Diagnostics for High Energy Accelerators

*Advance*ment through both innovation and precision

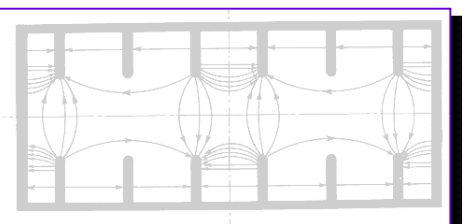
Use of laser probes Use of high power microwave transverse structures Use of selective coupling to precision cavities	Laserwire LOLA nanoBPM

This talk

Marc Ross, SLAC

24.06.2004

AAC04

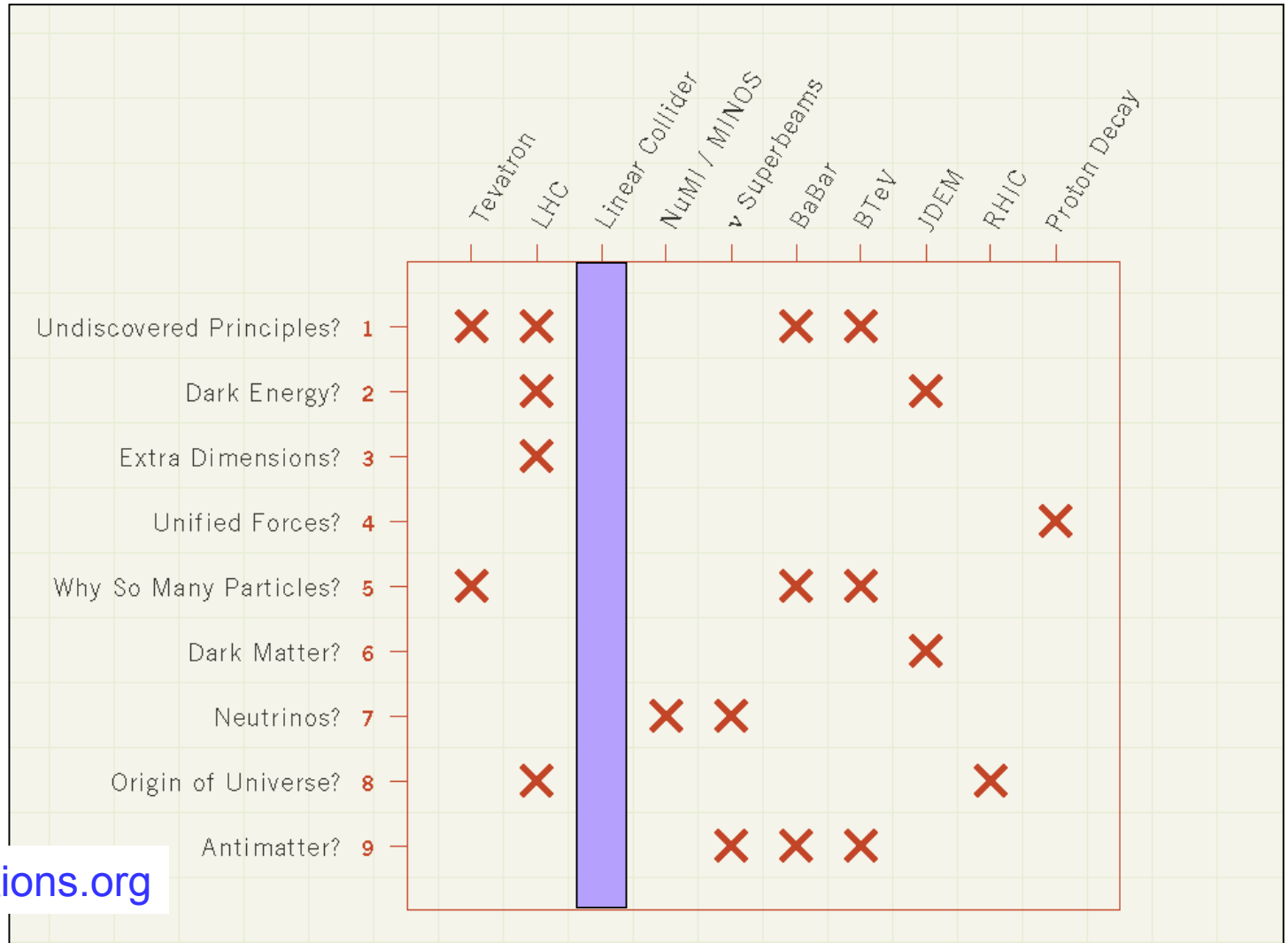


Quantum Universe:
The Revolution in 21st-Century Physics
- Spring 2004 -
HEPAP report commissioned by DoE/NSF

9 questions:

10 major facilities.

The Linear Collider is poised to answer 5 of the questions.

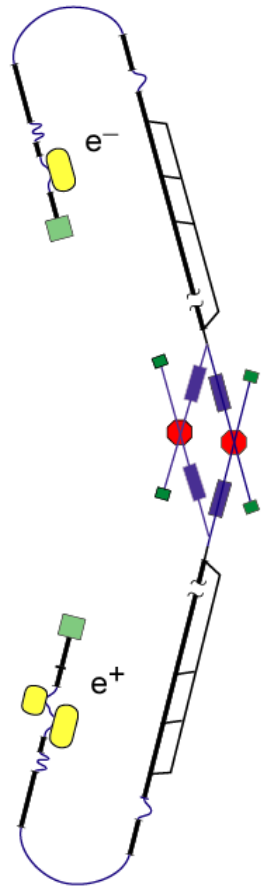


http://www.interactions.org

Peak Luminosity
2e34 →7,000 times larger than SLC

$$L = \frac{f_{rep}}{4\pi}\frac{n_b N^2}{\sigma_x \sigma_y} H_D \quad \Rightarrow \quad L = \frac{P_b N}{4\pi m c^2}\frac{H_D}{(\beta_x \beta_y)^{1/2}(\gamma\varepsilon_x \gamma\varepsilon_y)^{1/2}}$$

- Focusing $(\beta_x * \beta_y)^{-1/2}$ NLC/SLC → 3
  - ✓ Demonstrated at FFTB
- Disruption H_D NLC/SLC → 0.7
  - ✓ Demonstrated at SLC
- Emittance $(\gamma\varepsilon_x * \gamma\varepsilon_y)^{-1/2}$ NLC/SLC → 85
  - – Low Emittance Transport and Damping rings
- Beam power term $(P_b * N)$ NLC/SLC → 35
  - – Bunch trains, Particle sources, Collimation and MPS



technology choice for international Linear Collider

- Competition-driven RD for both SCRF and Normal conducting RF
  - (Structure fabrication process for copper structures)
- Crudely speaking:
  - Copper delivers energy – gradient is higher /
  - Superconducting RF delivers beam power → efficiency is higher
  - Both energy and power are needed
  - Both machines need precision beam monitoring / sophisticated power handling controls

needed: *"LONG TERM research and development"* in both *Luminosity* & Energy

- cost reduction and efficiency for Energy
- precision and beam dynamics for Luminosity
- witness shootout between warm and cold technology
  - to be concluded before the end of 2004

Test Facilities (Friday PM plenary)

- Test facilities needed for instrumentation
  - Small beams with precision control and stability

- FFTB at SLAC (soon to be dismantled)
- ATF at KEK → center for collider instrumentation RD

  - Work presented in this talk is centered at ATF –
    - (also short bunch diagnostics → TTF2 at DESY)

ATF

◦ ◦ ◦ ◦ ◦ ◦ ◦

1.3 GeV ultra-low emittance storage ring
Typical beam size: 50 x 5 μm x 5mm (x, y, z)
2 e10/micro bunch, 20 bunch trains at 2.8ns
3 Hz
22 weeks/year operation since 1997 (Oct-June)
14 Japanese; 8 International Institutes/Univ.
Dozens of students…

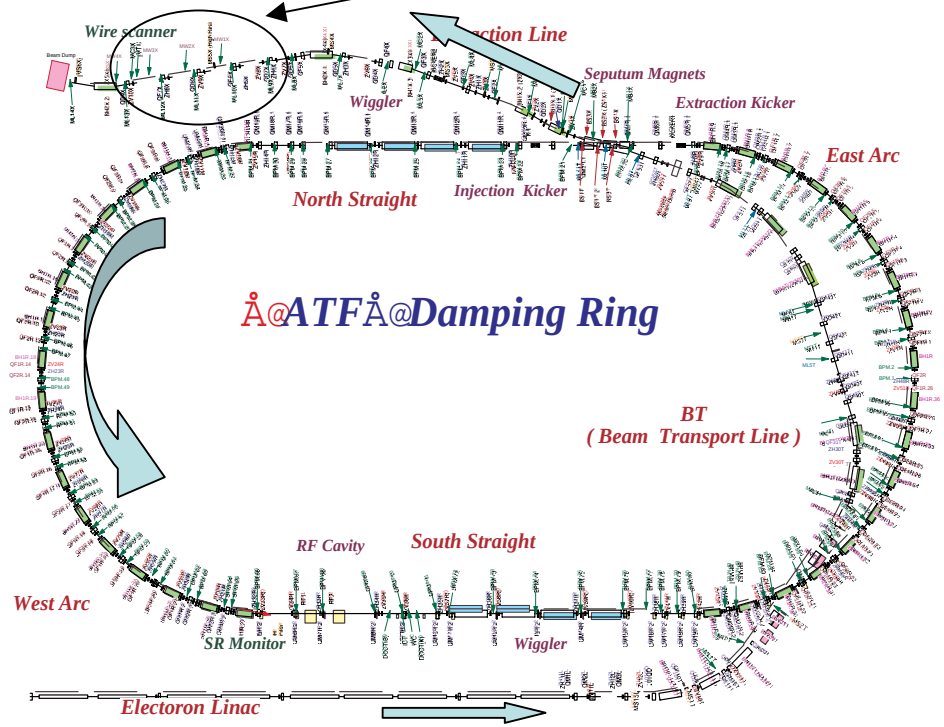
Half scale proto-type of GLC-DR.

Mission: generation&confirmation of LC low emittance e⁻ beam

ATF emittance goal was set to
X emit=2.5E-6(at 0 intensity)
Y emit=2.5E-8(at 0 intensity) 1% from X

(……)

Studies centered in this region



Success with precision diagnostics and controls

- innovation integrated with precision
- Test facilities needed
- RD character is different
- Linear Collider University – Based research
  - ‘LCRD’ – funded through DOE ~ 400K/yr since ’03.
  - Open for newcomers…

limits to *beam size diagnostics*

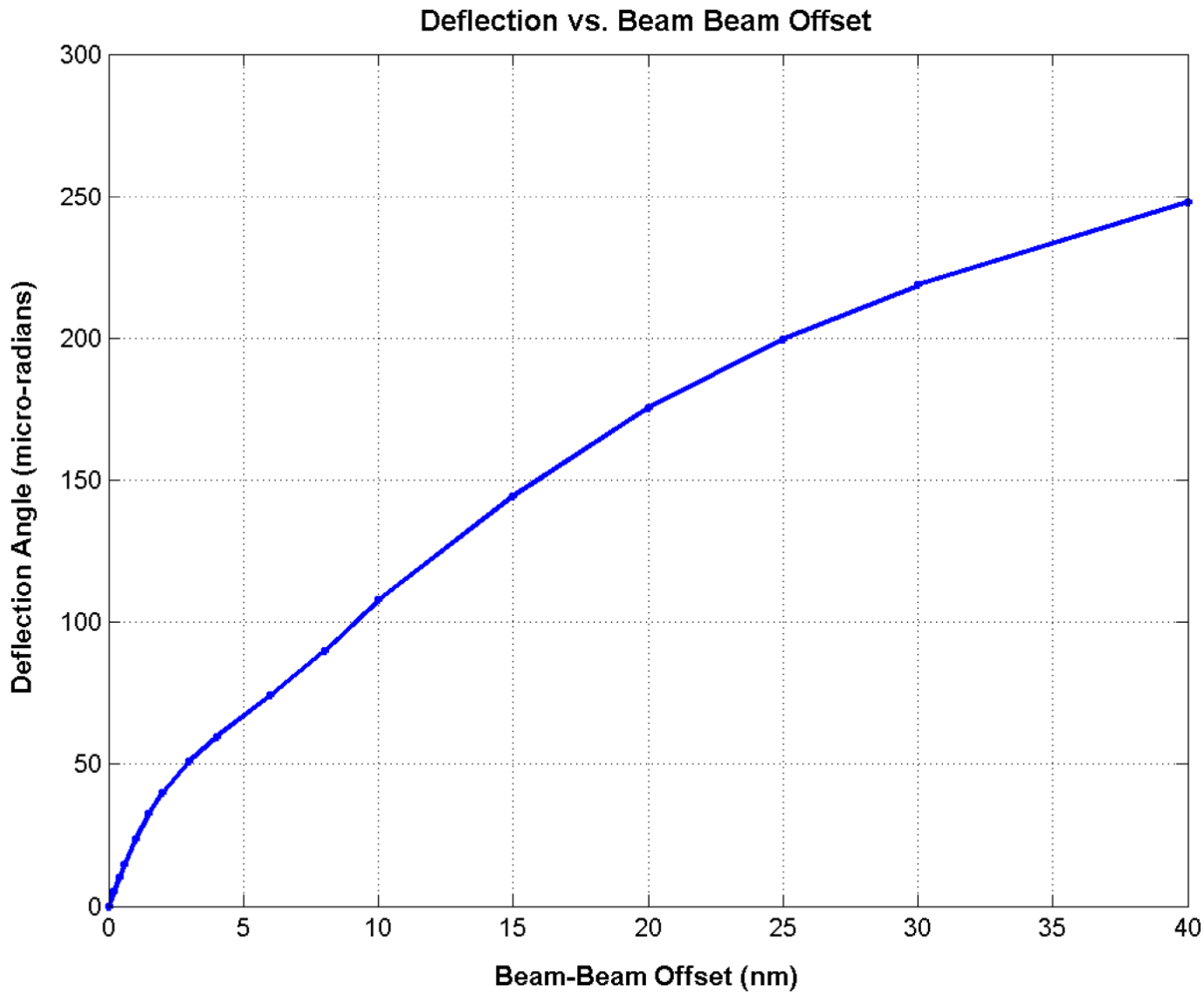
- Monitor limit scales roughly as size of probe
  - Laser probe : wire scanner ($\lambda/2$: r/2)
  - Microwave bunch length monitor
  - Synchrotron radiation / transition radiation

- 10's of nanometers transverse /
- 10's of microns bunch length

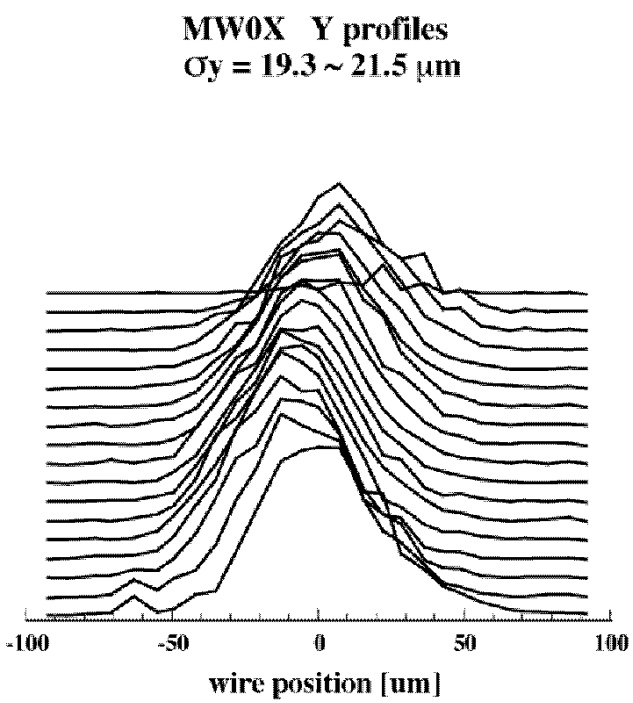
- How to improve on this?

