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Overview of Energy Recovery Linacs

Ivan Bazarov

Cornell High Energy Synchrotron Source

CORNELL UNIVERSITY LEPP

LABORATORY FOR ELEMENTARY-PARTICLE PHYSICS

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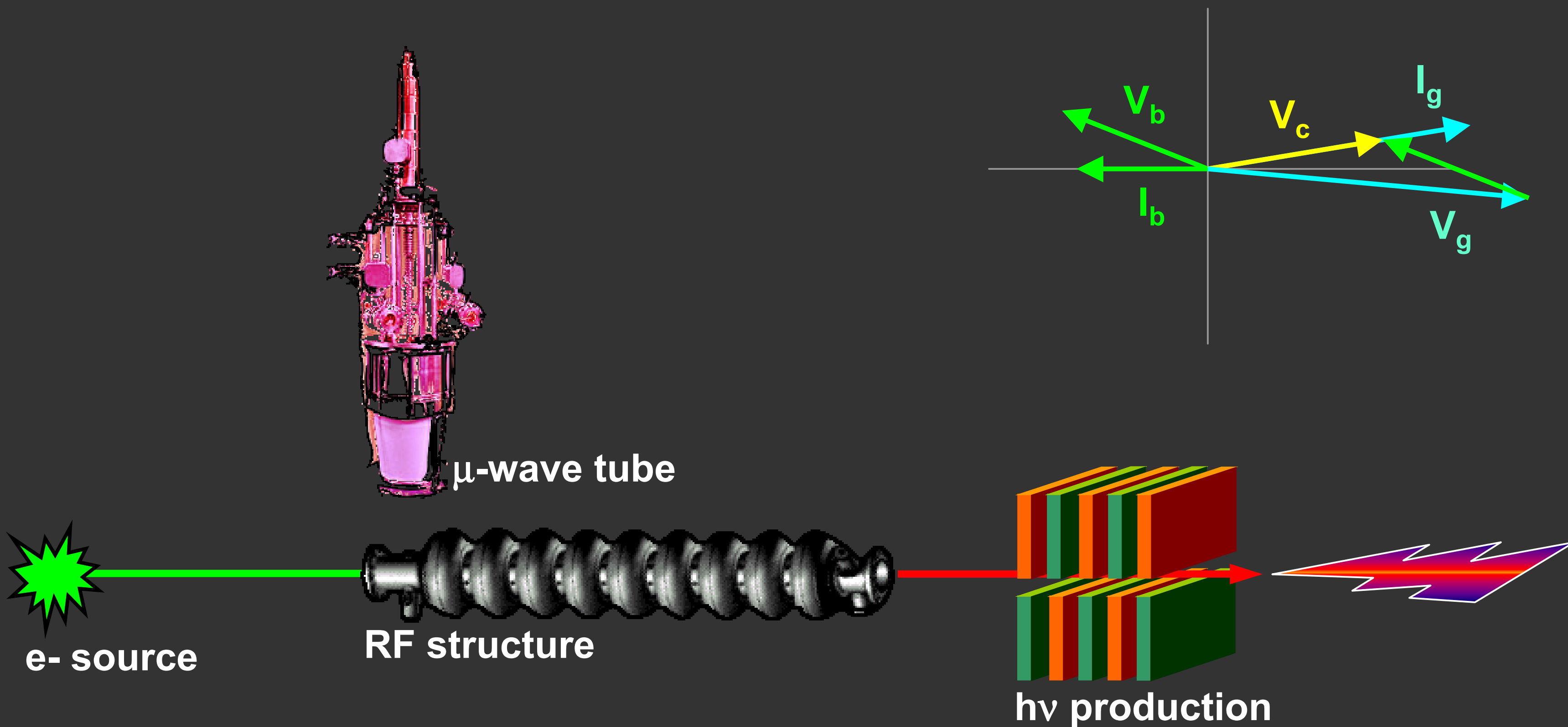
Talk Outline:

- Historical Perspective
- Parameter Space
- Operational ERLs & Funded Projects
- Challenges

ERL Concept: conventional linac



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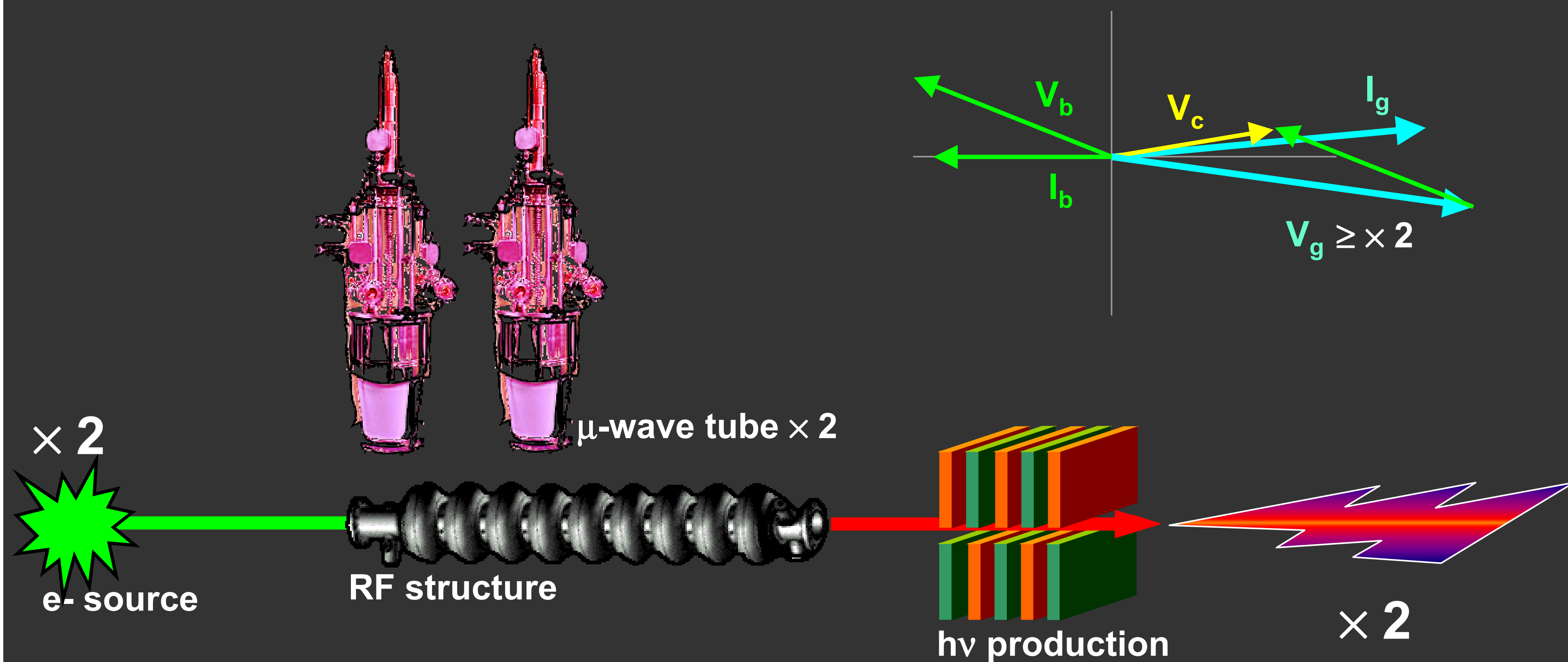
ERL Concept: conventional linac



