The JLab High Power ERL Light Source

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Jefferson Lab
Newport News, Virginia

ERL Workshop
Newport News
March 19, 2005

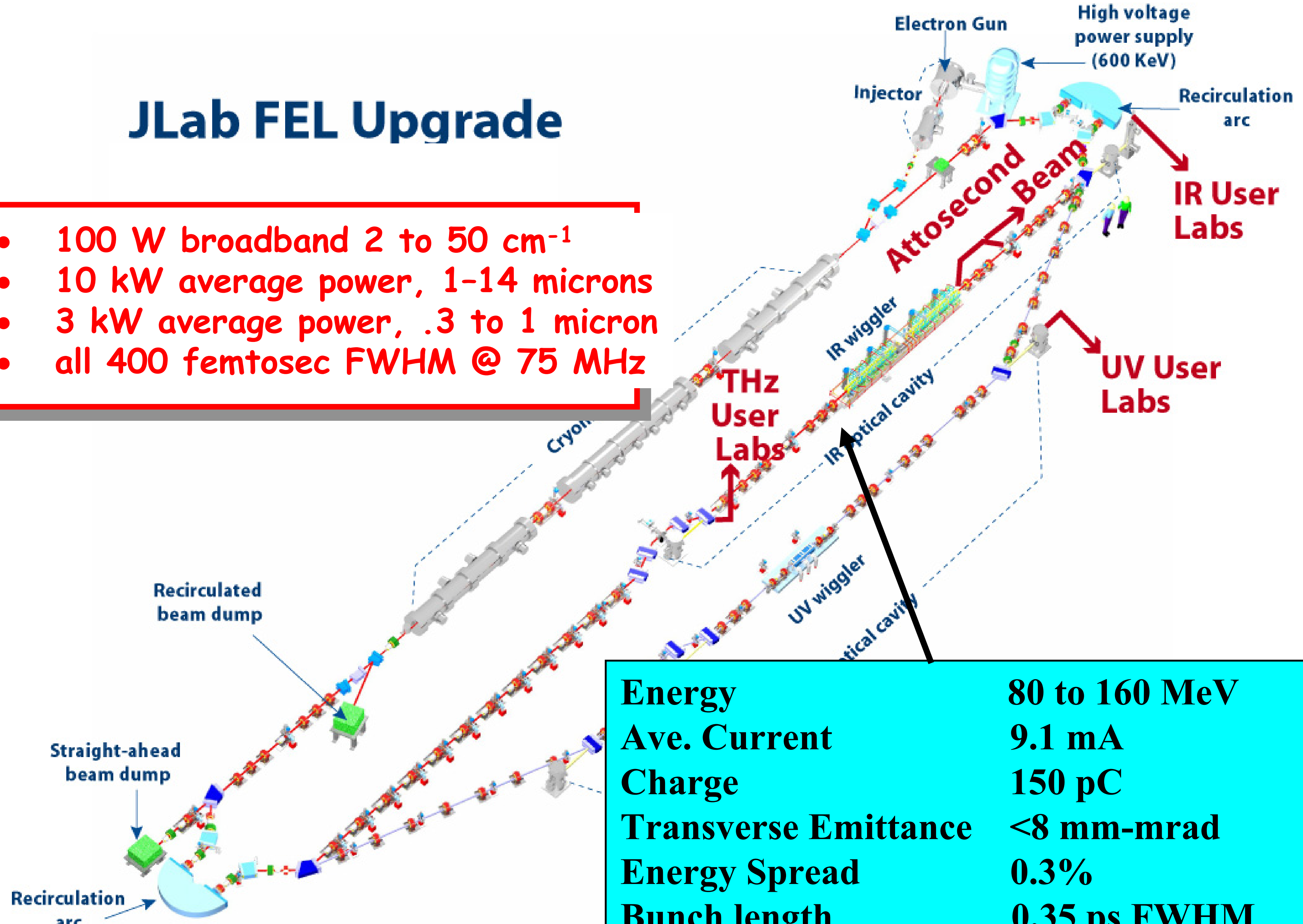
JLab IR/UV Upgrade

- **JLab IR Demo launched a new form of light source: an Energy Recovering Linac (ERL) based on srf technology**
- **The present IR/UV Upgrade extends the Demo's lasing performance and is a test bed for scaling ERLs to higher current, higher energies, higher beam brightness, and shorter wavelength operation**

- **This talk will present:**
  - **System description and performance**
  - **Status**
  - **User program**
  - **Introduction to our studies of ERL-related physics; details later by C. Hernandez *(Injectors)*, D. Douglas *(Transport)*, S. Benson *(Injector Diagnostics)*, E. Pozdeyev & C. Tennant *(BBU and HOMs)*, R. Rimmer *(High Current Cavities)*, and M. Shinn *(Drive Lasers)*, G. Krafft (*Phase Transfer Measurements*), K. Jordan *(Diagnostics)***

JLab FEL Upgrade

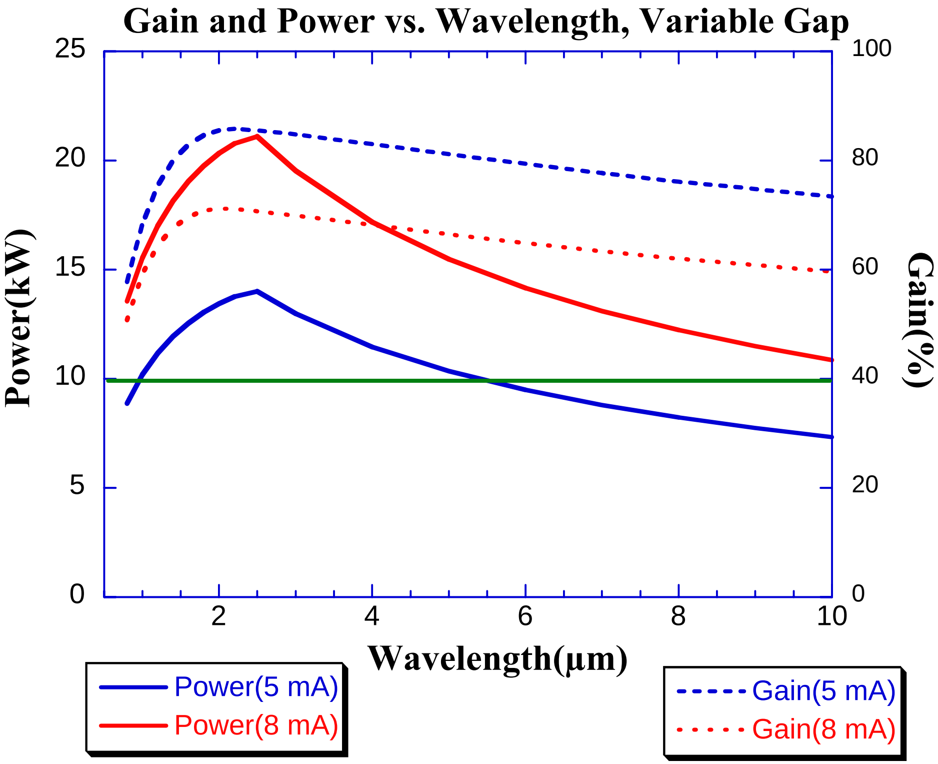
- 100 W broadband 2 to 50 cm^{-1}
- 10 kW average power, 1–14 microns
- 3 kW average power, .3 to 1 micron
- all 400 femtosec FWHM @ 75 MHz



