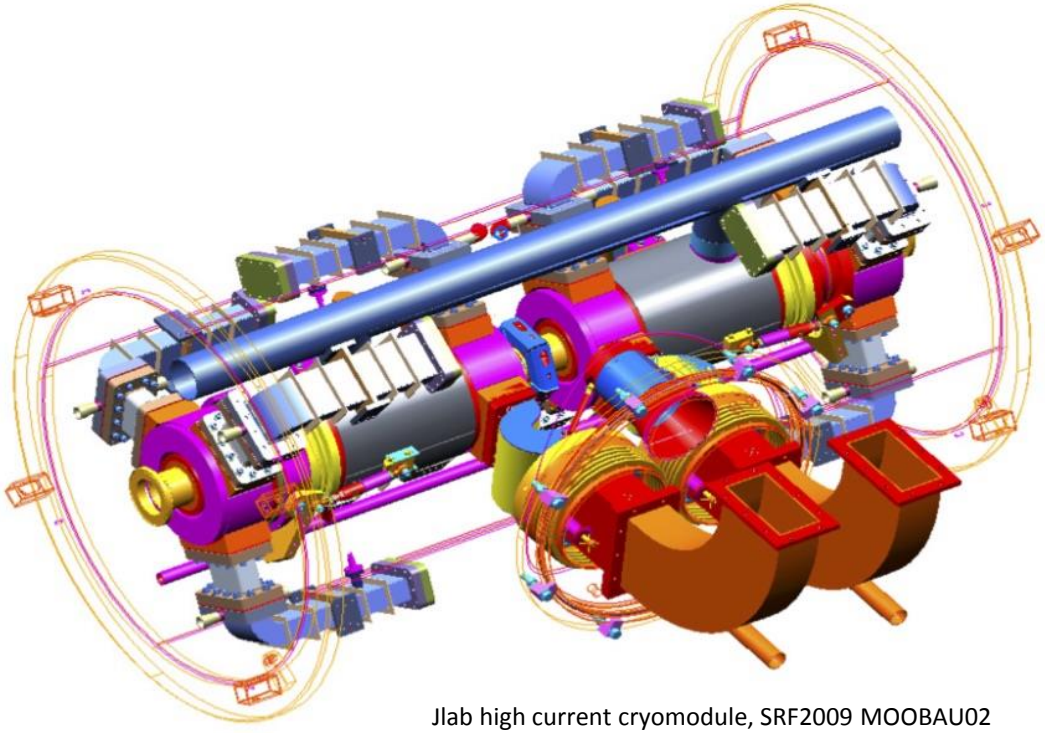
SRF Developments for ERLs



Jlab high current cryomodule, SRF2009 MOOBAU02

Bob Rimmer

Thursday, June 3, 2021

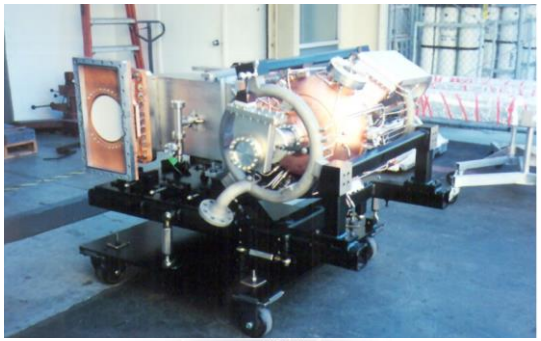
Overview

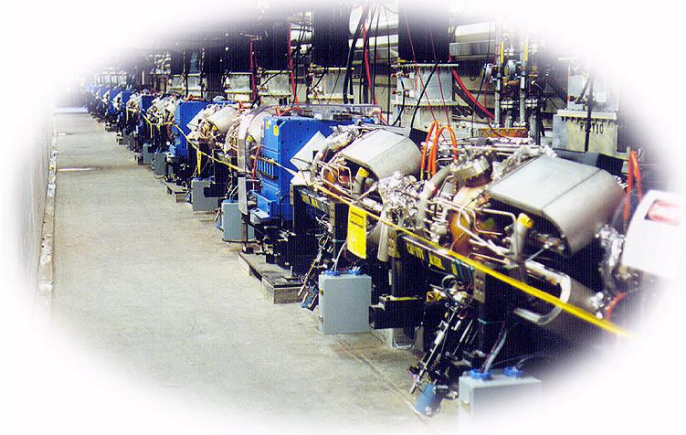
- Sorry this is not a comprehensive review !
- Why does SRF for ERL's need to be different?
- What are the technical challenges?
- What still needs to be done?
- Where do we go from here?

