INSTRUMENTATION
– A “Taste” of ILC Beam Instrumentation –

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Fermilab

Contents

- Introduction
  - ILC beam parameters, again
  - ILC beam instrumentation needs and requirements
- Basic electro-magnetic (EM) beam monitors
  - Image currents and beam current monitoring
  - Broadband beam position monitors
- Optical and other advanced beam monitors
  - Resonant beam monitors (cavity BPM, HOM instrumentation)
  - Various examples of beam monitors using transition radiation
  - Longitudinal bunch profile instruments (DMC & EOS)
  - Bunch arrival / beam phase monitoring
  - LASER wire scanner
- Final remarks

Introduction: Scope

This lecture **IS NOT**:

- A systematic teaching introduction into the field of beam instrumentation
- You will NOT hear a comprehensive overview on all ILC beam instruments and diagnostics

However, the next 40 min. will entertain you with

A "taste" of ILC beam instrumentation

- Many examples of ILC beam monitors, and related R&D
- Principle of function with no/minimum theory
- Outline specific instrumentation problems
- **Motivate YOU to become part of the team!**

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Intro: ILC Beam Parameters

Beam Parameters:

beam energy	=	2 x 250 GeV	bunch length σ_z	≈	300 µm *(187 GHz)*
luminosity L	=	2 x 10^{34}	vert. emittance $\gamma\,\varepsilon_y^*$	=	0.04 mm mrad
rep. frequency f_{rep}	=	5 Hz	RMS energy spread	=	0.1 %
macro pulse length t_{pulse}	=	969 µs	β_x^* (IP)	=	21 mm
# of bunches per pulse	=	2625	β_y^* (IP)	=	0.4 mm
bunch spacing Δt_b	=	369 ns *(2.2 MHz)*	hor. beamsize (IP) σ_x	=	620 nm
bunch charge	=	3.2 nC	vert. beamsize (IP) σ_y	=	5.7 nm

Special Offer!
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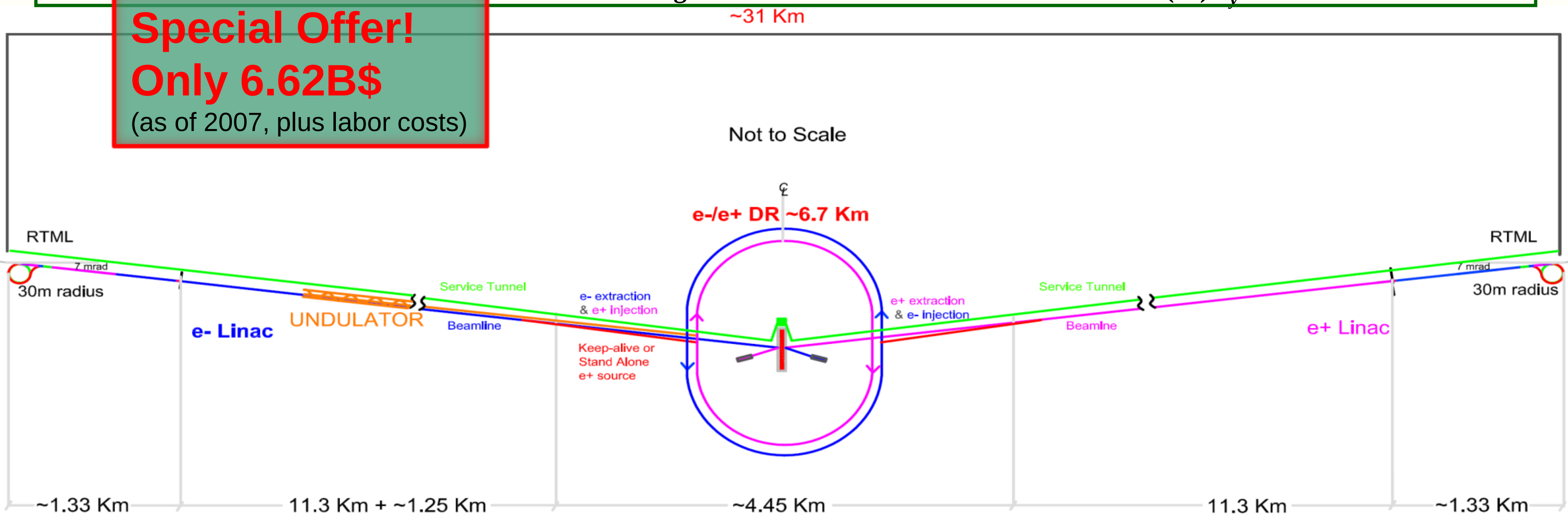
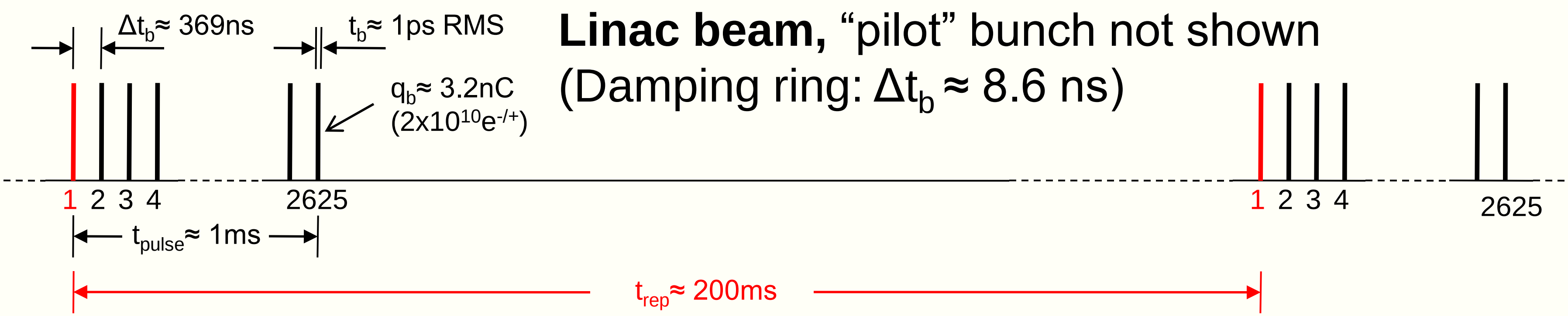
(as of 2007, plus labor costs)



Schematic Layout of the 500 GeV Machine

Intro: Beam Characteristics



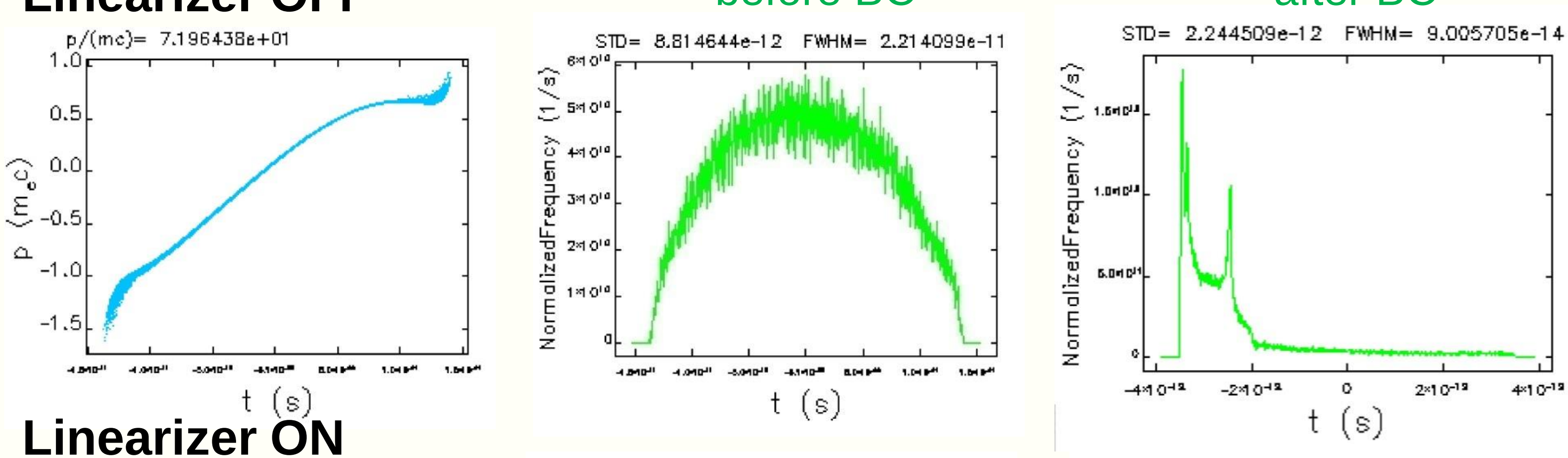
- **Charged particle bunches of ~ $2\text{x}10^{10}$ e^- or e^+**
- **"Ribbon" bunch, Gaussian-like profile**
  - **Along linac sections ~1 µm range vert., ~100 µm range hor.**
  - **RMS bunch length ~ 300 µm (1 ps)**
- **Non-linear field effects result in non-Gaussian particle distributions in the bunch**
  - **e.g. off-crest acceleration, CSR-effects (bunch compressor), wakefields**

Intro: Long. Bunch Gymnastics

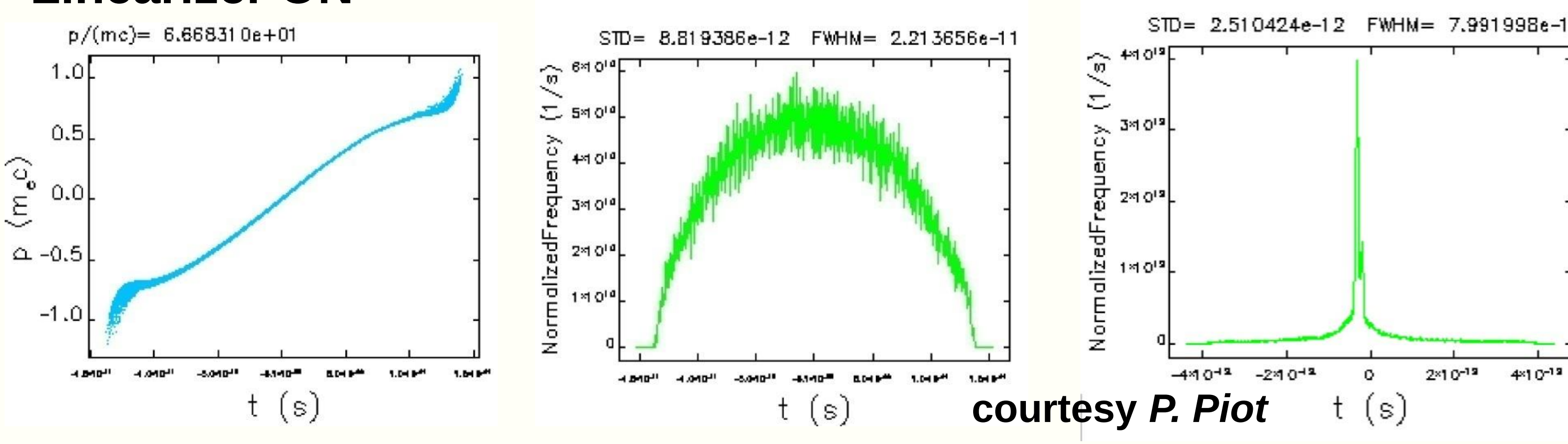
Energy chirp linearization using a 3rd harmonic cavity

- **Linearizer OFF**

before BC — after BC



- **Linearizer ON**



courtesy *P. Piot*

Intro: Beam Diagnostics

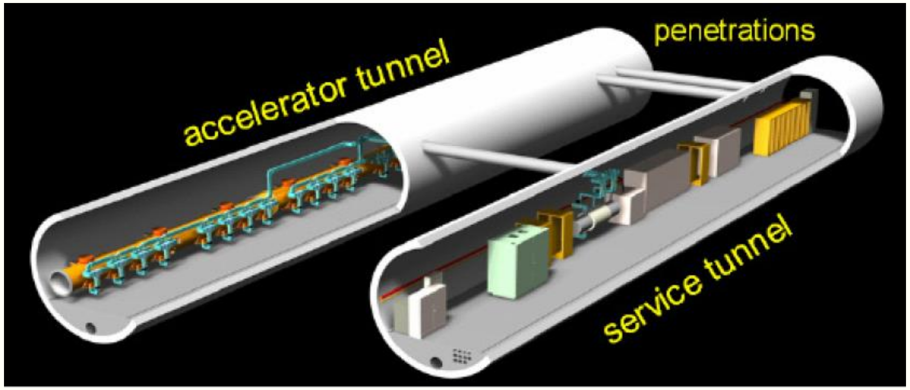
- Machine commissioning, error detection
  - Fundamental beam instruments, e.g. beam intensity (bunch charge), beam orbit (BPM), beam profile (screens, wire scanners)
  - Dynamic range, single bunch / single pass signal processing, time stamped data acquisition
  - Beam parameter characterization in each area
- Emittance preservation, luminosity optimization
  - High resolution instrumentation for beam position & energy, trans. and long. beam profile, bunch arrival timing
- Stable machine operation
  - Various slow and fast feedback systems, transverse intra-train IP feedback
- Machine protection (11 MW beam power, linac: 20 kW)
  - Beam loss monitor (BLM) system

