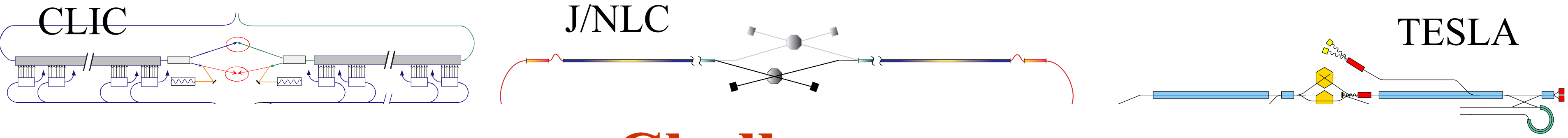
# Instrumentation Development
# Test Facilities and Plans

Beam Delivery challenges
Ongoing projects:
→$\sigma$_$z$

*Marc Ross*

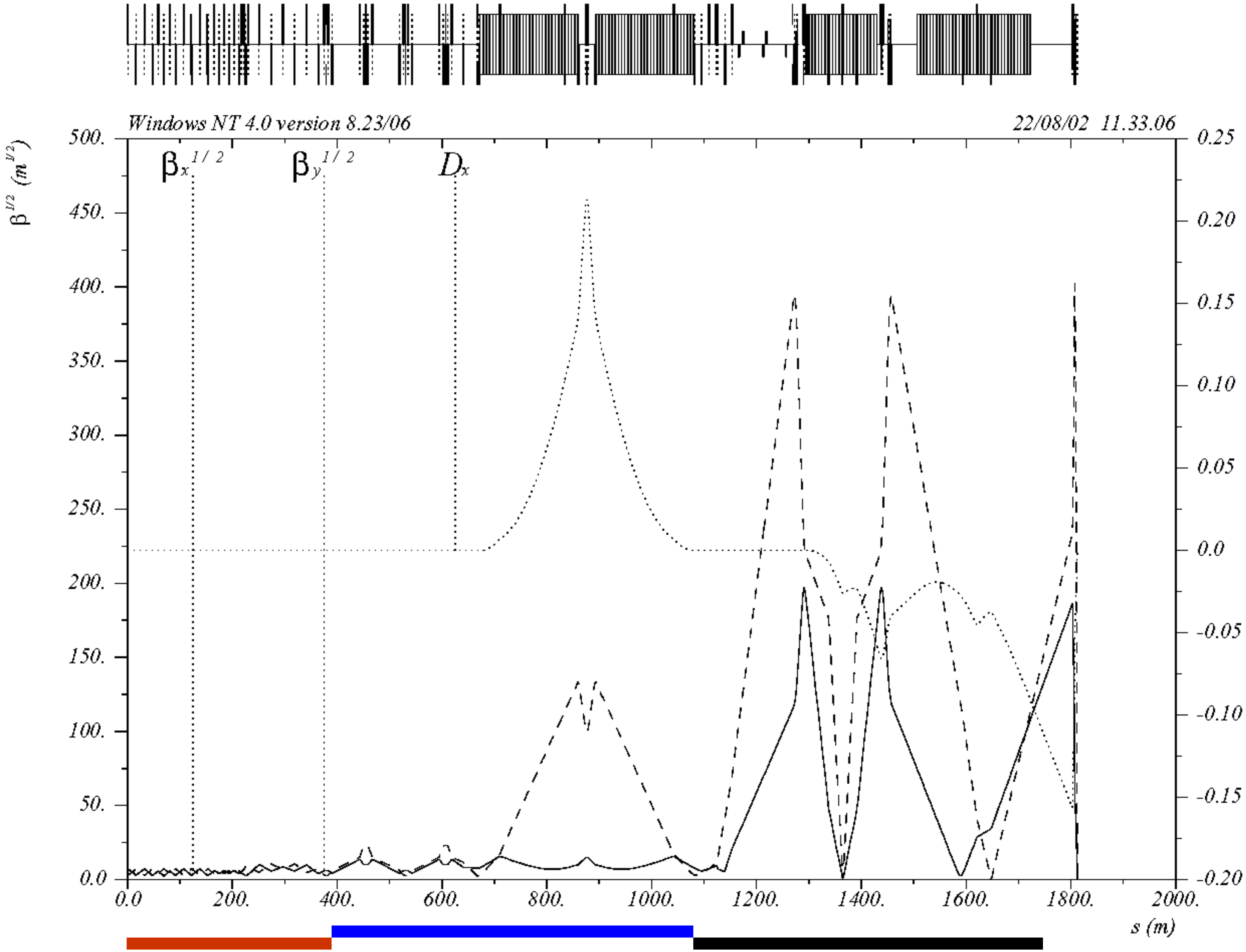


# Challenges:

- Damping Ring
- Linac
- Beam Delivery
  - Special requirements
  - Usually in small numbers
  - Difficult to prototype and test
  - Extreme optics design

