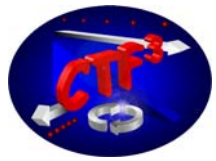


Longitudinal beam diagnostics at CTF3

Anne Dabrowski
CERN AB/BI

On behalf of all involved

CLIC Workshop 2008
15 October 2008

Longitudinal beam diagnostics @ CTF3

Brief comparison between CTF3 and CLIC longitudinal beam parameters

CTF3 Measurements

1. Time resolved energy
   - Segmented dump
2. Phase & bunch spacing manipulation
   - Streak Camera
   - Phase monitor (s)
3. Bunch length
   - Streak Camera
   - RF deflector
   - "RF pickup

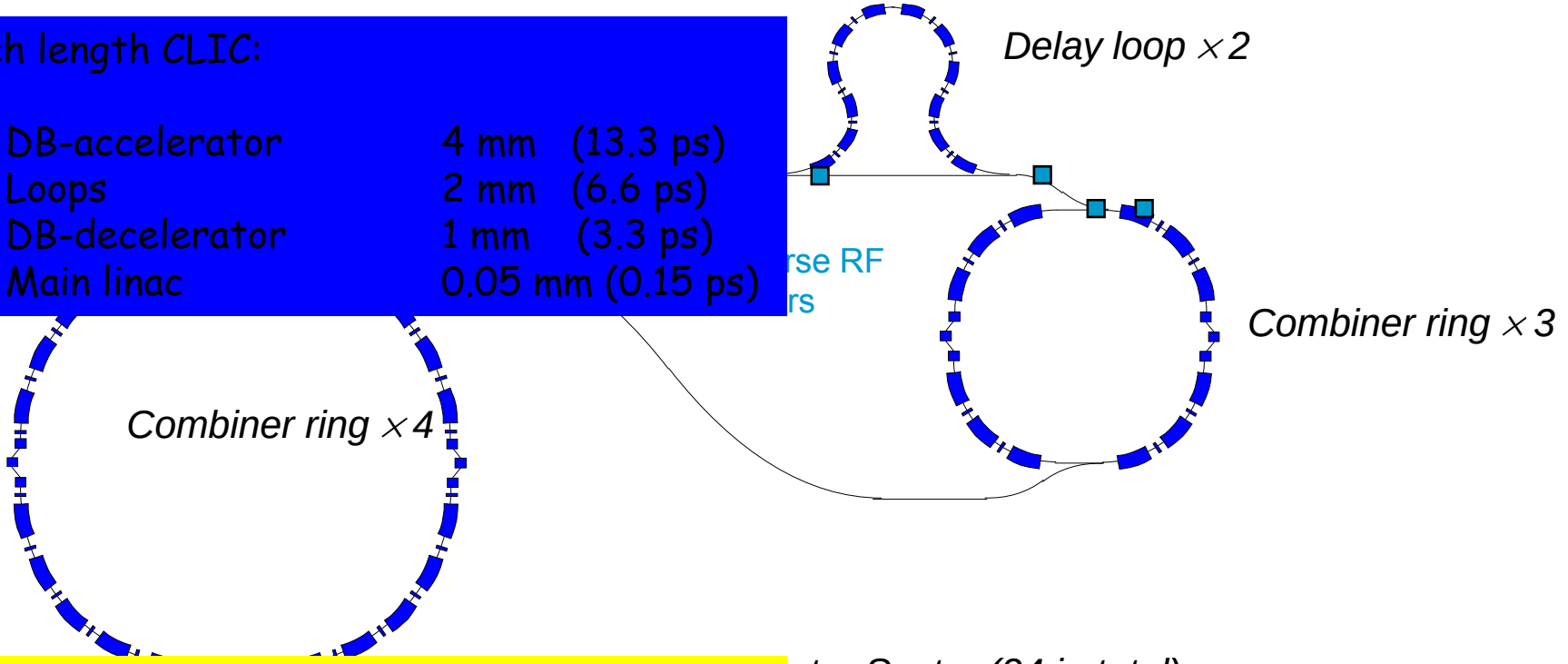
Future:

Combiner ring (bunch length & bunch combination) & CRM line (bunch length), TL2 (bunch length), CLEX - TBL (time resolved energy) CLEX – CALIFEs (bunch length)

CTF3 is here to test CLIC

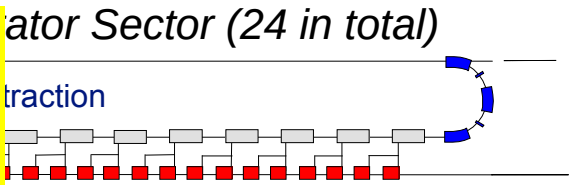
Bunch length CLIC:

DB-accelerator	4 mm (13.3 ps)
Loops	2 mm (6.6 ps)
DB-decelerator	1 mm (3.3 ps)
Main linac	0.05 mm (0.15 ps)

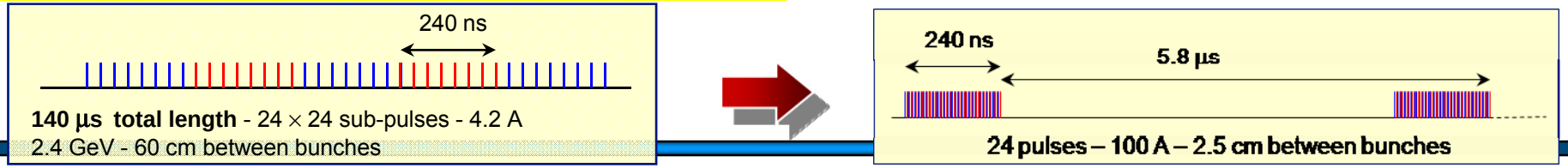


Bunch frequency multiplication:

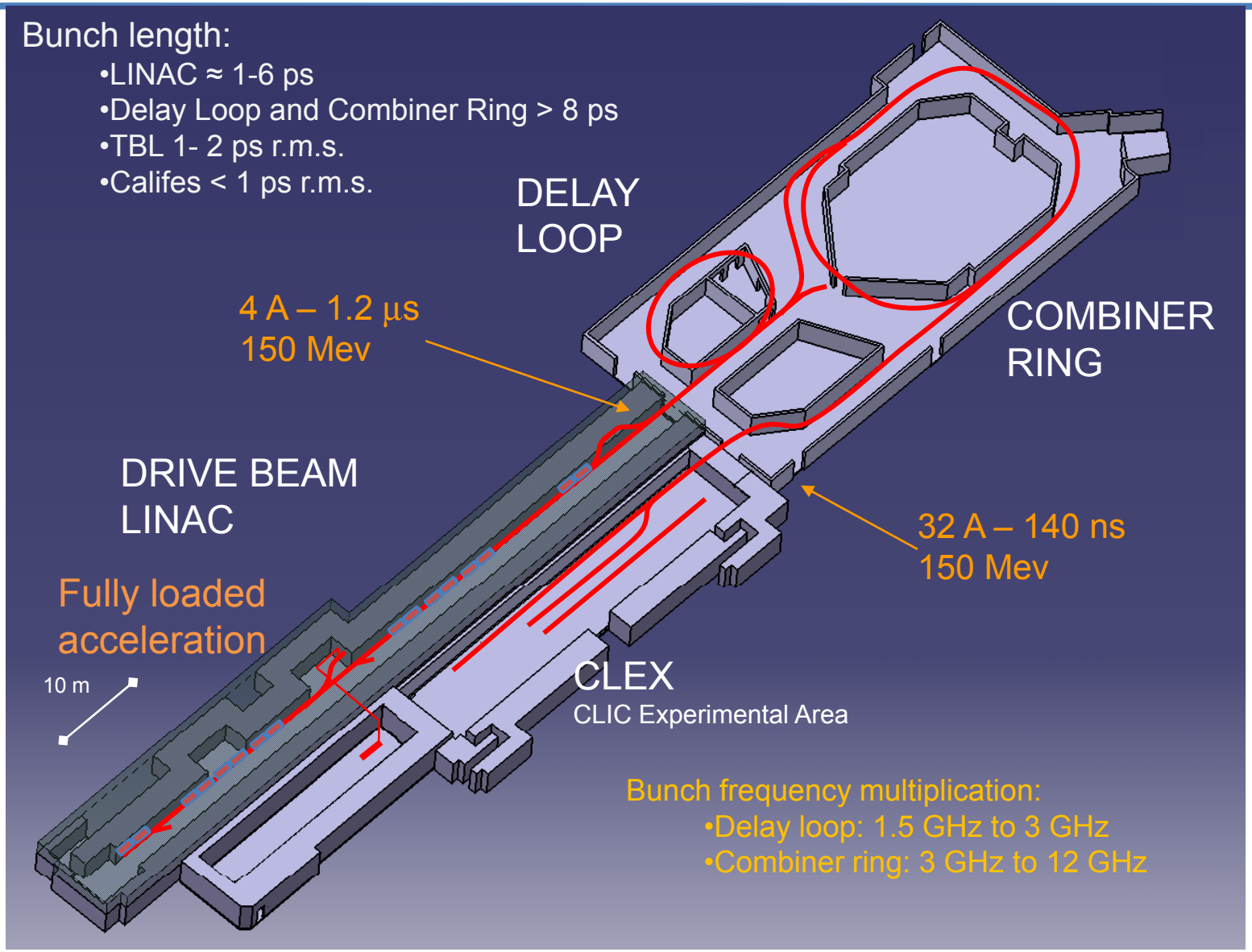
Delay loop:	0.5 GHz→1 GHz
Combiner ring 1:	1 GHz →3 GHz
Combiner ring 2:	3GHz →12 GHz



Drive beam time structure - final

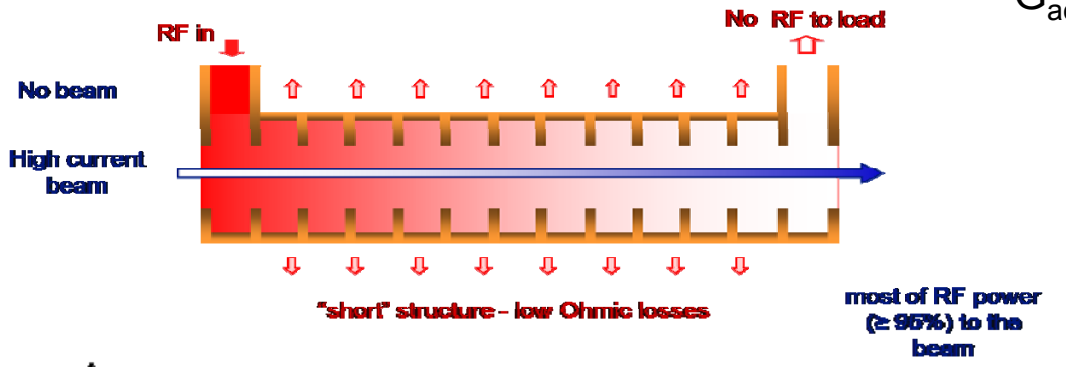


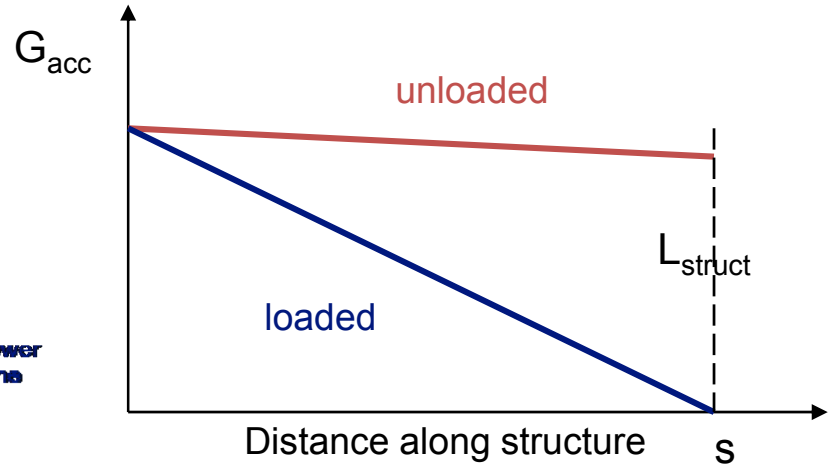
CTF3 Layout

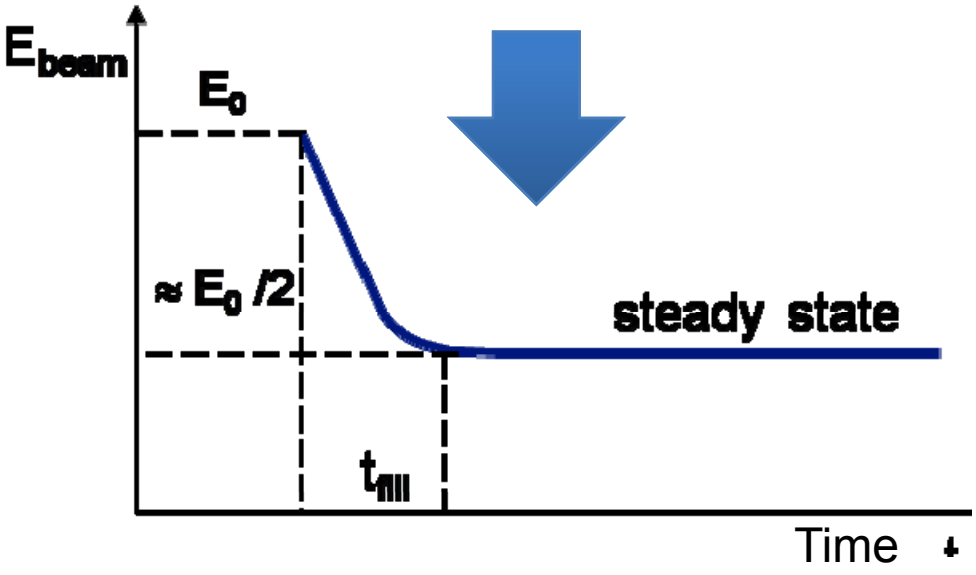

Bunch length:
•LINAC ≈ 1-6 ps
•Delay Loop and Combiner Ring > 8 ps
•TBL 1- 2 ps r.m.s.
•Califes < 1 ps r.m.s.
DELAY LOOP
4 A – 1.2 μs
150 Mev
COMBINER RING
DRIVE BEAM LINAC
32 A – 140 ns
150 Mev
Fully loaded acceleration
10 m
CLEX
CLIC Experimental Area
Bunch frequency multiplication:
•Delay loop: 1.5 GHz to 3 GHz
•Combiner ring: 3 GHz to 12 GHz

Fully loaded acceleration @CTF3

3 GHz TW Accelerating structures
95% the RF power is transferred to the beam







no power flows into load

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

➔head of beam accelerated more than the steady state

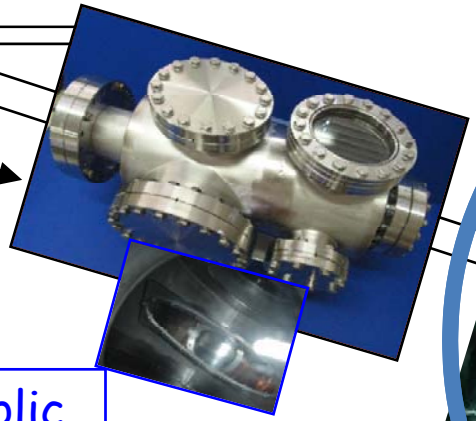
➔CTF3 requires time dependent energy measurement

