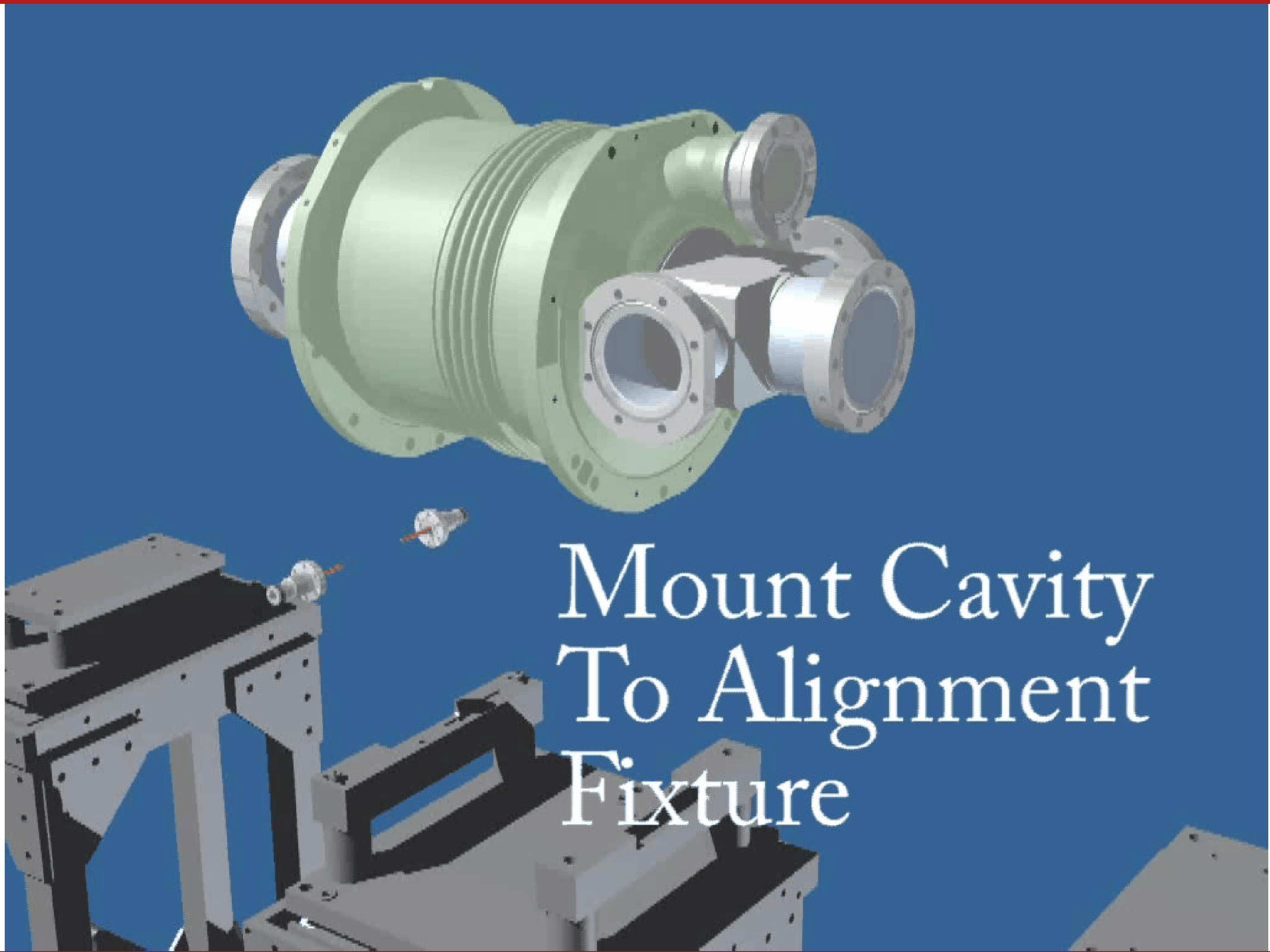
The energy recovery linac (ERL) as a new x-ray sources

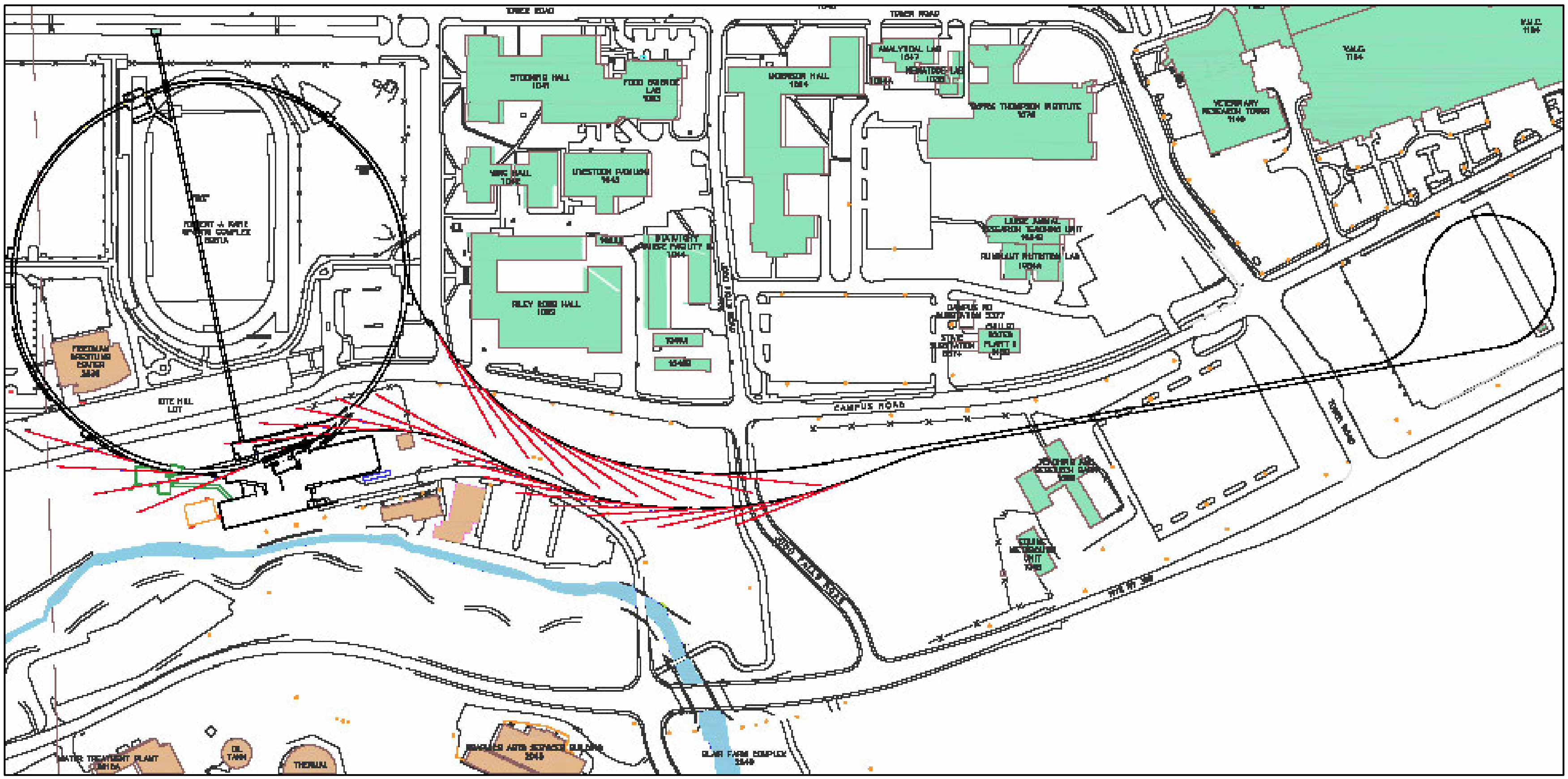
CHESS & LEPP



Injector assembly

The energy recovery linac (ERL) as a new x-ray sources

Georg H. Hoffstaetter
Cornell, LEPP / Physics Dep.



CESR @ Cornell

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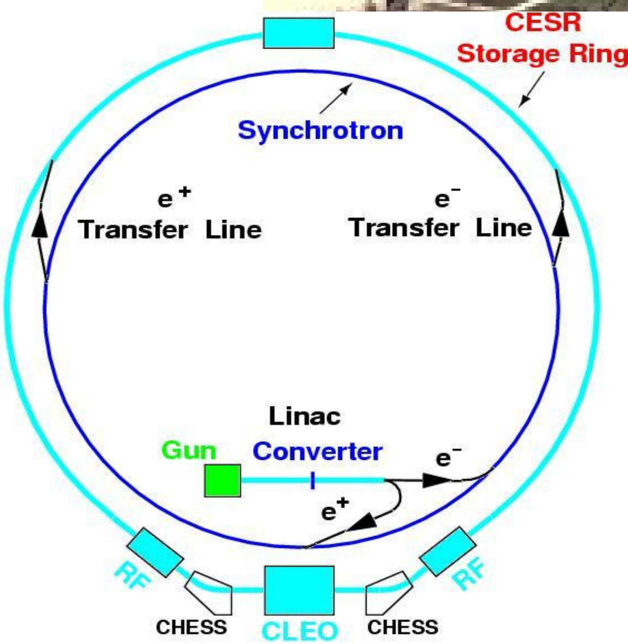

Microprobe: higher resolution from narrower x-ray beams

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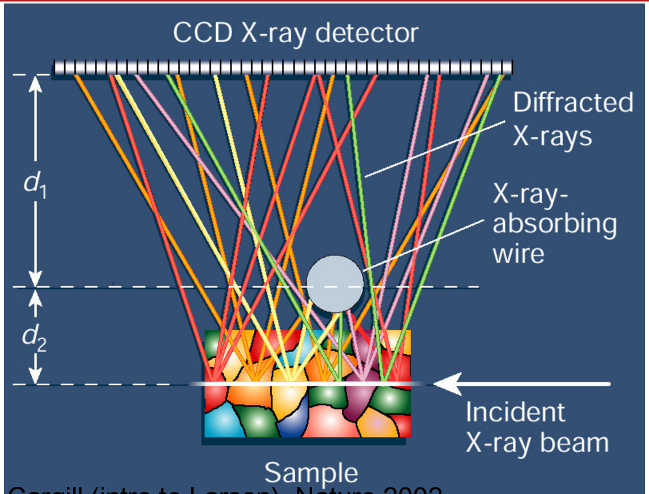
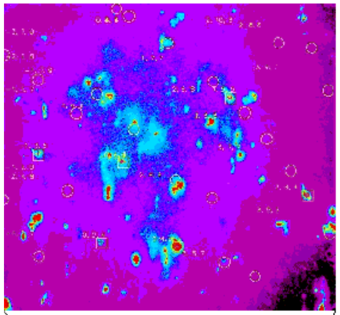