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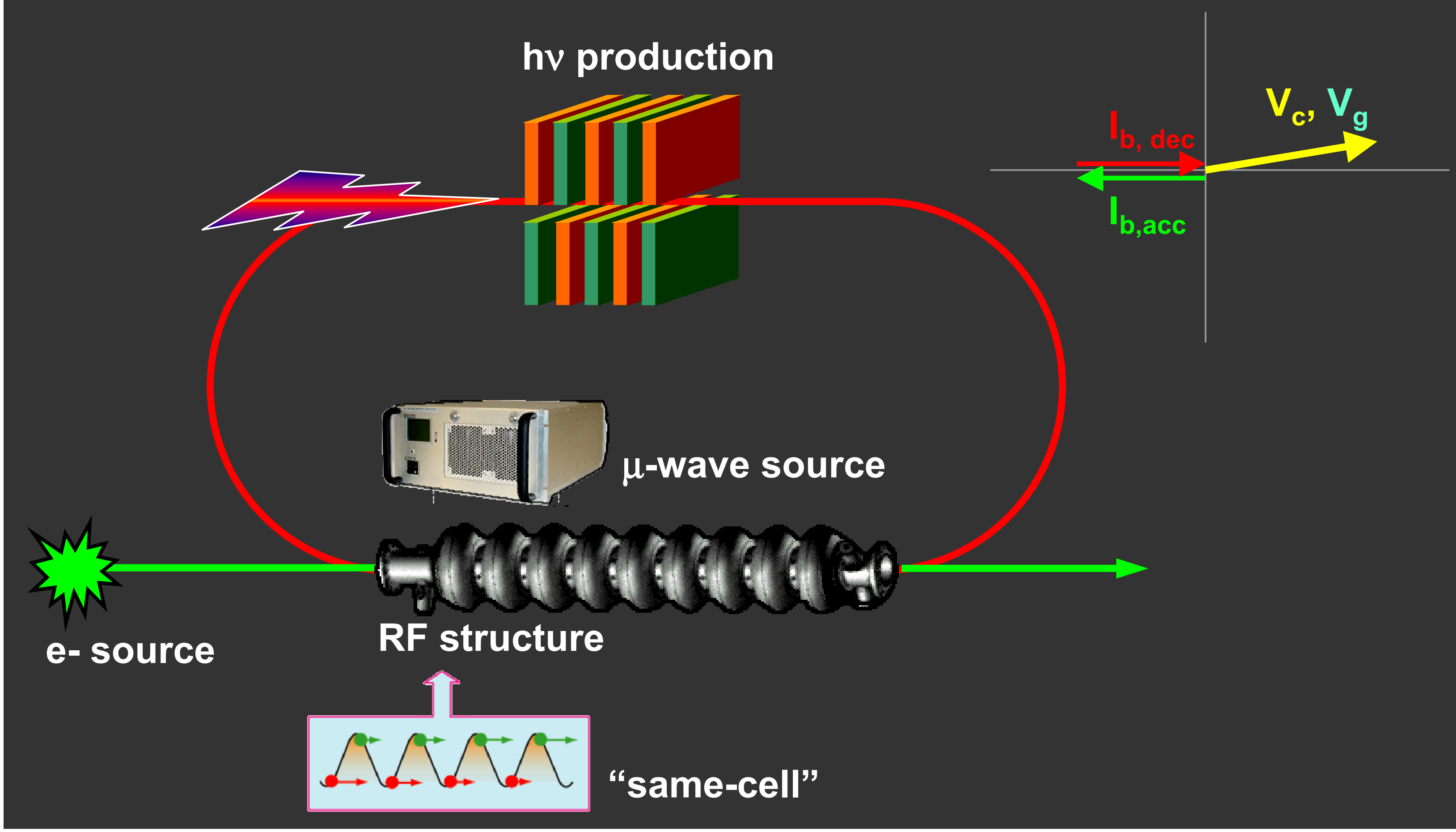
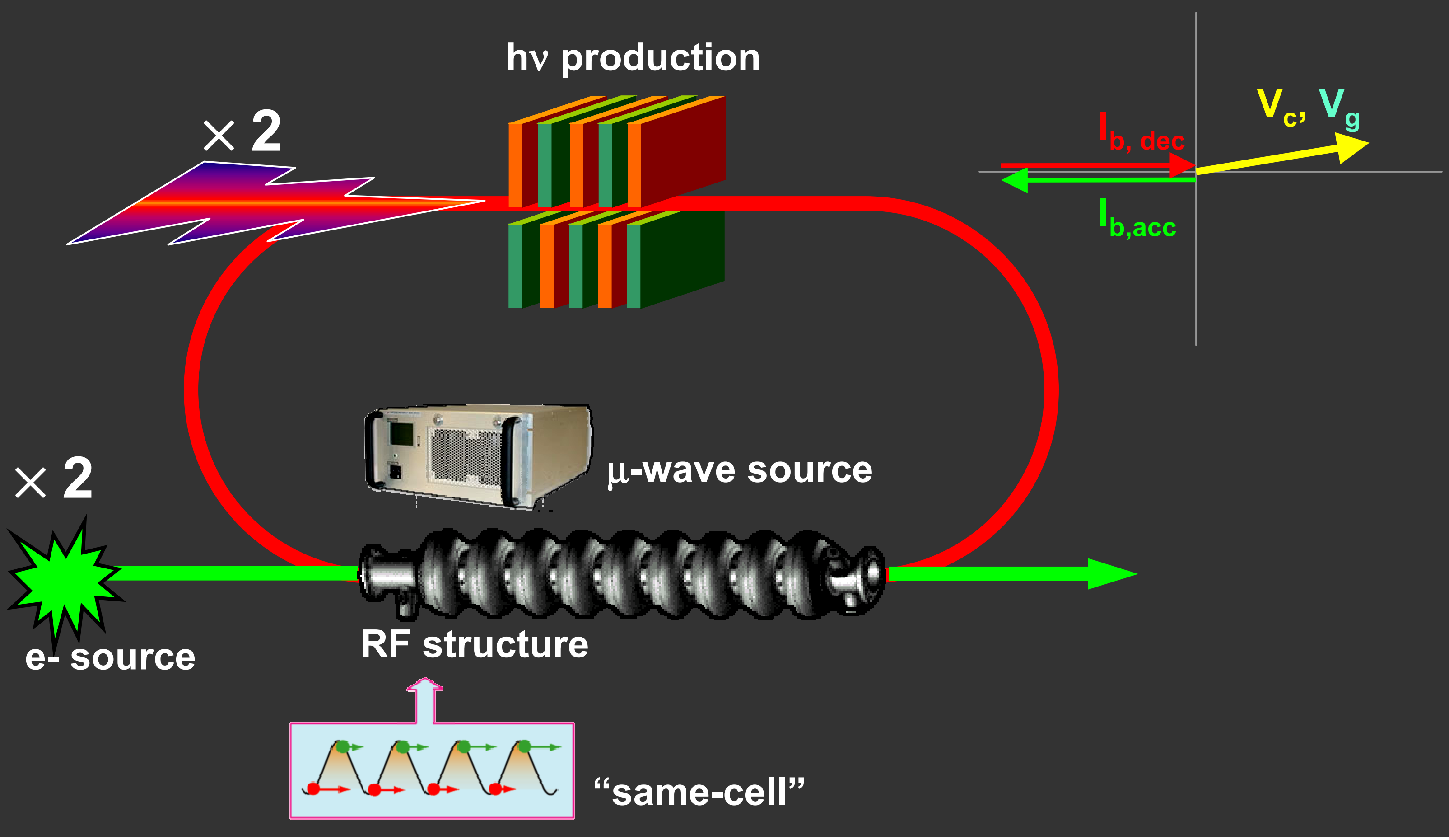
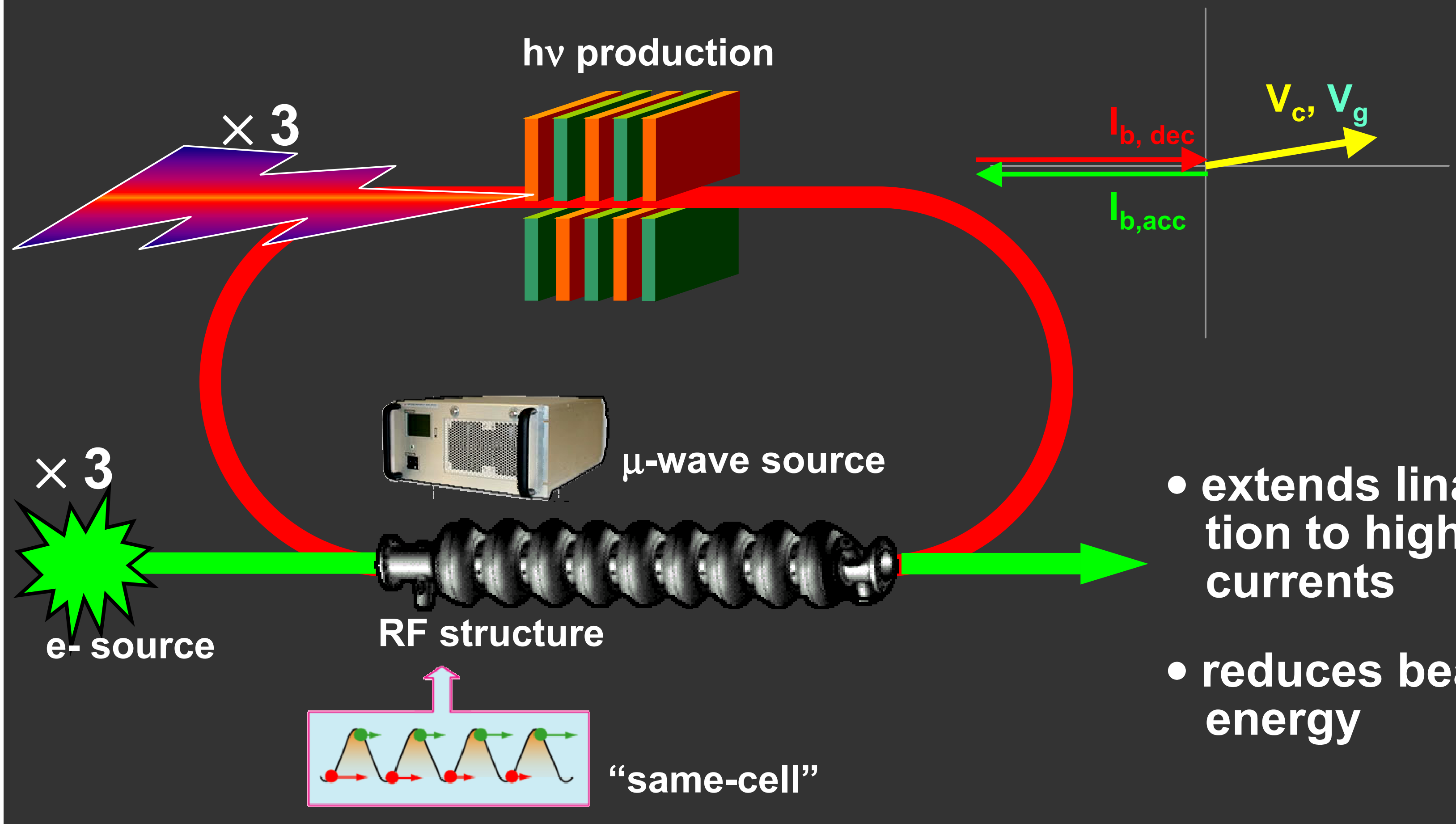
ERL Concept: energy recovery linac



ERL Concept: energy recovery linac

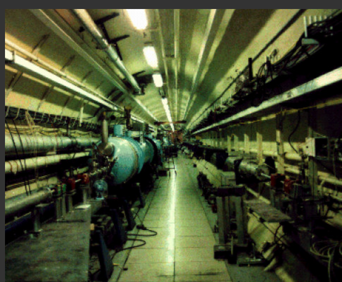


ERL Concept: energy recovery linac



- extends linac operation to high average currents
- reduces beam dump energy

ERLs: Historical Perspective



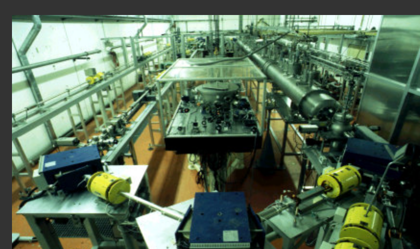
1986: Stanford SCA
T. Smith et al.
NIM A 259 (1987) 1

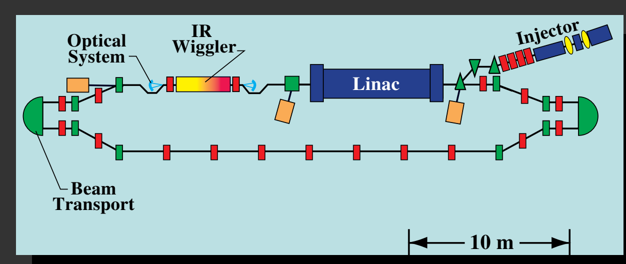
1965: M. Tigner
Nuovo Cimento
37 (1965) 1228

1990: S-DALINAC
(Darmstadt)

1999: JLAB DEMO-FEL
2002: JAERI FEL
2004: BINP FEL
2004: JLAB FEL Upgrade

2004: ERL-P
2004: BNL R&D ERL
2005: Cornell gets $





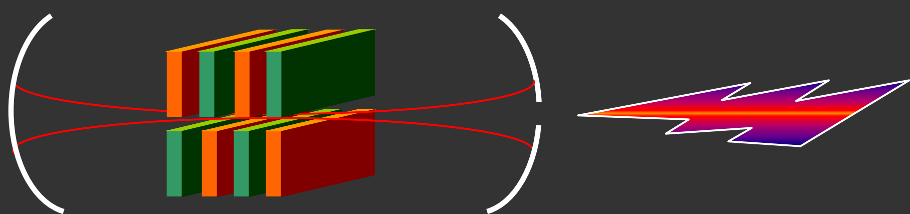
ERL Applications

- Light Sources
  - + FELs (low and high gain)
  - + Spontaneous emission
- Electron Cooling
- Electron-Ion Collider