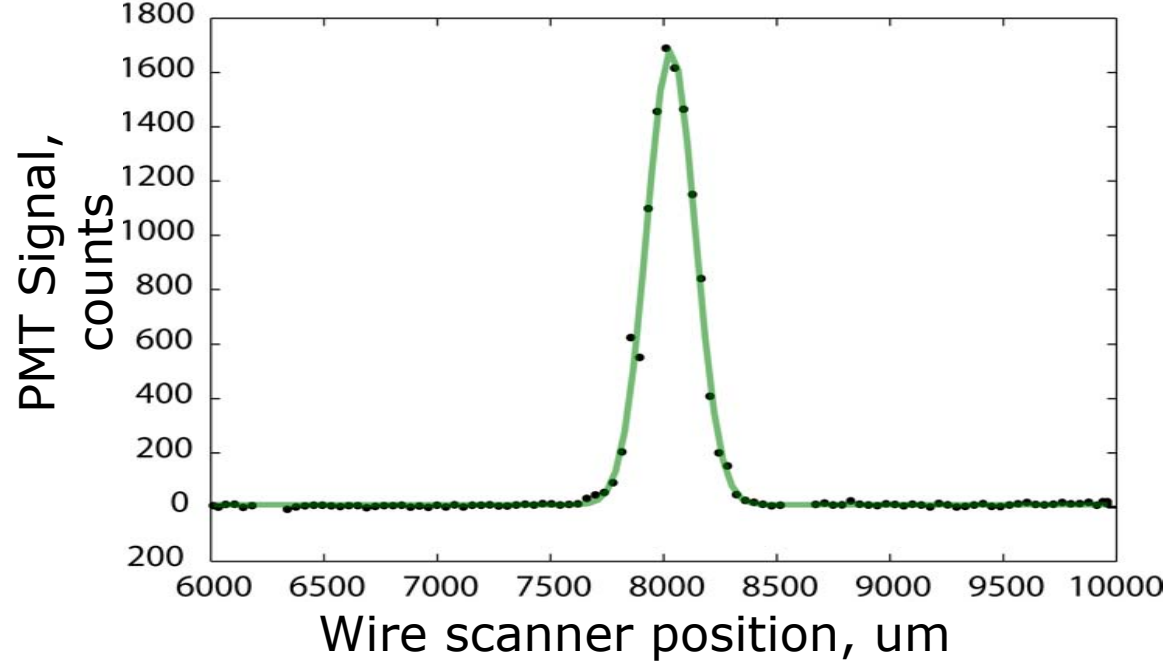
½ beam-beam deflection

- NLC simulation
- the only ‘real’ probe … the other beam
- converts nm offsets to μrad kicks!



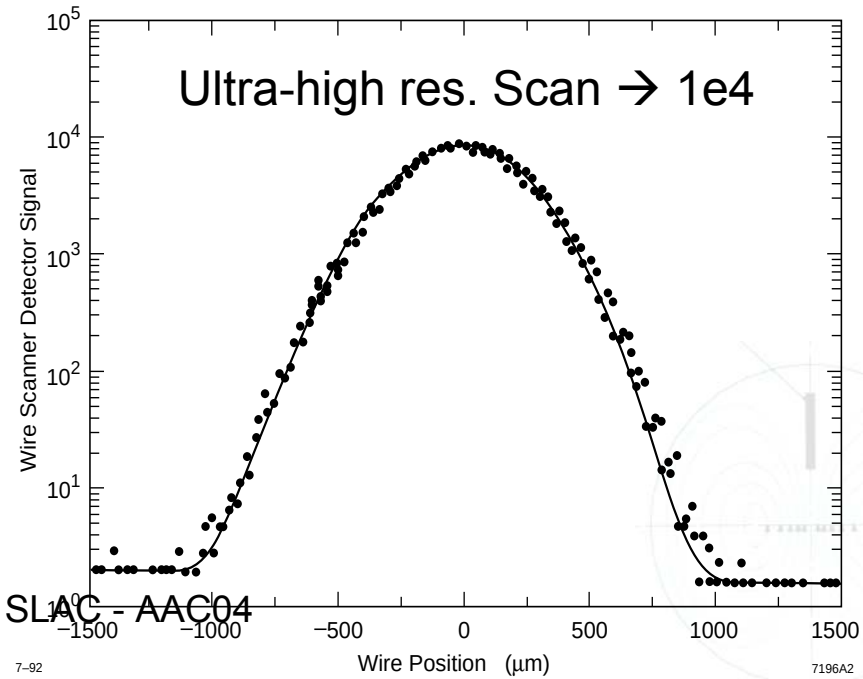
A. Servi

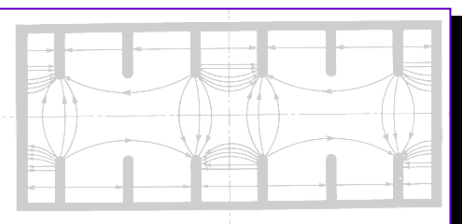




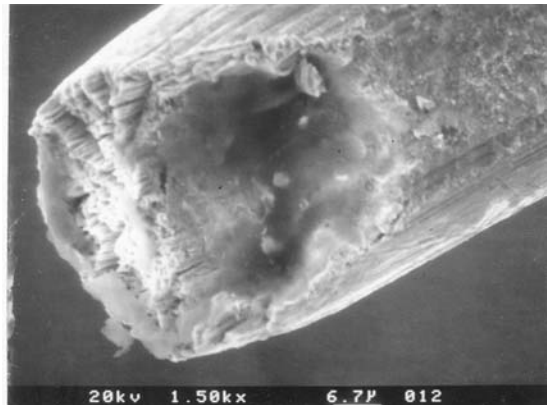
Multi-bunch scan – KEK ATF

Sample real *wire* scans [from SLC and KEK ATF]

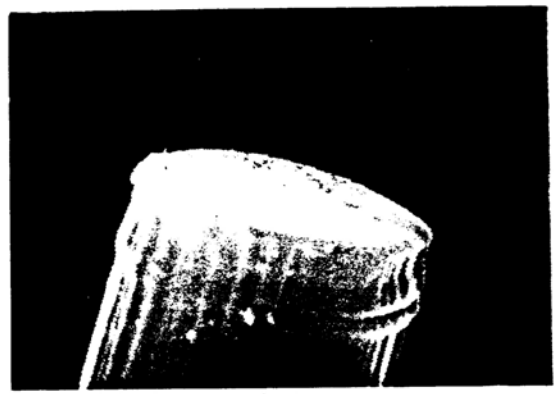


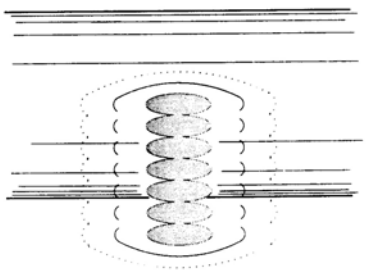


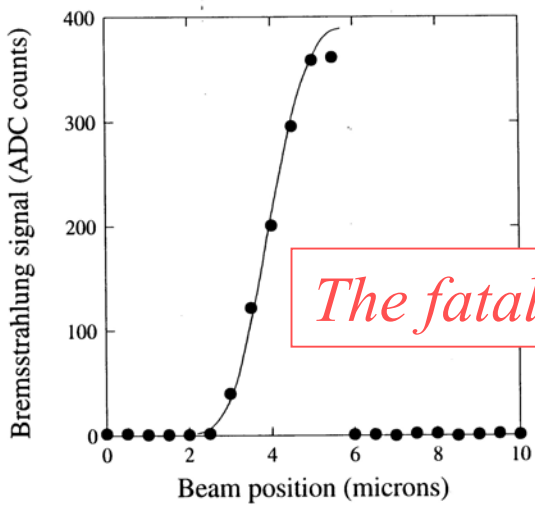
Broken wires from SLC & FFTB



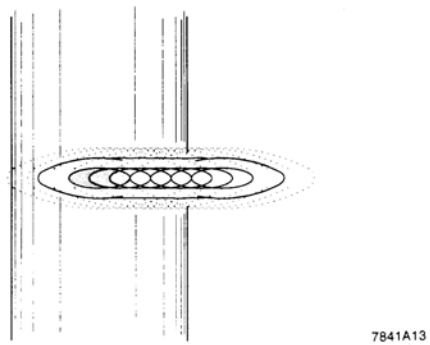
SLC 20 um W wire fractured by electrical arcing

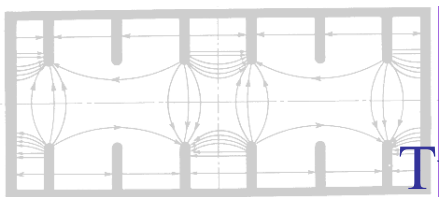






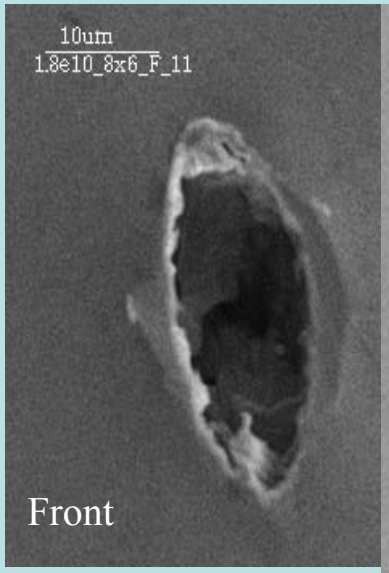
The fatal scan

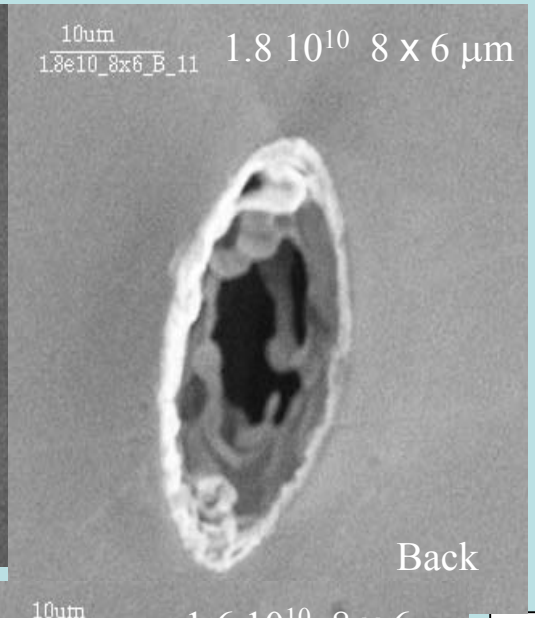


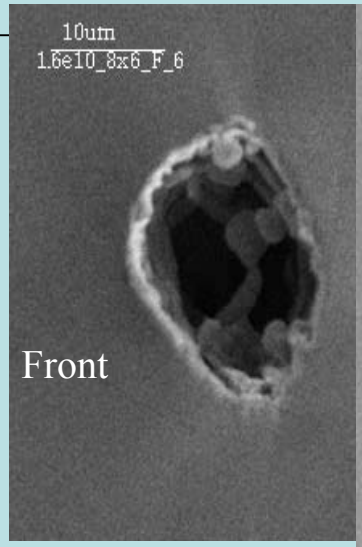


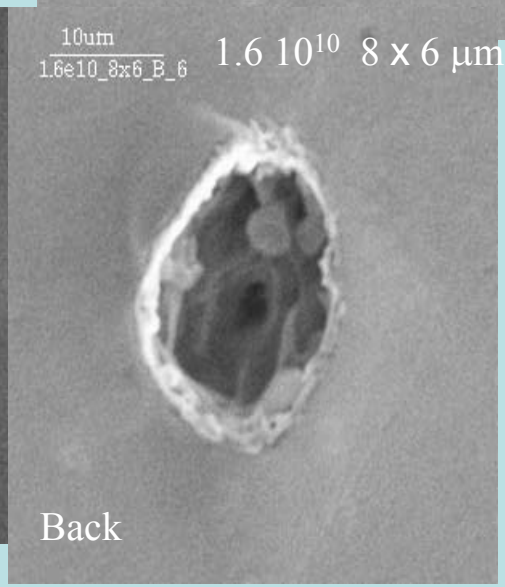
Two ways to slice a carbon (7um) wire with a flat beam:

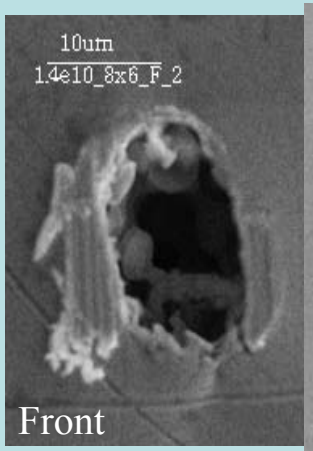
FFTB Single Pulse Damage Cu Coupon Test

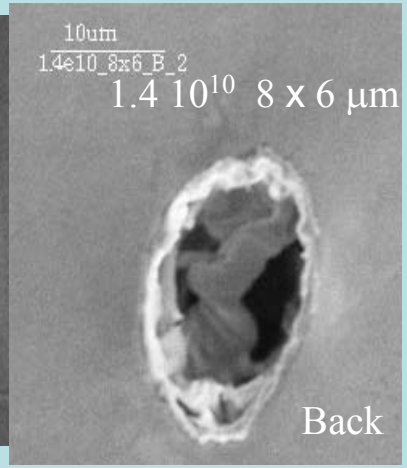


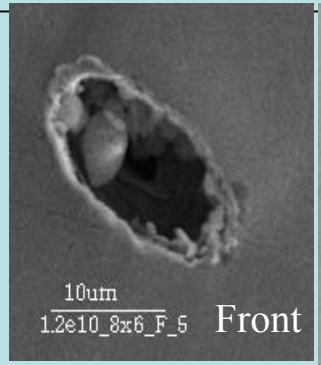




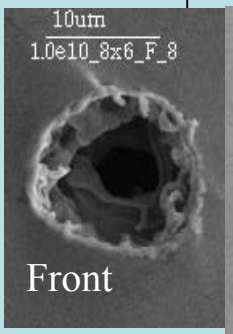


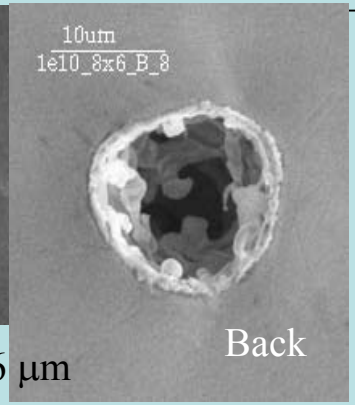






1.2 10^{10} 8 x 6 µm





1 10^{10} 8 x 6 µm

Front

Back

7 10^{9} 8 x 6 µm

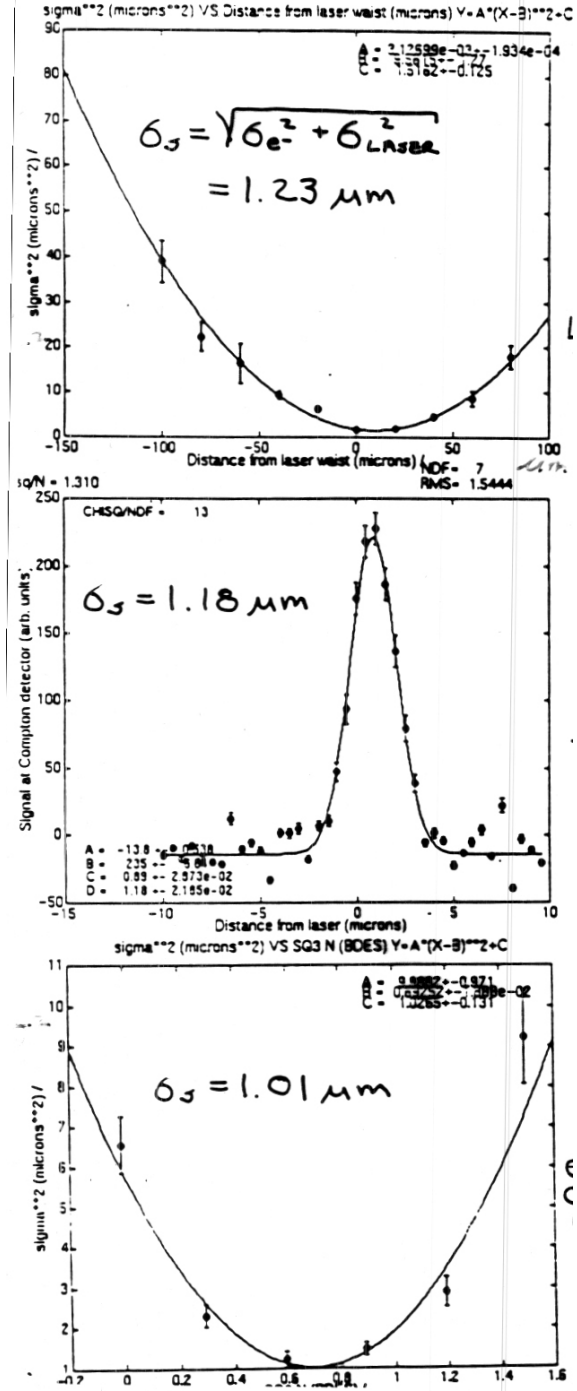
SLC Laserwire scans of full intensity 46.5 GeV beam

1996

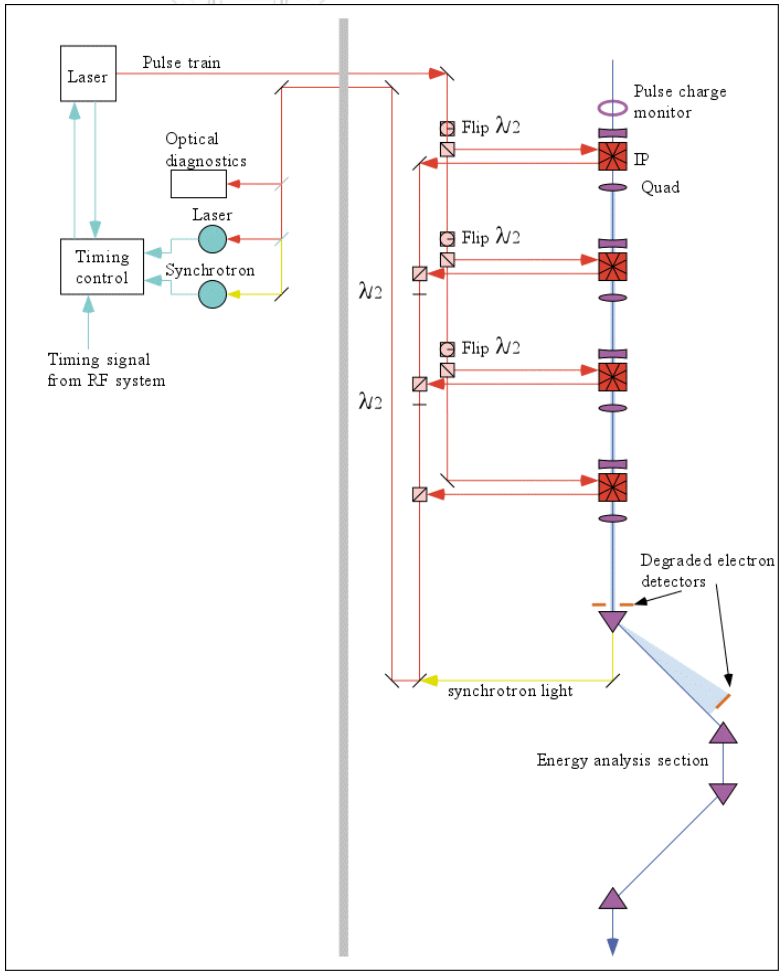
scan sequence used for waist centering

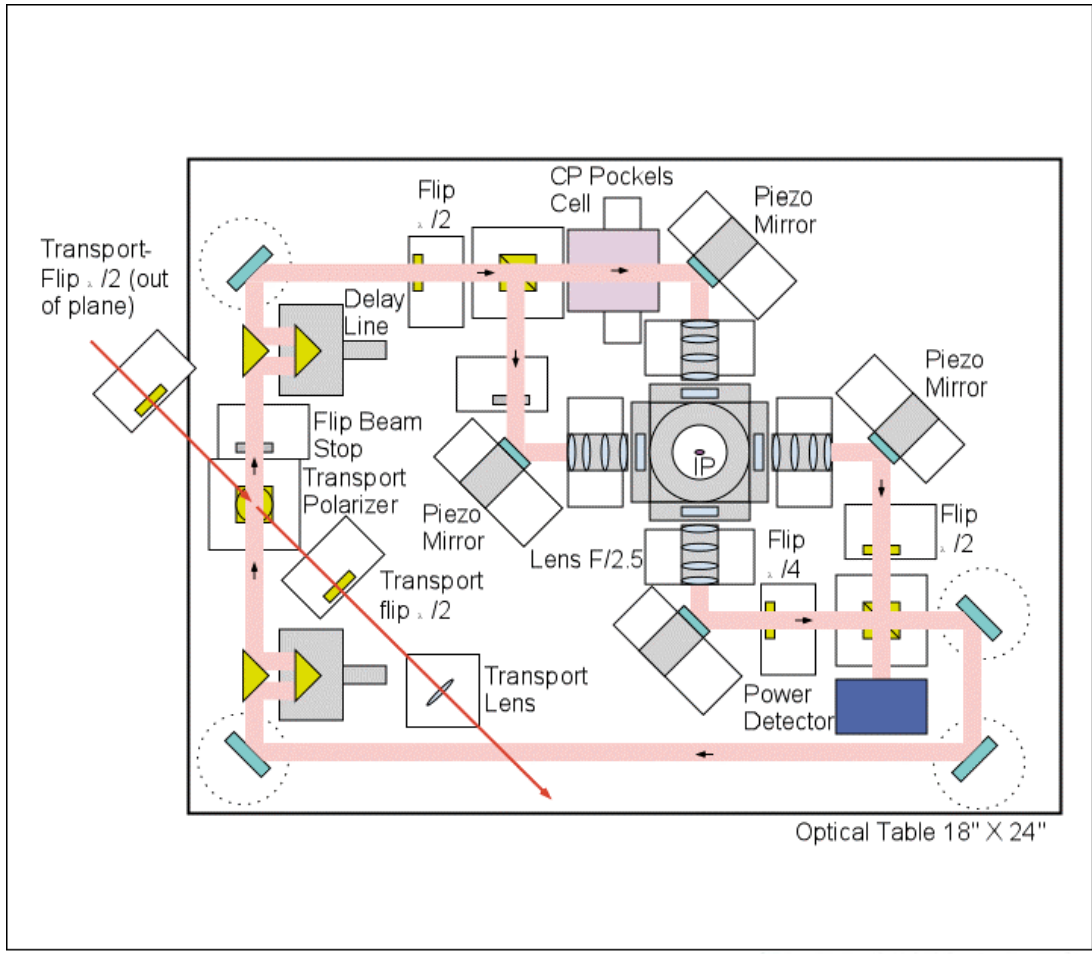
Single scan – each point one pulse

Example optimization scan sequence



NLC Laserwire schematic

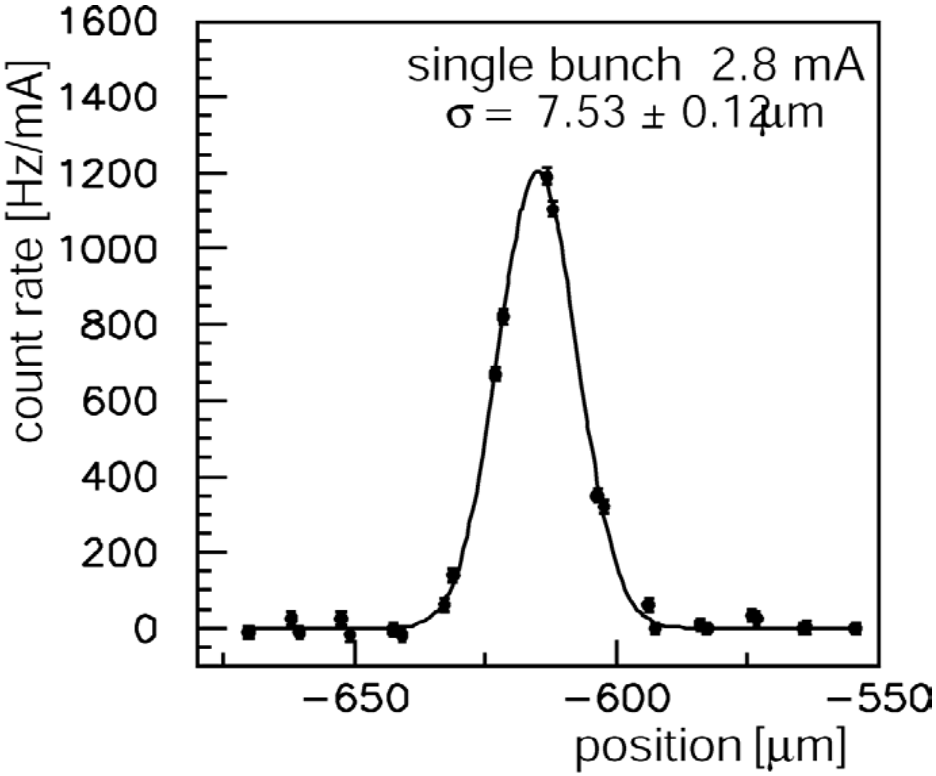


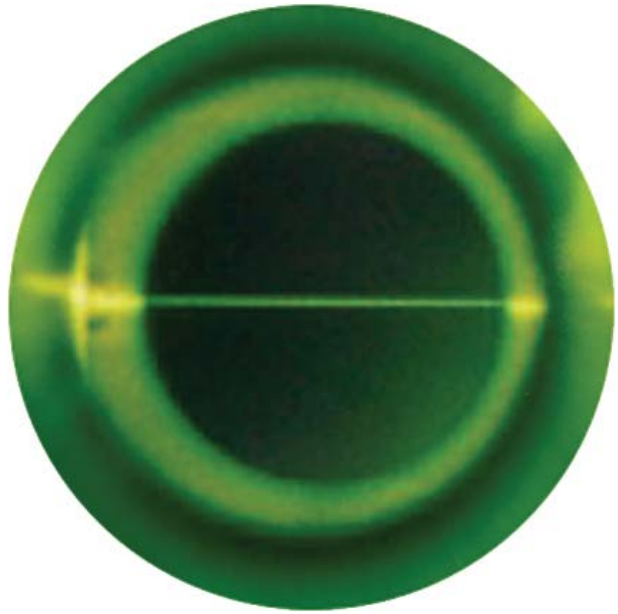


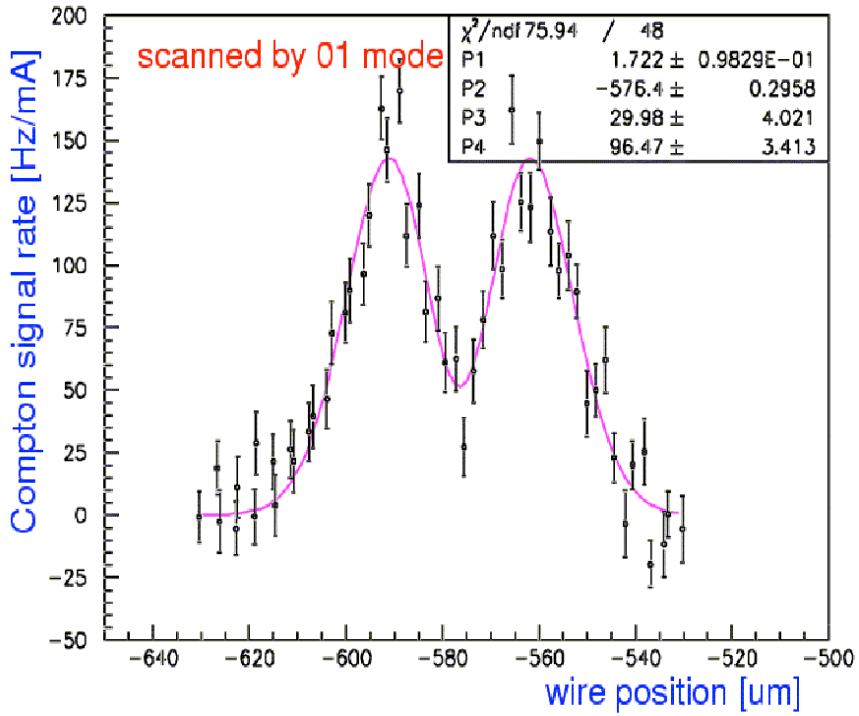
Plan view of a 'set'

c Beam's view of a single scanner

ATF Laserwire





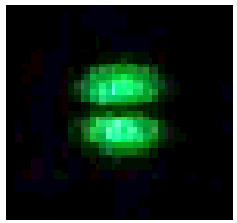


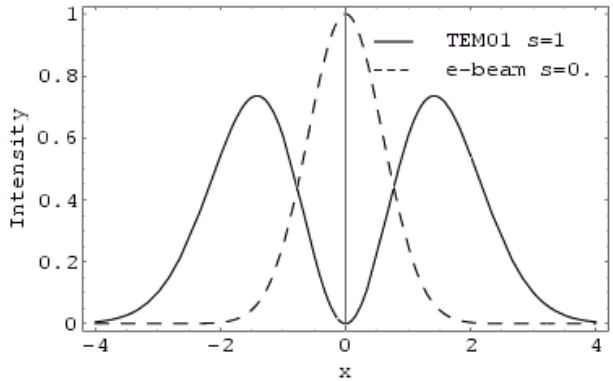
Precision CW cavity –
by far highest precision, highest reproducibility 'μm' beam size monitor – 1% device -
Inside ATF Damping Ring
Primary beam size monitor

