High Power ERL FELs

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Newport News VA

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Beijing, PRC

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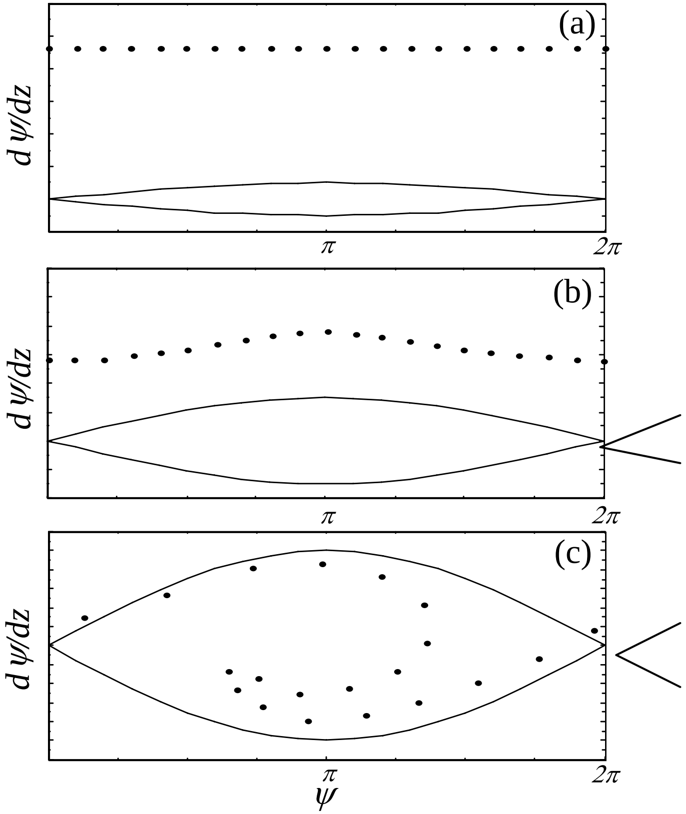
Background

- **First visit to Beijing 8-8-88 = Ba Ba Ba Ba   Very Lucky!**
- **Talked about FELs**



Phase space = fish

Fish = Yu

Yu   = Abundance!

Since 1988 much abundance in China, in SRF, and in FELs!

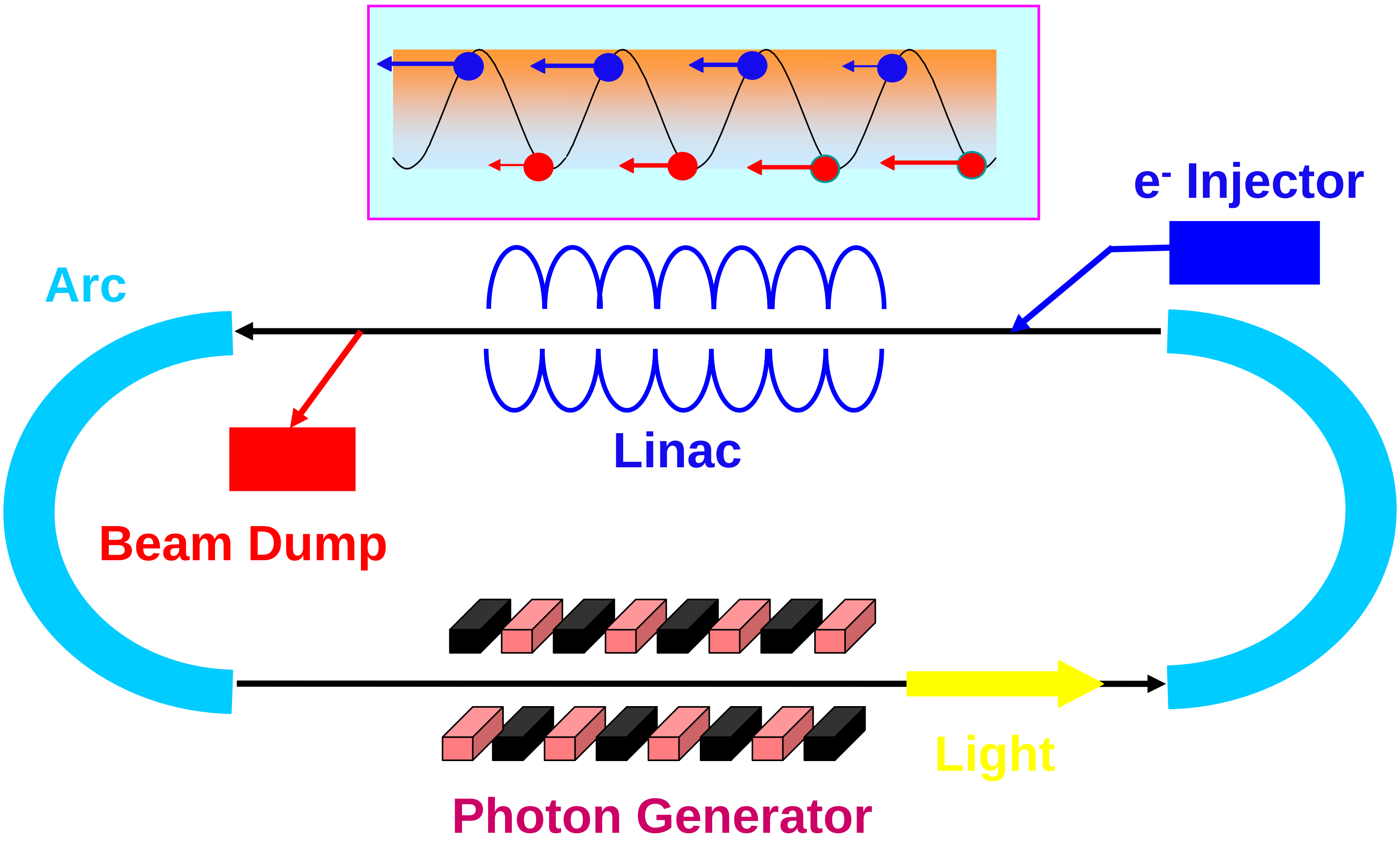
Outline

- ERL Background
- Operating High Power FELs
  - Recuperator at Novosibirsk
  - JAEA Superconducting ERL
  - JLab IR Upgrade
- Proposed
- RF limits for ERL FELs
- Supporting Technology Development
  - Injectors: srf guns, DC Gun

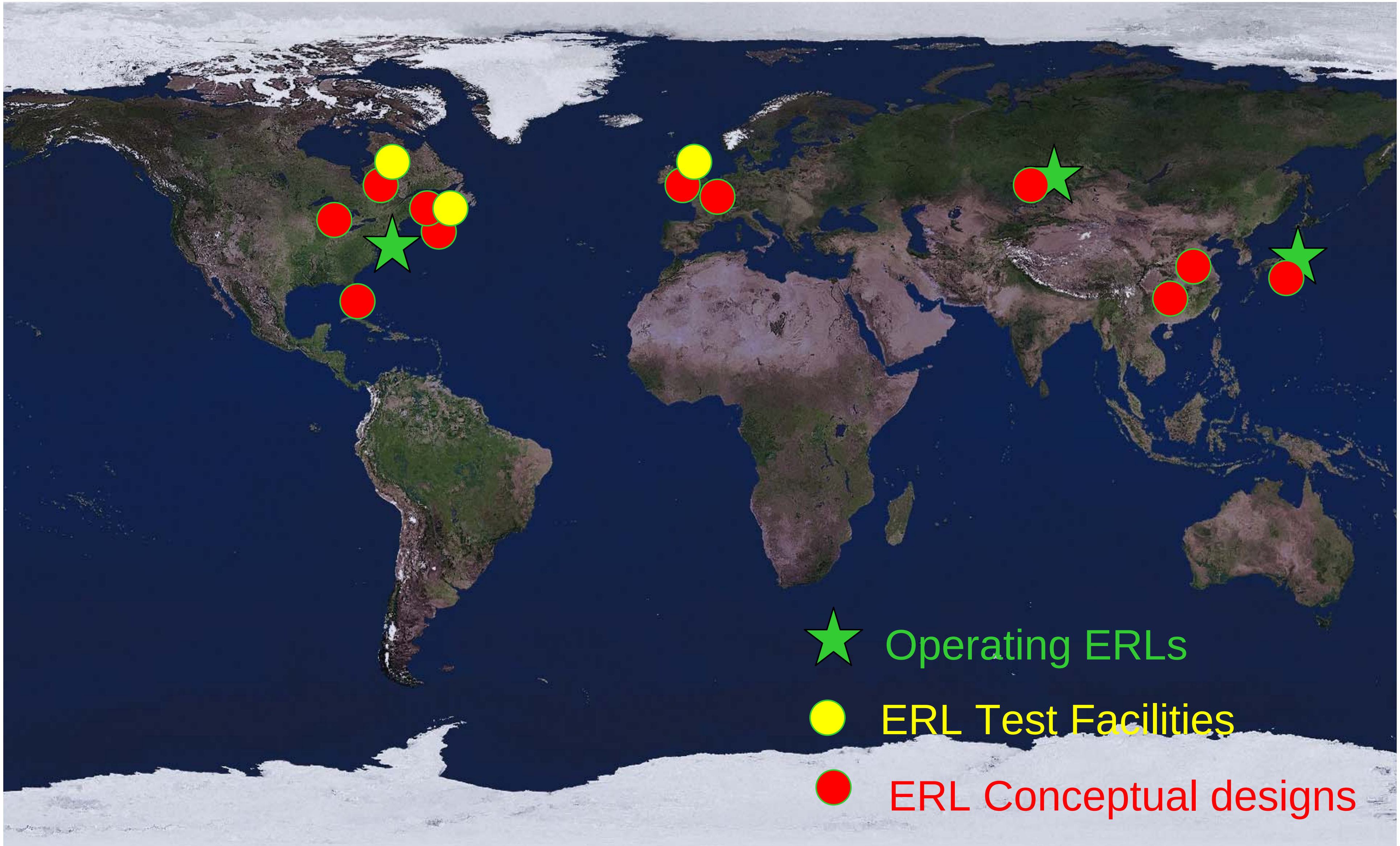
High Power FEL ERLs

- **ERL- A new form of linear accelerator where the energy is recycled rather than the electrons as in a storage ring forms the basis for the development of high power output**
  - **So far has only been done at <30 mA levels but it is believed that 100s of mA possible**
  - **ERL Benefits:**
    - **Reduced power consumption**
    - **Reduced rf required**
    - **Reduced power at the dump**
    - **Significantly reduced or eliminated neutron activation**
    - **Brighter light source beams**

Energy Recovering Linacs



Operating and Future ERLs



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 which can be of significantly lower emittance in both dimensions and shorter in time than a storage ring equilibrium
- In common with storage rings: An ERL possesses high average current-carrying capability enabled by the ER process, thus promising high efficiencies.

