# Longitudinal Diagnostics for CLIC

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Significant input from T. Lefevre, A. Gillespie, S. Jamison, P. Karataev

# Outline

- Overview of CLIC bunch length diagnostics requirements
- Selection of instrumentation choices, what, where and why?

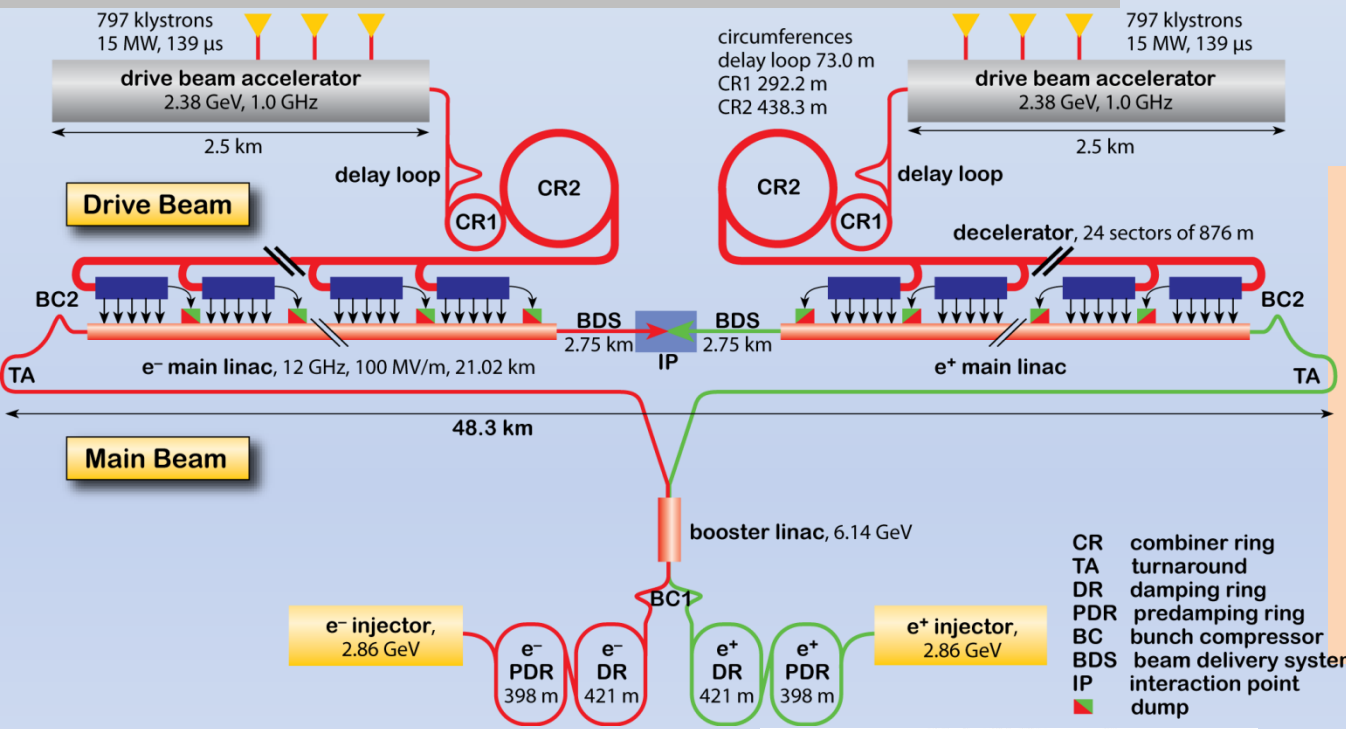
| Machine sub-system | No. | Technology choice | Tested @ |
|---|---|---|---|
| Main Beam | | | |
| E-&e+ injector complex | 10 | Streak / RF pickup | CTF3 |
| Pre-Damping and Damping rings | 4 | Streak / RF pickup | CTF3 |
| RTML | 12 | **EOS** / **CDR** | XFEL's |
| Main Linac and Beam Delivery system | 50 | **CDR** | XFEL's |
| Drive Beam | | | |
| DB source and Linac | 8 | Streak / RF pickup | CTF3 |
| Frequency multiplication complex | 16 | Streak / RF pickup | CTF3 |
| Transfer to tunnel | 4 | RF pickup | CTF3 |
| Turn-arounds | 192 | Streak / RF pickup | CTF3 |
| Decelerator and Dump lines | 96 | RF pickup | CTF3 |

- Bunch Length R&D needed in the context of CLIC

# Layout CLIC 3 TeV Complex

## Drive beam complex: 4mm - 1mm

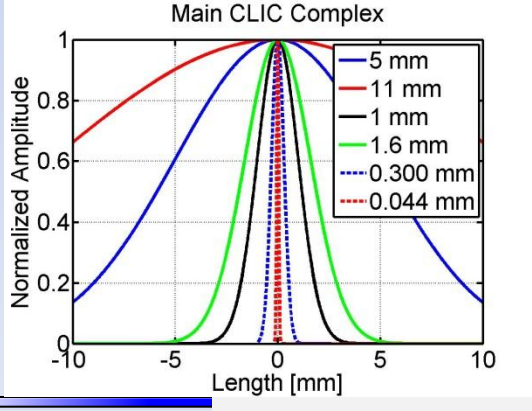
— CTF3 like, except total charge and energy increase

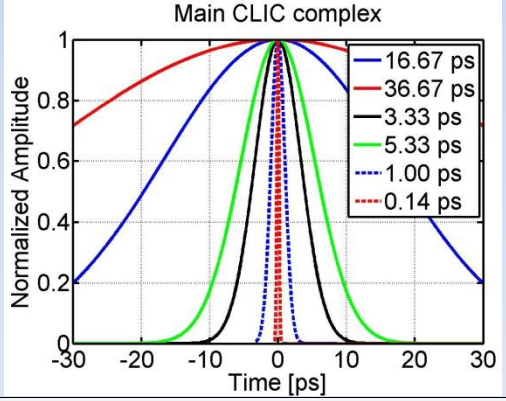


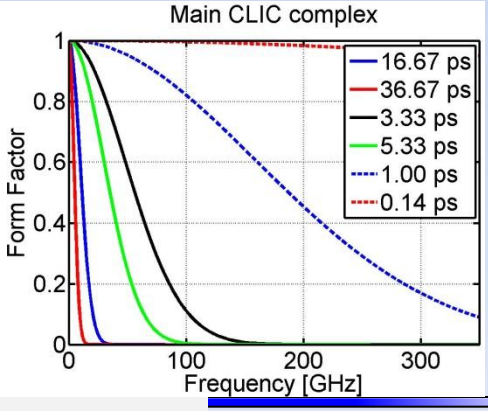

## Main beam complex: 11mm – 0.044mm

—Injector CTF3 like

—Bunch compressors and main linac more XFEL like except higher total charge, energy 2.8 GeV - 1.5 TeV, and bunch train compared to single bunch



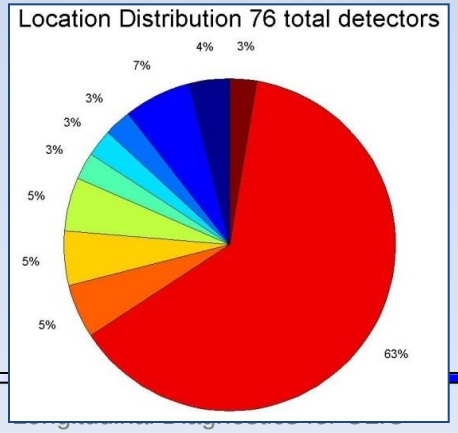



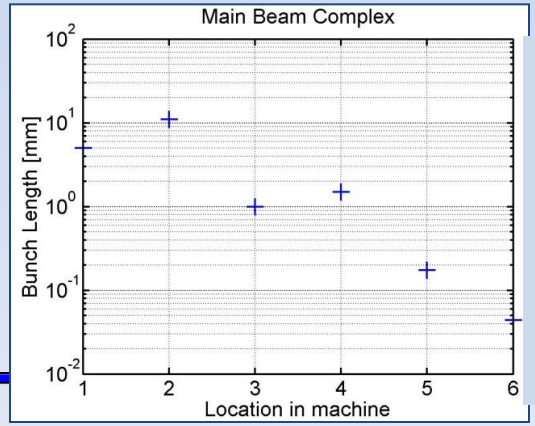




Plot Gaussian bunches, gross over simplification, but relevant to show order of magnitudes

# CLIC main beam complex requirement

| Machine Sub-Systems | Bunch length (mm) | Energy (GeV) | Resolution Bunch(ps) / Train(ns) | Quantity | Charge density ($nC/cm^2$) |
|---|---|---|---|---|---|
| $e^-$ injector Complex | 5 | → 0.2 | 2 / 10 | $3^P$ | $< 5\ 10^5$ |
| $e^+$ injector Complex | 11 | → 0.2 | 5 / 10 | $5^P$ | $< 5\ 10^5$ |
| Injector Linac ($e^-/e^+$) | 1 / 5 | → 2.86 | 0.5 /10 | $2^P$ | $< 5\ 10^5$ |
| Pre-Damping Rings (H/V) | 5 | 2.86 | 2 / 10 | $2^P$ | $< 5\ 10^6$ |
| Damping rings (H/V) | 1.6 | 2.86 | 0.5 /10 | $2^P$ | $< 5\ 10^8$ |
| **RTML** | | | | | $< 5\ 10^8$ |
| - Bunch compressors 1 | 0.300 | 2.86 | 0.1 /10 | $4^P$ | |
| - Booster Linac | 0.300 | 2.86 → 9 | 0.1 / 10 | 0 | |
| - Transfer lines - Turn arounds | 0.300 | 9 | 0.1 / 10 | 4 | |
| - Bunch compressor 2 | 0.044 | 9 | 0.02 / 10 | $4^P$ | |
| Main Linac | 0.044 | 9 →1500 | 0.02 / 10 | $48^L$ | $< 5\ 10^8$ |
| Beam Delivery System | 0.044 | 1500 | 0.02 / 10 | $2^P$ | $< 5\ 10^8$ |

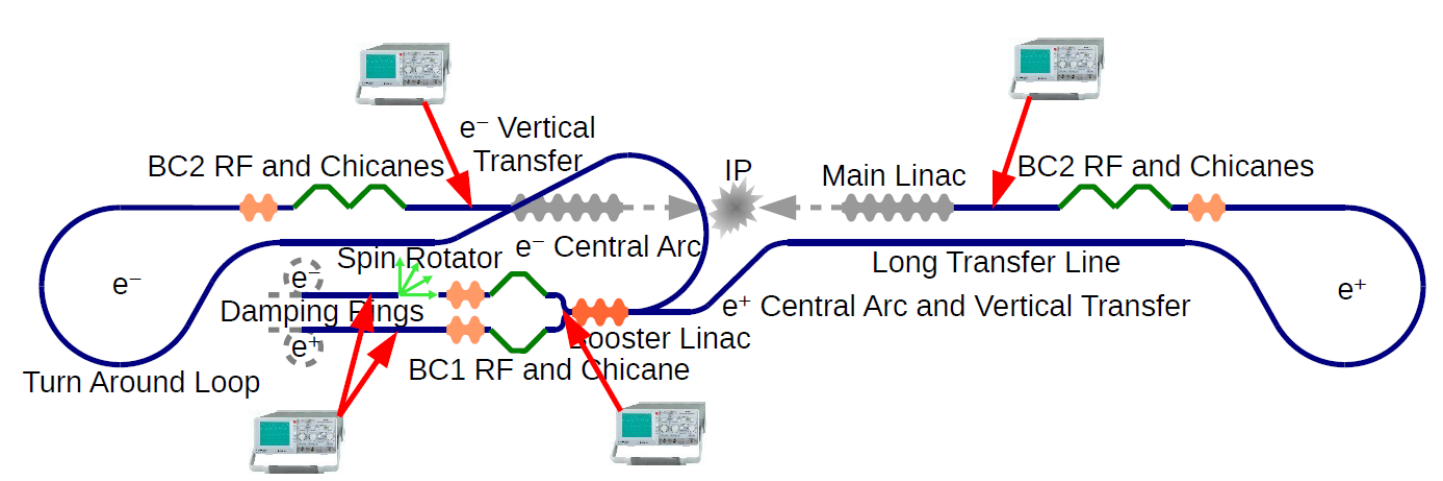



- Bunch profile (P) required whenever longitudinal phase space is manipulated (Bunch compressor)
- r.m.s. profile (L) needed for purpose of monitoring stability

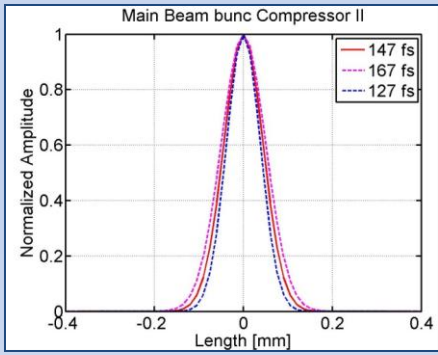
# Bunch Length Manipulation Main Beam

0.044 mm



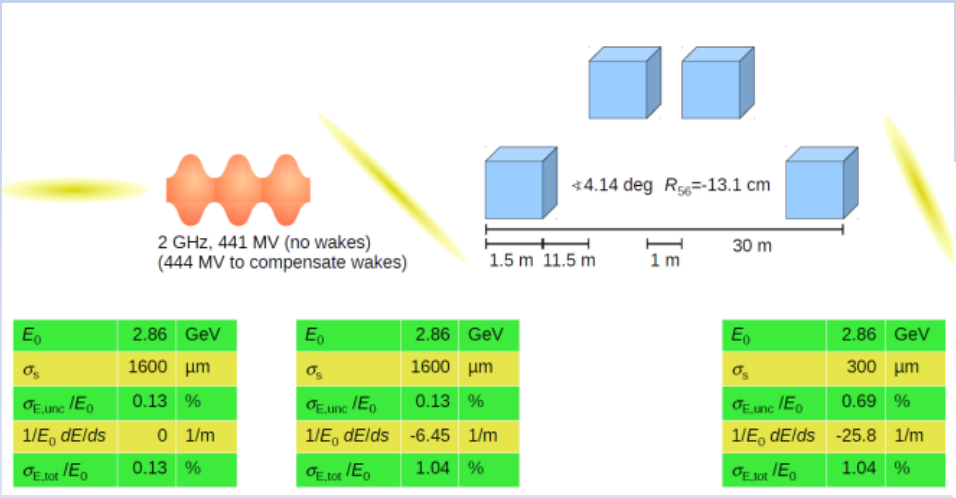

RTML diagnostics needs

F. Stulle




1.6 mm

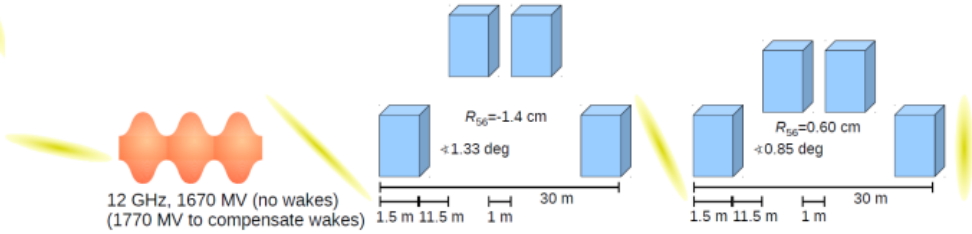
0.300 mm




| | | |
|---|---|---|
| $E_0$ | 2.86 | GeV |
| $\sigma_s$ | 1600 | µm |
| $\sigma_{E,unc}/E_0$ | 0.13 | % |
| $1/E_0\ dE/ds$ | 0 | 1/m |
| $\sigma_{E,tot}/E_0$ | 0.13 | % |

| | | |
|---|---|---|
| $E_0$ | 2.86 | GeV |
| $\sigma_s$ | 1600 | µm |
| $\sigma_{E,unc}/E_0$ | 0.13 | % |
| $1/E_0\ dE/ds$ | -6.45 | 1/m |
| $\sigma_{E,tot}/E_0$ | 1.04 | % |

| | | |
|---|---|---|
| $E_0$ | 2.86 | GeV |
| $\sigma_s$ | 300 | µm |
| $\sigma_{E,unc}/E_0$ | 0.69 | % |
| $1/E_0\ dE/ds$ | -25.8 | 1/m |
| $\sigma_{E,tot}/E_0$ | 1.04 | % |




| | | |
|---|---|---|
| $E_0$ | 9 | GeV |
| $\sigma_s$ | 300 | µm |
| $\sigma_{E,unc}/E_0$ | 0.22 | % |
| $1/E_0\ dE/ds$ | -8.21 | 1/m |
| $\sigma_{E,tot}/E_0$ | 0.25 | % |