Spectrometer lines for energy measurement

CCD Camera
- Integrated measurement
- Good spacial resolution

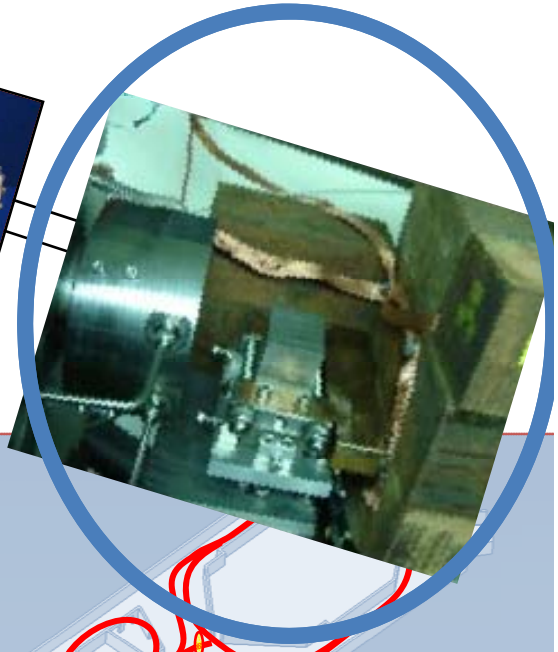
e^-

Bending Magnet



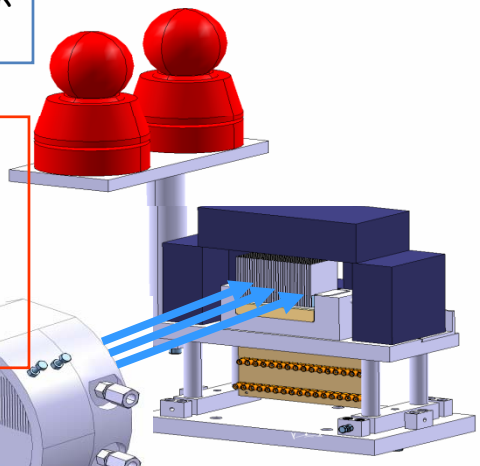
All spectrometers

Fixed parabolic OTR Screen

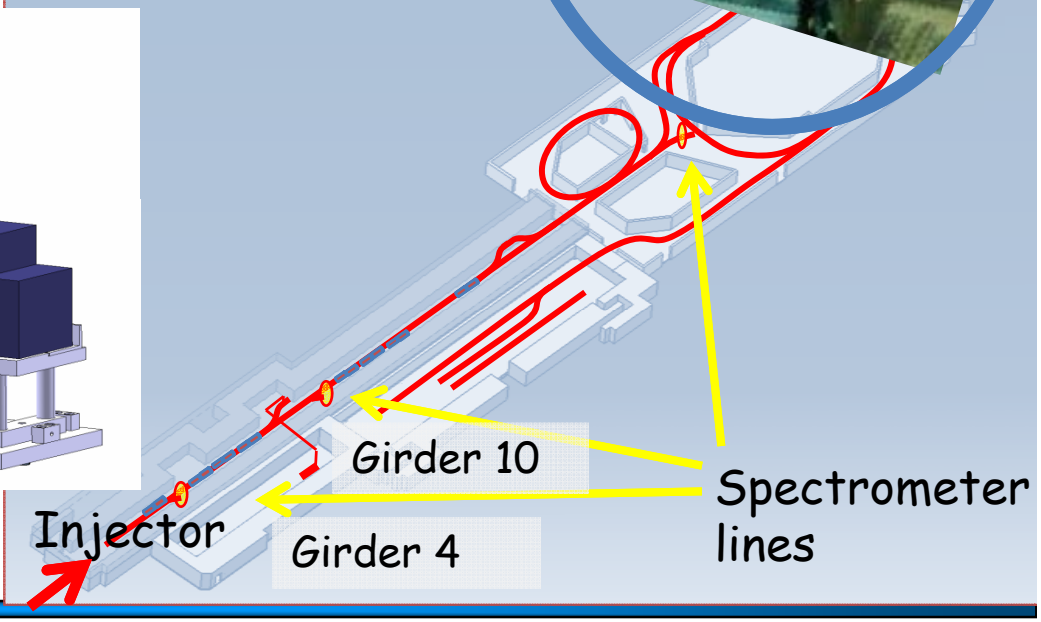


Collimator in Steel
- 32 vertical slits, 400um thick
- Water cooled

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

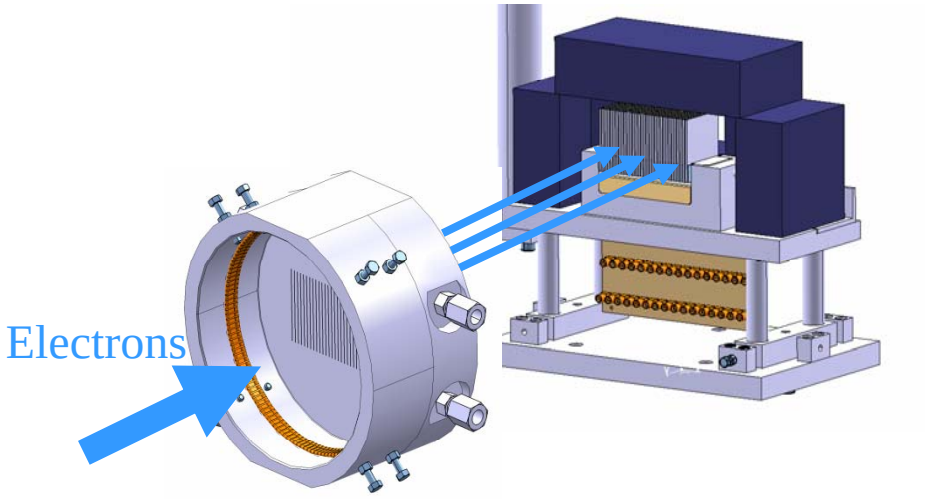


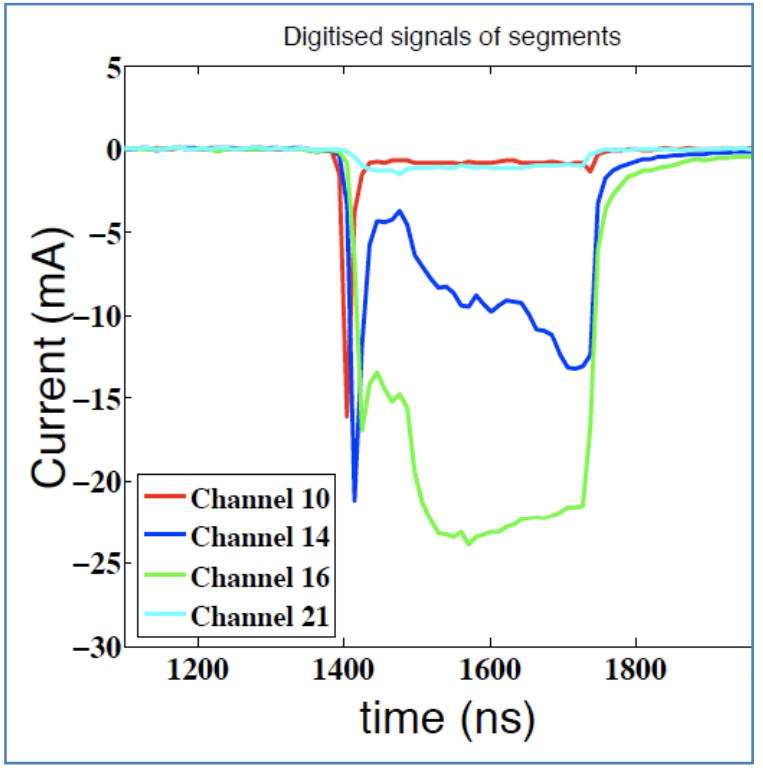
Electrons



Segmented dumps fully commissioned in 2008

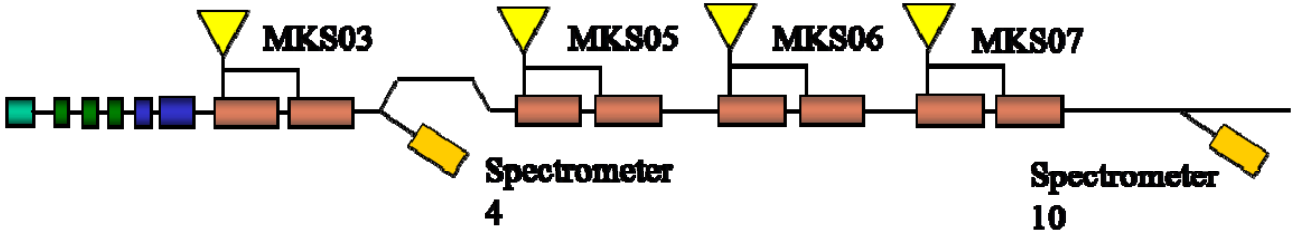
➔Noise level negligible
➔Cross talk between channels negligible
➔time response fast – limited by ADC to 10 ns

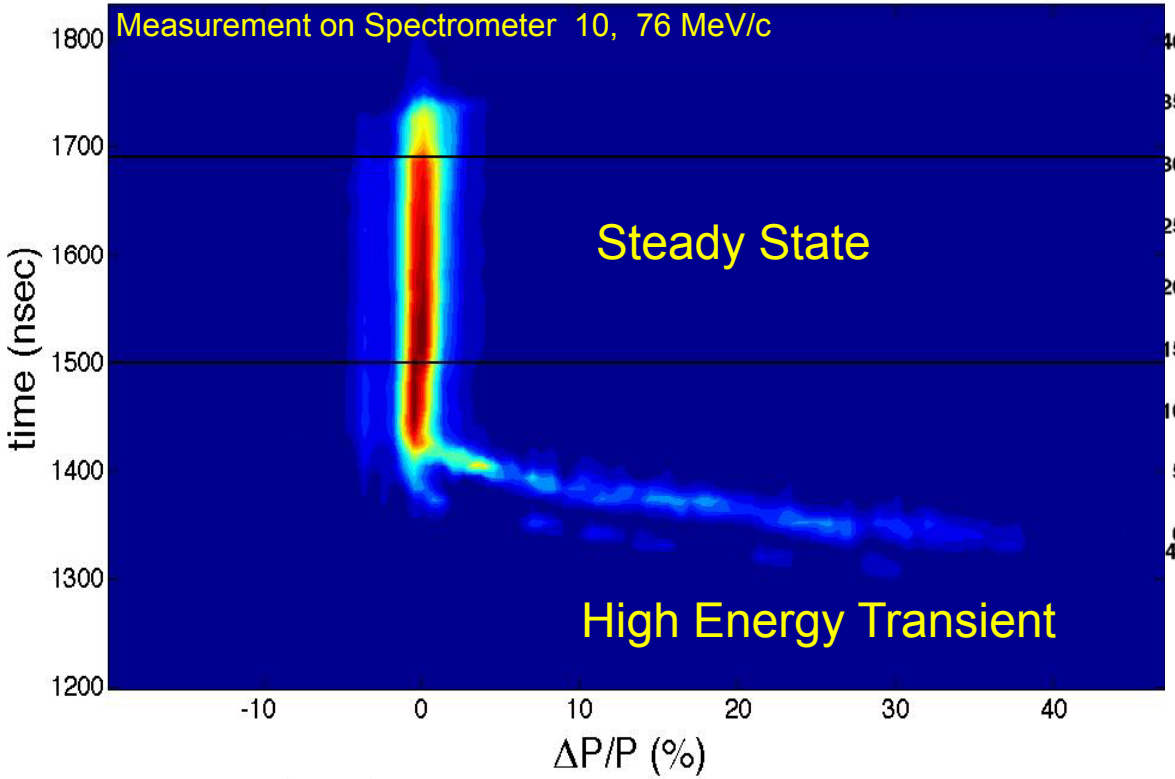


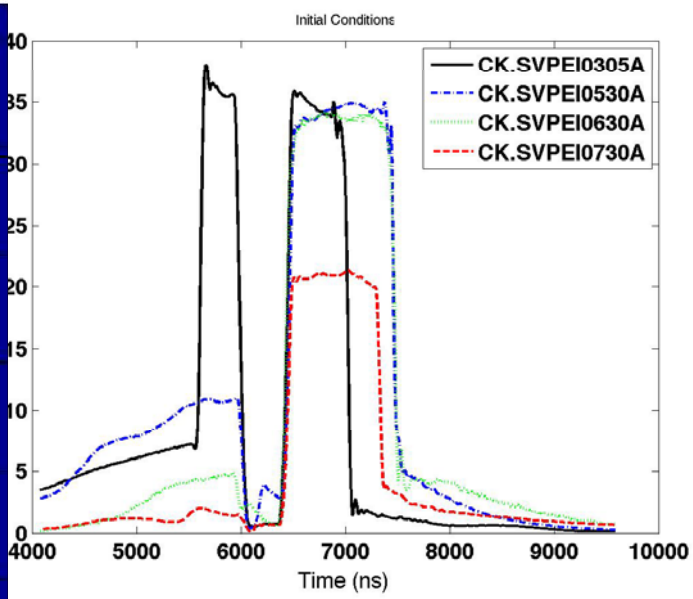


Full calibration done of each channel done with beam.
Combine signals from all channels to reconstruct the time resolved energy spectrum.
Resolution determined by geometry ➔ limited by multiple scattering

Transient compensation @ CTF3

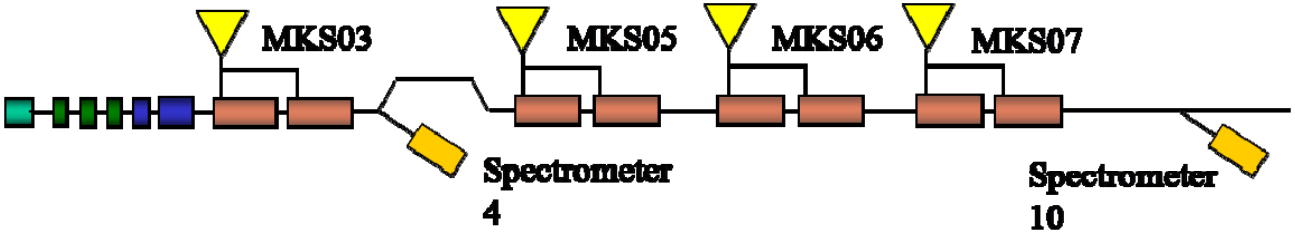


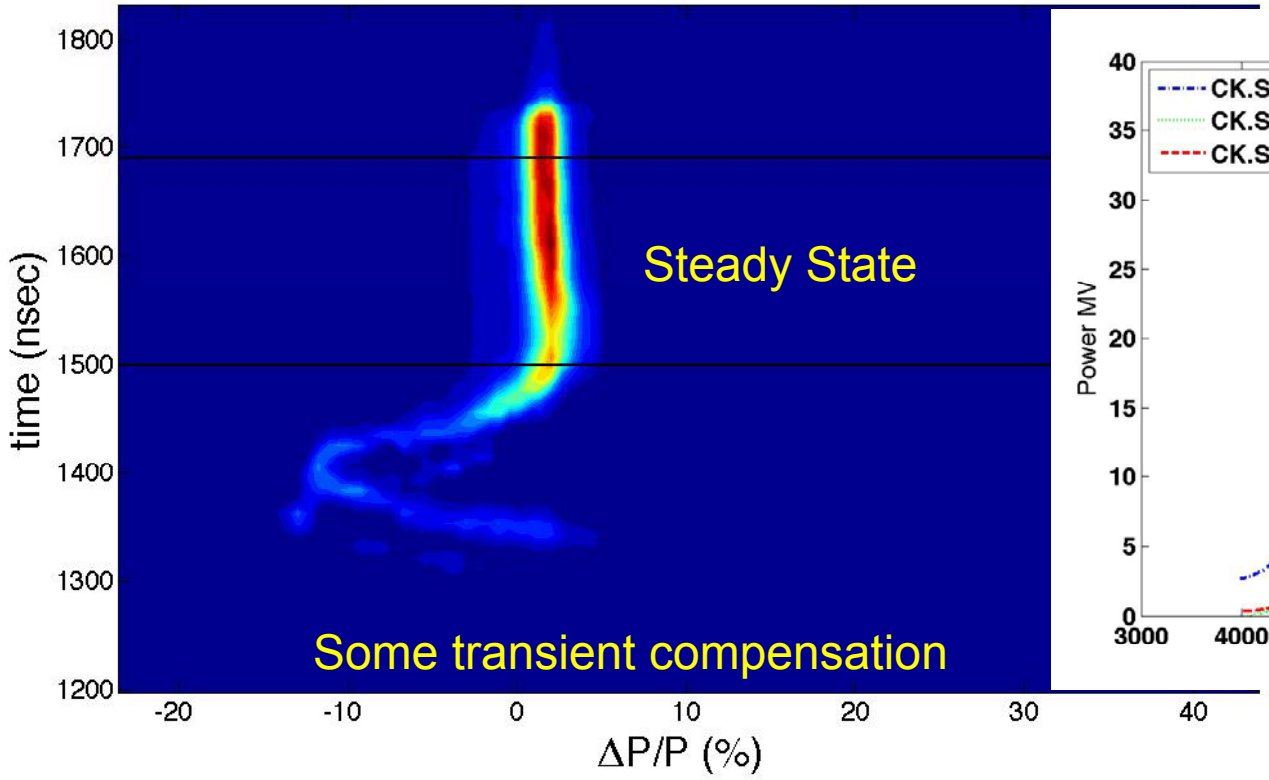


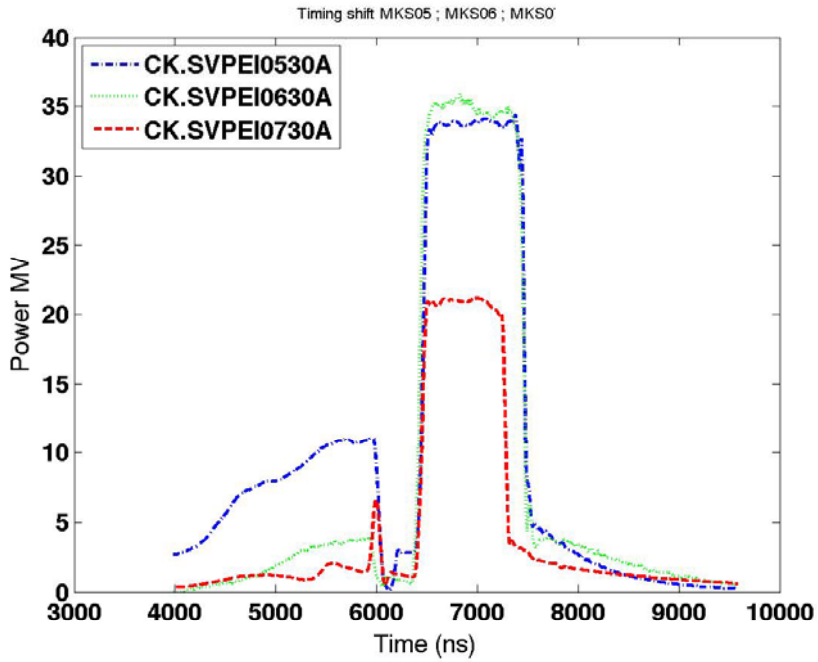


Energy measured with **segmented dump** on spectrometer 10, for nominal RF timings.
Transient 40% > energy than steady state

Transient compensation @ CTF3







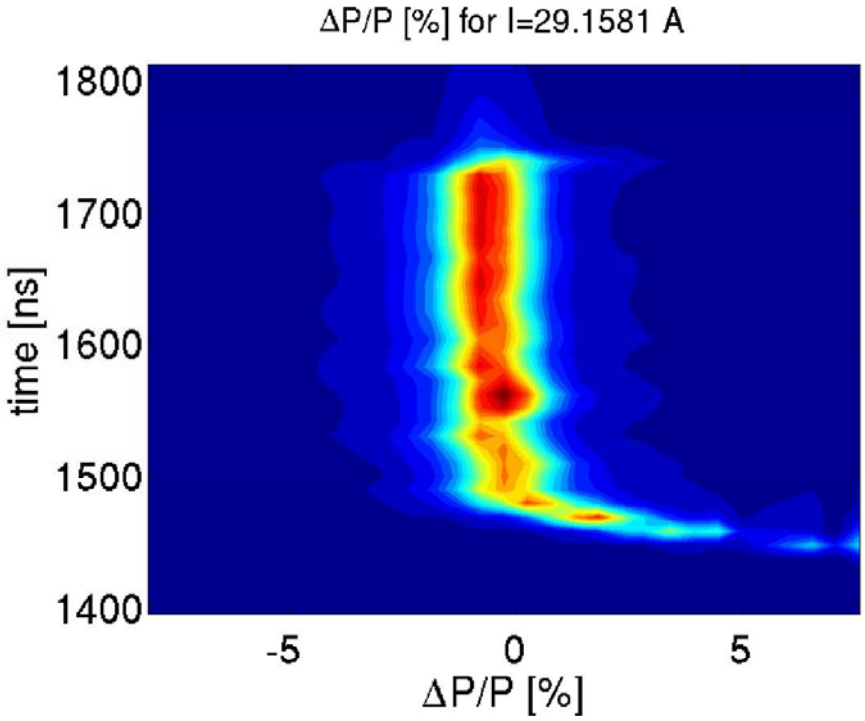
Delayed the RF timings in Klystrons 5,6 and 7

➔ accelerate head of the beam less than before ➔ Transient decreased from 40% to 15 %

segmented dump is useful for machine tuning

Important diagnostic to measure energy variations along the pulse
➔ adjust RF phase accordingly

Used **routinely** to setup the machine



Energy Measurement spectrometer 10

Reminder CTF3:

Current variation translates into energy variation because of fully loaded acceleration

… segmented dump can see this.

segmented dump for CLIC ?

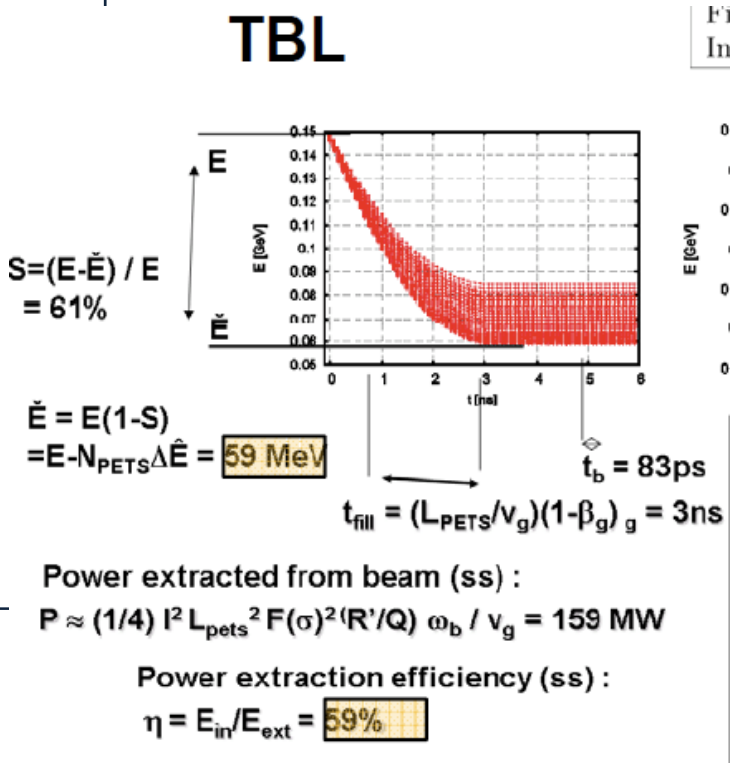
Segmented dump works very well in CTF3

CLIC Drive accelerator beam adaptations:
➔ higher energy (max 2.4 GeV (CLIC) / 0.15 GeV (CTF3))
➔ longer pulse train (140 μm compared to CTF3 1.5μm)
thermal considerations higher charge

Segmented dump to measure decelerated beams?

