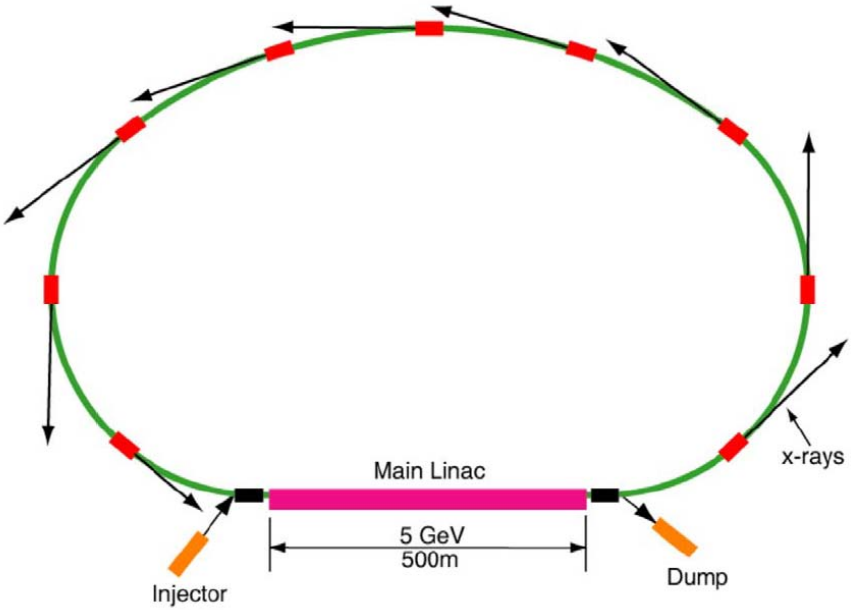
Overview of ERL R&D Towards Coherent X-ray Source

Ivan Bazarov

Cornell University



ERL x-ray light source concept

Acknowledgements

CLASSE

- Matthias Liepe for SRF slides; Georg Hoffstaetter for slides from his ERL'11 talk – and by proxy to the entire international ERL community

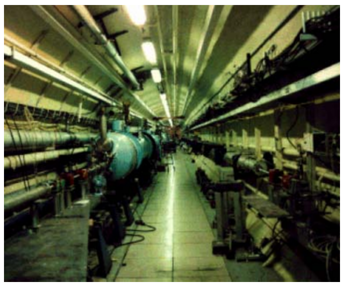
- Cornell team:
  - D. H. Bilderback, M. G. Billing, J. D. Brock, B. W. Buckley, S. S. Chapman, E. P. Chojnacki, Z. A. Conway, J. A. Crittenden, D. Dale, J. A. Dobbins, B. M. Dunham, R. D. Ehrlich, M. P. Ehrlichman, K. D. Finkelstein, E. Fontes, M. J. Forster, S. W. Gray, S. Greenwald, S. M. Gruner, C. Gulliford, D. L. Hartill, R. G. Helmke, G. H. Hoffstaetter, A. Kazimirov, R. P. Kaplan, S. S. Karkare, V. O. Kostroun, F. A. Laham, Y. H. Lau, Y. Li, X. Liu, M. U. Liepe, F. Loehl, L. Cultrera, C. E. Mayes, J. M. Maxson, A. A. Mikhailichenko, D. Ouzounov, H. S. Padamsee, S. B. Peck, M. A. Pfeifer, S. E. Posen, P. G. Quigley, P. Revesz, D. H. Rice, D. C. Sagan, J. O. Sears, V. D. Shemelin, D. M. Smilgies, E. N. Smith, K. W. Smolenski, A. B. Temnykh, M. Tigner, N. R. A. Valles, V. G. Veshcherevich, Z. Wang, A. R. Woll, Y. Xie, Z. Zhao

- NSF DMR-0807731 for ERL R&D support at Cornell

Outline

- Introduction & motivation
- Main technological challenges
- Alternative ideas
- Outlook

ERL development timeline



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

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

KEK, BESSY, China

1960

1970

1980

1990

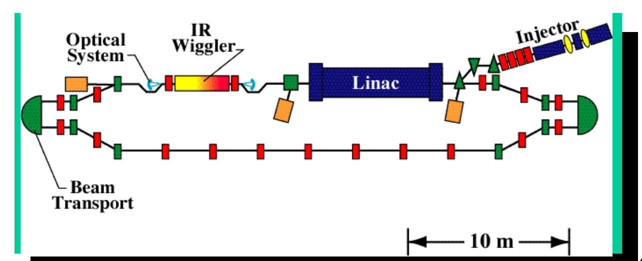
2000

2010

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

1998: BINP FEL
1999: JLAB DEMO-FEL
2002: JAEI FEL
2004: JLAB FEL Upgrade

1990: S-DALINAC
(Darmstadt)



Cornell ERL white paper (2000)

http://erl.chess.cornell.edu/papers/2000/ERLPub00_1.pdf

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White Paper

Synchrotron Radiation Sources for the Future

Sol Gruner[1,2,3], Don Bilderback[1,4], Maury Tigner[2,5]
[1] Cornell High Energy Synchrotron Source (CHESS)
[2] Department of Physics
[3] Laboratory of Atomic and Solid State Physics (LASSP)
[4] School of Applied and Engineering Physics
[5] Laboratory of Nuclear Studies (LNS)
Cornell University, Ithaca, NY 14853

discusses 10^23 brightness (s.u.) out of an ERL

- **Geoff Krafft and Dave Douglas talk about ERL-based X-ray light source around that time (slightly earlier); MARS proposal by Gennady Kulipanov et al. (1998)**

Progress in ERLs for Light Sources

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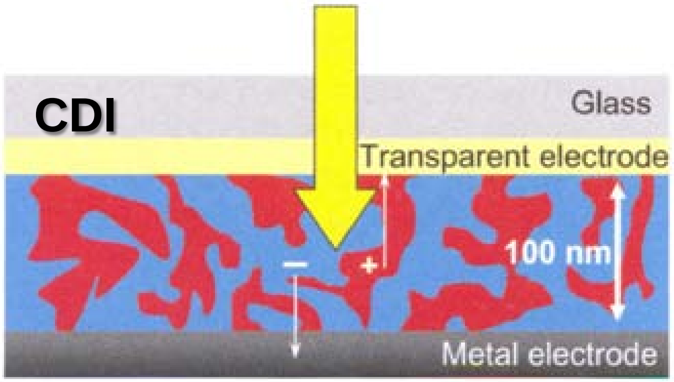
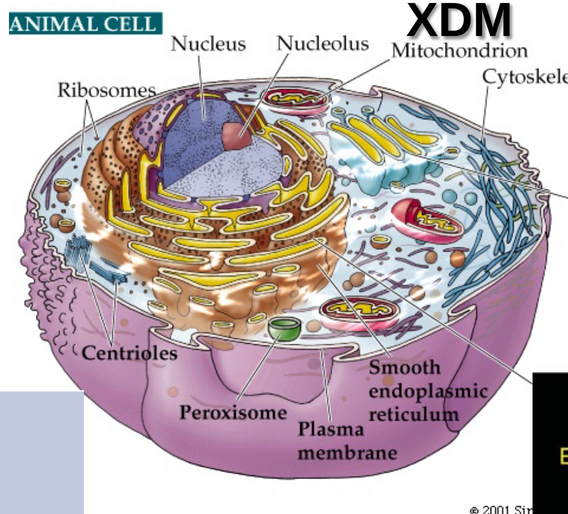
XDL'11 workshops – exciting science enabled by X-ray ERLs

