Beam Diagnostics II

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Material in these slides included from

T. Lefevre, E. Bravin, (DITANET instrumentation school 2009)
R. Jones, U. Raich (CAS 2008 & ASP2010 school)
H. H. Braun (CAS 2008), P. Frock (CAS 2008) M. Minty (CAS 2003)
Also talk R. Jones DITANET symposium

http://cas.web.cern.ch/cas/CAS_Proceedings.html
http://www.liv.ac.uk/ditanet/events/
https://espace.cern.ch/juas/SitePages/Home.aspx

Diagnostics Lecture Outline

- **Why do we need diagnostics**
- **What do we need to measure?**
  - Position
    - Capacitive BPM
  - Current
    - Wall current monitor
    - Faraday Cup
  - Transverse Profile (emittance, TWISS (αβγ) parameters)
    - Intercepting methods
      - » Scanning wires
      - » Radiative screens
      - » Scintillation screens
      - » Cerenkov targets
    - Non intercepting methods
      - » Synchrotron light
  - Beam Loss Detectors
  - Longitudinal Profile
    - Streak Camera
    - RF deflector
    - Electro optical techniques
    - RF power measurements and spectroscopy
  - Luminosity Detectors
- **Discuss diagnostics developments needed for new machines**

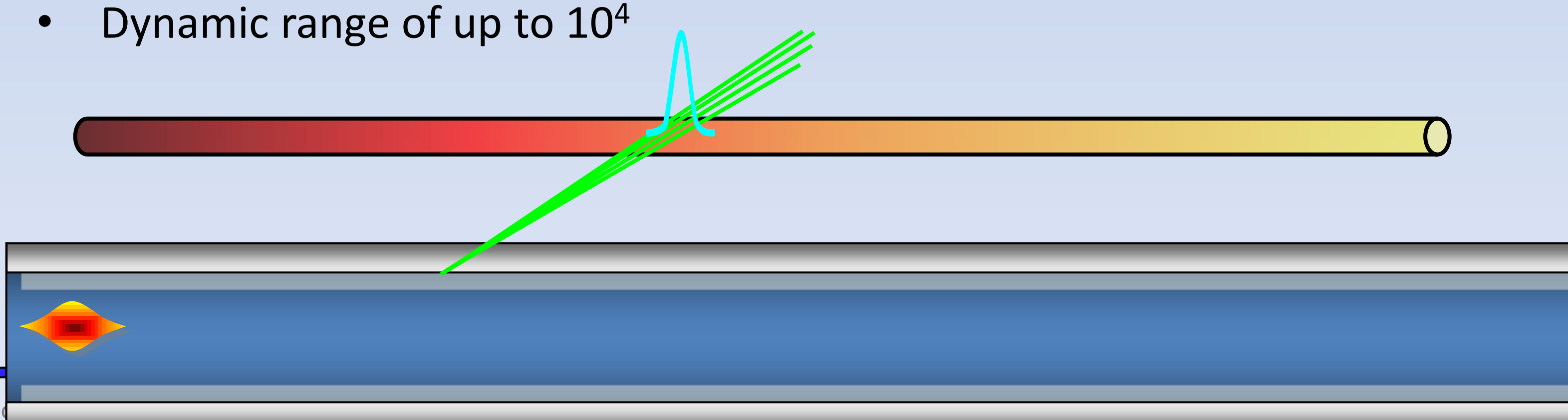
First Lecture

Second Lecture

Beam Loss Detectors

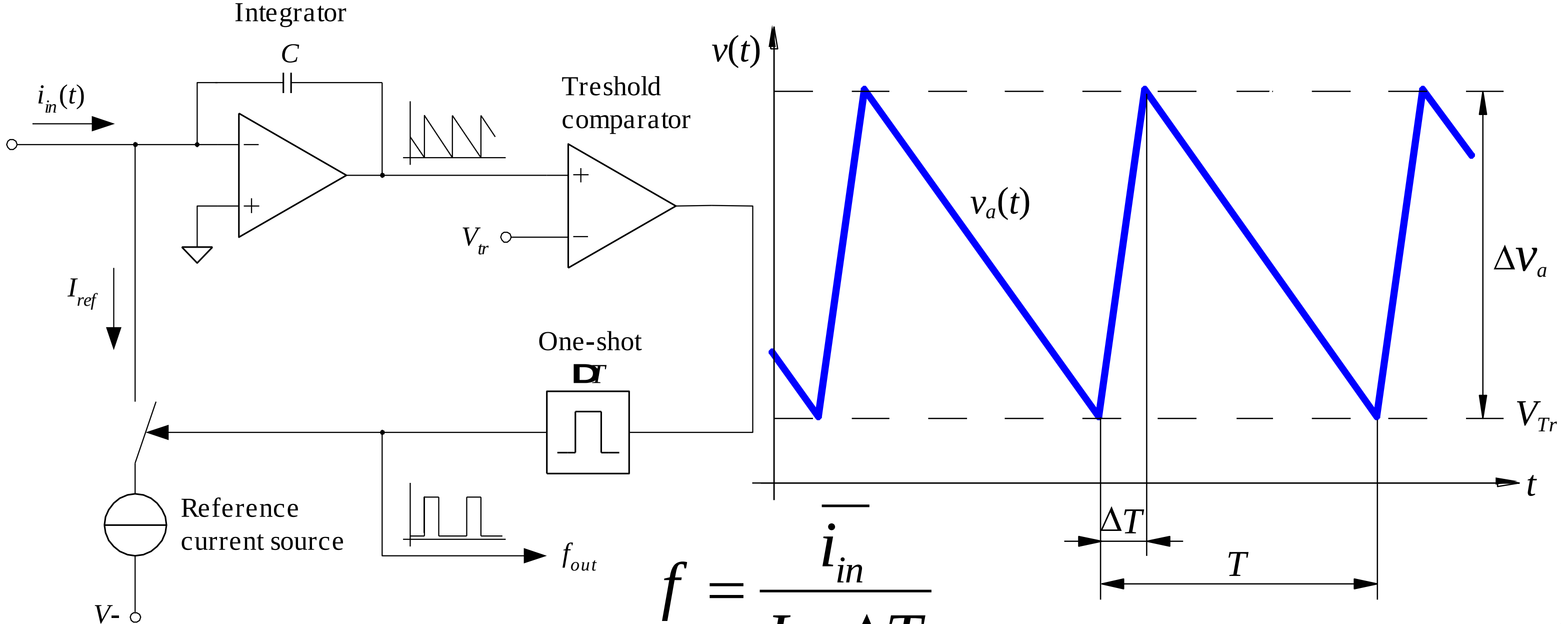
- Role of a BLM system:
  1. Protect the machine from damage
  2. Dump the beam to avoid magnet quenches (for SC magnets)
  3. Diagnostic tool to improve the performance of the accelerator and reduce background to the experiments and avoid irradiating machine elements (interventions)
  4. Set up the machine collimation system for LHC

- Common types of monitor
  - Long ionisation chamber (charge detection)
    - Up to several km of gas filled hollow coaxial cables
    - Position sensitivity achieved by comparing direct & reflected pulse
      - e.g. SLAC – 8m position resolution (30ns) over 3.5km cable length
    - Dynamic range of up to 10^4



Slide
R. Jones

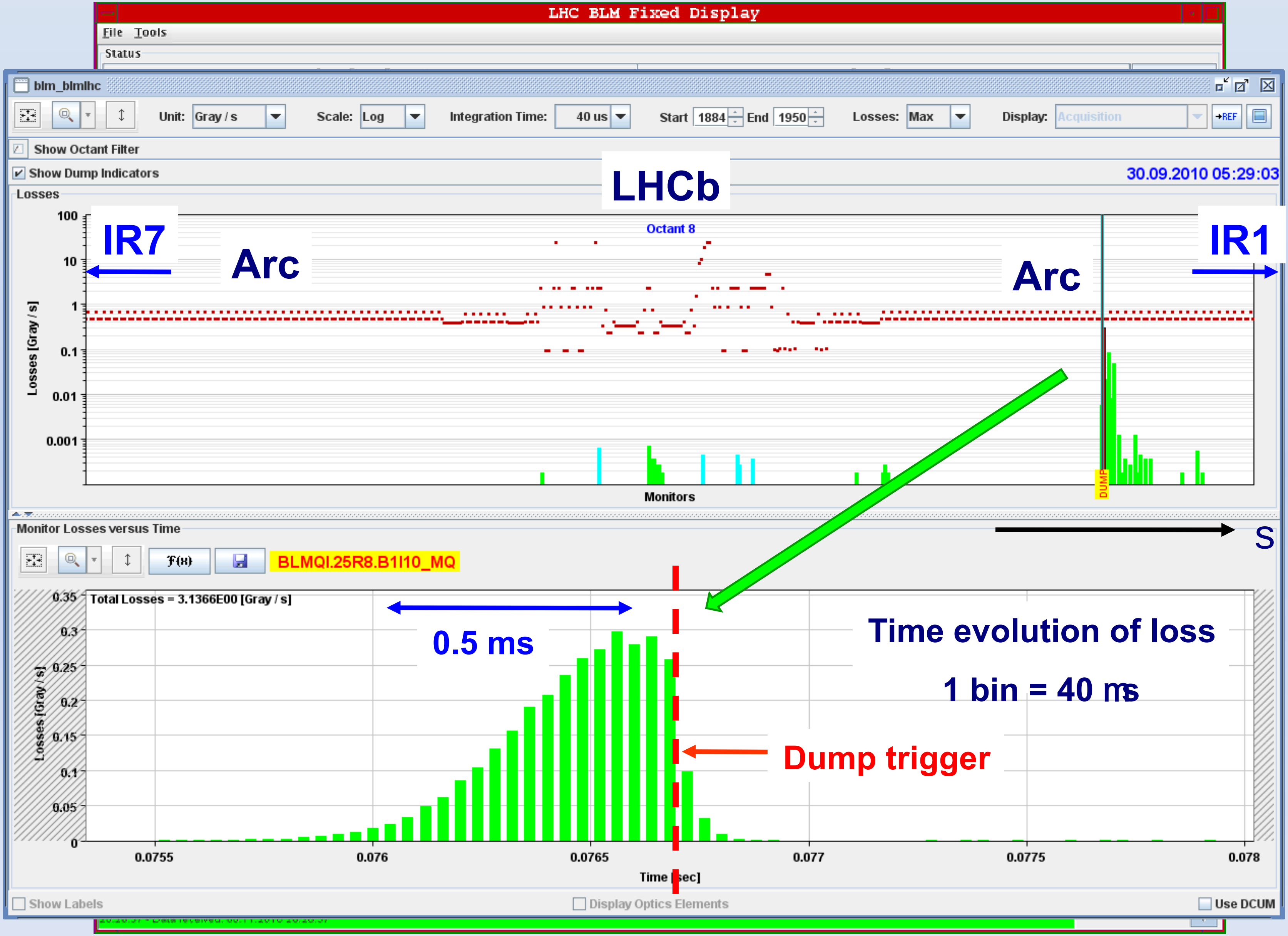
- Common types of monitor (cont)
  - Short ionisation chamber (charge detection)
    - Typically gas filled with many metallic electrodes and kV bias
    - Speed limited by ion collection time - tens of microseconds
    - Dynamic range of up to 10^8



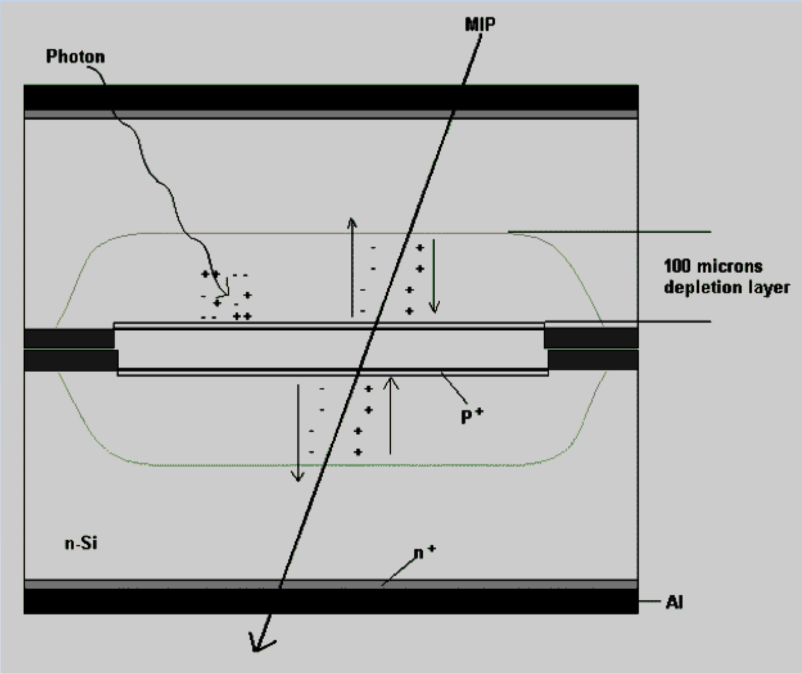
$$f = \frac{\overline{i_{in}}}{I_{ref}\Delta T}$$

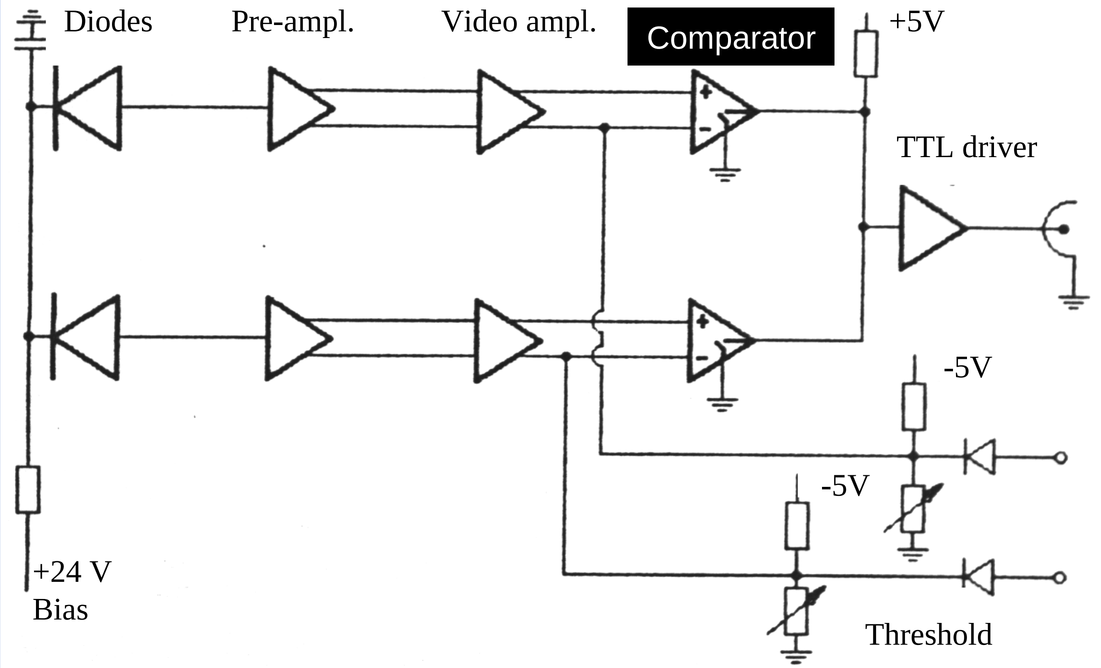
LHC

LHC Measurements using ionization chambers



- Common types of monitor (cont)
  - PIN photodiode (count detection)
    - Detect MIP crossing photodiodes
    - Count rate proportional to beam loss
    - Speed limited by integration time
    - Dynamic range of up to 10^9

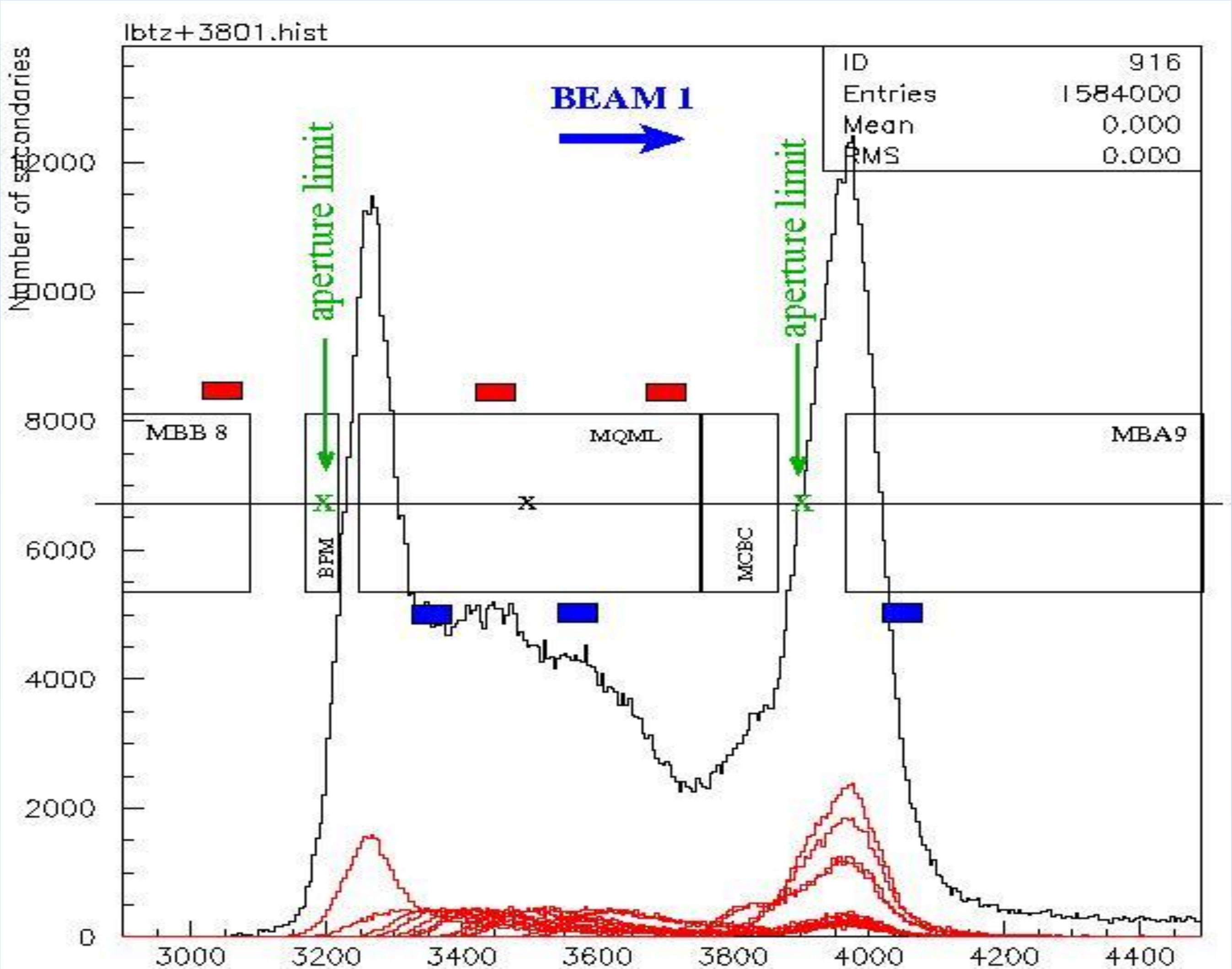




Slide R. Jones

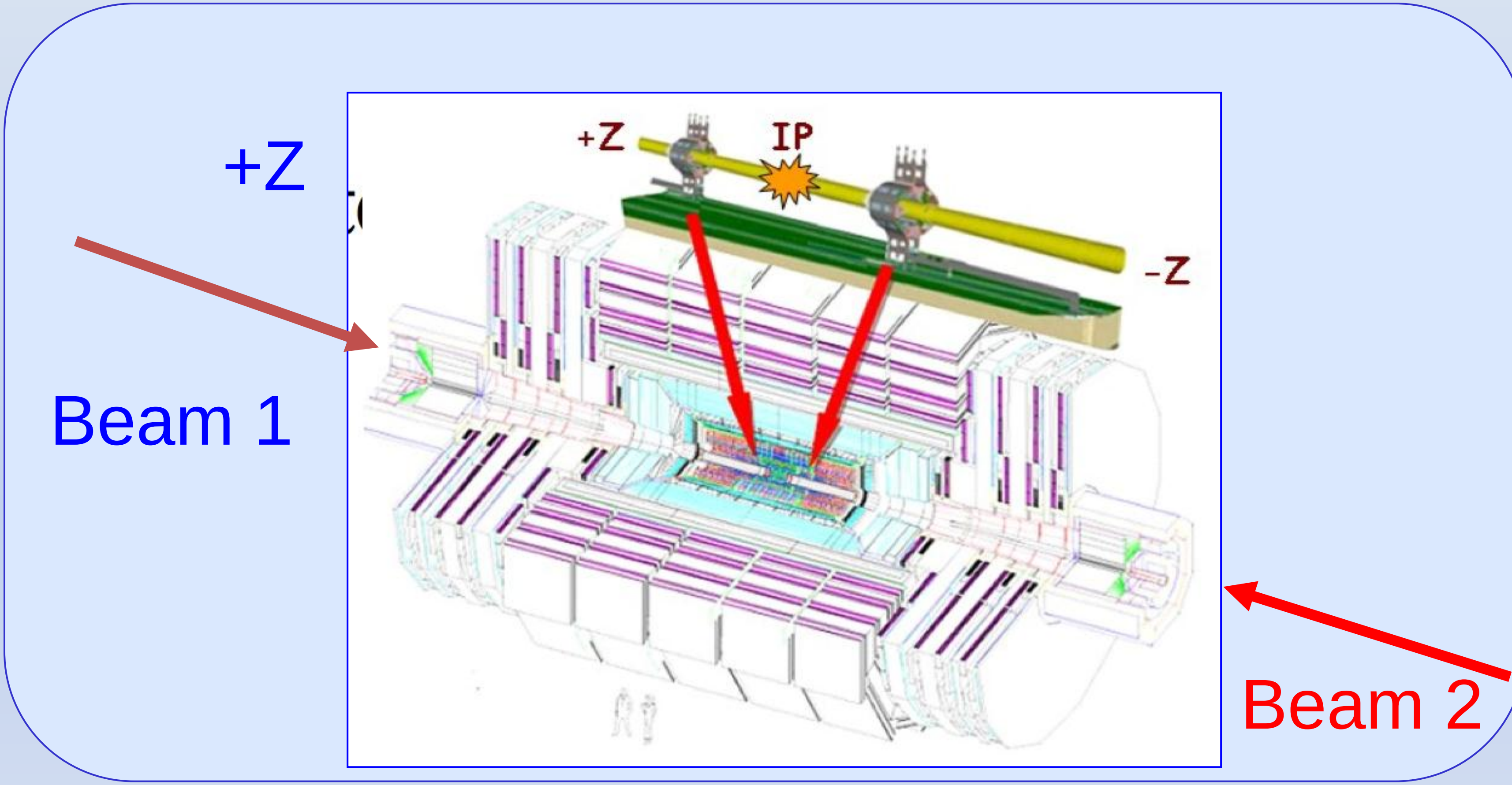
BLM Threshold Level Estimation

Preferred locations for beam losses and therefore for BLMs might be Collimators, scraper, aperture limits, and high **β** -functions…, therefore also the (superconducting) quadrupoles



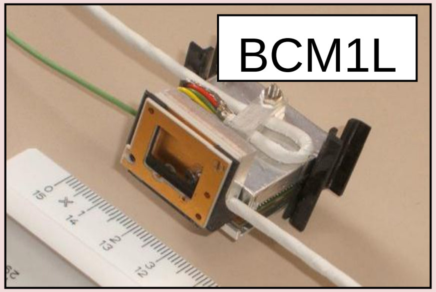
Slide R. Jones

Beam Loss Measurement by the Experiments



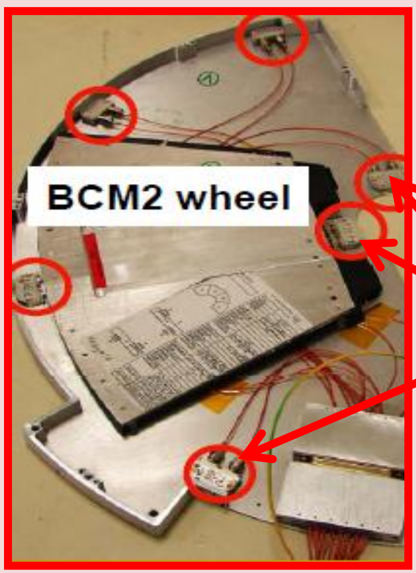
Beam loss measurements needed to protect sensitive LHC detector components from high beam loss / or unstable beams

Beam Loss Measurement by the Experiments



Z = ±1.8 m from IP
R = 4.5 cm
4 diamonds per side

Because of space limitations, and the requirements on radiation hardness, small polycrystalline diamond detectors are used.

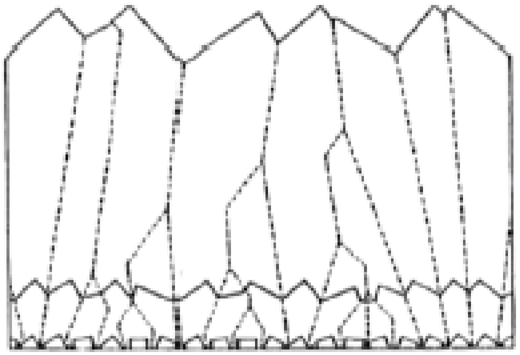


Z = ±14.4 m from IP
Inner ring:
- 4 diamonds, r=5 cm

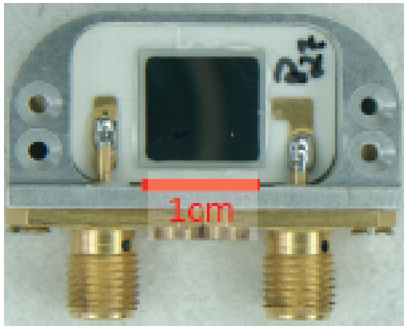
Outer ring
- 8 diamonds, r=28 cm

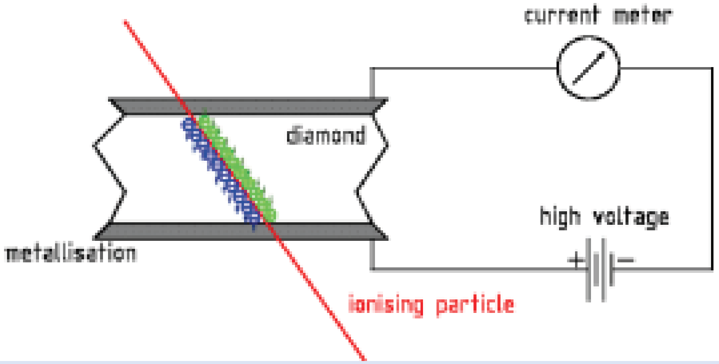
Diamond as detector

- Diamond produced by Chemical Vapour Deposition (CVD)
  - Can be either single-crystalline (BCM1F) or poly-crystalline (BCM2/1L).
- Metallised on both sides and a HV is applied.
- Works like a solid state ionisation chamber.
- More radiation hard than silicon due to higher displacement energy.
- Low dark current.
- Negligible temperature sensitivity.



Crossection trough poly-crystalline diamond

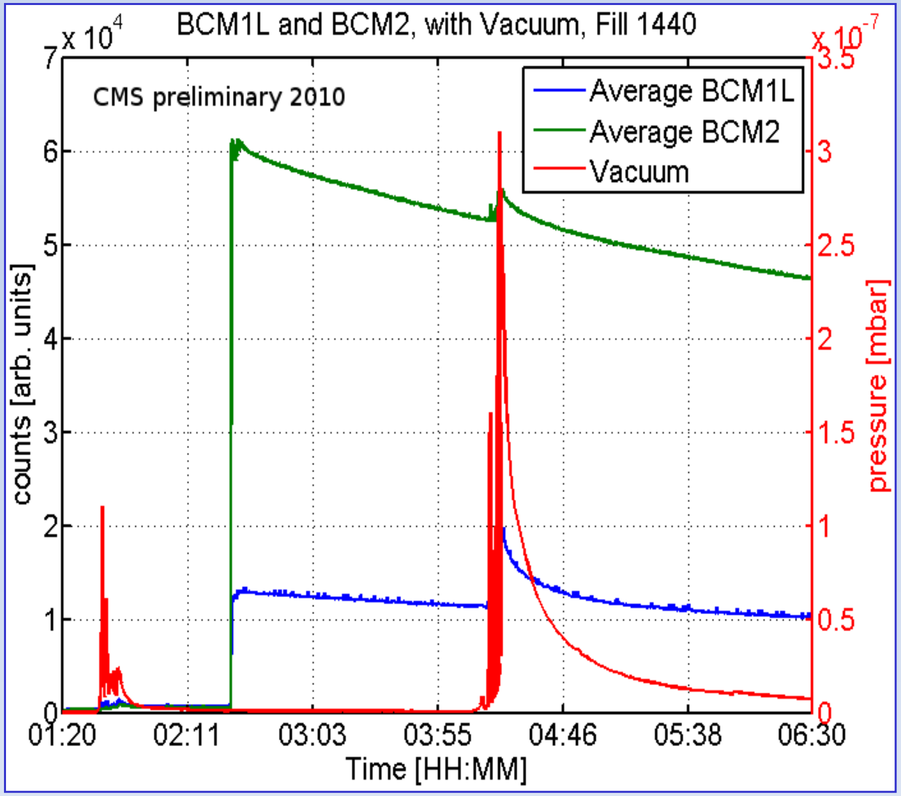


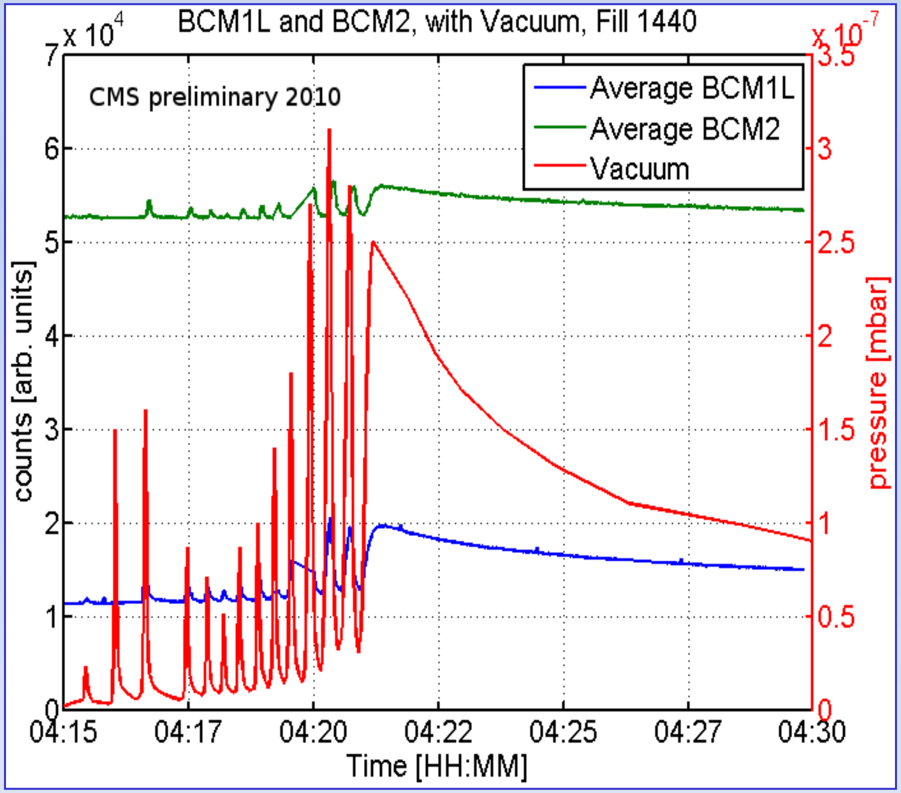


Beam Loss Measurement by the Experiments

These detectors are sensitive to:

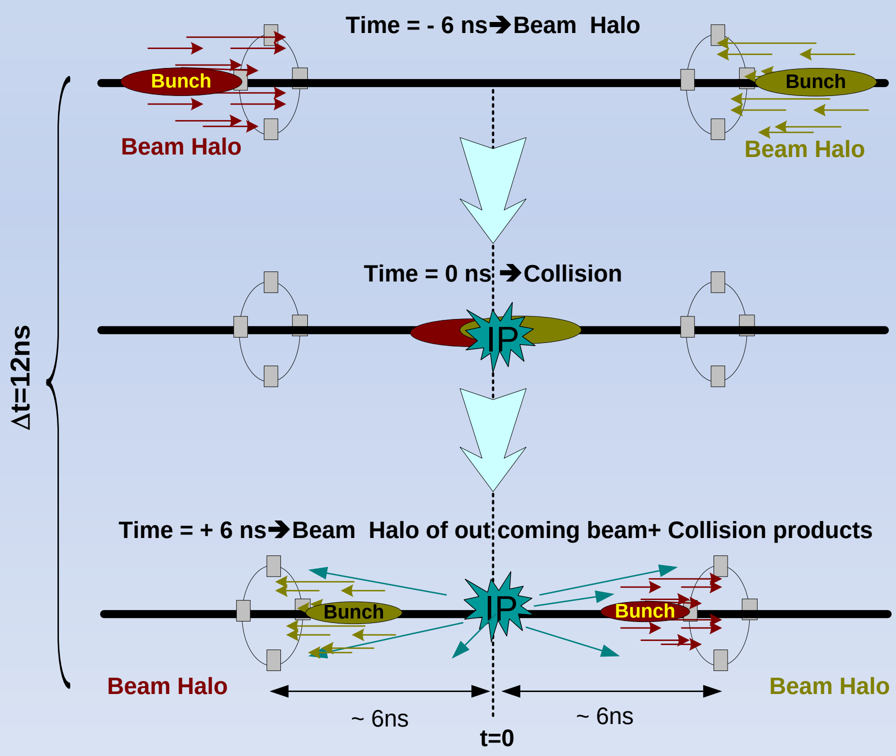
- luminosity and
- beam conditions that can cause high levels of backgrounds for the experiments



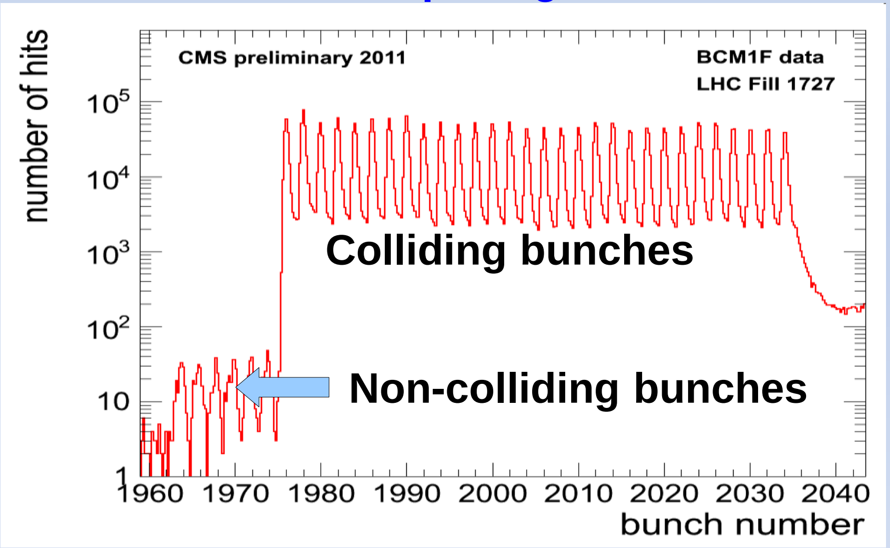


Beam Loss Measurement by the Experiments

If the Diamond detectors are coupled to fast front end electronics, then bunch-by bunch beam loss measurements are possible



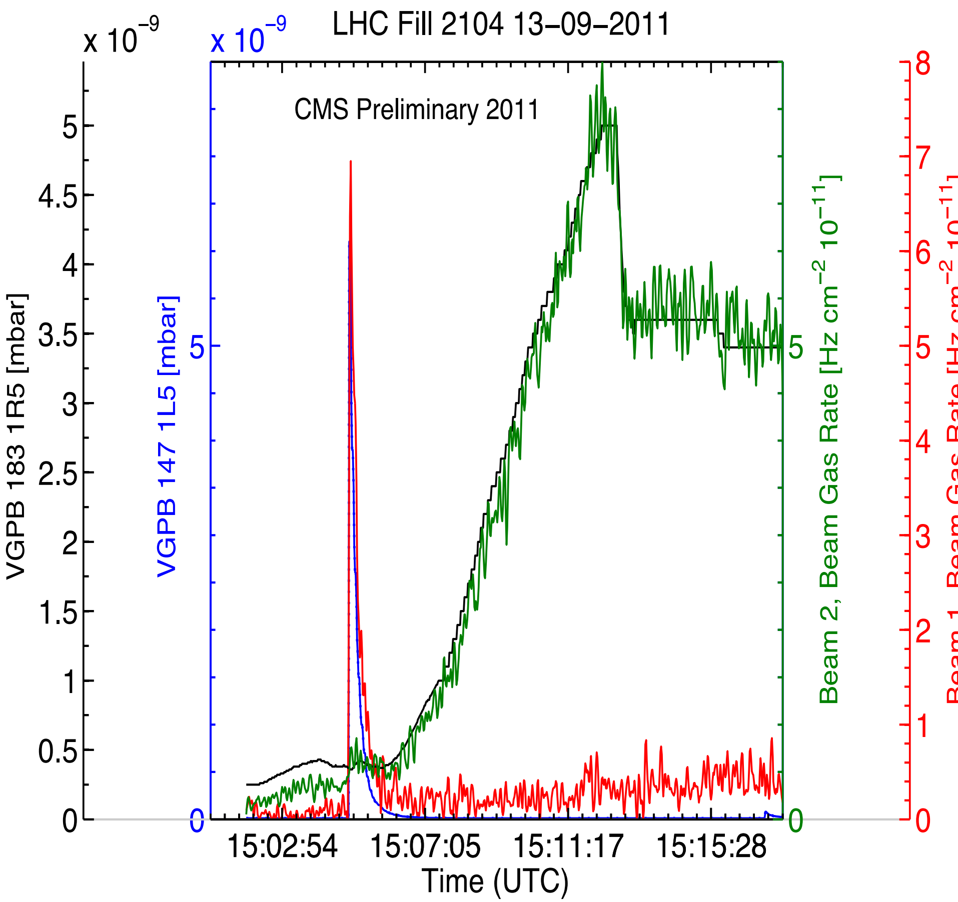
Zoom in 50ns bunch spacing from TDC data



Beam Loss Measurement by the Experiments

Interactions of the primary beam protons, with rest gas in the beam pipe (beam-gas interaction)

- Dominated by inelastic collisions small angles "parallel" to the inner pixel detector at low radius
- Flux relative to collisions $\sim 10^{-5}$ (pressure dependent)
- BCM1F measurement based on rate counting beam halo products from non-colliding bunches.

