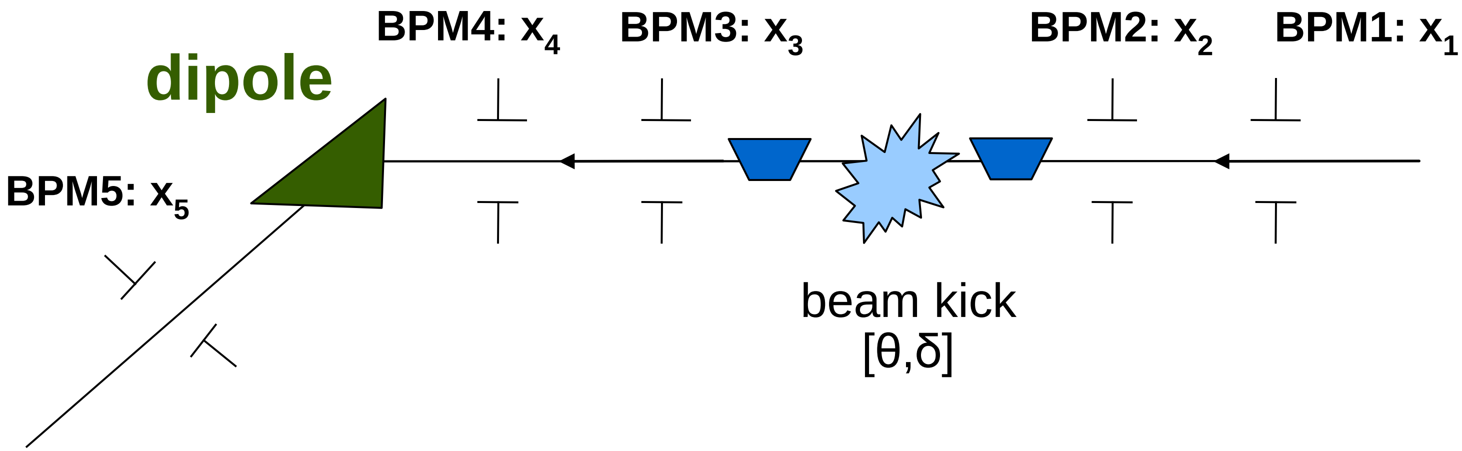
M. Johnson, CLIC Note 710



- 5 BPMs: incoming angle & offset, kick angle
- dipole + BPM5 for energy measurement

$$\vec{x} = A\vec{\theta}$$

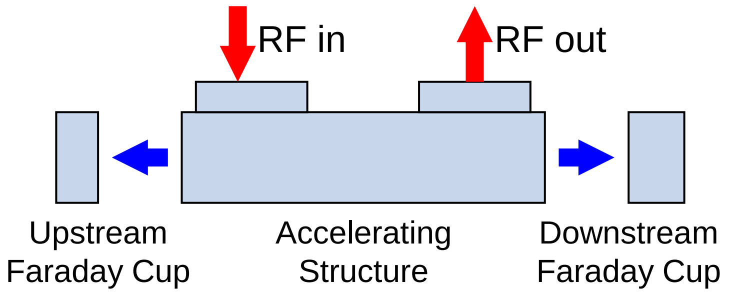
$$\vec{\theta} = (A^t A)^{-1} A^t \vec{x}$$

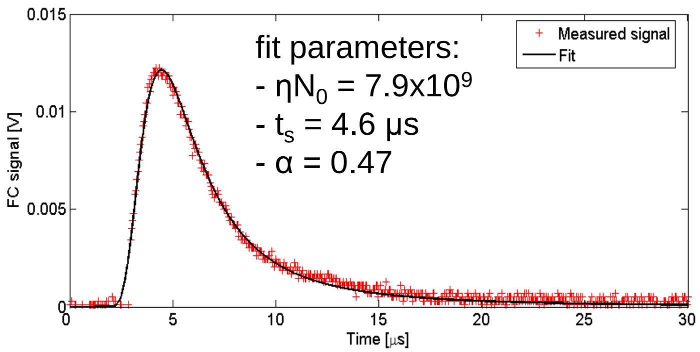
$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ R_{11}^{12} & R_{12}^{12} & 0 & 0 \\ R_{11}^{13} & R_{12}^{13} & R_{12}^{c3} & 0 \\ R_{11}^{14} & R_{12}^{14} & R_{12}^{c4} & 0 \\ R_{11}^{15} & R_{12}^{15} & R_{12}^{c5} & D^5 \end{pmatrix} \begin{pmatrix} x_1 \\ x_1' \\ \theta \\ dp/p \end{pmatrix}$$

