Physics Challenges for ERL Light Sources

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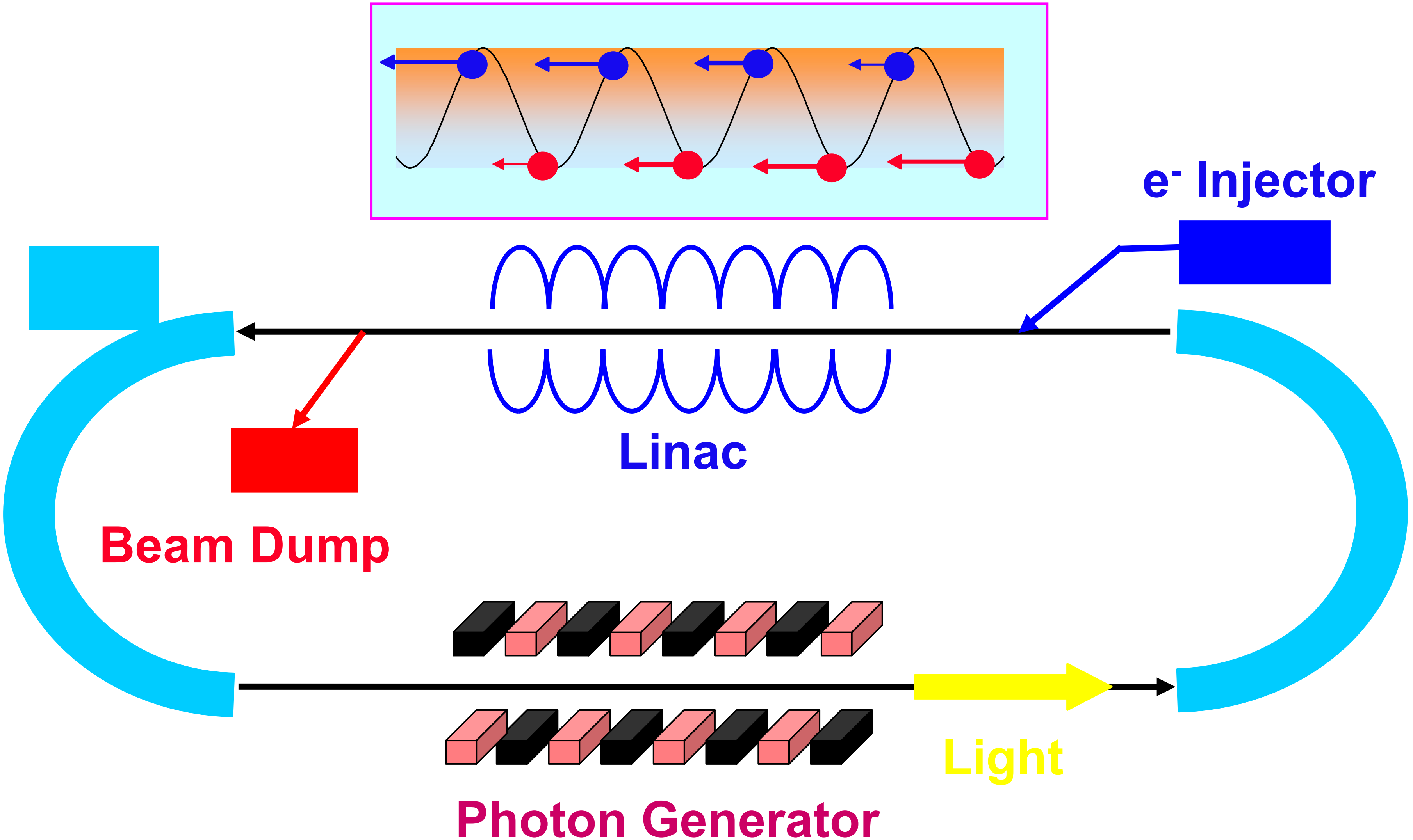
Outline

- ERL Light Source
- Promise of ERL Light Sources
  - Free Electron Laser ERLs
  - Synchrotron Light Source ERLs
- Realization of the promise
  - Challenge I: Generation and preservation of low emittance, high average current beam
  - Challenge II: Accelerator transport
  - Challenge III: High current effects in Superconducting RF
- A bright future: ERL LS projects and proposals worldwide
- Summary

Energy Recovery Linac Light Source



ERL vs. Storage Ring vs. Linac

- While an electron storage ring stores the same electrons for hours in an equilibrium state, an ERL stores the energy of the electrons.
- In an ERL electrons spend little time in the accelerator (~1 μs), therefore they never reach an equilibrium state.
- In common with linacs: In an ERL the 6-D beam phase space is largely determined by electron source properties by design.
- In common with storage rings: An ERL possesses high average current-carrying capability enabled by the ER process, thus promising high efficiencies.

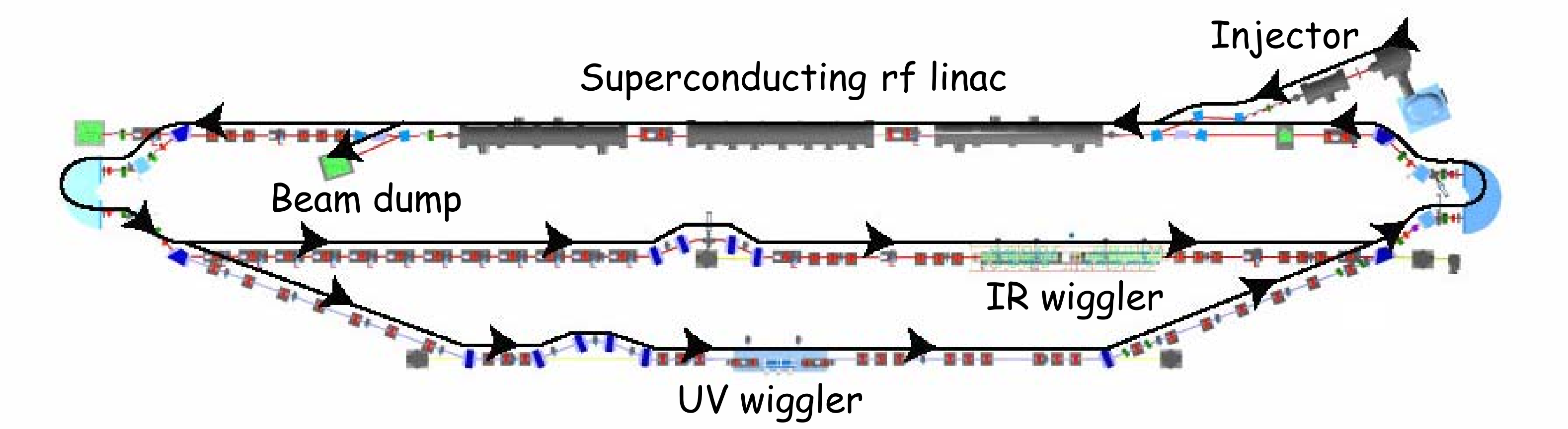
Reality and Promise of FEL ERLs

The promise:

High average laser power (~ 100 kW)
High overall system efficiency
Reduced beam dump activation

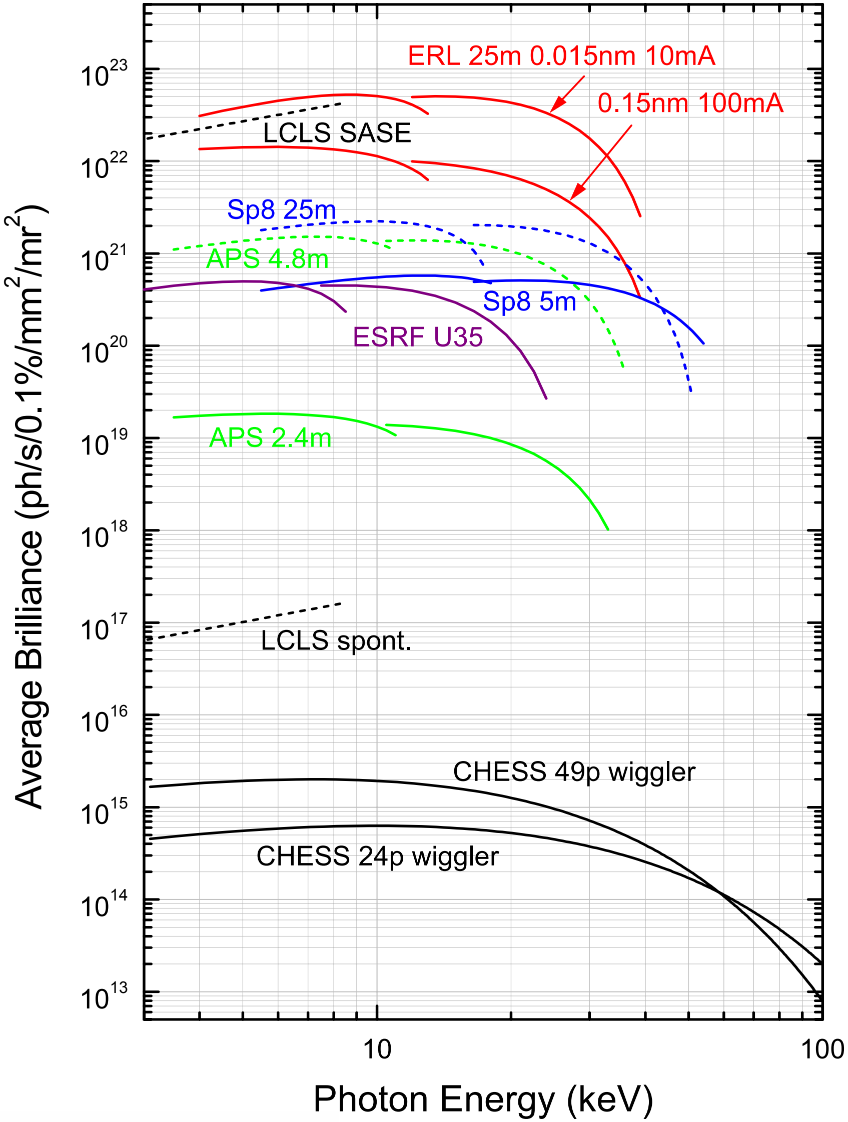
The reality:

