

Energy Recovery Linacs

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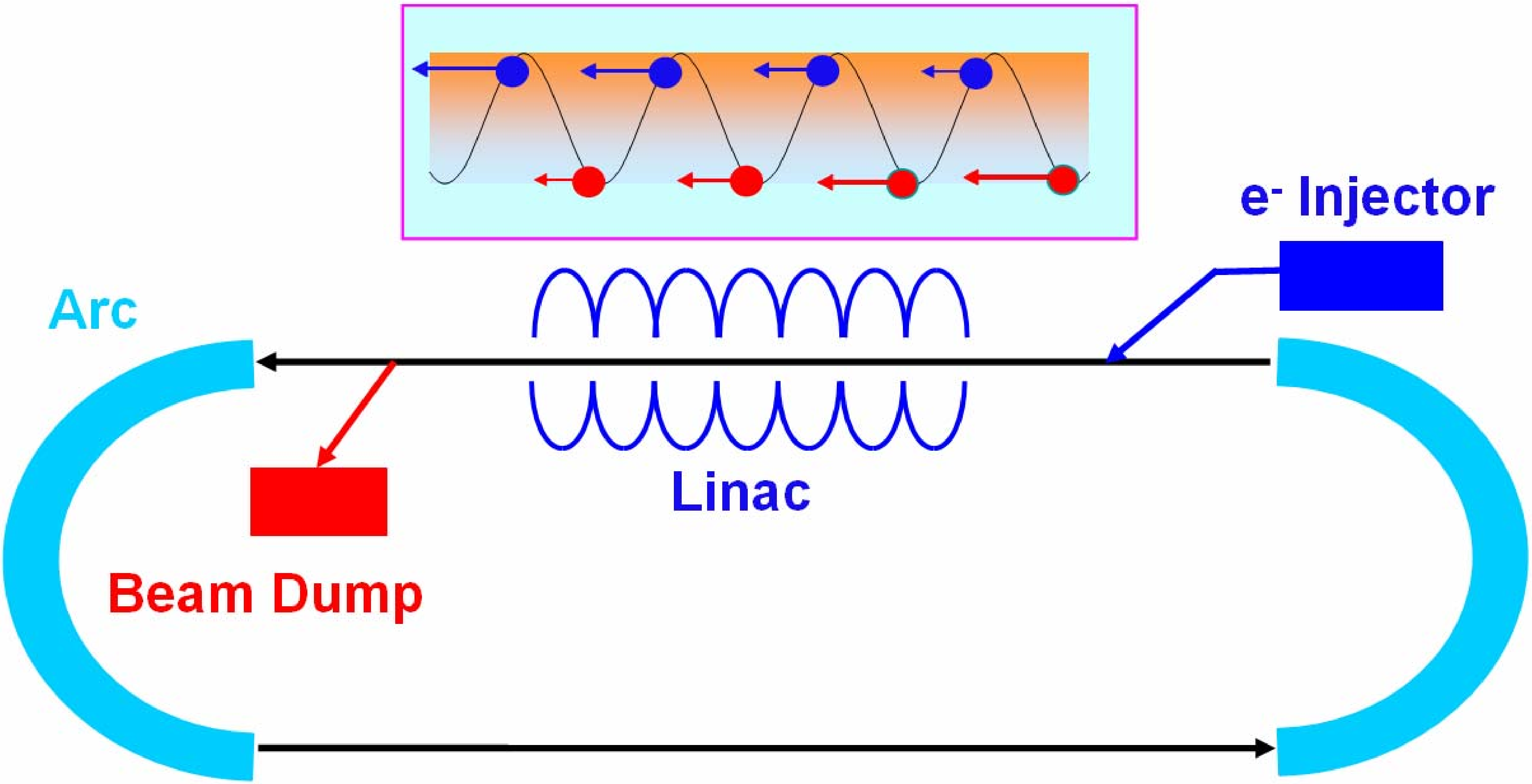
Outline

- Energy Recovery Linacs
- Presently Operating ERLs
- Envisioned ERL Applications
  - ERL Light Sources
  - ERLs for Nuclear Physics
- Accelerator Physics and Technology Challenges and Developments
- ERL Test Facilities worldwide
- Summary

Energy Recovery Linacs



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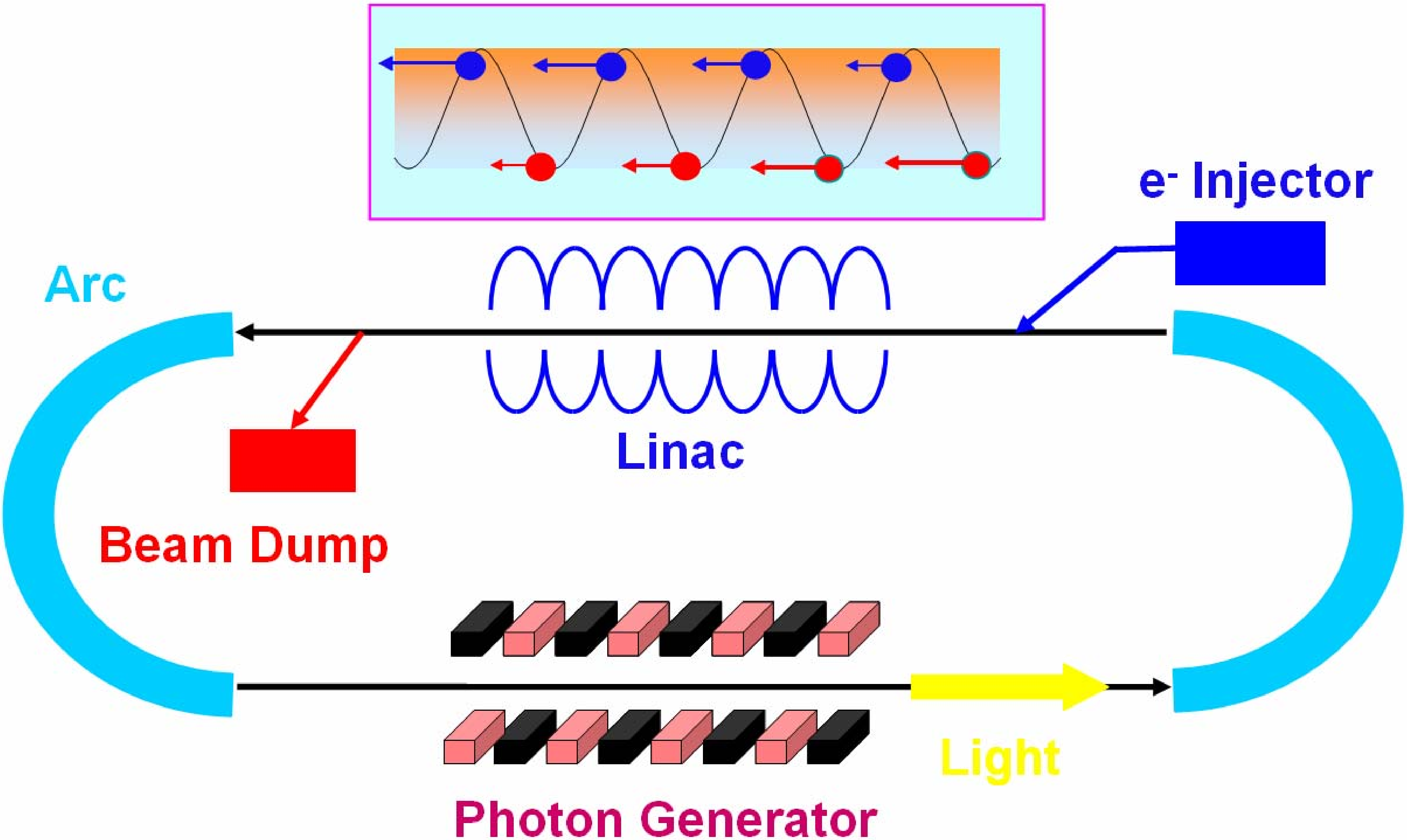
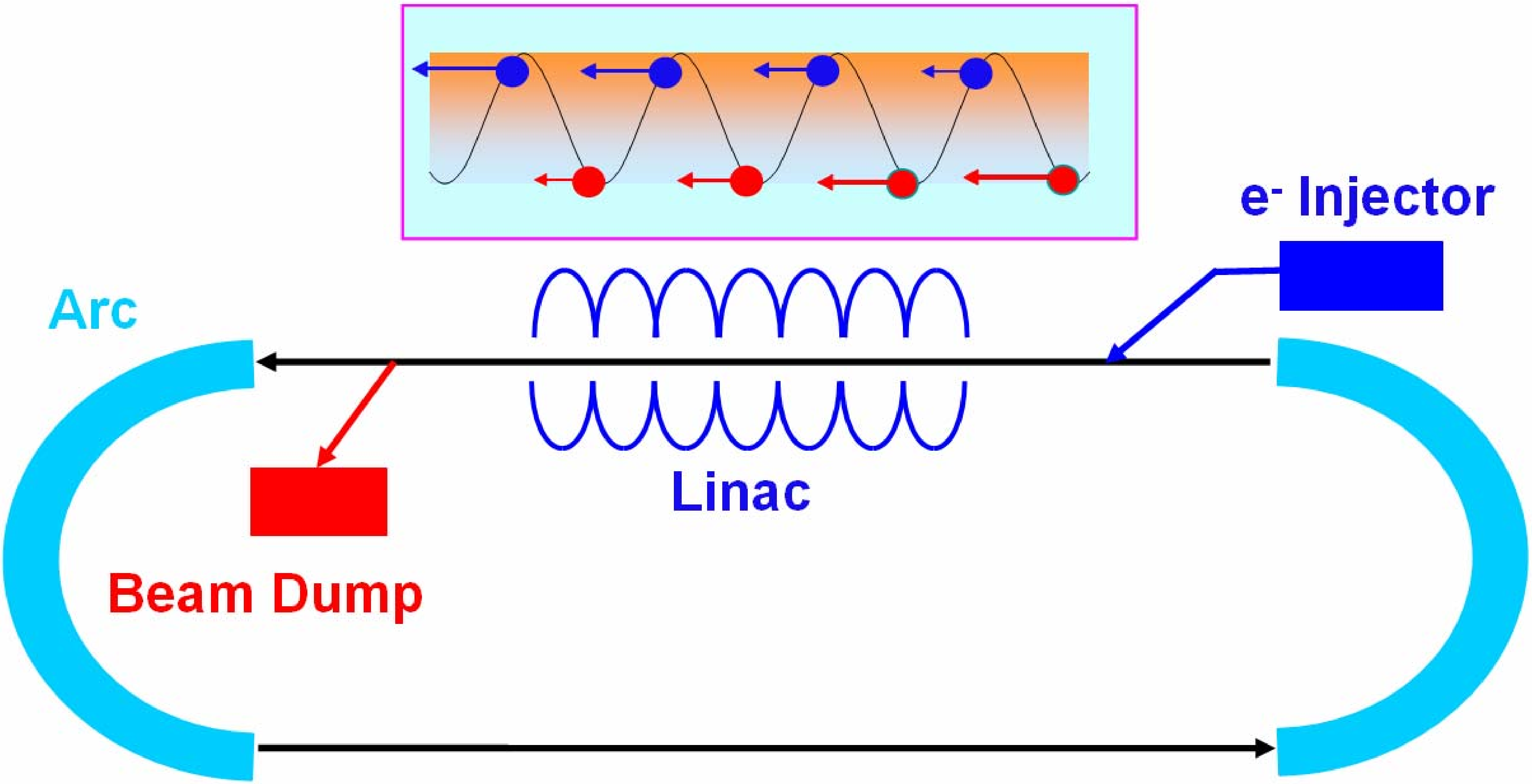


Energy Recovery Linacs



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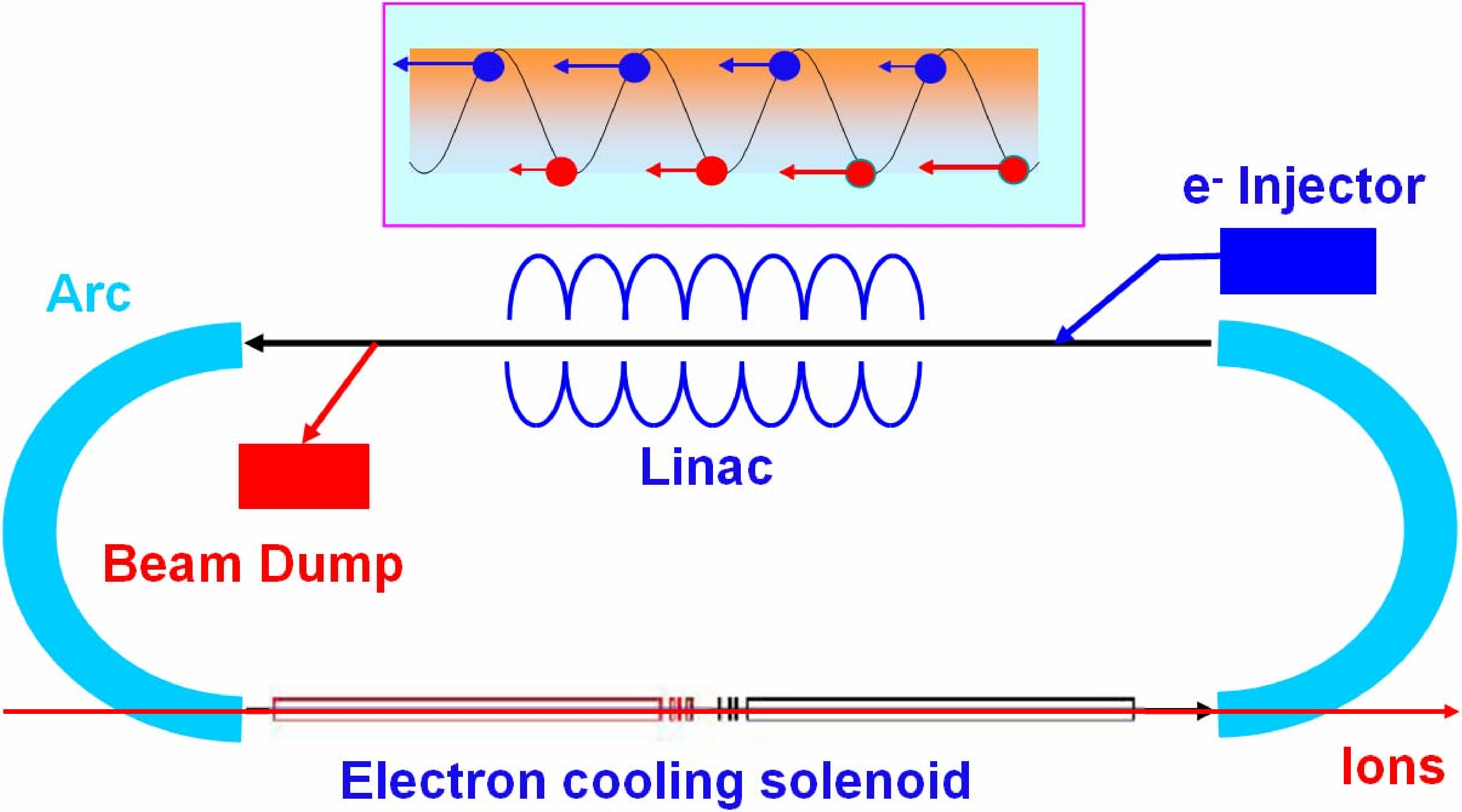

