RF Control Requirements in Energy Recovery Linacs

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Outline

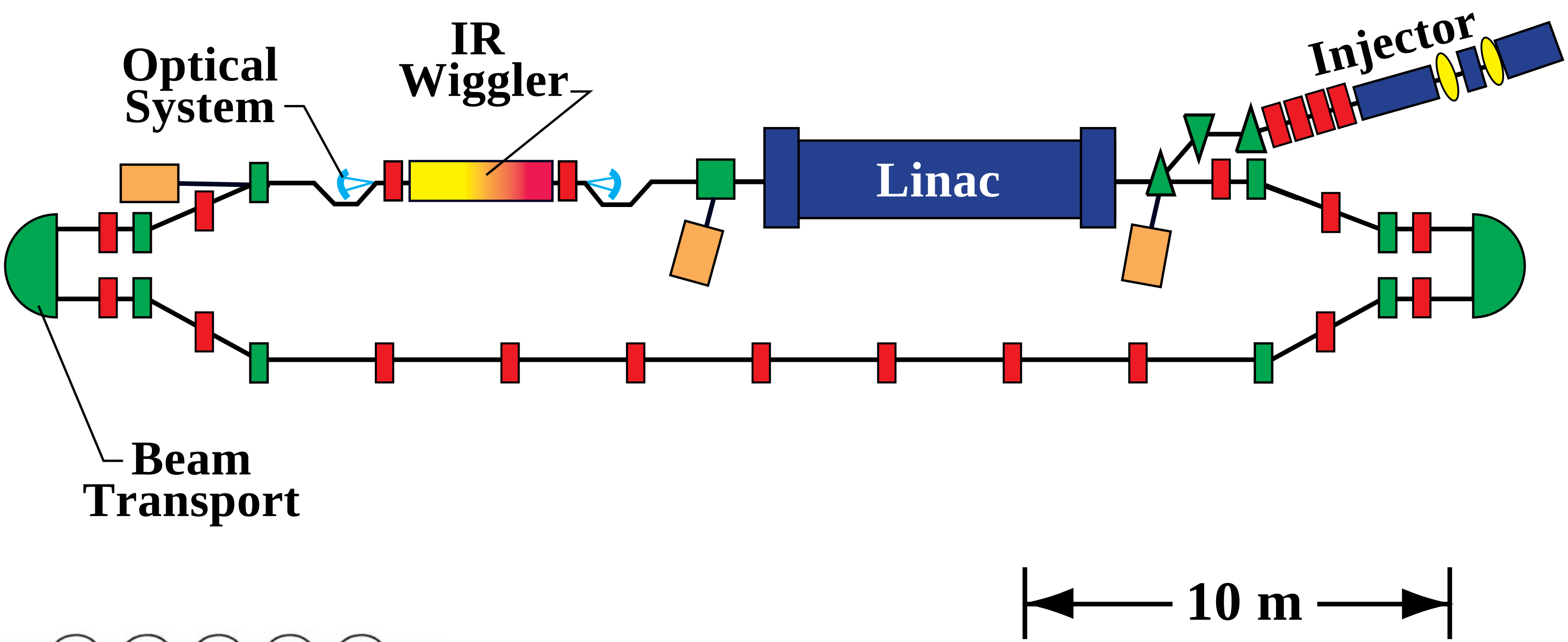
- Energy Recovery Linacs (ERLs)
  - ERL-based FELs / The JLab IR FEL and FEL Upgrade
  - ERL-based Synchrotron Light Sources / The Cornell ERL (Proposed)
  - ERL-based Colliders: eRHIC, EIC (Conceptual Designs)
- Efficiency of ERLs
  - Power Requirements
- Amplitude and Phase Stability Requirements
- RF Stability
- Conclusions

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.

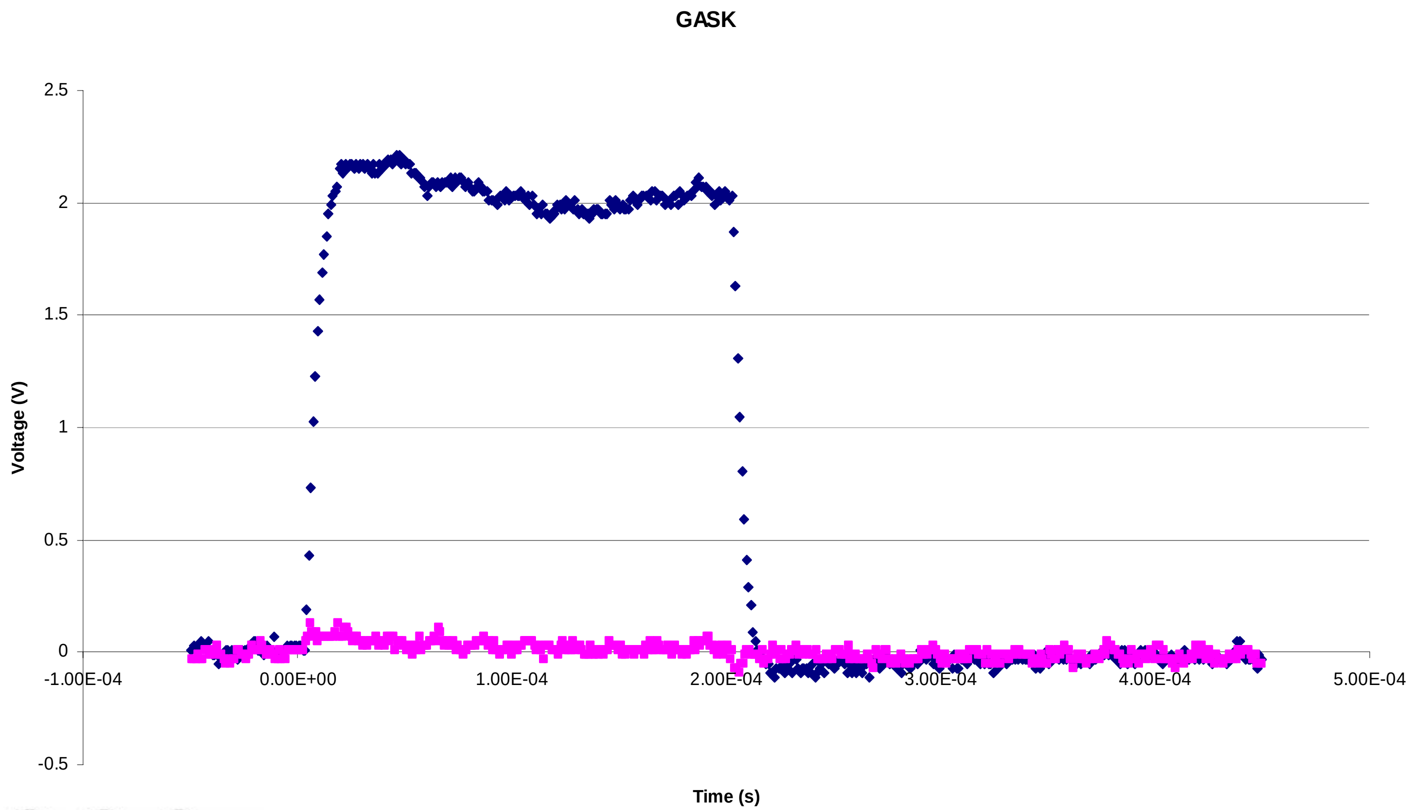
The JLab 1.7 kW IRFEL and Energy Recovery Demonstration

