RECIRCULATING AND ENERGY-RECOVERING LINACS

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Recirculating Linacs

RF Installation

Beam injector and dump

— Beamline

Linac

Recirculating Linac

Ring
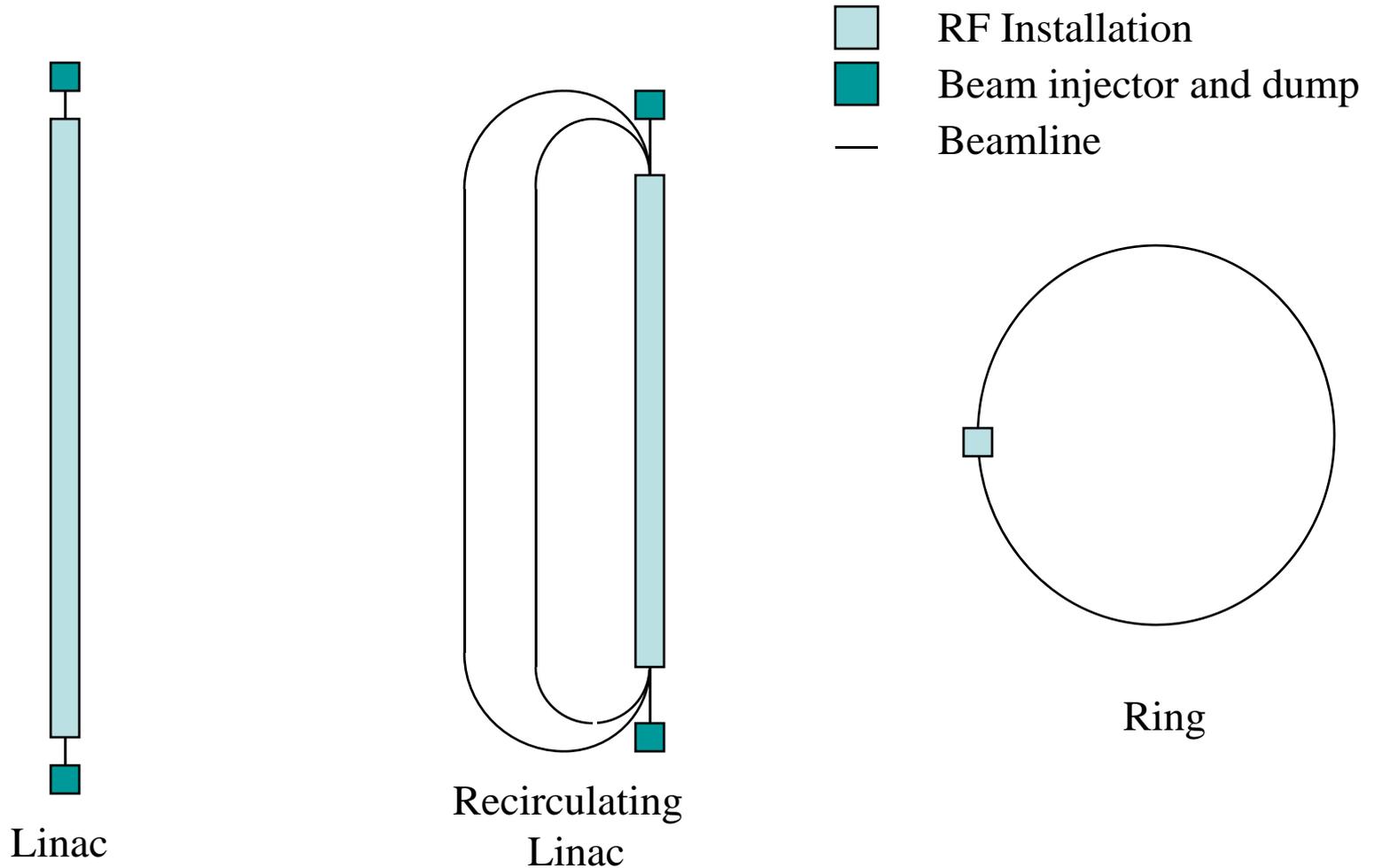
Why Recirculate?

- Performance upgrade of an installed linac
    - HEPL SCA doubled their energy this way

- Cheaper design to get a given performance
    - Microtrons, by many passes, reuse expensive RF many times to get energy up.
    - Penalty is that the average current has to be reduced (proportional to 1/number passes for the same installed RF).
    - CEBAF type machines: add passes until the "decremental" gain in RF system and operating costs pays for additional recirculating loop.
    - Jefferson Lab FEL and other Energy Recovered Linacs (ERLs) save the cost of higher average power RF equipment (and much higher operating costs) at higher CW operating currents by "reusing" the beam energy through beam recirculation.

Features of Recirculating Linacs and Storage Rings

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

Storage Rings

Up to now, the stored average current is much larger

Very efficient use of accelerating voltage

Technology well developed and mature (+ or -)

There's nothing you can do about synchrotron radiation damping

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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.**

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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
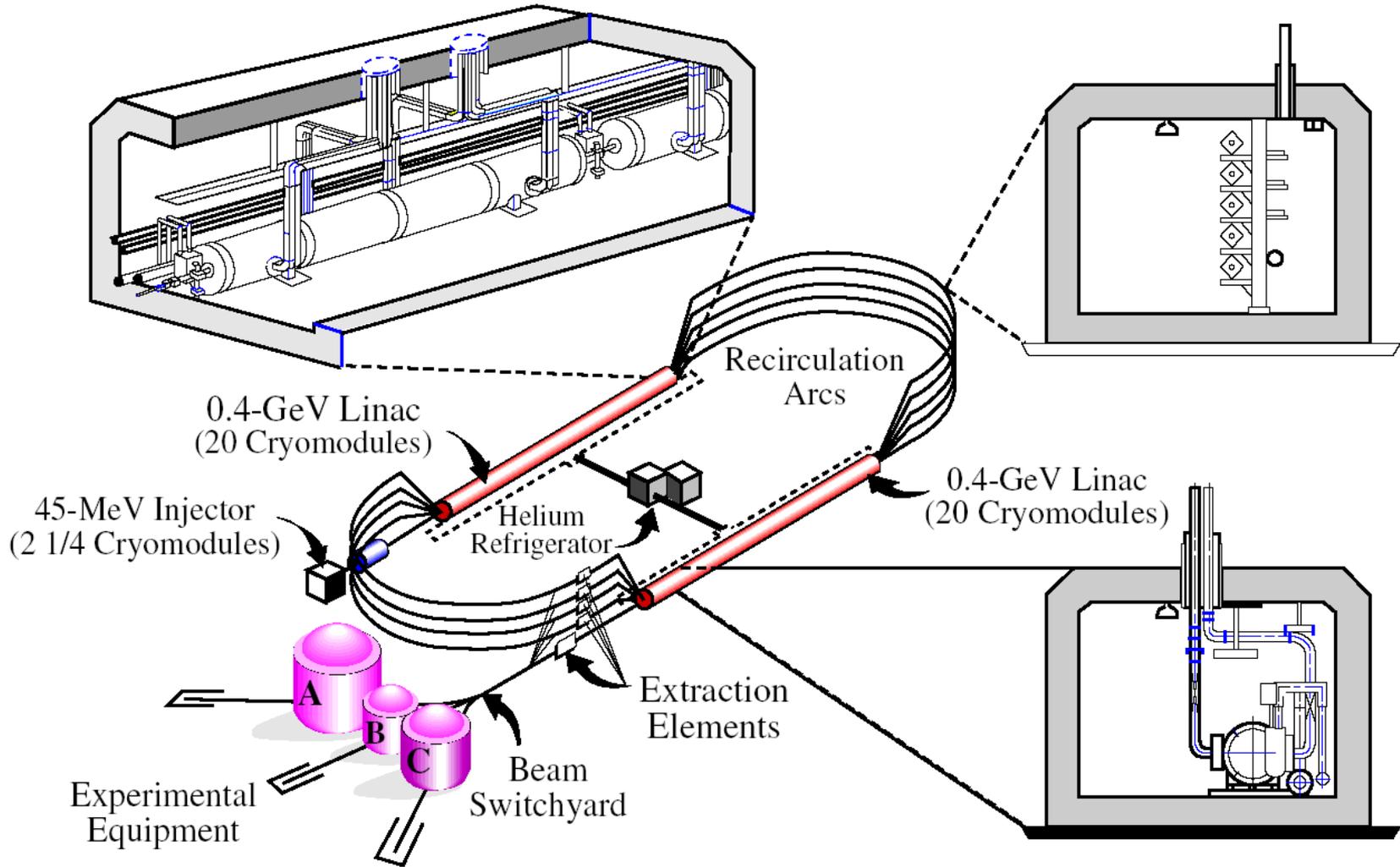
0.4-GeV Linac
(20 Cryomodules)

45-MeV Injector
(2 1/4 Cryomodules)

Recirculation
Arcs

Helium
Refrigerator

0.4-GeV Linac
(20 Cryomodules)

Extraction
Elements

A

B

C

Experimental
Equipment

Beam
Switchyard

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CEBAF Accelerator Layout
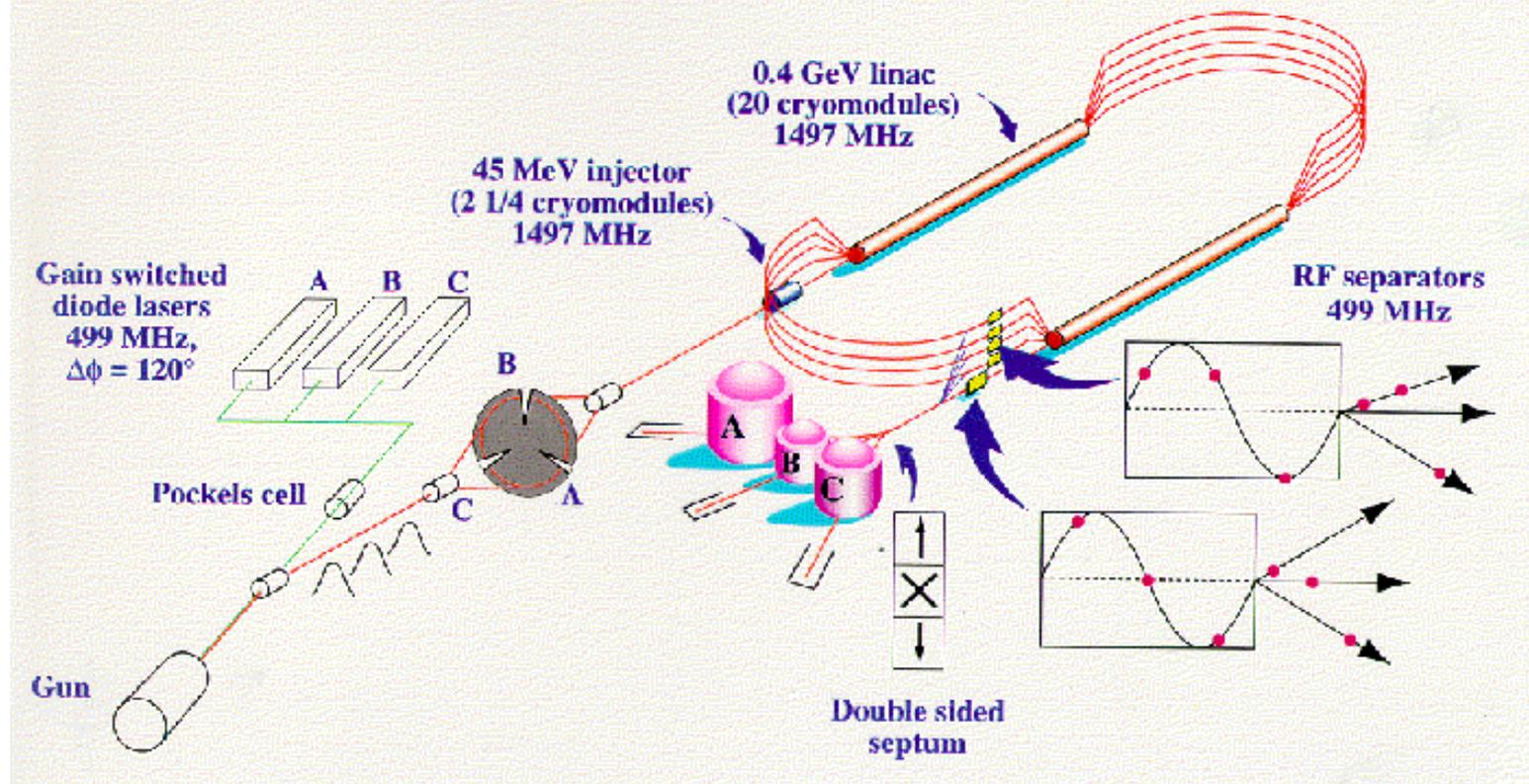
CEBAF Beam Parameters