Cargill (intro to Larson), Nature 2002

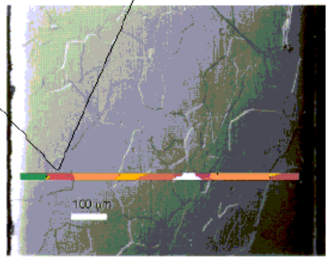
Differential-Aperture X-ray Microscopy (DAXM)

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

ERL: 100-1000 times smaller area



Orientation of crystals and Stress and strain in crystals



Ben Larson (2000), ERL science workshop, Cornelll

3-D Studies of Structure

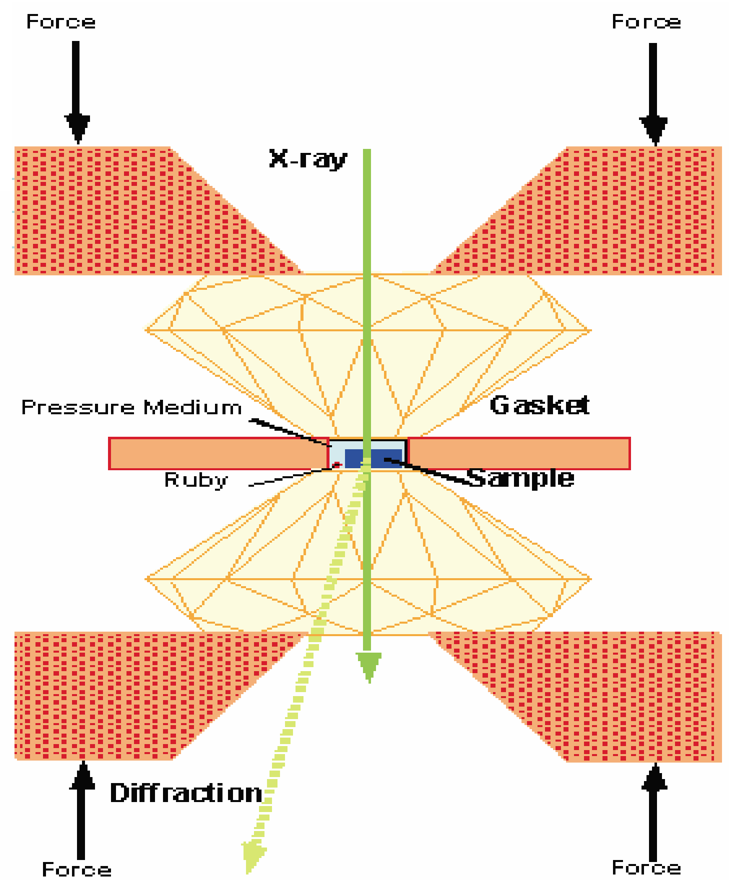
High pressure: more flux through a small probe

& LEPP

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

- HP experiments 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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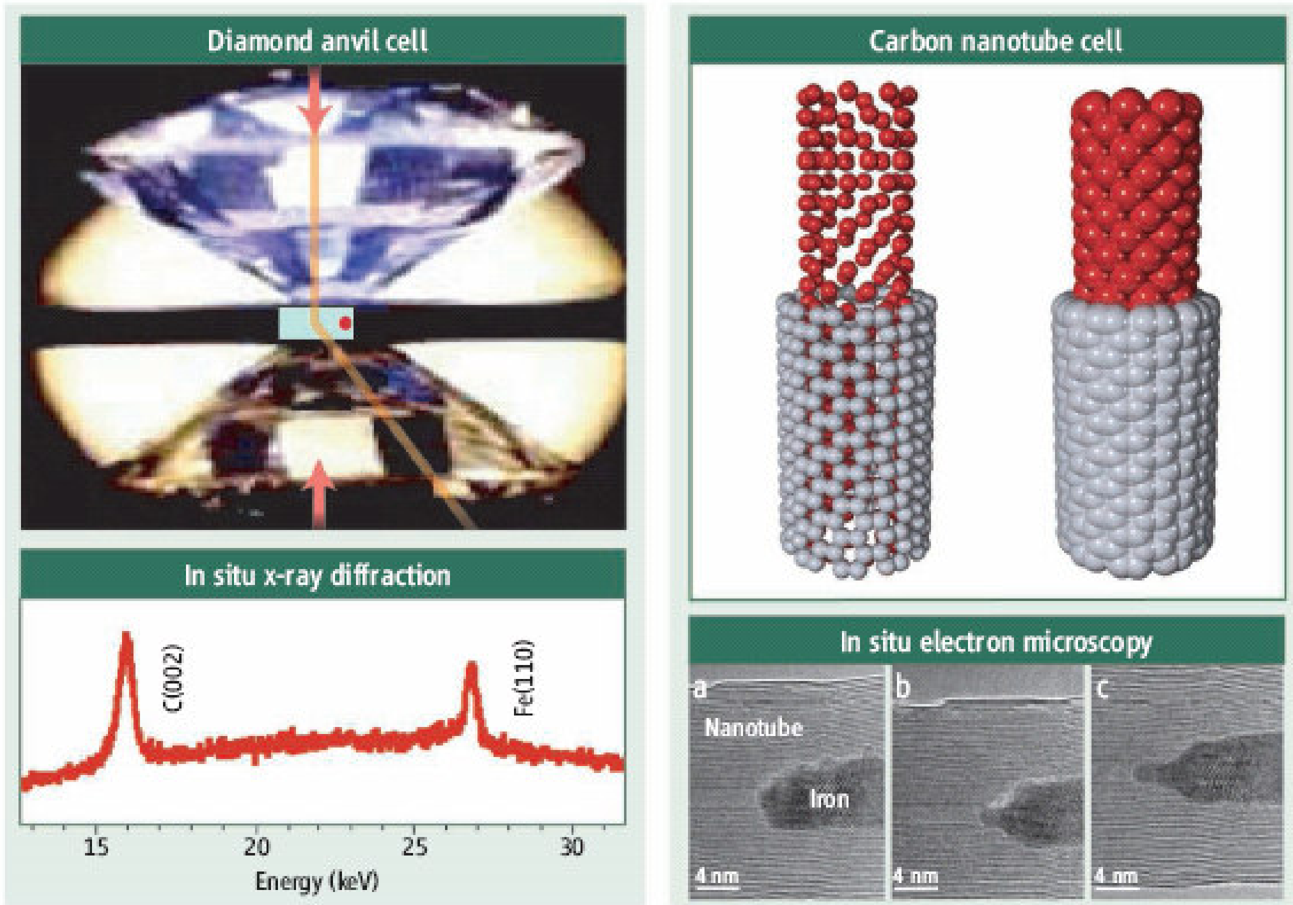
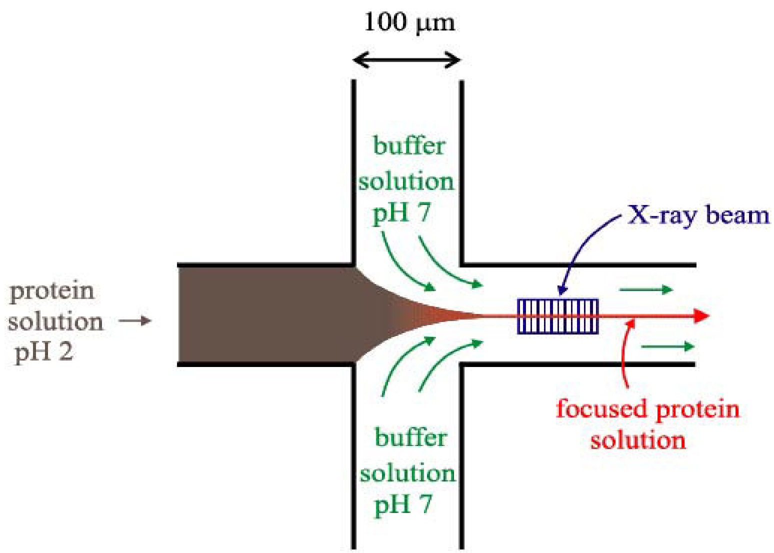


A matter of scale. (Left) A transparent diamond anvil cell allows in situ spectroscopic measurements of bulk samples. The red arrow represents an x-ray beam that is diffracted by the sample. (Right) A carbon nanotube self-compression cell enables in situ atomic-resolution snapshots at zero (a), intermediate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

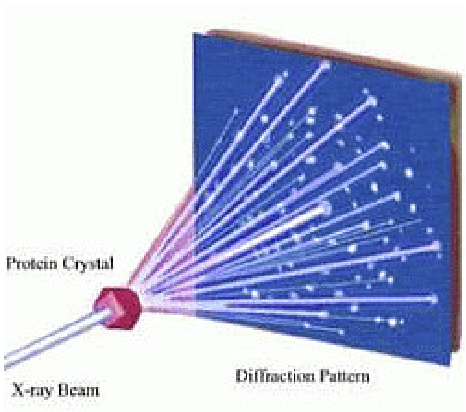
- **Examples: folding/unfolding of proteins & RNA; assembly of fibers; polymer collapse upon solvent changes; conformational changes upon ligand binding; monomer/multimer association.**
- **Microfabricated laminar flow cells access microsecond equilibration mixing times.**
- **Data acquisition entirely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

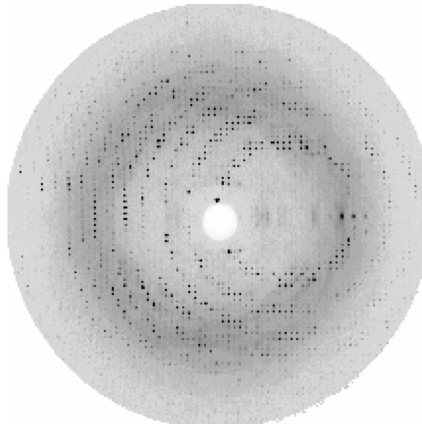


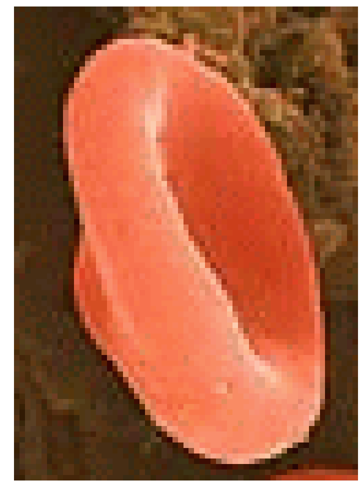
Thanks to Lois Pollack

Cornell Univ.