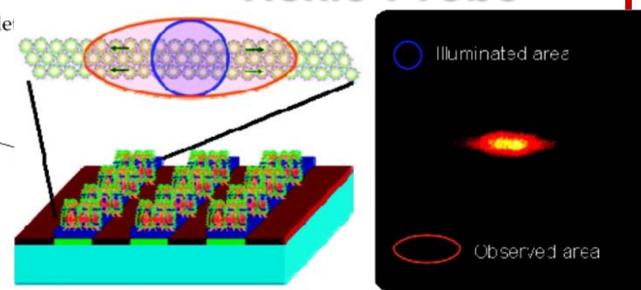
CDI



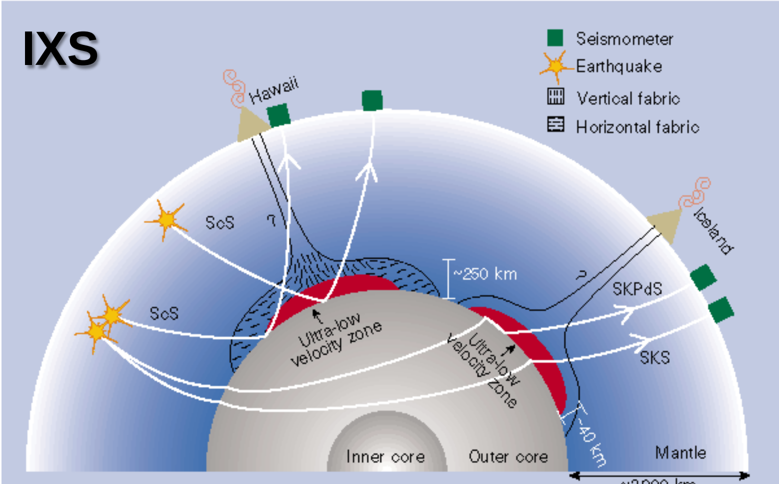
XDM



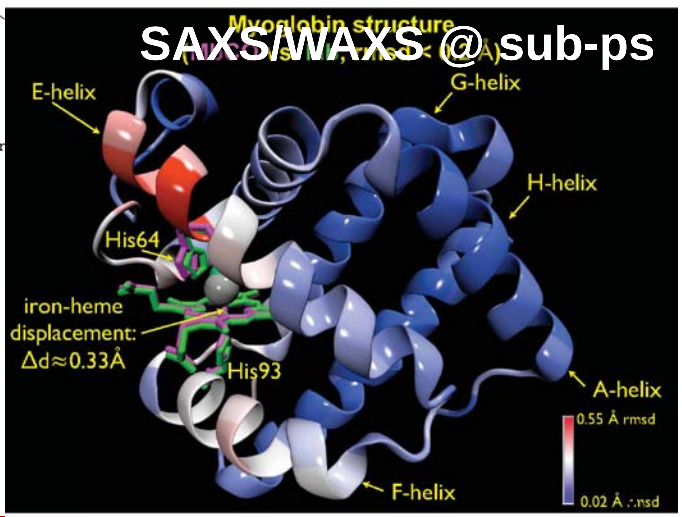
Tickle-Probe



IXS

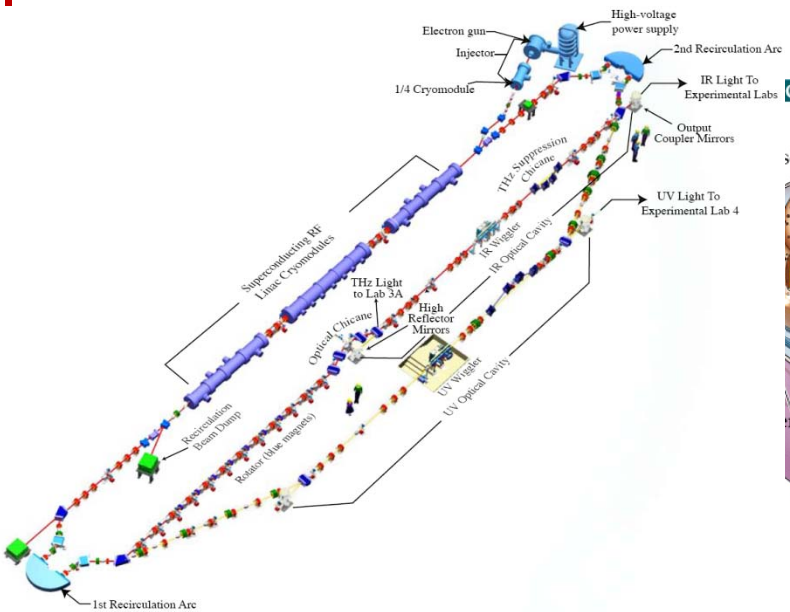


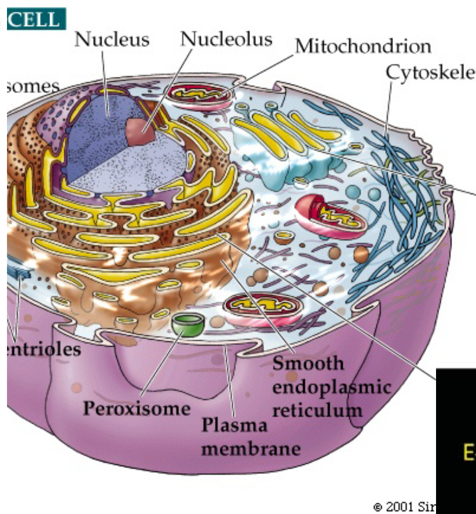
SAXS/WAXS @ sub-ps

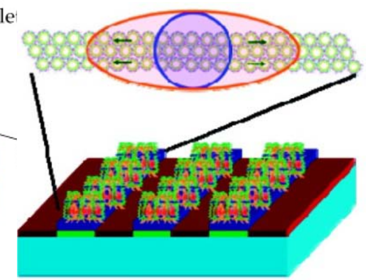


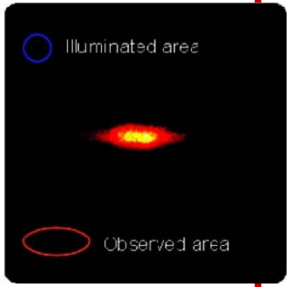
Progress in ERLs for Light Sources

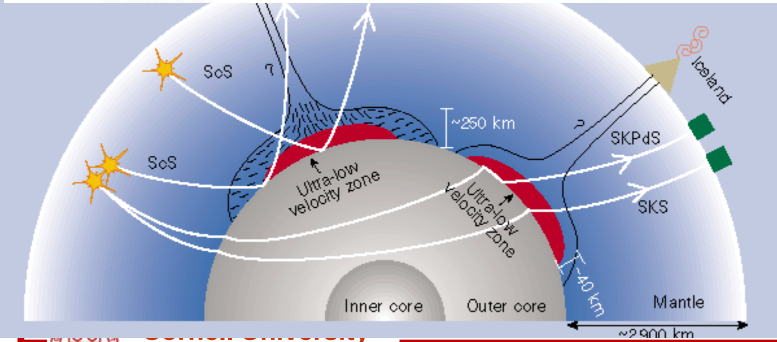
Operations at JLAB

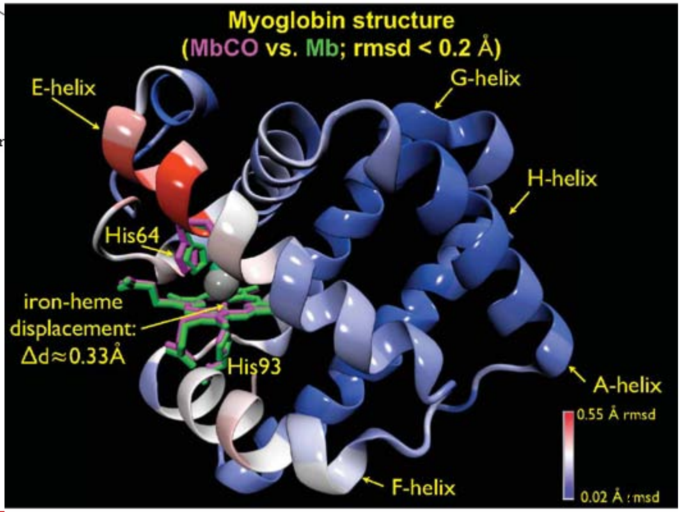






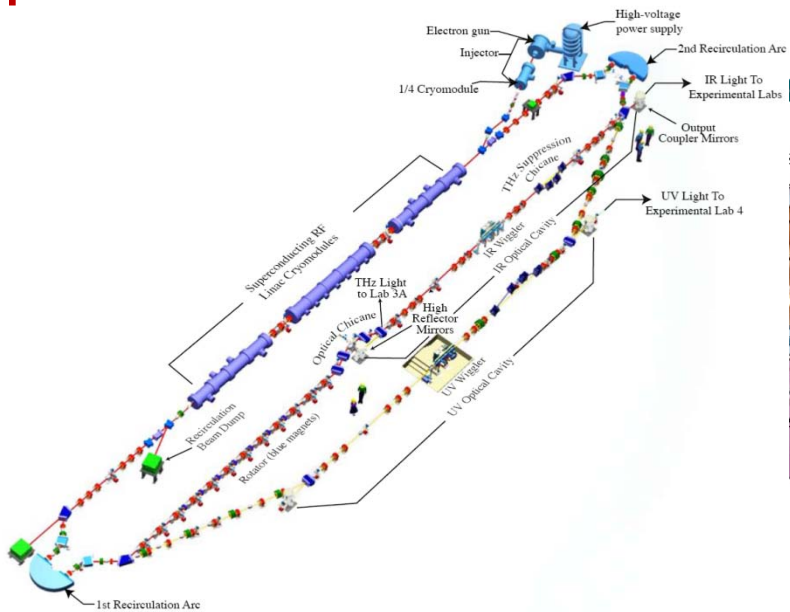


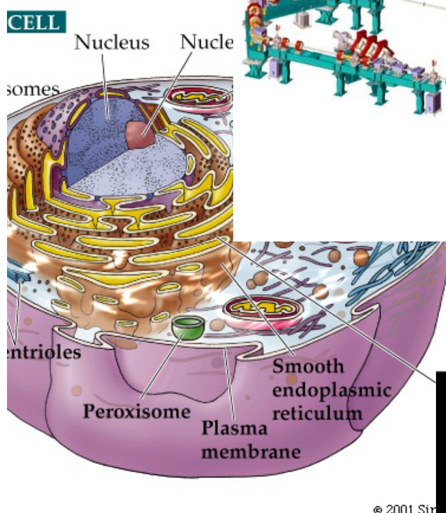


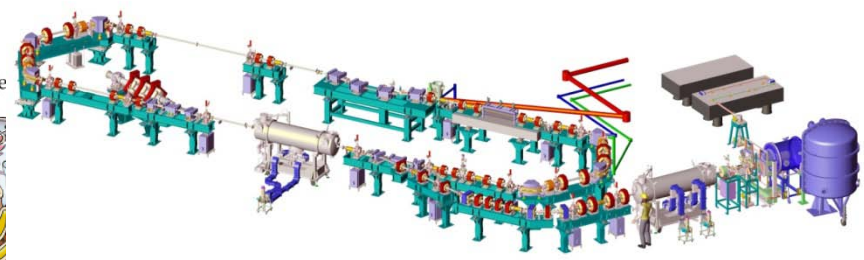


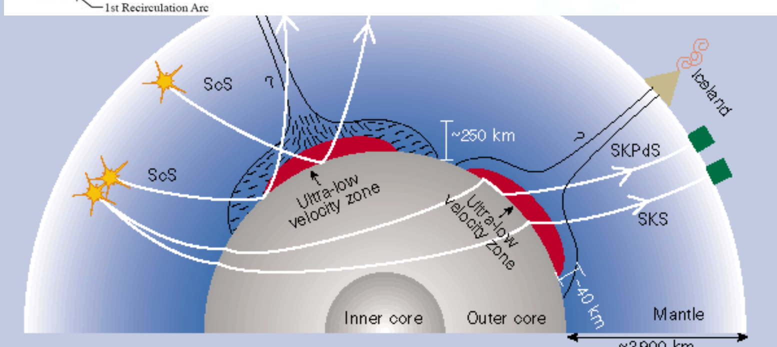
Progress in ERLs for Light Sources

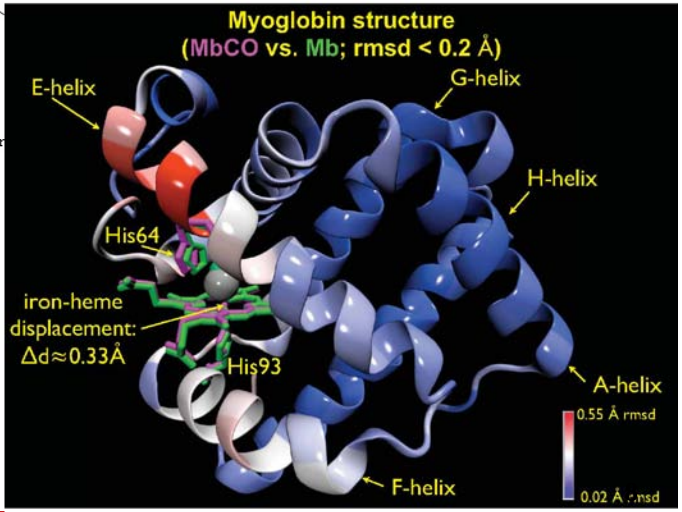
Operations at JLAB, Daresbury,











Progress in ERLs for Light Sources

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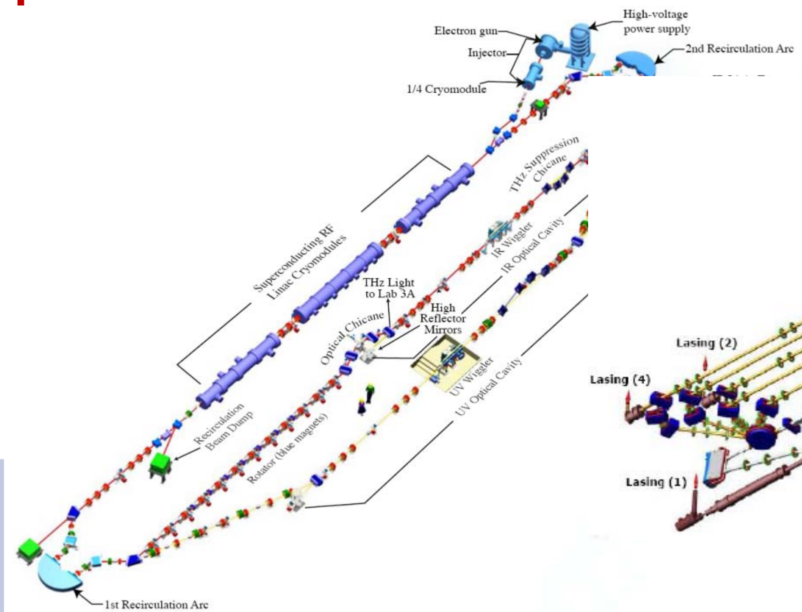
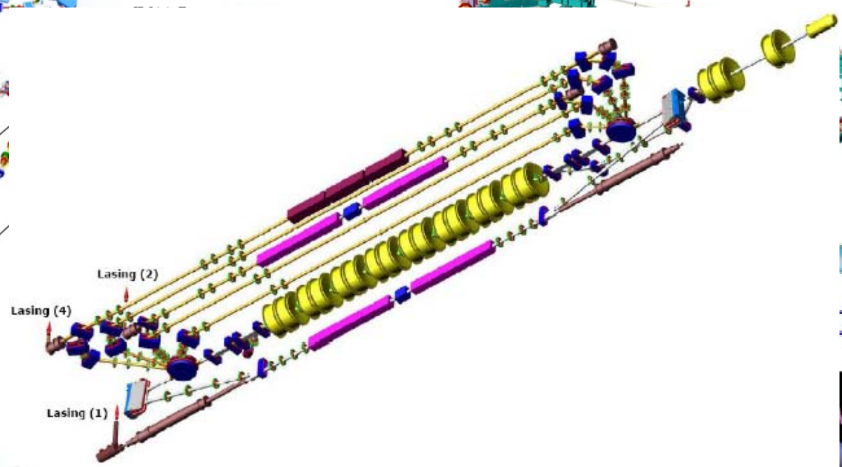
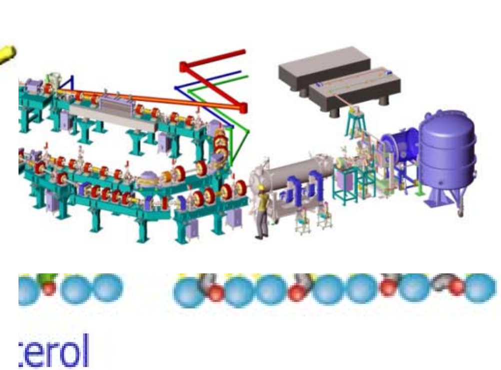
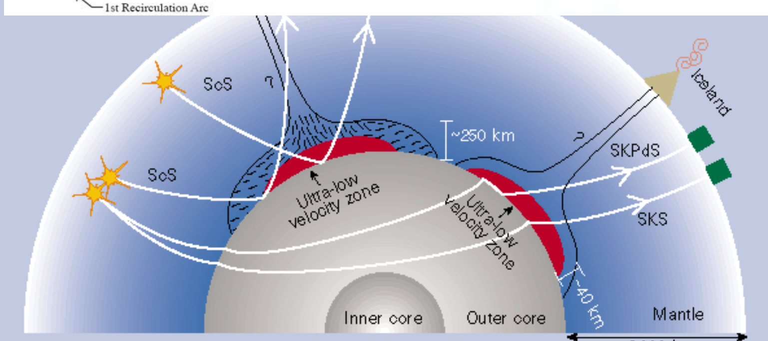
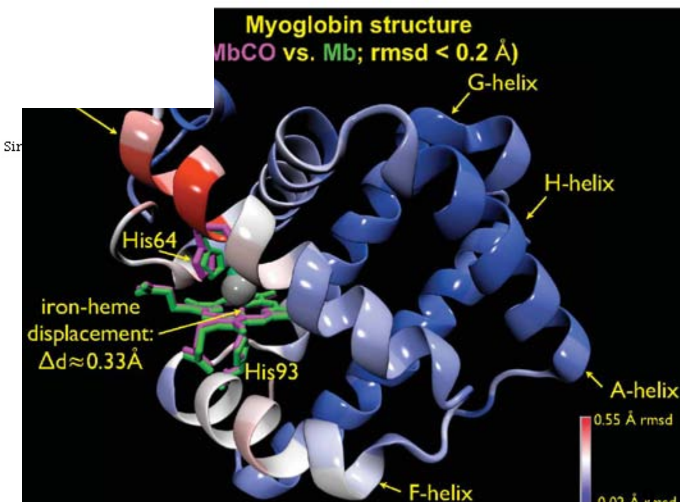
Operations at JLAB, Daresbury, BINP











