USPAS Course
on
Recirculated and Energy Recovered Linear Accelerators

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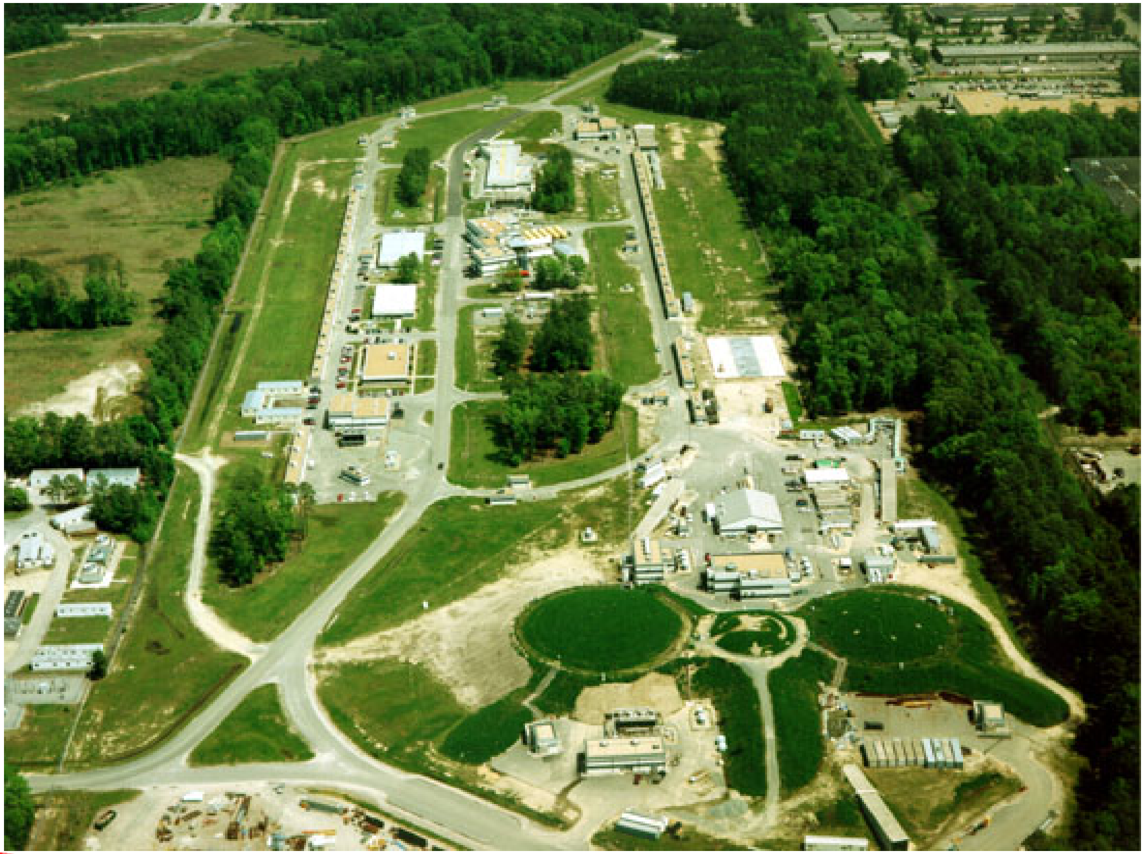
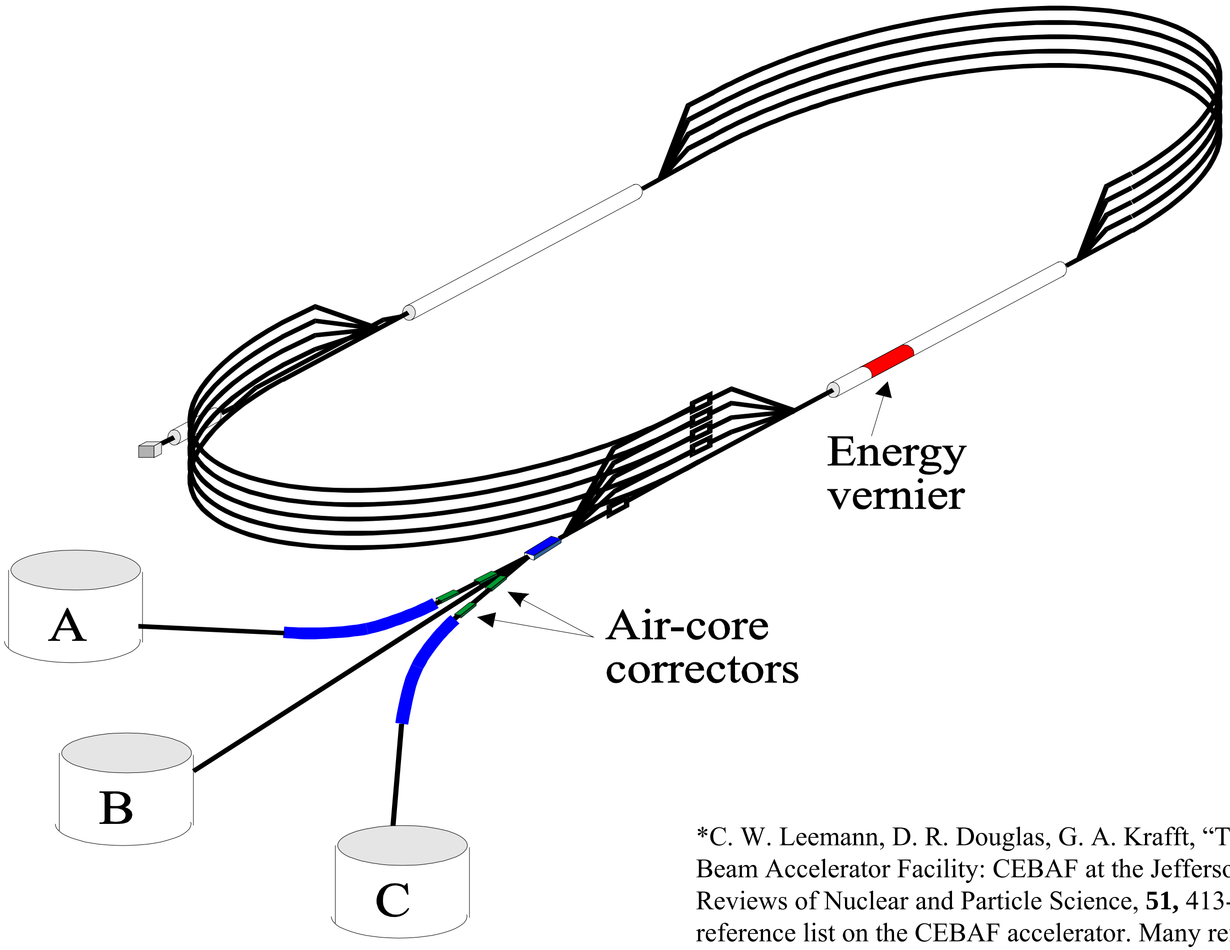
Lecture 15

Beam Performance at CEBAF at Jefferson Lab

- Most radical innovation (had not been done before on the scale of CEBAF):
  - choice of srf technology
- Until LEP II came into operation, CEBAF was the world's largest implementation of srf technology.



CEBAF Accelerator Layout*

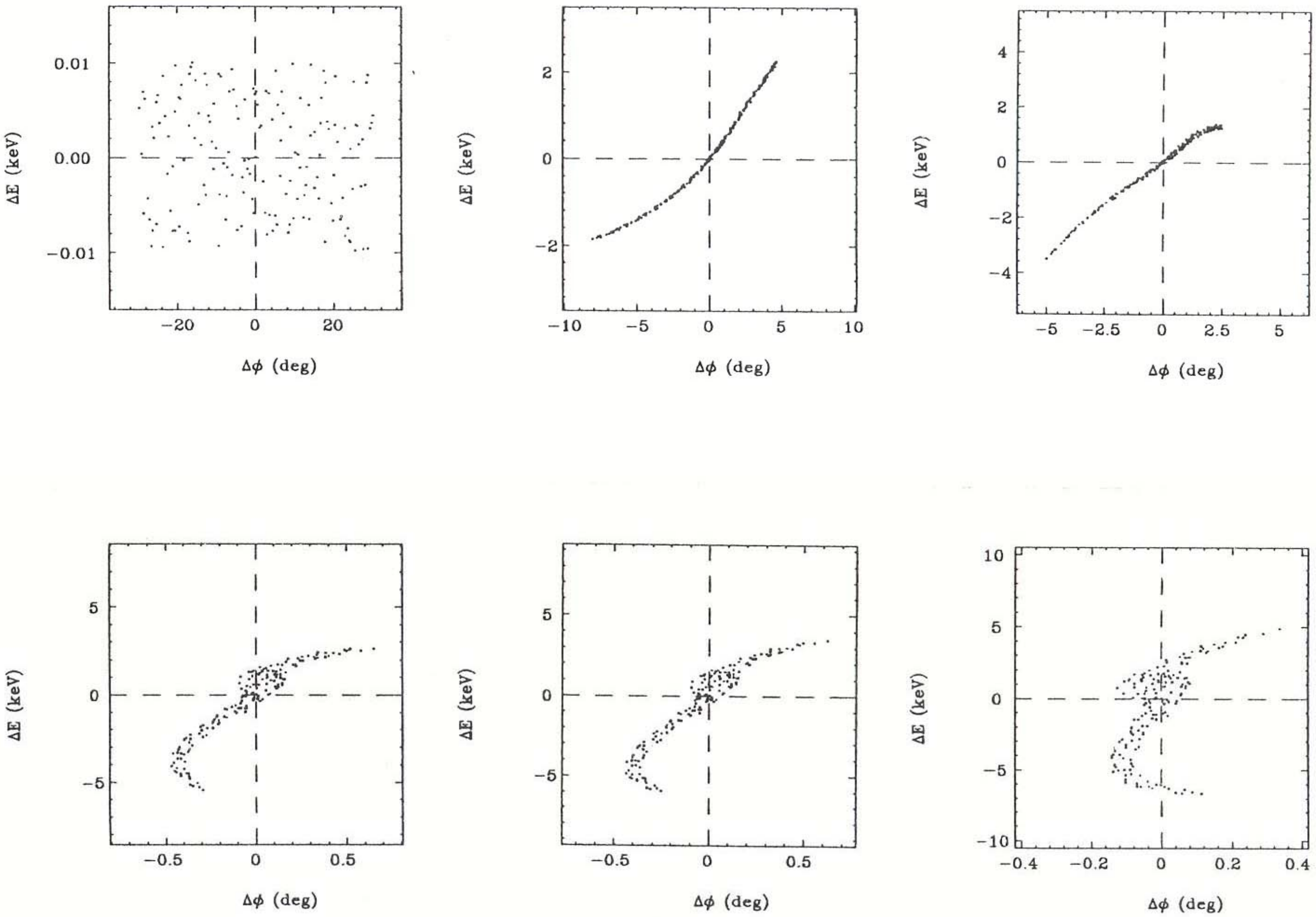


*C. W. Leemann, D. R. Douglas, G. A. Krafft, “The Continuous Electron Beam Accelerator Facility: CEBAF at the Jefferson Laboratory”, Annual Reviews of Nuclear and Particle Science, **51,** 413-50 (2001) has a long reference list on the CEBAF accelerator. Many references on Energy Recovered Linacs may be found in a recent ICFA Beam Dynamics Newsletter, #26, Dec. 2001: http://icfa-usa/archive/newsletter/icfa_bd_nl_26.pdf

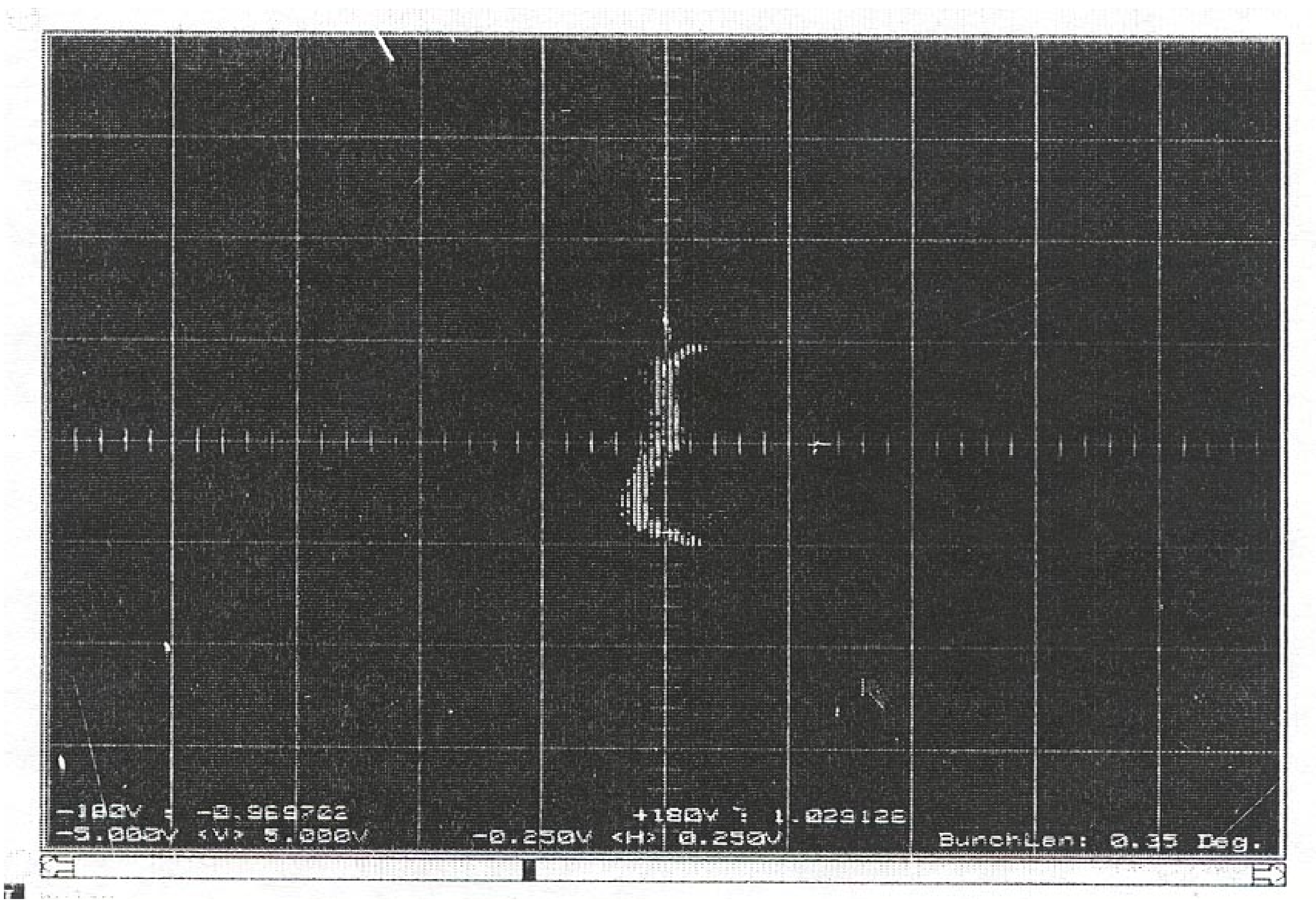
CEBAF Beam Parameters

Beam energy	6 GeV
Beam current	A 100 μA, B 10-200 nA, C 100 μA
Normalized rms emittance	1 mm mrad
Repetition rate	500 MHz/Hall
Charge per bunch	< 0.2 pC
Extracted energy spread	$< 10^{-4}$
Beam sizes (transverse)	< 100 microns
Beam size (longitudinal)	100 microns (330 fsec)
Beam angle spread	$< 0.1/\gamma$

