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USPAS Course on
4^{th} Generation Light Sources II
ERLs and Thomson Scattering

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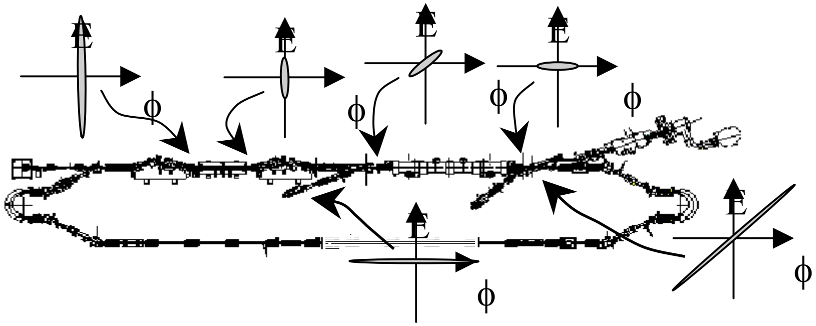
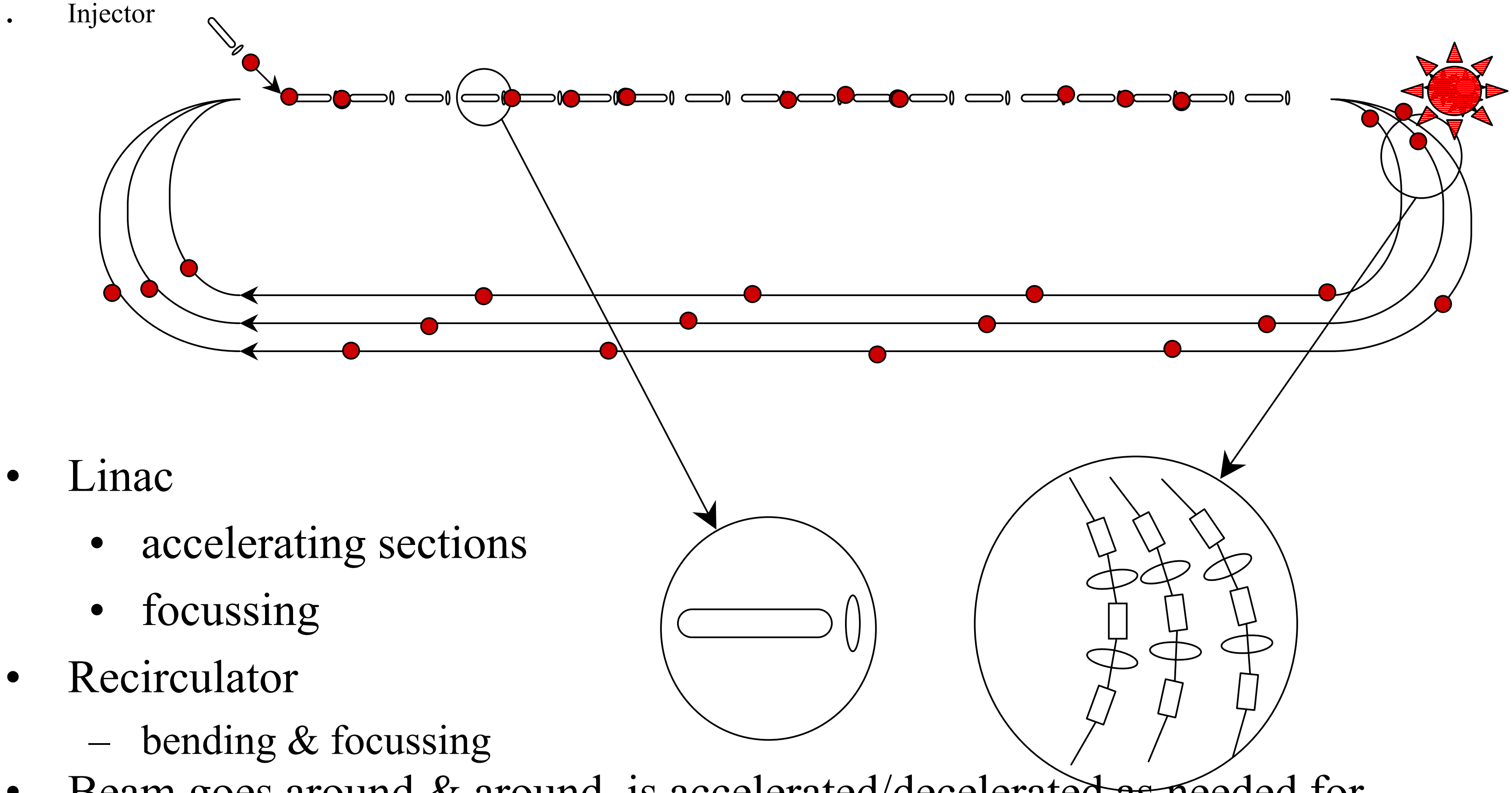
Introduction to Energy Recovering Linacs

Optics Issues for Recirculating Linacs



D. Douglas

The Naïve Recirculator



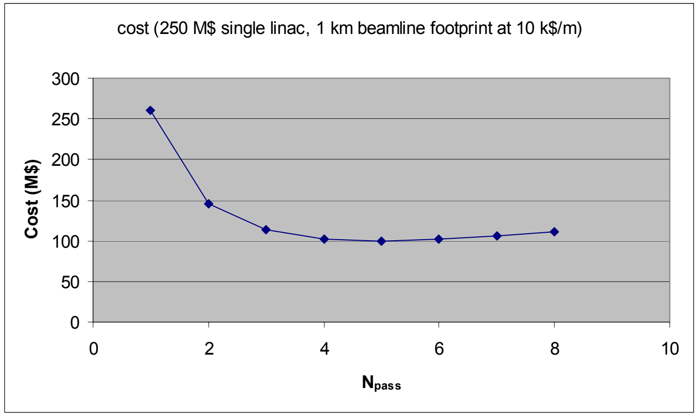
- Linac
  - accelerating sections
  - focussing
- Recirculator
  - bending & focussing
- Beam goes around & around, is accelerated/decelerated as needed for the application at hand

Design and Performance Issues

- How many passes?
  - 1 pass/0 recirculations = straight linac: $$$$$!!
  - 1 RF cell/ ~ ∞ recirculations = storage ring: performance!!
- Multipass focusing in linac(s)
  - Injection/final energy ratio, linac length, “halo”
- Machine design with recirculation
  - Transverse/longitudinal phase space control
    - Transverse matching; path length & compaction management
- Instabilities
  - BBU, other impedance driven effects, FEL/RF interaction, beam loss instability during energy recovery
- Beam quality degradation
  - Space charge, synchrotron radiation, CSR, environmental impedances

Number of Passes

- Cost/Performance optimization
  - RF costs $\propto 1/N_{pass}$
  - Beamline costs $\propto N_{pass}$
  - Typical cost optimum $N_{pass} > 1$



However!

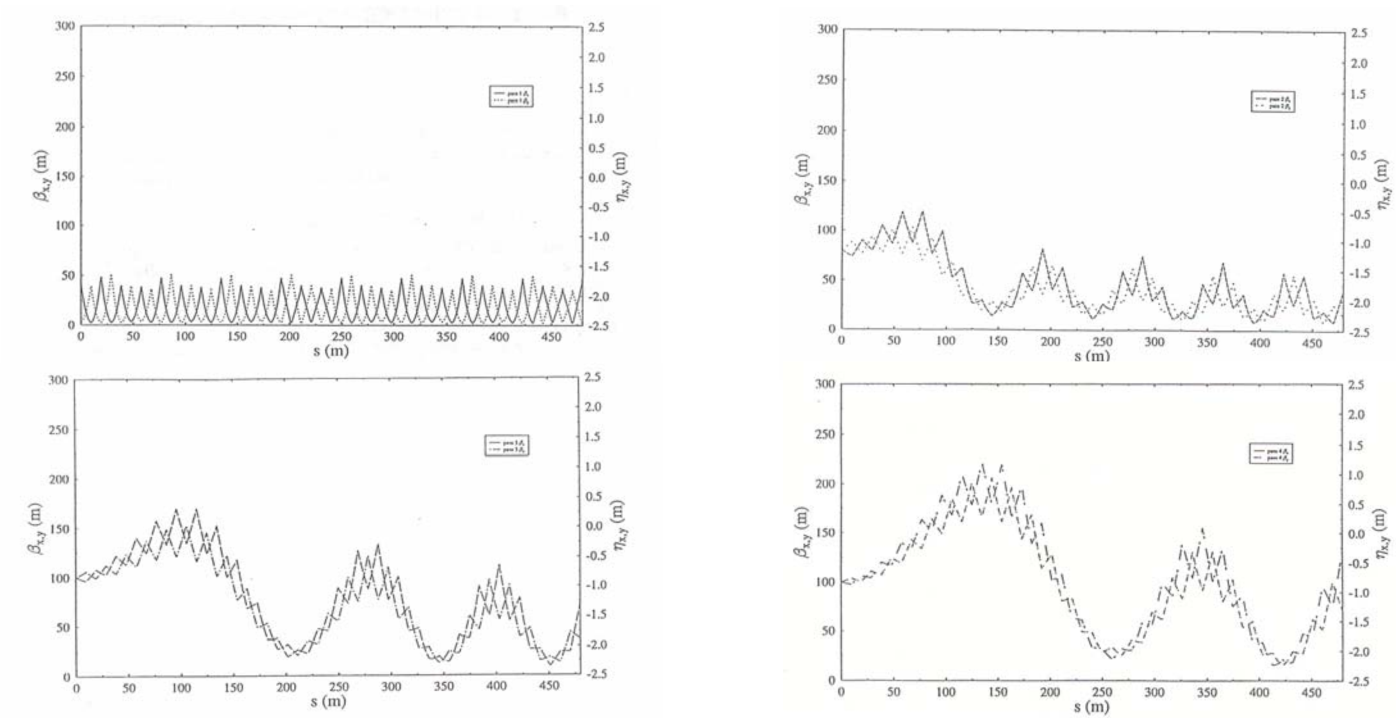
- Minimum is shallow, broad, and influenced by many additional factors:
  - Civil costs ("tunnel")
  - Single vs. split linac
  - Beamline complexity (& cost) grows *faster* than N_{pass}
  - Performance issues:
    - lower construction vs. higher commissioning costs
    - meeting user-driven performance requirements

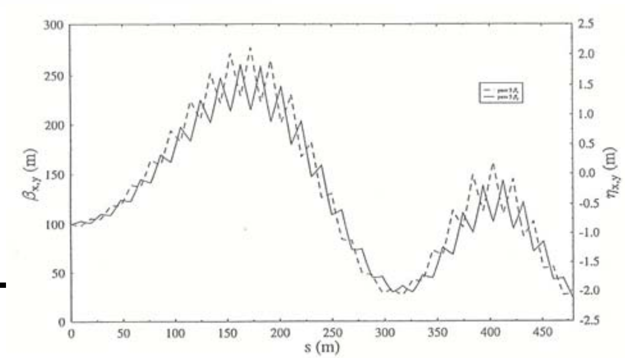
Beam envelope/spot size control is the *transverse optical issue in recirculating linacs*

- Recirculation leads to mismatch between beam energy and excitation of focusing elements
  - set focusing for first pass $\Rightarrow$ higher passes get "no" focusing/blow up (linac looks like a drift, β_{max} ~ linac length)
  - set focusing for higher passes $\Rightarrow$ first pass *over-focused*/blows up
  - Large envelopes lead to scraping, error sensitivity, lower instability thresholds
- Imposes limits on
  - injection energy (higher is better but costs more),
  - linac length (shorter is better but gives less acceleration), and/or
  - achievable control over β_{max}

CEBAF Envelopes

– FODO quad lattice with 120° phase advance on 1st pass





Panaceas

- Focus 1st pass as much as possible (whilst maintaining adequate betatron stability)

- Use a "split linac" – 2 halves rather than 1 whole
  - Shorter linac $\Rightarrow$ lower peak envelopes ("shorter drift length")
- *Linac interruptus*
- High injection energy
- "Graded gradient" focusing in energy-recovering linacs
- Use high gradient RF
- Use an "inventive" linac topology
  - "Counter-rotated" linacs
  - "Bisected" linac topology
  - "Asymmetric" linac topology

CEBAF Envelopes, reduced focusing

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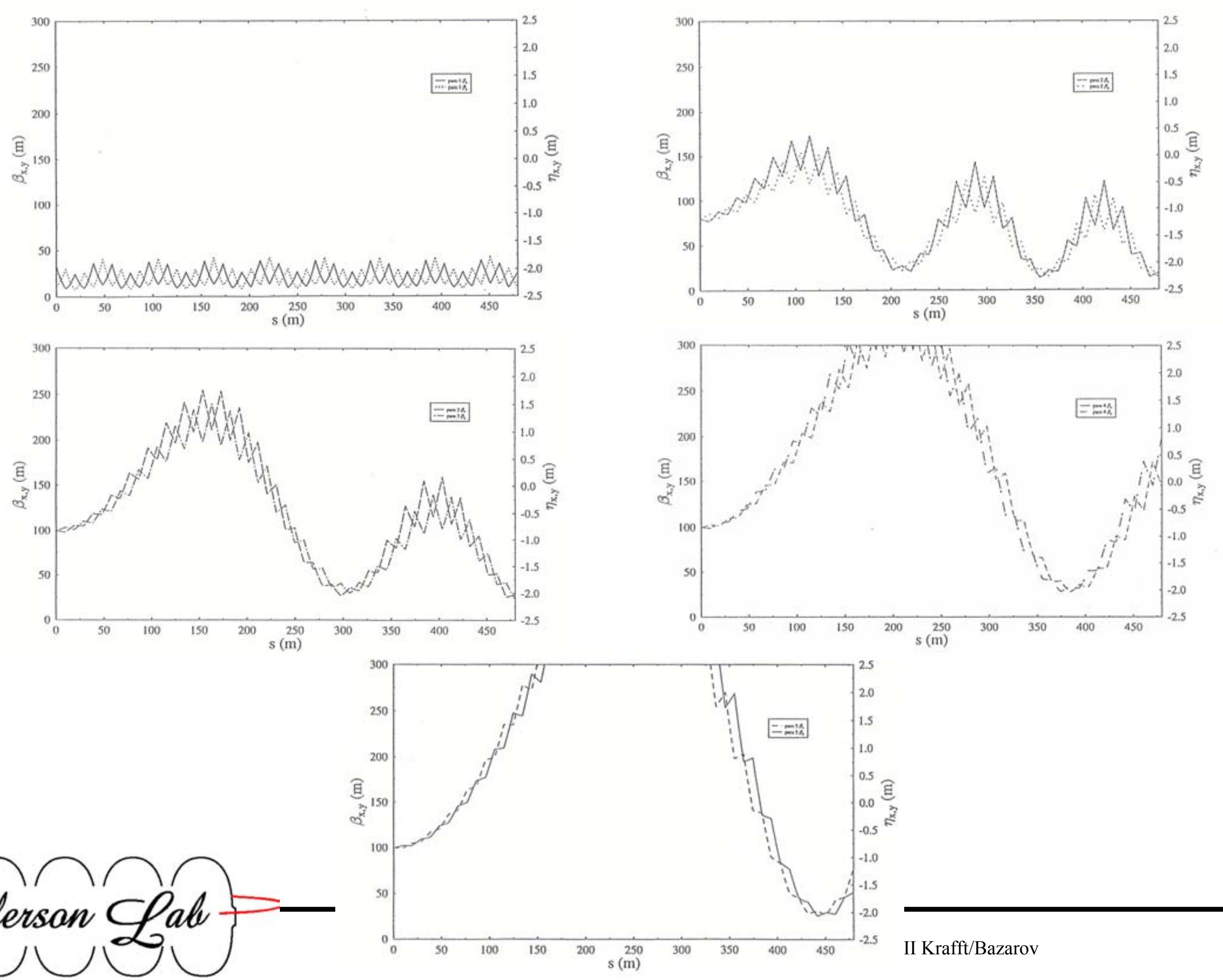
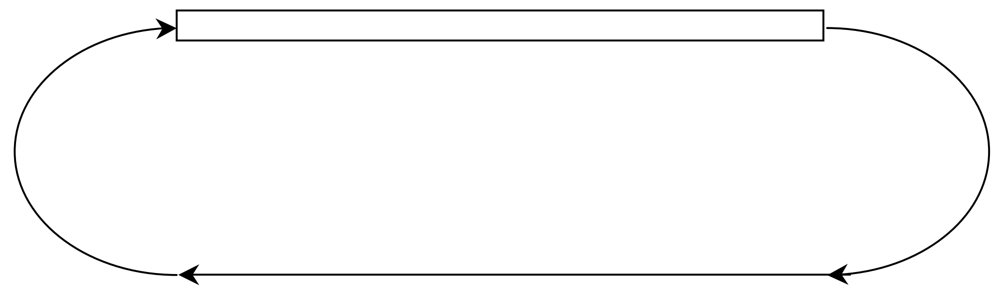
– FODO quad lattice with 60° phase advance on 1st pass

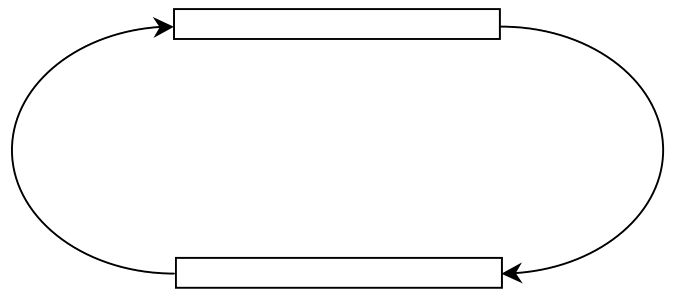


Single/Split Linac

Single Linac

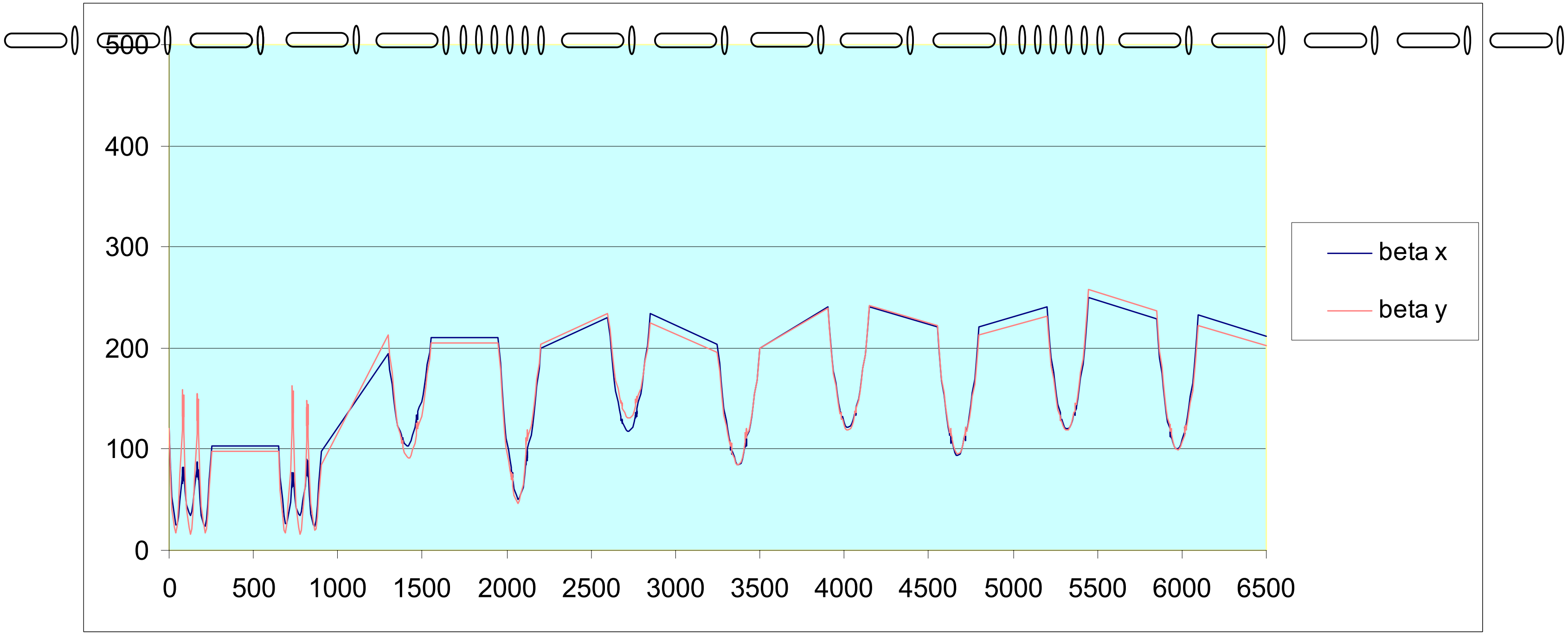


Split Linac



- shorter linacs $\Rightarrow$ lower peak envelopes ("shorter drift length")
- higher "injection" energy in 2nd linac $\Rightarrow$ even lower peak envelopes (relatively stronger focusing on higher passes)
- requires more complex beam transport system (multiple splitting/reinjection regions at ends of multiple linacs)

- periodically replace accelerating sections with high phase advance focusing insertions
  - Gives additional focusing on higher passes



Injection Energy

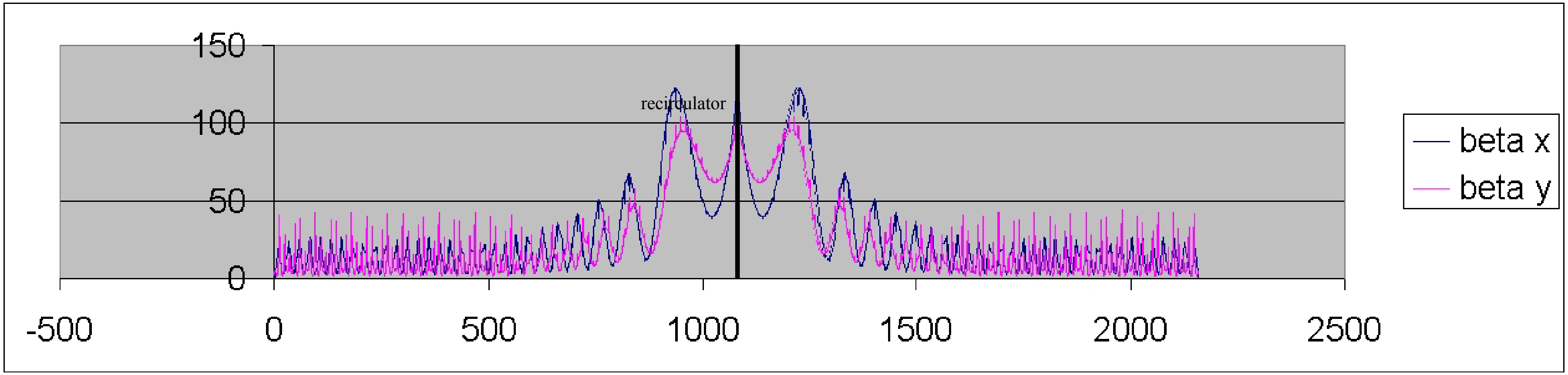
- Injection energy "must" be high enough to avoid significant levels of pass-to-pass RF phase slip
  - CEBAF E_{inj} = 45 MeV, $\delta\phi_{RF} \sim$ 1-2° on 1st pass, little thereafter
  - IR Demo FEL E_{inj} = 10 MeV, $\delta\phi_{RF} \sim$ 10° from pass to pass
- Injection energy "should" be high enough to allow adequate pass-to-pass focusing in a single transport system
  - "adequate" is system dependent
    - CEBAF (45 MeV ⇒ 4 GeV): $\beta_{max} \sim$ 200 m – adequate to run 200 μA
    - IR Demo (10 MeV ⇒ 45 MeV): $\beta_{max} \sim$ 25 m – adequate to run 5 mA
  - Higher is better (front end focusing elements stronger) but more expensive
    - SUPERCEBAF (1 GeV ⇒ 16 GeV), using same type of linac focusing as in CEBAF: $\beta_{max} \sim$ 130 m
- Naïve figure of merit: E_{final}/E_{inj}, with smaller being better

"Graded-gradient" Focusing

- There are 2 common focusing patterns:
  - constant gradient (all quads have same pole tip field; sometimes used in microtrons)
  - constant focal length (quad excitation tracks energy; often used in linacs)
- Neither works well for energy recovering linacs
  - Beam envelopes blow up, limiting linac length & tolerable $E_{final}:E_{in}$ ratio
- "Graded-gradient" focusing $\Rightarrow$ match focal length of quads to beam of lowest energy
  - Excitation of focusing elements increases with energy to linac midpoint, then declines to linac end
  - Allows "exact" match for half of linac, produces "adiabatically induced" mismatch in second half

"Graded-gradient" Focusing, cont.

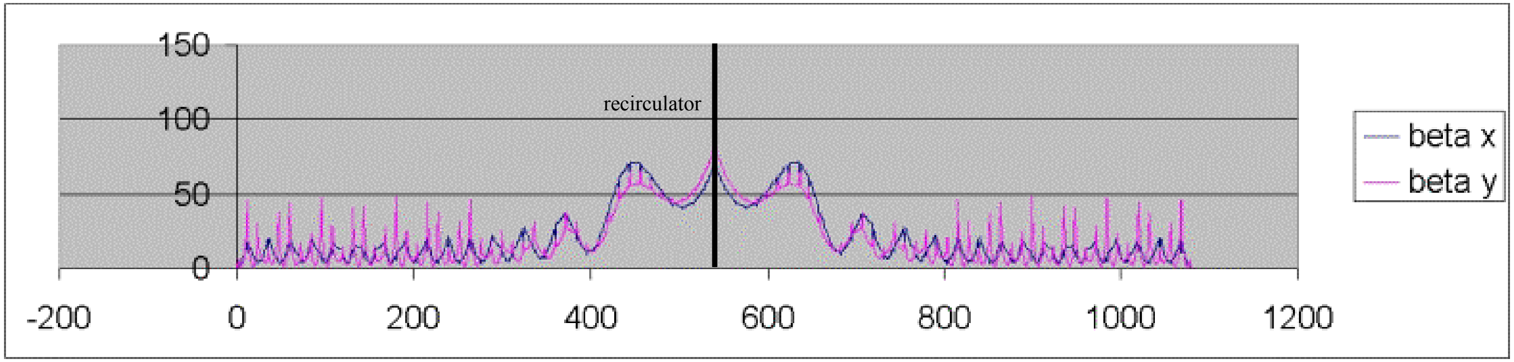
1 km, 10 MeV→10 GeV linac (111 MV/module), triplet focusing:



222 MV

High Accelerating Gradient

- Higher accelerating gradient very helpful in limiting beam envelope mismatch
  - Shortens linac
  - Increases excitation of front end (after 1st accelerating section) focusing elements, reducing mismatch on higher passes
  - ½ km 10 MeV→10 GeV linac (~222 MV/module), using triplets:



111 MV

High Accelerating Gradient, cont.

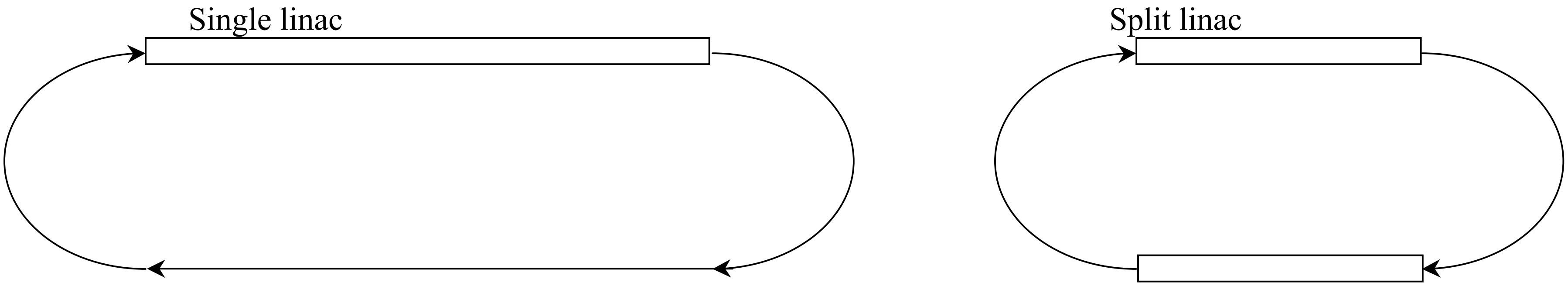
- "Focal Failure Factor"
  - Ratio of energies after 1st/before final accelerating section
  - Figure of merit for multipass mismatch – more descriptive than ratio of injected to final energies
  - For the two example machines:

Average Gradient	E after 1st	E before last	"FFF"
111 MeV/module	121 MeV	9889 MeV	~82
222 MeV/module	232 MeV	9778 MeV	~42

(compare to $E_{out}/E_{in} = 1000\ldots$)

"Inventive" Linac Topologies

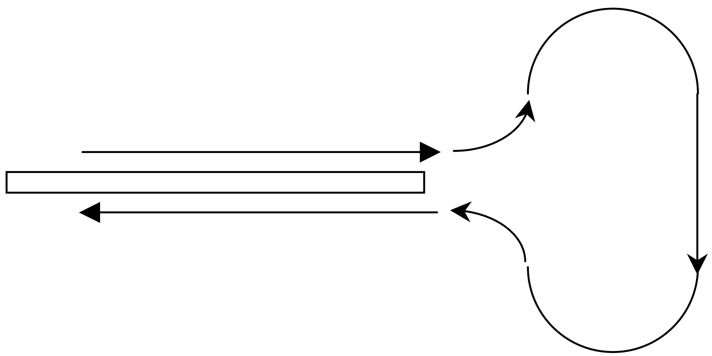
- Must transcend naïve topology to achieve adequate performance
- "Nominal" linac topologies:



- peak beam envelope ~ linac length on higher passes
- complex beam handling after linac/during reinjection, particularly for many passes

Topologies, cont.

- "counter-rotated" linac(s)

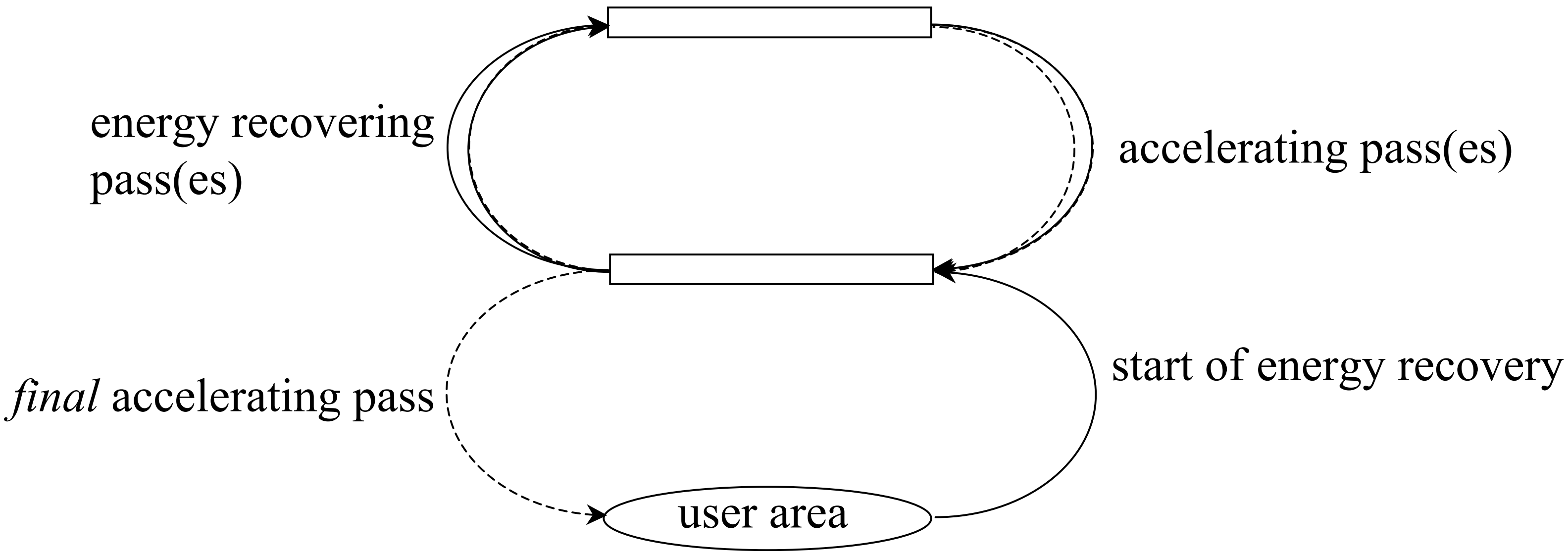


– recirculator directs 2nd pass (usually energy recovered) beam through linac antiparallel to 1st pass
  - ensures (in energy recovered system) exact match of focusing to energy throughout transport
  - beam-beam interaction can cause degradation of beam quality
  - requires specific cavity-to-cavity phase relation

More "Inventive" Linac Topologies

Split linacs allow at least two useful topological contortions:

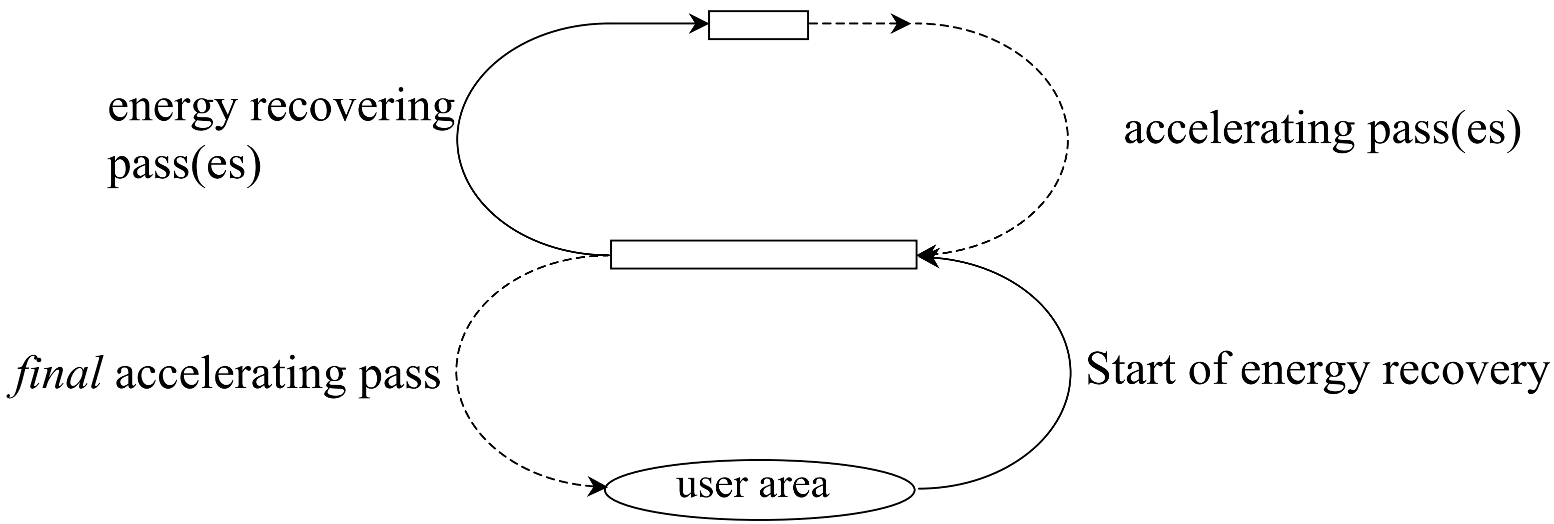
- "bisected" linacs



- modification of split linac reducing focal failure factor
- start energy recovery at *higher* energy linac
- requires an additional beam transport – approx. 1 pass equivalent
- allows extensible user area

Still More *"Inventive" Linac Topologies*

- "asymmetric" linac(s)



- modification of split/bisected linac topologies – allows further reduction of focal failure factor & linac length-induced mismatch
- 1st linac is "the problem" (weak front-end focussing, drift-like transport on higher passes) so make 1st linac *short*!
  - Shorter linac gives smaller β_{max}
  - Does degrade focal failure factor in 2nd linac with commensurate increase in β_{max}, but effect tolerable (esp. with 1st linac improvement)

Why it Matters ("Halo")

Performance of recirculated linacs may ultimately be limited by loss of "halo" – particles far from the beam core

- There is "stuff" in the beam not necessarily well described by core emittance, rms spot sizes, gaussian tails, *etc.*
- This "stuff" represents a small fraction ($<10^{-4}$? 10^{-5} ?) of the total current, but it can get scraped away locally, causing heating, activation, and damaging components
- Heuristically:
  - Higher current leads to more such loss
  - Smaller beam pipe results in greater loss
  - Bigger beam envelopes encourage increased loss

$$I_{loss} \propto I \times \frac{\beta}{a}$$

Phenomenology

- In CEBAF, BLM/BCMs induced trips ⇒ losses of ~1 μA out of 100 μA in 1 cm aperture where β ~100 m
  ⇒ proportionality const. ~ (1 μA/100 μA)x (0.01 m/100 m) ~ 10^{-6}
- In the IR Demo FEL, BLMs induce trips ⇒ losses of ~ 1 μA out of 5000 μA in 2.5 cm aperture where β ~5 m
  ⇒ proportionality const. ~ (1 μA/5000 μA)x (0.025 m/5 m) ~ 10^{-6}
- One might then guess

$$I_{loss} = 10^{-6} I \times \frac{\beta}{a}$$

which, in a 100 mA machine tolerating 5 μA loss in a 2.5 cm bore, implies you must have β ~ 1.25 m (*ouch!)*

Moral: There will be great virtue in clean beam and small beam envelope function values!