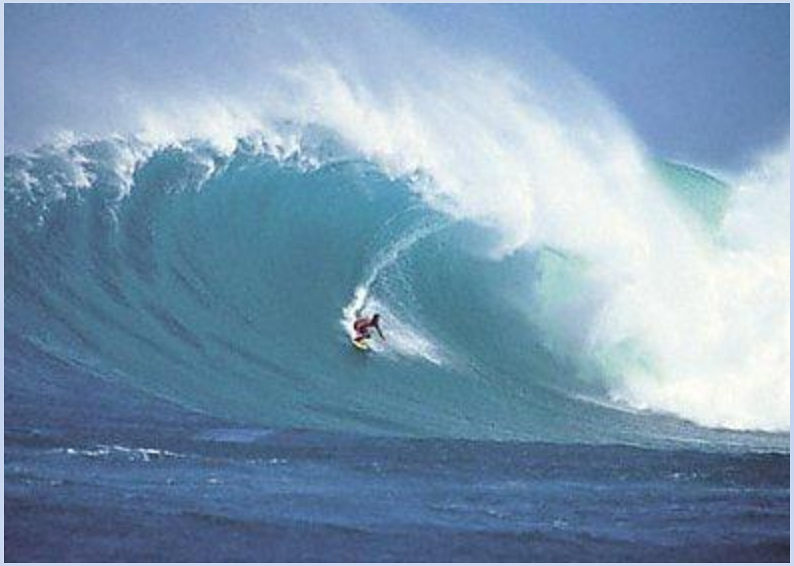


Measuring the longitudinal profile

How to accelerate Particles

DC Accelerator

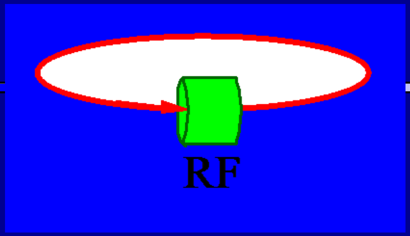
RF Accelerator



synchronize particle
with an
electromagnetic wave!

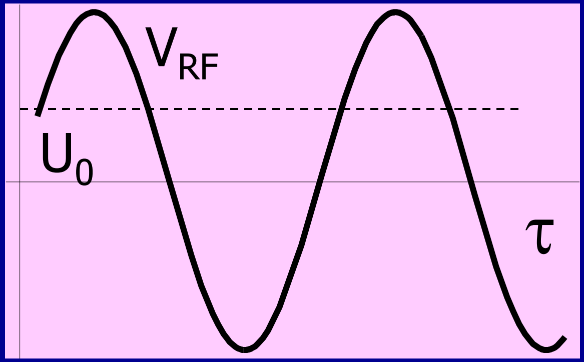
T. Lefevre

Longitudinal motion: compensating radiation loss U_0



$$f_{RF} = h \cdot f_0$$

- RF cavity provides accelerating field with frequency
  - h – harmonic number



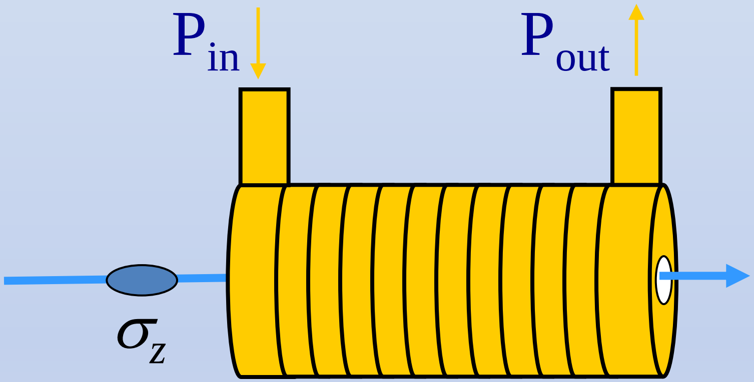
- The energy gain:

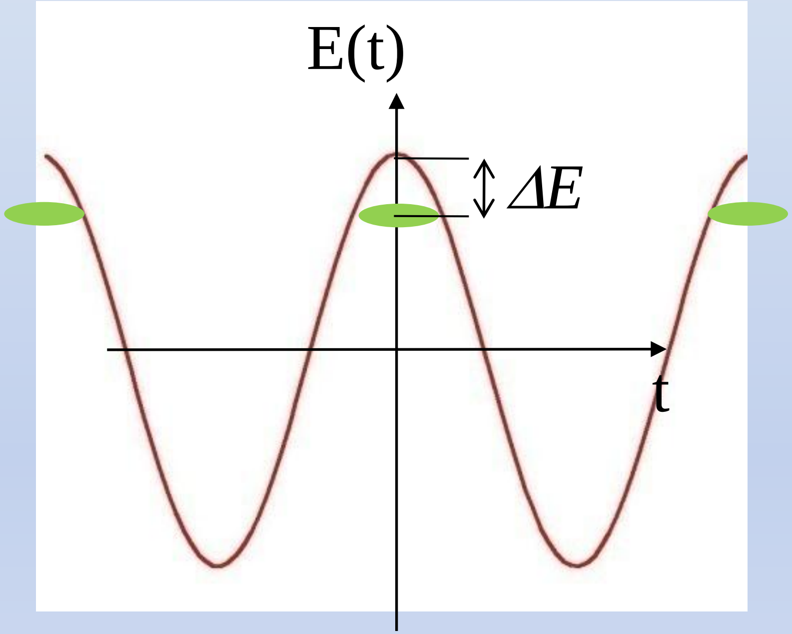
$$U_{RF} = eV_{RF}(\tau)$$

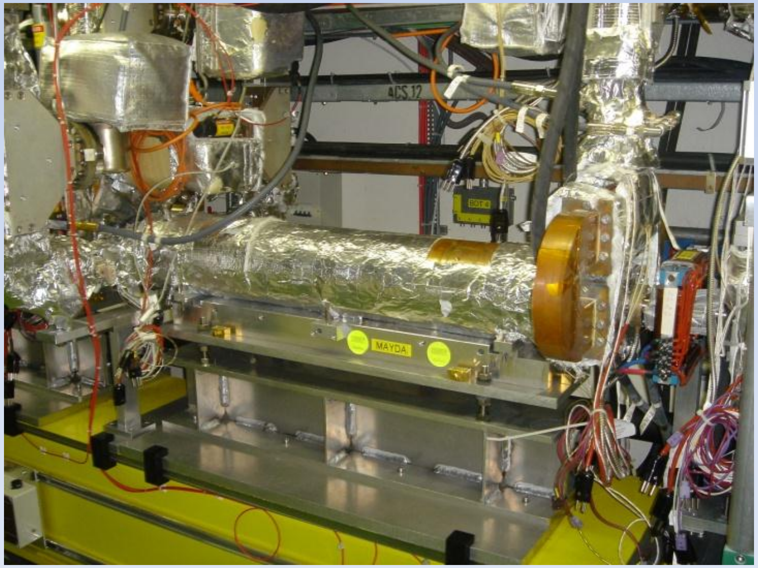
- Synchronous particle:
  - has design energy
  - gains from the RF on the average as much as it loses per turn U_0

Example of acceleration in a linear accelerator

Eq. 3GHz accelerating structures CTF3







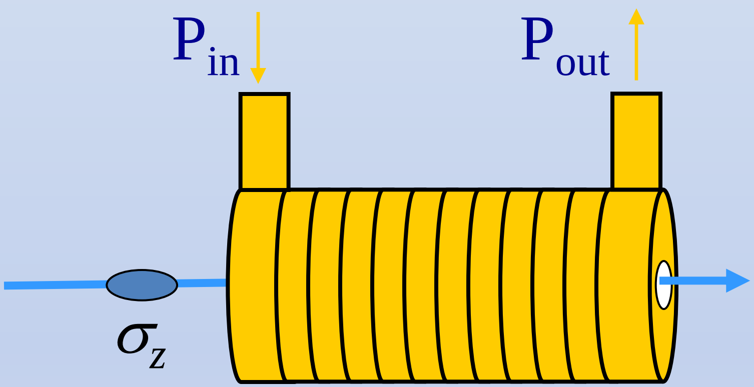
@ 3GHz

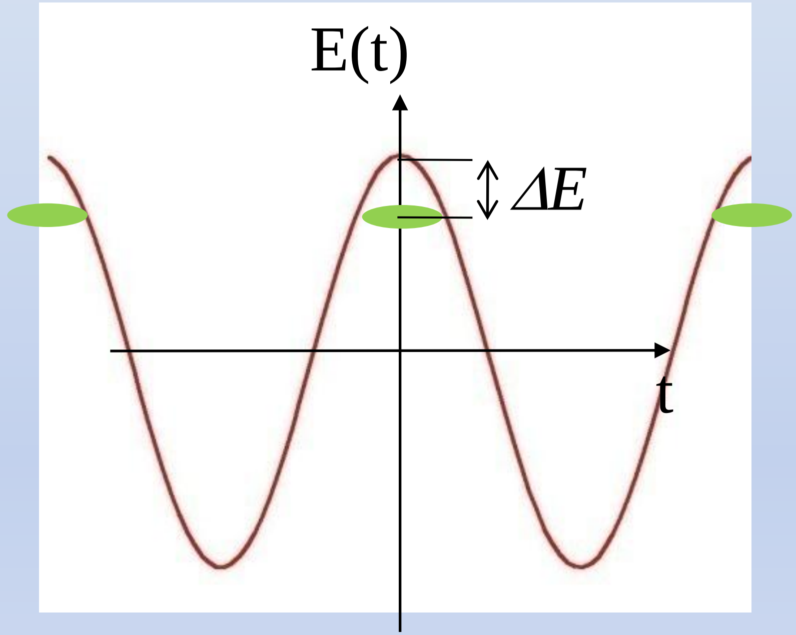
- 1 period ➔ "360 degrees" 333ps :
- Bunch spacing "1deg of 3 GHz"= 925fs
- "10 deg of 3 GHz"= 9.25 ps
- Cos(10 deg)=0.984

Longitudinal profile in accelerators

Example of acceleration in a linear accelerator

Eq. 3GHz accelerating structures CTF3





Question:

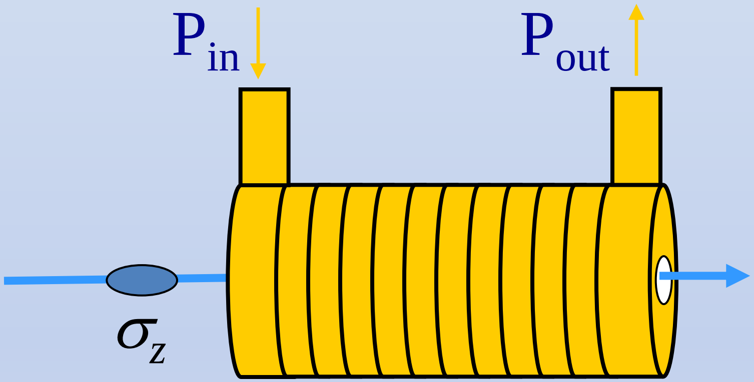
Given a 3 GHz accelerating RF electric field, and a bunch, with a Gaussian bunch length (r.m.s.) of 9.25 ps, sitting on the crest “maximum of electric field”, what is the total energy spread within the 1 sigma bunch length?

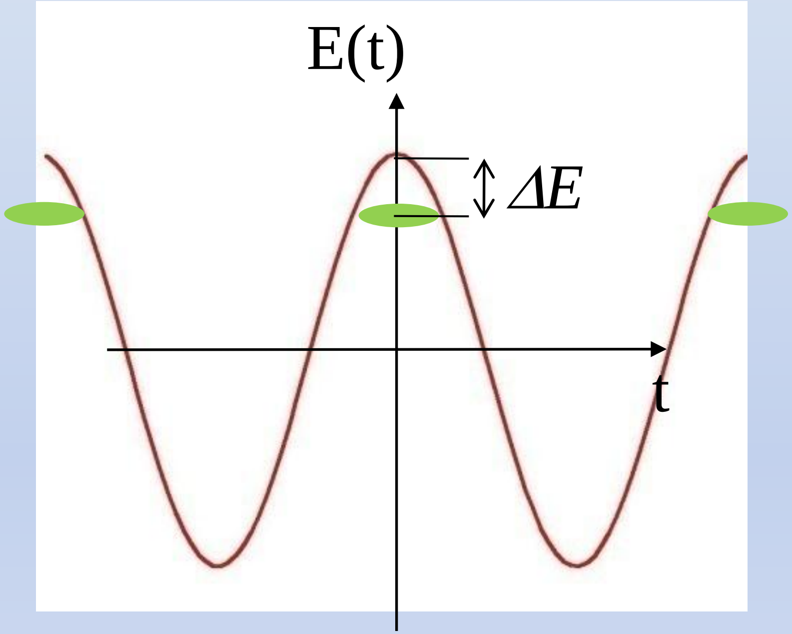
Answer:

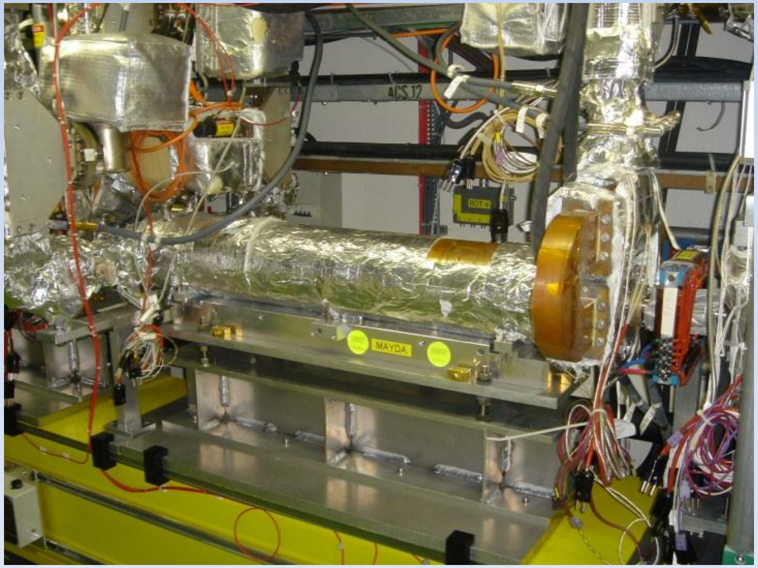
- Emax=E
- Emin=E*(0.984)
- $\Delta E/E \Rightarrow$ (Emax-Emin)/Emax =Emax(1-0.984)/Emax=1.6%

Example of acceleration in a linear accelerator

Eq. 3GHz accelerating structures CTF3

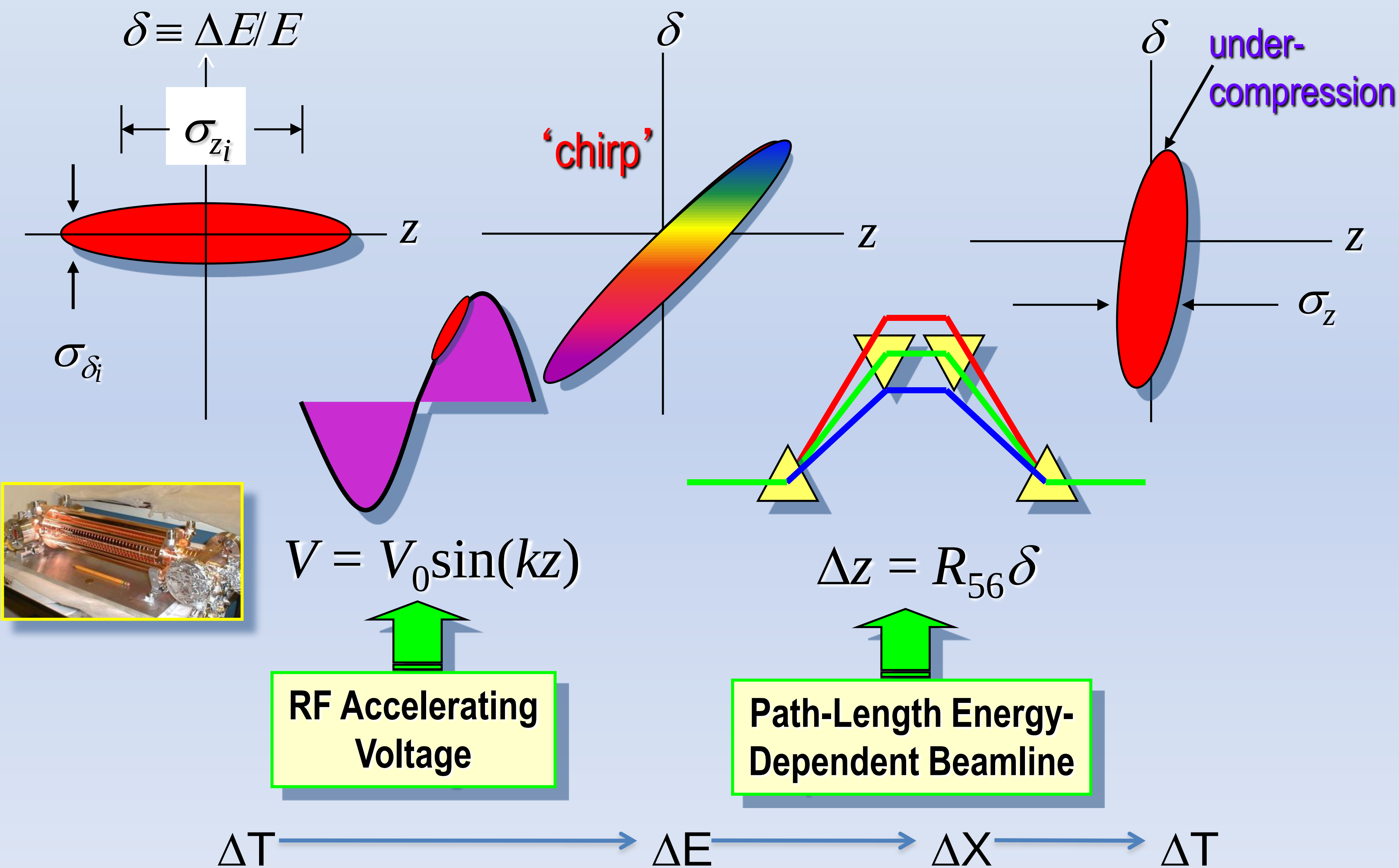




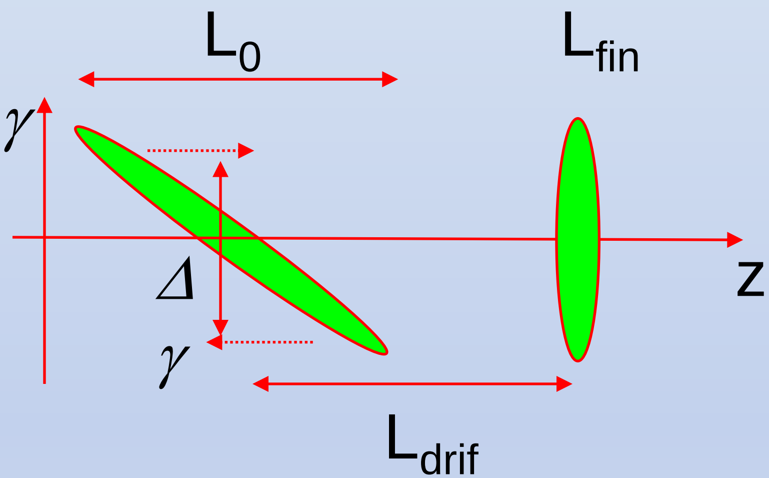


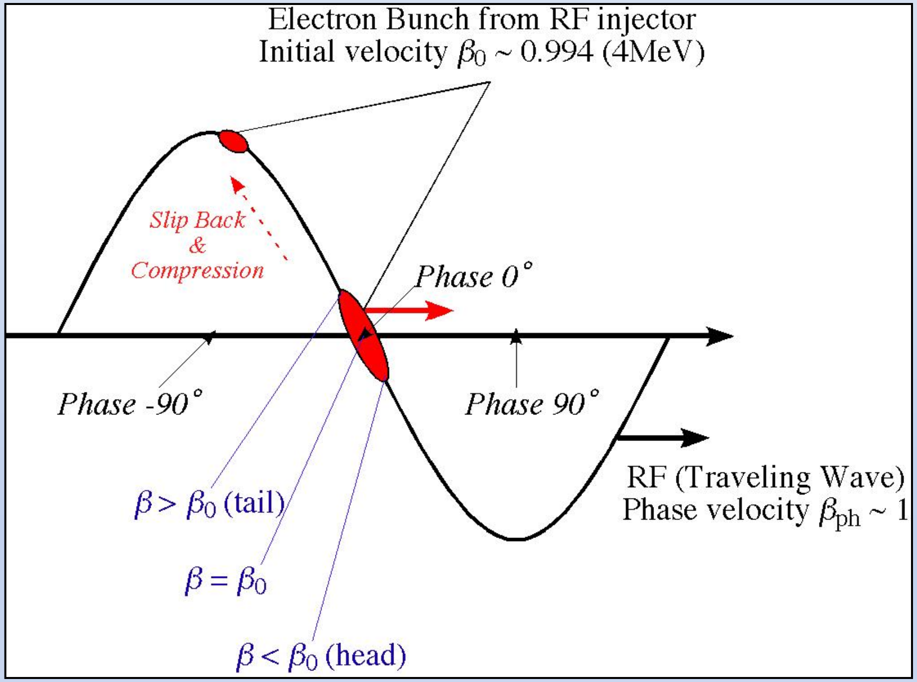
Bunch length and Energy spread are closely linked and we use this correlation in some longitudinal diagnostics

Compression Magnetic chicane



Short bunches by Ballistic/Velocity Compression





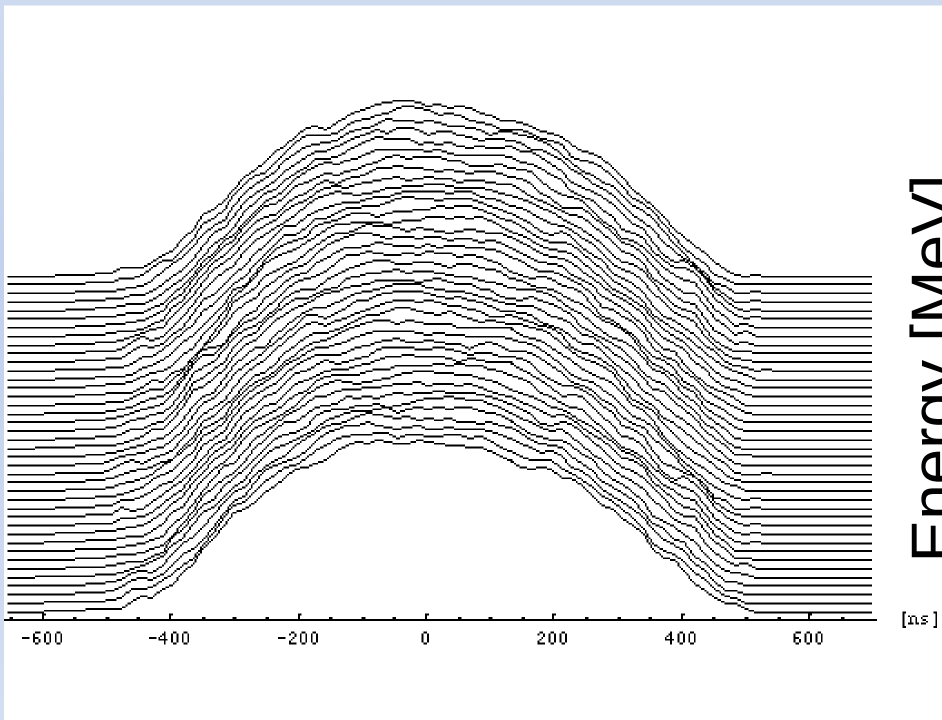
$\Delta T \rightarrow \Delta v_t$, $\Delta\gamma \rightarrow \Delta L \rightarrow \Delta T$

Provide a correlated velocity spread enough to produce, in a drift of length L_{drift} a *path difference* equal to ΔL

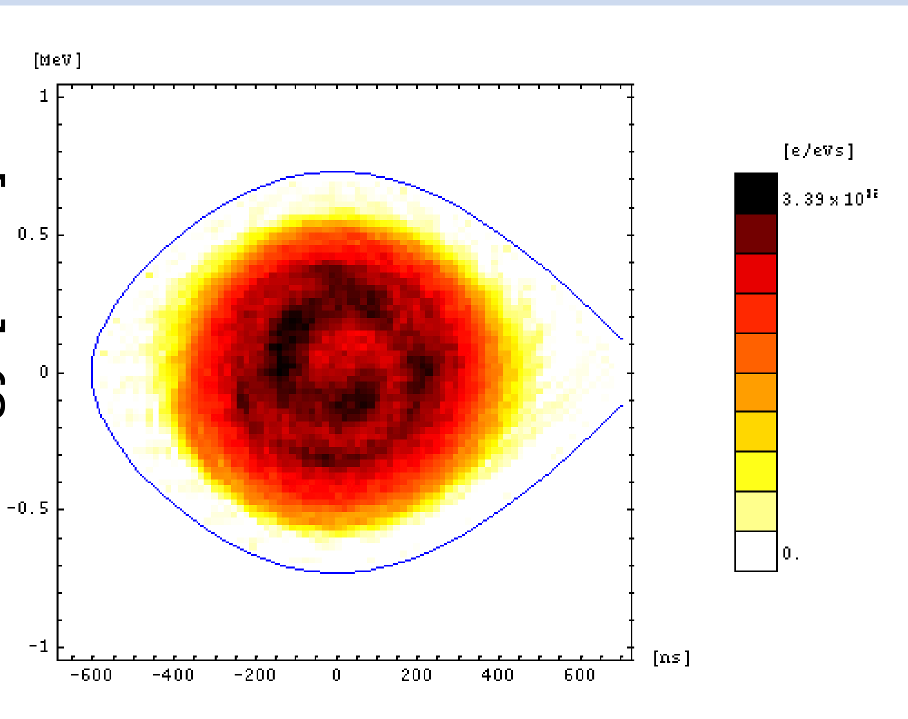
$$\Delta L = \left[\frac{L_{drift}}{\bar{\gamma}^2}\right]\frac{\Delta\gamma}{\bar{\gamma}}$$

P. Piot *et al*, PRSTAB 6 (2003) 033503
S.G. Anderson *et al*, PRSTAB 8 (2005) 014401

Reconstructed Longitudinal Phase Space



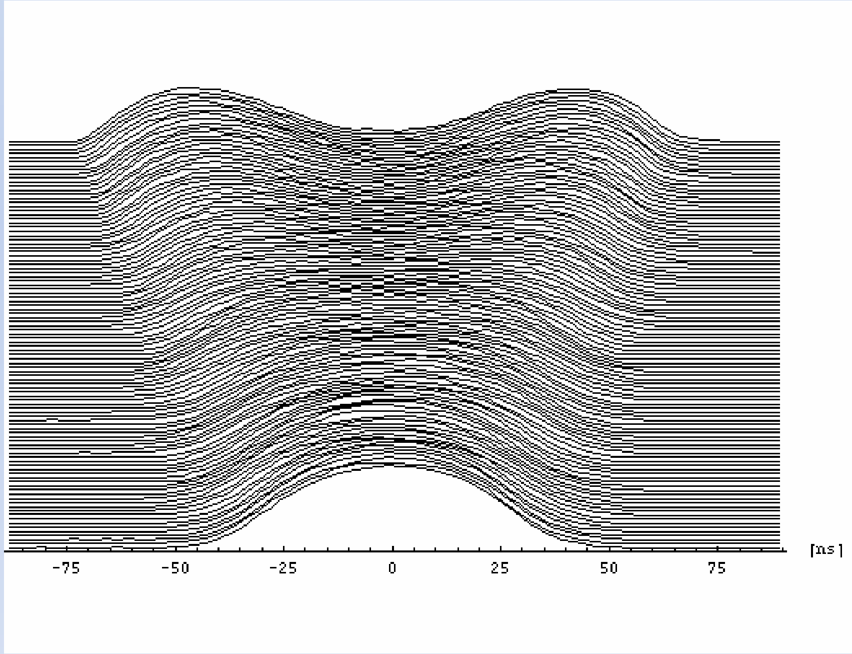
Energy [MeV]



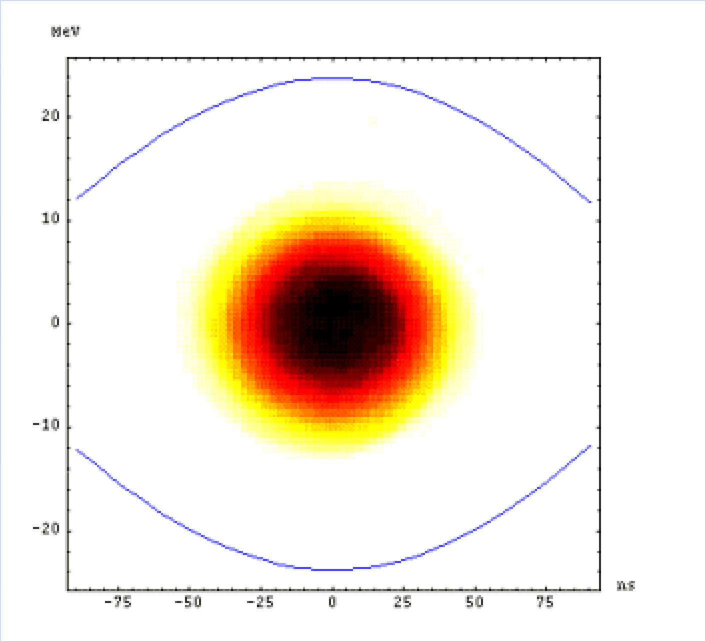
Time [ns]

U. Raich,
ASP2012

Reconstructed Longitudinal Phase Space during bunch splitting



Energy [MeV]



Time [ns]

U. Raich, ASP2012

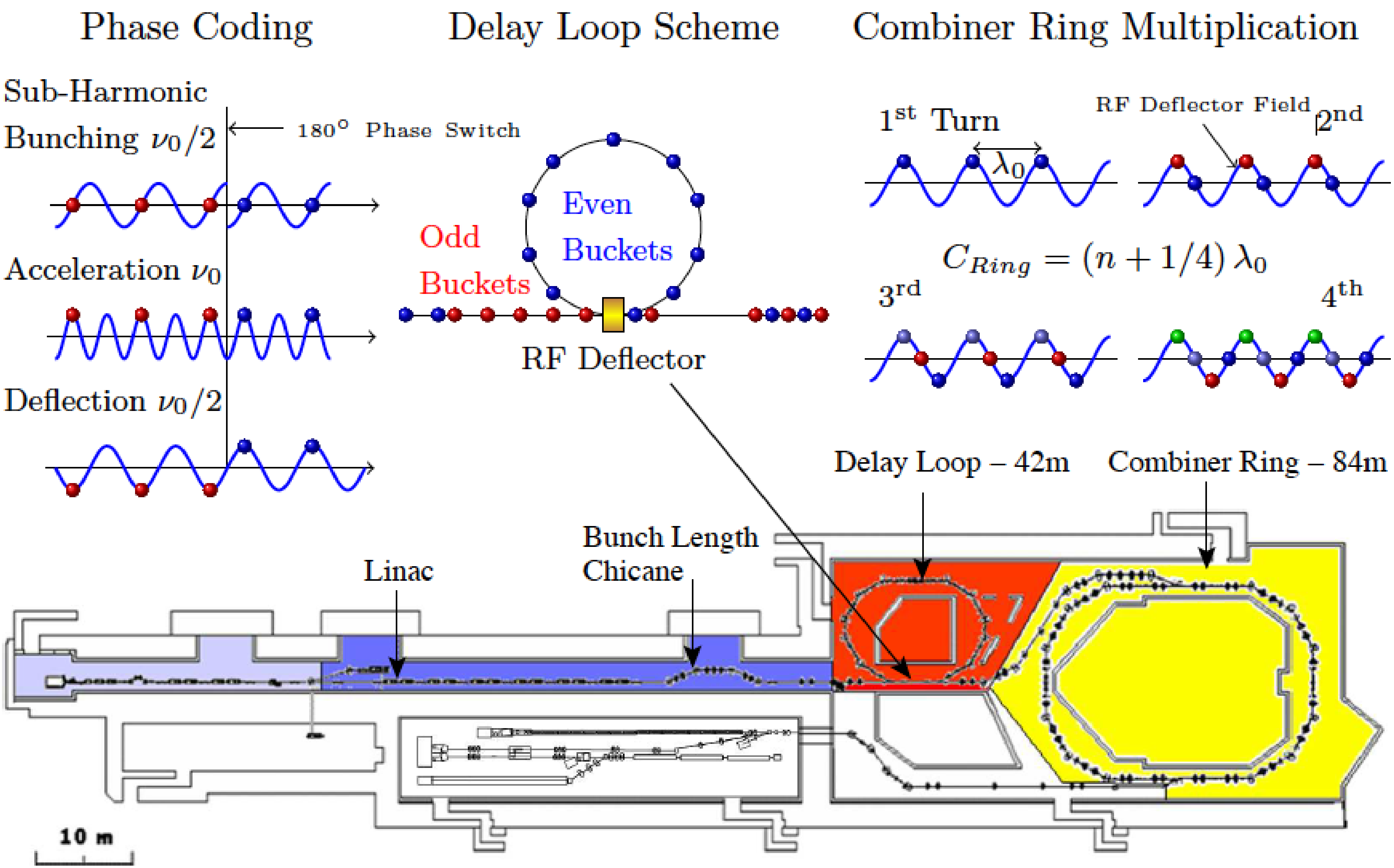


Figure 1. CTF3 complex and drive beam generation scheme.

