Accelerator Physics of Recirculating Electron Accelerators

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Talk Outline

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

USPAS Course Outline

COURSE: RECIRCULATING LINEAR ACCELERATORS

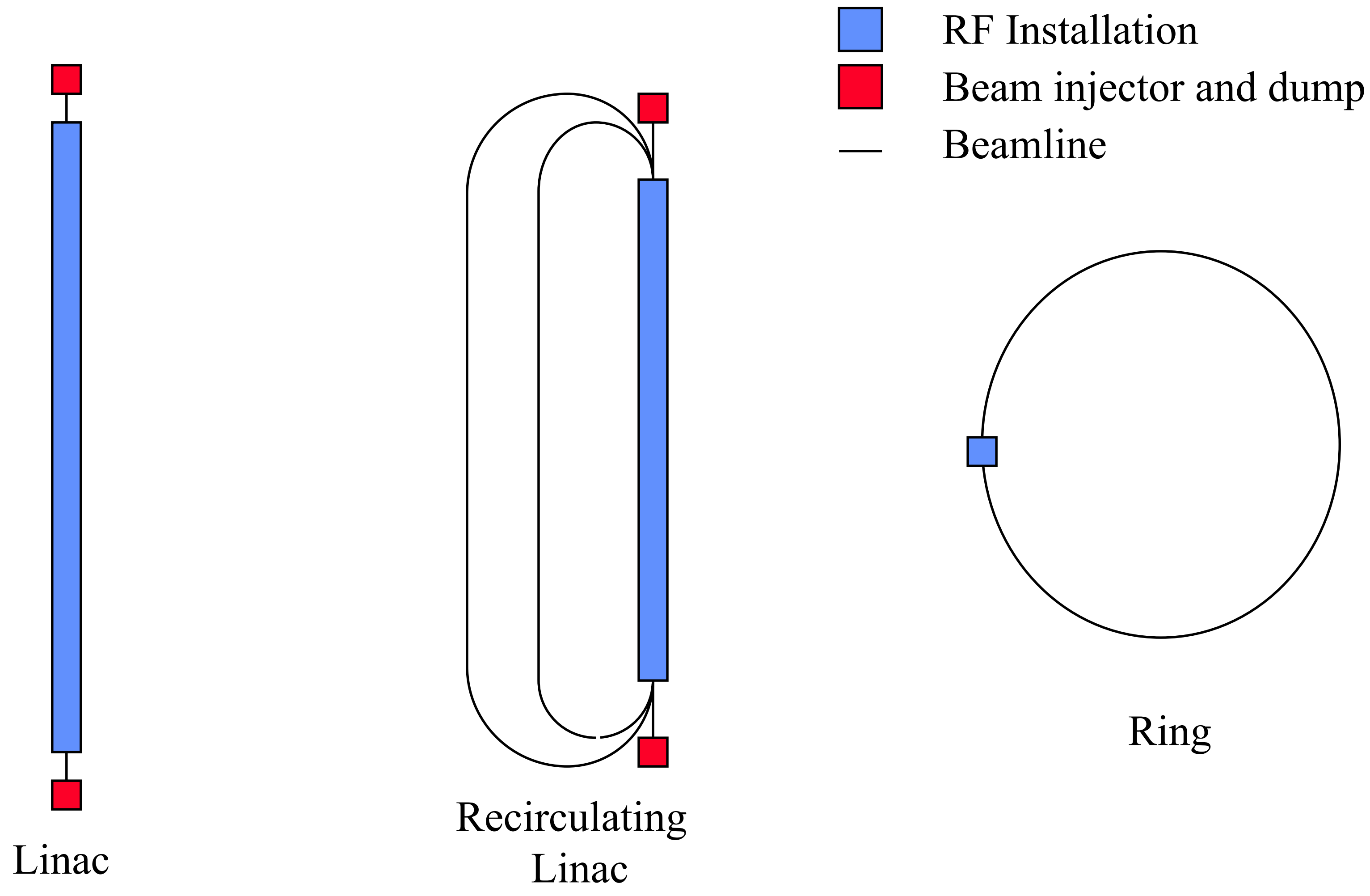
1. INTRODUCTION TO RECIRCULATING LINACS
   - Properties of Linacs (GK 1 Feb.)
   - Why Recirculate? (GK 1 Feb.)
   - Duty Factor, CW Operation (LM Tues., 6 Feb., 3:30-4:30, ARC 231)
   - Superconducting RF (SRF) (LM Tues., 6 Feb., 3:30-4:30, ARC 231)
2. EXAMPLES OF RECIRCULATING LINACS
   - Microtrons (GK Tues., 13 Feb., 3:30-4:30, ARC 231)
   - Polytrons (GK Tues., 13 Feb., 3:30-4:30, ARC 231)
   - Independent Orbit Recirculators: HEPL, Darmstadt, CEBAF (LM Tues., 20 Feb., 3:30-4:30, ARC 231)
   - Energy Recovery Linacs (ERLs)(LM Tues., 20 Feb., 3:30-4:30, ARC 231)
3. SINGLE PARTICLE DYNAMICS
   - Longitudinal Dynamics (GK Mon. and Tues., 26 and 27 Feb., 3:30-4:30, ARC 231)
     - Phase Stability
     - Longitudinal gymnastics
     - Correcting RF curvature (T566 or sextupoles)
   - Transverse Dynamics (DD Mon., 5 March, 3:30-4:30, ARC 231)
   - Basic considerations
   - Energy ratio limits
   - Beam Loss
4. RF ISSUES AND BEAM LOADING
   - Cavity Equations (LM Tues., 6 March, 3:30-4:30, ARC 231)
   - Phasors (LM Tues., 6 March, 3:30-4:30, ARC 231)
   - Optimization of loaded Q (LM Tues., 6 March, 3:30-4:30, ARC 231)
   - RF Instruments (GK Tues., 13 March, 3:30-4:30, CC L104 and Mon., 19 March, 3:30-4:30, ARC 231)
   - Energy Spread estimates (LM Tues., 20 March, 3:30-4:30, ARC 231)

5. COLLECTIVE EFFECTS
    - Multibunch
        - Transverse Instability (GK Mon., 26 March, 3:30-4:30, ARC 231)
          (JD Tues., 27 March, 3:30-4:30, CC L102)
          (RC Mon., 2 April, 3:30-4:30, ARC 231)
            - Cumulative
            - Multipass
                - Analytic formula for microtrons
                - TDBBU
        - Longitudinal Instability (LM Mon., 9 April, 3:30-4:30, ARC 231)
        - Ions Effects (LM Tues., 10 April, 3:30-4:30, ARC 231)
    - Single Bunch
    - CSR (GK Tues., 3 April, 3:30-4:30, ARC 231)
    - Transverse BBU (LM Mon., 16 April, 3:30-4:30, ARC 231)
    - Longitudinal wakes (LM Tues., 17 April, 3:30-4:30, ARC 231)
    - RF Instability (LM Tues., 1 May, 3:30-4:30, ARC 231)

6. TECHNOLOGY FRONTIERS
    - Electron Sources (GK Mon., 30 April, 3:30-4:30, ARC 231)
    - HOM Power Dissipation (LM Mon., 7 May, 3:30-4:30, ARC 231)
    - SRF Performance (LM Tues., 8 May, 3:30-4:30, ARC 231)
        - Frequency and Temperature Optimization

7. FUTURE APPLICATIONS
    - CEBAF Physics Upgrades (GK Mon., 14 May, 3:30-4:30, ARC 231)
    - FELs (LM Tues., 15 May, 3:30-4:30, ARC 231)
    - Synchrotron Light Sources (ERL, PERL)
      (GK Mon., 21 May, 3:30-4:30, ARC 231)
    - Electron-Ion Collider (EIC) (LM Tues., 22 May, 3:30-4:30, ARC 231)

Schematic Representation of Accelerator Types



Comparison between Linacs and Storage Rings

- Advantage Linacs

  Emittance dominated by source emittance and emittance growth down linac

  Beam polarization “easily” produced at the source, switched, and preserved

  Total transit time is quite short

  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

- 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 it generates

Why Recirculate?

- A renewed general interest in beam recirculation has been driven by the success in Jefferson Lab's high average current FEL, and the realization that it may be possible to achieve beam parameters "Unachievable" in linacs without recirculation or storage rings.

  Recirculated linac light source: Beam power is (100 mA)(5 GeV)=500 MW. Realistically, the federal govt. will not give you a third of a nuclear plant to run a synchrotron source. Pulse lengths of order 100 fsec or smaller may be possible in a ERL source: "impossible" at a storage ring. Better emittance too.

  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

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

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

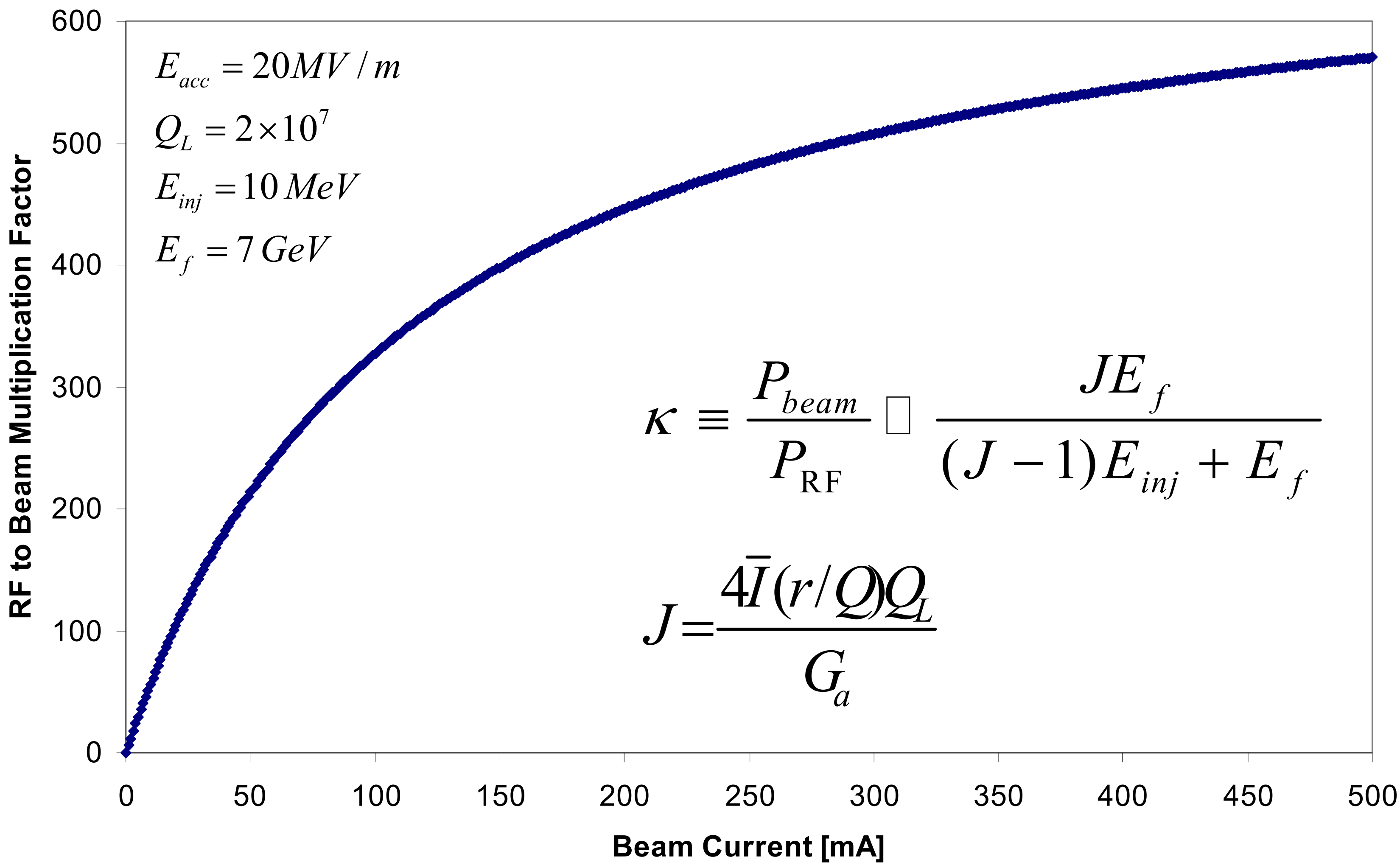
where P_{rf} is the RF power needed to accelerate the beam

- By the first law of thermodynamics (energy conservation!) $k < 1$ in any case that energy is NOT recycled out of the beam

- One the other hand, if energy IS very efficiently recycled out of the beam

$$k \approx 1/\eta >> 1$$

RF to Beam Multiplication Factor in an ideal ERL



Comparison Accelerator Types

Parameter	Electron Linac	Recirculated Linac	Ring
Accelerating Gradient[MV/m]	>50	1 NC, 10-20 SC	NA
Duty Factor	<1%	1	1
Average Current[mA]	<1	5 going to 100?	200
Average Beam Power[MW]	0.5	1.0 going to 700?	1400
Multiplication Factor	<1	<1 NC, 200? SC	1000
Normalized Emittance[mm mrad]	1	1	4
Bunch Length	100 fsec	100 fsec	20 psec

Best results by accelerator type, ? possibility, NC normal conducting, SC superconducting

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

- 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.

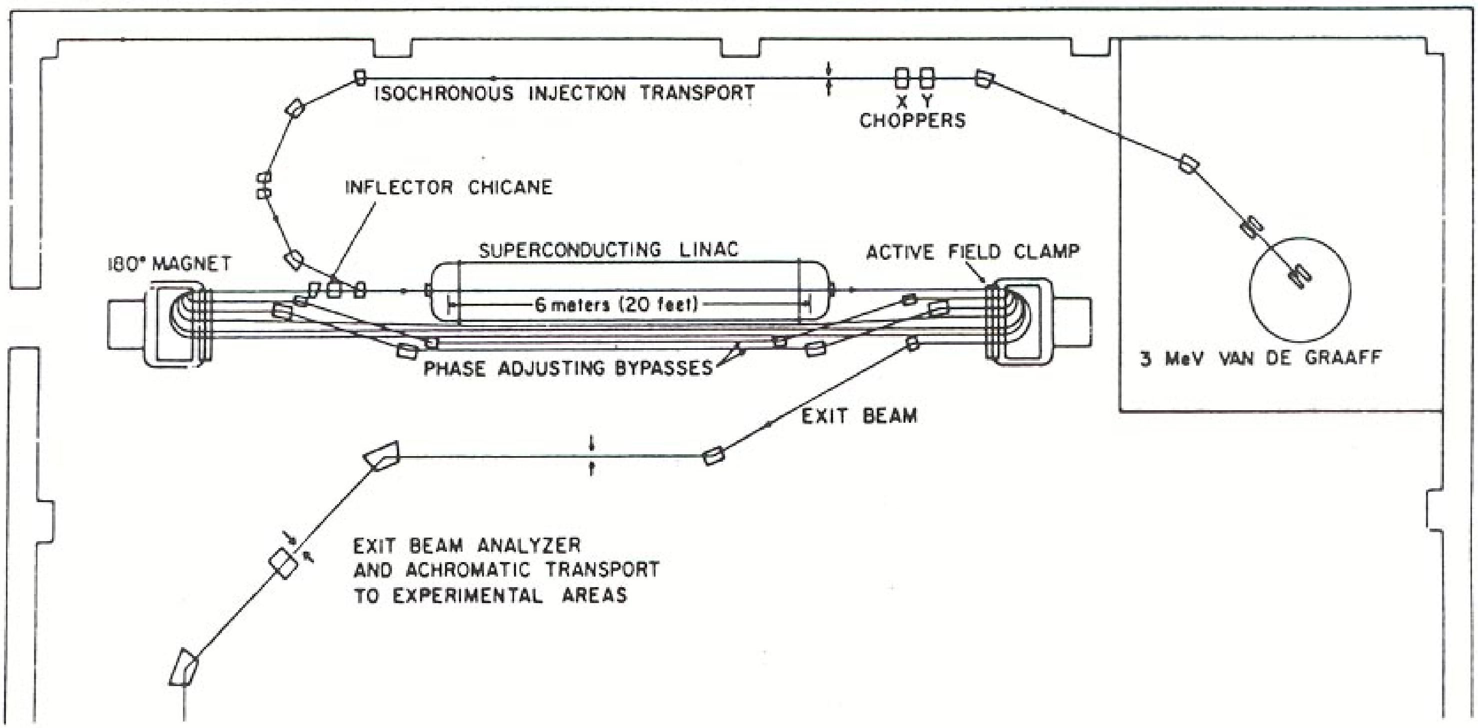
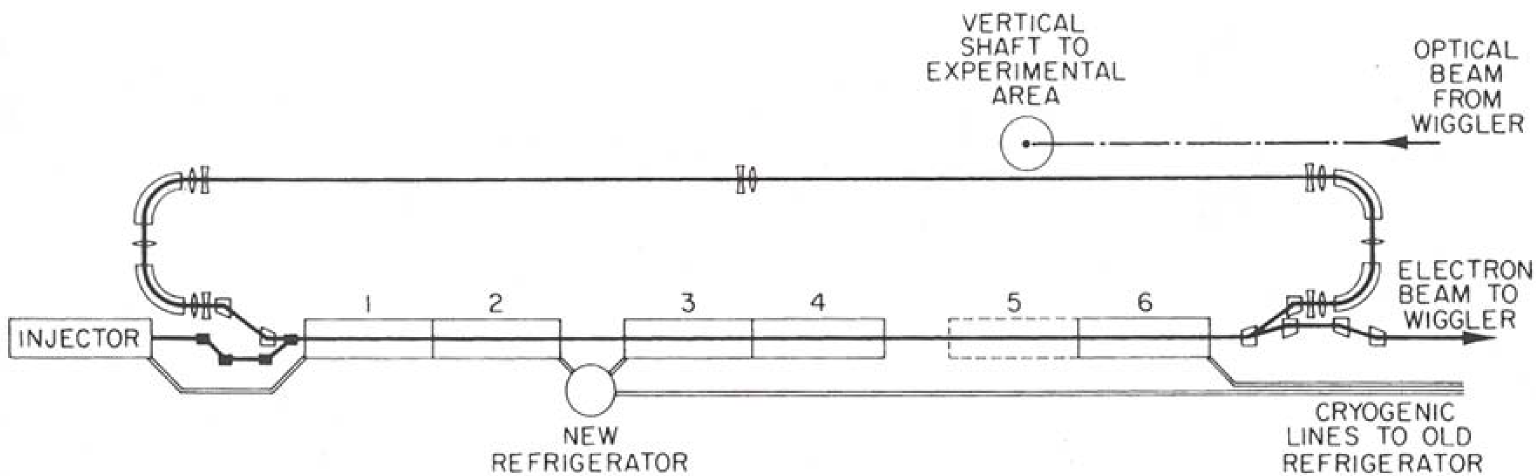


Figure 5.3 The second Illinois superconducting race-trace microtron, MUSL-2 (Axel *et al.*, 1977; © 1977 IEEE)

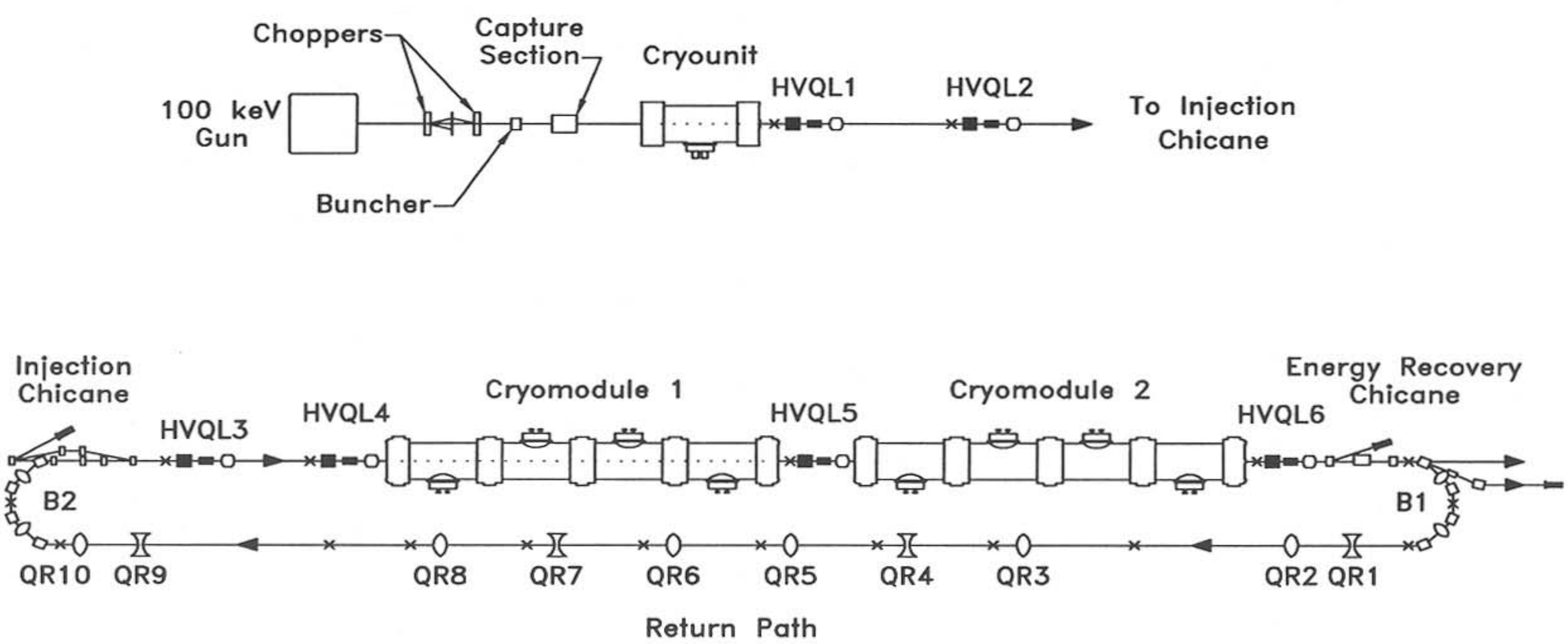
The SCA/FEL Energy Recovery Experiment

- 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.

