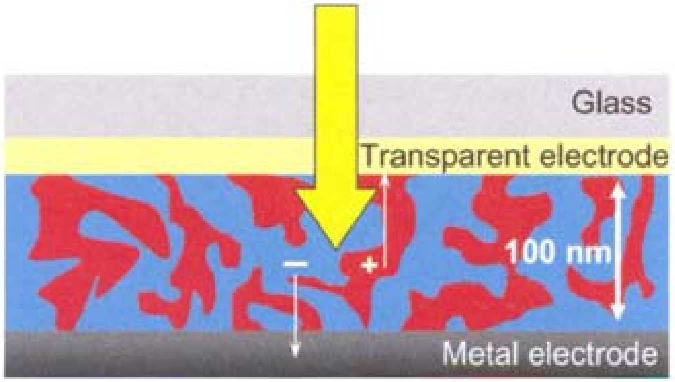
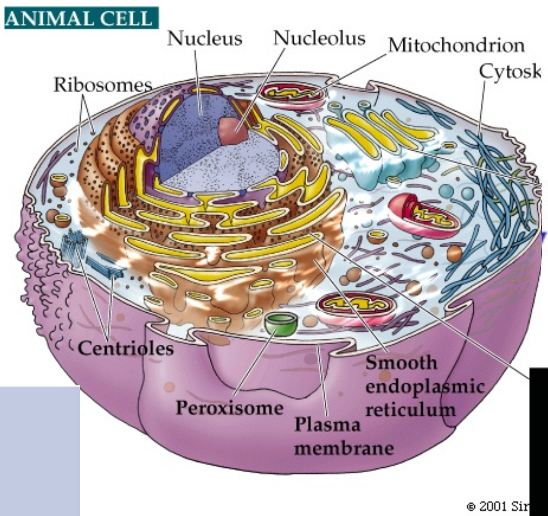
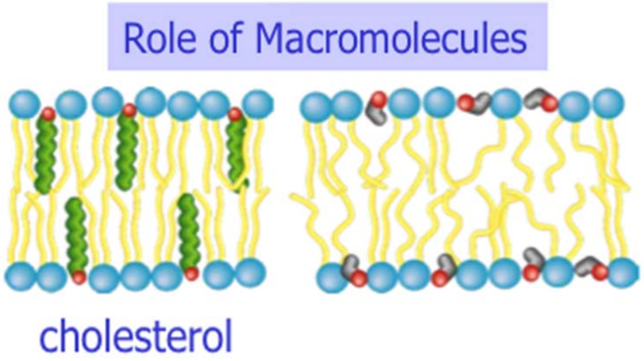
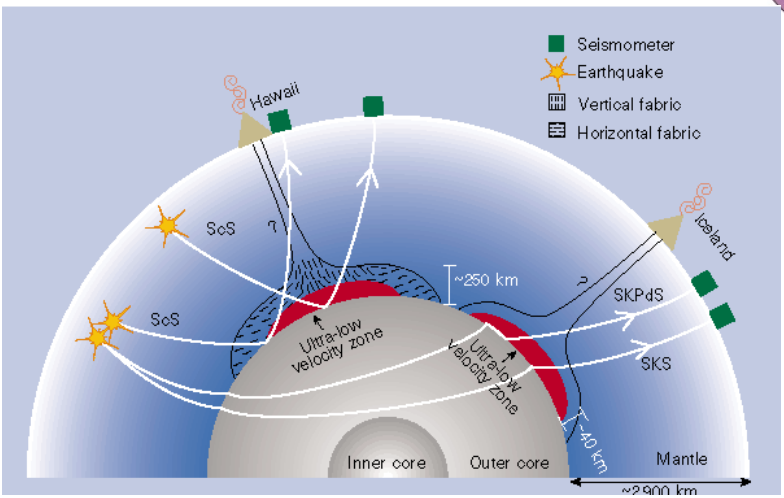
ERLs for Light Sources

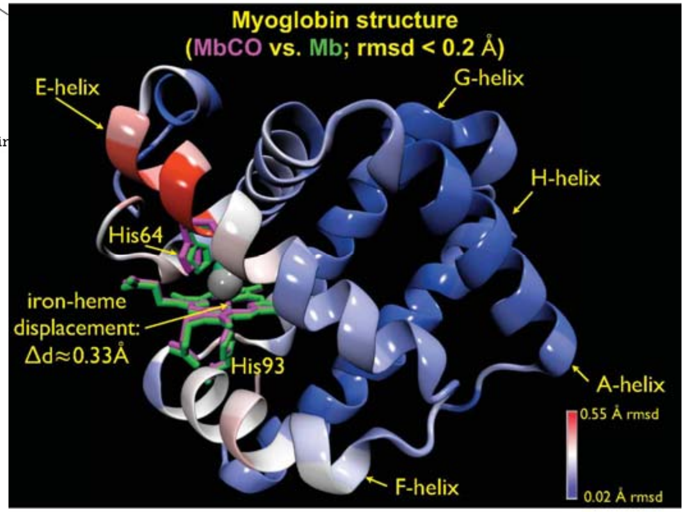
Georg Hoffstaetter
Cornell Physics Dept. / CLASSE



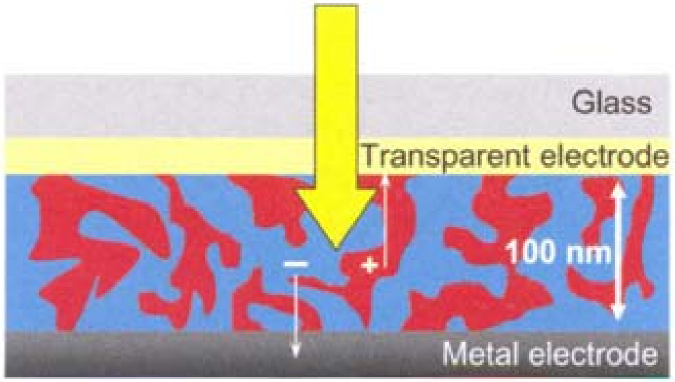


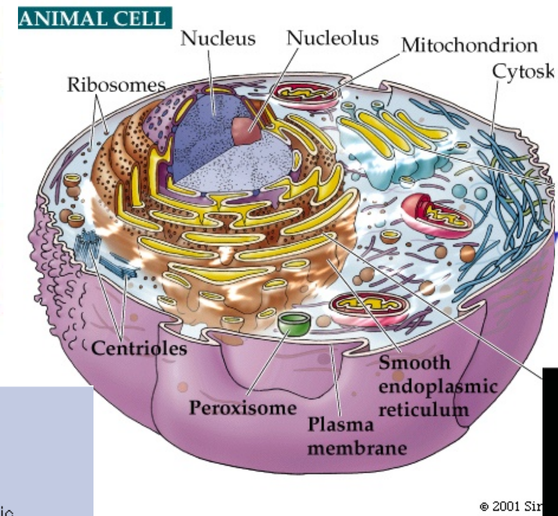


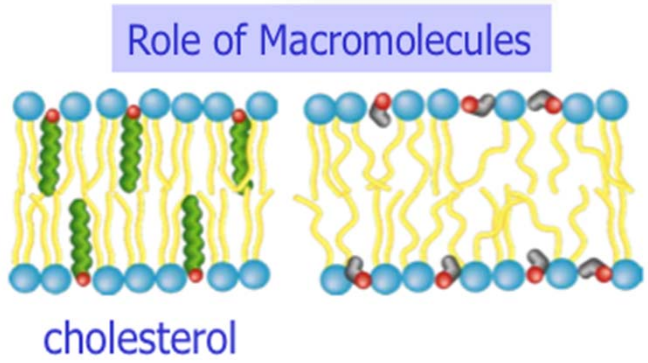


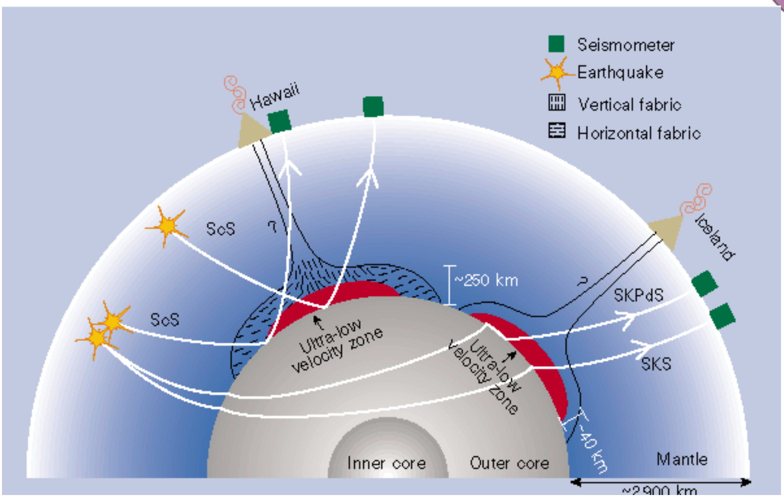


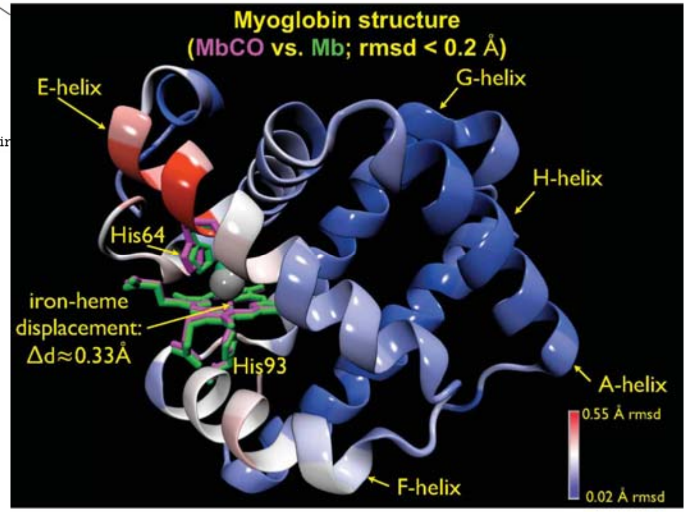
Progress in the science case for X-ray ERLs