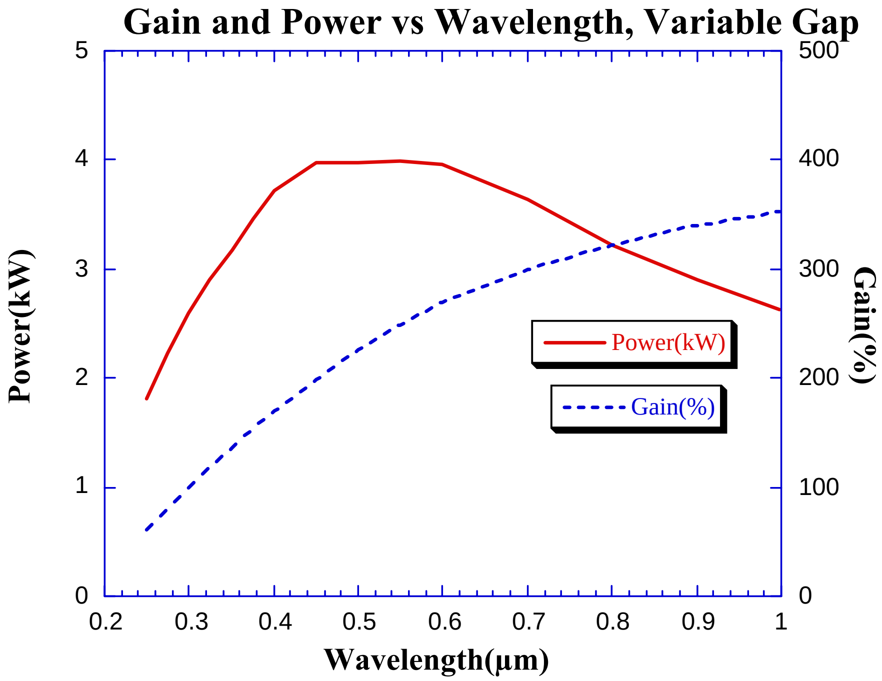
Energy	80 to 160 MeV
Ave. Current	9.1 mA
Charge	150 pC
Transverse Emittance	<8 mm-mrad
Energy Spread	0.3%
Bunch length	0.35 ps FWHM
Longitudinal Emittance	<80 kV-ps

IR/UV Upgrade FEL performance

IR Upgrade, 140 MeV linac

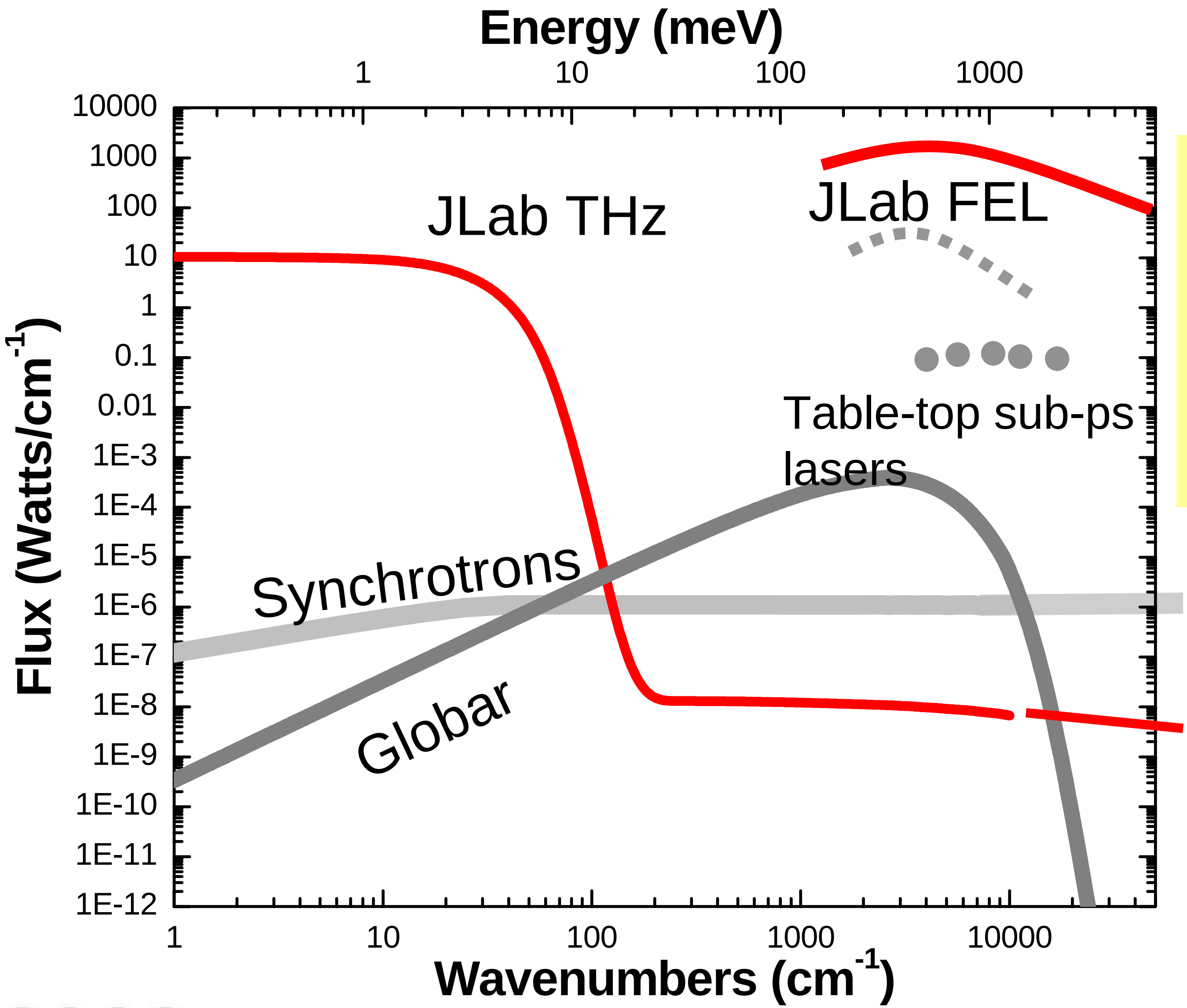


UV Upgrade, 160 MeV linac



Courtesy S. Benson

THz with sub-picosecond pulses is produced parasitically > 10^4 higher power than other sources!



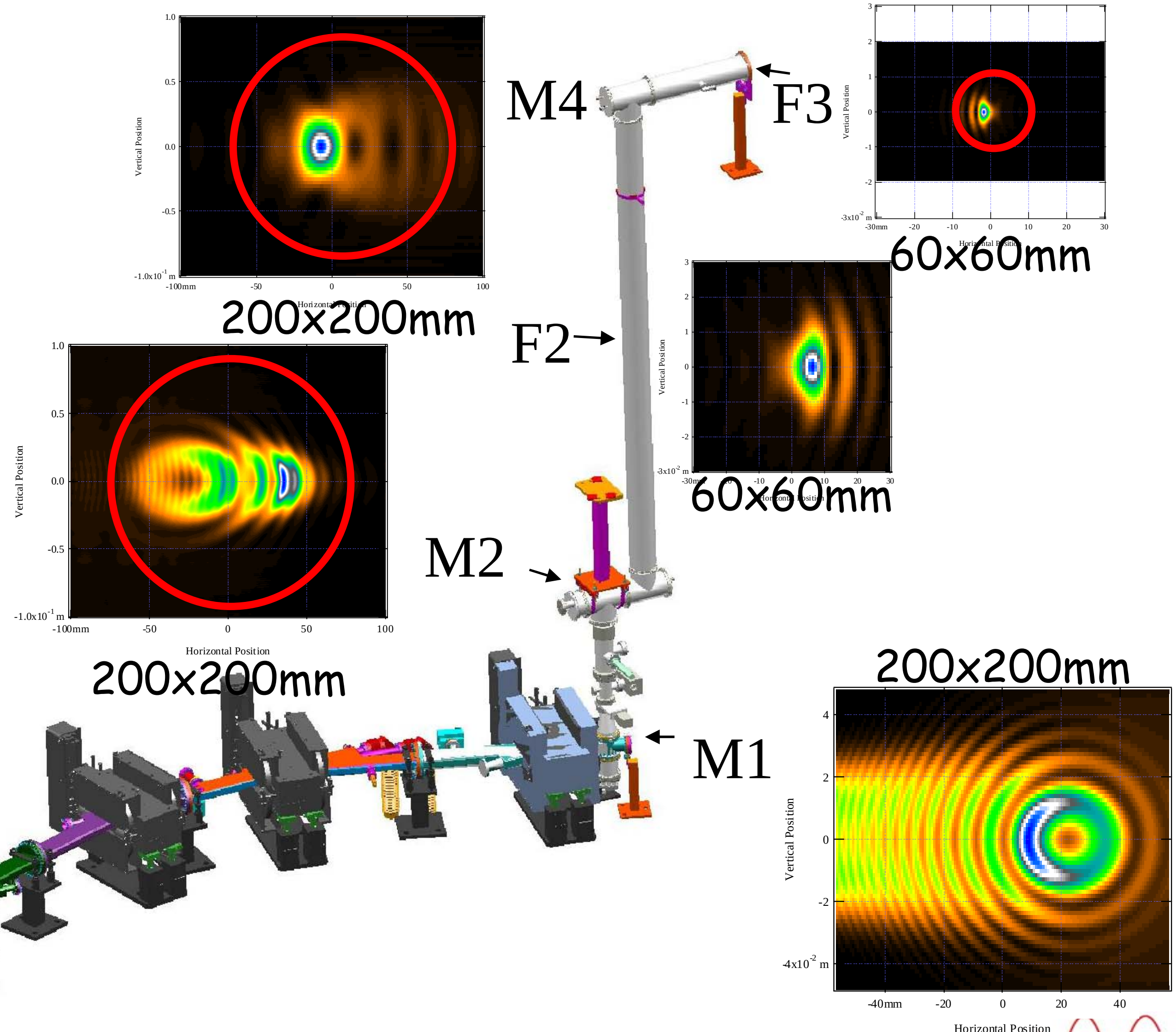
THz proof of principle:
Carr, Martin, McKinney, Neil, Jordan & Williams
Nature 420, 153 (2002)