Progress in ERLs for Light Sources

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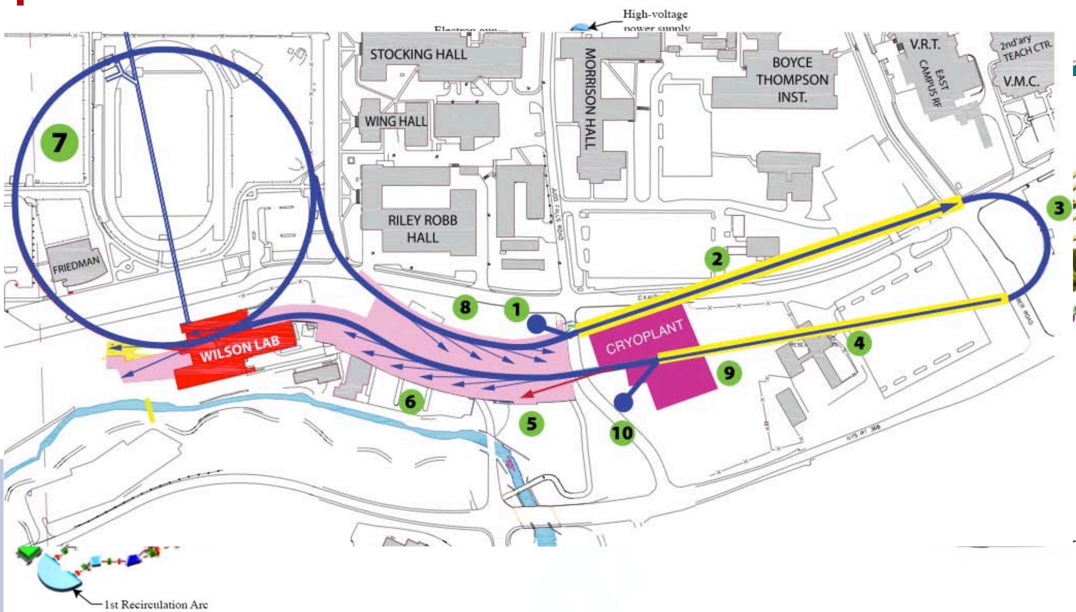
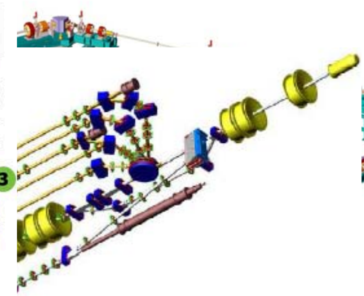
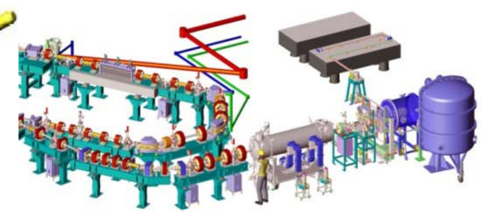
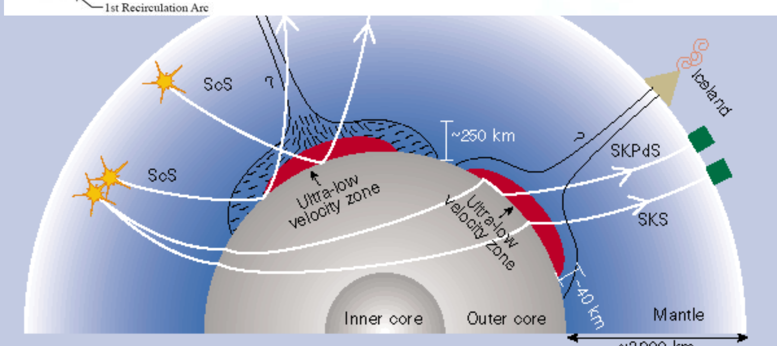
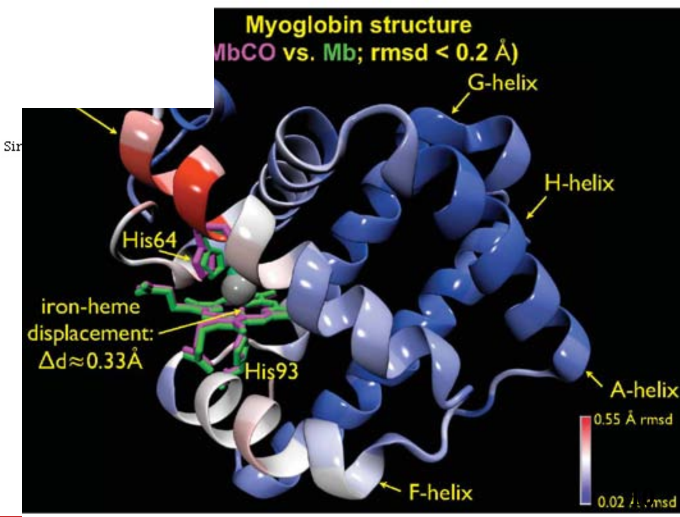
Operations at JLAB, Daresbury, BINP
Designs at Cornell











Progress in ERLs for Light Sources

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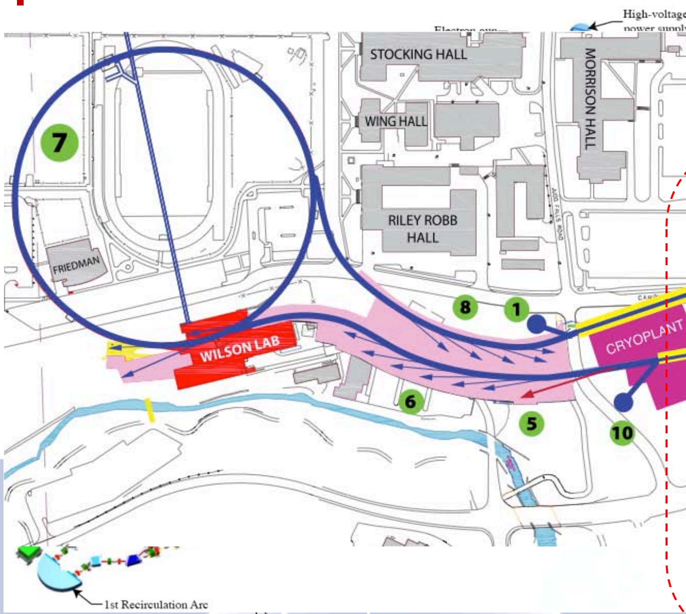
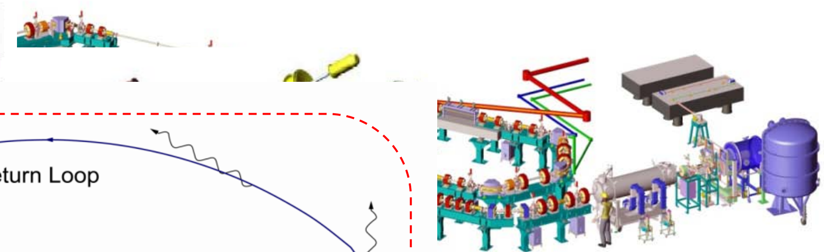
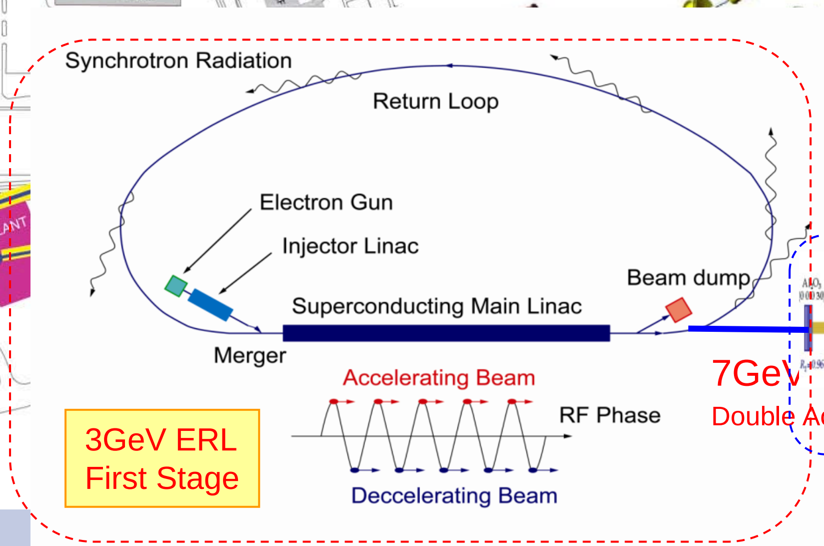
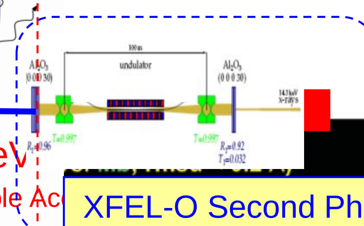
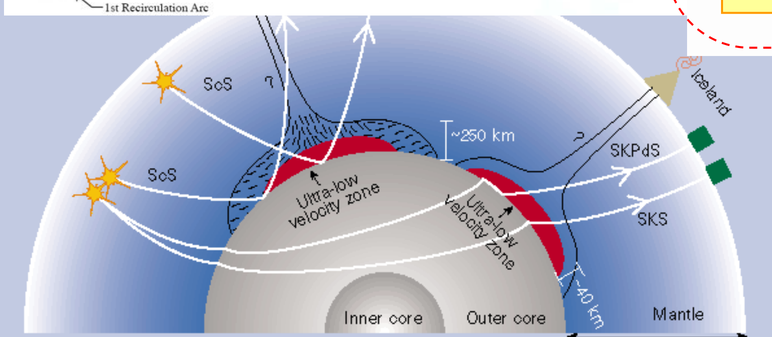
Operations at JLAB, Daresbury, BINP
Designs at Cornell, KEK/JAEA

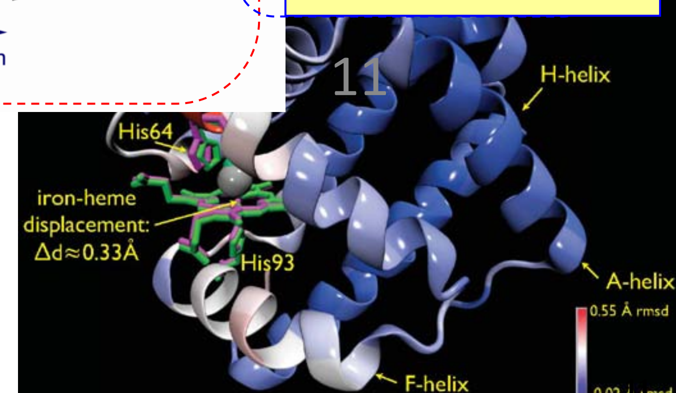








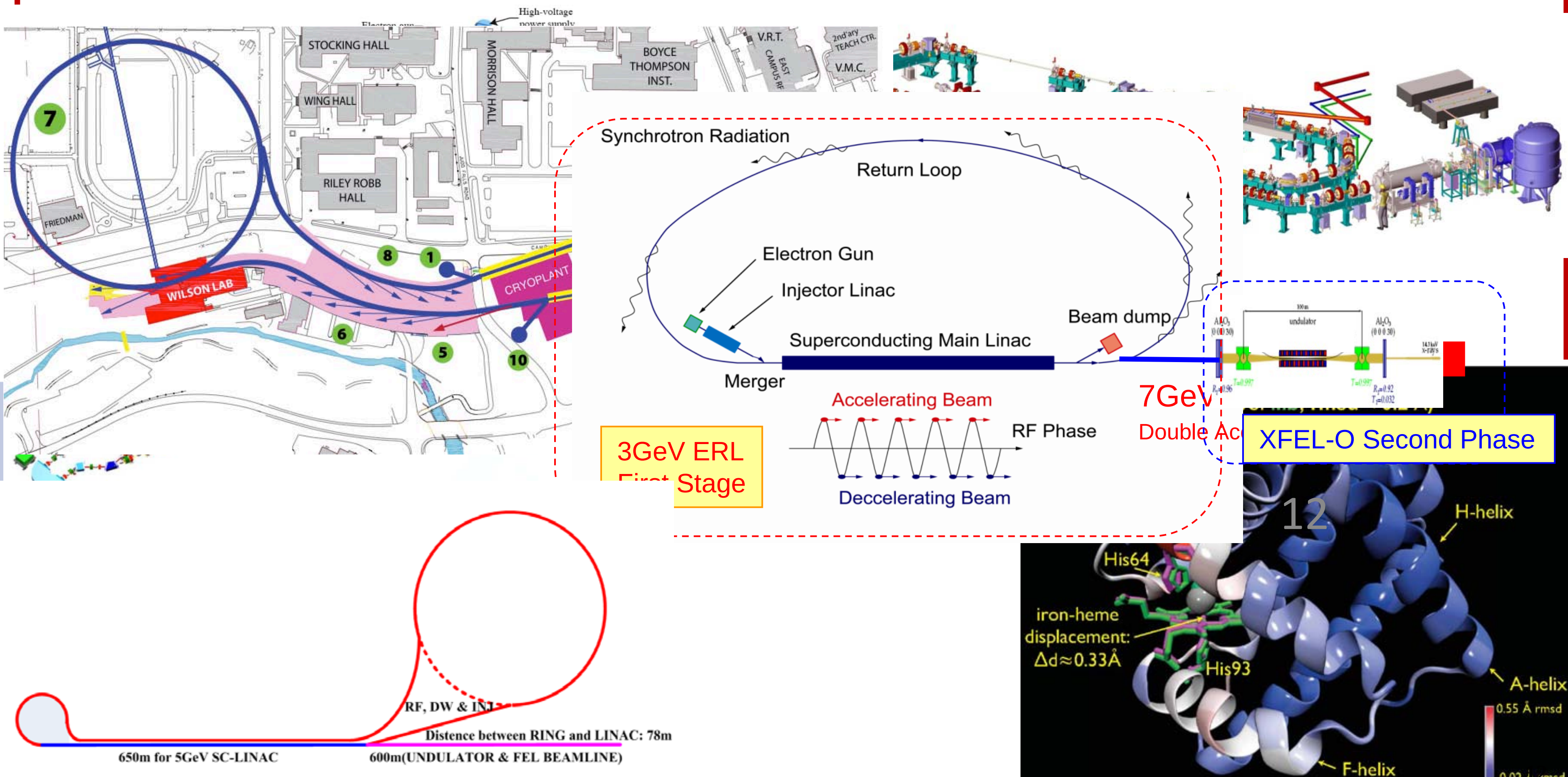




Progress in ERLs for Light Sources

CLASSE

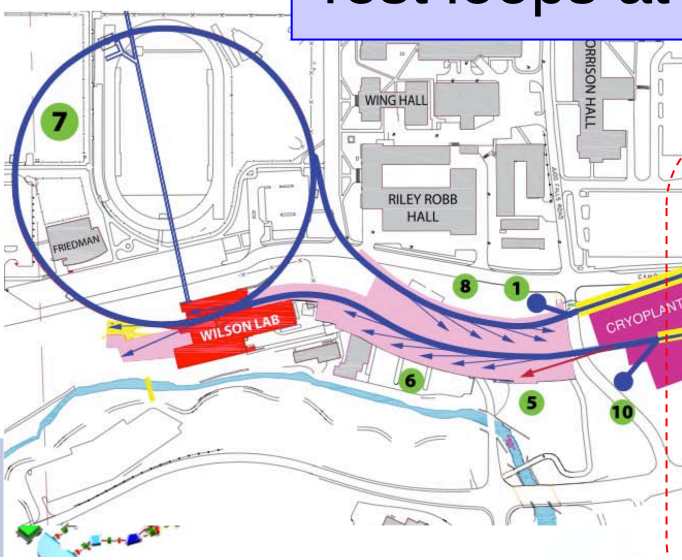
Operations at JLAB, Daresbury, BINP
Designs at Cornell, KEK/JAEA, BAPS

