Linac–Ring Colliders

L. Merminga and G. Krafft, Jefferson Lab
V. Lebedev, FNAL and I. Ben-Zvi, BNL

The Future of Particle Physics
Snowmass 2001
July 4 2001, Snowmass Village, CO

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Outline

- Physics Requirements
- Two Scenarios
- Energy Recovery Linacs / The JLab IR FEL
- Linac – Ring Point Designs
- Accelerator Physics Issues of Protons
- Accelerator Physics Issues of Energy Recovery Linacs
- Fundamental Luminosity Limitations
- R&D Topics
- Conclusions

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Physics Requirements

- Electron – proton colliders with the following requirements have recently been proposed as a means for studying hadronic structure:
  - Center-of-mass energy between 14 GeV and 100 GeV with energy asymmetry of about 1 – 6, which yields E_e=3 GeV to 10 GeV and E_p=15 GeV to 250 GeV
  - Luminosity at the 10^{33} cm^{-2} sec^{-1} level
  - Longitudinal polarization of both beams in the interaction region $\geq$ 50% –80%

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Two Scenarios

- Two accelerator design scenarios have been proposed:
  - ring – ring
  - linac – ring

- Linac – ring option presents advantages with respect to
  - spin manipulations
  - reduction of synchrotron radiation load in the detectors
  - wide range of continuous energy variability

- Feasibility studies were conducted at BNL (based on RHIC) and Jefferson Lab to determine whether the linac-ring option is viable. Self-consistent sets of parameters were derived

- Rf power and beam dump considerations require that the electron linac is an Energy Recovery Linac (ERL)

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Energy Recovery Linacs

- Energy recovery is the process by which the energy invested in accelerating a beam is returned to the rf cavities by decelerating the same beam.

- There have been several energy recovery experiments to date, the first one at the 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.

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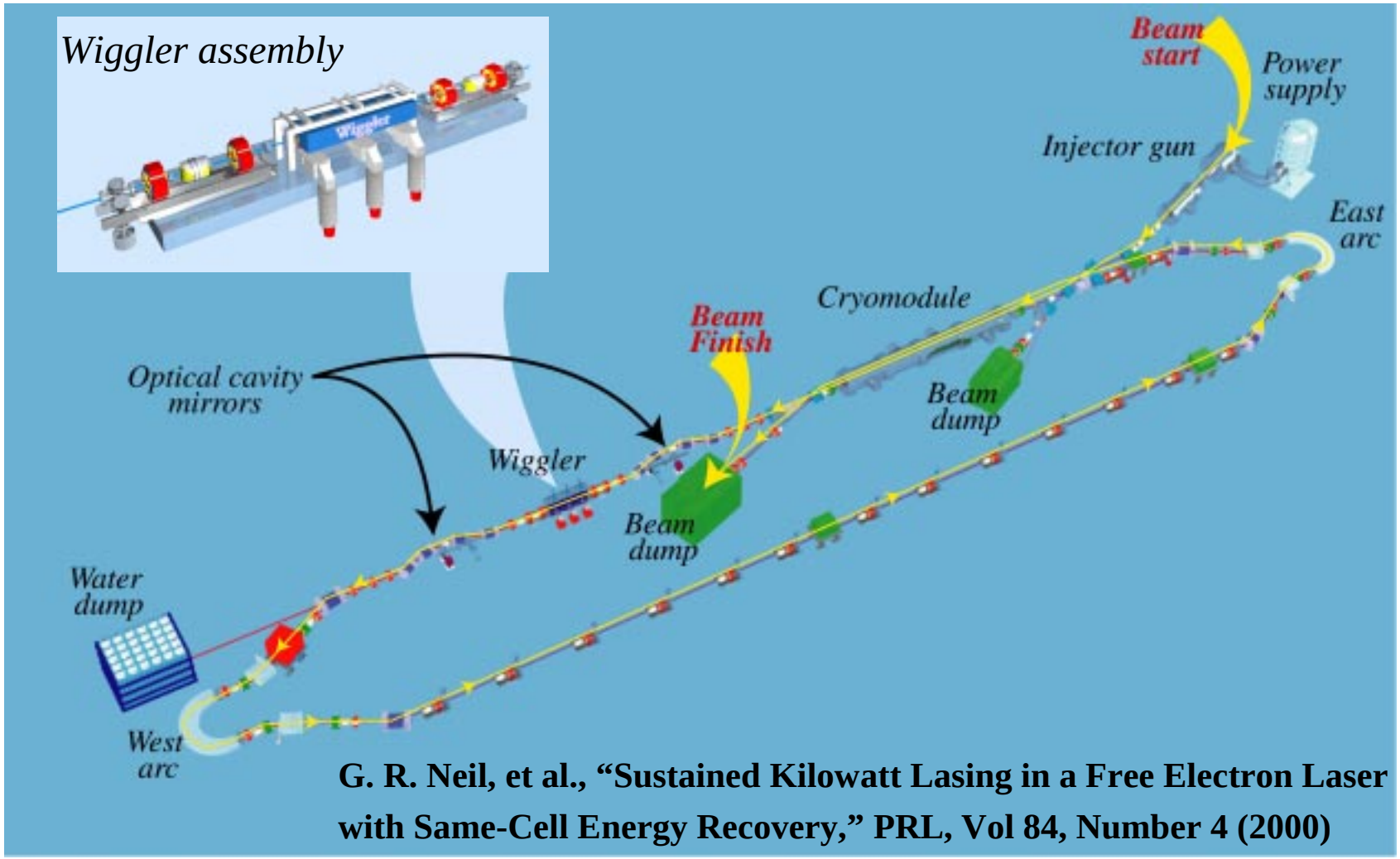
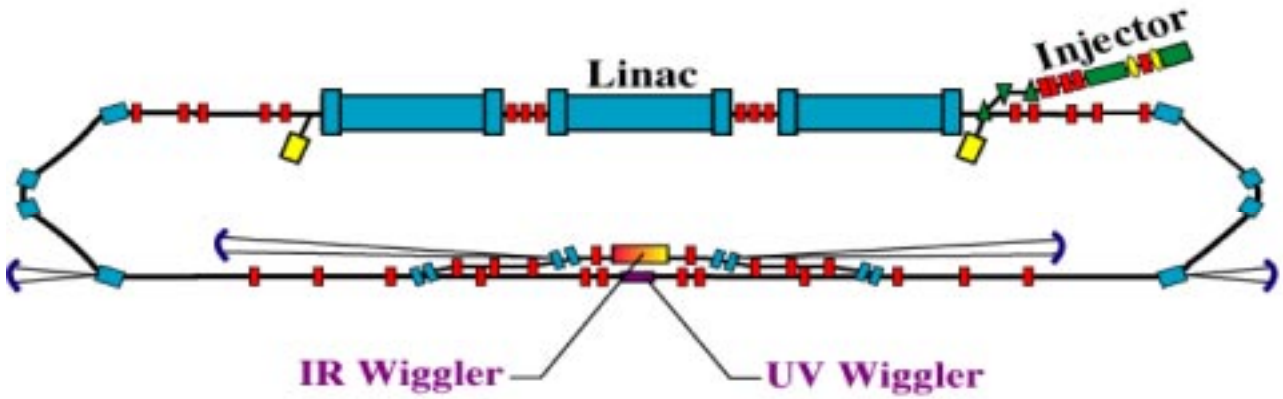
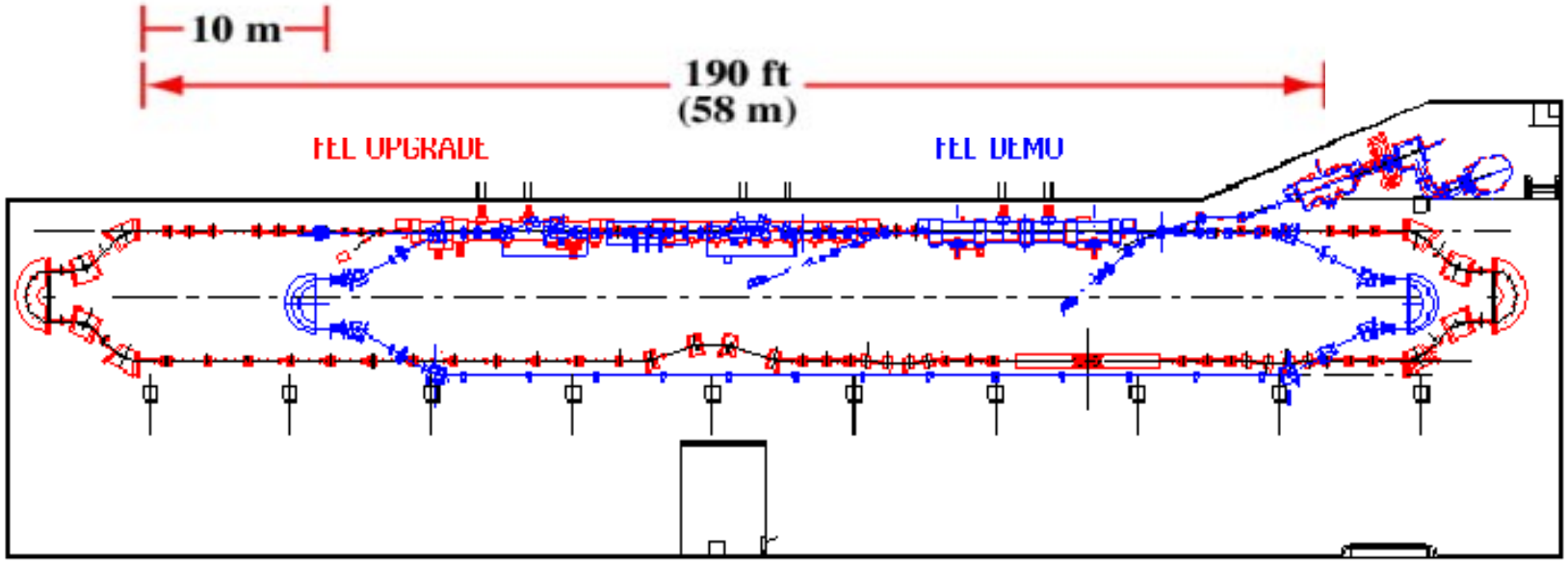
The JLab 1.7 kW IRFEL and Energy Recovery Demonstration