FELs

$\varepsilon_{x,y} = \lambda/4\pi \quad \Delta E/E = 1/4N_p \quad I_{peak}$

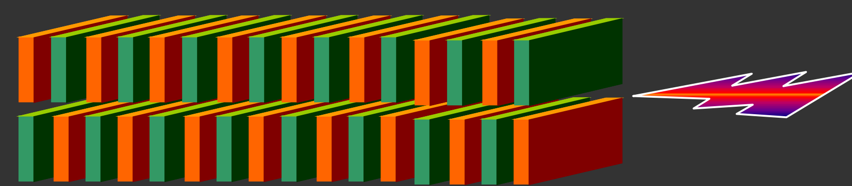
Low Gain



e.g. JLAB **40** MeV DEMO-FEL
$\varepsilon_n \le$ **13** mm-mrad, $\Delta E/E \le$ **0.25%**
I_{peak} = **60** A to lase at $\ge$ **3** μm

E $\le$ 100 MeV, I ~ 100 mA

High Gain



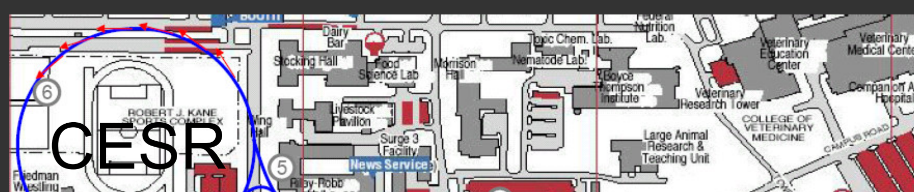
e.g. **0.7 GeV** 4GLS
$\varepsilon_n \le$ **3** mm-mrad, $\Delta E/E \le$ **0.1%**
I_{peak} = **1.5** kA to lase at **12** nm

E $\ge$ GeV, I ~ 1 mA

Spontaneous Emission ERL Light Source

Expectations:

- Emittance close to the diffraction limit (both planes)
- Brilliance ≥ 10^{22} ph/s/0.1%/mm^2/mr^2
- Energy spread ~10^{-4} (long undulators)
- Sub-ps pulses (at reduced rep. rate, ~MHz)

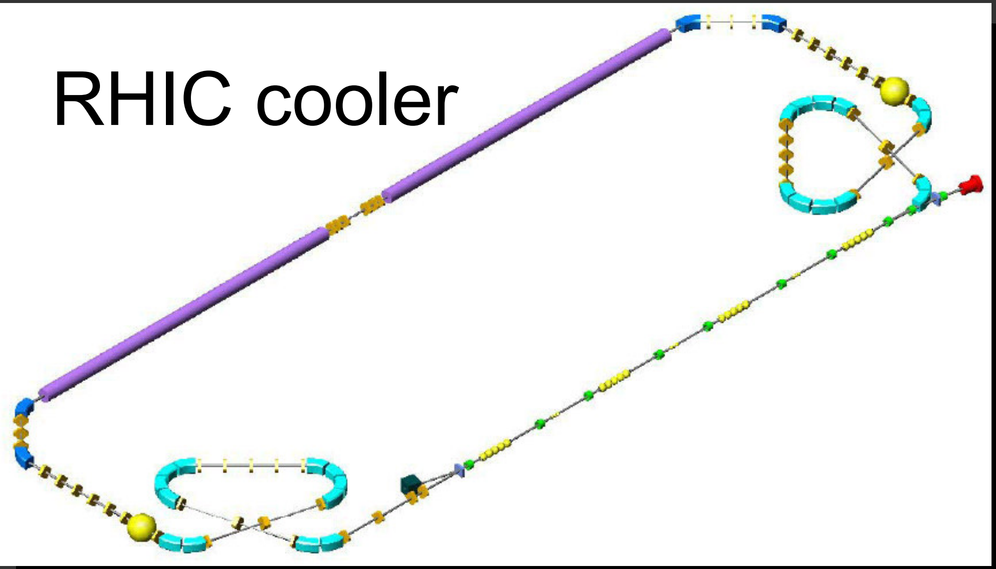


E ~ 5 GeV, I ≤ 100 mA, $\varepsilon_n \leq 0.6$ mm-mrad

Cornell's study of X-ray ERL

aetter, et al. RPPT026

Electron Cooling



Kewisch, et al. TPPE043

- E = 55 MeV
- I = 200 mA
- $\varepsilon_n \leq 40$ mm-mrad
- q = 20 nC
- $\Delta E/E \leq 3\times10^{-4}$
- magnetized beam

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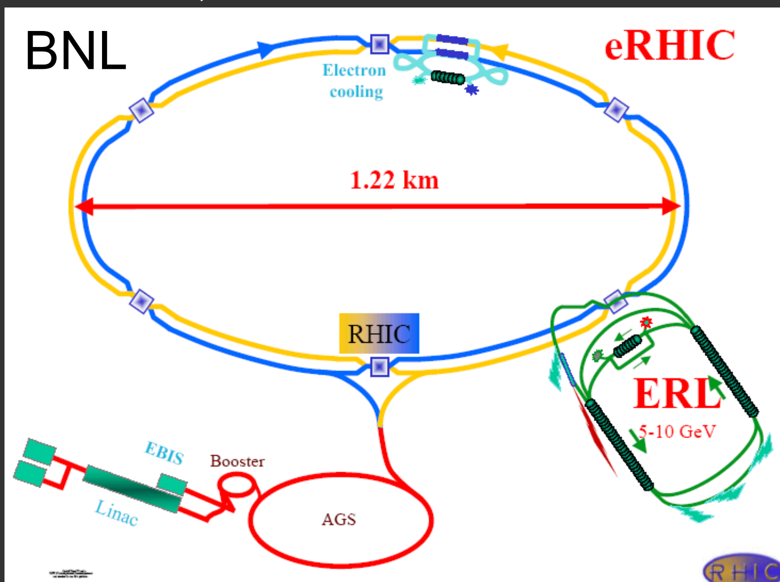
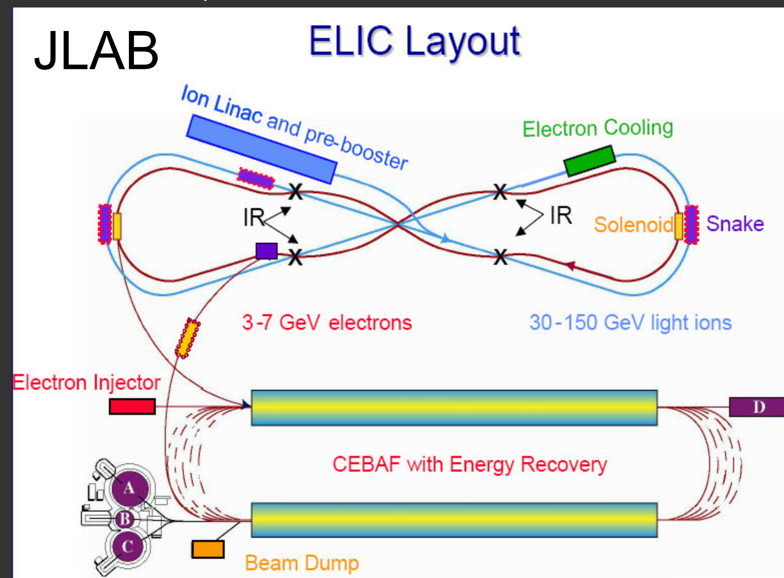
Electron-Ion Collider

Litvinenko, et al. TPPP043



Derbenev, et al. TPPP015



E = 2-10 GeV   I ~ 100s mA* ε_n ~ 10s mm-mrad

polarized beam from the gun

* injector's current with circulator ring can be much smaller

Operational ERLs

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JLAB FEL Upgrade

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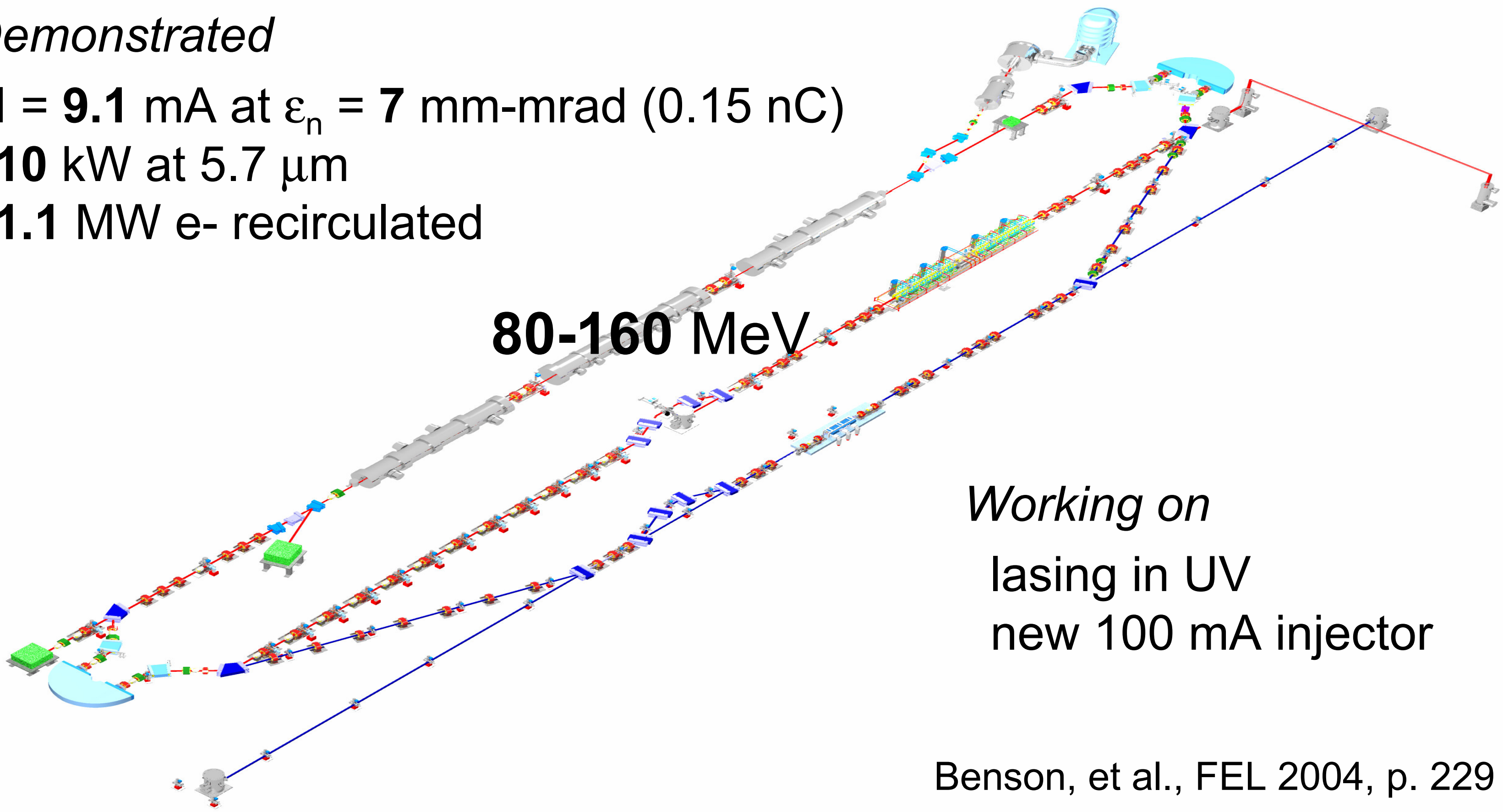
JLAB FEL Upgrade