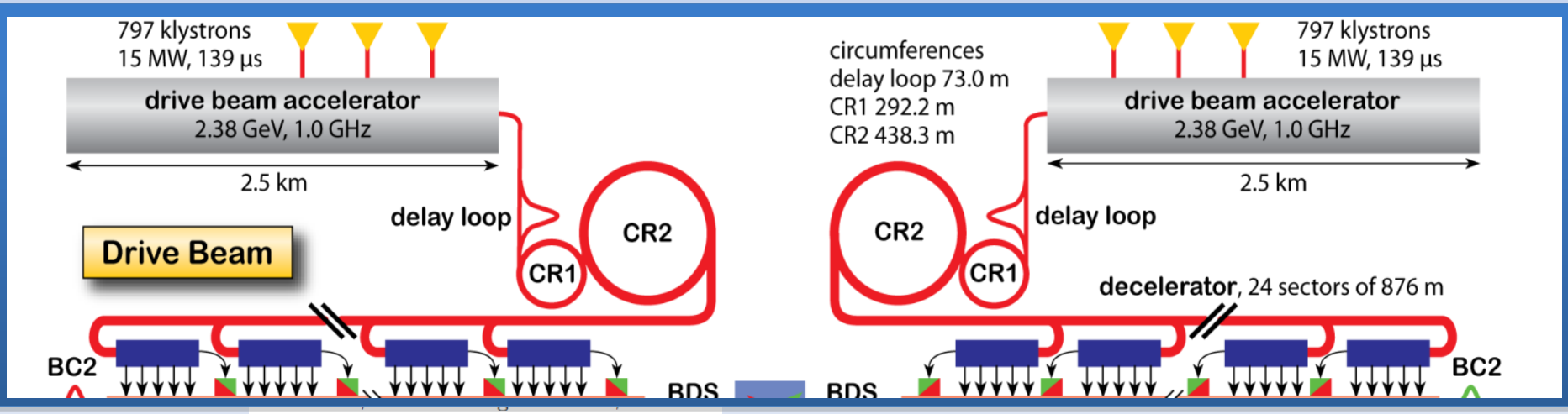
| | | |
|---|---|---|
| $E_0$ | 9 | GeV |
| $\sigma_s$ | 300 | µm |
| $\sigma_{E,unc}/E_0$ | 0.22 | % |
| $1/E_0\ dE/ds$ | -49.5 | 1/m |
| $\sigma_{E,tot}/E_0$ | 1.14 | % |

| | | |
|---|---|---|
| $E_0$ | 9 | GeV |
| $\sigma_s$ | 100 | µm |
| $\sigma_{E,unc}/E_0$ | 0.66 | % |
| $1/E_0\ dE/ds$ | -135 | 1/m |
| $\sigma_{E,tot}/E_0$ | 1.14 | % |

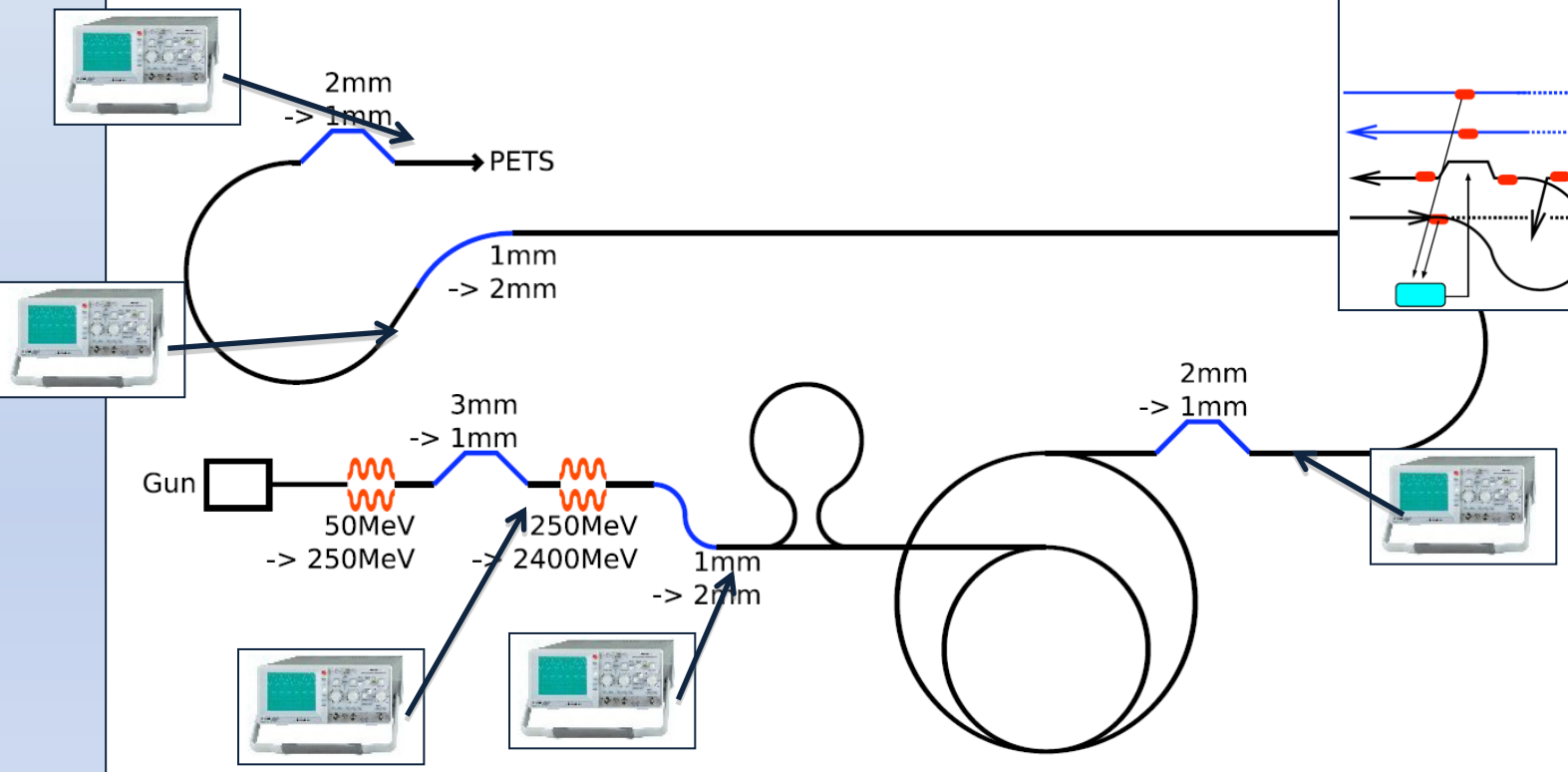
| | | |
|---|---|---|
| $E_0$ | 9 | GeV |
| $\sigma_s$ | 44 | µm |
| $\sigma_{E,unc}/E_0$ | 1.6 | % |
| $1/E_0\ dE/ds$ | 0 | 1/m |
| $\sigma_{E,tot}/E_0$ | 1.6 | % |

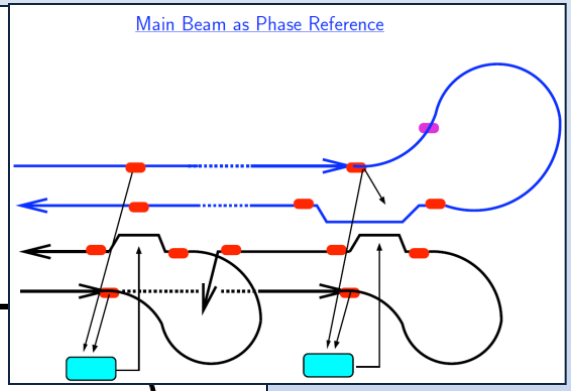
# CLIC Drive beam complex requirement

| Machine Sub-System | Bunch length (mm)/Spacing (GHz) | Energy (GeV) | Resolution Bunch (ps)/ Train (ns) | Quantity | Charge density ($nC/cm^2$) |
|---|---|---|---|---|---|
| Source and Linac | 4 / 0.5 | → 2.37 | 1 / 10 | 8 | < 40 $10^6$ |
| Frequency Multiplication<br>-Delay Loops – CR2 | 2 / (0.5 → 12) | 2.37 | 1 / 10 | 15 | < 40 $10^6$ |
| Transfer to Tunnel | 2 / 12 | 2.37 | 1 / 10 | 4 | < 40 $10^6$ |
| Turn arounds<br>- Bunch Compressor 1<br>- Turn-arounds<br>- Bunch Compressor 2 | 2 / 12<br>1.4 / 12<br>1 / 12 | 2.37 | 0.5 / 10 | 96 P<br>0<br>96 P | < 1.5 $10^6$ |
| Decelerator | 1 /12 | < 2.37 | 0.5 / 10 | 48 L | > 1.5 $10^6$ |
| Dump lines | 1 / 12 | < 2.37 | 0.5 / 10 | 48 L | > 1.5 $10^6$ |



# Drive Beam Compression and Phase Stabilisation Concept




- Early compression allows large energy chirp $\Rightarrow$ small $R_{56}$ $\Rightarrow$ larger energy tolerance

$\Rightarrow$ Energy error tolerance: $1.5 \times 10^{-4}$, gradient tolerance $1.5 \times 10^{-5}$, current tolerance $3 \times 10^{-5}$, phase tolerance $0.02^{\circ}$ at $1\,\mathrm{GHz}$

D. Schulte, CLIC Meeting October 8, 2010 8

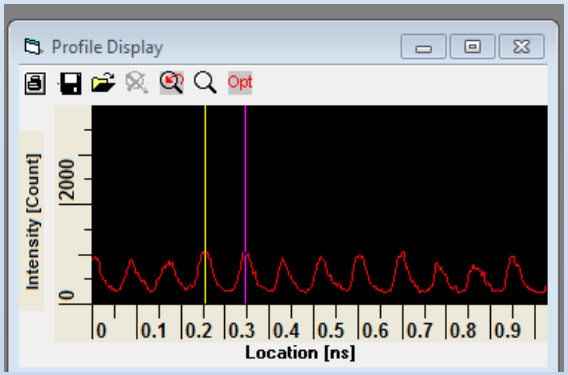
# Technology choices – Streak Camera

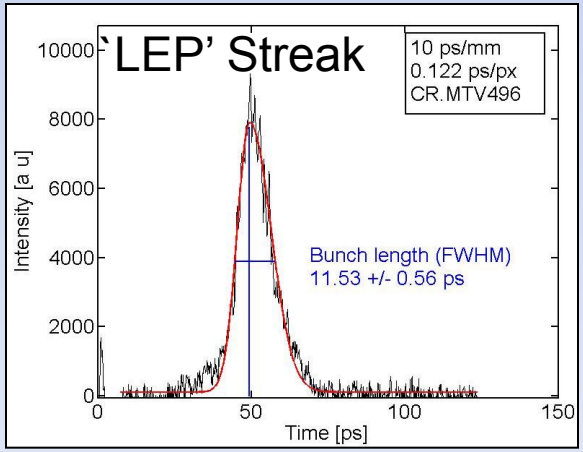
| Machine sub-system | No. | Technology choice | Tested @ |
|---|---|---|---|
| Main Beam | | | |
| E-&e+ injector complex | 10 | Streak / RF pickup | CTF3 |
| Pre-Damping and Damping rings | 4 | Streak / RF pickup | CTF3 |
| RTML | 12 | EOS / CDR | XFEL's |
| Main Linac and Beam Delivery system | 50 | CDR | XFEL's |
| Drive Beam | | | |
| DB source and Linac | 8 | Streak / RF pickup | CTF3 |
| Frequency multiplication complex | 16 | Streak / RF pickup | CTF3 |
| Transfer to tunnel | 4 | RF pickup | CTF3 |
| Turn-arounds | 192 | Streak / RF pickup | CTF3 |
| Decelerator and Dump lines | 96 | RF pickup | CTF3 |

- Provide up to 300 fs resolution
- Non-destructive if coupled to synchrotron light from the chicanes / rings
- Single shot bunch length measurement (move trigger trigger to get bunch length along the train)
- Can also provide bunch spacing measurements (at the sacrifice of time resolution)
- Require long optical line design to measure outside radiation environment

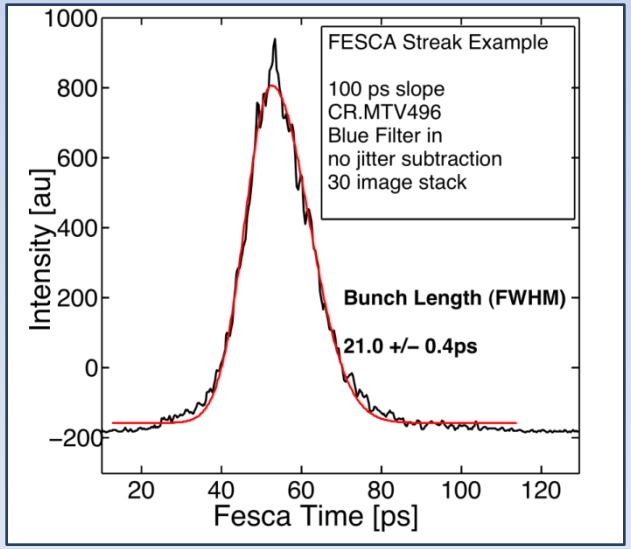
# Technology choice – Streak Camera

- CTF3 experience
  - 2/3 ps resolution with old “LEP” camera
  - expect > 300 fs with FESCA camera for short bunches
- Error contributions:
  - Timing calibration of sweep slope (resolution streak tube)
  - Jitter streak trigger (removed if single shot)
  - size in focus (slit)
  - Error from fit
  - Space charge photocathde
  - Long optical lines, longitudinal dispersion & chromatic effects ➔ use narrow-band optical filter
- Synchro-scan features allow bunch length monitoring turn by turn in rings (used in light sources)
- Can be used to cross-calibrate RF devices




Arbitrary examples from CTF3



# Technology choice – "RF pickups"

| Machine sub-system | No. | Technology choice | Tested @ |
|---|---|---|---|
| Main Beam | | | |
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| RTML | 12 | EOS / CDR | XFEL's |
| Main Linac and Beam Delivery system | 50 | CDR | XFEL's |
| Drive Beam | | | |
| DB source and Linac | 8 | Streak / RF pickup | CTF3 |
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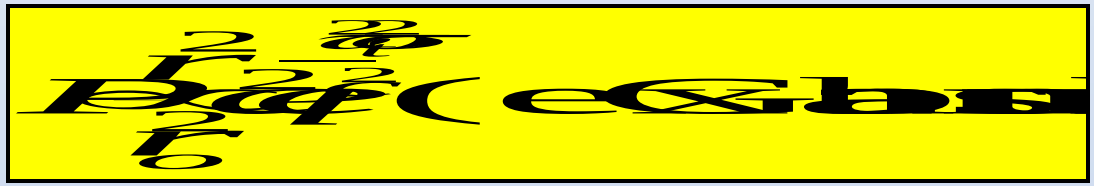
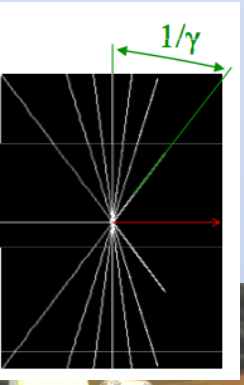
| Transfer to tunnel | 4 | RF pickup | CTF3 |
| Turn-arounds | 192 | Streak / RF pickup | CTF3 |
| Decelerator and Dump lines | 96 | RF pickup | CTF3 |