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

# CEBAF Accelerator

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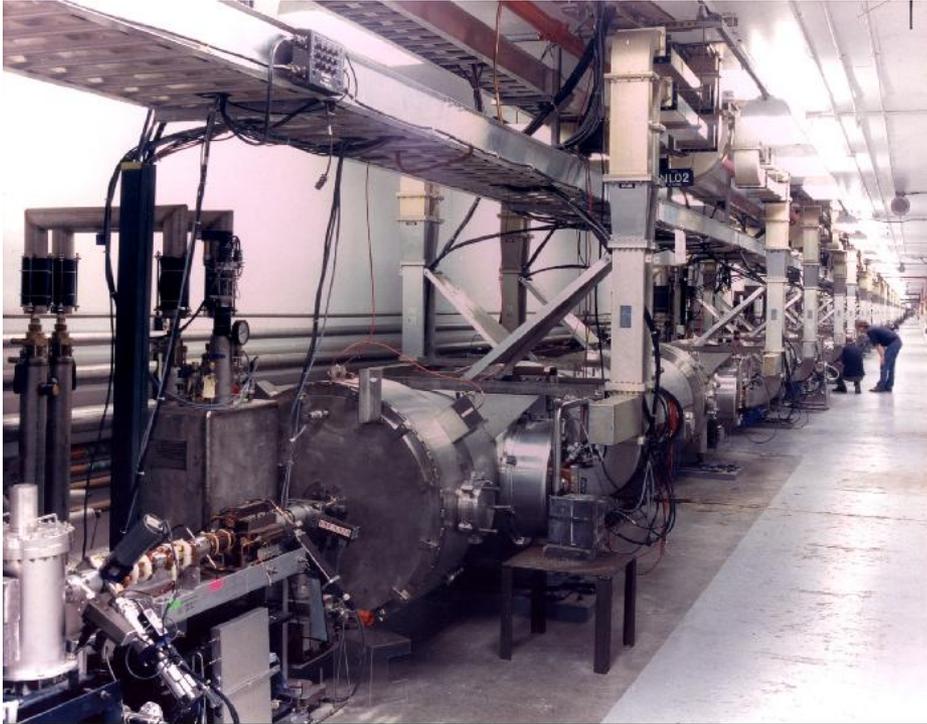
CEBAF Cavities
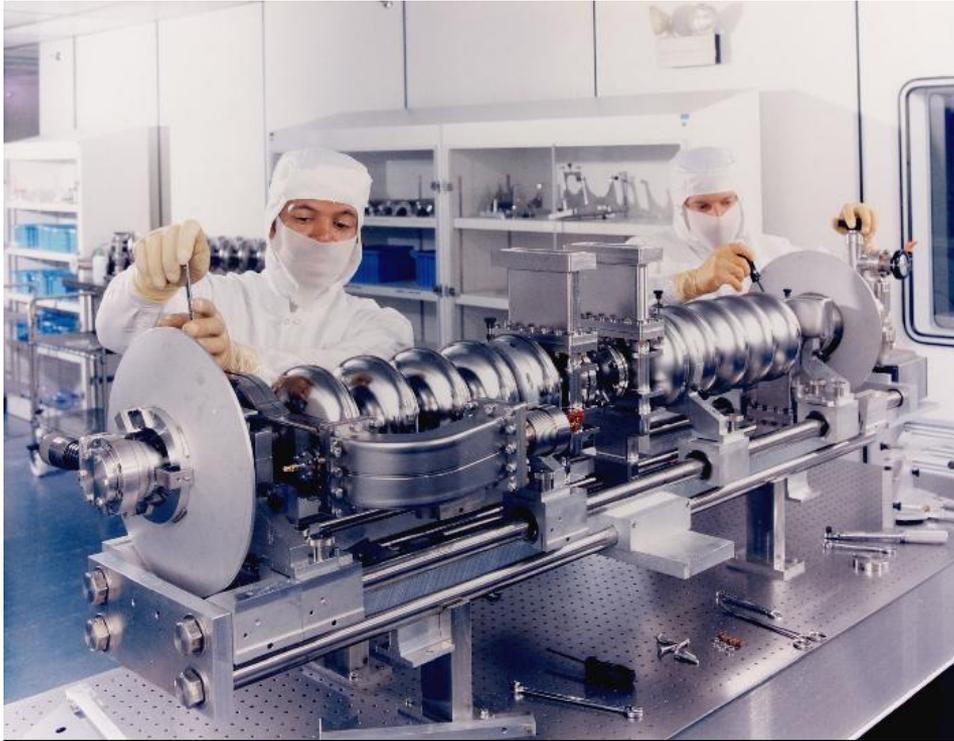
CEBAF Accelerator Upgrade Layout
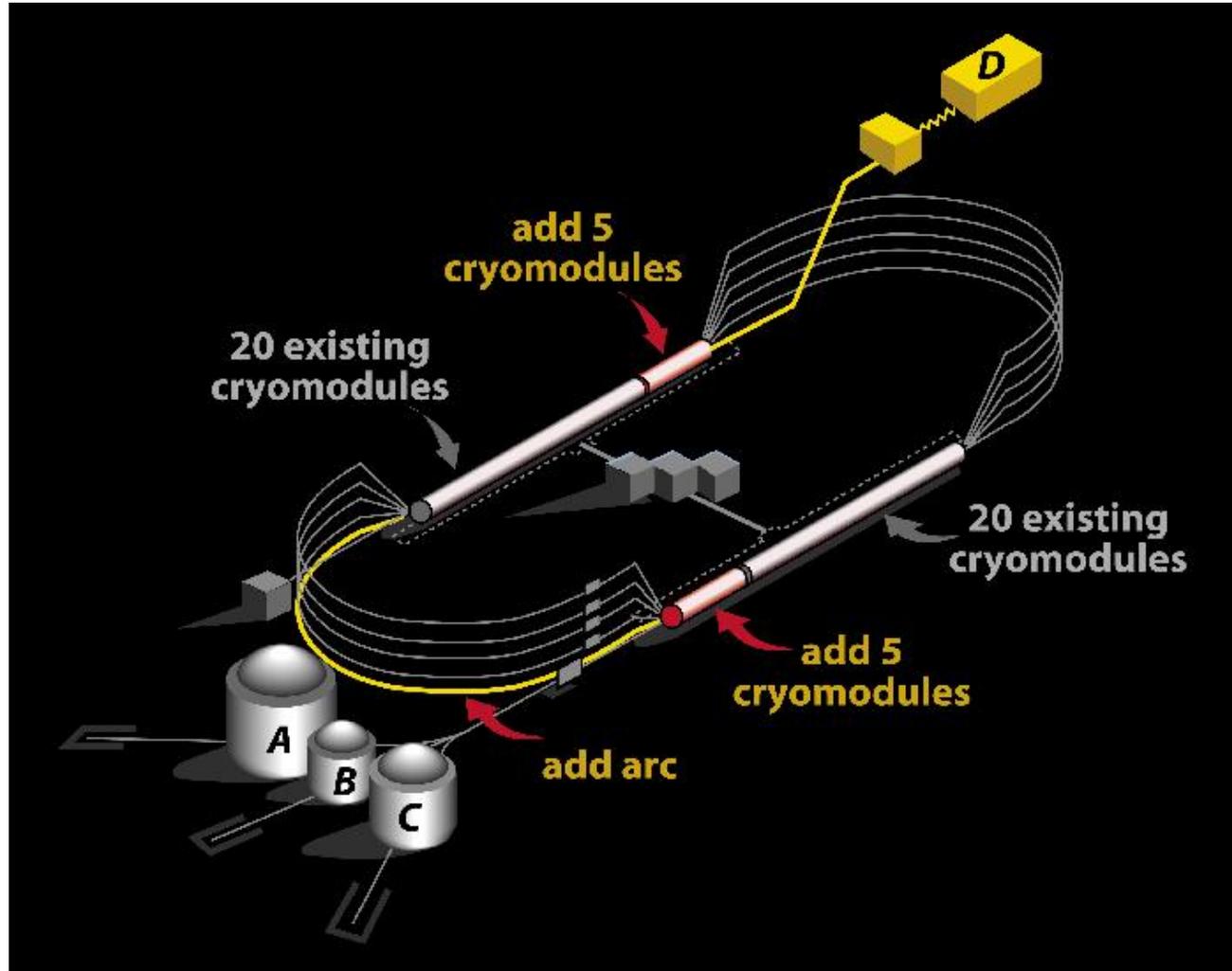
SRF Parameters for Upgrade

- **What is needed?**

  – **Present:**   **6 GeV / 5   passes = 1.2 GeV/pass = 0.6 GeV/linac**

  – **12 GeV:**   **12 GeV / 5.5 passes = 2.2 GeV/pass = 1.1 GeV/linac**

                   Need to add 0.5 GV/linac

Adding 0.5 GV/linac

- There are 5 empty zones at the end of each linac
- 12 Gev Can be achieved with a 100 MV cryomodule in each new zone.

Present cryomodules operate at 30 MV on average.

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100 MV Cryomodules - Gradient

- Simplest change would be to add more cells.

  – Present 8.5m-long cryomodules have 4.0m of active length.

  – 7-cell cavities would use 5.6m - OK

  – Gives 40% more voltage with the same gradient.

Prototype 7-cell cavity

- **40% helps but is not enough -- Need more gradient**

How much gradient is needed?

- **100 MV / 5.6 m   = 17.5 MV/m**
- **Add 10% for cavities that might be off-line**

19.2 MV/m

100 MV cryomodules - Q_0

- Will use one 5 kW cryo plant per linac

- Each plant must support:

  - Present needs of each linac

  - 5 new cryomodules (static and dynamic loads)

 - 250 W available at 2.05K for each new cryomodule

19.2 MV/m cw 250 W $\Big\}$ $Q_0 = 8 \times 10^9$

100 MV Cryomodule RF Power requirements

- **Beam power per cavity: 6.8 kW at 21 MV/m**

- **Actual $Q_{external}$ is 70% of optimum (use stub tuners)**

- **25 Hz of detuning**

    4 Hz   (2x the tuner resolution of 2 Hz)
    + 21 Hz   (6x the standard deviation of the existing cavities'
              noise spectrum)

- **Need gain.   Don't run the klystron into saturation.**

6.8 kW   **12.5 kW**

13 kW klystrons

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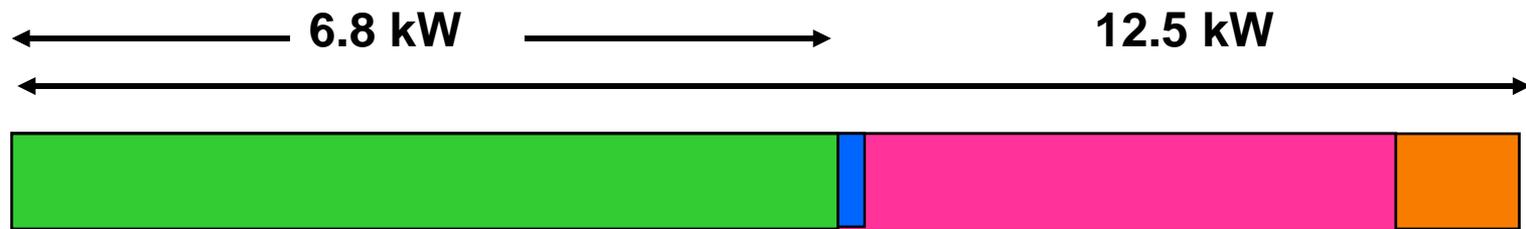
Completed Cavity String First Upgrade Prototype Cryomodule (80MV)