Demonstrated

I = **9.1** mA at ε_n = **7** mm-mrad (0.15 nC)
10 kW at 5.7 µm
1.1 MW e- recirculated



Working on

lasing in UV
new 100 mA injector

Benson, et al., FEL 2004, p. 229

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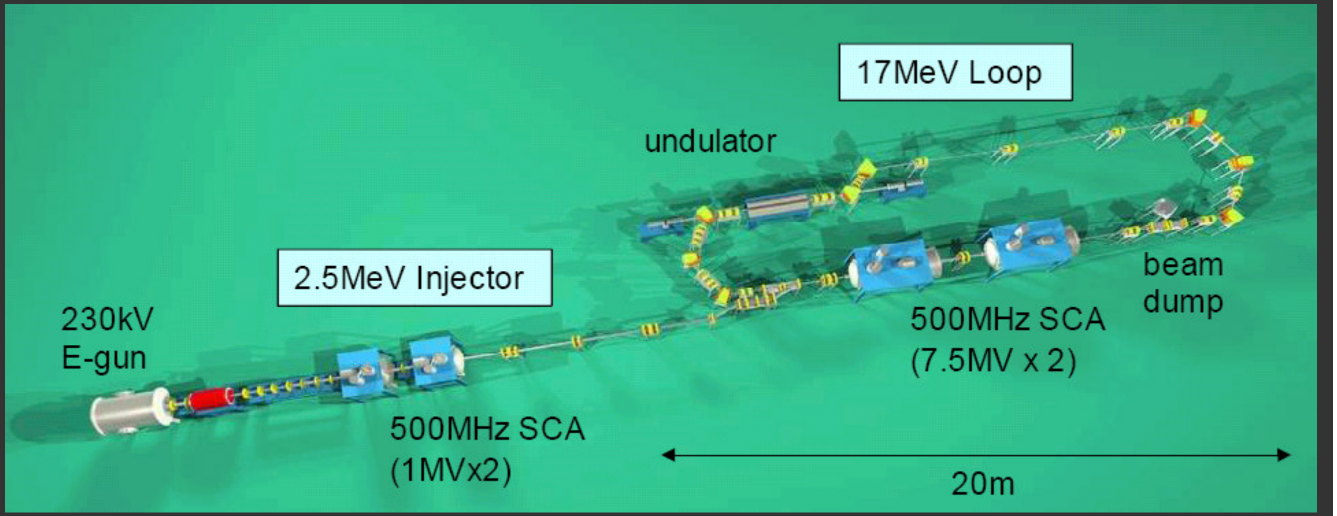
JAERI FEL

JAERI FEL

Hajima, et al., FEL 2004, p. 301



Demonstrated

I = **5** mA (1 ms pulse)

0.5 nC $\times$ 10 MHz

lasing at ~22 μm

Working on

injector upgrade (5 $\rightarrow$ 10 $\rightarrow$ 20 $\rightarrow$ 40 mA)

long pulse operation (1 s)

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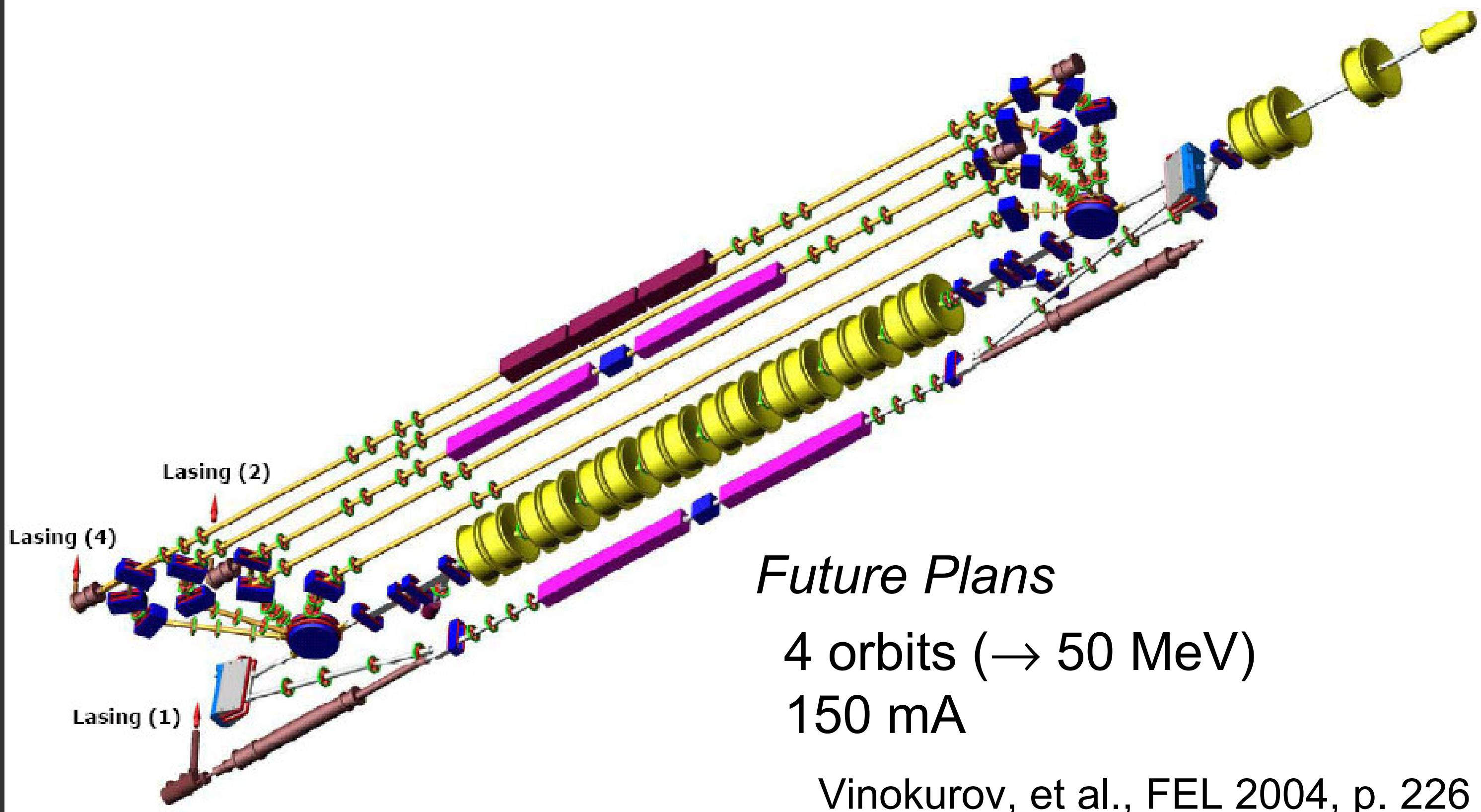
BINP Accelerator-Recuperator FEL

BINP Accelerator-Recuperator FEL



Future Plans

4 orbits ($\rightarrow$ 50 MeV)
150 mA

Vinokurov, et al., FEL 2004, p. 226

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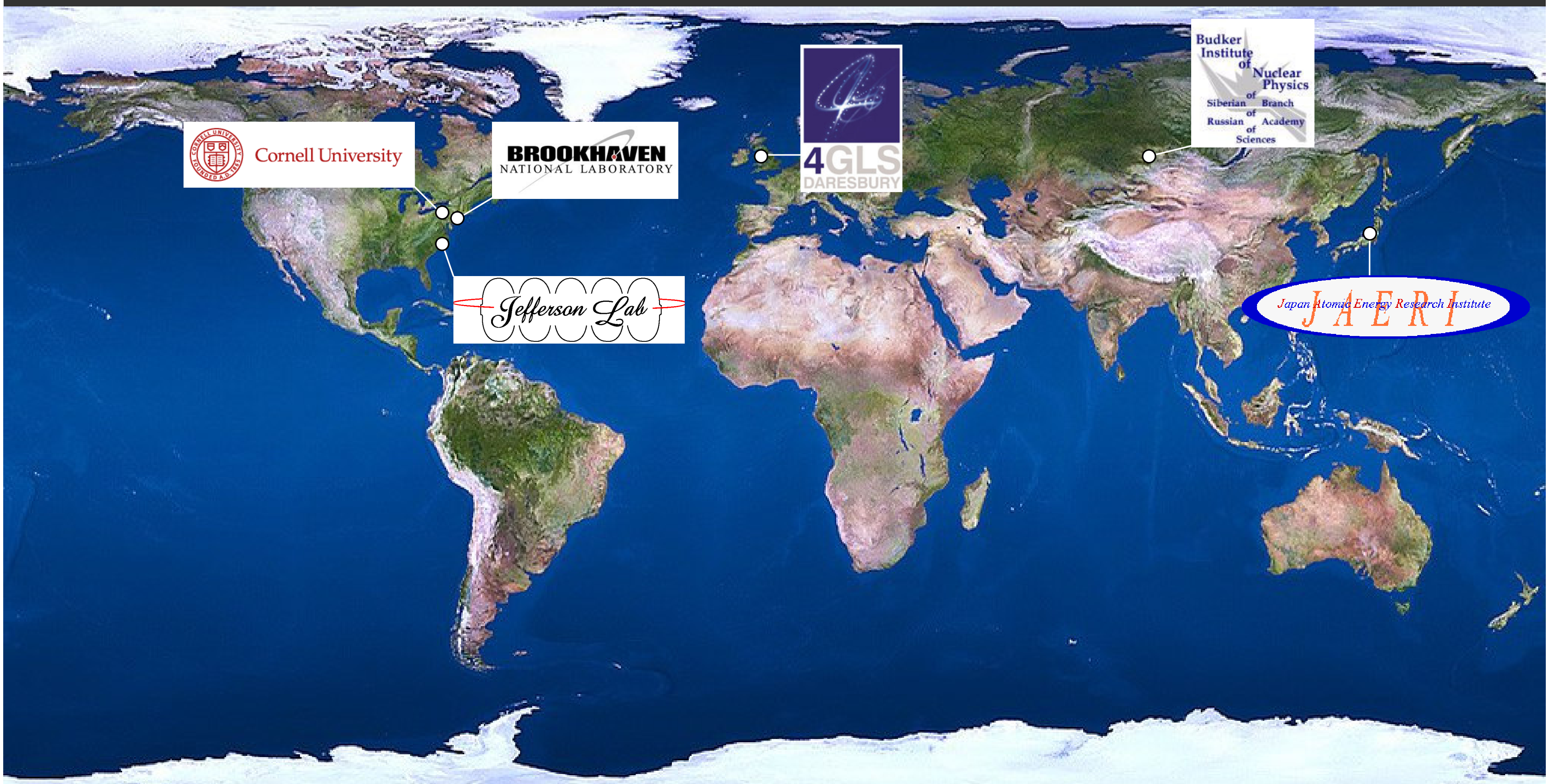
Ongoing ERL Work



