Energy Recovering Linacs for the Production of Synchrotron Radiation

Lia Merminga

Center for Advanced Studies of Accelerators
Jefferson Laboratory

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Outline

- User Requirements and Machine Parameters
- Energy Recovering Linacs (ERLs) as SR Sources
- Operating Jefferson Lab High-Power ERL-based FELs
- Proposed Upgrades to JLab ERL FELs
  - Scientific Potential
  - ERL Technology Test Accelerator
- JLab's complementary R&D paths to future ERL-based SR Sources
- Conclusions

User Requirements and Machine Parameters

- Many SR science applications require:
  - High average brilliance $\mathrm{B} \propto \frac{I}{\varepsilon^2}$
  - Full spatial coherence $\Rightarrow \quad \varepsilon < \lambda / 4\pi$
  - High temporal coherence $\Rightarrow$ small electron beam energy spread
  - High average flux $\propto I_{ave}$
  - Micro-x-ray beams $\Rightarrow$ small source size, round beams are desirable
  - Sub-ps x-ray pulses $\Rightarrow$ ultra-short electron bunches

Energy Recovering Linacs as SR Sources

- ERLs provide an alternate to storage rings and potentially powerful paradigm for the generation of bright, synchrotron light.
- ERLs are complementary to SASE X-FELs in performance characteristics.
- ERLs share many characteristics of linacs: 6-D beam phase space largely determined by electron source properties by design, in contrast to rings.
- In common with storage rings: ERLs possess high average current-carrying capability enabled by the ER process, thus promising similar efficiencies.

⇒ ERLs can provide:

low emittance (~0.1 nm-rad at 5 GeV)* both horizontal and vertical (round beams)

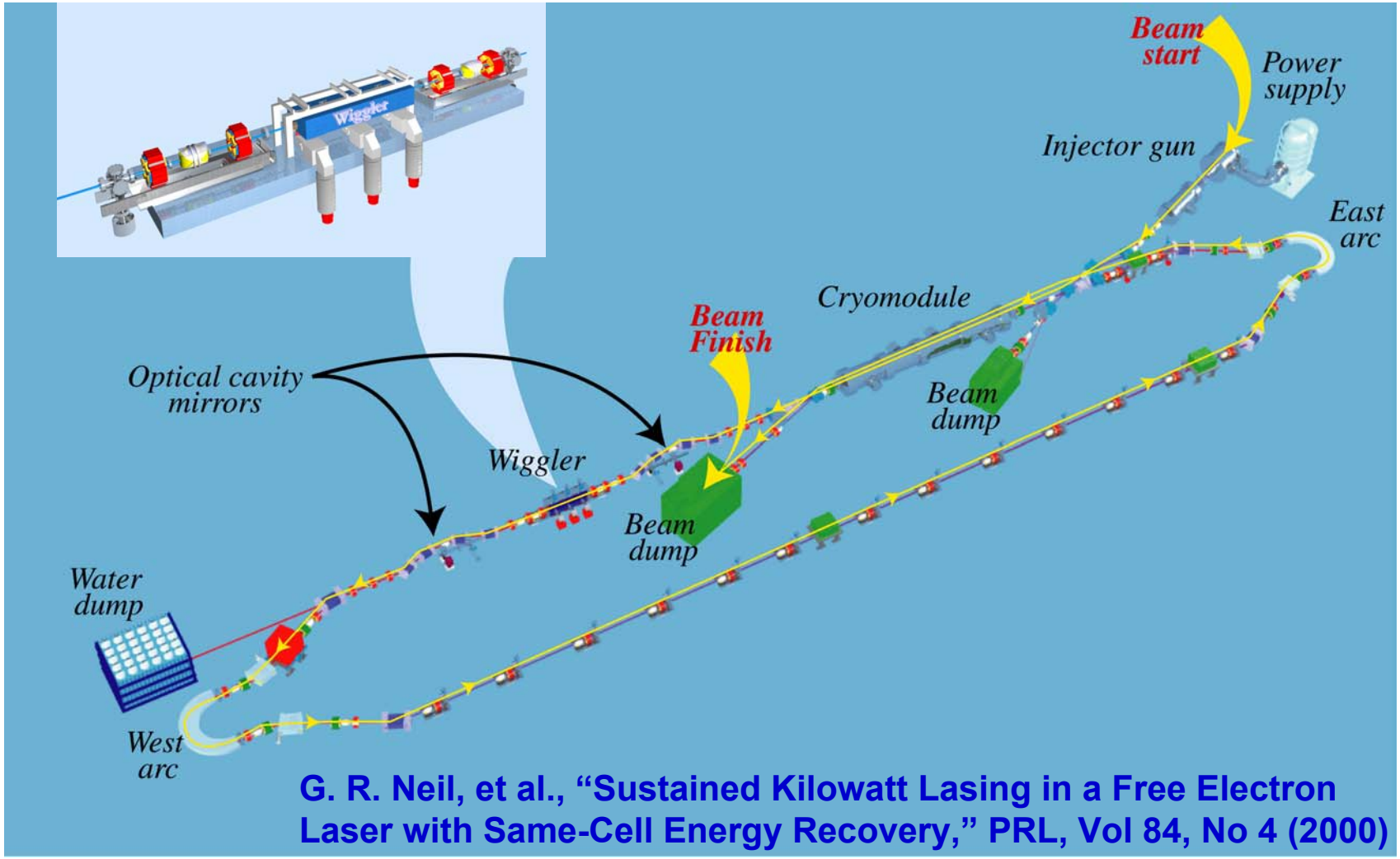
sub-ps bunch lengths (< 100 fsec)*, small energy spread

high average current (~100 mA)

variable filling patterns

* quantities are rms

The JLab 2 kW IR FEL Operating with Energy Recovery

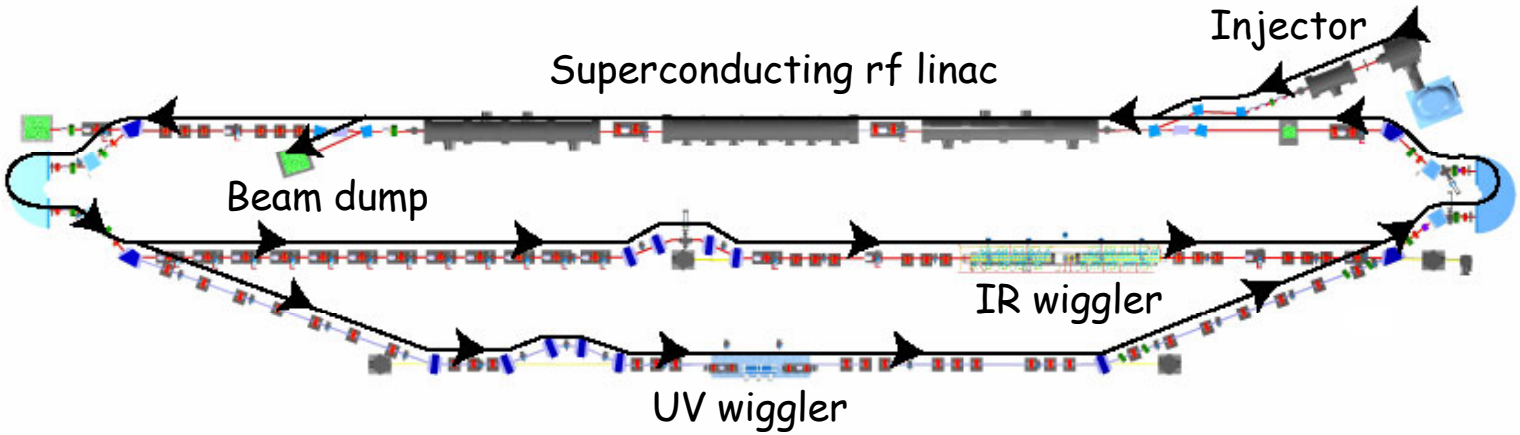


G. R. Neil, et al., "Sustained Kilowatt Lasing in a Free Electron Laser with Same-Cell Energy Recovery," PRL, Vol 84, No 4 (2000)

