Beam Performance at JLab/CEBAF Diagnostics and Metrics

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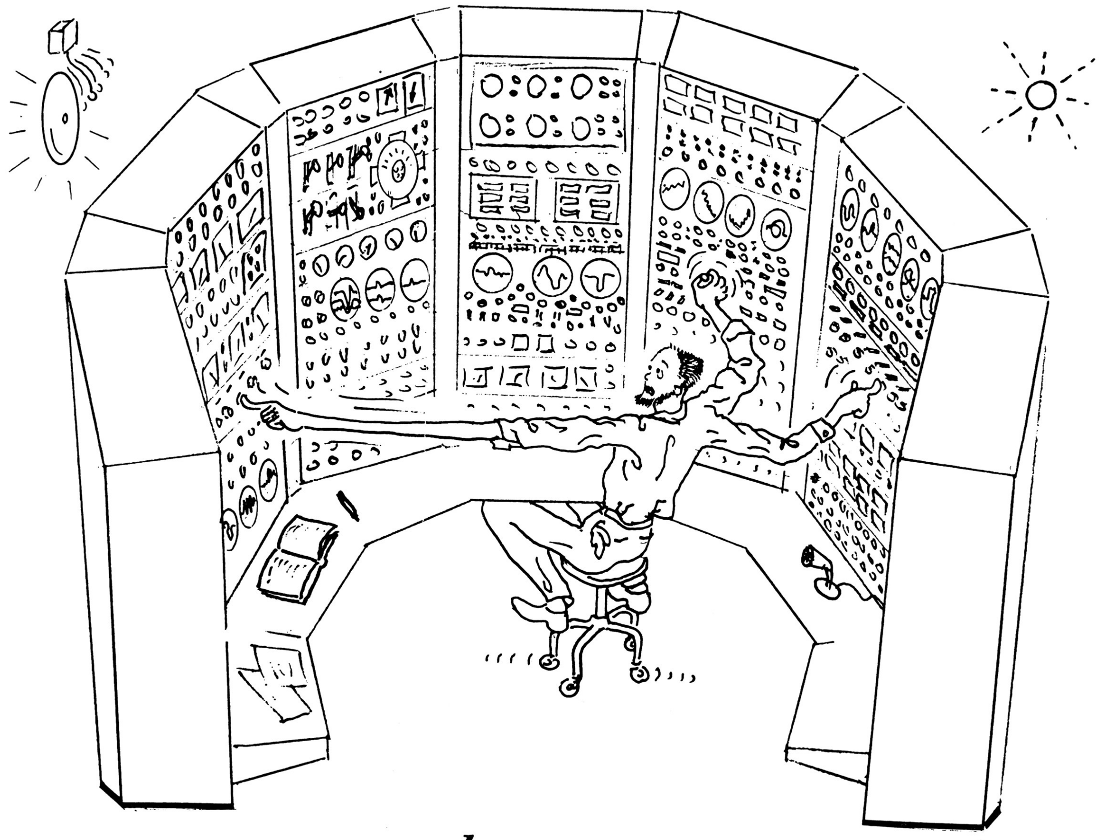
What's the Point?

- Introductory material
- What do we diagnose, and why?
  - Beam
  - Accelerator
- CEBAF beam requirements
- CEBAF diagnostic systems
  - Point in time
  - Continuous monitoring
  - Integral quantities for the user
- Upcoming changes for 12 GeV

The Accelerator As Seen By



. . . the operator

Dave Judd and Ronn MacKenzie, “The Cyclotron as seen by...” series, Magnet, Vol 11, No. 10, October 1967, p. 9-10

XBD9705-02293.TIF

Diagnostics Enable Operations

- Position
- Profile
- Time-of-flight
- Current
- Loss monitors
- Polarization

- Initial trajectory set-up
- Energy
- Energy spread
- RF set-up (gradient/phase)
- Lattice characterization
- Power density limits
- Emittance
- Intensity monitor
- Loss detection
- Protect vulnerable spots
- Photon converter ballistics
- Helicity correlations

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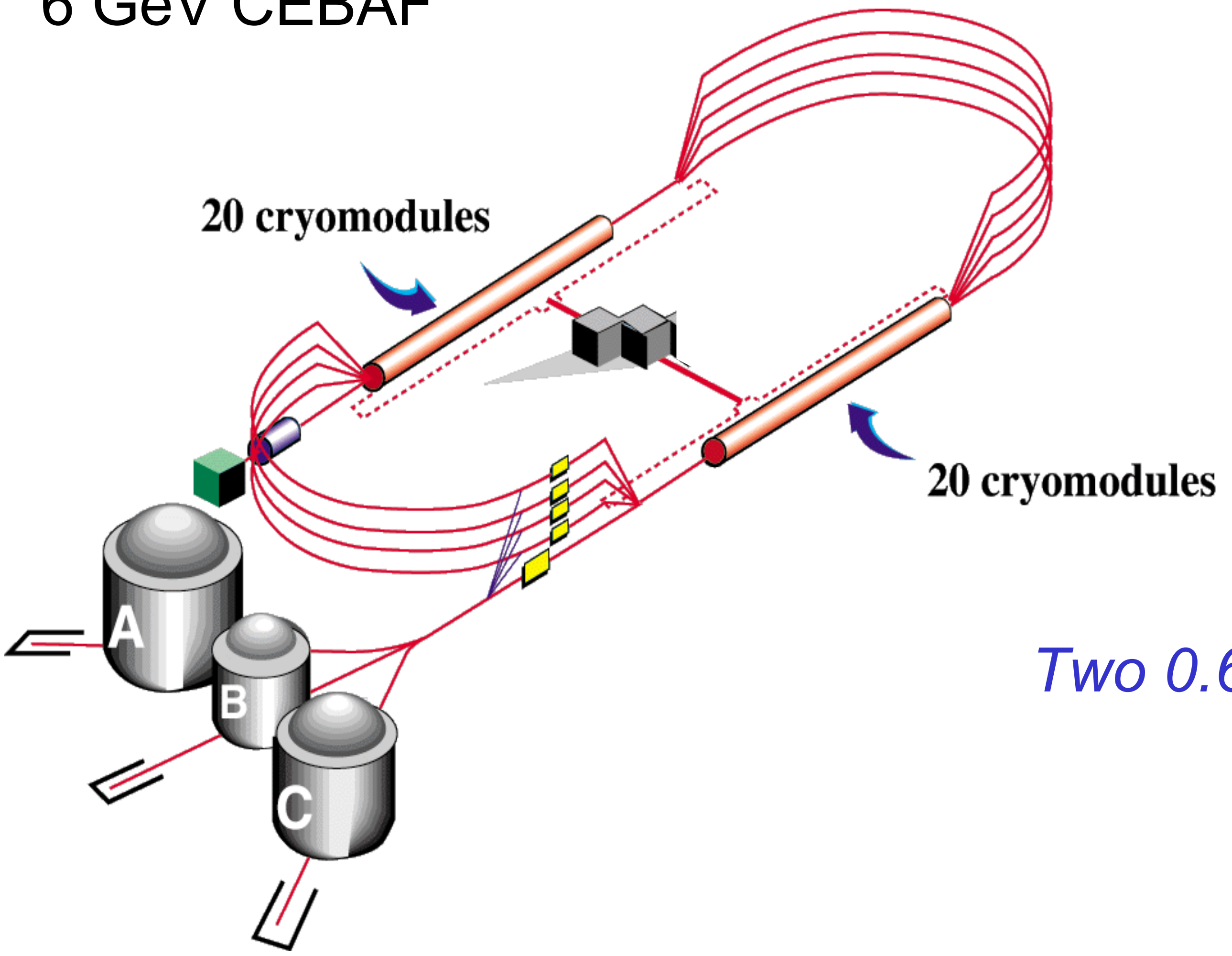
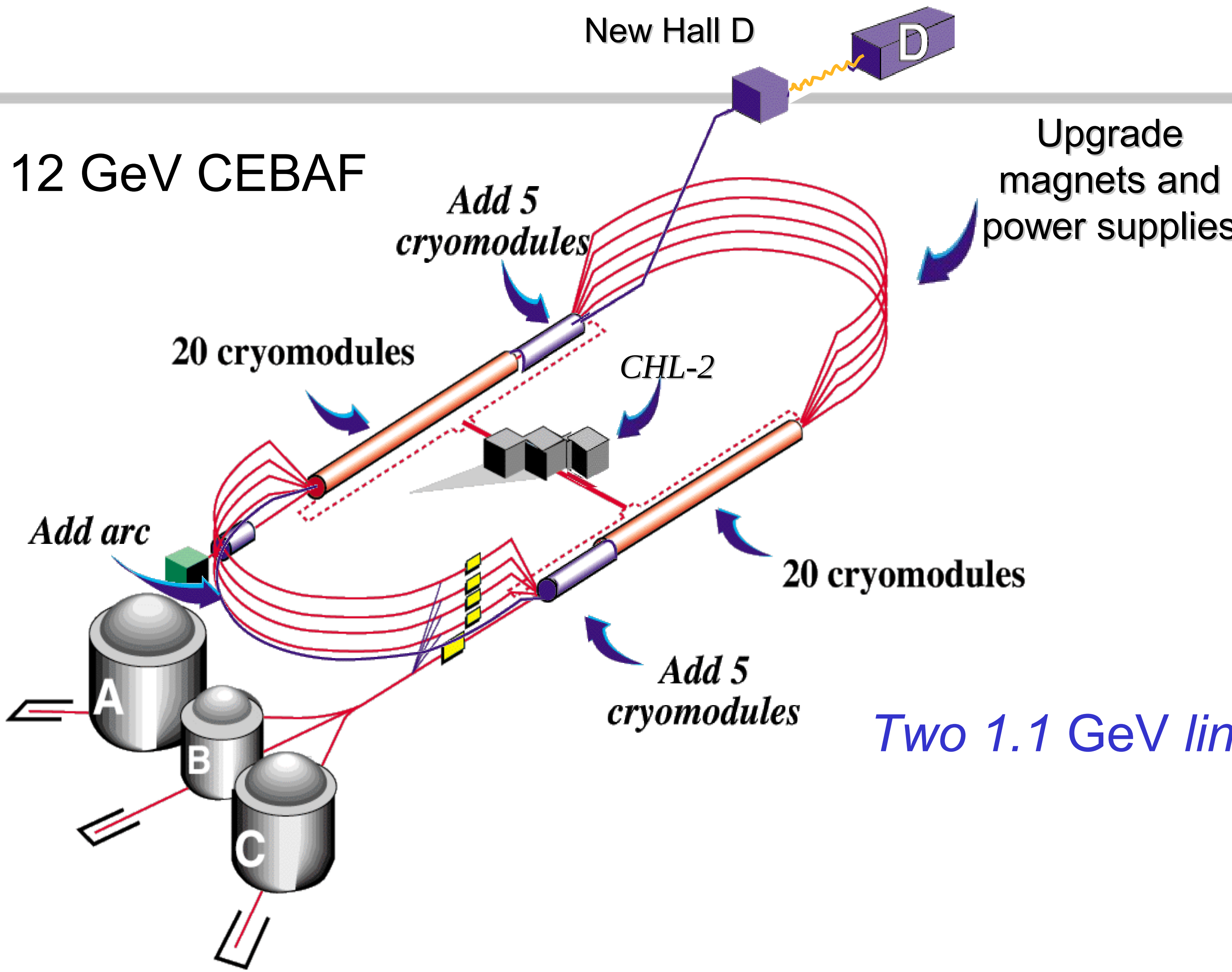
6 GeV CEBAF