Start with Beam Delivery…

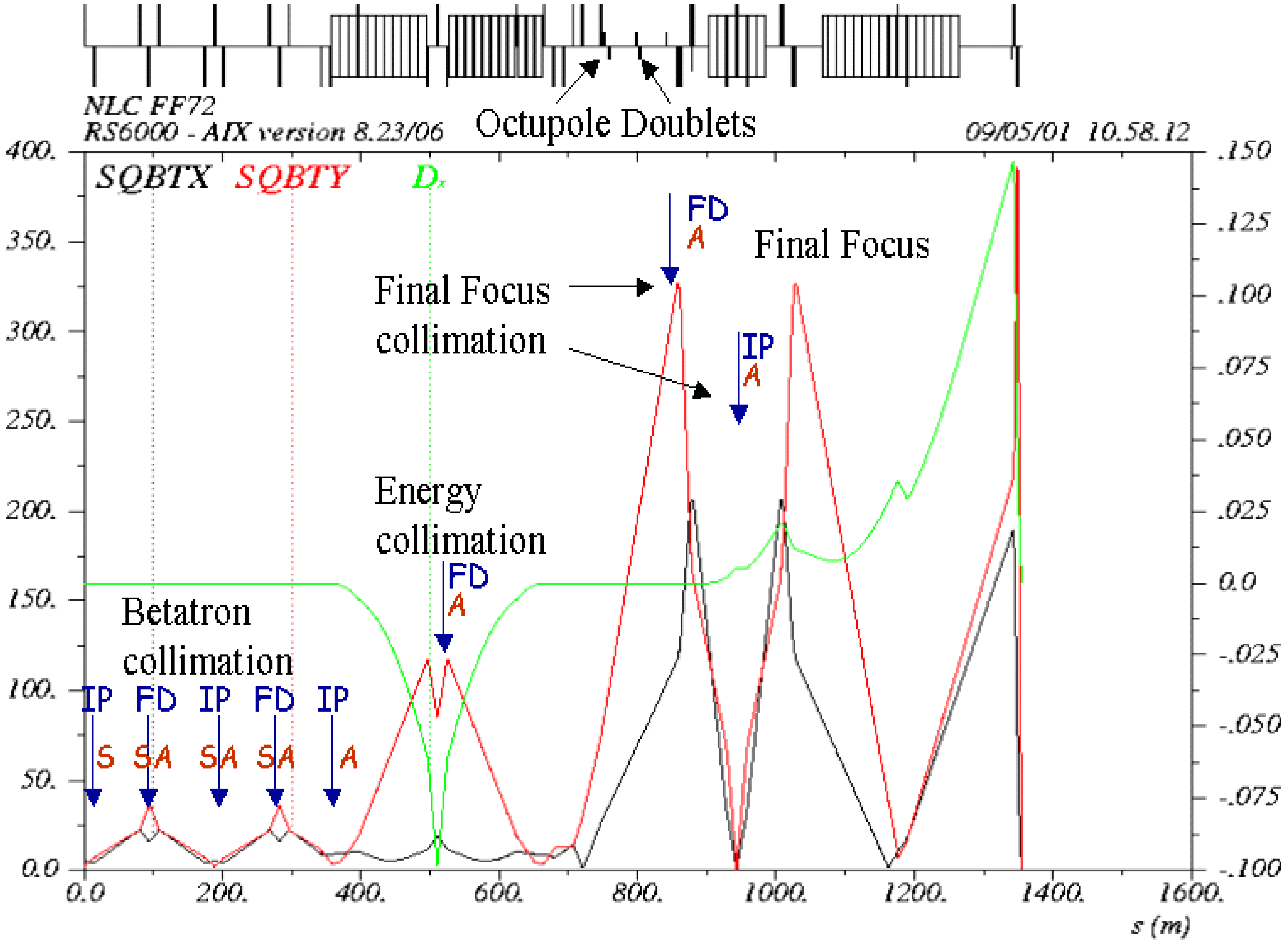
# NLC Beam Delivery Optics

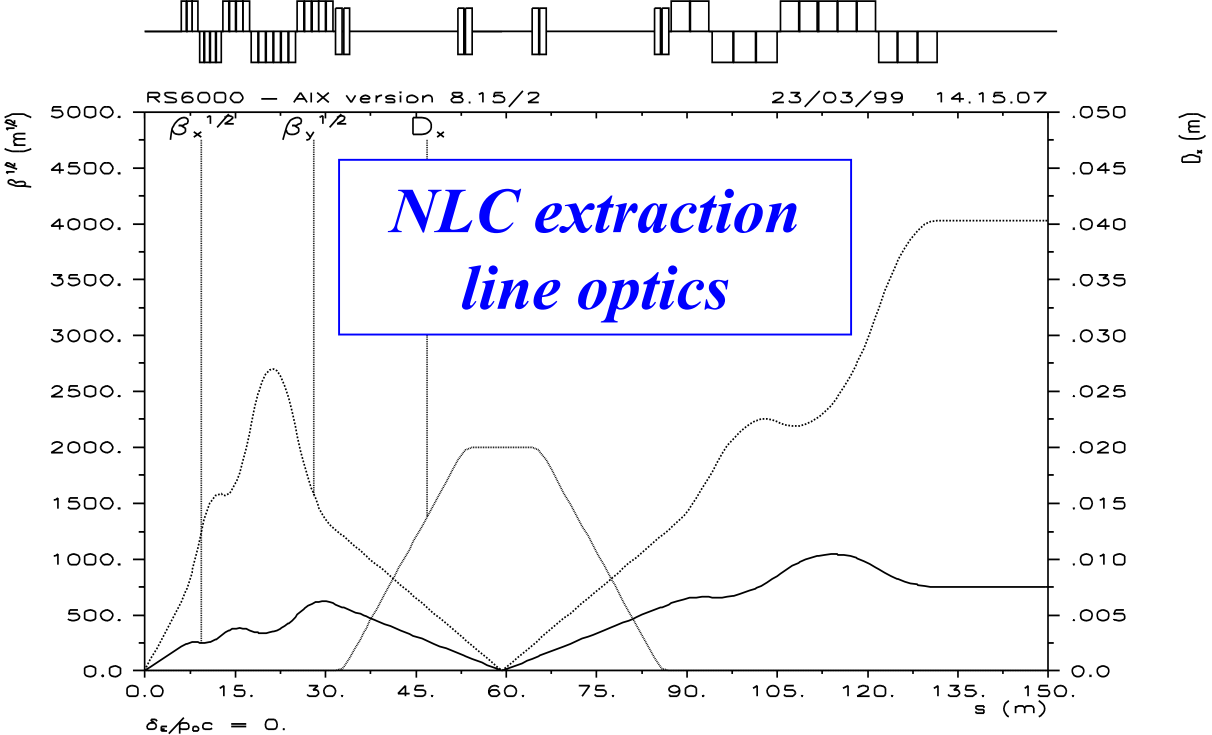


Collimation

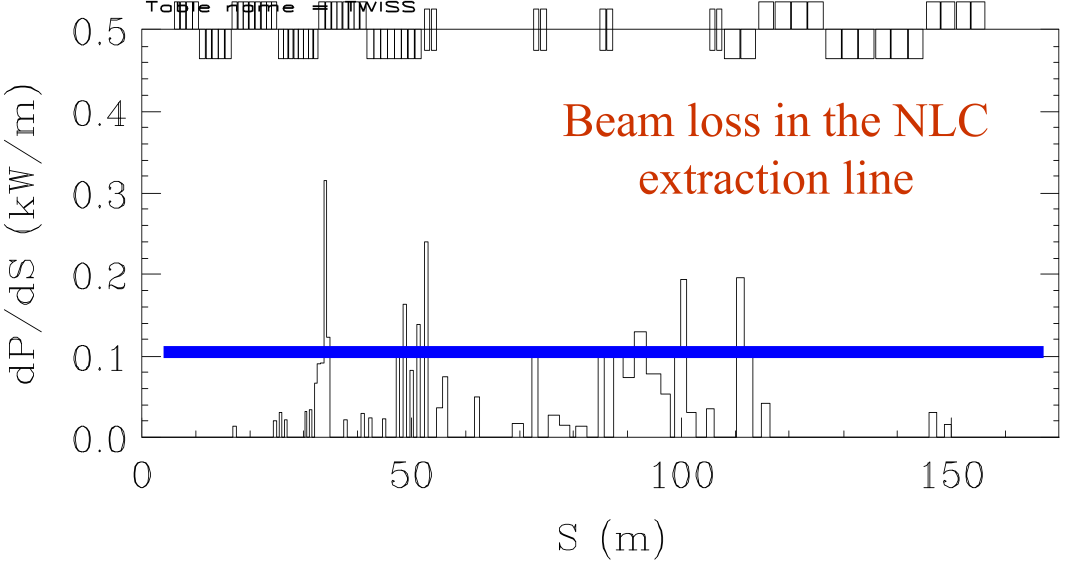
Diag - linac

Chromaticity corr


NLC FF72
RS6000 - AIX version 8.23/06
Octupole Doublets
09/05/01 10.58.12
SQBTX
SQBTY
Dx
FD
A
Final Focus
Final Focus
collimation
IP
A
Energy
collimation
FD
A
Betatron
collimation
IP
FD
IP
FD
IP
S
SA
SA
SA
A
400.
350.
300.
250.
200.
150.
100.
50.
0.0
.150
.125
.100
.075
.050
.025
0.0
-.025
-.050
-.075
-.100
0.0
200.
400.
600.
800.
1000.
1200.
1400.
1600.
s (m)



*NLC extraction line optics*



Beam loss in the NLC extraction line

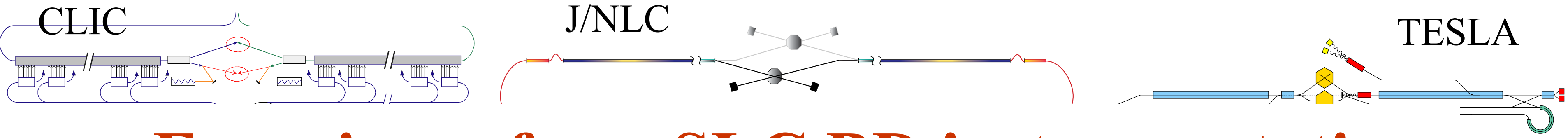
Broad band optics

Very low phase advance – wrap around focusing

SNS loss limit < 1W/m for exposure minimization (ALARA)

NLC limit <100 W/m (SLC experience)

Most beam instrumentation is affected over 10W/m



# Experience from SLC BD instrumentation

- Most added after completion
- Not designed into the optics
  - Not easy to fit in
- FFTB included several improvements - but had a different goal
- At one time - 2x12=24 scanners
  - About half of the SLC total!

- Needed:
  - Incoming matching
    - Emittance
    - Stability
  - Internal matching
  - Beam based alignment
    - Mgnt offset/IP tuning
  - Measure of collimation effectiveness
  - Energy / δ
  - Luminosity related
  - Disruption related

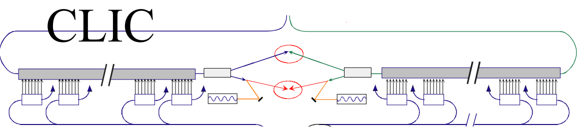
Complex optics with discrete phase advance / long range cancellation - new strategy

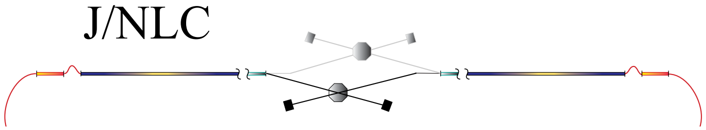
# Wire scanner ‘trials’ in the SLC BD

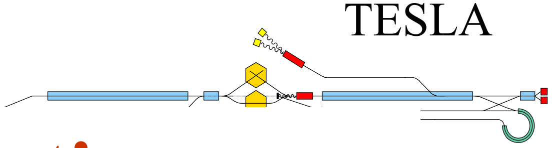
- Incoming emittance, matching and coupling (5)
- First virtual ‘IP’ - (1)
- Second IP - (3)
- Dispersion match (2)
- Angular divergence (1)

Wire scanner requirements –

- matching vs emittance -
- absolute accuracy vs scanner to scanner systematic difference







# Beam Delivery Instrumentation Requirements:

*Incoming matching & stability check:*

Collimation <-> correction

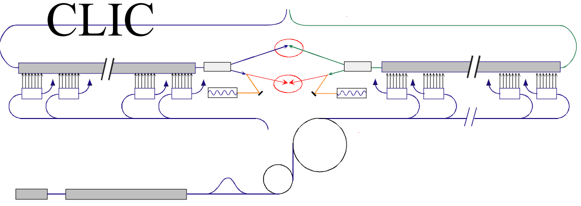
Correction <-> final doublet

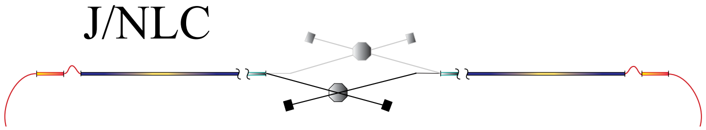
Extraction line

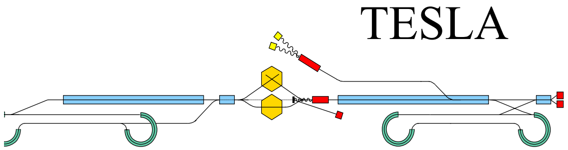
*Luminosity:*

- Short term variation
- Real-time precision
- Correlations (E,P…)
- Frequency of invasive measurements
- Luminosity vs δ
- Luminosity strategies

- Luminosity strategies depend on:
  - *Where the luminosity comes from*
  - *Geometric emittance*
  - *Pinch enhancement*
  - *Many dilutions…*
- IP beam instrumentation should provide this – real time –







# FFS corrections

- Corrections modeled after FFTB / SLC
  - Isn't (/wasn't) this only the beginning?
  - What were the problems with the above correction schemes?

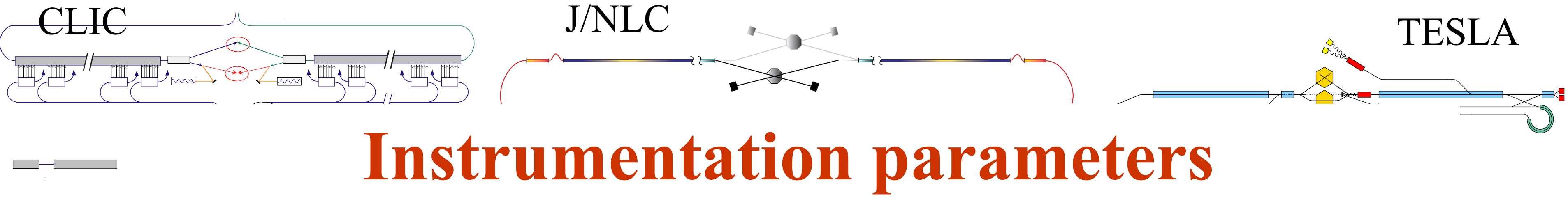
  - Took a long time
  - Did not always converge
  - Defeated by simple hardware problems/upstream problems
  - Did not identify specific error sources
- BBA issues:
  - Rotated BPM's
  - BPM systematics
  - Mover engineering

*'local' corr FF uses mover knobs for waist, η_xy & x<->y coupling*

# FFS tuning

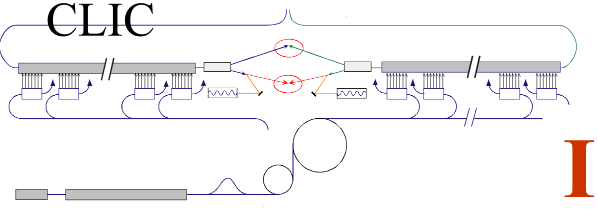
1. the quadrupoles are aligned using beam-based alignment techniques such as the shunting method,
2. the sextupoles are aligned in a similar manner,
3. trajectories are fit to verify the first-order optics and fix the phase advance between sextupoles,
4. the sextupoles are set to minimize the chromaticity,
5. *global tuning correctors (knobs) are used to tune both the first-order and the nonlinear corrections using luminosity measurements.*

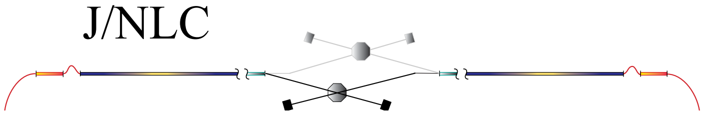
Instrumentation RD is needed to validate real-life high confidence BBA

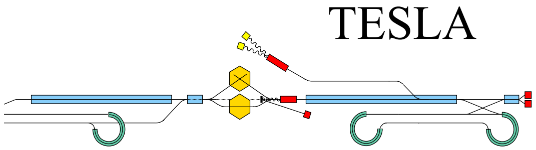


# Instrumentation parameters

| | |
|---|---|
| • BPM | $\sigma_{x,y}/10$ |
| • Transverse profile | Relative calibration to 5% |
| • Longitudinal profile/ | $\sigma_{x,y}/10$ |
| • $\delta$ | $\delta$ has features ~0.03%<br>(60um@20cm$\eta$ /6um@2cm$\eta$) |
| • Correlation | |
| • Beam loss | |
| • Secondary beam | |
| • Stability monitoring | |