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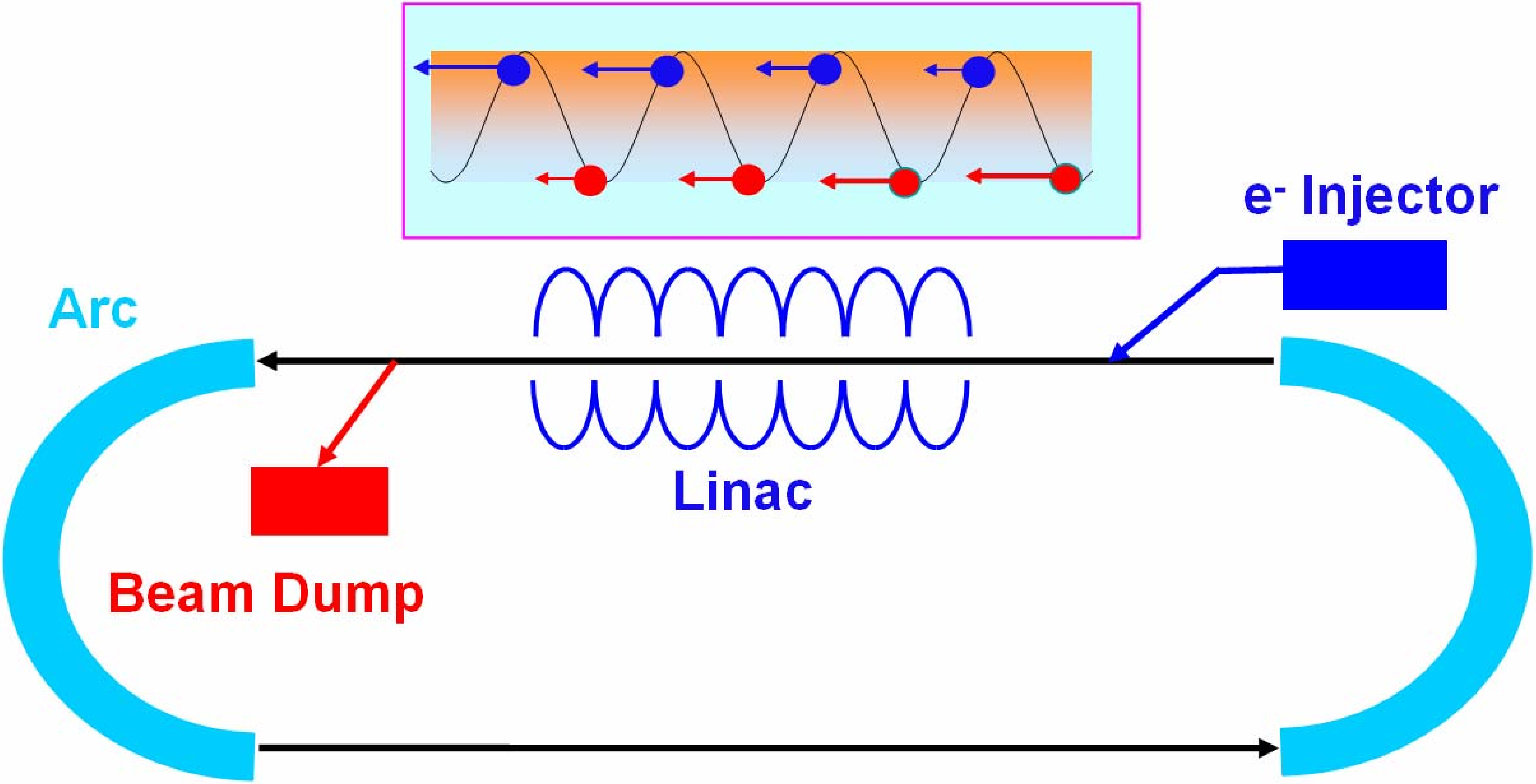
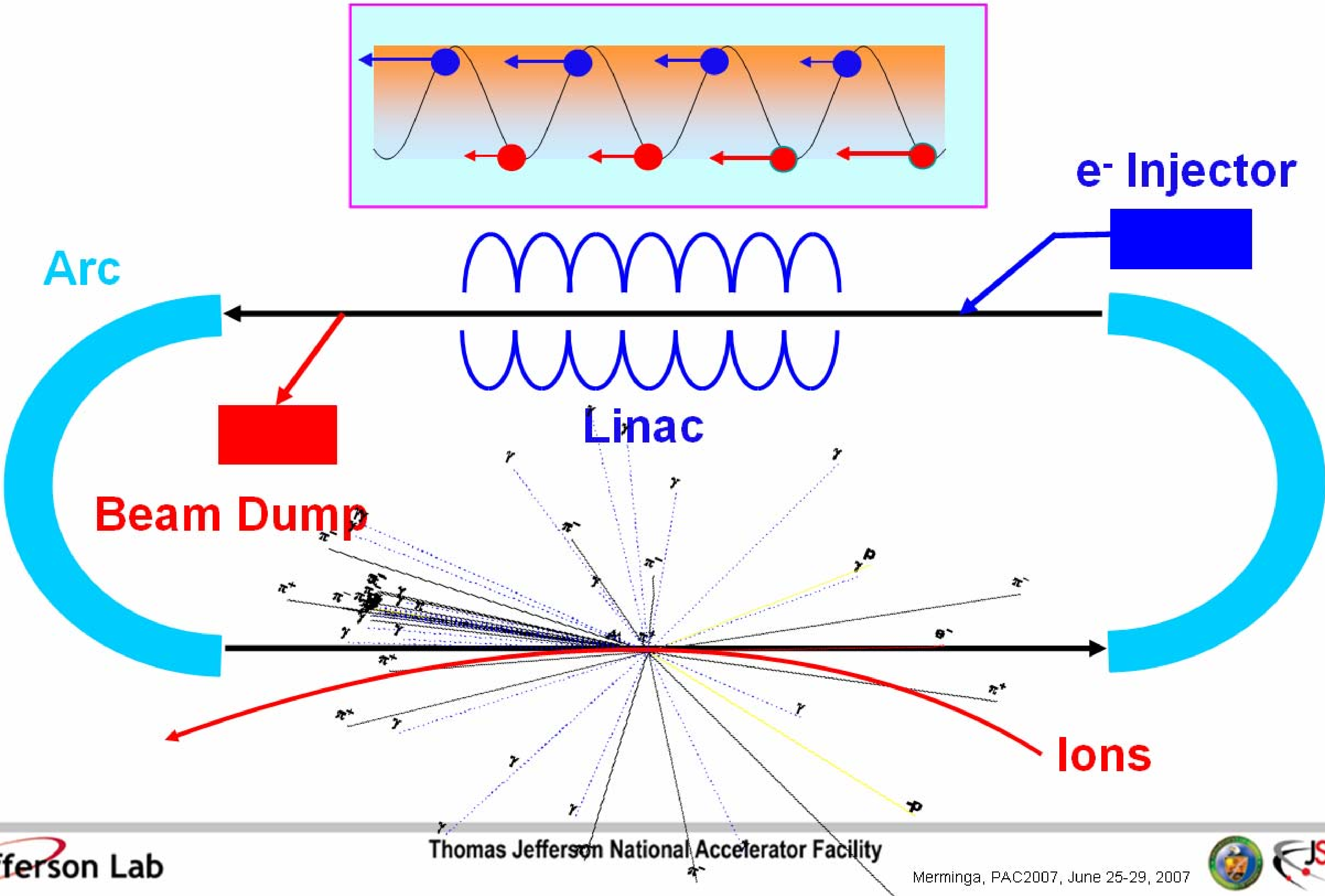
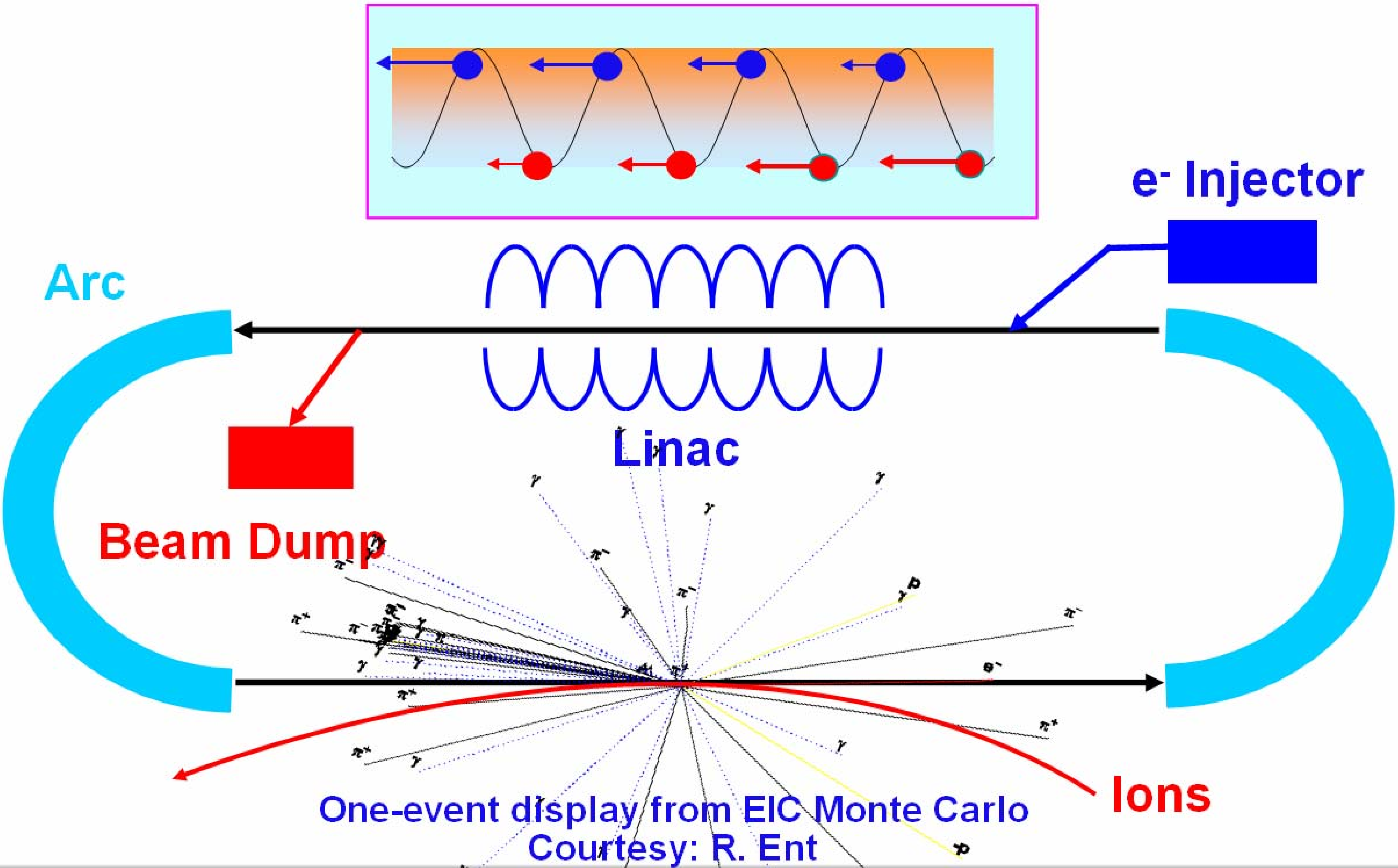


