Longitudinal Diagnostics at CTF3

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CERN BE/BI

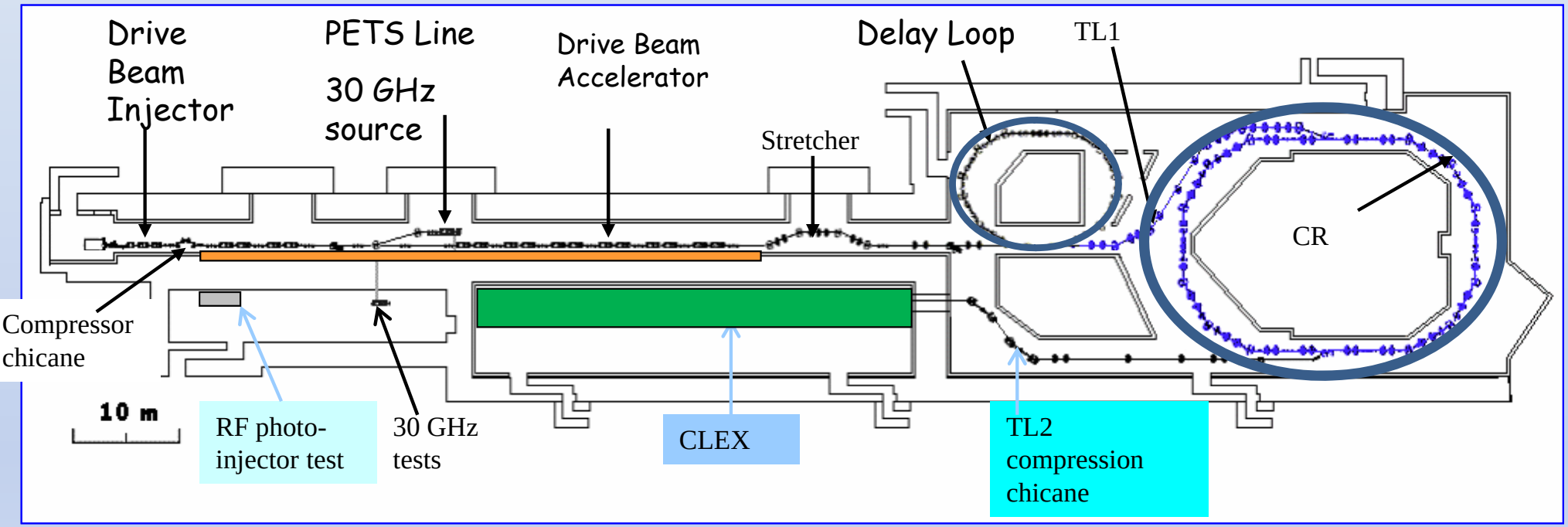
On behalf of CTF3 Collaboration

DITANET Workshop
Cockcroft Institute, UK
Longitudinal Beam Profile Measurements

Outline

- CTF3 Bunch Length regime
- CTF3 Longitudinal profile instrumentation
  - ✓ Optics based
    - Streak Camera
  - ✓ RF+Optics
    - RF deflector
  - ✓ RF based
    - Integrated power spectrum techniques with schotty diodes (“BPRW”)
    - Power spectrum based on microwave spectroscopy (“RF-pickup”)
- Bunch Length measurements planned for CLEX
- Califes probe beam and perspectives for Instrumentation Test Beam (ITB) line
- Outlook

Bunch length @ CTF3

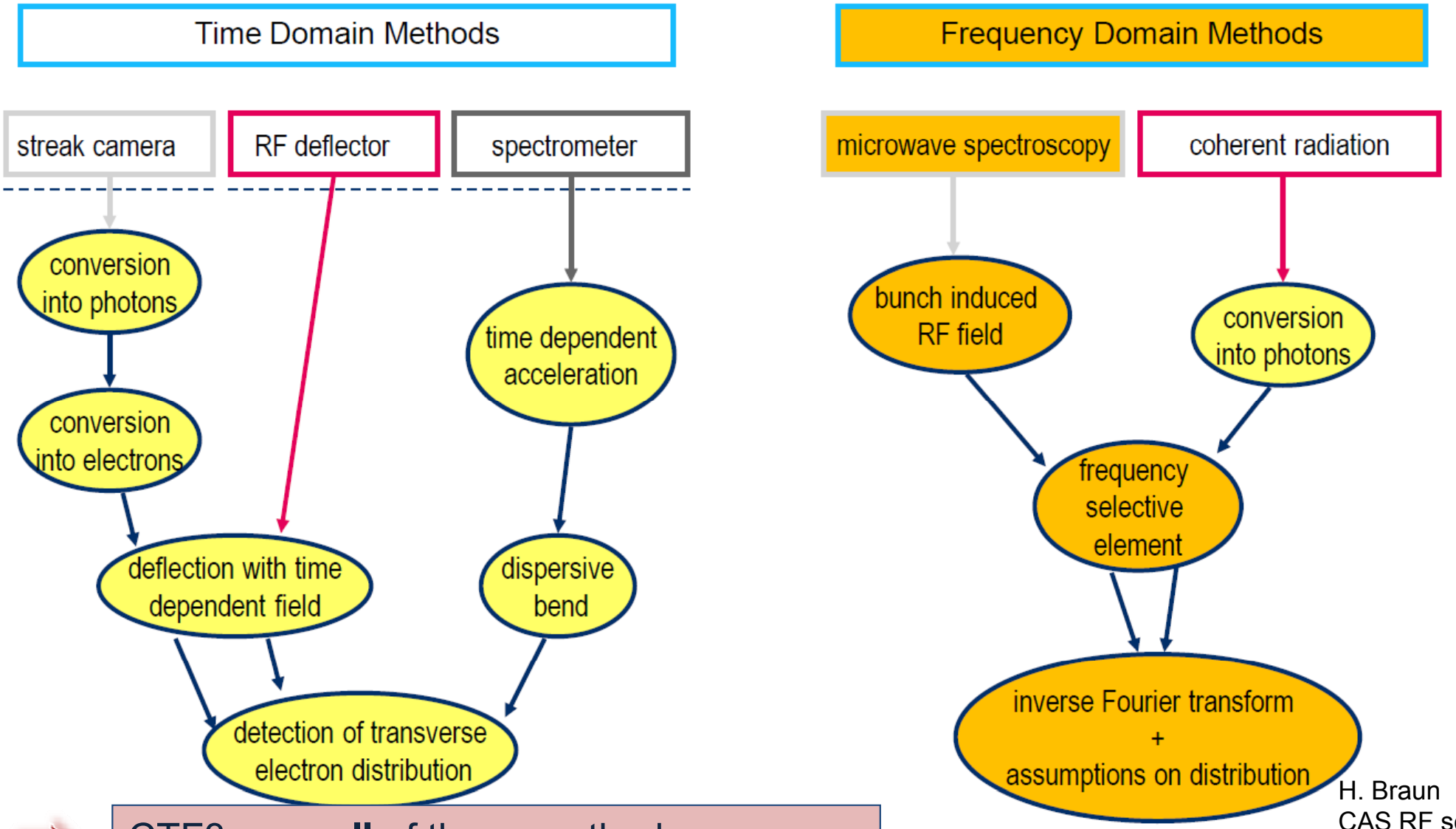


LINAC ≈ 1- 7 ps

Delay Loop and Combiner Ring > 8 ps

CLEX TBL/TBTS ≈ 1- 2 ps r.m.s
Califes < 1 ps r.m.s

Measurement methods for short bunch length



CTF3 uses **all** of these methods

Overview of Longitudinal Instrumentation

Longitudinal Bunch Profile

RF Deflecting Cavity, OTR

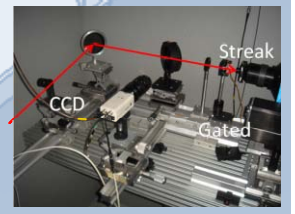
Streak Camera Synch Light, or OTR

Bunch Length Form Factor (r.m.s.)

BPR-W (Integrated Power over 25-40 GHz)

RF-pickup (Power at selected harmonics 30 – 170 GHz)

CDR Experiment – RHUL

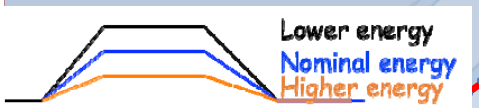


Combine Beam, 12 GHz Bunch Spacing

Stretching Chicane

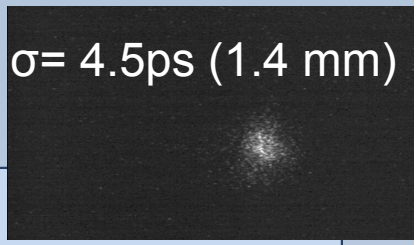
Compression chicane - TL2

2 Streak Labs, 1 more for 2010

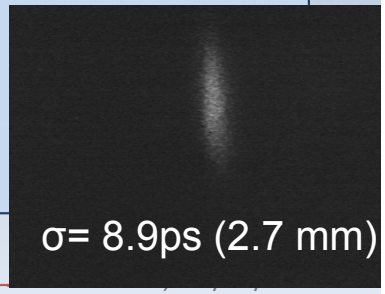


Cleaning Chicane

Injector, 1.5 GHz Bunch Spacing



- Linac ~ 1-7 ps
- Delay Loop and Combiner Ring > 8ps
- CLEX 1-2 ps
- Probe Beam (Califes) < 2 ps

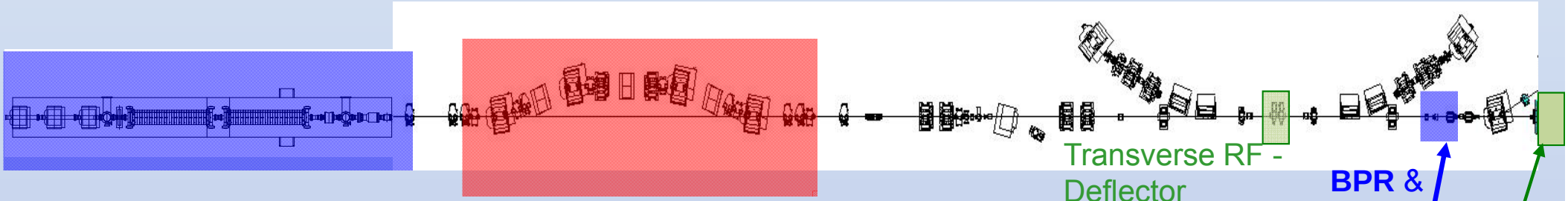


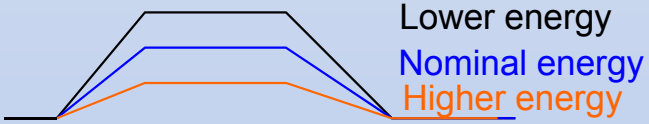
Bunch length manipulation using INFN Chicane

Accelerating structures @Girder 15

4 Bends INFN-Frascati Chicane

Delay Loop



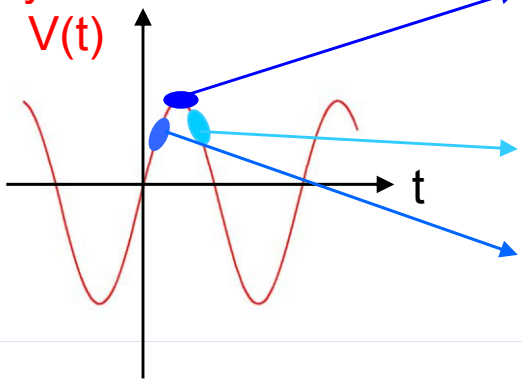


Scan phase of Klystron 15 to insert a time to energy correlation within the bunch

Convert energy correlation into path length modification and time correlation

Measure the Bunch frequency spectrum

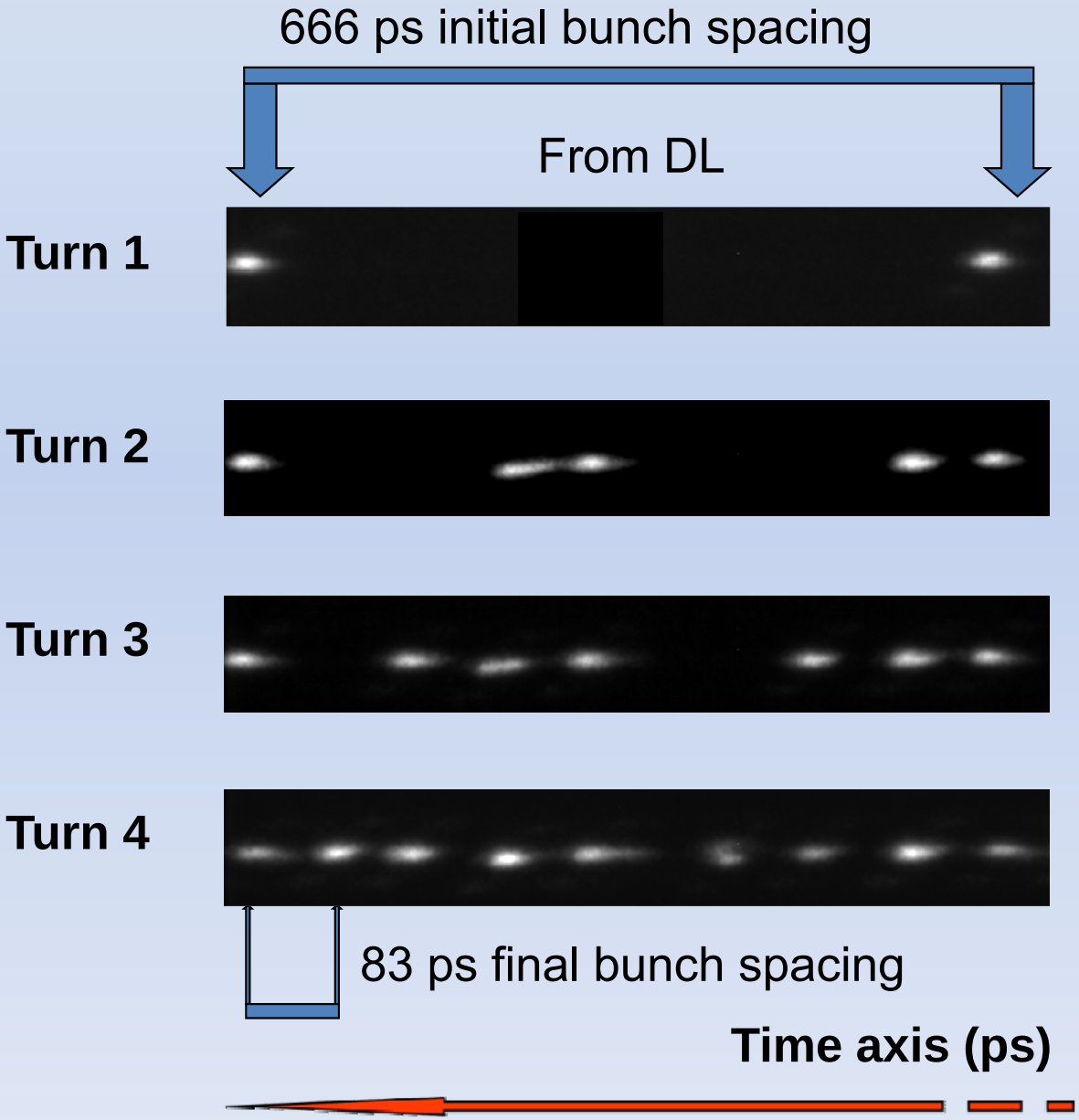
Measure bunch shape & length using RF deflector and OTR screen