Twin peaks laserwire

use TEM01 resonance mode in the optical cavity as a laserwire

good resolution for small beam size

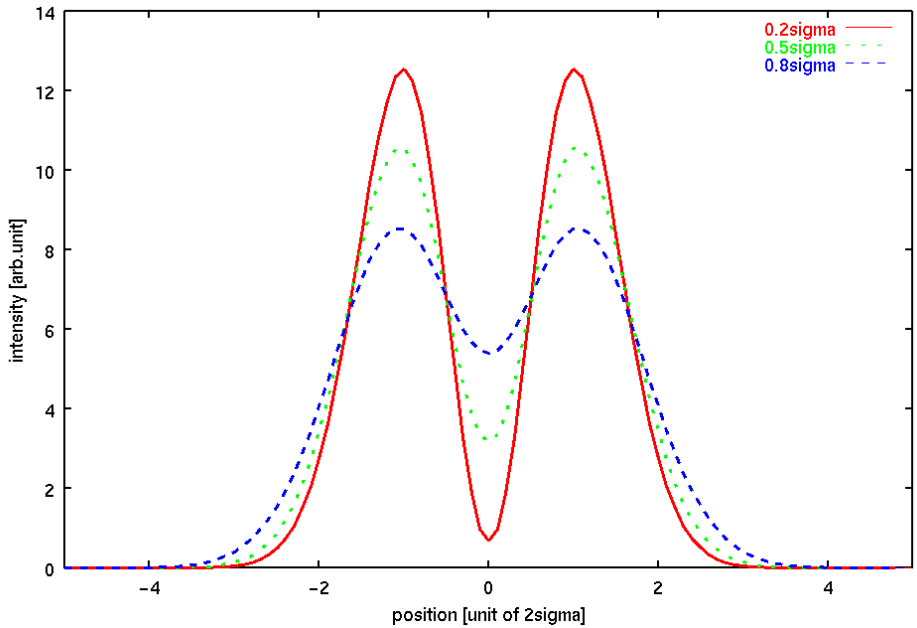




factor 2~3 resolution improvement

insensitive for beam orbit drift

scan free



Y. Honda – KEK ATF

limits to *position measurements*

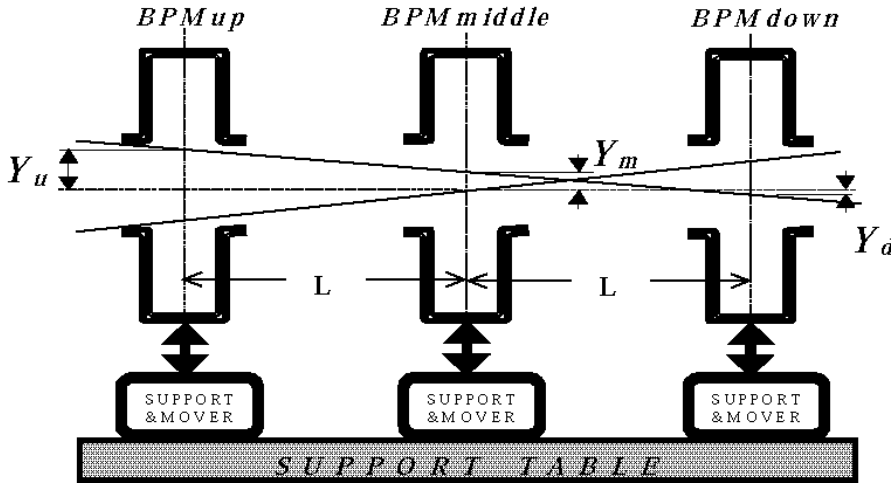
RF Cavity BPMs

- Loss factor: -100dBm @ 1 nm 1e10 ppb
- BB noise: -100dBm@20MHz – 20 C
- (-130dBm SC)

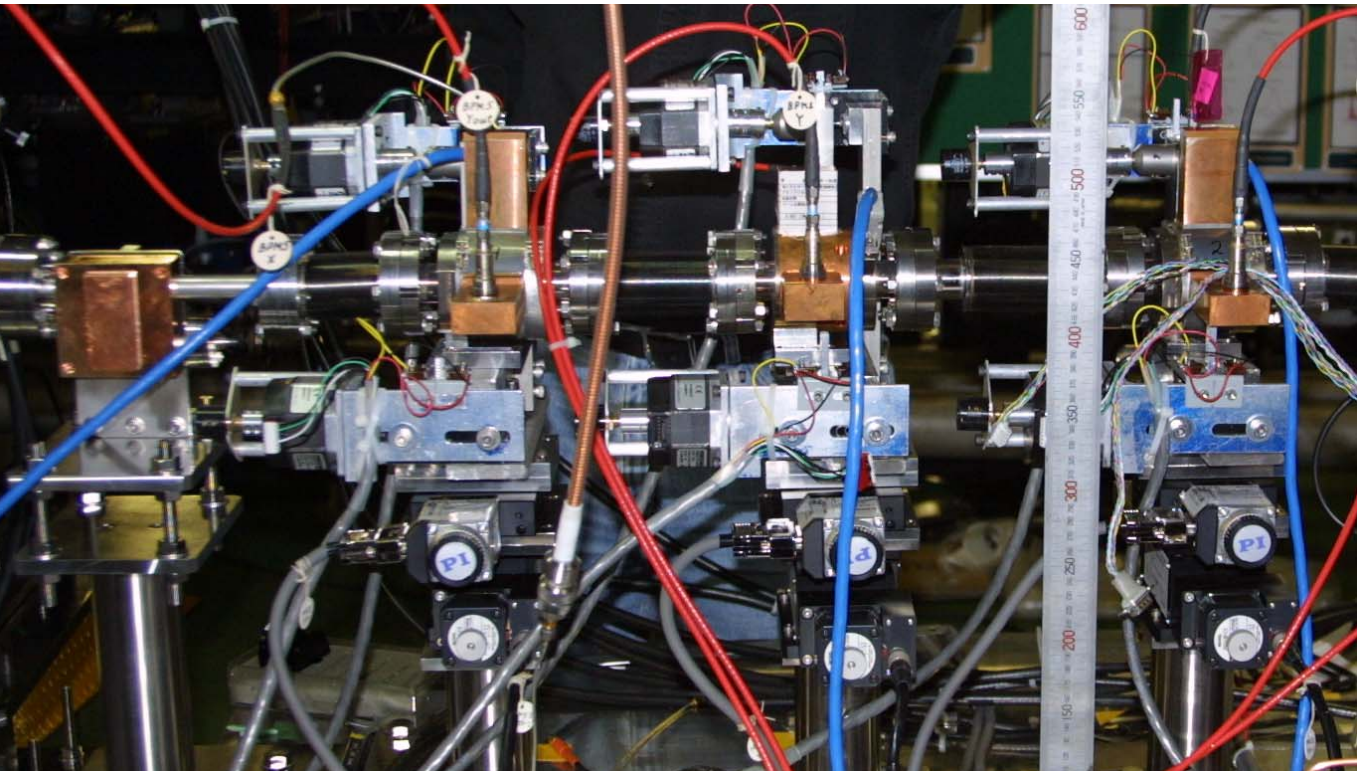
- Precision well beyond ability to hold it still !
  - Secondary effects:
  - Earth's field → energy fluctuations (BNL-ATF exp)
  - Stray currents
  - Wakefields
- What does it mean to measure the centroid of a 5 μm bunch with a precision of 5 nm?
  - Electron single pass schottky signal

Test nBPM's in sets of 3

- (BNL – ATF 1998/9)
  - 150nm resolution with large, unstable beam
  - Energy jitter and earth's field
- (FFTB / ATF 1997 & 2003)
  - 30 nm resolution with few micron beam
- Much better is possible

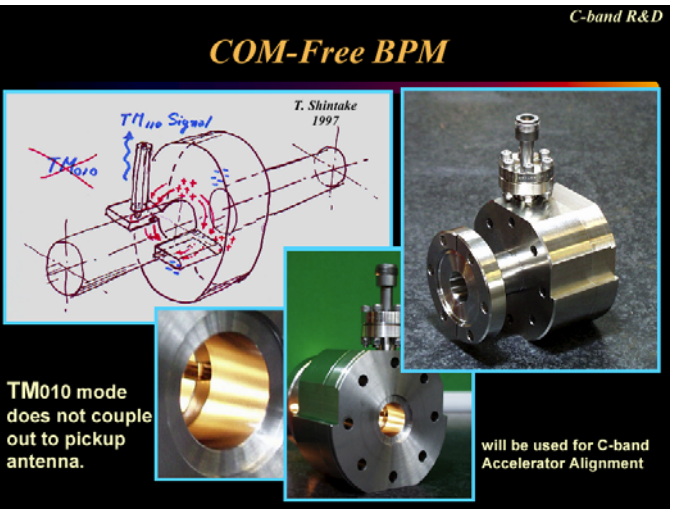


ATF (98)

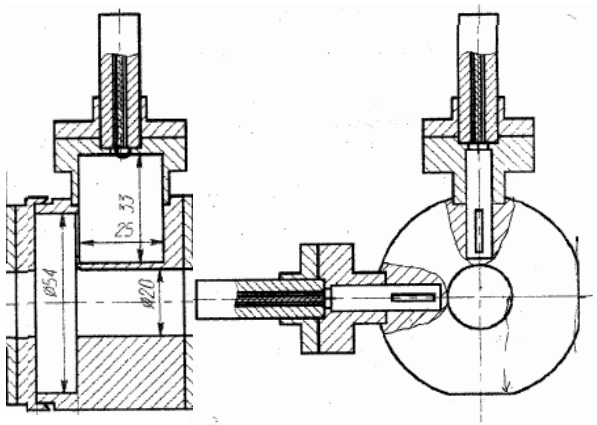


ATF(03)

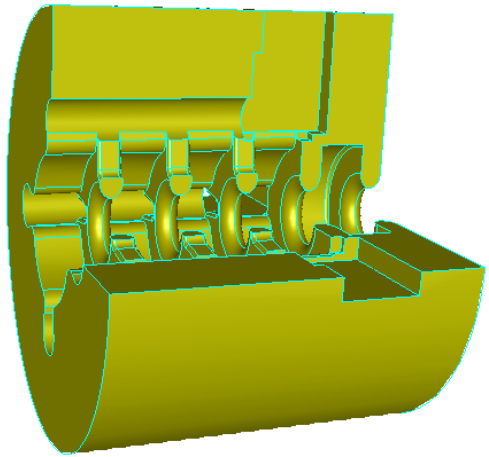
Magnetic coupling to suppress dominant monopole mode



T. Shintake, C-band structure design.

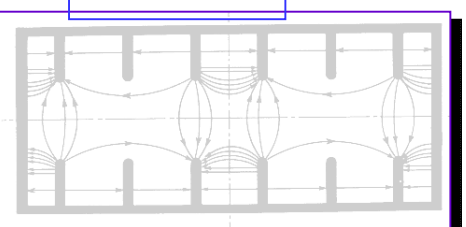


BINP for KEK ATF

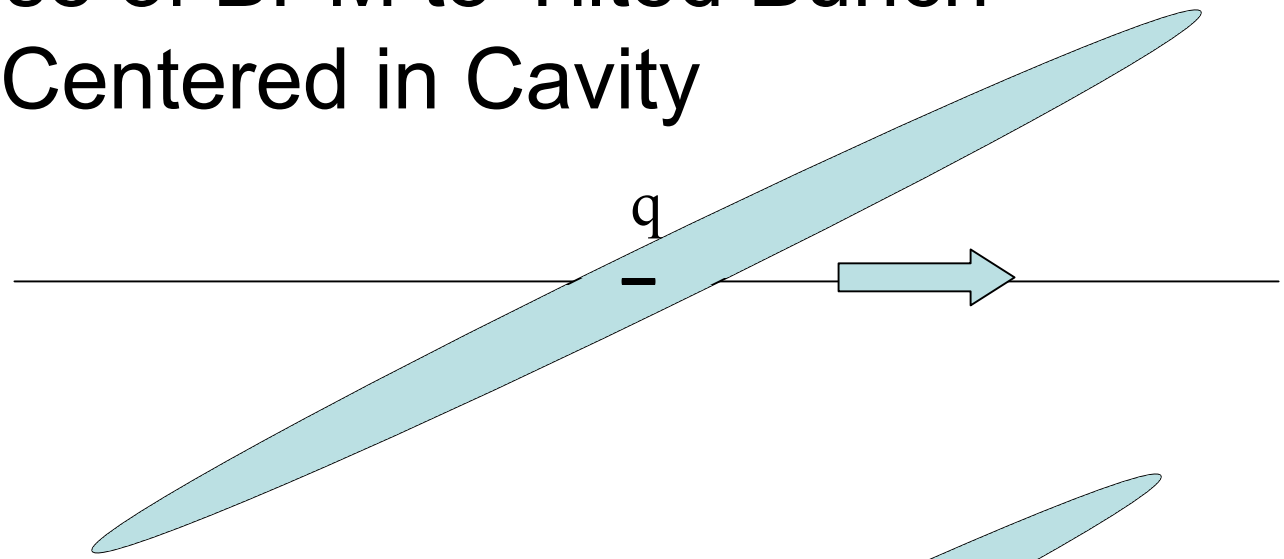


NLC DDS structure. Using slots to damp dipole wakefields. Signal used for SBPM. Micron resolution.