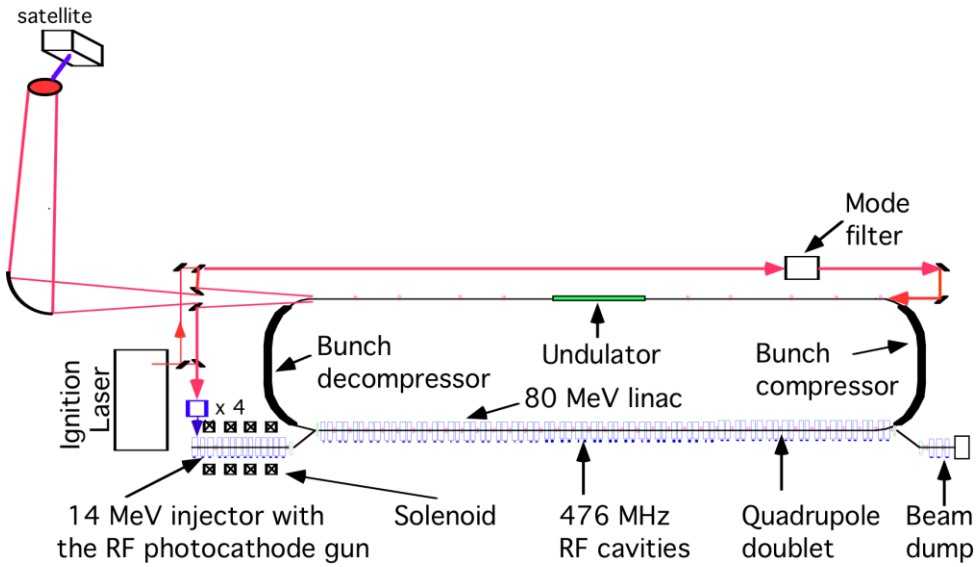
My first ERL: SELENE (but not SRF)

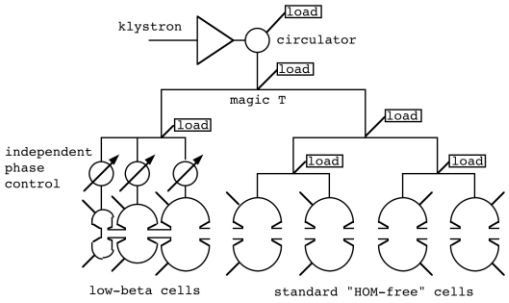
IR FEL for power beaming to satellites c.1998

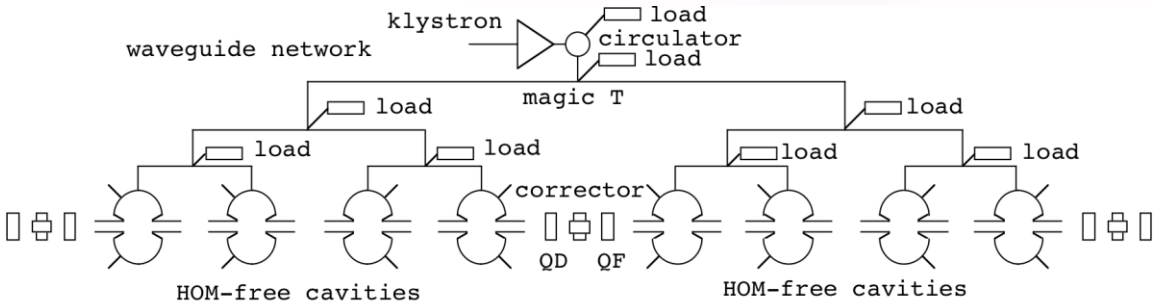
Ignition Feedback Regenerative Amplifier (IFRA)







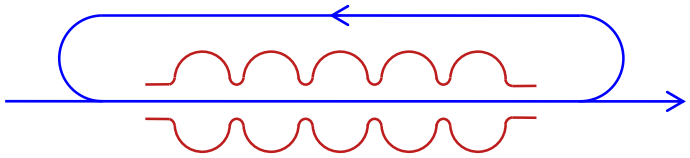




A. Zholents, R. Rimmer, O. Walter, W. Wan, M. Zolotorev, "FEL Design for Power Beaming", Free- Electron Laser Challenges II, Proceedings of SPIE, Vol. 3614, p.72, (1999).

Why does SRF for ERL's need to be different?

- An ERL is not a LINAC or a ring, it's something in between
- Re-circulating LINAC and ERL's pass the beam through the same cavities a finite number of times
  - Lower capital cost, higher efficiency
  - Ideal for CW or high rep-rate applications
  - Can excite Higher-Order Modes (HOMs) in cavities



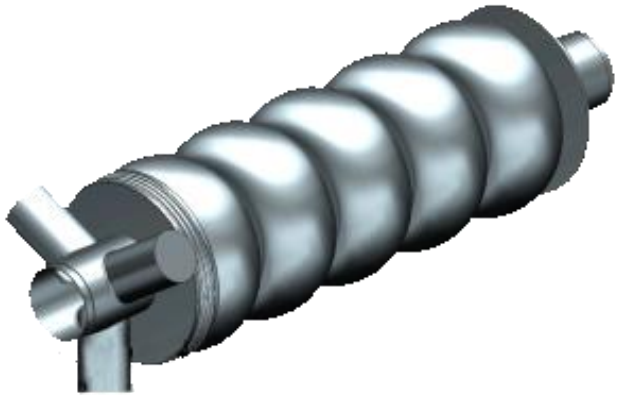
- Beam power can be recovered on decelerating phase (ERL)
- Circulating beam power can (should) exceed installed RF power
- Injector is not energy recovered (but it could be)
- Beam dump energy and power are reduced but not zero
- Non-equilibrium beam distributions
- May power an FEL, Compton source or internal target etc.

What are the technical challenges?

