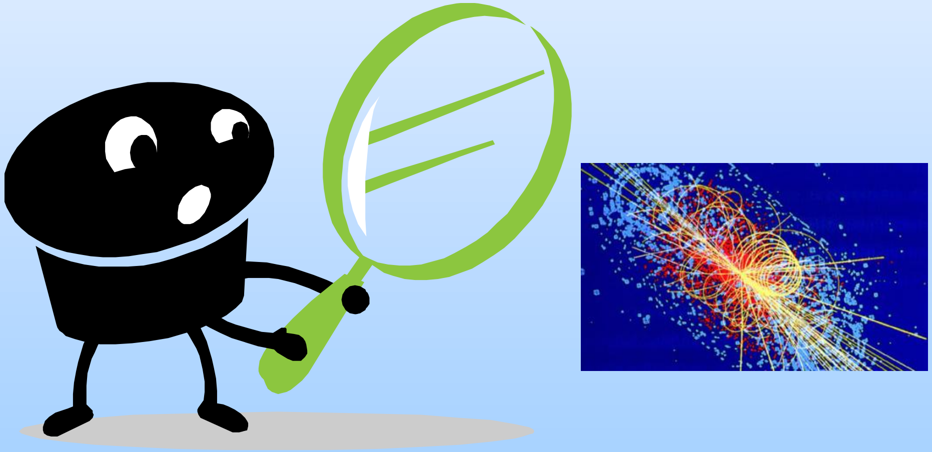
Challenges in Accelerator Beam Instrumentation

Manfred Wendt

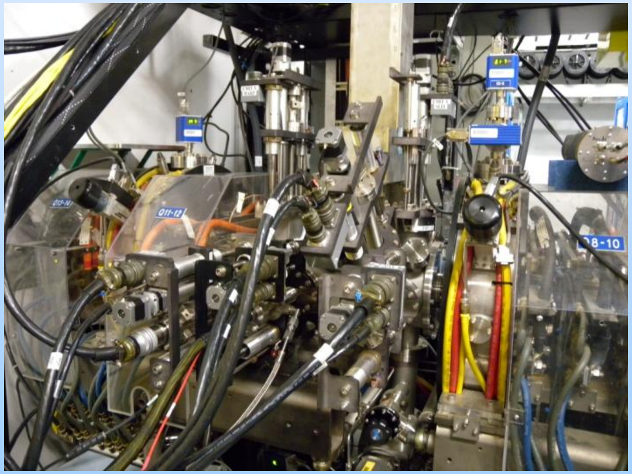
- Fermilab -

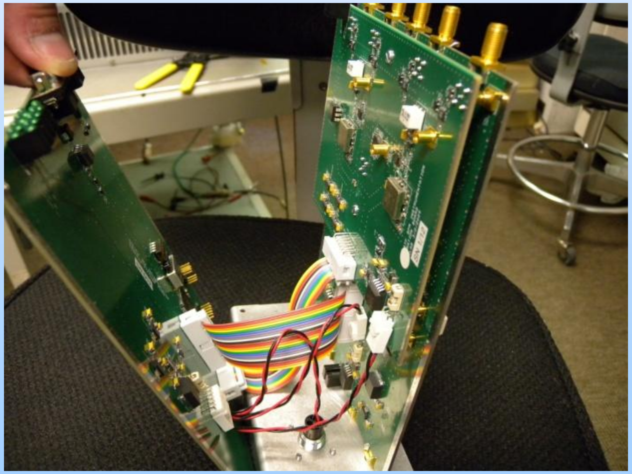
The discovery of the **Higgs** boson…
(at the TeVatron?!)



…would be far more entertaining than a presentation about

Beam Instrumentation and Diagnostics





Why Beam Instrumentation?

Particle acceleration needs:

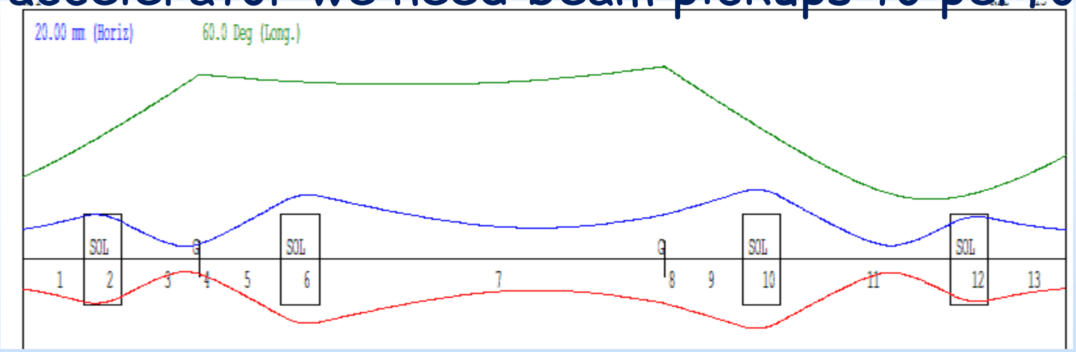
- **Guide fields**
  - Magnets (dipole, quad, sextupoles, other multipoles…)
  - Correction / steering magnets
  - Power supplies
  - Cooling water, etc., …sometimes cryogenics
- **Accelerating fields ($$$)**
  - Cavities, waveguides, couplers
  - Klystrons, modulators, PFNs, HV-supplies
  - Interlocks, control systems, and again sometimes cryogenics!
- **Vacuum**
  - Pipes, pumps, flanges, etc., …and a very clean environment!

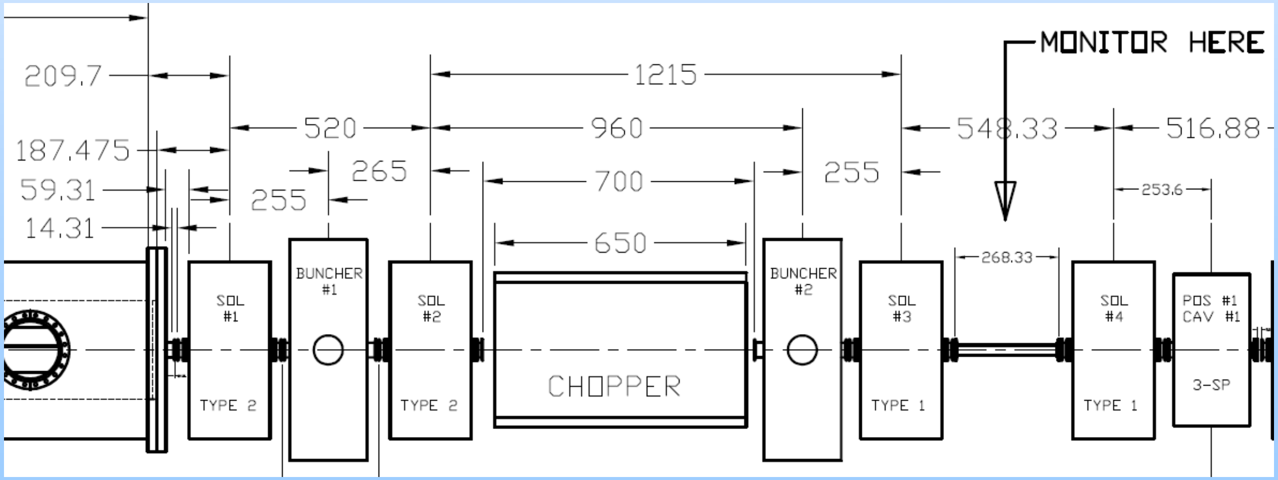
Why Beam Instrumentation?

- **Beam instrumentation and diagnostics**
  - Are eyes and ears to "watch" the particle beam
  - Most important during the commissioning period!
  - Help to spot errors and component failures.
  - Characterize beam parameters, and point out ways to meet and improve the beam quality
  - Detection elements of complex feedback systems (integrated, semi-automatic, human)

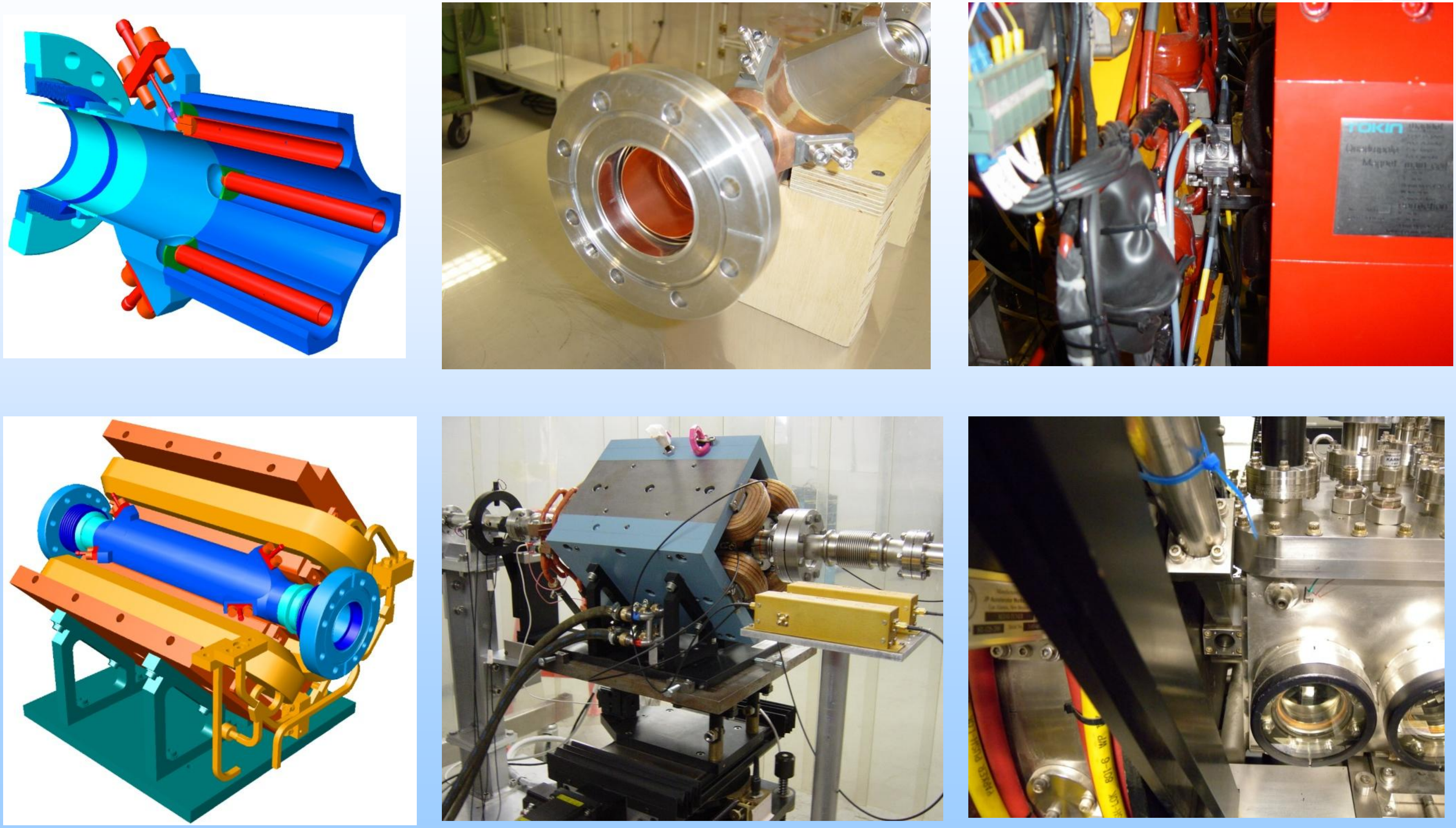
Don't forget Beam Diagnostics!

- During machine design and construction space for beam diagnostics often tends to get "forgotten"!
  - Tracking codes will show beam characteristics at any location, in a real accelerator we need beam pickups to perform this!





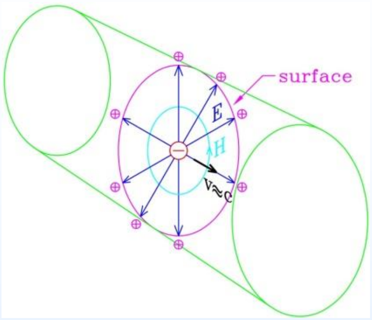
Beam Pickups which don't eat up much real-estate…

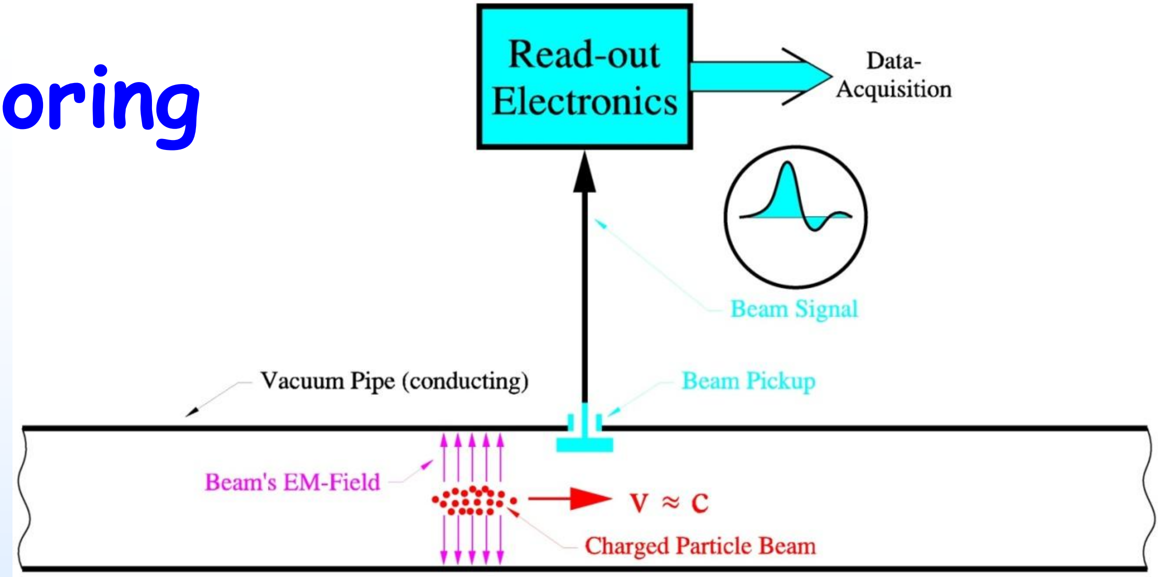


Beam Measurements

- **Beam characterization**
  - Beam intensity, bunch charge, beam current
    - Toroid, DCCT, wall current monitor
  - Beam orbit, beam position, beam energy, betatron / synchrotron tune, chromaticity, etc.
    - Beam position monitor (BPM), Schottky detector
  - Sliced beam / bunch parameters, e.g. transverse beam / bunch profile & emittance, bunch length & profile, energy spread, etc.
    - Wire-scanner, SEM multiwire, e-beam scanner, ionization profile monitor (IPM), Schottky detector, electro-optical methods, DMC
  - Beam losses, beam halo, beam tails
    - Loss monitors, vibrating wire, mode-locked laser wire
- **Feedback systems**
  - Orbit feedback, long. and trans. damping systems (BPMs)