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



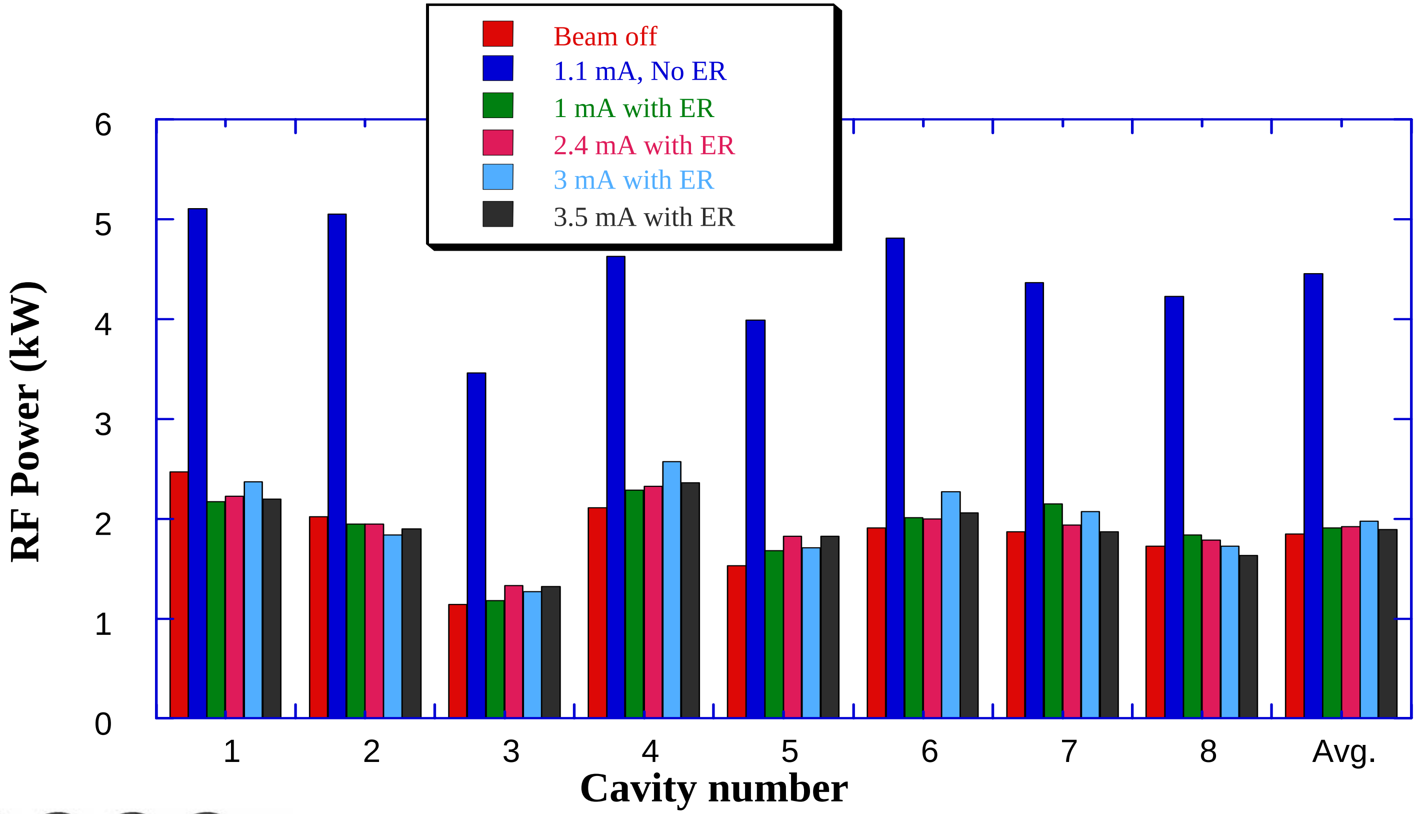
Energy Recovery Works

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).

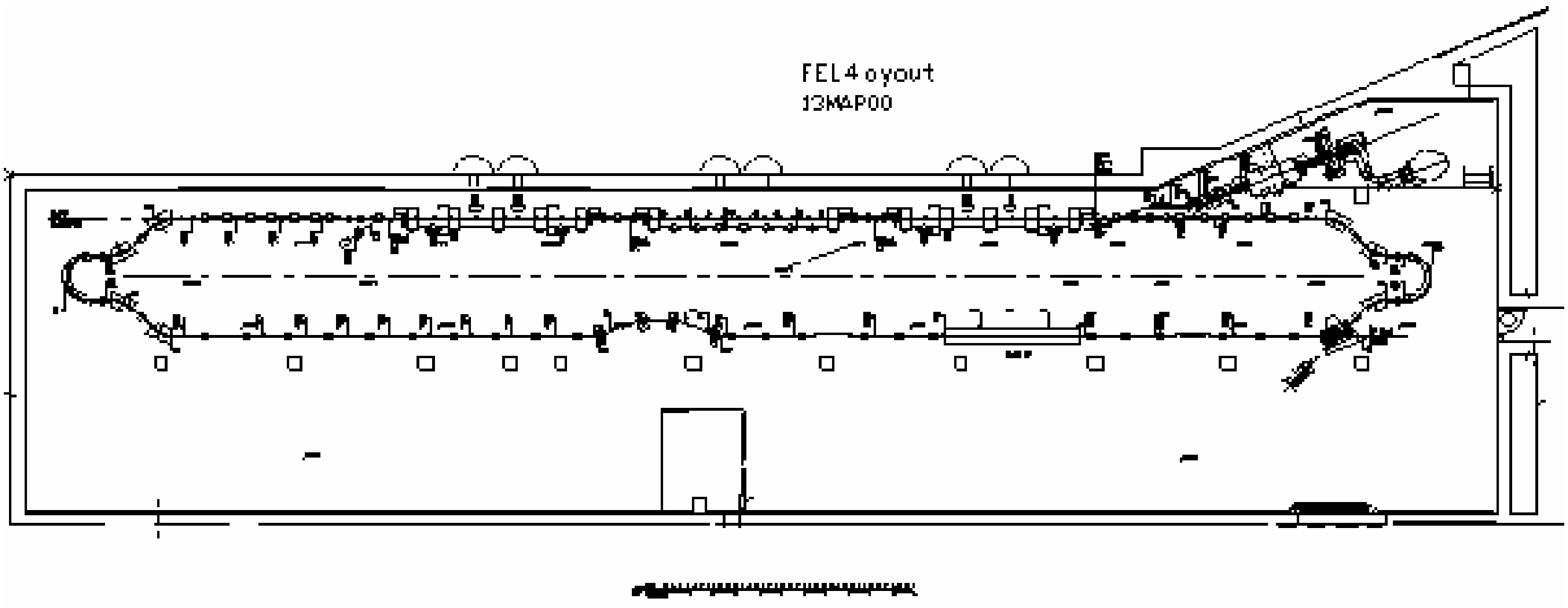


Energy Recovery Works (cont'd)