TBL @ CTF3 energy spread 61%
CLIC decelerator energy spread 90%
Transient in decelerated beam ~1 ns

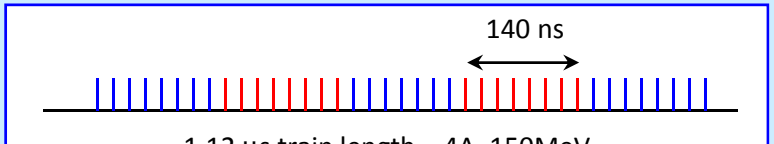
For the TBL:
Use to bench mark code
Request for one device with intra bunch space timing required …
Need 80 ps time resolution in order to study the beam physics in detail and benchmark the code

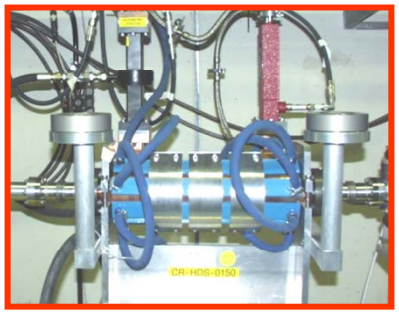


Measure bunch frequency combination

Bunch frequency multiplication by a factor 8 : from 1.5 to 12GHz

Initial time structure

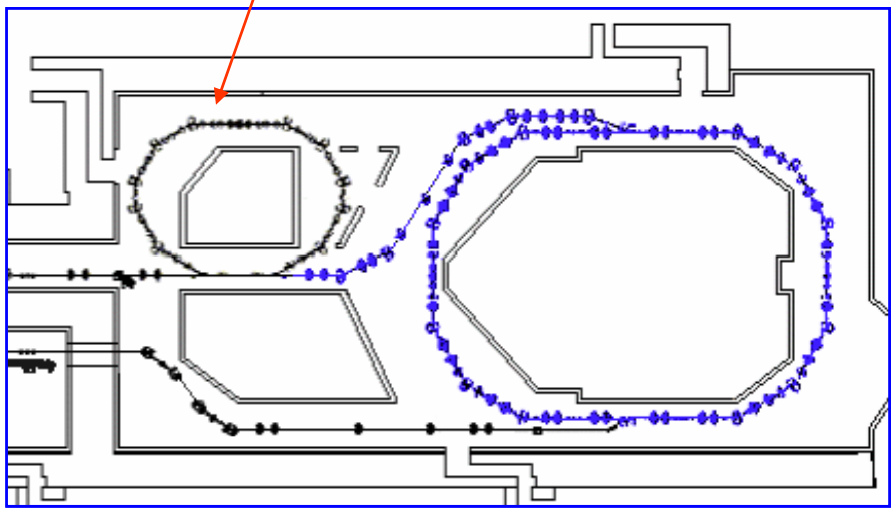


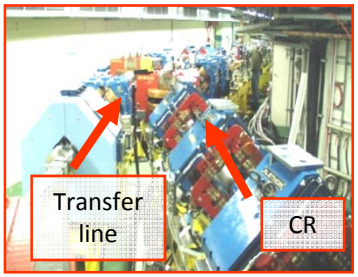


RF deflectors for injections in the rings

42m Delay loop x2

Linac



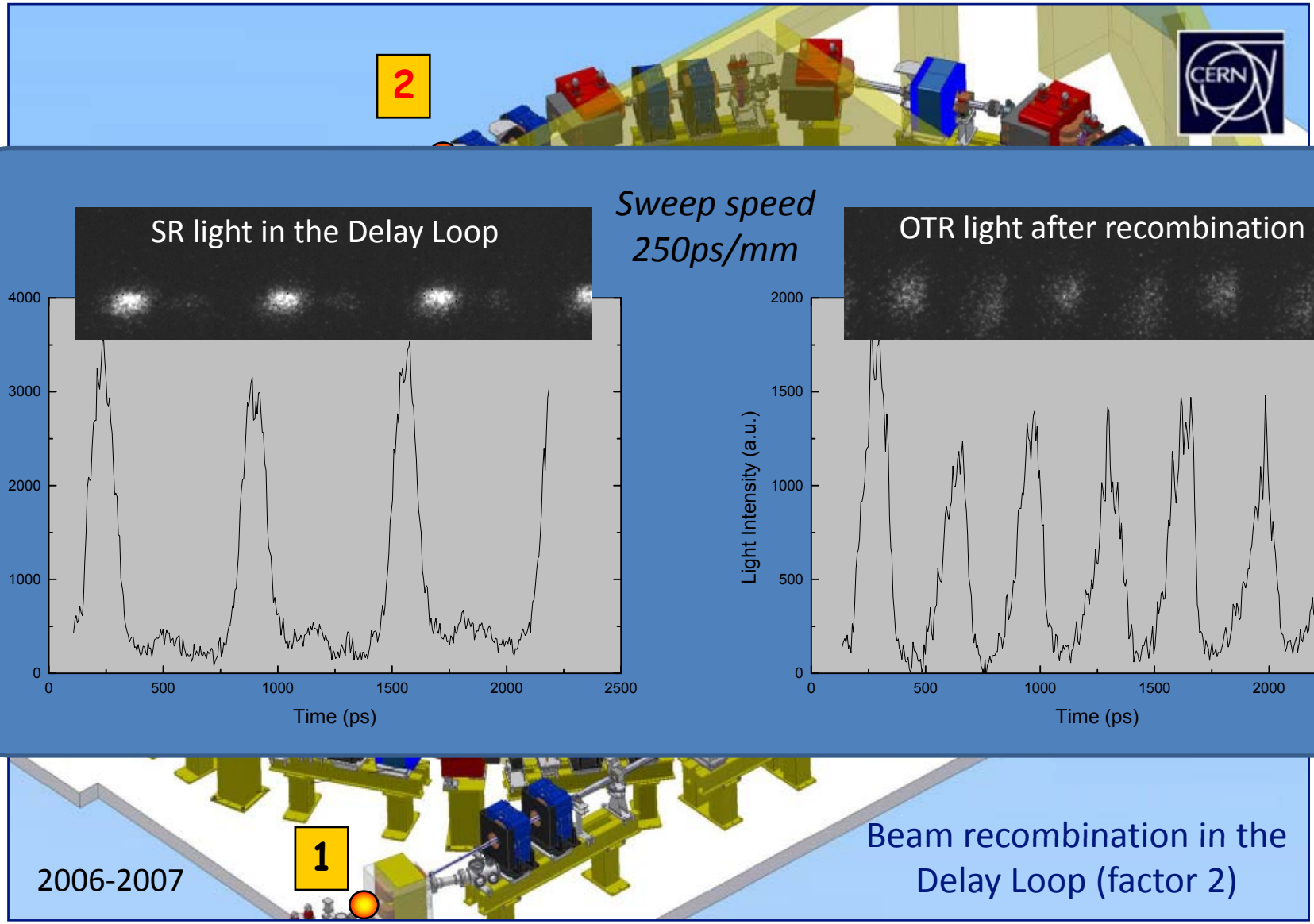


84m Combiner ring (x4)

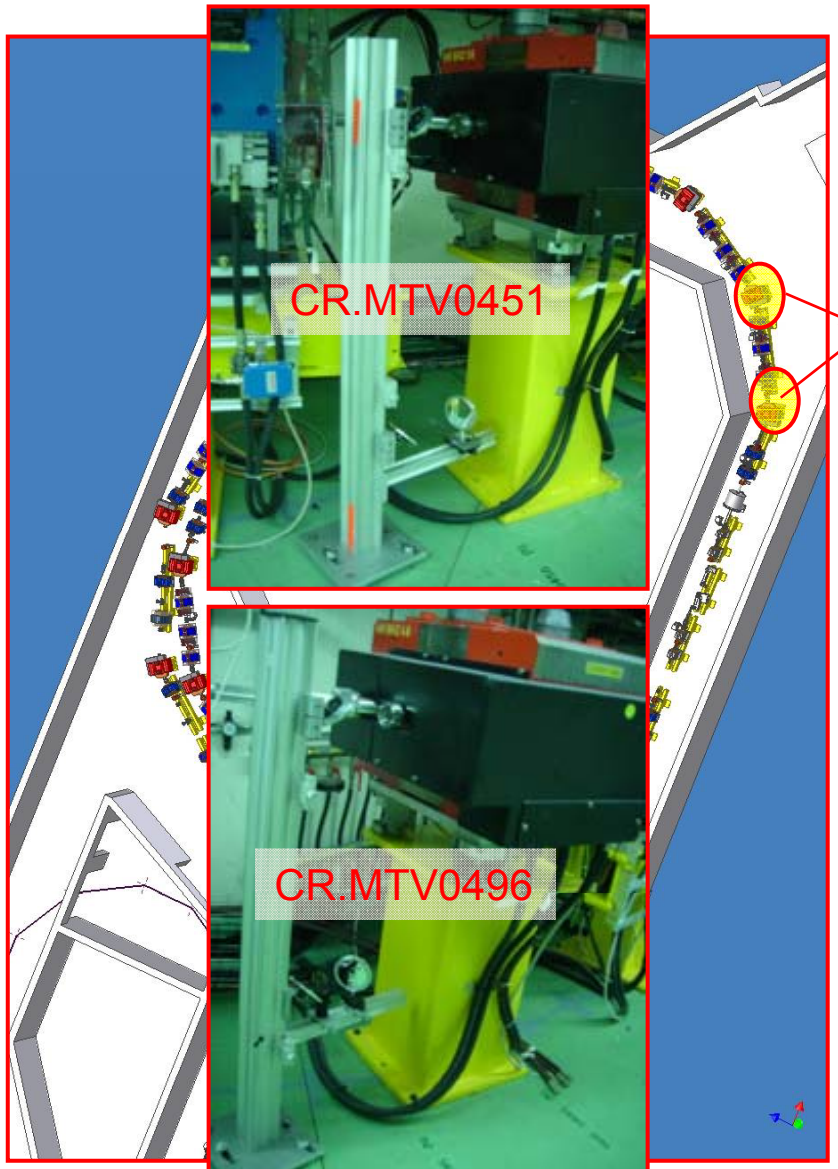
CLEX

Final time structure

Delay Loop


2
SR light in the Delay Loop
Sweep speed
250ps/mm
OTR light after recombination
Light Intensity (a.u.)
Time (ps)
Light Intensity (a.u.)
Time (ps)
1
2006-2007
Beam recombination in the
Delay Loop (factor 2)

Streak Camera @ CTF3

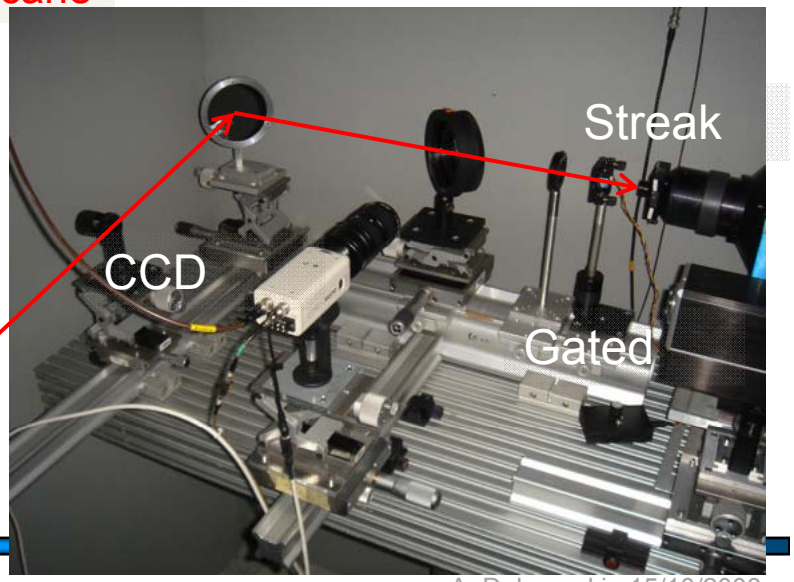


2 new optical lines installed in 2007/2008 on the Combiner ring

Optical Chicane

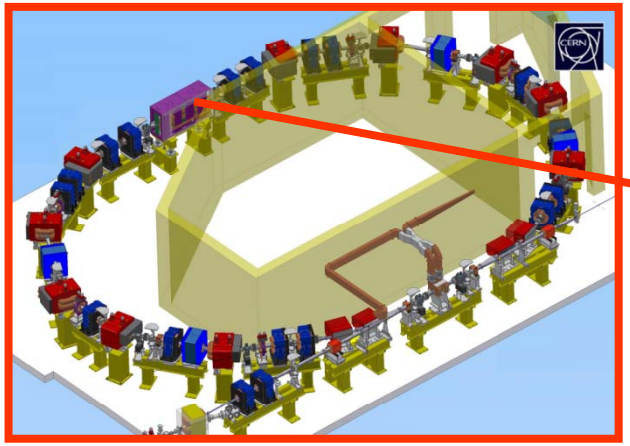
New SC lab

Ready to make measurements

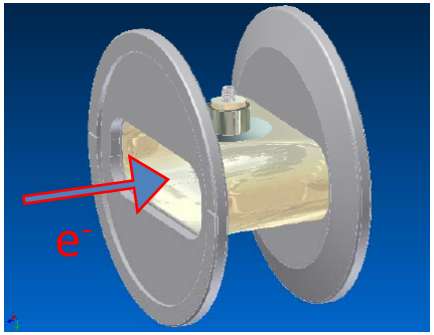


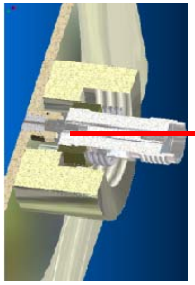
Phase monitor – delay loop

‘ The optimisation of the combination is done by adjusting the delay loop length with a magnetic wiggler’



‘To measure phase error in the RF bunch combination’





RF antenna

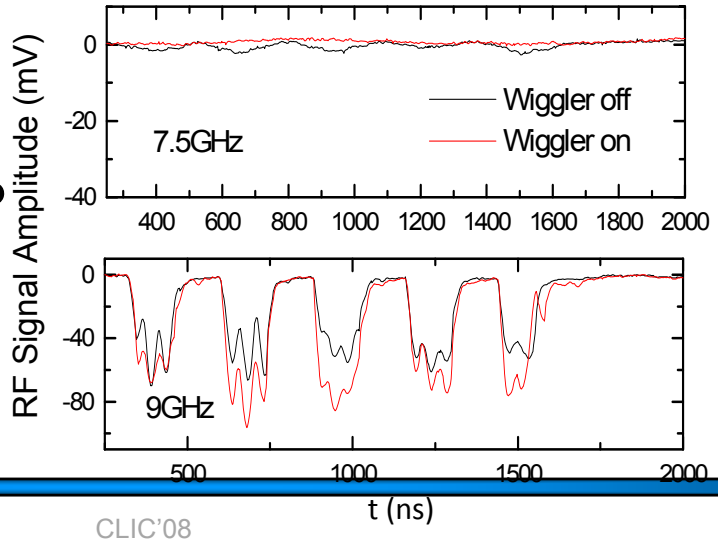
RF Bandpass filter

7.5 GHz

9 GHz

Diodes

Digital Oscilloscope

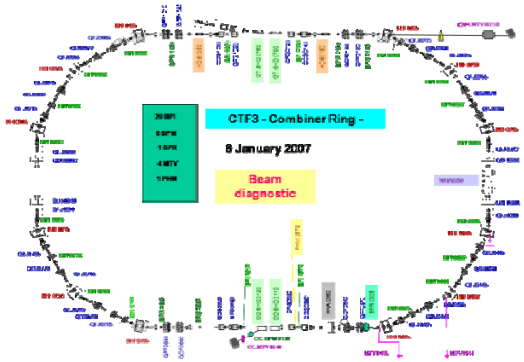


Better RF combination
- 7.5GHz
- 9GHz

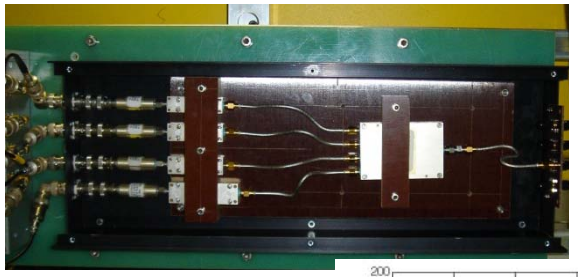
Phase monitor – Combiner ring

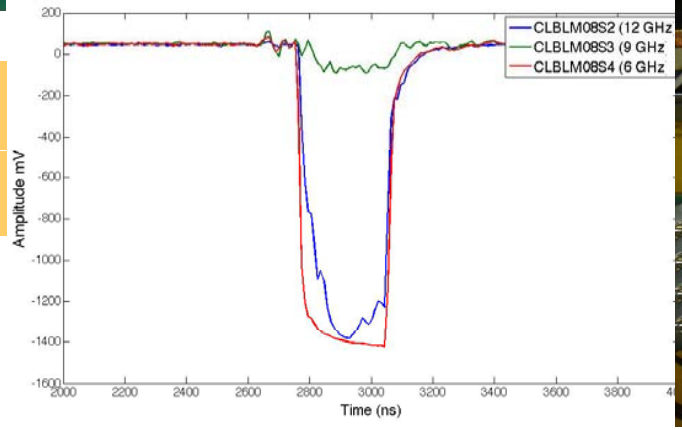
3 GHz bunch spacing beam at entrance of CR
… 12 GHz bunch spacing at the exit

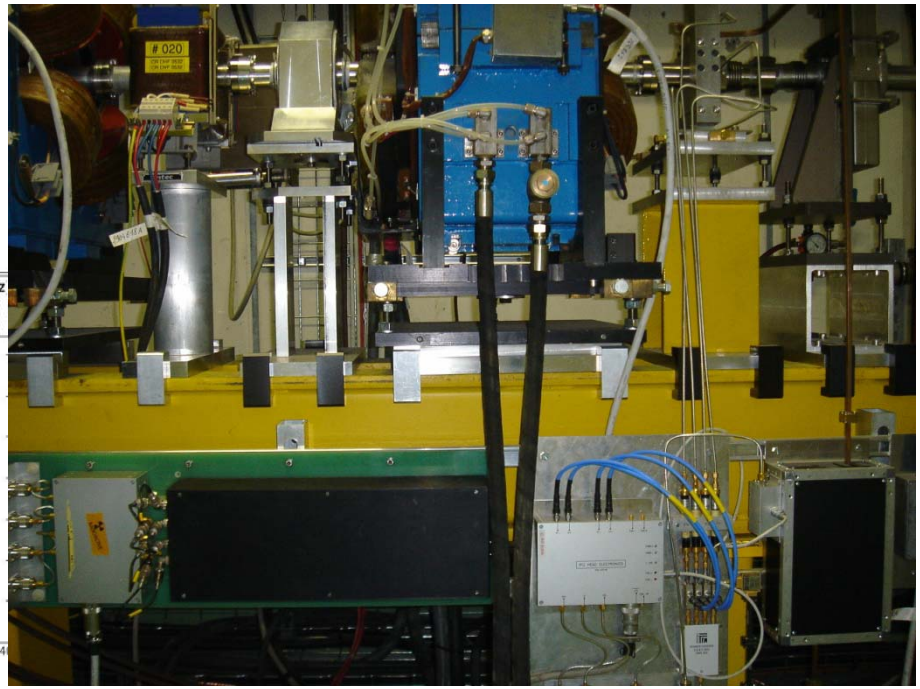
Installed 2008



➔Relative amplitudes of 6 GHz, 9 GHz, 12 GHz, 15 GHz signals will give evolution of the combination
➔Use BPR.0505 antanae pickup
➔Bandpass filter ➔ Diode ➔ ADC