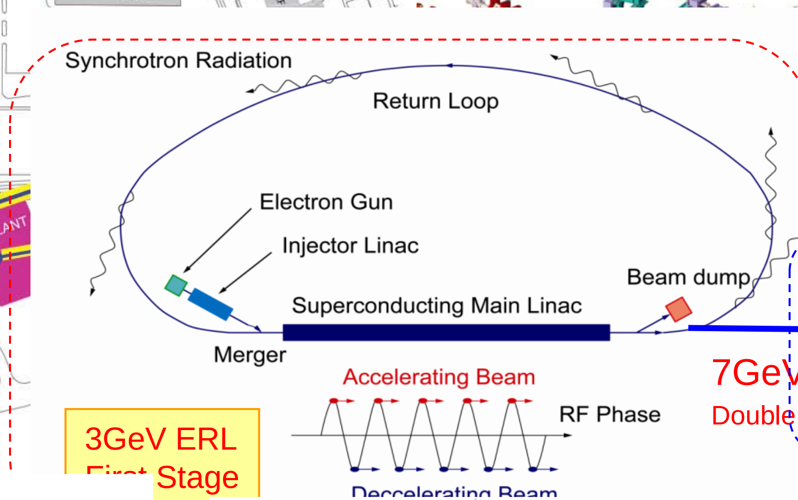


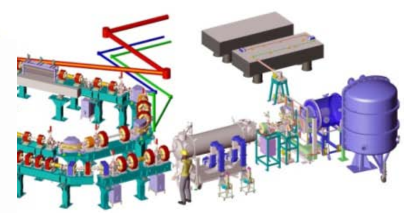
Progress in ERLs for Light Sources

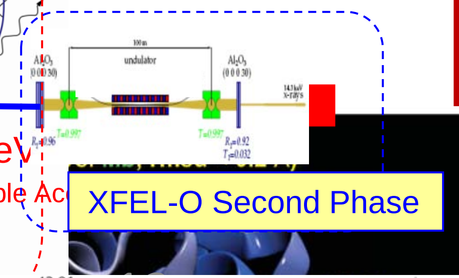
CLASSE

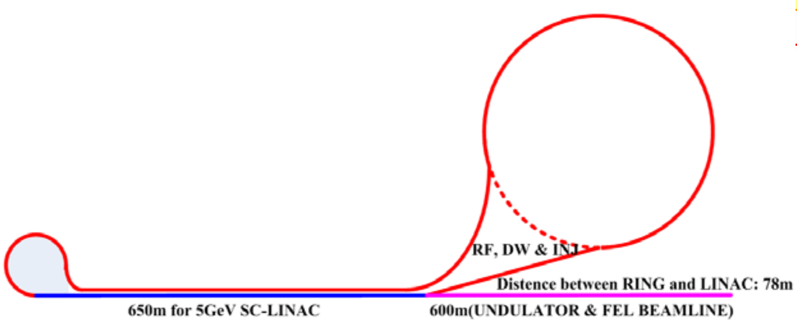
Operations at JLAB, Daresbury, BINP
Designs at Cornell, KEK/JAEA, BAPS
Test loops at KEK

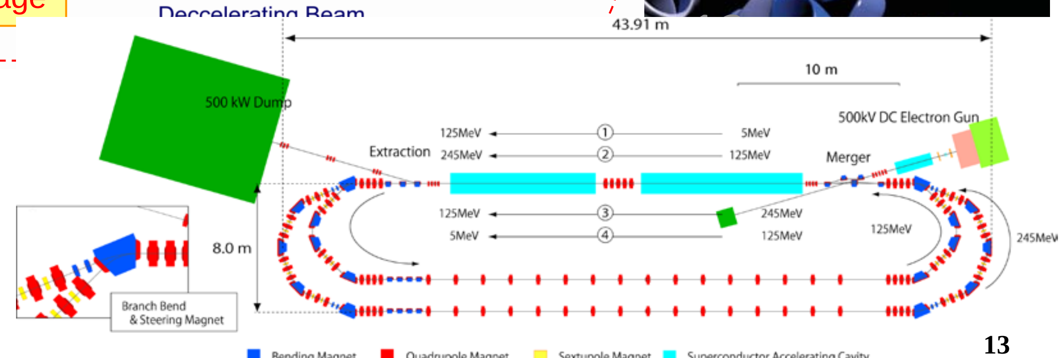












Progress in ERLs for Light Sources

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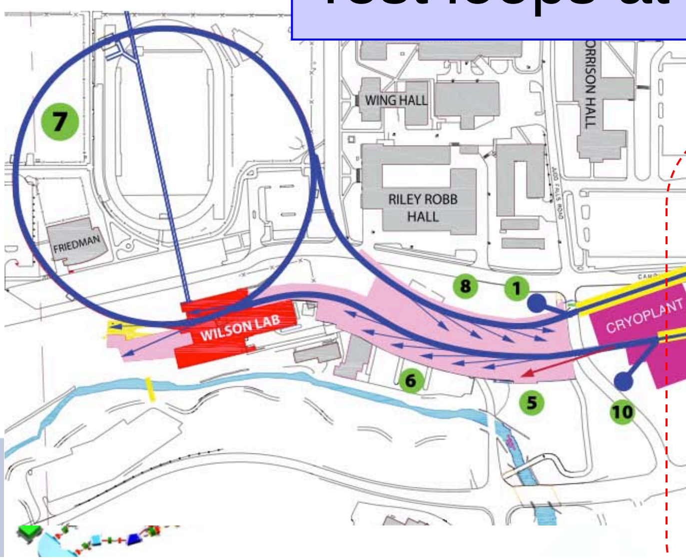
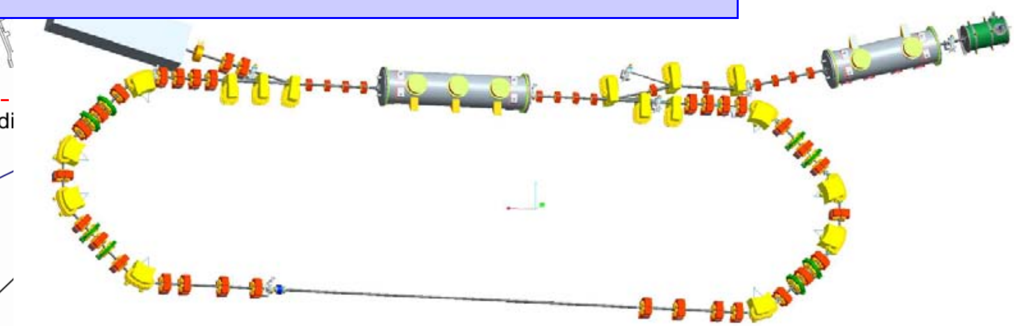
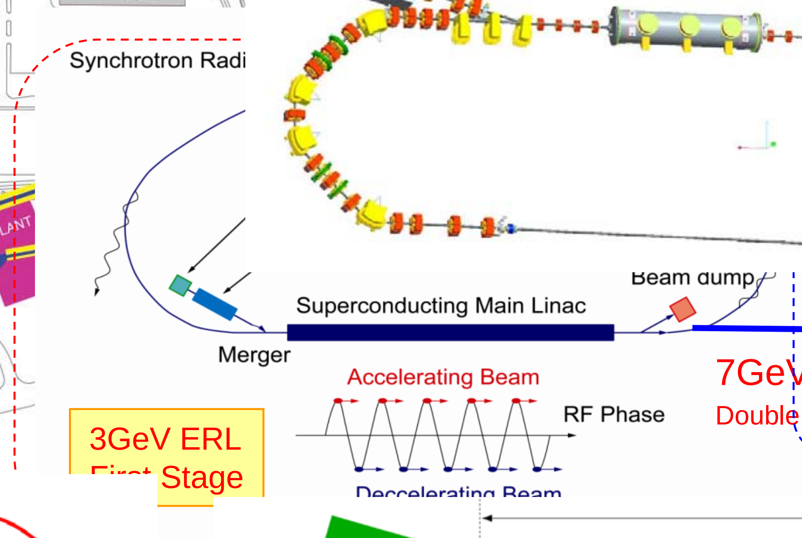
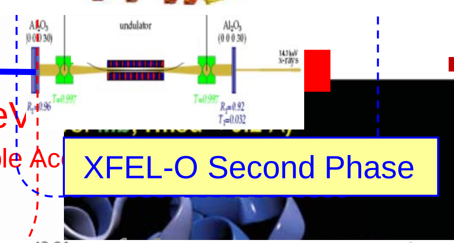
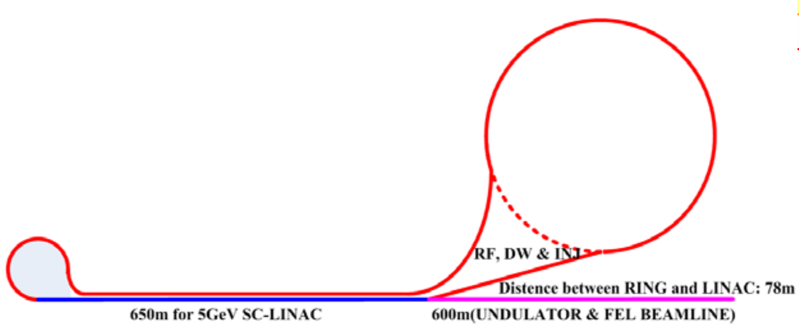
Operations at JLAB, Daresbury, BINP
Designs at Cornell, KEK/JAEA, BAPS
Test loops at KEK, HZB

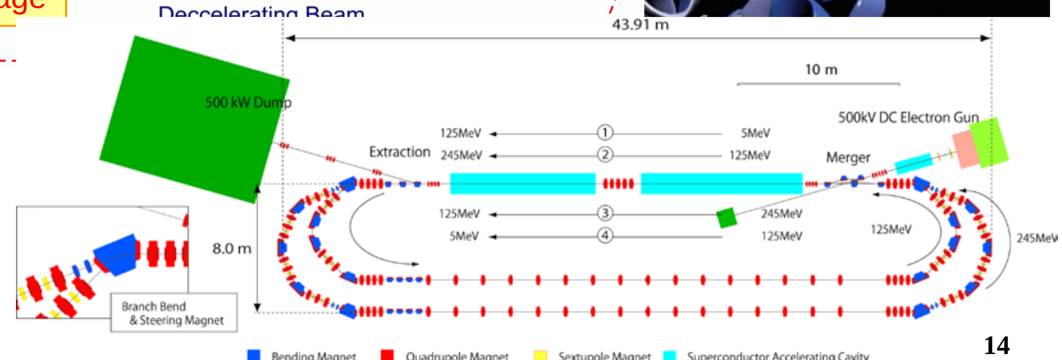












Progress in ERLs for Light Sources

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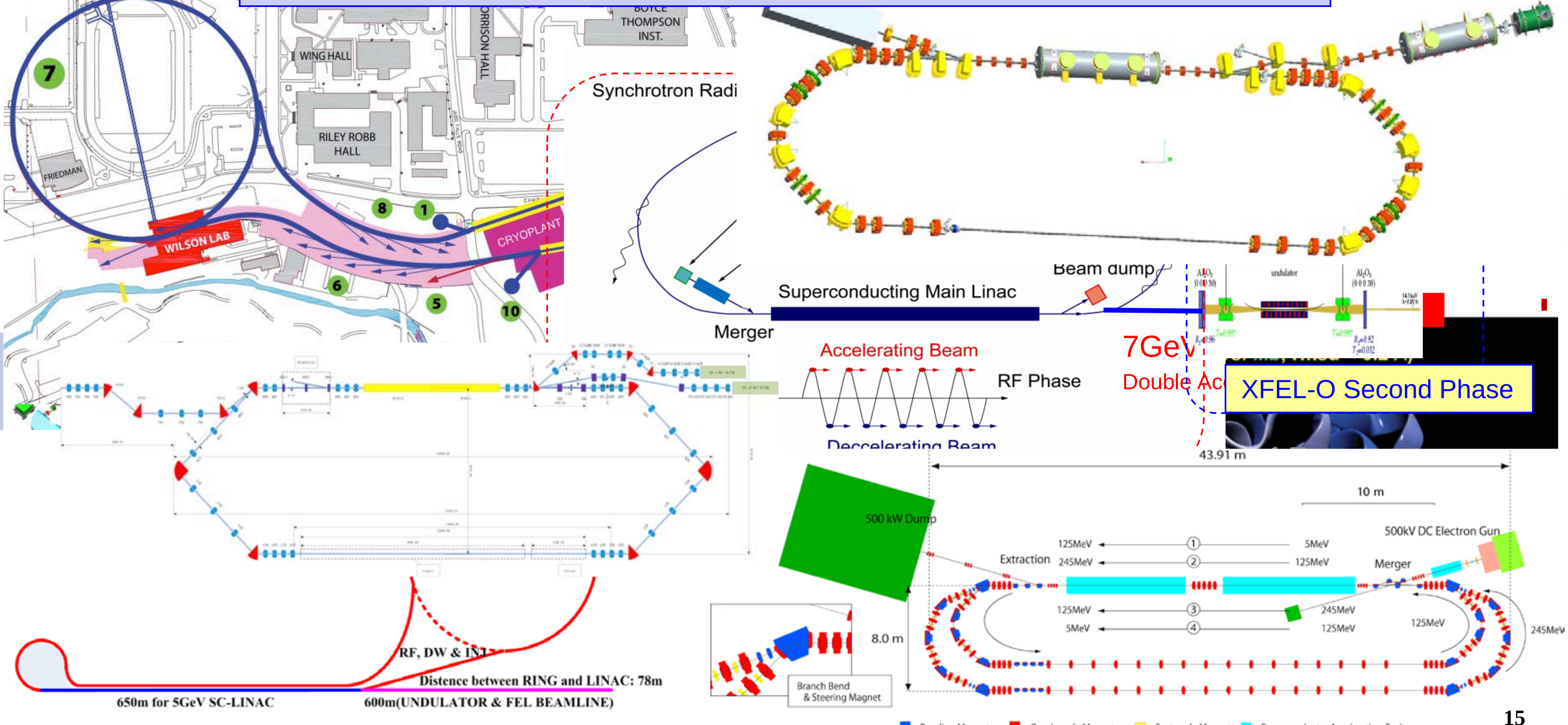
Operations at JLAB, Daresbury, BINP
Designs at Cornell, KEK/JAEA, BAPS
Test loops at KEK, HZB, IHEP