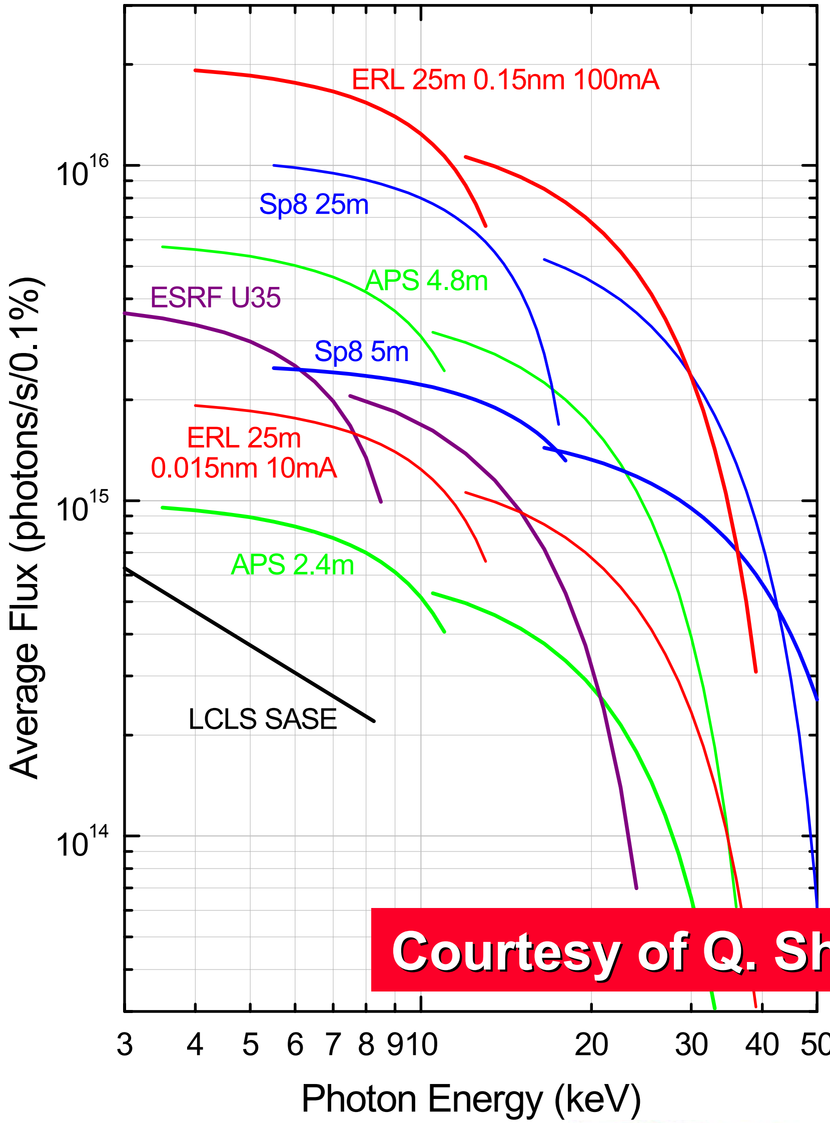
JLab 10kW IR FEL and 1 kW UV FEL



Achieved 8.5 kW CW IR power on June 24, 2004!
Energy recovered up to 5mA at 145 MeV, up to 9mA at 88 MeV

