Energy Recovering Linacs

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Outline

- Introduction and Historical Development
- Energy Recovering Linacs (ERL) Landscape
- Accelerator Physics and Technology Issues of ERLs
  - Generation and Preservation of Low Emittance, High Current Beams
  - Beam Transport
  - Beam Stability
  - RF and SRF Issues
- Conclusions

Storage Rings and Linacs

- For several decades electron storage rings have fulfilled demands for high current beams with high efficiency and increasingly improved performance
- However,
  - 6-D phase space in a storage ring is limited by the equilibrium between quantum excitation and radiation damping
  - Bunch charge density and beam life time limited by Touschek effect
- Linacs can produce low emittance and energy spread and very short bunches
- However,
  - The beam power required for high current operation has limited linacs to relatively low average currents (~ 1 mA)

Energy Recovery

- 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

- As a result:
  - 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})
  - Reduces induced radioactivity (shielding problem) if beam is dumped below the neutron production threshold

Energy Recovering Linacs promise efficiencies approaching those of storage rings, while maintaining beam quality characteristics of linacs: superior emittance and energy spread, sub-ps bunches and flexibility

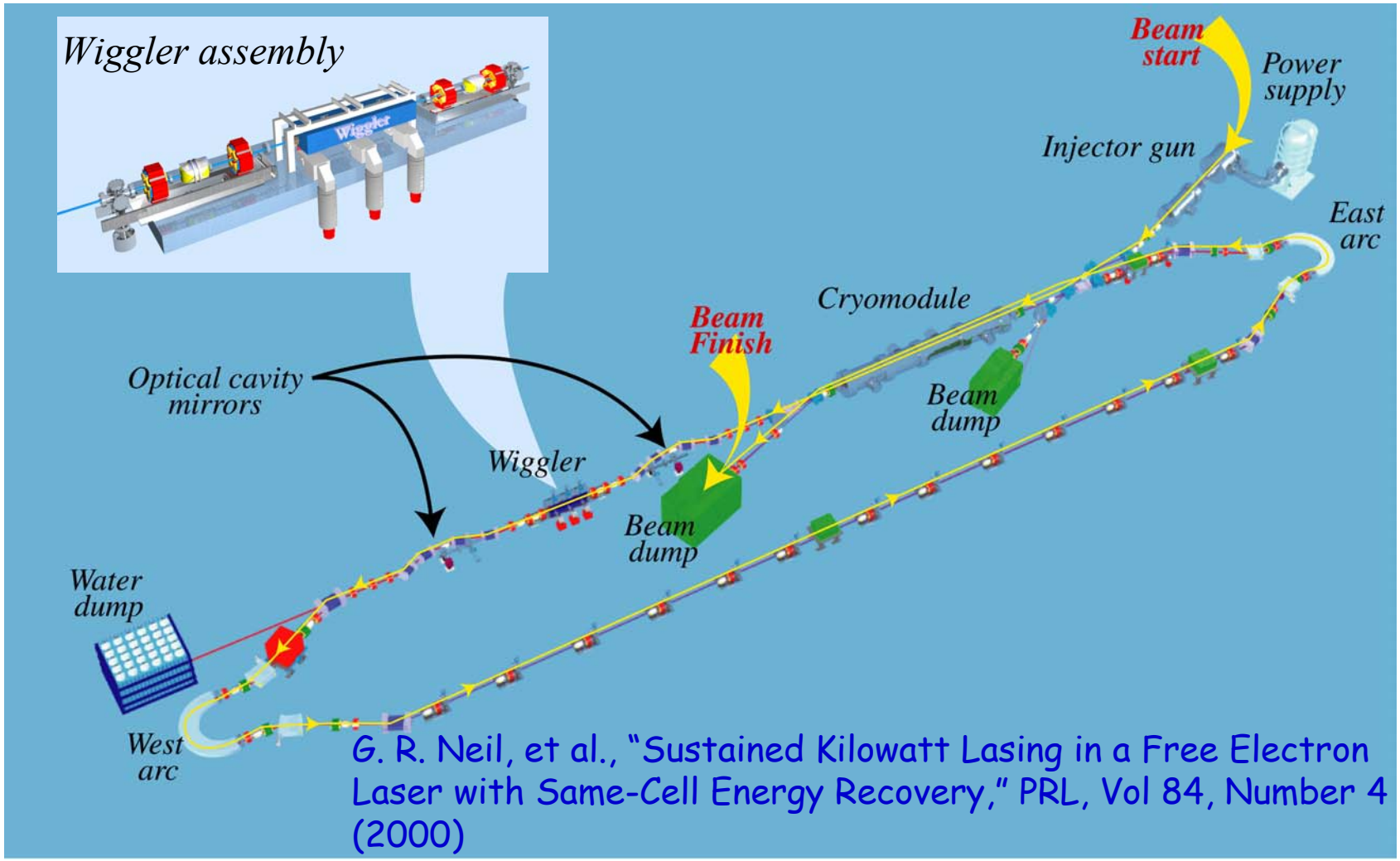
A Brief History

- The concept of energy recovery first appears in literature by Maury Tigner*
- 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)