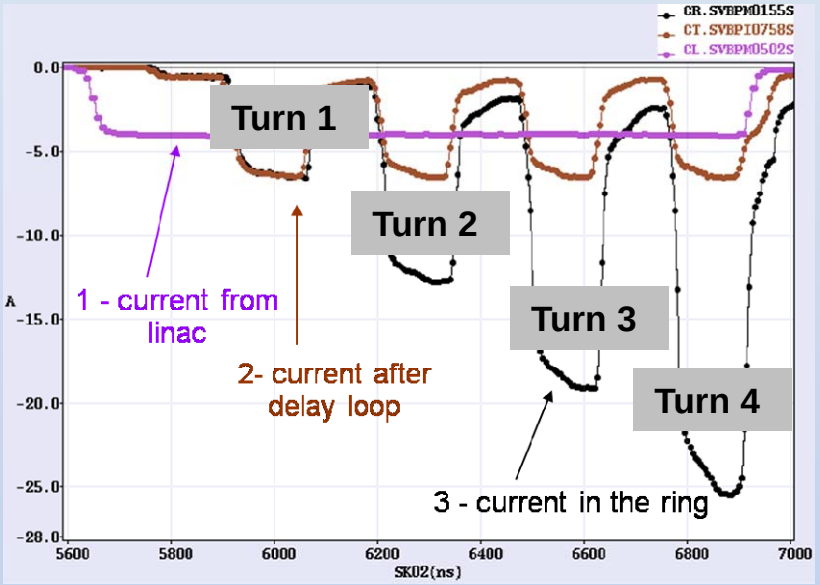


- On-crest Acceleration – the bunch length is conserved through the chicane
- Negative Off-crest Acceleration – the bunch gets longer
- Positive Off-crest Acceleration – the bunch gets shorter

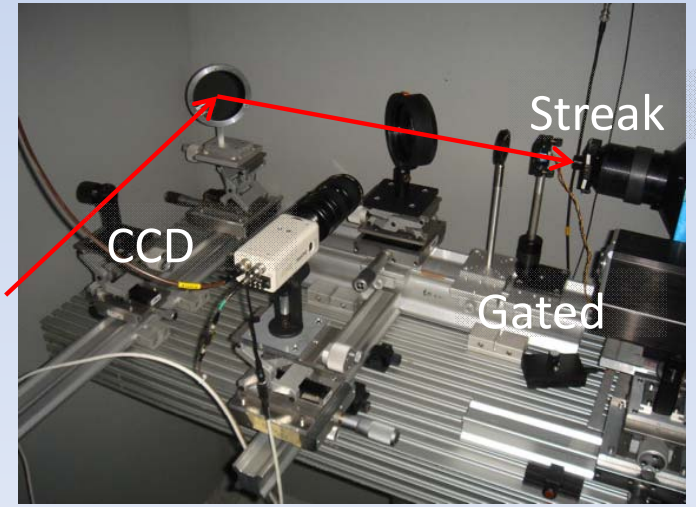
Bunch Combination in CTF3 Combiner Ring

Streak camera Measurement





Current Multiplication Measured with BPMS



CTF3 Bunch Frequency spectrum

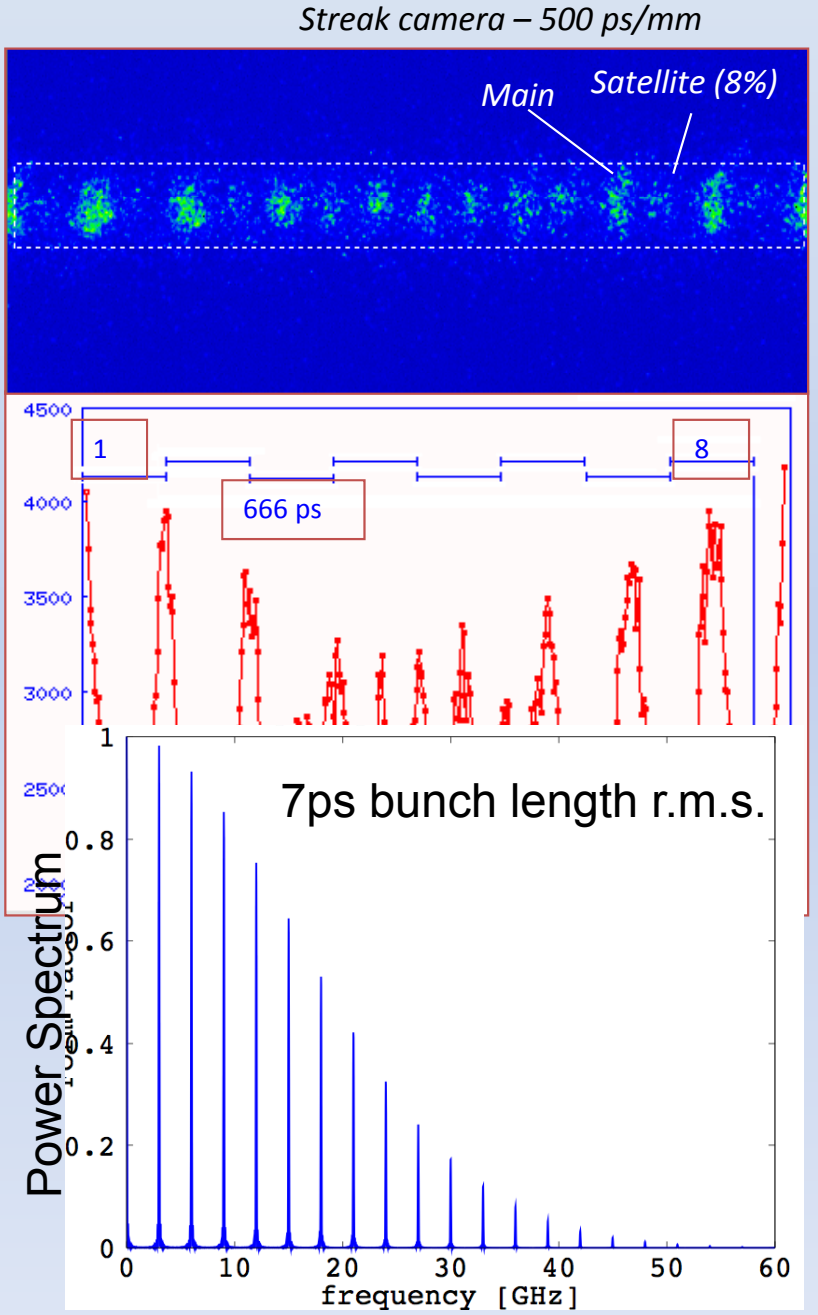
Nominal operation:

- Linac 1.5 GHz bunched beam, 1.2 μs pulse
- Satellite bunches contain 8-12% (2009) of bunch charge and have a different longitudinal emittance
- Fast phase switch (5ns) of 180 degrees every 140 ns

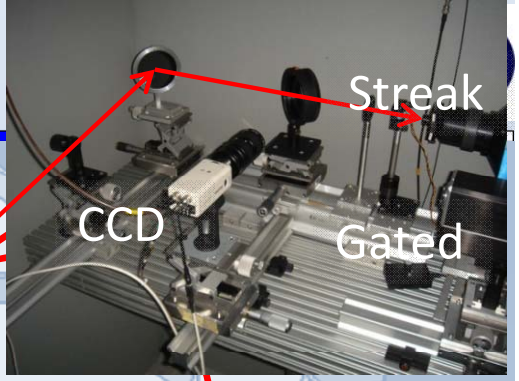
Preferred beam for diagnostics studies:

- 3.0 GHz (333.3ps bunch spacing)
- No sub-harmonic bunching system
- No phase switches

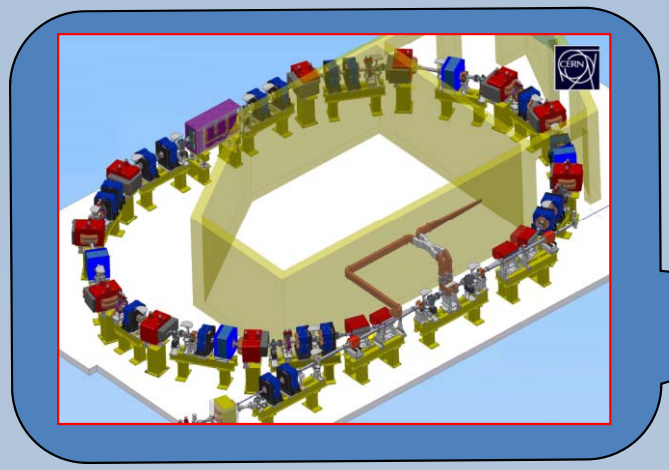
➡ This is the beam that I will focus on for this talk



Streak Camera in CTF3



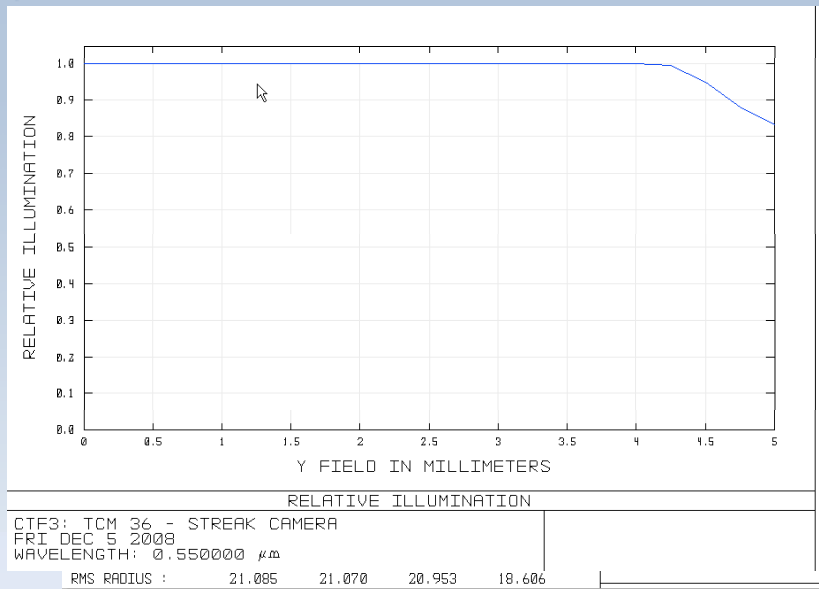
Long optical lines to the streak camera Laboratory



2008
- o CR Optics lab
- o 2 Synchrotron Radiation optical lines commissioned

2 Optical lines in 2006
- o Synchrotron Radiation in the Delay Loop
- o OTR at the end of linac CT line

Optical lines simulated with Zemax
- •high transmission
- •minimal abberation and chromatic effects
- •local focal point in the labs for both lines
- •Re-image focus down towards streak

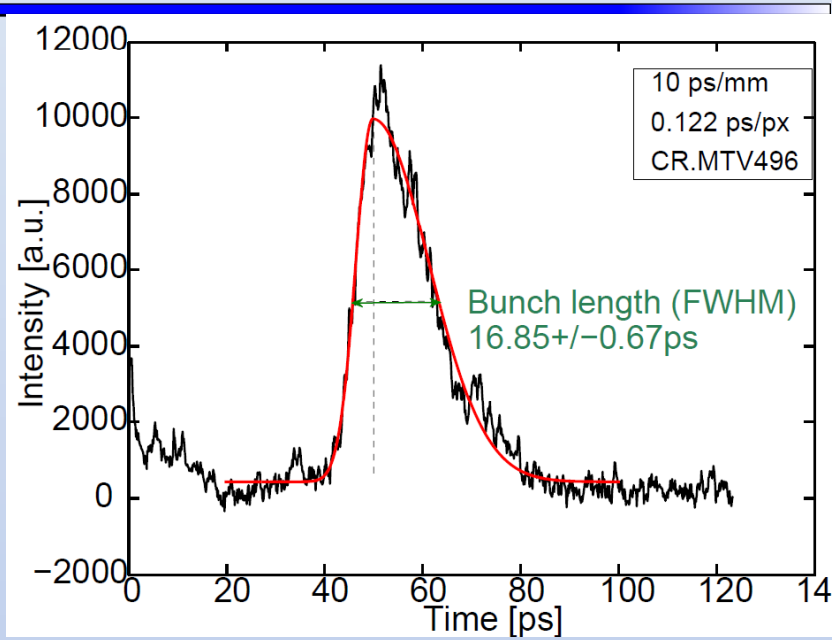


Streak Camera – Bunch Length Measurement

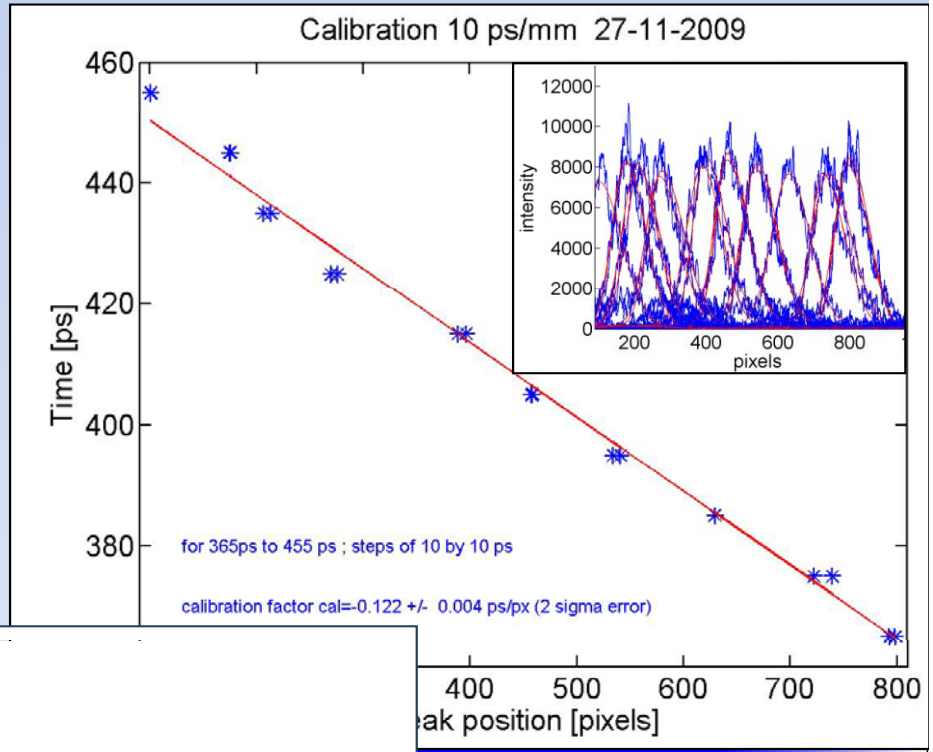
- Bunch Shape
  - A **Skew Gaussian bunch shape**

$$y = ae^{-\frac{(x-\mu)^2}{2\sigma^2(1+\alpha\cdot sgn(x-\mu))}} + off$$

- Measure calibration factors
  - Result **0.122 ± 0.004 ps/pixel (2 sigma) for 10ps/mm**