Structural biology: more flux through microcrystals

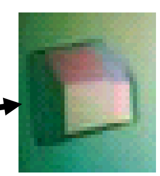


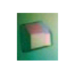




ERL enables new crystallographic method

1. Obtaining good crystals is rate limiting. Easier to obtain microcrystals. Radiation limits crystals to >~$(20\mu m)^3$.
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.





?

Phase contrast: more coherent beams (e.g. more like a plane wave)

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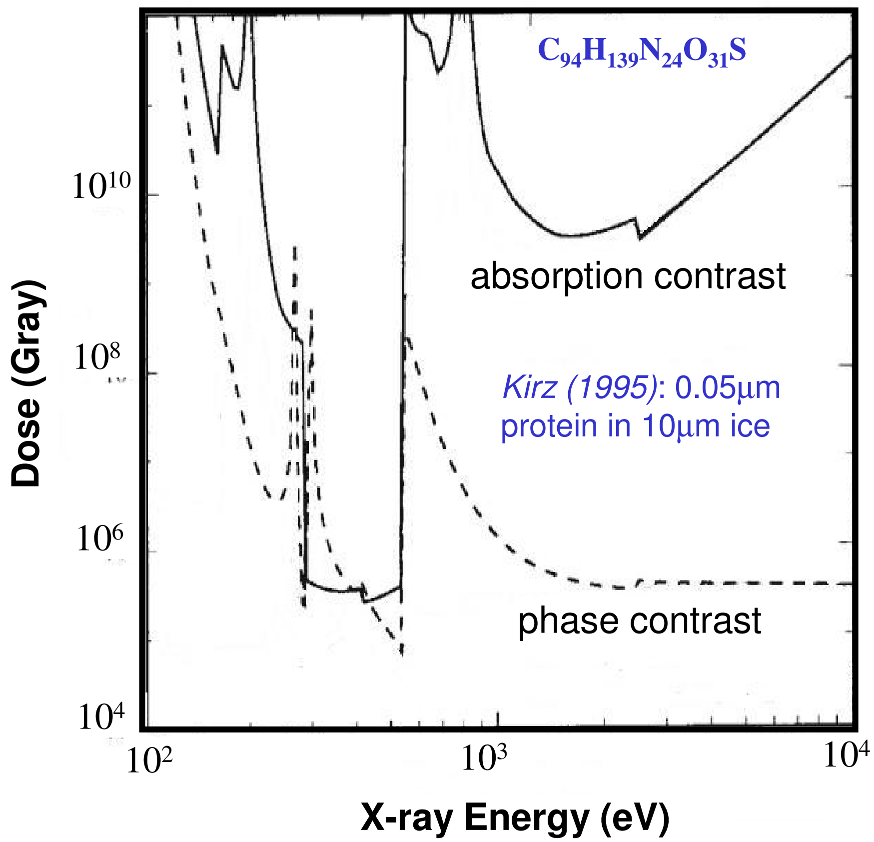
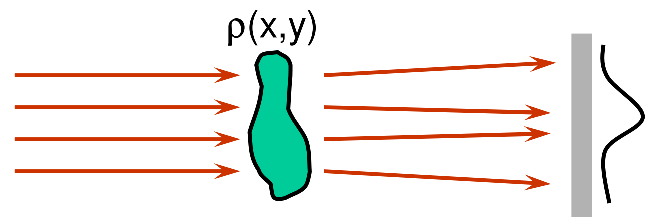




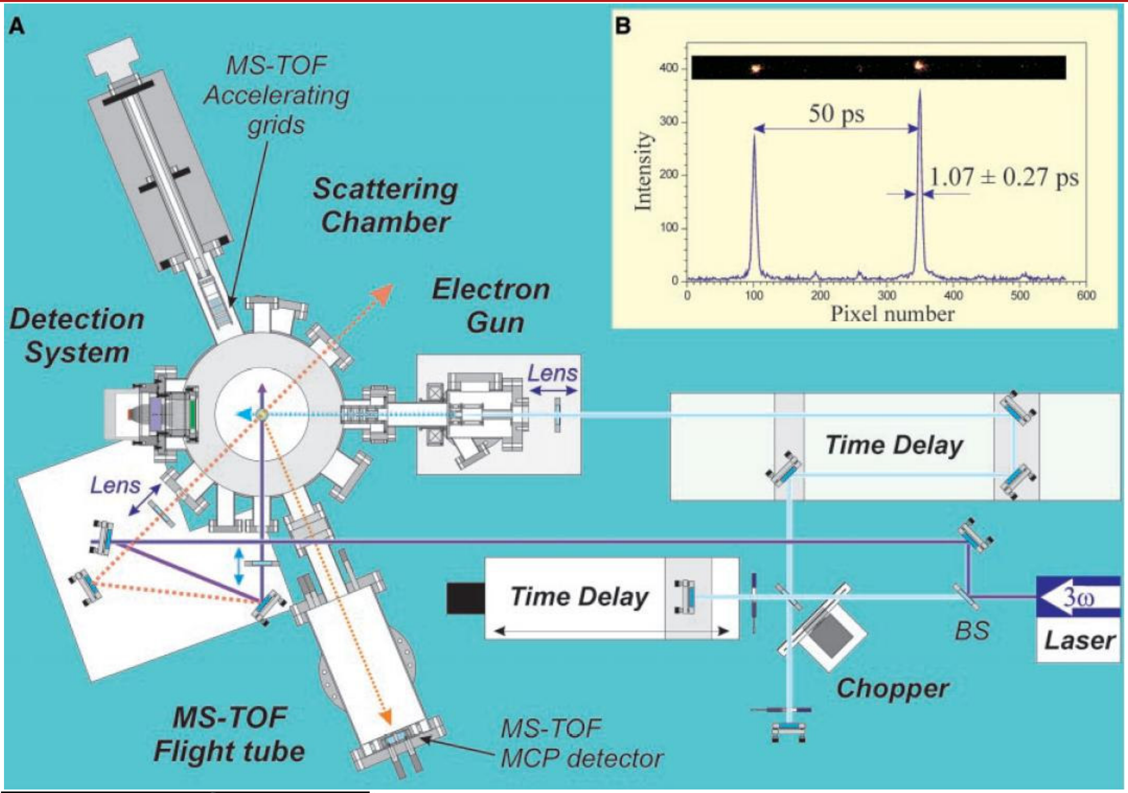
Refraction index: $n = 1 - \delta - i\beta$

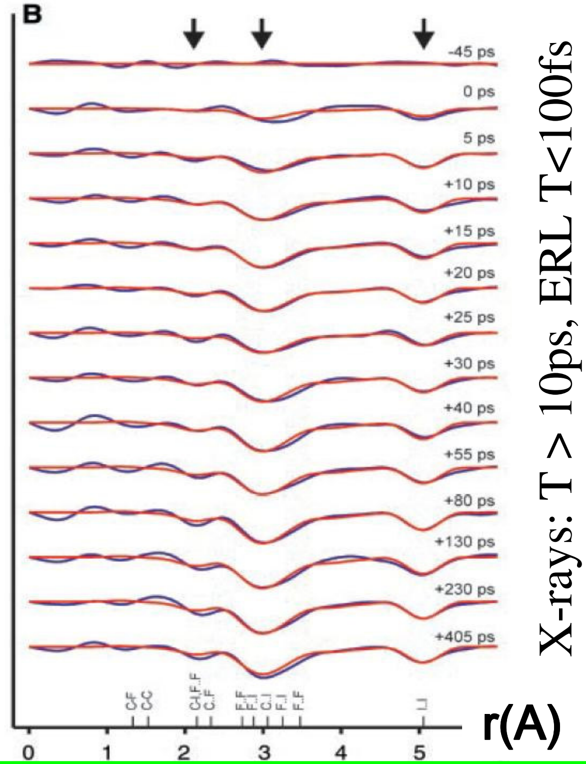
- Phase contrast is 10^4 - 10^6 higher than absorption contrast for protein in water at hard x-rays energies
- Required dose reduced due to phase contrast

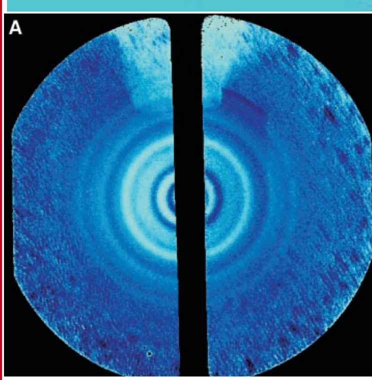
In general, phase contrast requires more coherent x-ray beams