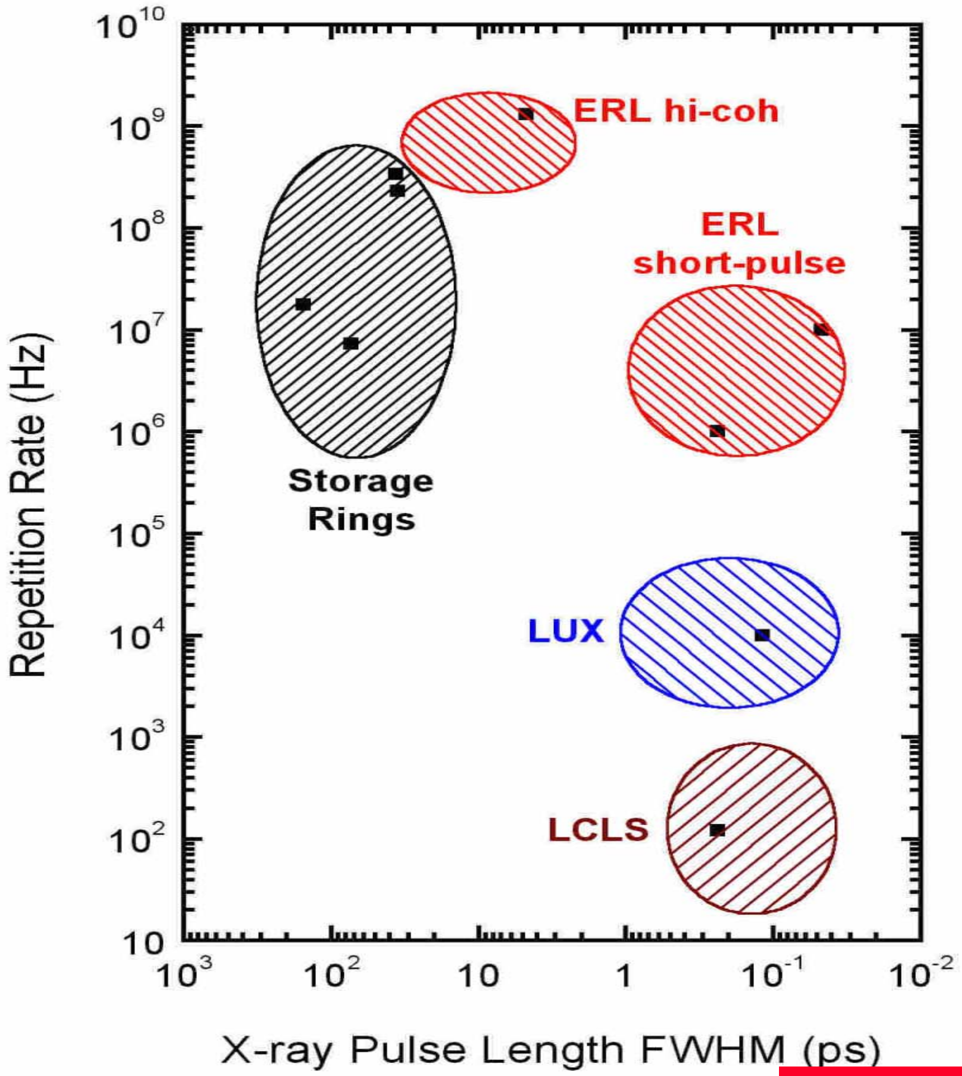
Promise of Synchrotron Light ERLs

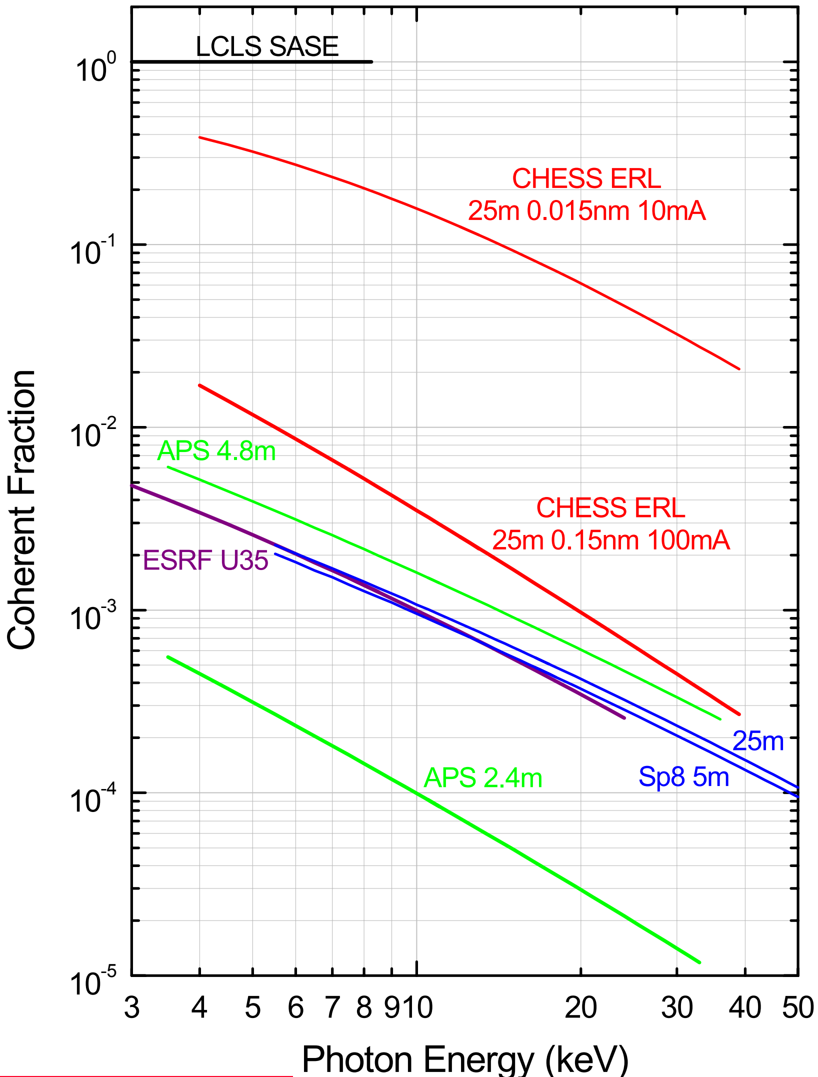




Courtesy of Q. Shen

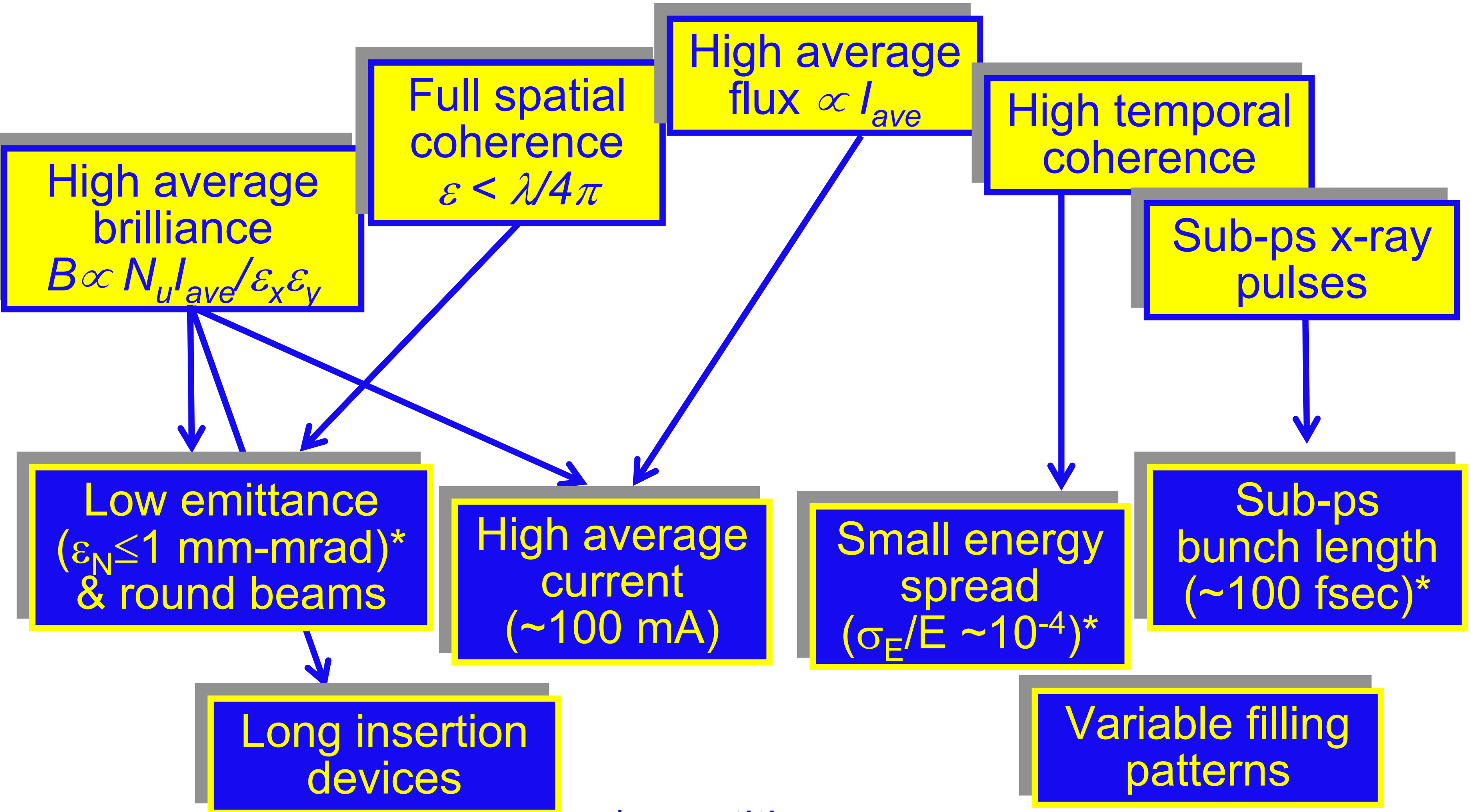
Promise of Synchrotron Light ERLs





Courtesy: Q. Shen

SL User Requirements and Beam Properties



*quantities are rms

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

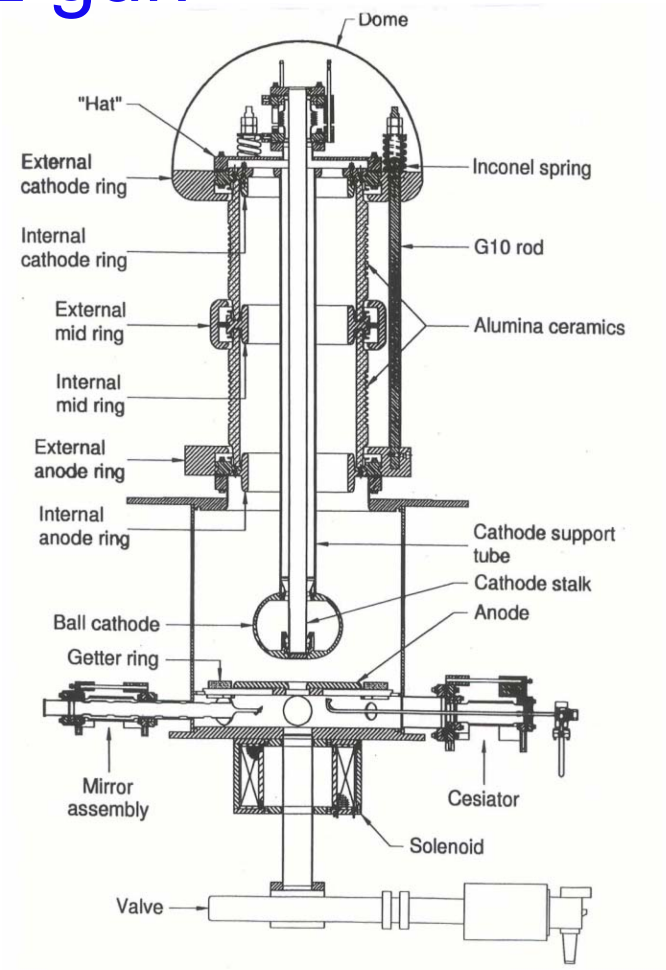
Ia. High accelerating gradients or high repetition rate? Or both?

Ib. Getting beyond the space charge limit

DC photoinjectors

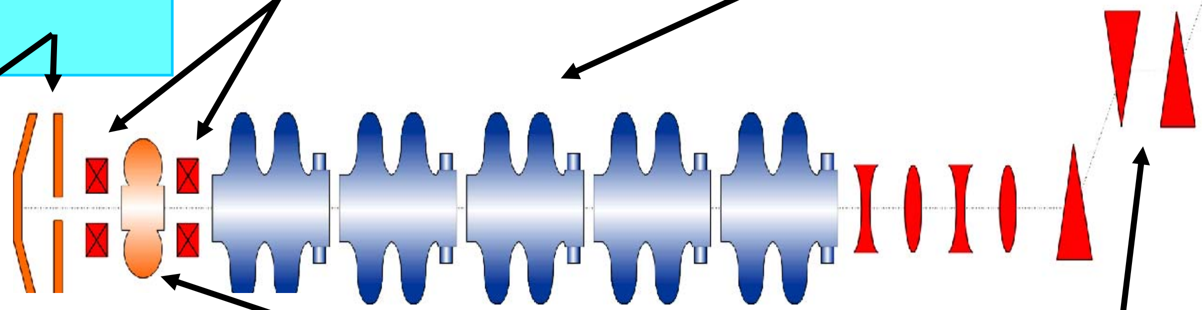
State-of-the-art: JLAB FEL gun

- High repetition rate up to 75 MHz
- $\varepsilon_{N,rms}$~7-15 mm-mrad for Q~ 60 –135 pC (measured at the wiggler)
- Average current up to 9 mA
- Cathode voltage: 350 – 500 kV

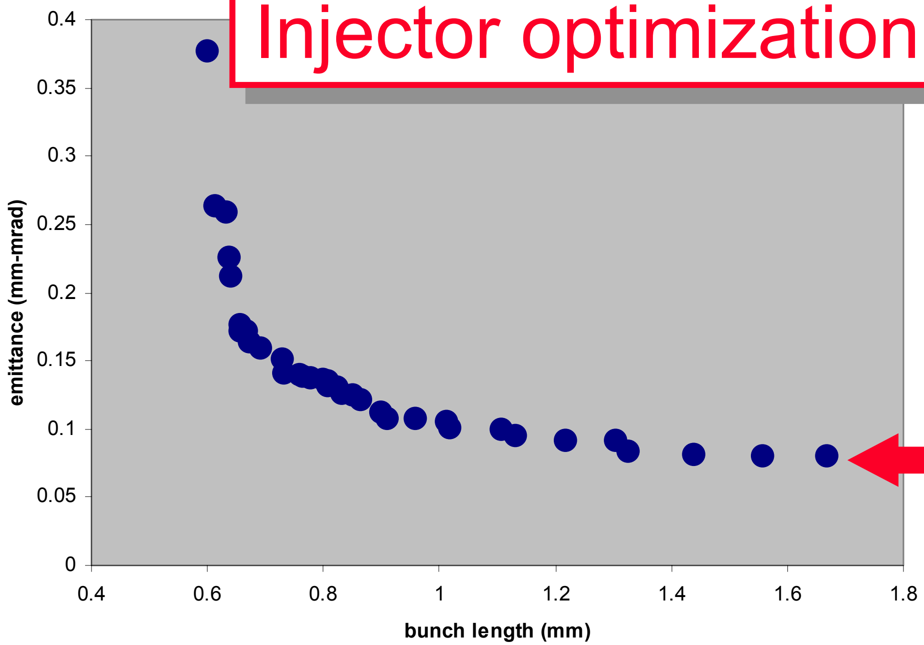


Beyond the space charge limit

Cornell ERL Prototype Injector Layout



Injector optimization



Courtesy of I. Bazarov

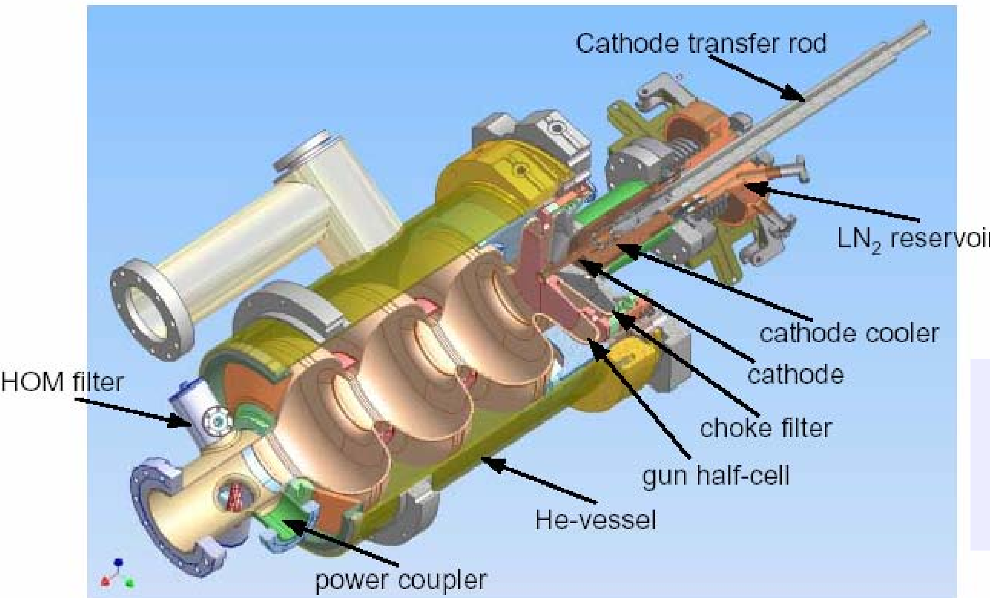
0.1 mm-mrad, 80 pC, 3ps

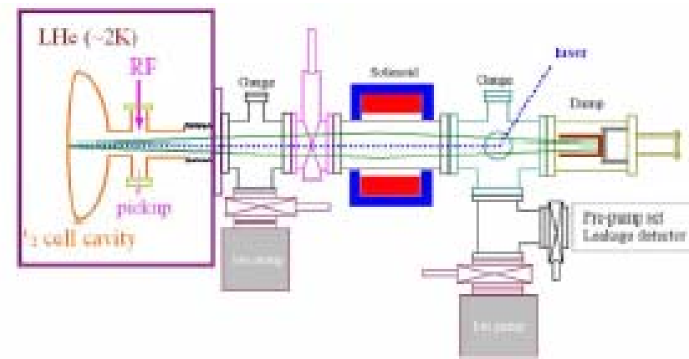
RF photoinjectors

- High accelerating gradients (~100 MV/m) to rapidly accelerate electrons beyond the space charge regime, thereby reducing emittance growth.
- To date RF guns have produced best normalized emittances:
  e_N~ 1 μm at Q~ 0.1 – 1 nC , but at relatively low rep rate (10-100 Hz)
- Boeing gun operated at 433 MHz with 25% duty factor
- Challenge: Balance high gradient (low emittance) with high rep rate (thermal effects)

SRF photoinjectors

- High CW RF fields possible
- Significant R&D required





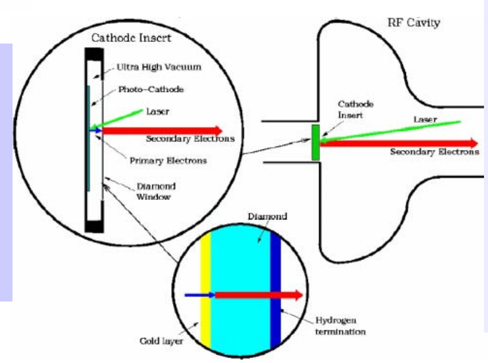
BNL/AES/JLAB development

High I_{ave} & brightness gun under test:
1.3 GHz ½-cell Nb cavity at 2K

Rossendorf proof of principle experiment:

1.3 GHz, 10 MeV

77 pC at 13 MHz and 1 nC at < 1 MHz



BNL development

SRF gun
with diamond
amplified cathode

Challenge II: Accelerator Transport

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

IIa. Longitudinal matching

IIb. Coherent Synchrotron Radiation

IIc. Transverse matching

Longitudinal Matching

Requirements:

- Synchrotron Light ERLs:

  Short X-ray pulses may require bunching during acceleration

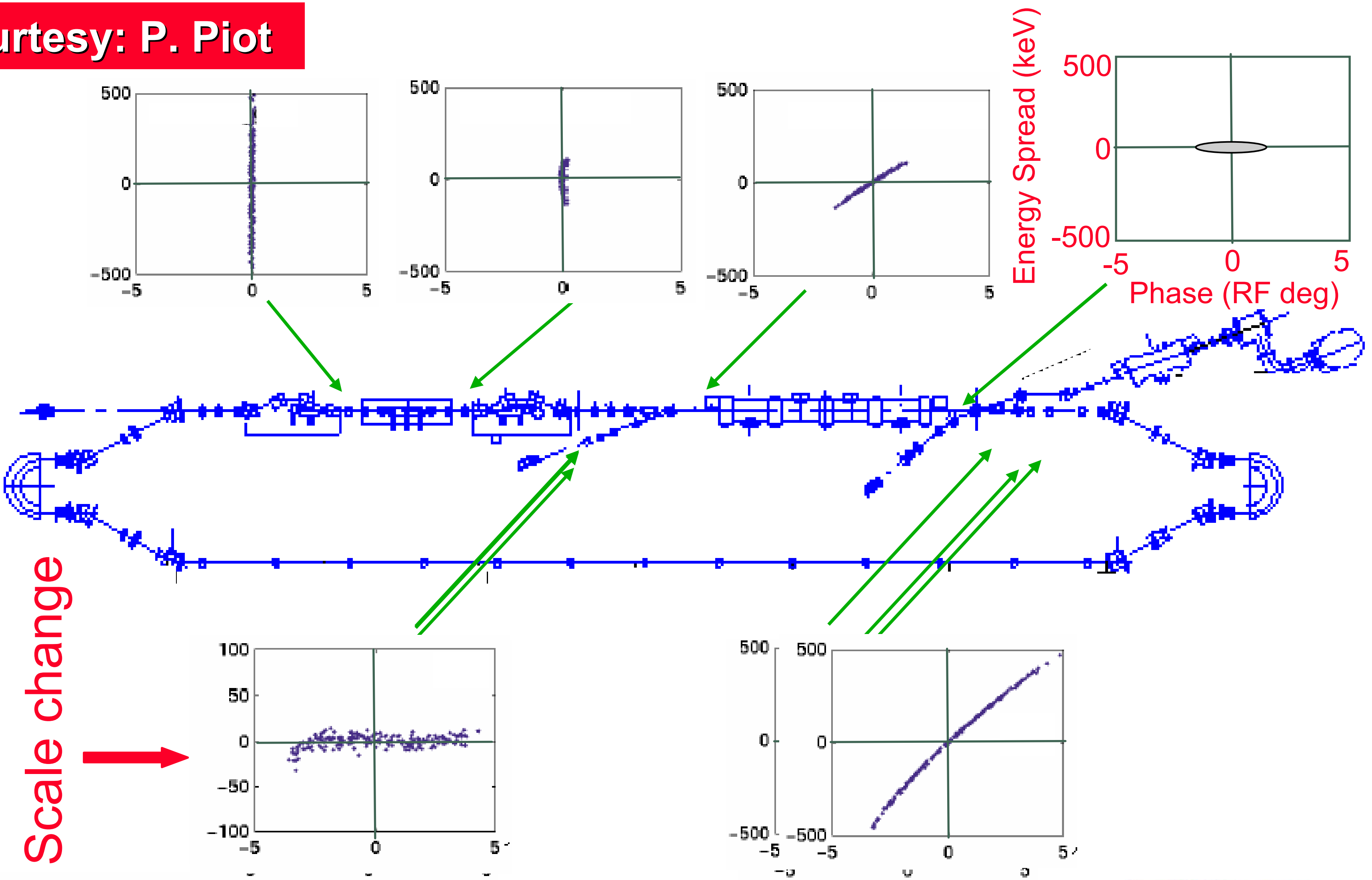
- FEL ERLs:
  - High peak current (short bunches) at the FEL
  - Large energy spread after lasing ($\delta E/E \sim 10\%$) must be decompressed
  - Small energy spread at the dump

The challenge:

Nonlinear distortions in phase space must be corrected for minimum bunch length and proper energy recovery

Longitudinal Dynamics in JLAB 2 kW FEL

Courtesy: P. Piot

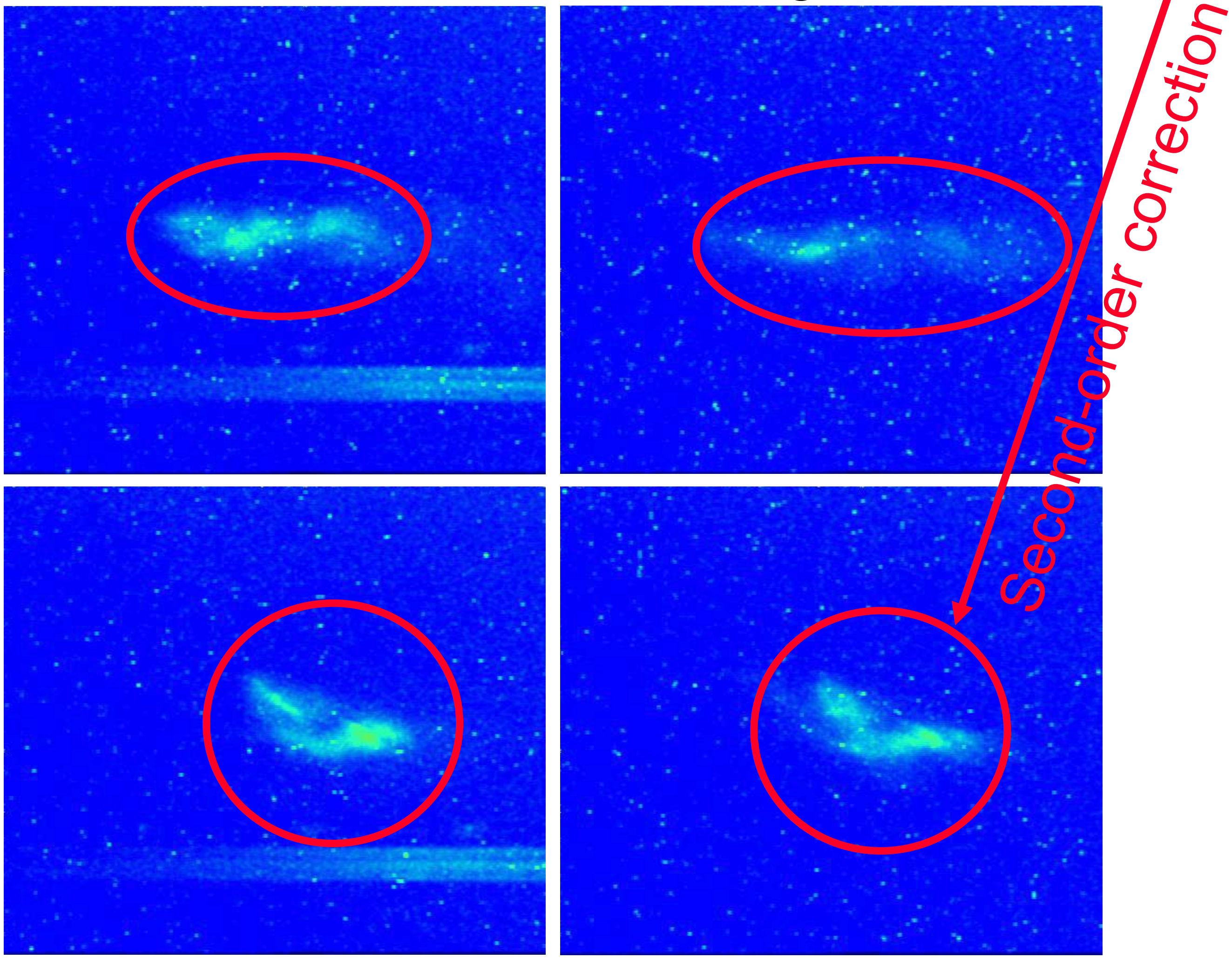


Why We Need the “Right” T_{566}

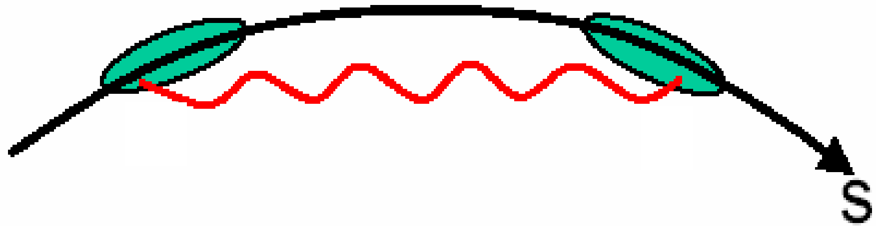
lasing off | lasing on

sextupoles off

sextupoles on



Coherent Synchrotron Radiation



Radiation wavelength longer than bunch length: coherent emission.

Radiation from the bunch tail catches up with the head can increase energy spread and emittance → potentially serious for high brightness beam quality preservation.

In SL ERLs bunch charge relatively small (~0.1 nC) and bunch length ~0.1-1 ps, however emittance preservation important. CSR needs to be studied.

Challenge: Minimize emittance growth due to CSR.

Optics schemes are being developed to minimize the effects.

Transverse Matching

Requirement:

- Synchrotron Light ERLs: High energy (GeV scale) demonstration of energy recovery. A significant extrapolation from FEL ERL paradigm (~ 100 MeV).

The challenge:

- Demonstrate sufficient operational control of <u>two coupled beams</u> of <u>substantially different energies</u> in a <u>common transport channel</u>, in the presence of steering, focusing errors.

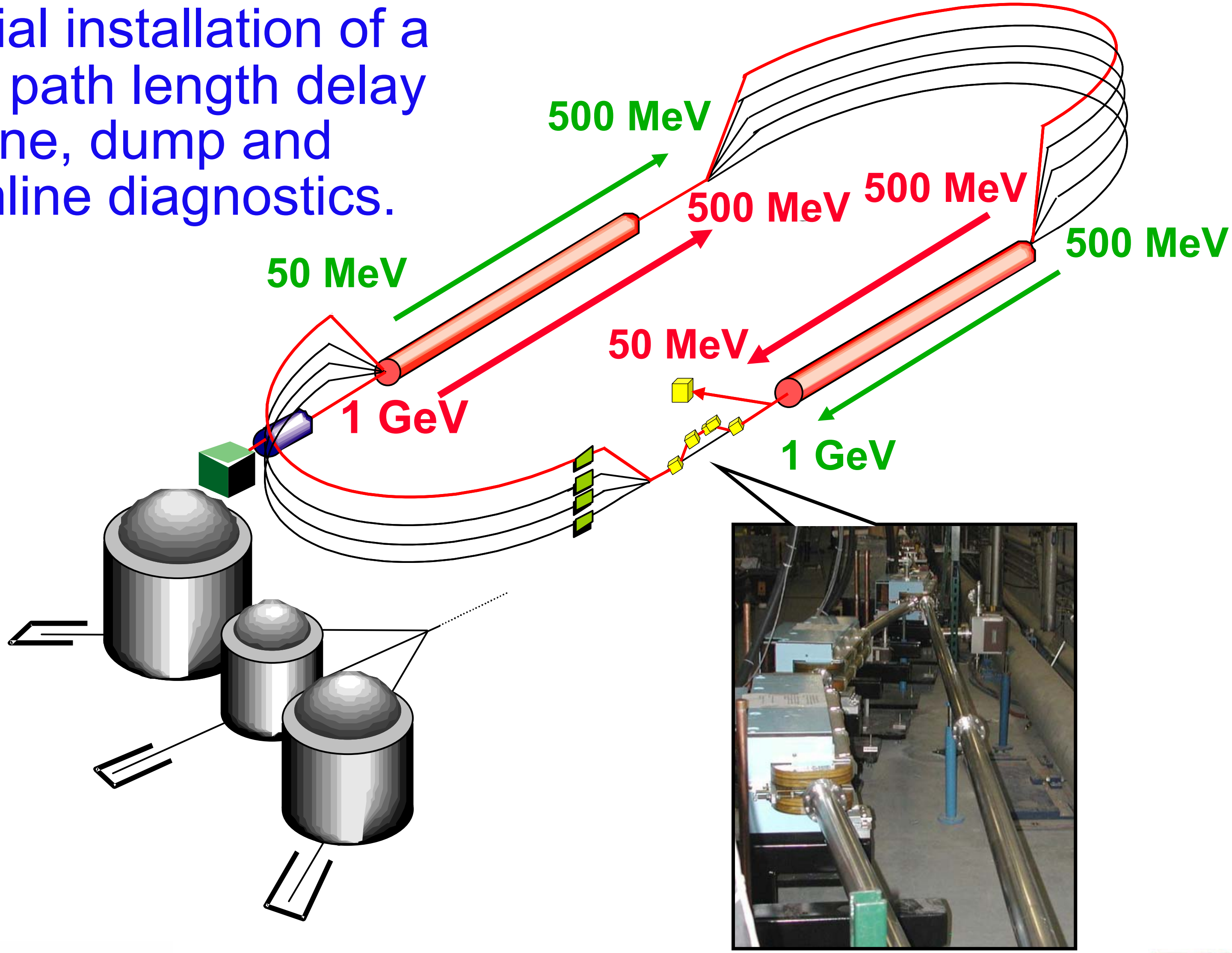
CEBAF-Energy Recovery Experiment

- **CEBAF-ER** is a 1 GeV demonstration of energy recovery in CEBAF – 40 cryomodules.
  - Quantify evolution of transverse phase space during acceleration and energy recovery.
  - Test the dynamic range of system: large ratio of final-to-injected (E_{fin}/E_{inj}) beam energies

Larger E_{fin}/E_{inj} ratio ⟶ higher ERL efficiency!