# Instrumentation RD - *ongoing*

- BPM
  - Multi-bunch, multi-purpose
  - Better calibration
  - Much more intensive RD urgent
  - Significant advances possible
- Xverse Profile (tnt) *
  - Laser, OTR, ODR
- Bunch length (tnt) *
  - Deflection structure
- Correlations (tnt) *
  - Cavity BPM
- Special interaction region (tnt)

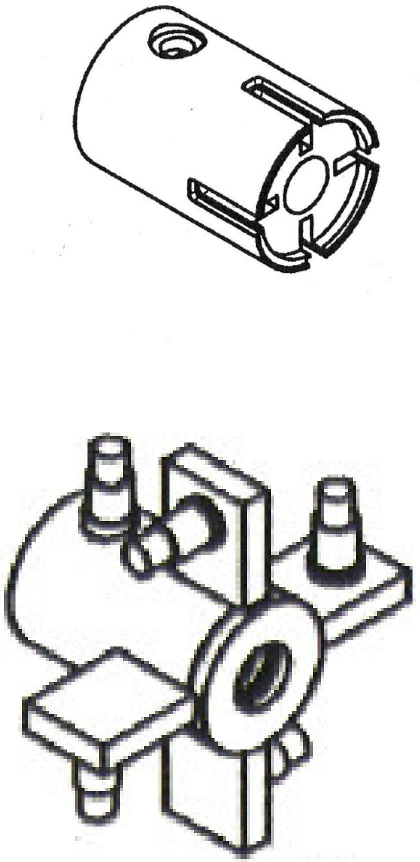
tnt ==totally new technology

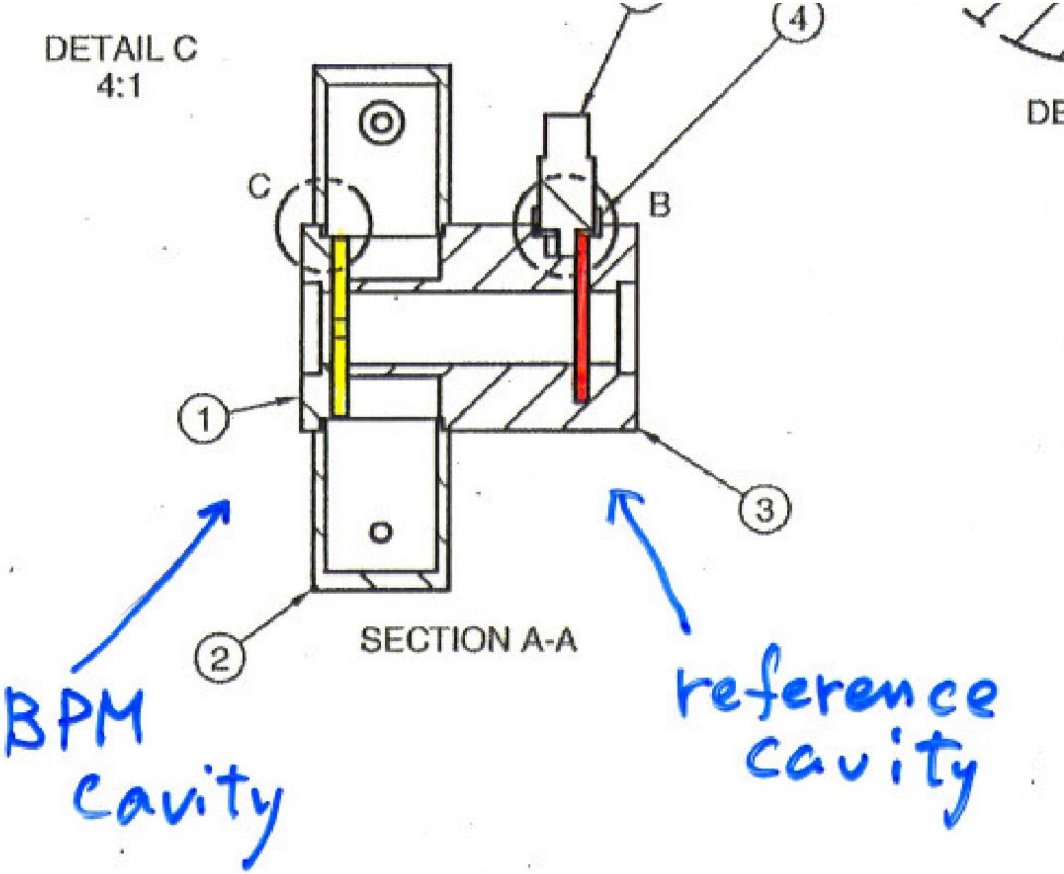
BPM’s are the most expensive and most critical monitors

* Something actually happening

# μWave cavity BPM
X-band

Naito/Li





12 mm bore

Very good resolution possible – 25 nm achieved in FFTB
few nm possible by <u>limiting spatial dynamic range</u>

*RD challenge to improve TM110 mode*

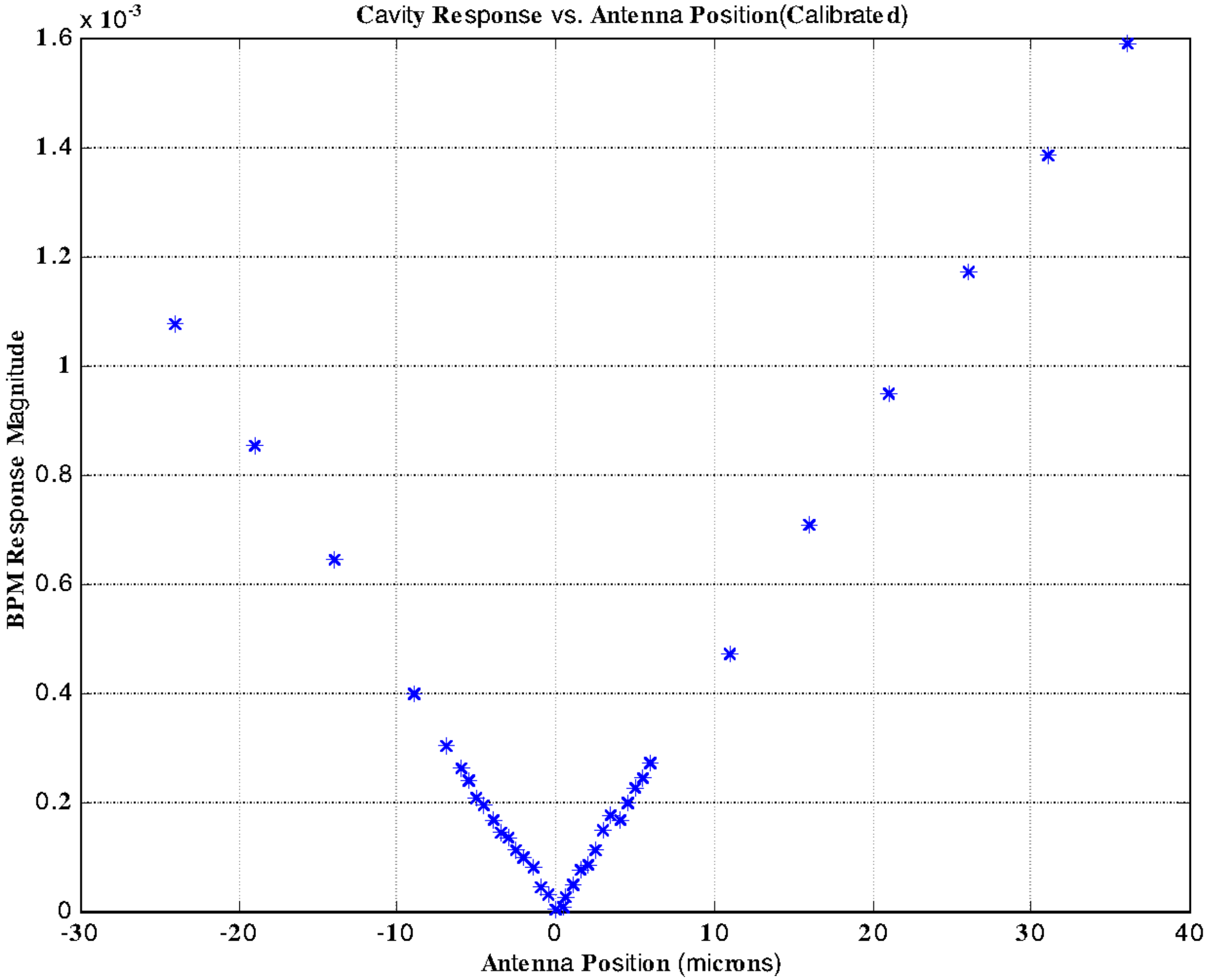


Fig. 28 Position scan(calibrated)