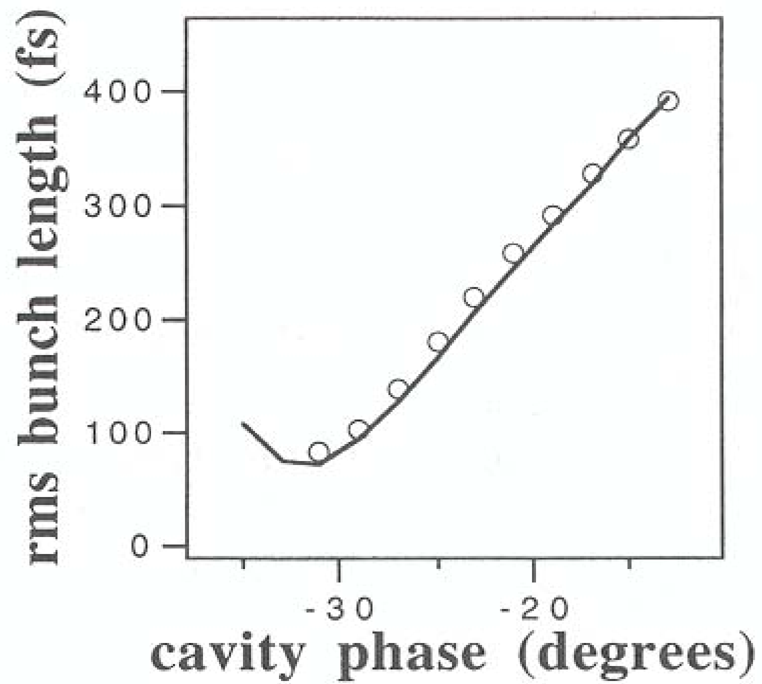
Calculated Longitudinal Phase Space



Some Early Results

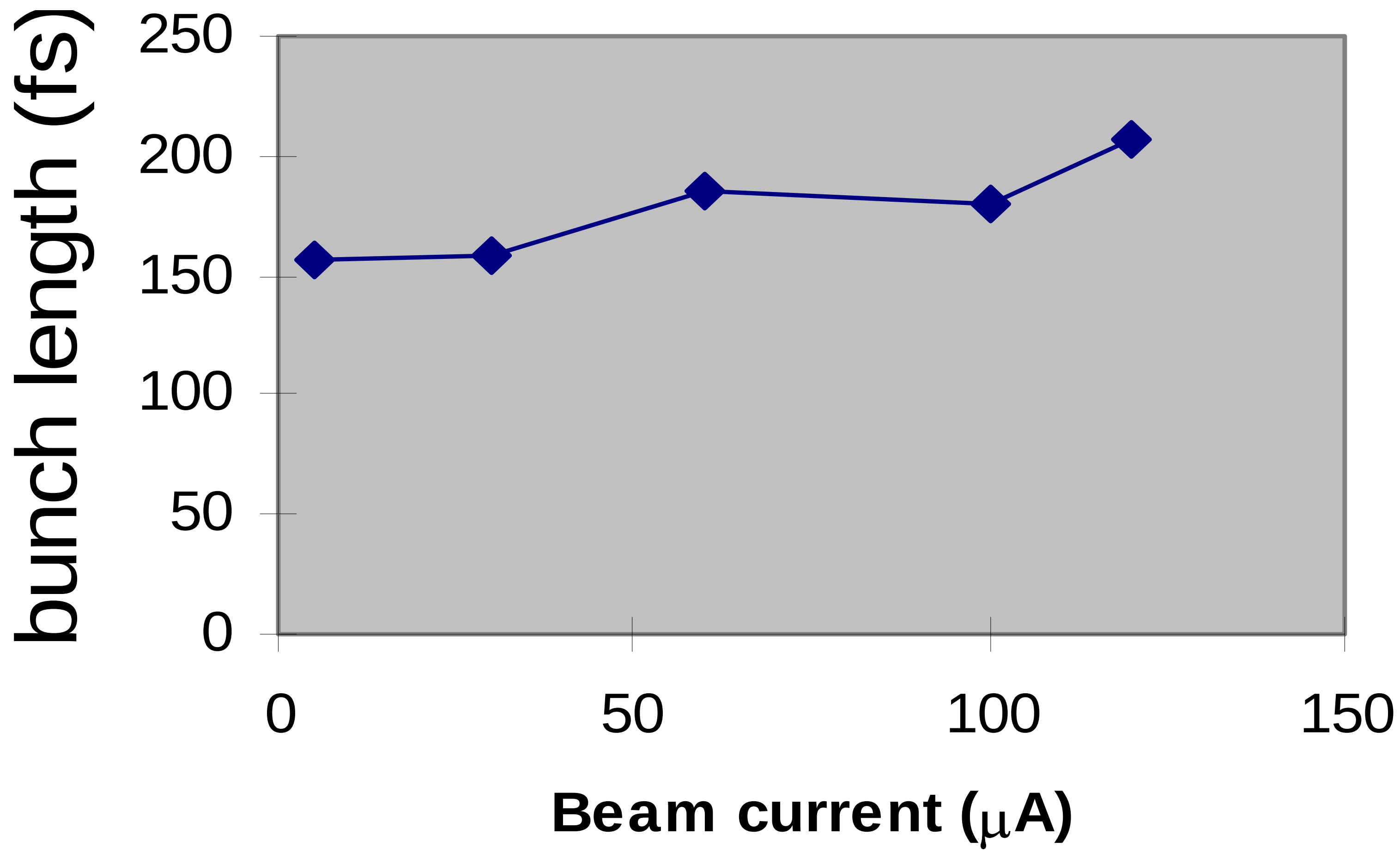


Short Bunches in CEBAF



Wang, Krafft, and Sinclair, Phys. Rev. E, 2283 (1998)

Short Bunch Configuration



Kazimi, Sinclair, and Krafft, *Proc. 2000 LINAC Conf.*, 125 (2000)

Path Length System

Elements

- Fundamental mode pickup cavities at end of either linac
- Precision phase detectors
- 10 Msample/sec triggered transient recorder
- Software

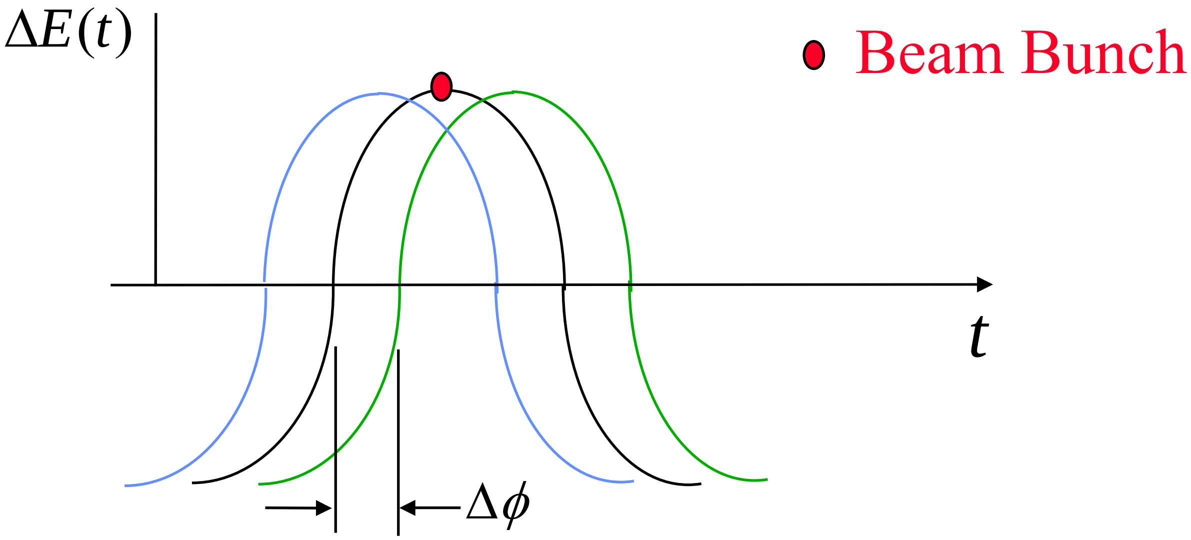
Beam conditions

- Around 3 microA macropulse current
- 4 microsec beam pulse

Performance

- Several tenths of a degree single shot
- Under one tenth of a degree (185 fsec/56 micron) with averaging
- M56 to under 10 cm

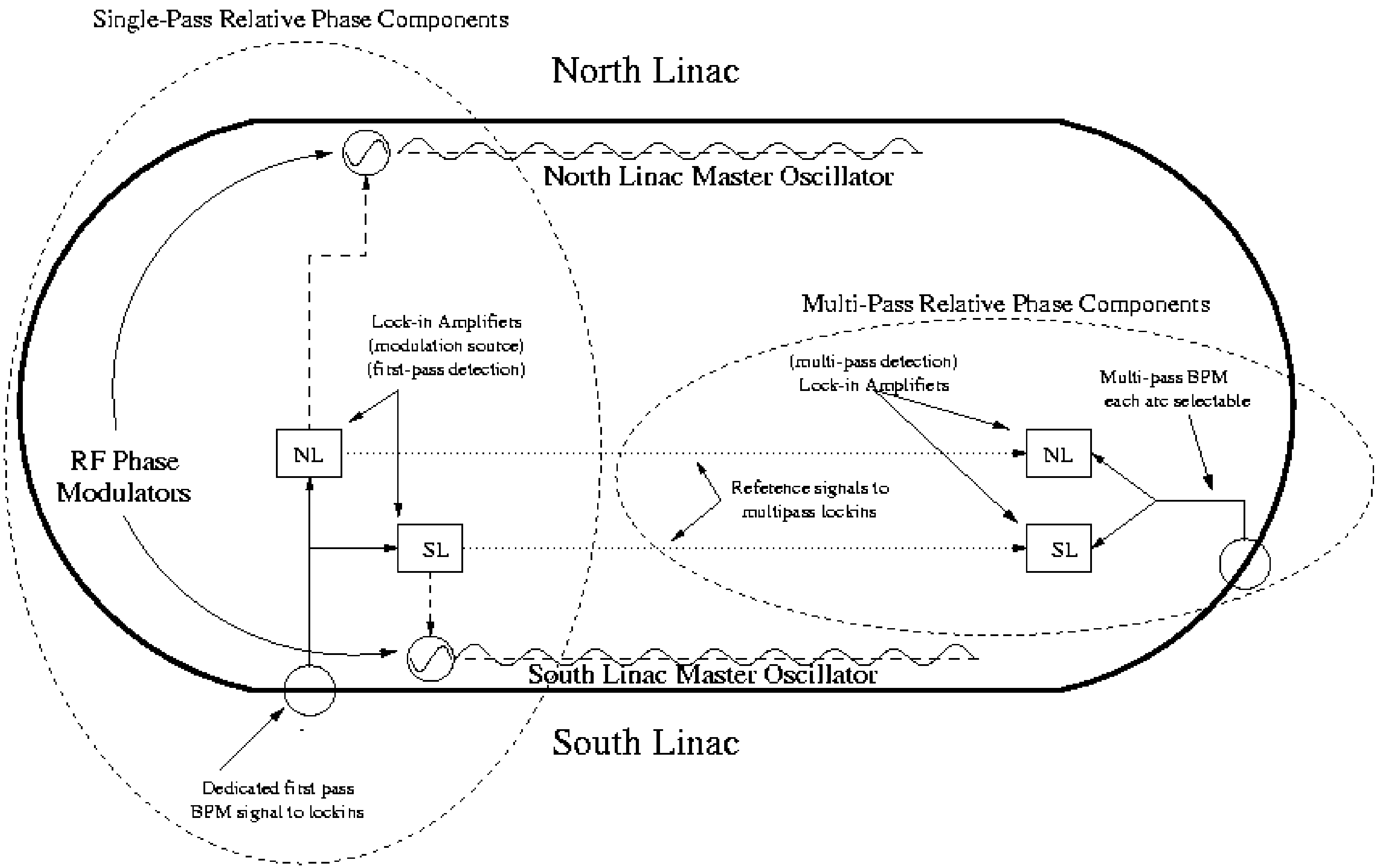
Beam Based Phase Monitoring



Bunch "Crested" when $d\Delta E / dt = 0$

- Get offset by phase modulating around operating point and measuring the energy fluctuation at the same frequency

