Status of the Jefferson Lab FEL Program

C. Tennant for the JLab FEL Team

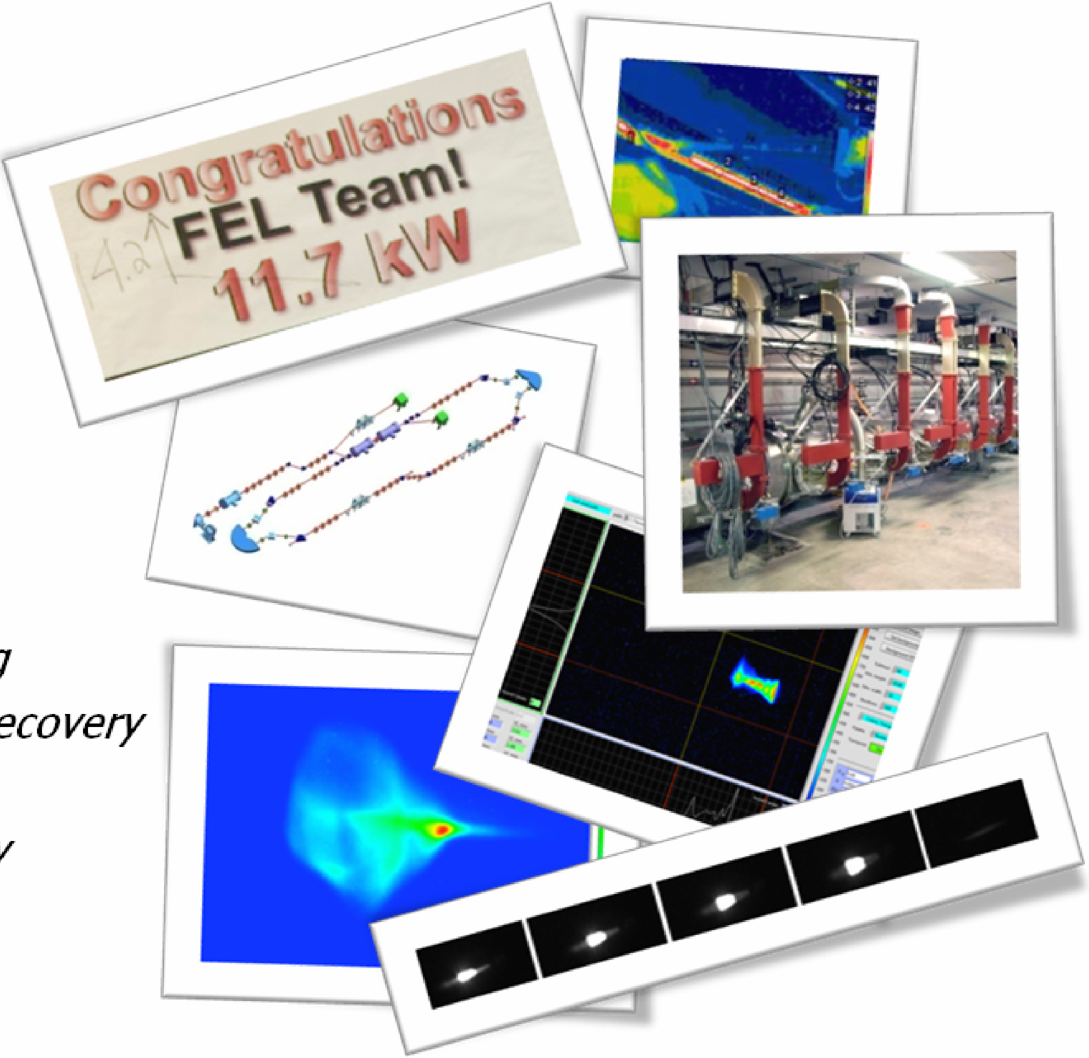
PAC09

VANCOUVER

(DISTRIBUTION STATE A)

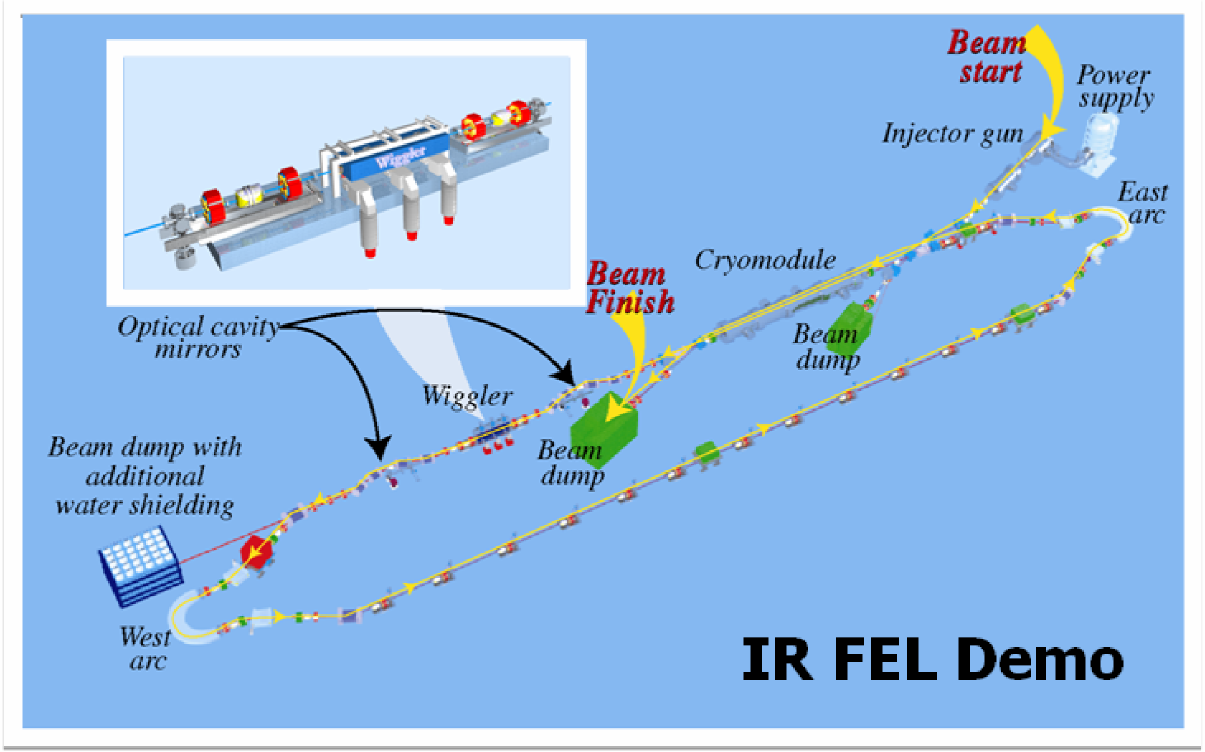
Outline

- **JLab FEL: Past**
- **JLab FEL: Present**
  - Status Update
  - Collective Effects
    - ✓ *Beam Breakup*
    - ✓ *Long. Space Charge*
    - ✓ *Coherent SR*
  - Other Issues for ERLs
    - ✓ *Longitudinal Matching*
    - ✓ *Incomplete Energy Recovery*
    - ✓ *RF Transients*
    - ✓ *Magnetic Field Quality*
- **JLab FEL: Future**



JLAB FEL: PAST

Jefferson Lab FEL: Past



- Chose SRF linac to maintain superior beam quality
- CW operation allows high average output power at modest charge per bunch
- Invoking energy recovery increases system efficiency
- The IR FEL Demo recovered 48 MeV of 5 mA beam through a single cryomodule
- Established a world record of 2.3 kW output laser power

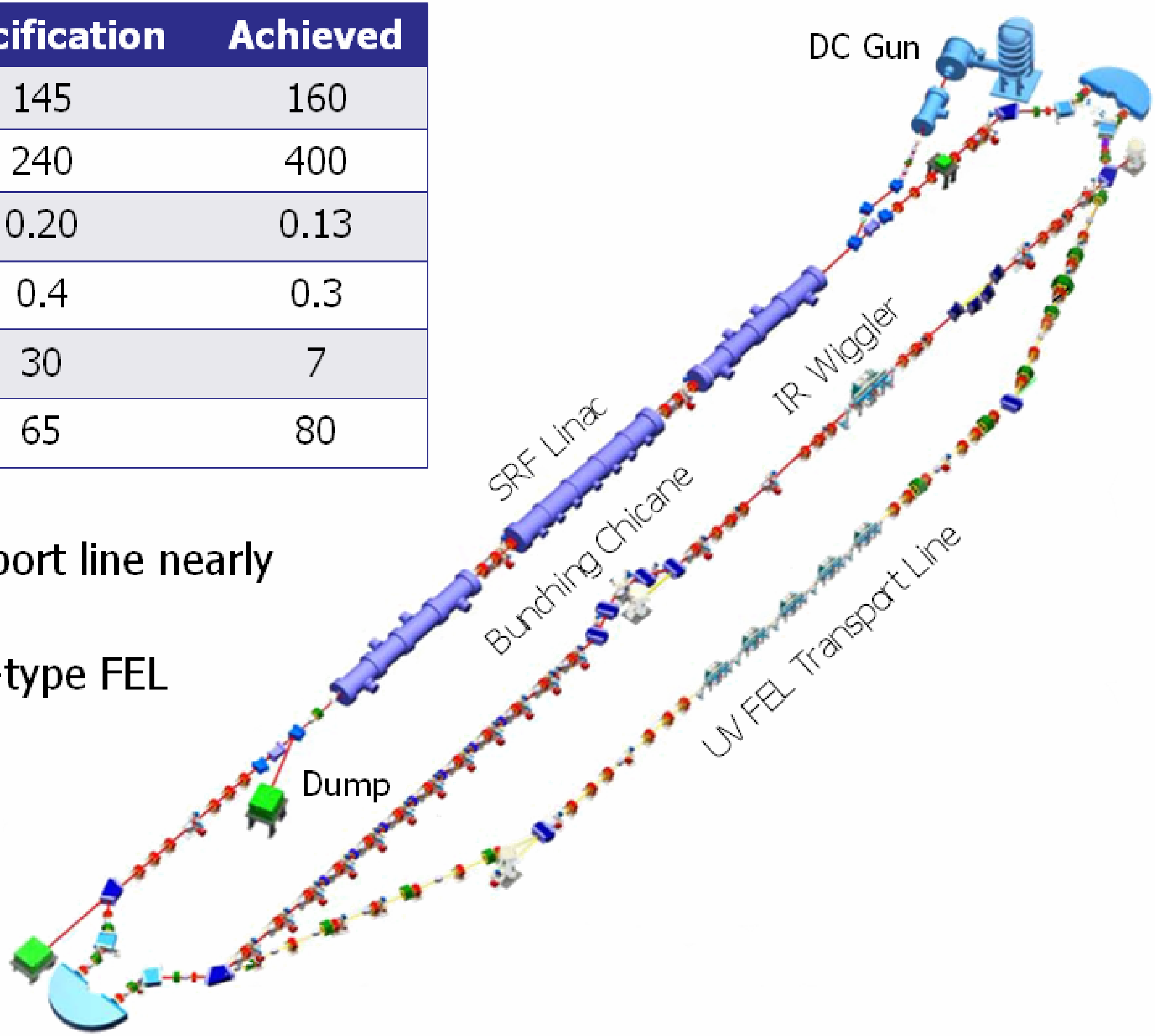
G. Neil et al., PRL (2000)

- JLAB FEL: PAST
- JLAB FEL: PRESENT
  - Status

Jefferson Lab FEL: Present

Beam Parameters	Specification	Achieved
Energy {MeV}	145	160
Peak Current {A}	240	400
σ_t {ps} at wiggler	0.20	0.13
$\sigma_{\Delta E}$ {%} at wiggler	0.4	0.3
$\varepsilon_{x,y}$ (rms) {mm-mrad}	30	7
ε_z (rms) {keV-ps}	65	80

- Installation of UV transport line nearly complete
- Option to test amplifier-type FEL

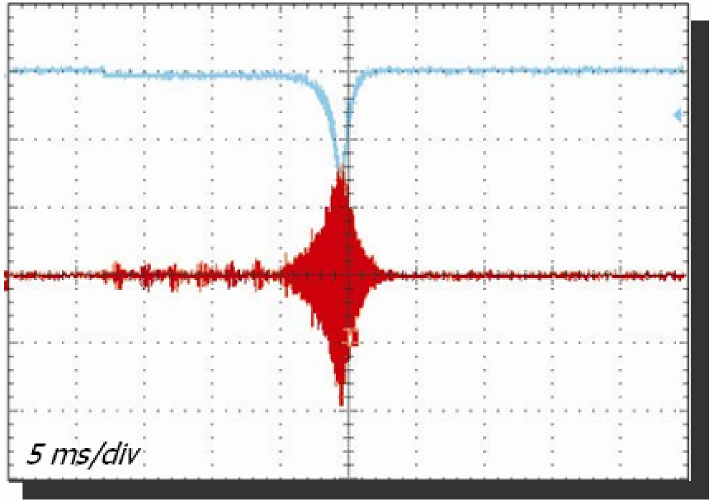


K. Jordan et al., PAC 2007

Real Time FEL Tuning

- JLAB FEL: PAST
- **JLAB FEL: PRESENT**
  - Status
  - **Collective Effects**
    - ✓ *Beam Breakup (BBU)*
    - ✓ *Longitudinal Space Charge (LSC)*
    - ✓ *Coherent Synchrotron Radiation (CSR)*

Benchmarking BBU Simulation Codes



- Simulate BBU in the FEL with several codes
- Experimentally measure the threshold current using variety of techniques
- Simulation codes have been benchmarked with experimental data

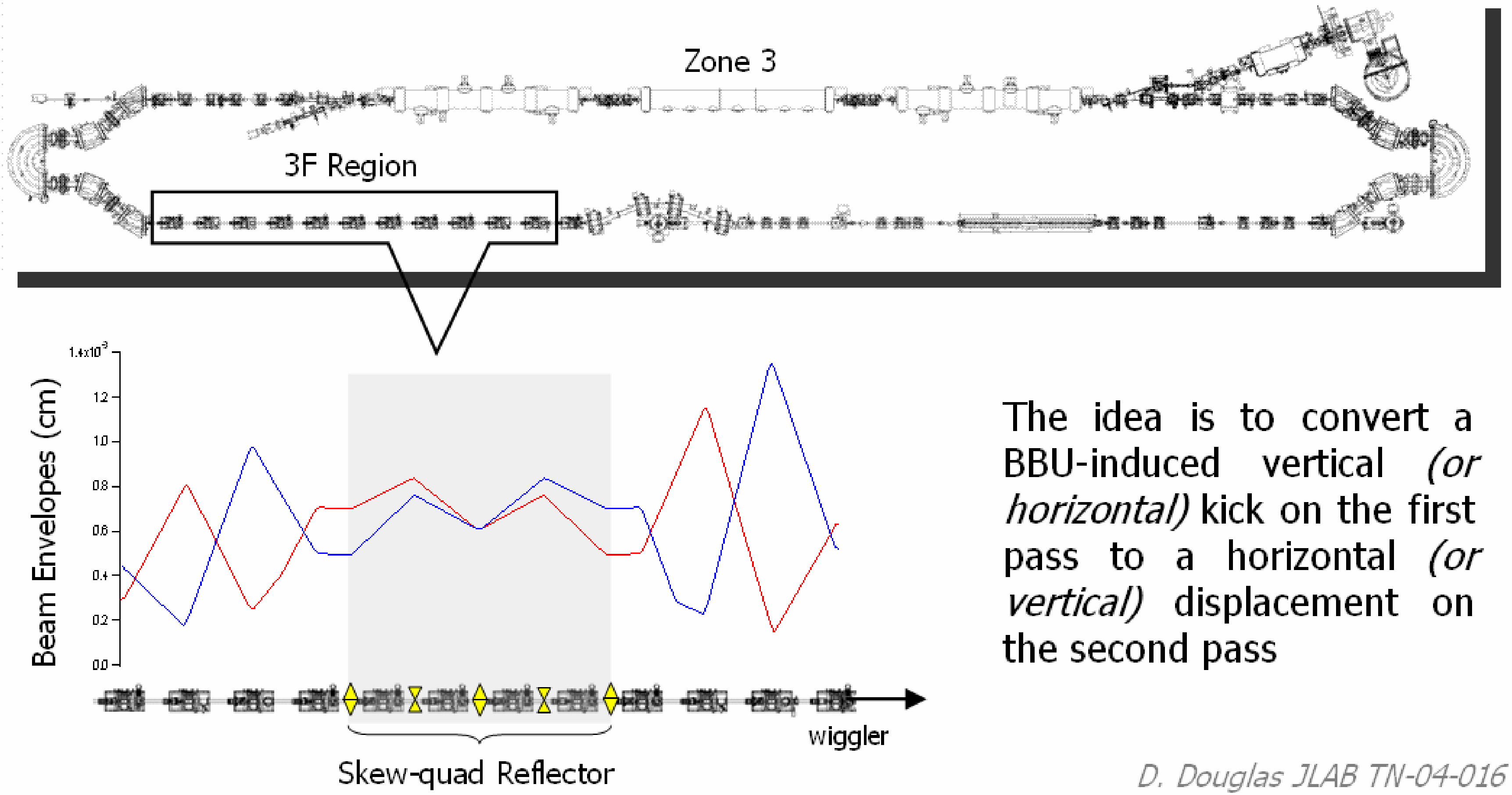
D. Douglas et al., PRST-AB (2006)

- Screenshot of the HOM voltage and power during beam breakup
- Identify the cavity and HOM causing BBU

	Method	$I_{threshold}$ (mA)
Simulation	**MATBBU** *(Yunn,*	2.1
	TDBBU *(Krafft,*	2.1
	GBBU *(Pozdeyev)*	2.1
	BI *(Bazarov)*	2.1
Experiment al	Direct Observation	2.3 ± 0.2
	Growth Rates	2.3 ± 0.2
	Kicker-based BTF	2.3 ± 0.1
	Cavity-based BTF	2.4 ± 0.1
Analytic	Analytic Formula	2.1

Implementing a Coupled Reflector

5 skew quadrupoles were installed in the backleg of the FEL to (locally) interchange the horizontal and vertical phase spaces