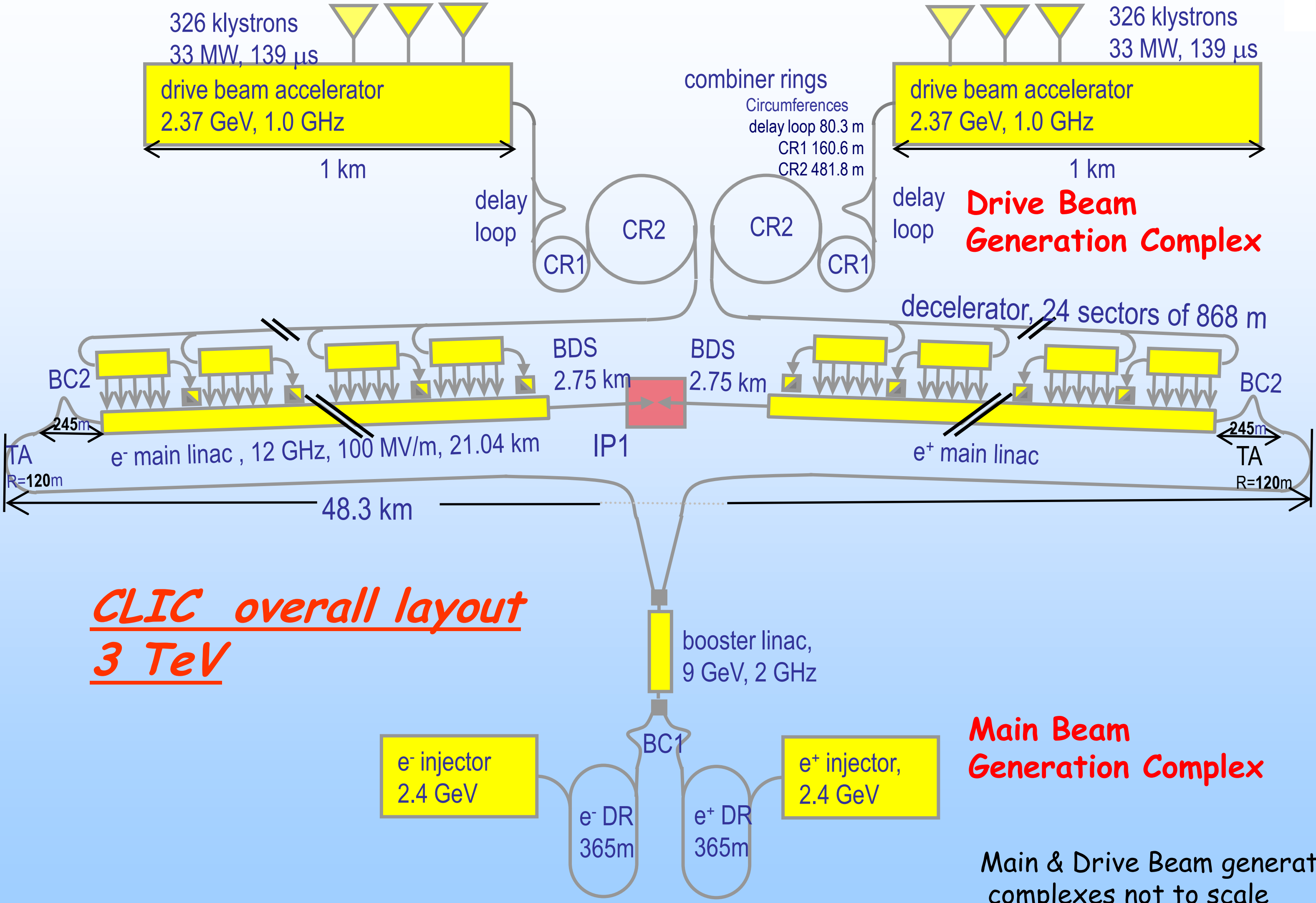
Beam Monitoring





- **Beam detector**
  - Non (minimum) invasive
    - EM antenna (magnetic, capacitive, EM coupling)
    - Scattering with rest gas or photons (IPMs, laser wire)
  - Invasive
    - Foils, screens, wires (TR, scintillation, SEM)
- **Read-out, control & data acquisition system**
  - Analog & digital signal processing
  - Motion control, technical interlocks, safety
  - Auxiliary systems (timing, trigger, PS, etc.)

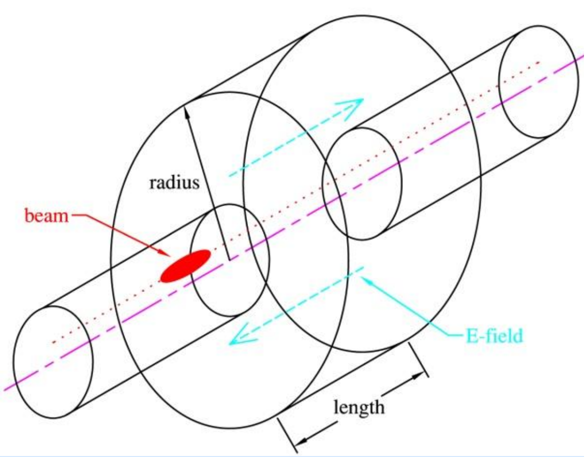
Challenging Accelerators → Diagnostics

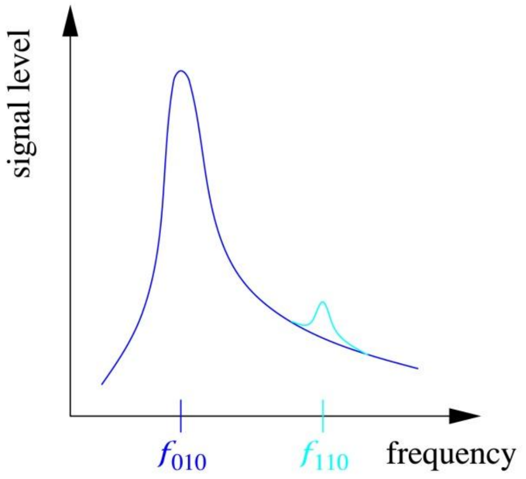


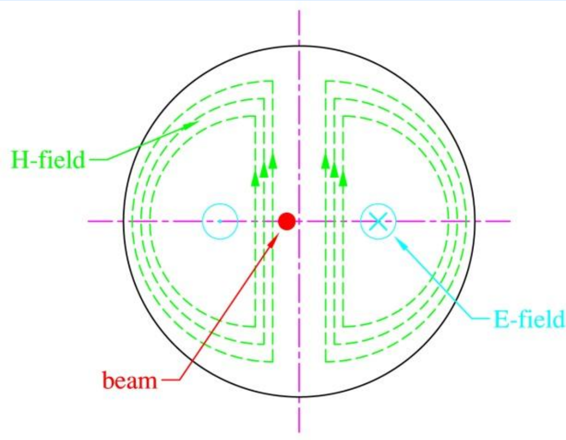
Beam Diagnostics Requirements

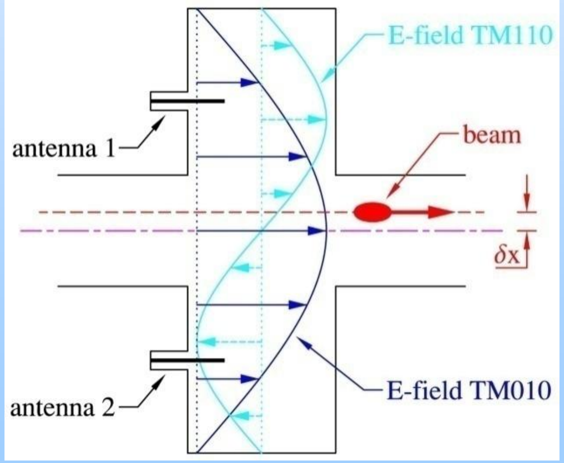
- **Lepton machines, e.g. LCLS, XFEL,** ILC, CLIC
  - Longitudinal beam dynamics
    - high bunch charge density (kA)
    - Short bunches, typically 50…500 fsec RMS
  - Beam instrumentation in the femto-second, nano-meter ranges.
  - Large number of components (HEP machines)
    - CLIC: 96 km beam-lines, ~200.000 beam monitors (52.821 BPMs most with sub-micrometer resolution, 142812 HOM monitors).
- **Hadron machines, e.g. SNS, LHC,** Project X, ADS, (NuFact, *μ*-Collider)
  - High beam power (Project X: 2 MW and more)
    - Non-invasive instrumentation (laser wire, e-beam scanner)
    - Beam loss mitigation (beam halo and tails characterization)
  - Instrumentation for non-relativistic beams, CW-beams

High Resolution BPMs









- "Pillbox" cavity BPM
  - Eigenmodes:

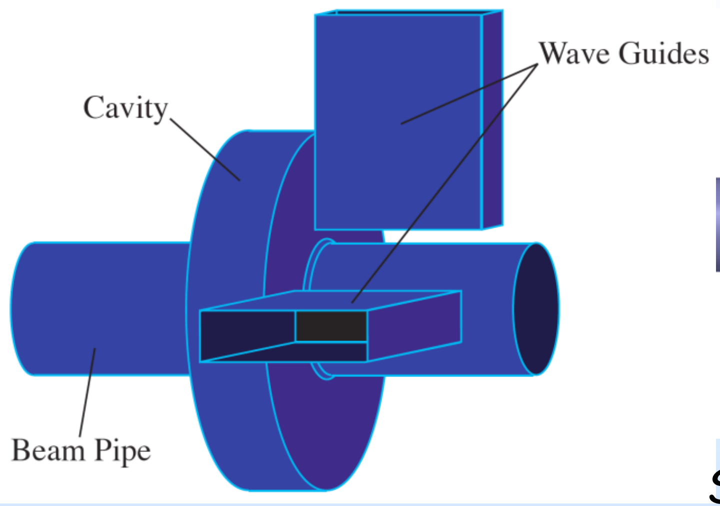
$$f_{mnp} = \frac{1}{2\pi\sqrt{\mu_0\varepsilon_0}}\sqrt{\left(\frac{j_{mn}}{R}\right)^2 + \left(\frac{p\pi}{l}\right)^2}$$

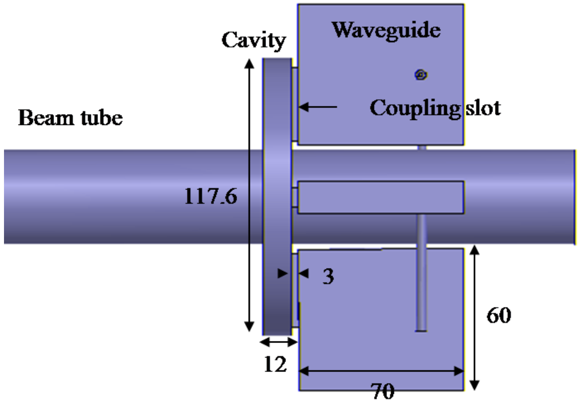
  - Beam couples to

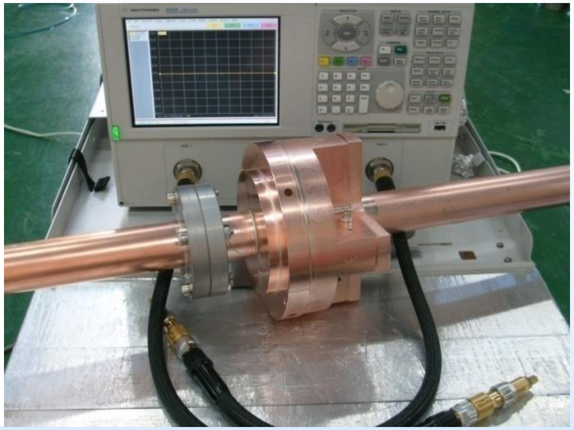
$$E_z = CJ_1\left(\frac{j_{11}r}{R}\right)\cos\emptyset\, e^{i\omega t}$$

    dipole (TM_{110}) and monopole (TM_{010}) modes
  - Common mode (TM_{010}) suppression by frequency discrimination
  - Orthogonal dipole mode polarization (xy cross talk)
  - Transient (single bunch) response (Q_L)
  - Normalization and phase reference

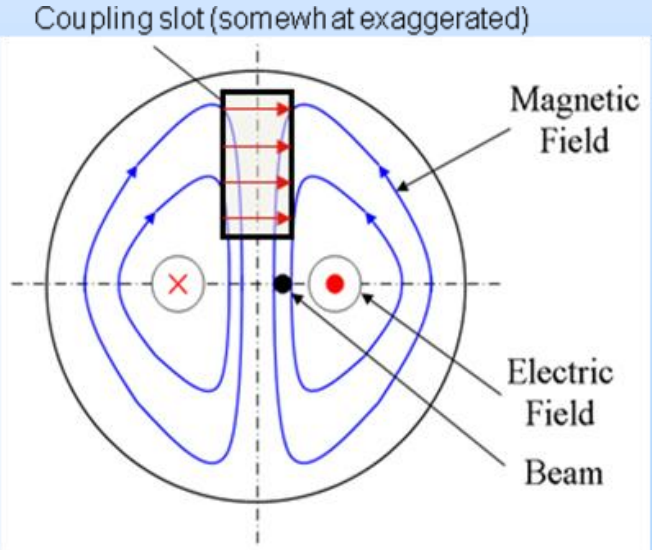
CM-"free" Cavity BPM







S-Band cavity BPM for ATF2 (KNU-LAPP-RHUL-KEK)



- **Waveguide TE$_{01}$-mode HP-filter**

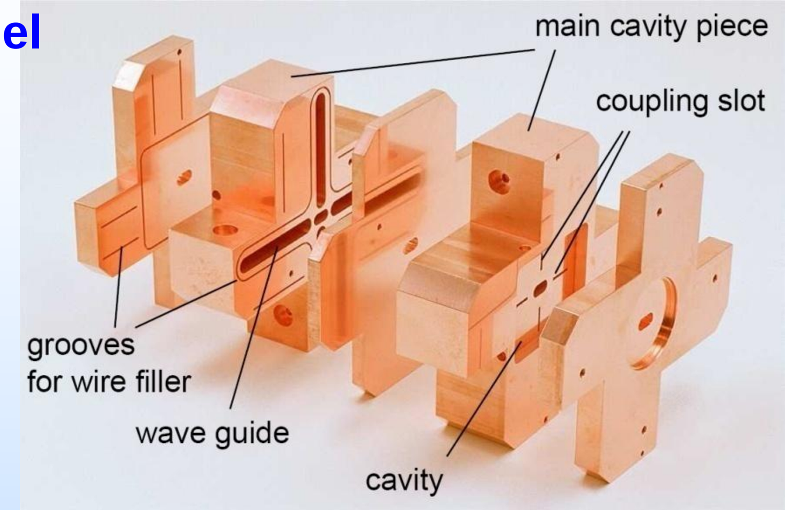
$$f_{010} < f_{10} = \frac{1}{2a\sqrt{\varepsilon\mu}} < f_{110}$$

between cavity and coaxial output port

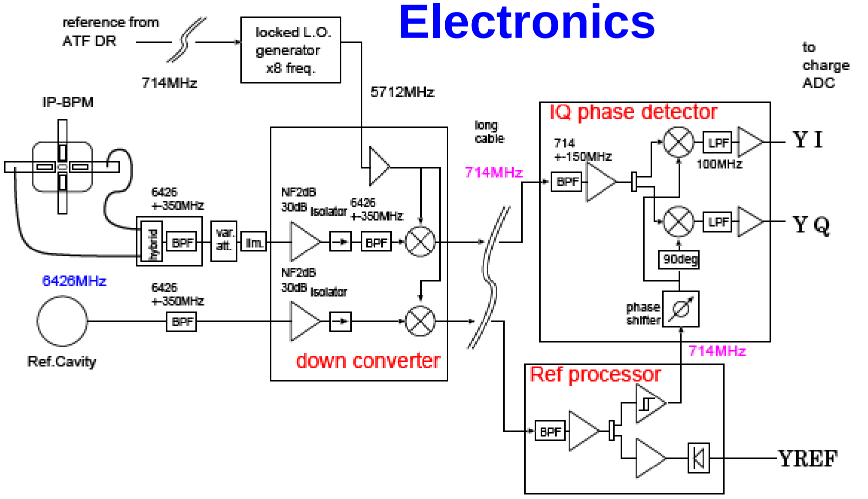
- **Finite Q of TM$_{010}$ still pollutes the TM$_{110}$ dipole mode!**