Energy Recovery Linacs



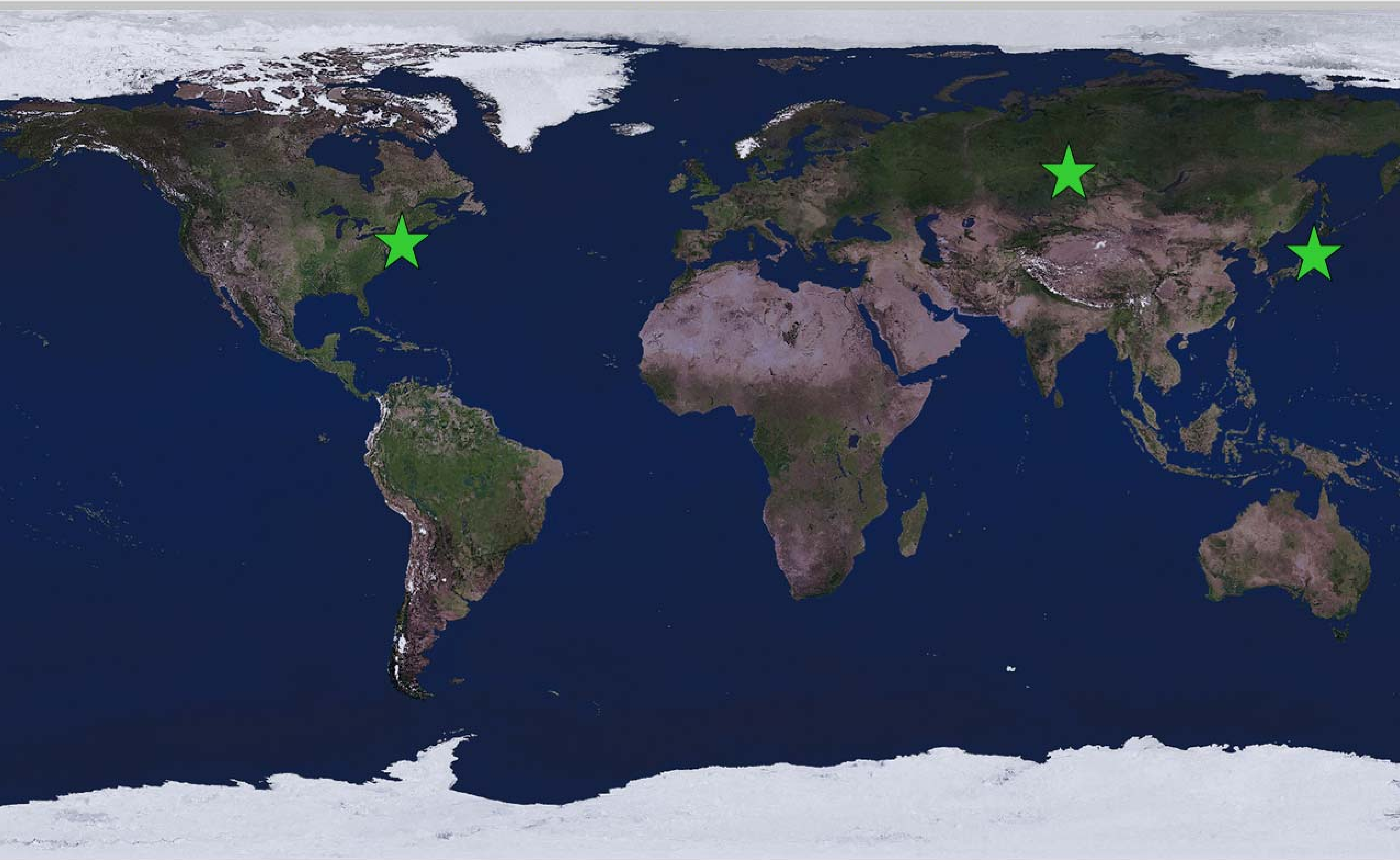
Energy Recovery Linacs



ERL vs. Storage Ring vs. Linac

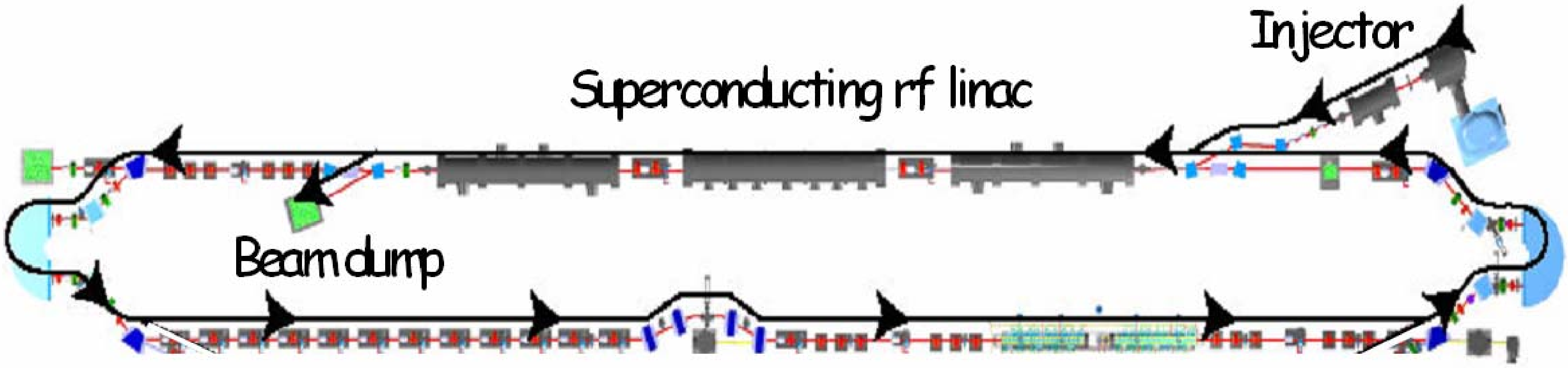
- While an electron storage ring stores the same electrons for hours in an equilibrium state, an ERL stores the energy of the electrons.
- In an ERL electrons spend little time in the accelerator (~1 μs), therefore they never reach an equilibrium state.
- In common with linacs: In an ERL the 6-D beam 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.

Presently Operating ERLs



The Jefferson Lab IR FEL Upgrade

Energy recovered up to 9.1 mA at 150 MeV

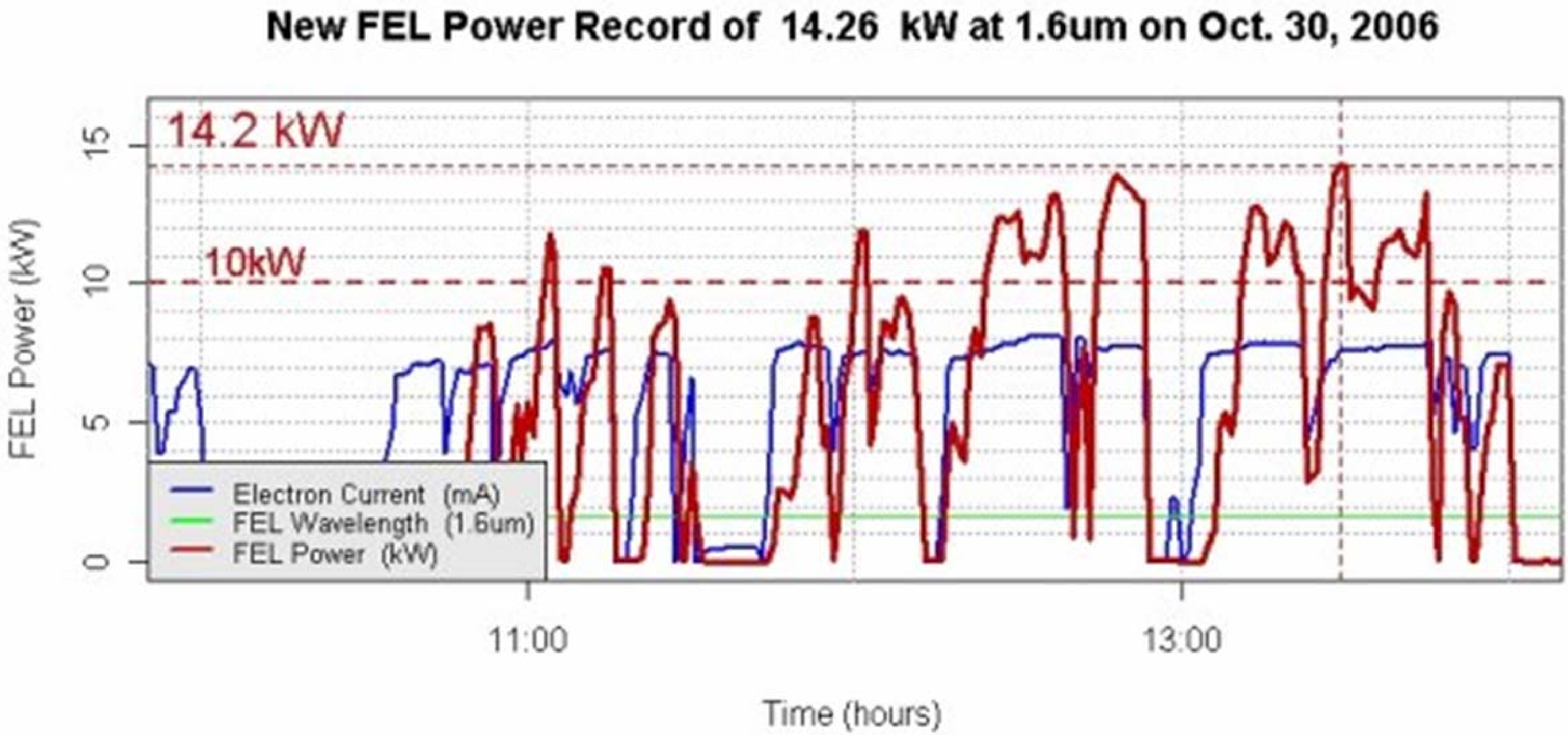


JLab IR FEL Electron Beam Parameters	Design	Achieved
Energy (MeV)	145	160
Bunch charge (pC)	135	270
Average current (mA)	10	9.1
Bunch length* (fs)	200	120
Norm. emittance* (mm-mrad)	30	7
Max. Bunch rep. rate (MHz)	74.85	74.85

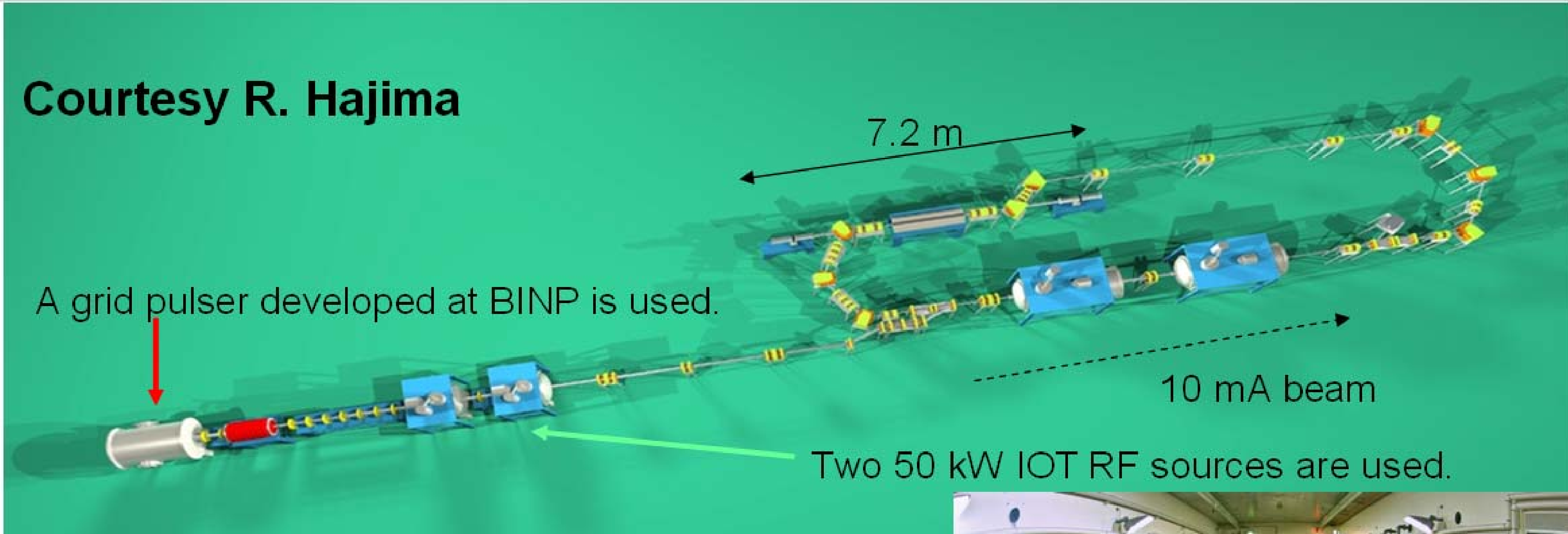
*Quantities are rms

High-Power Record at JLAB FEL

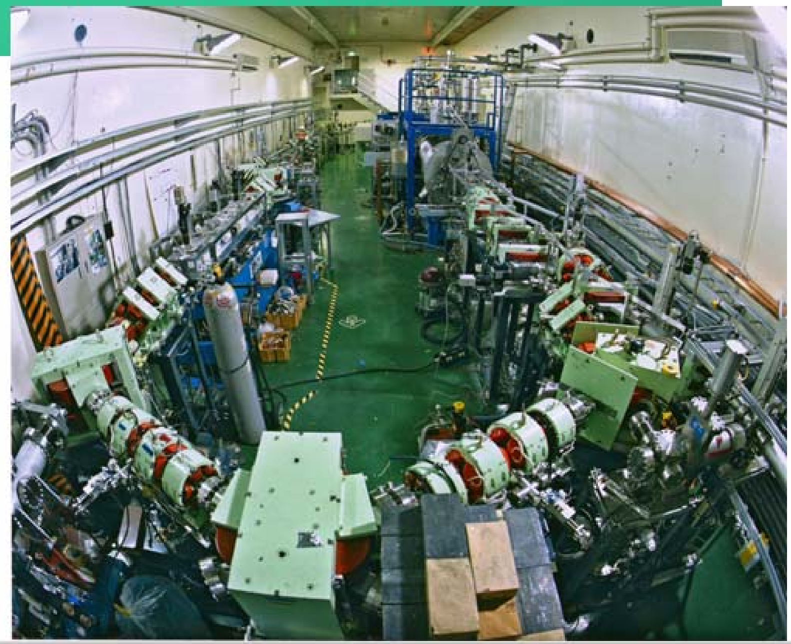
Achieved 14.2 kW CW light power at 1.6 μm on October 30, 2006!