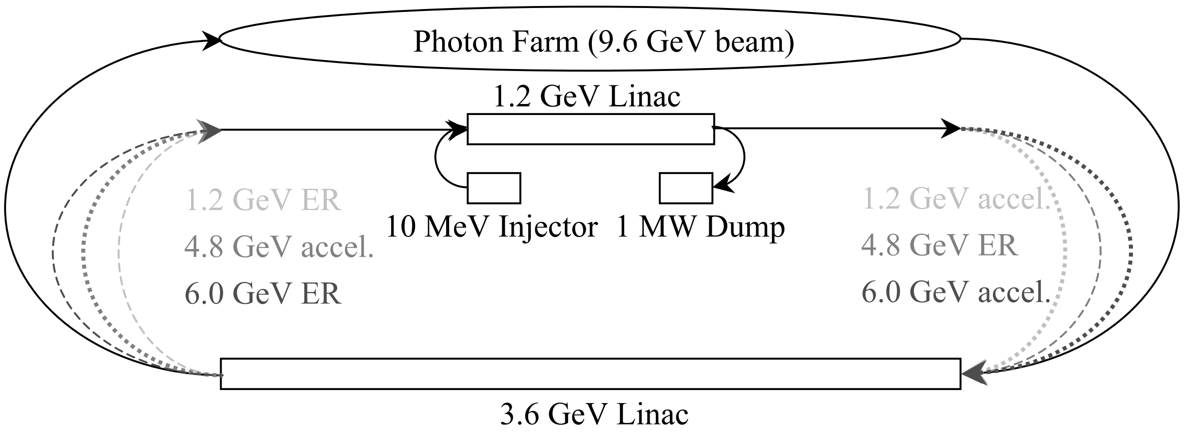
Example: An Energy-Recovered Linac for SR

- The "JLab Energy-Recovering Bisected Assymmetric Linacs", or JERBAL, is a 10 GeV driver for SR production

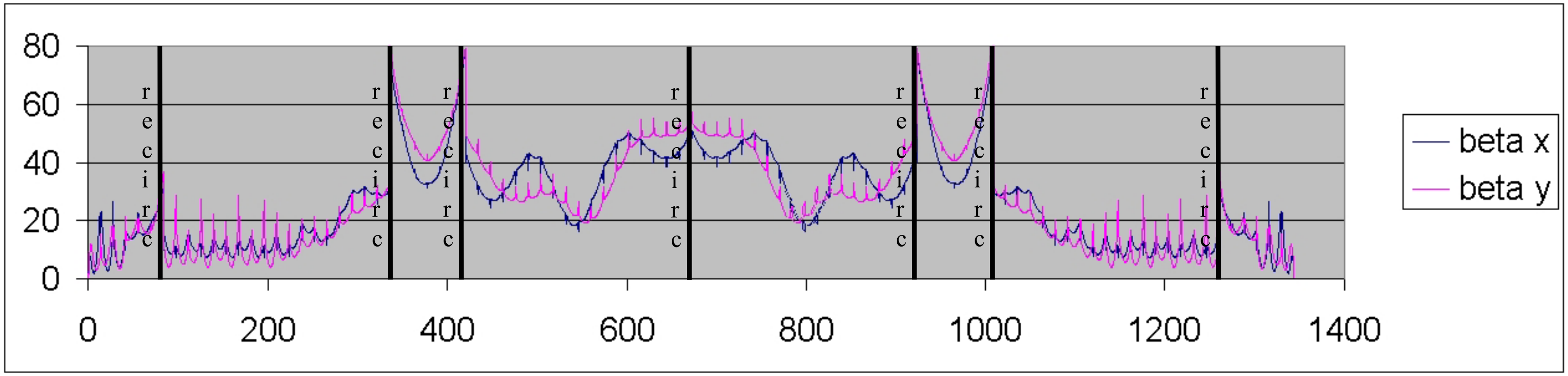
JERBAL Machine Parameters	
Machine Topology	4 pass (2 accelerating, 2 energy recovering) bisected asymmetric linac pair
Injection Energy	10 MeV
Final Energy	9.6 GeV
Single pass energy gain	Linac 1: 1.2 GeV Linac 2: 3.6 GeV
Linac accelerating structure	Linac 1: 6 cryomodules Linac 2: 18 cryomodules
Linac focussing structure	triplet, graded-gradient
RF Gradient	25 MV/m
Cryomodule structure	16 5-cell 1.497 GHz CEBAF cavities
Cryomodule energy gain	200 MeV
Current	100 mA
Beam power	Injected 1 MW Full 1 GW Dumped 1 MW

JERBAL, cont.

- Machine configuration:

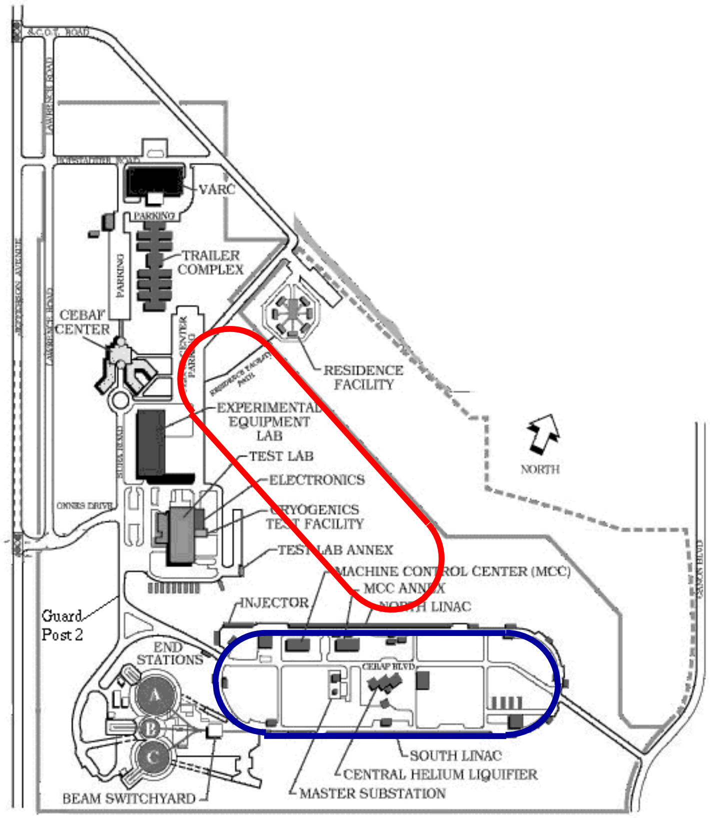


– Transverse optics



JERBAL, cont.

- Site plan



Machine Design Process

- Set # passes
  - Cost/performance optimization
- Characterize linac optics
  - a dominant feature of the machine behavior; once under control, the "rest" of the machine – the recirculator – can be specified
- Develop recirculator design

Recirculator Design Requirements (which of course apply to the full linac as well!)

- Preservation of beam quality & stability:
  - Space charge
  - BBU/other environmental impedance & wake effects
  - SR (incoherent & coherent) degradation of phase space
  - FEL/RF interaction
  - Beam loss instability during energy recovery
- Transverse phase space control, as in linac
  - Typically requires betatron matching, *e.g.,* into/out of linacs
  - Dispersion management; relates to:
- Manipulation of longitudinal dynamics
  - Path length control (pass-to-pass RF phase)
  - Momentum compaction control
- User support requirements
  - Extraction systems
  - Production of multiple beams
  - Configuration of SR properties

Recirculator Features

It is often useful to employ a functionally modular design philosophy: the recirculator consists of a sequence of beam line modules, each with a specific & more or less self-contained function

Examples of functions:

- Beam separation/recombination
  - Dispersion management
- Transverse (betatron) matching
  - Beam envelope, phase advance management (e.g., for BBU)
- Arcs
  - Bend, SR production/management, longitudinal matching
- Utility transport
  - path length adjustment,
  - extraction,
  - insertion devices
  - interaction regions

Conclusions, Advice, Polemic

- Keep gradients high, linacs short, envelopes and dispersions low.
- Use lots of symmetry and periodicity.
- When basing decisions on cost, base them on cost to the taxpayer, not your own project budget
  - don't skimp on construction costs only to blow the commissioning budget
  - Take the long view – optimize cost from groundbreaking to 1st PRL, not just within a project phase
- Remember – as a machine designer, the operator is your best friend. She knows what works and what doesn't. Listen!!!
- Spend time driving beam. Suffering breeds greatness.

Typical Recirculator Configuration

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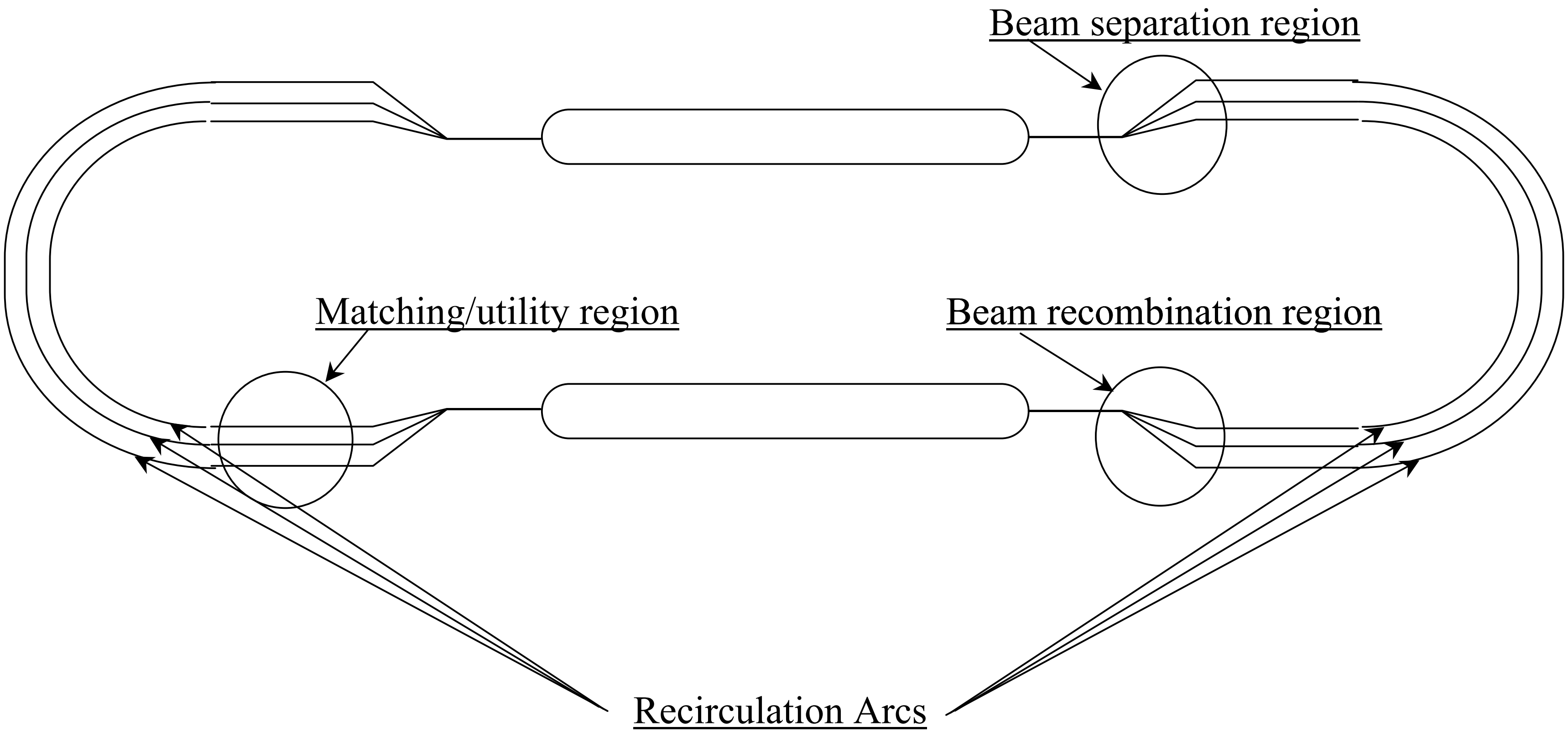
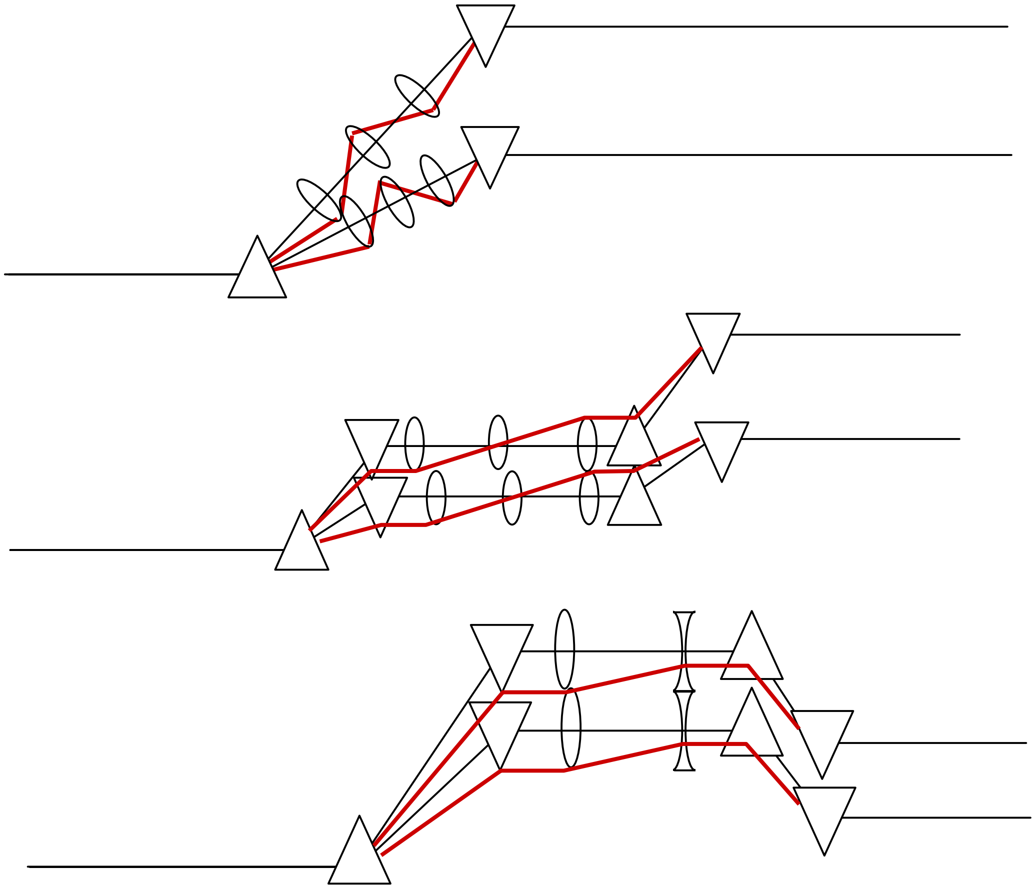


Beam Separation & Recombination

- The recirculator must
  - accommodate multiple beams at significantly different energies, or
  - separate the beams, transport each energy individually and recombine for further acceleration
- Typically (though not always – *e.g.,* microtrons) simpler to separate beams
- Design choices:
  - H or V split
  - Dispersion suppression or not (“yes” is simpler – “functional modularity” – and helps maintain beam quality (SR))
    - Method of dispersion suppression

Spreader styles



Simple, but requires strong focusing & is error sensitive

More complex & congested but focusing weaker, less error sensitive, more robust

Least congested, weakest focussing, most robust, but requires the most space

Betatron matching

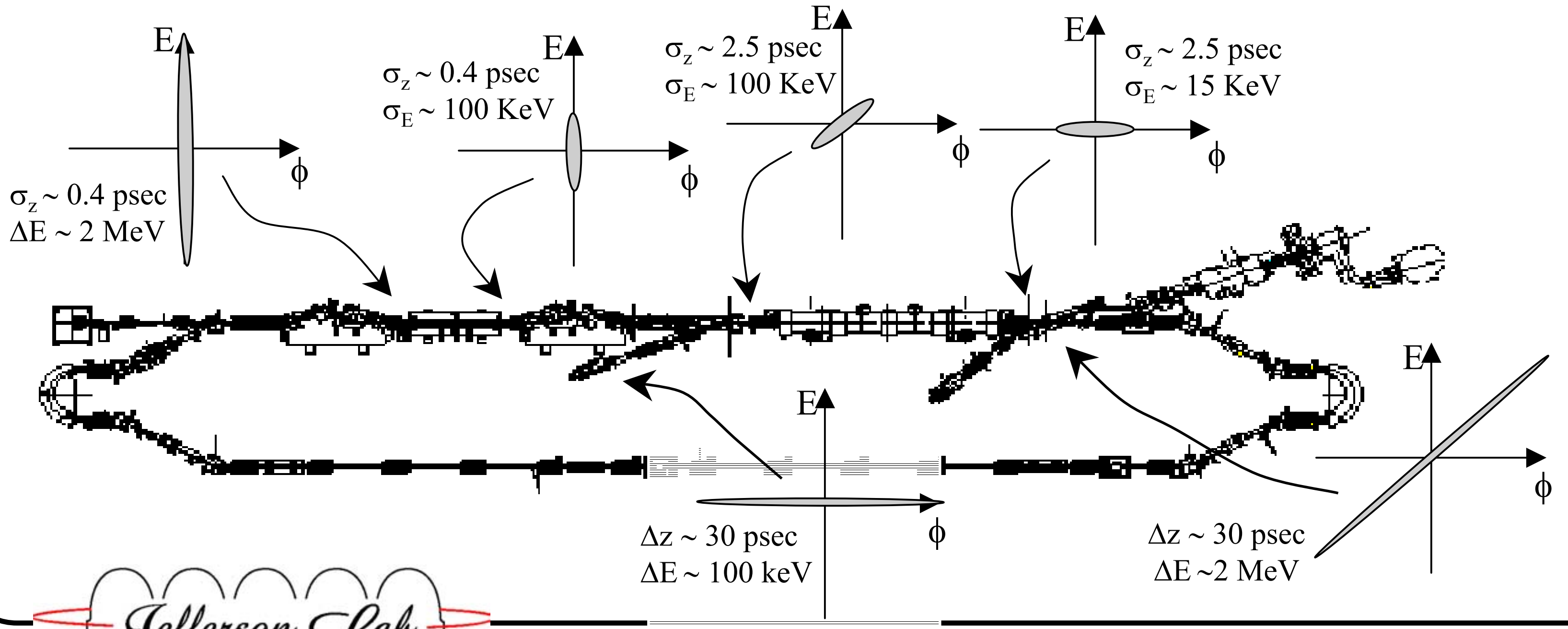
- As in linac(s), beam envelope control is a significant performance issue
  - Made more manageable by beam separation; only 1 beam to deal with at a time
- Use quad telescopes within each recirculator transport line to match beam envelopes from linac to recirculator and from recirculator back to linac
  - gives best behavior in recirculator
  - allows some independent control over transverse optics in linac on each pass (through adjustment of reinjection condition)
  - allows control of turn-to-turn phase advance (BBU control)
  - can be used to compensate uncontrolled lattice errors
    - "beam envelopes" and "lattice functions/transfer matrices" are distinct objects in a beam transport system!

Arcs

- Used to transport beam “around the corner”
- Provided means of longitudinal phase space management
  - IR Demo provides example
  - Compaction management
- Can be source of beam quality degradation
  - Synchrotron radiation
  - CSR

IR Demo Longitudinal Matching/Energy Recovery

- Requirements on phase space:
  - 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



Why we need the "right" T_{566}

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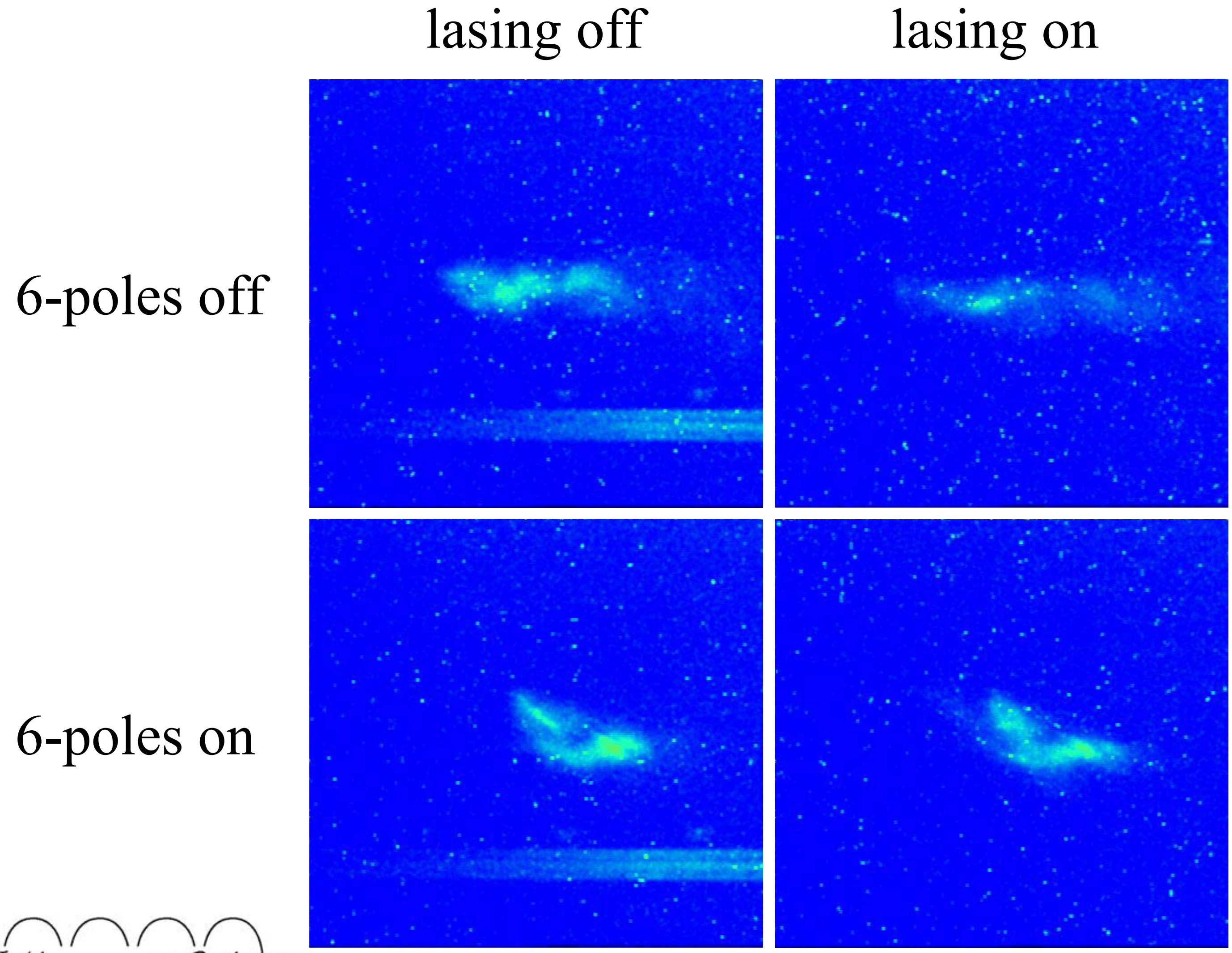
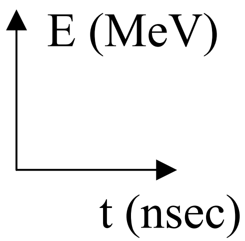
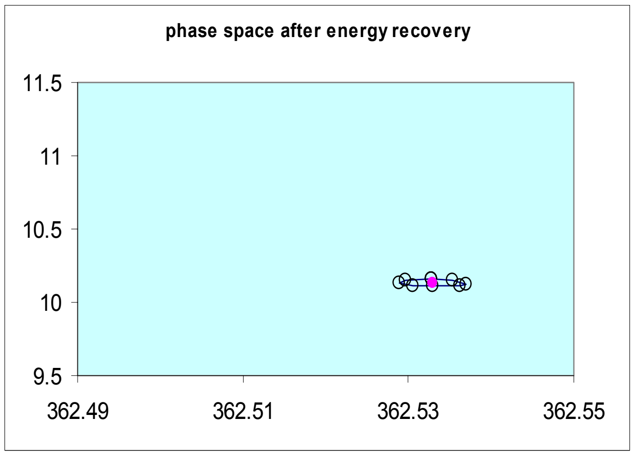


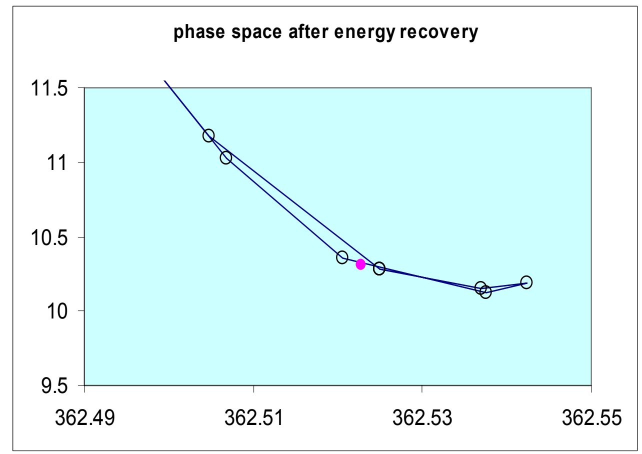
Phase space at 10 MeV Dump



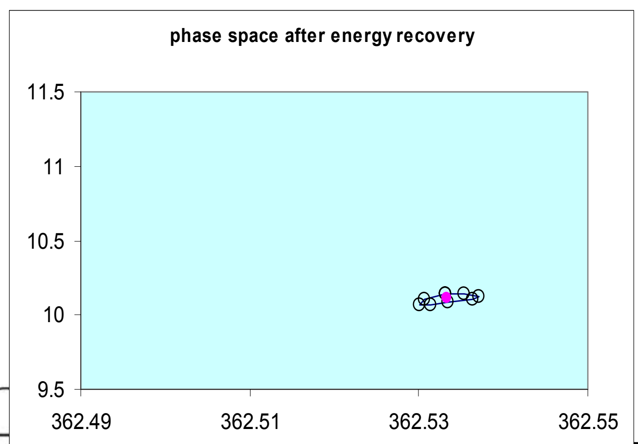
lasing off | lasing on

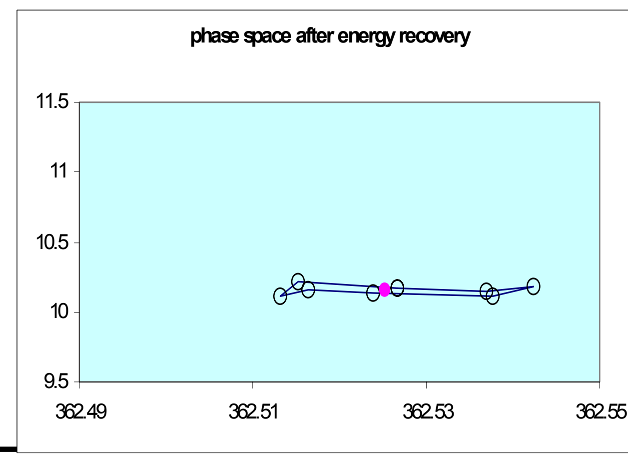
6-poles off





6-poles on





Momentum Compaction Management

- "Momentum Compaction" (M_{56}) is a handle on longitudinal phase space given to you by the lattice

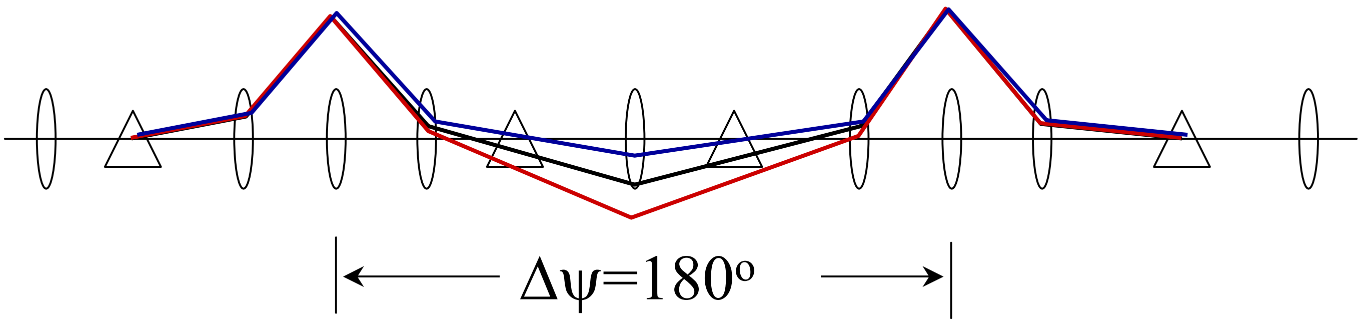
$$\delta l = M_{56}\, \delta p/p = \int \eta\, d\theta\, \delta p/p$$

(warning – this is NOT the same as the storage ring α_p)

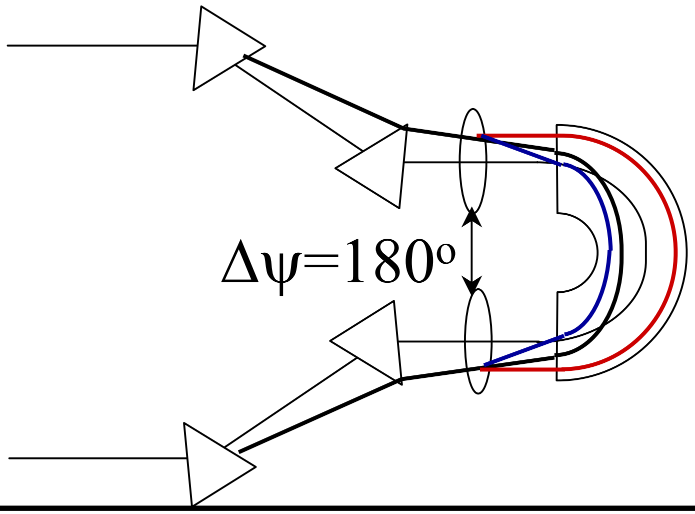
- By changing M_{56} you alter the phase energy correlation in longitudinal phase space (the tilt of the bunch) and can thereby "match"
  - Consider M_{56} to be a longitudinal drift; you're changing its length
- Alter M_{56} (T_{566}, … etc.) by altering the dispersion (second order dispersion, … etc.) pattern

Momentum Compaction Management Examples

- In CEBAF (one superperiod):

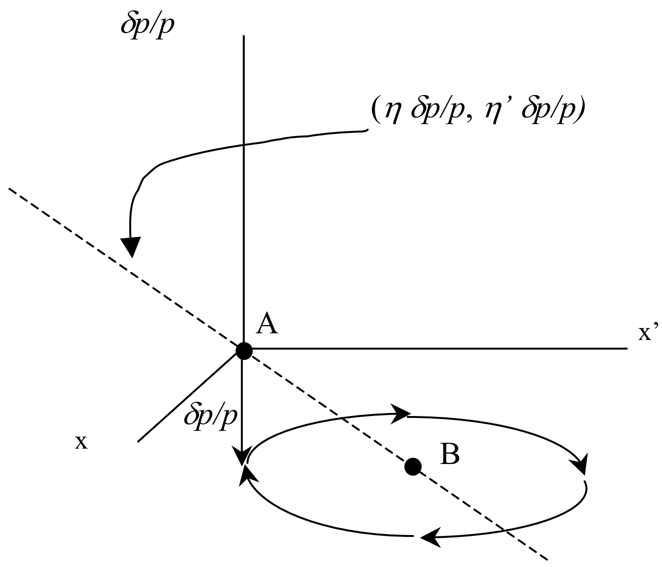


- In the IR Demo (one end-loop):



Quantum Excitation/Synchrotron Radiation

- A mechanism for phase space degradation:



–an on-momentum electron at origin of phase space (A)

–emits photon at dispersed location, energy shifts by δp/p

–electron starts to betatron oscillate around dispersed orbit (B)

–emittance grows

Estimate of degradation

- Estimate of effect:

$$\sigma_E^2 = 1.182\times 10^{-33}\ \mathrm{GeV^2 m^2}\ \frac{\gamma^7}{\rho^2}$$

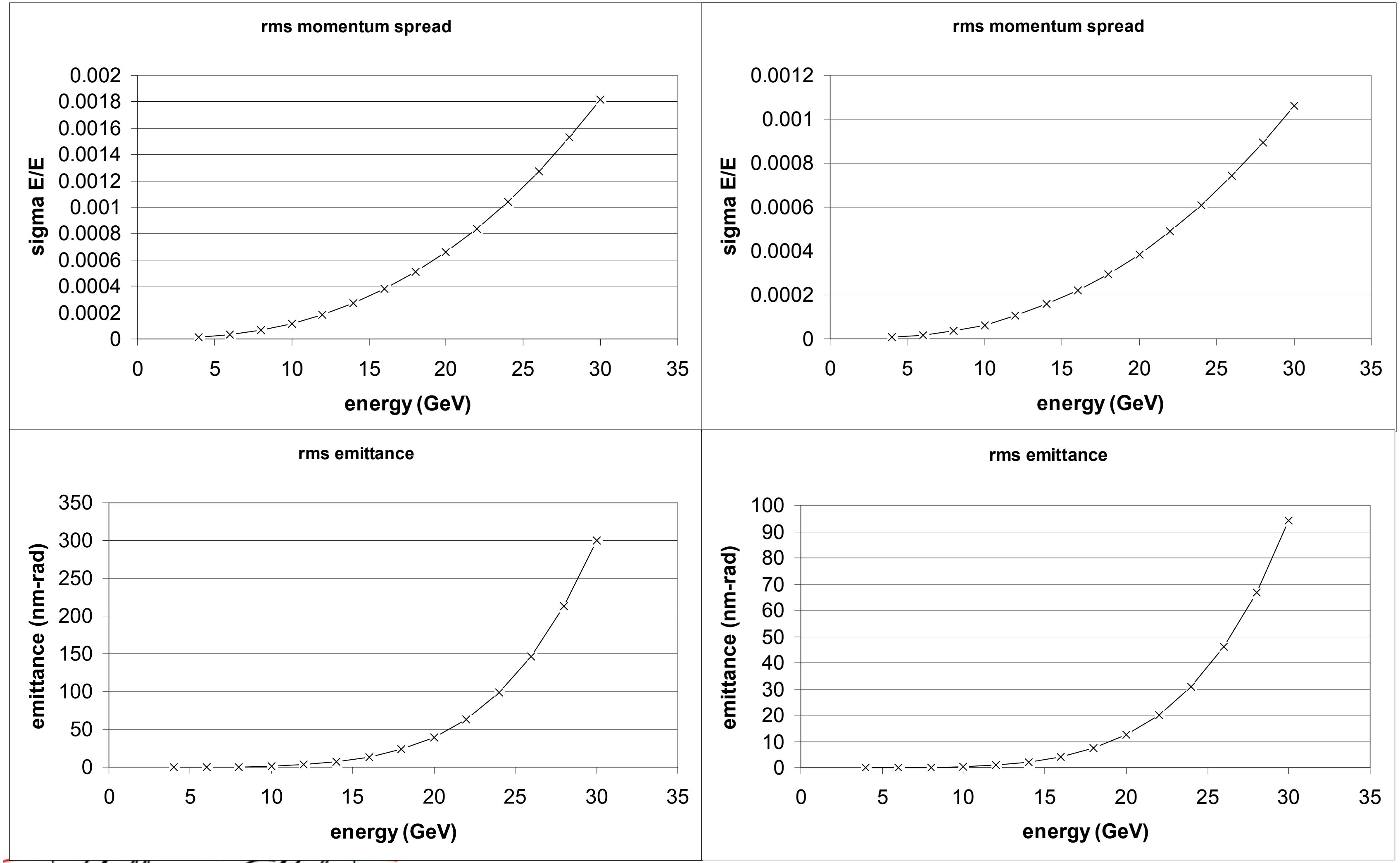
with

$$\Delta\varepsilon = 1.32\pi\times 10^{-27}\ \mathrm{m^2-rad}\ \frac{\gamma^5}{\rho^2}\left\langle H\right\rangle$$

$$\left\langle H\right\rangle = \frac{1}{L}\int_{bends} ds\left(\frac{1}{\beta}\right)\left\{\left[\eta^2 + \left(\beta\eta' - \frac{1}{2}\beta'\eta\right)^2\right]\right\}$$

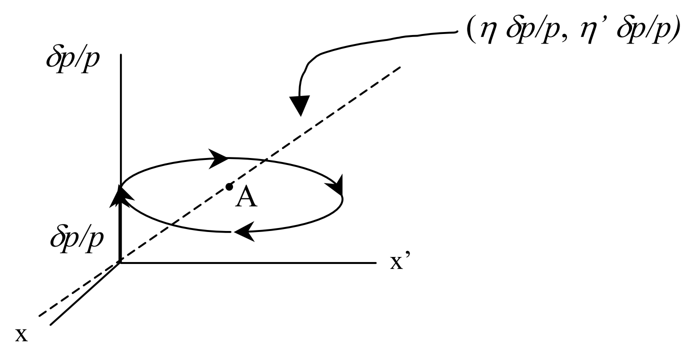
  - "just like storage rings" – except that within a recirculator arc there's no damping (it happens in the linac – adiabatically) and so there's not an equilibrium
  - limit effect by keeping dispersion, beam envelopes under control