Bench test of cavity BPM

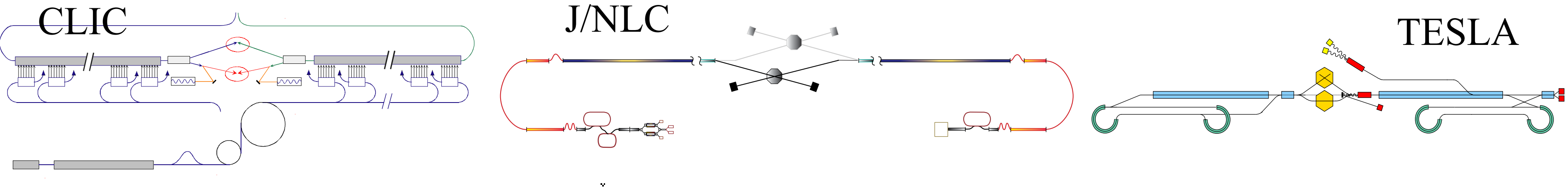
Naito - 2002

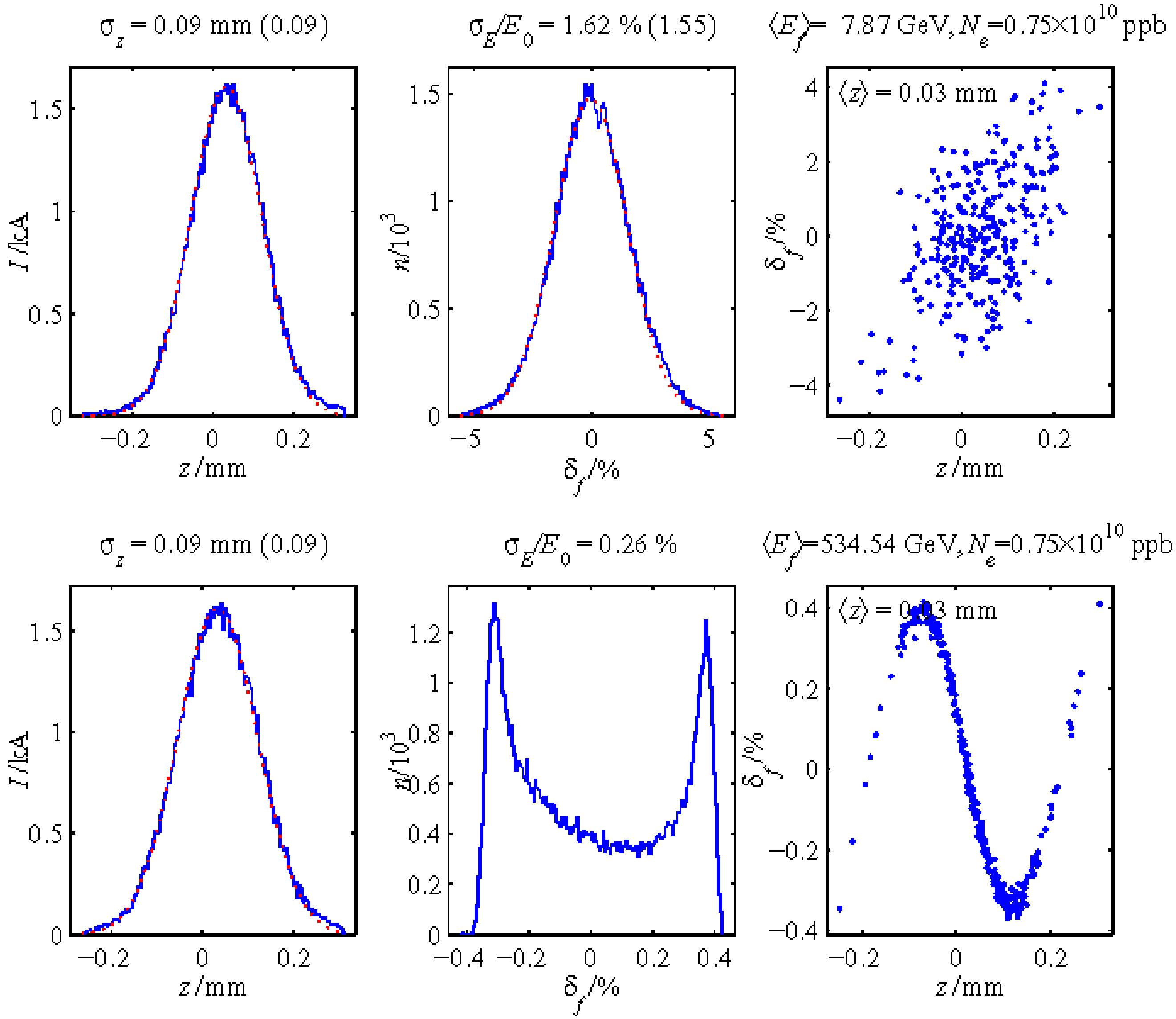
# Longitudinal distribution & correlations

- Many dilutions initially appear as linear correlations
  - Linac single bunch wakes foremost
  - Collision sensitivity
- IP is surrounded by ‘crab’ type cavities
  - *x* and *y*
  - Useful for both correction and monitoring
  - How will this work?
- What additional methods can be used to monitor longitudinal distribution and correlations?

Electro-optics

Cavity BPM signals





## Longitudinal Dynamics

Bunch length,

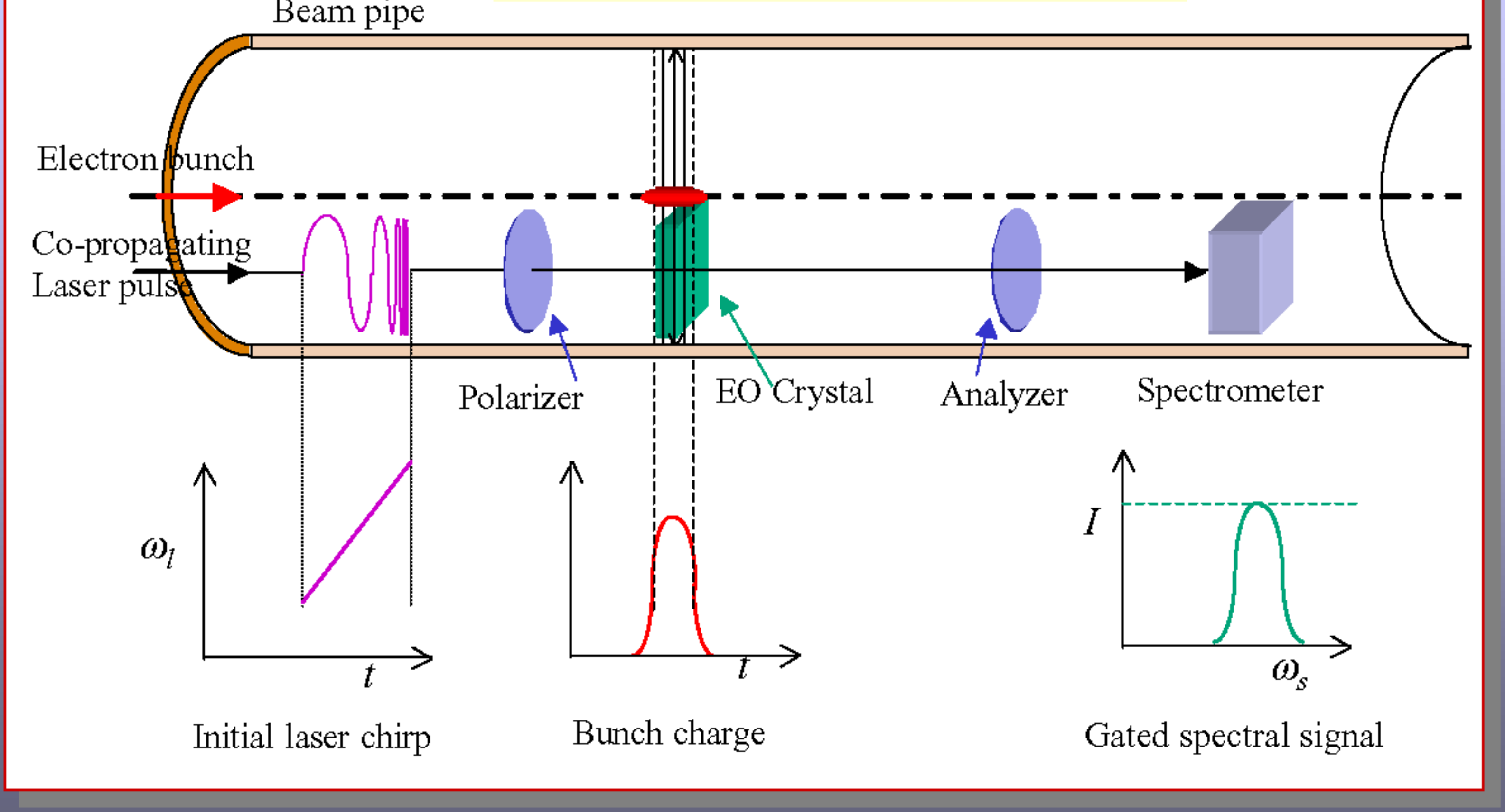
Energy spread,

Correlation

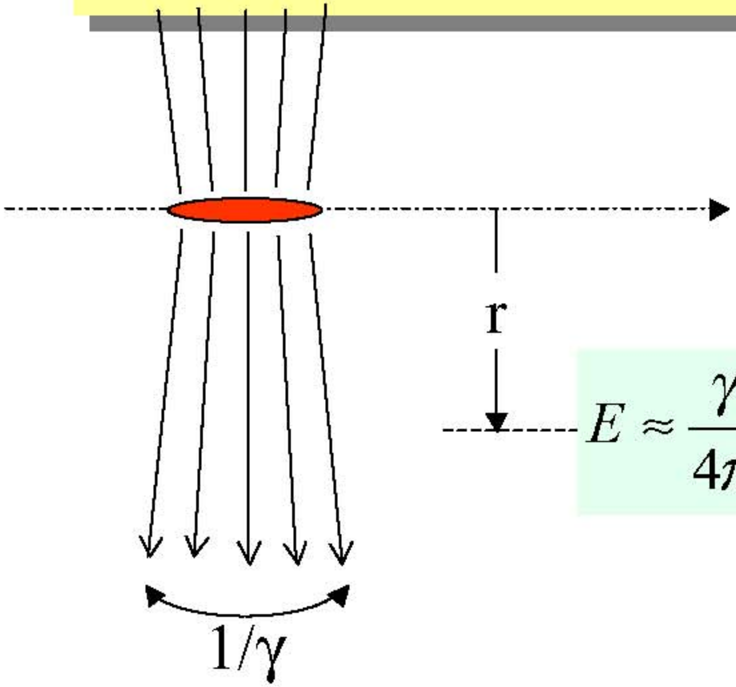
At the beginning and end of the linac

# Principal of Electro Optic Detection

- Electric field from bunch modulates transmission of chirped laser pulse



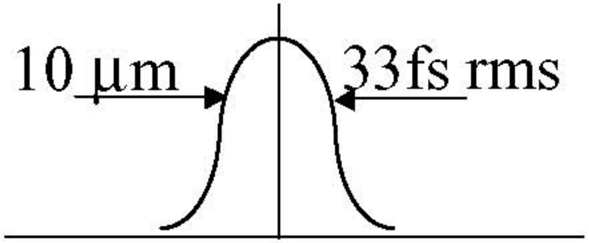
# Electric Field from a Relativistic Bunch