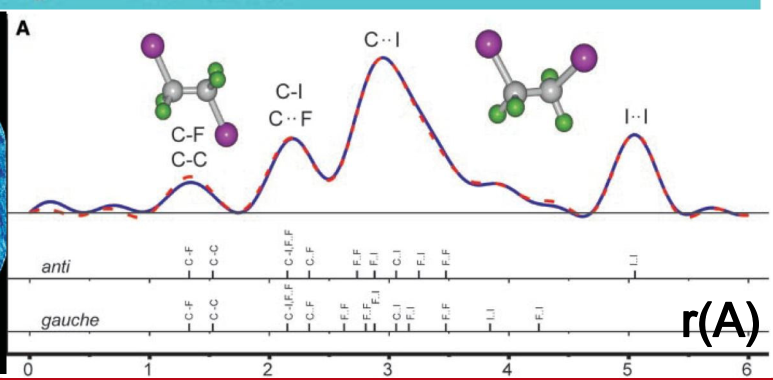
Ultra-fast Electron Diffraction

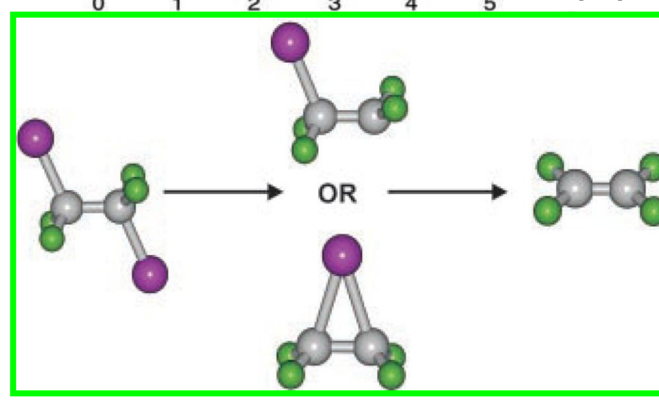
CHESS & LEPP











Radiation production

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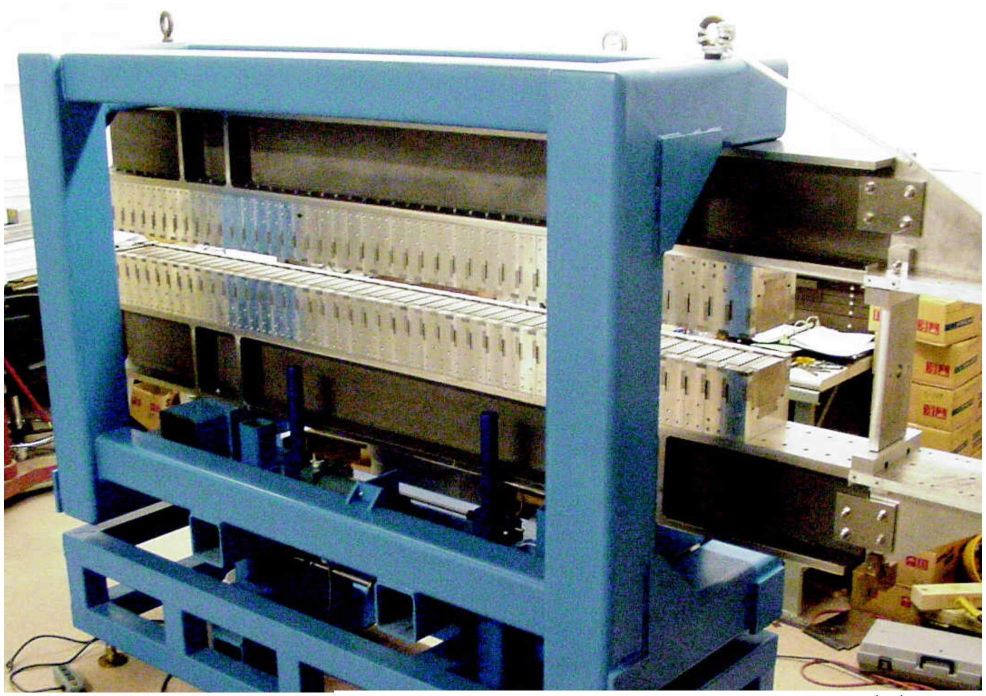