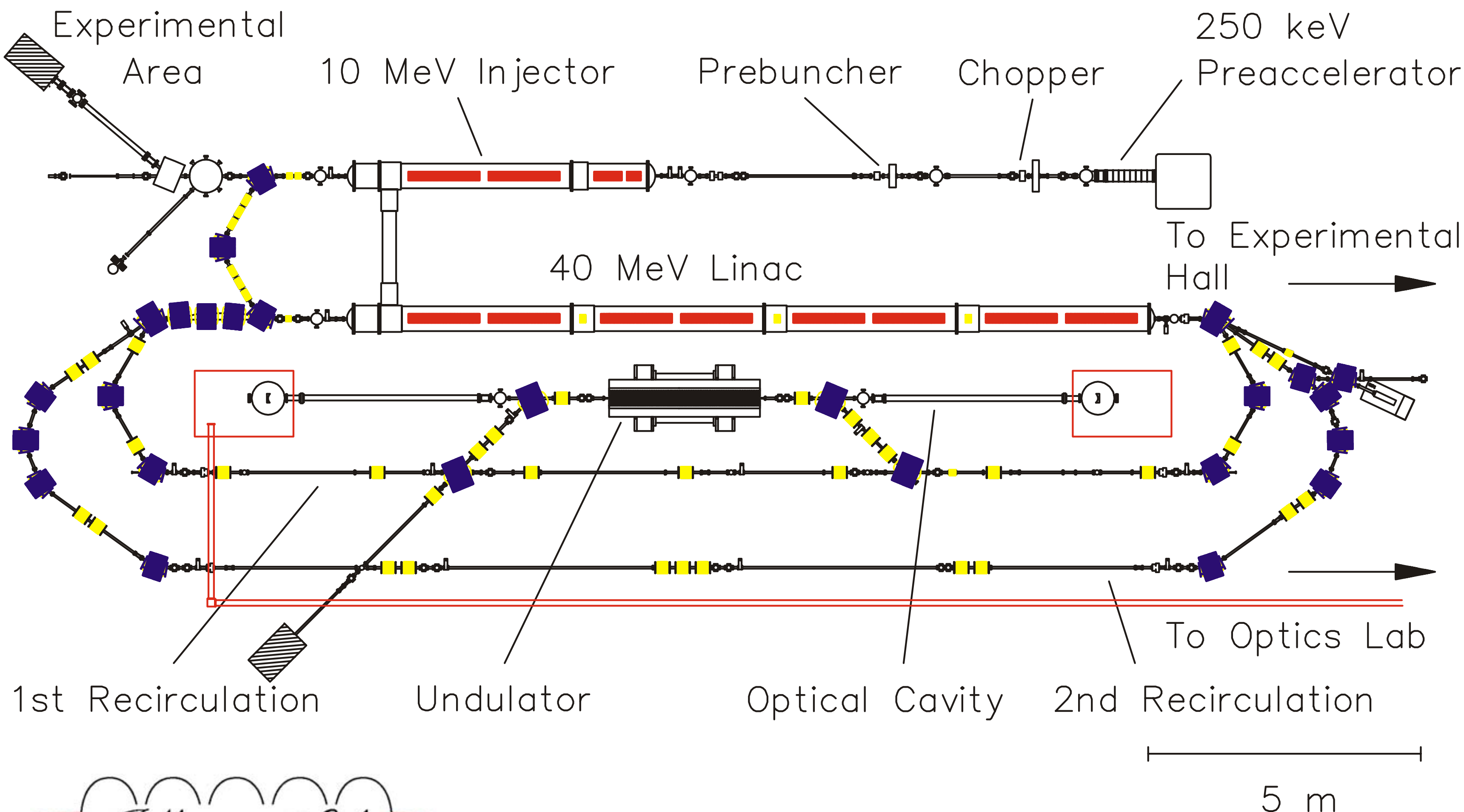


The CEBAF Injector Energy Recovery Experiment

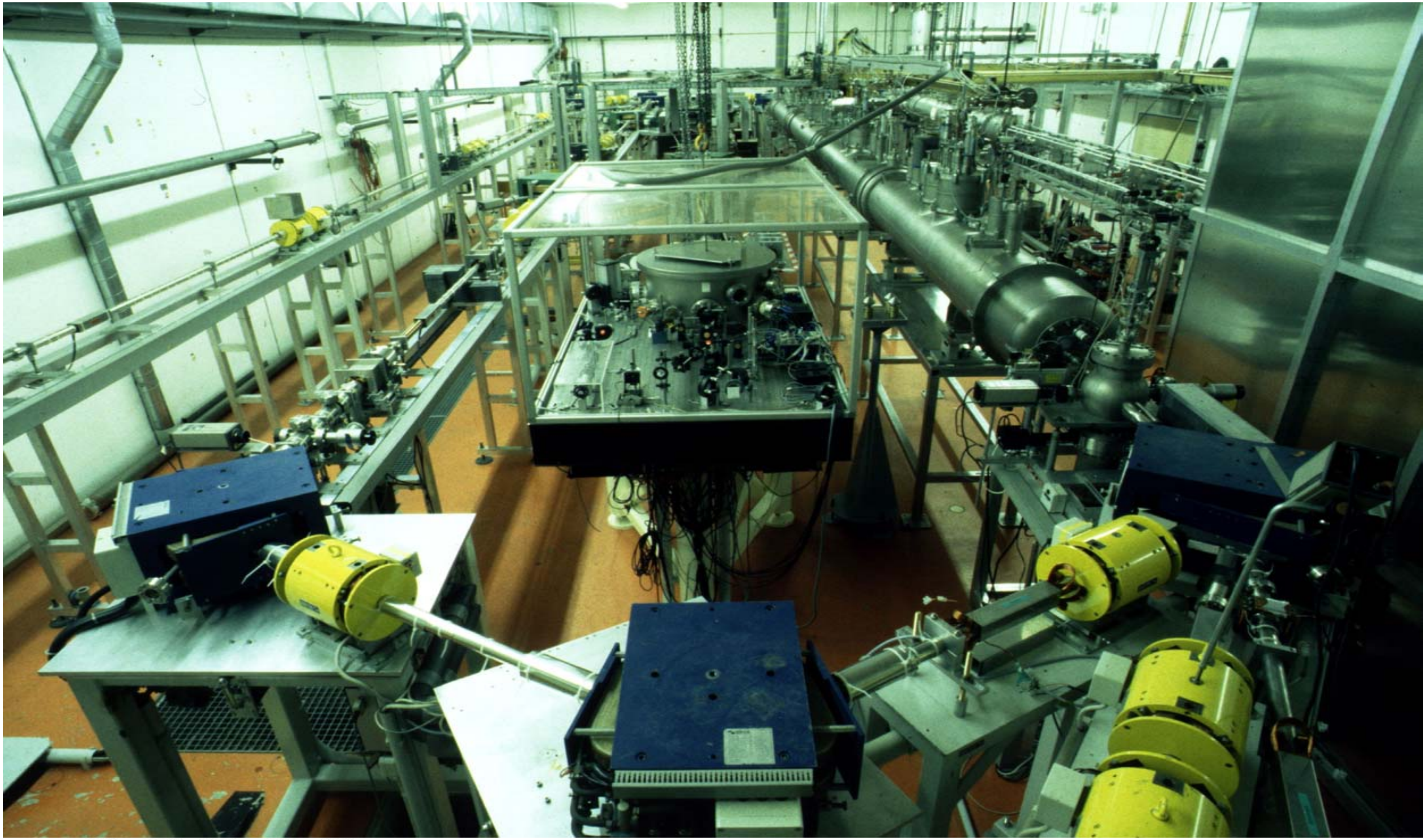
N. R. Sereno, "Experimental Studies of Multipass Beam Breakup and Energy Recovery using the CEBAF Injector Linac," Ph.D. Thesis, University of Illinois (1994)



Layout of S-DALINAC (Darmstadt)



S-DALINAC



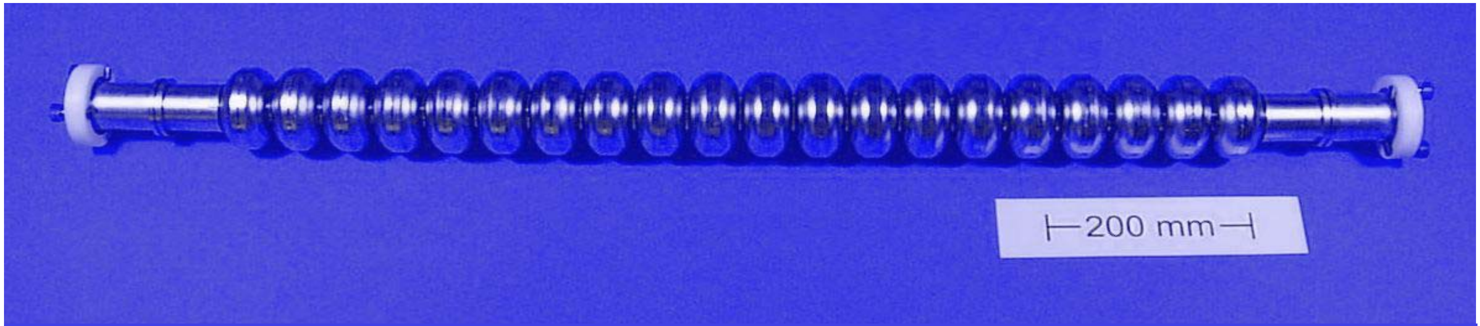
S-DALINAC Beam Parameters

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

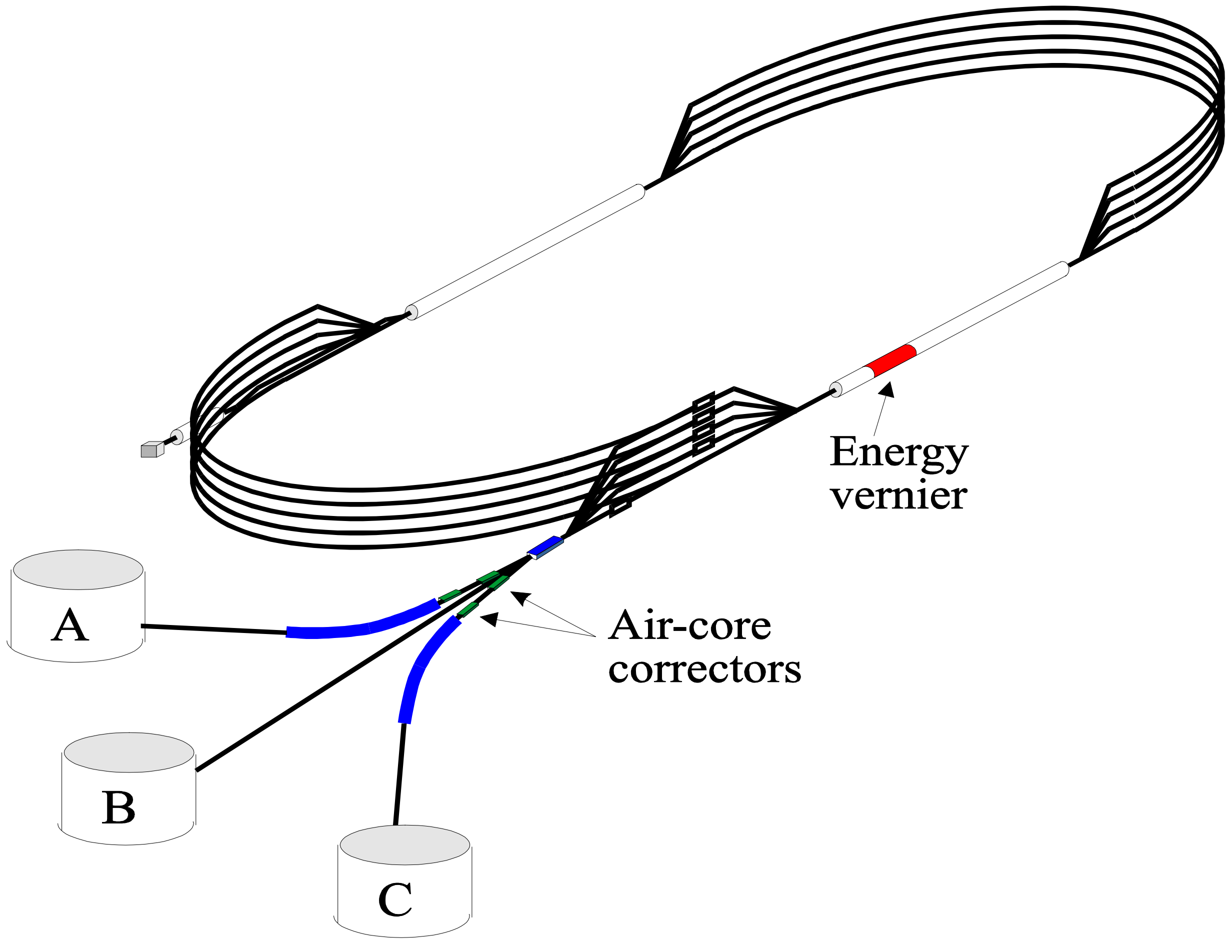


Material:	Niobium (RRR=280)
Frequency:	3 GHz
Temperature:	2 K
Accelerating Field:	5 MV/m
Q_0/Q_L:	$3\cdot10^9$ / $3\cdot10^7$
$\Delta f/\Delta l$:	500 Hz/μm

The CEBAF at Jefferson Lab

- 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.