G. R. Neil, et al., "Sustained Kilowatt Lasing in a Free Electron Laser with Same-Cell Energy Recovery," PRL, Vol 84, Number 4 (2000)

The JLab 10 kW IRFEL Upgrade Project





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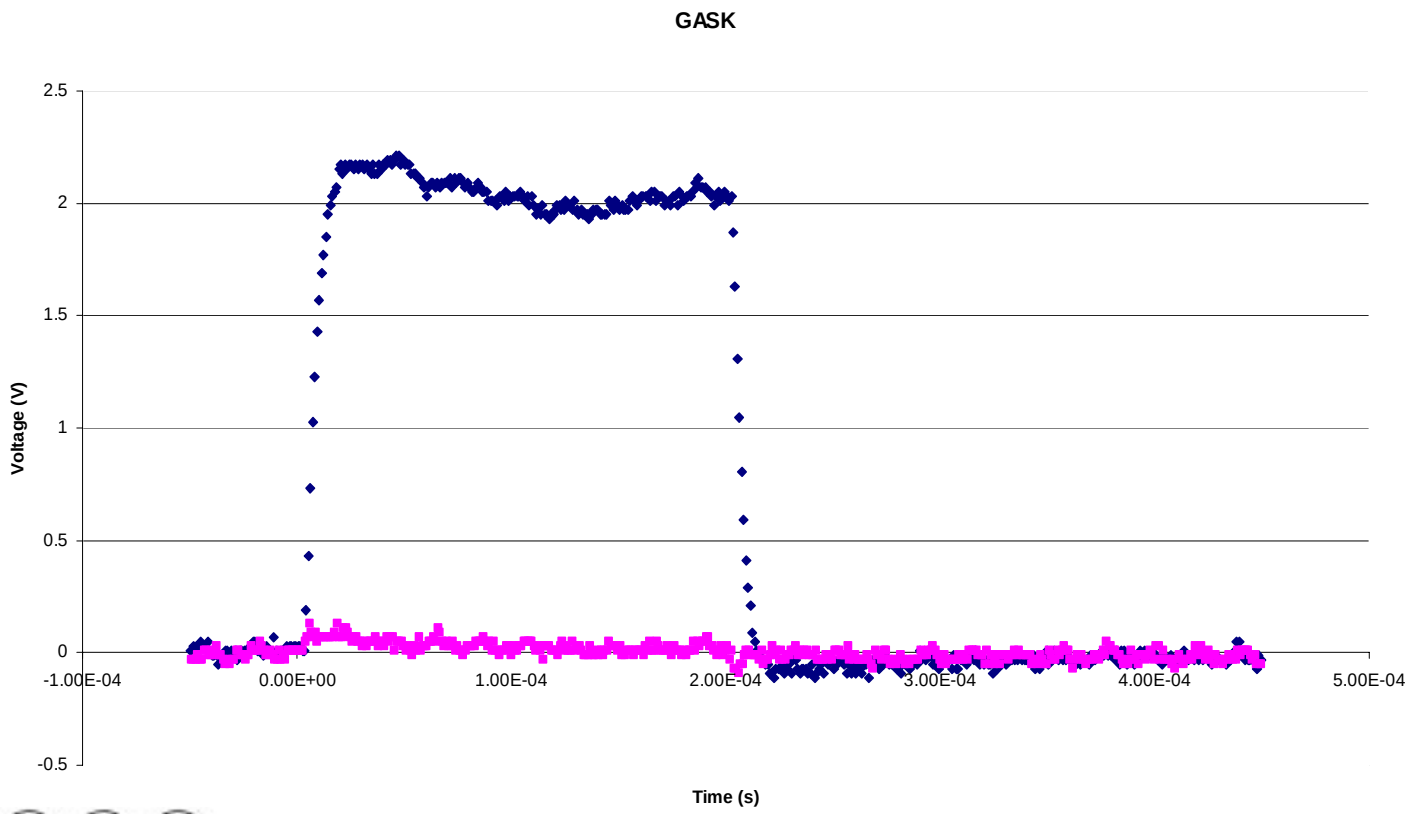
Energy Recovery Works

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).



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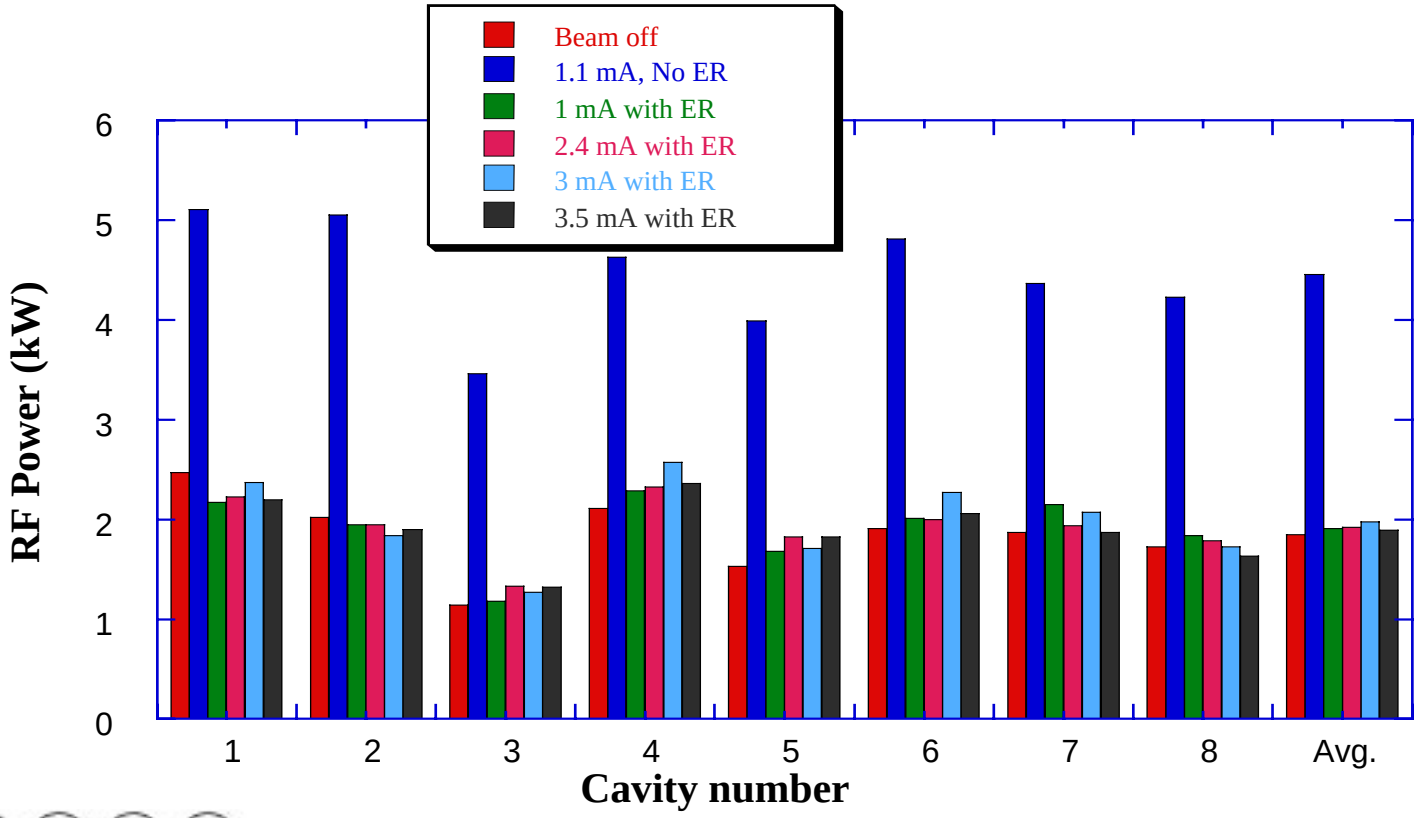
Energy Recovery Works

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.



