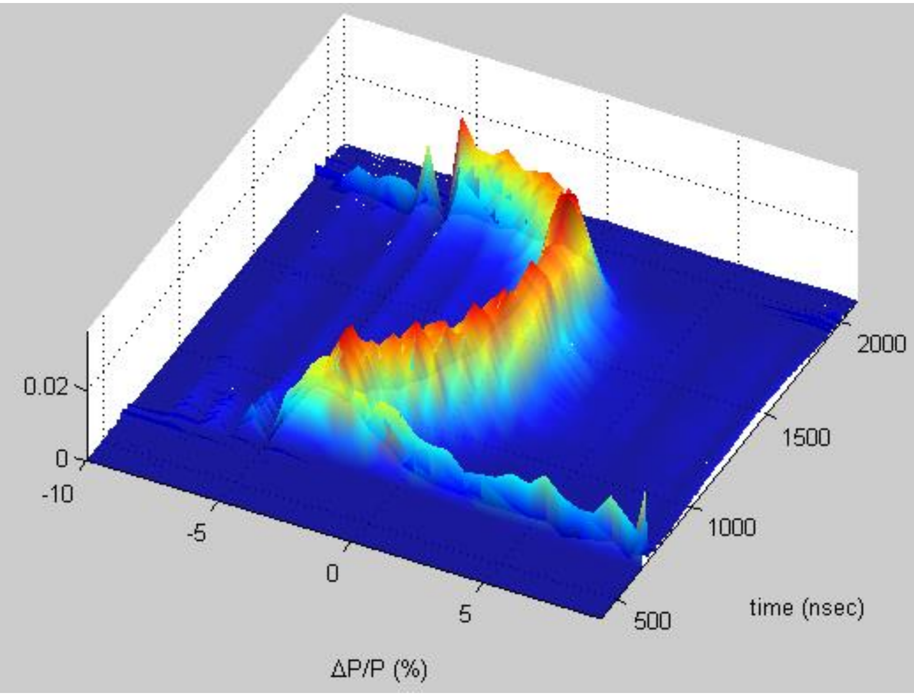
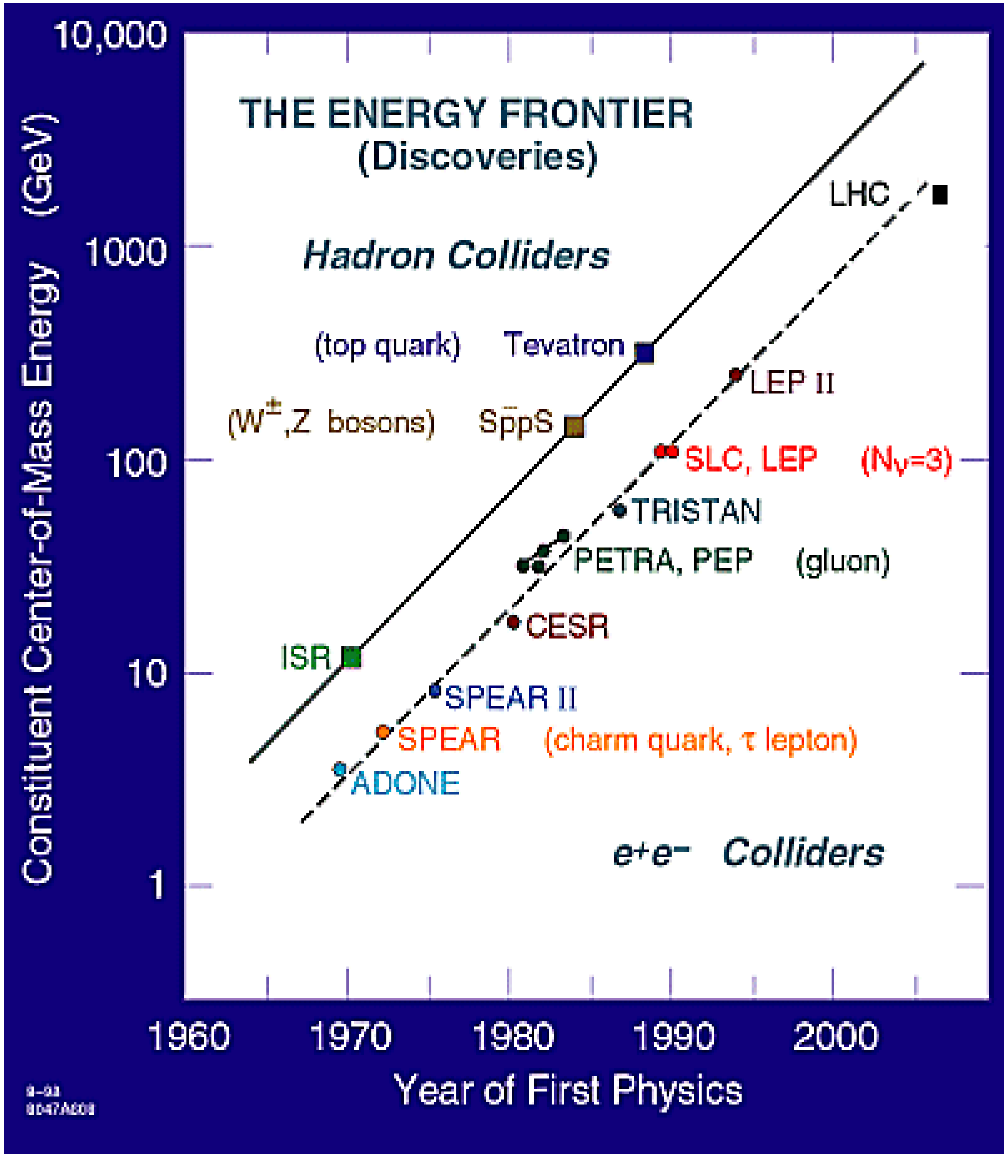
Diagnostics Examples from CTF3

Frank Tecker - CERN

- Introduction CLIC / CTF 3
- CTF3 diagnostics
  - Longitudinal
  - Transverse
  - Other



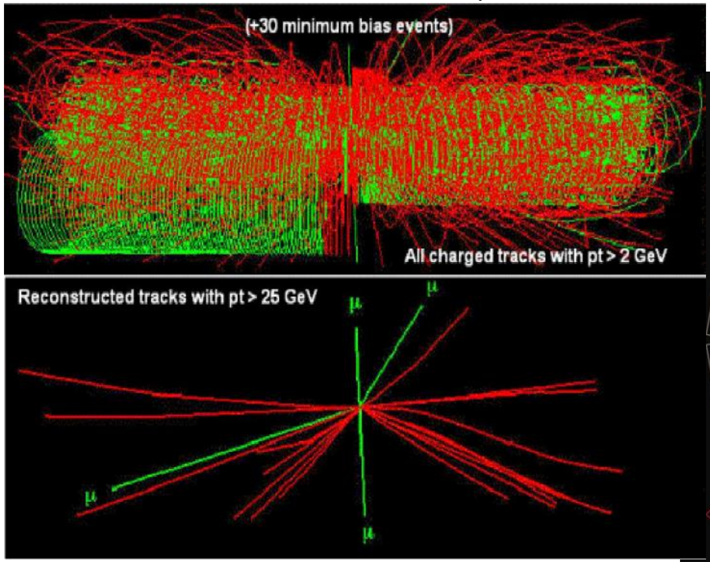
Path to higher energy

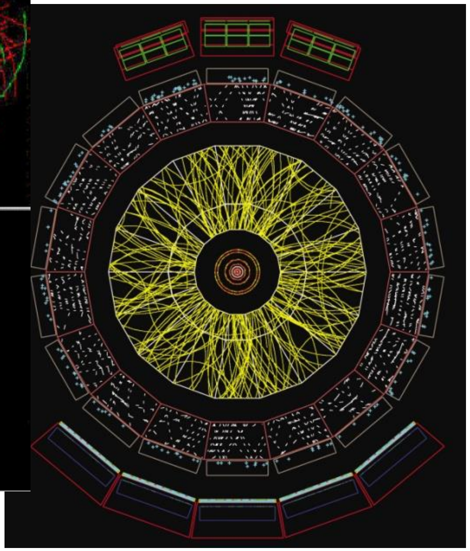


- History:
  - Energy constantly increasing with time
  - Hadron Colliders at the energy frontier
  - Lepton Colliders for precision physics
- LHC has found the Higgs with $m_H = 126\ \mathrm{GeV}/c^2$
- A future Lepton Collider would complement LHC physics

LHC vs. Lepton Collisions

LHC: H → ZZ → 4μ

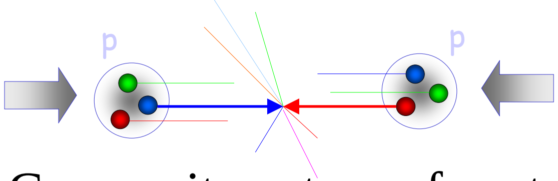




ALICE: Ion event

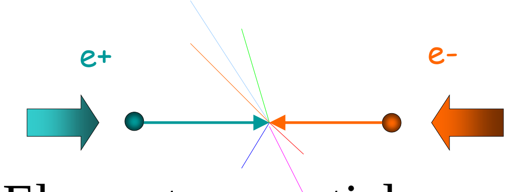
LEP event: $Z^0 \rightarrow$ 3 jets

- Hadron Collider (p, ions):



  - Composite nature of protons
  - Can only use p_t conservation
  - Huge QCD background

- Lepton Collider:



  - Elementary particles
  - Well defined initial state
  - Beam polarization
  - produces particles democratically
  - Momentum conservation eases decay product analysis

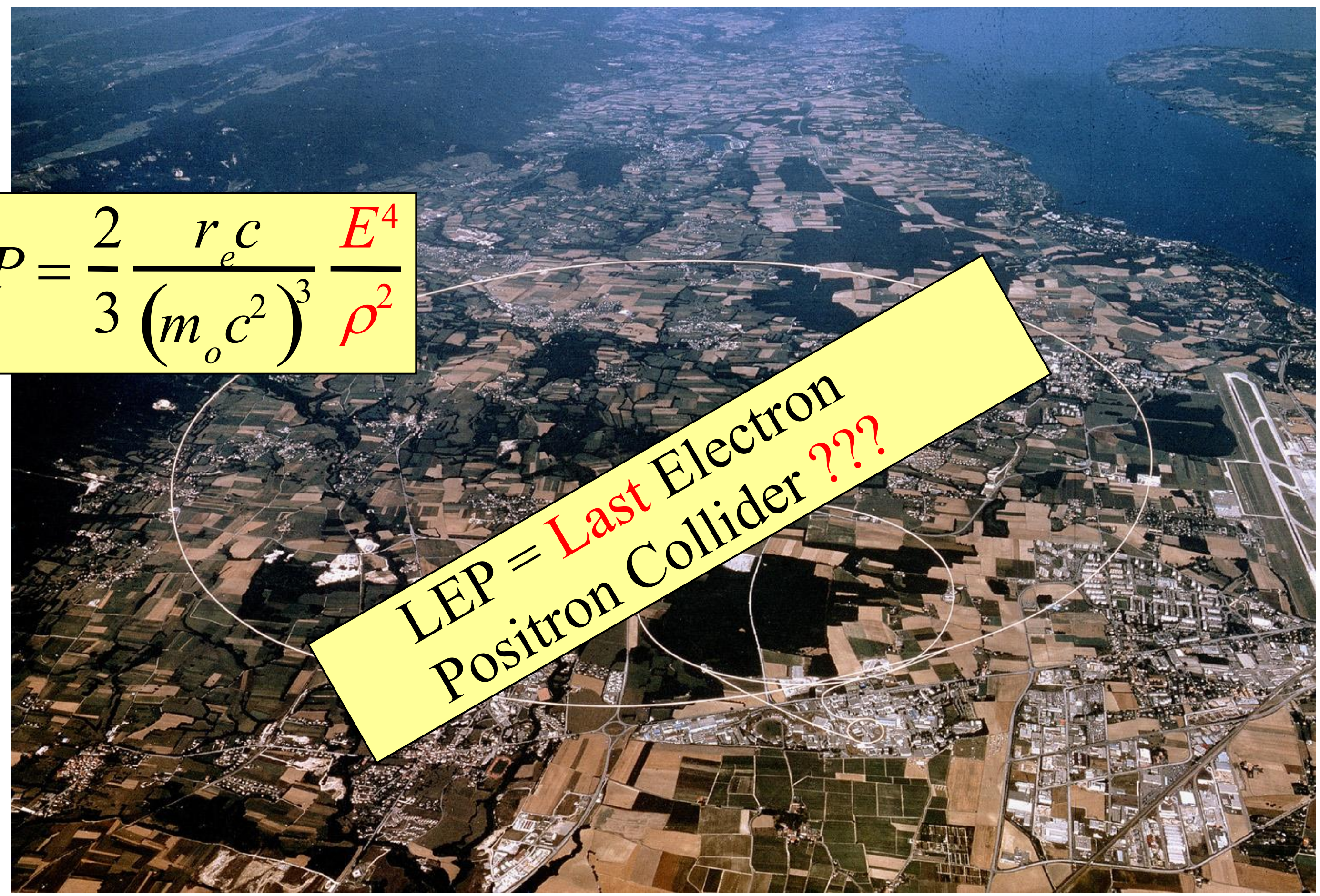
Much more precise analysis with leptons => precision measurements of particle properties

The LEP collider

- LEP (Large Electron Positron collider) was installed in LHC tunnel
- e+ e- circular collider (27 km) with E_{cm}=200 GeV

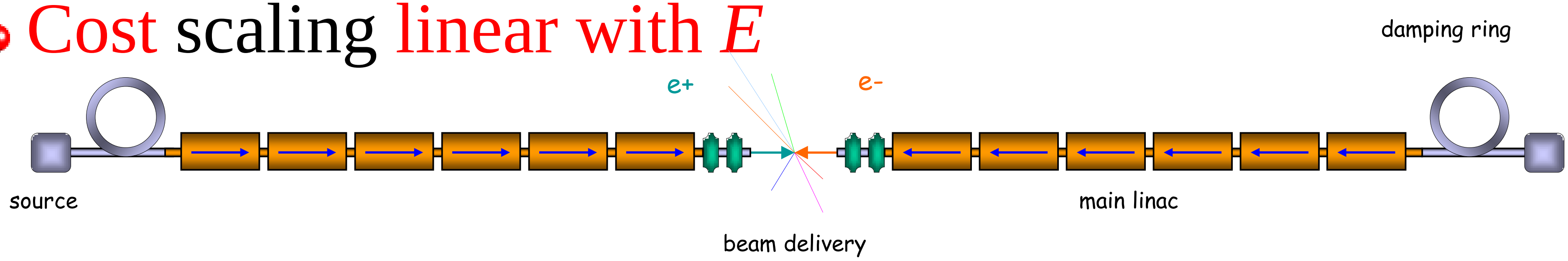
- Problem for any ring:
  Synchrotron radiation
- Emitted power:
  scales with E^4 !!
  and $1/m_0^3$ (much less for heavy particles)
- This energy loss must be replaced by the RF system !!
- particles lost 3% of their energy each turn!

$$P = \frac{2}{3} \frac{r_e c}{(m_o c^2)^3} \frac{E^4}{\rho^2}$$



The solution: a Linear Collider

- NO bending magnets ⇒ NO synchrotron radiation
- but: A lot of accelerating structures !!!
- Cost scaling linear with E



- **Storage rings:**
  - accelerate + collide every turn
  - 're-use' RF + 're-use' particles
- => efficient

- **Linear Collider:**
  - one-pass acceleration + collision

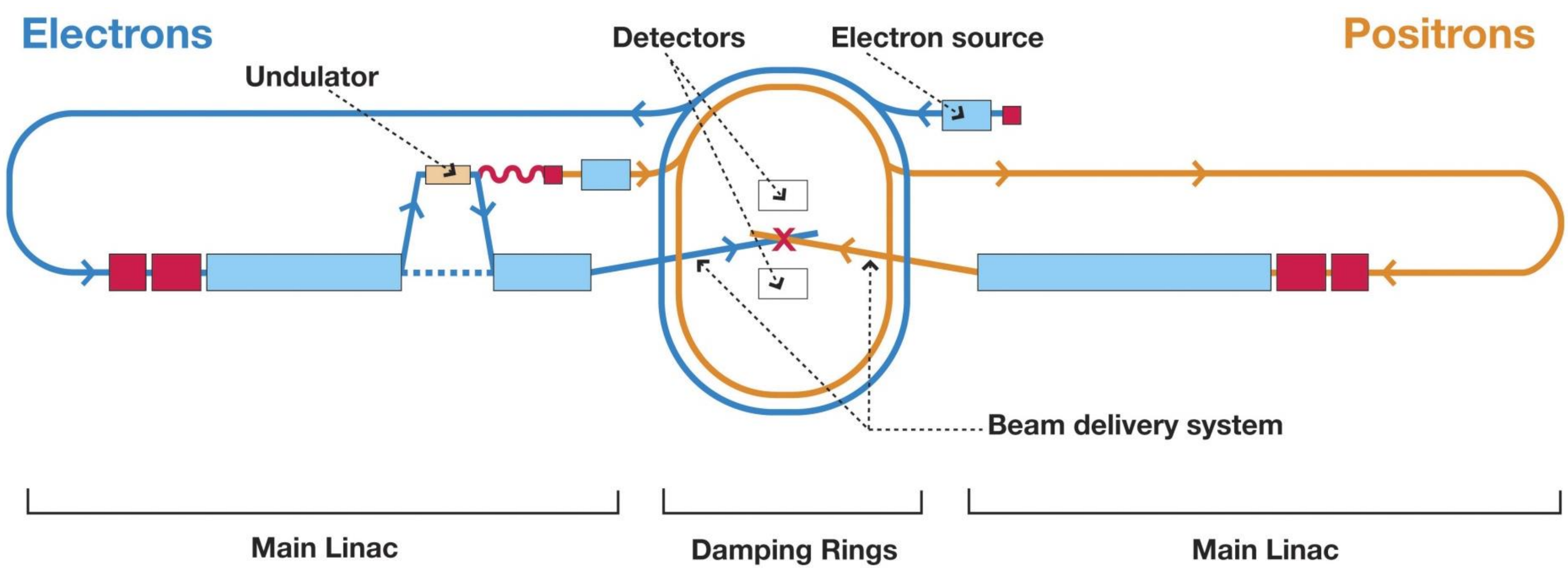
  => need
  - high gradient (acceleration)
  - small beam size

  to reach high event rate (Luminosity)

Linear Collider projects

- ILC (International Linear Collider)
  - Superconducting technology
  - 1.3 GHz RF frequency
  - ~31 MV/m accelerating gradient
  - 500 GeV centre-of-mass energy
  - upgrade to 1 TeV possible
- CLIC (Compact Linear Collider)
  - normalconducting technology
  - 100 MeV/m
  - multi-TeV energy range (nom. 3 TeV)

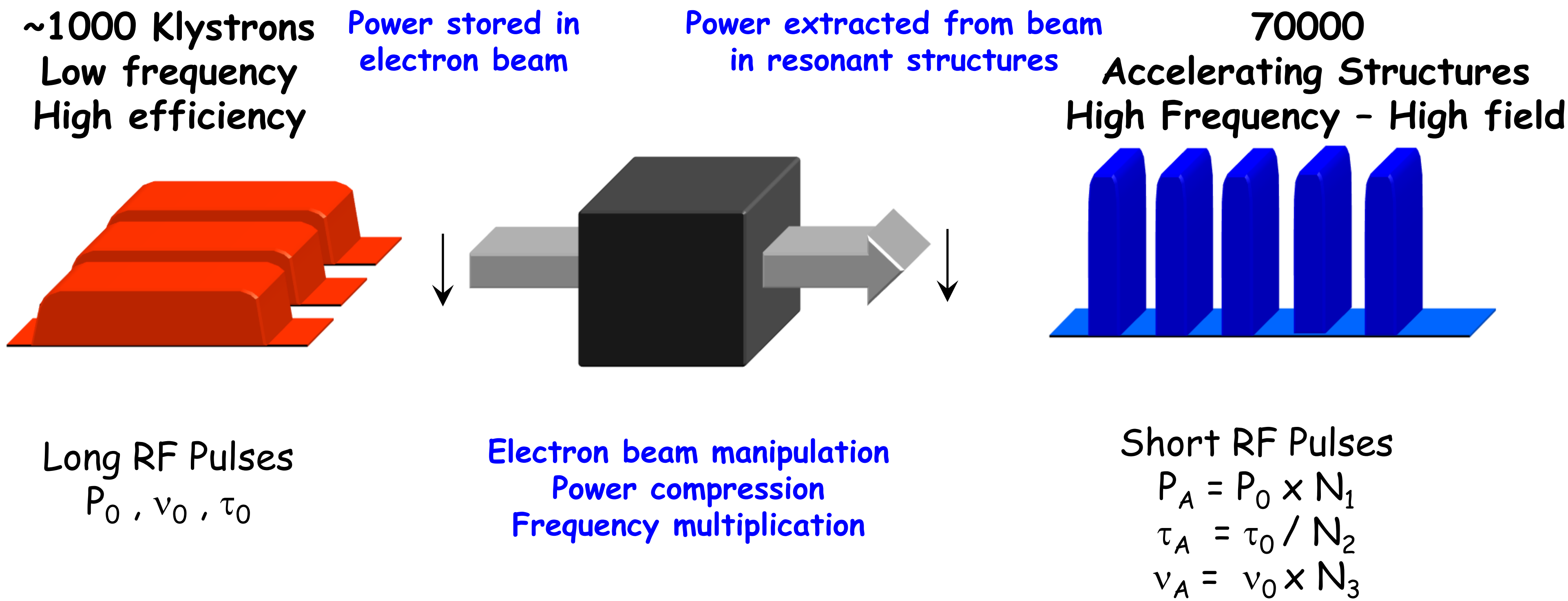
~35 km total length



CLIC scheme

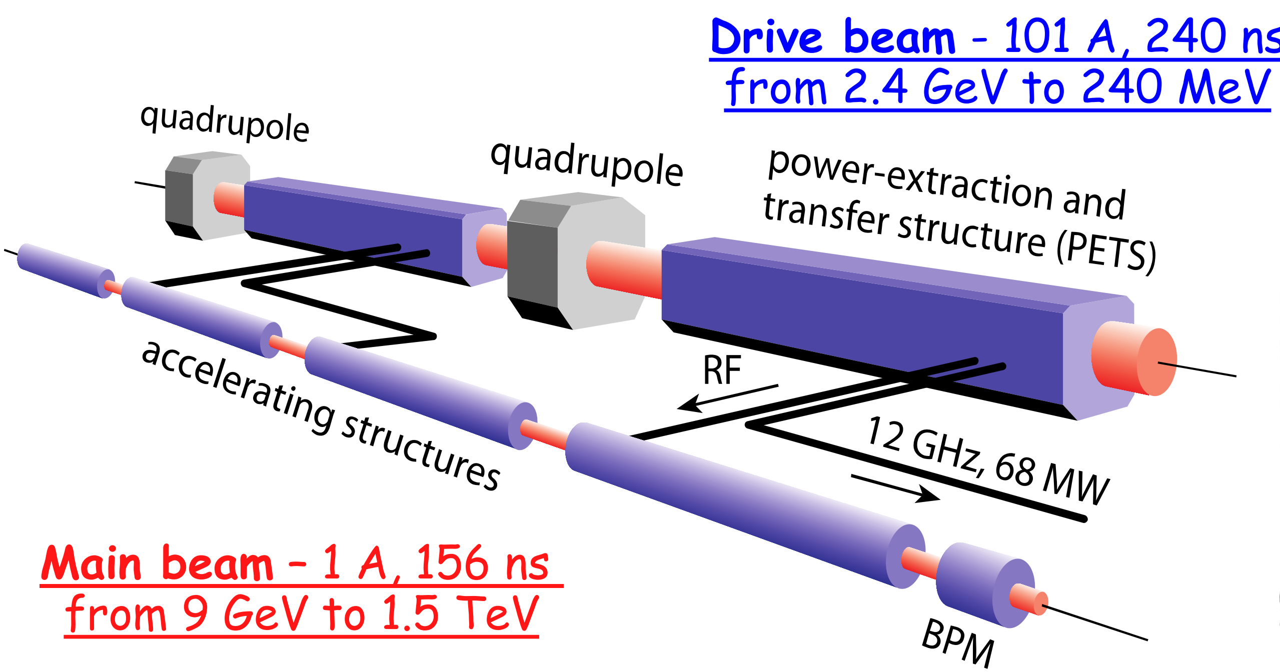
- Very high gradients (~100 MV/m) possible with NC accelerating structures at high RF frequencies (>12 GHz) for short RF pulses
- Extract RF power from an intense electron “drive beam”
- Generate efficiently long pulse + compress it (in power + frequency)

=> **Need short bunches with the correct time structure (12 GHz)**

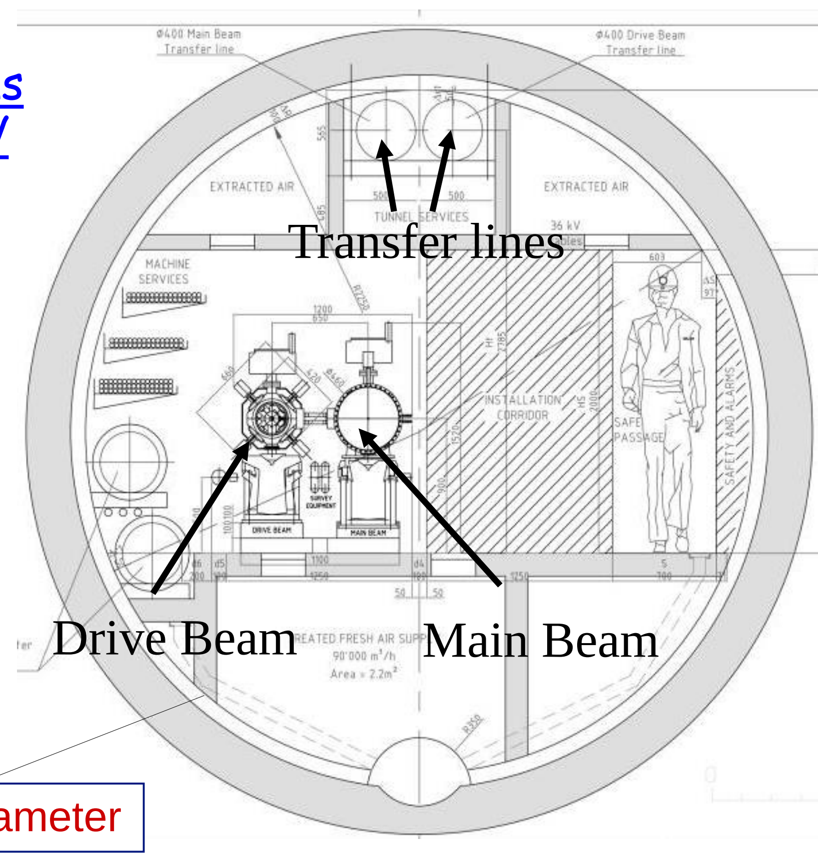


CLIC two beam scheme

- High charge electron Drive Beam (low energy)
- Low charge Main Beam (high collision energy)
- => Simple tunnel, no active elements
- => Modular, easy energy upgrade in stages
  380 GeV => ~1.5 TeV => 3 TeV