$$E \approx \frac{\gamma N_e e}{4\pi\varepsilon_0 r^2}$$

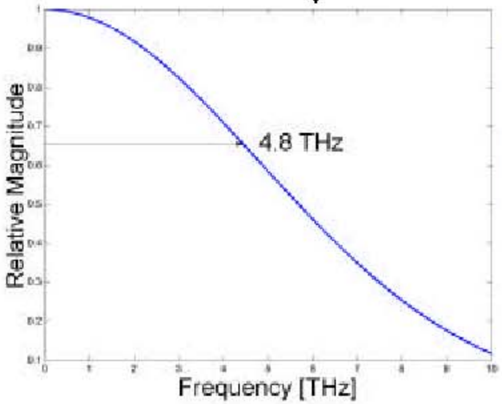
1 nC 30 GeV 1 cm away

$E = 5\ \mathrm{GVm^{-1}}$



Frequency components

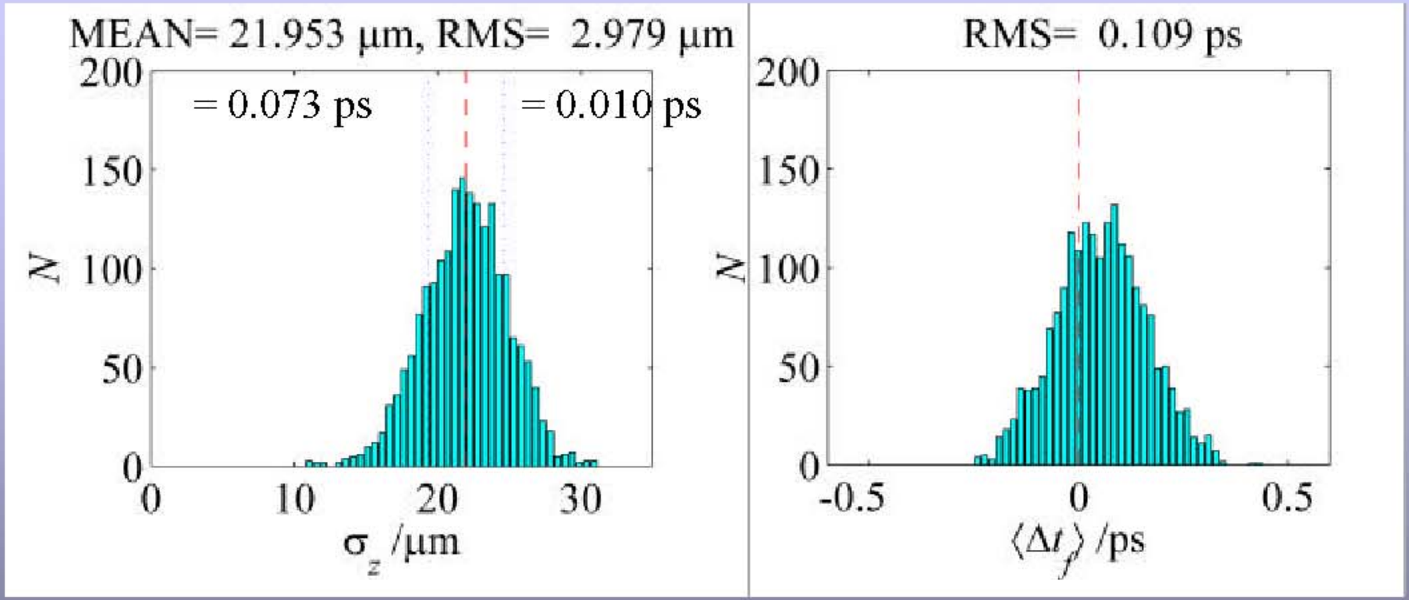
$$F(\omega) = e^{-\frac{\omega^2\sigma^2}{2}}$$



Wakefield bandwidth

# Timing jitter is an issue with ultra-short bunches

- LCLS simulation, M. Borland

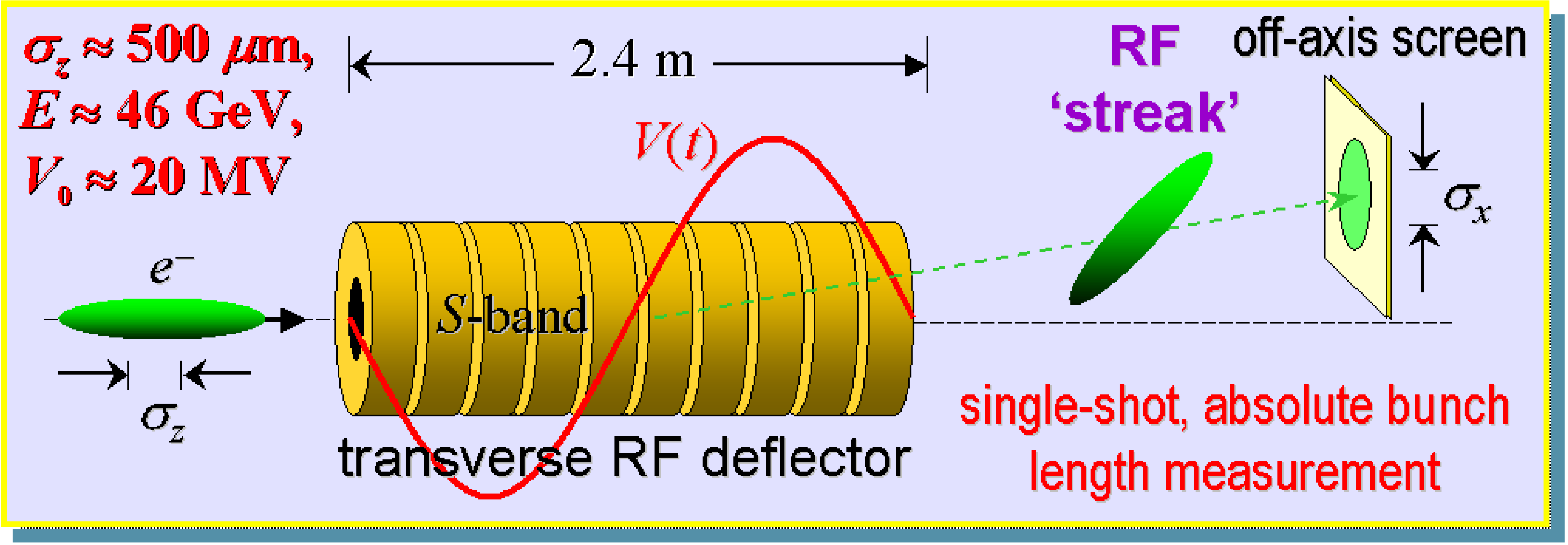


Expected variation in bunch length at end of linac

Expected variation in bunch arrival time at end of linac

# Transverse deflection

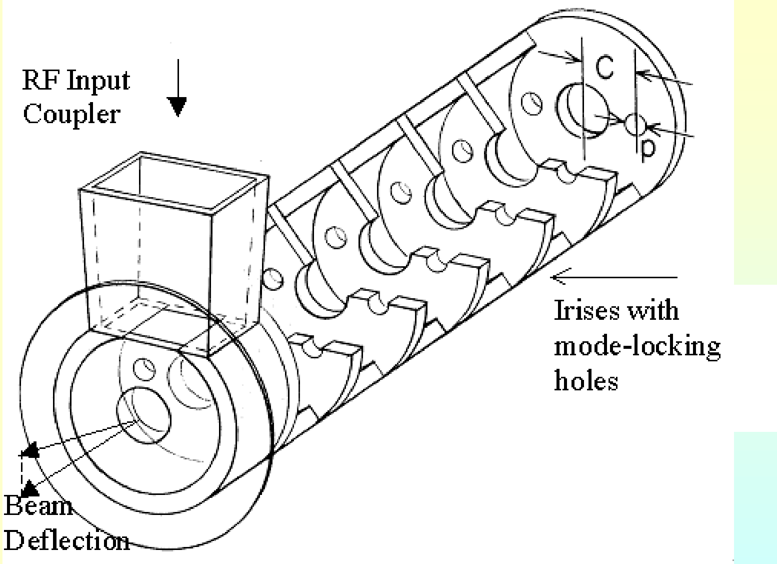
Old idea – 1965 'LOLA IV'
Testing in linac sector 29

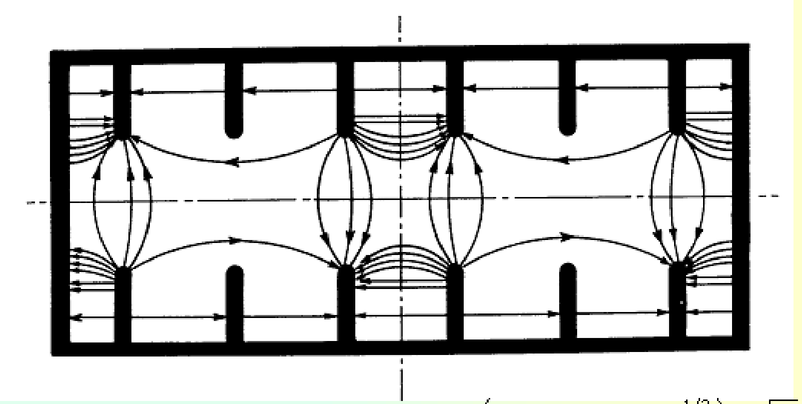


single-shot, absolute bunch length measurement

Brute force
Calibrated
Expensive
Excellent resolution

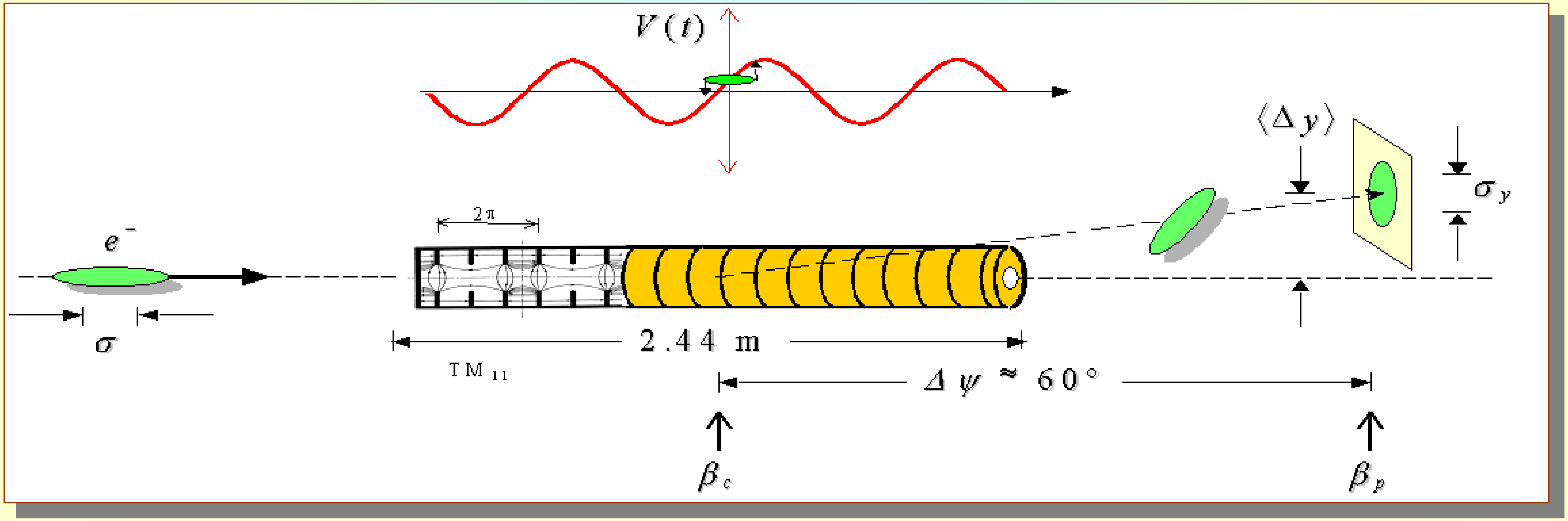
SLAC LCLS – Krejcik/Emma (EPAC 02)
SLAC/DESY TTF2