- Measurement of the jitter
  - **5.5 ps ± 0.2 (2 sigma)**
  - Contribution from trigger and beam
- Slit size contribution to measurement
  - **FWHM in focus 14.8±0.9 pixels (2 sigma)**
  - 350 µm

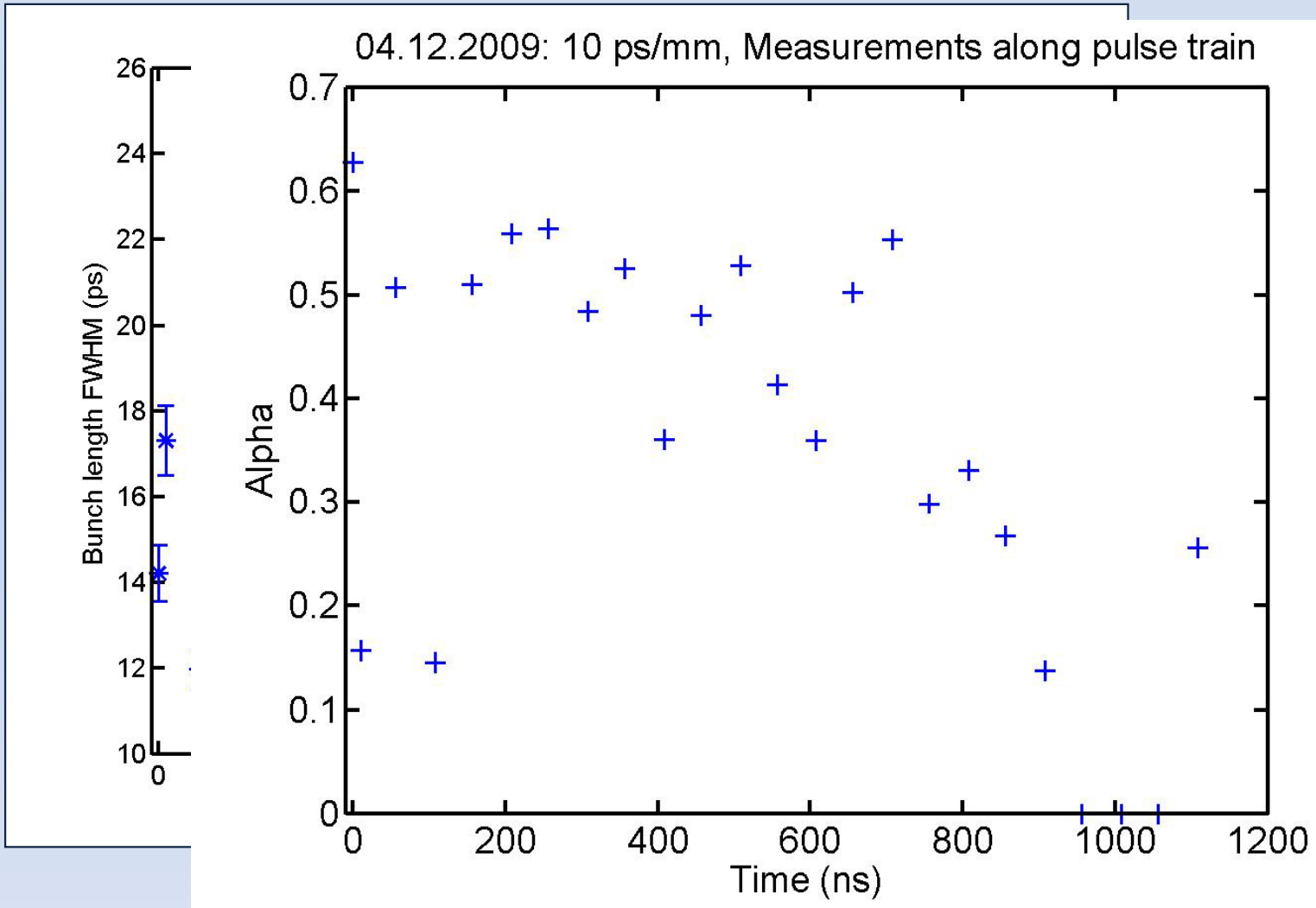


Propagate all error contributions …

Typical **measurement error on FWHM is 4% (2 sigma)**

Bunch Length measurement along pulse train

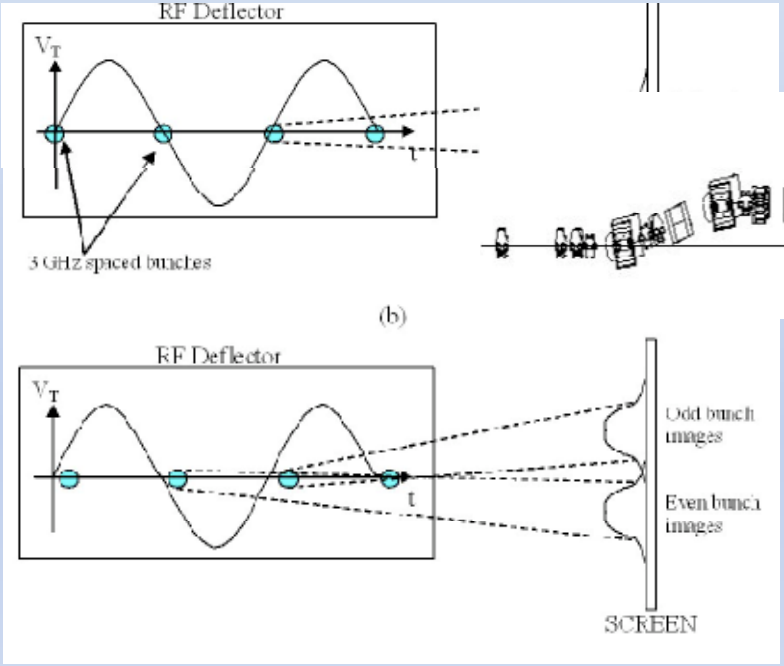
- Streak Camera in Combiner Ring using MTV 0496 (zero dispersion point)
- 3 GHz uncombined beam, by-passing the delay loop
- 50 ns sampling
- 2 sigma error bars



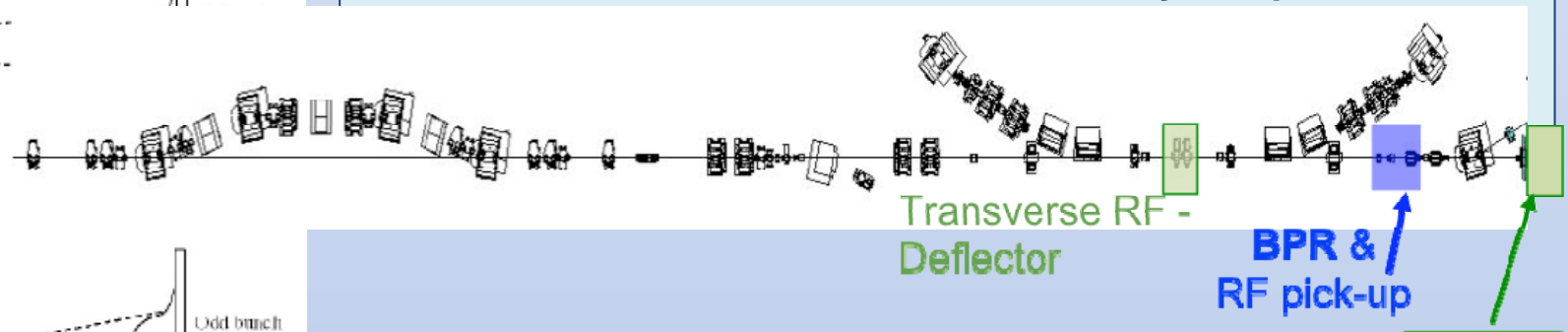
Use Streak Camera measurement and this bunch length variation to **cross calibrate other bunch length instruments**

Bunch Length 3 GHz beam, 1.5 GHz deflector

Time integrated, destructive measurement
Modify machine optics to use deflector at zero crossing & high power (less stable) for best resolution



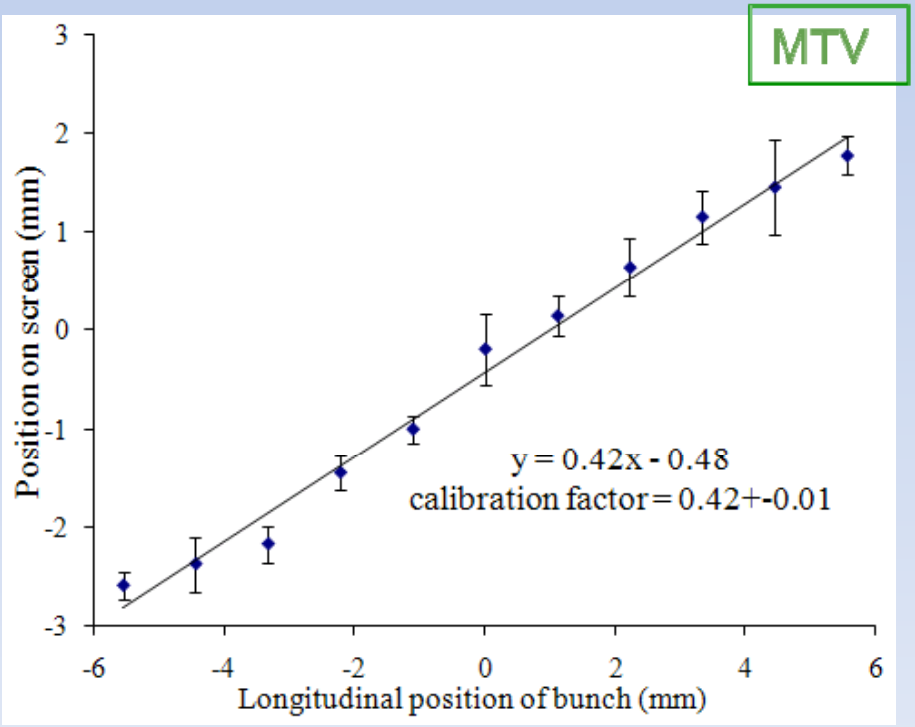
Measurement procedure:



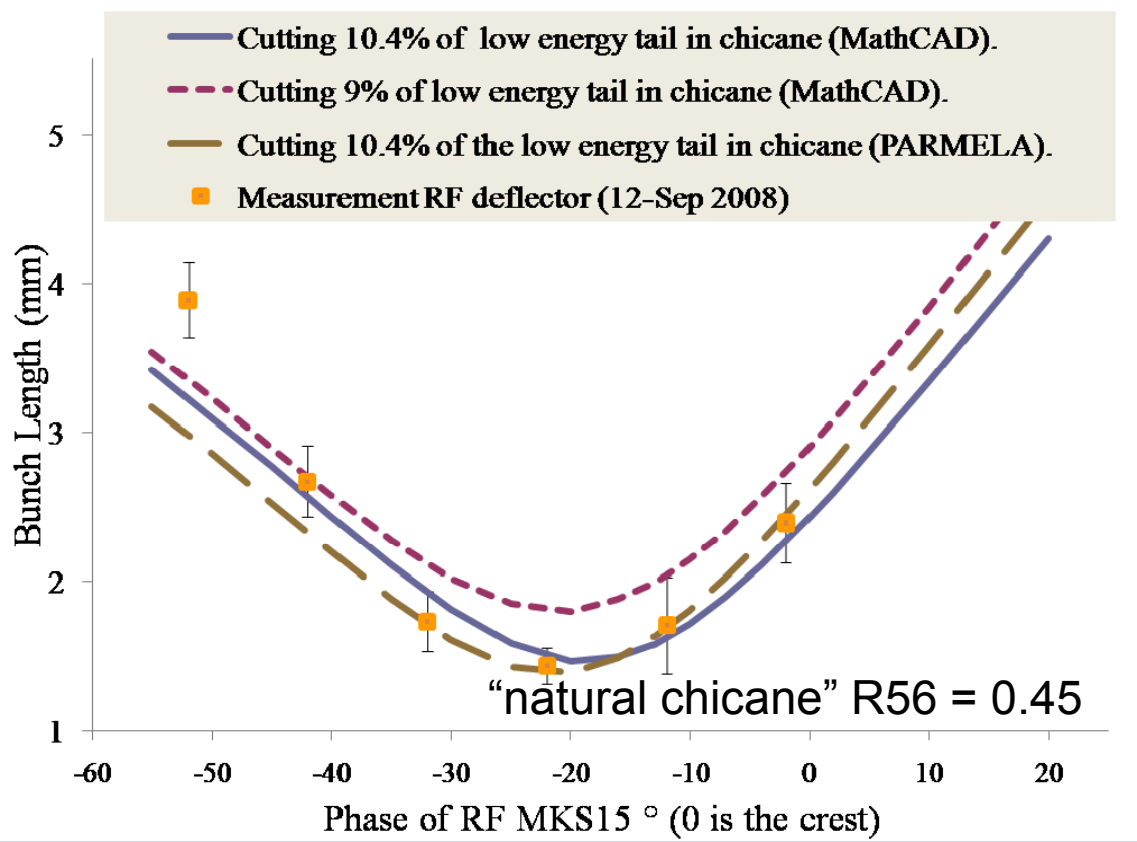
$$\sigma_{z\mathrm{rms}} = \frac{1}{\mathrm{CAL}} * \sqrt{\sigma^2_{x_{\mathrm{rms}}(\mathrm{RF_{ON}})} - \sigma^2_{0x_{\mathrm{rms}}(\mathrm{RF_{OFF}})}}$$