MO Modulation System Layout



Courtesy: Michael Tiefenback

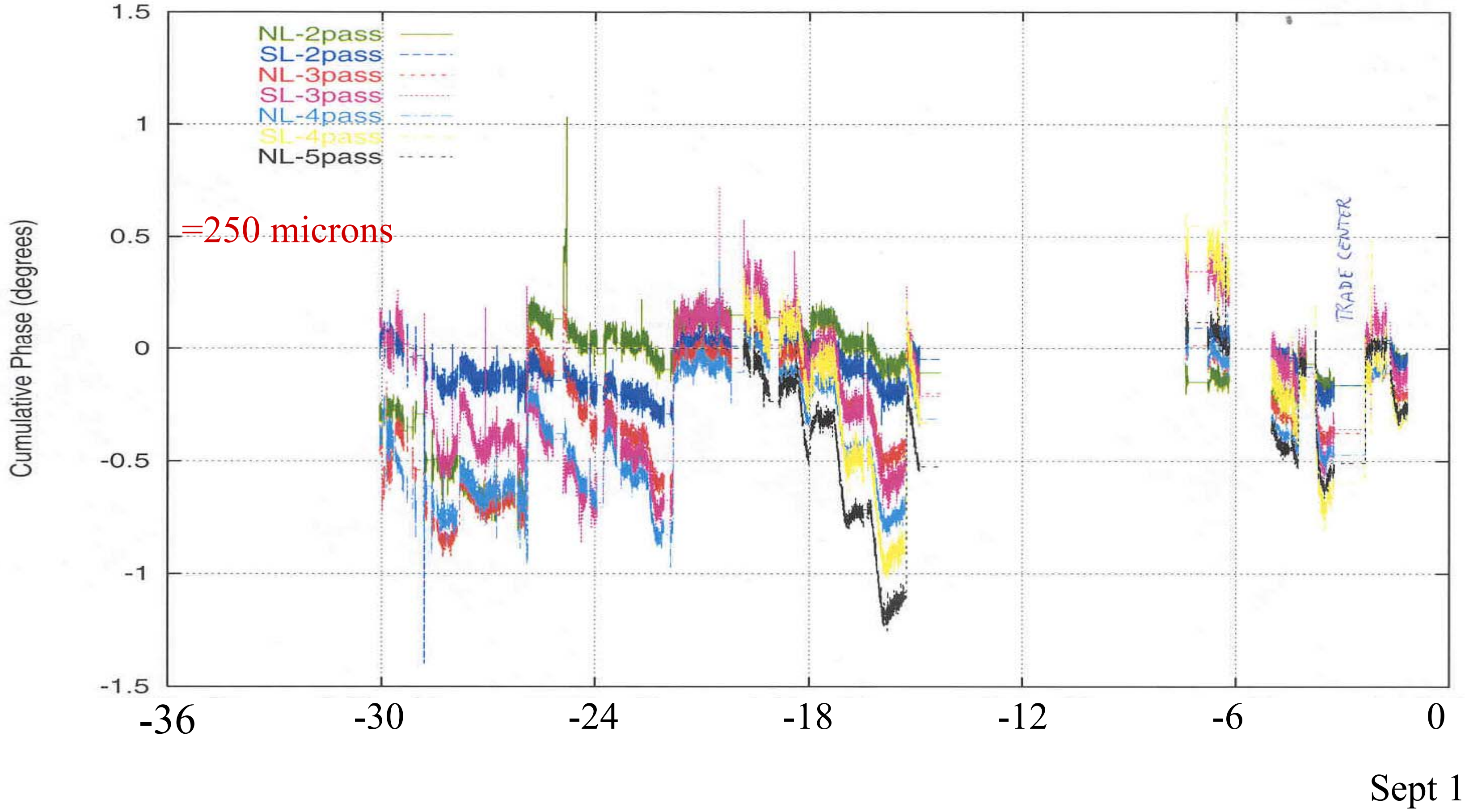
Multi-Pass Beam-RF phase detection

- Pass to Pass Phase Drift => Relative Energy Drifts
- Goal: Stabilization of Multi-Pass Beam-RF phases
- Small phase reference modulation for each linac
  - +/- 0.05 degree Phase Modulation
  - Amplitude Modulation suppressed
- Beam Position Detection in Recirculation Arcs (η = 2.5 m)
  - Multiplexed beam position monitor electronics
  - Each pass individually selectable
  - Measures Cumulative Phase Error (vector gradient sum)
- Phase information is available during CW running
  - On-line monitoring of drifts in recirculation path length
  - Corrections can be made on-line (non-invasive)
- Simultaneous Single- and Multi-Pass phase measurement
  - Equalize Single- and Multi-Pass phases
  - Single-Pass feedback system then keeps all passes on crest

Beam-RF Relative Phase Resolution

- Single-Pass phase resolution ~ 0.2 degrees, beam to RF
  - Finer than the phase set point resolution of 0.1 degree
- Multi-Pass phase resolution
  - Minimum desired measurement resolution: 0.2 degree
  - Expected resolution 0.1 degree
  - Improved over Single-Pass value because of higher dispersion
- Typical phase error feedback limit +/- 0.2 degrees (0.12 degree deadband)

Multipass Phase Shifts



Time (Days)

Courtesy: Michael Tiefenback

Feedback System Elements

Beam position and energy stabilization

- 6 dimensional phase space

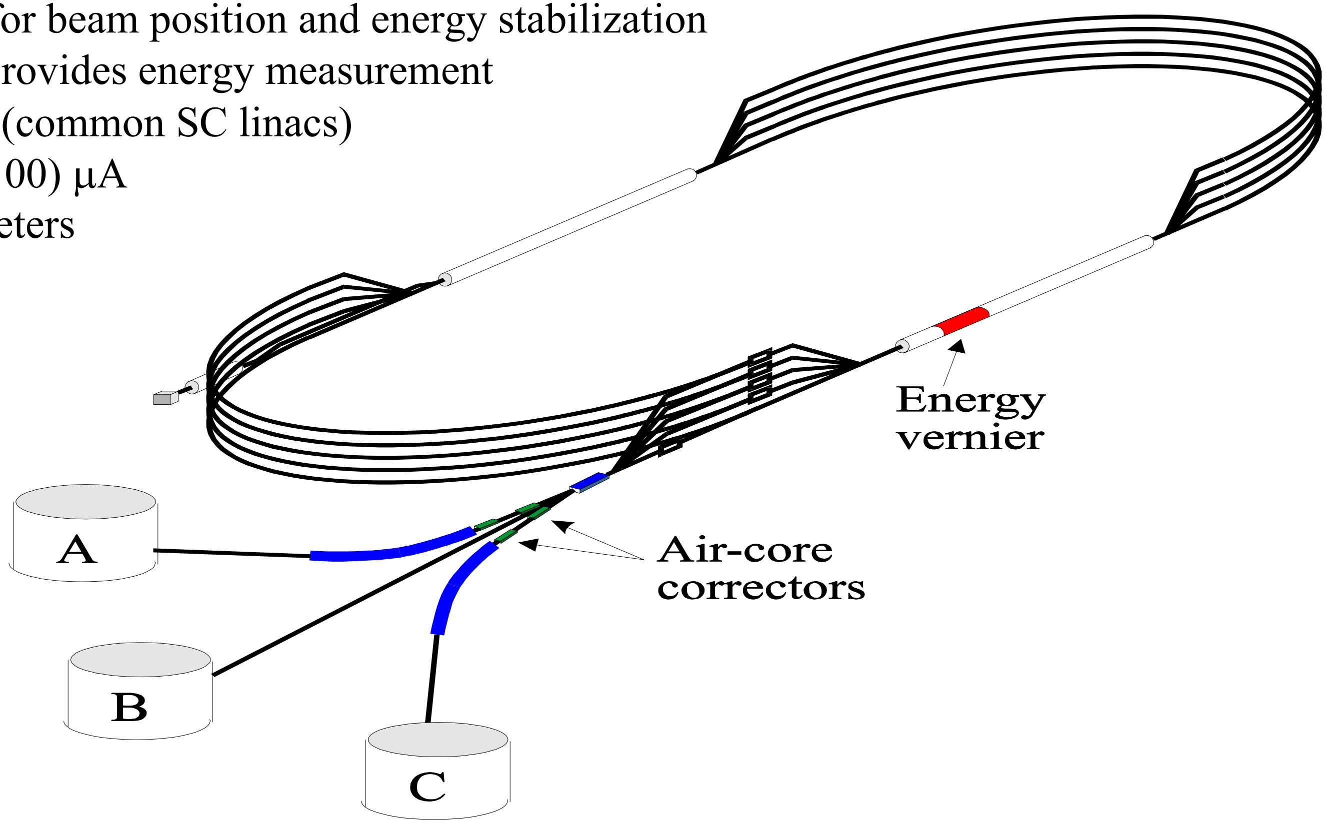
Fast feedback system for beam position and energy stabilization

➢ Only one hall line provides energy measurement

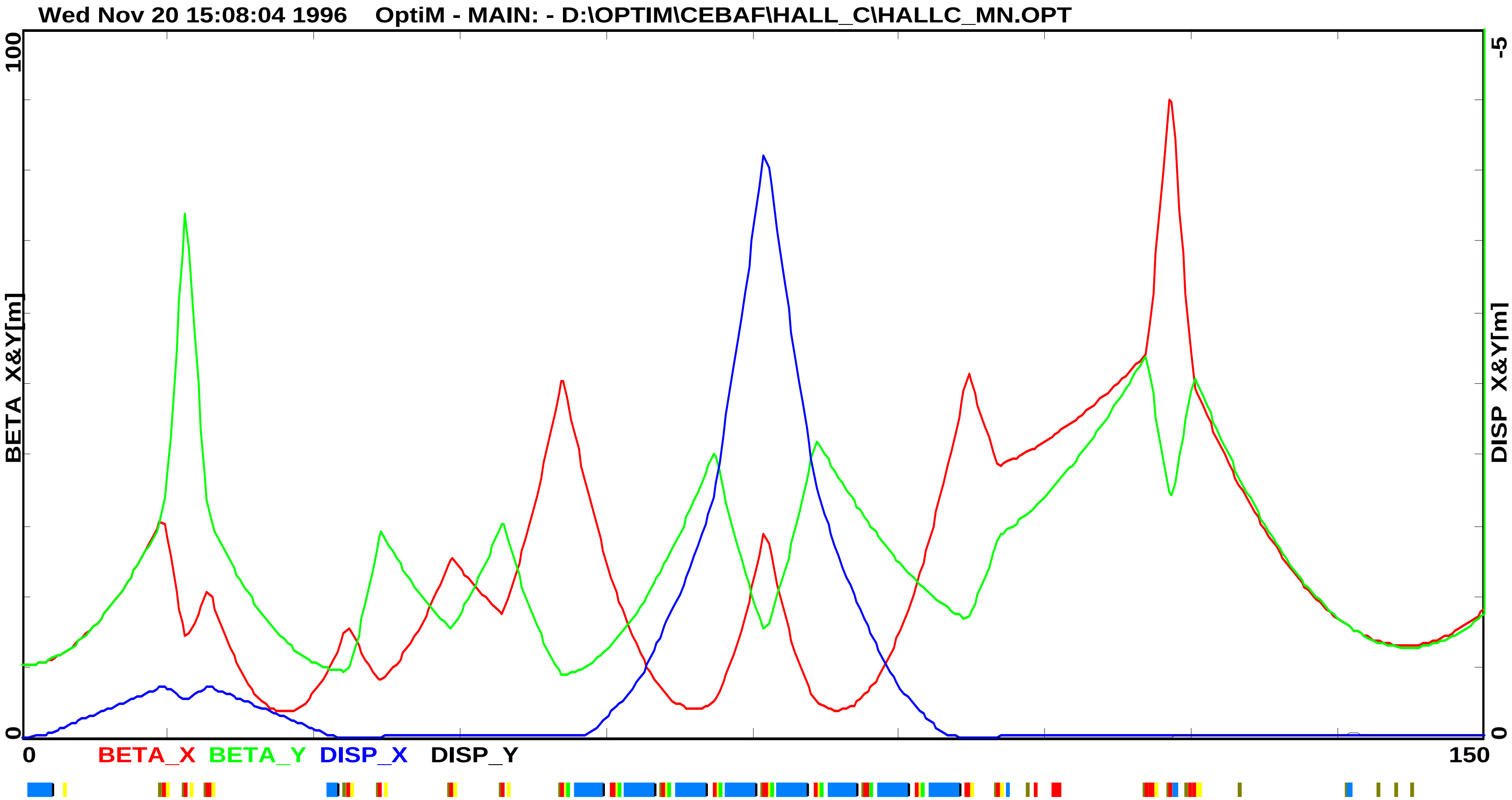
- Two-hall operation (common SC linacs)