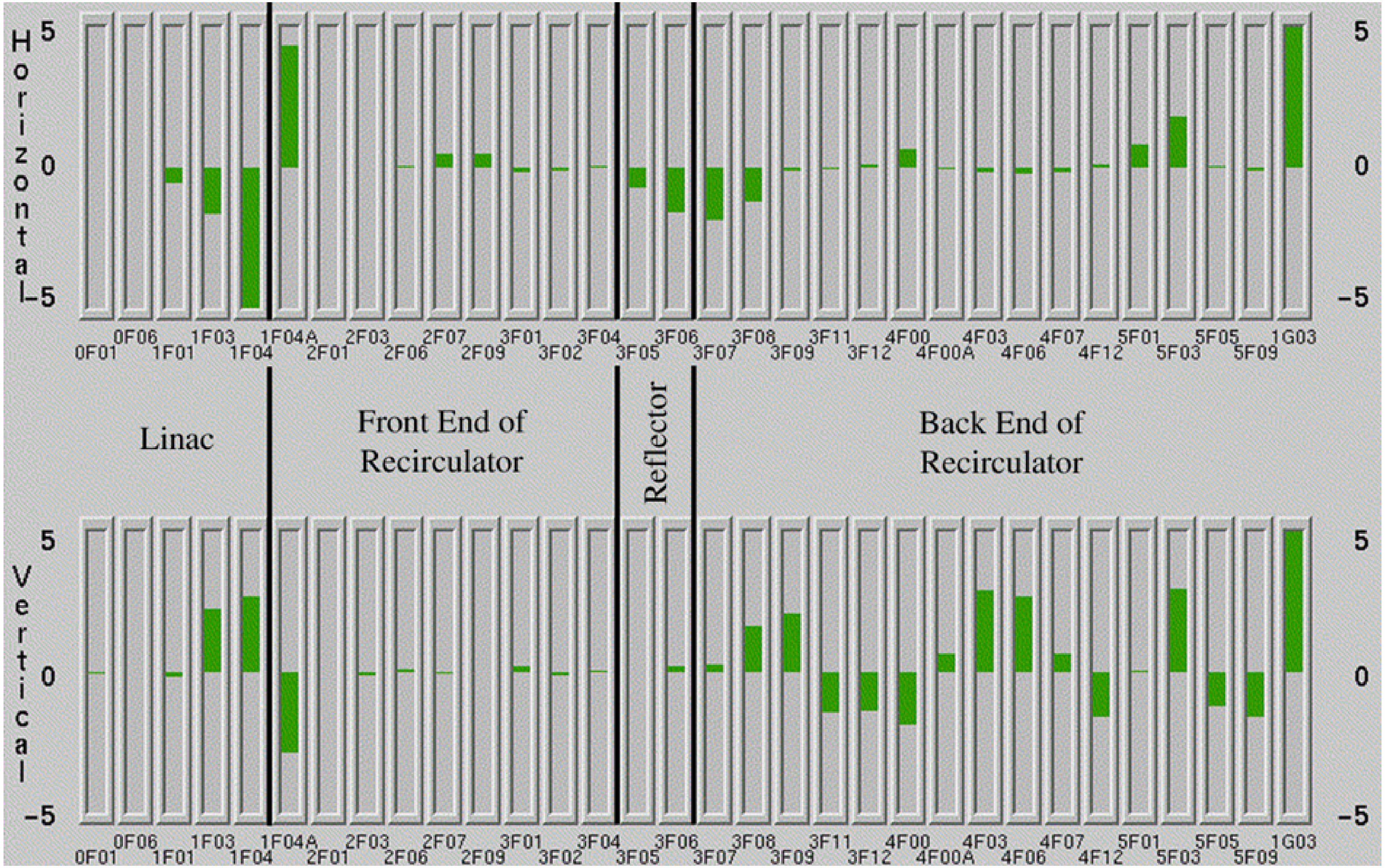


The idea is to convert a BBU-induced vertical *(or horizontal)* kick on the first pass to a horizontal *(or vertical)* displacement on the second pass

D. Douglas JLAB TN-04-016

Operational Use of a Reflector

- Launch sine- and cosine-like trajectories and to ensure proper coupling is achieved



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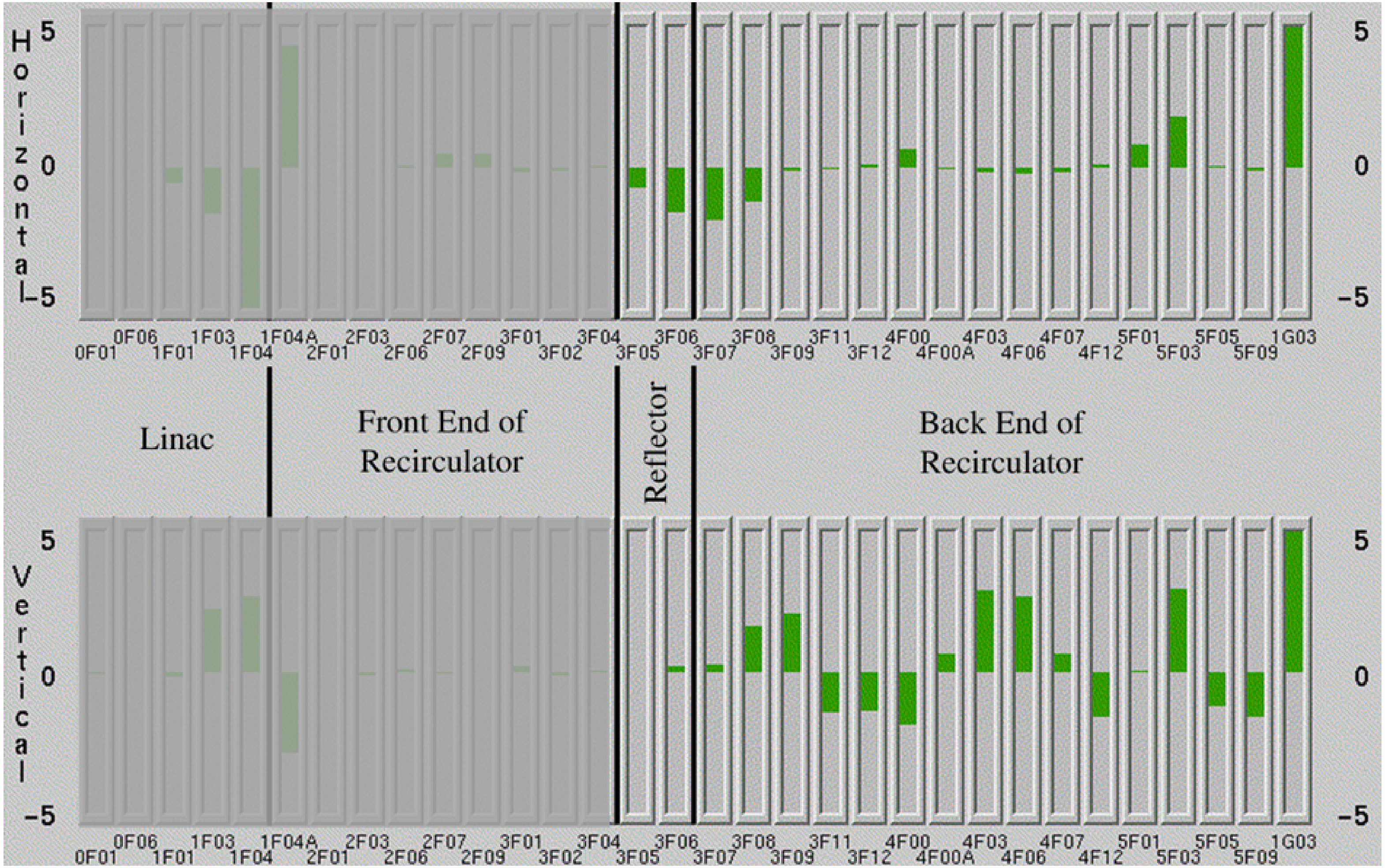

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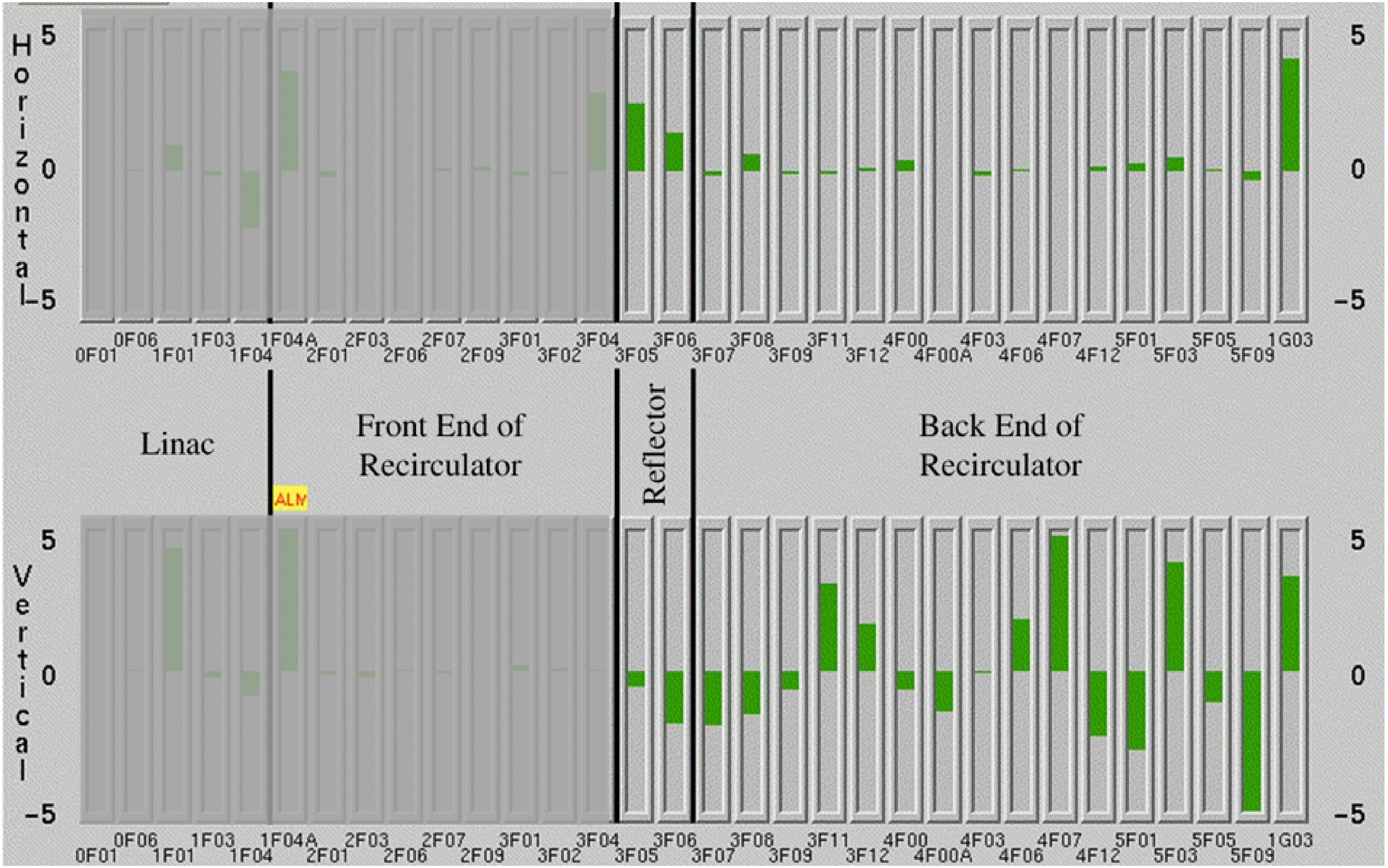
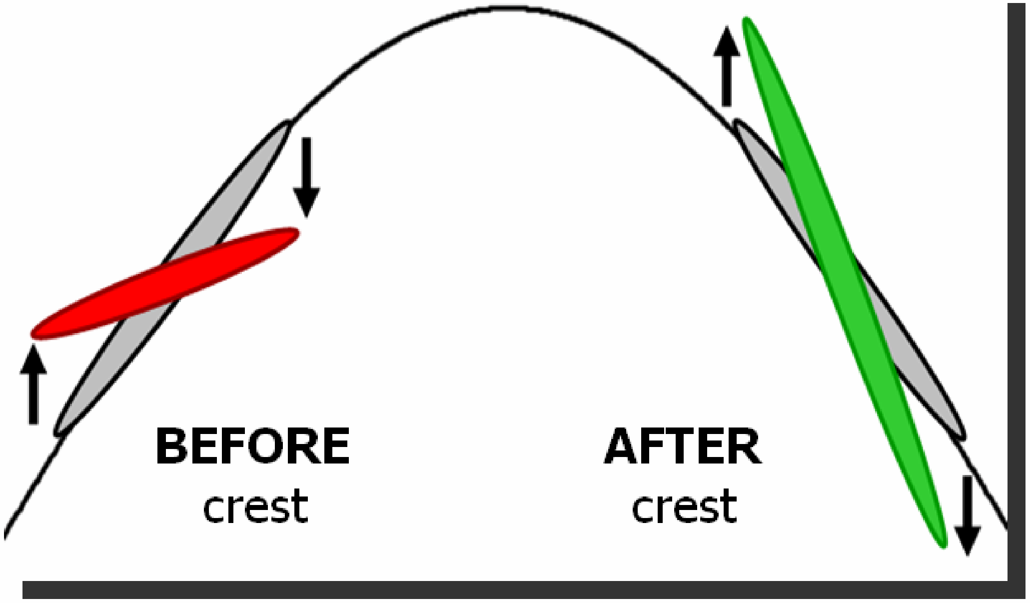


(courtesy D. Douglas)

Space Charge Force

- At 135 pC transverse space charge does not present problems
- However longitudinal space charge does
- Initial signature: momentum spread **asymmetric** about linac on-crest phase

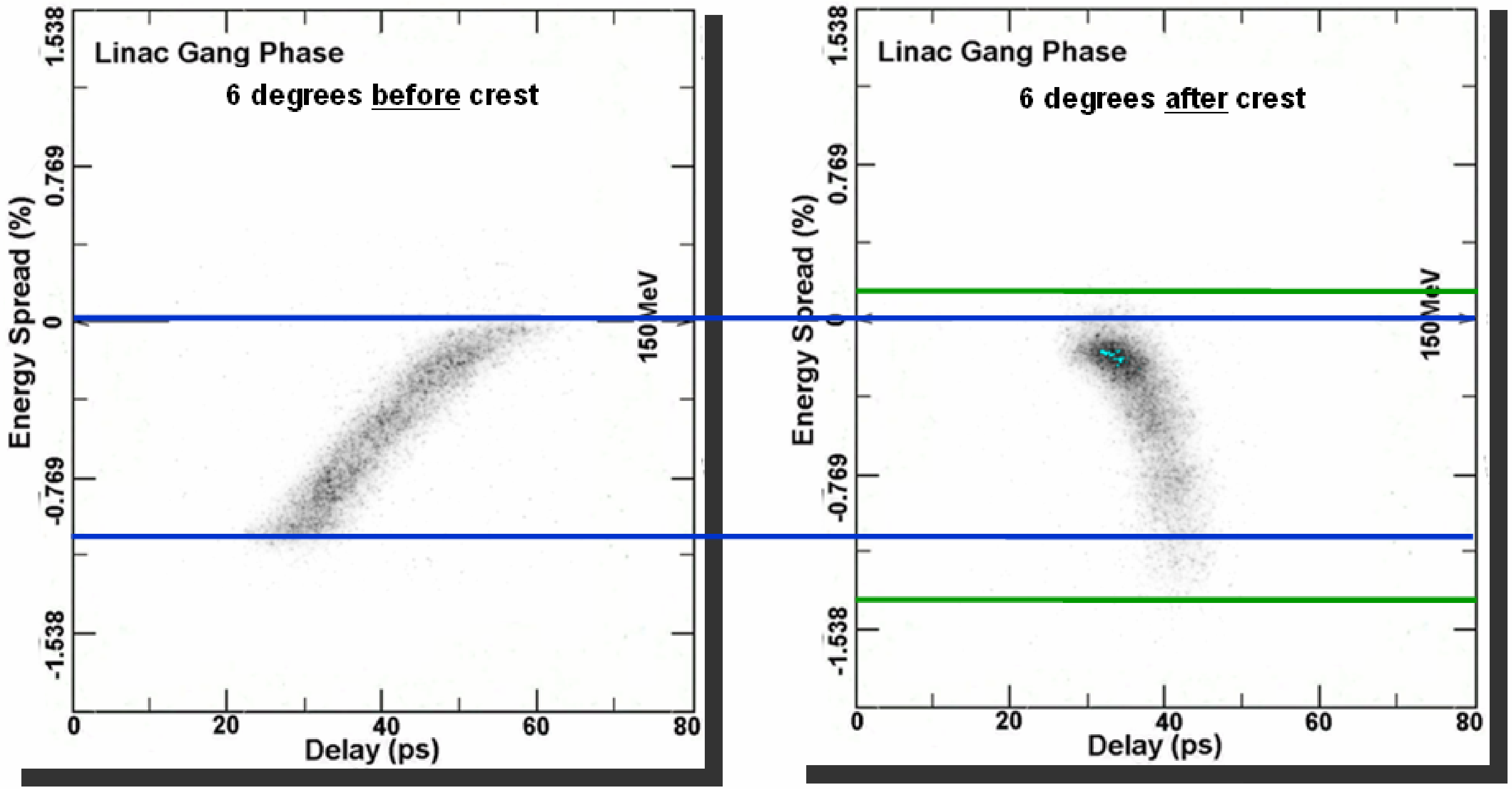
- Head of bunch accelerated, tail of bunch decelerated
  - ✓ Before crest (head at low energy, tail at high) observed momentum spread *reduced*
  - ✓ After crest (head at high energy, tail at low) observed momentum spread *increased*



- Small changes in injector setup allowed us to increase the bunch length at injection which alleviated LSC; additionally, uncorrelated energy spread reduced

C. Hernandez-Garcia et al., 2004 FEL Conference

Measurements Showing LSC Effects



S. Zhang et al., 2006 FEL Conference

Streak camera measurements showing longitudinal phase space at the midpoint of the first 180° bend at a bunch charge of 110 pC

(observed bunch compression is due to non-zero M_{56} from linac to measurement point)