ERL Light Sources Promise

High average

Why? Condensed matter studies move from X-ray statics to X-ray dynamics.

How do proteins work?

How are short range atomic correlations established and lost?

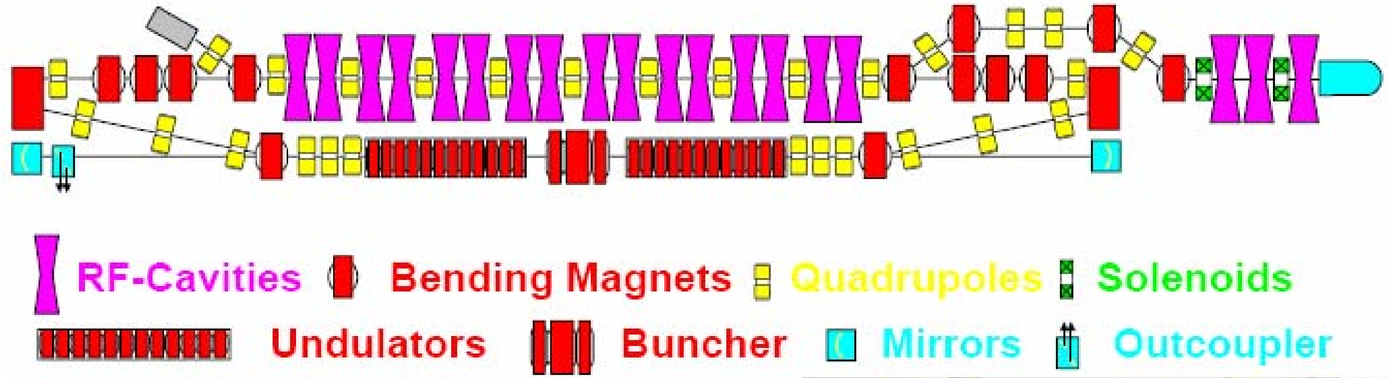
devices

patterns

*quantities are rms

The Novosibirsk High Power THz FEL

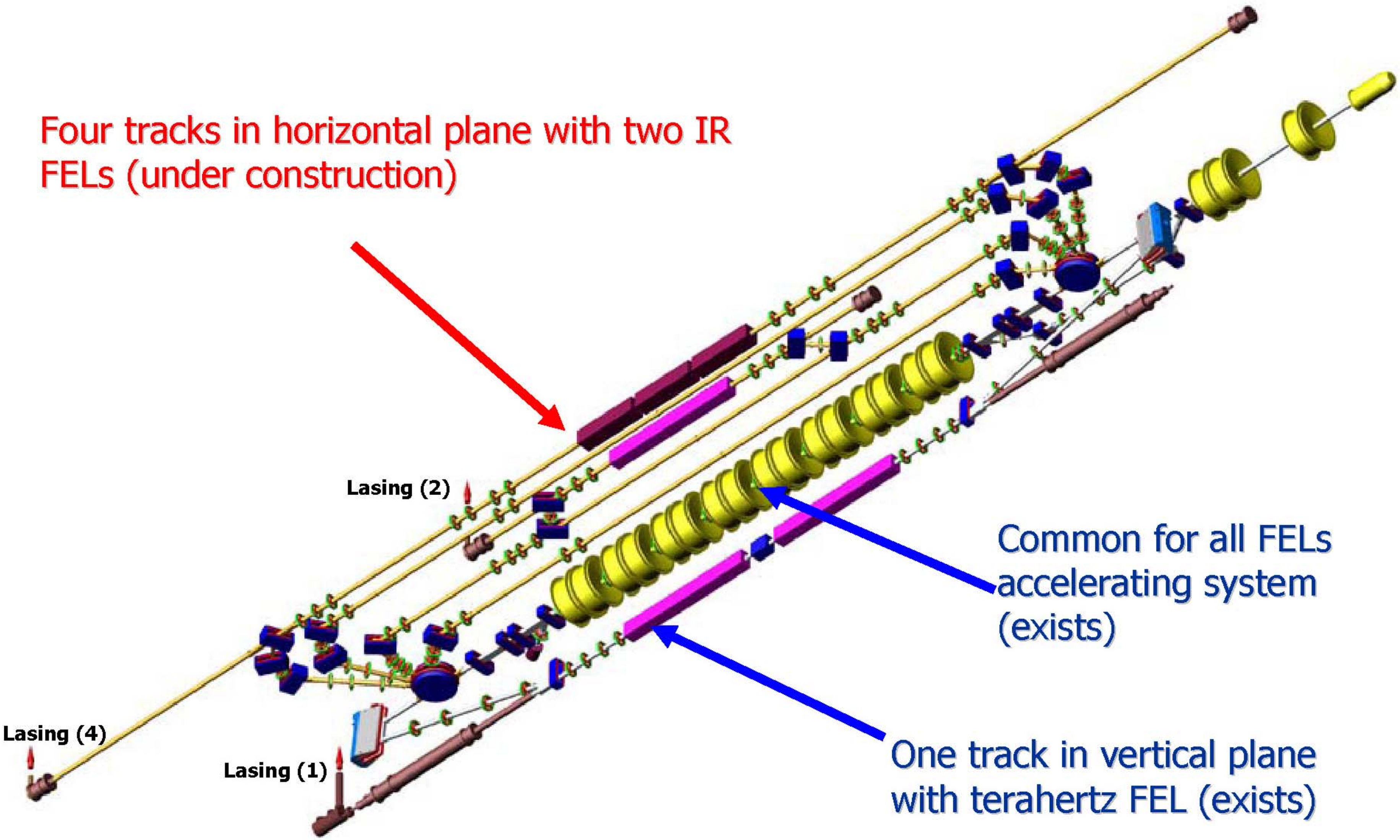
Energy recovered highest average current to date: 30 mA at 1.7 nC per bunch



	May 2005	Plans
RF frequency, MHz	180	180
Bunch repetition rate, MHz	**22.5!**	90
Maximum average current, mA	**30!**	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

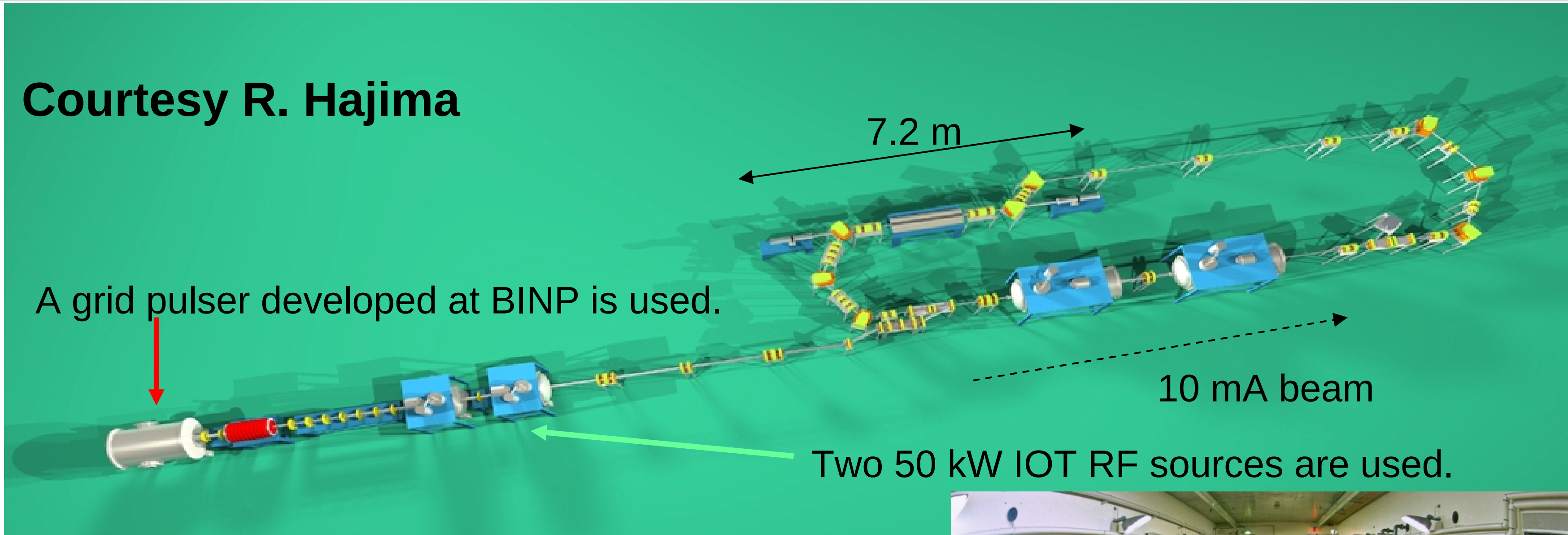
Courtesy N. Vinokurov

Full scale Novosibirsk FEL (bottom view)