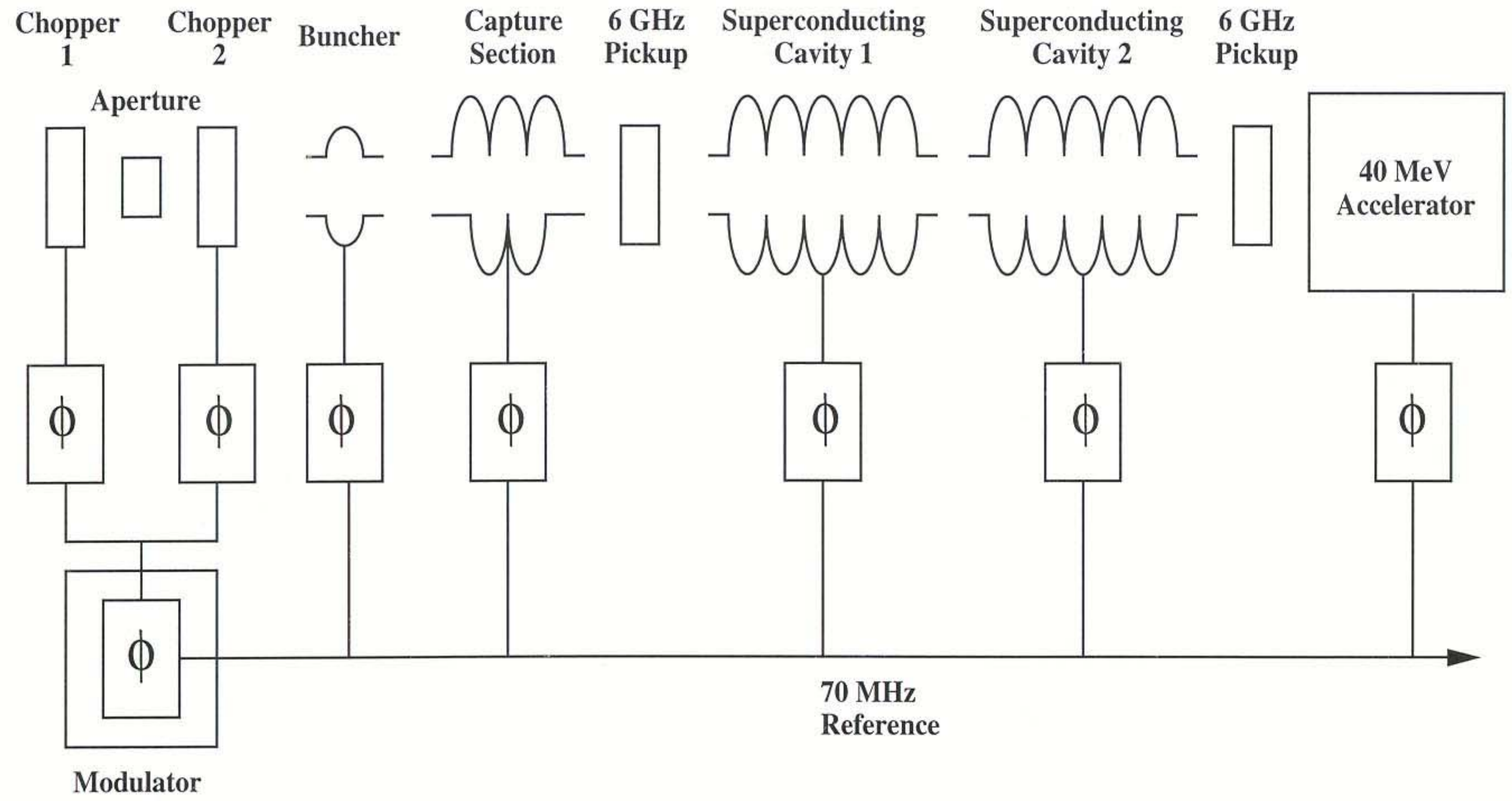
CEBAF Accelerator Layout



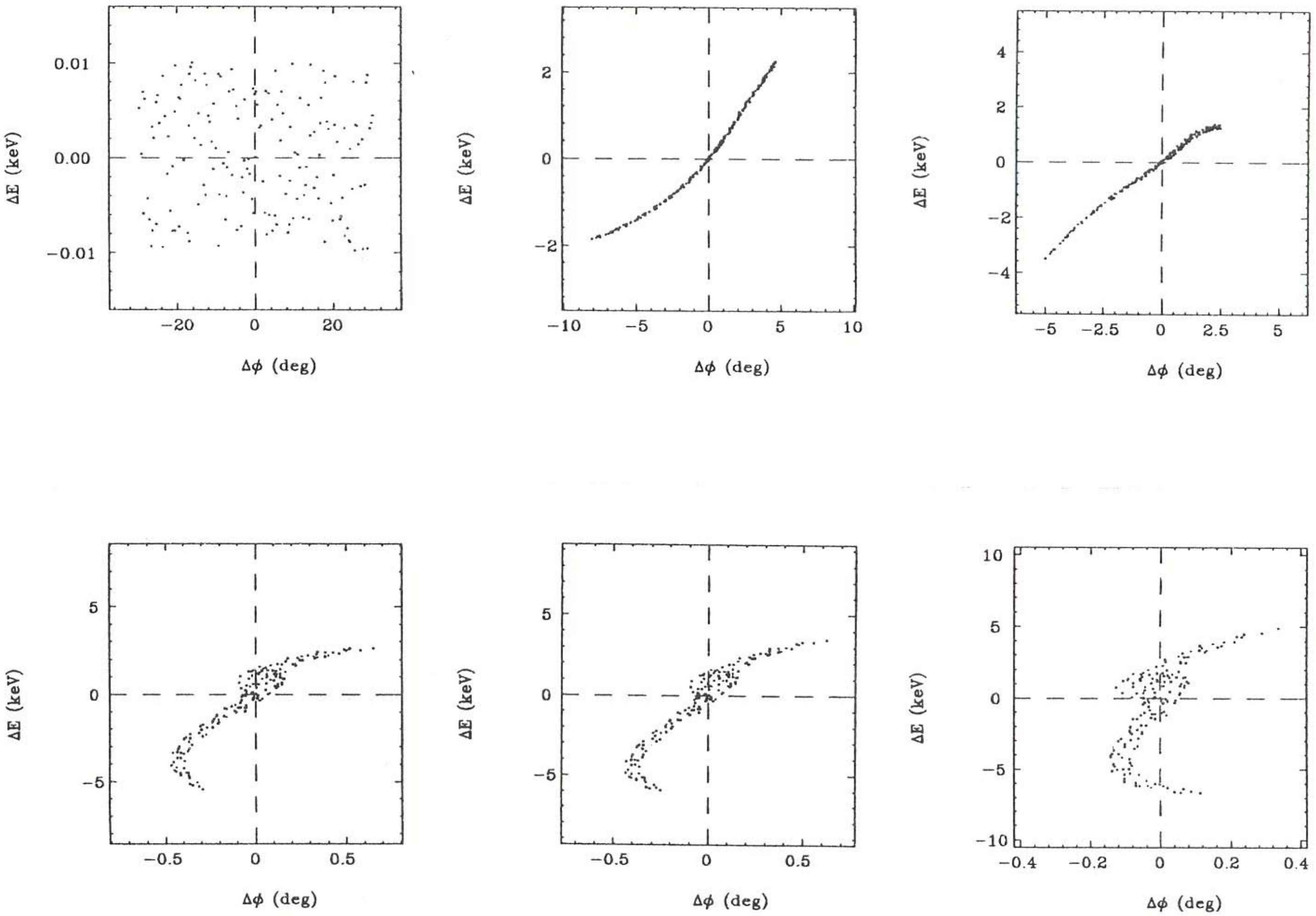
CEBAF Beam Parameters

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

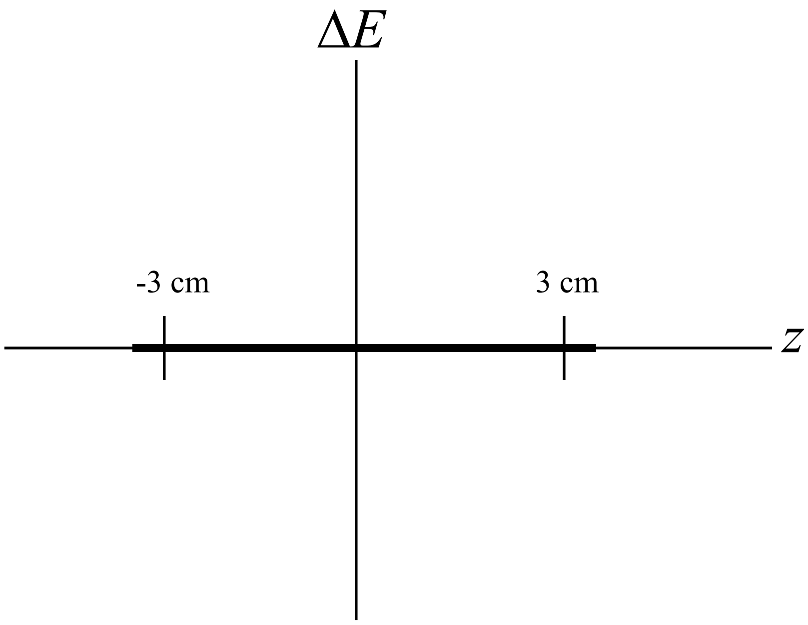
Schematic of CEBAF Injector

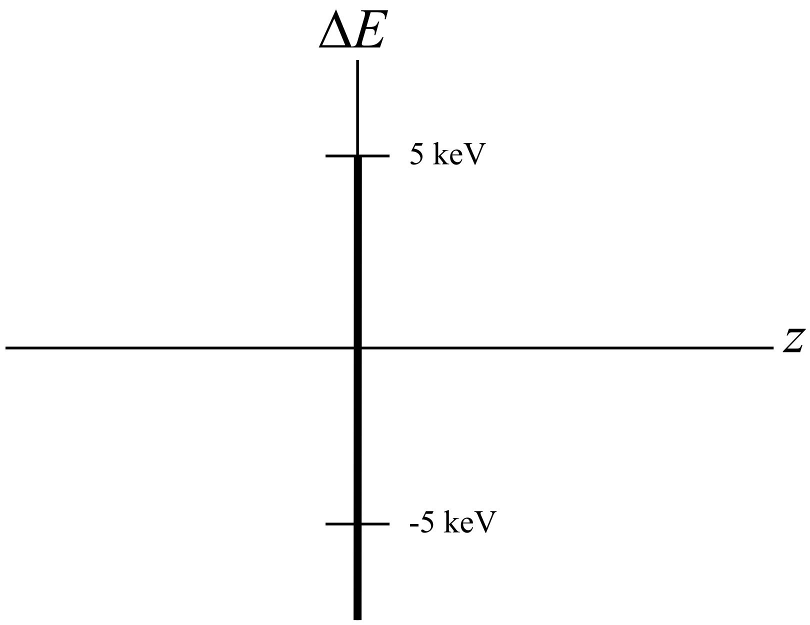


Calculated Longitudinal Phase Space



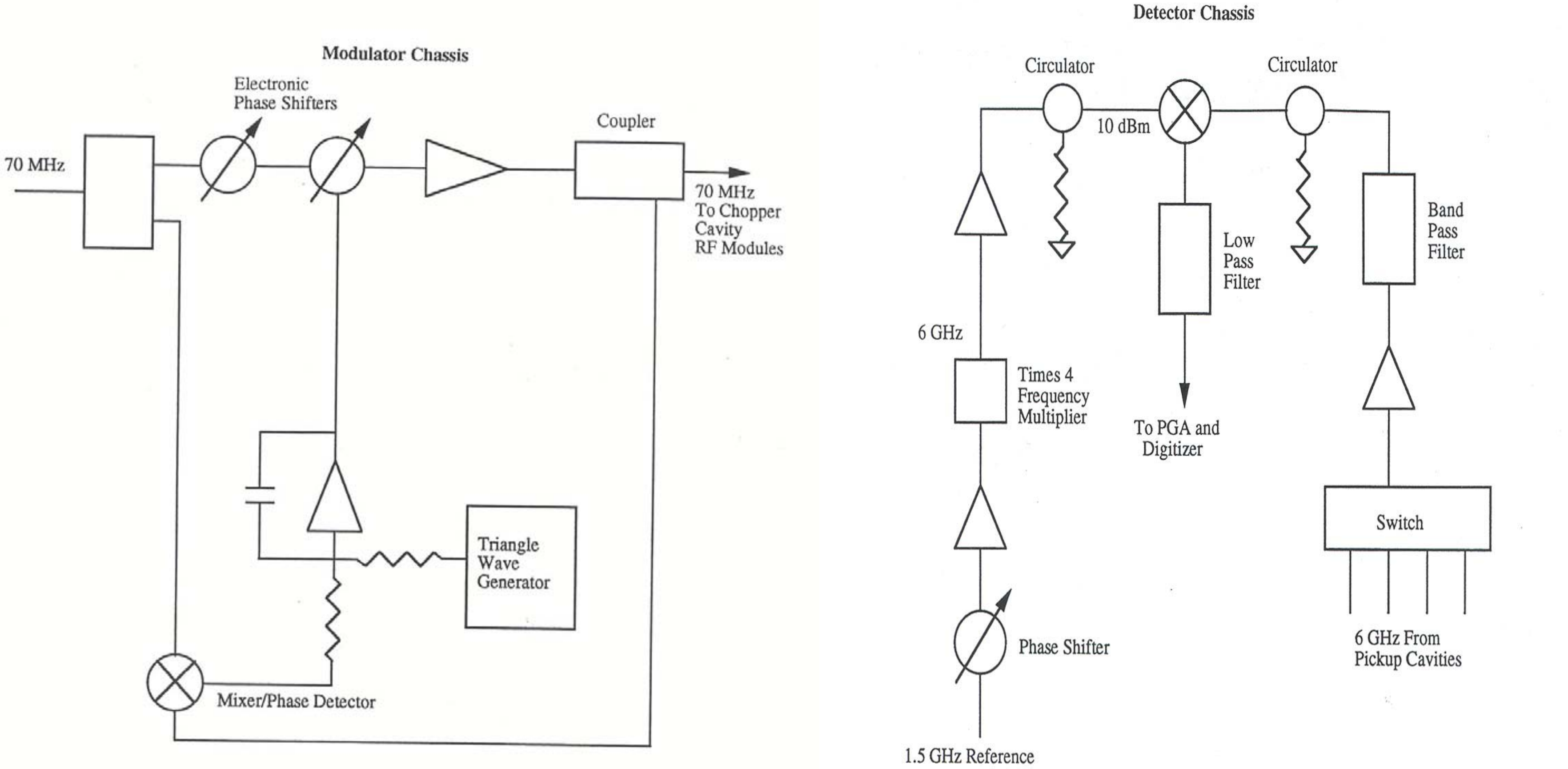
Phase Space from CEBAF Bunching



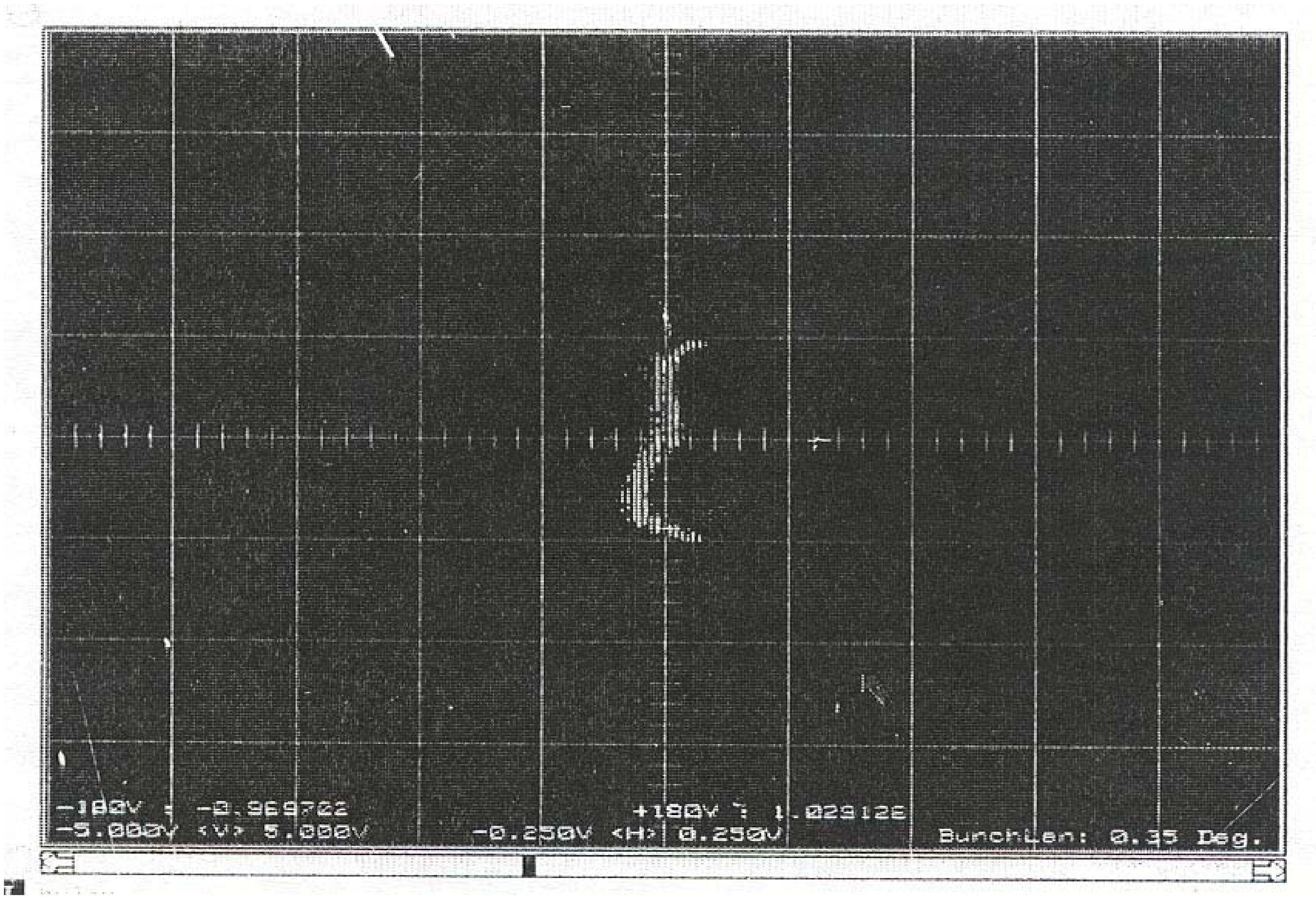


Phase Transfer Technique

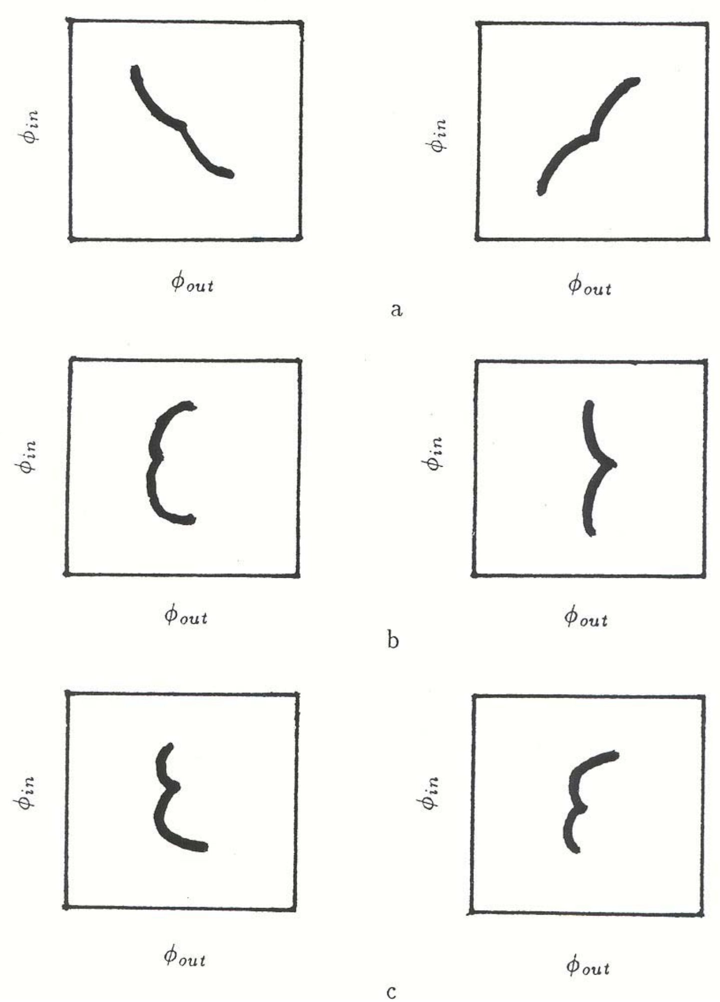
Simultaneously, digitize phase modulation and arrival time determined by a phase detector



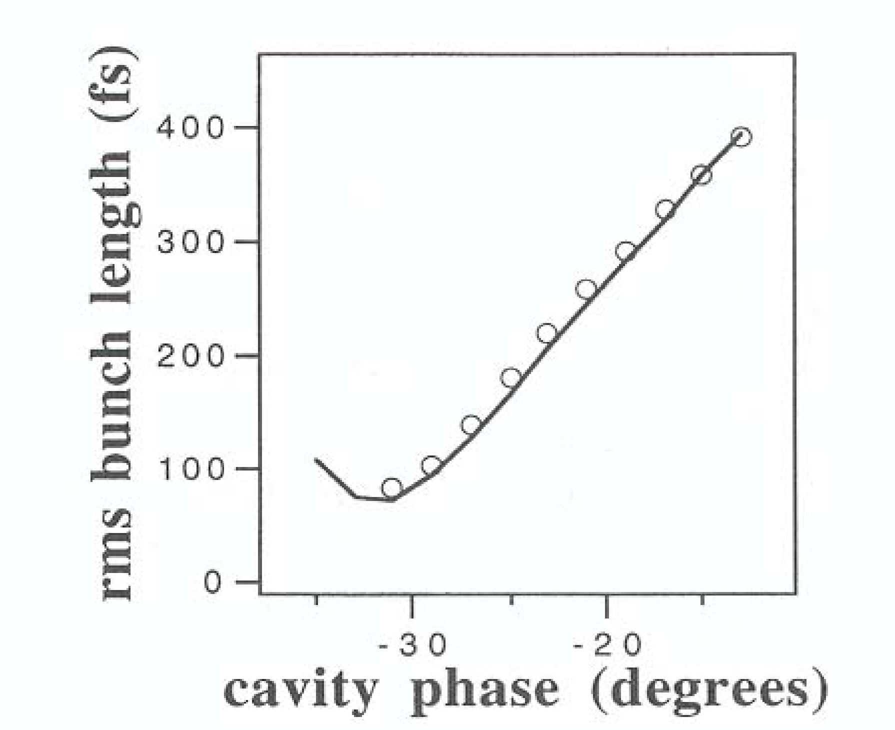
Some Early Results



Phase Space Correction Scheme

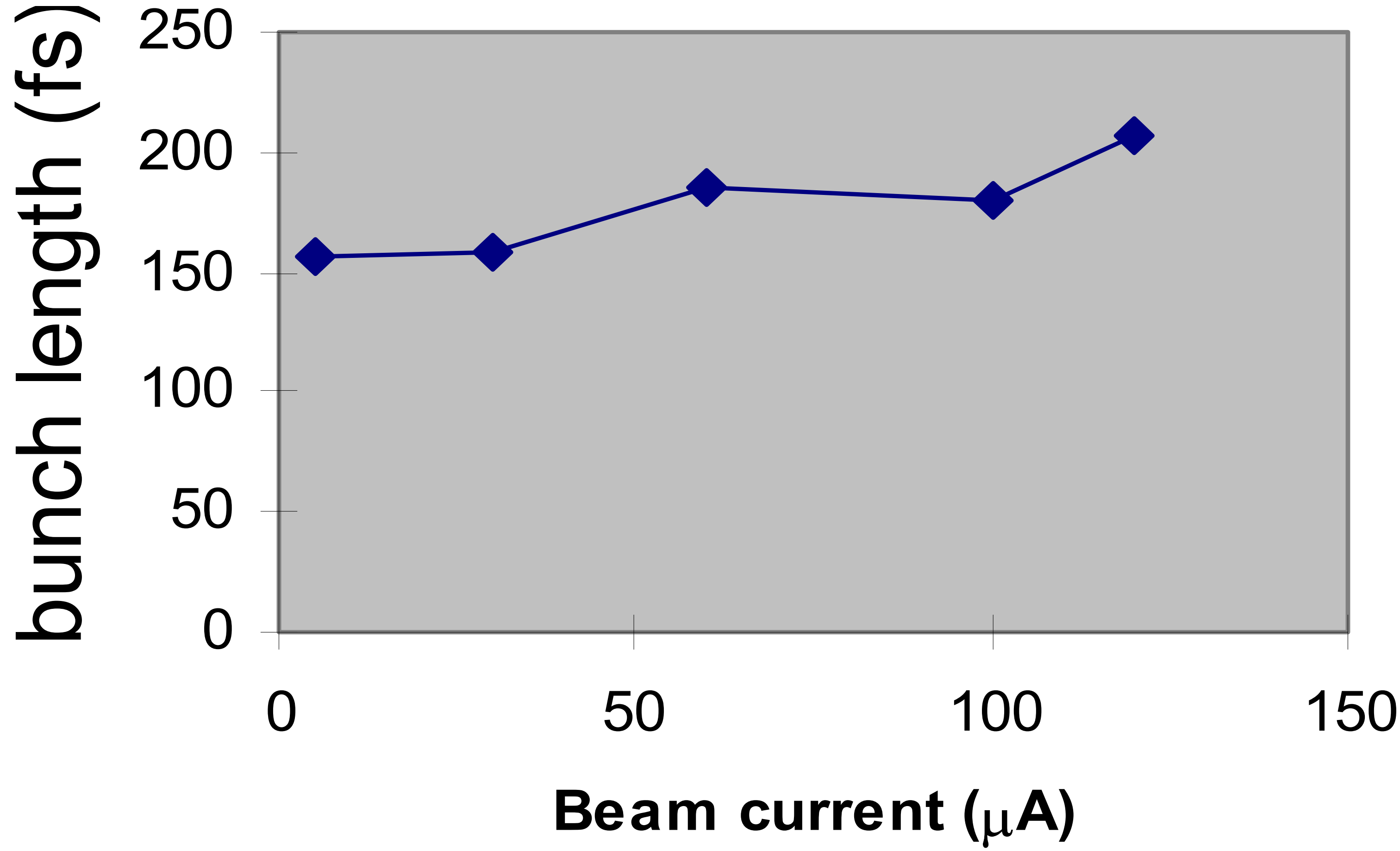


Short Bunches in CEBAF



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

Short Bunch Configuration



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

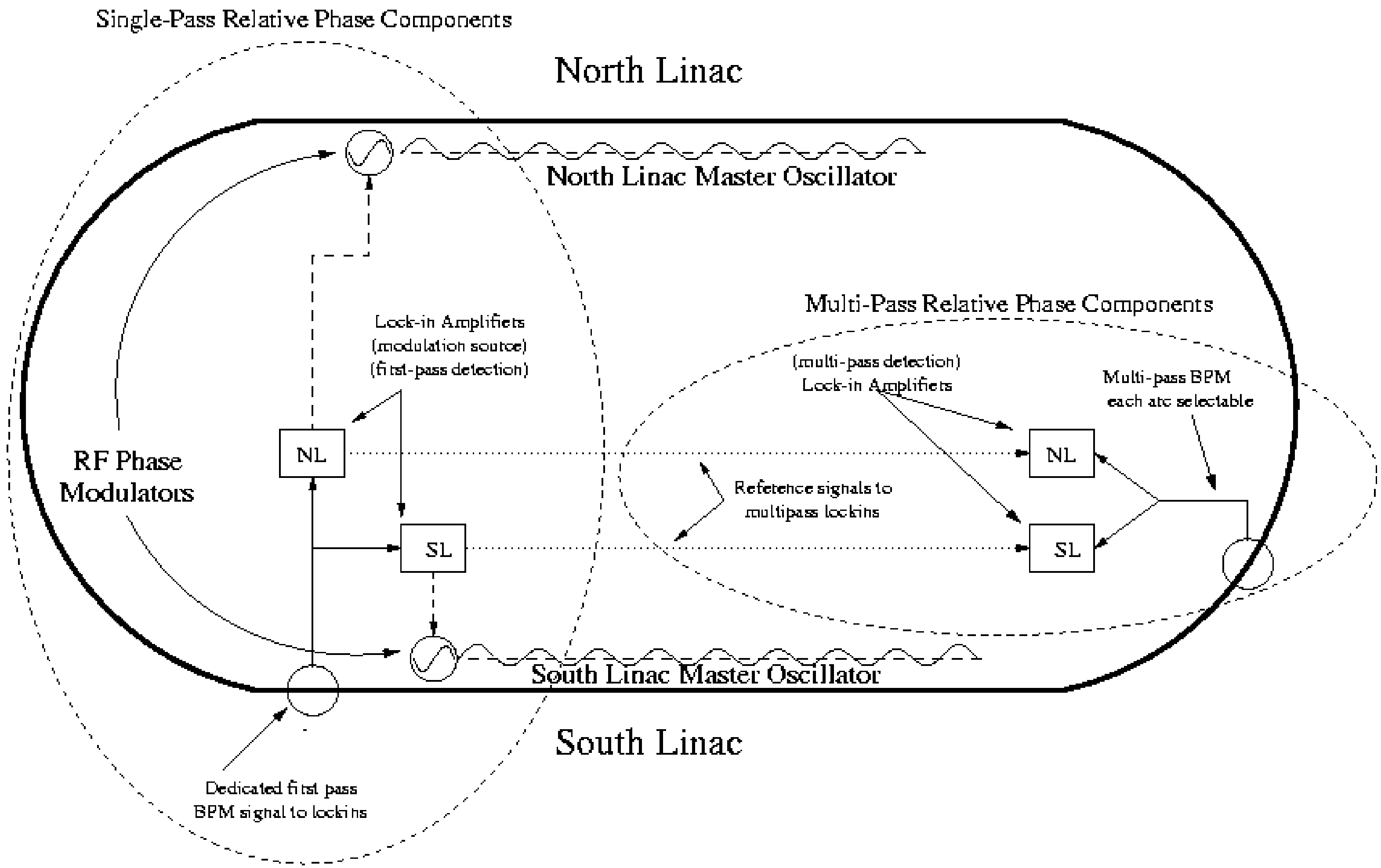
Performance

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

First-Pass MO Modulation System

- Small phase reference modulation for each linac
  - +/- 0.05 degree Phase Modulation
  - Amplitude Modulation suppressed
- Coherent detection of resultant beam energy modulation
  - Beam Position detection in dispersive region (η = 1.4 m)
- CW beam to linac global relative phase measurement
  - Independent for each linac for first pass beam
  - Simultaneous availability for both linacs
  - Used in software feedback system compensate hardware drifts

MO Modulation System Layout



Courtesy: Michael Tiefenback

Multi-Pass Beam-RF phase detection

- Pass to Pass Phase Drift => Relative Energy Drifts
- Goal: Stabilization of Multi-Pass Beam-RF phases
- Utilizes existing MO Modulation signals
- 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)