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**
  - **Stanford SCA/FEL**
  - **Los Alamos FEL**
  - **CEBAF front end**

- **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 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)
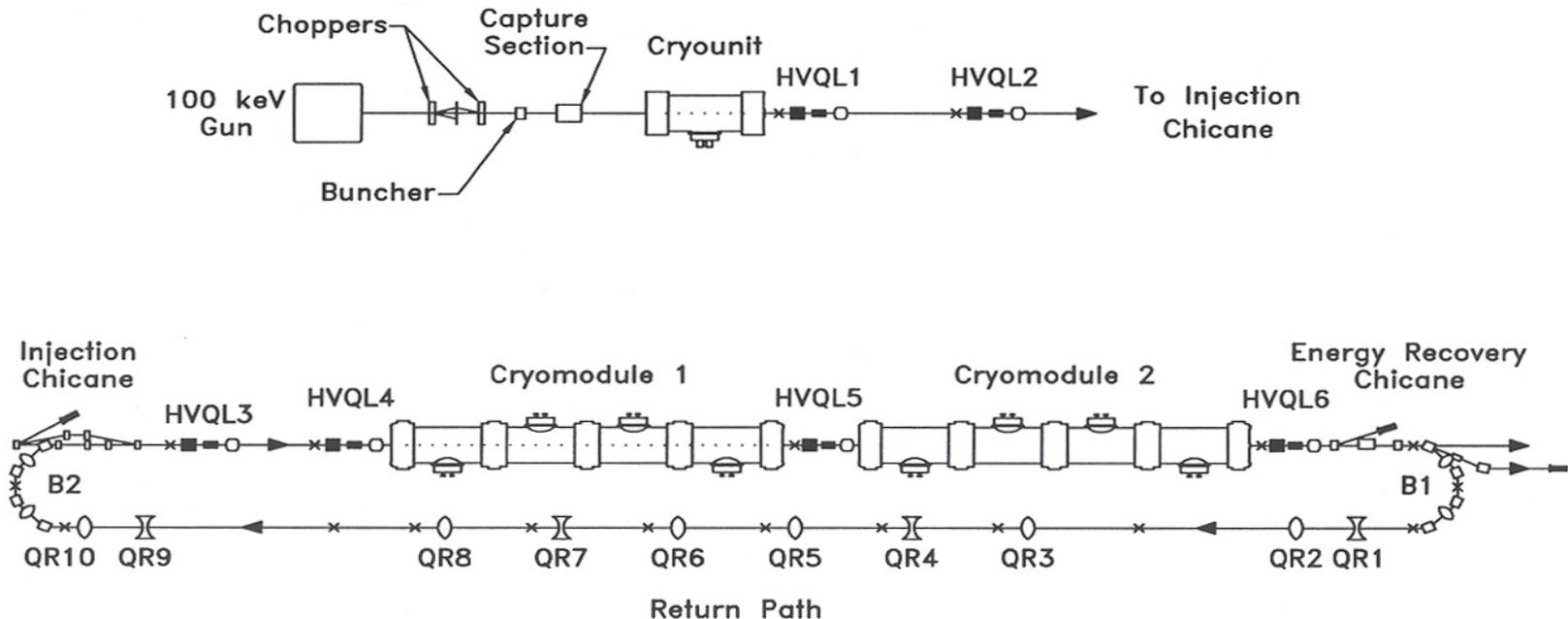
The JLab 2.13 kW IRFEL and Energy Recovery Demonstration

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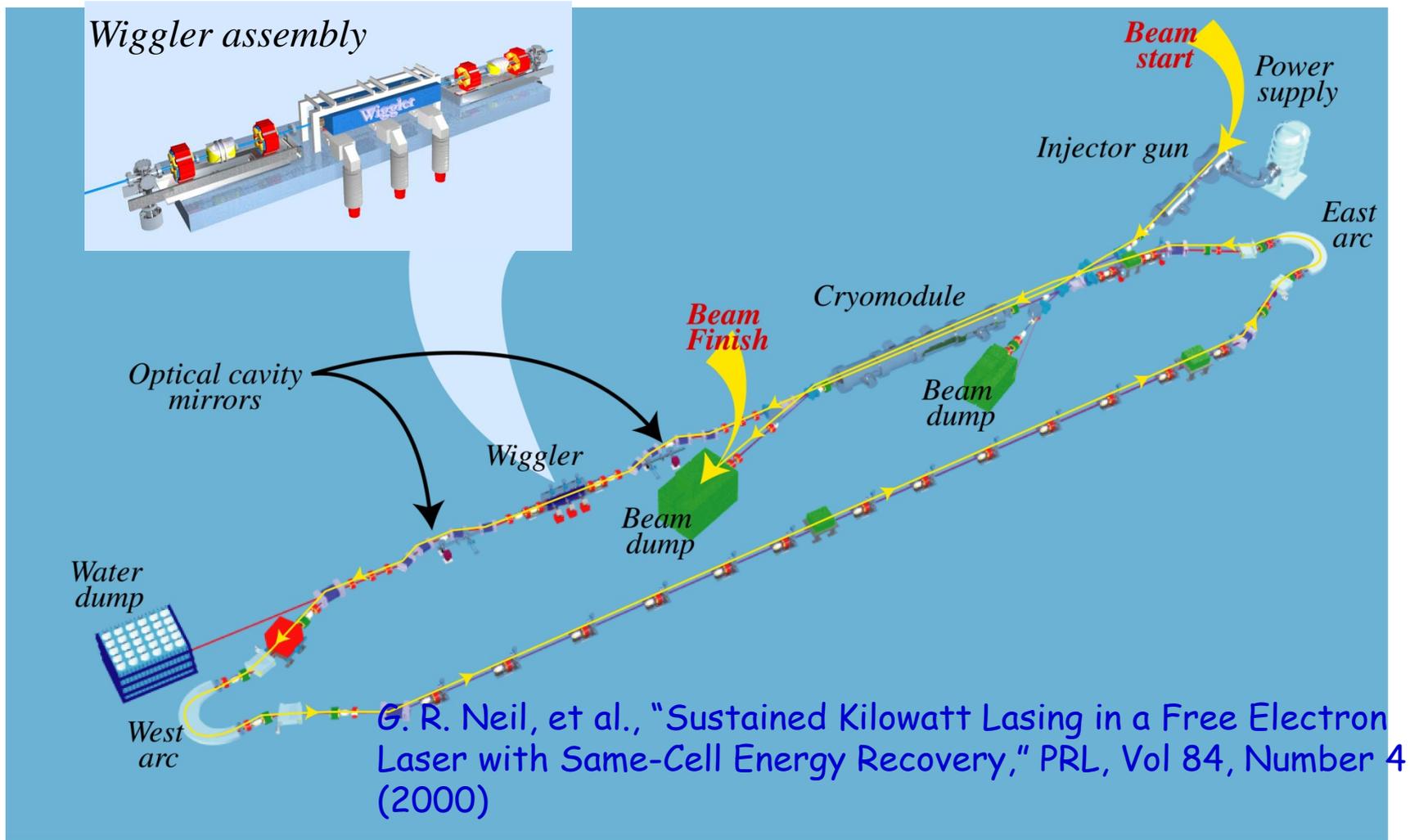
State of the Art in ERL Technology

JLab IR FEL Upgrade
Achieved 14.2 kW CW IR power on October 30, 2006
Energy recovered up to 9.1 mA at 150 MeV
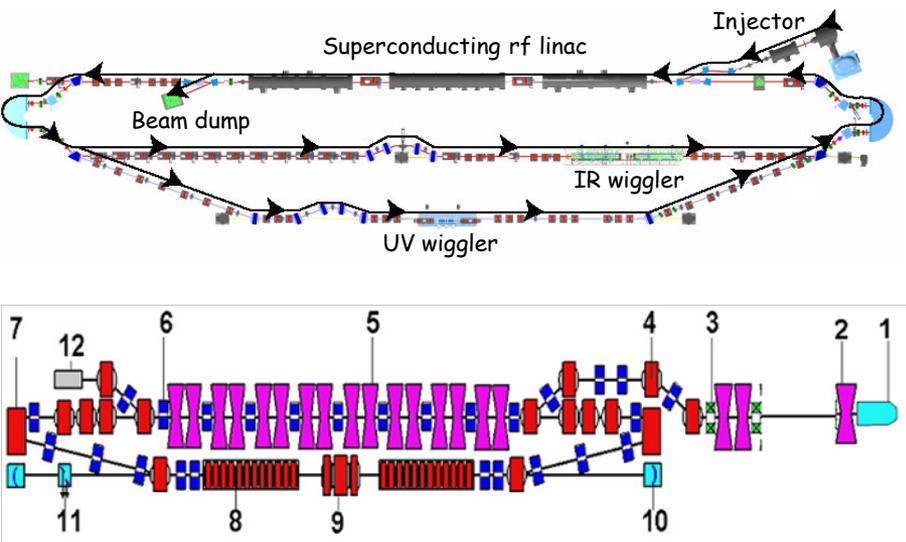
| JLab IR FEL Electron Beam Parameters	Design	Achieved
Energy (MeV)	145	160
Bunch charge (pC)	135	150
Average current (mA)	10	9.1
Bunch length* (fs)	400	150
Norm. emittance* (mm-mrad)	30	7
Max. Bunch rep. rate (MHz)	74.85	74.85

*Quantities are rms

Novosibirsk High Power THz FEL
Energy recovered highest average current to date:
### 20 mA at 1.7 nC per bunch using 180 MHz NC RF