Energy Recovery Installations:

Successful tests for ERL beam dynamics, controls, and technology

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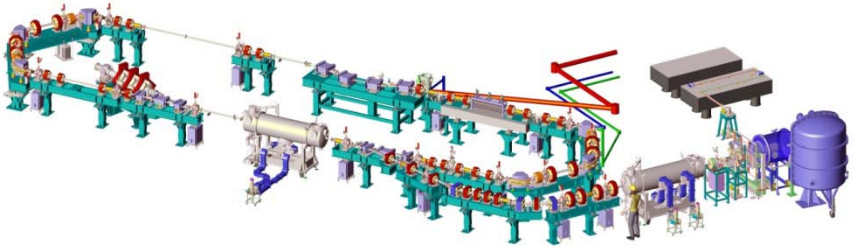
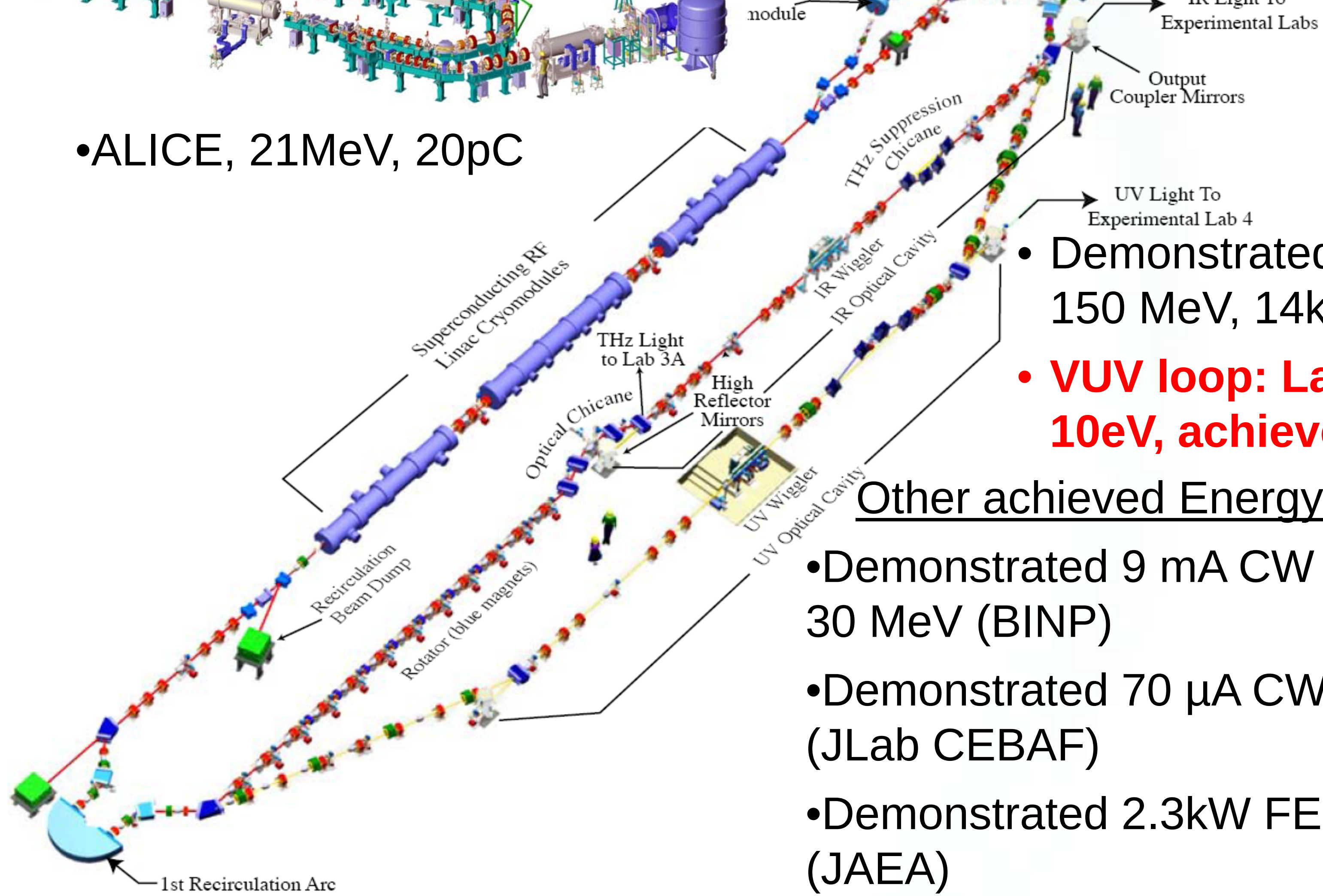


•ALICE, 21MeV, 20pC



- Demonstrated 9 mA CW at 150 MeV, 14kW (Jlab FEL)
- **VUV loop: Lasing at 10eV, achieved 2010**

<u>Other achieved Energy Recovery</u>

•Demonstrated 9 mA CW two-pass at 30 MeV (BINP)

•Demonstrated 70 µA CW at 1 GeV (JLab CEBAF)

•Demonstrated 2.3kW FEL, 17MeV (JAEA)

New test installations

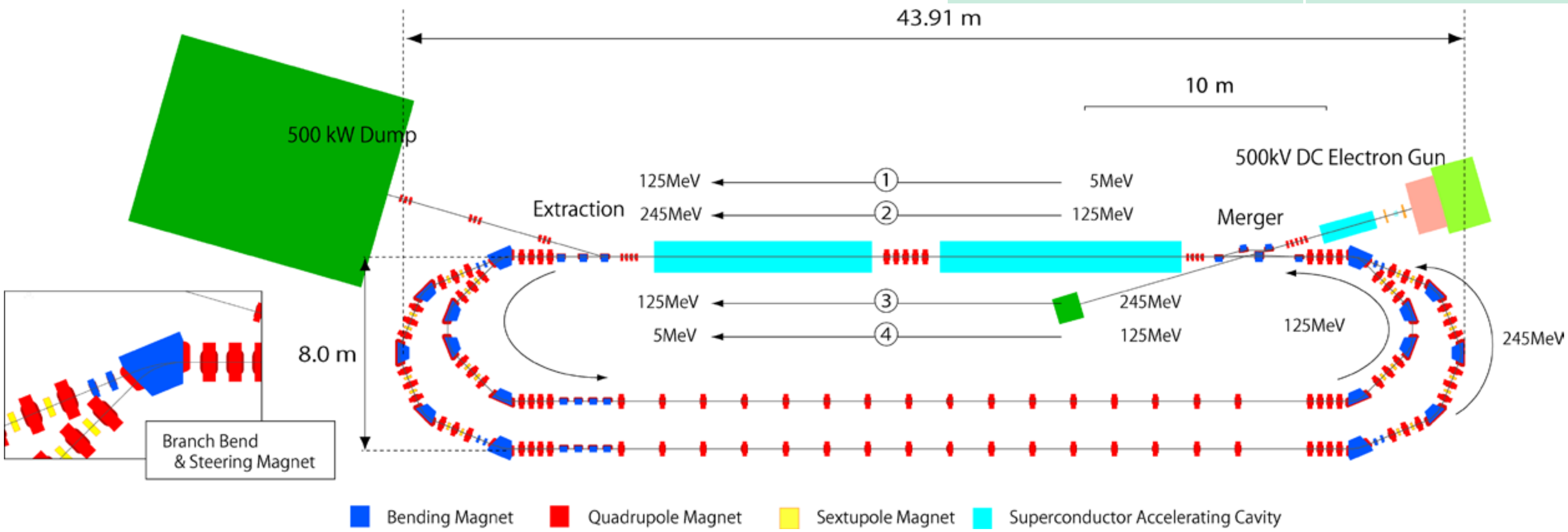
Double Loop Compact ERL (KEK)

- **Why did we choose a double loop circulator?**

It is for saving

construction area
number of accelerator cavities
running cost of the refrigerators

Injection energy	5-10 MeV
Full energy	245 MeV
Electron charge	77 pC
Normalized emittance	< 1 mm-mrad
Bunch length	1-3 ps



Layout of double loop Compact ERL

New test installations
BNL, KEK, BESSY, and IHEP

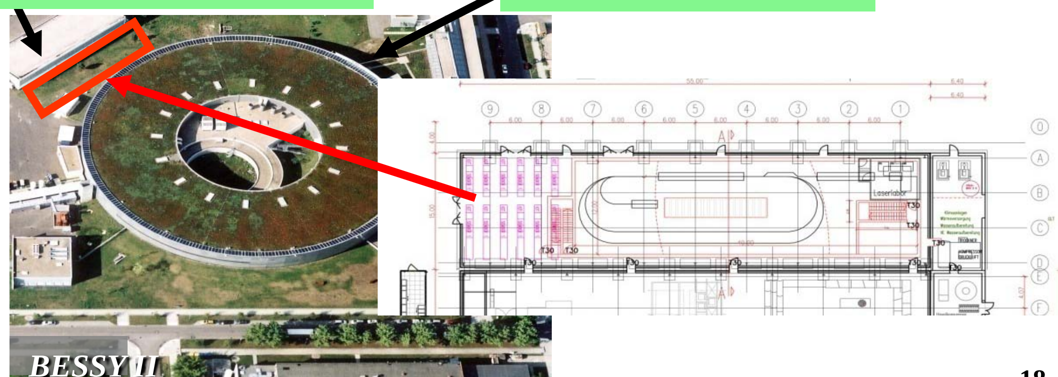
IHEP Compact TF-- 35 MeV-10 mA

BNL ERL test for coherent e-cooling of RHIC

BERLinPro: ERL demonstration facility

Cryogenic plant

BESSY II



ERL X-ray source R&D

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- **Essentials**
  - SRF (high Q_0 , Q_L for low operation cost; HOM damping for > 100mA; cost-efficient cryomodule design & fabrication)
  - Photoinjector (demonstrate high current, longevity, brightness)
  - Generic facility strawman (undulators, magnets, power budget, cryoplant)
- **And beyond**
  - Multi-turn designs (depends on how cheap/efficient SRF can be made)
  - Marry XFEL solutions (simultaneous low rep rate beam operation with high current – e.g. KEK design)

Significant photoinjector developments

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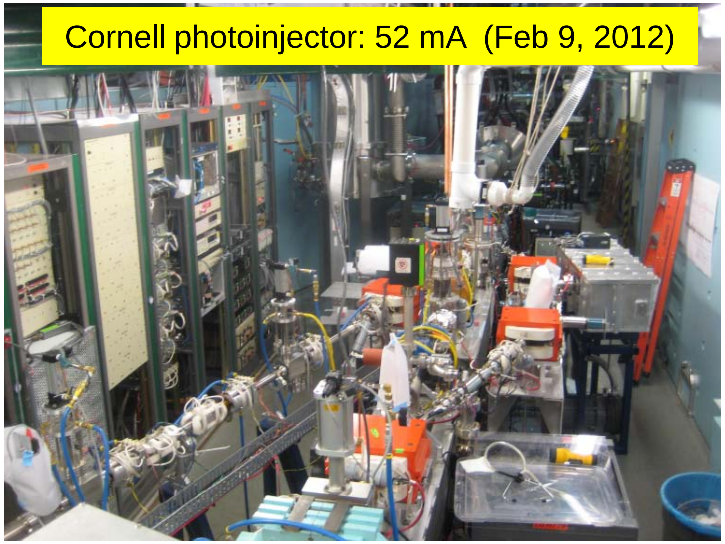
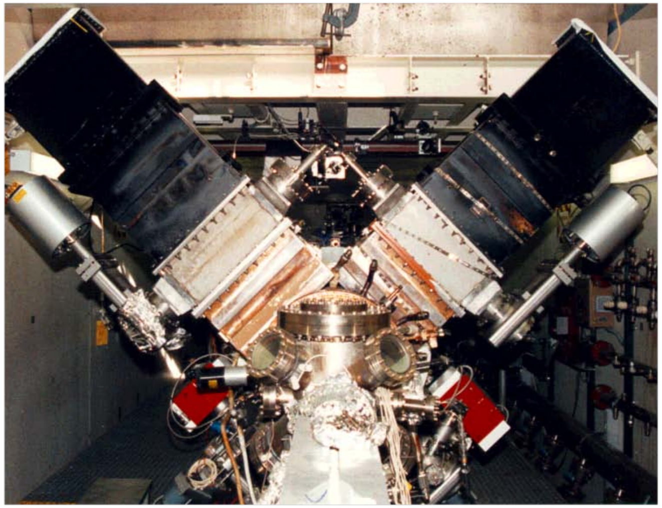
- First beam from new SRF electron sources (HZB/JLAB for ERLs; Niowave/NPS; more coming up)
- More new guns (DC, NCRF, and SRF) with ~100mA in mind either being commissioned or under construction
- Cornell photoinjector highlights (over the last year):
  - Maximum average current of 50 mA from a photoinjector demonstrated (Feb 2012)
  - Demonstrated feasibility of high current operation (~ kiloCoulomb extracted with no noticeable QE at the laser spot)
  - Original emittance spec achieved: now getting x1.8 the thermal emittance values, close to simulations (Sept 2011)
  - Beam brightness @5GeV same as 100 mA 0.5x0.005nm-rad SR