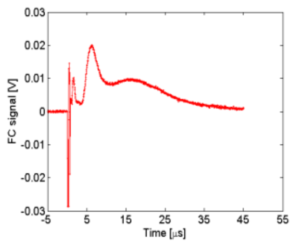
Ion Currents from RF Breakdown

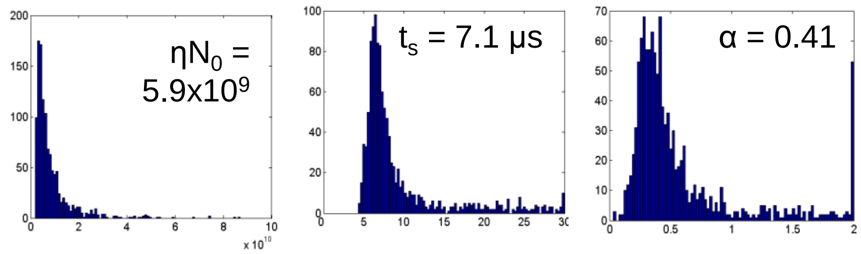
studied in CTF3 mid-linac test stand

- arrival time profile at Faraday cup consistent with "hot Coulomb" explosion, allows calculation
  - amount of particles ($>10^{10}$)
  - temperature ($> 10^5$ K)
- need detailed analysis to improve understanding
  - sometimes multiple peaks