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ERL Light Sources

FEL ERLs

Synchrotron Light ERLs

TBA (Optical Unit) + ID

Main Linac

Injector

Dump

x-rays
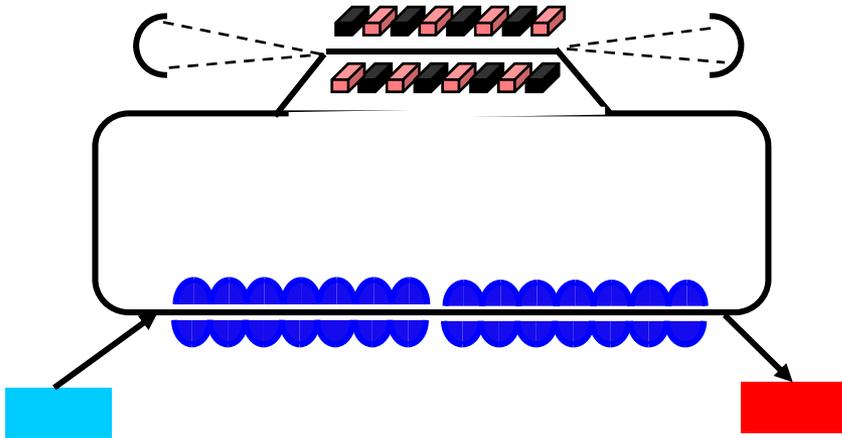
Requirements

Energy ~ 120 MeV

Charge ~ 0.1 - 1 nC/bunch

Emittance ~ 5-10 mm-mrad

Average current ~ 100 mA
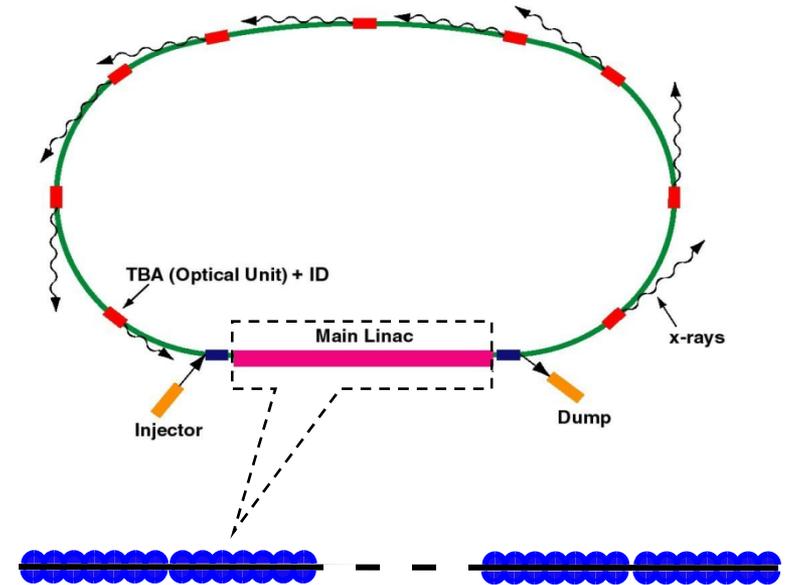
Requirements

Energy ~ 1 GeV

Charge ~ 0.1 nC/bunch

Emittance ~ 0.1 mm-mrad

Average current ~ 100 mA

ERLs for Nuclear and Particle Physics

Electron Cooling of hadron storage rings
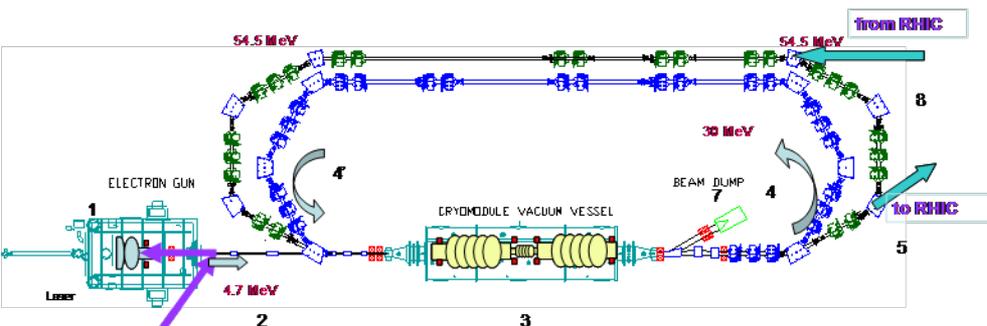
Provide electron beams for high-luminosity electron-ion colliders
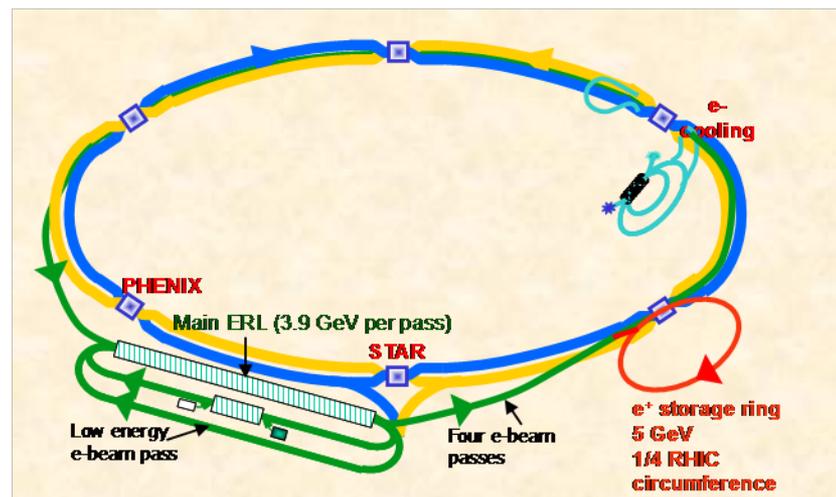
Requirements

Energy ~ 50 MeV

Charge ~ 5 nC/bunch

Emittance ~ 3 mm-mrad

Average current ~ 50-100 mA

Requirements

Energy ~ 10-20 GeV

Charge ~ 10-20 nC/bunch

Emittance ~ 20 mm-mrad

Average current ~ 250 mA

Polarization ~ 80%

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Demonstration of Energy Recovery

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).

GASK
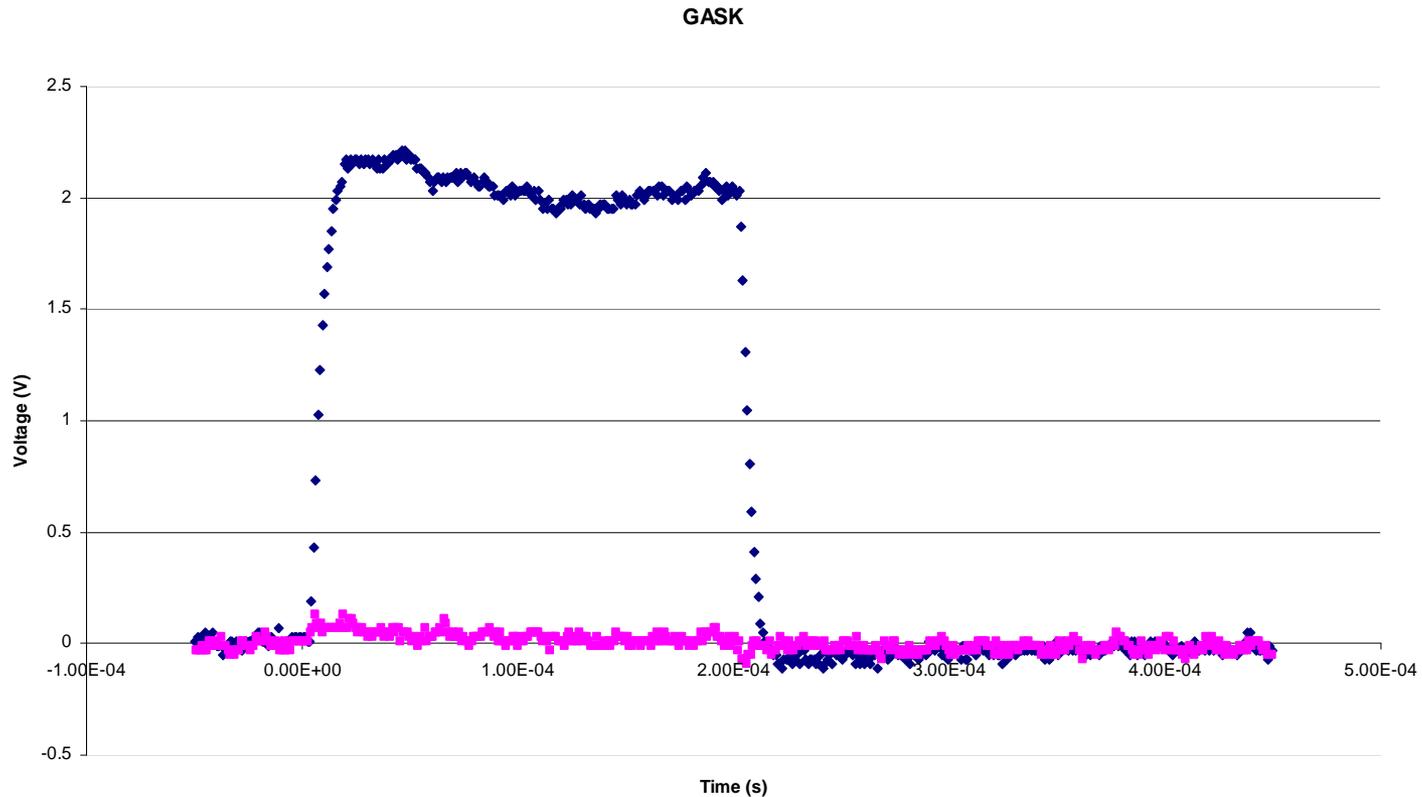
Demonstration of Energy Recovery

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
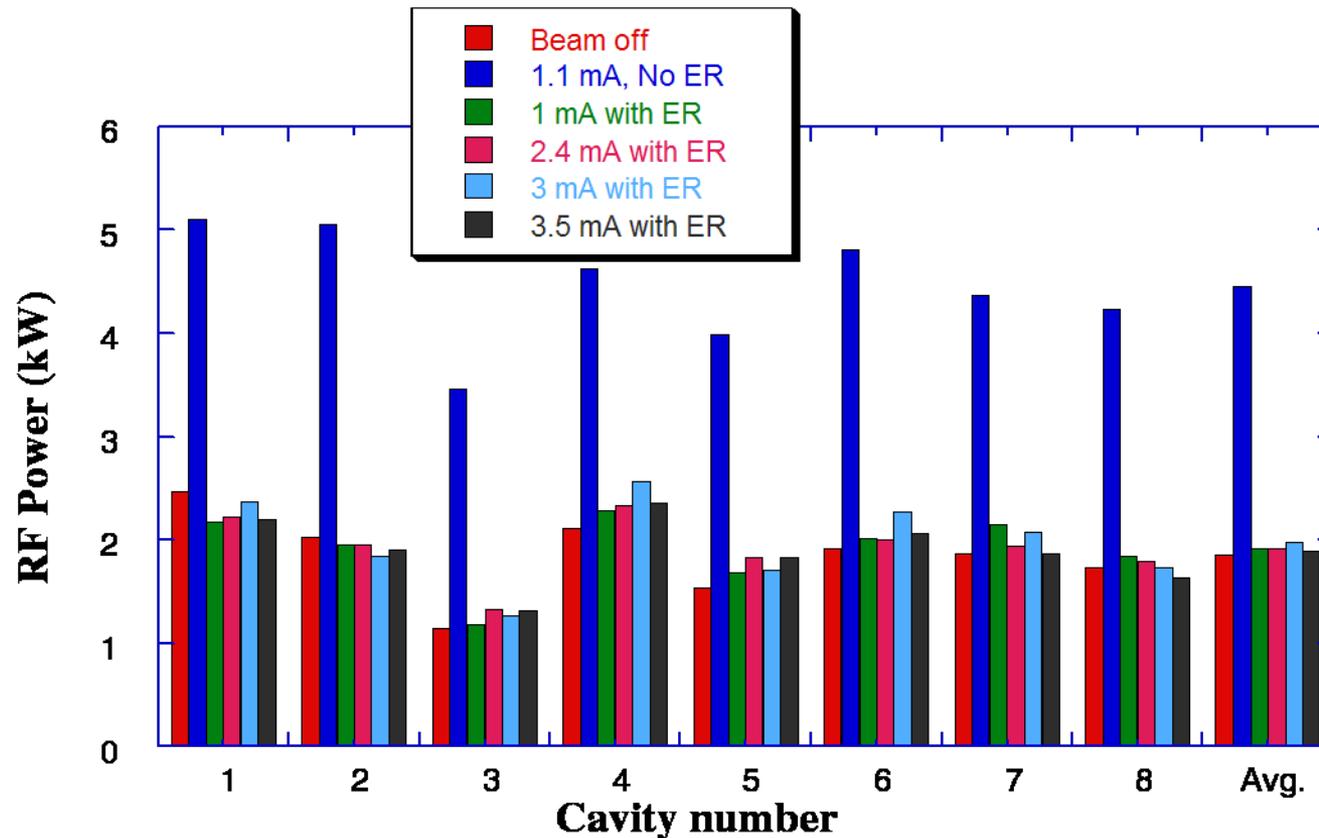
Features of Energy Recovery

- **With the exception of the injector, the required rf power is nearly independent of beam current**

  - **Increased overall system efficiency**

  - **Reduced rf capital cost**

- **The electron beam power to be disposed of at beam dumps is reduced by ratio of E_{max}/E_{inj}**

  - **Thermal design of beam dumps is simplified**

  - **If the beam is dumped below the neutron production threshold, then the induced radioactivity (shielding problem) will be reduced**

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RF to Beam Multiplication Factor for an Ideal ERL

$$J = \frac{P_b}{P_g} = \frac{\text{Power absorbed by accelerated beam}}{\text{Generator power needed to create and control rf fields}}$$

$$J = \frac{VI}{\frac{V_c^2}{2\left(\frac{R}{Q}\right)Q_L}} = \frac{2I}{E}\left(\frac{R}{lQ}\right)Q_L$$

$$\kappa = \frac{\text{Accelerated beam power}}{\text{Installed rf power}}$$

$$\kappa = \frac{JE_f}{(J-1)E_{inj} + E_f}$$

RF to Beam Multiplication Factor for an Ideal ERL

$$E_{acc} \quad 20\,MV/m$$

$$R/lQ \quad 1000 \quad /m$$

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

$$E_f \quad 7\,GeV$$

RF to Beam Multiplication Factor

Beam Current (mA)