- Can have regenerative Beam Break Up (BBU)
  - Worse than a LINAC but better than a ring
  - HOMs need to be damped
  - HOM power needs to be safely dissipated (~kW's)
- Suggests cavity optimized for this application
  - Cell shape for high current
  - Frequency optimized for application
  - HOM dampers for high power
- Suggests cryomodule optimized for this application
- Need a high current electron source and injector
- Need to control beam losses
- Any radiated or dissipated power comes from the RF
- Transient beam loading on start up or due to changes in beam loading (e.g. FEL on-off)
- Need a moderate power Beam dump (possible to reduce)

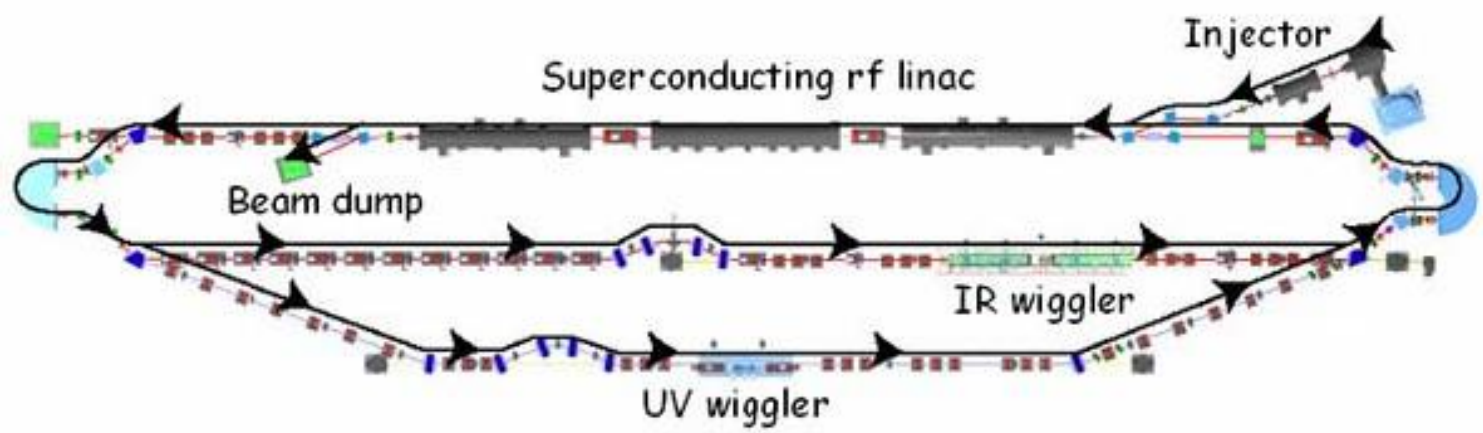
What has been done?

- Cavities designed specifically for ERLs, ERL injectors ✓
- Demo of energy recovery with gain (beam power > RF power) ✓
- Demo of LLRF running with high Qext ✓
- Demo of high energy (~1 GeV) ✓
- Demo of multi-pass ✓
- Demo of FEL beam quality ✓



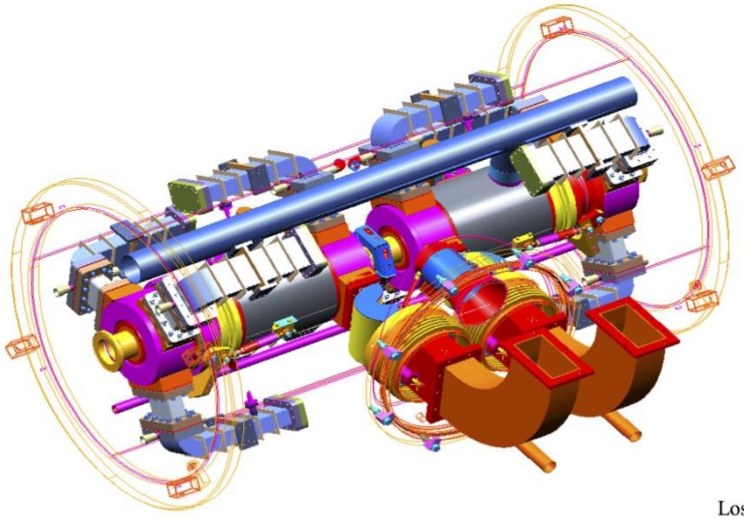
JLab 10 kW FEL

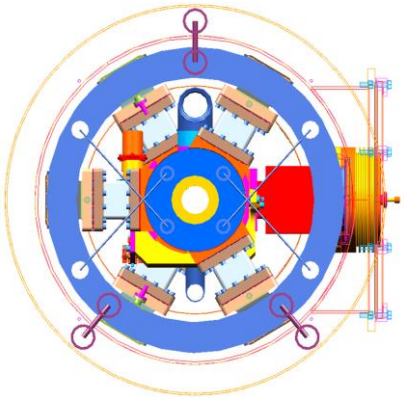
- Fourth-generation light source with energy recovery
- IR branch 14 kW world record
- UV branch > 1 kW.