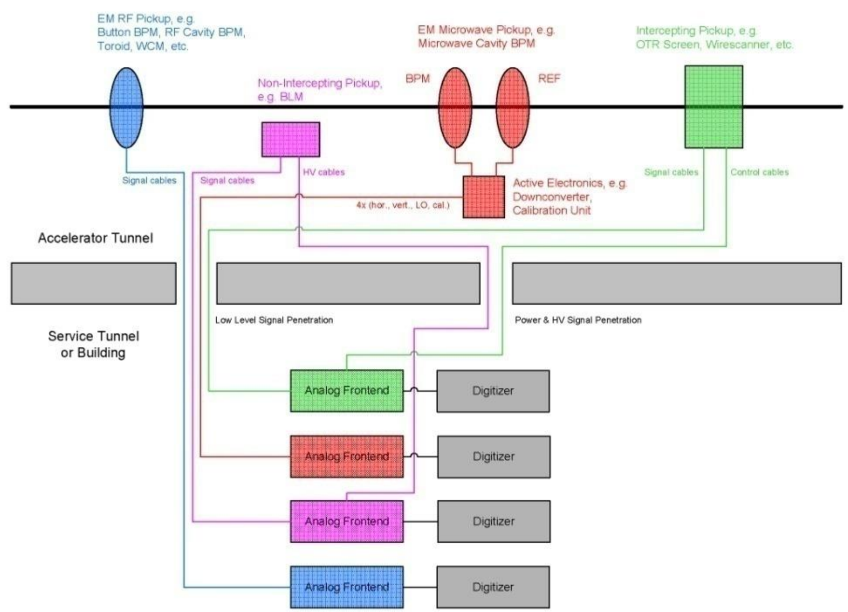
Intro: ILC Beam Instruments

- ~ 2000 Button/stripline BPM's (10-30 / 0.5 µm resolution)
- ~ 1800 Cavity BPM's (warm, 0.1-0.5 µm resolution)
- 620 Cavity BPM's (cold, part of the cryostat, ~ 1 µm)
- 21 LASER Wirescanners (0.5-5 µm resolution)
- 20 Wirescanners (traditional)
- 15 Deflecting Mode Cavities (bunch length)
- ~ 1600 BLM's
- Other beam monitors, e.g. toroids, bunch arrival / beam phase monitors, wall current monitors, faraday cups, OTR & other screen monitors, sync light monitors, streak cameras, feedback systems, etc.
- Read-out & control electronics for all beam monitors

Instrumentation Costs: ~100M$, plus labor

Intro: Tunnel Hardware





- **Beam Instruments:**
  - **Intercepting or non-intercepting pickup stations, often part of the beam vacuum system, located in the accelerator tunnel.**
  - **Read-out, control, and data acquisition electronics, located in the service tunnel, wire connections through penetrations.**
  - **Auxiliary system, e.g. racks, crates, PS, timing,…**

EM Beam Monitoring

- **Beam Pickup**
  - Converts the beam's EM field into a electric signal by use of antenna(s), etc.
  - Part of the vacuum system
  - ILC: Typically operate in the RF & microwave range

- **Read-out Electronics**
  - Detects, amplifies, and modifies the signal to extract the wanted beam parameter (often digital signal processing)

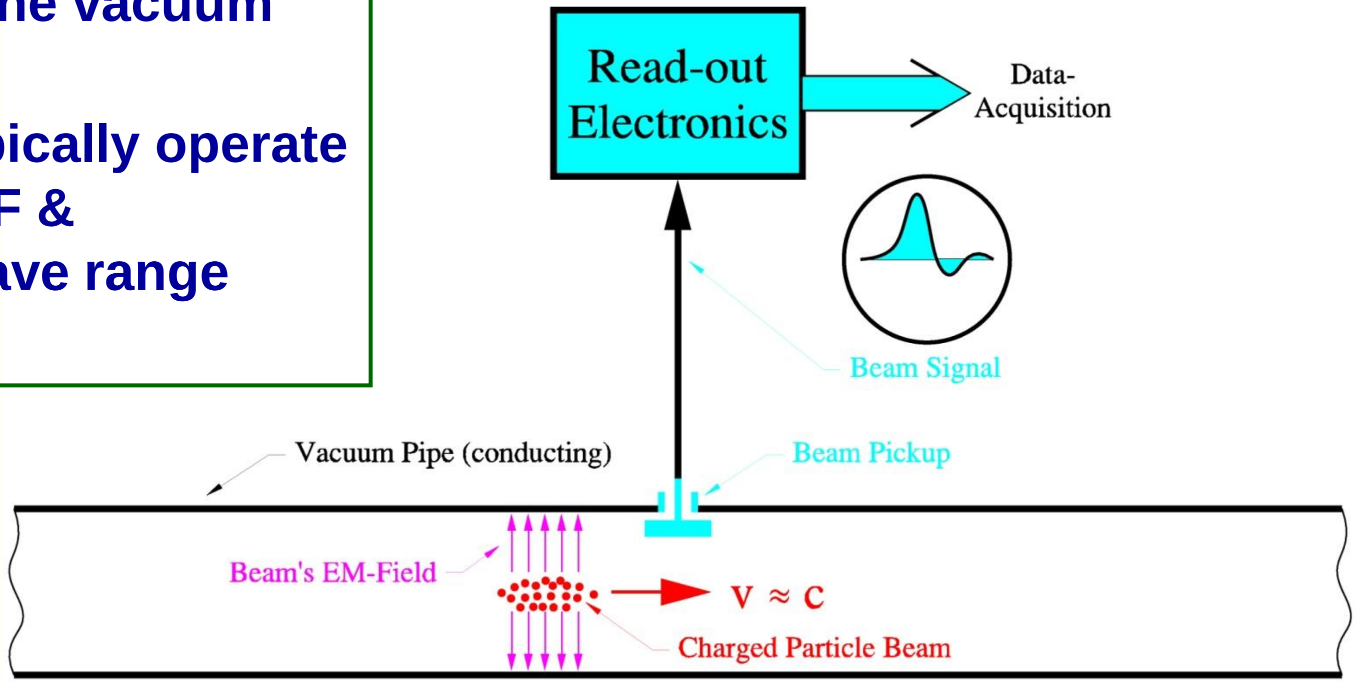
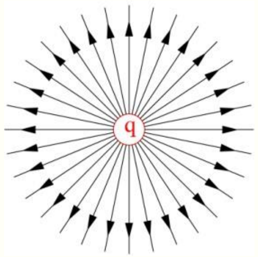
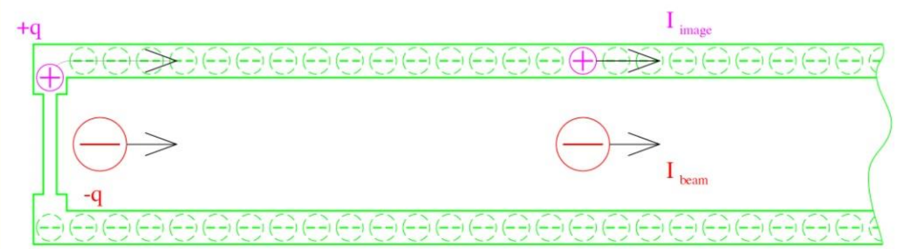
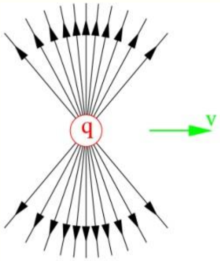


Image Currents



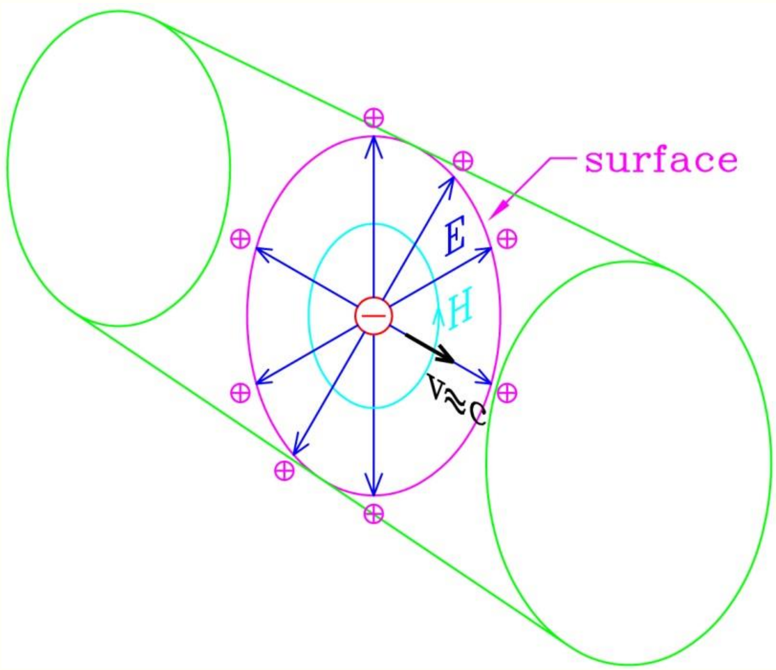




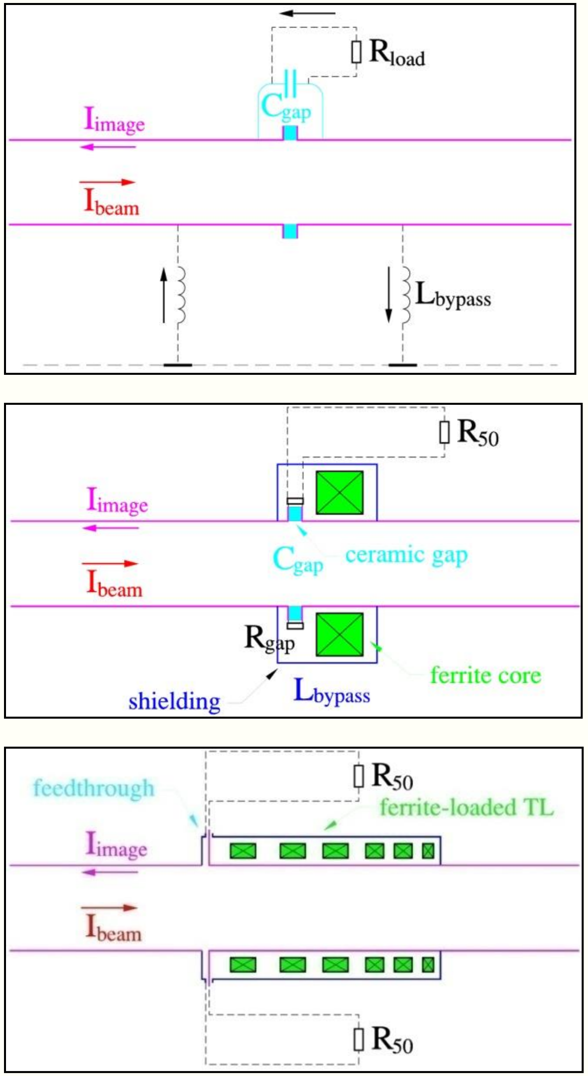
- **Image currents**
  - **Flow on the inner surface of the conducting vacuum chamber**
  - **Compensate the beam charge**
  - **At v ≈ c have a *pancake*-like TEM field**

$$\mathbf{E} = \frac{q}{4\pi\varepsilon_0} \frac{1-\beta^2}{\left(1-\beta^2 \sin^2\theta\right)^{3/2}} \frac{\mathbf{r}}{r}$$

where θ references to the direction of $\boldsymbol{v}$



Simple Beam Current Monitors



- **Single particle (*q*=*e*) impulse response *z(t)***

$$i_{beam}(t) = q\,\delta(t)$$

$$v_{gap}(t) = -\frac{1}{C_{gap}} \int_{-\infty}^{t} i(\tau)\,d\tau = -\frac{q}{C_{gap}}$$

$$v_{out}(t) = i_{beam}(t)\,z(t)$$

- **Transfer impedance *Z(ω)* of a beam pickup**

$$v_{out}(t) = \int_{-\infty}^{t} z(t-\tau)\,i_{beam}(\tau)\,d(\tau)$$

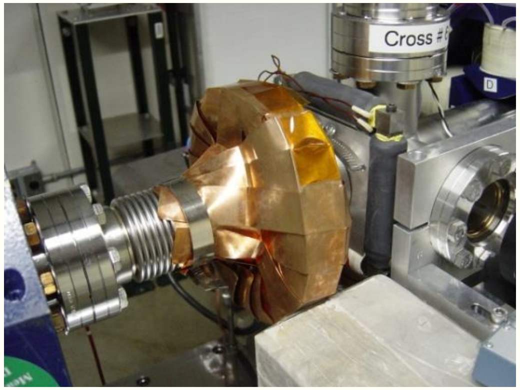
$$V_{out}(\omega) = I_{beam}(\omega)\,Z(\omega)$$