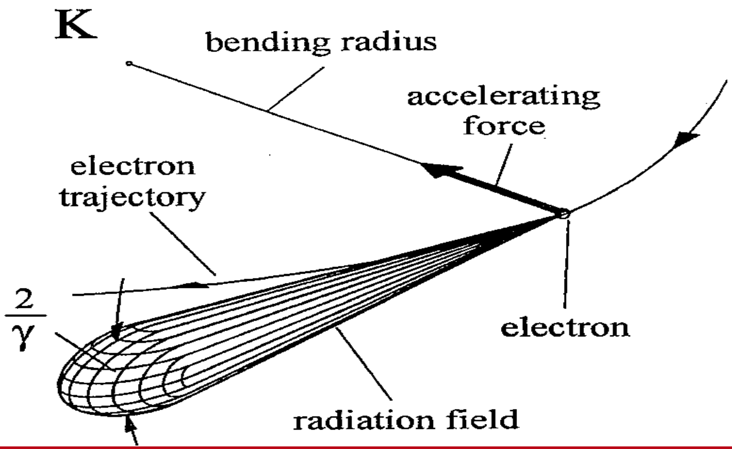

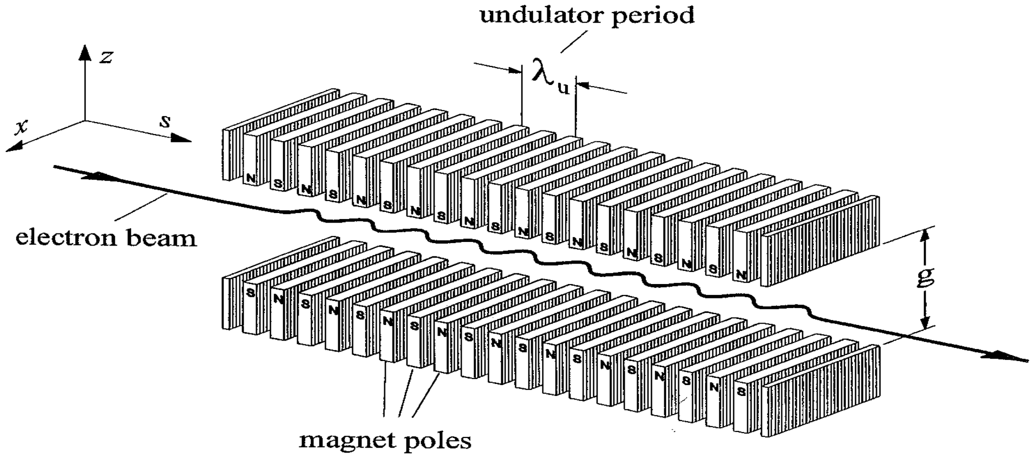

Lasing at JLAB with the ERL-FEL

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Wiggler gap

Hole Outcoupler

High Reflector

Beam in control room

Radiation from bending magnets

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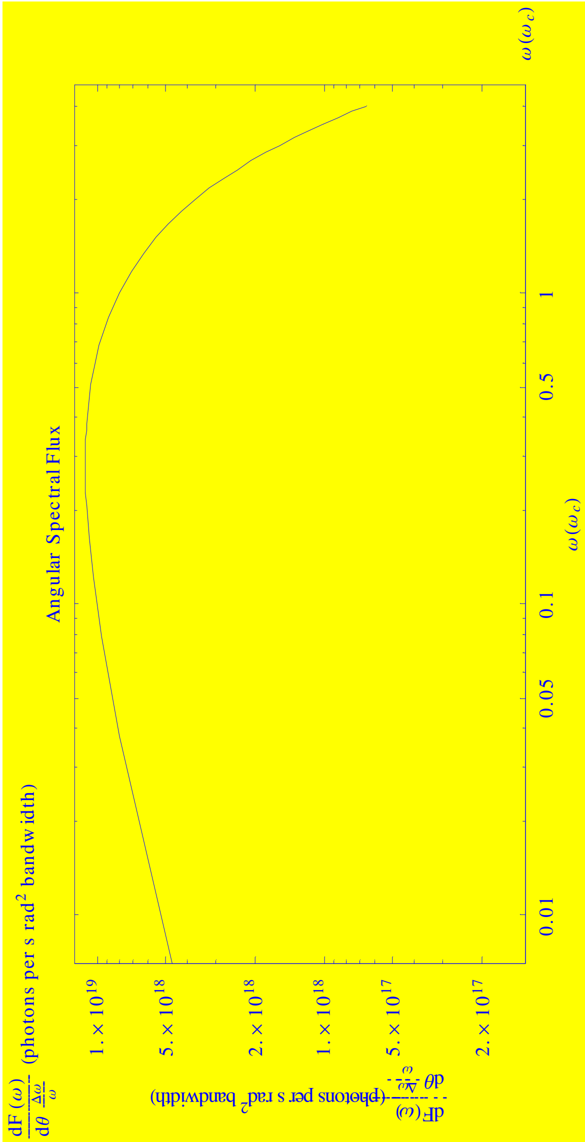
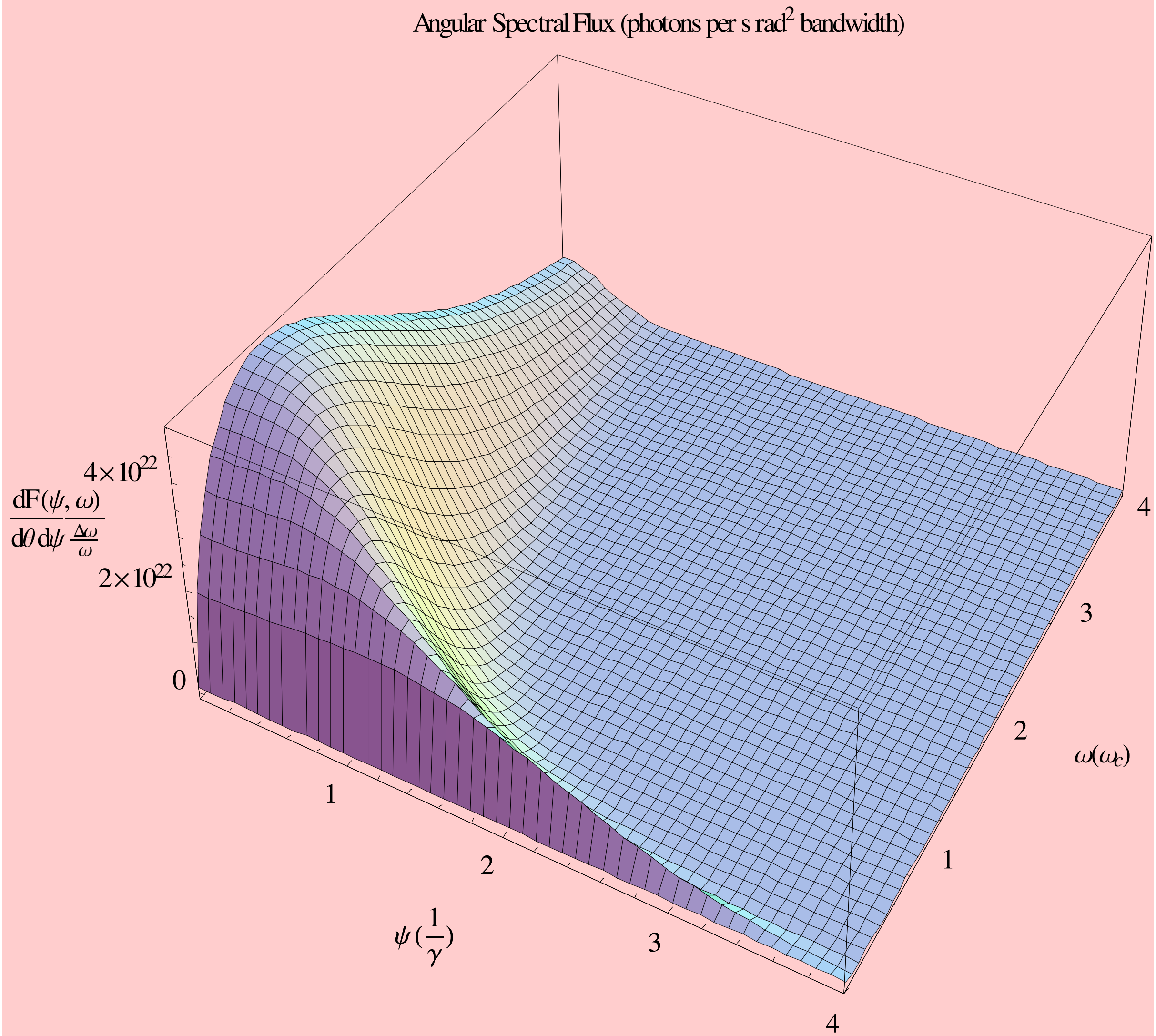
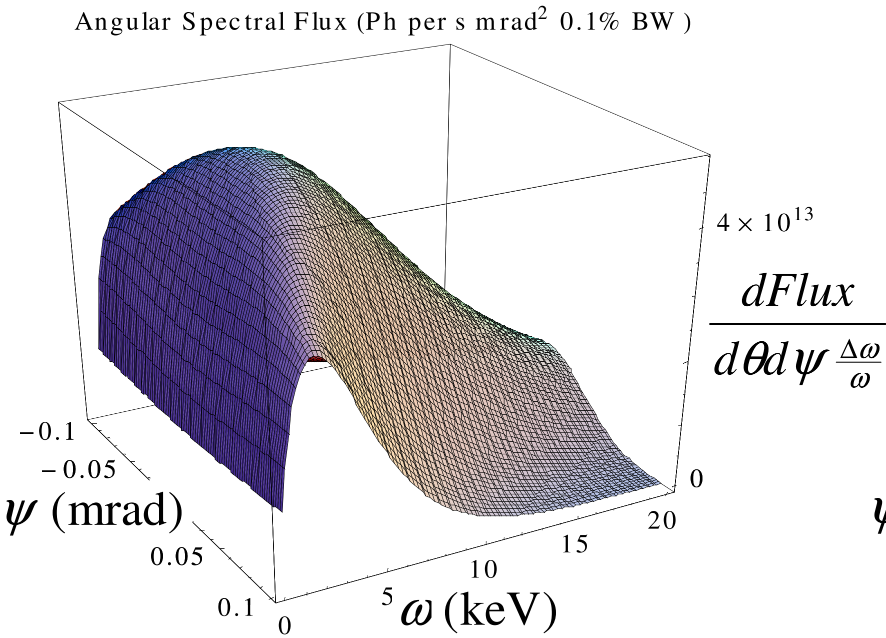
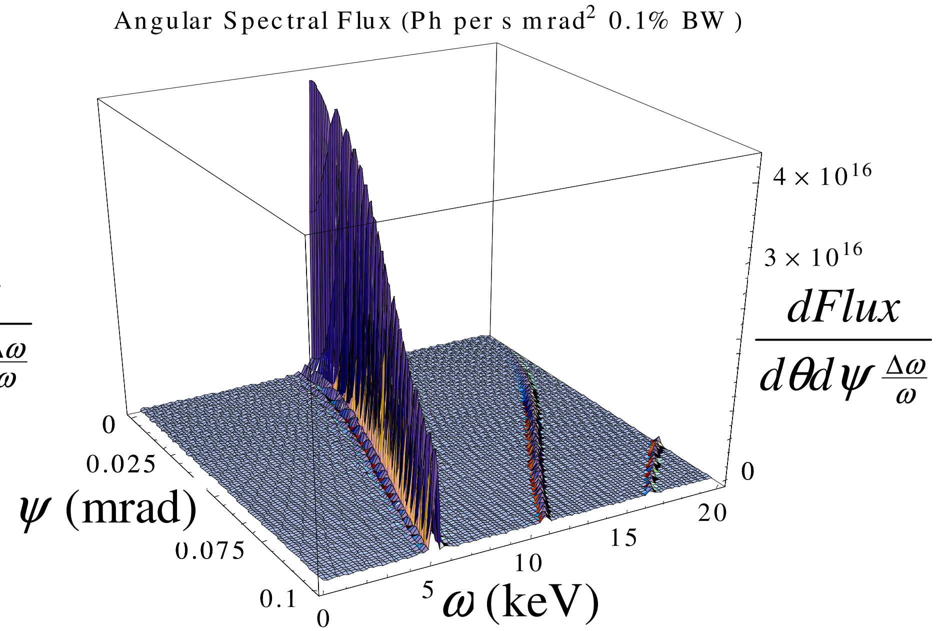
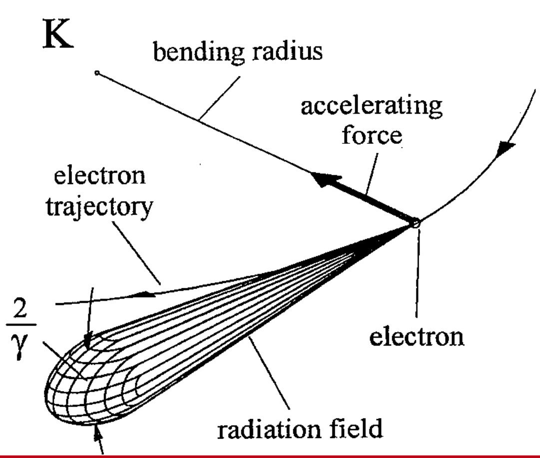