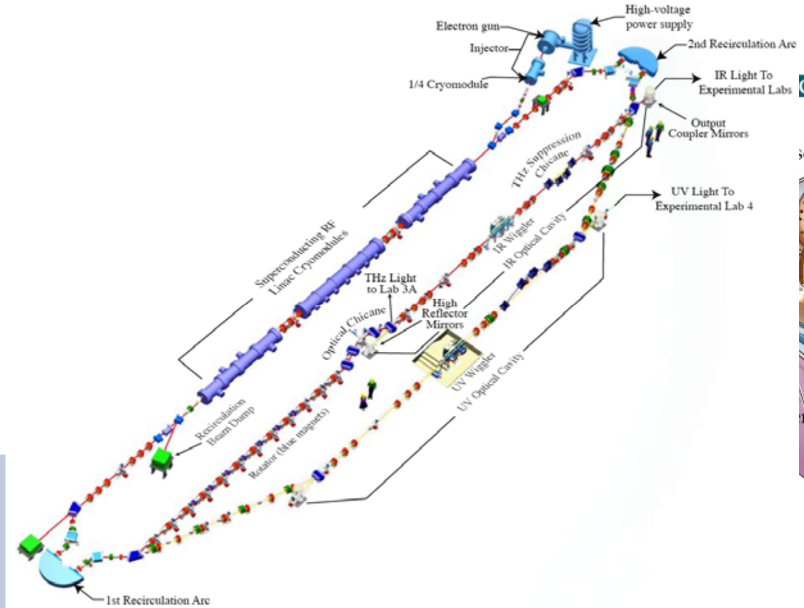


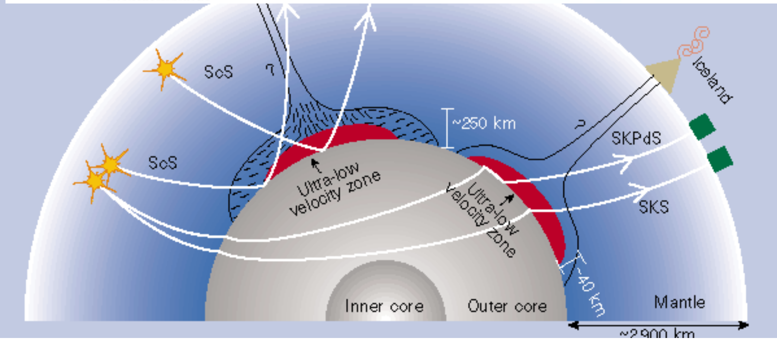


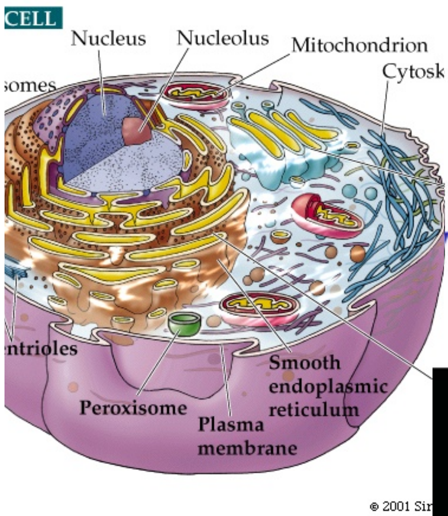


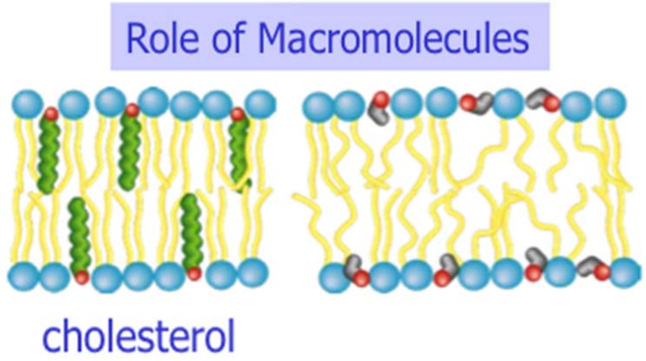
Progress in ERLs for Light Sources

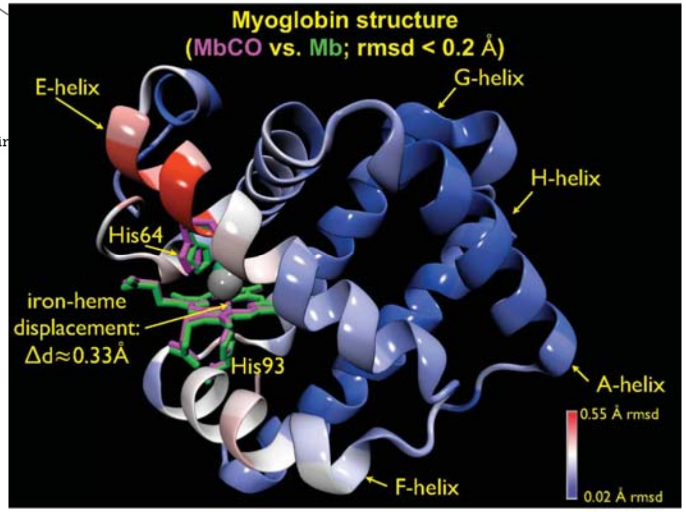
Operations at JLAB





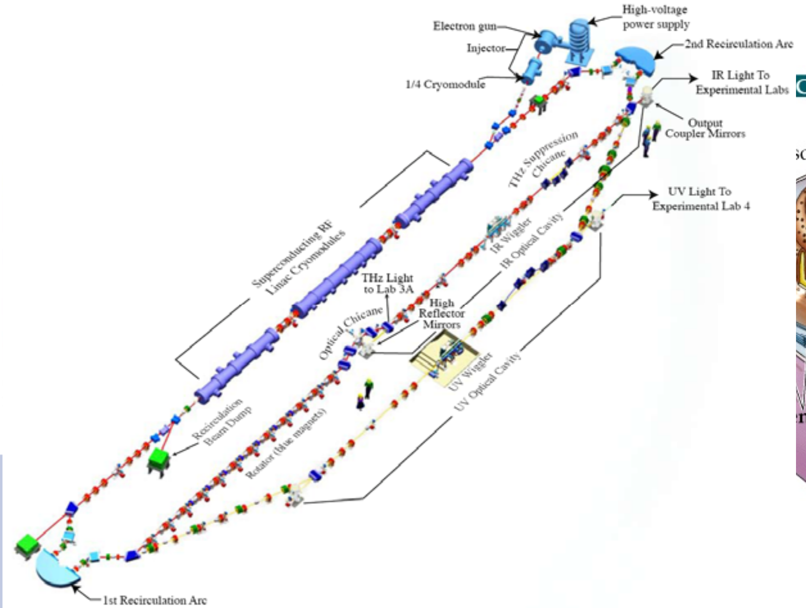


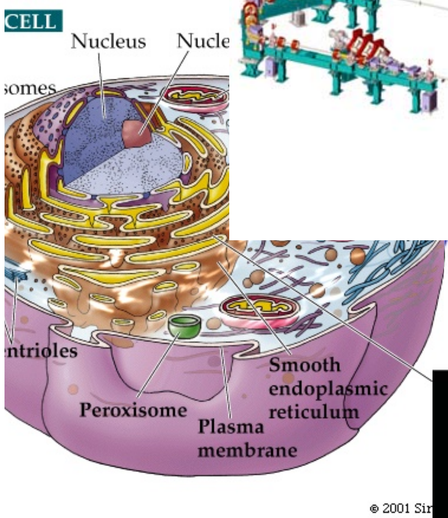


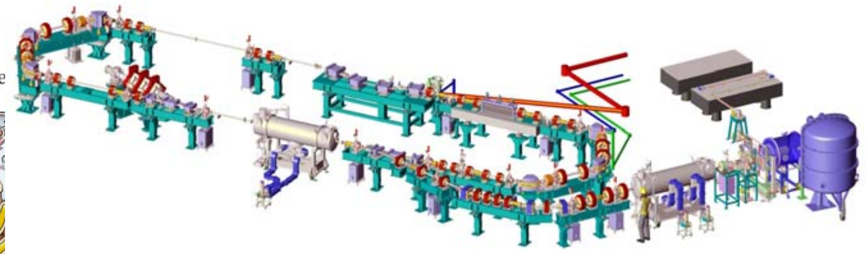


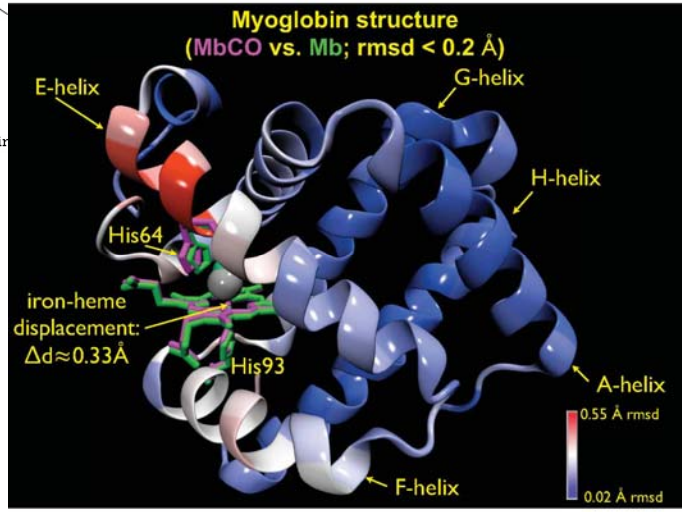
Progress in ERLs for Light Sources

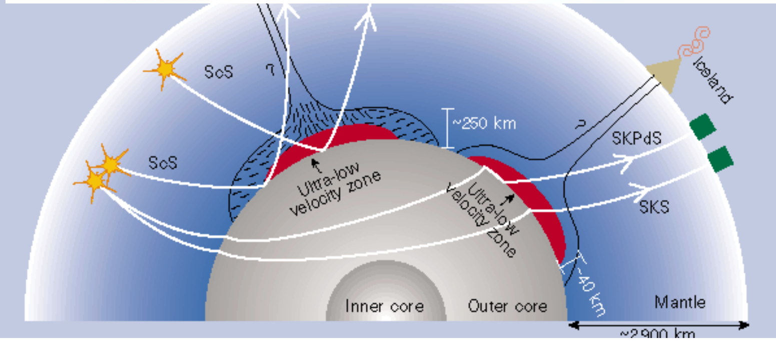
Operations at JLAB, Daresbury,





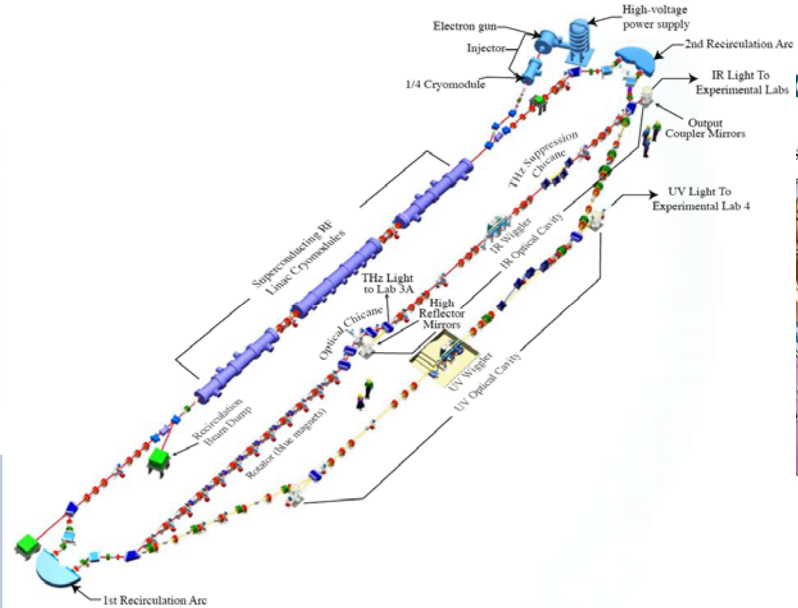


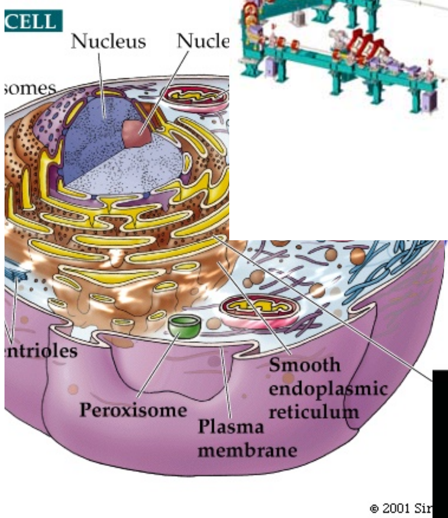


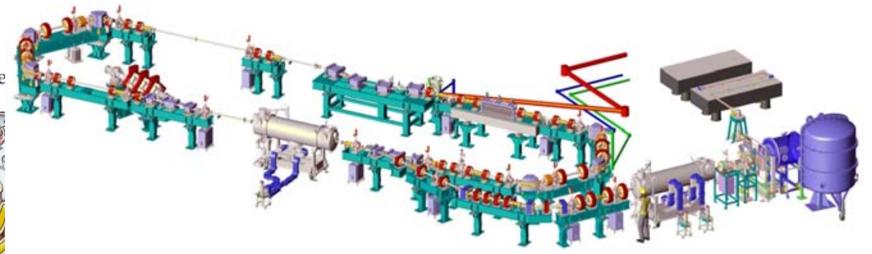


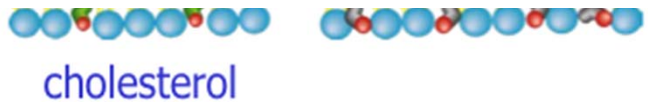
Progress in ERLs for Light Sources

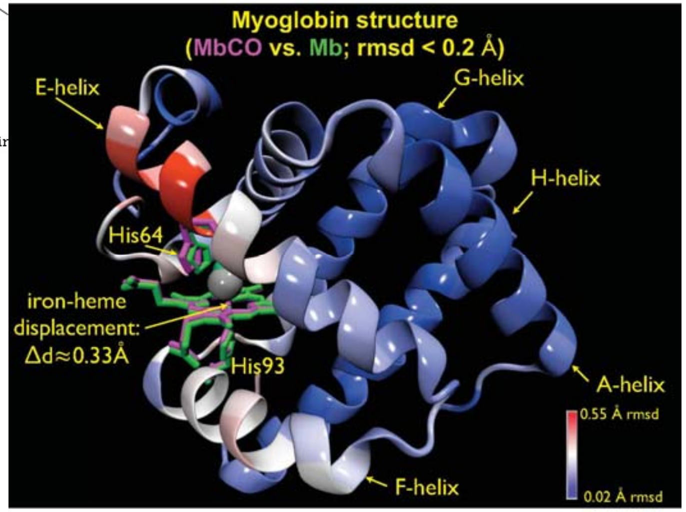
Operations at JLAB, Daresbury, BINP

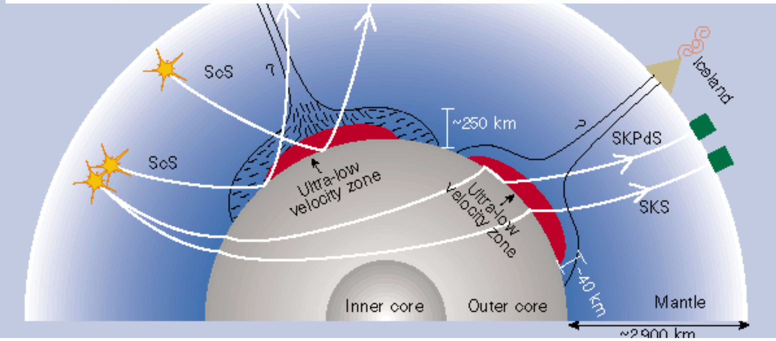






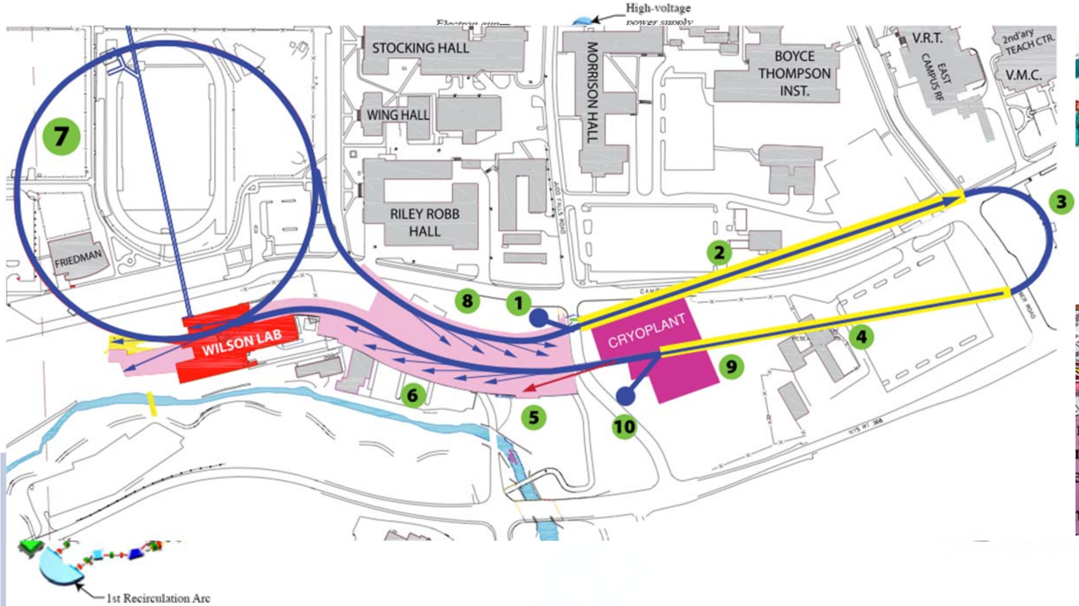


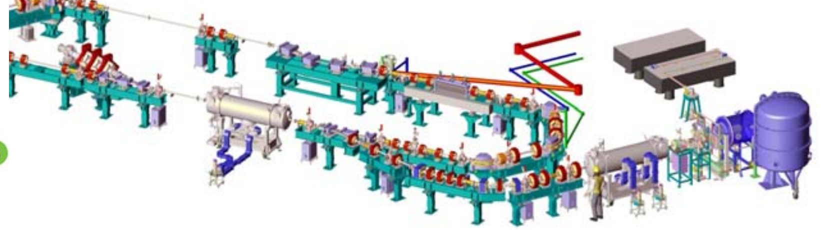


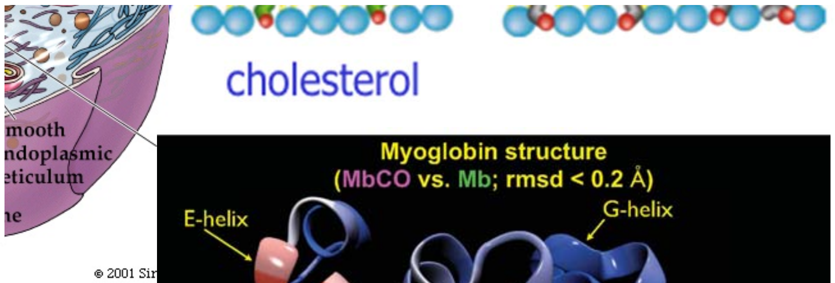


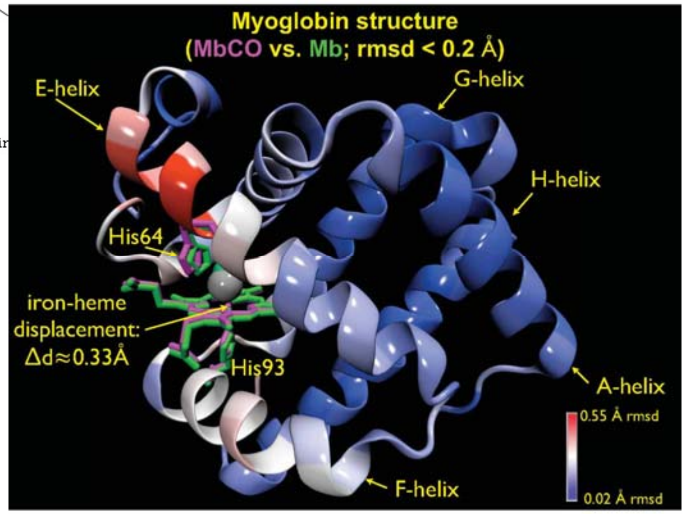
Progress in ERLs for Light Sources

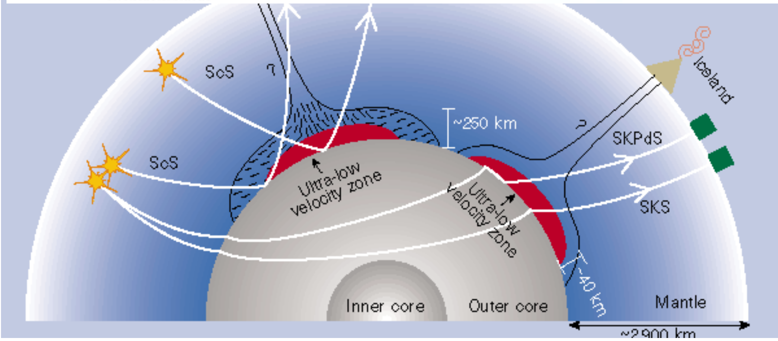
Operations at JLAB, Daresbury, BINP
Designs at Cornell