JAEA ERL FEL

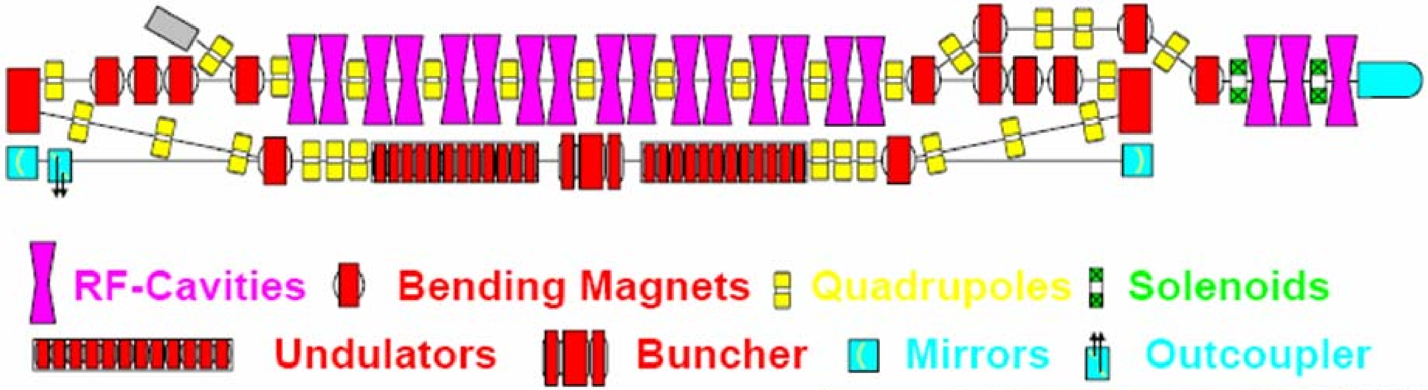


Energy = 17MeV
FEL : λ = 22μm
Bunch charge =400pC
Bunch length = 12ps (FWHM)
Bunch rep. = 20.8 MHz
Macro pulse = 0.23ms x 10Hz



The Novosibirsk High Power THz FEL

Energy recovered highest average current to date: 20 mA at 1.7 nC per bunch



	May 2005	Plans
RF frequency, MHz	180	180
Bunch repetition rate, MHz	11.2	90
Maximum average current, mA	20	150
Maximum electron energy, MeV	12	14
Normalized beam emittance, mm*mrad	30	15
Electron bunch length in FEL, ns	0.07	0.1
Peak current in FEL, A	10	20

Envisioned ERL Applications

- Free Electron Lasers
- Spontaneous Emission Light Sources
- Electron Cooling
- Electron-Ion Colliders