Longitudinal profile in accelerators

Within space charge limits:

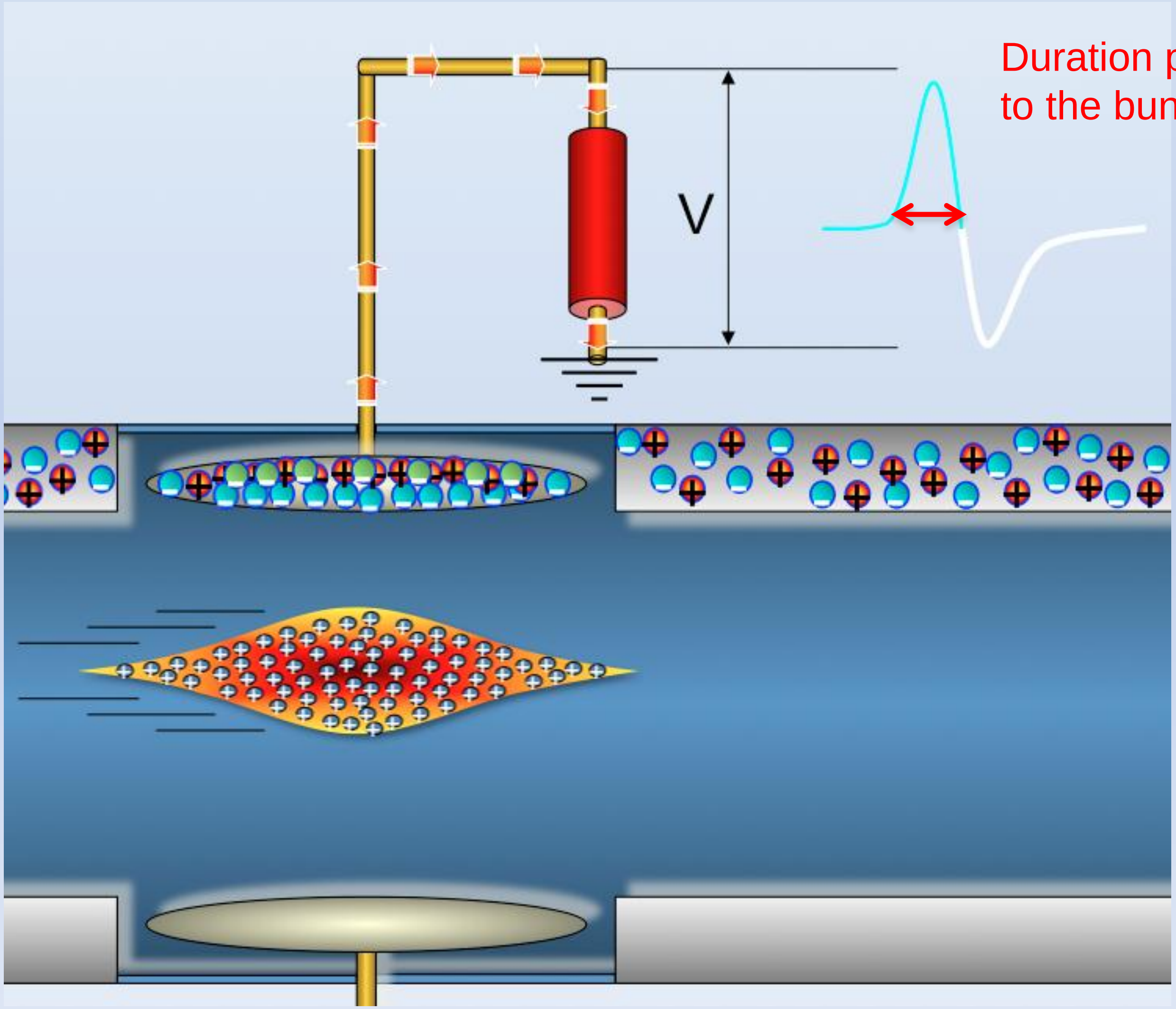
- Develop machine with highest luminosity for a e- linear collider
- Brightness for a radiation source or neutron source

H^- @ SNS	100ps
H^+ @ LHC	230ps
e^- @ ILC	500fs
e^- @ CLIC	130fs
e^- @ XFEL	80fs
e^- @ LCLS	60fs
e^- @ LCLS (low charge)	< 1-3 fs (indirect measurement – diagnostics are not that fast! Currently best resolution ~ 10 fs)

T. Lefevre

Longitudinal Measurements

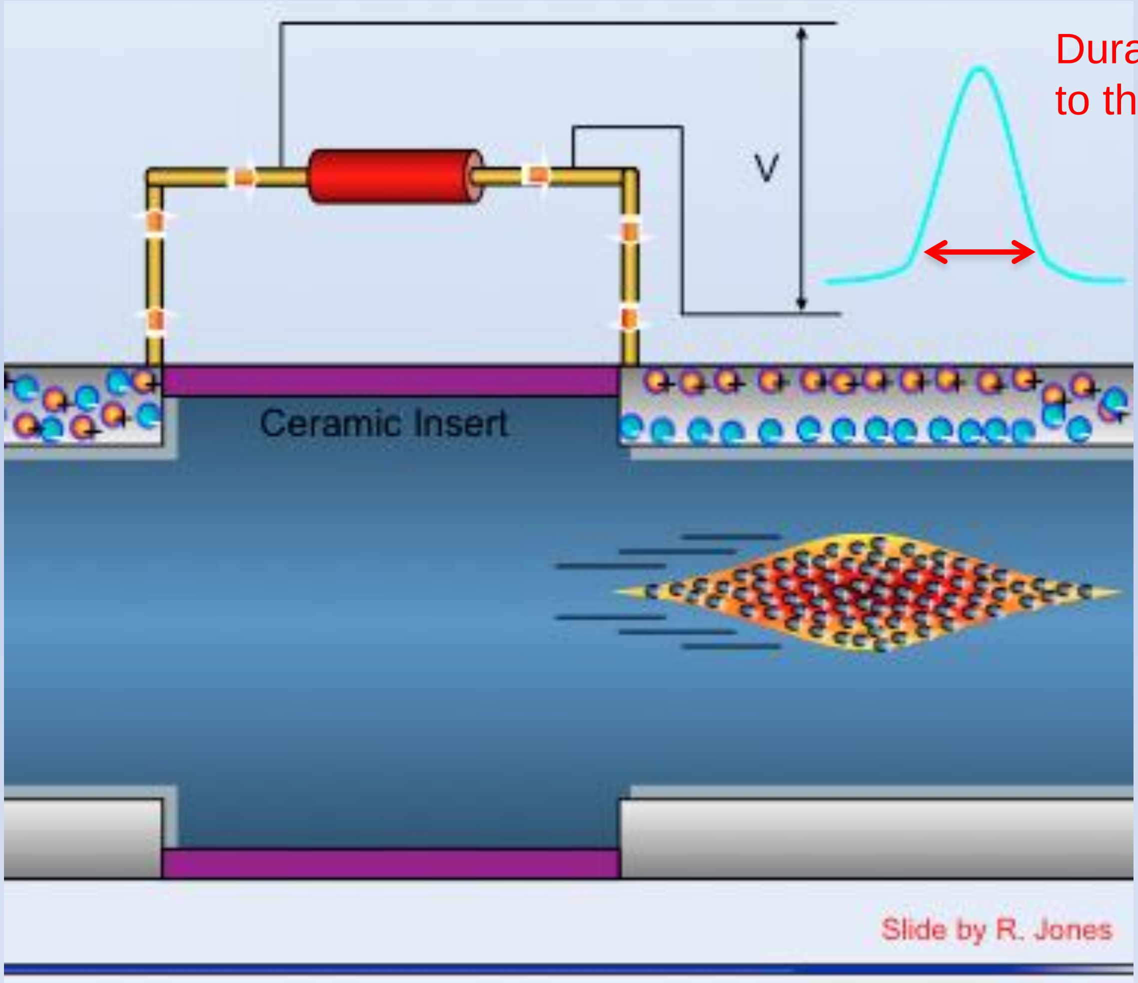
The bunch length is encoded in this differential BPM signal



Duration proportional
to the bunch length

Longitudinal Measurements

The bunch length is encoded in this proportional wall current signal



Duration proportional to the bunch length

So, are we done? Do we need additional diagnostics to measure the bunch length?

What about the longitudinal profile?

Why the fuss about measuring the longitudinal profile, if one can measure it with a BPM?

Proton synchrotron:

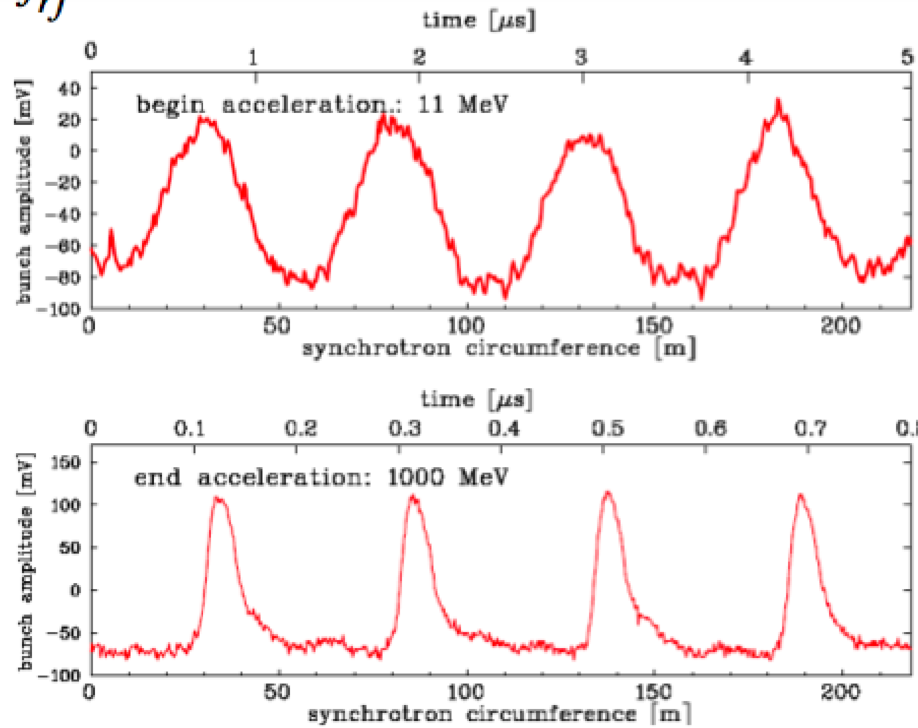
1 MHz < f_{rf} < 30 MHz typically

R=1 MΩ for large signal i.e. large Z_t

C≈100 pF ⇒ $f_{cut} = 1/(2\pi RC) \approx 10$ kHz

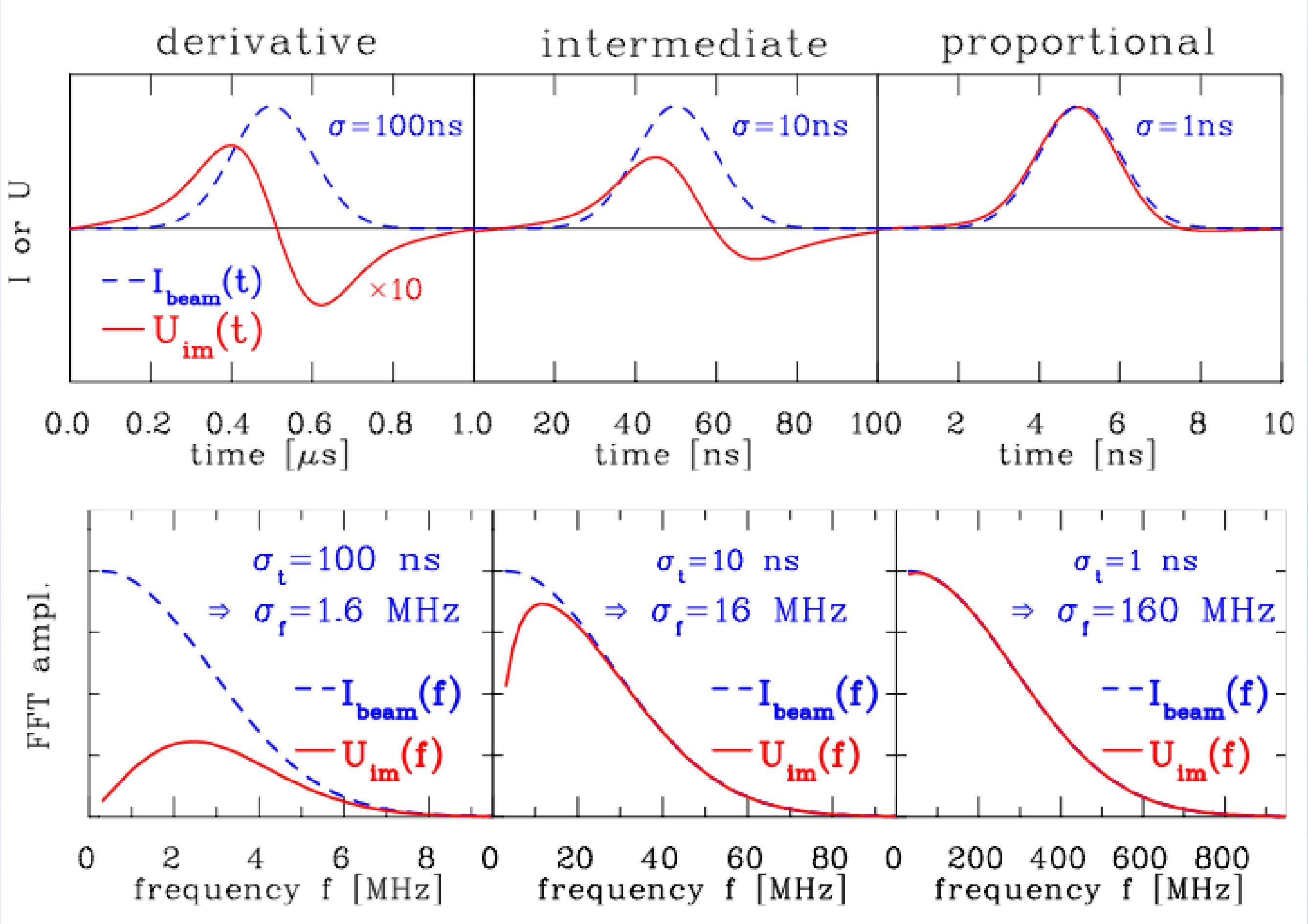
Example: non-relativistic GSI synchrotron

f_{rf}: 0.8 MHz → 5 MHz



P. Forck, P. Kowina, D. Liakin, GSI, CAS, May 30th, 2008

Longitudinal Profile from "BPM" type measurement



- The pick-up signal is a direct image of the bunch time structure, only when the f_beam >> f_low_cutoff = 1/(RC)
- And f_high_cutoff >> highest frequency component in the beam spectrum
- Satisfying both these criteria, especially for machines with short bunches << 1ns is difficult or impossible

P. Forck, P. Kowina, D. Liakin, GSI, CAS, May 30th, 2008

Short bunch length measurements

RF manipulation

Use RF devices to convert time information into spatial information

Laser-based beam diagnostics

Using short laser pulses and sampling techniques

Incoherent EM radiation

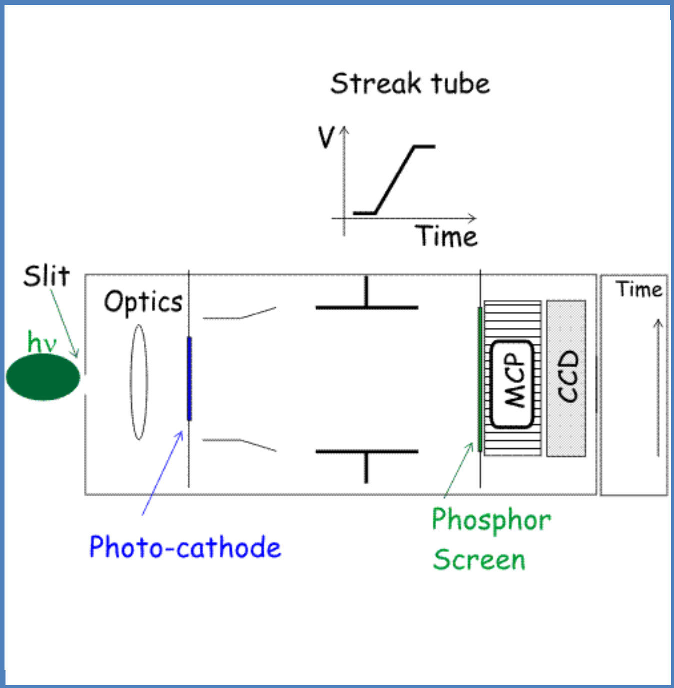
1. Produce visible light
2. Analyse the light pulse using dedicated instruments

Coherent EM Radiation

Based on the measurement of the bunch frequency spectrum

Slide T. Lefevre

Streak Camera



'Streak cameras uses a time dependent deflecting electric field to convert time information in spatial information on a CCD'

Mitsuru Uesaka et al, ***NIMA 406 (1998) 371***

200fs time resolution obtained using reflective optics and 12.5nm bandwidth optical filter (800nm) and the Hamamatsu FESCA 200

<u>Limitations : Time resolution of the streak camera :</u>

(i) Initial velocity distribution of photoelectrons : *narrow bandwidth optical filter*
(ii) Spatial spread of the slit image: *small slit width*
(iii) Dispersion in the optics

Slide T. Lefevre

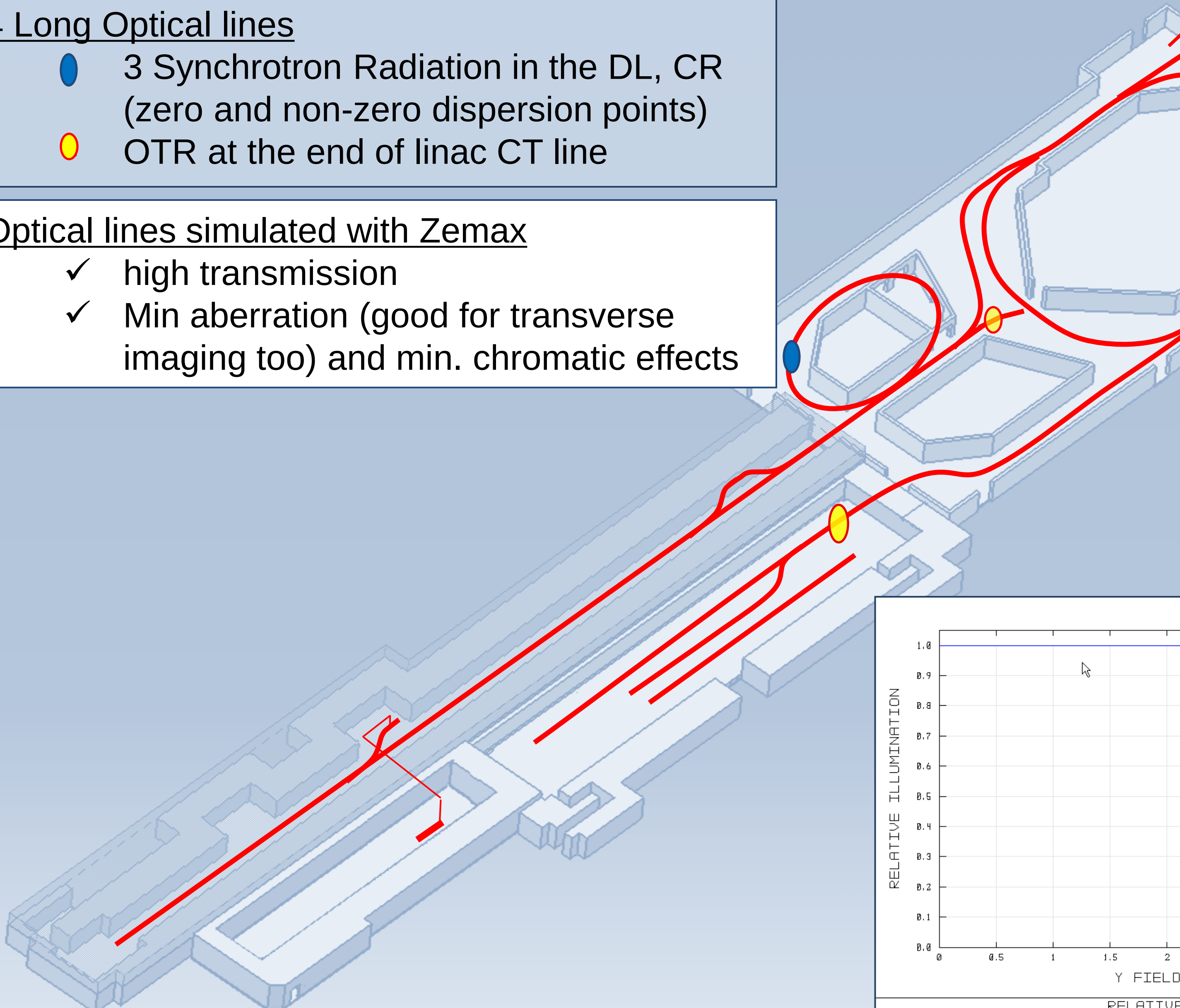
Streak cameras in CTF3

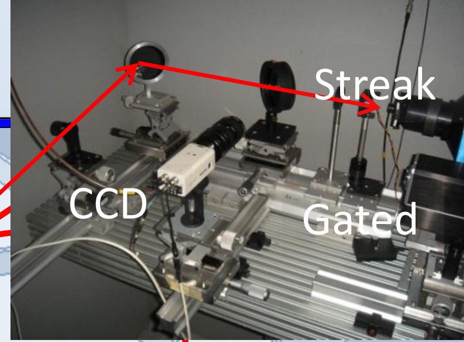
<u>4 Long Optical lines</u>

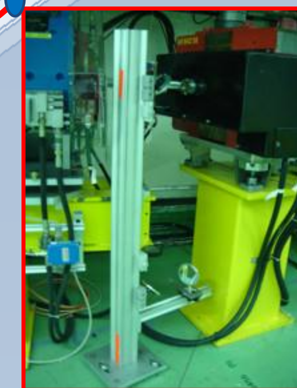
- 3 Synchrotron Radiation in the DL, CR (zero and non-zero dispersion points)
- OTR at the end of linac CT line

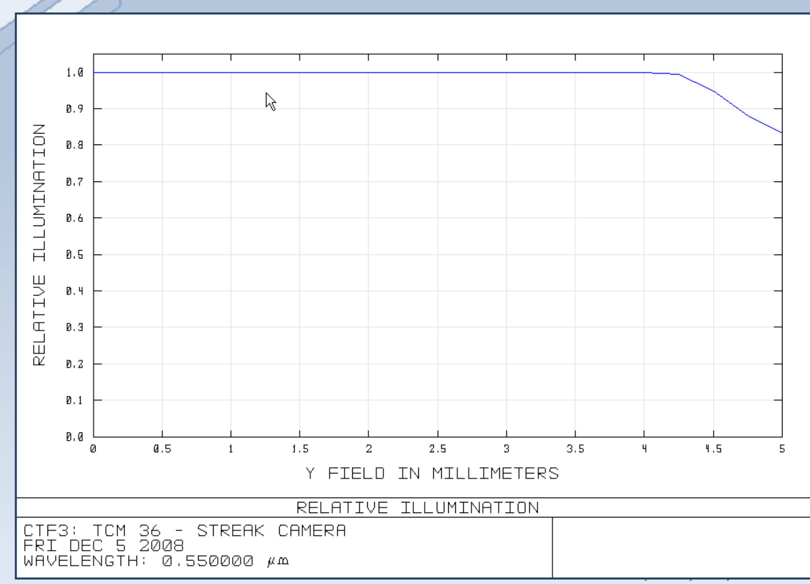
<u>Optical lines simulated with Zemax</u>

- ✓ high transmission
- ✓ Min aberration (good for transverse imaging too) and min. chromatic effects



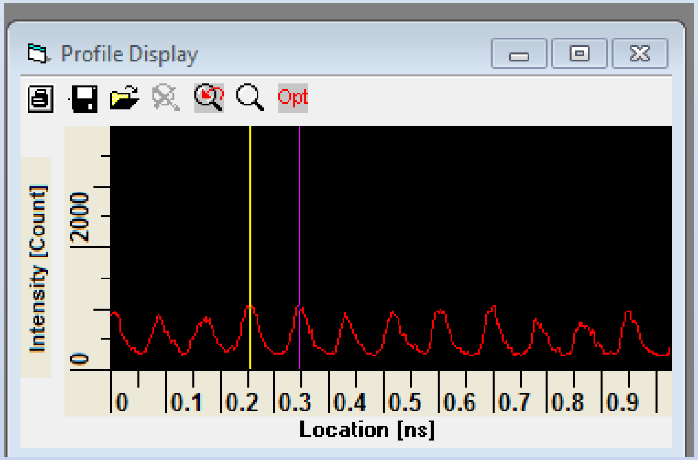


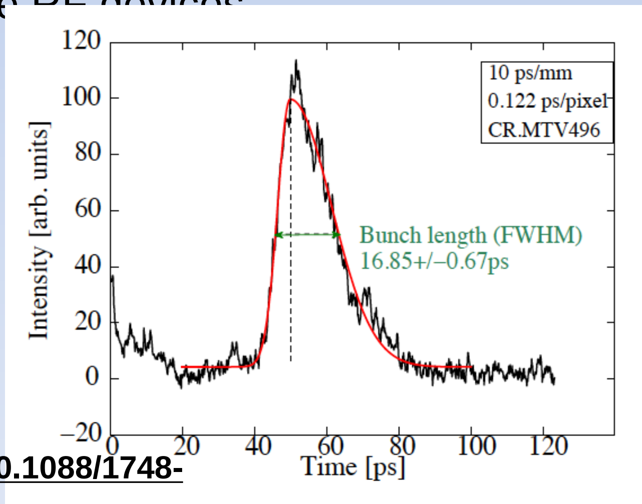




Streak Camera

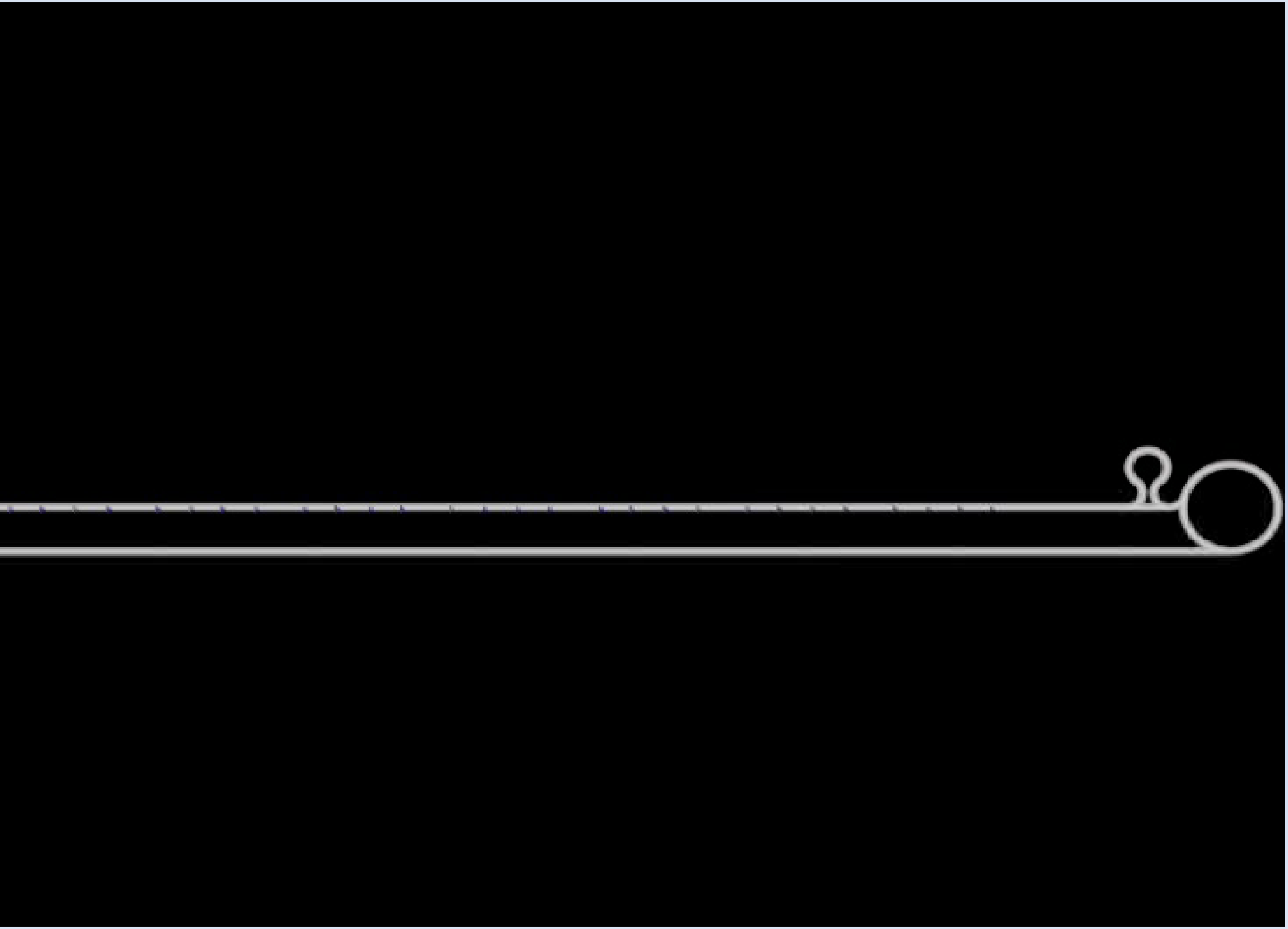
- CTF3 experience
  - 2/3 ps resolution with old “LEP” camera
  - expect 300 fs with FESCA camera for short bunches
- Error contributions:
  - Timing calibration of sweep slope (resolution streak tube)
  - Jitter streak trigger (removed if single shot)
  - size in focus (slit)
  - Error from fit
  - 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