Example of magnitude: CEBAF, SUPERCEBAF

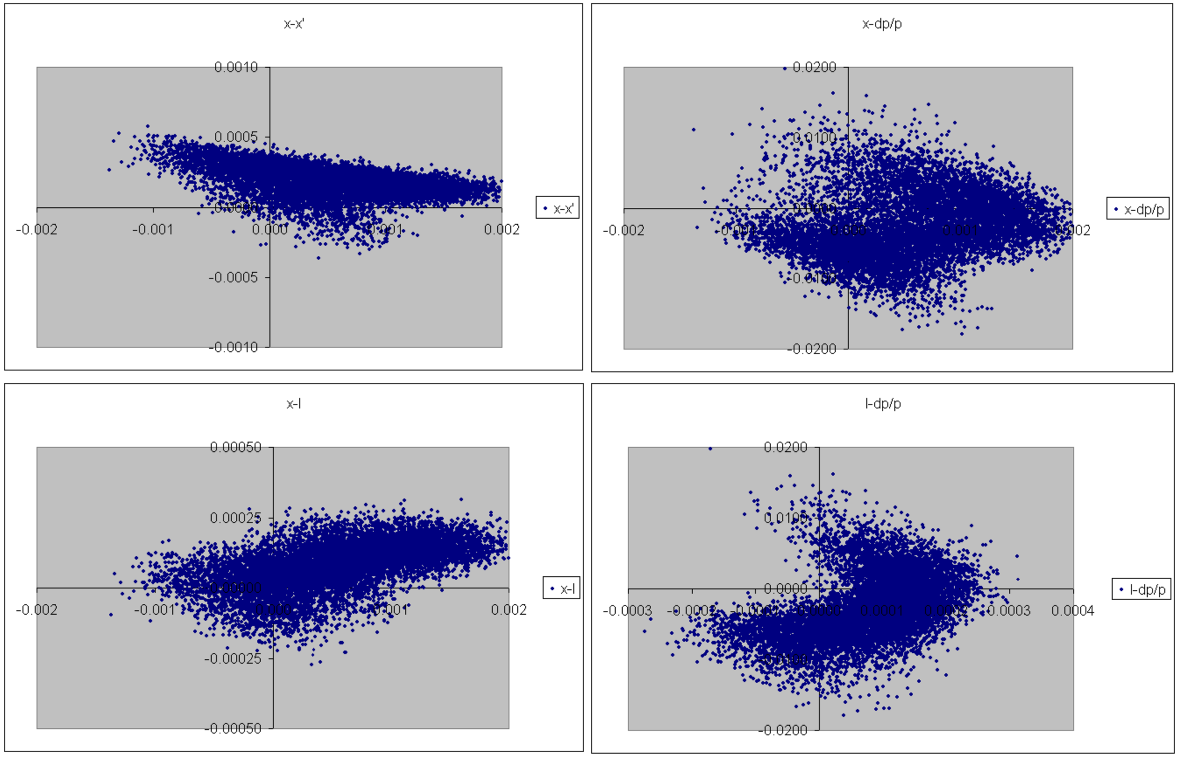


Coherent Synchrotron Radiation

- Another mechanism for phase space degradation:
  - electromagnetic field radiated from tail of bunch during bending accelerates energy of head
  - accelerated electron at head begins to betatron oscillate around dispersed orbit, emittance grows



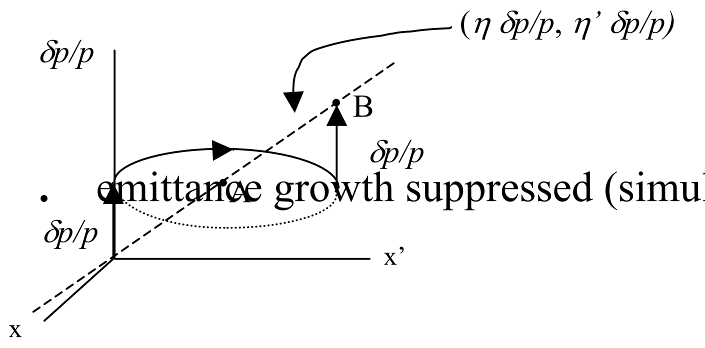
Coherent Synchrotron Radiation In IR Upgrade

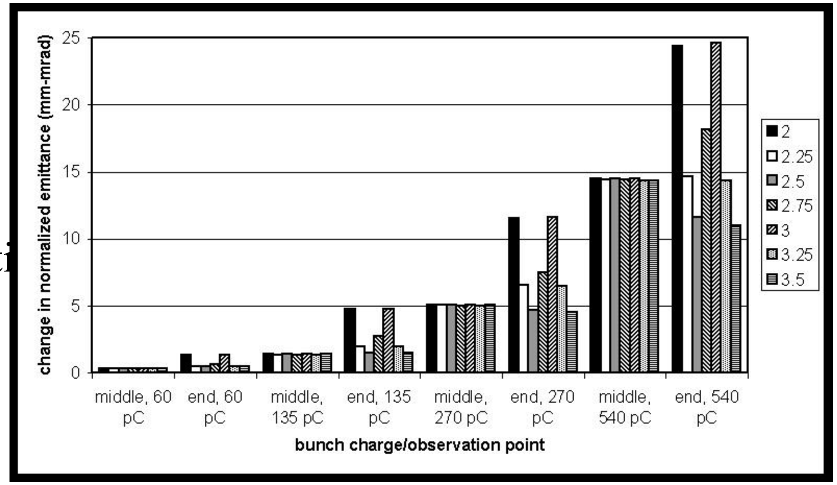


Images of initially Gaussian phase space after simulated transport through IR Upgrade

Coherent Synchrotron Radiation - Suppression

- Effect is *coherent* – so can be suppressed
  - image bunch in 6-d phase space from radiation point to homologous downstream point
    - same envelopes, dispersion, half betatron wavelength away with isochronous transport
  - distribution the same ⇒ radiation pattern identical ⇒ head of bunch gets *same* energy shift – *and move ONTO the dispersed orbit!*
  - emittance growth suppressed (simulati





Utility transport

- Extraction
  - CEBAF multibeam production
- Path length control
  - CEBAF doglegs
  - FEL path length adjustment
- Use of insertion devices
  - FEL wiggler insertion
- Interaction Regions

Single Particle Optics for Recirculating Linacs

- The Naïve Recirculator
  - Machine description
  - Innocence Endangered: Design/performance issues
    - # passes
    - Multipass focussing in linacs
    - Halo
    - JERBAL
    - Transverse/longitudinal phase space control; matching, path length & compaction management
    - Instabilities
      - BBU, other impedance driven effects, FEL/RF interaction, beam loss instability during energy recovery
    - Beam quality degradation
      - Space charge, synchrotron radiation, CSR, environmental impedances

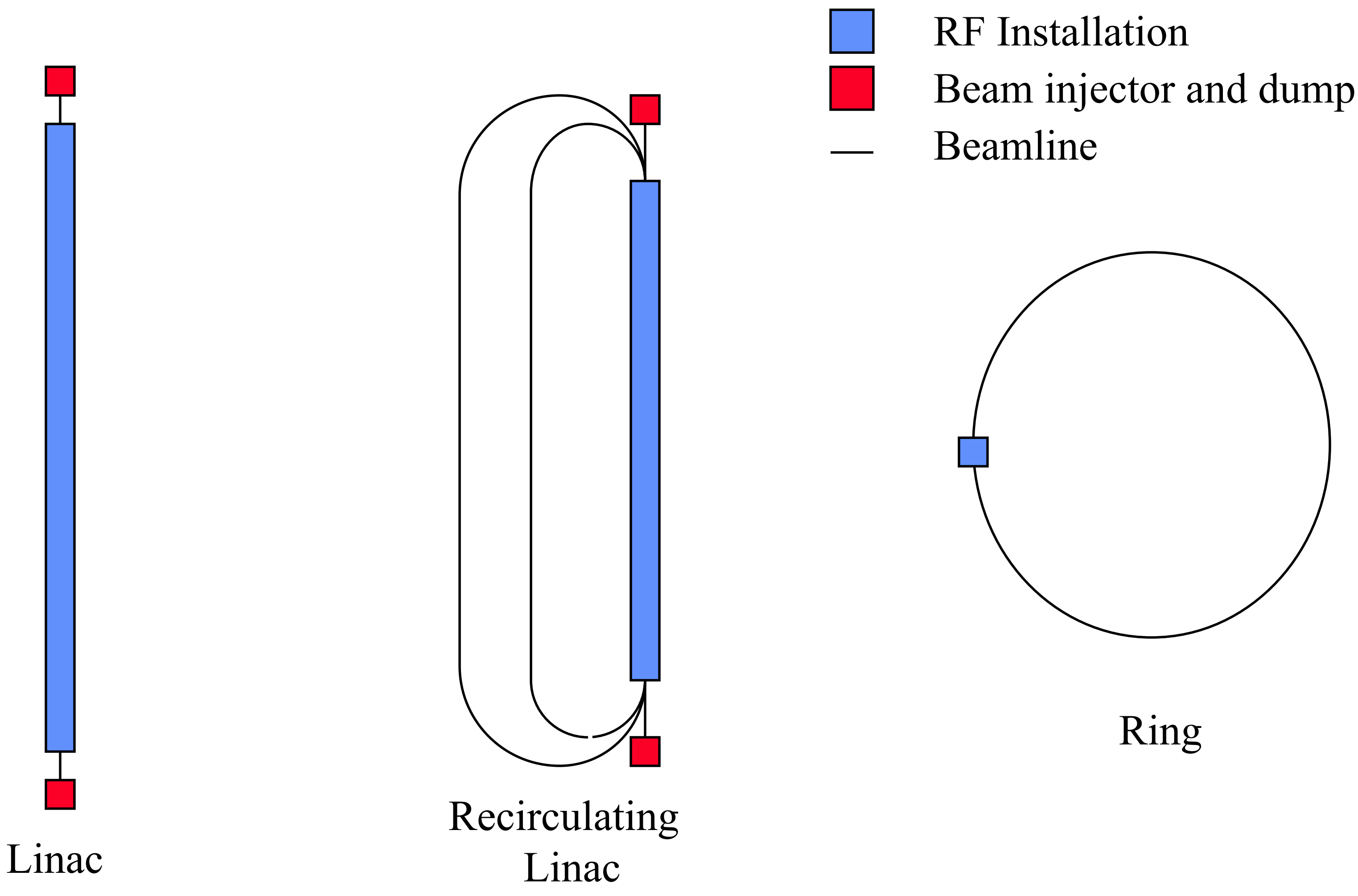
- Machine design process
  - Set pass count
  - Characterize linac optics
  - generate arc design
- Cost optimization - # passes, single/split linacs
- Multipass focussing effects
  - Types of focussing:
    - Constant gradient
    - Constant focal length
    - Graded gradient
  - Energy ratio (E_{in}:E_{out}) limitations and the virtue of high accelerating gradient; focal failure factor
  - Bisected linac topology

- Recirculation arc design
  - Functional modularity
  - Beam separation (extraction)/recombination (reinjection) geometry
    - Single step
    - Staircase
    - Overshoot
  - Beam quality preservation
    - Incoherent synchrotron radiation control
      - Energy spread ~g5/r2
      - Emittance excitation ~ <H>g7/r2, H ~ b2, h2
    - CSR control & compensation (e.g ½ betatron wavelength correction in IR Demo; don't squeeze entire phase at one time; keep betas, etas small)
    - Space charge control (don't squeeze entire phase space at one time)
  - Matching
    - Transverse – linac to recirculator, vice versa
    - Longitudinal phase space management
      - Orthogonal knobs useful: e.g. IR Demo – path length, M_{56}, T_{566} all decoupled & more or less separate from transverse

Talk Outline

- Recirculating Linacs Defined and Described
- Review of Recirculating SRF Linacs
  - University of Illinois
  - Darmstadt
  - CEBAF
- Summary of Present State-of-the-art
- Energy Recovering Linacs
  - Stanford SCA
  - CEBAF Beam Recirculation Experiment
  - Jefferson Lab IRFEL
- Future Possibilities
  - High Energy Electron Cooling (BNL)
  - Electron-Ion Colliders (BNL, JLAB)
  - Recirculated Linac Light Sources (Cornell/JLAB, BNL, Berkeley)
  - Higher Power Lasers
- Conclusions

Accelerator Types



Comparison: Linacs/Storage Rings

- **Advantage Linacs**

Total transit time is quite short

Emittance dominated by source emittance and emittance growth down linac

Beam polarization "easily" produced at the source, switched, and preserved

Beam is easily extracted. Utilizing source control, flexible bunch patterns possible

Long undulators are a natural addition

Bunch durations can be SMALL

Comparison Linacs and Storage Rings

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- **Advantage Storage Rings**

  Up to now, the stored average current is much larger

  Very efficient use of accelerating voltage

  Technology well developed and mature

- **Disadvantage of Storage Rings**

  Technology well developed and mature

  There's nothing you can do about synchrotron radiation damping and the emittance and bunch length it generates

Why Recirculate?

- A renewed general interest in beam recirculation has been driven by the success of Jefferson Lab’s high average current FEL, and the realization that it may be possible to achieve beam parameters “unachievable” in either linacs without recirculation or storage rings, separately.

  – Easily understood example: Recirculated Linac Light Source. In a “typical” synchrotron light source the beam power is (100 mA)(5 GeV)=500 MW. For ecomonic and beam dumping reasons, a non-recovered linac is not a suitable driver (500 MW is a third of a nuclear plant!). A recirculated linac arrangement that is energy recovered (beam is both accelerated and decelerated in the same RF structures) overcomes this limitation. On the other hand, pulse lengths of order 100 fsec and small emittance are demonstated in recirculated linacs. Such parameters are “impossible” (for the full beam current!) at a storage rings.

  – The limits, in particular the average current carrying capacity of possible designs, are unknown and may be far in excess of what the FEL can do!

Power Multiplication Factor

- An advantage of energy recovered recirculation is nicely quantified by the notion of a power multiplication factor:

$$k = P_{b,ave} / P_{rf}$$

where P_{rf} is the RF power needed to accelerate the beam

- By the first law of thermodynamics (energy conservation!) $k < 1$ in any linac not recirculated. Beam recirculation with beam deceleration somewhere is necessary to achieve $k > 1$

- If energy IS very efficiently recycled from the accelerating to the decelerating beam

$$k >> 1$$

High Multiplication Factor Linacs

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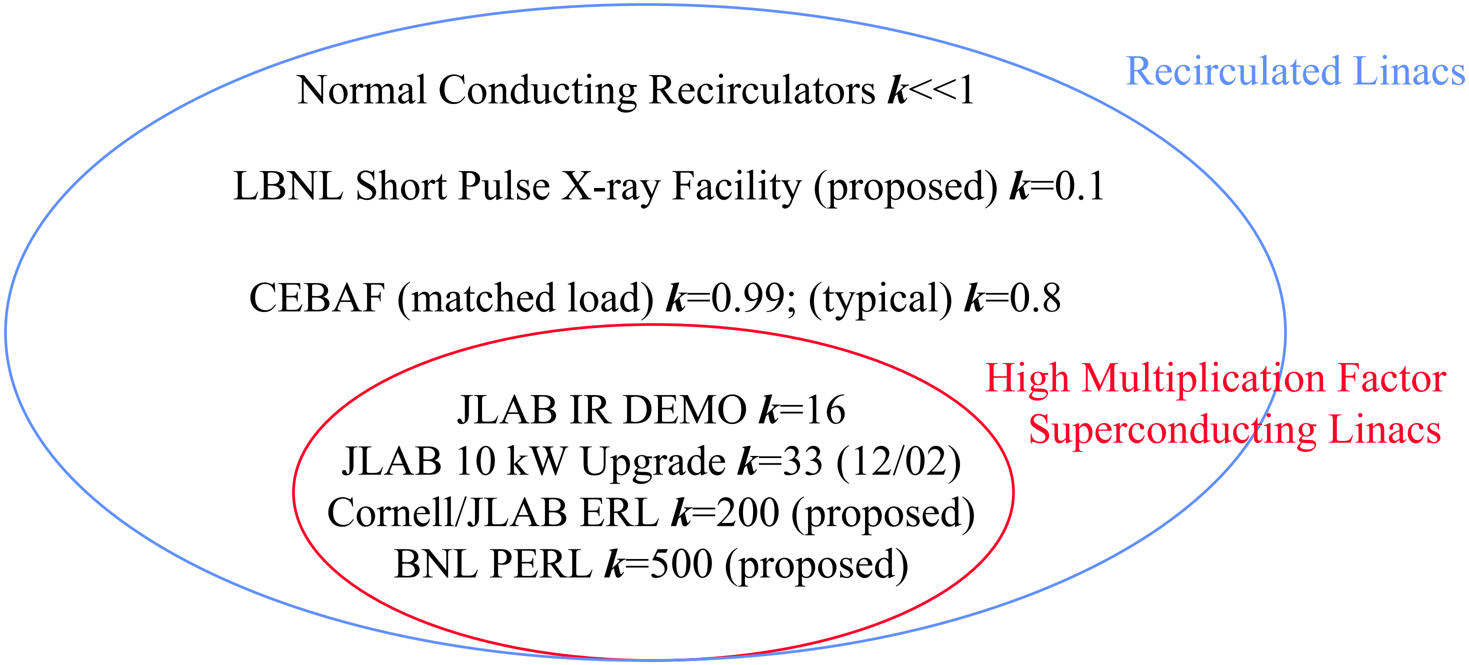

Will use the words “High Multiplication Factor Linac” for those designs that feature high k.

Comparison Accelerator Types

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Parameter	High Energy Electron Linac	High *k* Recirculated Superconducting Linac	Ring
Accelerating Gradient[MV/m]	>50	10-20	NA
Duty Factor	<1%	1	1
Average Current[mA]	<1	5 going to 100	1000
Average Beam Power[MW]	0.5	0.25 going to 700	3000
Multiplication Factor	<1	13 going to 200	1000
Normalized Emittance[mm mrad]	1	1	4
Bunch Length	100 fsec	100 fsec	20 psec

Best results by accelerator type

Upsides to Beam Recirculation

- Possibilities to reuse same RF installation to accelerate the beam many times.
- Possibilities, utilizing energy recovery, to increase the average current being accelerated, without necessarily increasing the size and capital and operating costs of the RF installation.
- Possibilities of making the beam power multiplication factor much greater than 1, and at a level approaching, and maybe even exceeding (if we're lucky!), that of storage rings.
- By comparison to storage rings, the possibility of beams with smaller emittance for the same average current, and with much greater flexibility and control in the longitudinal distribution delivered to the users.

Challenges for Beam Recirculation

- Additional Linac Instability
  - Multipass Beam Breakup (BBU)
  - Observed first at Illinois Superconducting Microtron
  - Limits the average current at a given installation
  - Made better by damping HOMs in the cavities
  - Best we can tell at CEBAF, threshold current is around 20 mA, similar in the FEL
  - Changes based on beam recirculation optics
- Turn around optics tends to be a bit different than in storage rings or more conventional linacs. Longitudinal beam dynamics gets coupled strongly to the transverse dynamics.
- HOM cooling will perhaps limit the average current in such devices.

Challenges for Beam Recirculation

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- High average current source to provide beam
  - Right now, looks like a good way to get there is with DC photocathode sources as we have in the Jefferson Lab FEL.
  - Need higher fields in the acceleration gap in the gun.
  - Need better vacuum performance in the beam creation region to reduce ion back-bombardment and increase the photocathode lifetimes.
  - Goal is to get the photocathode decay times above the present storage ring Toushek lifetimes. (In contrast to what some of the advocacy literature one reads might lead you to believe, this goal may NOT be so easy to achieve!)

- Beam dumping of the recirculated beam can be a challenge.

Recirculating SRF Linacs

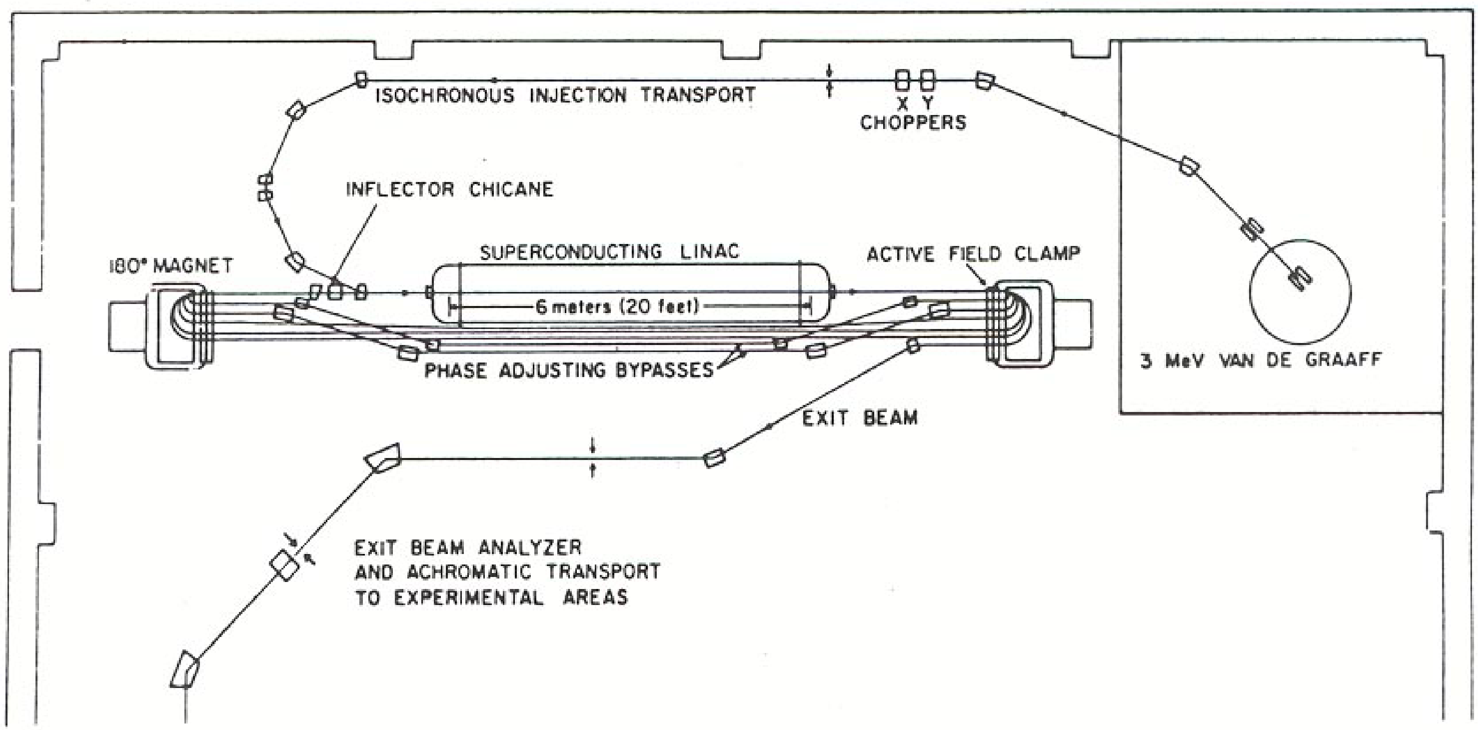
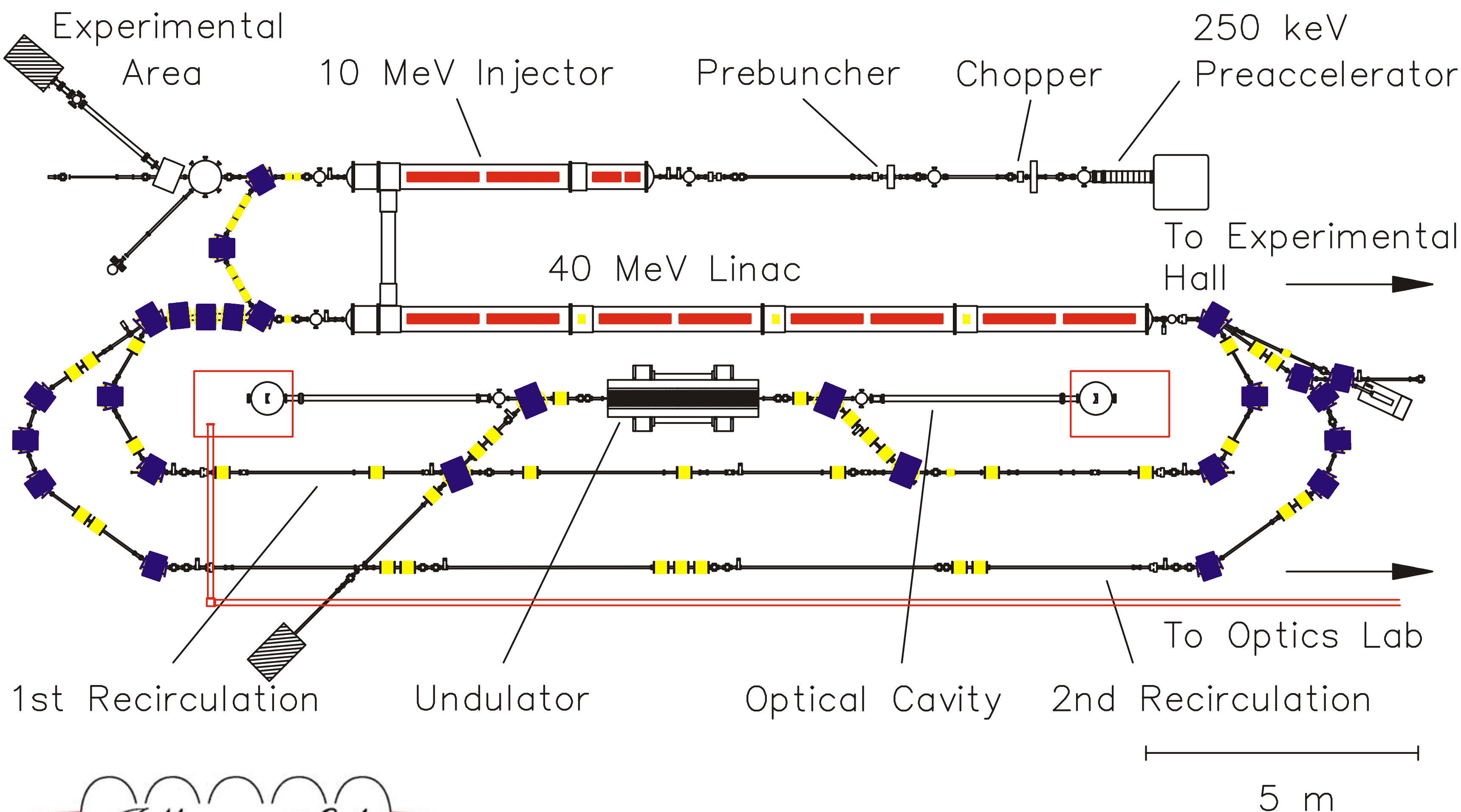
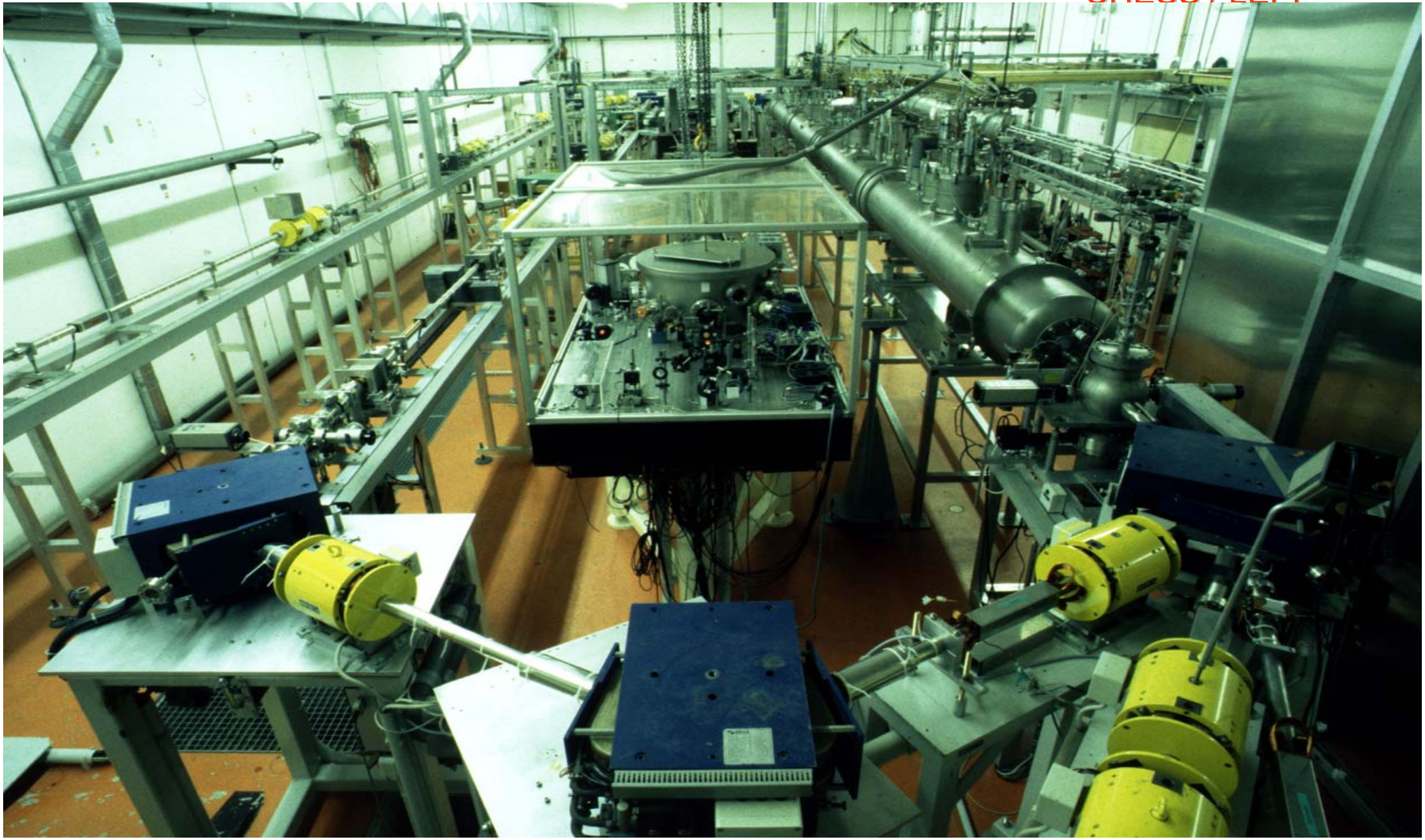


Figure 5.3 The second Illinois superconducting race-trace microtron, MUSL-2 (Axel *et al.*, 1977; © 1977 IEEE)

Layout of S-DALINAC (Darmstadt)



S-DALINAC



S-DALINAC Beam Parameters

Experiments	Energy (MeV)	Current (μA)	Mode	Time (h)
(γ,γ')	2.5 – 10	50	3 GHz, cw	6400
LEC, PXR	3 – 10	0.001 - 10	3 GHz, cw	2100
HEC, PXR	35 – 87	0.1	3 GHz, cw	800
(e,e'), (e,e'x)	22 – 120[1)]	5	3 GHz, cw	7800
FEL	30 – 38	2.7 A_{peak}	10 MHz, cw	2900
				Σ 20000

1) Dutycycle 33%

Resolution: ΔE_{FWHM} = 50 keV @ 85 MeV, $\Delta E/E = \pm 3 \cdot 10^{-4}$

Superconducting 20-Cell Cavity

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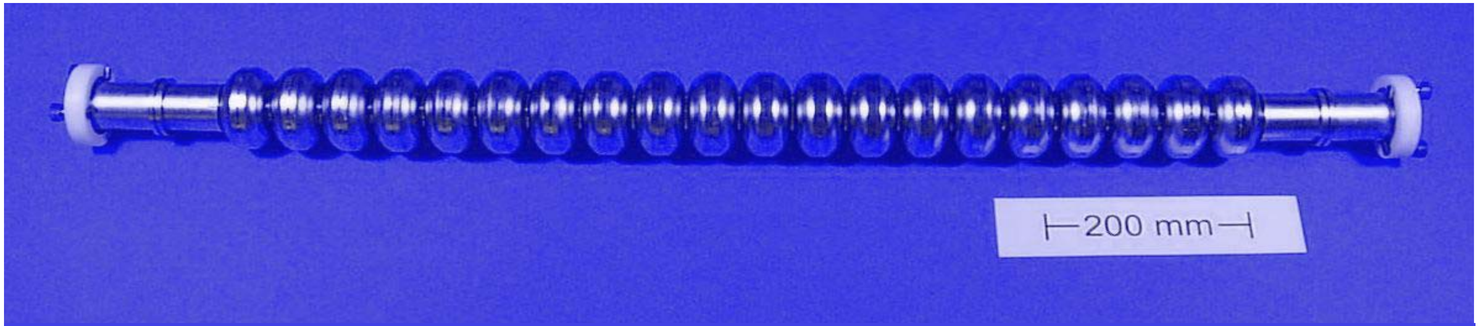

Material:	Niobium (RRR=280)
Frequency:	3 GHz
Temperature:	2 K
Accelerating Field:	5 MV/m
Q_0/Q_L:	$3\cdot10^9$ / $3\cdot10^7$
$\Delta f/\Delta l$:	500 Hz/μm

The CEBAF at Jefferson Lab

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

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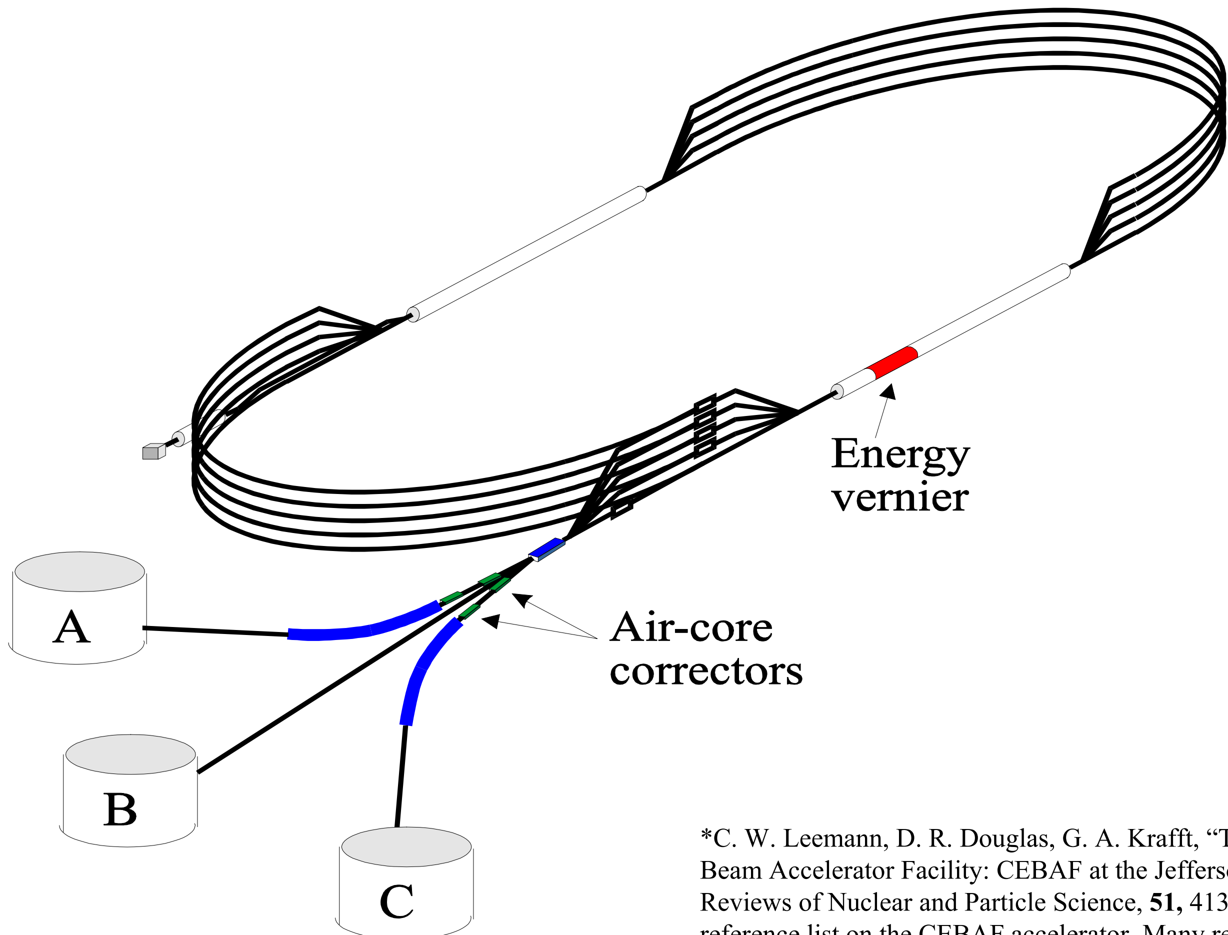
CEBAF Accelerator Layout*

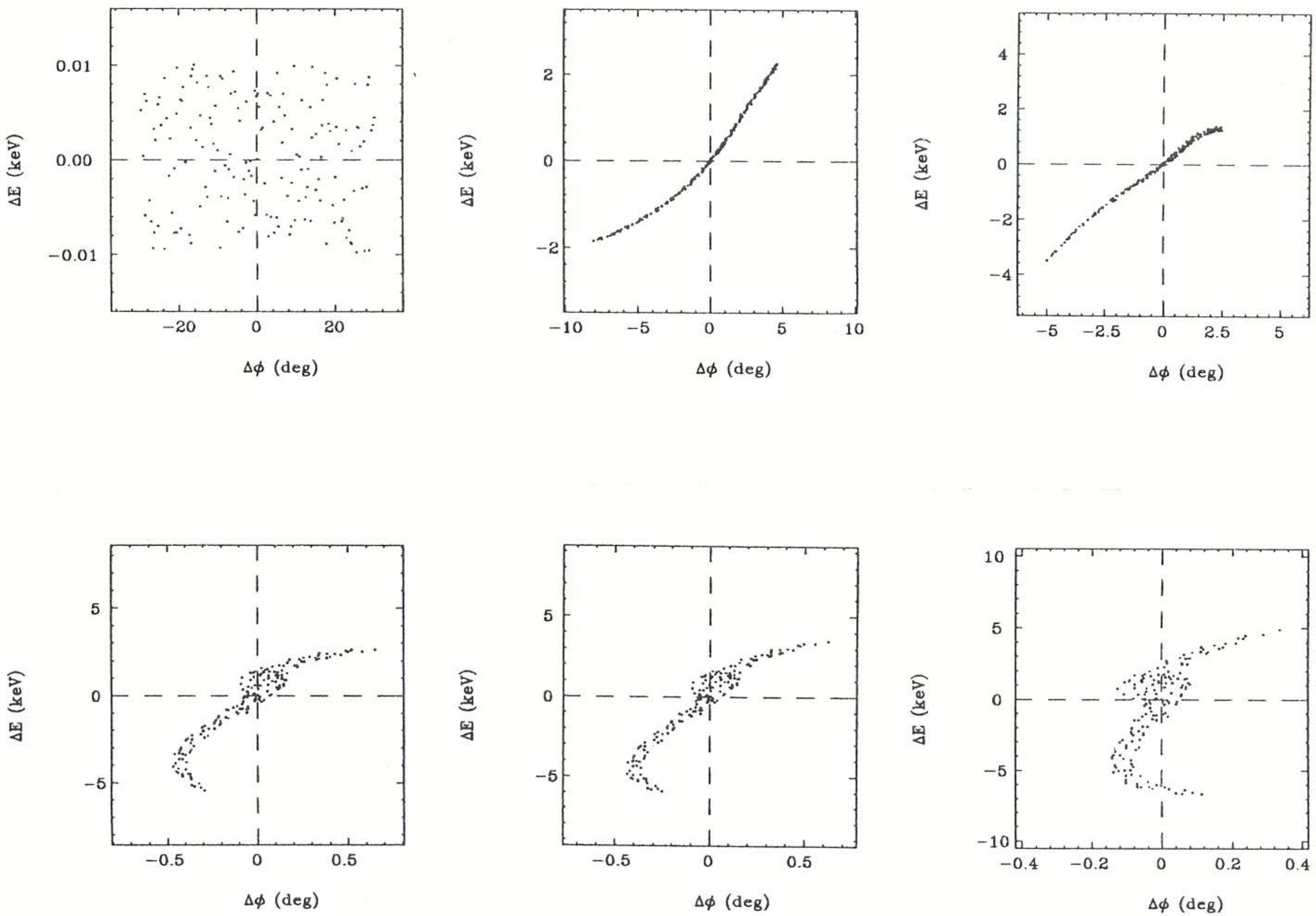


*C. W. Leemann, D. R. Douglas, G. A. Krafft, "The Continuous Electron Beam Accelerator Facility: CEBAF at the Jefferson Laboratory", Annual Reviews of Nuclear and Particle Science, **51,** 413-50 (2001) has a long reference list on the CEBAF accelerator. Many references on Energy Recovered Linacs may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