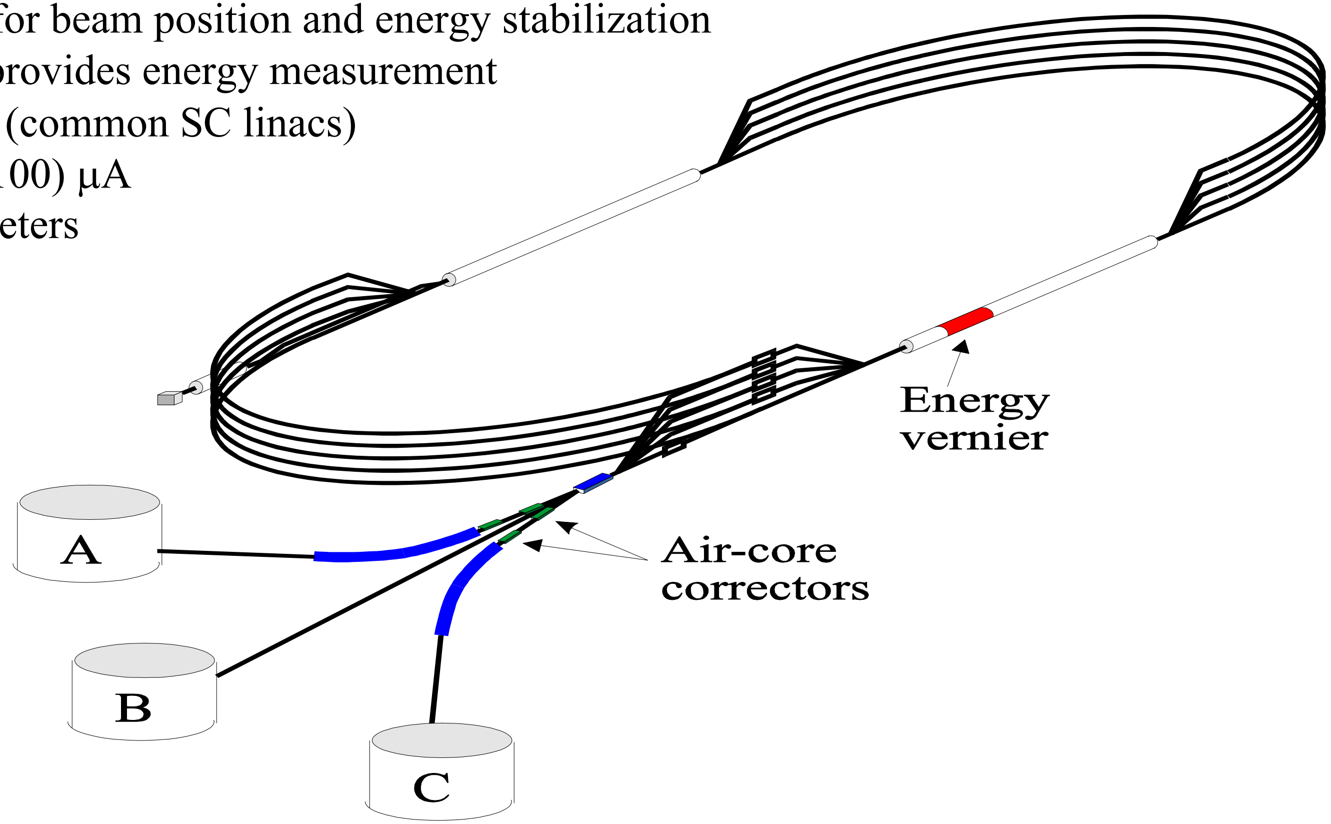
Feedback System Elements

Beam position and energy stabilization

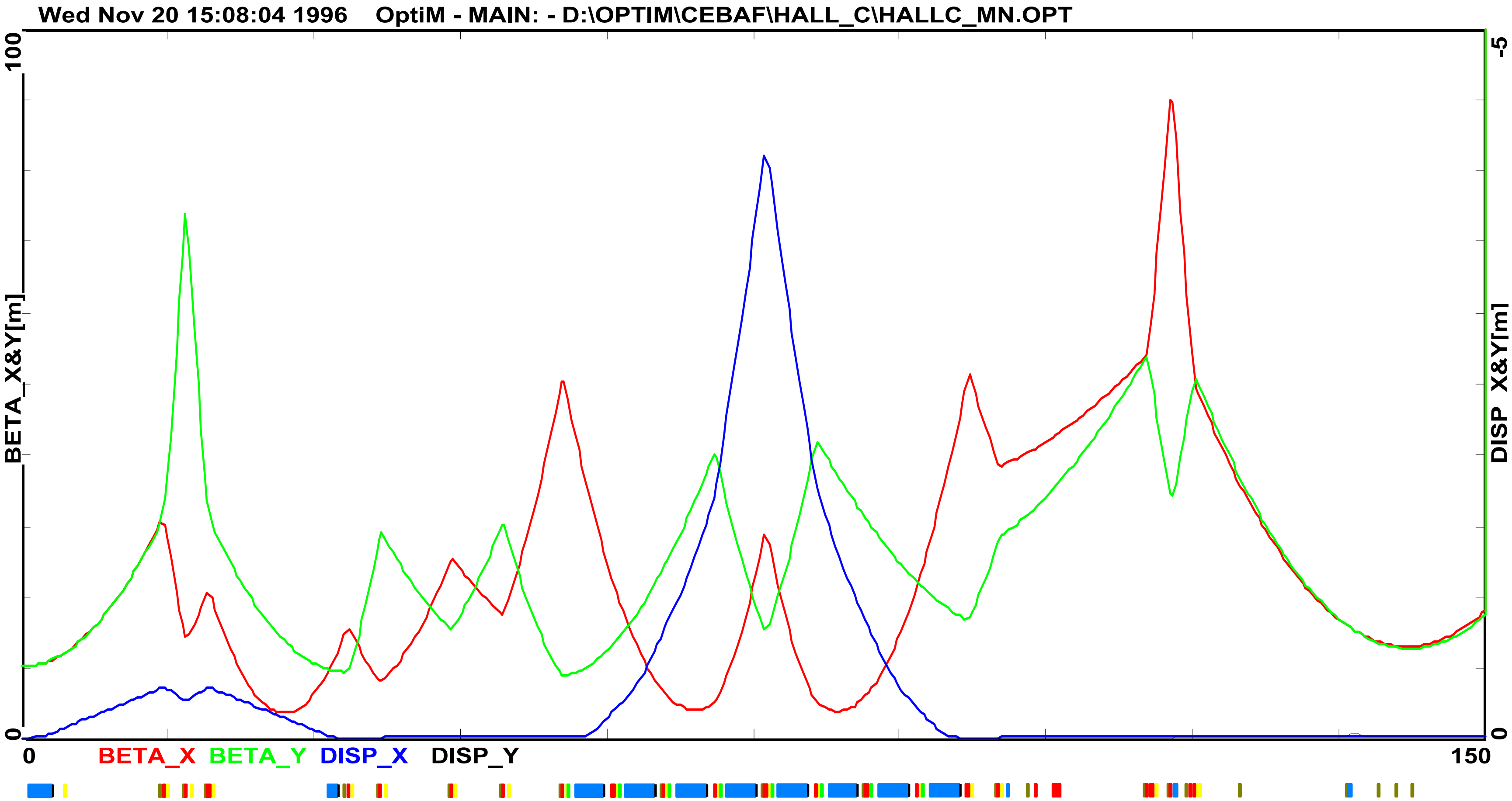
- 6 dimensional phase space

Fast feedback system for beam position and energy stabilization

- ➢ Only one hall line provides energy measurement
- Two-hall operation (common SC linacs)
- ➢ Halls A & C - (1 - 100) μA
  Magnetic spectrometers
- ➢ Hall B - (1 -10) nA
  4π detector

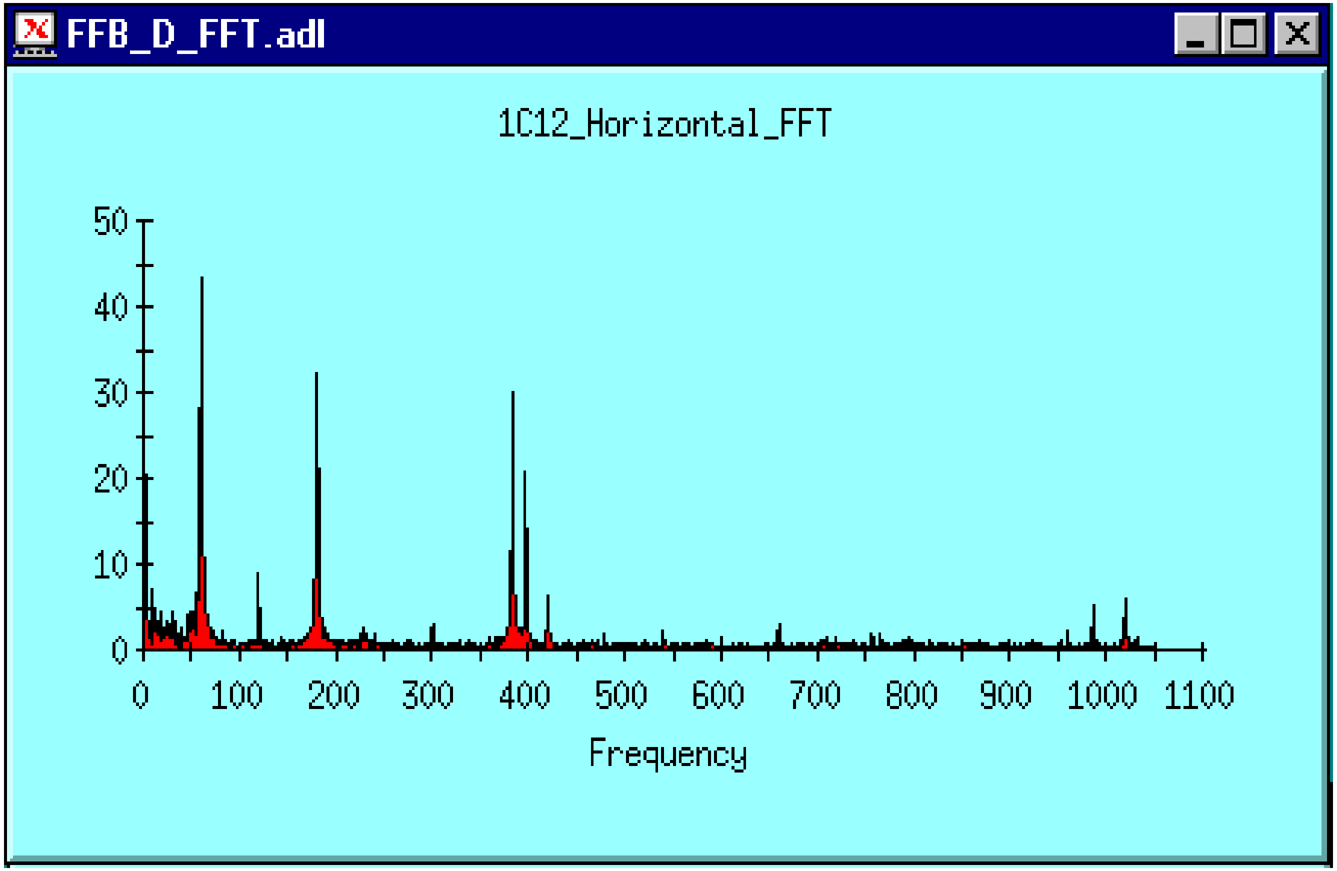


Dispersion Suppressed Optics



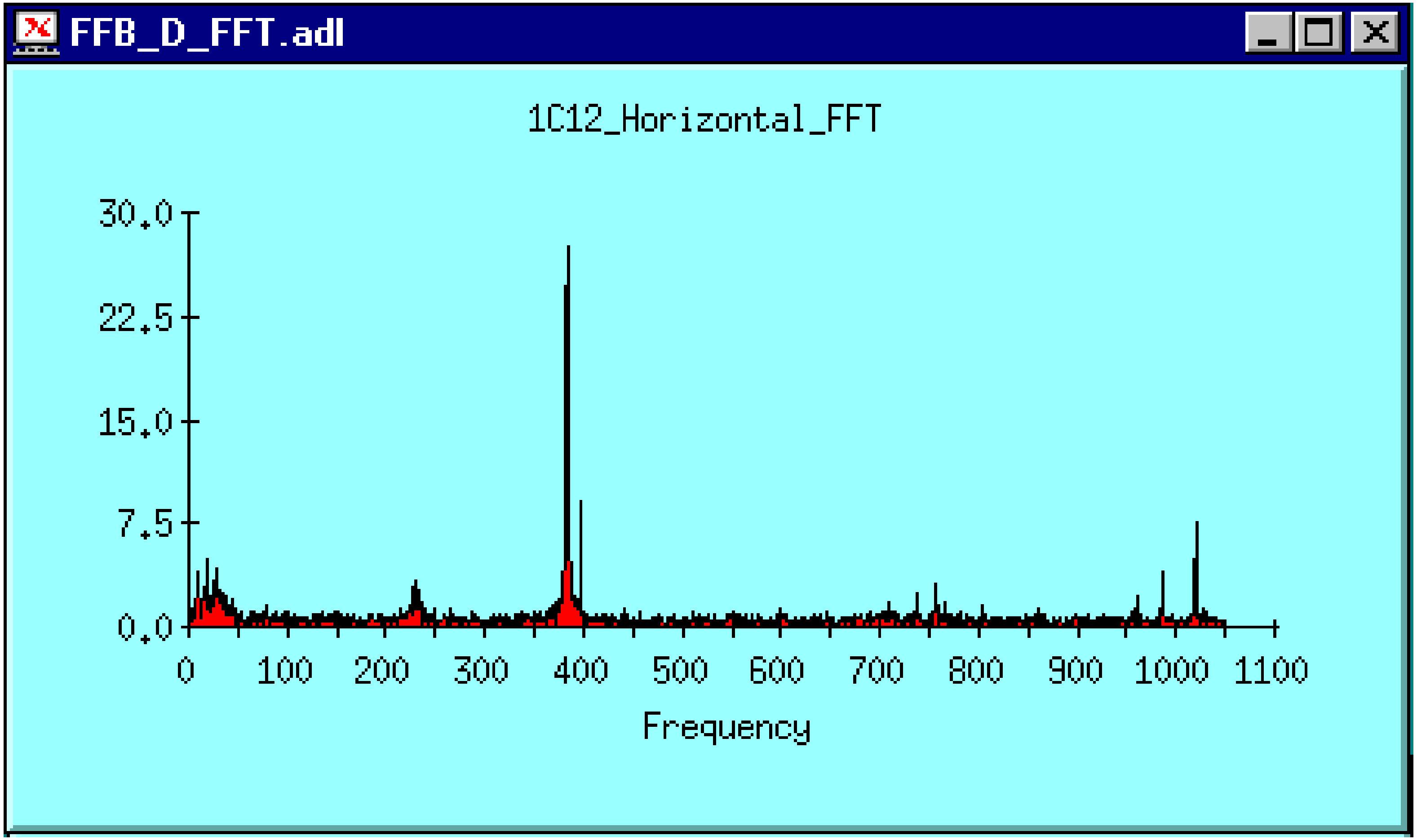
Courtesy: Valeri Lebedev

Fast Feedback Off



Courtesy: Valeri Lebedev

Fast Feedback Residual Fluctuations



Courtesy: Valeri Lebedev

Fast Feedback rms position fluctuations

FFB_O_bpm_val.adl

Hall A Fast FeedBack BMP/Corrector Values

Horiz Position (microns)

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

Vert Position (microns)

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

Horiz Corrector (gauss-cm)

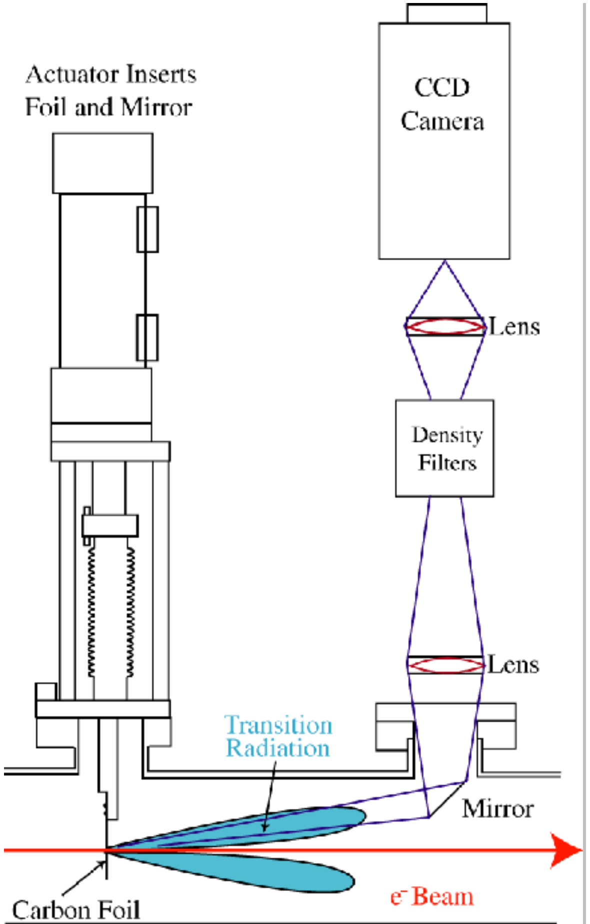
	min	max	mean	Std Dev
1C04H	-4.95	31.38	4.79	4.29
1C07H	-19.92	12.59	-8.06	4.03

Vert Corrector (gauss-cm)

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

Courtesy: Valeri Lebedev

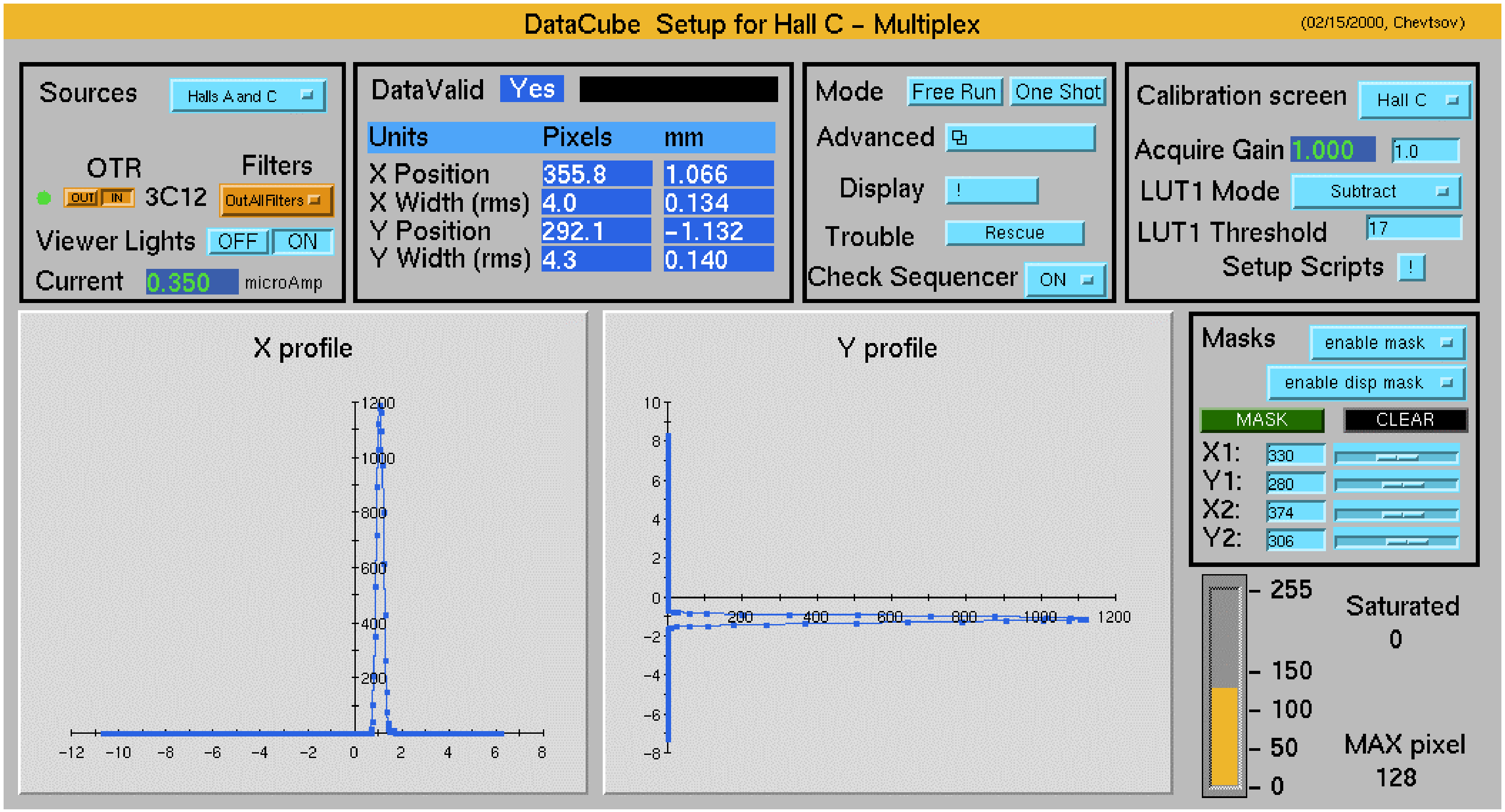
Beam Diagnostics: OTR



SIMPLIFIED DIAGRAM
OF THE FORWARD OTR MONITOR

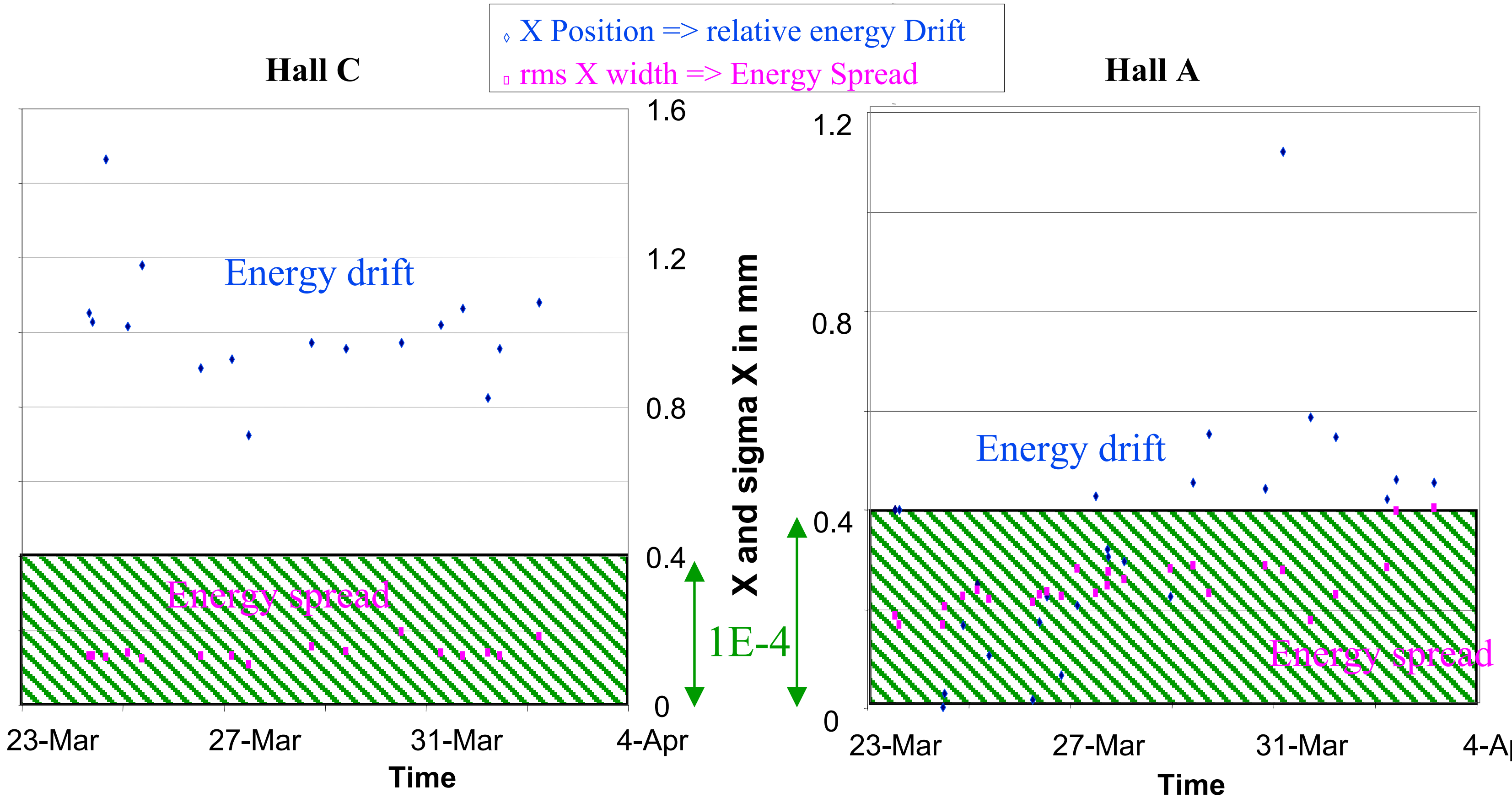
- ¼ µm carbon foil, 10 X 10 mm square
- Can stay in maximum CEBAF CW beam current (200 µA)
- Dynamic range: 0.2 to 200 µA with neutral density filters.
- Continuous monitoring during beam delivery for $E \geq 2$ GeV
- Open frame => not invasive upon insertion.
- Effect of foil on beam:
  - Energy loss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