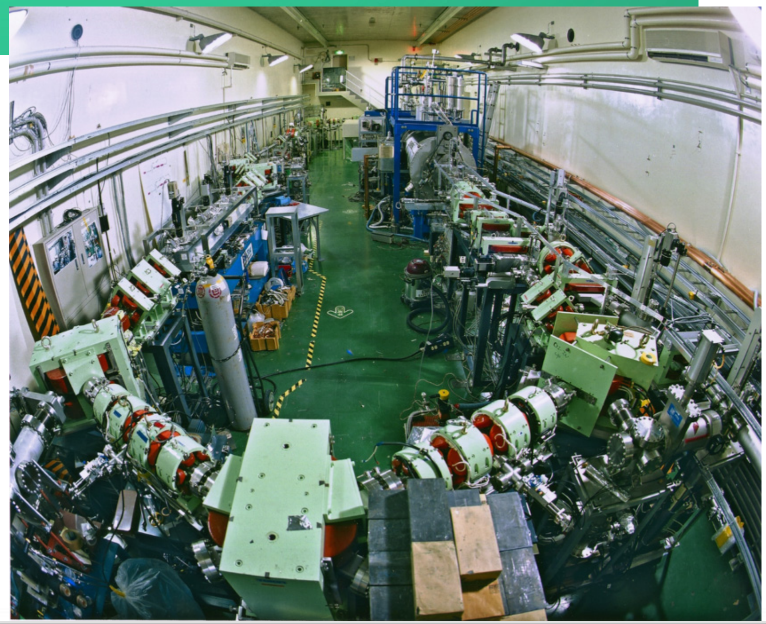


Courtesy N. Vinokurov

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



JAEA ERL FEL

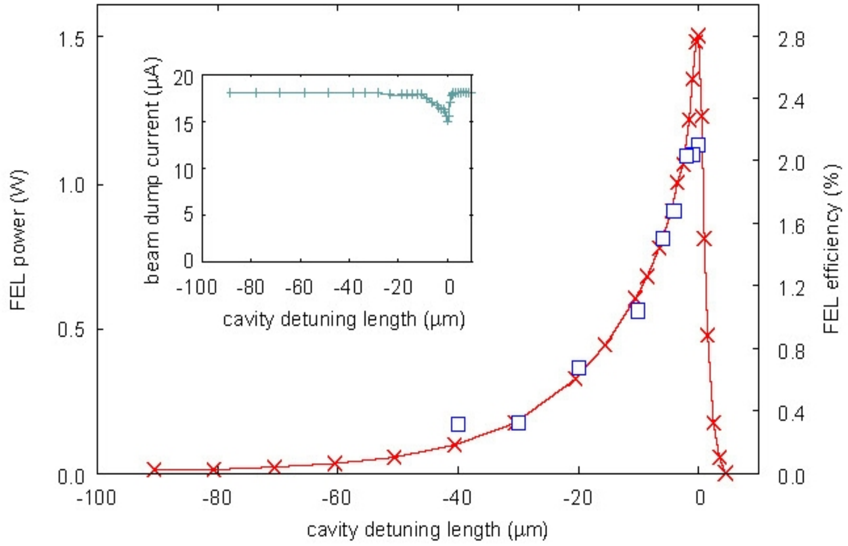


Figure 3: FEL power measured as a function of δL at macropulse length of 230 μs. FEL efficiencies obtained from the energy distributions of the exhausted electron beam are shown by open squares. The efficiencies near zero detuning length cannot be measured with our energy analyzer due to the limited energy acceptance, and they are determined from measured FEL power. The inset shows the beam dump current with respect to δL.

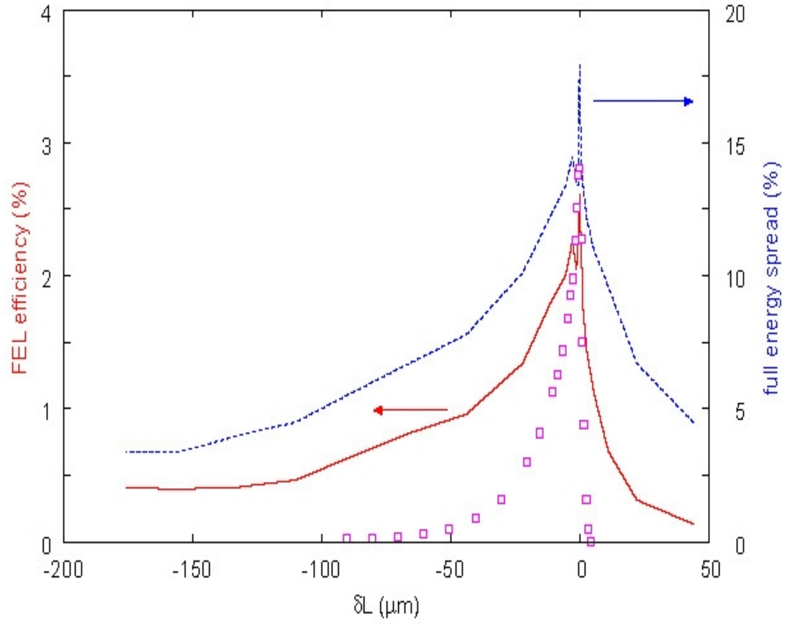
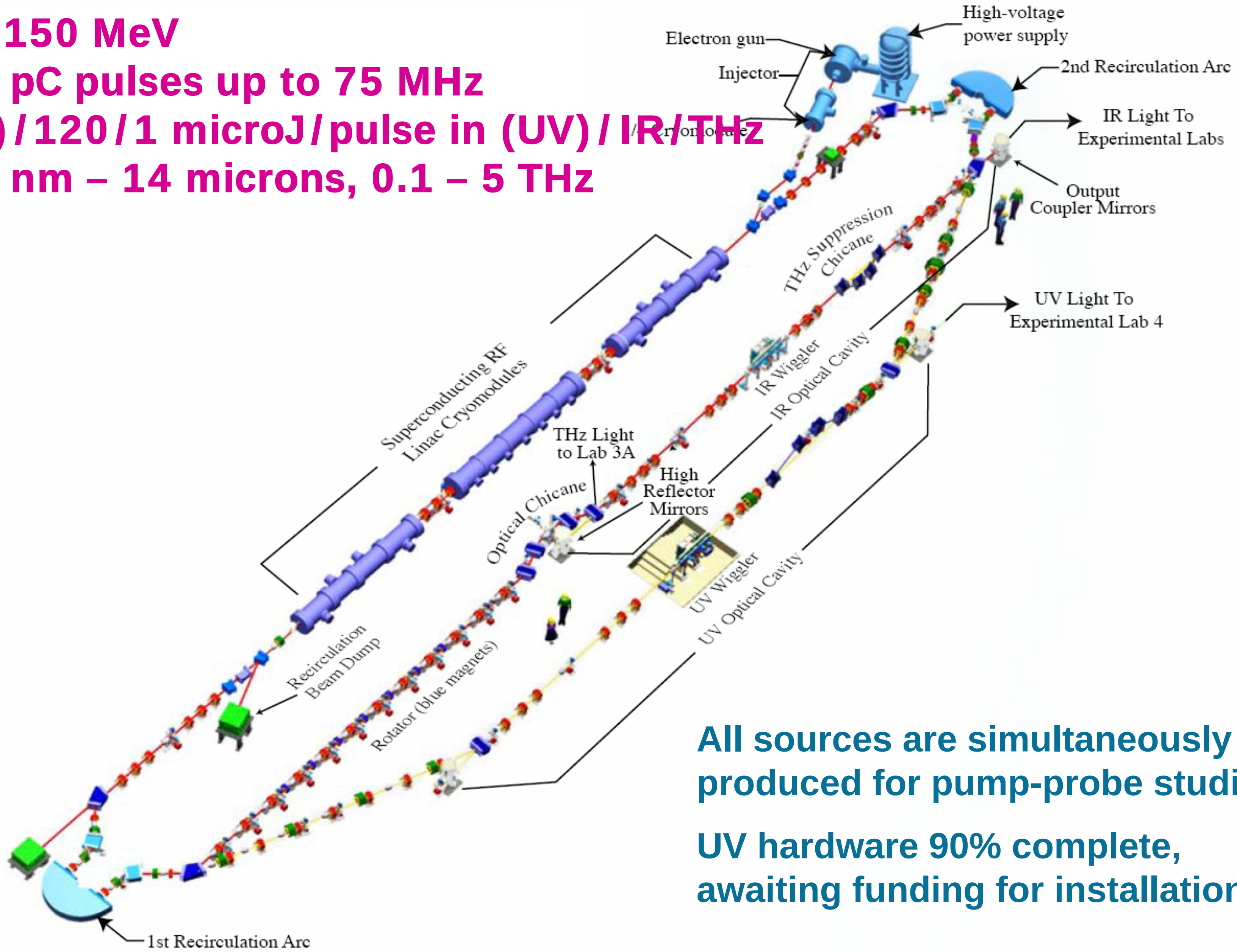


Figure 4: FEL efficiencies as a function of δL obtained from a one-dimensional time-dependent FEL simulation (solid line) and corresponding beam energy spread (dotted line). Measured FEL efficiencies are also plotted as open squares for comparison.