➢ Halls A & C - (1 - 100) μA
  Magnetic spectrometers

➢ Hall B - (1 -10) nA
  4π detector

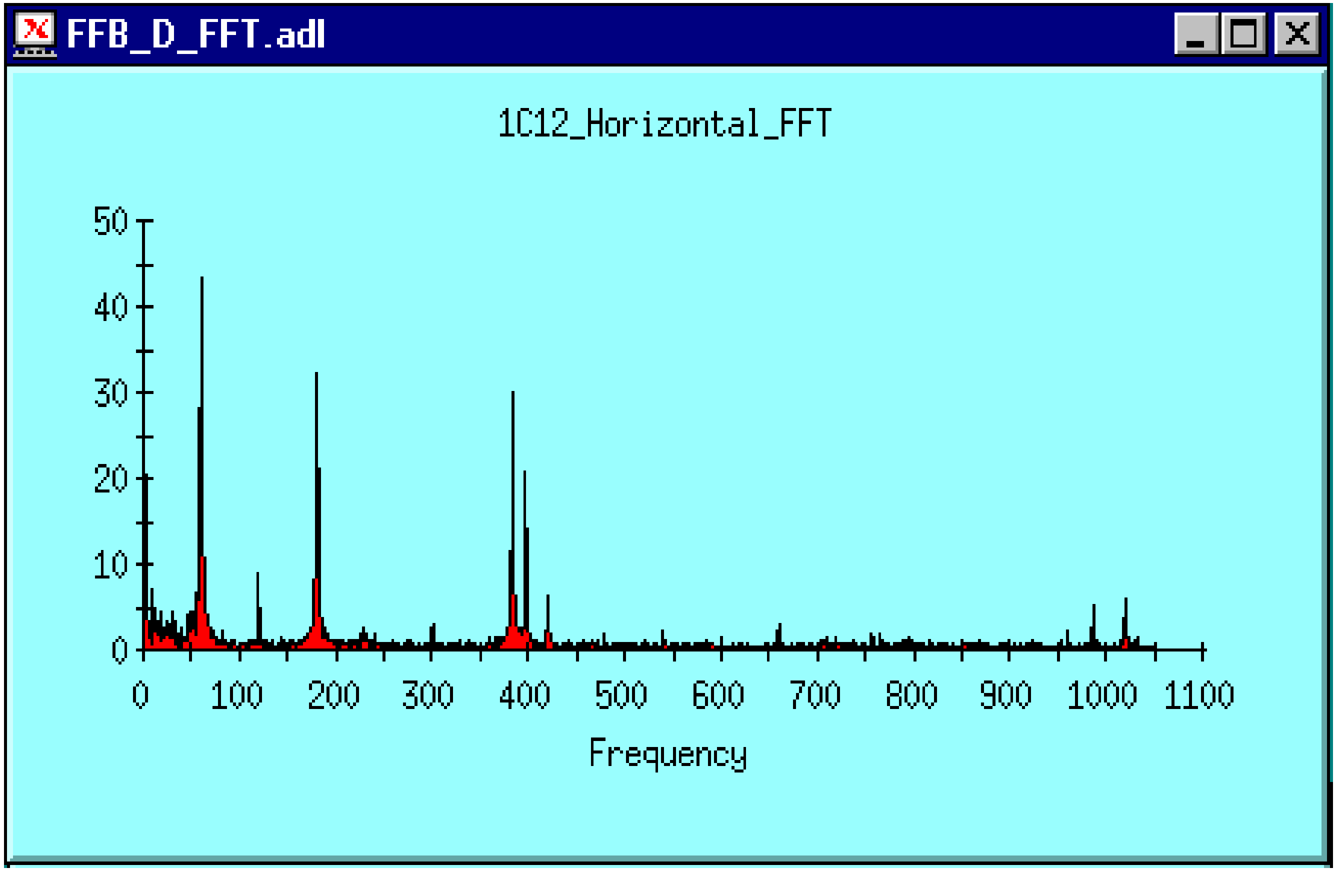


Dispersion Suppressed Optics



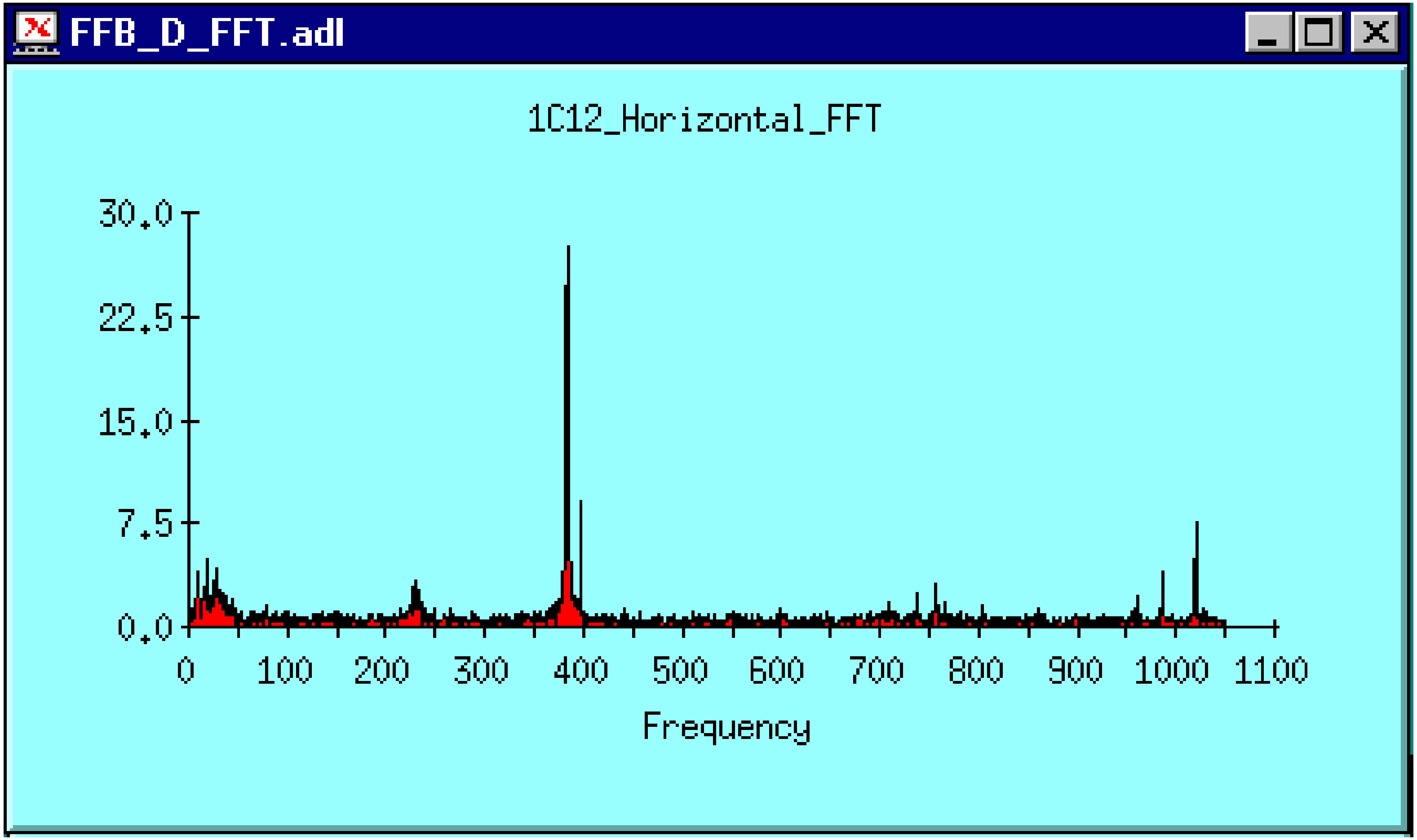
Courtesy: Valeri Lebedev

Fast Feedback Off



Courtesy: Valeri Lebedev

Fast Feedback Residual Fluctuations



Courtesy: Valeri Lebedev

Fast Feedback rms position fluctuations

FFB_0_bpm_val.adl

Hall A Fast FeedBack BMP/Corrector Values

	Horiz Position (microns)					Vert Position (microns)					
	min	max	mean	Std Dev	Outliers	min	max	mean	Std Dev	Outliers	
1C07	-49	45	6	10	0	-43	46	-2	11	0	1C07
1C08	-70	60	3	14	3	-25	45	12	11	0	1C08
1C11	-5	97	52	19	0	-60	76	12	18	0	1C11
1C12	-91	101	7	42	0	-24	75	27	12	0	1C12
1C14	-28	35	3	11	0	-26	88	43	13	0	1C14
1C16	-44	41	-8	14	0	-31	56	15	9	0	1C16
1C18	-77	2	-42	11	0	-17	71	33	12	0	1C18
1C20	-59	10	-28	11	0	-17	80	36	14	0	1C20

Horiz Corrector (gauss-cm)

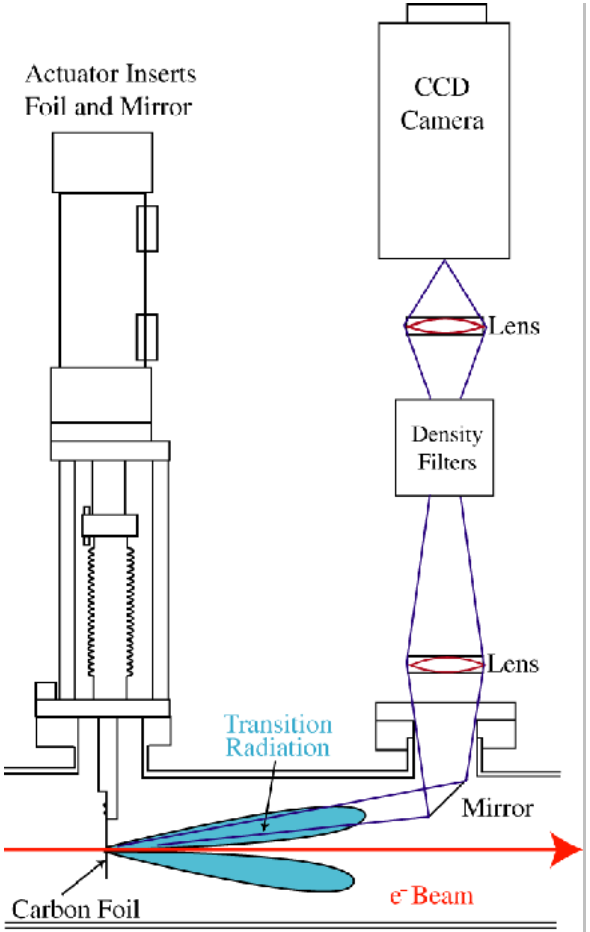
	min	max	mean	Std Dev
1C04H	-4.95	31.38	4.79	4.29
1C07H	-19.92	12.59	-8.06	4.03

Vert Corrector (gauss-cm)

	min	max	mean	Std Dev
1C02V	-9.71	13.70	3.28	2.22
1C07V	5.29	33.74	25.40	4.37

Courtesy: Valeri Lebedev

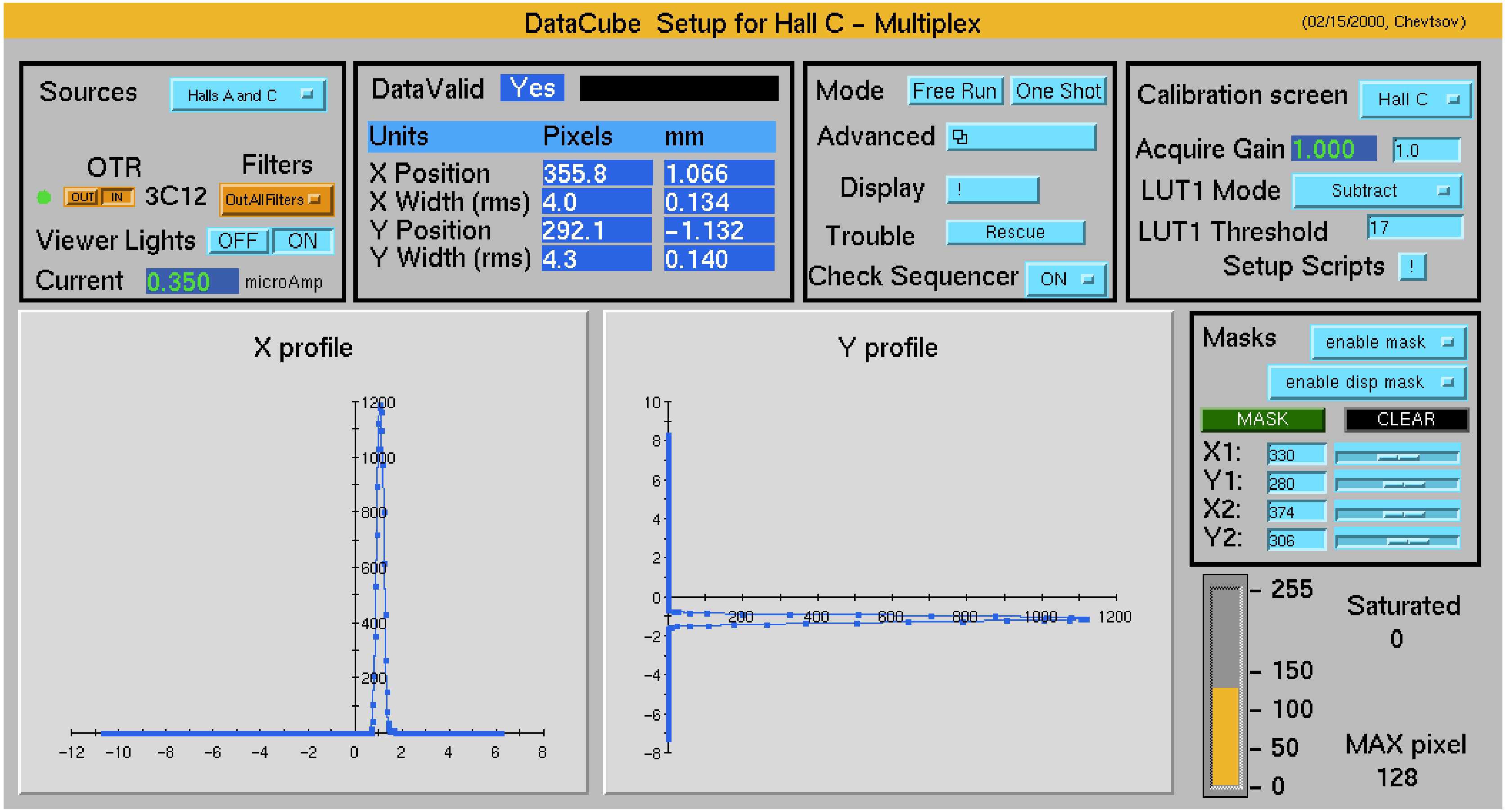
Beam Diagnostics: OTR



SIMPLIFIED DIAGRAM
OF THE FORWARD OTR MONITOR

- ¼ µm carbon foil, 10 X 10 mm square
- Can stay in maximum CEBAF CW beam current (200 µA)
- Dynamic range: 0.2 to 200 µA with neutral density filters.
- Continuous monitoring during beam delivery for $E \geq 2$ GeV
- Open frame => not invasive upon insertion.
- Effect of foil on beam:
  - Energy loss => negligible
  - Beam scattering: OK for E > 2GeV; at 1.2 GeV, limit is ~ 50 µA (radiation level on sensitive electronics on beamline).
- Resolution limited by CCD camera to ≈ 60 µm. Could be improved, but is OK.
- Update rate : 5 measurements / second for 2 instruments simultaneously.