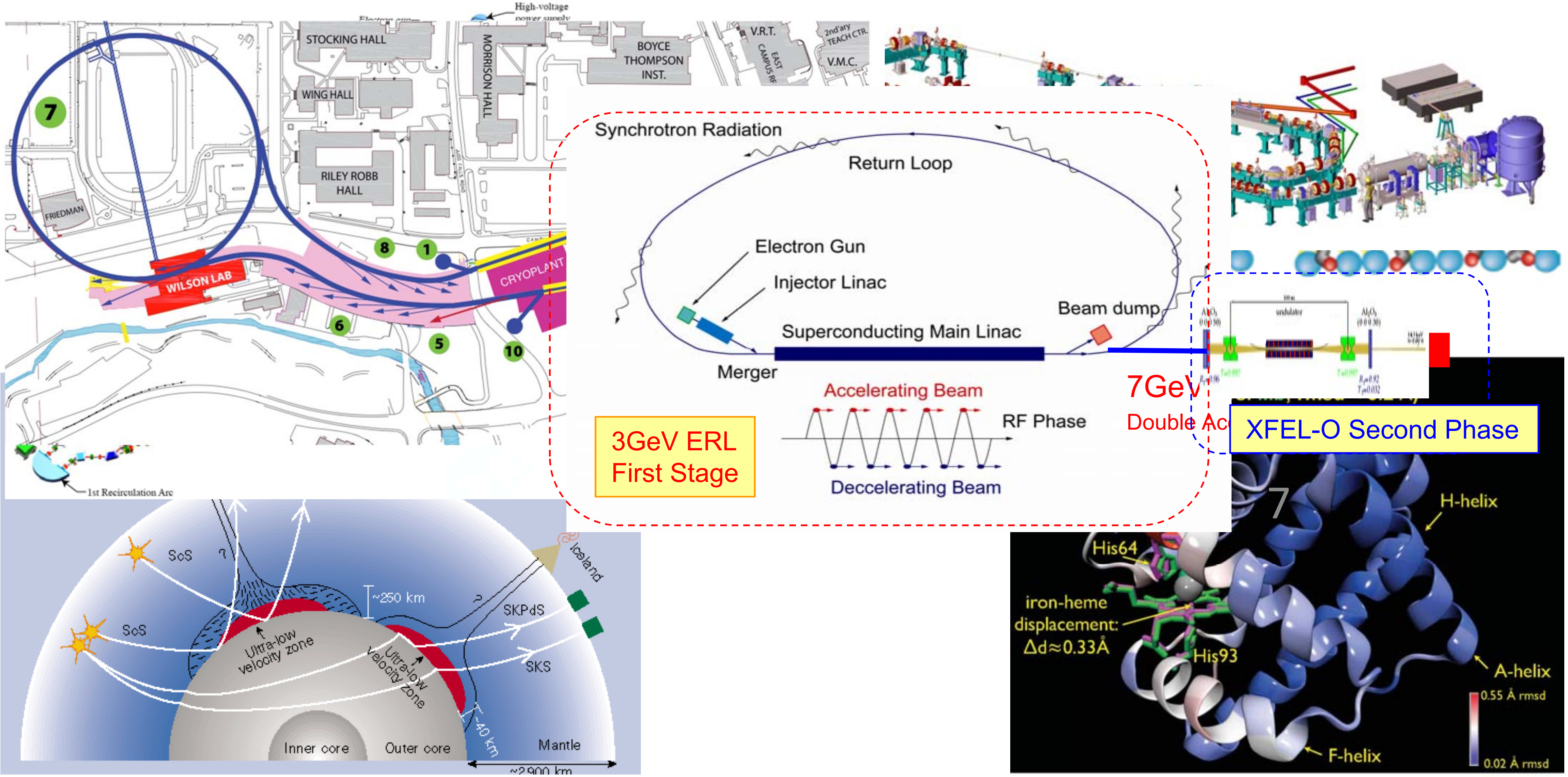






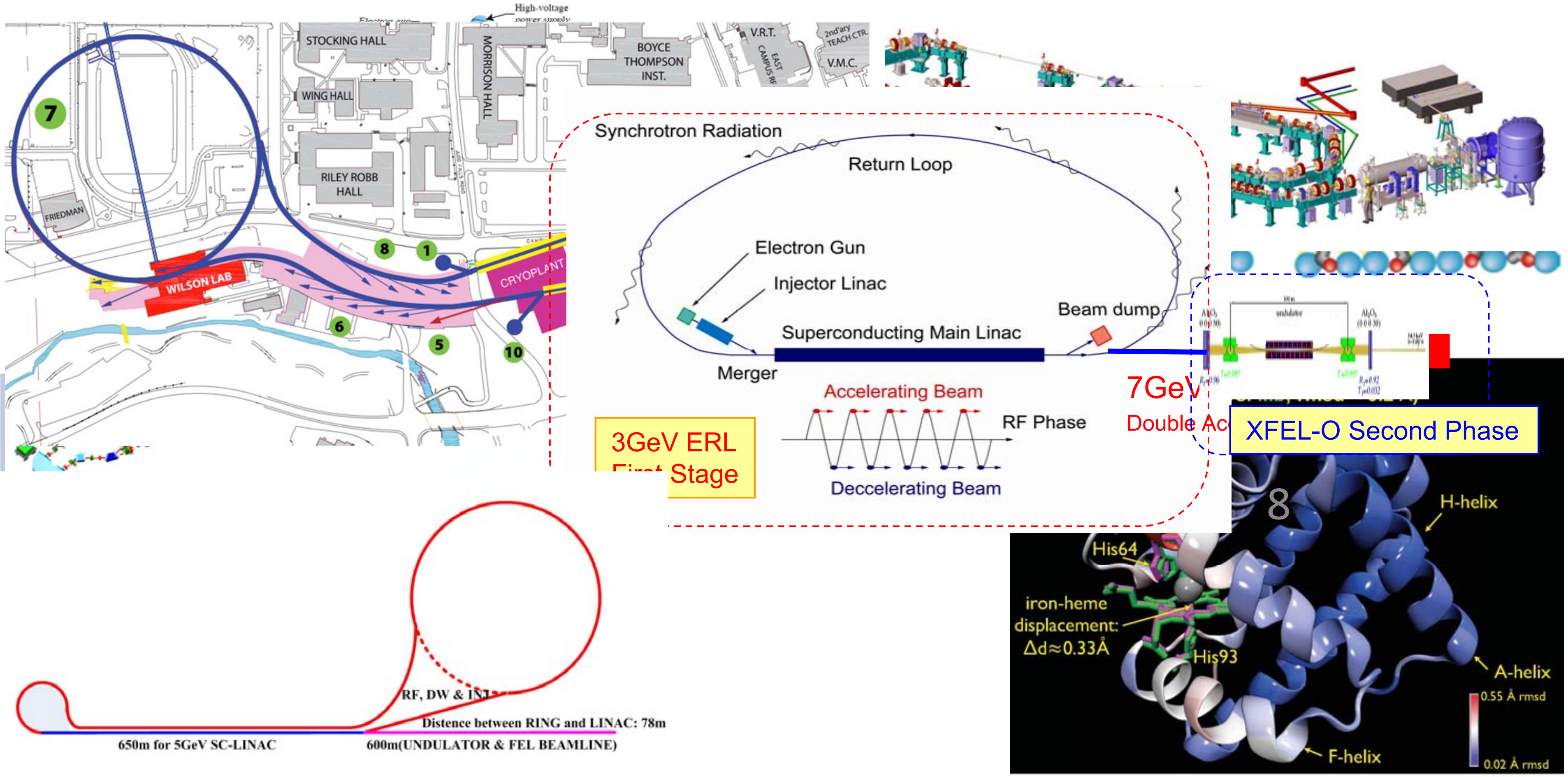
Progress in ERLs for Light Sources

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



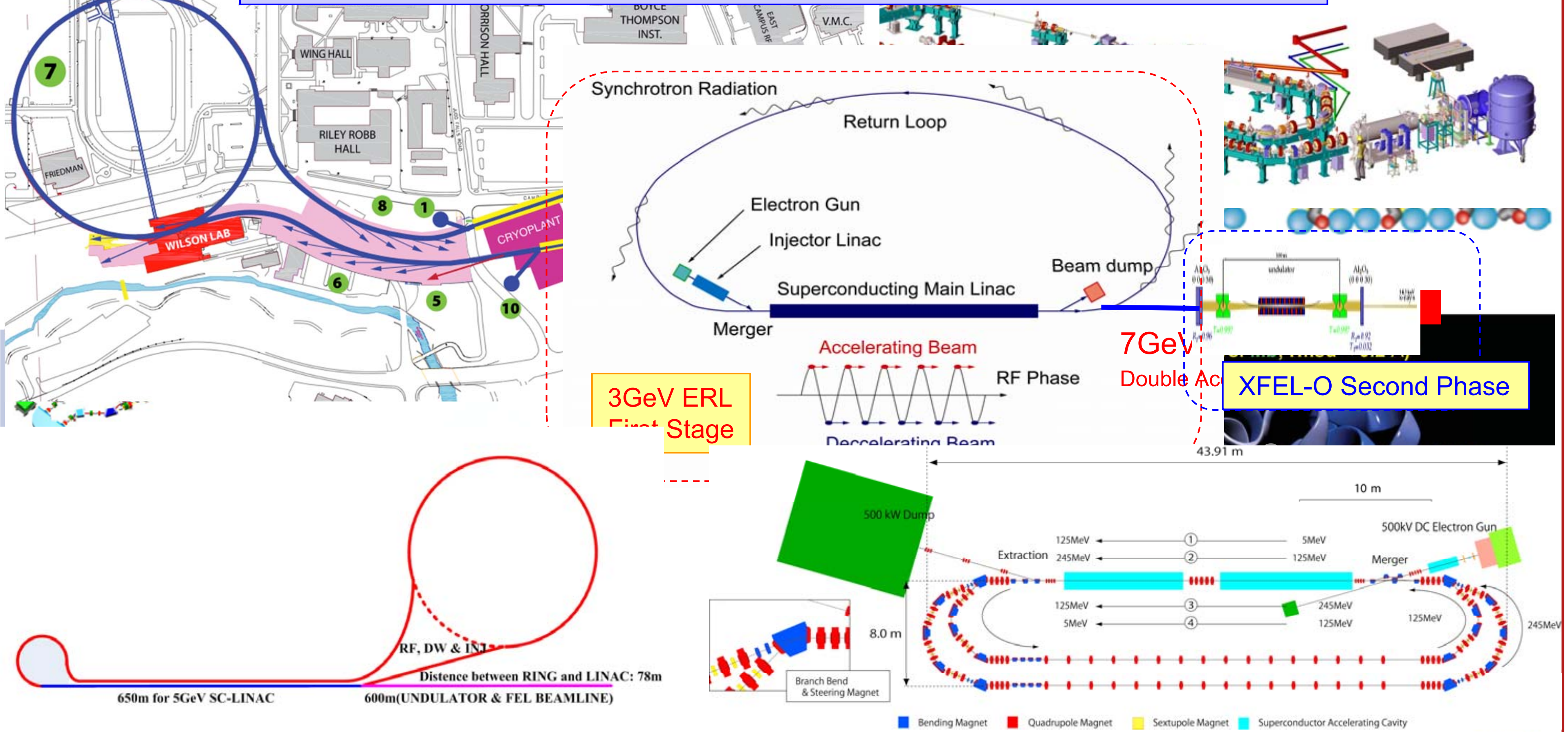
Progress in ERLs for Light Sources

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



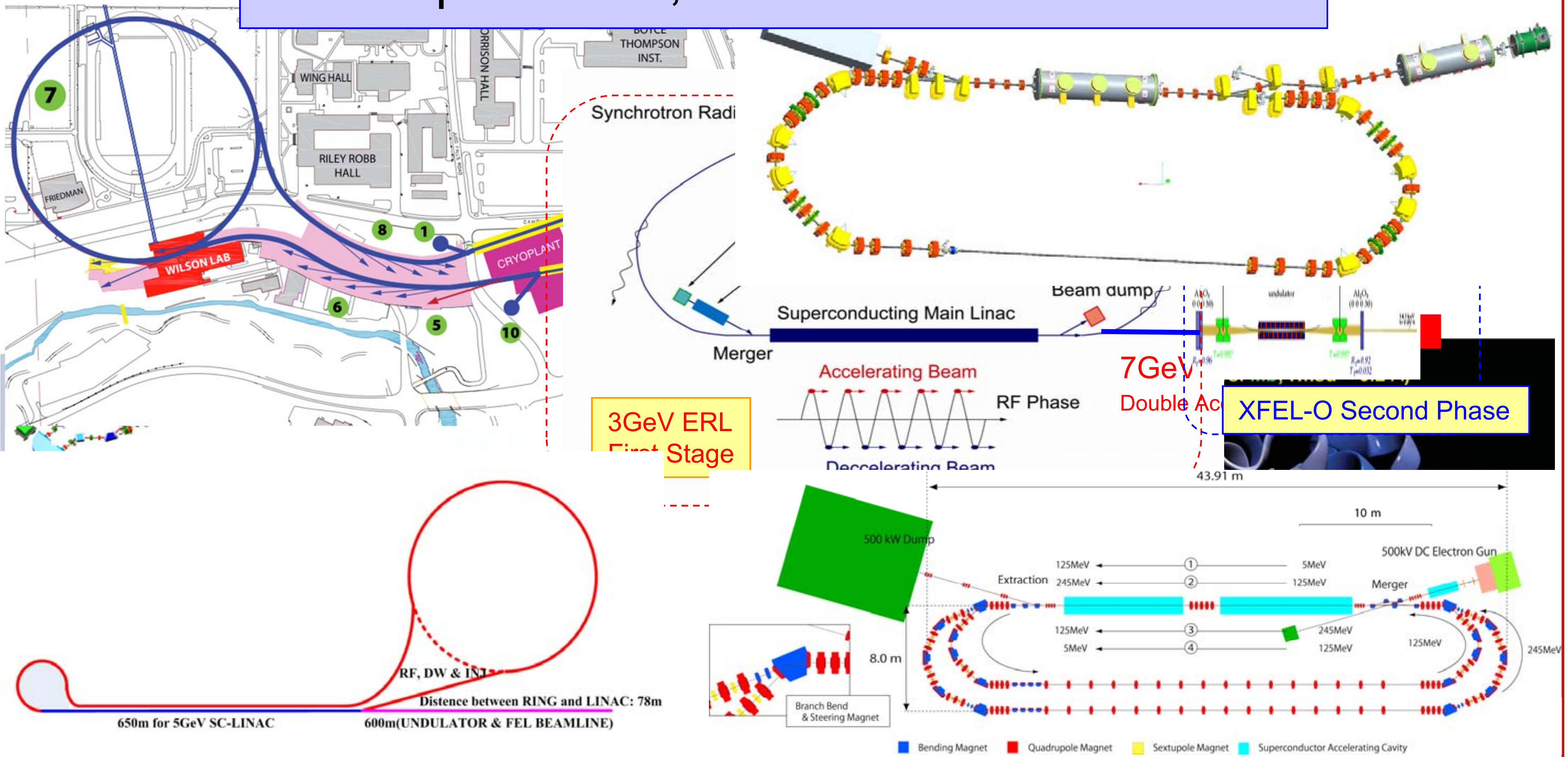
Progress in ERLs for Light Sources

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



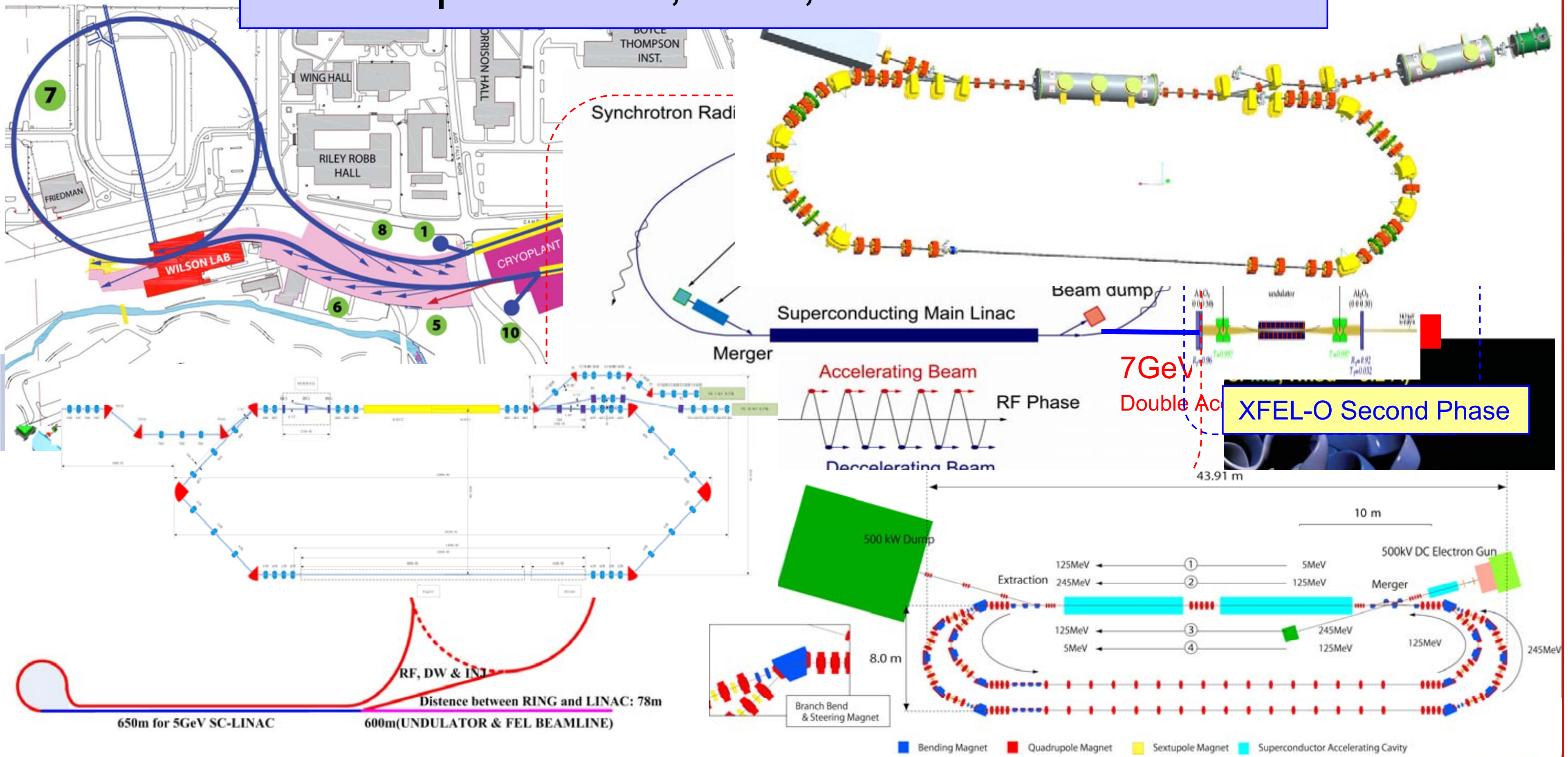
Progress in ERLs for Light Sources

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



Progress in ERLs for Light Sources

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



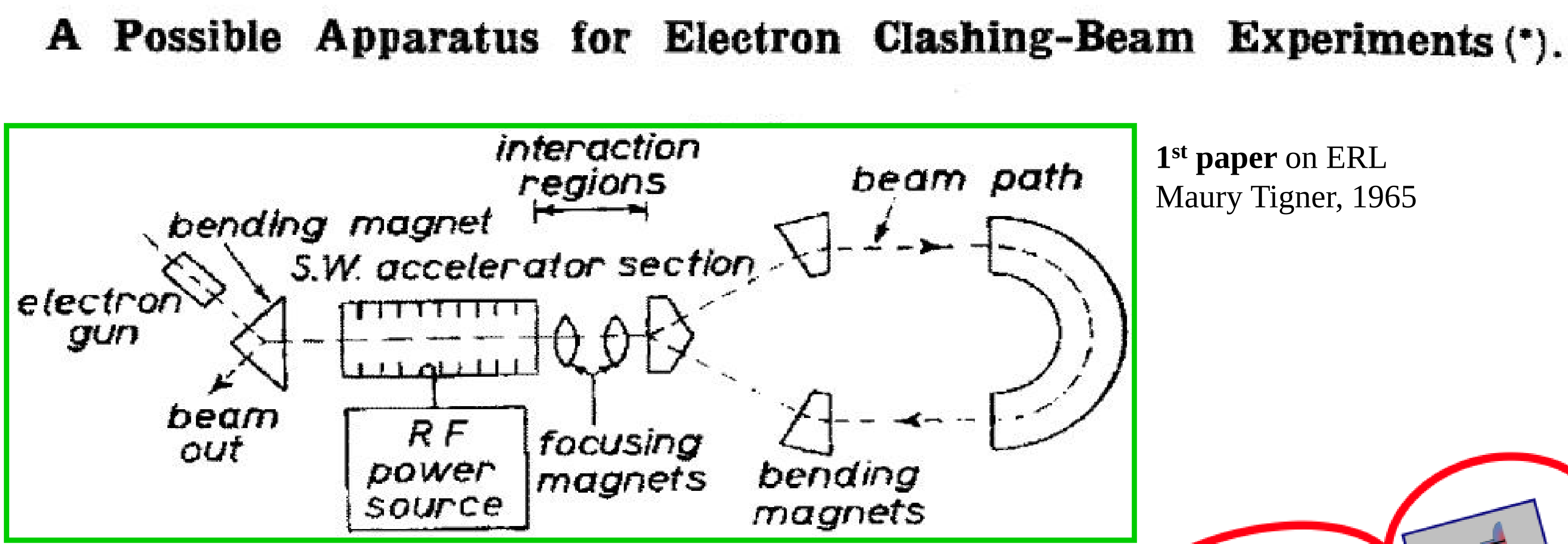
ERL progress since the last ERL Workshop

1. Why a better light source? What can an ERL do for us?
   - Progress in x-ray ERLs' science case (XDL2011 Workshops)
2. ERL light source projects
   - VUV from the JLAB ERL / operation of Alice
   - Projects under R&D
3. Electron sources
   - Start and progress of several SRF guns (BNL, Dresden, HZB, JLAB, NPGS)
   - 25mA CW operation from DC guns (Current spec for brightness mode)
4. High power injectors
   - Progress in SRF injector linac
   - Progress in beam dynamics (approaching theoretical limits)
5. ERL main linacs
   - Cavities desensitized to BBU
   - ERL performance specs met in vertical cavity test (16MV/m, 2.E10)
   - Collaborative international ERL cryomodule assembly

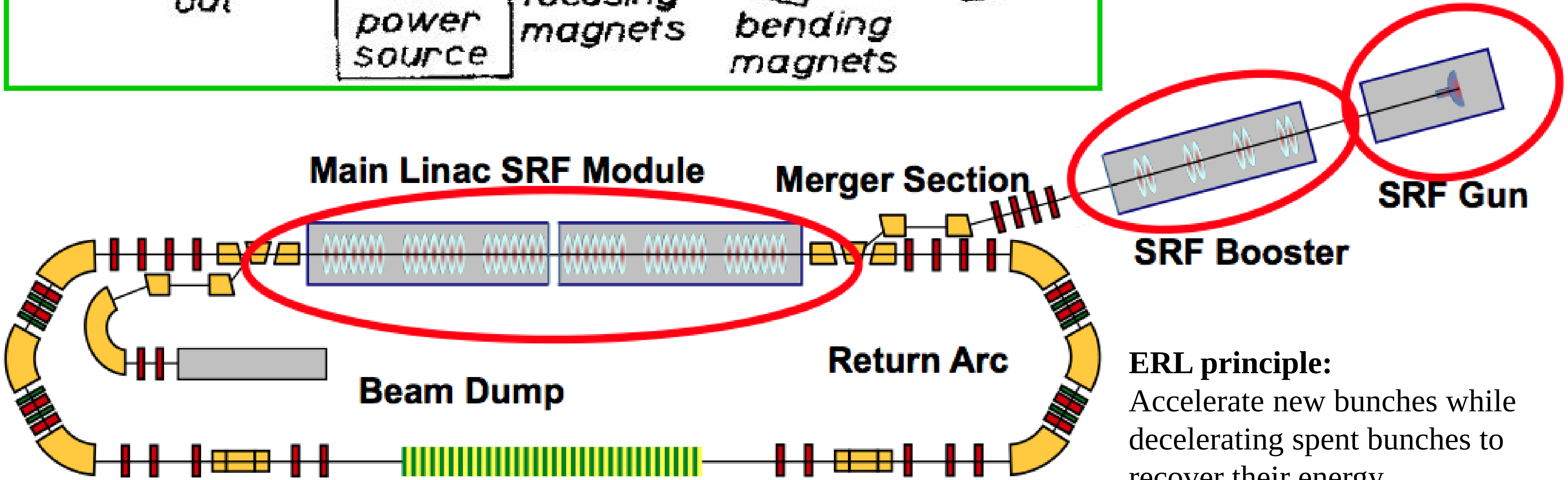
Thanks for slides and information from …

- Ryoichi Hajima (for JAEA)
- Hiroshi Kawata (for KEK)
- Jiuqing Wang (for the IHEP ERL-TF group)
- Ilan Ben-Zvi (for BNL)
- George Neil (for JLAB)
- Andreas Jankowiak and Jens Knobloch (for HZB)
- Matthias Liepe, Ivan Bazarov, Chris Mayes (for Cornell)

The ERL principle



1st paper on ERL
Maury Tigner, 1965



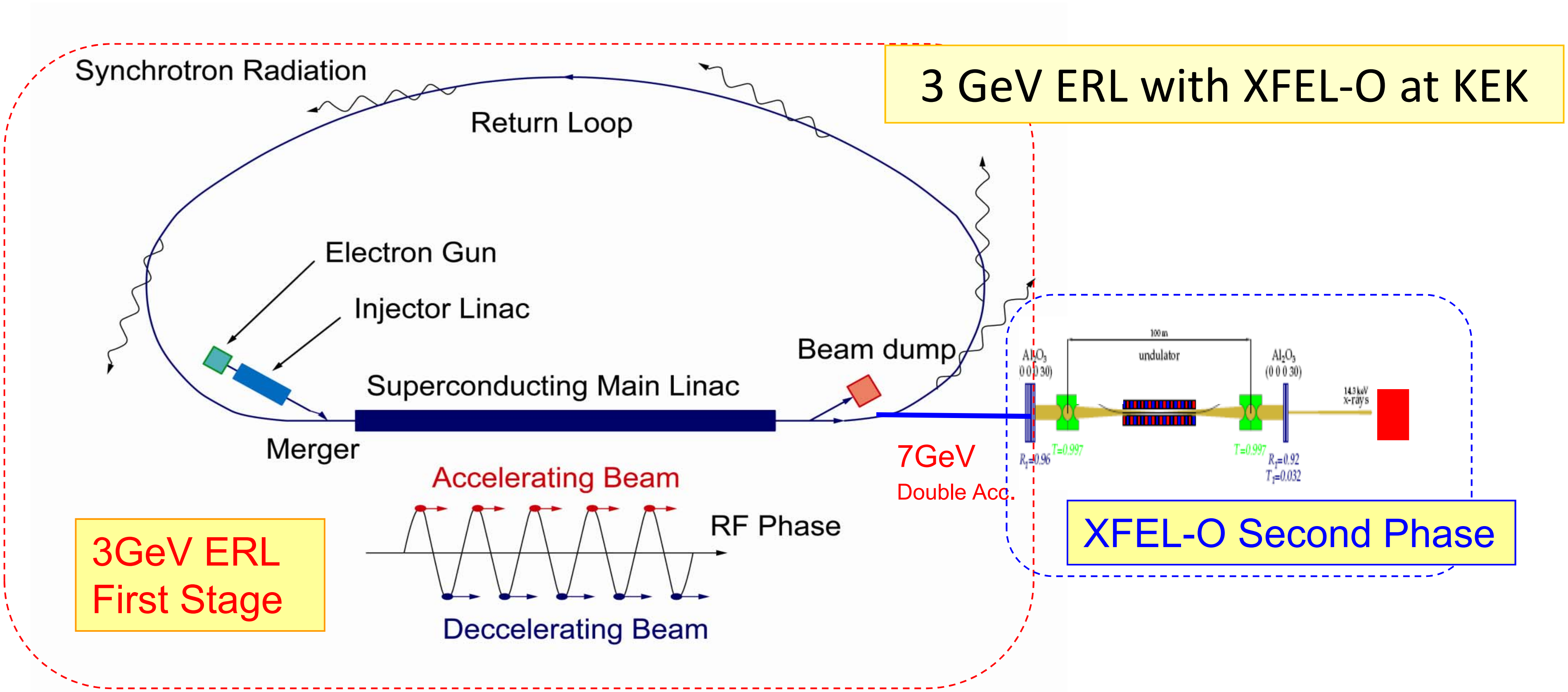
HZB: BERLinPro test loop

ERL principle:
Accelerate new bunches while decelerating spent bunches to recover their energy.