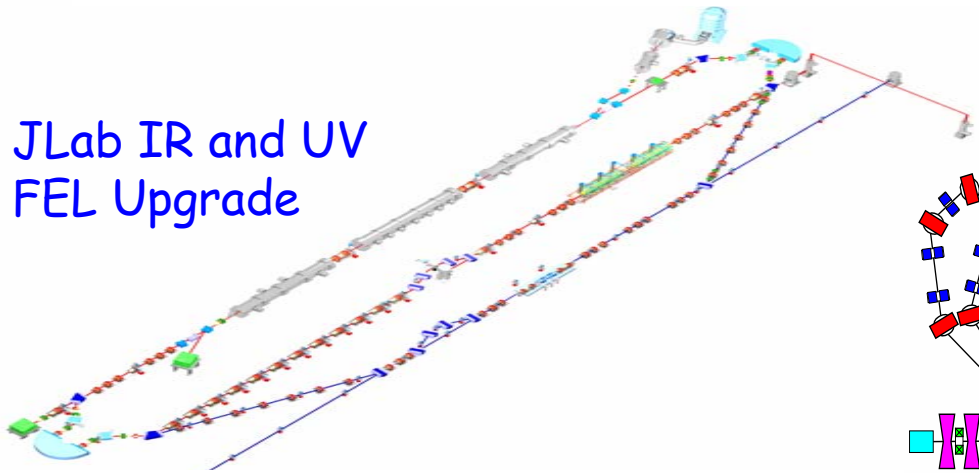
The JLab 2.1 kW IRFEL and Energy Recovery Demonstration



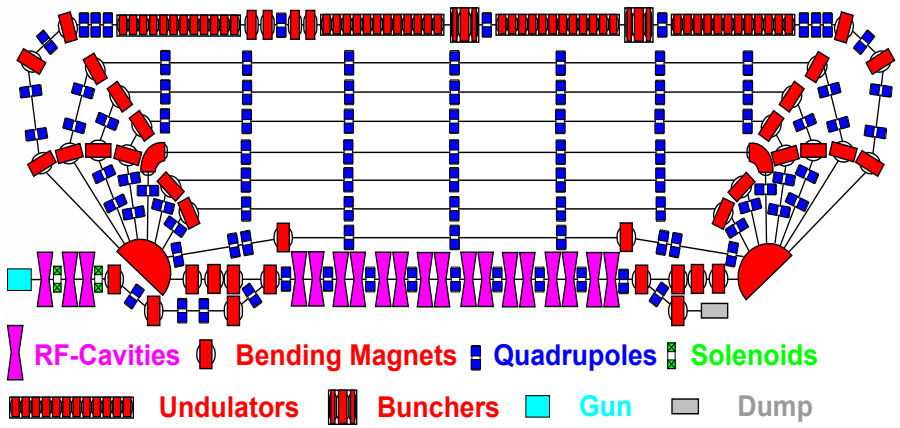
G. R. Neil, et al., "Sustained Kilowatt Lasing in a Free Electron Laser with Same-Cell Energy Recovery," PRL, Vol 84, Number 4 (2000)