Courtesy
G. Williams

Terahertz beamline transports visible to 5 mm wavelengths to user lab

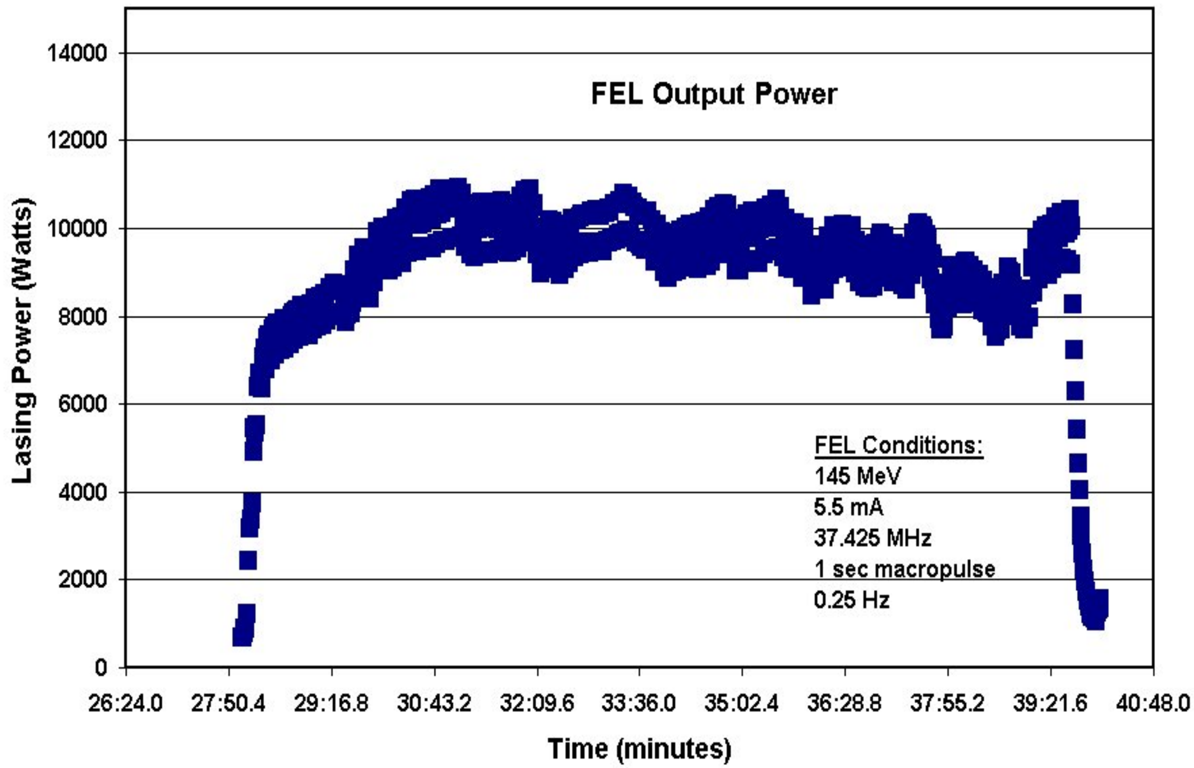
JLab THz beam with optical ray-tracing

Calculating THz patterns in near field is complex: modification to SRW by Oleg Chubar, Paul Dumas



JLab FEL Upgrade Status

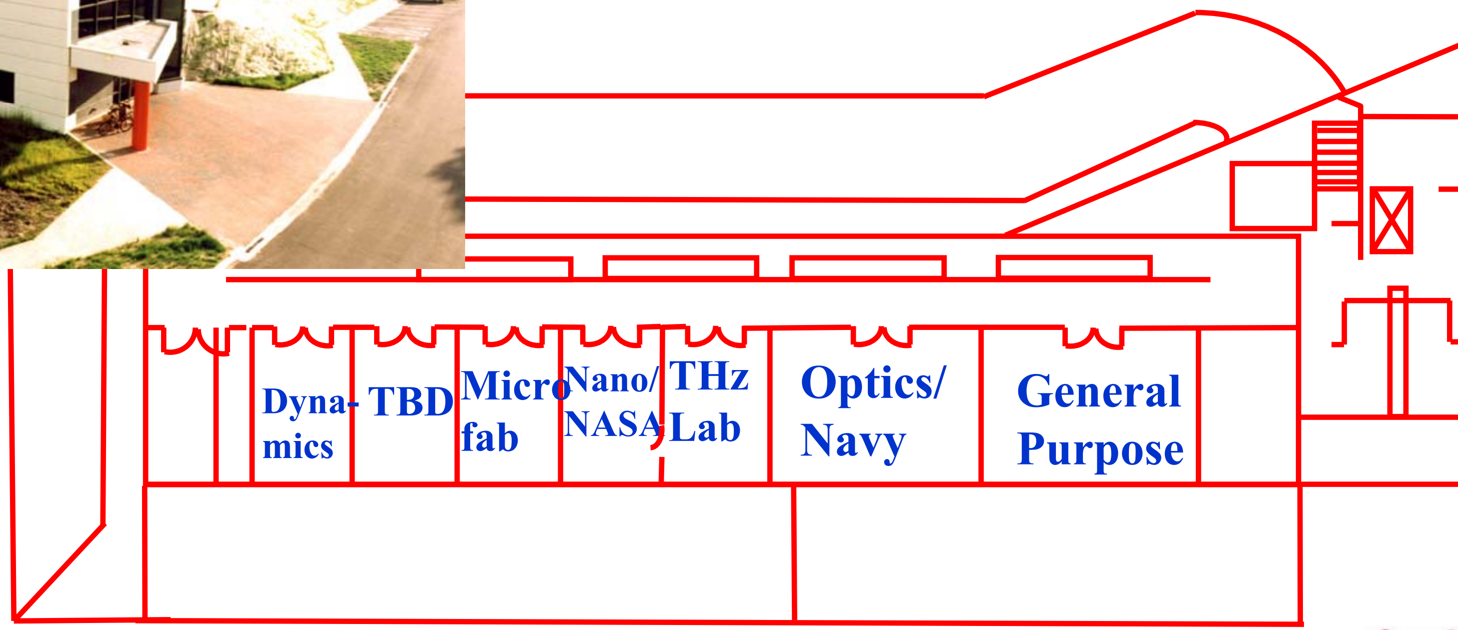
- THz system installed and is ready to begin user experiments
- IR Upgrade FEL at JLab starting up at 10 kW
  - 10 kW average power lasing achieved at 6 microns
  - Multi-kW powers at 2.8 and 10 microns.
  - Broadly tunable at lower power
  - User experiments begin in 1 month
- UV beamline
  - Installation in summer
  - User experiments late next fall