Two 0.6 GeV linacs

12 GeV CEBAF



Two 1.1 GeV linacs

Beam Requirements

Parameter	Nominal Value and Range	stability (during 8 hours) (note 1)	helicity correlated imbalance averaged over 1 hour
Rms spot size at the target	A: σ_x and σ_y = 50 to 200 μm; B: 50 < σ_x and σ_y < 250 μm; C: σ_x and σ_y = 100 to 500 μm A & C may request specific sizes (note 2)	A & C: 25% of requested value; B: any value within nominal range	A & C: 100% of nominal size; B: 60 μm
Angular divergence at target	$\sigma_{x'}$, $\sigma_{y'}$ < 100 μradian	50% of value	100% of beam divergence tolerance
Beam position	value requested by experiment within 3 mm of optics axis	drifts A: < 50% of spot size; B: < 120 μm; C: < 250 μm; transients A, B, C: < 1mm	A & C < 10 μm; B < 60 μm
Beam direction	request by experiment (within 1 mradian of optics axis to dump center)	< 50 μr (1/2 beam divergence tolerance)	100% of beam divergence tolerance
Energy (average)	multipass operation: 0.63 to 5.75 GeV; 1 pass single hall operation: 0.33 GeV to 0.63 GeV	A or C: $\Delta_E/E < 1\times10^{-4}$ B: $\Delta_E/E < 5\times10^{-4}$ $\Delta_E/E < 1\times10^{-3}$ over days for all	100% of energy spread tolerance
100% of energy spread tolerance	A & C: $\sigma_E/E < 5\times10^{-5}$ for E>1GeV B: $\sigma_E/E < 4\times10^{-4}$	A & C: $\sigma_E/E < 5\times10^{-5}$ for E>1GeV B: $\sigma_E/E < 4\times10^{-4}$	N/A

Beam Requirements

Parameter	Nominal Value and Range	stability (during 8 hours) (note 1)	helicity correlated imbalance averaged over 1 hour
Background (Beam halo) close to the target	A, B, C: < $1x10^{-4}$ outside of 5 mm radius (notes 3 & 4)	any value within the nominal range	100% of nominal halo tolerance
CW average current (Note: 5 & 6)	1 μA < A < 120 μA 1 nA < B < 1 μA 1 μA < C < 120 μA A+C < 180 μA ; A + C < 800 KW A or C < 180 μA (single hall)	within +/- 5% of nominal value (includes high frequency fluctuations)	A < 200 ppm; B & C< 1000 ppm 3 Halls: excursions of 5 sec samples up to 5 x nominal value are acceptable.
Polarization (current negotiated by Physics/Accelerator Divisions)	> 70% all halls with currents up to 100 μA in A or C	polarization > 70%	N/A
Effective duty factor DF	loss (1-DF) including trips: <5% 0.33 < E < 5 GeV (5 + (E-5)*20) %: 5 < E < 6 GeV	N/A	N/A

note 1: With continuous monitoring the beam is good when within tolerances. With invasive diagnostics, one does not know beam quality between measurements. User accepts the uncertainty or provides a continuous non-invasive diagnostic.
note 2: Some beam size requests in the range will require distinct Moller optics and beam-delivery-on-target optics
note 3: After the halo monitors for halls A and C are operational
note 4: Hall A requested for FY2002 that the total halo outside a 5 mm radius be < 10-6
note 5: Lower currents can be delivered with relaxed tolerances
note 6: Proper impingement on beam dump has to be checked with accelerator operation (centering on dump face, current density on dump face, visibility on dump viewer, amount of radiation in the hall, on the site, etc…)
J-C. Denard; beam parameters

Beam Polarization

- Crucial late accelerator addition
  - Targeting ever-smaller effects (10^{-7}, 10^{-8}, ?)
- Requires polarimetry
  - Mott, Moller, Compton, et al.
  - Systematic error goals ever-decreasing
- Spin flip rate (30 Hz ➞ 960 Hz)
  - Dead time at transition becomes significant
- Helicity correlation:
  - kHz monitoring
  - Position vs. polarization (nm scale average)
  - Net charge balance ($<10^{-8}$)

Helicity Correlation Performance

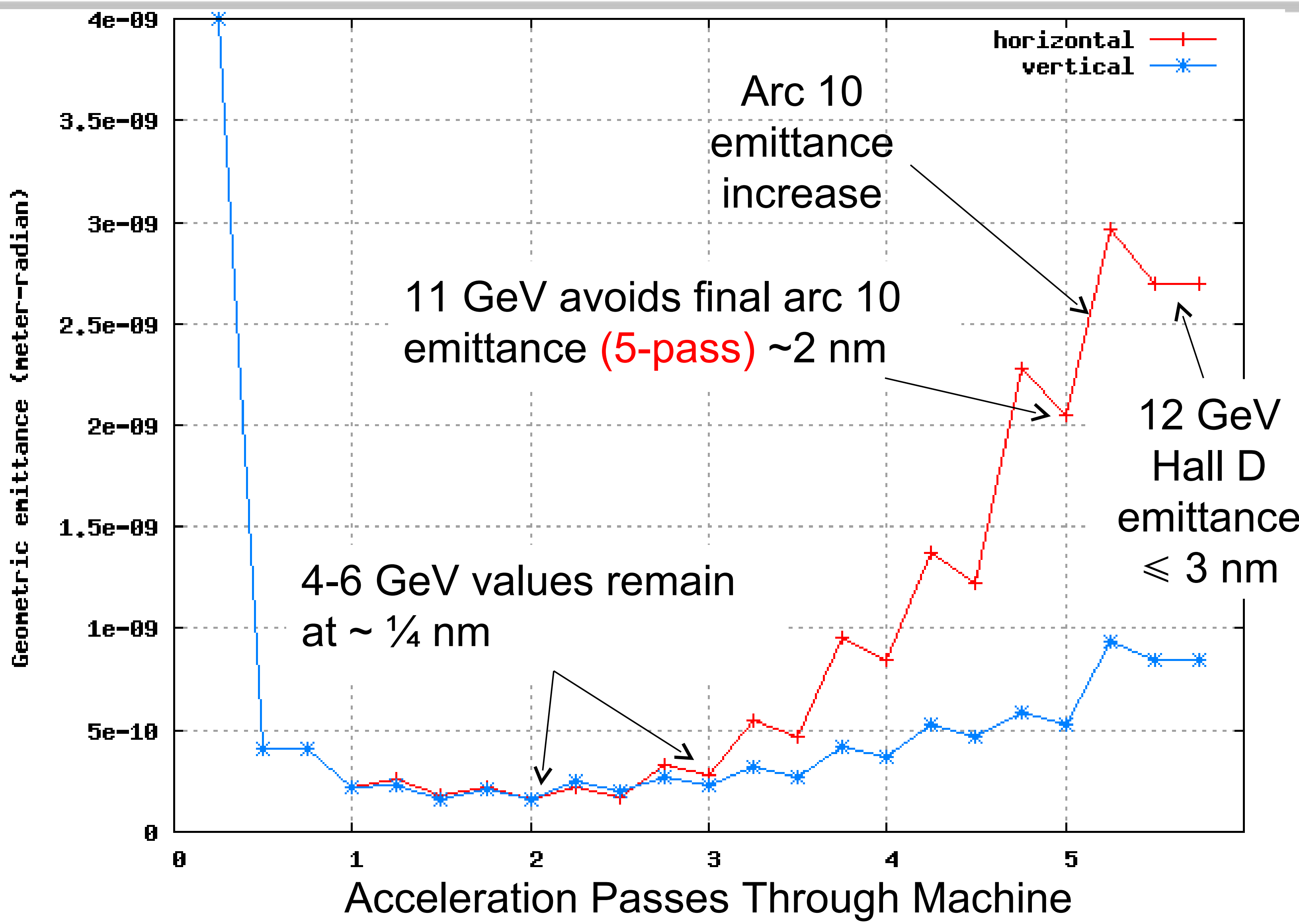
Asymmetry	Half-wave plate in	Waveplate in uncertainty	Half-wave plate out	Waveplate out Uncertainty
Charge (ppb)	19	82	-36	85
Energy (ppm)	-21	0.8	22	0.8
X position (nm)	-6	1	6	1
X' angle (nrad)	0.3	0.04	-0.1	0.04
Y position (nm)	11	1	8	1
Y' angle (nrad)	1	0.07	-0.6	0.07

From Leckey, John Poague IV, THE FIRST DIRECT MEASUREMENT OF THE WEAK CHARGE OF THE PROTON. Ph.D. dissertation, JLAB-PHY-12-1483

Special Challenges for 12 GeV

- Ever-tightening helicity correlation targets
- Manage emittance growth
  - Match envelope within high-energy arcs
  - Control M_{56} for low-emittance arc optics
    - Double-Bend Achromat
    - Theoretical Minimum Emittance
- Set-up/monitoring of sub nA beam
- Halo control
  - Hall D coherent bremsstrahlung target
  - Current above 200 μA
  - Beam power near 1 MW
- Envelope control in open-ended system
  - Improved Twiss parameter measurements

Geometric Emittance at 12 GeV (out years)



BPM Rationale at JLab

- Driven by site needs
  - Linac multi-pass separation
  - Fast FeedBack position and energy stabilization
  - nA beam sensitivity for all experimental halls
- Exploits digital receiver technology
- Control system (intended as CW) updates @ 1 Hz
  - 7 kHz parallel output used for helicity correlations
- Multiple pickups used for variable needs
  - Wires in CEBAF
  - Striplines in FEL (shunt impedance)
  - Cavity BPMs for sub-nA response

Selected BPM Parameters at JLab

BPM System	Current (μA)	Resolution (μm)	Special Features
Original 4-ch.	3--200	100	Continuous analog signals for lock-in use
Linac SEE	1--1000	50	Resolves 4 μsec linac fiducials (pass-by-pass)
Transport SEE	0.1-180	50	Multi-kHz for FastFeedBack in halls
nA BPM (cavity)	0.001-100		Very low current
nA digital 4-ch.	10s of nA	100	Low current, 10 kHz rate
	50 pA	100	10 Hz (for positrons?)