ERLs for Free Electron Lasers

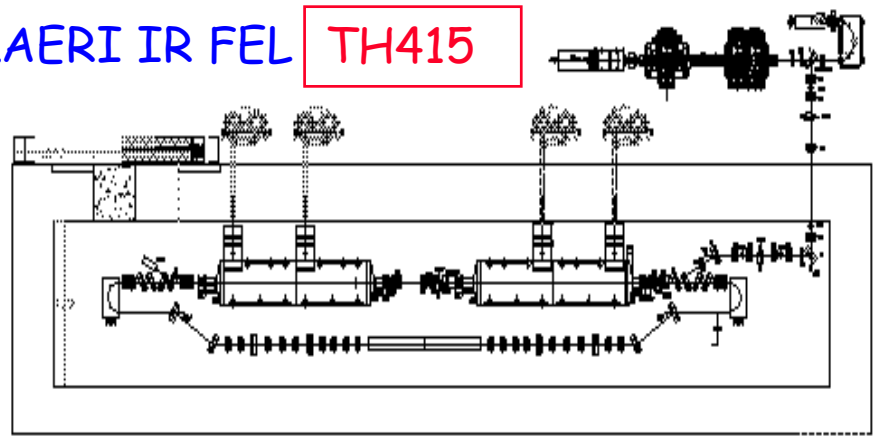
JLab IR and UV
FEL Upgrade



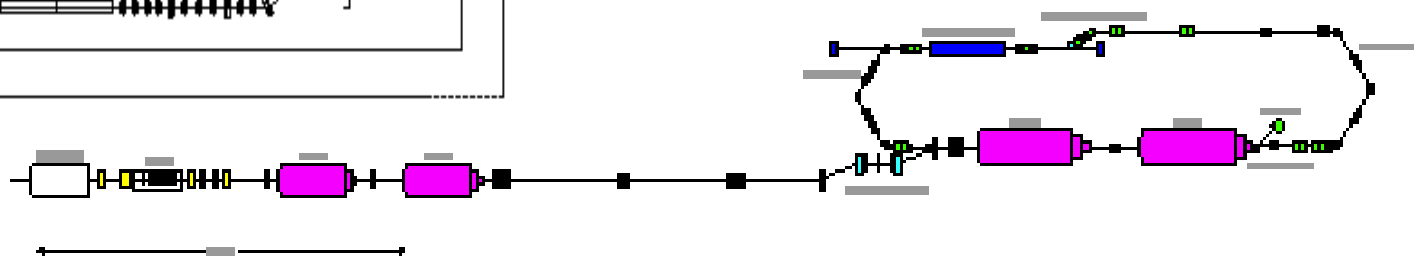
BINP Accelerator-Recuperator FEL



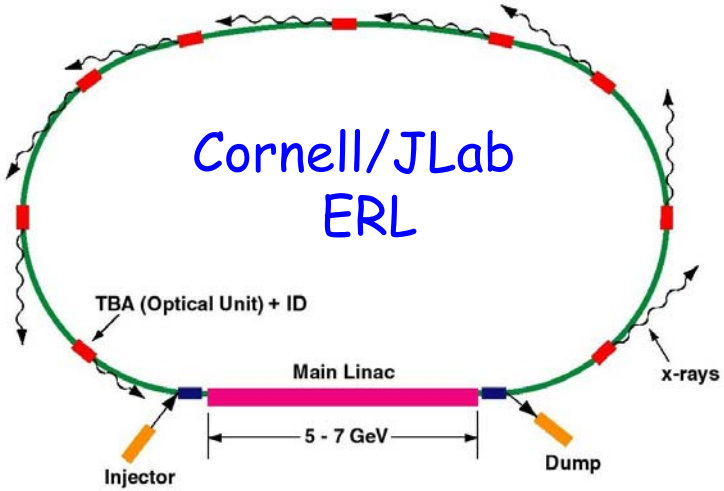
KAERI IR FEL TH415

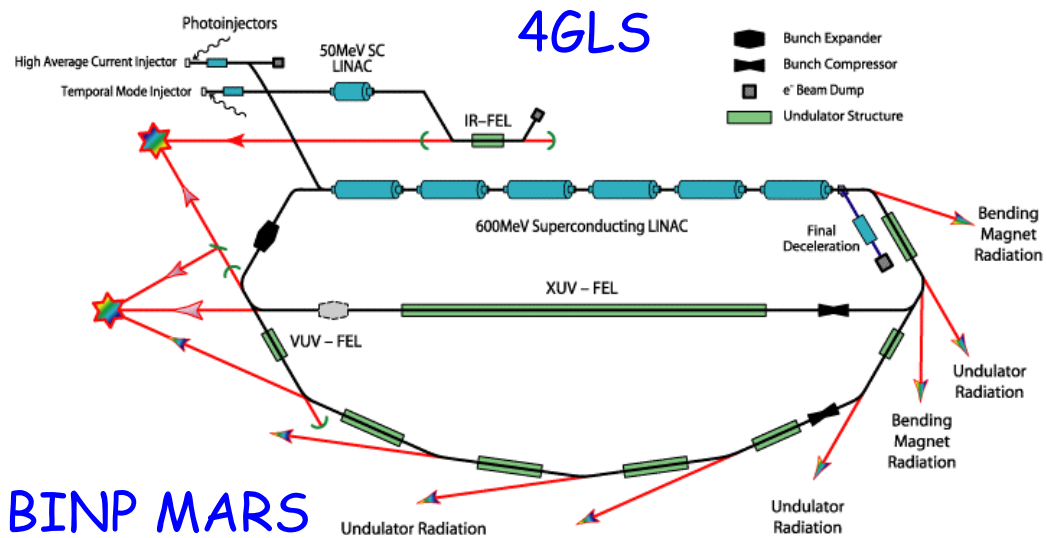


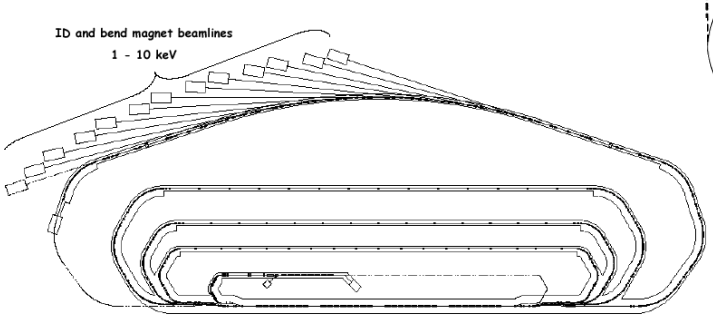