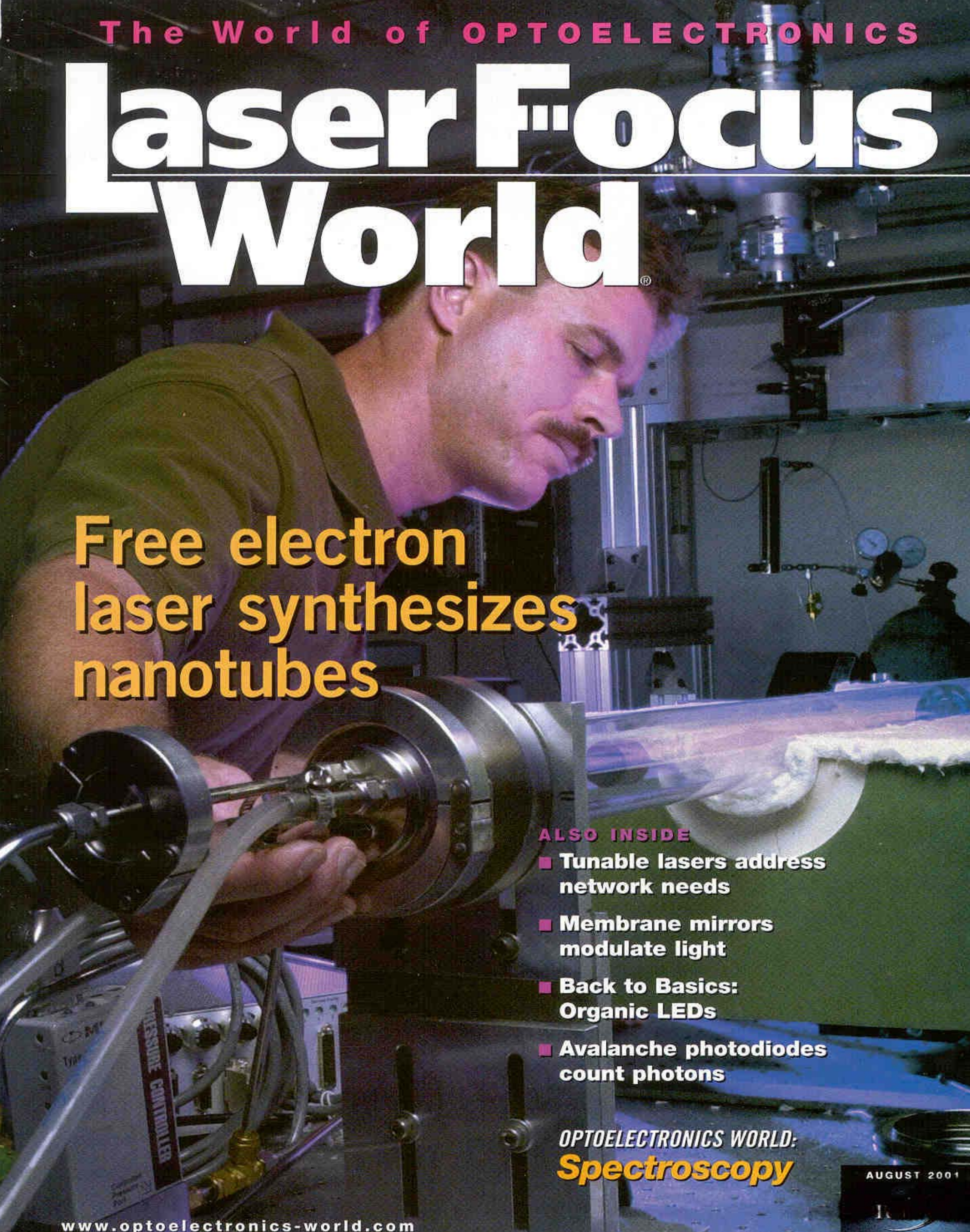


THE FREE ELECTRON LASER USER FACILITY

The FEL has a versatile user facility developing applications for basic science, industry, biology and defense.

7 User labs, each with a different area of focus.





Jefferson Lab

FEL Science Research 2000/2001

Interactions of Hydrogen in Group IV Semiconductors with Intense Infrared Resonant Radiation G. Lüepke, CWM , L. Feldman, N. Tolk, and M. Budde, Vanderbilt

Laser Target Interactions in PLD A. Reilly, M. Kelley, CWM, and M. Shinn, JLab

FEL Polymer Ablation for Reflective Sails, M. Kelley, CWM, J. Clarke and S. Reich, Northrop Grumman

Long lived Amide I Vibrational Modes in Myoglobin, R. Austin, Princeton

Synthesis and Characterization of carbon nanotubes and Si and Ge nanowires for use in NLO Composites, B. Holloway, CWM, M. Smith, NASA, Langley, P. Ecklund et al. Penn. St.

Laser-Plasma Material Interactions in Dense and Reactive Gas Atmosphere, P. Schaaf, U. Gottingen, Germany

Investigating key accelerator physics issues for ERLs and extending performance is a key goal of our program

- Beam generation at high peak and average brightness
  - Cathode life
  - Halo production
  - Power issues: windows, etc.
- Maximizing accelerator gradients
- Higher Order Mode (HOM) damping and cooling
- Beam transverse stability (BBU, etc., suppression)
- Brightness preservation, transverse and longitudinal
  - Coherent Synchrotron Radiation (CSR)
  - Space charge effects
  - Wakefields

Studies of major ERL challenges:

Injector

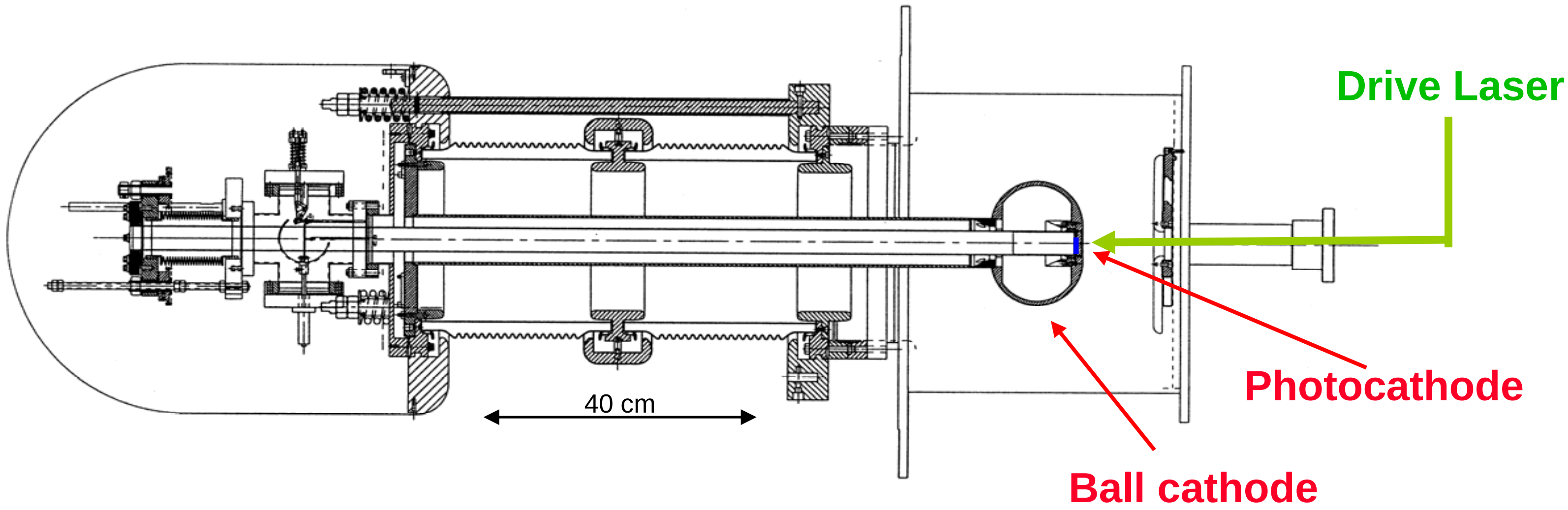
- **Low emittance current production & preservation**
- **Photocathode longevity at high average current**
- **RF Power handling**

Linac:

- **BBU in the main linac (HOMs power and damping)**
- **Longitudinal phase space preservation in bunching (curvature correction)**
- **Beam loss, halo**

JLab High Brightness Gun

Courtesy C. Hernandez



Extremely reliable, high QE

Delivered 5.5 kiloCoul from one cathode

Same cathode for 2 years, 400 Coul/cesiation

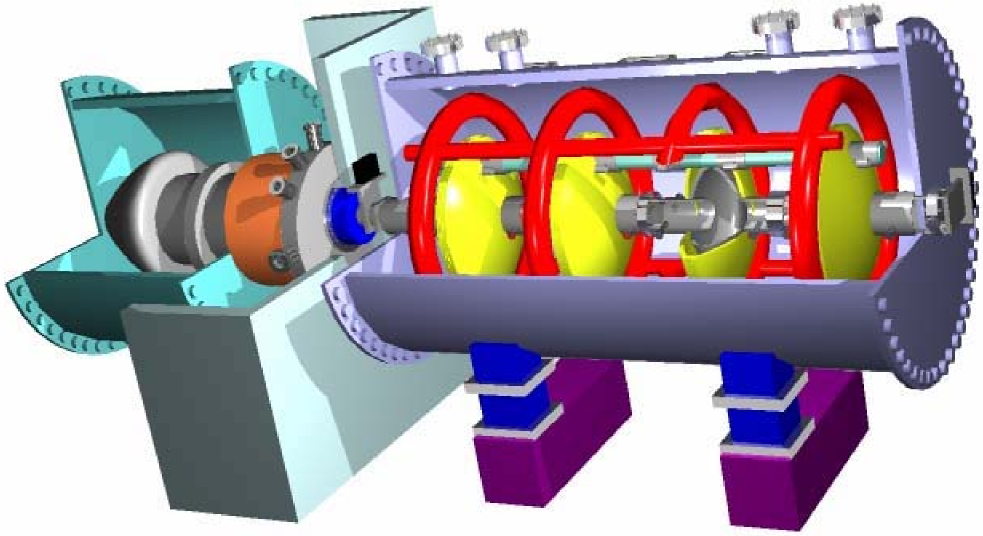
< 7 mm mrad for 135 pC, 10 MeV (most growth is in capture)

Low halo, low field emission (essential!)

