X-ray applications and accelerator physics for the Cornell ERL

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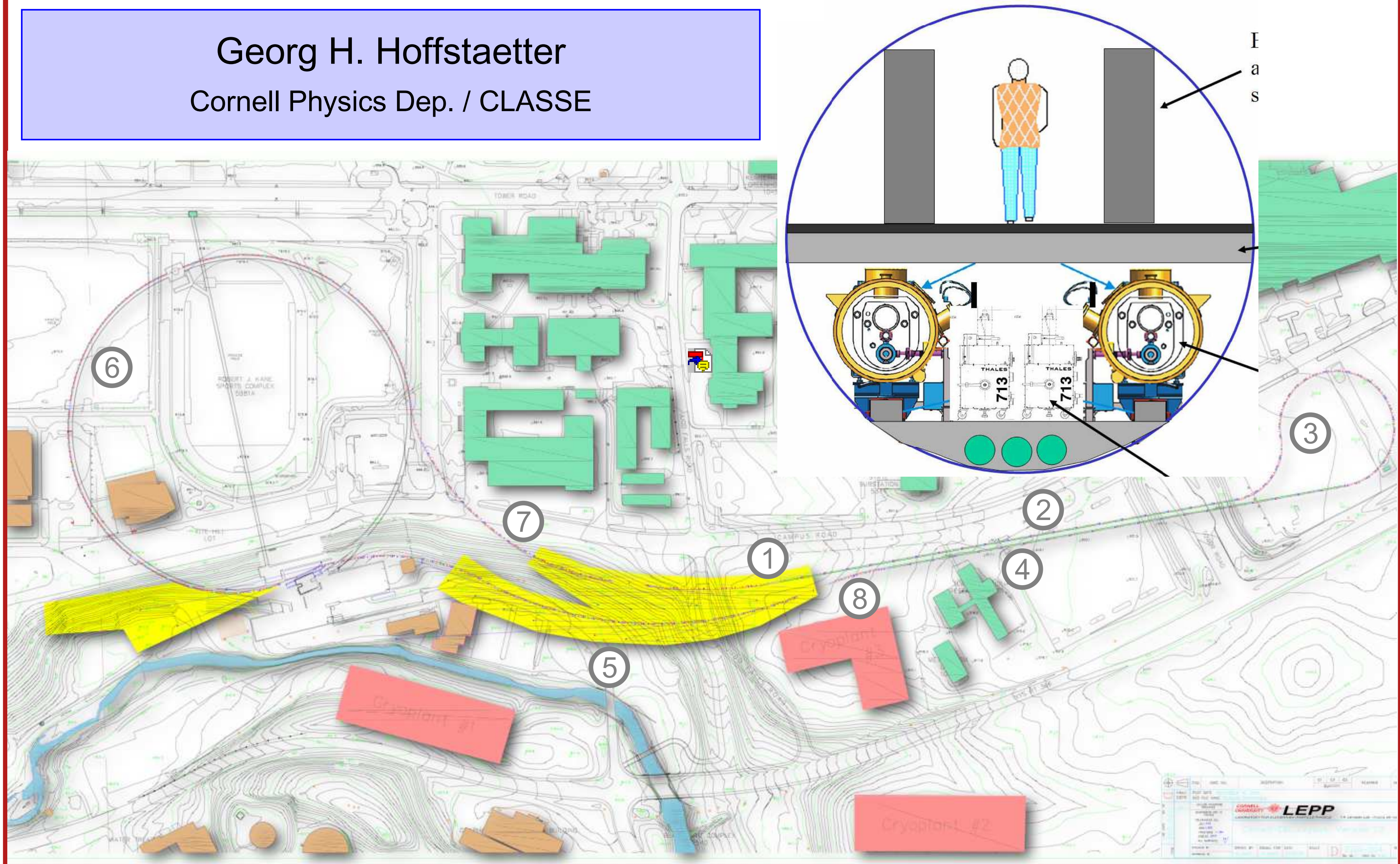
Cornell Physics Dep. / CLASSE



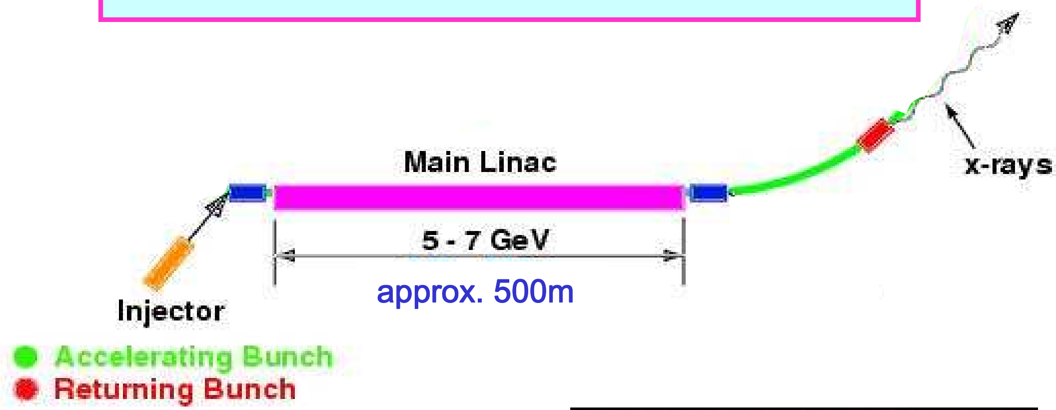
Overview

- Principle and history of ERLs
- How good of an X-ray source could an ERL be?
- What could it do?
- What remains challenging and what challenges are being addressed?

Principle of an X-ray ERL

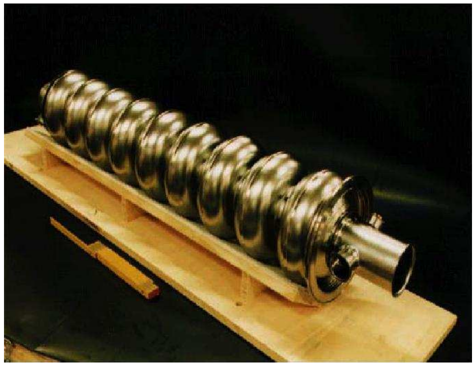
X-ray analysis with highest resolution in space and time:

5GV*100mA = 0.5GW
(good size power plant)



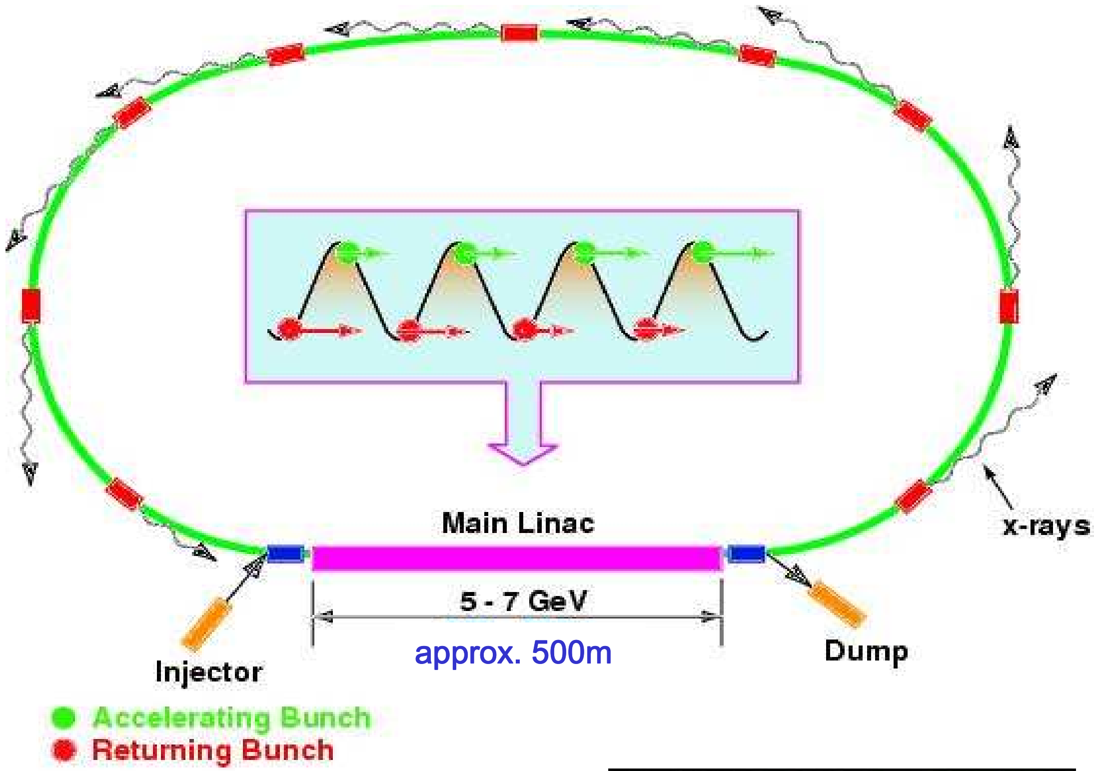
Challenges:

- Low emittance, high current creation
- Emittance preservation
- Beam stability at insertion devices
- Accelerator design
- Component properties, e.g. SRF



Principle of an X-ray ERL

X-ray analysis with highest resolution in space and time:



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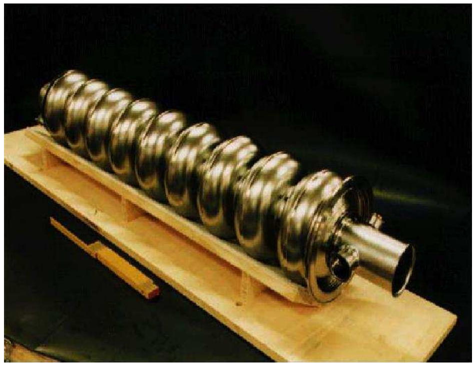
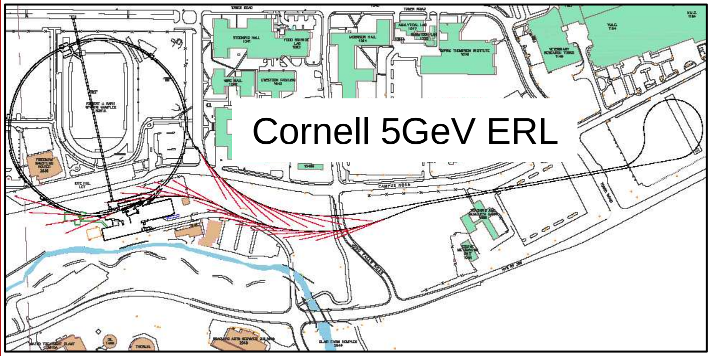
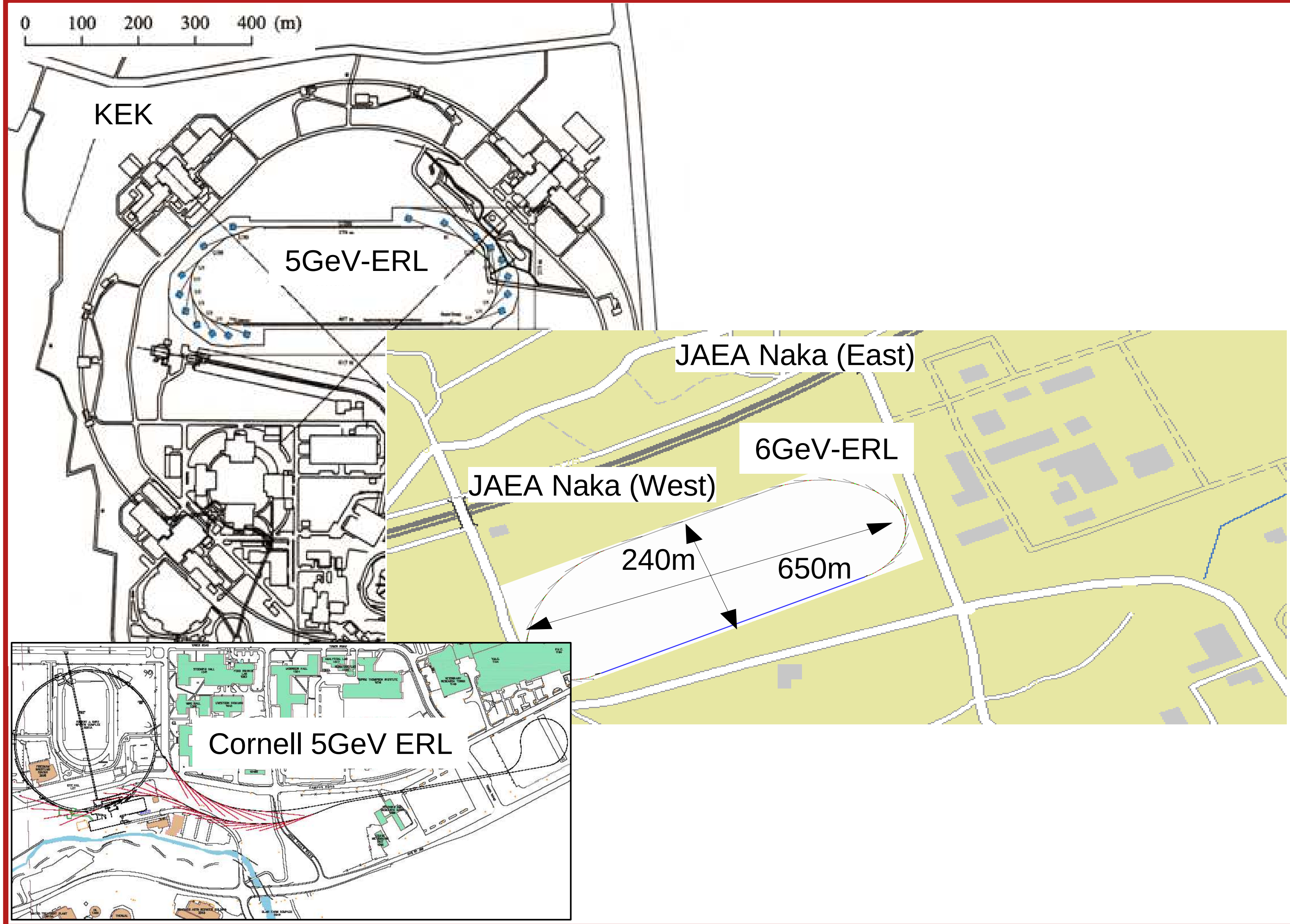


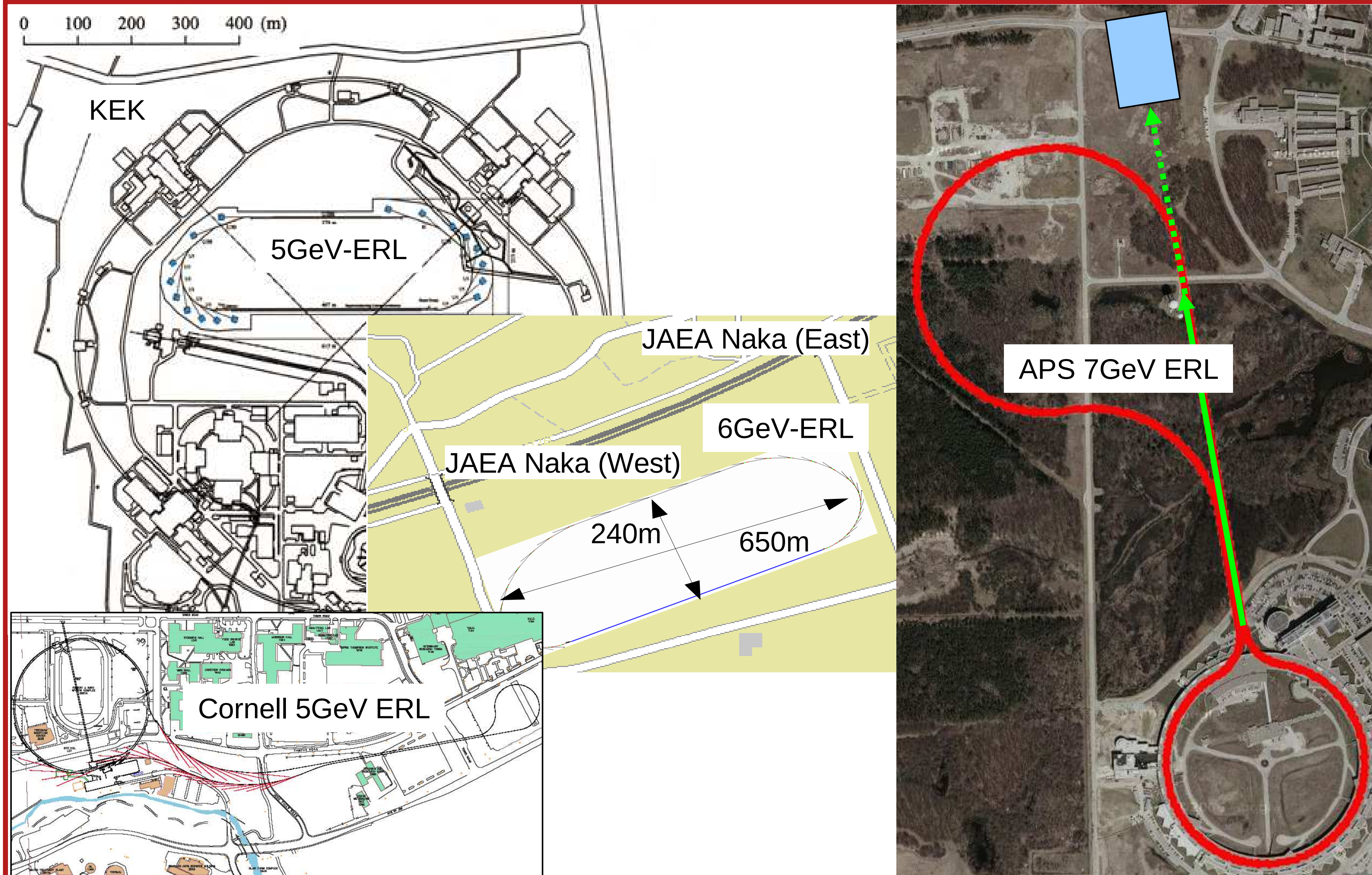
Cornell ERL



Cornell / KEK / JAEA ERLs



Cornell / KEK / JAEA / APS ERLs

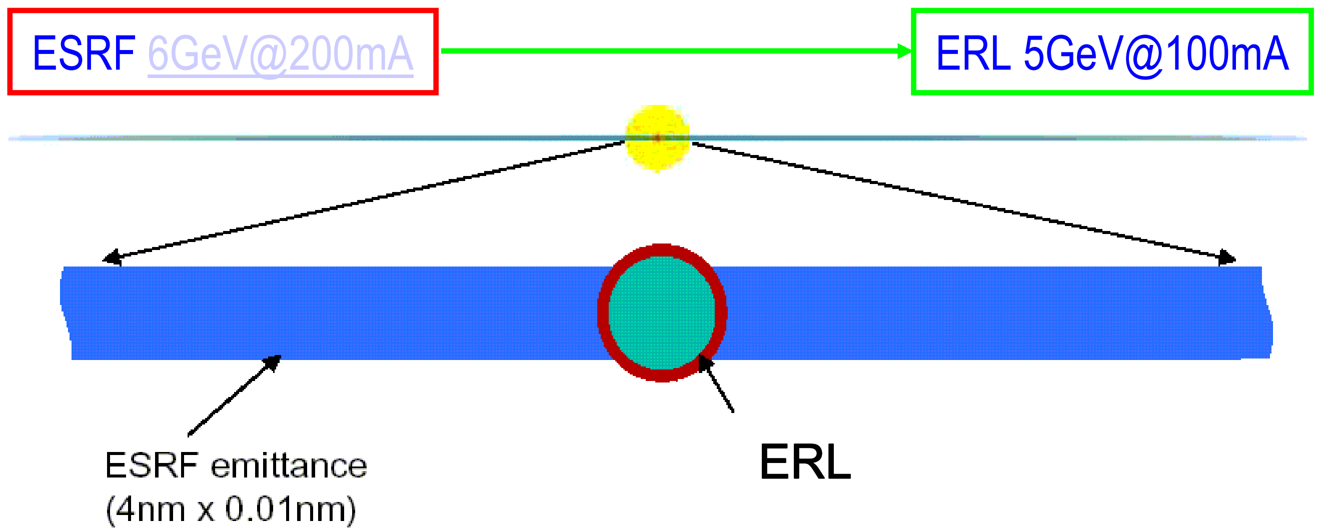


The injector: goals for the ERL

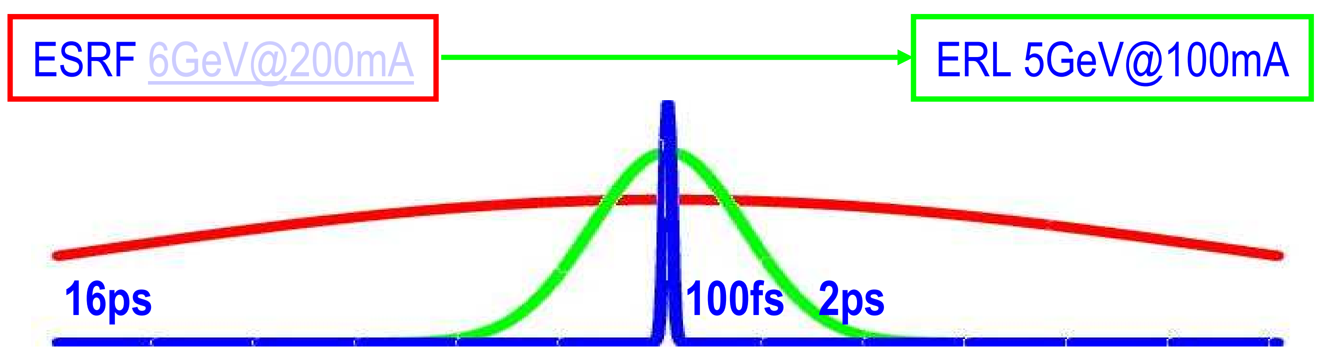
	Energy recovered modes			One pass	
Modes:	(A) Flux	(B) Coherence	(C) Short-Pulse	(D) High charge	Units
Energy	5	5	5	2.5	GeV
Current	100	25	100	0.1	mA
Bunch charge	77	19	77	1000	pC
Repetition rate	1300	1300	1300	0.1	MHz
Norm. emittance	0.3	0.08	1	5.0	mm mrad
Geom. emittance	31	8.2	103	1022	pm
Rms bunch length	2000	2000	100	50	fs
Relative energy spread	0.2	0.2	1	3	10^{-3}
Beam power	500	125	500	0.25	MW
Beam loss	< 1	< 1	< 1	<1	micro A

Advantages of ERL beams

Transverse emittance reduction:

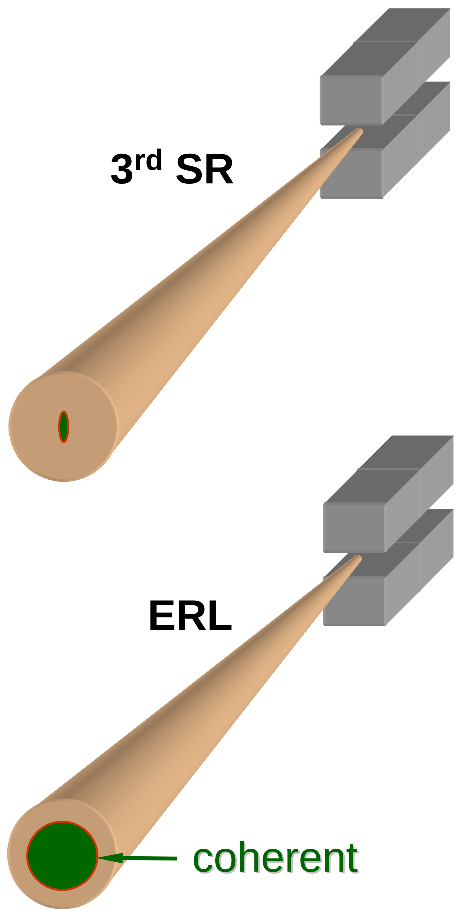


Bunch-length reduction:



Smaller Beams and more Coherence

- Coherent x-ray diffraction imaging
- It would, in principle, allow atomic resolution imaging on non-crystalline materials.
- This type of experiments is completely limited by coherent flux.