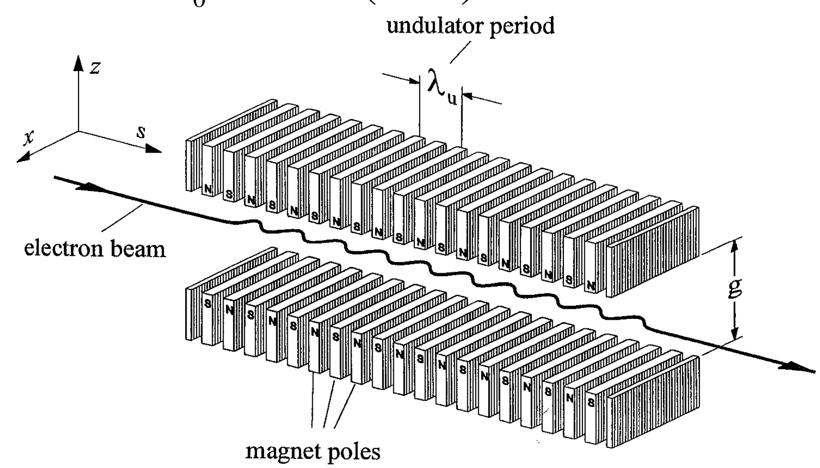


Photon flux in Bends and Undulator

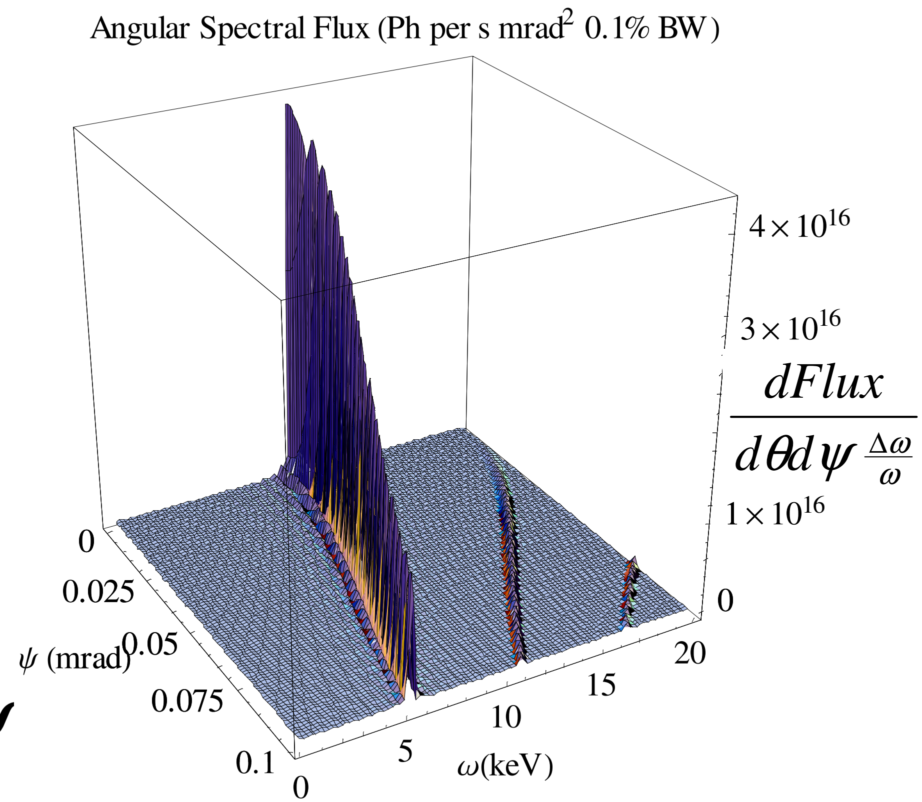








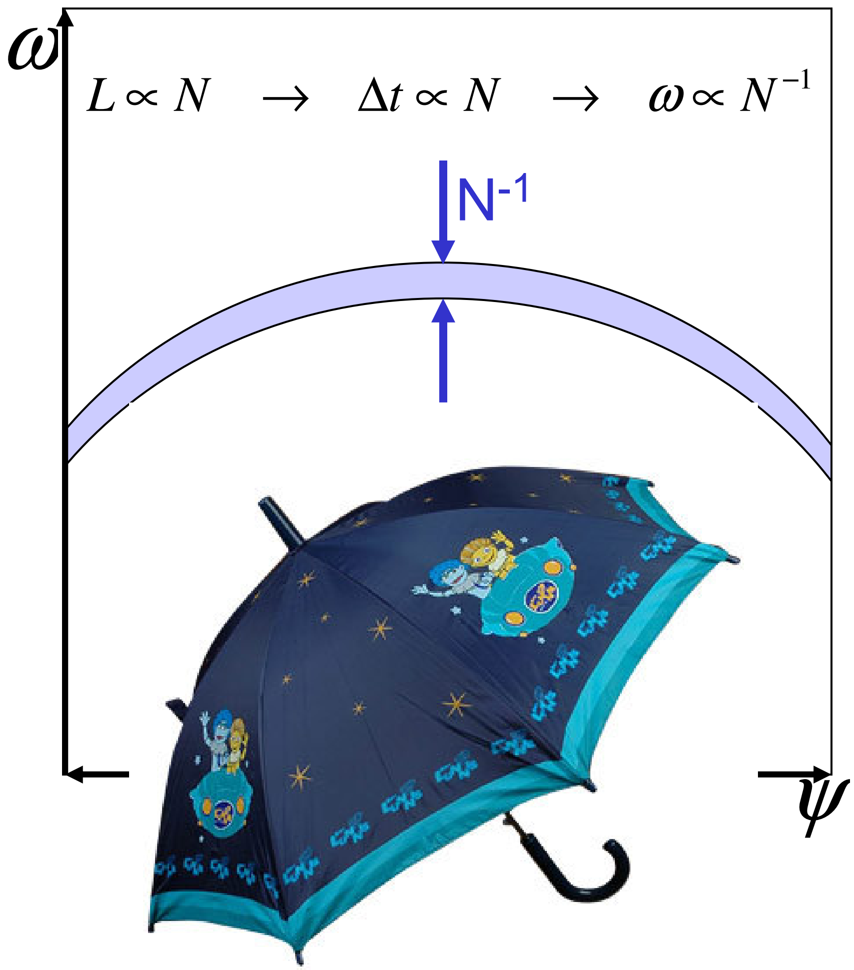
The umbrella of N-pole undulator radiation

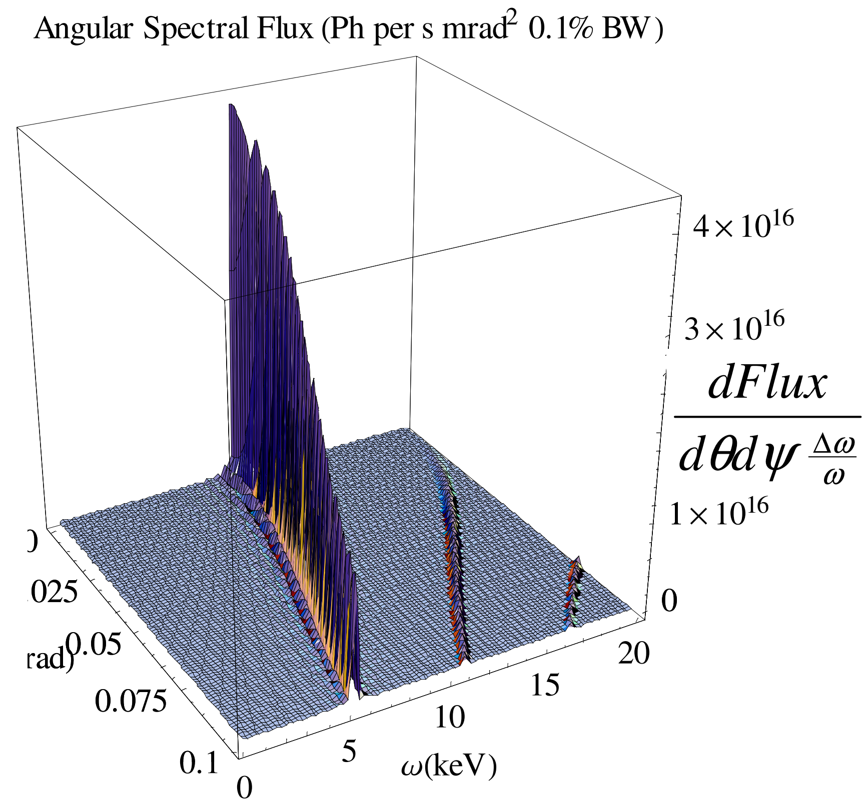


$$F_{total} \propto N$$

Flux from N poles is N times the flux from one pole

The umbrella of N-pole undulator radiation





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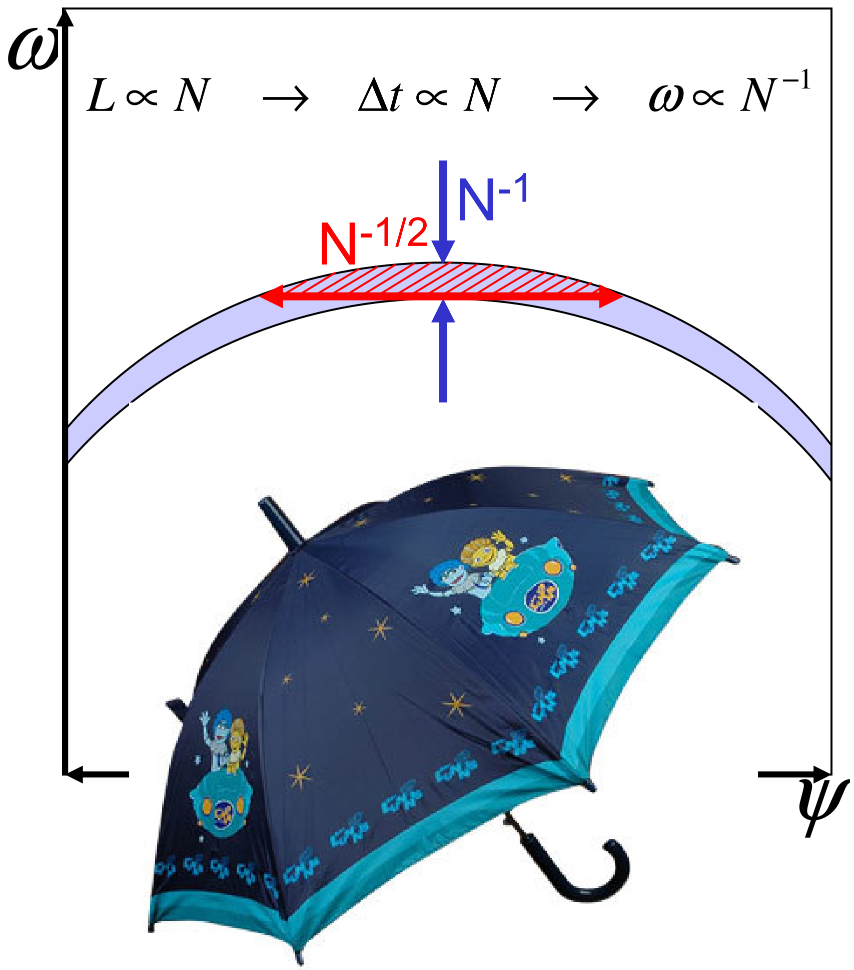
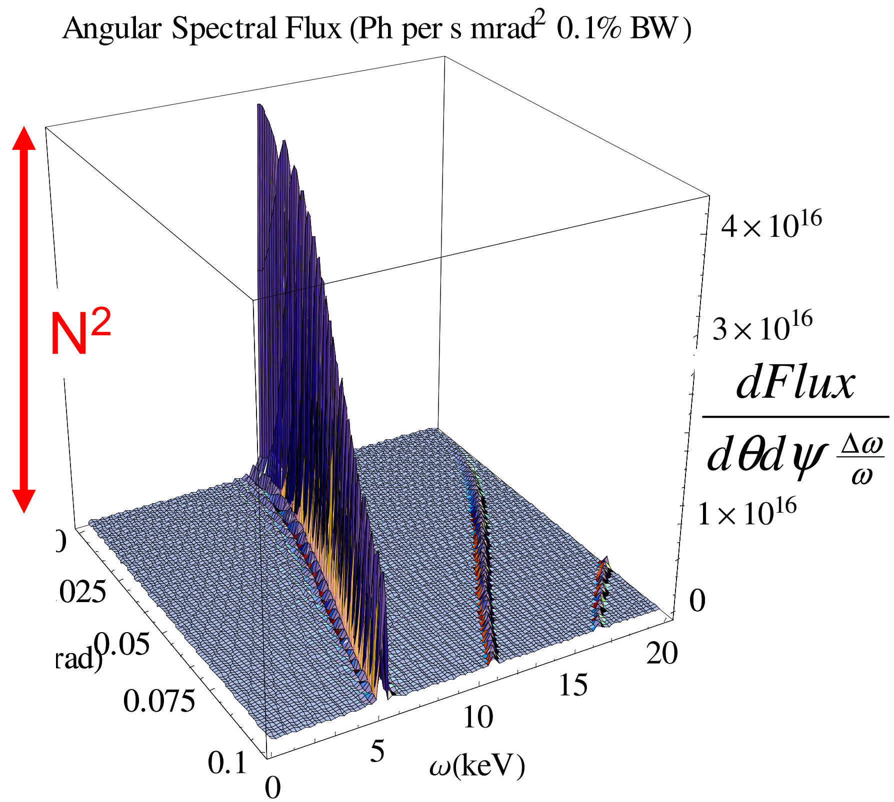