KEK C-Band IP-BPM R&D for the ILC

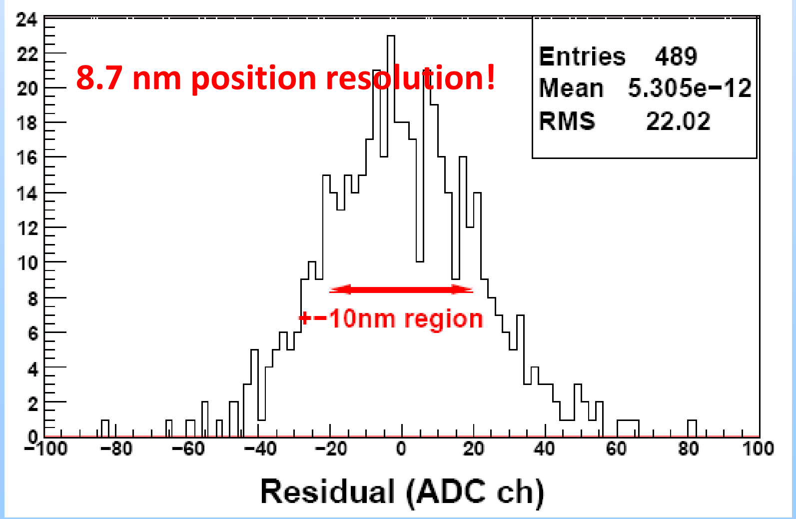
Model



Electronics



Results



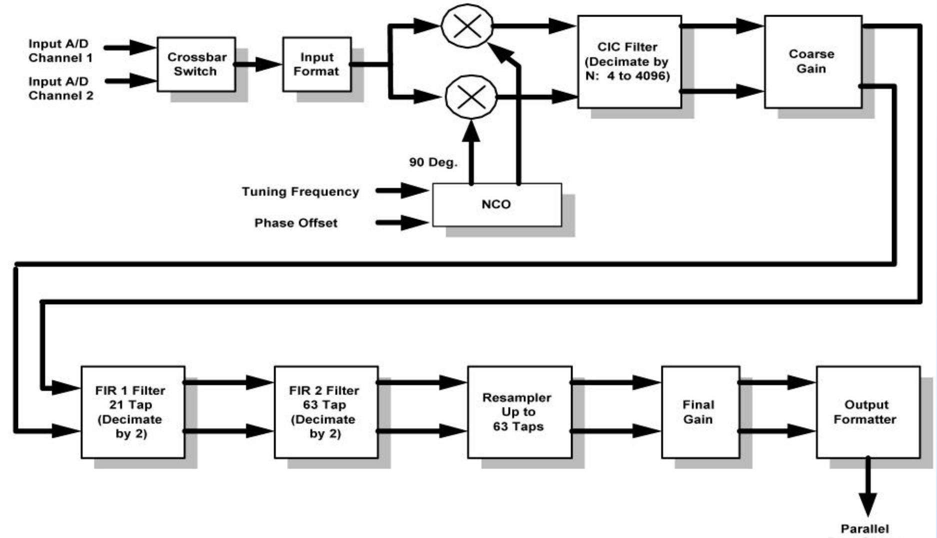
Characteristics

- Narrow gap to be insensitive to the beam angle.
- Small aperture (beam tube) to keep the sensitivity.
- Separation of x and y signal. (Rectangular cavity)
- Double stage homodyne down converter.

Design parameters

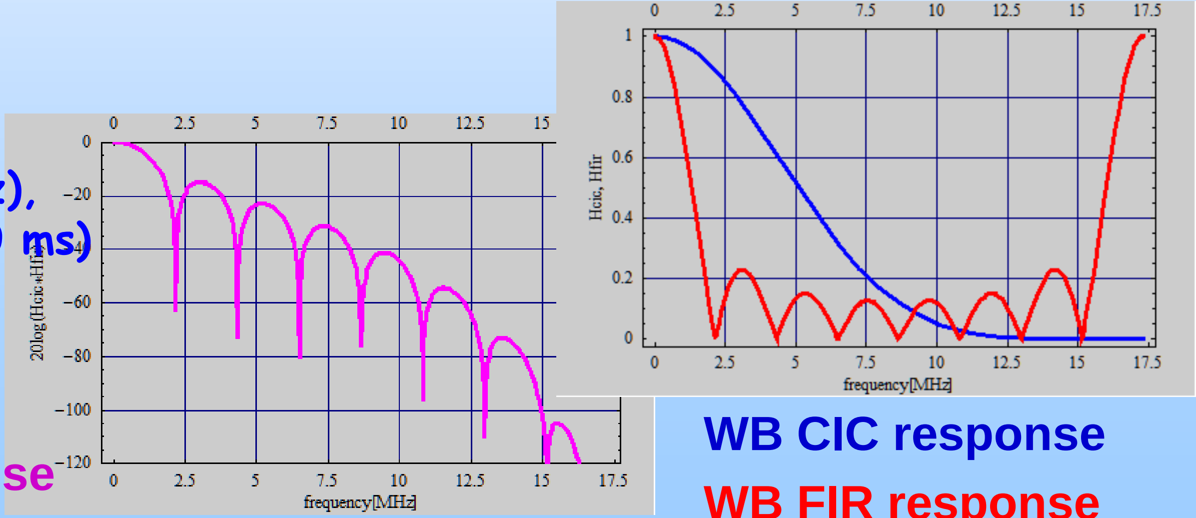
Port	f (GHz)	β	Q_0	Q_{ext}
X	5.712	1.4	5300	3901
Y	6.426	2	4900	2442

Digital “Button”-BPM Signal Processing



- *Graychip* digital downconverter
  - 4 independent channels per ADC
  - NCO set to f_{IF} = 15.145 MHz (downconvert to DC baseband)
  - ADC clock set to 32 samples per revoltion: $f_{CLK} = 32 \times f_{rev}$ = 69.2 MHz
  - Decimation and filtering for wide- and narrowband mode using CIC and FIR digital filters
  - Simultaneous DDC operation of beam and calibration signals!

- Wideband TBT mode (BW ~ 1 MHz)
  - 5 stage CIC: decimate by 4
  - CFIR: 7-tap boxcar, decimate by 2
  - PFIR 1-tap, no decimation
- Narrowband mode (BW ~ 1 kHz), t_{dec} = 158.7 μs, 1280 pt (~200 ms)
  - 5 stage CIC: decimate by 2746
  - CFIR: 21-tap RRC, decimate by 2
  - PFIR: 63-tap RRC, decimate by 2

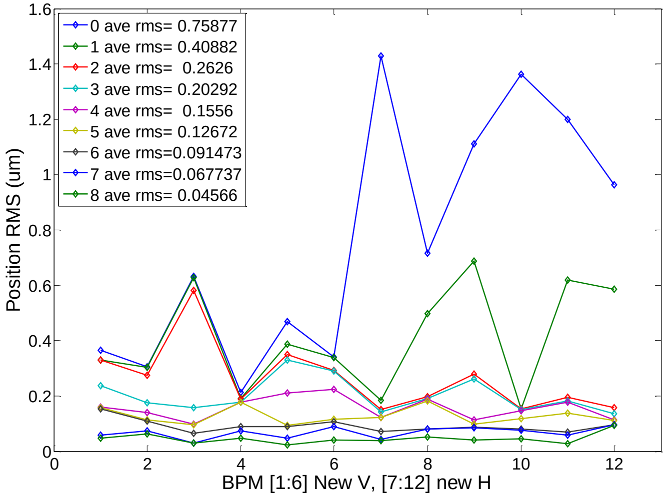


WB mode magnitude response

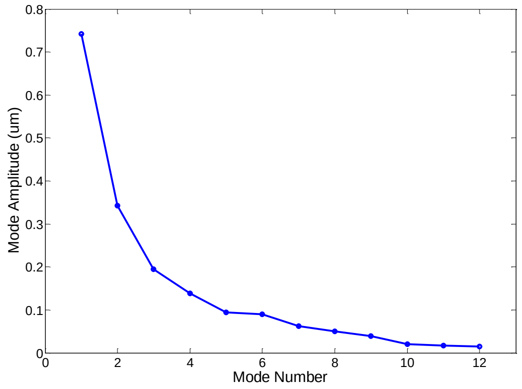
WB CIC response

WB FIR response

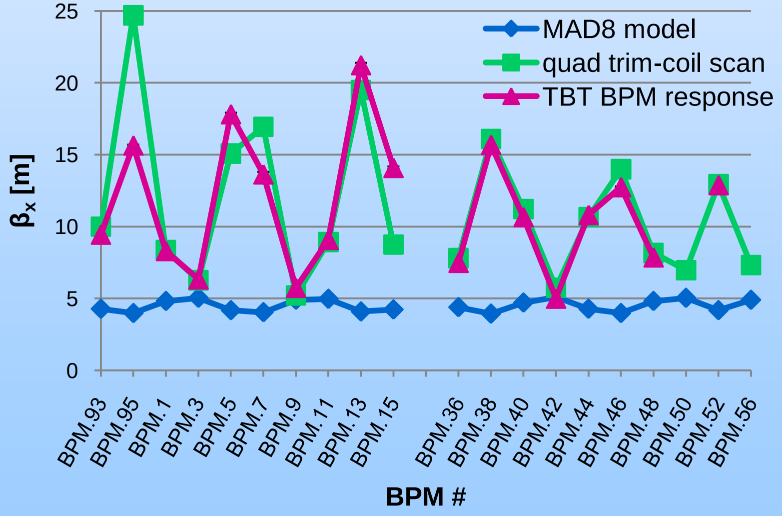
ATF Damping Ring BPM Measurements

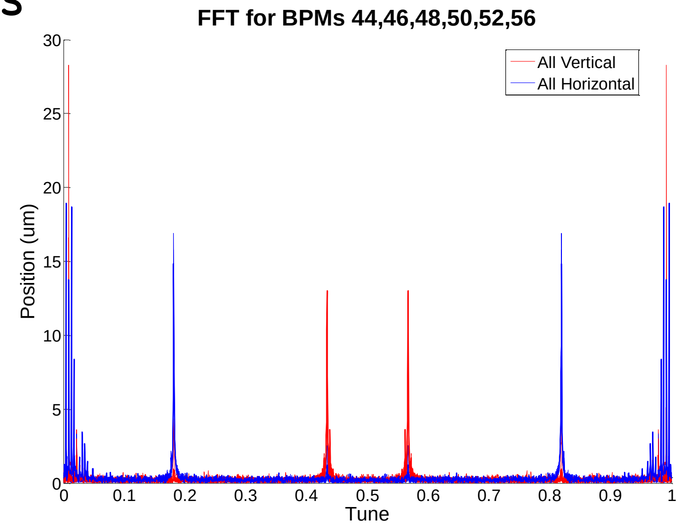


- Narrowband mode 400,000 turns after injection (beam damped)
- Take 1280 samples (~200 msec)
- 126 tap box-car filter to reject 50 Hz
- Apply SVD analysis

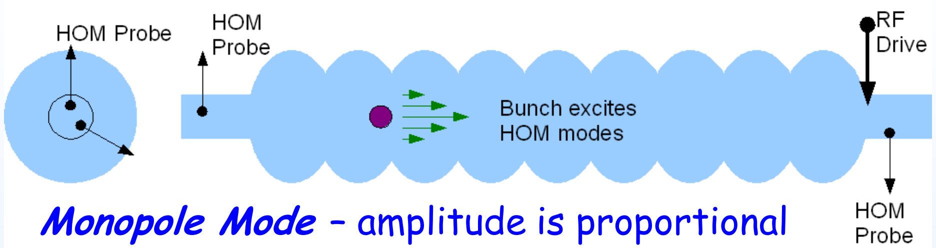


Kicked Beam TbT BPM Response Studies

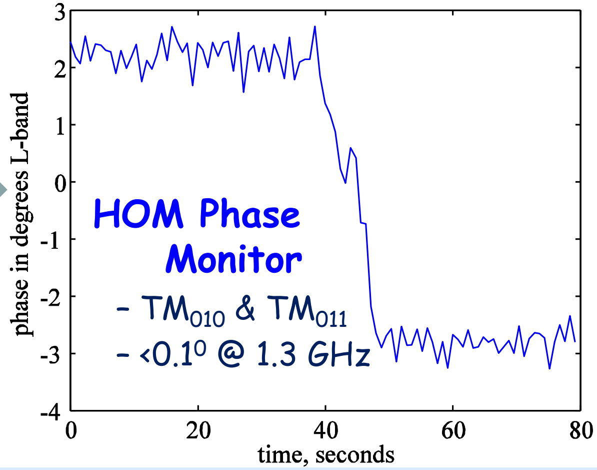




HOM Signal Diagnostics

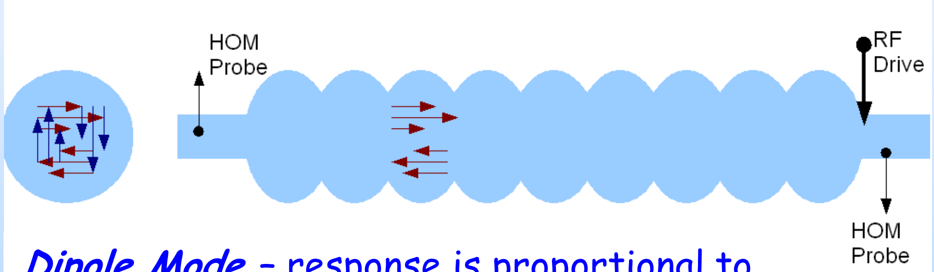


Monopole Mode – amplitude is proportional to bunch charge. Mode and RF Drive present on HOM coupler allows for a relative beam phase measurement

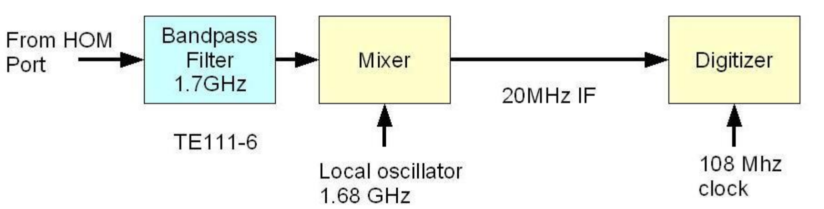


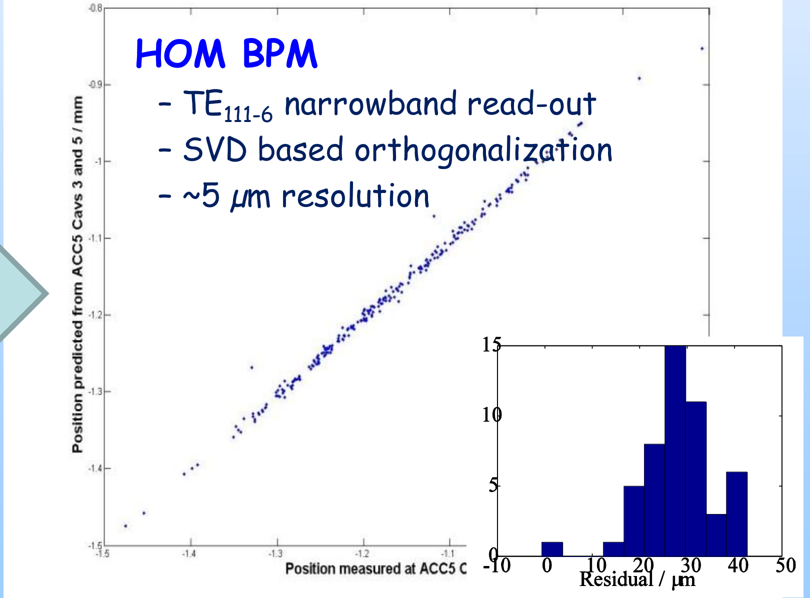
HOM Phase Monitor

- TM$_{010}$ & TM$_{011}$
- <0.1^{0} @ 1.3 GHz



Dipole Mode – response is proportional to beam trajectory and charge. Can be calibrated against BPMs.