Boeing/LANL RF gun tribute



The Boeing 433 MHz RF Photocathode Gun



D.H. Dowell/MIT Talk, May 31, 2002

- **New current record is 52 mA at Cornell**
  - **beats Dave Dowell's 32 mA record of *20 years*!**
- **More in my photoinjector overview talk**

courtesy M. Liepe

Main Linac Cavity Development and high Q_0

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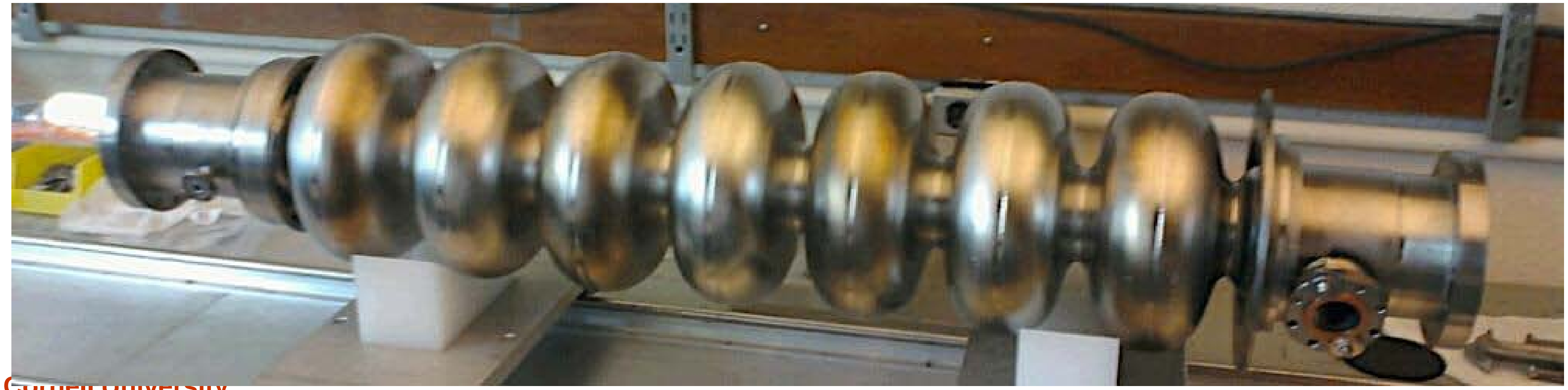
Specs: Support ERL operation with >100 mA; must minimize cryogenic wall losses ($Q \sim 2 \cdot 10^{10}$ at 1.8 K)

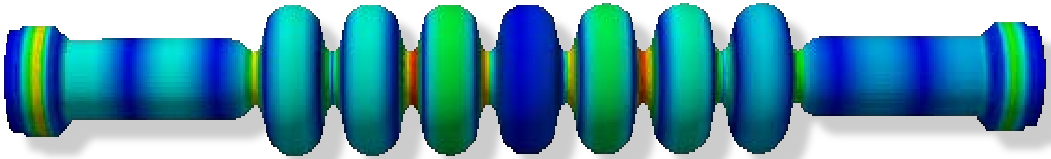
Completed :

- **RF design**
- **Mechanical design**
- **Cavity fabrication**
- **Vertical cavity RF test**
- **Horizontal cavity test in cryomodule**
- **Meets ERL specs: 16 MV/m, $Q_0 \sim 2 \cdot 10^{10}$**



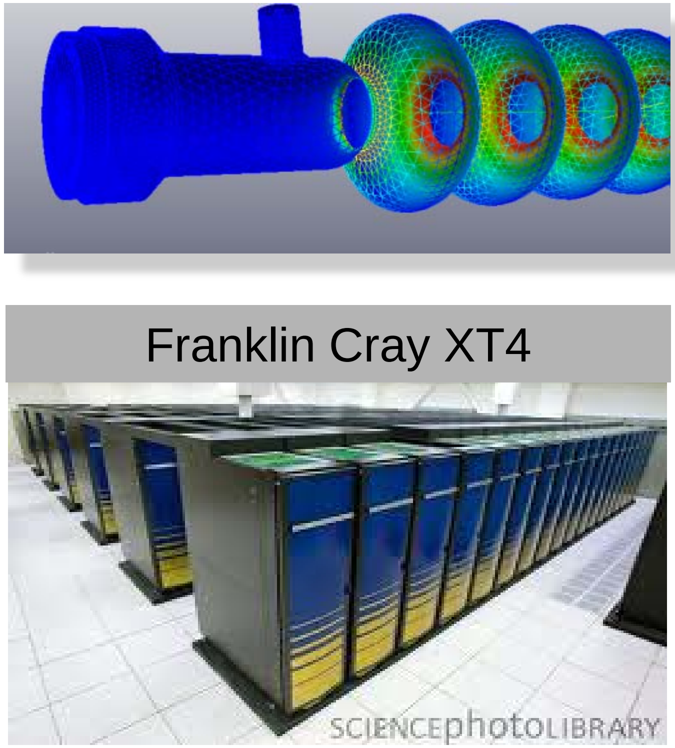
courtesy M. Liepe

RF Optimization for >100 mA ERL Operation (I)

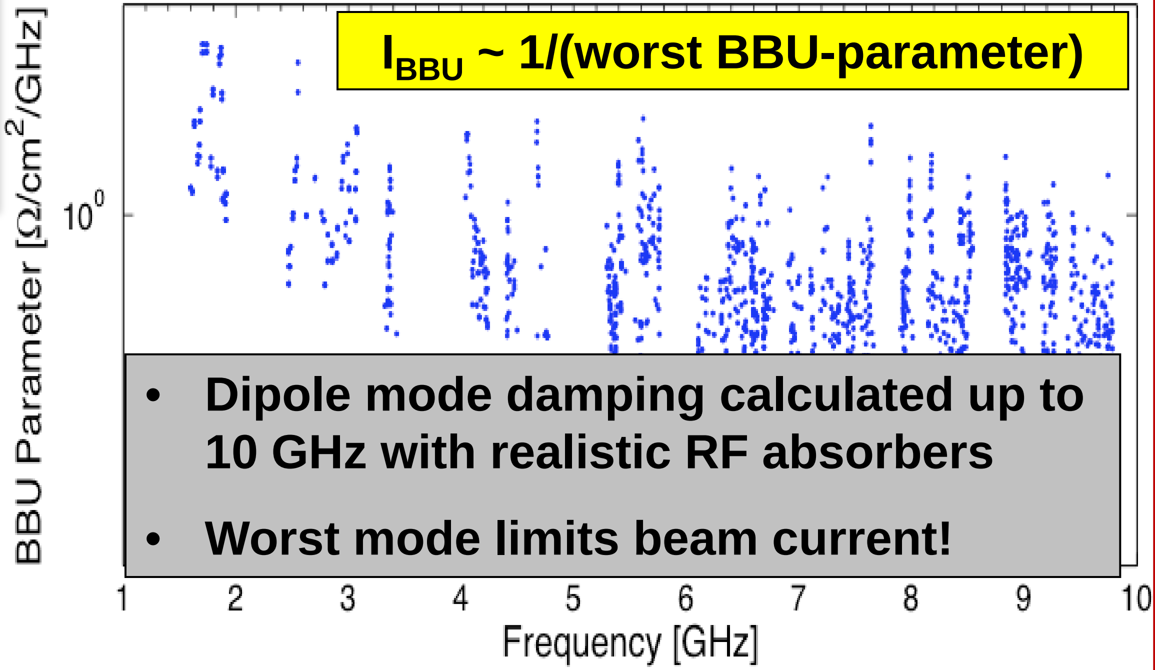


Cell shape optimization:

- **~20 free parameters**
- **Full Higher-Order Mode characterization (1000's of eigenmodes)**
- **Verification of robustness of cavity design**



Franklin Cray XT4



- **Dipole mode damping calculated up to 10 GHz with realistic RF absorbers**
- **Worst mode limits beam current!**

RF Optimization for >100 mA ERL Operation (II)

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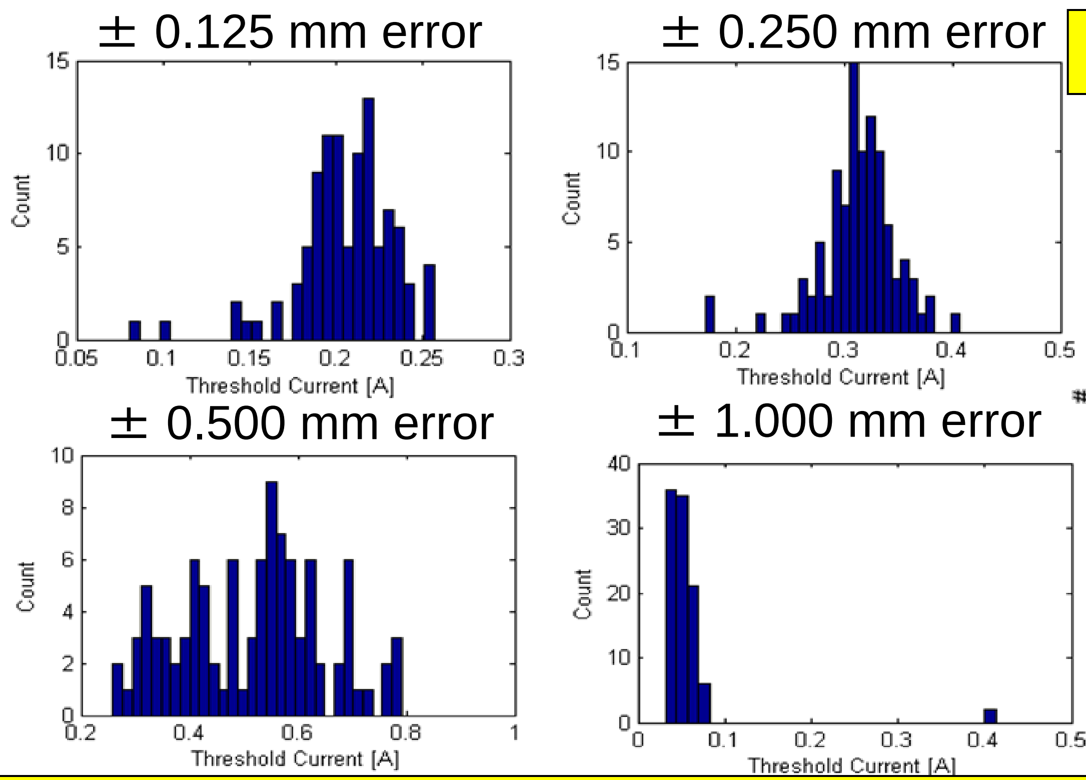
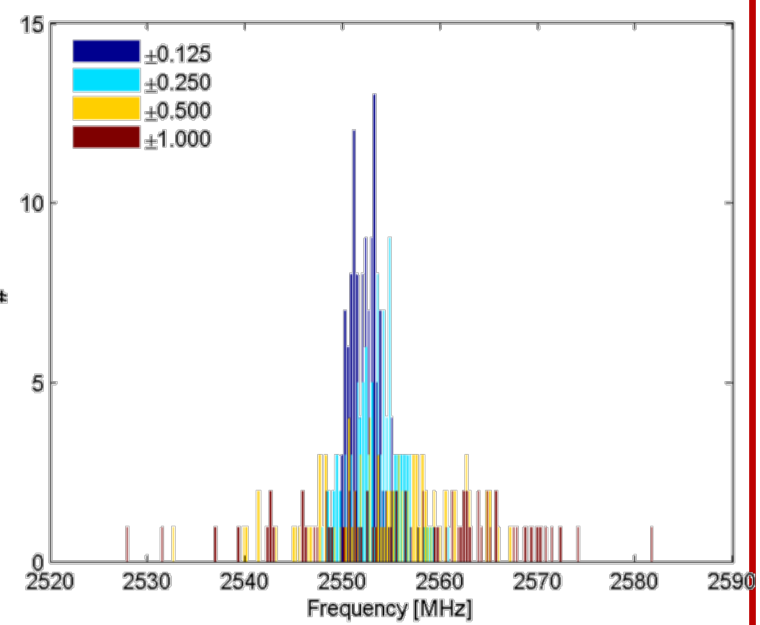
Optimize Cavity W.R.T. BBU parameter → **Introduce realistic shape variations (400 cavities)** → **Compute dipole HOMs to 10 GHz (1692 modes /cavity)** → **Generate realistic ERL (x100)** → **Compute BBU current**



Key: simulate realistic linac



Optimized cavity shape robust up to ±0.25 mm shape imperfections!

courtesy M. Liepe

RF Optimization for >100 mA ERL Operation (III)

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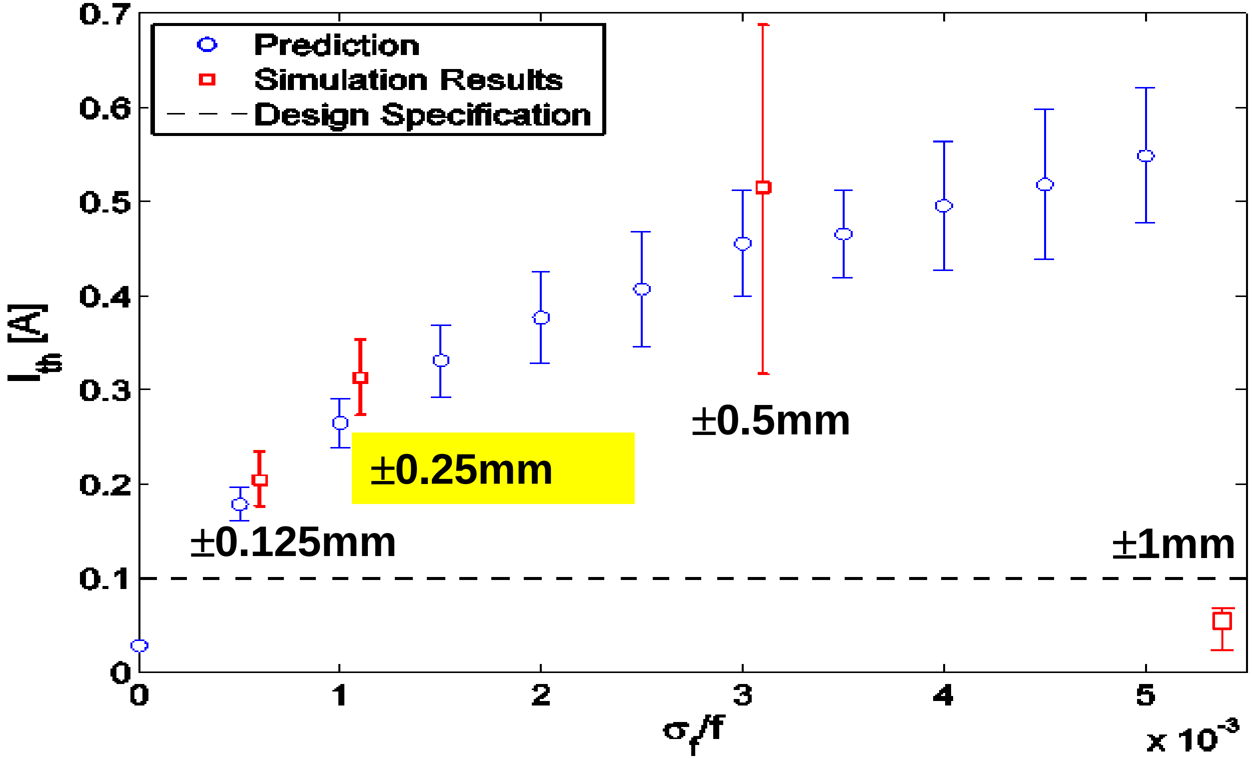
Results of Beam-Break-Up simulations:
Note: includes realistic fabrication errors and HOM damping materials!