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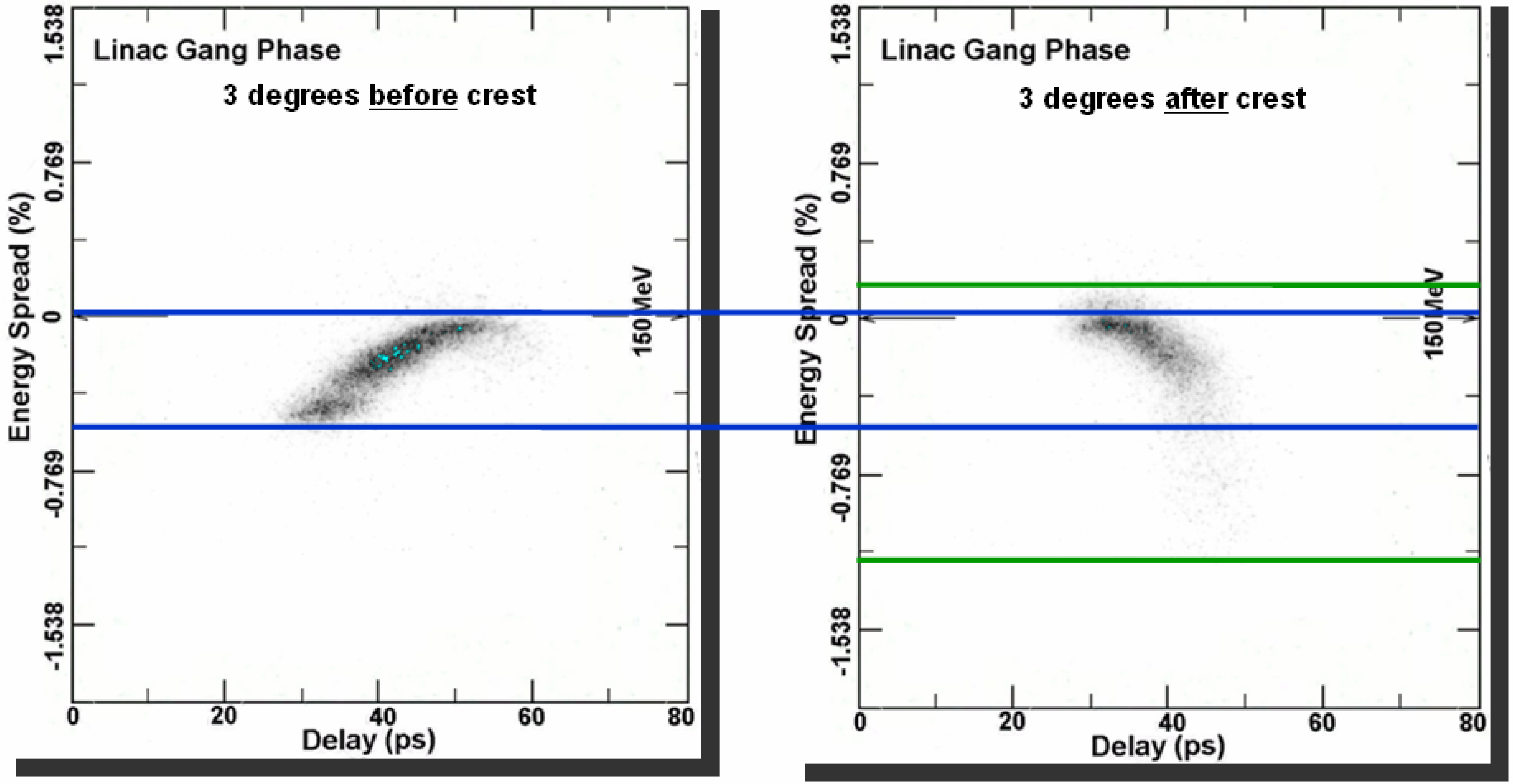

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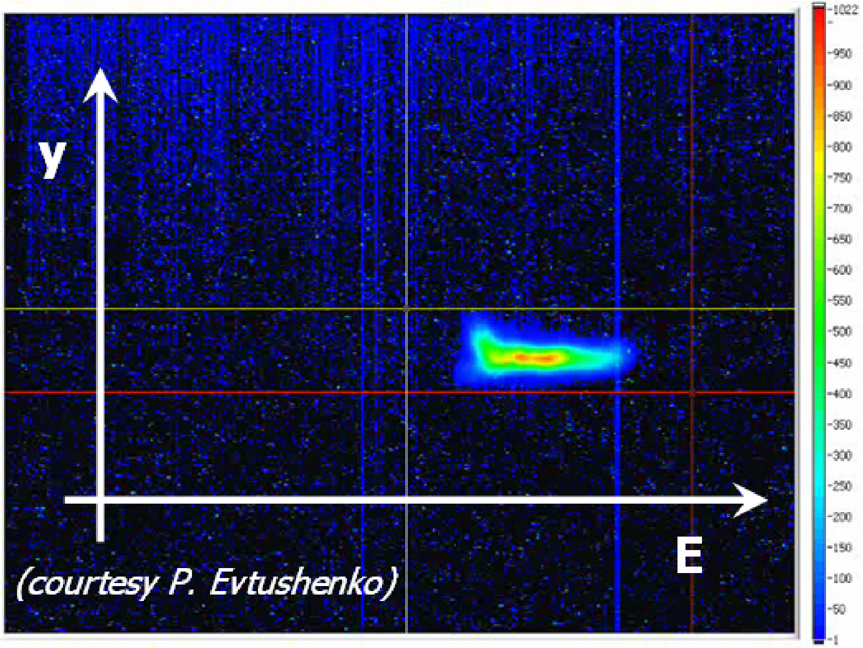
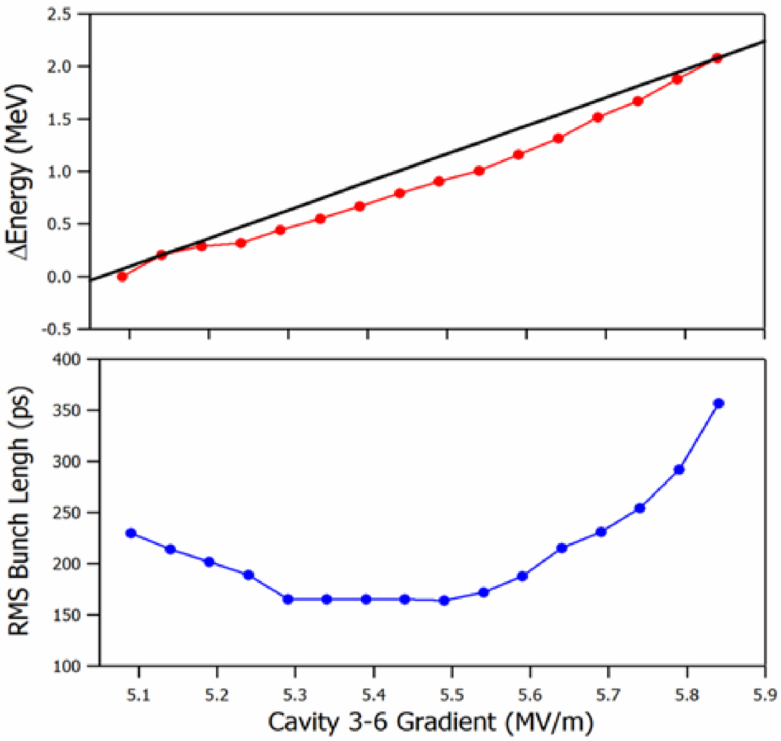
Coherent Synchrotron Radiation

- CSR does not present an operational impediment (used it as a diagnostic)
- In the past we had generated so much CSR (THz) that we heated the FEL mirrors up and distorted them, limiting power output
- Observe beam filamentation as we vary bunch length compression
  (change energy → offset through sextupoles → modify M_{56})





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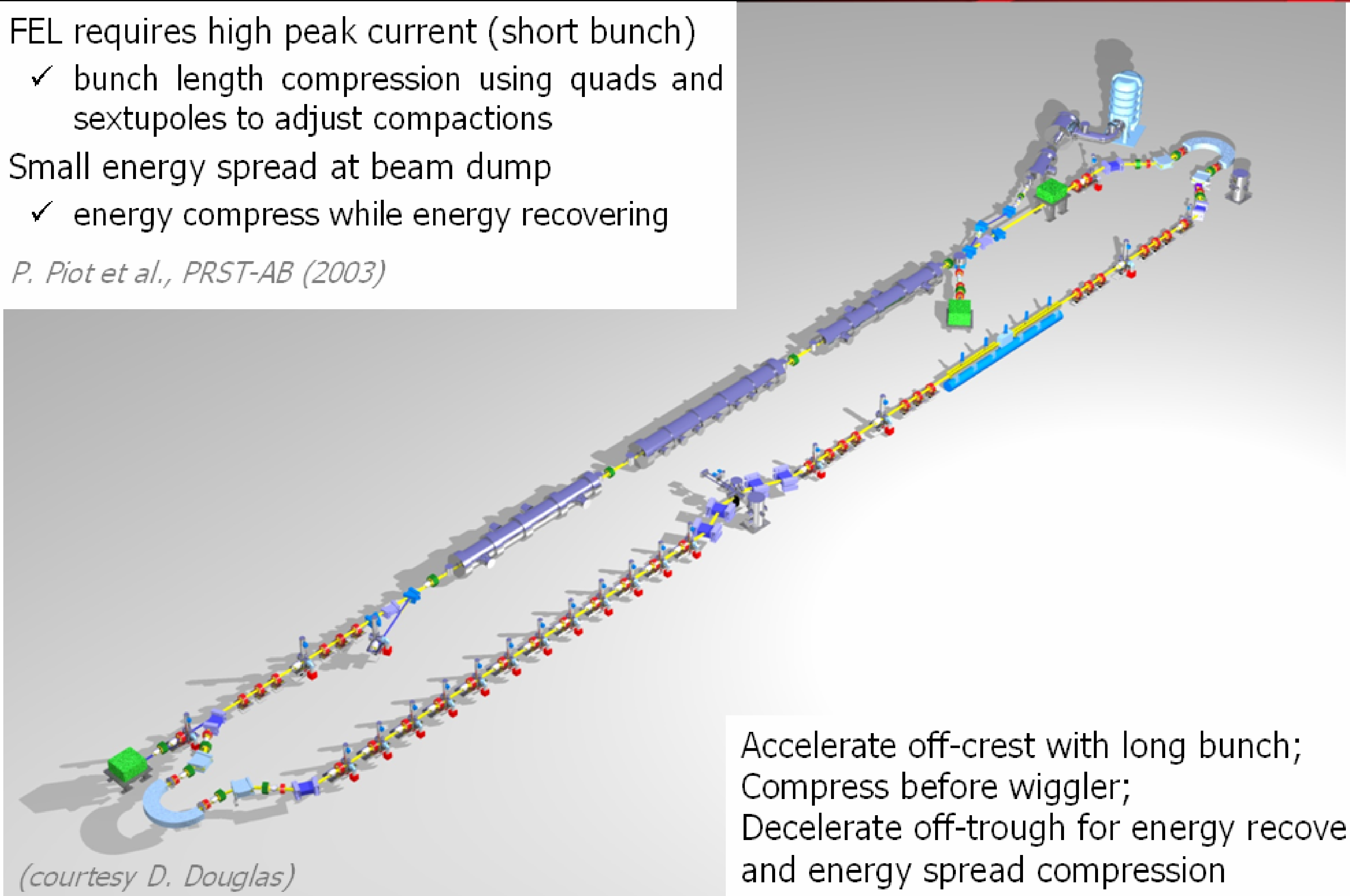
    - ✓ *RF Transients*
    - ✓ *Magnetic Field Quality*

Longitudinal Beam Dynamics in the FEL

- FEL requires high peak current (short bunch)
  - ✓ bunch length compression using quads and sextupoles to adjust compactions
- Small energy spread at beam dump
  - ✓ energy compress while energy recovering

P. Piot et al., PRST-AB (2003)



(courtesy D. Douglas)

Accelerate off-crest with long bunch;
Compress before wiggler;
Decelerate off-trough for energy recovery and energy spread compression

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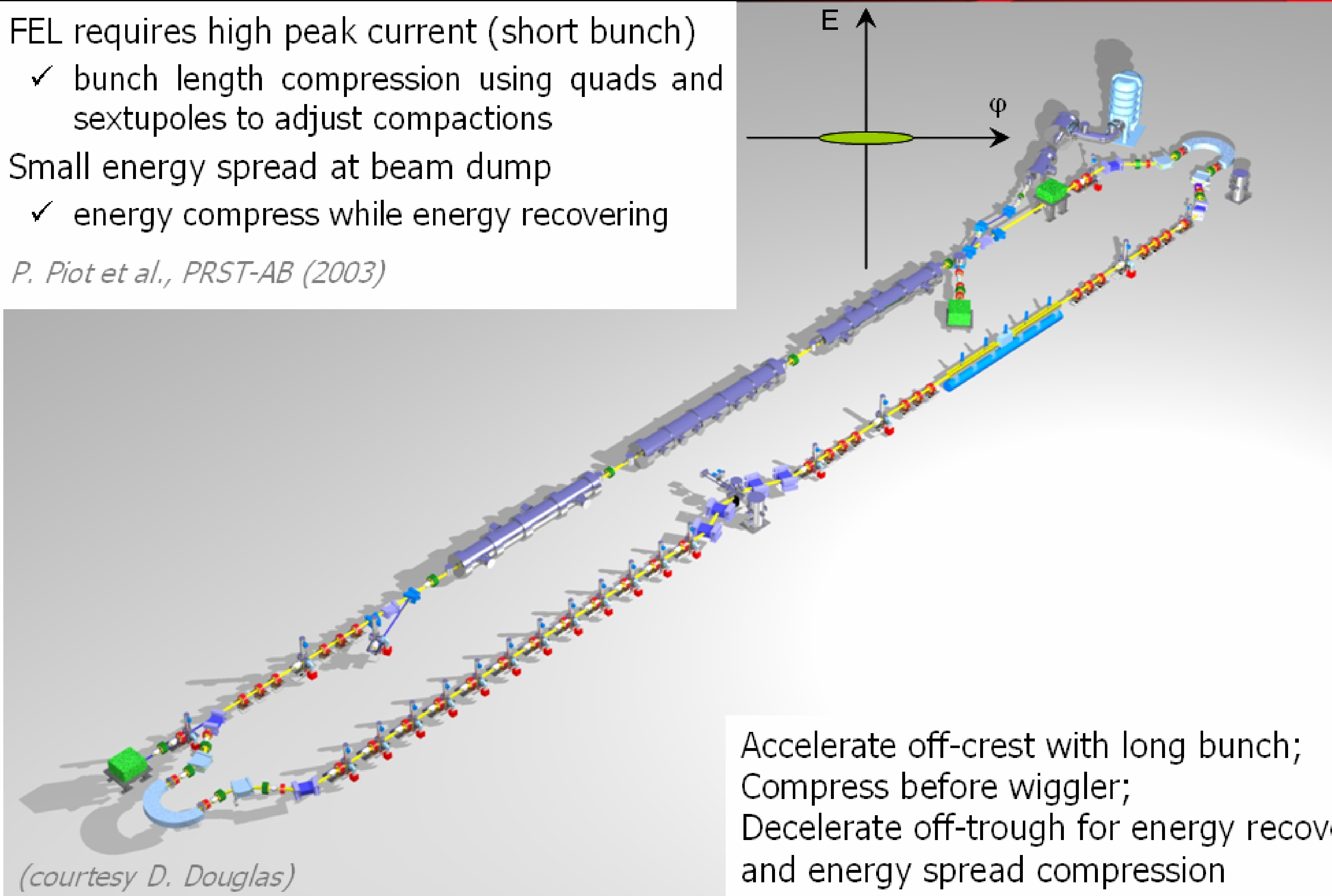

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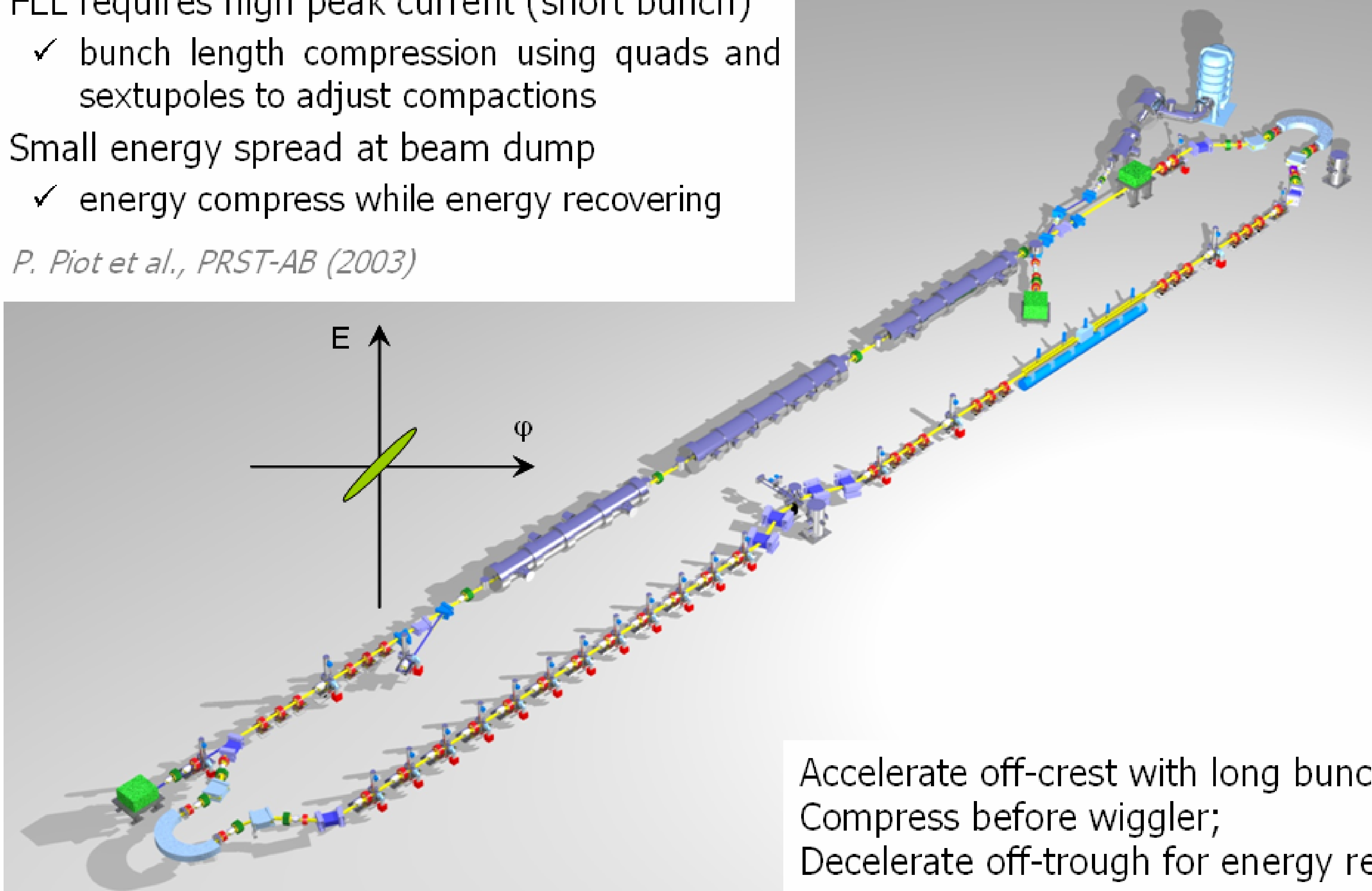