The JLab 10kW IR FEL and 1 kW UV FEL

Presently under commissioning

First light achieved on June 17, 2003

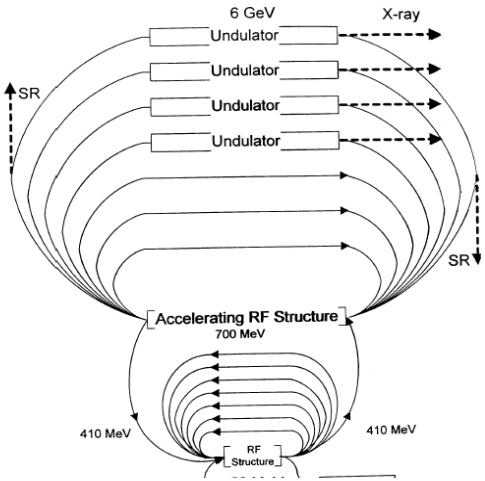


Evolution of System Parameters of the JLab FELs

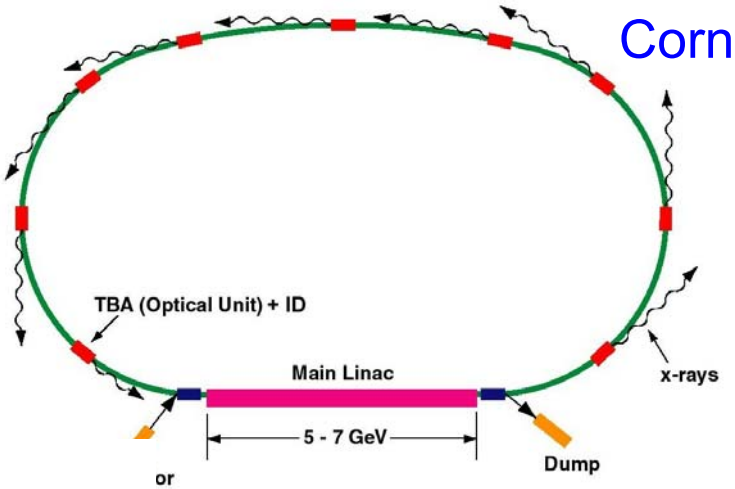
	Achieved	IR 2003	UV 2004
Energy (MeV)	20-48	80-210	200
I_{ave} (mA)	5	10	5
Beam Power (kW)	240	2000	1000
Charge/bunch (pC)	135	135	135
Rep. Rate (MHz)	18.75-75	4.7-75	2.3-75
Bunch Length* (psec)	0.4(60 pC)	0.2	0.2
Peak Current (A)	>60 A	270	270
σ_E/E *	<0.25%	0.5%	0.125%
e_N* (mm-mrad)	5-10	<30	<11
FEL ext. efficiency	>0.75%	1%	0.25%
FEL power (kW)	2.1	>10	>1
Induced energy spread (full)	6-8%	10%	5%

* rms

Proposed ERL-based SR Sources Worldwide

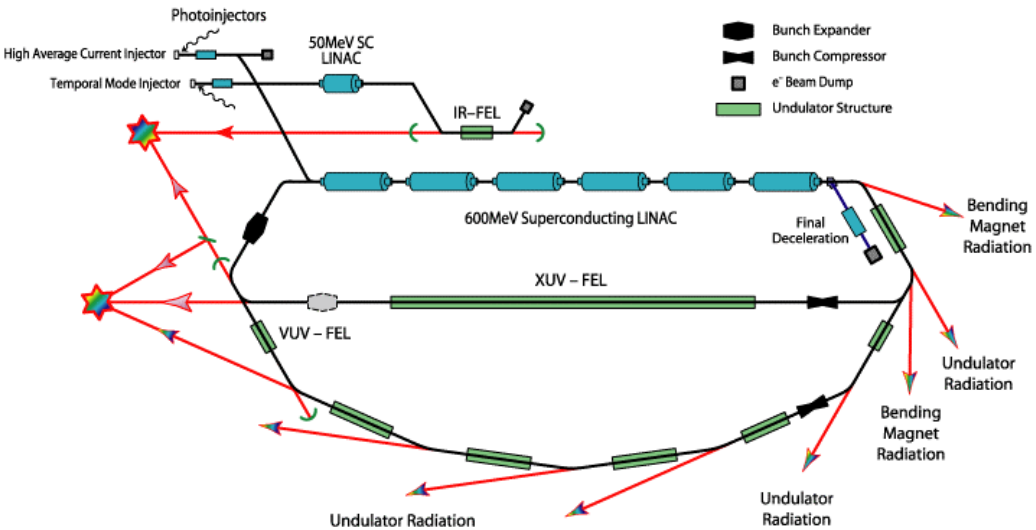


BINP MARS

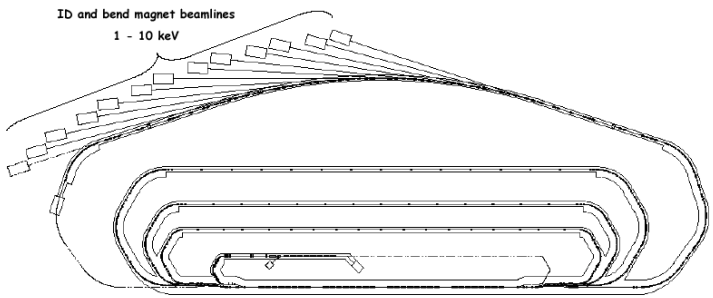


Cornell ERL

4GLS



* LBNL LUX



* Recirculating linac only, maintain ER option as future upgrade

Jefferson Lab Energy-Recovering FEL Scientific User Facility

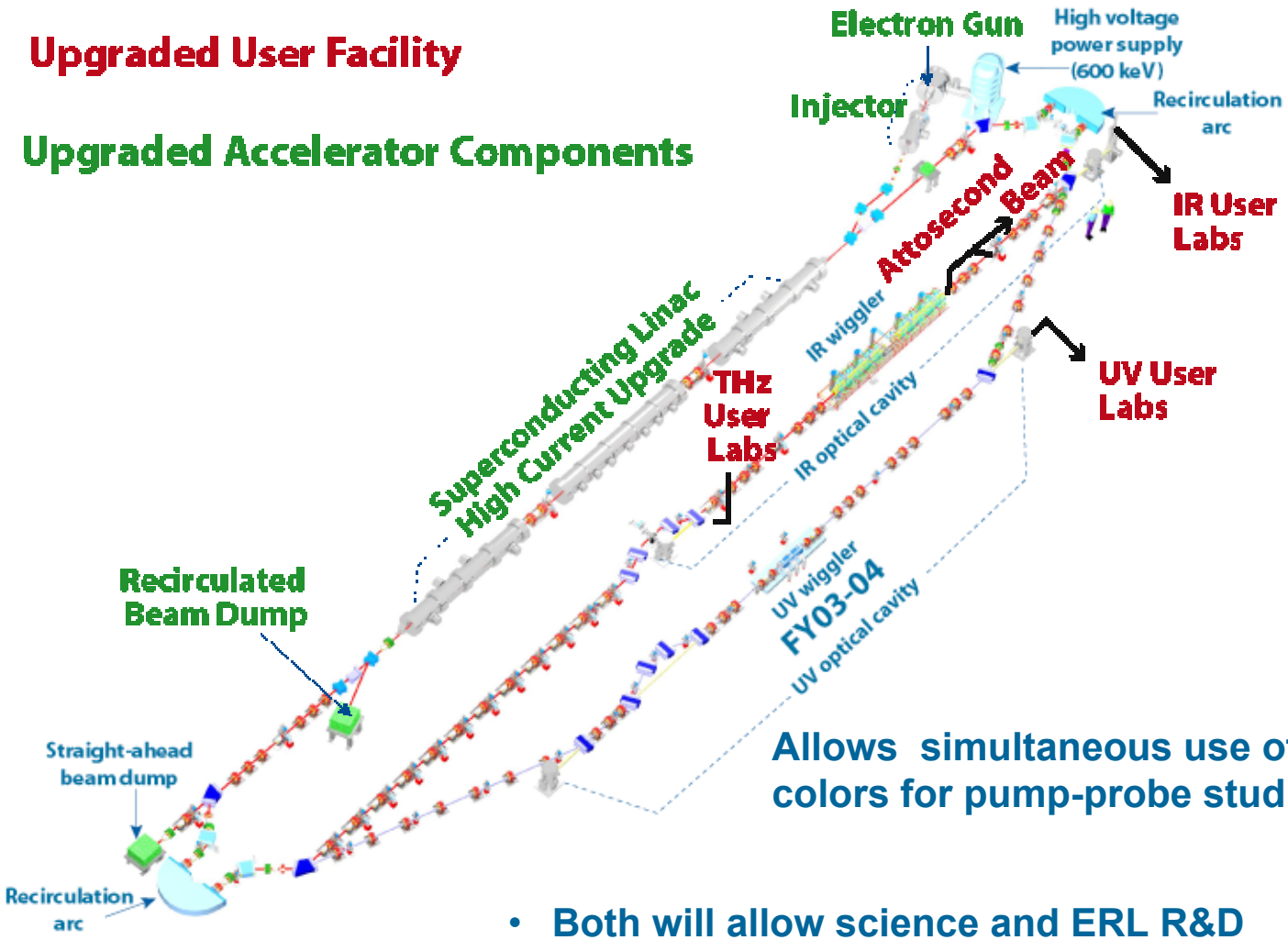
To explore the potential and feasibility of ERL-based SR sources,

Jefferson Lab has proposed a further upgrade of the FEL, which will:

1. Fill a scientific gap addressed by high brightness, ultra-short-pulse THz to UV light.

2. Contribute to the technology foundation for the development of energy recovering linacs for use as high-brightness, short-pulse x-ray sources.