Courtesy Hajima JAEA

JLab Energy Recovered Linac

E = 150 MeV
135 pC pulses up to 75 MHz
(20) / 120 / 1 microJ / pulse in (UV) / IR / THz
250 nm – 14 microns, 0.1 – 5 THz

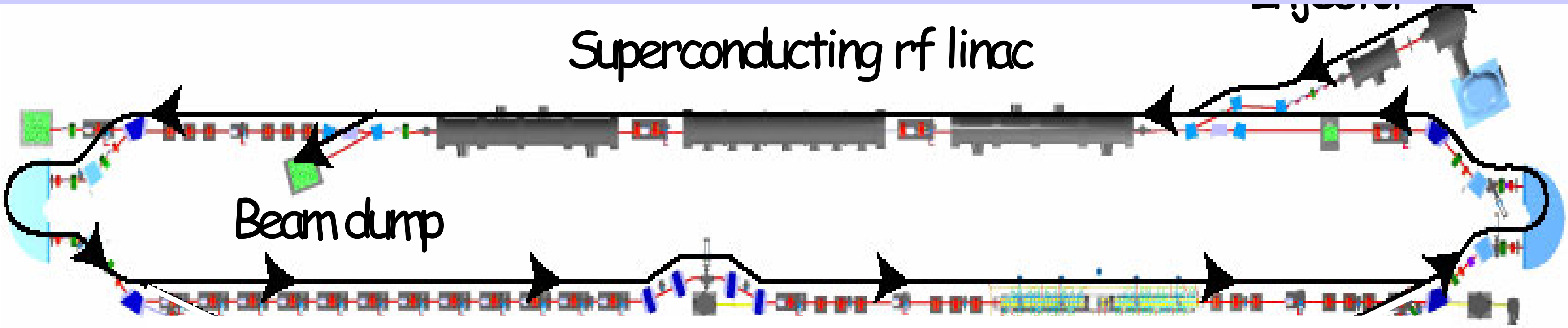


All sources are simultaneously produced for pump-probe studies

UV hardware 90% complete, awaiting funding for installation

The Jefferson Lab IR FEL Upgrade

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

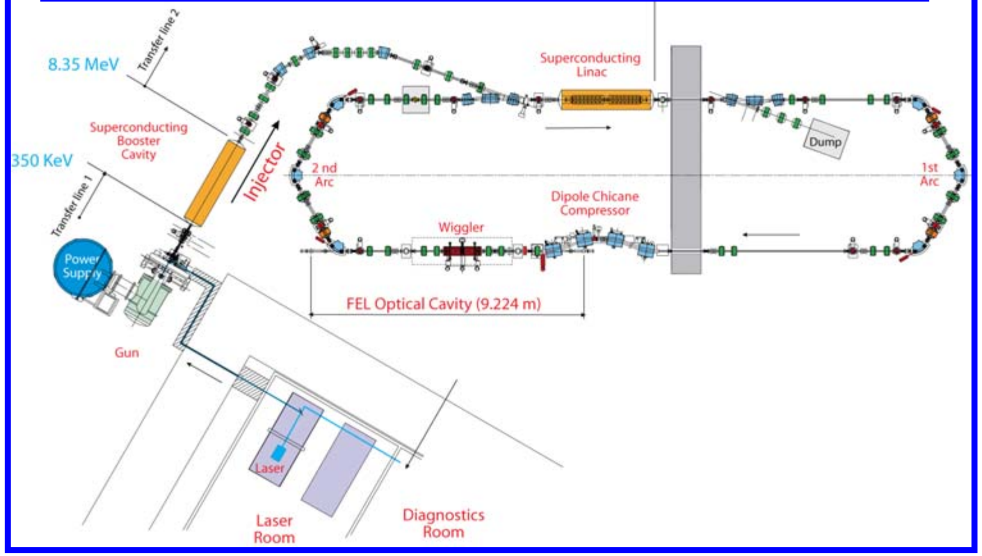


JLab IR FEL Electron Beam Parameters	Design	Achieved
Energy (MeV)	145	160
Bunch charge (pC)	135	270
Average current (mA)	10	9.1
Bunch length* (fs)	500	150
Norm. emittance* (mm-mrad)	30	7
Max. Bunch rep. rate (MHz)	74.85	74.85