CEBAF-ER Experiment

Special installation of a $\lambda_{RF}/2$ path length delay chicane, dump and beamline diagnostics.



CEBAF-ER Preliminary Results

- Demonstrated a significant operational extension of energy recovery to high energy (1 GeV), through a large (~1 km circumference), superconducting RF system (40 cryomodules).
- Demonstrated feasibility of energy recovery with ratio of final-to-injected energy up to 50:1 (1GeV⇄20 MeV).
- No significant emittance dilution was measured as a result of the energy recovery process. No surprises were uncovered.

"The CEBAF ER Experiment" MOPKF087

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

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).

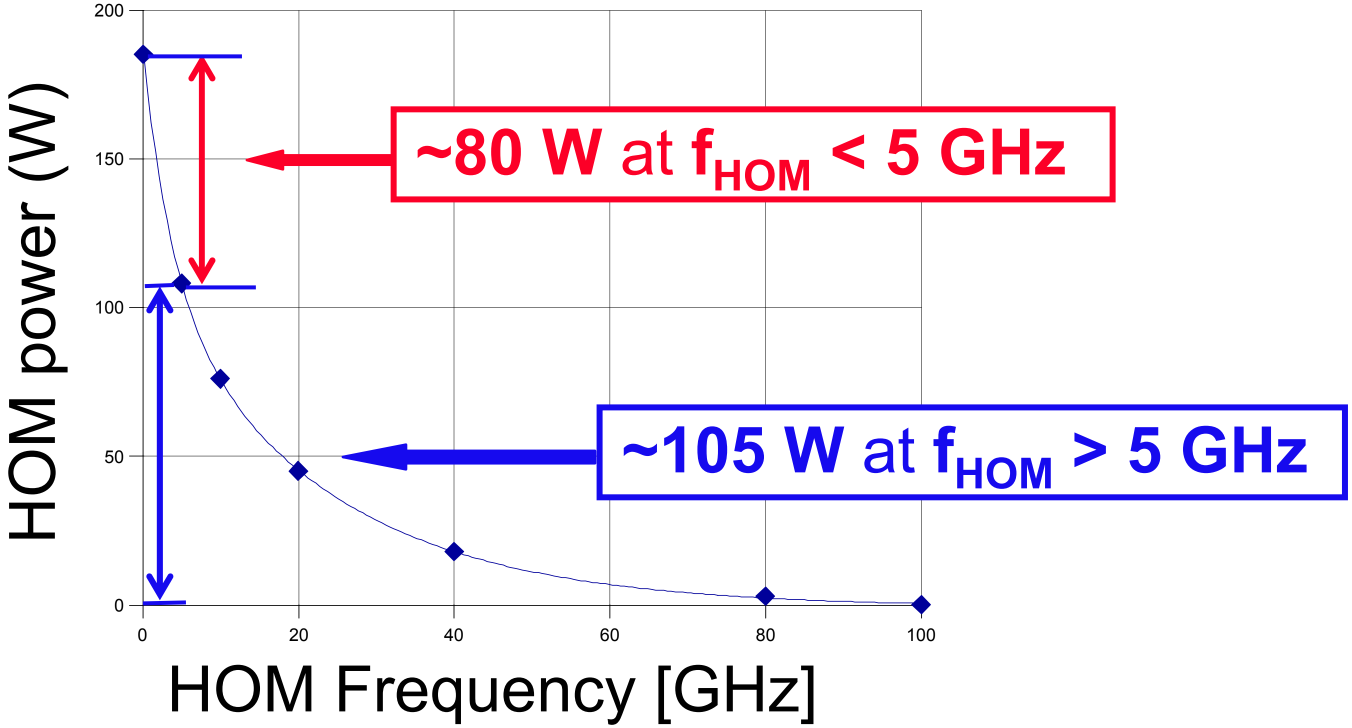
The challenge:

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

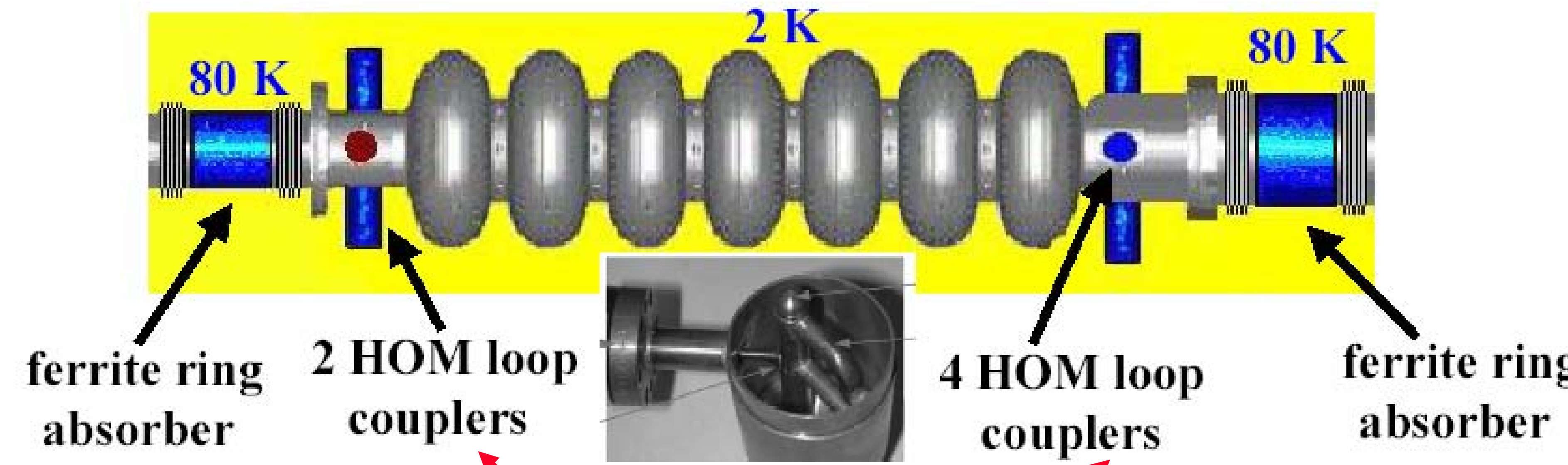
Frequency Distribution of HOM Power

Monopole Mode Single Bunch Power Excitation per 9-Cell Cavity

$\sigma_{bunch} = 0.7$ mm, $q_{bunch} = 77$ pC
$P_{total} = 185$ W



HOM damping scheme for the Cornell ERL



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

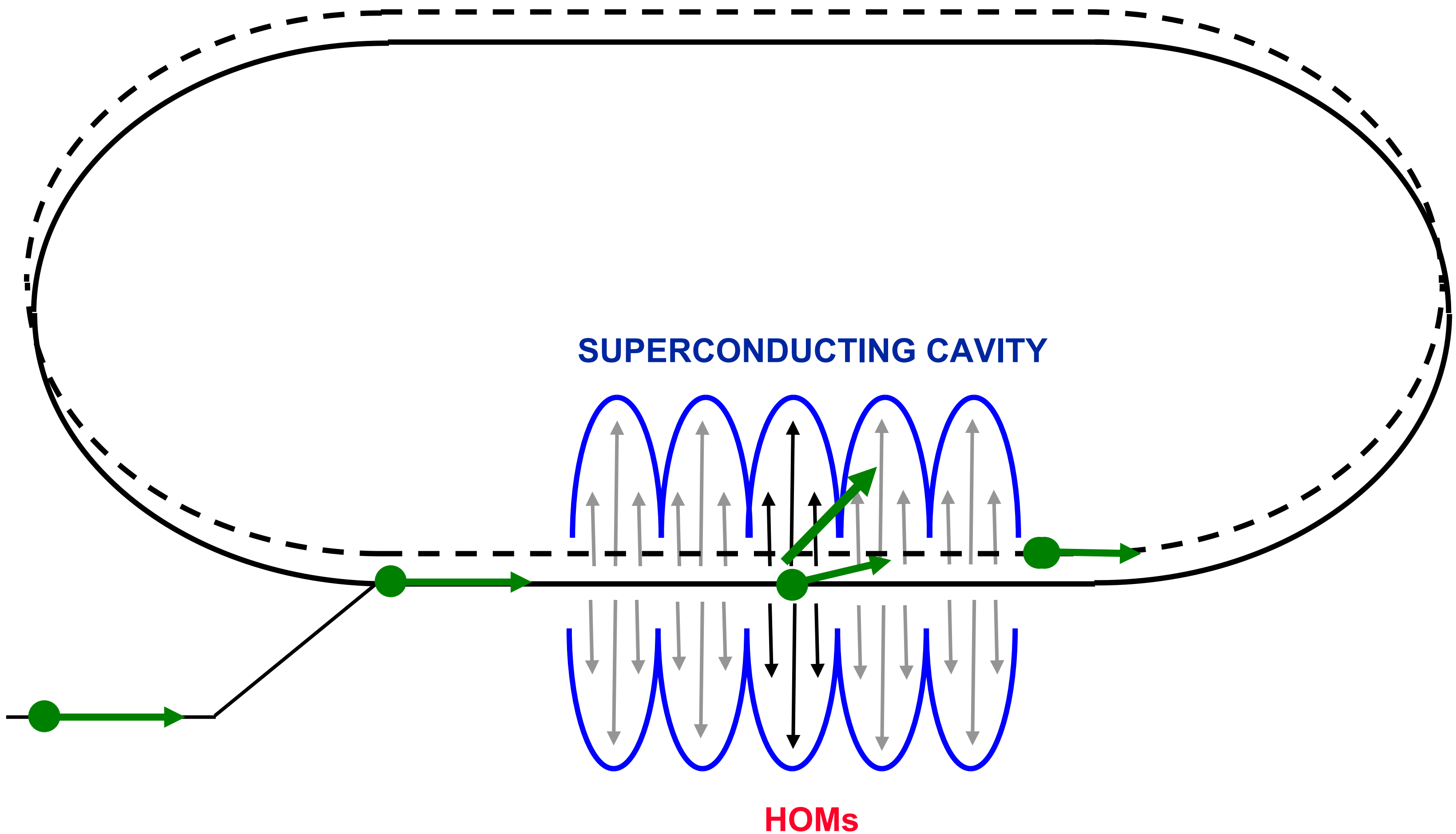
f_{HOM} > 5 GHz
Propagate along structure, get absorbed by ferrite rings at 80 K