Talks by C. Hernandez: injector, M. Shinn: drive laser, S. Benson: injector diagnostics

AES/JLab Hybrid DC/SRF photoinjector -748.5MHz for amp level capability

- SBIR development by AES Corp. and JLab
- Begins assembly this year, testing begins next year
- Single cell cavities
- High power couplers/windows
- Low frequency for larger window area and more stored energy



JLab concept of a high voltage DC gun married to a low frequency rf cavity (shown here with SNS cavities)

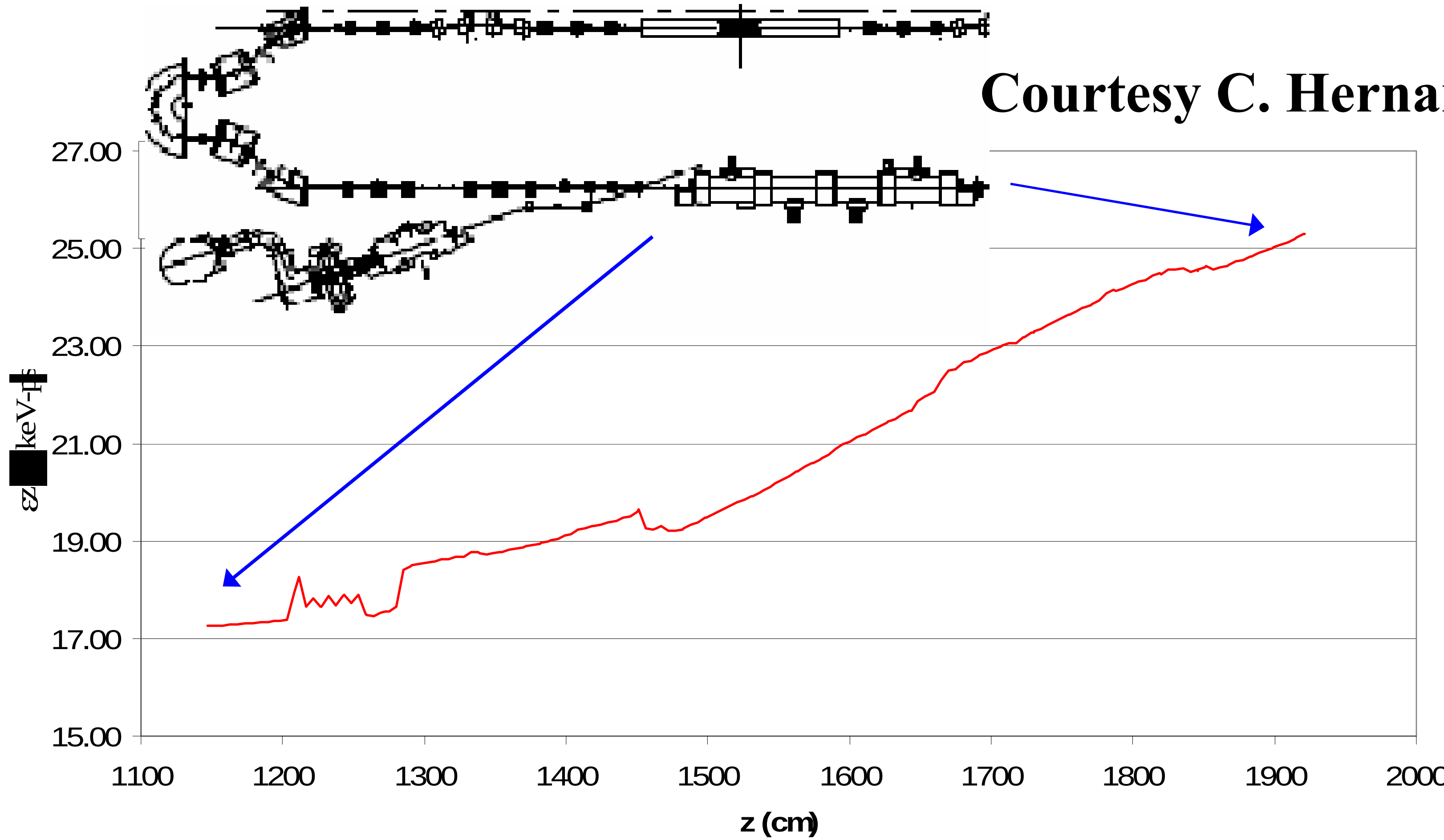
JLab Injector Approach - Philosophy

- Highest average brightness is produced by lowest charges at highest frequency (J.B. Rosenzweig PAC95 p. 957-960)
  - Works for synchrotron emission but an FEL needs high peak current, contrary to this scaling
  - Result for us is a compromise: highest frequency for which charge (when later bunched to high peak current) has sufficient photon gain
  - Leave the bunch long during acceleration to preserve longitudinal and transverse brightness
    - Especially important at higher charges

PARMELA predicts intrinsic longitudinal emittance grows >50% through the first cryomodule alone.