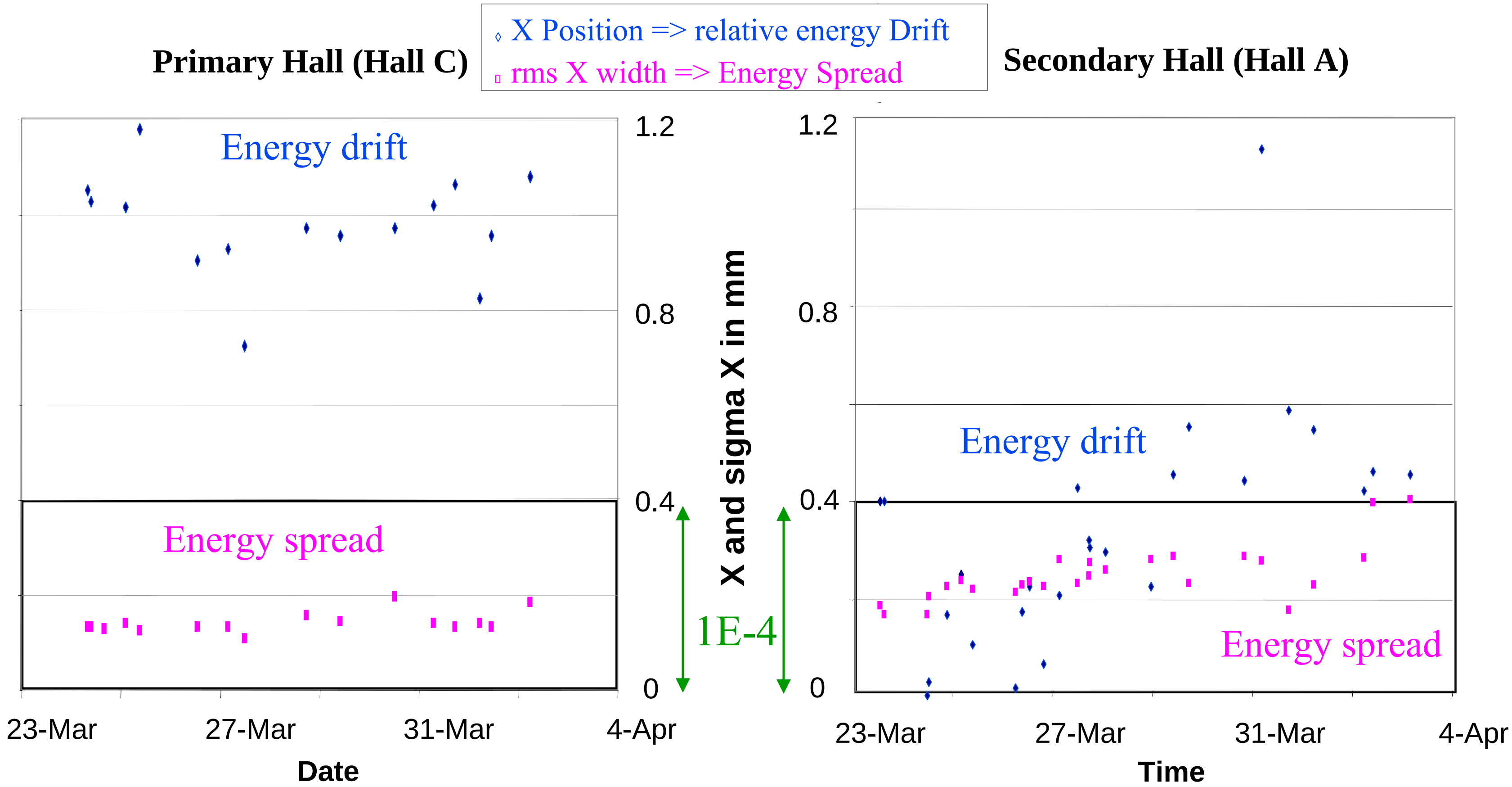
"MaxVideo 200" Image Processor Control Screen



Courtesy: Jean-Claude Denard

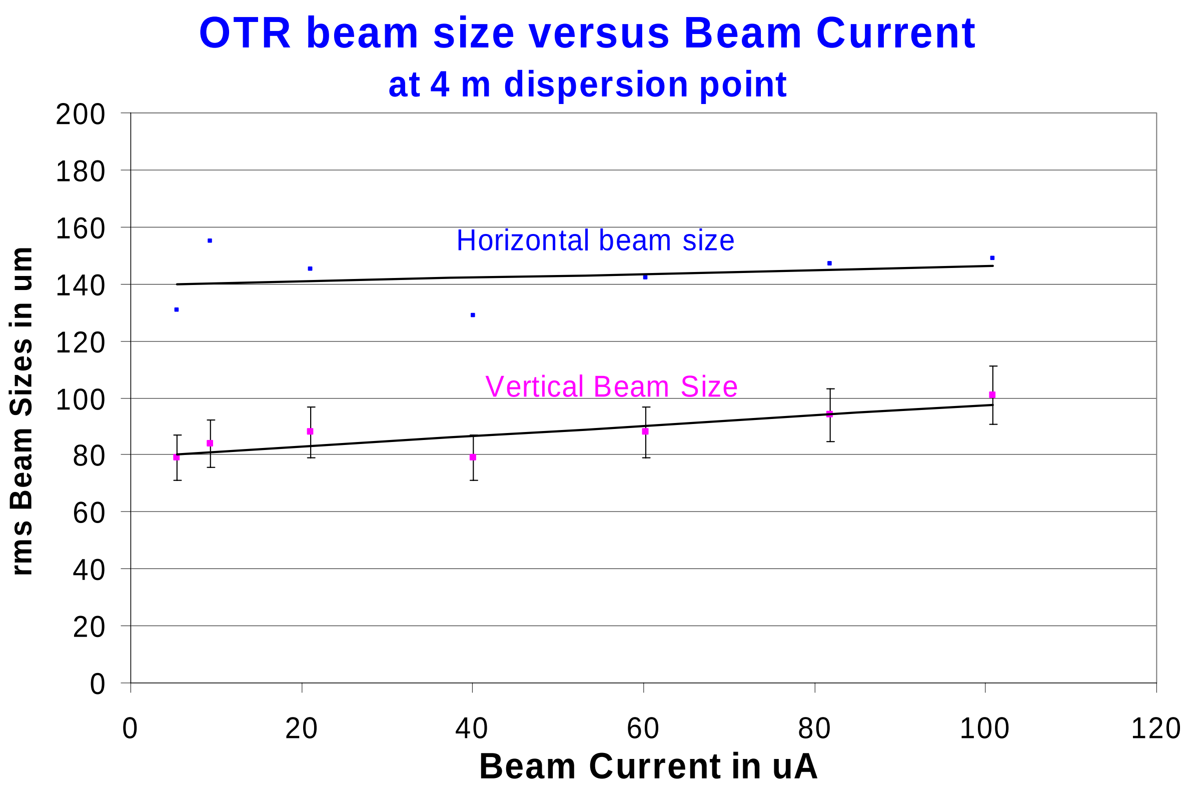
dp/p data: 2-Week Sample Record

Energy Spread less than 50 ppm in Hall C, 100 ppm in Hall A



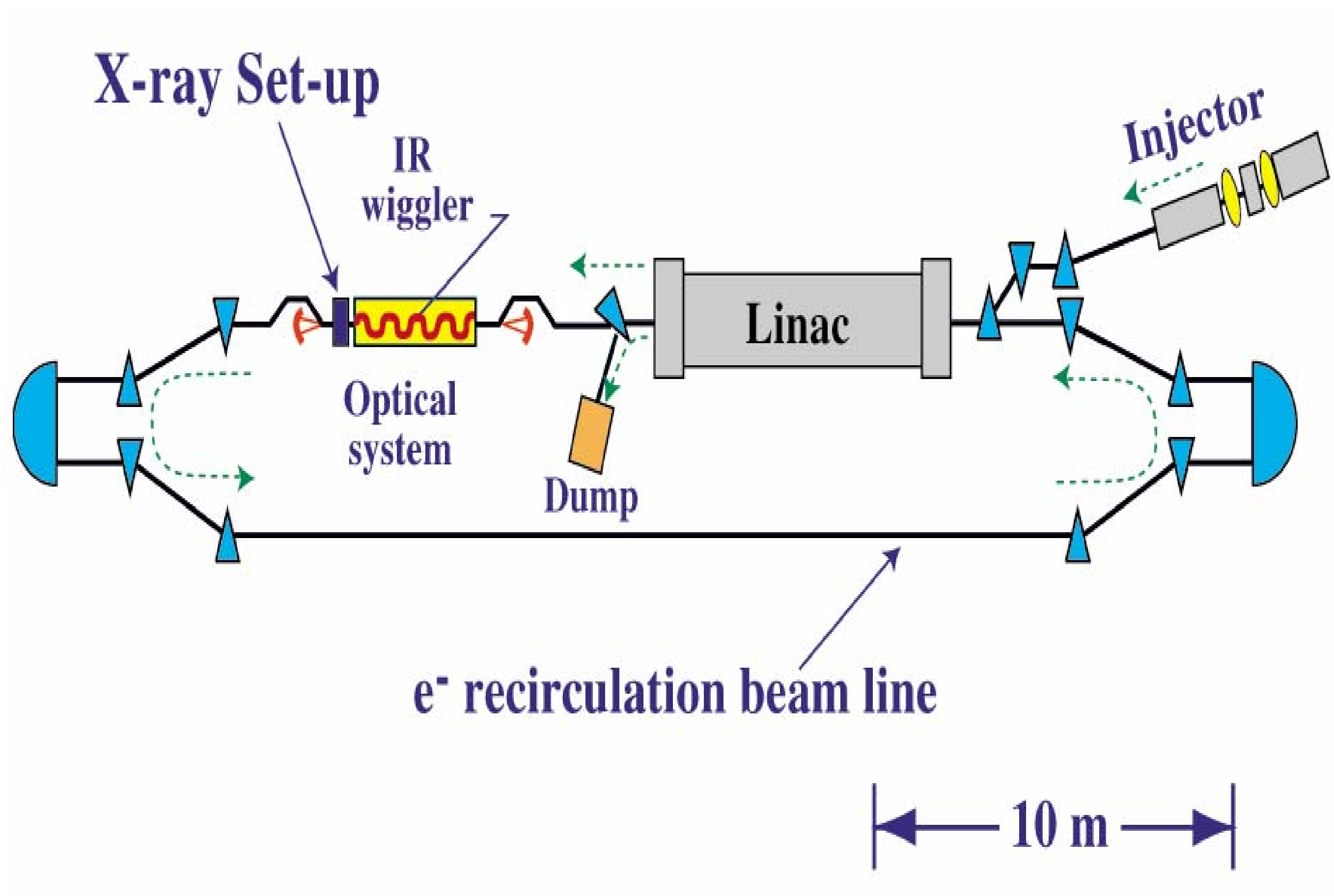
Courtesy: Jean-Claude Denard

dp/p Stability versus Beam Current



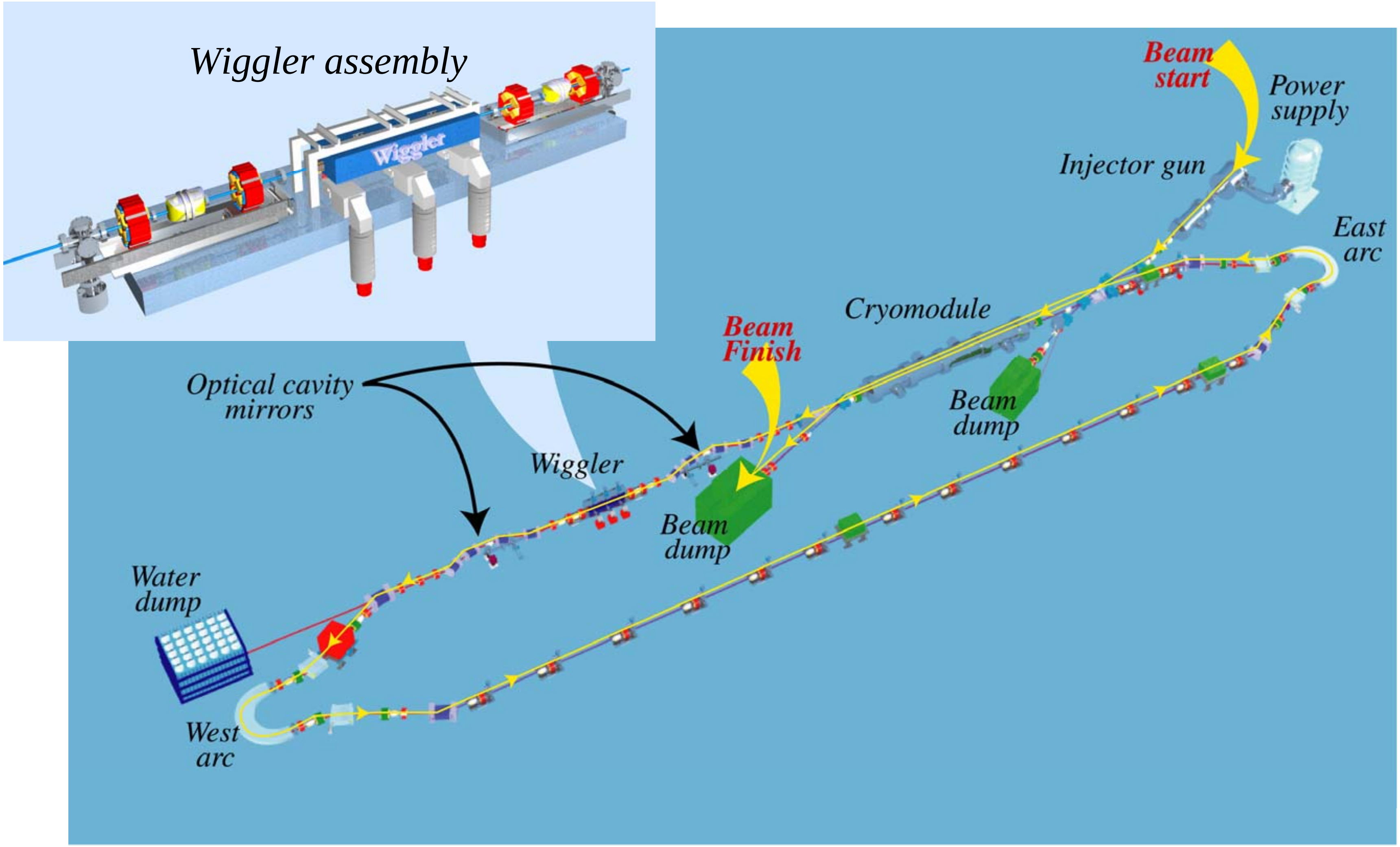
Courtesy: Jean-Claude Denard

Jefferson Lab FEL



Neil, G. R., *et. al*, *Physical Review Letters*, **84,** 622 (2000)