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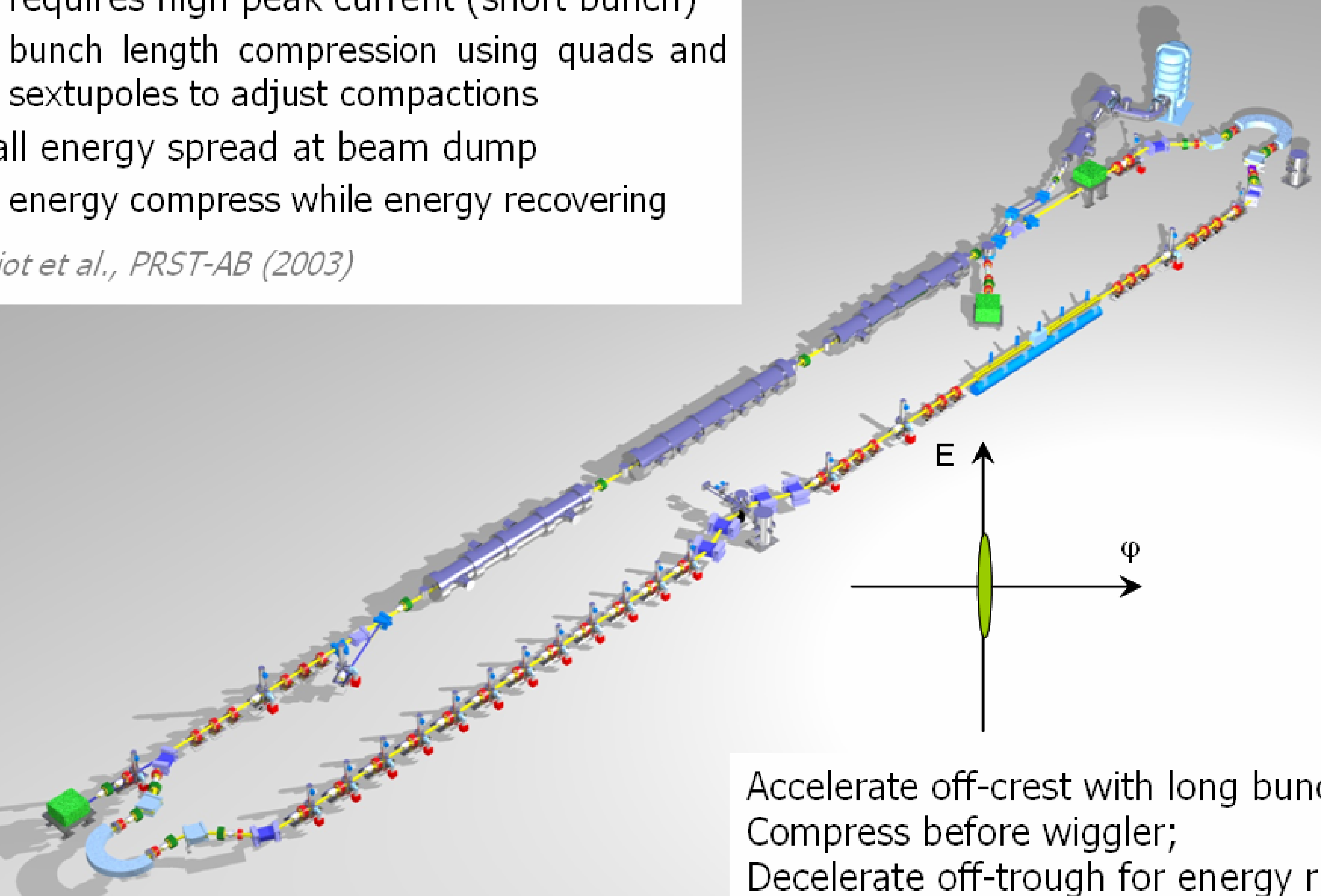

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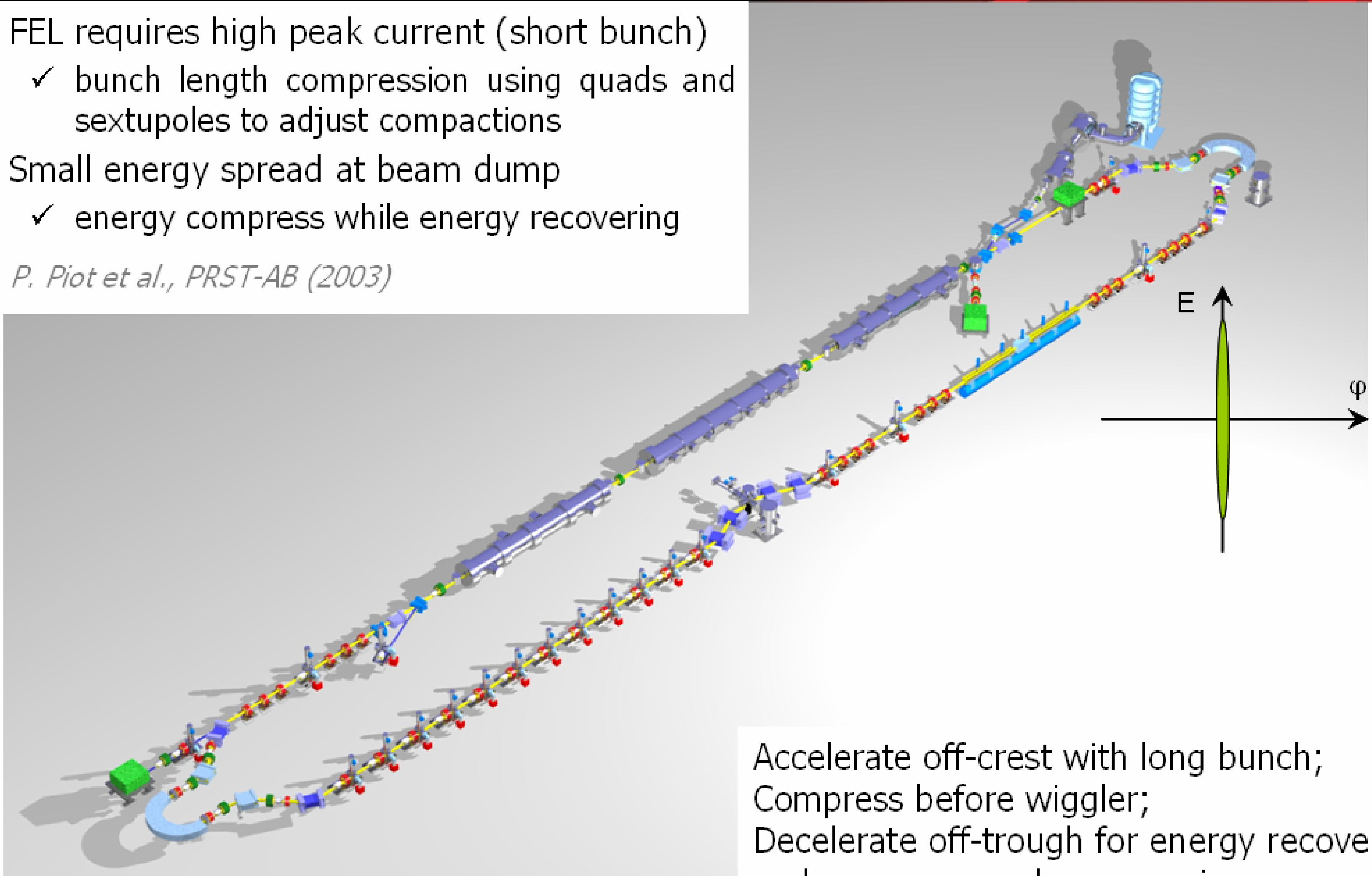

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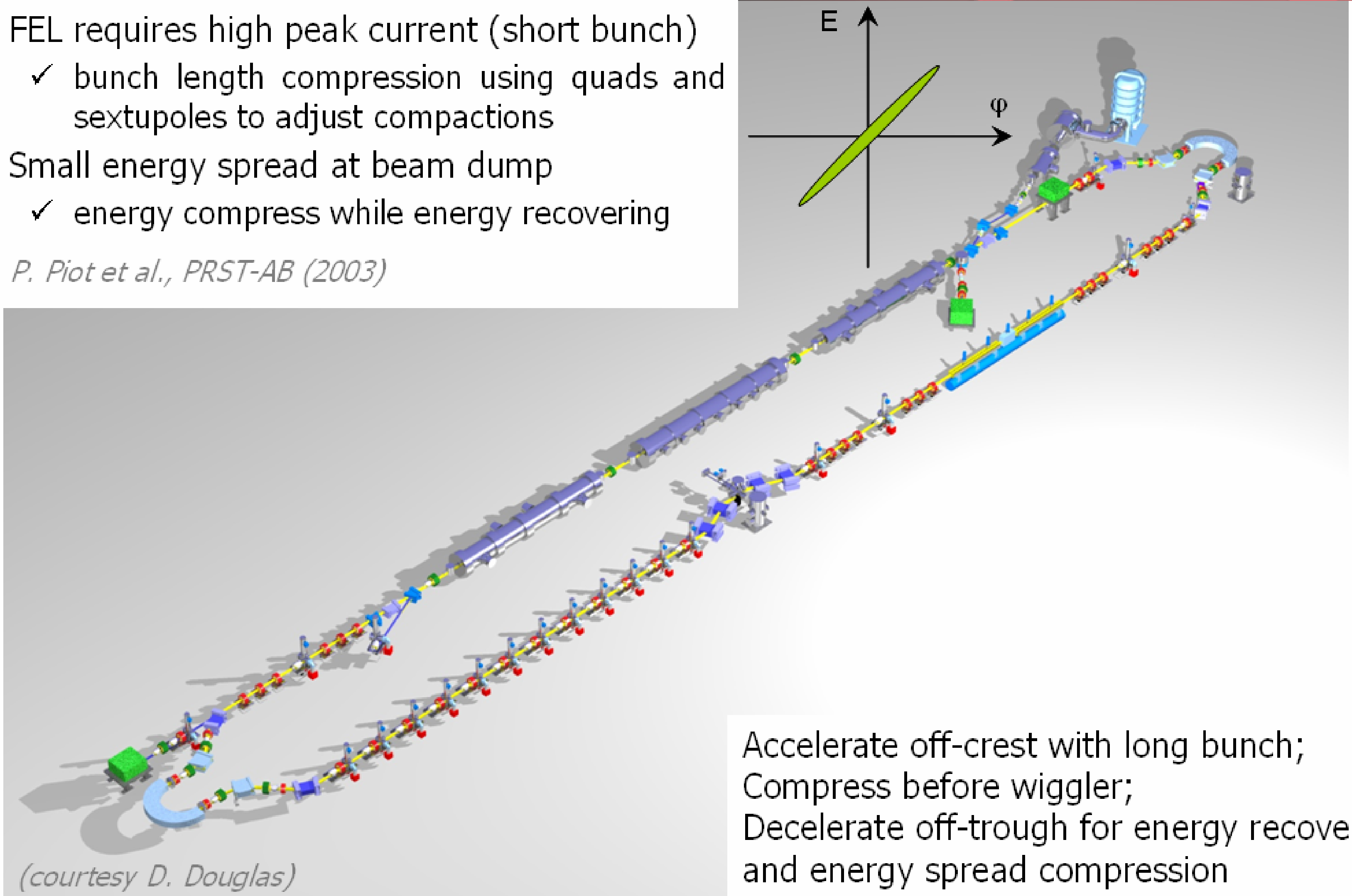

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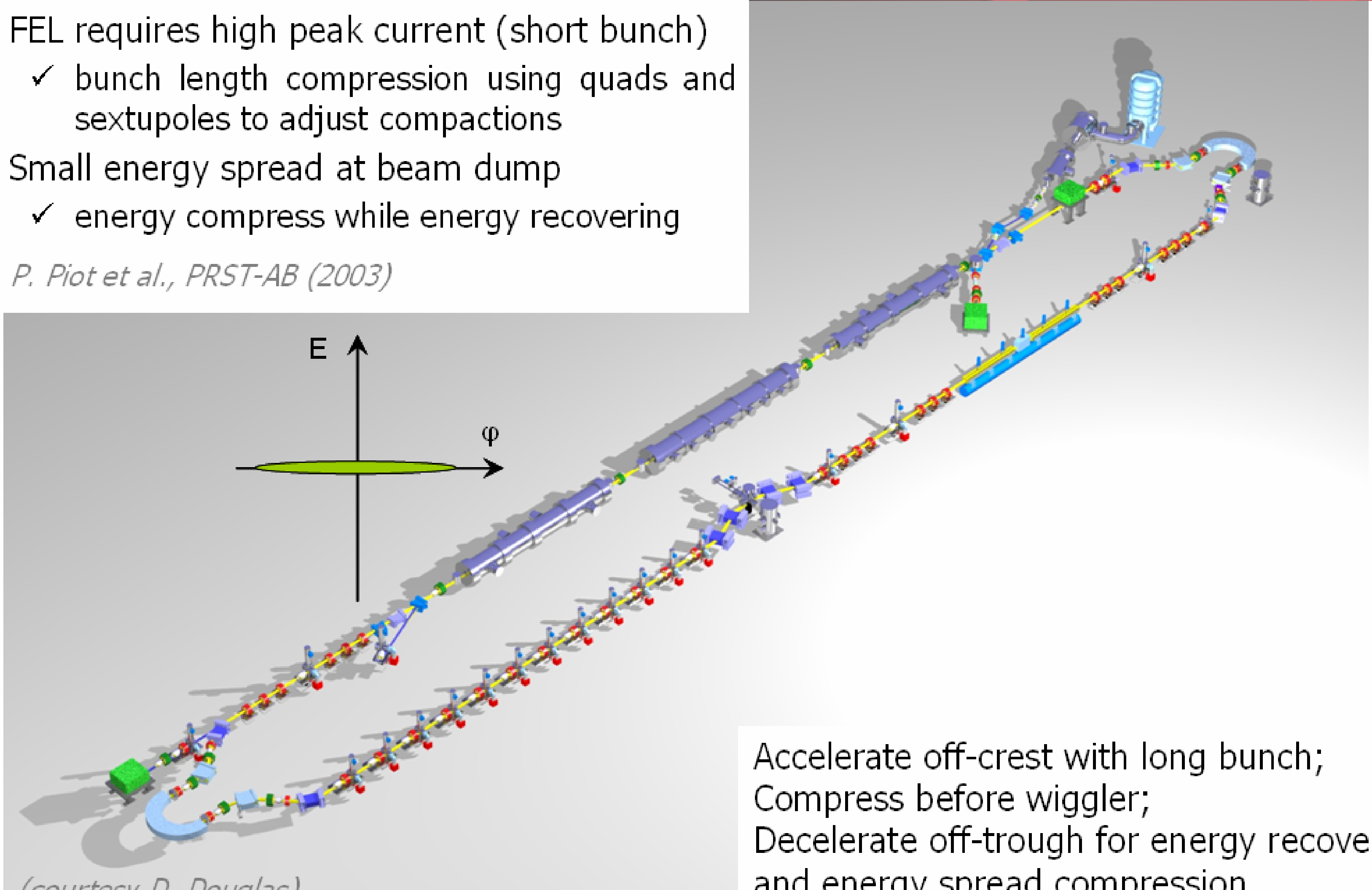

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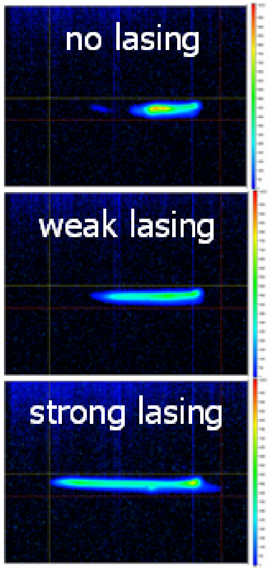
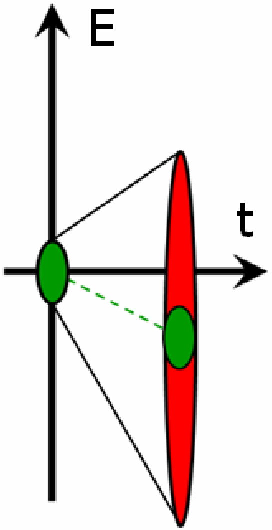
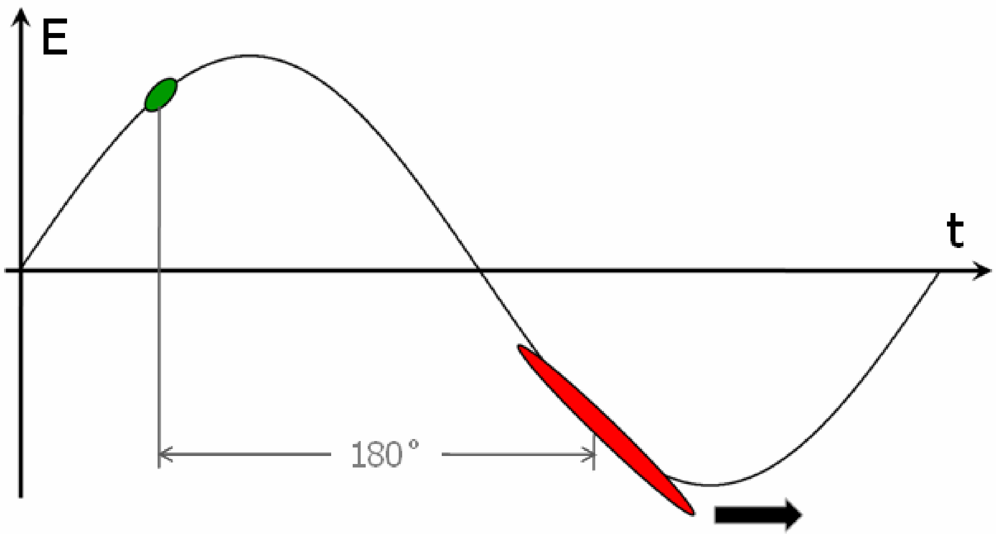
Incomplete Energy Recovery