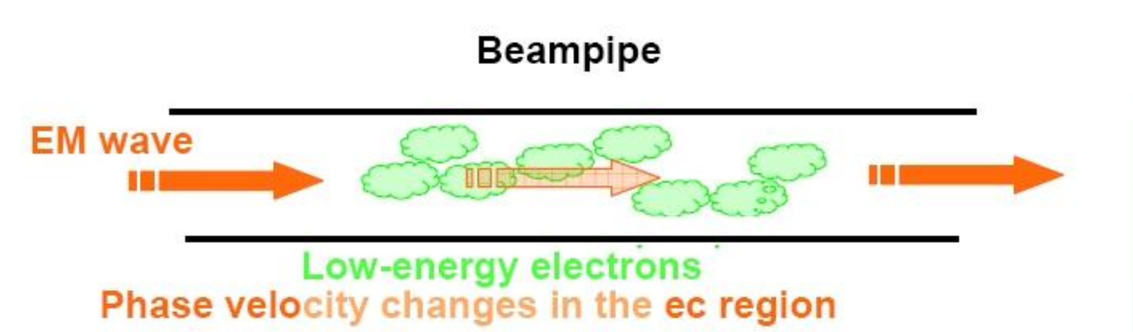




HOM BPM

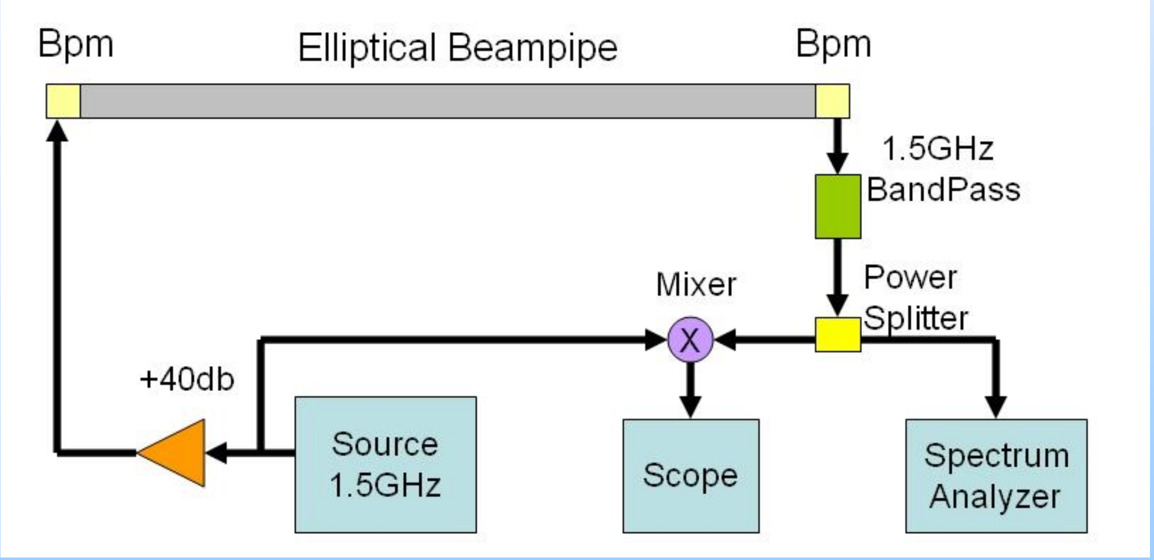
- TE$_{111-6}$ narrowband read-out
- SVD based orthogonalization
- ~5 μm resolution

μWave eCloud Measurements



From plasma physics, expect a microwave travelling down a waveguide to experience a phase shift due to a homogeneous plasma

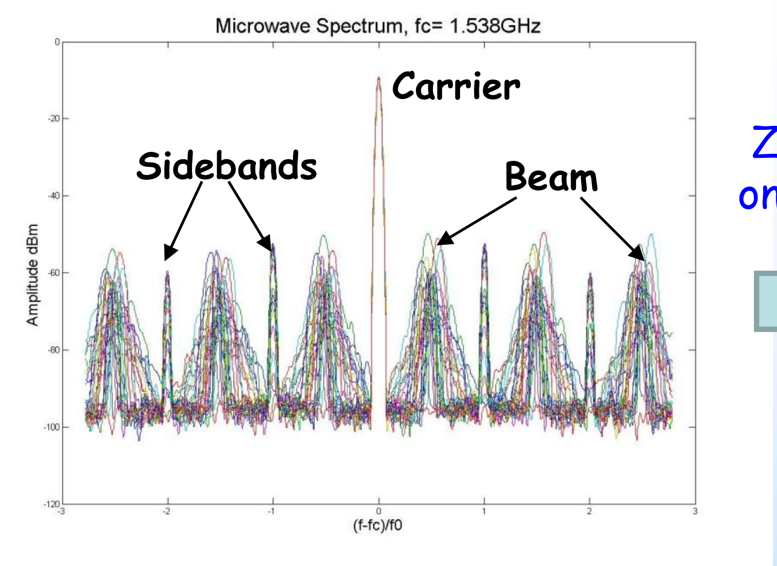
$$\frac{\Delta\phi}{l} = \frac{\omega_p^2}{2c\sqrt{\omega^2 - \omega_c^2}} \qquad \omega_p^2 = 4\pi\rho_e r_e c^2$$



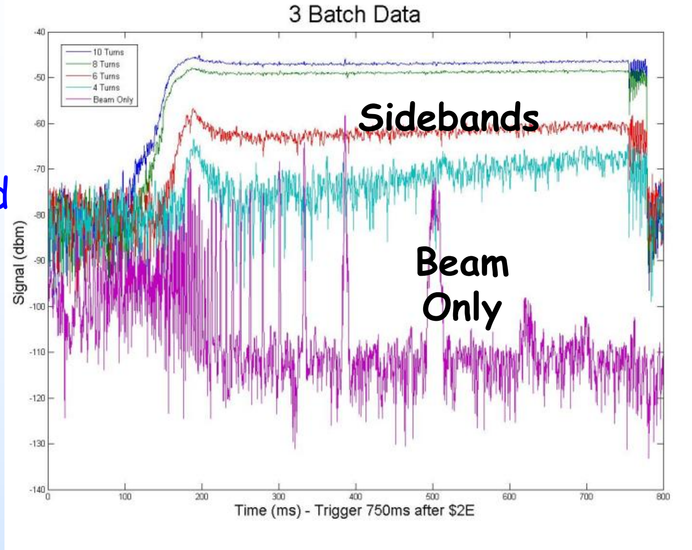
Phase Modulation – beam structure gives PM modulated sidebands

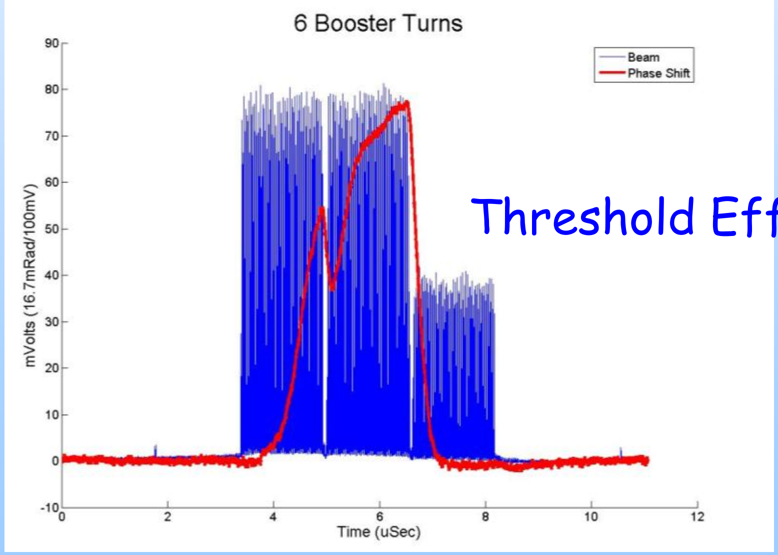
Direct Measurement – mix signal to baseband and -> phase shift dc offset. Can observe average phase shift within a machine turn

μWave eCloud Measurement Results



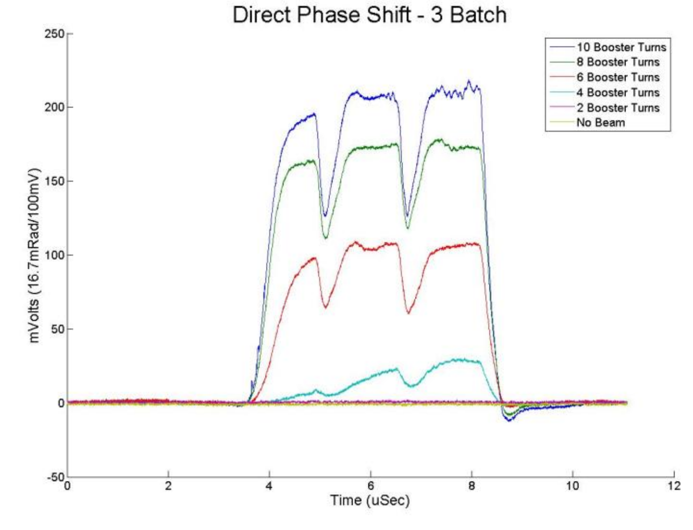
Zero Span on sideband





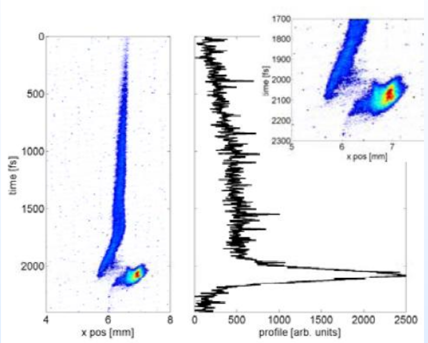
Threshold Effect

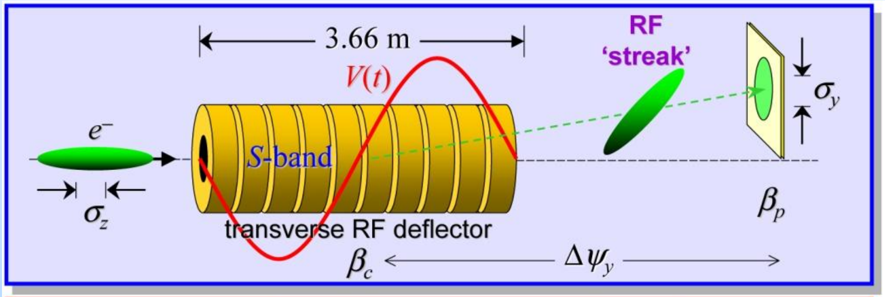
Vary Bunch Intensity



Deflecting Mode Cavity

- **DMC, RF streak camera, "LOLA" (SLAC S-Band DMC):**
  - Dipole mode cavity, deflecting an off-center bunch
  - High resolution bunch length measurement
  - Single pass measurement, but intercepting
  - Accurate calibration(!)
  - $$$





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

$$\langle \Delta y \rangle = \frac{eV_0}{E_0}\sqrt{\beta_c \beta_p}\,\sin\Delta\psi_y \sin\varphi, \qquad V_0 \approx \left(1.6\ \text{MV/m/MW}^{1/2}\right) L\sqrt{P_0}$$

$\sigma_z \approx 25\ \mu\text{m}$ $\quad$ $\Delta\psi_y \approx 15.8°$

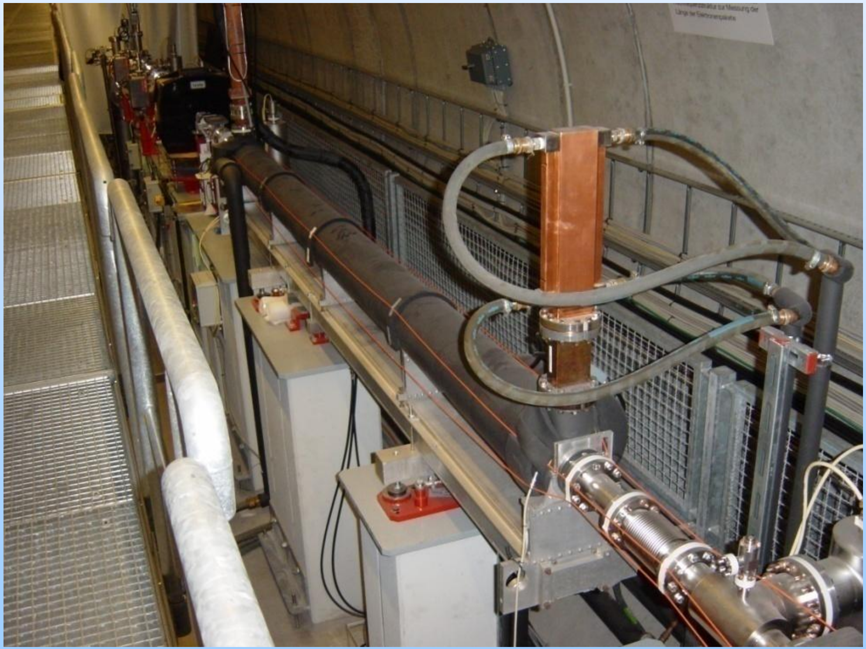
$E_0 \approx 0.6\ \text{GeV}$ $\quad$ $\varphi \approx 0°$