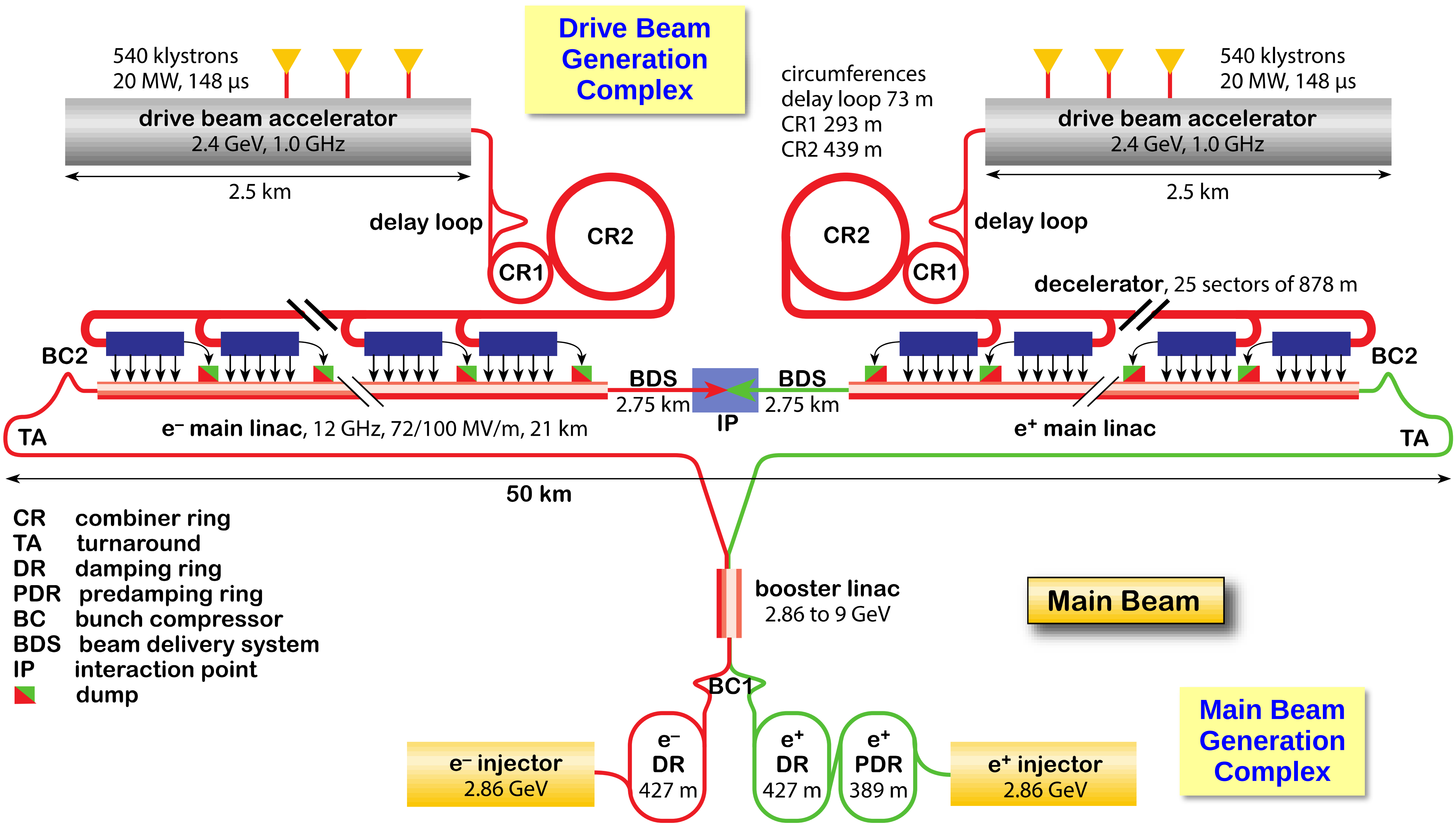


CLIC TUNNEL
CROSS-SECTION

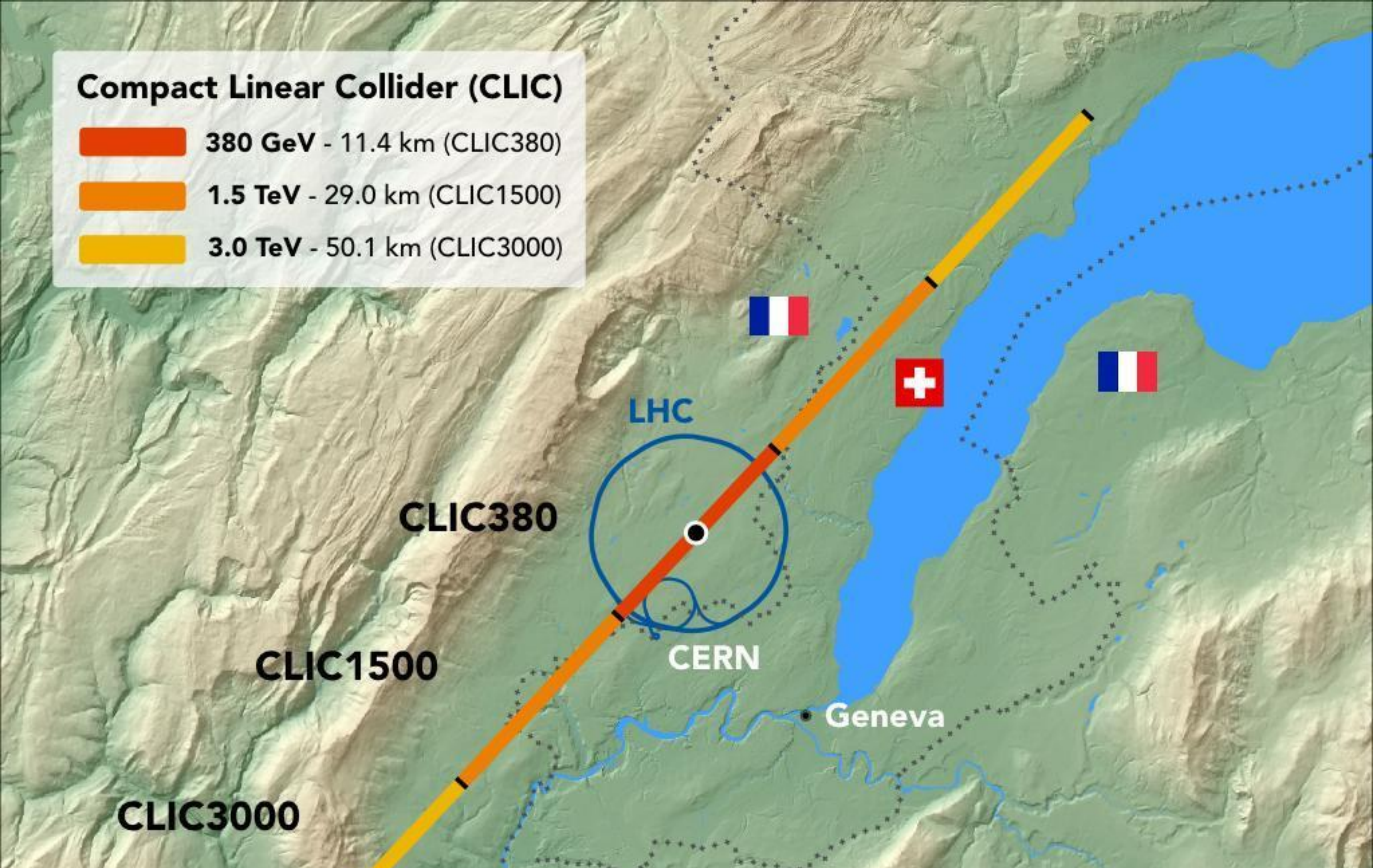


5.6 m diameter

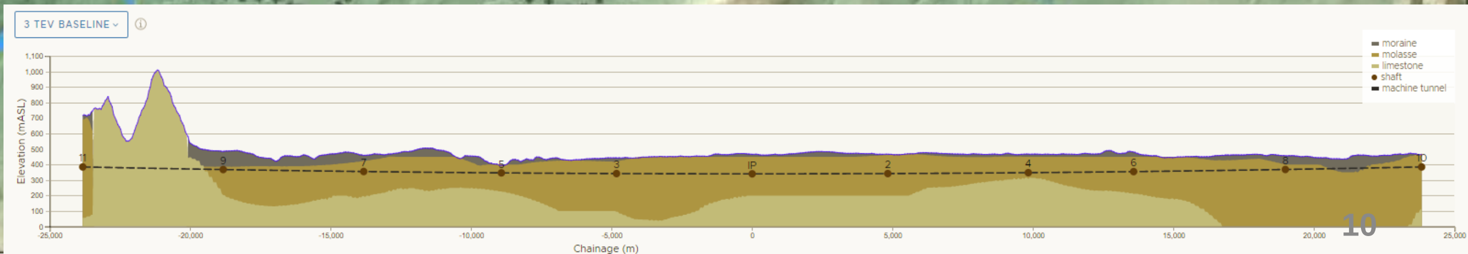
CLIC – overall layout – 3 TeV



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



Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
LHC
CLIC380
CLIC1500
CLIC3000
CERN
Geneva

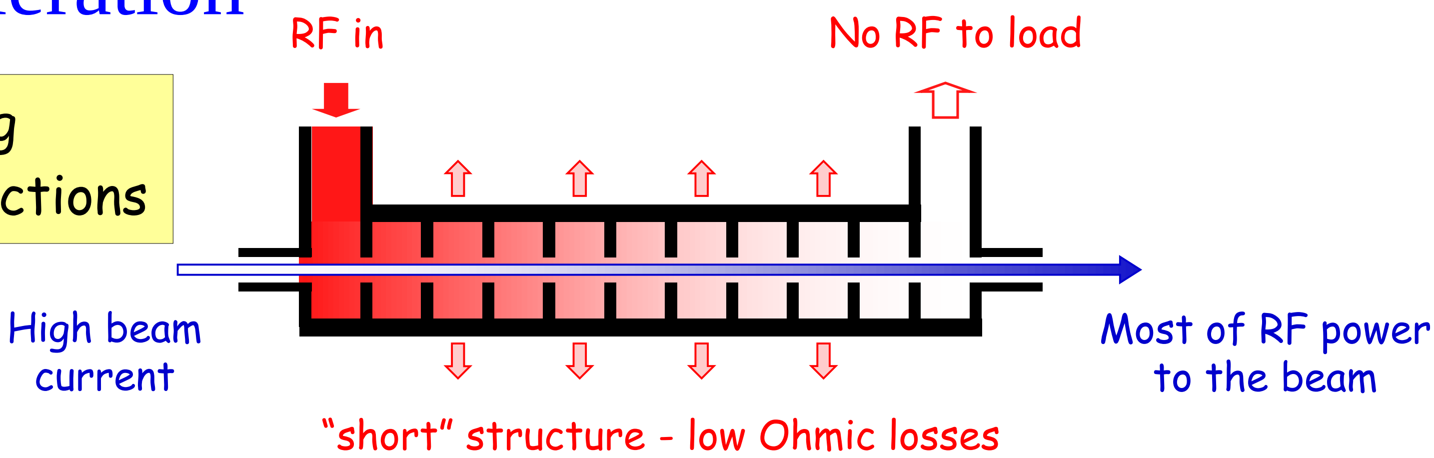


3 TEV BASELINE
moraine
molasse
limestone
shaft
machine tunnel
Elevation (mASL)
Chainage (m)

Drive beam generation basics

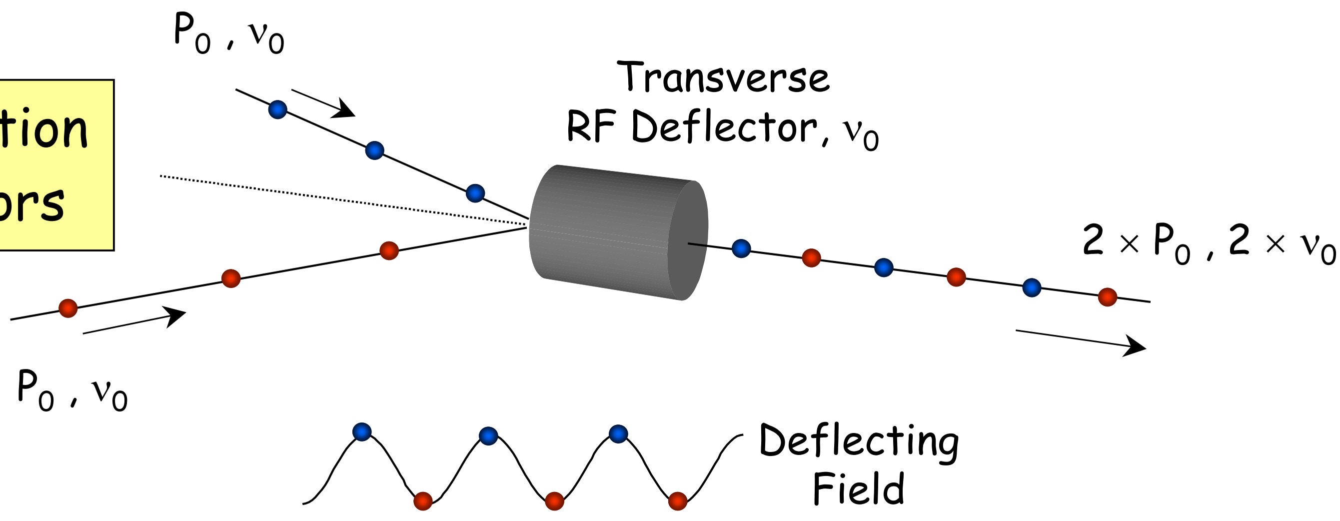
- Efficient acceleration

Full beam-loading acceleration in TW sections

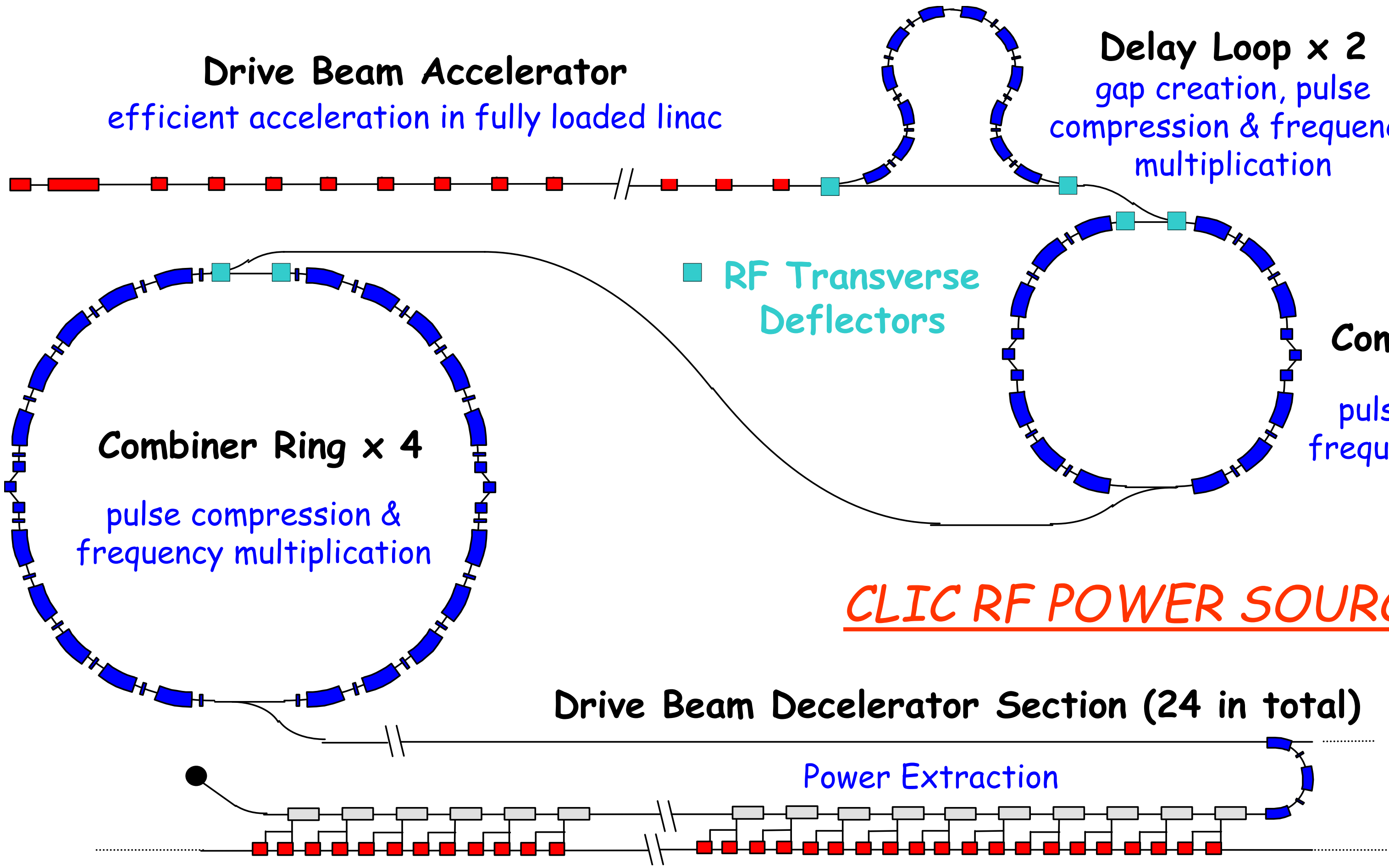


- Frequency multiplication

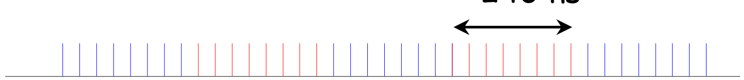
Beam combination/separation by transverse RF deflectors



CLIC Drive Beam generation

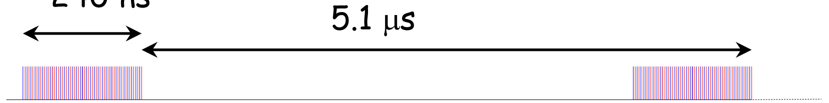


Drive beam time structure - initial



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

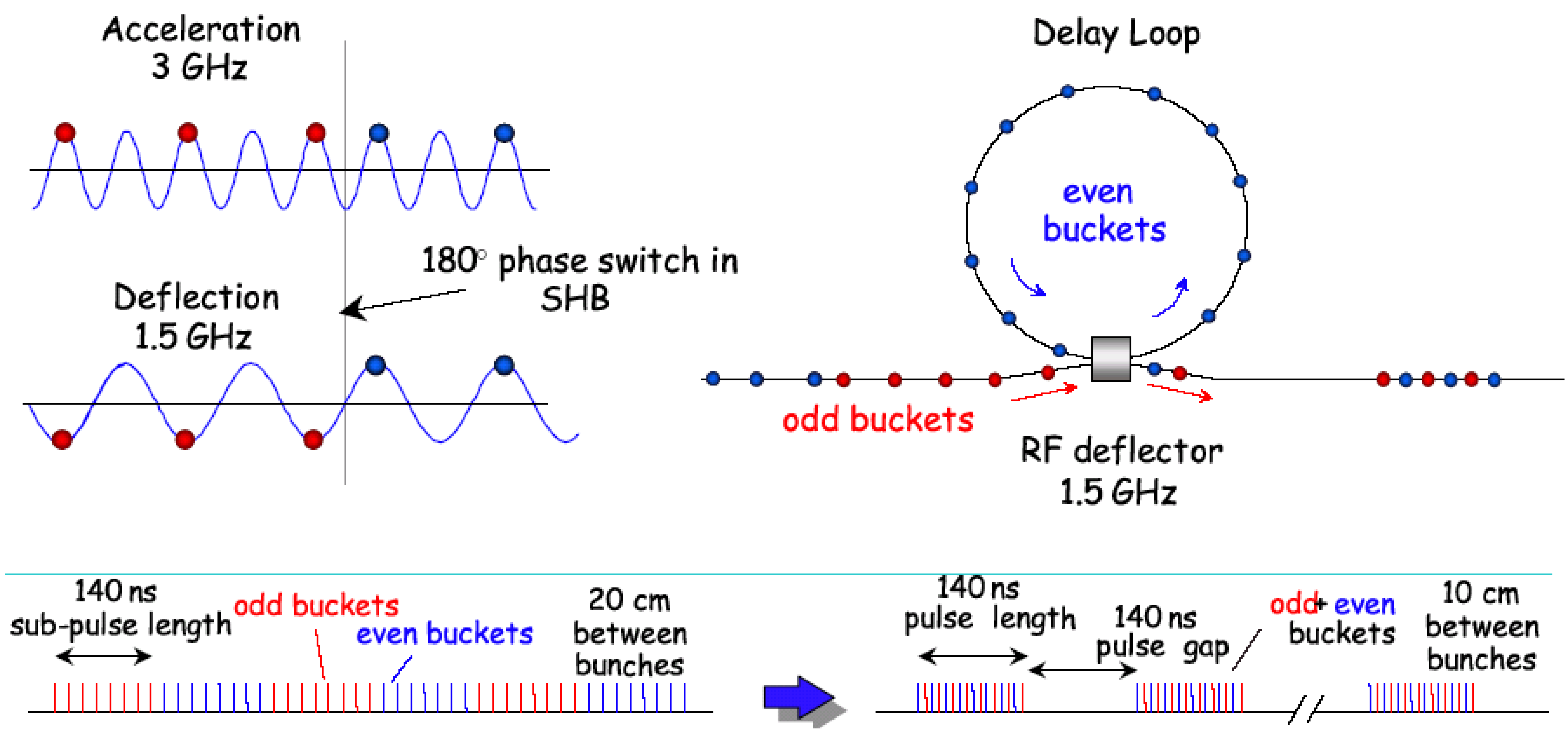
Drive beam time structure - final



24 pulses – 100 A – 2.5 cm between bunches

Delay Loop Principle

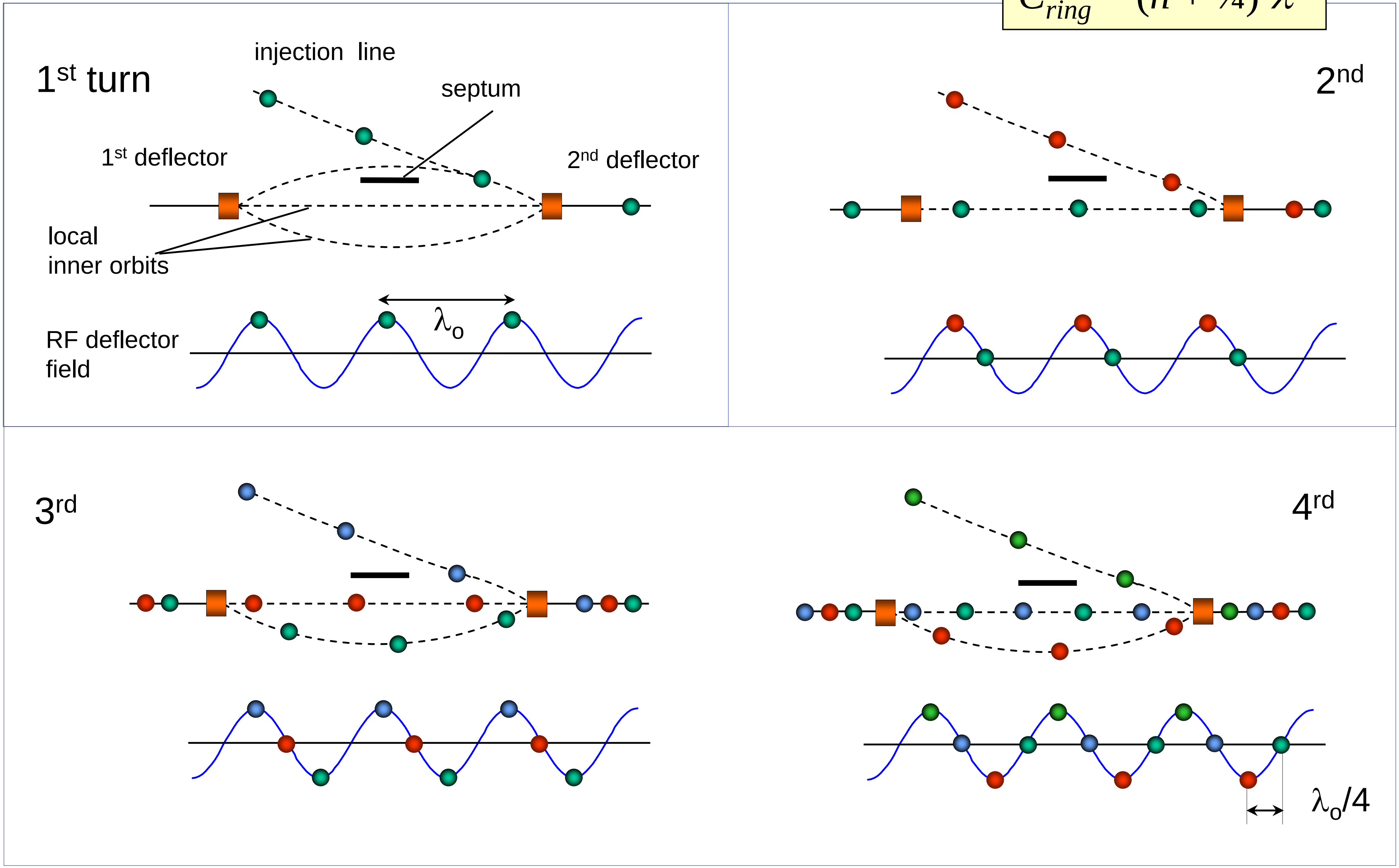
- **double repetition frequency and current**
- parts of bunch train delayed in loop
- RF deflector combines the bunches



RF injection in combiner ring

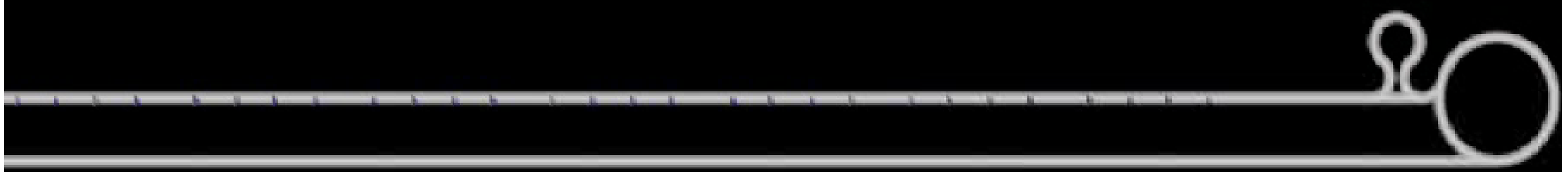
- combination factors up to 5 reachable in a ring

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



Lemmings Drive Beam

Beam Diagostic:
Lemming counters -> Intensity
Lemming speed -> Momentum, Energy
Lemming path -> Position overlap
Lemming distance -> Longitudinal Combination
Lemming shape -> Transverse overlap

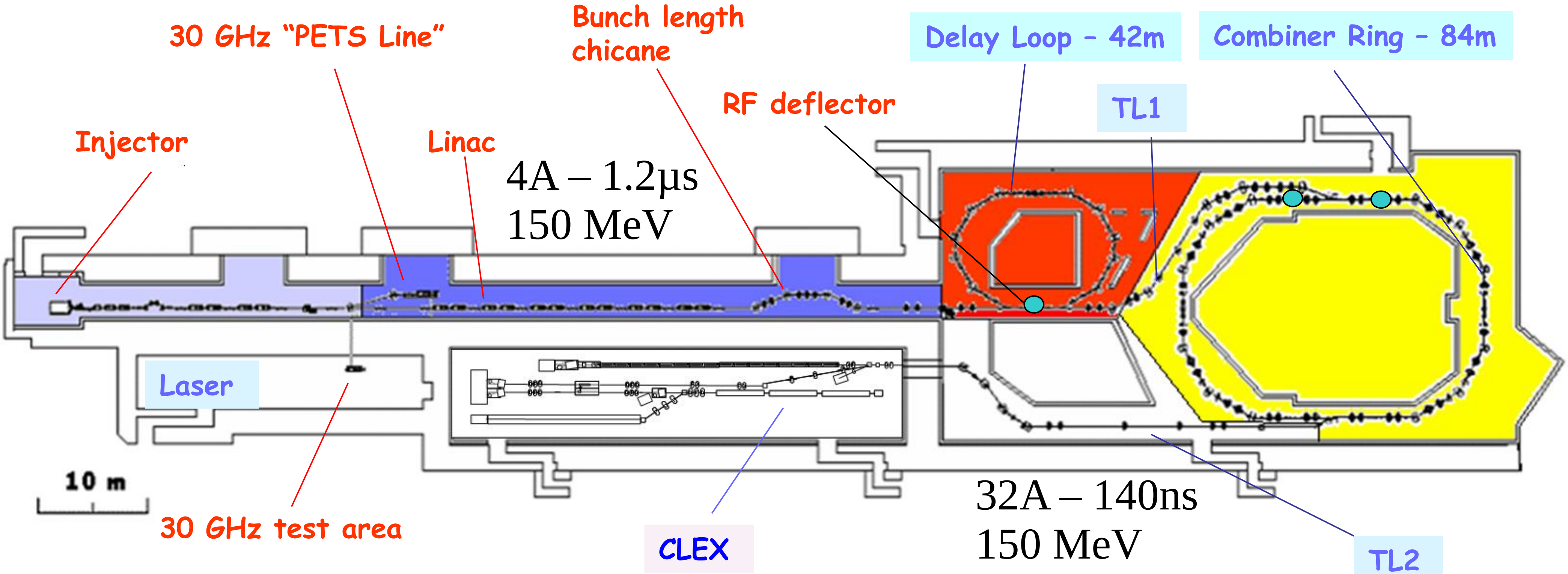


Disclaimer:
No animals were hurt for this movie!!