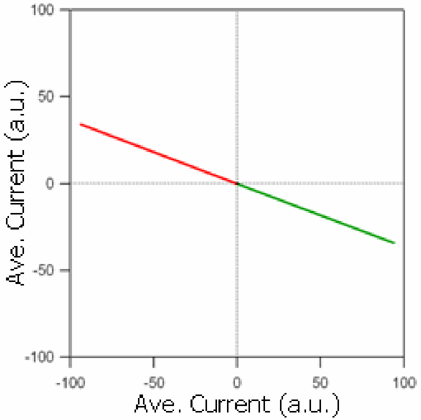






- During lasing, the beam central energy drops and energy spread increases
- Deceleration must occur far enough up the RF waveform to prevent beam from falling into trough
- To first order the deceleration phase must exceed:

$$\phi = \cos^{-1}\left(1 - \frac{1}{2}\frac{\Delta E}{E}\right)$$



S. Benson et al., 2004 FEL Conference

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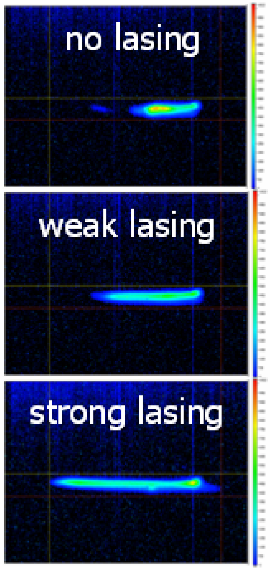

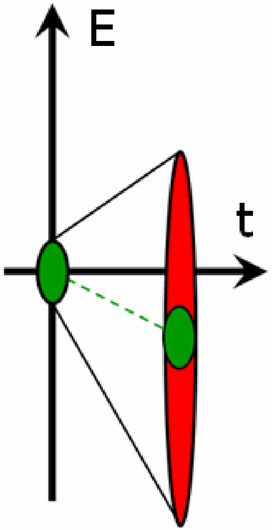

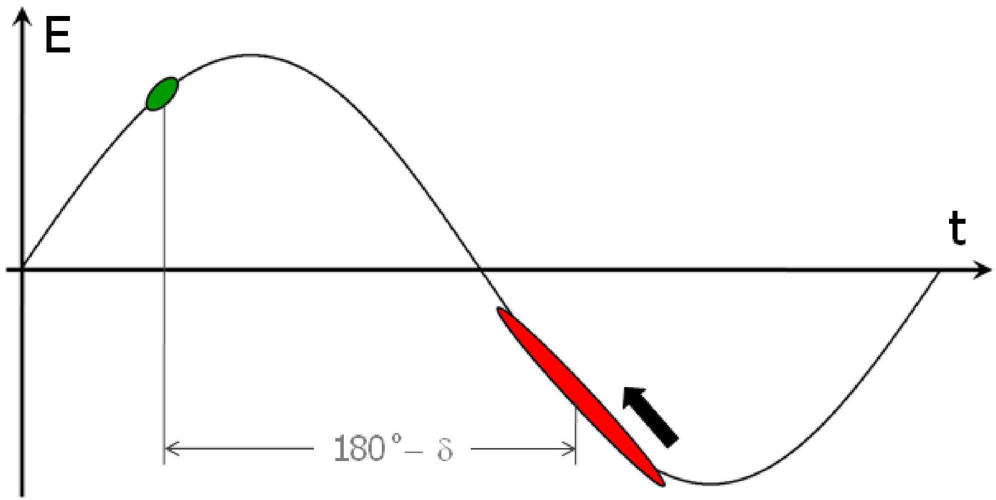

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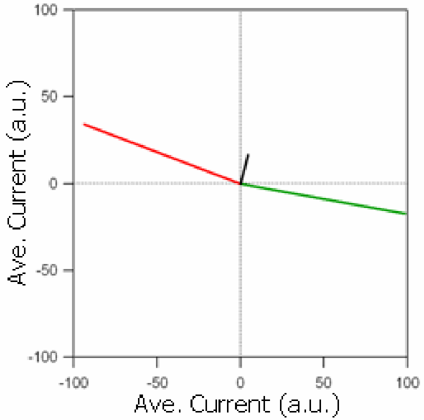
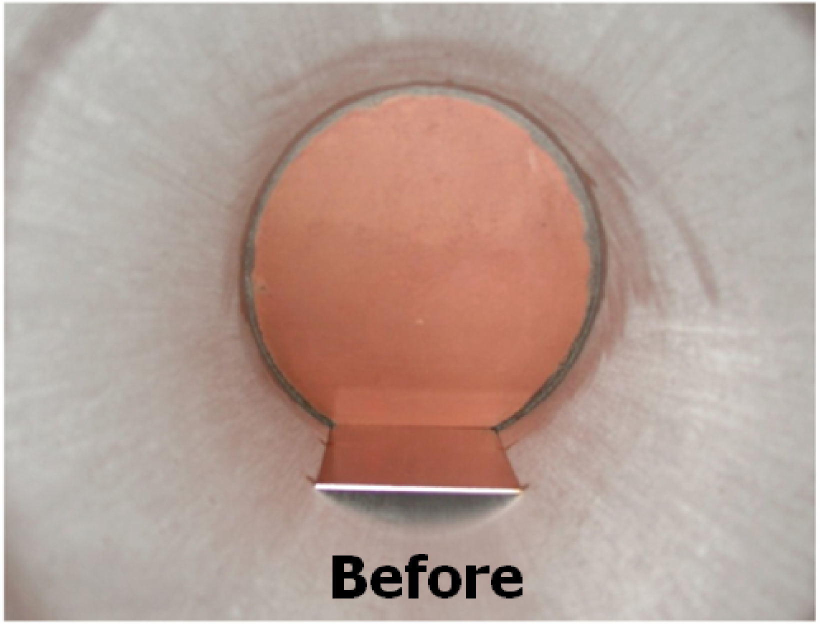
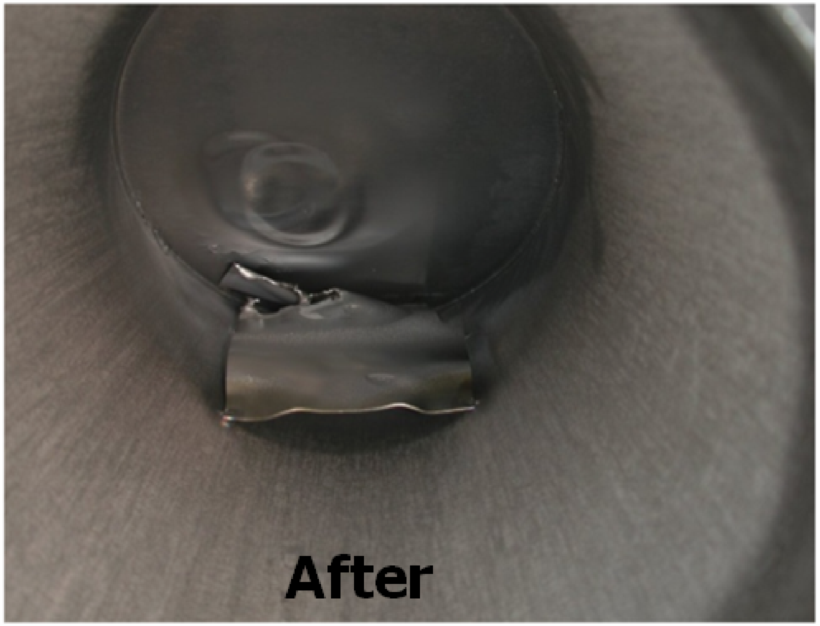


S. Benson et al., 2004 FEL Conference

Consequences of Momentum Tails

- IR FEL Demo electron beam dump (10 MeV and 5 mA)

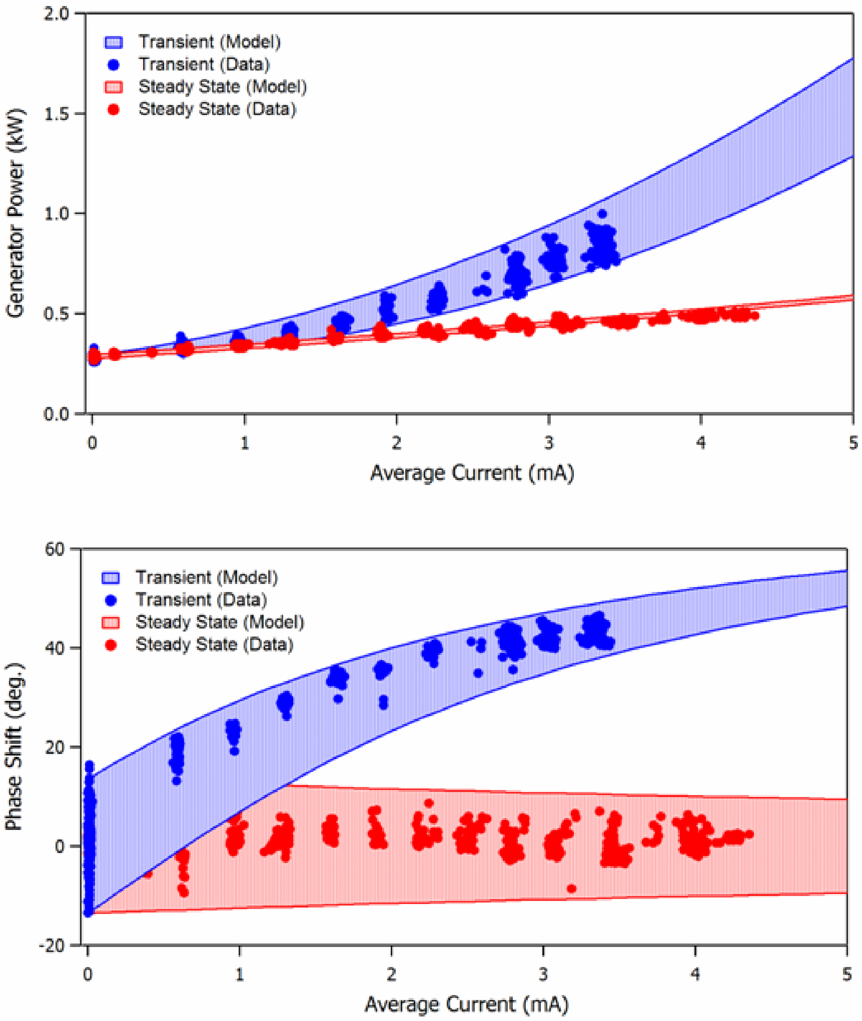




- Offset of beam on dump – energy tail
- Inability to run very high extraction efficiency
- Can get around by running farther out of trough

RF Transients in ERL-based FELs

- Lasing *decreases* the central energy of the bunch
- Coupled with the nonzero momentum compaction (M_{56}) of the recirculator lattice, this generates a change in the path length (phase shift)
- Thus the RF system must deal with a phase shift of *several degrees* as the laser turns on and off
- RF must have enough overhead to deal with incomplete energy recovery and transients due to lasing
- Measured data showing generator power as a function of beam current for steady-state conditions (red) and during a transient (blue)



T. Powers et al., 2007 ERL Workshop

Field Quality Limits on ERLs

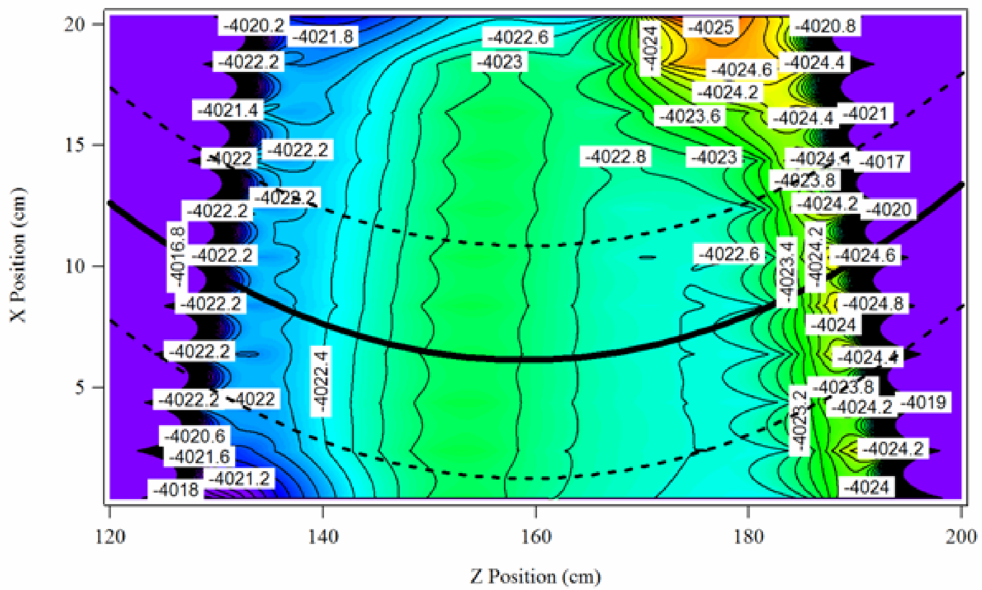
- Magnetic field quality can limit ERL performance
  1) Poor field quality leads to transverse steering errors
  2) Steering errors in conjunction with non-zero M_{52} leads to phase errors
  3) Phase shifts effectively increase the energy spread at the dump

- For a fixed final energy spread, the relative field error must decrease as the linac energy gain increases

$$\Delta E = -\left(\frac{2\pi M_{52}}{\lambda_{RF}}\right) E_{linac} \sin\phi_o \left(\frac{\Delta B}{B}\right)\theta$$

- Spectrometer grade dipoles in the FEL Upgrade
- With typical parameters, get $\Delta E \sim 500$ keV, close to what we measure (300-400) keV

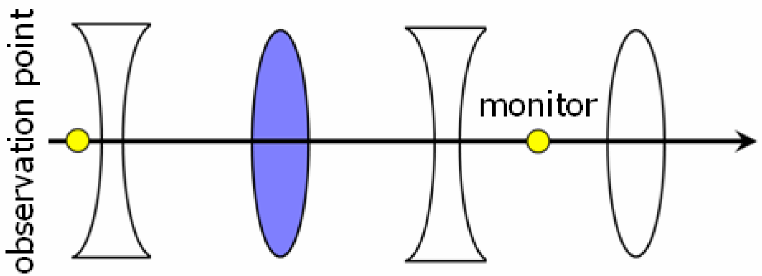
D. Douglas, JLAB-TN-02-002

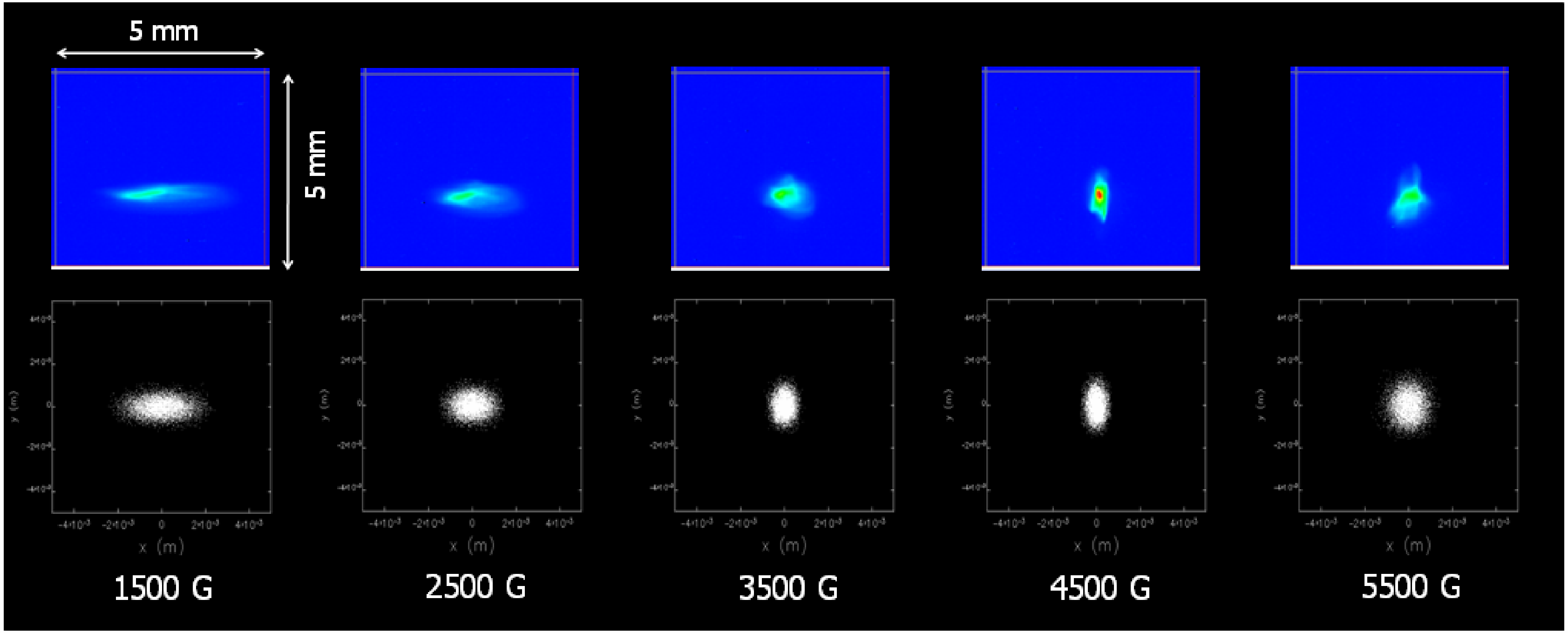


Data from Upgrade dipole exhibiting 10^{-4} field homogeneity

Transverse Phase Space Tomography

- 3F region setup as six 90° matched FODO periods
- Scan quad from 1500 G to 5500 G and observe beam at downstream viewer
- This generates an effective rotation of 157° of the horizontal phase space