$(\beta_c\beta_p)^{1/2} \approx 51\ \text{m}$ $\quad$ $\lambda \approx 105\ \text{mm}$

$\gamma\varepsilon_y \approx 5\ \mu\text{m}$ $\quad$ $\sigma_{y0} \approx 317\ \mu\text{m}$

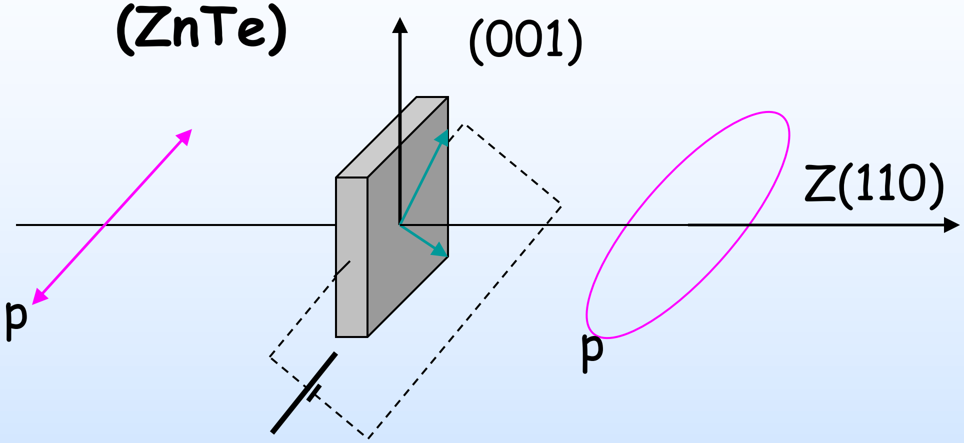
$L \approx 3.66\ \text{m}$, $V_0 \approx 25\ \text{MV}$,
$P_0 \approx 18\ \text{MW}$
$\boldsymbol{\sigma_y \approx 925\ \mu\text{m}}$

P. Emma (SLAC)

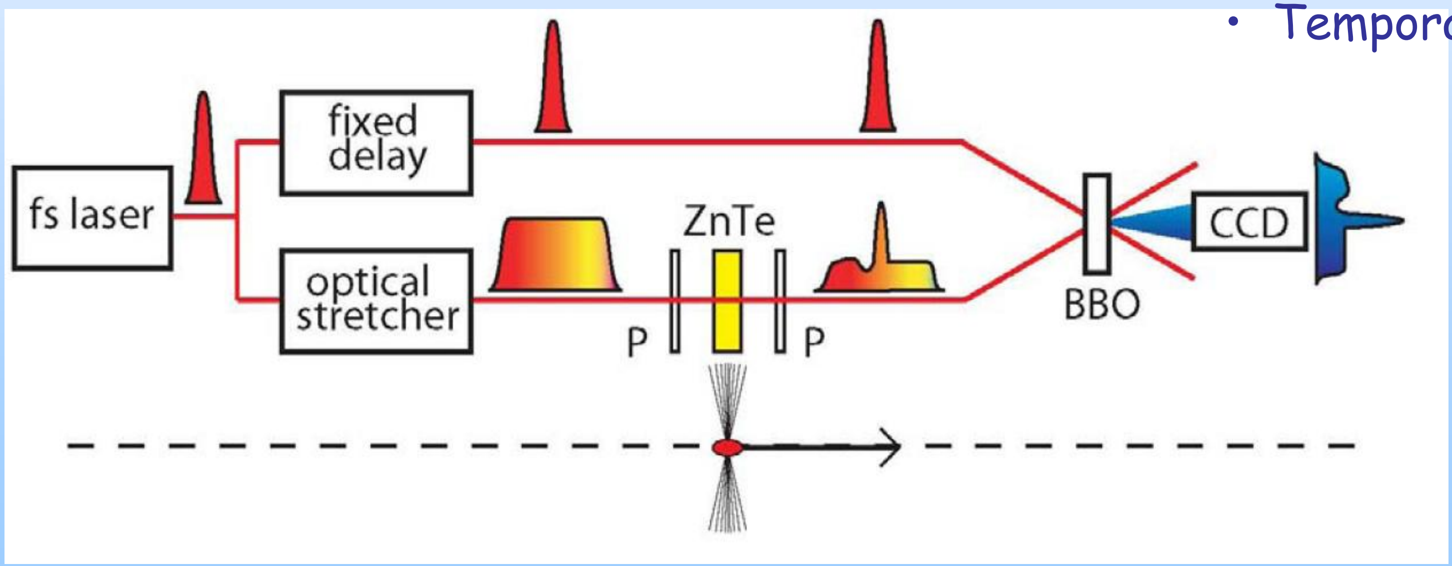


Electro-optical Sampling (EOS)

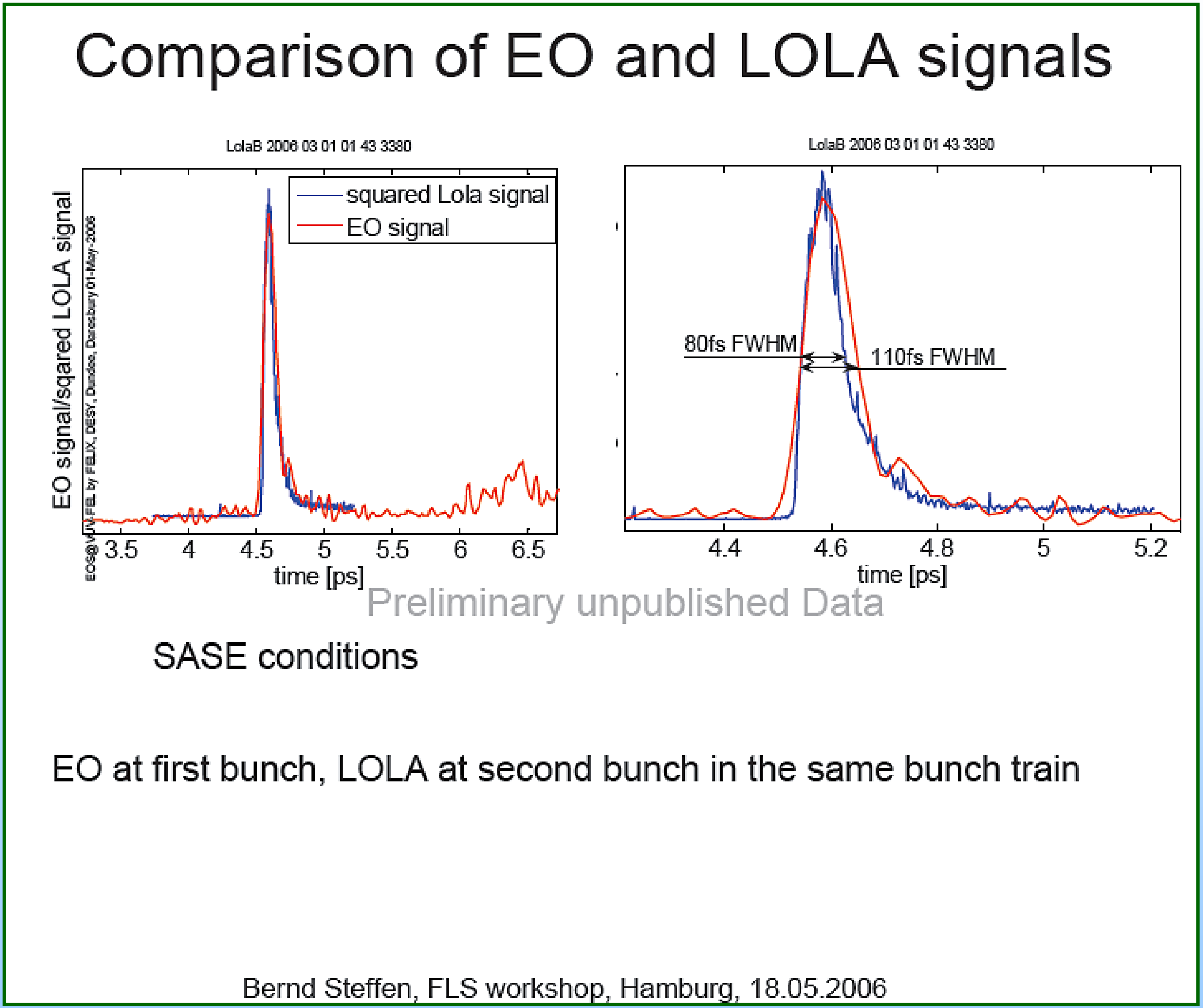
Pockel's effect (ZnTe)



- **EOS bunch length measurement:**
  - ZnTe Pockel's effect
  - Sampling Methods:
    - Scanning delay
    - Spectral decoding
    - Spacial decoding
    - Temporal decoding



DMC vs. EOS



Comparison of EO and LOLA signals

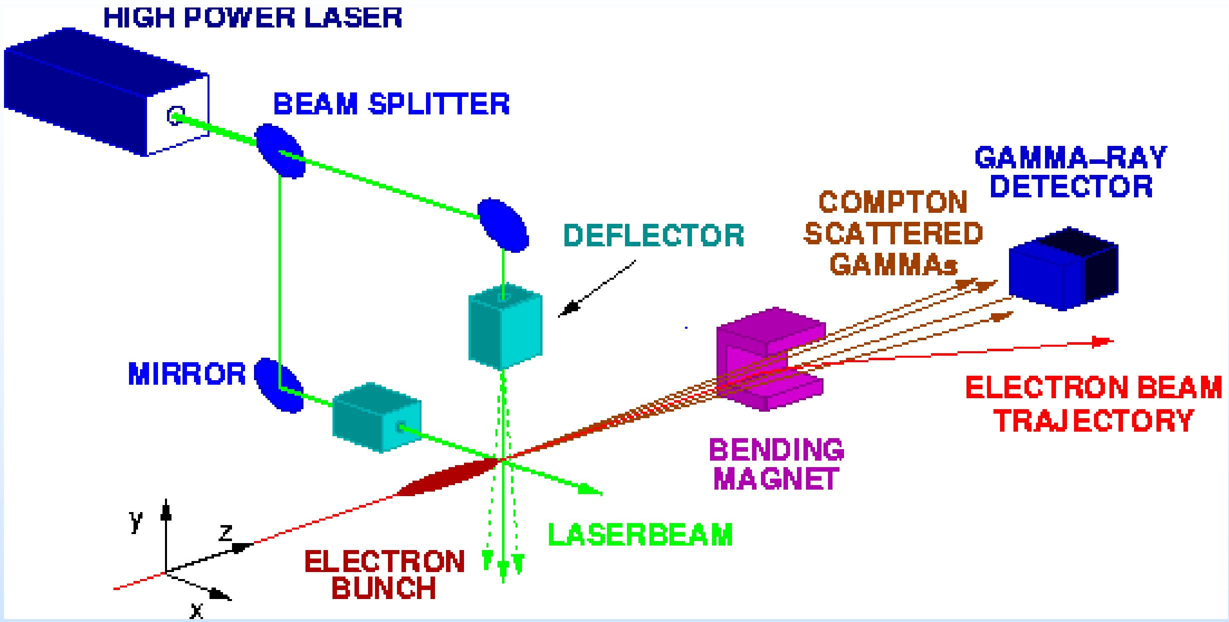
Preliminary unpublished Data

SASE conditions

EO at first bunch, LOLA at second bunch in the same bunch train

Bernd Steffen, FLS workshop, Hamburg, 18.05.2006

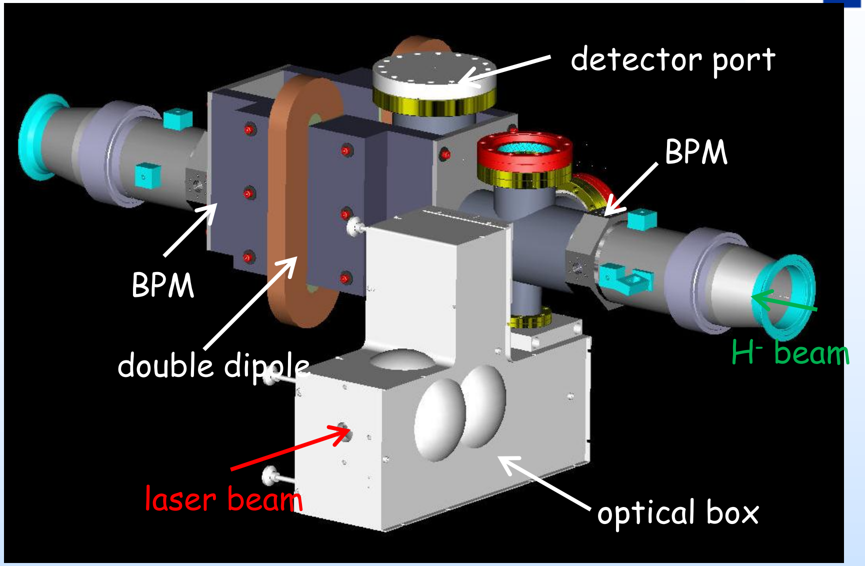
Laser Profile Monitor (Laser-Wire)

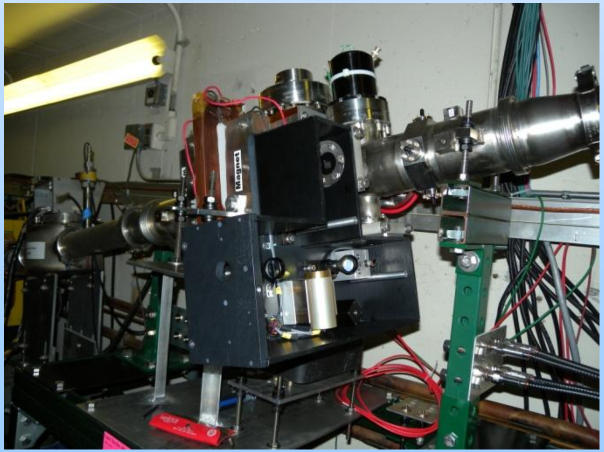


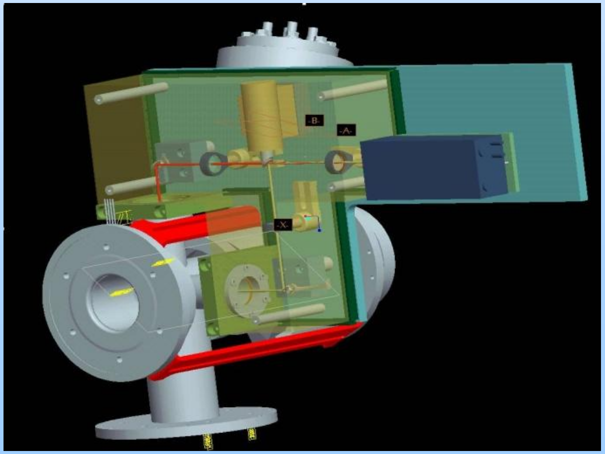
- **Principle of operation**
  - Focused laser beam is scanned perpendicular to the particle beam ($\sigma_{\text{laser-beam}} << \sigma_{\text{particle-beam}}$).
  - Lepton beam profile (beam energy > ~1 GeV)
    - *Compton scattered gamma intensity vs. galvanometer position*
  - H^- hadron beam profile (photo-detachment: $H^- + \gamma \rightarrow H^0 + e^-$)
    - *Stripped electron intensity vs. galvanometer position*