Calibration Factor:

Change the phase of RF deflector
➔longitudinal mm vs. position on screen



Bunch Length 3 GHz beam, 1.5 GHz deflector



Longitudinal dynamics simulation work advancing by **H. Shaker**

Compression curve measured as a function of MKS15 phase & compared to simulation

Measurement sensitive to:

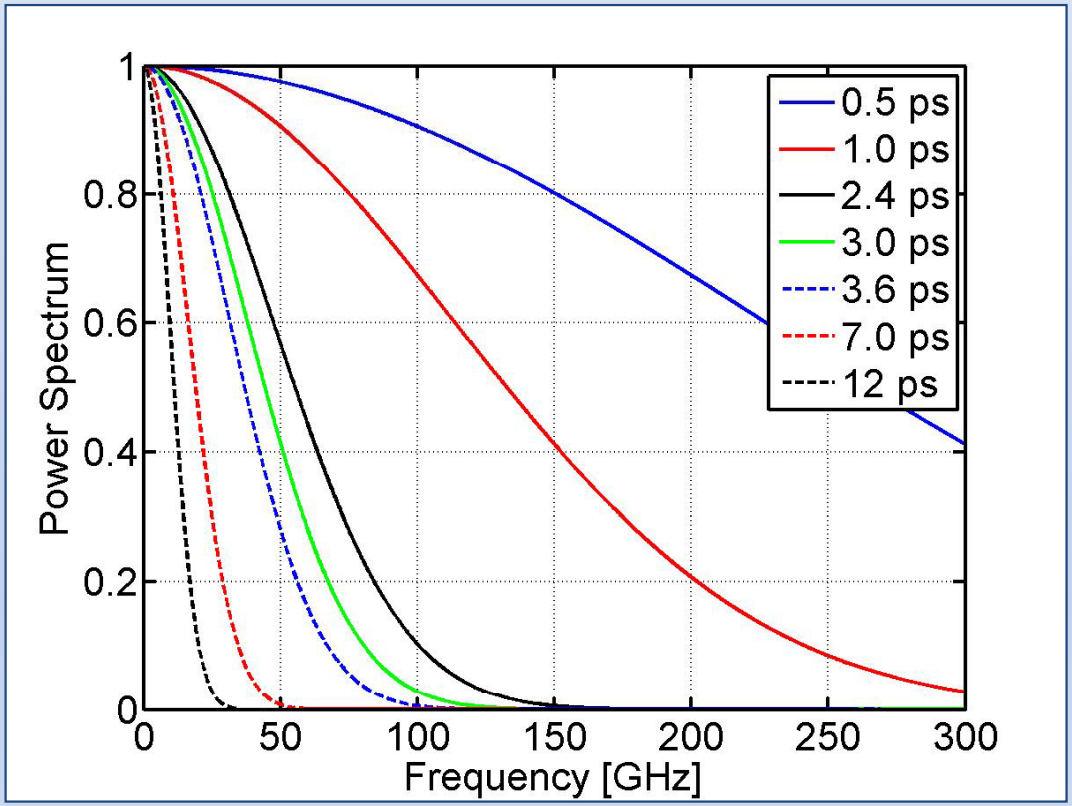
- Setup of injector
- Jitter from the gun
- Stability of RF along whole linac
- Stability & power of RF for RF deflector
- Linear response of OTR screen – small effect

Integrated measurement along pulse train

- Over-estimate of bunch length
- Error contributions from phase and bunch length variation along the pulse

➔Measurements repeated with the 3 GHz deflector in CR and OTR screen in CRM line and studies ongoing

CTF3 Bunch Frequency spectrum

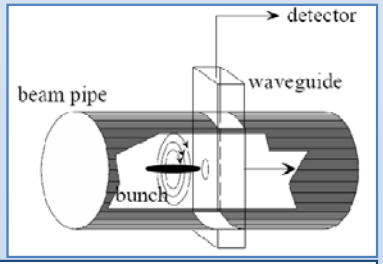


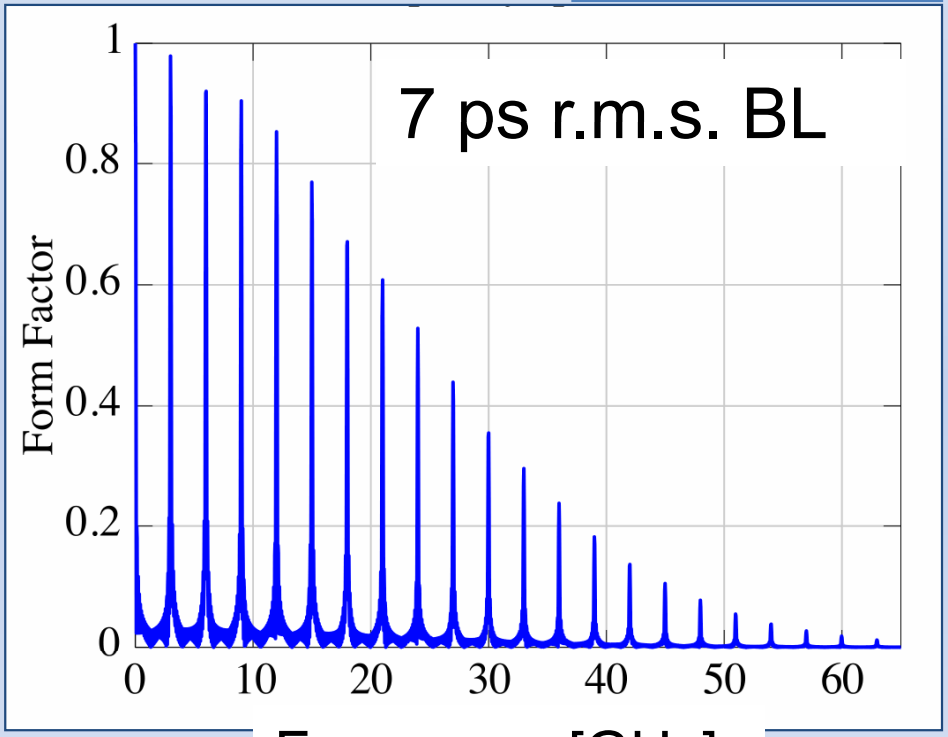
Example: Assumption Gaussian Bunch

$$i_b(t) = \frac{q_b}{\sqrt{2\pi}\sigma_b}\exp\left(\frac{-t^2}{2\sigma_b{}^2}\right)$$

$$F_b(\omega) = \frac{q_b\sigma_b}{\sqrt{2\pi}}\exp\left(\frac{-\omega^2\sigma_b{}^2}{2}\right)$$

$$P_b(w) \propto F_b(\omega)^2$$



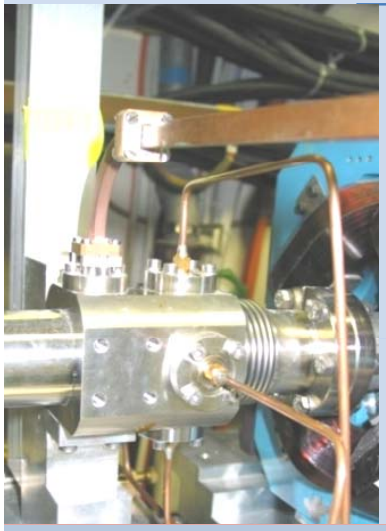


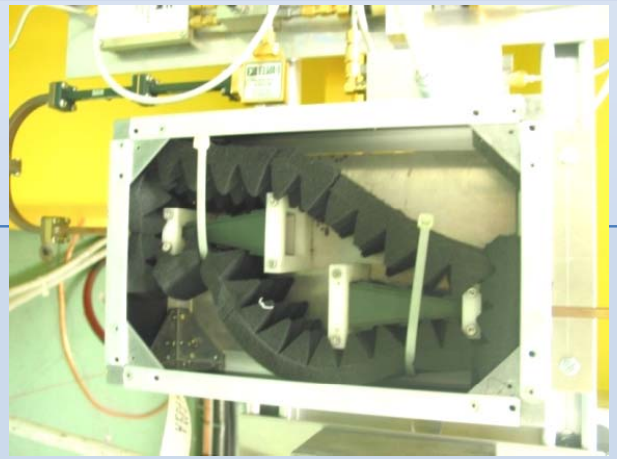
Peaks are spaced by 3 GHz

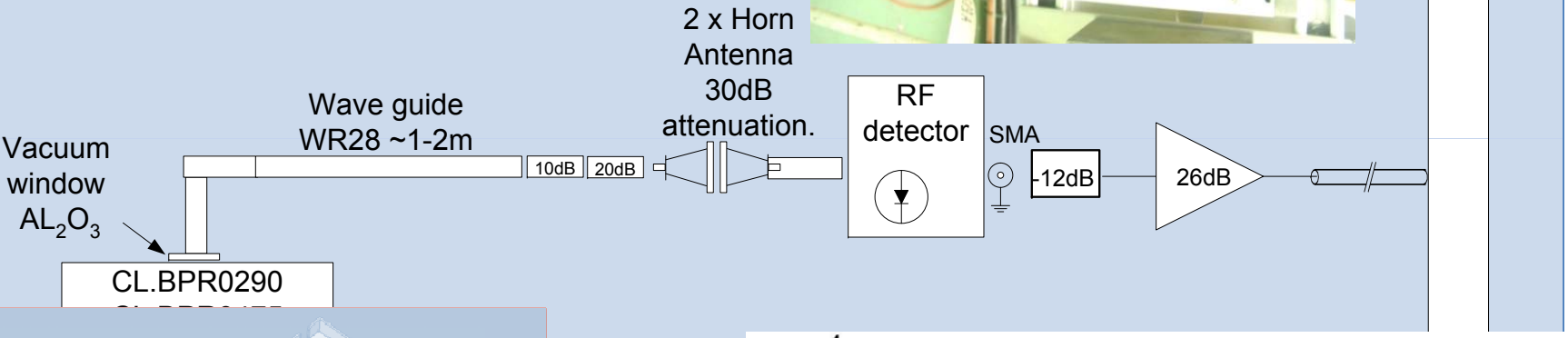
Envelope single bunch, bunch-length

RF Techniques – r.m.s. bunch length - BPRW

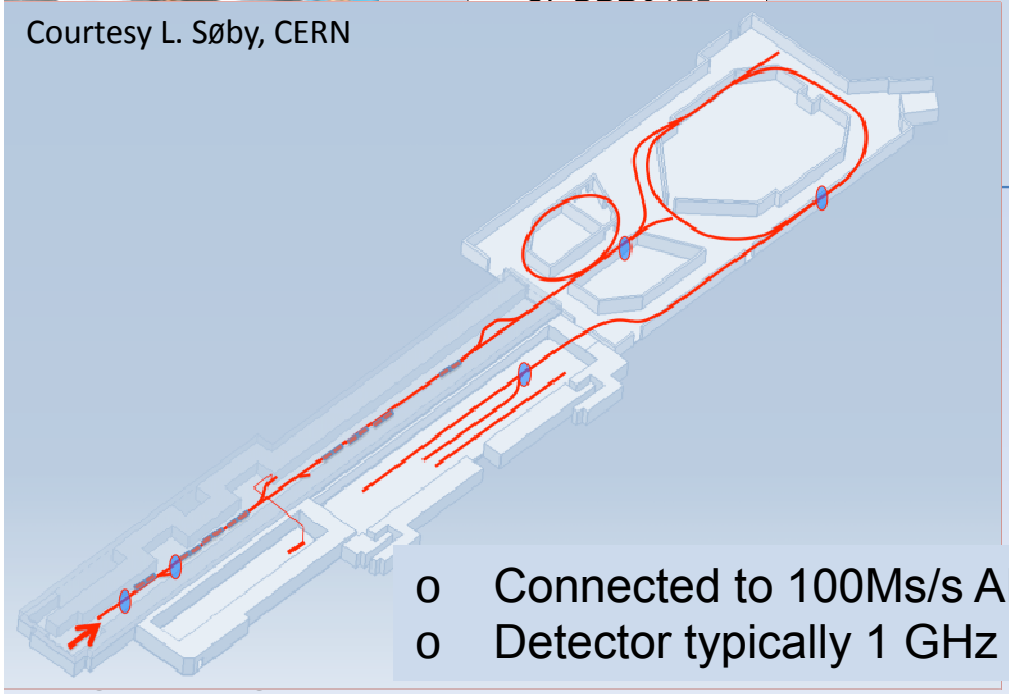
$$P \propto \frac{r}{r_o}^2 q^2 e^{-\frac{\varpi^2 \sigma_t^2}{c^2}} \text{ (example Gaussian bunch shape)}$$