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Benefits of Energy Recovery

AC Power Draw in IR Demo: 1.7 kW FEL output

Beam 5 mA, 48 MeV

Component	With Energy Recovery (measured)	Without Energy Recovery (estimates)	
Injector RF	220 kW	220 kW	
Linac RF	175 kW	700 kW	
He Refrigerator	70 kW	70 kW	(Estimated)
Magnets, Computers, etc.	43 kW	23 kW	
Total	508 kW	1013 kW	

G. R. Neil, FEL Conference 1999, Hamburg Germany.

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Benefits of Energy Recovery

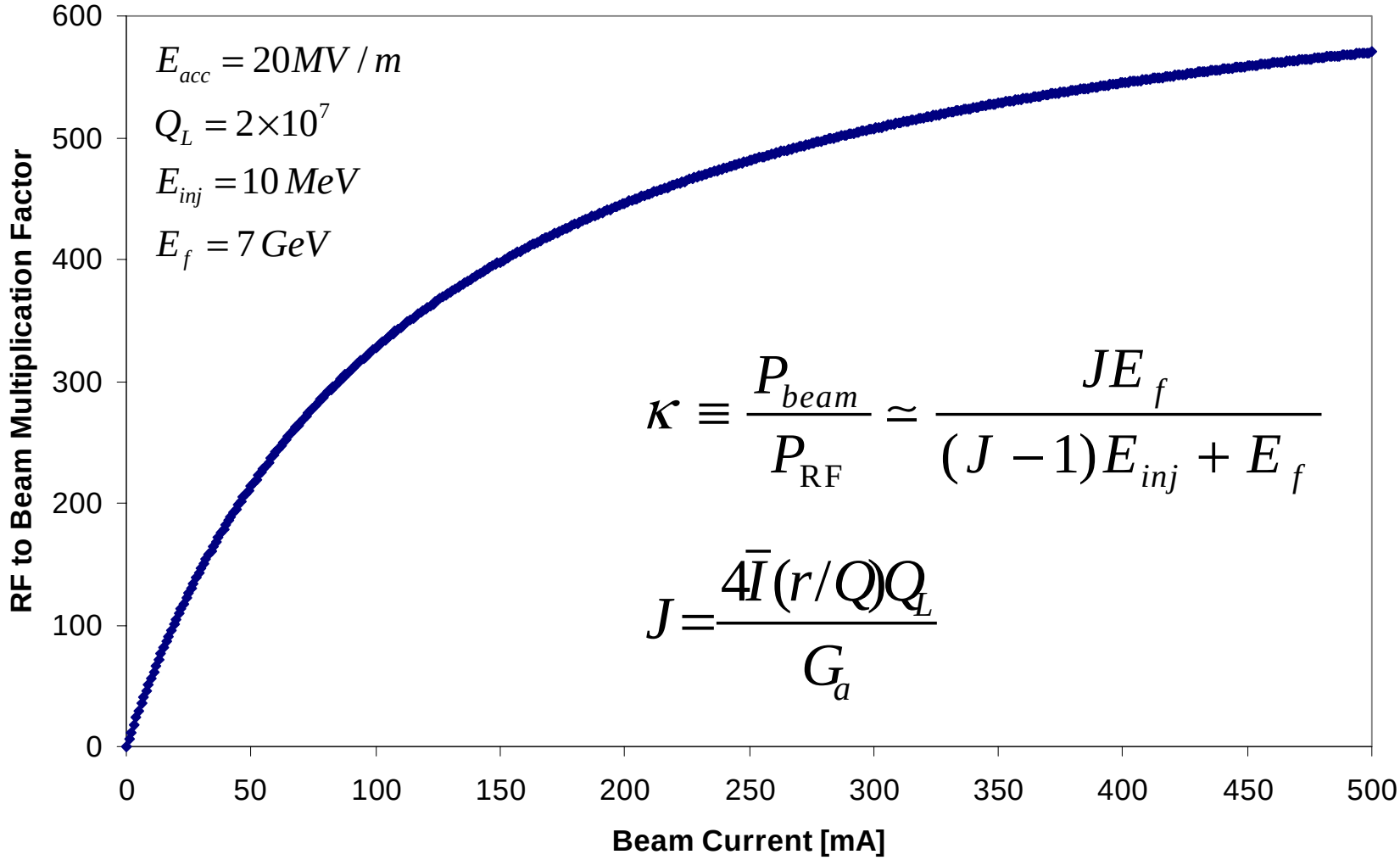
AC Power Draw in IR Upgrade: 10 kW FEL output

Beam 10 mA, 160 MeV

Component	With Energy Recovery (estimates)	Without Energy Recovery (estimates)	
Injector RF	350 kW	350 kW	
Linac RF	525 kW	4200 kW	
He Refrigerator	100 kW	100 kW	
Magnets, Computers, etc.	100 kW	40 kW	
Total	1075 kW	4690 kW	

G. R. Neil, FEL Conference 1999, Hamburg Germany

RF to Beam Multiplication Factor for an ideal ERL



Benefits of Energy Recovery

- Required rf power becomes nearly independent of beam current.
- Increases overall system efficiency.
- Reduces electron beam power to be disposed of at beam dumps (by ratio of E_{fin}/E_{inj}).
- If the beam is dumped below the neutron production threshold, then the induced radioactivity (shielding problem) will be reduced.

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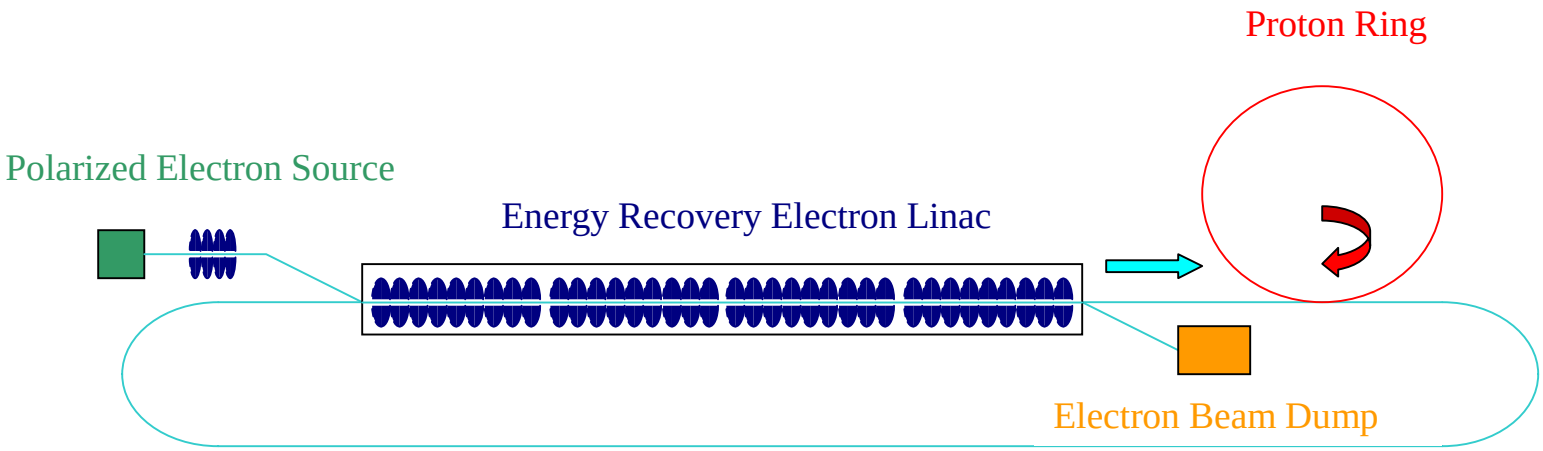
Linac–Ring Schematic Layout



Assume linac uses TESLA-style cavities at 20 MV/m and Q_0~$1x10^{10}$

Linac–Ring Collider Reasoning and Point Design 1

- Input parameters: $E_e = 5$ GeV and $E_p = 50$ GeV

- Reasoning:
  - Set electron beam size at IP based on projected source performance
  - Set proton beam parameters at Laslett tuneshift limit
  - Determine number of electrons per bunch
  - Determine collision frequency

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Electron Beam Parameters at the IP

- Assume $\varepsilon_n \sim 60\ \mu m$ at $Q \sim 1.75$ nC

  (Emittance dilution in linac will be addressed below)

- At $E_e = 5$ GeV, $\varepsilon_e = 6$ nm
- For $\beta^* = 10$ cm, $\sigma_e^* = 25\ \mu m$

(Round beams are assumed for electrons and protons)

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Proton Beam Parameters

- For $\sigma_z \approx \beta_p^*$ Laslett tuneshift sets a limit on N_p / σ_p^{*2}

$$\Delta \nu_L = \frac{N_p r_p}{4 \pi \gamma_p^3 \varepsilon_x} \frac{C}{\sqrt{2\pi}\,\sigma_z}$$

- We assume: $\Delta\nu_L \leq 0.004$

- For $\varepsilon_{n,p}$ = 2 μm (LHC, RHIC), β^* = 10 cm =>

  σ_p^* = 60 μm

  and

  $N_p = 1 \times 10^{11}$

  at the Laslett tuneshift limit.

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Number of Electrons per Bunch

N_e is limited by:

- Beam-beam tuneshift of proton beam

$$\xi_p = \frac{N_e r_p \beta_p^*}{4\pi\gamma_p \sigma_e^{*2}}$$

- For $\xi_p = 0.004$, $N_e = 1.1 \times 10^{10}$

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Collision Frequency

- Maximize f_c subject to constraints:
  - Parasitic collisions
  - User requirements based on current understanding
  - Electron cloud effect
- Assume bunch separation of 6.66 nsec or

$$f_c = 150 \text{ MHz}$$

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Luminosity of Point Design 1

$$L = \frac{N_e N_p f_c}{2\pi[\sigma_e^{*2} + \sigma_p^{*2}]}$$

$I_e = 0.264$ A

$I_p = 2.4$ A

$f_c = 150$ MHz

$\sigma_e^* = 25$ μm

$\sigma_p^* = 60$ μm

$L = 6.2 \times 10^{32}$ cm^{-2} sec^{-1}

Point Design 2

- Input parameters: E_e=5 GeV and E_p=50 GeV
- Cooling of protons is assumed
- Electrons and protons have equal beam size at the IP
- Electron beam parameters remain the same
- This optimization yields:

$$I_e = 0.264 \text{ A}$$

$$I_p = 2.4 \text{ A}$$

$$\sigma_e^* = 25\ \mu\text{m}$$

$$\sigma_p^* = 25\ \mu\text{m}$$

$$L = 2.1 \times 10^{33}\ \text{cm}^{-2}\ \text{sec}^{-1}$$

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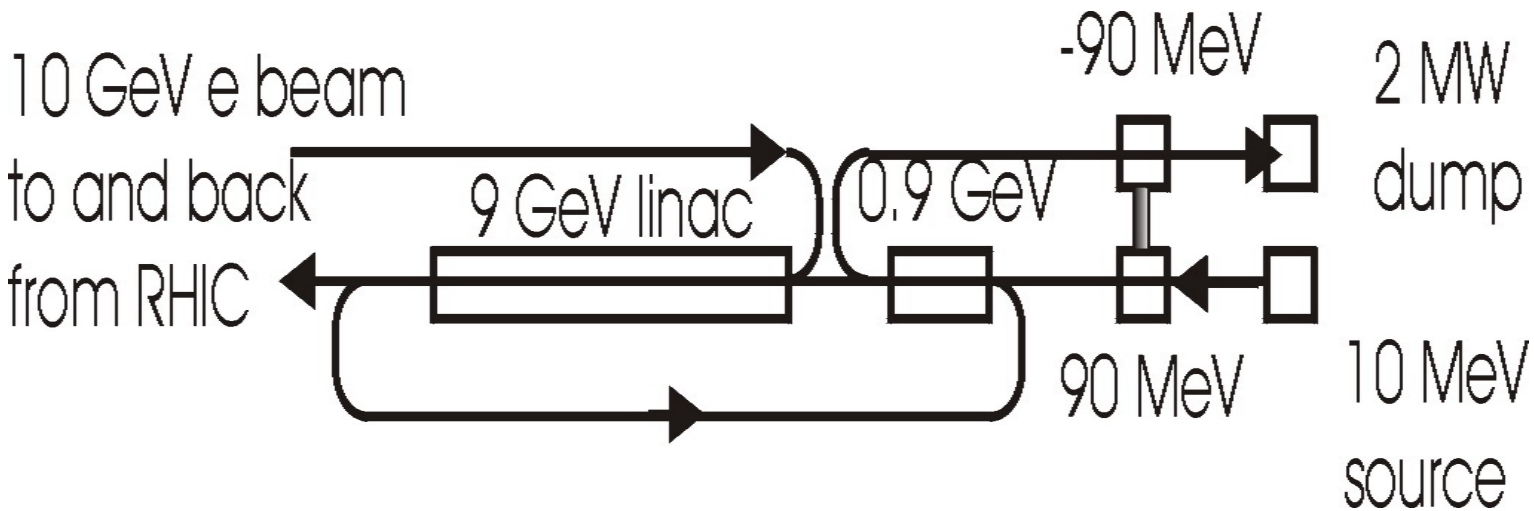
Point Design 3: The eRHIC Linac-Ring Scenario



- Input parameters: E_e=10 GeV and E_p=250 GeV
- I_e= 0.270 A

  I_p = 0.83 A

  σ_e* = 33 μm $\Rightarrow$ L = 1.14 x 10^{33} cm^{-2} sec^{-1}

  σ_p* = 33 μm

  f_c = 56 MHz

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Parameter Table

Parameter	Units	**Point Design 1**		**Point Design 2**		**eRHIC**	
		e^- Linac	p-Ring	e^- Linac	p-Ring	e^- Linac	RHIC (p)
Beam Energy	GeV	5	50	5	50	10	250
Proton Cooling	-	-	No	-	Yes	-	Yes
Ring Circumference	m	-	460	-	460	-	3833
N_{bunch}	ppb	1.1×10^{10}	1×10^{11}	1.1×10^{10}	1×10^{11}	3×10^{10}	$.93 \times 10^{11}$
f_c	MHz	150		150		56	
I_{ave}	A	0.264	2.4	0.264	2.4	0.270	0.83
σ^*	μm	25	60	25	25	33	33
ε	nm	6	36	6	6	2.5	2.5
β^*	cm	10	10	10	10	36	36
σ_z	cm	0.1	10	0.1	10	0.3	10
ξ_{pr}	-	-	0.004	-	0.004	-	0.0046
$\Delta\nu_L$	-	-	0.004	-	0.024	-	0.001
D_e	-	0.78	-	4.6	-		-
Luminosity	$cm^{-2}sec^{-1}$	6.2×10^{32}		2.1×10^{33}		1.14×10^{33}	

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Accelerator Physics Issues of Protons

- Intrabeam scattering: Transverse
  Point design 1: τ_{tr} = 36 minutes
  Point design 2: τ_{tr} = 32 seconds

- Intrabeam Scattering: Longitudinal
  Point design 1: τ_{tr} = 160 minutes @ σ_E/E=3e-3
  Point design 2: τ_{tr} = 14 minutes @ σ_E/E=3e-3

- Collective Effects
  - Longitudinal mode coupling $\Rightarrow N_p < 6 \times 10^{12}$
  - Transverse mode coupling instability $\Rightarrow N_p < 1.8 \times 10^{12}$

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Emittance growth of the electrons due to a single collision

- A single collision disrupts the electron beam and causes emittance growth
- Electron beam with degraded phase space has to be recirculated and energy recovered
- Adiabatic antidamping can result in scraping and beam loss in the cryomodules
- Therefore, amount of tolerable beam loss at the linac exit imposes a limit on tolerable emittance growth due to collision. This in turn imposes a limit on N_p
- In the small disruption limit:

$$\varepsilon_n^2 = \varepsilon_{0,n}^2 + (0.194\, r_e\, N_p)^2$$

$$\Rightarrow \quad N_p \leq 1.5 \times 10^{12} \text{ ppb}$$

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Accelerator Physics Issues of ERLs

- Source
- Accelerator Transport
- Beam Loss
- Collective Effects
  - Single-bunch effects
  - Multipass, Multibunch Beam Breakup (BBU) Instabilities
- HOM Power Dissipation

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High Current Source of Polarized Electrons

- High average current (~ 250mA), high polarization (~80%) electron source is a significant technological issue
  - State of the art in high average current, polarized sources:

    ~1 mA at 80% polarization [C. Sinclair, JLab]

Hartmann, Sinclair et al., eRHIC Workshop, April 2000

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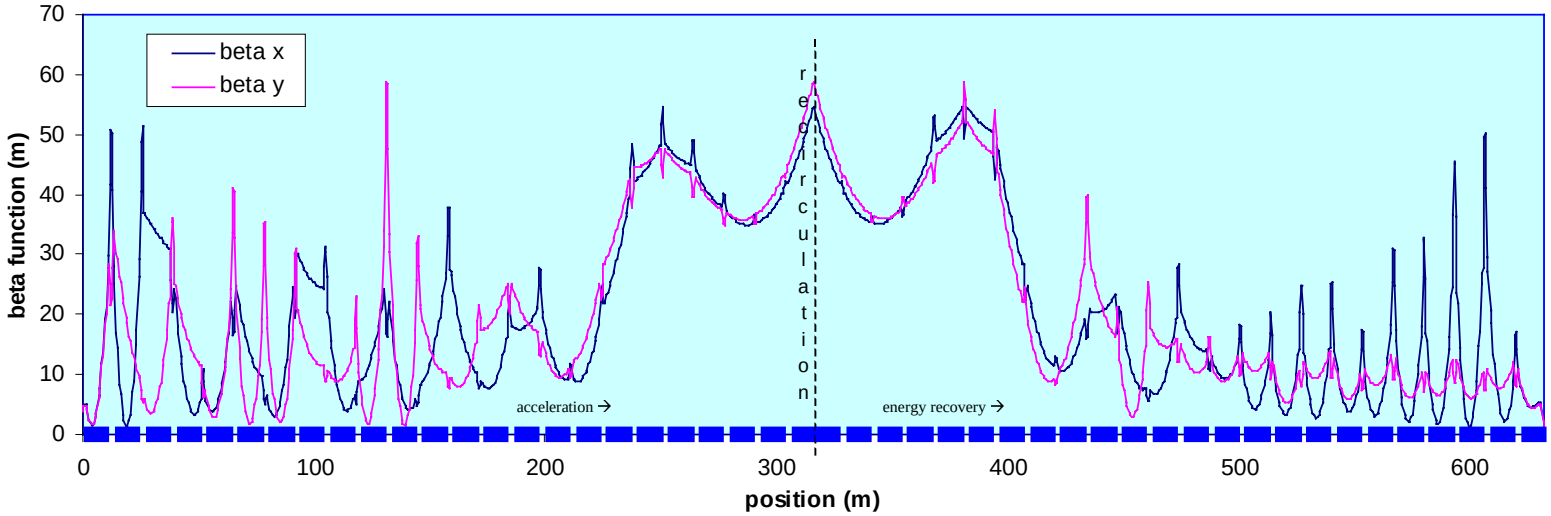
Linac Optics

- Two beams of different energies must remain confined in the same focusing channel. A possible solution (I. Bazarov, Cornell University) for a 5 GeV ERL



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Beam Loss

- IR FEL experience:
  - Loss in the cryomodule ≤ 0.1 μA (Radiation measurements)
  - Loss at wiggler entrance < 1 nA
  - Loss in recirculation arc ≤ 0.1 μA (BLMs)

  ⇒ At energies > 10 MeV,

  beam loss ≤ 0.1 μA out of 5 mA (~60pC @ 75MHz)

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Single-bunch Effects

- Single-bunch, single-pass effects: limit bunch charge
  - Energy spread induced by variation of longitudinal wakefield across bunch

    For TESLA cavities, $k_{loss} \sim 8.5$ V/pC at $\sigma_z = 1$ mm,

    the induced relative energy spread at 5 GeV is

    $$\sigma_E/E \sim 5 \times 10^{-4}$$
  - Emittance growth induced by single-bunch transverse BBU

    $$\Rightarrow \quad N_e < 1.5 \times 10^{11}$$
  - Minimize strength of impedance source (SRF better!)