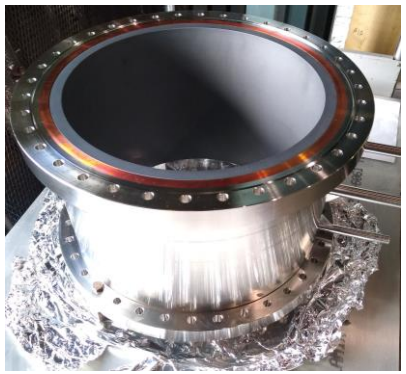


	IR Branch	UV Branch
Wavelength range (microns)	1.5 – 14	0.25 - 1
Bunch Length (FWHM psec)	0.2 - 2	0.2 - 2
Laser power (kW)	> 10	> 1
Repetition Rate (cw operation, MHz)	4.7 – 75	4.7 - 75

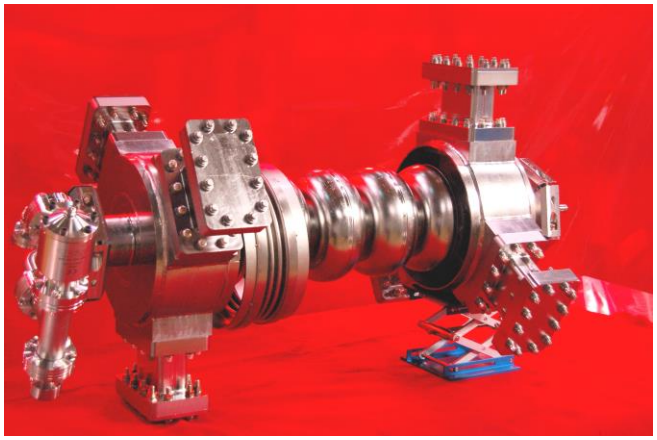
Example of ERL specific cavity and cryomodule design

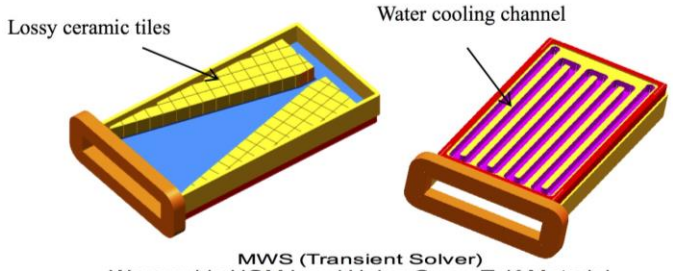


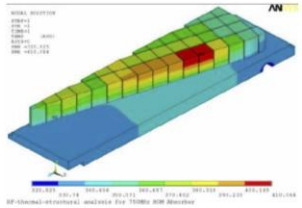




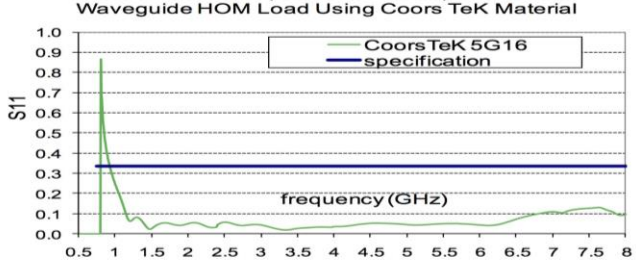
Beam line HOM absorber

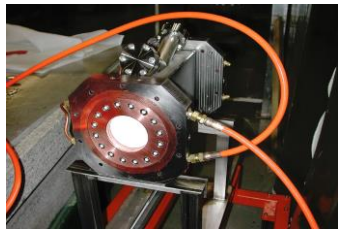






Temperature distribution



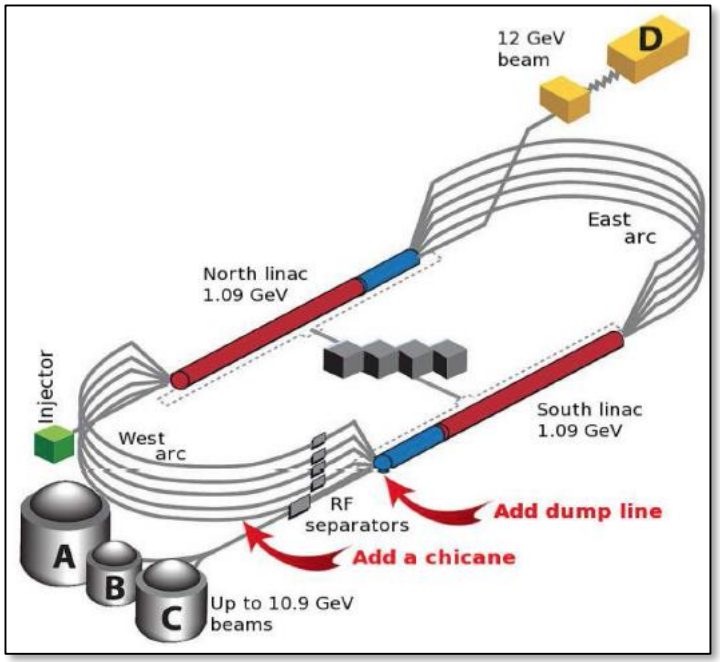


High power load design and simulation results

JLAB UPGRADE AND HIGH CURENT CAVITY DEVELOPMENTS Proceedings of SRF2009, Berlin, Germany MOOBAU02
J. Preble, J. Hogan, F. Marhauser, R. A. Rimmer, H. Wang, Jefferson Lab, Newport News, VA 23606 U.S.A.