Legend:
- QI=10^8 (red)
- QI=2 10^7 (blue)
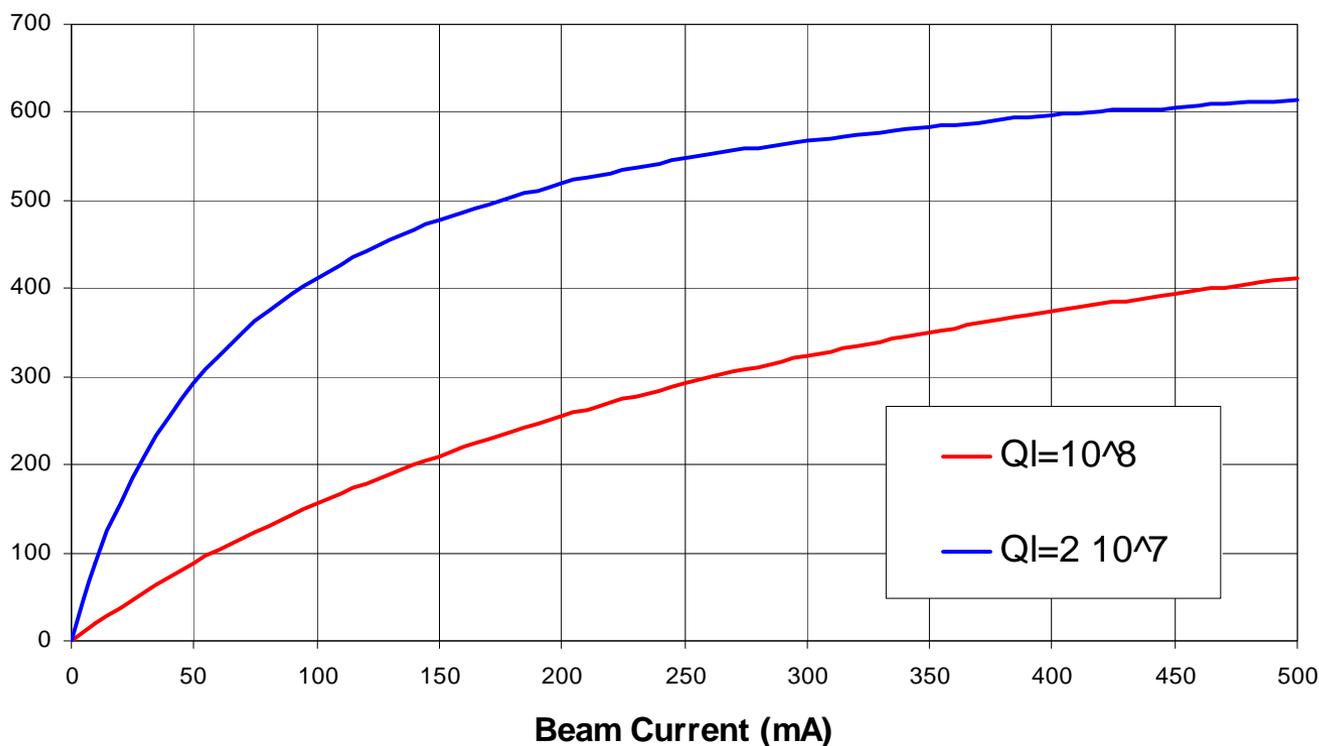
RF to Beam Multiplication Factor for an Ideal ERL

- **The efficiency of an ERL (as measured by the rf to beam multiplication factor) increases with current**

  - **Asymptotic value is E_{max}/E_{inj}**

- **The efficiency increases with the loaded Q of the energy-recovering cavities**

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User Requirements and Beam Properties

High average flux $\propto I_{ave}$

Full spatial coherence
$\varepsilon < \lambda / 4\pi$

High average brilliance
$B \propto N_u I_{ave} / \varepsilon_x \varepsilon_y$

High temporal coherence

Sub-ps x-ray pulses

Low emittance
$(\varepsilon_N \leq 1 \text{ mm-mrad})*$
& round beams

High average current
(~100 mA)

Small energy spread
$(\sigma_E / E \sim 10^{-4})*$

Sub-ps bunch length
(~100 fsec)*

Long insertion devices

Variable filling patterns

*quantities are rms
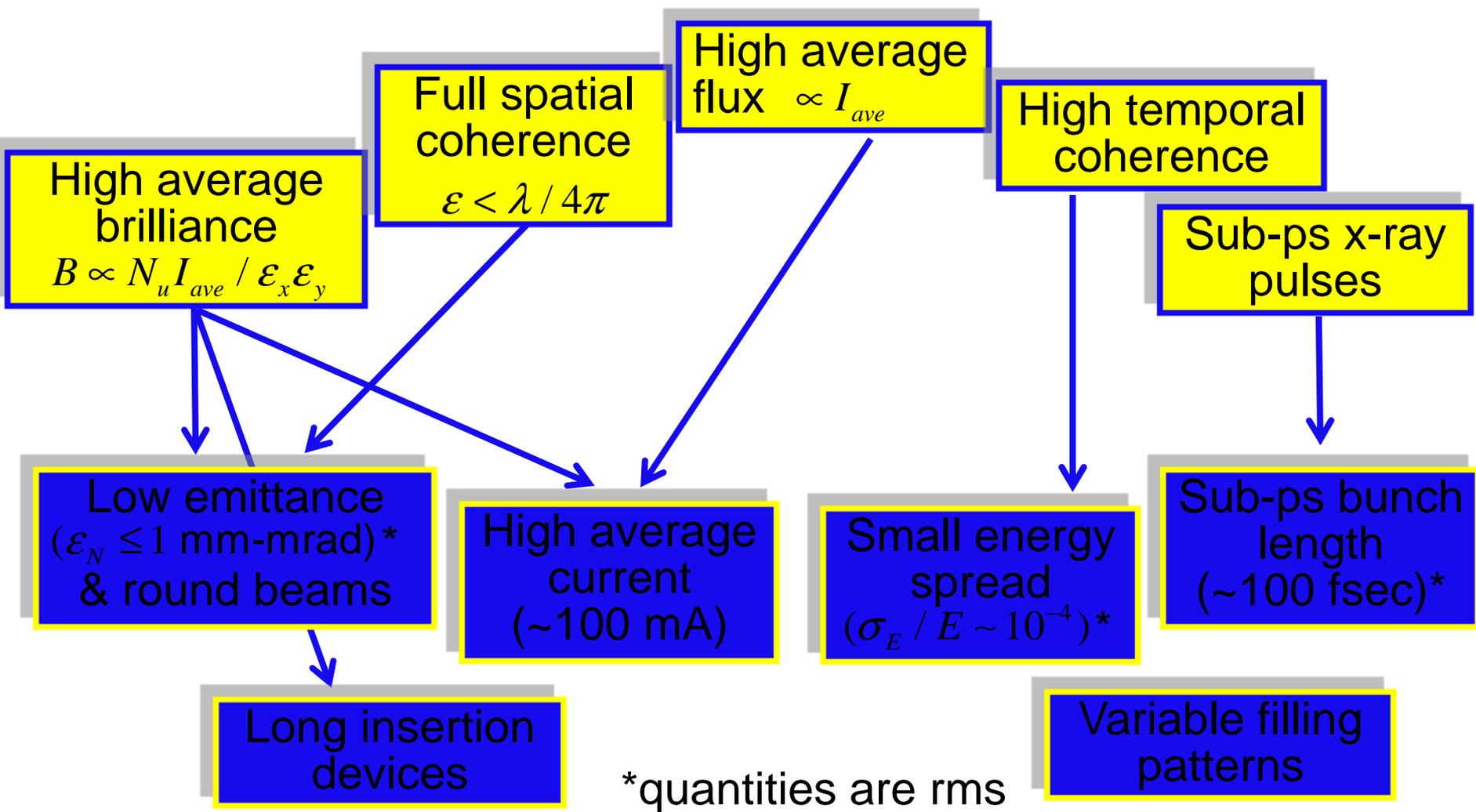
Accelerator Physics & Technology Issues of ERLs

- **Accelerator Transport**
  - **Longitudinal Matching**
  - **Transverse Matching**
  - **Beam Loss**
- **CSR**
- **RF Control in ERLs (High Q_l)**
- **Collective Effects**
  - **Single-bunch Effects**
  - **Multipass, Multibunch Beam Breakup (BB.U) Instabilities**
- **HOM Power Dissipation**
- **Beam Loss**
- **Photocathode Longevity**
- **High Q_0**

Three Main Challenges

- Generation and preservation of low emittance, high average current beams

- Accelerator transport

- High current effects in superconducting rf

Challenge I: Generation and Preservation of Low Emittance, High Average Current Beams

In an ERL, highest quality beam must be produced at the source, and preserved in the low- energy regime

Ia. High accelerating gradients or high repetition rate? Or both?

Ib. Getting beyond the space charge limit

DC Photoinjectors under construction/testing

- **Cornell:**
  500 – 750 kV, 1.3 GHz, 100 mA

- **JLab/AES:**
  500 kV, 750 MHz, 100 mA

- **Daresbury ERLP:**
  Duplicate of JLab FEL gun, 6.5 mA

- **JAEA:**
  250 kV, 50 mA gun, superlattice photocathode

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RF photoinjectors

- To date RF guns have produced best normalized emittances:

 $\epsilon_{N,rms} \sim 1\ \mu m$ at $q \sim 0.1 - 1$ nC , but at relatively low rep rate (10-100 Hz)

- Challenge: Balance high gradient (low emittance) with high rep rate (thermal effects)

State-of-the-art: Boeing gun

- Repetition rate 433 MHz at 25% DF

- Average current 32 mA

Planned RF Photoinjectors

- **LANL/AES:** 700 MHz,100 mA

Vacuum Pumps
Vacuum Chamber with Pumps
Bucking Solenoid Magnet
Cathode Backplate Cooling
Focusing Solenoid Magnet
Ridge Loaded Waveguide

Normal Conducting Injector (LANL & AES)
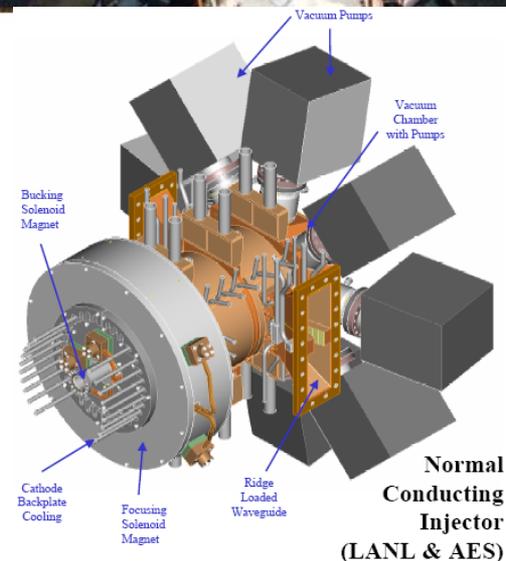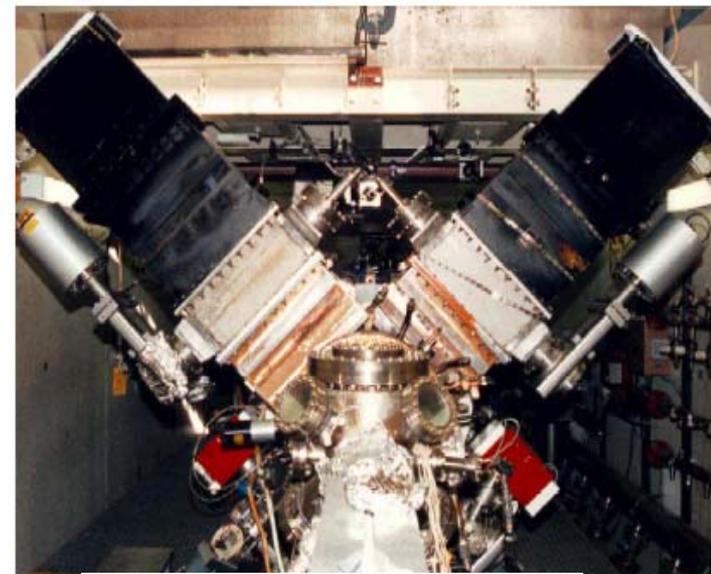
SRF photoinjectors