- **Wall current monitor response:**

$$Z_{WCM}(\omega) = \frac{R_{load}}{1 + j\left(\omega R_{load}\, C_{gap} - R_{load} / L_{bypass}\, \omega\right)}$$

$1/\omega_{hi}$ $\quad$ ω_{lo}

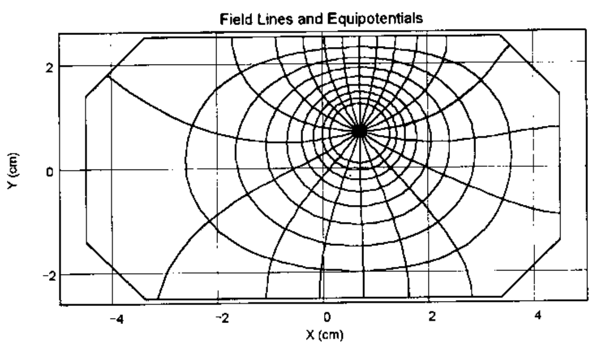
Toroids

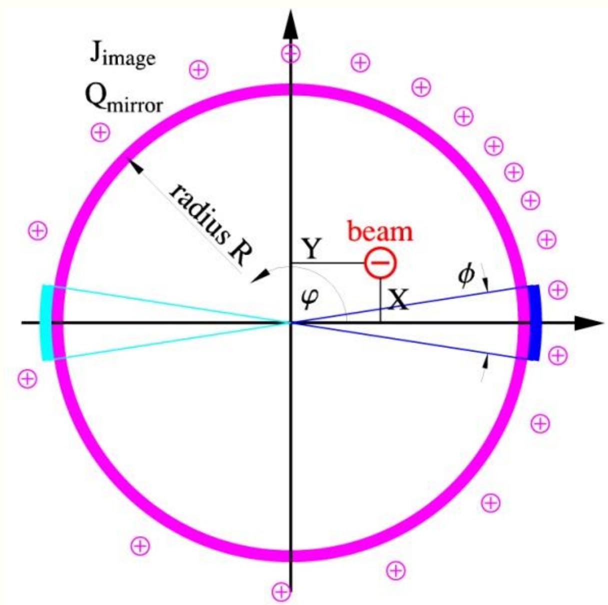


courtesy *Bergoz*

- **AC CT (high-pass char.** $Z_{ACCT}(\omega)=\frac{j\omega L_s}{(1+j\omega L_s/R_{load})N_s}$ **)**
  - Ceramic gap, ferrit core, shielding, calibration winding(!)
- **DC CT (used in ring accelerators)**
  - Coupled CT's with compensation feedback for DC measurements.
- **CCC (for dark current measurements)**
  - SC current comparator (SQUID-based).

Broadband BPM Pickups





- **Fields and image charges of an off-center beam (circular pipe):**

$$J_{image}(X,Y,\varphi) = -\frac{I_{beam}}{2\pi R}\frac{R^2-(X^2+Y^2)}{R^2+X^2+Y^2-2R(X\cos\varphi+Y\sin\varphi)}$$

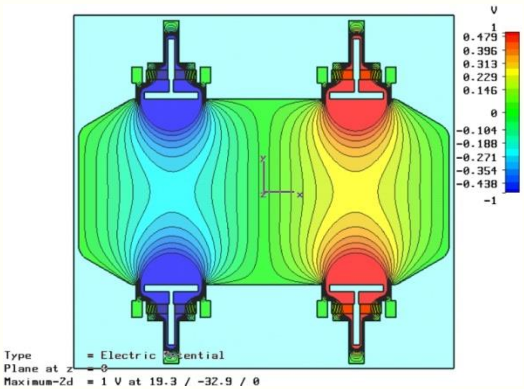
- **Ideal pickup electrode (*x=X/R, y=Y/R*)**

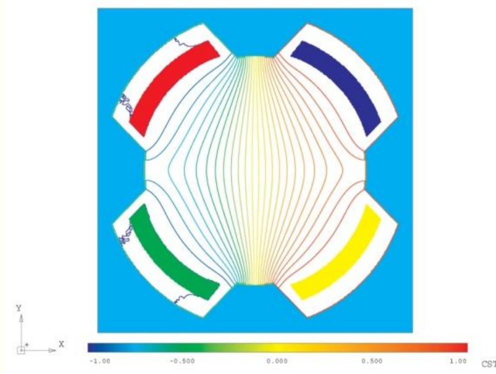
$$I_{elec}(x,y,\phi) = -\frac{2I_{beam}}{\pi}\arctan\frac{[(1+x)^2+y^2]\tan(\phi/4)-2y}{1-x^2-y^2}$$

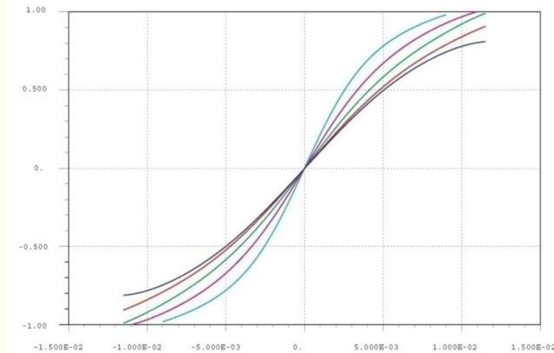
- **Beam position monitor (BPM)**
  - **Symmetric arranged electrodes**
  - **Common mode signal (I_{beam})**
  - **Beam intensity normalization (*Δ/Σ*)**
  - **Powerful beam instrument (beam orbit, optics, errors, emittance, etc.)**

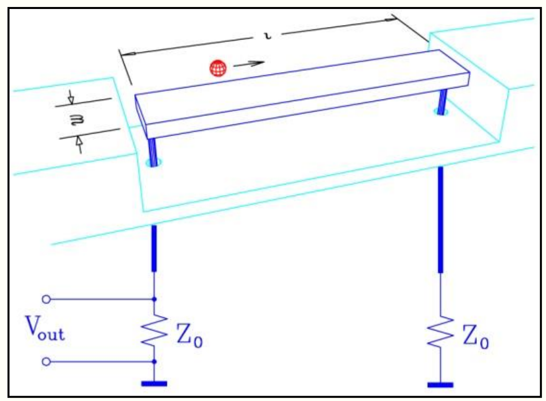
$$V_{elec}(x,y,\omega) = s(x,y)\,Z(\omega)\,I_{beam}(\omega)$$

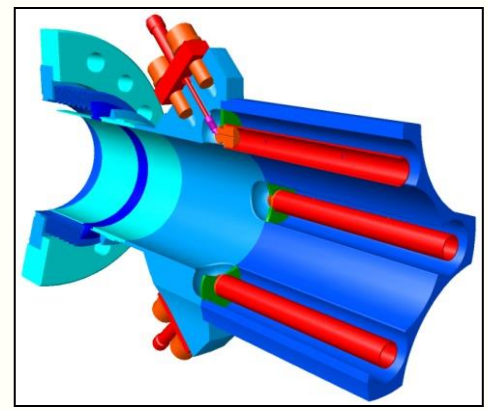
Button & Stripline BPMs

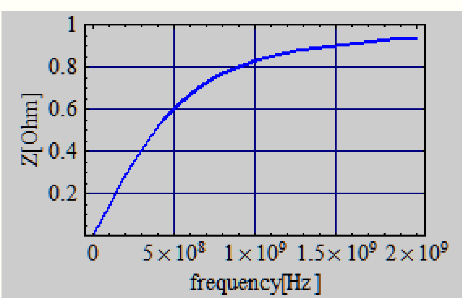






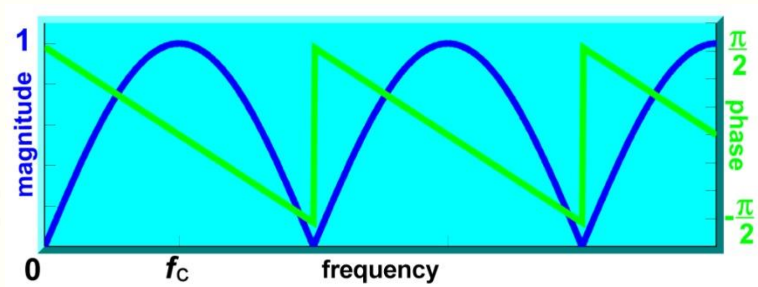






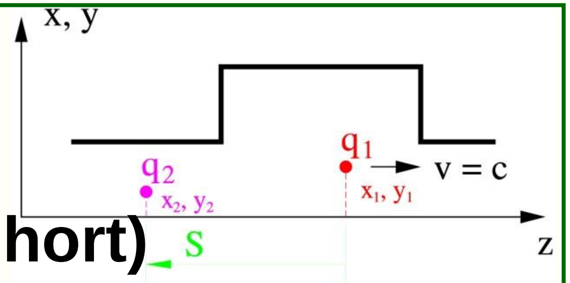
$$Z_{button}(\omega) = Z_0 \frac{r_{button}}{4r_{pipe}} \frac{2r_{button}}{c_0 Z_0 C_{button}} \frac{j\omega Z_0 C_{button}}{1 + j\omega Z_0 C_{button}}$$

$$Z_{stripline}(\omega) = jZ_0 \exp\left(-j\frac{\omega l}{c_0}\right)\sin\left(\frac{\omega l}{c_0}\right)$$



Wakefields, Wakepotential & HOM

$$\mathbf{F} = \frac{d\mathbf{p}}{dt} = q_2(\mathbf{E} + c_0 e_z \times \mathbf{B})$$

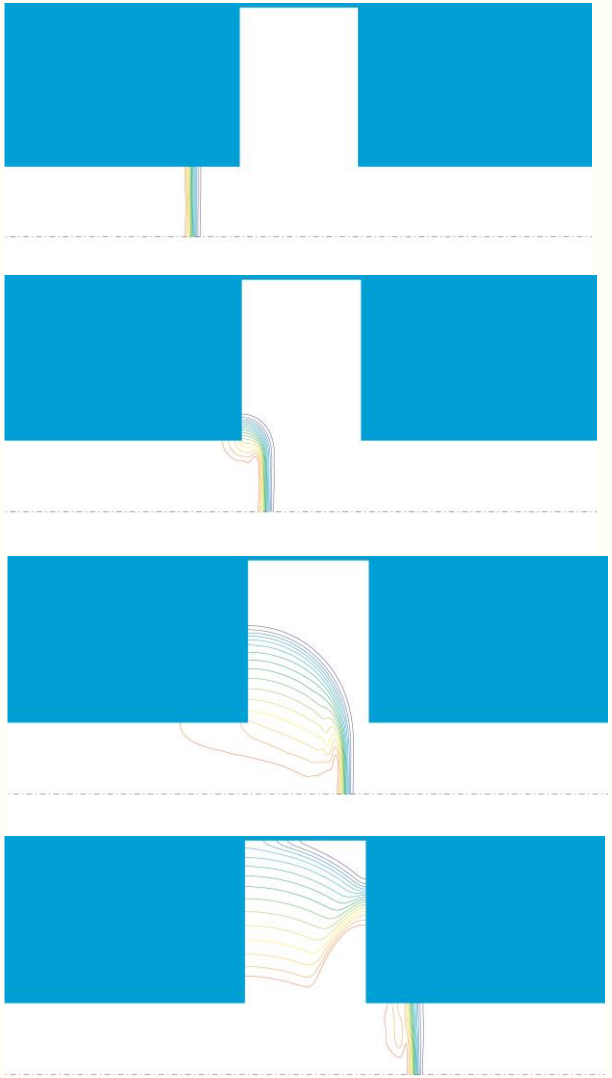


- **Wakefields (long, short)**
  - **A (point) charge q_1, acts on a test charge q_2 in presence of discontinuities (here: cavity) with the *Lorenz* force F.**
- **Wakepotential:**