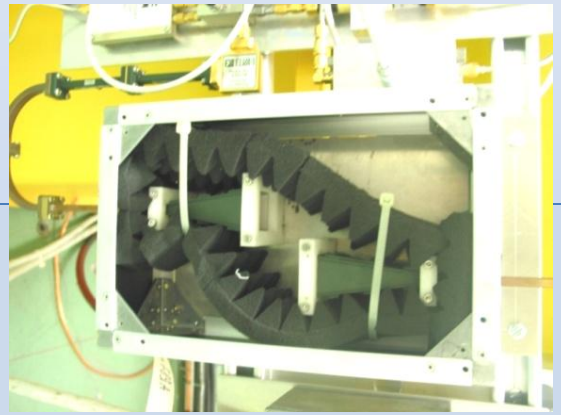
- Measure the power of the direct EM field of the beam, picked-up by a waveguide pickup
- Easy to implement in machine, and non-invasive
- Single-shot bunch length measurement along the pulse train
- D-band waveguide devices allow bunch length reach ~ 300 fs
- Require cross-calibration with another device – since transfer function of the pickup difficult to acquire from simulation
- Based on single diodes or down-mixing techniques for better resolution

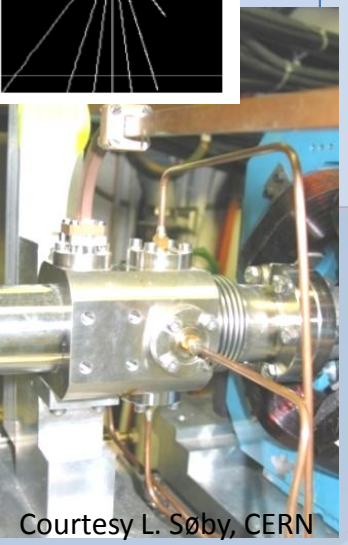
# “RF pickups” Tested @ CTF3 - BPRW



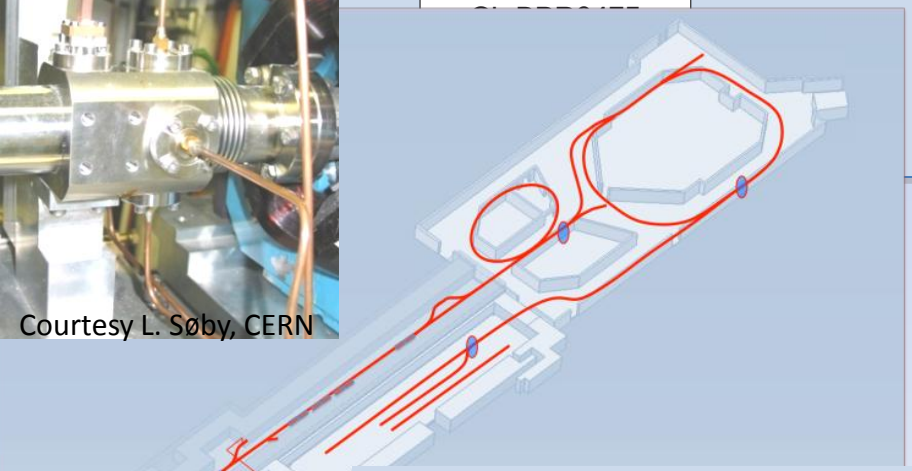


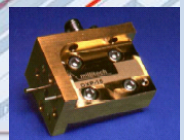

Measure directly EM field of passing bunch

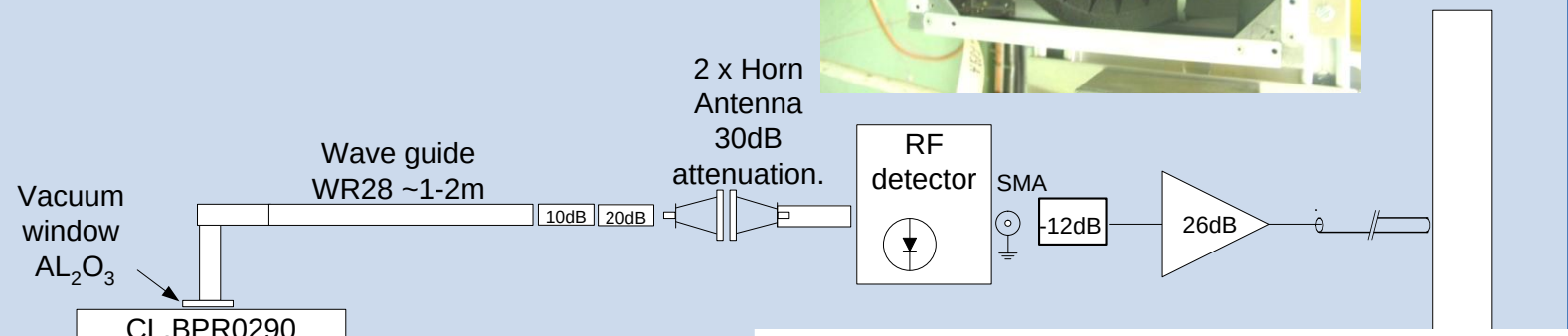




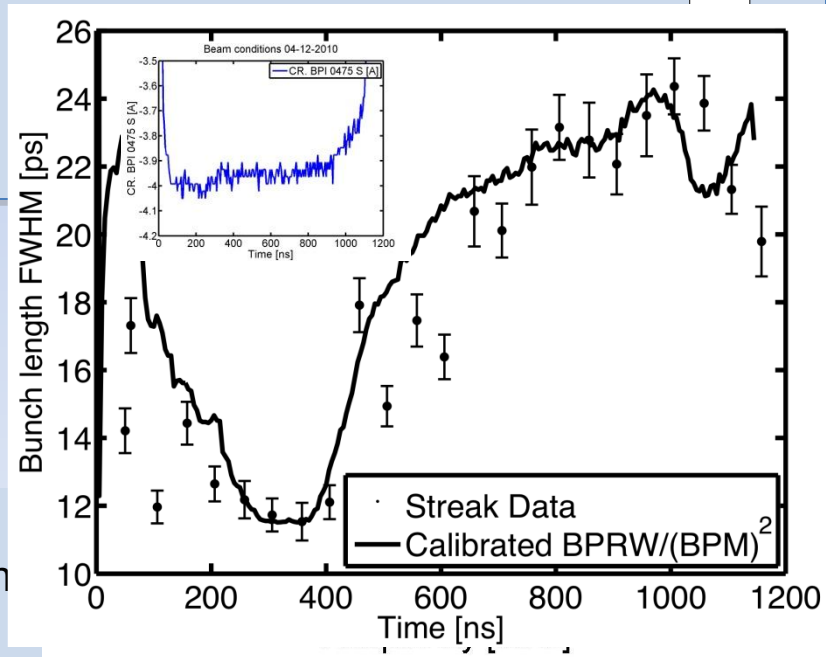
Courtesy L. Søby, CERN



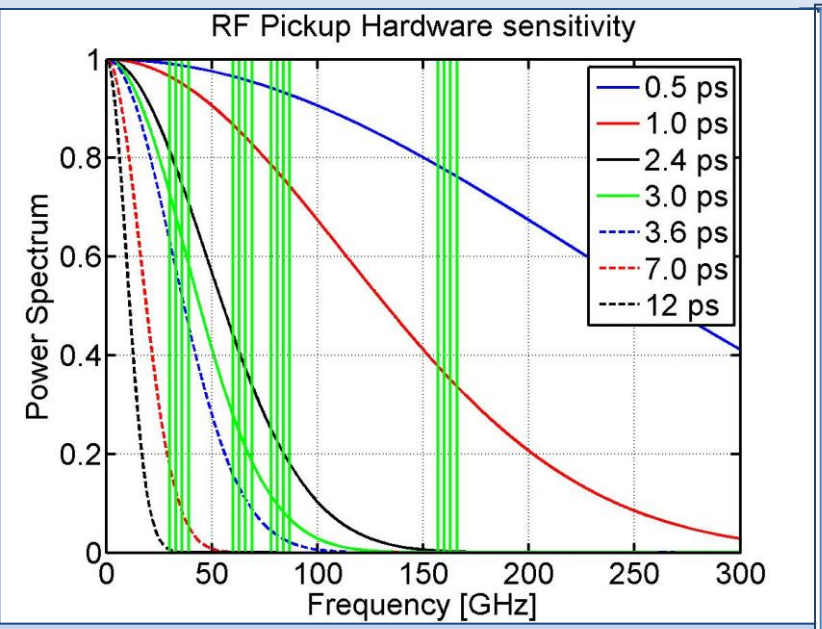


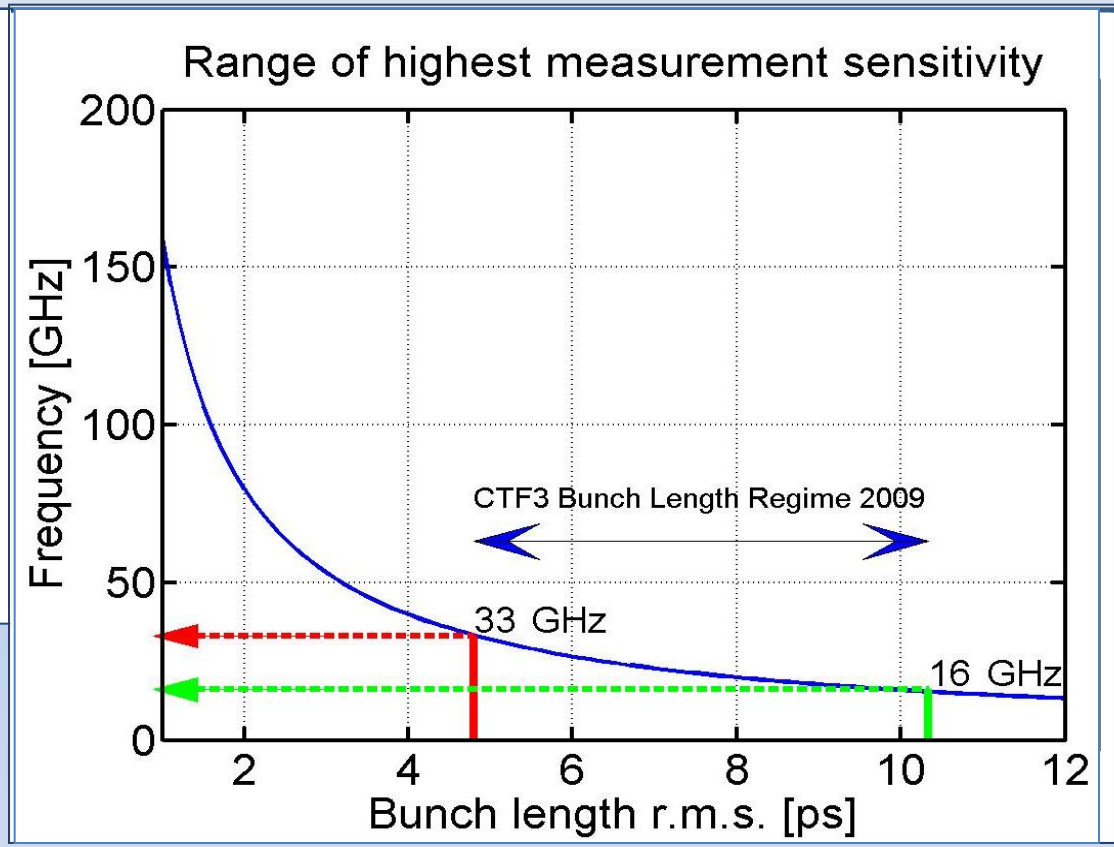



- Connected to 100Ms/s ADC
- Detector typically 1 GHz bandwidth
- Diode linear response with power



# “RF pickups” Tested @ CTF3 – microwave spectrometer




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

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

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

- Measure the power of frequency harmonics
- Self – calibrating if bunch length scan is performed
- Sensitive to bunch envelope **and** the relative position of bunches with the bunch train (down-mixing)

Refer: CTF3 instrumentation talk WG-6 this afternoon

# Technology choice – Coherent Diffraction Radiation

| Machine sub-system | No. | Technology choice | Tested @ |
|---|---|---|---|
| Main Beam | | | |
| E-&e+ injector complex | 10 | Streak / RF pickup | CTF3 |
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- No intrinsic resolution limit
- Operate target at high impact parameter - non-interceptive
- Single shot measurement possible – if use grating spectrometer
- Measure bunch length evolution along the pulse train

# Technology choice – Coherent Diffraction Radiation

Principle: bunch length / shape dependent emission of coherent radiation

$$S(\omega) = [N_e + N_e(N_e - 1)F(\omega)]S_e(\omega)$$

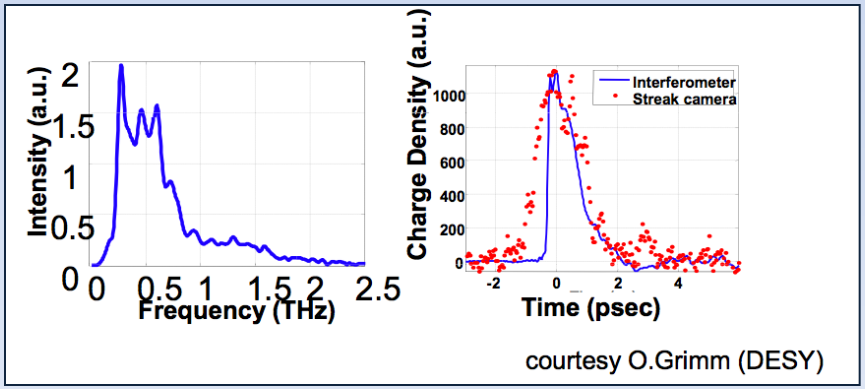
Reconstruction of the form factor, based on Kramers-Kronig approximation

$$\rho^2(k) = \frac{S_{coh}(k)}{N_e^2 S_e(k)}, k = \omega / c;$$

$$S_{coh}(k) = \text{Experimentally measured CDR spectrum}$$

$$\rho^2(k) = \text{bunch form factor}$$

$$S_e(k) = \text{single electron spectrum}$$

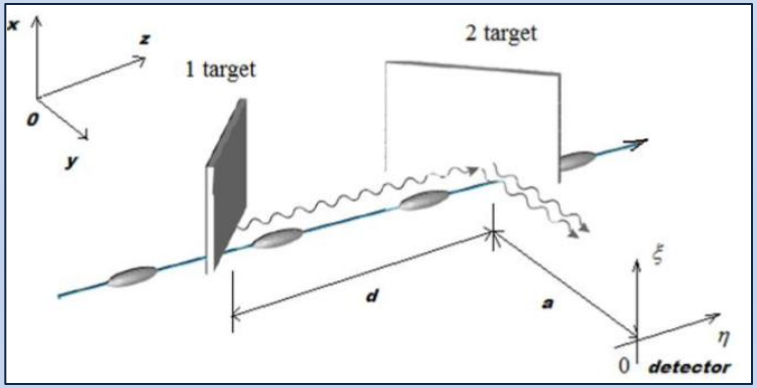


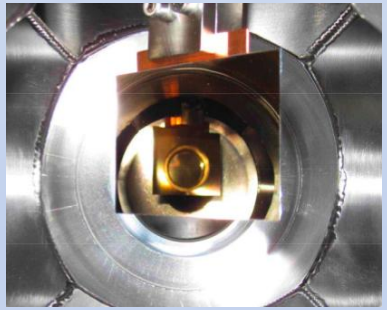

Example:
Using coherent synchrotron radiation and the spectrum measured with a Martin – Puplett interferometer, compared to streak camera