Wire pickup antennae assumed unless otherwise noted

Wire Scanner Improvements Continue

Wire scanners
- Projected beam profiles
- Wire-limited resolution
- W/Re 25 μm wire
- Carbon fiber

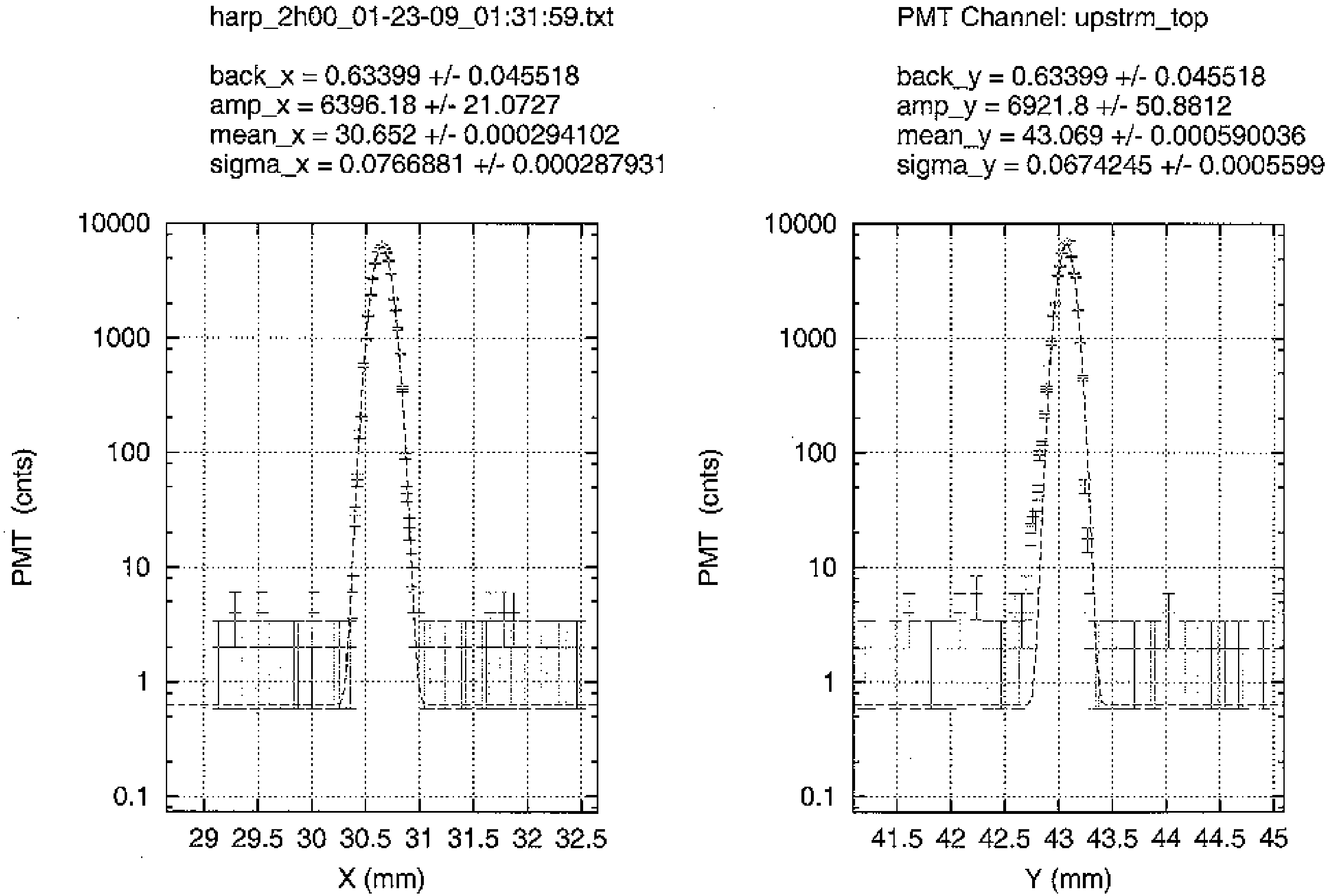
Flexible out-coupling
- Direct wire-reading
- PMT in radiation field

Destructive to beam
(Can be reciprocal)

High dynamic range harp
- PMT/scaler readout
- Used routinely in Hall B
- > 10^4:1 dynamic range

High dynamic range system for beam extraction region is in preparation
- Measure each circuit Twiss parameters
- Envelope data for
  - Recirculation match
  - Extraction match

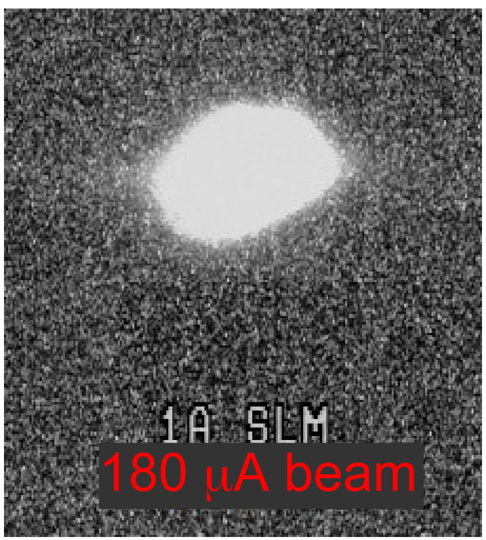
High dynamic range profile monitors

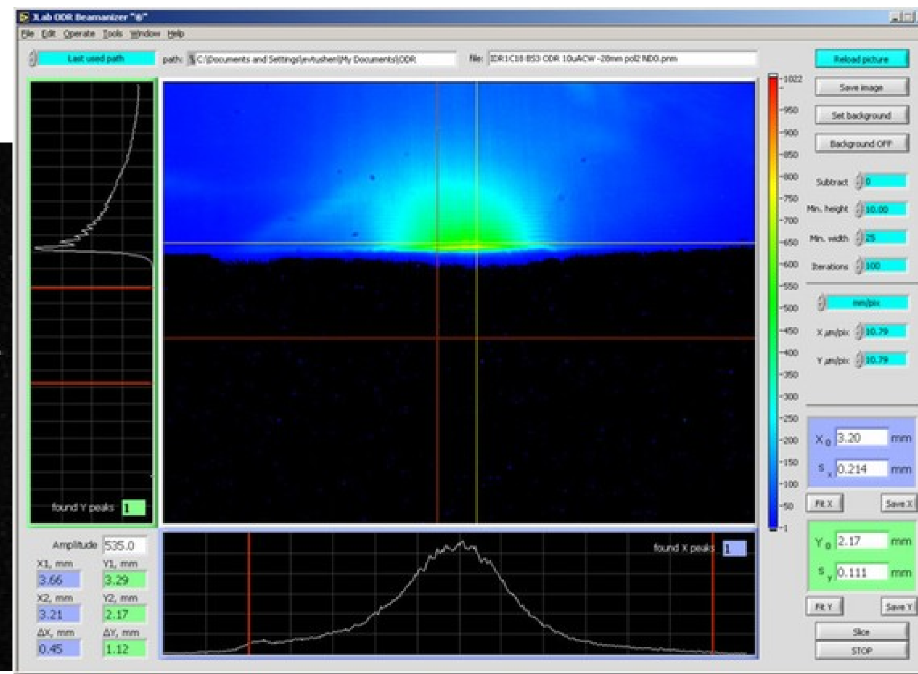


5-pass beam to Hall B, 5892 MeV

Minimally Invasive / Parasitic Monitoring

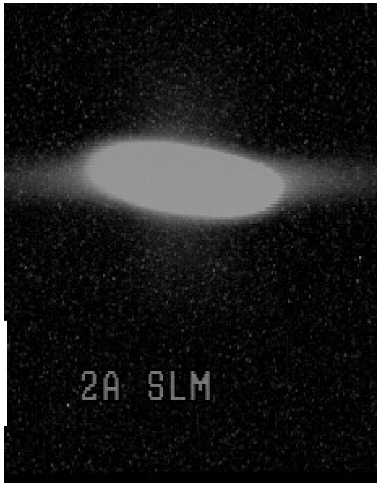
- Required for CW monitor
  - Synchrotron Light
- SLM profile monitors in
  - Arcs 1A, 2A
  - Hall B transfer line
  - Hall A dispersion peak
- Optical Diffraction Radiation
  - Initial work promising
  - Non-intercepting
  - 10 μA CW beam for photo

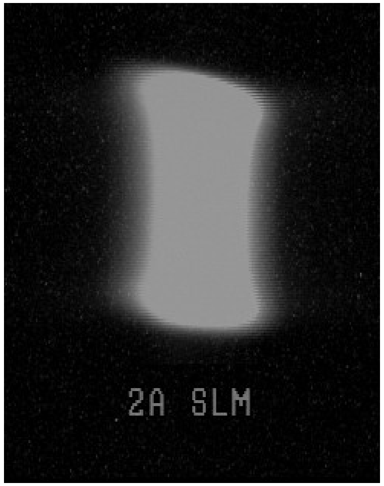




Synchrotron Light Monitor In Action

- Common fault: klystron saturation as current rises
  - economize line power
- Symptom: loss of energy lock and loss of beam
- One day it was different
- Vertical oscillation, not horizontal, as for energy
- Confirmed via RF measurements as BBU
- Direct RF signals from
  - BPM electrodes
  - RF cavity HOM ports





Absolute Beam Energy

- "Ninth Dipole" Project (P. Vernin / CEA, France)
- Precise inter-calibration of nine 3-m dipoles
- Above-ground dipole
  - Series-connected
  - Temperature-matched
- Tunnel ambient fields accurately mapped
- Field integral measured with scanning coils/NMR
- Electron (and tunnel) bend angle measured
- Precise momentum from field integral and bend angle (quads de-Gaussed)

- e-p system (medium-energy elastic scattering)
- Another French project for Hall A

- Standard transferred to other systems
- Calibration of dipole strings for Hall A/C (ambient earth's field effect is reversed)
- Absolute beam orbit used to correct energy relative to dipole field
- Matches beam energy measurements to within 5×10^{-4} relative precision