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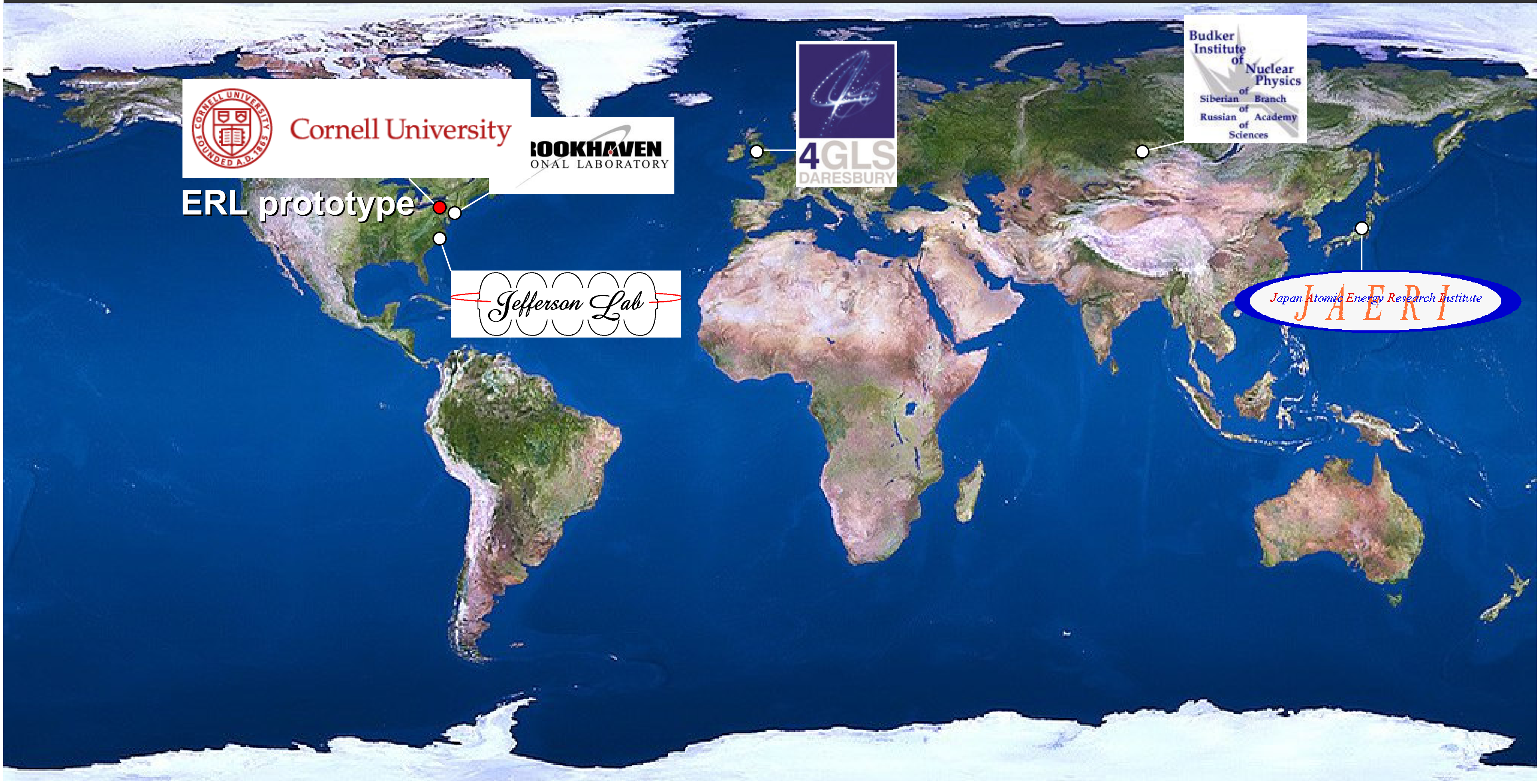
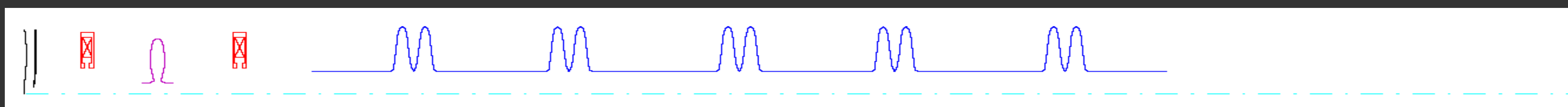
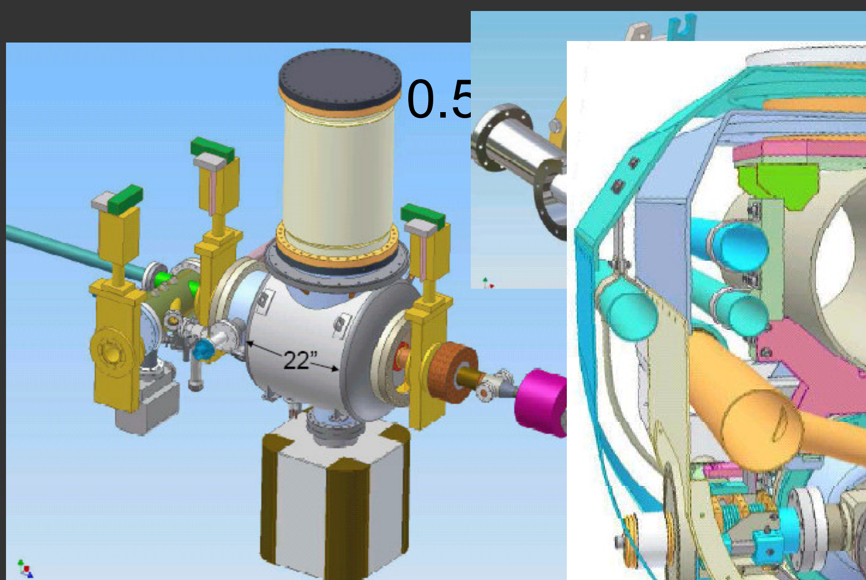
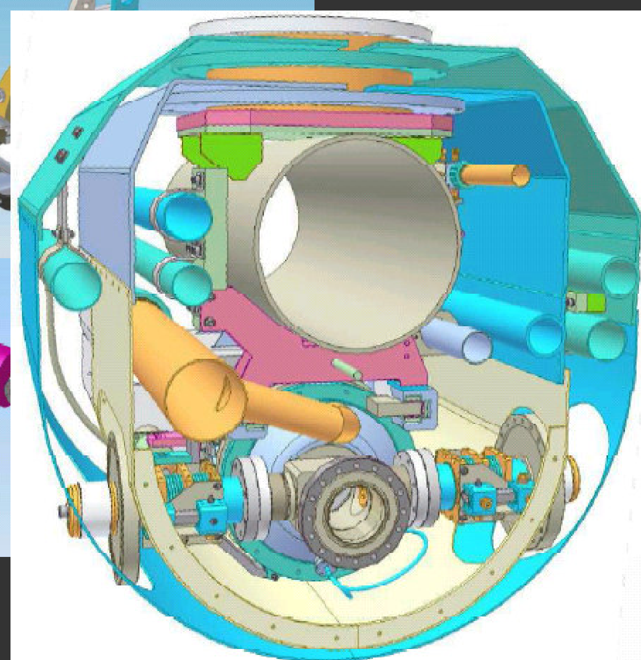
Cornell ERL Prototype