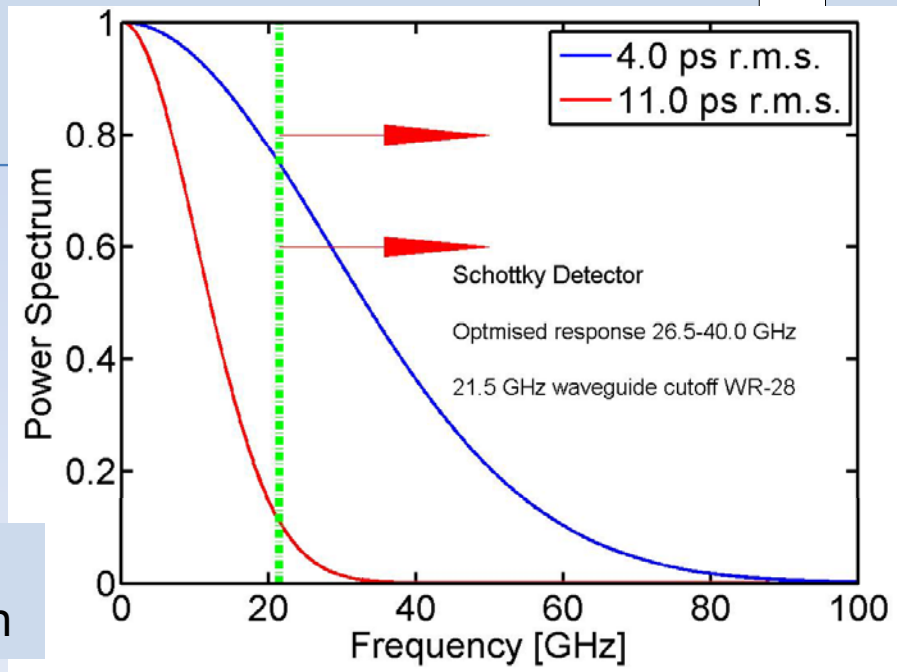




Courtesy L. Søby, CERN

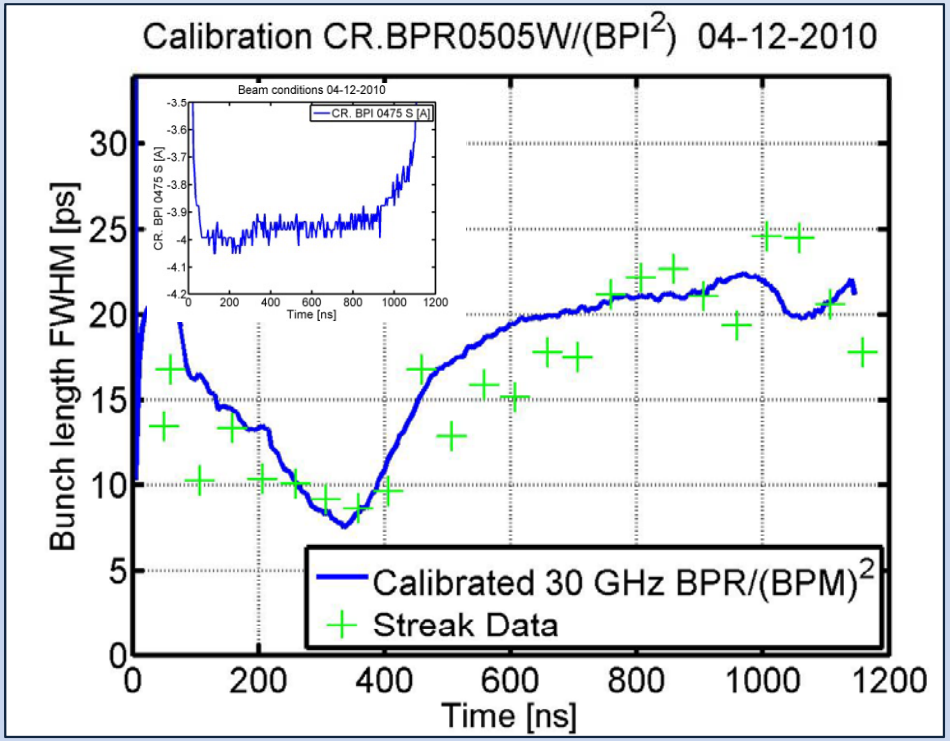


- Connected to 100Ms/s ADC
- Detector typically 1 GHz bandwidth



BPRW Power measurement compared to streak Camera

- Data used: 04-12-2010
- Beam conditions: 3 GHz 4 Amp beam
- Use time resolved bunch length from Streak
- Assume quadratic function for fit

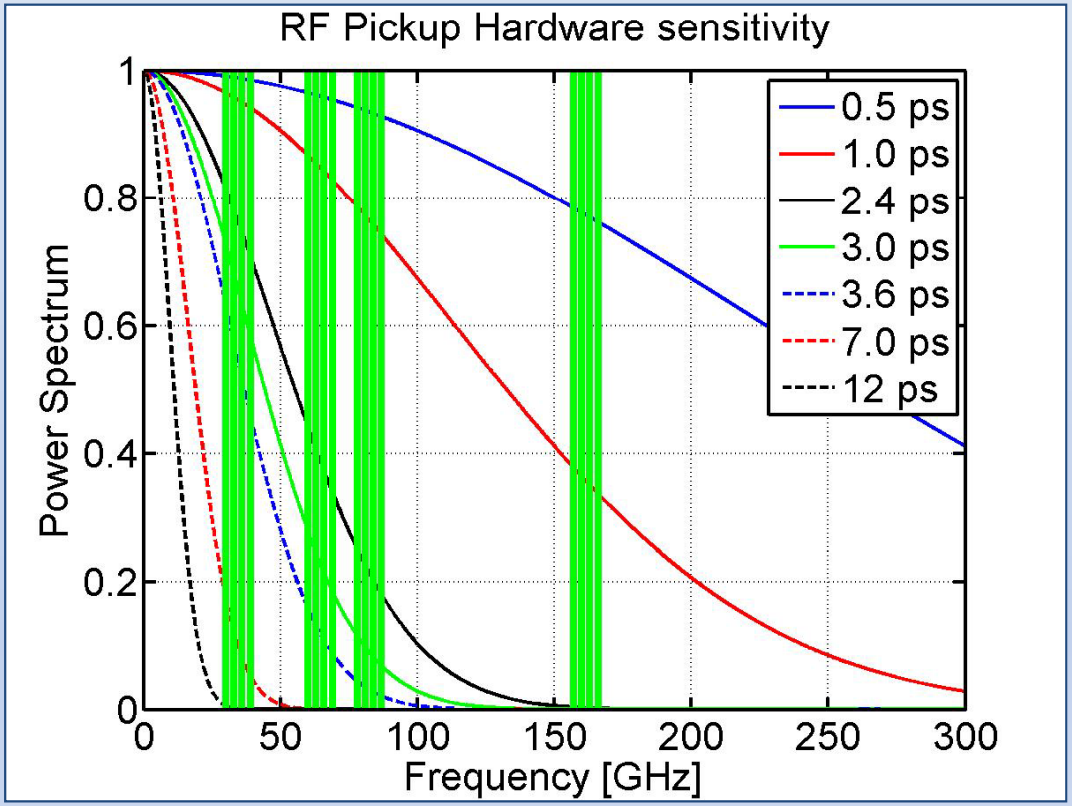


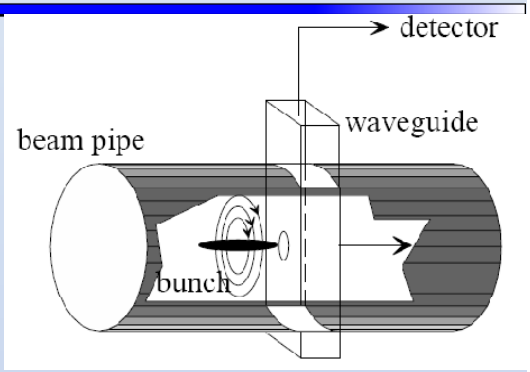
Application of Calibration:

- BPR and Streak in good agreement
- Exercise should be repeated with different beams to study systematics and verify current and position normalization
- Error in calibration large (40% error 2 sigma)
- Measurement of BPM, BPR and Streak relevant for a good calibration

✓ BPR's used as Online bunch length measurement available today!

CTF3 Microwave Spectroscopy – “RF pickup”





PhD thesis C.Martinez

Measure the **power spectrum** of the beam at each frequency:

1. 30;33;36;39 GHz
2. 60;63;66;69 GHz
3. 75;78;81;84 GHz
4. 159;162;165;168 GHz

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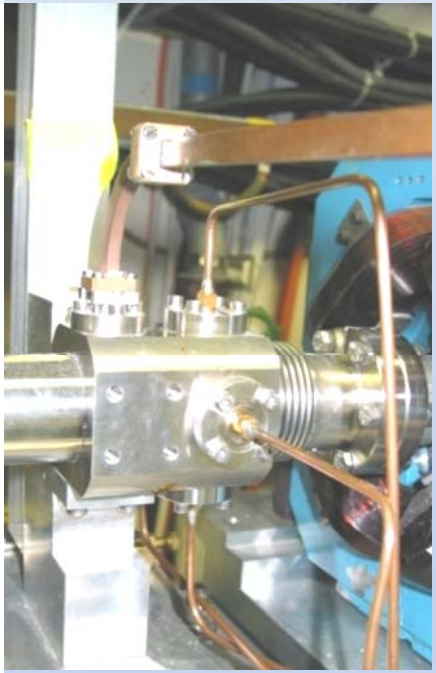
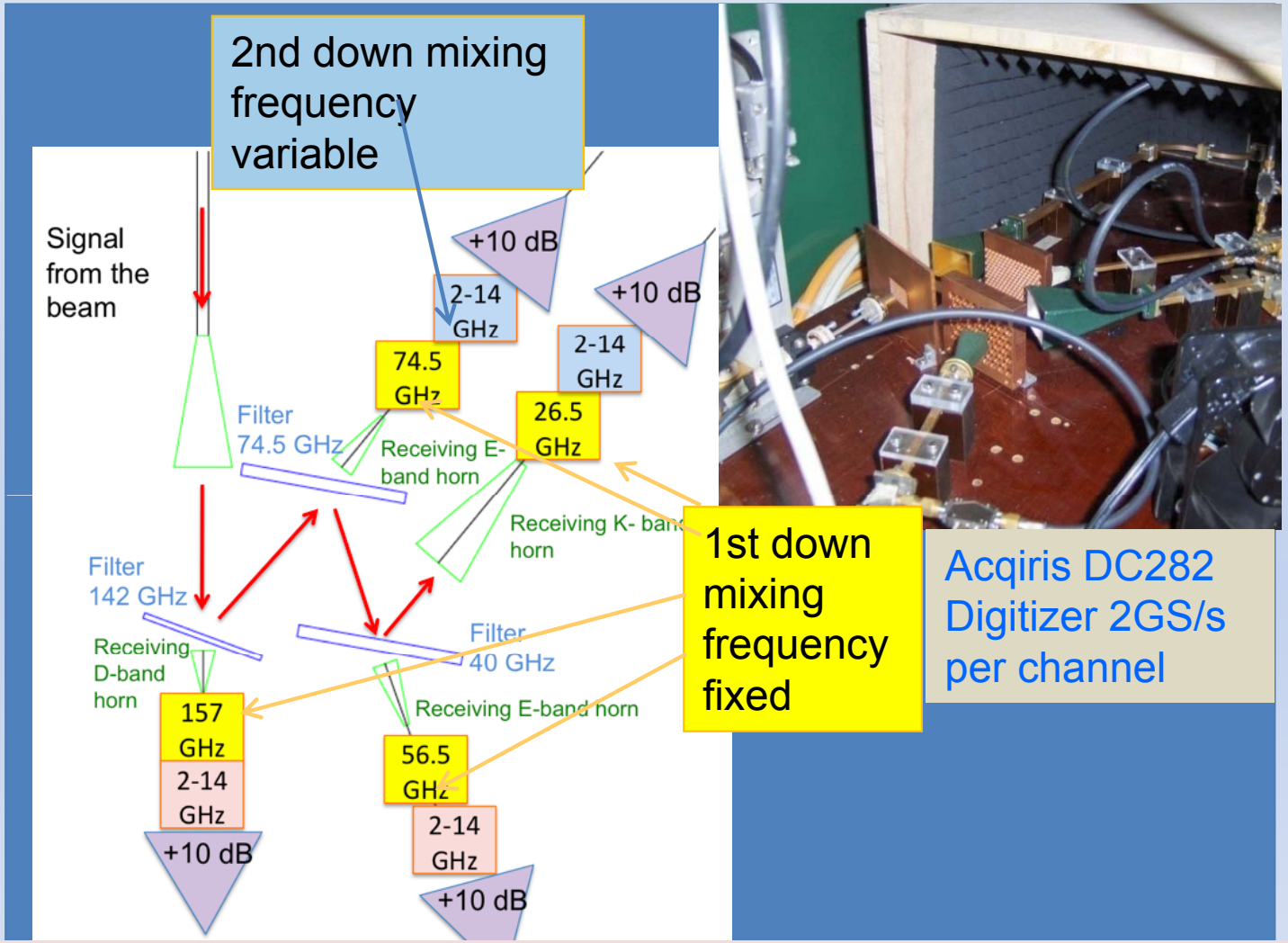
Setup @ CTF3 was installed & first data taking in Nov 2006

- Non-intercepting device
- easy to implement in machine
- sub-ps resolution (300fs CTF3), **self calibrating** if bunch length scan is performed
- RF deflector and/or a streak camera @CTF3 provide an excellent cross calibration of device

CTF3 Bunch Length Measurement – “RF pickup”





Acqiris DC282 Digitizer 2GS/s per channel

Transmission transparent for high Freq < 170 GHz, very thin 0.150 +- 0.005 mm thick diamond window (ε_r~6 at 30 GHz) designed and successfully brazed by S Mathot @ CERN EN/MME on a Test Titanium sample