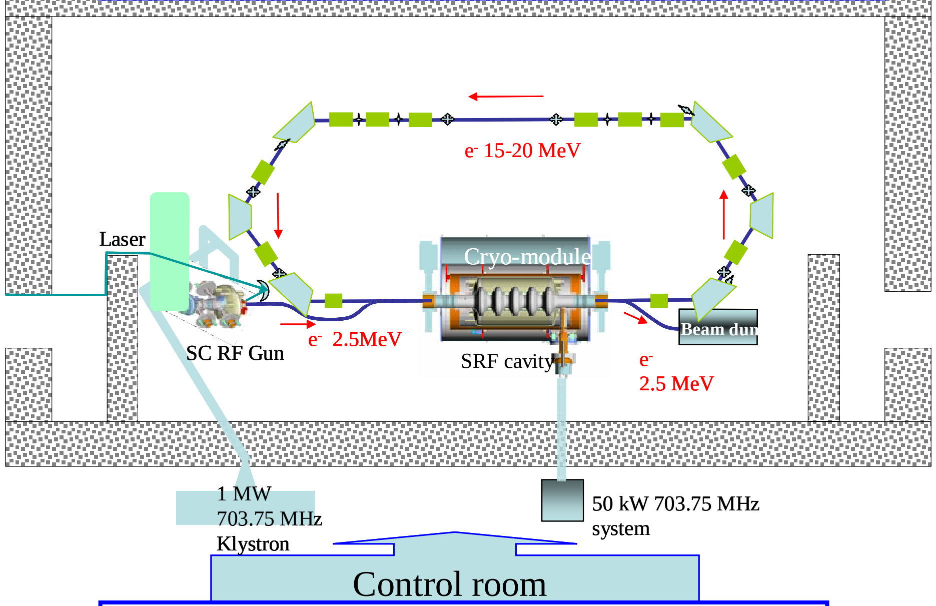
*Quantities are rms

ERL Test Facilities in assembly and test

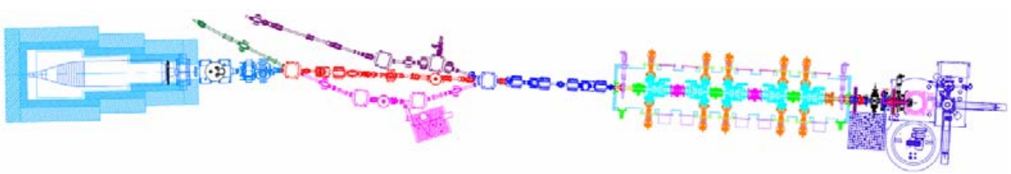
Daresbury ERL Prototype



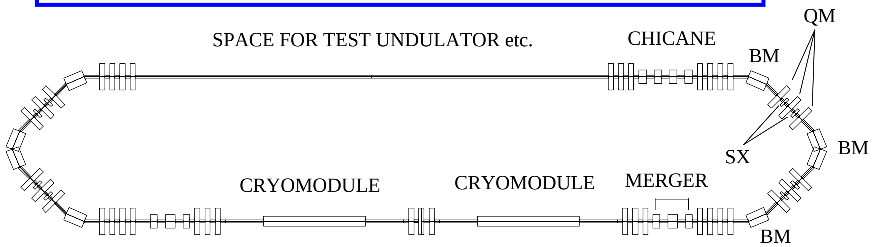
BNL R&D ERL



Cornell ERL Prototype Injector

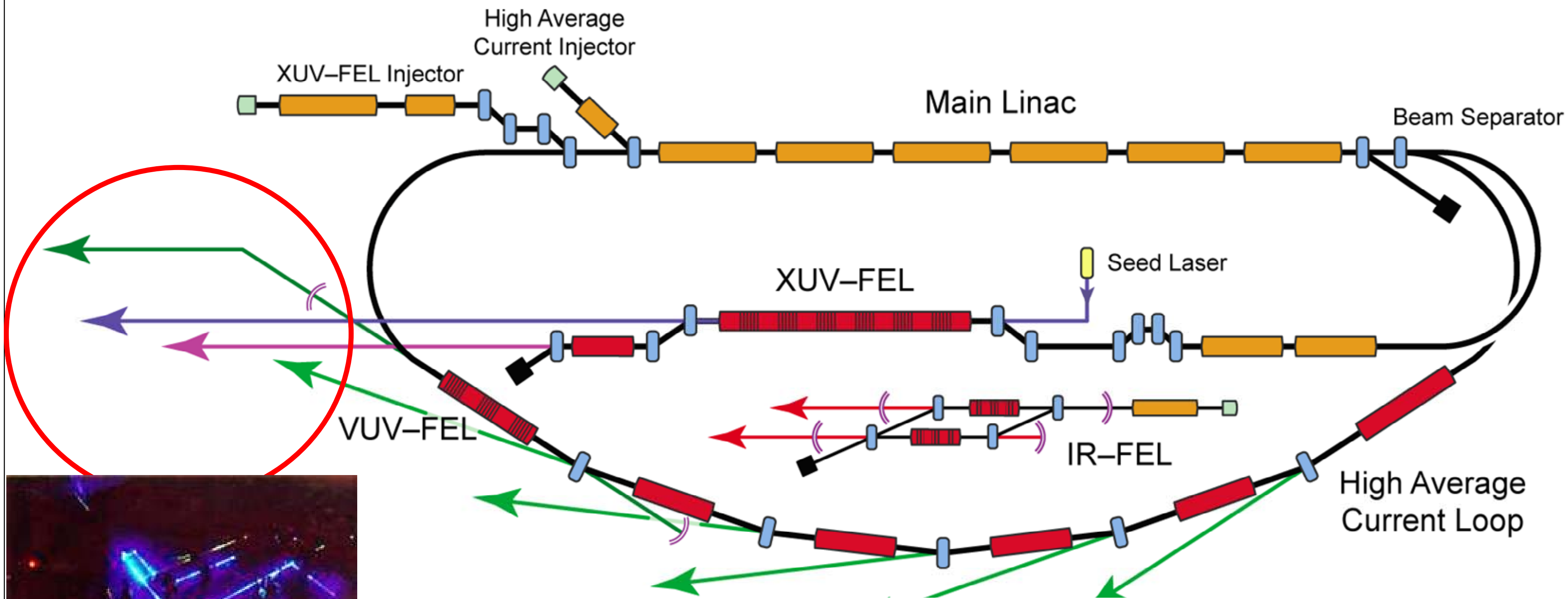


Japan Test ERL



Future ERL Light Sources: an example shows the possibilities

4GLS

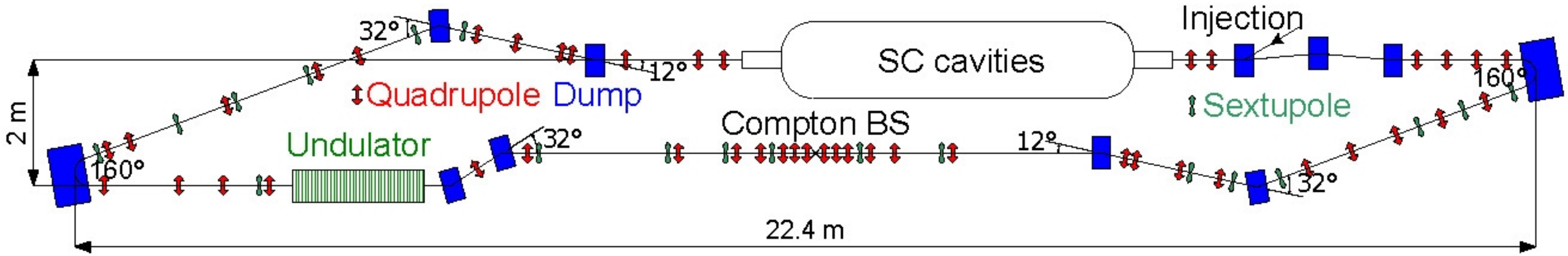


plus
laser sources

IR FEL Oscillator
VUV FEL Oscillator
XUV Amplifier
Spontaneous sources
All synchronized < psec

A PROJECT OF A HIGH-POWER FEL DRIVEN BY AN SC ERL AT KAERI

A.V.Bondarenko, S.V.Miginsky, Budker Institute of Nuclear Physics, Novosibirsk, Russia
B.C.Lee, S.H.Park, Y.U.Jeong, Y.H.Han, Korea Atomic Energy Research Institute, Daejeon, Korea



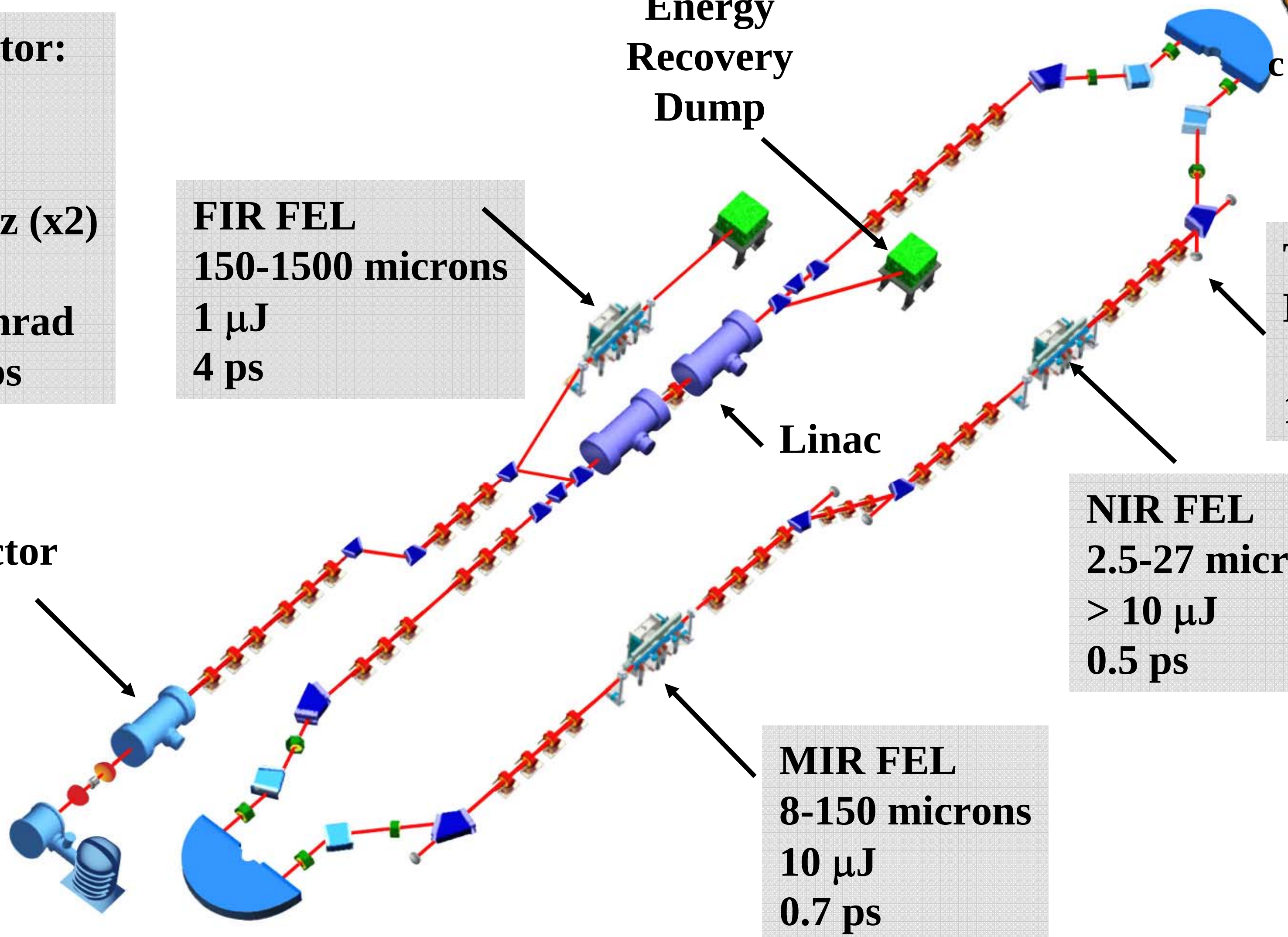
- bunch duration: 100 ps;
- number of electrons per bunch: 10^{10};
- electron energy (full): 10 MeV;
- repetition rate: 5.6 MHz;
- emittance: 2π mm·mrad;
- energy spread (relative): $6 \cdot 10^{-3}$.

FEL2007 MOPPH064

Big Light FEL for NHMFL

Accelerator:

60 MeV
3 mA
10.7 MHz (x2)
135 pC
10 mm mrad
80 keV-ps



Required Development

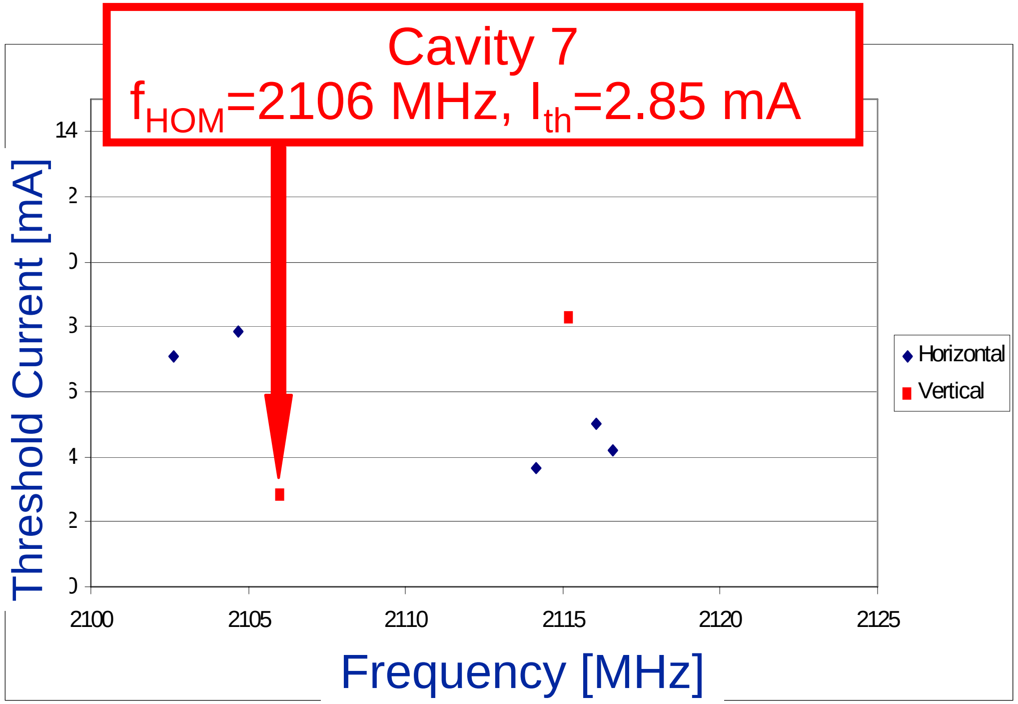
- Physics Control Requirements
  - BBU (physics done, engineering solutions)
  - CSR
  - Longitudinal space charge