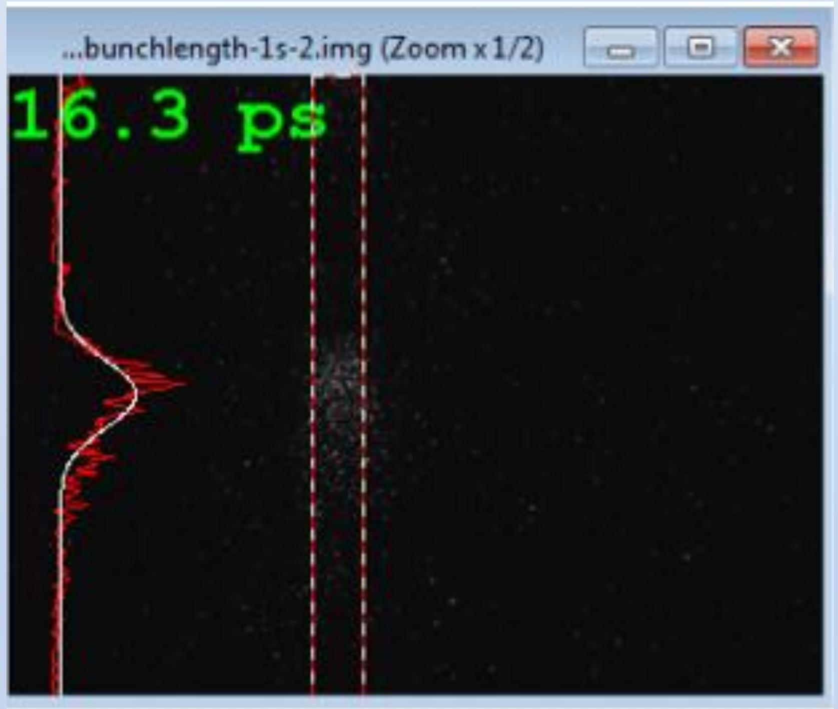


Dabrowski et al 2012 JINST **7** P01005 **doi:10.1088/1748-0221/7/01/P01005**

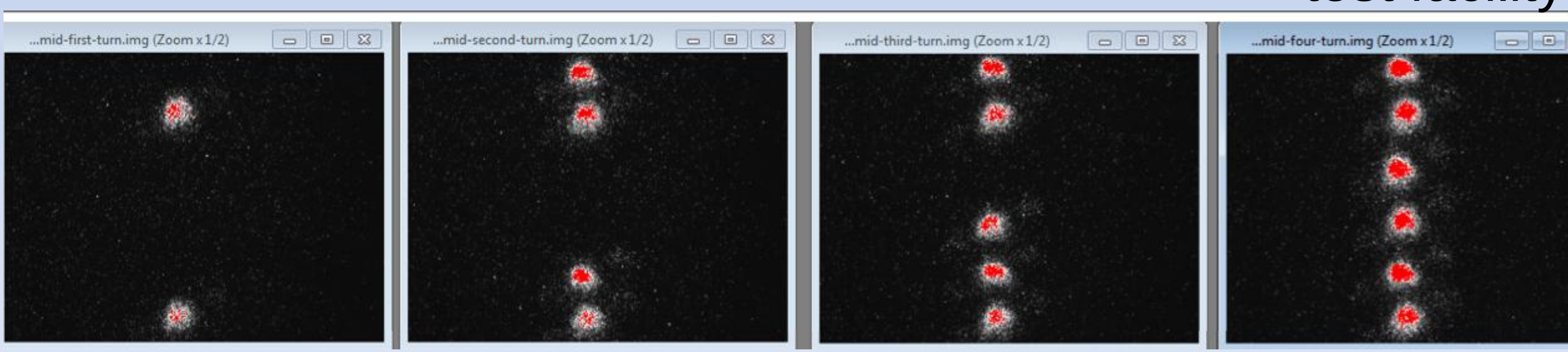
Drive Beam Generation Scheme



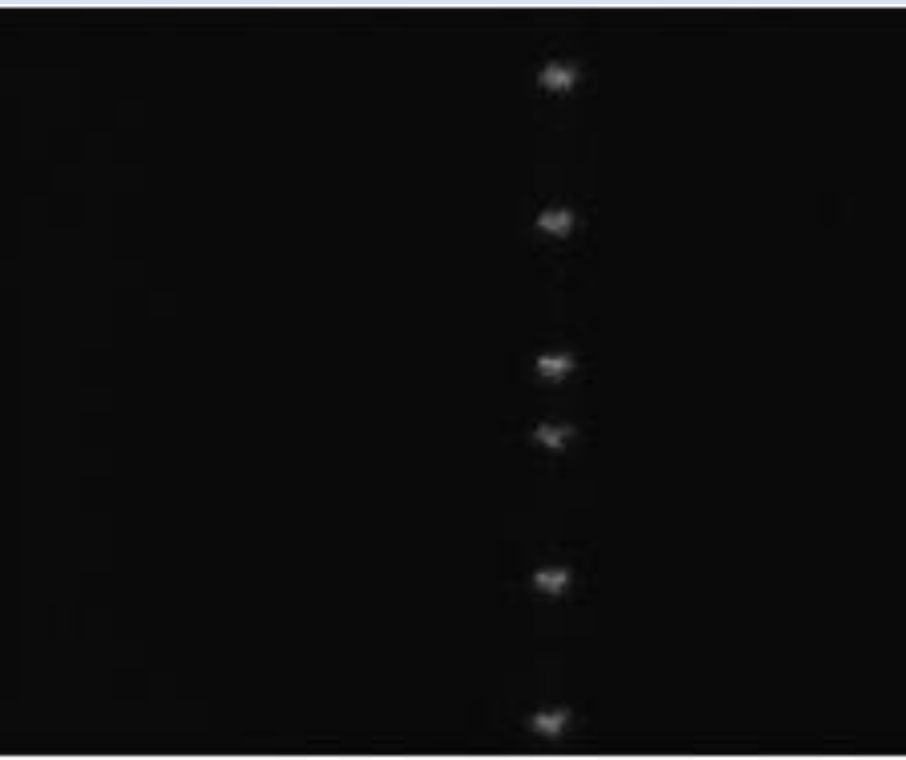
Courtesy Alexandra Anderssen

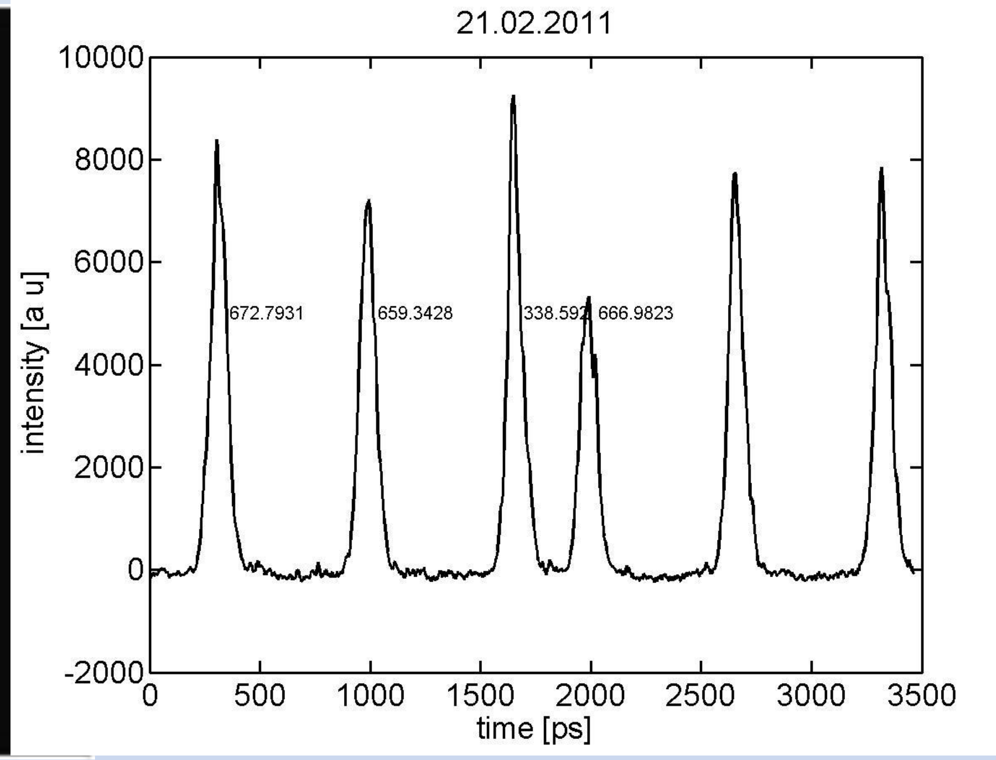


From CLIC test facility



“Phase coding” measurement of the PHIN Laser with Steak Camera





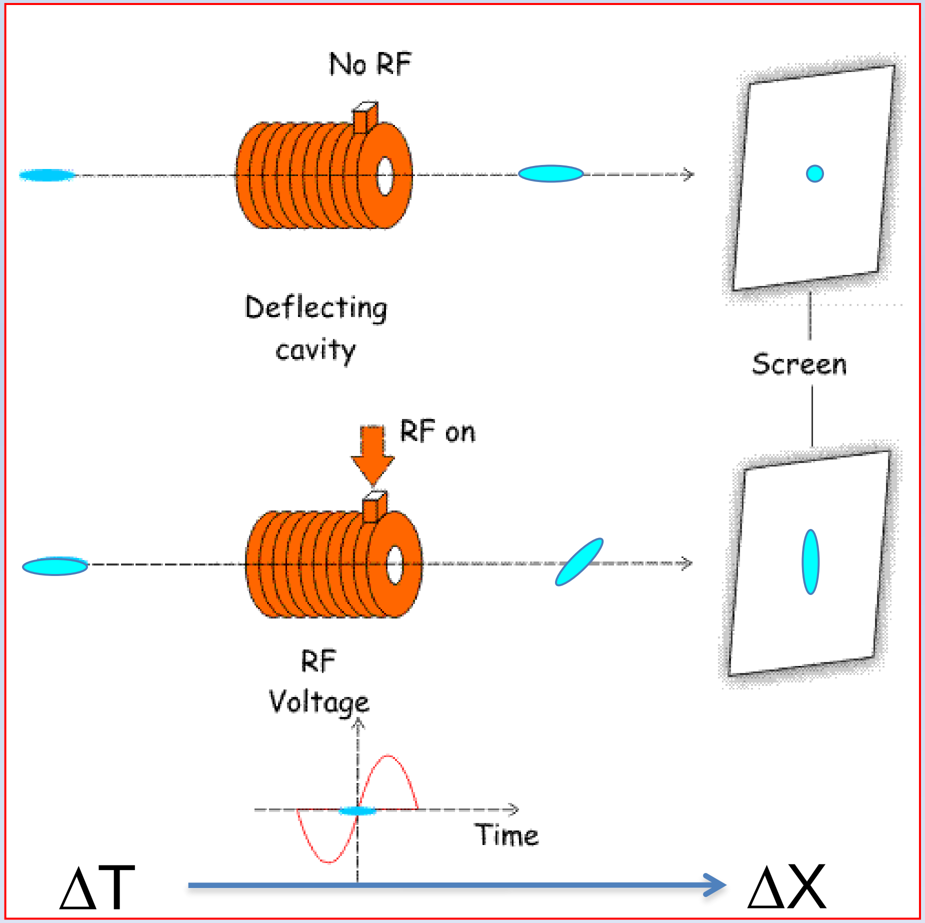
Measurement of the electron beam as demonstration of “phase coding”:

333ps switching between two consecutive bunches measured with the Cherenkov-radiation.
Fast amplitude variations are due to laser oscillator noise.

Marta Csatari et al, IPAC11

RF Deflecting Cavity

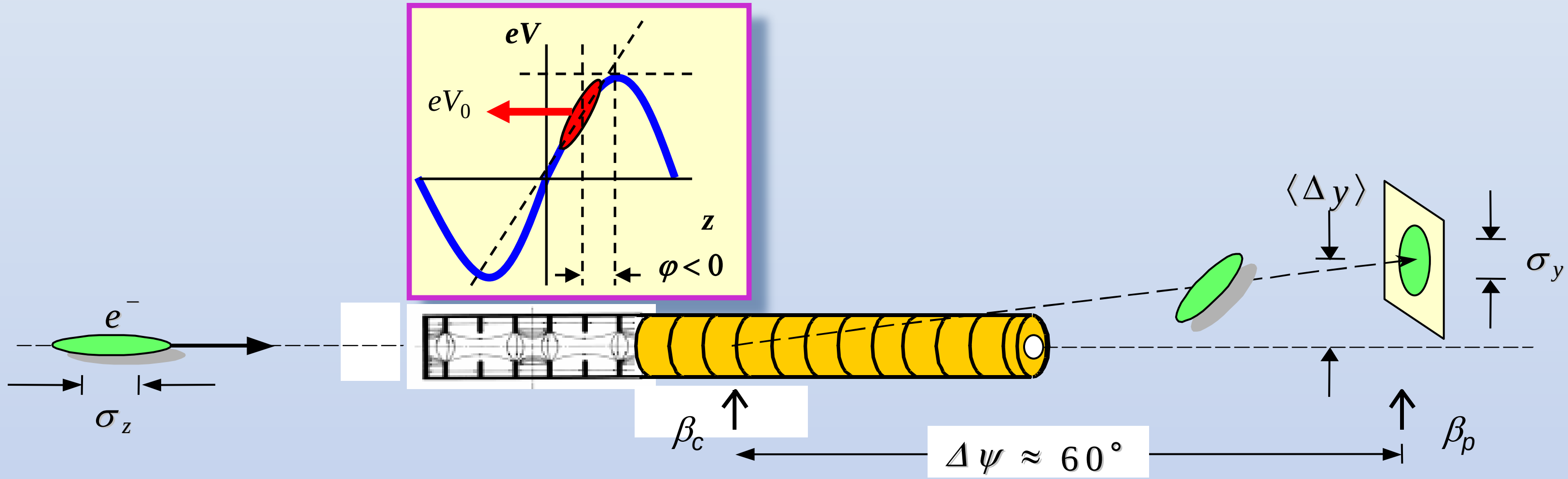
- The RF Deflector acts as relativistic streak tube.
- The **time varying** deflecting field of the cavity transforms time into a spatial information
- The bunch length correlates to the beam size at a downstream position



Slide T. Lefevre

P. Emma et al, LCLS note LCLS-TN-00-12, (2000)

RF Deflecting Cavity



Beam profile RF off

Deflecting Voltage

Beam profile RF on

$$\sigma_y = \sqrt{\sigma_{y_0}^2 + \sigma_z^2 \beta_c \beta_p \left(\frac{2\pi}{\lambda} \frac{eV_0}{E_0} \sin(\Delta\Psi) \cos(\varphi) \right)^2}$$

Bunch length

Beta function at cavity and profile monitor

RF deflector wavelength

Beam energy

Betatron phase advance (cavity-profile monitor)

$\sin\Delta\psi = 1$, β_p small
Make β_c large

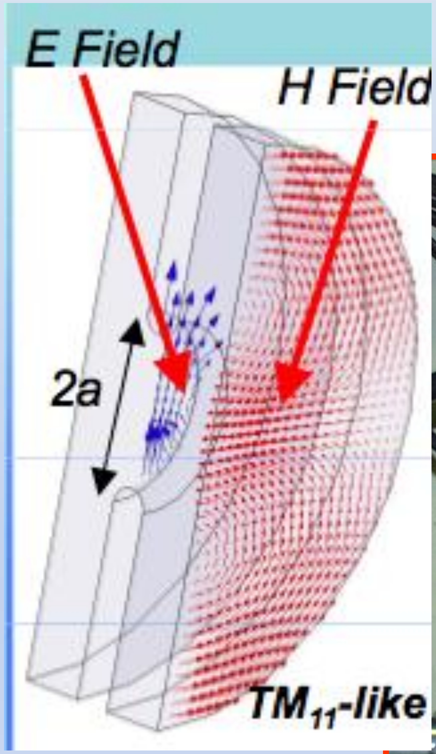
RF deflector phase

Beam offset on the screen

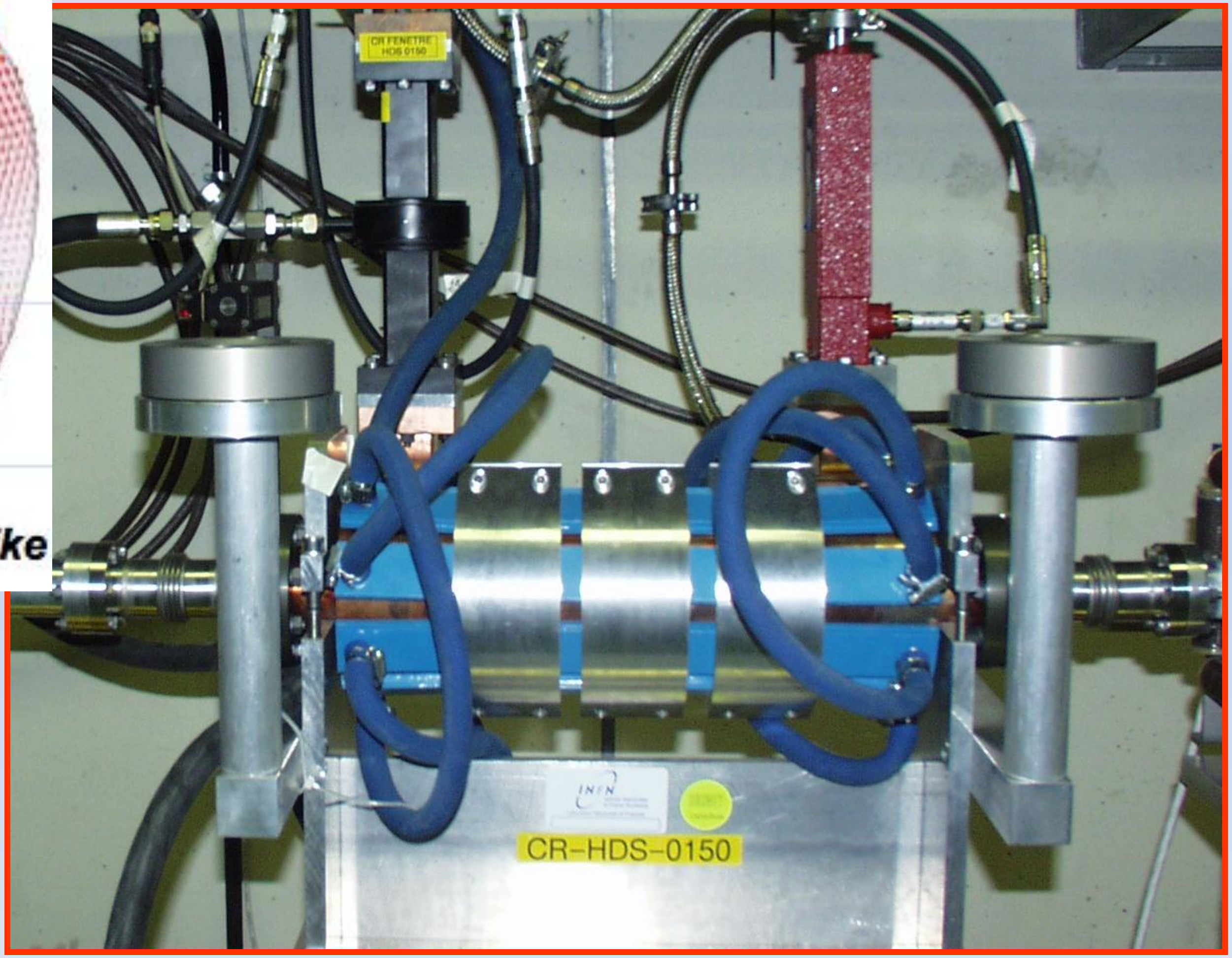
$$\Delta y(z) \approx \frac{eV_0}{E_0} \cdot \sqrt{\beta_c \beta_p} \sin(\Delta\Psi) \left(\frac{2\pi}{\lambda} - z\cos(\varphi) + \sin(\varphi) \right)$$

Slide T. Lefevre

RF Deflecting Cavity



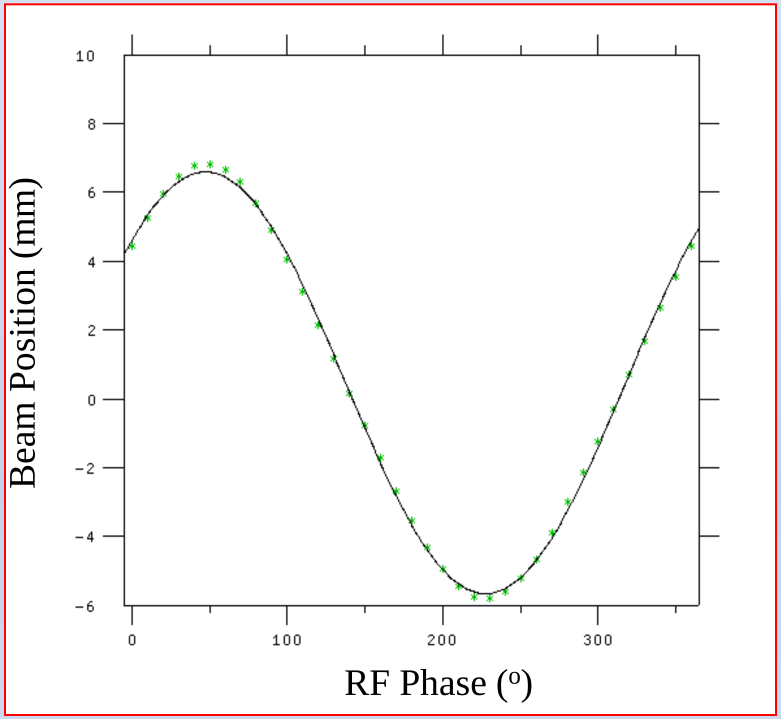
CTF3 – 33 cm

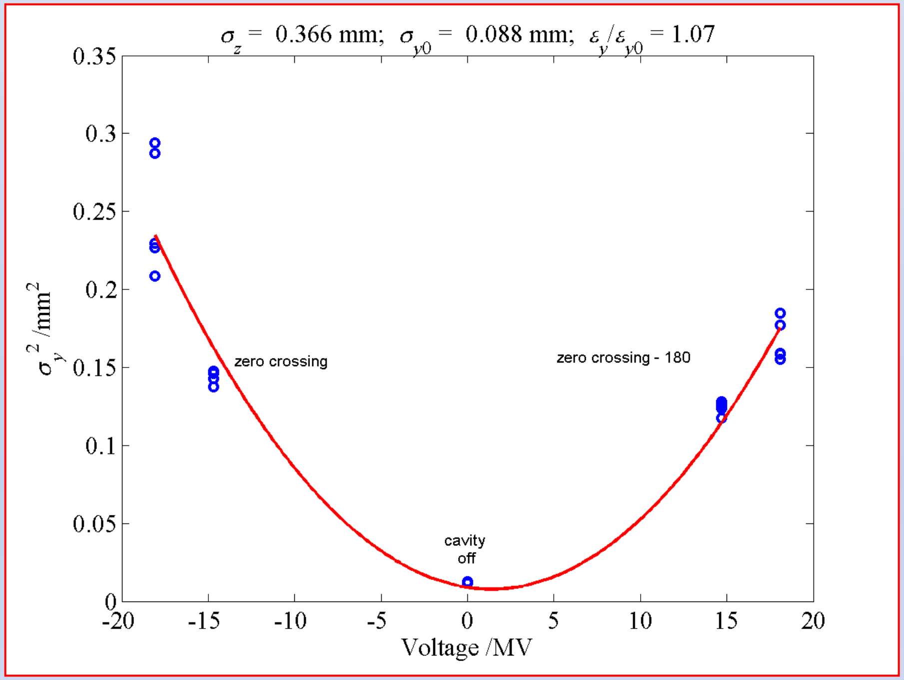


RF Deflecting Cavity

LOLA @ Flash – 3.6 m

Calibration of RF Deflector



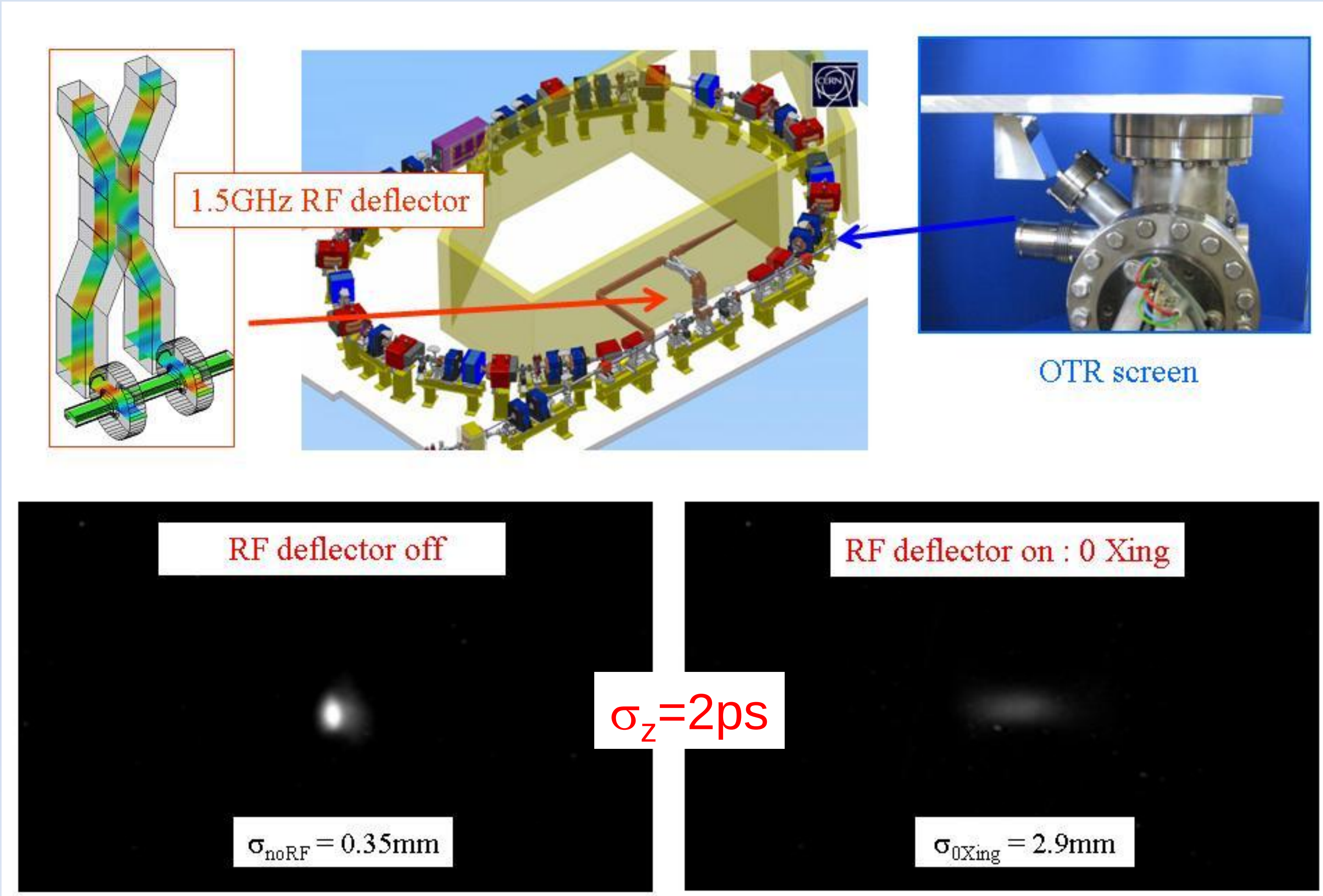


Use a Beam Position Monitor close to the Profile monitor to calibrate the deflection angle

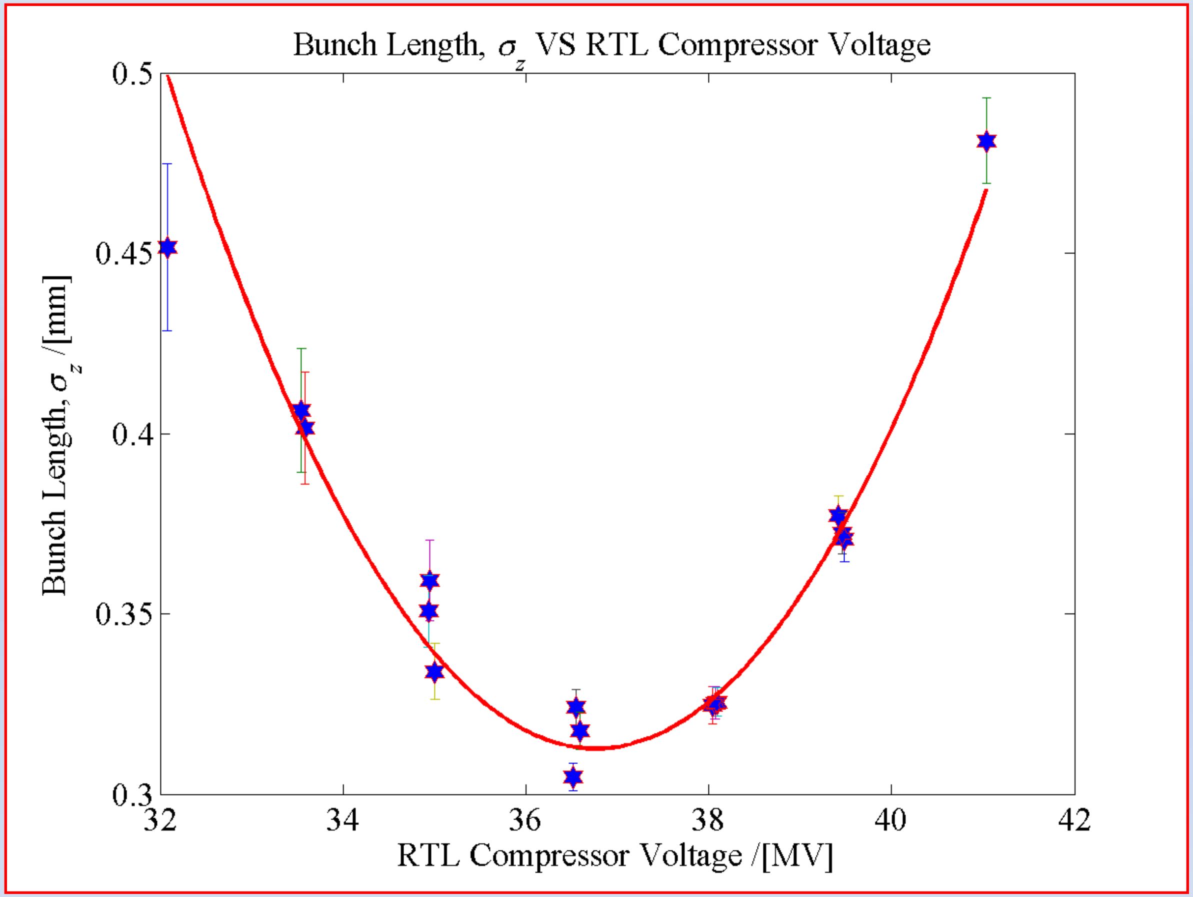
Make a power scan at zero crossing and (zero crossing – 180°) to check if there is no perturbation from linac wakefields

ΔX(mm) → $\Delta\varphi$(°) ΔT(ps)

1.5 GHz RF deflector setup CTF3



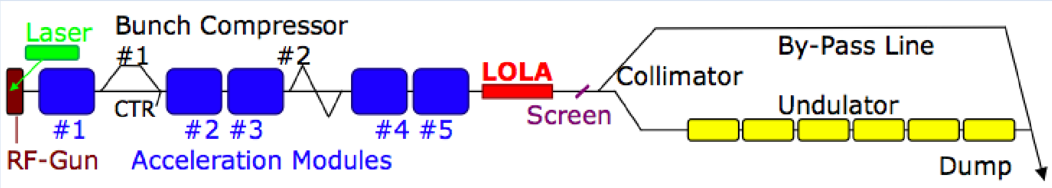
Measuring bunch compression curve

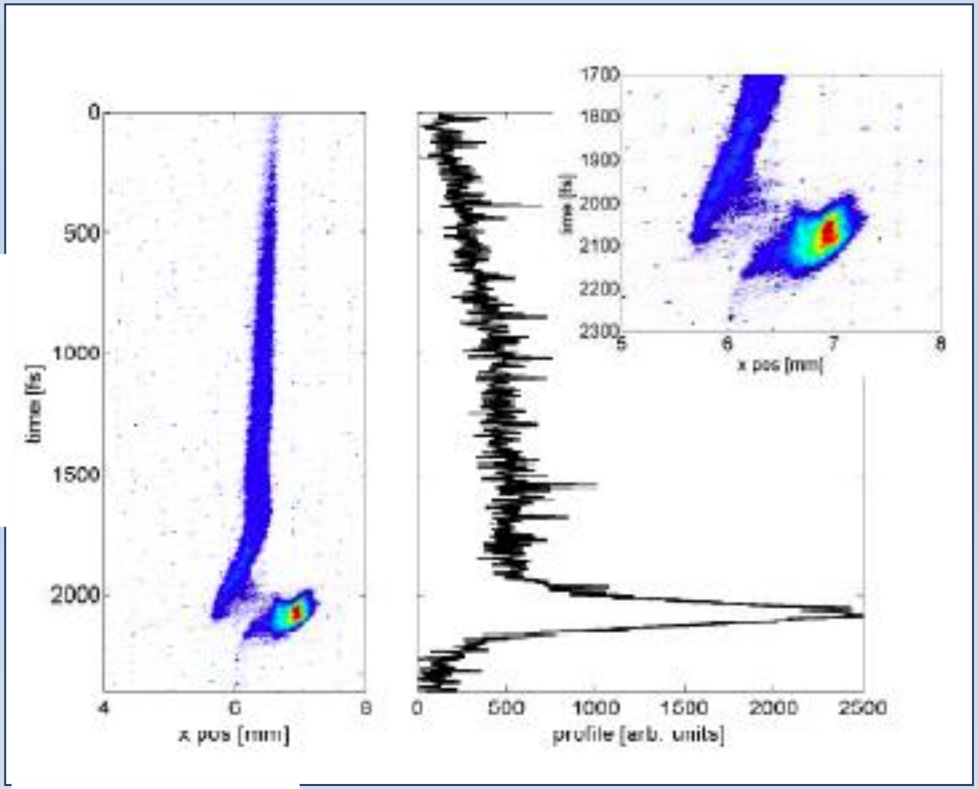


σ_z = 300μm @ SLAC in 2002

R. Akre *et al*, SLAC-PUB-8864, SLAC-PUB-9241, 2002

Bunch length measurement @ Flash





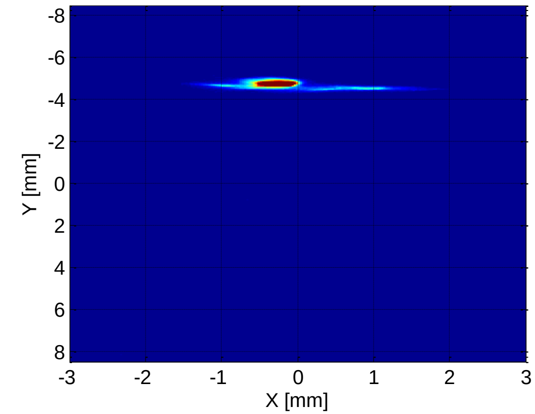
Time [fs]

X pos mm

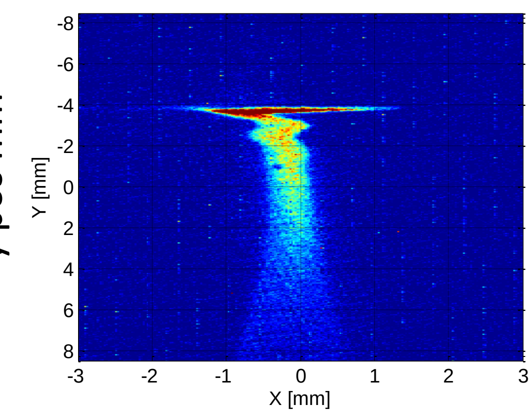
→ Resolution of 4fs/pixels

M. Hüning *et al*, Proceeding of the27th FEL conference, Stanford, 2005, pp538

LOLA off:



LOLA on:

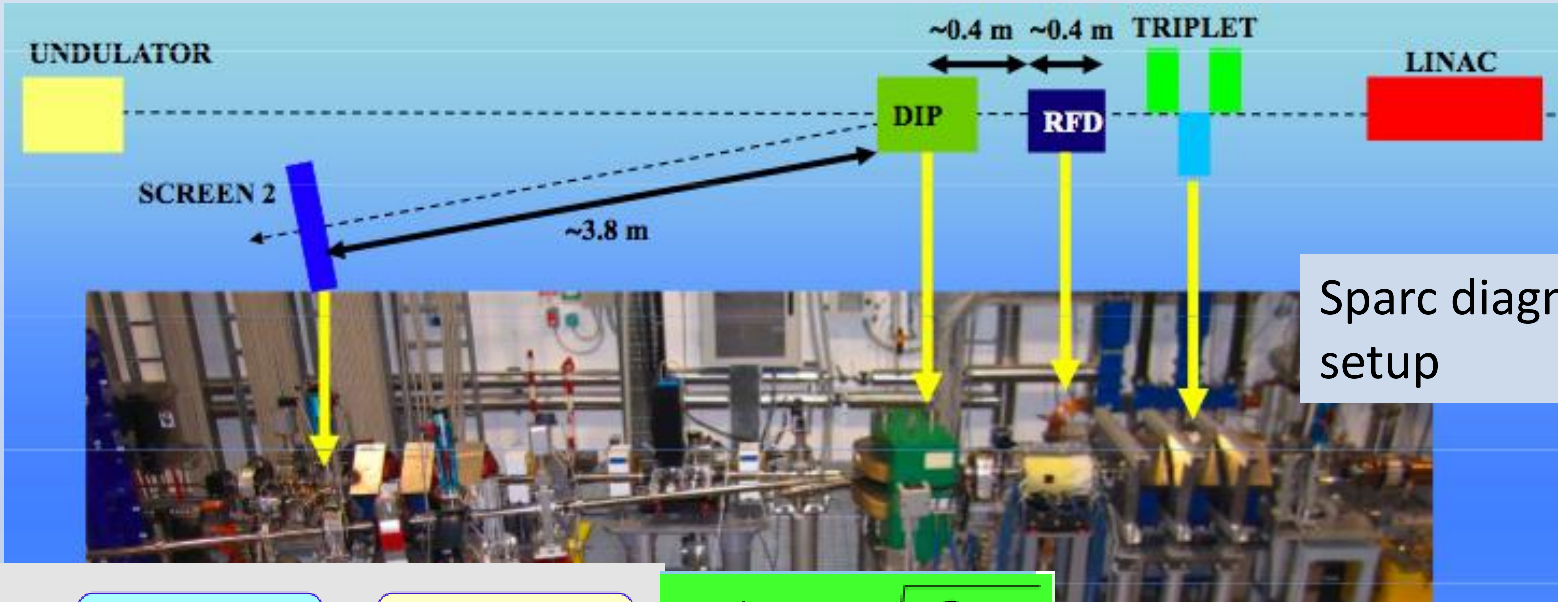


y pos mm

X pos mm

Full longitudinal phase space measurement

Simultaneous bunch length and the energy spread using RF deflectors + dipole



Sparc diagnostics setup

$$x_{\max}(s) = \left|D_x(s)\cdot\delta\right| + \sqrt{\varepsilon_x\beta_x(s)}$$

$$\left.\frac{\Delta E}{E}\right|_{\substack{emitt\\res}} = \frac{\sqrt{\varepsilon\beta_{H\_S}}}{D_S}$$

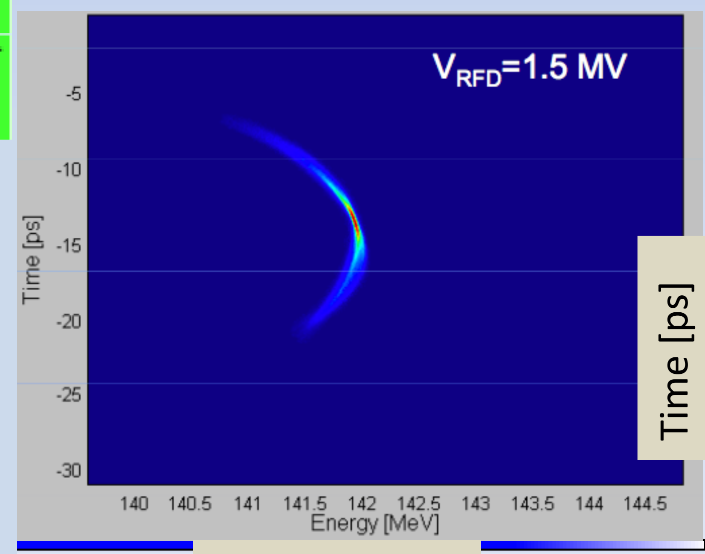
Import considerations in calibration:

•Acceptance: size of the screen in x and y must be large enough

•RF deflector primarily deflecting mode. Residual longitudinal mode, cause energy change to beam

•Vertical beam size profile estimated with RF deflector off

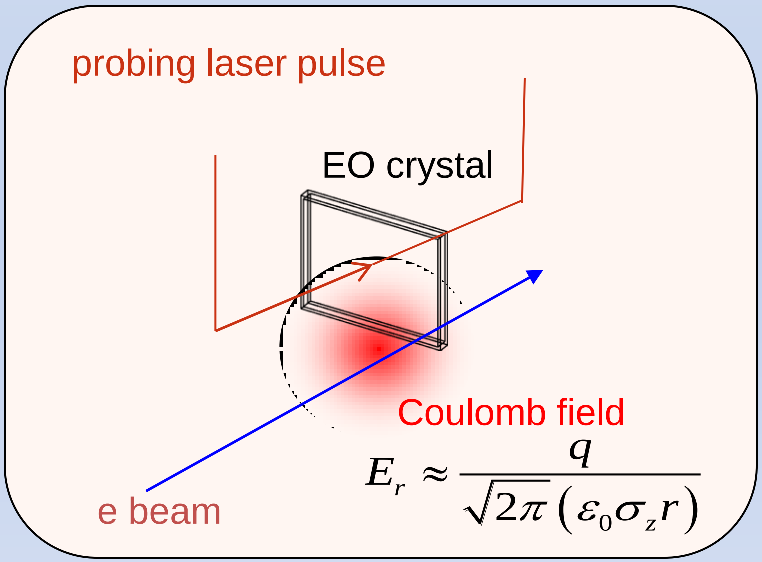
•What about estimation of x transverse size distribution

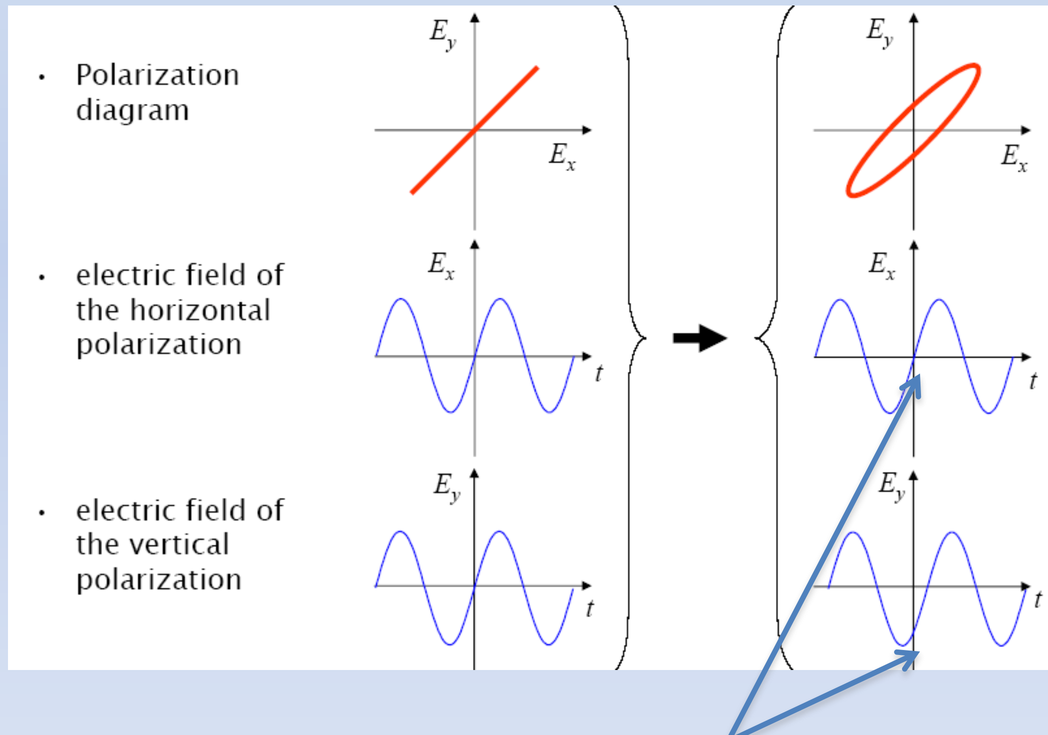


Electro-optical sampling

‘This method is based on the polarization change of a laser beam which passes through a crystal itself polarized by the electrons electric field’

E-field induced birefringence in EO-crystal : Pockels effect



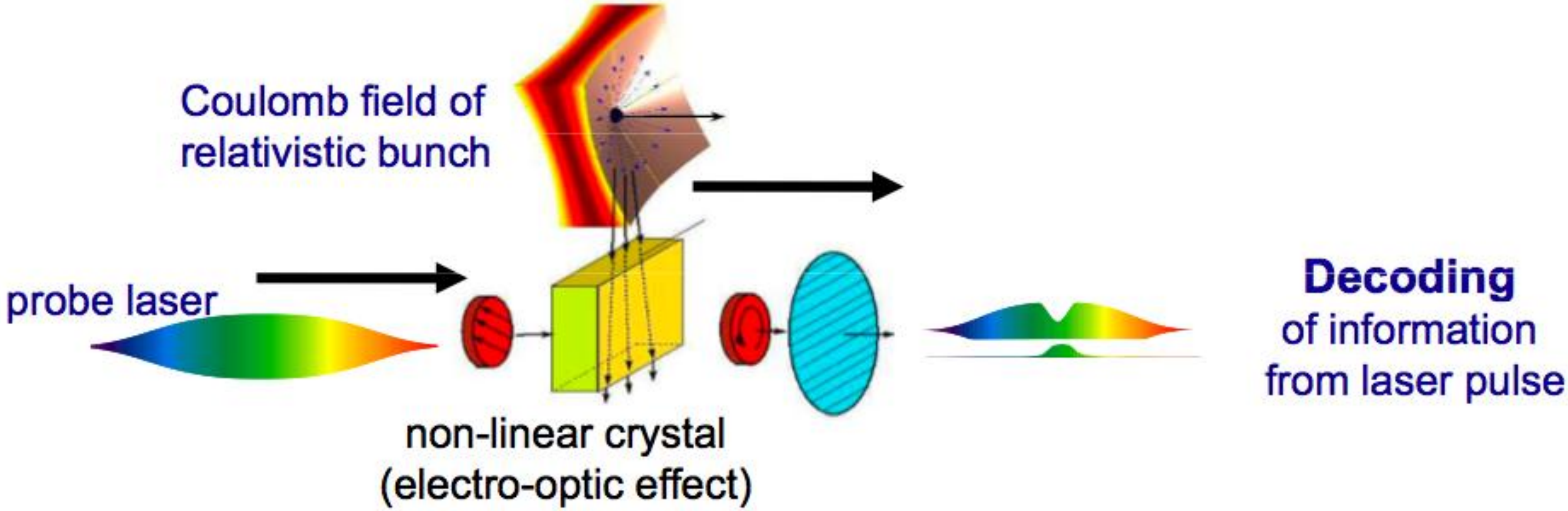


$$G = \frac{2pd}{l_0}\left(n_x - n_y\right) = \frac{2pd}{l_0} n_0^3 r_{41} E_r$$

Relative phase shift between polarizations increases with the beam electric field

Slide: T. Lefevre

Electro-optical diagnostics principle



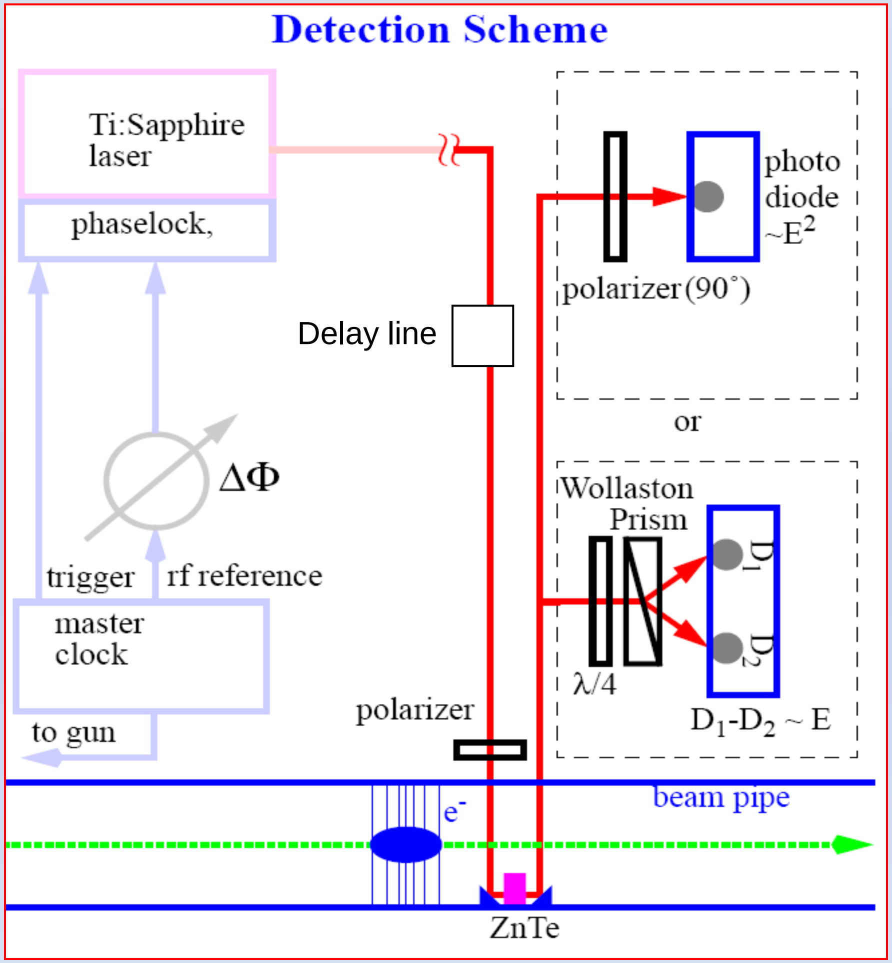
Encoding

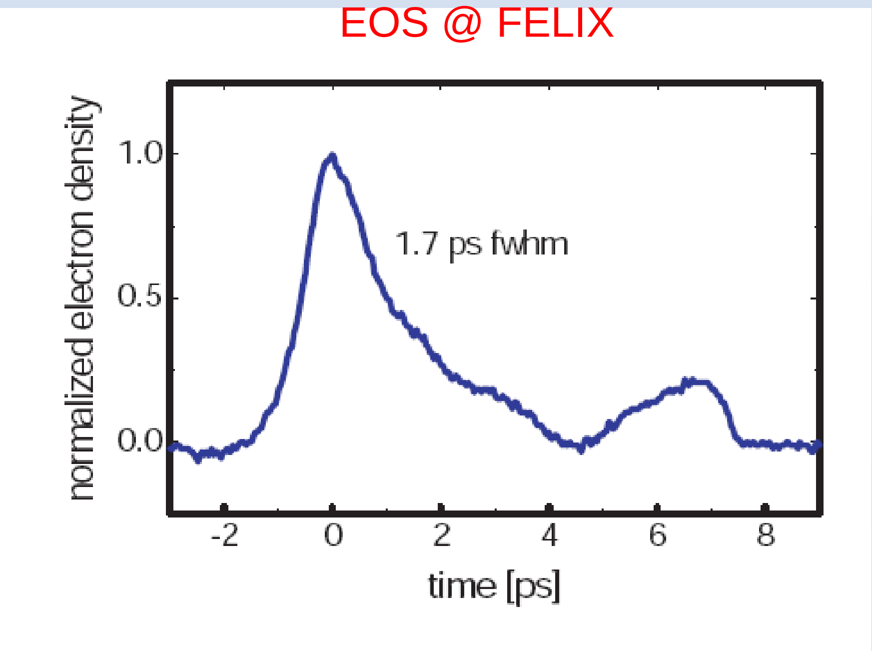
- same for all techniques
- limiting factor for high time resolution techniques

Decoding

- choices for complexity
- limiting factor for spectral decoding

Electro-optical diagnostics example



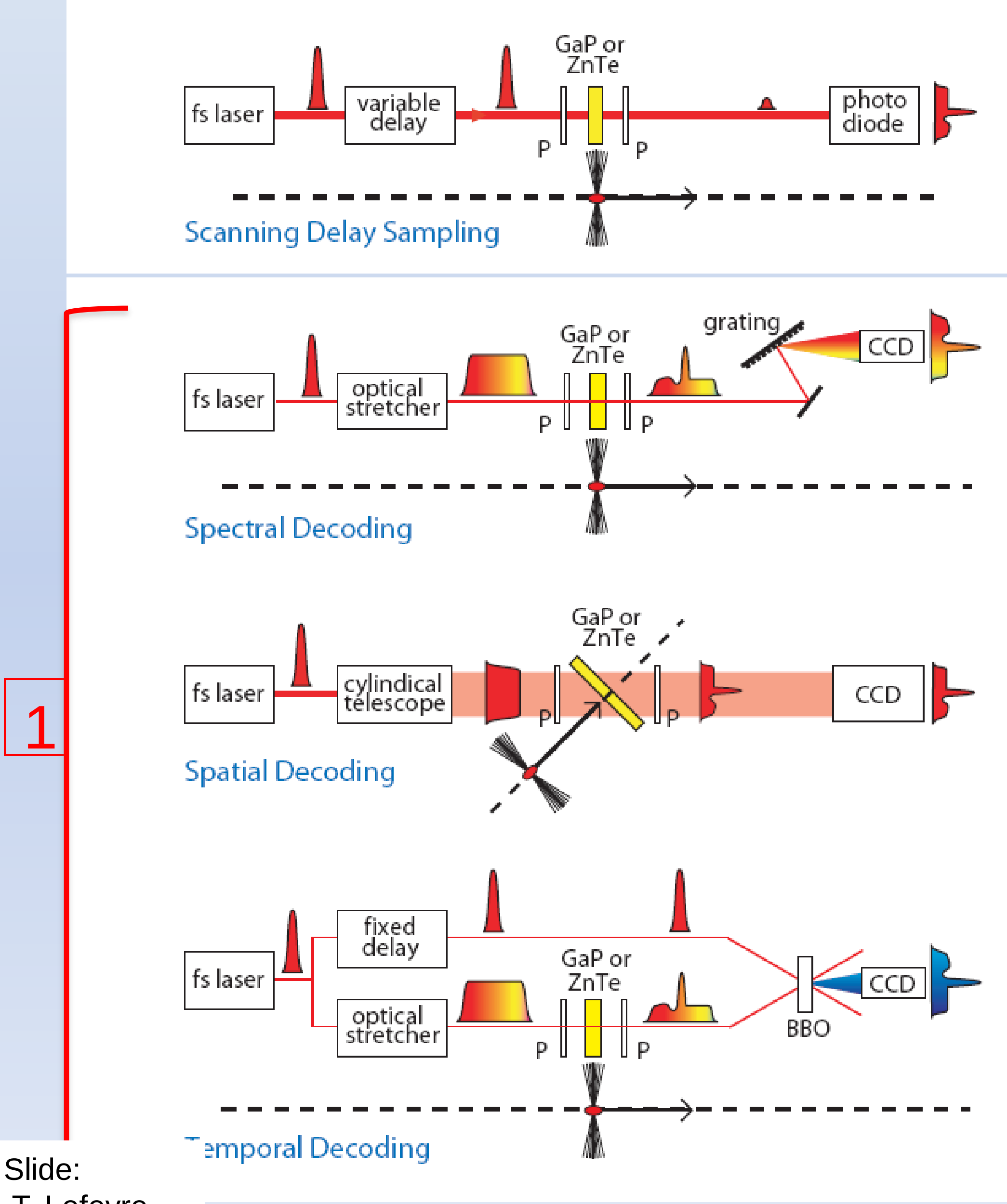


Using 12fs Ti:Al2O3 laser at 800nm and ZnTe crystal 0.5mm thick and a beam of 46MeV, 200pC, 2ps.

X. Yan *et al*, PRL 85, 3404 (2000)

Slide: T. Lefevre

Electro Optic based bunch length monitors



Slide:
T. Lefevre

1. Sampling:

- multi-shot method
- arbitrary time window possible

2. Chirp laser method, spectral encoding

- laser bandwidth limited~ 250fs

Wilke *et.al.*, PRL 88 (2002) 124801

3. Spatial encoding:

- imaging limitation ~ 30-50 fs

Cavalieri *et. al*, PRL 94 (2005) 114801

Jamison *et. al*, Opt. Lett. 28 (2003) 1710

Van Tilborg *et. al*, Opt. Lett. 32 (2007) 313

4. Temporal encoding:

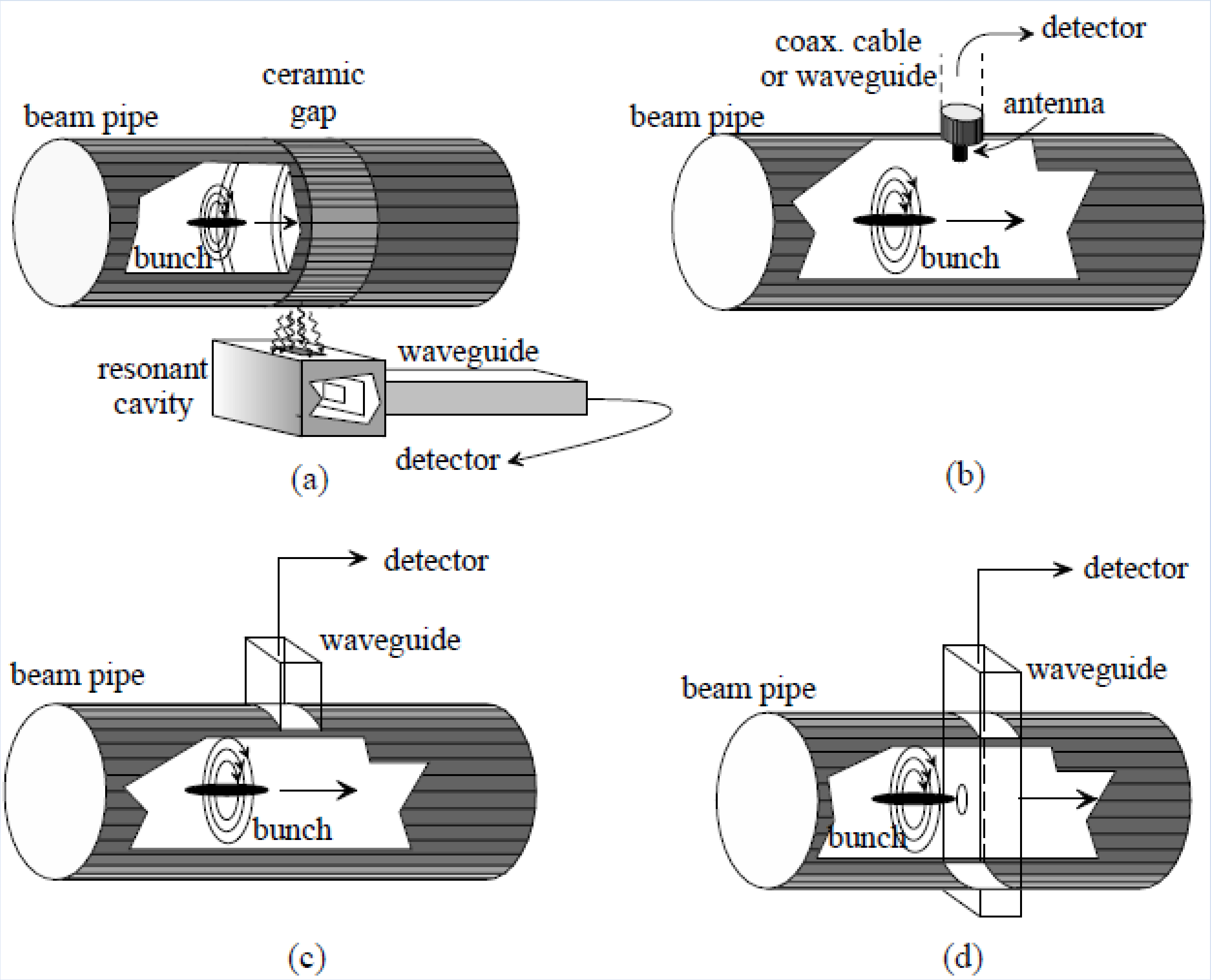
- laser pulse length limited ~ 30fs

Berden *et.al*, PRL 93 (2004) 114802

Jamison *et. al*, Phys Rev Lett, 99,164801 (2007)

Jamison et al Phys Rev ST 12 032802 (2009)

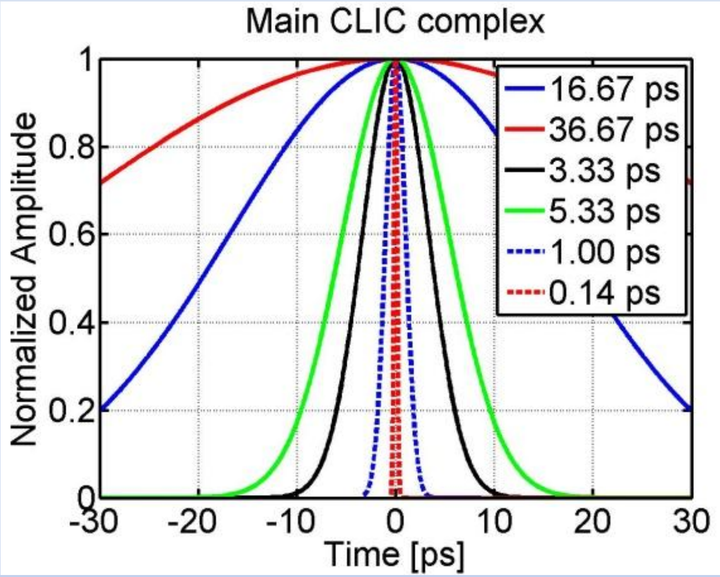
Sample the electron bunch field

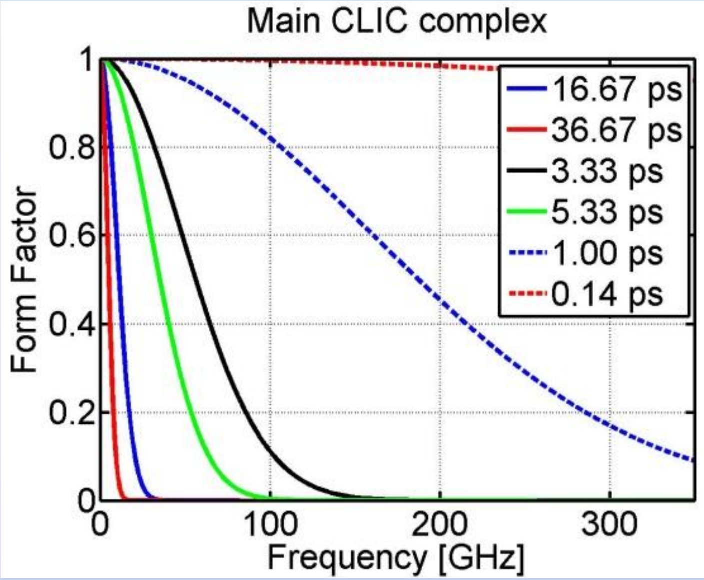


PhD thesis C.Martinez

CERN-THESIS-2009-011
01/09/1999

Time vs Frequency domain for a single Gaussian bunch





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

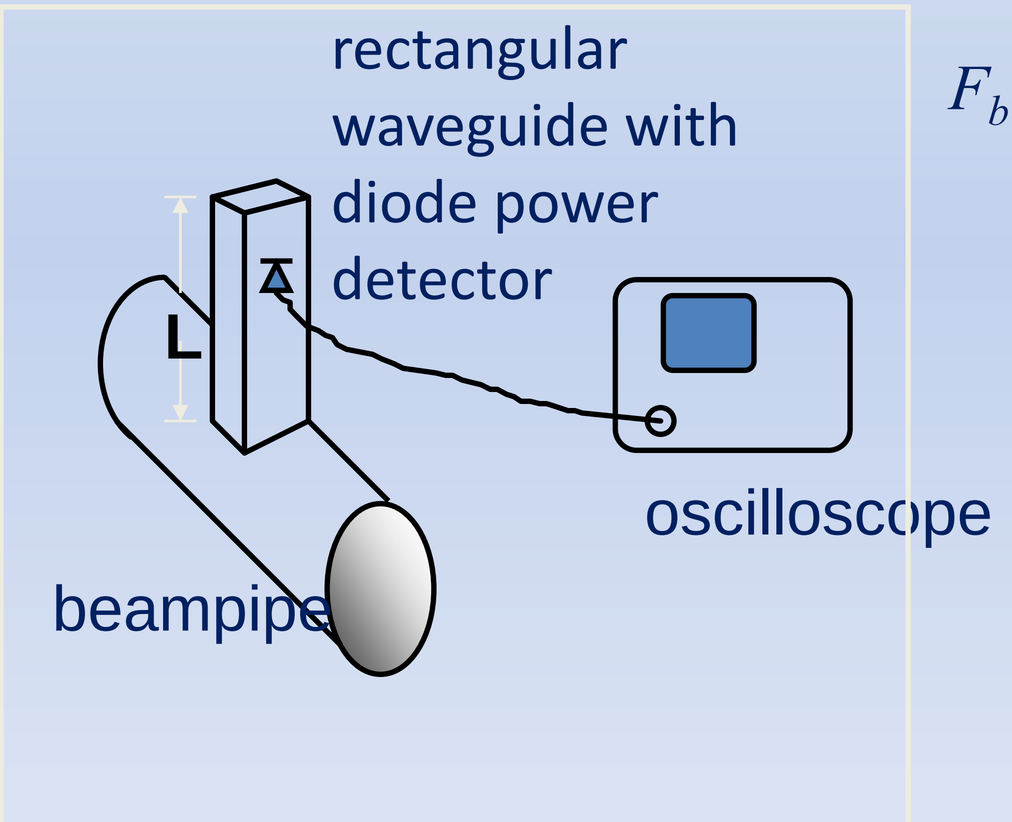
- Gaussian bunch distribution

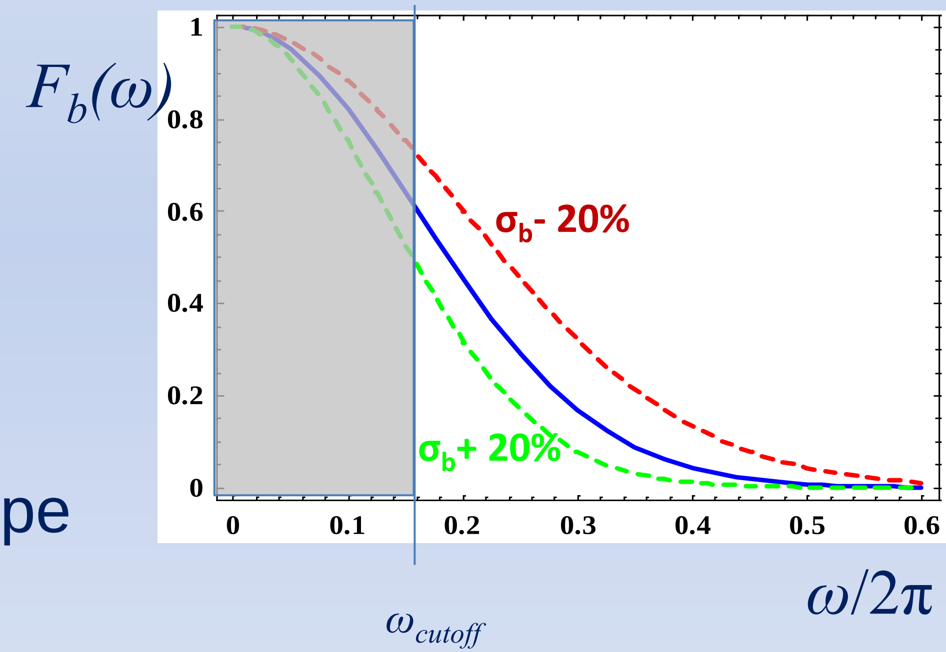
$$F_b(\omega) = \frac{q_b \sigma_b}{\sqrt{2\pi}} \exp\left(\frac{-\omega^2 \sigma_b^{\ 2}}{2}\right)$$

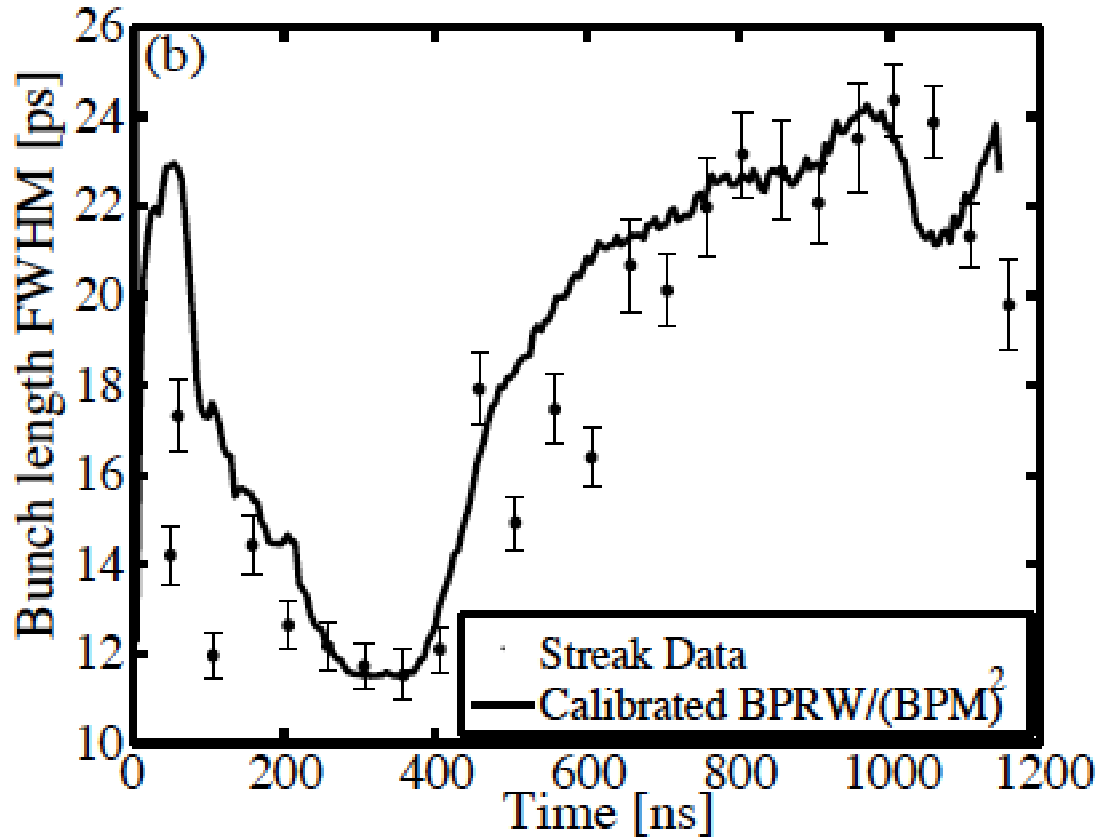
- Corresponding single bunch form factor

A very simple system to measure the EM power of the beam

Choose rectangular waveguide with $\omega_{cutoff} \approx \omega_{opt}$.
Connect waveguide to beampipe.
Detector will measure integrated spectrum integrated above ω_{cutoff}







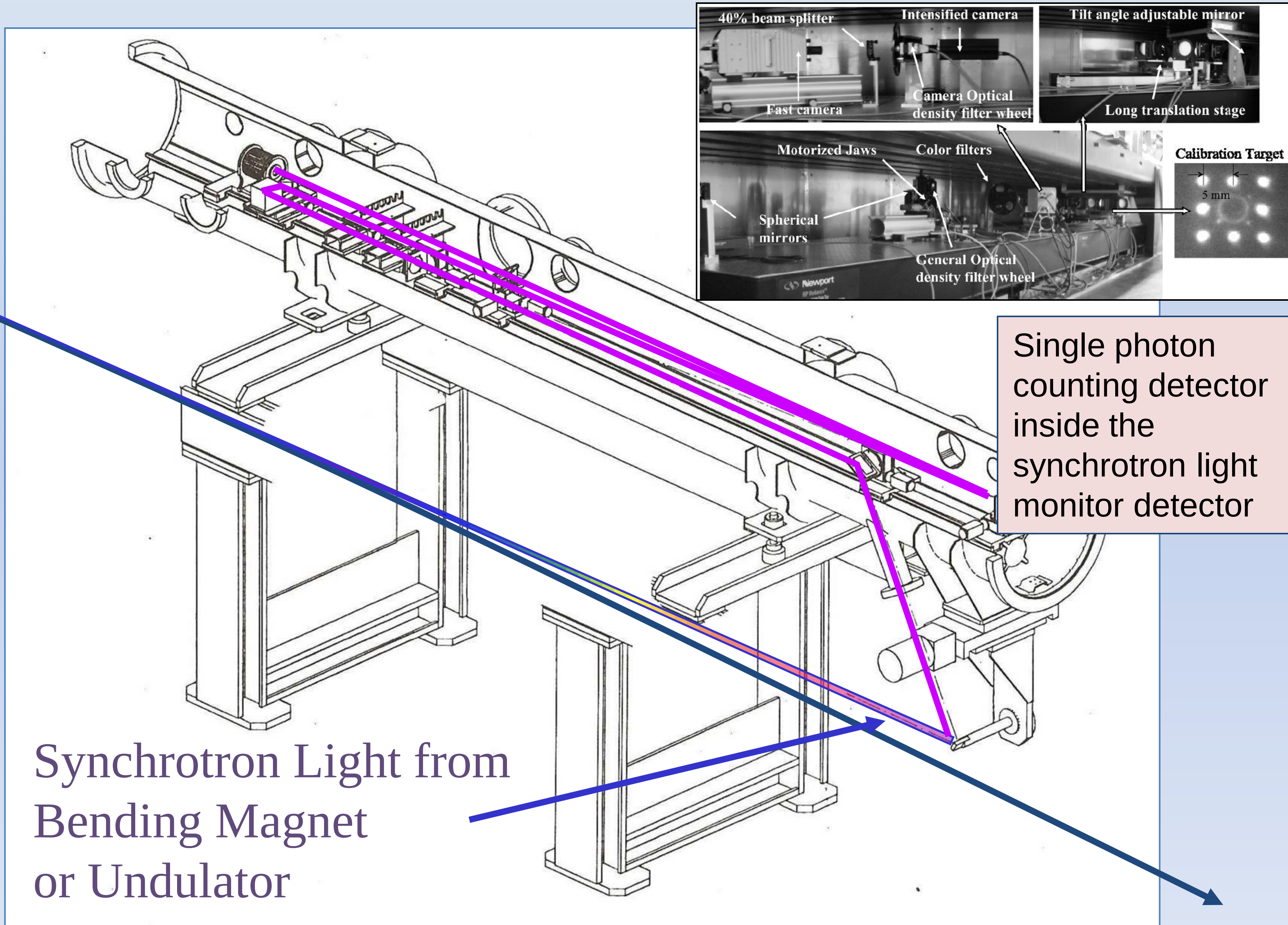
(b) The calibrated BPRW signal compared to streak camera measurement.