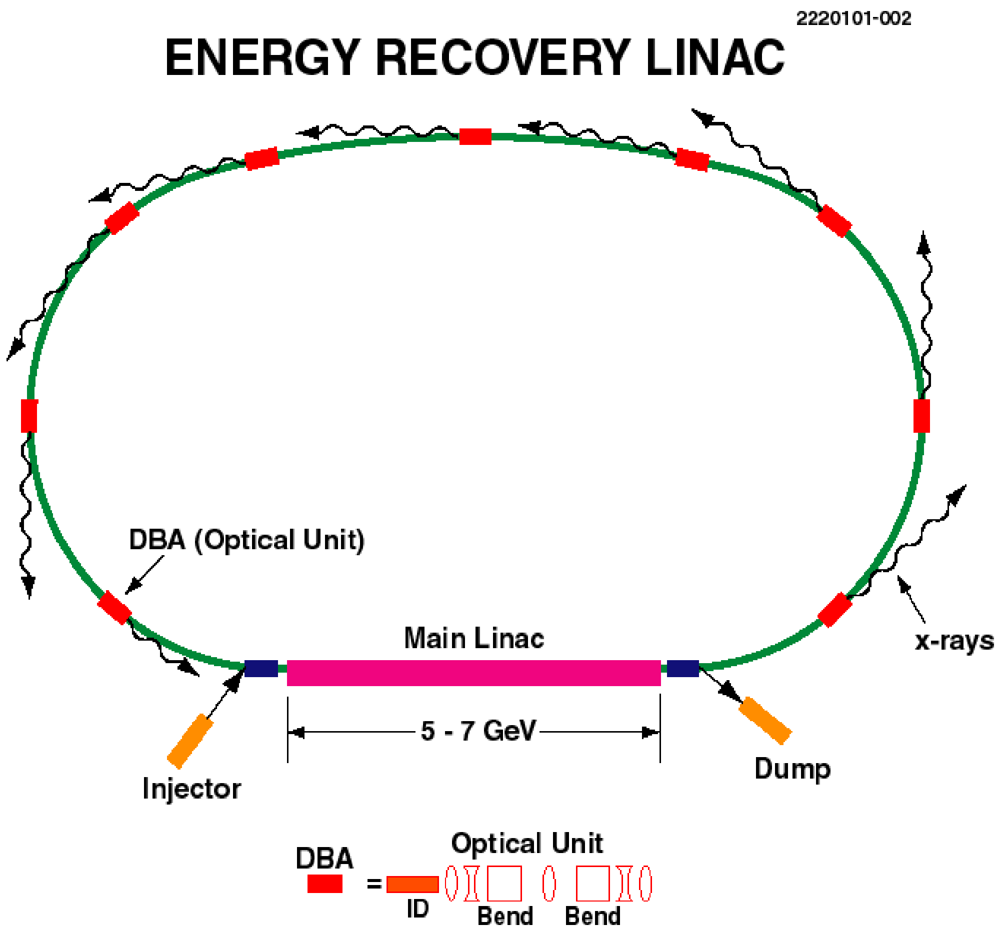
With energy recovery the required linac rf power is ~ 16 kW, nearly independent of beam current. It rises to ~ 36 kW with no recovery at 1.1 mA.