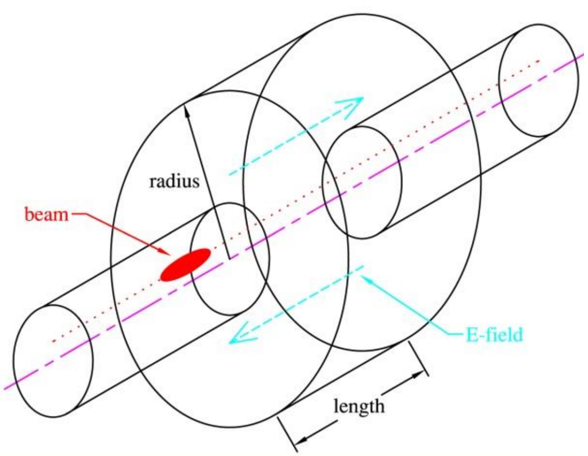
$$\mathbf{W}(x_2, y_2, x_1, y_2, s) = \frac{1}{q_1}\int_0^L dz(\mathbf{E} + c_0 e_z \times \mathbf{B})_{t=(z+s)/c_0}$$

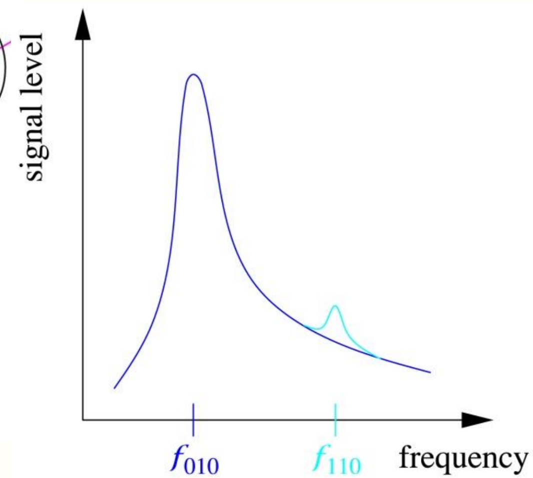
  - **Long. – trans.: *Panofski-Wenzel***
- **Higher order modes (HOM):**
  - **Multipole expansion for cyl. sym. struct.**

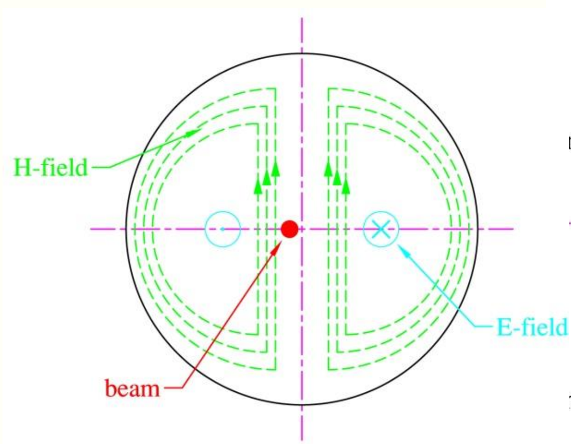
$$W_\perp^{(n)}(s) = c_0 \sum_i \left(\frac{R^{(n)}}{Q}\right)_i \sin\left(\frac{\omega_i s}{c_0}\right) \exp\left(\frac{-\omega_i s}{2(Q_{ext})_i c_0}\right)$$

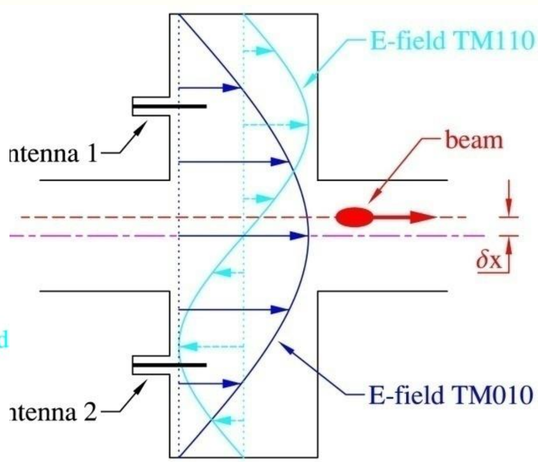


Cavity BPM



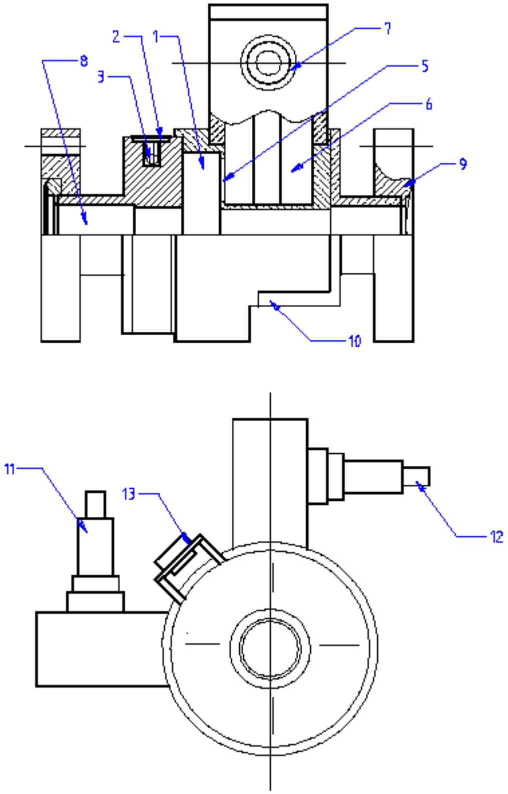






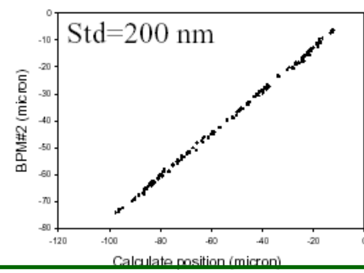
- **“Pillbox” cavity BPM**
  - **Generates dipole (TM_{110}) and monopole (TM_{010}) modes**
  - **Needs common mode (TM_{010}) suppression!**
  - **Orthogonal dipole mode polarization (xy cross talk)**
  - **Transient (single bunch) response (Q_L)**
  - **Normalization and phase reference**
  - **Special needs for cryogenic installation**

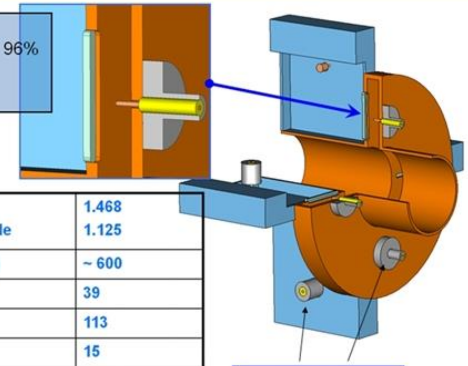
CM-free Cavity BPMs



Cross-sectional view of BINP cavity BPM 6426 MHz, (5p. in KEK ATF + 1p.). 2000.

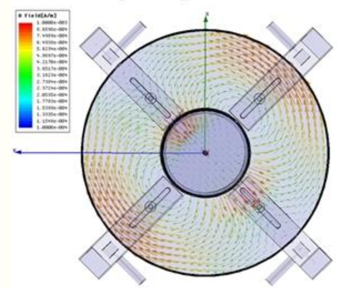
1.- Cavity sensor .
2- Heater.
3 – Temperature sensor.
5 – Coupling slot.
6 – Output waveguide.
7 – Output feedthrough.
8 – Beam pipe.
9 – Vacuum flange.
10 – Support plate.
11 – Y position output.
12 - X position output.
13 – Heater control connector.





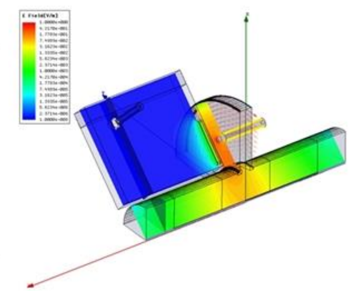
Frequency, GHz, dipole monopole	1.468 1.125
Loaded Q (both monopole and dipole)	~ 600
Beam pipe radius, mm	39
Cell radius, mm	113
Cell gap, mm	15
Waveguide, mm	122x110x25
Coupling slot, mm	51x4x2

Dipole TM_{11} mode



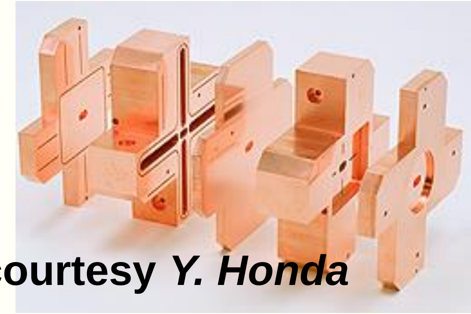
Magnetic coupling with waveguide

Monopole TM_{01} mode

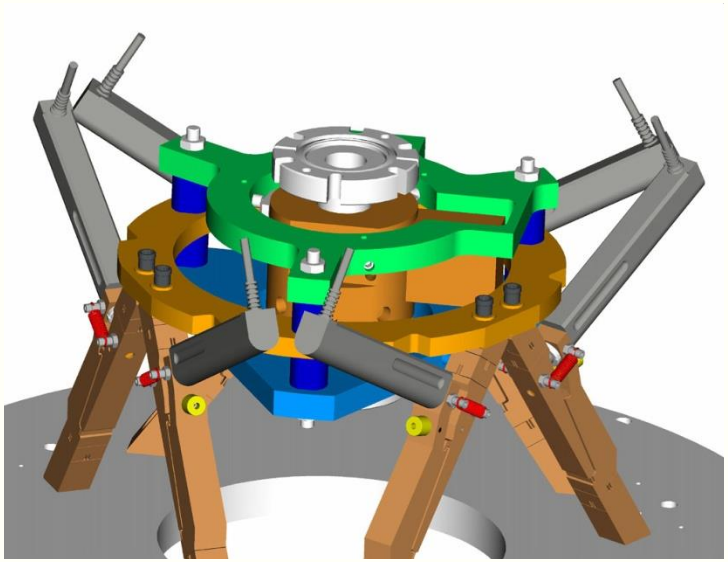


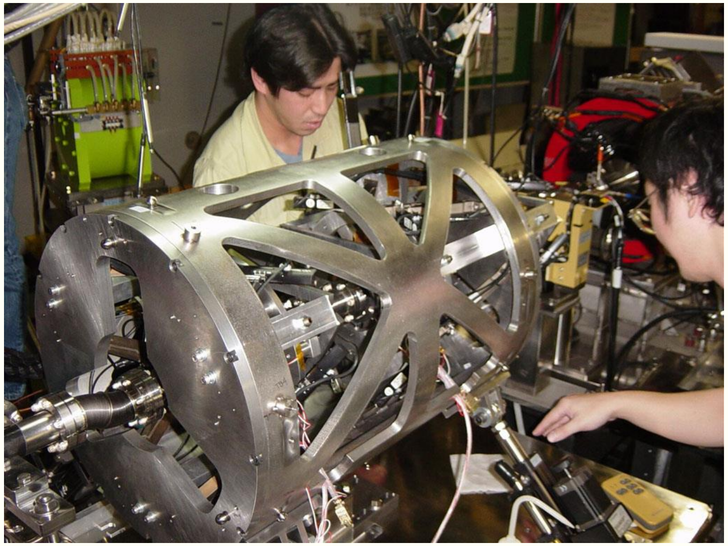
No coupling with waveguide

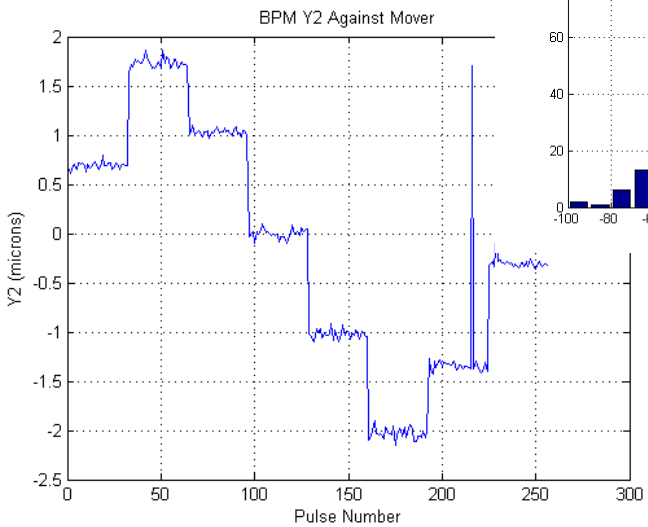
- Uses waveguides to suppress the common modes (slot coupling)
- Resolution <20 nm demonstrated (ATF)
- “Cold” design without reference cavity