Future ERL FELs

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

Typical Requirements

Energy ~ 100 - 600 MeV

Charge ~ 0.1 - 1 nC/bunch

Transverse emittance ~ 1 - 10 mm-mrad

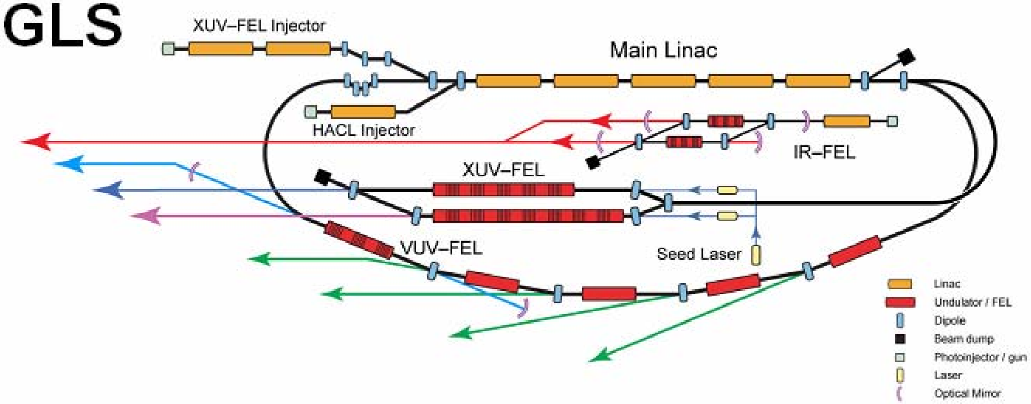
Longitudinal emittance ≤ 100 keV-ps

Average current ~ 1 - 100 mA

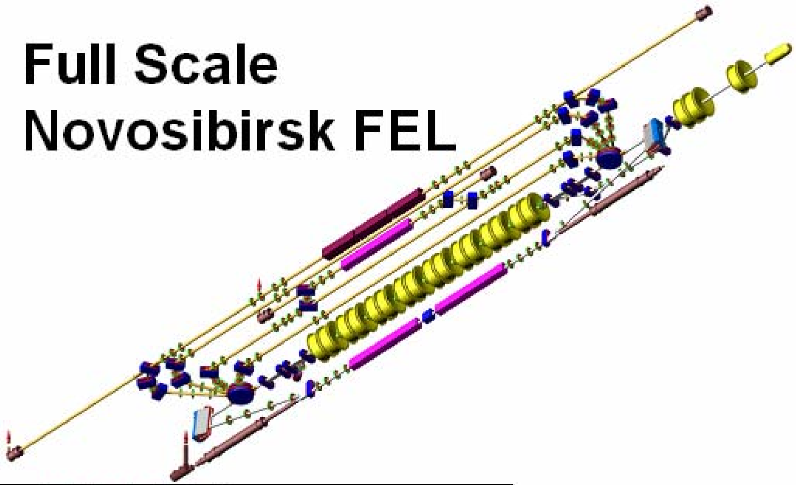
MOZBC03 Neil

Future ERL FELs: Designs/Concepts

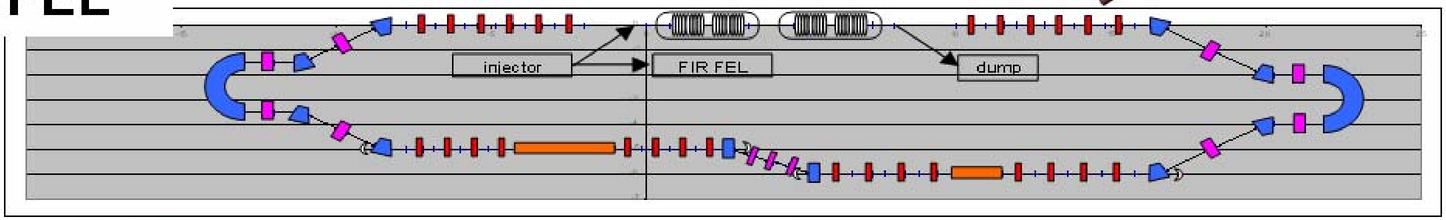
4GLS

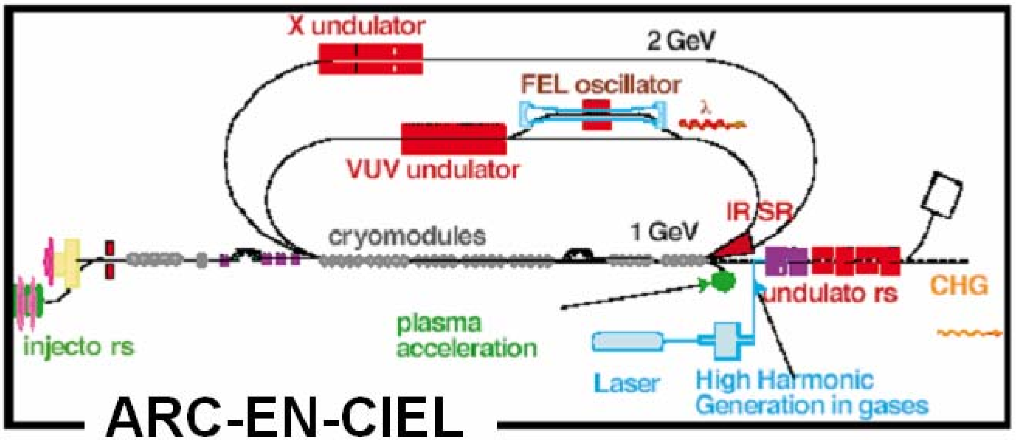


Full Scale Novosibirsk FEL

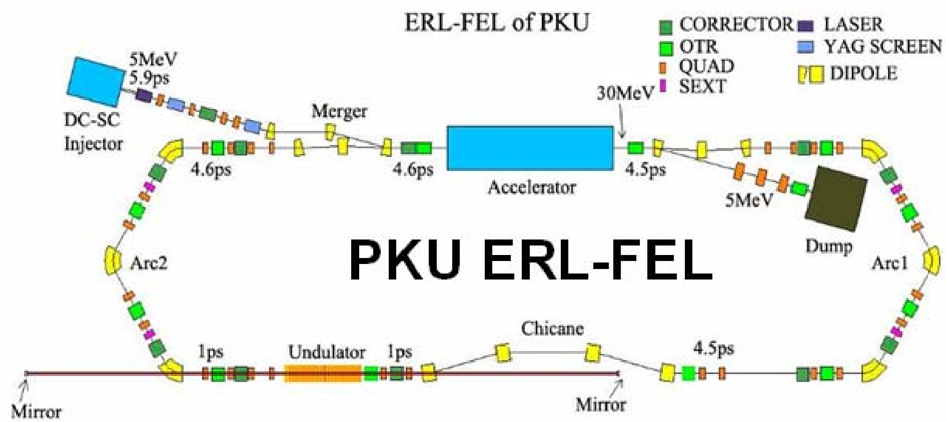


NHMFL FEL



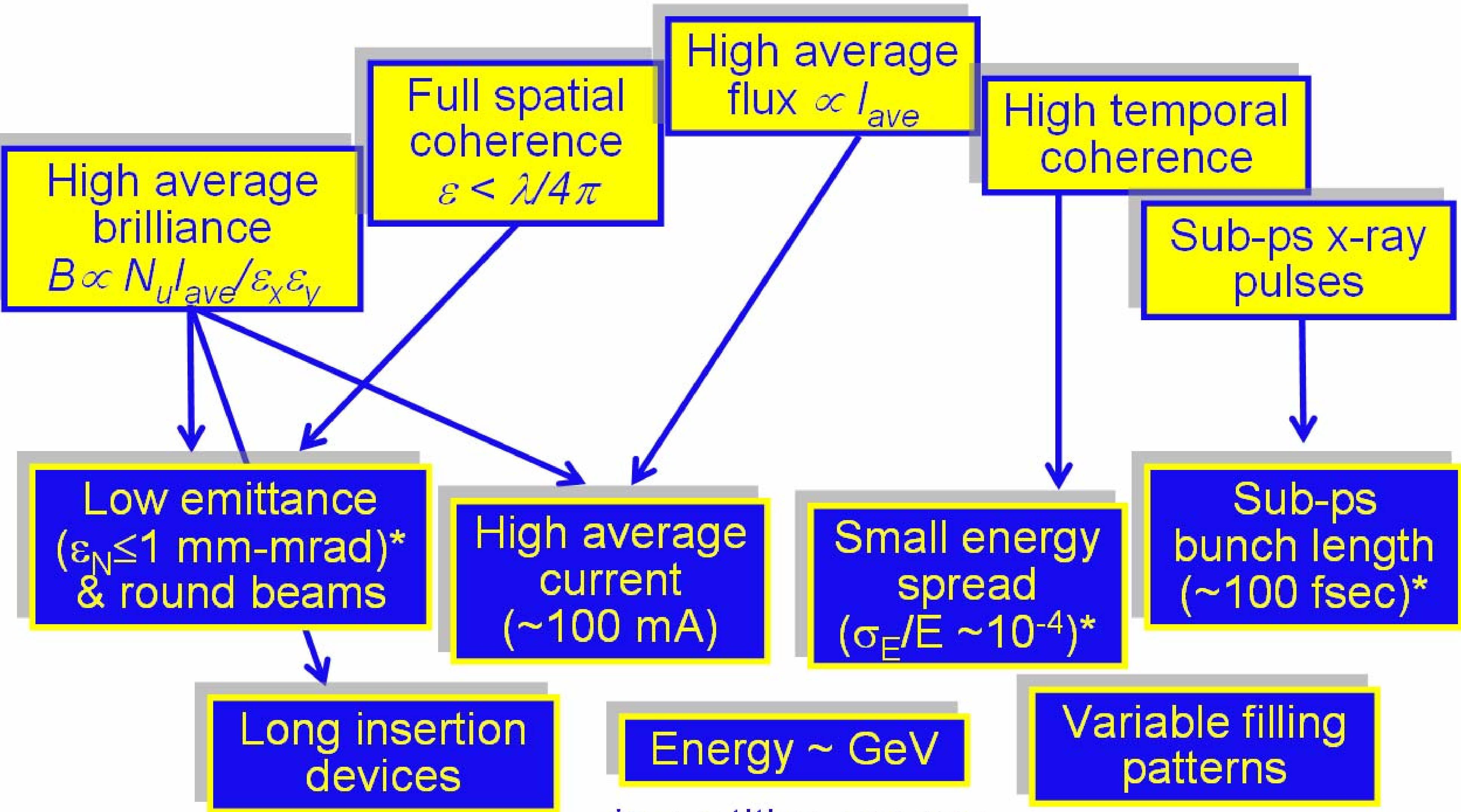


ARC-EN-CIEL



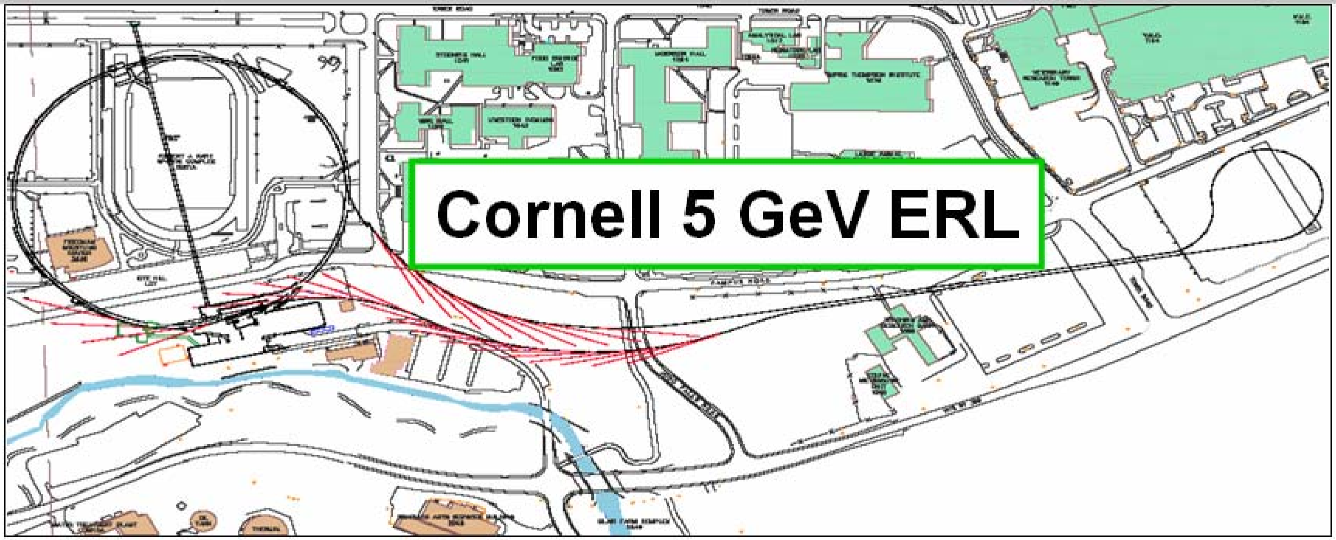
PKU ERL-FEL

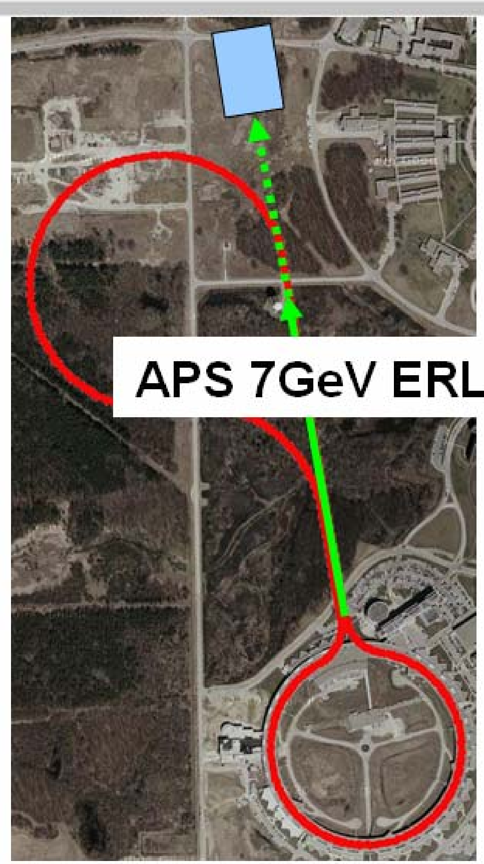
Spontaneous Emission ERL Light Sources

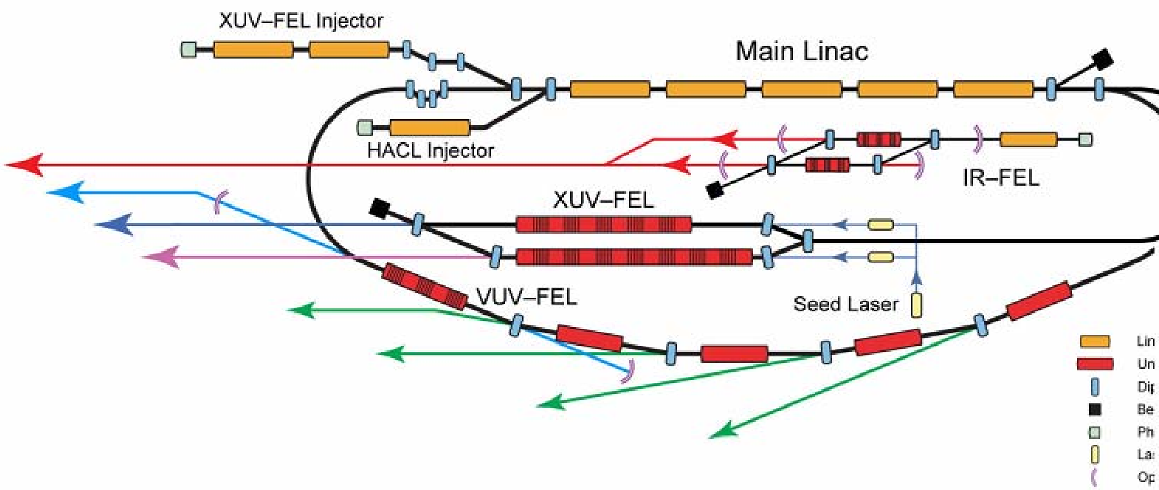


*quantities are rms

Designs of ERL Light Sources



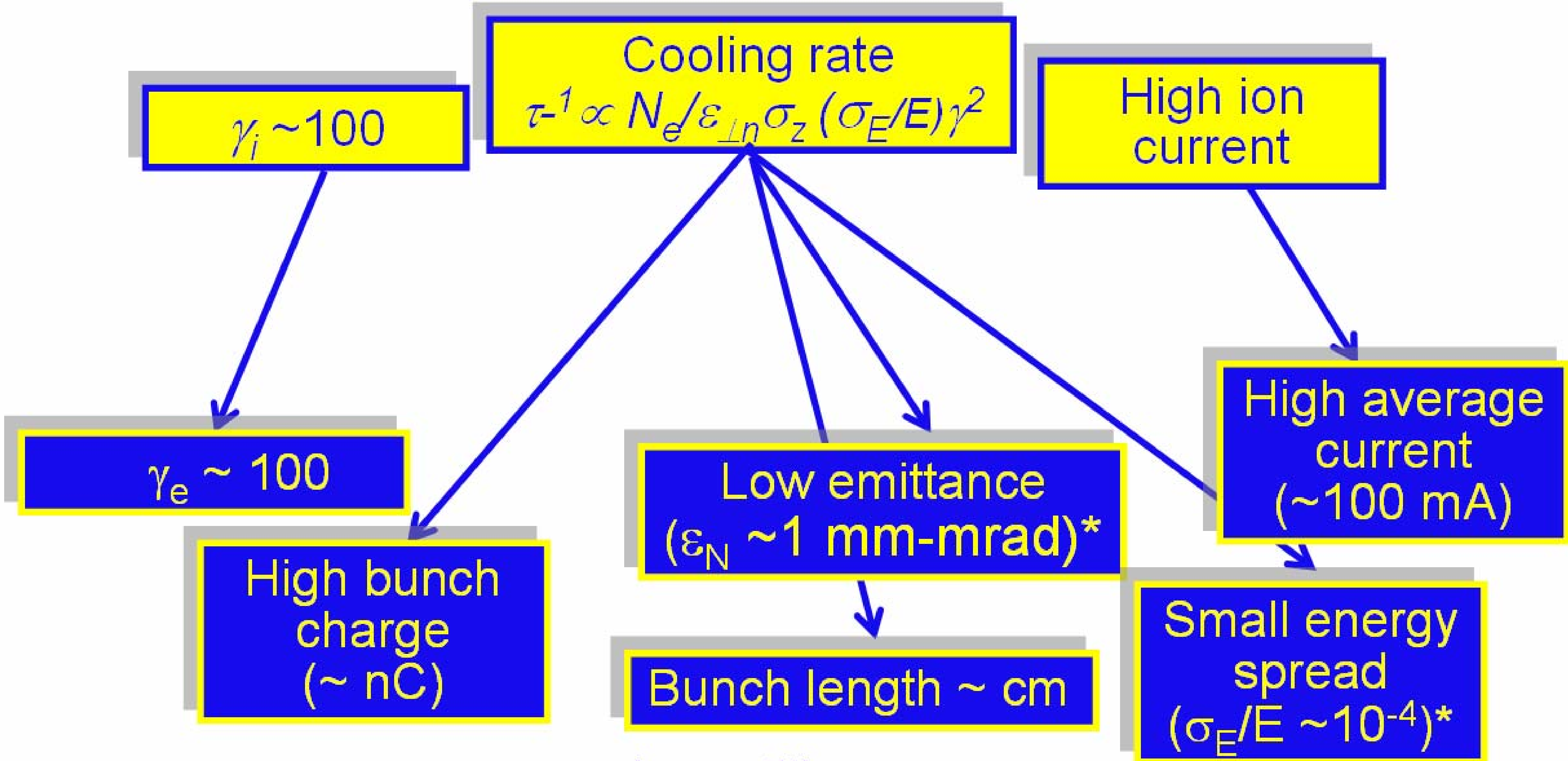




4GLS 550 MeV ERL

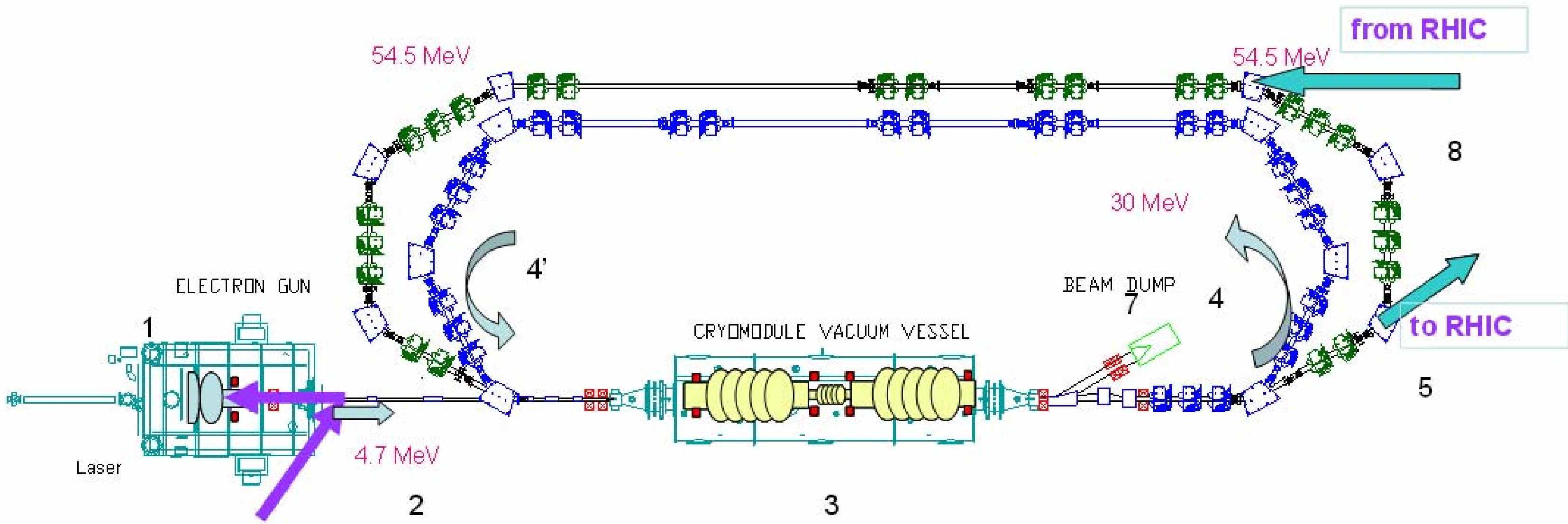
ERLs for Electron Cooling

ERLs provide the only credible concept for electron cooling of high-energy colliding beams



*quantities are rms

RHIC-II Electron Cooler



Design Parameters

Energy 54 MeV

Charge 5 nC/bunch

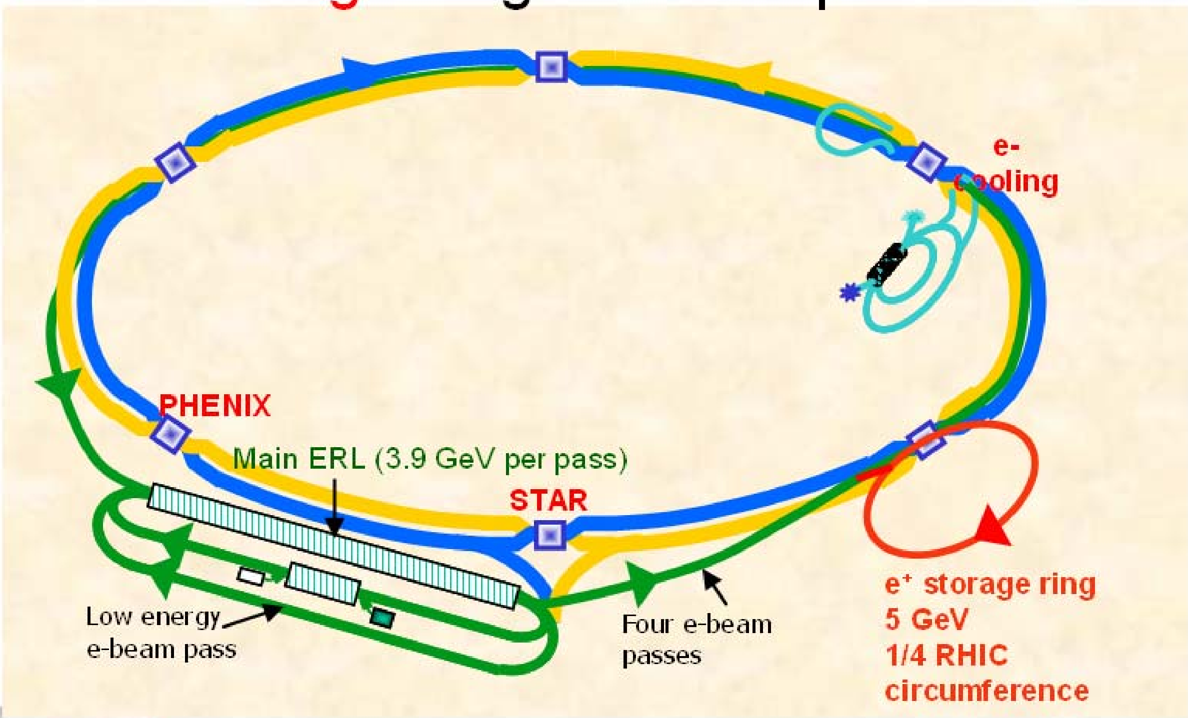
Emittance ≤ 4 mm-mrad

Average current ~ 50 mA

WEOCKI03 Ben-Zvi

ERLs for Electron-Ion Colliders

- Advantages:
  - Potential luminosity increase compared to ring-ring due to higher allowed beam-beam tuneshift of the electron beam ($\xi_e \sim 0.5$)
  - Easy electron spin manipulations
- Challenge: High current polarized electron source



ERL eRHIC Requirements

Energy ~ 10-20 GeV

Charge ~ 10-20 nC/bunch

Emittance ~ 20 mm-mrad

Average current ~ 250 mA

Polarization ~ 80%

WEZAKI02 Ptytsin

Accelerator Physics and Technology Challenges and Developments

- Generation and preservation of low emittance, high current beam
- Accelerator transport
- High current effects in Superconducting RF

Generation and Preservation of Low Emittance, High Current Beam

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

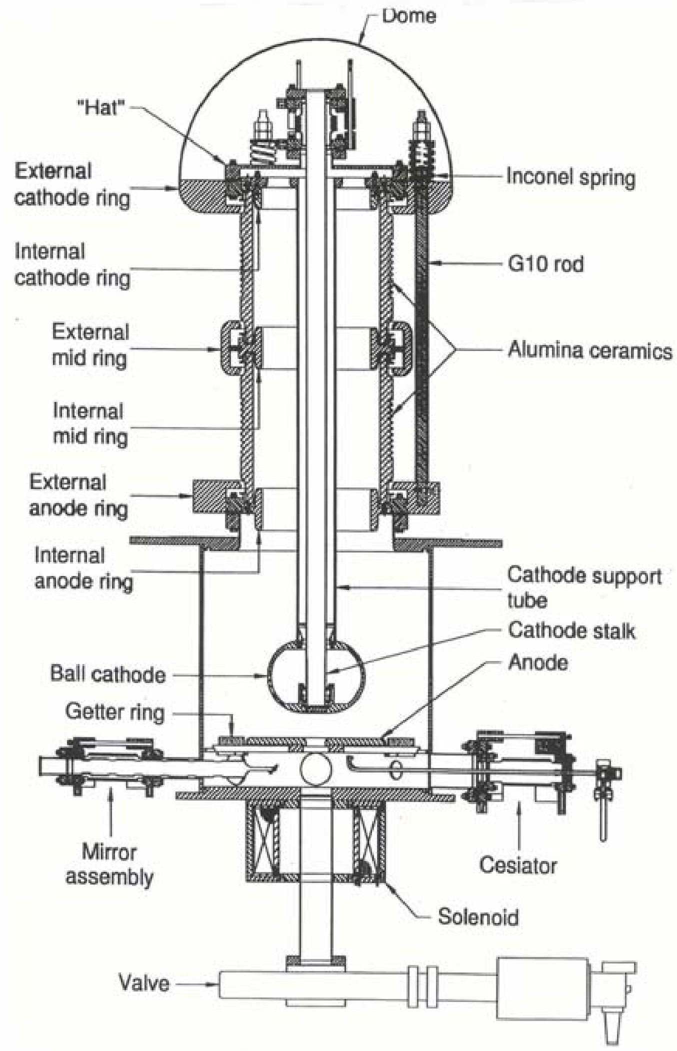
a. High accelerating gradients or high repetition rate? Or both?