JAERI IR FEL TH404

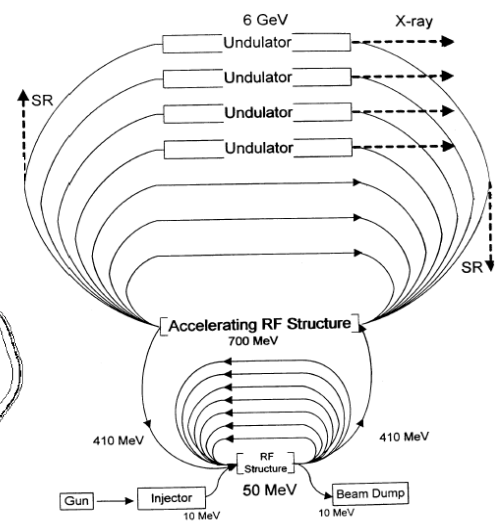


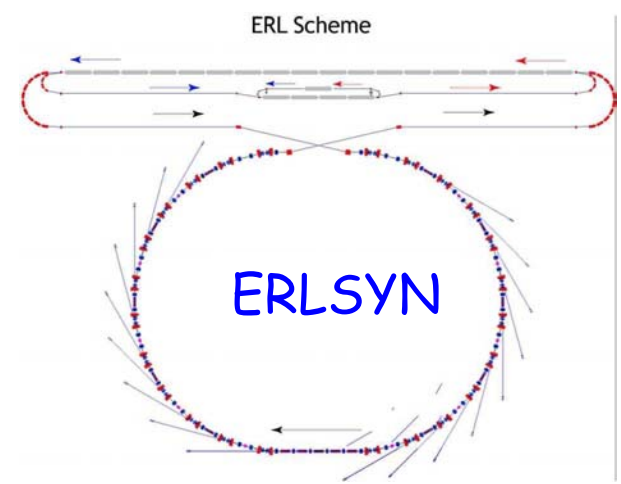
ERLs for Synchrotron Light Sources





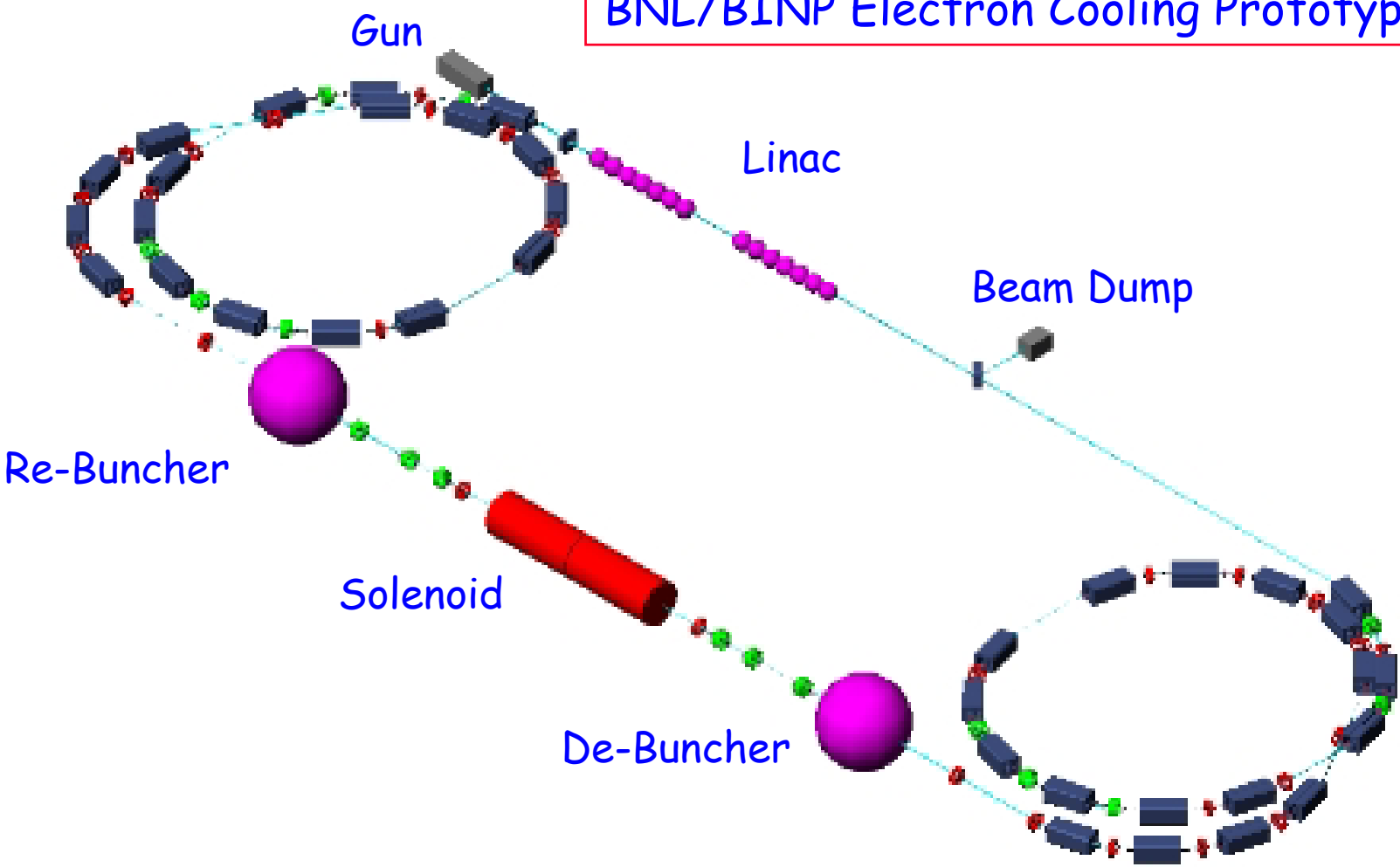




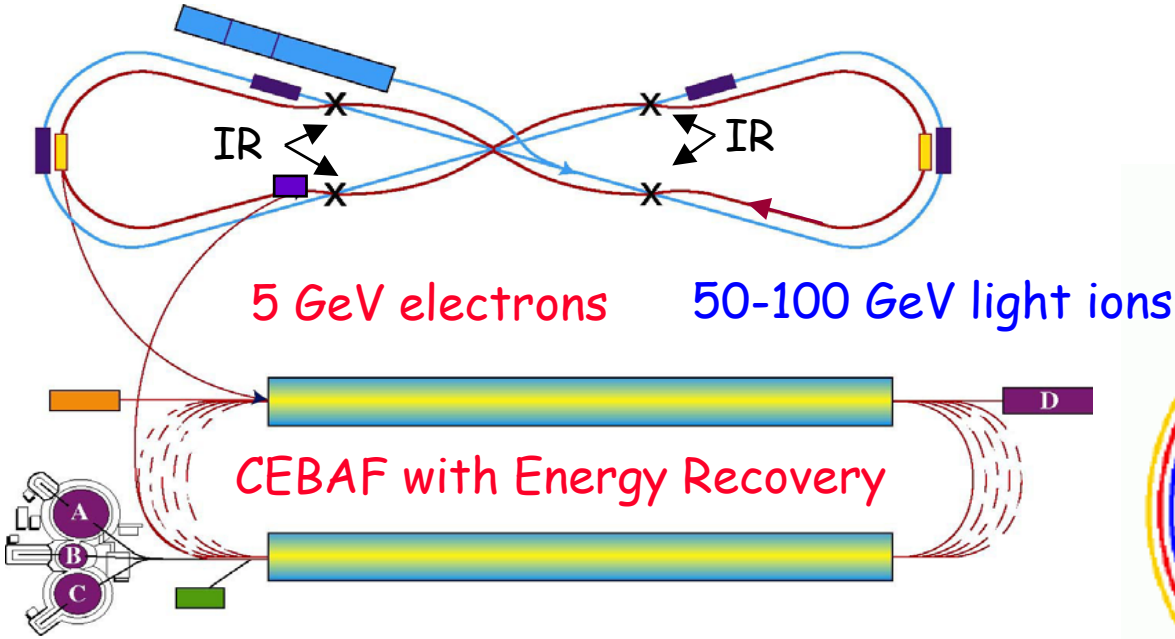


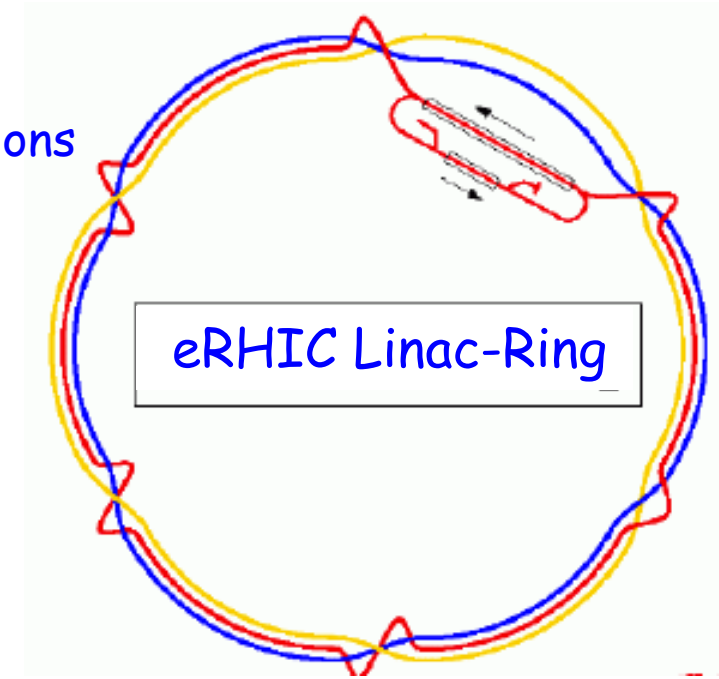