Factor 100 more coherent flux for ERL for same x-rays, or provide coherence for harder x-rays

How large is the advantage of ERLs ?

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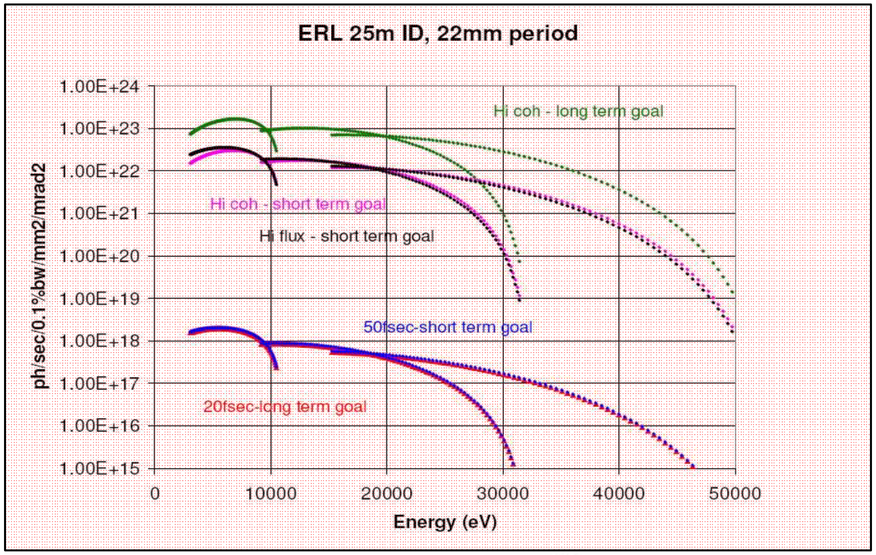
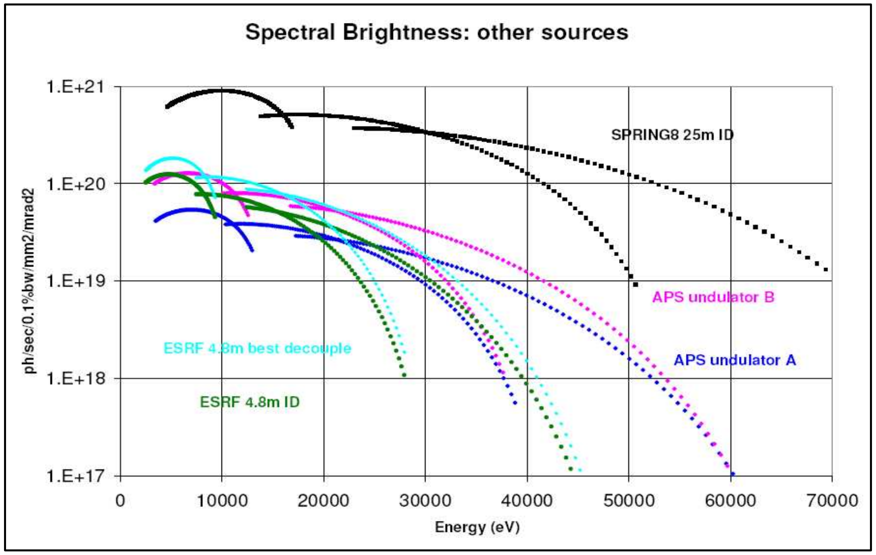
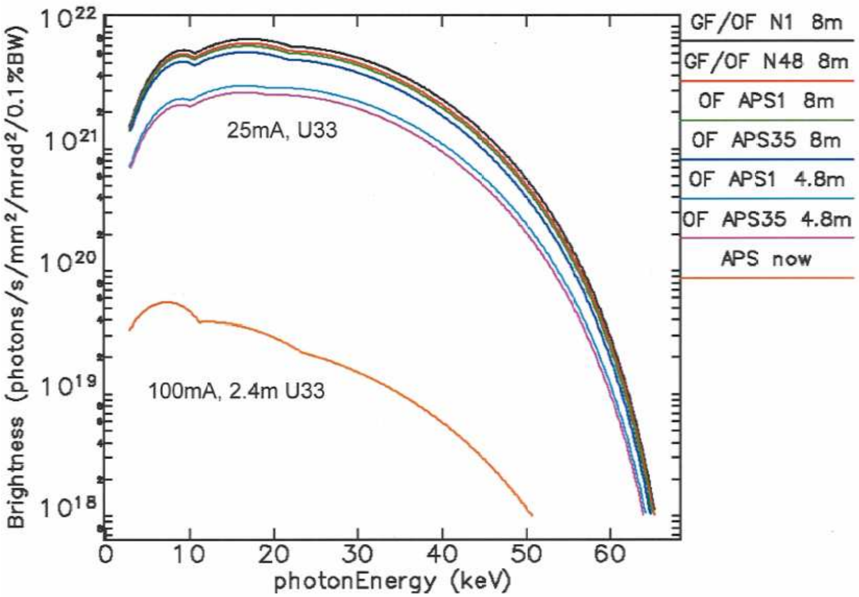


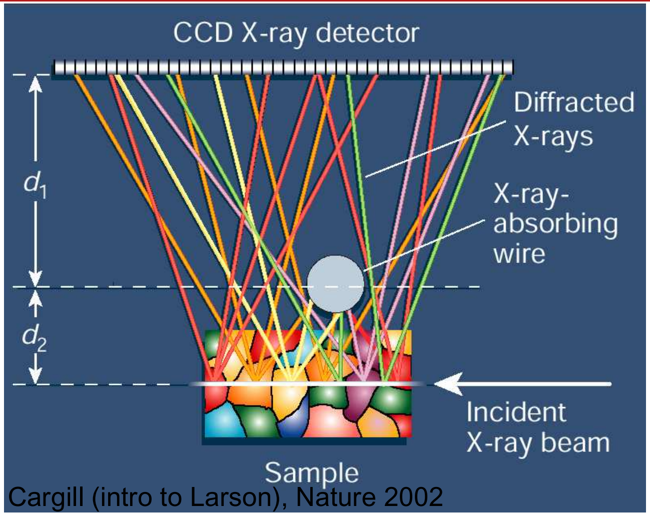




ERL workshops on areas of opportunity

1	nanoprobe	spot $\leq$ 1nm
2	timing experiments	$\tau\sim$ 1 ps flexible pulse structure
3	hard x-ray coherent scattering (XPCS)	diffraction limited at 10KeV
4	soft x-ray coherent scattering	
5	high energy scattering	E >> 10 KeV (Compton, PDF)
6	coherent imaging	

Microprobe: higher resolution from narrower x-ray beams

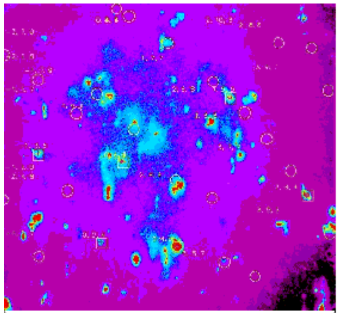


Cargill (intro to Larson), Nature 2002

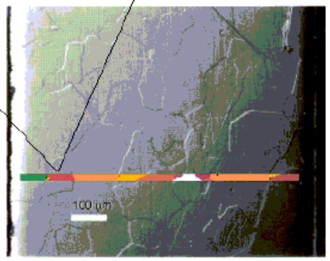
Differential-Aperture X-ray Microscopy (DAXM)

- Smaller beams lead to better spatial resolution (currently sub μm)

ERL: smaller area



Orientation of crystals and Stress and strain in crystals



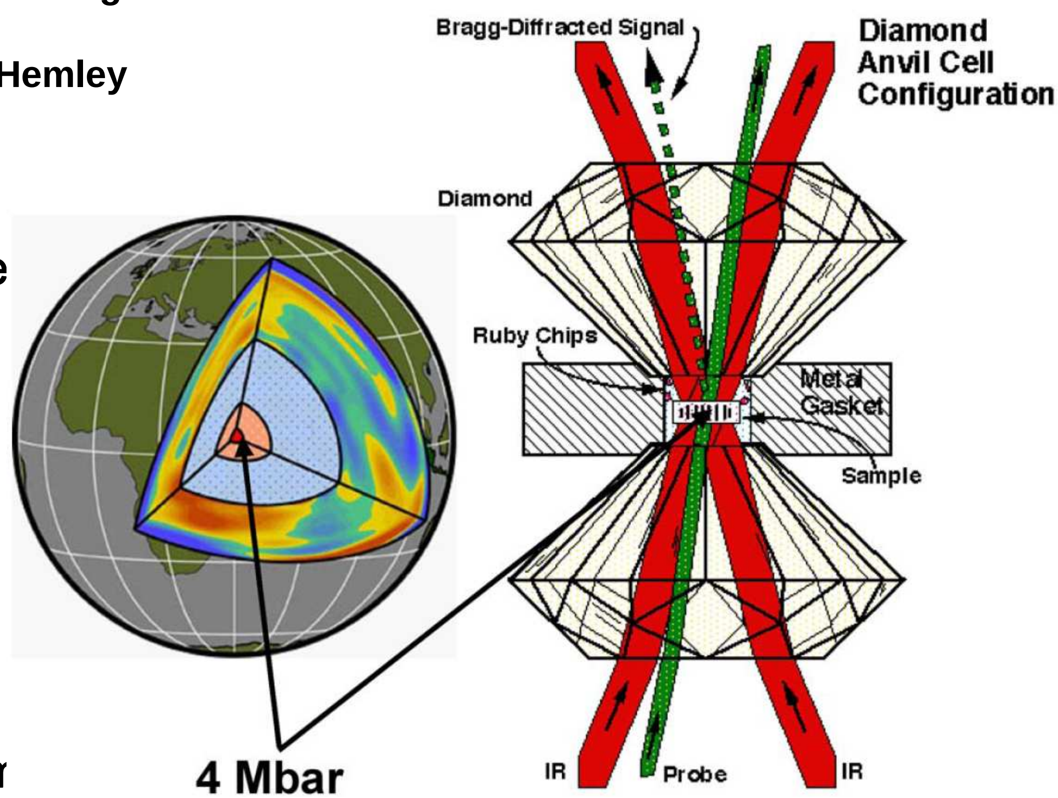
Ben Larson (2000), ERL science workshop, Cornelll

3-D Studies of Structure

High pressure: more flux through a small probe

High Pressure: Materials, Engineering, Geological and Space Sciences.
J. B. Parise, H.- K. Mao, and R. Hemley
at ERL Workshop (2000)

- HP experiments for μm sample are brightness-limited. Time resolved experiments for plasticity, rheology measurements, phase transitions, etc. are especially photon starved.
- Higher P ⇒ smaller samples.
- No ideal pressurization medium ⇒ need to scan sample.
- Peak-to-background critical.
- ERL will greatly extend pressures and samples that can be studied.



Parise, Hemley & Mao

High pressure in carbon nanotubes

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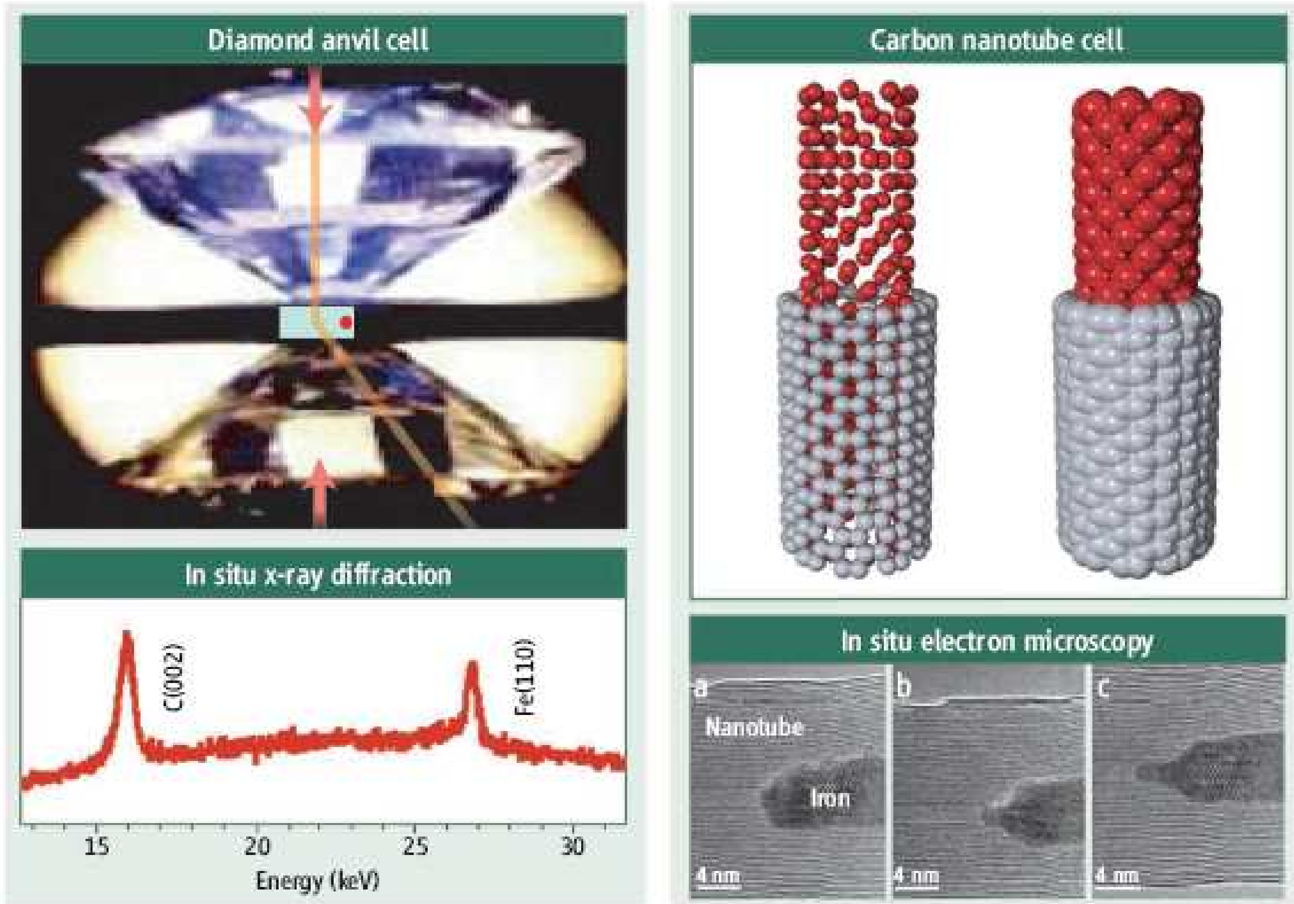
Up to 1600GPa with multi-wall nanotubes.

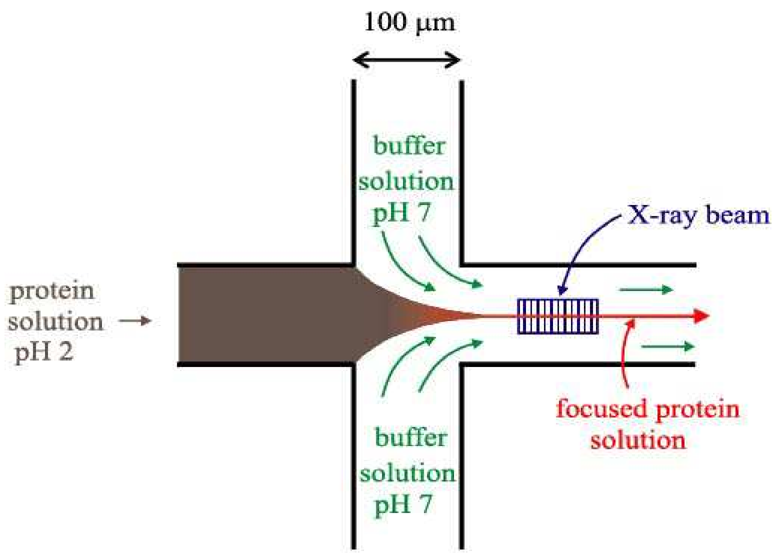


A matter of scale. **(Left)** A transparent diamond anvil cell allows in situ spectroscopic measurements of bulk samples. The red arrow represents an x-ray beam that is diffracted by the sample. **(Right)** A carbon nanotube self-compression cell enables in situ atomic-resolution snapshots at zero (a), intermediate (b), and high (~40 GPa) (c) pressure.

Wang &Zhao, *Science*, **312** (2006) 1149; Sun et al., *Science*, **312** (2006) 1199.

Bio and polymer science: more flux through thin sheet probes

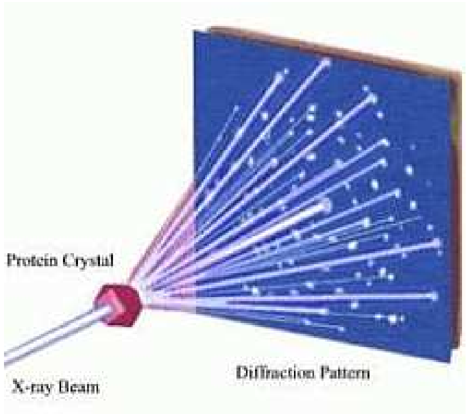
- **Examples: folding/unfolding of proteins & RNA; assembly of fibers; polymer collapse upon solvent changes; conformational changes upon ligand binding; monomer/multimer association.**
- **Microfabricated laminar flow cells access microsecond equilibration mixing times.**
- **Data acquisition entirely limited by source brilliance. The ERL will extend time scales from present milliseconds to microseconds.**

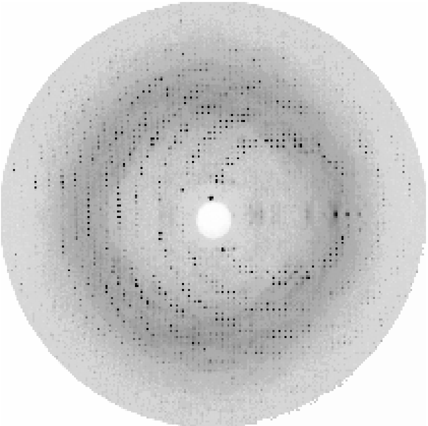


Thanks to Lois Pollack

Cornell Univ.

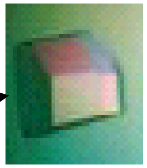
Coherent beams from ERLs





ERL enables new crystallographic method

1. Obtaining good crystals is rate limiting. Easier to obtain microcrystals. Radiation limits crystals to >~(20μm)^3.
2. Single image sufficient to determine orientation matrix.
3. Plate microcrystals in random orientations onto ultrathin film support.
4. Scan film w/microbeam, recording diffraction images.
5. ERL microbeam intensity and low divergence allows this to be done with micron-sized crystals.