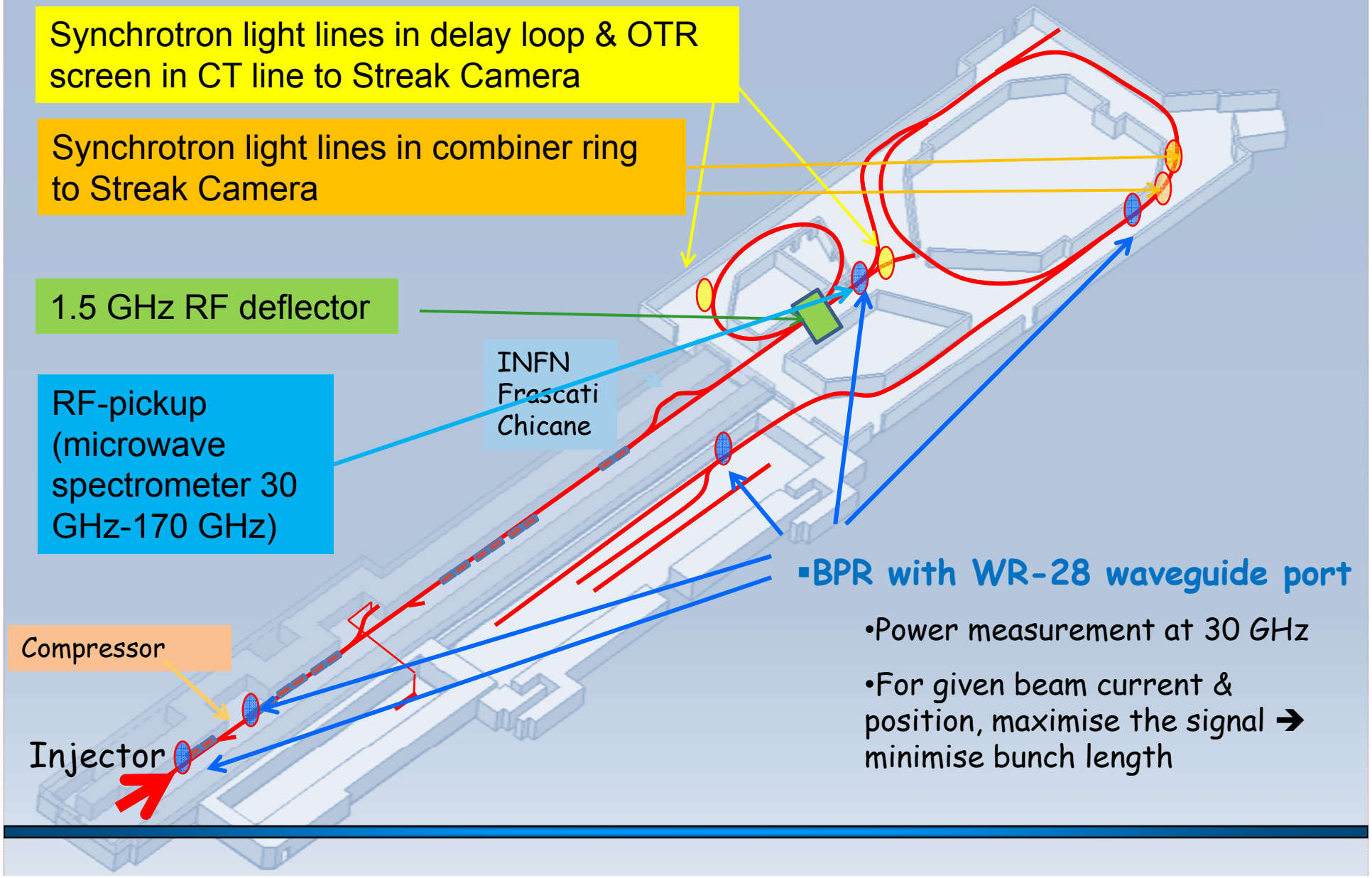






•Signals good (3GHz beam 1 turn)
•Ready to measure combination!

Bunch length

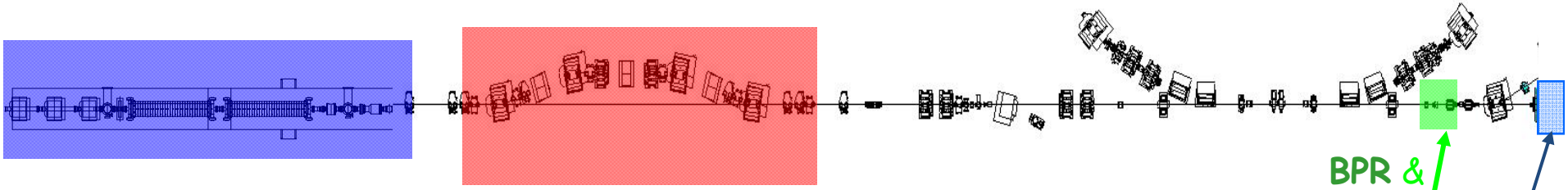


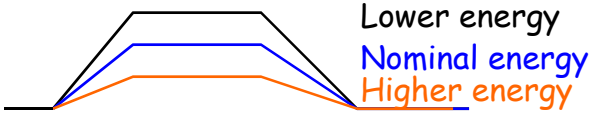
Bunch length manipulation using INFN Chicane

Accelerating structures @Girder 15

4 Bends INFN-Frascati Chicane

Delay Loop





Changing the phase of Klystron 15 to insert a time to energy correlation within the bunch

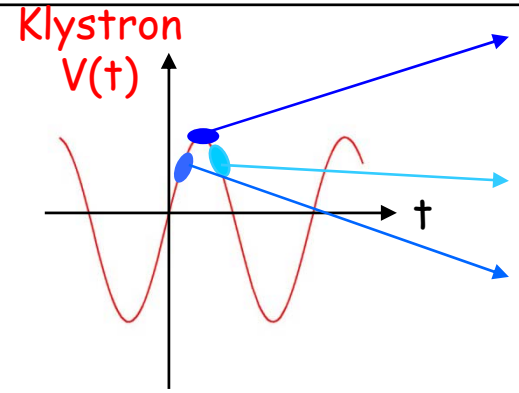
⇨

Convert energy correlation into path length modification and time correlation

⇨

Measure the Bunch frequency spectrum

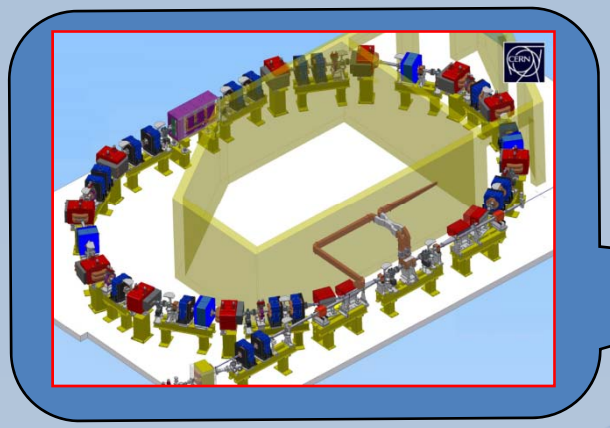
Measure bunch shape & length using RF deflector and OTR screen

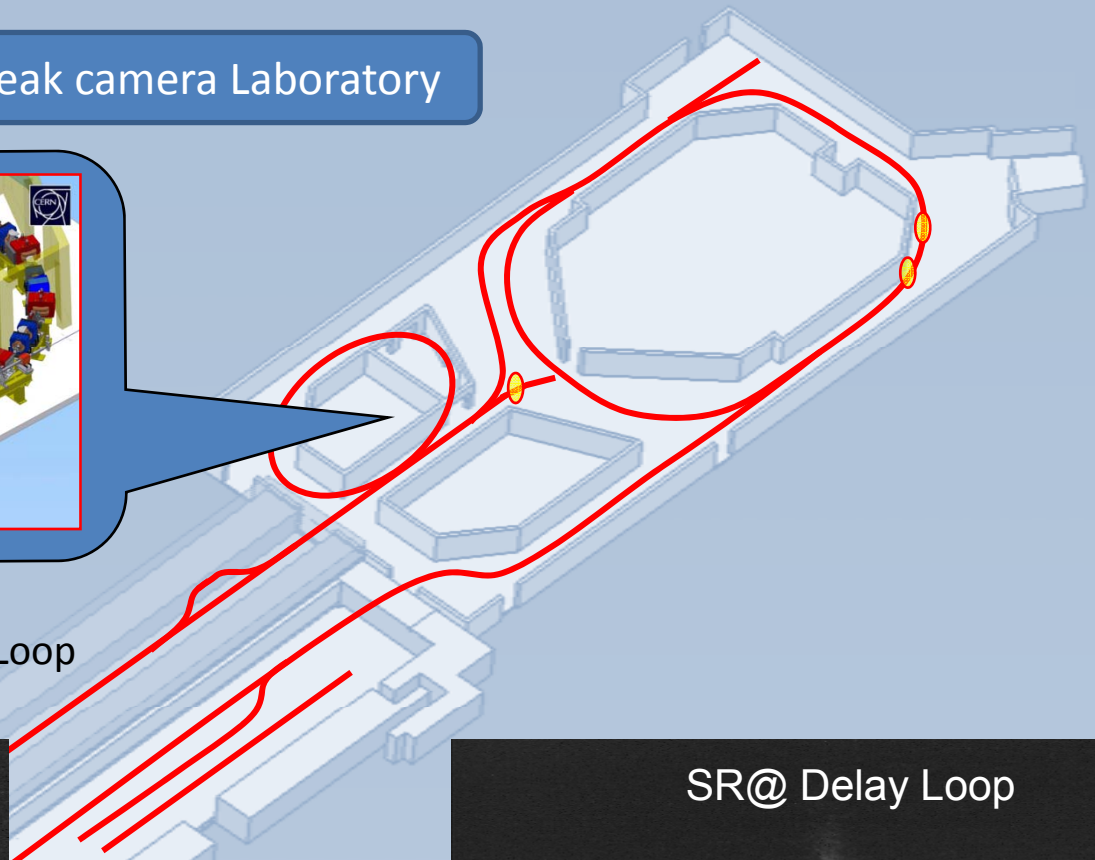


- On-crest Acceleration – the bunch length is conserved through the chicane
- Negative Off-crest Acceleration – the bunch gets longer
- Positive Off-crest Acceleration – the bunch gets shorter

Streak Camera @ CTF3

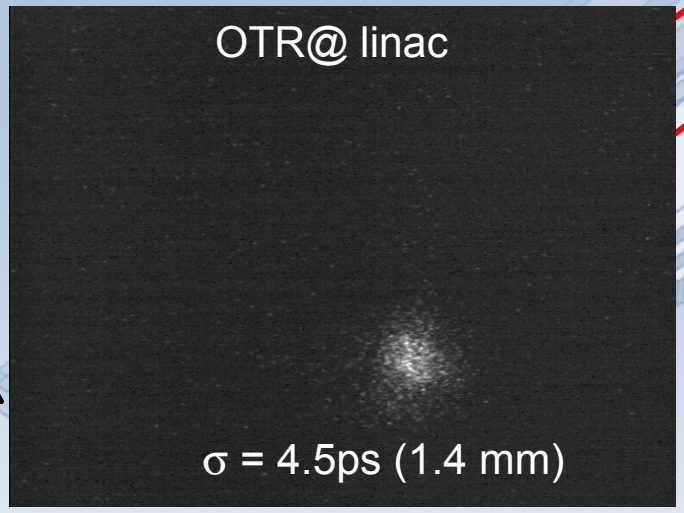
Long optical lines to the streak camera Laboratory



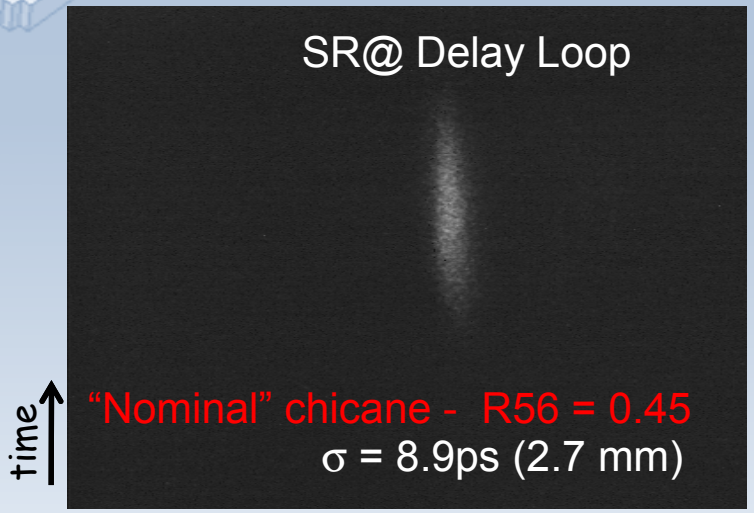


2 Optical lines in 2006

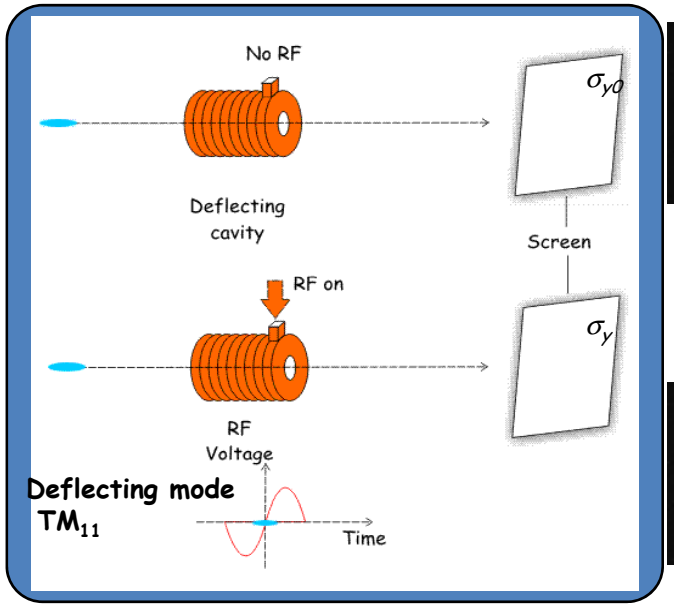
- Synchrotron Radiation in the Delay Loop
- OTR in the linac in TL1

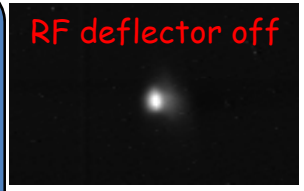


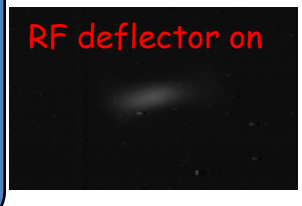
Sweep speed of 10ps/mm



Bunch length with 1.5 GHz RF Deflector







Deflecting Voltage

RF deflector phase

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

Bunch length

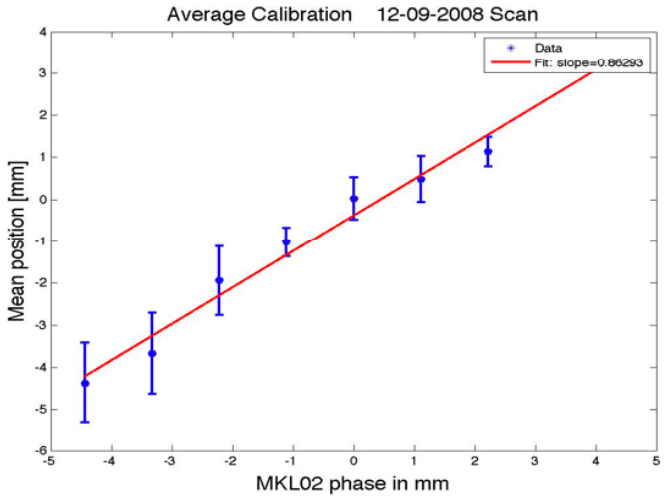
Beta function at cavity and profile monitor

RF deflector wavelength

Beam energy

Betatron phase advance (cavity-profile monitor)

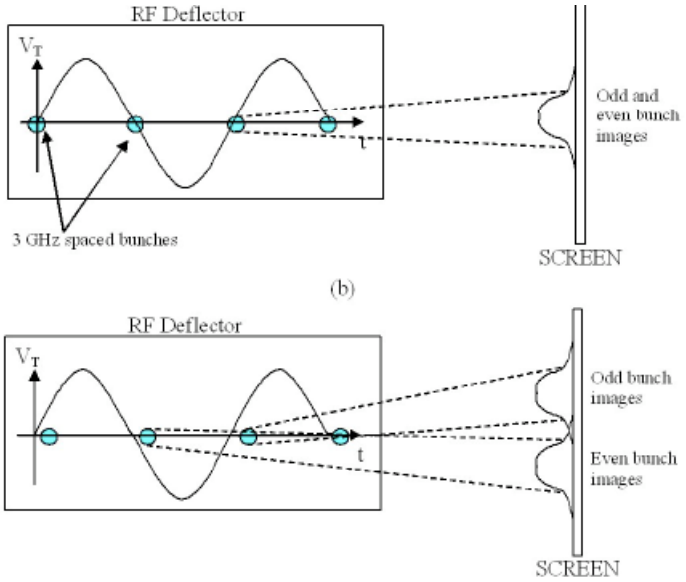
$$\sigma_{z_{rms}} = \frac{1}{CAL} * \sqrt{\sigma^2_{x_{rms}(RFon)} - \sigma^2_{x_{rms}(RFoff)}}$$



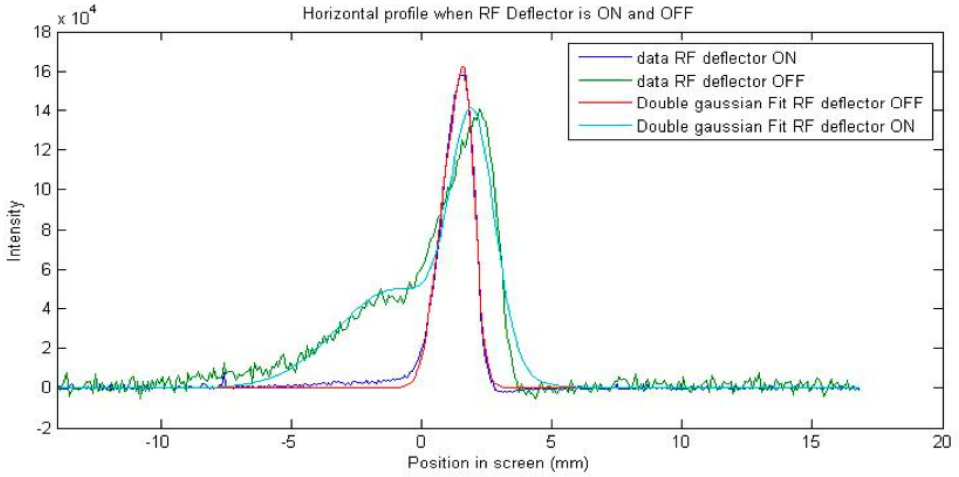
Calibration scan, changing the phase of RF deflector➔longitudinal mm vs. position on screen

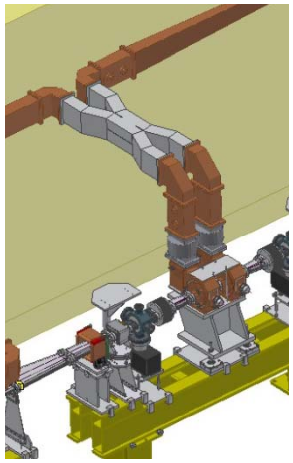
Bunch length with 1.5 GHz RF Deflector

Bunch length measurments 2008 with 3 GHz beam

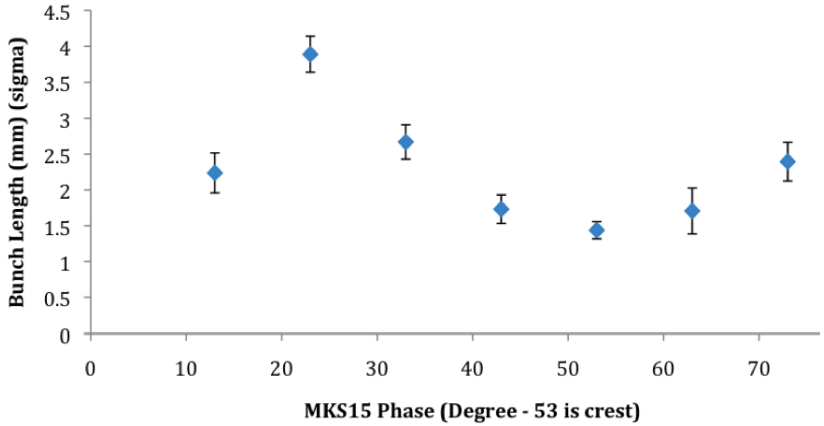


Necessary to move off the zero crossing, to separate two neighbouring bunches, followed by corrector magnet to re-steer bunch to center.