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Multipass - Multibunch BBU Instabilities

- Collective effects driven predominantly by high-Q superconducting cavities and can potentially limit average current

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

- Instabilities can result from the interaction of the beam with
  - transverse HOMs $\Rightarrow$ Transverse BBU
  - longitudinal HOMs $\Rightarrow$ Longitudinal BBU
  - fundamental accelerating mode $\Rightarrow$ Beam Loading Instabilities

- Transverse BBU is the limiting instability

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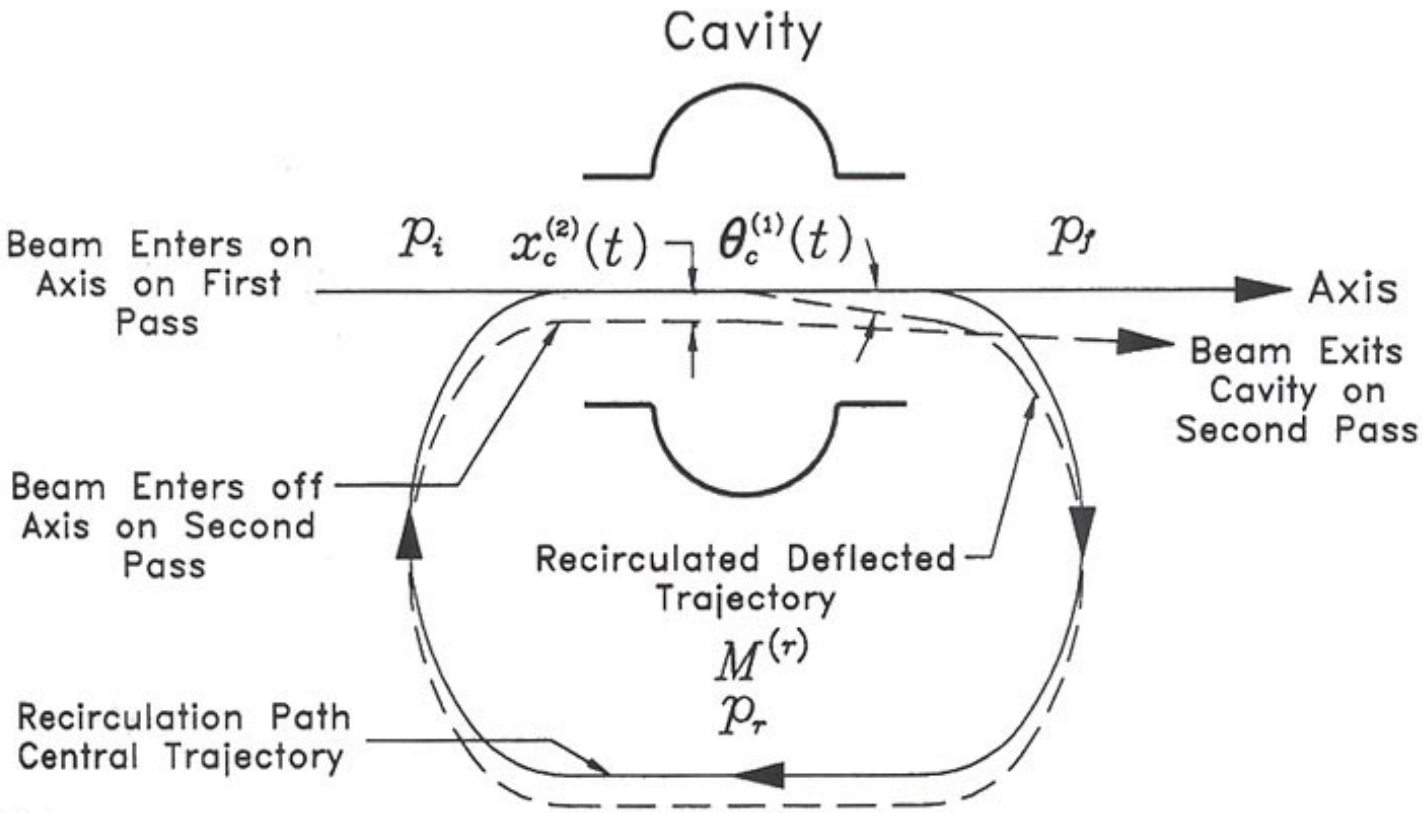
Transverse BBU Instability



Transverse BBU (cont'd)

- TDBBU*: 2d beam breakup code used for simulations
- Simulations give threshold of ~ 230 mA
- Typical growth rate of the instability is ~2 msecs.
- Feedback (similar to B-Factories) may be possible
  (B-Factory bunch-by-bunch feedback at 4 nsecs works!)
- Experiments in the IRFEL aim towards experimental verification of TDBBU

*Developed by Krafft, Bisognano and Yunn

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FEL BBU Experiment: Preliminary Conclusions

- Threshold current in the IR FEL varies between 7 mA and 32 mA, under various beam and accelerator configurations
- Under the nominal FEL configuration, threshold current is between 16 mA and 21 mA
- For the nominal FEL configuration, TDBBU prediction is 27 mA $\Rightarrow$ agreement within ~40%
- Observed optics dependence has not been quantified yet

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HOM Power Dissipation

- Power dissipated by the beam in HOMs, primarily longitudinal: depends on product of bunch charge and average current

$$P_{diss} = 2k_{||}Q\bar{I}$$

- For TESLA cavities, k_{loss} ~ 8.5 V/pC for σ_z=1 mm and I_{ave} = .264 A

P_{diss} ~ 8 kW per cavity

- IR FEL: I_{ave} = 5 mA, P_{diss} ~ 6 W per cavity

- Measurements of HOM power vs. bunch charge and bunch repetition frequency were carried out in the IRFEL

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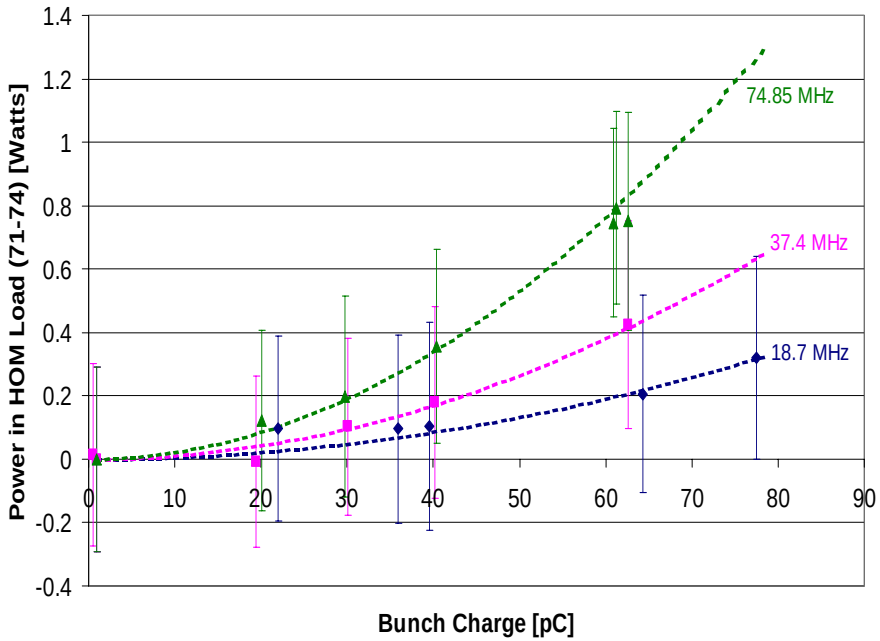
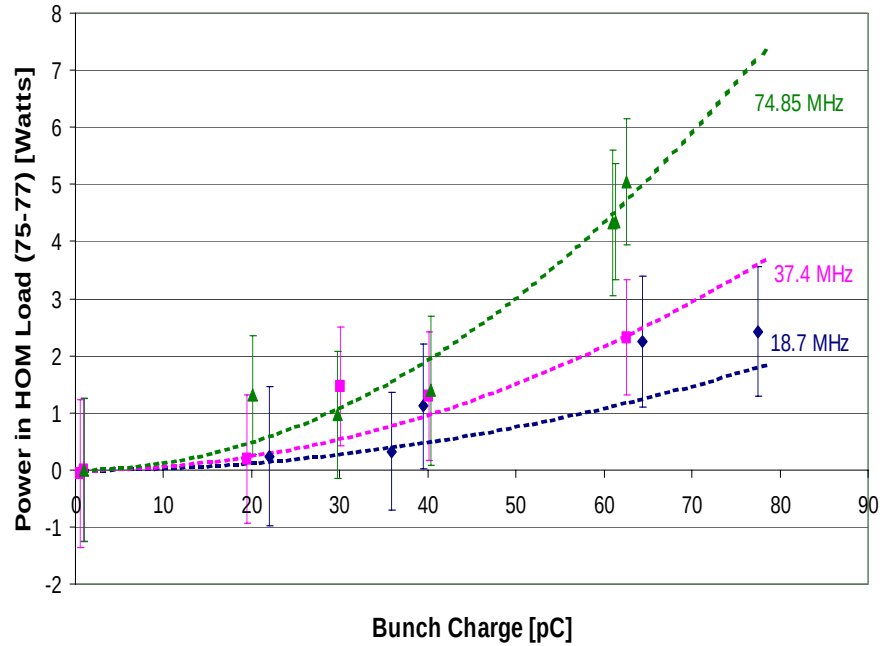
Measurements of HOM Power vs. Bunch Charge





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

$\Downarrow$

$k_{\parallel}^{total} = 9.4$ V/pC

$\Rightarrow$ agreement within 15%

$k_{\parallel}^{URMEL} = 11.0$ V/pC

Conclusions from HOM Experiment

- We observed the expected functional dependence of HOM power on bunch charge and bunch repetition frequency:

$$P_{HOM} \propto Q^2 f_{bunch}$$

- Loss factor for CEBAF cavities derived from measurements agrees with calculation (URMEL) within 15%

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“Where have all the losses gone?”