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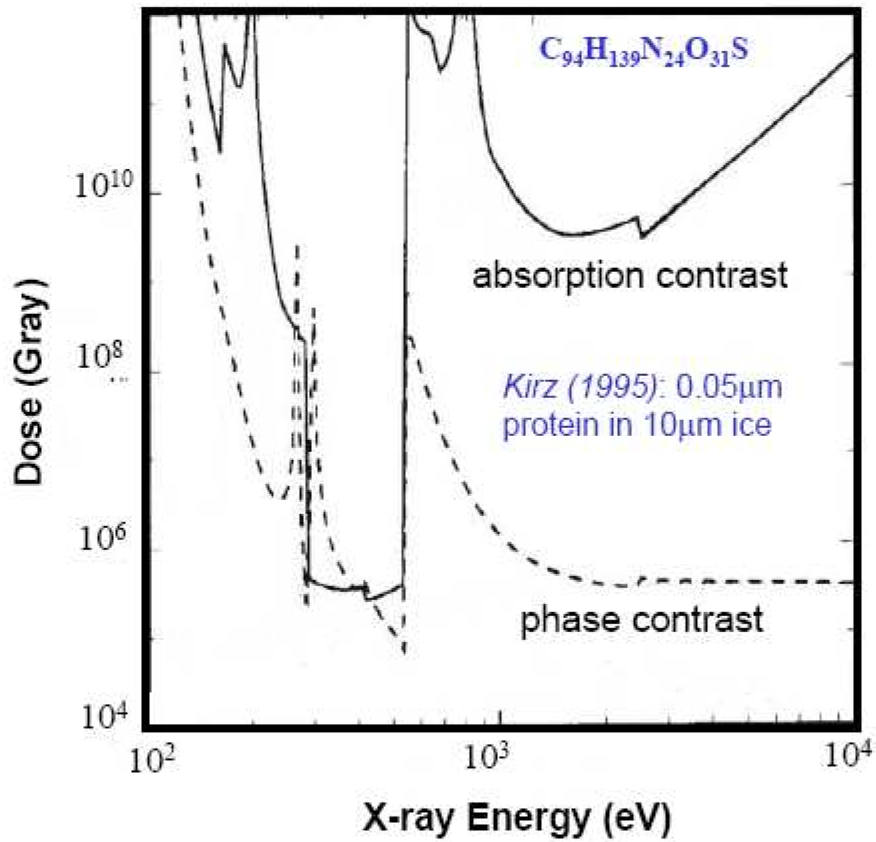
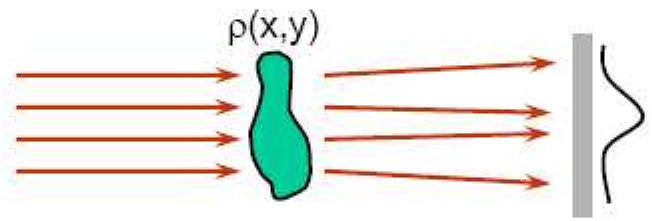
Coherent beams from ERLs





Refraction index: $n = 1 - \delta - i\beta$

- Phase contrast is 10^4 - 10^6 higher than absorption contrast for protein in water at hard x-rays energies
- Required dose is reduced with phase contrast

In general, phase contrast requires more coherent x-ray beams

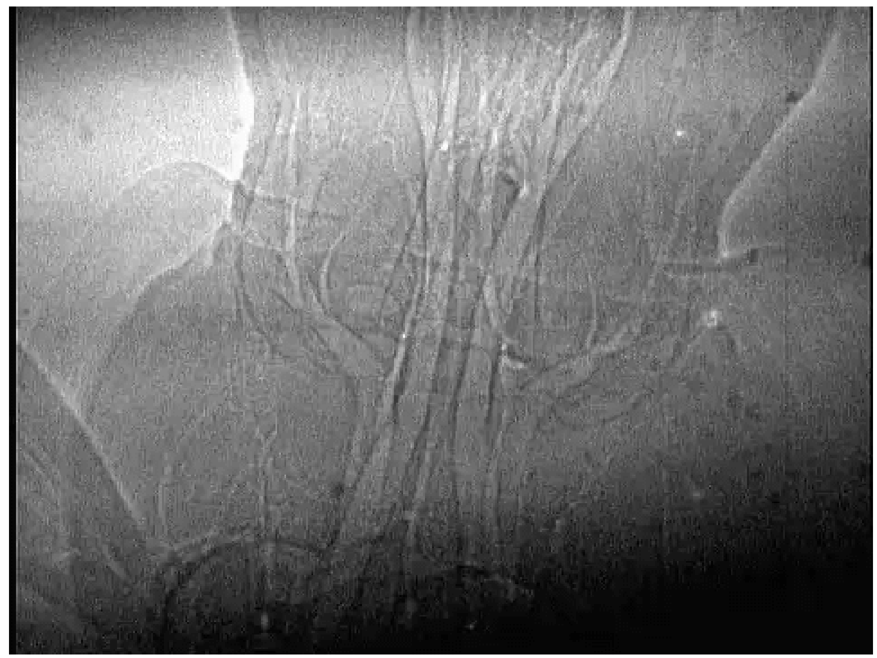
Real-time insect breathing

Tracheal Respiration in Insects Visualized with Synchrotron X-ray Imaging

Mark W. Westneat,*[1] Oliver Betz,[1,2] Richard W. Blob,[1,3]
Kamel Fezzaa,[4] W. James Cooper,[1,5] Wah-Keat Lee[4]
Field museum of Chicago & APS, Argonne National Lab.

Science (2003) 299, 598-599.

- Animal functions
- Biomechanics
- Internal movements
- New findings



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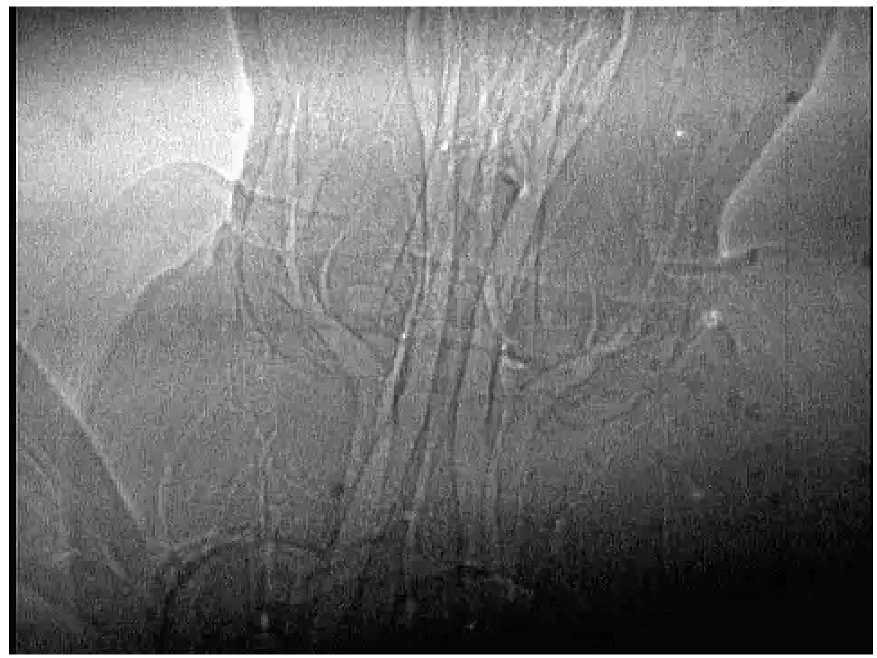
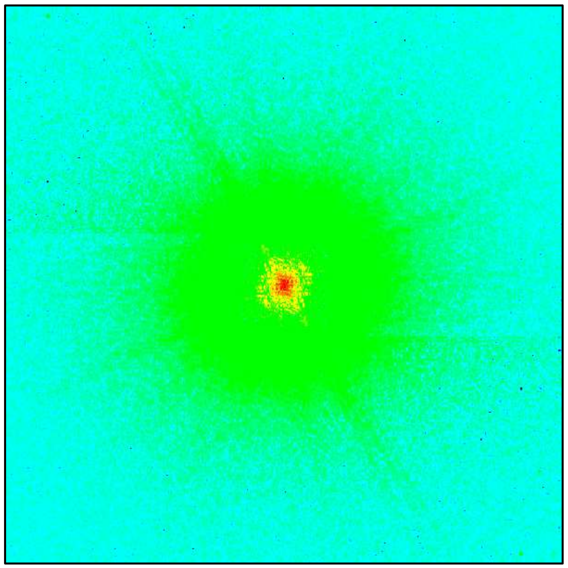
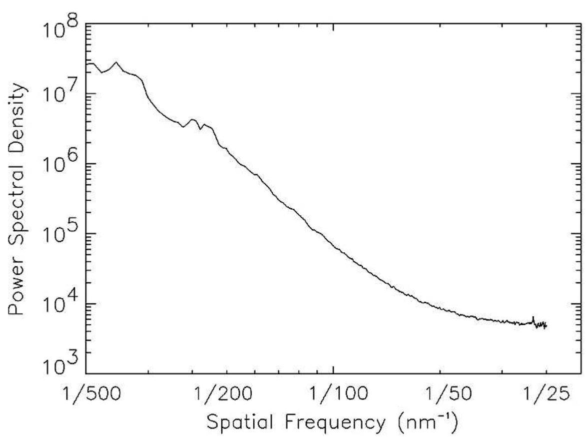


- ERL would extend these studies to much higher lateral resolution (sub µm) and faster time scales

Coherent imaging





Miao et al., *Proc. Nat. Acad. Sci.* (2003)

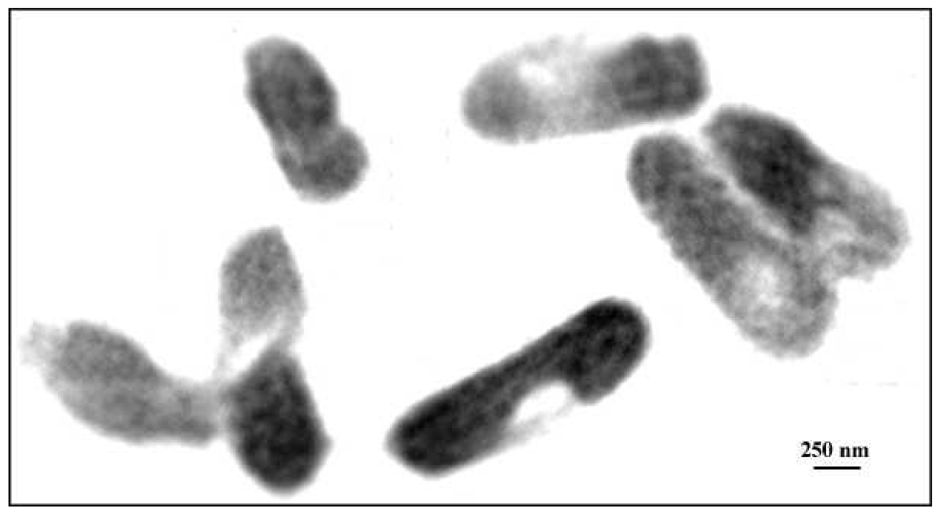
E. Coli bacteria ~ 0.5 μm by 2 μm

Labeled with maganese oxide

SPring-8, λ = 2 Å, pinhole 20 μm

Total dose to specimen ~ 8×10^6 Gray

Diffraction image to ~30nm resolution

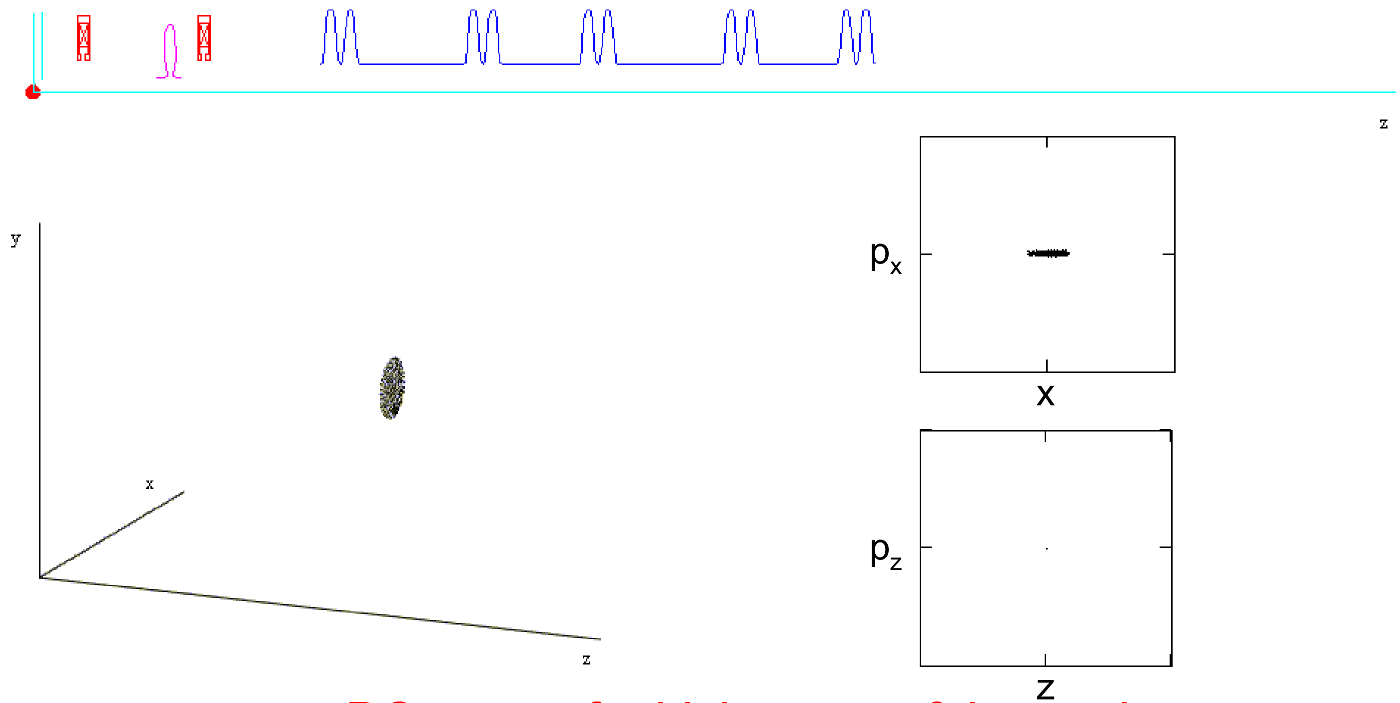


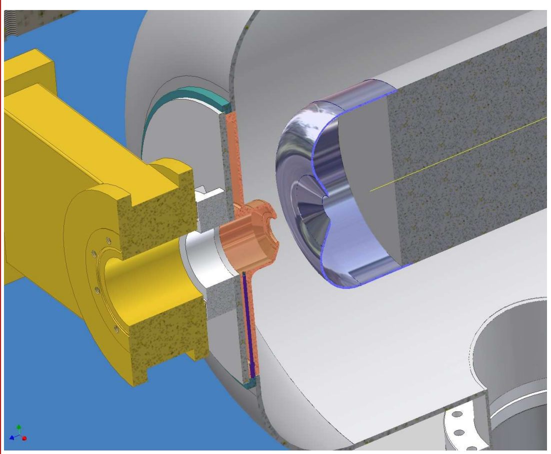
ERL workshops on areas of opportunity

- Do we understand the makeup of the Earth and planets?
- How does life behave at the bottom of the ocean?
- Can we meet the challenges of the energy crisis?
- Can we improve polycrystalline materials?
- How do macromolecules (proteins) behave in solution?
- Can we find he structure of life?
- Do we understand the glass transition?

•Can we see structural changes on the ps timescale?

The injector: round beam optimization





DC source for high current & low emittances

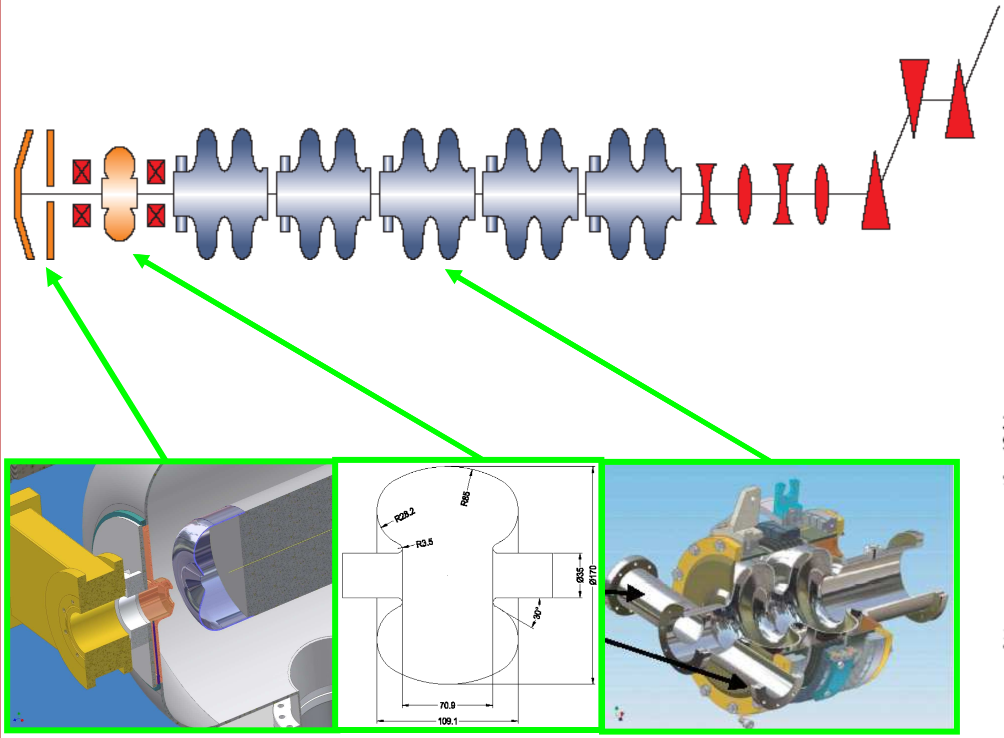
- Simulations show 10 times smaller emittances than previously thought possible, and 50 times smaller than standard.
- Gun development, coating for low field emission
- Photocathode development, neg. el. affinity GaAs, cooled
- Laser beam shaping

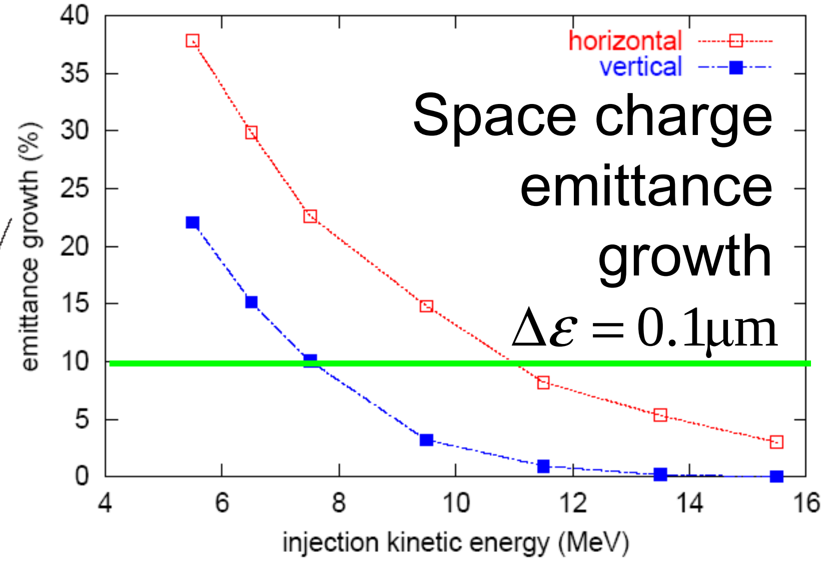
The injector optimization

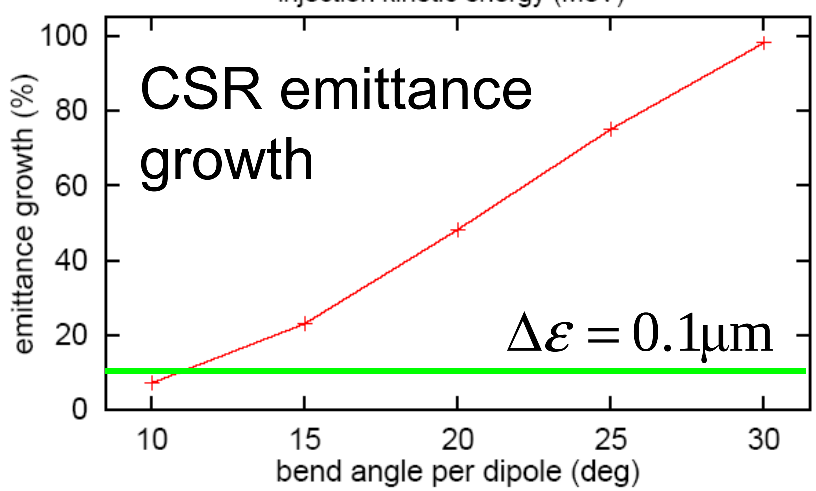
HIGH BRIGHTNESS, HIGH CURRENT INJECTOR DESIGN FOR THE CORNELL ERL PROTOTYPE*

2003 Particle Accelerator Conference

I.V. Bazarov† and C.K. Sinclair







(1) Challenges for x-ray ERLs

- **Production of low emittances + limiting emittance growth**
  - **Optics in the linac for very different energies (0.01 - 5GeV)**
  - **Limit coupler kicks / cavity misalignments**
  - **Limit optics errors and adjust fields to radiated energy**
  - **Low emittance growth optics similar to light sources**

Cornell Injector prototype:
Verification of beam production

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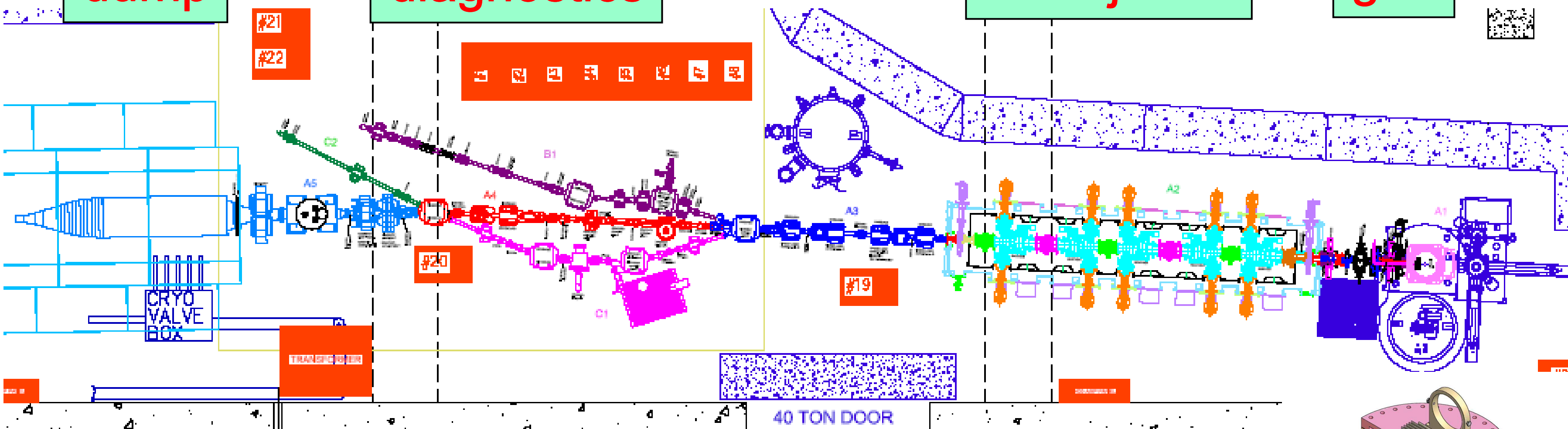
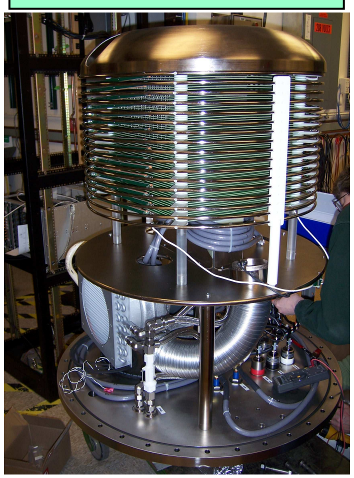
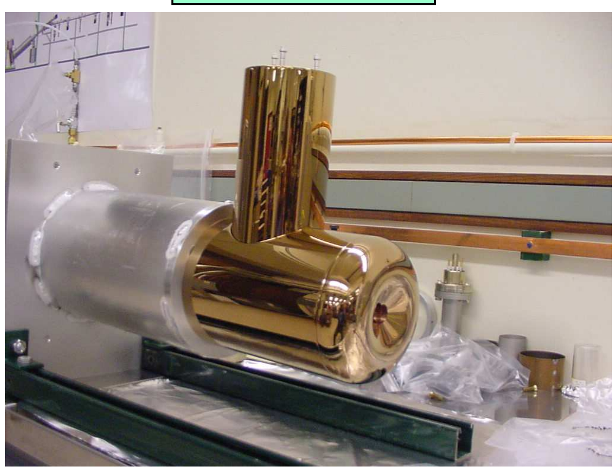
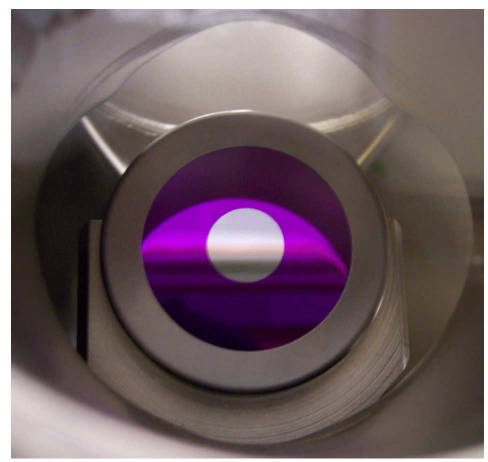
dump | diagnostics | SC injector | gun