The JLab 10 kW FEL Upgrade

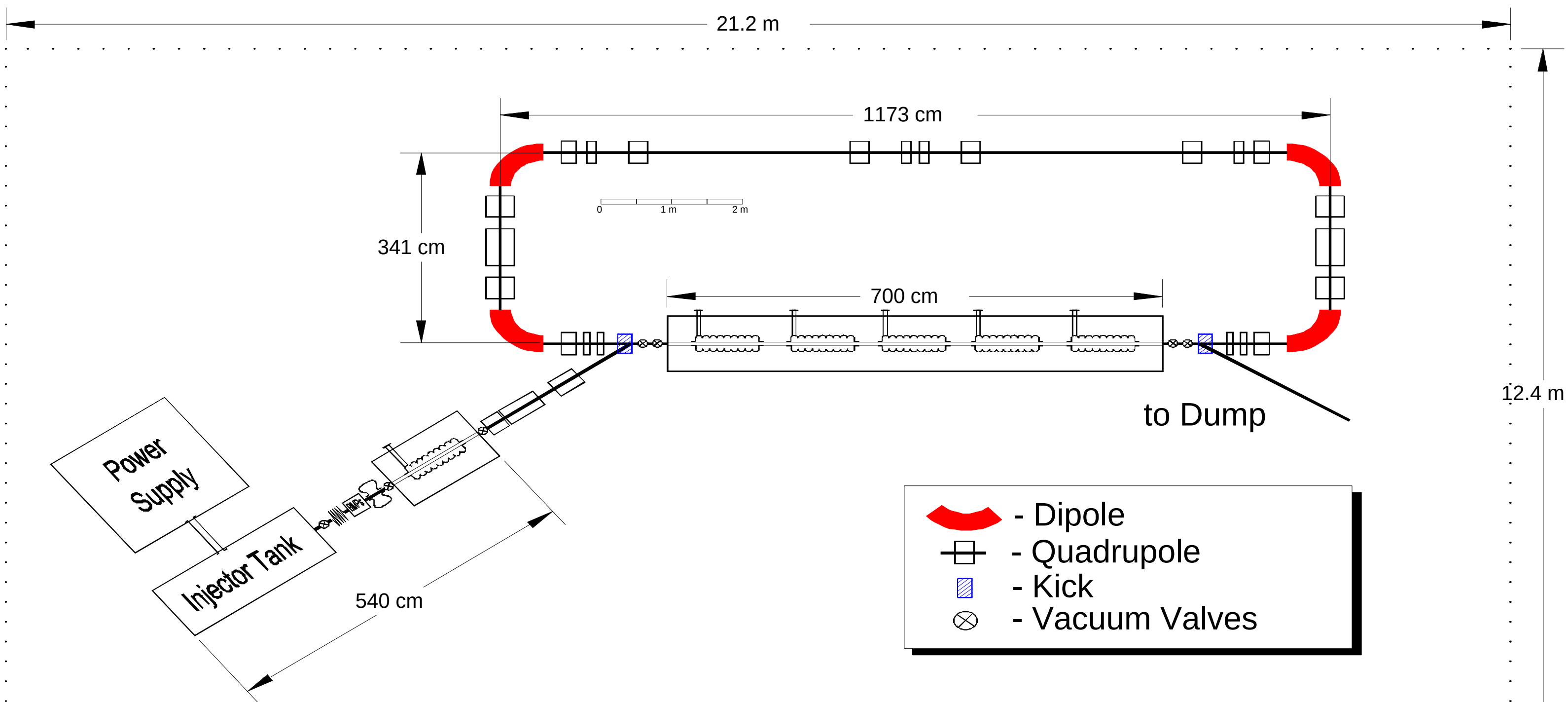


Cornell ERL

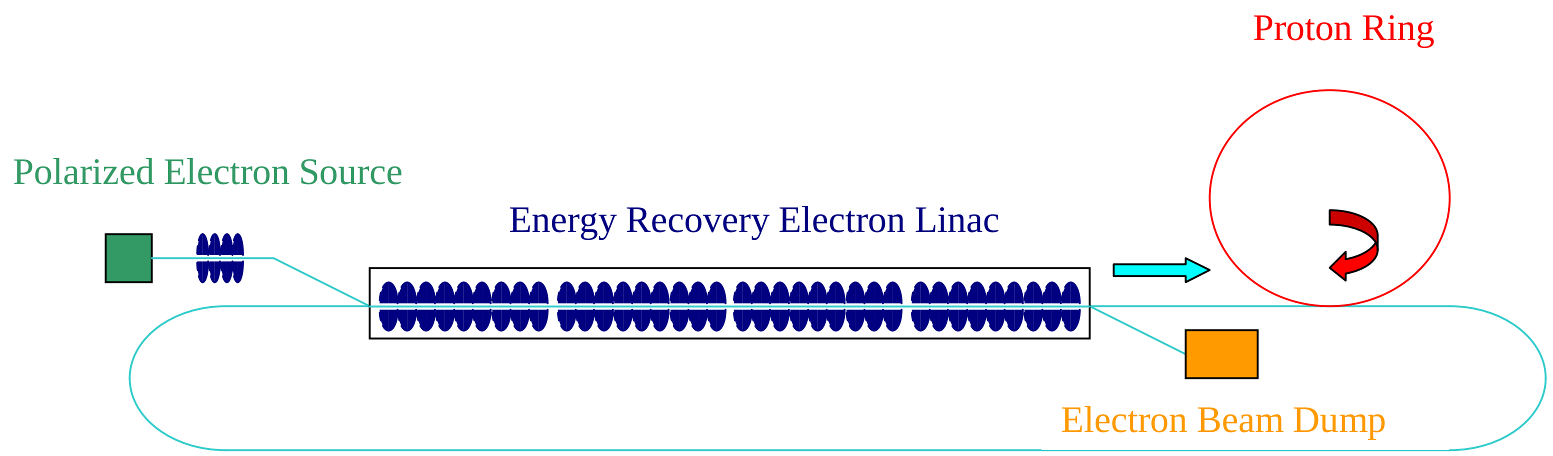


DBA=Double Bend Acromat

Cornell ERL Prototype



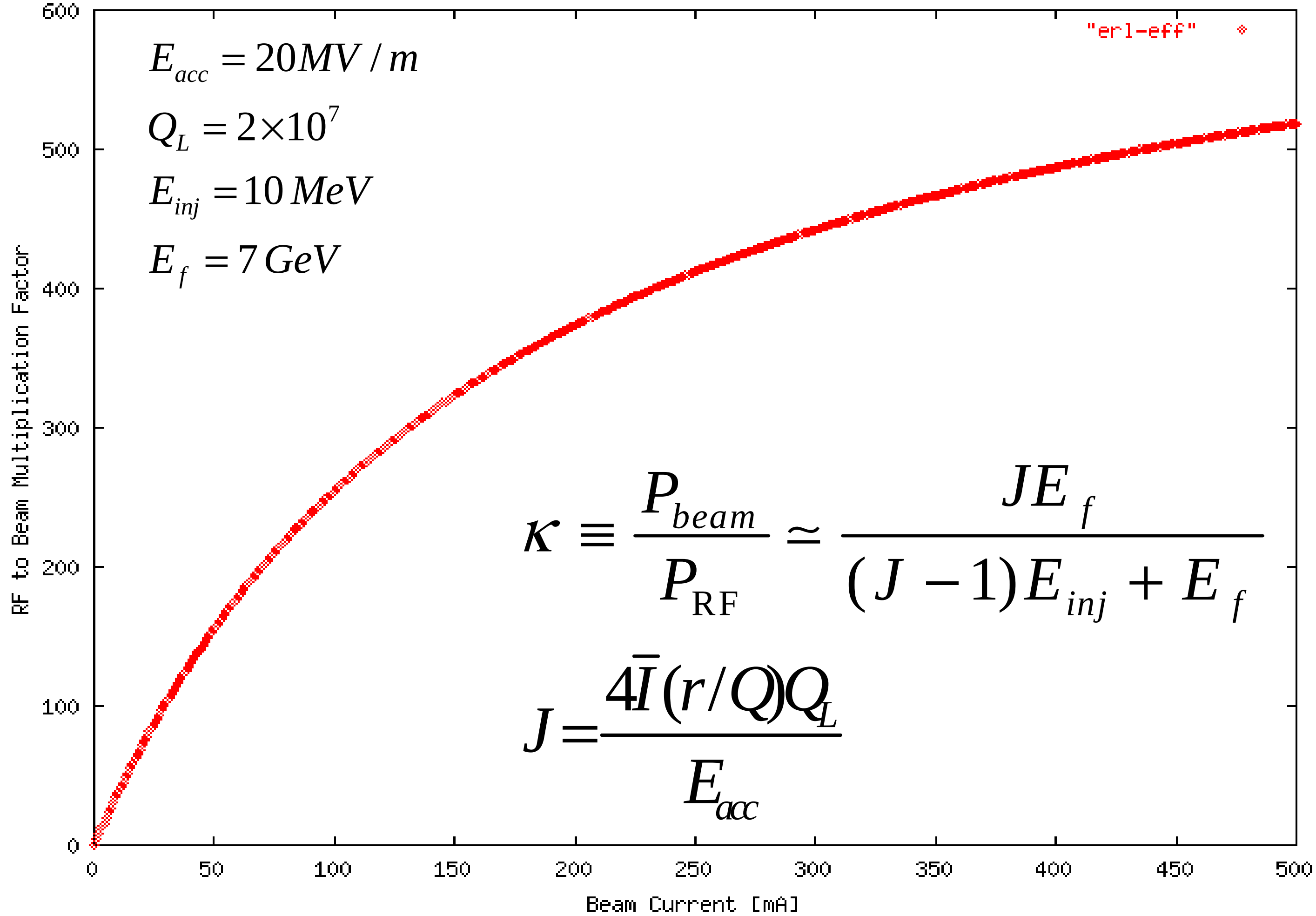
Linac–Ring Collider: Schematic Layout



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.