Cornell ERL Prototype







E = 5-15 MeV

beam power ≤ 0.5 MW

max current 0.1 A

q = 0.01-0.4 nC

ε_n = 0.1-1 mm-mrad

Liepe, et al. TPPT094, 090
Sinclair, et al. WPAE025

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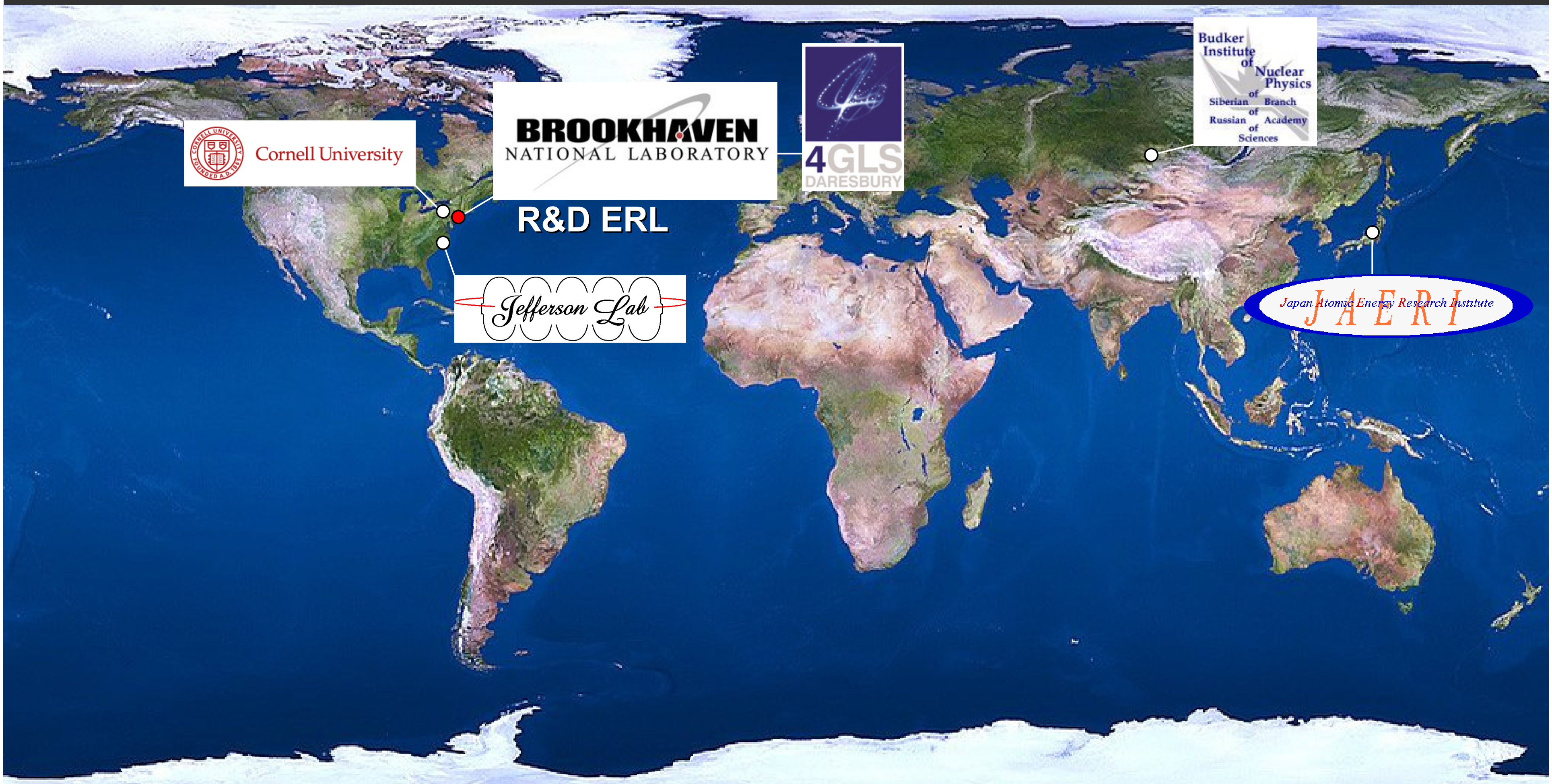
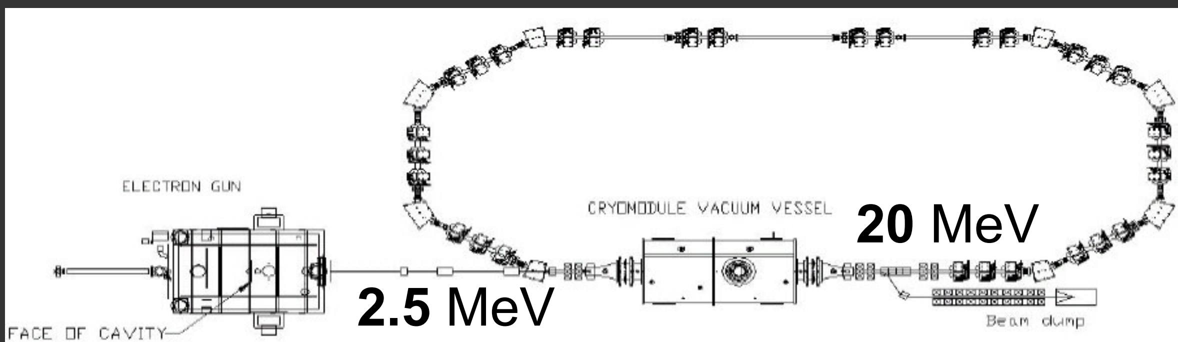
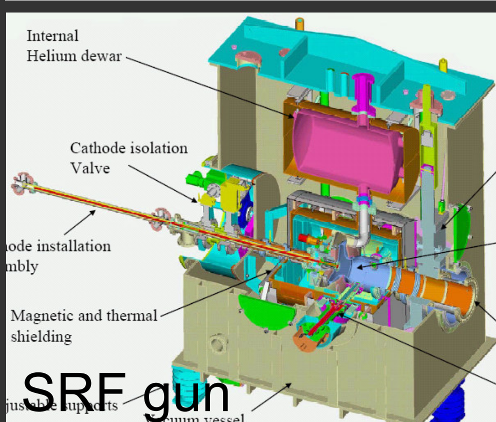
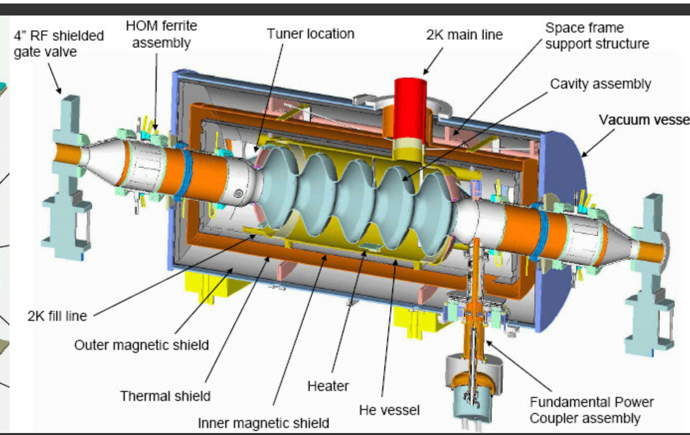
BNL R&D ERL



BNL R&D ERL







q ~ 20 nC
ε_n ~ 30 mm-mrad
I_{max} = 0.2 A

q ~ 1.3 nC
ε_n ~ 1-3 mm-mrad
I_{max} = 0.5 A

Ben-Zvi, et al. RPPE009
Litvinenko, et al. RPPT032
Kayran, et al. RPPT022

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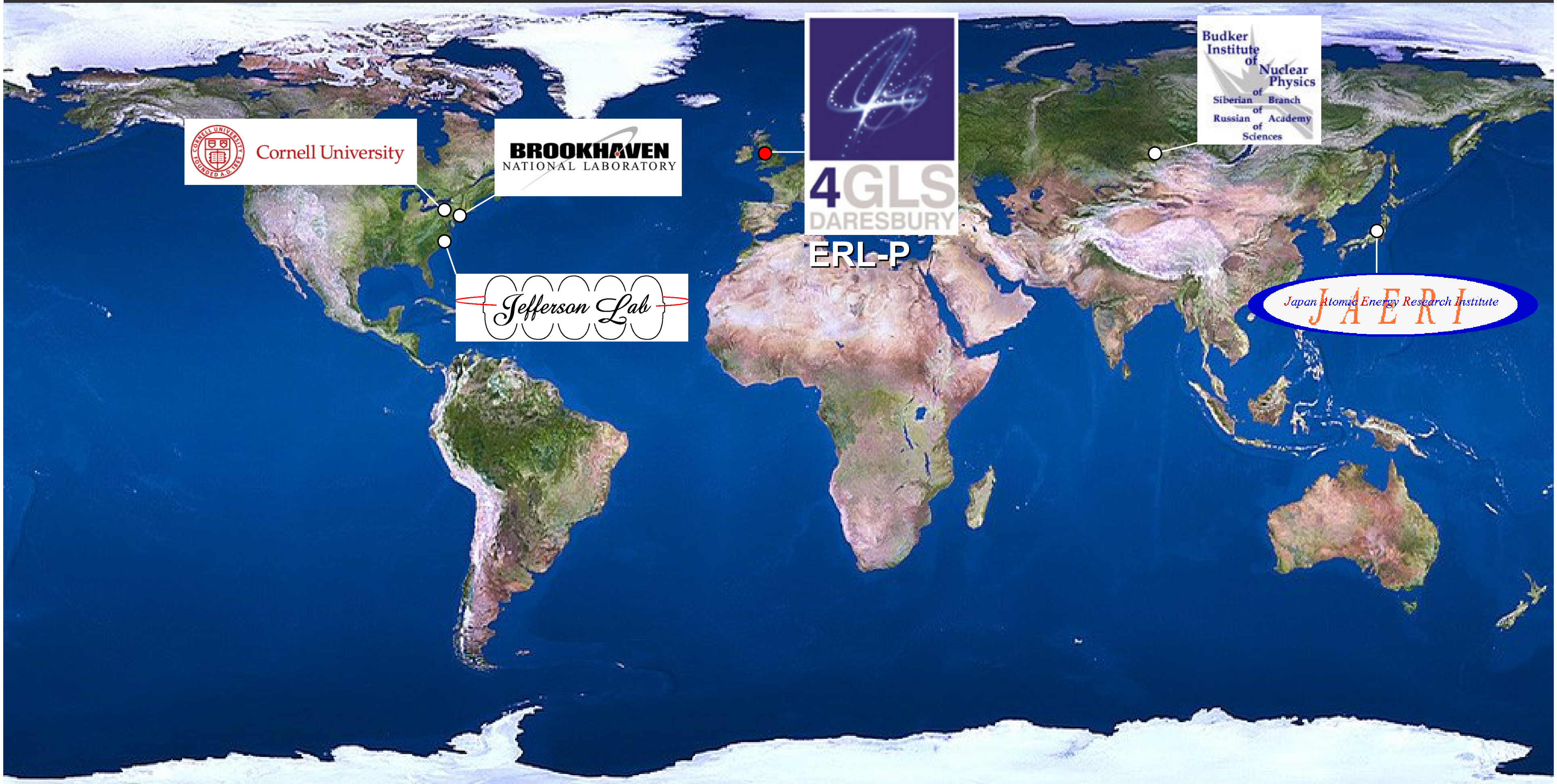
Daresbury ERL-P



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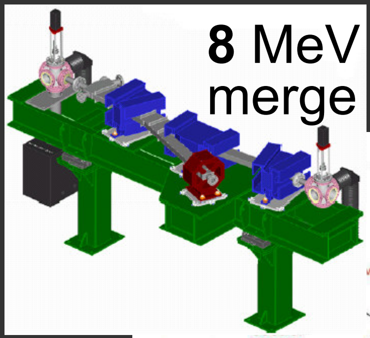
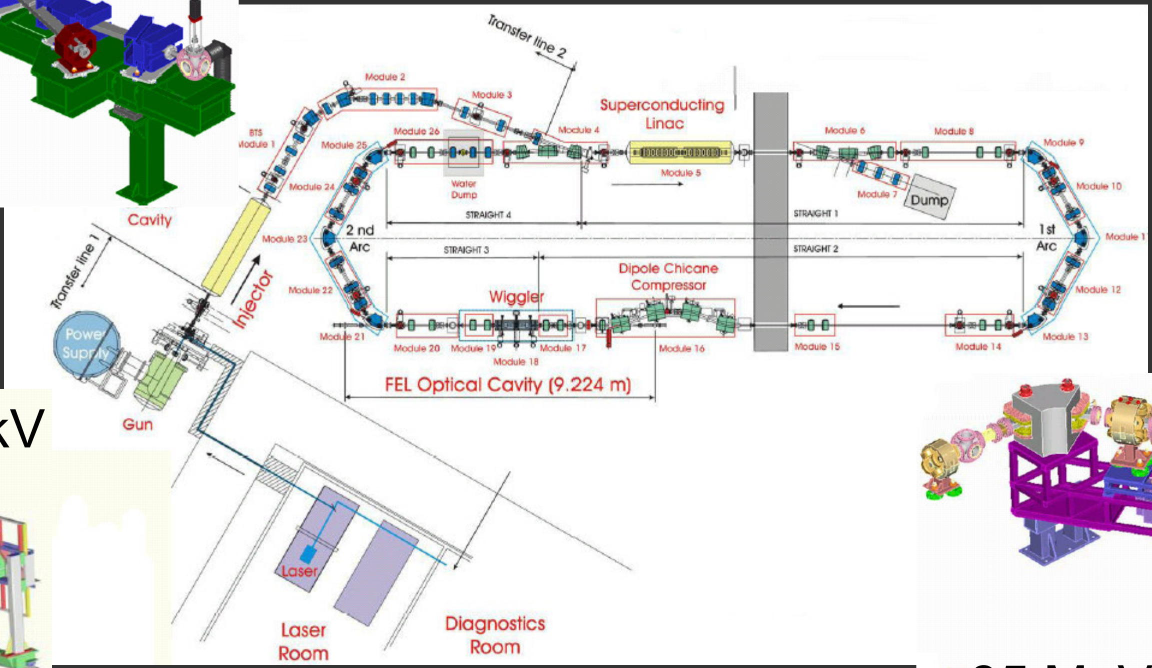
Daresbury ERL-P

Poole TOAB005





Challenges

- High current & low emittance beam production
- Emittance control
- Beam/orbit stability
- SRF issues
- Instrumentation & diagnostics

Injector

- Three gun types DC/NCRF/SRF
- Cathode QE/longevity/E_{therm}
- Laser for optimal shape
- Emittance compensation

Exploring: SE cathode amplifier (Chang, et al. RPPE032)

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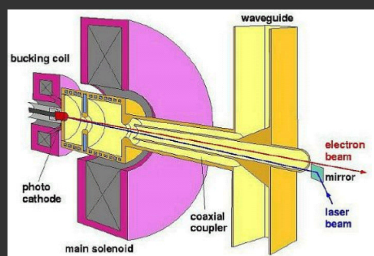
Cathode Field ← E_{therm}

NCRF

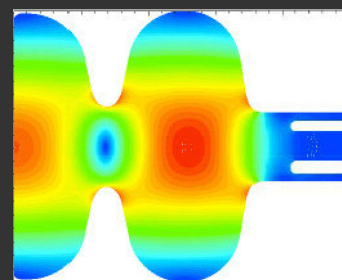


pulsed!