Thinnest window ever brazed at CERN

➔Window has been installed since 2009, and holds good vacuum

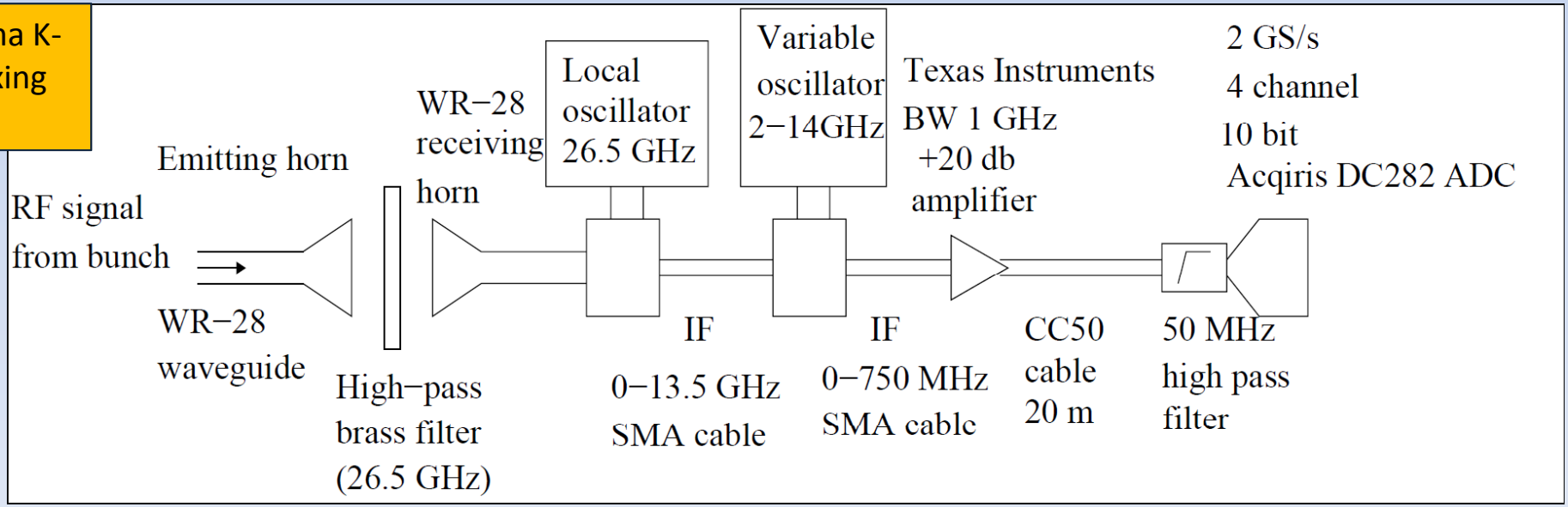
Example of one down mixing stage - RF-pickup

Example:

1. 33 GHz beam harmonic (11th of 3 GHz)
2. ADC is 2 GS/s, typically use 4000 points, 2 micro second time window, delta t = 0.5 ns
3. Depending on the period of the bunch length variations along the pulse & parasitic noise optimize the choice of the second LO mixing stage
4. choose to down mix to a high frequency LO signal, choose 716 MHz

Beam acceleration	Beam harmonic #	Beam harmonic	Fixed first Mixing	Variable Mixing	IF	IF (measured)
2.99855 GHz	11	32.984 GHz	26.5 GHz	7.2 GHz	716 MHz	735 MHz

Example Schema K-band down mixing scheme



RF-pickup signals

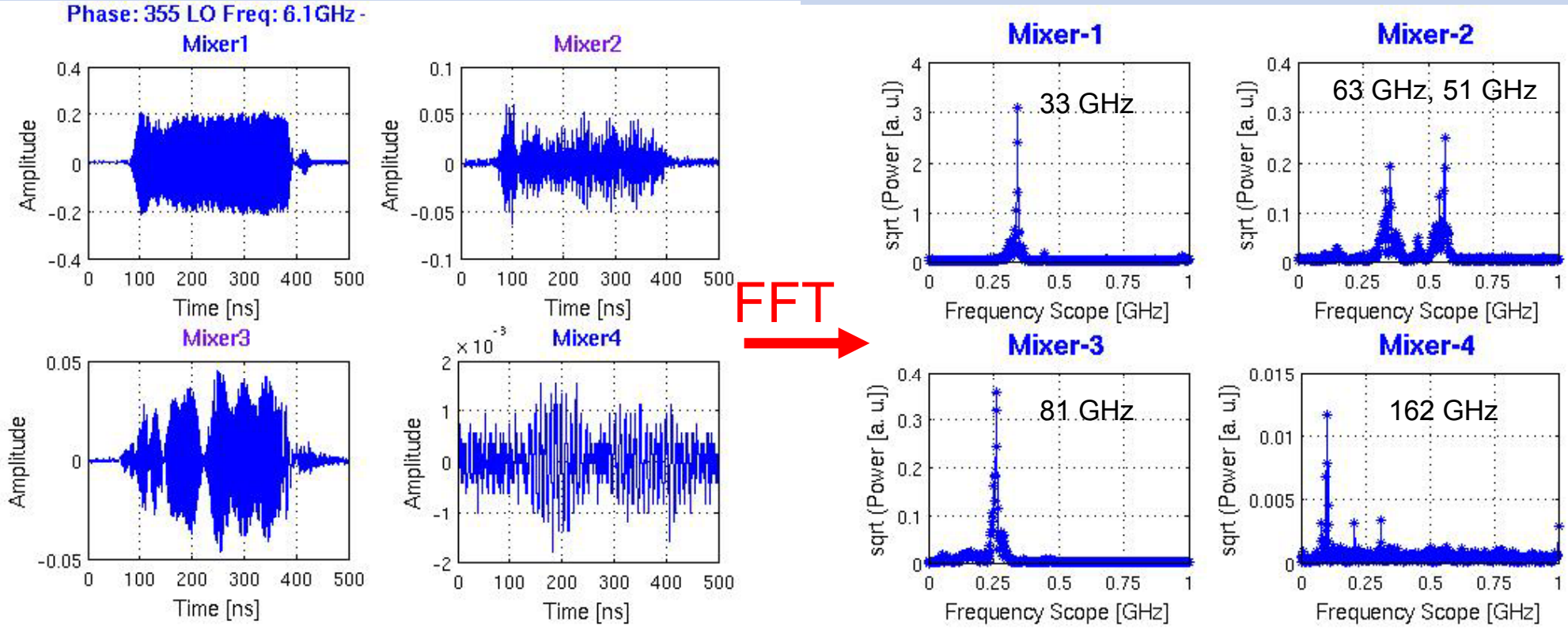
Example:

Synthesizer (second down-mixing stage) set at 5300 MHz

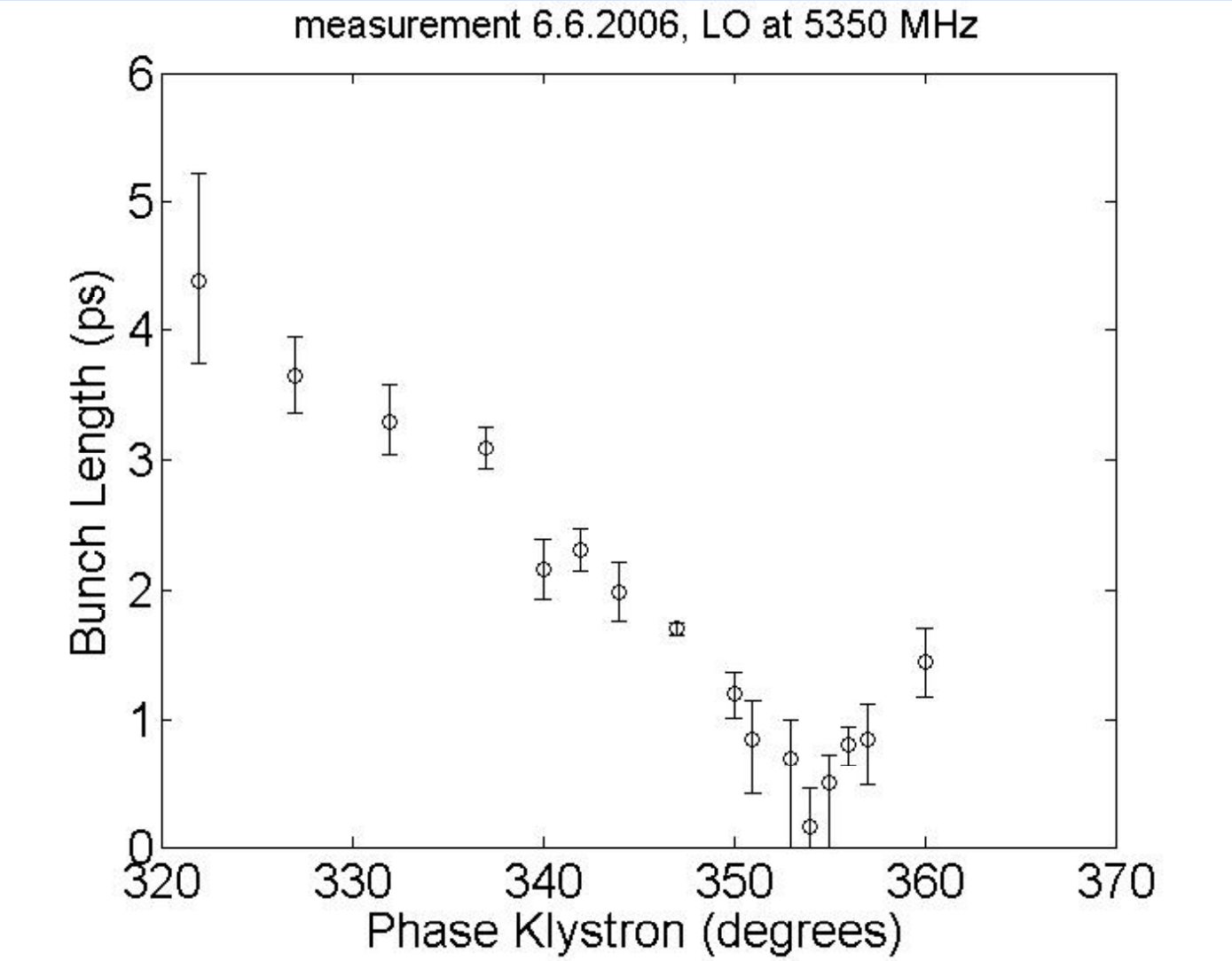
phase MKS15 355 degrees, 06-12-2006

Raw signals from the beam in time domain

Transformed signals (Raw FFT unfiltered)



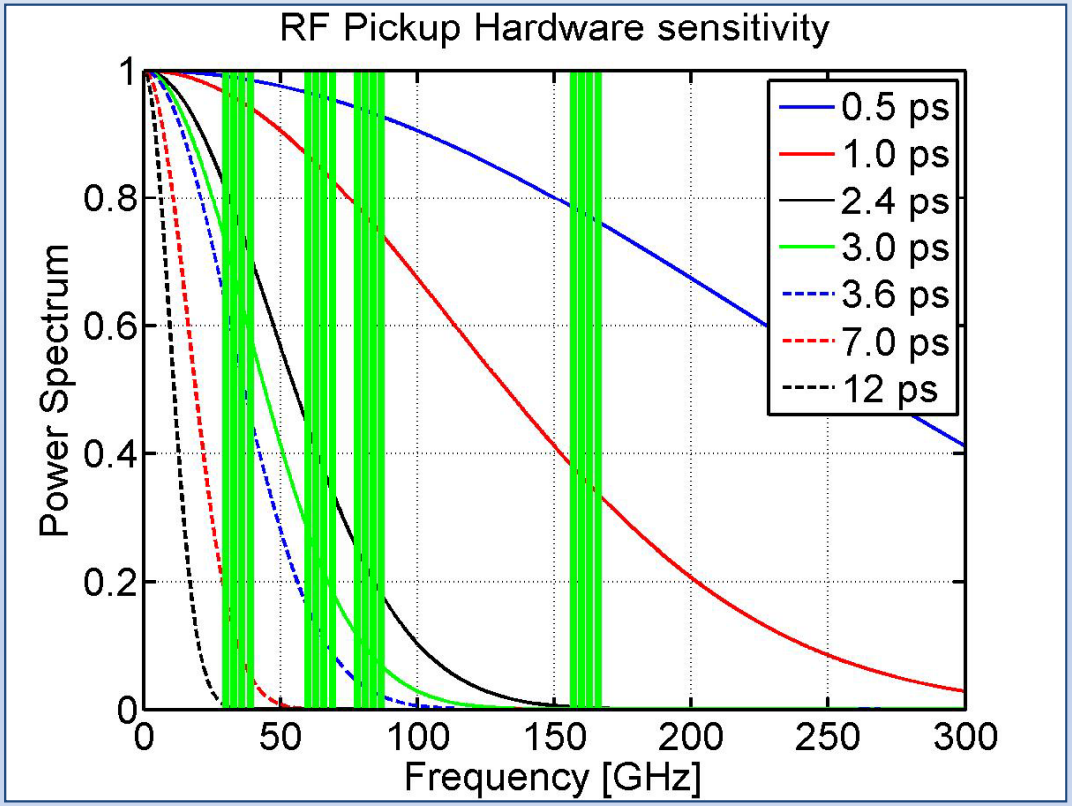
RF-pickup result 2006 – Self Calibration

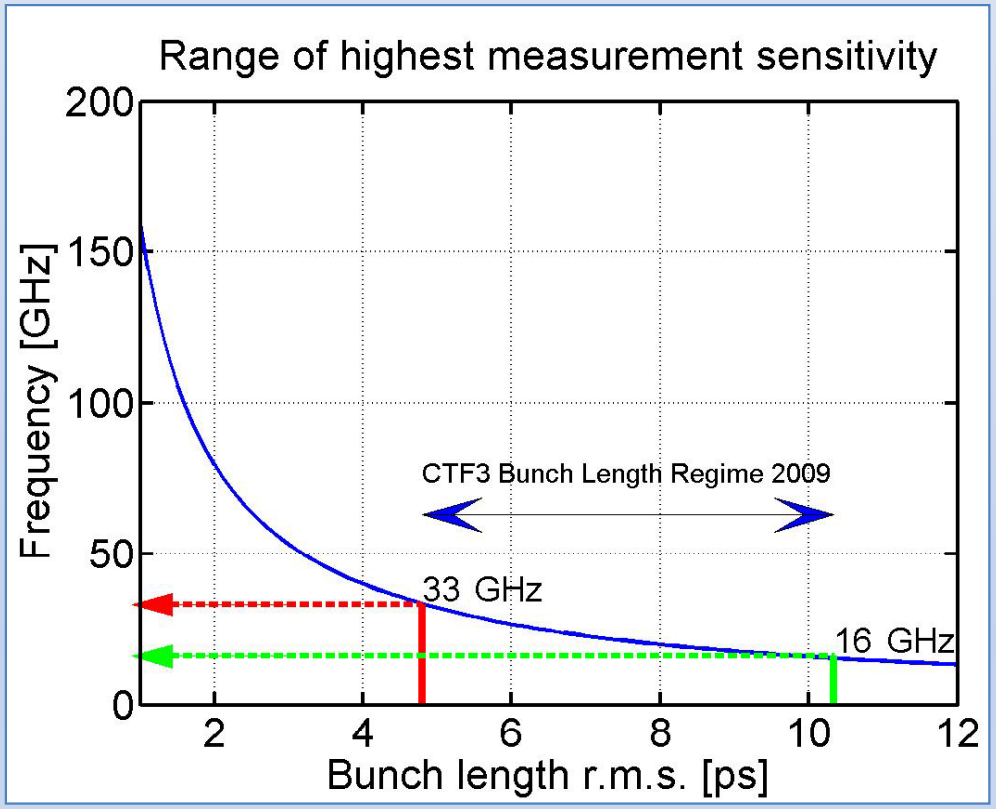


PAC07 proceedings:

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

CTF3 Microwave Spectroscopy – “RF pickup”





$$i_b(t) = \frac{q_b}{\sqrt{2\pi}\sigma_b}\exp\left(\frac{-t^2}{2\sigma_b{}^2}\right)$$

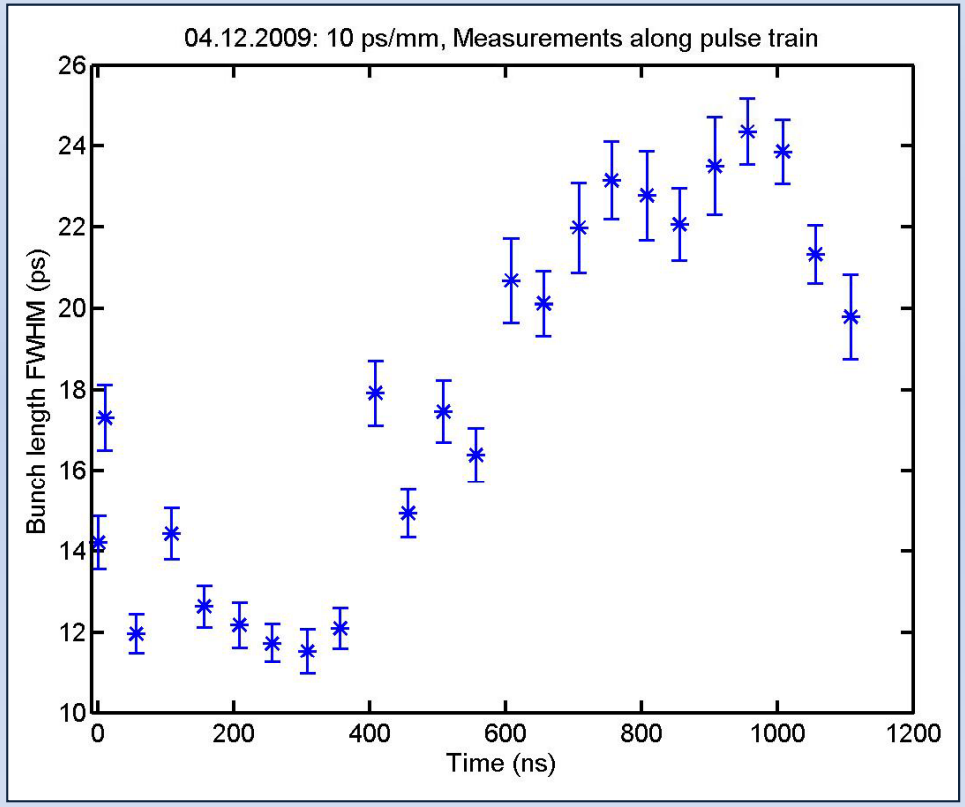
$$F_b(\omega) = \frac{q_b\sigma_b}{\sqrt{2\pi}}\exp\left(\frac{-\omega^2\sigma_b{}^2}{2}\right)$$

$$\frac{d^2F_b(\omega)}{d\omega^2} = 0 \quad \Rightarrow \quad \omega_{opt} = \frac{1}{\sigma_b}$$

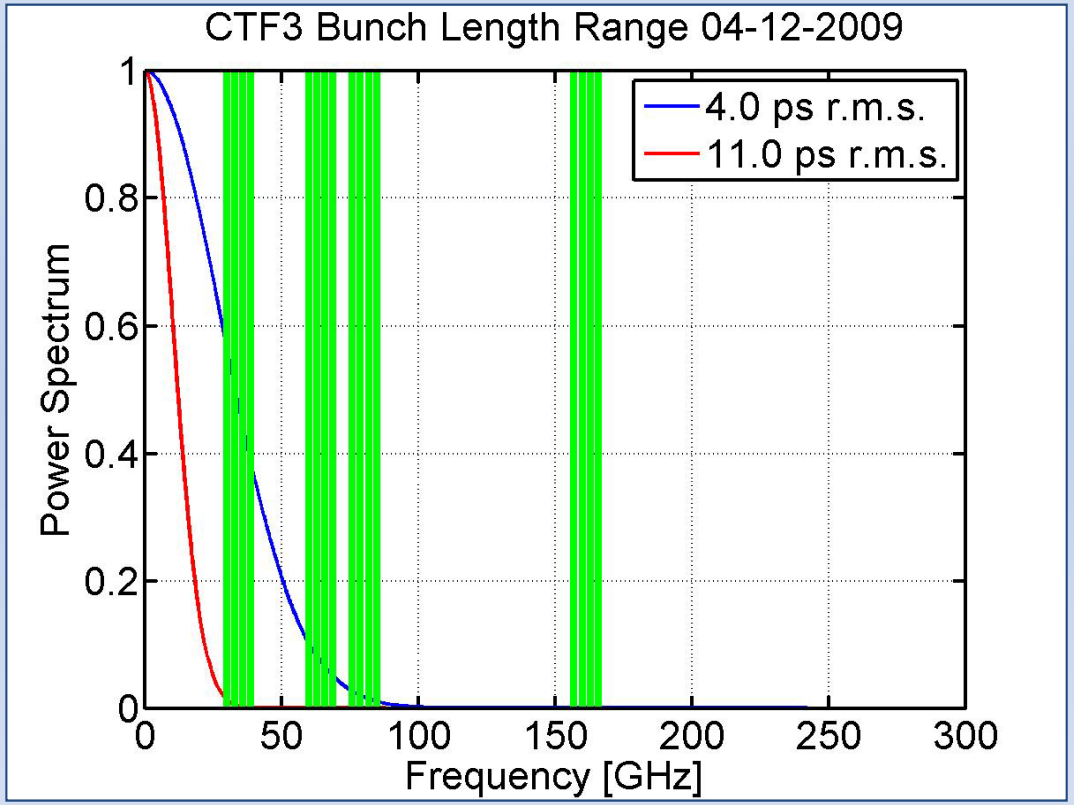
- For highest bunch length sensitivity
  - choose correctly the corresponding frequency band for measurement

Compare RF pickup (waveguide down mixing) to Streak

Bunch Length Measurement with Streak



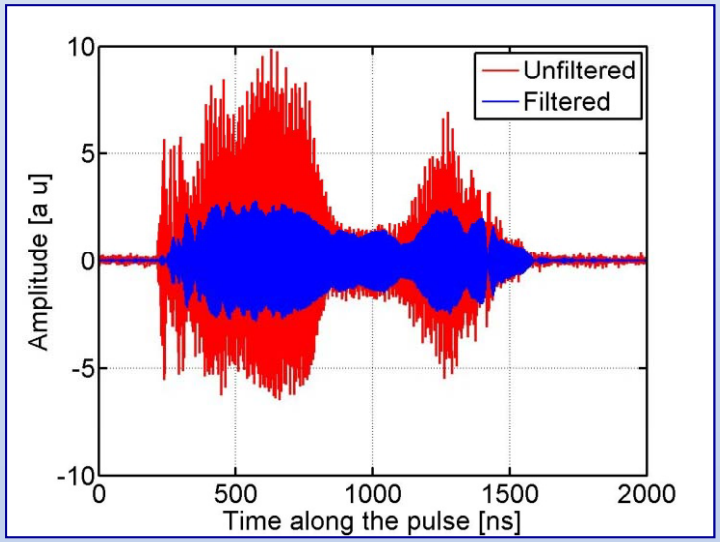
Corresponding power spectrum expected



Expect highest sensitivity in 30-39 GHz frequency band detectors

Similarly Compare RF pickup (down mixing) to Streak

Power measurement in time domain



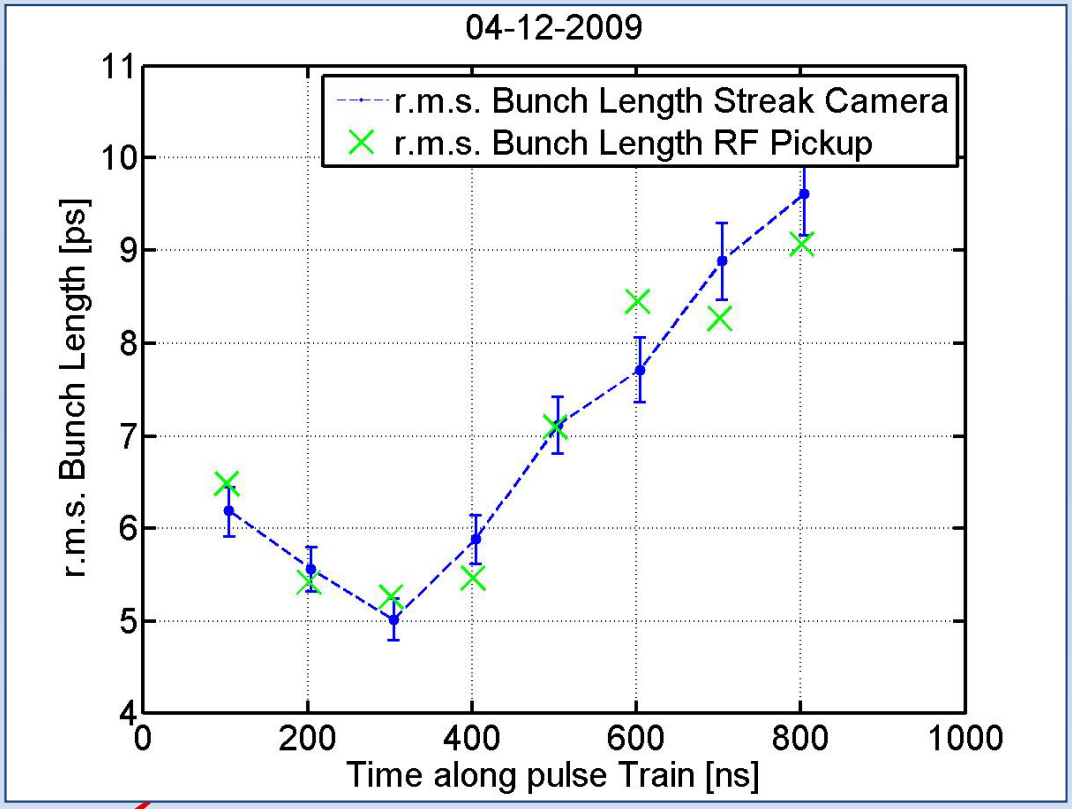
Corresponding Frequency domain

Apply Band pass filter to isolate beam signal

Correspond power (33 GHz) to bunch length Streak

Bunch length measurement along pulse train

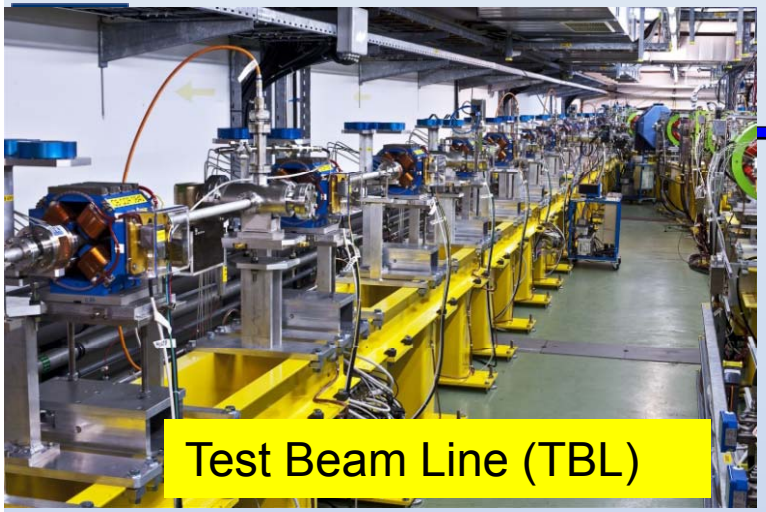
Calibrated RF-pickup 33 GHz form factor



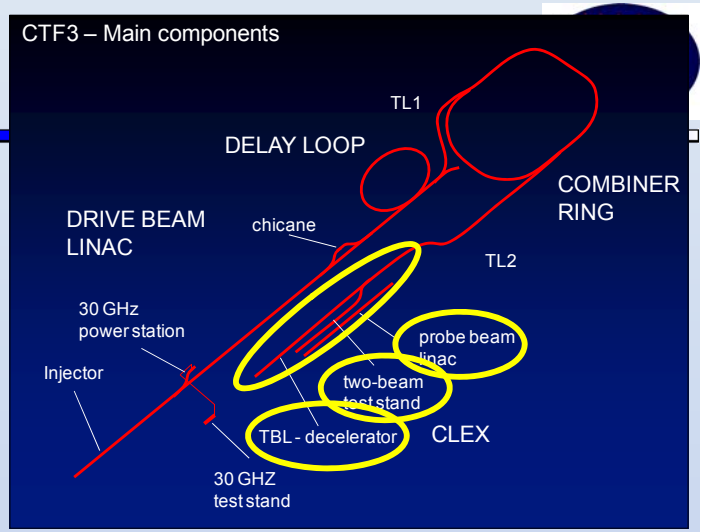
Good agreement between RF pickup and Streak in the Steady state part of the pulse

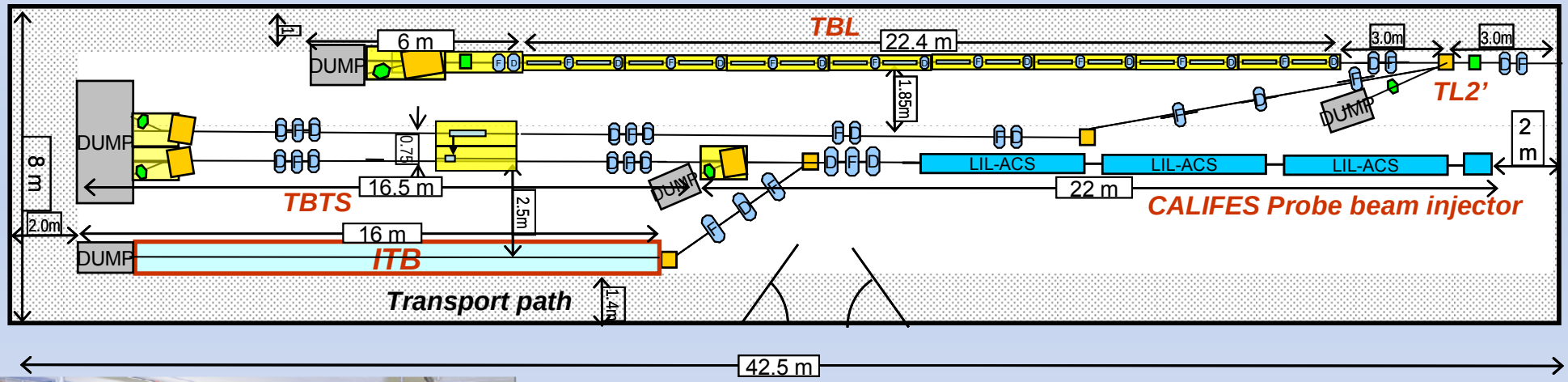
==> Must apply this calibration in 2010, and study systematics