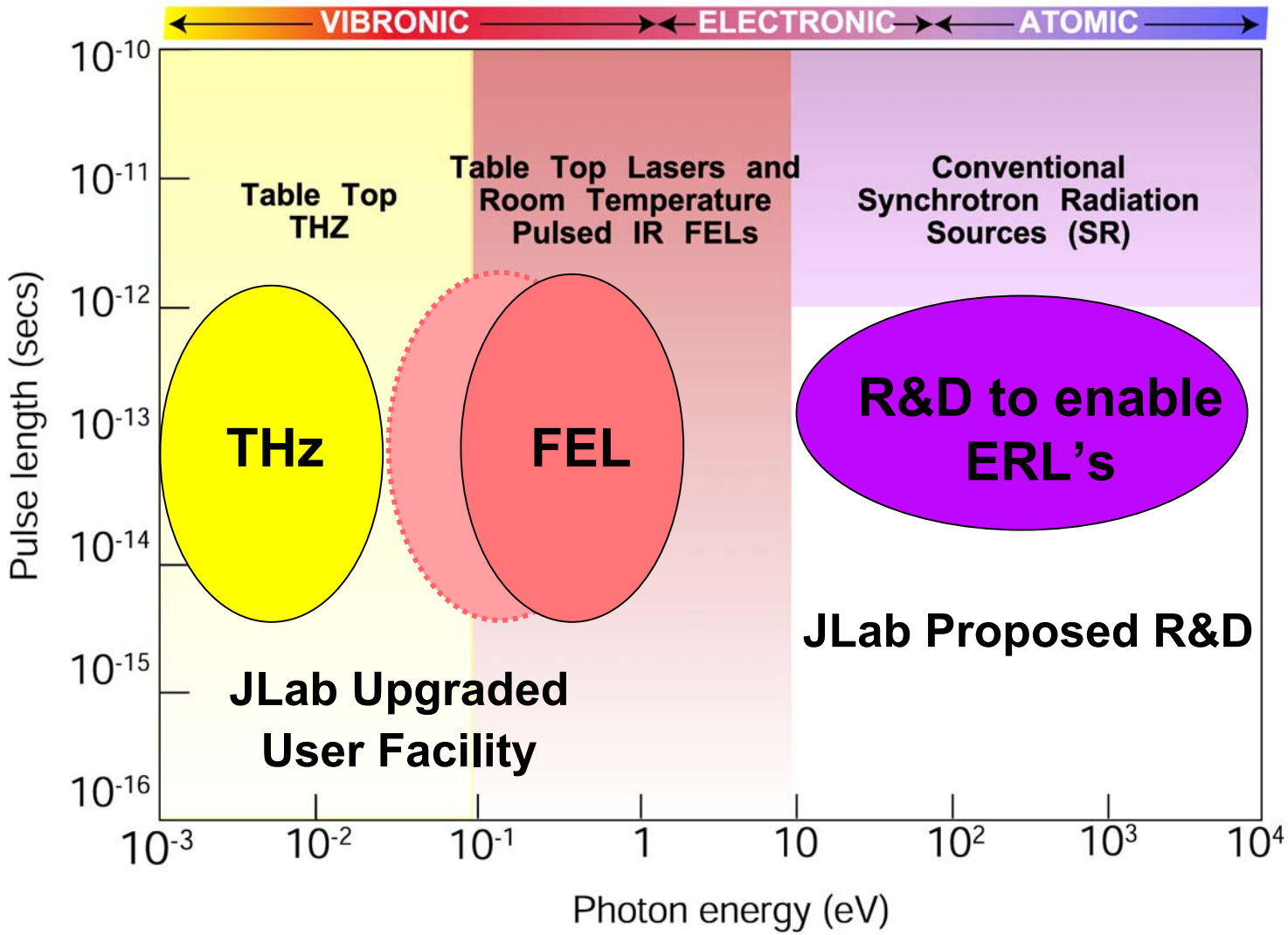
JLab FEL Facility Upgrade



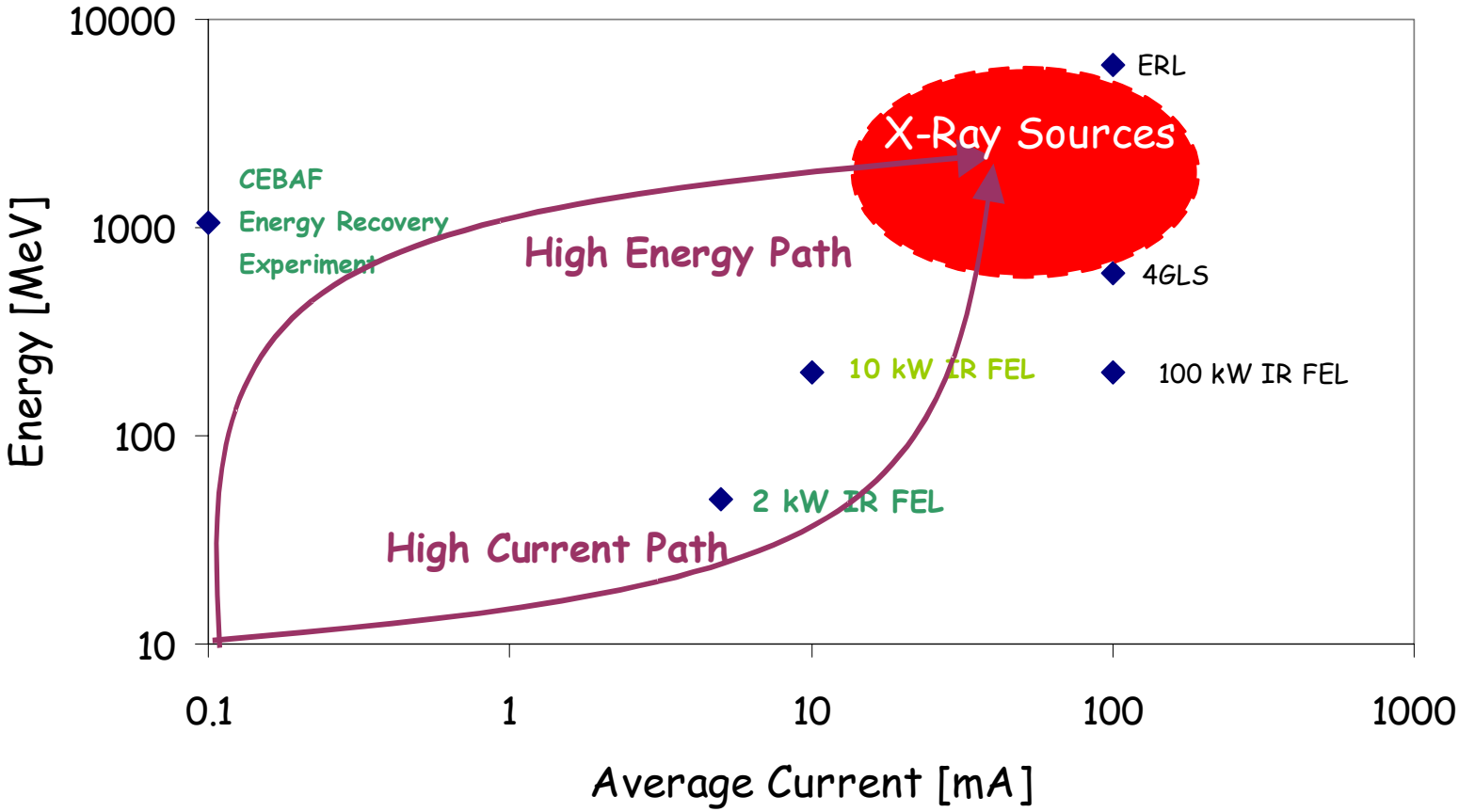
Allows simultaneous use of multiple colors for pump-probe studies

- Both will allow science and ERL R&D
- Attosecond beam generation concept developed in collaboration with Alexander Zholents of LBNL

Canvas of Science-Driven Accelerator-Based Light Sources



Jefferson Lab offers two complementary R&D paths to future ERL-based x-ray facilities