FNAL / BNL Laser Profile Monitor

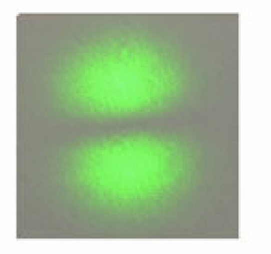
- **Laser Profile Monitor details**
  - Q-switch laser
  - Laser energy: 50 mJoule
  - Wavelength: 1064 nm
  - Pulse length: 9 nsec
  - Fast rotating mirrors (±4⁰ / 100 μsec)
  - e^- detector: scintillator & PMT

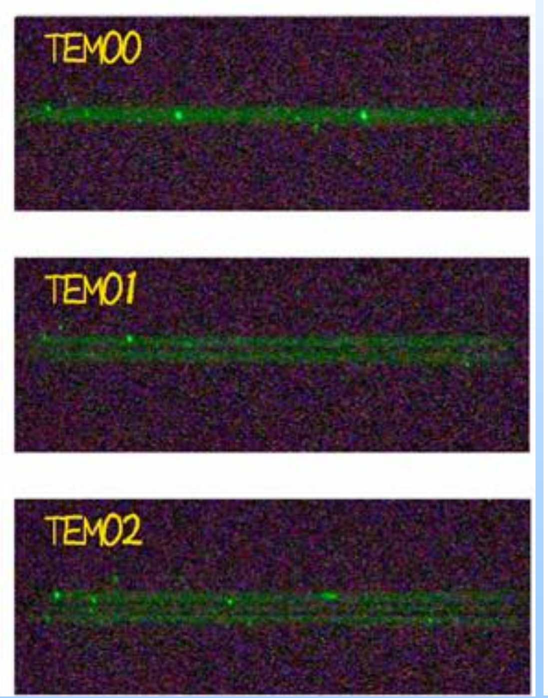


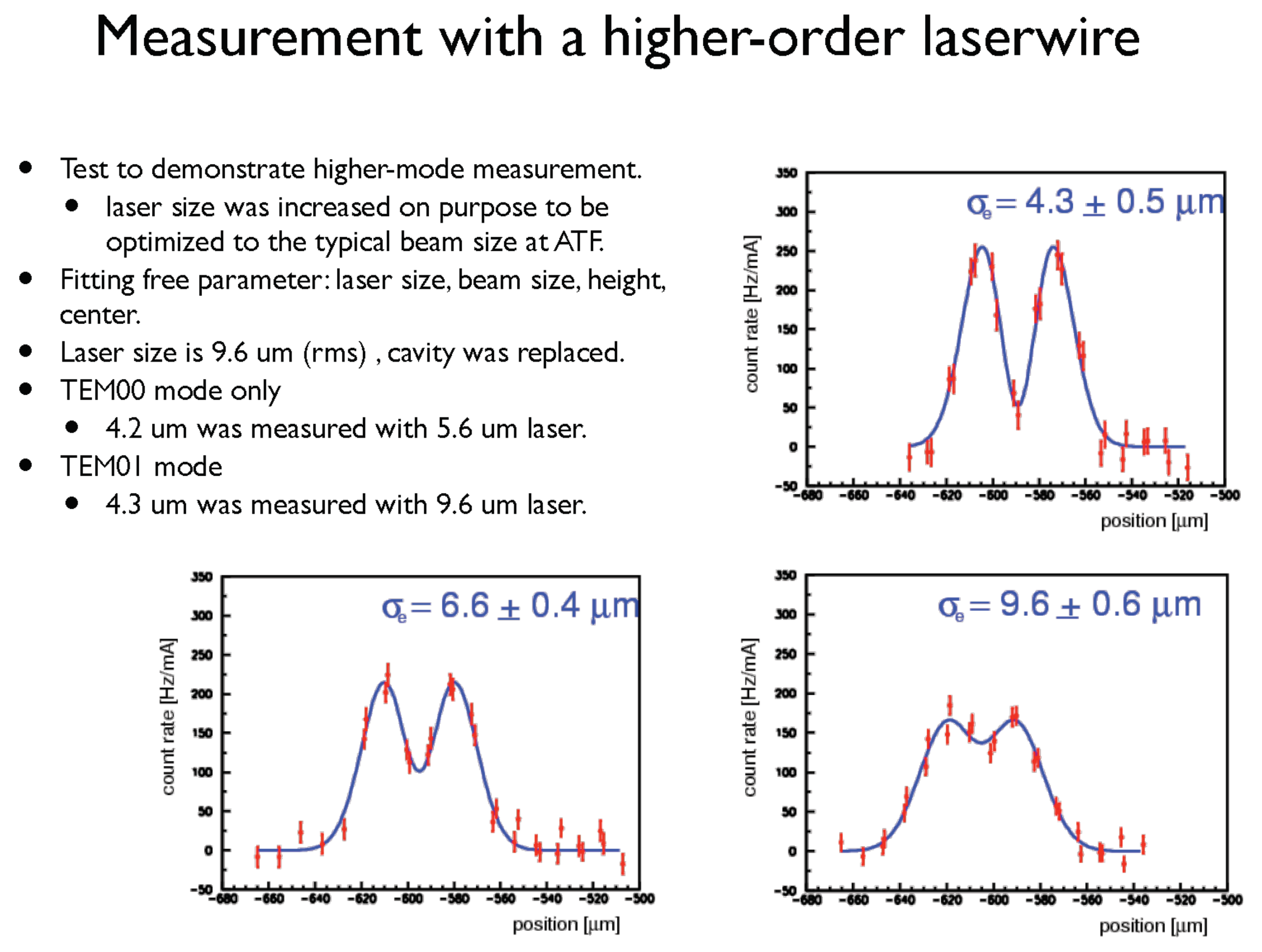




Laser-Wire with Optical Cavity







Measurement with a higher-order laserwire

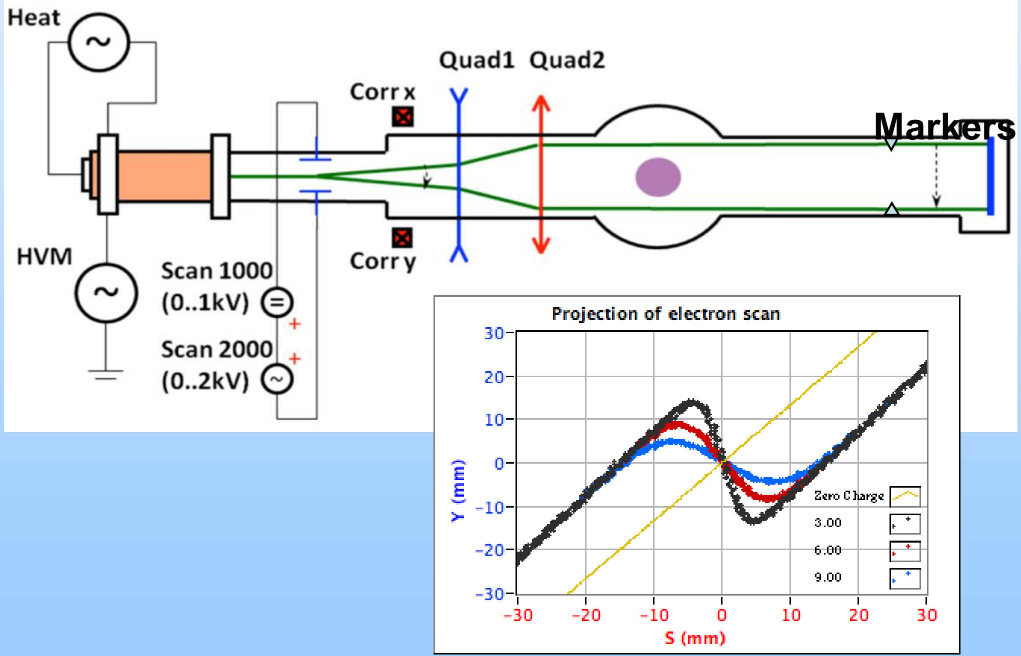
- Test to demonstrate higher-mode measurement.
  - laser size was increased on purpose to be optimized to the typical beam size at ATF.
- Fitting free parameter: laser size, beam size, height, center.
- Laser size is 9.6 um (rms) , cavity was replaced.
- TEM00 mode only
  - 4.2 um was measured with 5.6 um laser.
- TEM01 mode
  - 4.3 um was measured with 9.6 um laser.

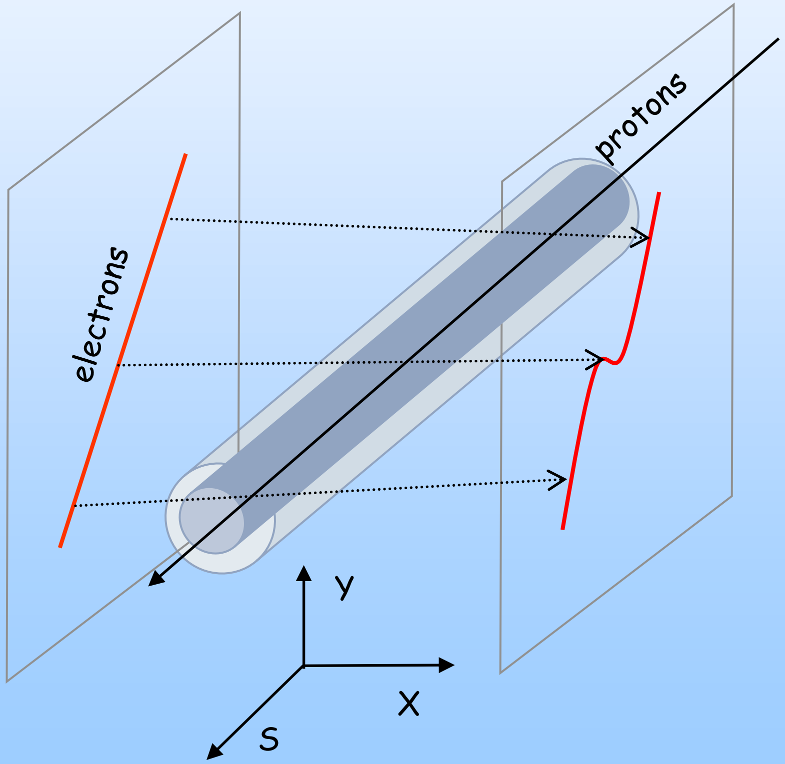
Electron Beam Scanner

- **Look at the deflected projection of a tilted sheet of electrons due to the proton beam charge**
  - Neglect magnetic field (small displacement of projection)
  - Assume path of electrons is straight (they are almost straight)
  - Assume net electron energy change is zero (if symmetric).

→ $$\frac{d\theta_0(x)}{dx} = \int_L \frac{e}{mv^2} \frac{\delta(x,y)}{\varepsilon_0} dy$$

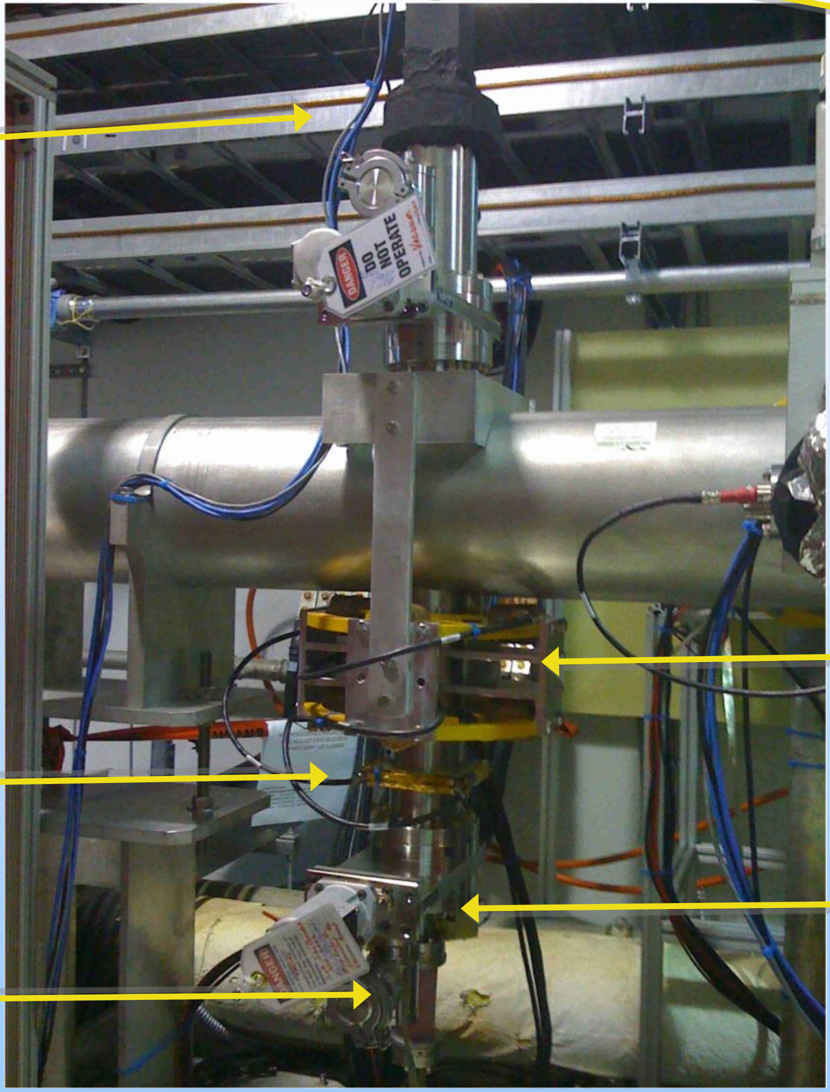
or, take the derivative to get the profile