Optimized cavity with ±0.25 mm shape imperfections supports ERL beam currents well above 100 mA!

Some of this work is summarized in N. Valles & M. Liepe, PAC'11, TUP064, p. 937

Mechanical Design for efficient Cavity Operation

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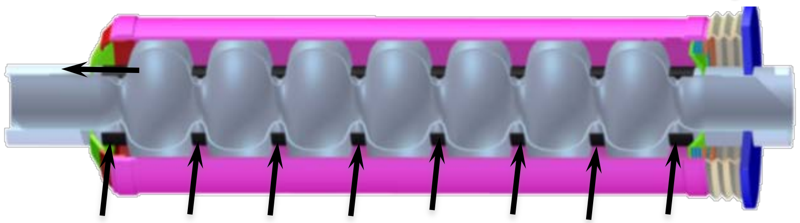
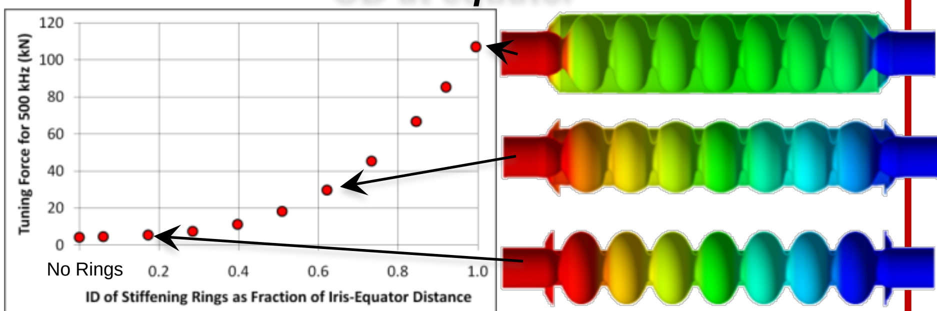
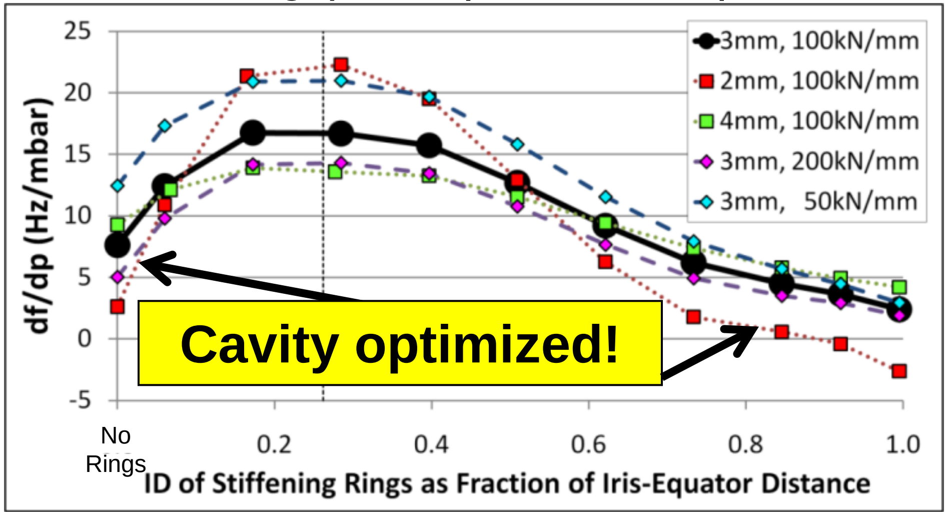
- Small bandwidth cavity vulnerable cavity microphonics (frequency modulation), especially by helium pressure fluctuations
- Diameter of cavity stiffening rings used as free parameter to reduce df/dp
- ANSYS simulations: large diameter rings and no rings at all have smallest df/dp
- Build two prototype cavities (with and without rings) to explore both options

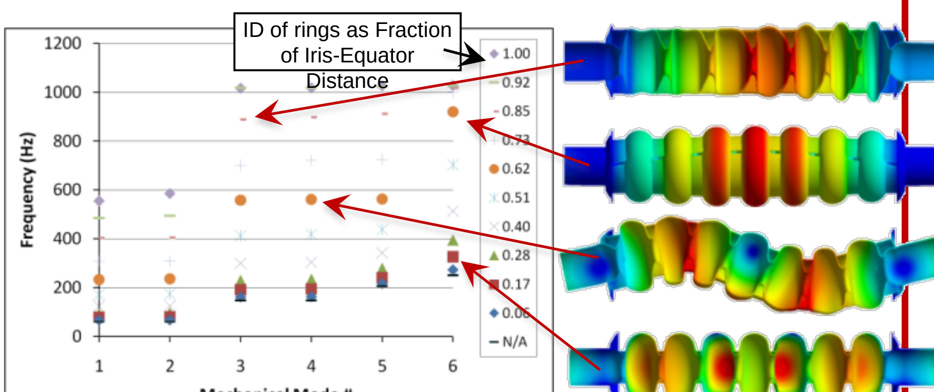
Model of Cornell ERL Main Linac Cavity



Stiffening rings can vary from ID at iris to OD at equator







S. Posen & M. Liepe, PRST-AB 15 (2012) 022002

courtesy M. Liepe

Prototype Cavity Fabrication

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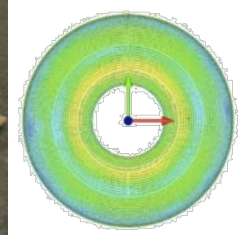
Electron Beam Welding

Quality control: CMM and frequency check



Finished main linac cavity with very tight (±0.25 mm) shape precision
⇒ important for supporting high currents (avoid risk of trapped HOMs!)

Vertical Performance Test of Prototype Cavity

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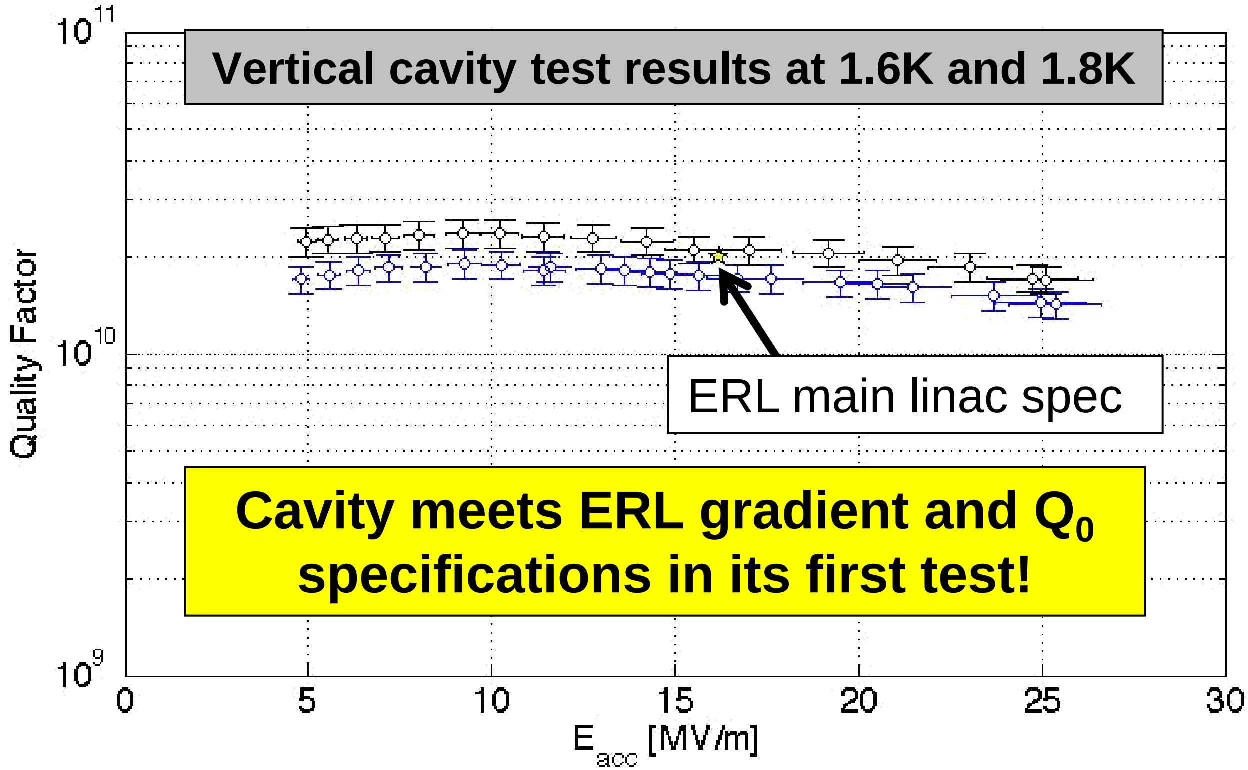
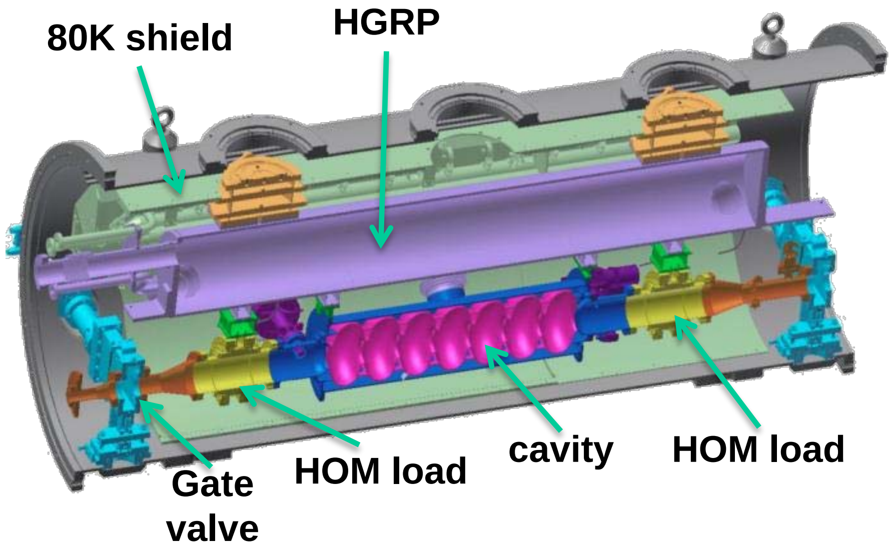
- **Cavity surface was prepared for high Q_0 while keeping it as simple as possible: bulk BCP, 650C outgassing, final BCP, 120C bake**



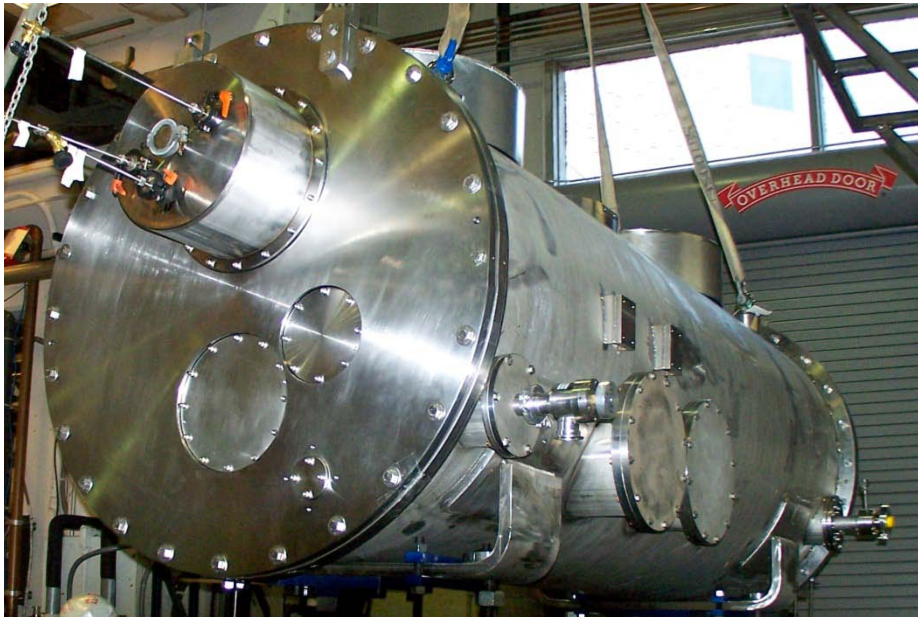
The achievement of high Q is relevant not only to Cornell's ERL but also to Project-X at Fermilab, to the Next Generation Light Source, to Electron-Ion colliders, spallation-neutron sources, and accelerator-driven nuclear reactors.

courtesy M. Liepe

One-Cavity ERL Main Linac Test Cryomodule



- **Assembled and currently under testing at Cornell:**
  - First full main linac system test
  - Focus on cavity performance and cryogenic performance