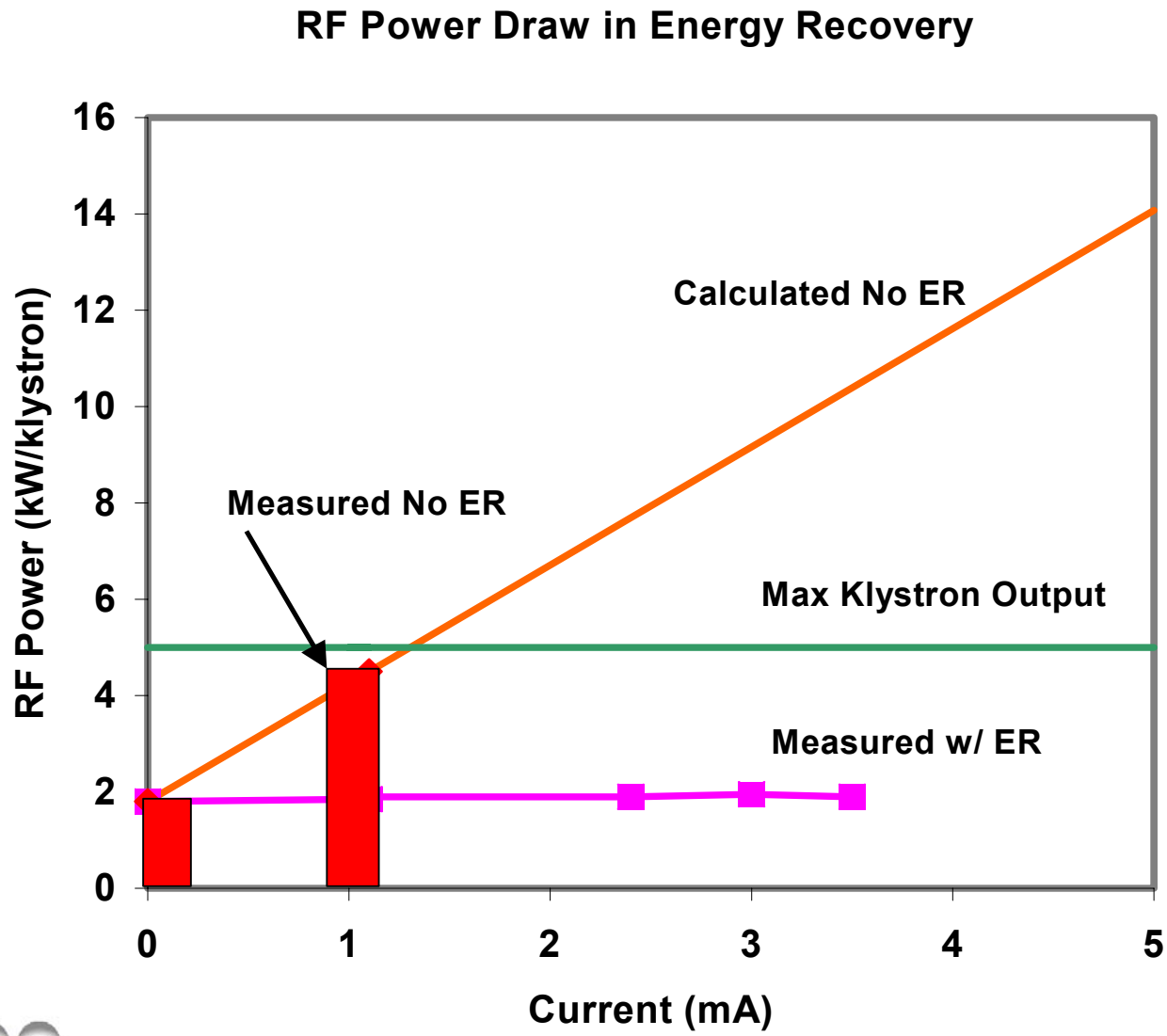


JLab accelerators are ideal test accelerators for demonstrating feasibility of proposed ERL-based SR sources.

Elements of an ERL R&D

- Generation and preservation of low emittance, high current beams
  - ~ 0.1 nC per bunch
- Stability at high average current
- High energy (~ GeV scale) demonstration of energy recovery

Energy Recovery Works



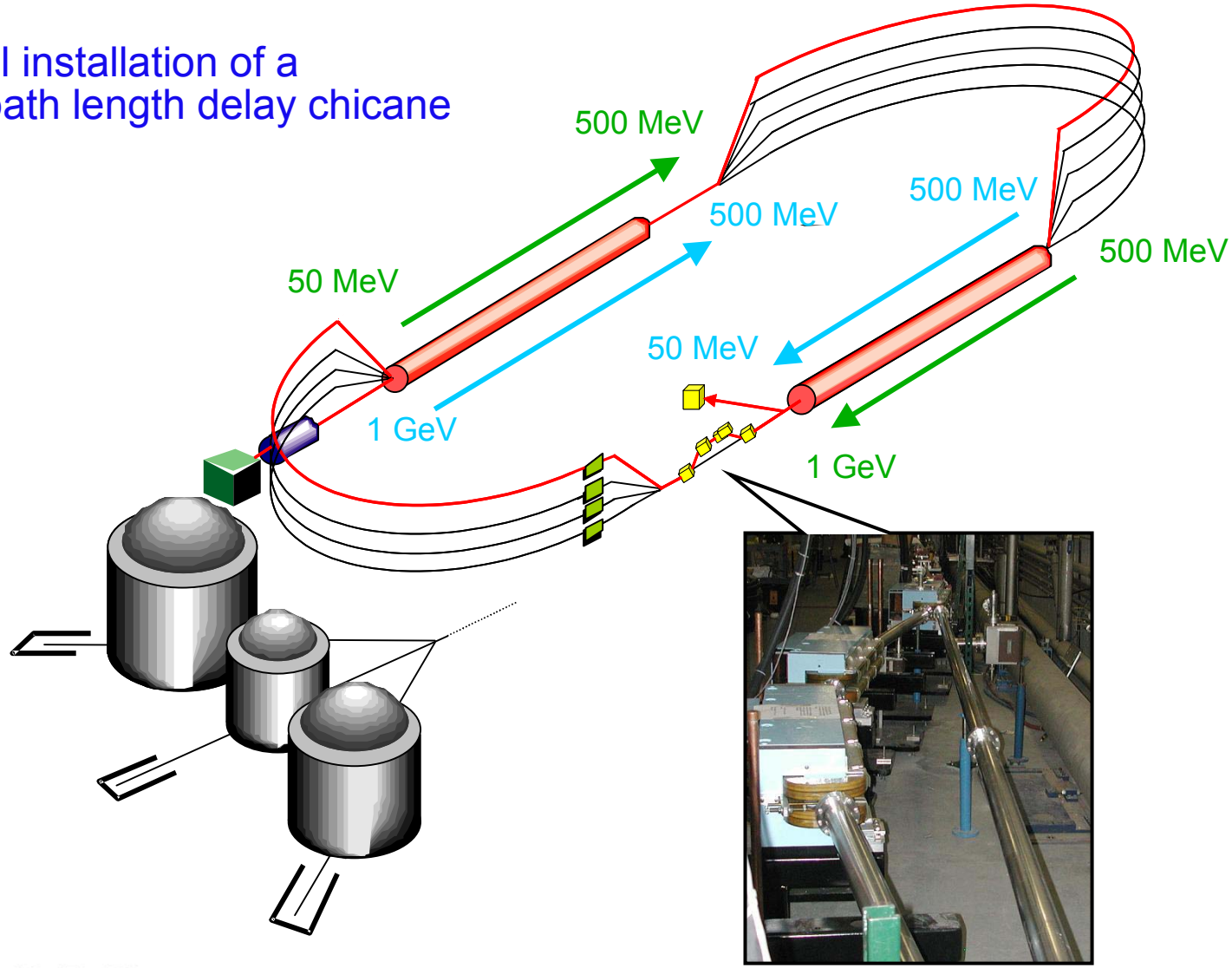
CEBAF Energy Recovery at 1 GeV

- CEBAF-ER: 1 GeV scale demonstration of energy recovery at CEBAF.
- Variable final-to-injection energy ratio to test system's dynamic range.
- Beam emittance, momentum spread measurements to quantitatively characterize phase space during acceleration and energy recovery.
- Large dynamic range (6 decades of intensity) beam profile measurements of energy recovered beam to quantify particle loss.
- RF measurements to characterize the efficiency of energy recovery.