Energy Recovery in CEBAF: the ER@CEBAF Experiment

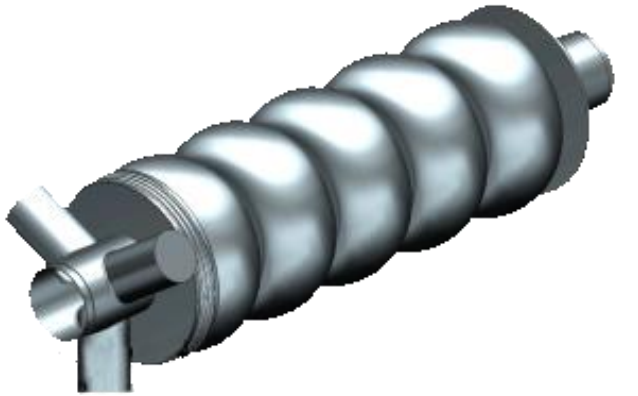
- JLAB expertise:
  - GeV scale ERL, single pass @CEBAF (2003)
  - 1.3 MW circulated power ERL @LERF
  - Basis for our contribution to EIC ERL e-cooling
- Next: multi-pass high-energy ERL experiment at CEBAF
  - highest-energy, largest installed SRF ERL demo
  - Collaborations with BNL since 2015, Daresbury since 2019
  - JLab PAC conditionally approved in 2016
  - JLAAC 2019 green light to start planning
- Motivated by
  - ERL scaling and physics questions
  - JLab ERL physics core competency
  - high-energy ERL long-term interest
    - LHeC, FCC-ee ERL concept
  - Complementarity to high-power ERL demonstrators (e.g. CBETA, PERLE)
- 2020-21: develop plans to install dipoles for recirculation chicane
- Current beam dynamics studies:
  - Multi-pass linac optics design using Genetic Algorithm (PhD thesis of Isurumali Neththikumara, ODU in collaboration with Arthur Vandenhoeke, Univ. of Brussels)
  - Longitudinal matching and mitigation of phase-space distortion (PhD thesis of Gus Perez, Univ. of Liverpool in collaboration with Peter Williams, Daresbury)



Jefferson Lab

What still needs to be done?

- Cavities designed specifically for ERLs, ERL injectors ✓
- Demo of energy recovery with gain (beam power > RF power) ✓
- Demo of LLRF running with high Qext ✓
- Demo of high energy (~1 GeV) ✓
- Demo of multi-pass ✓
- Demo of FEL beam quality ✓
- Demo of reliable gun **?**
- Demo of high current (>100 mA) **X**
- Demo of user/industrial application **X**
- Demo of reliable high-current multi-pass ERL using optimized cavities with physics quality beam (**PERLE**)



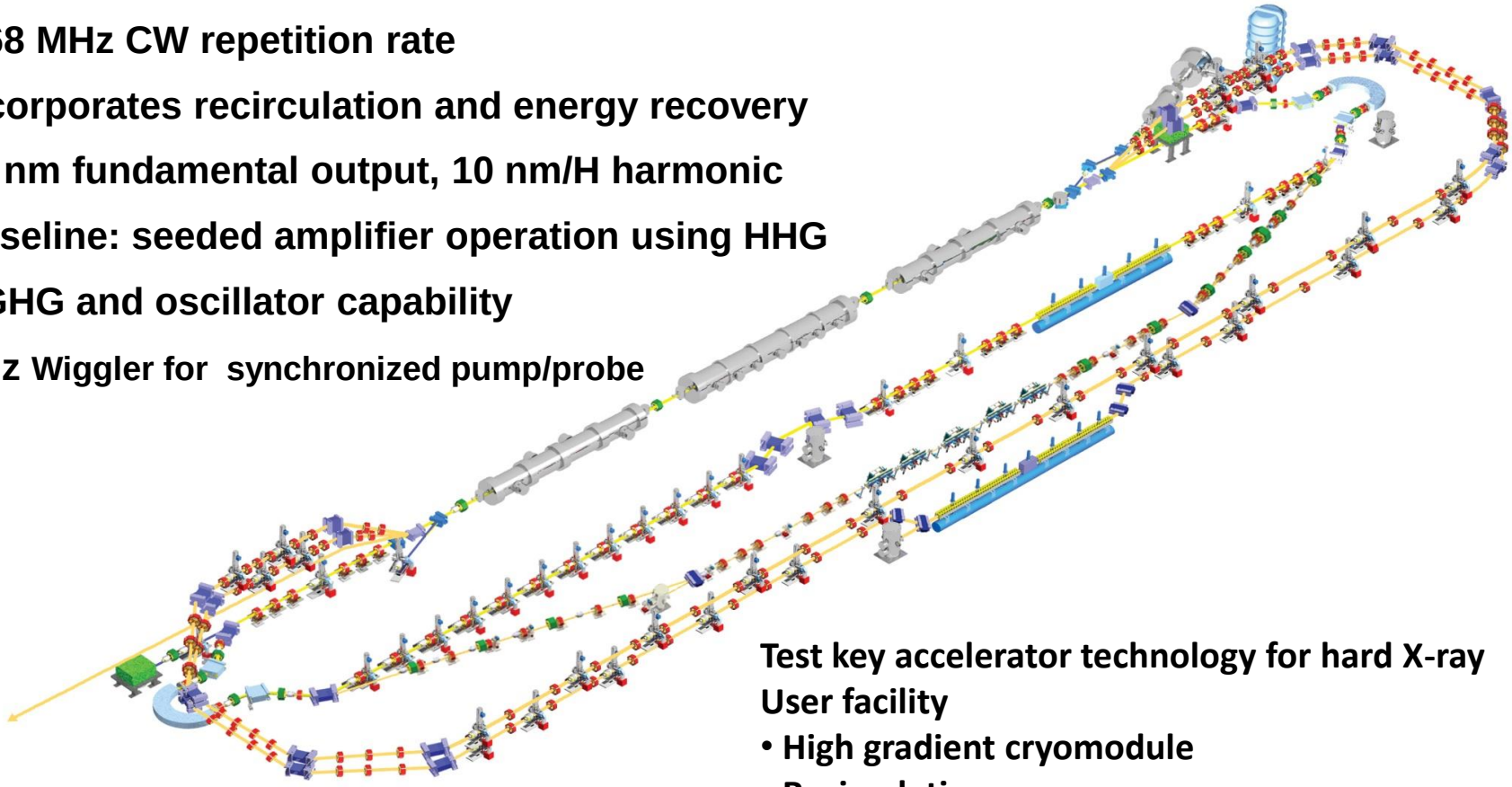
Where do we go from here?