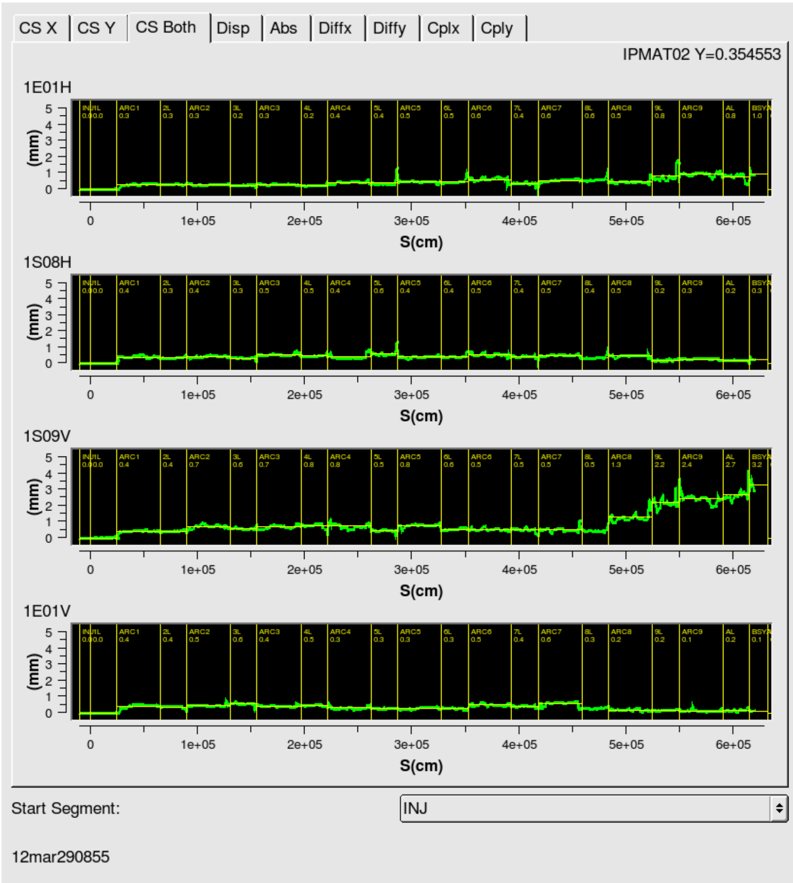
Courant-Snyder "Envelope Monitor"

- Standard ellipse to circle phase-space transformation
$$\left(x, x'\right) \rightarrow \left(x/\sqrt{\beta}, \left(x' + \alpha x/\beta\right)/\sqrt{\gamma}\right)$$ == (u,v)

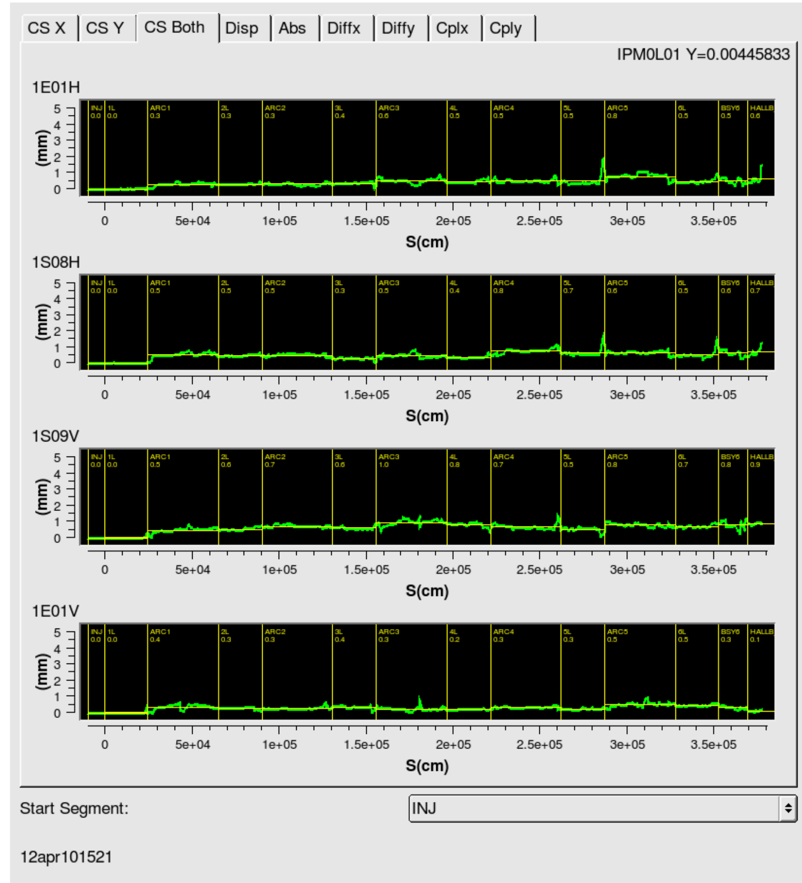
- $(u^2 + v^2) * p_z$ constant along the trajectory
- In a lattice with "similar" Twiss values
  – $u^2 + v^2$ will drift as mismatch develops
  – phase errors accumulate
- Can be re-tuned to the original "area constant"
- Cumulative phase error grows
- The envelope (β) can be well-behaved
- The slopes (α) will incidentally be close

Differential Orbit Analyzer: C-S Plot

Third trace grows while fourth shrinks: needs tuning



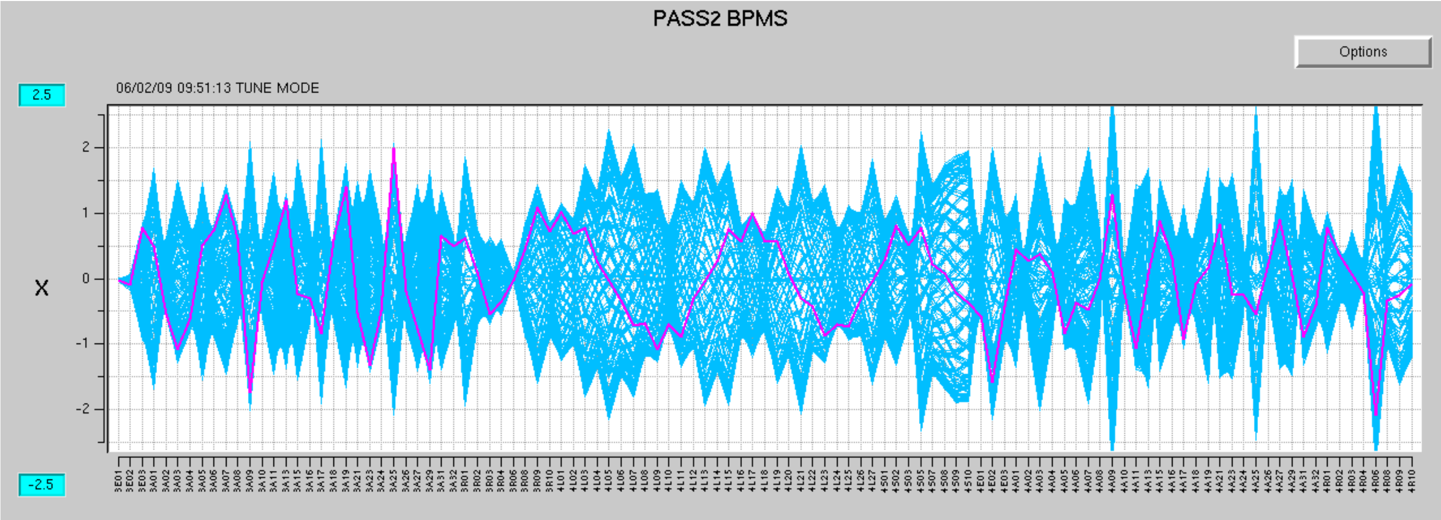
Adequately tuned; all traces sensibly constant



Two differential orbits tracked in each transverse plane

More Than Two Orbits Per Plane

- Trace a bundle of rays (with a beam-like character)
- The x_{peak} (and x_{rms}) curves are proportional to $\sqrt{\beta}$
- Local (x,x') plots will be transformed phase ellipses
- Read the Twiss parameters from the plots if the BPMs are adequately accurate (x' from short-range model)
- Or fit transfer functions, calculate new Twiss values, and rematch as needed



Engineering Physics Ph.D. Project (Ryan Bodenstein, U.Va), developing transfer line tuning package.

Energy Stability Monitors

- Arc energy locks and Fast FeedBack
- Multiple BPMs separate energy from steering
- Energy remains well-matched to dipole field
- Deviations are tracked and compensated by FFB to ~100 Hz bandwidth
- Arc locks (1 Hz BPMs) correct only at sub-Hz bandwidth
- Precision energy monitoring and correction allows on-line tuning of single cavities to peak energy
- Tolerance ~ 2 degrees
- Also enables inter-cavity normalization
- Global absolute calibration of all 330 SRF systems

Phase Modulation System (MOMod)