A. Bogacz, et al., "CEBAF Energy Recovery Experiment," Proc. PAC 2003

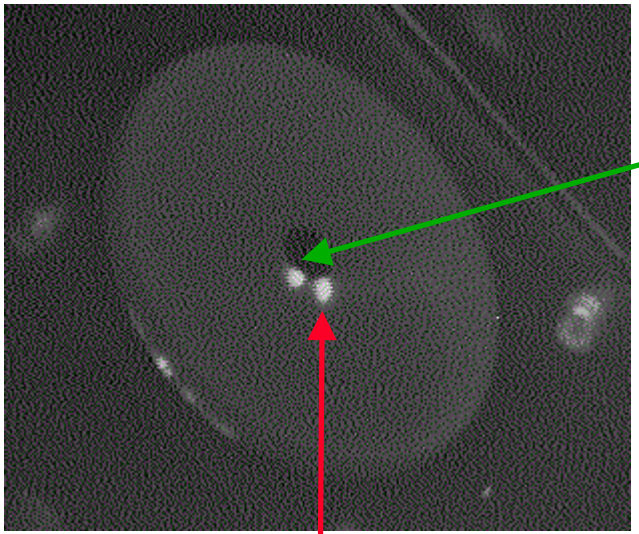
CEBAF-ER Experiment

Special installation of a
$\lambda_{RF}/2$ path length delay chicane

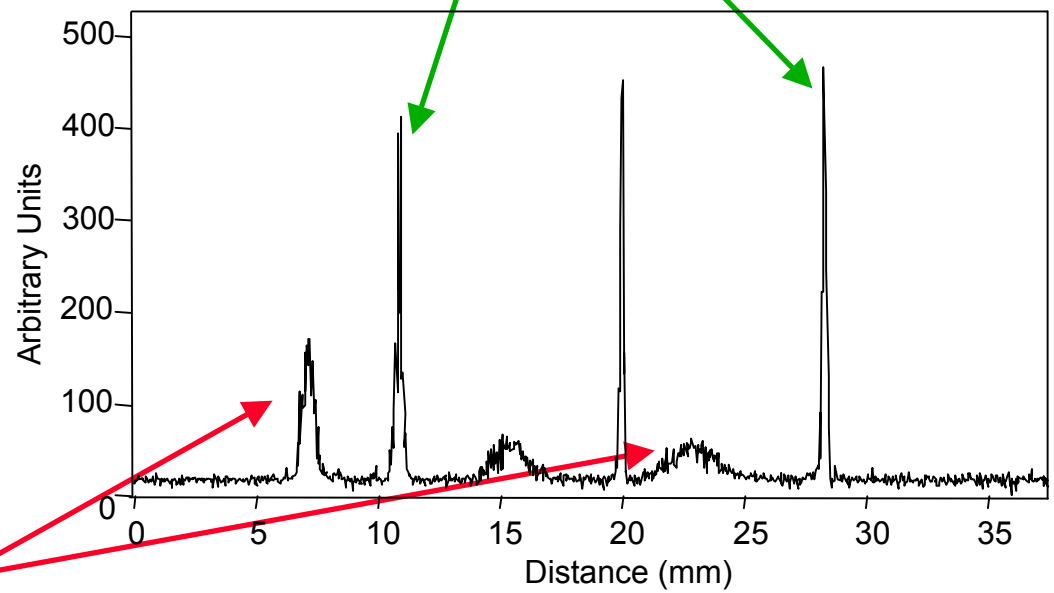


CEBAF-ER Emittance Measurements

Beam profiles at end of South Linac



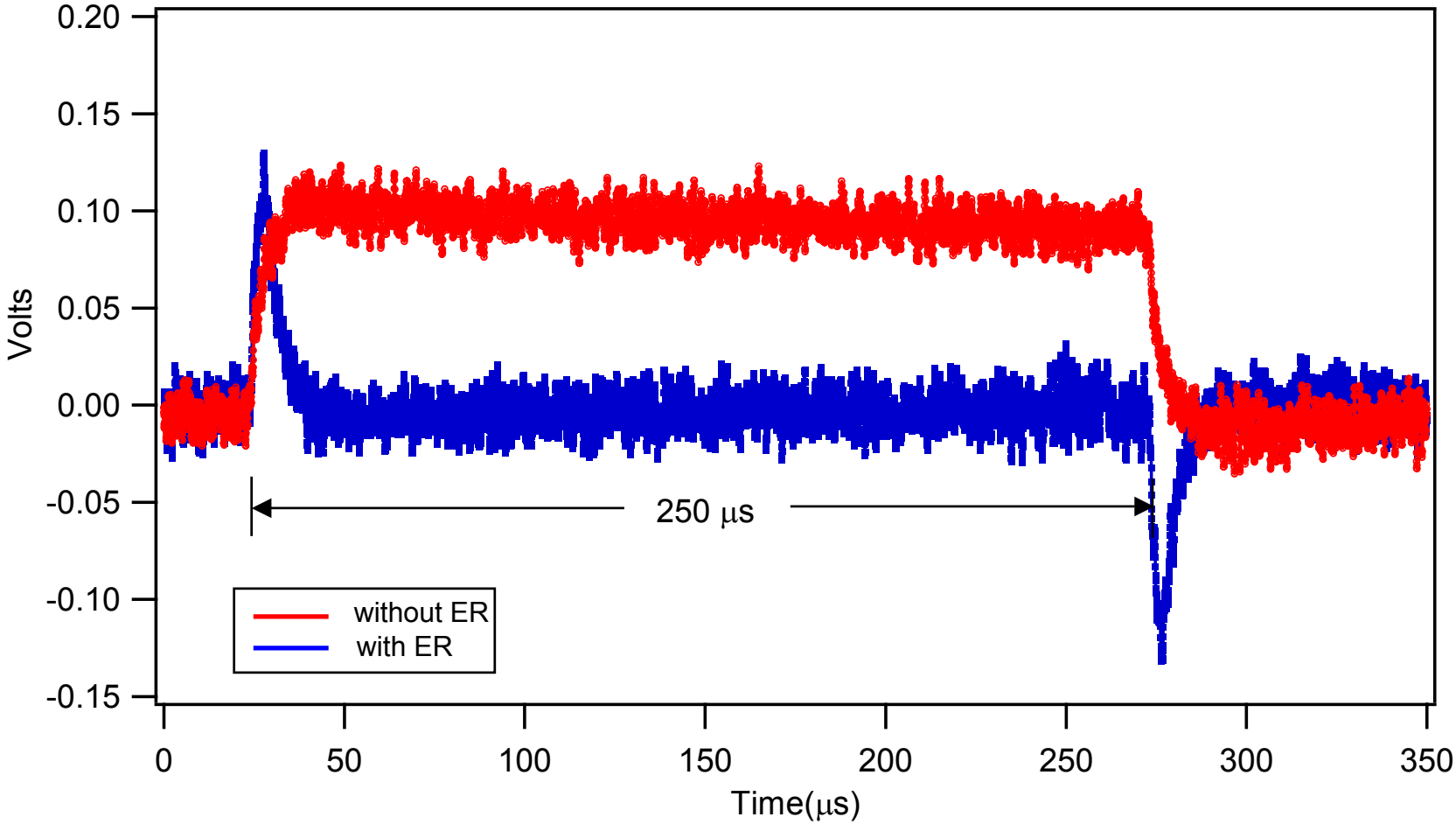
~ 1 GeV Accelerating beam



~ 55 MeV Decelerating beam

RF System Response

Gradient modulator drive signals **with** and **without** energy recovery in response to 250 μsec beam pulse entering the RF cavity



CEBAF-ER Preliminary Results

- 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 beam current accelerated to 1056 MeV and energy recovered at 56 MeV
- Tested the dynamic range on system performance by demonstrating high final-to-injection energy ratios of 20:1 and 50:1
- Beam profile measurements were obtained with 5-6 decades dynamic range with no measurable halo (i.e. particles outside the Gaussian core).

Conclusions

- ERLs offer a powerful new paradigm for the generation of bright beams used in the production of synchrotron radiation.
- JLab operates the only ERL-based light source.
- Future upgrades will explore the scientific utility and potential of a broad spectrum of radiation
- Using the JLab accelerators we are pursuing R&D to validate ERL-based light source designs for the light source community.
- How close are we to the construction of an ERL-based SR source? Given the R&D programs sustained we should be able to design and be ready to build within 3-5 years.

Acknowledgments

We thank our collaborators:

Cornell University

Daresbury Laboratory

Brookhaven National Laboratory

Lawrence Berkeley National Laboratory

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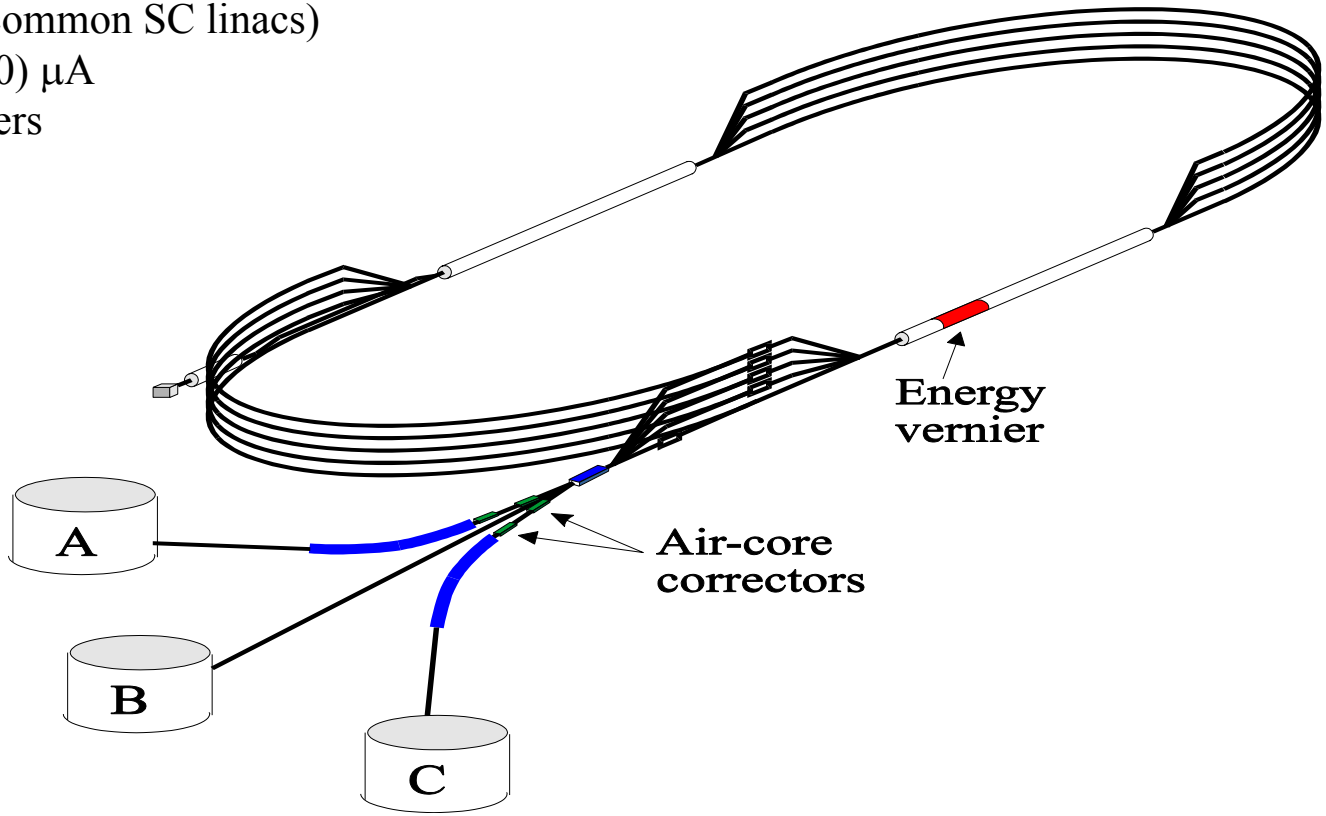
Feedback System Elements