- The fraction of HOM power dissipated on cavity walls depends on the bunch length and increases with the HOM frequency, due to $Q_0 \sim f^2$ degradation from BCS theory
- It can limit I_{ave} and I_{peak} due to finite cryogenic efficiency
- A simple analytic model suggests that the fraction on the walls is much less than the fundamental mode load
- Engineering studies on HOM absorbers are highly recommended

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Beam-Beam Kink Instability

- The beam-beam force due to the relative offset between the head of the proton bunch and the electron beam will deflect the electrons. The deflected electrons subsequently interact with the tail of the proton bunch through beam-beam kick.
- The electron beam acts as a transverse impedance to the proton bunch, and can lead to an instability.
- In the linear approximation, and disregarding the evolution of the wake within the proton bunch, a stability criterion has been derived [Li, Lebedev, Bisognano, Yunn, PAC 2001]

$$D_e \xi_p \leq 4\nu_s$$

- For the case of equal bunches and linear beam-beam force, chromaticity appears to increase the threshold of the instability [Perevedentsev, Valishev, PRST '01].
- The instability has been observed in numerical simulations [R. Li, J.Bisognano, Phys. Rev. E (1993)] during the beam-beam studies of linac-ring B-Factory. The code is presently being used to simulate unequal bunches and a nonlinear force. We also expect chromaticity to be beneficial in this case.

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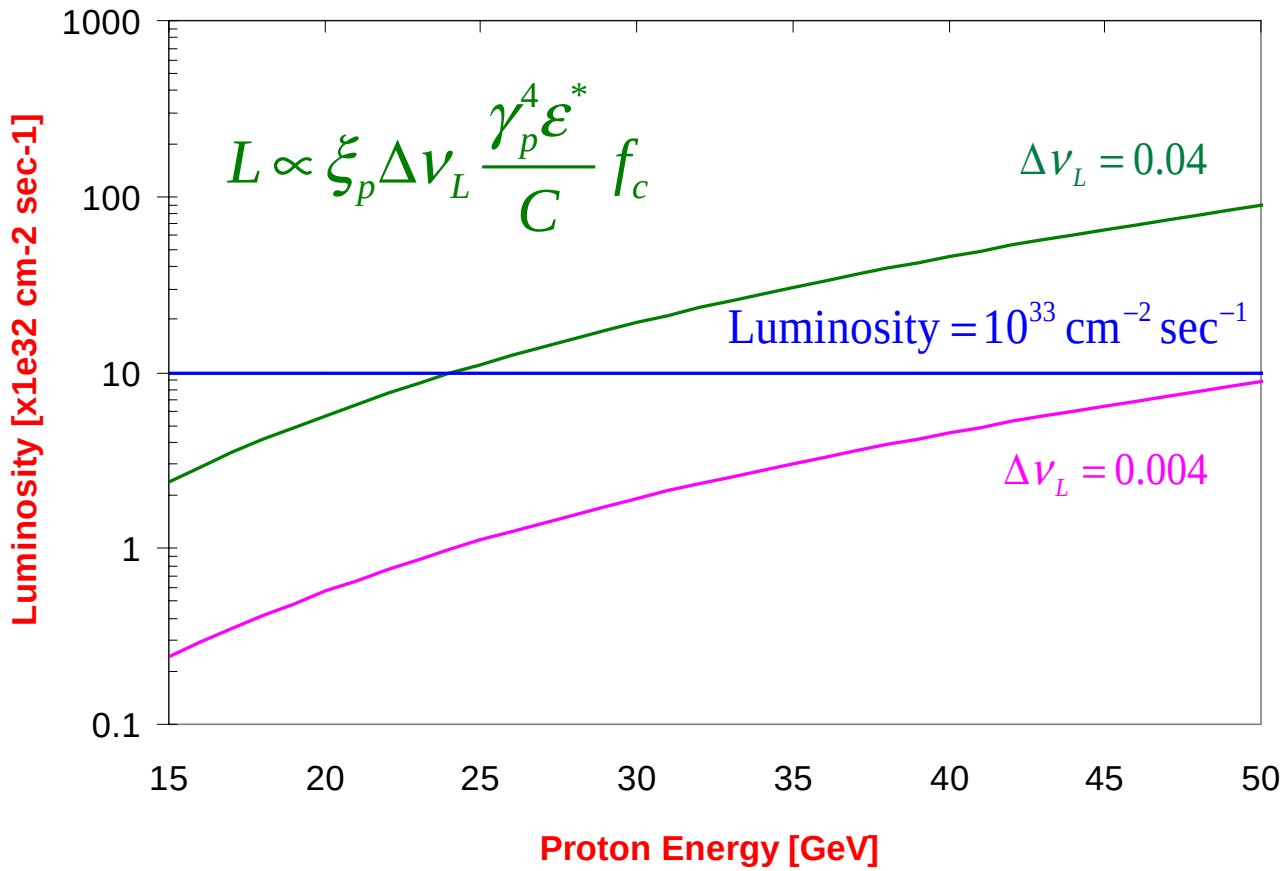
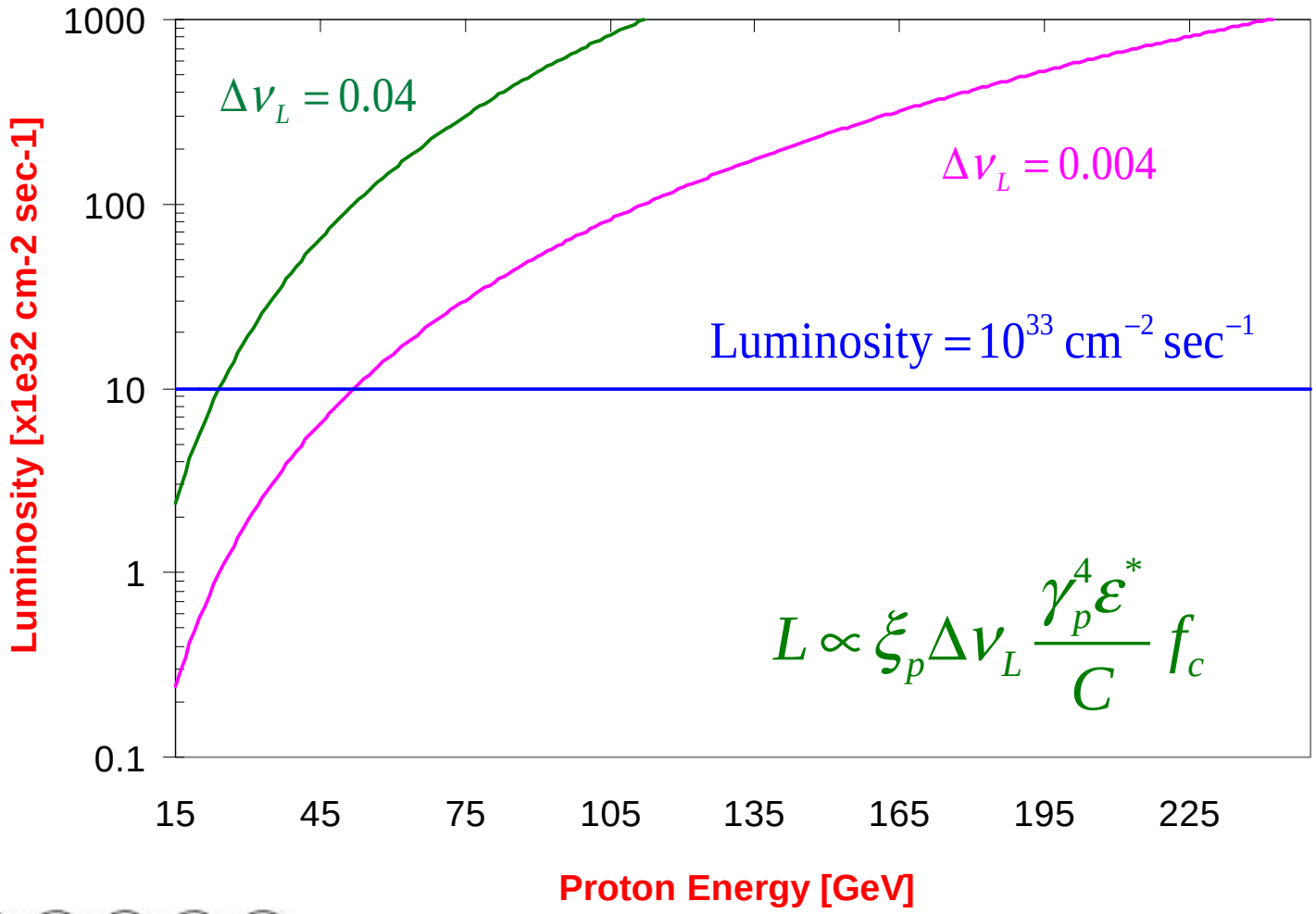
Fundamental Luminosity Limitations