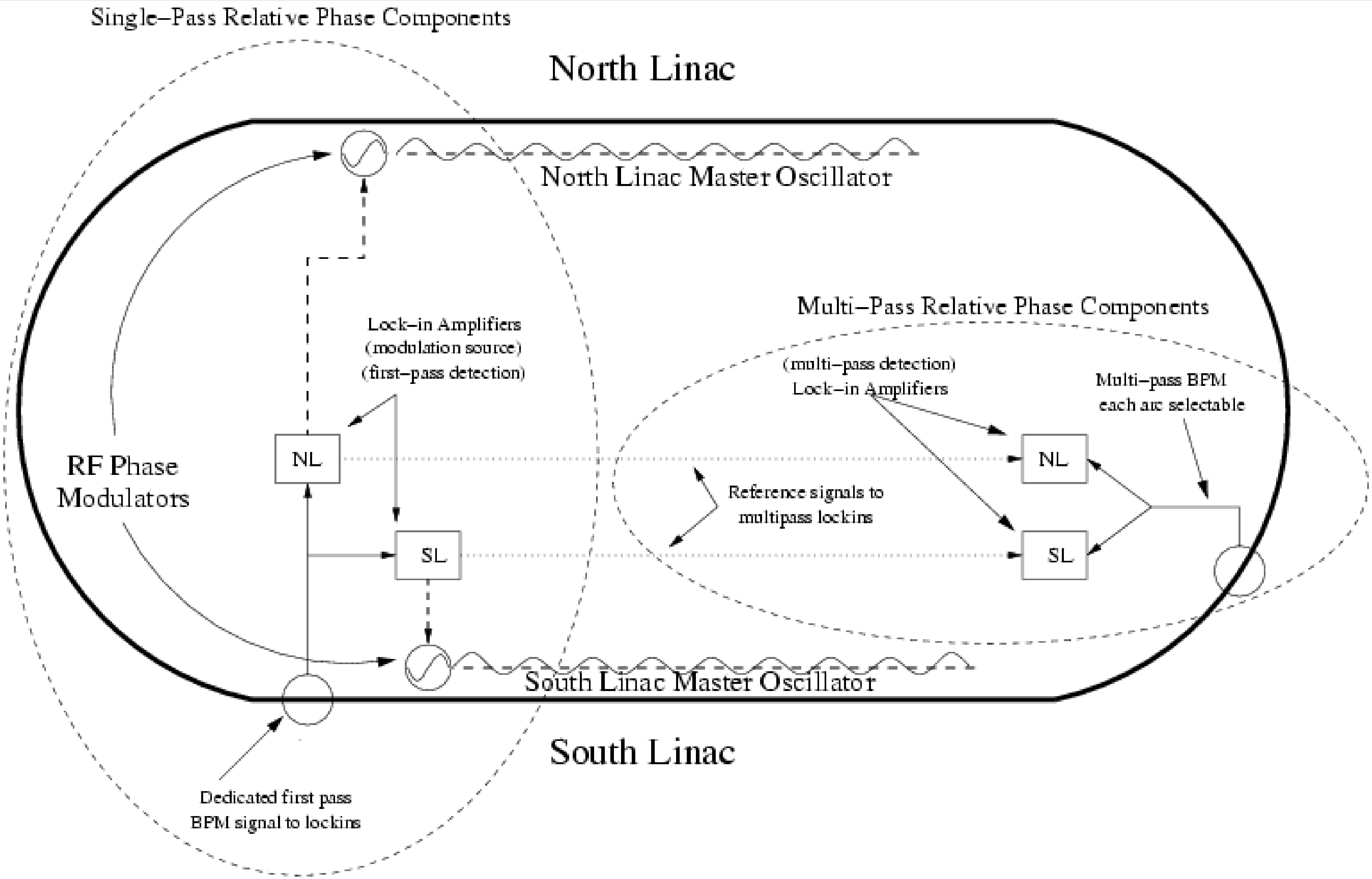
MOMod – M(aster)O(scillator)Mod(ulator) Principle:

- Modulate linac phase +/- 0.04 degrees (390 +/- 7 Hz)
- Dispersively detect first harmonic energy modulation
- Feed back on linac phase to null signal
- First pass regulation typically +/- 0.02 degrees
- Drifts of higher passes indicates path length error

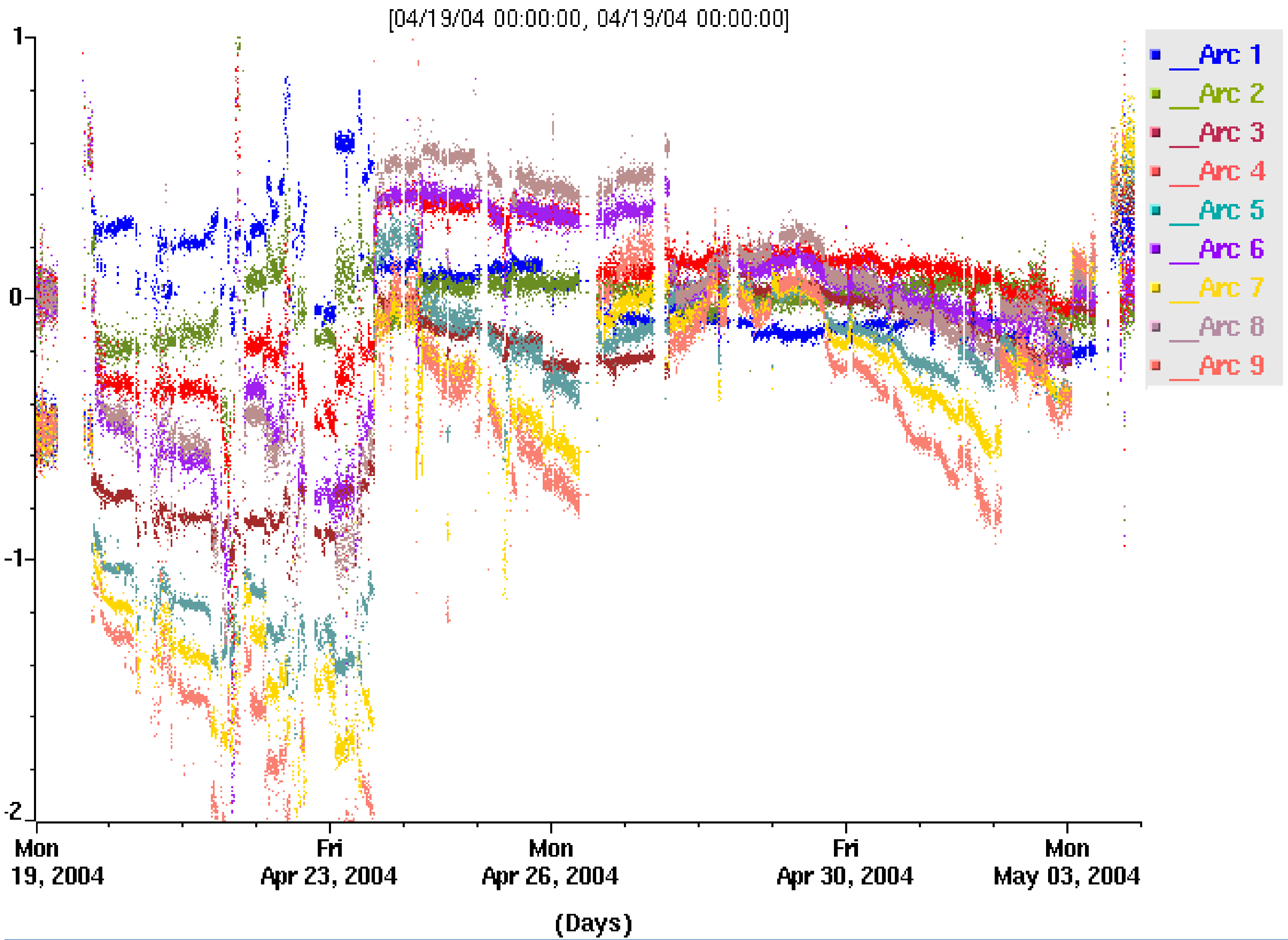
Mechanism and purpose:

- Lock-in amplifiers monitor energy at a single BPM
- Controls first-pass RF phase
  - Other systems regulate beam energy
- Simultaneous energy control for all passes requires:
  - First pass gradient and phase control
  - All passes on-crest (control circulation time)