- High CW RF fields possible

- Significant R&D required

- Two major developments in progress:

  - Rossendorf 3 ½-cell Nb cavity

  - BNL/AES ½-cell Nb cavity with diamond amplified photocathode

The Rossendorf SRF gun
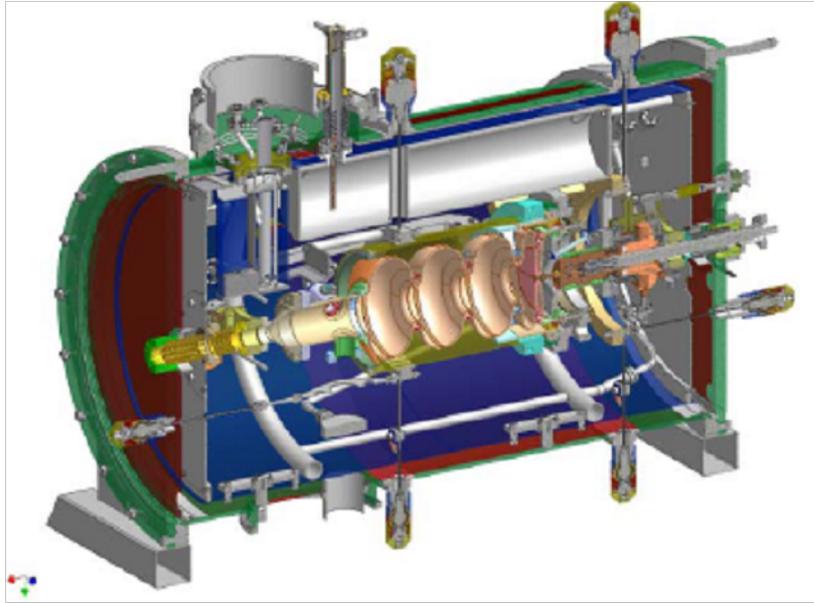
1.3 GHz, 9.5 MeV, CW operation
3 modes of operation:
- 77 pC at 13 MHz
- 1 nC up to 1 MHz (1 mA)
- 2.5nC at 1 kHz

	ELBE mode	high charge mode	BESSY-FEL
RF frequency		1.3 GHz	
beam energy		9.5 MeV	
operation		CW	
drive laser		262 nm	
photocathode		Cs_2Te	
quantum efficiency		]1 %	]2.5 %
average current		1 mA	2.5 μA
pulse length	5 ps	20 ps	50 ps
repetition rate	13 MHz	[1MHz	1 kHz
bunch charge	77 pC	1 nC	2.5 nC
transverse emittance	1.5 μm	2.5 μm	3.0 μm

BNL/AES Ampere-class SRF gun

Diamond amplified photocathode
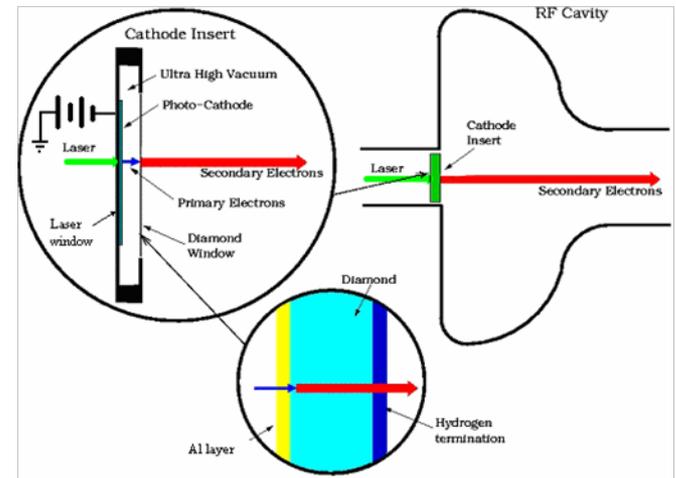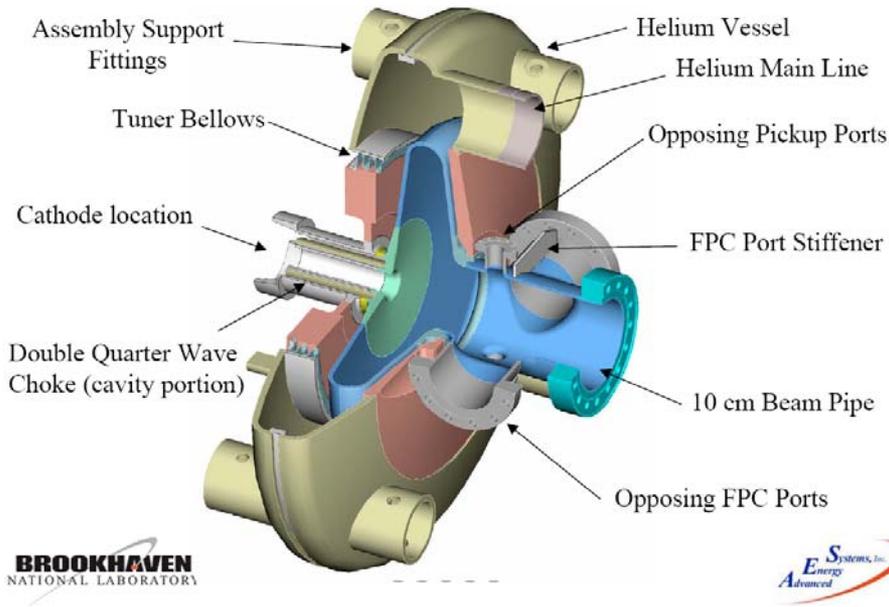
703.75 MHz, 2.5 MeV, 500 mA, CW operation
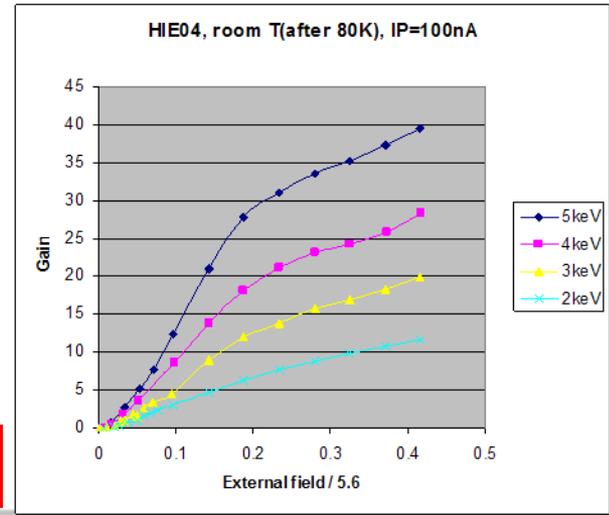
Courtesy: I. Ben-Zvi

Challenge II: Accelerator Transport

6-D emittance preservation and phase space management during acceleration and energy recovery

IIa. Wakefield effects (resistive wall)
**IIb. Halo and beam loss**
IIc. Beam stability and diagnostics

Power Loss due to Resistive Wall

Wiggler chamber heating

- Observed drift in optical diagnostics traced to beam-induced heating of wiggler chamber.

- Temperature rise depends both on current and bunch length; 3.5 mA CW beam, 150 fs rms bunch length generated ~ 200 W deposited on wiggler vacuum chamber.

- Observations consistent with resistive wall wakefield effects.

- The combination of short bunch length and high average intensity beams present new challenges in future ERLs.

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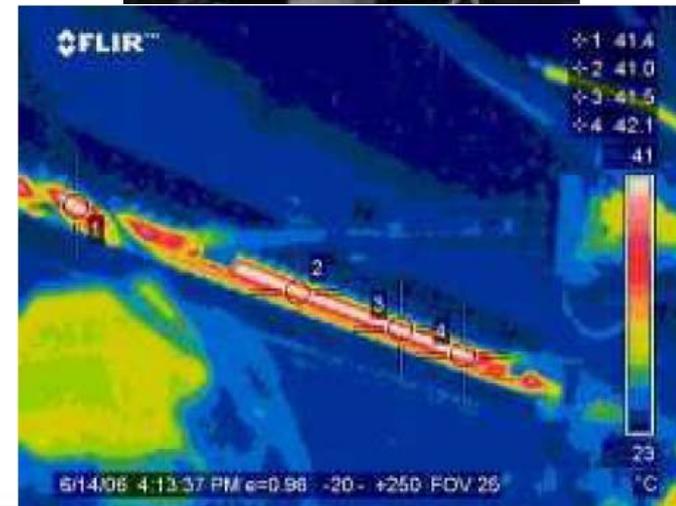
Halo and Beam Loss

Beam loss an issue due to:
- direct damage to equipment
- unacceptable increase in vacuum pressure
- cryogenic load in the linac
- radiation damage to equipment

Beam loss may result from:
- Scraping of beam halo due to space charge, drive laser scattered light, field emission
- Optical mismatch in beam transport

Beam losses in the JLab FEL during ~10 mA operation:
- <1 µA loss set by Beam Loss Monitoring system
- Actual losses <100 nA in worst locations, ~10 nA in most locations
- 10-20 nA at the wiggler

Presently managed by beam optical methods resulting in improvements by more than an order of magnitude.

In future 100 mA ERLs beam loss must be controlled to better than 1 PPM
-> Mitigation likely to also include collimation
-> Need for improved machine protection systems

Beam Stability and Diagnostics

- Bunch-to-bunch variations in charge, position, angle will likely have to be controlled

- Measurements at CEBAF:
  Orbit stability ~2-4 µm (with implementation of feedback)
  Energy stability ~1×10^{-4} (with implementation of feedback)
  Energy spread stability ~2×10^{-5} (continuously monitored in CW mode during machine operations)

- Unique to ERLs is the need to diagnose and control short bunches, the need to deal with tune up modes, and the high average beam power.

- Diagnostics development in the areas of:
  - Real-time, non-invasive techniques that will allow continuous monitoring of transverse and longitudinal beam properties
  - Synchronization systems
  - Improved machine protection systems

- Much interesting work is needed on this topic.

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Challenge III: High Current Effects in Superconducting RF

Beam stability and beam quality preservation, and cryogenic efficiency during acceleration/deceleration of high average current, short bunch length beams in SRF environment

IIIa. Efficient extraction of HOM power

IIIb. Stability against multipass beam breakup

IIIc. RF control and stability under max practical Q_L

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HOM Power Dissipation

- High average current, short bunch length beams in SRF cavities excite HOMs. On average, HOM power loss per cavity is:

$$P_{HOM} = 2\, k_{||}\, Q_{bunch}\, I_{ave}$$

and extends over high frequencies (~100 GHz).

The challenge:

- Adequate damping of HOMs and extraction of HOM power with good cryogenic efficiency.