- Technology
  - Lower Q_0 - operating cost
  - Simplified cryomodule - capital cost

- Physics and Technology
  - Injector - sets performance limits

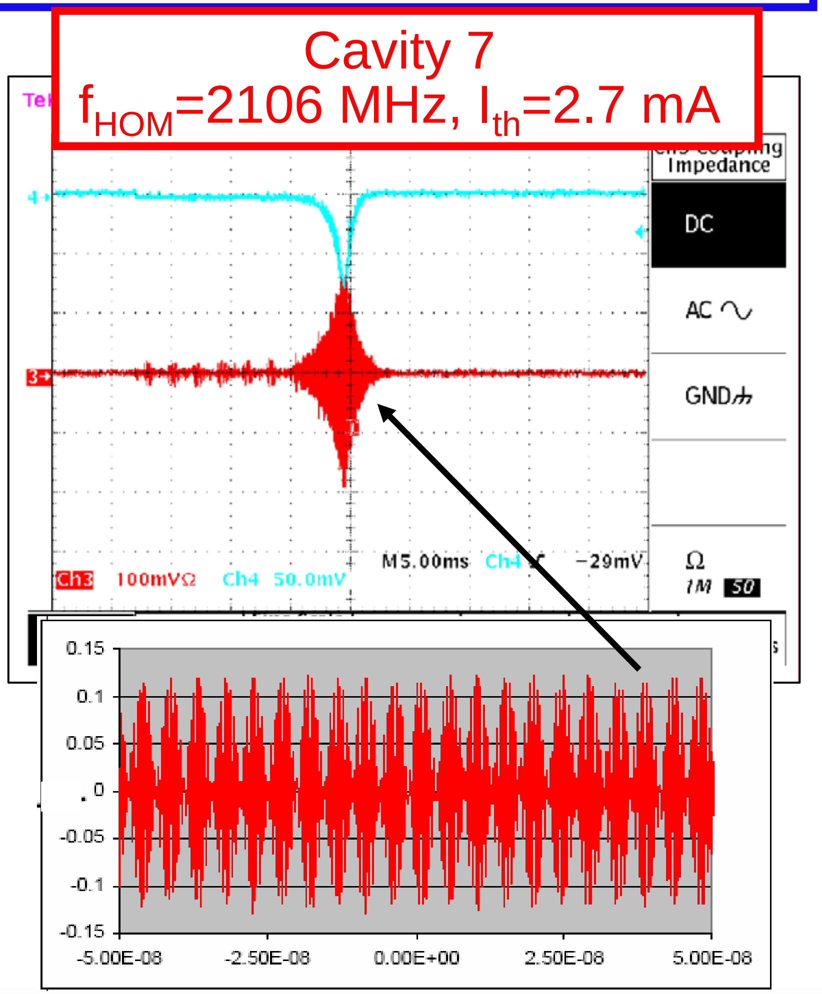
BBU Simulation and Observation

BBU simulations of the JLAB 10 kW FEL



HOM data based on measurements
Model recirculation matrix

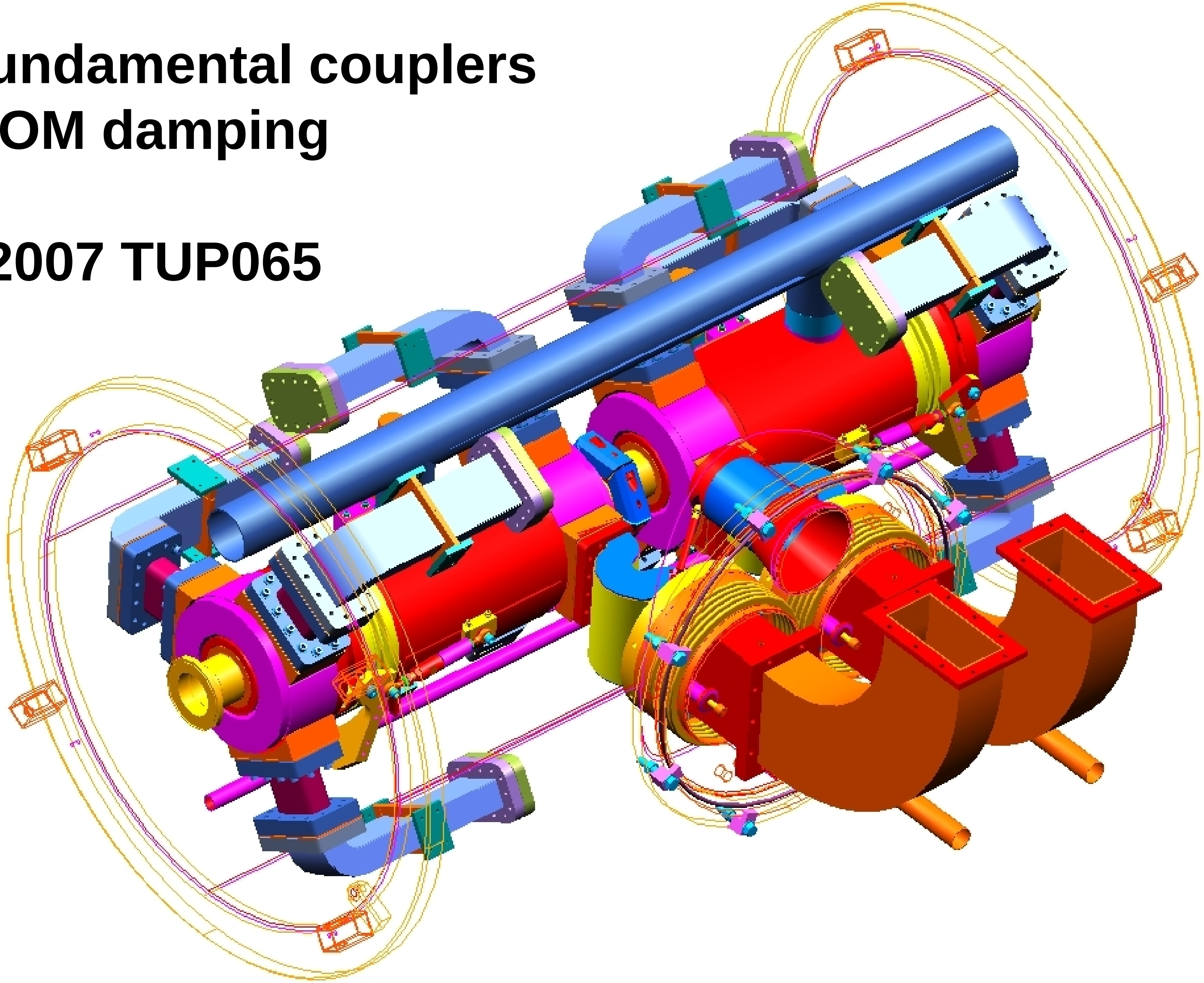
BBU observation in the JLAB 10 kW FEL



Cavity cell shape optimization for High Current

High power fundamental couplers
Waveguide HOM damping

Rimmer SRF2007 TUP065



Loaded Q for FEL ERLs

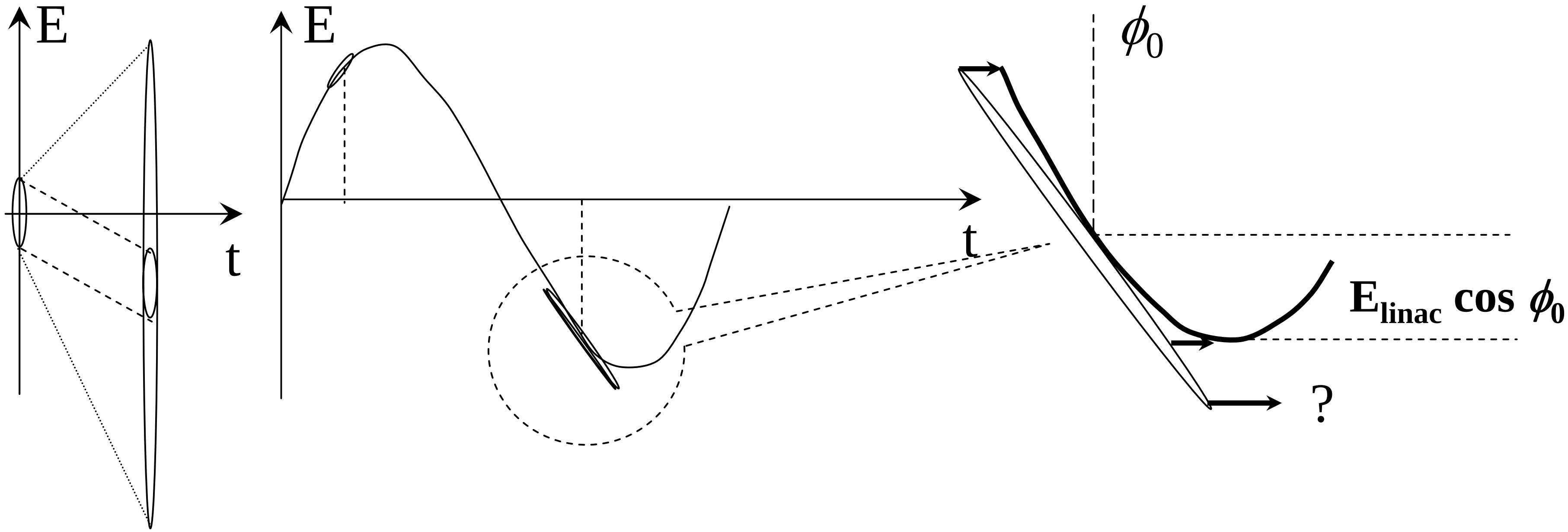
- **In an ERL without FELs acceleration/deceleration on crest/trough could allow for loaded Q> 10^7 and minimal rf power draw**