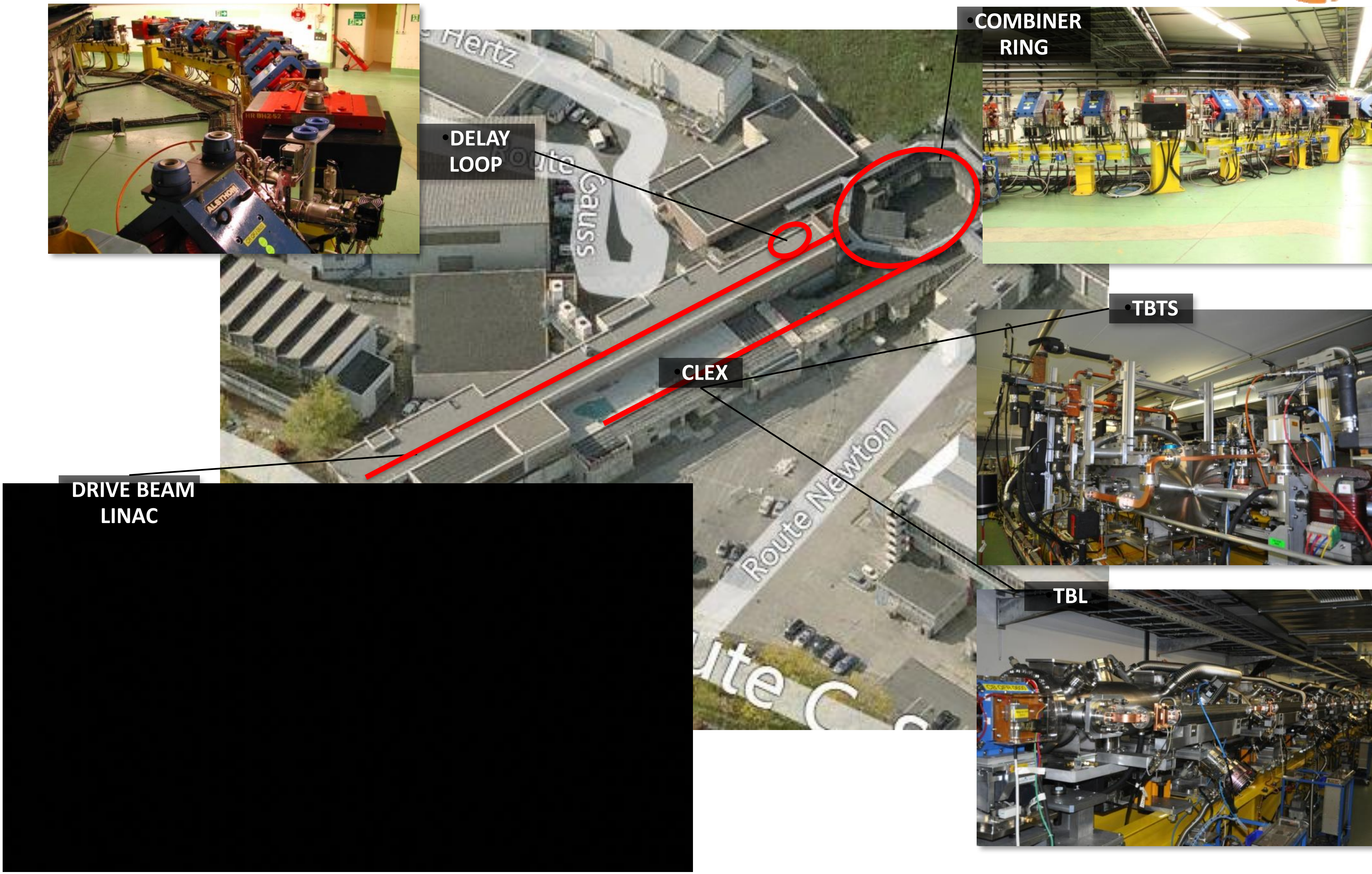
Alexandra Andersson

CTF 3

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

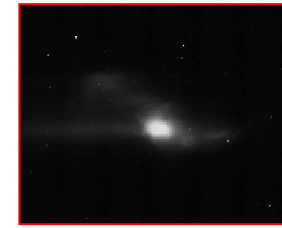


CLIC Test Facility (CTF3)



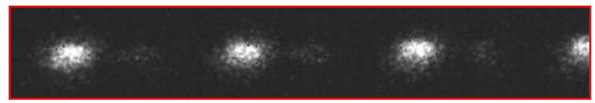
CTF3 Instrumentation Overview

- Screens (OTR, fluorescence) for beam imaging

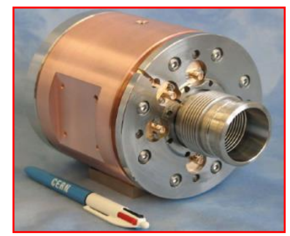


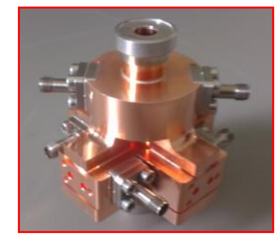
- Several technologies of Beam loss monitors

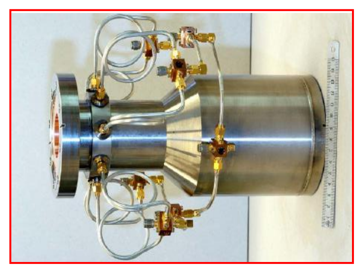
- Longitudinal profile with RF deflecting cavity, streak camera and electro-optical monitors



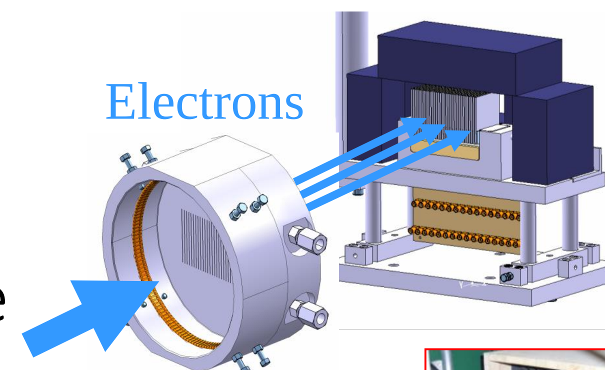
- Large variety of Beam Position Monitors
  - High resolution cavity BPMs
  - Inductive pick-up
  - Strip-line BPM







- Fast Wall Current Monitors
- Segmented dump: time resolved beam profile

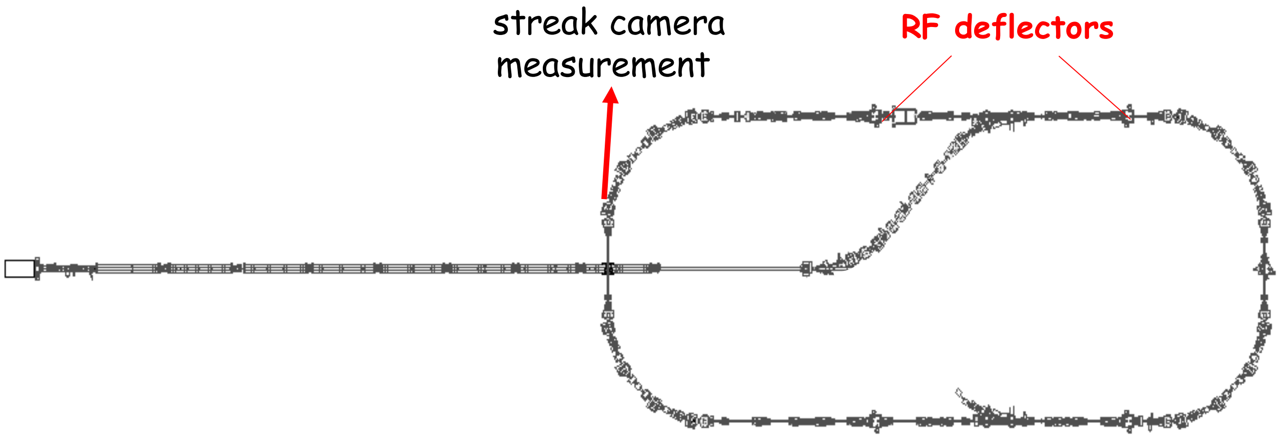


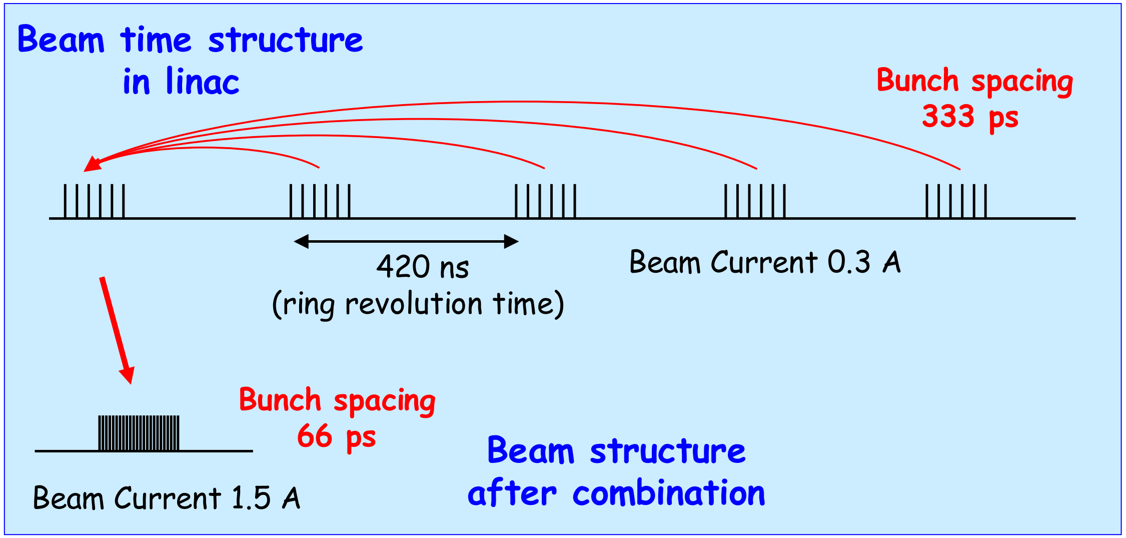
- mm wave detectors: bunch length/spacing measurements

Demonstration of RF recombination

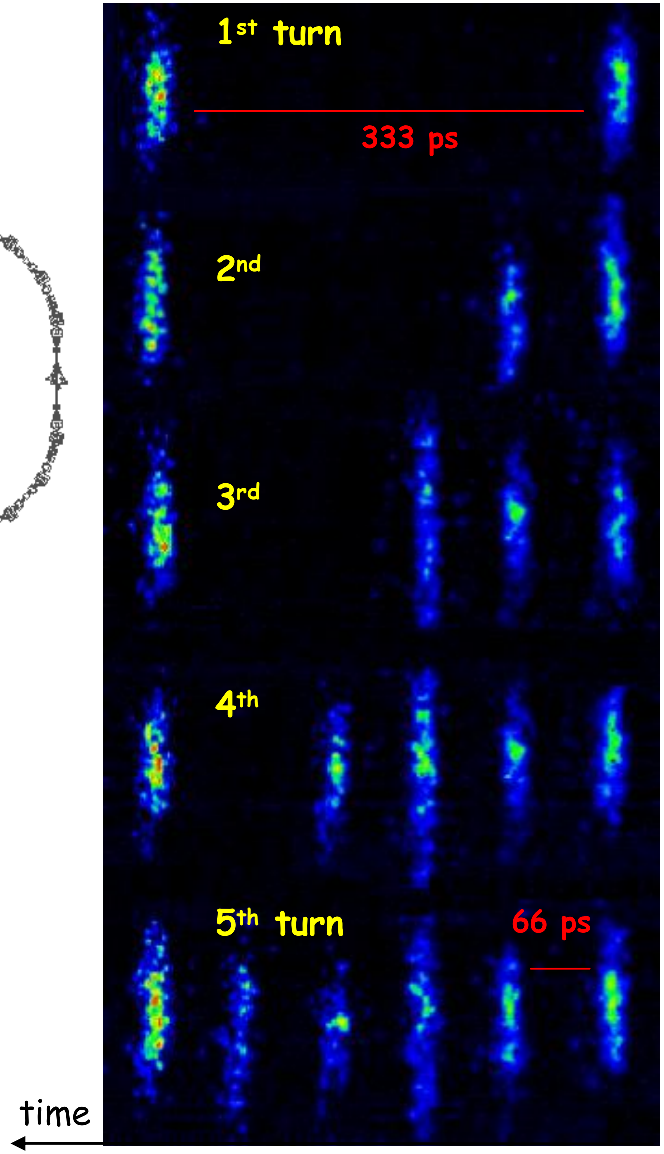
CTF3 - PRELIMINARY PHASE

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





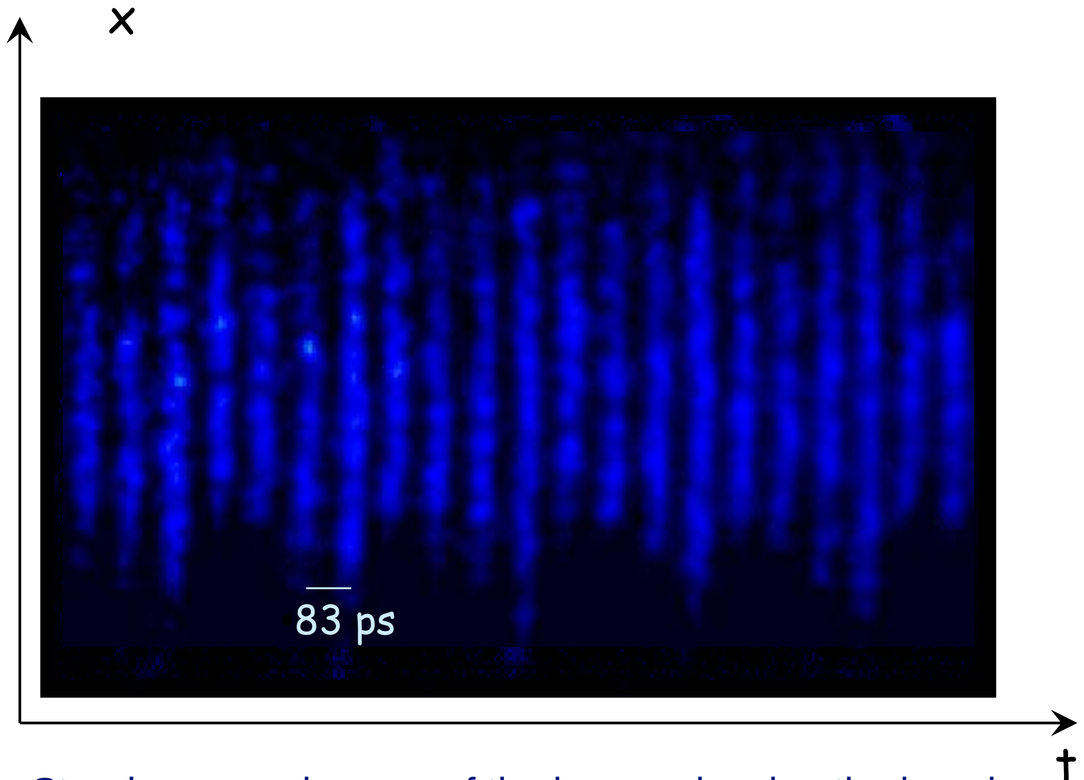
Streak camera image of beam time structure evolution



CTF3 preliminary phase (2001-2002)

RF injection in combiner ring

Combination factor 4



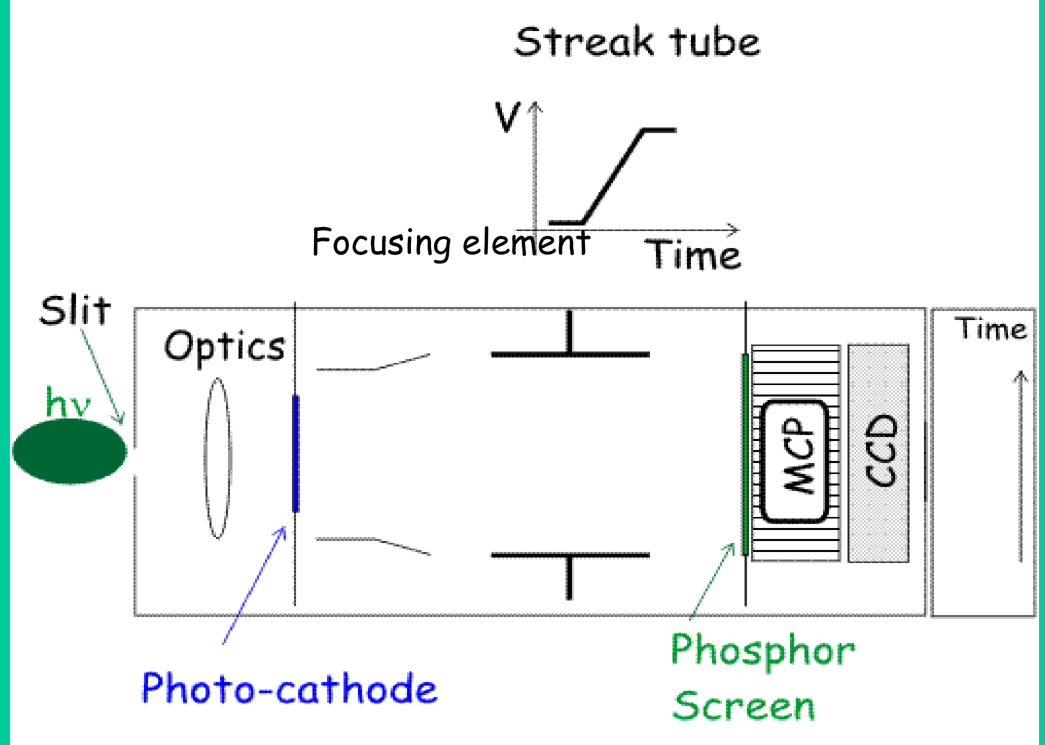
Streak camera images of the beam, showing the bunch combination process

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

Streak Camera

Use Synchrotron light produced in the rings or OTR/Cherenkov screens in a linac

‘Streak cameras uses a time dependent deflecting electric field to convert time information in spatial information on an intensified CCD’



200 fs time resolution at best using state of the art Cameras : FESCA 200

Limitations :

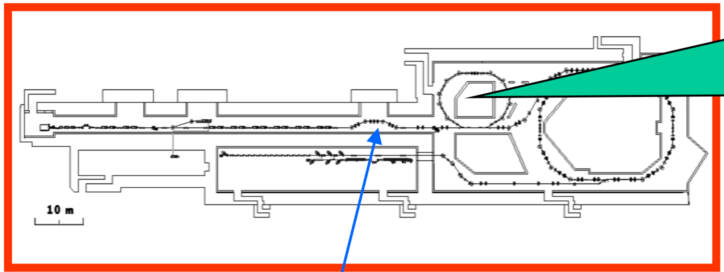
(i) Initial velocity distribution of photoelectrons : *narrow bandwidth optical filter*

(ii) Spatial spread due to the size of the slit

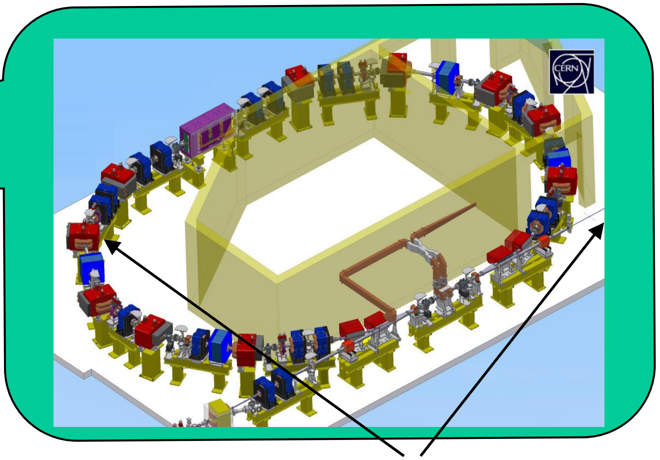
(iii) Dispersion in the optics

Streak Camera – Bunch Length

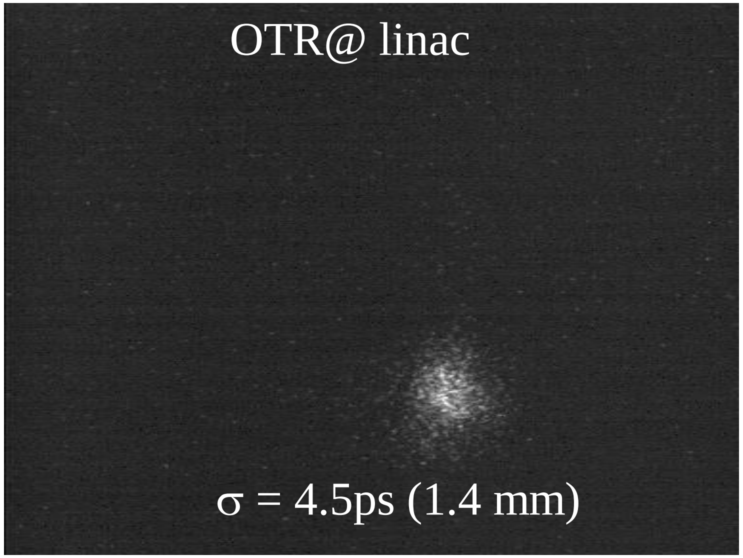
‘ CTF3 Complex’



Bunch length can be manipulated at the end of the linac using a magnetic chicane

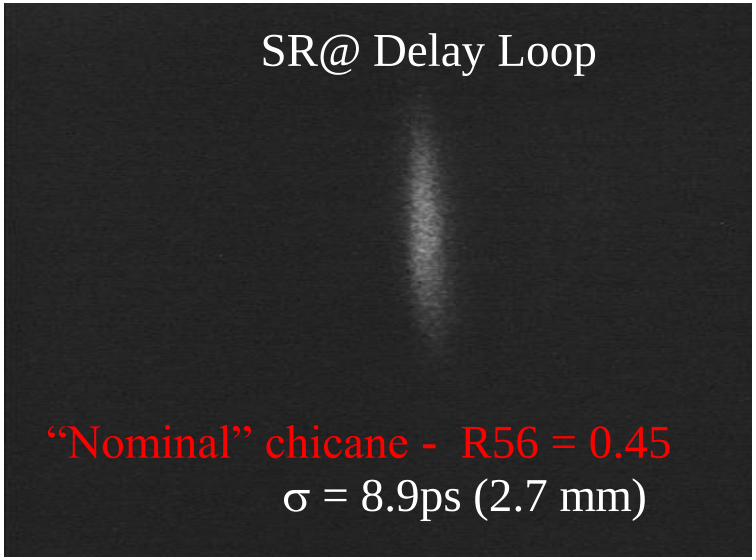


2 Optical lines to the streak camera
Synchrotron Radiation in the Delay Loop
OTR in the linac at the exit of the Delay Loop



time

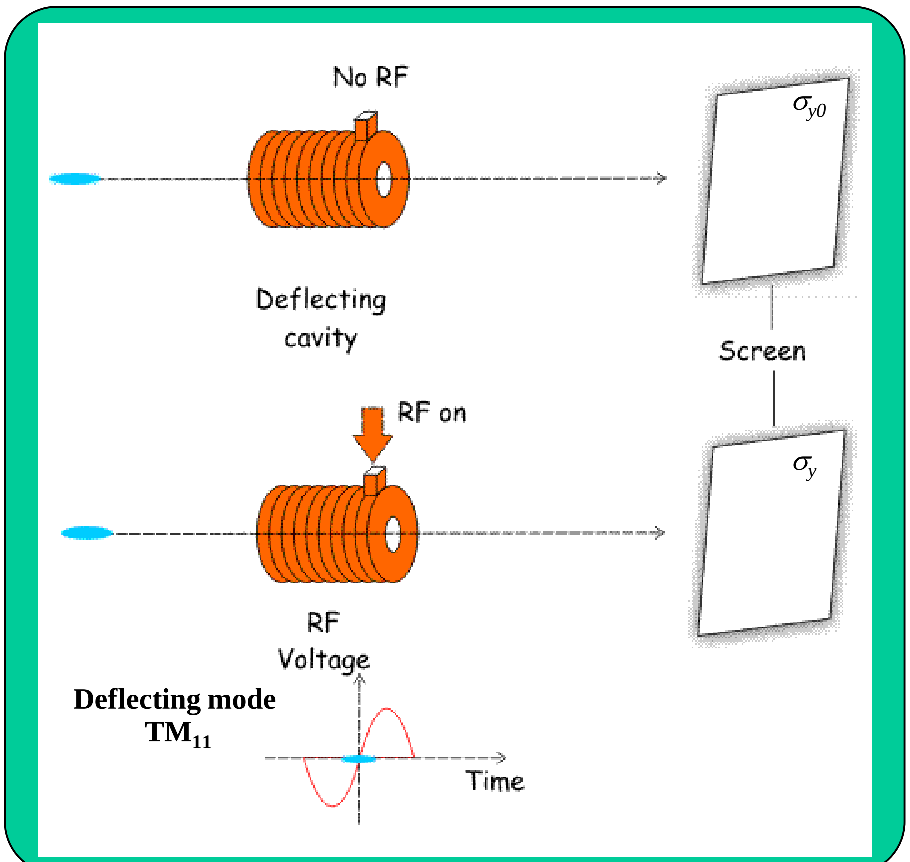
Sweep speed of 10ps/mm



RF Deflector – Bunch Length

Old (1960-70’s) idea to use RF deflector as a bunch length monitor

- *The RF Deflector can be seen as a relativistic streak tube.*
- *The time varying deflecting field of the cavity transforms the time information into a spatial information*
- *The bunch length is then deduced measuring the beam size at a downstream position using a screen (or Laser Wire Sanner)*



$$\sigma_y = \sqrt{\sigma_{y0}^2 + \sigma_z^2 \beta_c \beta_p \left(\frac{2\pi e V_0}{\lambda_{rf} E_0} \sin \Delta\psi_y \cos\varphi_{rf} \right)^2}$$

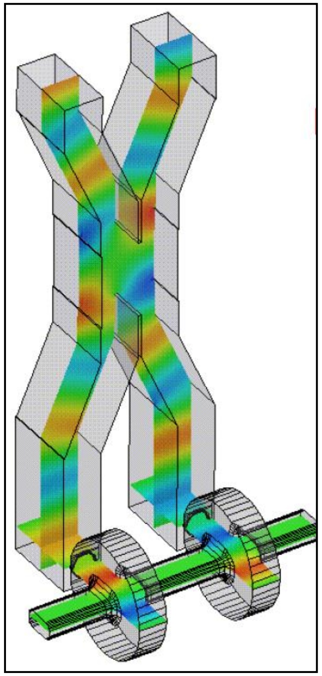
- Deflecting Voltage (V_0)
- RF deflector phase (φ_{rf})
- Bunch length (σ_z)
- Beta function at cavity and profile monitor ($\beta_c \beta_p$)
- RF deflector wavelength (λ_{rf})
- Beam energy (E_0)
- Betatron phase advance (cavity-profile monitor) ($\Delta\psi_y$)

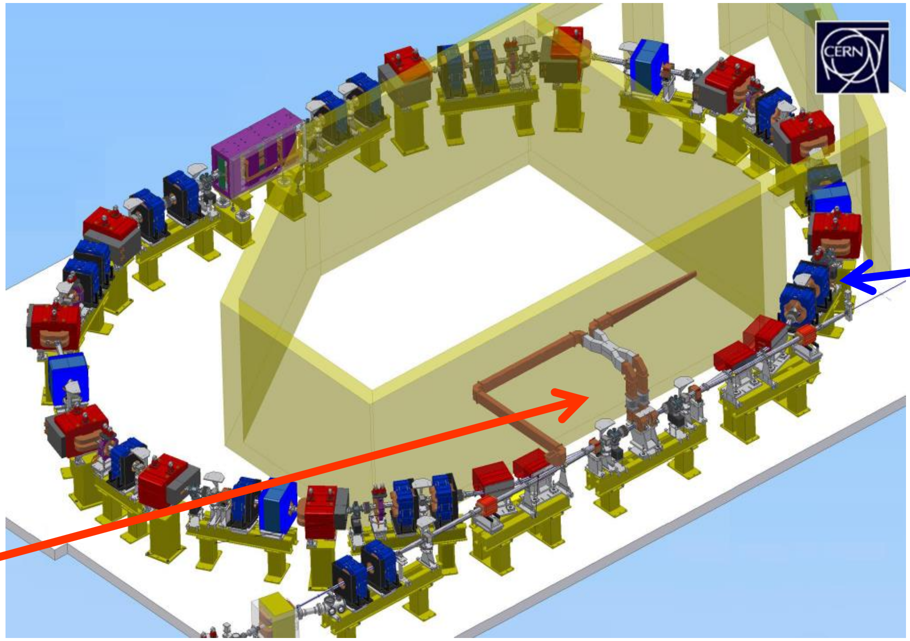
<u>Resolution will depend on :</u> *(sub-100fs)*

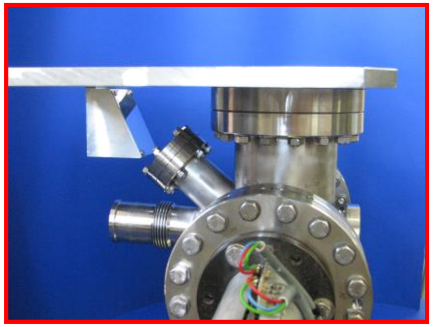
- Screen spatial resolution
- *Deflecting power*
- *Beam optic between the deflector and screen*

Delay Loop RF Deflector

- Bunch Length Measurement with the 1.5GHz RF Deflector of the Delay Loop -



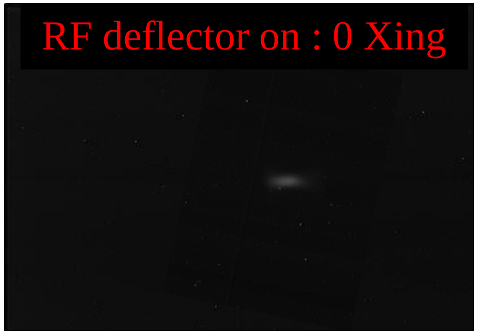




OTR screen

- Maximum power of 20MW
- 5degrees @1.5GHz = 9.25ps (4mm)