“MaxVideo 200” Image Processor Control Screen



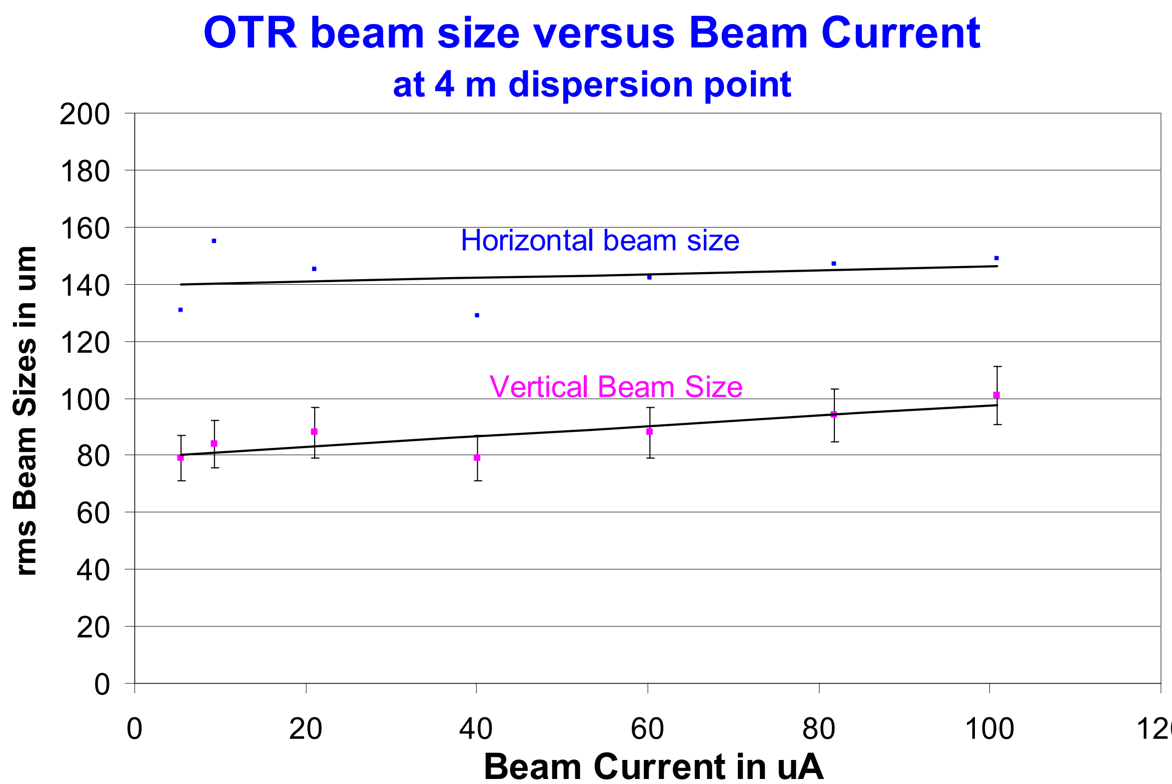
Courtesy: Jean-Claude Denard

dp/p data: 2-Week Sample Record



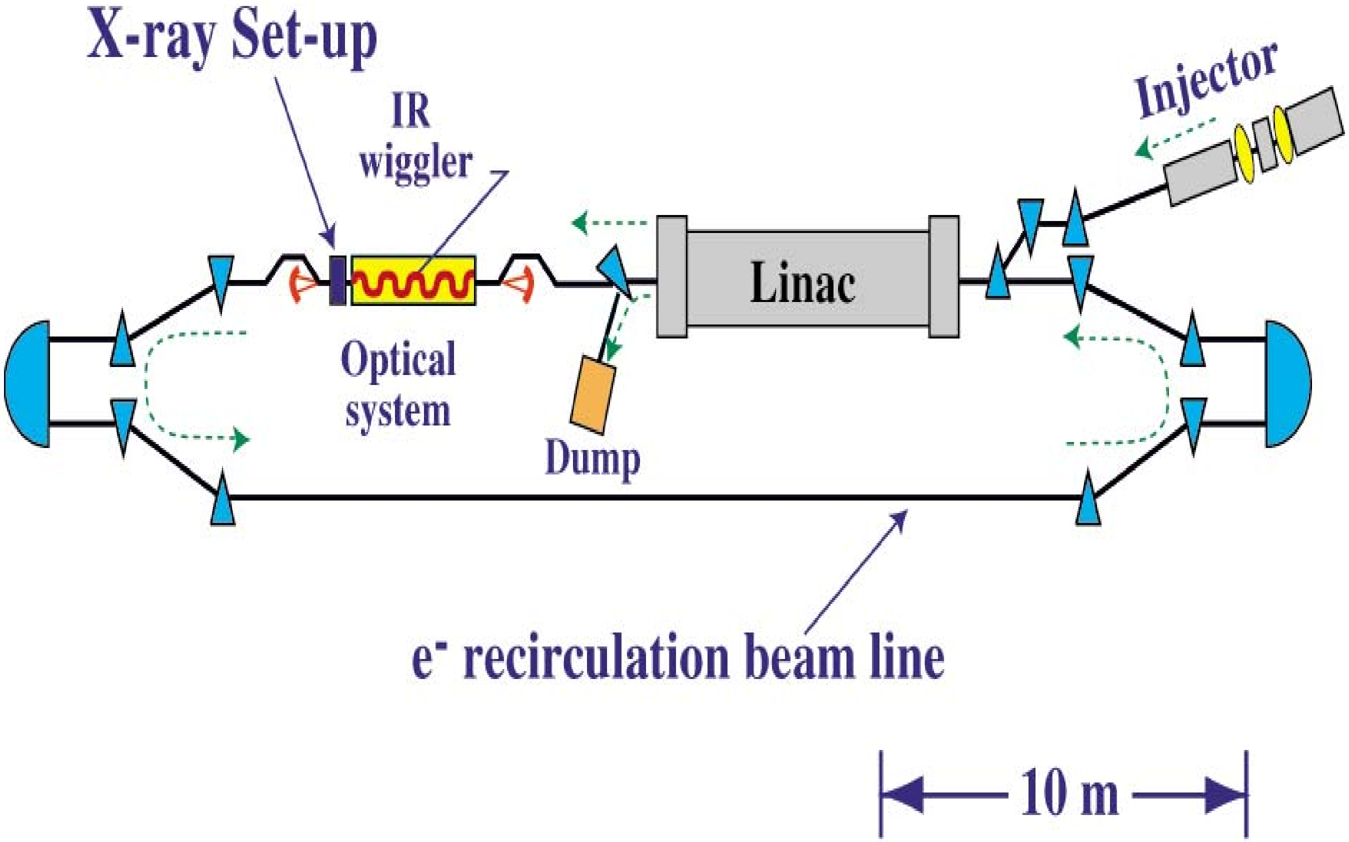
Courtesy: Jean Claude Denard

dp/p Stability versus Beam Current

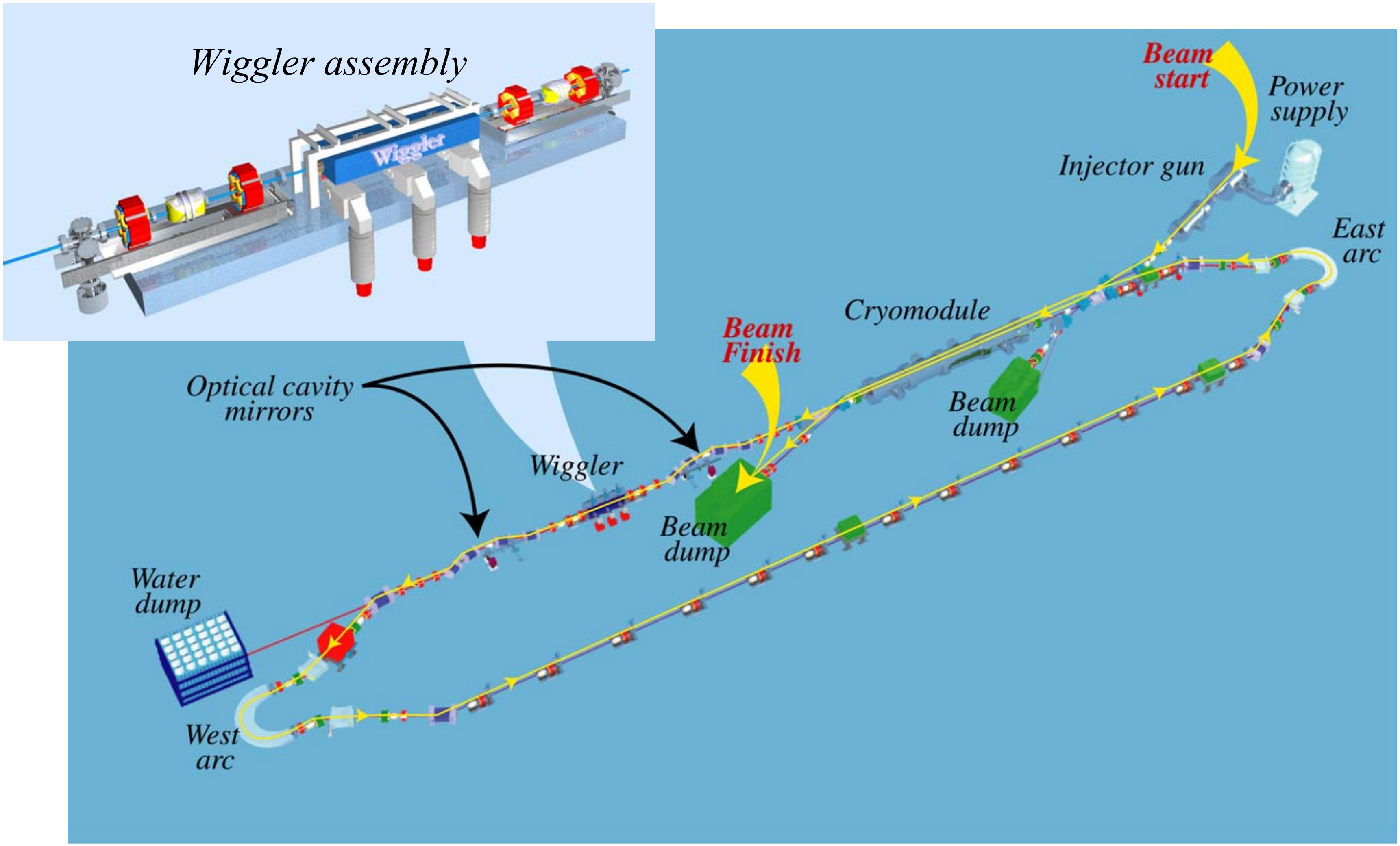


Courtesy: Jean-Claude Denard

Jefferson Lab FEL



The Jefferson Lab IR FEL

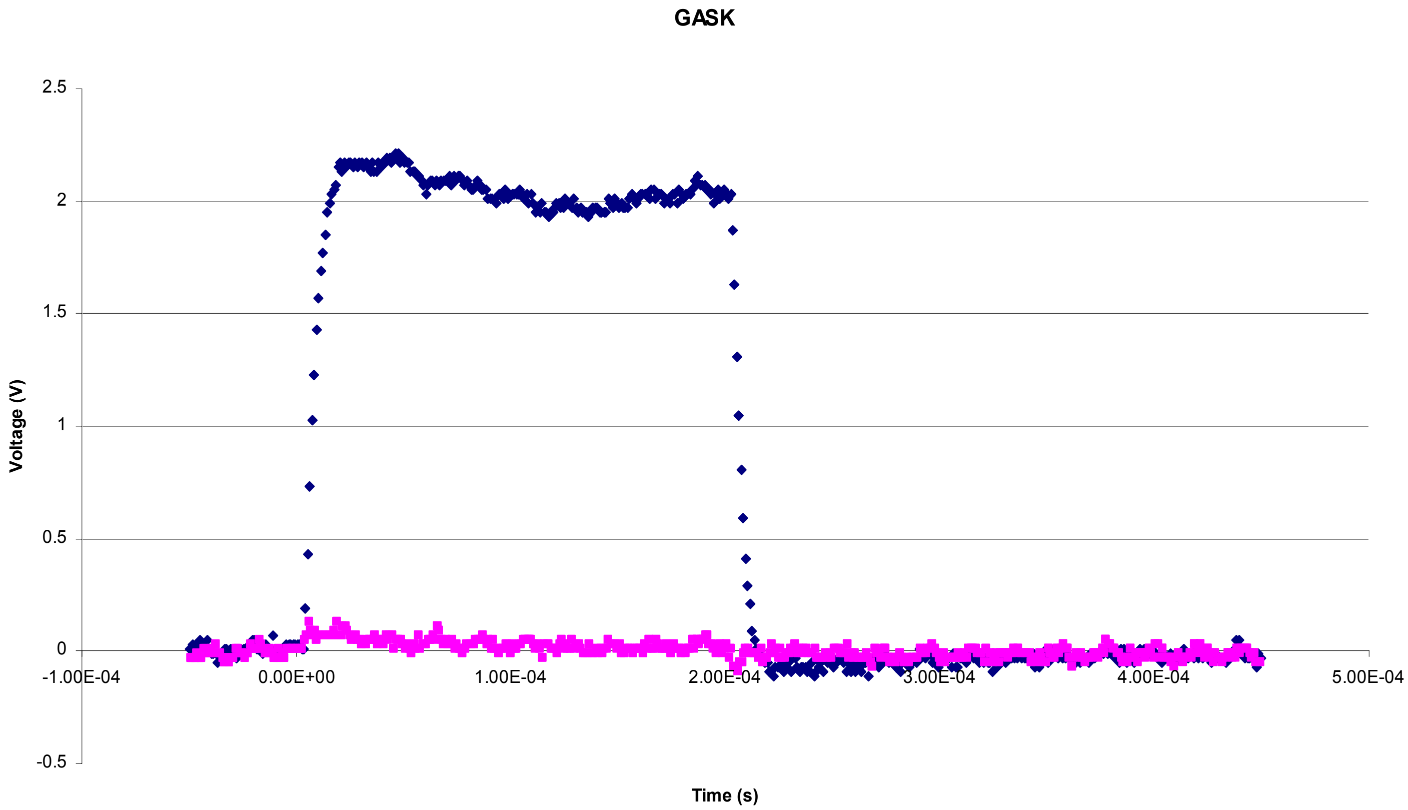


FEL Accelerator Parameters

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

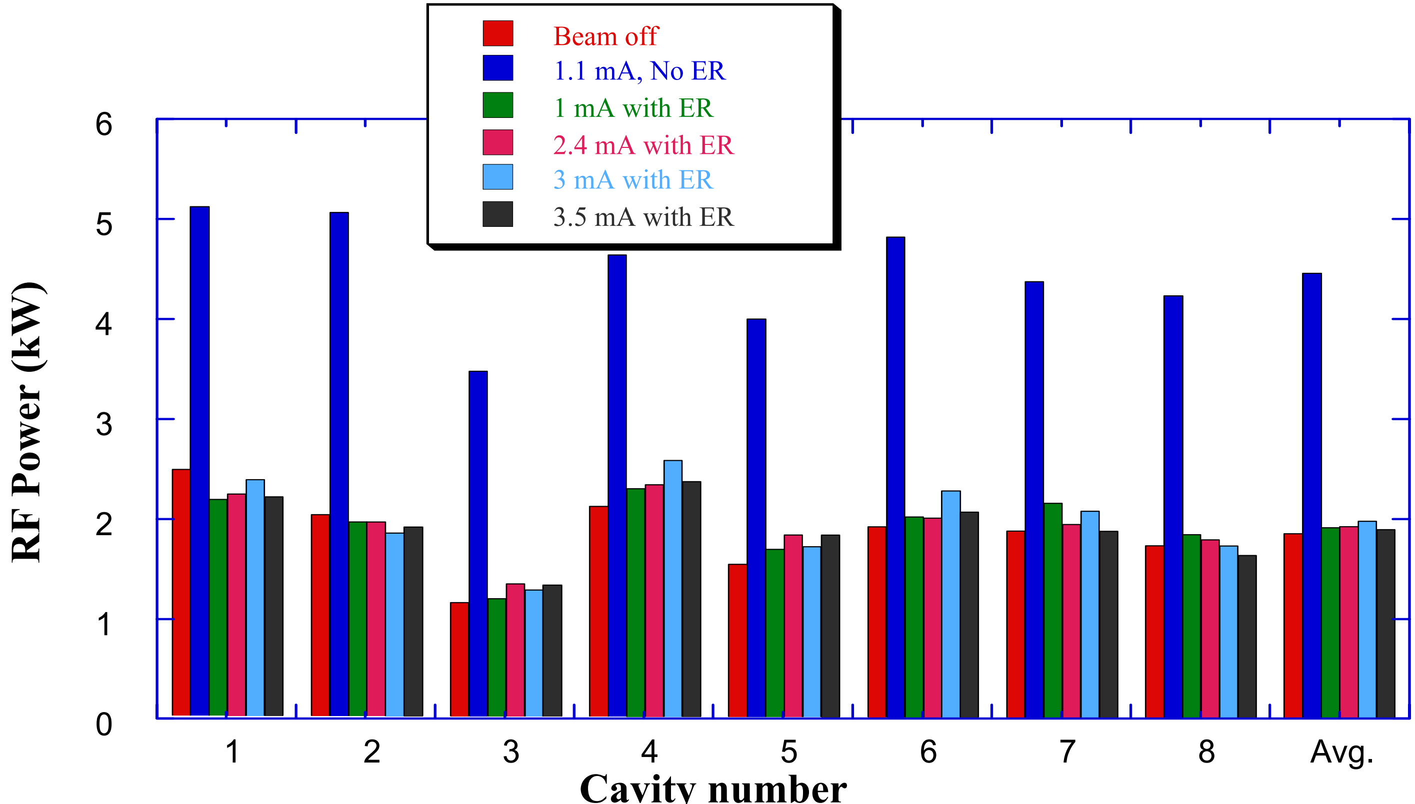
ENERGY RECOVERY WORKS

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

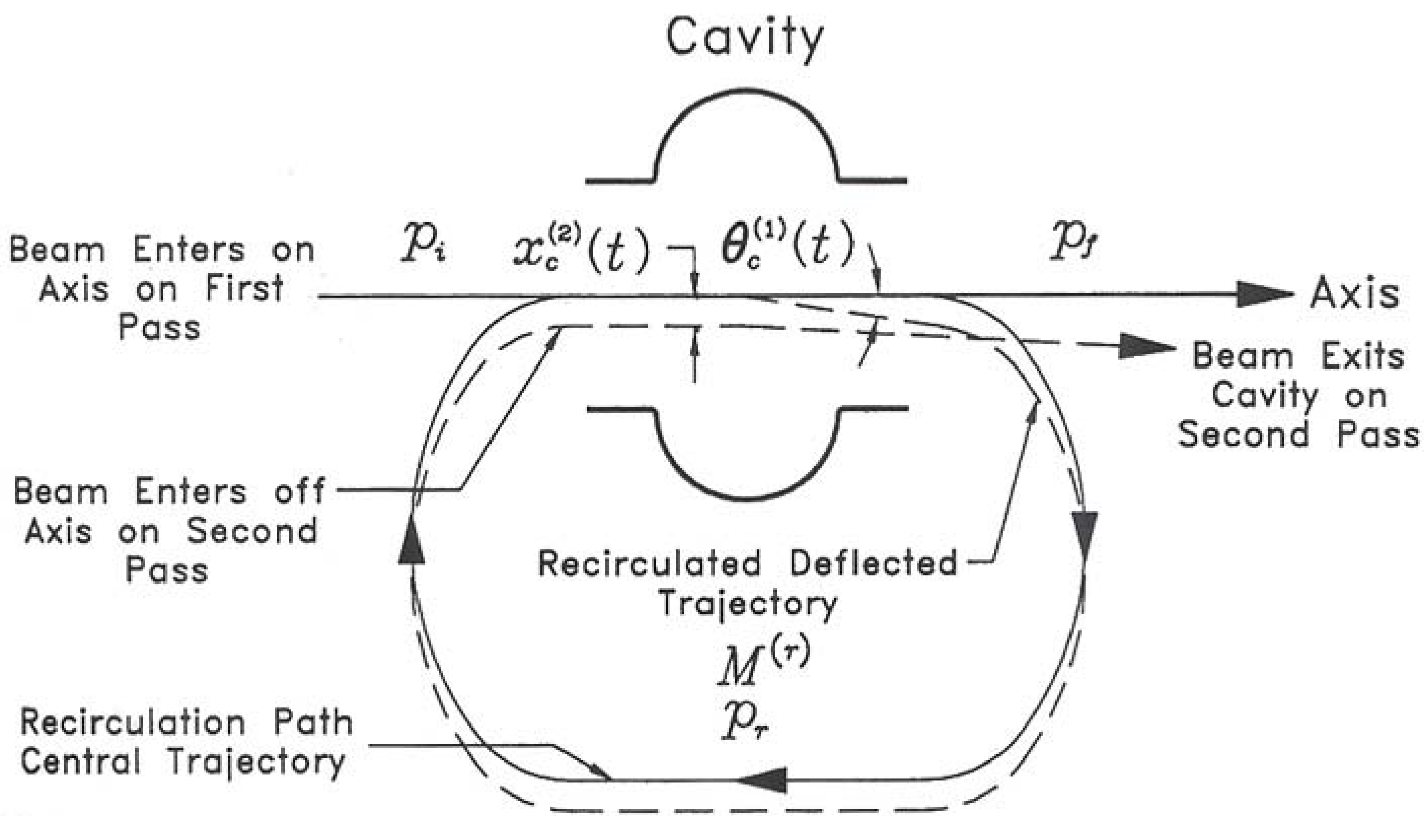


RF Power Requirements with Energy Recovery

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.



Instability Mechanism



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

Threshold Current

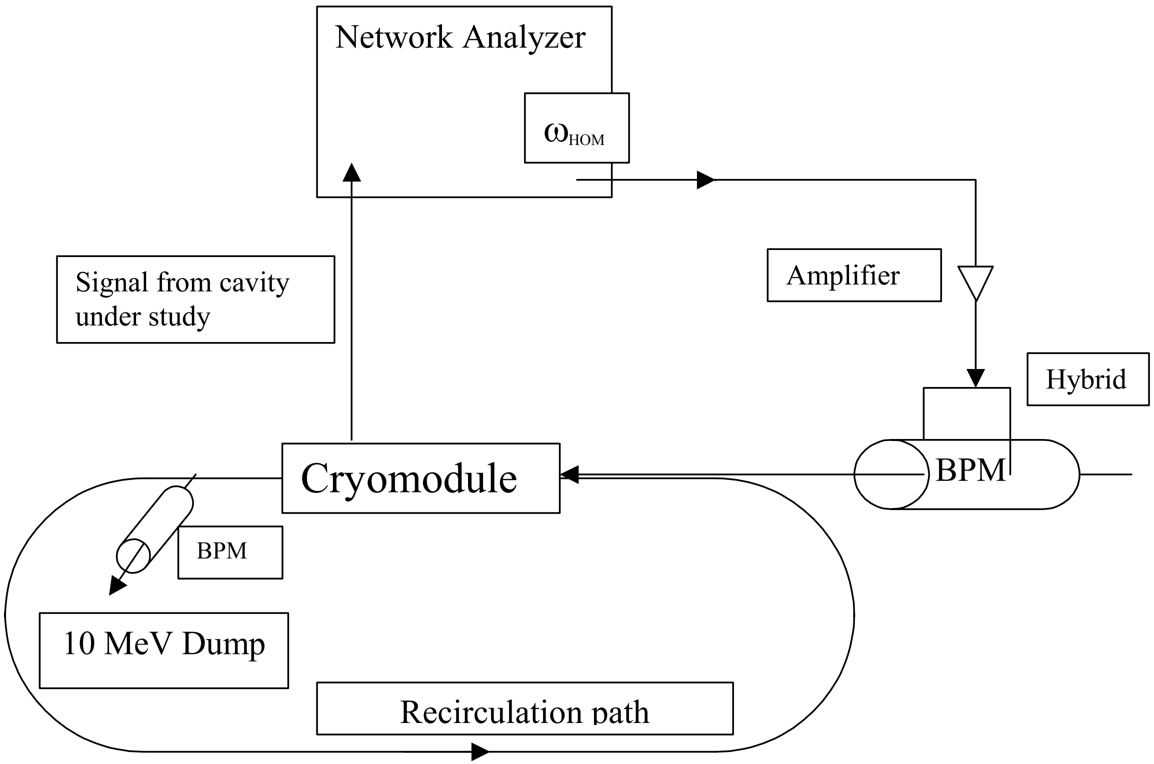
If the average current exceeds the threshold current

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

have instability!