The Jefferson Lab IR FEL

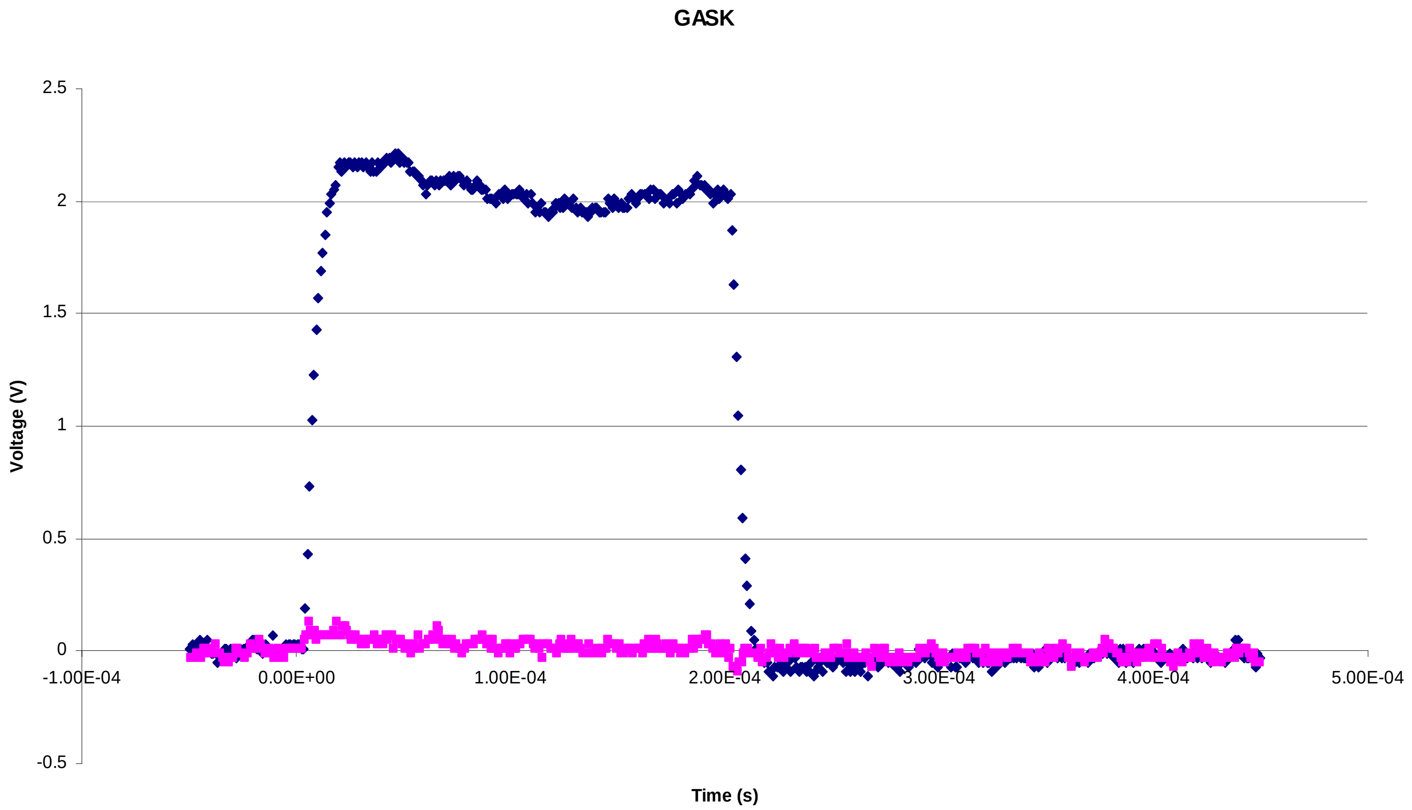


FEL Accelerator Parameters

Parameter	Designed	Measured
Kinetic Energy	48 MeV	48.0 MeV
Average current	5 mA	4.8 mA
Bunch charge	60 pC	Up to 135 pC
Bunch length (rms)	<1 ps	0.4±0.1 ps
Peak current	22 A	Up to 60 A
Trans. Emittance (rms)	<8.7 mm-mr	7.5±1.5 mm-mr
Long. Emittance (rms)	33 keV-deg	26±7 keV-deg
Pulse repetition frequency (PRF)	18.7 MHz, x2	18.7 MHz, x0.25, x0.5, x2, and x4

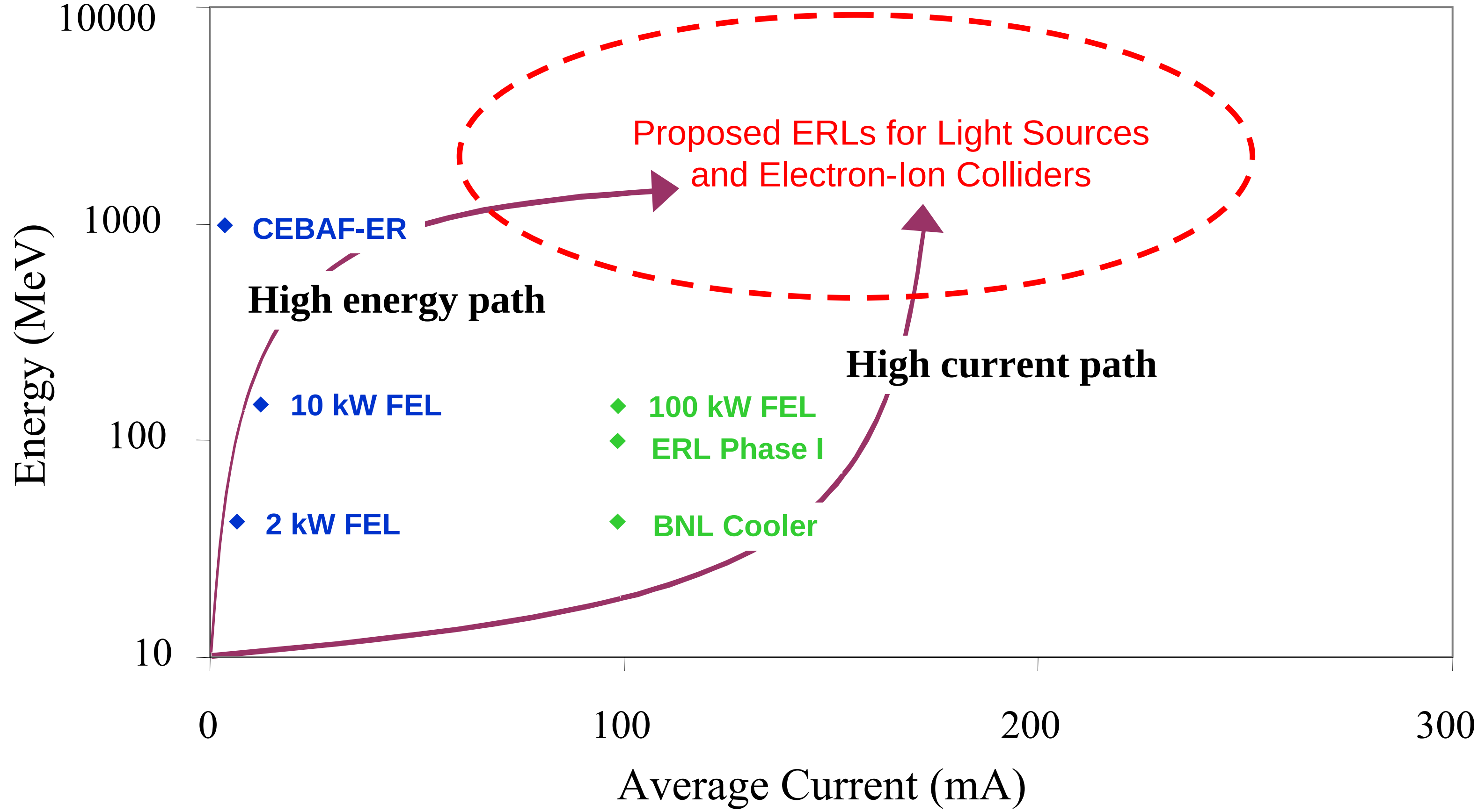
ENERGY RECOVERY WORKS

Gradient modulator drive signal in a linac cavity measured without energy recovery (signal level around 2 V) and with energy recovery (signal level around 0).



Courtesy: Lia Merminga

ERL Landscape

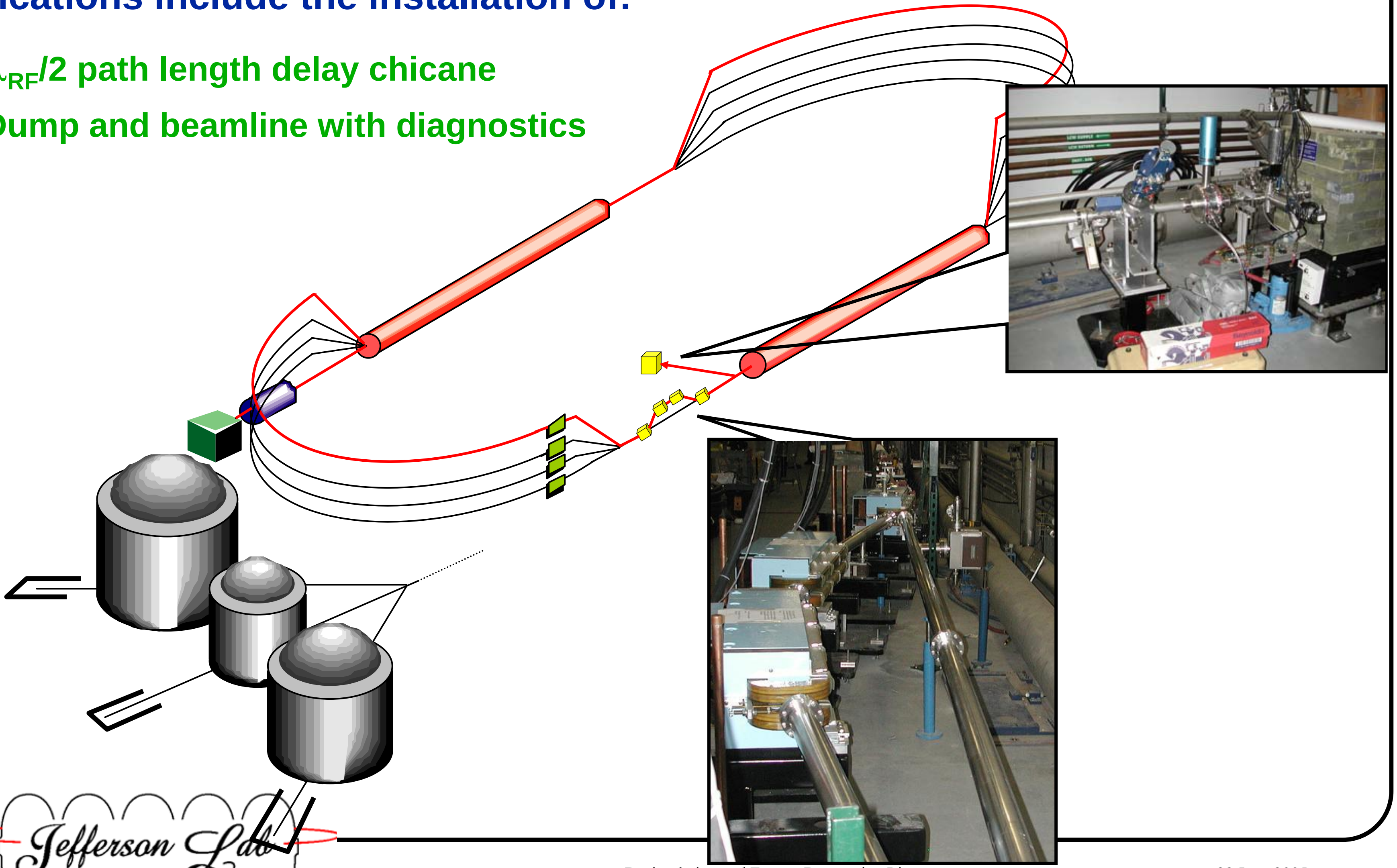


In an effort to address the issues of energy recovering high energy beams, Jefferson Lab performed a minimally invasive energy recovery experiment utilizing the CEBAF superconducting, recirculating, linear accelerator