Courtesy: M. Liepe

Multipass Beam Breakup

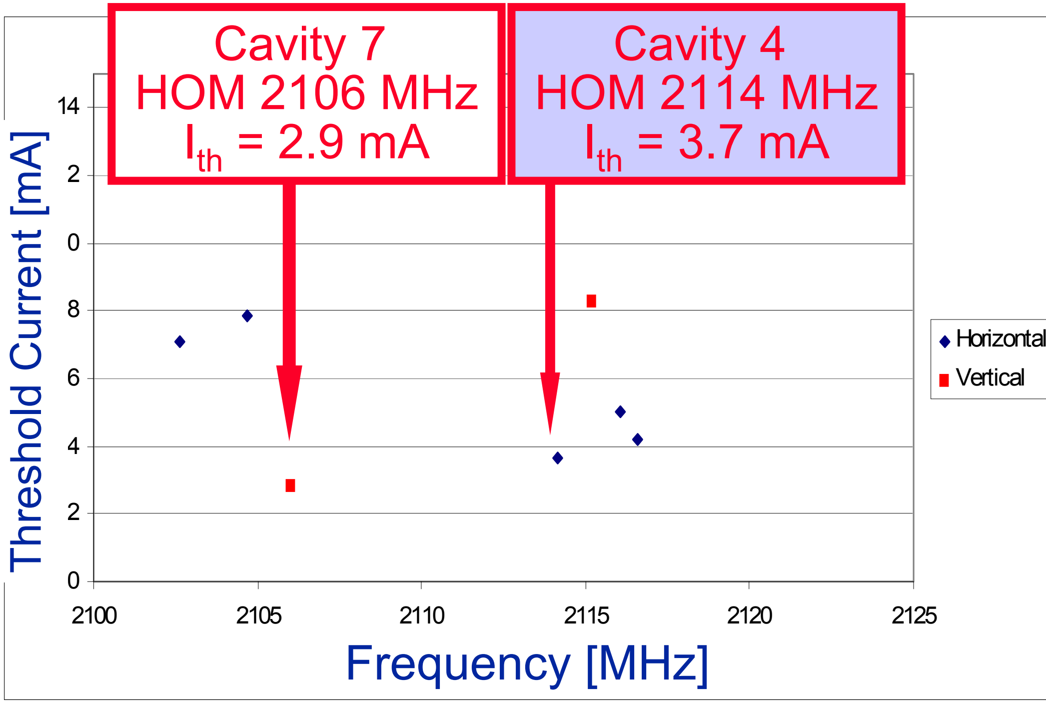
- In recirculating linacs, multipass beam breakup (BBU), driven predominantly by high-Q superconducting cavities, can potentially limit the average current.
- The “feedback” system formed between beam and cavities is closed and instability can result at sufficiently high currents.
- Energy recovering linacs can support enough beam current to reach the threshold of the instability.

Multipass Beam Breakup



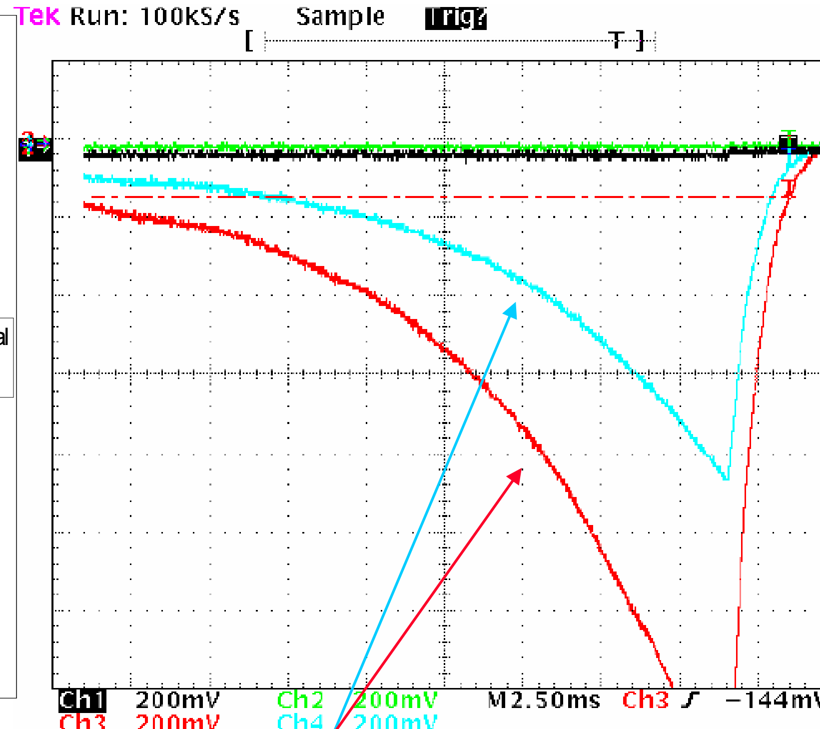
BBU Simulation and Observation

BBU simulations of the JLAB 10 kW FEL (145 MeV)



HOM data based on measurements
Model recirculation matrix

BBU observation in the JLAB 10 kW FEL (88MeV)



Cavity 4
Schottky diode signals
at 3.0 mA CW current

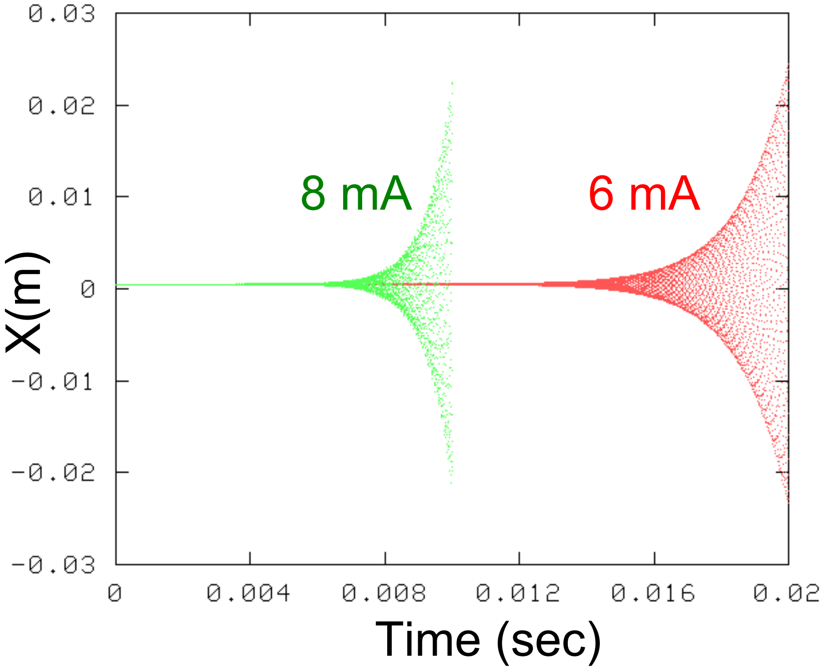
Growth Rate vs. Beam Current

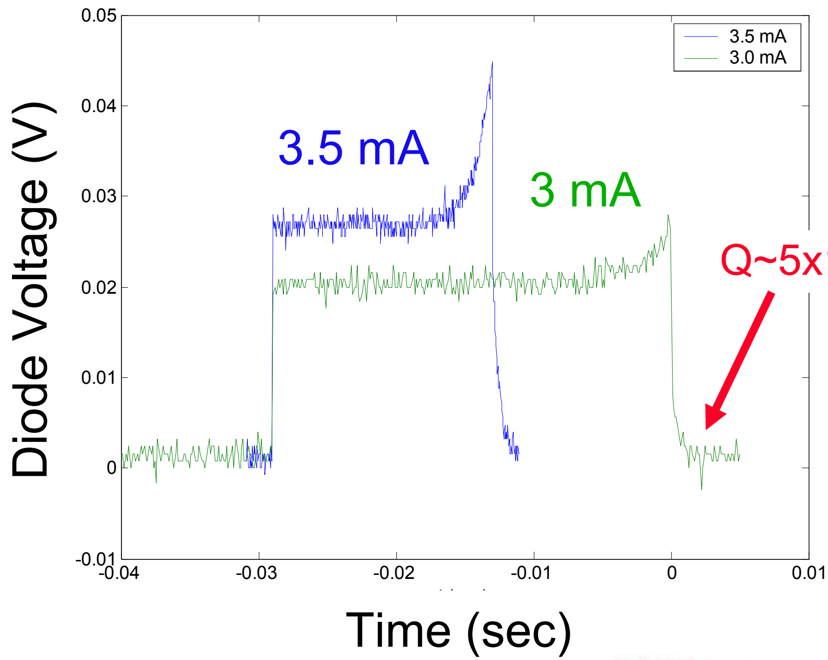
I_b = 6mA and 8mA
(I_{th} = 4 mA)
τ_6/τ_8=2 (2 and 1 msec)
Amplitude exponentially grows