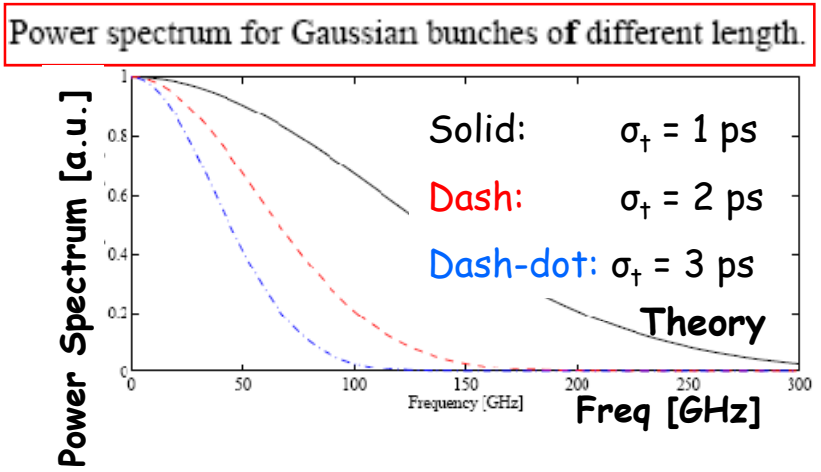


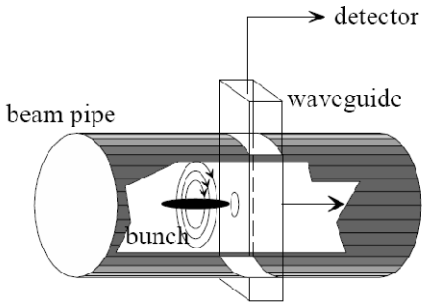
Result, bunch length vs. Phase MKS15



"natural chicane" R56 = 0.45

Bunch length measurement with "RF Pickup"





(30 – 39) ; (45-69) ; (78-90) & (147-171) GHz

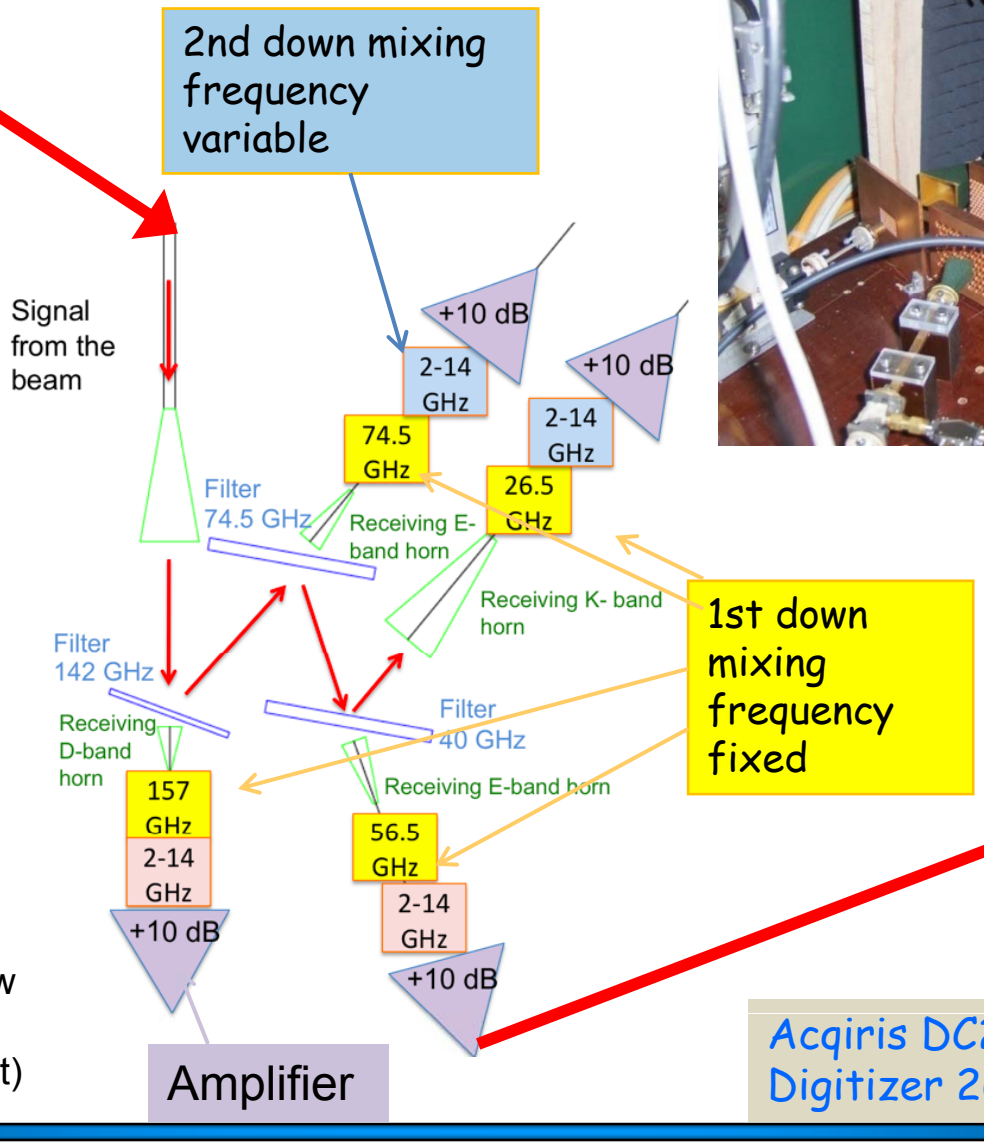
➔Non-intercepting device, easy to implement in machine, sub-ps resolution, **self calibrating** if bunch length scan is performed
➔**Much** less expensive than RF deflector with power source.
➔RF deflector and/or a streak camera @CTF3 can provide an excellent cross calibration of device … this aspect is currently under study @ CTF3

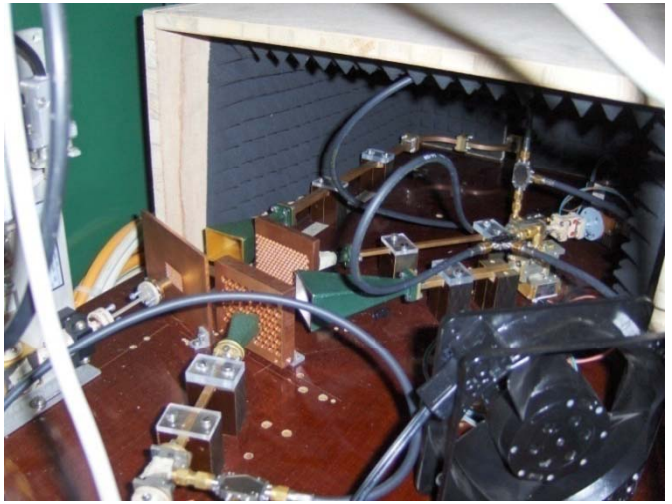
PAC07 proceedings, http://doc.cern.ch/archive/electronic/cern/preprints/ab/ab-2007-070.pdf

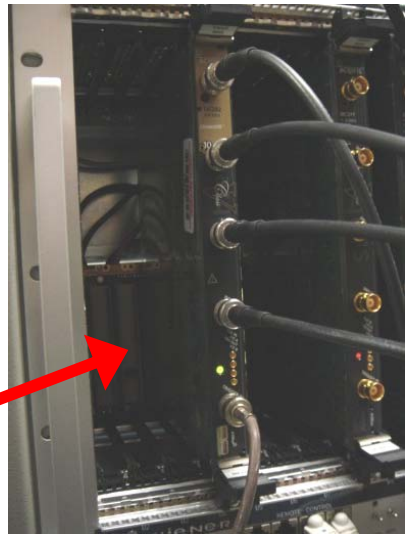
Bunch length measurement with "RF Pickup"

BPR WR-28 waveguide port

0.500 ± 0.005 mm
thick CVD diamond window
ε_r~6 at 30 GHz
Brazed at CERN (S. Mathot)





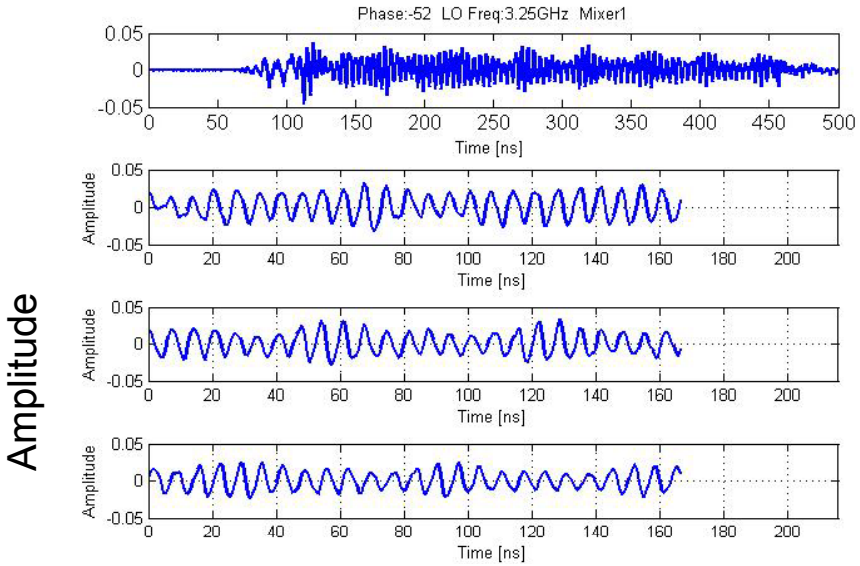


Acqiris DC282 Compact PCI Digitizer 2GS/s per channel

Bunch length measurement with "RF Pickup"

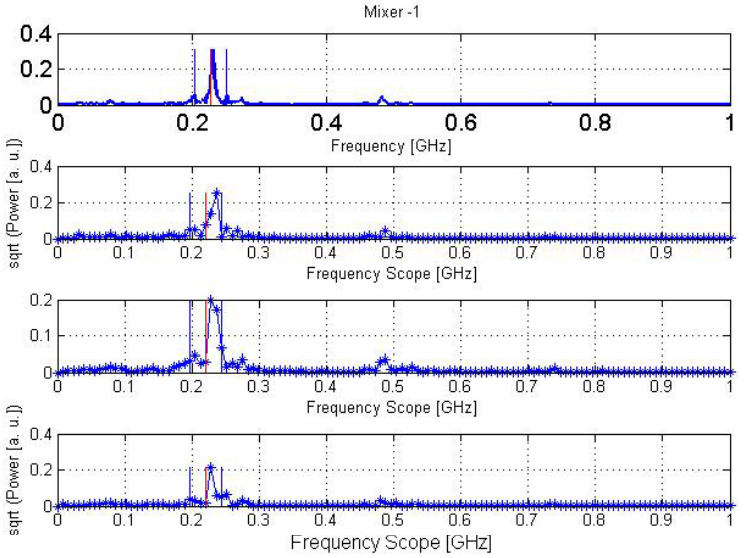
Typical signal

Full time window Mixer 1 – 30 GHz



FFT

from 30 GHz harmonic



Time [ns]

Frequency after down-mixing (GHz)

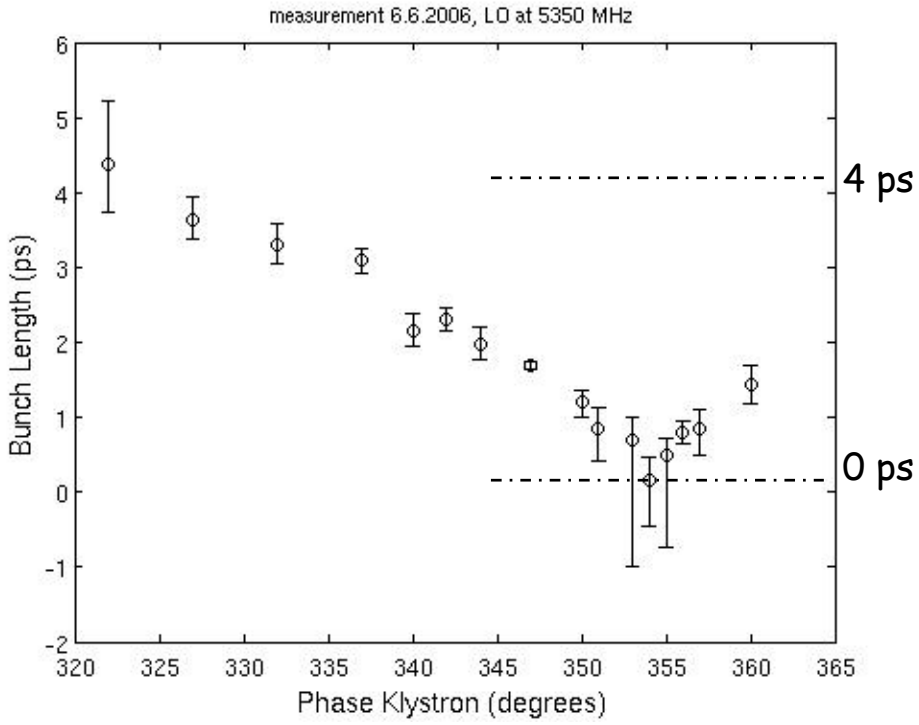
1/3 of time window Mixer1 30 GHz

Advantage ➔ Split up the signal & measure the bunch length variation along the pulse
Similar plots for other mixing stages … 33, 36 … 60, 63 …78, 81 etc… GHz

Bunch length measurement with "RF Pickup"

Minimise the χ^2 function.
Extracted r.m.s bunch length (mm).
Extract also the response coefficients of each frequency.
The evolution of the bunch length with respect to the phase of the last Klystron can be seen

$$\chi^2 = \sum_{j}^{16} \sum_{i}^{3} ((A_i e^{(-(2\pi f_i)^2 (\sigma_j)^2} - y_{ij})^2 / \sigma_{ij}^2)$$



Measurement in December 2006
Chicane in compression

Benchmarking this detector vs. the RF deflector is in progress

Future Activities

Measurements in the combiner ring of beam combination:

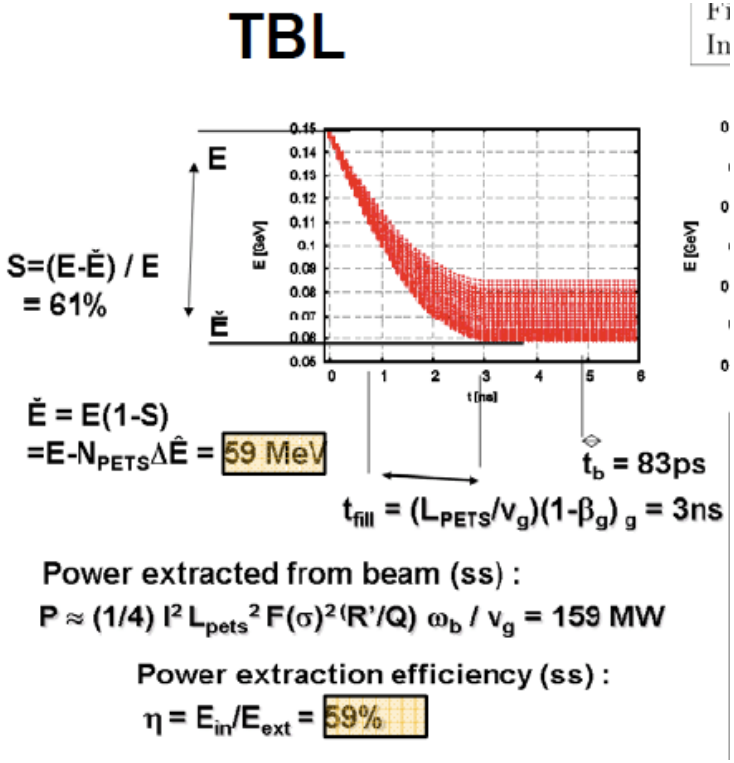
- Streak Camera
- Phase Monitor

Continue with installation and design of Coherent Diffraction Radiation experiment (Royal Holloway)

- aims to reconstruct the longitudinal bunch shape
- non-invasive

Design and install non-destructive bunch length measurements for CALIFEs (<1 ps) and TBL/TBTs (< 3ps)

- Design time resolved energy measurement to measure decelerated beam in TBL ➔ energy spread of 61%
- Want VERY fast time resolution ➔ see intra bunch spacing 83ps
- Work just starting … CERN/Ditanet PHD start April 2009



Conclusion

CTF3 Highlights

➔Optical lines to **Streak Camera in & after DL** successfully measured:
** bunch length, ** 180 degree phase switching & ** Bunch frequency multiplication **2005-2007**

➔**Phase monitor also used to tune the wiggler for the delay loop measurement**

➔Bunch length measurements with **RF deflector and RF Pickup** →cross check of the two devices in progress … a second Streak Camera would be a perfect investment as a third check/calibration & study of single bunch shape for bunches > 1ps

➔Segmented dumps for time resolved energy measurement, commissioned and perform excellently ➔ measured the beam loading compensation

2008 (and beyond) focus

➔Make combination measurements using the new Phase monitor in the CR and the Streak camera

➔Continue with work just started on the Coherent Diffraction experiment for bunch length