Comparison of a 30 GHz RF based power measurement and streak camera

Dabrowski et al 2012 JINST **7** P01005 **doi:10.1088/1748-0221/7/01/P01005**

Longitudinal Density monitor @ the LHC

Longitudinal Density monitor @ the LHC



Beam

Single photon counting detector inside the synchrotron light monitor detector

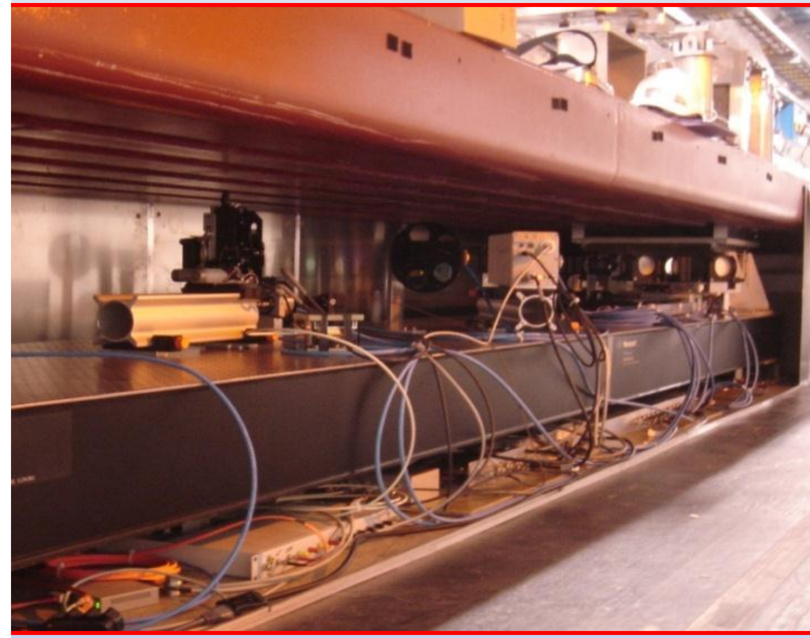
Synchrotron Light from Bending Magnet or Undulator

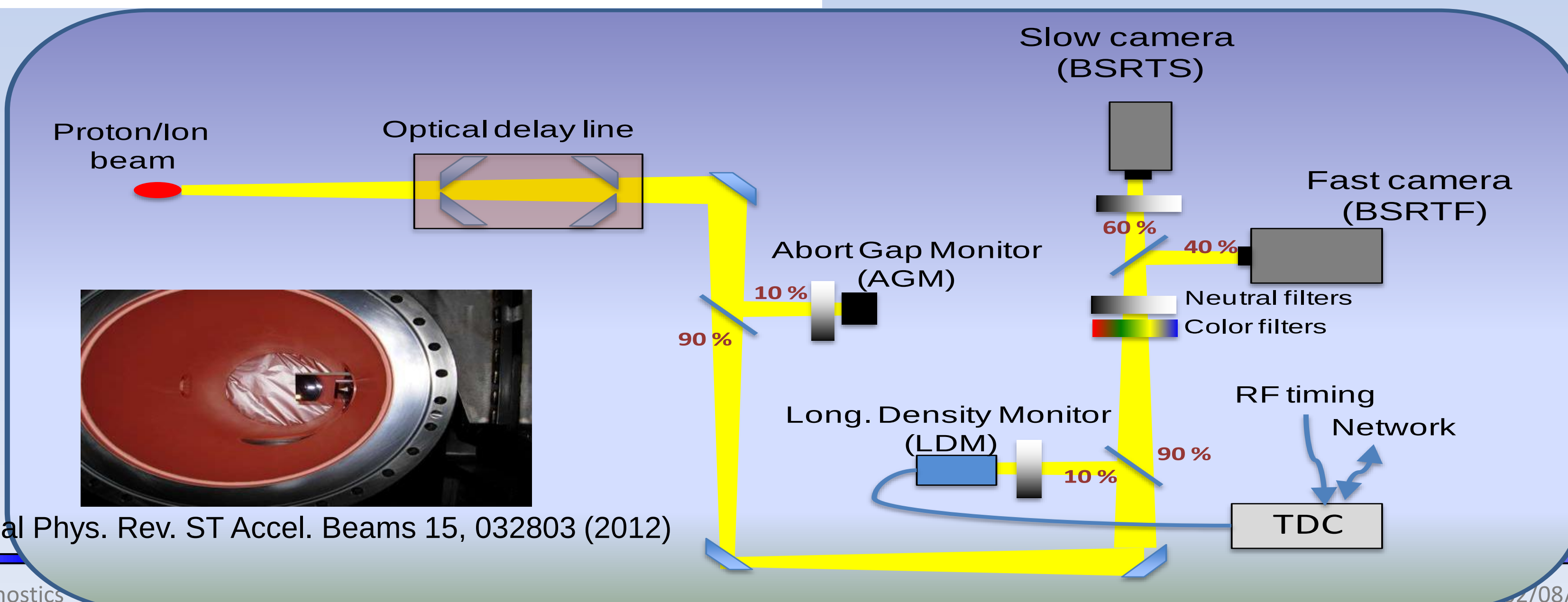
Phys. Rev. ST Accel. Beams 15, 032803 (2012)

T. Lefevre; Rhodri Jones

Beam Current via Longitudinal Density Monitor

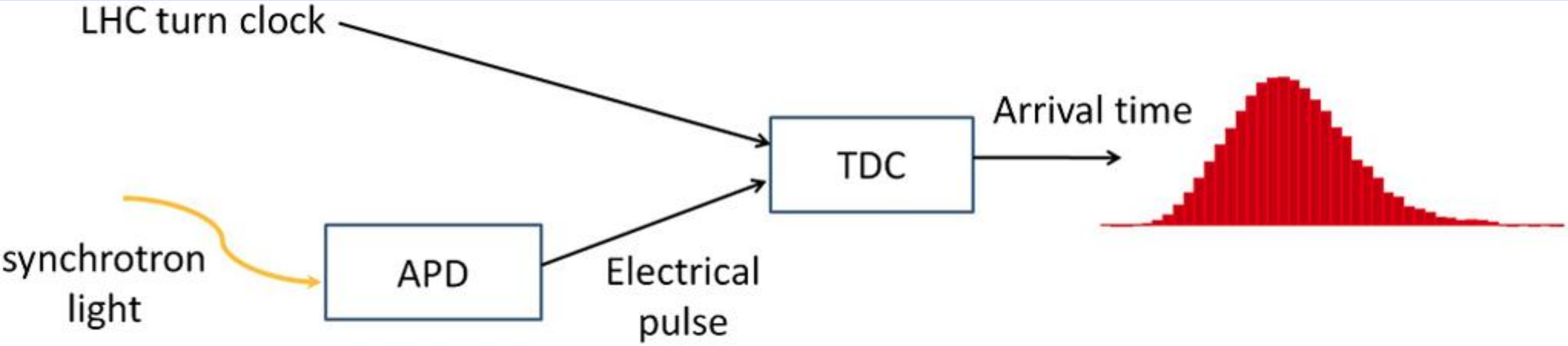
- Monitor should measure the population of bunch charge as a function of time in the orbit
- Based on imaging synchrotron light
- Systematics: dependence on beam position
- The difficulty to evaluate the debunched beam population





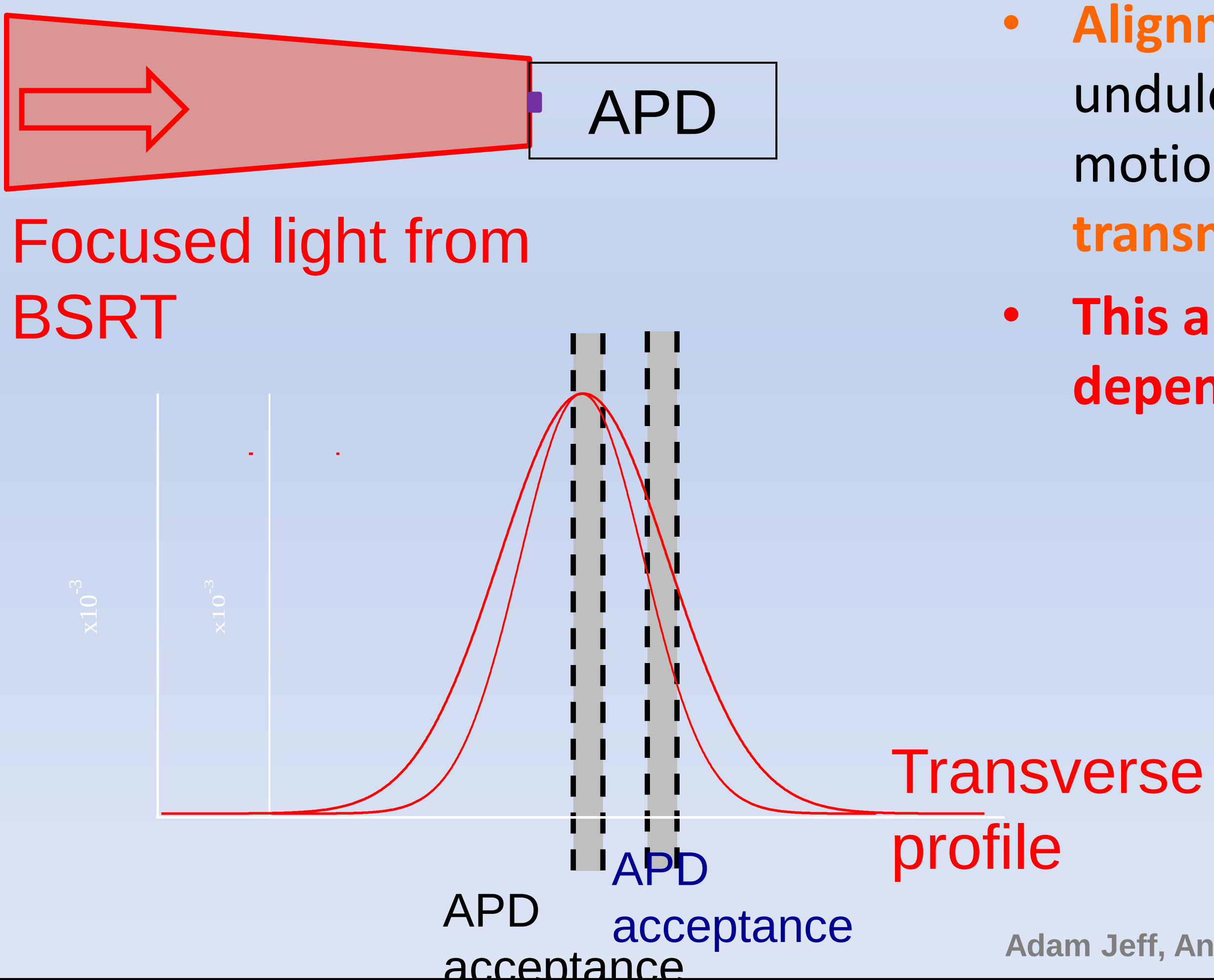
A. Jeff et al Phys. Rev. ST Accel. Beams 15, 032803 (2012)

Longitudinal Density monitor @ the LHC



- The avalanche photodiode (APD) detects incoming photons and produces an electrical pulse.
- This is time stamped by a time to digital converter (TDC) and a histogram of arrival times is created.

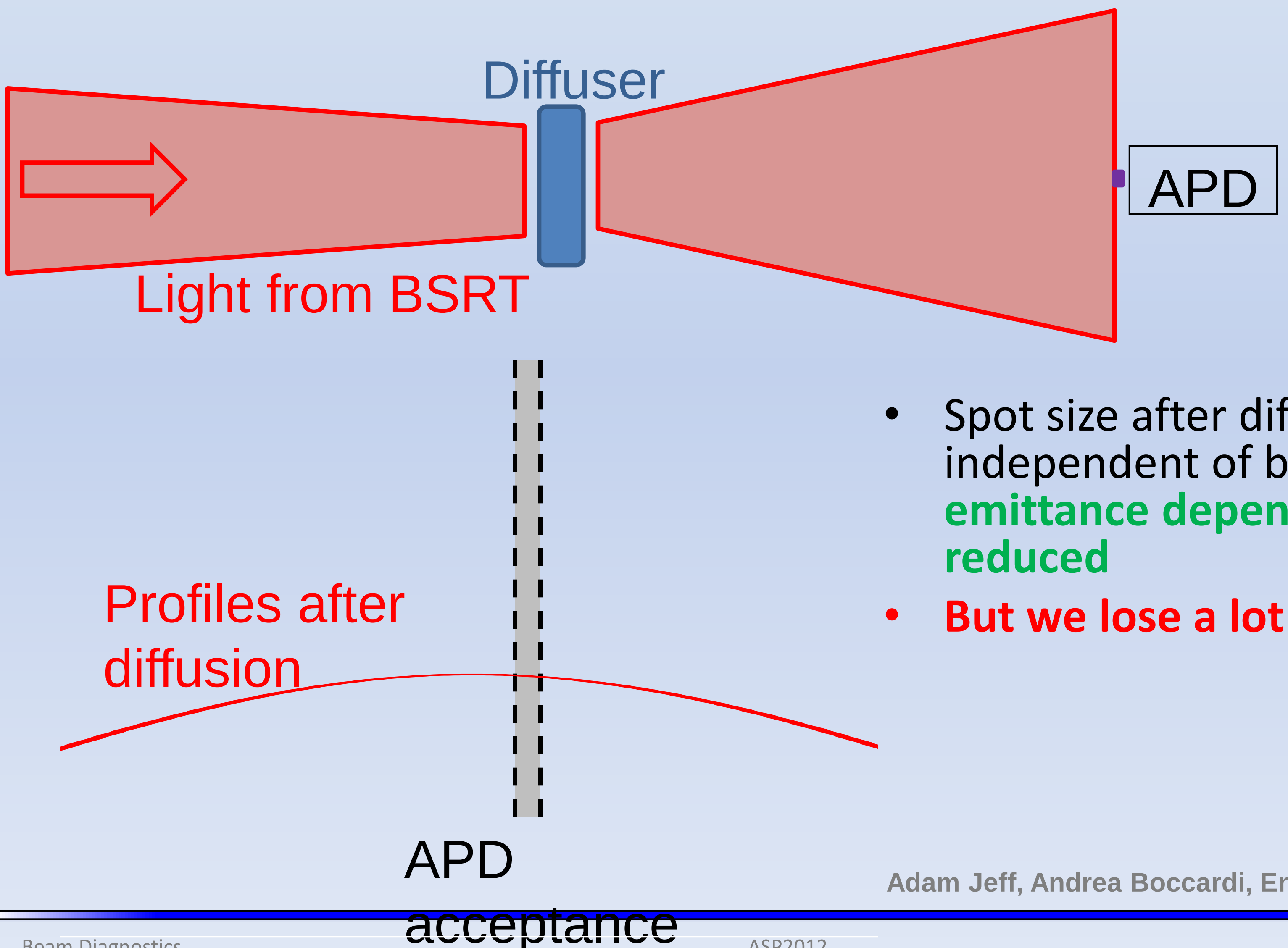
A. Jeff et al Phys. Rev. ST Accel. Beams 15, 032803 (2012)



- The APD has a small acceptance w.r.t. incoming beam size.
- **Alignment variations** (from undulor to D3 or due to beam motion) **can modify the transmission**.
- **This also introduces a dependence on beam size**.

Adam Jeff, Andrea Boccardi, Enrico Bravin et al, CERN

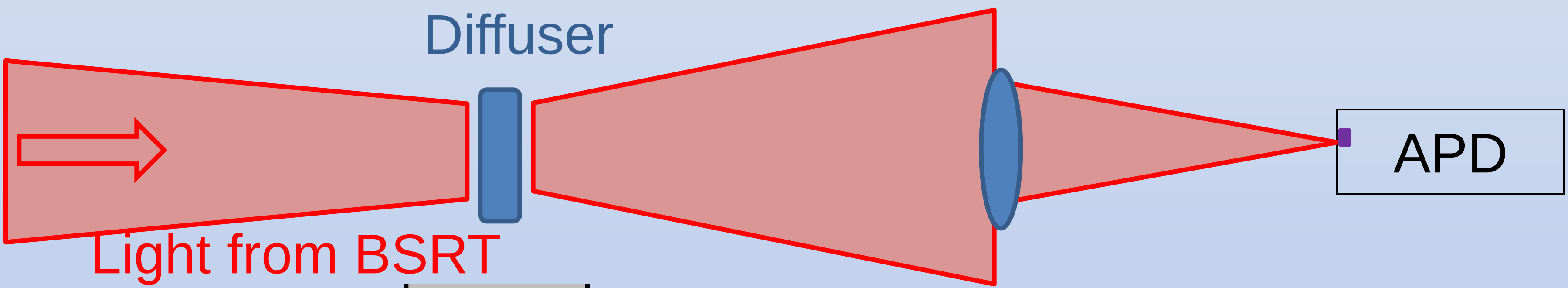
Beam Current via LDM: Emittance/Alignment Dependence

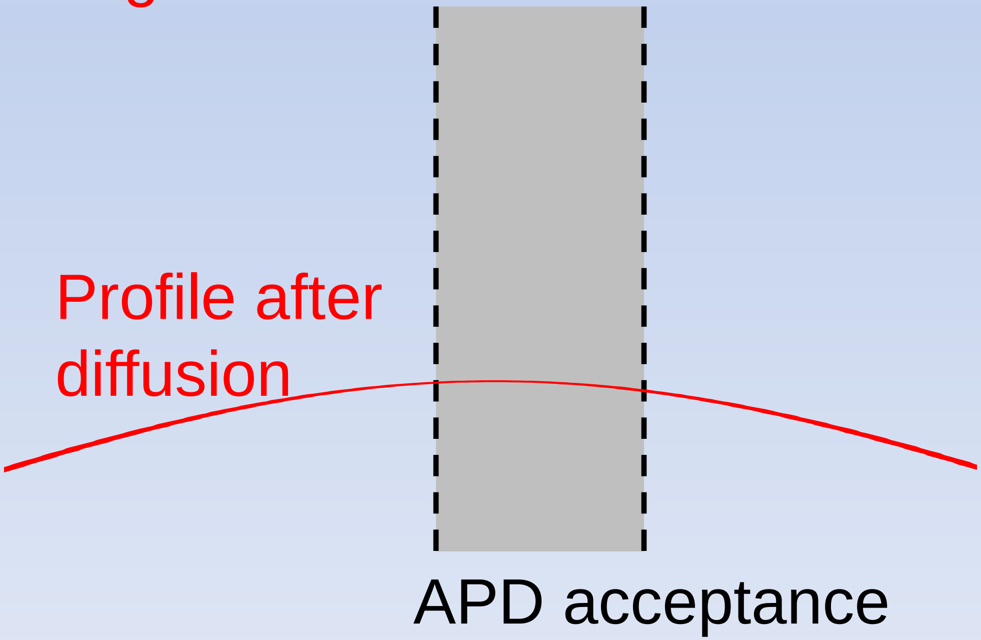


- Spot size after diffuser ~ independent of beam size -> **emittance dependence reduced**
- **But we lose a lot of light**!

Adam Jeff, Andrea Boccardi, Enrico Bravin et al, CERN

Beam Current via LDM: Emittance/Alignment Dependence





- Spot size after diffuser ~ independent of beam size -> **emittance dependence reduced**
- **Good coupling efficiency, plenty of light!**

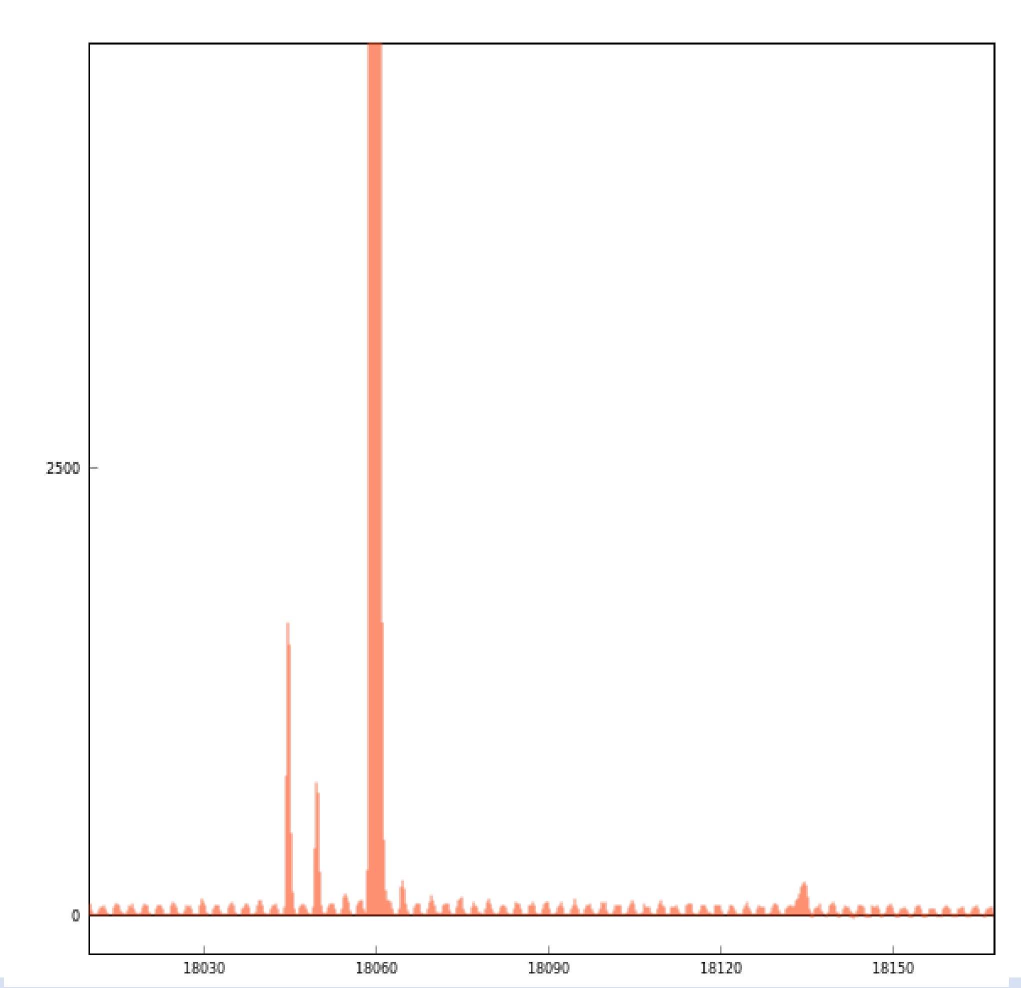
Adam Jeff, Andrea Boccardi, Enrico Bravin et al, CERN

Longitudinal Density monitor Measurements

Single Synchrotron Light photons

counting with precise time of arrival detection

(~50 ps time resolution, $>10^4$ dynamic range)



A. Jeff et al Phys. Rev. ST Accel. Beams 15, 032803 (2012)

Luminosity

The rate of collisions is given by the luminosity

The luminosity is defined as $$L = \frac{\dot{N}_i}{s_i}$$

And can also be derived from the beam parameters

$$L = \frac{N_{b1} N_{b2} f_{rev} k_b}{2\pi\sqrt{(\sigma_{x1}^2+\sigma_{x2}^2)(\sigma_{y1}^2+\sigma_{y2}^2)}} \cdot \exp\left[-\frac{(\bar{x}_1-\bar{x}_2)^2}{2(\sigma_{x1}^2+\sigma_{x2}^2)} - \frac{(\bar{y}_1-\bar{y}_2)^2}{2(\sigma_{y1}^2+\sigma_{y2}^2)}\right]$$

Beams current

Beams size

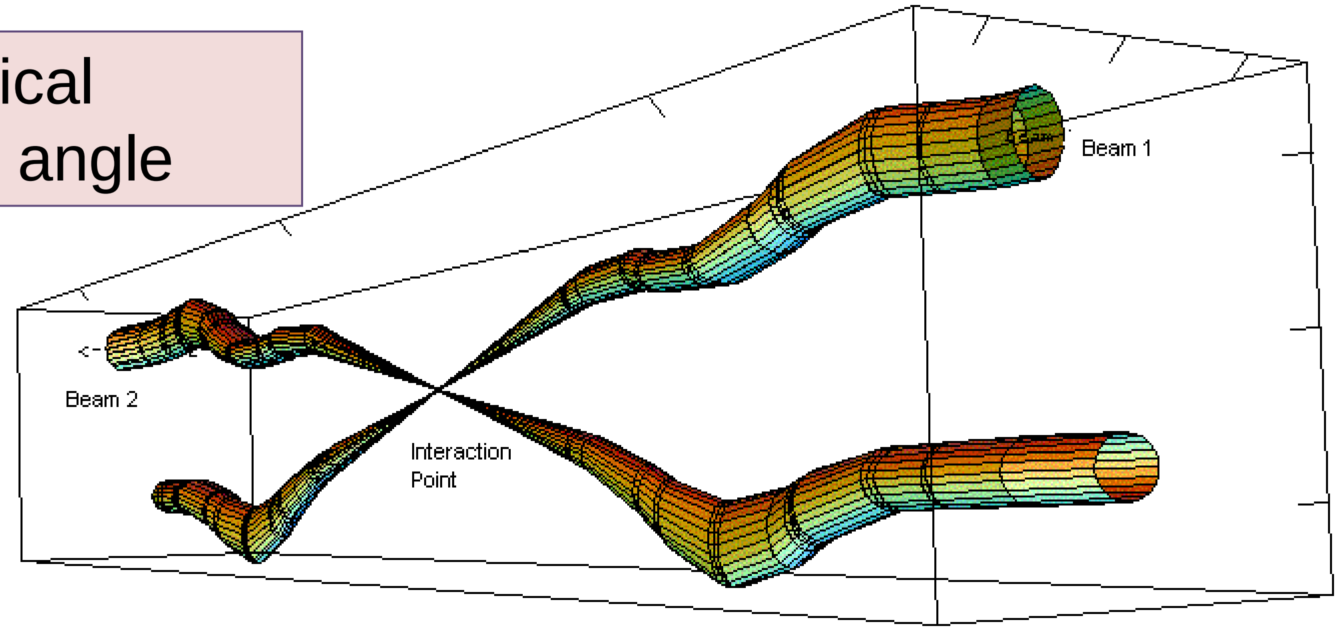
Beams overlap

Luminosity

The tracking detectors of the experiments can measure directly the transverse luminous region in the experiment.

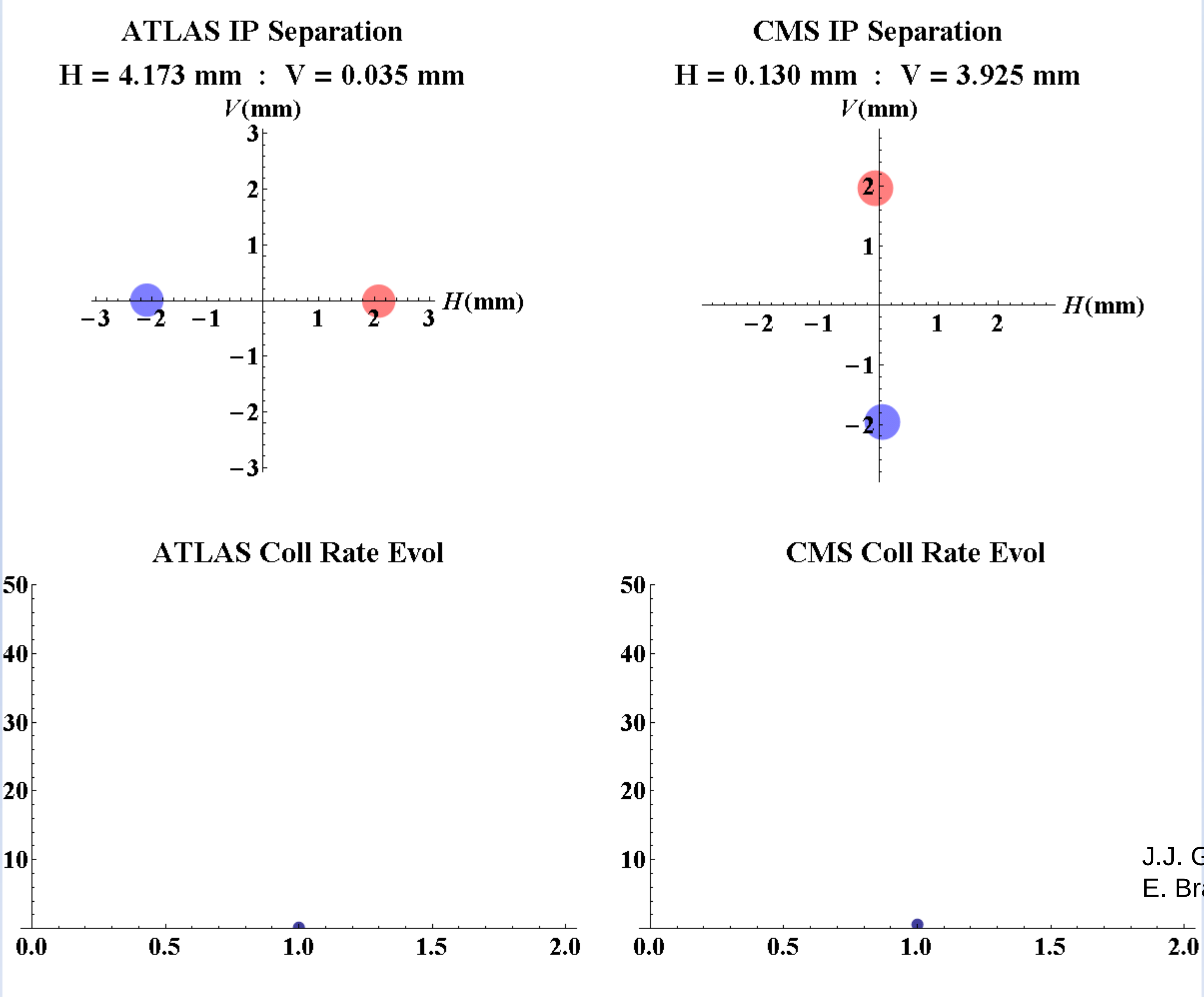
The LHC can optimize the luminosity experiments, by maximizing the rate measured in a luminosity sensitive detector as function of beam position of the beams.

IP 1 vertical crossing angle



Relative beam sizes around IP1 (Atlas) in collision

Luminosity



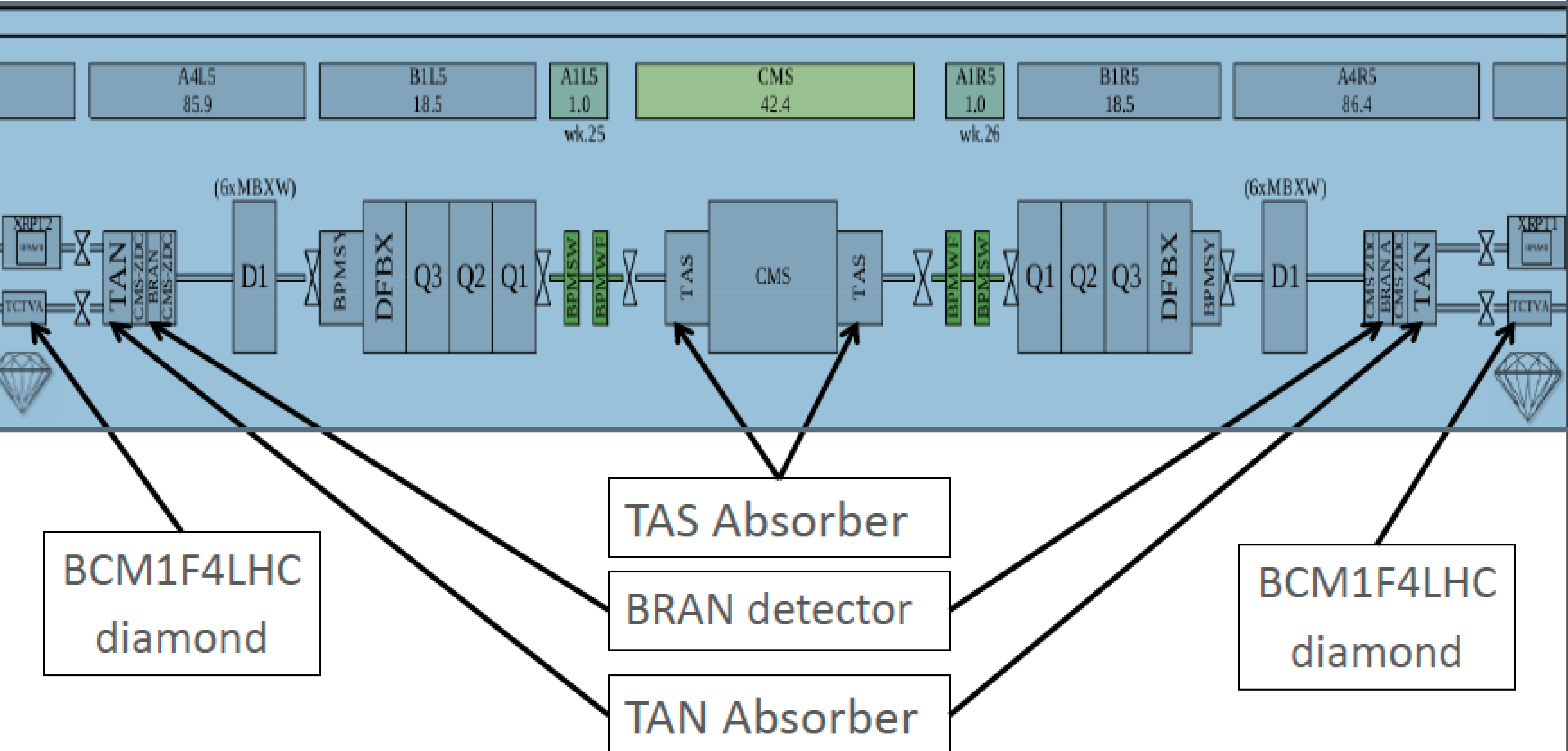
J.J. Gras
E. Bravin CERN

Measuring the Luminosity

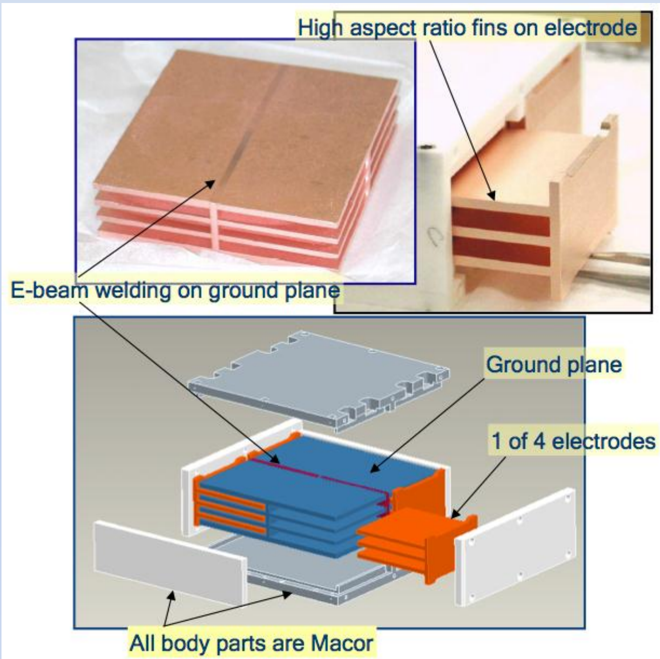
- The experiments are the best possible luminosity monitor!
- Some time they do not deliver online information and a back-up solution is needed
- Machine luminosity monitors (just small particle detectors that count the rate of debris from the collisions)
- Can be a simple scintillator pad

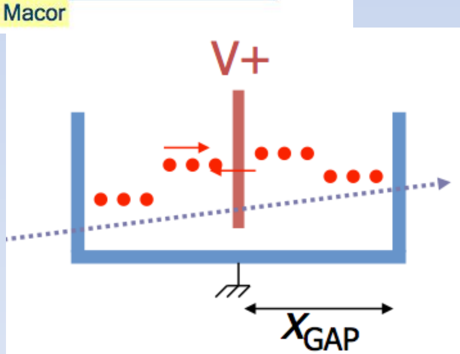
Setup of LHC around CMS

- Several quadrupoles (MQXA & MQXB) and one dipole (MBXW- reduction of beam separation), collimators and absorbers on each side of CMS