How can X-ray beams be improved ?

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

} all of the above



Science at the Hard X-ray Diffraction Limit (XDL2011)

Don Bilderback* and Georg Hoffstaetter*, Cornell University

Presentation at ERL11, October 20, 2011

- Cornell hosted six, two-day international workshops in June of 2011 with 488 participants
- Focus was diffraction limited, high-repetition rate, hard x-ray sources, such as Energy Recovery Linacs (ERLs) and Ultimate Storage Rings (USRs).
- These source will provide high coherent flux and ultra-intense nanometer-scale x-ray probes.
- X-ray pulses occur at MHz to GHz repetition rates with durations of 50 fs to 10s of ps.

Participants in the 2nd workshop on Biomolecular Structure

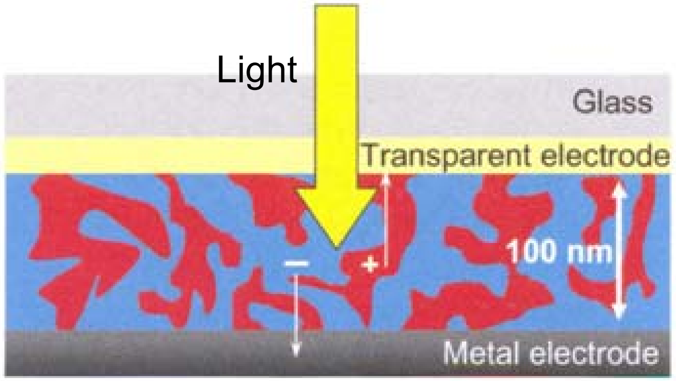
- Organizers & Sponsors: Cornell, DESY, SLAC, KEK with additional US Federal support from NSF and DOE
- *for the organizers, speakers, and editors of XDL2011 workshops

XDL 2011 Photon Factory CHESS SSRL DESY

Determine 3D Nanomorphology for Improving Organic Solar Cells

Harald Ade, North Carolina State University

From XDL2011: Diffraction Microscopy, Holography and Ptychography using Coherent Beams

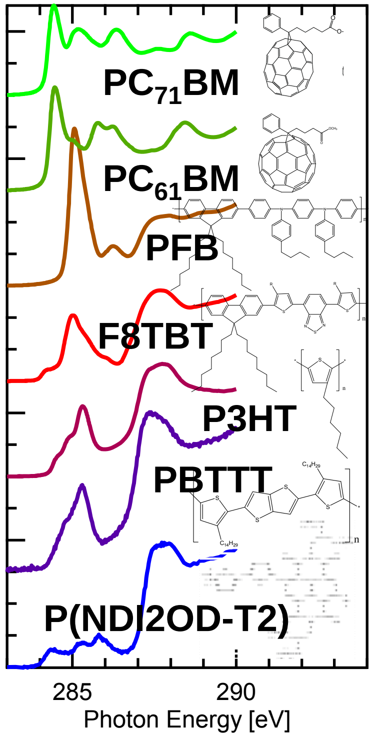


Solution-processed organic solar cells are attractive as low-cost photovoltaic technology. They can be spin-coated or printed like a newspaper or ink-jet coated onto flexible substrates of plastic or glass. Currently most designs are based on bulk heterojunction (BHJ) structures of 100 to 200 nm thickness. Even a two-phase description is idealistic. A complex morphology of at least three phases might have to be considered. To be efficient, the inter-digitated electrodes must be only separated by 10 to 30 nm.

To establish full control, one needs to control the average domain size, domain size distribution, domain purity and domain interface widths. For each of these novel materials systems, the miscibility, morphology and domain purity, connectivity of domains, crystallinity, phase and interface properties need to be measured in order to understand device performance deeply and rationally seek processing and materials improvements.

Characterization of 3D structure of organic blends with ~10 nm resolution poses a key technical challenge. High-resolution hard x-ray scattering, electron tomography and TEM have only limited electron density contrast for these polymer/polymer blends, limiting the use of conventional tools for these materials. **A new suite of analysis tools such as 3D resonant ptychography or holography with compositional sensitivity are required**.

These forms of coherent imaging require bright sources and would be well matched to an **Energy Recovery Linac.** Ideally, multiple energies near the carbon K 1s absorption edge (i.e. 260-320 eV) are utilized to provide maximum compositional sensitivity. **Thus, advanced imaging tools enabled by an ERL would be able to make tremendous contributions to improving Organic Solar Cells.**

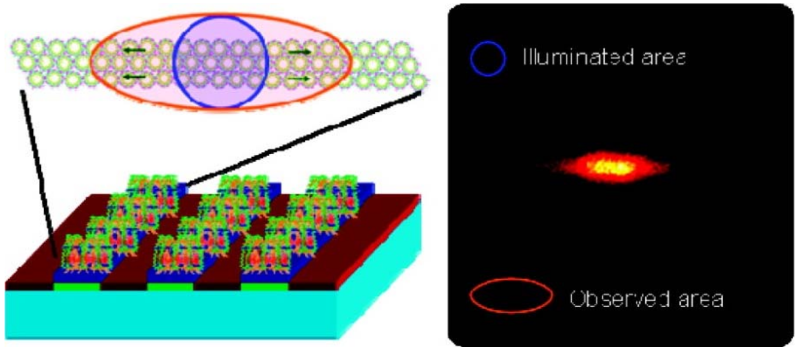


XDL 2011
Photon Factory
CHESS
SSRL
DESY

Tracking energy flow in light-harvesting antenna-proteins

Ed Castner, Rutgers

From XDL2011: Ultrafast Science with "Tickle and Probe"



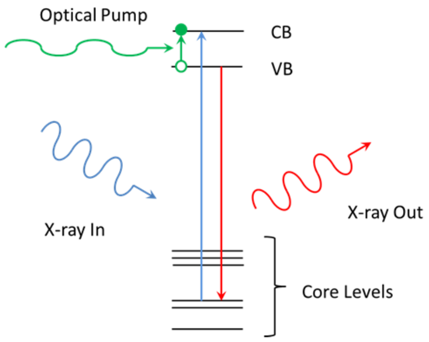
[We] report the first observation of long-range transport of excitation energy within a biomimetic molecular nanoarray constructed from LH2 antenna complexes from Rhodobacter sphaeroides.

Escalante, et al., *Nano Letters, 2010.* **10**(4): p. 1450-1457

Biomimetic researchers copy or incorporate biological processes or components into engineered materials, processes, or devices. For example, light-harvesting antenna-proteins collect solar energy and efficiently transport the resulting electron-hole pair to a photosynthetic reaction center where chemical synthesis occurs. The ability of light harvesting molecules to efficiently guide energy makes them intriguing candidates for components in nanofabricated photonic devices.

The electronic excitations travel up to 50nm and are believed to last for 100's of ps in an individual protein. In the example on the left, an nanofabricated array of antenna-proteins transports the excitation over microns.

Resonant Inelastic X-ray Scattering (RIXS) measurements provide access to the unoccupied electronic structure information present in XAS and correlate it with the occupied electronic structure information present in XES measurements, producing a complete description of valence excitations.

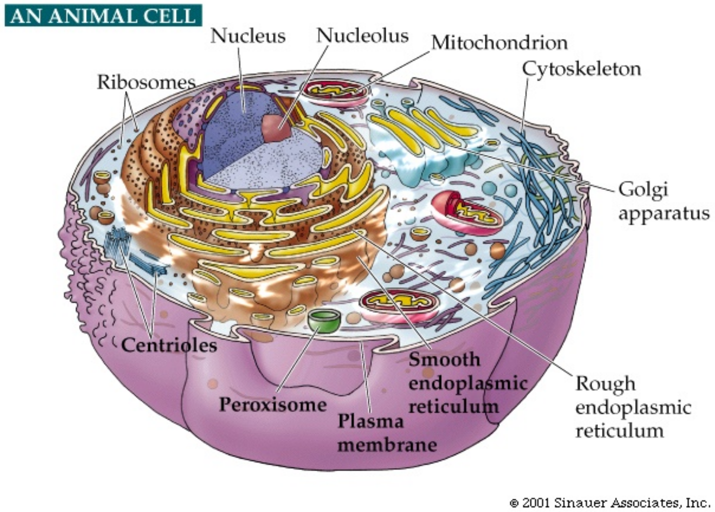


Temporally (ps) and spatially (10 nm) resolved RIXS could **map the migration of the electronic excitation following (optical) photoexcitation.** The energy tunability, high spectral brightness, few nm x-ray spot sizes, and high repetition rate, sub-ps pulses of the ERL/USR enable this type of measurement.

Structures of biological cells with < 10 nm resolution in 3D

Chae Un Kim, Cornell University

From XDS2011: Diffraction Microscopy, Holography and Ptychography using Coherent Beams



Visualization of sub-cellular components in 3D at high resolution is essential to understanding how cells function. However, the currently existing microscopic techniques have limitations for this purpose. Optical microscopy cannot provide high enough resolution (typically worse than 200 nm) and electron microscopy is poorly suited for thick cellular samples, requiring >1,000 sections.

X-ray diffraction microscopy (XDM) is a lensless microscopic technique and uses the high penetration power of X-rays to image biological cell (of a few microns in size) at high resolution in 3D. **XDM offers potential to image whole cancer cells or the structure and connectivity of the sub-cellular organelles in 3D at 5-10 nm resolution.**

The fundamental image resolution of XDM for biological samples is set by radiation damage. A variety of cryopreservation methods have been developed, including ambient plunge-freezing and high-pressure cryocooling techniques. The cryopreservation of hydrated samples replaces water with either low-density amorphous (LDA) or high-density amorphous (HDA) ice. Both LDA and HDA ice exhibit density fluctuations, whose structure and origins are presently poorly understood, which limit the use of cryopreservation for XDM.

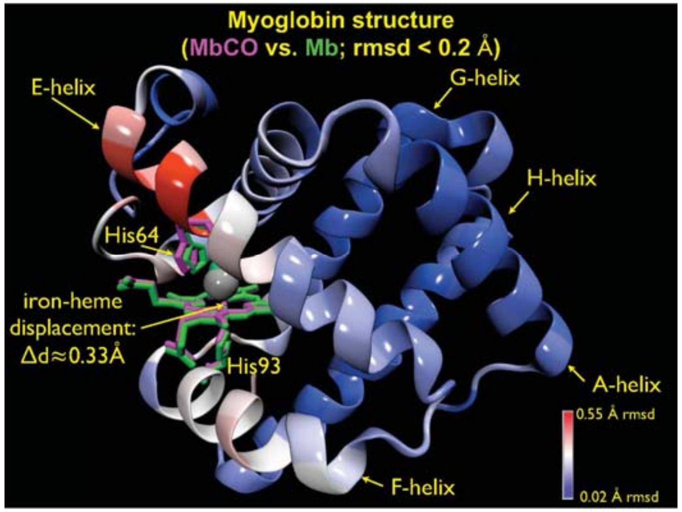
Probing local structures of HDA/LDA ice requires highly brilliant/coherent nano-focused X-ray beams. The X-ray sources such as ERLs/USRs provide an ideal X-ray probe for this types of study. After better accounting for these density fluctuations, we anticipate that **the highly brilliant and coherent X-ray beams from ERLs/USRs will allow, for the first time, study of cellular structures in 3D with 5 to 7 nm spatial resolution. Other applications are the imaging of chromosomes and origins of crack formation in solid state materials.**

XDL 2011 · Photon Factory · CHESS · SSRL · DESY

New opportunities in time-resolved solution scattering of proteins

Phillip Anfinrud, NIH

Workshop 2: Biomolecular Structure from Nanocrystals and Diffuse Scattering



Structural changes in myoglobin upon laser flash photolysis of bound CO, as a proxy for O_2 binding, have been determined using Laue methods. The duration of the storage ring pulse limited the time resolution to ~100 ps.

(from Cho et al., PNAS 2010 **107**,7281)

The ability to observe **structural changes in biomolecules while they function** has been a goal of cellular biology for many decades. **NMR is limited** to tens of microseconds, the need for large quantities of (often) isotopically-labelled material, lengthy scan times, and difficulties of reaction initiation in the NMR machine.

Time-resolved SAXS (Small Angle X-ray Scattering) & WAXS (Wide-Angle X-ray Scattering) are valuable complements to time-resolved Laue crystallography, time-resolved laser spectroscopy, and computational modeling - and increasingly useful in studies of protein structure, function, and dynamics. **Time-resolved solution SAXS patterns are exquisitely sensitive** to protein volume changes and mass transport into and out of the protein. **Time-resolved WAXS fingerprints contain a wealth of structural information down to 2.5 Å**, and provide **stringent constraints** for models of conformational states and structural transitions between them.

In practice, x-ray pulses are directed through a flow of specimen solution to mitigate radiation damage. The minimum time resolution achievable using x-rays from storage rings is limited by the x-ray pulse width to ~100 ps. ERLs improve the time resolution of SAXS/WAXS to **~100 fs, orders of magnitude better** than with present day storage rings.

Understanding Planetary Interiors with an ERL

J.M. Jackson & D. Zhang / Caltech

Workshop 4: High Pressure Science at the Edge of Feasibility

An understanding of the dynamics & composition of planetary interiors will lead to new insights about the solar system and better interpretation of seismic data collected here on earth. This depends on knowledge of material characteristics such as melt viscosity, elastic constants, sound velocity and thermodynamic parameters of liquid-iron alloys and other earth materials, at pressures in excess of 100GPa and temperatures greater than 1000K.

The ERL will deliver 100 times the flux/unit energy/square micron of existing storage rings or those under construction, in the energy range of interest here. This will enable new classes of experiments, like momentum-resolved inelastic scattering (IXS) on individual grains within assemblages inside diamond anvil cells (DAC)….

X-ray stimulated nuclear resonance measurement of acoustic vibrations yield sound speed, IXS reveals anisotropy & phonon dispersion, melting & structural phases are identified by diffraction, and emission & absorption spectroscopies provide chemical information. The ERL will enable delivery of unprecedented sub 100nm focused beams for: selection and imaging of individual grains, measuring diffusion constants at microsecond time scales, and revealing liquid dynamics in the pico- to nano-second range….

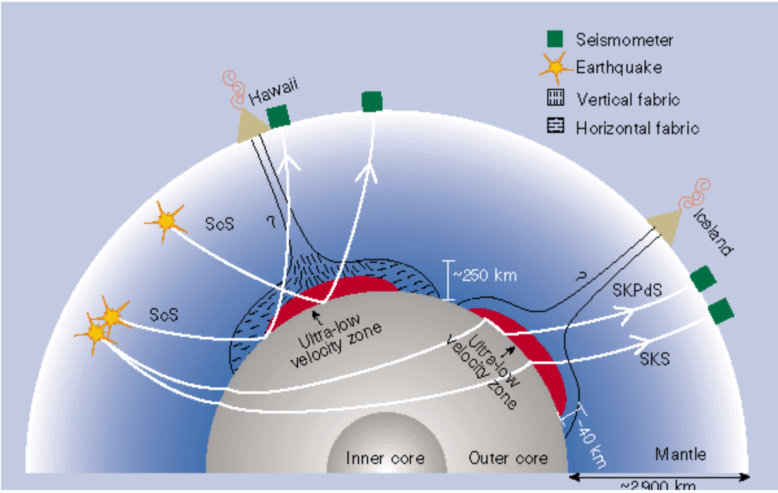


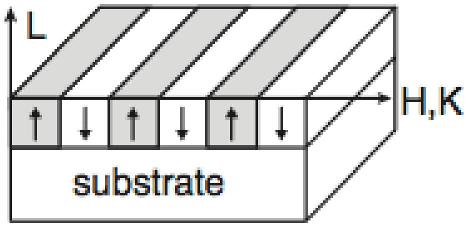
Figure illustrates why knowledge of p-,s-wave sound speed and material properties through the core, mantle and interface region is essential for seismic interpretation.

Speed Limits for Ferroelectric/Multiferroic Switching

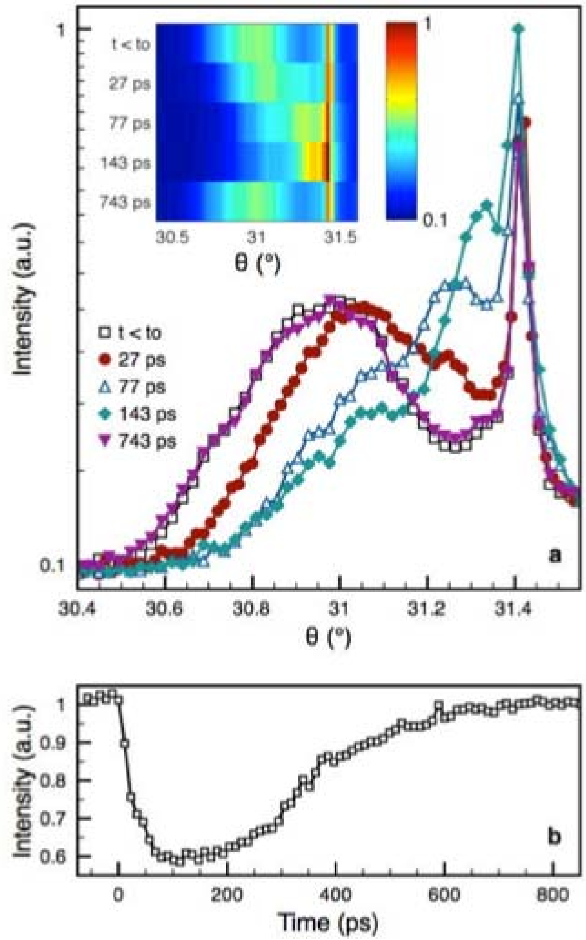
Aaron M. Lindenberg, SLAC National Accelerator Laboratory

Workshop 3: Ultrafast Science with "Tickle and Probe"

Complex-oxide multiferroic materials are promising candidates for advanced technological applications. A high-repetition-rate, ultrafast, hard x-ray source will provide the capability to study the speed limits to switching in these materials.



Similar to ferromagnets, ferroelectrics minimize their energy by breaking into antiphase domains, frequently with a characteristic length scale. Short range ordering of these domains produces diffuse x-ray scattering features in addition to the sharp Bragg peaks from the lattice.



The ferroelectric stripe phase of $PbTiO_3$ can by destroyed or enhanced by an ultrafast optical pulse with rapid relaxation on few nanosecond time-scales, enabling high-rep-rate experiments of ultrafast switching and nucleation dynamics.