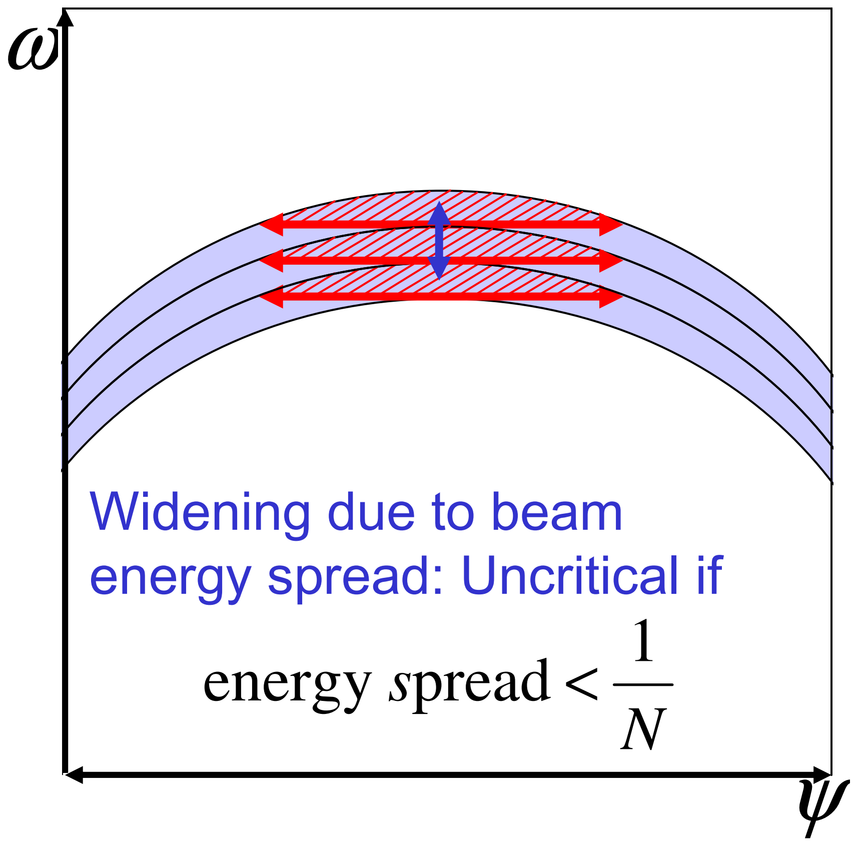


$$F_{total} \propto N$$

The power in the central cone is in dependent of N

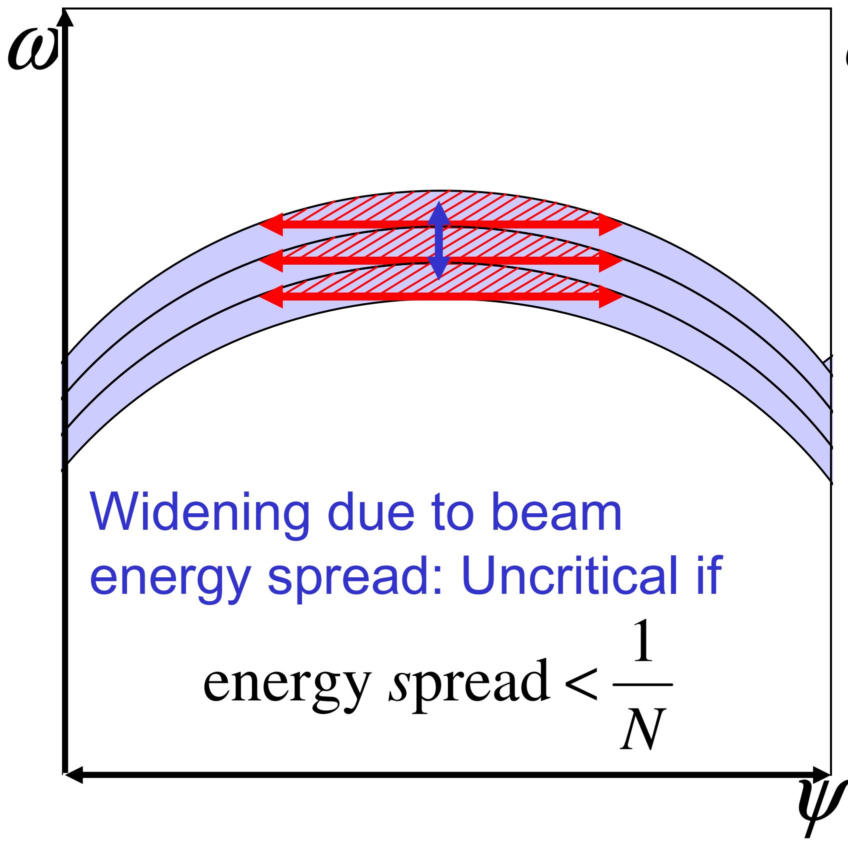
Flux from N poles is N times the flux from one pole