RF to Beam Multiplication Factor for an ideal ERL



$$E_{acc} = 20 MV/m$$

$$Q_L = 2 \times 10^7$$

$$E_{inj} = 10\, MeV$$

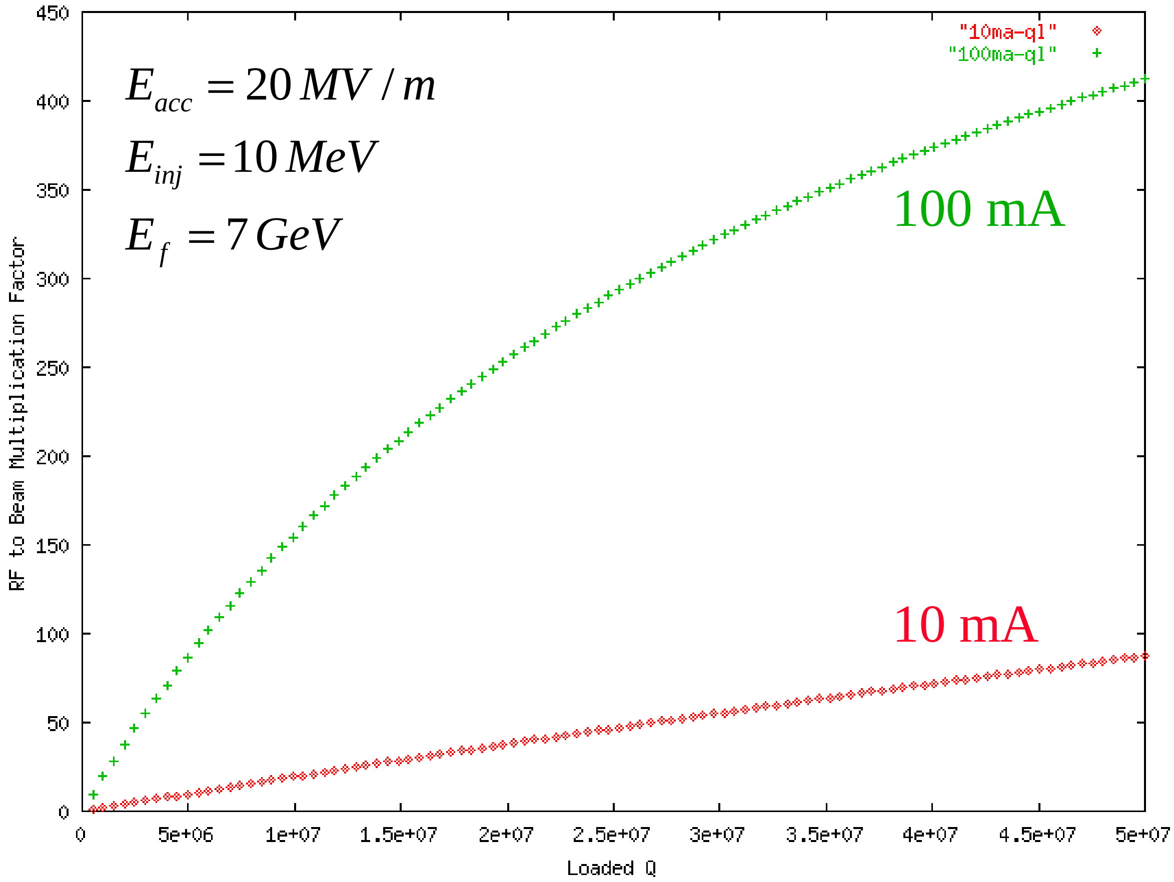
$$E_f = 7\, GeV$$

$$\kappa \equiv \frac{P_{beam}}{P_{\mathrm{RF}}} \simeq \frac{JE_f}{(J-1)E_{inj} + E_f}$$

$$J = \frac{4\bar{I}(r/Q)Q_L}{E_{acc}}$$

Krafft, Merminga, 2000

Multiplication Factor vs. Loaded Q



Can we further improve the ERL efficiency?

- In practice, for an ideal ERL (I_{tot}=0, $\Delta\psi$=180^o):

$$\beta_{opt} = \sqrt{1+\left(\frac{2Q_0\delta f_m}{f_0}\right)^2}$$

δf_m is the maximum microphonic noise to be controlled

- In order to further improve the ERL efficiency, the following questions are of primary importance:
  - What is the maximum achievable Q_L?
  - Microphonics control?
  - Lorentz force detuning?

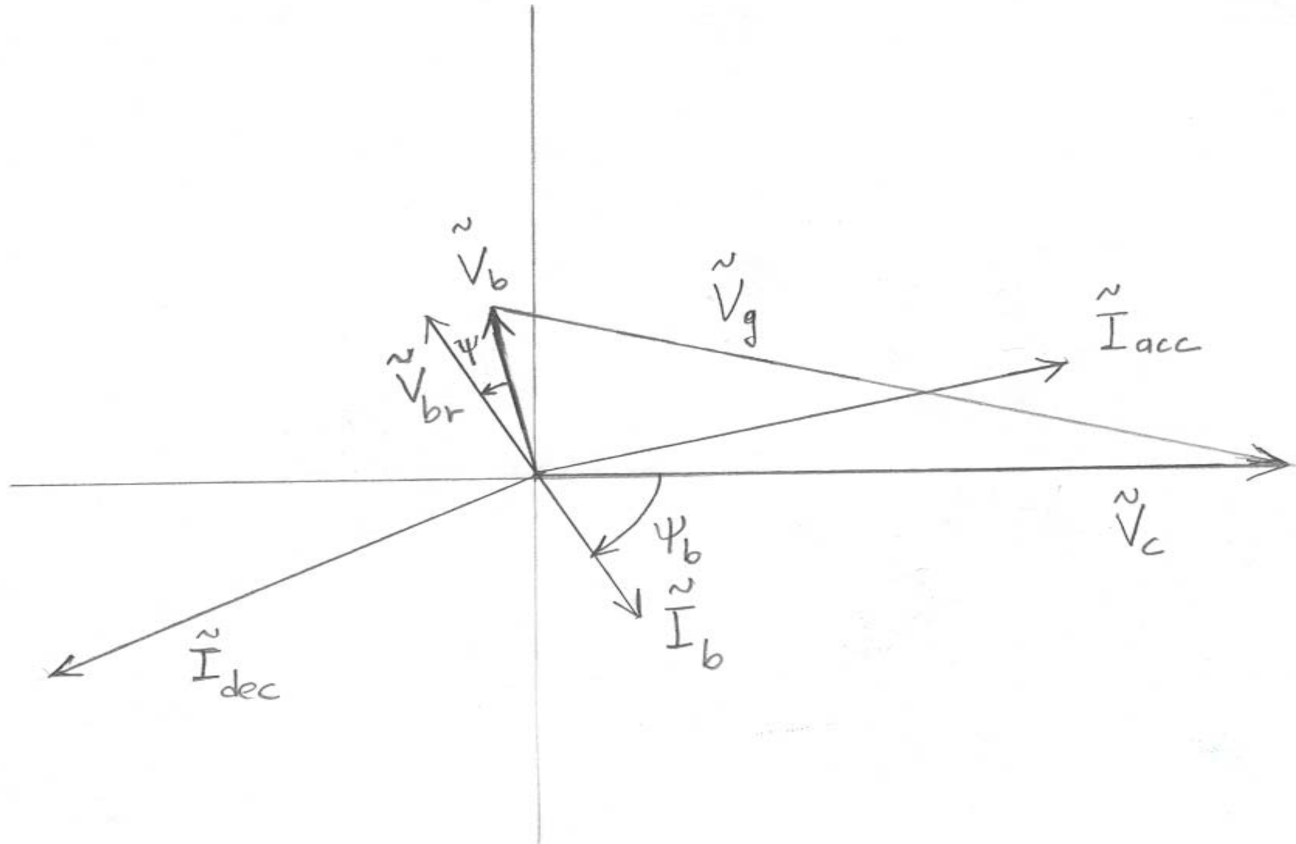
Real ERLs

- Phases may not differ by precisely 180^o
  - Typical expected path length control adjustment leads to ~ 0.5^o deviation from 180^o
  - In an FEL, if machine is setup so that beam current vectors cancel with FEL on, then with FEL off, there can be up to 5^o deviation from perfect cancellation
- Beam loss may occur, resulting in beam vectors of unequal magnitude
- Beam current fluctuations