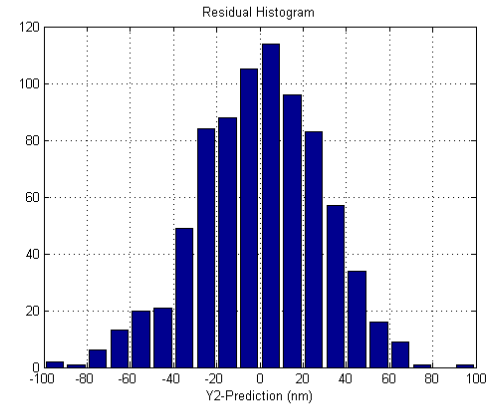


courtesy *Y. Honda*



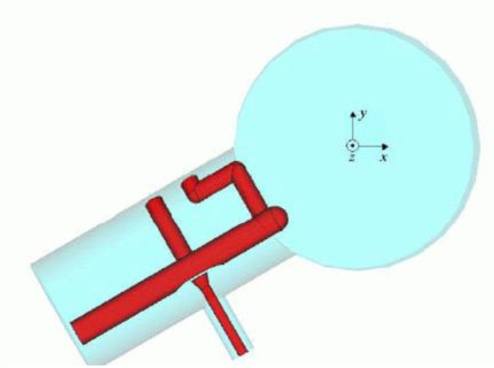


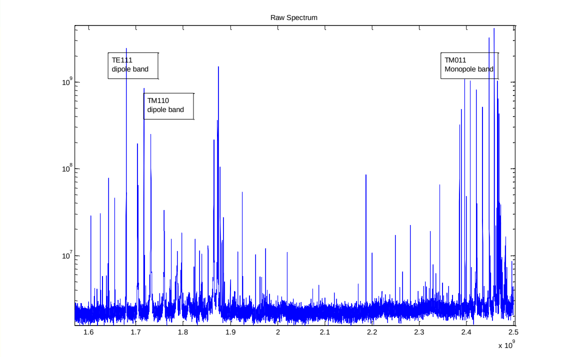


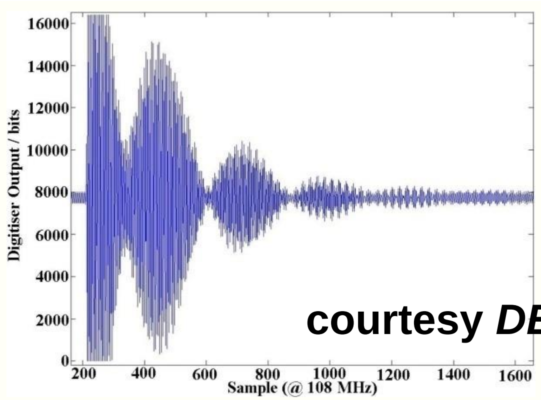


- **Cavity BPM development (ATF)**
  - **Hexapod and spaceframe (LLNL), alignment in 6 degrees of freedom**
  - **24 nm (RMS) resolution, dual-downconverter & digitizer**

HOM Signals for Beam Monitoring







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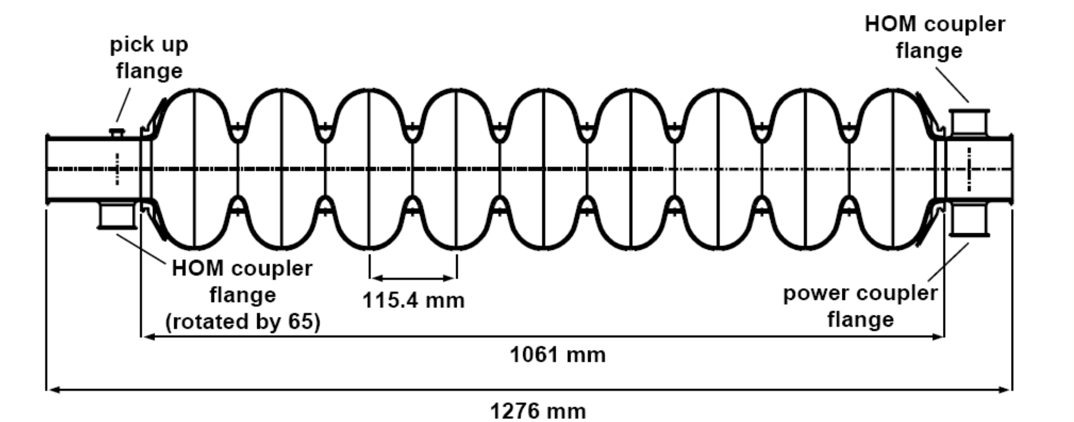
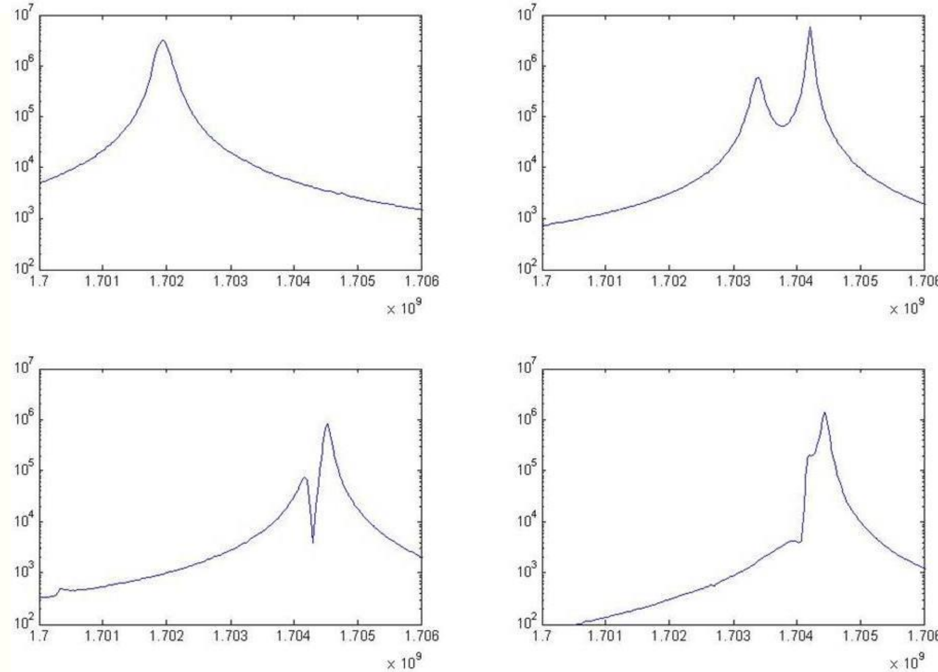
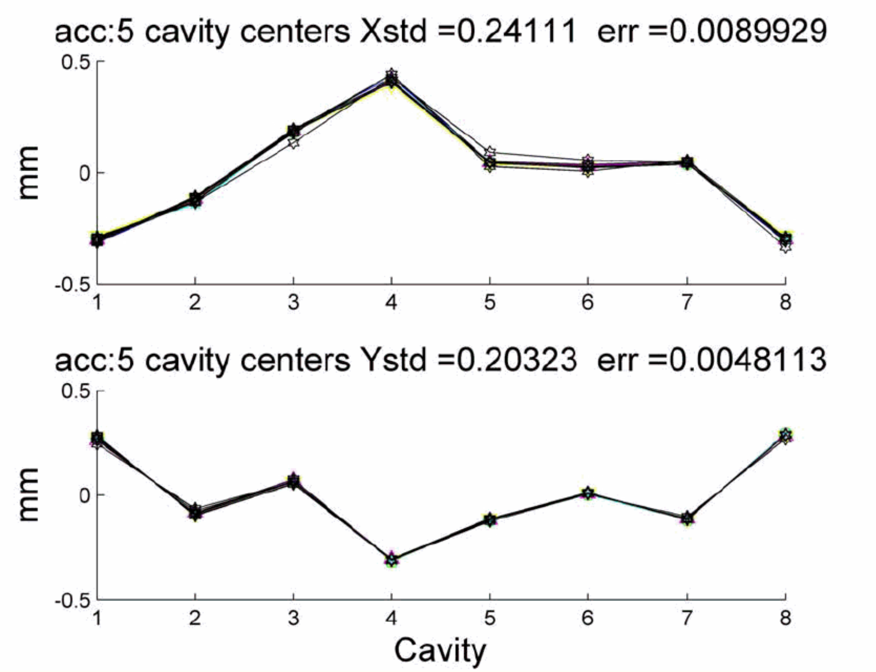
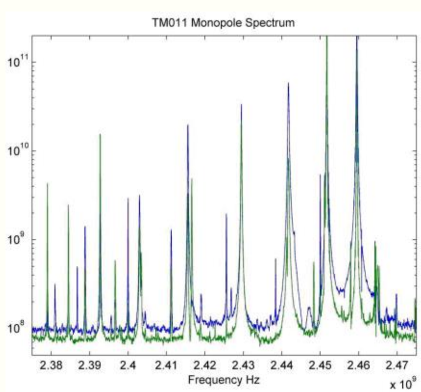
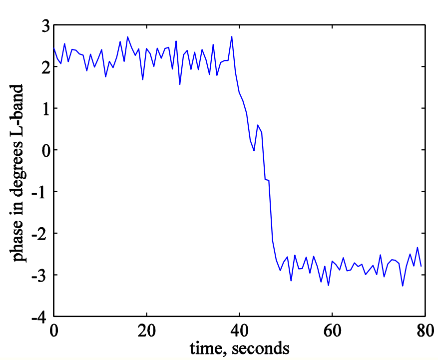




HOM Beam Position & Phase

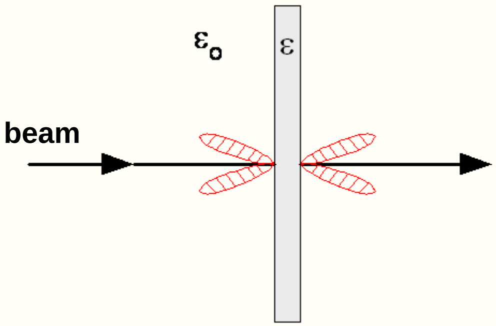




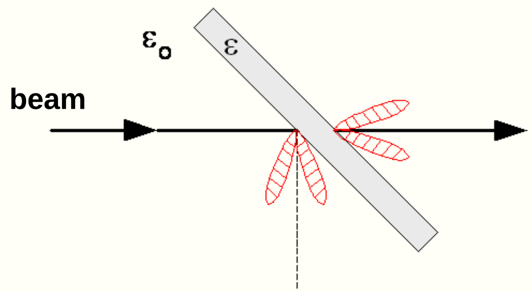


- **HOM as BPM**
  - **TE_{111-6} narrow band read-out**
  - **Beam-based calibration data, to orthogonalize the polarization planes of the excited eigenmodes per SVD algorithm.**
  - **~ 5 µm resolution**
- **HOM as phase monitor**
  - **Comparison of the leaking 1.3 GHz fundamental (TM_{010}) to the first monopole HOM (TM_{011})**
  - **Broadband Scope analysis**
  - **<0.1^0 @ 1.3 GHz resolution**

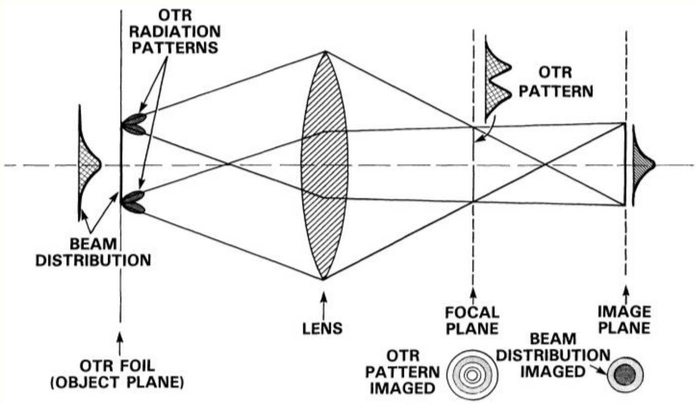
Optical Transition Radiation (OTR)