T=430C ferroelectric phase ($PbTiO_3$ on $DyScO_3$)

•Reversible optically - induced switching from ferroelectric to paraelectric phase at fluences <100 μJ/cm^2

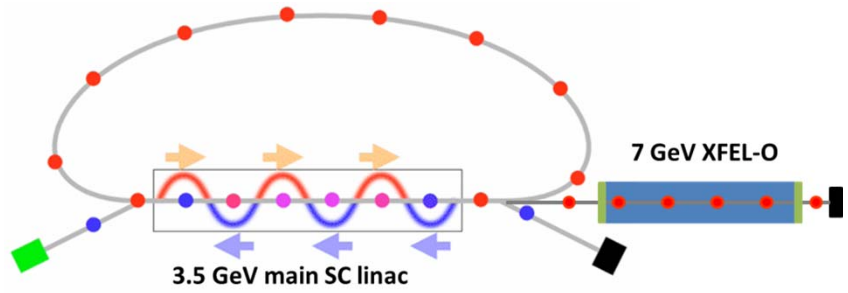
•Recovers on few hundred picosecond time-- - scale

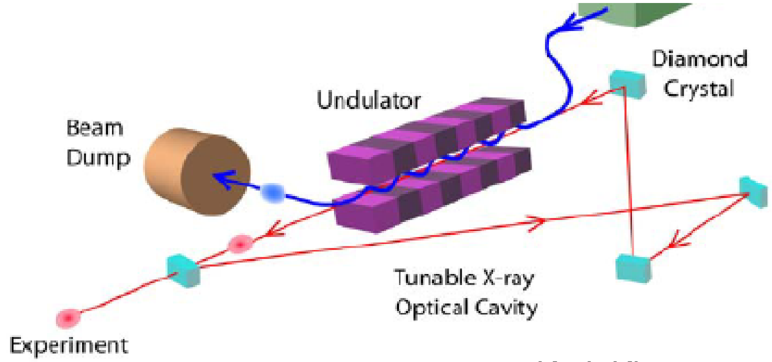
The flux of the ERL/USR will enable ultrafast, high-repetition rate, pump-probe studies with much less intense pump pulses. One expects flux increases of 10^4 relative to existing slicing and low-alpha sources

Towards Fourier-limited X-ray Science

Shin-ichi Adachi, Photon Factory, KEK & PREST, JST

From XDL2011: Ultrafast Science with “Tickle and Probe”

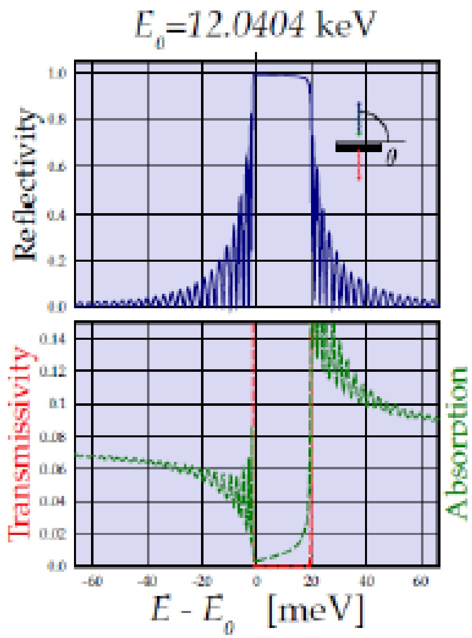




K.-J. Kim

A continuous sequence of ultralow emittance multi-GeV electron bunches and a low-loss optical cavity constructed from high-reflectivity Bragg crystals can create an X-ray FEL Oscillator (XFELO). The x-ray beam from an XFELO would be Fourier transform limited, have tunable wavelength, and the peak power would be small enough to not adiabatically damage samples. The beam will have an average **spectral brightness 10^3-10^5 x greater** than available on existing or planned sources.

X-ray Beam Properties	
Photons/pulse	10^9
Rep rate	1-100 MHz
dE/E	10^{-6}
τ	1 ps
K.-J. Kim, et al., Phys. Rev. Lett. **100** (24) (2008).	



Y. Shvyd'ko

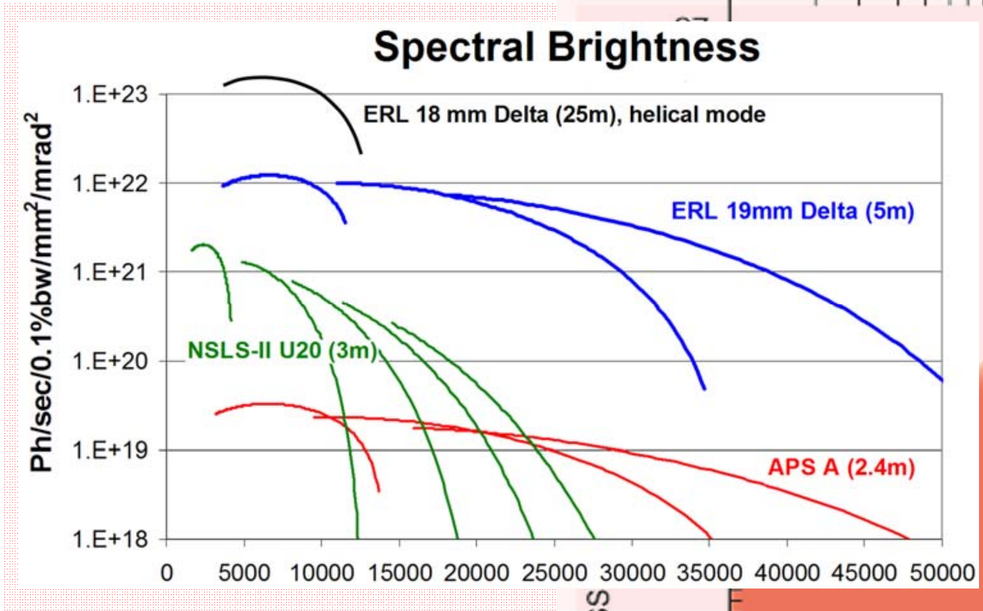
The X-ray beams produced by an XFELO would be fully Fourier-limited, upgrading existing techniques or enabling novel ones such as nonlinear X-ray optics, inelastic scattering, two-photon correlation spectroscopy, and transient grating spectroscopy. For example, the meV energy resolution would enable inelastic scattering studies of thermally generated excitations in small samples.

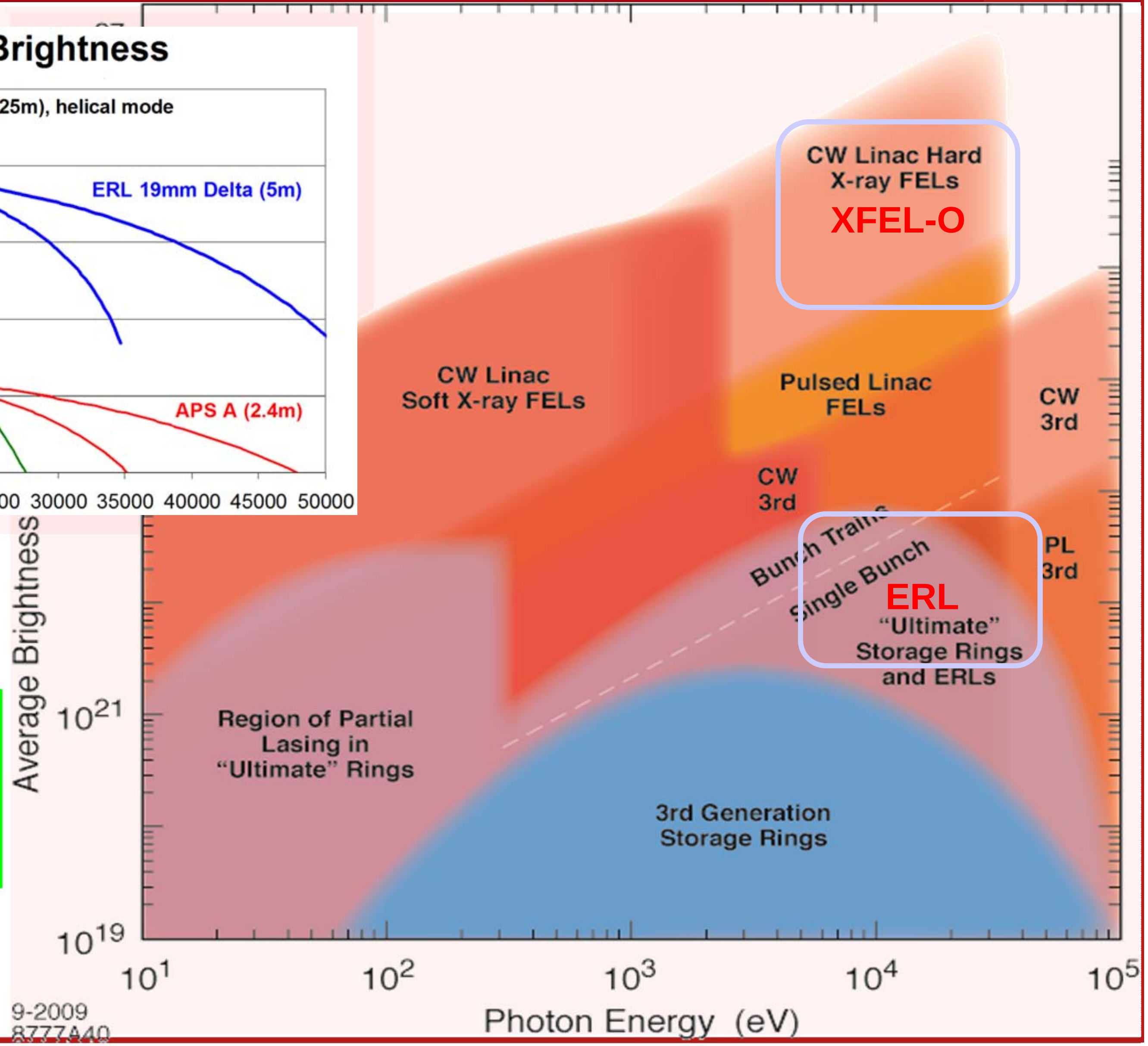
XDL 2011 Photon Factory CHESS SSRL DESY

Beam goals for Cornell ERL

	Energy recovered modes			One pass	
Modes:	(A) Flux	(B) Coherence	(C) Short-Pulse	(D) High charge	Units
Energy	5	5	5	5	GeV
Current	100	25	100	0.1	mA
Bunch charge	77	19	77	1000	pC
Repetition rate	1300	1300	1300	0.1	MHz
Norm. emittance	0.3	0.08	1	5.0	mm mrad
Geom. emittance	31	8.2	103	1022	pm
Rms bunch length	2000	2000	100	50	fs
Relative energy spread	0.2	0.2	1	3	10^{-3}
Beam power	500	125	500	0.5	MW

Average spectral brightness for hard x-rays





Exceedingly large average spectral brightness is one large advantage for ERLs, but by far not the only one.

Advantages of ERL beams for light sources

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

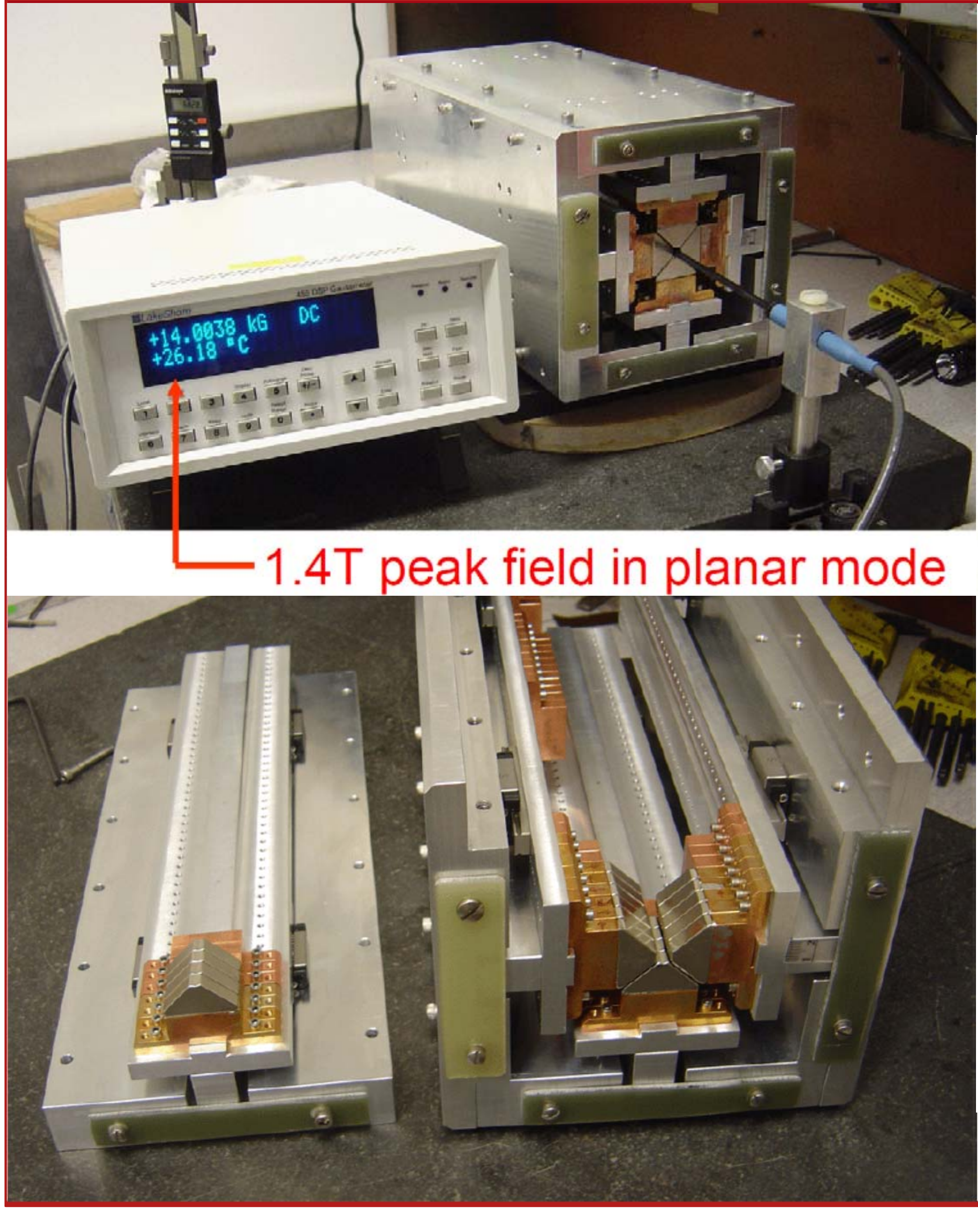
1) Beam size vs. divergence can be optimized on each undulator straight section, without limitations by dynamic apertures.

   APS: one set of beta functions
   ESRF: two sets of beta functions (hi, low)
   ERL: all choices are possible, not "one size fits all"

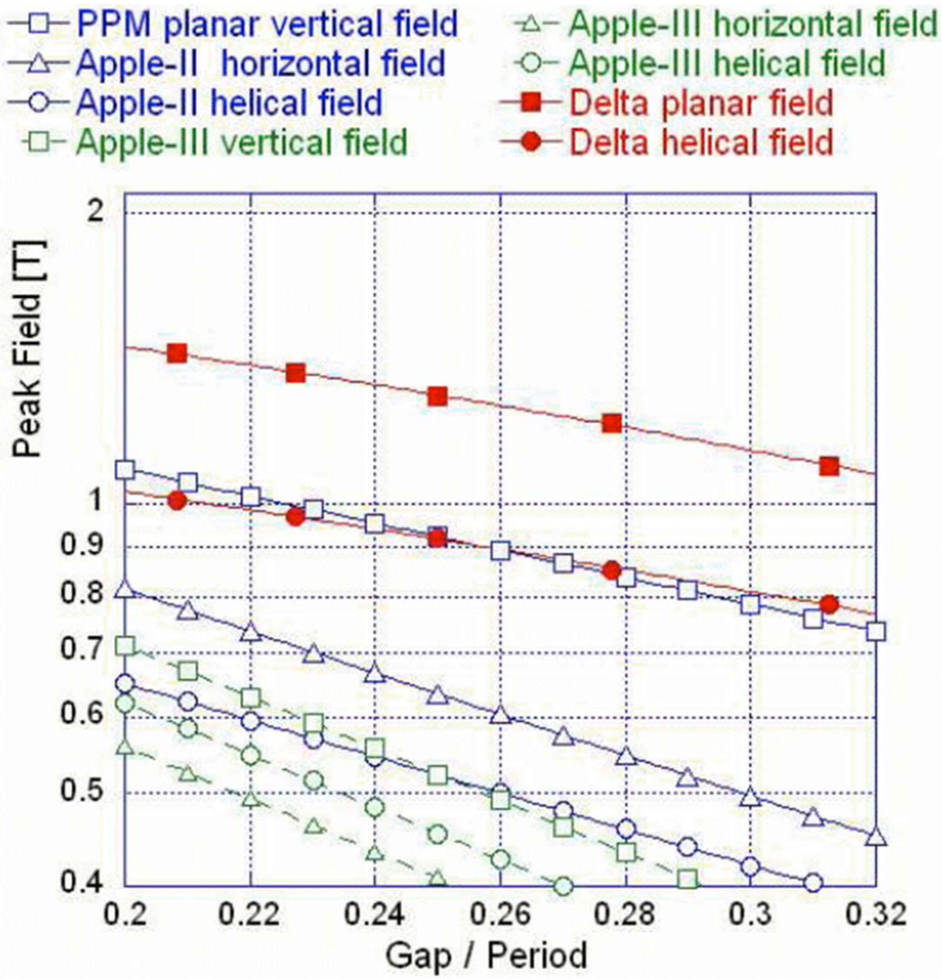
2) Move position of minimum electron beam waist along straight section by changing quadrupole settings, without moving components, e.g. move apparent x-ray source point to compensate for changes in focal length on refractive lenses and zone plates, or move x-ray focus to the sample.

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.