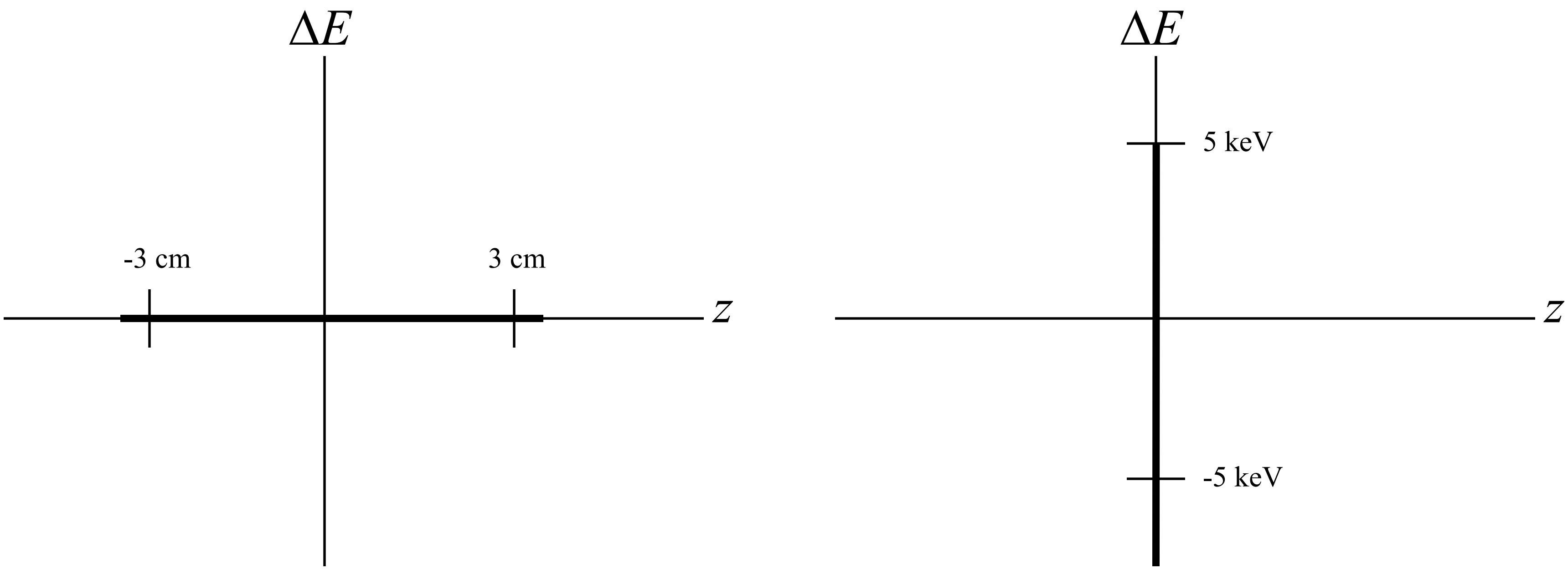
CEBAF Beam Parameters

Beam energy	6 GeV
Beam current	A 100 μ A, B 10-200 nA, C 100 μ A
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 - CORNELL UNIVERSITY CHESS / LEPP

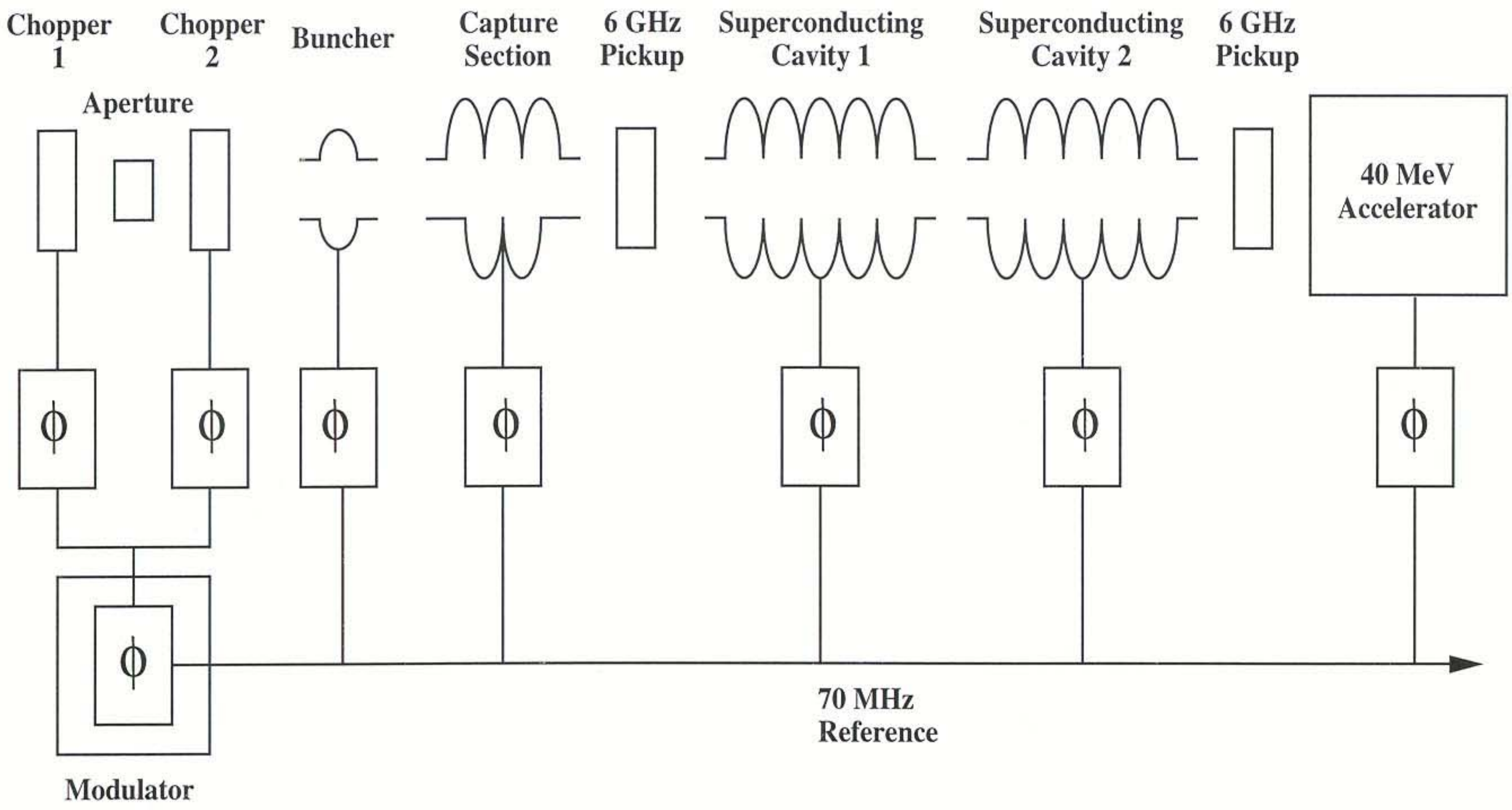


Phase Space from CEBAF Bunching



>100 bunching factor!

Schematic of CEBAF Injector Phase Distribution



Phase Transfer Technique

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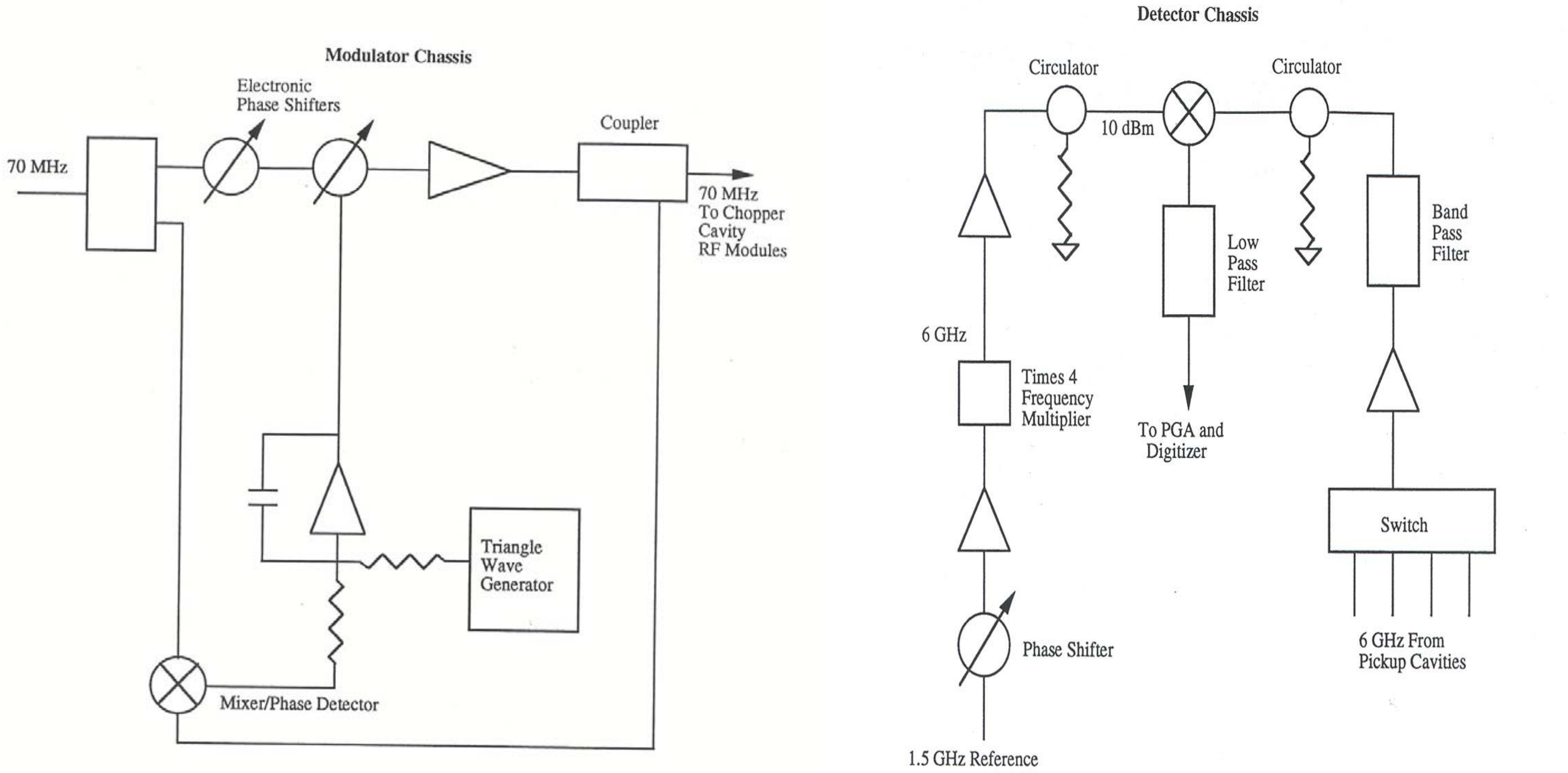
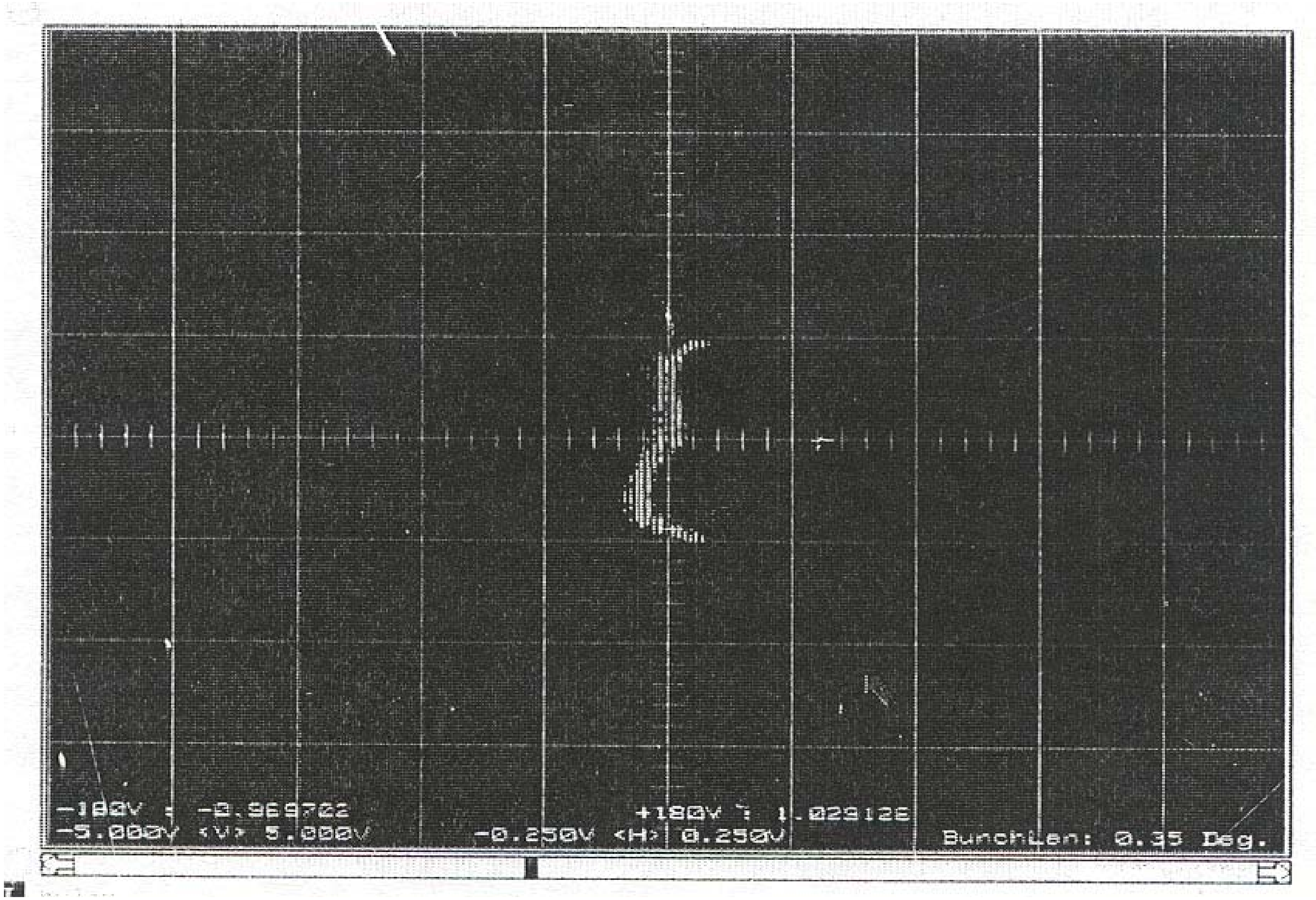
Simultaneously, digitize phase modulation and arrival time determined by a phase detector



Some Early Results



Phase Space Correction Scheme

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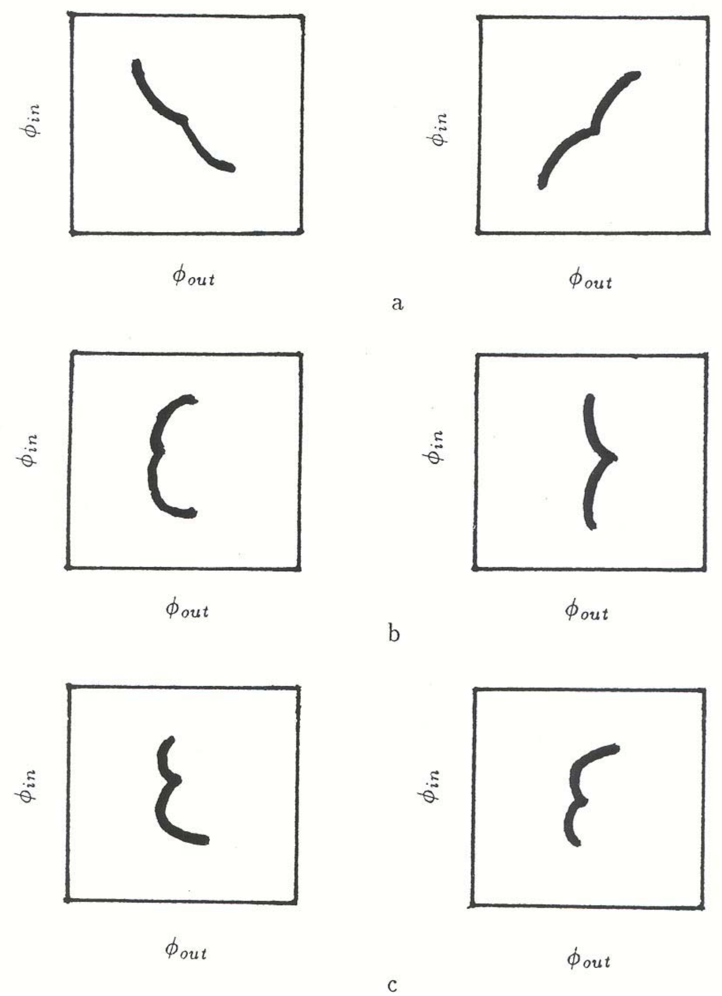

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Short Bunches in CEBAF

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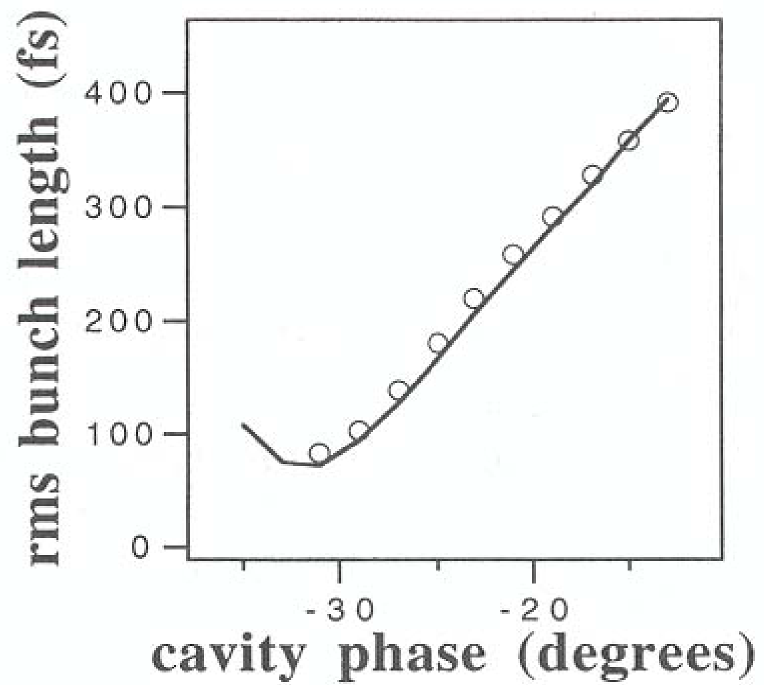
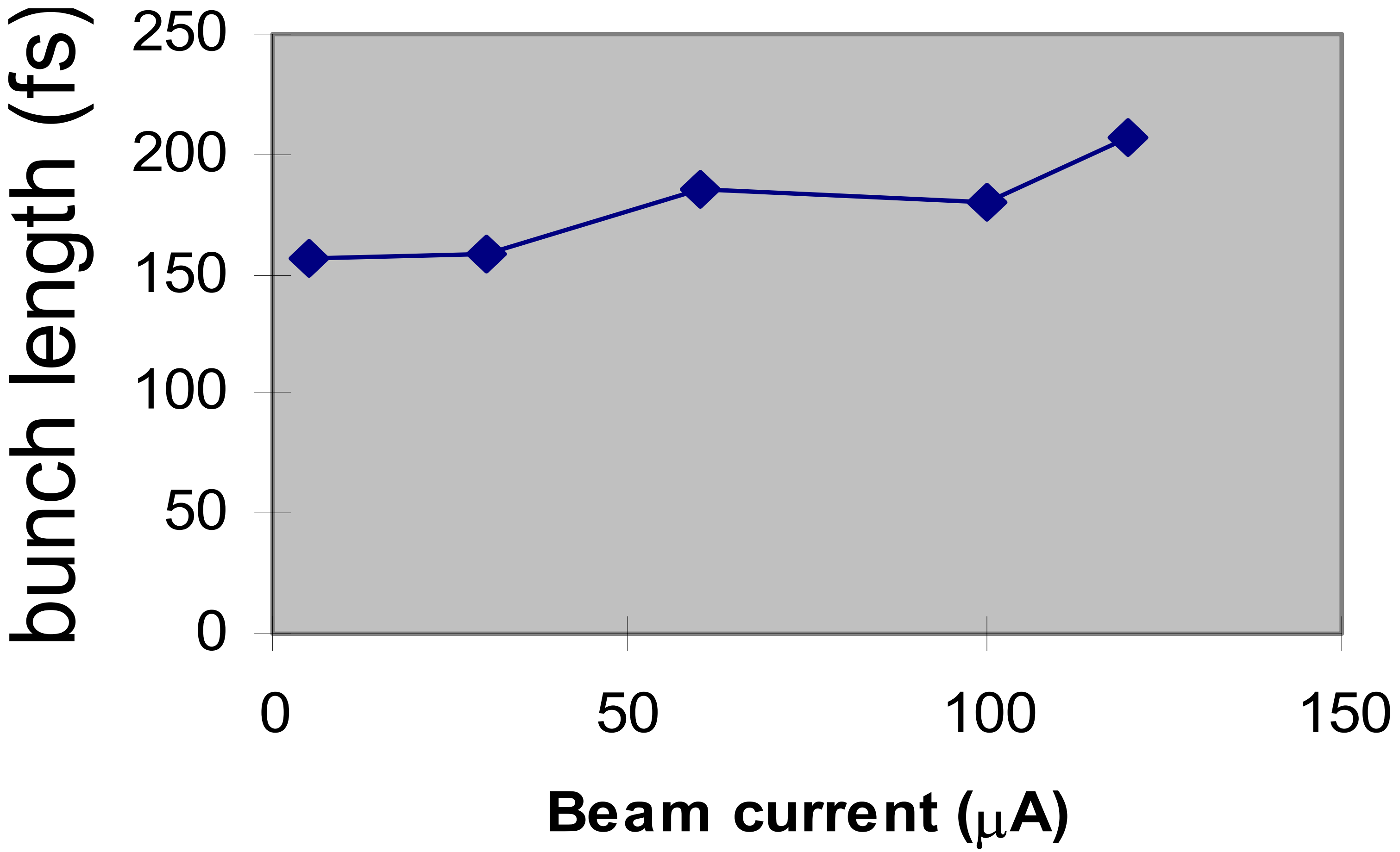


Wang, Krafft, and Sinclair, Phys. Rev. E, 2283 (1998)

Short Bunch Configuration

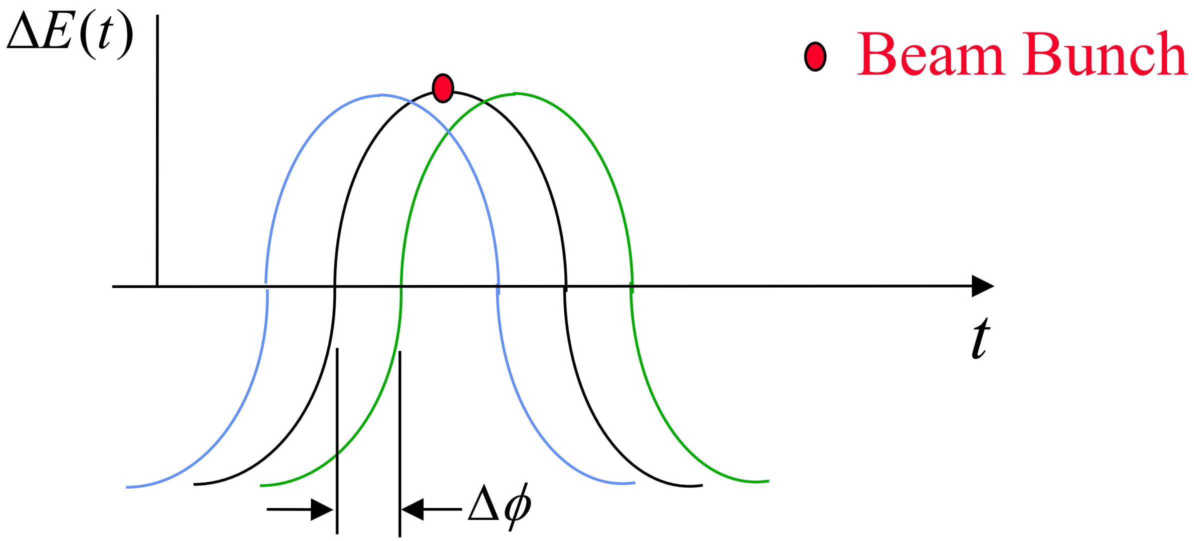


Kazimi, Sinclair, and Krafft, *Proc. 2000 LINAC Conf.*, 125 (2000)

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

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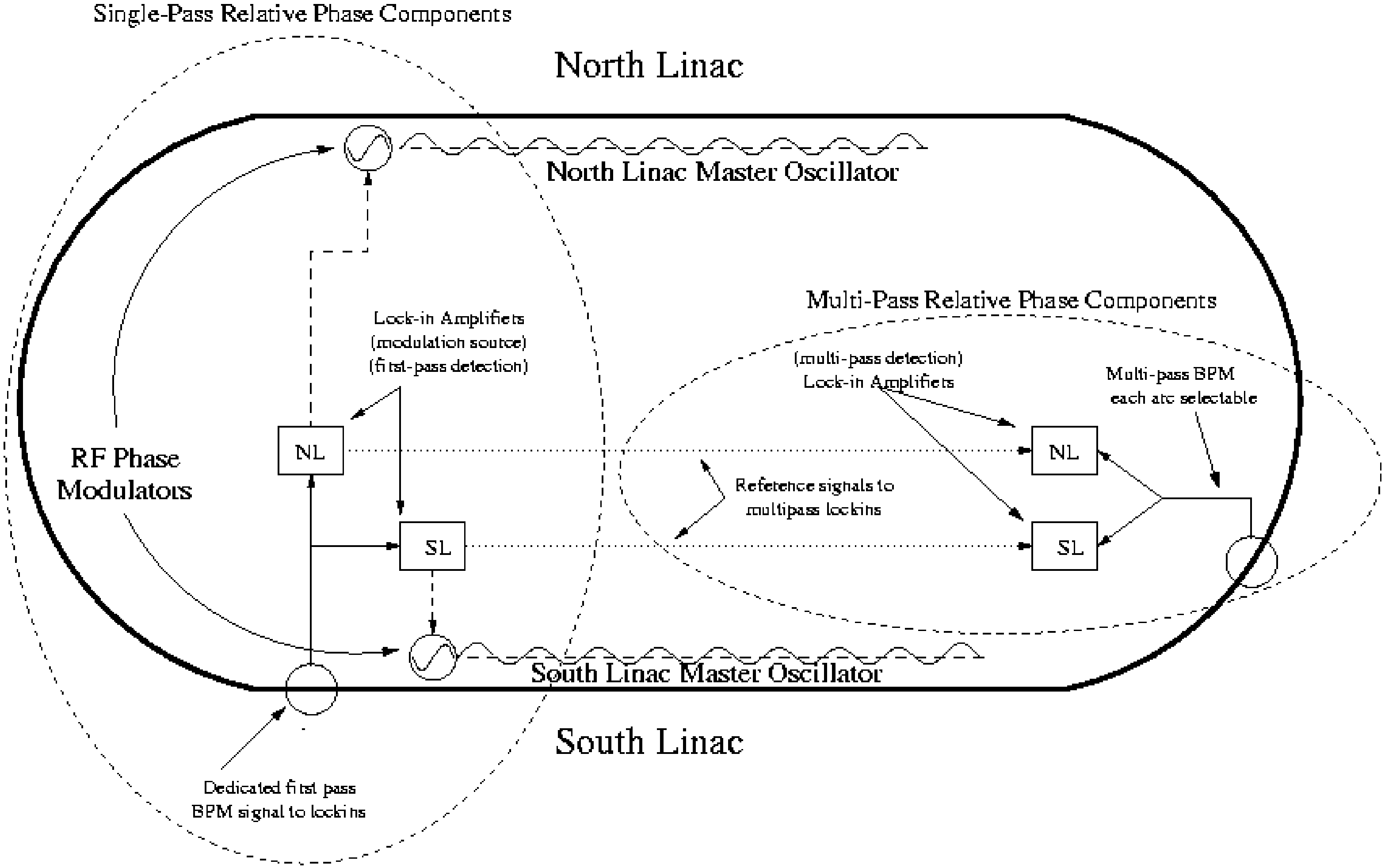

Courtesy: Michael Tiefenback

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

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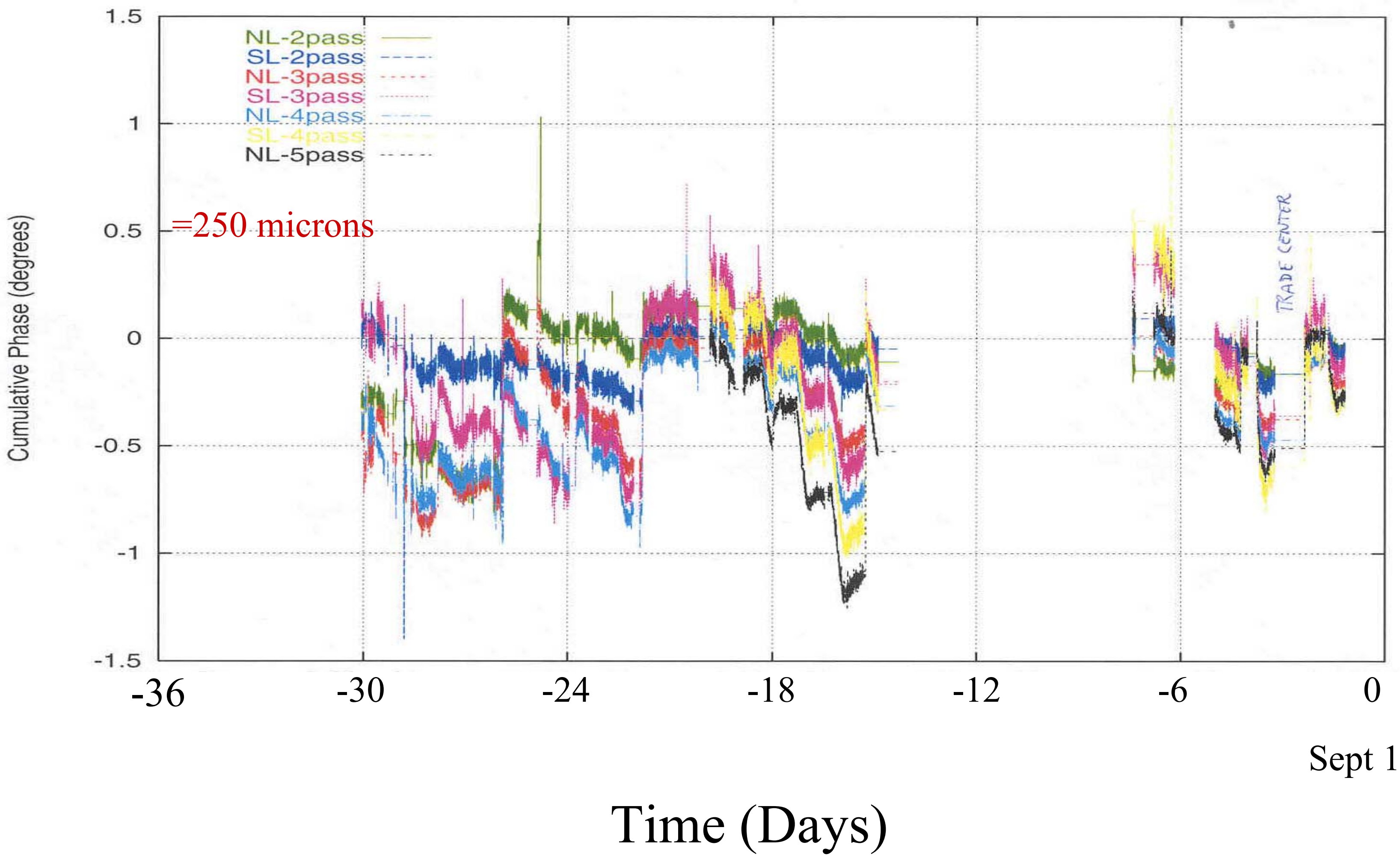

Courtesy: Michael Tiefenback

Feedback System Elements

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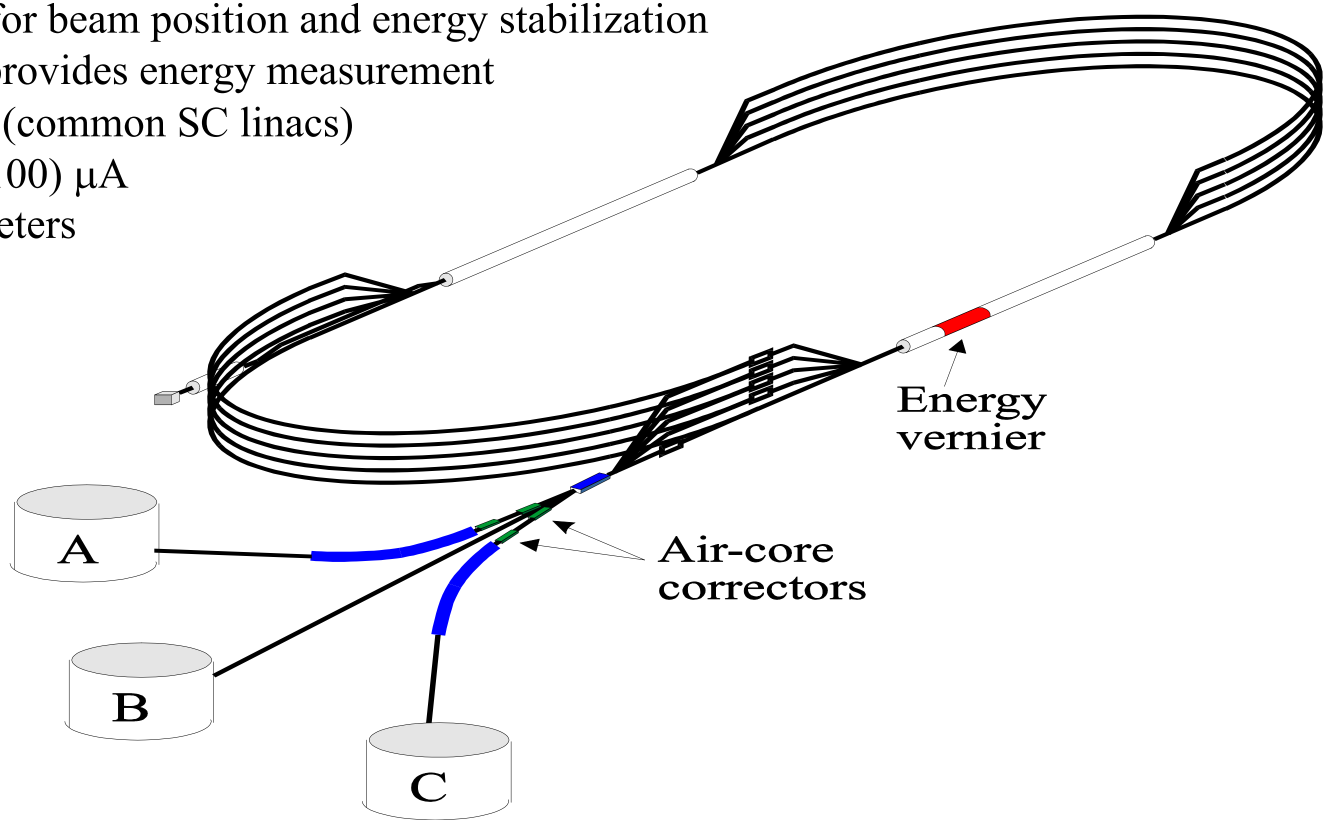
Beam position and energy stabilization