E_{cath} = 120 MV/m
τ_{laser} = 2.7 ps rms
σ_{laser} = 0.5 mm rms

$\tau_{laser} \rightarrow z$ = 0.08 mm

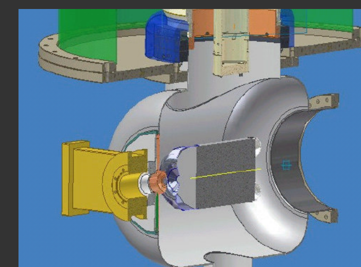
SRF



E_{cath} = 43 MV/m
τ_{laser} = 5.8 ps rms
σ_{laser} = 0.85 mm rms

$\tau_{laser} \rightarrow z$ = 0.12 mm

DC



E_{cath} = 8 MV/m
τ_{laser} = 13 ps rms
σ_{laser} = 2 mm rms

$\tau_{laser} \rightarrow z$ = 0.12 mm

1 nC

2×18 MV/m   2×6 MV/m   2×1 MV/m

s a m e   s i m u l a t e d   e m i t t a n c e

$E_{cath} / E_{s.charge}$ = $E_{cath} / E_{s.charge}$ = $E_{cath} / E_{s.charge}$

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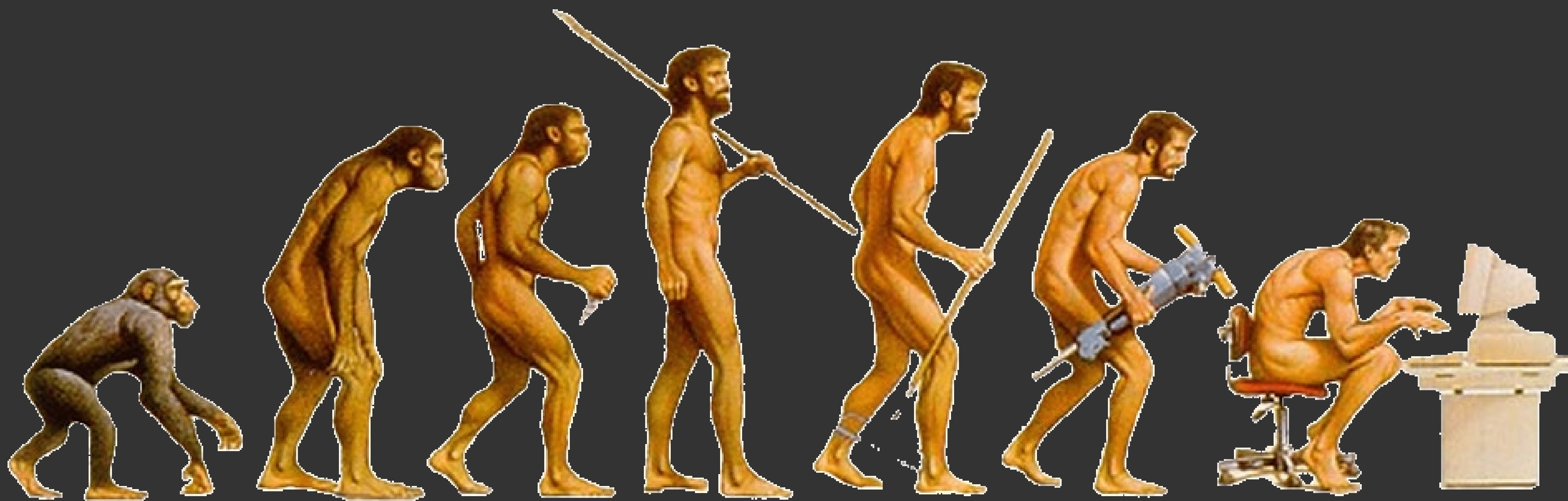
Evolving Into Optimal Injector Design



Parallel Multiobjective Evolutionary Algorithm

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Evolving Into Optimal Injector Design

> 20 variables optimization

through

parallel evolutionary algorithms

Bazarov, et al. WPAP031

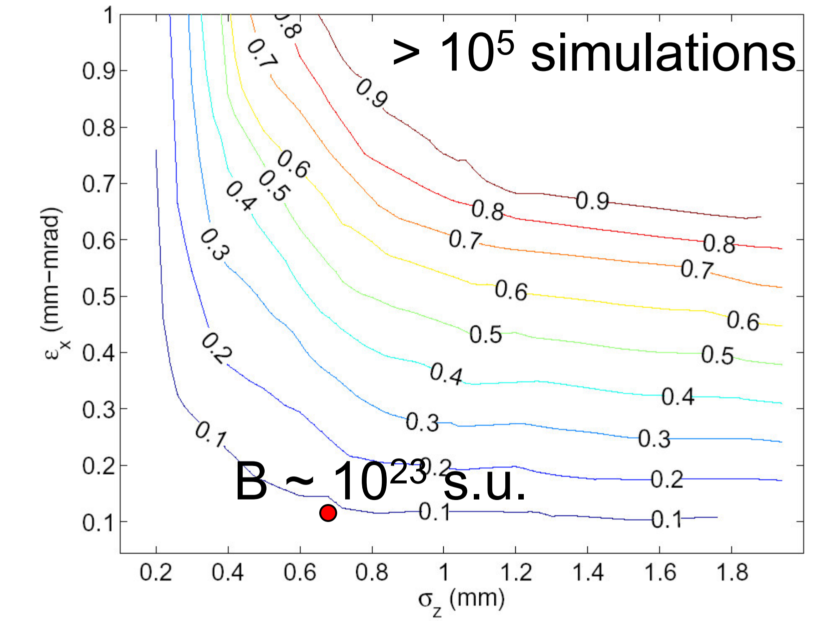

FIG. 10: Transverse emittance vs. bunch length for various charges in the injector (nC).

$\varepsilon_n[\text{mm-mrad}] \approx (0.73+0.15/\sigma_z[\text{mm}]^{2.3}) \times q[\text{nC}]$

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Emittance Control

- All of the many issues of pulsed linacs
- For non-FEL LS, I_{peak} can be ~10 A $\rightarrow$ little CSR
- Emittance growth due to SR is important for $E \geq 5$ GeV; well understood.
- Good experience from JLAB FEL on longitudinal phase space manipulations with lattice when energy spread becomes important

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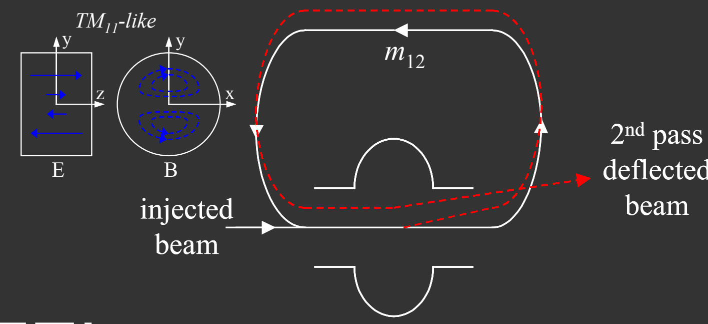
BBU: Measurements

Tennant TOAC004



Extensive BBU study at JLAB FEL

+ Three different methods of the threshold
  - direct observation
  - BTF measurement of $Q_{eff} = Q / (1 – I/I_{th})$
  - growth rate of HOM power $\tau_{eff} = \tau / (1 – I/I_{th})$
+ Good agreement between measurements (2.5 mA) and simulations (2.7 mA)
+ Various BBU suppression techniques increase the threshold by up to ×100 times: a) phase advance; b) coupling; c) passive/active Q-damping