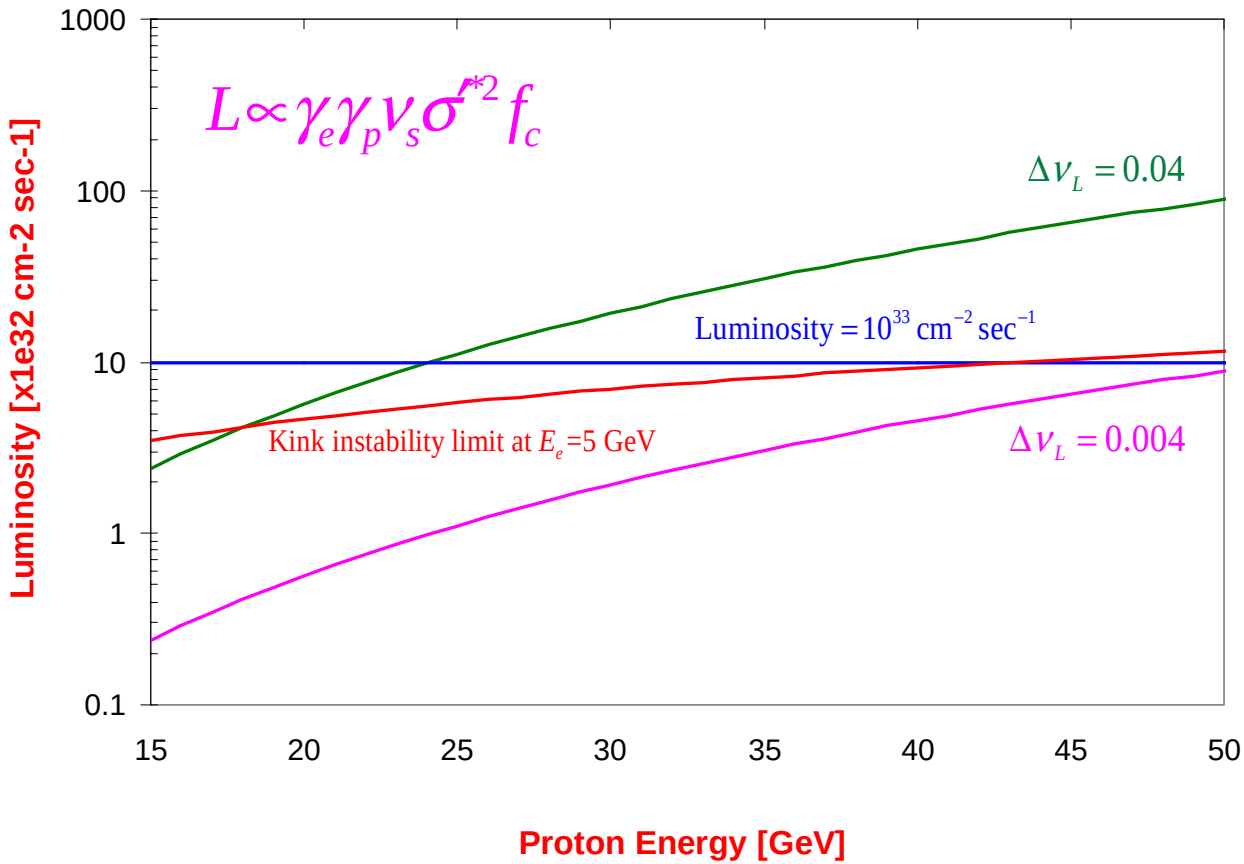


Luminosity vs. proton beam energy at the Laslett and beam-beam tuneshift limits, for two values of the Laslett tuneshift: 0.004 and 0.04. In both cases ξ_p=0.004

Fundamental Luminosity Limitations (cont'd)



Fundamental Luminosity Limitations (cont'd)



Luminosity vs. proton beam energy at the stability limit of the beam-beam kink instability (linear approximation: $D_e \xi_p \leq 4\nu_s$)

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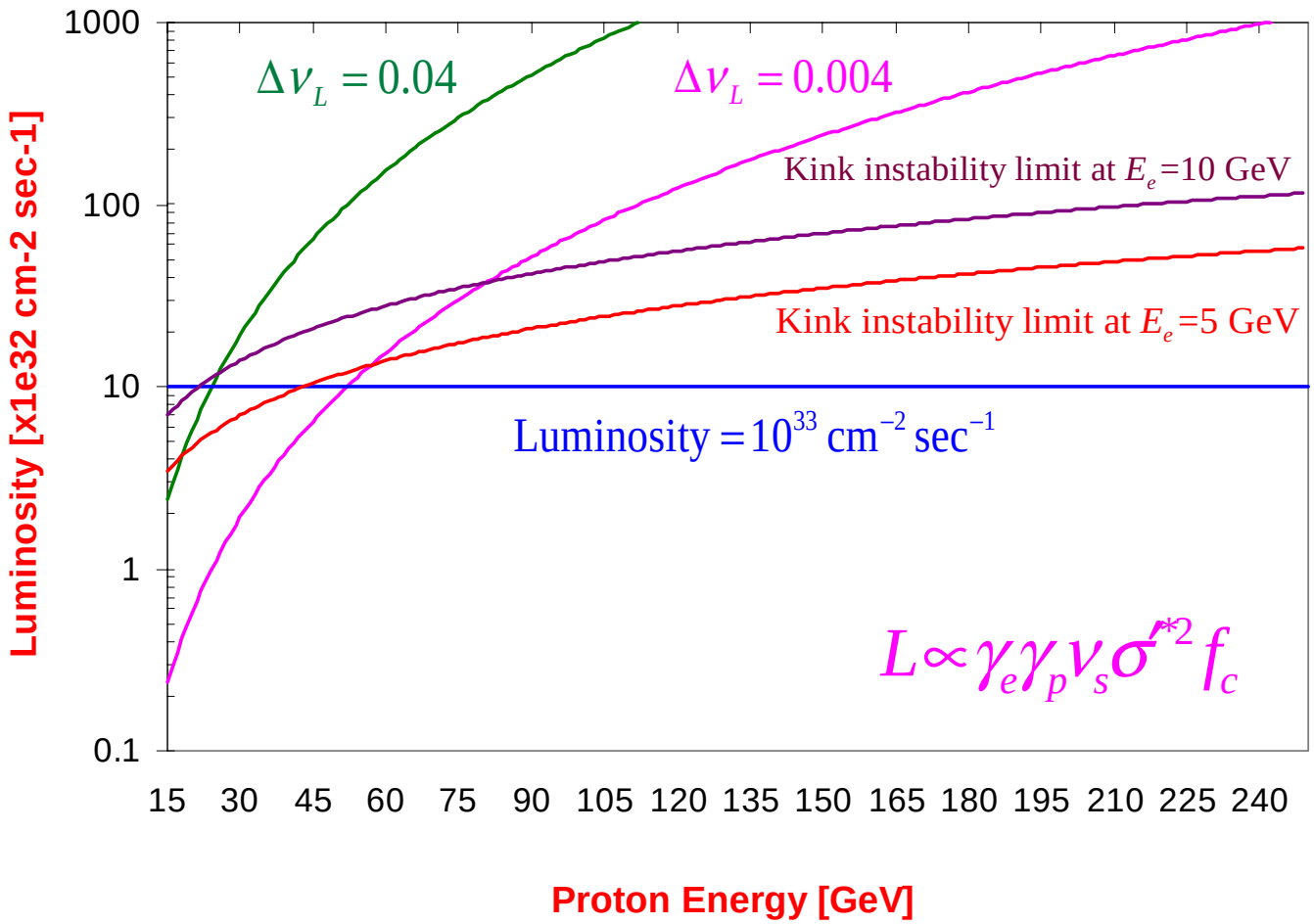
Fundamental Luminosity Limitations (cont'd)



R&D Topics

- High average current (~ 250mA), high polarization (~80%) electron source
  - State of the art in high average current, polarized sources:
    ~1 mA at 80% polarization [C. Sinclair, JLab]
- High average current demonstration of energy recovery
  - Multibunch beam breakup instability
  - HOM power dissipation
  - Control of beam loss
- Electron cooling and its ramifications on Laslett and beam-beam tuneshifts
- Theoretical and if possible, experimental investigation of the beam-beam kink instability

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Conclusions

- Self-consistent sets of parameters has been developed for linac-ring colliders
- Luminosities of several 10^{32} up to 10^{33} appear feasible
- No accelerator physics showstoppers have been found.
- Several important issues have been identified that would require focused R&D
- ERL: Cornell University in collaboration with Jefferson Lab, is proposing a high average current (100 mA), high Energy Recovery Linac (5-7 GeV) for a next generation light source and is planning to address some of the technical issues with a smaller scale prototype (100 mA, 100 MeV)
- PERL: Similar proposal is being pursued at BNL