$$V_0 \approx \left(1.6\ \mathrm{MV/m/MW}^{1/2}\right) L \sqrt{P_0}$$

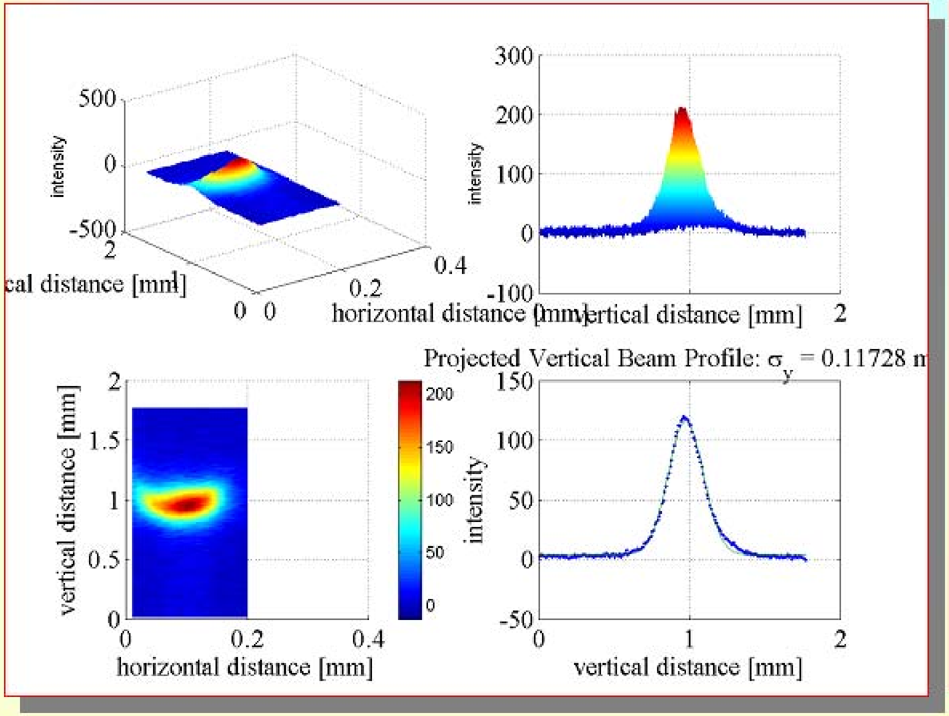
$$bunch\,lenght,\ \sigma_Z \approx \frac{\lambda_{rf}}{2\pi}\frac{E_S}{\left|eV_0 \sin\Delta\psi \cos\varphi\right|}\sqrt{\frac{\left(\sigma_y^2-\sigma_{y0}^2\right)}{\beta_d\beta_s}}$$



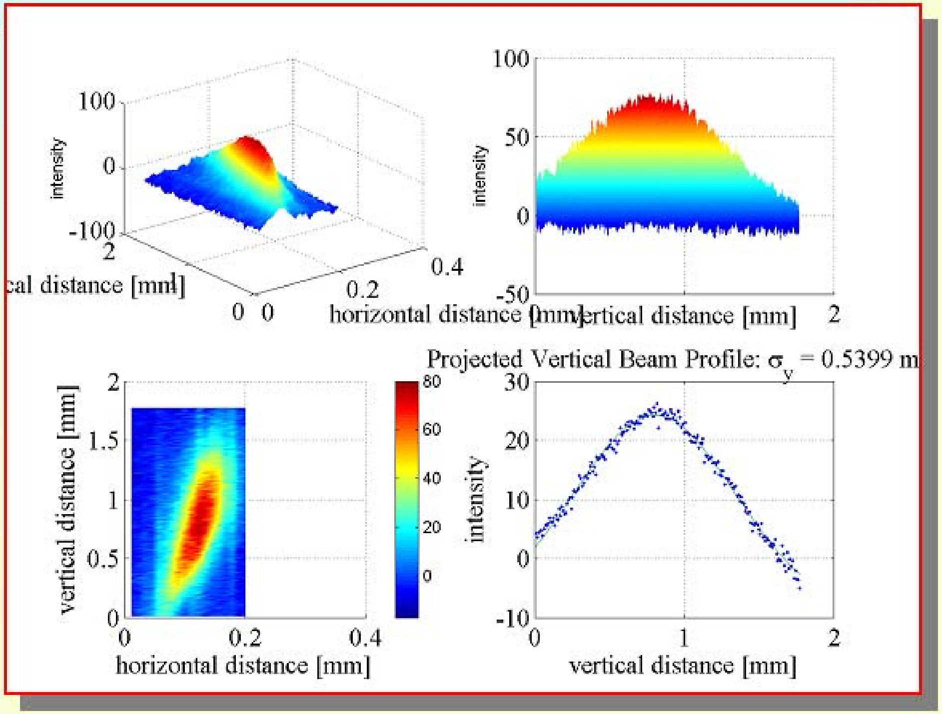
# Profile Monitor Images

Damped, scavenger bunch at end of the linac

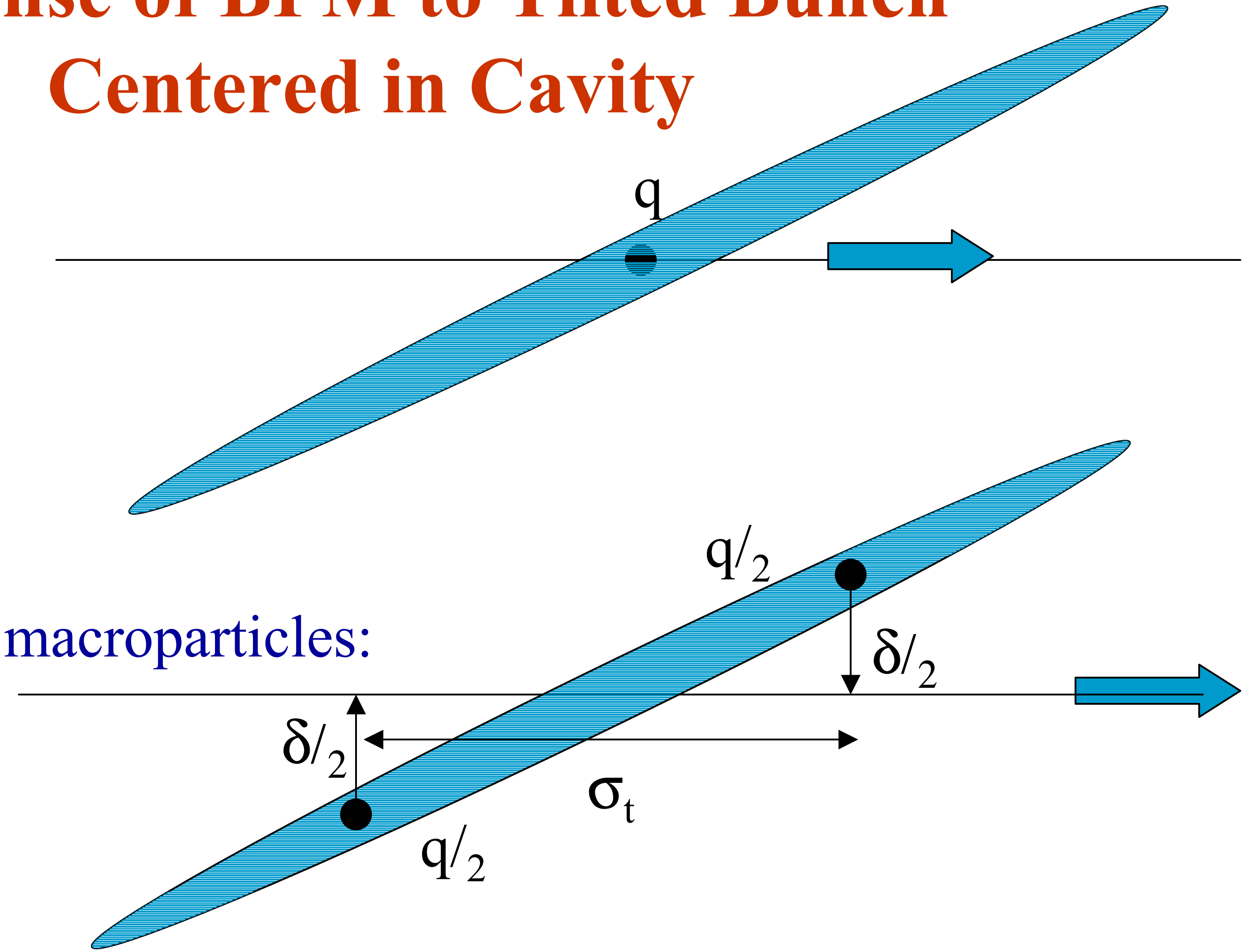
Transverse Cavity OFF



Transverse Cavity ON



# 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 $\delta$

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

- Centered, extended bunch tilted at slope $\delta/\sigma_t$
- Tilt signal is in *quadrature* to displacement

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

- The amplitude due to a tilt of $\delta/\sigma$ is down by a factor of:

  with respect to that of a displacement of $\delta$

  (~bunch length / Cavity Period )

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

# Example

- Bunch length $\sigma_t = 200\ \mu\text{m}/c = 0.67$ ps
- Tilt tolerance $d = 200$ nm
- Cavity Frequency $F = 11.424$ GHz
- Ratio of tilt to position sensitivity $\frac{1}{2}\pi f \sigma_t = 0.012$
- A bunch tilt of 200 nm / 200 μm (1 mrad) yields as much signal as a beam offset of 0.012 * 200 nm = 2.4nm
- Need BPM resolution of ~ 2 nm to measure this tilt
- Challenging!
  - Getting resolution
  - Separating tilt from position
- Use higher cavity frequency?

Need 1 mrad tilt sensitivity for linac tuning

# Angled trajectories

- A trajectory that is not parallel to the cavity axis also introduces a quadrature signal (in phase with ‘tilt’ signal)
- Projected ‘dipole’ sensitivity is increased by $\sigma_z$/cavity length
  - ~ 50