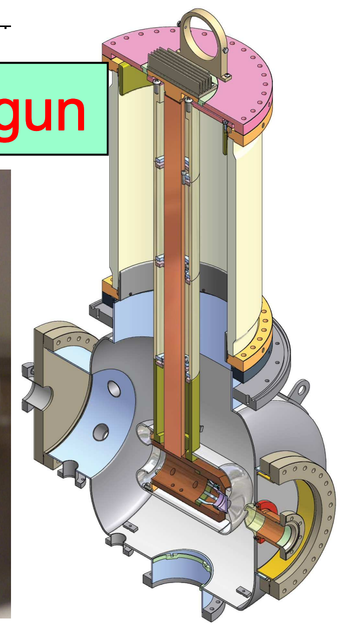


Power sup. | Cathode | Photo emitter | gun

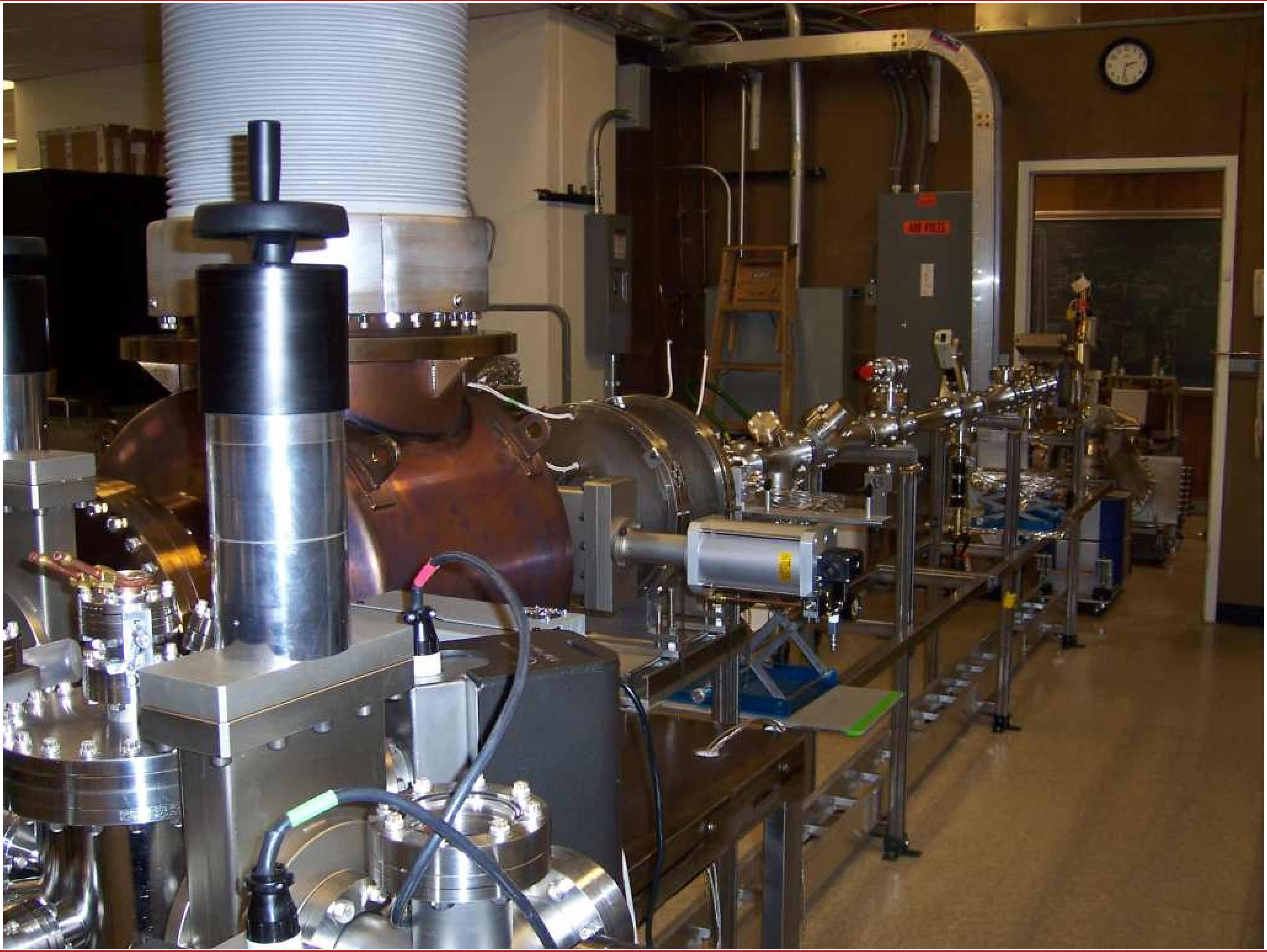




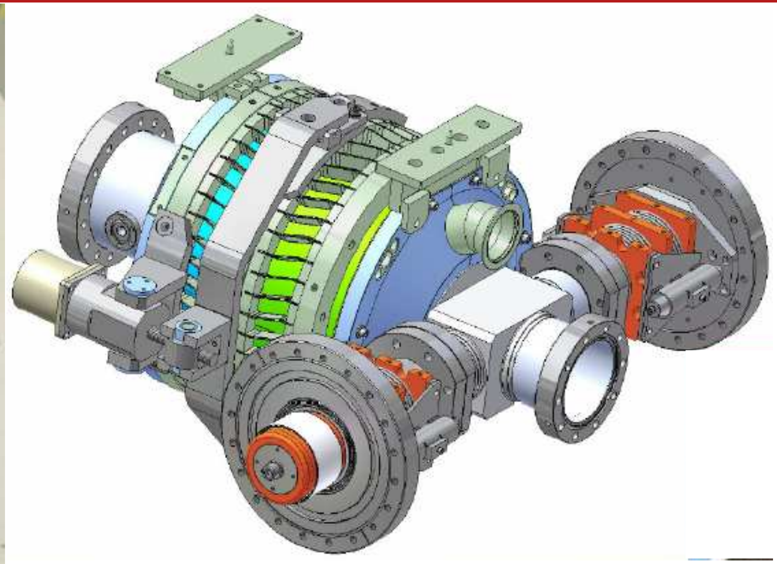




Gun prototype: well advanced

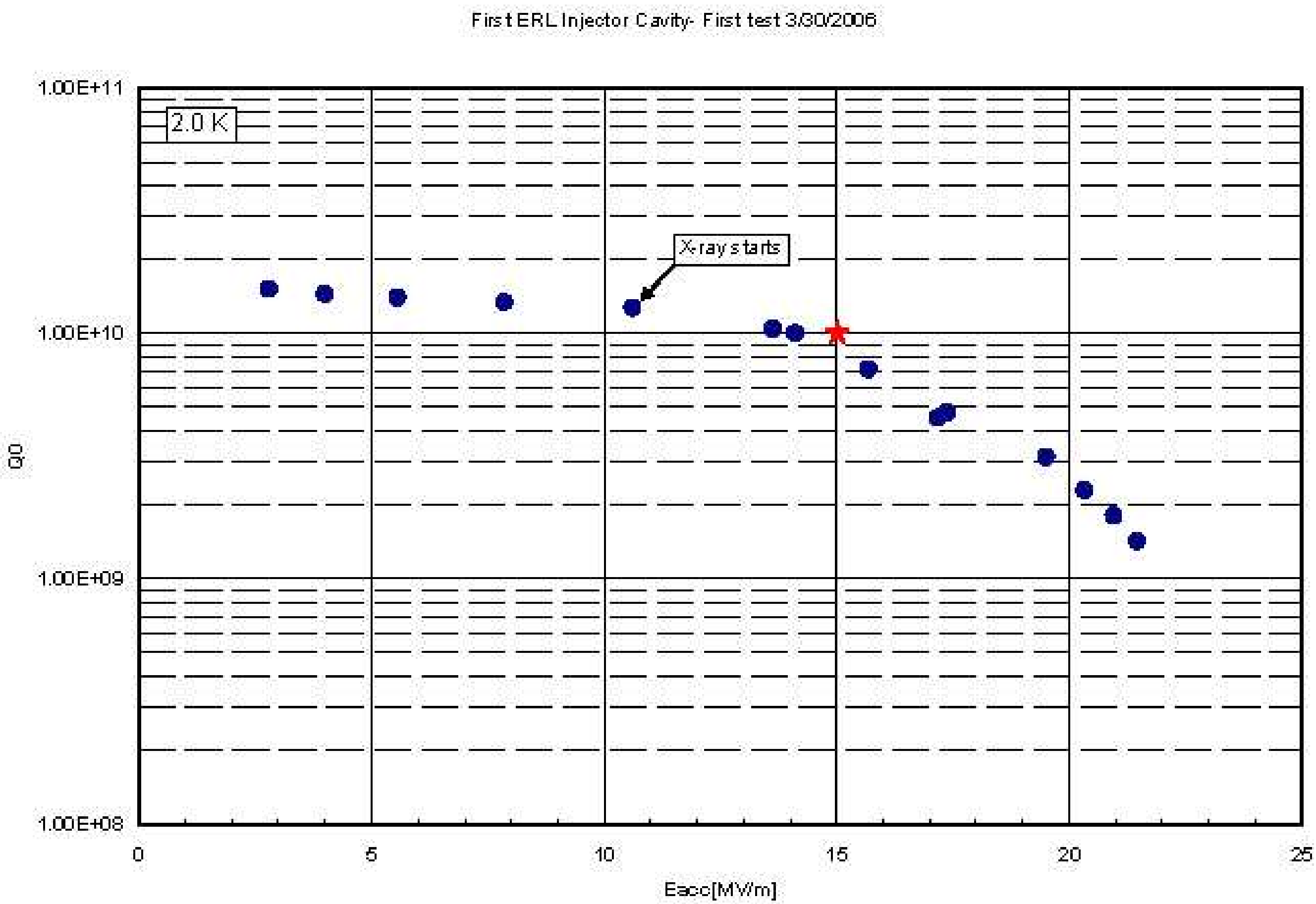


ERL accelerator R&D and construction

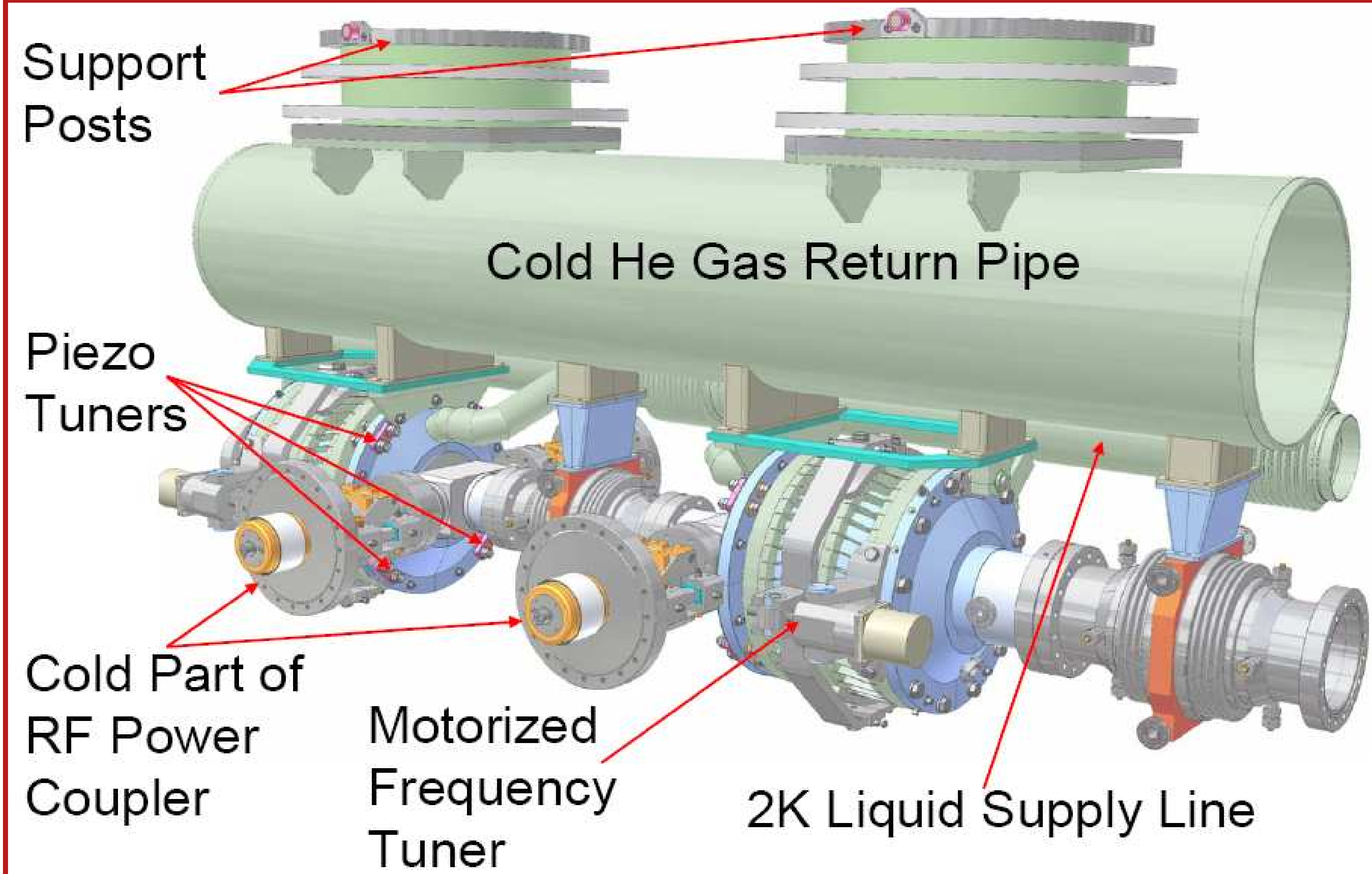


Superconducting Cavities, high power input coupler, and high precision frequency tuners are all developed and build at Cornell (with outside collaborators)

First vertical test



Assembly of the injector accelerator



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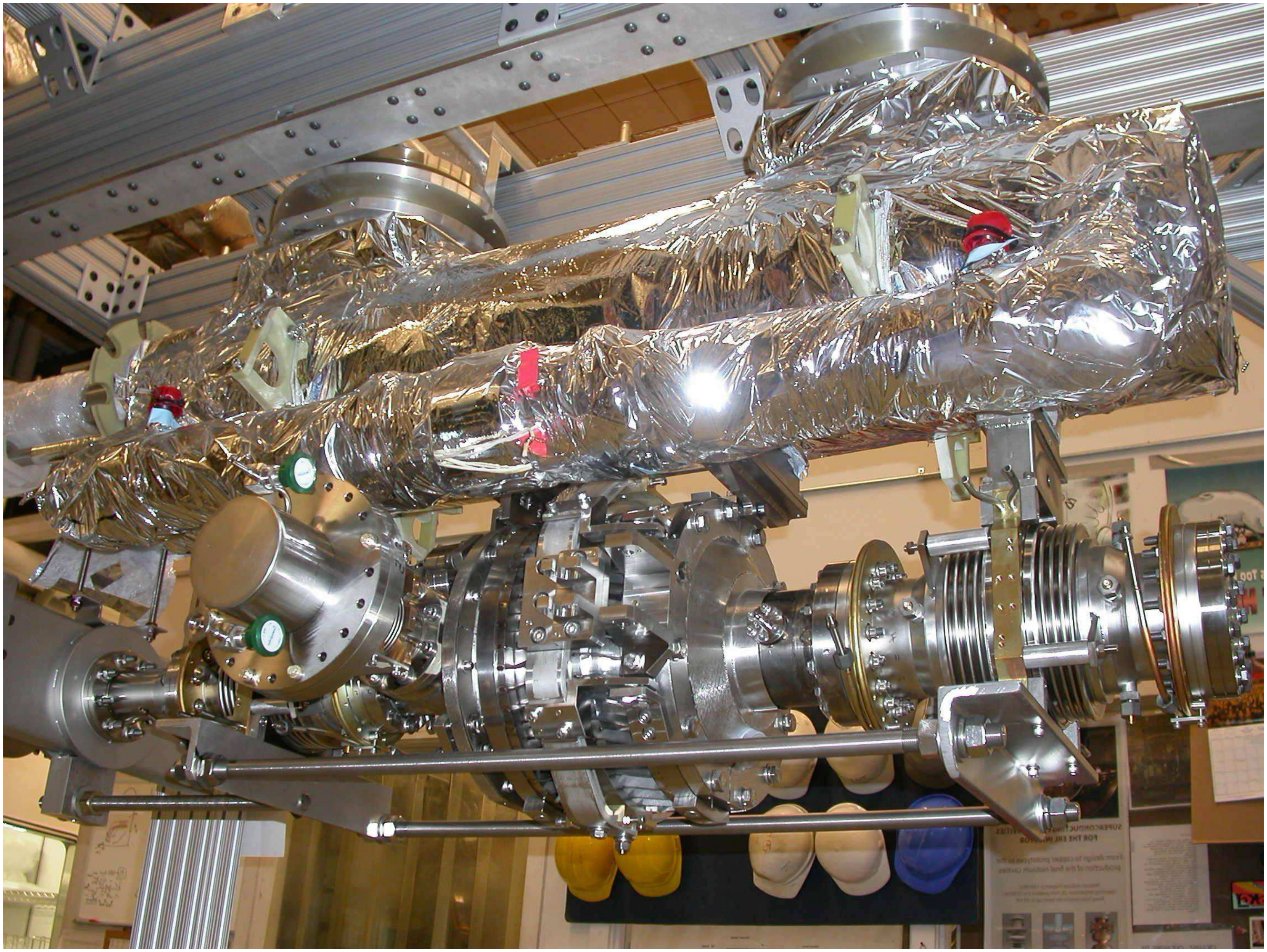
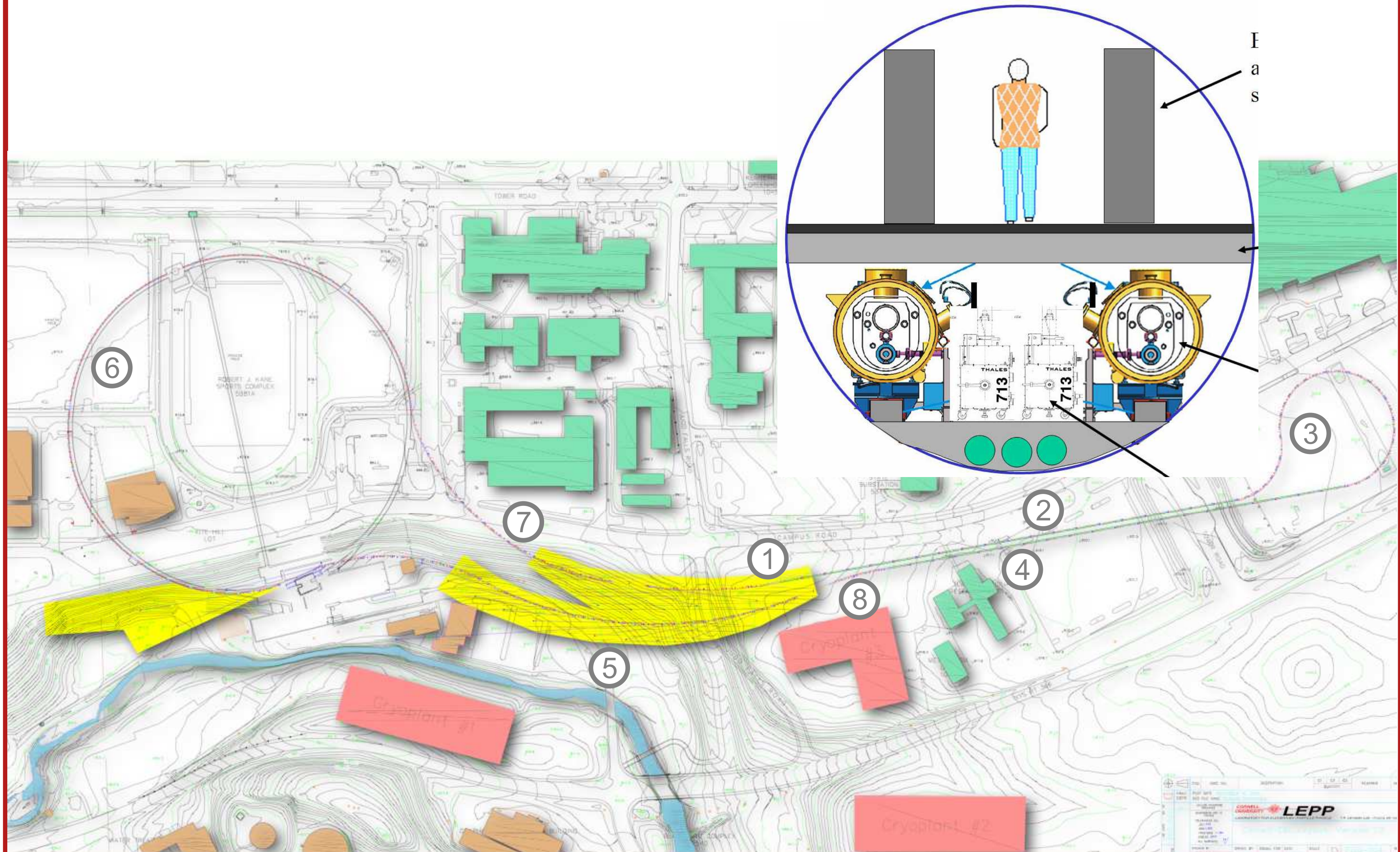