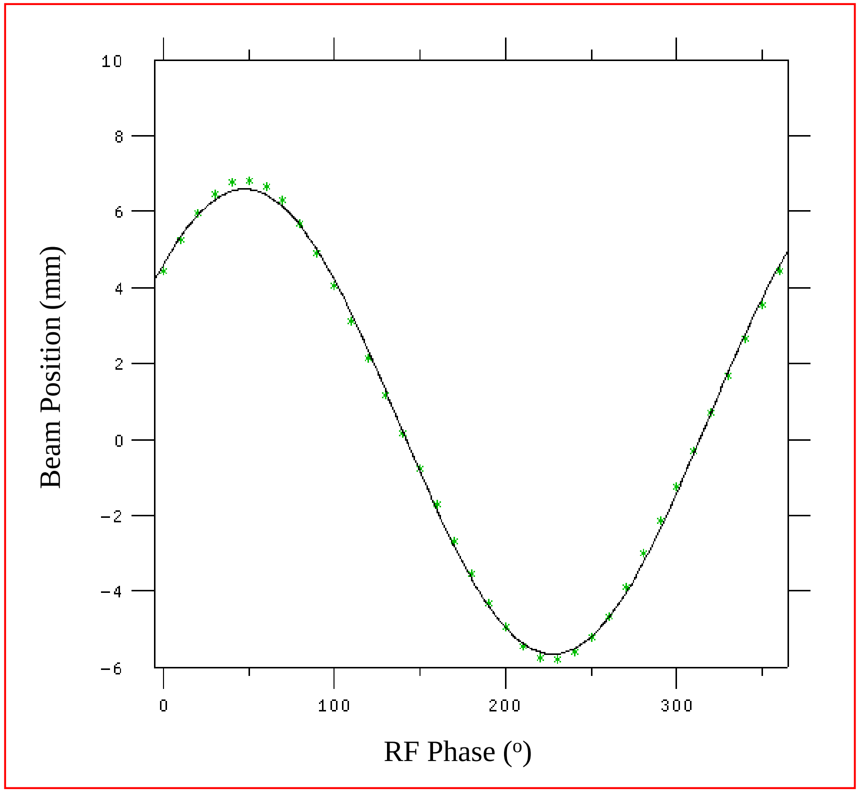
With this setting, the resolution is better than 1ps



σ_{noRF} = 0.35mm
σ_{0Xing} = 2.9mm (6.7ps)

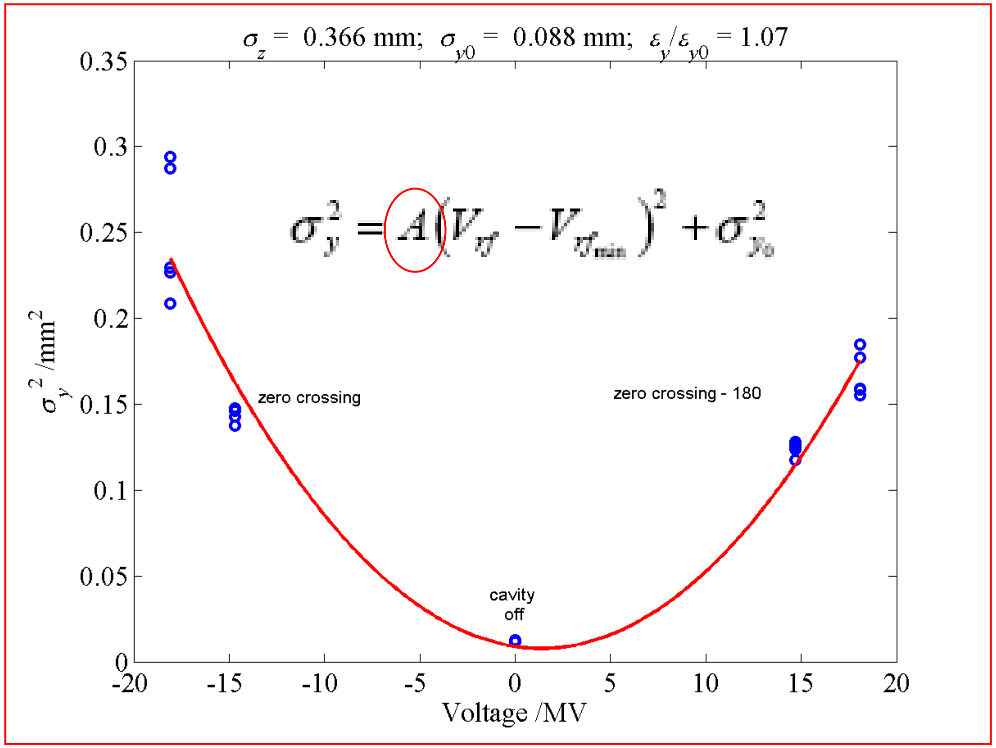
Delay Loop RF Deflector

- Calibration of RF Deflector -



Use a Beam Position Monitor close to the Profile monitor to calibrate the deflection angle

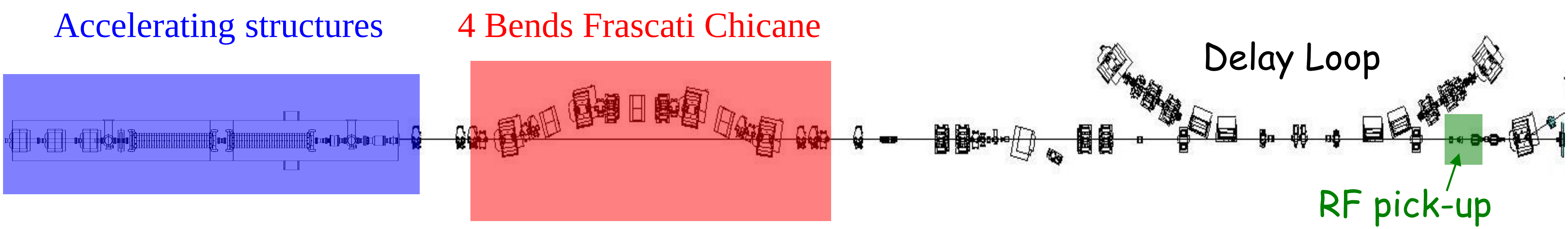
R34 = transfer Matrix element from cavity to the BPM



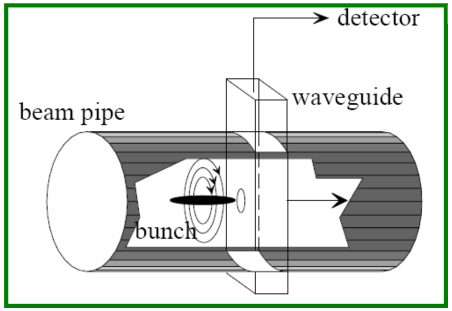
Make a power scan at zero crossing and (zero crossing – 180°) to check if there is no perturbation from linac wakefields

$$\sigma_z = A^{1/2} \frac{E_0 \lambda_{rf}}{R_{34} 2\pi}.$$

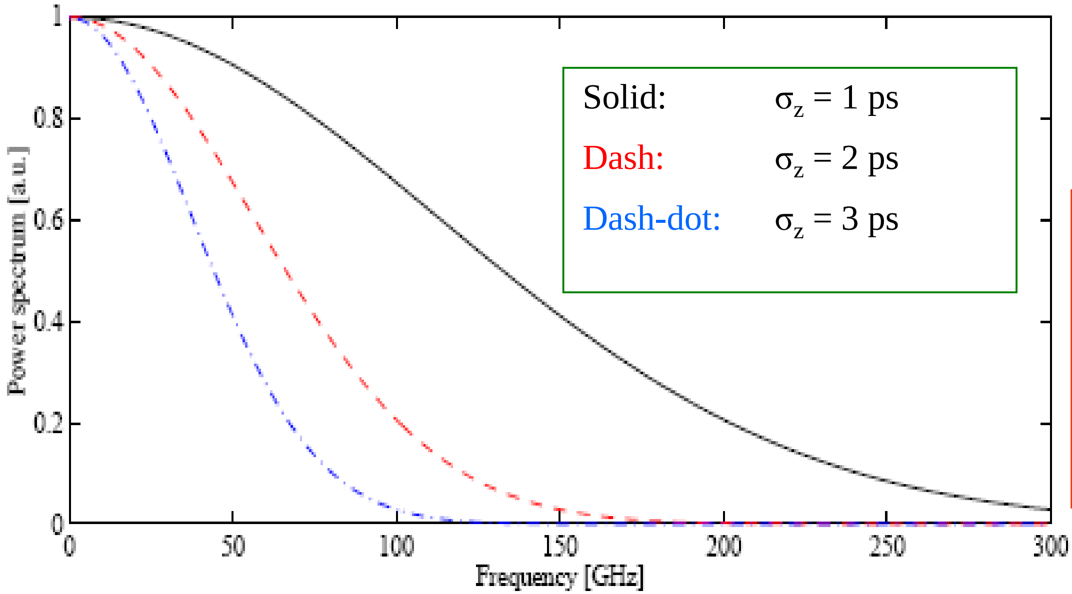
RF pick-up for bunch length monitoring



Advantages : Non-intercepting, Easy, lower cost
Short comings : Sensitive to beam position and current sensitive
Need a cross calibration with the RF deflector and/or a streak camera



'Measure the bunch frequency spectrum'

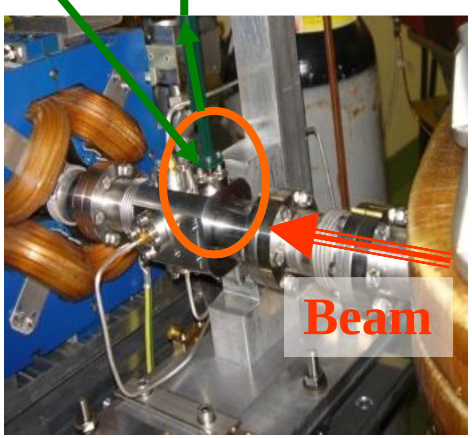


- Max frequency @ 170 GHz → Bunch length measurements of 0.3ps
- Design a thin diamond RF window for improved transmission at high frequency

RF pick-up for bunch length monitoring

BPR

WR-28 Waveguide
~20m

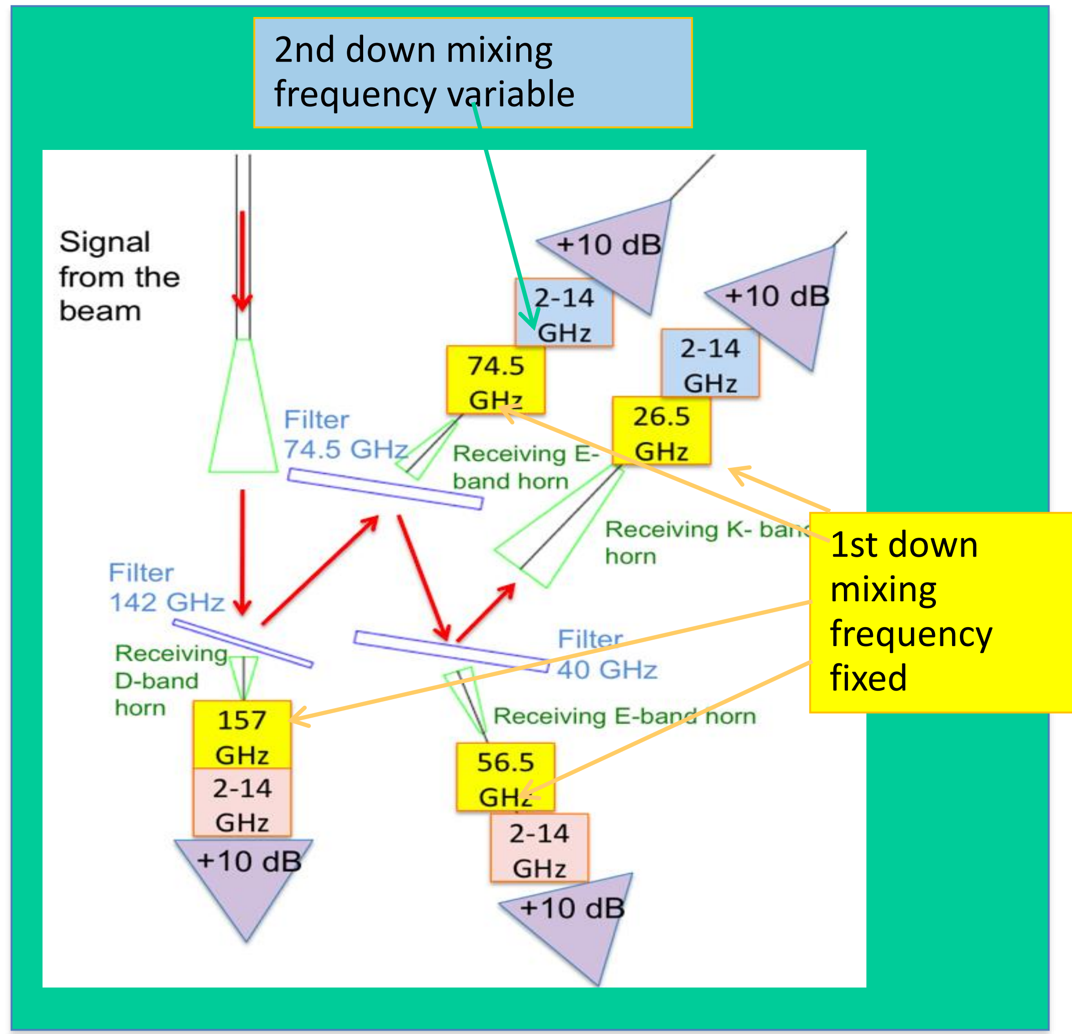


Filters, Horns and mixers

- Reflecting low pass filter - **4** frequency-band detection stages
- Series of 2 down mixing stages at each detection station.

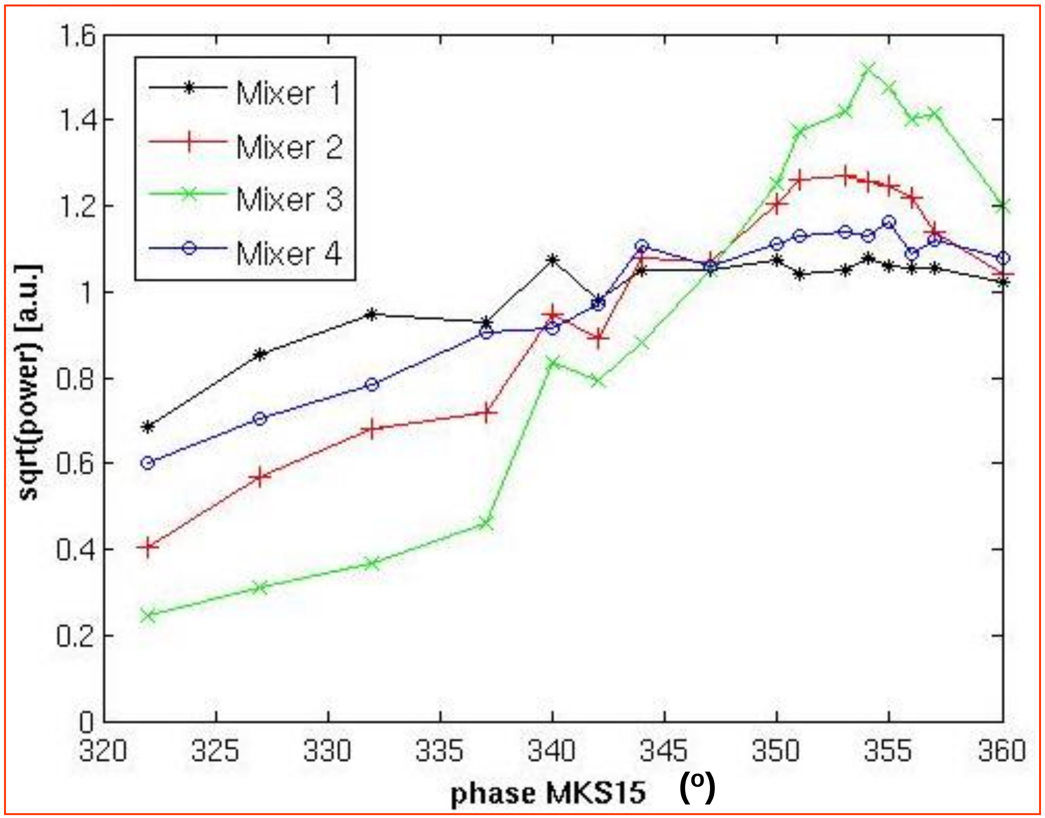
Acqiris DC282 Compact PCI Digitizer

4 channels, 2 GHz bandwidth, 2-8 GS/s sampling rate

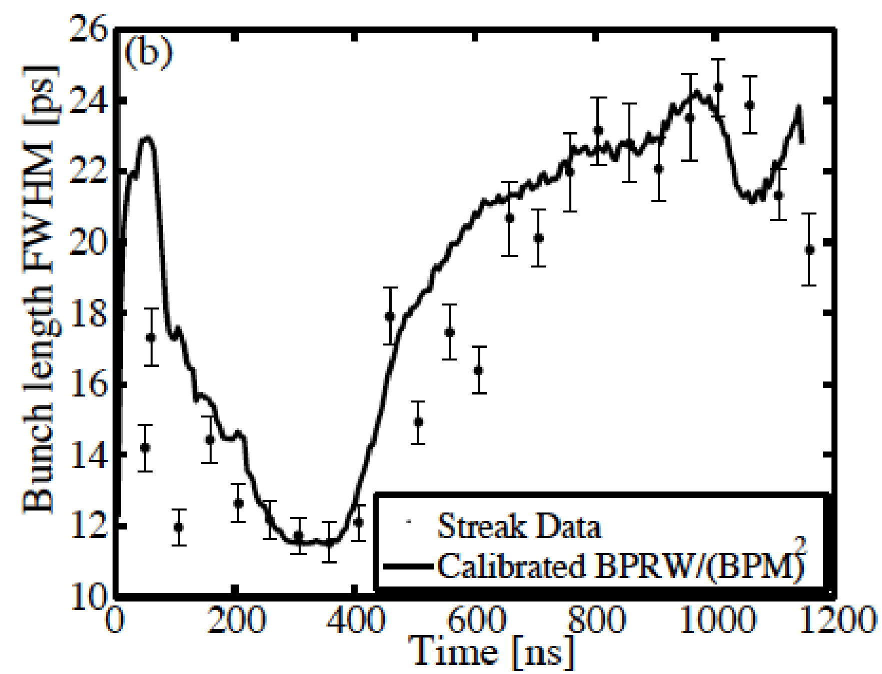


RF pick-up for bunch length monitoring

‘ Changing the phase of a klystron ’



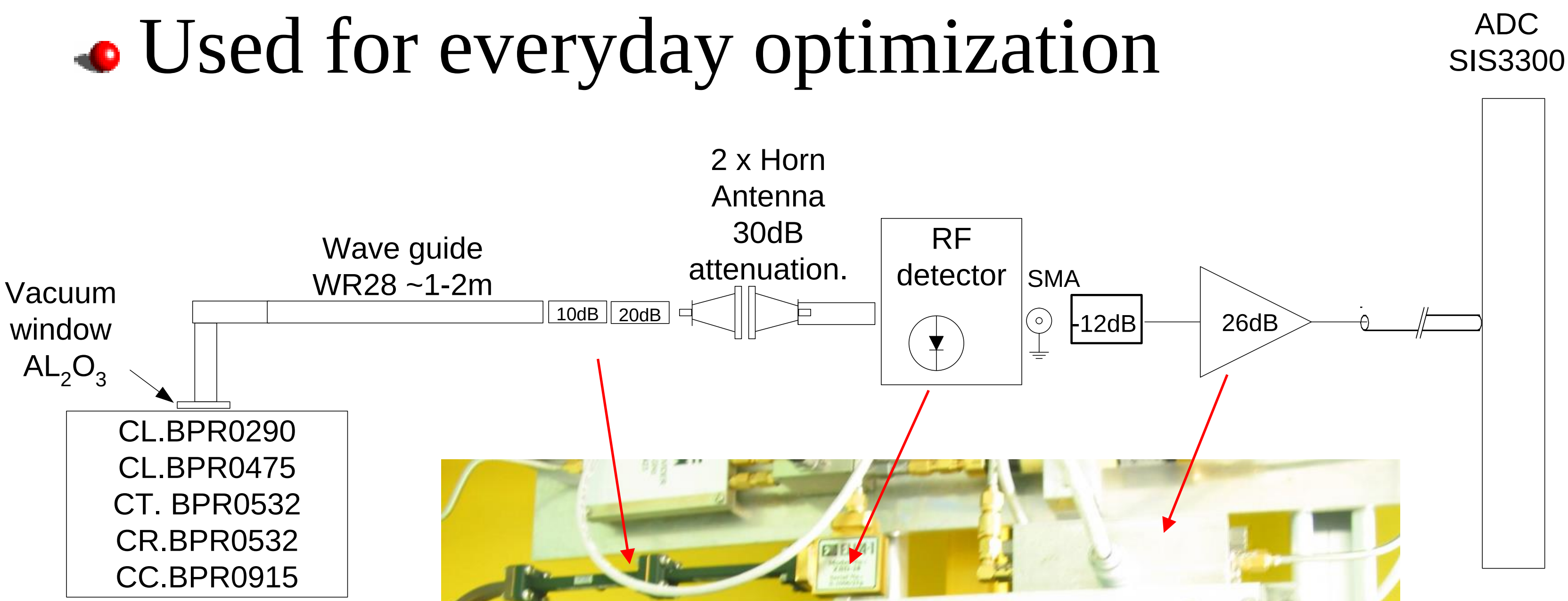
Bunch length along the train’

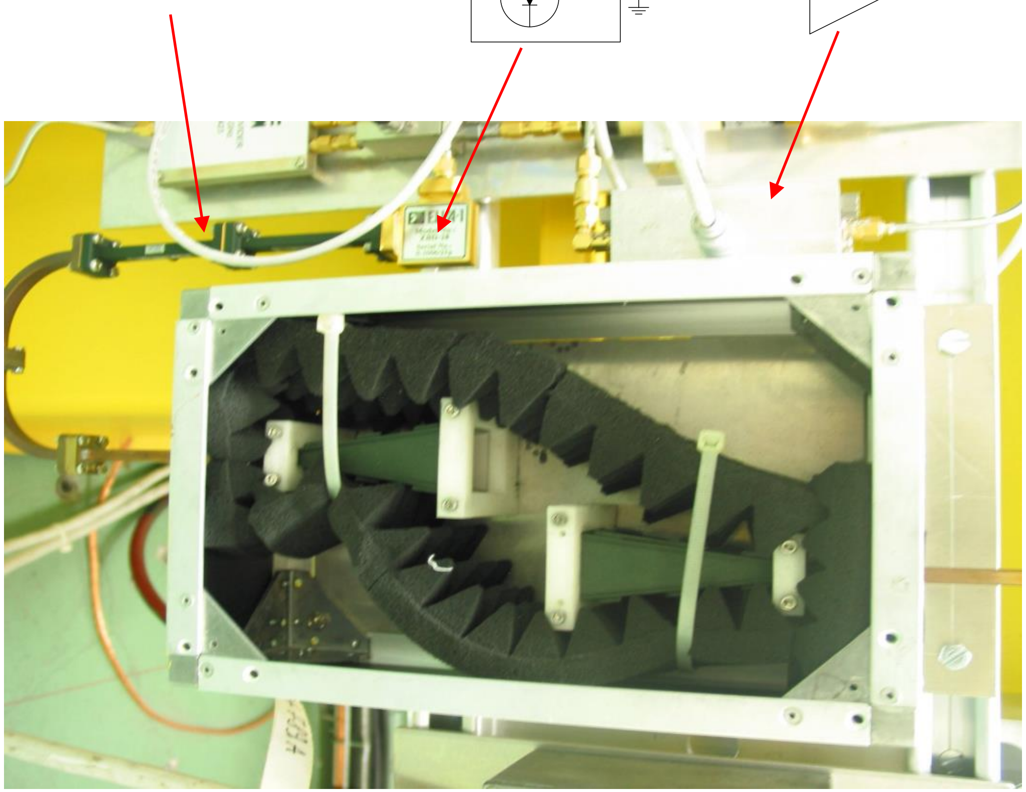


(b) The calibrated BPRW signal compared to streak camera measurement.

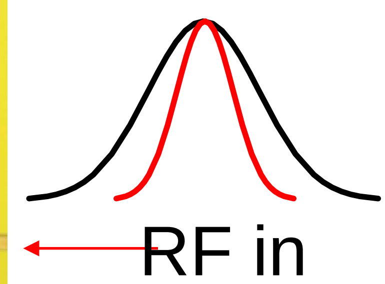
Bunch length: Waveguide Pick-up

- More power entering waveguide for shorter bunches
- Used for everyday optimization



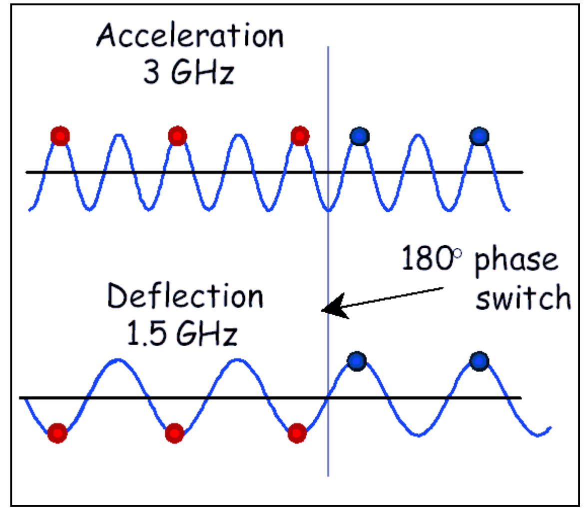


Waveguide electronics



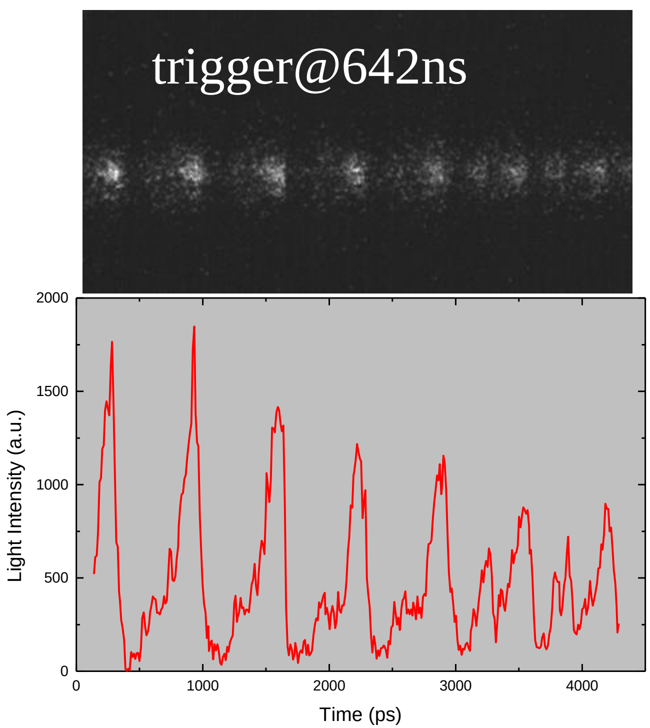
Phase switch of the Sub-harmonic bunching system

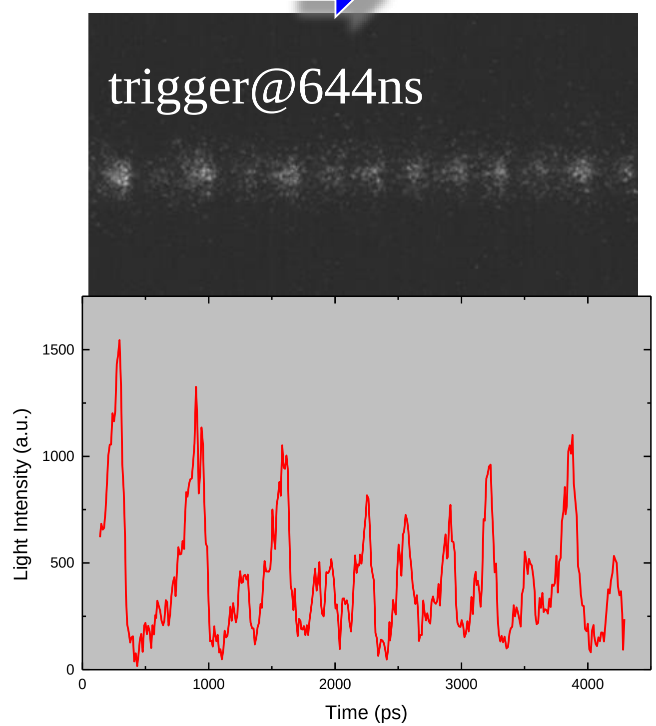
Phase coding in the sub-harmonic bunching system