In an FEL ERL <u>this is not recommended</u>

- **With no beam loading RF Power ~ $1/Q_L$ (loaded Q). With perfect energy recovery you can operate with a few hundred watts of RF power per cavity rather than 3 kW to 4 kW per cavity with high Q BUT….**
- **You must decelerate off trough to compress energy spread during deceleration**
- **Accelerated and decelerated beams are less than 180° out of phase which results in beam loading in both power and phase.**

Illustrated……

Offset phase on return sets limit on energy spread



- FEL Interaction: beam central energy drops, beam energy spread grows
- Recirculator energy must be matched to beam central energy to maximize acceptance
- Beam rotated, curved, torqued to match shape of RF waveform
- Maximum energy can't exceed peak *deceleration* available from linac!

$$(\Delta E/E)_{FEL}/2 < E_{linac} \cos \phi_0$$

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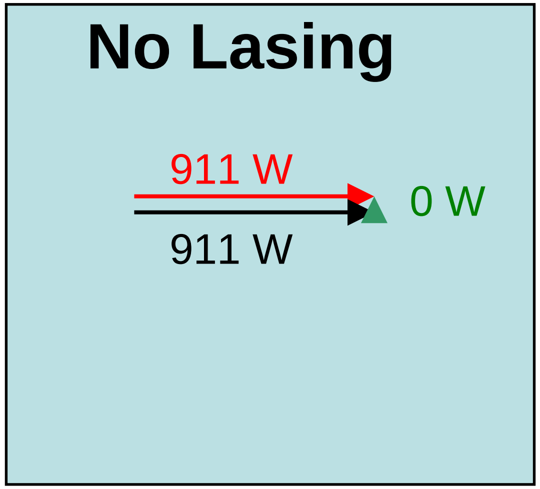
- You must decelerate off trough to compress energy spread during deceleration
- **Accelerated and decelerated beams are less than 180° out of phase which results in beam loading in both power and phase.**
- **Mechanical tuners compensate for 85% of the beam loading in CW mode.**
- **During lasing turn-on the RF system must provide the transient power and phase shift necessary.**
- **Lower Q_L minimizes the transient effects**

Rf phase vector diagrams

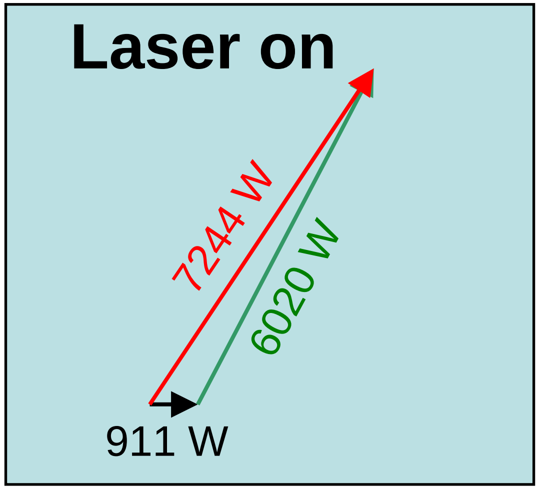
The M56 between the end of our FEL and the linac is ~0.2m

Lasing at 2% efficiency the phase shift is 7.2 degrees of rf at 1500MHz

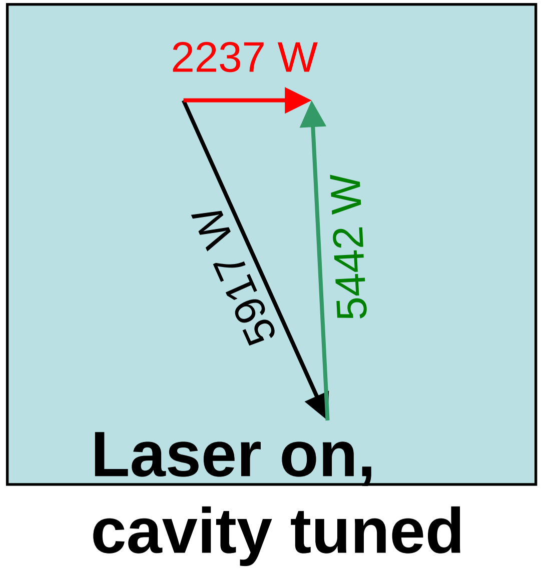
10 MV/m, +10º accel/decel
Generator power phasor



Same but return delayed-7.2º
Instantaneous power phasor

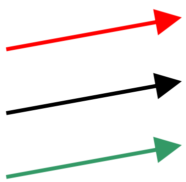


Same but return delayed-7.2º, tuner minimizes power phasor



$Q_L \sim 6 \times 10^6$

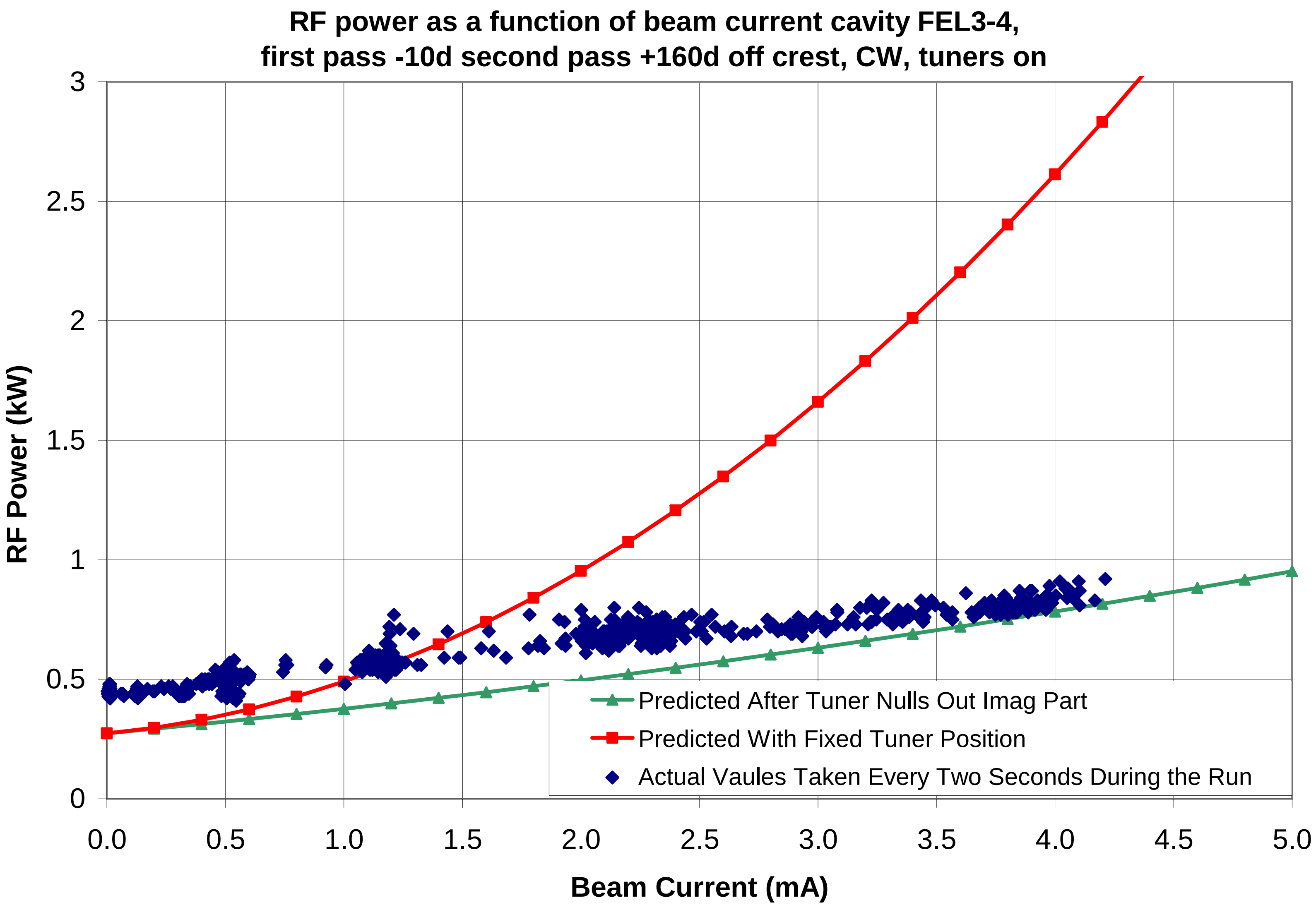
High Q_L only makes this shift worse!