ERL for Electron Cooling

BNL/BINP Electron Cooling Prototype



ERLs for Electron-Ion Colliders

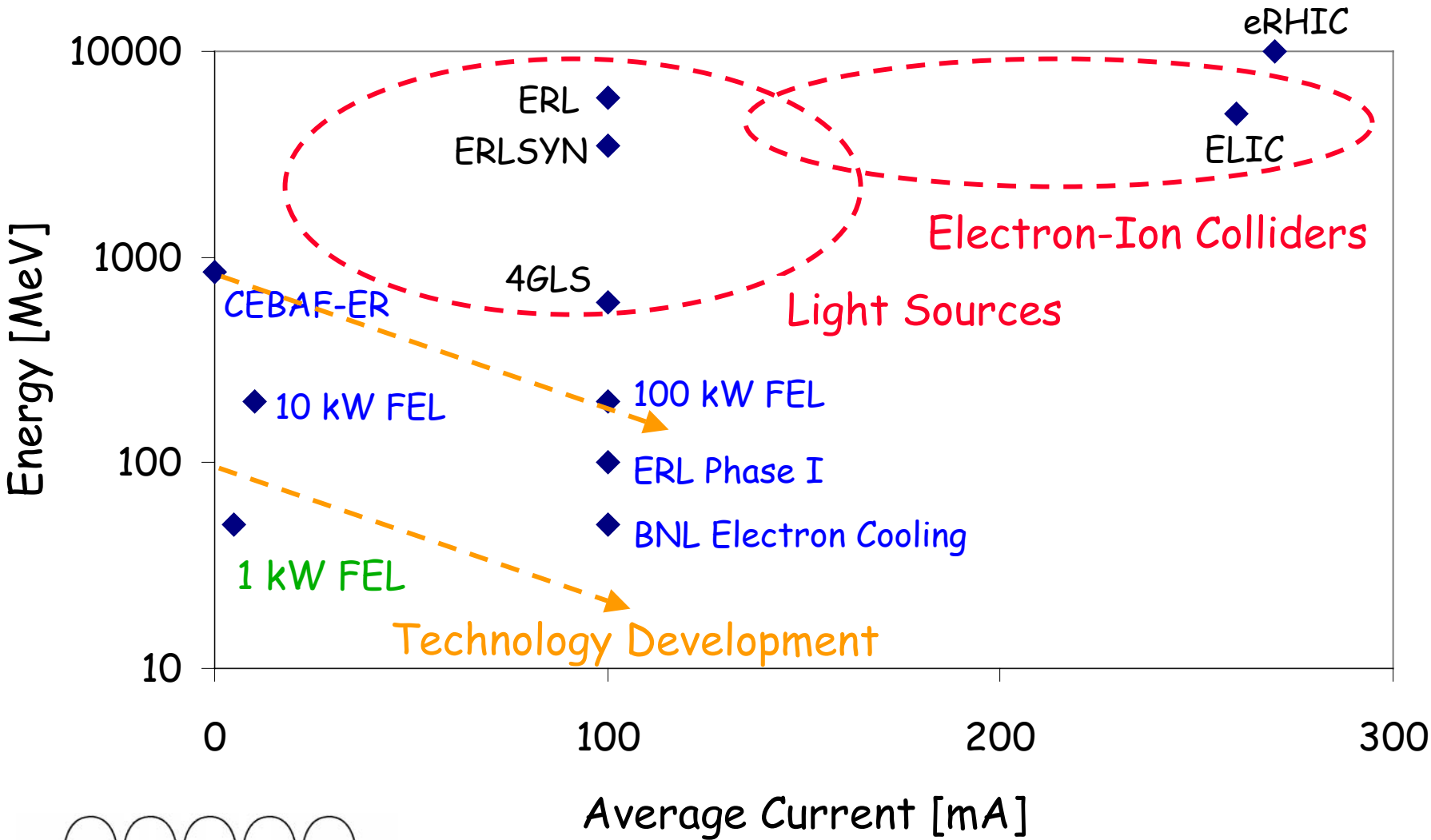




ELIC: An Electron - Light Ion Collider based at CEBAF at $L > 10^{34}$ cm^{-2} sec^{-1}

eRHIC: An Electron-Ion Collider based at RHIC at $L \sim 10^{33}$ cm^{-2} sec^{-1}