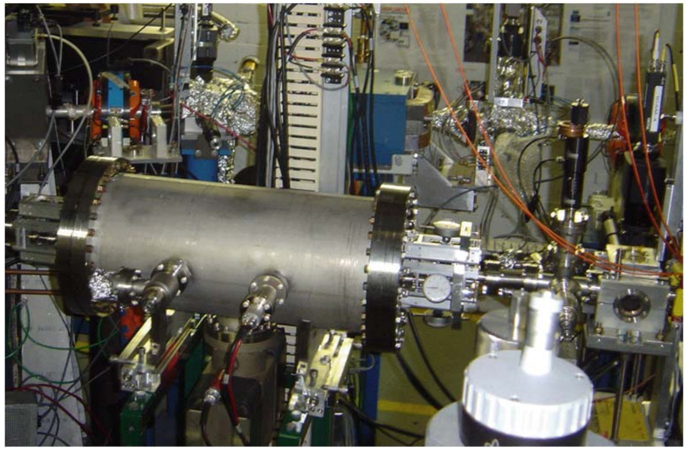
Undulators for small emittances for round beams
Cornell's Delta Undulator



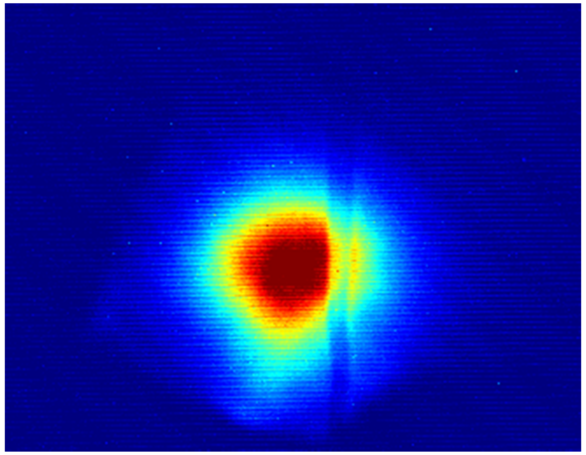
Prototyped at Cornell, to be used at LCLS



Undulators for small emittances for round beams
Cornell's Delta Undulator

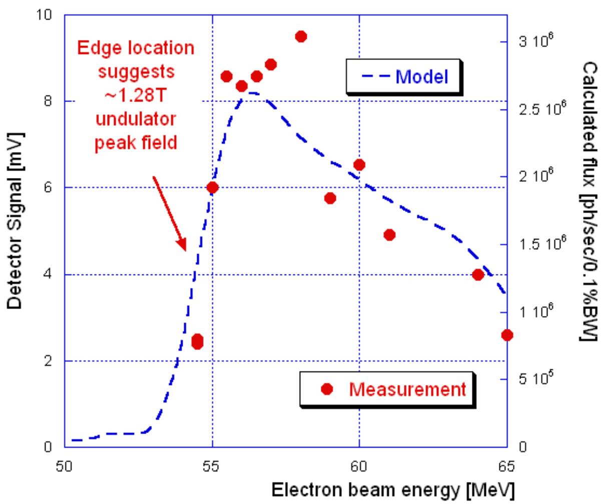


30cm long prototype of Delta undulator installed in beam line #2 at ATF (BNL)



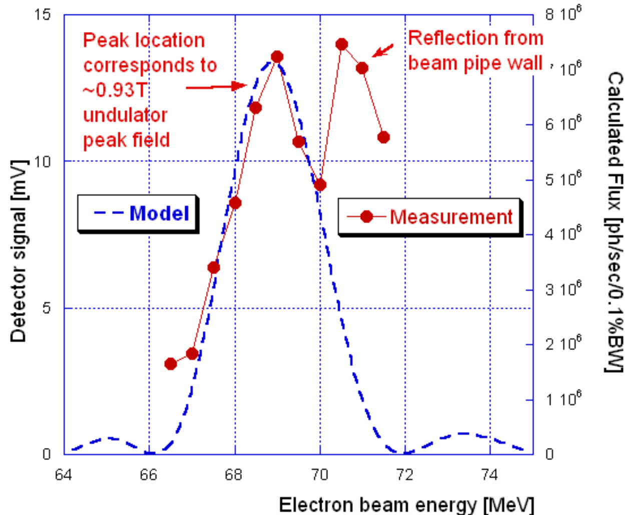
Electron beam image on flag downstream of the undulator

Delta undulator in planar mode.
5300nm radiation flux as a function of electron beam energy for ~60mm DIA slit. Dec 18, 2009



Fundamental harmonics in planar mode

Delta undulator in helical mode.
3600nm radiation flux as a function of electron beam energy through ~10mm DIA slit. Dec 18, 2009



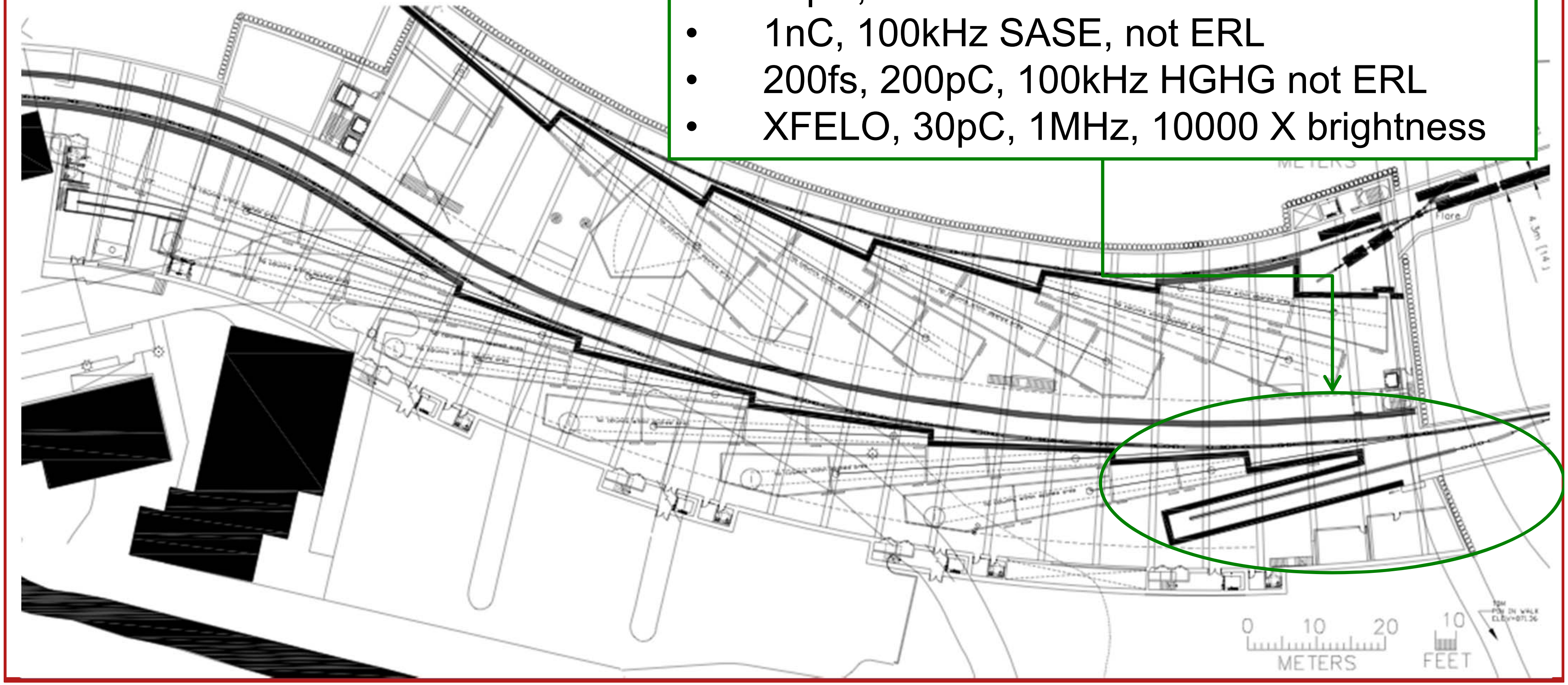
Fundamental harmonics in helical mode

Advantages of ERL beams: Short pulses, synchronized and simultaneous with small emittances

- Standard bunch lengths in ERLs: 50fs to 2ps for high currents 1.3GHz (ERL mode)
- ERL driven FELs are possible, because beams can be sufficiently short
- Because ERLs have linacs, the shorter bunch lengths that other linacs propose could also be created in the linac of an ERL.

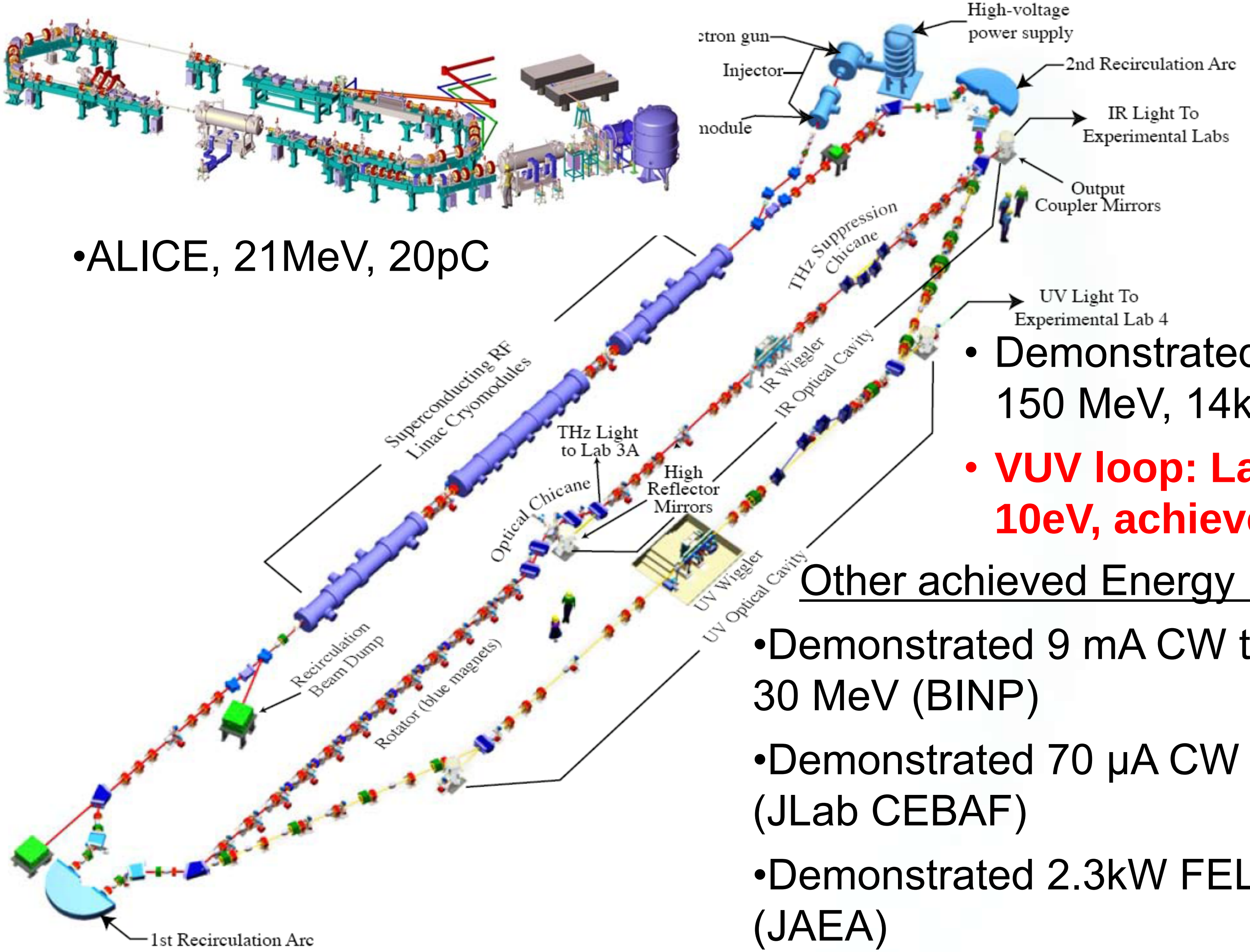
Test of simultaneous linac and ERL operation:

- 77pC, 1.3GHz ERL
- 1nC, 100kHz SASE, not ERL
- 200fs, 200pC, 100kHz HGHG not ERL
- XFELO, 30pC, 1MHz, 10000 X brightness



Energy Recovery Installations:

Successful tests for ERL beam dynamics, controls, and technology



•ALICE, 21MeV, 20pC

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

Other achieved Energy Recovery

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

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

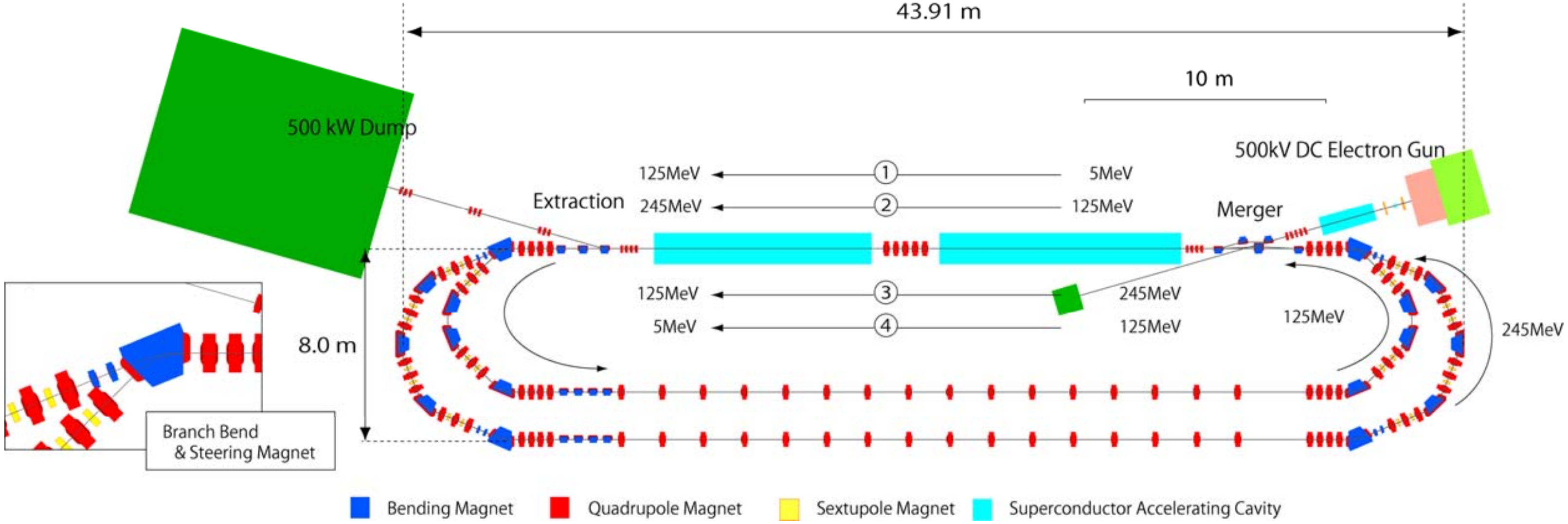
•Demonstrated 2.3kW FEL, 17MeV (JAEA)

New test installations, e.g. Double Loop Compact ERL (KEK)

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

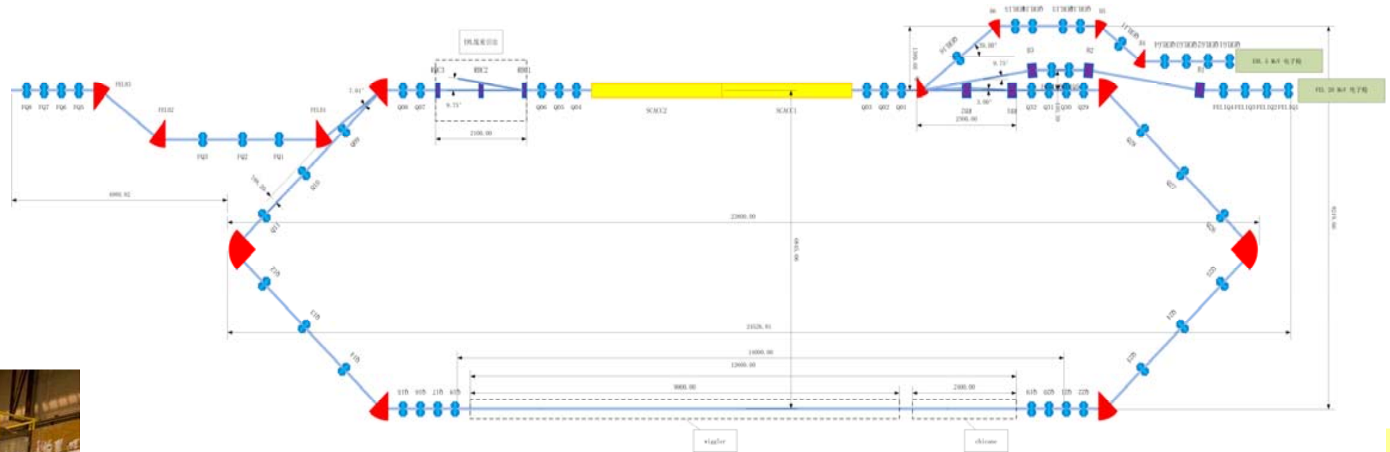
- **Why did we choose a double loop circulator?**

It is for saving
construction area
number of accelerator cavities
running cost of the refrigerators



Layout of double loop Compact ERL

New test installations, e.g.
BNL, KEK, BESSY, and IHEP



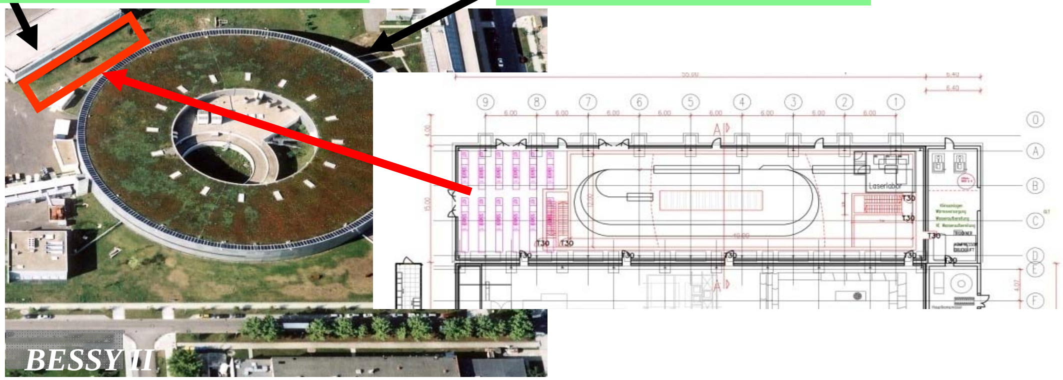
IHEP Compact TF-- 35 MeV-10 mA

BNL ERL test for coherent e-cooling of RHIC

B*ERL*inPro: ERL demonstration facility

Cryogenic plant

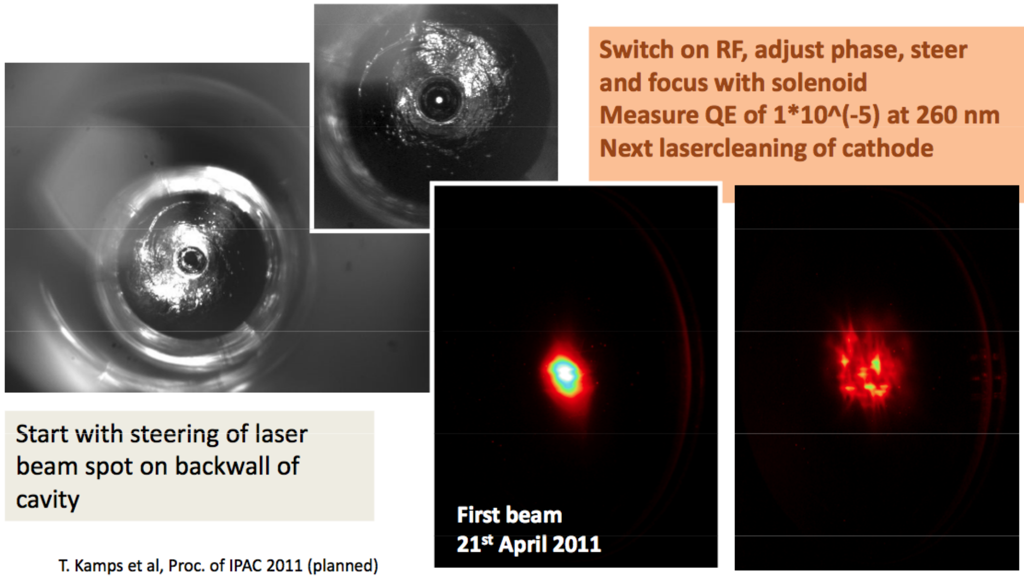
BESSY II



Some Milestones for the ERL community

- Beam from new and more SRF electron sources (At HZB/JLAB for ERLs)
- Hardware developments at KEK (cw coupler, 9-cell cavities, injector cavities, …)
- 25mA (high coherence mode current parameters) reached for DC guns
- Theoretical emittance limits approached for 77pC (giving 100mA at 1.3GeV)
- Low BBU prototype cavity with ERL specs in vertical test (16MV/m, 2.e10)

First beam of photoelectrons from Pb cathode generated and accelerated at 21st Aptil 2011, < 2 years after project approval