List of desired x-ray beamlines

5 GeV ERL: table of beamlines — last changes: Sept. 04, 2006 by GH

#	Function	Application	ID	L(m)	β(m)	Mode	beam	E range	BL length
1	Inelastic Scattering	meV resolution	U	25	12	"		$20<E_g(KeV)<30$	70m
2	Diagnostic beamline	machine diagnostics	U	2.5	2.5	all modes	pink, mono	"	70m
3	Protein crystallography III	micro-focus	U	2.5	1.25	"	"	"	70m
4	Nanoprobe	1 nanometer beams	U*	2.5	0.5	Hi-Coh		1<E*(Kev)<10	70m
5	microscope, nanoprobe	TXM, STXM	U	2.5	0.5	"	"	"	70m
6	phase contrast, topography	biomed, matscience	U	2.5	0.5	Hi Coh	mono	<25KeV	200m
7	coherent diffraction, XPCS	microscopy, dynamics		U	25	5.0	pink, mono	<25KeV	80m
8	Protein crystallography II	MAD	U	5.0	1.0	"	"	"	70m
9	SoftX microscope	biomaterials	helU	5.0	2.5	Hi Flux	mono	<5KeV	70m
10	SoftX, XMCD, ARPES	mag/elect materials	helU	5.0	2.5	"	vari-polariz	<5KeV	70m
11	High Energy Scattering	PDF, Compton, etc	U	5.0	2.5	"	high K & n	>100KeV	80m
12	Protein crystallography I	high throughput	U	5.0	2.5	Hi-flux	tuneable	<25KeV	70m
13	Materials science I	high pressure	U	5.0	2.5	Hi-flux		20<E(KeV)<40	70m
14	Materials science II	general application	U	5.0	2.5	"		5<E(KeV)<30	70m
15	Materials science III	resonant el&inelastic	U	5.0	2.5	"	ΔE(eV)<1	<25KeV	70m
16	GSAXS, XPCS, SAXS	polymers, liquids	U	5.0	2.5	"	pink & 1%bw	"	70m
17	ASAXS, micro-SAXS	catalys	U	5.0	2.5	"	"	"	70m
18	Femtosecond science	pump-probe, etc	U	25	5	Ultra-fast	timing	<25KeV	70m

5GeV ERL extension to CESR



One pass, high charge mode (D)

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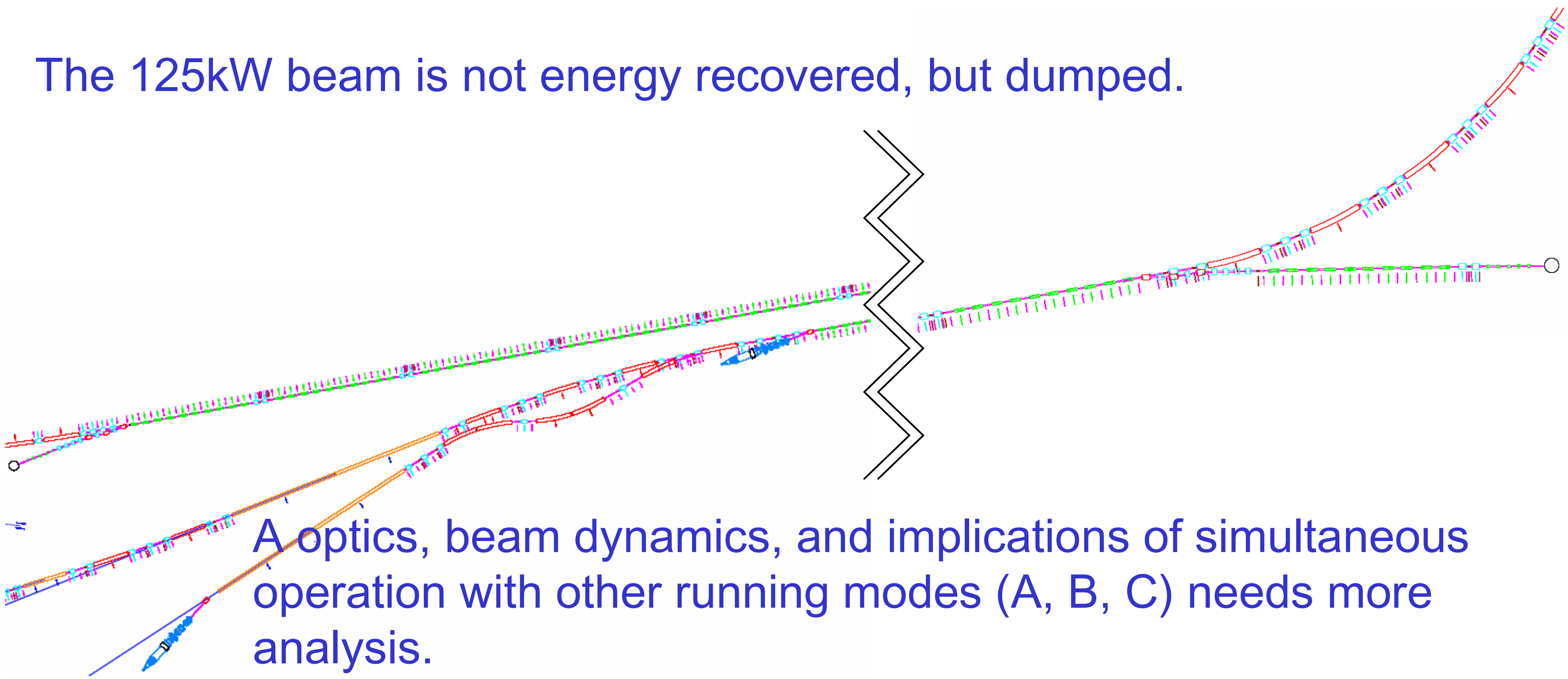
A separate injector linac injects into the second 2.5GeV linac at 100kHz with up to 1nC per bunch.

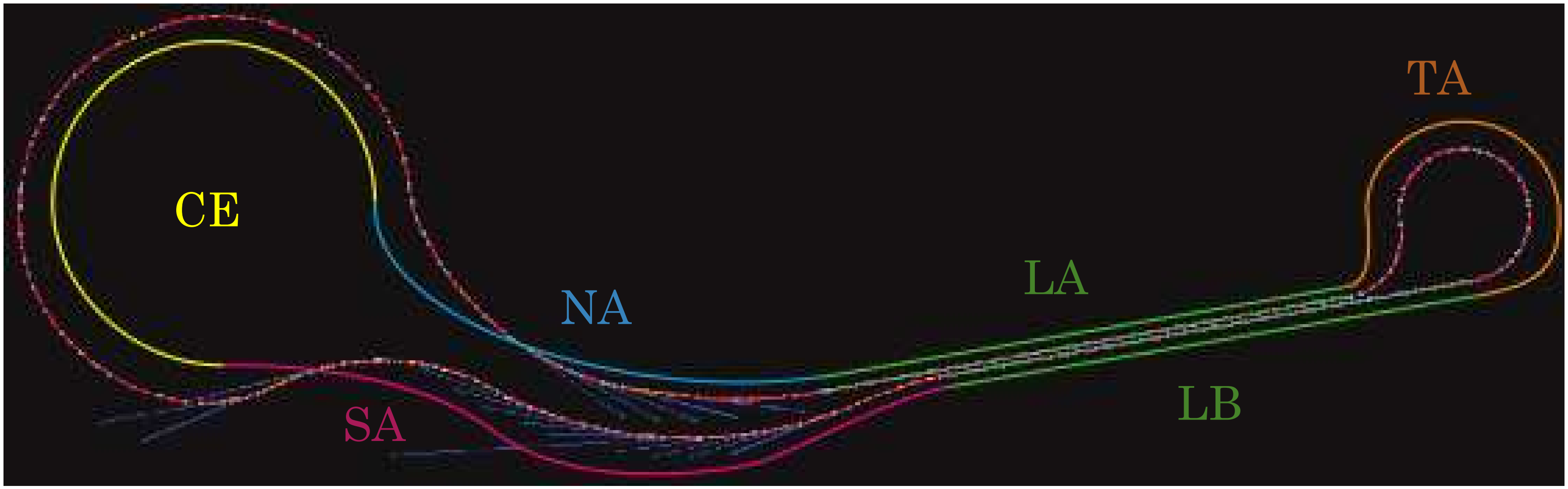
Two-stage bunch compression with 3rd-harmonic linearizer cavity at low energy produces bunches as short as 50fs.

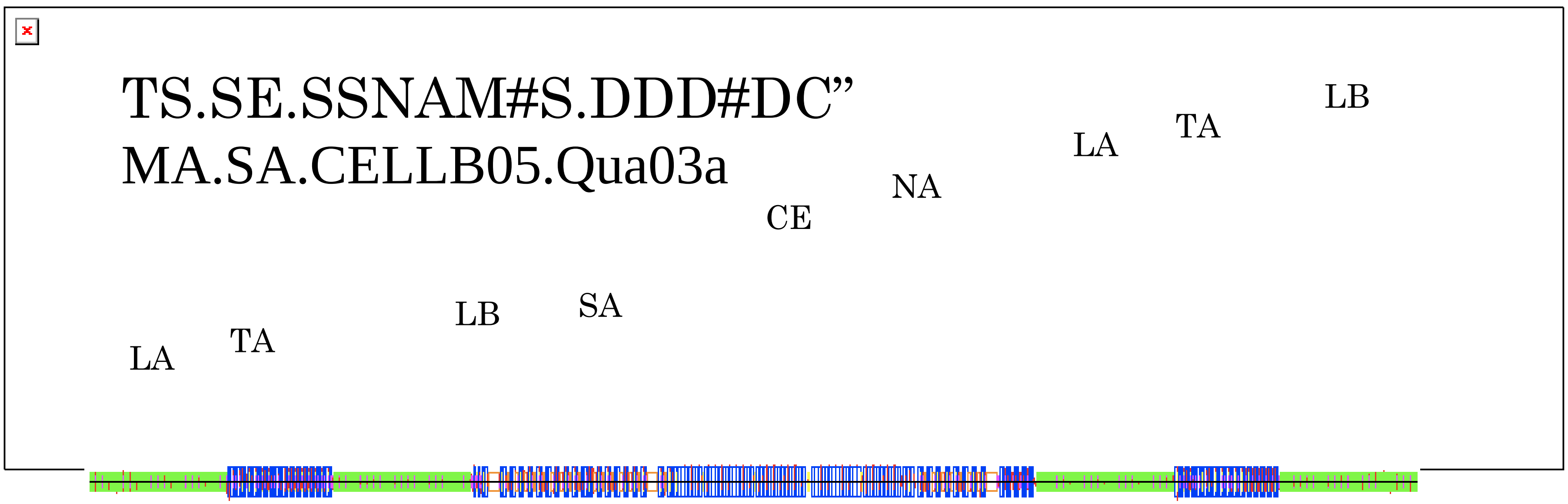
The 125kW beam is not energy recovered, but dumped.



A optics, beam dynamics, and implications of simultaneous operation with other running modes (A, B, C) needs more analysis.

Incoherent Synchrotron Radiation (ISR)

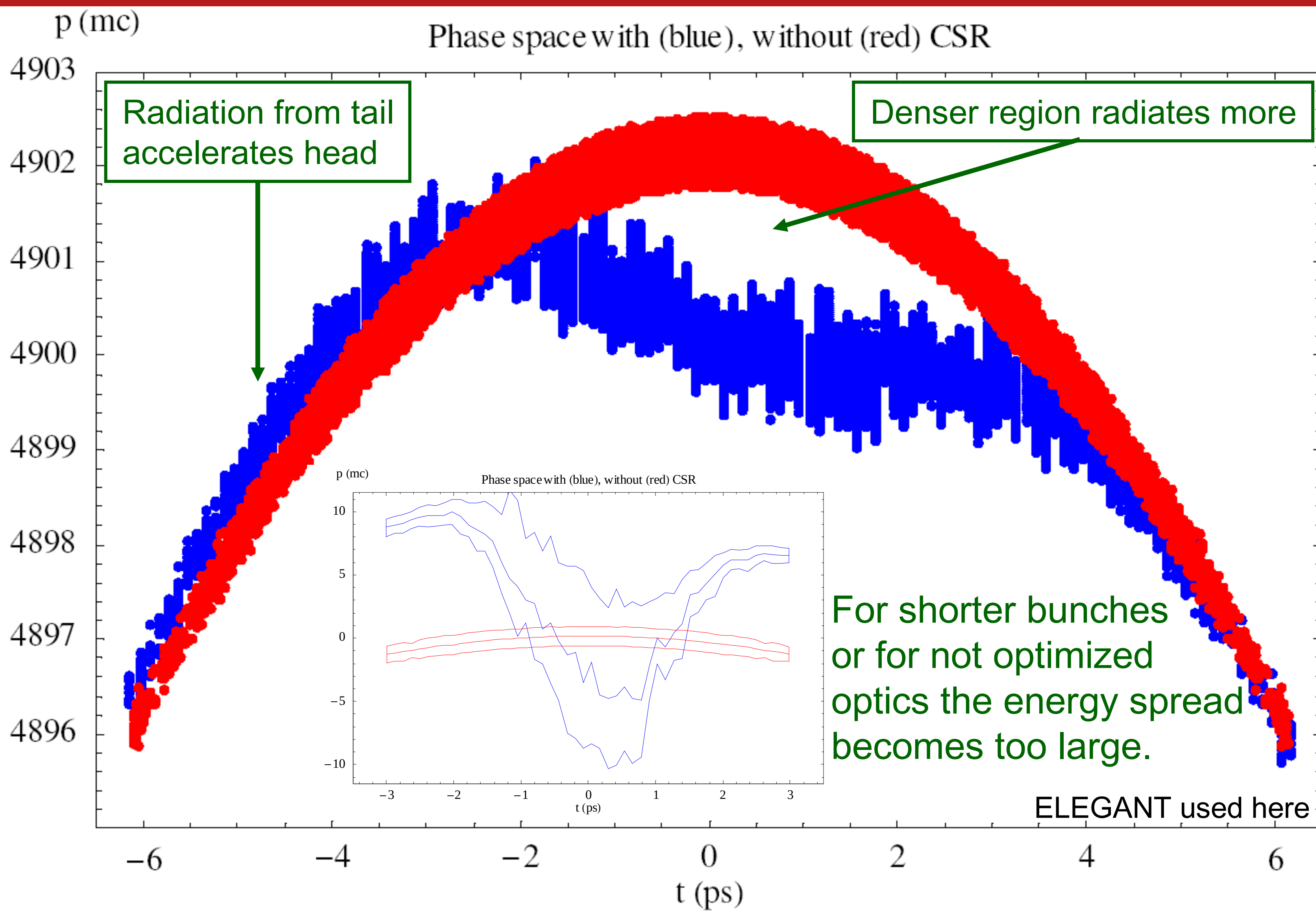




(2) Challenges for x-ray ERLs

- Limit energy spread after deceleration by a factor of 500
  - Accurate time of flight correction, including sextupoles
  - Limit energy spread from wake fields
  - Limit energy spread from intra beam scattering (IBS) and rest gas scattering
  - Limit energy spread from incoherent / coherent synchrotron radiation (ISR / CSR)

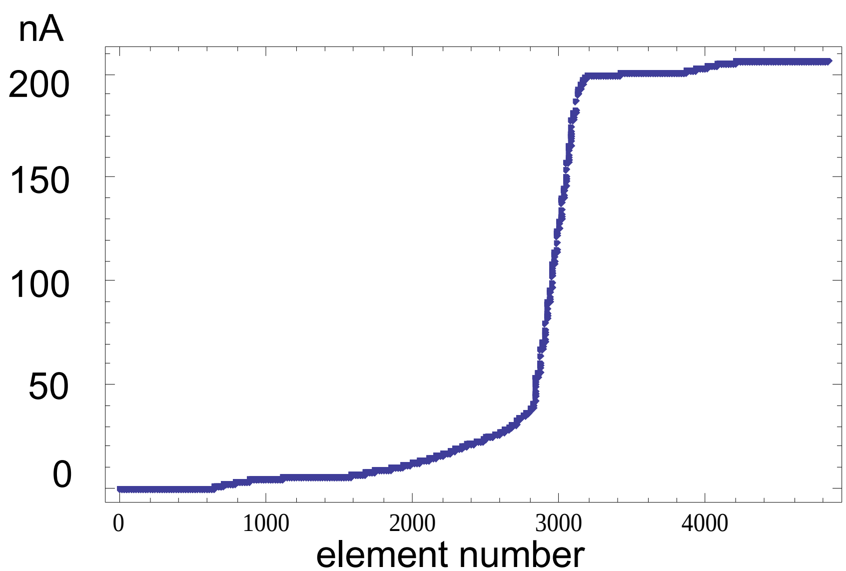
CSR in ERL bends

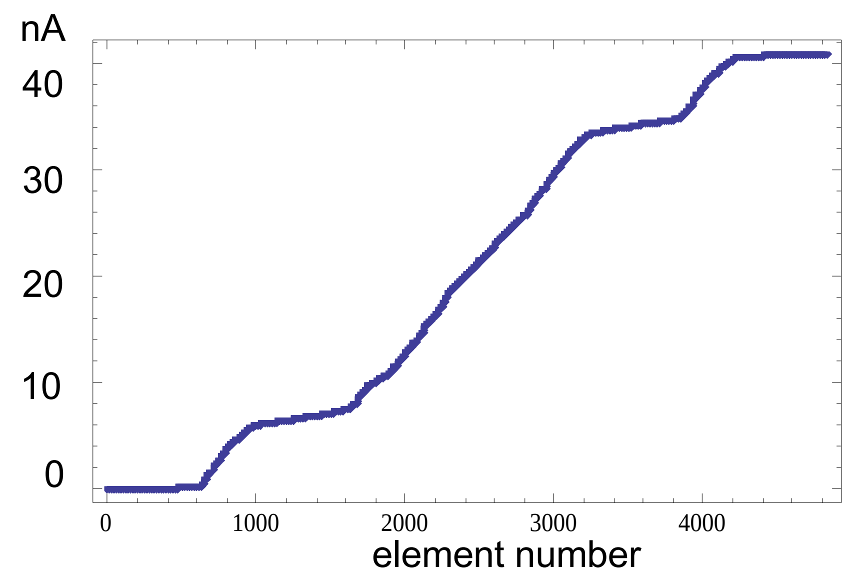


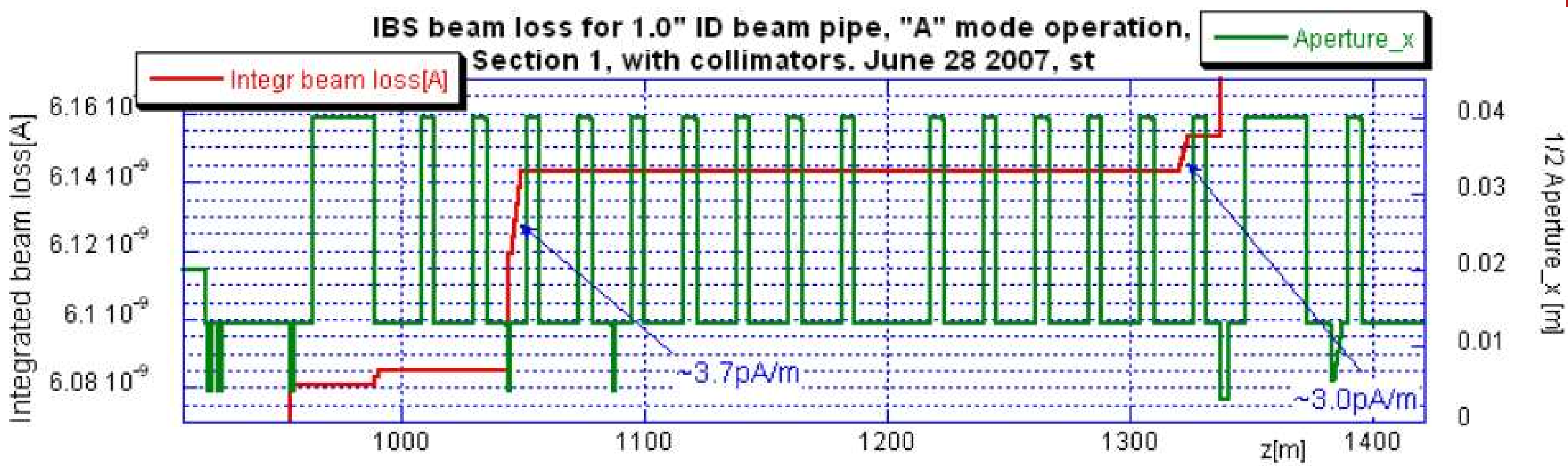
(3) Challenges for x-ray ERLs

- **Beam loss concerns**
  - **Beam loss from IBS / Tourschek**
  - **Rest gas scattering**
  - **Disturbance from ions / ion removal**
  - **Halo development**

Scattering and background: IBS

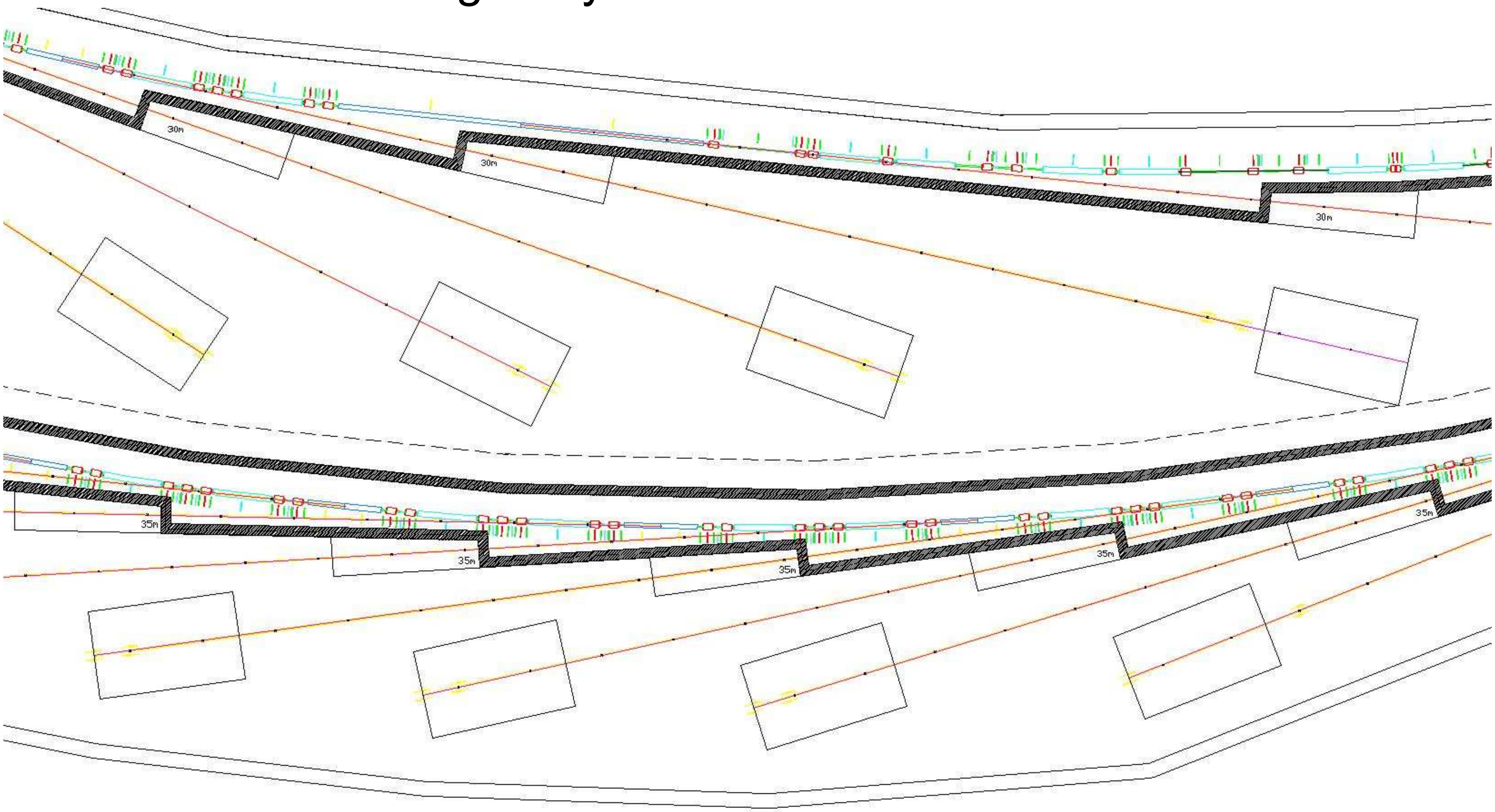






Shielding and x-ray optics

1st optics at 35m after center of undulator, outside shielding wall.
80m long x-ray beamlines.