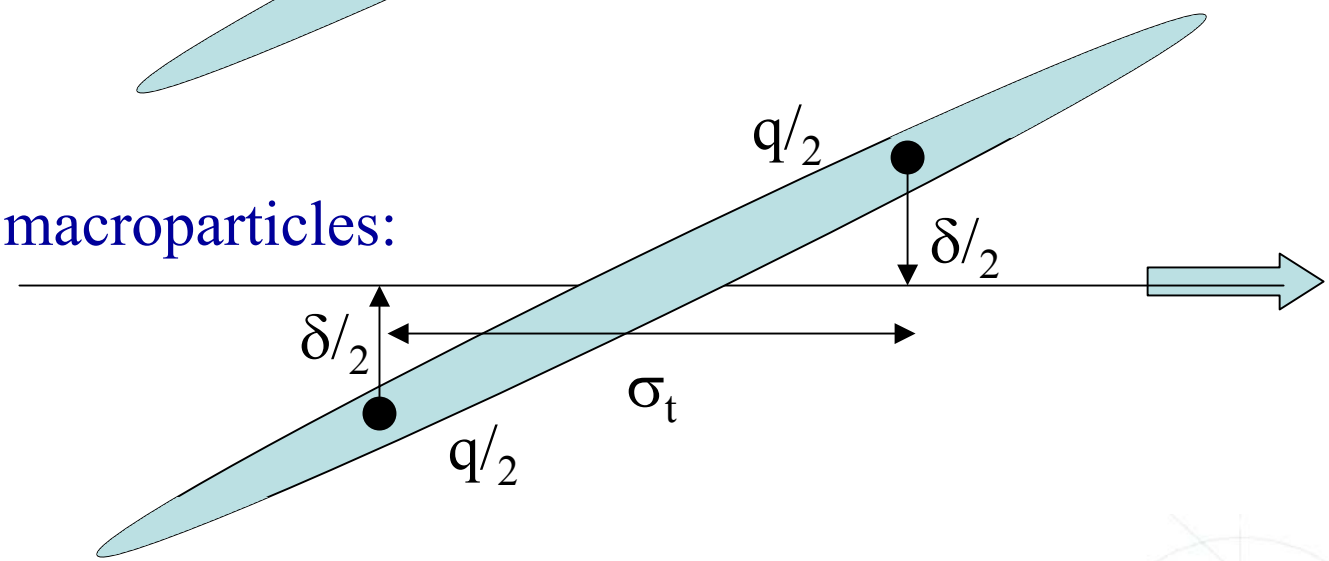
Z. Li



Response of BPM to Tilted Bunch Centered in Cavity



Treat as pair of macroparticles:



$$V(t) = a\frac{q}{2}\frac{\delta}{2}\sin\omega(t-\frac{\sigma_t}{2}) - a\frac{q}{2}\frac{\delta}{2}\sin\omega(t+\frac{\sigma_t}{2}) = \frac{a\delta q}{2}\cos\omega t\sin\frac{\omega\sigma_t}{2}$$

Tilted bunch

- Point charge offset by δ

$$V_y(t) = aq\delta \sin(\omega t)$$

- Centered, extended bunch tilted at slope δ/σ_t
- <u>Tilt signal is in *quadrature* to displacement</u>

$$V_t(t) = \frac{a\delta q}{2} \cos \omega t \sin \frac{\omega \sigma_t}{2}$$

- The amplitude due to a tilt of δ/σ is down by a factor of:

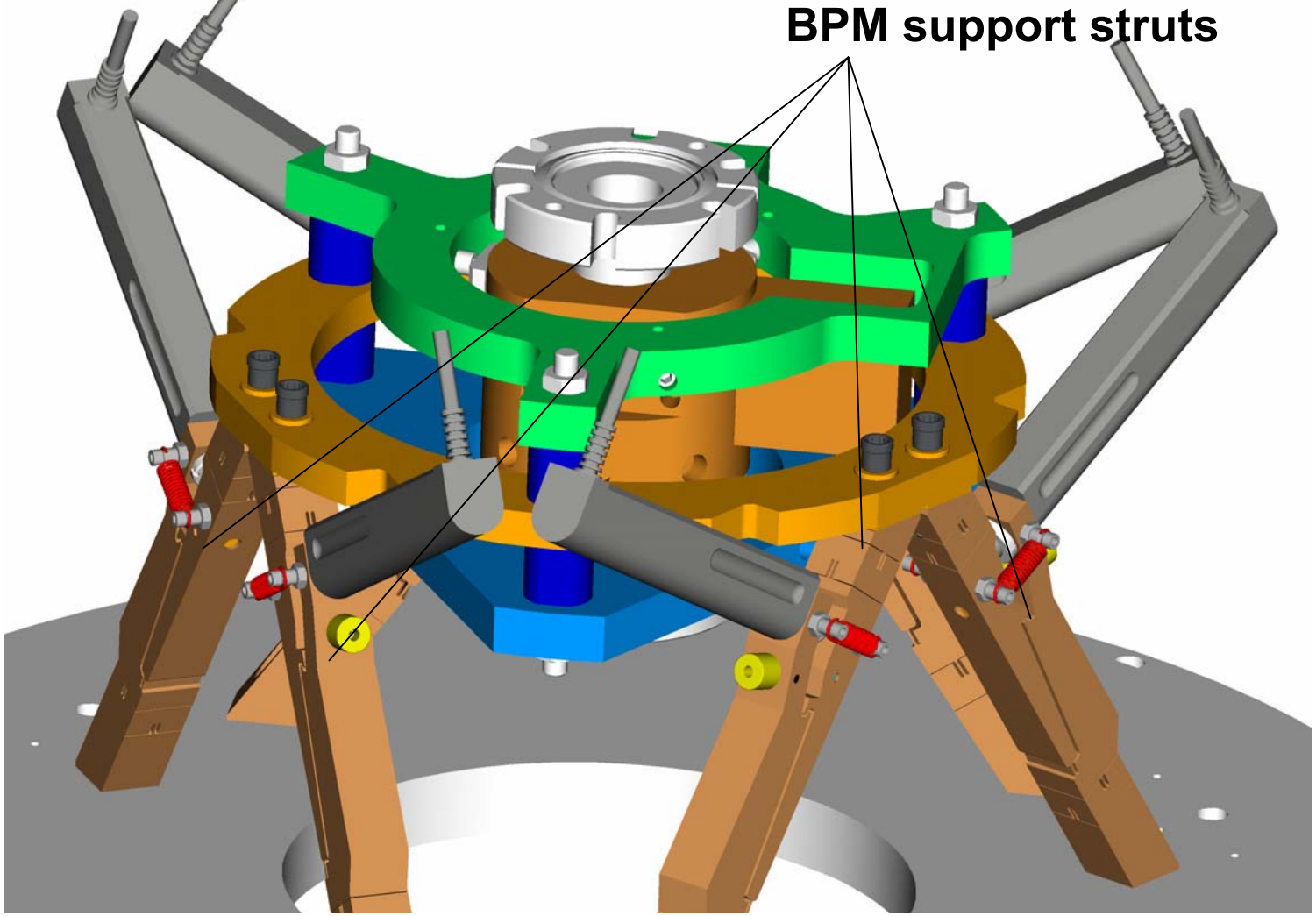
  with respect to that of a displacement of δ

  (~bunch length / Cavity Period)

$$V_t / V_y = \frac{\omega \sigma_t}{4} = \frac{\pi \sigma_t}{2T}$$

2 nanometer resolution with a 200 um beam using X-band cavity BPM`s gives 1 mrad tilt resolution – a very powerful tool for linac emittance control