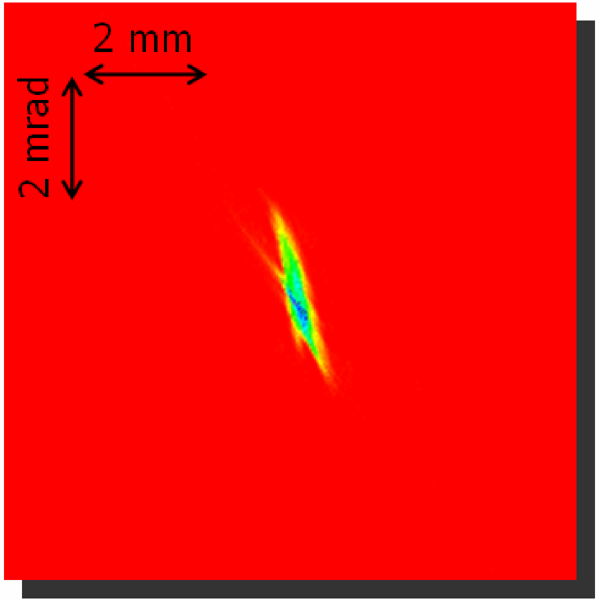


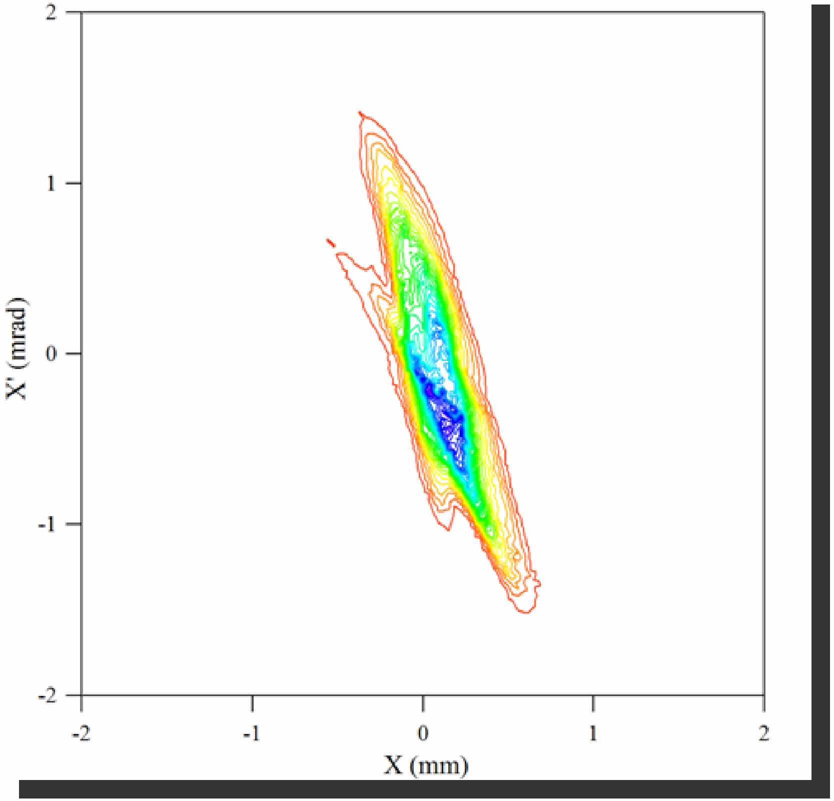


Phase Space Reconstruction

- Use Maximum Entropy algorithm *(J. Scheins, TESLA 2004-08)*
  - Most likely solution while minimizing artifacts
- Reconstructed horizontal phase space at 115 MeV
- Extracted parameters:

$$\varepsilon_n = 15.36 \text{ mm-mrad}$$
$$\beta_x = 0.48 \text{ m}$$
$$\alpha_x = 1.14$$





C. Tennant et al., JLAB-TN 09-021

Summary

- After extended down in 2007/2008, in operational mode again
- Plan to complete installation of UV line → begin commissioning
- Successfully manage collective effects
  - ***BBU*** *– beam optical suppression techniques*
  - ***LSC*** *– modify injected bunch, judicious choice of acceleration phase*
  - ***CSR*** *– use of de-bunching chicane*
- The Upgrade is a valuable testbed for studying collective effects
  - Studies of CSR and LSC are planned for later this year
- The Upgrade is the only operating FEL based on a CW superconducting ERL

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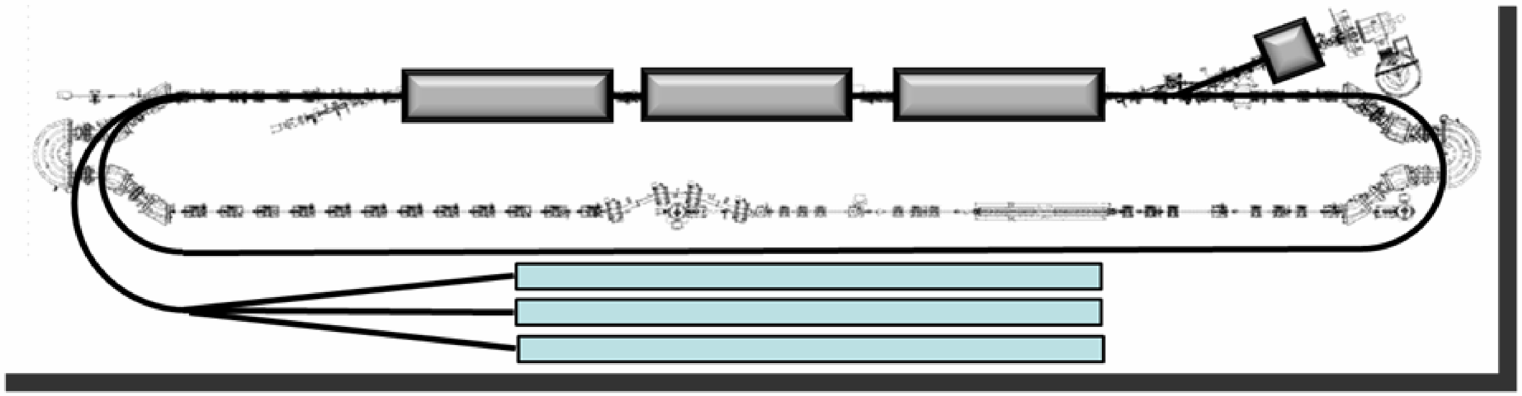
- **JLAB FEL: FUTURE**

The Jefferson Lab FEL (Upgrade)^2



Use FEL as a test bed to address next generation soft x-ray light source technologies:

- Replace existing cryomodules with ones optimized for high real estate gradient
- Achieve 300 MeV/pass
- Investigate limits of multipass operation and deal with CSR, LSC, compression methodologies, etc…

Upgrade Parameters	Achieved	Phase II
Energy (MeV)	160	600
Bunch charge (pC)	270	200
Ave. current (mA)	9.1	1
Bunch length* (fs)	120	30
$\varepsilon_{x,y}$* (mm-mrad)	7	2
Max. Rep. Rate (MHz)	74.85	5.0

**quantities are rms*

(courtesy G. Neil)

Jefferson Lab Areas of Expertise

DC Photocathode Gun

- CW operation at 9.1 mA (75 MHz) with 122 pC/bunch
- Routinely delivers >5 mA CW and pulse current at 135 pC

Superconducting RF

- Jefferson Lab has processed over half the world's SRF cavities
  - ✓ CEBAF (438) + SNS (84) + FEL (26) operating CW
- The only producer of SRF accelerators from the physics requirements to commissioned hardware
- At CEBAF alone we have over 50 cavity-centuries of operating experience

Beamline Design

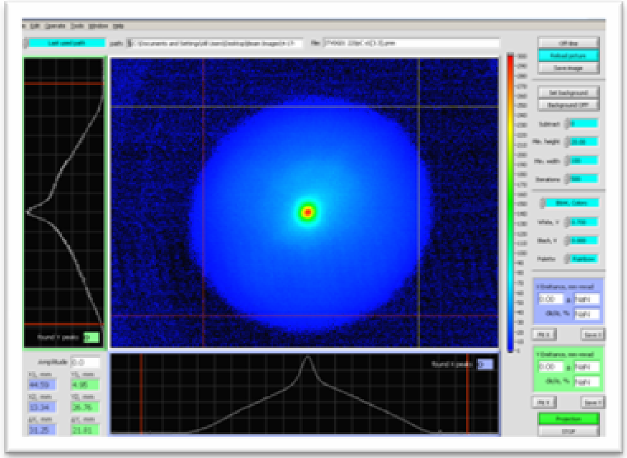
- Longitudinal phase space management
  (bunch compression to wiggler and energy compression to dump)
- Robust transport
  (5 MeV injector setup with 270 pC)
- Handle in excess of 1 MW beam power
- Successful management of collective effects

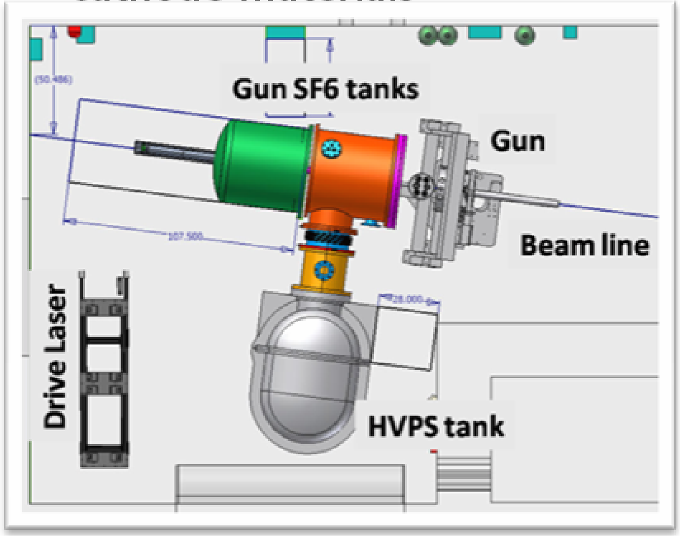
The Jefferson Lab FEL Team

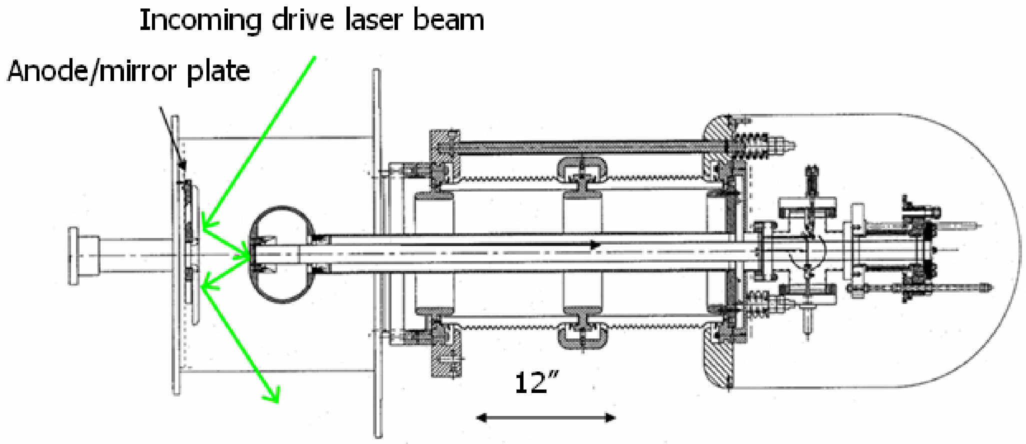
The FEL has been supported by the Office of Naval Research, the Joint Technology Office, the Commonwealth of Virginia, the DOE Air Force Research Laboratory, The US Army Night Vision Lab, and this work by under contract DE-AC05-060R23177.

The FEL Gun Test Stand (GTS)

- Testing gun high voltage performance with coated electrodes for field emission suppression
- Dedicated operations for electron beam characterization at high charge
- Characterizing photocathode lifetime with improved methods and materials for better vacuum conditions
- A semi-load lock system for increased productivity during cathode change-out and for testing different cathode materials

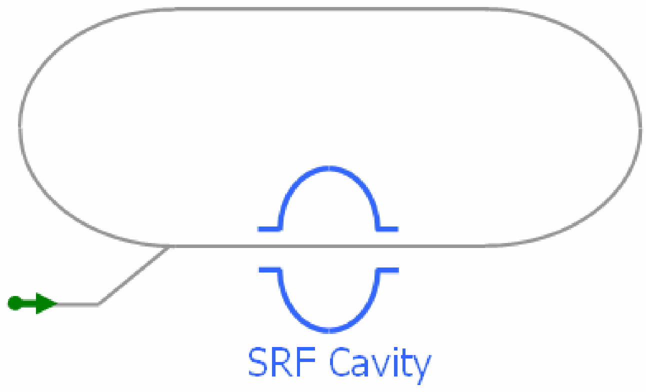






(courtesy C. Hernandez-Garcia)

Multipass Beam Breakup (BBU)



For the case of a two-pass ERL with a single cavity, containing a single HOM the equation for the BBU threshold current is given by

$$I_{th} = -\frac{2V_b}{k(R/Q)Q_L M^* \sin(\omega T_r)}$$

$$M^* \equiv M_{12}\cos^2\alpha + (M_{14} + M_{32})\cos\alpha\sin\alpha + M_{34}\sin^2\alpha$$

and remains valid only when $M^*\sin(\omega T_r) < 0$.

The threshold depends on:

- Damping of the cavity (i.e. impedance)
- Lattice design (recirculation optics)
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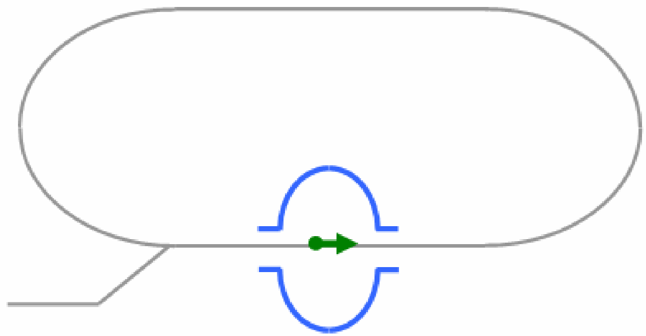

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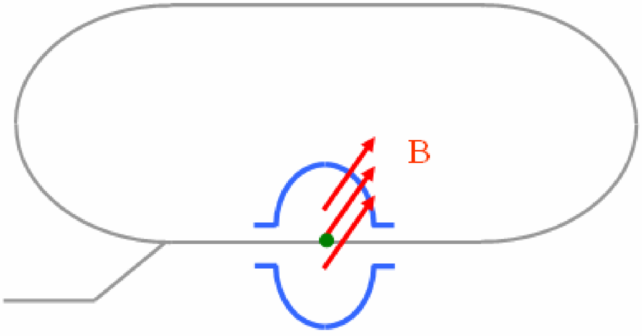

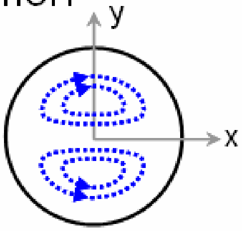

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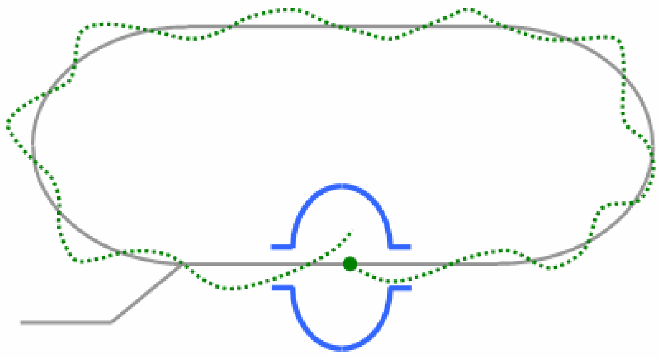

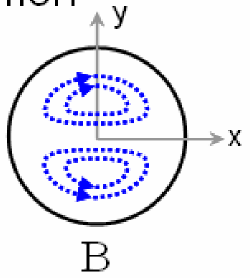

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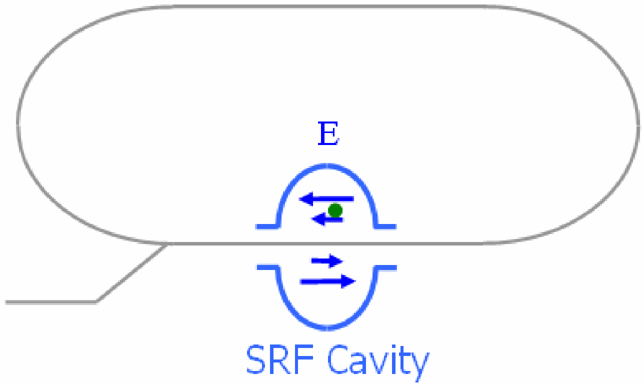

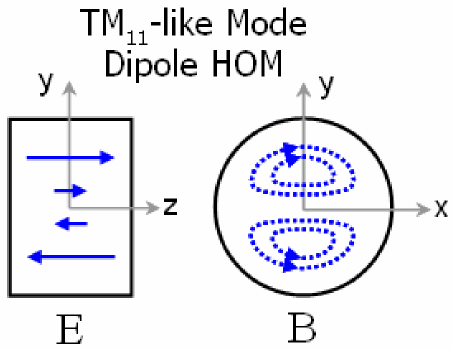

Transverse BBU: a positive feedback between the (recirculated) beam and insufficiently damped HOMs

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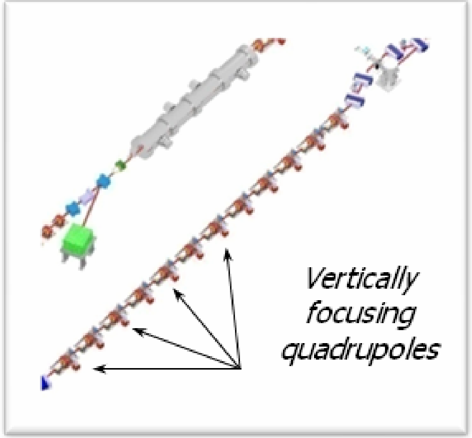
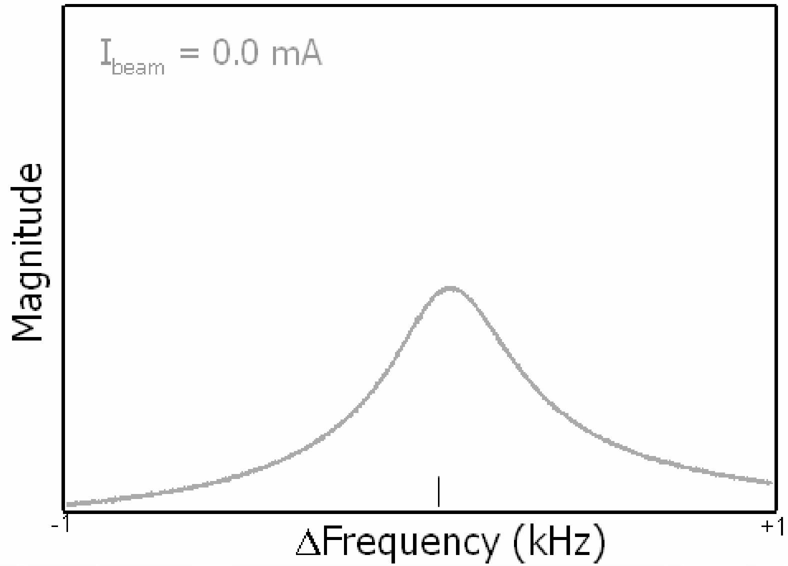
BBU Suppression Techniques

- Modify betatron phase advance → point-to-point focusing
- By returning the beam on-axis through the cavity, the beam can no longer exchange energy with the HOM
- Measurements indicate the HOM causing beam breakup (2106 MHz) is oriented *vertically*
- Change four vertically focusing quadrupoles in recirculator to vary the vertical phase advance