Kube, CAS 2008,
O. Grimm PAC07

# Technology choice – Coherent Diffraction Radiation

- 62 detectors required for CLIC
- 20 fs resolution on the r.m.s. of the 147 ps bunch length required
- Collaboration between CERN and group of **Pavel Karatev, Royal Holloway, Univ. of London** to develop a high resolution, non-destructive, cost effective CDR detector to be tested at CTF3




- Concept based on 2 targets, eliminate coherent background and to compensate for any kick due to wake fields
- Full single bunch emission simulations using ACE3P code T3P
- High impact parameter (non-destructive)
- R&D into developing a broadband, room-temperature and highly sensitive Schottky Barrier Detector
- Pyroelectric detector also under test for interferometric measurements
- Grating spectrometer being considered

R&D updates, see talk Konstantin Lekomtev WG6 this afternoon

# Technology choice – Electro-optical detectors

| Machine sub-system | No. | Technology choice | Tested @ |
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| Main Beam | | | |
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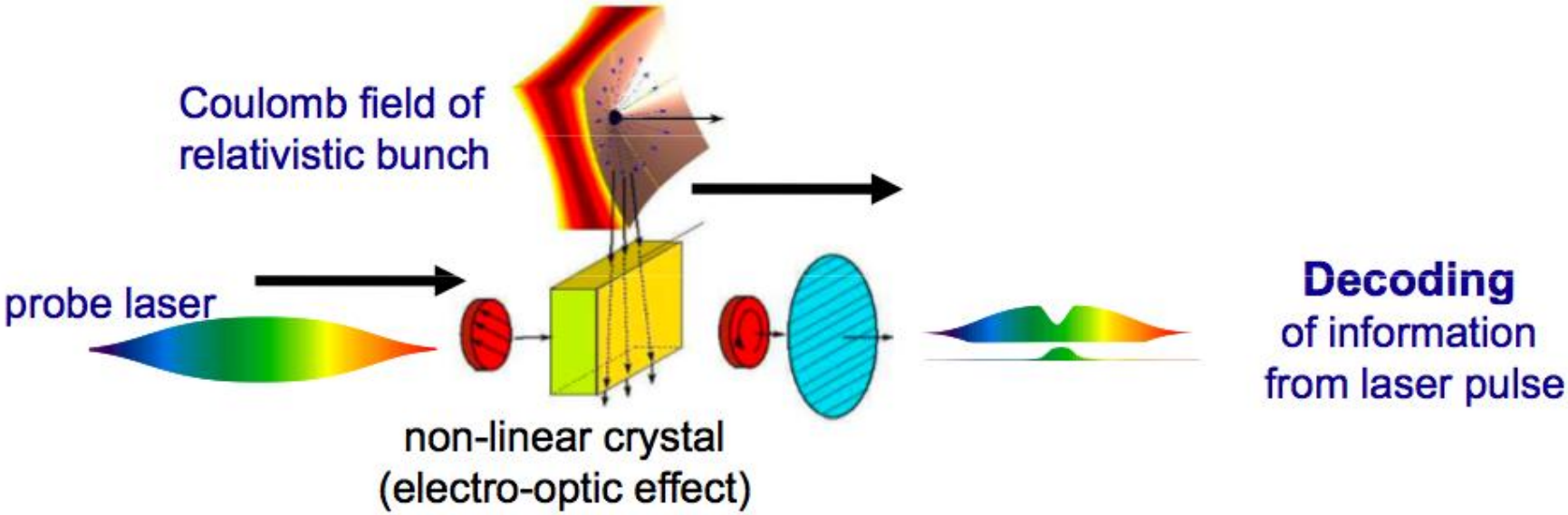
- Single-shot, non-destructive, longitudinal profile (and arrival time monitor), cover necessary bunch profile measurement range 1000fs–150fs
- See r.m.s differences of 150 Δ20 fs (BCII)
- Do you need this for a feedback loop? High repetition rate? Single bunch or bunch train? This should be clarified by beam dynamics to narrow technology choices

# Physics electro-optical detectors




## Encoding

- same for all techniques
- limiting factor for high time resolution techniques

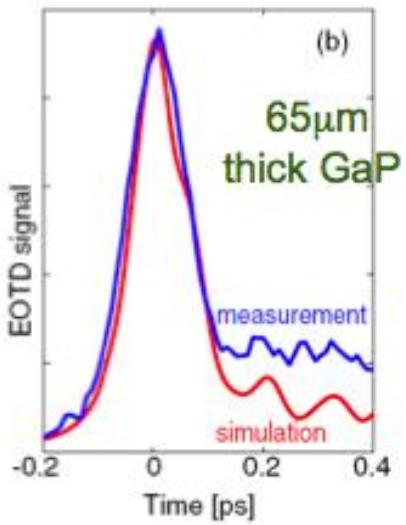
## Decoding

- choices for complexity
- limiting factor for spectral decoding

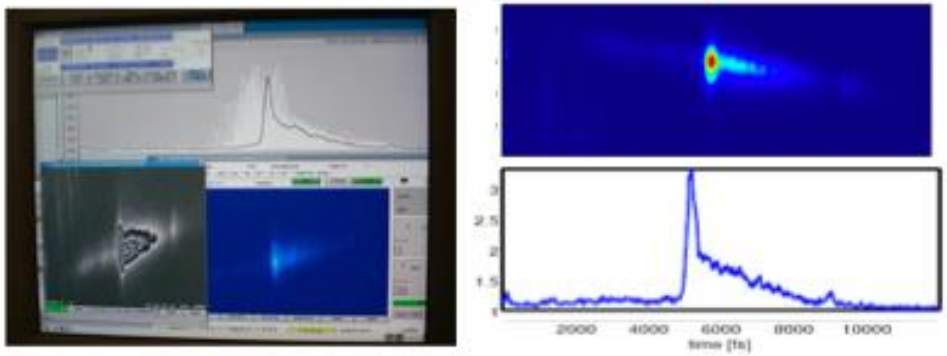
# Electro-optical detector used for feedback

## Electro-optic experiments on FLASH

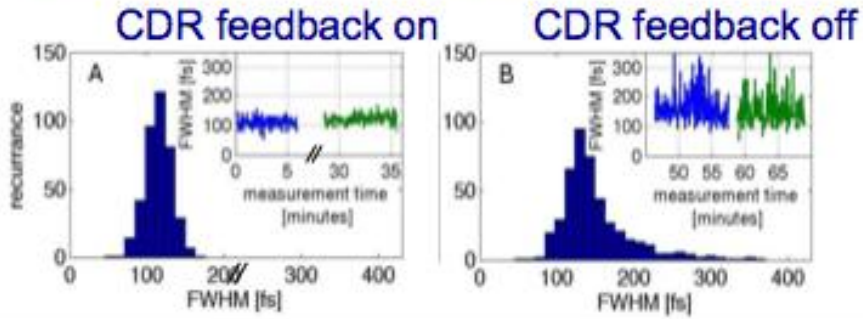
high time resolution
(+ wakefields ?)




realtime control-room profiles




observing stabilising effect of slow feedback




Control-room diagnostic… BUT only with laser room preparation and support

Science & Technology Facilities Council

Steven Jamison, CTC, CERN September 21, 2010

ASTeC

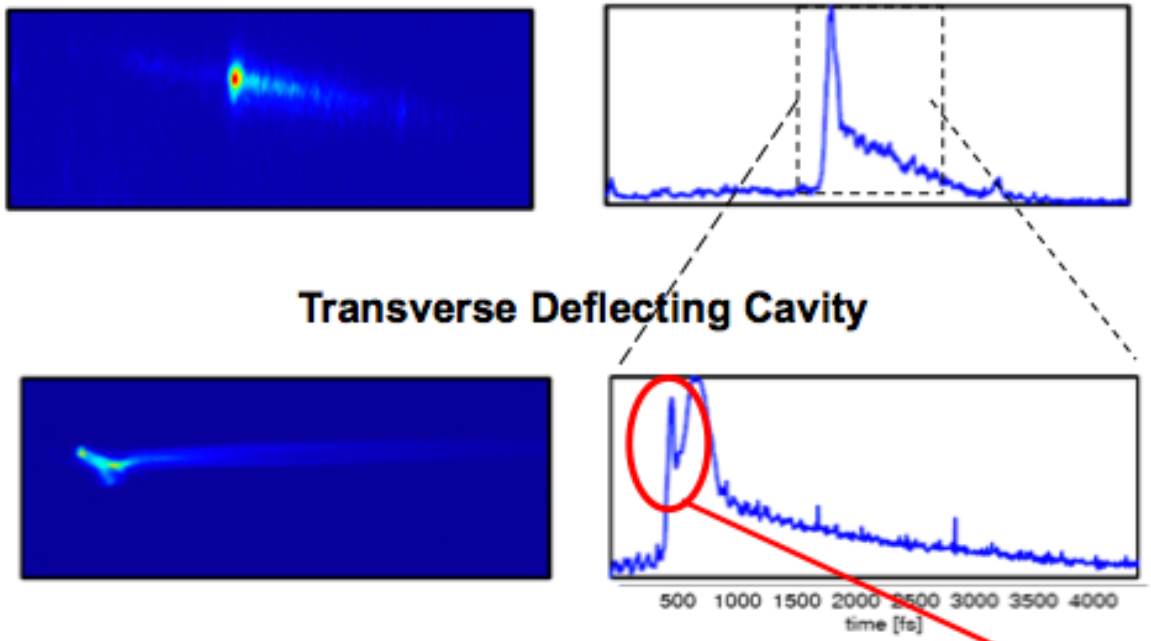
DUNDEE

# Electro-optical detector compared to RF deflector

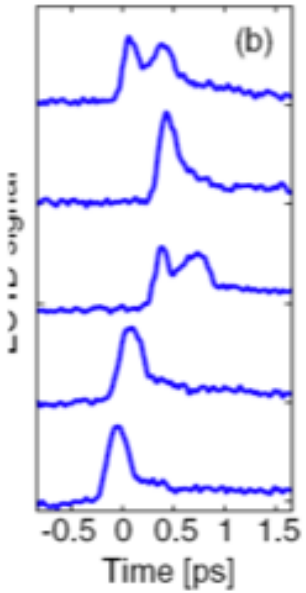
## Temporal decoding time resolution

comparison with RF deflecting cavity

**Electro-optic**




***shot-shot variations***




*Phys Rev Lett* ***99****, 164801 (2007)*
*Phys. Rev. ST,* ***12****, 032802 (2009)*

**not observable in (existing) EO…**

Resolution limited by both material properties & laser pulse duration

Science & Technology Facilities Council — Steven Jamison, CTC, CERN September 21, 2010 — ASTeC — University of Dundee

# Electro-optical detector R&D for CLIC

Collaboration established between Steve. Jamison (ASTEC, STFC Daresbury) and Allan Gillespie (Univ. Dundee) to develop EOS detectors for CLIC parameters

- Push the limits of temporal decoding for highest CLIC resolution needs
- Spectral up-conversion to be further developed for potential shorter time scales
  - For example to feedback on the r.m.s. ➔ make sure spectrum stays stable
  - Relatively easy laser requirements
- DITANET Early Stage Researcher position (PhD) on Electro-Optical Techniques for CLIC advertised

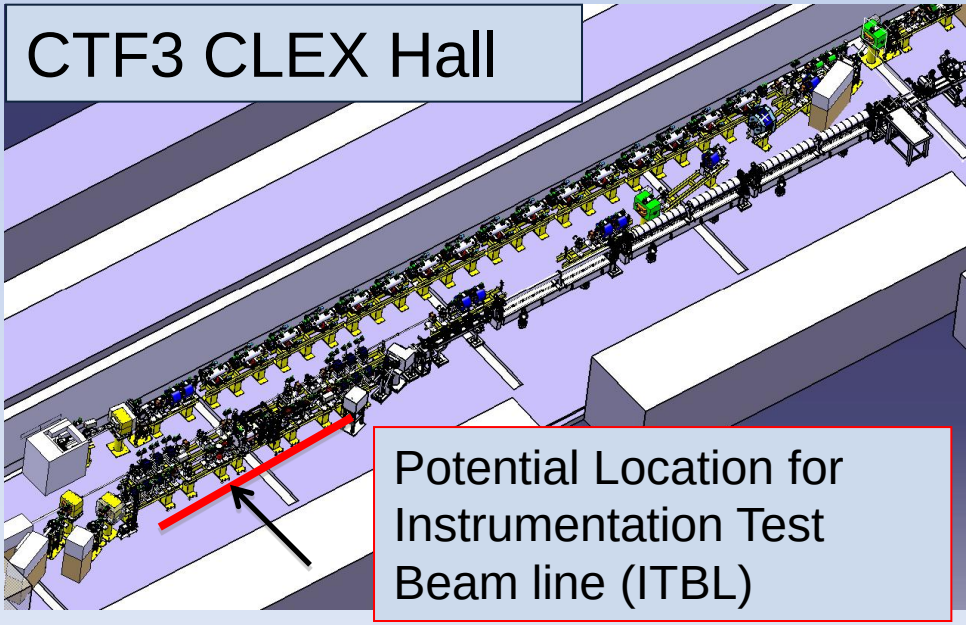
DITANET
Diagnostic Techniques for particle Accelerators - a European NETwork

# Electro-optical detector R&D for CLIC

- Exploration of Electro-optics measurement in Califes Instrumentation Test Beam Line (ITBL):
  - using a compact fiber based EOS setup
  - developing EOS competencies at CERN
  - test new detector concepts

- Exploit the potential of ITBL for instrumentation development in beam loss, energy spread, beam position and bunch length

| | CALIFES specifications |
|---|---|
| Bunch charge | 0.6 nC |
| Energy | 170 MeV |
| Energy dispersion | 2% |
| Emittance | <20 π mm.mrad |
| Bunch train | 1 – 32 – 226 |
| Bunch length | 0.75 ps |

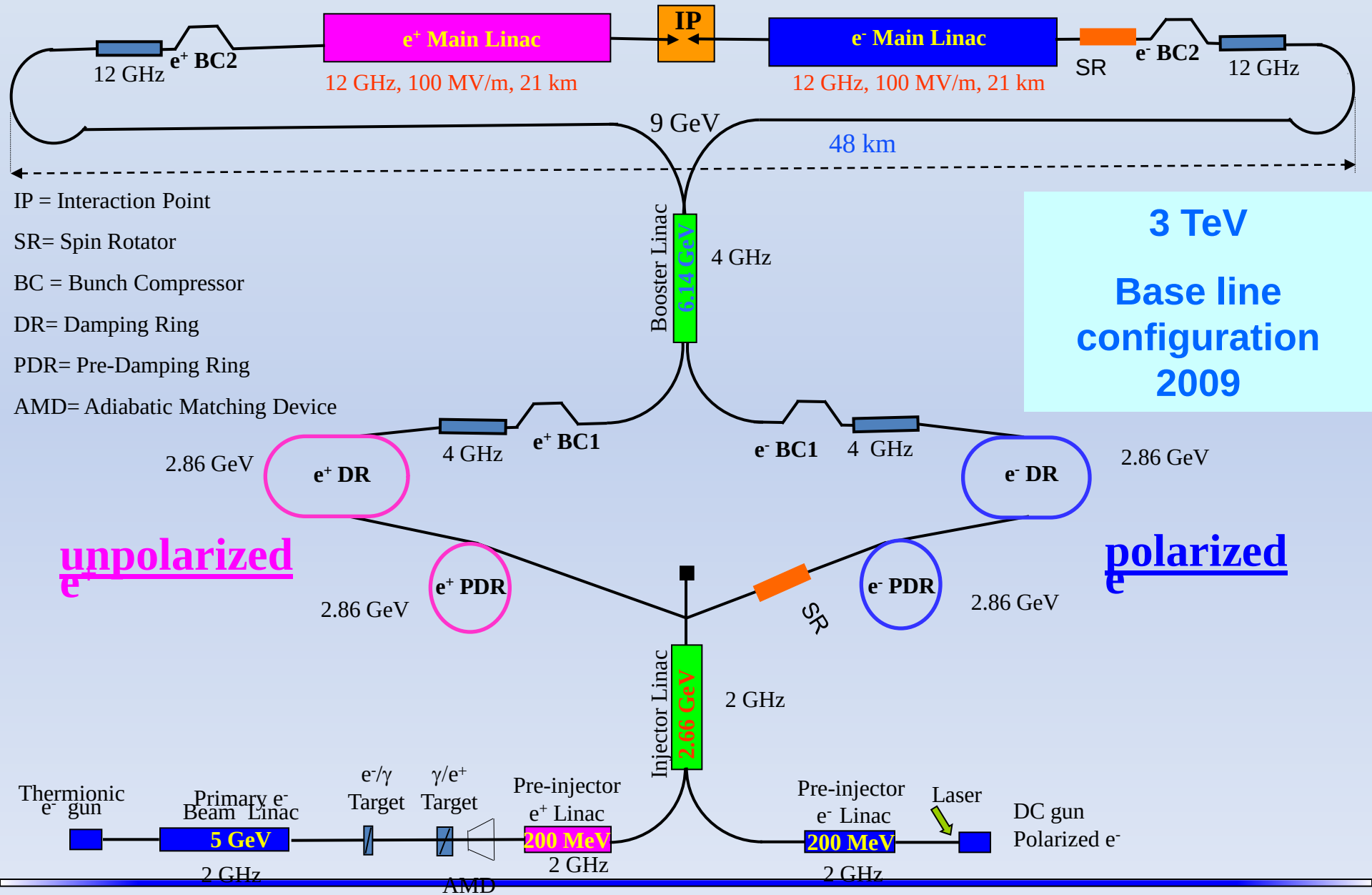


# Conclusion

- Strategy for diagnostics development for longitudinal profile diagnostics for CLIC identified
- The technology for the CLIC Drive Beam can mostly be tested at CTF3
- For shorter bunches, need collaboration with X-FEL community
- Detector R&D needs to be focused on adapting existing instrumentation designs to CLIC parameters and resolution needs
- Instrumentation Test Beam Line of Califes being investigated as a potential location for a compact laser based EOS setup ➔ developing EOS competencies at CERN
- Exploit the potential of ITBL for instrumentation development in beam loss, energy spread, beam position and bunch length