Preliminary Test Results of First ERL Main Linac Cavity in Test Cryomodule

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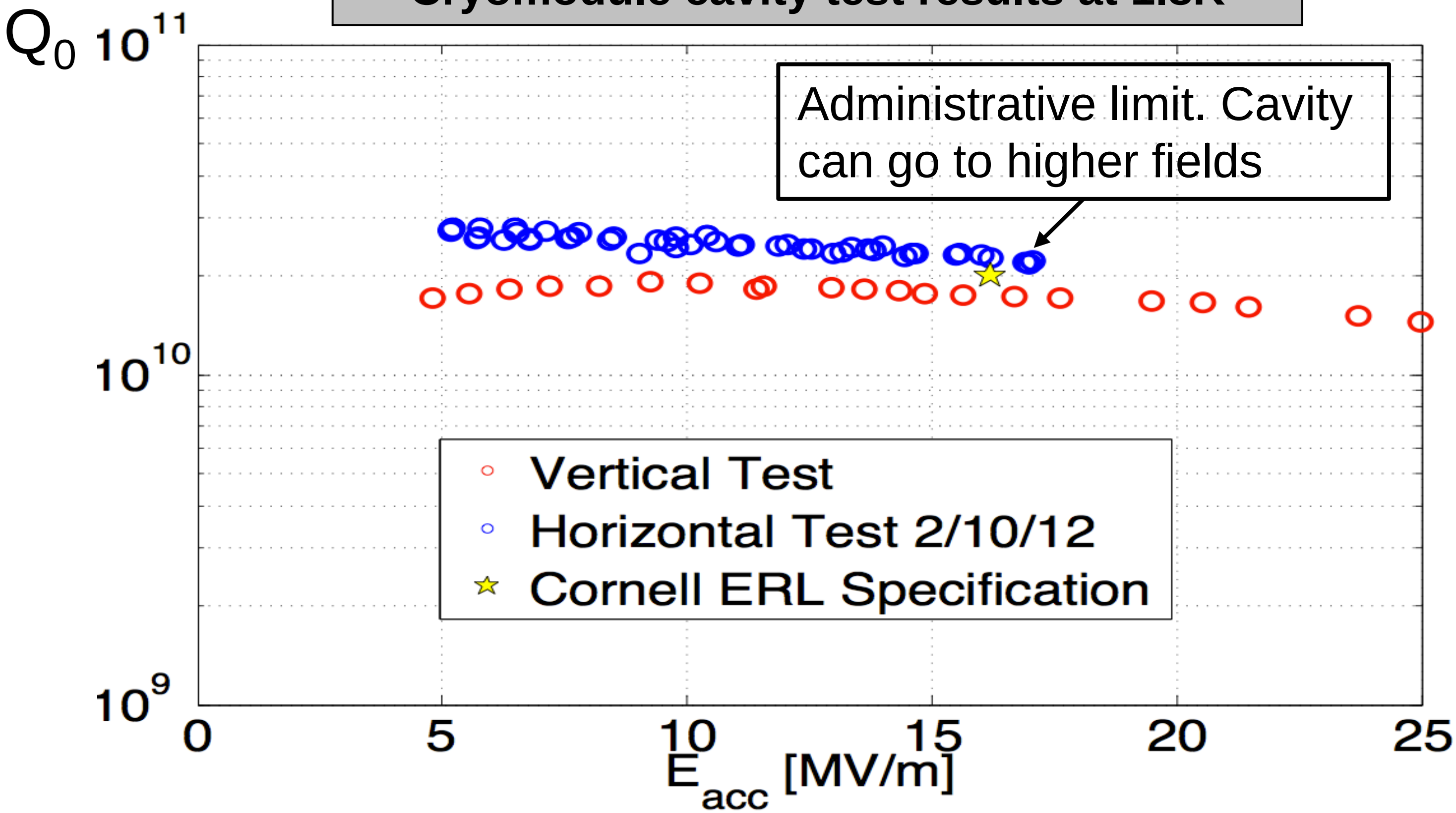
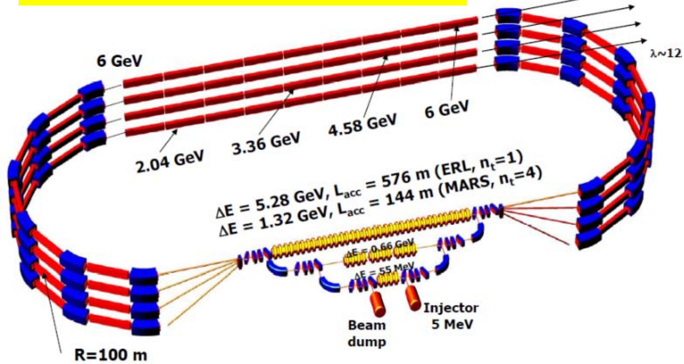
Cryomodule cavity test results at 1.8K



Cavity exceeds ERL gradient and Q_0 specifications in its first cryomodule test!

Alternative & developing ideas

MARS by G. Kulipanov et al.



- **MARS**
  - **Trade off current for higher undulator N~10^4, use many passes**
  - **Much reduced injector requirements can use lower gradient linac**
  - **Becomes less appealing as injector & SRF performance/efficiency improves**

- **Moderate number, e.g. two-pass, approaches**
  - **Several labs pursuing, capital and operational cost savings**
  - **Full energy CW linac is a nice investment if can afford**

- **Extend ERL's to x-ray free electron laser techniques**
  - **Not appealing for GHz rep. rates; instead use simultaneous operation with a lower rep rate beam**

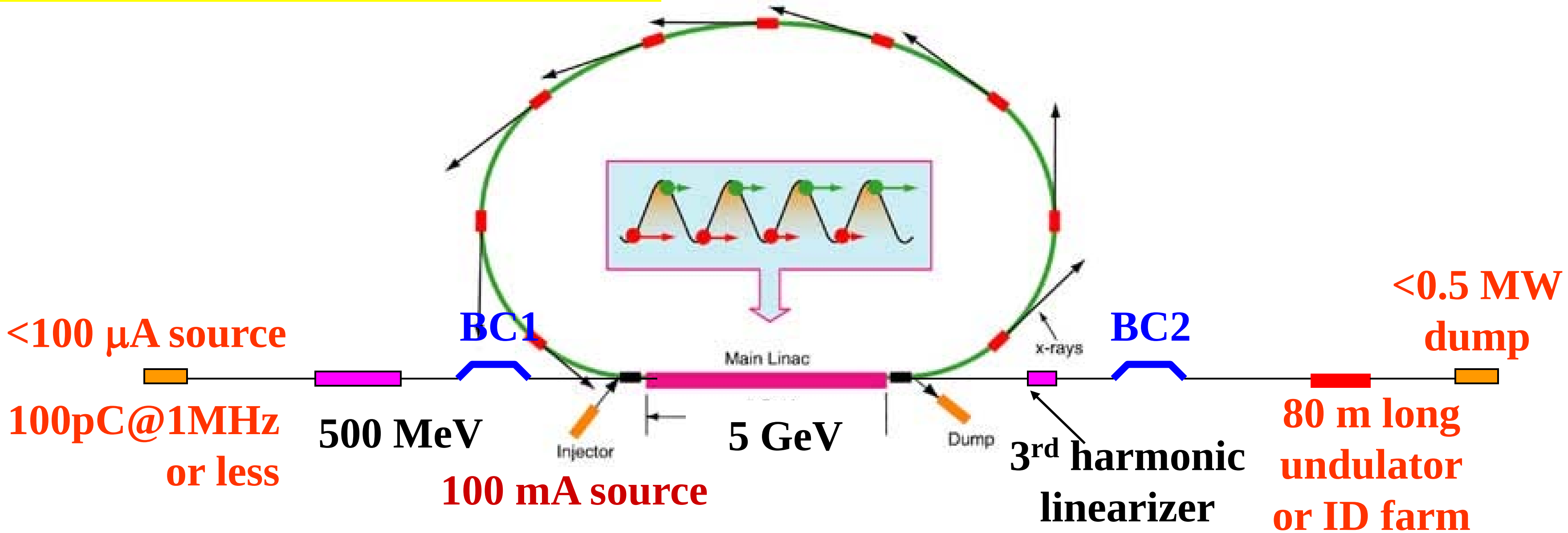
When to use energy recovery

Rep. rate	Beam power @ 5GeV	
100pC @ 100MHz	50MW	Absolutely
100pC @ 10MHz	5MW	↓ Maybe
100pC @ 1MHz	0.5MW	↓ No
100pC @ 0.1MHz	0.05MW	

- Simultaneous operation with high current at e.g. XFELO specs
- Keep additional (unrecovered) RF load ~1-2kW per SRF cavity

Simultaneous short pulses for XFEL and generic ERL running

from Cornell ERL Science Workshops, June 2006

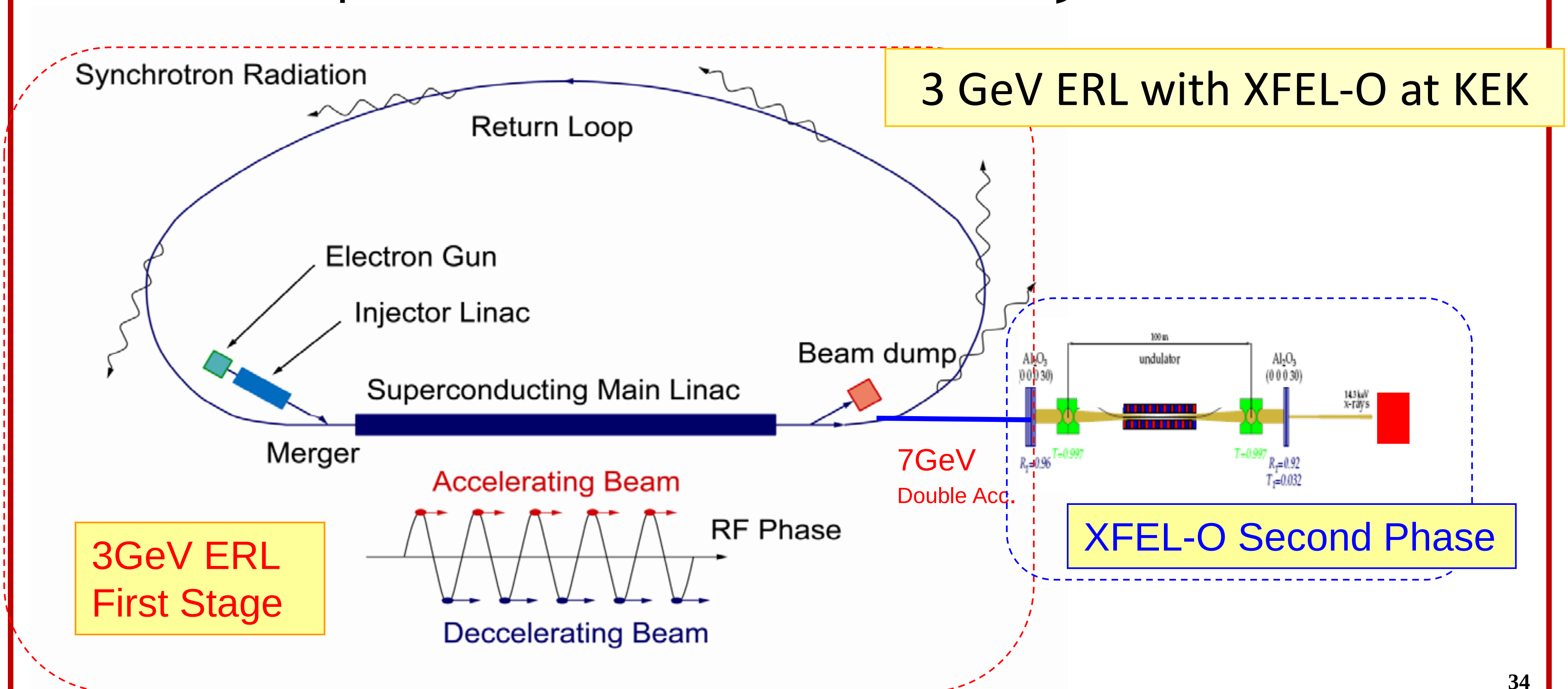


- **Initial analysis to meet XFELO specs shows it's doable using non-energy recovered beamline**

KEK plans for ERL with XFELO
Others to follow?

- Narrower and less divergent e-beams
- More mono-energetic e-beams
- Shorter pulses

} all of the above



Summary & Outlook

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- **Based on demonstrated source performance: if a hard X-ray ERL were to be built today, it would already be the brightest quasi-CW source of x-rays**
- **There is a long list of technical issues still requiring attention, but also great progress over the last 2 years**
- **Further light source evolution calls for free-electron laser techniques married to ERLs (or rather its CW linac at a reduced bunch rep rate) to enhance brightness and better control coherence**

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END

Advantages of ERL beams for light sources

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ERLs have advanced, science enabling capabilities:

a) Large currents for Linac quality beams

b) Continuous beams with flexible bunch structure

c) Small emittances for round beams

[similar transverse properties have recently been proposed for 3km long rings]

d) Openness to future improvements

[today's rings can also be improved, improvements beyond ring performances mentioned under c) may be harder to imagine]

e) Small energy spread (2.e-4 rather than conventional 1.e-3)

f) Variable Optics

g) Short bunches, synchronized and simultaneous with small emittances

Thus : many advantages beyond increased spectral brightness !

The breadth of science and technology enabled is consequently very large and the ERL will be a resource for a very broad scientific community.

X-ray ERLs are at the beginning of a development sequence, and extensions can be envisioned, e.g. XFEL-O.

Advantages of ERL beams: Variable electron optics

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1) Beam size vs. divergence can be optimized on each undulator straight section, without limitations by dynamic apertures.
   - APS: one set of beta functions
   - ESRF: two sets of beta functions (hi, low)
   - ERL: all choices are possible, not "one size fits all"

2) Move position of minimum electron beam waist along straight section by changing quadrupole settings, without moving components, e.g. move apparent x-ray source point to compensate for changes in focal length on refractive lenses and zone plates, or move x-ray focus to the sample.

3) There may be other New Features (e.g. optimizing flux through a collimator, monochromator because of extra free knobs) that can be developed because x-ray ERLs are at the start of development.