T. Kamps et al, Proc. of IPAC 2011 (planned)

I_{max} = 20nA for 8kHz
2ps long bunches

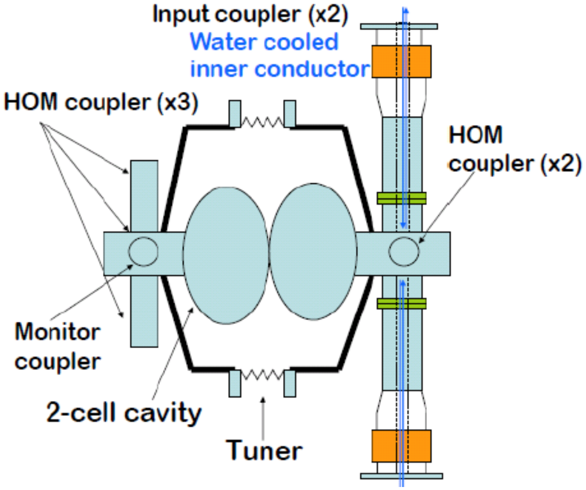
λ_{Laser} = 260nm, 4.76eV
QE of Pb = 6.5E-5
Can be > 5 X better

W_{tot} = 1mJ
W_{pulse} = 0.125μJ

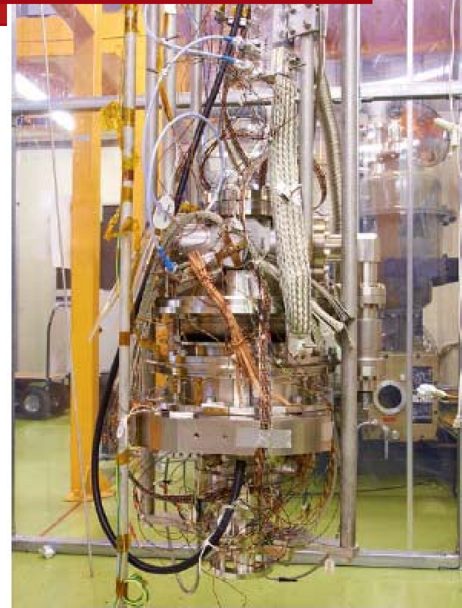
q_{bunch} = 2.5pC

New 1.5cell at Jlab with better coating

R&D of injector for cERL test loop at KEK



Three 2-cell cavities
with 5 HOM couplers



Set-up of VT

	V_{acc} [MV]	P_{rf} [kW]
Cavity-1	1.5	10
Cavity-2	2.5	25
Cavity-3	2.5	25

(I_{beam} = 10 mA, P_{rf} /coupler)

Six power couplers for double feed system

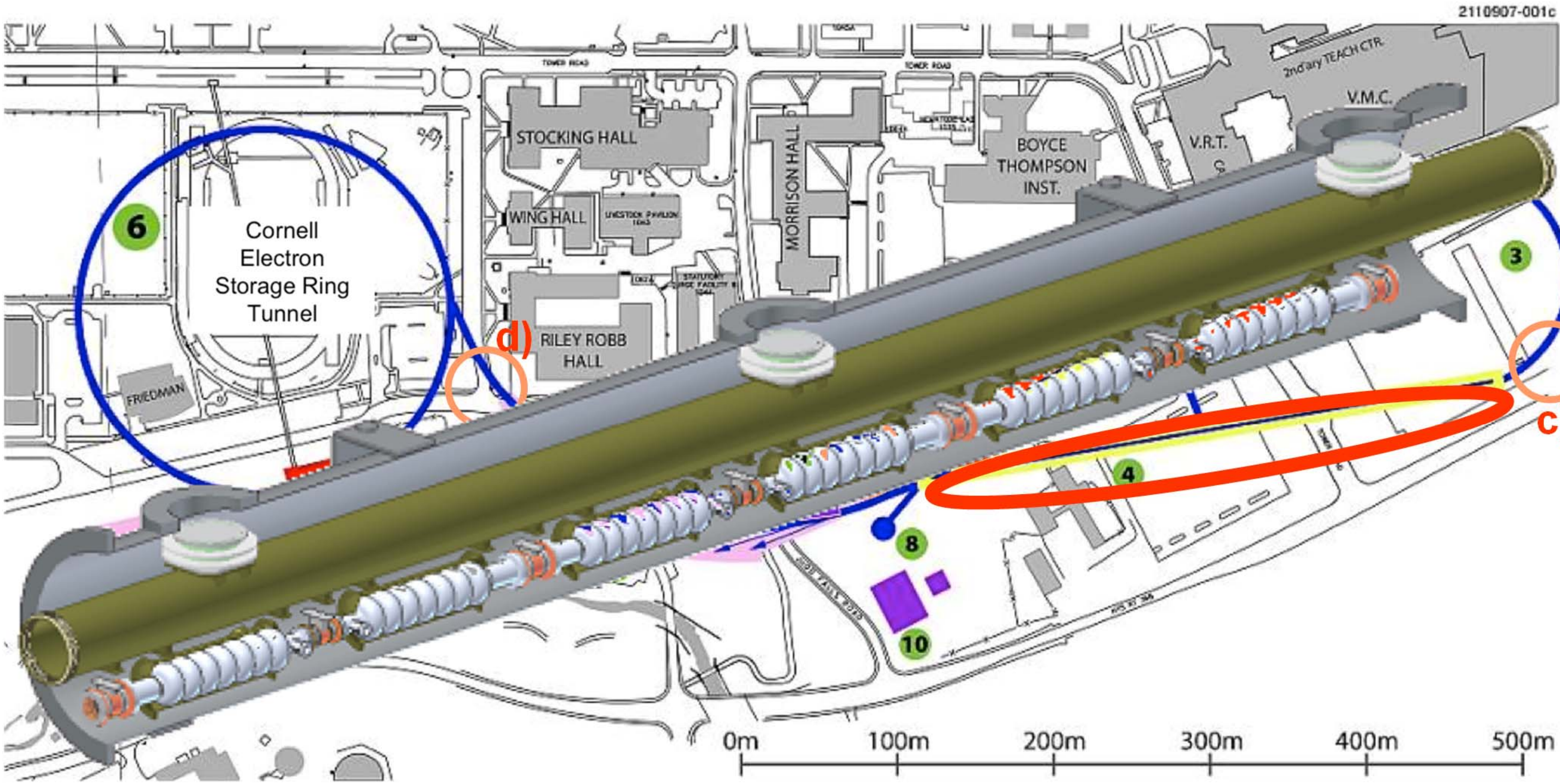
Six cw input couplers

High power test stand

- Each 2-cell cavity has 5 HOM couplers
- Vertical tests in progress
- Module assembling starts early 2012

Construction of a full ERL cryomodule at Cornell

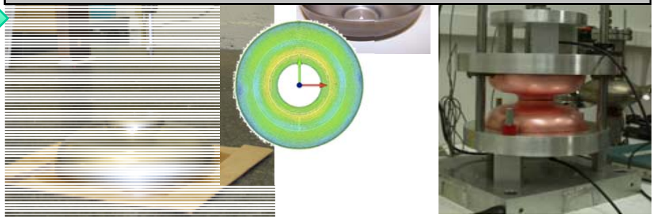
- 7-cell cavities, optimized for > 200mA BBU limit even for 1/4mm construction errors
- 6 cavities and one SC focusing and steering unit
- Cavity specs: Eacc = 16MV/m, Q0 = 2.E10



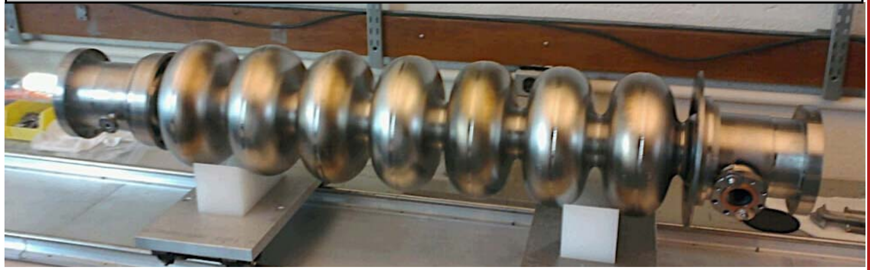
ERL cavity fabrication and measurement

Electron Beam Welding

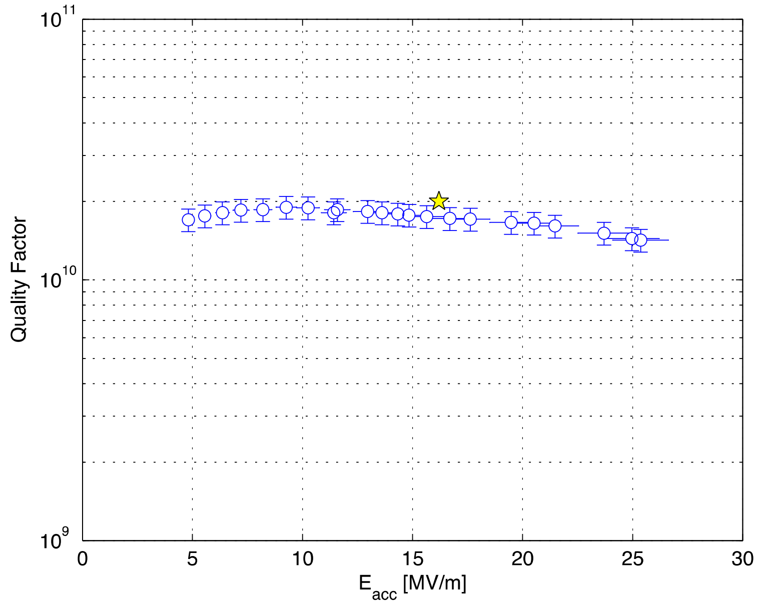
Quality control: CMM and frequency check



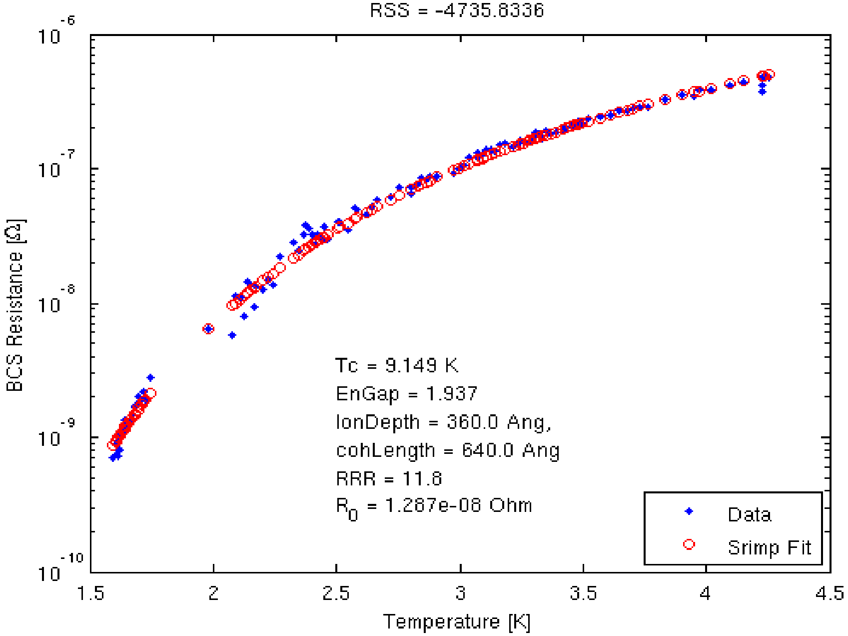
Finished main linac cavity with ±0.25 mm shape precision



Q vs. E for 1st prototype Cornell ERL cavity



Shrimp fit for Residual resistivity of 13 nOhm



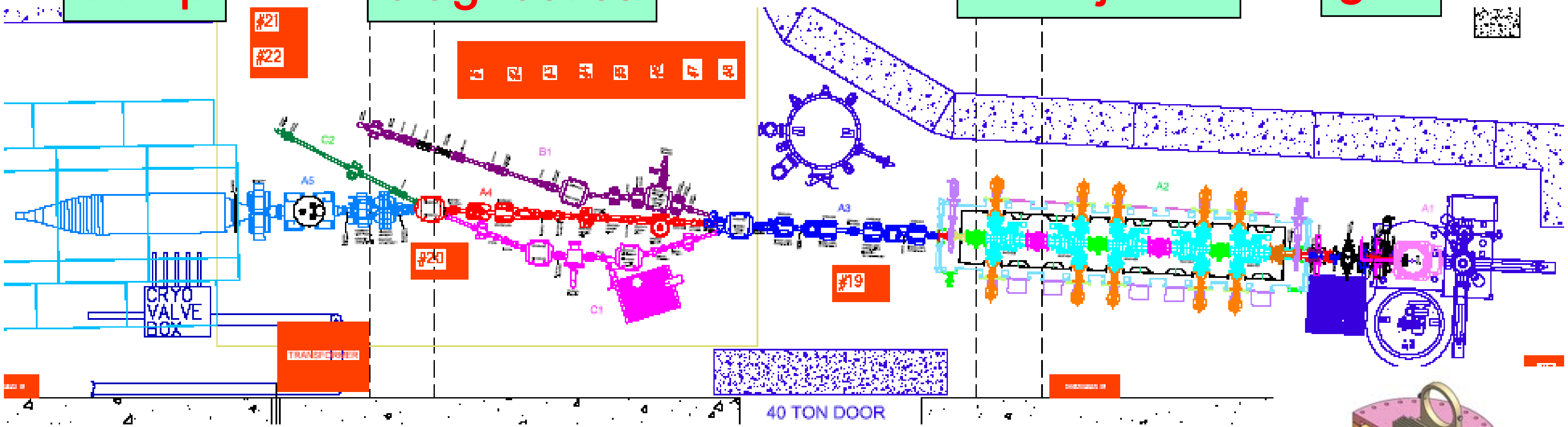
Cornell Injector prototype: Verification of beam production

dump

diagnostics

SC injector

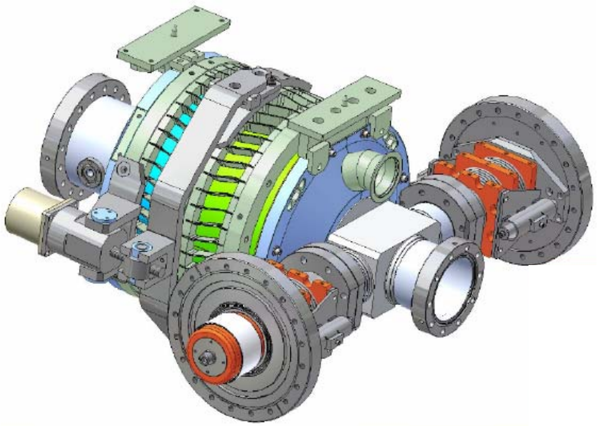
gun



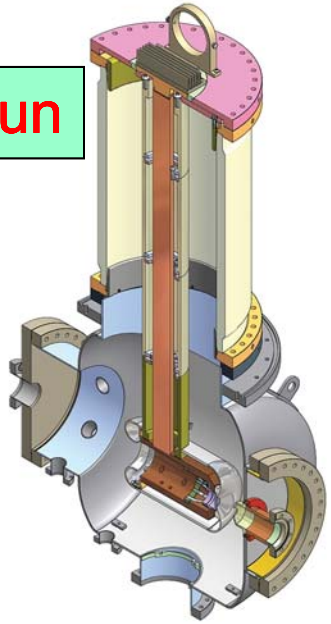
HOM absorb.

CW coupler

Dressed cavity



gun



Milestones at Cornell's injector

Peak DC-power supply voltage: 750kV
Peak DC-gun voltage: 440kV (of 500kV required with beam)

Peak DC-beam current: 25mA (up to brilliance mode spec)
Peak bunched-beam current: 25mA with GaAs / 20mA with CsK_2Sb for 8h

Peak charge per bunch: 200pC (more than needed)

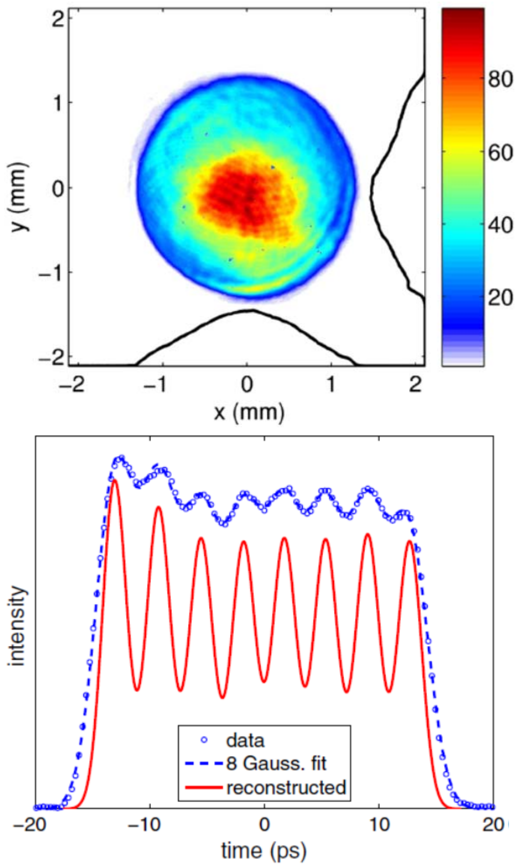
Typical bunch length: 2ps (up to spec)

Smallest normalized thermal emittance: 0.25 mm mrad/mm radius
Smallest normalized emittance after injector at 80pC: 0.8 mm mrad
For this gun, 0.5 mm mrad is theoretical limit !
This bunch in a 5GeV ERL would produce X-rays brighter than any ring today.