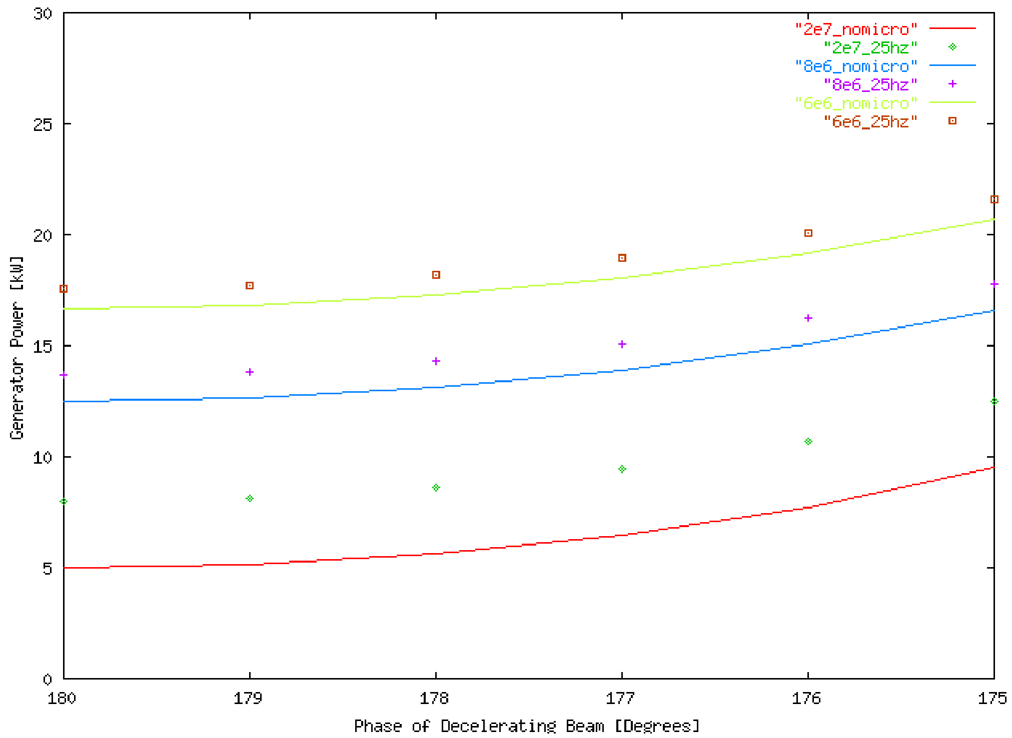
$\Longrightarrow$ All of the above give rise to a net beam loading vector, typically of reactive nature in the case of phase errors