Consistent with experimental evidence

Courtesy C. Hernandez



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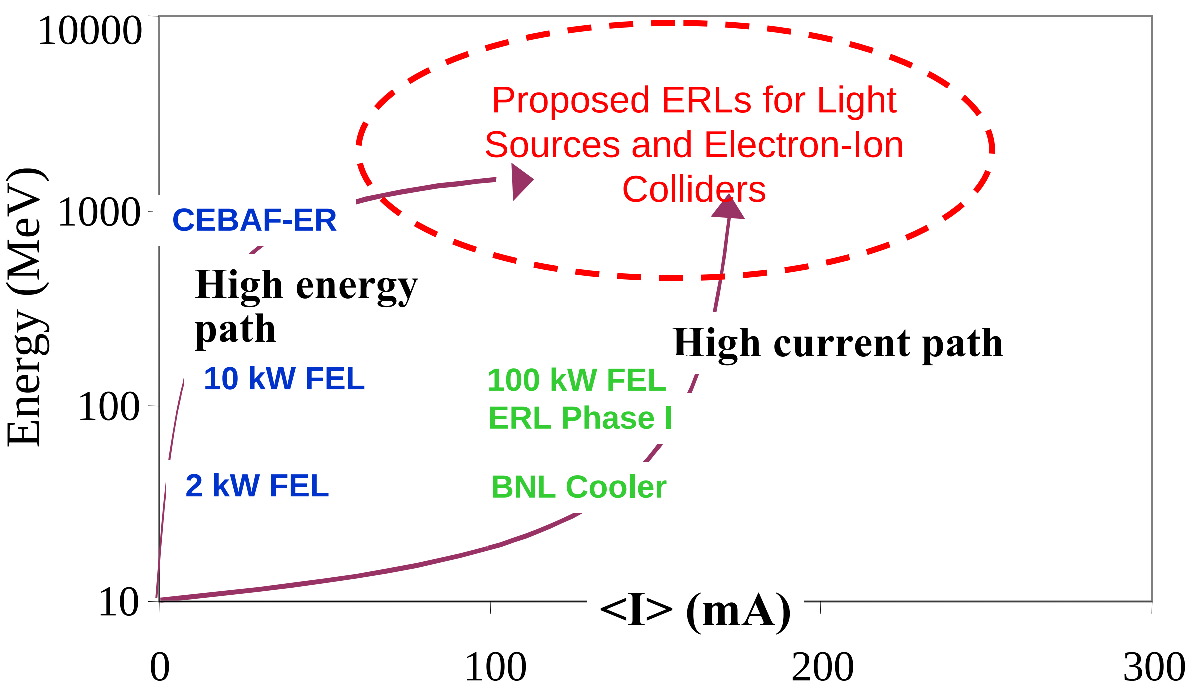
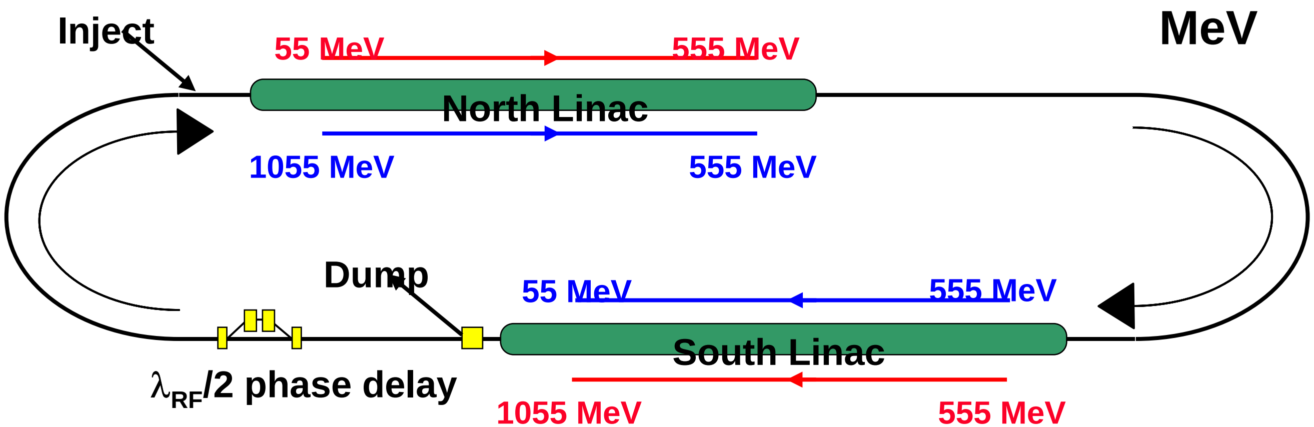
CEBAF Energy Recovery Experiment



Proposed by D. Douglas in JLAB TN-01-018

Motivation: Validate high E_{acc}/E_{inj}

Achievement: 80 μA of CW beam accelerated to 1055 MeV and energy recovered at 55 MeV



Stability in Energy Recovering Linacs

- **Collective effects can potentially limit ERL average current; the physics and scaling is well understood.**
  - **We have several codes to predict instability thresholds**
  - **Experiments confirm code predictions to high accuracy**
  - **Several approaches to increase BBU limit have been successfully tested**

L. Merminga, G. Neil, and B. Yunn, "Scaling of Wakefield effects in Recirculating Linacs" PAC2001, Paper RPAH050.

George R. Neil and Lia Merminga, "Technical Approaches for High Average Power FELs", Reviews of Modern Physics 74, 685 2002.

Lia Merminga, "RF Stability in Energy Recovering FELs: Theory and Experiment" Nuclear Instruments and Methods in Physics Research A483, 107 2002

Talks at this workshop by E. Pozdeyev, C. Tennant

Stability in Energy Recovering Linacs

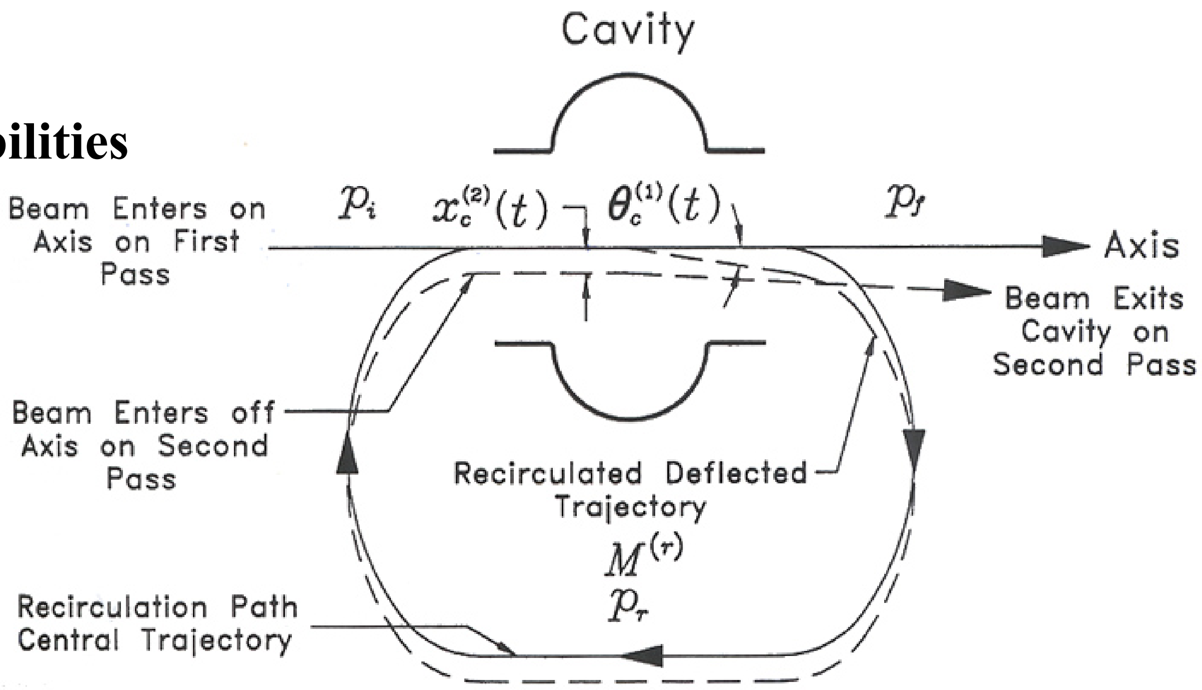
In a recirculating linac, the feedback system formed between beam and cavities is closed and instabilities can result at sufficiently high currents

Instabilities can result from the interaction of the beam with:

Fundamental mode - beam loading instabilities

Transverse HOMs - transverse BBU

Longitudinal HOMs - longitudinal BBU



Courtesy: N. Sereno, Ph.D. Thesis (1994)

Instability Threshold

- There is a well-defined threshold current that occurs when the power fed into the mode equals the mode power dissipation

- An analytic expression that applies to all instabilities:

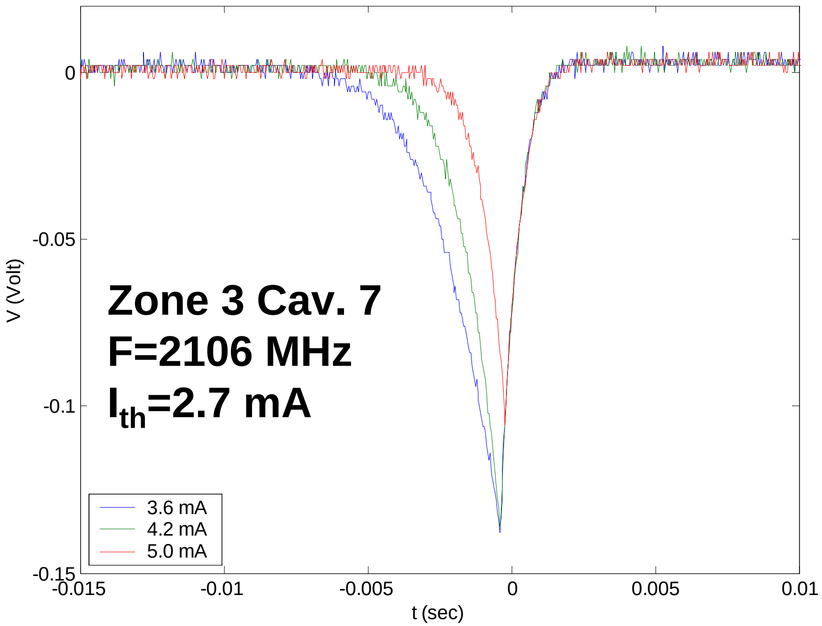
$$I_{th}^{(1)} = \frac{-2 p_r c}{e(R/Q)_m Q_m k_m M_{ij} \sin(\omega_m t_r + l\pi/2)}$$