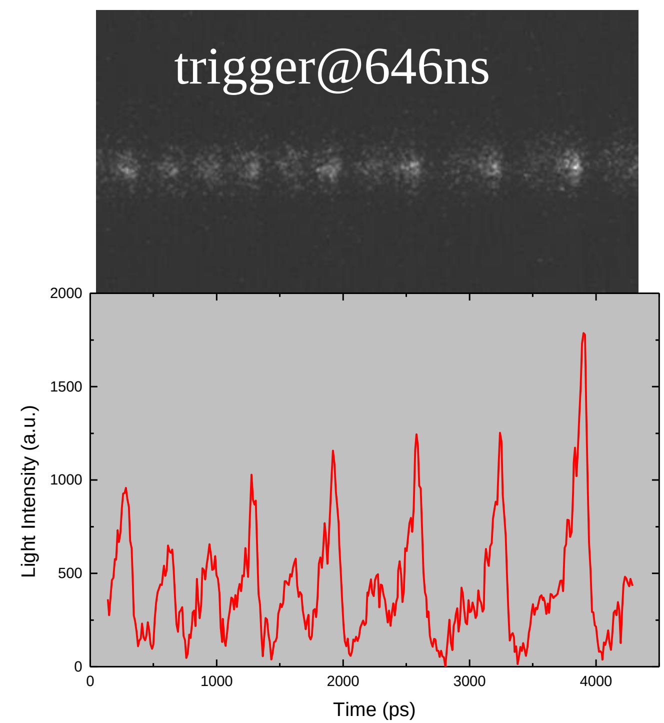


Streak camera sweep speed 500ps/mm

Phase Switch ~ 5-6 ns ; 8 % satellite

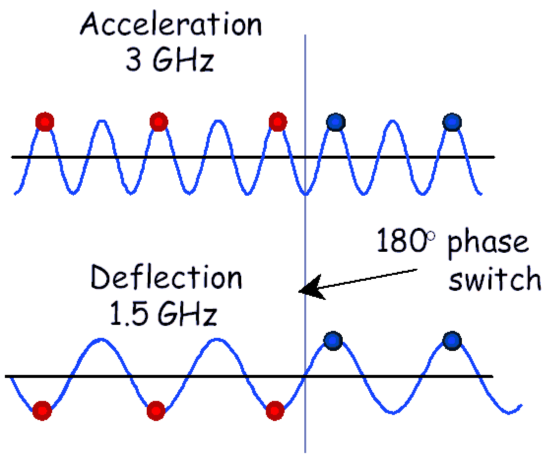




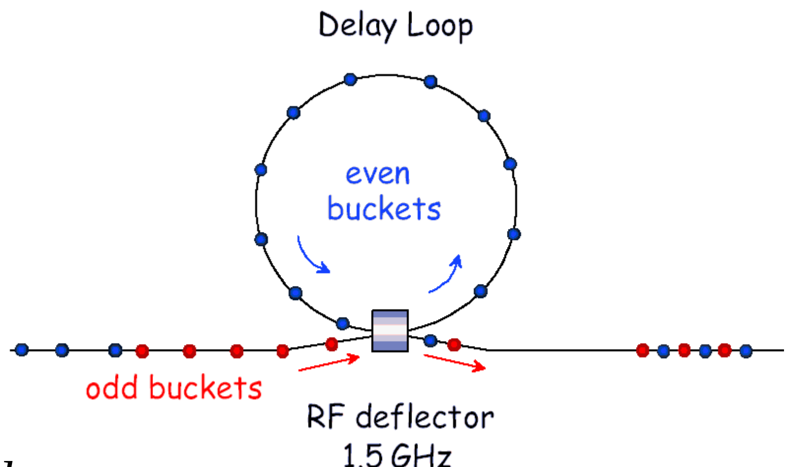


Delay Loop bunch train combination

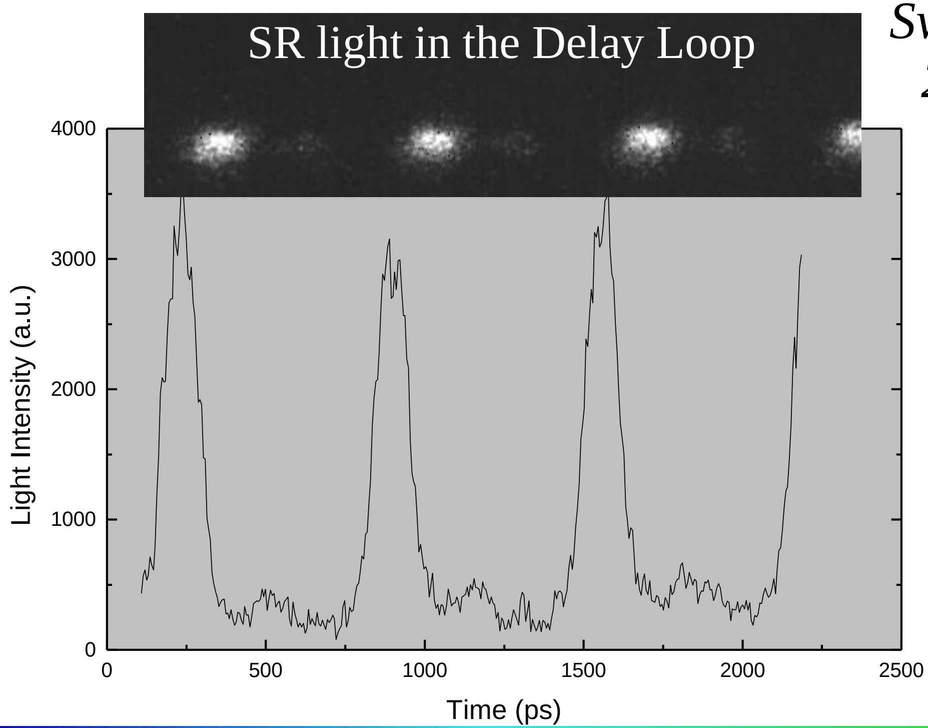
Phase coding in the sub-harmonic bunching system

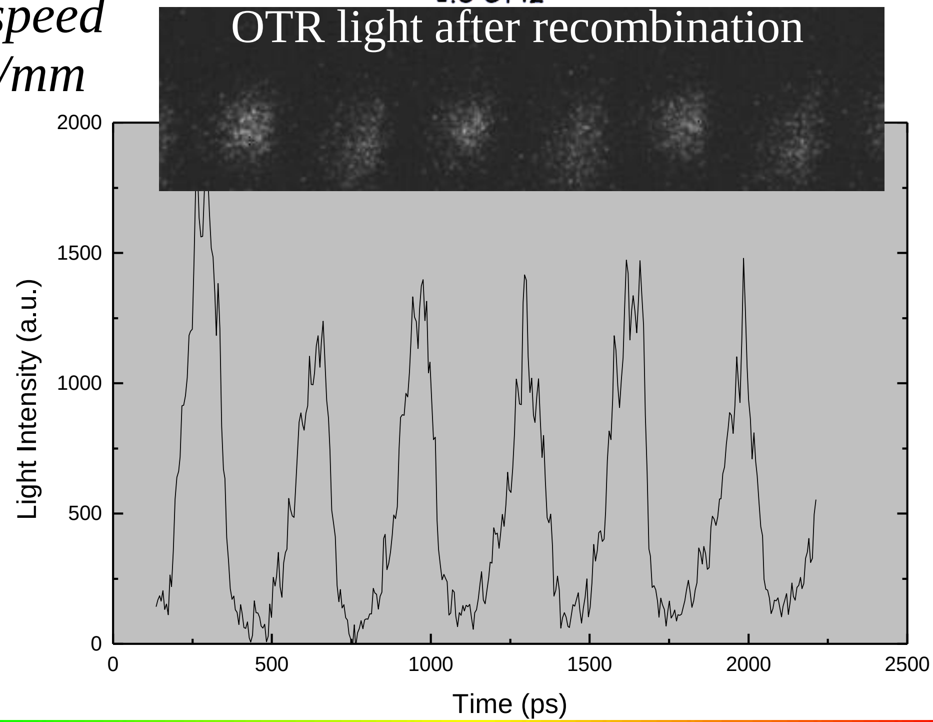


Bunch frequency multiplication in delay loop



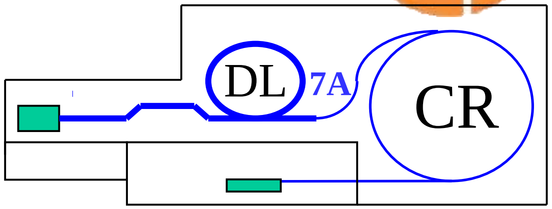
Sweep speed 250ps/mm

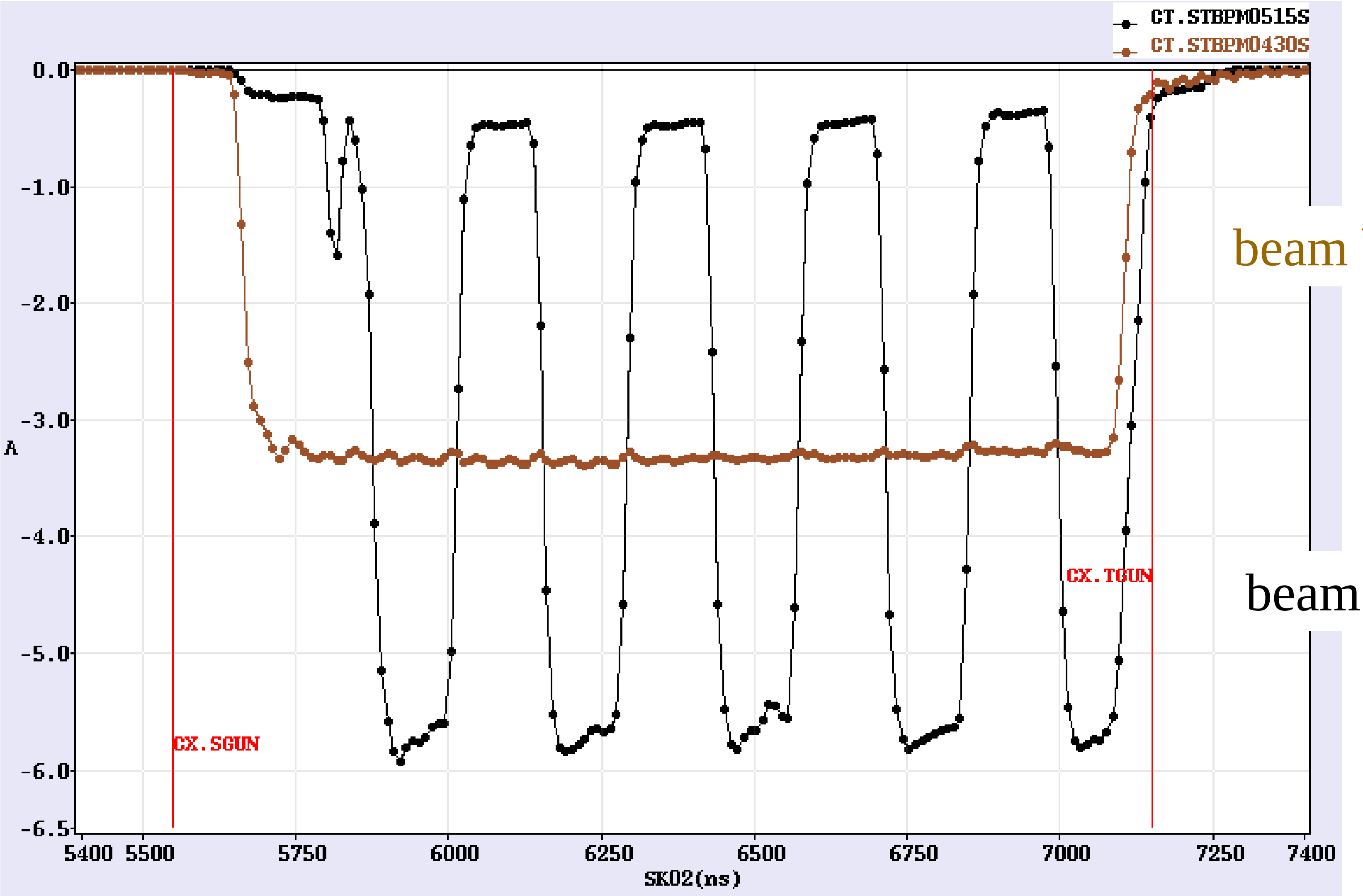




Delay Loop – full recombination - BPMs

- 3.3 A after chicane =>
  < 6 A after combination (satellites)



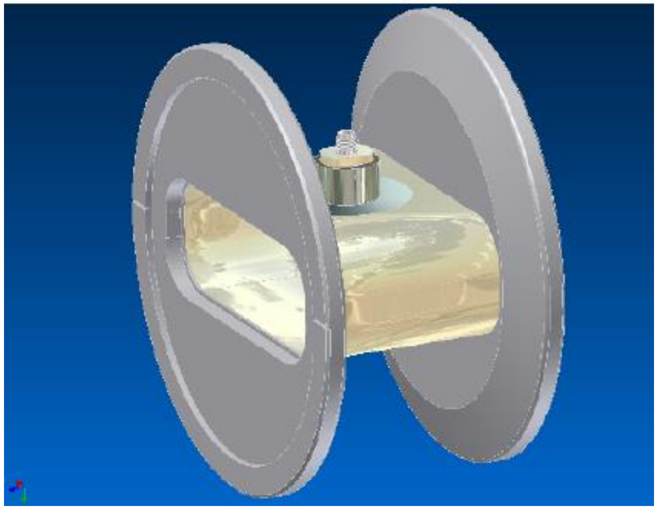


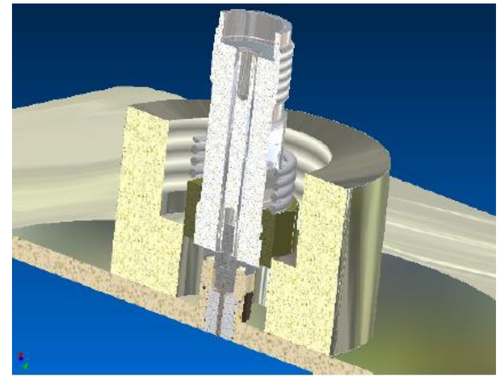
beam **before** the DL

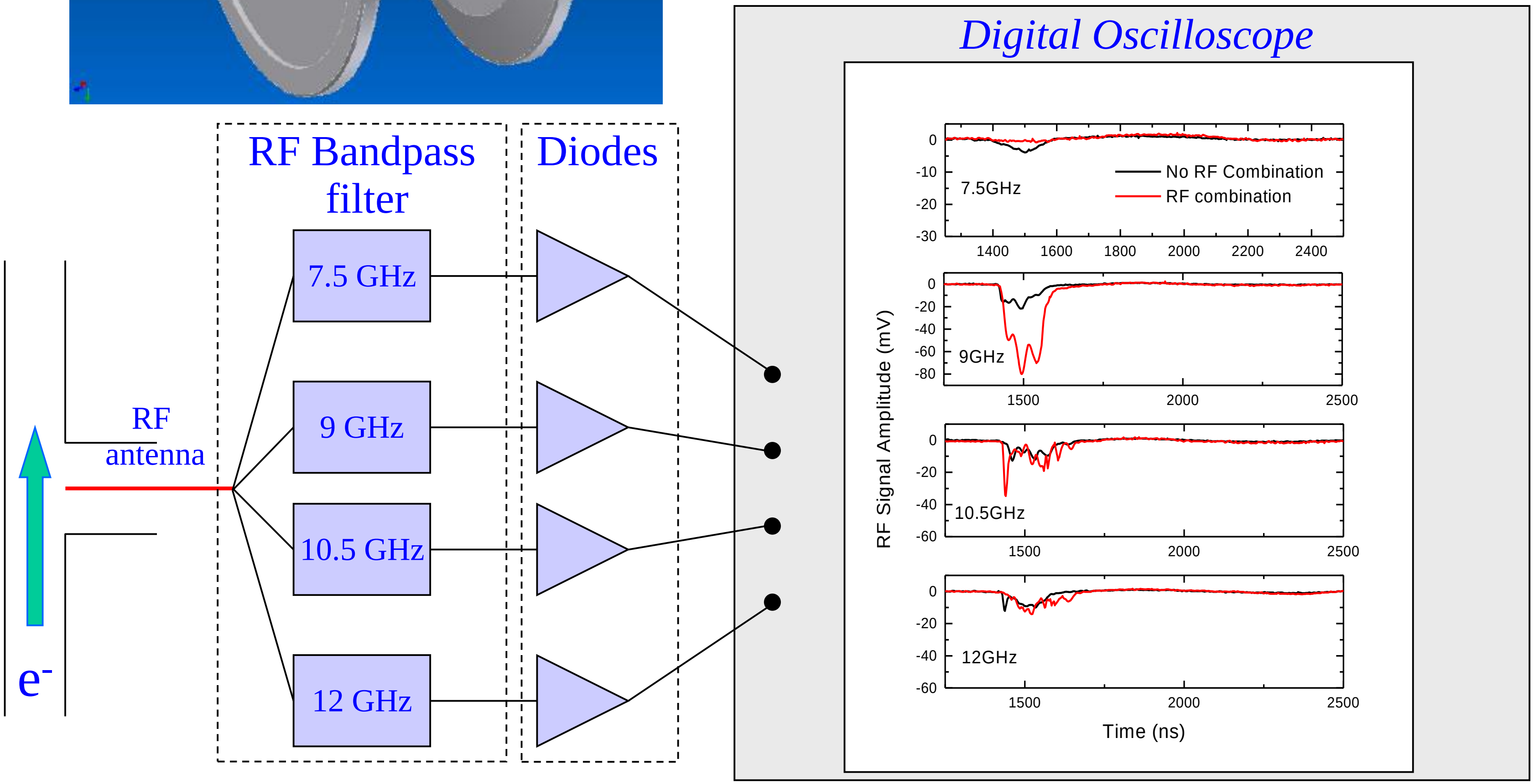
beam **after** the DL

Phase Monitor for CTF3 bunch train combination

‘To measure phase error in the RF bunch combination’

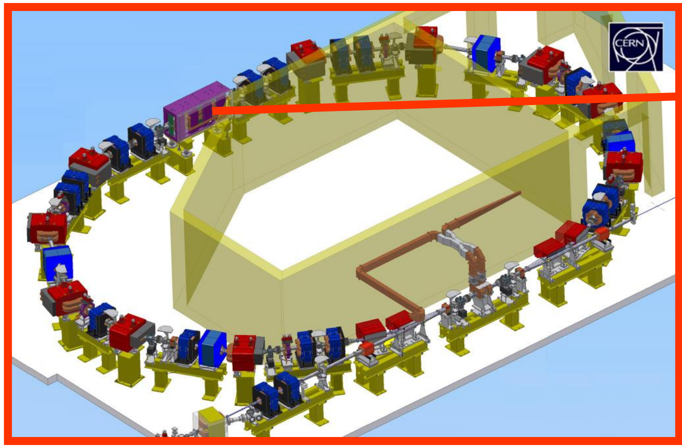


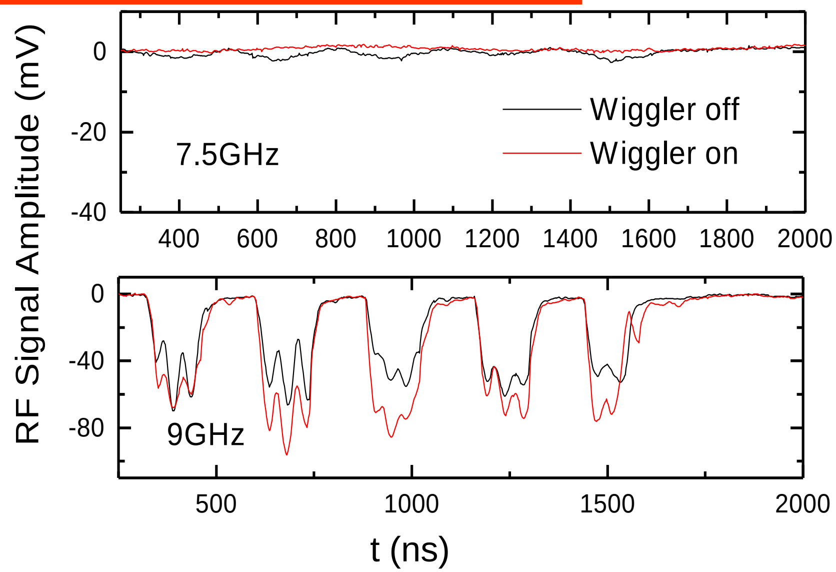




Phase Monitor for CTF3 bunch train combination

Adjust the delay loop length with a magnetic wiggler

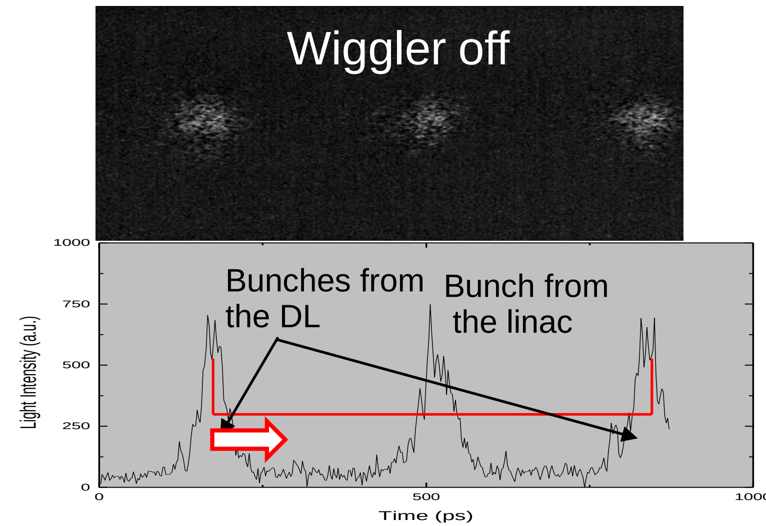




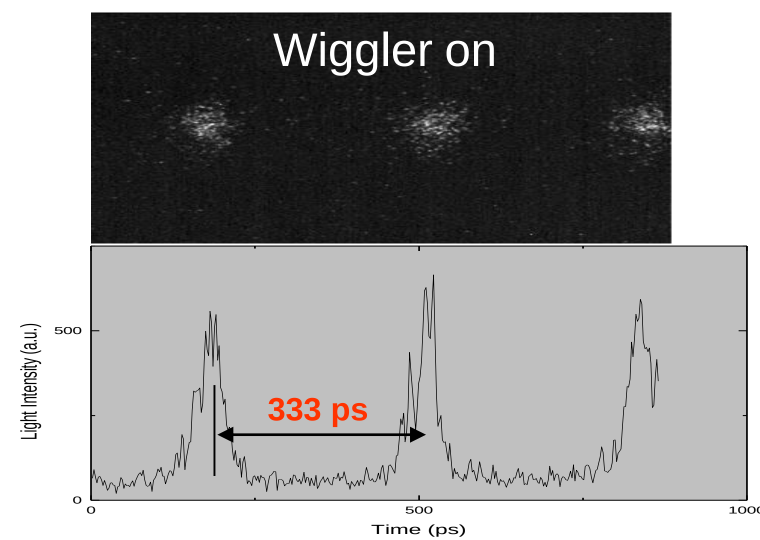
Better RF combination

- 7.5GHz
- 9GHz

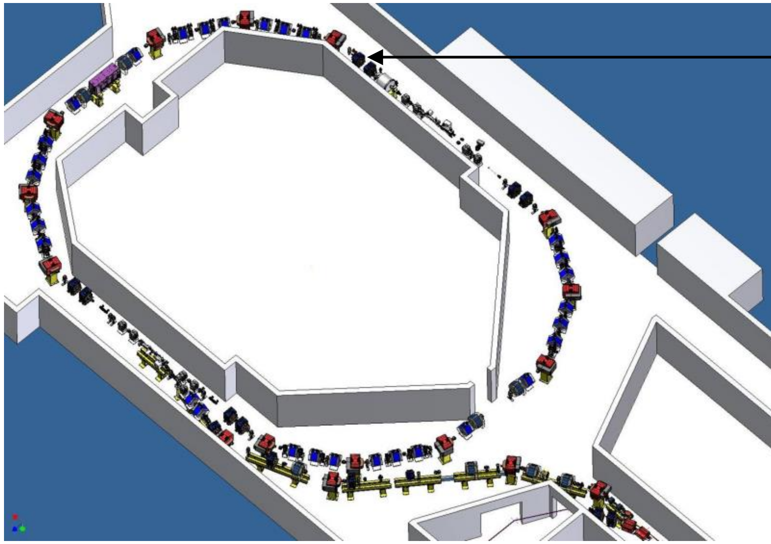
OTR light and sweep speed 100ps/mm



Bunches from the DL later by 12ps (3.6mm)

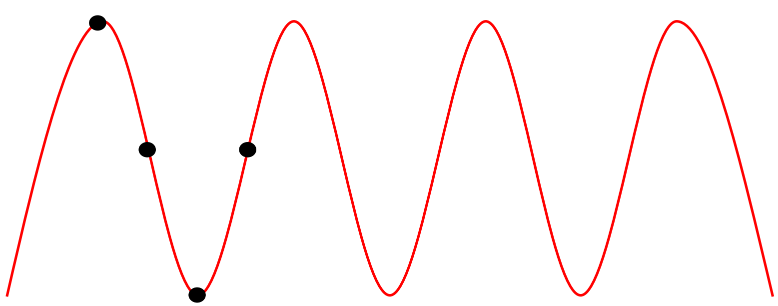


Path length: Button Pick-up's (BPR)

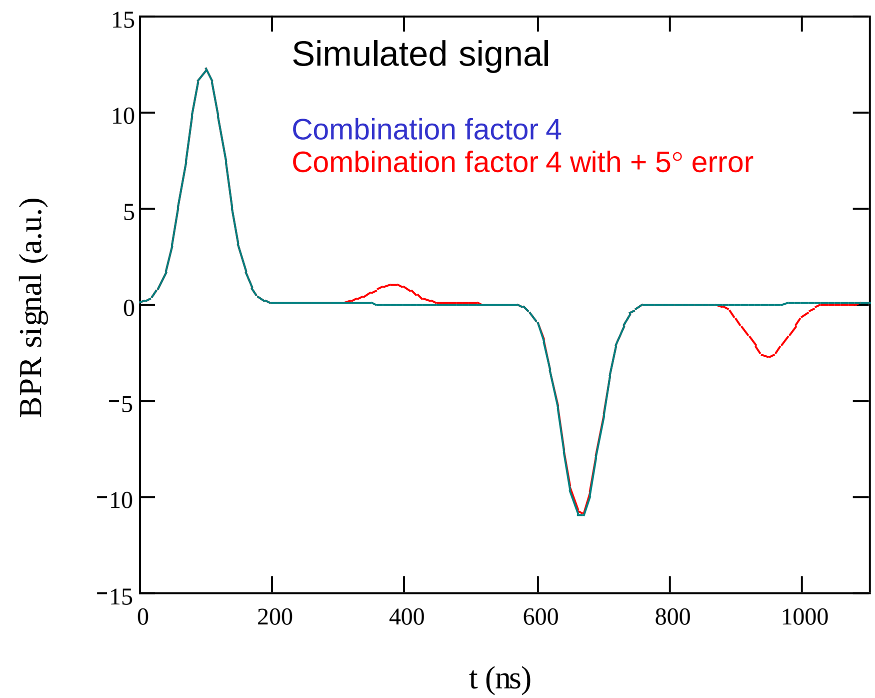


BPR – RF phase monitor

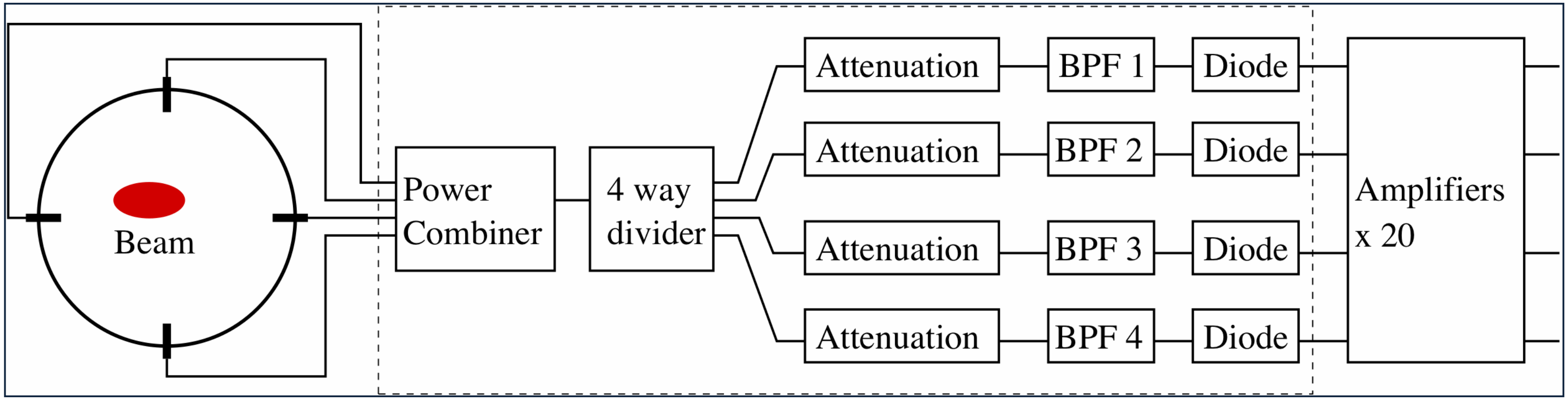
- Pickup signal mixed with 3 GHz reference signal
- Reference phase adjustable
- Combiner ring path length for factor 4: $N * \lambda + \frac{\pi}{2}$
- Bunches have 90° phase advance (3 GHz) per turn