Ion focusing

- Ion are quickly produced due to high beam density

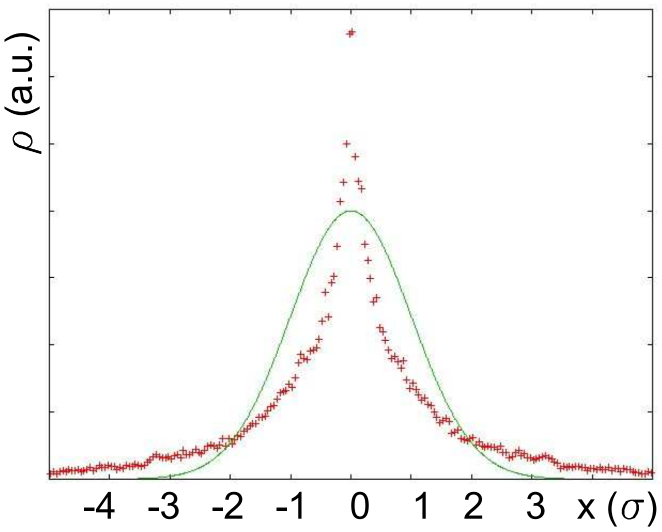
Ion	σ_{col}, 10MeV	σ_{col}, 5GeV	τ_{col}, 5GeV
H_2	$2.0 \cdot 10^{-23}\mathrm{m}^2$	$3.1 \cdot 10^{-23}\mathrm{m}^2$	5.6s
CO	$1.0 \cdot 10^{-22}\mathrm{m}^2$	$1.9 \cdot 10^{-22}\mathrm{m}^2$	92.7s
CH_4	$1.2 \cdot 10^{-22}\mathrm{m}^2$	$2.0 \cdot 10^{-22}\mathrm{m}^2$	85.2s

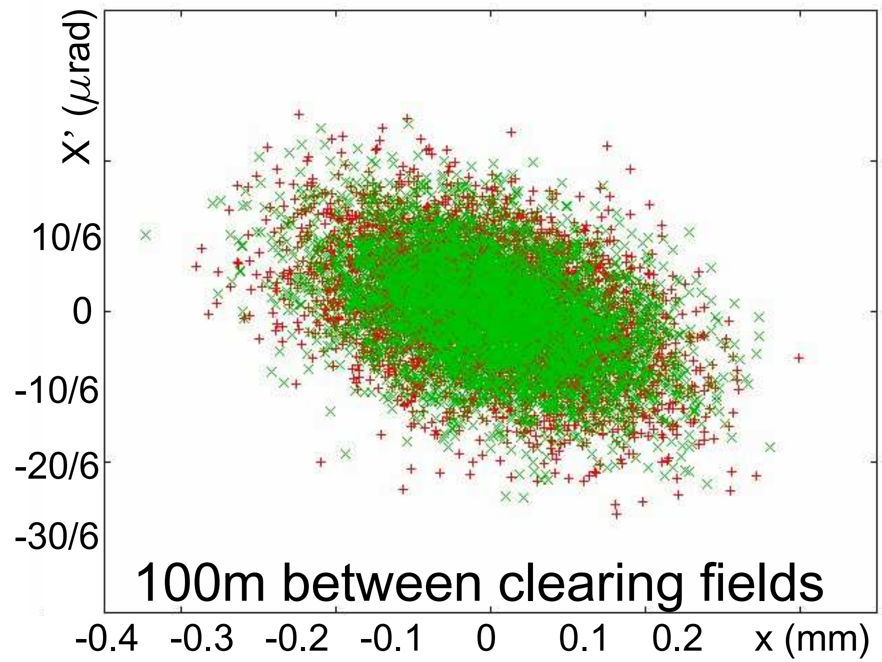
- Ion accumulate in the beam potential. Since the beam is very narrow, ions produce an extremely steep potential – they have to be eliminated.

- Conventional ion clearing techniques:
  1) Long clearing gaps have transient RF effects in the ERL [2ms every 7ms].
  2) Short gaps have transient effects in injector and gun and produce more beam harmonics that excite HOMs [0.4 ms every 7ms].
  3) DC fields of about 150kV/m have to be applied to appropriate places of the along the accelerator, without disturbing the electron beam.

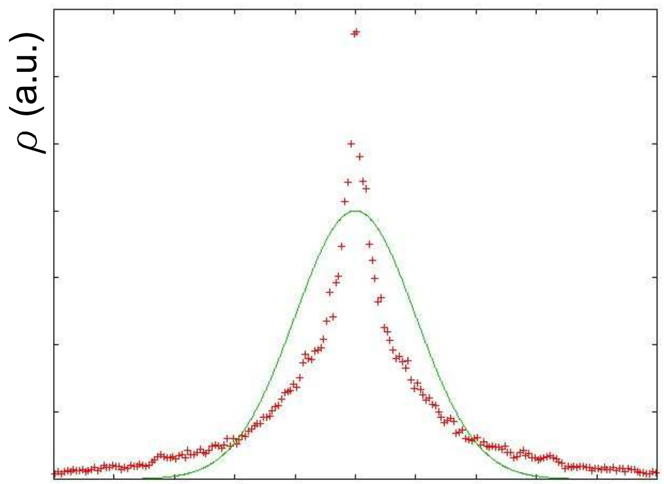
     But remnant ion density before clearing can still cause emittance growth.

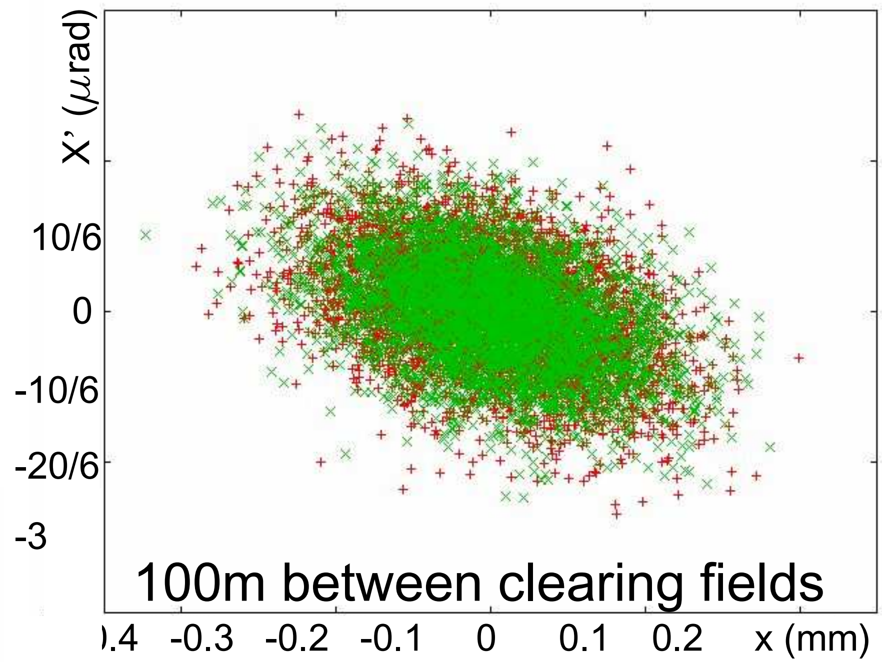
Ions in an ERL beam

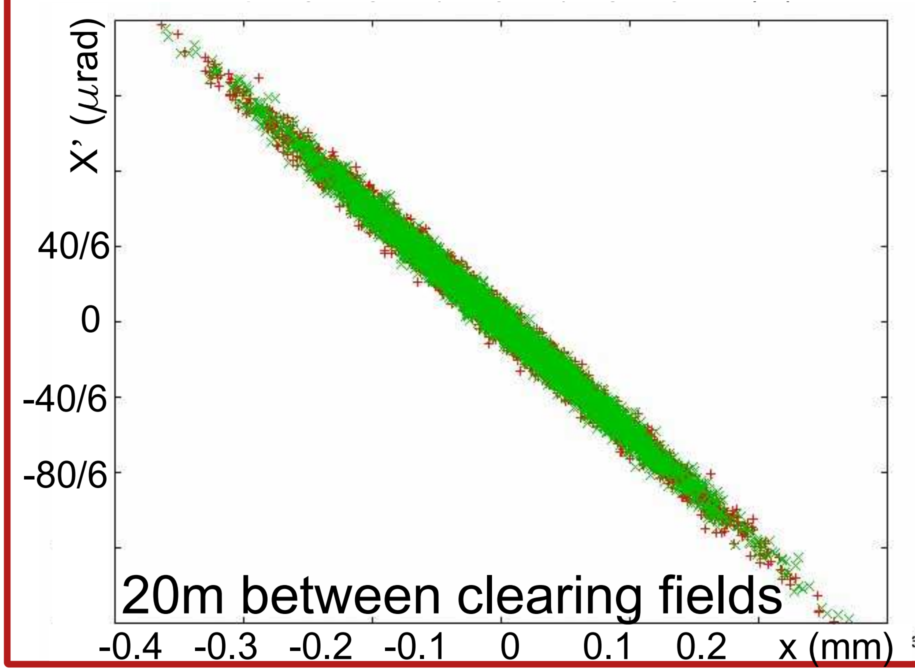




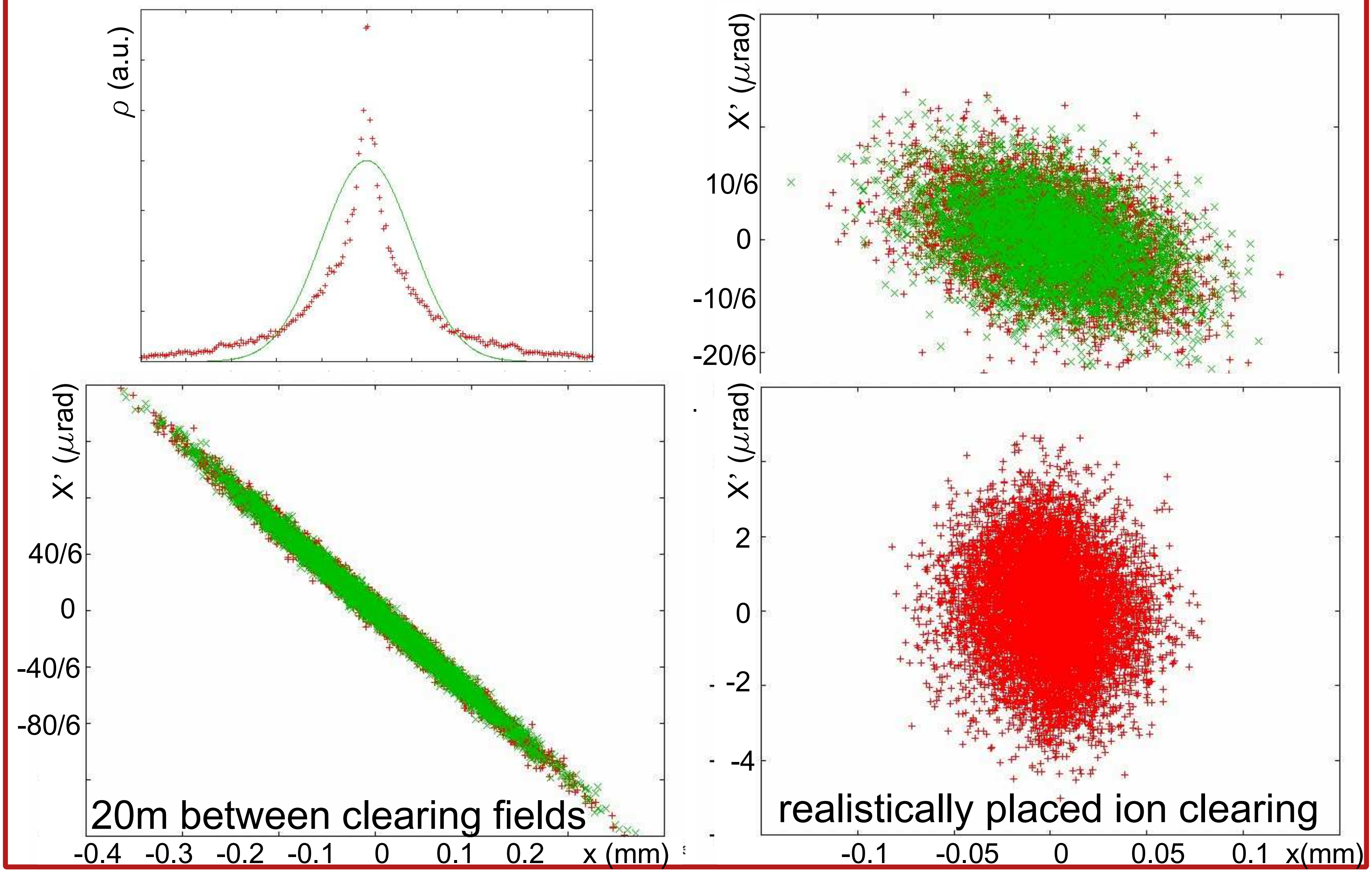
Ions in an ERL beam







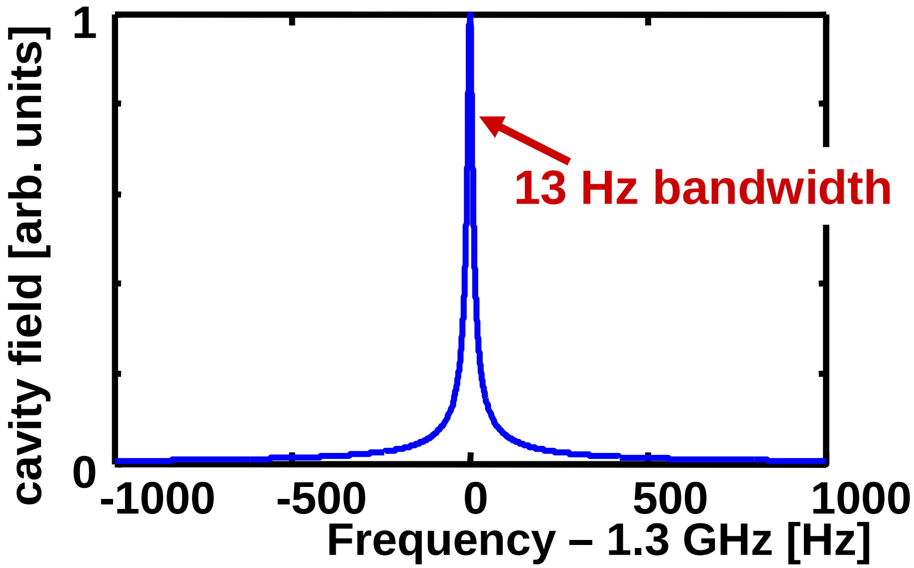
Ions in an ERL beam

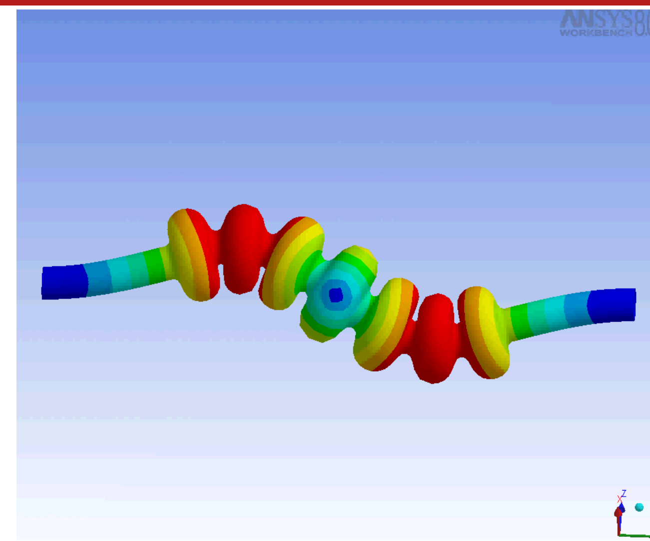


(4) Challenges for x-ray ERLs

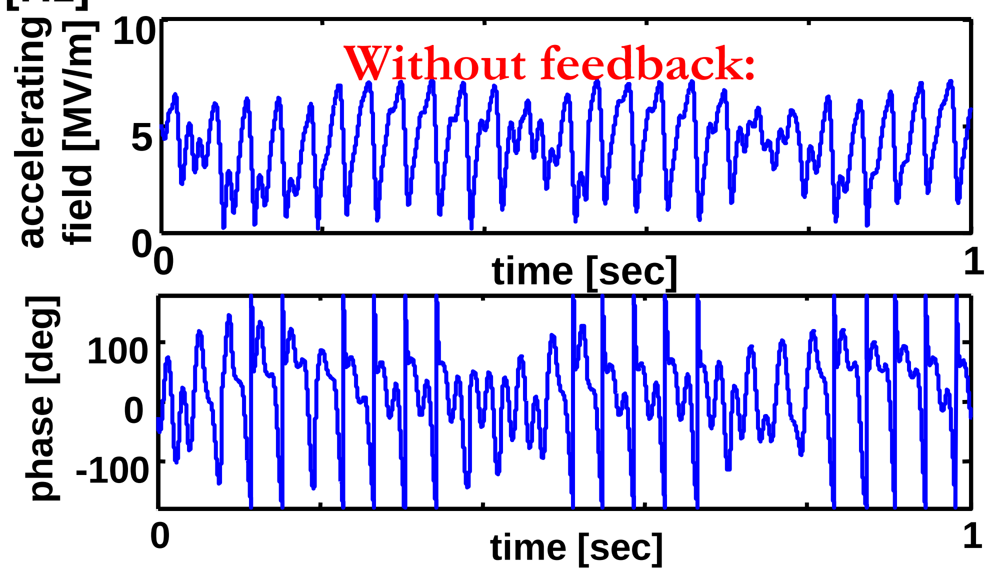
- **Superconducting RF challenges**
  - **Phase and amplitude control for very narrow frequency window (10^{-8})**
  - **Avoid heating / Higher order mode absorption**
  - **Limit cooling power**

Cavity control for SC linacs (ERL & ILC)

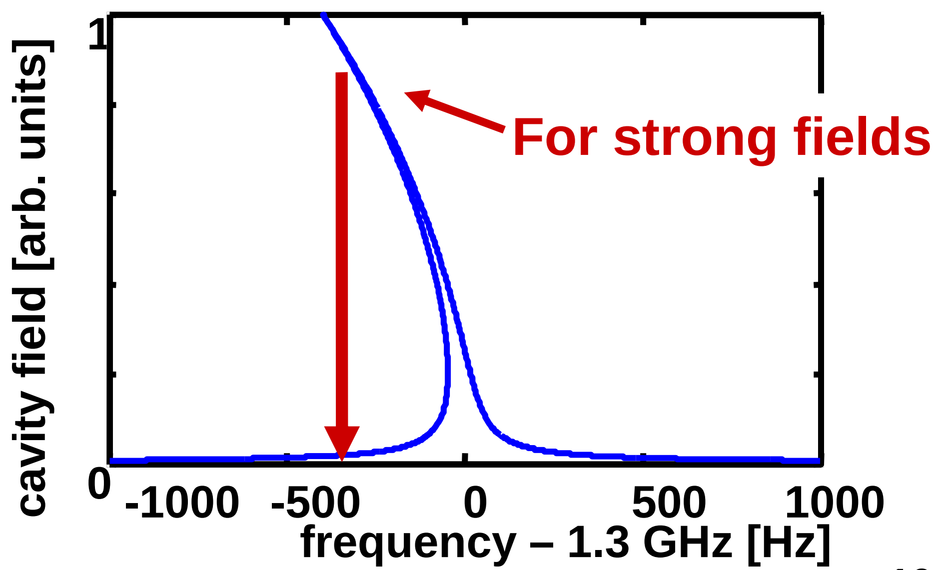


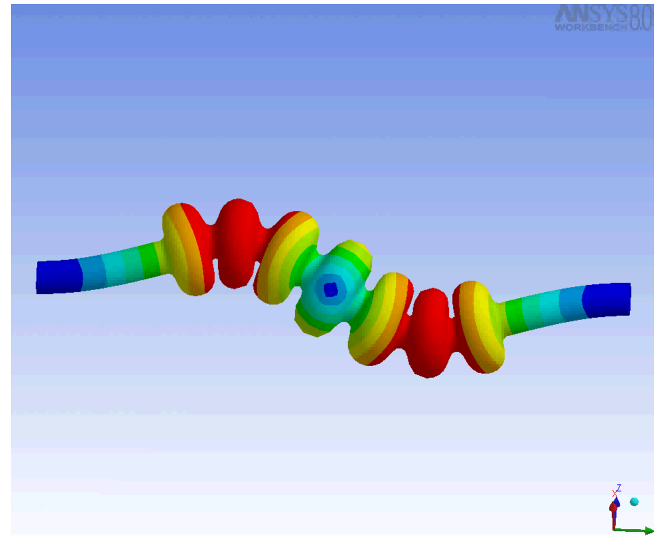


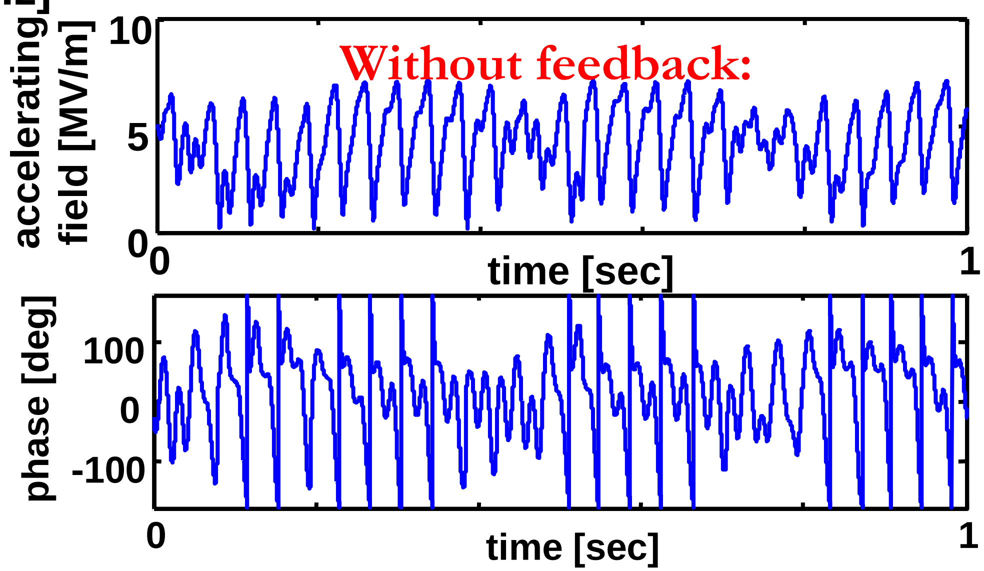
- Run cavity with lowest possible bandwidth for ERL.
- But frequency stabilization becomes very critical.