- For i,j = 1,2 or 3,4 and $m \rightarrow \perp$ HOM $\Rightarrow$ Transverse BBU
- For i,j = 5,6 and $m \rightarrow ||$ HOM $\Rightarrow$ Longitudinal BBU
- For i,j = 5,6 and $m \rightarrow$ Fundamental mode $\Rightarrow$ Beam-Loading Instabilities
- $l=1$ for longitudinal HOMs and l=0 otherwise

see Merminga, Douglas, Krafft, Ann. Rev. Nucl. Part. Sci. 2003

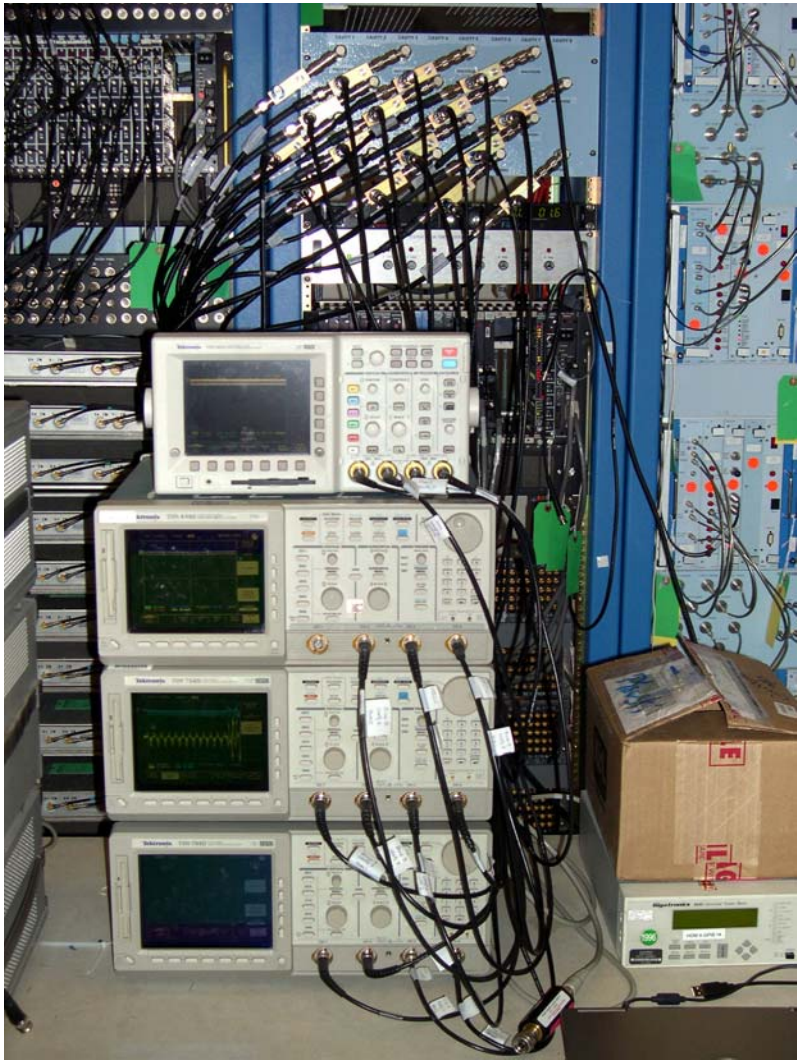
Regenerative BBU in the JLAB FEL Upgrade

See talk by E. Pozdeyev for details



HOM power, measured by Schottky diodes, vs. time for I_b=3.6, 4.2, and 5 mA. The rise time depends on the beam current as

$$\tau = \tau_0 \frac{I_{th}}{I - I_{th}}$$



BBU can still be suppressed even if cavity damping is insufficient

BBU suppression techniques demonstrated: talk by C. Tennant

		Effect on 2106 MHz HOM	Considerations for Implementation
Q-Damping	Damping Circuit	5 x I_{th}	• Works for only *1 mode per cavity* • Not as effective at raising the threshold as beam optical methods • Does not effect beam optics
	3-Stub Tuner	1.5 x I_{th}	
Beam Optics	Phase Trombone	*Stabilized*	• Can *stabilize* the mode against BBU • What are the effects on other HOMs? • Do they prevent reaching the requirements needed for a suitable lasing configuration?
	Pseudo-Reflector*	*Stabilized*	

*Rand R., Smith T., Beam Optical Control of Beam Breakup in a Recirculating Electron Accelerator, Particle Accelerators, Vol. II, pp. 1-13 (1980).

Studies of major ERL challenges:

Injector

- **Low emittance current production & preservation**
  - **Achieving thermal emittance from gun (emittance compensation)**
- **Photocathode longevity at high average current (vacuum)**

Linac:

- **BBU in the main linac (HOMs power and damping)**
- **Longitudinal phase space preservation in bunching (curvature correction)**
- **Beam loss, halo**

HOM, wakefield and collective radiation power handling

Important for high average currents; substantial power is generated and ends up somewhere

Wouldn't you like to choose where that is?

For example, 100 W of THz ended up on our FEL mirror (to our dismay)

See R. Rimmer talk for practical cavity solutions

HOM Power Dissipation, Theory

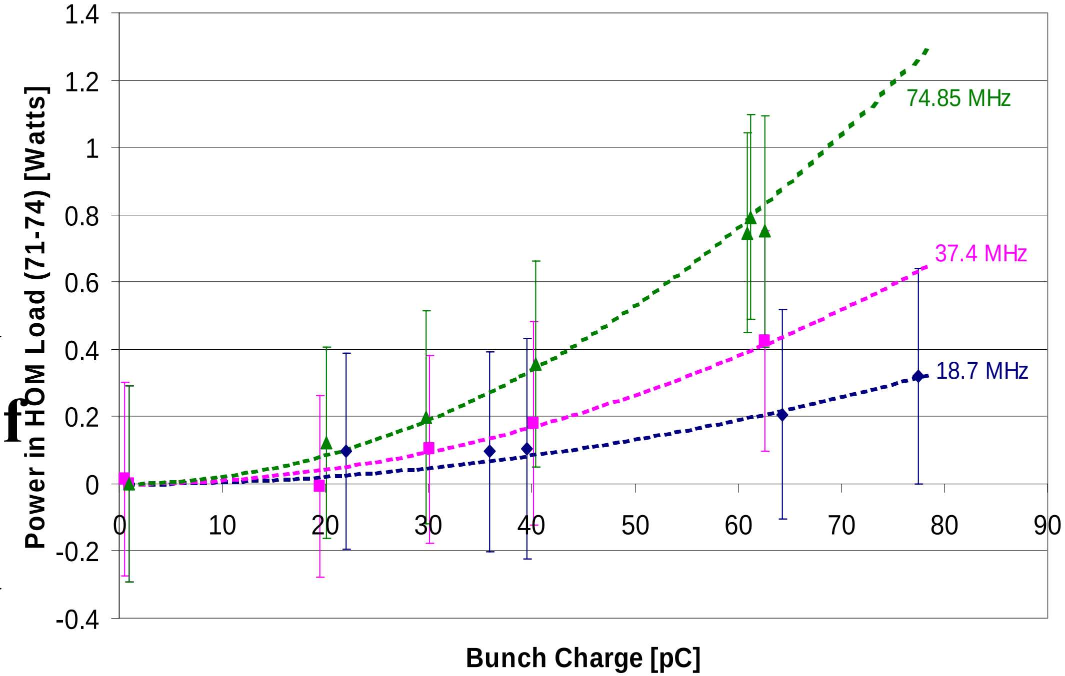
Fraction of HOM power dissipated on cavity walls increases with HOM frequency, due to $Q_0 \sim \omega^2$ degradation from BCS theory

Experiment:

>90% of HOM power is in modes < 100 GHz

Power dissipated on cavity walls is a strong function of bunch length, $\sigma^{-5/2}$