BRAN Chamber Design



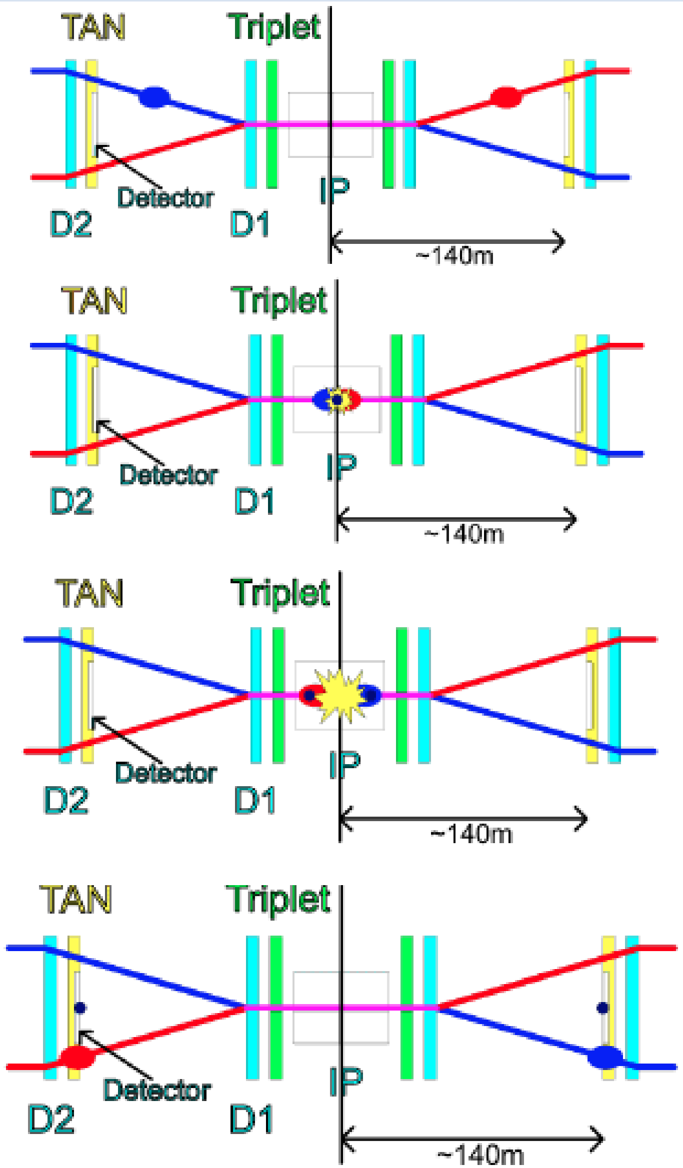


- 4 quadrant hi-pressure Ar-N_2 ionization chamber
- Located in the TAN on both sides of IP1 and IP5
- Designed to measure
  - the relative bunch × bunch luminosity
  - collisions at 25 ns bunch spacing
- Quadrant nature allows measurement of crossing angle

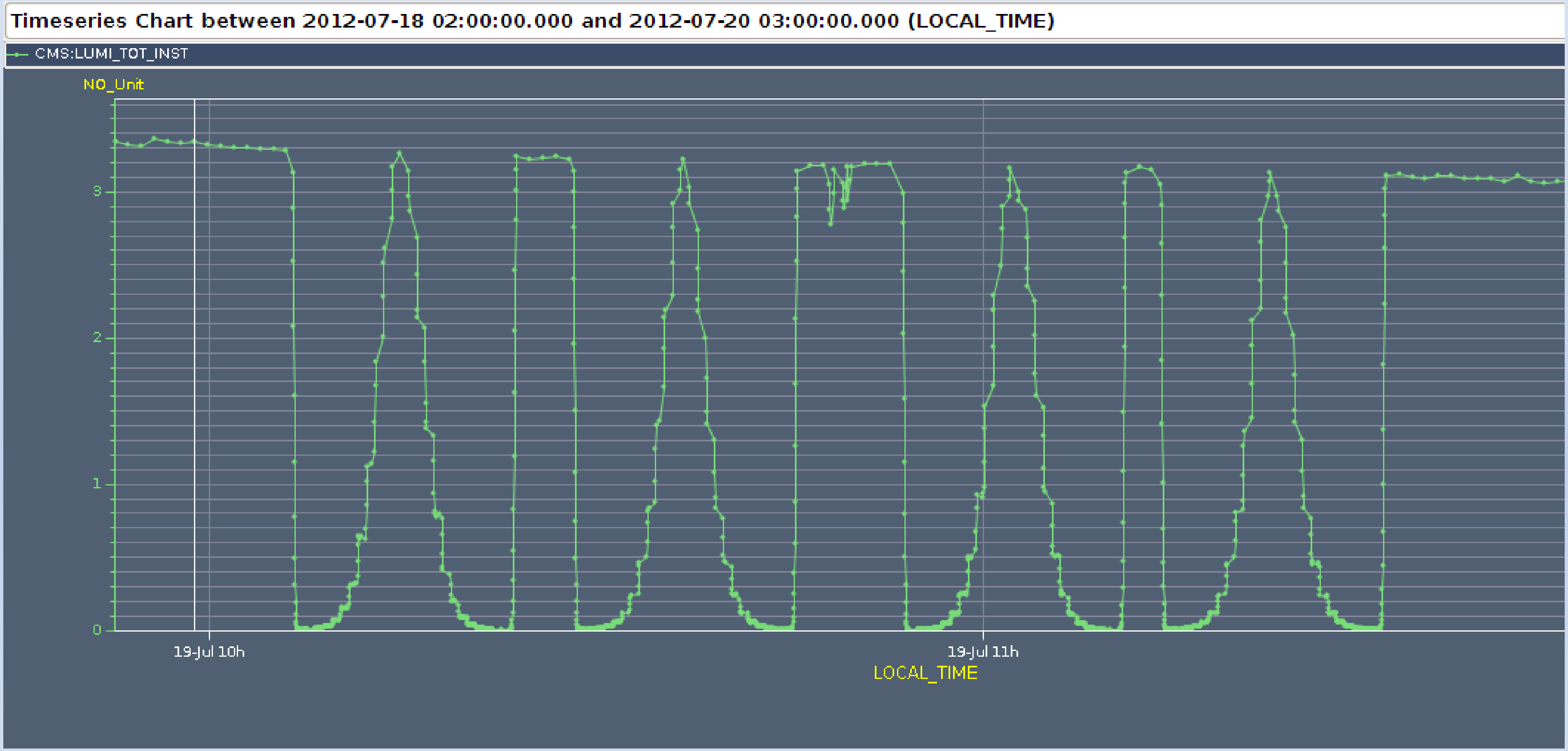
H. Matis - LUMI Days 2012 - March 1

Luminosity monitoring using the BRAN

- BRAN is a monitor
- Measures the machine lumi
- Is a ionization chamber
  - 94% Ar and 6% N_2
- Protons collide and produce collision products (charged and neutral)
- Charged particles will be deflected
- Neutral particles will be detected by the BRAN
- Rate of the detection of neutral particles is proportional to luminosity



Machine Tuning of the luminosity



- Scan one beam across the other one at the IP and maximize the luminosity

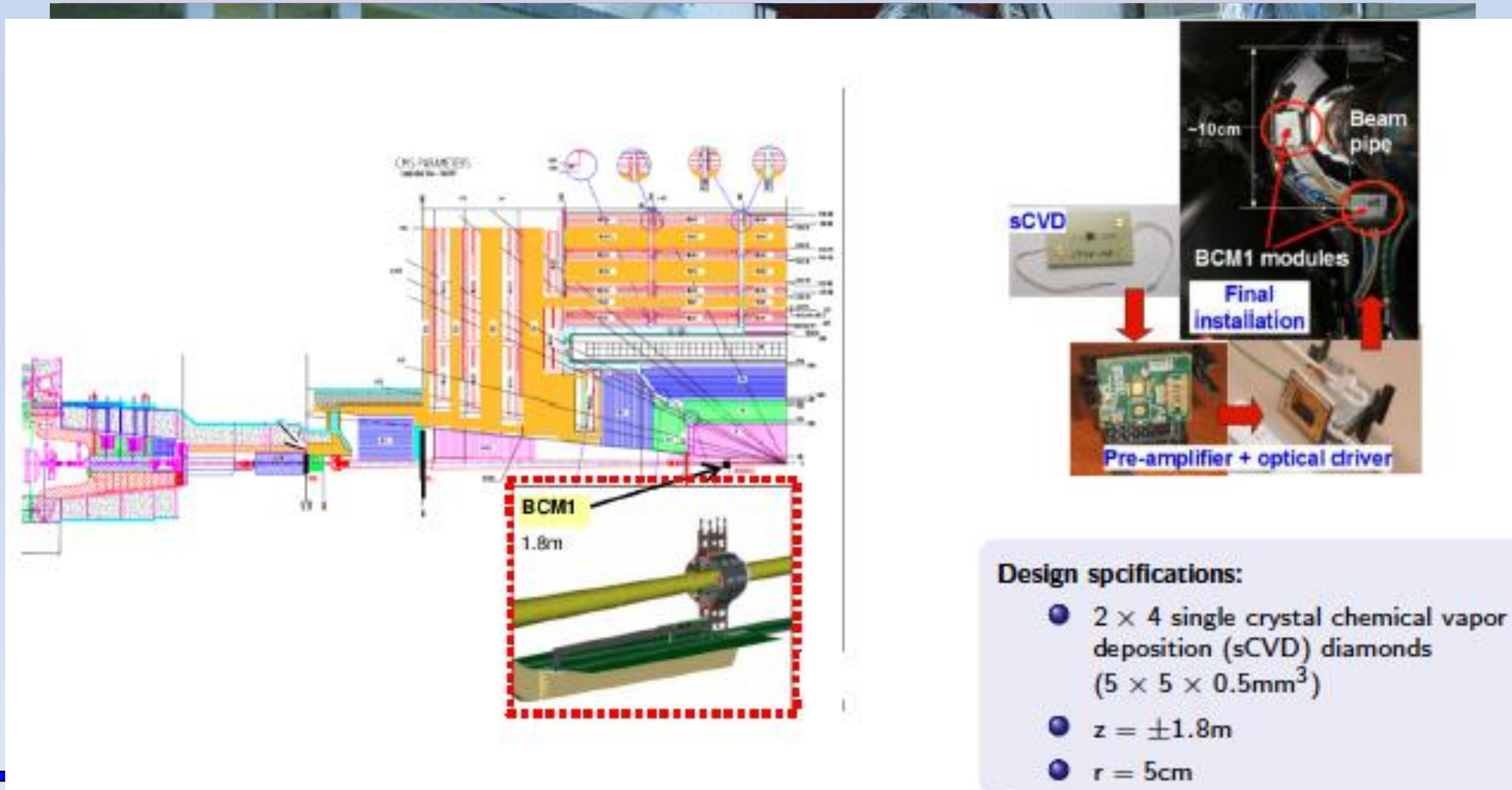
Important aspects for designing a luminosity detector:

- It must not saturate with rate
- It must be linear with rate
- It must be stable
- Measure at a rate which allows bunch-by bunch luminosity measurements
- Should be simple and online when ever there is beam in the machine

Experiment’s Detectors to measure the luminosity

In the CMS experiment to measure the luminosity we count:

- Number of pixel clusters (linear since 20 M pixels)
- Vertex counting
- Use hadron calorimeter (count number on non-occupied towers)
- Hits in diamond sensors close to the beam pipe
- ➔ Future count number of tracks in a diamond telescope



Remember 2 luminosity formulas

$$L = \frac{\dot{N}_i}{\sigma_i} = \frac{\mu_{vis} \times n_b \times f_b}{\sigma_{vis}}$$

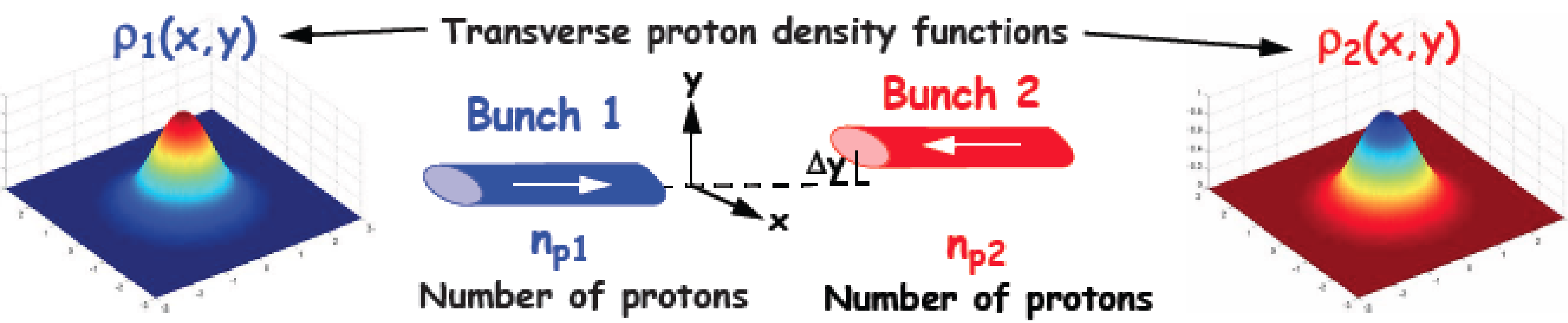
$$\sigma_{vis} = \varepsilon \times \sigma_{inel} \times \sigma_{vis}$$

- $\mu \equiv$ average number of inelastic collisions
- $f_{orbit} \equiv$ orbit frequency ($= 11246$ Hz)
- $n_b \equiv$ number of colliding bunches ($\lesssim 1380$)
- $\sigma_{inel} \equiv$ inelastic pp cross-section

$$L = \frac{N_{b1} N_{b2} f_{rev} k_b}{2\pi\sqrt{(\sigma_{x1}^2+\sigma_{x2}^2)(\sigma_{y1}^2+\sigma_{y2}^2)}} \cdot \exp\left[-\frac{(\bar{x}_1-\bar{x}_2)^2}{2(\sigma_{x1}^2+\sigma_{x2}^2)} - \frac{(\bar{y}_1-\bar{y}_2)^2}{2(\sigma_{y1}^2+\sigma_{y2}^2)}\right]$$

Use the VDM scan technique to measure the beam parameters, and extract the visible cross section, which is your calibration constant, for a particular detector to convert a rate to a luminosity

How to get the absolute luminosity calibration



Beam separation scans provide absolute luminosity calibration

$$\mathcal{L}_{peak} = f_r n_1 n_2 \iint \rho_1(x,y)\rho_2(x,y)\,dx\,dy$$

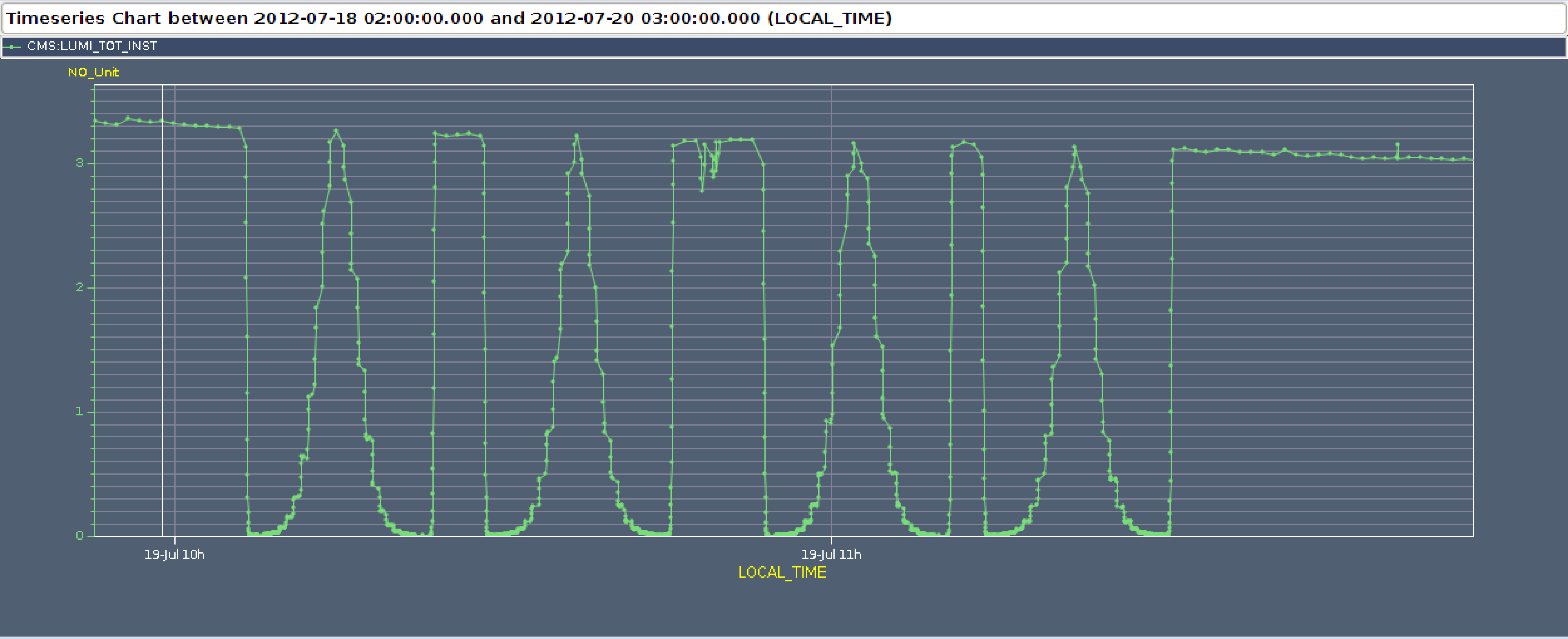
$$= f_r n_1 n_2 \frac{1}{2\pi \Sigma_x \Sigma_y}$$

Σ_x, Σ_y - convolved beam widths

$n_1\ n_2$ - bunch population product

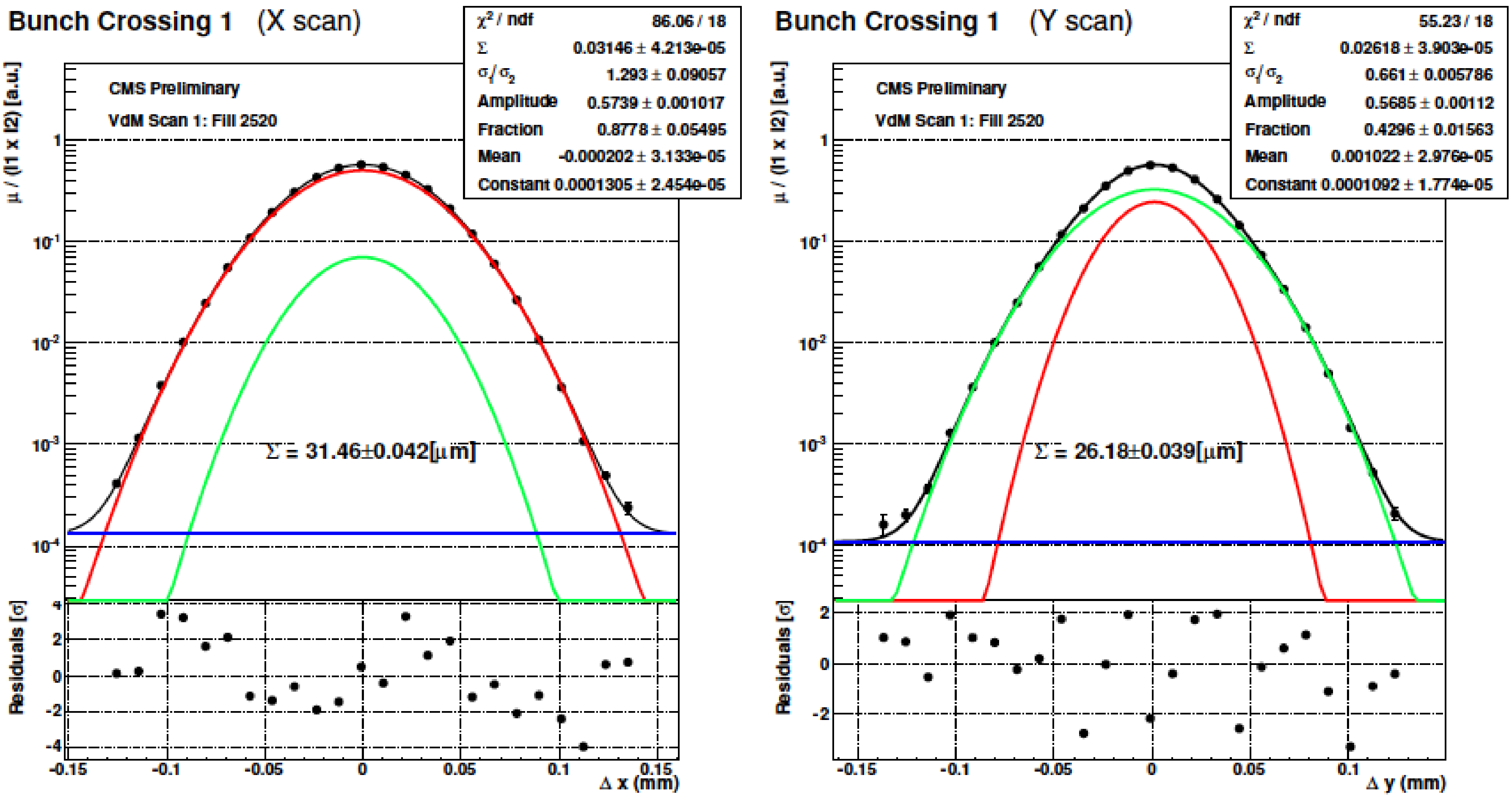
S. van der Meer, CERN-ISR-PO-68-31 (1968)

How to get the absolute luminosity calibration

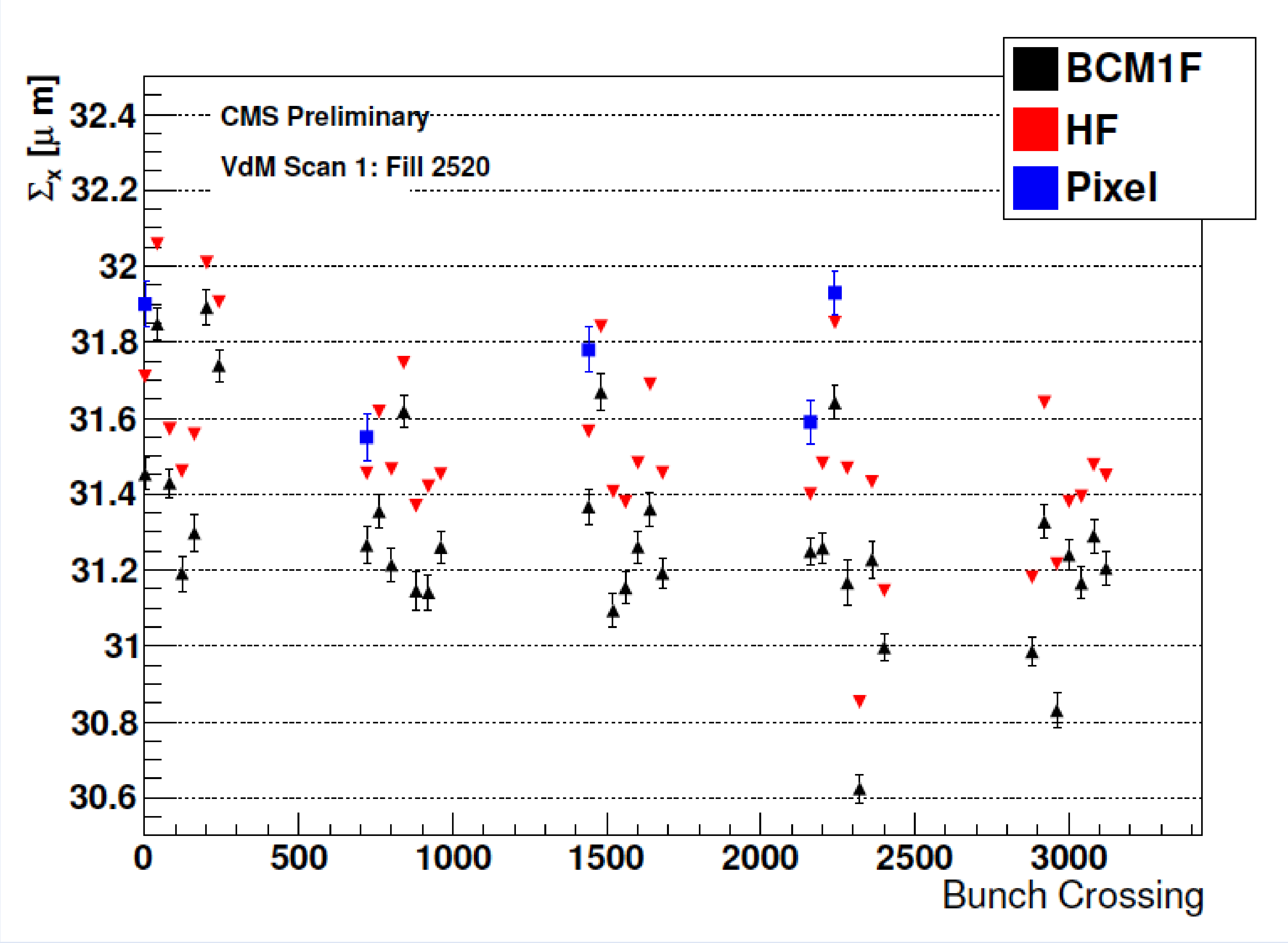


Van der Meer Calibration Results

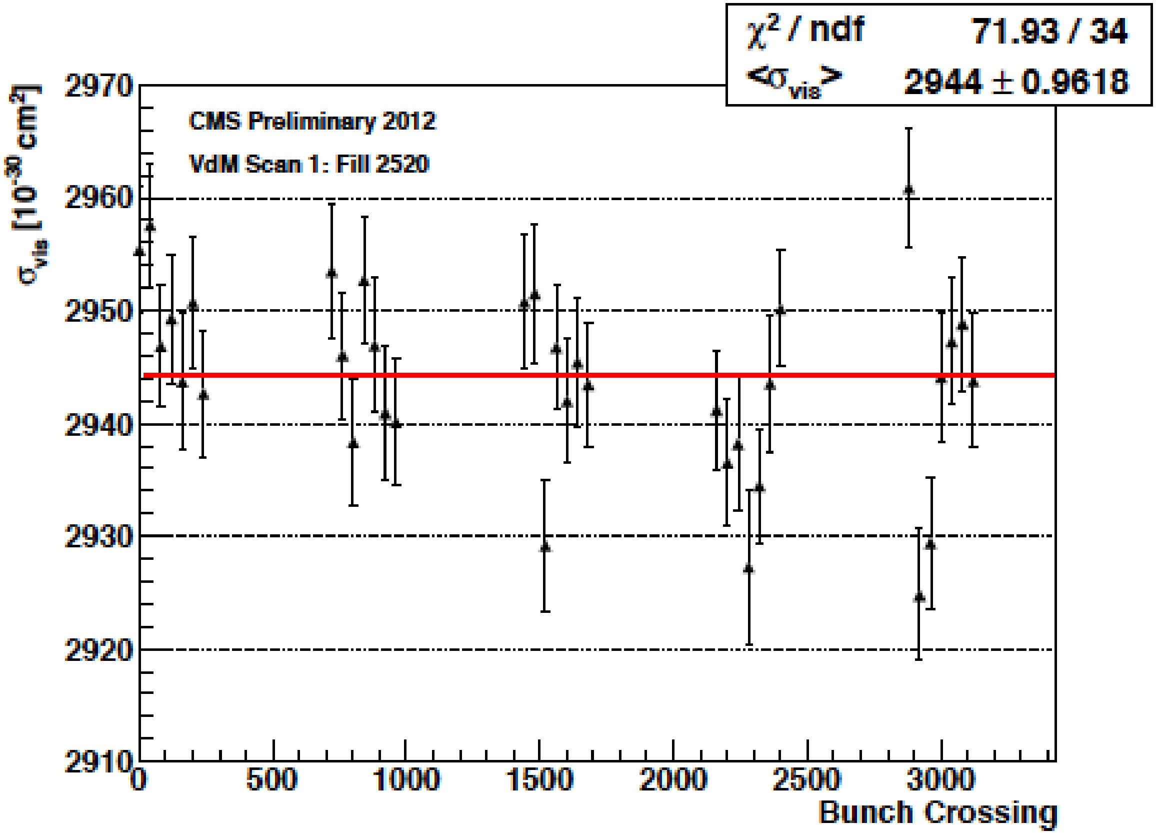
Overlap region is measured for scans in the x (left) and y (right) directions



Bunch-by-bunch measurement of the beam overlap with different detectors



Bunch-by-bunch Results for σ_{vis}



$$\sigma_{vis} = \pi \Sigma_Y \Sigma_X \frac{(\mu_{X,peak} + \mu_{Y,peak})}{N_1 N_2} \Rightarrow \sigma_{vis} \approx 2.94\text{mb} \qquad (3)$$

Trends for new accelerators

Bigger, Faster, Better!

High energy machines for particle physics

- LHC, HL-LHC, HE-LHC (CERN)
- CLIC/ILC (R&D)

High current machines

- Neutron sources – material science
  - SNS (US), ESS (Sweden), CSNS (China), IFMIF (Japan), …
- Neutrino Production
  - T2K (JPARC, Japan), NuMI/Nova (FNAL, US), CNGS (CERN), Project-X (FNAL, US), …

High Brightness machines

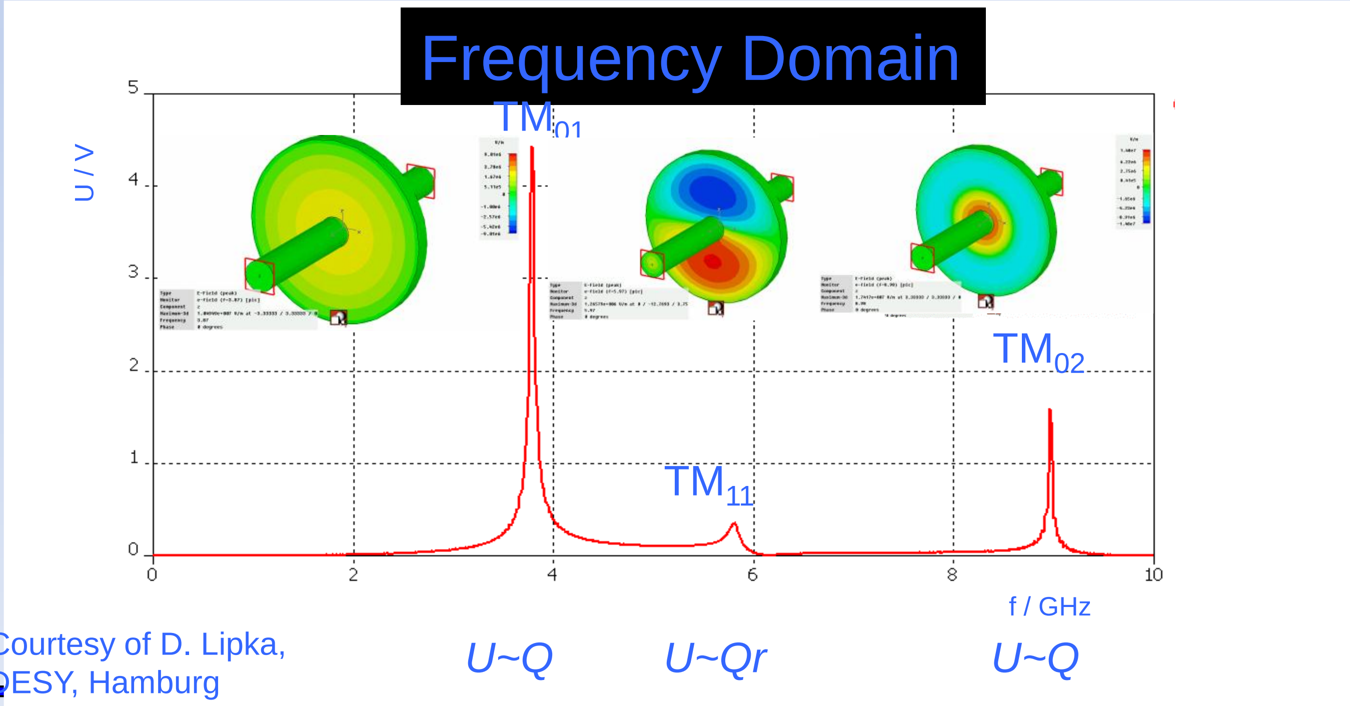
- X-ray Free Electron Lasers – probing complex, ultra-small structures
  - LCLS (SLAC, US), European XFEL (DESY, DE), …

Compact or Exotic!