b. Achieving the thermal emittance from the injector

DC photoinjectors

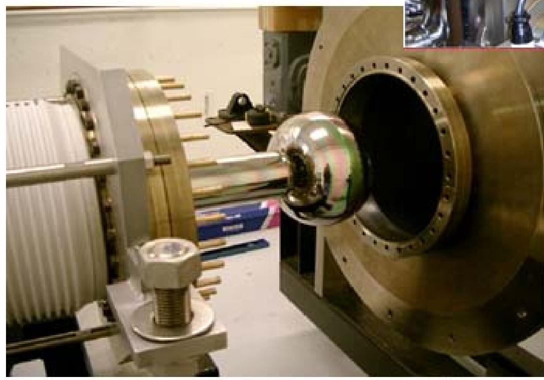
State-of-the-art: JLAB FEL gun

- High repetition rate up to 75 MHz
- $\varepsilon_{N,rms}$~ 7 - 10 mm-mrad for q ~ 60 - 135 pC/bunch (measured at the wiggler)
- Average current up to 9 mA
- Cathode voltage: 350 – 500 kV



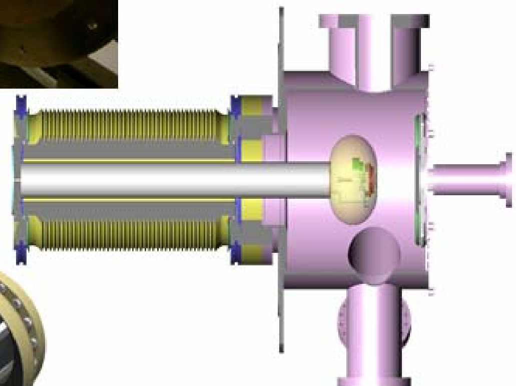
DC Photoinjectors under construction/testing

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

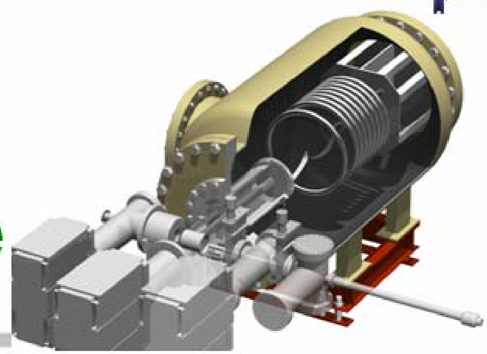


- **JLab Gun/AES Injector:**
  500 kV, 750 MHz, 100 mA

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

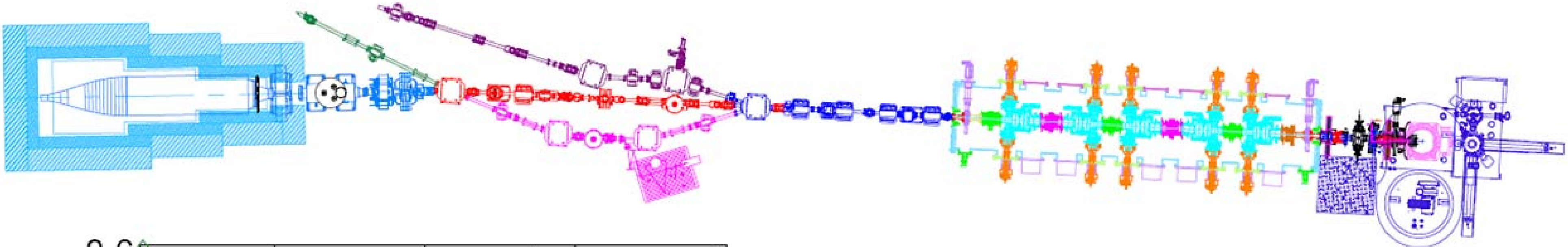


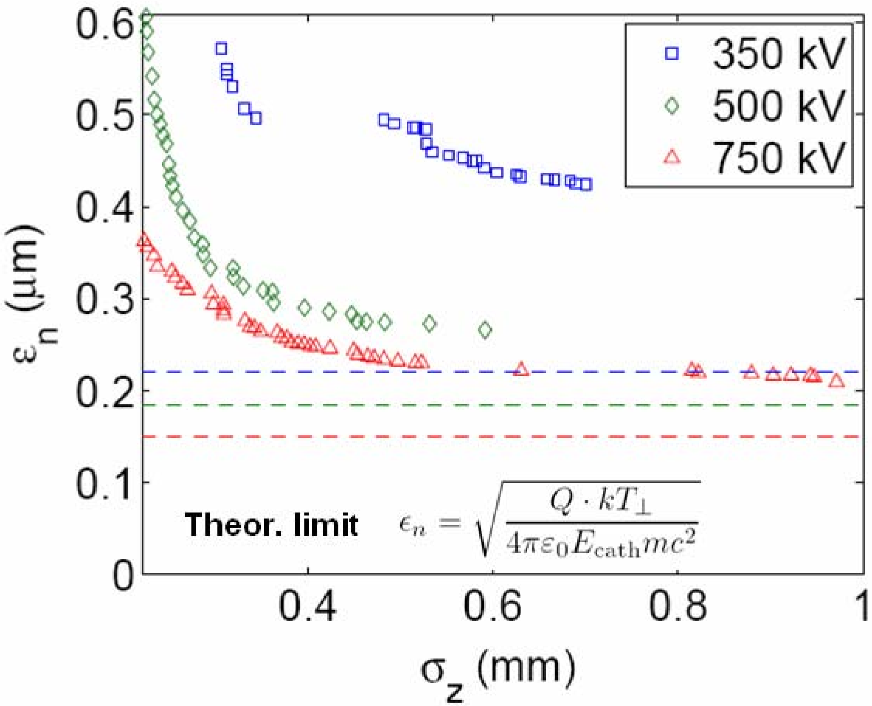
- **JAEA:**
  250 kV, 50 mA gun,
  superlattice photocathode



Achieving Thermal Emittance

Cornell ERL Prototype Injector Layout





Injector optimization 77 pC/bunch

Courtesy: I. Bazarov

0.2 mm-mrad, 77 pC, 3ps

Dominated by thermal emittance

Injector optimization also pursued by Hajima (JAEA), Hannon (JLab).

RF photoinjectors

- To date RF guns have produced best normalized emittances:

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

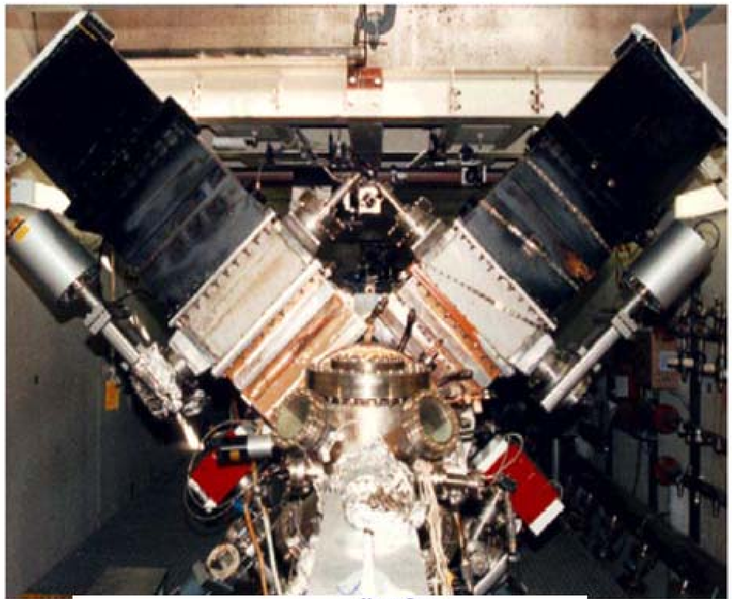
- Challenge: Balance high gradient (low emittance) with high rep rate (thermal effects)

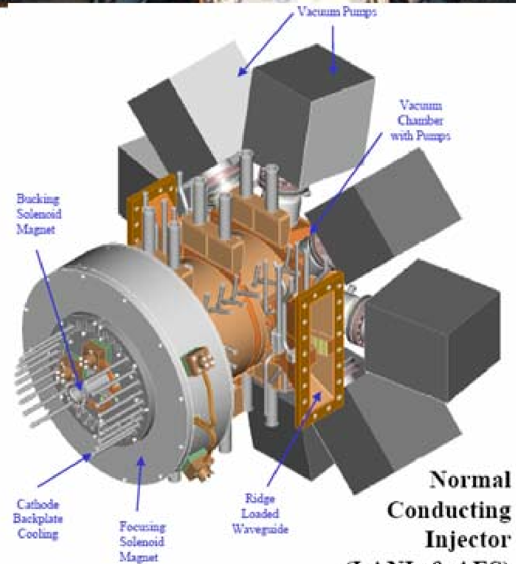
State-of-the-art: Boeing gun

- Repetition rate 433 MHz at 25% DF
- Average current 32 mA

Planned RF Photoinjectors

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





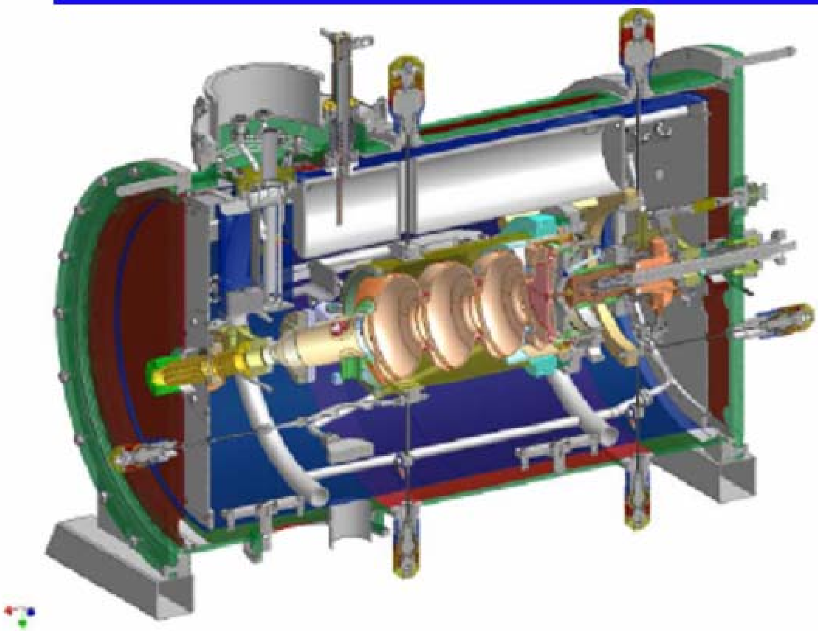
Normal Conducting Injector (LANL & AES)

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

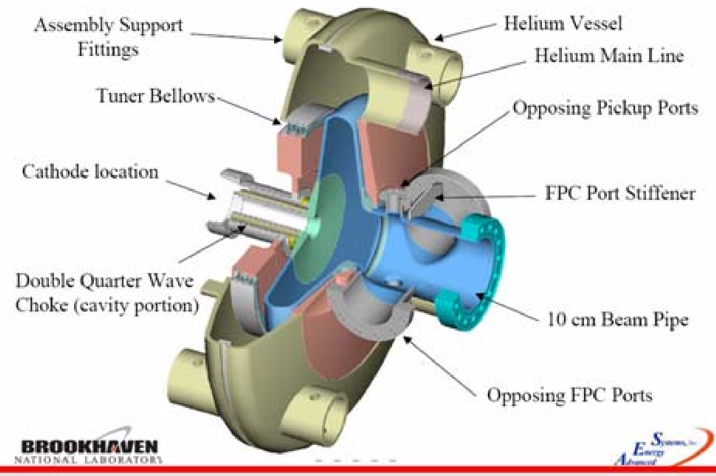
SRF photoinjectors (cont'd)

Rossendorf SRF gun

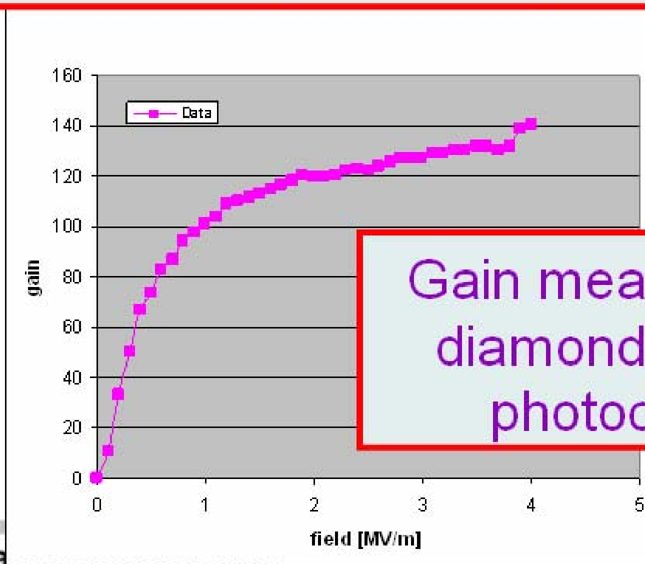


1.3 GHz, 9.5 MeV, CW
3 modes of operation:
- 77 pC at 13 MHz
- 1 nC up to 1 MHz (1 mA)
- 2.5nC at 1 kHz

BNL/AES SRF gun



703.75 MHz, 2.5 MeV, 500 mA CW



Gain measured from diamond amplified photocathode

Accelerator transport

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

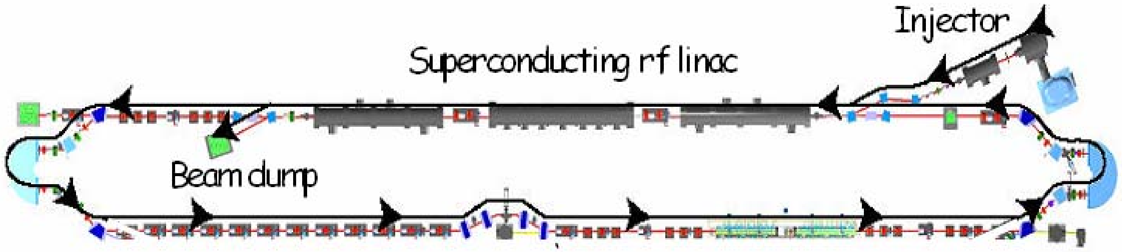
a. Longitudinal matching

b. CSR/LSC, Wakefields

c. Halo and beam loss

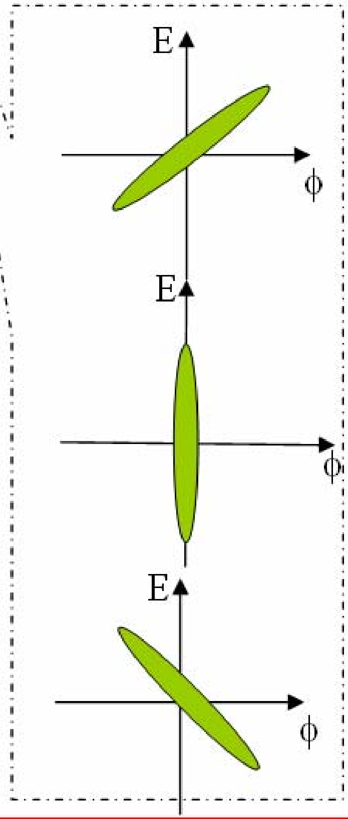
d. Beam stability and diagnostics

CSR/LSC at the JLab FEL Upgrade



Synchrotron radiation images of beam at dispersed location.