Power dissipated on cavity walls is much less than fundamental mode load



$k_{||total}$ = 9.4 V/pC

$\Rightarrow$ agreement = 15%

$k_{||URMEL}(\sigma_z = 1\ ps)$ = 11.0 V/pC

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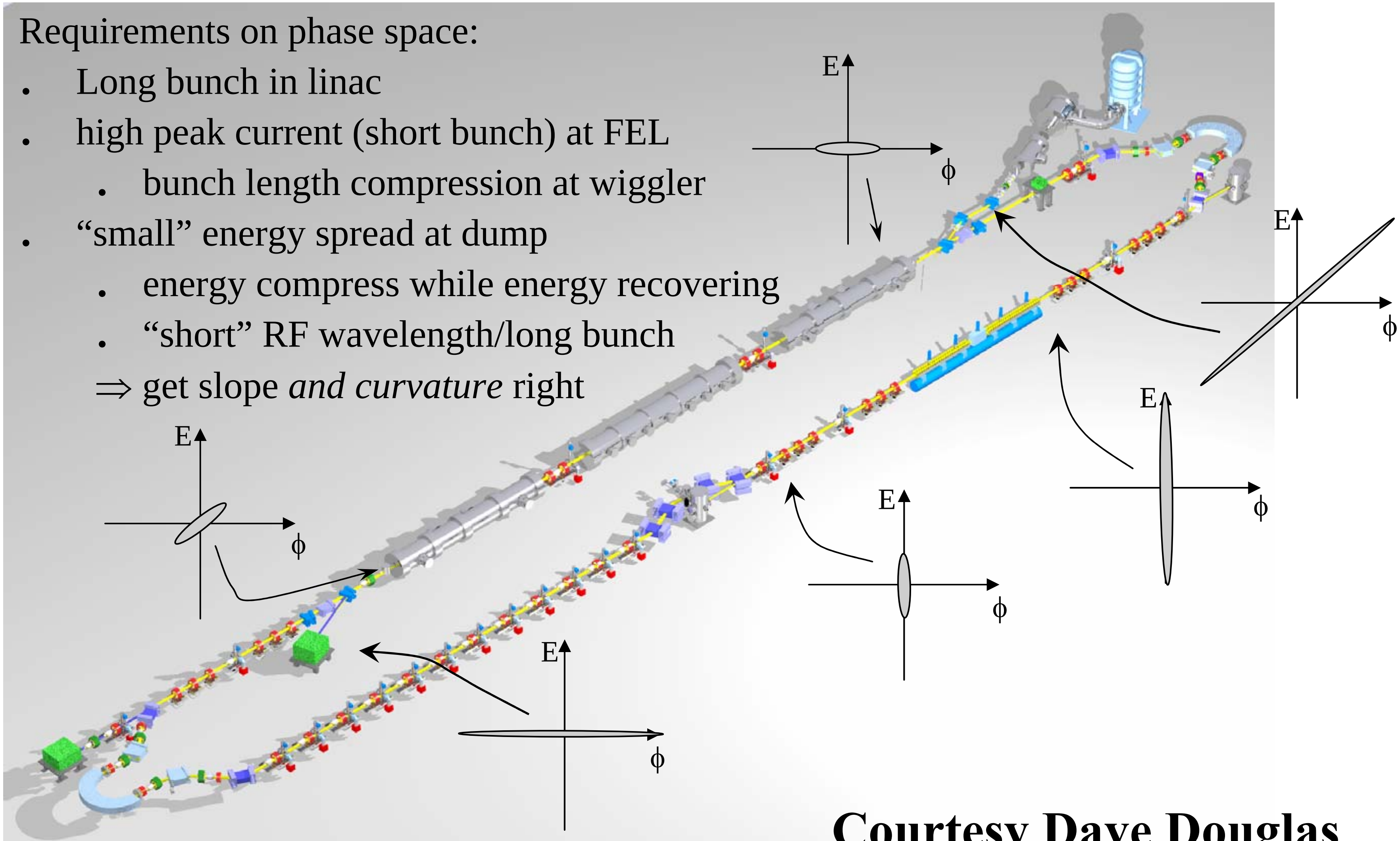
Linac:

- **BBU in the main linac (HOMs power and damping)**
- **Longitudinal phase space preservation in bunching (curvature correction) – must be careful that non-linearities don't dominate (talk by D. Douglas)**
- **Beam loss, halo**

Longitudinal matching: high order terms important

Requirements on phase space:

- Long bunch in linac
- high peak current (short bunch) at FEL
  - bunch length compression at wiggler
- "small" energy spread at dump
  - energy compress while energy recovering
  - "short" RF wavelength/long bunch
  - ⇒ get slope *and curvature* right



Courtesy Dave Douglas

Controlling nonlinearities with sextuples and octupoles is validated by high order transport measurement

Figure 1: initial optimized setup

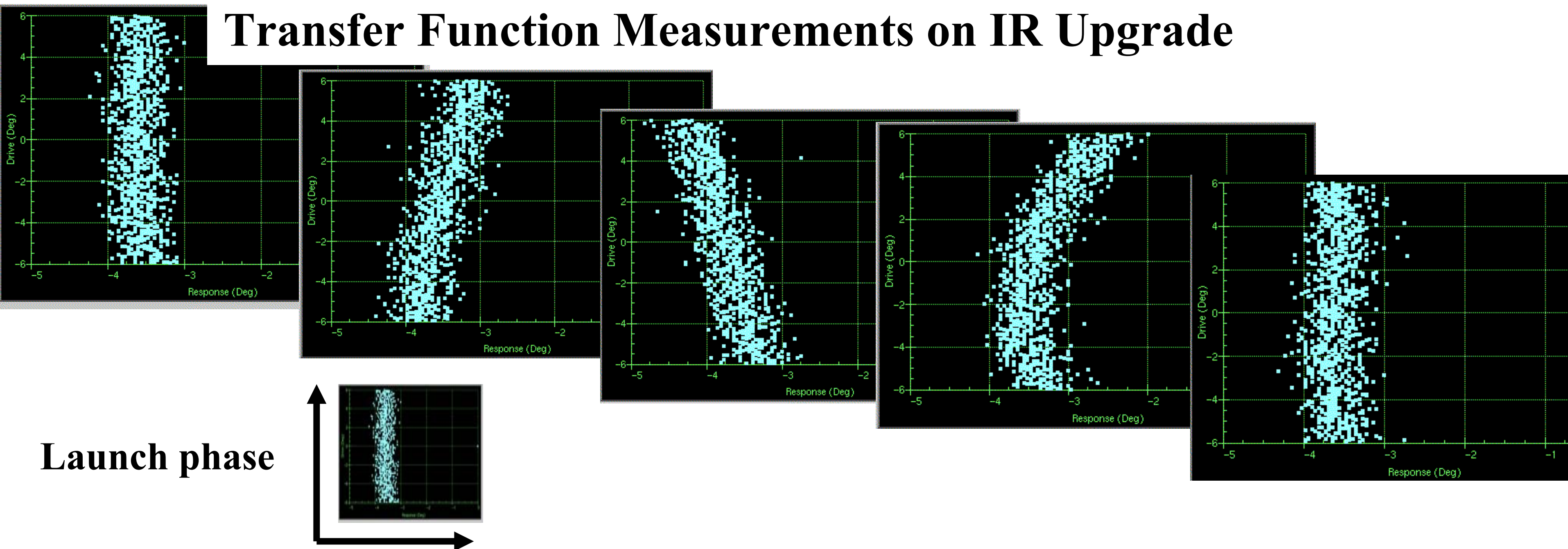
Figure 2: lower trim quads to -185 g from initial -215 g

Figure 3: raise trim quads to -245 g

Figure 4: quads back at -215, but sextupoles 2000 g below design, at 10726 g-cm

Figure 5: back to start: trim quads -215 g sextupoles at 12726 g-cm

Transfer Function Measurements on IR Upgrade



Launch phase

Arrival phase

Courtesy Dave Douglas, S. Benson

Halo: must keep local loss less than 1 μA

- When matching was properly done the IR Demo electron beam showed less than 100 nA interception on the beam line when 5 mA was circulating
- Similar level is found for IR/UV Upgrade but as bunch charge increases the production and control of halo is expected to become more difficult
    - Halo can show up as longitudinal addition, not just transverse; this means it get accelerated to a different energy
    - Small halos can lead to big losses at pinch points in transport (large beam, high dispersion)

Summary

- JLab IR/UV Upgrade ERL is becoming a productive User facility with exceptional performance in several wavelength bands
- Much progress has been made to advance the technology and understanding to levels which permit the next generation of light sources
- We are addressing key issues for ERLs including generating high average brightness beams and then preserving and controlling them through the acceleration and recovery process.
- Many "opportunities" exist for further work to resolve challenges especially in the injector

This work was accomplished with the help of lots of others at JLab

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