Quads changed +200 G



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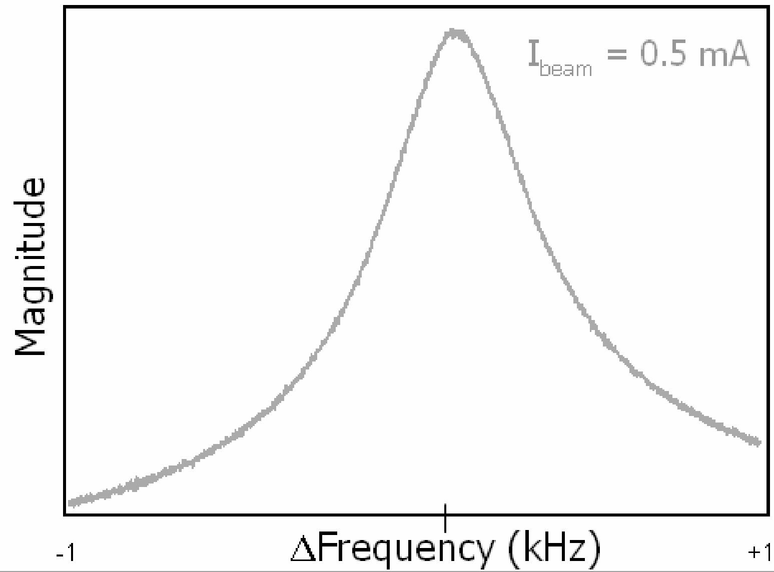

D. Douglas et al., PRST-AB (2006)

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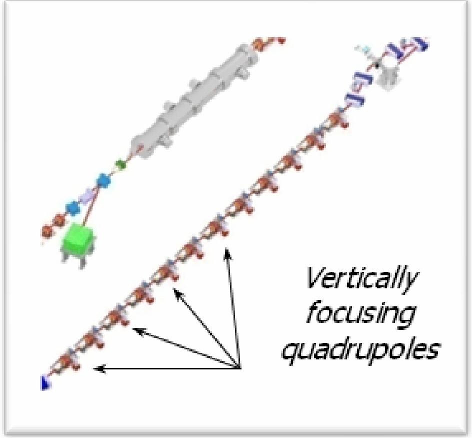

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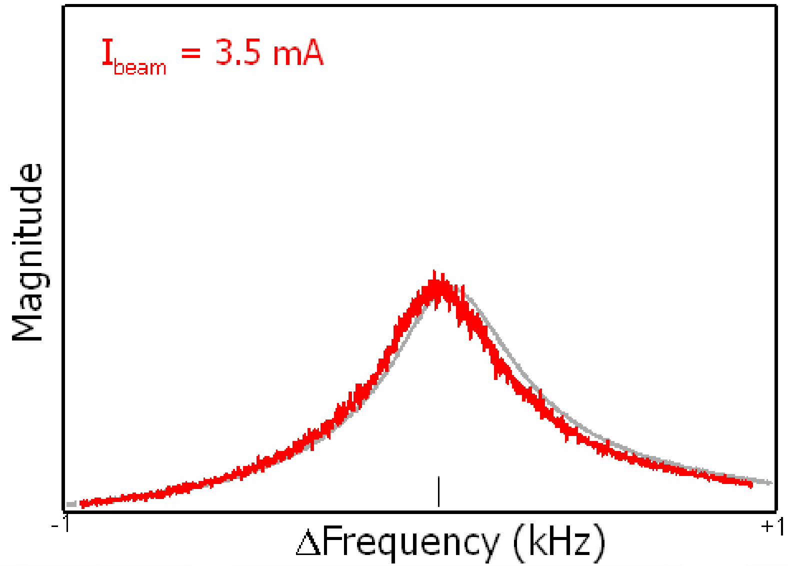

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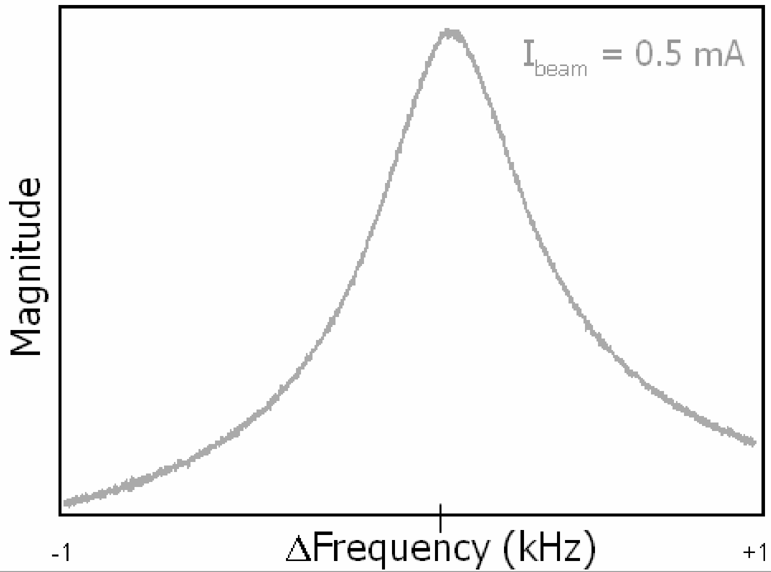

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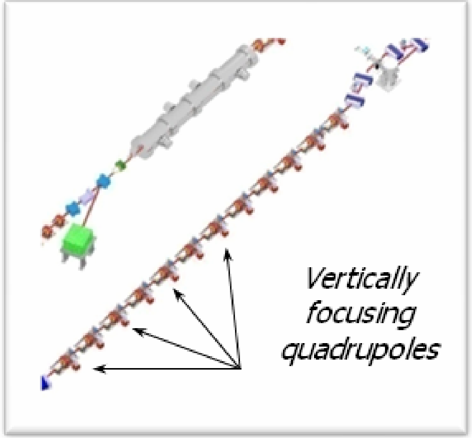

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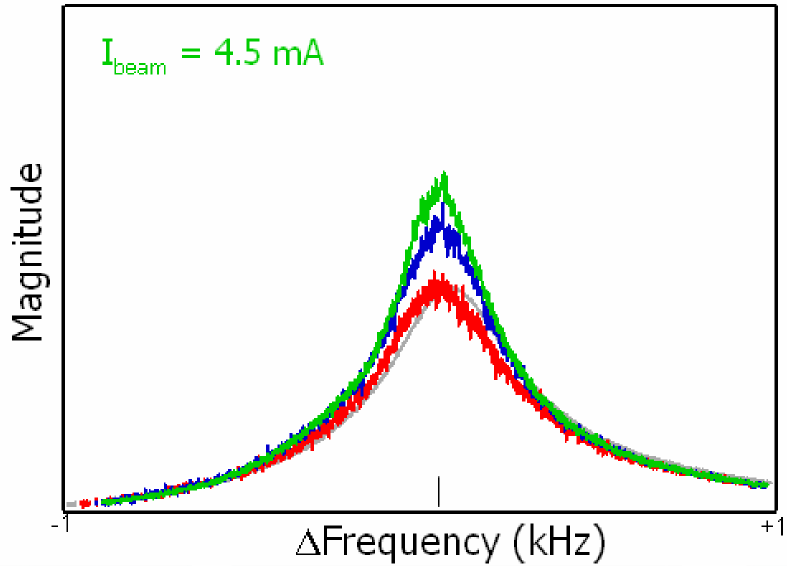

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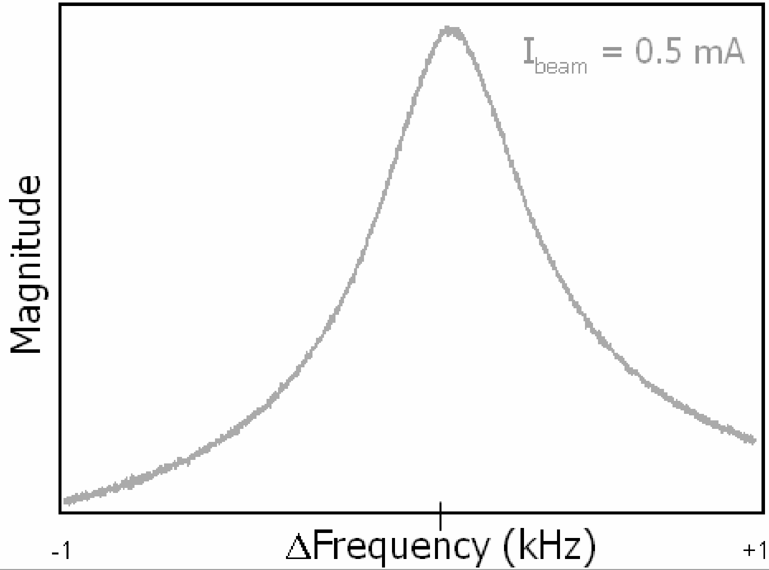

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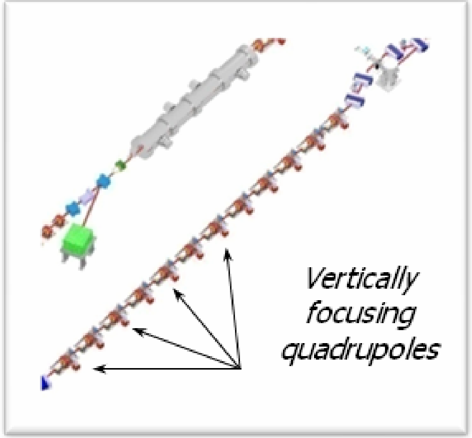

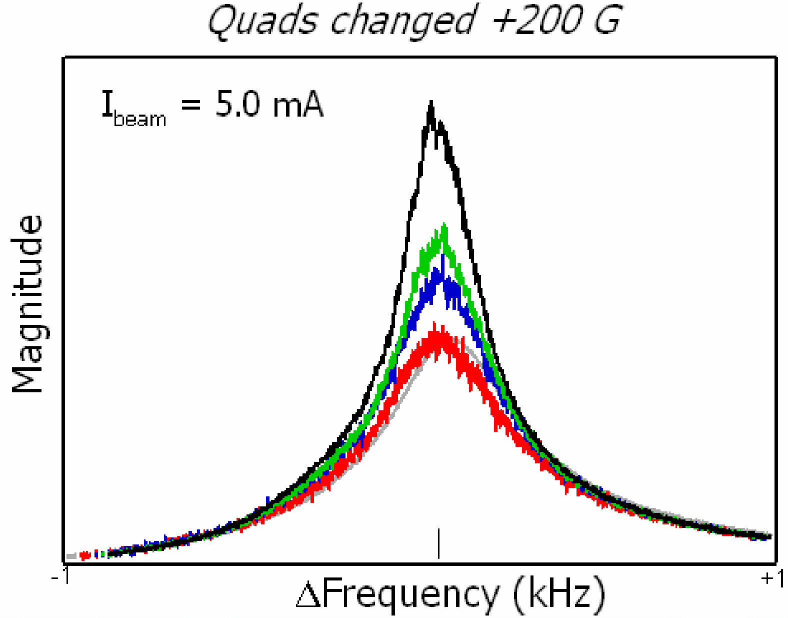

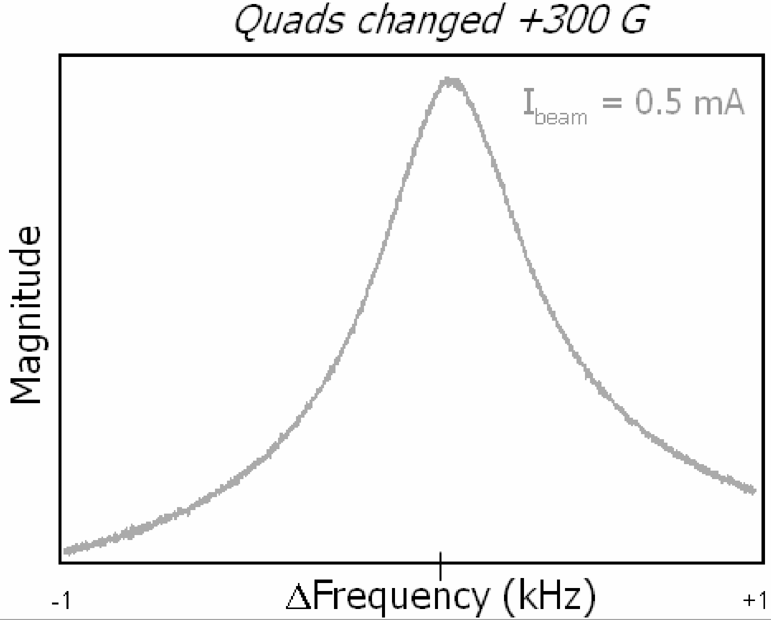

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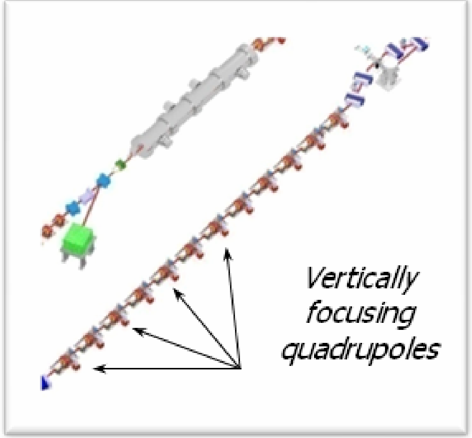

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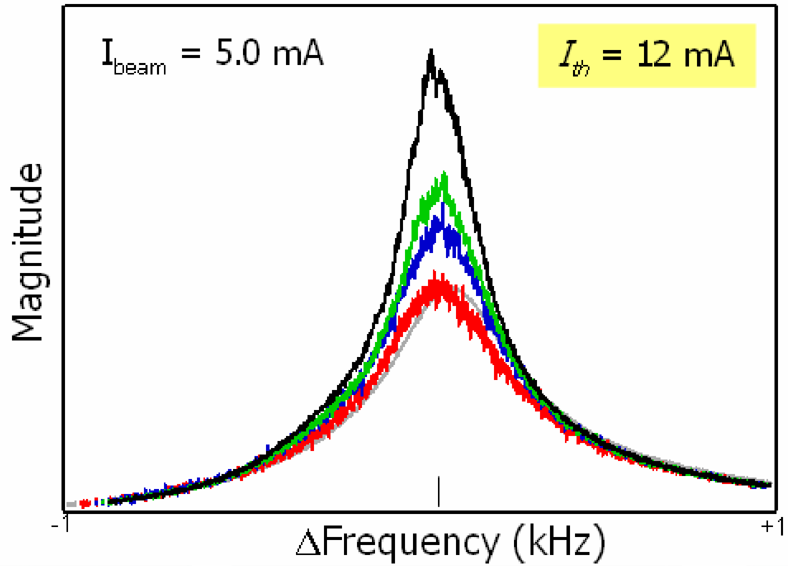

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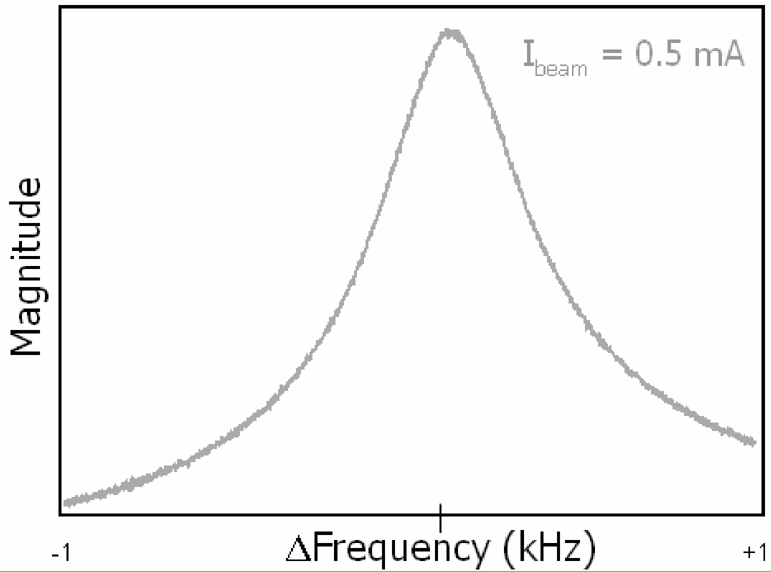

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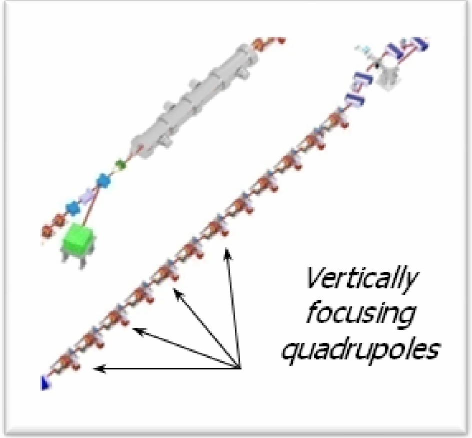

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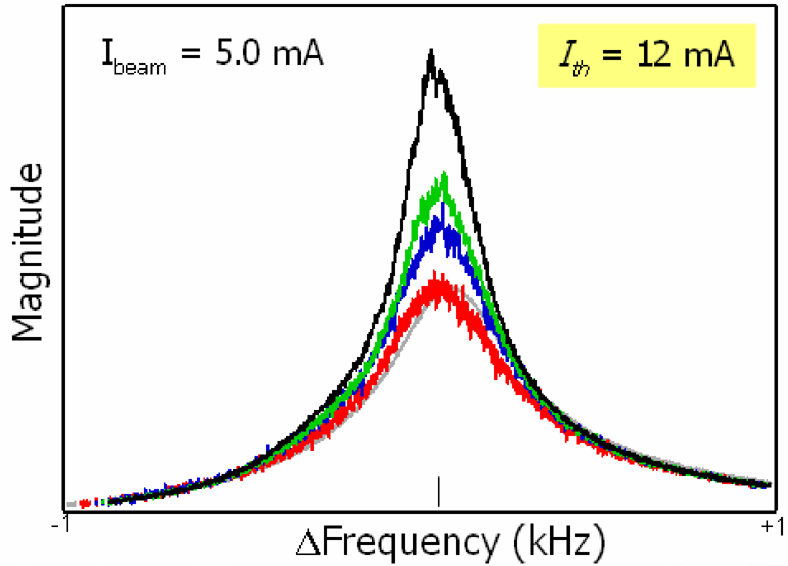