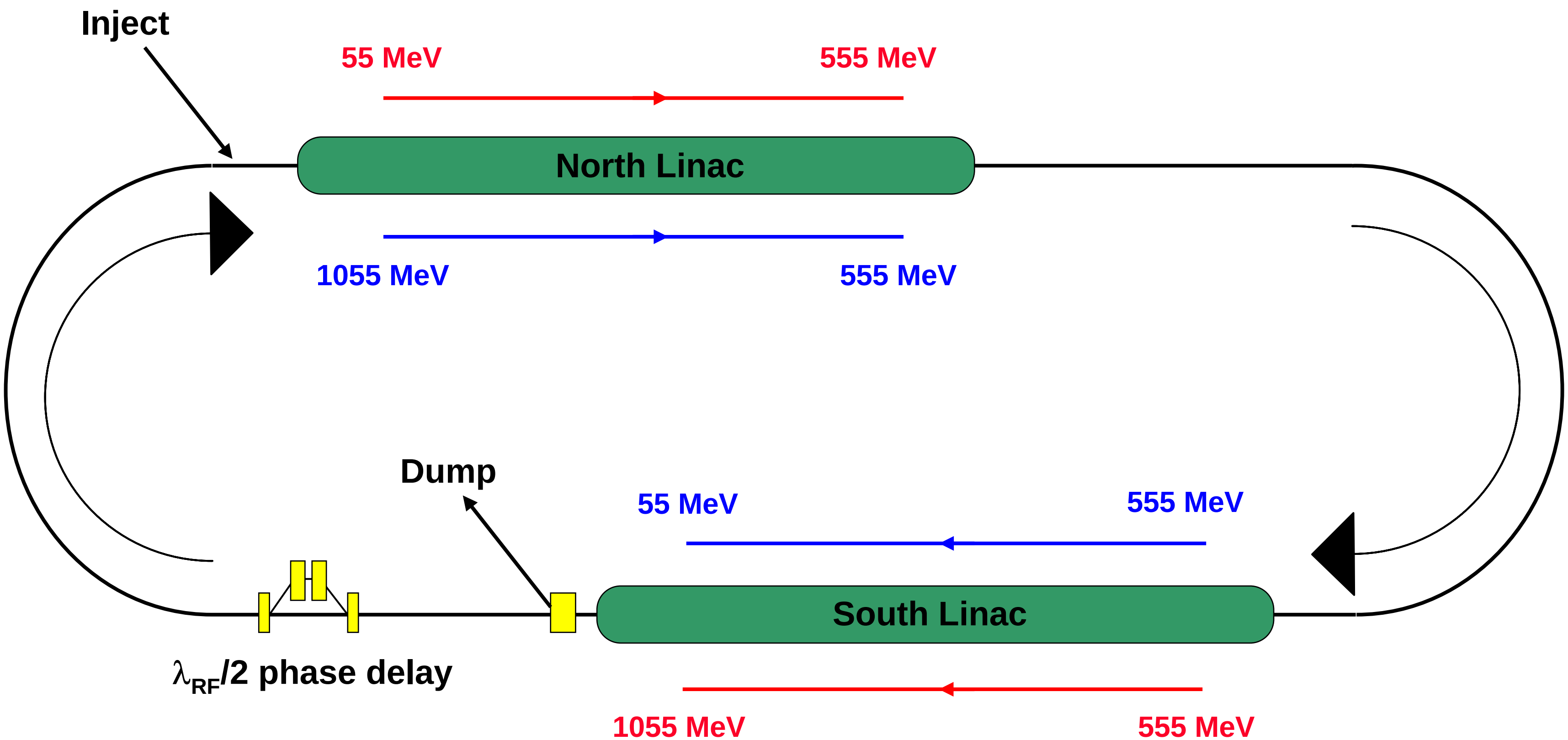
CEBAF Modifications

Modifications include the installation of:

- $\lambda_{RF}/2$ path length delay chicane
- Dump and beamline with diagnostics



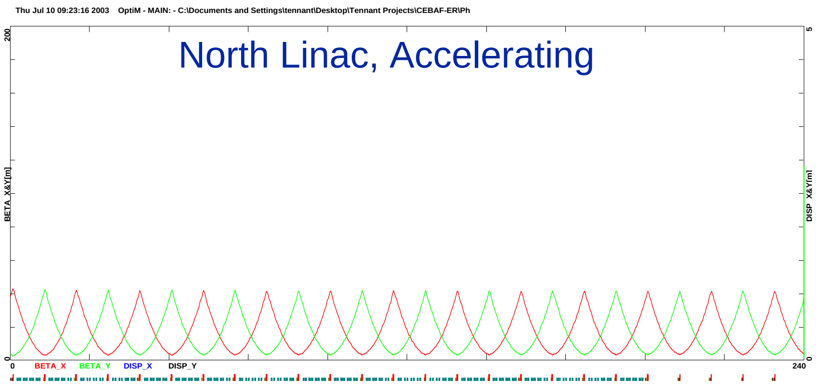
"1 Pass-Up / 1 Pass-Down" Operation

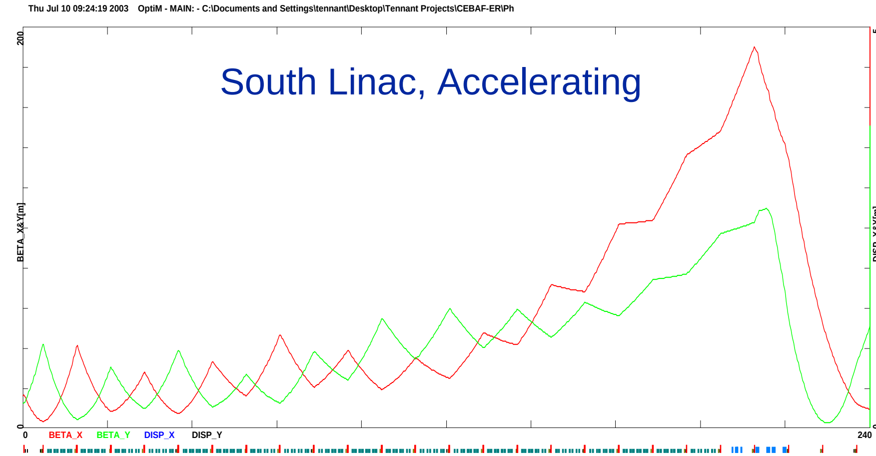


Machine Optics

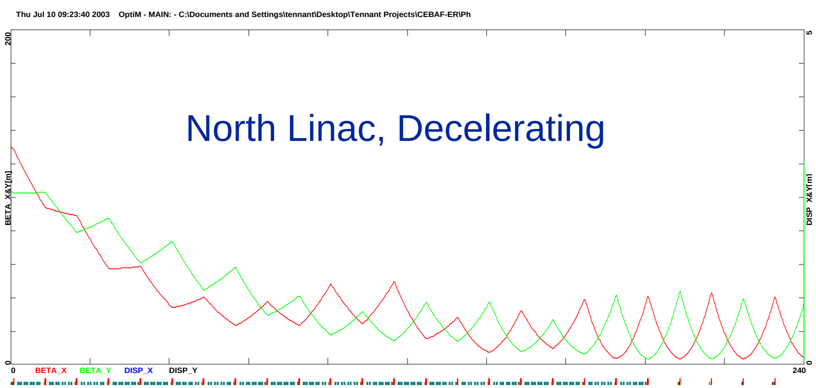
Linacs - standard 120° lattice for the lowest energy beam in each linac and mismatched optics on the other pass.

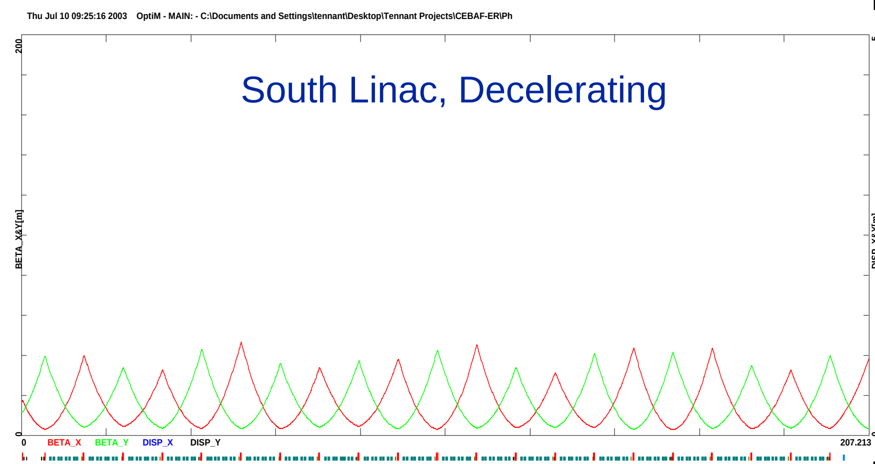
200 m





200 m



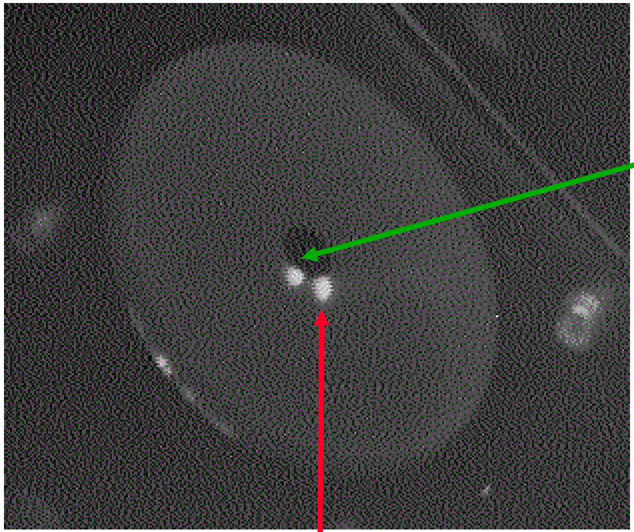


240 m

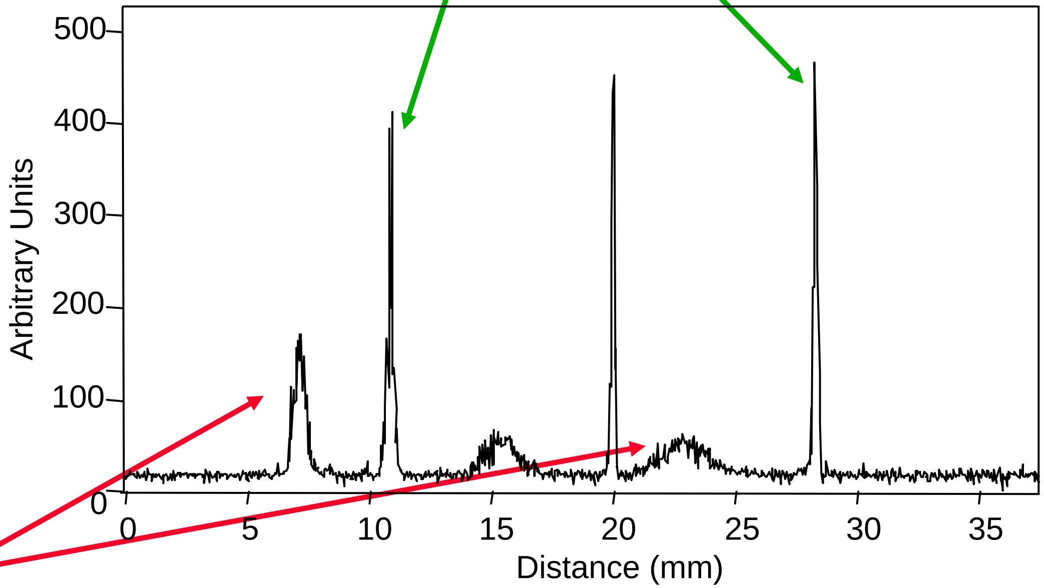
240 m

CEBAF-ER Experimental Run

Beam viewer near the exit of the South Linac



~ 1 GeV Accelerated beam



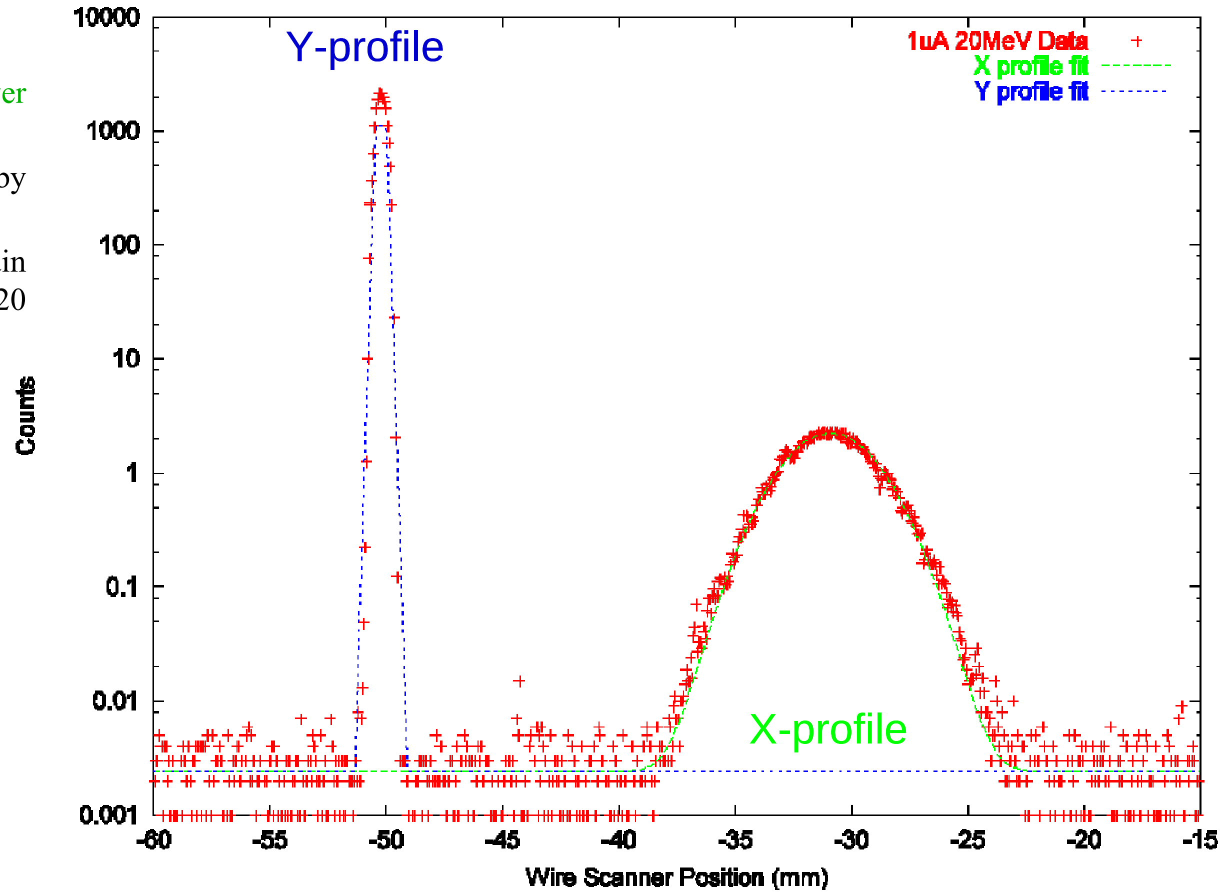
~ 55 MeV Decelerated beam

3-wire scanner x 2 beams = 6 peaks

Beam Profiles of ER Beam (cont'd)

- Beam profiles (20 MeV, 1μA beam) measured with a wire scanner and 3 downstream PMTs