# EXTRA SLIDES

# CLIC Main Beam Injector Complex



# Streak Camera

# CTF3 Bunch Frequency spectrum

**Nominal operation:**

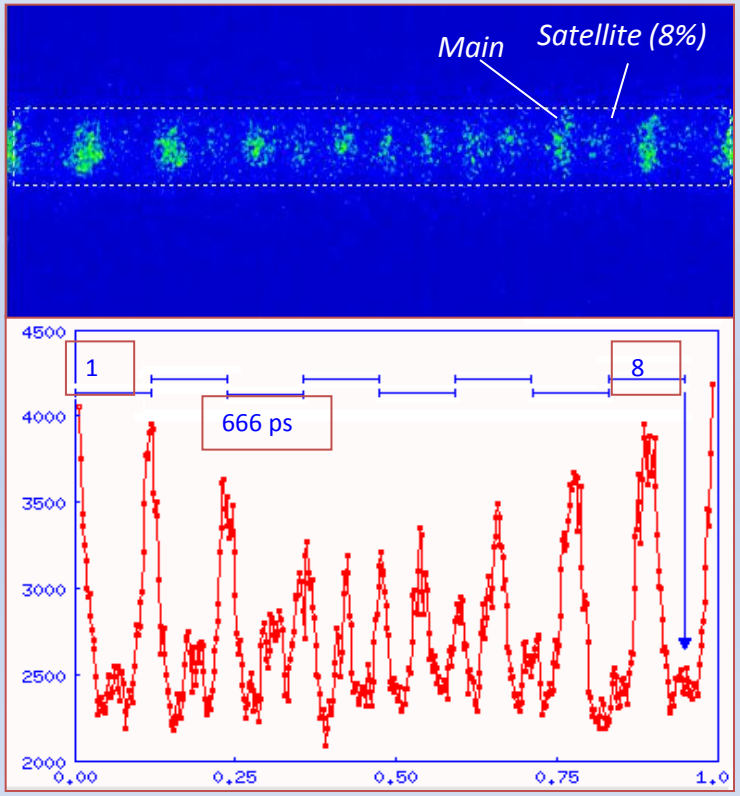
- 1.5 GHz bunched beam
- satellites contain 8-12% (2009) of bunch charge and have a different longitudinal emittance
- Fast phase switch (5ns) of 180 degrees every 140 ns

**Preferred beam for understanding diagnostics:**

- 3.0 GHz
- No sub-harmonic bunching system
- No phase switches

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

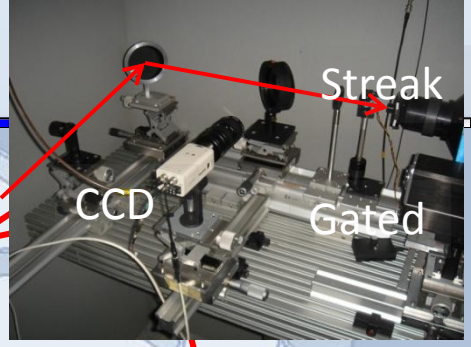
*Streak camera – 500 ps/mm*



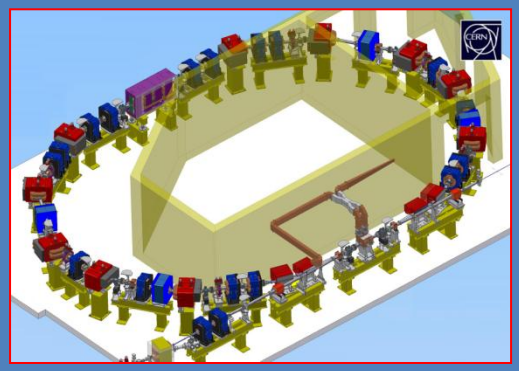

Switch time

8.5 · 666 ps = 5.7 ns

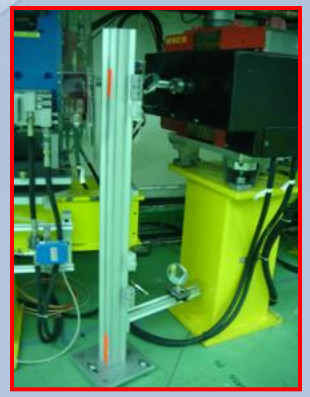
# Streak Camera in CTF3




Long optical lines to the streak camera Laboratory

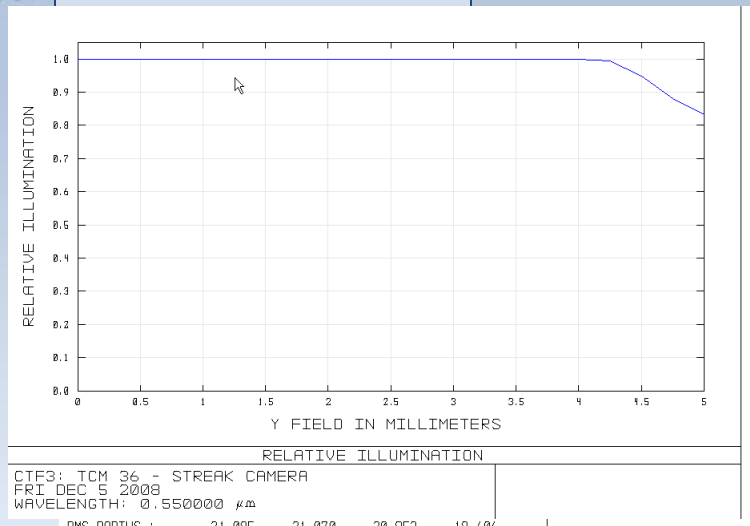


2008
- CR Optics lab
- 2 Synchrotron Radiation optical lines commissioned



2 Optical lines in 2006
- Synchrotron Radiation in the Delay Loop
- 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



# CTF3 Layout

# Overview of Longitudinal Instrumentation

## Longitudinal Bunch Profile

- RF Deflecting Cavity, OTR
- Streak Camera Synch Light, or OTR

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

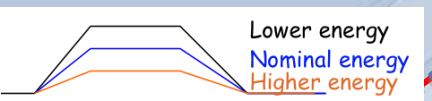
- BPR-W (Integrated Power over 25-40 GHz)
- RF-pickup (Power at selected harmonics 30 – 170 GHz)
- CDR Experiment

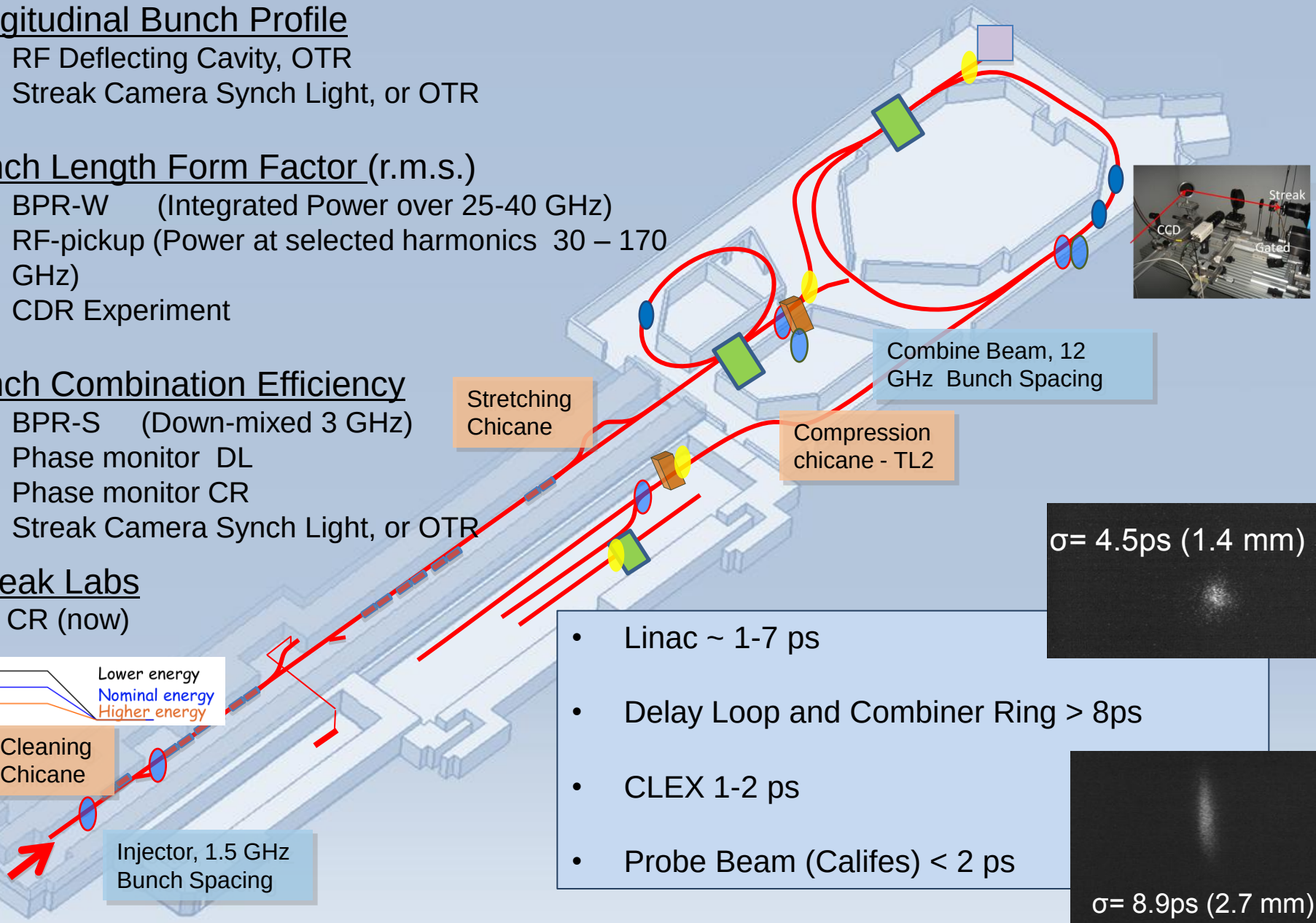
## Bunch Combination Efficiency

- BPR-S (Down-mixed 3 GHz)
- Phase monitor DL
- Phase monitor CR
- Streak Camera Synch Light, or OTR

## Streak Labs

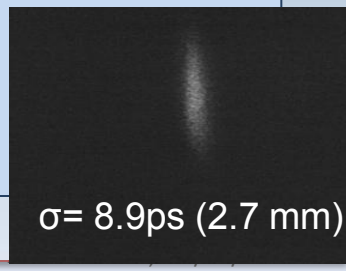
DL, CR (now)




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



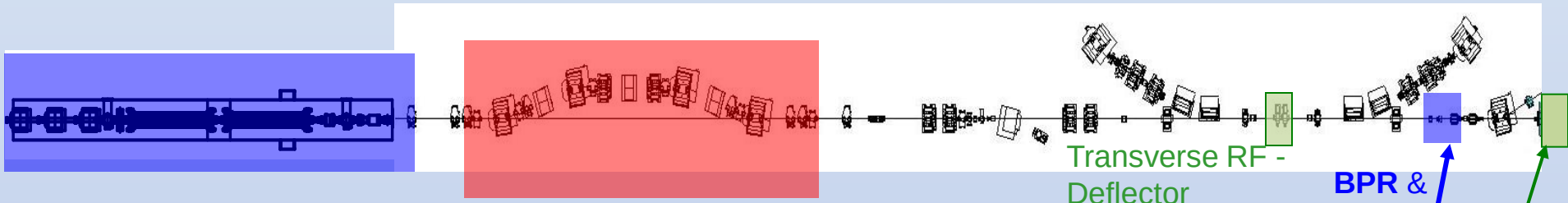



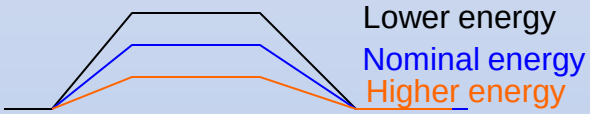
# Bunch length manipulation using INFN Chicane

Accelerating structures @Girder 15

4 Bends INFN-Frascati Chicane

Delay Loop



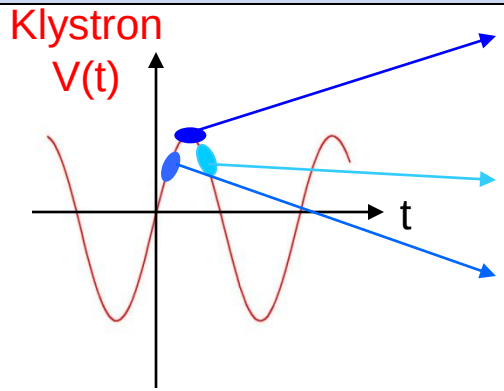




Scan phase of Klystron 15 to insert a time to energy correlation within the bunch