$\Longrightarrow$ Increase of rf power requirements and reduction of κ

Energy Recovery Phasor Diagram

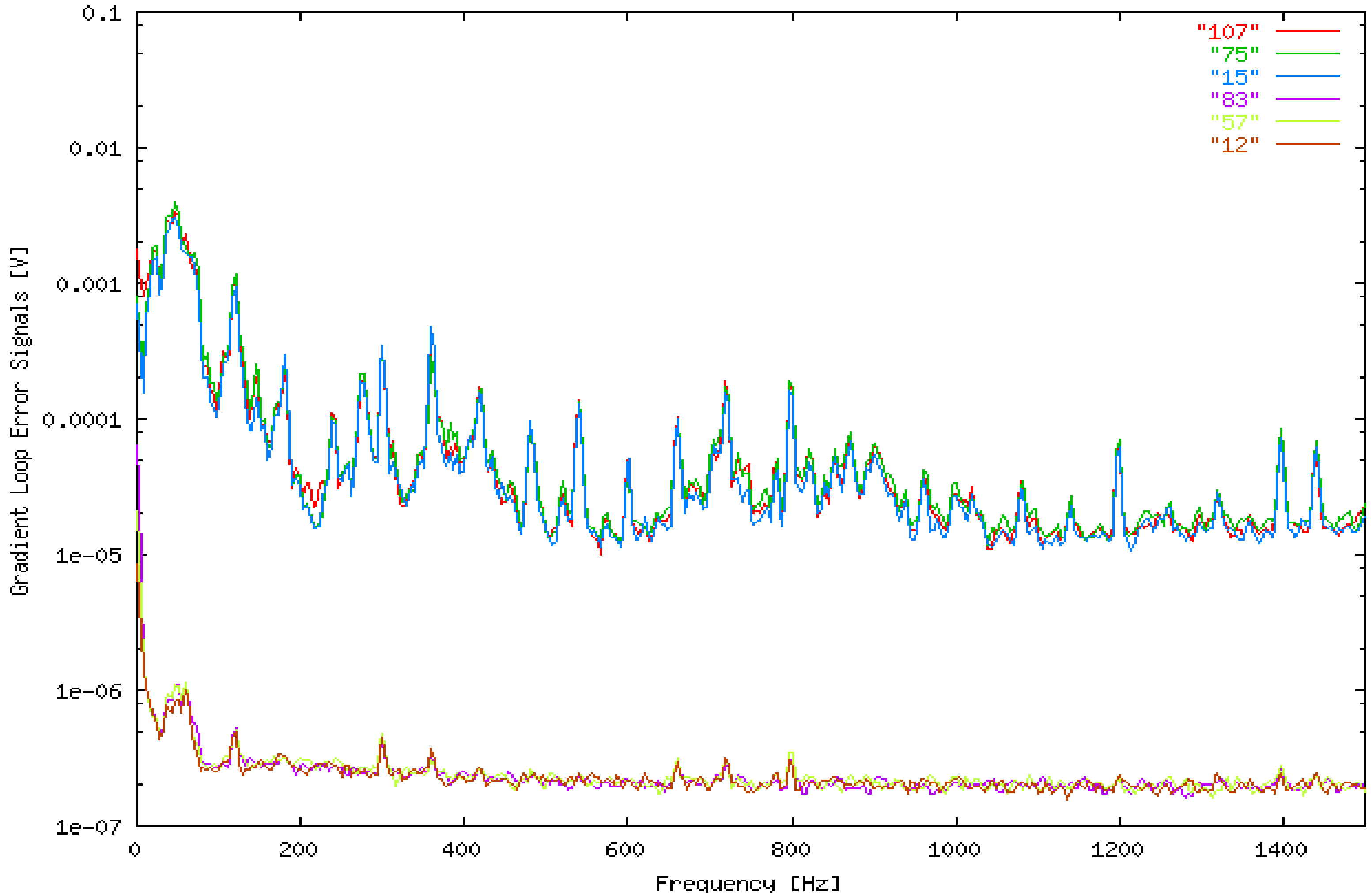


Power Requirements

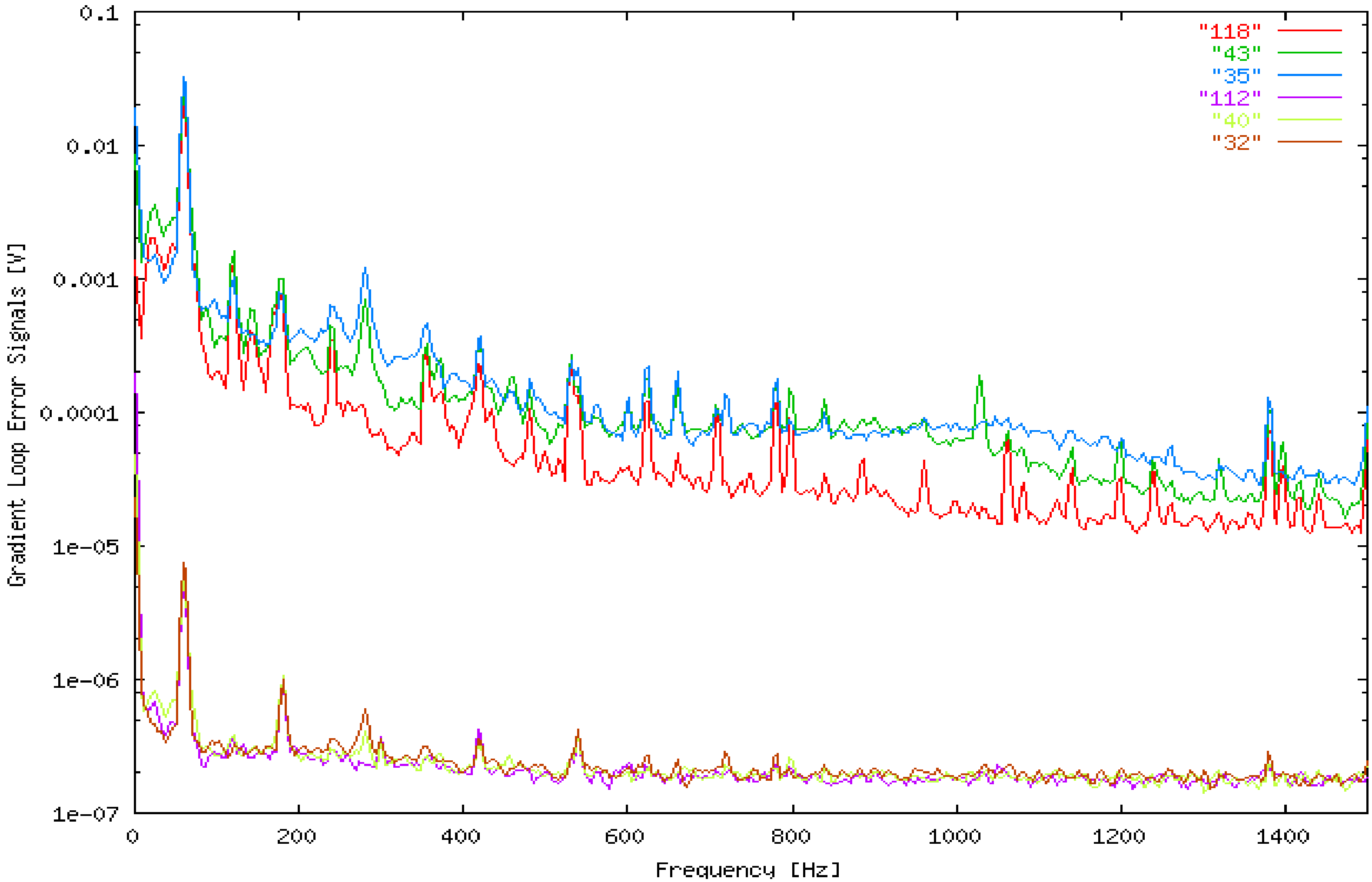


- Is there a better way to deal with sudden increase in power demands (predicted or unpredicted)?
- Can the requirements on tuners be met?
- Quality of regulation as function of beam current?

RF Control (Linac)



RF Control (Injector)



Jefferson Lab

Thomas Jefferson National Accelerator Facility

Amplitude and Phase Stability Requirements

- End users impose certain phase and amplitude stability requirements in order for the energy spread and timing jitter specifications at the interaction point (FEL, undulator, interaction region) to be met
- These requirements determine characteristics of the LLRF control system, including gain and bandwidth of the feedback loops
- In ERLs, additional constraints on the LLRF system design may be imposed due to possible longitudinal instabilities