$$\tau_I = \tau_0 \frac{I_{th}}{I - I_{th}}$$

Calculated from
the data measured
in pulsed regime
I_{th} = 2.34 mA

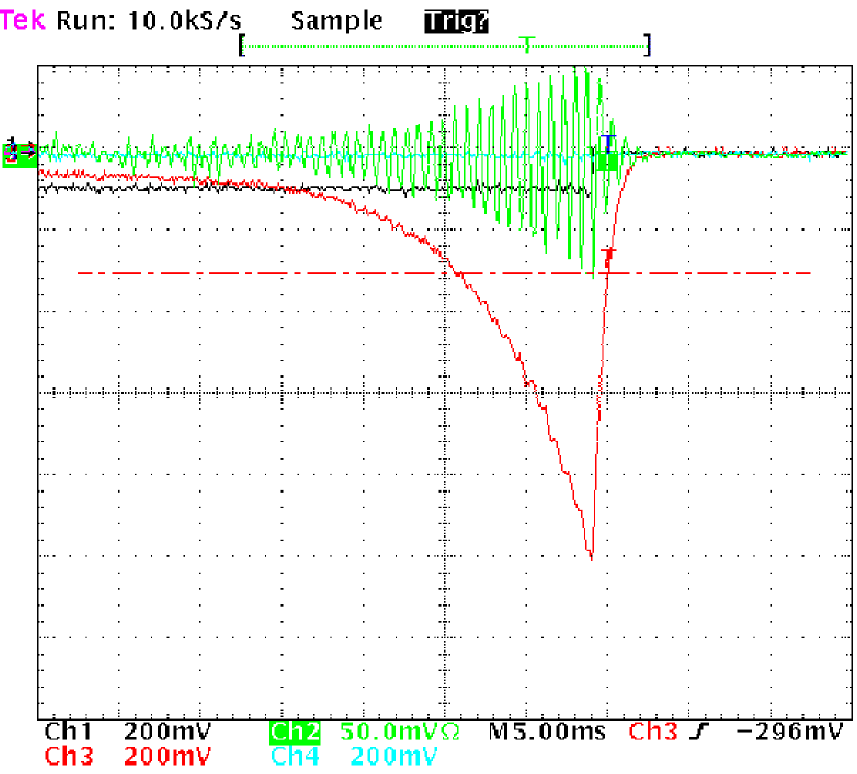
Measured (CW)
$I_{th} \cong 2.3$ mA





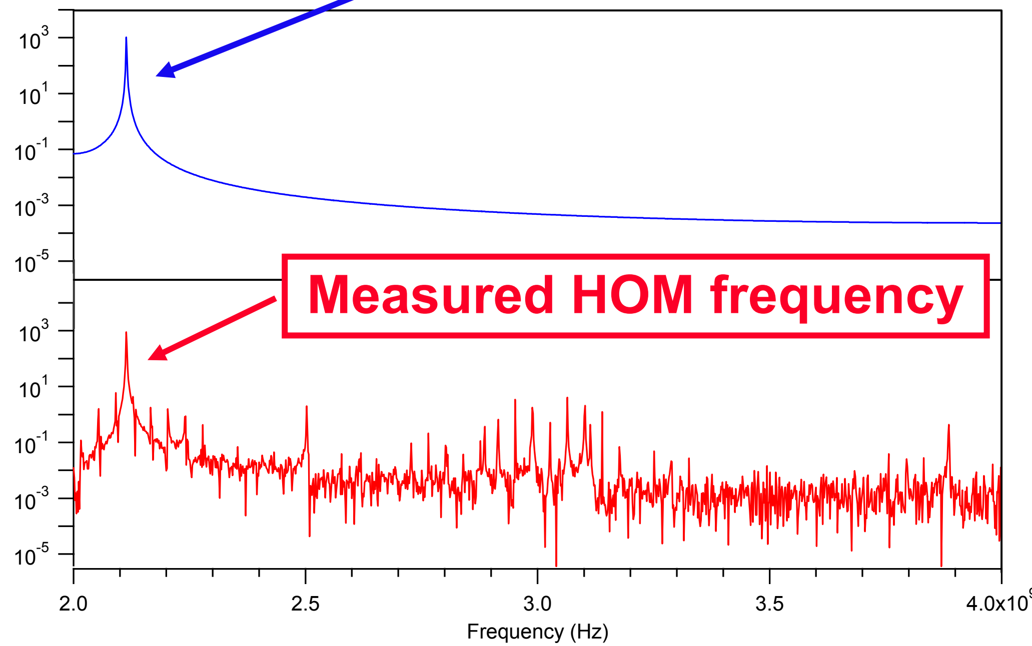
Beam Breakup Measurements

Cavity voltage measured:
directly at HOM port
after going through Schottky diode



Predicted HOM frequency 2114.2 MHz

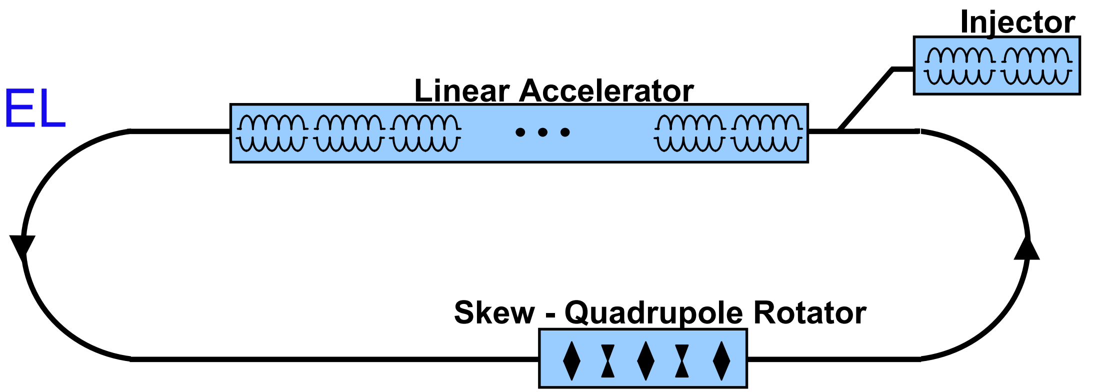
Measured HOM frequency

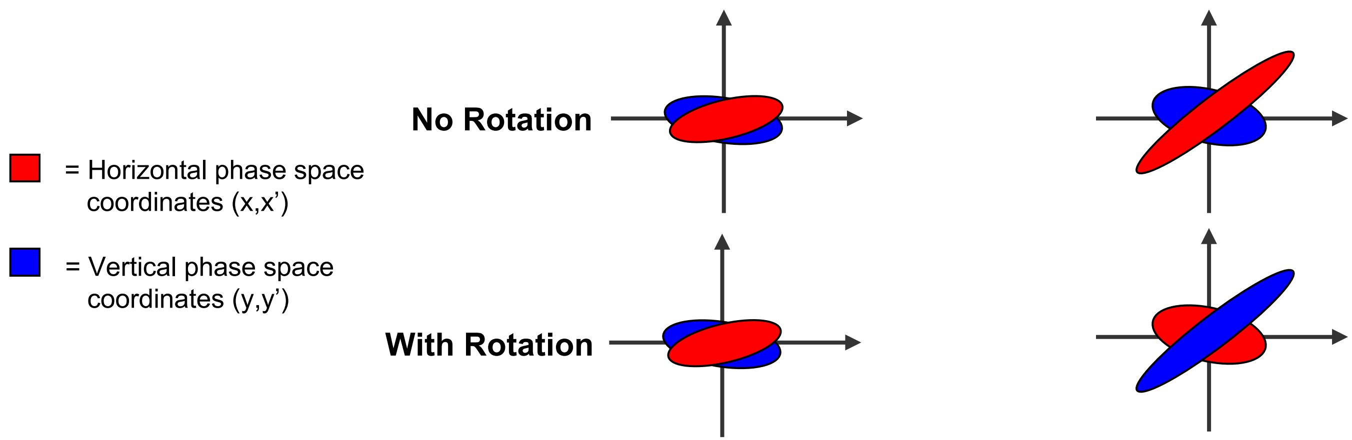


Suppressing Beam Breakup

“Reflecting” or “Rotating” Beam Optics: Phase space is rotated such that x′ -> y and y′ -> x leading to higher threshold currents

Skew quads installed in JLAB FEL
Ready for tests.

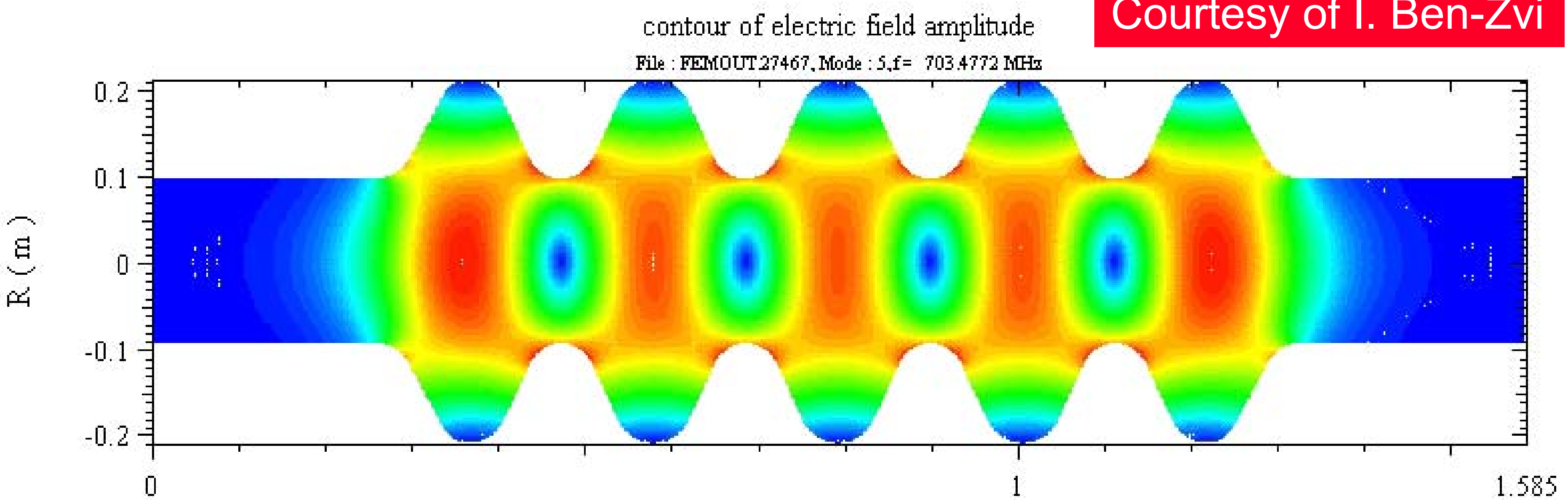




R. Rand and T. Smith, Particle Accelerators 1980, Vol. II, pp. 1-13

Lower Frequency SRF Development

Courtesy of I. Ben-Zvi



Develop CW SRF cavity for high intensity beams:

Large bore, 700 MHz cavity with ferrite HOM dampers and high beam break-up threshold

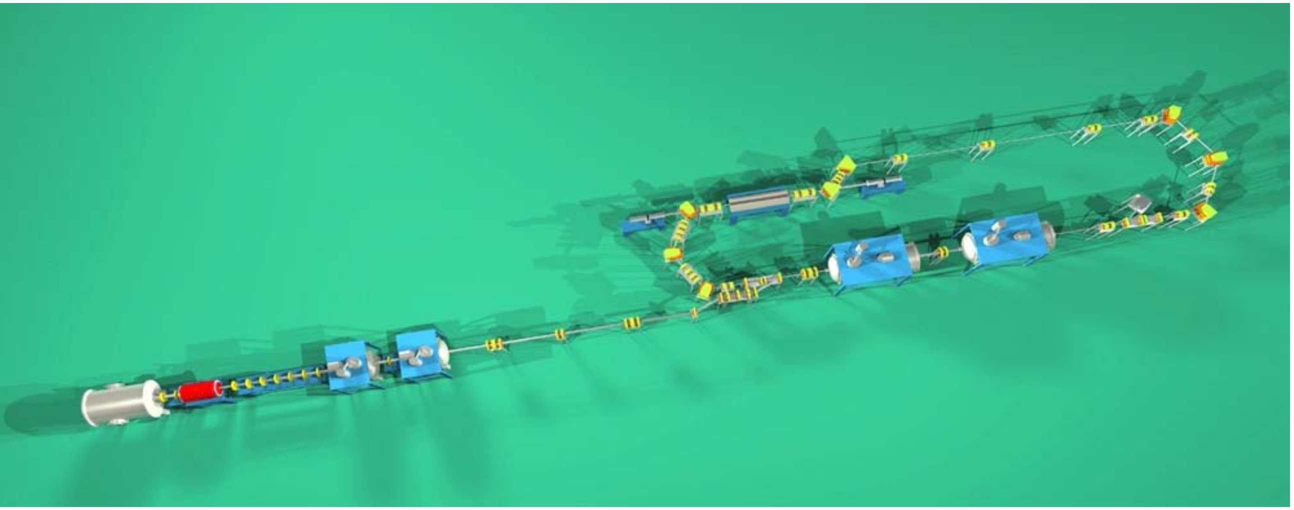
BNL-JLAB collaboration

Predicted BBU threshold current > 1 Amp!

How close are we?