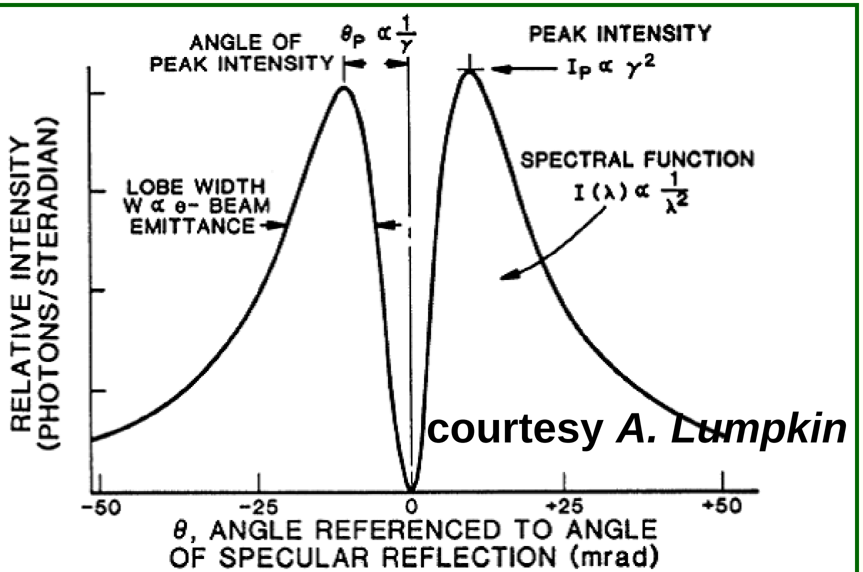


Normal Incidence



Oblique Incidence





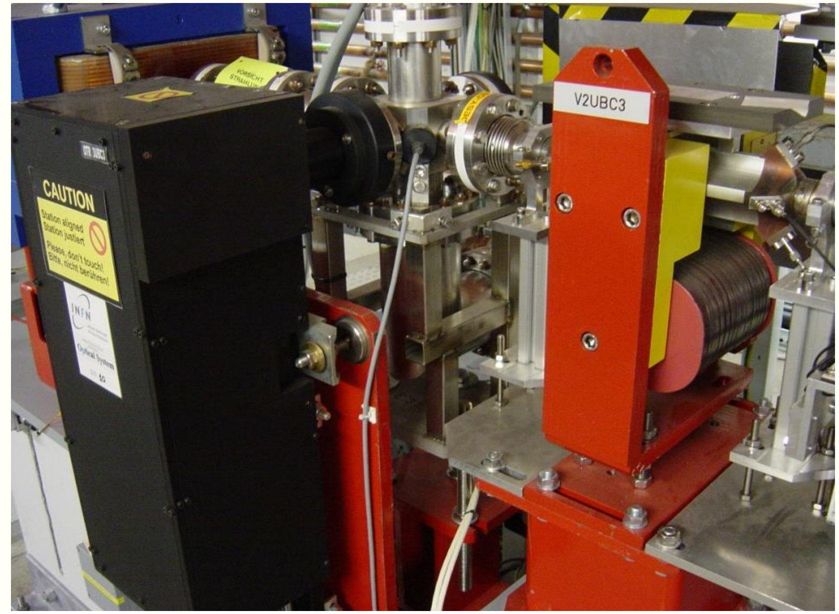
courtesy *A. Lumpkin*

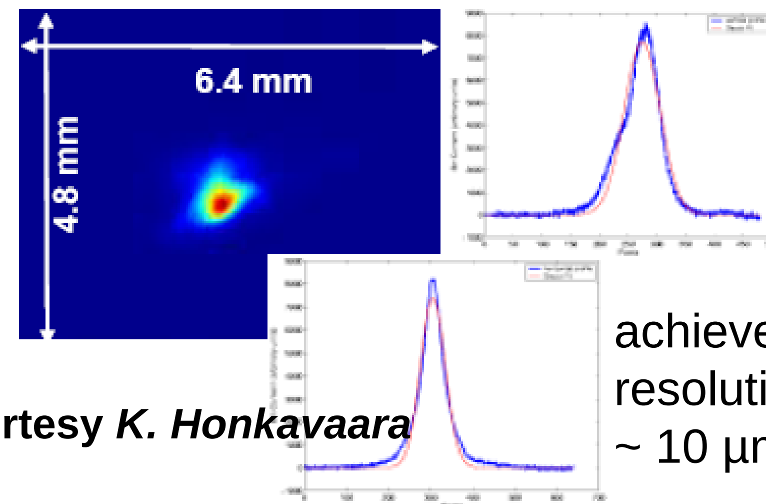
- **Transition radiation**

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

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

Transverse OTR Beam Monitors

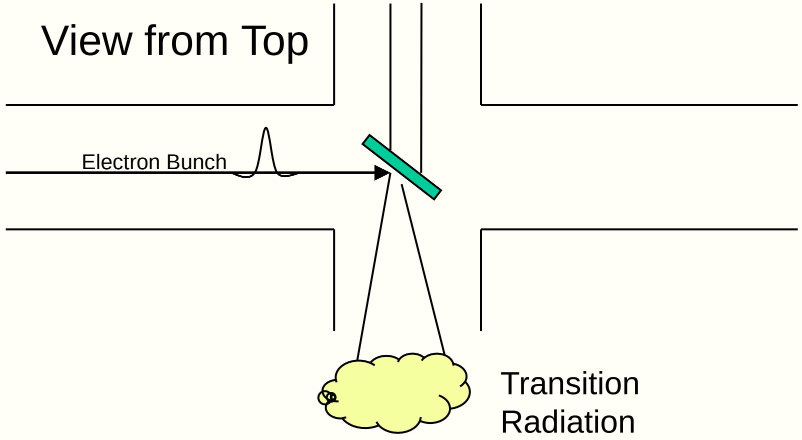


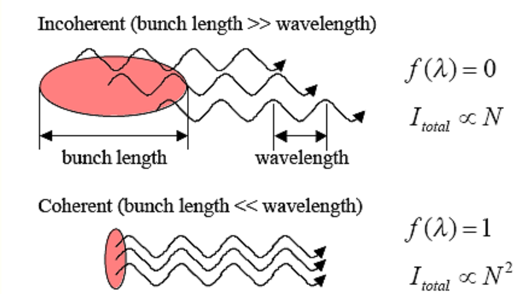


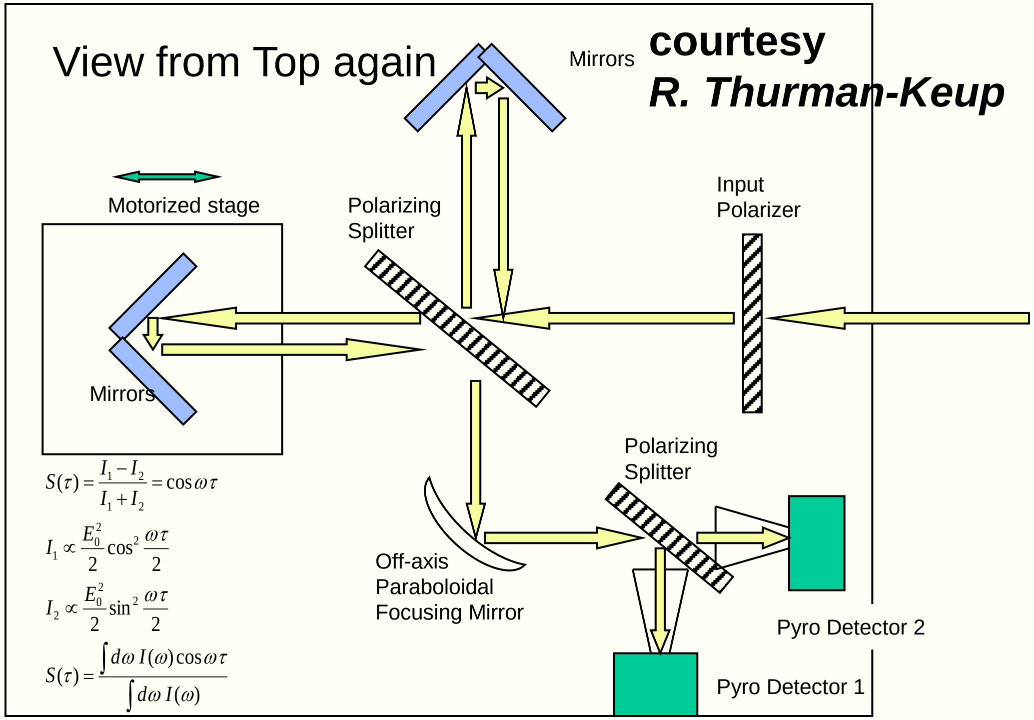
courtesy *K. Honkavaara*

achieved resolution:
~ 10 µm (RMS)

Bunch Length Interferometer





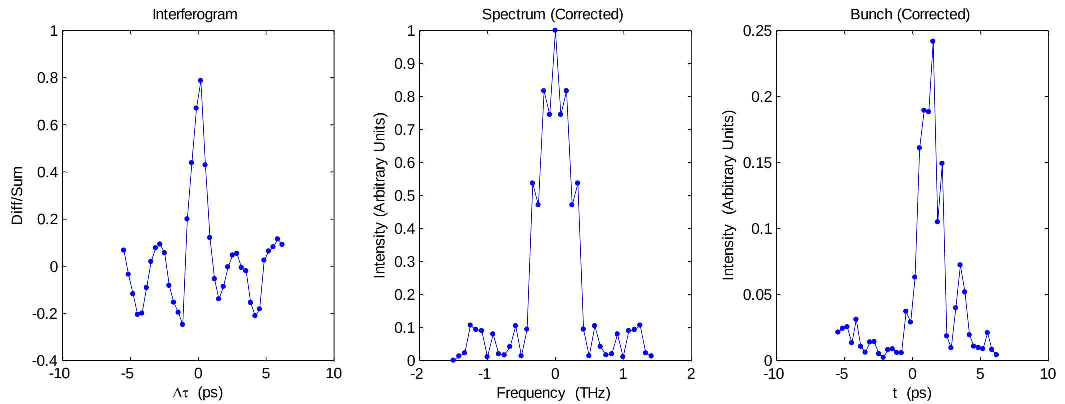


$$I(\omega)=I_0(\omega)\left(\overset{\text{Incoherent}}{N}+\overbrace{N(N-1)\left|F(\omega)\right|^2}^{\text{Coherent}}\right)$$

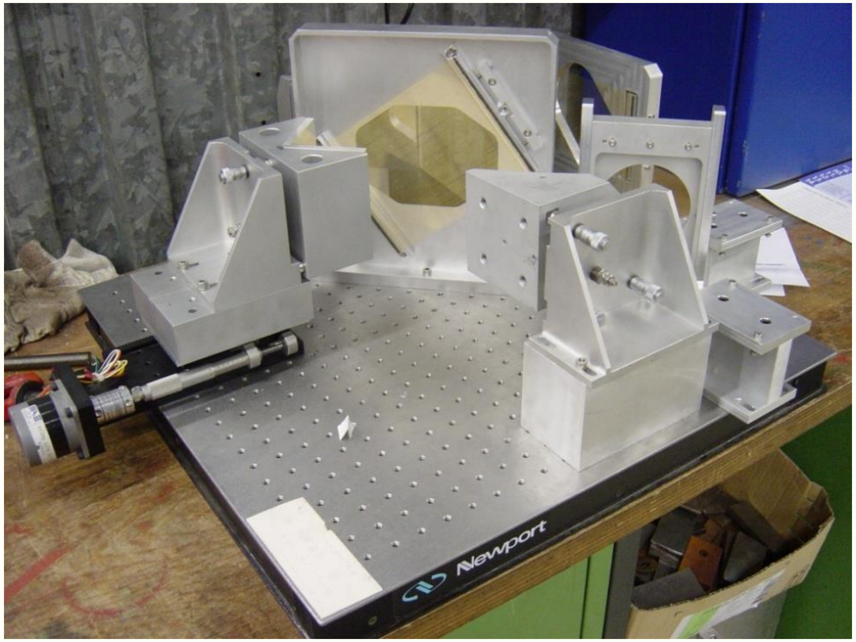
$$F(\omega)=\frac{1}{Q}\int d^3x\rho(\vec{x})e^{-i\omega(\vec{x}\cdot\hat{n})}$$

- **Martin-Puplett interferometer**
  - **Needs many beam pulses to resolve the temporal convolution**
  - **Difficult to calibrate the detectors**

OTR Interferometers



- **Detector elements**
  - **Molectron pyro-electric (cheap, calibration)**
  - **Golay cell (expensive)**

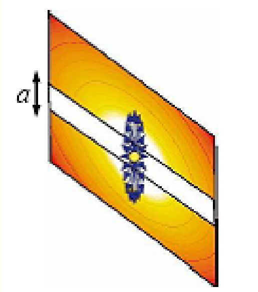


Martin-Puplett interferometer (courtesy *DESY*)

Michelson interferometer (courtesy *U of Georgia & NIU*)