need method to study in presence of beam

RF Breakdown: a Reliability Issue

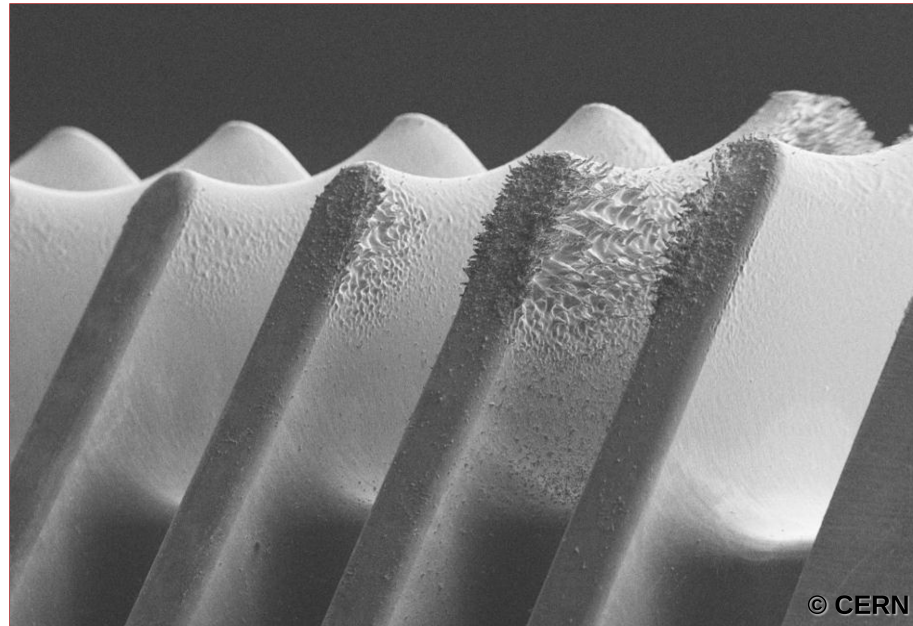
Conditioning required

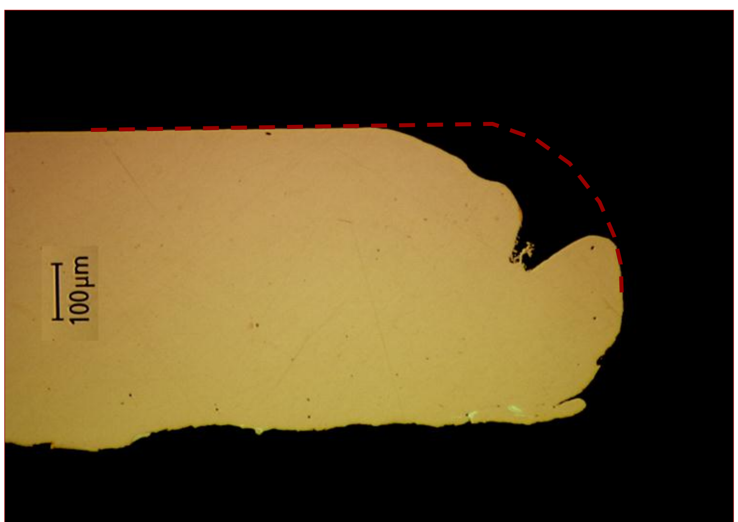
- to reach nominal gradient

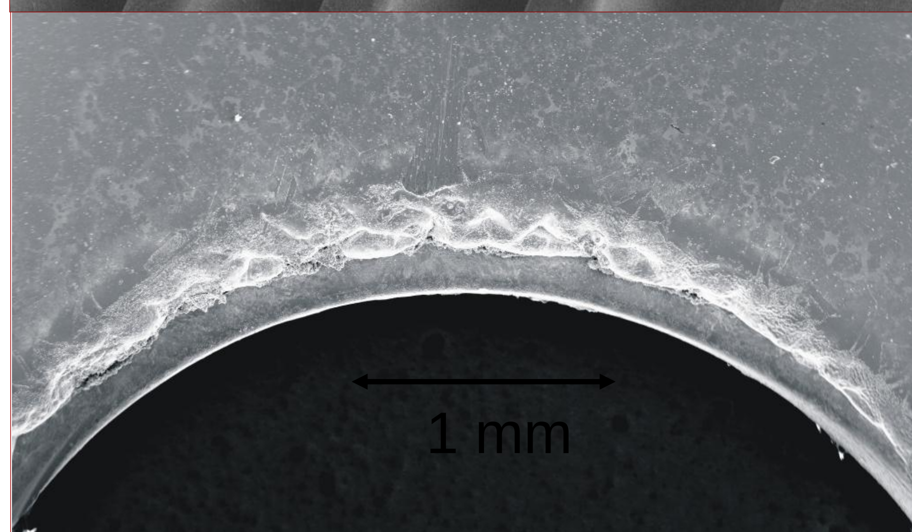
but

- damage by excessive field

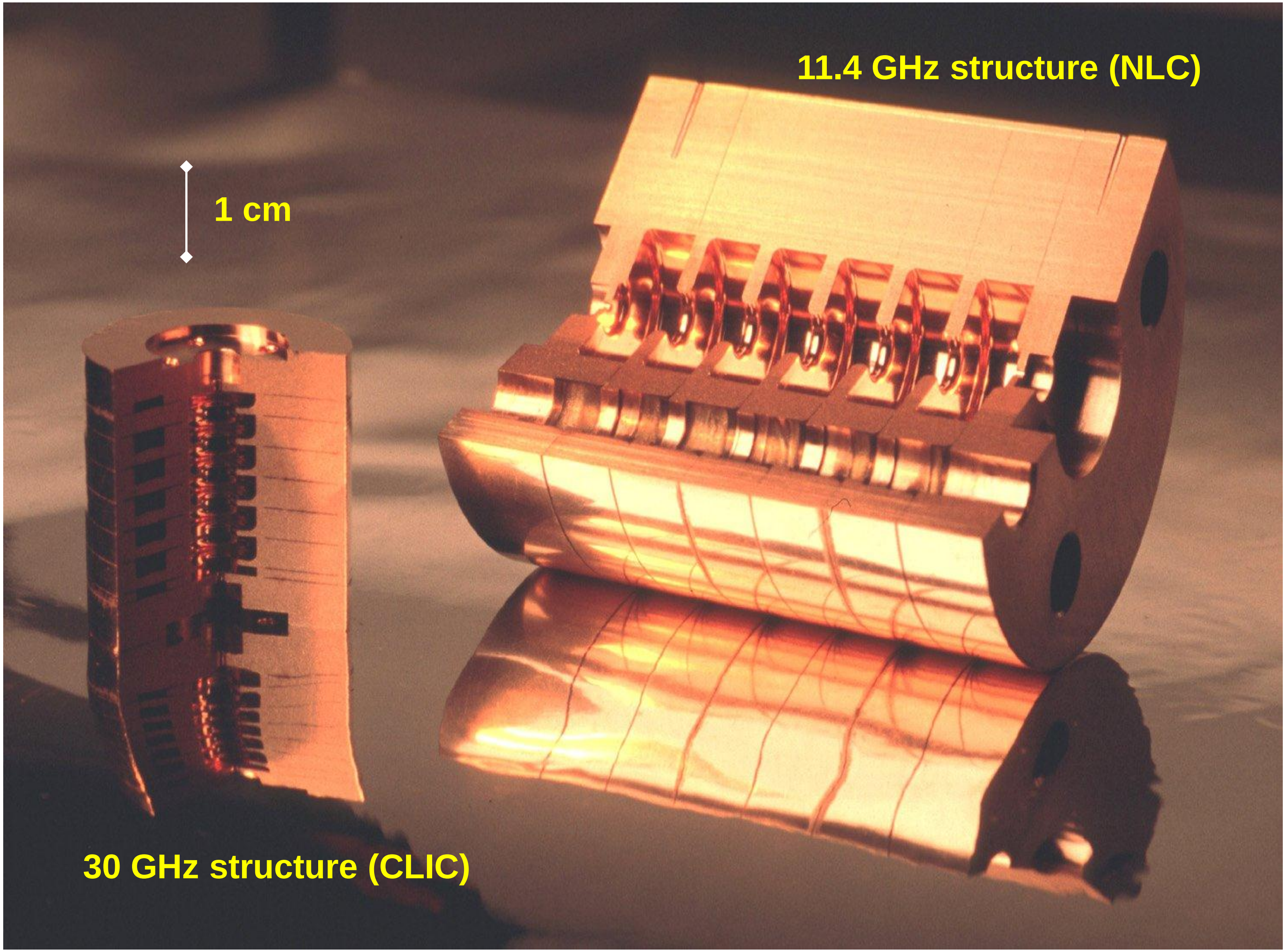
Physics phenomena not yet completely understood!







High Frequency Iris Loaded Waveguide Structures



High Frequency Structures

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- CLIC type
- T18_vg2.4_disk

- designed at CERN
- build by KEK
- tested at SLAC

- E_{acc} = 106 MV/m
- 11.424 GHz
- 230 ns pulse length
- 10^{-6} breakdown rate (BDR)

Frequency	11.424	GHz
Cells	18+input+output	
Filling Time	36	ns
Length	29	cm
Iris Dia. a/λ	15.5~10.1	%
Group Velocity: v_g/c	2.61-1.02	%
S_{11}/ S_{21}	0.035/0.8	
Phase Advace Per Cell	2π/3	
Power Needed $<E_a>$=100MV/m	55.5	MW

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Conclusions

- Reached first milestones towards feasibility demonstration:
  - Drive beam generation with appropriate time structure and fully loaded acceleration.
  - Two-beam acceleration with CLIC prototype structures.
- Continued operation and enhancements:
  - Optimize beam and two-beam acceleration.
  - Investigate RF breakdown effects on beam.
  - 12 GHz klystron powered test stand.

Many thanks to all colleagues, their work and their suggestions!