NB, For $T_{12}\sin(\omega_{\lambda} t_{r}) < 0$, there is also a threshold current but it is not necessary that $\kappa << 1$. Perturbation analysis fails and the full dispersion relation must be solved.

Transverse BBU: Experiment



Typical RF Cavity Response to Beam Excitation

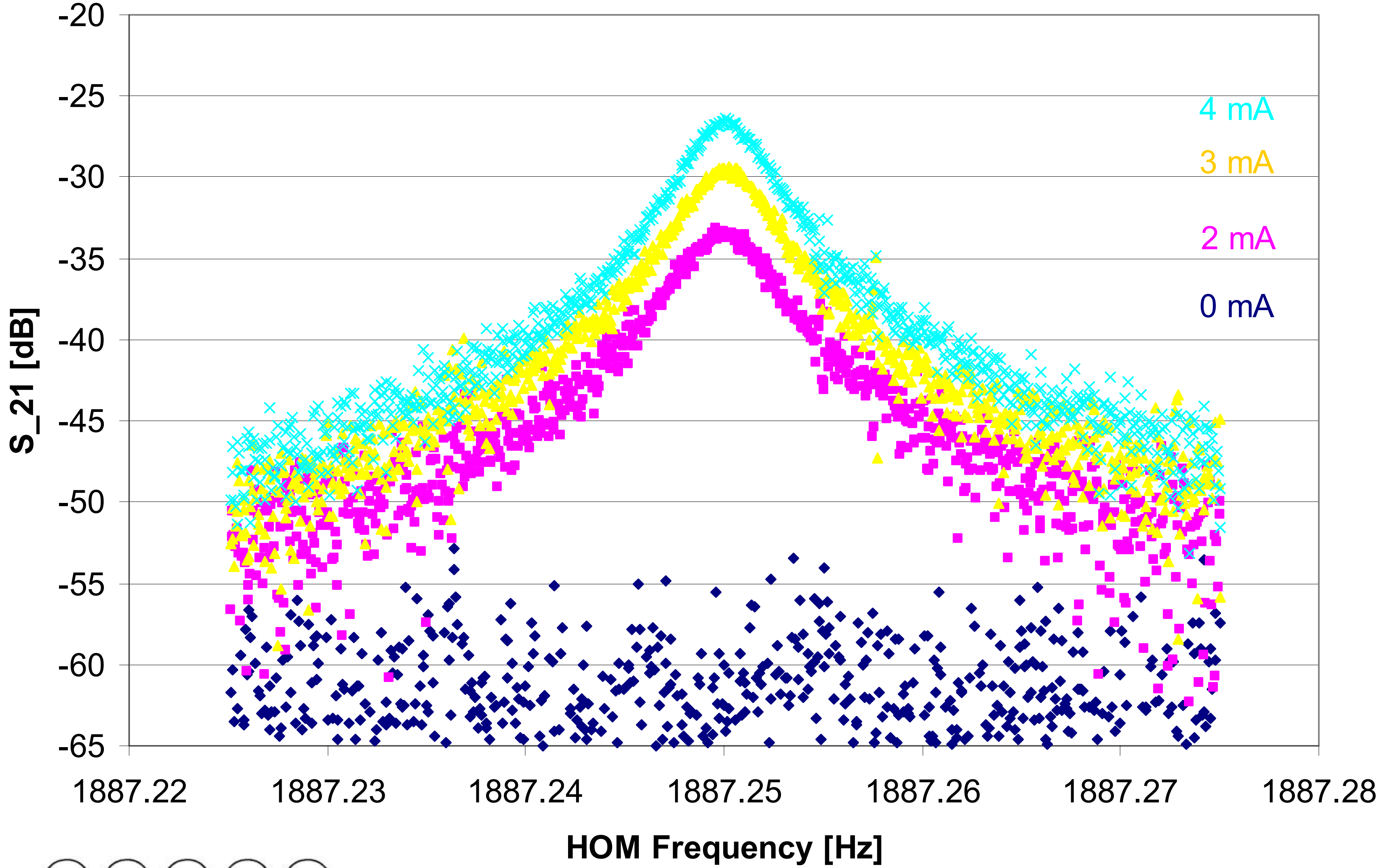


Table of BBU Data

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

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

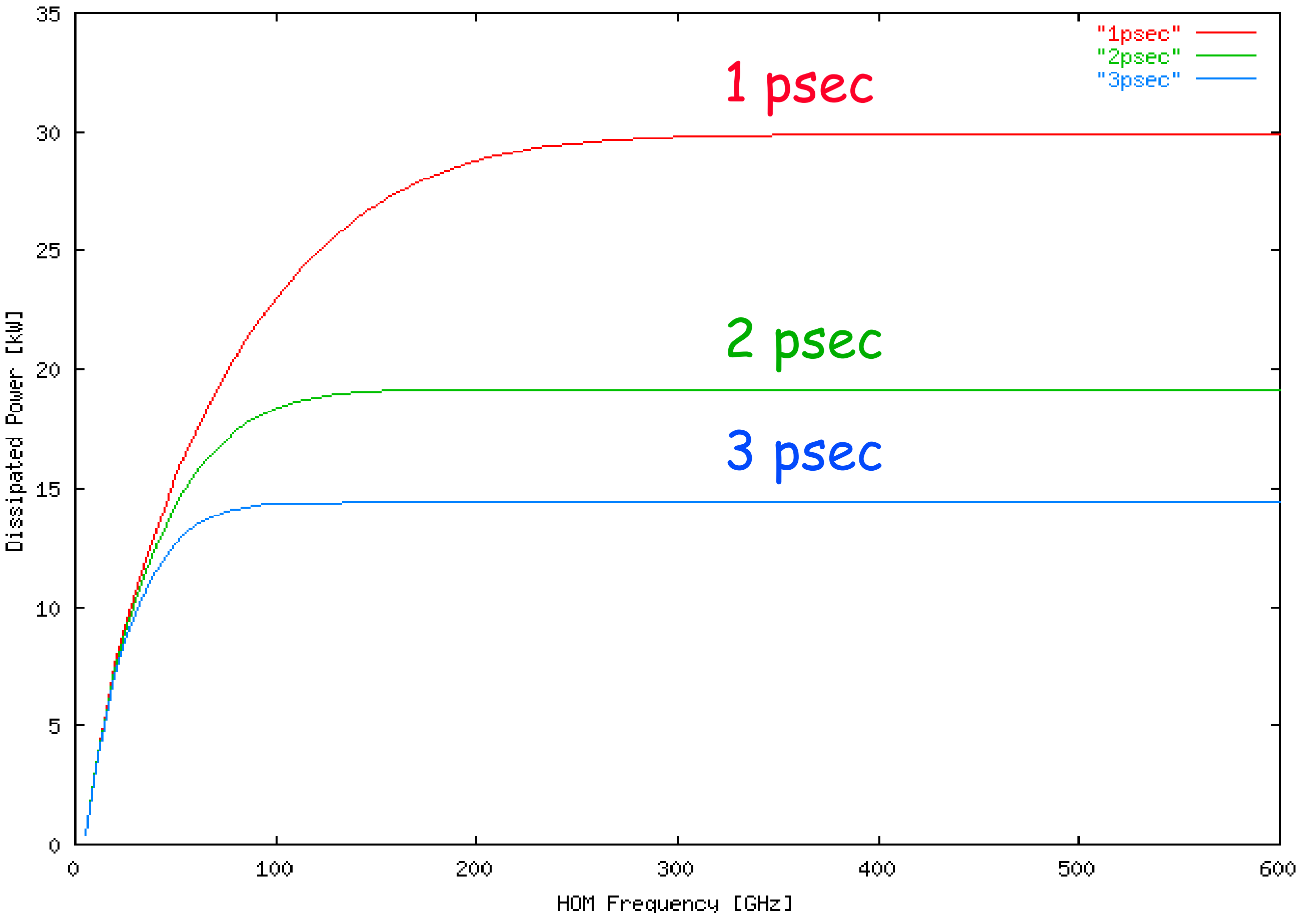
- Fraction of HOM power dissipated on cavity walls depends on the bunch length

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

HOM Power Dissipation: Theory

- 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

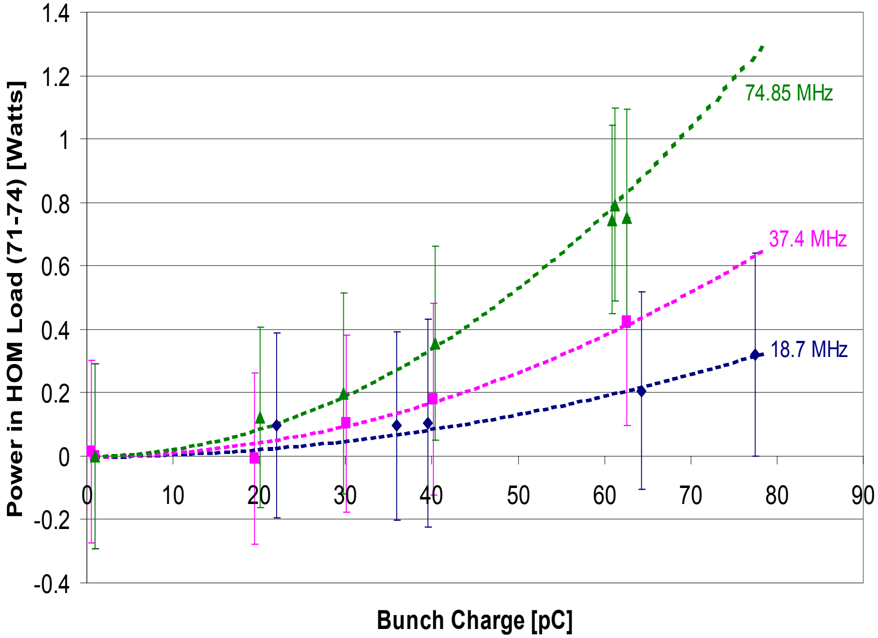
Frequency Distribution of HOM power

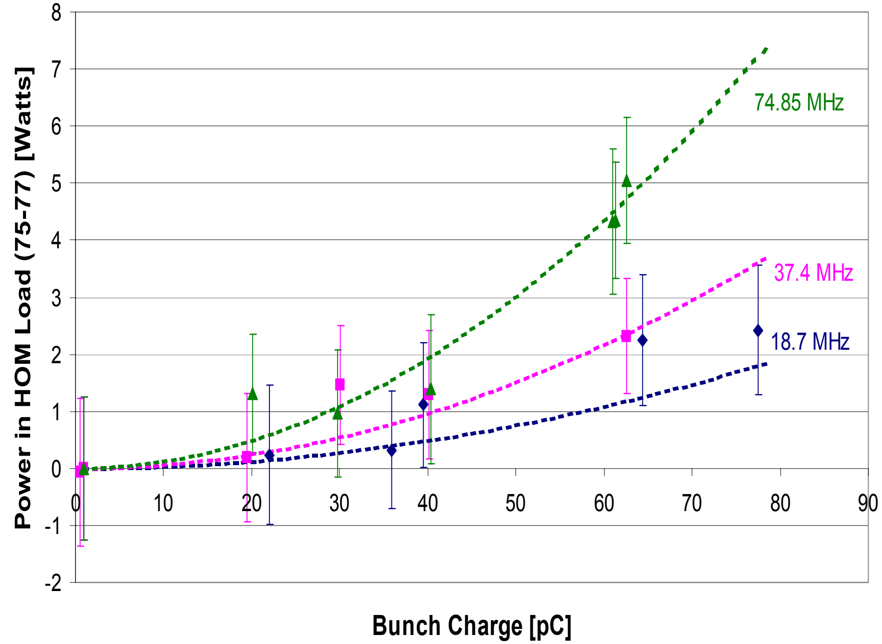


HOM Power: Experiment

- 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

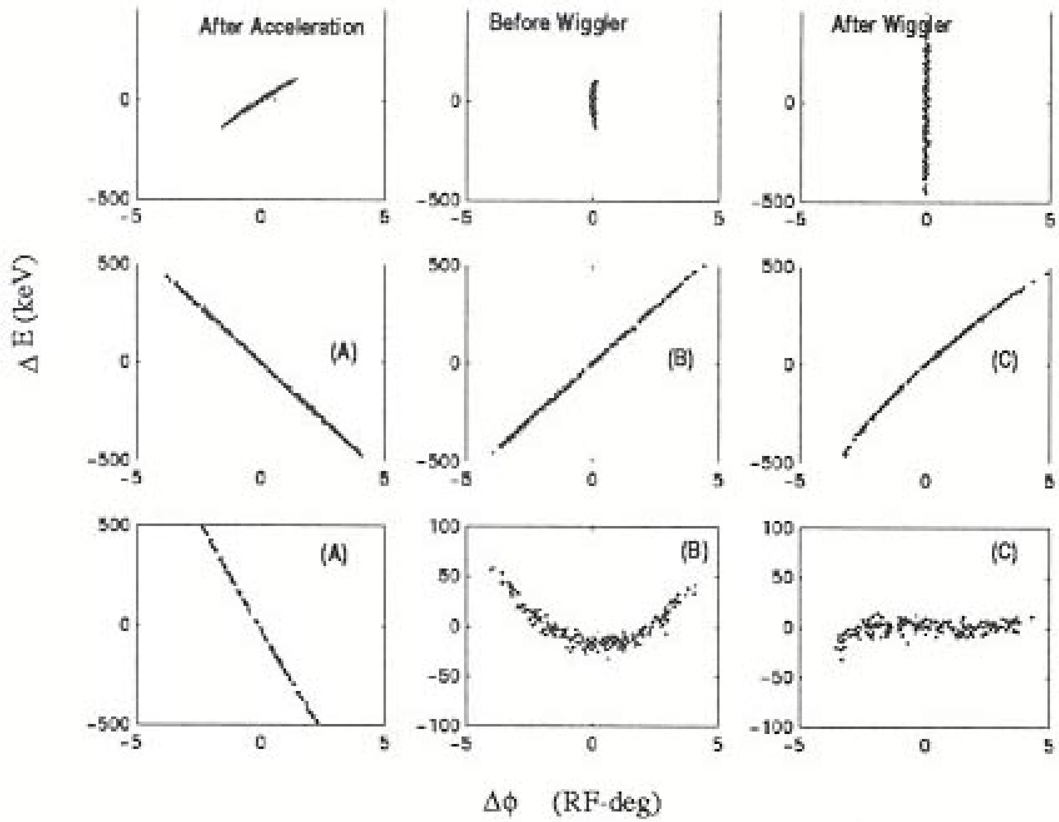
$\Downarrow$

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

$\Rightarrow$ agreement within 15%

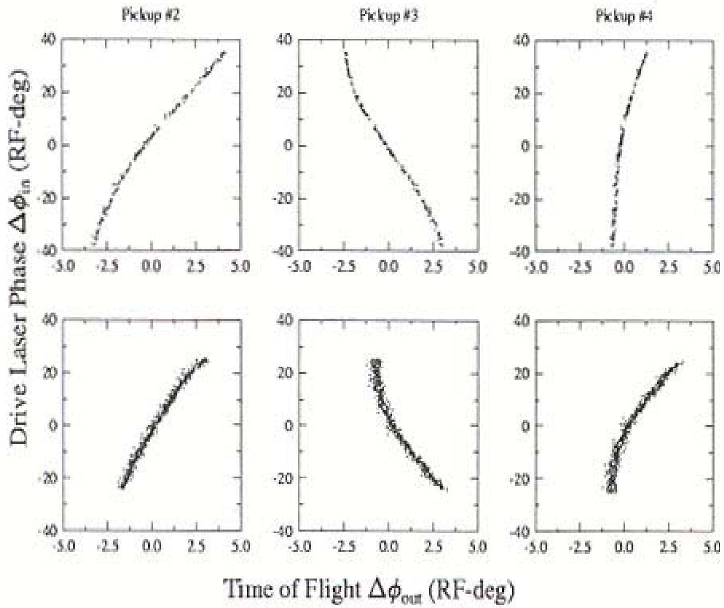
$k_{||}^{URMEL} = 11.0$ V/pC

Longitudinal Phase Space Manipulations



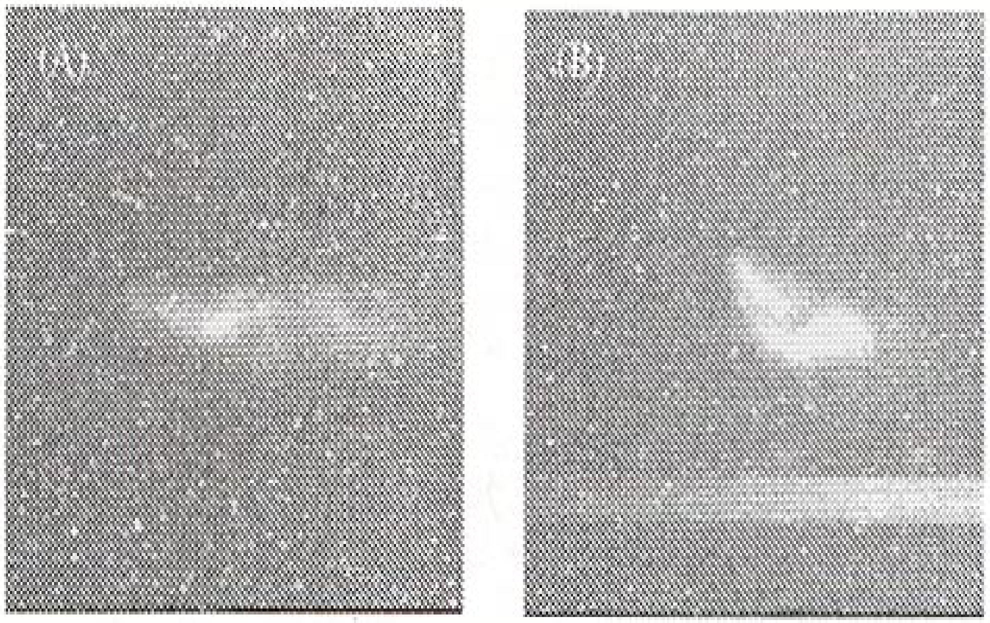
Simulation calculations of longitudinal dynamics of JLAB FEL

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

Correction of Nonlinearities by Sextupoles



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"

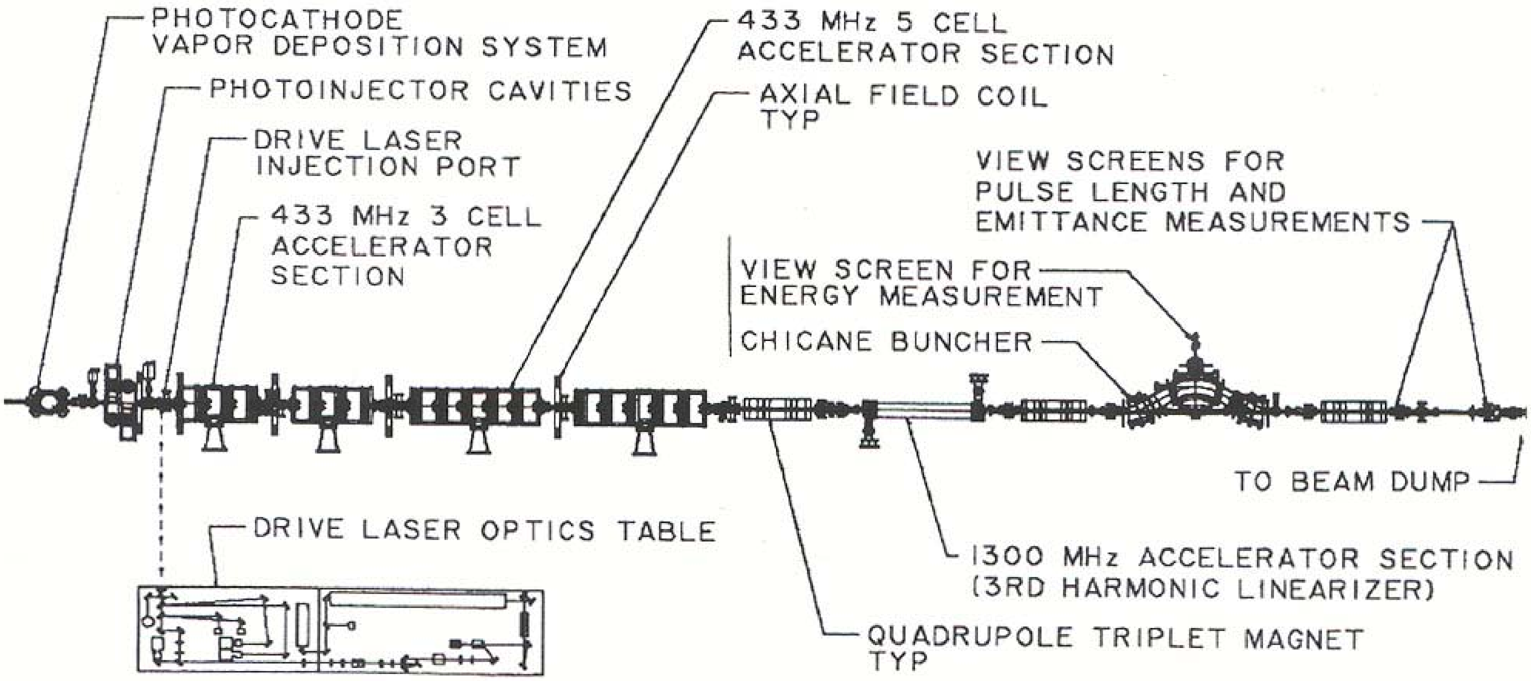
$$V_c = V_0 \cos\theta \approx V_0\left(1-\frac{\theta^2}{2}+\cdots\right)$$

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

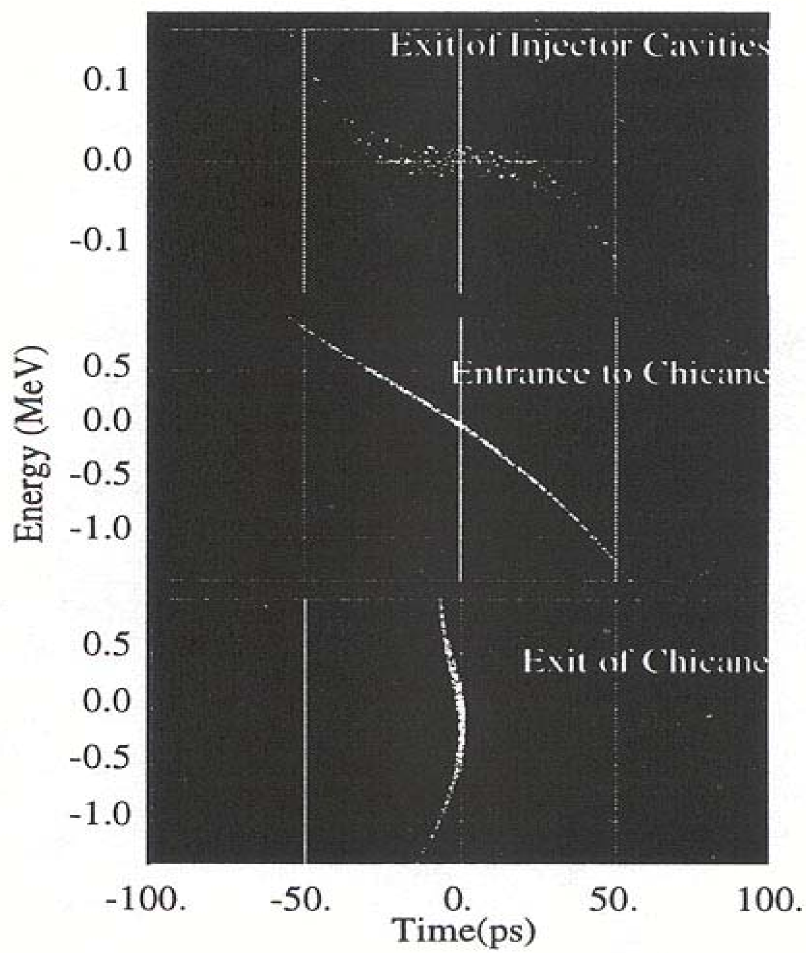
$$V_c - V_{lin} = \frac{8V_0}{9} + o\left(\theta^4\right),$$ independent of phase!