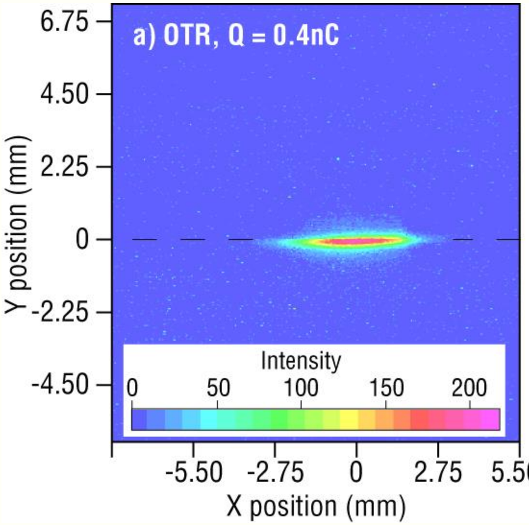
Optical Diffraction Radiation

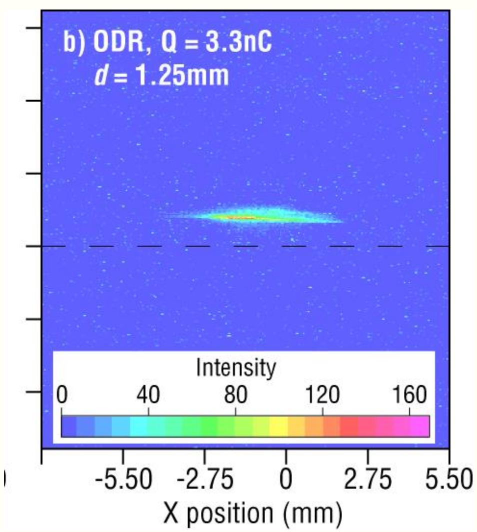
- **Optical diffraction radiation (ODR):**
  - **Near field effect between EM fields of the beam close to a conducting screen**
    Intensity: $$I \propto \exp\left(-\frac{2\pi a}{\gamma\lambda}\right)$$
  - **DR impact parameter:**



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

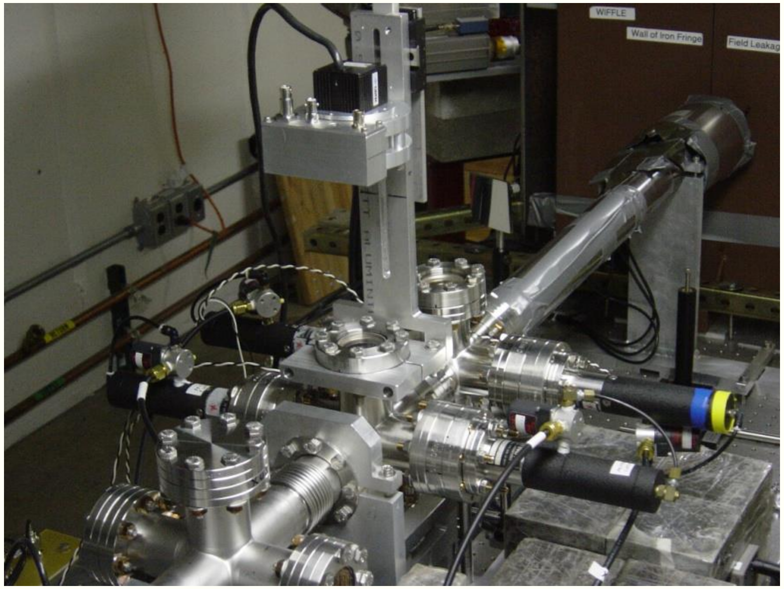
  - **Non-intercepting beam measurement!**

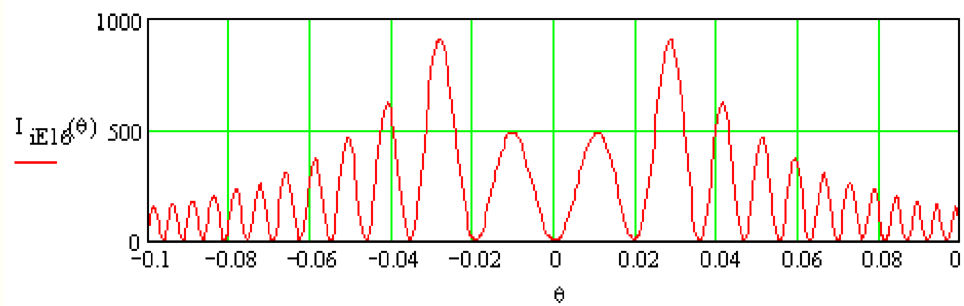


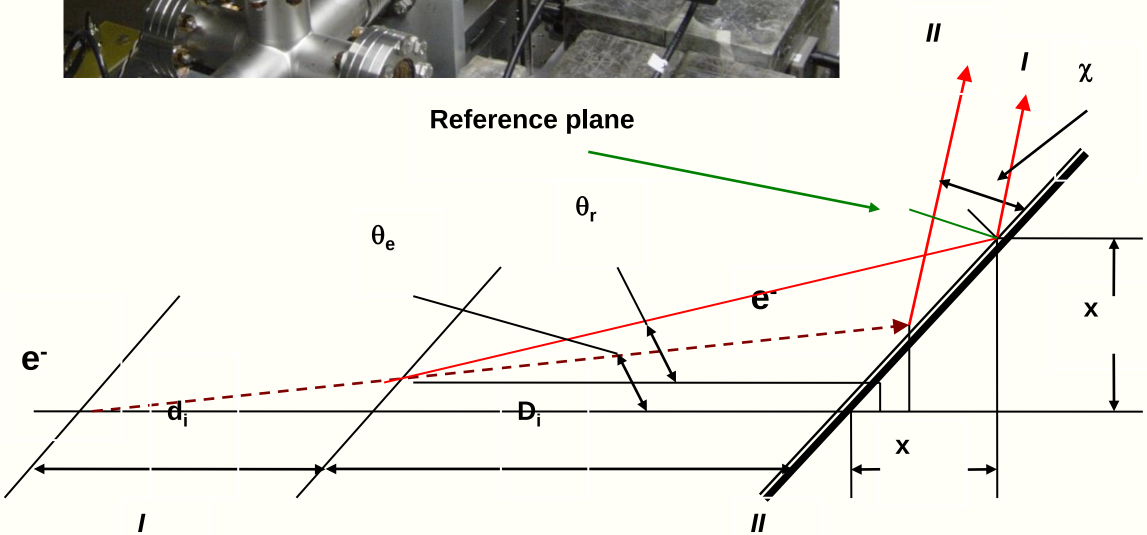


courtesy *A. Lumpkin*

OTR Interferometer







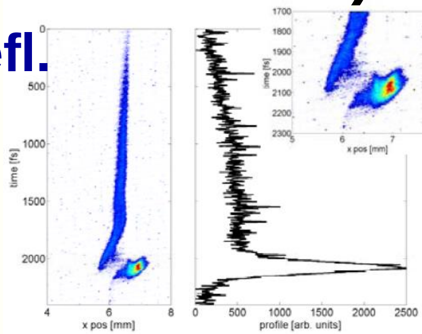
courtesy *G. Kazakevich*

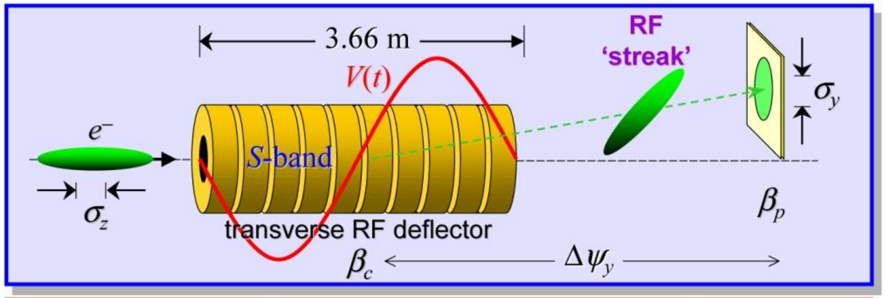
OTRI:

A beam passing two thin foils, allows the measurement of additional beam parameters (energy, energy spread, divergence), derived from the OTR interference pattern.

Deflecting Mode Cavity

- **DMC, RF streak camera, “LOLA” (SLAC S-Band DMC):**
  - Dipole mode cavity, TM_{11} 2π traveling wave defl.
  - High resolution bunch length measurement
  - Single pass measurement, but intercepting
  - Accurate calibration(!)





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

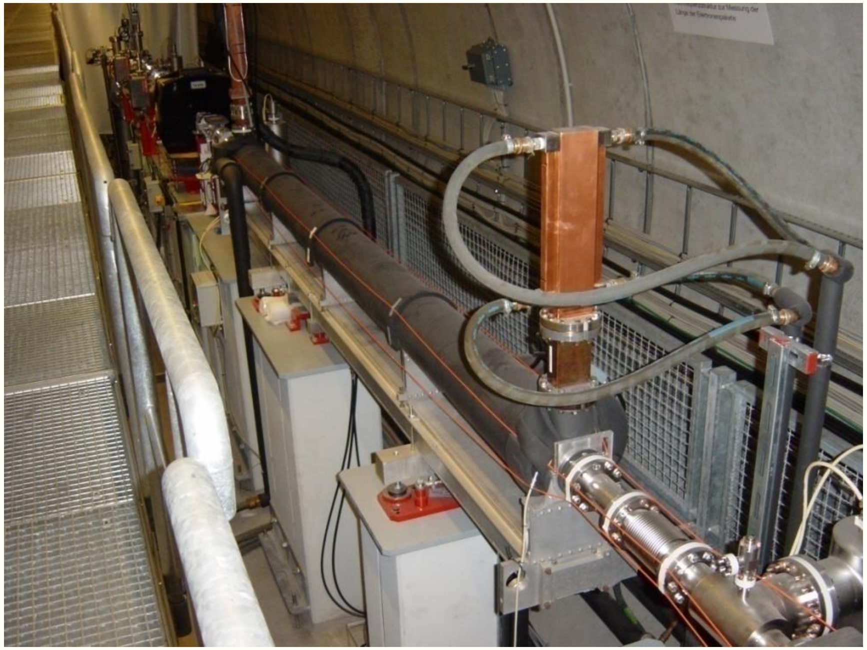
$$\langle \Delta y \rangle = \frac{eV_0}{E_0} \sqrt{\beta_c \beta_p} \sin\Delta\psi_y \sin\varphi, \qquad V_0 \approx \left(1.6\ \mathrm{MV/m/MW}^{1/2}\right) L \sqrt{P_0}$$

$\sigma_z \approx 25\ \mu m$
$E_0 \approx 0.6$ GeV
$(\beta_c\beta_p)^{1/2} \approx 51$ m
$\gamma\varepsilon_y \approx 5\ \mu m$

$\Delta\psi_y \approx 15.8°$
$\varphi \approx 0°$
$\lambda \approx 105$ mm
$\sigma_{y0} \approx 317\ \mu m$

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

P. Emma (SLAC)



Electro-Optical Sampling (EOS)

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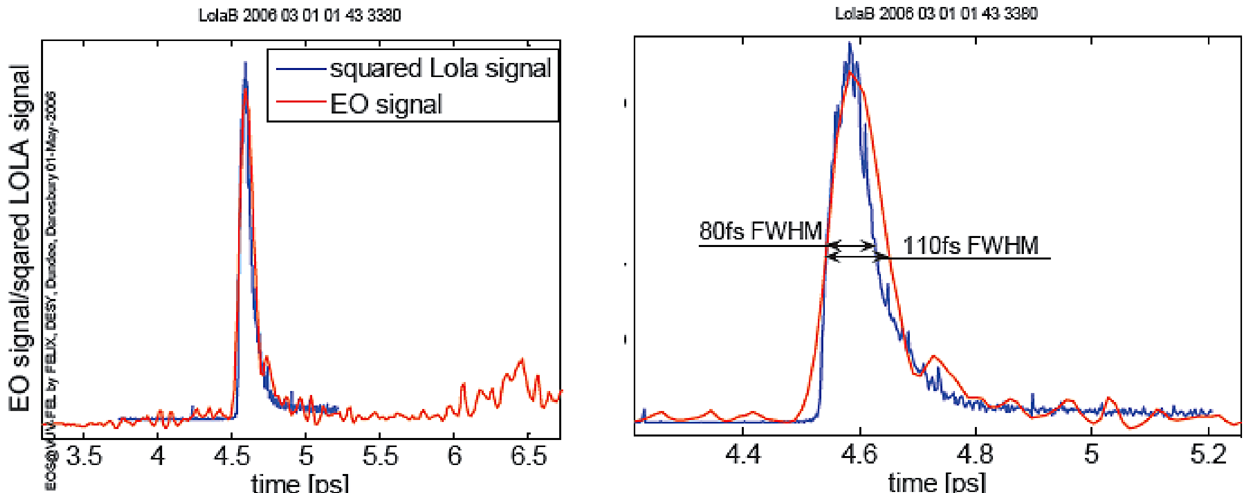
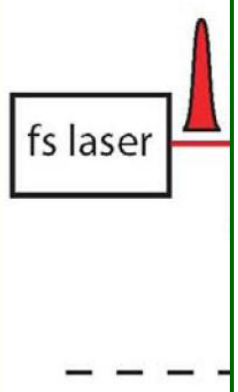
Comparison of EO and LOLA signals