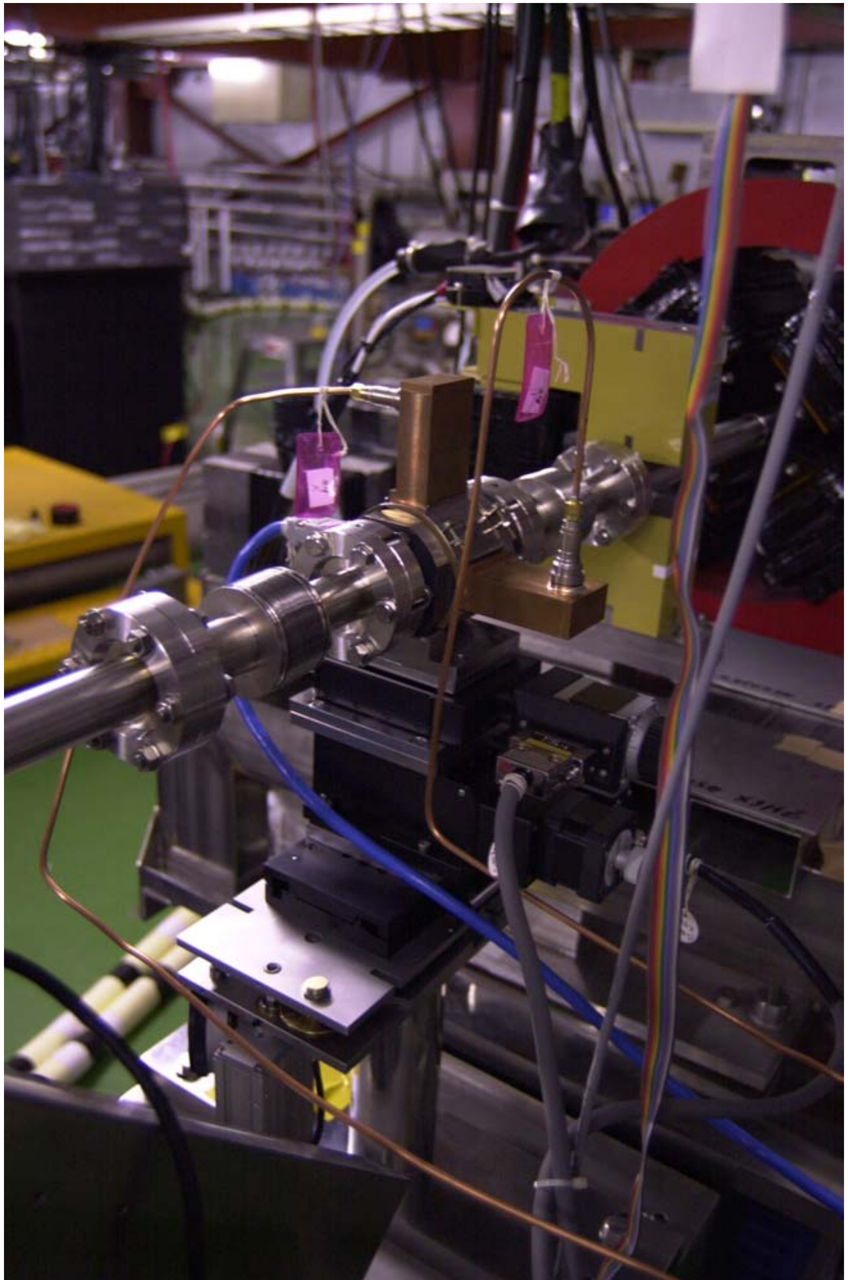
Relative normalized precision
Beam position/beam traj angle

$\sigma_{y\ res}/\sigma_y \sim 5\%$
$\sigma_{y'\ res}/\sigma_{y'} \sim 10x$

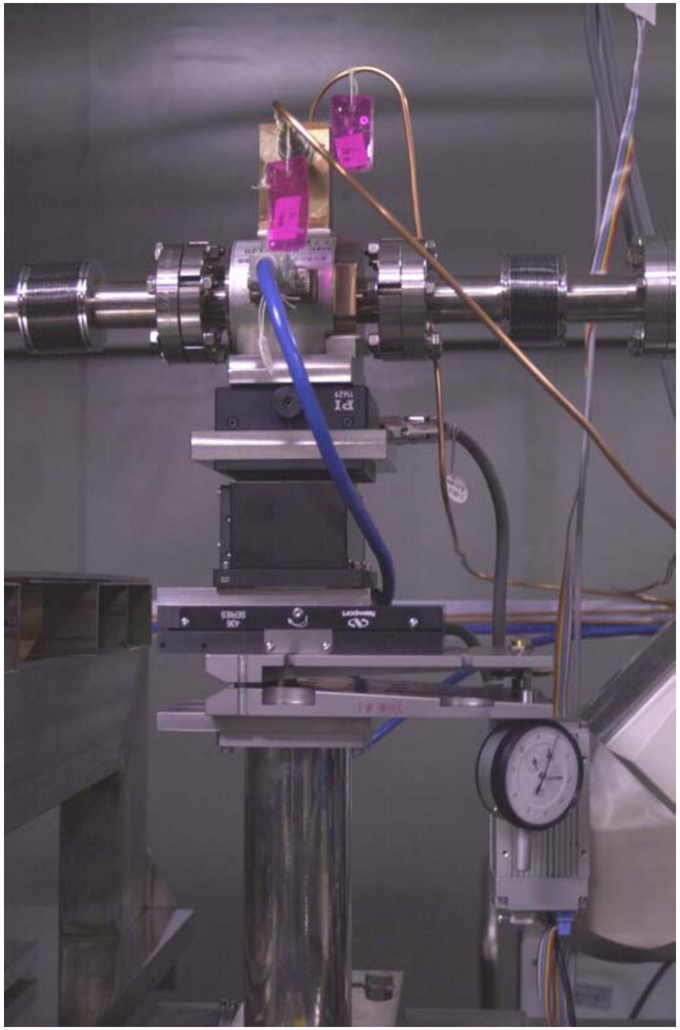
| Cavity BPM | | | | |
|---|---|---|---|---|
| | FFTB (Shintake) | ATF ext line (Vogel) | X-band (Naito) | |
| f | 5.712 | 6.426 | 11.424 | (GHz) |
| position resolution | 20 | 200 | 200 | (nm) |
| Vt/Vy (200um sig_z) | 0.6% | 0.7% | 1.2% | (.5 pi sig_t f) |
| achieved 'projected dipole resolution' (200um sig_z) $\delta$ | 3.3 | 29.7 | 16.7 | um |
| achieved 'tilt' angle resolution | 17 | 149 | 84 | mrad |
| achieved 'trajectory angle resolution' | 3 | 26 | 30 | urad |
| cavity 'length' | 15 | 15 | 8 | mm |

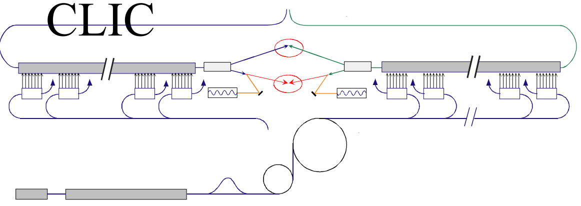
ATF $\sigma_z$ ~ 8mm gives expected tilt resolution ~ 0.1mrad

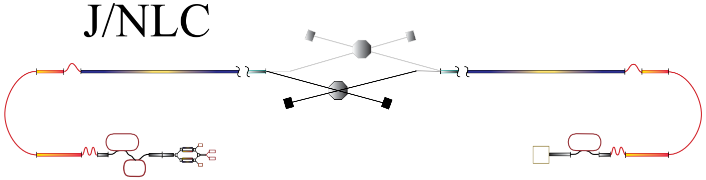
# ATF Cavity BPM – V. Vogel / H. Hayano

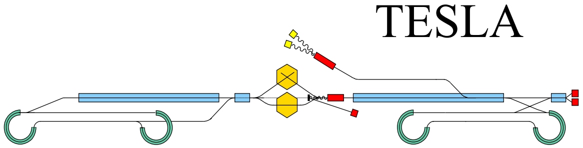


ATF extraction line
C-band cavity
L = 12mm, Radius = 26mm, f = 6426MHz, $\lambda$=46.6mm
Movers – x, y, pitch (*y*-*z*)







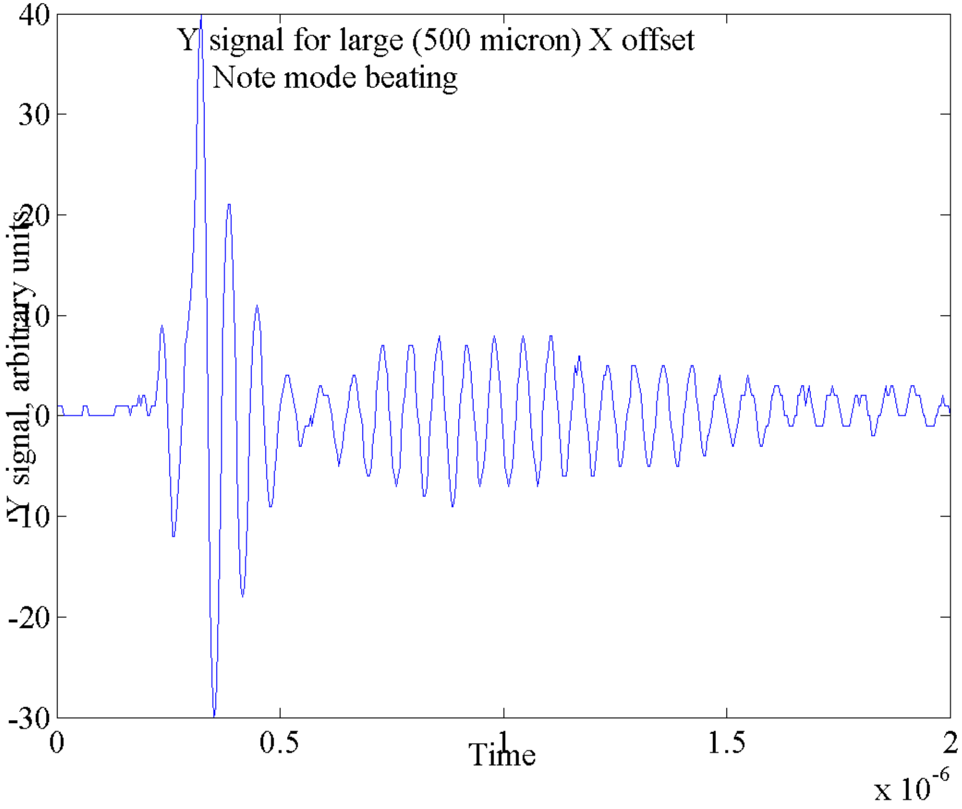


# Problem (?) with cavity BPM:

Signal beating with offset in only one plane

If there is a large offset in one plane, and little in the other, we see beating between modes

(nominally cylindrically symmetric cavity)