Convert energy correlation into path length modification and time correlation

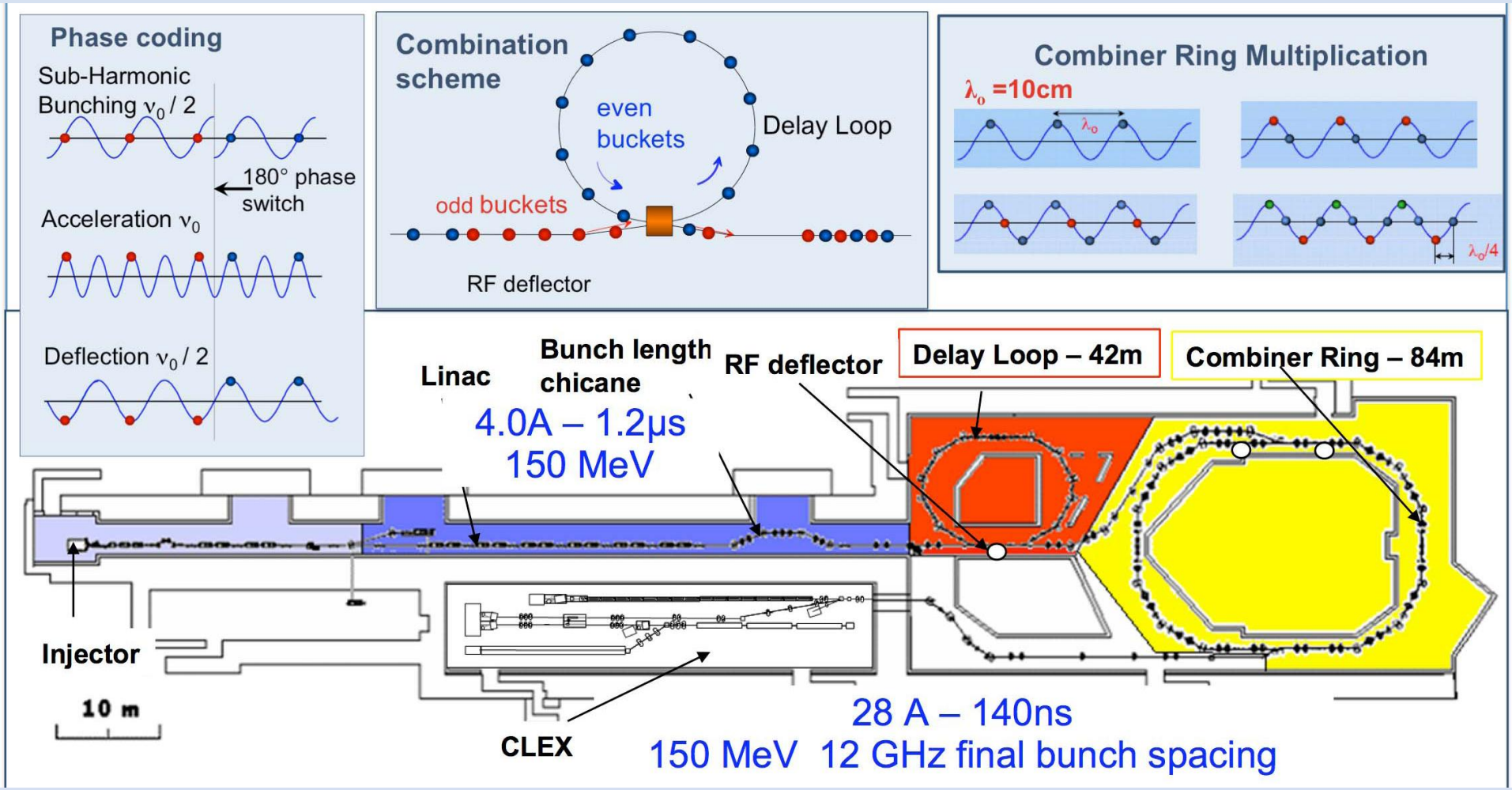
Measure the Bunch frequency spectrum

Measure bunch shape & length using RF deflector and OTR screen



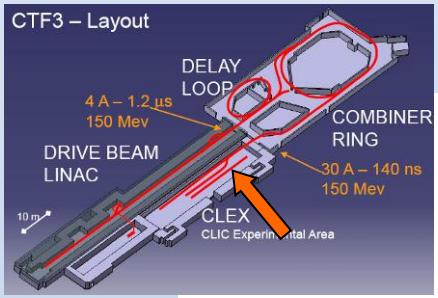

- On-crest Acceleration – the bunch length is conserved through the chicane
- Negative Off-crest Acceleration – the bunch gets longer
- Positive Off-crest Acceleration – the bunch gets shorter

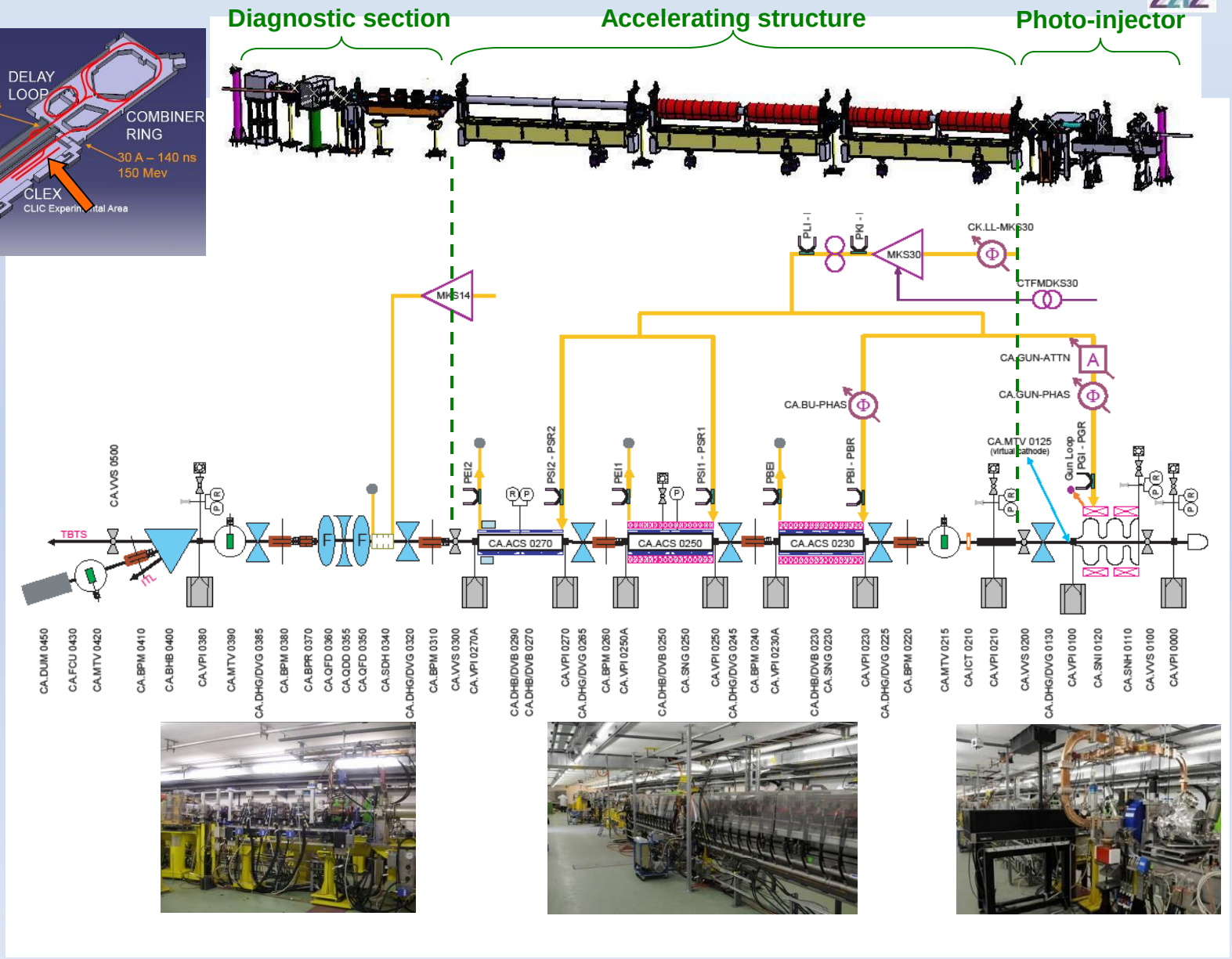
# CTF3 complex and Bunch manipulation



# ITBL

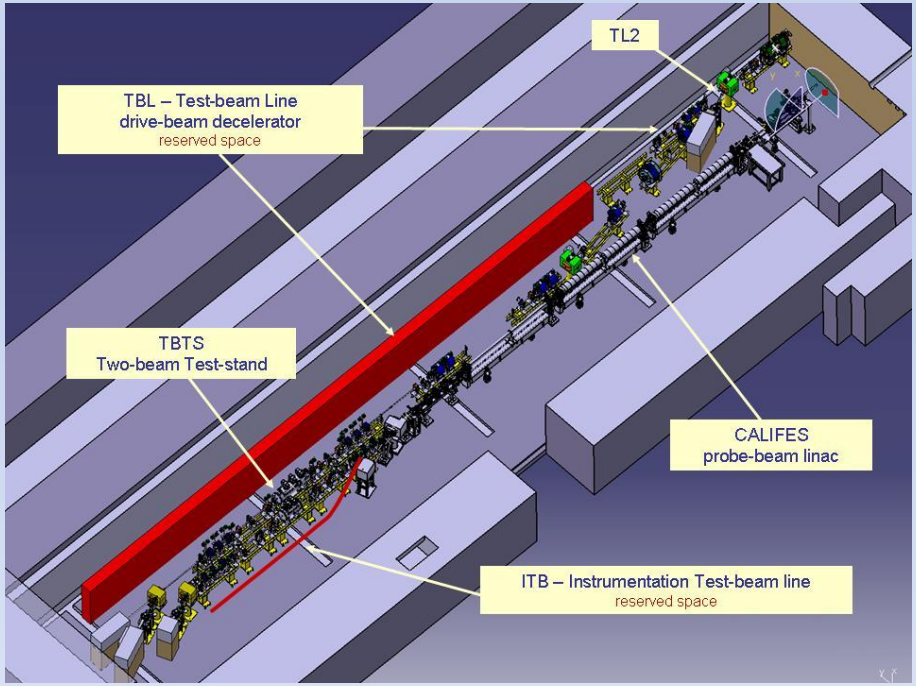
# Short bunches - CALIFES



# Another use of CALIFES beam: the ITB project

- 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.)
- The reservation for the ITB was foreseen from the initial CLEX construction sketch.
- But now this place is used for TBTS tank installation, then for complete module installation.

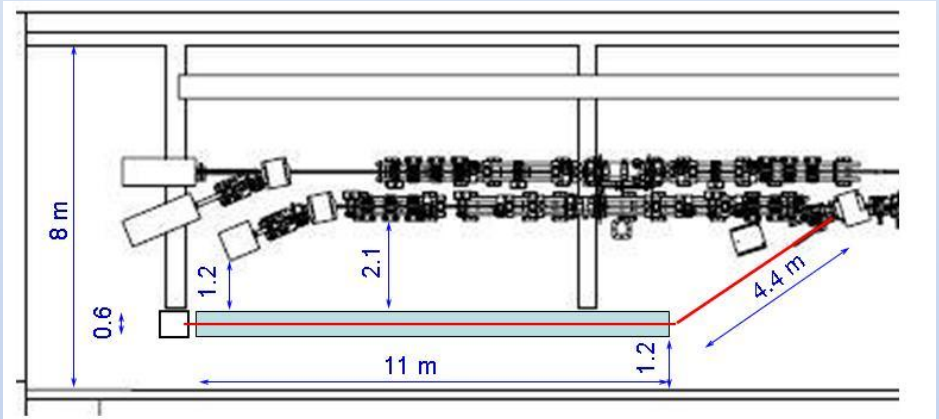



CTF3 Collaboration Meeting - 6/5/ 2010

Califes status - Wilfrid Farabolini

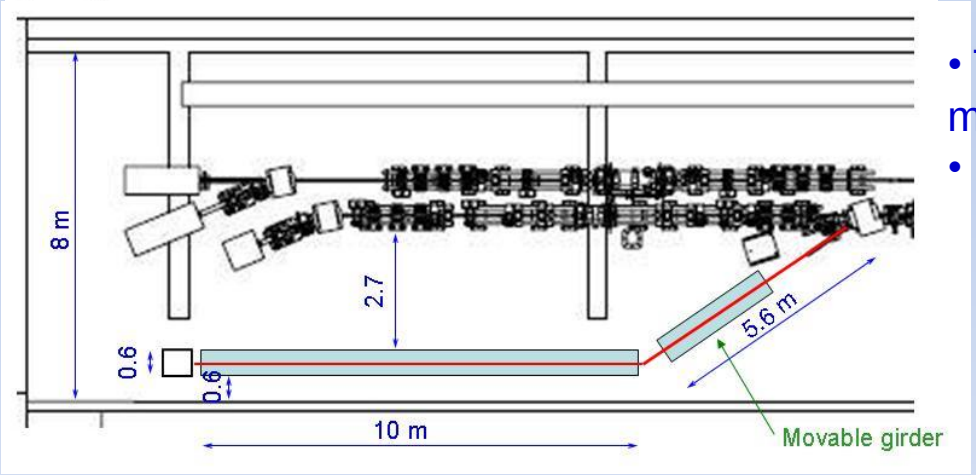
# ITB line alternatives

1



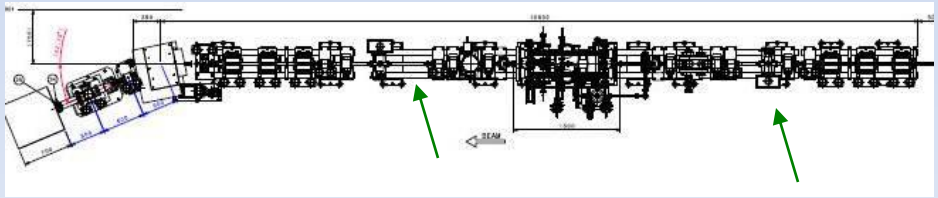

- The clearance for ACS tank trolley (1.2m) is marginally respected.
- But the complete module will request even larger space to be installed

2




- The clearance for the complete module is foreseen
- But a movable girder is to be used

3

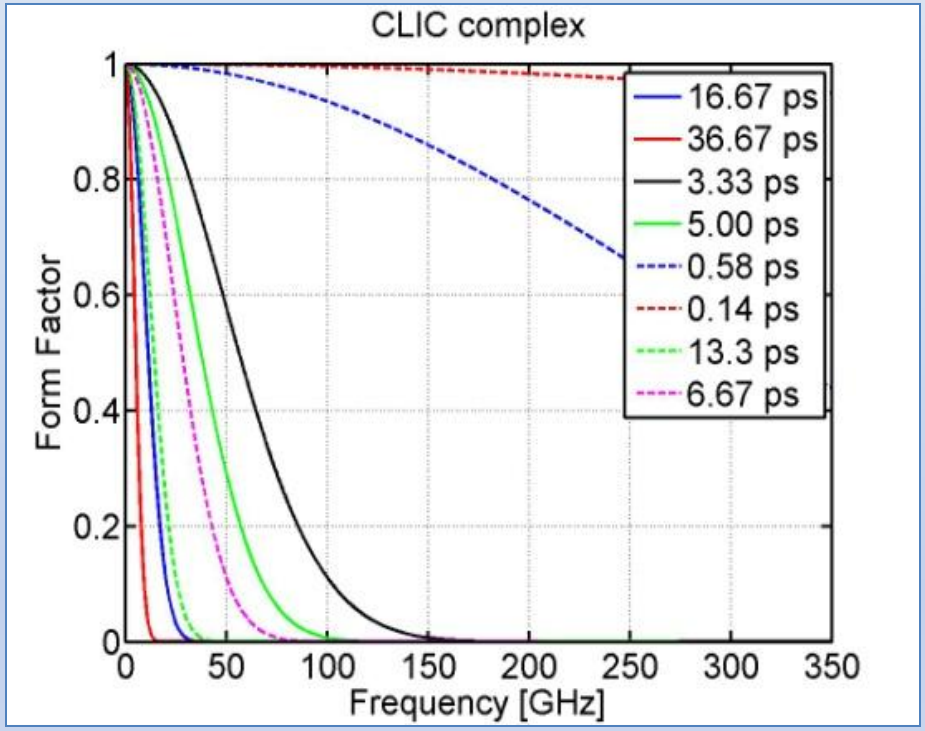


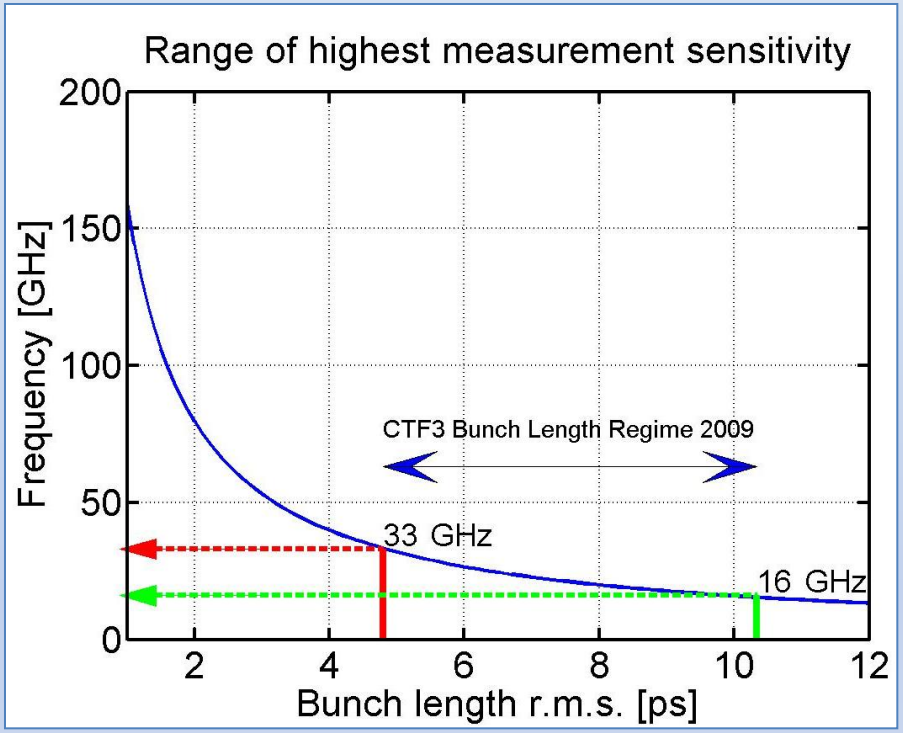
930 mm 530 mm

- No new line but use of available space in the actual TBTS
- Cheap, immediately available and less intrusive solution
- But limited space and no chicane for $R_{56}$