Overall MOMod Layout

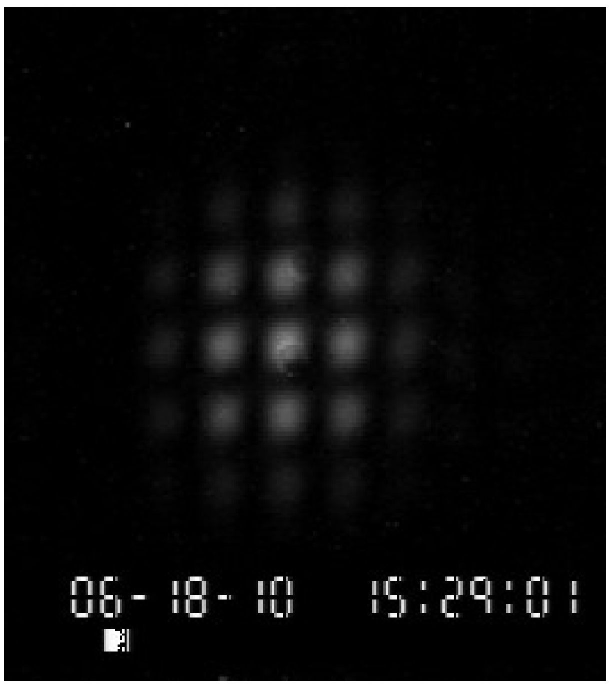


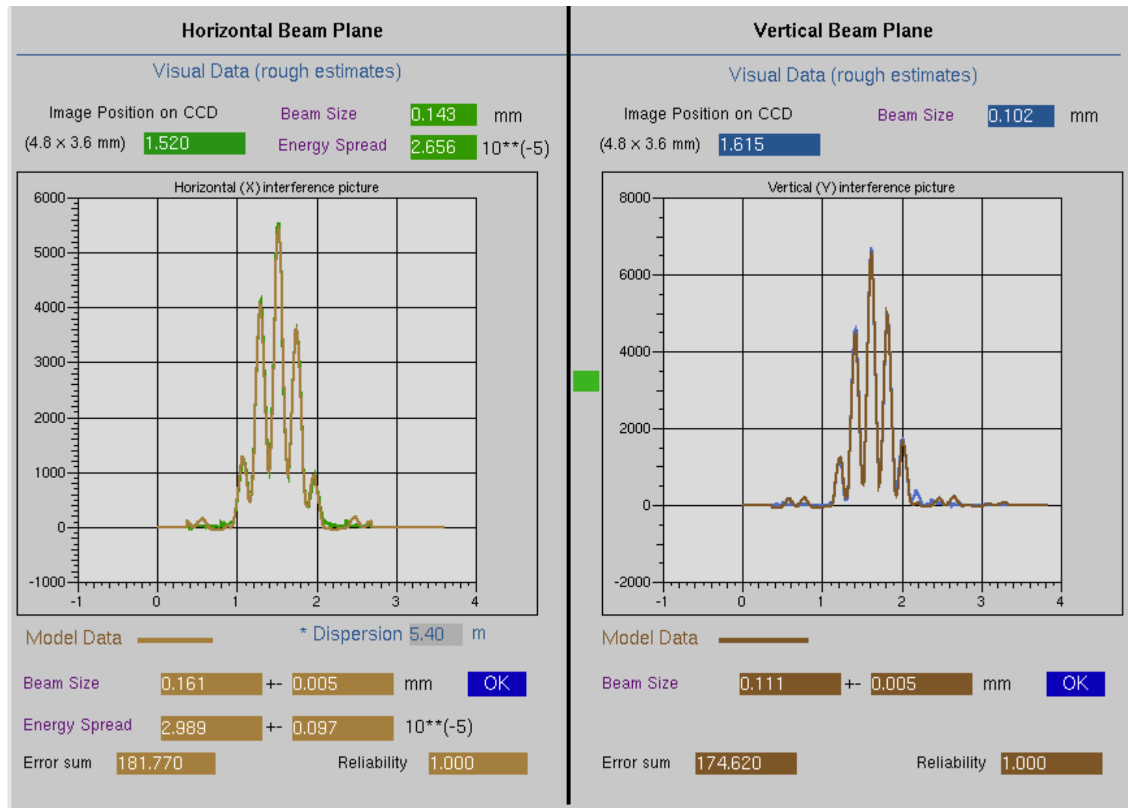
On-line (CW) Multi-pass Path Monitor



Energy Spread Monitors

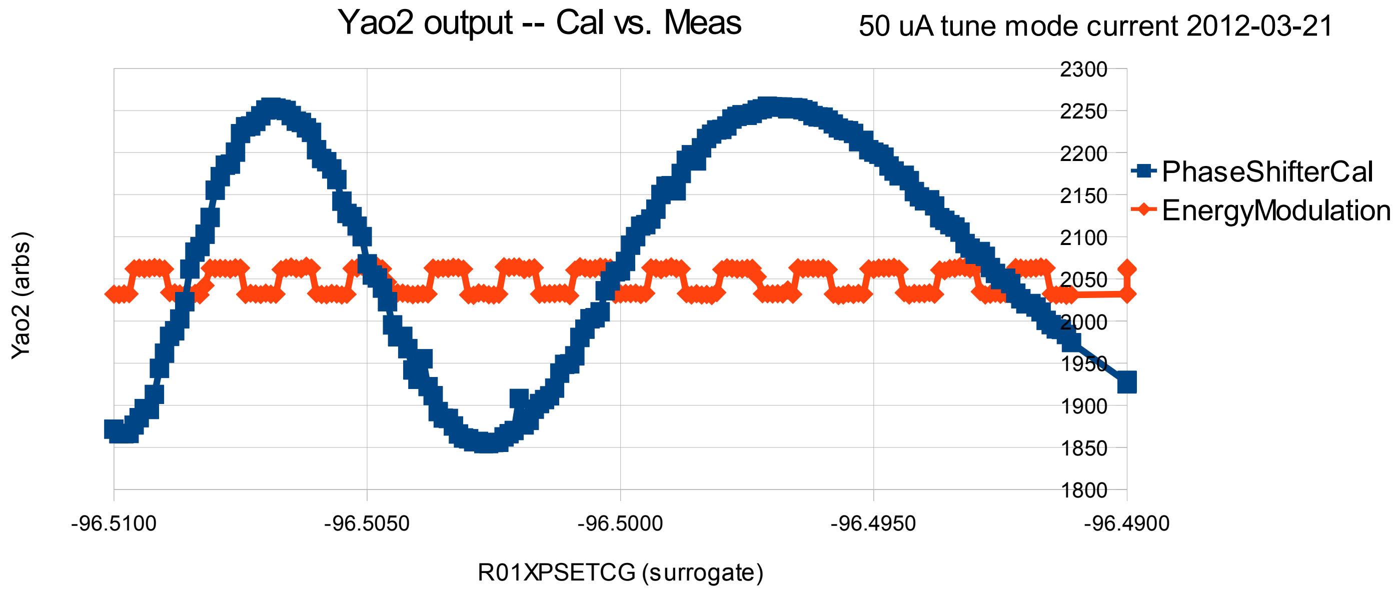
- Energy spread comes from RF regulation errors, finite bunch length, and energy spread from injector
- Synchrotron Light Interferometer in Hall A monitors beam size at low-β, dispersively dominated point.





Bunch Length / Bunch Formation

- Time-of-flight ("Yao technique") for zero-order set-up
  - Modulate T_{in}, measure T_{out} correlation
  - Zero modulation out indicates a longitudinal focus
  - Empirical tuning accommodates finite current
- Can also measure static M_{56} for a beam line



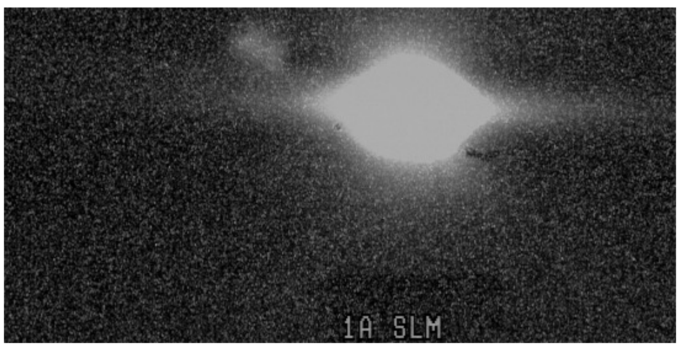
Phase shifter calibration (blue) plus the result of a 0.48% relative momentum modulation. The injection chicane M56 is ~ -25 cm.

Bunch Length in North Linac @ 180 μA

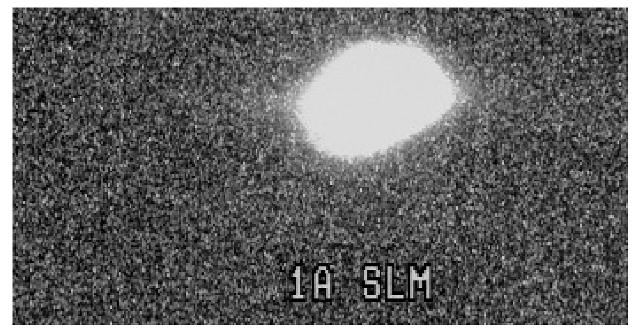
- Initial set-up
- On-crest photos (A1, A2)
- -4 degrees (B1), η = 5m
- Bunch duration ~3.5 psec

- Magnetic compression (M_{56} = -25 cm)
- -4.5 degrees (B2), η = 5m
- Bunch shortened by half