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# Frequency Distribution of HOM Power

Monopole Mode Single Bunch Power Excitation per 9-Cell Cavity

σ_{bunch} = 0.7 mm, q_{bunch} = 77 pC
P_{total} = 185 W

~80 W at f_{HOM} < 5 GHz

~105 W at f_{HOM} > 5 GHz

HOM power (W)

HOM Frequency [GHz]
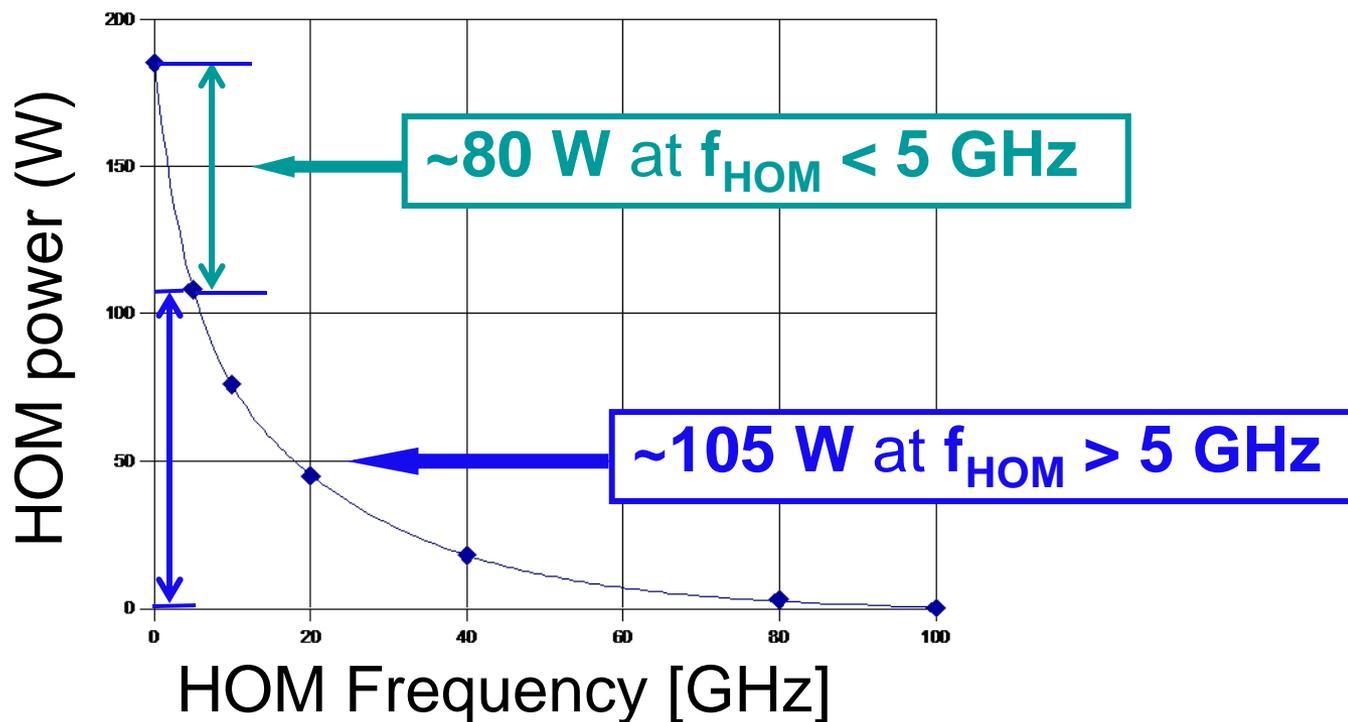
HOM damping scheme for the Cornell ERL

80 K   2 K   80 K

ferrite ring absorber

2 HOM loop couplers

4 HOM loop couplers

ferrite ring absorber

f_{HOM} < 5 GHz
Absorbed at room temperature loads

f_{HOM} > 5 GHz
Propagate along structure, get absorbed by ferrite rings at 80 K

Courtesy: M. Liepe

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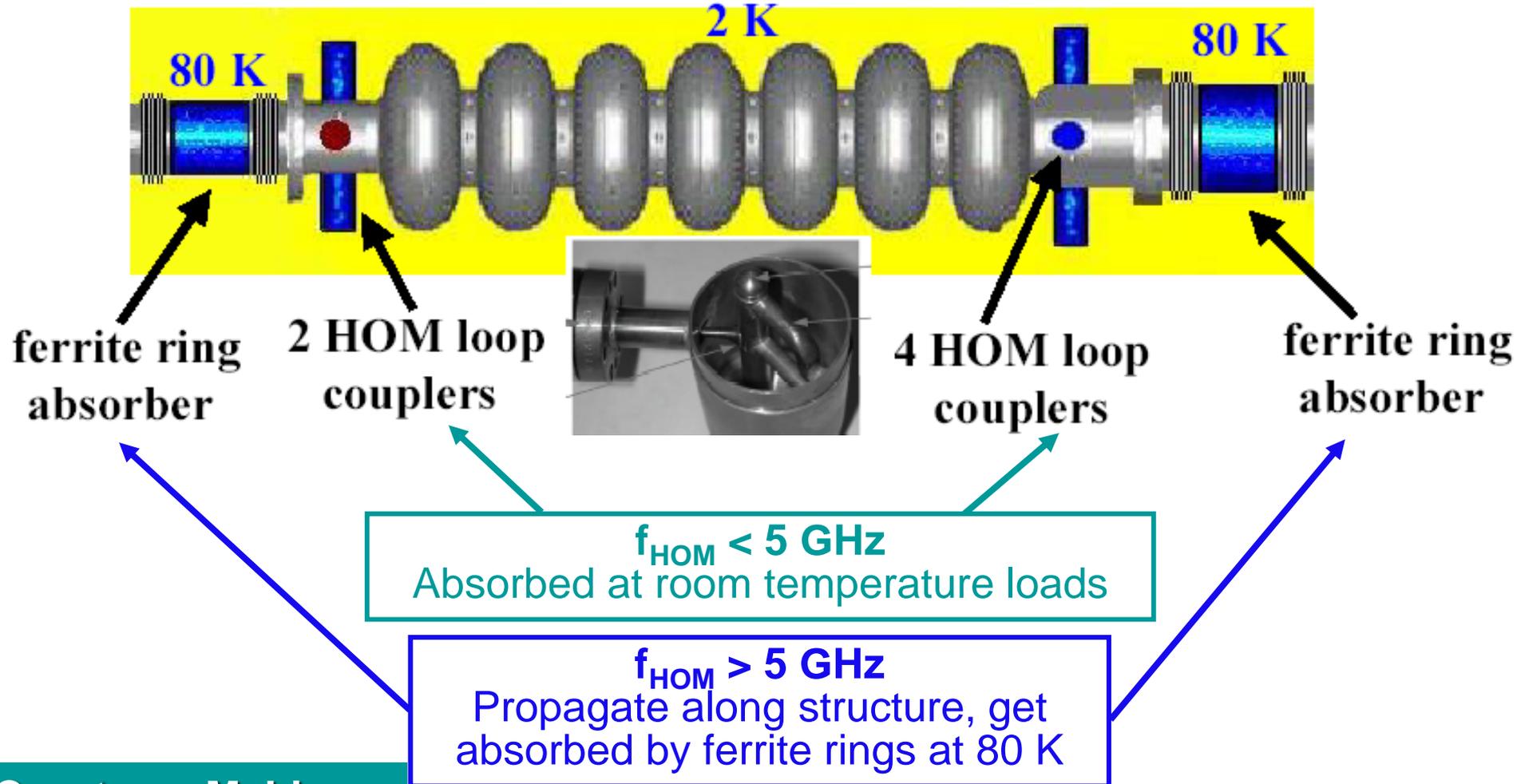
Multipass Beam Breakup

- In recirculating linacs, multipass beam breakup (BBU), driven predominantly by high-Q superconducting cavities, can potentially limit the average current.

- The "feedback" system formed between beam and cavities is closed and instability can result at sufficiently high currents.

- Energy recovering linacs can support enough beam current to reach the threshold of the instability.

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Multipass Beam Breakup

SUPERCONDUCTING CAVITY

HOMs

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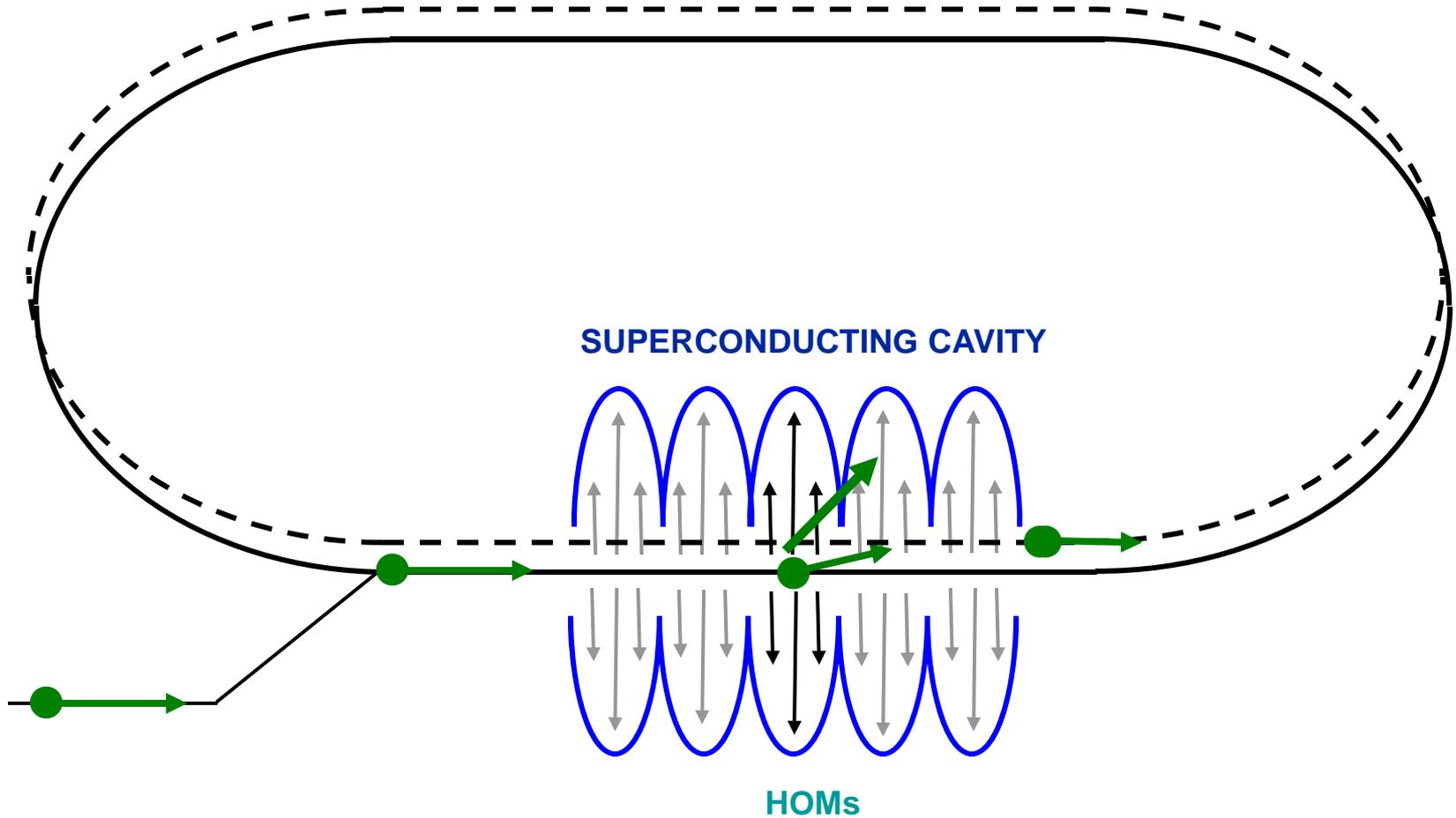
Instability Threshold

- **There is a well-defined threshold current that occurs when the power fed into the mode equals the mode power dissipation**

- **An analytic expression that applies to all instabilities:**

$$I_{th}^{(1)} = \frac{-2 p_r c}{e(R/Q)_m Q_m k_m M_{ij} \sin(\omega_m t_r + l\pi/2) e^{\omega_m t_r / 2 Q_m}}$$

- **For i,j = 1,2 or 3,4 and m HOM   Transverse BBU**
- **For i,j = 5,6 and m || HOM   Longitudinal BBU**
- **For i,j = 5,6 and m Fundamental mode   Beam-Loading Instabilities**
- **$l=1$ for longitudinal HOMs and l=0 otherwise**

Suppressing Beam Breakup

Three methods:

1. Q-damping
    Active Damping led to $5 \times I_{th}$
    3-stub tuner led to $1.5 \times I_{th}$
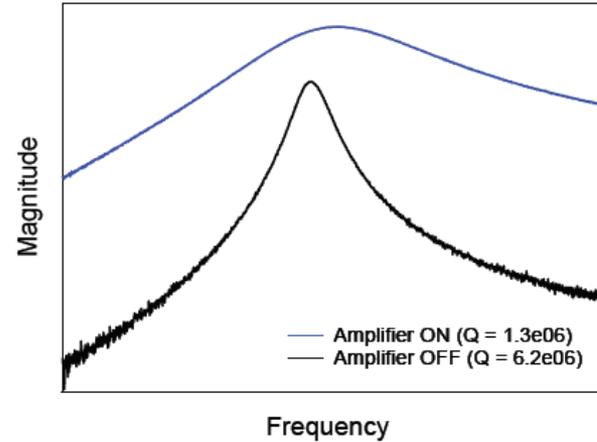
2. Beam optical schemes
    "Phase trombone" *stabilized*
    "Reflecting" or "Rotating" optics* led to $5 \times I_{th}$