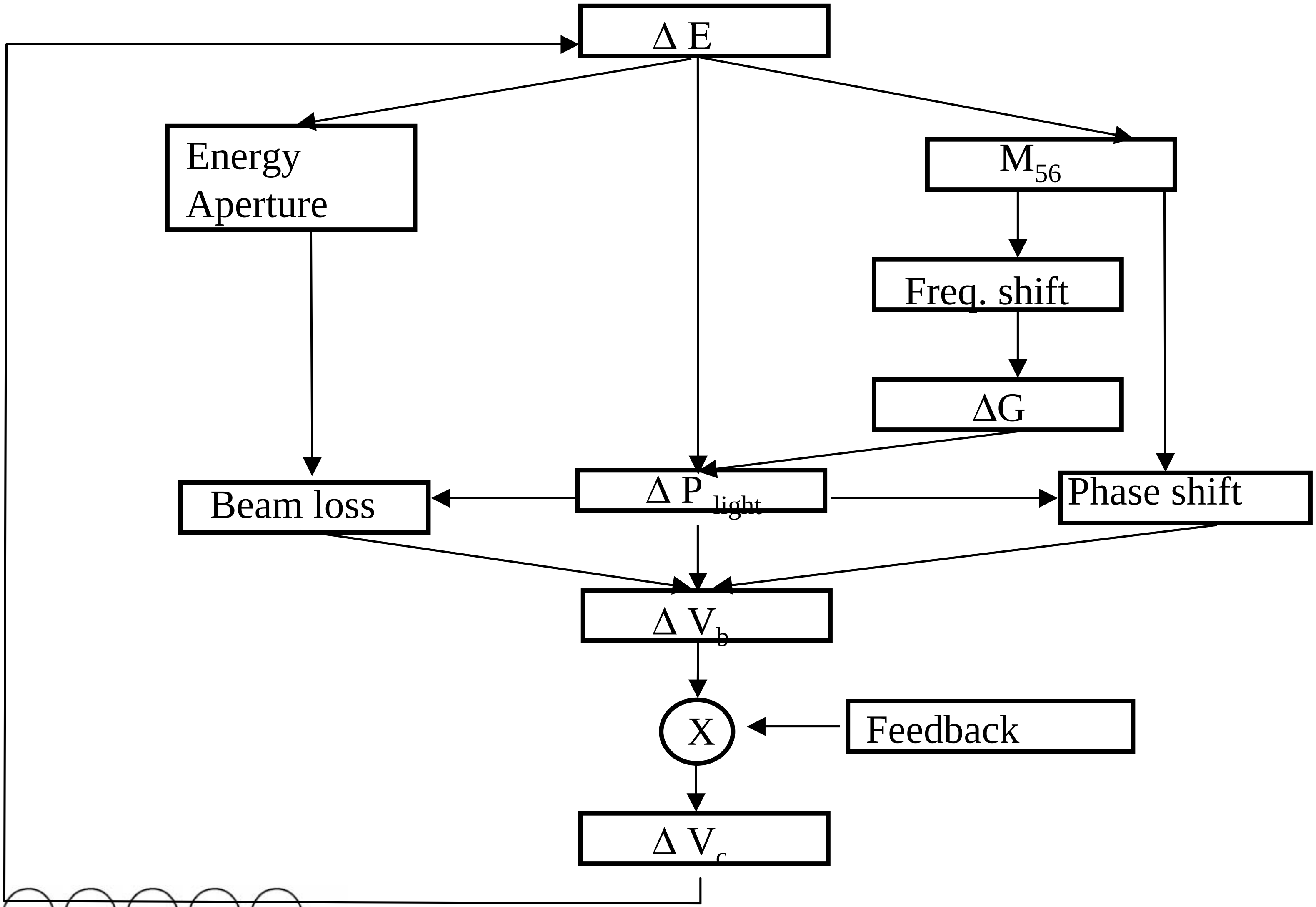
RF Instabilities

- Instabilities can arise from fluctuations of cavity fields.
- Two effects may trigger unstable behavior:
  - Beam loss which may originate from energy offset which shifts the beam centroid and leads to scraping on apertures.
  - Phase shift which may originate from energy offset coupled to M_{56} in the arc
- Instabilities predicted and observed at LANL, a potential limitation on high power recirculating, energy recovering linacs.

M_{56} is the momentum compaction factor and is defined by:

$$\Delta l = M_{56} \frac{\Delta E}{E}$$

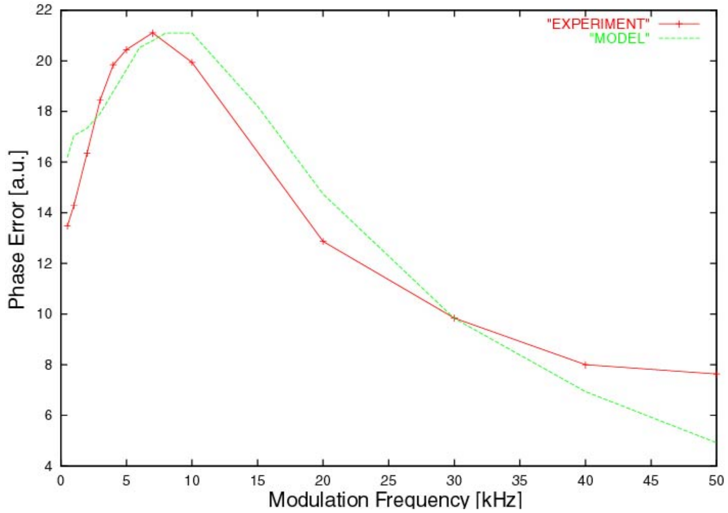
RF STABILITY FLOW CHART

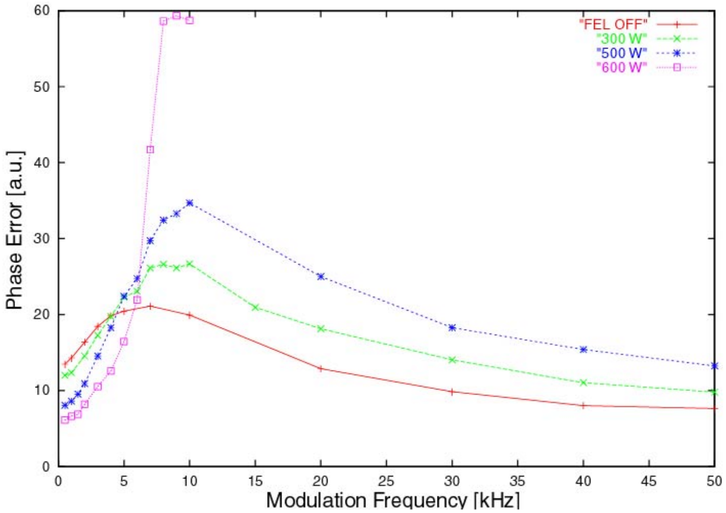


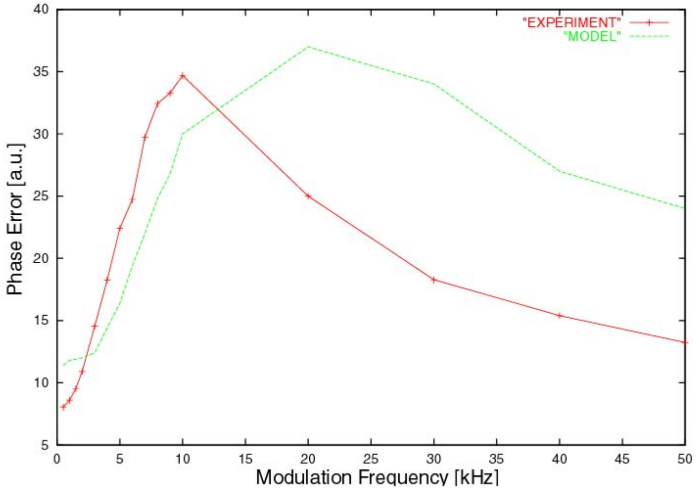
RF Stability Model

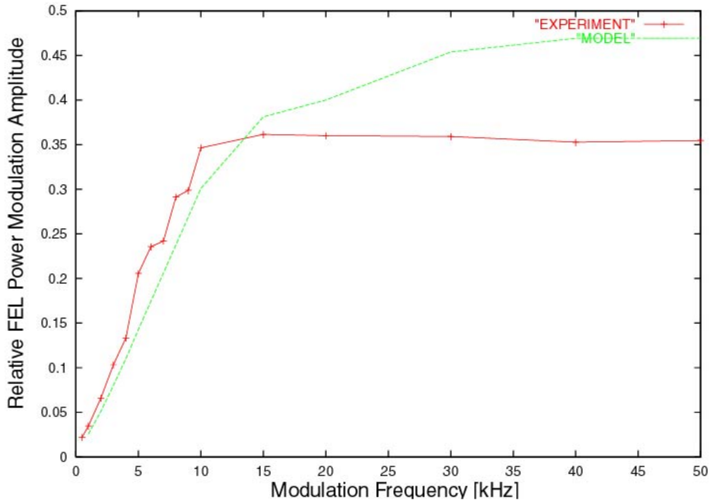
- Developed model of the system that includes beam-cavity interaction, low level rf feedback and the FEL; it was solved analytically and numerically
- Model predicts instability exists in the IRFEL, however is controlled by LLRF feedback
- When FEL is off, experimental data from the IRFEL are quantitatively consistent with the model. With FEL on, model reproduces data qualitatively

FEL/RF INTERACTION: EXPERIMENT VS MODEL









Conclusions

- Energy recovery linacs are very efficient devices for certain applications
- We have asked two questions:
  - Can we increase the efficiency of ERLs by optimizing the rf control system design?
  - Can we ensure stability at high average currents with better rf control system design?