- 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

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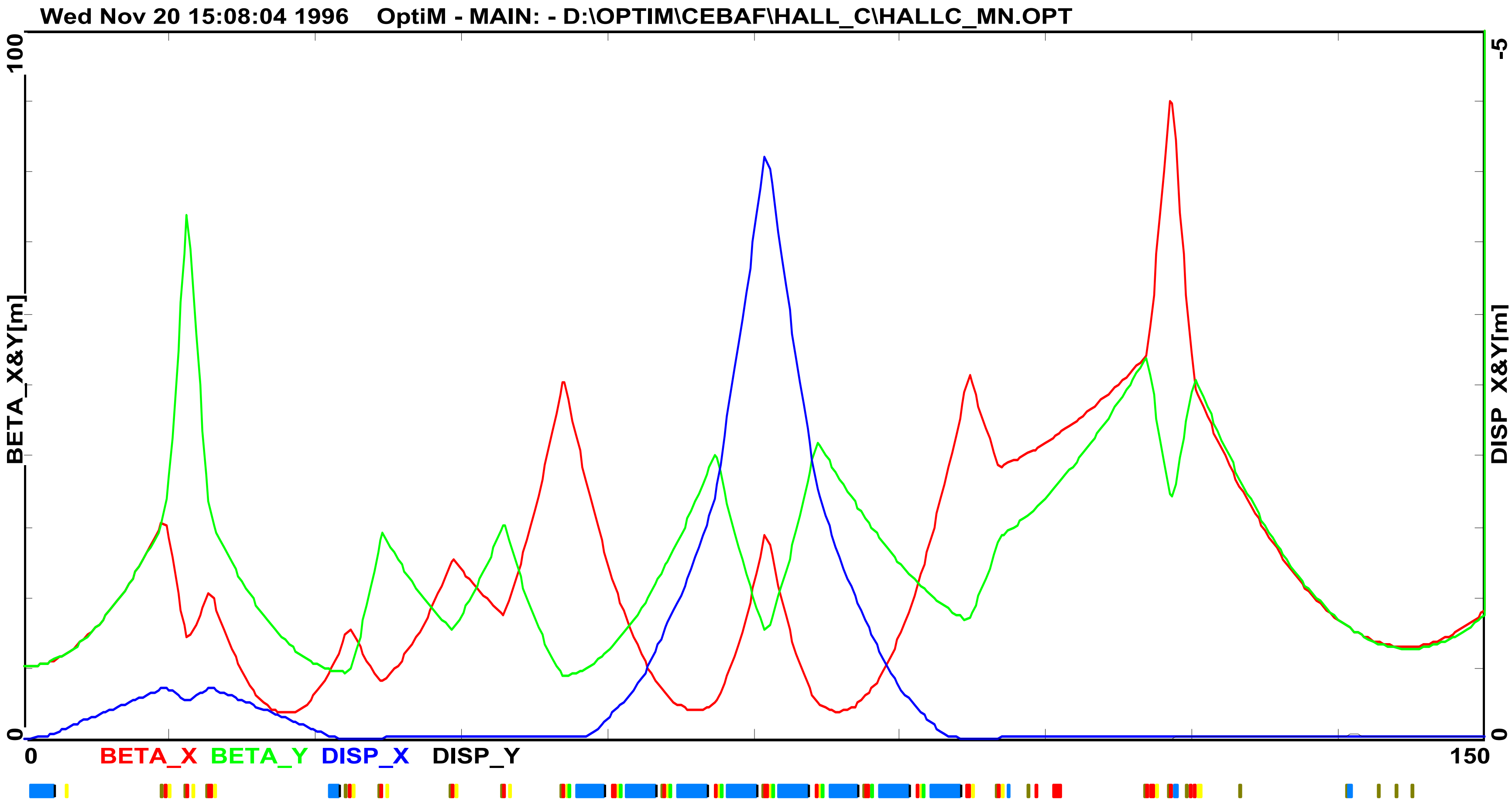
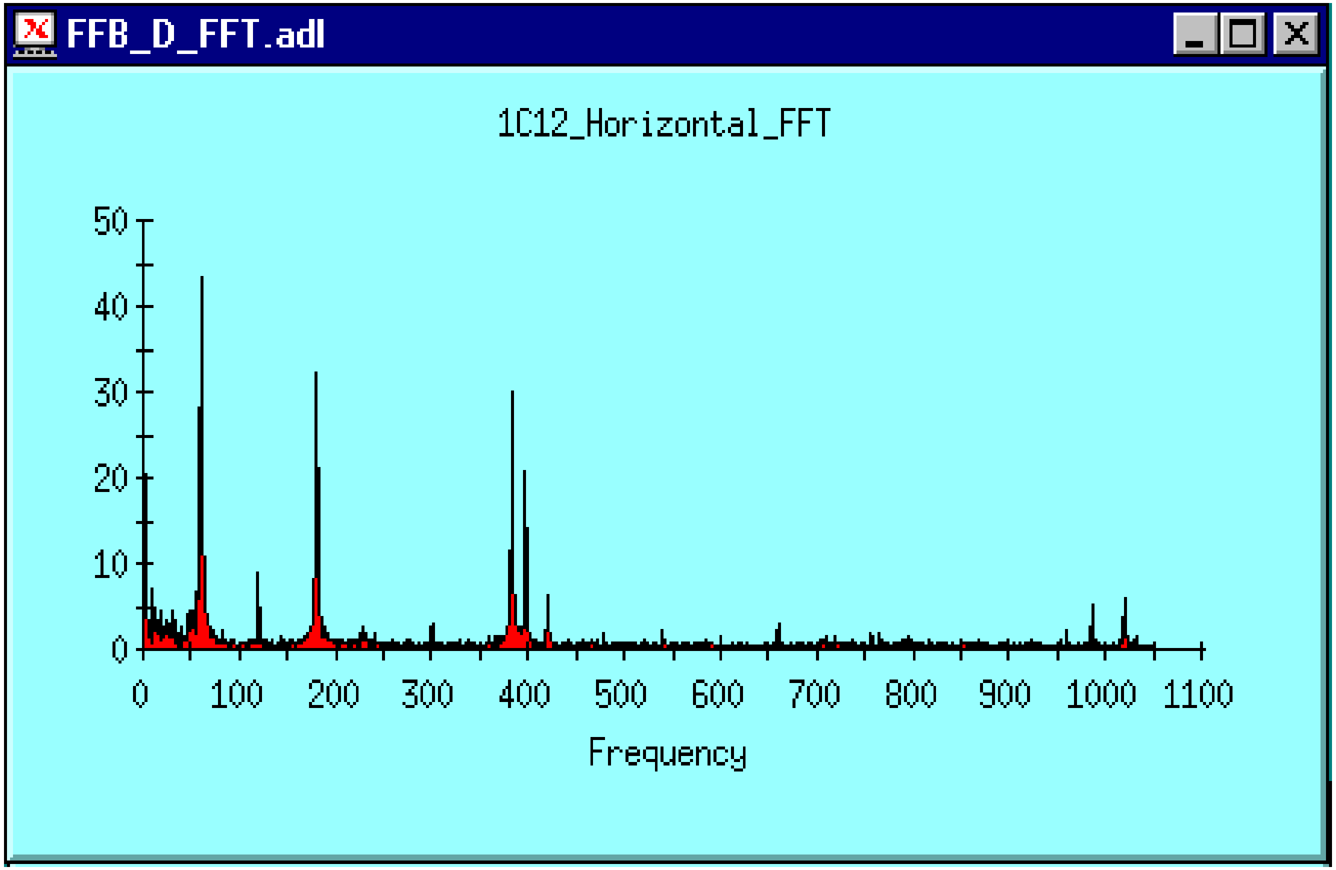


Courtesy: Valeri Lebedev

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Fast Feedback Off



Courtesy: Valeri Lebedev

Fast Feedback Residual Fluctuations –

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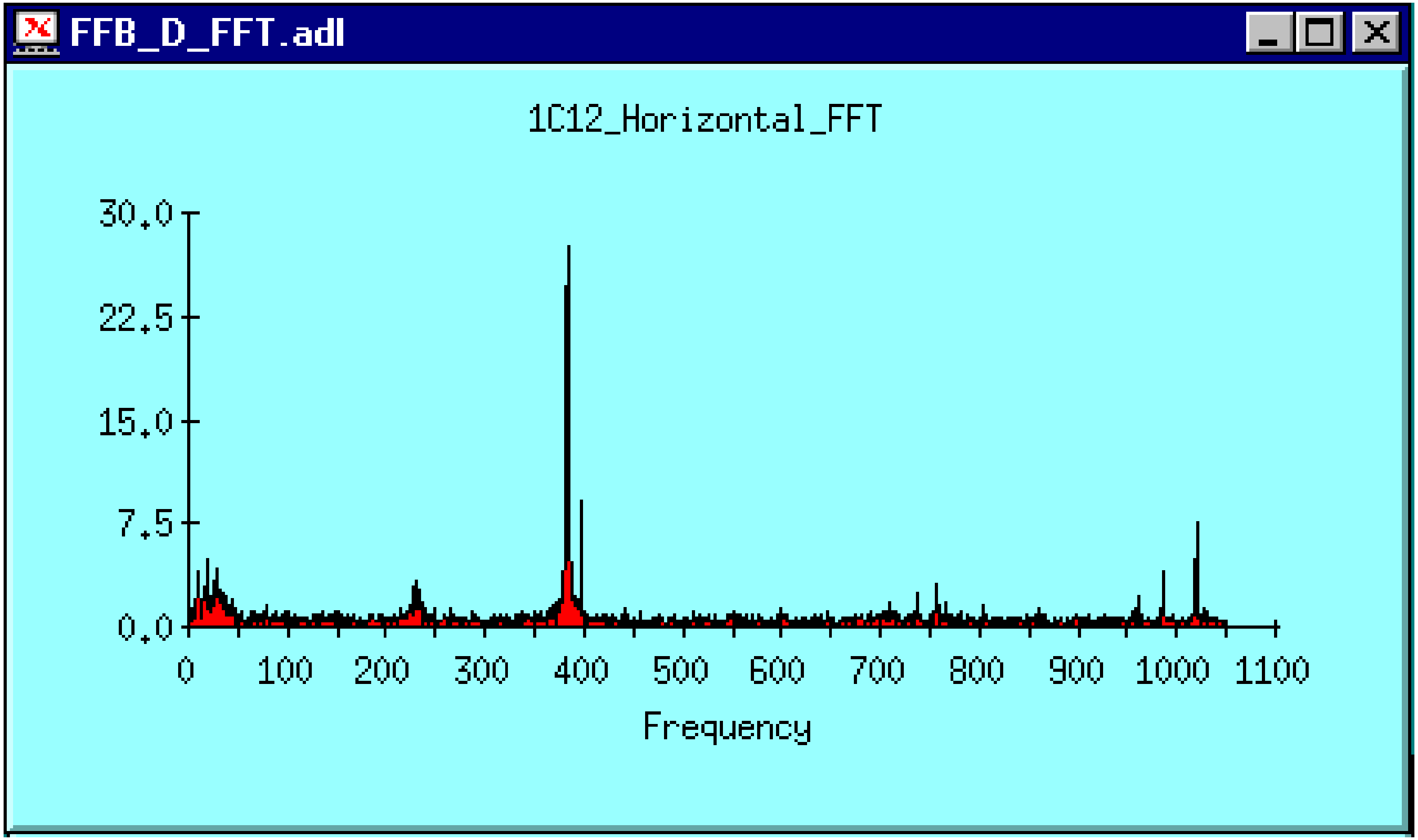

Courtesy: Valeri Lebedev

Fast Feedback rms position fluctuations

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FFB_0_bpm_val.adl

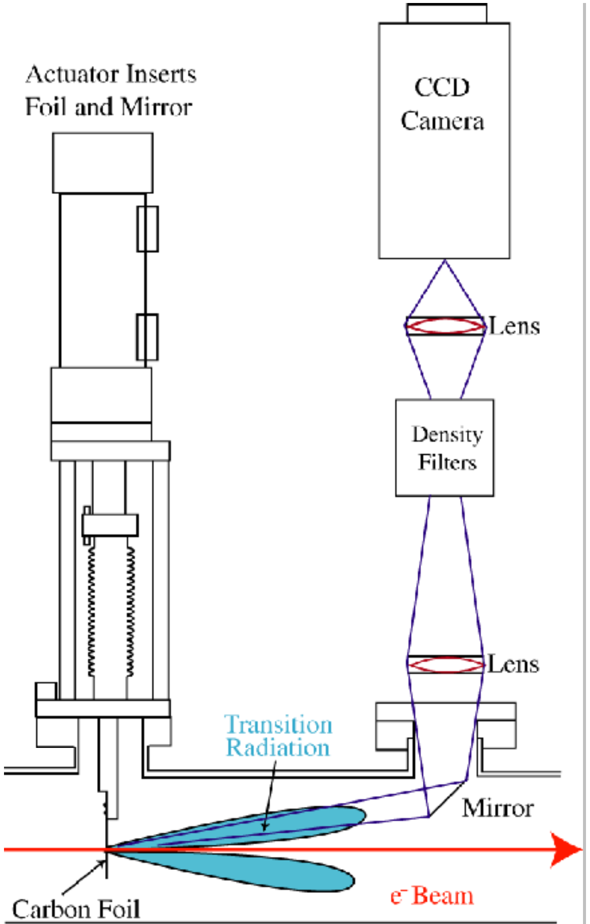
Hall A Fast FeedBack BMP/Corrector Values

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

	Horiz Corrector (gauss-cm)					Vert Corrector (gauss-cm)				
	min	max	mean	Std Dev		min	max	mean	Std Dev	
1C04H	-4.95	31.38	4.79	4.29	1C02V	-9.71	13.70	3.28	2.22	SI
1C07H	-19.92	12.59	-8.06	4.03	1C07V	5.29	33.74	25.40	4.37	

Courtesy: Valeri Lebedev

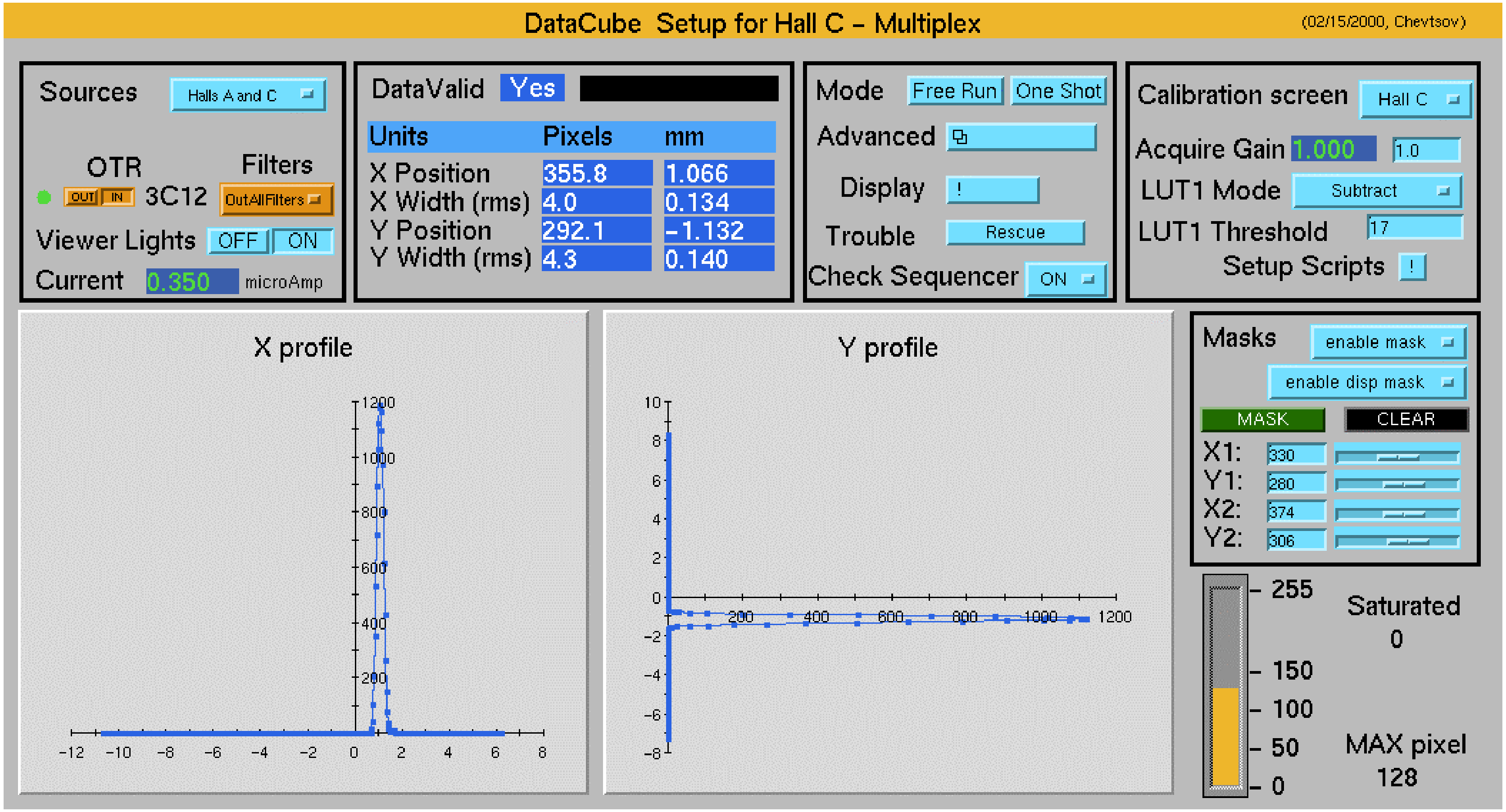
Beam Diagnostics: OTR



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 ≥ 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

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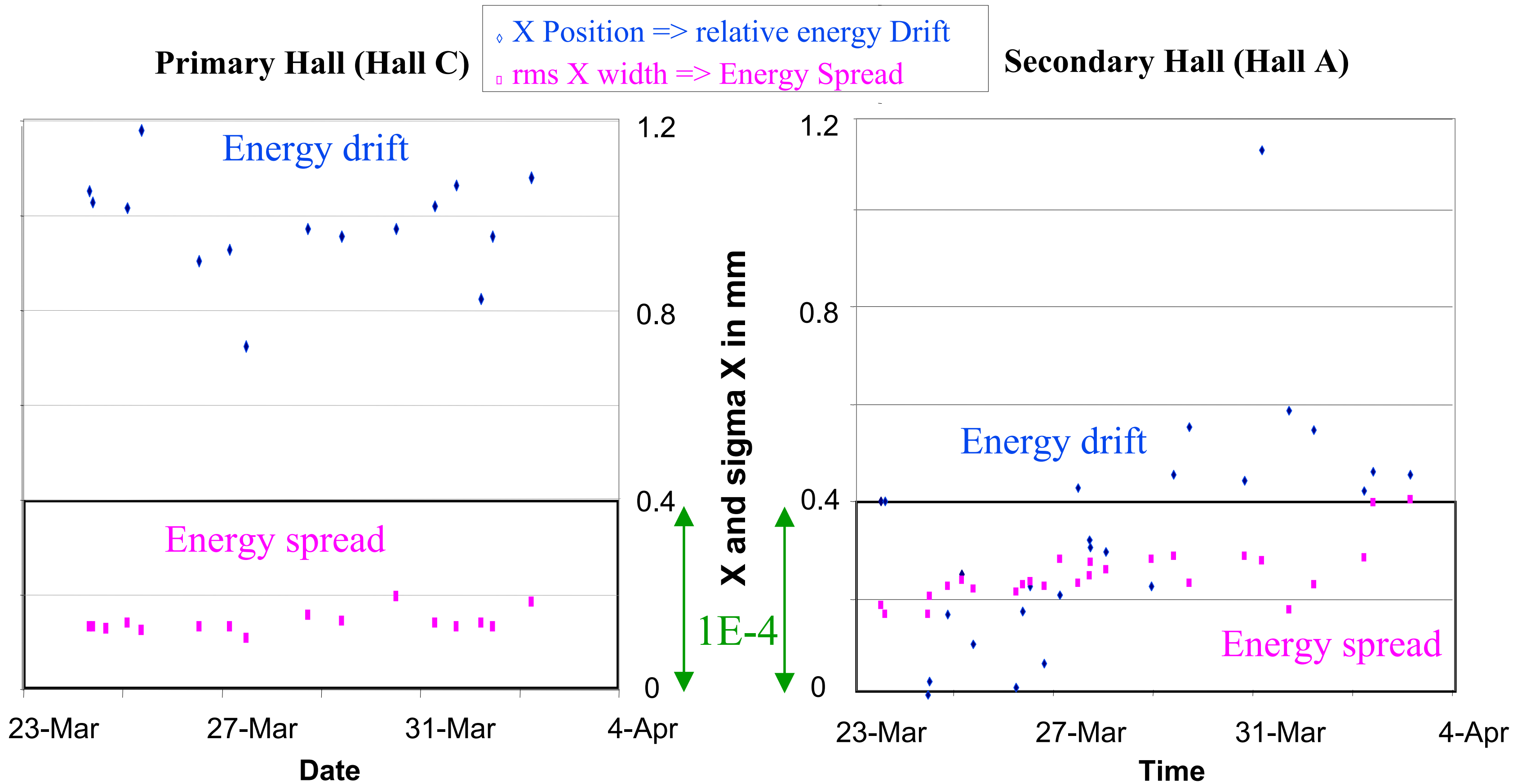
Energy Spread less than 50 ppm in Hall C, 100 ppm in Hall A



Courtesy: Jean-Claude Denard

dp/p Stability versus Beam Current

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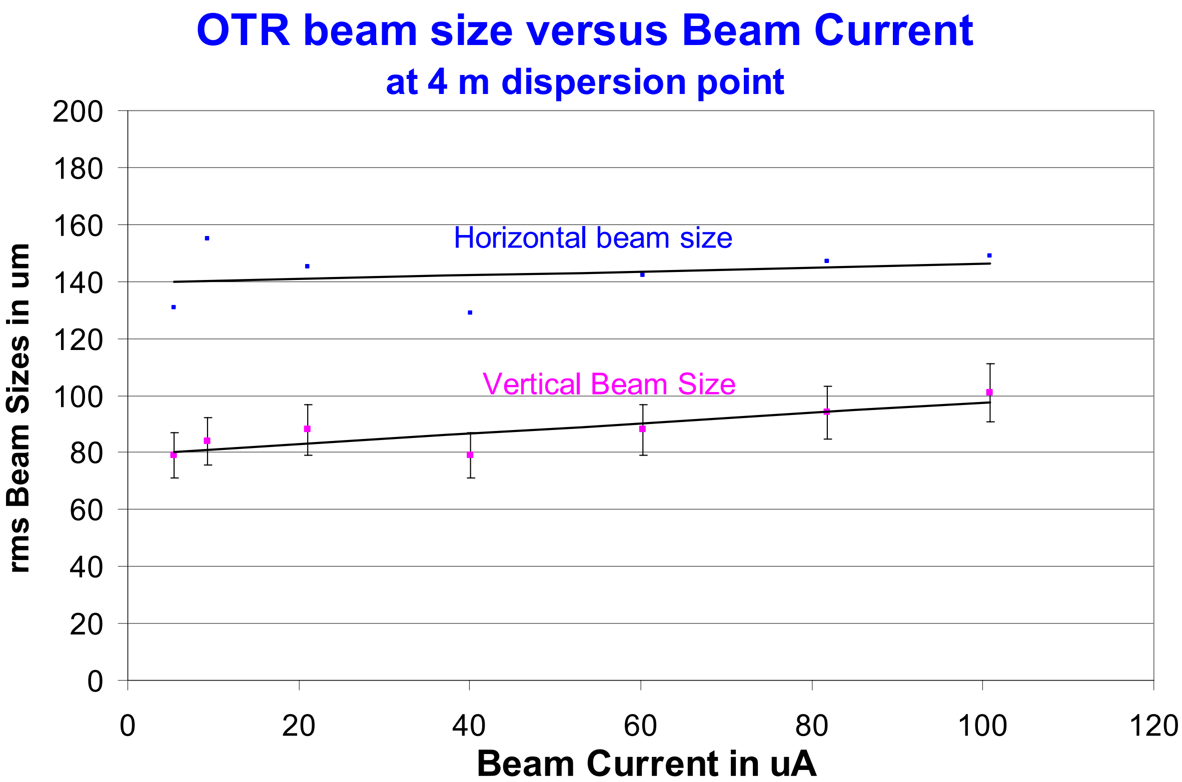


Courtesy: Jean-Claude Denard

Energy Recovering Linacs

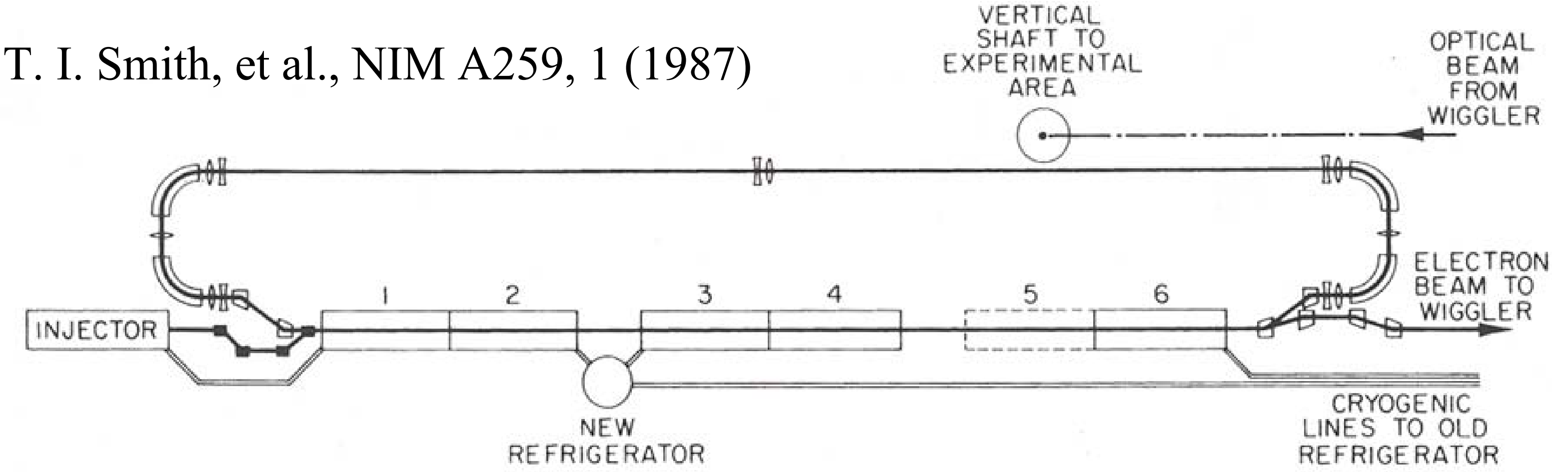
- The concept of energy recovery first appears in literature by Maury Tigner, as a suggestion for alternate HEP colliders*
- There have been several energy recovery experiments to date, the first one at Stanford SCA/FEL**
- Same-cell energy recovery with cw beam current up to 5 mA and energy up to 50 MeV has been demonstrated at the Jefferson Lab IR FEL. Energy recovery is used routinely for the operation of the FEL as a user facility

* Maury Tigner, Nuovo Cimento 37 (1965)
** T.I. Smith, et al., "Development of the SCA/FEL for use in Biomedical and Materials Science Experiments," NIMA 259 (1987)

The SCA/FEL Energy Recovery Experiment

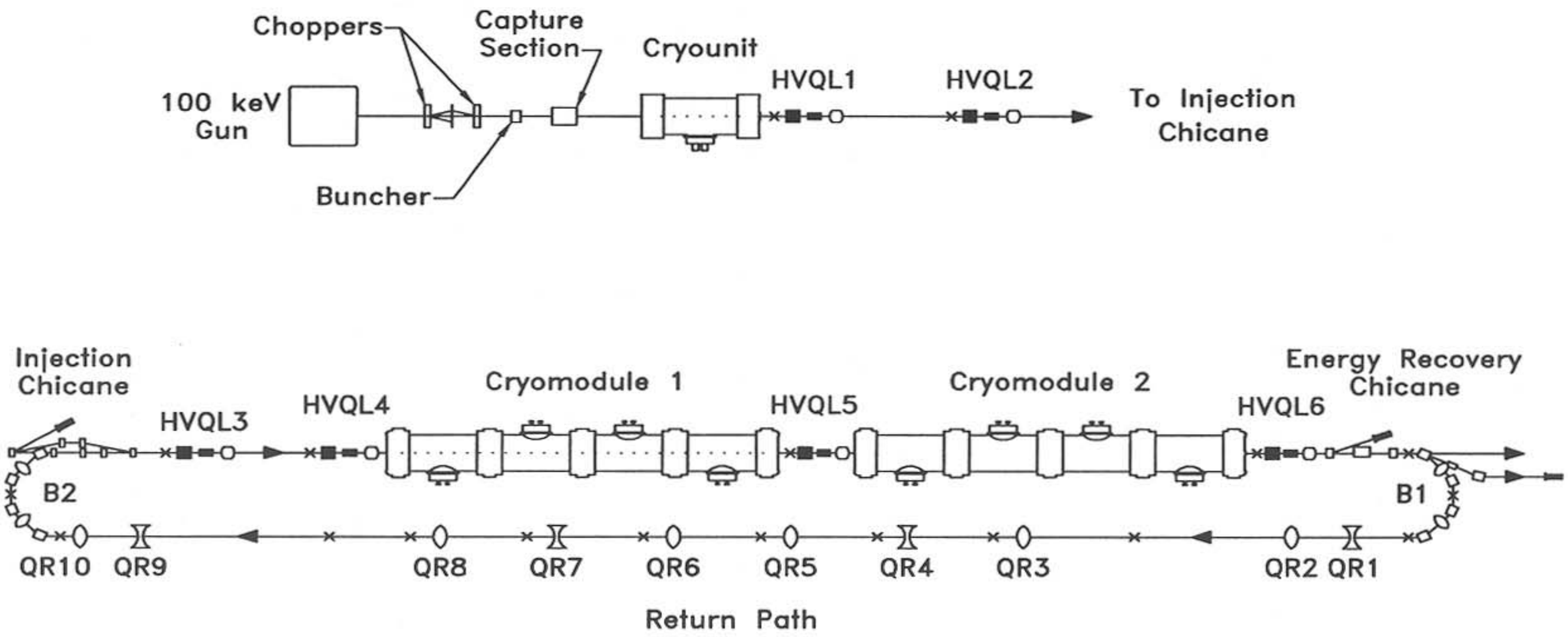
- Same-cell energy recovery was first demonstrated in the SCA/FEL in July 1986
- Beam was injected at 5 MeV into a ~50 MeV linac
- The previous recirculation system (SCR, 1982) was unsuccessful in preserving the peak current required for lasing and was replaced by a doubly achromatic single-turn recirculation line.
- All energy was recovered. FEL was not in place.

T. I. Smith, et al., NIM A259, 1 (1987)



The CEBAF Injector Energy Recovery Experiment

N. R. Sereno, "Experimental Studies of Multipass Beam Breakup and Energy Recovery using the CEBAF Injector Linac," Ph.D. Thesis, University of Illinois (1994)



Jefferson Lab FEL

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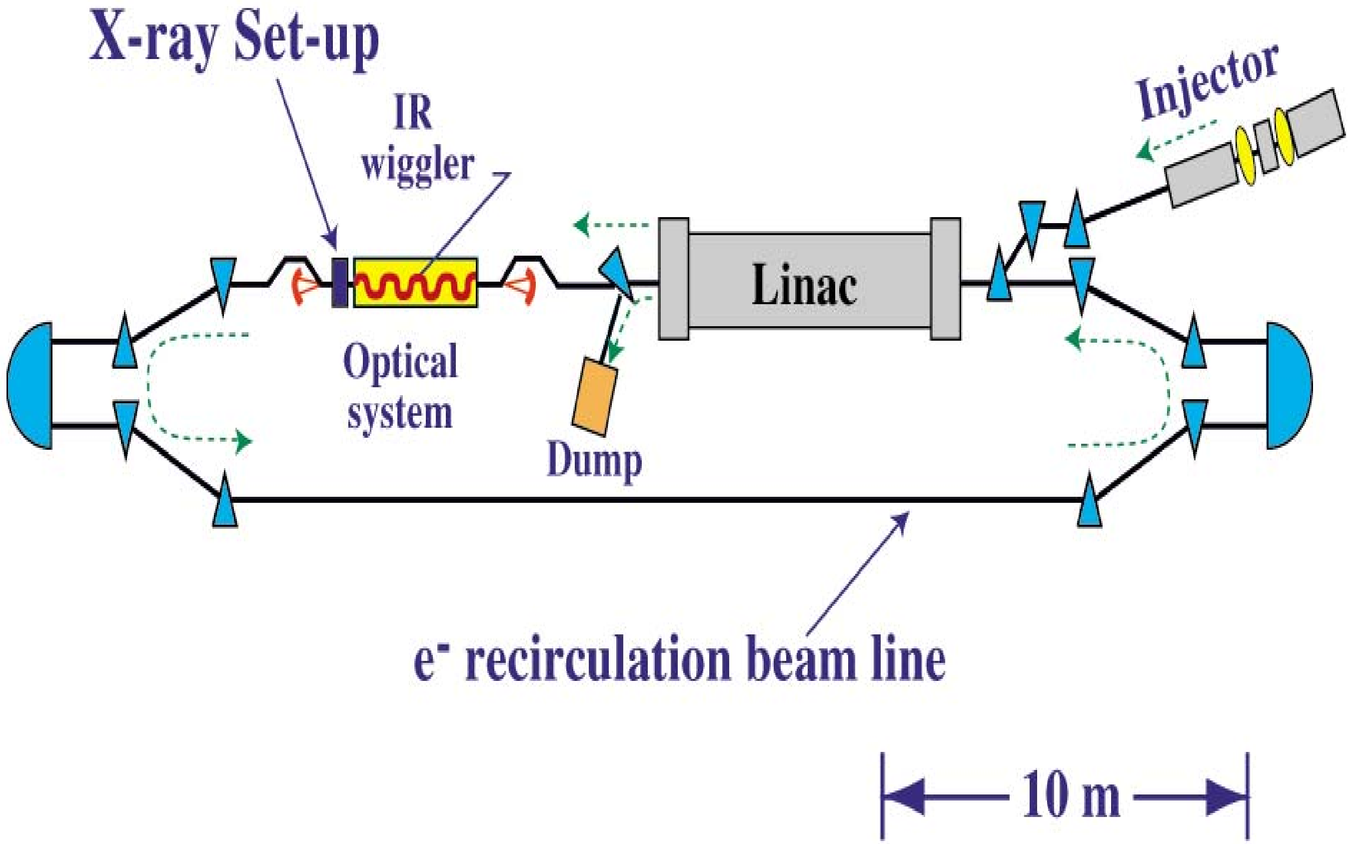

Neil, G. R., *et. al, Physical Review Letters,* **84,** 622 (2000)

The Jefferson Lab IR FEL

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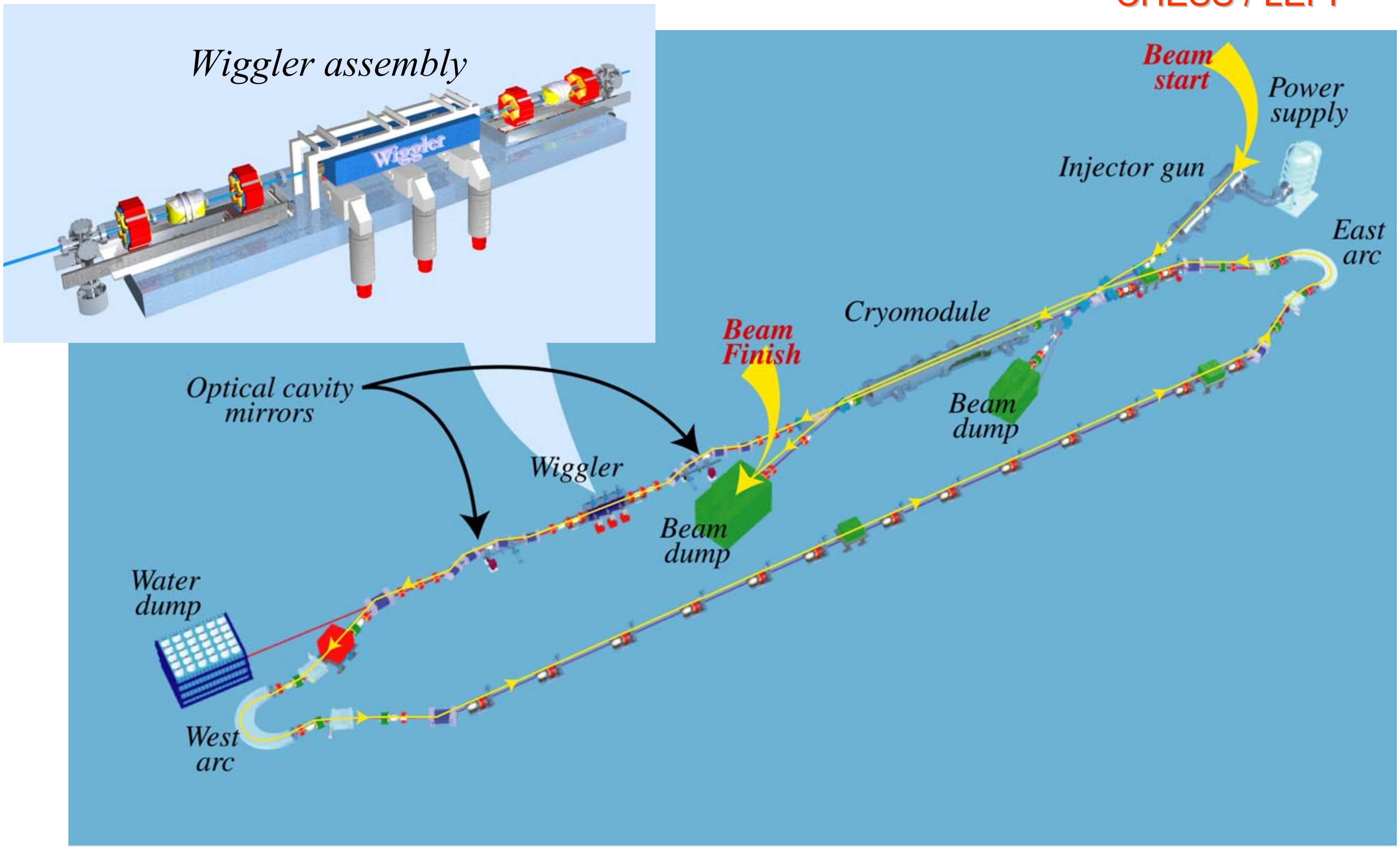

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FEL Accelerator Parameters

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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

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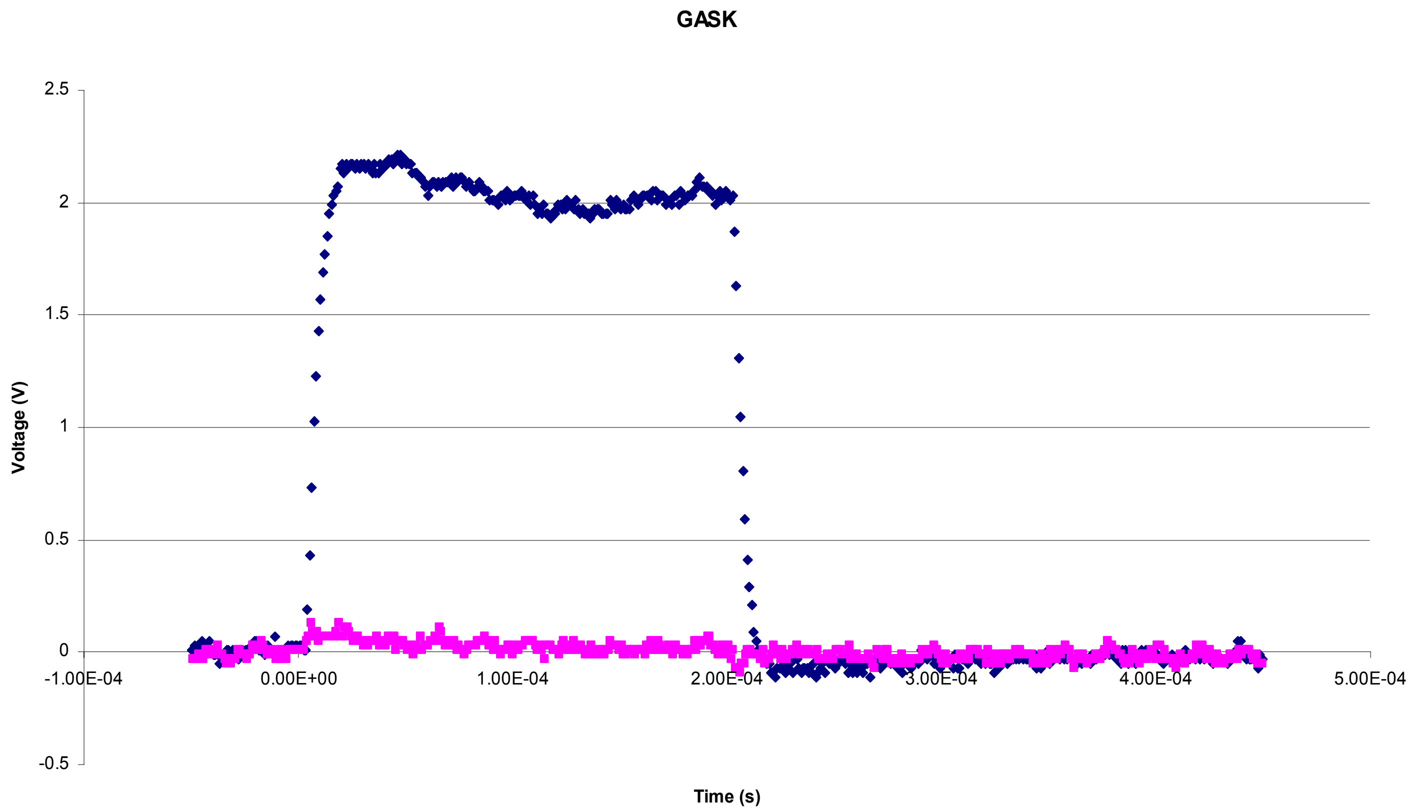
Gradient modulator drive signal in a linac cavity measured without energy recovery (signal level around 2 V) and with energy recovery (signal level around 0).