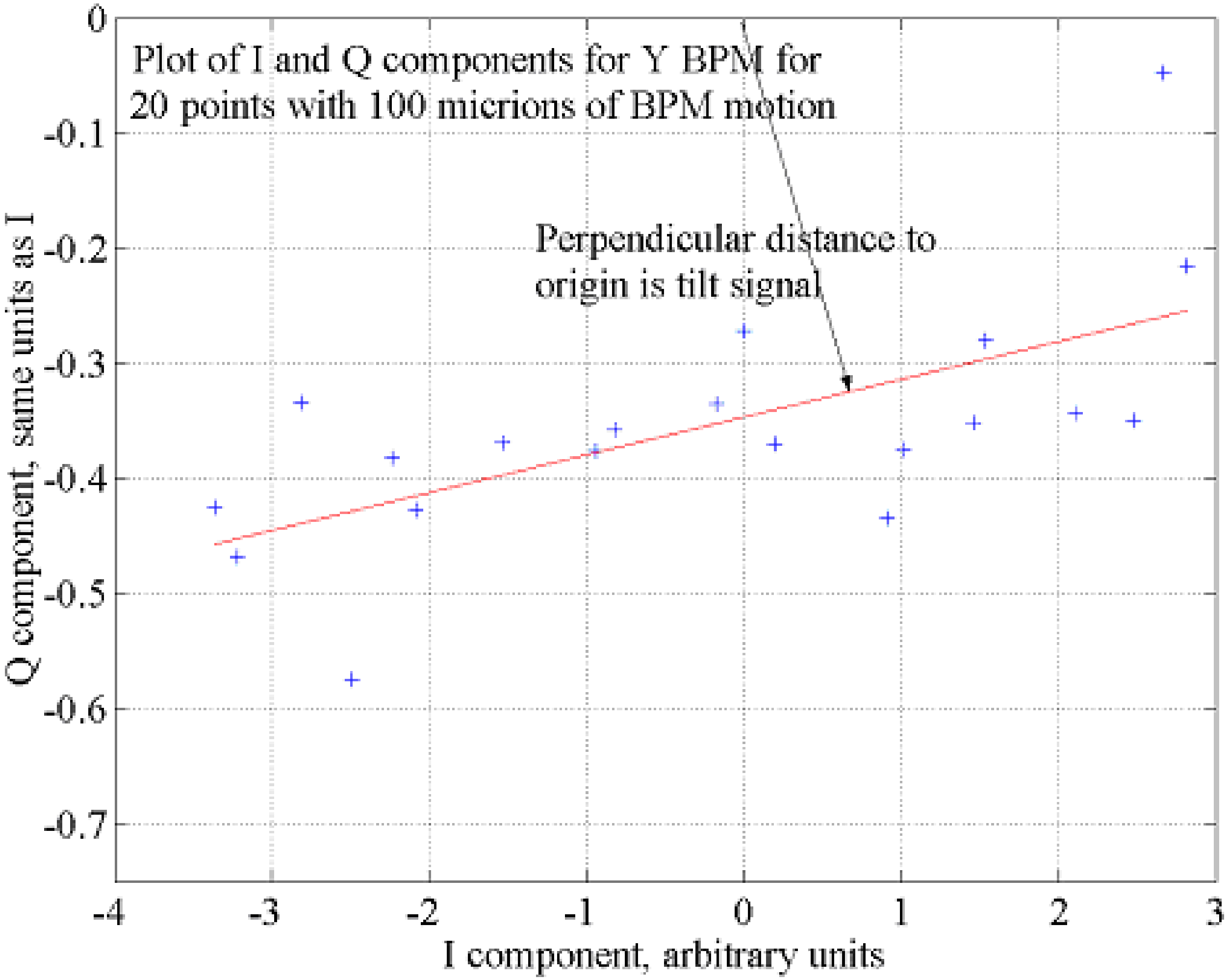


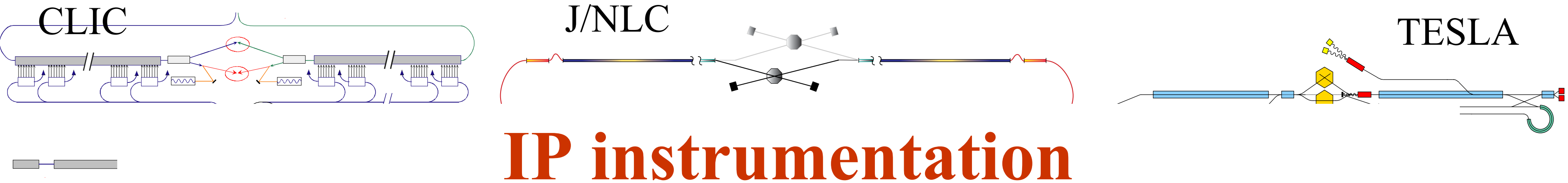
# Angle signals from ATF cavity BPM

I Q response as the cavity is moved vertically using mover

The angle is arbitrary (phase offset between ref and BPM cavity)

A ‘monopole’ beam with an axial trajectory should give a (0,0) response at some point

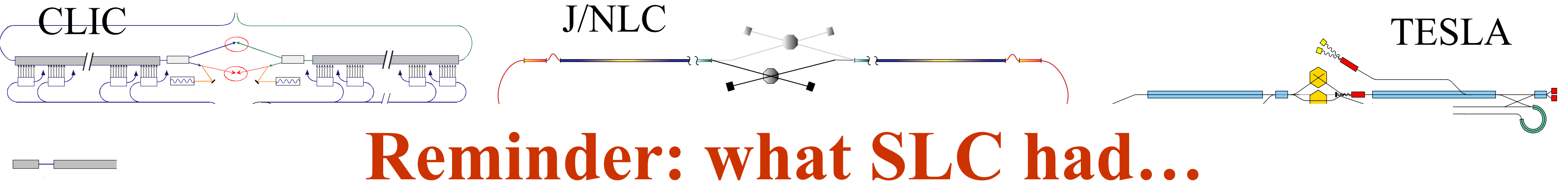




# IP instrumentation

- $\sigma_z$, $J(z)$
- $x \leftrightarrow z$, $y \leftrightarrow z$, $E \leftrightarrow z$
  - *IP is surrounded by ‘crab’ cavities*
- $\sigma_{x,y}$
- BSM
  - E, **P**, geometric
- Pair monitor
- Rad bha bha

- Position
- Angle
- Timing
- Feedback
- Extraction line loss



# Reminder: what SLC had…

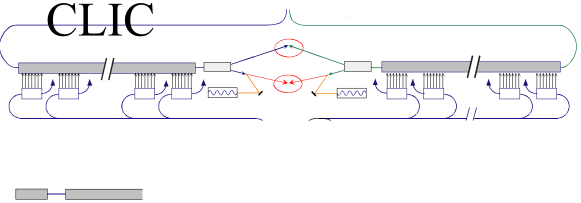
6 channel (spatial) γ BSM

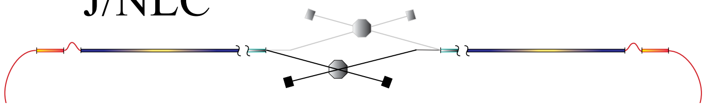
- Always used sum signal
- Ethylene pressure E_cut 0.3 Atm.

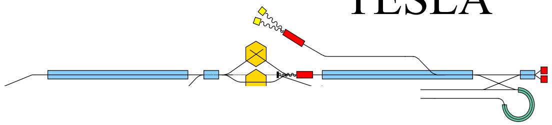
Rad. bha-bha monitor

- Parasitic energy band – $0.85>E/E_b>.65$

Invasive – wire scanners and screen profile monitors





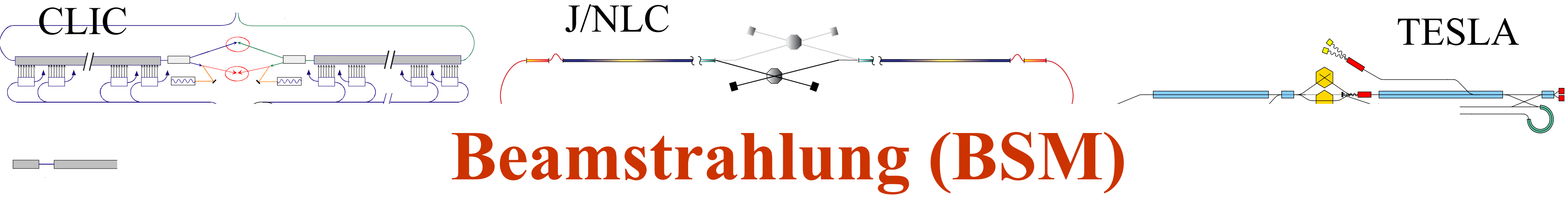


# Disruption

- NLC 1.5
- TESLA 1.8
- SLC 1.4 @150 Z’s/hr

*Disruption tightens geometric tolerances*

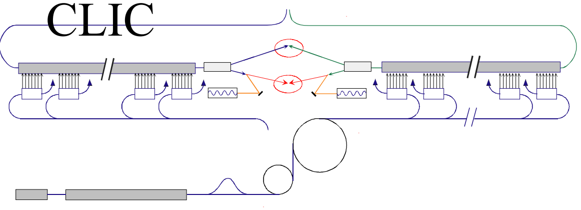
- Bunch length
- Longitudinal distribution
- $y\ z$ / $x\ z$ correlations
- Δt
- Crab cavity system

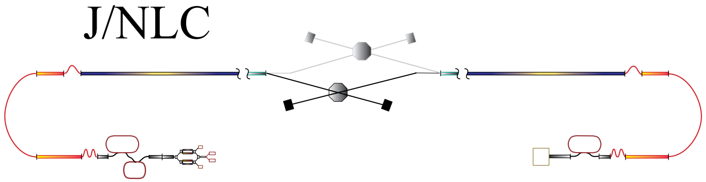


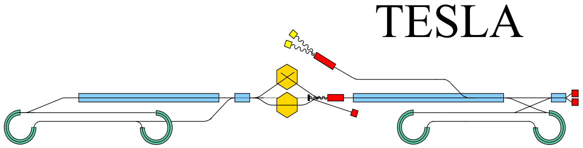
# Beamstrahlung (BSM)

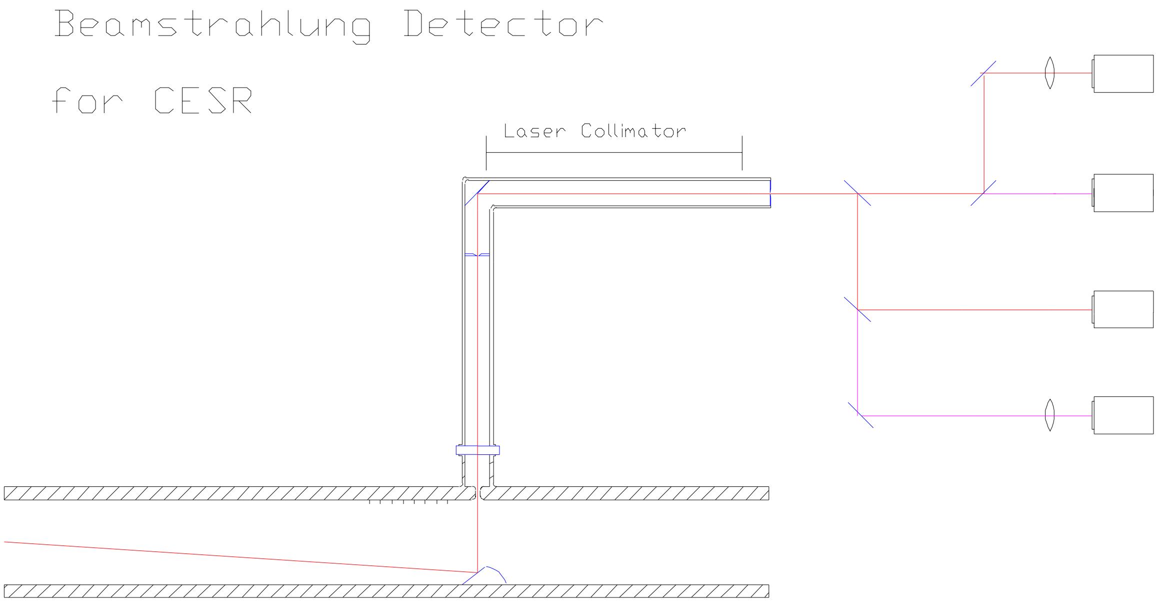
- (Bonvicini et.al. at CESR)

- Power
  - BSM 3-4% of beam power → TESLA <u>300KW</u> / NLC <u>400KW</u>
- Divergence
  - 300 μrad rms
- Distribution
  - Non-Gaussian, non-symmetric









the BSM must be an integral part of the machine