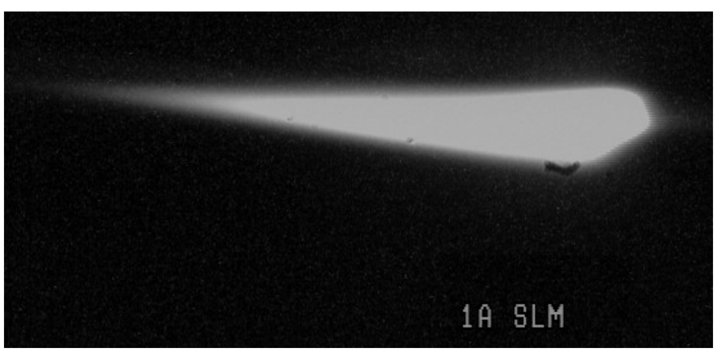
A1



A2



B1

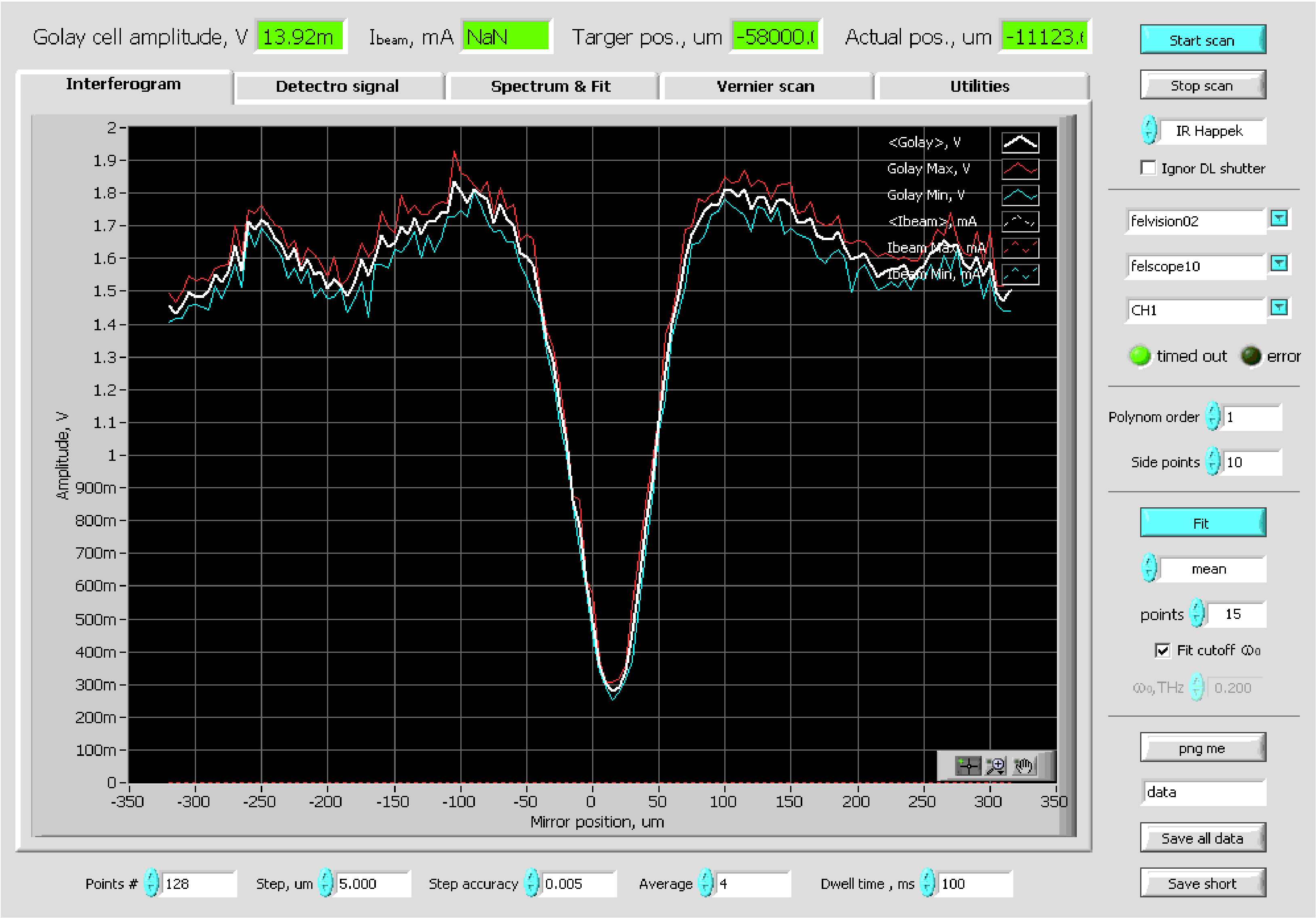


B2

Coherent Radiation Effects

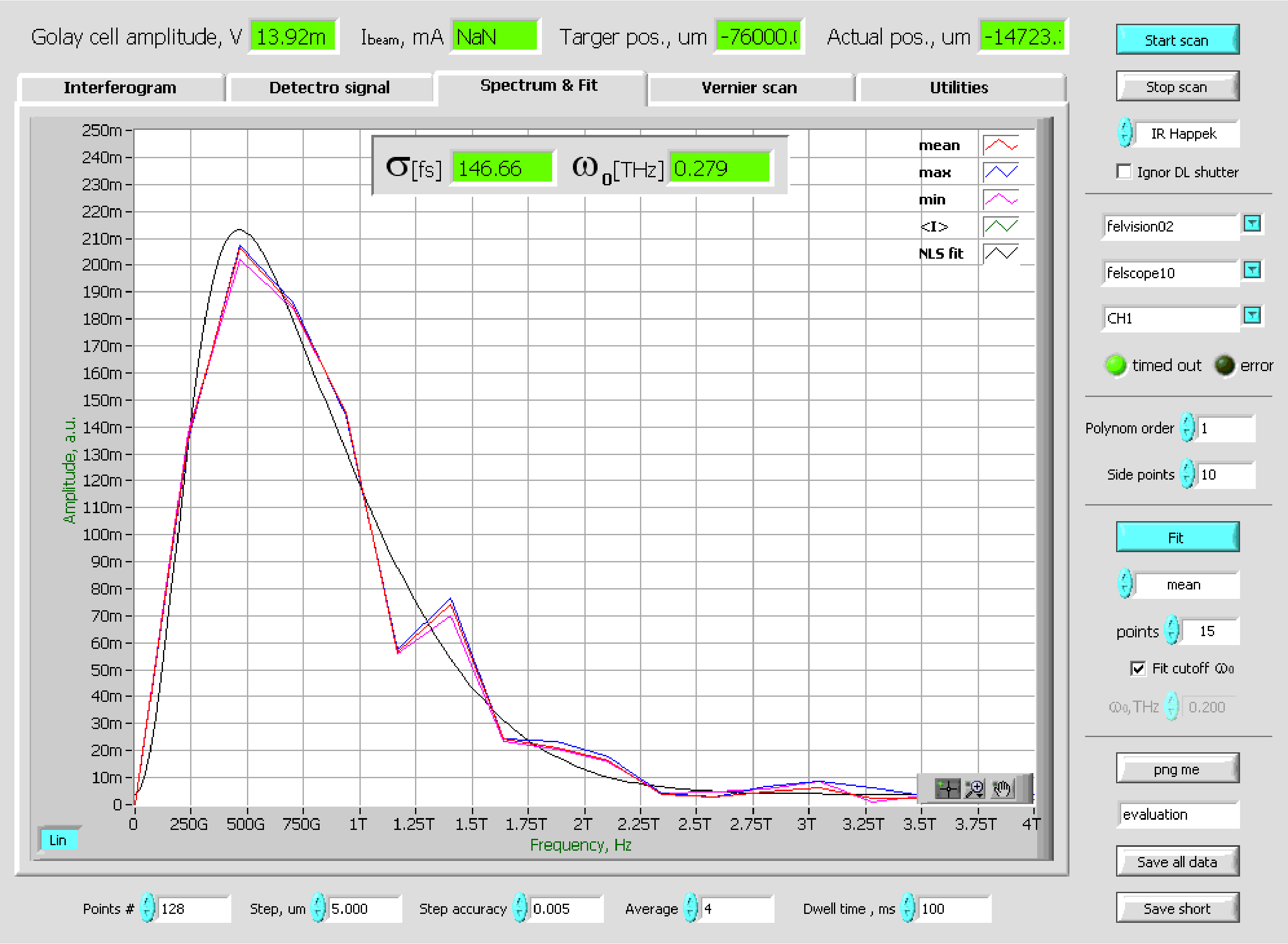
- Coherent Transition Radiation
  - FEL bunch length measurement mechanism
  - FEL example measurement above was fitted to a Gaussian bunch of duration approximately 146 fs
- CSR was attempted in CEBAF as a bunch length indicator but the whisker diode used was too vulnerable to spark-down in the injector

Coherent Transition Radiation Bunch Length Happek Data



Courtesy Pavel Evtushenko

Coherent Transition Radiation Bunch Length Fit (146 fs)



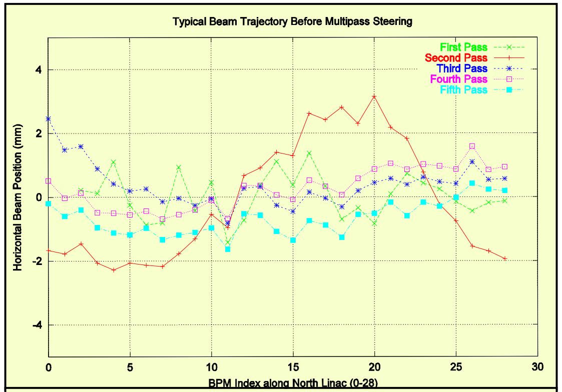
Courtesy Pavel Evtushenko

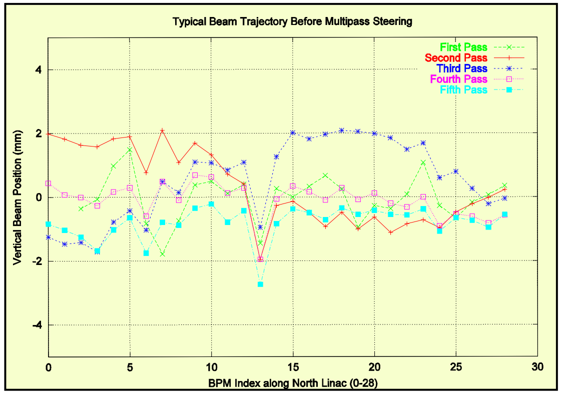
Ground Motion Tracking

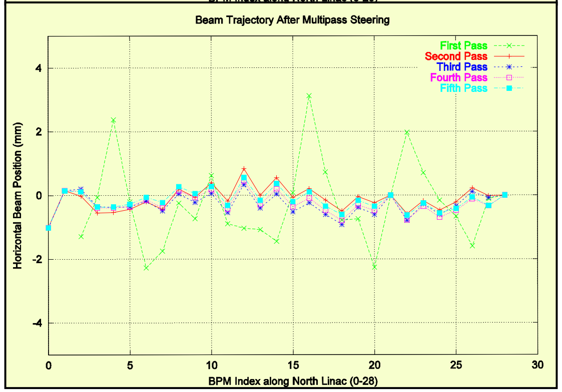
- Multiple beam energies in a common transport line:
- Unique all-on-center solution: it has to be perfect
- Multipass BPM data contain survey data which can be read, maintained and fed back to set-up

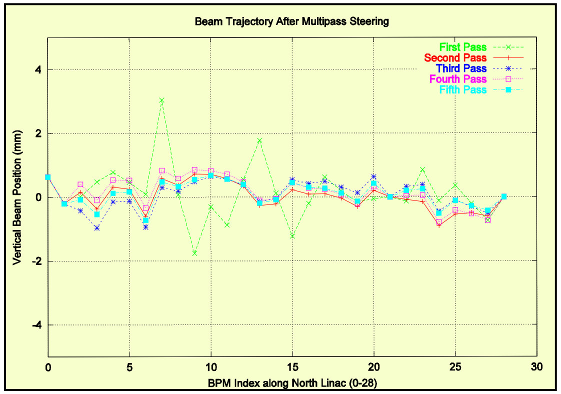
- Orbits as-found; progressively further off-axis at higher energy

- Use correctors to offset quadrupole centers to common axis







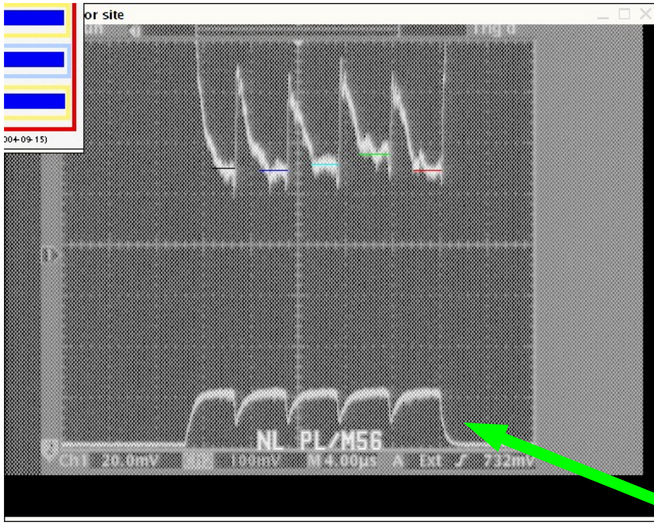


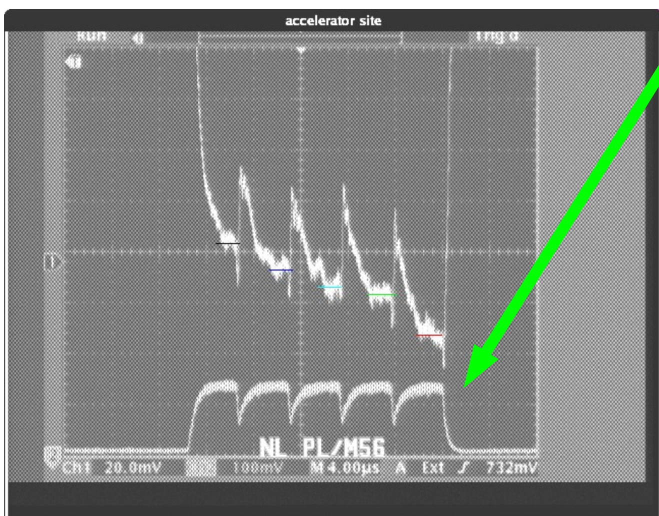
Thermal Expansion of Tunnel

- Thermal cycles change the accelerator circumference
- Annual thermal cycle moves machine by millimeters
- October 2010 Expansion Test
- Raised tunnel water supply temperature 14 degrees F
- North and South Linac tune mode time-of-flight systems monitored path length changes
- Intended to model 12 GeV thermal load
- Estimated as 40% test of 12 GeV tunnel heating