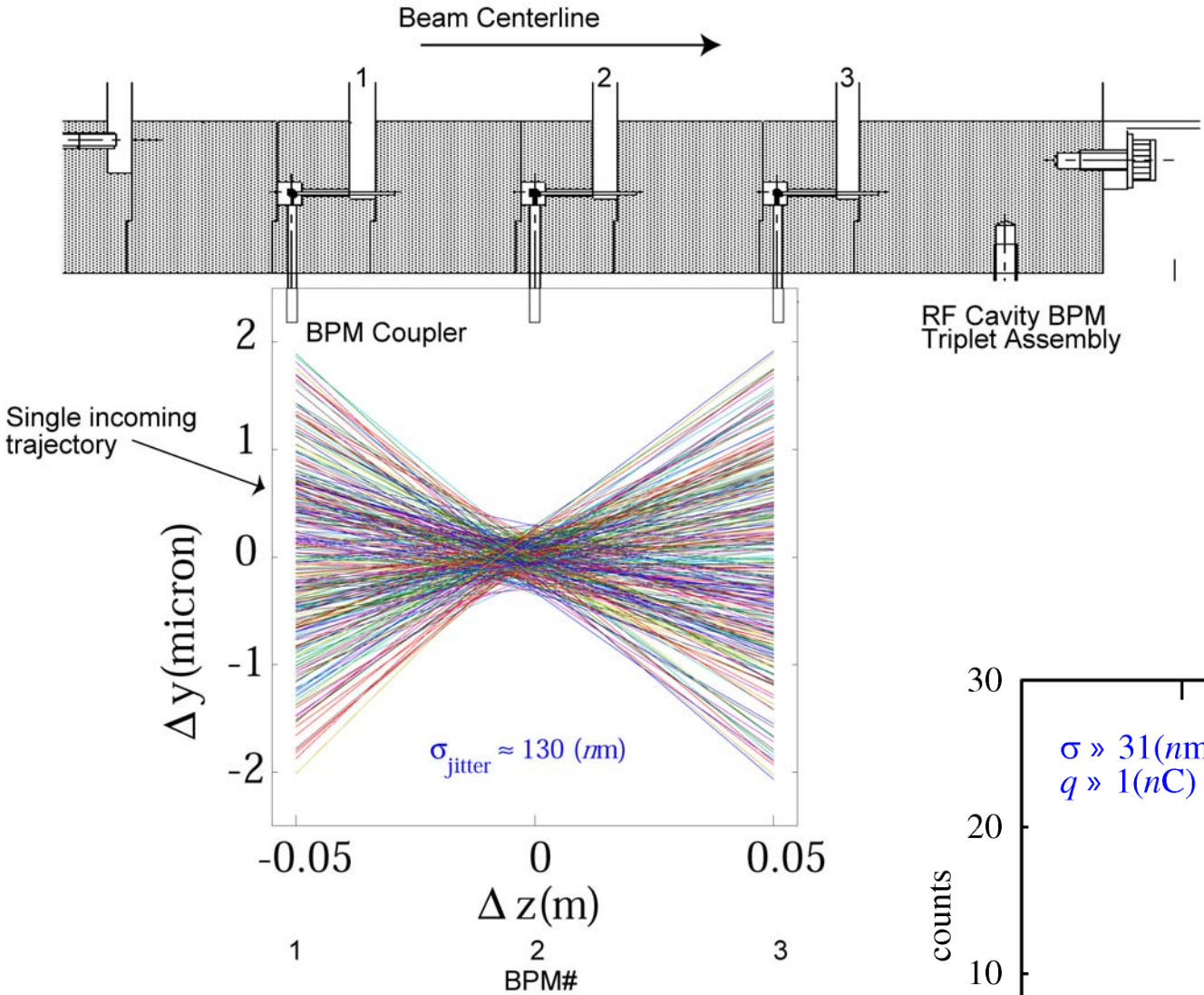
Ultra-stiff hexapod BPM mover

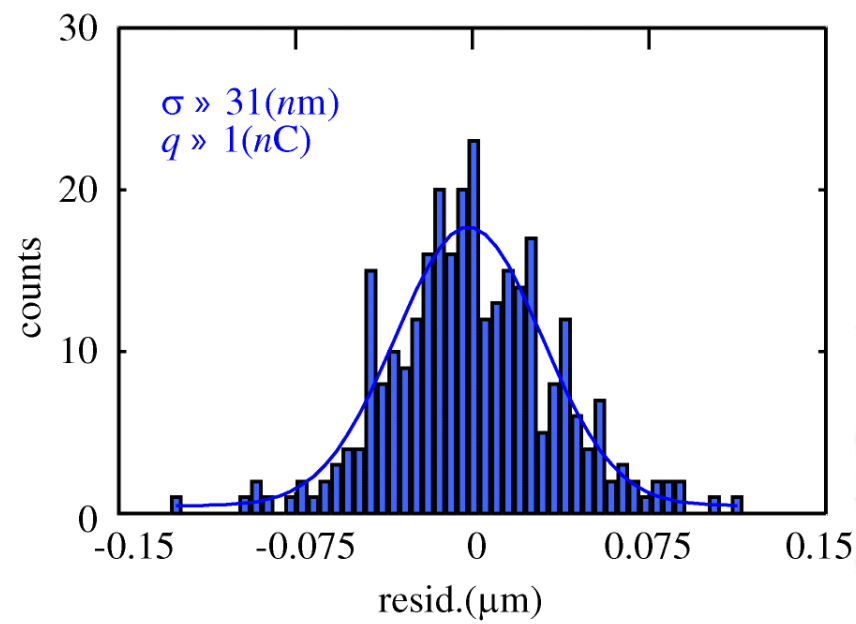


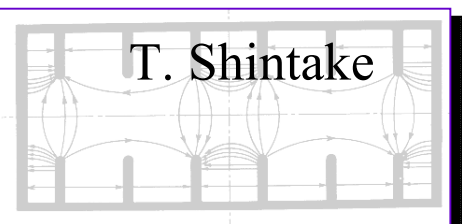
LLNL

Precision flexure struts

FFTB IP C-band cavity BPM triplet



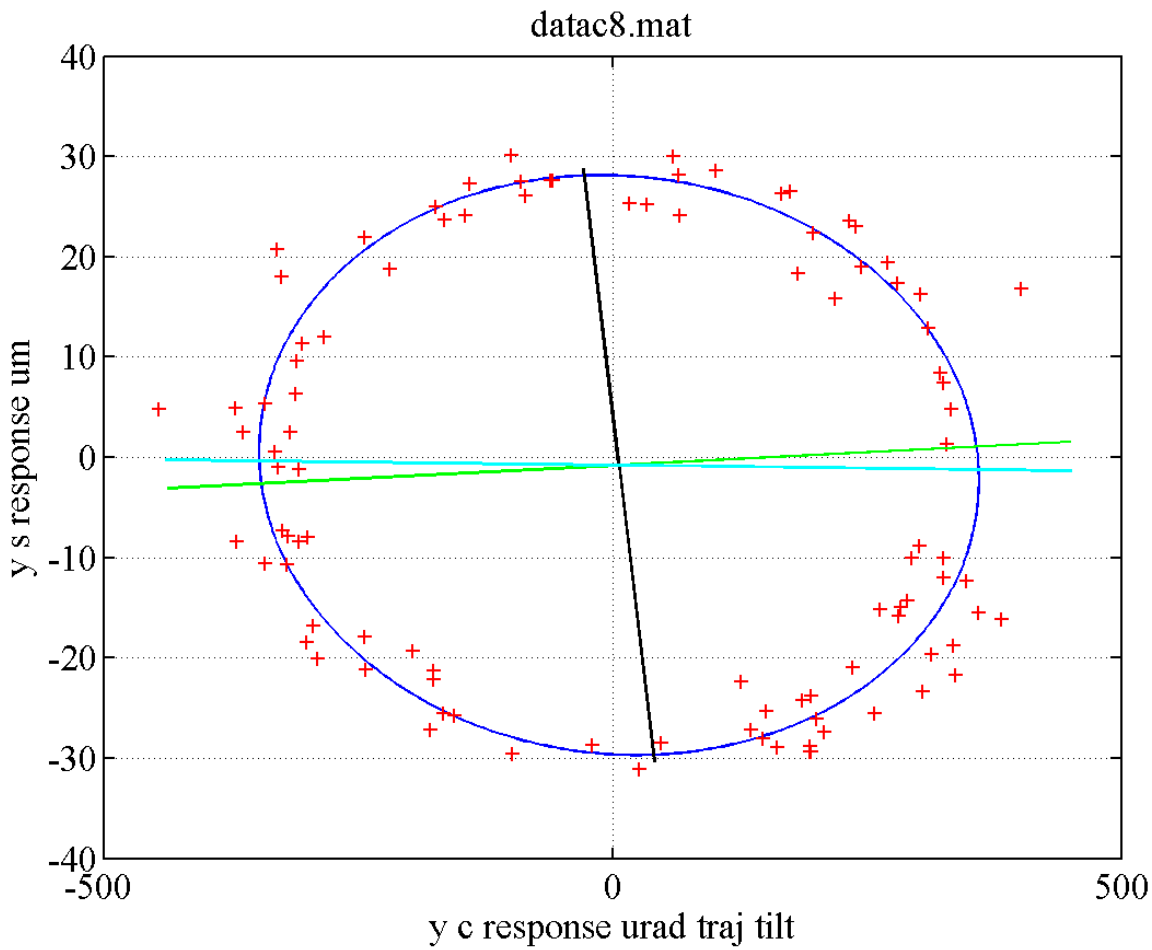




Marc Ross, SLAC

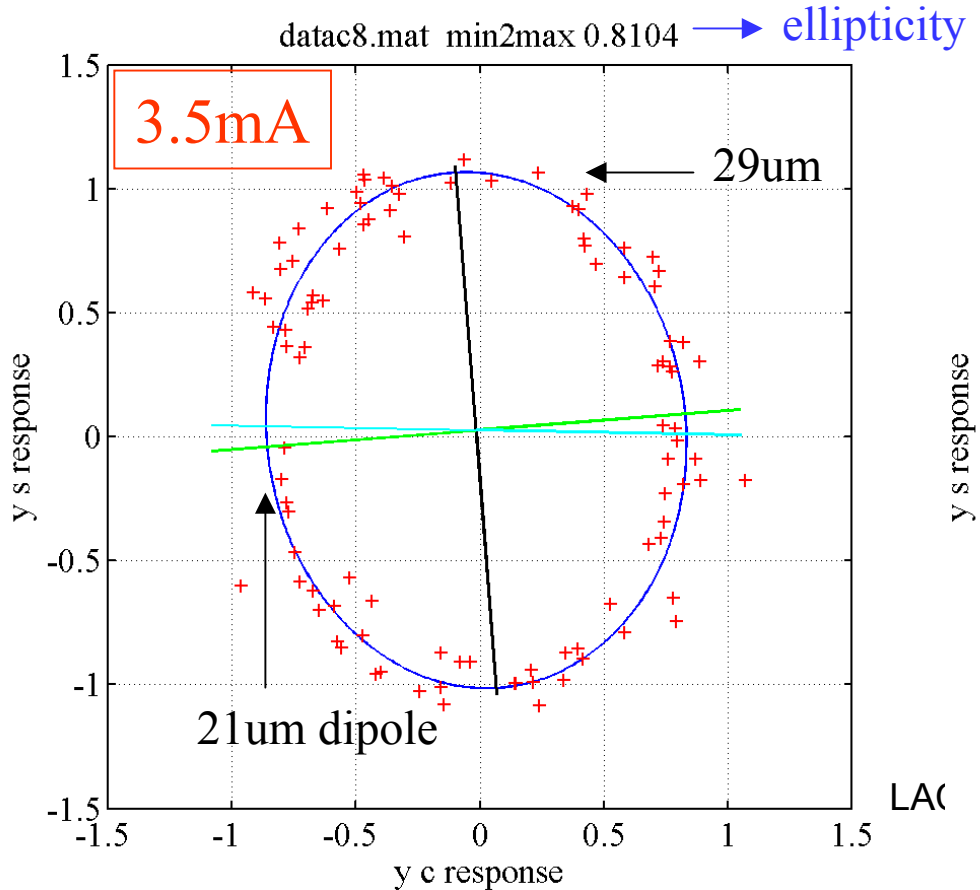
Deflection (crab) cavity on; phase arbitrary

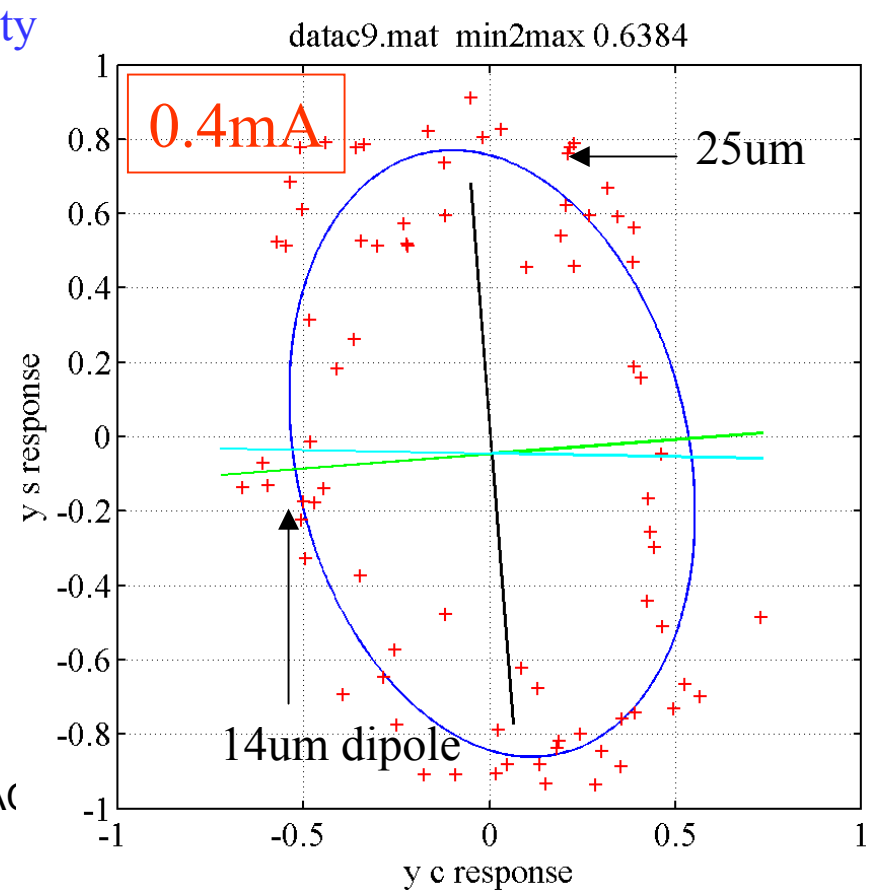
- I/Q cavity response with deflection cavity at full voltage
- Axes show directions of pure displacement (black) and pure angle (bluish) (green is 90 from pure displacement)
  - Tilter motion is not quite orthogonal
- Ellipticity is the ellipse aspect ratio
- This plot shows equivalent ‘angle trajectory’



Comparison – 3.5 and .4 mA

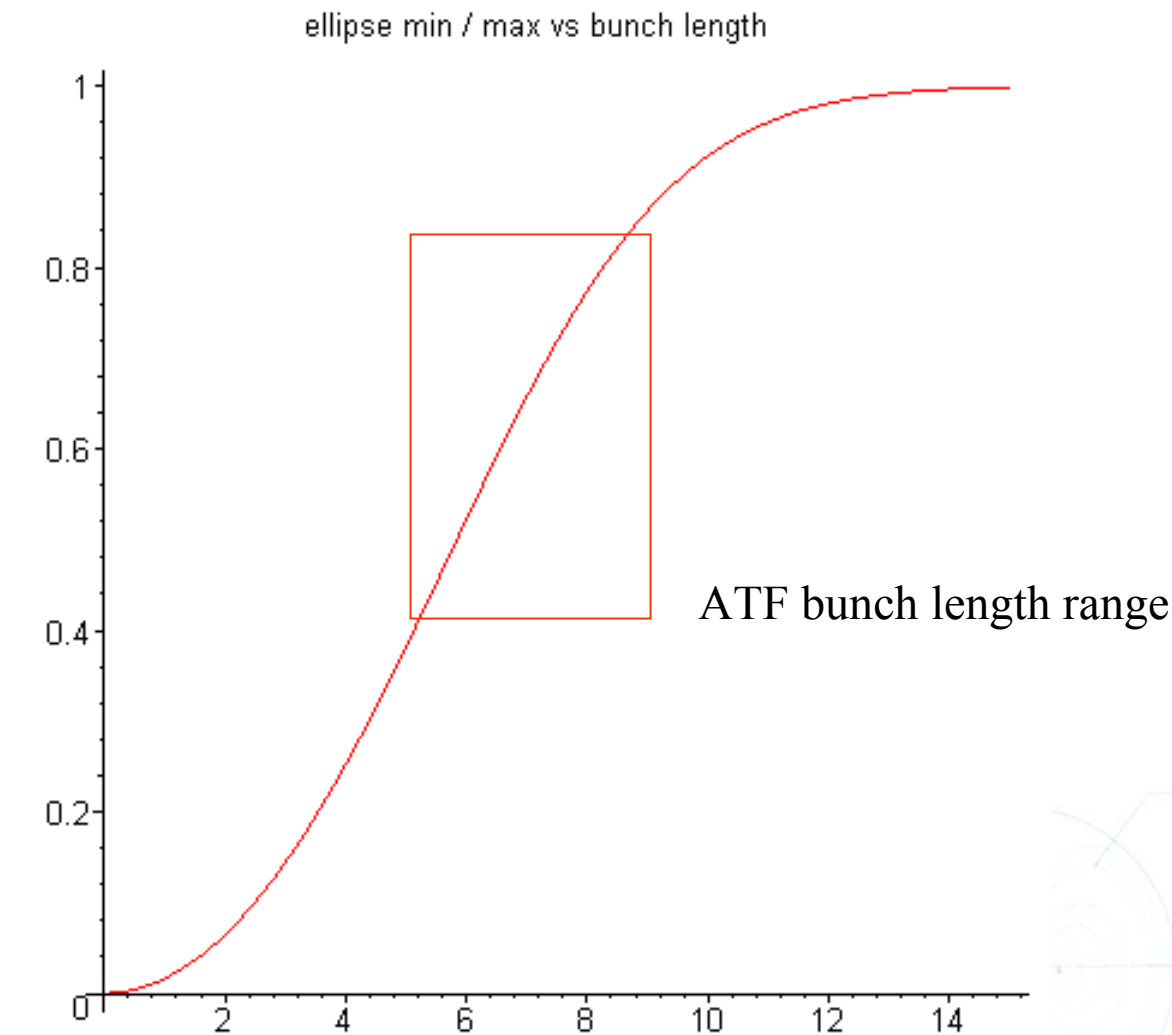
- Effective beam tilt scale 'full width dipole projection' is 0.9 of displacement for 8 mm bunch (scales with bunch length)
- See 29 um peak to peak kick at full I and 20 um projected dipole at monitor
  - Good vertical streak of 7 um beam!
  - Tilt angle 20um/8mm = 2.5 mrad





Estimate of bunch length from ellipticity

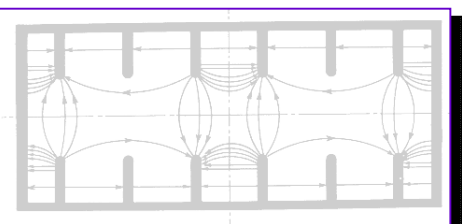
- Ellipse min/max vs bunch length (mm) for C-band
- Only length scale used is RF wavelength



Summary of bunch length measurements

Data file	Condition	ellipticity	bunch length (mm)	Streak Camera ATF-01-01
datac8	nominal I= 3.5mA	0.81	8.5	9.0
datac9	0.39 mA	0.64	6.9	6.3
datac10	1.7 mA	0.74	7.7	7.5
datac11	.465 mA	0.61	6.6	6.8
datac12	0.3mA Vc 150 KV	0.79	8.3	8.8

- First bunch length measurement made entirely using dipole RF cavities



Deflection Cavities

- bunch length / phasing example
- serious need for precision / calibration
  - not met with COTR / E-O

- Correlation monitor needed for managing low emittance transport in strong wake regime
  - precision ‘slice emittance’

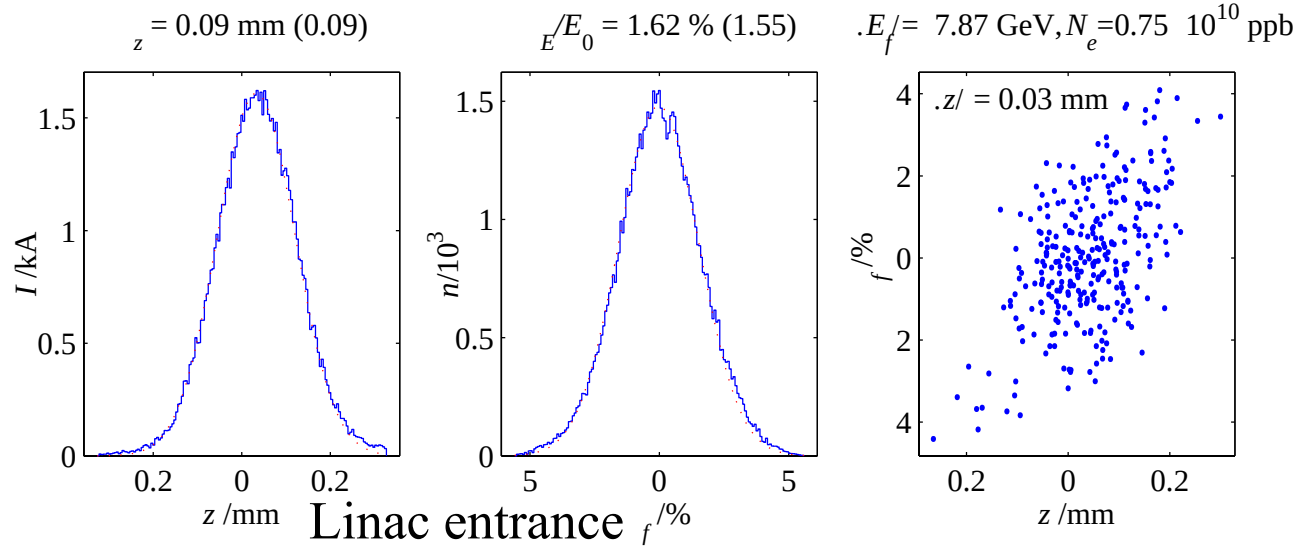
- Example: ‘LOLA’ installation at DESY – TTFVUVFEL
  - LOLA is an abbreviation formed from the names of the secondary beam separator designers (SLAC~60’s)
  - installed late 2003 – testing soon