ERL Landscape

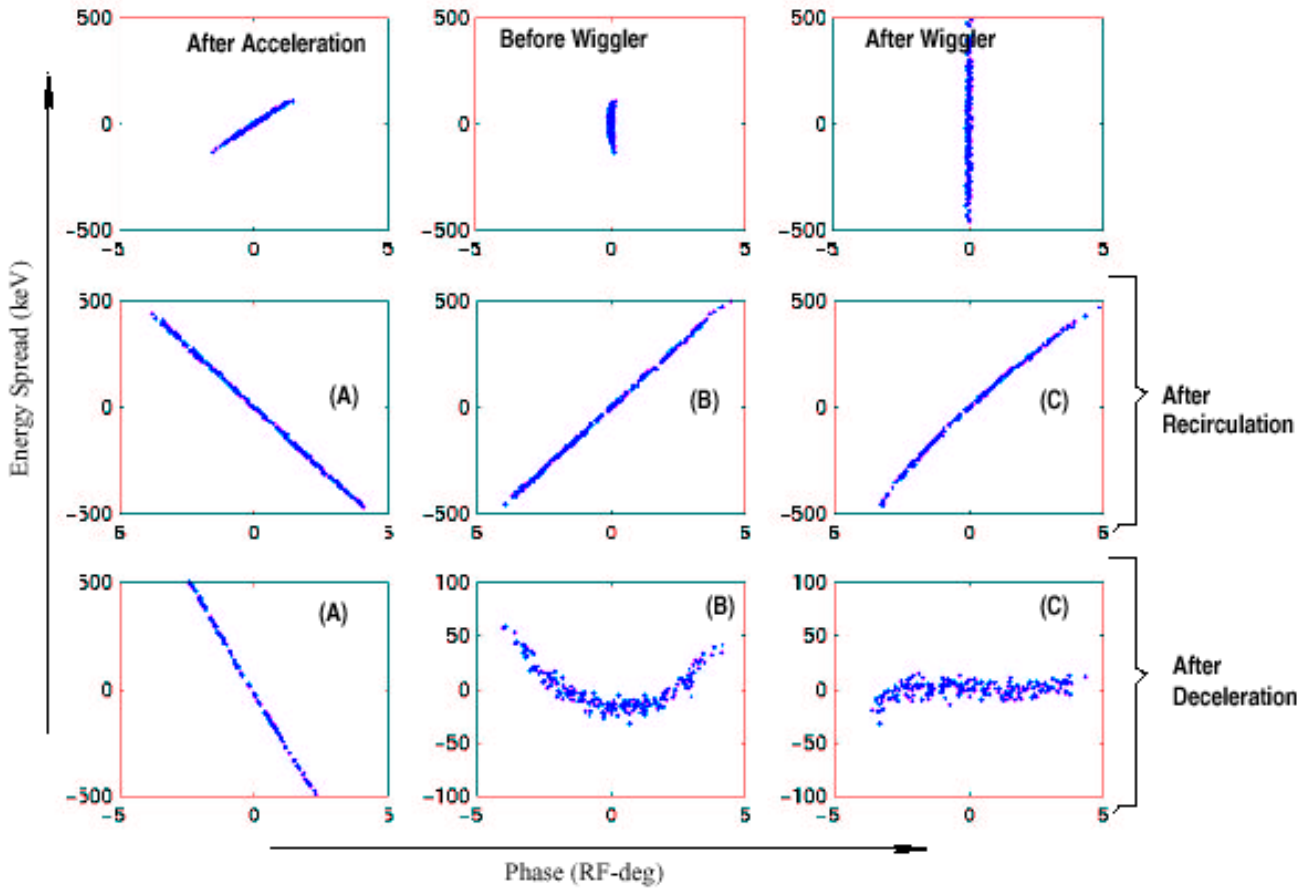


Generation and Preservation of Low Emittance, High Current Beams

- Generation
  - High average current (~100 mA), low emittance (ε_n~1 mm-mrad) beams is a challenge
  - Laser-driven photoemission guns appear likely candidates

- Preservation
  - Emittance compensation
  - CSR emittance degradation
  - Wakefield effects in cavities and beam lines
  - Ion effects
  - Halo formation, control and removal

Longitudinal Phase Space Manipulations



Nonlinear distortions in phase space *must* be corrected for proper energy recovery