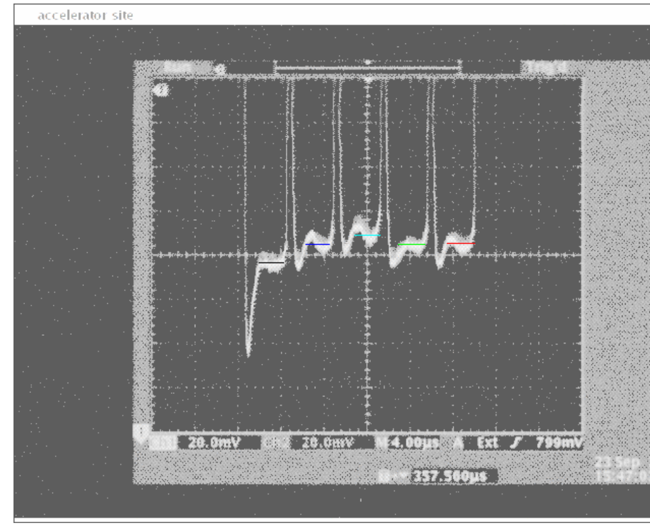
Expansion Test (October 2010)

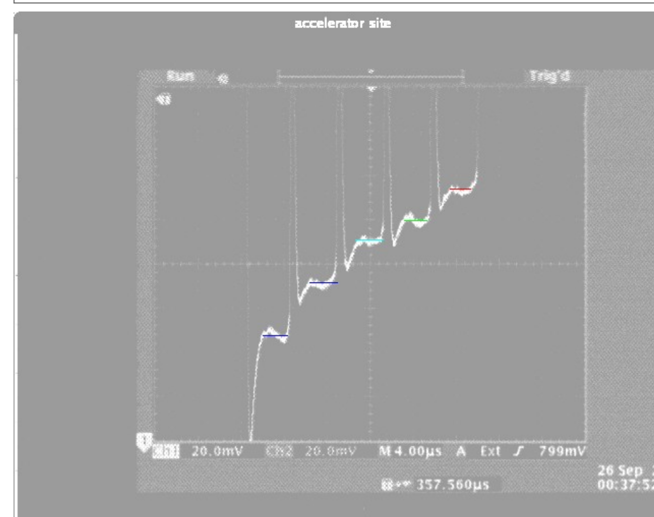
North Linac





South Linac



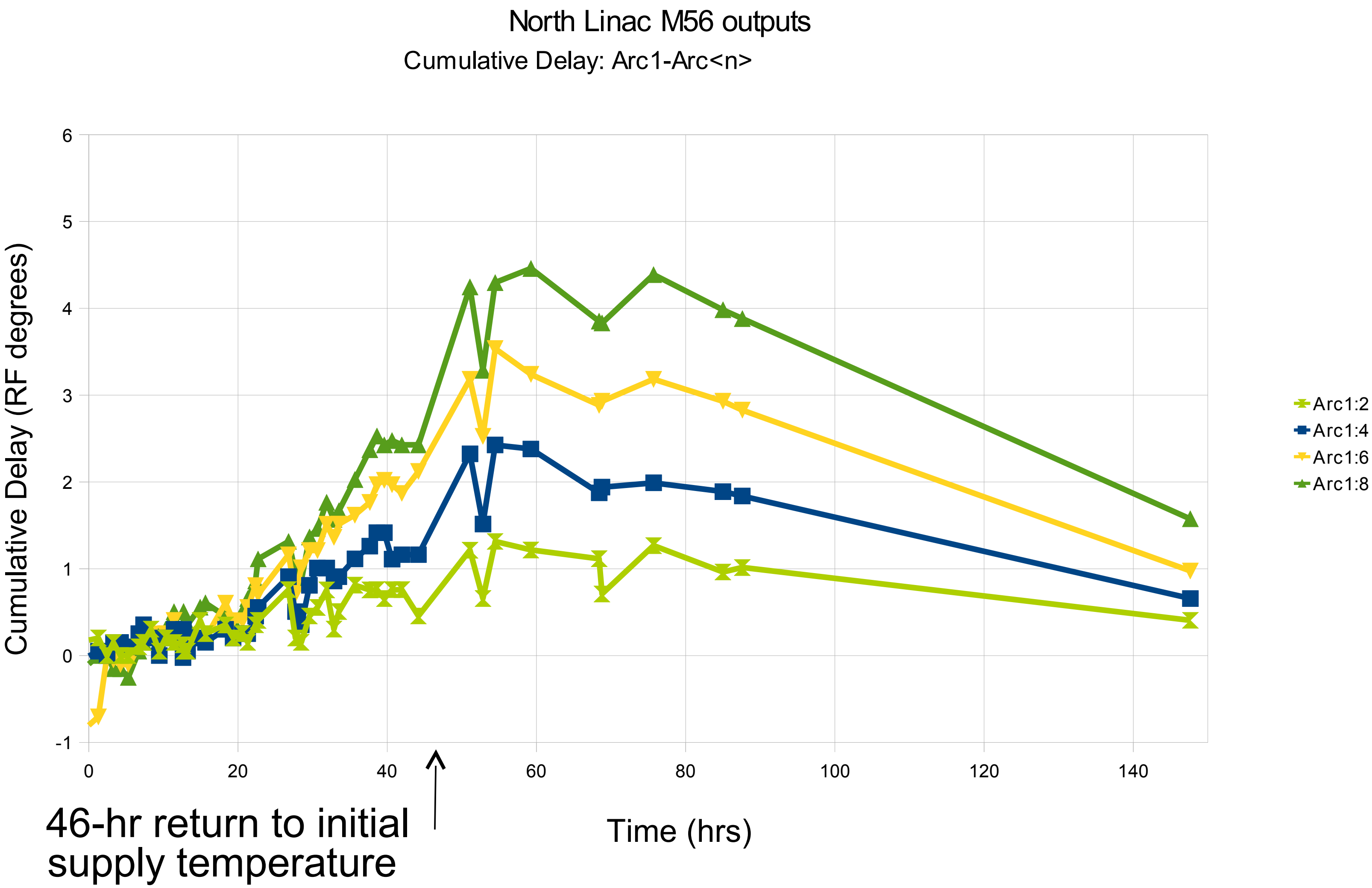


Before (above) and mid-run (lower) traces for linacs

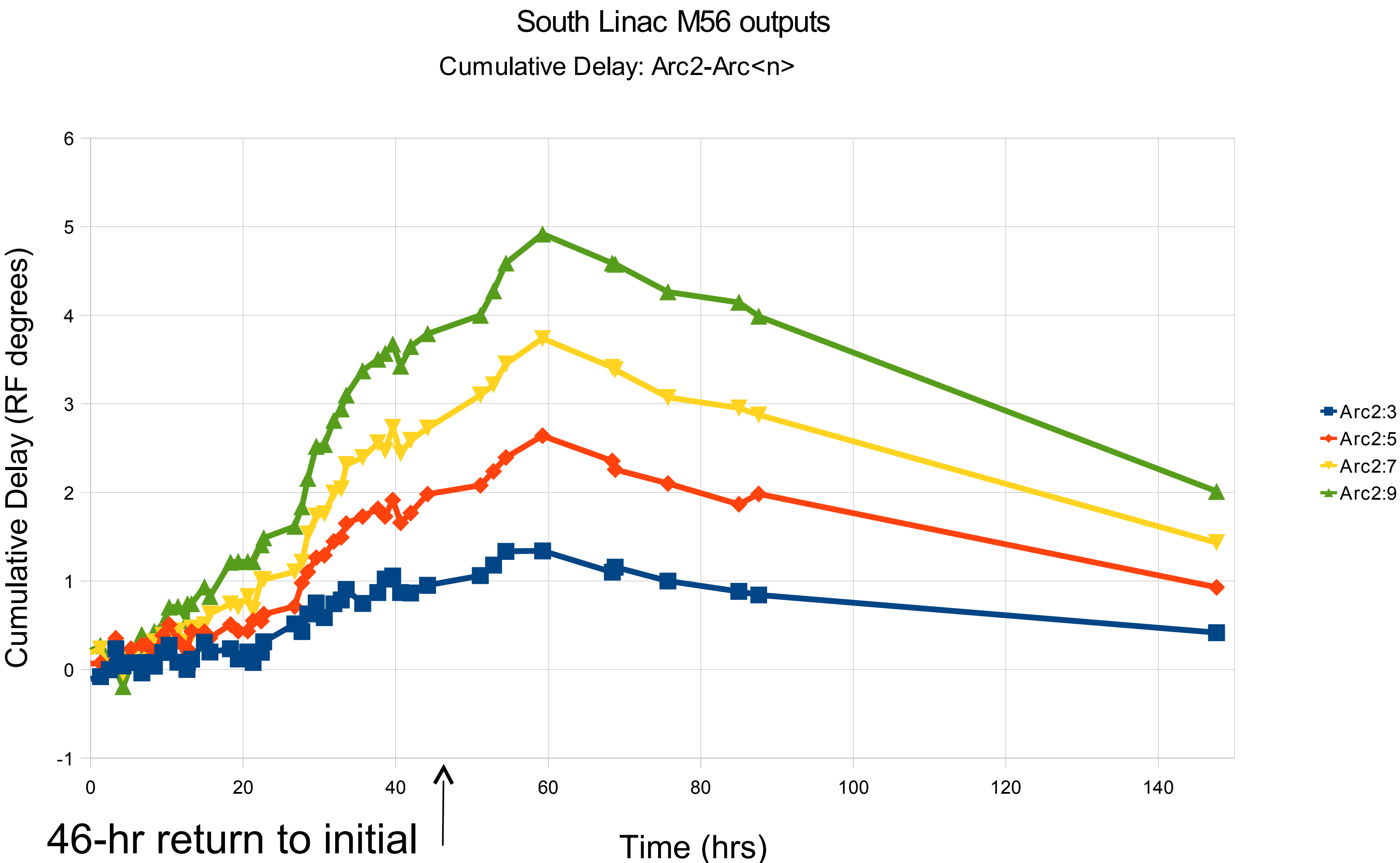
Current traces monitor 5 pass transport for beam loss.

The two systems have an instrumental sign difference in response for time-of-flight.

NL Path Length Monitor During Expansion Test



SL Path Length Monitor During Expansion Test



46-hr return to initial supply temperature

Future Diagnostic Opportunities

- Full-current CW profiles at targets

- Low-current monitoring of sub-nA beams
  - Digital receiver development
  - Possible positron applications
  - Optical applications, synchrotron light?
  - kHz position readout supports nA Fast FeedBack

- Open-ended systems do not self-diagnose
  - Beam line transforms beam rather than defines it
  - Twiss parameters must be coaxed from beam
  - Independent laser sources for 3 halls
    - Independent variability

The immediate user: the operator

- Diagnostics are components of larger systems
- Purpose: enable the operator to satisfy the user
- Request: “make it as good as yesterday”
  “(better is OK, too...)”
- Uses:
  - Initial set-up
  - Fine-tuning
  - Monitoring
  - Improving
- The beam reveals the machine properties
- Iteratively improve the machine, the beam, the mach...