- **Rare radioactive isotope machines**
  - FAIR (GSI, DE), HIE-ISOLDE (CERN)
- **Anti-matter machines**
  - ELENA (CERN), FAIR (GSI, DE)
- **Medical proton/ion therapy machines**

- **Unprecedented request for precision**
  – Positioning down to well below the micron level
- **Treatment of increasingly more data**
  – Bunch by bunch measurements for all parameters
- **Dealing with high beam powers**
  – Non-invasive measurement techniques
  – Robust and reliable machine protection systems
- **Dealing with the ultra-fast**
  – Measurements on the femto-second timescale
- **Dealing with the ultra-low**
  – Measurement of very small beam currents

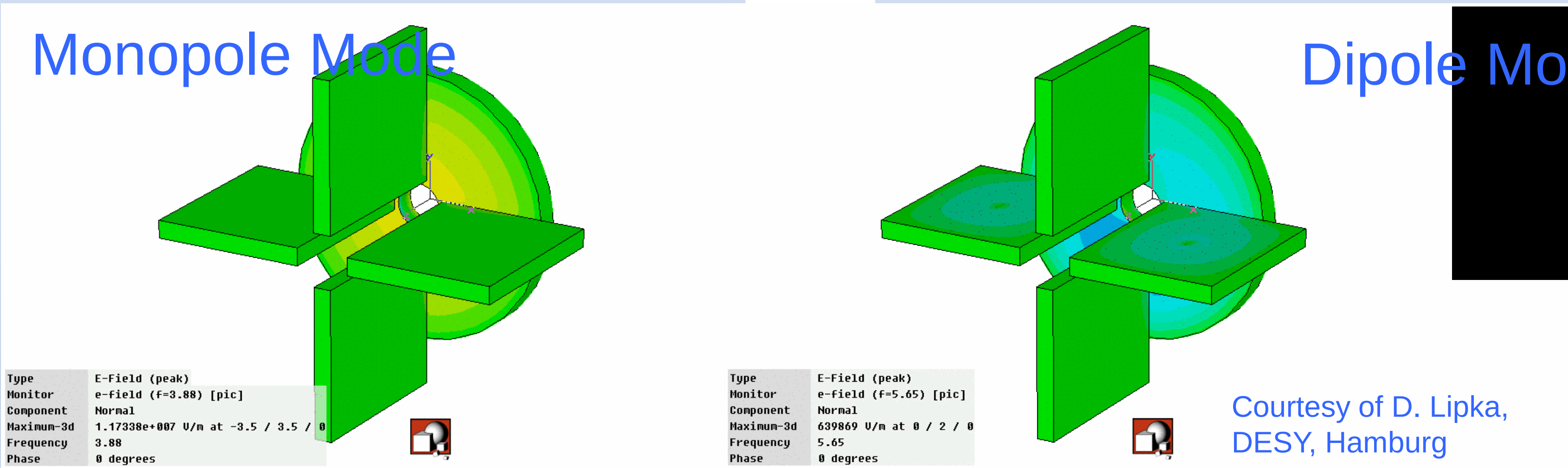
- Standard BPMs give intensity signals which need to be subtracted to obtain a difference which is then proportional to position
  - Difficult to do electronically without some of the intensity information leaking through
    - When looking for small differences this leakage can dominate the measurement
    - Typically 40-80dB (100 to 10000 in V) rejection ⇒ tens micron resolution for typical apertures
- Solution – cavity BPMs allowing sub micron resolution
  - Design the detector to collect only the difference signal
    - Dipole Mode TM_{11} proportional to position & shifted in frequency with respect to monopole mode



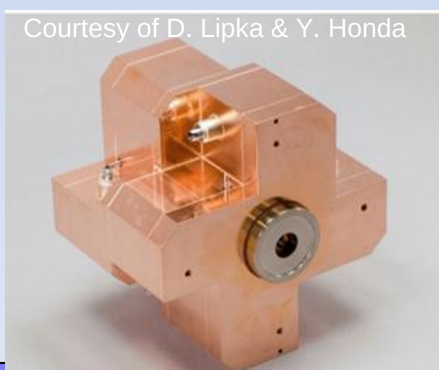
Courtesy of D. Lipka, DESY, Hamburg

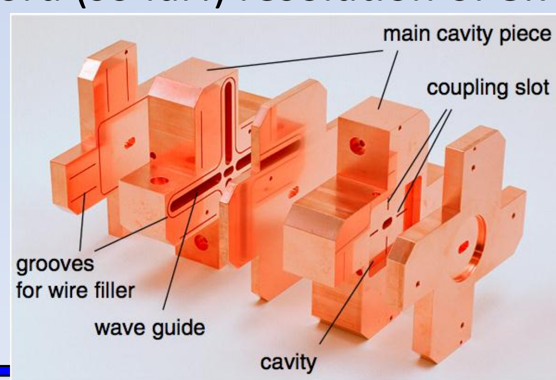
Slide R. Jones, CERN

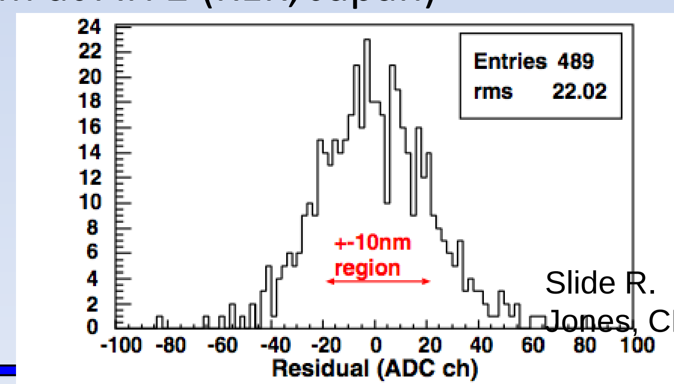
- Obtain signal using waveguides that only couple to dipole mode
  - Further suppression of monopole mode



- Prototype BPM for ILC Final Focus
  - Required resolution of 2nm (yes nano!) in a 6 × 12mm diameter beam pipe
  - Achieved World Record (so far!) resolution of 8.7nm at ATF2 (KEK, Japan)



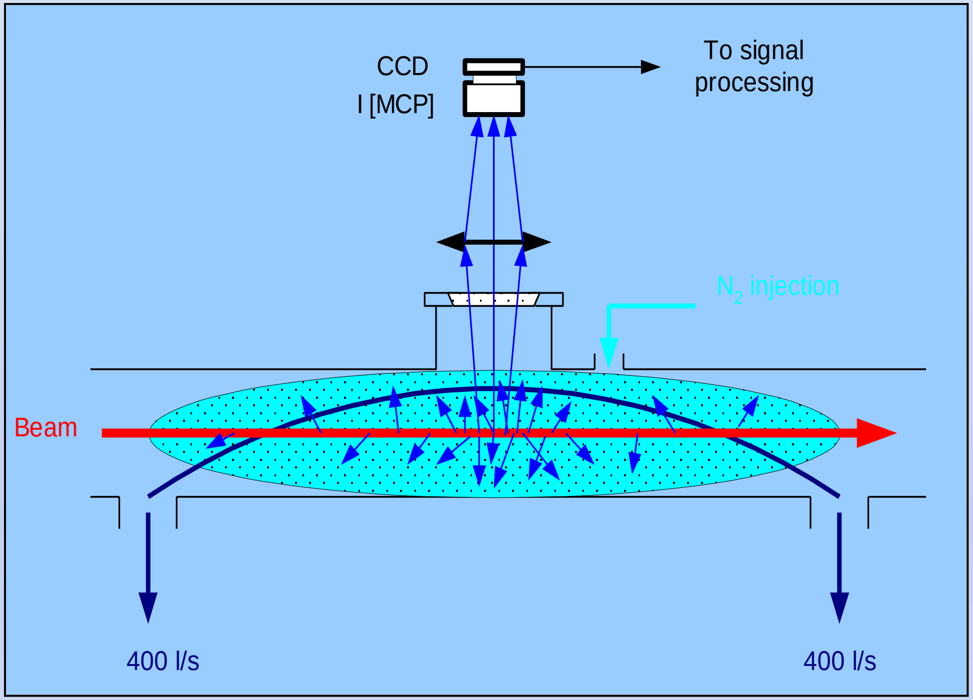


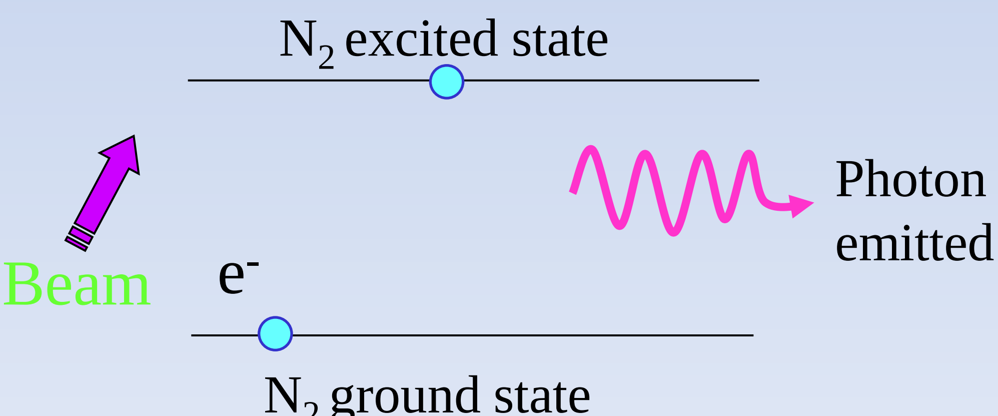


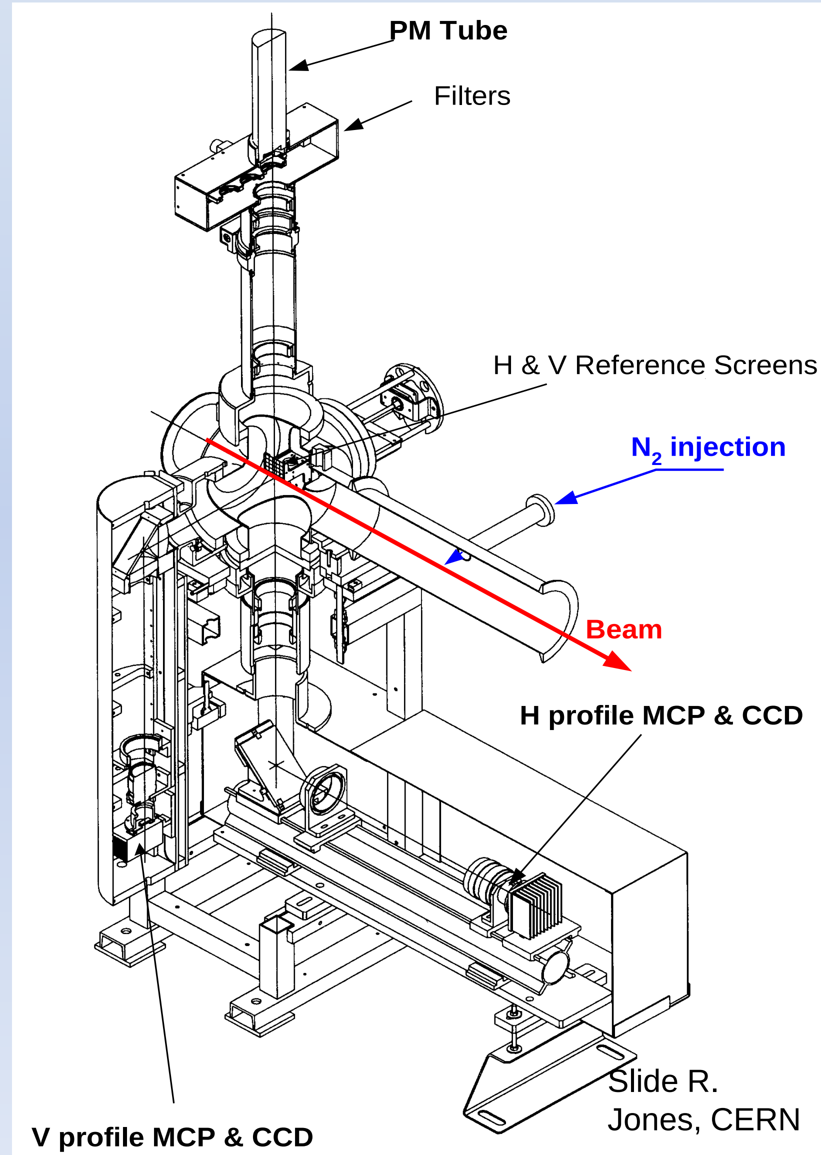
Slide R. Jones, CERN

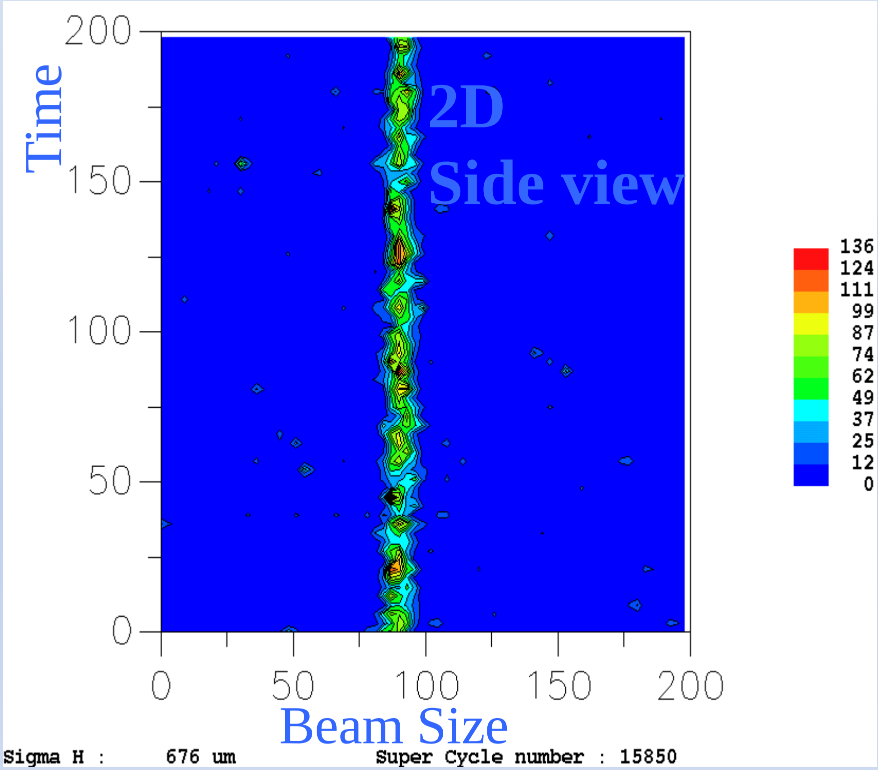
Need for non-invasive beam diagnostics

Luminescence Profile Monitor







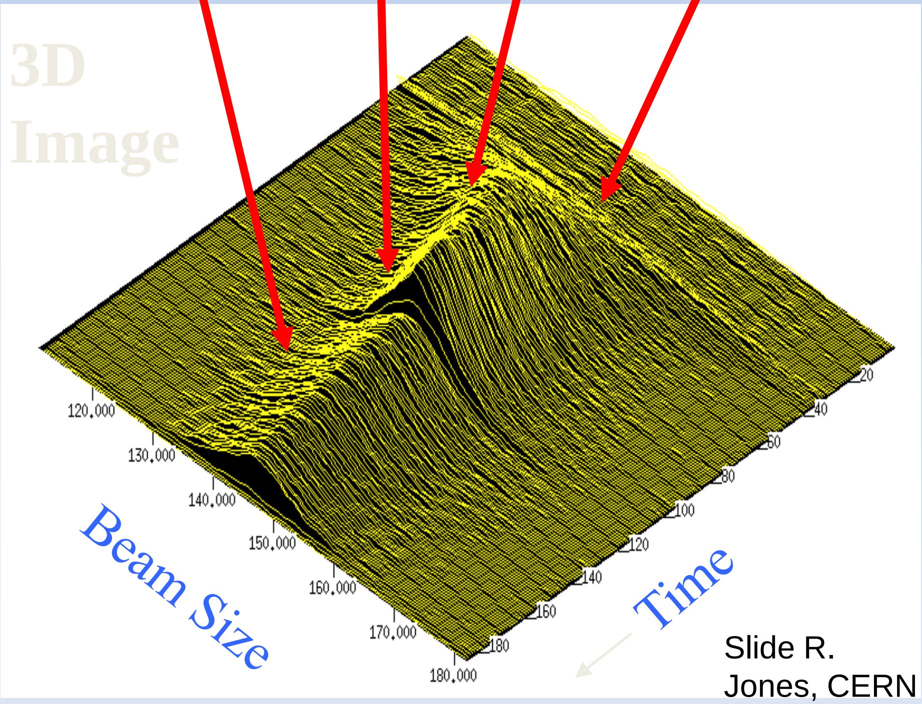


Beam size shrinks as beam is accelerated

Fast extraction

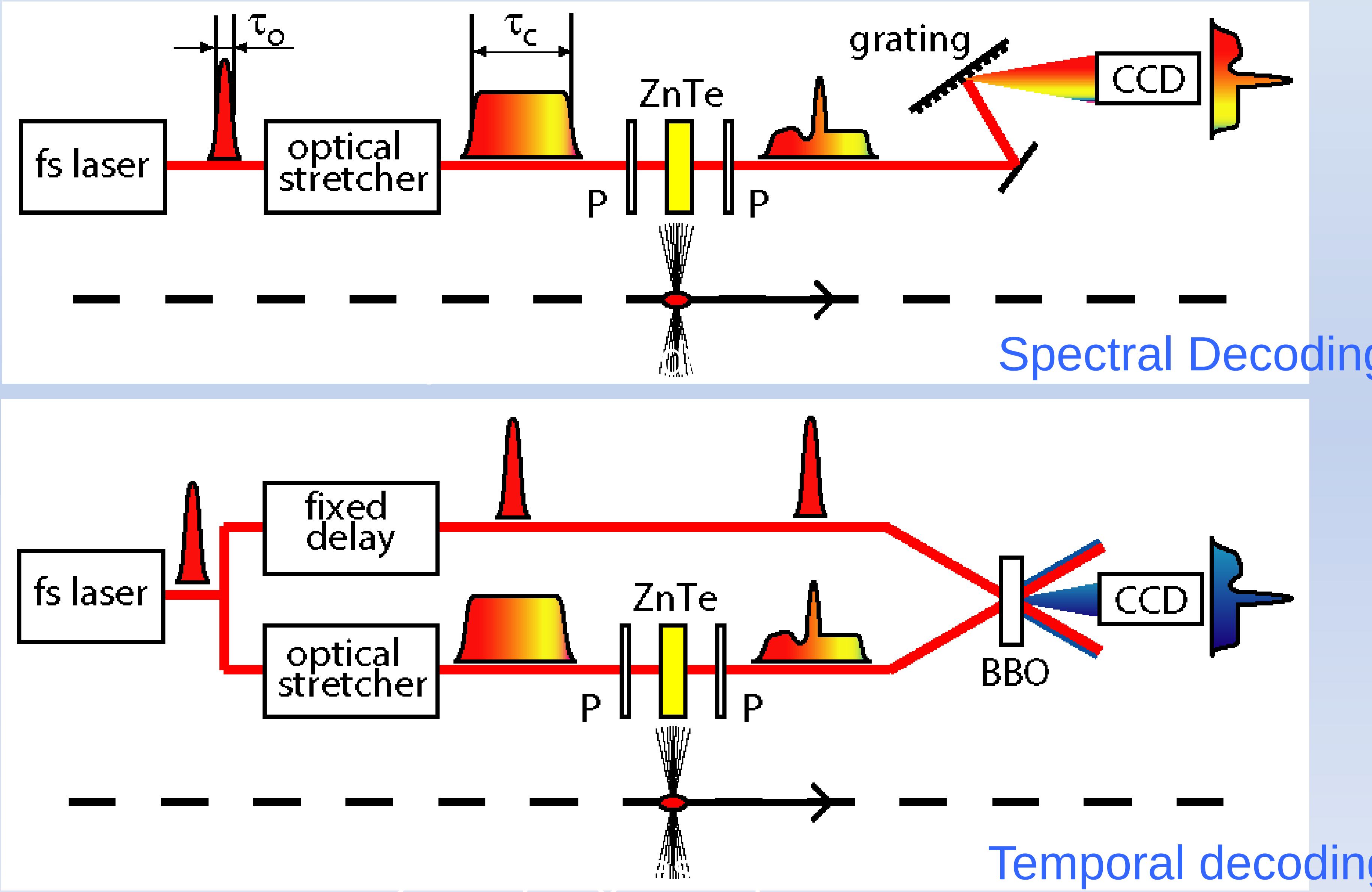
Injection

Slow extraction



CERN-SPS Measurements

- Profile Collected every 20ms
- Local Pressure at ~5×10^{-7} Torr


fs laser
optical stretcher
ZnTe
P
P
grating
CCD
Spectral Decoding
fs laser
fixed delay
optical stretcher
ZnTe
P
P
BBO
CCD
Temporal decoding

A whole field opening in X-ray beam instrumentation

X-ray imaging and position monitors are becoming essential to make full use of the new generation of X-FEL beam accelerators

The diagnostics characterize the FEL x-ray beams in terms of their spatial distribution and their intensity. There is a capability to attenuate the x-rays as well as for aperturing. There will be capability to measure the spontaneous spectrum from individual undulators. Mirrors deflect the x-rays from the bremsstrahlung radiation and provide horizontal separation for the different x-ray instruments in the experimental hall. Finally, radiation shielding and collimation are provided and instrumentation is needed for all beam loss monitoring.

Beam Diagnostics is a growing field
The European commission is funding various networks on detector developments and beam instrumentation, open to applicants from all nationalities.

Those programs where CERN is also a participant can be found at:

http://cerneu.web.cern.ch/cerneu/eu_projects/fp7/

Note: ARDENT and DITANET networks have helped to sponsor the school

http://ardent.web.cern.ch/ardent/ardent.php?link=jobs
http://cerneu.web.cern.ch/cerneu/eu_projects/fp7/#DITANET

Networks, for beam diagnostics in particular:

"**Optimization of Particle Accelerators**"
http://cerneu.web.cern.ch/cerneu/eu_projects/fp7/#oPAC

"**LAsers for Applications at Accelerator facilities NETwork**"
http://cerneu.web.cern.ch/cerneu/eu_projects/fp7/#LA3NET

Useful:

Using the definition of a rad radiation dose as 100 ergs per gram leads to another definition, in terms of *MIPs*.

$$1\,rad = \frac{100\,ergs}{gram} \cdot \frac{MeV}{1.6 \cdot 10^{-6}\,ergs} \cdot \frac{MIP \cdot gram}{2\,MeV \cdot cm^2} = 3.1 \cdot 10^7\,MIPs\ per\ cm^2$$

So now we can describe the response of a beam loss monitor in terms of either energy deposition (100 ergs/gram), or in terms of a charged particle (MIPs) flux (3.1-10^7 MIPs/cm^2). (from R. Shafer)

Radiative techniques

'Convert particles into photons'

Incoherent and Coherent radiation

The possibility of intense coherent synchrotron radiation (SR) in an electron storage ring was proposed by F.C.Michell in 1982. A srnall bunch of the electrons might emit coherent SR at wavelengths which are comparable to or longer than the longitudinal bunch length.

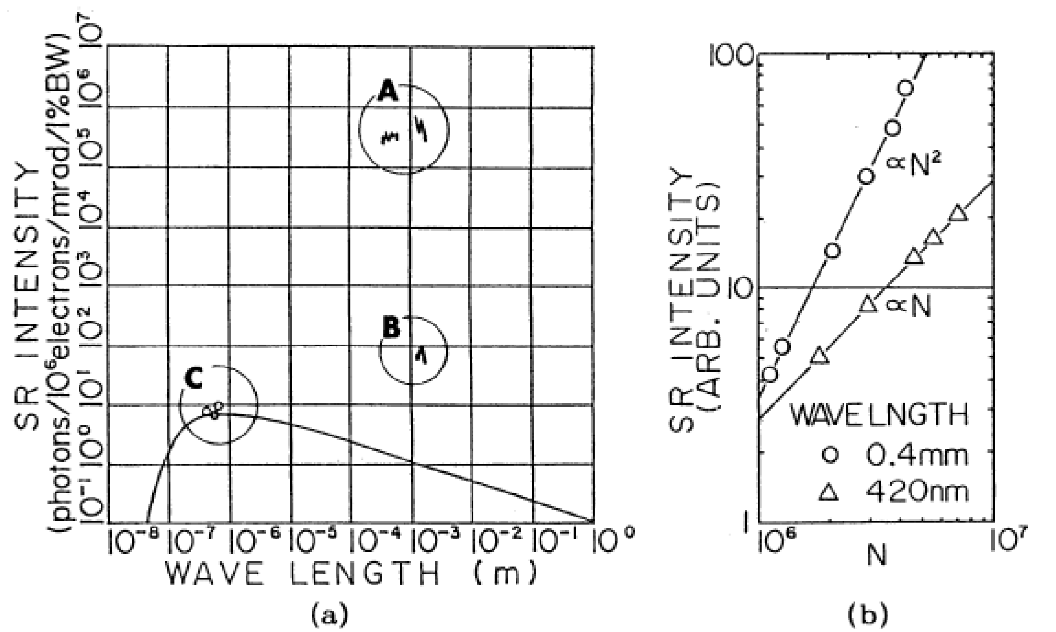


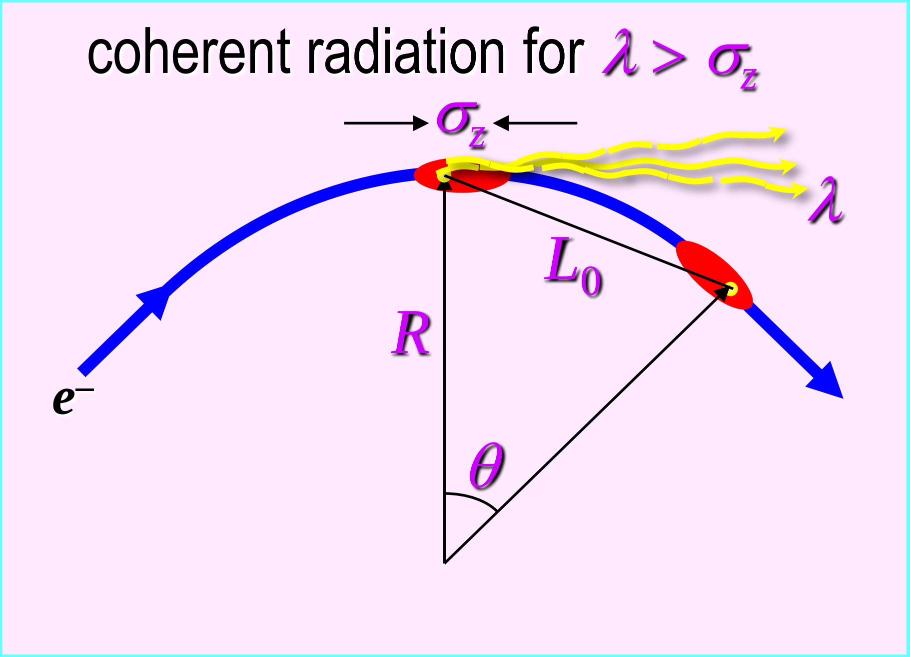
FIGURE 2. Observed SR spectra (a) and beam current dependence of the SR intensity (b). (a) Data in circle "A" and "C" are the spectra for the bunch length of 1.7 mm, and in "B" for 15 mm. All the data are measured with the same optical system. A solid curve shows the incoherent SR intensity calculated for this experimental condition. These intensities are normalized for a bunch of 10^6 electrons. (b) N is the number of electrons in a bunch, which is proportional to the beam current. The values of intensity should not be compared between two wavelengths.

Measurement at Tohoku 300 MeV Linac

COHERENT SYNCHROTRON RADIATION
Particle Accelerators, 1990, Vol. 33, pp. 141-146
cdsweb.cern.ch/record/1125893/files/p141.pdf

Coherent Synchrotron Radiation in Magnetic Chicane

- Powerful radiation generates energy spread in bends
- Energy spread breaks achromatic system
- Causes bend-plane emittance growth (short bunch worse)



- Knowing the bunch length is important for understanding the source of energy loss
- For diagnostics, measuring the fraction of coherent and incoherent radiation, can give us information on the bunch length

Rings; **Emission of SR in bending magnets results in**

- Electron energy spread which increases bunch length
  *Typical bunch lengths are ~**50 picoseconds***
- Betatron oscillations which cause emittance growth
  Emittance scales as $\varepsilon \sim E^2\theta^3$
  (θ is the angle of bending in each bend magnet)
  Third generation rings have $\varepsilon \sim 5\text{x}10^{-9}m$

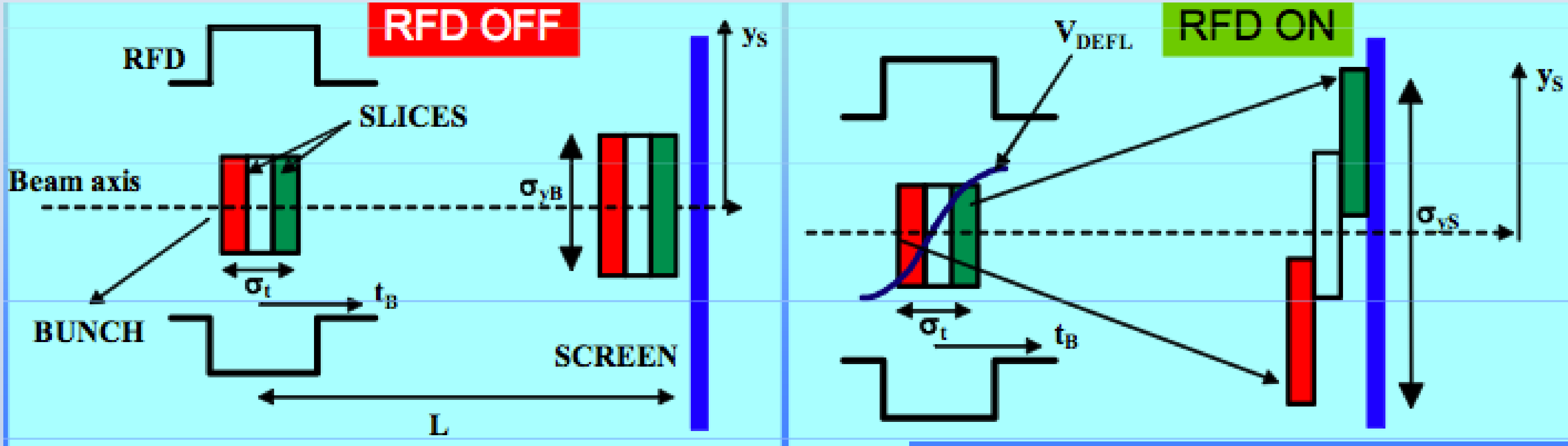
Linacs: **No bends, hence no SR emission (except compressors)**

- Electron emittance determined mainly by source (gun) emittance
- Emittance scales with **(electron energy)$^{-1}$** $\varepsilon \sim 1/E$
  reach diffraction-limited emittance, $\varepsilon = l/4p = 10^{-11}m$ *for l~1.5Å*
- Bunches can be compressed to ***sub-picosecond*** levels

Reminder talk H. Winick

*Emittance is the product of beam size and divergence; meters x radians

RF Deflecting Cavity



$$y_S \cong \left(\frac{V_{DEFL}}{E/e}\omega_{RF}L\right)\left(t_B + \frac{\Delta\phi_{RF}}{\omega_{RF}}\right)$$

K_{cal}

$$R_{34} = \sqrt{\beta_S \beta_{defl}}\sin\Phi_{s\_defl}$$

resolution

$$\sigma_{y_S}^2 \cong K_{cal}^2 \sigma_{t_B}^2 + \sigma_{y_B}^2$$

$$\sigma_{t_B\_RES} = \frac{\sigma_{y_B}}{K_{cal}} = \frac{\sqrt{\varepsilon_y \beta_S}}{K_{cal}}$$

Courtesy D. Alesini, Frascati

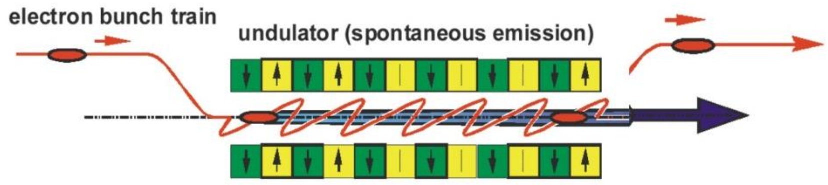
Very bright electron beams from linacs open the path to short wavelength Free-Electron Lasers

Interaction of a ***bright electron beam*** with a strong ***optical field*** in an ***undulator magnet*** results in a ***density modulation*** of the electron bunch at the ***optical wavelength*** → ***coherent emission***

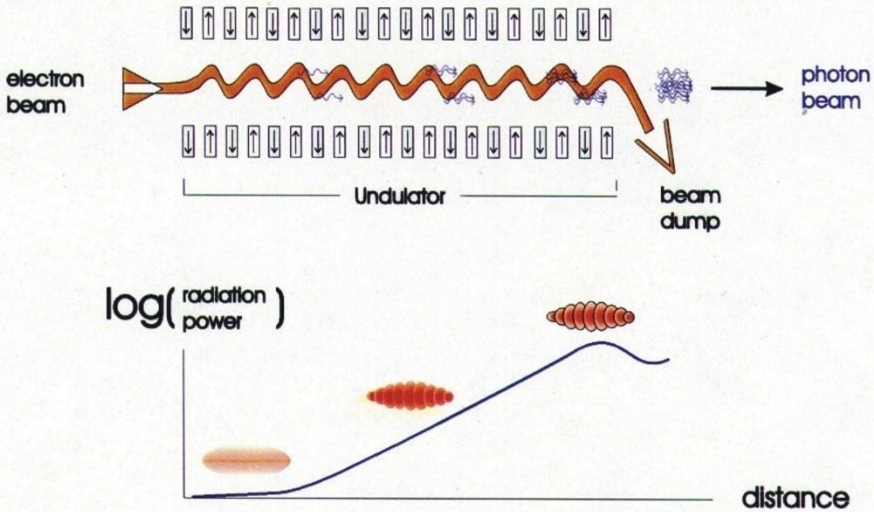
i.e.; proportional to the square of the number of electrons (N^2) within an optical wavelength rather than linearly with N as in spontaneous synchrotron radiation.

Linac-driven Light Sources - Toward the 4th Generation

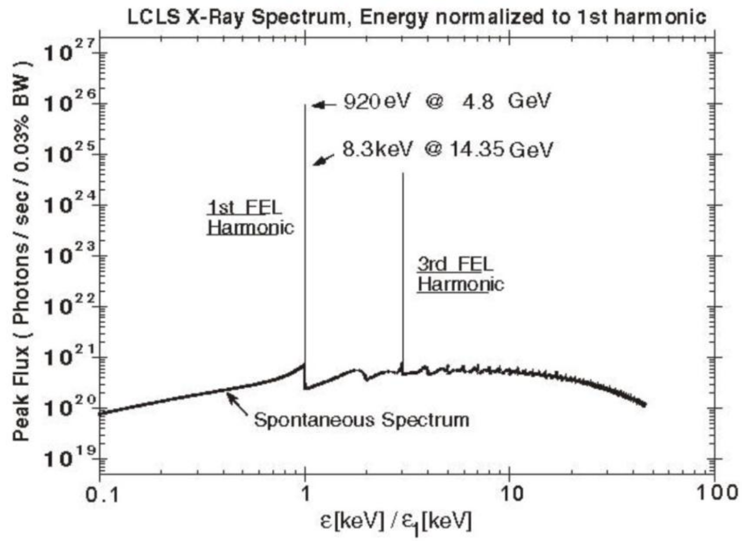
Conventional Undulator - Spontaneous Emission



Long Undulator - Self Amplified Spontaneous Emission (SASE)



LCLS Performance

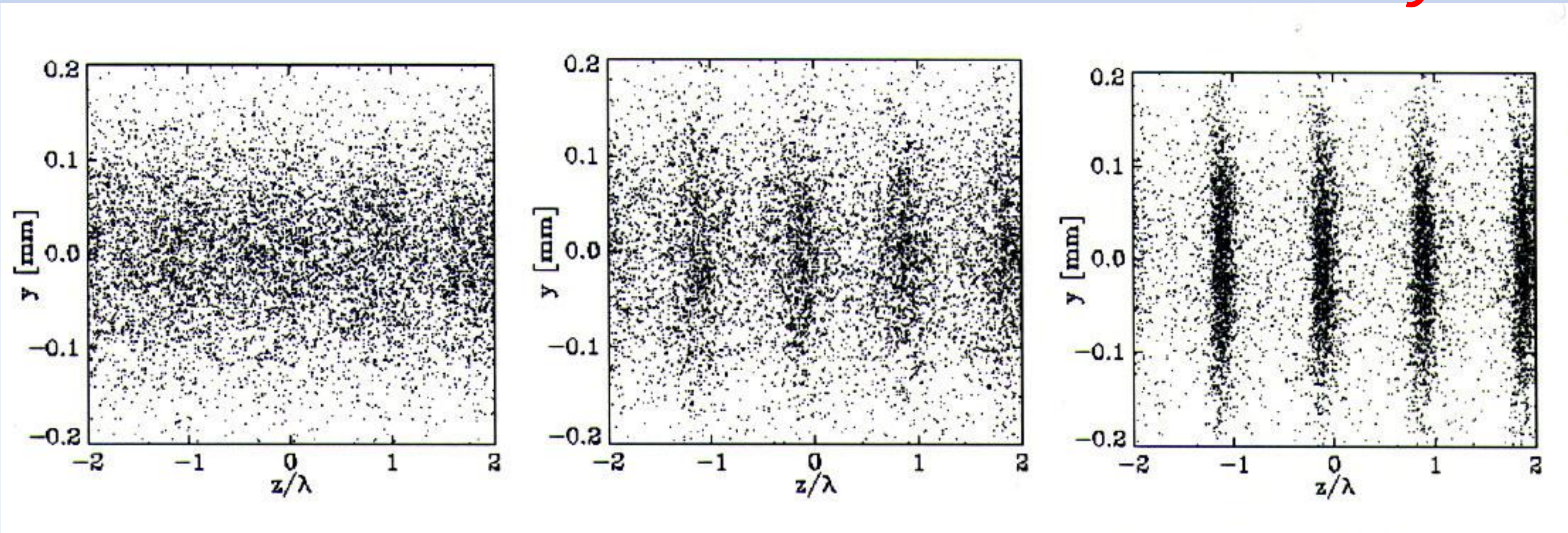


- **SASE gives 10^6 intensity gain over spontaneous emission**
- **FELs and ERLs can produce ultrafast pulses (of order 100 fs or less)**

The X-ray Laser operates by grouping electrons so that they work together to produce many more X-rays than each electron alone.

One thousand electrons packed closely together can radiate ***one million*** times more than a single electron!!

Bunched electrons radiate coherently



START MIDDLE END