# RF Techniques

# Choosing frequency measurement range



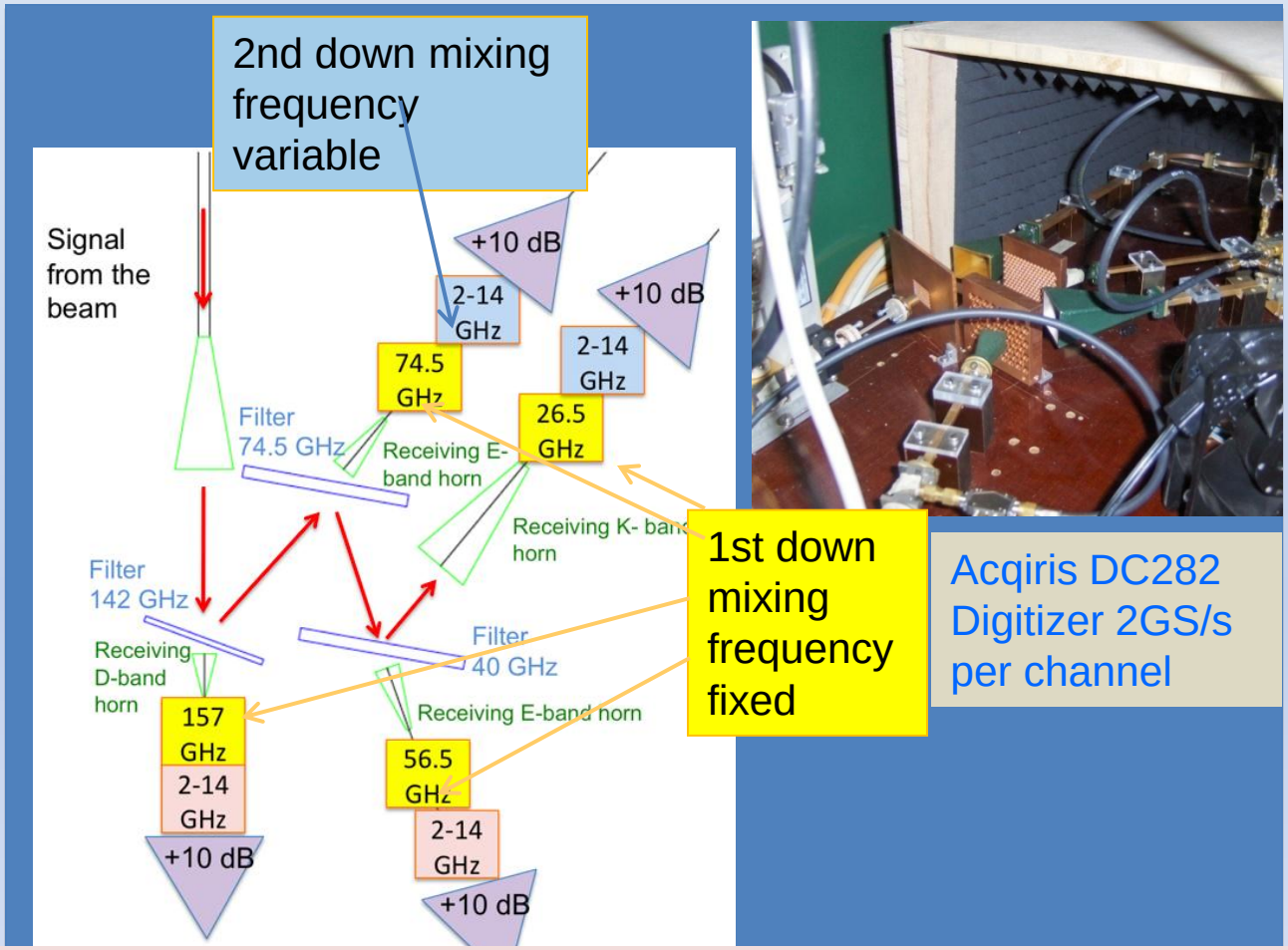

$$i_b(t) = \frac{q_b}{\sqrt{2\pi}\sigma_b} \exp\left(\frac{-t^2}{2\sigma_b^2}\right)$$

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

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

- Design RF-type detector to be most sensitive to bunch length changes
- K-band BPRW (like in CTF3) best adapted to bunch lengths 4ps – 7ps
- Technique in general – D-band waveguide components > 300 fs

# CTF3 Bunch Length Measurement – “RF pickup”




Transmission transparent for high Freq < 170 GHz, very thin 0.150 +- 0.005 mm thick diamond window ($\varepsilon_r$~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

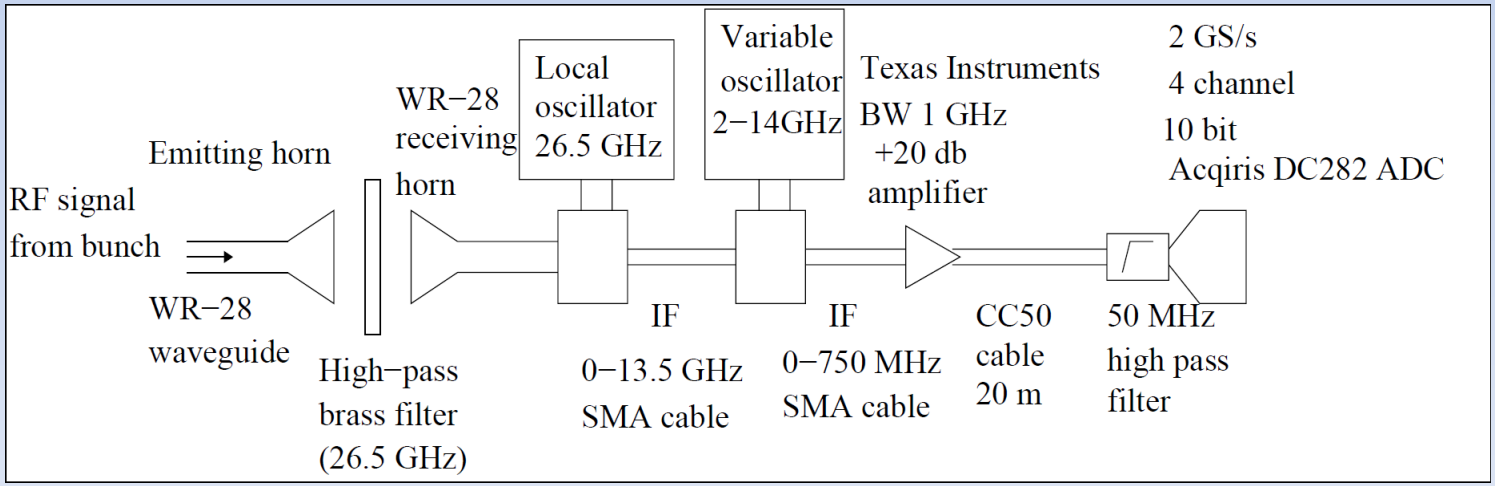
# Example of one down mixing stage - RF-pickup

## 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

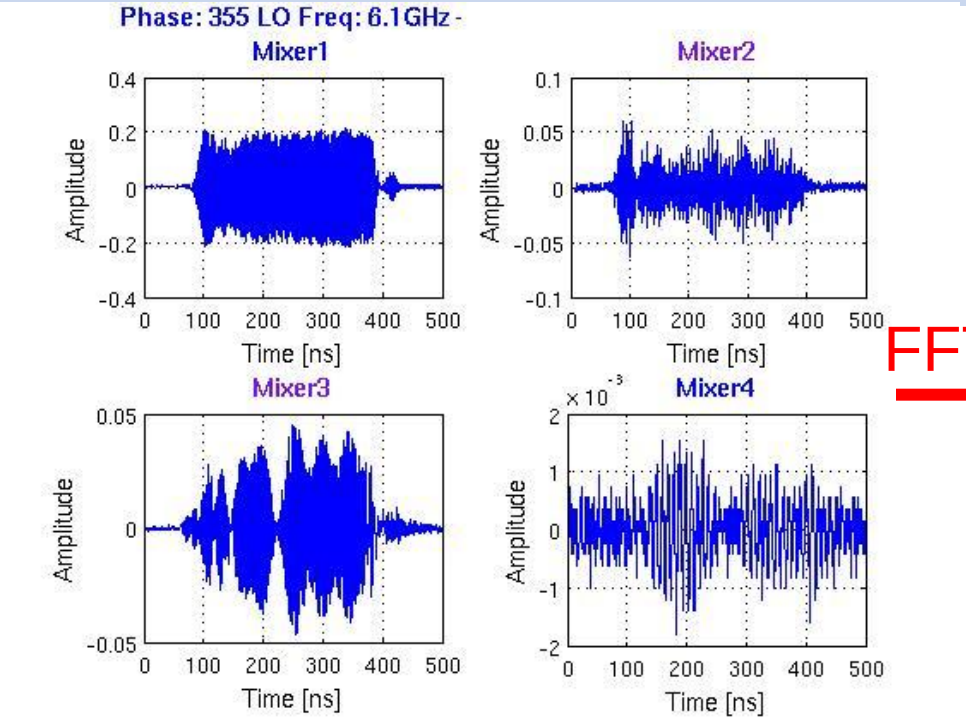
Example:

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

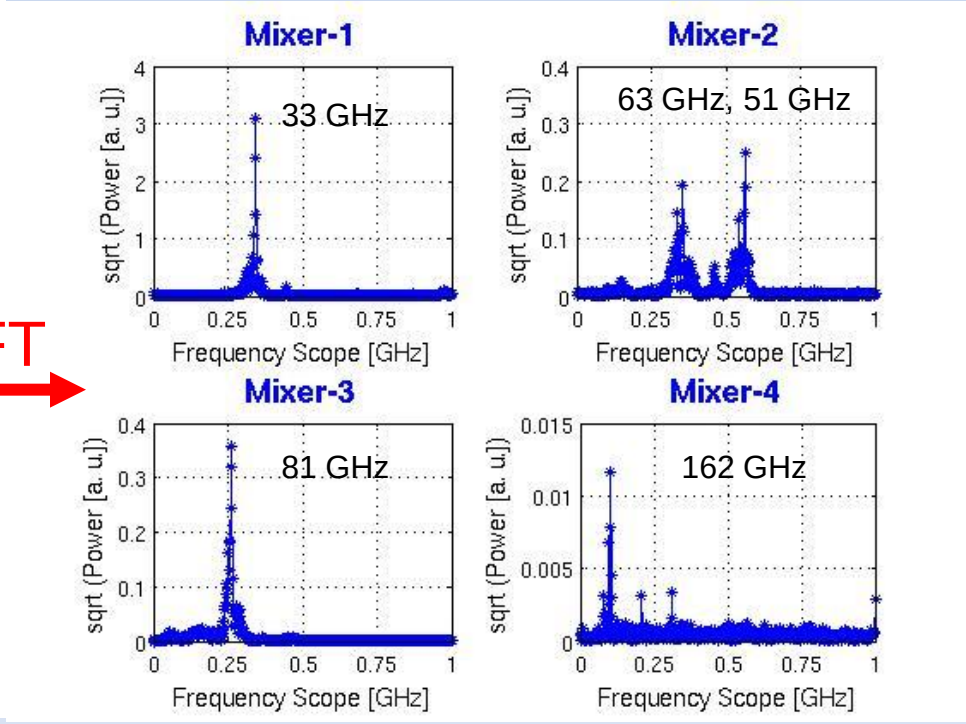
phase MKS15 355 degrees, 06-12-2006

Raw signals from the beam in time domain

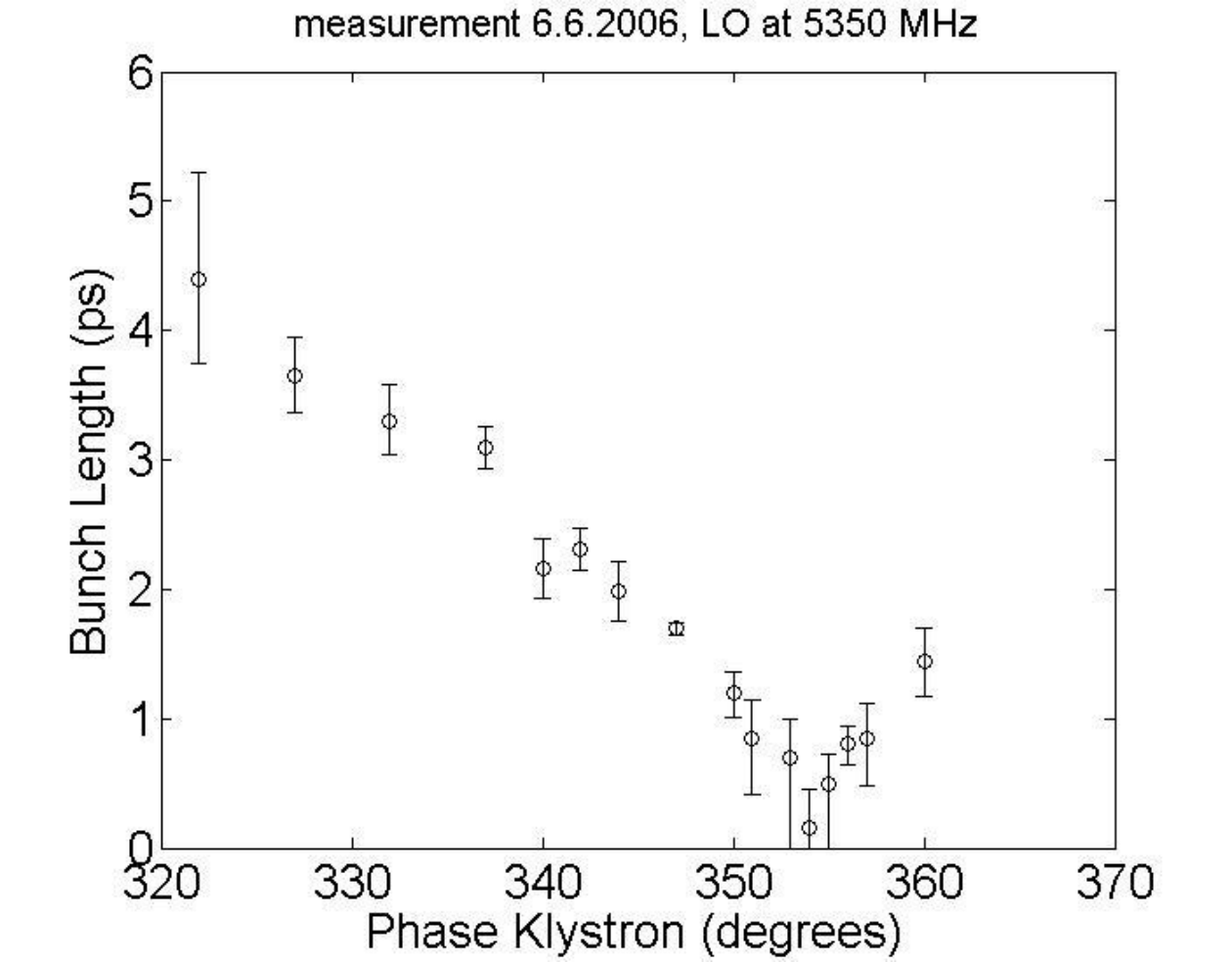
Transformed signals (Raw FFT unfiltered)