Observed signal

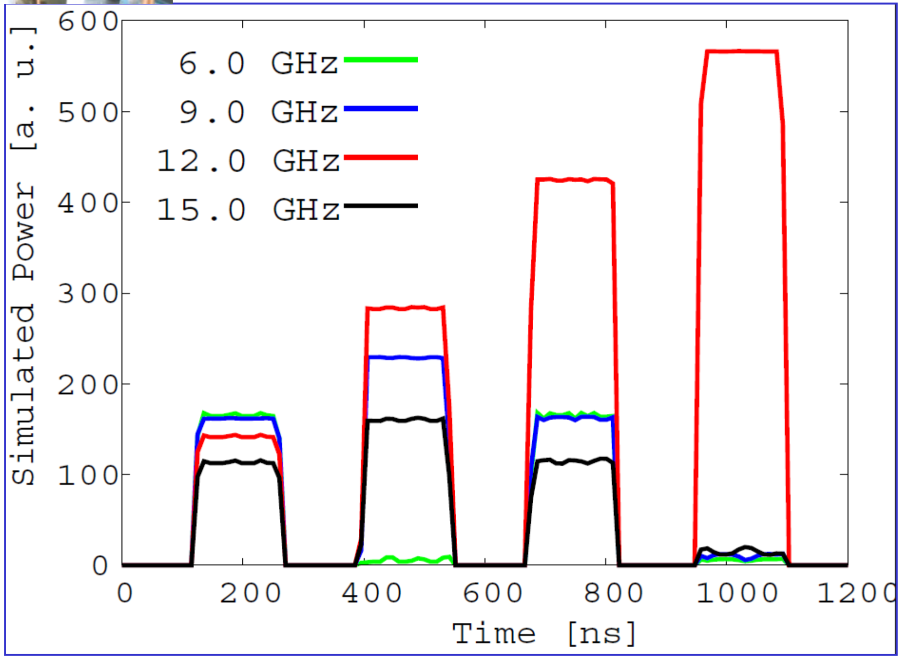


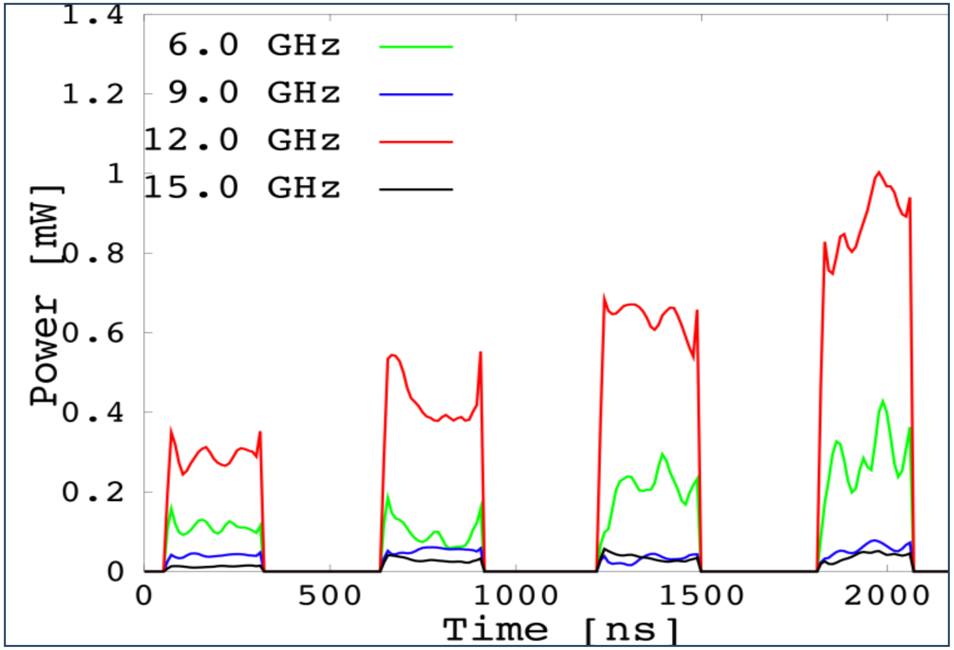
Phase Monitor – sensitivity to CR ring length errors



Simulation of perfect combination x4
4th turn – all power in 12 GHz

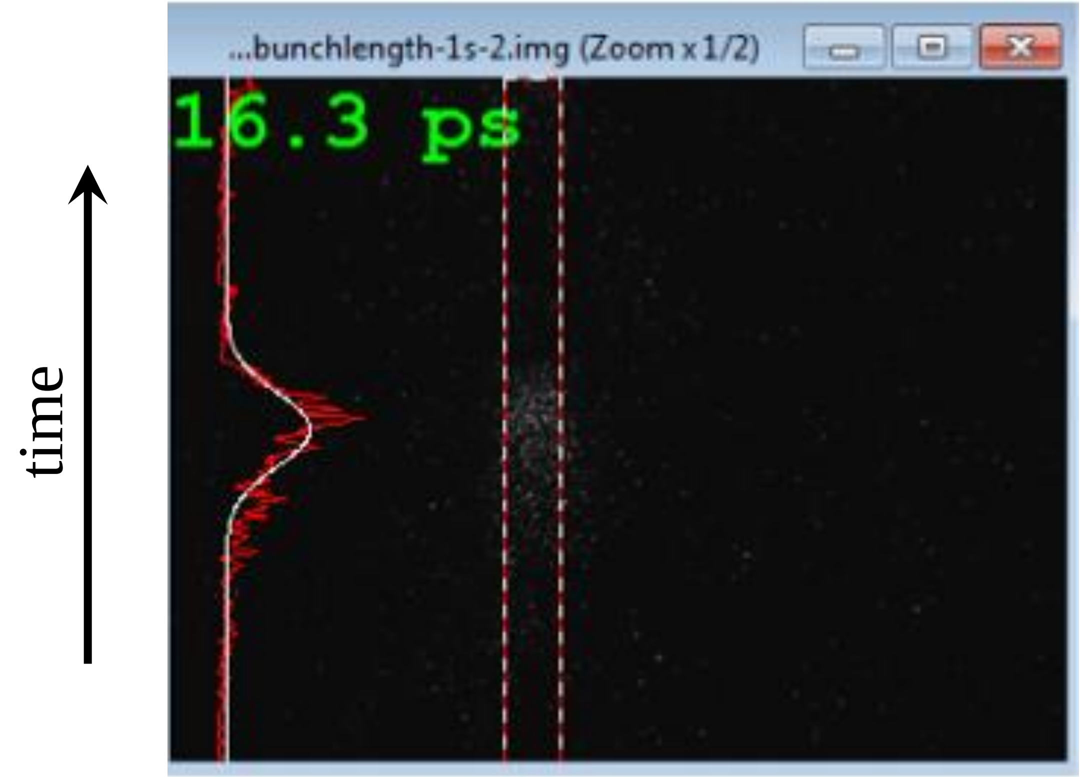
Measured combination not perfect yet !
Intensity loss in 4th turn and small phase errors



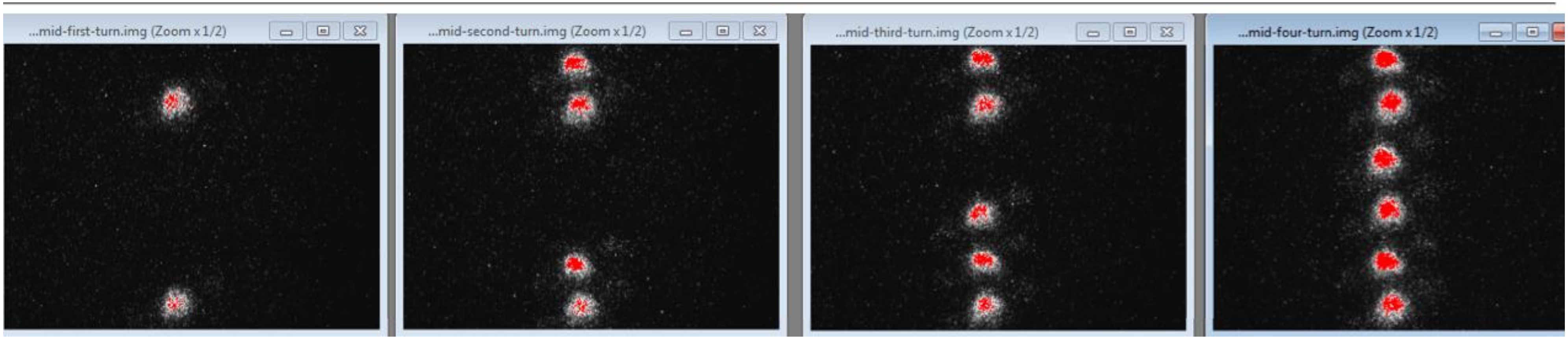


CR - 200 fs Streak Camera

- Single bunch:
  - Bunch length

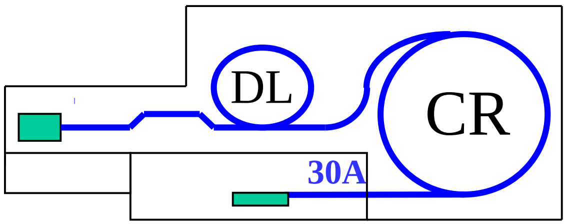


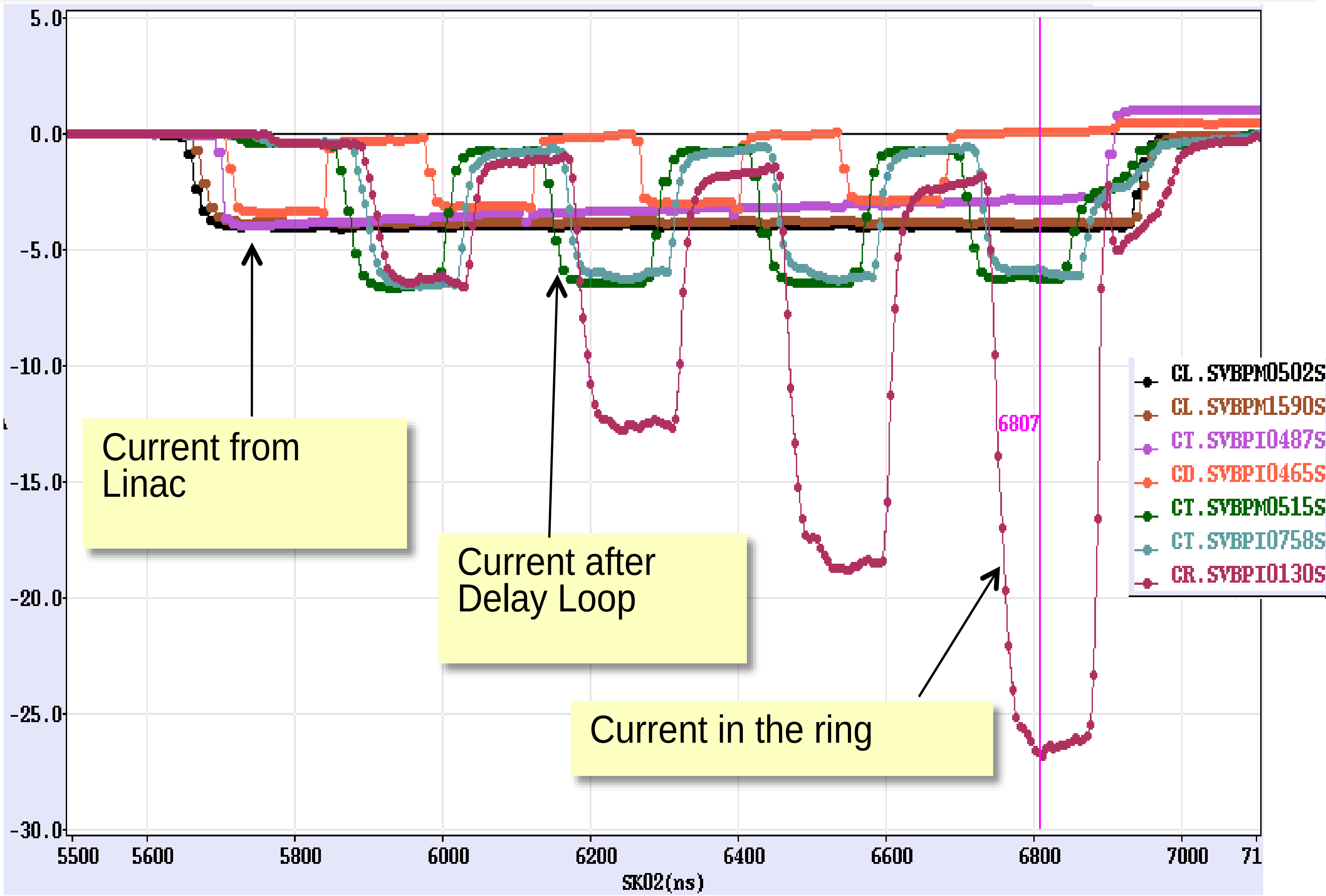
- Multi-bunch:
  - Bunch distance



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**



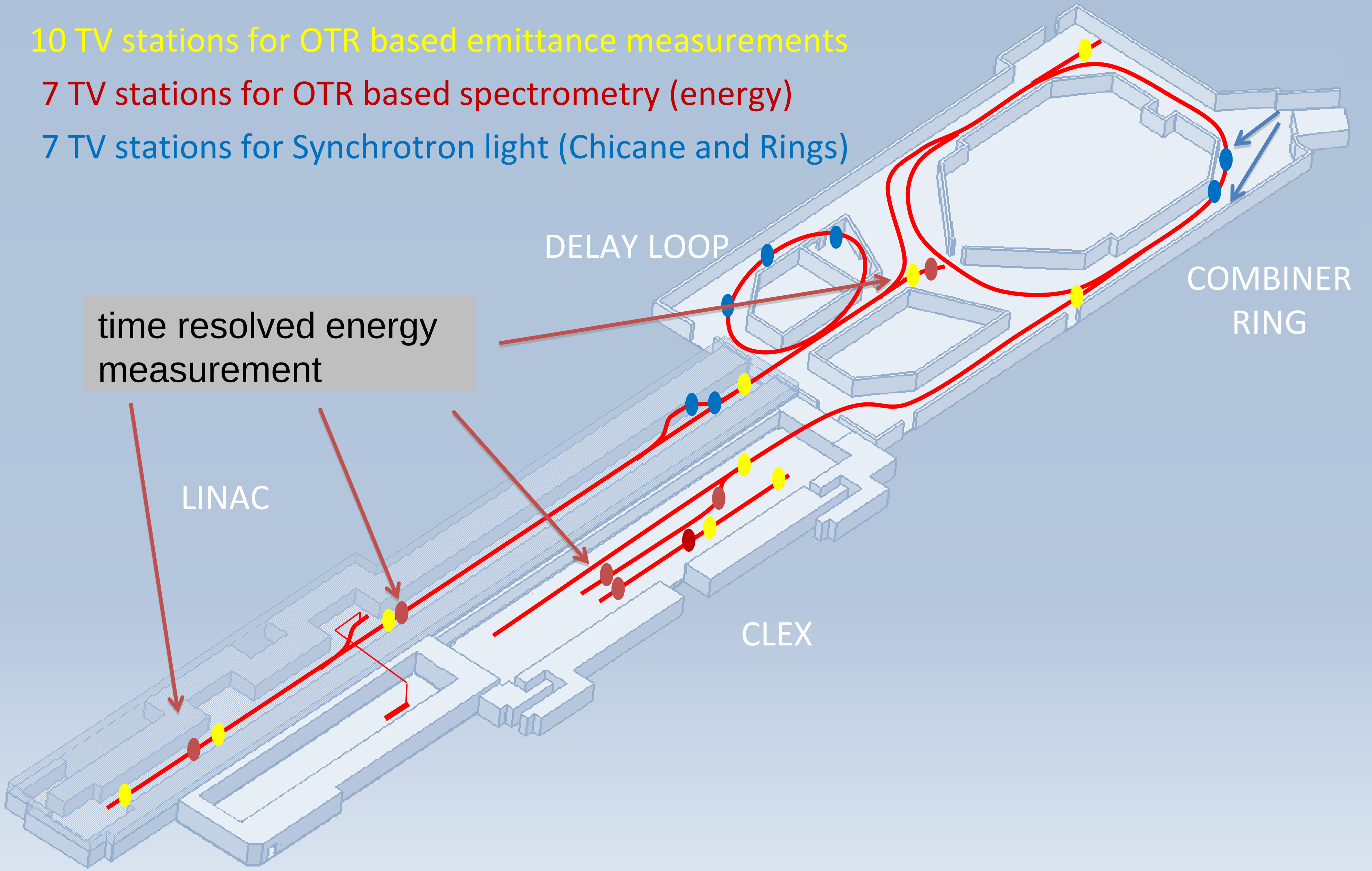


Profile monitors @ CTF3

10 TV stations for OTR based emittance measurements

7 TV stations for OTR based spectrometry (energy)

7 TV stations for Synchrotron light (Chicane and Rings)



Segmented Dump for time resolved energy measurement

Installed in spectrometer lines

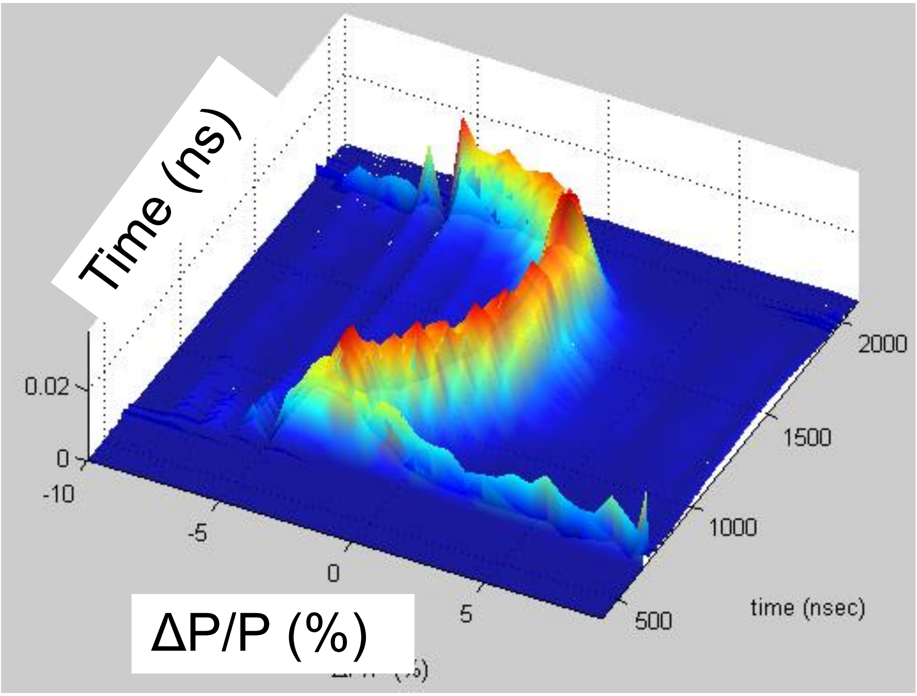
Why measurement important?

Check the phase of the RF (as a function of time) in each accelerating cavity is set correctly

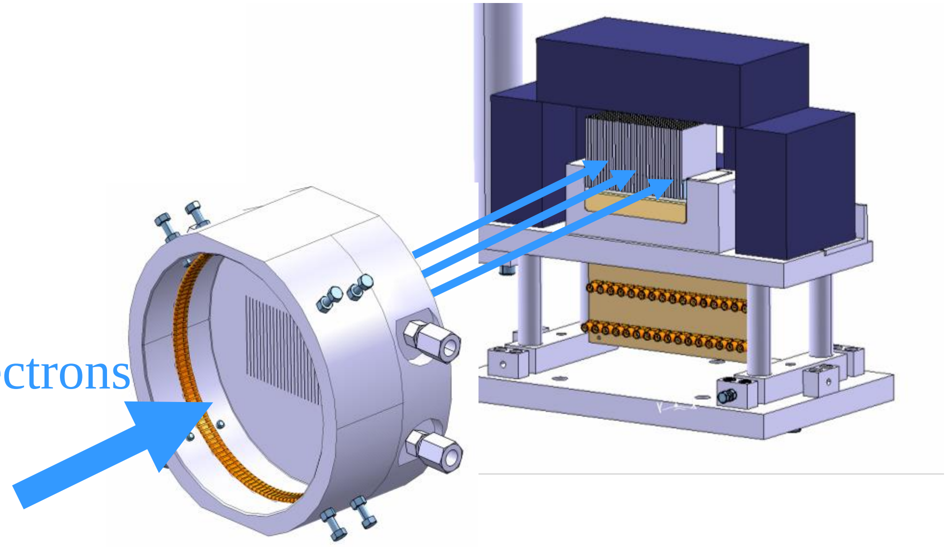
@CTF3, fully loaded acceleration:

➔any current variation in the pulse, translates into an energy variation

➔transient



32 Tungsten plates (2mm thick) spaced by ~1mm
Current read directly with 50Ω impedance to ground ➔ fast < 1ns

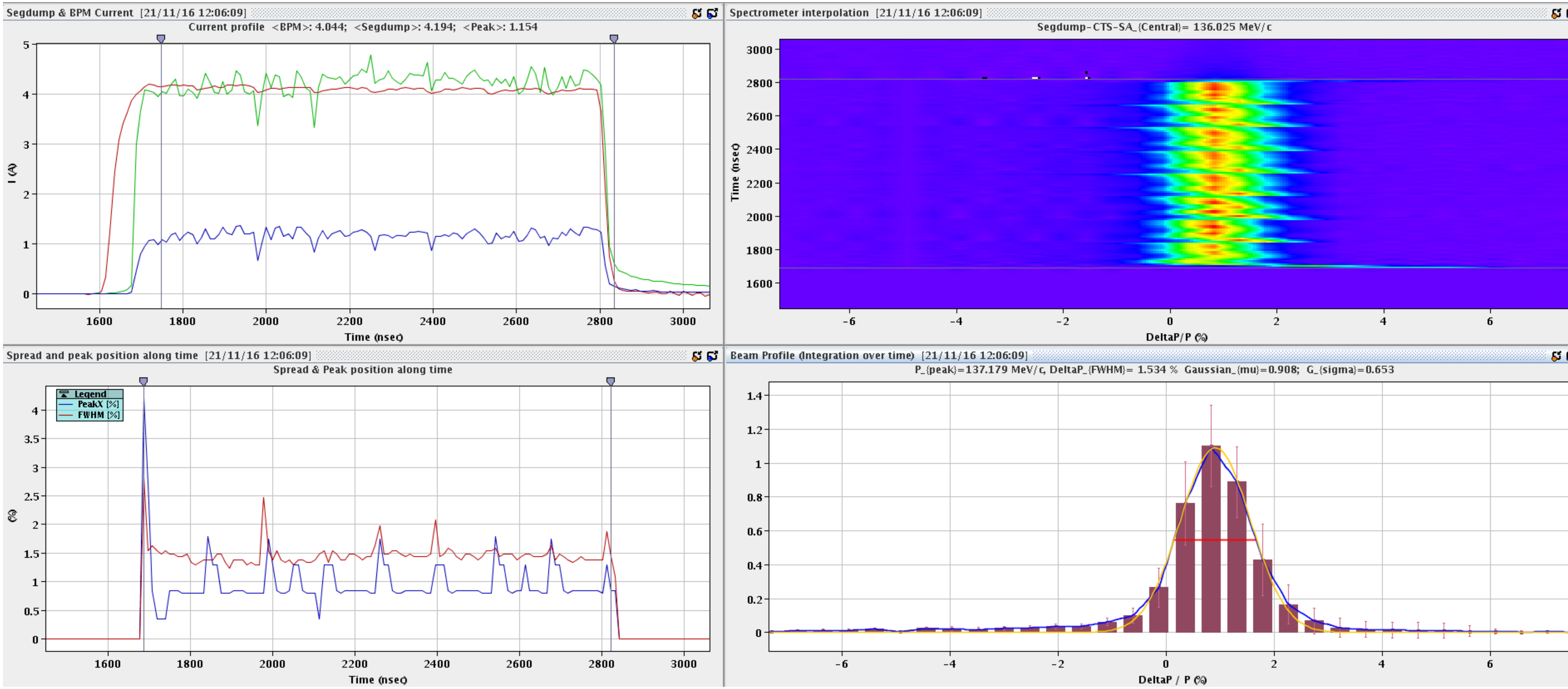


Resolution determined by geometry
(limited by multiple scattering)

Full calibration of each channel with beam

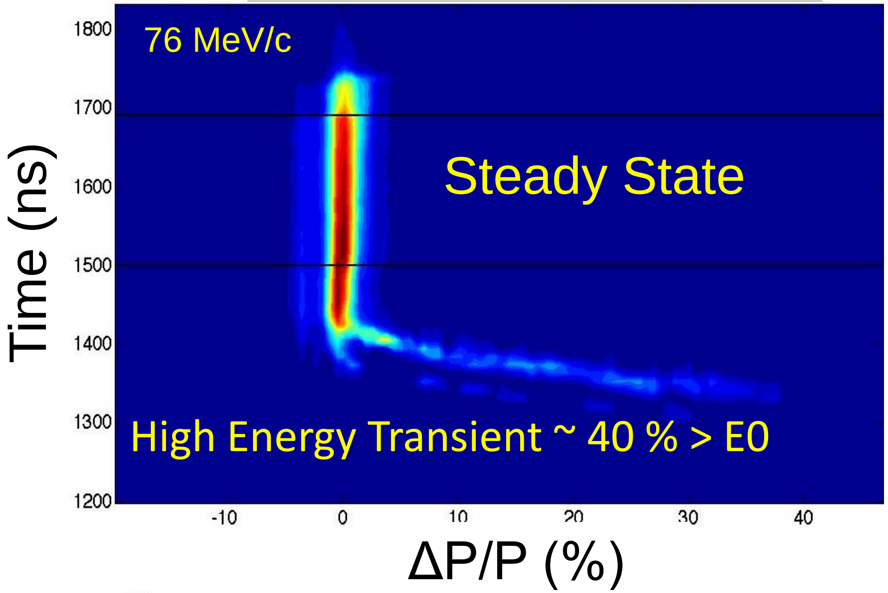
Use of segmented dump

- Tool including calibration
- Allowed Injector and Linac optimization
  - dp/p = 0.7%, emittance 60/40 mm mrad (H/V)

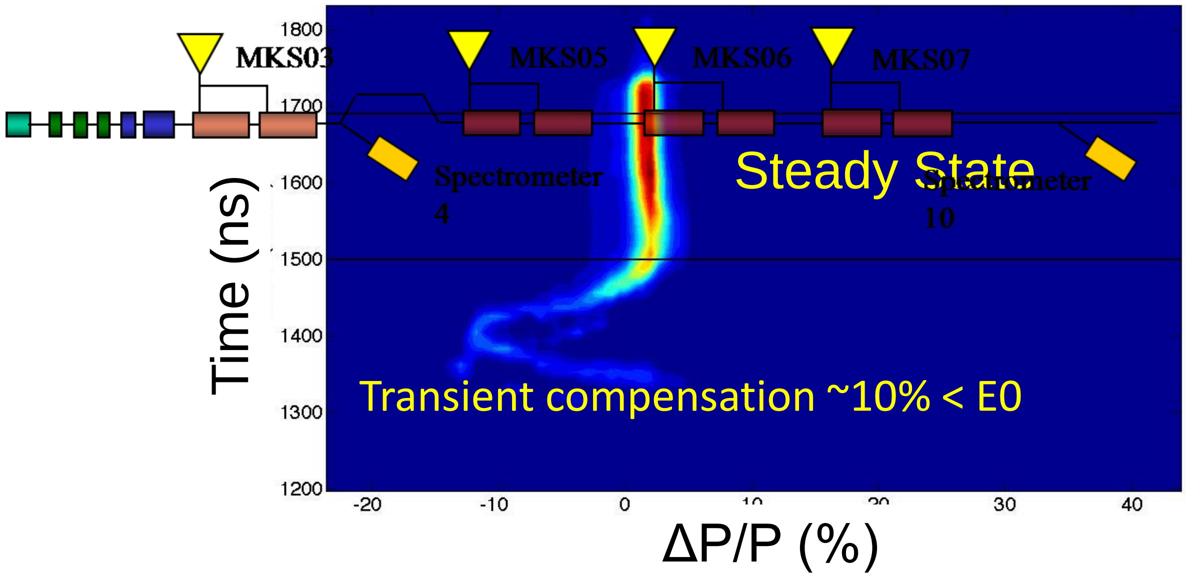


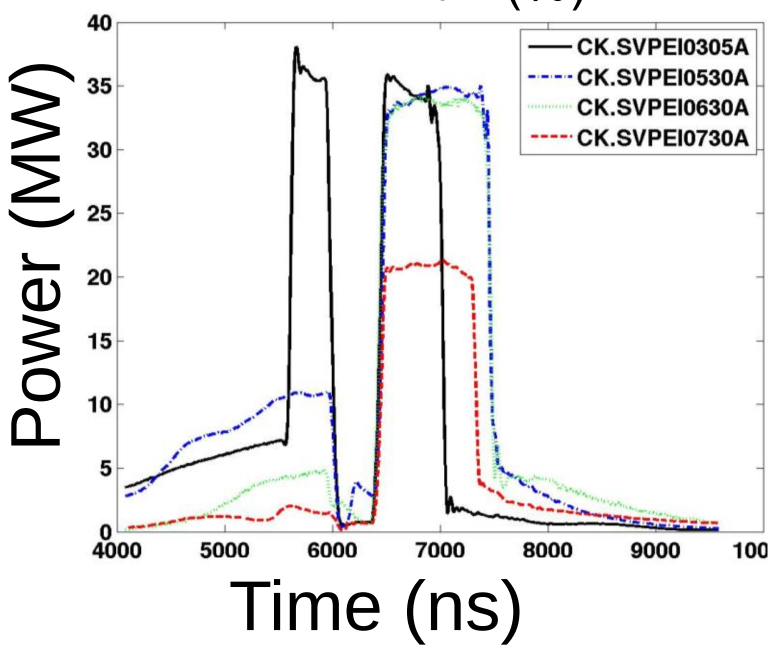
Transient compensation for full beam loading accelerating structure