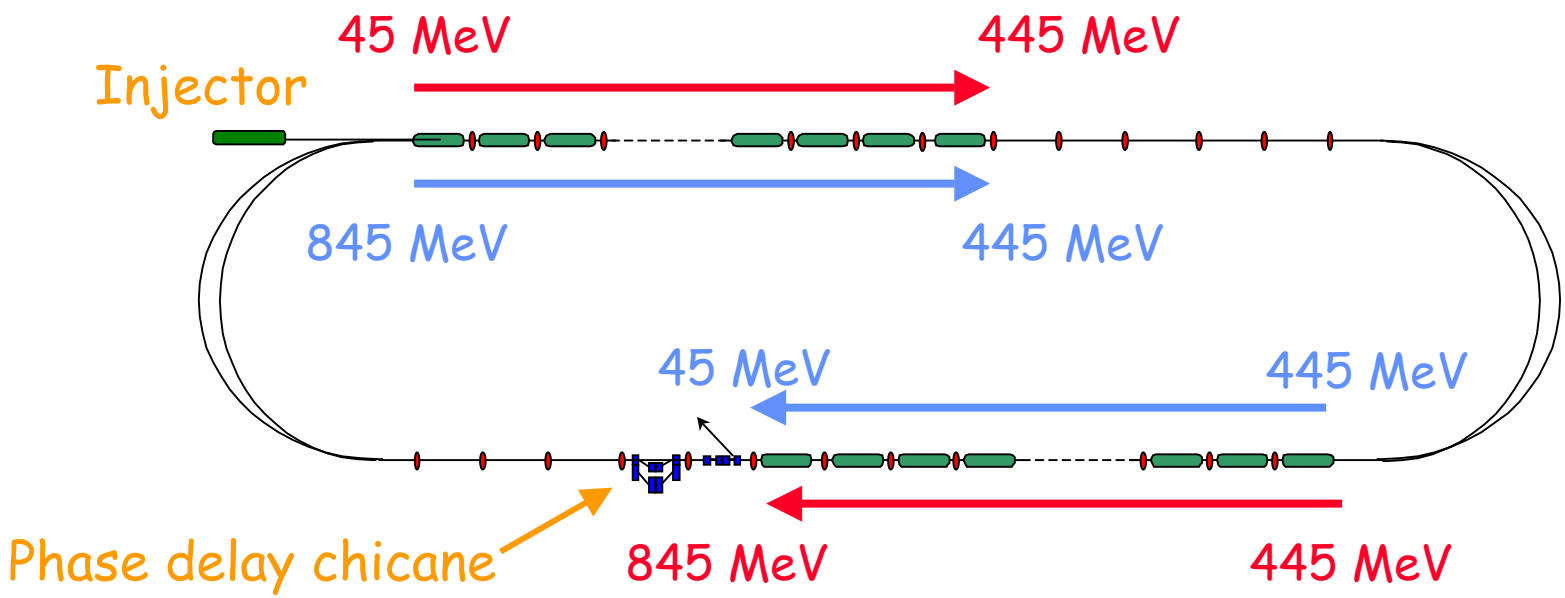
Transverse Matching

- Linac Optics
  - Two beams of different energies must remain confined in the same focusing channel
  - Adiabatic antidamping

- CEBAF-ER: An experiment designed to address transverse beam dynamics aspects of energy recovery in large scale systems

High Energy Demonstration of Energy Recovery

- 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

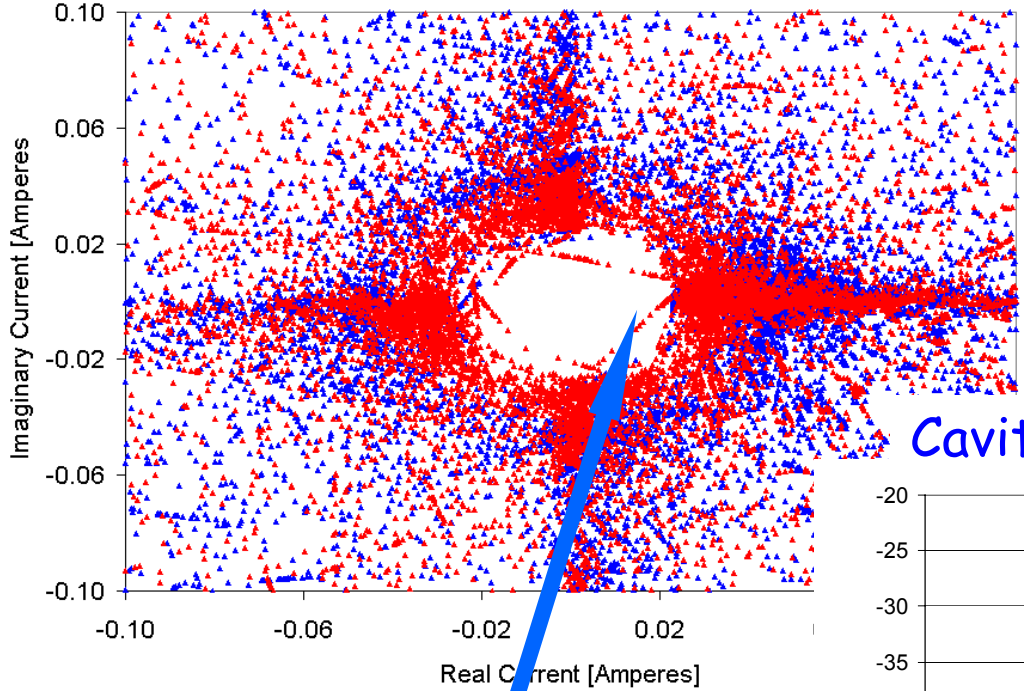


Beam Stability

- Collective effects driven predominantly by high-Q superconducting cavities and can potentially limit average current
- In a recirculating linac, in general, the feedback system formed between beam and cavities is closed and instabilities can result at sufficiently high currents
- An energy recovering linac can support enough current to reach the thresholds of the instabilities
- Instabilities can result from the interaction of the beam with
  - fundamental accelerating mode -> beam loading instabilities
  - transverse HOMs -> transverse BBU
  - longitudinal HOMs -> longitudinal BBU

Transverse BBU appears to be the limiting instability at present

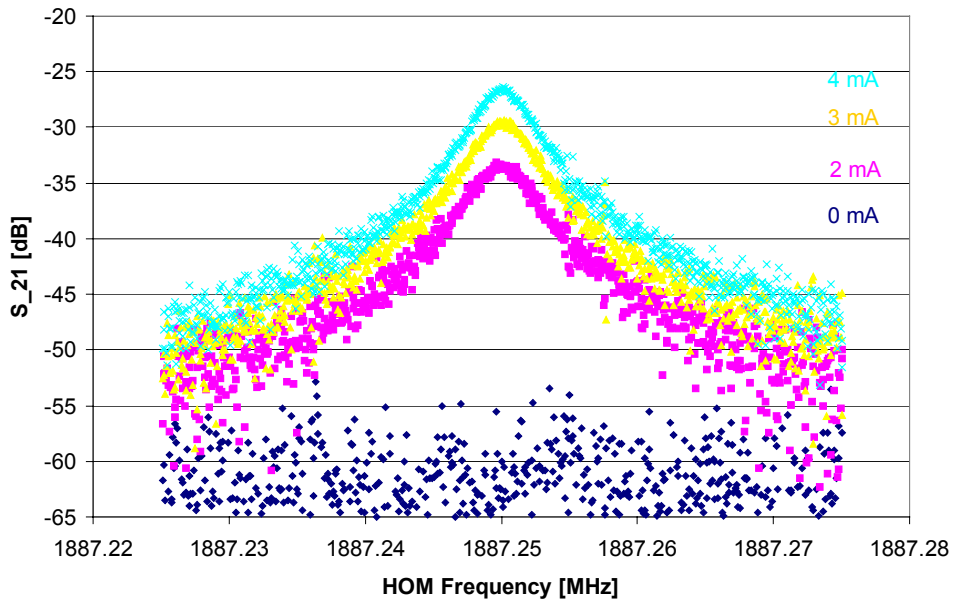
BBU Stability Studies: Theory and Experiment