Linac σ_z simulation

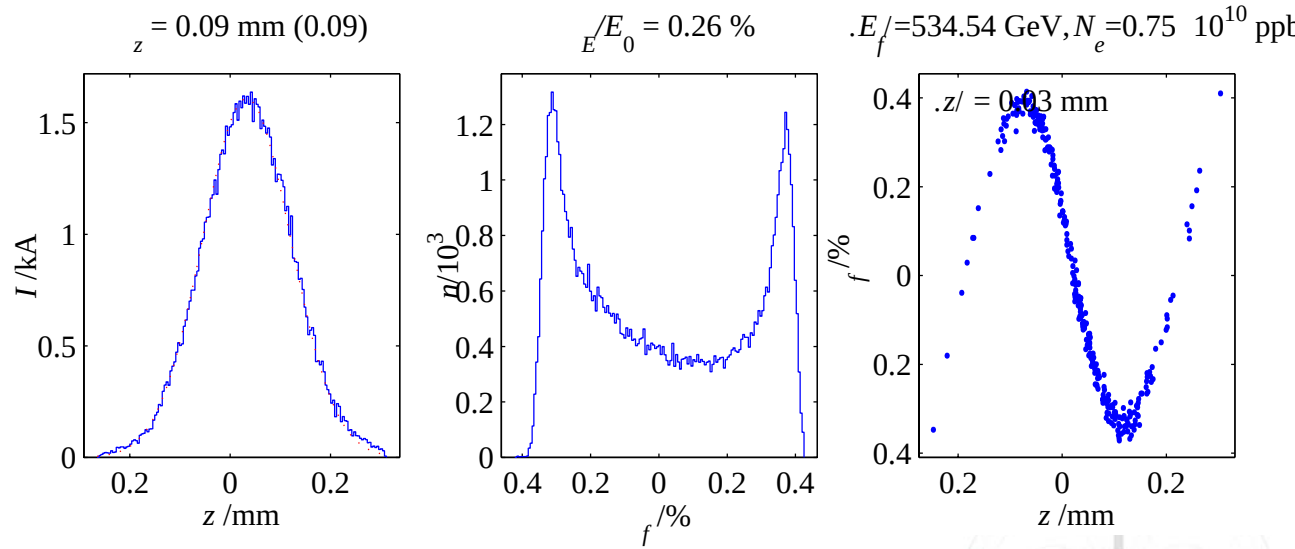
Asymmetry in σ_z is important for minimum σ_E

Coherent radiation monitors do not provide the detail required

(P. Emma)



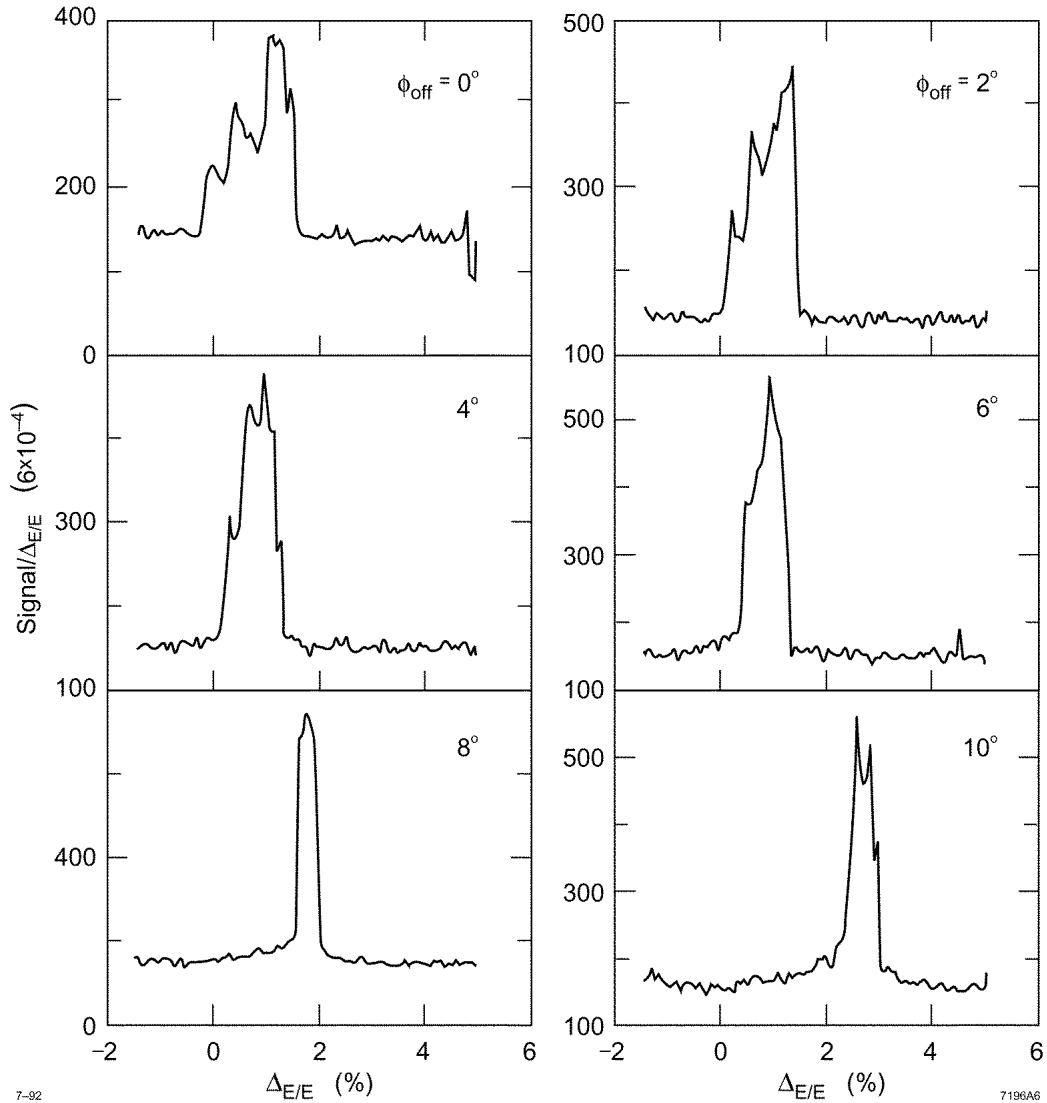
Linac entrance

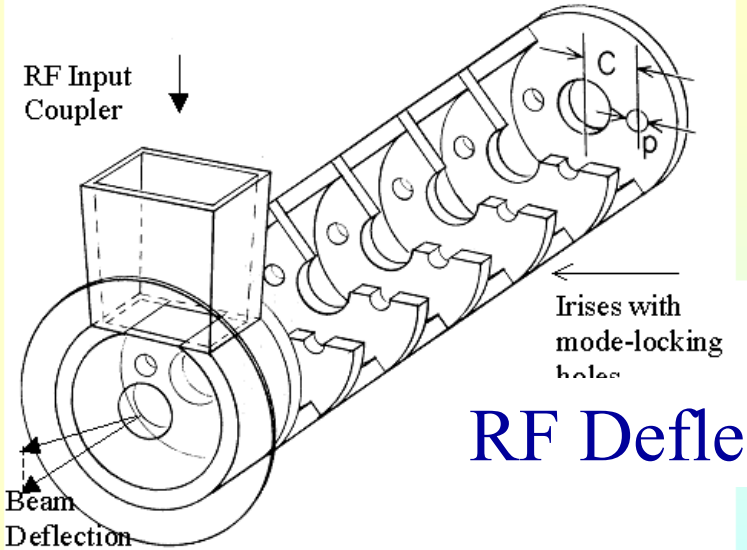


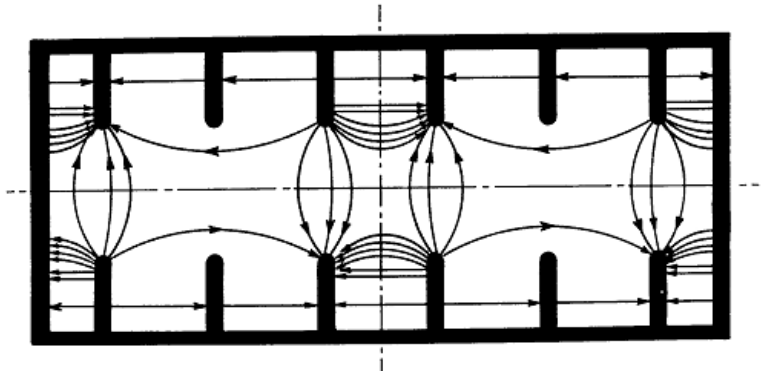
Linac exit

SLC longitudinal profiles

- Energy spread as average linac phase is changed
- much more interesting profiles seen in FFTB E16x

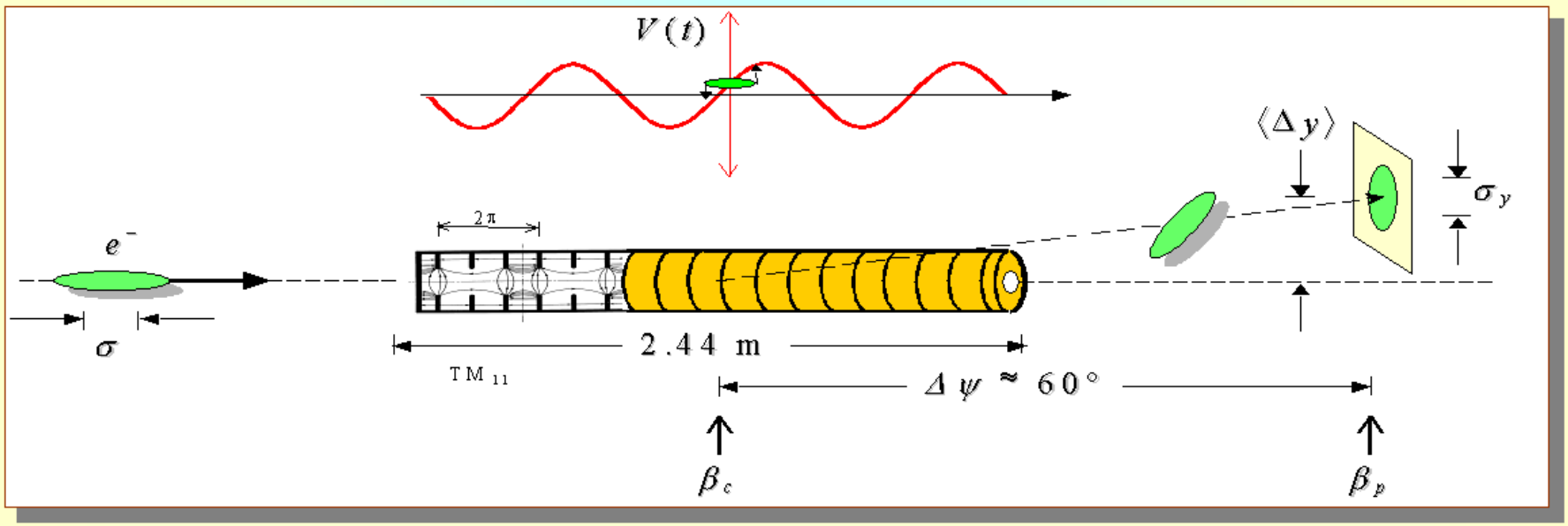






RF Deflecting Structure and Profile Mon.

$$bunch\,lenght, \sigma_Z \approx \frac{\lambda_{rf}}{2\pi} \frac{E_S}{|eV_0 \sin\Delta\psi \cos\varphi|} \sqrt{\frac{\left(\sigma_y^2 - \sigma_{y0}^2\right)}{\beta_d \beta_s}}$$



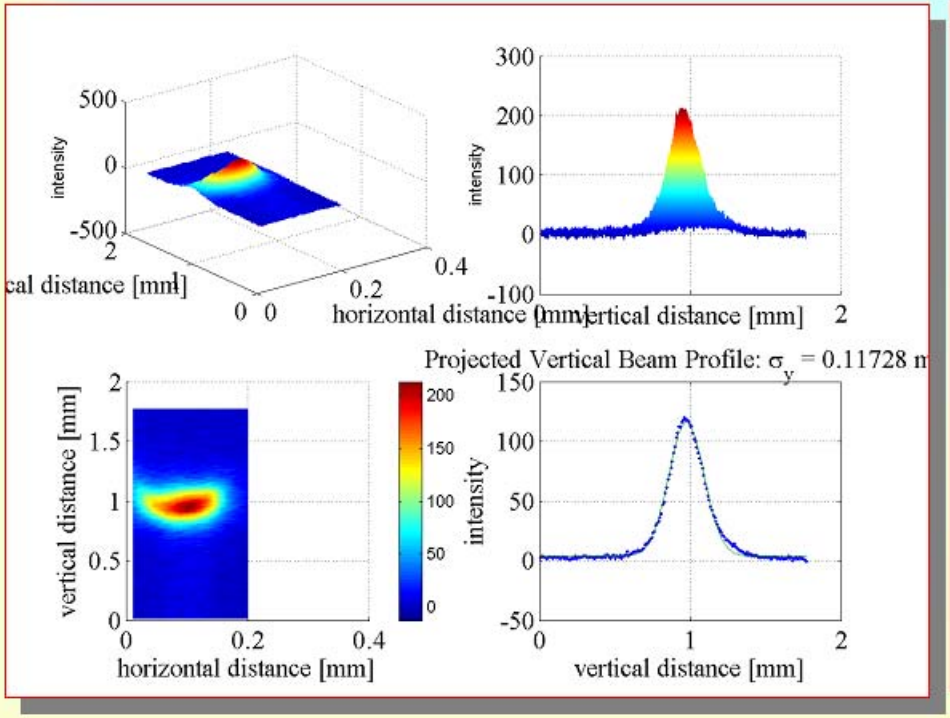
S-band at DESY for FEL bunch length diagnostics