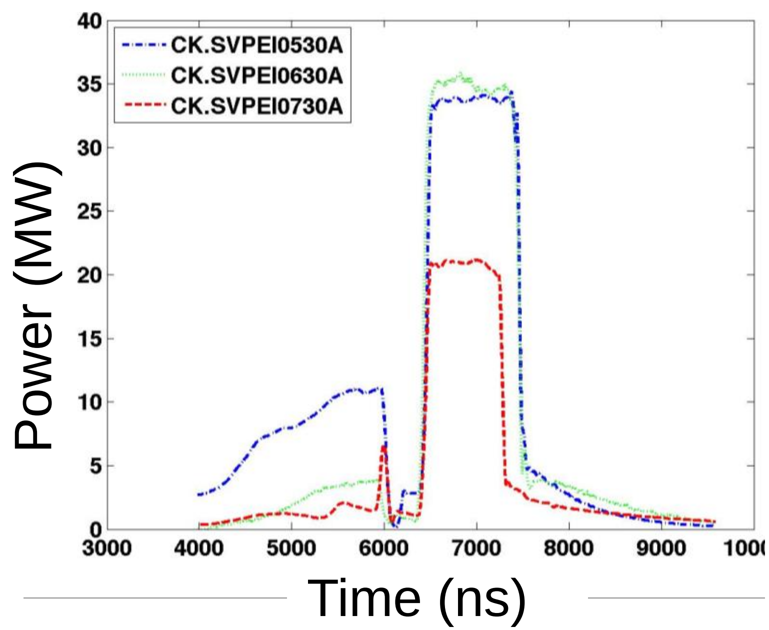
Nominal RF settings



Adjusted RF arrival timing

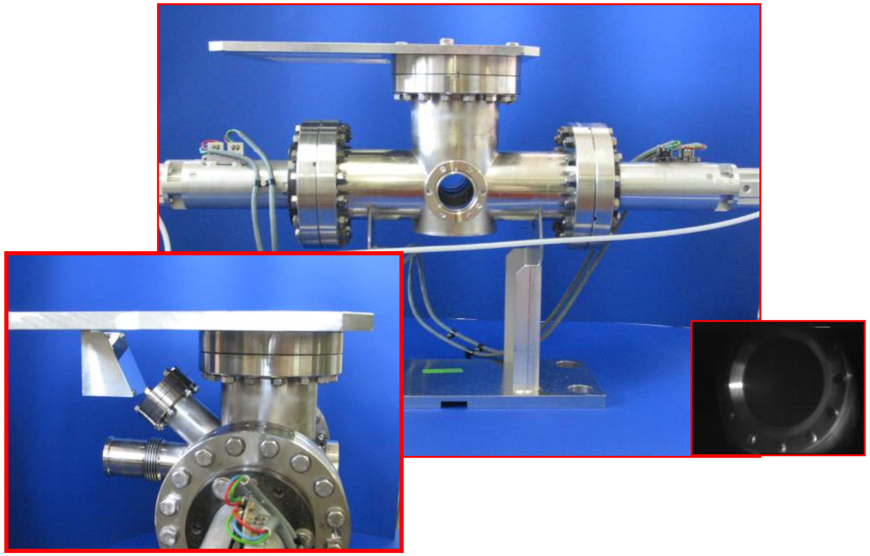






Screens and Optical Systems

In the Linac (Quad scan)
for emittance measurements



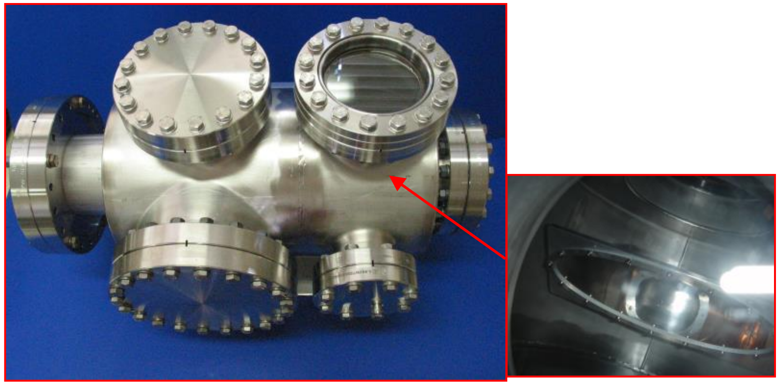
Backward OTR screens :

Two screens mounted on pneumatic arms
Screens tilted to 20° (observation at 40°)
10μm thick Aluminum foil (~90% reflectivity)
100μm thick Carbon foil (~26% reflectivity)
Active Size : Ø3cm

Scan in X

Scan in Y

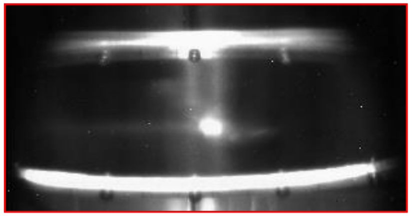
In the spectrometer line
for Energy and Energy spread measurements



Backward OTR screen :

Fixed screen tilted at 45° (observation at 90 °)
10μm thick Aluminum foil (~90% reflectivity)
Active Size : 10cmx4cm

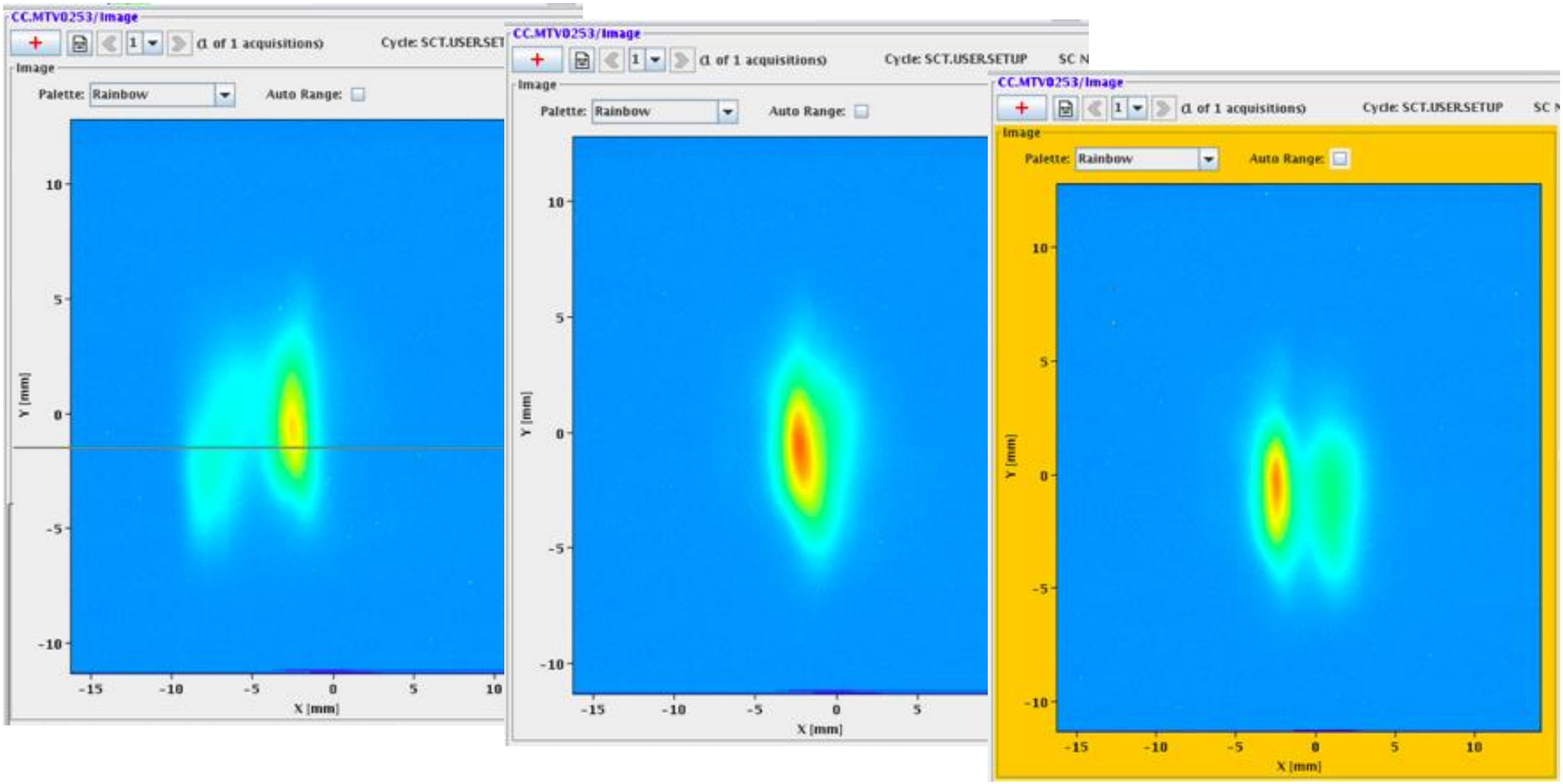
Light off



Light on

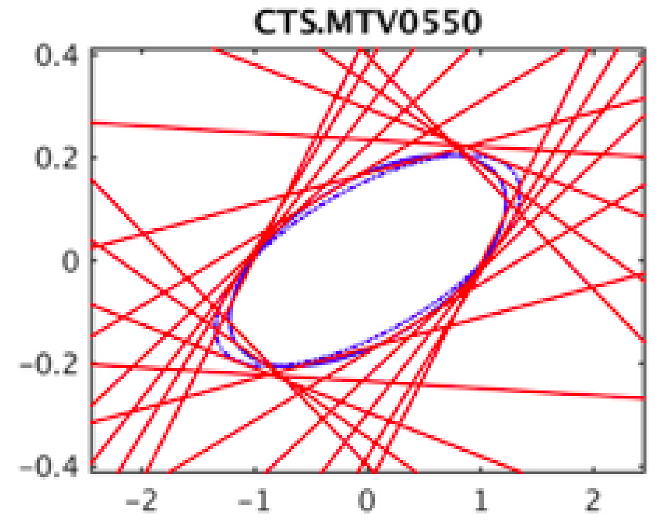
Direct Screen Observation

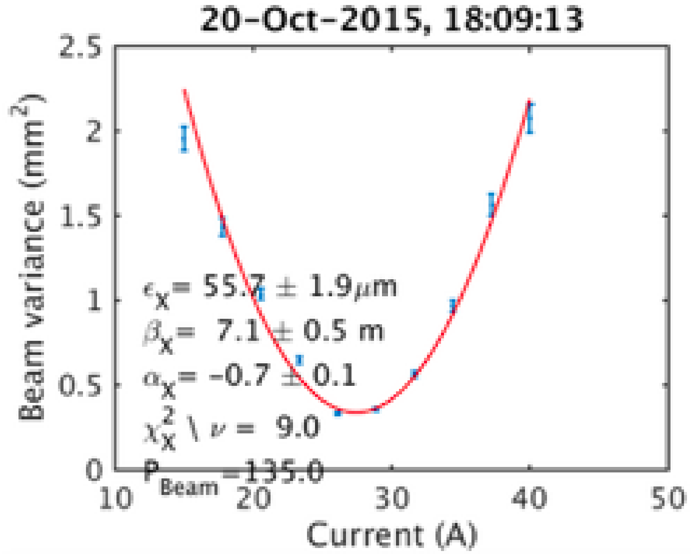
- Very useful for bunch shape diagnostics
- Here an example for DL 2x recombination



Quadrupole Scans

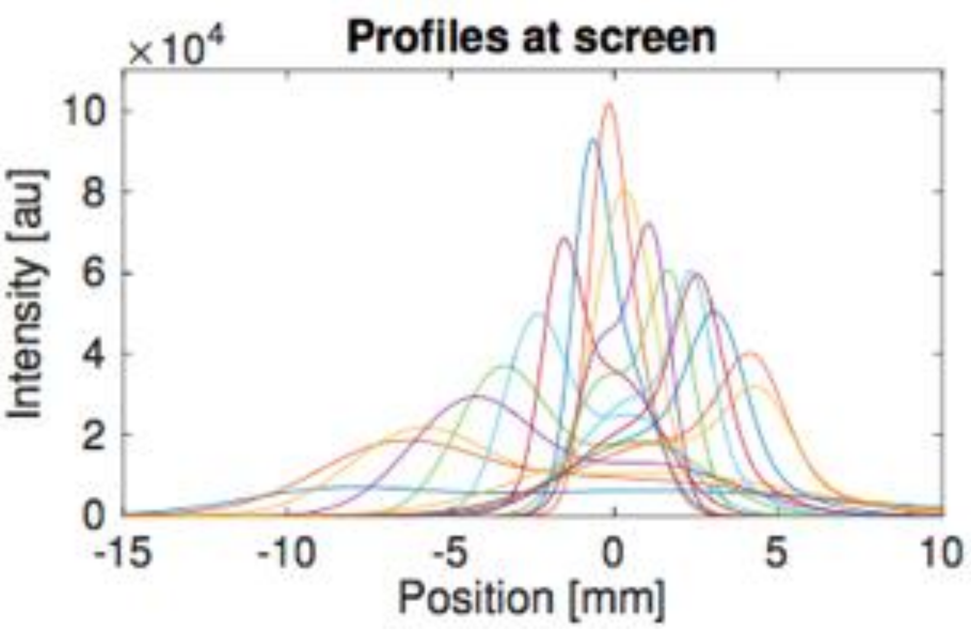
- Measure profile on screen
- Fit the profile width
- Change quadrupoles upstream
  => phase advance changing
  => phase space projection changes
- Calculate the transfer matrix with the known quadrupole strengths
- Fit initial beam parameters (α,β,ε)

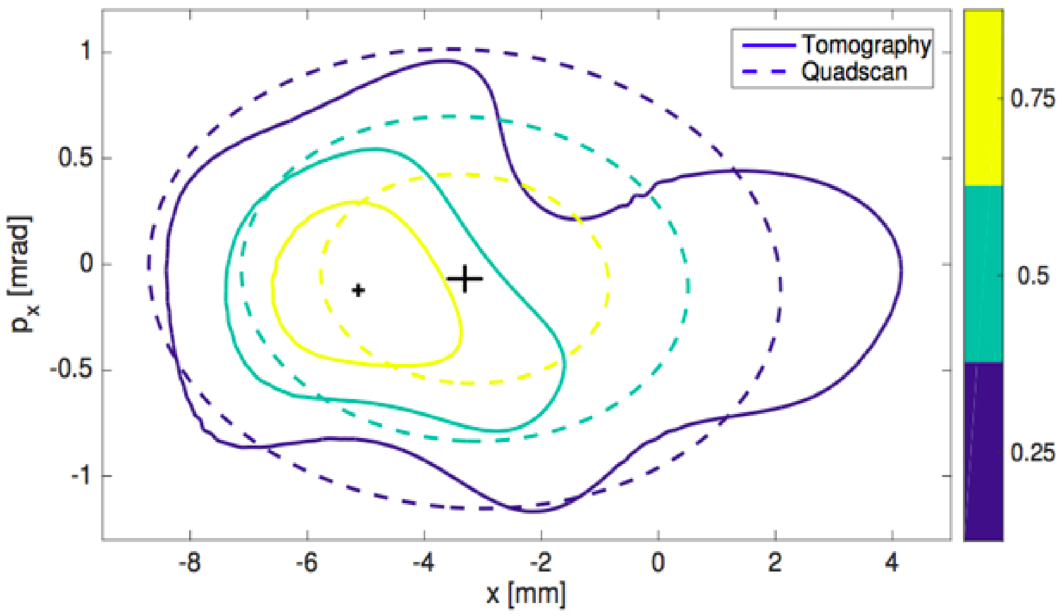




Quad Scan Tomography

- Using quad scan full profile data
- Each quadrupole setting corresponds to a phase space rotation
- Applying Inverse Radon transform reconstructs the phase-space distribution

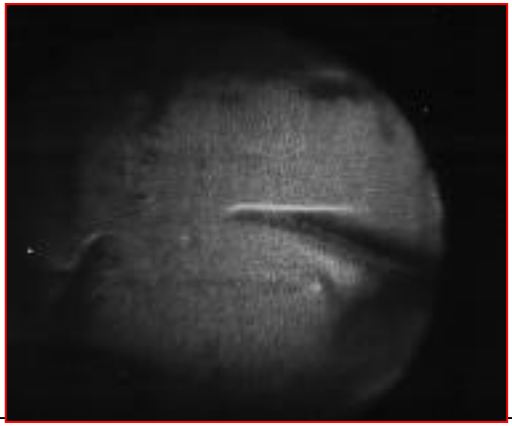




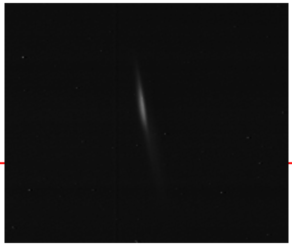
Improving the surface quality of the screens

High reflectivity screens for low charge beam

Thin Al foil is fragile

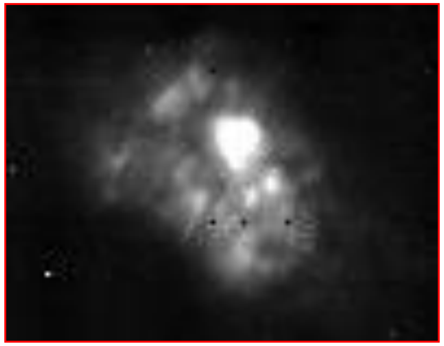


Using 200μm Si wafer with a very good surface quality
Adding an Aluminum coating to provide an excellent reflectivity coefficient (90%)



Thermal resistant material for high charge beam

Non homogeneous surface of C

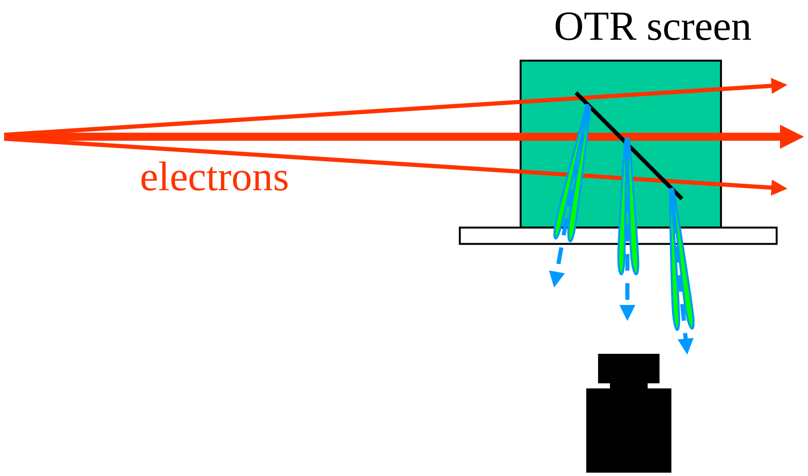


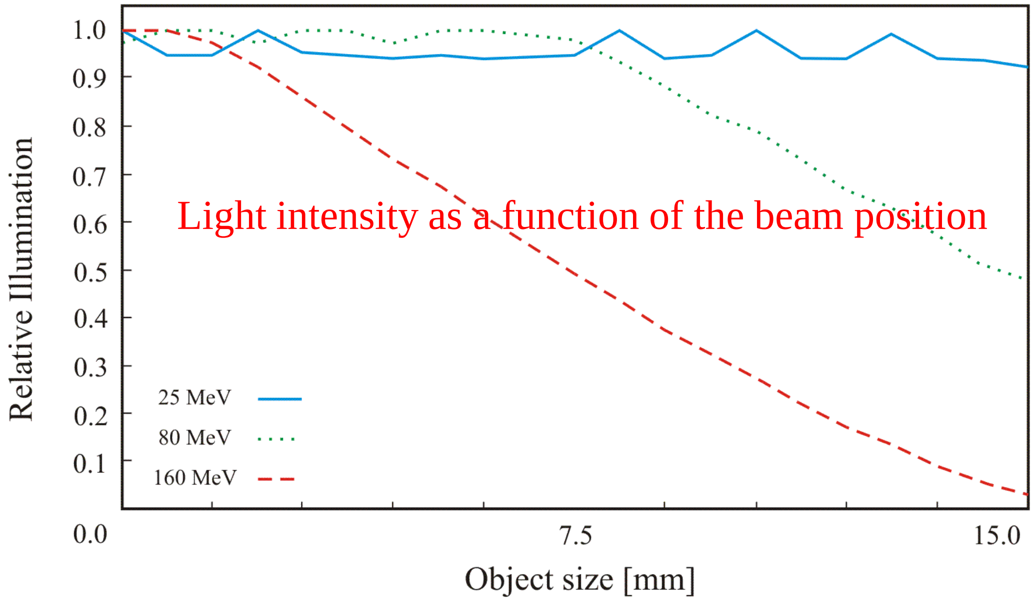
200μm thick Polished CVD (Chemical vapor deposition) SiC

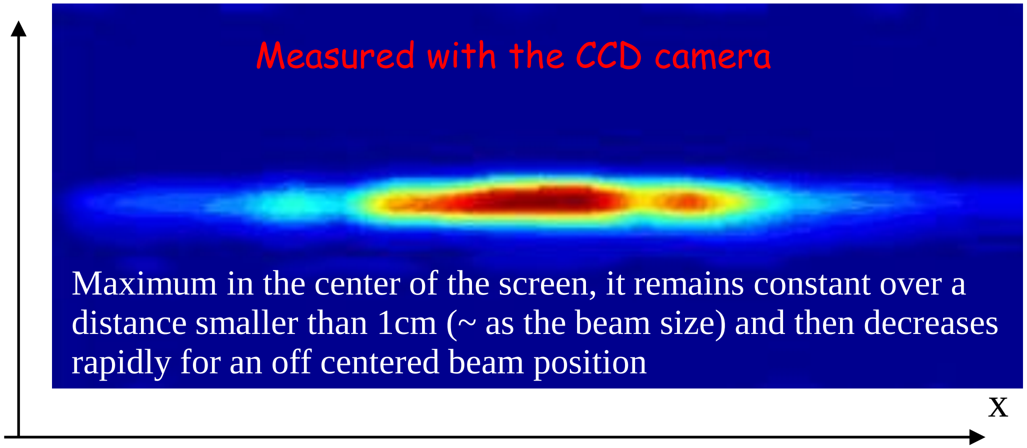
30% Reflectivity coefficient

Screens and Optical Systems

- Problem due to the non-homogeneous illumination of the OTR screen
- Due to the finite acceptance of the optical system, the small angular aperture (~1/γ) of the OTR light and the size of the screen
- Effect enhanced if the beam angle is stronger and for higher beam energy





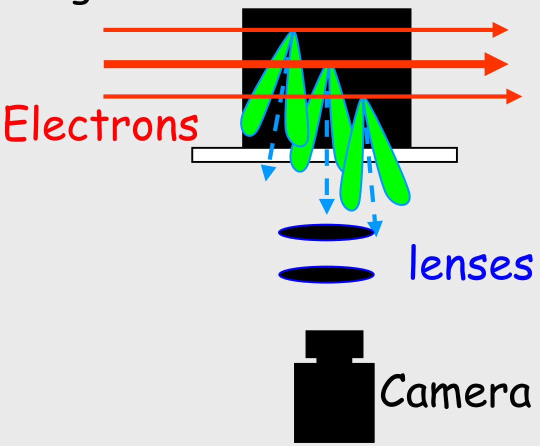


Diffusive Screens in the Spectrometer Lines

Beam size is bigger in the dispersive region

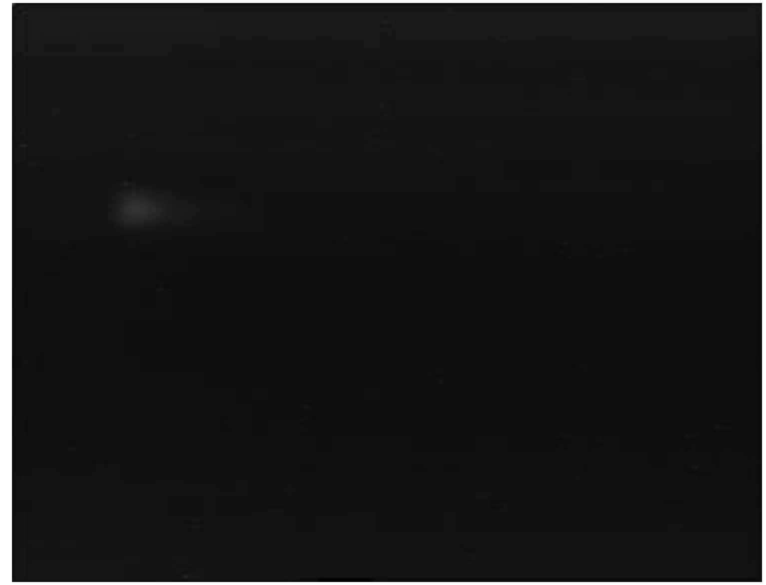
Diffusive screen

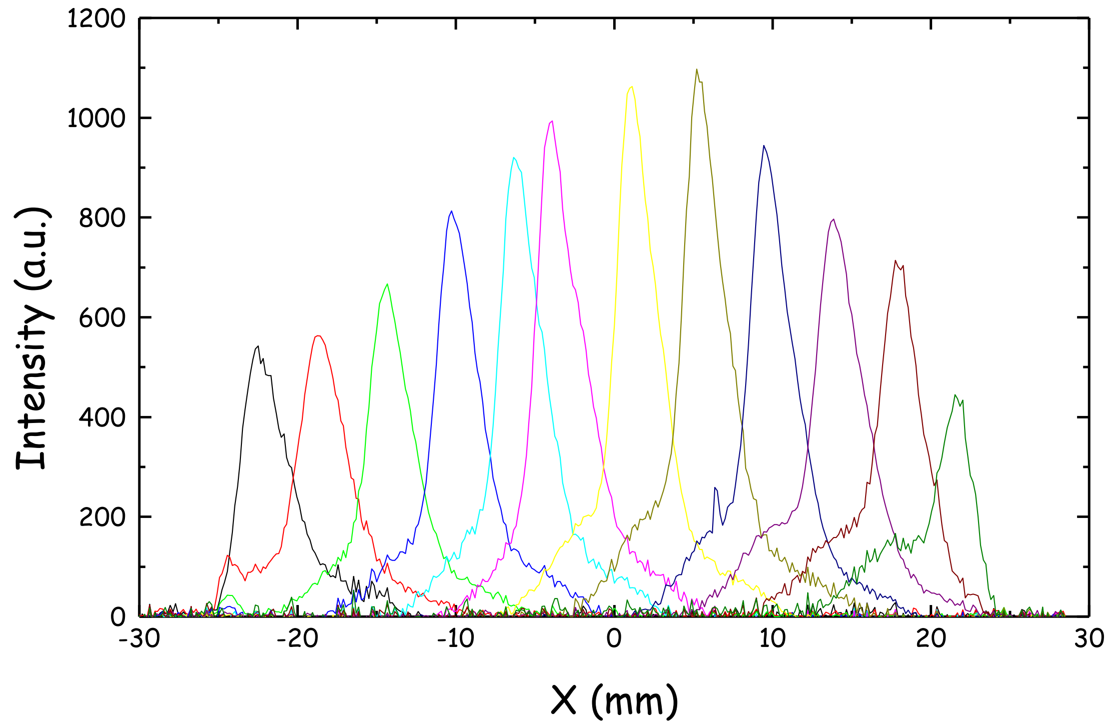
Using diffusive Aluminum foil



Enlarge the OTR lobe

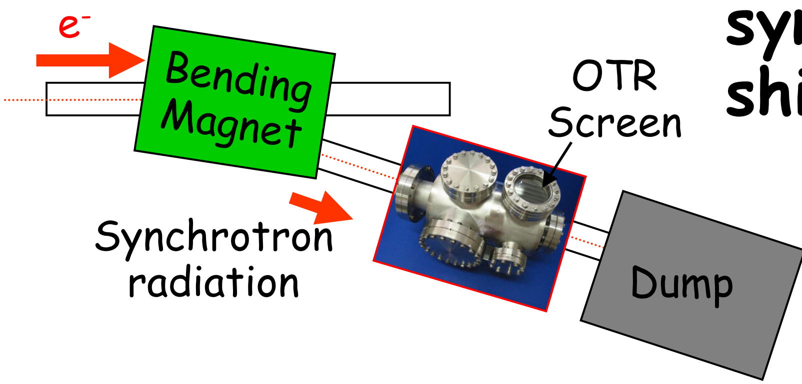
Less light intensity in the middle of the screen