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

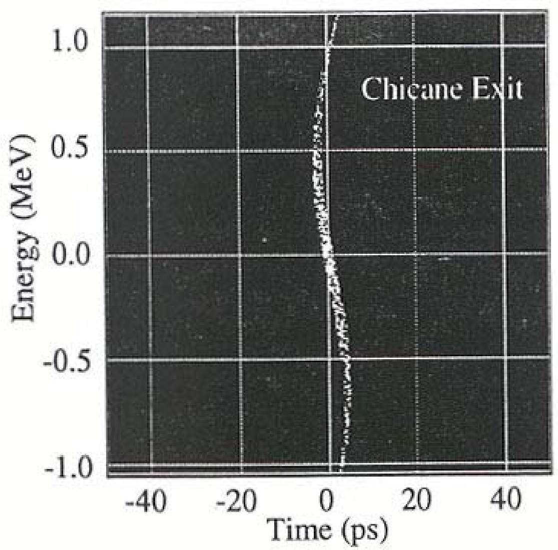
Boeing High Average Power FEL

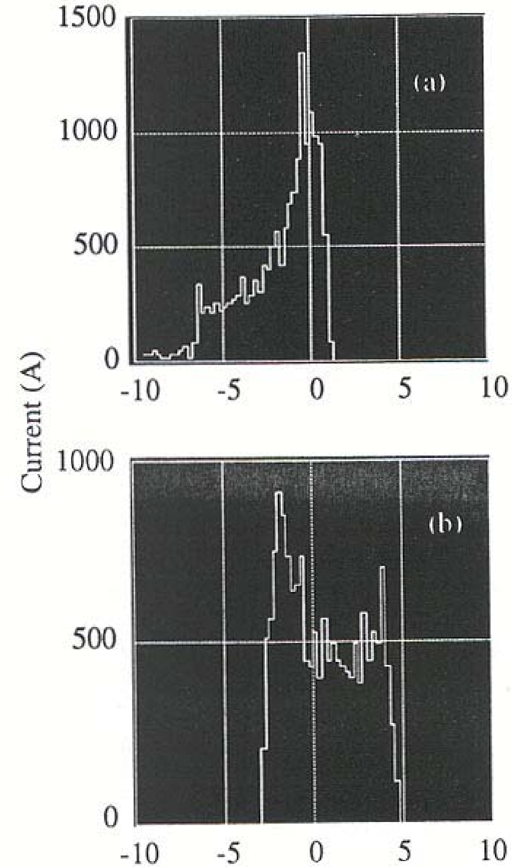


Phase Space Evolution Without Linearizer

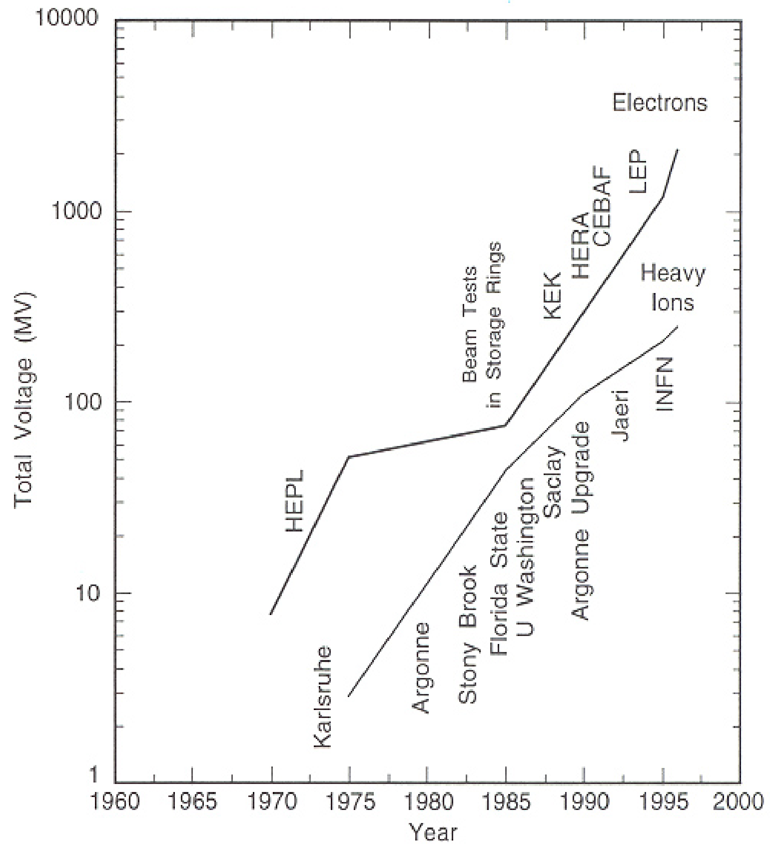


Correction of Nonlinearities by "Linearizers"





State of the Art in SRF in 2000



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

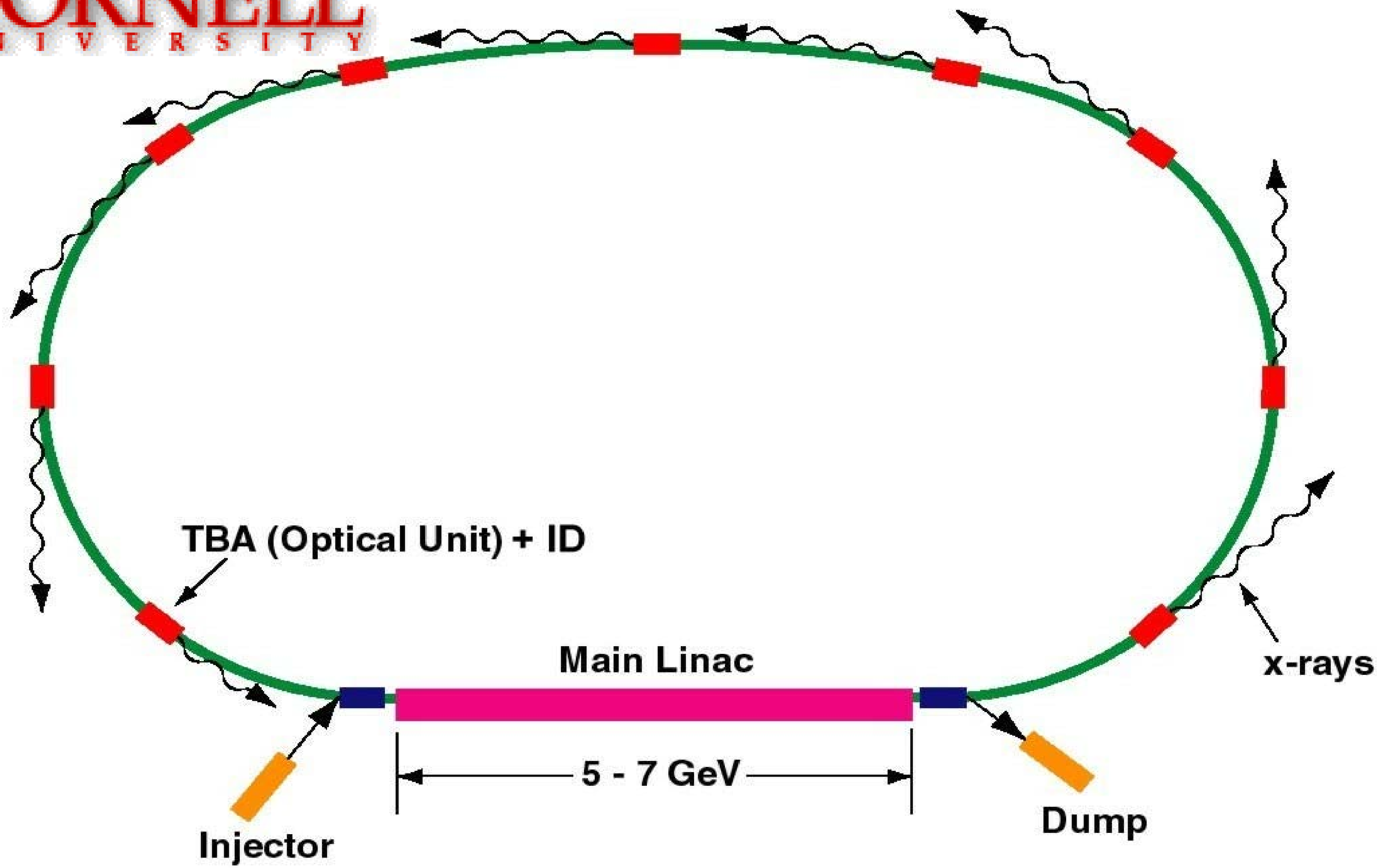
Brookhaven PERL Projects

- 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

ERL X-ray SR Source Conceptual Layout



ERL Sample Parameter List

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

- Diffraction limited X-ray source

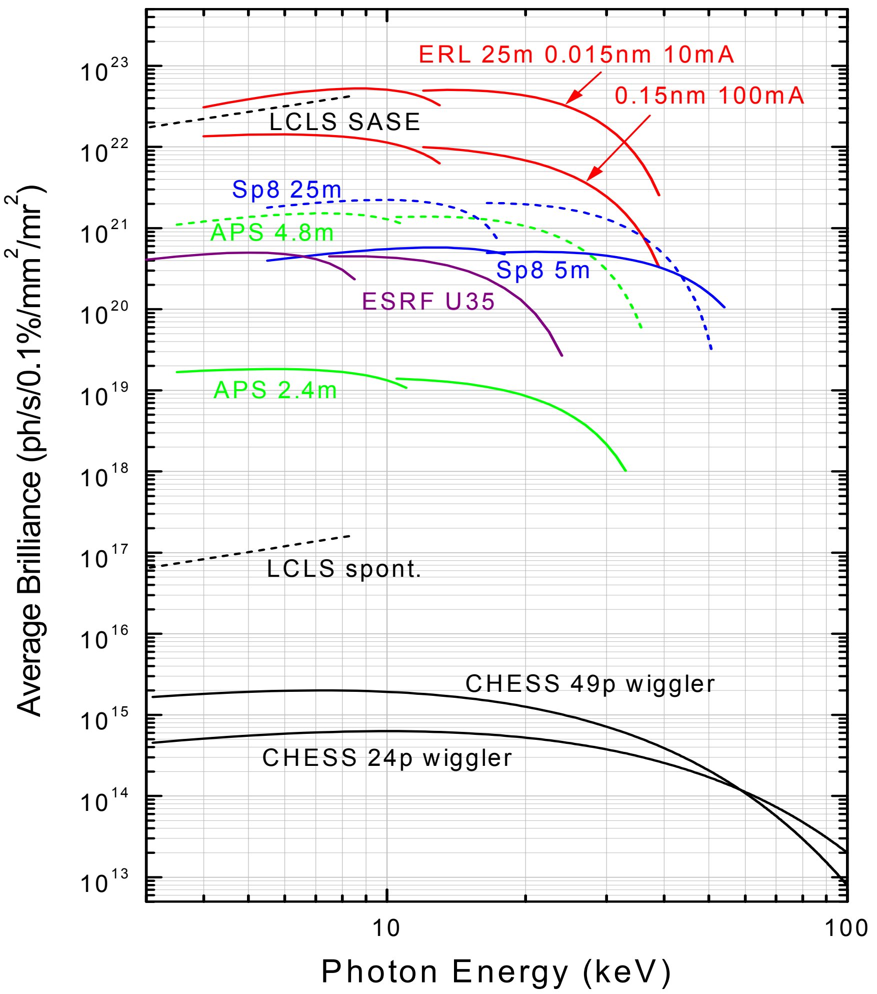
$$B \propto \frac{I}{\varepsilon^2} = \frac{fQ}{\varepsilon_{th}^2 + AQ^p}$$

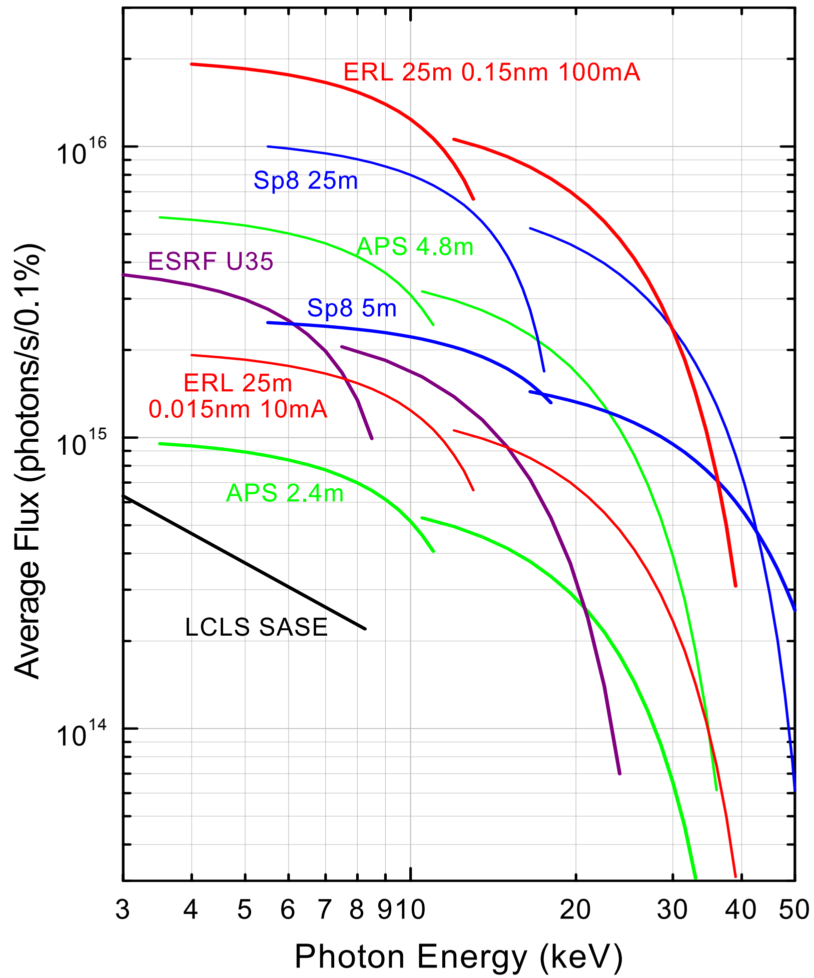
- For any power law dependence on Q

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

- If the space-charge generated emittance exceeds the thermal emittance from whatever source, you've already lost the game!
- BEST BRILLIANCE AT LOW CHARGES, once a given design and bunch length is chosen!

ERL X-ray Source Average Brilliance and Flux



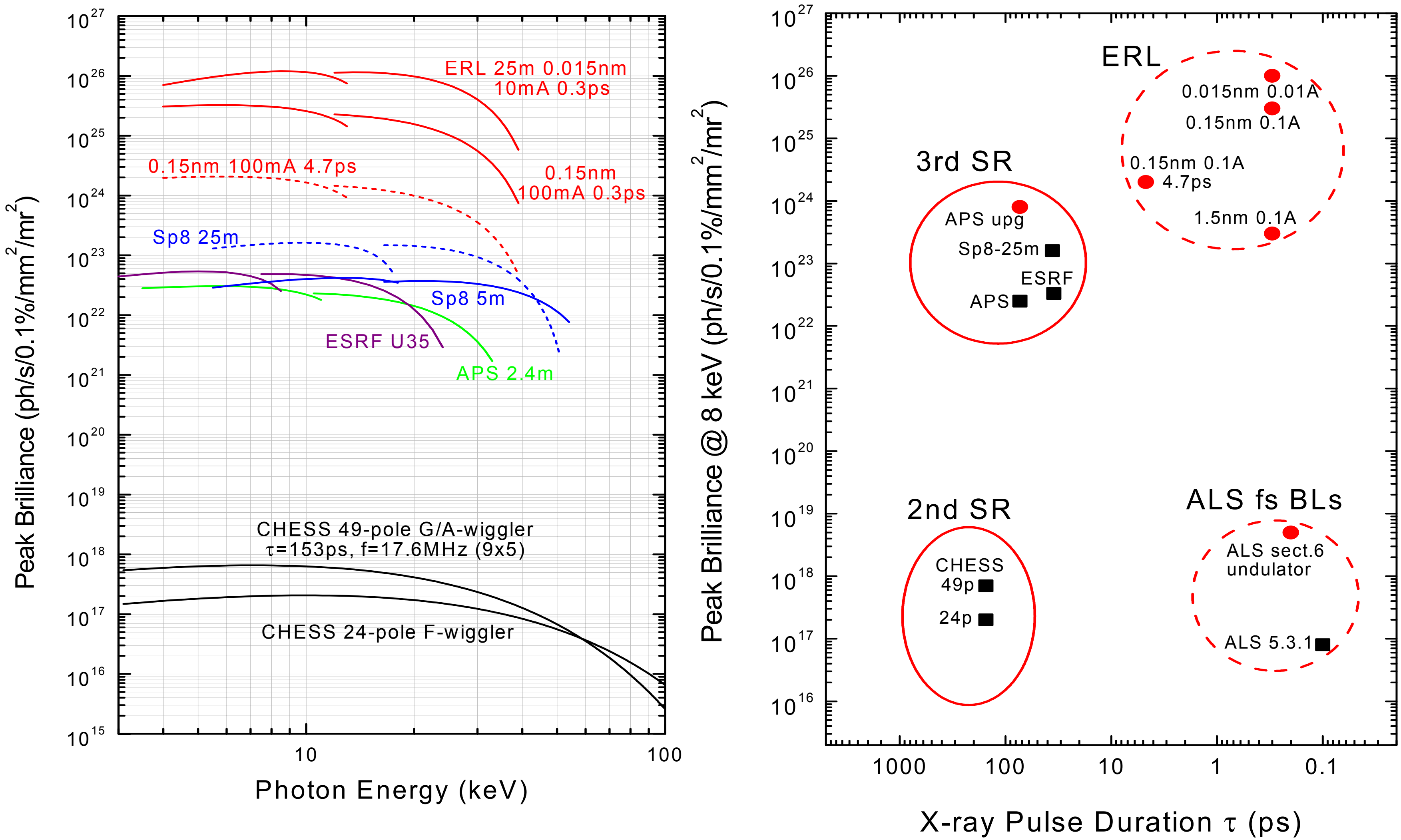


Courtesy: Q. Shen

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 results 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



Courtesy: Q. Shen

Challenges to be resolved

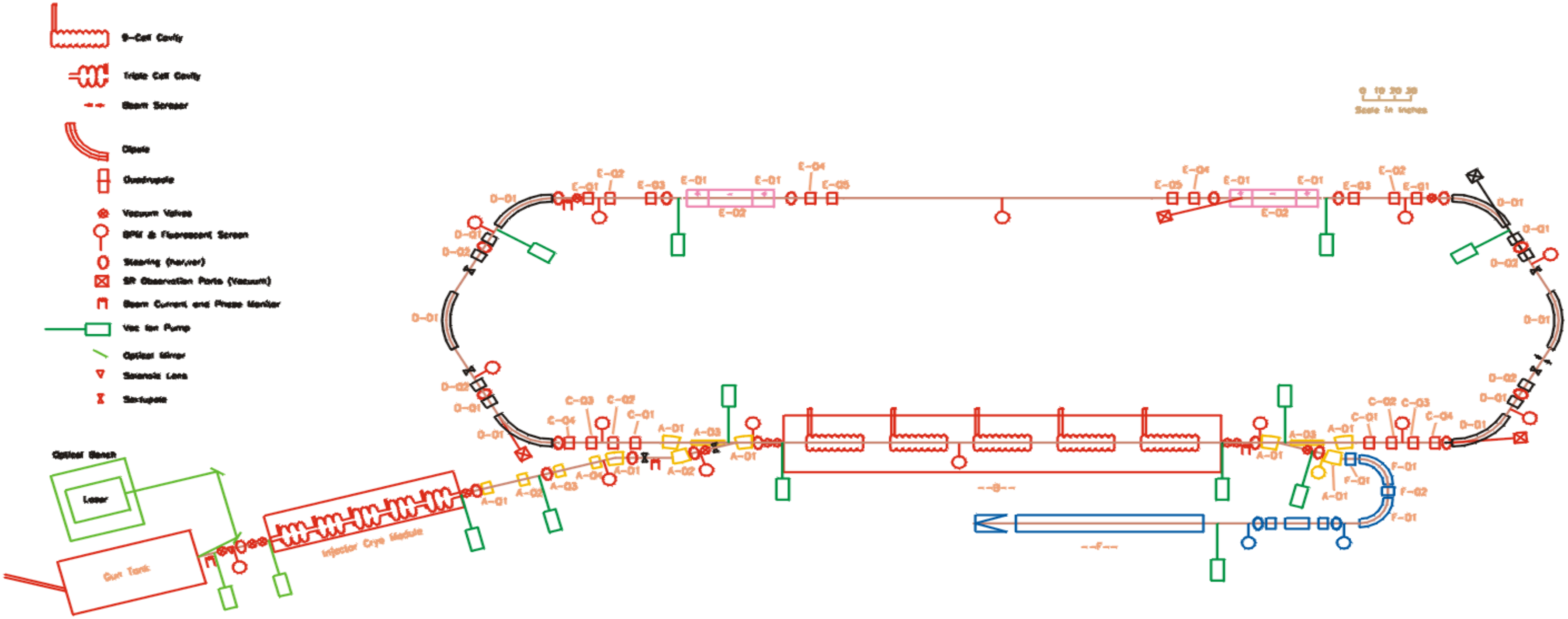
- Low emittance production & preservation
  - Achieving thermal emittance from gun (emittance compensation)
  - CSR, wakes (77 pC, not 1 nC!)
- Photocathode longevity at high average current (vacuum)
- Longitudinal phase space preservation in bunching (curvature correction)
- BBU in the main linac (HOMs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

ERL Prototype

CORNELL UNIVERSITY

We plan to begin work in the fall!