Beam position and energy stabilization

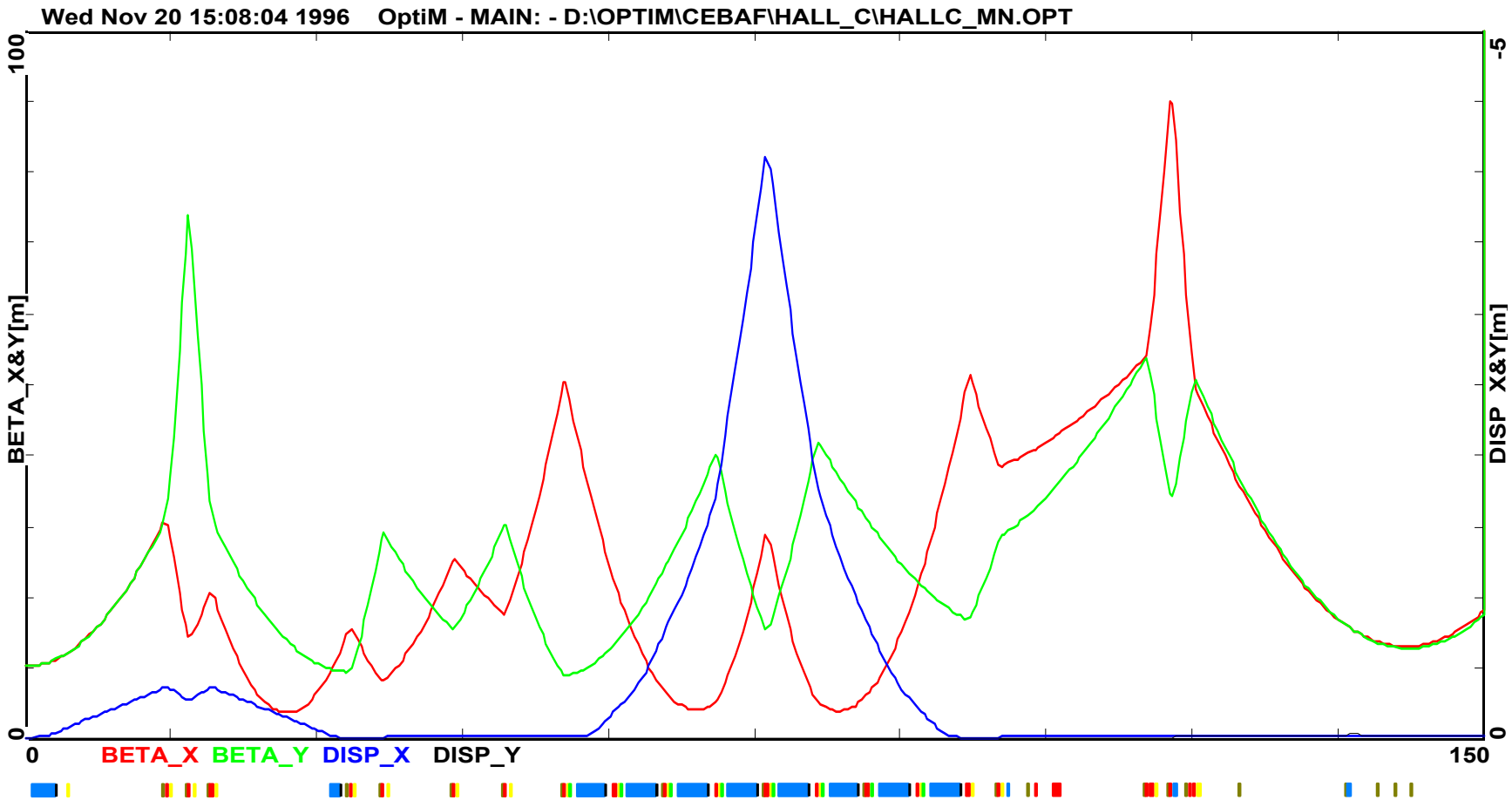
- 6 dimensional phase space

Faast 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

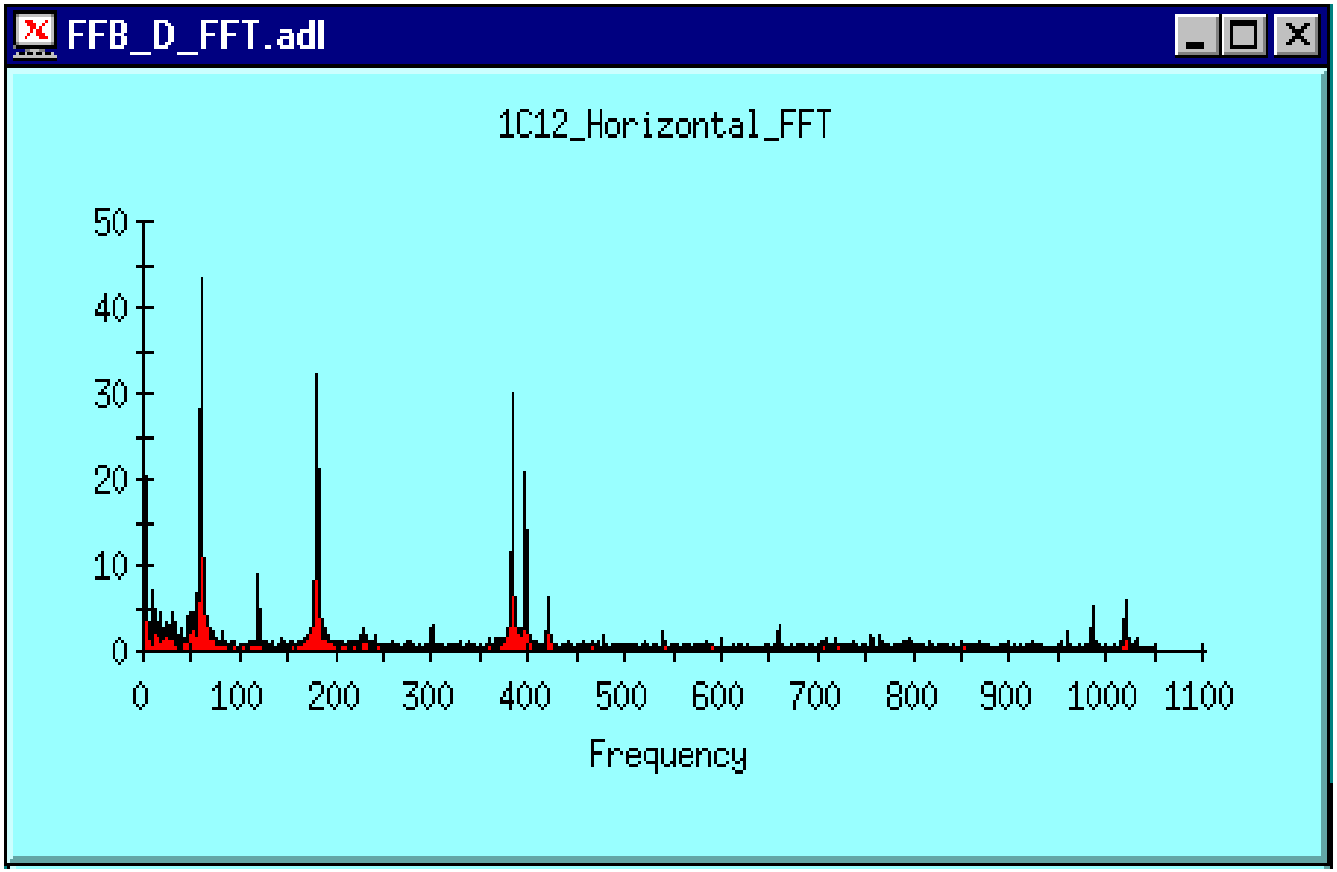


Dispersion Suppressed Optics



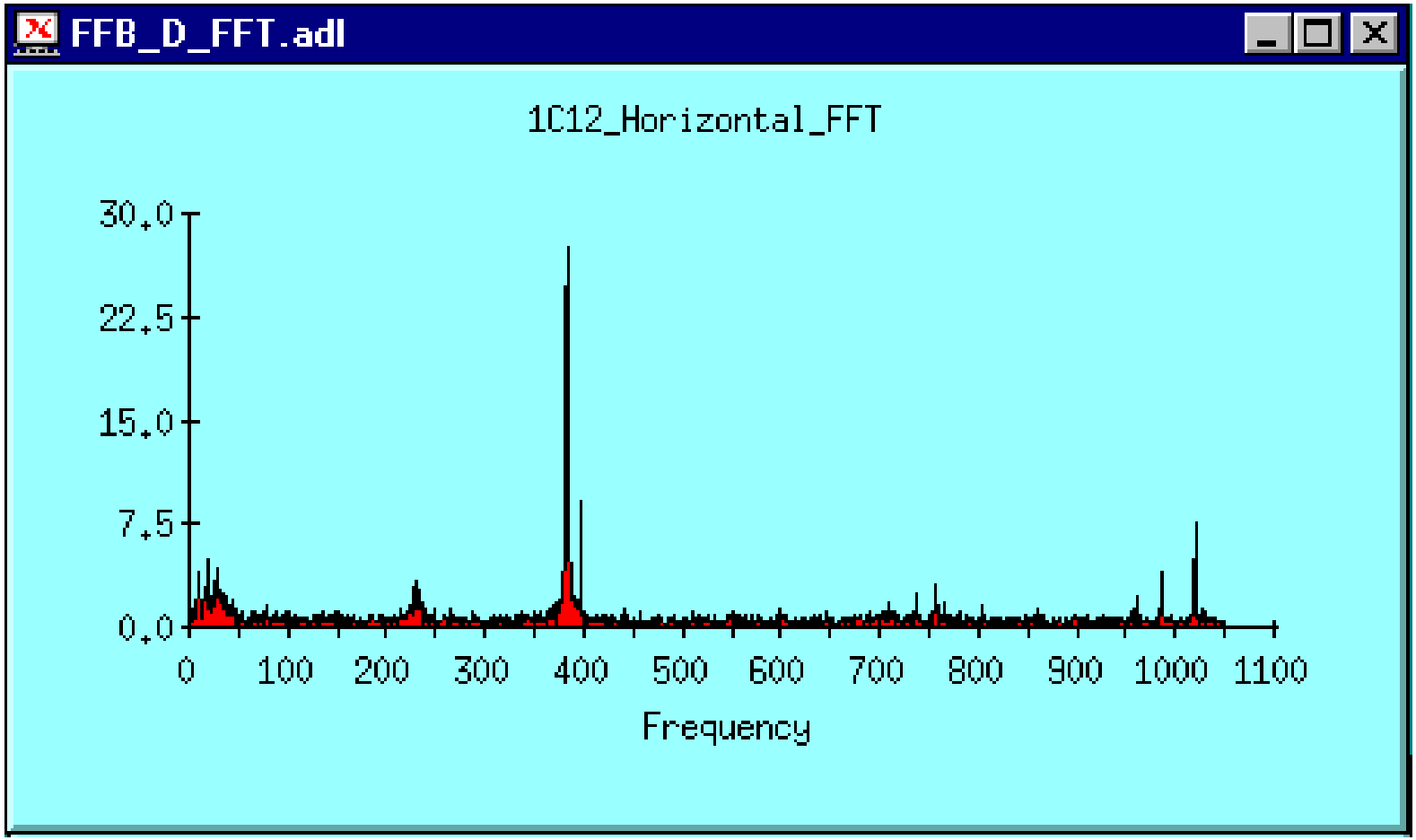
Courtesy: Valeri Lebedev

Fast Feedback Off



Courtesy: Valeri Lebedev

Fast Feedback Residual Fluctuations



Courtesy: Valeri Lebedev

Fast Feedback rms position fluctuations

FFB_O_bpm_val.adl

Hall A Fast FeedBack BMP/Corrector Values

Horiz Position (microns)

	min	max	mean	Std Dev	Outliers
1C07	-49	45	6	10	0
1C08	-70	60	3	14	3
1C11	-5	97	52	19	0
1C12	-91	101	7	42	0
1C14	-28	35	3	11	0
1C16	-44	41	-8	14	0
1C18	-77	2	-42	11	0
1C20	-59	10	-28	11	0

Vert Position (microns)

	min	max	mean	Std Dev	Outliers
1C07	-43	46	-2	11	0
1C08	-25	45	12	11	0
1C11	-60	76	12	18	0
1C12	-24	75	27	12	0
1C14	-26	88	43	13	0
1C16	-31	56	15	9	0
1C18	-17	71	33	12	0
1C20	-17	80	36	14	0

Horiz Corrector (gauss-cm)

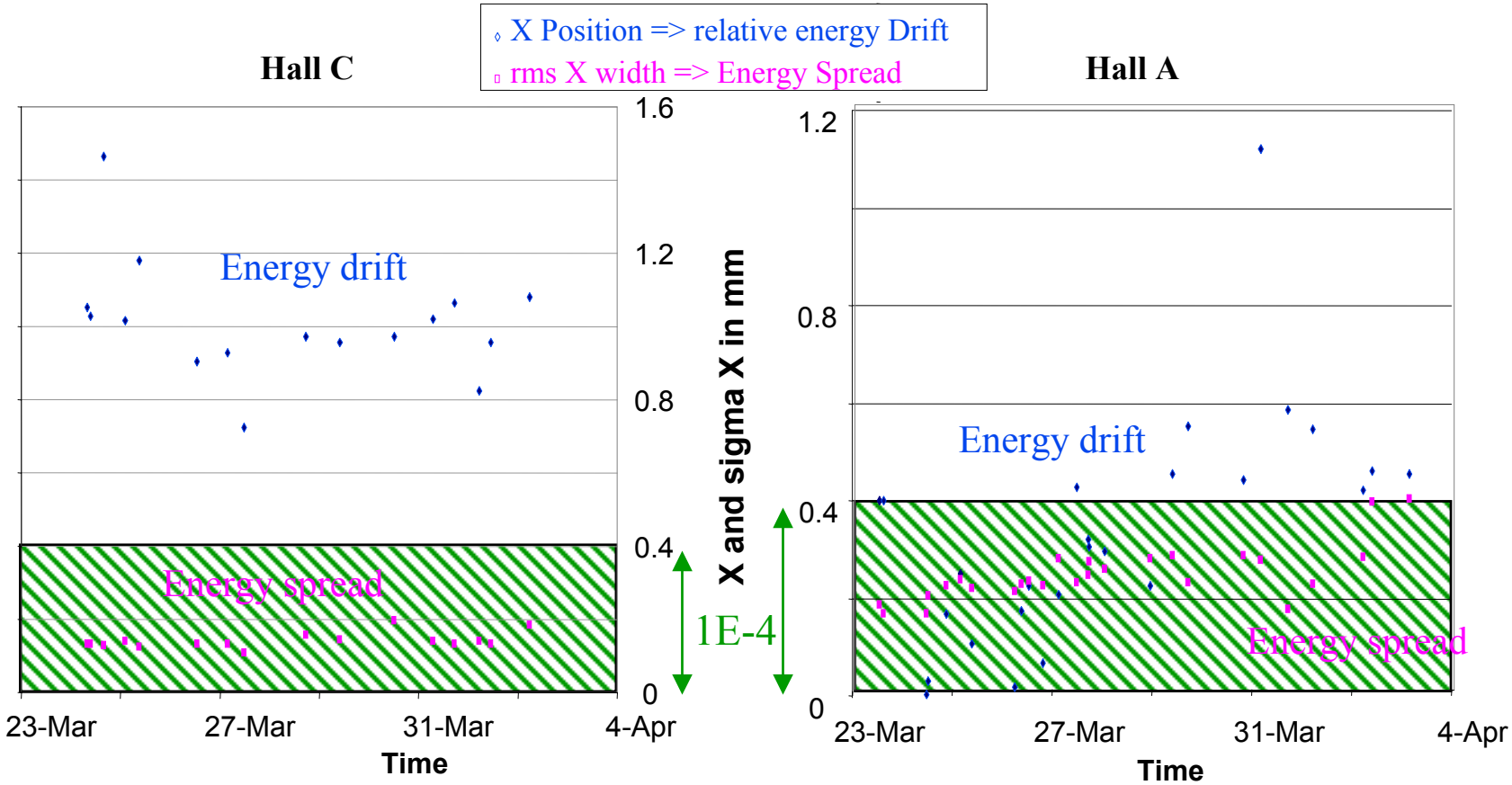
	min	max	mean	Std Dev
1C04H	-4.95	31.38	4.79	4.29
1C07H	-19.92	12.59	-8.06	4.03