Klystron Power
"Cavity" Power
"Beam" Power

Yes, I know power isn't a vector;
length shown is **E**

RF Power as a function of current



Technology Development

- Although other technologies are required the injector is key to short wavelength and high power

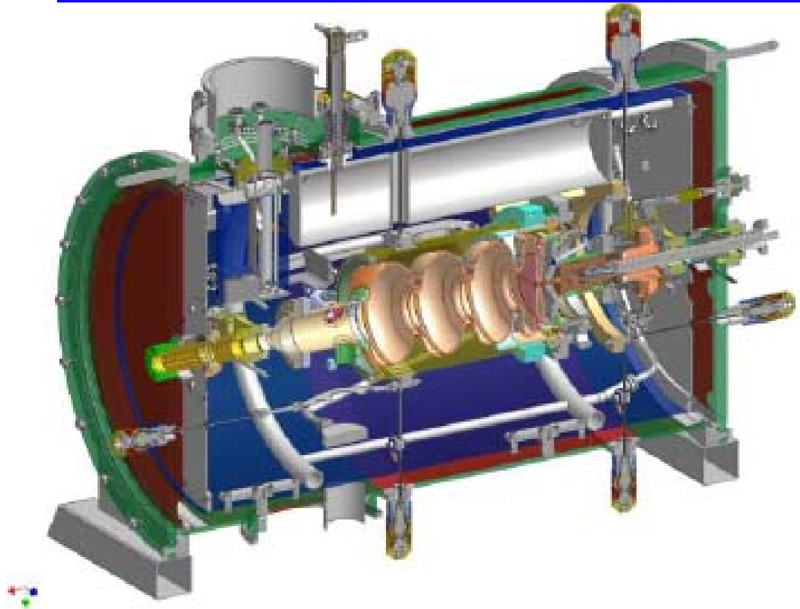
- SRF – much promise
- DC –best performance to date

(Peking U. design combines both)

Goal: High brightness at high average current

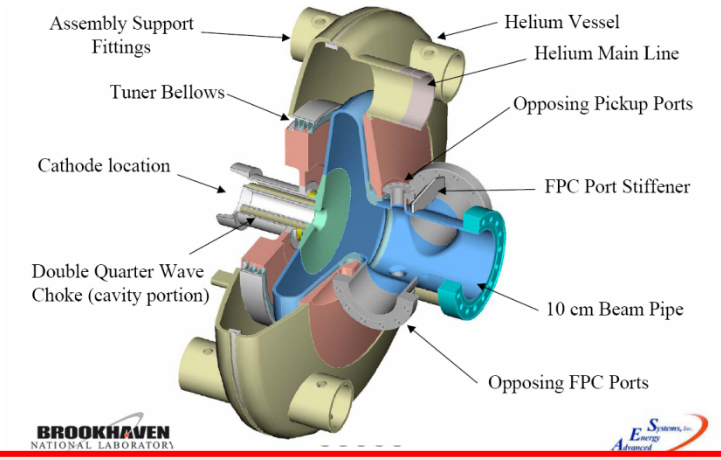
SRF photoinjectors

Rossendorf SRF gun

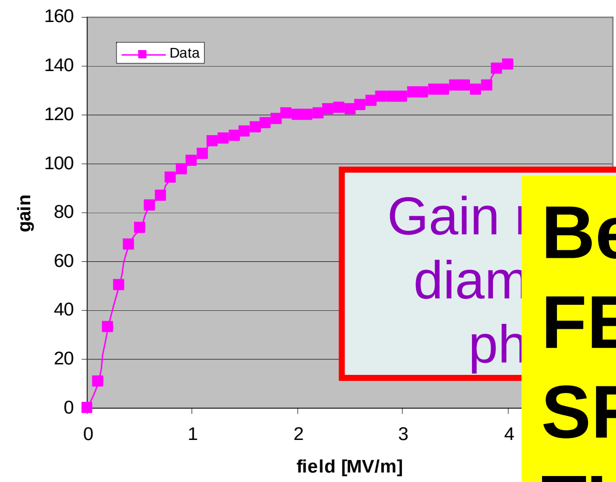


1.3 GHz, 9.5 MeV, CW
3 modes of operation:
- 77 pC at 13 MHz
- 1 nC up to 1 MHz (1 mA)
- 2.5nC at 1 kHz

BNL/AES SRF gun



703.75 MHz, 2.5 MeV, 500 mA,CW



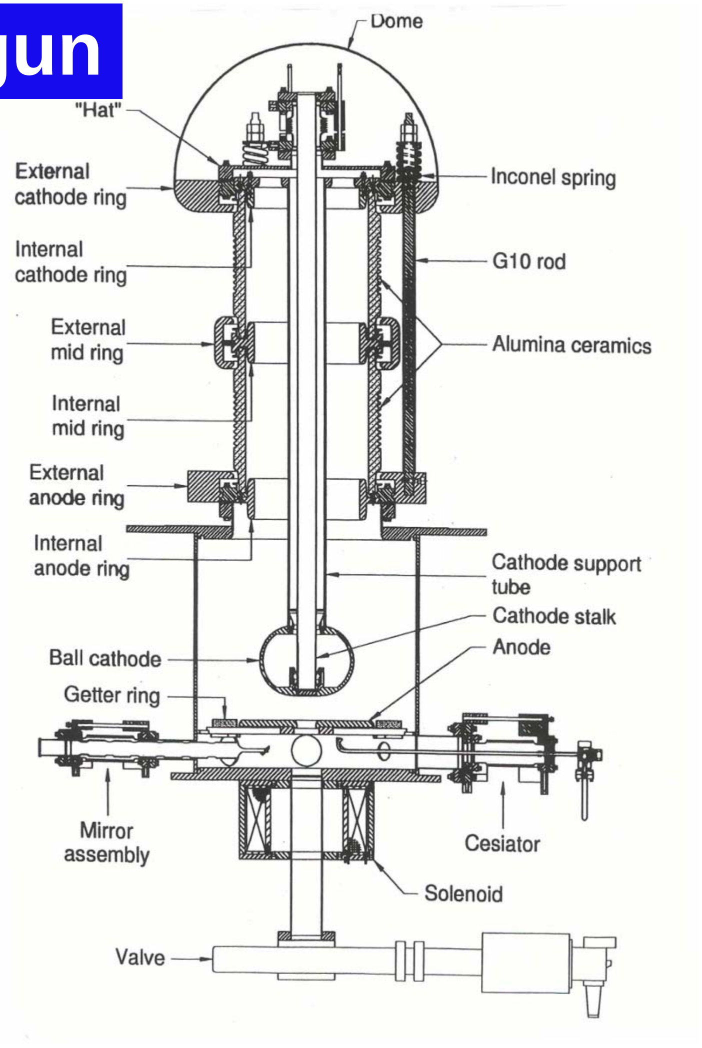
Gain r
diam
ph

Ben-Zvi FEL2007, SRF2007 TUP42, 43

DC photoinjectors

CW State-of-the-art: JLAB FEL gun

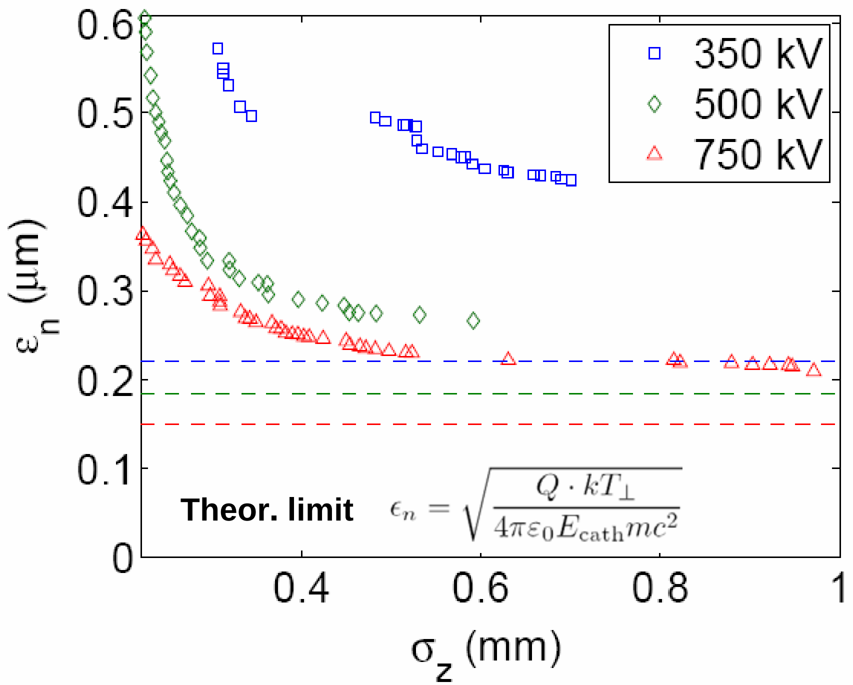
- **75 MHz repetition rate**
- **$\varepsilon_{N,rms}$~ 7 mm-mrad for**
  q ~ 135 pC/bunch
  (measured at the wiggler)
- **Average current up to 9 mA**
- **Cathode voltage: 350 – 500 kV**



Reaching ultimate emittance limit in a DC gun

Cornell ERL Prototype Injector

K-J Kim, FEL2007
1 Angstrom FEL Oscillator!



Multi-parameter optimization achieves <0.3 mm-mrad, 80 pC dominated by cathode temperature

Courtesy: I. Bazarov

Summary

Lots of activity in ERL based FELs and related light sources

Much progress in achieving higher power

ABUNDANT challenges to keep researchers employed for many years!

Acknowledgements

Too many to get all of them!

Lia Merminga provided major help in pulling together the ERL activities. Please see her invited talk from PAC'07.

I am also grateful to Ryoichi Hajima, Vladimir Litvinenko, Matt Poelker, Dave Douglas, Gwyn Williams, Bob Rimmer, Steve Benson, Michelle Shinn, Carlos Hernandez-Garcia, Susan Smith, Pavel Evtushenko, and Nikolay Vinokurov for providing slides, information, and support