3.5 year construction, 1.5 year measurements



Beam Energy	100 MeV	Charge per bunch	77 pC
Injection Energy	5 MeV	Emittance, norm.	2* µm
Beam current	100 mA	Shortest bunch length	100* fs

* rms values

Conceptual Design of a Compact 100 kW IR FEL

- Top Level Requirements
  - FEL Power = 100 kW
  - FEL wavelength = 1 micron
  - Compact Design
- Design Principles
  - Use as high a gradient as technologically available, since compactness is of essence and refrigerator is NOT an issue
  - Use as high a bunch rep rate as possible and as low charge per bunch as possible. This greatly alleviates single bunch dynamics issues, such as wakefields and CSR
- Reasoning
  - FEL wavelength (1 micron) + one 1.3 GHz cryomodule (compact design) + 10 MeV injection energy (we know how to do) set the the beam energy to 170 MeV
  - 100kW + efficiency ~0.6% set I_{ave}~100mA
  - Low bunch charge sets bunch rate at 1300 MHz
  - FEL Gain + longitudinal gymnastics set bunch length at wiggler
  - Slippage + gain set number of wiggler periods

Parameter Table

Parameter Table for a compact, 100 kW FEL at 1 µm wavelength, based on 805MHz, 1.3GHz and 1.5GHz rf linacs, LM & SVB, Nov. 2000

Parameters	Units	Scenario 1	Scenario 2	Scenario 3	Scenario 4
e^- beam					
E_{inj}	MeV	10	10	10	10
E_{beam}	MeV	170	170	200	170
Q_{bunch}	pC	80	125	125	70
f_{rf}	MHz	1300	805	805	1500
f_{bunch}	MHz	1300	805	805	1500
I_{ave}	mA	104	100	100	100
$\sigma_z^{wiggler}$	psec	0.1 (30µm)	0.1	0.1	0.1
I_{peak}	A	320	500	500	280
ε_n	mm mrad	6	7.5	7.5	5.6
ε_{long}	keV psec	50	62.5	62.5	46.6
$\Delta E/E_{after\ FEL}$	%	5-6	5-6	5-6	5-6
FEL					
P_{FEL}	kW	100	96	110	101
$\eta_{ext}\,\eta_{opt}$	%	0.57	0.56	0.55	0.57
η_{opt}	%	78.4	78.0	78	78.5
K_w		1.6	1.6	1.64	1.6
λ_w	cm	6	6	8	6
g_w	cm	2.4	2.4	3.25	2.4
N_w		28	28	28	28
L_w	m	1.68	1.68	2.24	1.68
G_{ss}	%	76.4	109.6	103.2	67.7
$L_{opt\ cav}$	m	64	48	60	60
z_R	Cm	60	60	80	60
$Q_{opt\ cav}$		5	4	4	5.56
$P_{mirror\ loading}$	KW/cm^2	73.4	100.4	97.6	93.8
RF					
E_{acc}	MV/m	20	12	14	19 (20)
Q_0		2×10^{10}	1×10^{10}	1×10^{10}	8×10^{9}
L_{cav}	m	1.04	1.12	1.12	0.7
N_{cav}		8	12	12	12
N_{CM}		1	3	3	?
L_{CM}	m	~12	6.2 (β=1)	6.2 (β=1)	~10
R/Q /cavity	Ω	~1000	~600	~600	~700
P_{wall}/cavity	W	20	30	41	31.6 (35)
P^{TOTAL}_{wall}	W	160	360	492	380 (420)
P_{HOM}/cavity	W	160(k//=10V/pC)	200(k//=8V/pC)	200(k//=8V/pC)	140
P^{TOTAL}_{HOM}	kW	1.3	2.4	2.4	1.7

Scale-up Issues

I can do no better than just quote the prototype proposal Cornell and Jlab have prepared.

3.3 Prototype Accelerator Physics and Technology Issues and Experiments

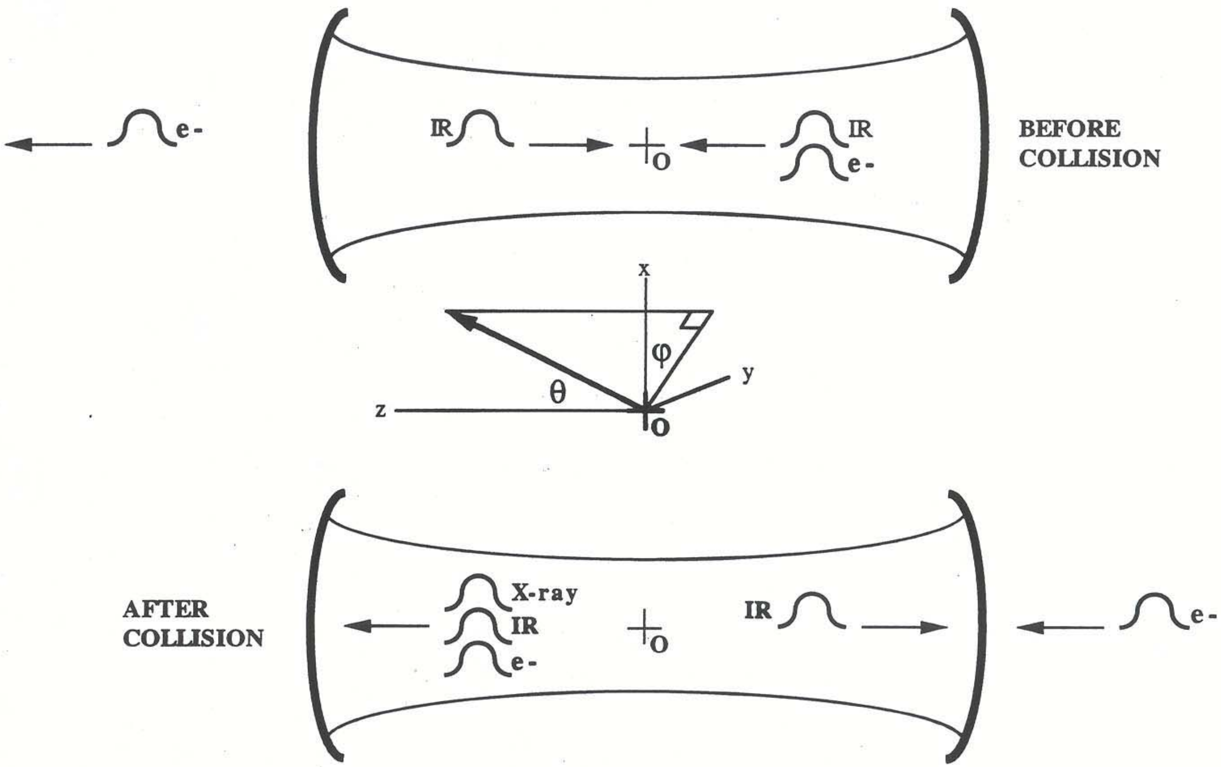
- 3.3.1 Coherent Synchrotron Radiation and Non-inertial Space Charge
- 3.3.2 Ions
- 3.3.3 Gun Performance
- 3.3.4 Injector Performance
- 3.3.5 Linac Transverse Stability
- 3.3.6 RF Stability
- 3.3.7 Higher Order Mode Cooling
- 3.3.8 Emittance Preservation

And of course the quantification of CW beam loss

Short-Pulse (100-1000 fsec) X-Rays

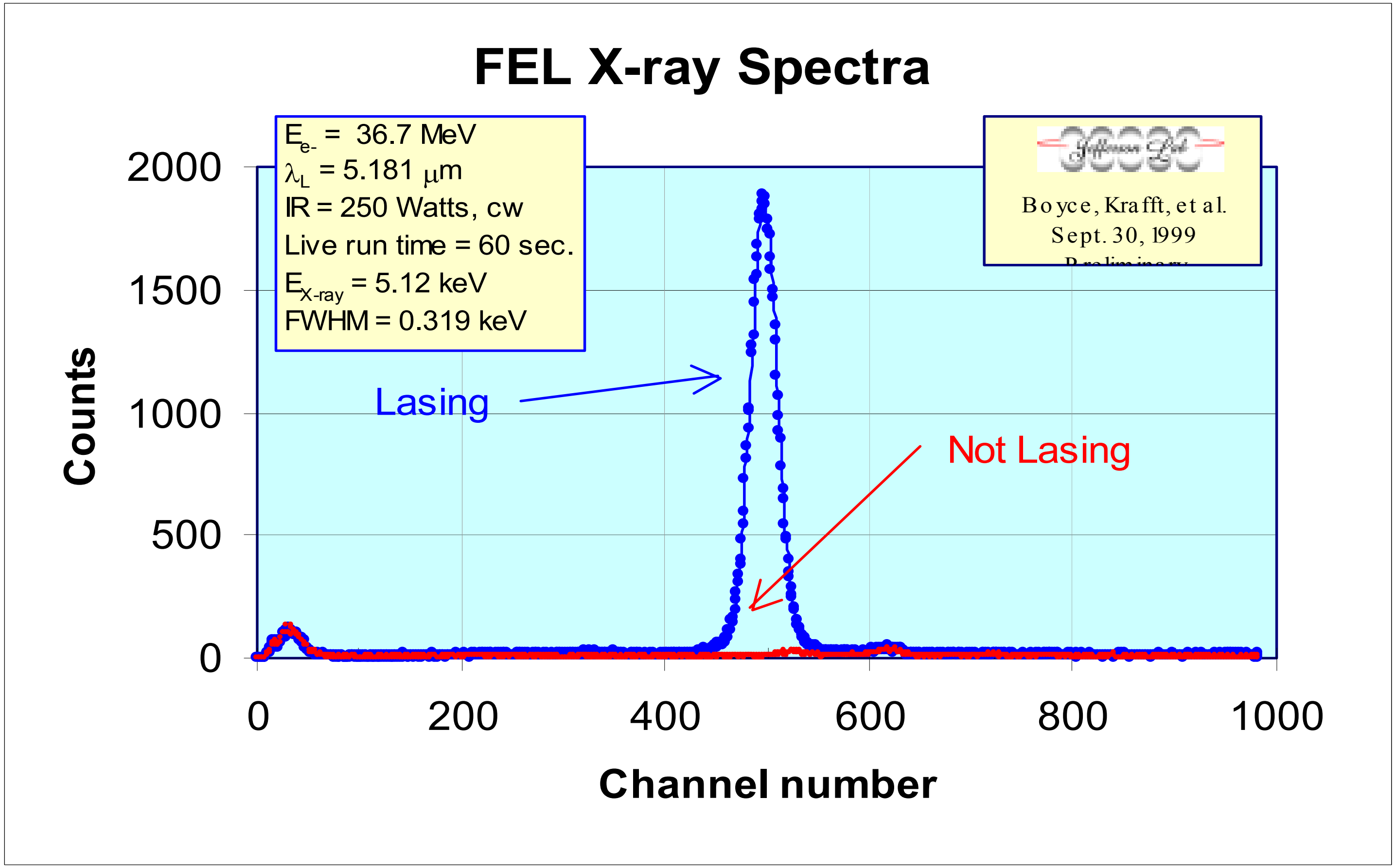
- About 4 years ago, after a Science article by Schoenlein, et al., I spent some time trying to figure out how we could do same work at Jlab. Settled on a Thomson scatter source that has recently produced a substantial X-ray flux.
- In mean time LBNL proposed short-pulse source based on short-pulse laser 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

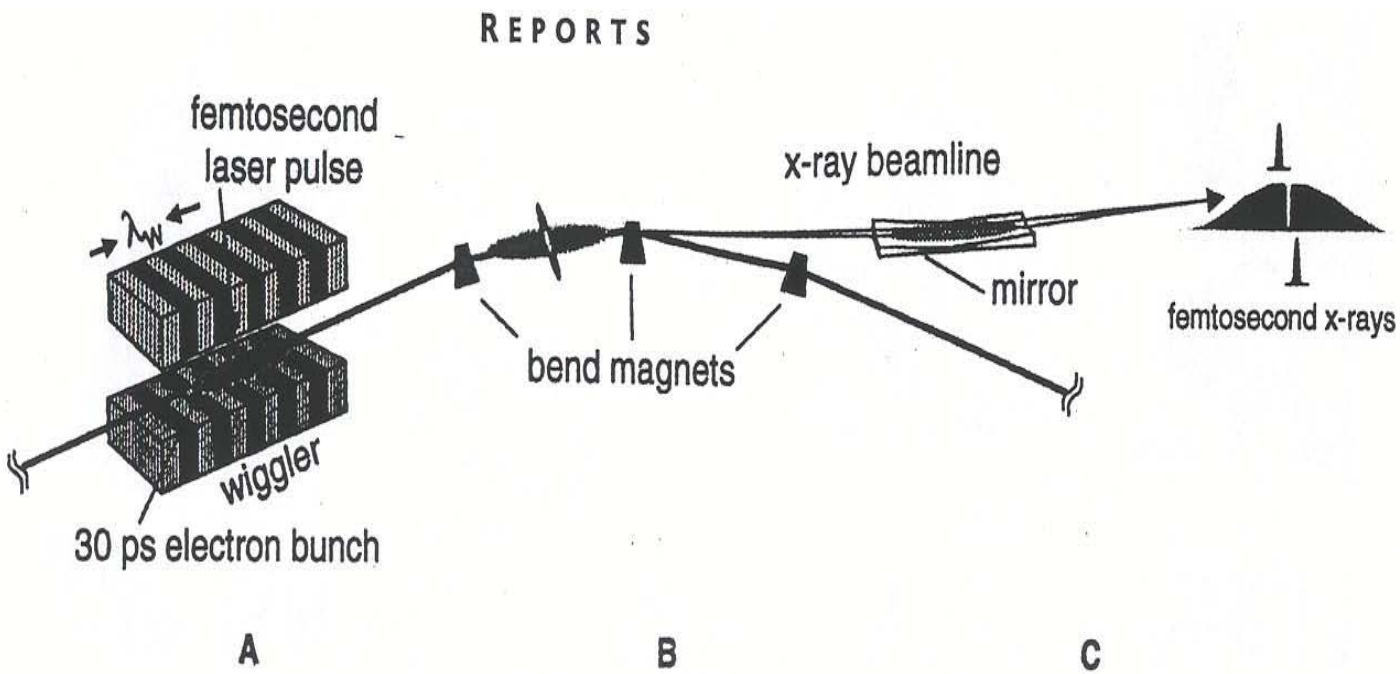


SCATTERING GEOMETRY

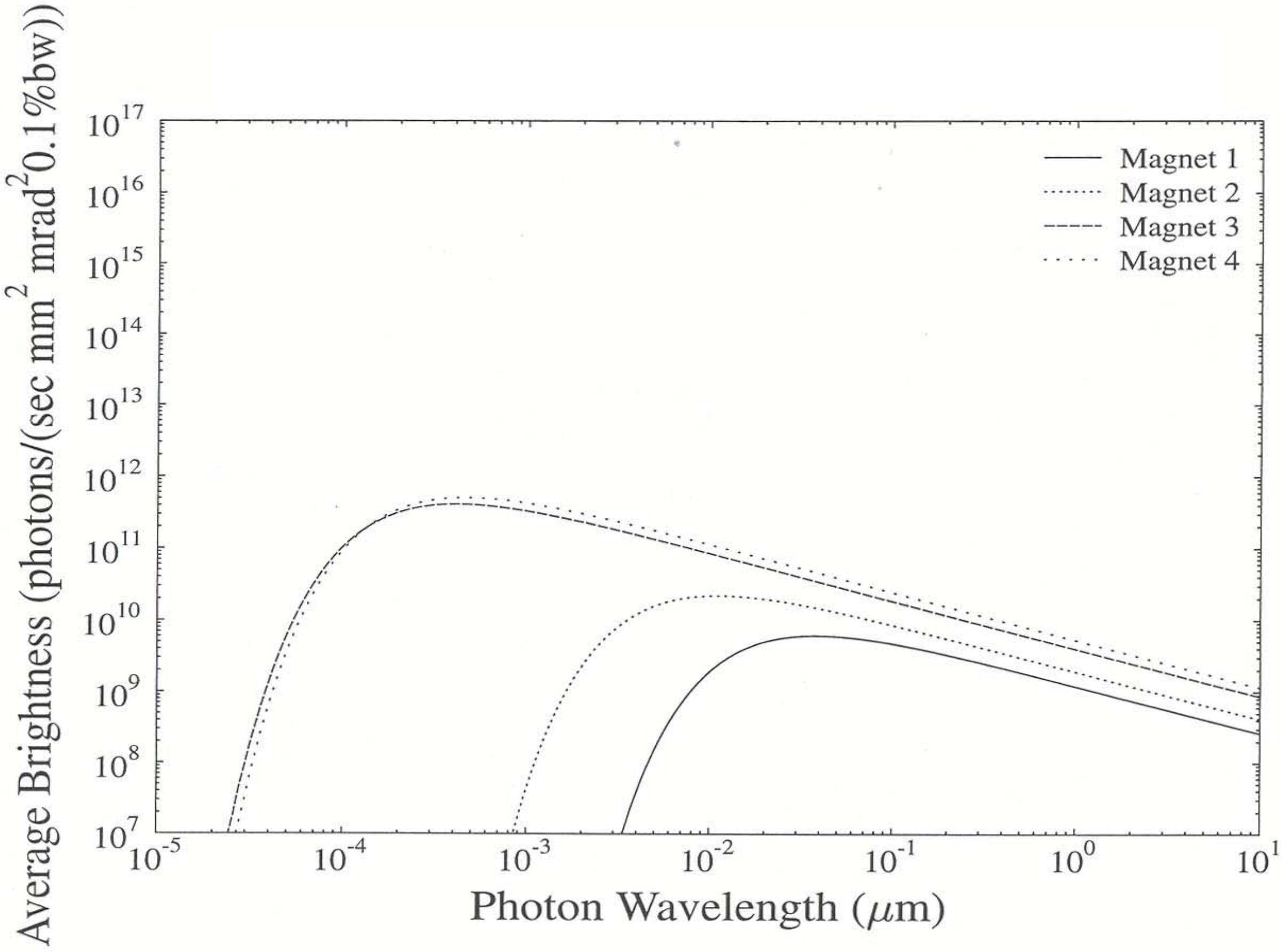
60 sec FEL Short-pulse X-ray Spectrum



Berkeley Short Pulse X-ray Facility

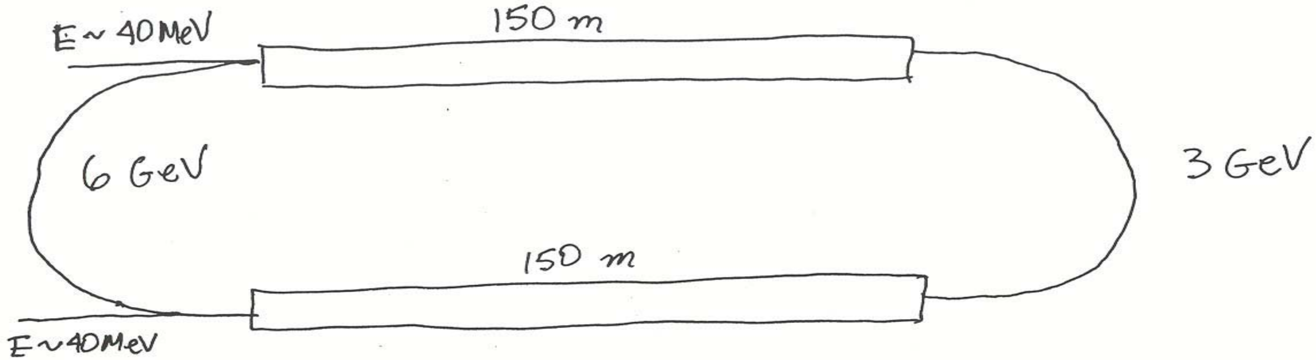


AVERAGE BRILLIANCE FROM CEBAF BENDS



Viewslide at ICFA 4th Gen., April 1999

INTERESTING?



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

$I \sim$ 10-20 mA

$l_B \sim$ 100 fsec $\qquad f_B \sim$ 1-10 MHz

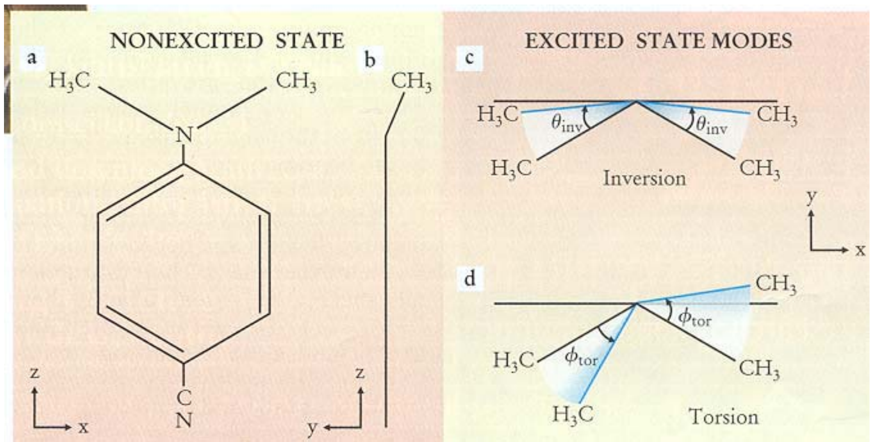
$\frac{\Delta E}{E} \sim$ SEVERAL $\times 10^{-5}$

SEVERAL \$100 M

Doubling Time Calculation

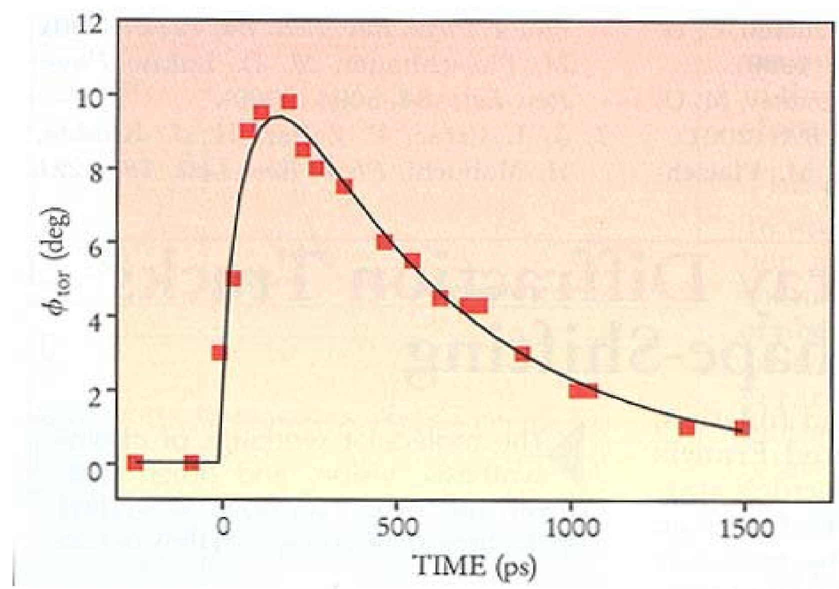
- At ICFA meeting at Argonne in 1999, I presented previous viewgraph, emphasizing short pulses to Bob Schoenlein, Alan Jackson, Kwang-Je Kim, John Galayda, and others. The best response I got was from the organizers; I should sit down with Kulypanov and talk, which we did. Assuming 2 interested individuals in April 1999 and 60 interested individuals (the attendance at this meeting!) in August 2001, one computes a doubling time of roughly ½ year.
- If we can maintain the same growth rate in interest, we'll have the whole APS along for the ride in about 4.2 years!

Interesting New Direction?



$C_9H_{10}N_2$ Bending

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



CONCLUSIONS

• I've given you some indication of the historical development of recirculating, and in particular 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.

•I've given you some indication of near-term plans for development of higher current Energy Recovered SRF linacs.

•I've indicated why recirculating SRF linacs, especially those that are energy recovered, may become more common in future recirculating linac light applications.