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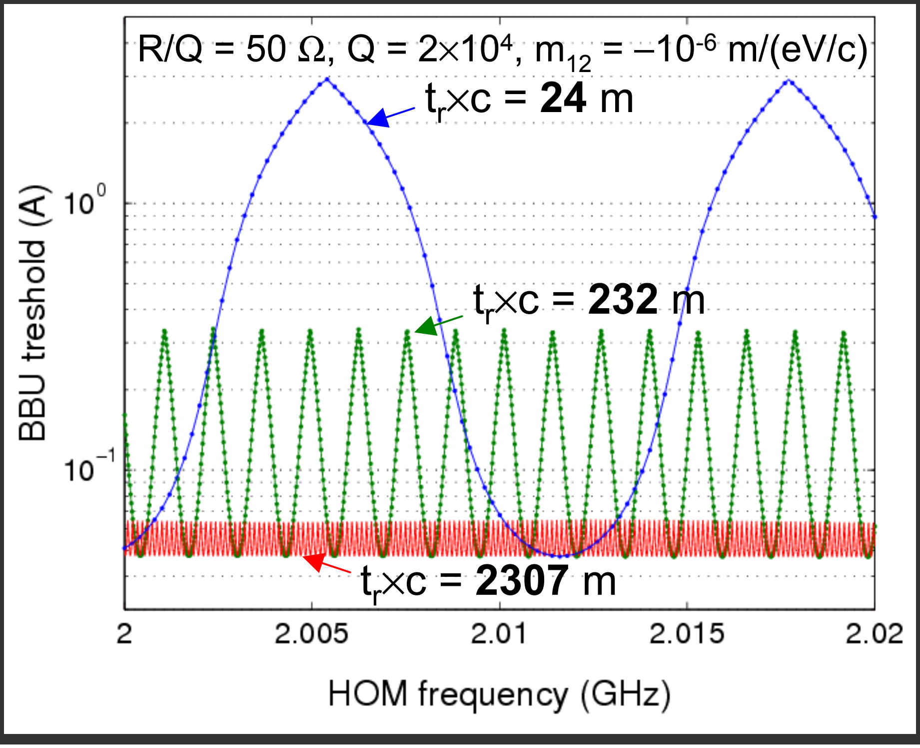
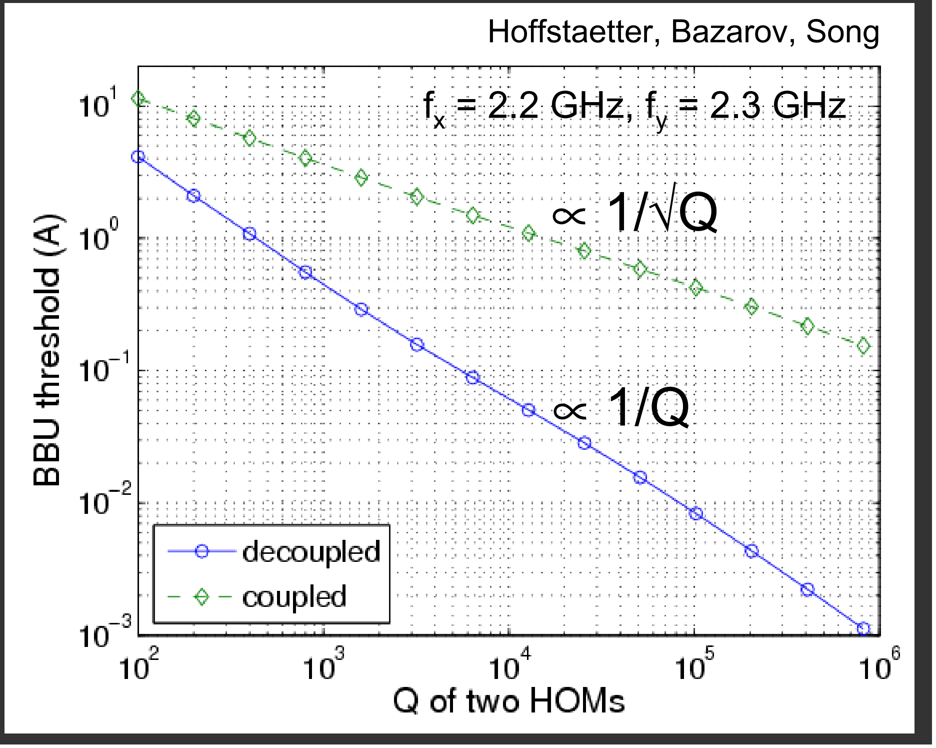
BBU: Theory & Computation

- Several different codes (JLAB, Cornell, JAERI)
- Mature theory; excellent agreement with codes





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Orbit Stability

- Sub-micron stability (rms) is required for ERL LS in both horizontal and vertical planes
- E.g. CEBAF demonstrates 20 μm rms (limited by BPM noise)
- 10^{-4} energy stability is needed
- demonstrated at CEBAF

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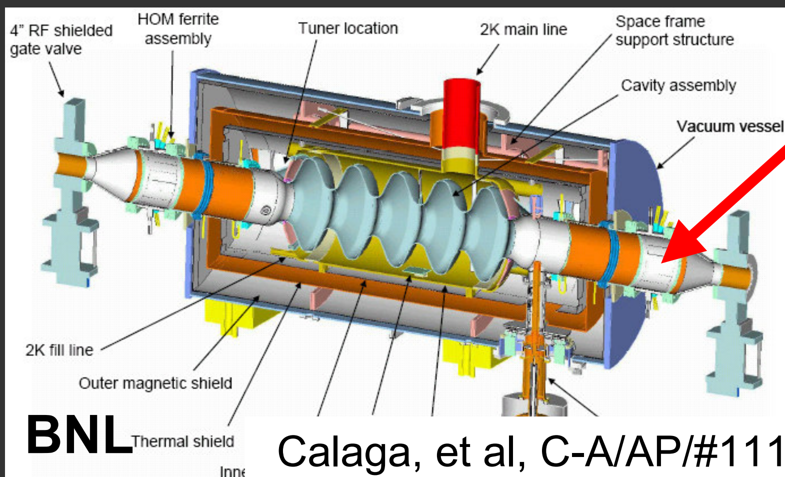
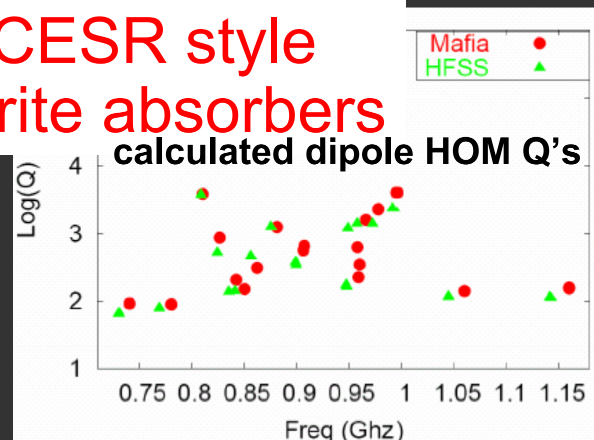
SRF Challenges

- $Q_0 = 2\times10^{10}$ at 15-20 MV/m is desirable
- cavity/cryomodule design that minimizes microphonics
- $Q \leq 10^4$ for primary dipole and $Q \leq 10^3$ for (resonant) monopole HOMs is desired
- smart HOM power handling
- superior LL RF control

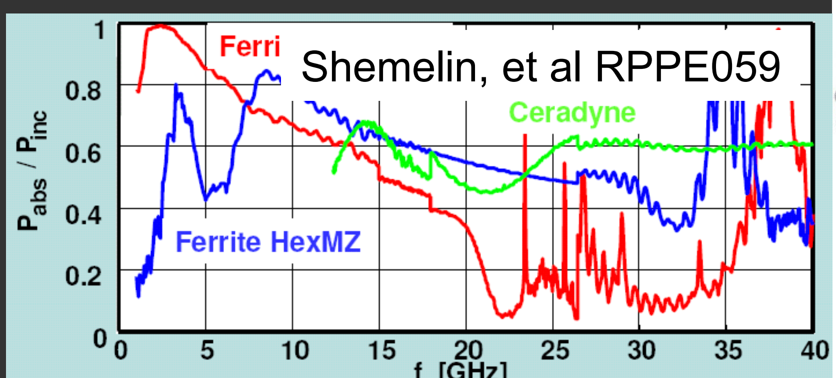
High Current SRF Cavities

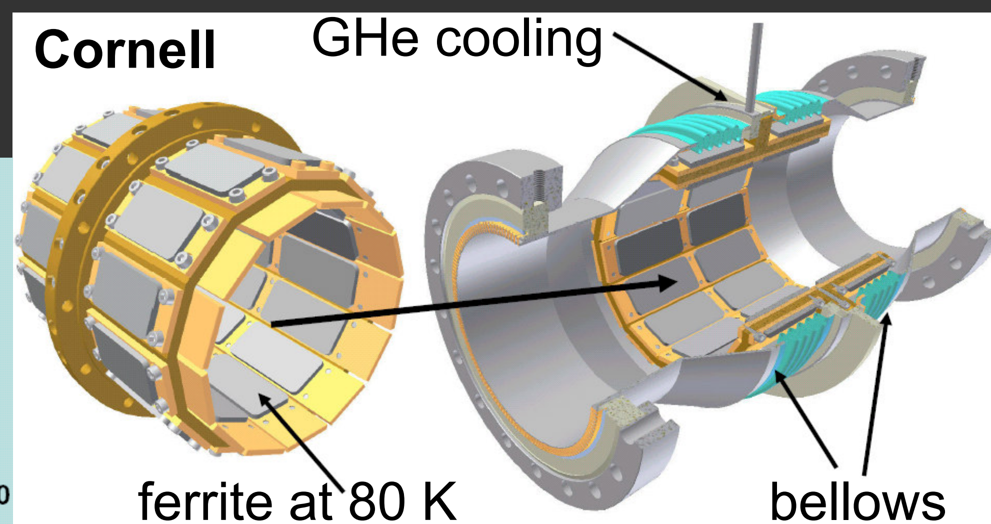


CESR style ferrite absorbers



optimized cavity shape





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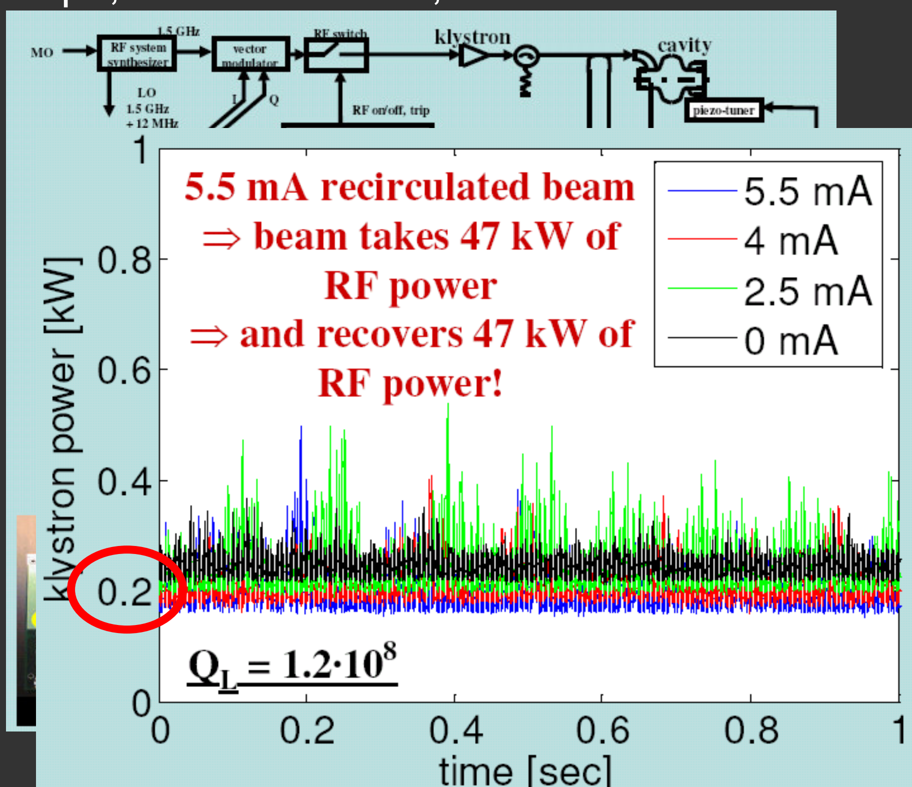
Cornell Low Level RF Control System

Liepe, et al. WPAT040, ROAC002



- Successfully tested at JLAB FEL

Demonstrated:

+ Q_L = **1.2×10^8** with I = 5.5 mA energy recovered beam
+ Field stability **10^{-4}**
+ Phase stability **0.02°**

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Summary

- Good progress on several fronts
- Much remains to be done
- R&D on ERLs to intensify in the next few years
- Proposals for large scale ERLs to follow after

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Acknowledgements

- Cornell ERL group
- JLAB collaborators: CASA and FEL team
- ERL community

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1st International ERL 2005 ICFA Workshop