- Many low-power ERLs have been demonstrated
- Many large ERL's have been proposed
- Much technology has been developed, JLAB, Alice, C-ERL, CBeta
- High energy 5-pass demonstration in CEBAF planned
- New materials e.g. Nb_3Sn at 4K?
- Need a convincing high-power demonstration: PERLE
- Need compelling applications
  - Light source? (Lithography?)
  - Isotopes?
  - High-energy electron cooling in EIC
  - Electron-Hadron Collider?

Proposed JLAMP FEL at Jlab (declined)

Offered unparalleled average brightness in the soft X-ray region

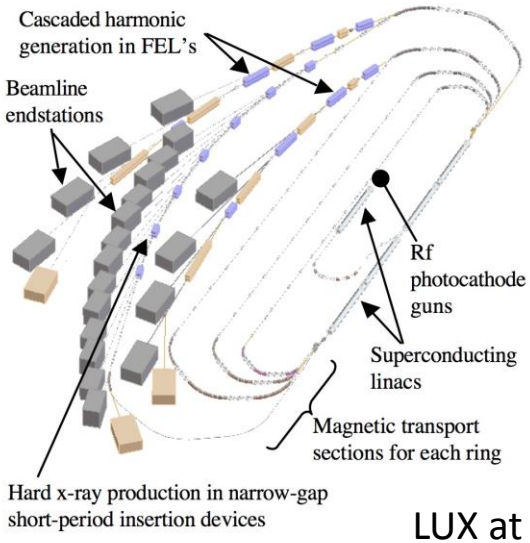
- **600 MeV, 2 pass acceleration**
- **200 pC, 1 mm mrad injector**
- **4.68 MHz CW repetition rate**
- **Incorporates recirculation and energy recovery**
- **10 nm fundamental output, 10 nm/H harmonic**
- **Baseline: seeded amplifier operation using HHG**
- **HGHG and oscillator capability**
- **THz Wiggler for synchronized pump/probe**



Test key accelerator technology for hard X-ray User facility

- **High gradient cryomodule**
- **Recirculation**
- **High brightness CW injector**

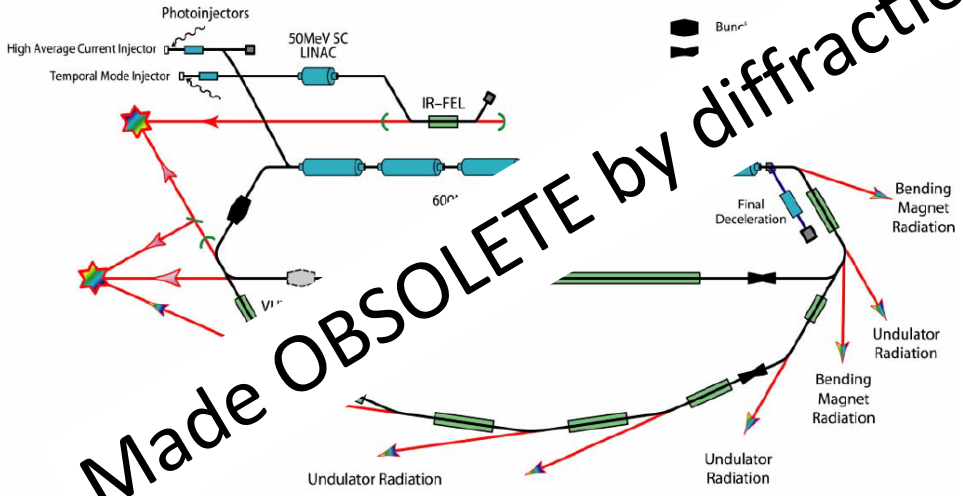
ERL and hybrid light source proposals



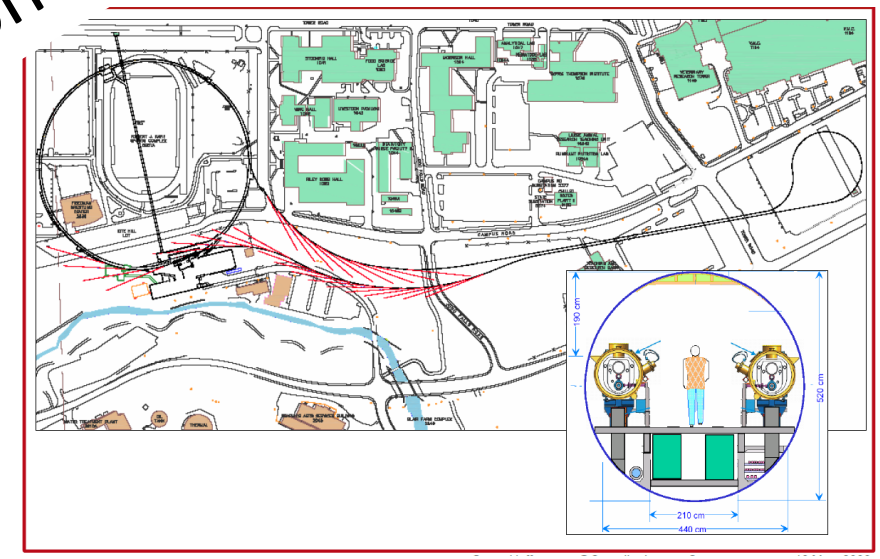
LUX at LBNL

APS ERL Concept

Made OBSOLETE by diffraction limited storage rings!