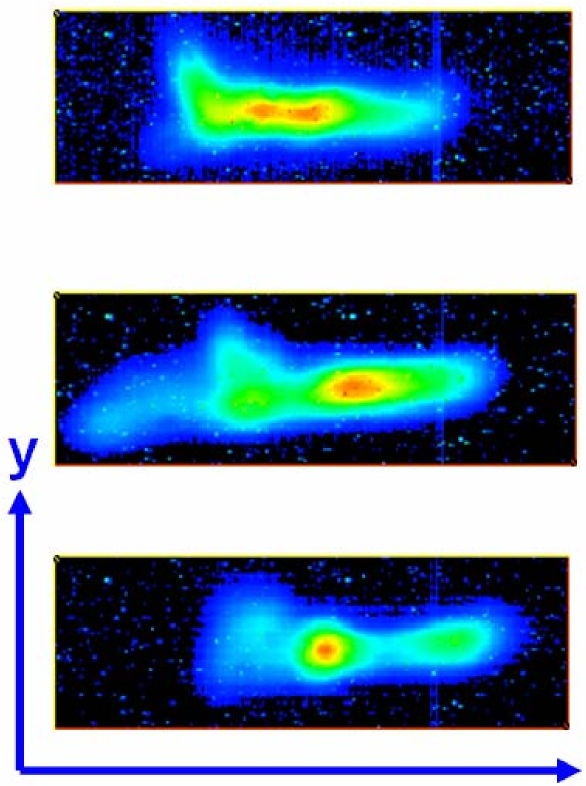
As bunch compression is varied, at constant incoming energy spread, collective effects affect the energy spread and bunch distribution. Observed features consistent with CSR/LSC effects during bunch compression. Quantitative investigation on-going.



Under compression

Perfect compression

Over compression



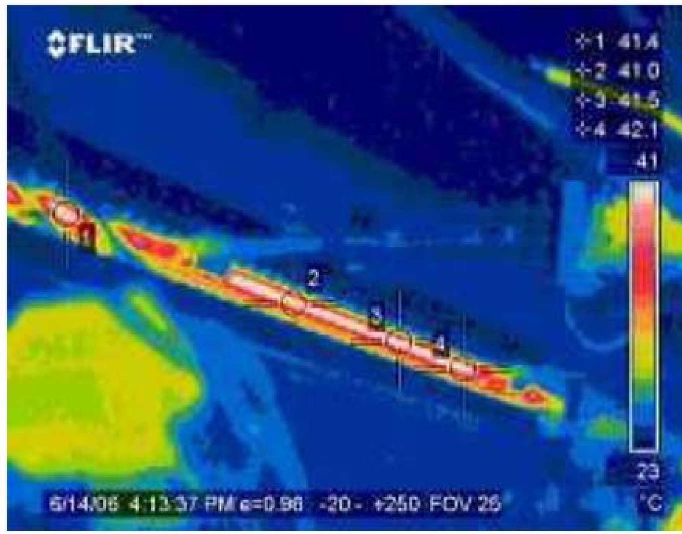
Courtesy: D. Douglas, P. Evtushenko, R. Li

Power Loss due to Resistive Wall

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

Wiggler chamber heating

- Approximately 200 W deposited on wiggler vacuum chamber (L=2m, g=15 mm) with 3.5 mA CW beam, 150 fs rms bunch length.



- Observed beam-induced heating of wiggler chamber in JLab FEL Upgrade consistent with resistive wall wakefield effect.

High current effects in Superconducting RF

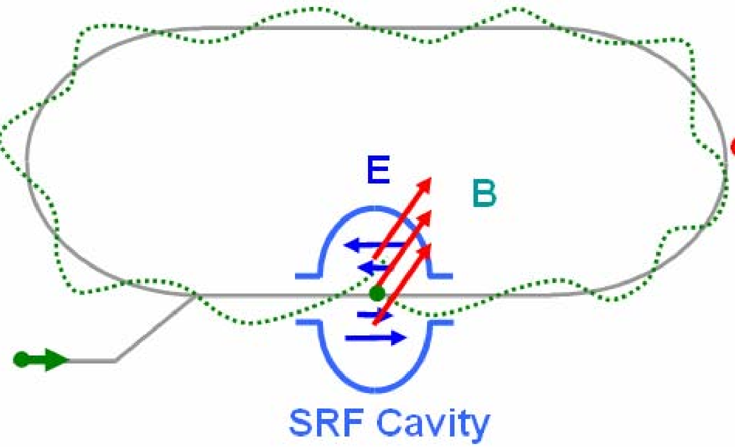
Beam stability and beam quality preservation, and cryogenic efficiency during acceleration/deceleration of high average current, short bunch length beams in SRF environment

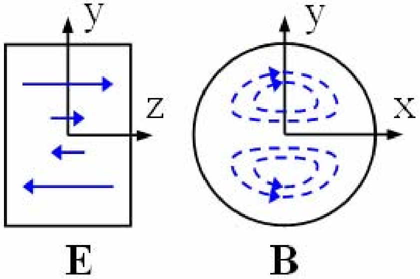
a. Efficient extraction of HOM power

b. Stability against multipass beam breakup

c. RF control and stability under max practical Q_L

Multipass Beam Breakup



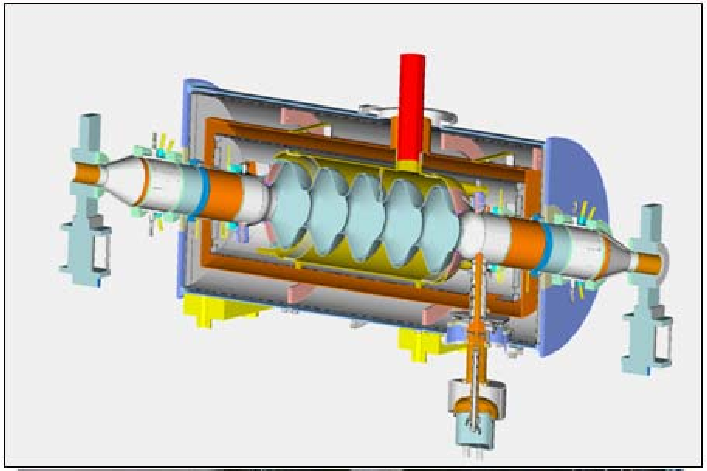


- Driven predominantly by high-Q superconducting cavities can potentially limit the average current.
- BBU a mature theory, in excellent agreement with simulations. Experimentally determined threshold at the JLab FEL (2.5 mA) in good agreement with simulations (2.7 mA).
- Beam-optical and Q-damping schemes effective in raising threshold.
- Recent design optimization of 1.3 GHz, 9-cell cavity for high current ERL operation results in thresholds that support 2-pass ERL operation at 100mA (I_{thr}~300 mA).

R. Hajima, et al.

Ampere-class Cavity Designs

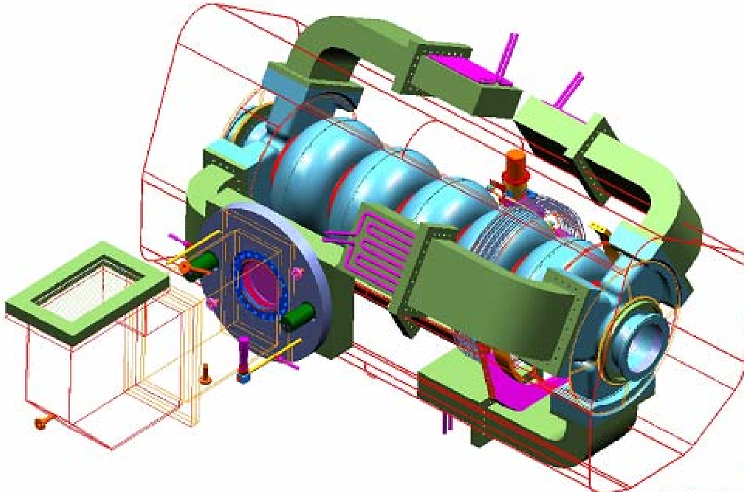
BNL "Single mode" cavity: All HOMs damped.

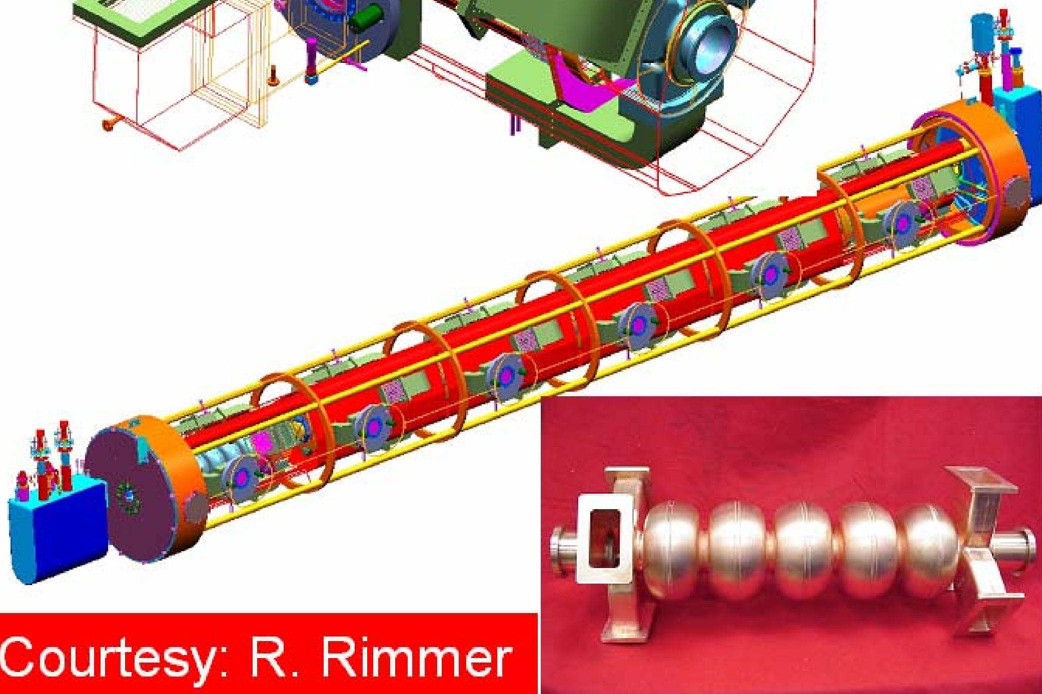


Advanced Energy Systems, Inc.