FFT



# RF-pickup result 2006 – Self Calibration




**PAC07 proceedings:**

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

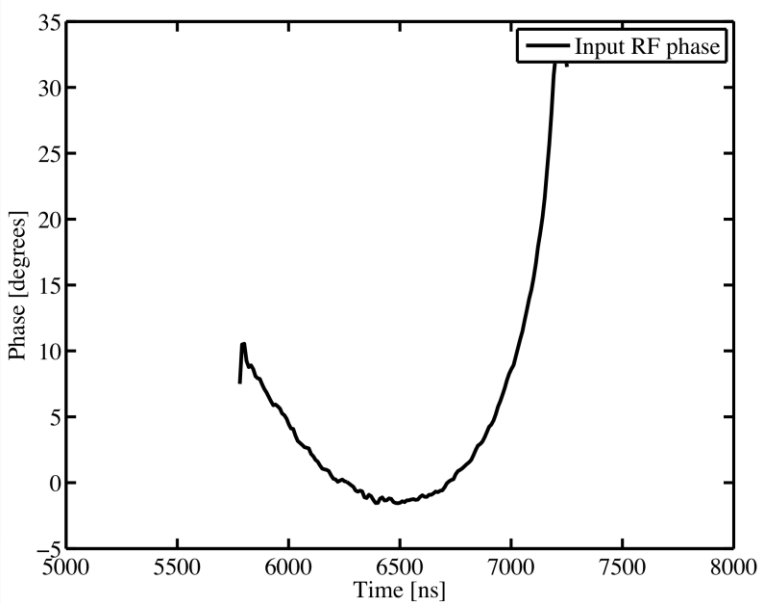
# Reason for bunch length variation along pulse train

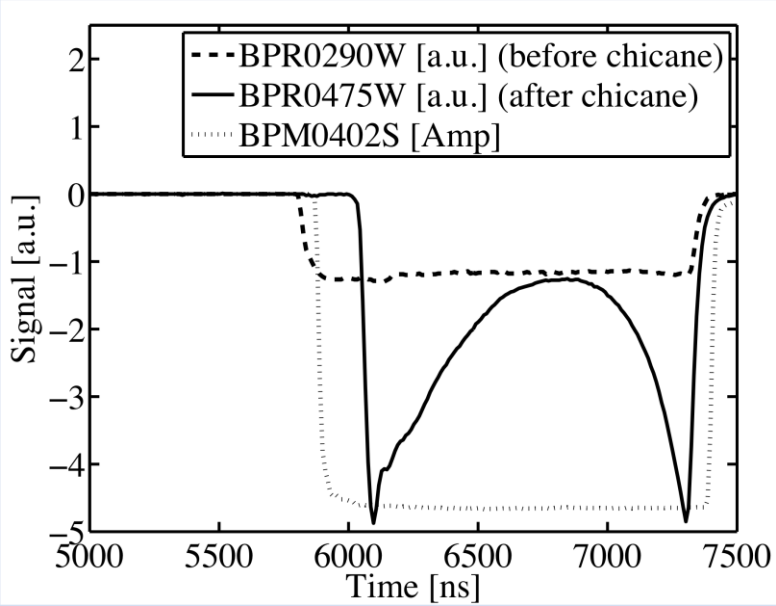
# Energy gain and Bunch Lengthening

Due to the pulse compression system, phase sag along the Klystron pulse ~ 5-15 (see talk CTF3 Collaboration meeting of A. Dubrovskiy)

- not all bunches see same RF phase
  - Difference energy gain of one bunch with respect to another
  - Within a single bunch, the head and tail of bunches to have different energy

Example of RF phase for MKS03

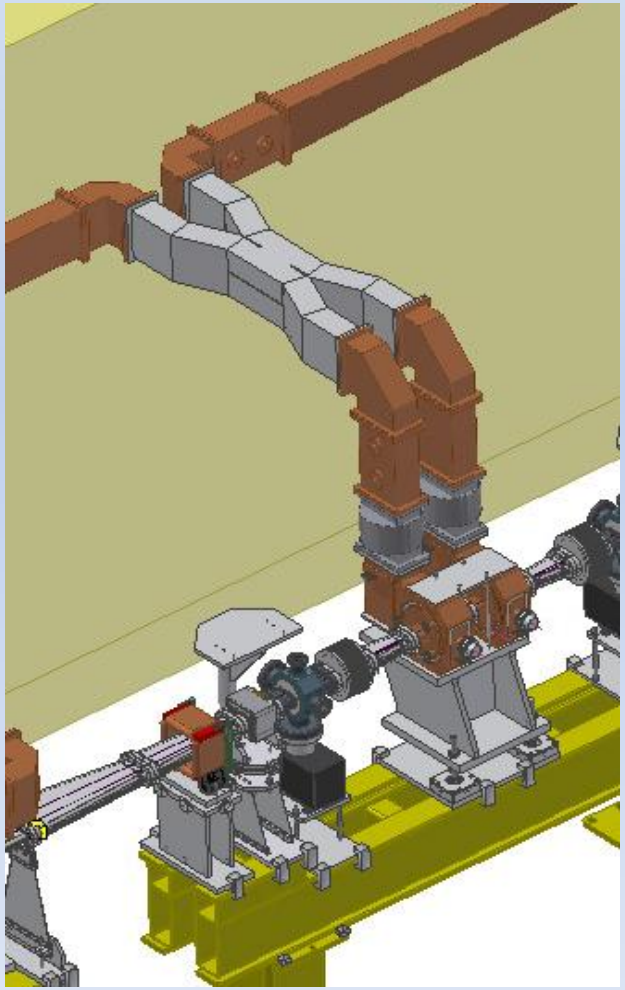



- Bunch length variation along the pulse train is a feature in CTF3 (to a greater / lesser extent depending on RF)
- Time resolved bunch length diagnostics essential

# RF Deflector CTF3 info

# 1.5 GHz Rf deflector

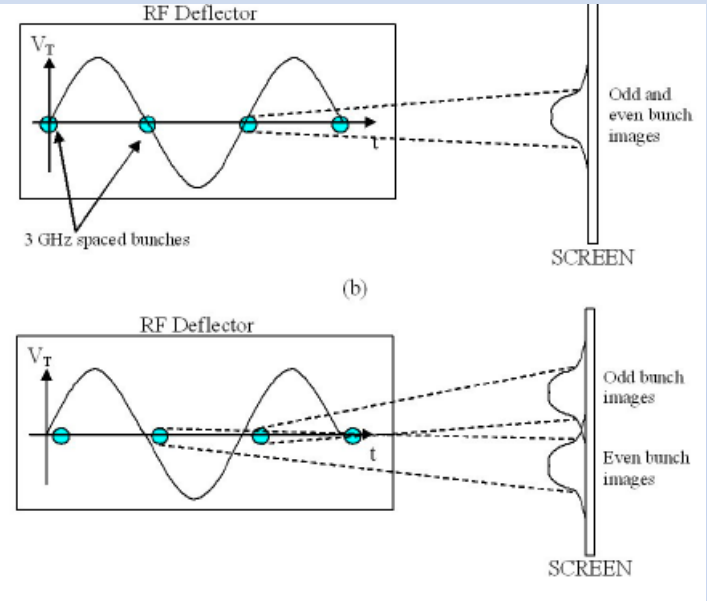


**Frequency multiplicatio n x 2**

| | |
|---|---|
| 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%** |

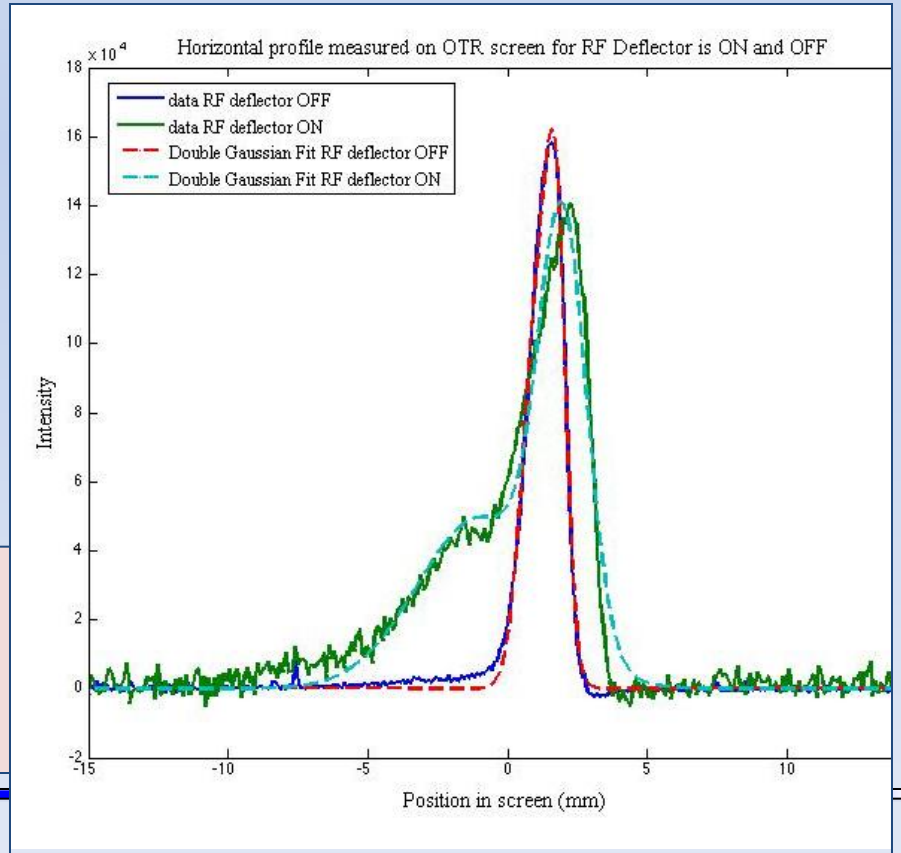
# Bunch Length 3 GHz beam, 1.5 GHz deflector

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




Measurement procedure:

•Move OFF the zero crossing, to separate two bunches
•Use corrector magnet to re-steer bunch to center of screen.

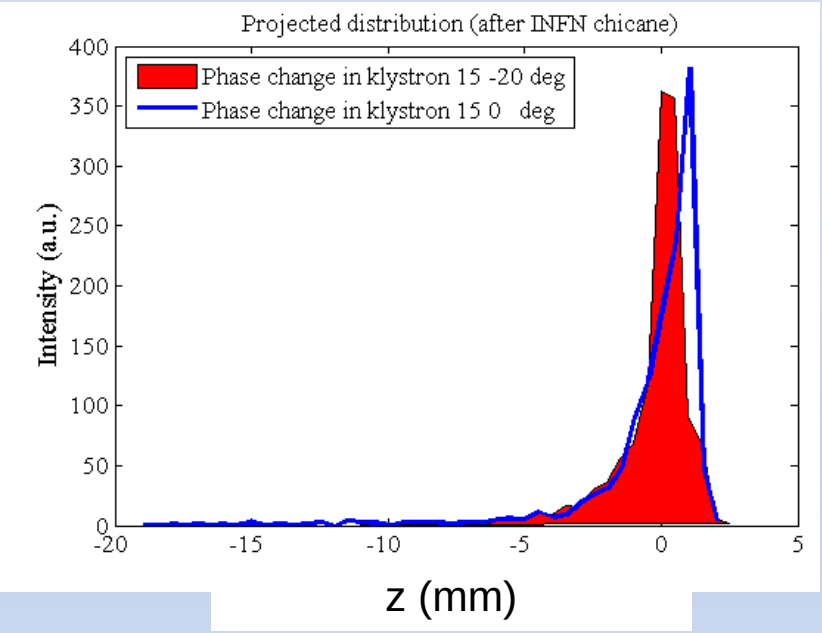


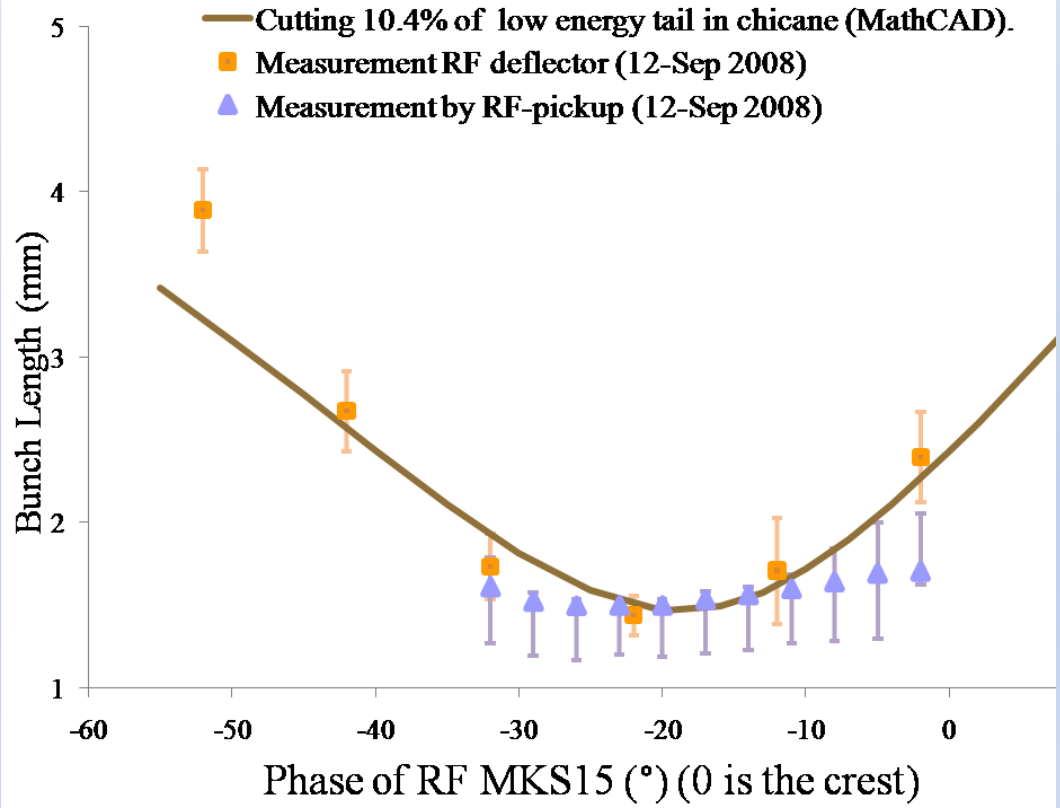

Calibration Factor:

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

# RF-pickup compared to RF-deflector

Bunch Shape from Simulation




RF-Deflector, RF-pickup and Simulation seem to give comparable results:

➔However, in order to be more sure of simulation conditions, need to take note of injector settings & estimate low energy cut in chicane & measure loaded RF signals in all accelerating structures

➔ Bunch shape variation needs to be studied in more detail to reliable calibrate the pickup

➔ Machine should be stable throughout the scan

➔ Here RF pickup measurement shows time variation along the pulse (but use average)