UK Daresbury ERL Photon Source Concept



CORNELL/CESR ERL Concept

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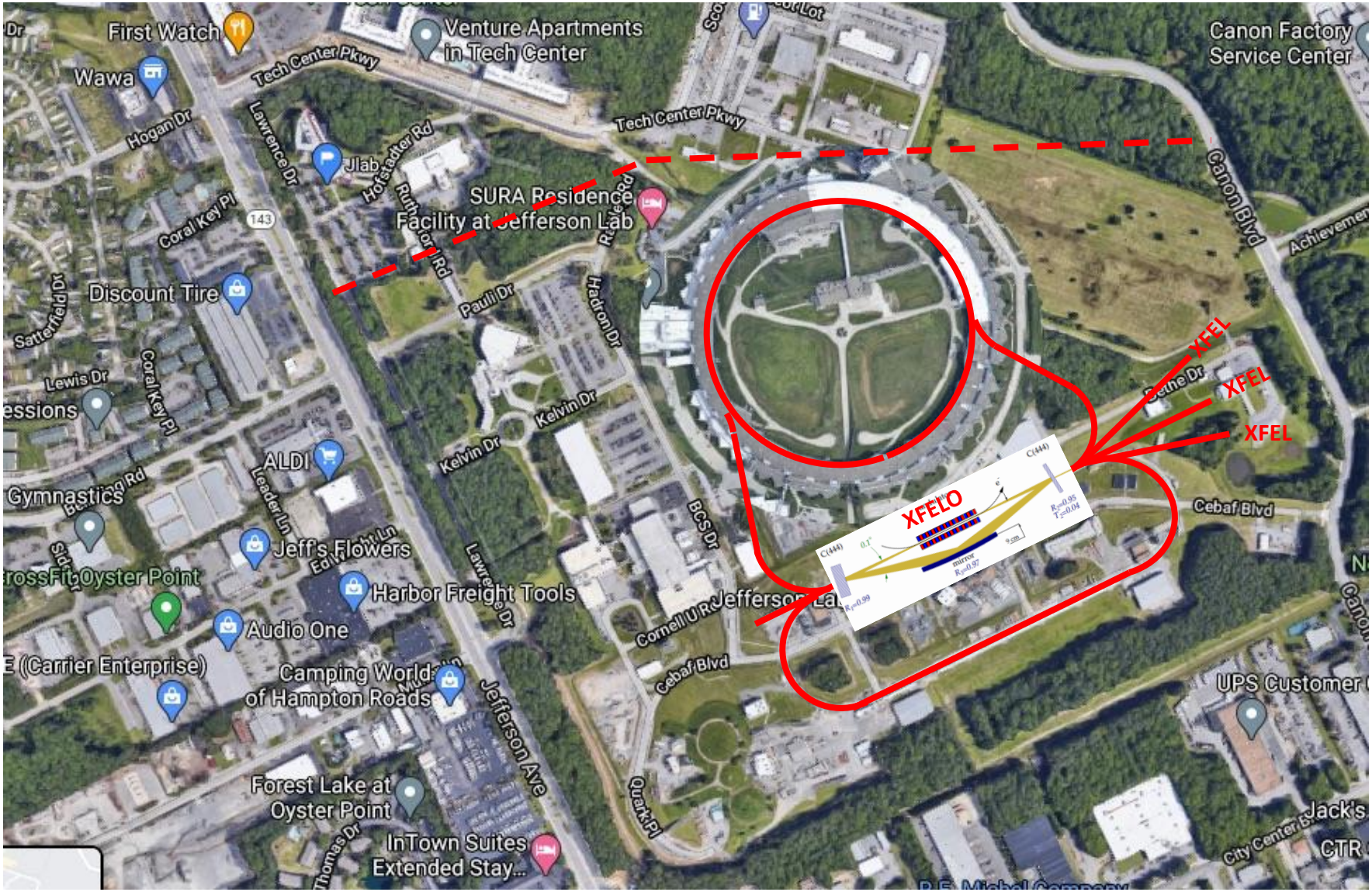
What if? Light source at Jlab?