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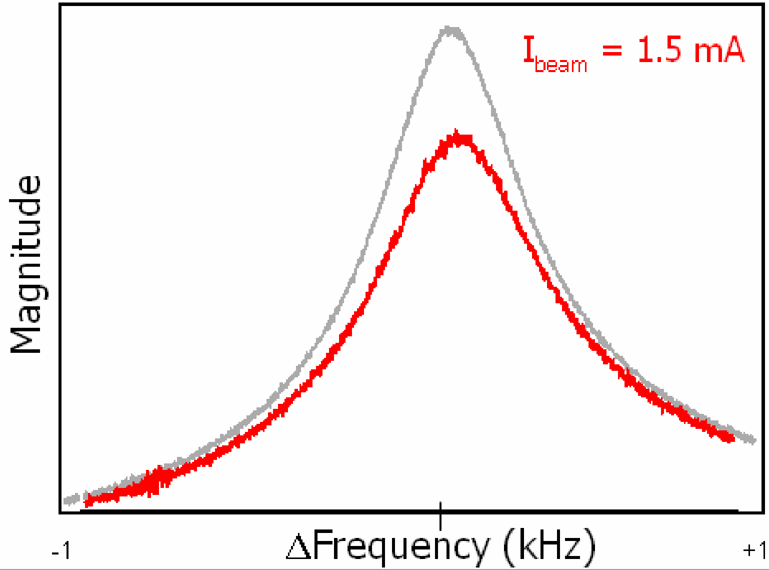

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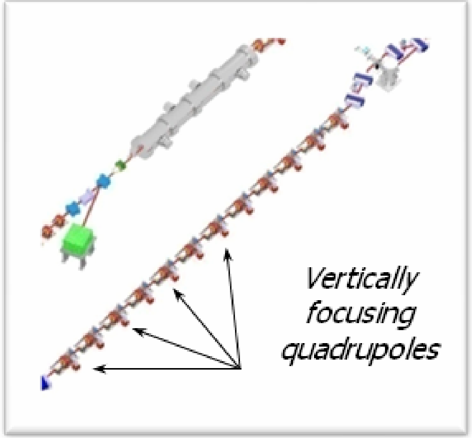

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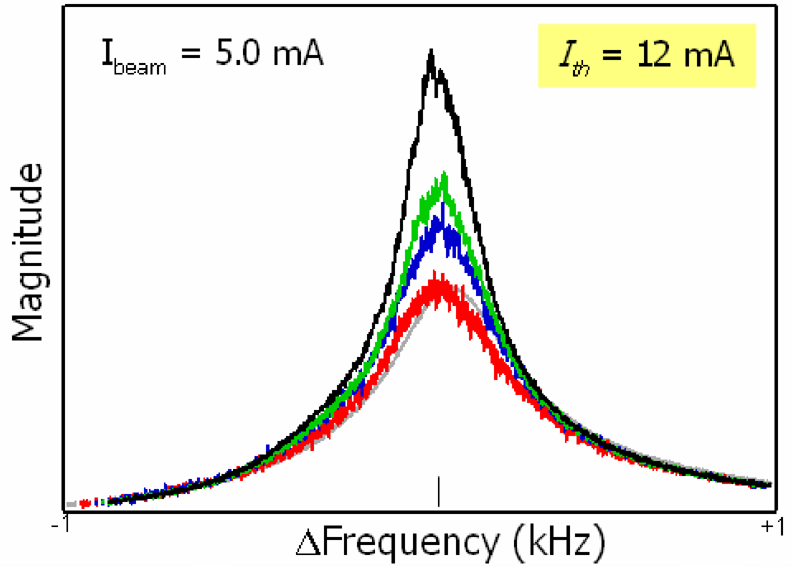

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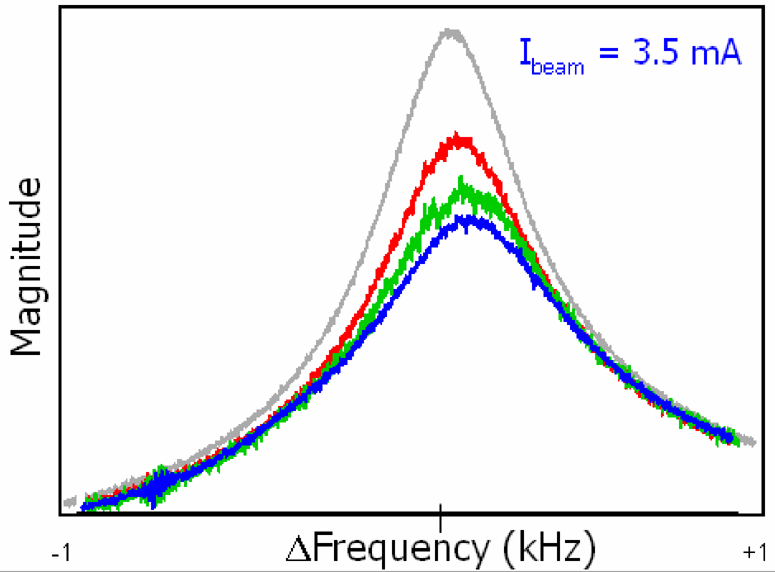

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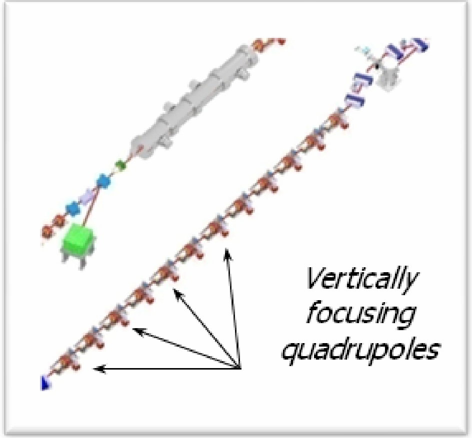

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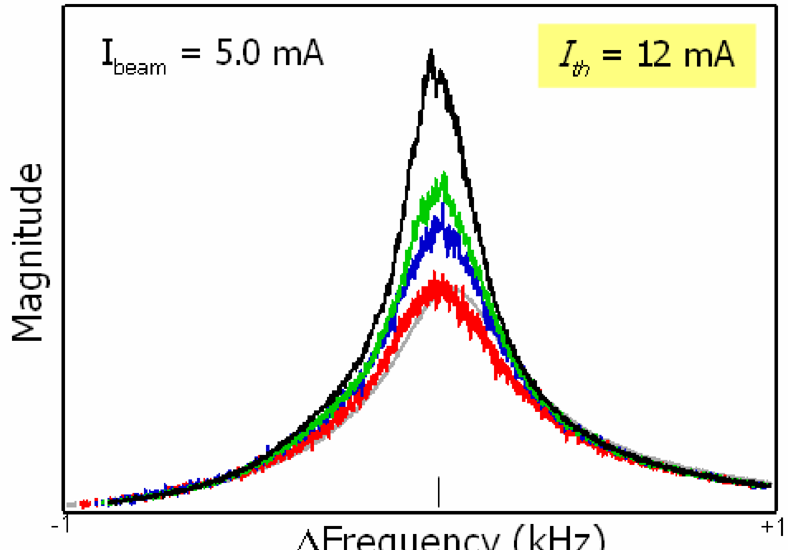

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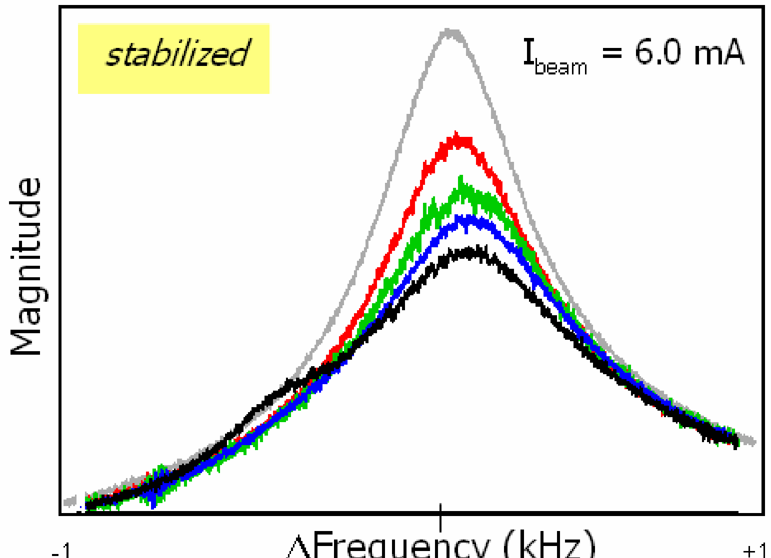
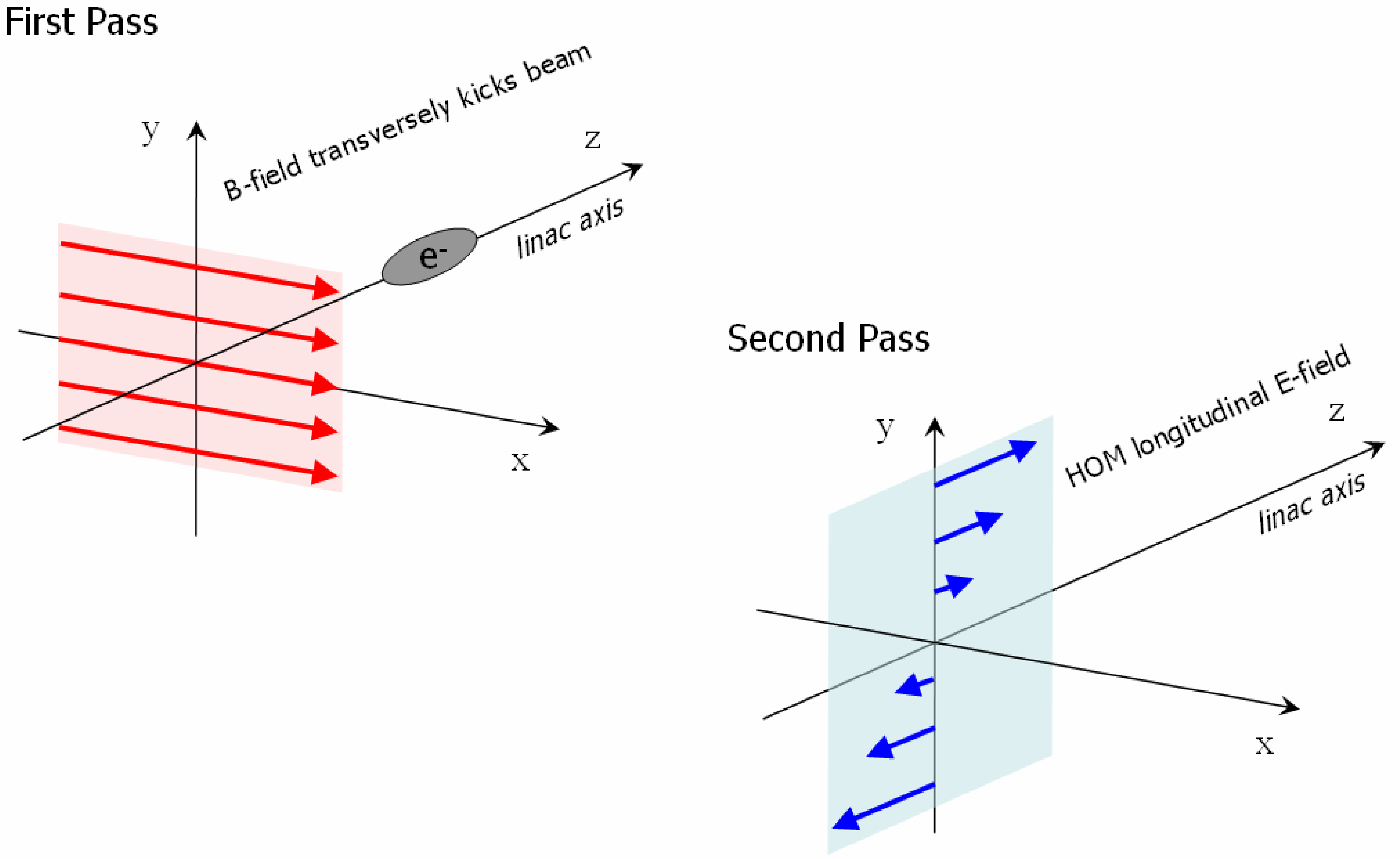


D. Douglas et al., PRST-AB (2006)

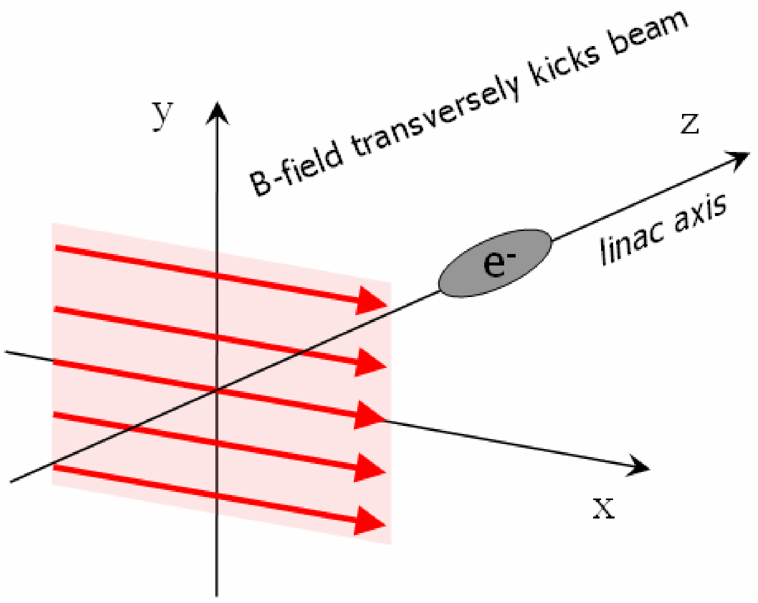
Coupled Optical Control of BBU



Rand and Smith, Particle Accelerators (1980)

Coupled Optical Control of BBU

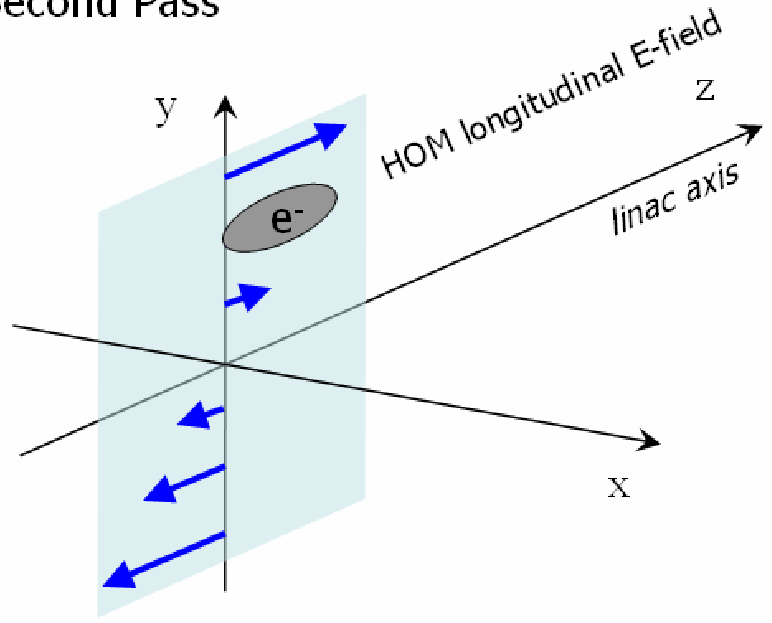
First Pass



Second Pass: Decoupled Optics

The y kick results in a y displacement on the second pass and the bunch is in a region of longitudinal electric field.

Second Pass

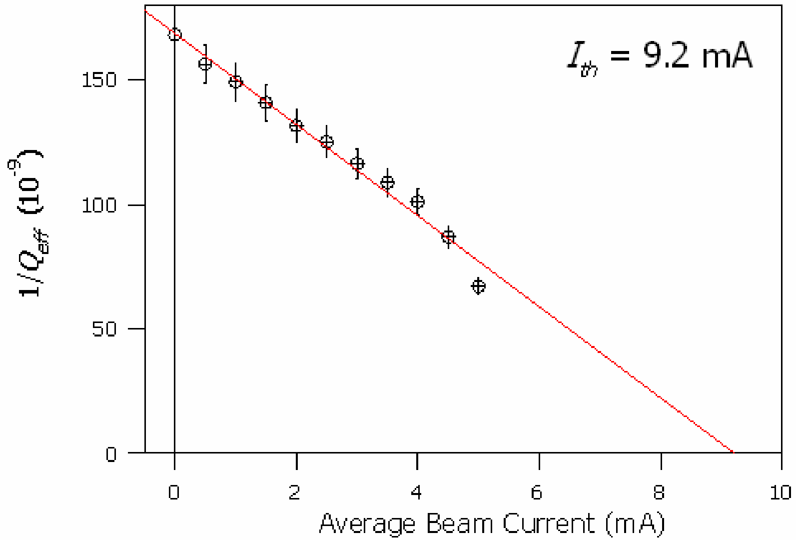


Rand and Smith, Particle Accelerators (1980)

Effect of Reflector and 90° Rotation

Reflection

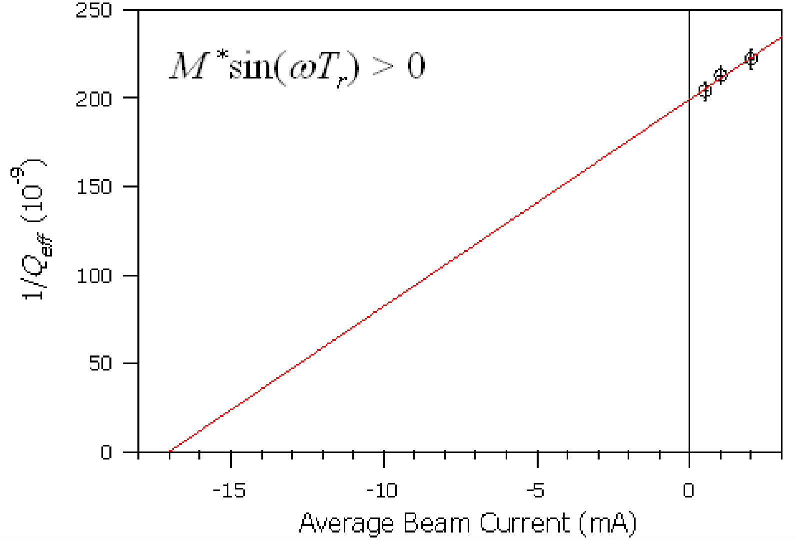
- The effect of the reflector is to increase the threshold due to the 2106 MHz HOM by a factor of 5 – from 1.8 mA to 9.2 mA
- Also investigated the stability of several other potentially dangerous HOMs with the reflector activated



Rotation

(= Reflecton + Point-to-Point Focusing)

- Adjusting the vertical phase advance creates a nearly 90° rotation from the cavity back to itself
- This has the effect of stabilizing the dangerous HOM; however setup was sensitive to beam loss



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