Courtesy: Lia Merminga

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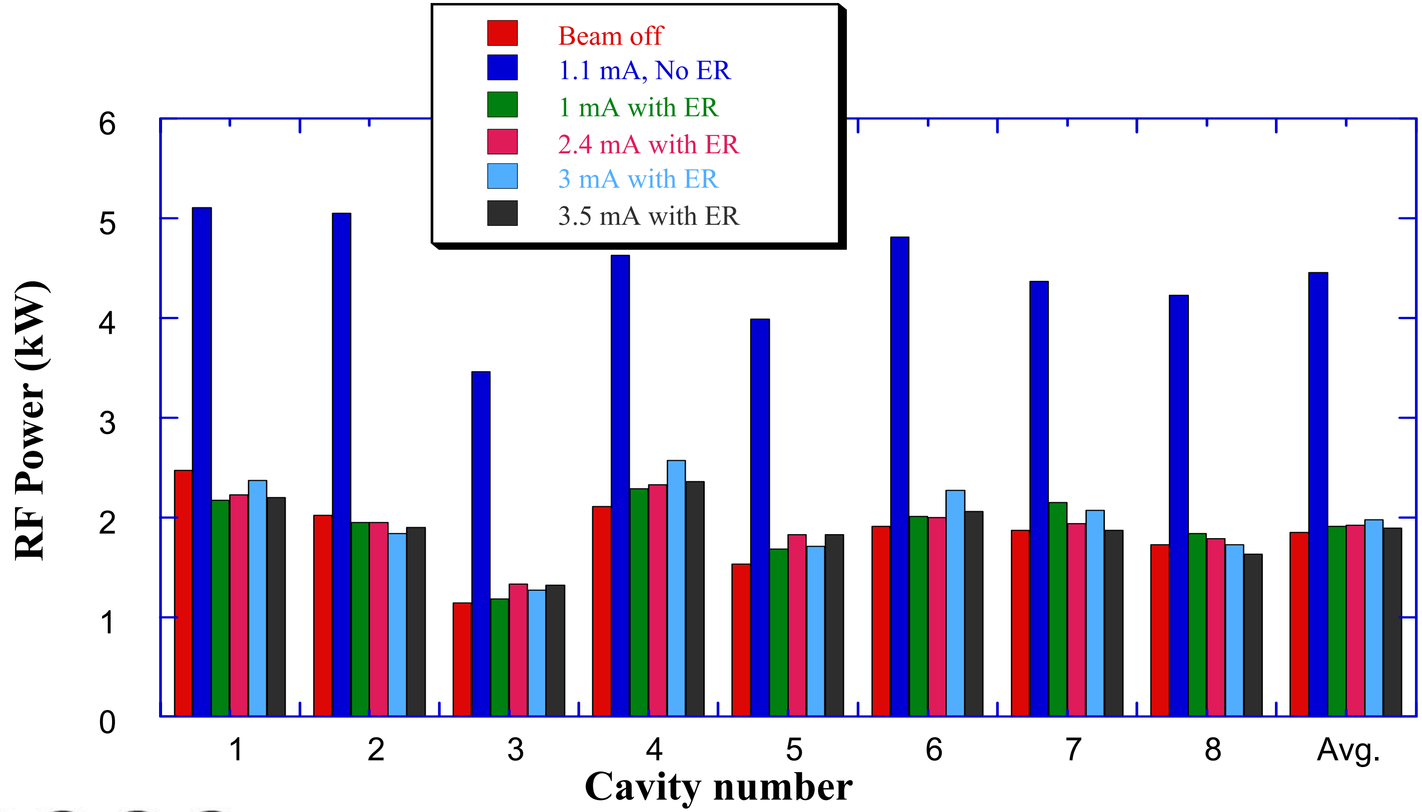
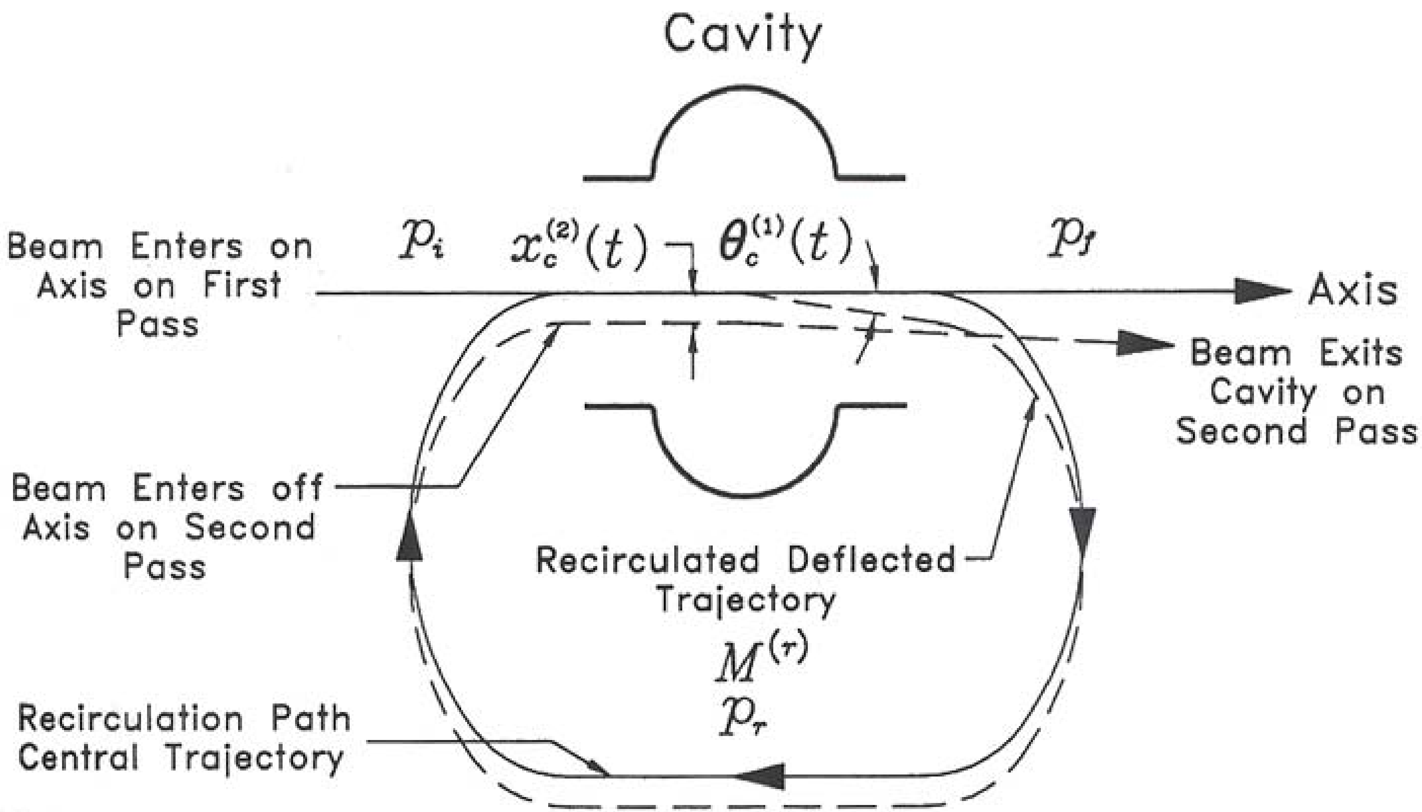
RF Power Requirements with Energy Recovery

With energy recovery the required linac rf power is ~ 16 kW, nearly independent of beam current. It rises to ~ 36 kW with no recovery at 1.1 mA.



Courtesy: Lia Merminga

Instability Mechanism



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

Threshold Current

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Growth Rate

$$\mathrm{Im}(\omega) \approx -\frac{\kappa \sin(\omega_\lambda t_r)}{2t_0} - \frac{\omega_\lambda}{2Q_\lambda}$$

where

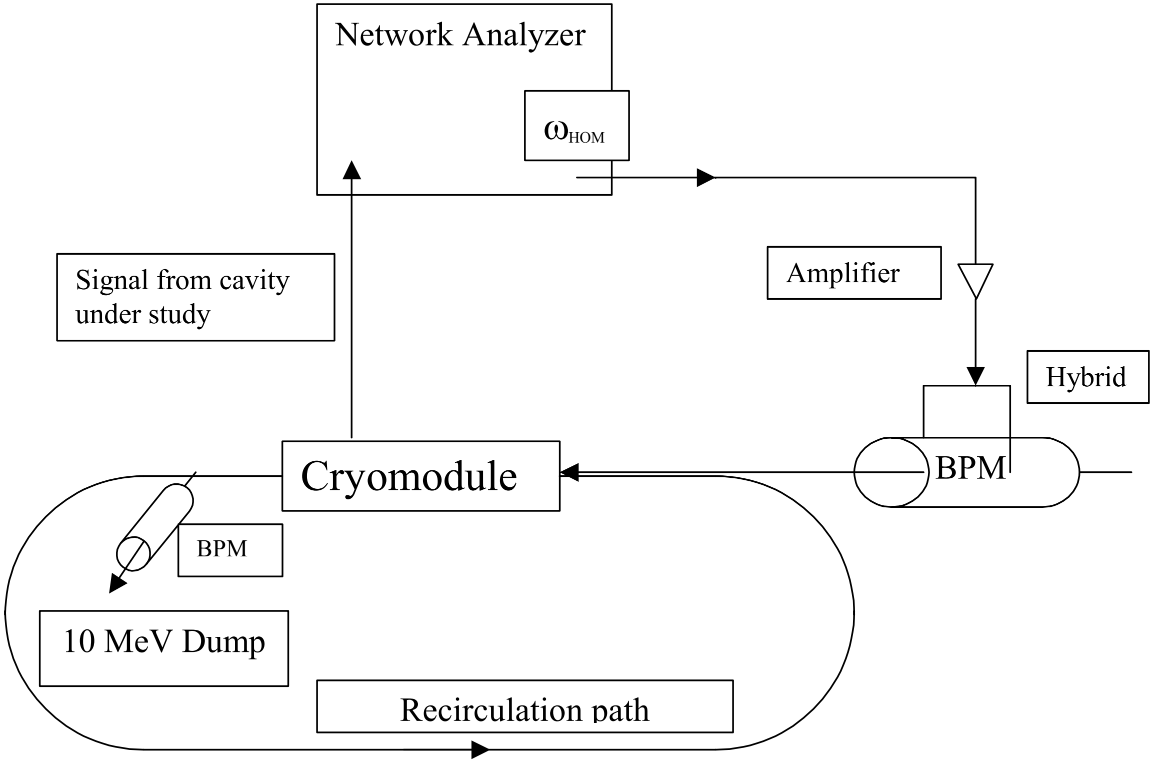
$$\kappa = (R/Q)_\lambda k_\lambda^2 e T_{12} I_0 t_0 / 2$$

If the average current exceeds the threshold current

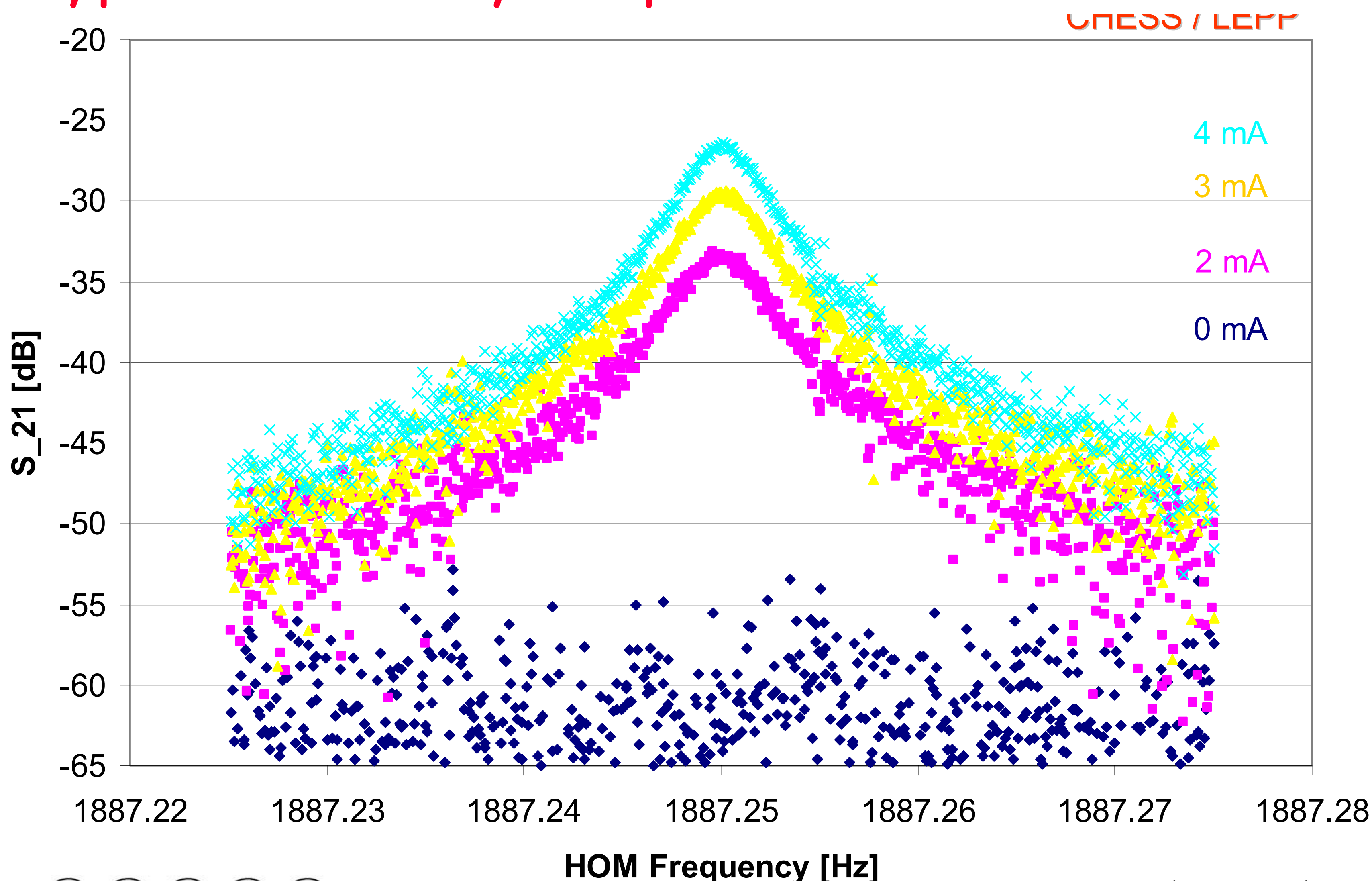
$$I_{th} = \frac{1}{e} \frac{2\omega_\lambda}{(R/Q)_\lambda Q_\lambda k_\lambda^2 |T_{12} \sin(\omega_\lambda t_r)|}$$

have instability (exponentially growing cavity amplitude!)

Transverse BBU: Experiment



Typical RF Cavity Response to Beam Excitation



Courtesy: Lia Merminga

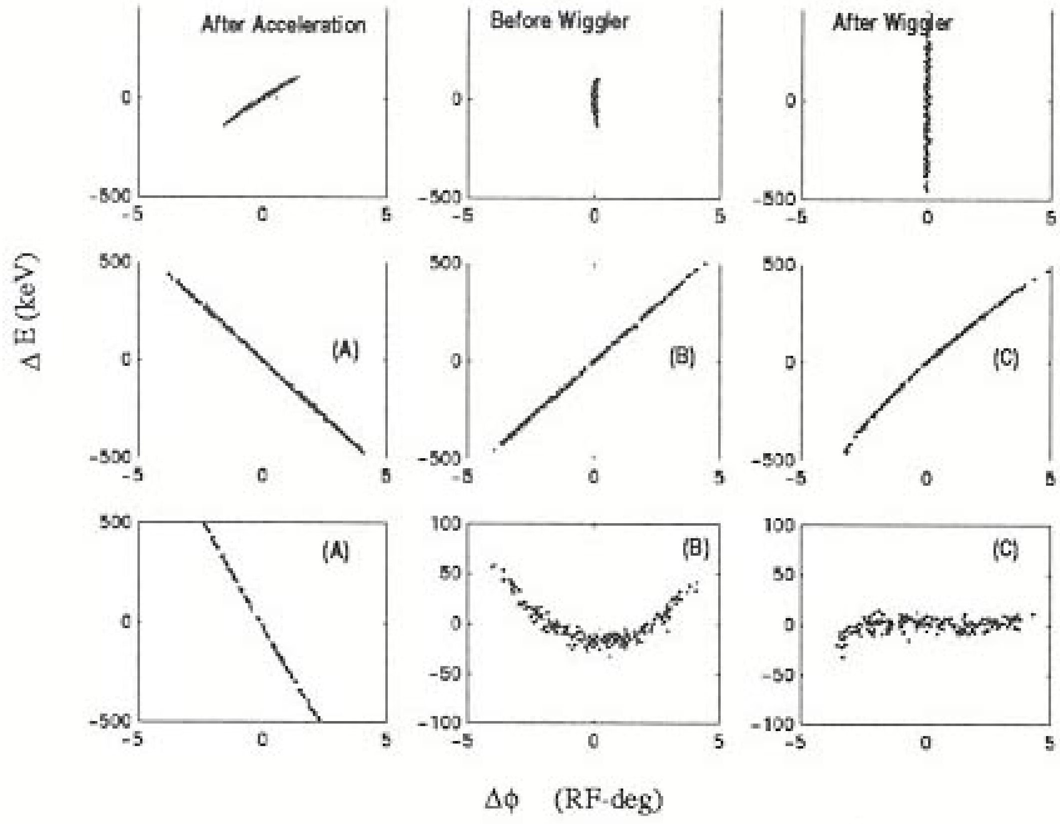
Table of BBU Data

Cavity	HOM Freq. (Measured)	R/Q (Meas.)	Q (Meas.)	Energy	Optics Setting	I_{th}
	[MHz]	[Ω]		MeV		mA
4	1730	0.08	3.8×10^7	48	Nominal	16
4	1730	0.08	3.8×10^7	37	1	18.4
4	1895	22.02	1.6×10^5	48	Nominal	21.4
4	1895	22.02	1.6×10^5	37	1	15.6
4	1895	22.02	1.6×10^5	37	Nominal	<0
5	1818	13.74	4.5×10^4	37	2	15.0
5	1818	13.74	4.5×10^4	37	3	6.9
5	1887	22.21	4.0×10^5	37	3	12.5
5	1887	22.21	4.0×10^5	37	4	11.3
5	1887	22.21	4.0×10^5	37	2	32.0
5	1887	22.21	4.0×10^5	37	3	16.4

Conclusions from BBU Experiment

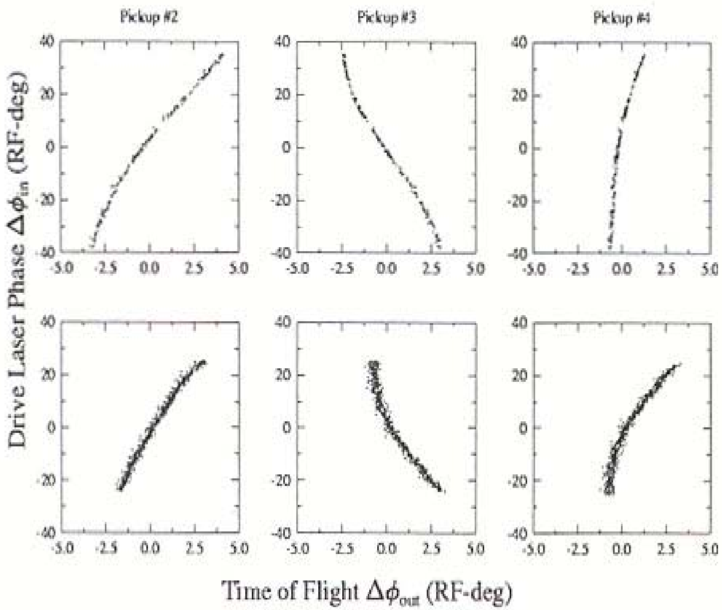
- Threshold current in the IR FEL recirculating linac varies between 7 mA and 32 mA for varying accelerator setup
- Under the nominal FEL configuration, threshold current is between 16 mA and 21 mA
- Theoretical prediction is 27 mA $\Rightarrow$ agreement within ~40%
- Observed optics dependence has not been quantified yet
- New analysis tools have been developed

Longitudinal Phase Space Manipulations



Simulation calculations of longitudinal dynamics of JLAB FEL

Transfer Function Measurements



Experiment		
# 2	0.1172	0.0008
# 3	-0.0801	0.0016
# 4	0.0911	0.0006
Simulation		
# 2	0.1070	0.0007
# 3	-0.0834	0.0003
# 4	0.0256	0.0004

Longitudinal Nonlinearities Corrected by Sextupoles

Sextupoles Off

Nominal Settings

Basic Idea is to use sextupoles to get T_{566} in the bending arc to compensate any curvature induced terms.

Correction of Nonlinearities by "Linearizers"

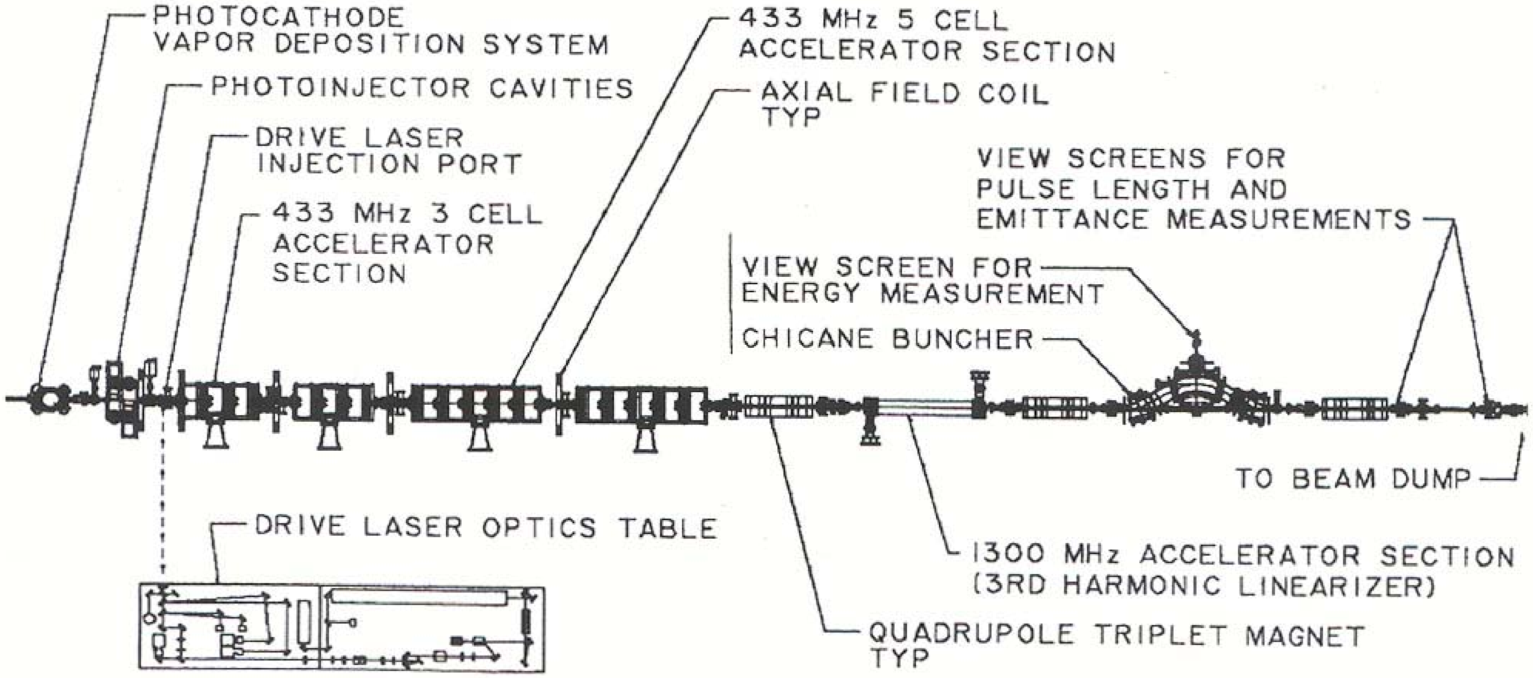
$$V_c = V_0 \cos\theta \approx V_0\left(1 - \frac{\theta^2}{2} + \cdots\right)$$

$$V_{lin} = \frac{V_0}{9}\cos 3\theta \approx \frac{V_0}{9}\left(1 - \frac{9\theta^2}{2} + \cdots\right)$$

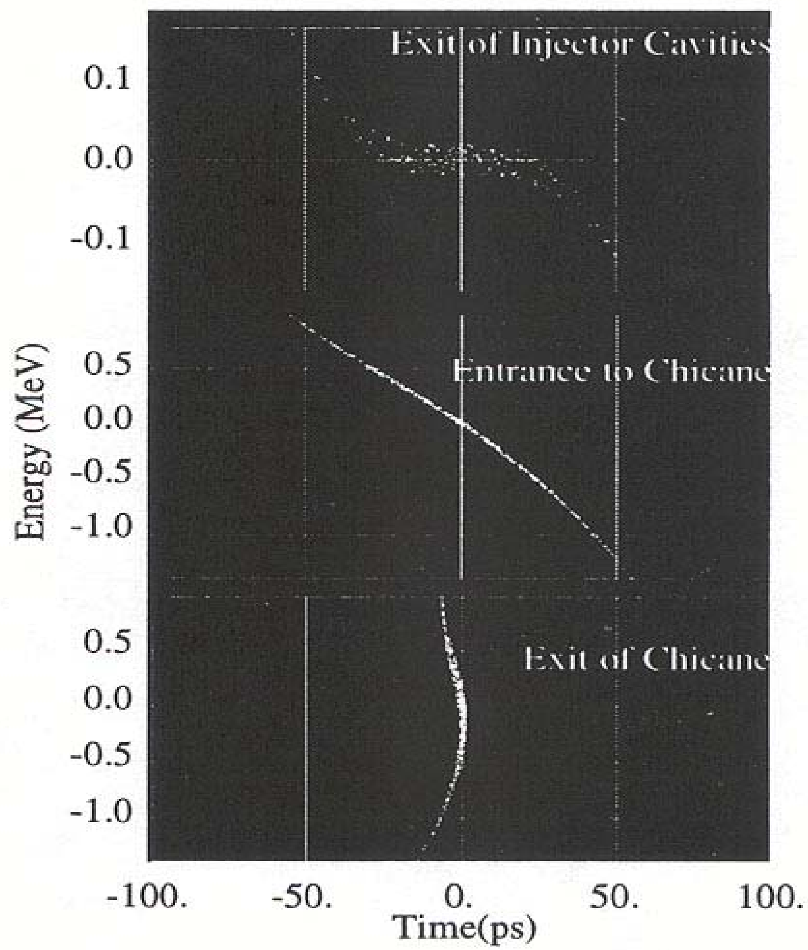
$$V_c - V_{lin} = \frac{8V_0}{9} + o\left(\theta^4\right),$$ independent of phase!

T. Smith, Proc. 1986 Int. Linac Conf., p. 421 (1986)
Dowell, D., et. al., Proc. 1995 PAC, p. 992 (1995)

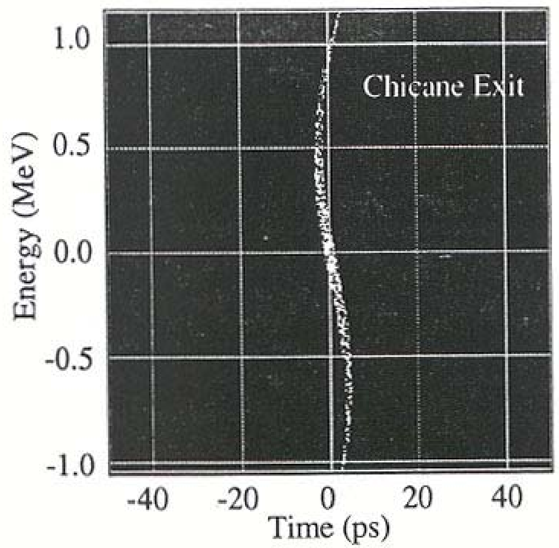
Boeing High Average Power FEL

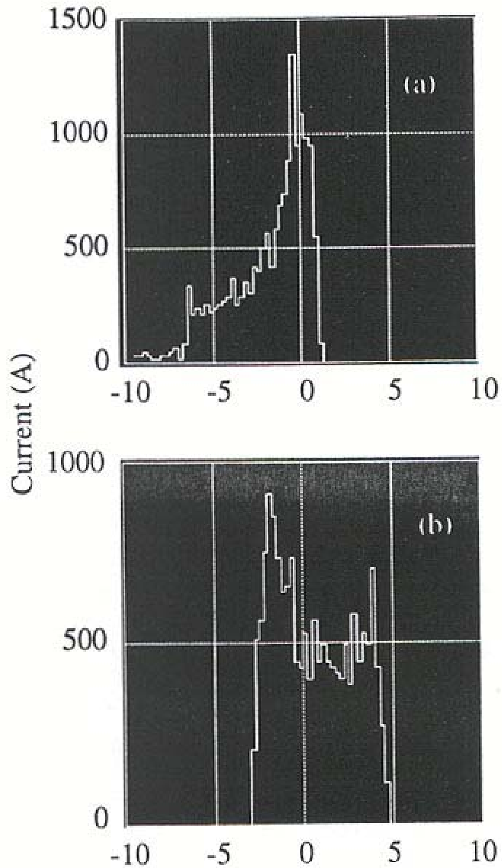


Phase Space Evolution Without Linearizer



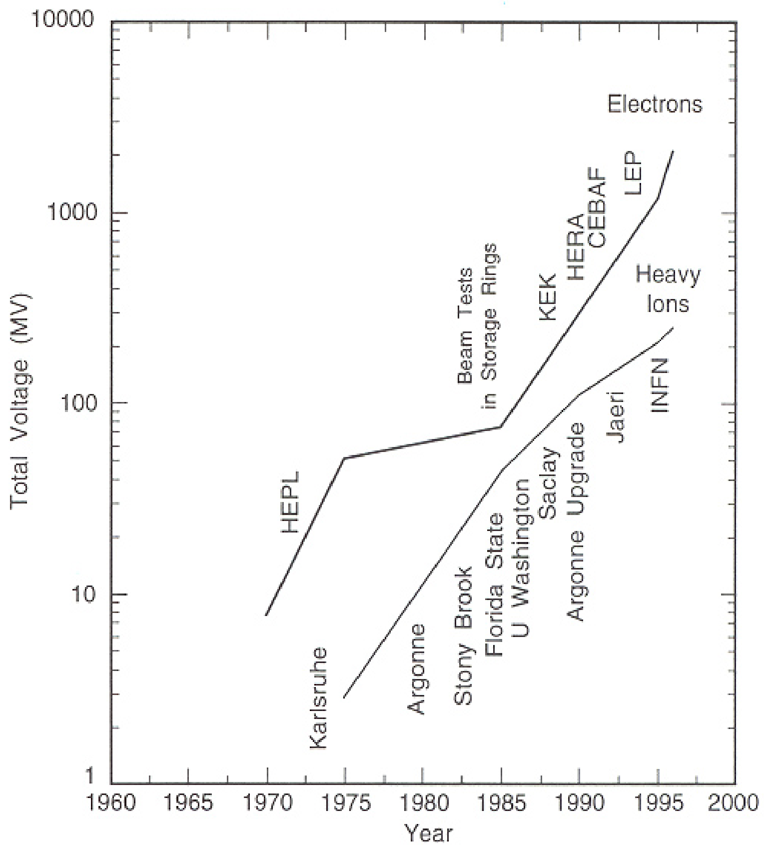
Correction of Nonlinearities by "Linearizers"





State of the Art in SRF in 2000

Total installed voltage capability with srf cavities for electron and heavy-ion accelerators.