Stability plot of complex current [A] with 100 HOM frequency distributions

Threshold current = 20 mA

Cavity response to beam excitation



Initial measurements on the JLab IR FEL are used to benchmark the codes

RF Issues

- In the absence of beam loading, Q_{ext} optimization dominated by amplitude of microphonic noise
- Example: In the Cornell/JLab ERL linac cavities
  optimum $Q_{ext} = 2.6 \times 10^7 \Rightarrow P_g = 8$ kW per cavity assuming 25 Hz microphonic noise
- Higher Q_{ext} implies higher ERL efficiency
- RF control becomes challenging in the presence of microphonic detuning, and a net beam loading vector resulting from beam loss or phase errors

TH444

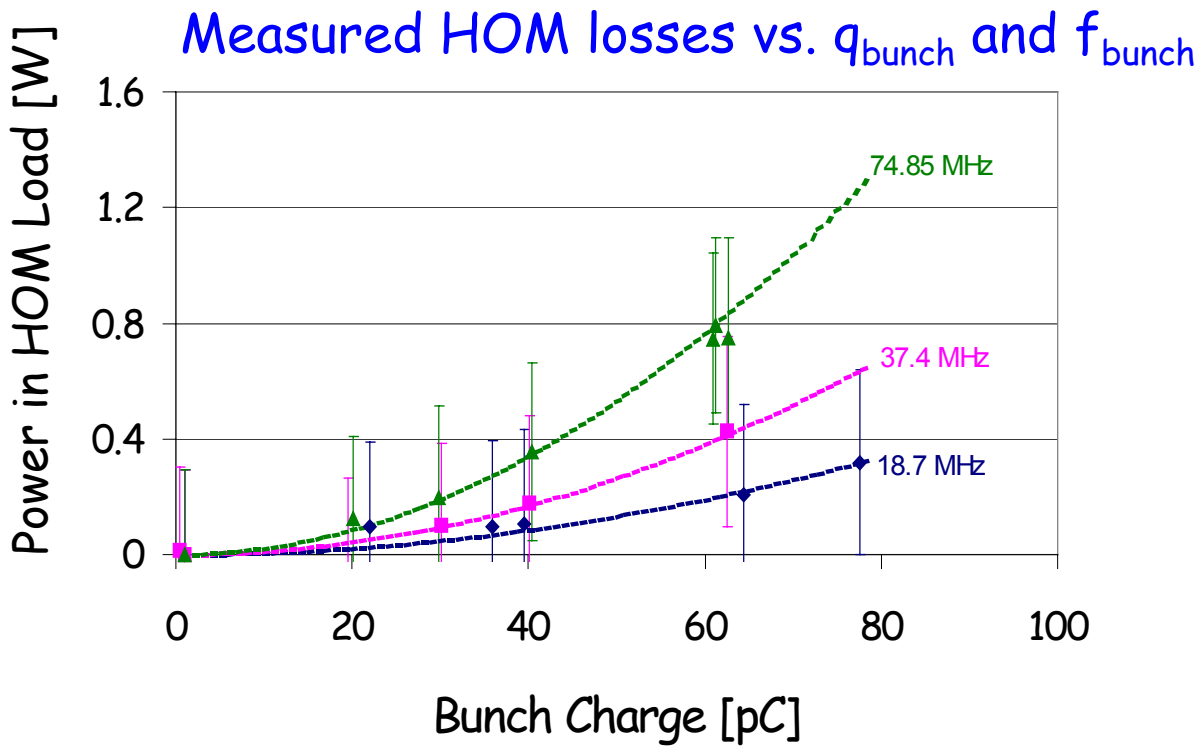
SRF Issues

- High gradient (~20 MV/m) at high Q_0 (~1×10^{10}) has not been demonstrated in cw, high average current operating conditions
- Stronger damping of HOMs necessary for BBU stability
- Efficient extraction of HOM power generated by *sub-ps* short bunches

Energy recovering linacs will operate at levels beyond existing state of art in SRF technology

HOM Power Losses

Fraction of HOM power dissipated on cavity walls can potentially limit I_{peak} and I_{ave}



- HOM losses exhibit correct scaling behavior with q_{bunch} and f_{bunch}
- Experimentally determined loss factor agrees with URMEL within 25%

Extrapolation to Higher Currents

- 5 mA energy recovering linac: JLab IR FEL
  Stability threshold ~ 27 mA
- 10 mA energy recovering linac: JLab IR FEL Upgrade
  Stability threshold ~ 50 mA if Q~ 10^5
- 100 mA energy recovering linac: Cornell/JLab ERL
  Stability threshold ~ 200 mA

- Where is the limit?
  - Better damping of HOMs in multi-cell cavities
  - Bunch-by-bunch transverse feedback, similar to the B-Factory (4 nsec!) may be possible

  ⇒ I_b ~ 0.5 – 1 A conceivable?

- Something else?

Conclusions

- Energy recovering linacs are an emerging and potentially powerful application of RF superconductivity for a wide variety of applications

- We are just starting to understand the limits of energy recovering linacs

- Important accelerator physics and technology issues to be addressed with:
  - the 10 mA and 100 mA JLab FEL Upgrades
  - the 100 mA Cornell/JLab ERL Prototype (Proposal has been submitted to NSF)
  - the 100 mA BNL Electron Cooling Prototype

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