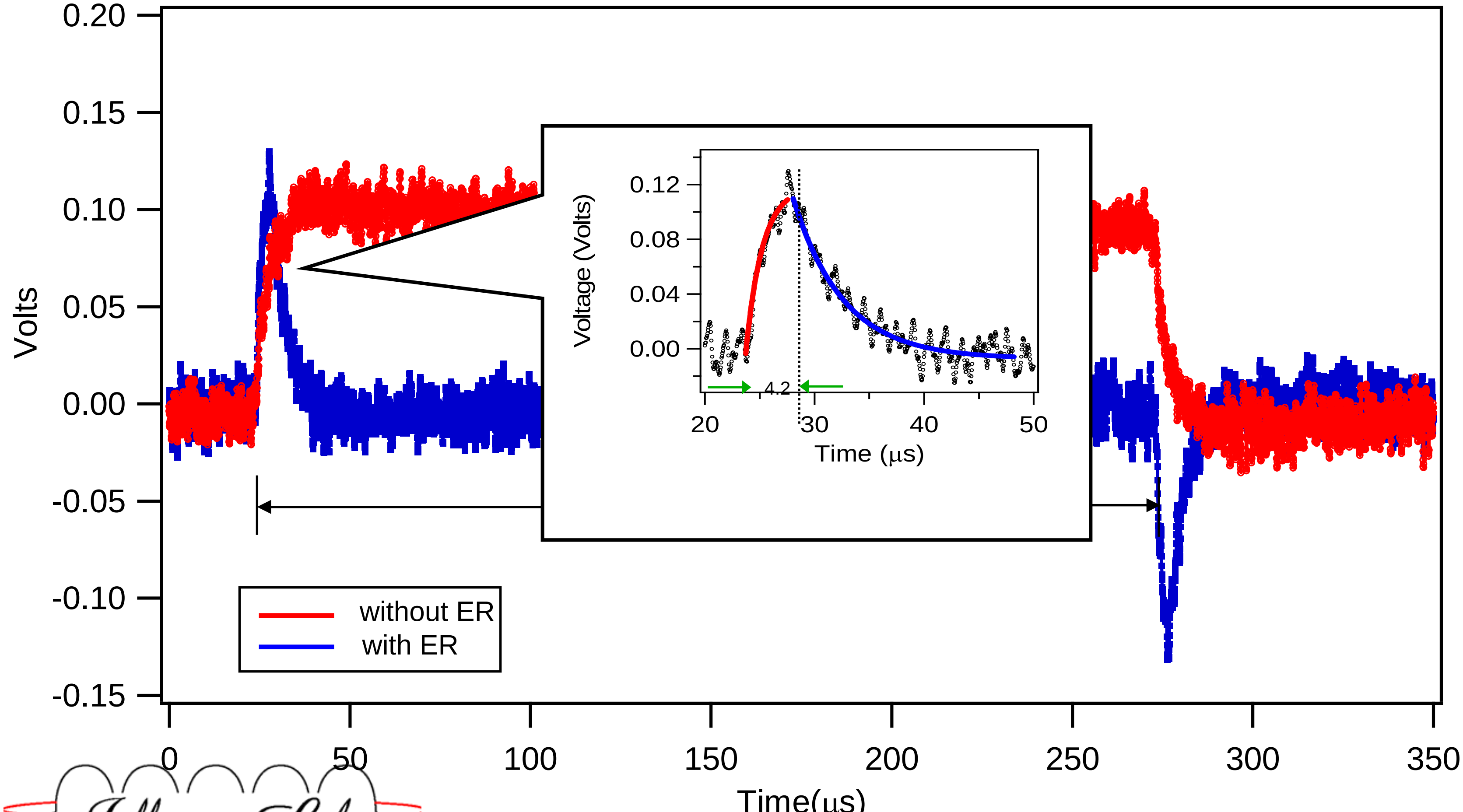
- The Y-profile shows a good Gaussian fit over 6 orders of dynamic range.
- The width of the X-profile is scaled by ($\Delta E/E$) from the E_{inj} = 55 MeV case.
- Width of X-profile could potentially explain the increased scraping observed at E_{inj} = 20 MeV.



(courtesy A. Freyberger)

RF Response to Energy Recovery

- Gradient modulator drive signals **with** and **without** energy recovery in response to 250 µsec beam pulse entering the RF cavity *(SL20 Cavity 8)*



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Conclusions

- **Achievements**
  - Demonstrated the feasibility of energy recovering a high energy (1 GeV) beam through a large (~1 km circumference), superconducting (39 cryomodules) machine.
  - 80 μA of CW beam accelerated to 1055 MeV and energy recovered at 55 MeV.
  - 1 μA of CW beam, accelerated to 1020 MeV and energy recovered at 20 MeV, was steered to the ER dump.
  - Tested the dynamic range on system performance by demonstrating high final-to-injector energy ratios (E_{final}/E_{inj}) of 20:1 and 50:1.
- **Future Activities**
  - Important accelerator physics and technology challenges are topics of vigorous research at JLab. They will also be addressed experimentally by a number of prototypes, such as the 10 mA JLab FEL, 100 mA FEL upgrade and continued activities with CEBAF-ER.

E02-102 Collaboration

I would like to acknowledge and thank the members of the CEBAF-ER collaboration:

Kevin Beard
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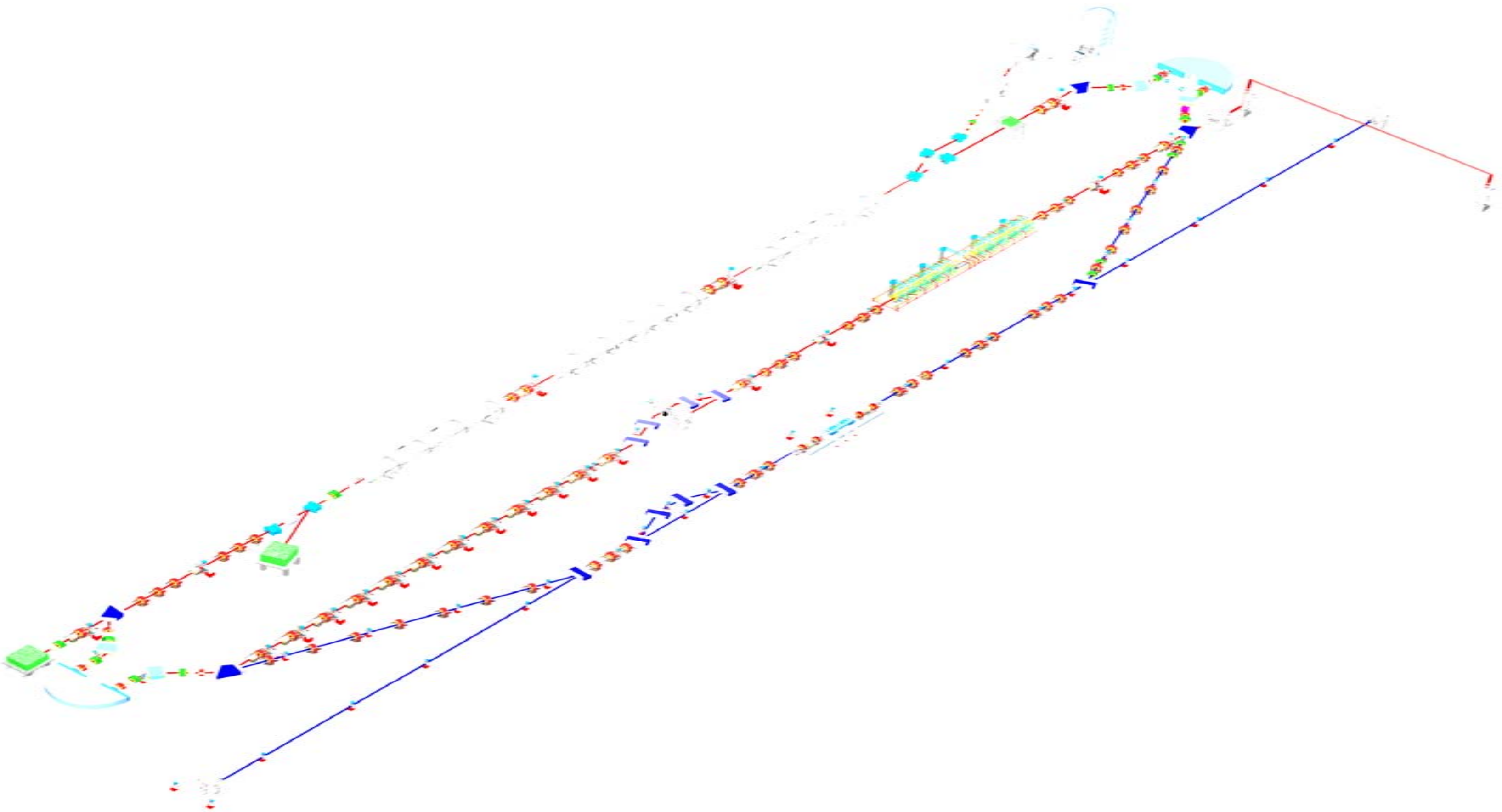
Yu-Chiu Chao
Swapan Chattopadhyay
David Douglas
Arne Freyberger
Andrew Hutton
Lia Merminga
Mike Tiefenback
Hiro Toyokawa

IR FEL 10 kW Upgrade



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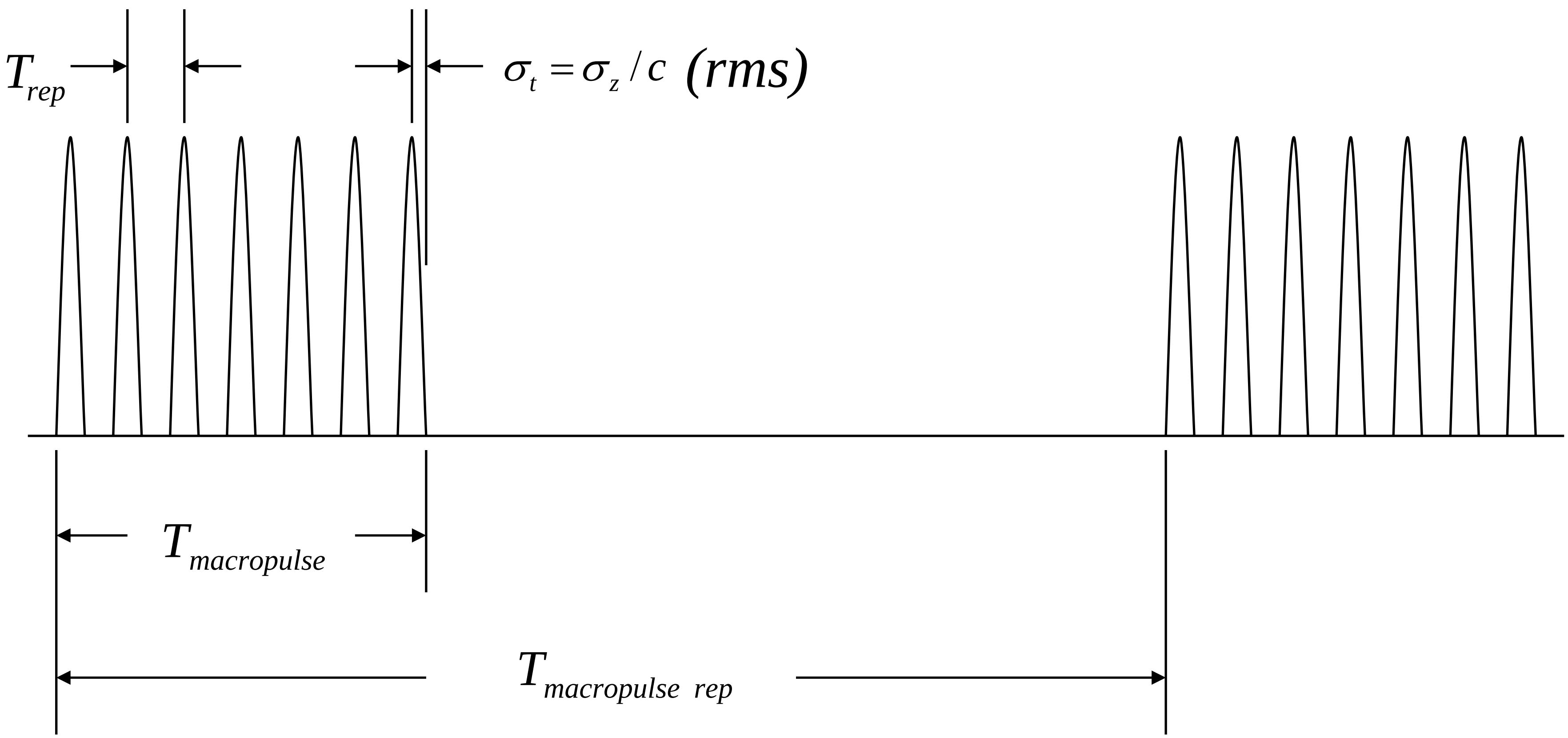
IR FEL 10 kW Upgrade Parameters

Parameter	Design Value
Kinetic Energy	160 MeV
Average Current	10 mA
Bunch Charge	135 pC
Bunch Length	<300 fsec
Transverse Emittance	10 mm mrad
Longitudinal Emittance	30 keV deg
Repetition Rate	75 MHz

Recent Results From FEL Upgrade

- Achieved basic accelerator parameters and FEL operating characteristics
- Multipass Beam Breakup (BBU) Instability observed directly with high current beam and studied as shown in previous material
- FEL bend chicanes operate as high average power THz sources due to emission of Coherent Synchrotron Radiation. This heat load added nontrivial complexity to the operation of the FEL optical resonater.
- With BBU suppressed 9.1 mA, recirculated current
- Beam charge-per-bunch of 135 pC
- Time averaged 10 kW laser power at several microns

Recirculated Linacs Have Flexible Timing



Timing Possibilities

Parameter	ERL Possibilities	Jlab FEL Demonstrated
σ_t^*	100 fsec – 10 psec	< 330 fsec
Repetition Rate	1 MHz – 1.3 GHz	2 – 75 MHz
Macropulse Duration	1 microsecond - CW	1 microsecond - CW
Macropulse Repetition Frequency	1 Hz-10 kHz	0.5 Hz – 60 Hz

* In Jlab FEL, fluctuation in pulse centroid measured less than 1 sigma