Courtesy: I. Ben-Zvi

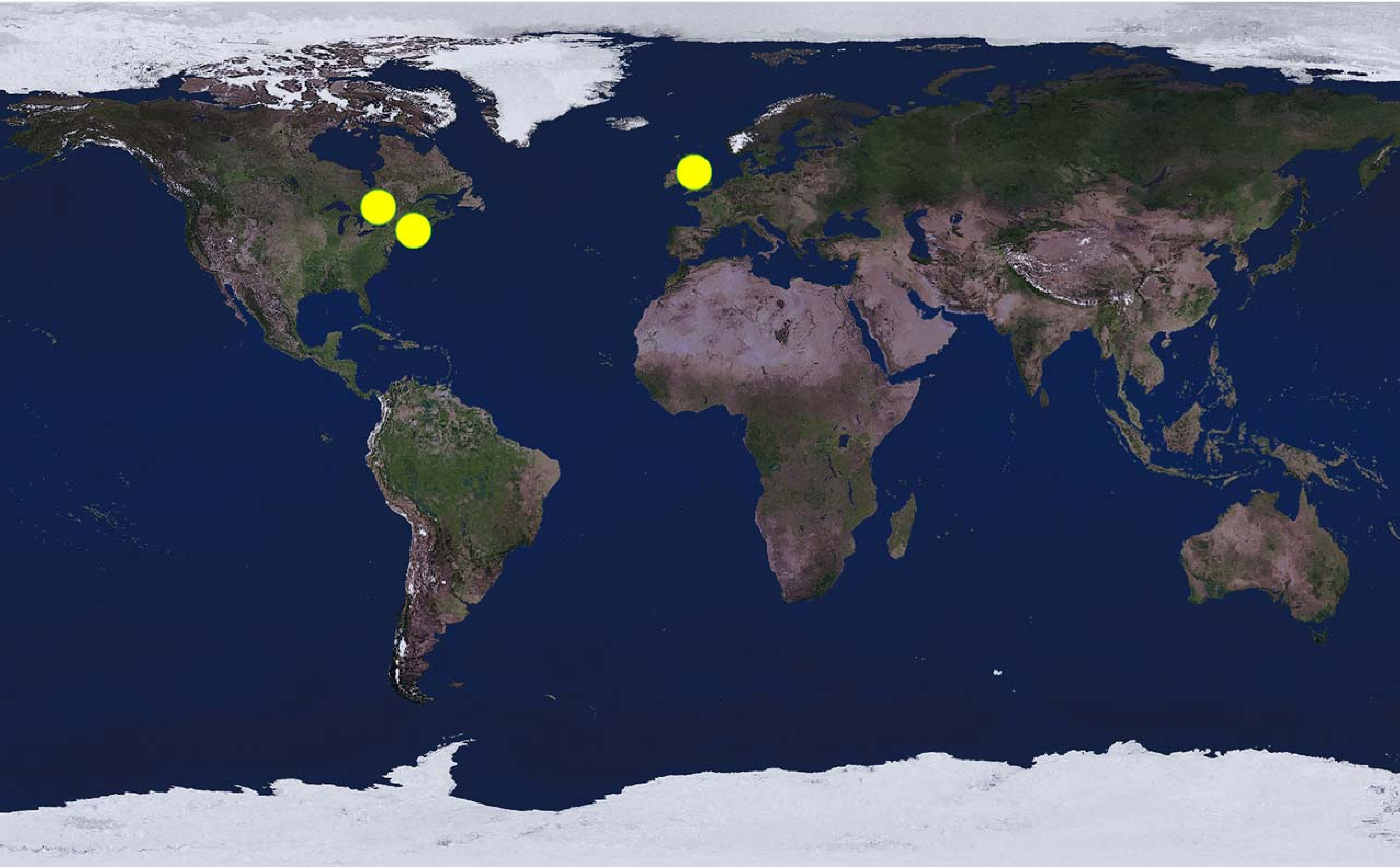
JLAB cavity/cryomodule concepts





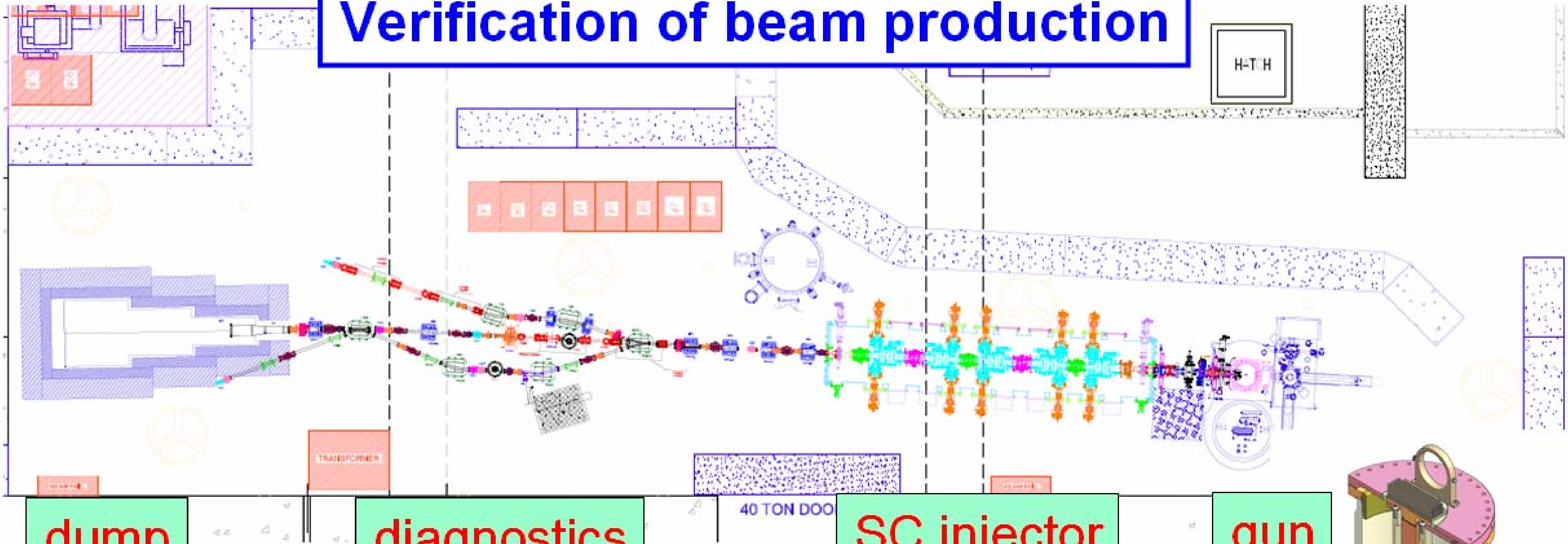
Courtesy: R. Rimmer

ERL Test Facilities

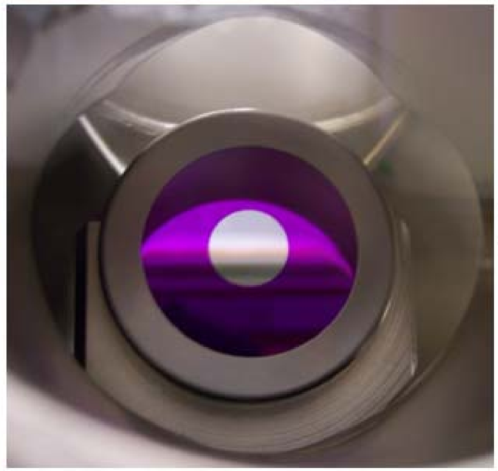


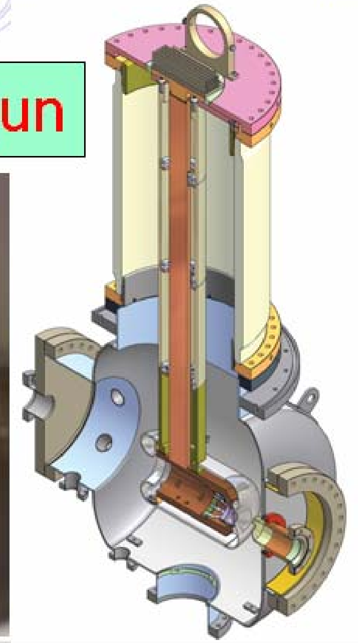
Cornell Injector prototype

Verification of beam production



dump | diagnostics | SC injector | gun





Daresbury ERLP

Gun Commissioning July/August 2006

First beam August 2006

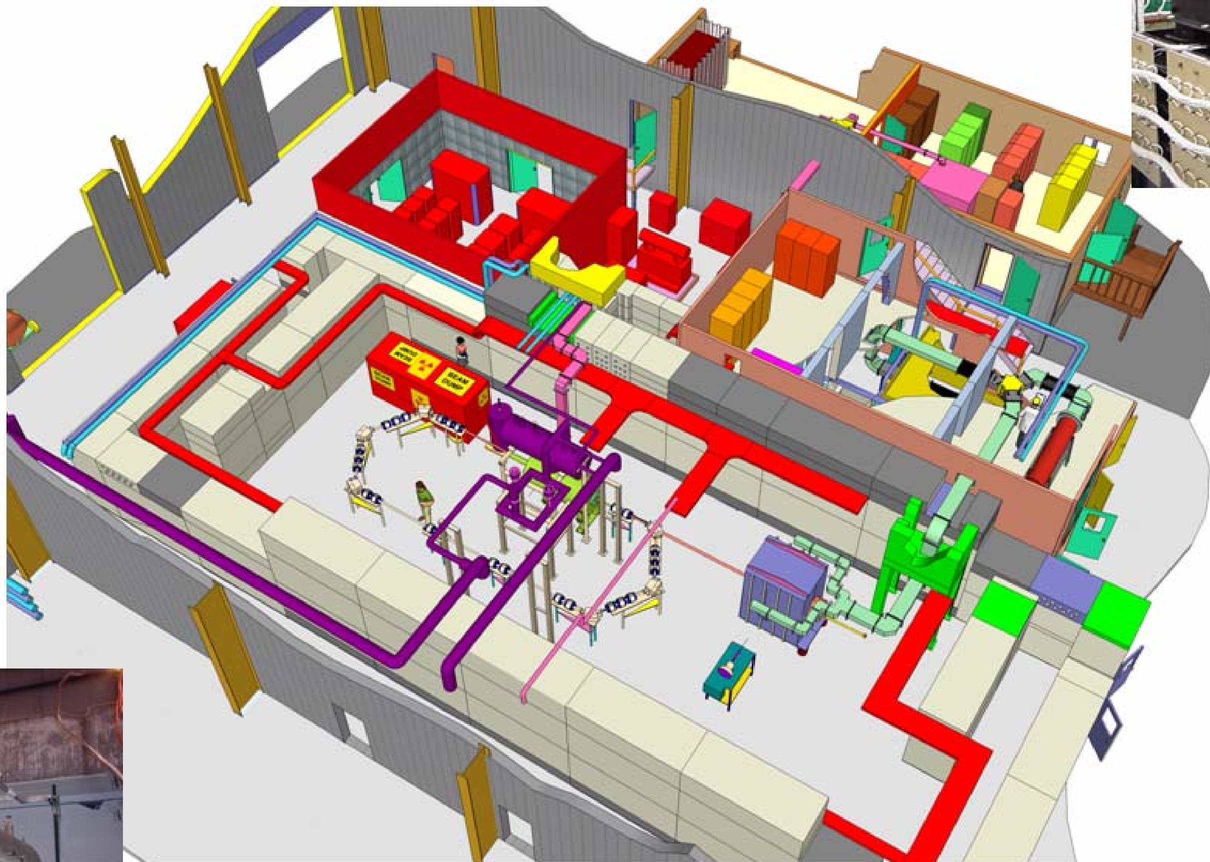
Energy recovery Christmas 2007!

BNL R&D ERL

20 MeV, 0.5 ampere
Commissioning to start Feb 2009

Klystron PS

Klystron



Summary

- ERLs provide a powerful and elegant paradigm for a broad range of applications, from high-power FELs and high average brightness, short-pulse radiation sources to electron cooling devices and high luminosity electron-ion colliders.
- The fundamental principles of ERLs have been established by the pioneering ERL-FELs presently in operation.

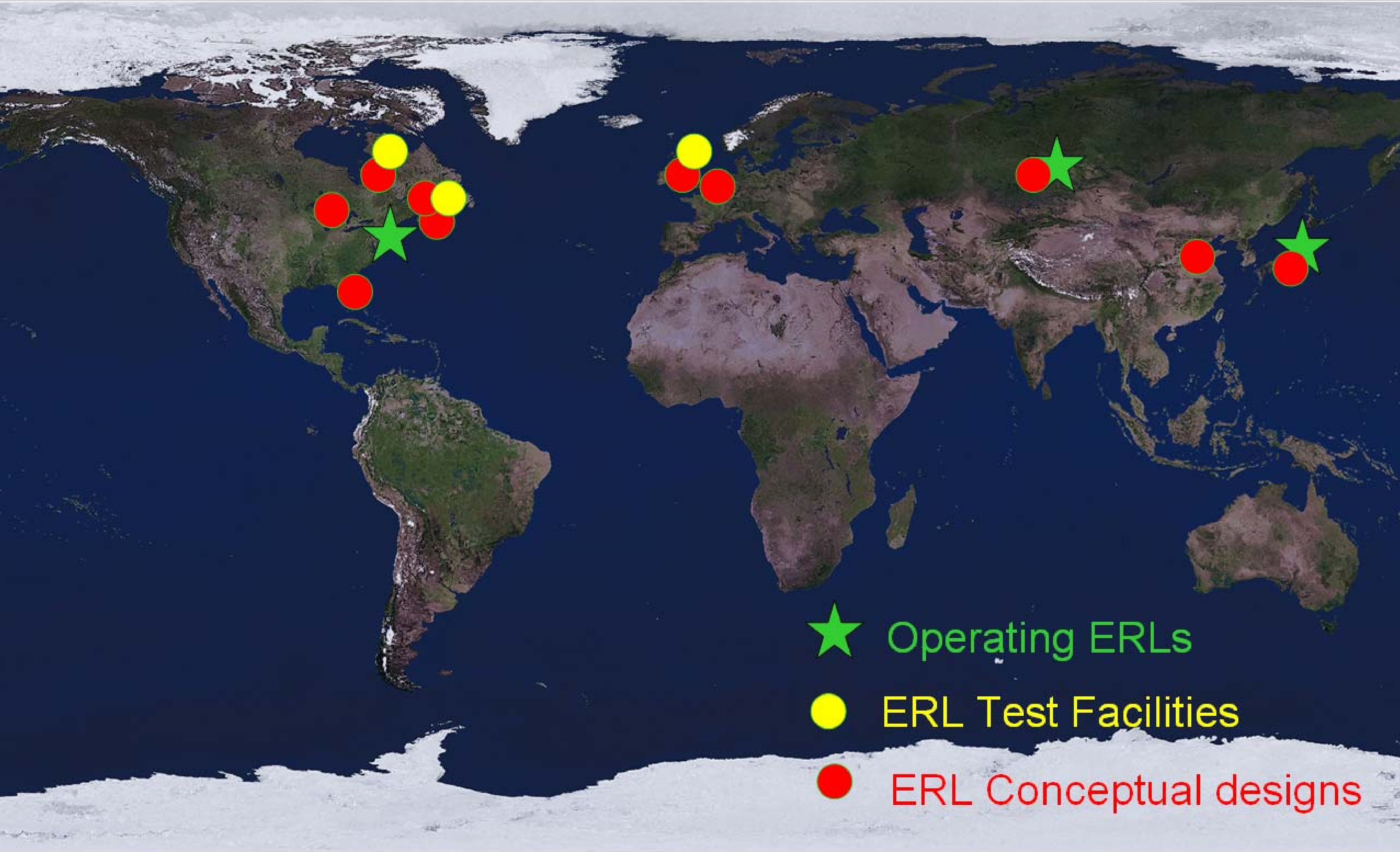
Summary (Cont'd)

- There are technical challenges and R&D opportunities that need to be addressed for the realization of next generation ERLs.
- In the past few years, tremendous progress has been made:
  - Test facilities are under construction/commissioning.
  - Vigorous R&D activities in many labs to resolve outstanding 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 ERL facilities will be constructed

Operating and Future ERLs




ERL07
41st Advanced ICFA Beam Dynamics
Workshop on Energy Recovery Linacs
Daresbury Laboratory, UK
May 21-25, 2007

Next ERL workshop

See you at Cornell for ERL2009

Acknowledgments

- I. Bazarov (Cornell)
- I. Ben-Zvi (BNL)
- S. Benson (JLAB)
- J. Clarke (Daresbury)
- J. Delayen (JLAB)
- S. Derbenev (JLAB)
- D. Douglas (JLAB)
- Pavel Evtushenko (JLAB)
- R. Hajima (JAERI)
- G. Hoffstaetter (Cornell)
- G. Krafft (JLAB)
- C. Leemann (JLAB)
- Rui Li (JLAB)
- M. Liepe (Cornell)
- G. Neil (JLAB)
- R. Rimmer (JLAB)
- S. Smith (Daresbury)
- N. Vinokurov (BINP)
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