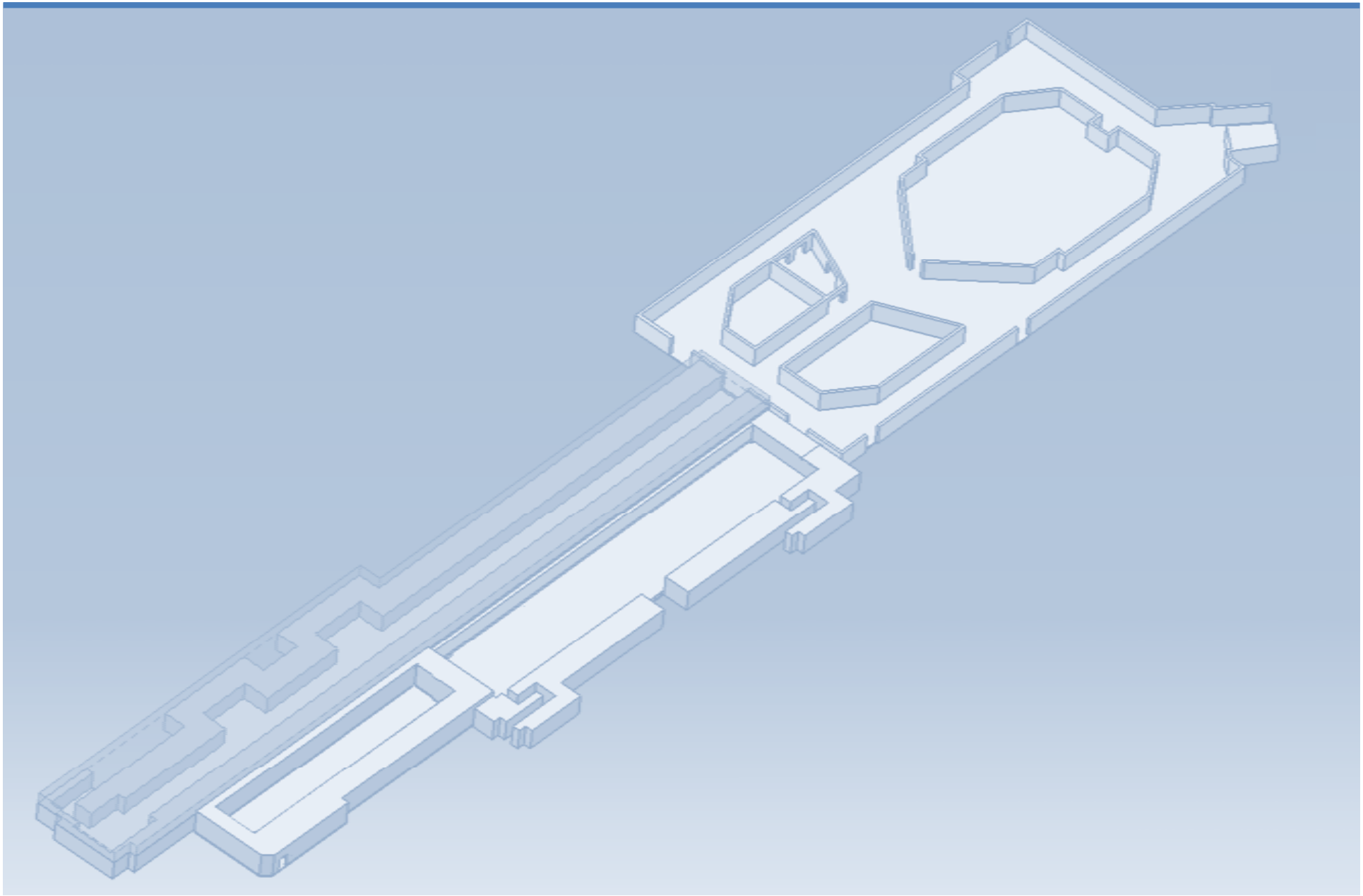
➔Designing a non-destructive bunch length monitoring system for **TBL & Califes (collaboration with CEA/Saclay)**

➔Prepare a new **Streak Camera laboratory for CLEX?**

➔Would need to ***Invest* in New Streak Camera (± 180 K euro) for CLEX/CR (one old Streak camera's not sufficient for all of CTF3's needs!!)**

➔ **Design time resolved energy measurement for TBL (CERN PhD Student will start in April 2009)**

Extra slides

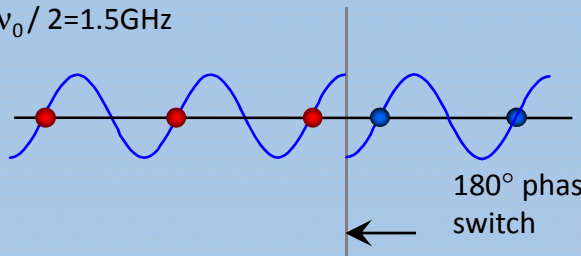


Bunch Frequency Multiplication

Phase coding

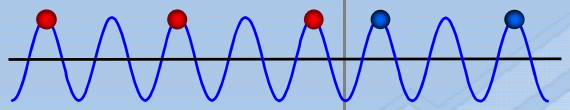
How to "code" the sub-pulses

Sub-Harmonic Bunching
ν_0 / 2=1.5GHz

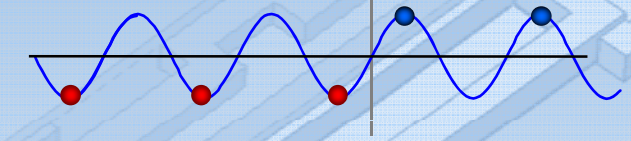


180° phase switch

Acceleration ν_0=3GHz



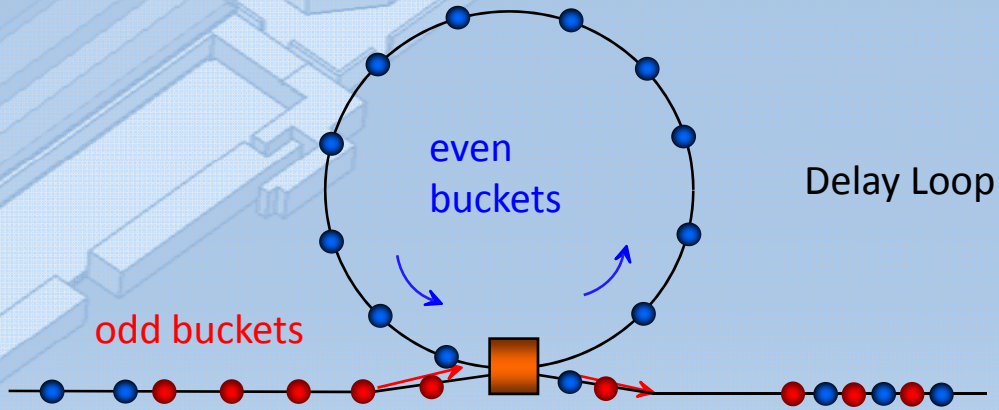
Deflection ν_0 / 2=1.5GHz



Gap creation & first multiplication × 2

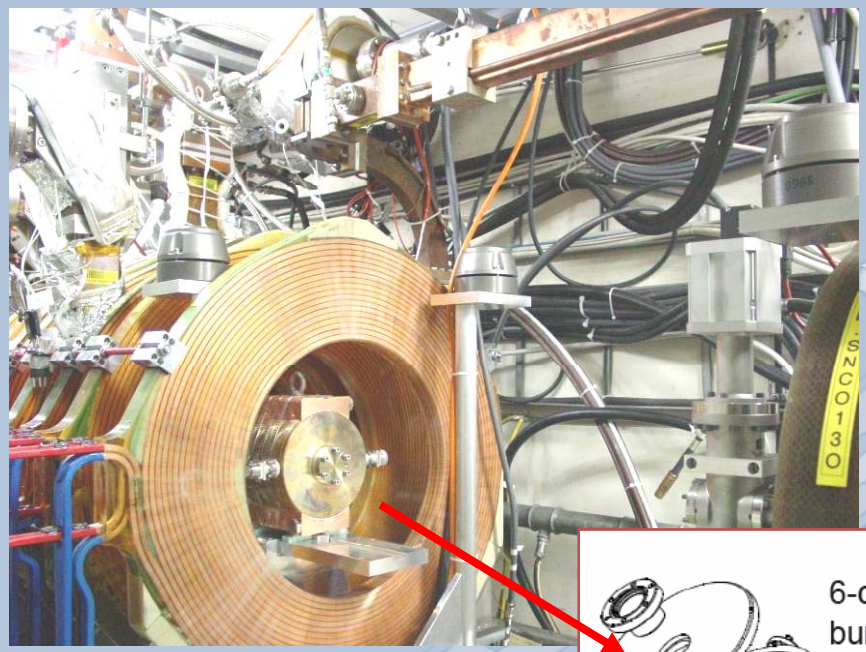
$$L_{delay} = n\,\lambda_0 = c\,T_{sub\text{-}pulse}$$

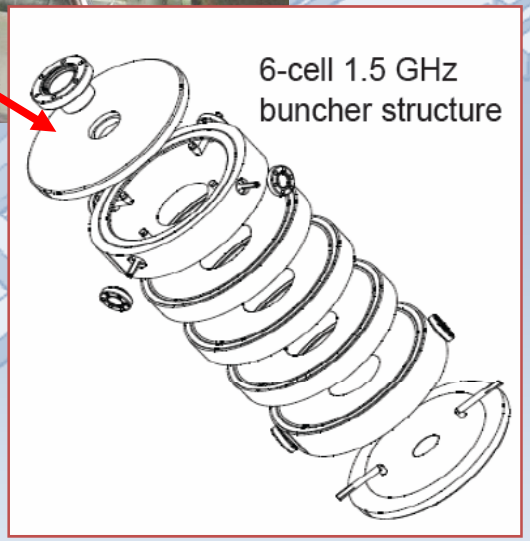
Combination scheme



Sub-Harmonic Bunching System

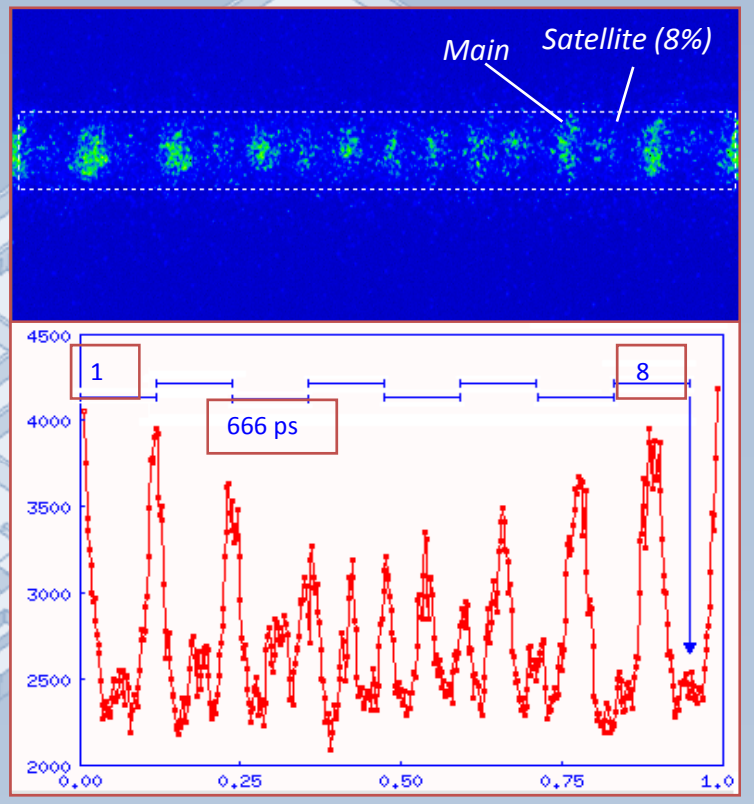
Fast phase switch from SHB system (CTF3)





3 TW Sub-harmonic bunchers, each fed by a wide-band TWT

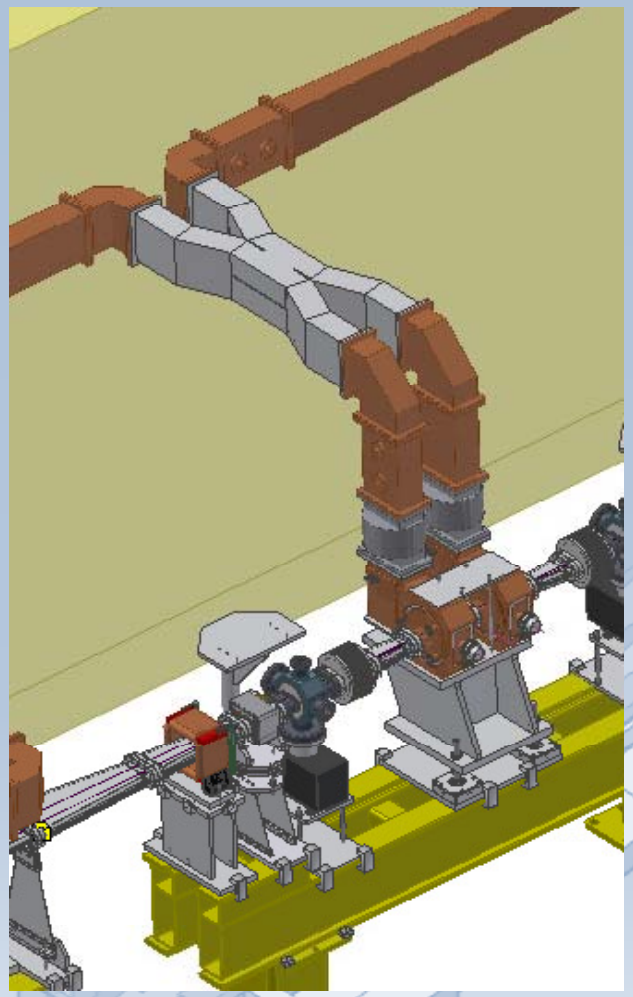
Streak camera – 500 ps/mm



Switch time

8.5 · 666 ps = 5.7 ns

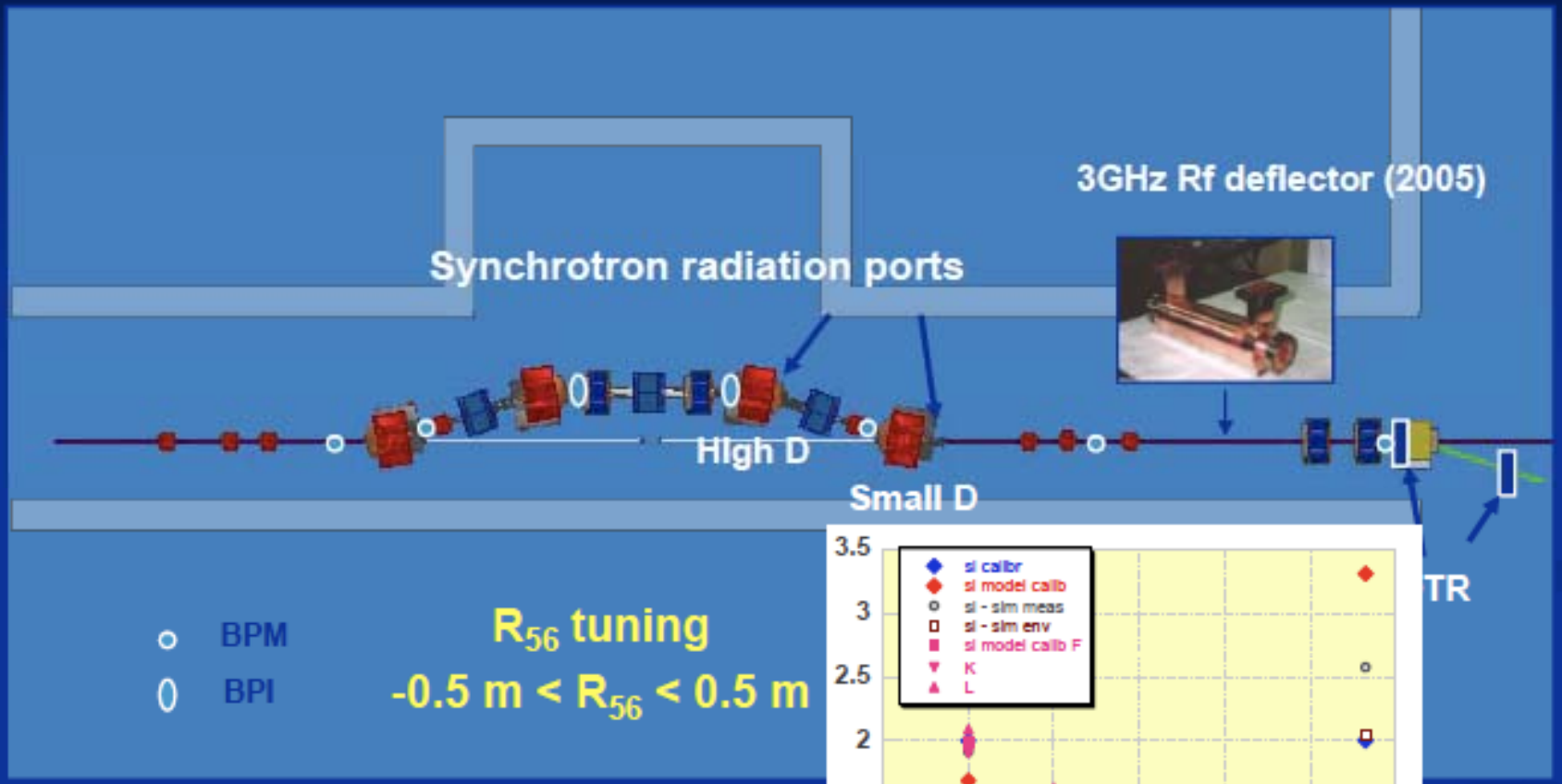
1.5 GHz Rf deflector



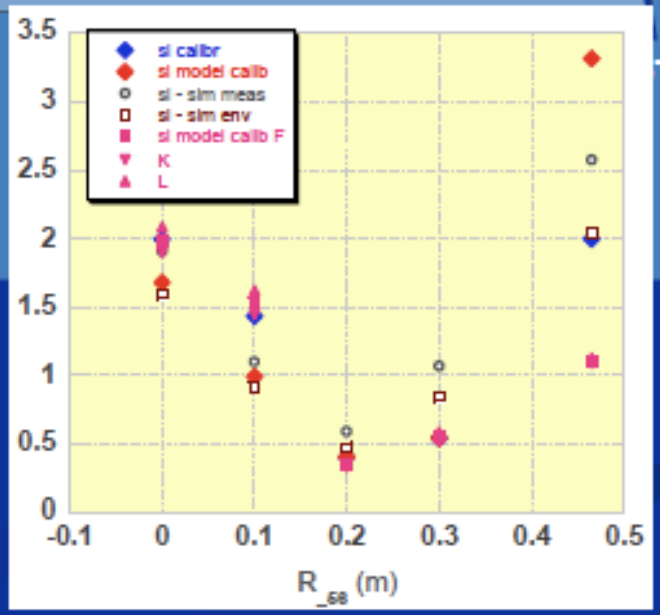
Frequency multiplicatio n x 2

Frequency **[GHz]**	**1.499275**
angle of deflection **[mrad]**	**15**
Max. Beam energy **[MeV]**	**300**
Klystron output Power **[MW]**	**20**
Sub-train length **[ns]**	**140**
# of sub-trains	**10**
RF pulse length **[μs]**	**5**
Deflecting field non-uniformity	**<1%**