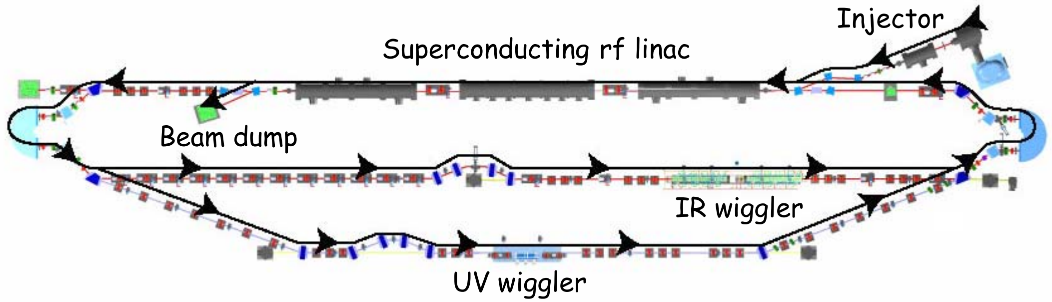
- Beam energy of 5-7 GeV – up by 5-7
- 1300-1500 MHz bunch repetition rate – up by 17-20
- 100 mA or higher average beam current – up by 10
- Normalized rms emittance ~1-2 mm-mrad at full energy – down by 5-10
- Bunch length from ~ 1 ps to < 0.1 ps – down by 4

Presently Operating FEL ERLs



JAERI FEL

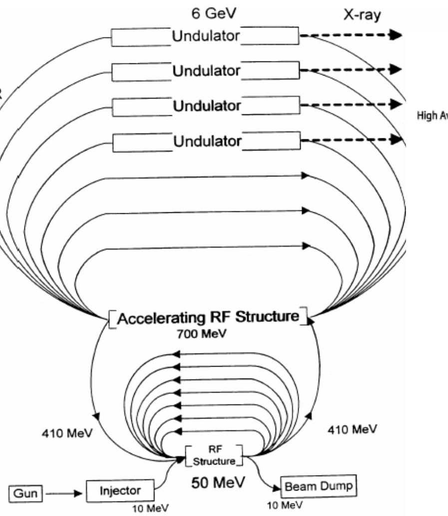
BINP
Recuperator FEL
180 MHz NC RF



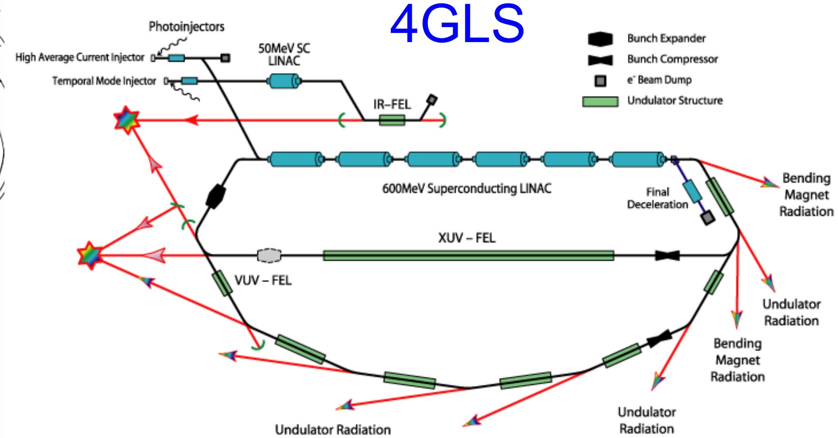
JLAB FEL

A bright future: Synchrotron Light ERL Proposals Worldwide

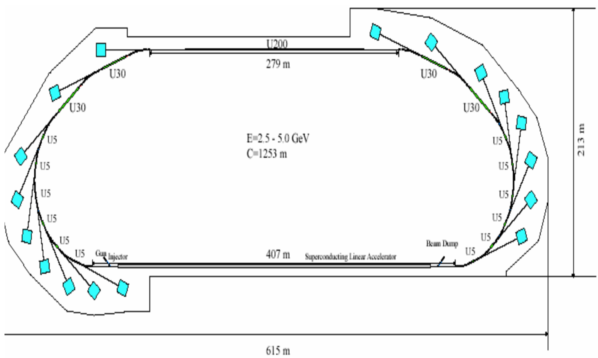
BINP MARS



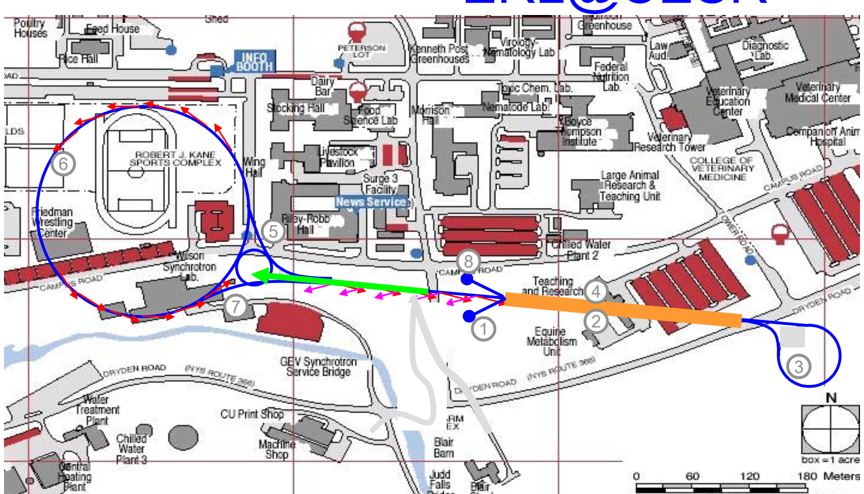
4GLS



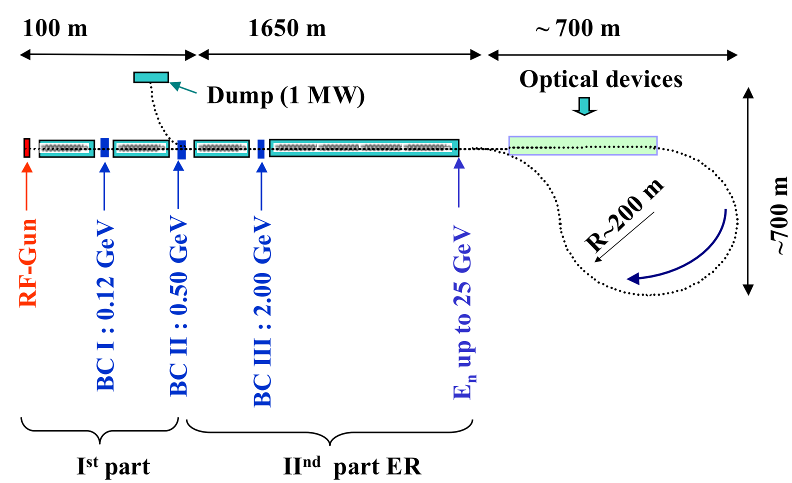
ERL at KEK



ERL@CESR

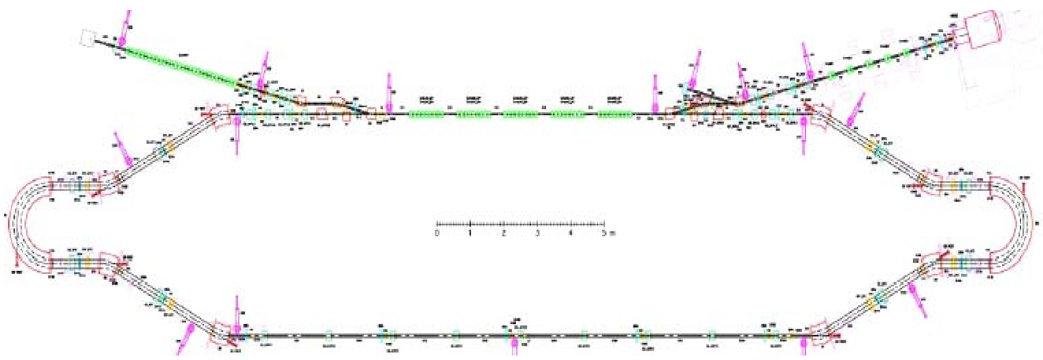


XFEL ERL

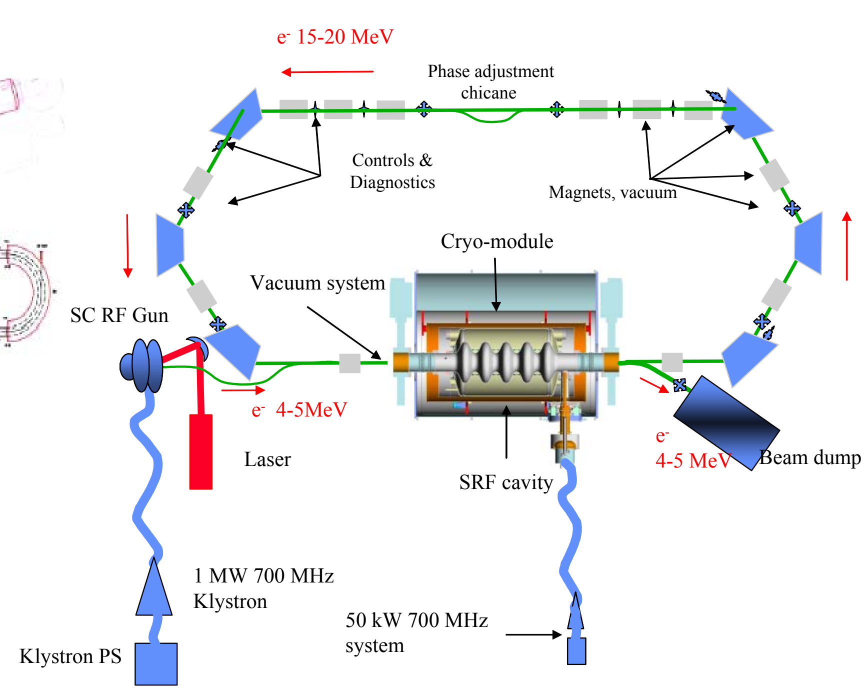


Operated by the Southeastern Universities Research Association for the U.S. Department of Energy

Proposed ERL Test Facilities

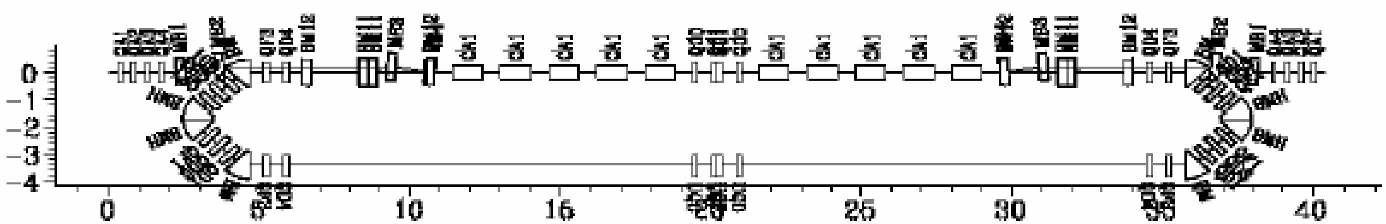


Cornell ERL Prototype



BNL ERL Prototype

KEK ERL Prototype



Summary

- ERLs provide a powerful and elegant paradigm for high average brightness, short-pulse radiation sources.
- The pioneering ERL FELs have established the fundamental principles of ERLs.

Summary (Cont'd)

- The challenges and R&D opportunities for the realization of next generation ERL light sources are centered around:
  - Source brightness
  - Emittance preservation
  - High current effects in SRF systems
- The fundamentals of these challenges are understood. Vigorous R&D activities in many labs to resolve outstanding physics and engineering issues.

Summary (Cont'd)

- The multitude of ERL projects and proposals worldwide promises an exciting next decade as:
  - Existing ERLs will reach higher performance
  - R&D issues will be resolved, and
  - New ERLs will be constructed

Acknowledgments

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