Cavity control for SC linacs (ERL & ILC)







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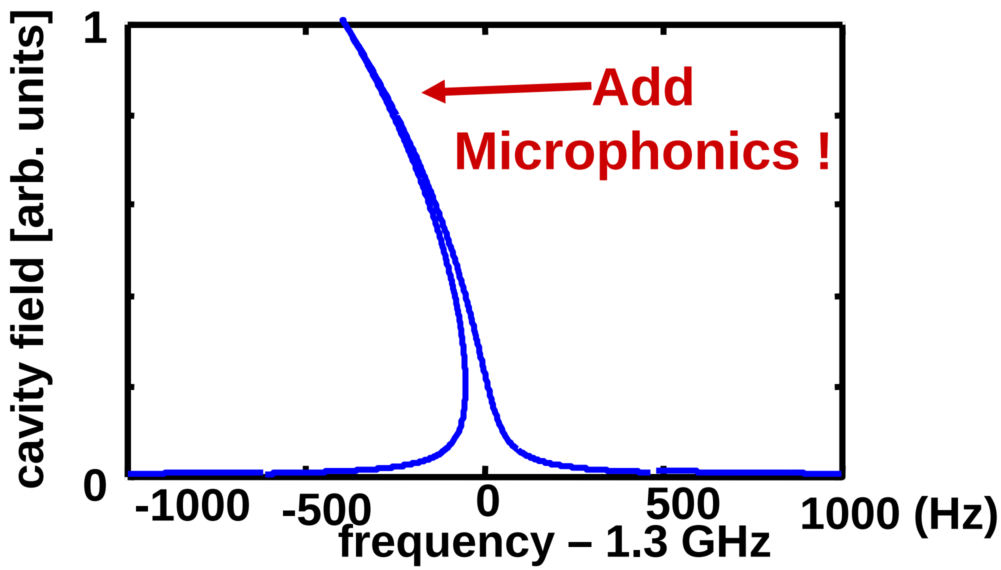

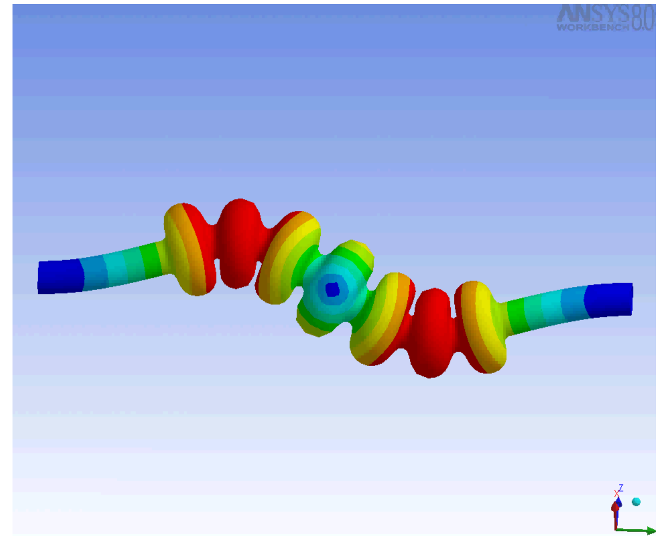

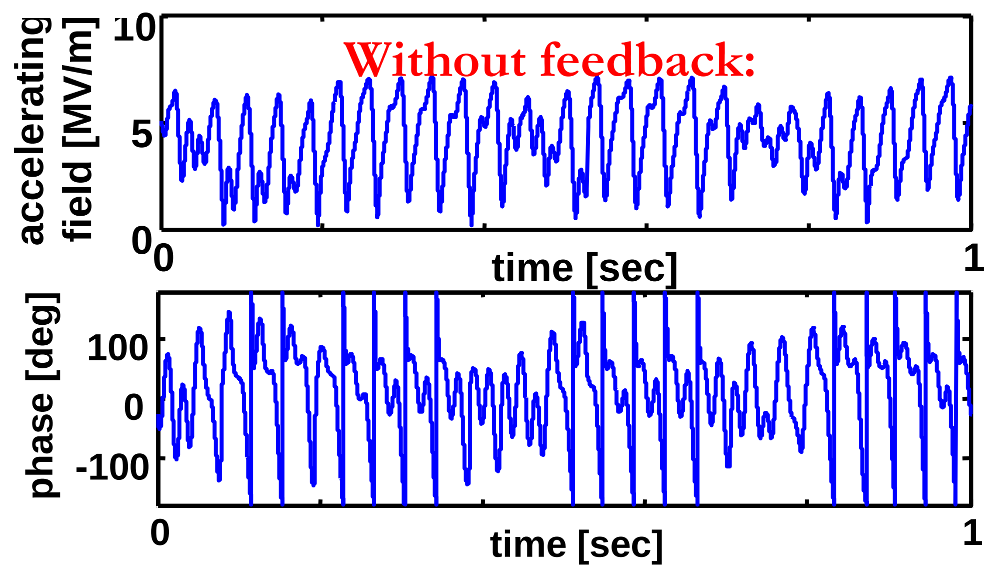

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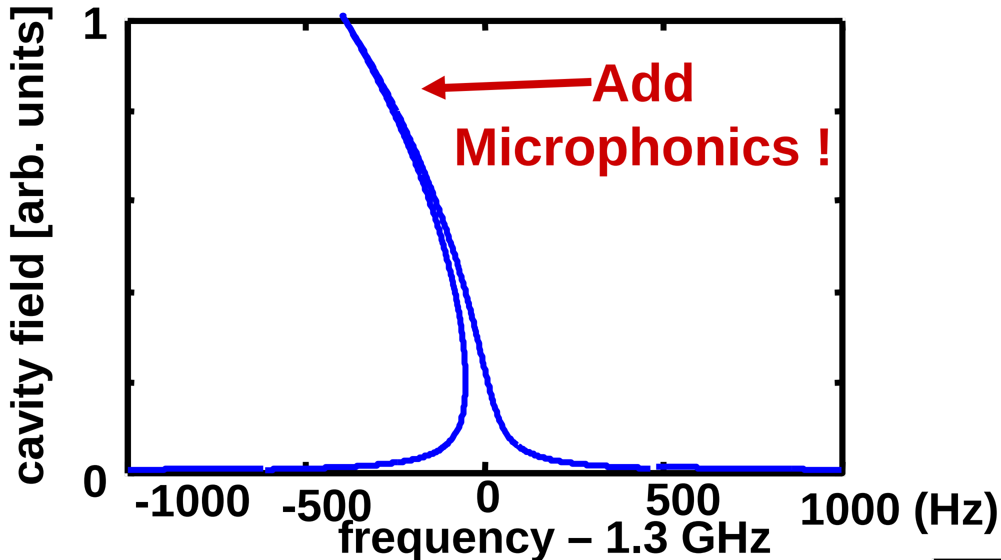
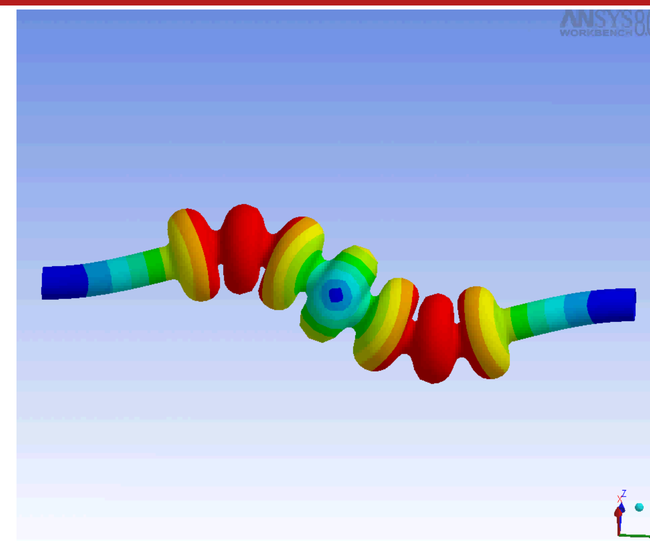
Cavity control for SC linacs (ERL & ILC)





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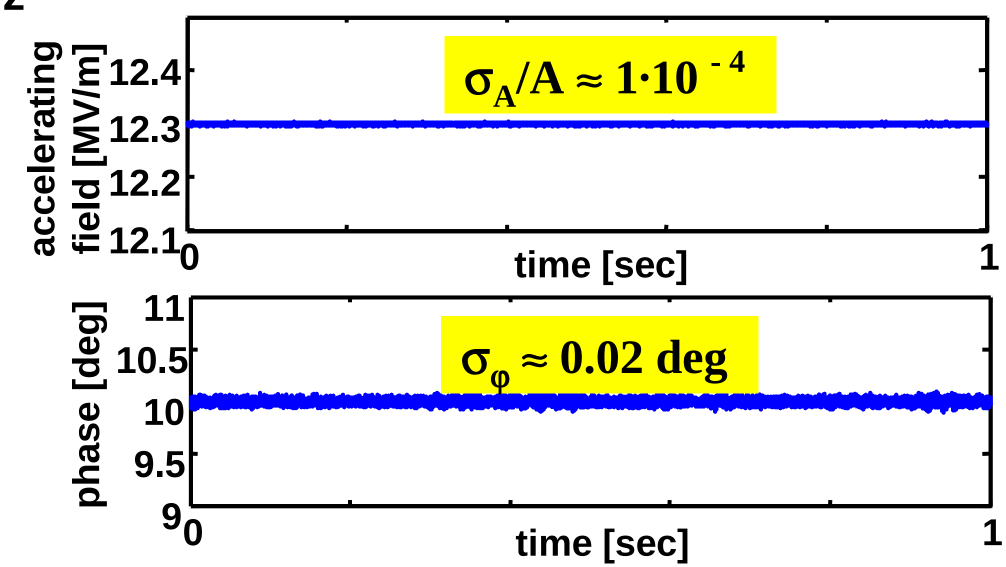
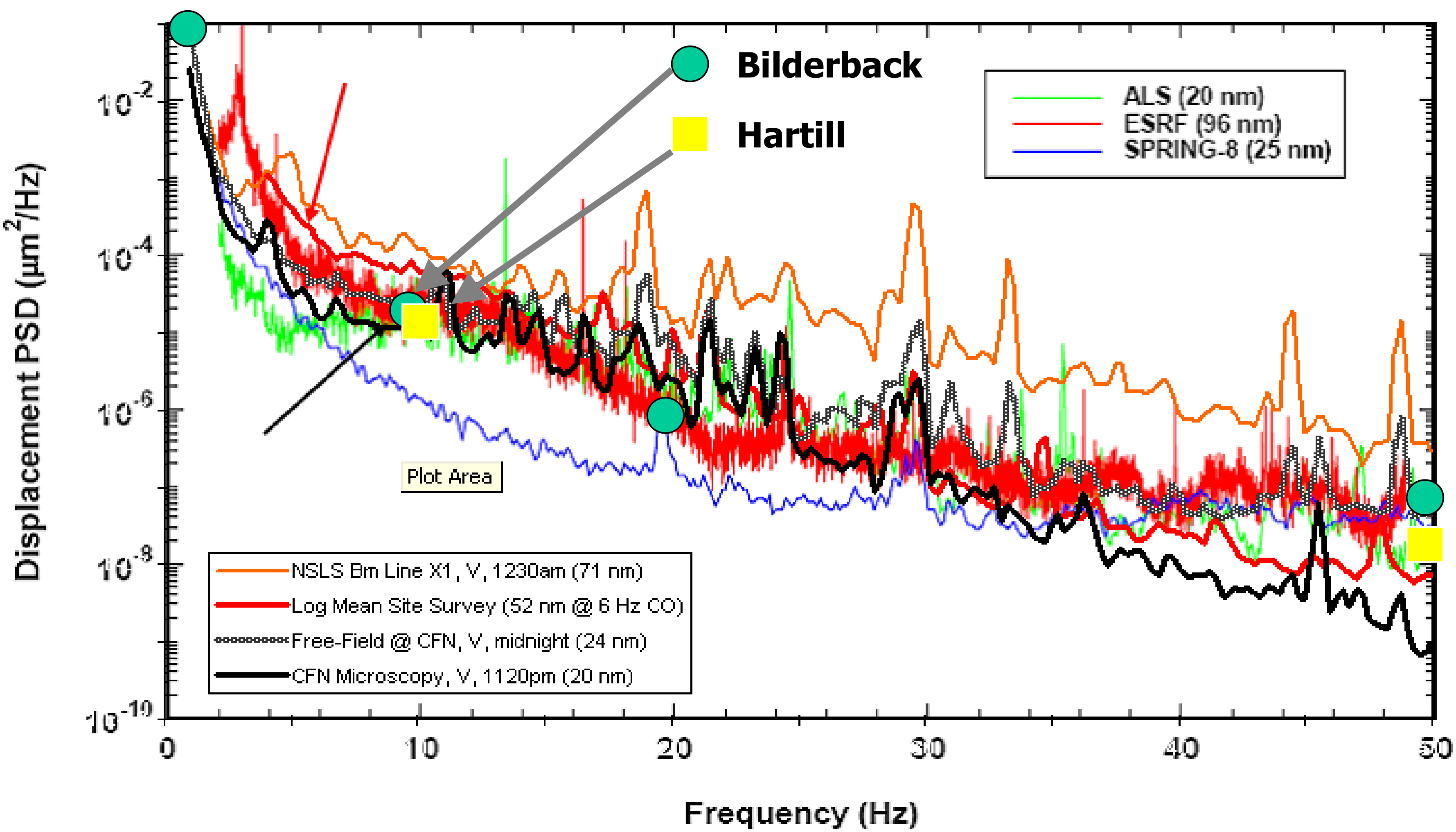
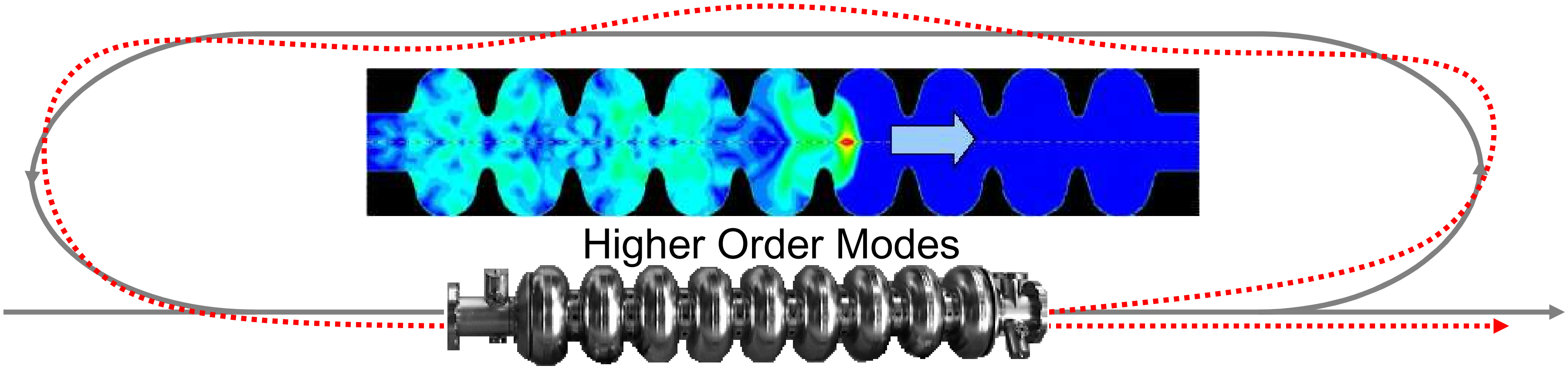


Vibration measurements

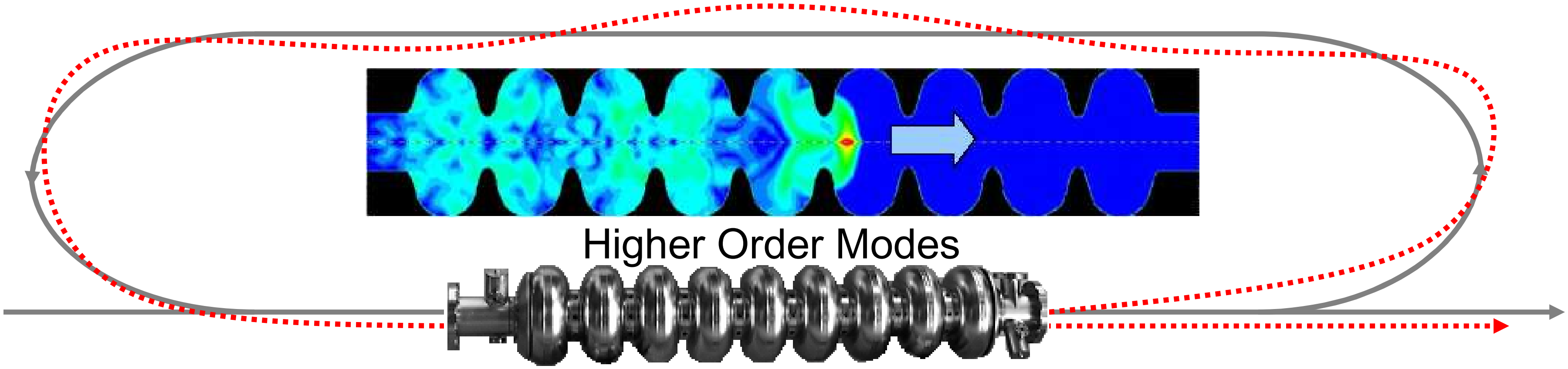


BBU: Collective Instabilities



$$V_x(t) = T_{12}\,\frac{e}{c}\int_{-\infty}^{t} W_x(t-t')V_x(t'-t_r)I(t')dt'$$

BBU: Collective Instabilities



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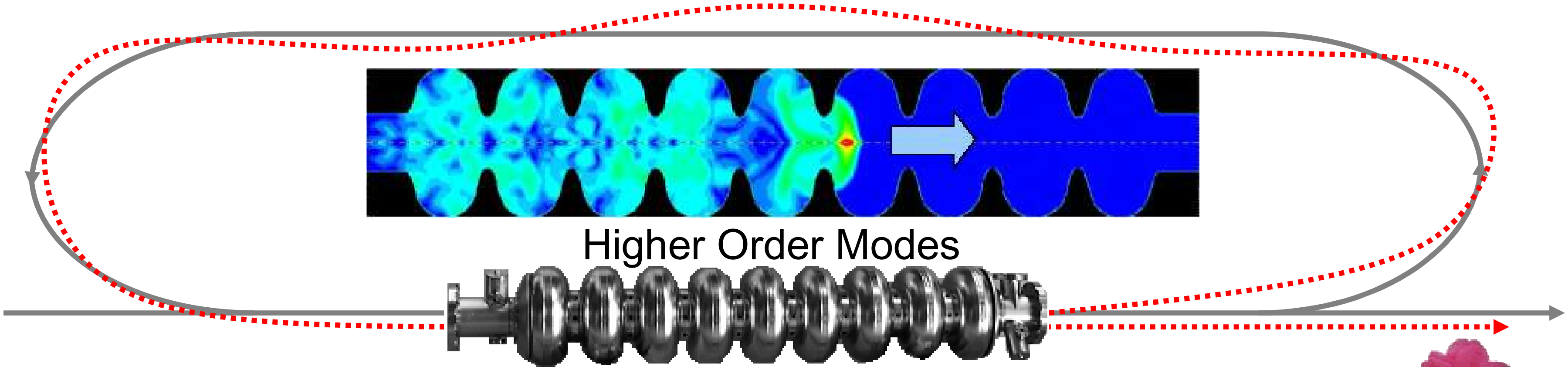


$$V_x(t) = T_{12}\,\tfrac{e}{c}\int_{-\infty}^{t} W_x(t-t')V_x(t'-t_r)I(t')dt'$$

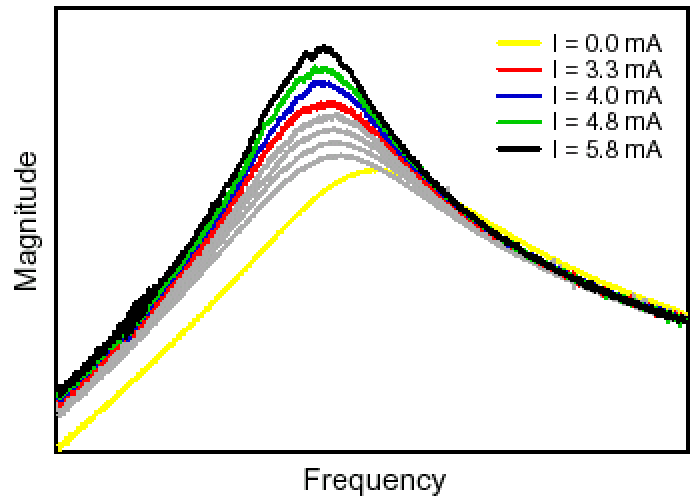
HOM with BBU: Starting from Noise

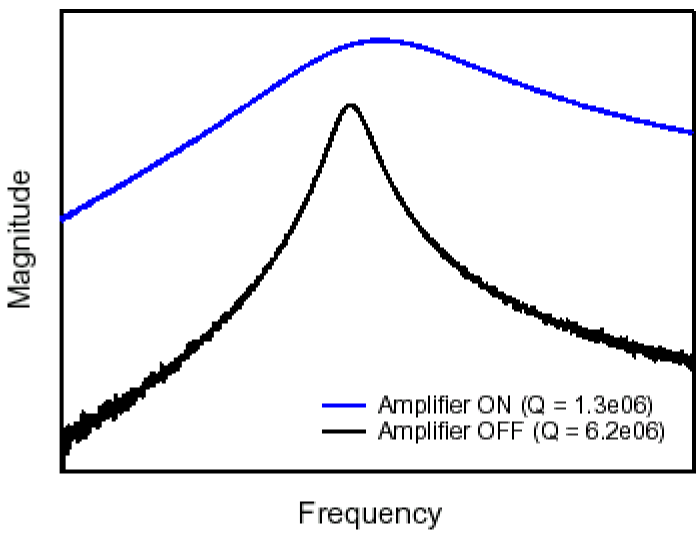
Recall… $I_{threshold} \propto \frac{1}{Q_{HOM}}$