2106 MHz in Cavity 7

$Q_L = 5.9e{+}06$
$I_{th} = 9$ mA
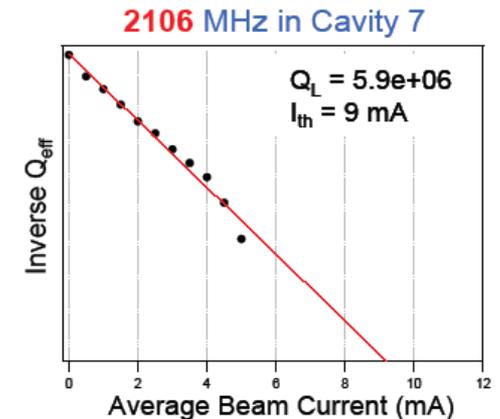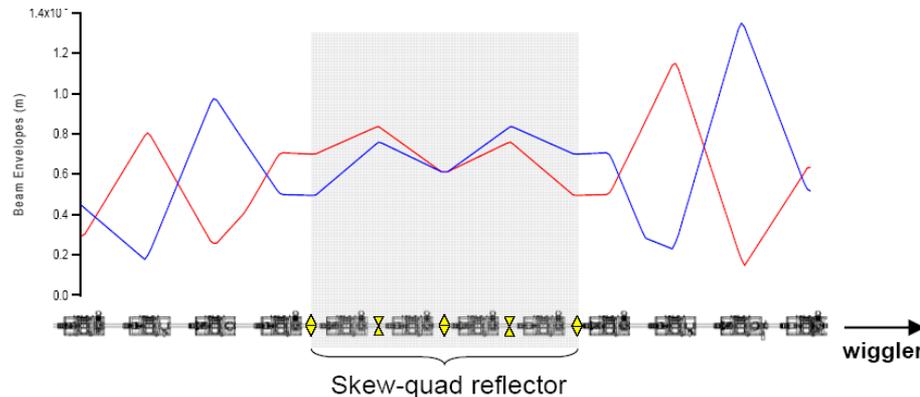
3. Beam-based feedback

*R. Rand and T. Smith, Particle Accelerators 1980

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Lower Frequency SRF Development

contour of electric field amplitude
File : FEMOUT.27467, Mode : 5, f= 703.4772 MHz
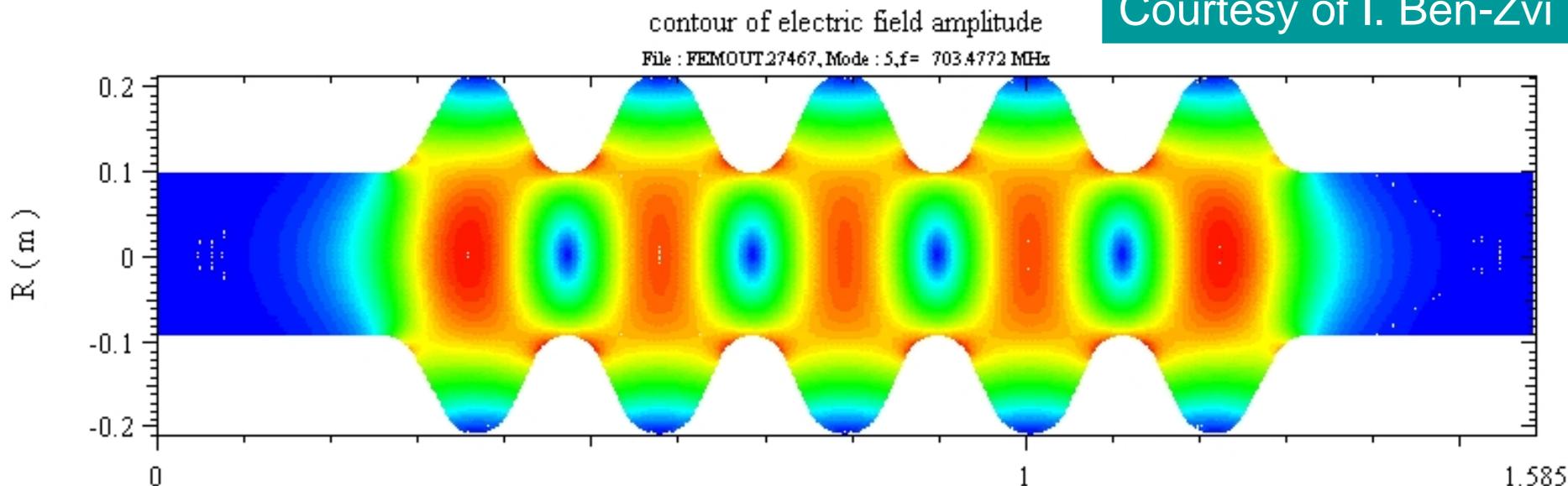
Develop CW SRF cavity for high intensity beams:
Large bore, 700 MHz cavity with ferrite HOM
dampers and high beam break-up threshold
BNL-JLAB collaboration

Predicted BBU threshold current > 1 Amp

Jefferson Lab

BNL Ampere-class cavity

SRF ERL cavity for ampere-class current.

"Single mode":
All HOMs damped.

Multi ampere rating.
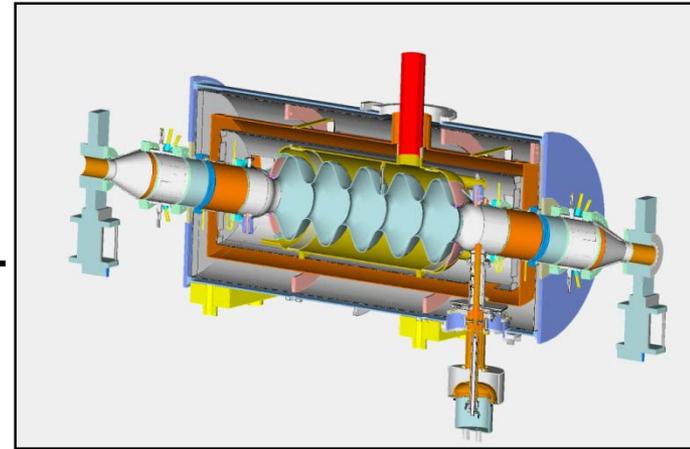
TDBBU
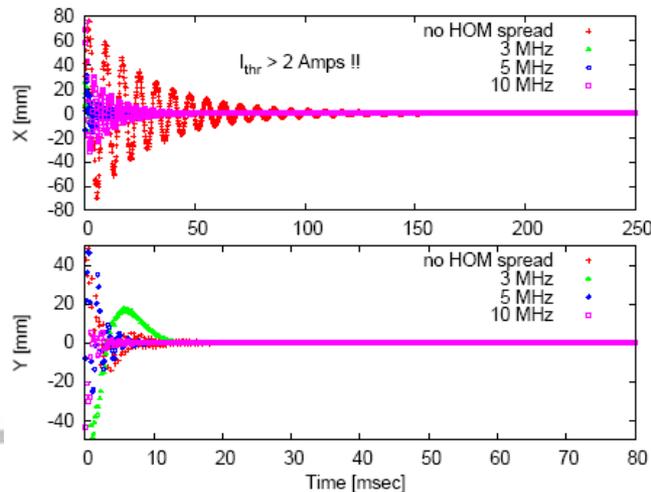
Courtesy of I. Ben-Zvi

JLab Ampere-class Cavity

Cavity test result
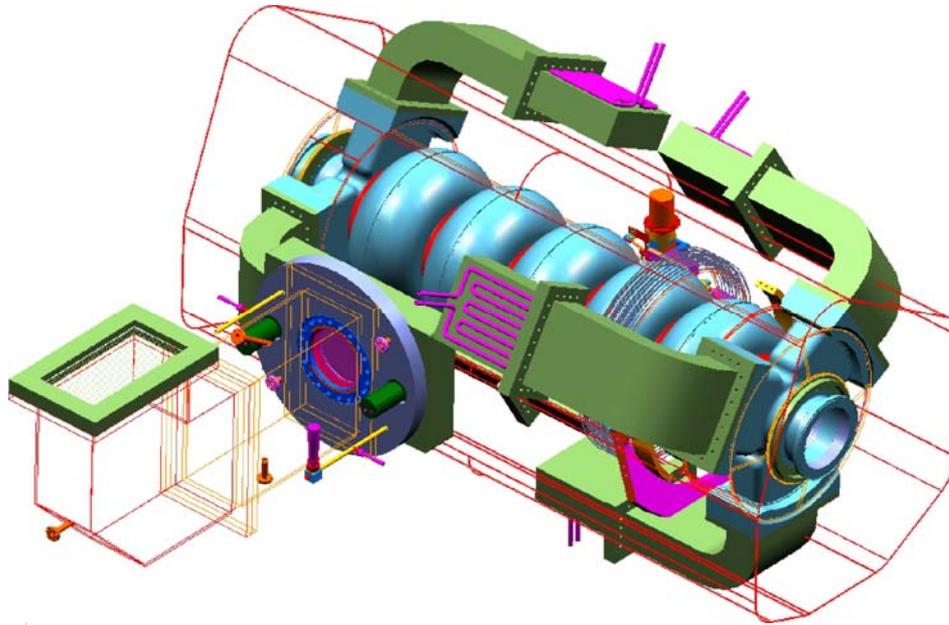
Cryomodule concept
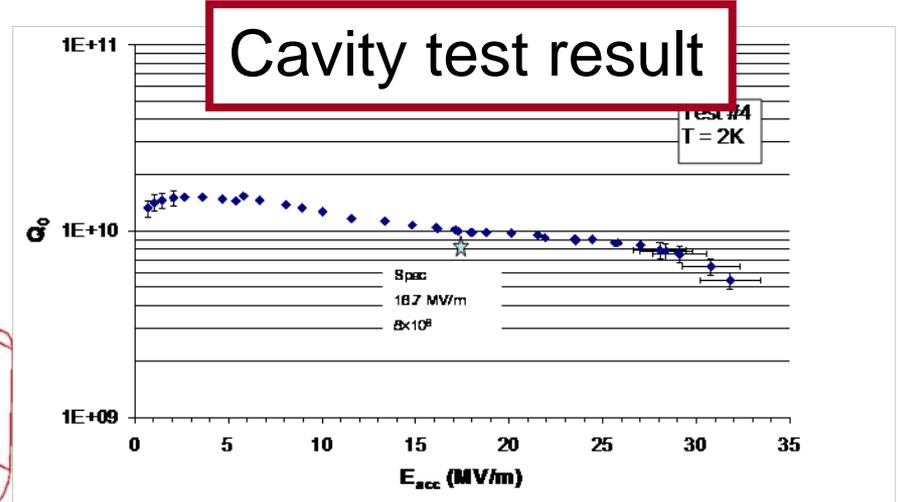
1500 MHz Cu prototype

Courtesy of R. Rimmer

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RF Control in ERLs

- **Accelerating and decelerating beam phases may not differ by precisely 180°**

  - **Typical expected path length control adjustment leads to ~ 0.5^o deviation from 180°**

FEL on   **FEL off**
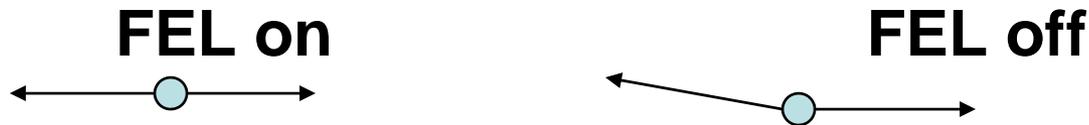
- **Beam loss may occur, resulting in beam vectors of unequal magnitude**

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

- **Increase of rf power requirements and reduction of efficiency**