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

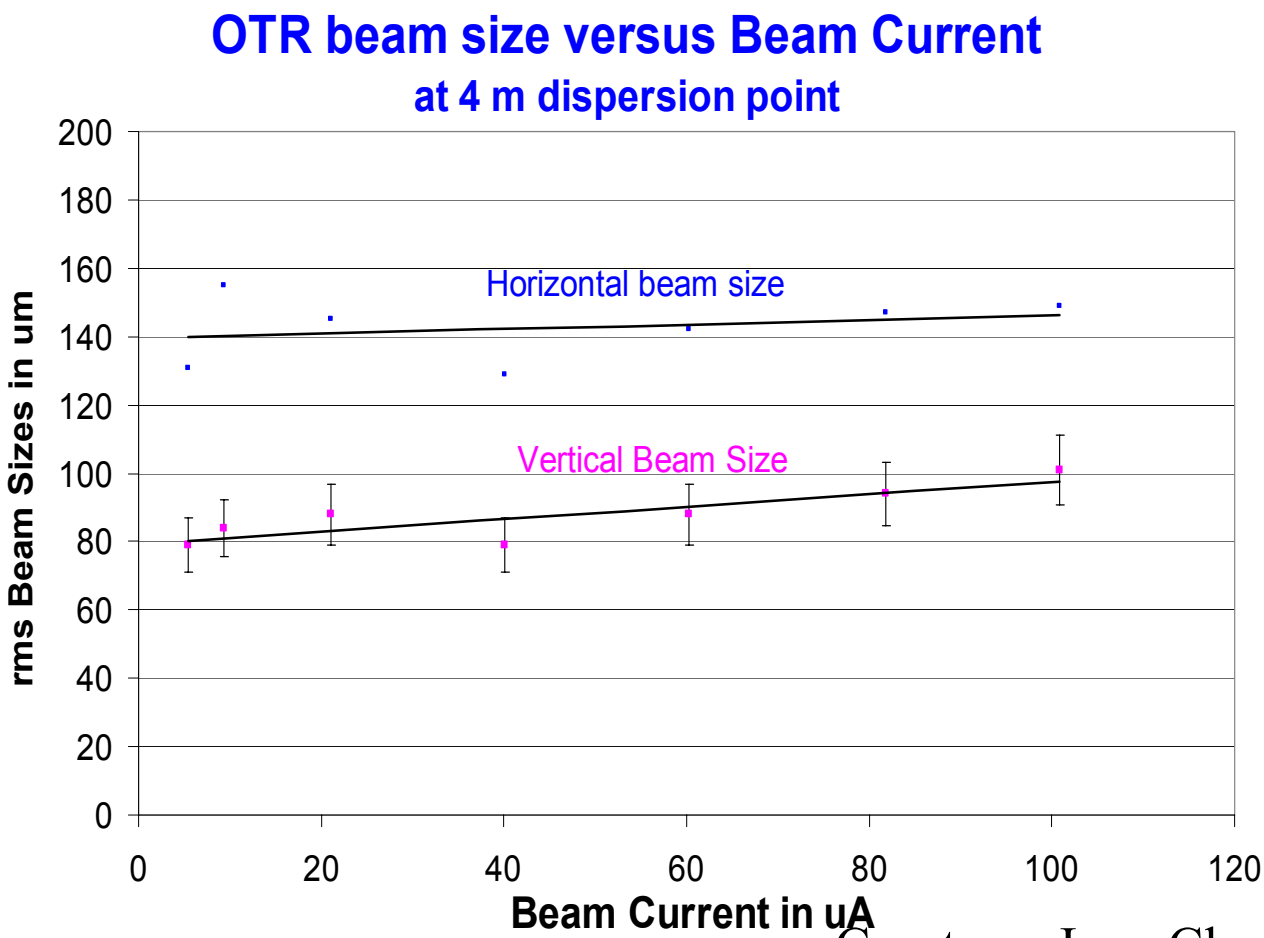
Courtesy: Valeri Lebedev

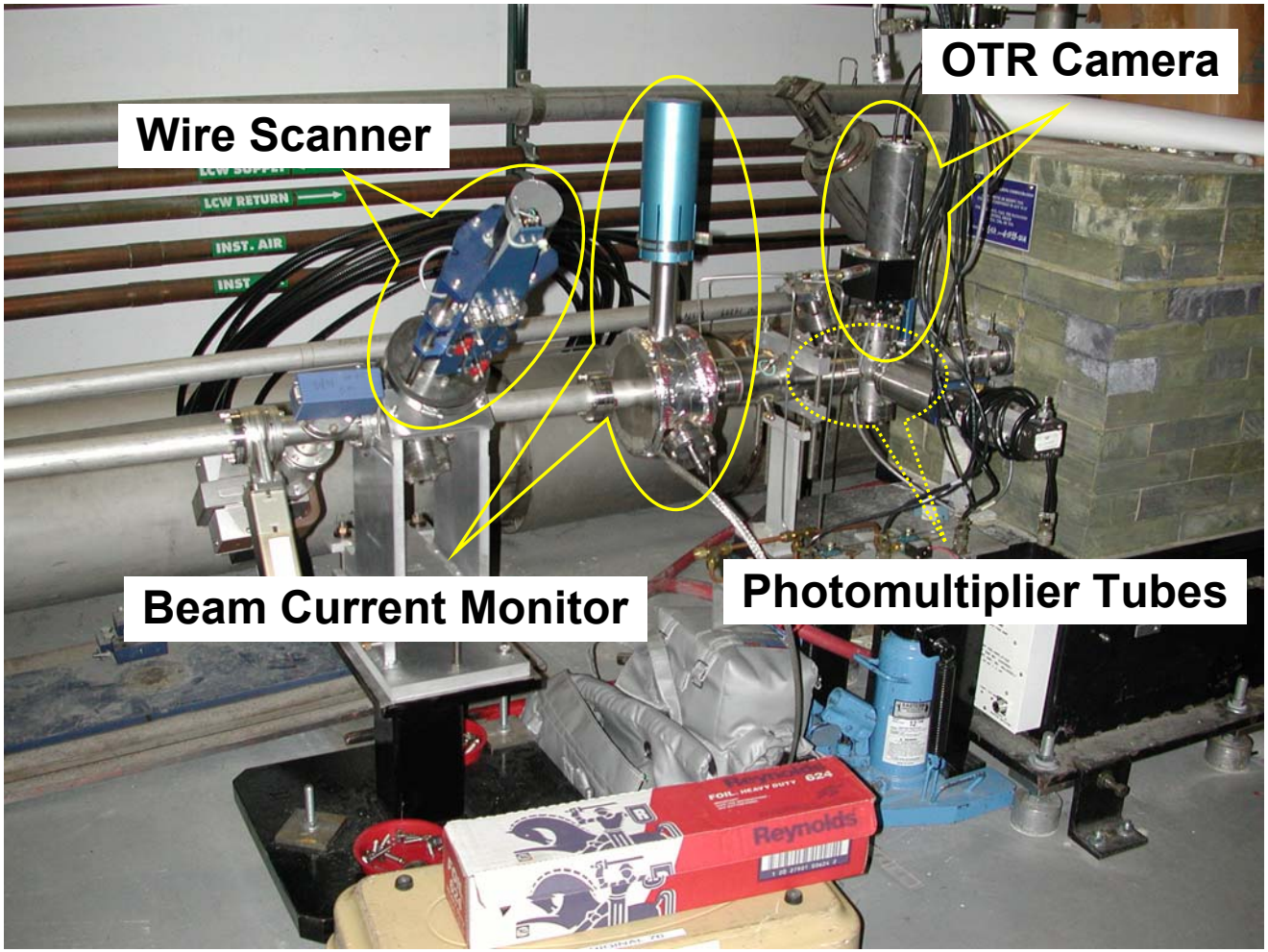
dp/p data: 2-Week Sample Record



Courtesy: Jean Claude Denard

dp/p Stability versus Beam Current



Courtesy: Jean-Claude Denard

Dump-Line Diagnostics