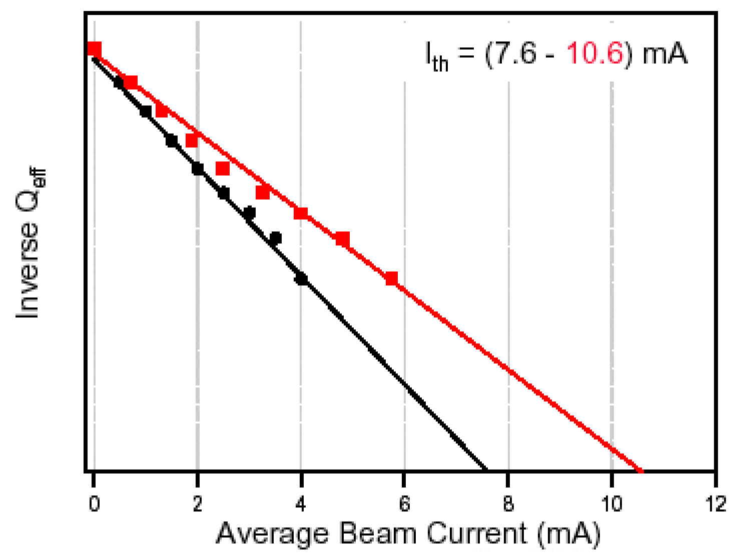
- Damping circuit easily reduced the *Q* of the 2106 MHz mode by a factor of 5

  (Above a factor of about 10, the system becomes sensitive to external disturbances)

- The threshold is increased accordingly: from 2 mA to ~10 mA

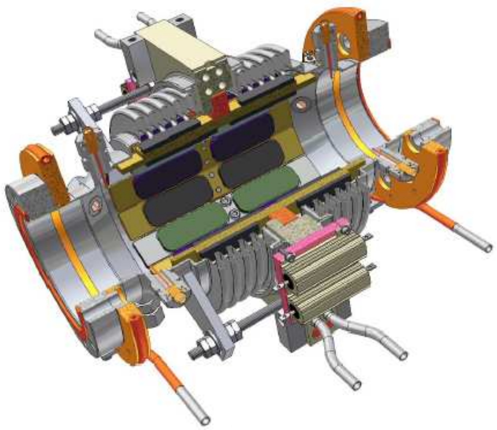






HOM absorbers a la Cornell

From design

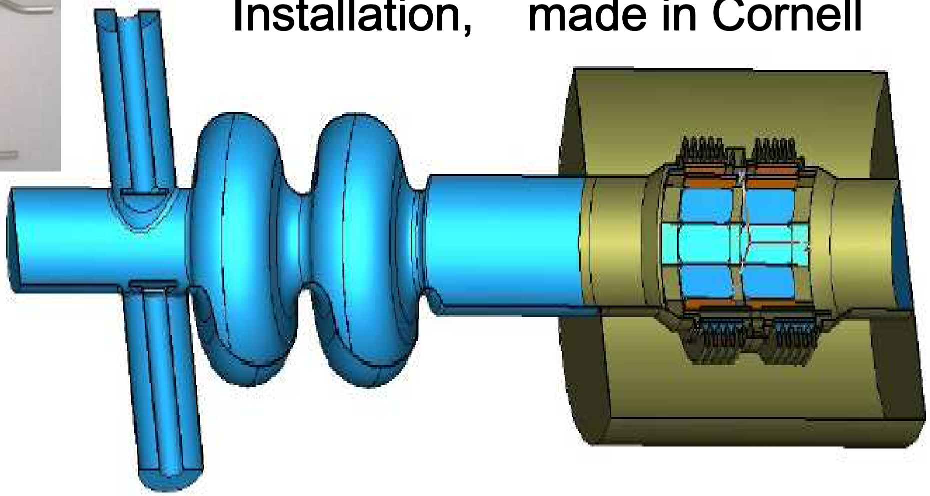


to production and

The Cornell-type HOM absorbers:

- first developed for CESR
- adopted internationally
- Refined for the ERL

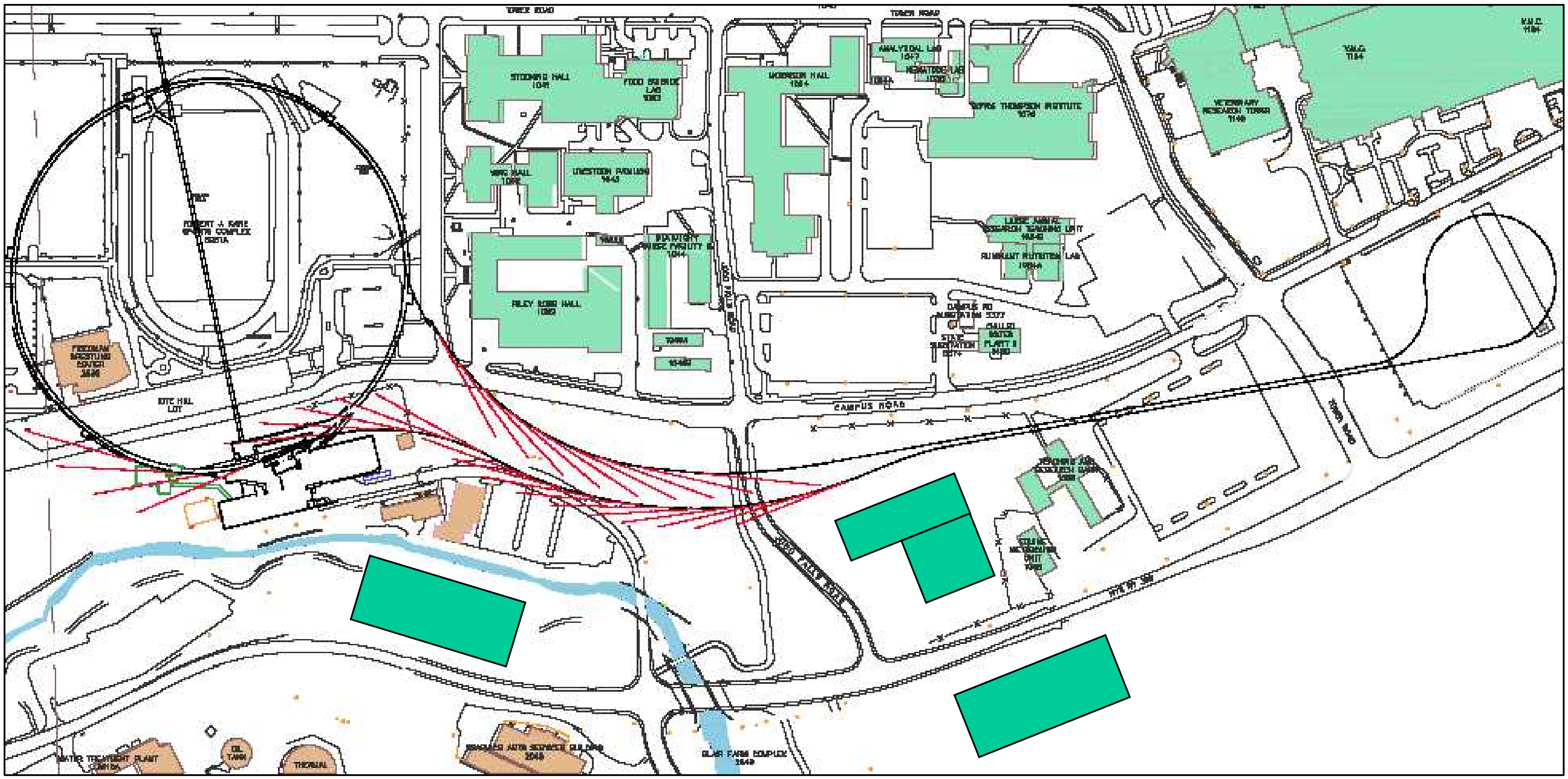
Installation, made in Cornell



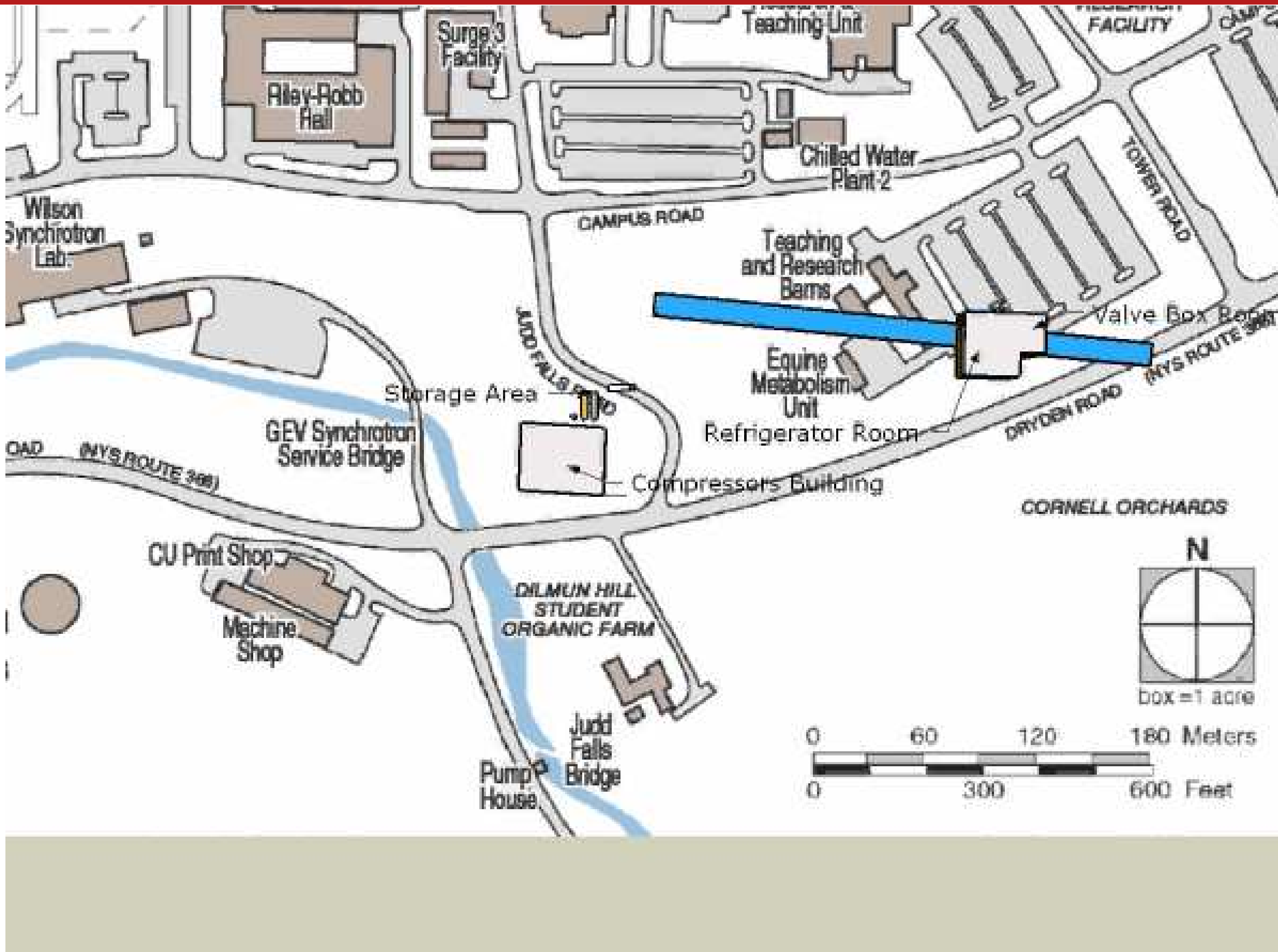
HOM absorbers quickly reduce unwanted field components.

Cryogenic building

Two designs: 25 X 55 X 7m and 35 X 65 X 12m



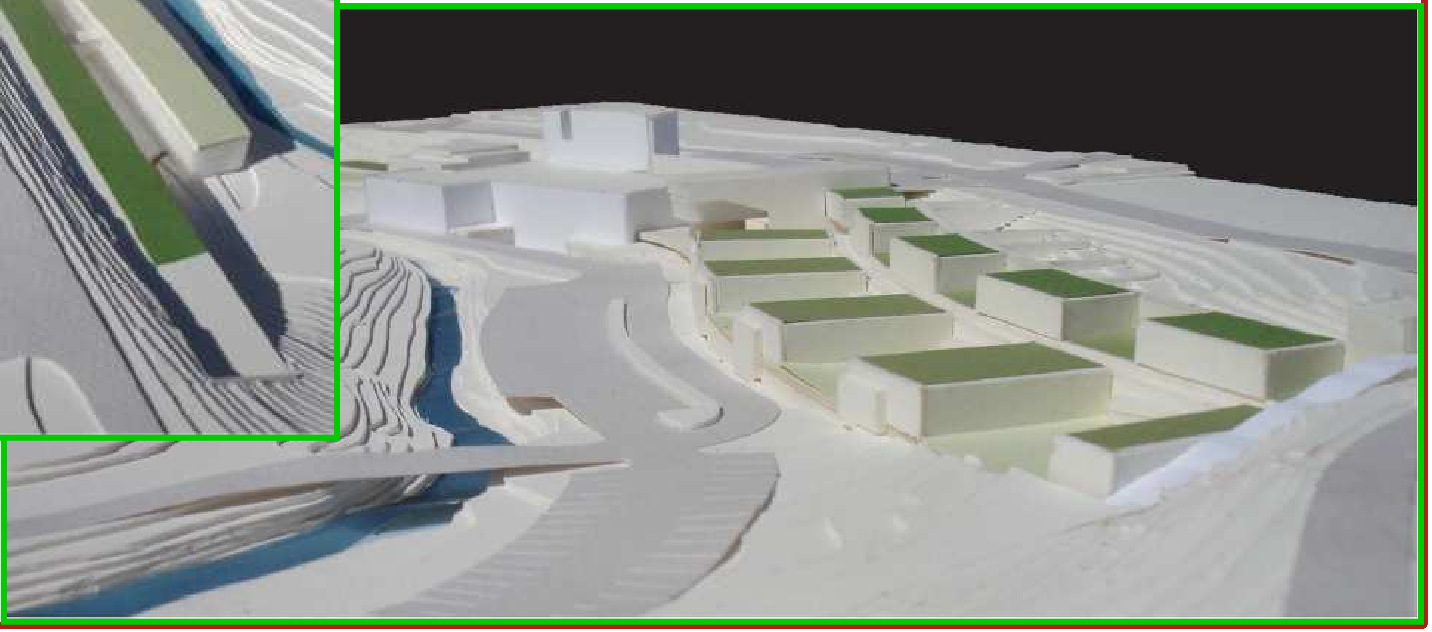
Cryogenic building



Conceptual building design

New floor space:
likely as large as existing Wilson lab.

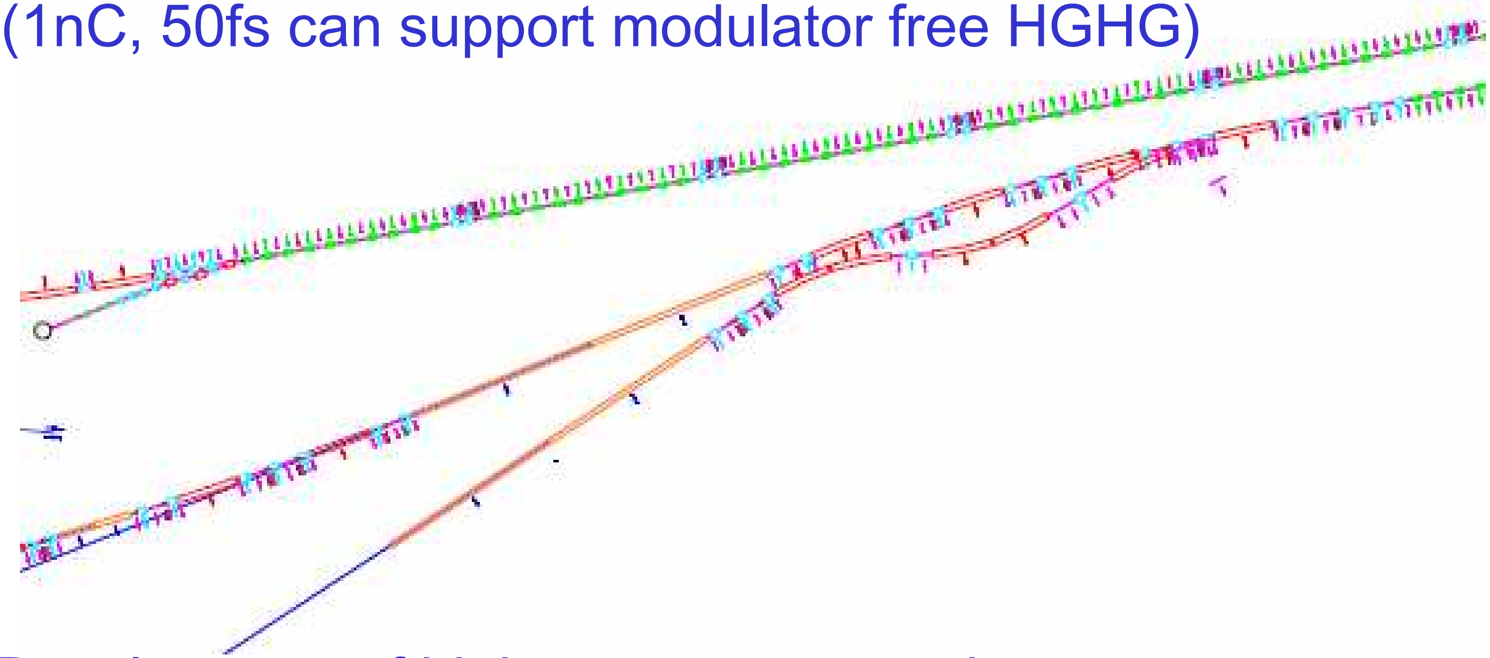
Beamline location:
out of the hillside next to existing Wilson lab



Future accelerator developments

1) SASE FEL development in parallel with ERL operation (1nC, 50fs can support SASE amplification)

2) HGHG development in parallel with ERL operation
(1nC, 1ps can support radiator/modulator HGHG)
(1nC, 50fs can support modulator free HGHG)



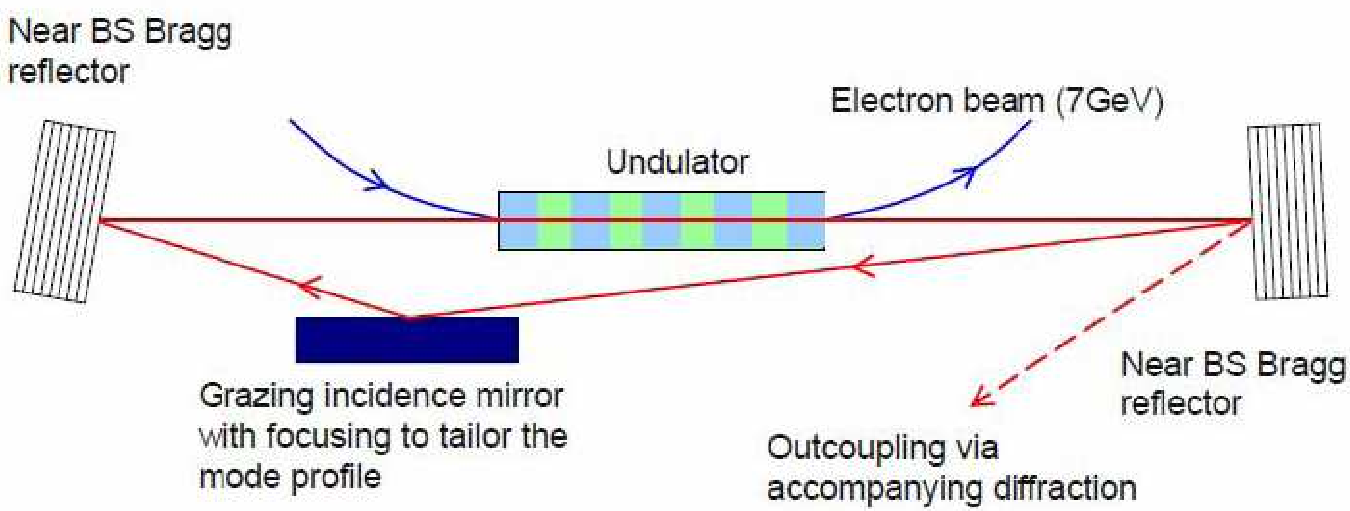
3) Development of higher current operation

Amplifier FEL operation

K-J. Kim

A Novel Concept for X-Ray Optical Cavity Using Near Backscattering & Accompanying Diffraction

(KJK & Shvyd'ko)



- Cornell-ERL parameters scaled to 7-GeV (19-60pC, 2ps, ε=6pm, ΔE/E=0.02%) → $\varepsilon < \lambda / 4\pi$ for 1Å
- FEL single-pass gain ~ 50% for 60pC, Lu=23m case.
- Energy spread of 0.05% (after FEL lasing) is acceptable for ERL operation.

From ERL07 Workshop

Conclusions and Contributors*

Injector parameters	Ivan Bazarov, Charlie Sinclair
User requirements for layout and beam parameters	Don Bilderback, Dana Richter
Layout, optics considerations, ISR, CSR	Chris Mayes
Coupler kicks	Brandon Buckley
Ion effects with clearing electrodes	Christian Spethmann, Yi Xie
Ion gap options	Bob Meller
Cavity alignments, orbit correction techniques, BBU	Changsheng Song
BPM solutions for 2 beams, ERL impedances	Mike Billing, Mark Palmer
Transverse orbit feedback considerations	Jerry Codner, Don Hartill , John Sikora
x-ray loads	Mike Forster
Gas and pressure profile	Yulin Li
Gas and Touschek scattering, beam halo, collimation	Sasha Temnykh, Mike Ehrlichmann
Radiation shielding	Ken Finkelstein, , Steve Gray, Val Kostroun
Code developments	Dave Sagan

Cornell has an experienced team of accelerator experts who have laid out an ERL for the Cornell campus that extends the CESR ring, and have defined working modes that accommodate all considered accelerator physics issues.

* Several people contributed to more than one subject.