SNS Electron Beam Scanner

Camera



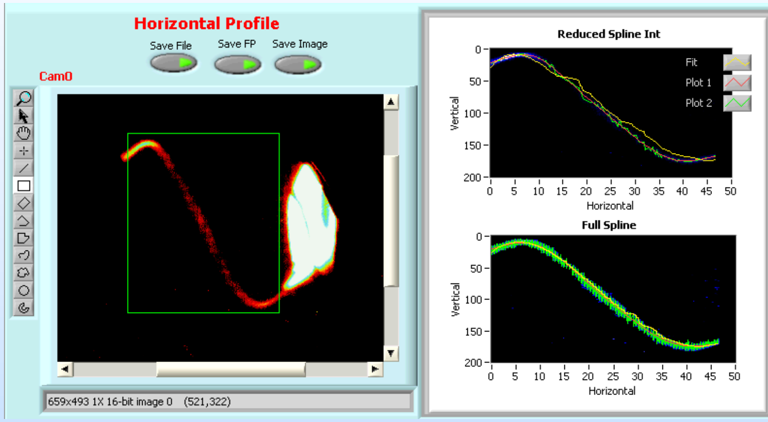
Screen

Quadrupoles

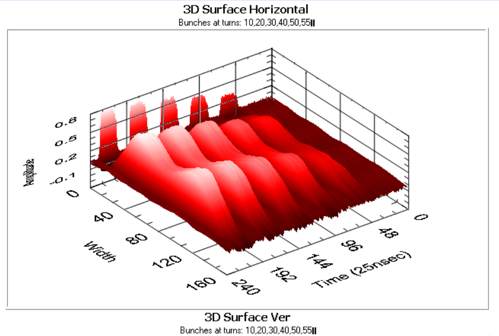
Corrector

Deflector

Electron gun

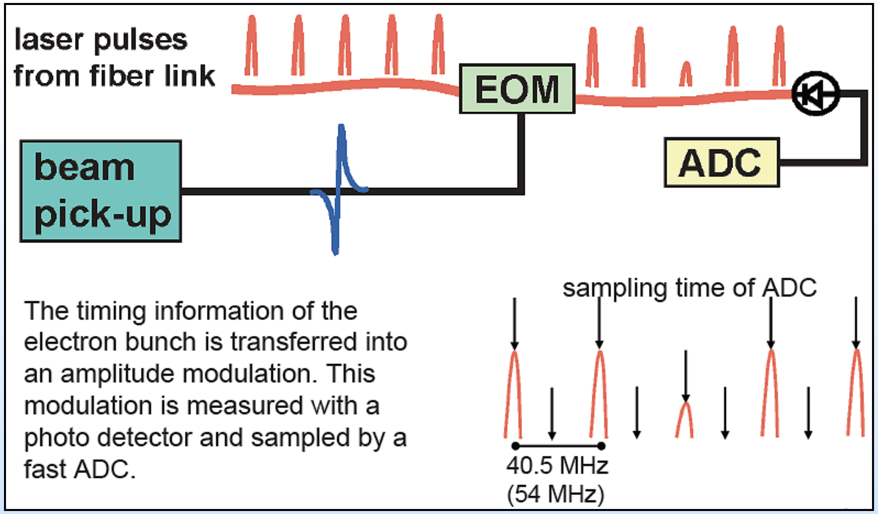


659x493 1X 16-bit image 0 (521,322)

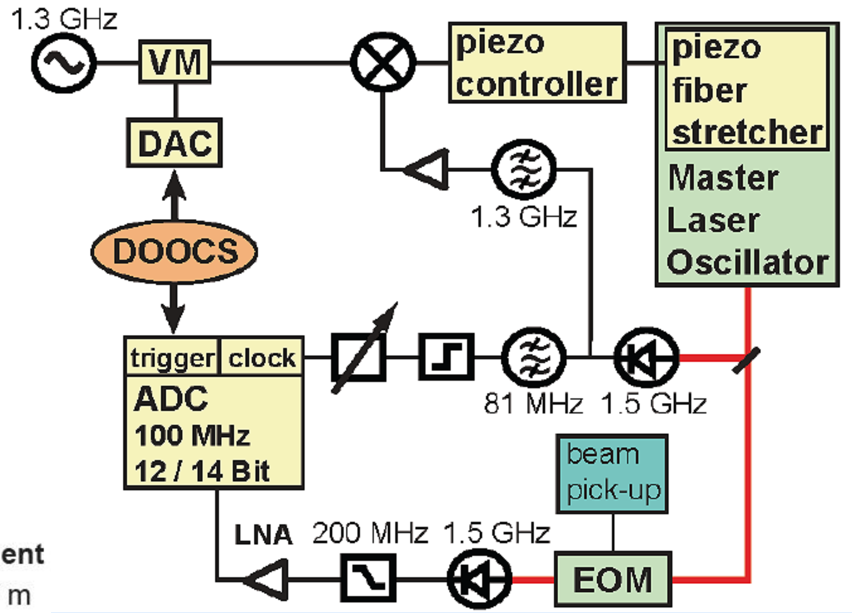


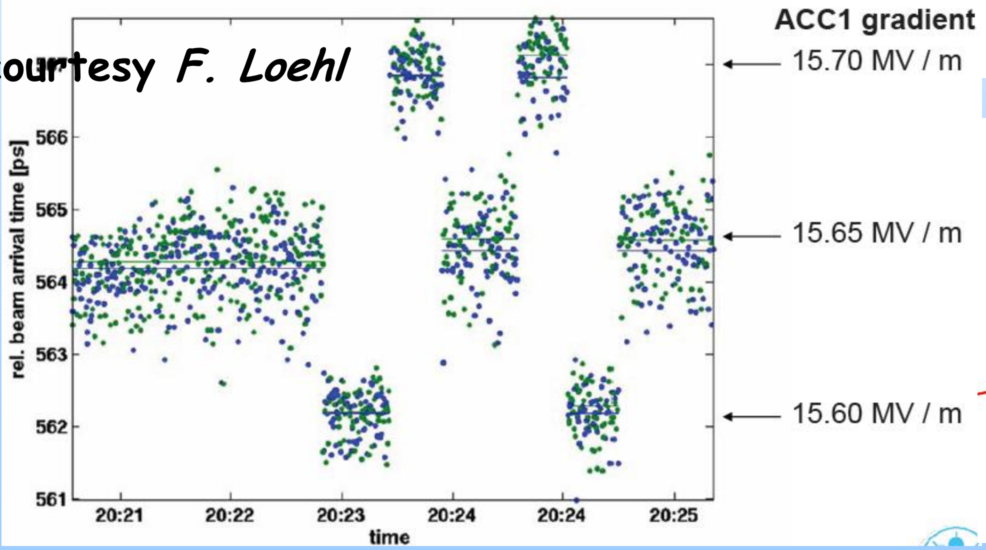
3D plot of turns 10,20,30,50, and 55.

Bunch Arrival / Beam Phase

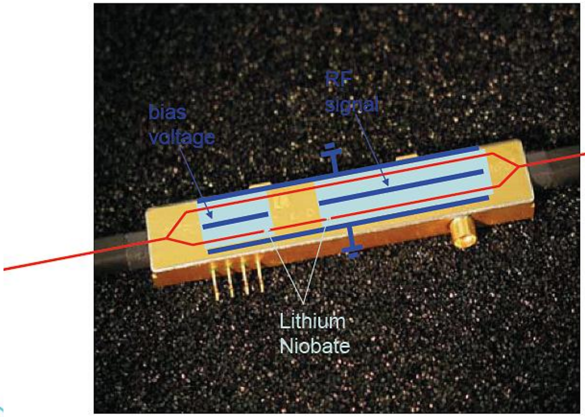


The timing information of the electron bunch is transferred into an amplitude modulation. This modulation is measured with a photo detector and sampled by a fast ADC.





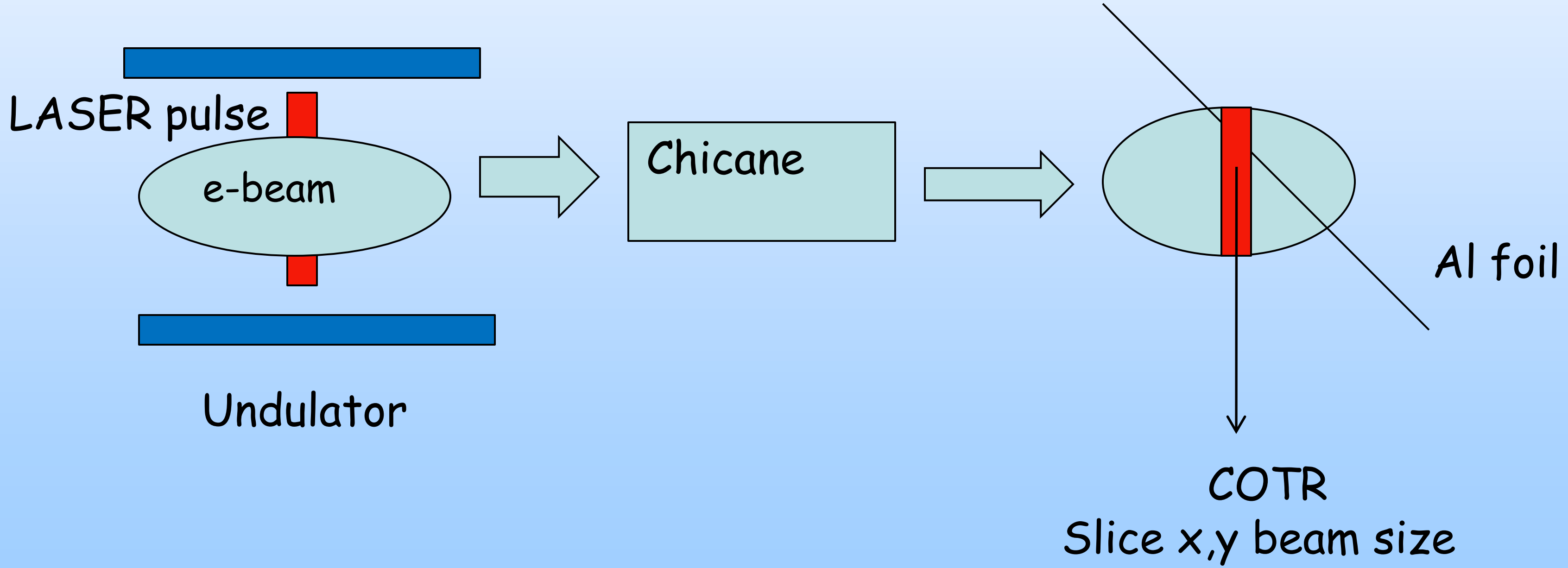
courtesy *F. Loehl*



Commercially available with bandwidths up to 40 GHz
(we use a 10 GHz version)

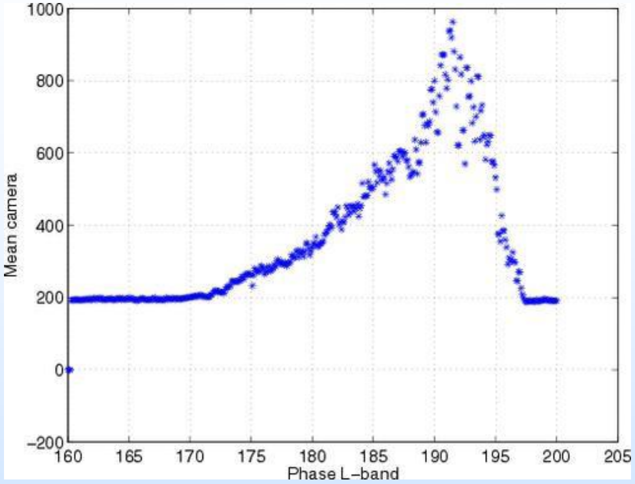
Optical Replica

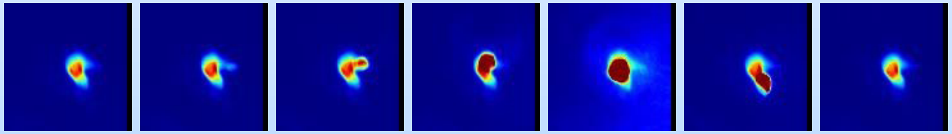
- Use laser to selectively energy modulate a slice of the longitudinal profile or the whole profile within the short undulator. The Chicane's R_{56} then converts to density modulation in z direction or microbunching.

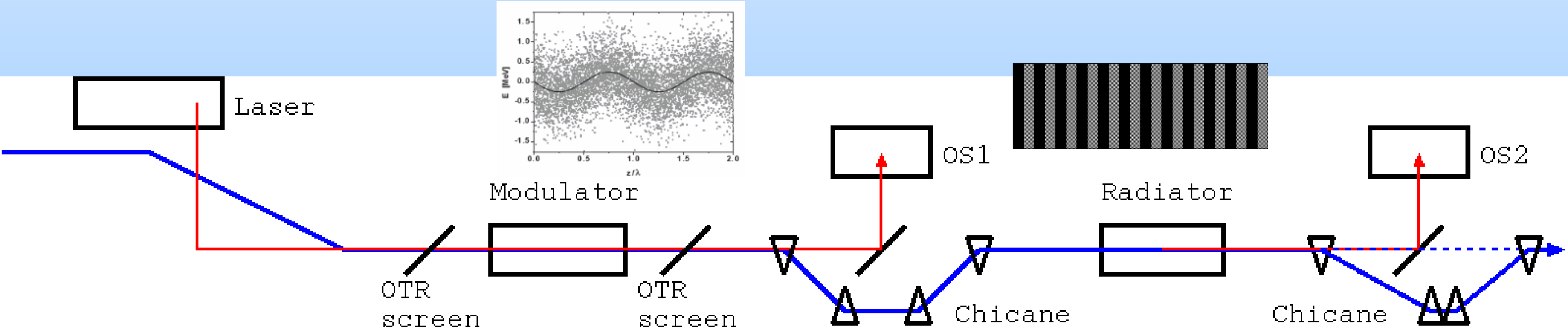


Optical Replica System @ FLASH

- **Problem: measure ultra-short bunches in the 10s of fs range: EOS, TEO, LOLA, ORS**
  - too fast for electronics (10 Gs/s, 100 ps)
  - but laser folks know (autocorrelation, FROG)
- **Solution: make an optical copy of the electron bunch and analyze that with laser methods**







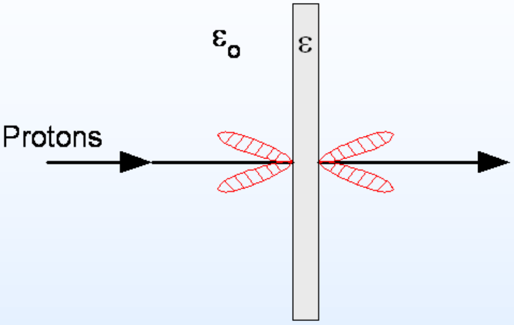
Thanks for staying awake!

- …and thanks to my colleagues at Fermilab who helped preparing this presentation!
- Also thanks to many other beam diagnostics experts, from whom I shamelessly copied several of the presented examples.