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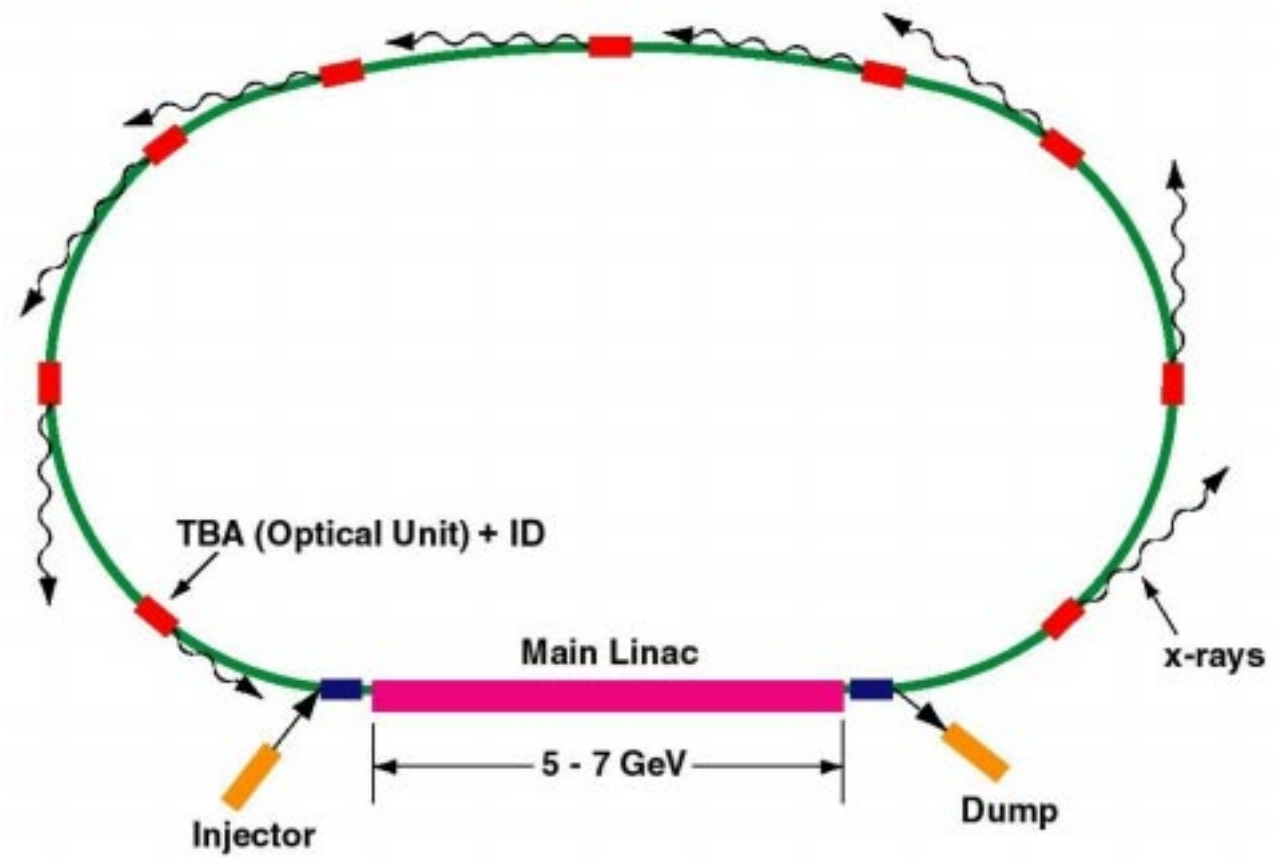
ERL X-ray SR Source Conceptual Layout



Courtesy I. Bazarov, PAC 2001

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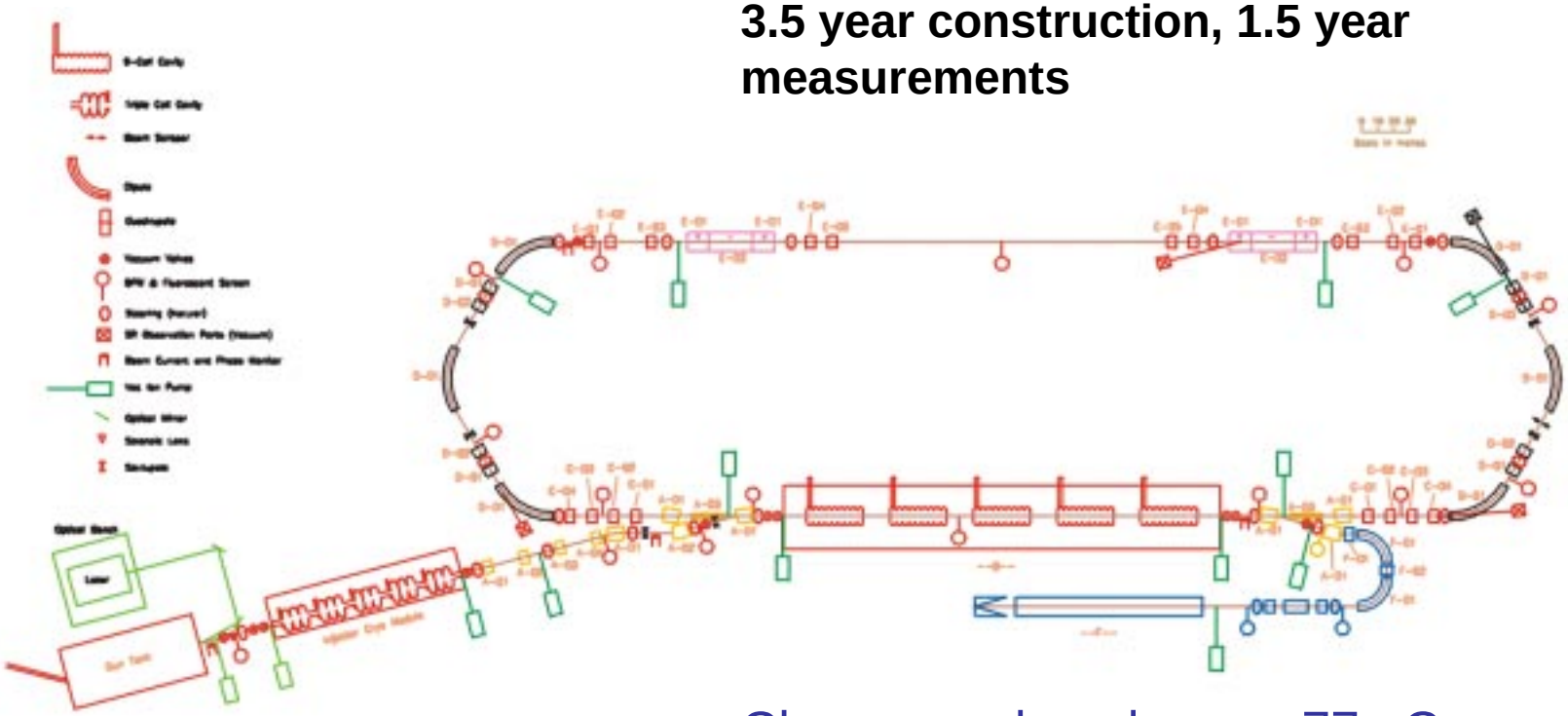
ERL Prototype

We plan to begin work in the fall!

3.5 year construction, 1.5 year measurements

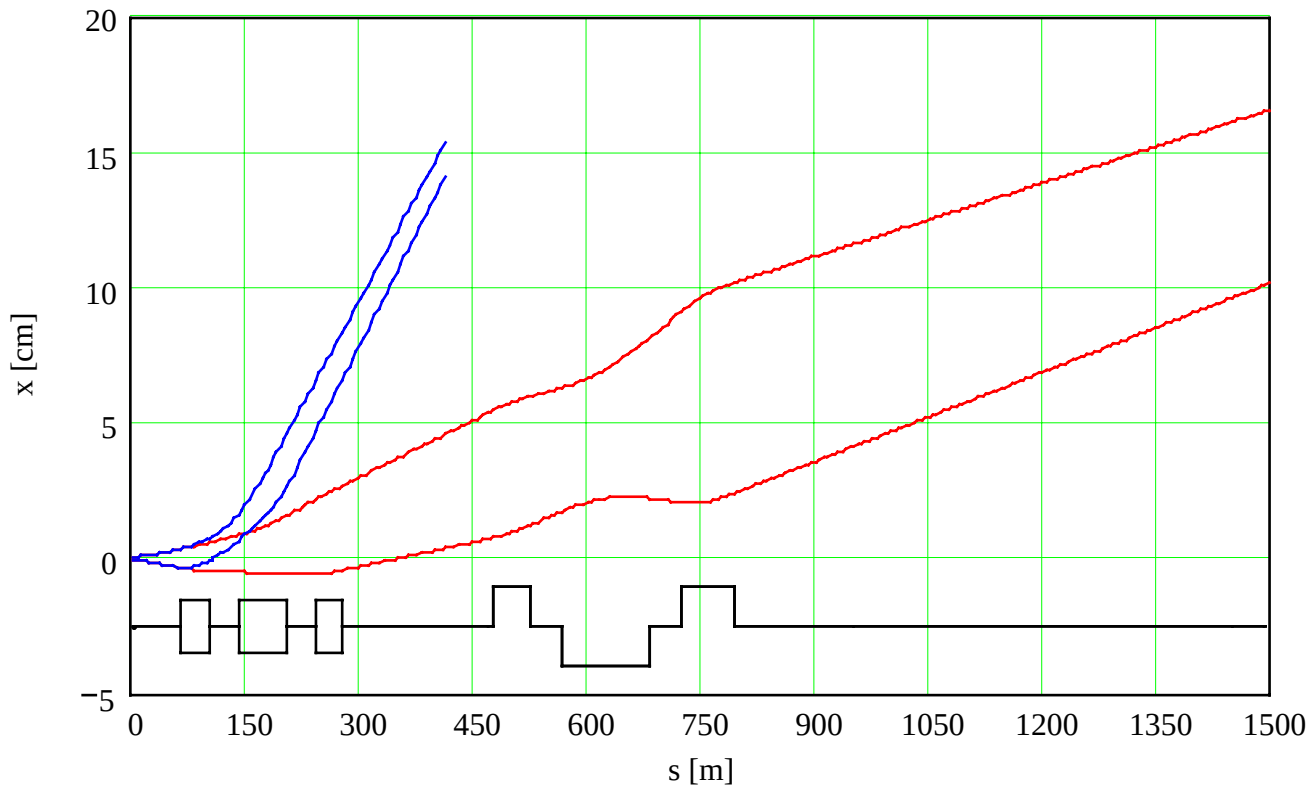


Beam Energy	100 MeV	Charge per bunch	77 pC
Injection Energy	5 MeV	Emittance, norm.	2* μm
Beam current	100 mA	Shortest bunch length	100* fs

Courtesy I. Bazarov, PAC 2001

Jefferson Lab
Thomas Jefferson National Accelerator Facility
Operated by the Southeastern Universities Research Association for the U. S. Department of Energy

Example of Interaction Region Design



Example of the interaction region design for $\beta^* = 6$ cm.