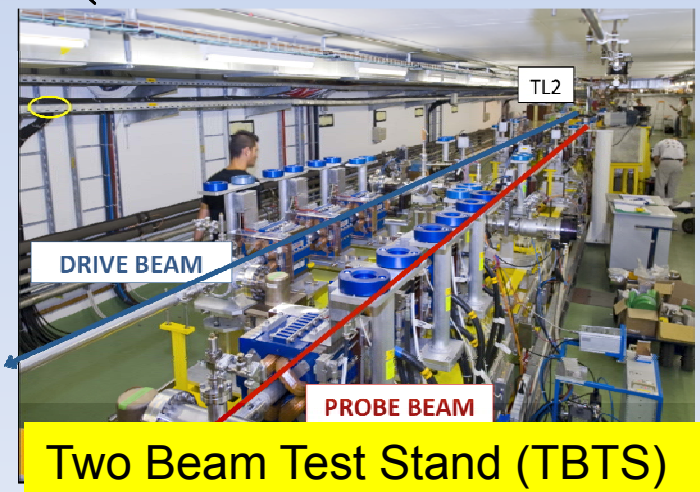
CLEX Area

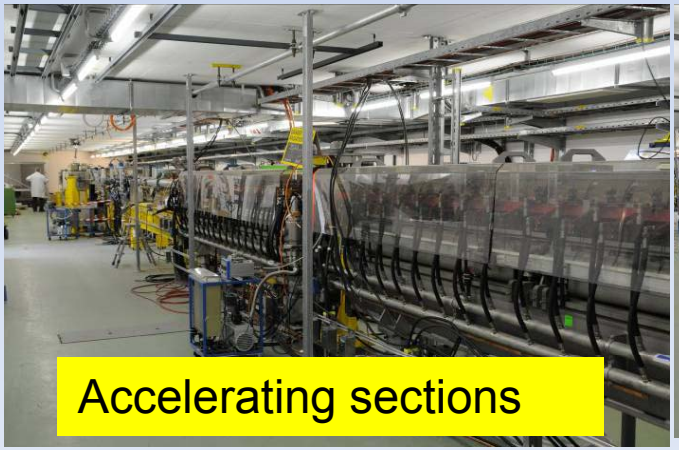


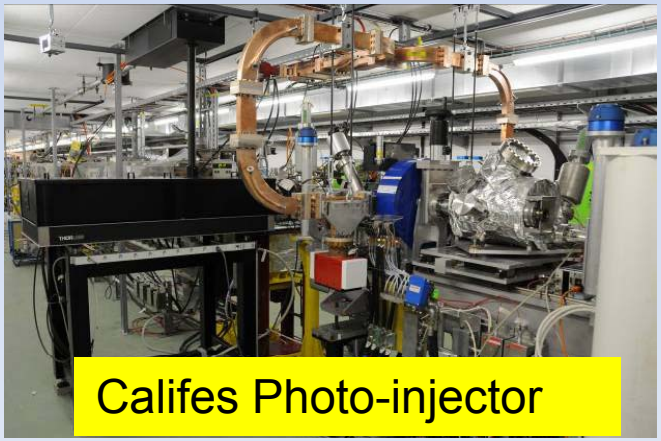
Bunch form factor input in power production simulations









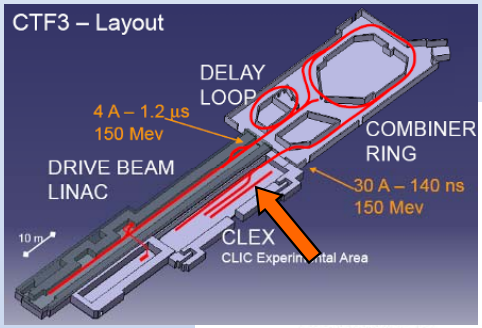


Bunch Length Measurement foreseen for CLEX - **2010**

- Long Optical lines and New Streak Lab for Streak Camera measurement in CLEX
  - ✓ FESCA200 Streak Camera (300 fs resolution) arrive in July 2010
  - ✓ 20 m optical line being designed
  - ✓ Special attention to longitudinal dispersion through lenses and air
  - ✓ Parabolic mirrors are being considered instead of achromatic lenses

- Non-destructive high frequency RF based bunch length monitoring measurement
  - ✓ High frequency Waveguides and diode components ordered (CTF3 & NWU)

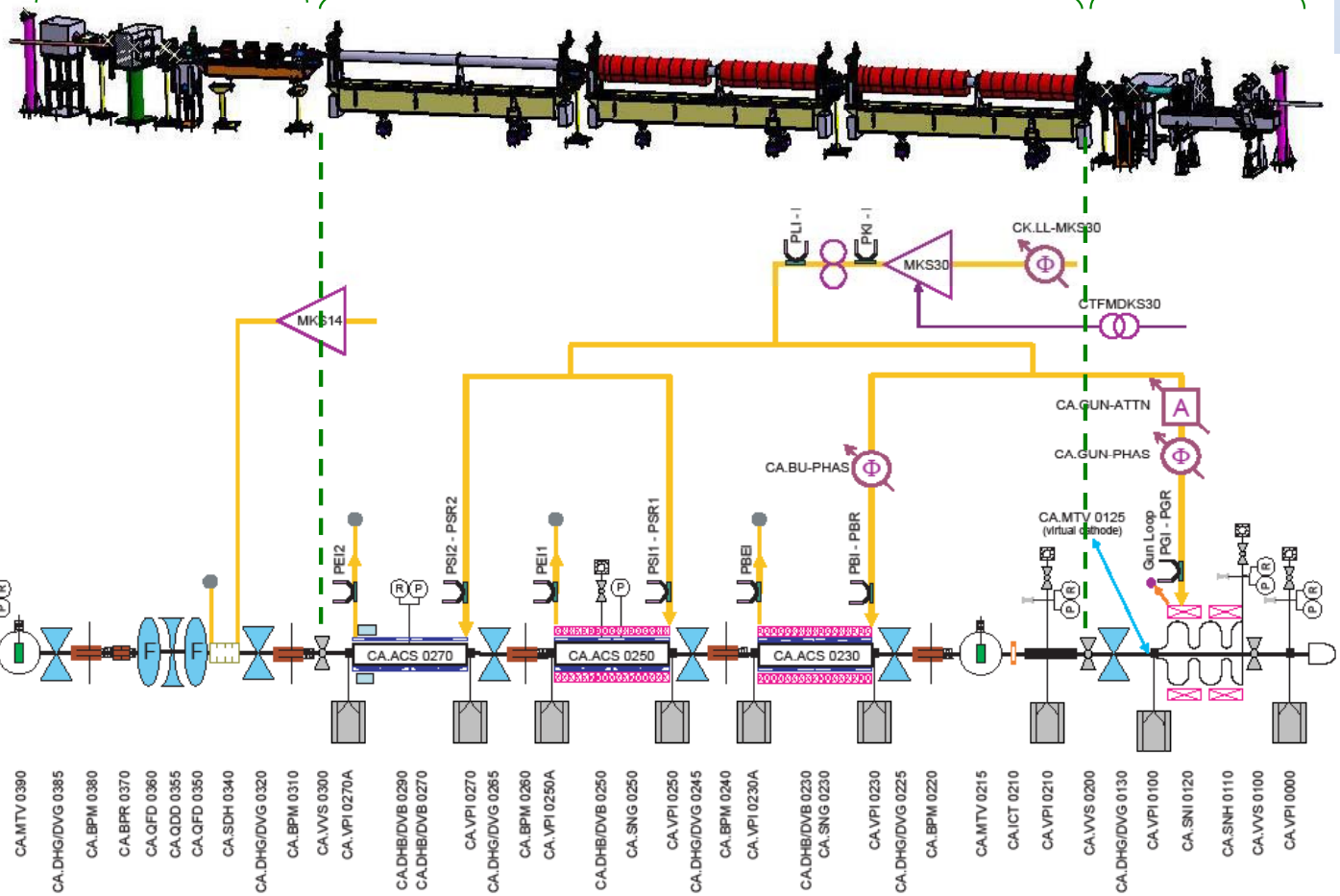
Short bunches – Photo-injector



Diagnostic section

Accelerating structure

Photo-injector



Diagnostics section

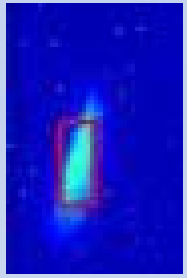
Accelerating sections

Califes Photo-injector

Measurement Examples

	CALIFES specifications	Obtained
Bunch charge	0.6 nC	0.25 nC
Energy	170 MeV	<144 MeV
Energy dispersion	± 2%	2%
Emittance	<20 π mm.mrad	21.3 π mm.mrad
Bunch train	1 – 32 – 226	any number from 1 to 226
Bunch spacing	0.667 ns	0.667 ns
Bunch length	**0.75 ps**	**1.42 ps**
repetition rate	5 Hz	5 Hz

.24 mm



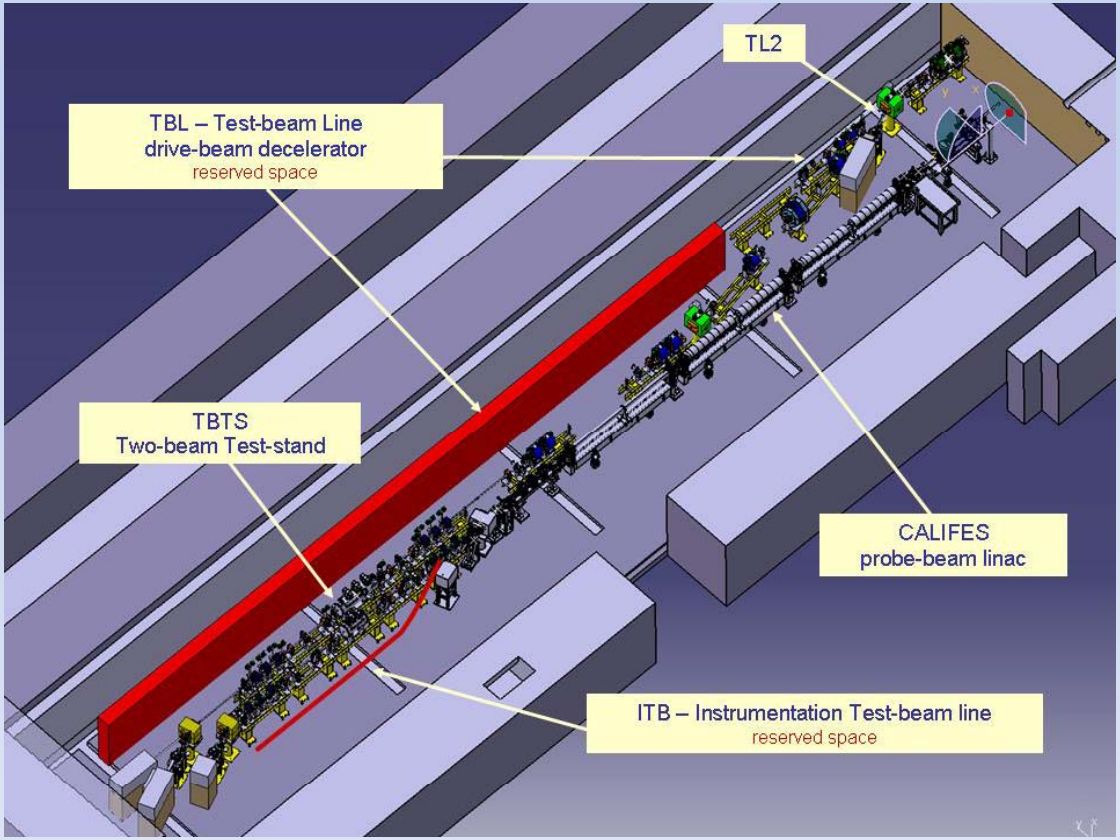
1.47 mm

Deflecting Cavity

obtained 1.42 ps
(without phase shifter)

Califes Beam for proposed ITB project

- ITB – Instrumentation Test Beam Line ➔ beam line extension of Califes proposed to test diagnostics
- Several institutes have shown interest for testing diagnostics with the CALIFES beam (RHUL, Uppsala University, LLR) and/or are ready to participate to the development of the ITB (CEA Saclay, Uppsala U.)
- CTF3 Accepting Instrumentation Test proposals ➔ to justify building the line



Califes status - Wilfrid Farabolini

Conclusions

- **CTF3 has commissioned diagnostics based on:**
  - Streak Camera
  - RF deflector
  - Integrated power spectrum techniques with schotty diodes (“BPRW”)
  - Power spectrum based on microwave spectroscopy (“RF-pickup”)
- **Robust Bunch Length Measurement** with Streak Camera
- **Calibration of non-destructive RF bunch length measurements allows operators to online tune the machine**
  - BPRW 21.5-40 GHz waveguide port
  - RF pickup
- Bunches in CTF3 during 2009 were long &bunch length variation along the pulse train:
  - Sub-pico second studies for RF pickup not possible (expectations for 2010)
  - Integrated and time dependent measurements need to be correctly compared
- **Design** of bunch length measurement for CLEX **has started**
  - Long Optical lines to New Streak Camera Lab with new FESCA 200 Streak Camera
  - Non destructive RF based bunch length measurement techniques
- Bunch length measurements started on **Califes** – 1.4 ps ➔ should be **0.75 ps** once new phase shifter is commissioned
- **Test Beam line (TBL)** could offer a place for interesting sub-pico second bunch diagnostics testing