Stretcher / compressor chicane



Bunch length measurements

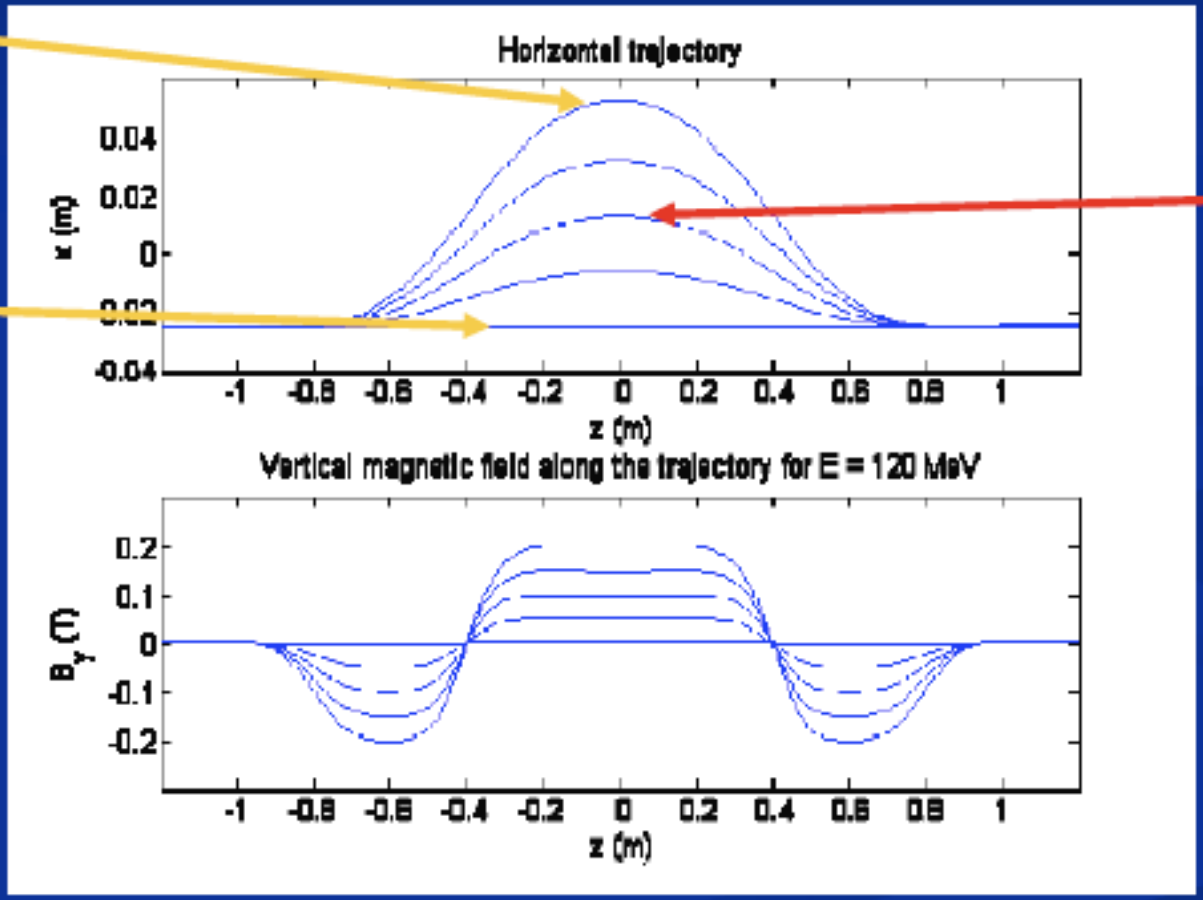


PATH TUNING WIGGLER (9 MM RANGE)

+5 mm

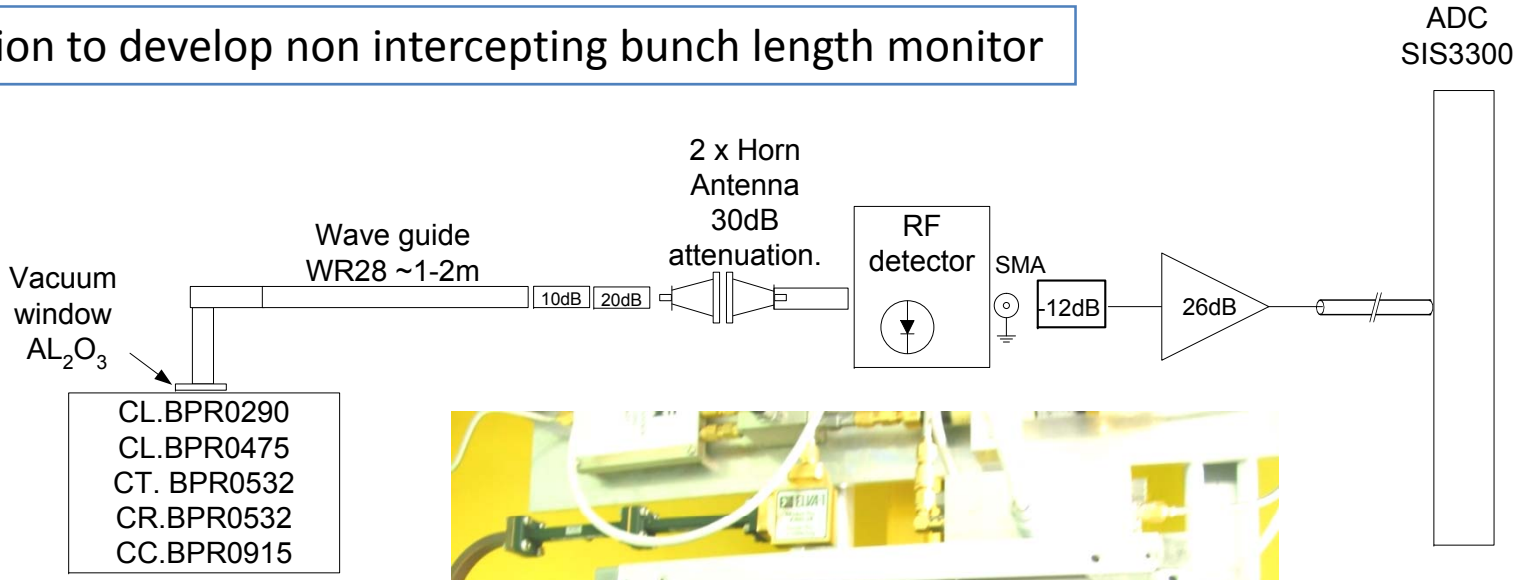
- 4 mm

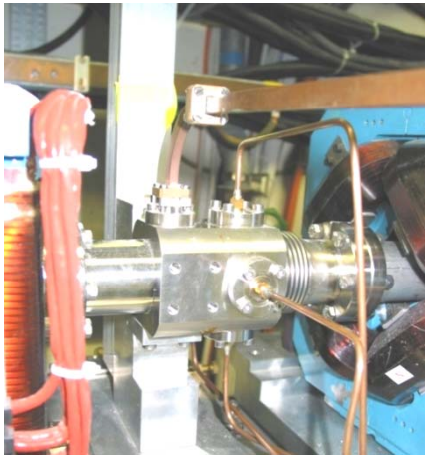
nominal

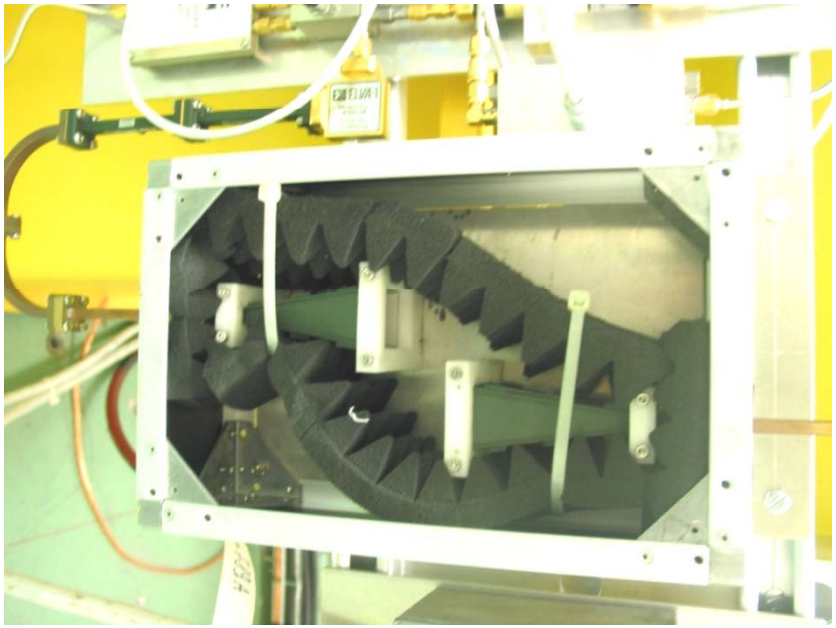


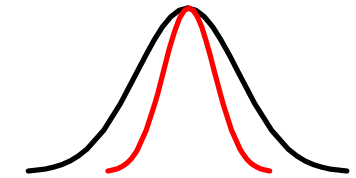
Waveguide Pick-up's (BPR)

Motivation to develop non intercepting bunch length monitor







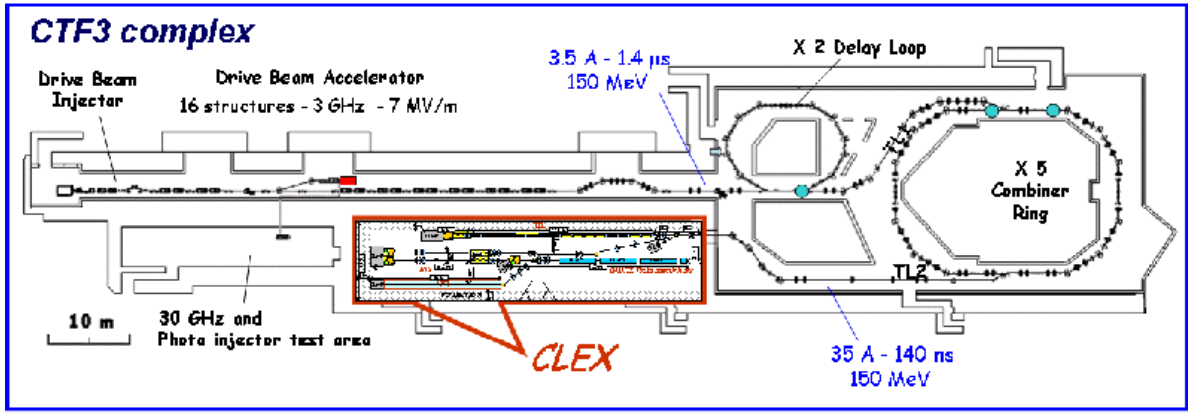


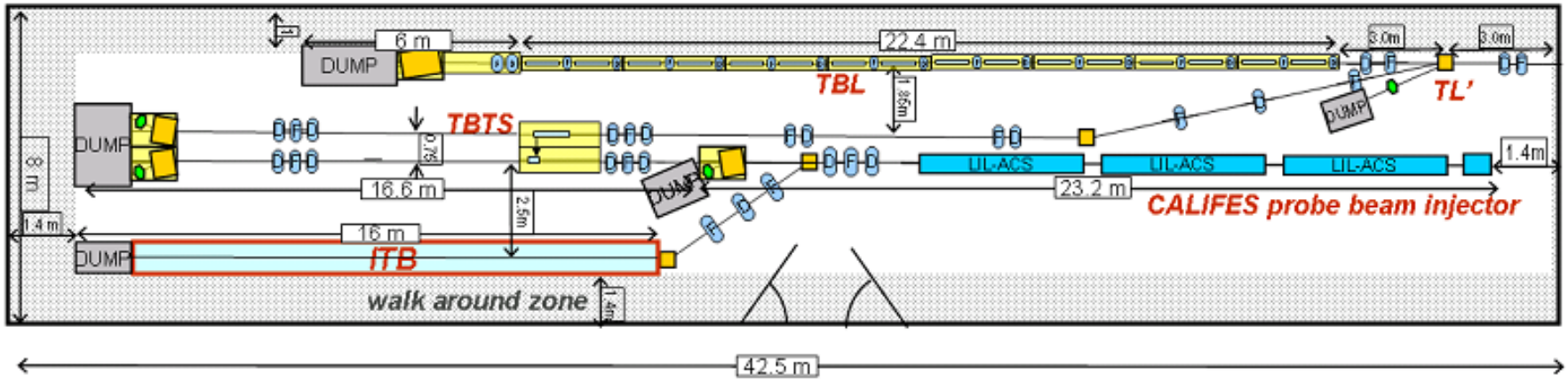
RF in

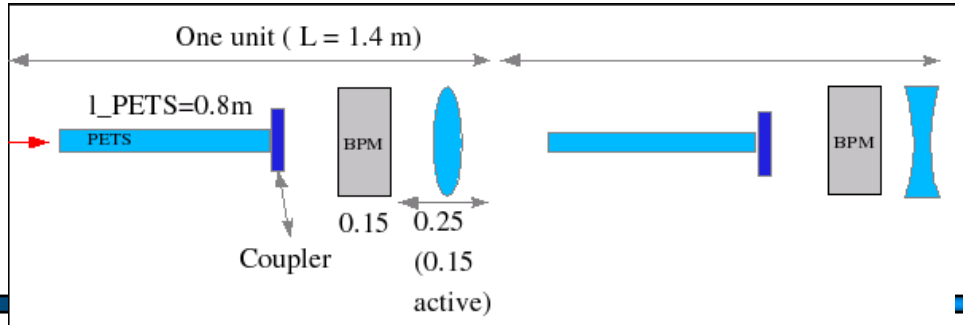
Shorter bunches means more power

Developed by L. Soby, CERN

What comes next on CTF3





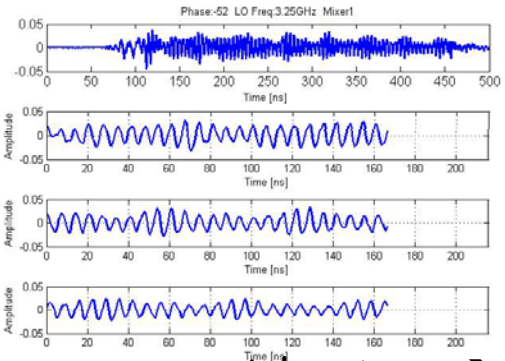


Lattice: 16 units of one of each:

- PETS + coupler
- Quad
- BPM

Bunch length measurement with "RF Pickup"

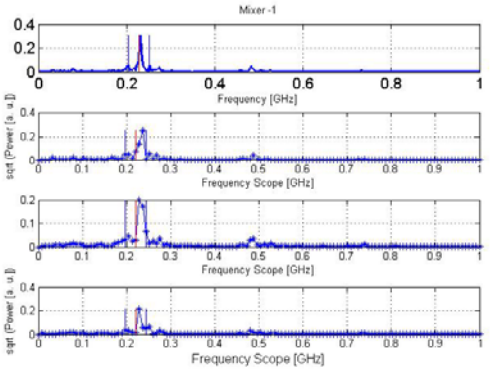
Typical signals



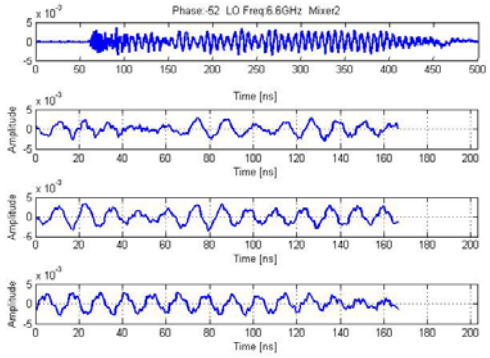
Full time window Mixer 1

FFT

1/3 of time window Mixer1



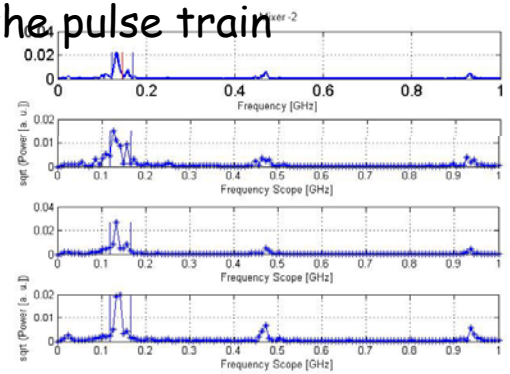
Advantage ➔ Measure the bunch length along the pulse train

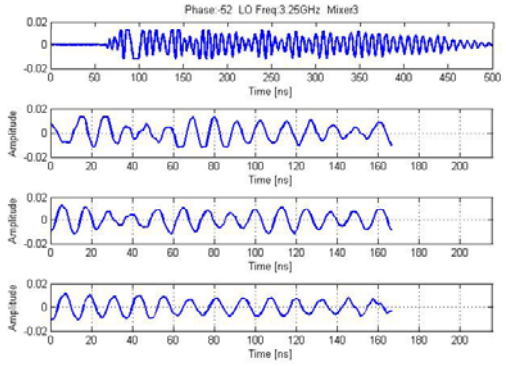


Full time window Mixer 2

FFT

1/3 of time window Mixer2

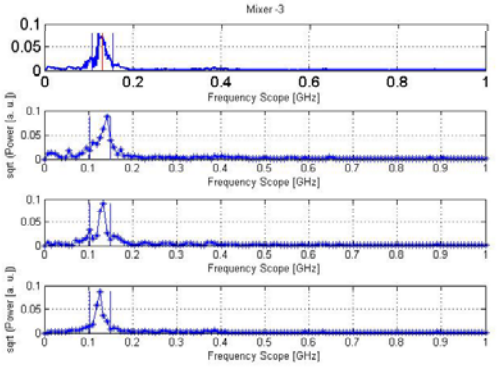




Full time window Mixer 3

FFT

1/3 of time window Mixer3



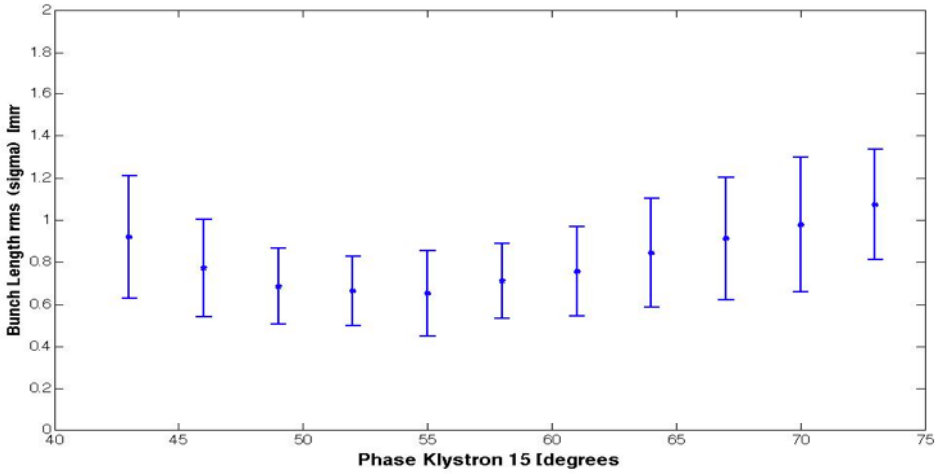
Bunch length measurement with "RF Pickup"

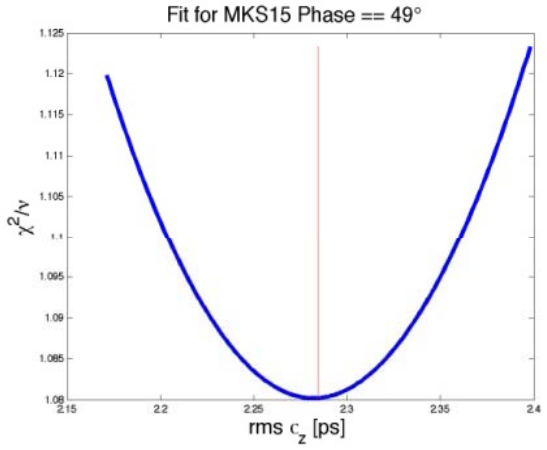
Bunch length measurments 2008

Minimise the χ^2 function.
Extracted r.m.s bunch length (mm).
Extract also the response coefficients of each frequency.
The evolution of the bunch length with respect to the phase of the last Klystron can be seen

$$\chi^2 = \sum_{j}^{16}\sum_{i}^{3}((A_i e^{(-(2\pi f_i)^2(\sigma_j)^2} - y_{ij})^2/\sigma_{ij}^2)$$

The χ^2/ν for the fit was $\chi^2/\nu=1.08$.