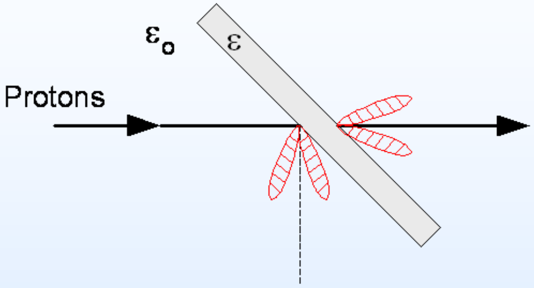
- As of limited time, many methods and novel approaches could not be mentioned, e.g. OTR, ODR, vibrating wire, interferometric methods, etc.
- More material can be found at the bi-yearly diagnostics workshops DIPAC & BIW (see also JACoW)
  - http://dipac09.web.psi.ch/
  - http://www.als.lbl.gov/biw08/

Backup

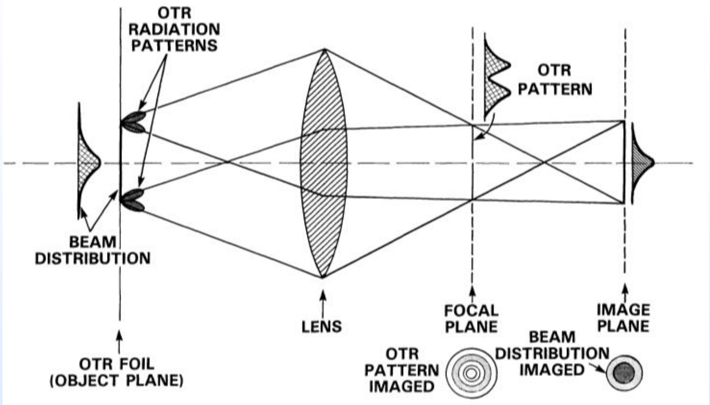
Optical Transition Radiation (OTR)

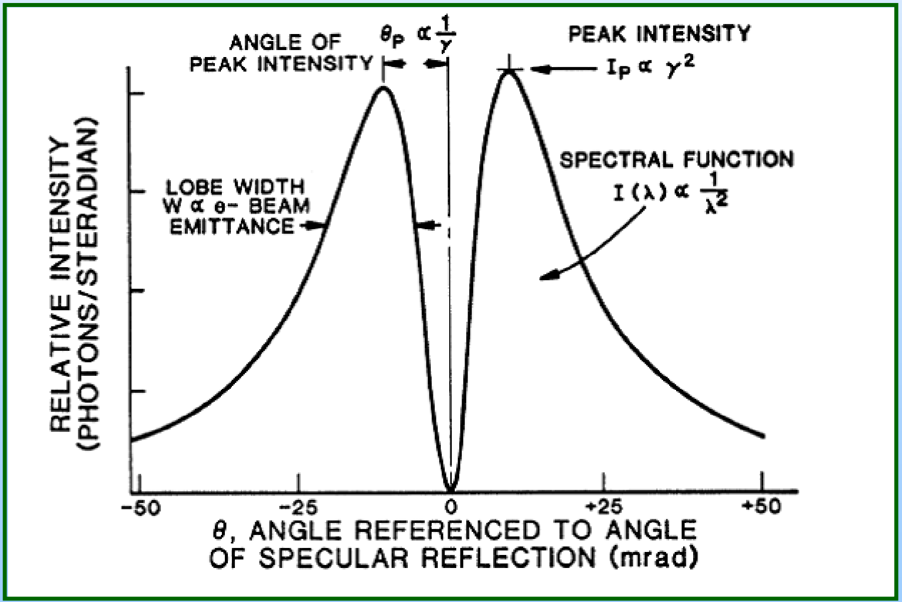


Normal Incidence



Oblique Incidence





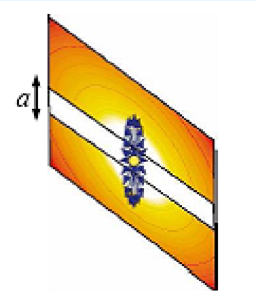
- **Transition radiation**

$$\frac{d^2U}{d\omega d\Omega} \approx I(\omega,\theta) = \frac{e^2}{hc_0}\,\frac{1}{\pi^2\omega}\,\frac{\theta^2}{(\gamma^{-2}+\theta^2)^2}$$

  - Charged particles passes through a media boundary
  - Monitoring of trans. beam profile (-> emittance), bunch length and energy

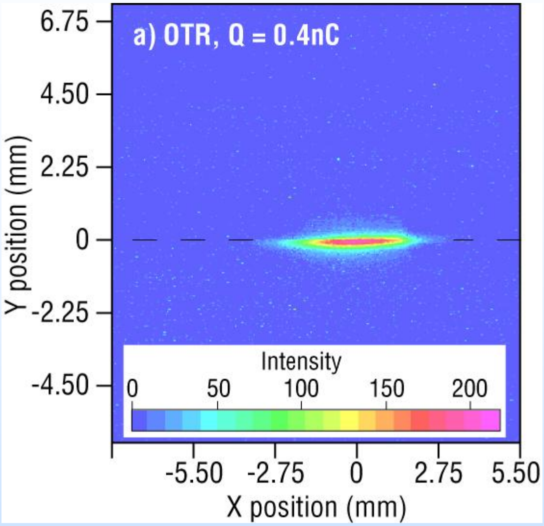
Optical Diffraction Radiation

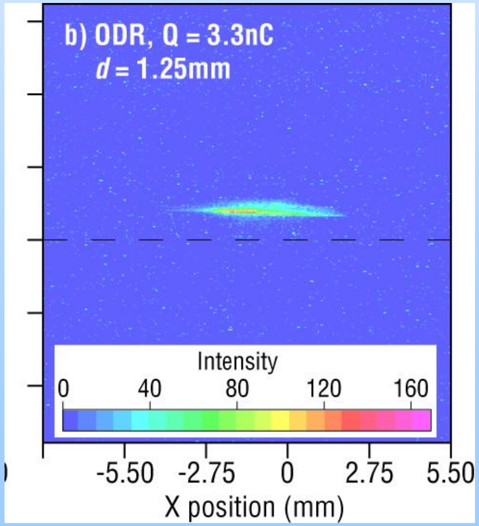
- **Optical diffraction radiation (ODR):**
  - Near field effect between EM fields of the beam close to a conducting screen
    Intensity: $I \propto \exp\left(-\frac{2\pi a}{\gamma\lambda}\right)$
  - DR impact parameter:



$$\frac{\gamma\lambda}{2\pi} \rightarrow \text{if } a \begin{cases} \gg \dfrac{\gamma\lambda}{2\pi} & \text{weak radiation} \\ = \dfrac{\gamma\lambda}{2\pi} & \text{DR} \\ \ll \dfrac{\gamma\lambda}{2\pi} & \text{TR} \end{cases}$$

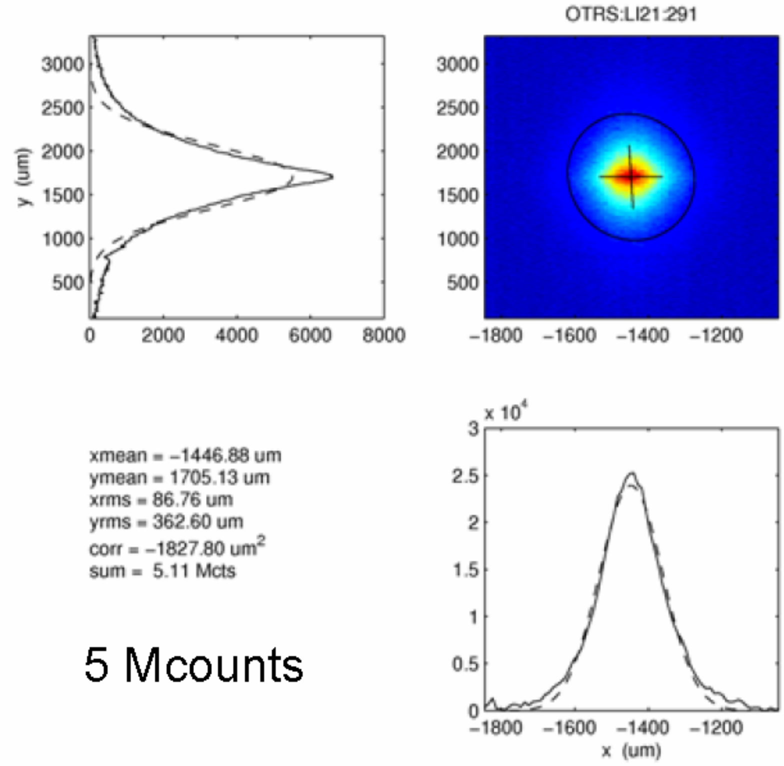
  - Non-intercepting beam measurement!





COTR for compressed beam

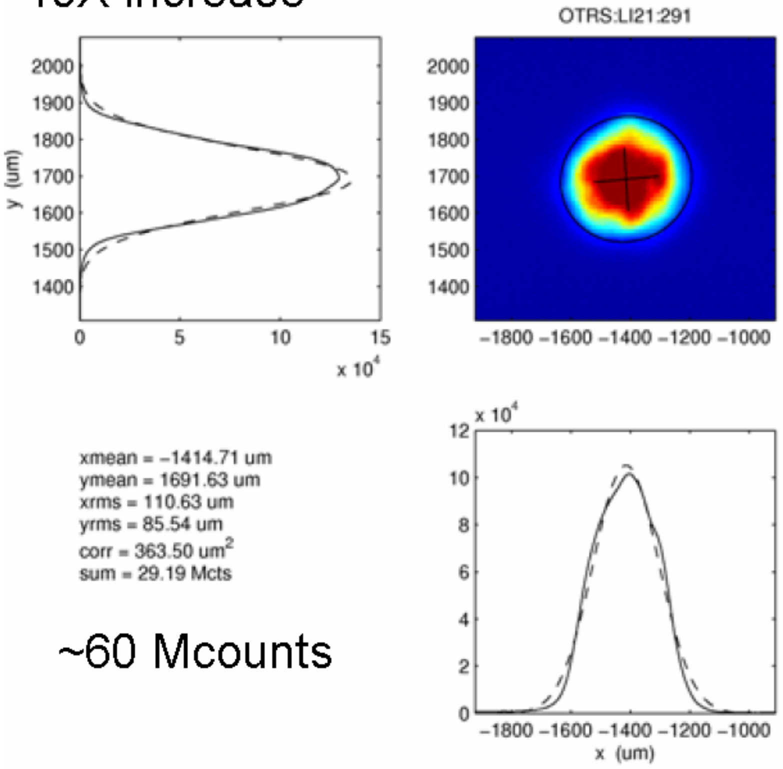
OTR after BC1, normal compression
250pC, upstream OTR foil inserted
In compressor Chicane to spoil
Longitudinal Phase space



```
xmean = -1446.88 um
ymean = 1705.13 um
xrms = 86.76 um
yrms = 362.60 um
corr = -1827.80 um2
sum =  5.11 Mcts
```

5 Mcounts

With upstream foil removed, signal
Is saturated. Neutral density filters
Give approximately 60M counts
10X increase



```
xmean = -1414.71 um
ymean = 1691.63 um
xrms = 110.63 um
yrms = 85.54 um
corr = 363.50 um2
sum = 29.19 Mcts
```

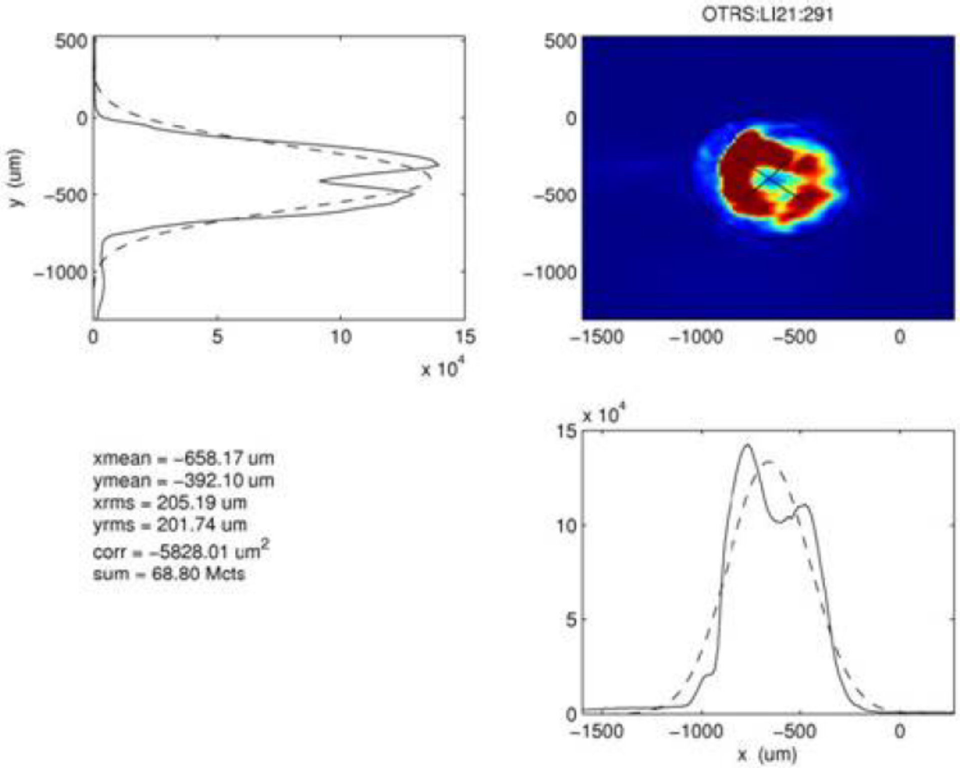
~60 Mcounts

COTR at maximum BC1 compression

COTR with injector phases
set for maximum compression
In BC1. Integrated signal ~100X
Incoherent

The toroidal shape is expected
From the circular polarization of
The OTR light.

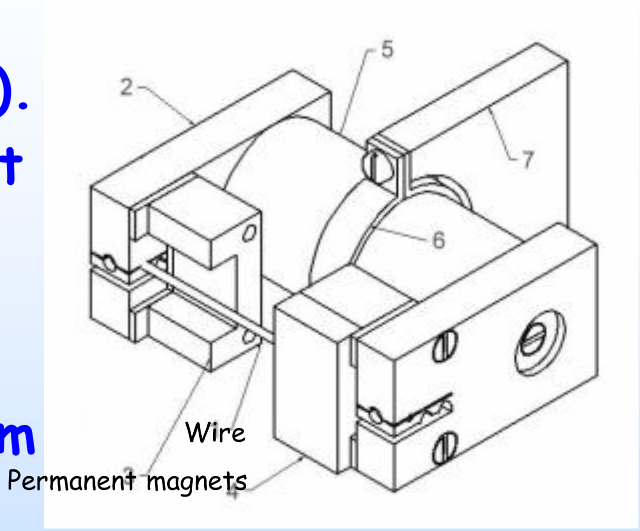
Interference produces a signal
Proportional to the spatial derivative
Of the source.



xmean = −658.17 um
ymean = −392.10 um
xrms = 205.19 um
yrms = 201.74 um
corr = −5828.01 um^2
sum = 68.80 Mcts

Vibrating Wire

- An oscillating current is applied to the wire that due the presence of the magnetic fields starts to oscillate (driven oscillator).
- The wire is part of active oscillator circuit that drives the oscillation on the natural mechanical resonance of the wire at few kHz (tuned oscillator)
- The interaction of the cable with the beam ultimately generates heating and the consequent temperature change and dilation in the wire causes a shift in the mechanical resonance.
- The frequency shift is proportional to the number of particles in the part of the beam interacting with the wire, so that by scanning the wire trough the beam it is possible to measure the beam profile.



$$\frac{\Delta f}{f} = K \, \Delta T \propto N_{\text{particles}}$$

Mechanical property constant

Vibrating Wire

- Relatively slow response time (tenths of seconds in air, seconds in vacuum)(vacuum)
- Very sensitive, best for measuring , low intensity beams and halos
- Already tested with ions, protons, electrons and photons.