Courtesy: Jean Delayen

High Energy Demonstration of Energy Recovery

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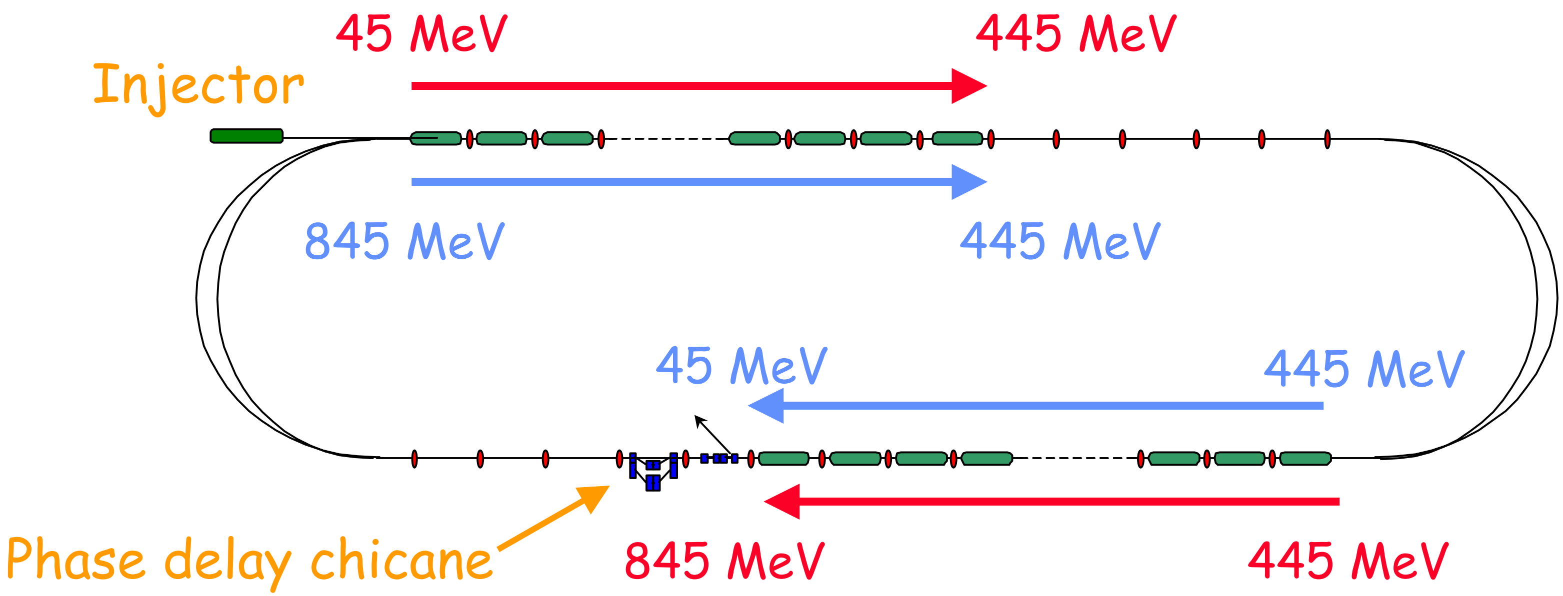
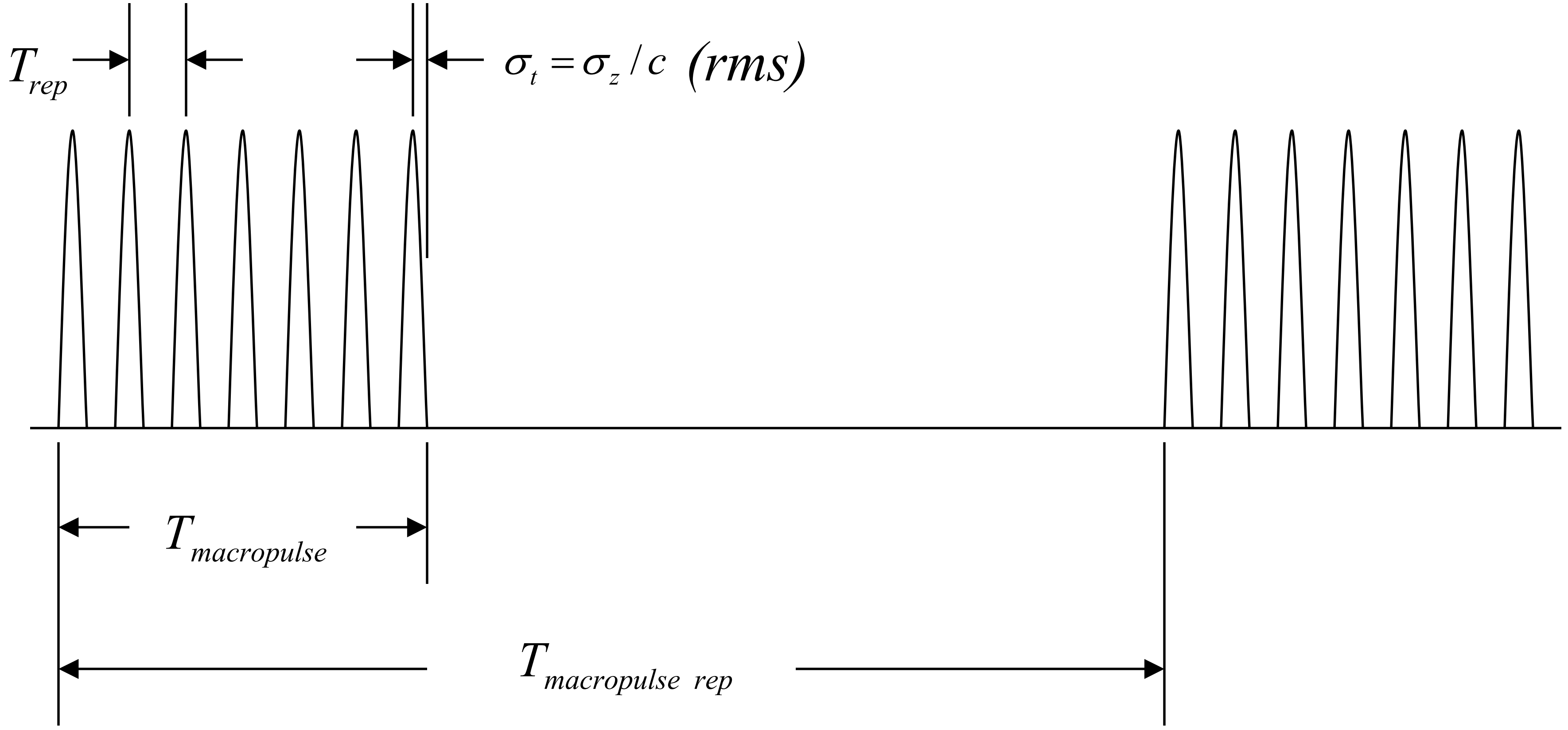
- Beam will be accelerated from 45 MeV to 845 MeV and energy recovered to 45 MeV. Plan to inject at 10 to 20 MeV and test energy recovery with energy ratio up to 80
- Beam properties, beam halo to be measured at several locations
- Experiment is approved and scheduled for March 2003



D. Douglas, A. Bogacz

Recirculated Linacs Have Flexible Timing



Timing Possibilities

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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

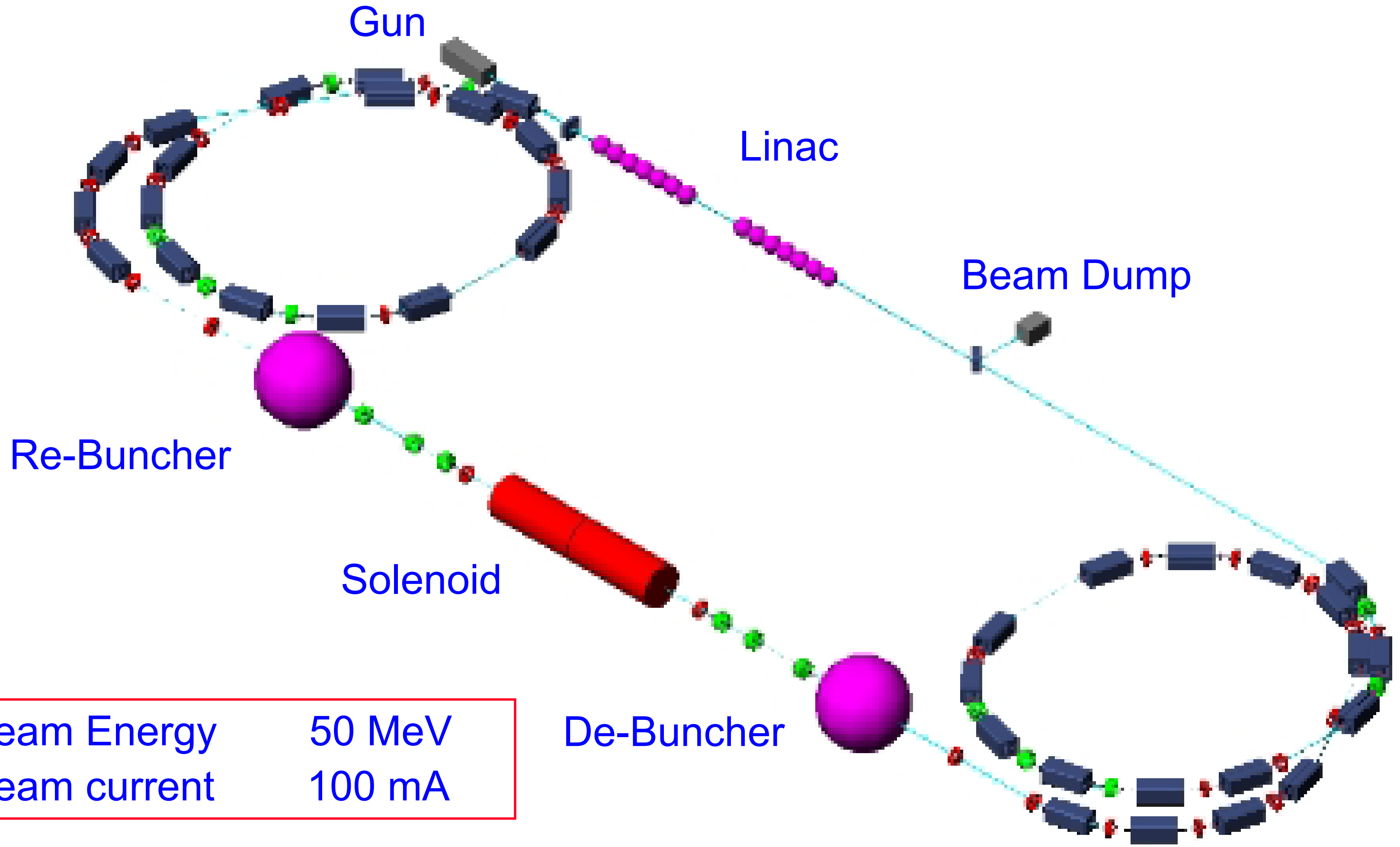
Brookhaven PERL Projects

- Showed 4 PDF viewslides, available at Brookhaven, dealing with the energy recovered linac plans being developed there.

  http://nslsweb.nsls.bnl.gov/nsls/org/PERL/Gun_Wkshp/Ben-Zvi.pdf

- Electron Cooling with a PERL
- eRHIC
- PERL Light Source

The BNL Electron Cooling Prototype



Beam Energy	50 MeV
Beam current	100 mA

Courtesy: I. Ben-Zvi

Electron–Light Ion Collider @ L $>10^{34}$ $cm^{-2}s^{-1}$

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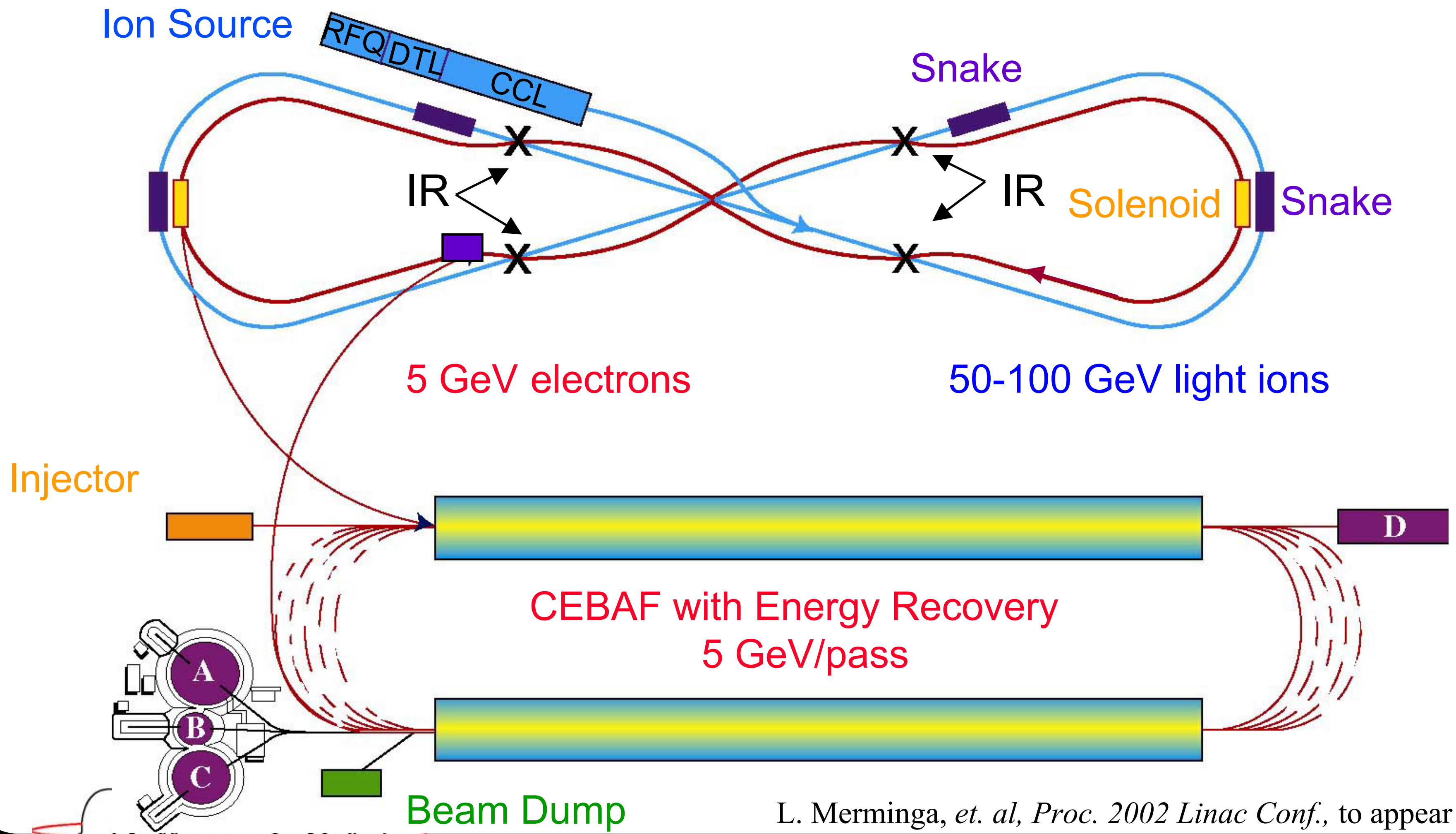
One accelerating & one decelerating pass through CEBAF



L. Merminga, *et. al, Proc. 2002 Linac Conf.*, to appear

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ERL Phase II X-ray SR Source Conceptual Layout

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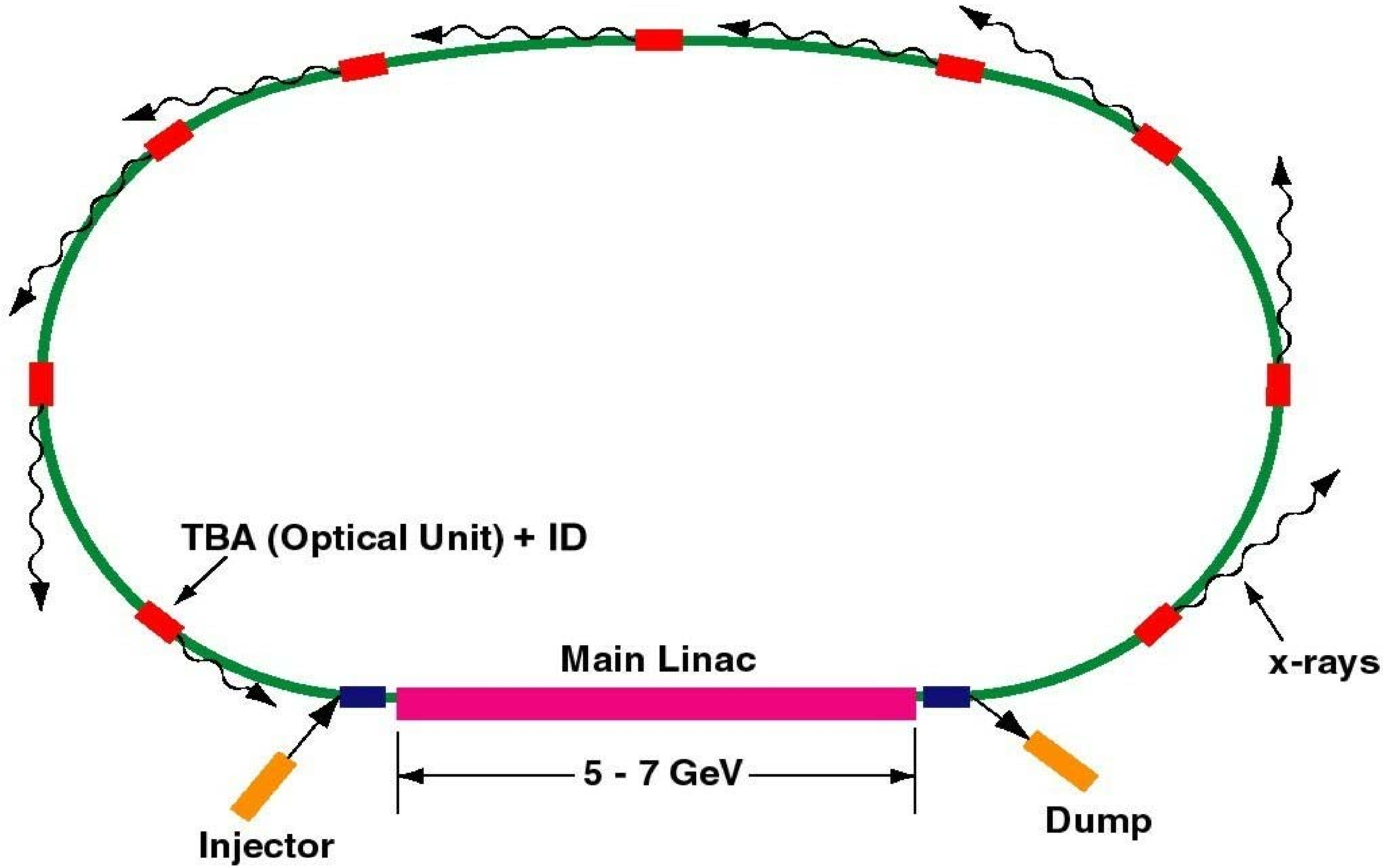

ERL Phase II Sample Parameters - CORNELL UNIVERSITY CHESS / LEPP

Parameter	Value	Unit
Beam Energy	5-7	GeV
Average Current	100 / 10	mA
Fundamental frequency	1.3	GHz
Charge per bunch	77 / 8	pC
Injection Energy	10	MeV
Normalized emittance	2 / 0.2*	µm
Energy spread	0.02-0.3*	%
Bunch length in IDs	0.1-2*	ps
Total radiated power	400	kW

* rms values

Brilliance Scaling and Optimization

- For 8 keV photons, 25 m undulator, and 1 micron normalized emittance, X-ray source brilliance

$$B \propto \frac{I}{\varepsilon^2} = \frac{fQ}{\varepsilon_{th}^2 + AQ^p}$$

- For any power law dependence on charge-per-bunch, Q, the optimum is

$$AQ^p \approx \varepsilon_{th}^2 / (p-1)$$

- If the "space charge" generated emittance exceeds the thermal emittance ε_{th} from whatever source, you've already lost the game!
- BEST BRILLIANCE AT LOW CHARGES, once a given design and bunch length is chosen!
- Unfortunately, best flux at high charge

ERL X-ray Source Average Brilliance and Flux

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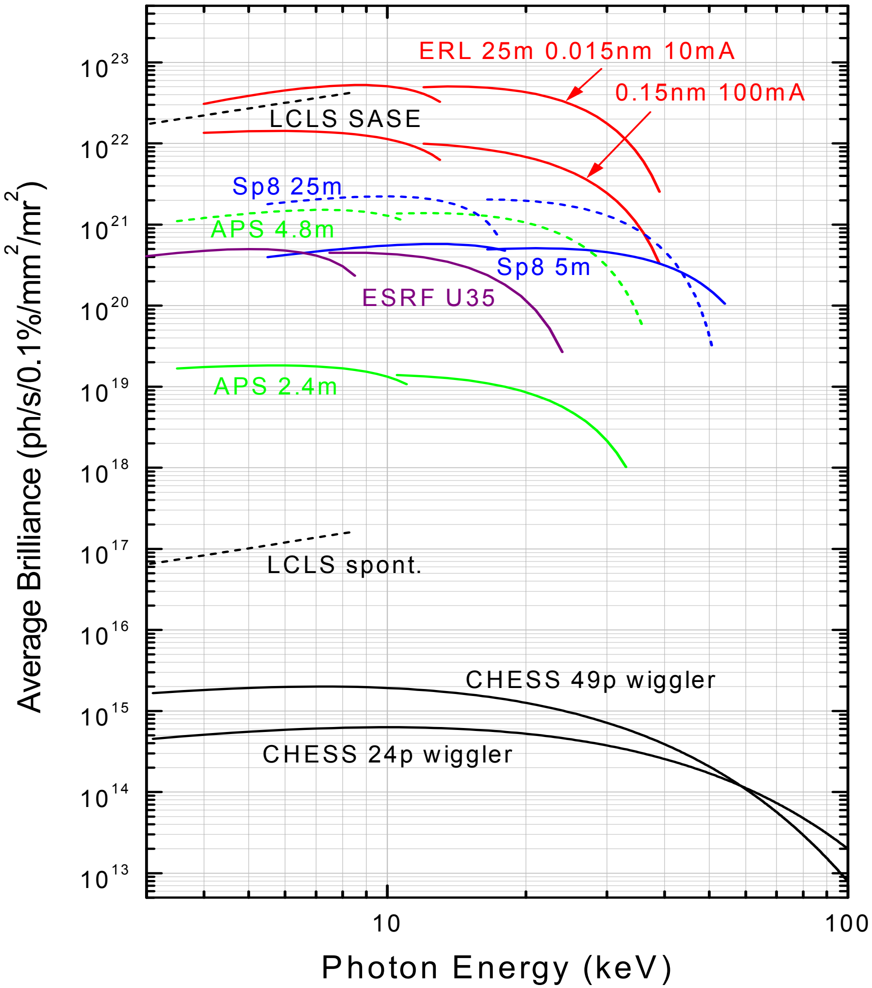

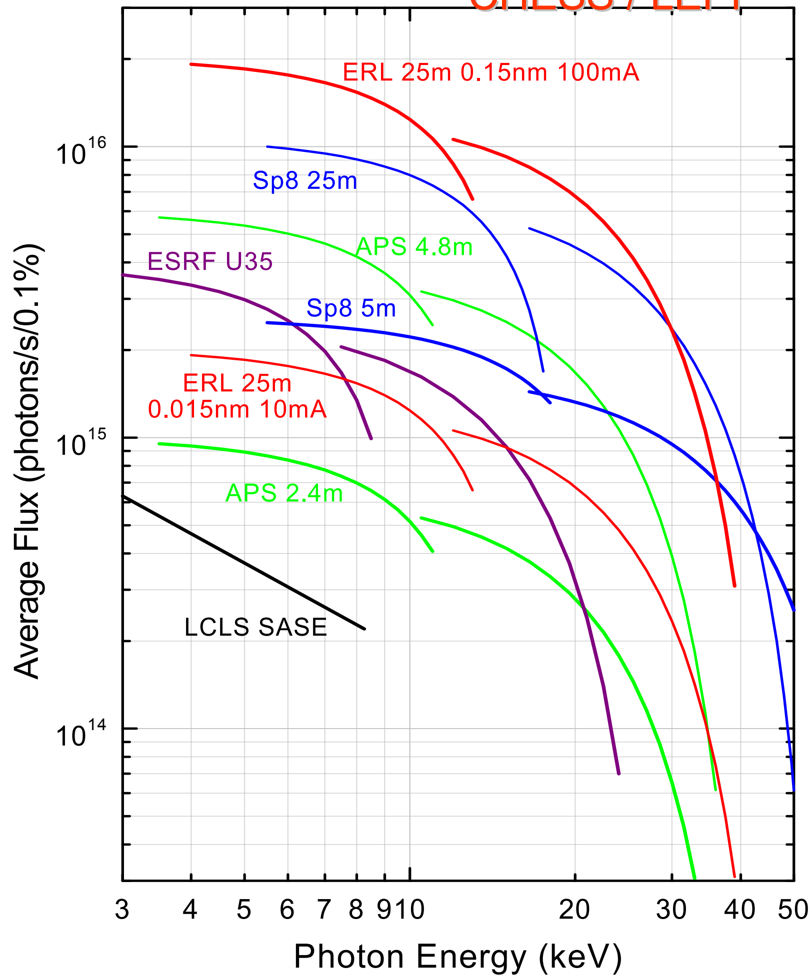

Courtesy: Qun Shen, CHESS Technical Memo 01-002, Cornell University

Short Pulses

- In high brilliance mode, with bunch lengths above several mm, there shouldn't be any problem with the micro m emittance level.
- There is great interest in finding short-pulse (<100 fsec) modes of operation.
- CSR is probably the emittance limiter for short-bunch operation, and I think it unlikely that one would be able to run short bunches and high brightness simultaneously. On the plus side, I don't think this is a "problem" for the users I've interacted with. My guess is that we'll lose 1-2 orders of magnitude in brilliance going to short pulses; this result is still far better than any proposed competitor.
- The curve brilliance vs. charge for constant bunch length will require some sort of simulation beyond what can be done easily now. Having this curve is EXTREMELY important for evaluating a short-bunch mode of operation. One should sit at the top of this curve for maximum short-pulse brilliance, whatever the anticipated repetition rate.

ERL Peak Brilliance and Ultra-Short Pulses

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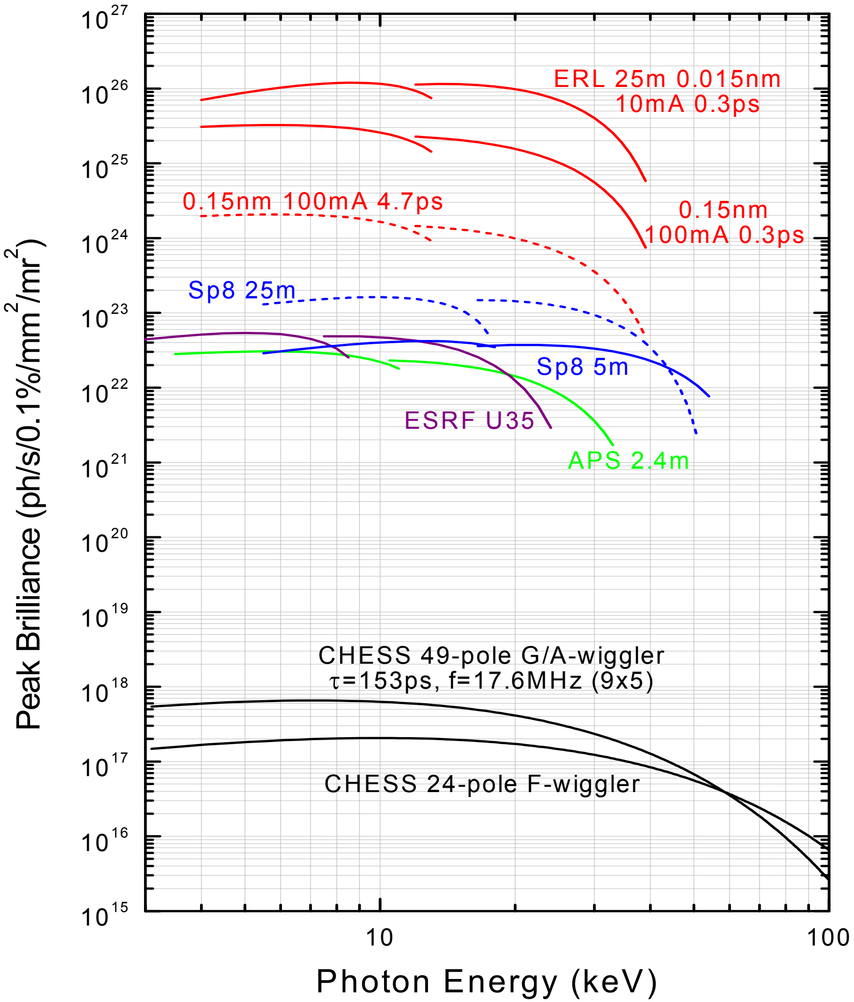

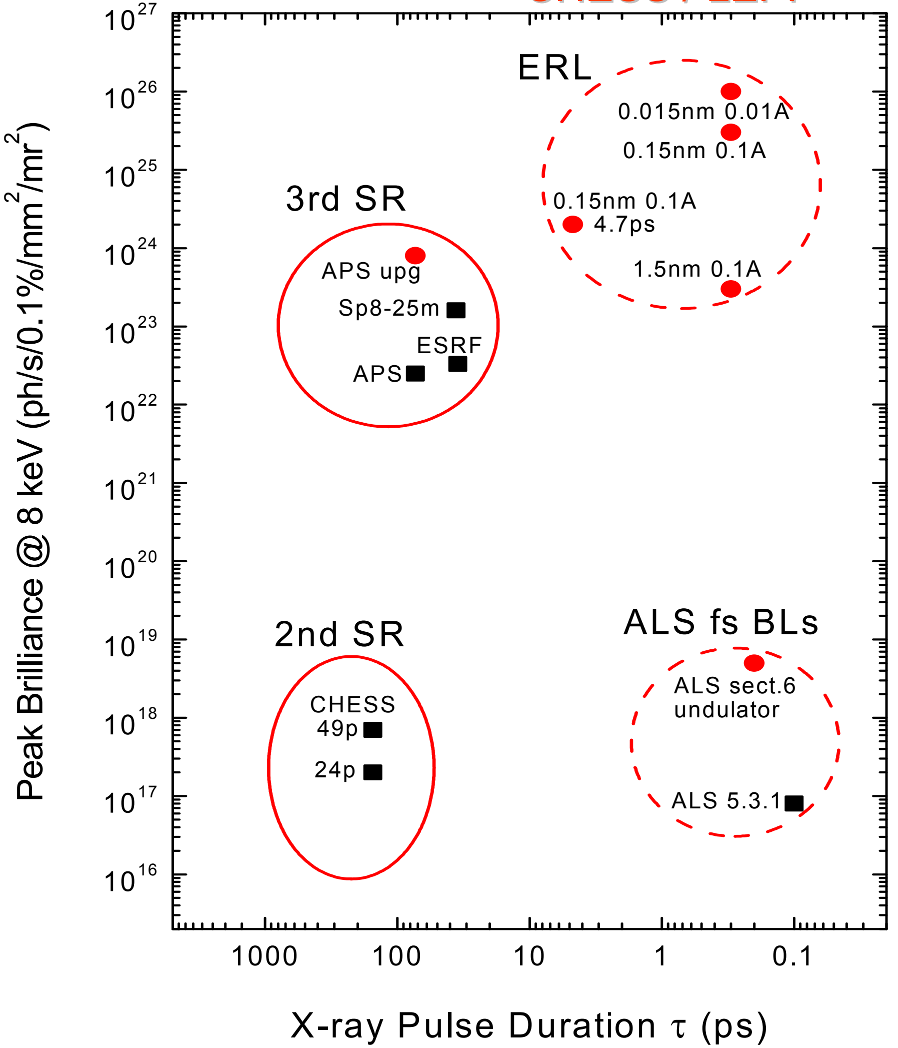

Courtesy: Q. Shen, I. Bazarov

Phase I ERL

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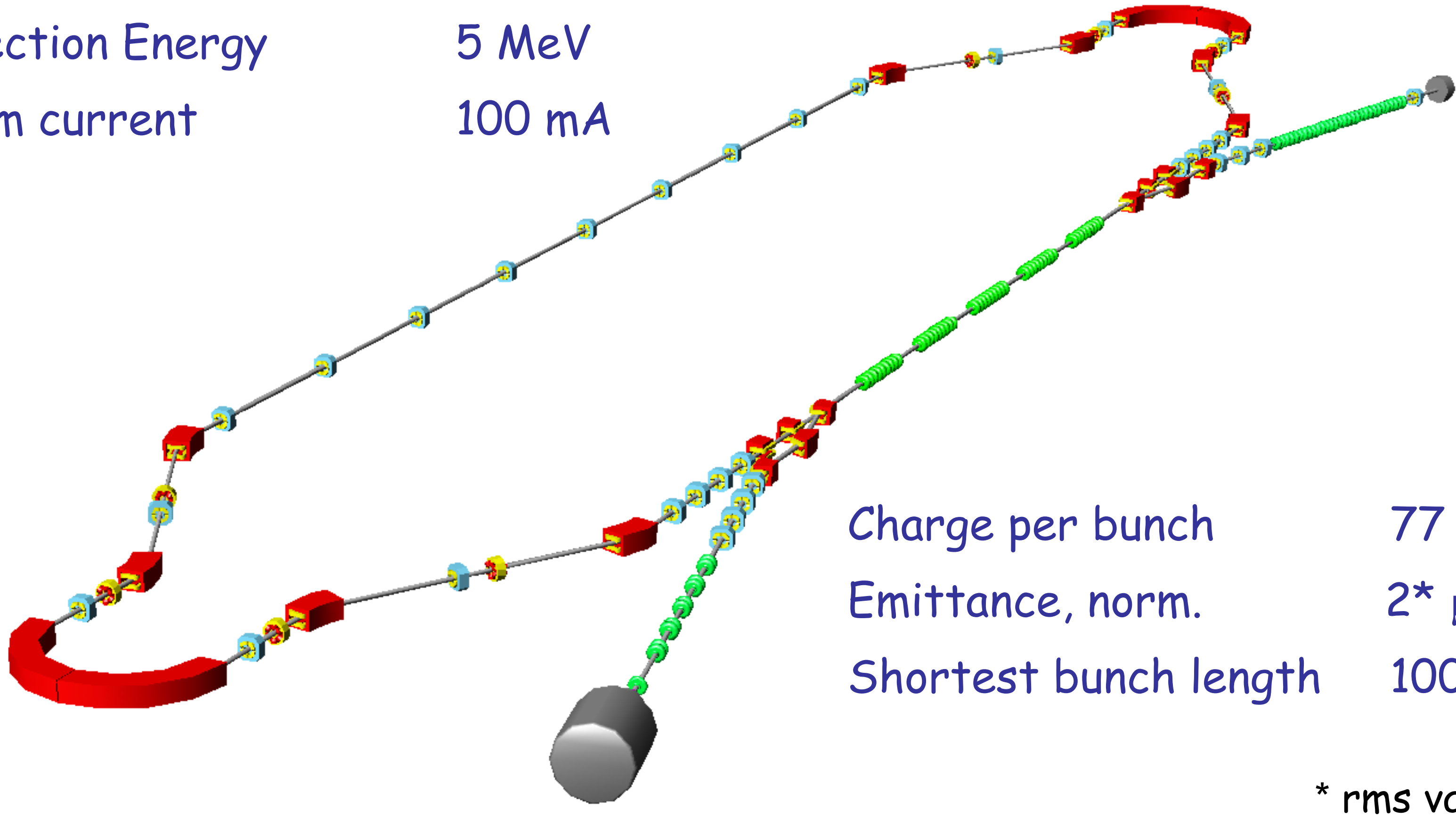
Beam Energy	100 MeV
Injection Energy	5 MeV
Beam current	100 mA



Charge per bunch	77 pC
Emittance, norm.	2* μm
Shortest bunch length	100* fs

* rms values

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Simulations Results (E_{inj}=5 MeV)

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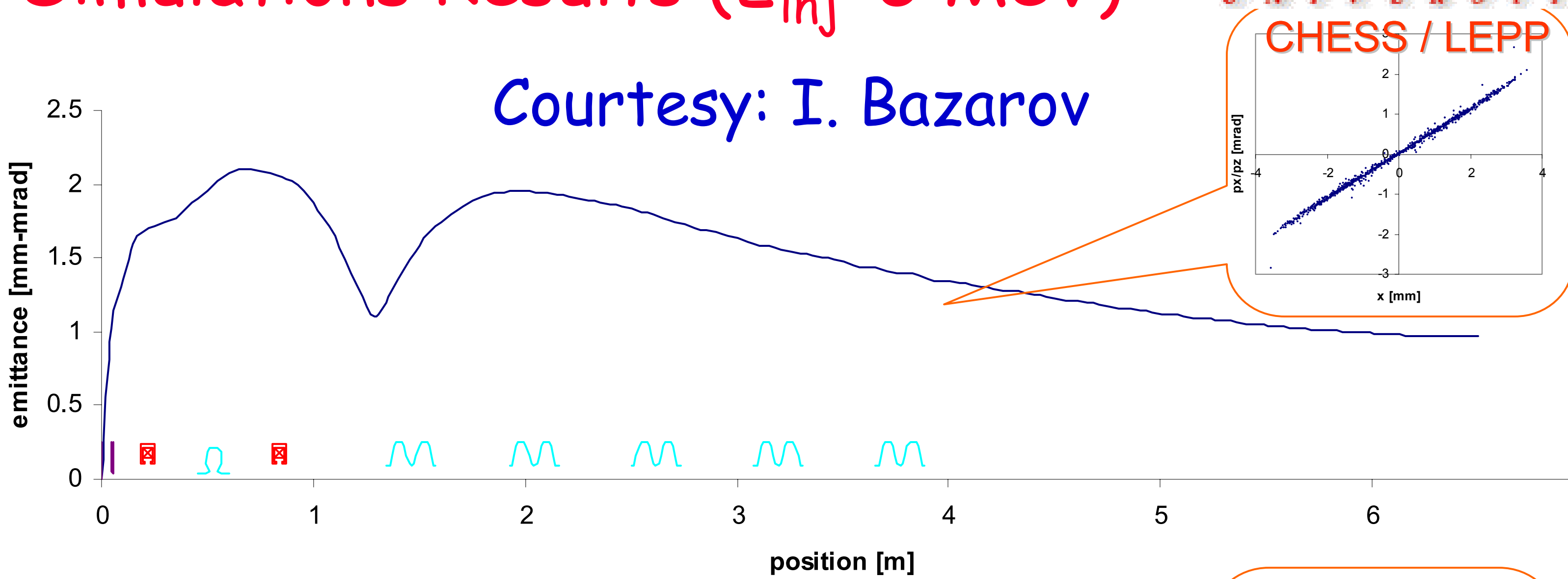
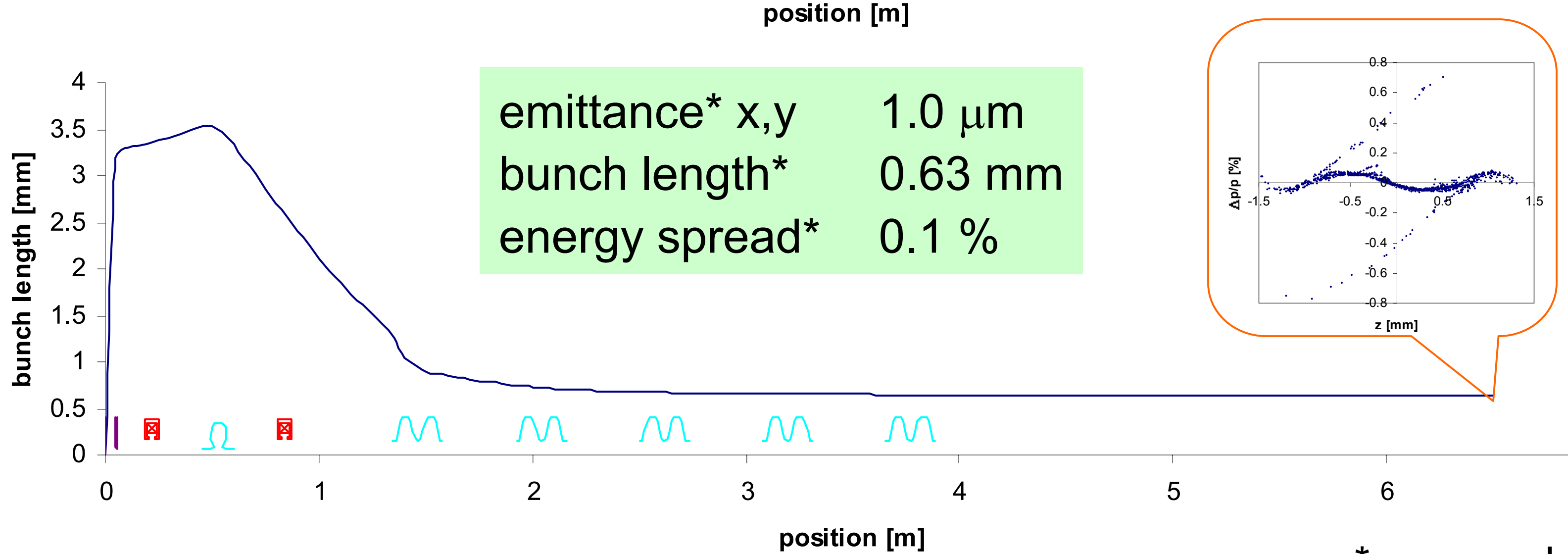
Courtesy: I. Bazarov