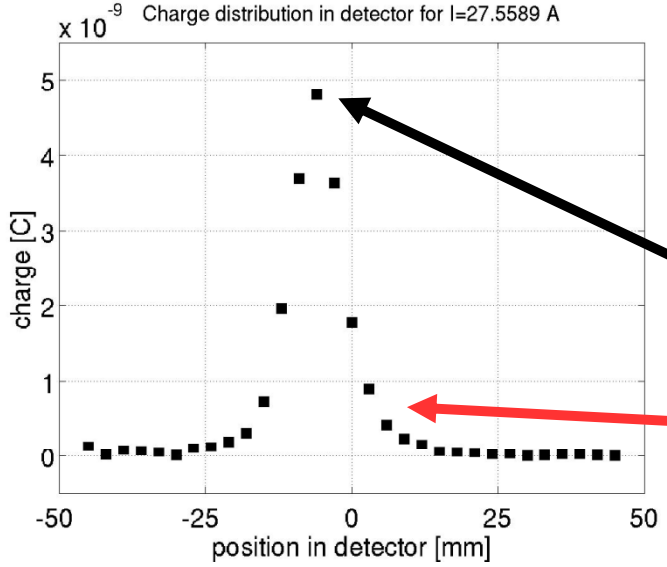


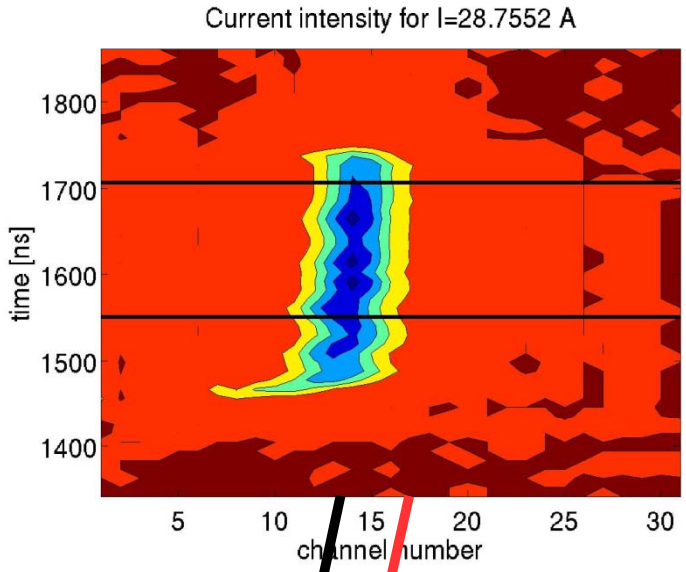


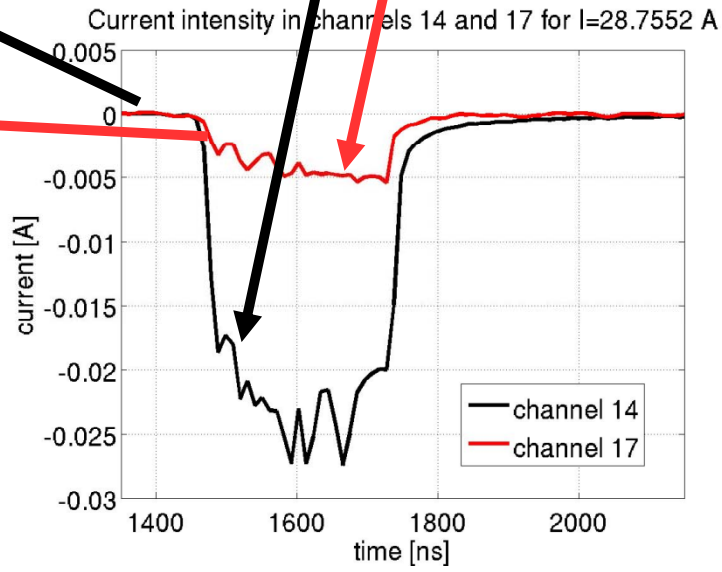
RF pickup seems to measure shorter bunches than RF deflector
Systematic studies ongoing to disentangle the reasons for enhanced sensitivity to high frequencies.

Calibration strategy – segmented dump

calculate charge intensity

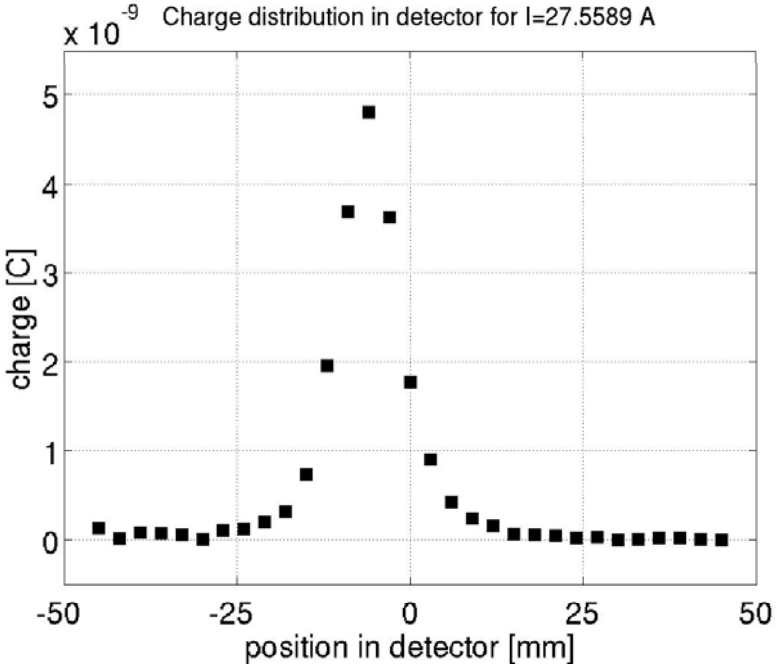


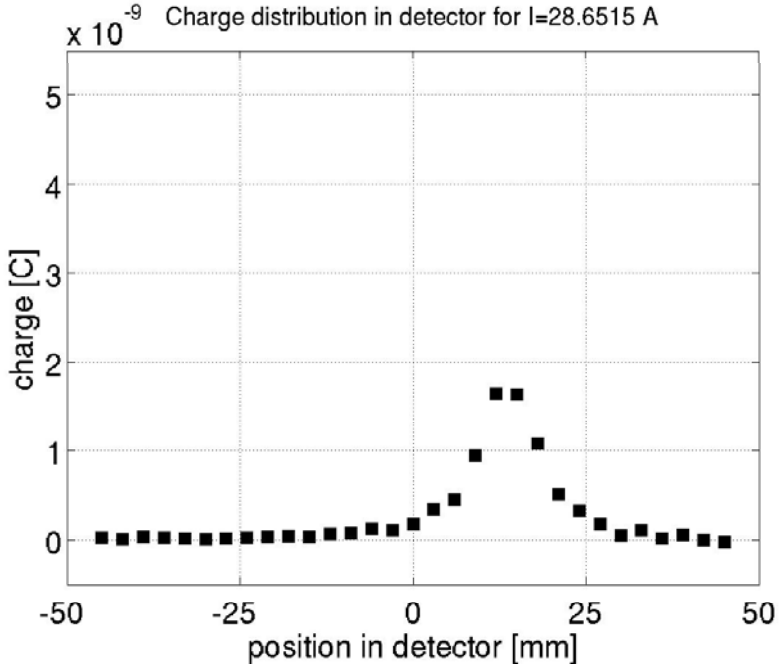




I=28.76 A

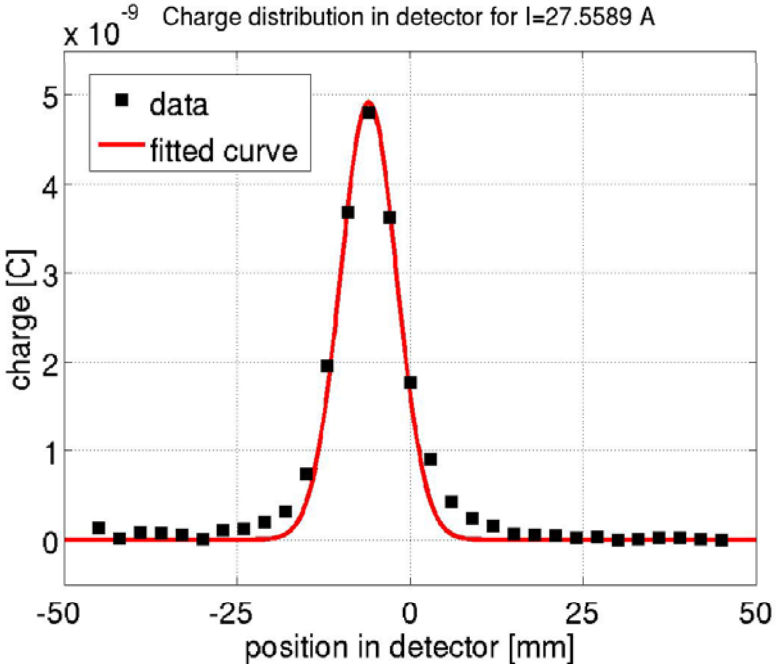
Calibration strategy

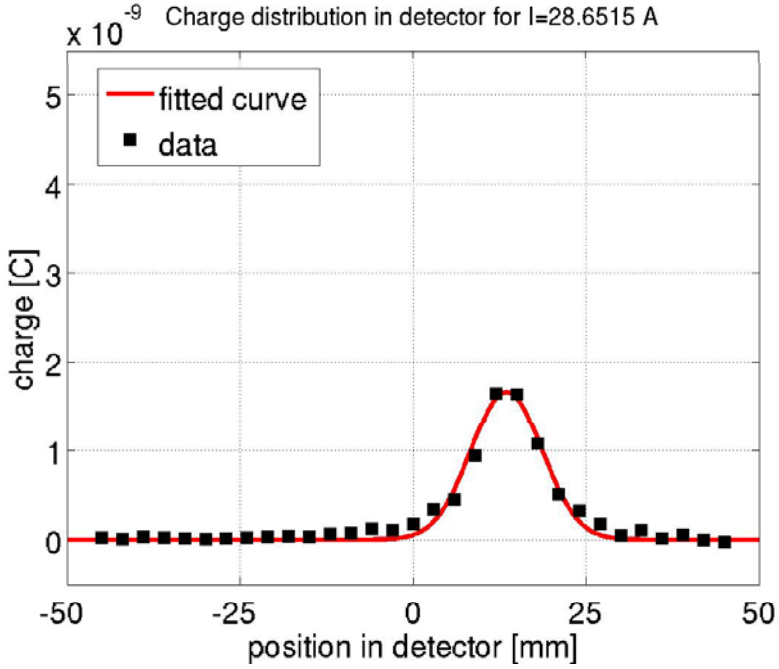




- Integrate over time – plot charge distribution

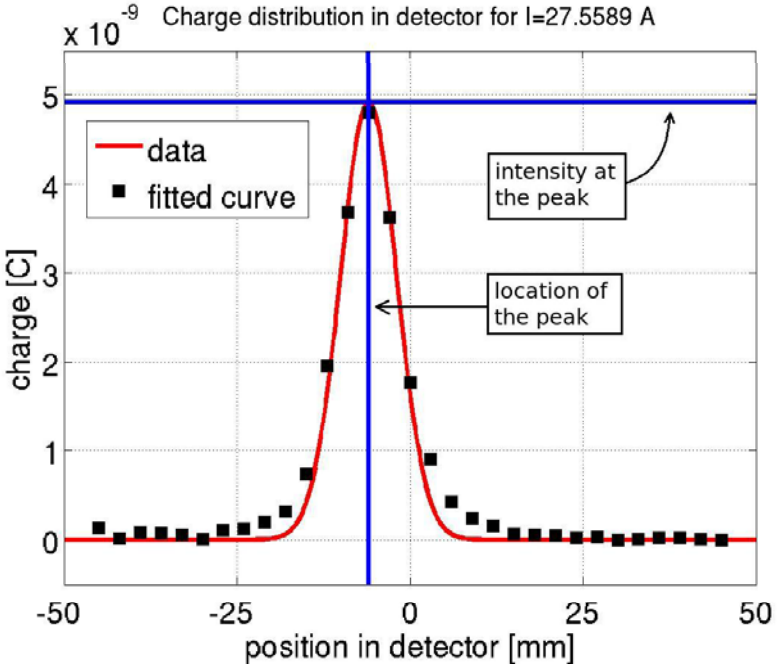
Calibration strategy – segmented dump

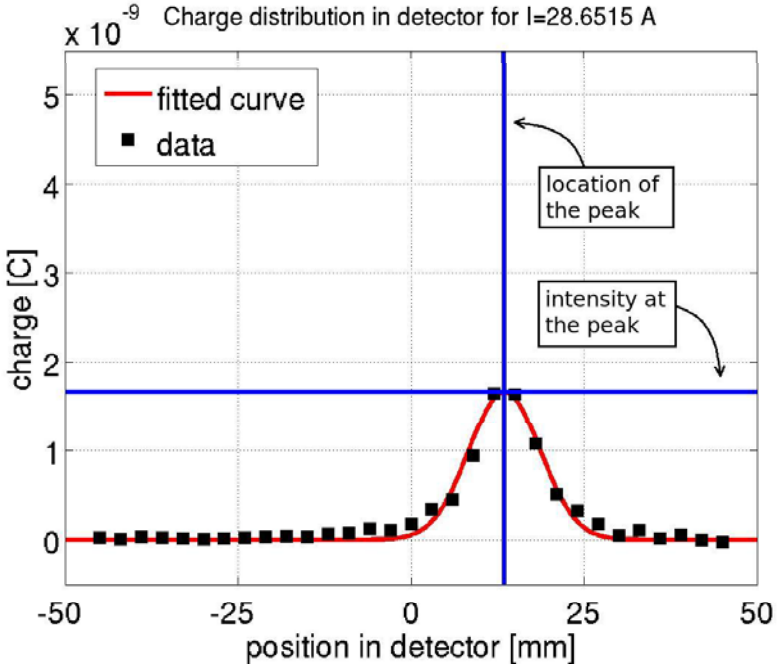




- Integrate over time – plot charge distribution
- Fit to a gaussian distribution

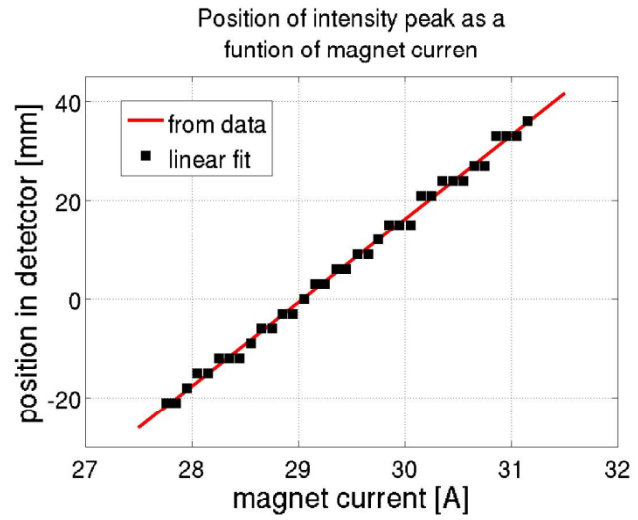
Calibration strategy

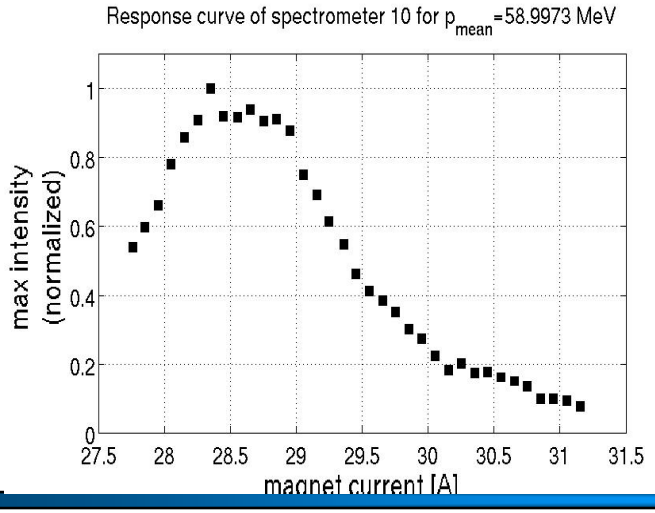


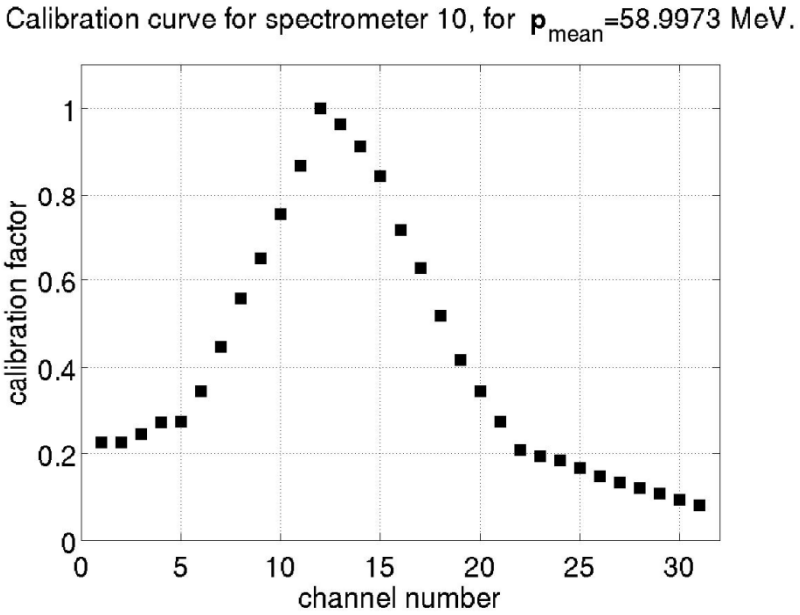


- Integrate over time – plot charge distribution
- Fit to a gaussian distribution
- Extract value and position of the peak, (and fwhm)

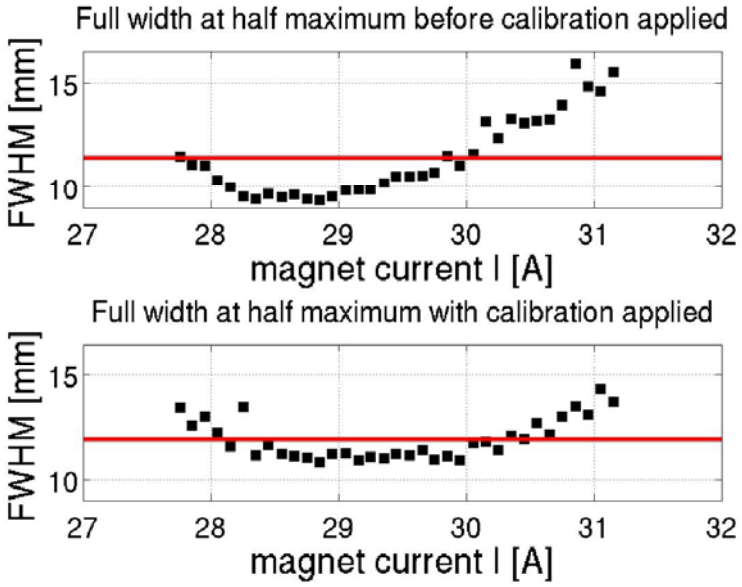
Calibration curve







Checking the calibration - result



One beam through whole scan

- one beam size

Deviation before: 16.9 %

with calibration: 8.2 %

Calculate fwhm of a Gauss fit (of charge distribution) before calibrated (for all I)

- Apply calibration and redo the fit