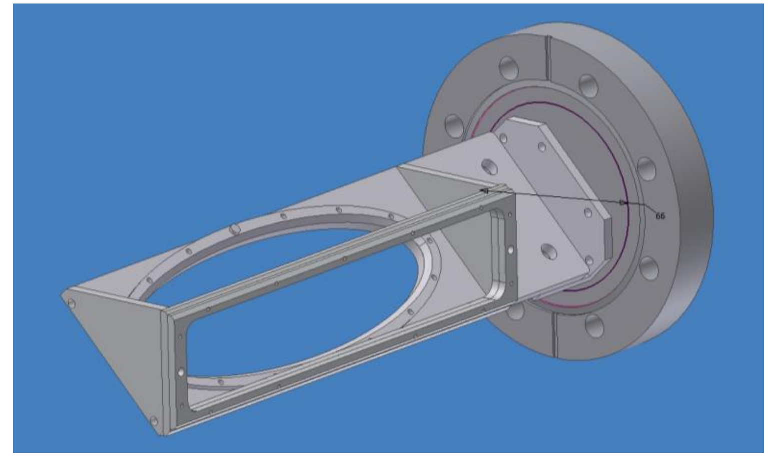


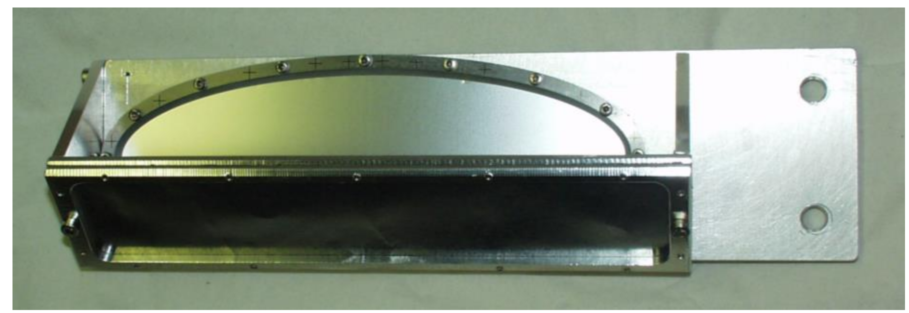
Deformation of the beam profile due to synchrotron radiation

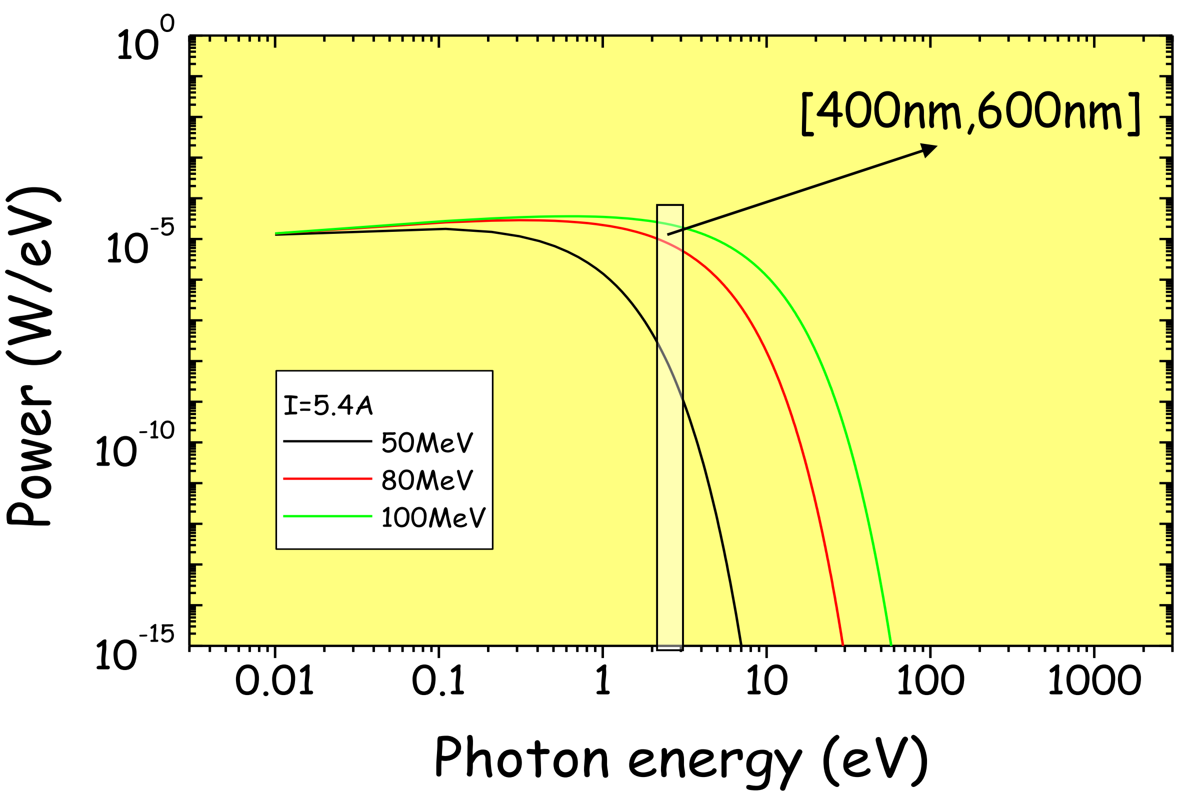
Synchrotron radiation in the spectrometer line



Carbon foil as synchrotron light shielding







At 50 MeV:
$1.5\ 10^{-9}$(SR) $7.7\ 10^{-3}$ (OTR)

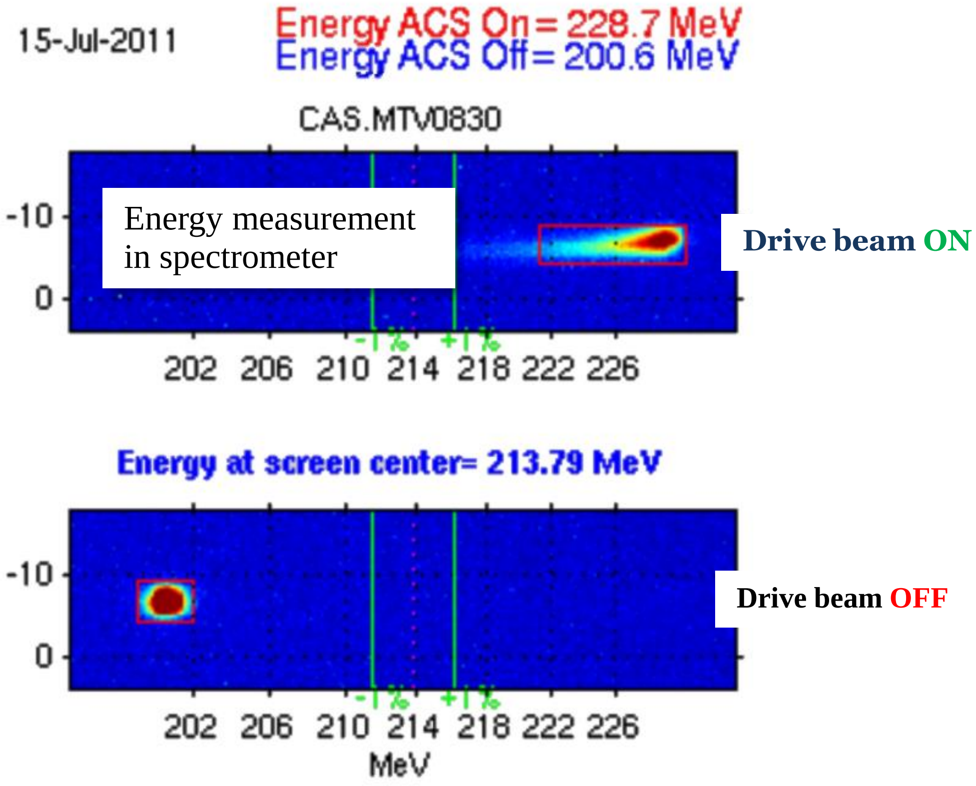
At 80MeV :
$5\ 10^{-4}$(SR) $8.6\ 10^{-3}$ (OTR)

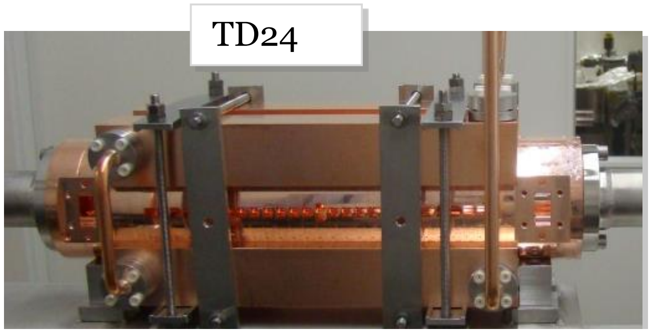
At 100MeV :
$4\ 10^{-3}$(SR) $9\ 10^{-3}$ (OTR)

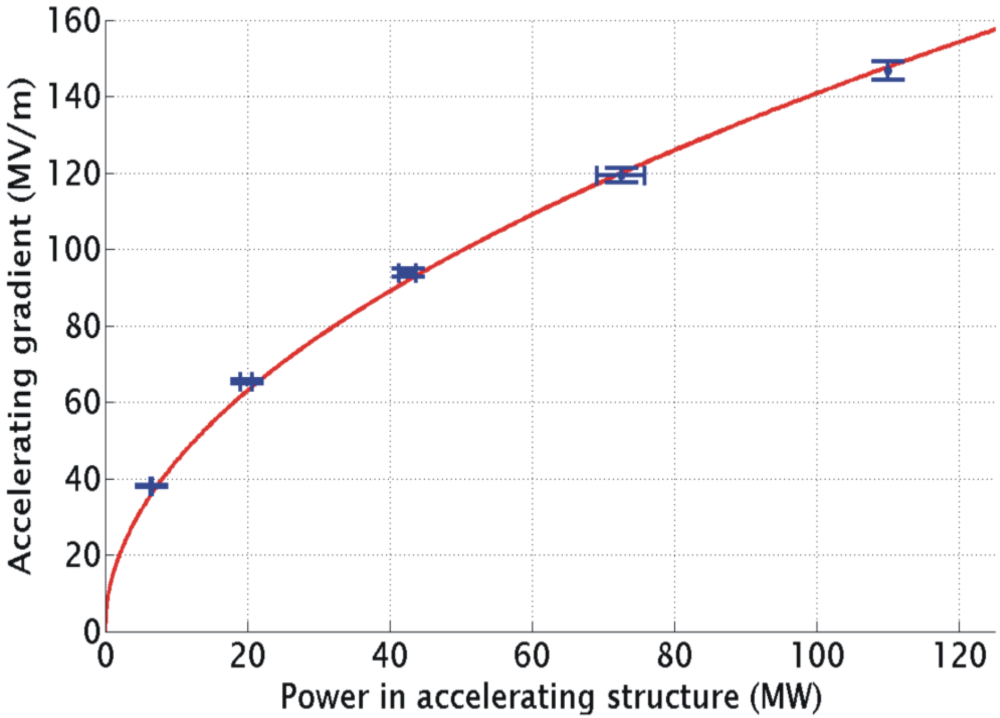
Achieved Two-Beam Acceleration

- Maximum probe beam acceleration measured: 31 MeV

  => Corresponding to a gradient of 145 MV/m





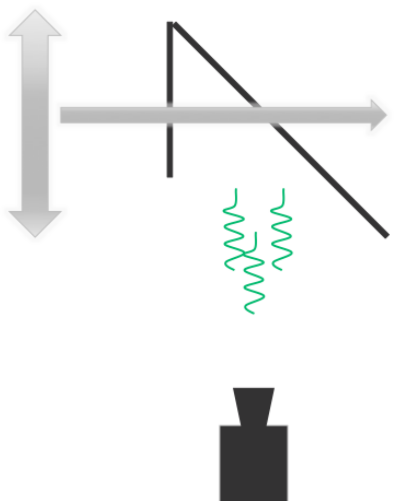


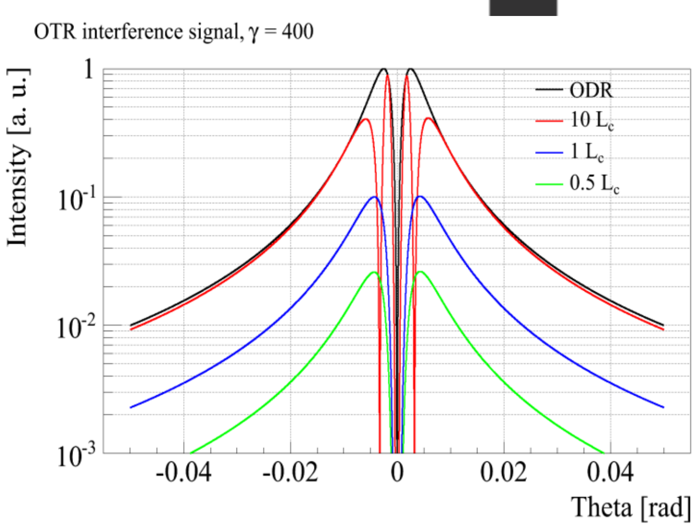
Other Diagnostic Experiments

OTR interference

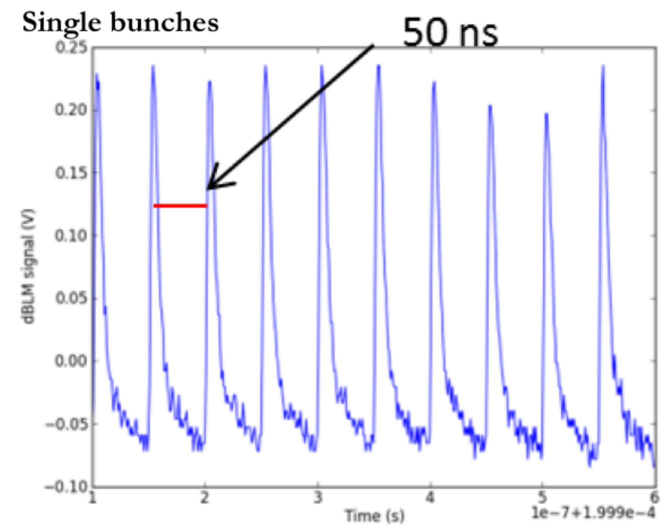
Experimental results : Wartski (1975) for distances >> L_c
Califes: $L_c \cong 2.5$ cm @ 200 MeV, $\lambda = 500$ nm
Ideal to study the coherent regime

<u>*S. Mazzoni,*</u>
<u>*T. Lefevre*</u>

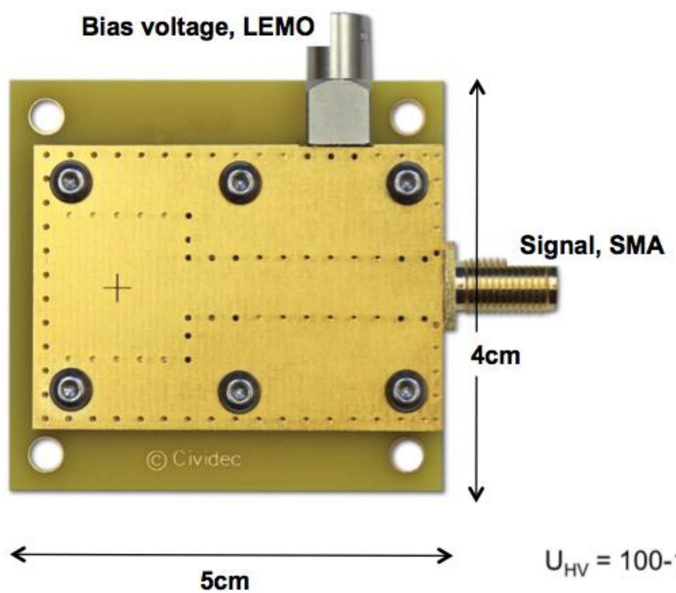




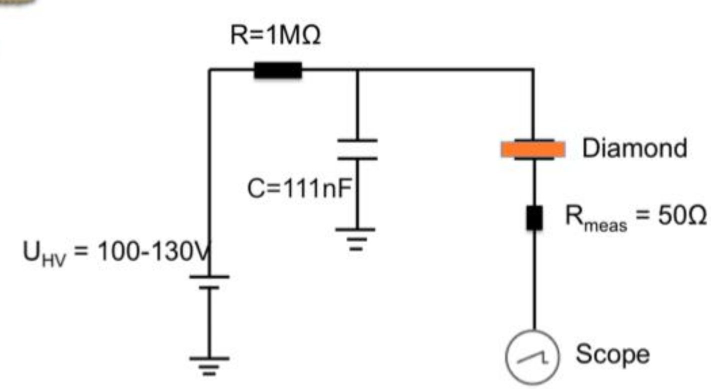
Diamond beam loss detectors



<u>*F. Burkart, O. Stein,*</u>
<u>*W. Farabolini*</u>

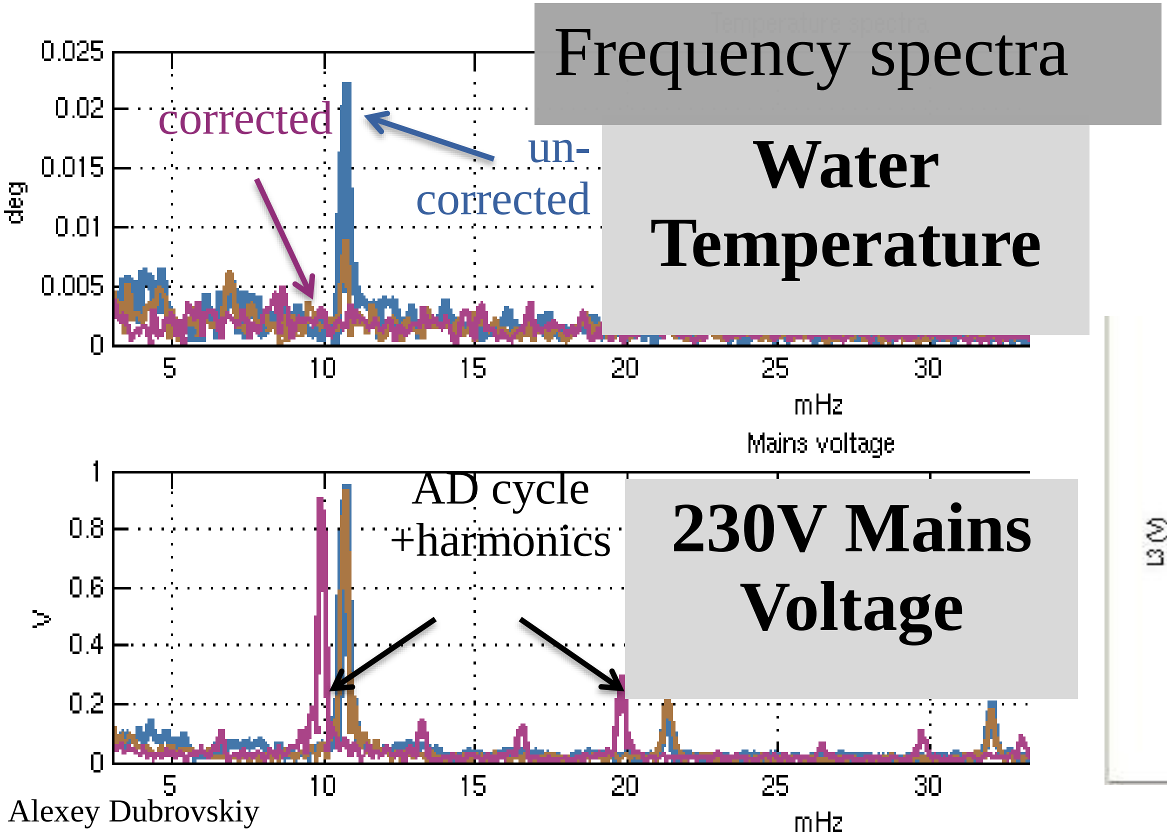


- **Nanosecond time resolution.**
- **Radiation hard.**
- **Wide dynamic range (1e – 5E9e).**

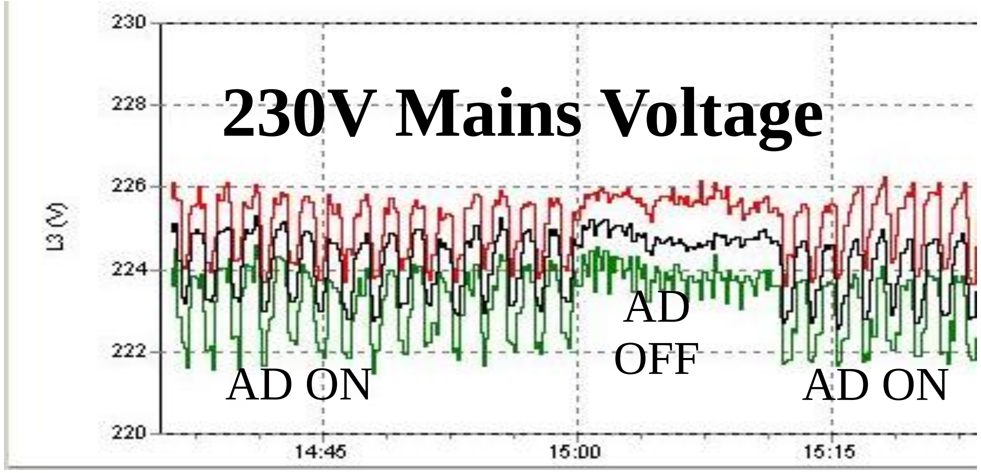


Measuring Antiprotons ☺

- RF pulse compression needed water temperature regulation with <0.05°C stability
- observed variations with ~2 min period
- found 230V mains variation with this period caused by AD (Antiproton Decelerator) cycle
- => water station regulation corrected



Alexey Dubrovskiy



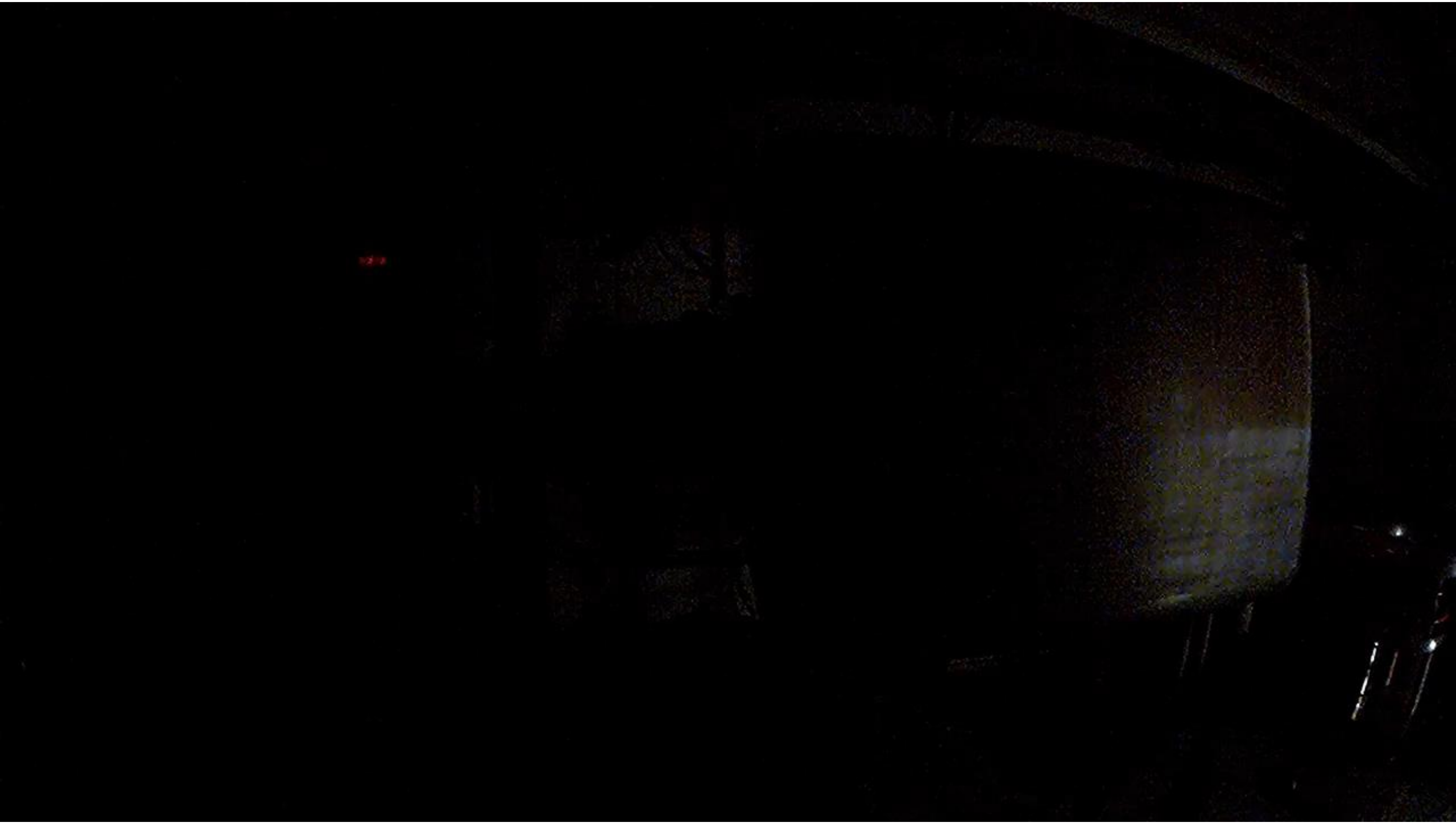
Denis Arnoult

Innovative Beam Instrumentation

- Problems with our thermionic gun (145kV)
  - HV breakdowns
  - affected gun electronics
- All available diagnostics was not conclusive
  - no apparent vacuum activity
- => desperate need of new diagnostics

- Bypassed BI
- We didn't have any CO driver for the new tool
- But was working!
- It was a GoPro Hero 4

Gun action cam



Conclusions

- CTF3 has shown the CLIC feasibility
  - stable Drive Beam generation
  - high gradient RF performance
- Good, diverse diagnostics is absolutely essential to optimize the performance
- Your accelerator is only as good as your diagnostics!
- Thank you for your attention!!!

What happened to CTF3?

- No immediate plan for dismantling
- A part (CALIFES) is used as CLEAR for
  - Beam Instrumentation tests
  - Plasma lens experiments
  - Irradiation studies

Acknowledgements

- Many thanks to **all** my colleagues from CTF3
- In particular:
  - Thibaut Lefevre
  - Roberto Corsini
  - Piotr Skowronski
  - Davide Gamba
  - Lars Søby
  - Alexandra Andersson
  - Anne Dabrowski

Additional Slides

Overview: Position and intensity monitors

	BPE	BPM	BPI	BPS	PBPM	BPR
Transverse sensitivity, Δ= Σ [mm]	30	30	33 / 50		12	~10
Resolution pos.	0.1mm	0.1mm			200nm	0.1mm
Relative precision (3/4 half aperture)	0.2%	1%	1%	1%	1%	1-5%
Longitudinal transfer impedance [Ω]	0.17 / 1.7	0.1 / 1				0.1 / 1
Resolution current [mA]	12 / 1.2	10 / 3				12 / 1.2
Low frequency cut off Δ / Σ [kHz]	1 / 1	10 /0.15	~20 / 0.3			1kHz
High frequency cut off	200MHz	200MHz	200MHz		50MHz	200MHz (10MHz)
Calibration	Yes	Yes	Yes	Yes	Yes	No
ID / Length [mm]	46 / 130	40 / 168	90*39/240		6	40 / 196
Number of feedthroughs	4	0	0	0	0	5
Waveguide	--	--	--	--	--	WR28
Flange types	DN40CF / DN100CF	DN40CF	Racetrack		Helicoflex 10.9*7.7	DN40CF
Max. bake-out temperature	130 °C	130 °C	130 °C	130 °C	130 °C	130 °C

Lars Søby