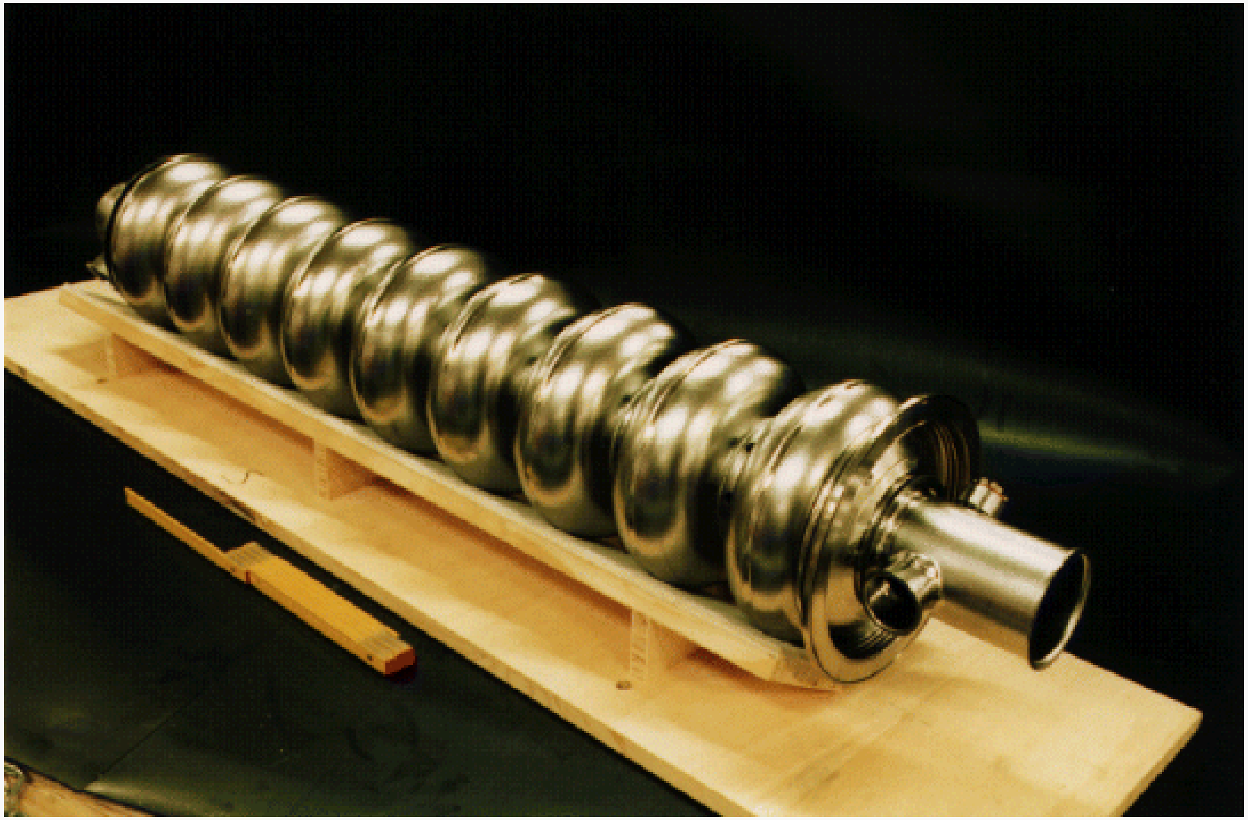


emittance* x,y	1.0 µm
bunch length*	0.63 mm
energy spread*	0.1 %

* r.m.s. value

Superconducting RF Technology

9-cell 1.3 GHz cavity



Superconducting RF cavities (Q ~ 10^{10} @ 20 MV/m)

Accelerator Physics & Technology

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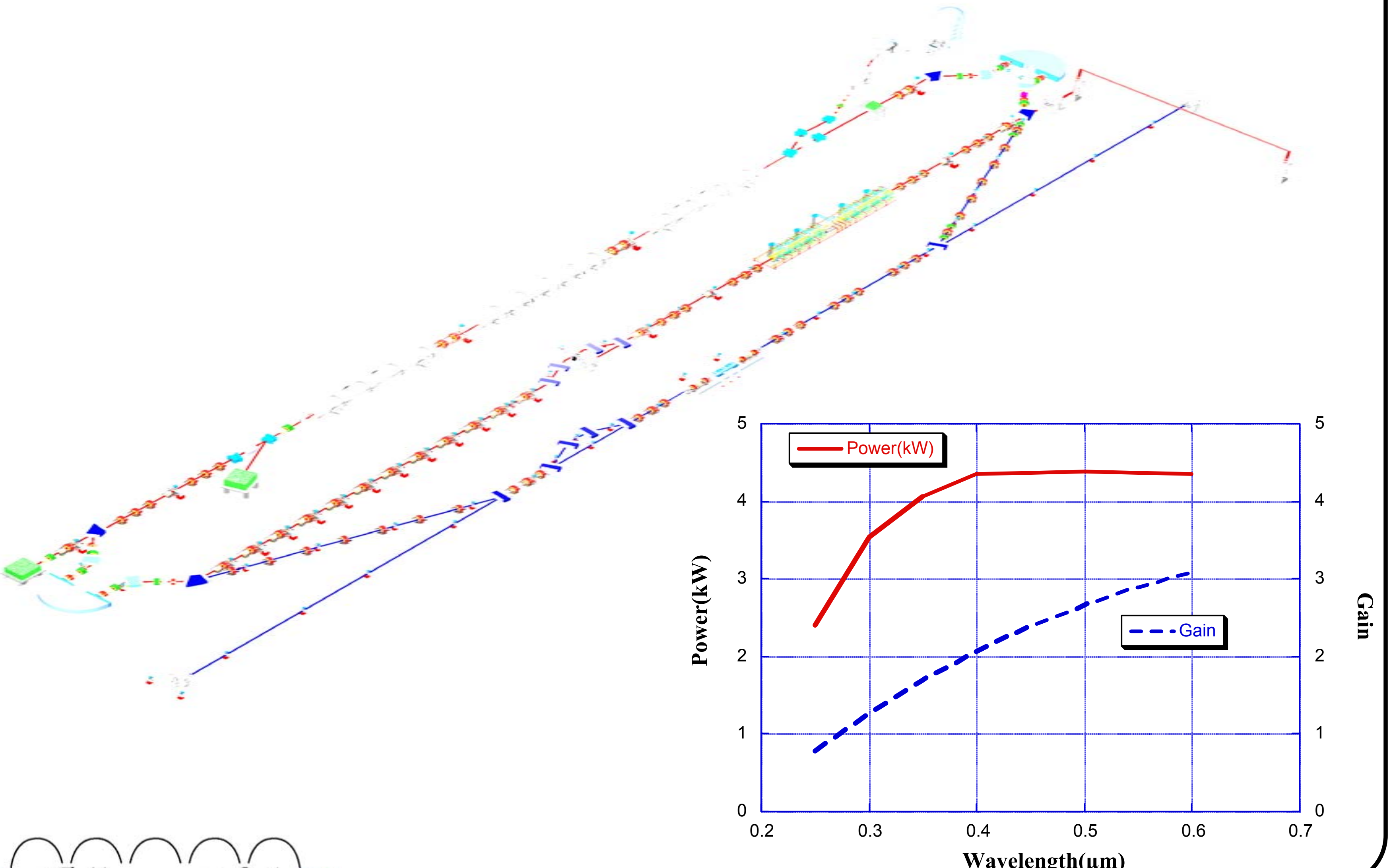
- Low emittance production & preservation
  - Achieving thermal emittance from gun (emittance compensation)
  - CSR, wakes (77 pC, not 1 nC!)
- Photocathode longevity at high average current (vacuum)
- Longitudinal phase space preservation in bunching (curvature correction)
- BBU in the main linac (HOMs damping)
- Beam loss ~ μA (halo)
- Highest Q_0 possible (reduced heat load and best efficiency)
- Highest Q_L possible (fighting microphonics)
- Diagnostics …

IR FEL 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

Conclusions

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- In this talk I've introduced the ideas of Beam Recirculation and Energy Recovery and discussed how these concepts may be combined to yield a new class of accelerators that can be used in many interesting applications. I've given you some indication of the historical development of recirculating SRF linacs.
- I've given you some indication of the current status of the single existing recirculating high energy linac, and of the highest average current energy recovered linac in existence.
- The present knowledge on beam recirculation and its limitations in a superconducting environment, leads us to think that recirculating accelerators of several GeV energy, and with beam currents approaching those in storage ring light sources, are possible.
- Cornell University, in collaboration with Jefferson Laboratory has proposed to the United States National Science Foundation to build a prototype superconducting energy recovery linac as a proof-of-principle for the high average current injector, and as a way to investigate in detail some of the limitations of ERLs.

HOM Power

- High average current, short bunch length beams in srf cavities excite HOMs. Power in HOMs, primarily longitudinal:

$$P_{HOM} = k_{||}\, Q^2\, f_{bunch}$$

- For I_{ave}= 100 mA, Q = 0.5nC $\Rightarrow$ P_{HOM}~ 1 kW per cavity for $k_{||}$=10.3 V/pC at σ_z~ 0.7mm

- In the IRFEL: I_{ave}= 5 mA, P_{diss}~ 6 W

- Fraction of HOM power dissipated on cavity walls depends on the bunch length

- It can potentially limit I_{ave} and I_{peak} due to finite cryogenic capacity

HOM Power Dissipation: Theory

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- The fraction of HOM power dissipated on cavity walls increases with HOM frequency, due to $Q_0 \sim \omega^2$ degradation from BCS theory
- We developed a model that estimates fraction of power dissipated on the walls and specifies HOM-power extraction efficiency required
- We found:
  - > 90% of HOM power is in modes < 100 GHz
  - Power dissipated on the cavity walls is a strong function of bunch length, $\sigma^{-5/2}$
  - Fraction of power dissipated on the walls is much less than the fundamental mode load

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Frequency Distribution of HOM power

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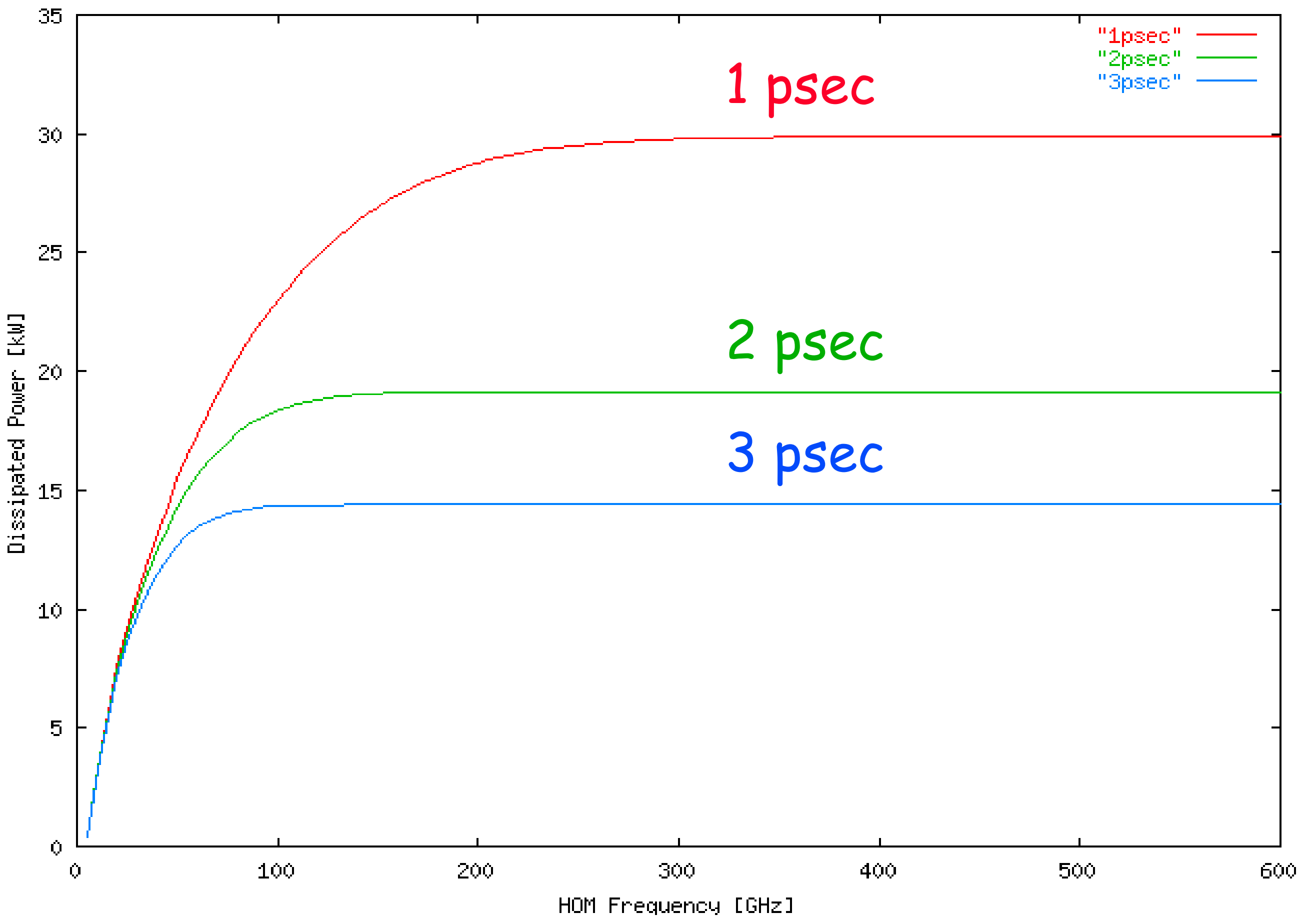
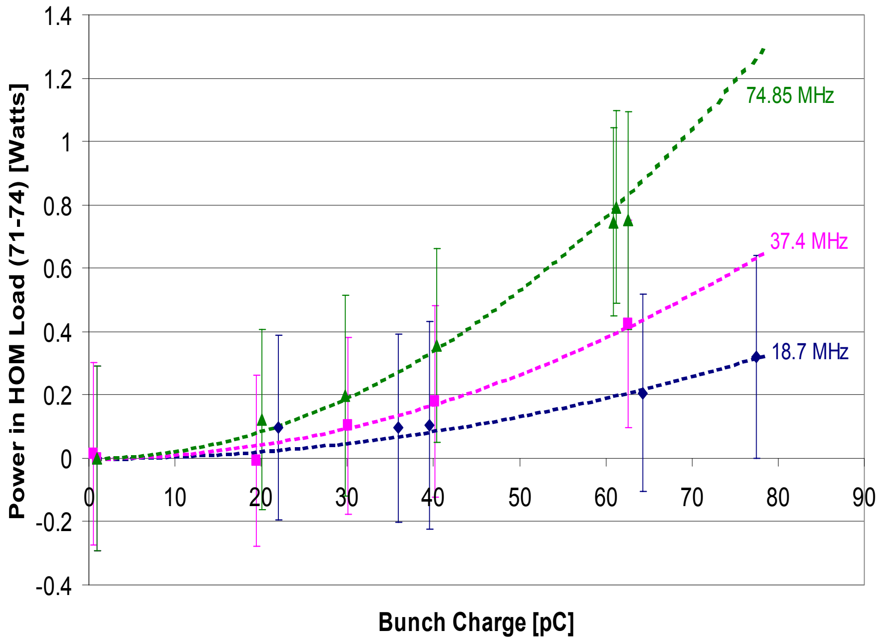
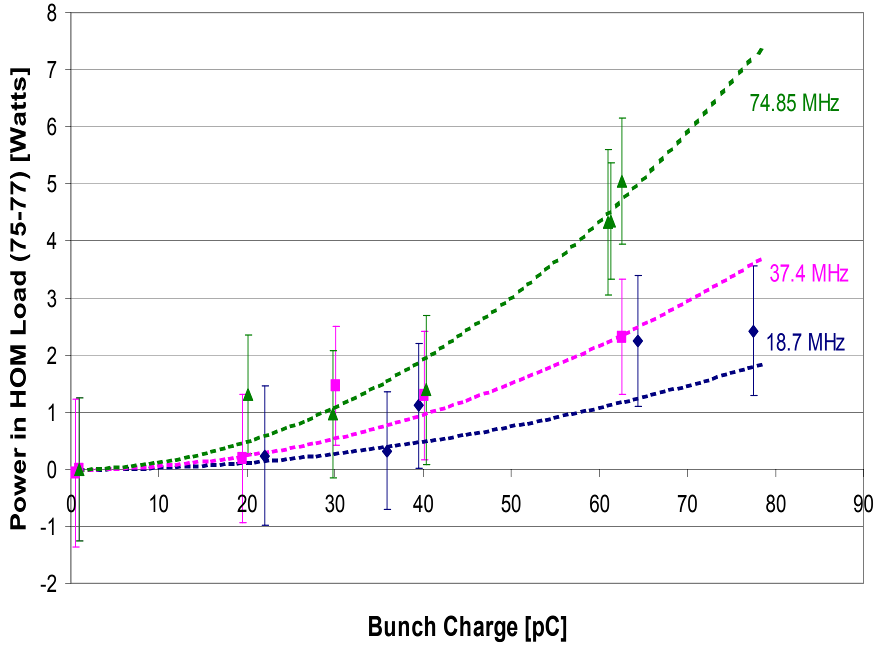


HOM Power: Experiment

- HOM power dissipation may impose design choices to improve cryogenic efficiency
- HOM power was measured with temperature diodes placed on the two HOM loads of the 5-cell CEBAF cavity
- Measurements were repeated at different values of the bunch charge and bunch repetition frequency

HOM Power vs. Bunch Charge





$k_{||}^{(1)} = 1.4$ V/pC + $k_{||}^{(2)} = 8.0$ V/pC

⇓

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

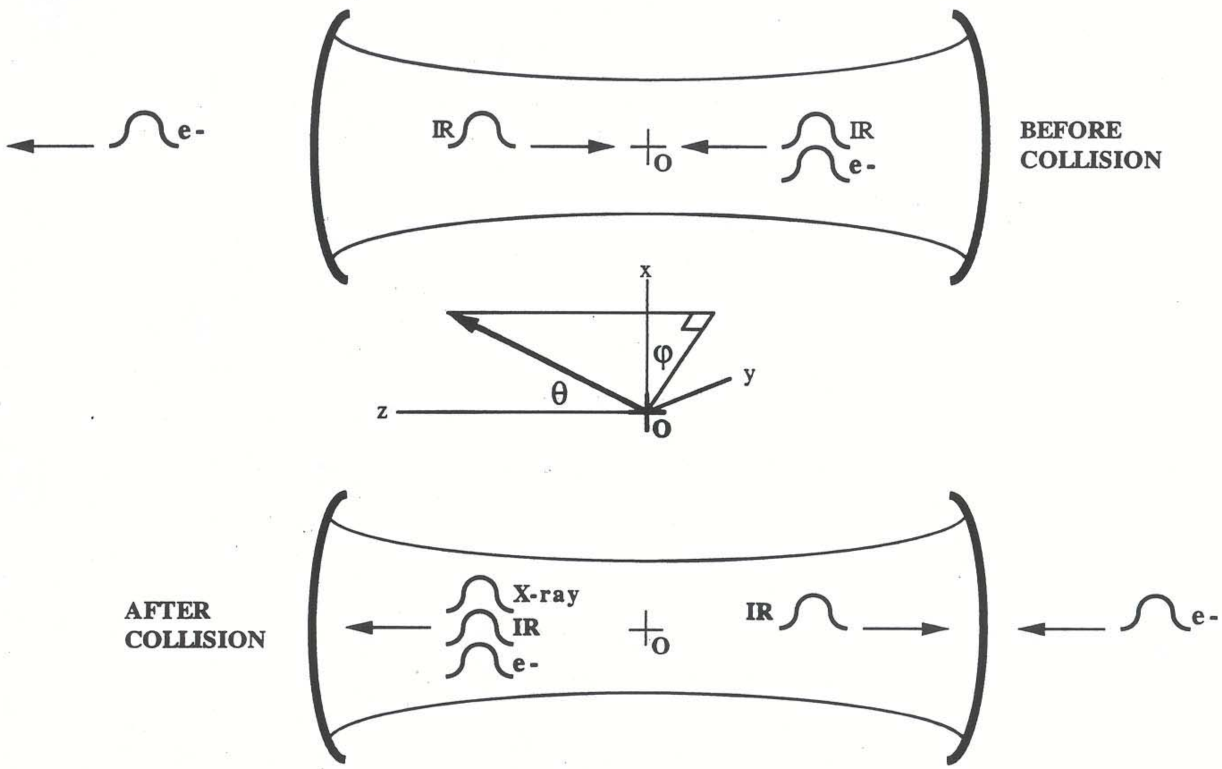
⇒ agreement within 15%

$k_{||}^{URMEL} = 11.0$ V/pC

Short-Pulse (100-1000 fsec) X-Rays –

- About 4 years ago, after a Science article by Schoenlein, et al., I spent some time trying to figure out how we could do same work at Jlab. Settled on a Thomson scatter source that has recently produced a substantial X-ray flux.
- In mean time LBNL proposed short-pulse source based on short-pulse laser and the Inverse FEL interaction.
- In this idea, only a small portion (<1%) of the beam is actually used to generate X-rays. By comparison, a CEBAF-like machine can achieve at least 1% of ½ A, and in principal make at least as many X-rays.
- The only question is whether you can make the pulses short enough.
- The answer is yes, as we've seen, under 100 fsec was done many years ago on the nuclear physics accelerator.

SCATTERING GEOMETRY



SCATTERING GEOMETRY

60 sec FEL Short-pulse X-ray Spectrum

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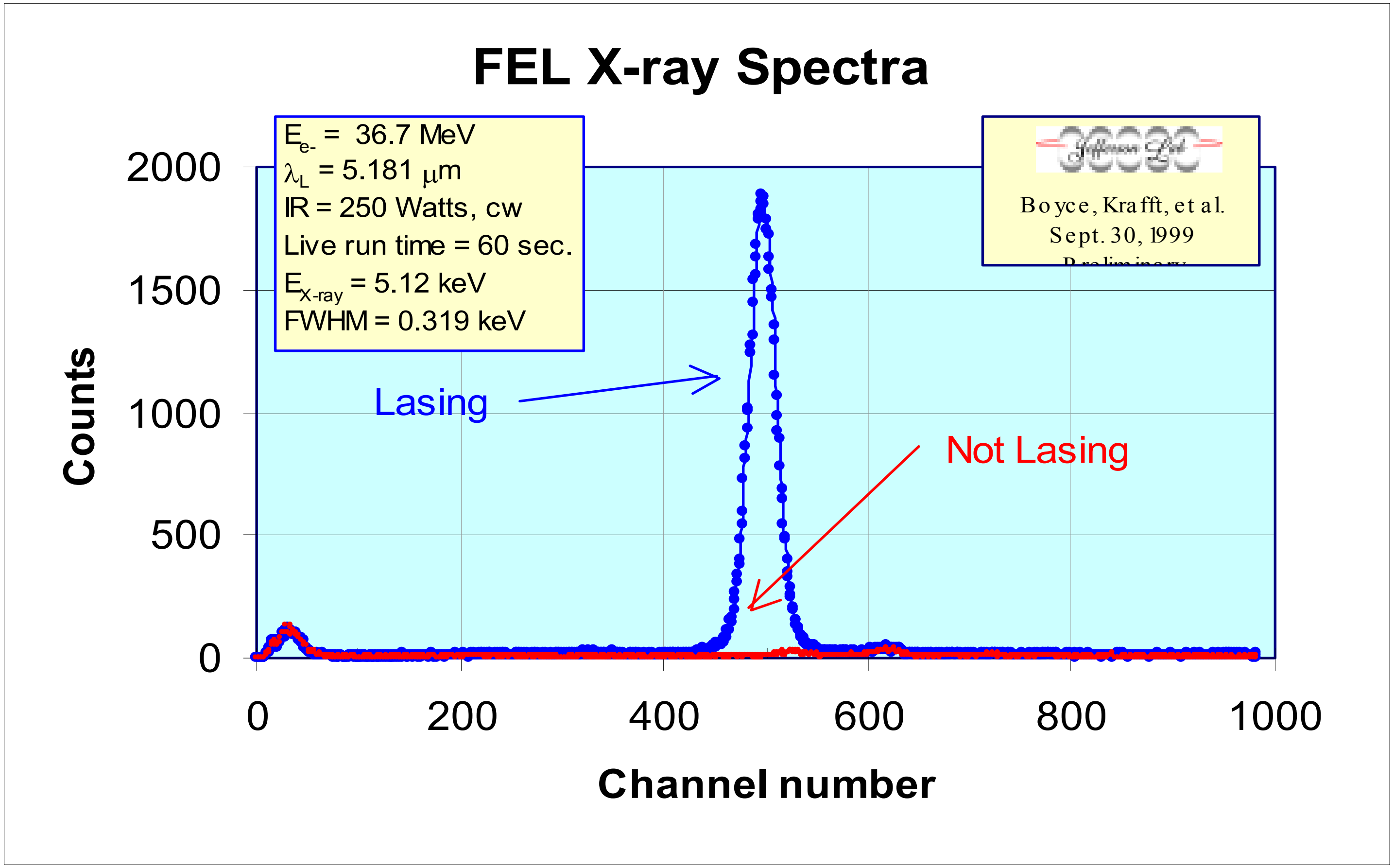

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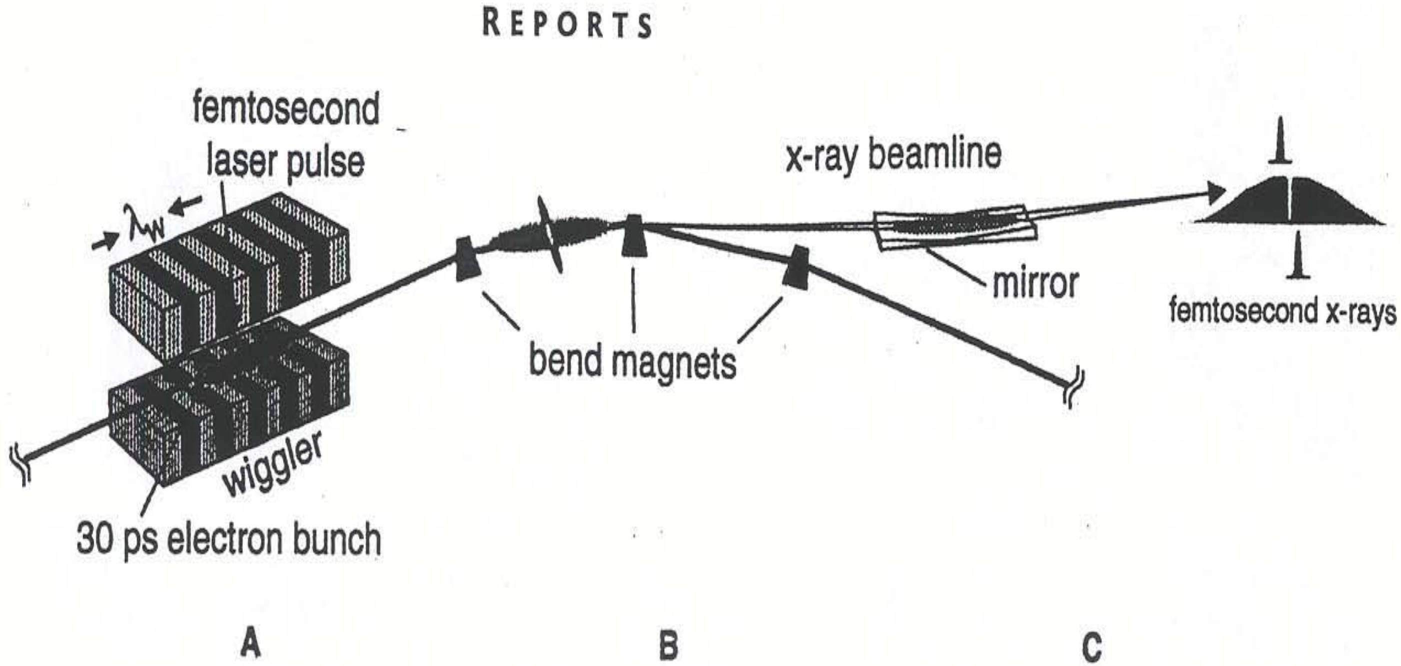
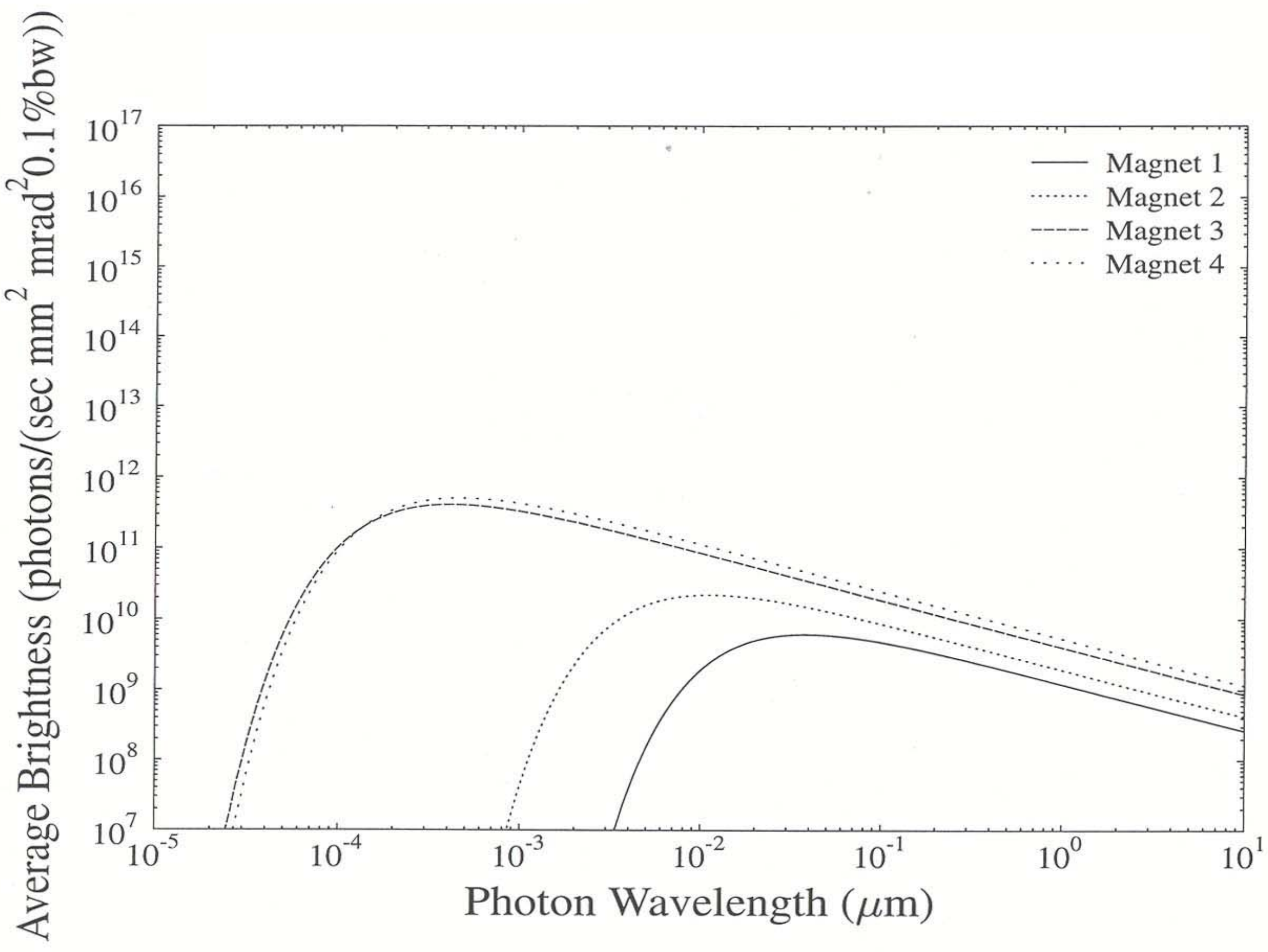
Berkeley Short Pulse X-ray Facility

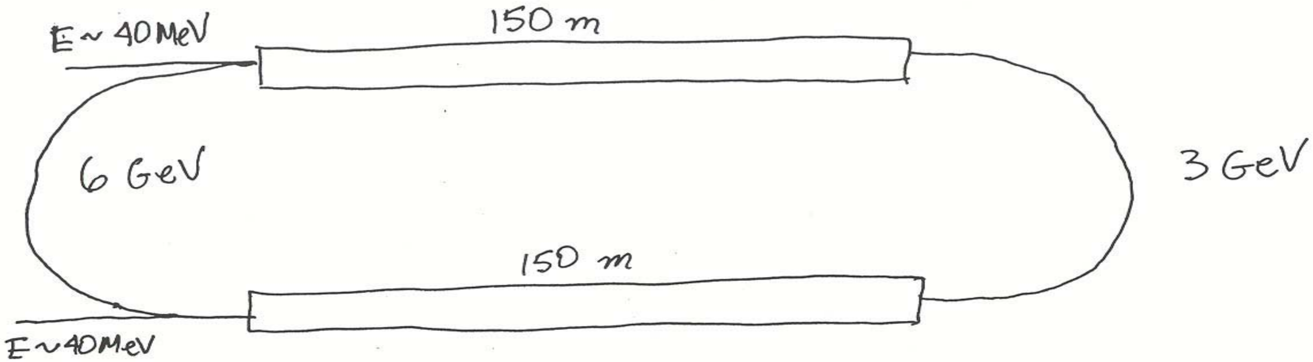


AVERAGE BRILLIANCE FROM CEBAF BENDS



Viewslide at ICFA 4th Gen., April 1999

INTERESTING?



$\varepsilon \sim 10^{-9}$ m rad

$I \sim$ 10-20 mA

$\ell_B \sim$ 100 fsec $f_B \sim$ 1-10 MHz

$\frac{\Delta E}{E} \sim$ SEVERAL $\times 10^{-5}$

SEVERAL \$100 M

Interesting New Direction?

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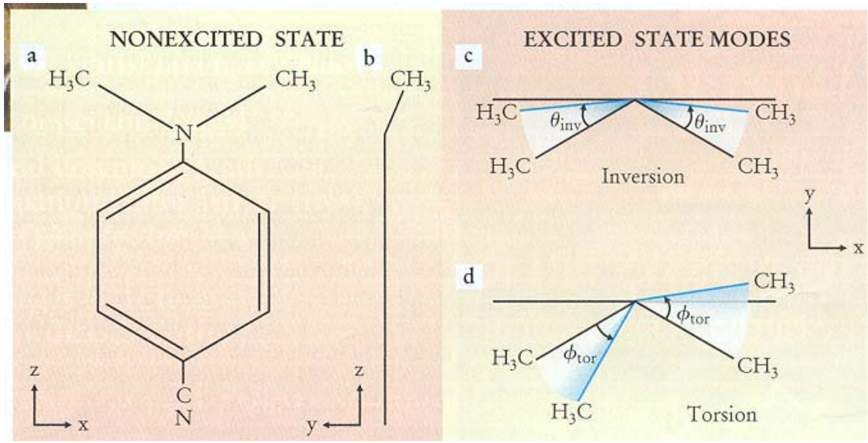
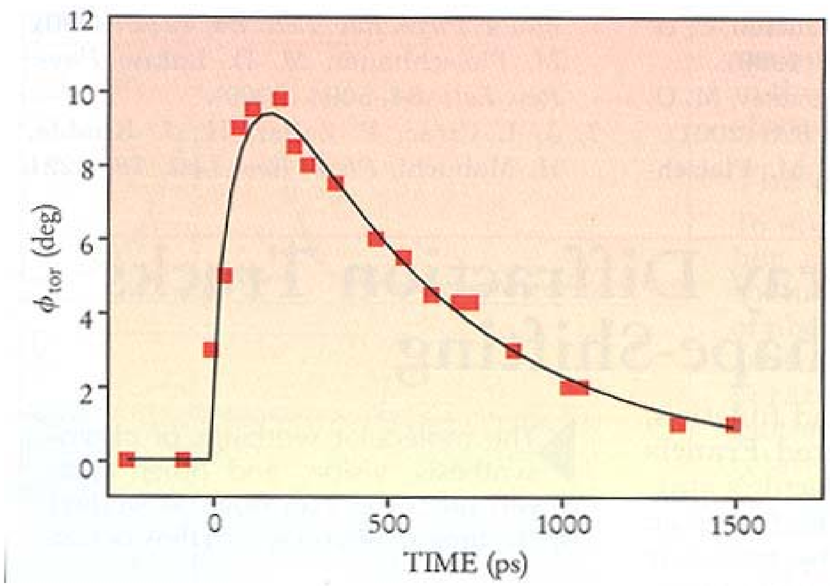
CHESS / LEPP



$C_9H_{10}N_2$ Bending

Techert, Schotte, and Wulff, March PRL (2001), quoted in *Physics Today*



Thomas Jefferson National Accelerator Facility