Largest SRF-injector cavity Q0: 1.e10 (of 2.e10 required)
Largest injector-coupler power: 60kW (of 100kW required)
Largest SRF-cavity voltage: 13MV/m (up to spec)

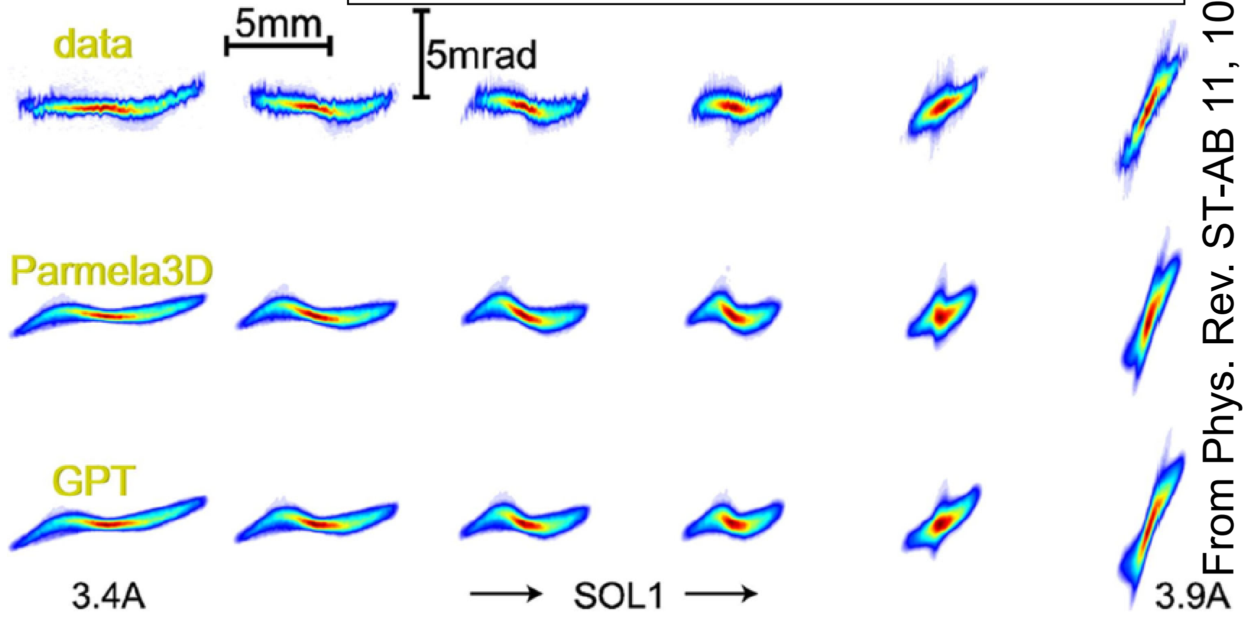
Understanding of emittances

Beam properties at the cathode



Fixed slits phase space measurements

- Corrector coils for beam scanning
- 10 micron precision slits
- 1 kW beam power handling



From Phys. Rev. ST-AB 11, 100703 (2008)

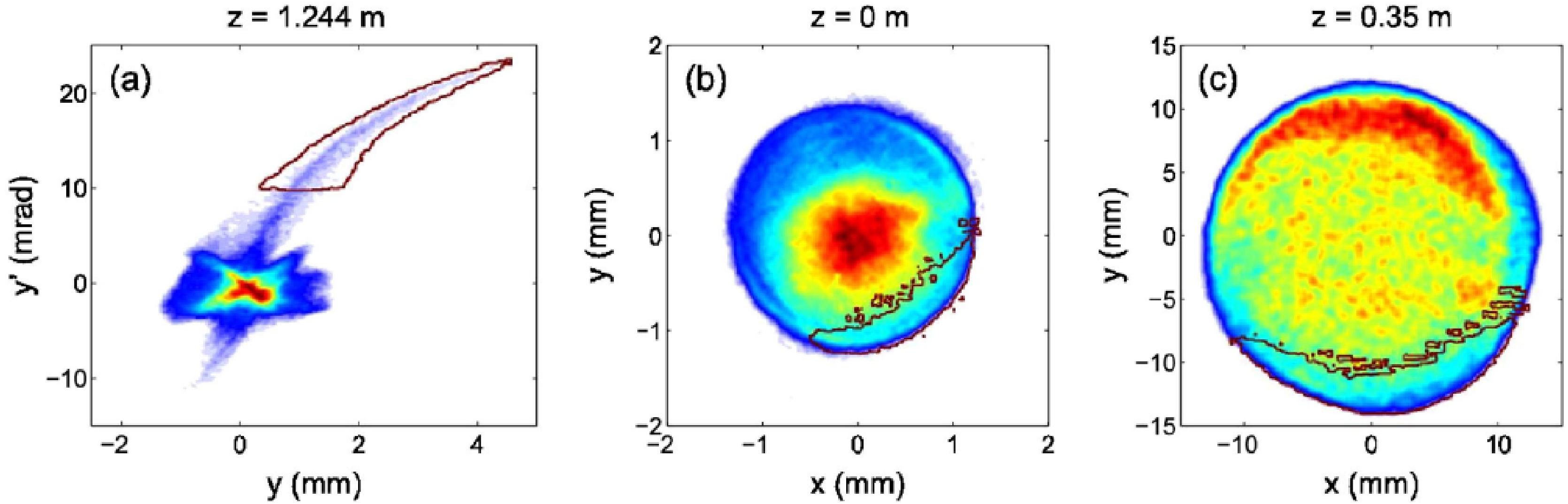
Are transported through the accelerator, measured in a fixed slit phase space measuring system, and compared with simulations.

Good agreement with theory gives confidence that the very small simulated emittances can be achieved.

Understanding of emittances

Asymmetric phase space distribution leads to reduced brightness

This Brightness reduction has been traced back to asymmetric photon distributions on the cathode.



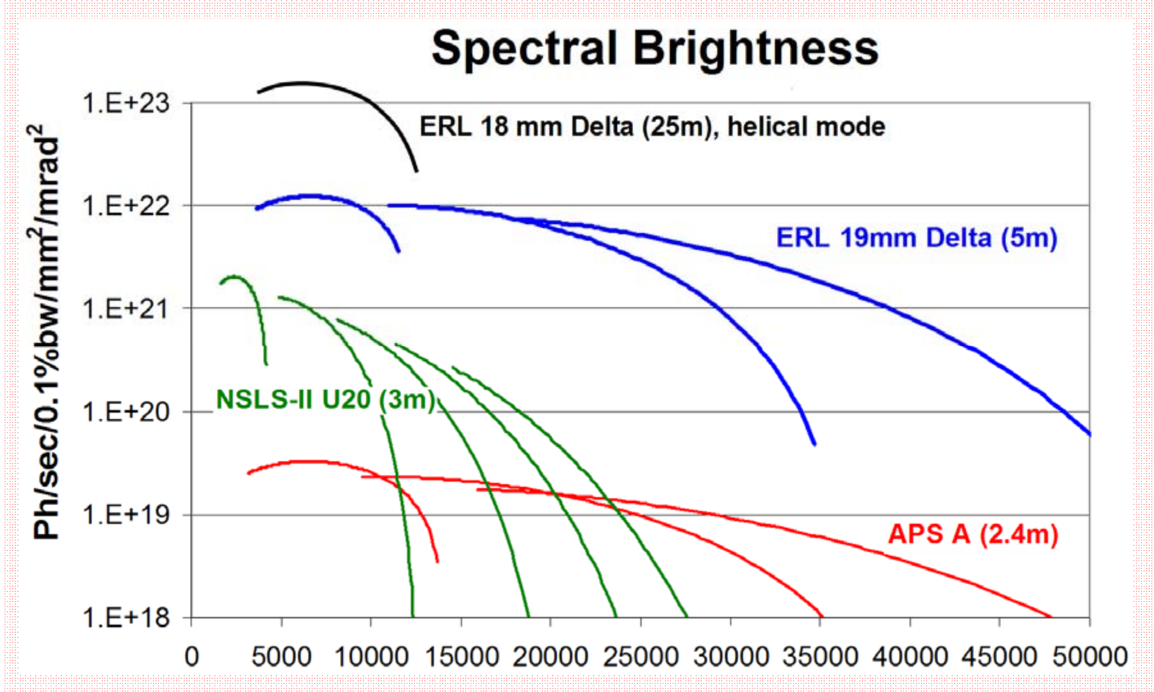
From Phys. Rev. ST-AB 11, 100703 (2008)

Are transported through the accelerator, measured in a fixed slit phase space measuring system, and compared with simulations.

Gun milestones:

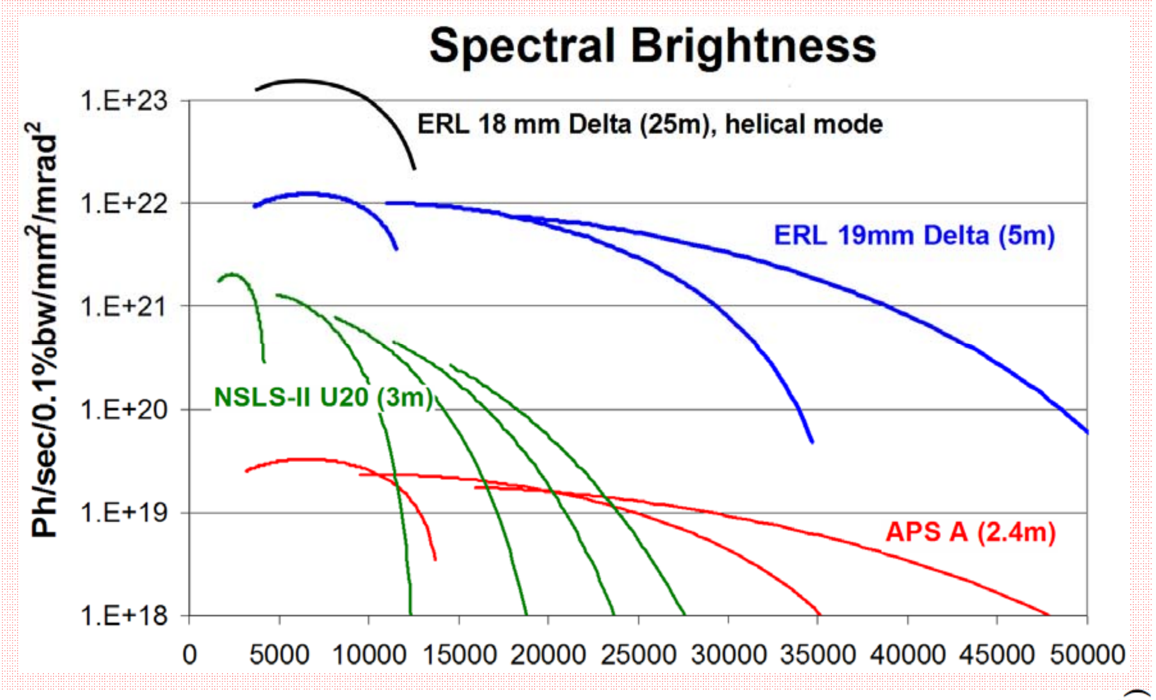
- Highest current: 25mA
- Highest voltage: 430kV
- Highest bunch charge: 80pC
- Emittance at 350keV: 0.8μm

Small emittances produce large spectral brightness



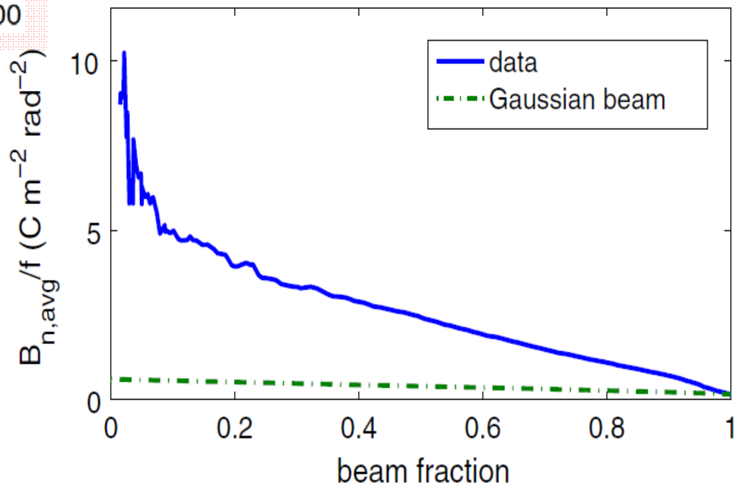
Exceedingly large average spectral brightness is one large advantage for ERLs, but by far not the only one.

Small emittances produce large spectral brightness



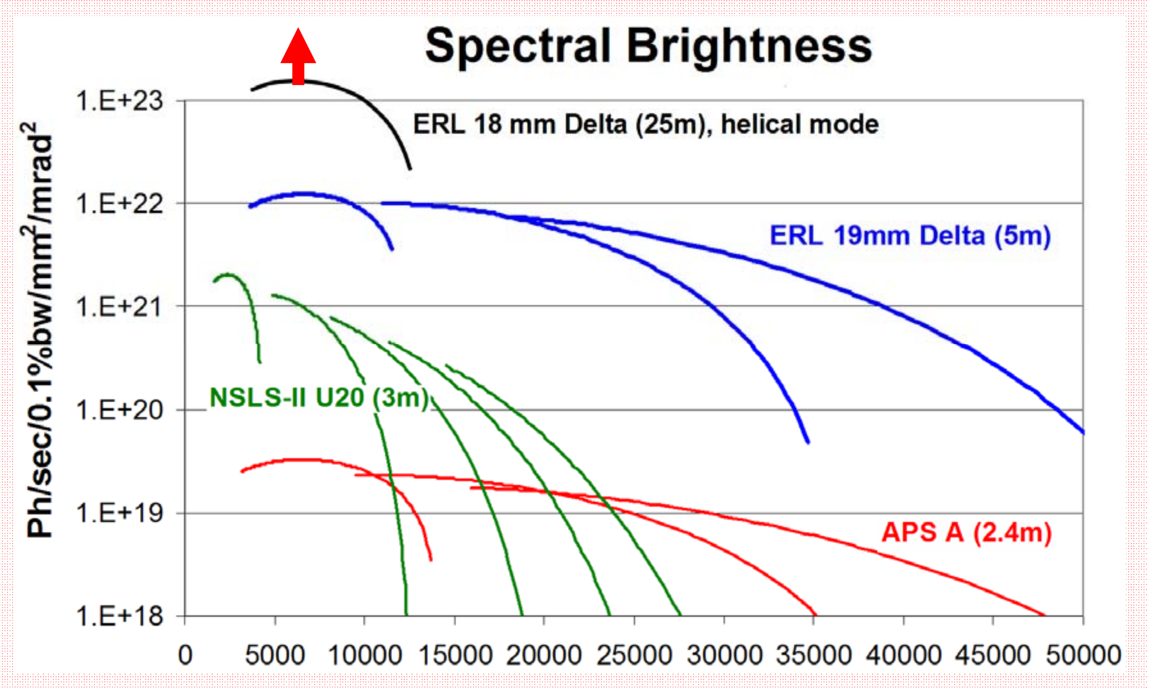
Exceedingly large average spectral brightness is one large advantage for ERLs, but by far not the only one.

Electron beams from ERLs can have much higher brightness, especially in the core of the beam.



Measurement from phase 1a

Advantages of ERL beams
Openness to future improvements



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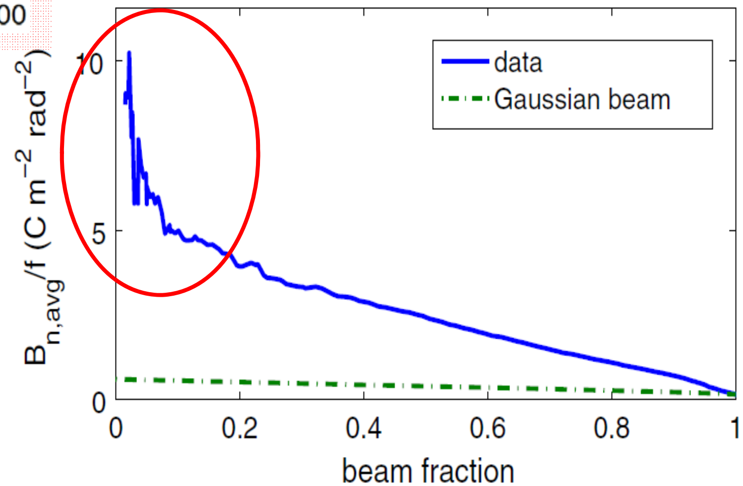


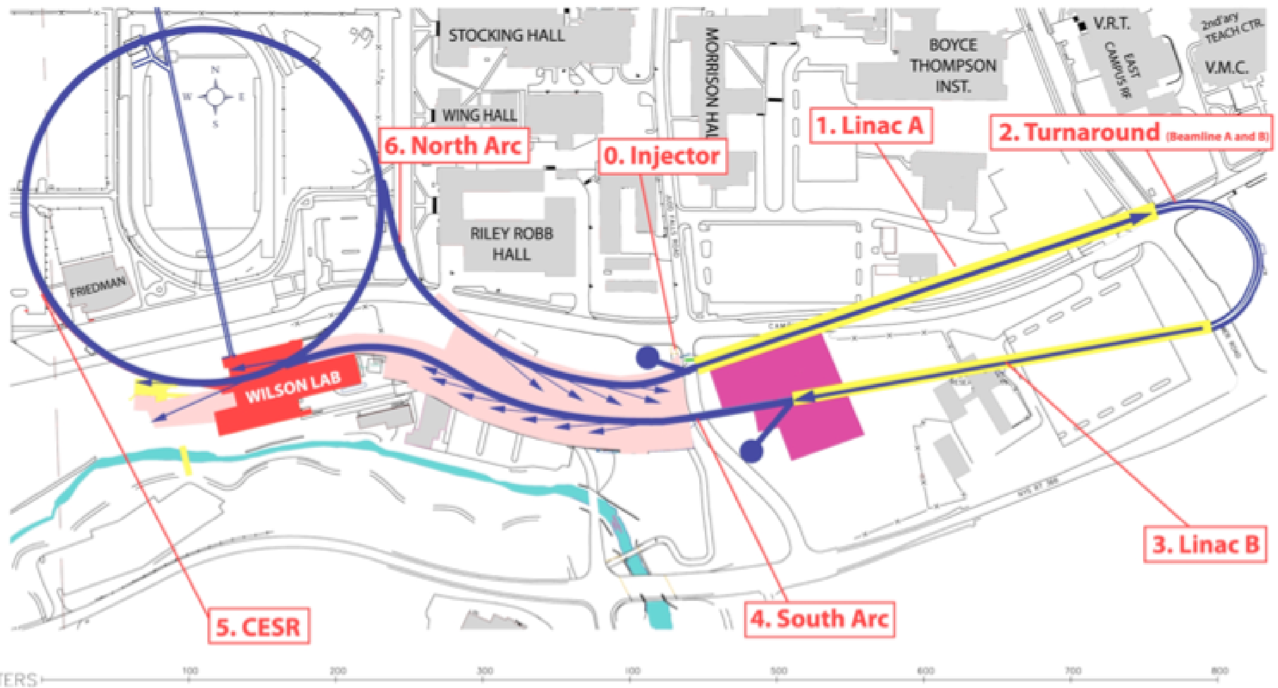
Measurement from phase 1a

Project Design Definition Report (PDDR)

Editors: Georg Hoffstaetter, Sol Gruner, Maury Tigner

Contributors: I. V. Bazarov, S. A. Belomestnykh, 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, T. Miyajima, C. E. Mayes, J. M. Maxson, A. Meseck, 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, U. Sae-Ueng, D. C. Sagan, J. O. Sears, V. D. Shemelin, C. K. Sinclair, D. M. Smilgies, E. N. Smith, K. W. Smolenski, Ch. Spethmann, C. Song, T. Tanabe, A. B. Temnykh, M. Tigner, N. R. A. Valles, V. G. Veshcherevich, Z. Wang, A. R. Woll, Y. Xie, Z. Zhao

Special Thanks: Chris Mayes is acknowledged for tireless editorial help and layout organization, and Sherrie Negrea for language editing.



Out for comments by selected advisors.

530 pages between conceptual design and engineering design.

Getting ready for suitably timed submission to the NSF.

Supporting documents of the PDDR

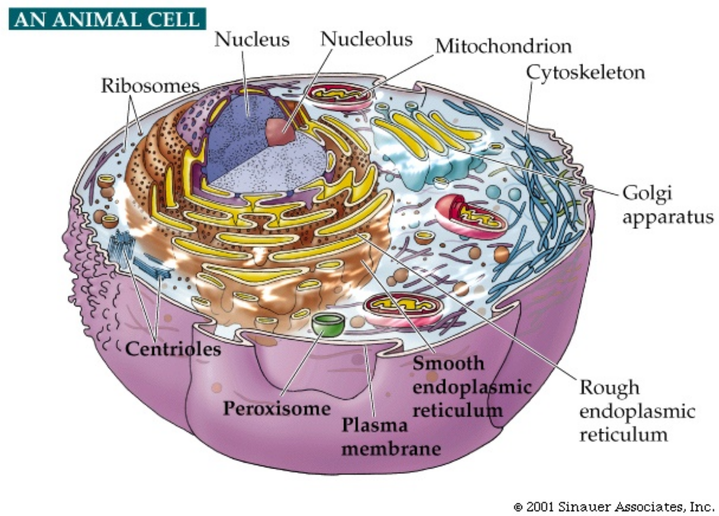
Studies for ERL Phase 2 (hard x-ray source construction)

a) Design decisions: Geometry, accelerator components layout, technical choices, beam dynamics analysis, radiation protection.
b) Proposal for electron-beamline construction
c) Proposal for large cryogenic plant
d) X-ray science building design
e) Tunnel design and construction study
f) Underground Technology advisory panel report
g) Environmental impact study

All these are to some extend reflected in the PDDR.

International X-ray ERL R&D is going forward with significant momentum.

And for good reasons.



Have a great Workshop ERL11 !