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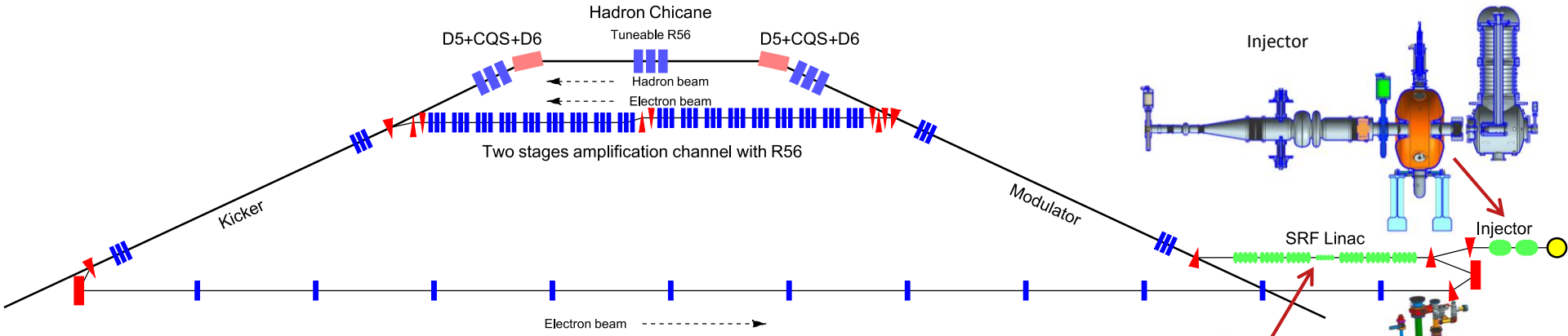
EIC high energy electron cooling

- Single Pass **150 MeV ERL**, 98.5 MHz bunch frequency
- **8 x 591 MHz, 5-cell** elliptical + **1.77 GHz** third harmonic
- Maximum 180 MV installed voltage, Eacc **15.8 MV/m**
- 8 x 591 MHz, **65 kW CW**, SSA RF Power Amplifiers
- **1 nC** per bunch, **~100 mA** single pass current
- Injector: DC photocathode gun, 197 MHz buncher, 591 MHz acceleration, 1.77 GHz linearizer.

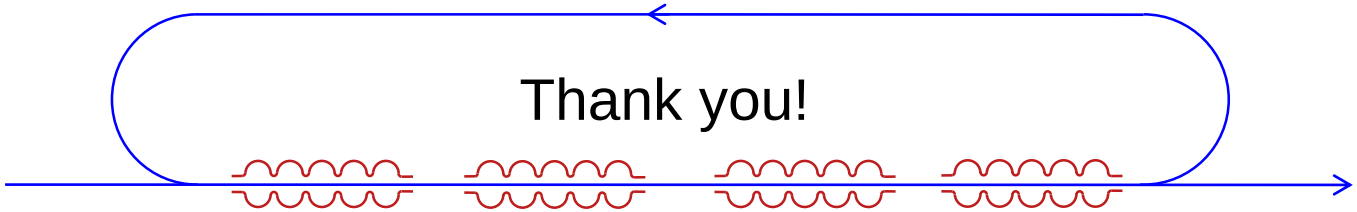


Cooler- 591 MHz ERL cavity

"The accelerator design progress for EIC strong hadron cooling", E. Wang et. Al., TUPAB036 Proc. IPAC21, Brazil.

Conclusions

- ERL concept is well proven
- ERL technology is well developed
- Many demos worldwide with increasing sophistication
- Need a final demo with all features simultaneously (PERLE)
  - Technology demonstrator/test bed
  - High-current
  - Multi-pass
  - Optimized cavities and cryomodules
  - Physics quality beam
  - Operated as a user facility
- Need compelling applications
  - Compact light sources (Lithography?)
  - High-Energy electron cooling
  - eh Collider


Thank you!

Back up

RF power options

Klystrons

- Limited vendors, high cost, low efficiency

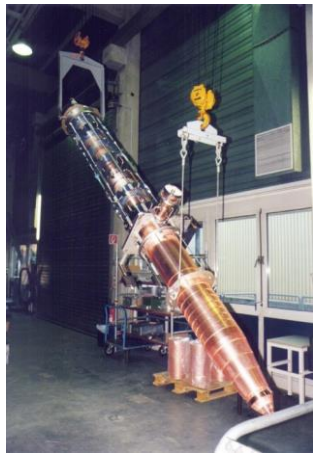
IOT's

- Better efficiency, becoming obsolete

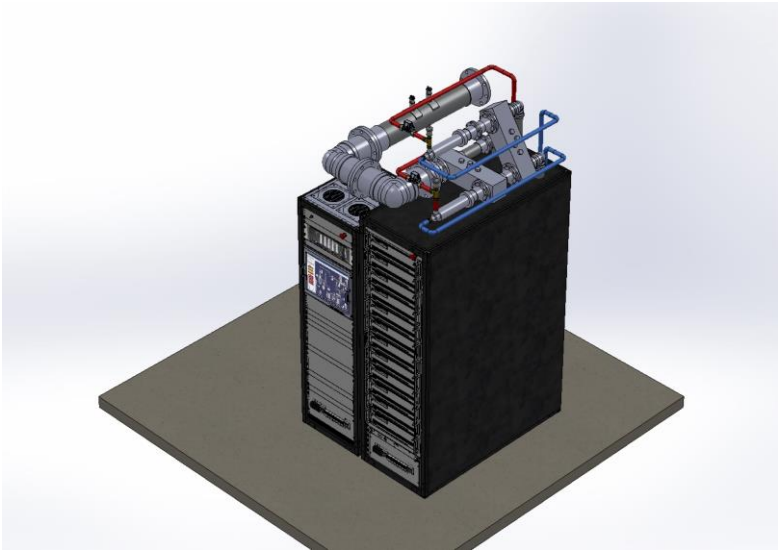
SSA's

- High efficiency
- Reliability and redundancy
- Costs falling, supply growing

IOT



MW klystron



50 kW SSA module