Preliminary unpublished Data

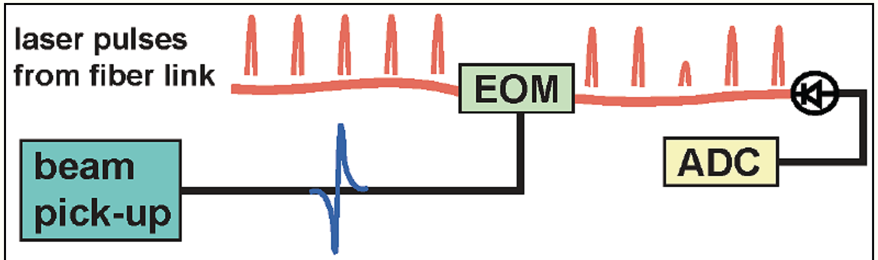
SASE conditions



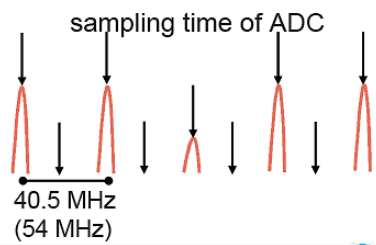
EO at first bunch, LOLA at second bunch in the same bunch train

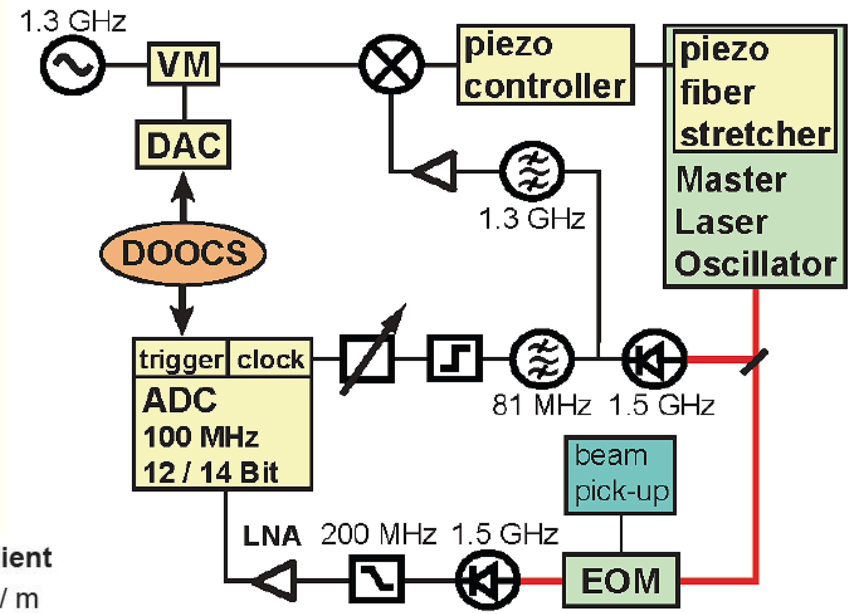
Bernd Steffen, FLS workshop, Hamburg, 18.05.2006

Bunch Arrival / Beam Phase

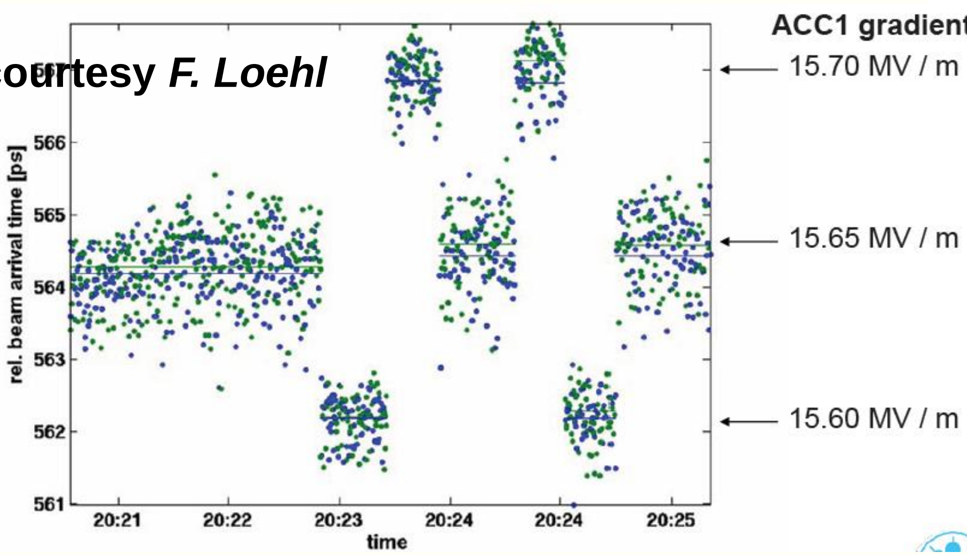


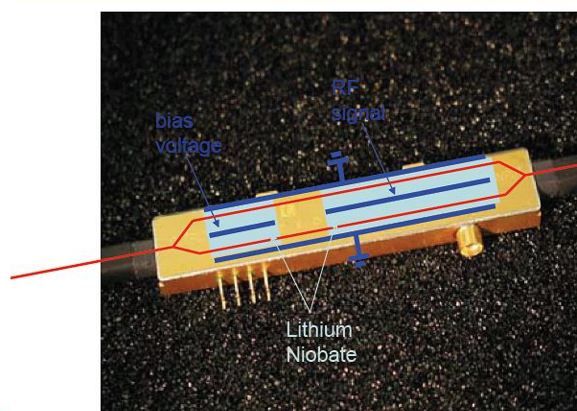
The timing information of the electron bunch is transferred into an amplitude modulation. This modulation is measured with a photo detector and sampled by a fast ADC.





courtesy *F. Loehl*



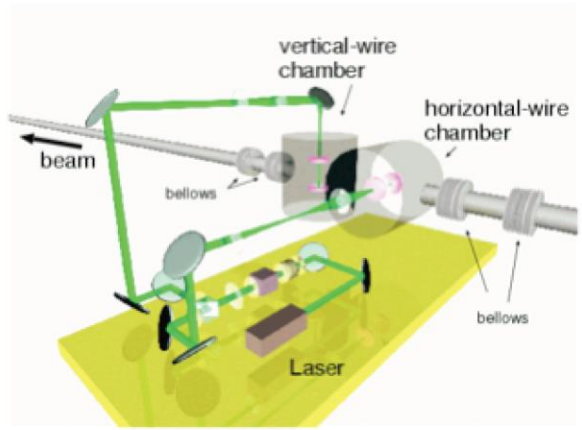


Commercially available with bandwidths up to 40 GHz
(we use a 10 GHz version)

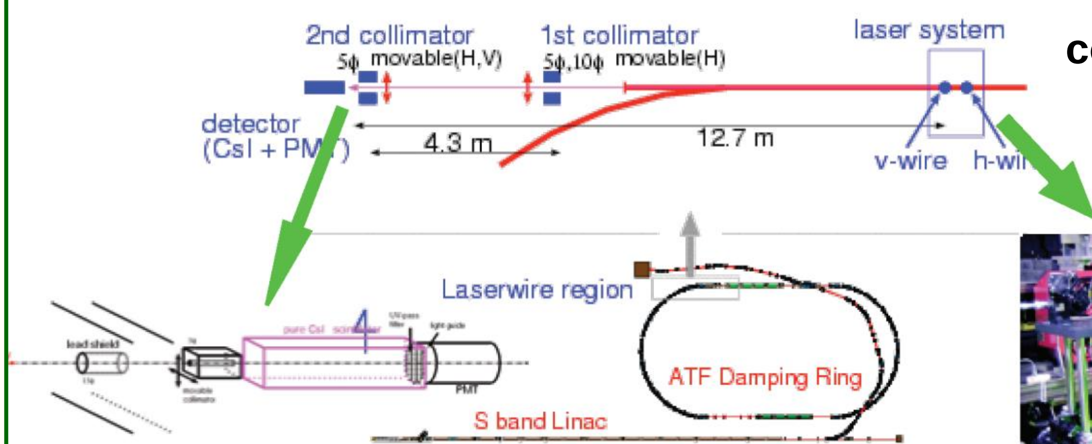
LASER Wire Scanner

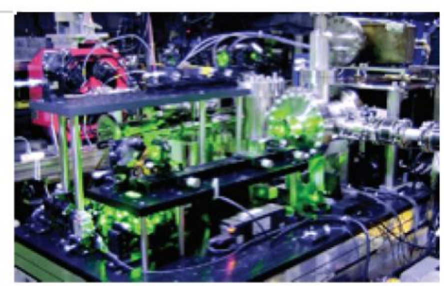
Setup

- ATF Damping ring
  - 5 micron (Y), 100 micron (X), typical beam size.
  - horizontal and vertical cavity
  - scan by mover table.
- detection
  - CsI scintillator, counting.
  - Compton edge is 28 MeV.



courtesy *Y. Honda*





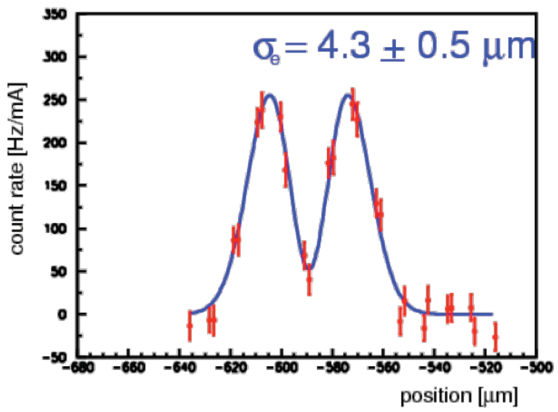
LASER Wire with Optical Cavity

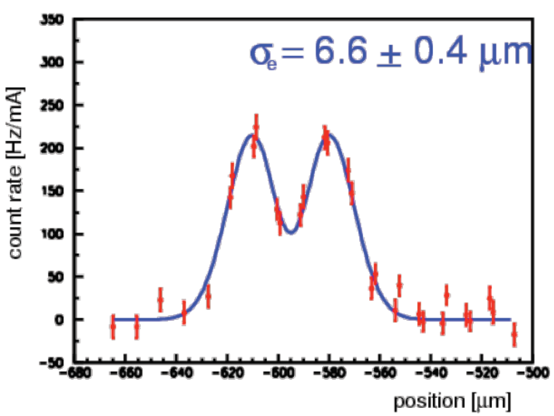
Fermilab

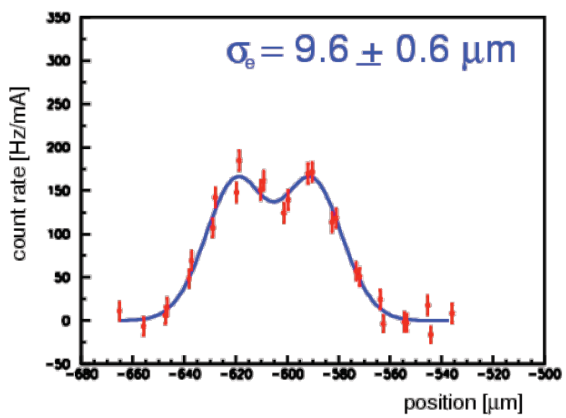
Measurement with a higher-order laserwire

courtesy *Y. Honda*

- 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.







Final Remarks

- **Missing in this presentation:**
  - Analog & digital signal processing, trigger & clock signals (sub-picosecond), ADC & FPGA technology, clock distribution, etc.
  - Programming techniques, system integration, instrument control.
  - Calibration methods
  - Beam loss monitors and machine protection system
  - Feedback systems, e.g. IP-feedback (FONT)
- **ILC instrumentation R&D requires BEAM!**
  - Test facility accelerators, e.g. FLASH, ATF, ESA, A0, NML,…
  - International collaboration groups on specific R&D projects.
- **Toward the EDR**
  - Collect information (email addresses, documents, status quo)
  - Identify uncovered R&D areas, ILC instrumentation requirements.
  - Defining next R&D steps, NML instrumentation,…

THANK YOU!