data from SLAC short LOLA structure installed for SPPS

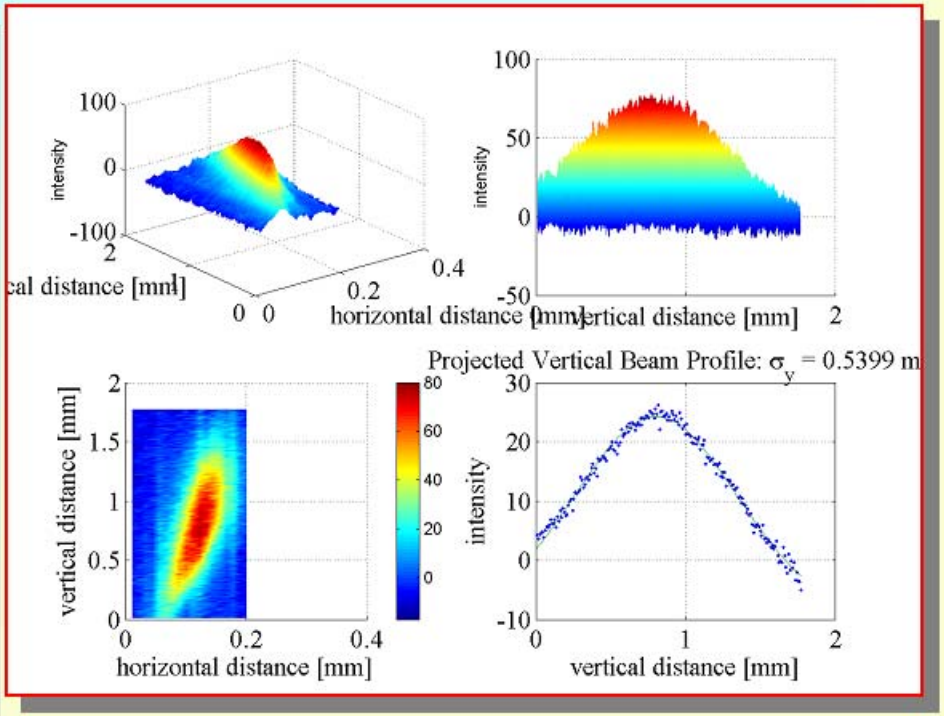
Profile Monitor Images

Damped, scavenger bunch at end of the linac

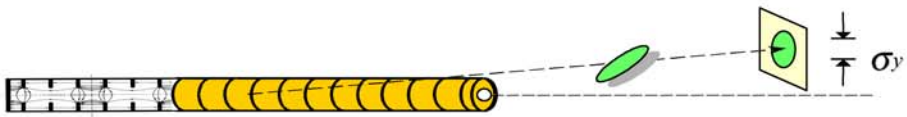
Transverse Cavity OFF



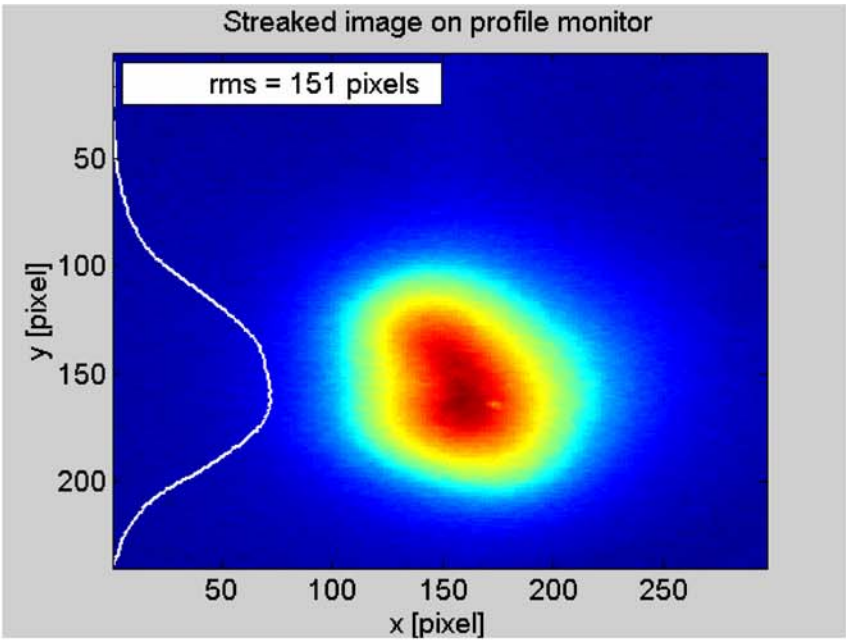
Transverse Cavity ON



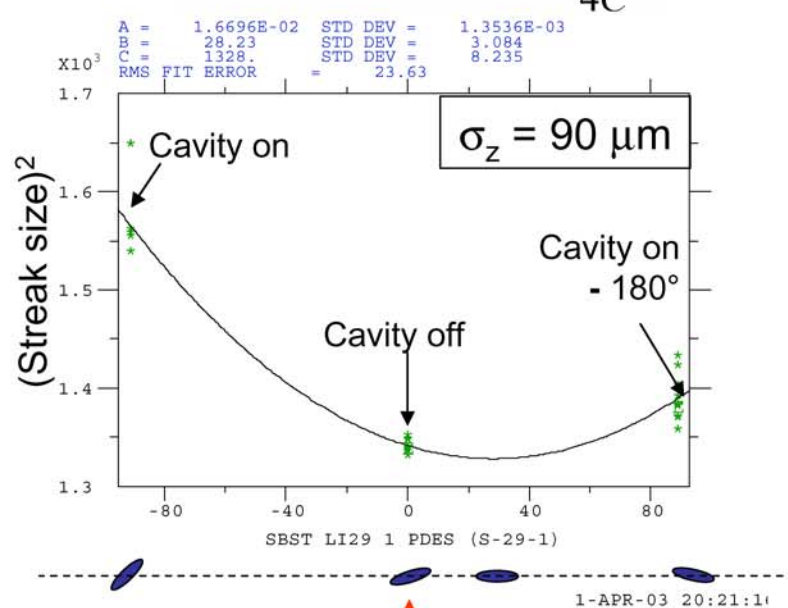
Bunch Length Measurements with the RF Transverse Deflecting Cavity

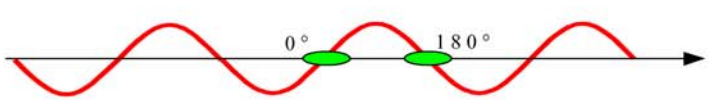


Bunch length reconstruction
Measure streak at 3 different phases



$$\sigma_y^2 = A\phi_{rf}^2 + B, \quad \sigma_z = \frac{\lambda_{rf}\sqrt{A}}{4C}$$

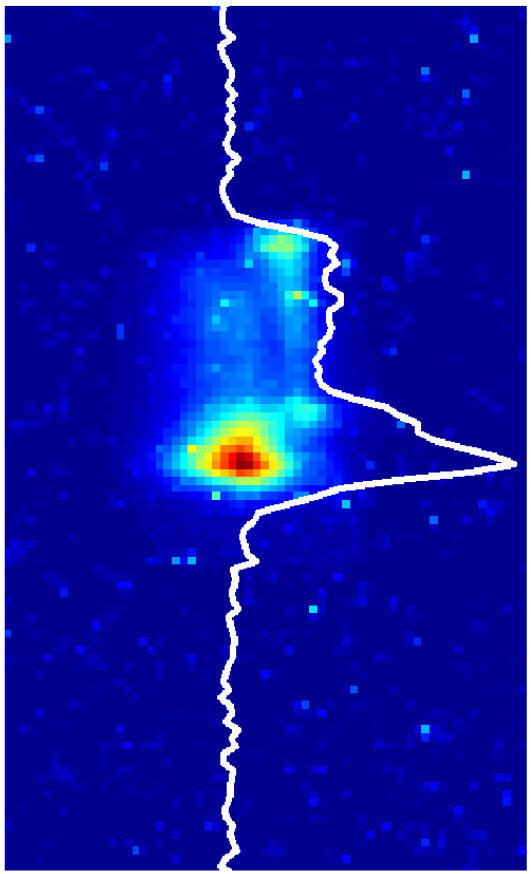




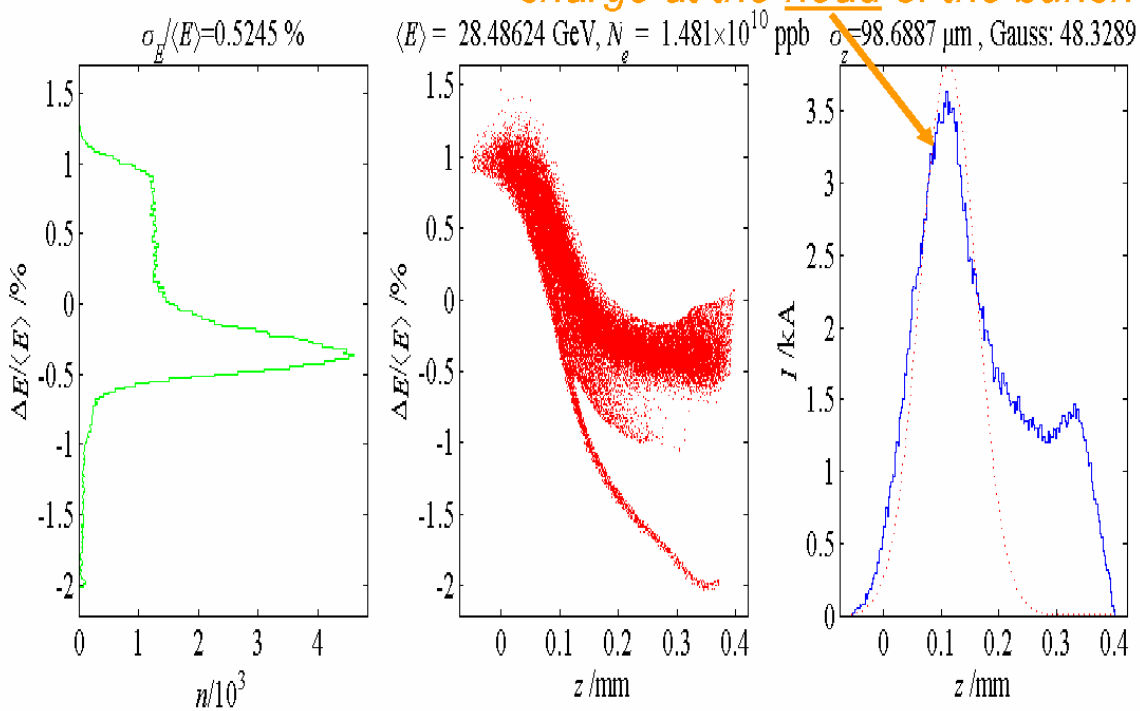
Asymmetric parabola indicates incoming tilt to beam

Krejcik/Emma - LCLS

Measured and predicted energy spread of a compressed bunch

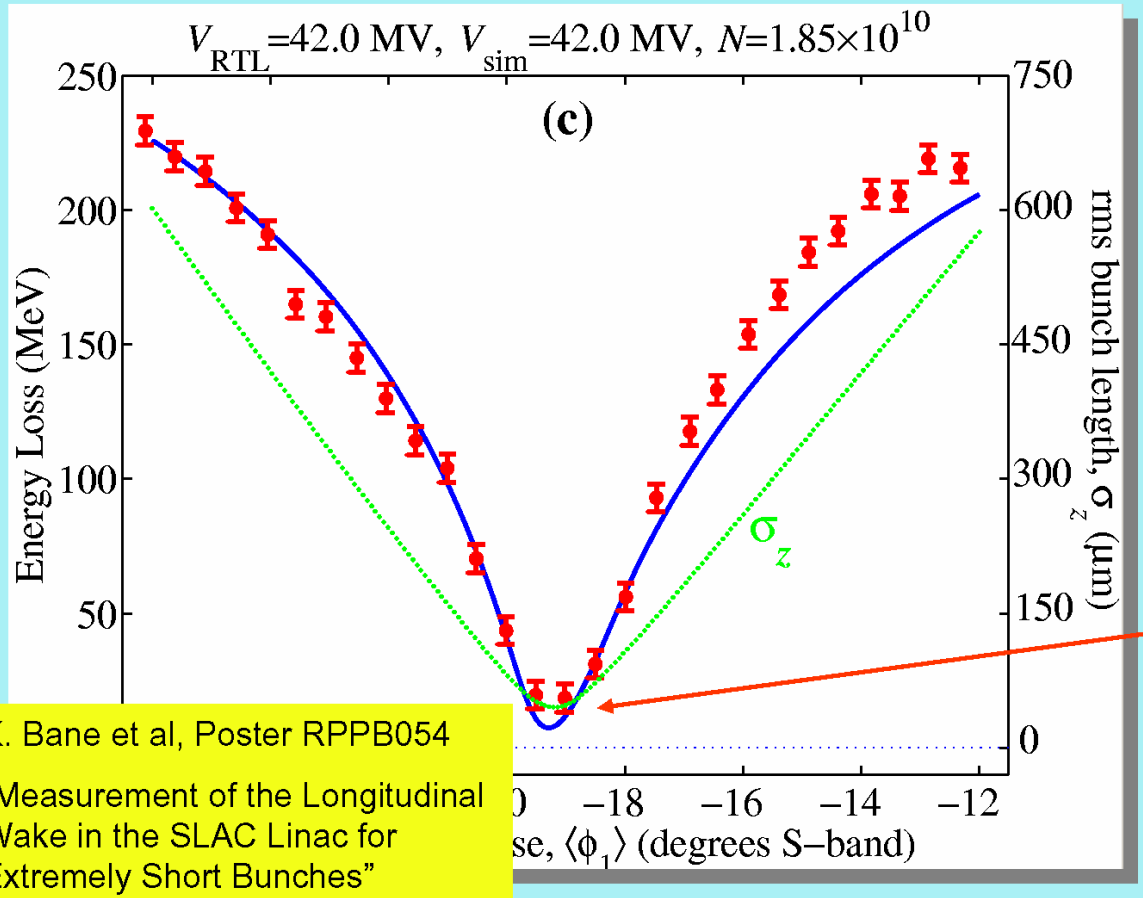


Special setup to give 100 μm bunch length with more charge at the head of the bunch



Measured at end of linac

Relative bunch length measurement based on wakefield energy loss scan



Energy change measured at the end of the linac

as a function of the linac phase (chirp) upstream of the compressor chicane

Shortest bunch has greatest energy loss

K. Bane et al, Poster RPPB054

"Measurement of the Longitudinal Wake in the SLAC Linac for Extremely Short Bunches"

Predicted wakeloss___

For bunch length σ_z __

Krejcik/Emma - LCLS

Conclusions

- Precision beam diagnostics rely on innovative techniques within the range of small scale RD
- high resolution time / bunch length diagnostics remain a frontier for FEL/HEP machines
- Test facilities combining low emittance short bunch length are needed
  - ATF 50 5 5000 (x,y,z – μm) – compression system to be added 05/06
  - FFTB 50 30 20 – to be decommissioned 05.