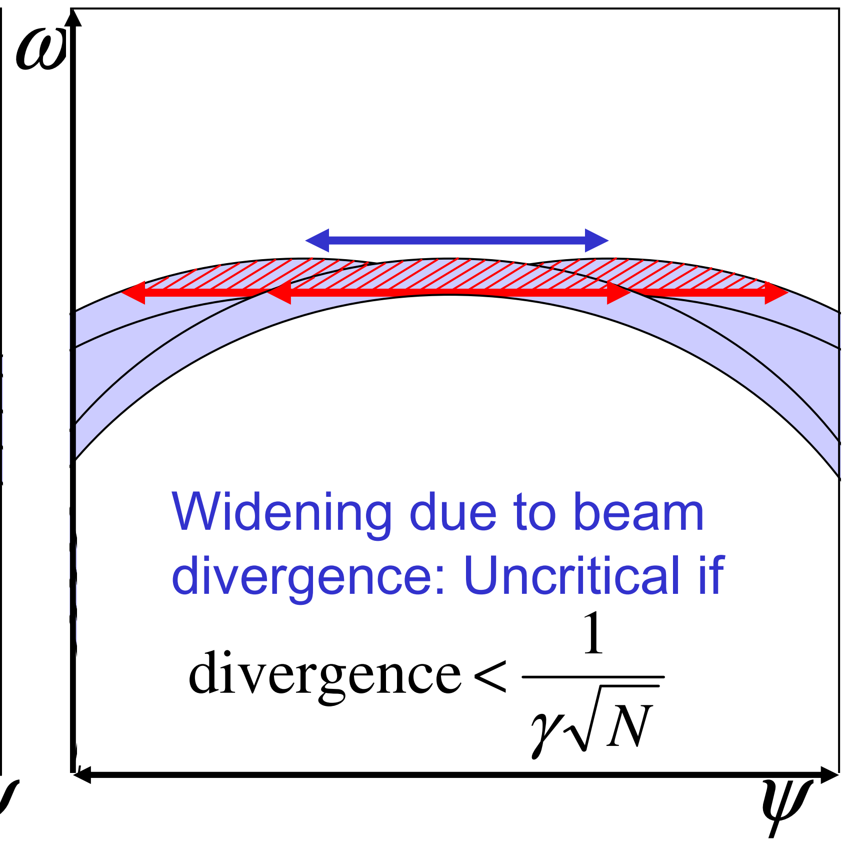
Brightness reduction by beam properties



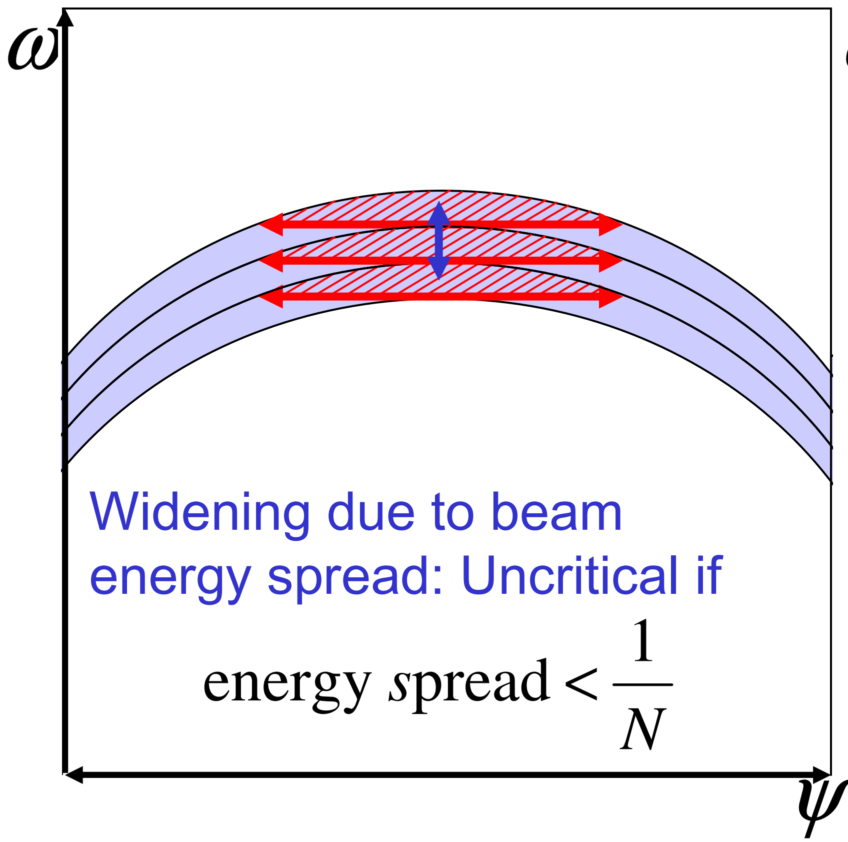
$$\text{energy spread} < \frac{1}{N}$$

Brightness reduction by beam properties



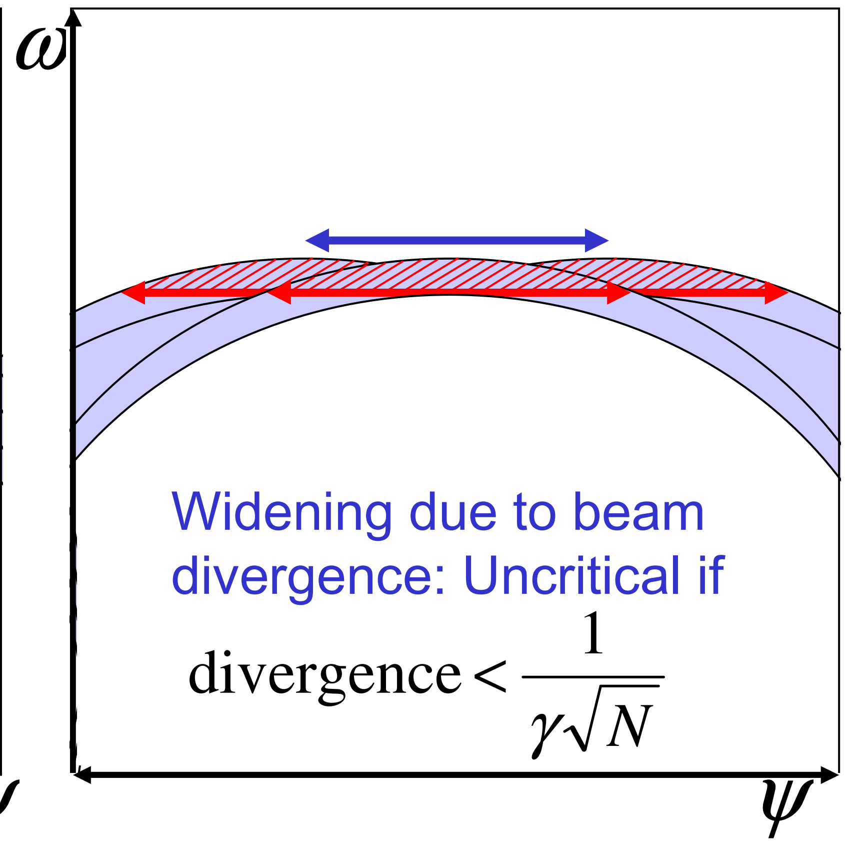


Brightness reduction by beam properties



Widening due to beam energy spread: Uncritical if

$$\text{energy spread} < \frac{1}{N}$$



Widening due to beam divergence: Uncritical if

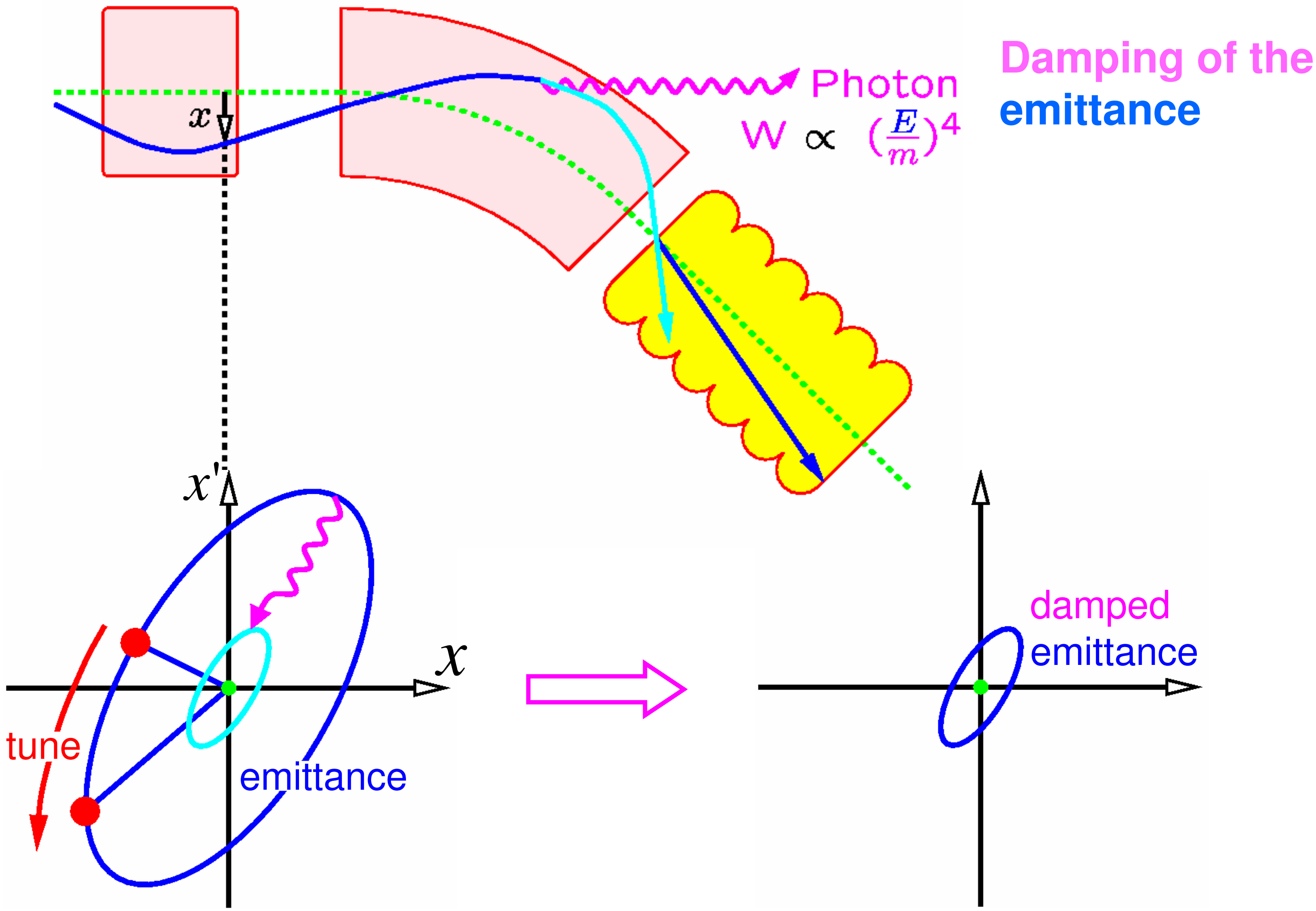
$$\text{divergence} < \frac{1}{\gamma\sqrt{N}}$$

Diffraction: The minimal spot size that can produce such a divergence is:

$$\text{spot size} < \frac{\lambda}{\text{divergence}}$$

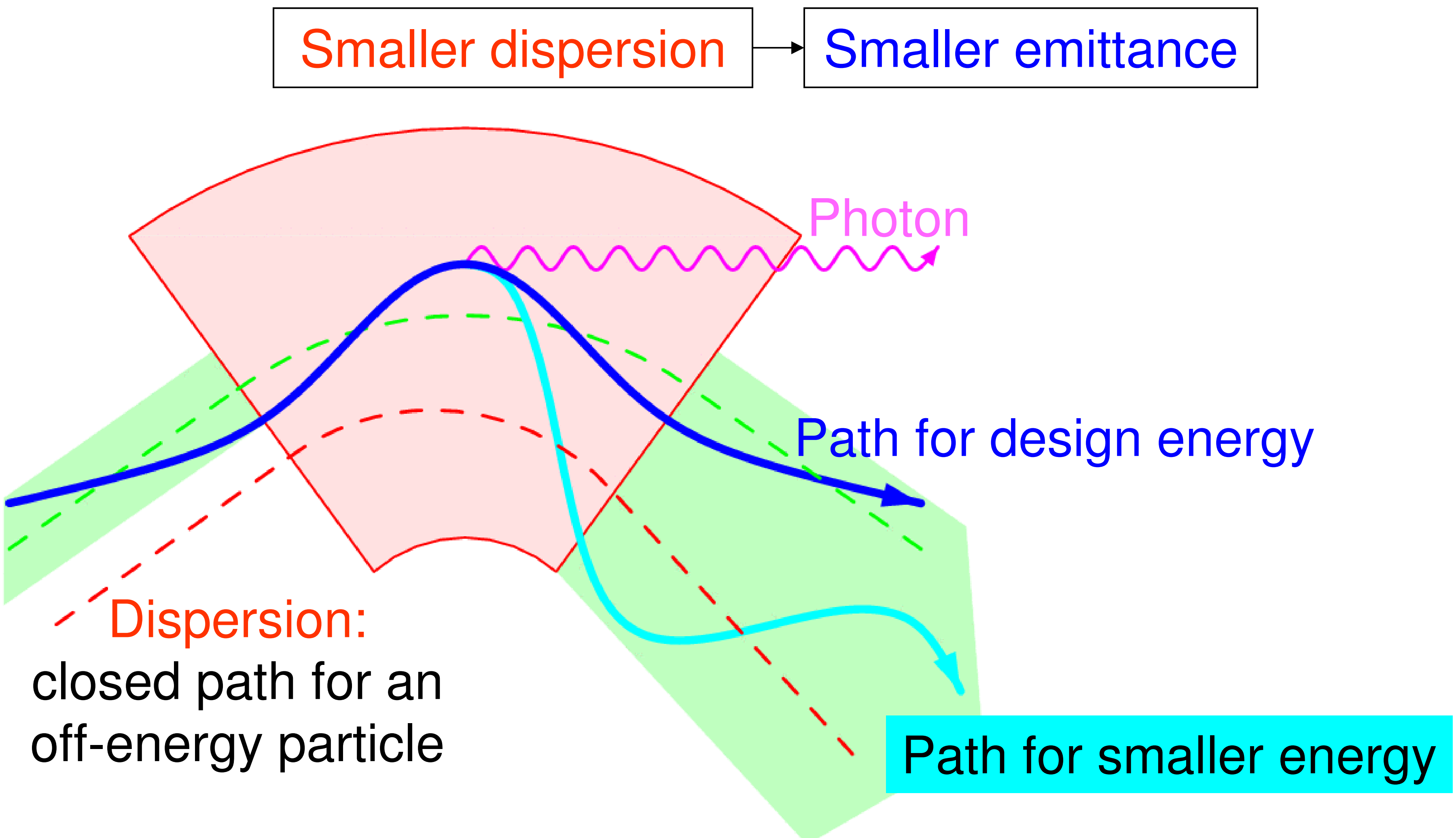
If a beam with this divergence in an undulator has a such a small spot size, then the beam properties do not dilute the radiation characteristics.

Emittance Damping



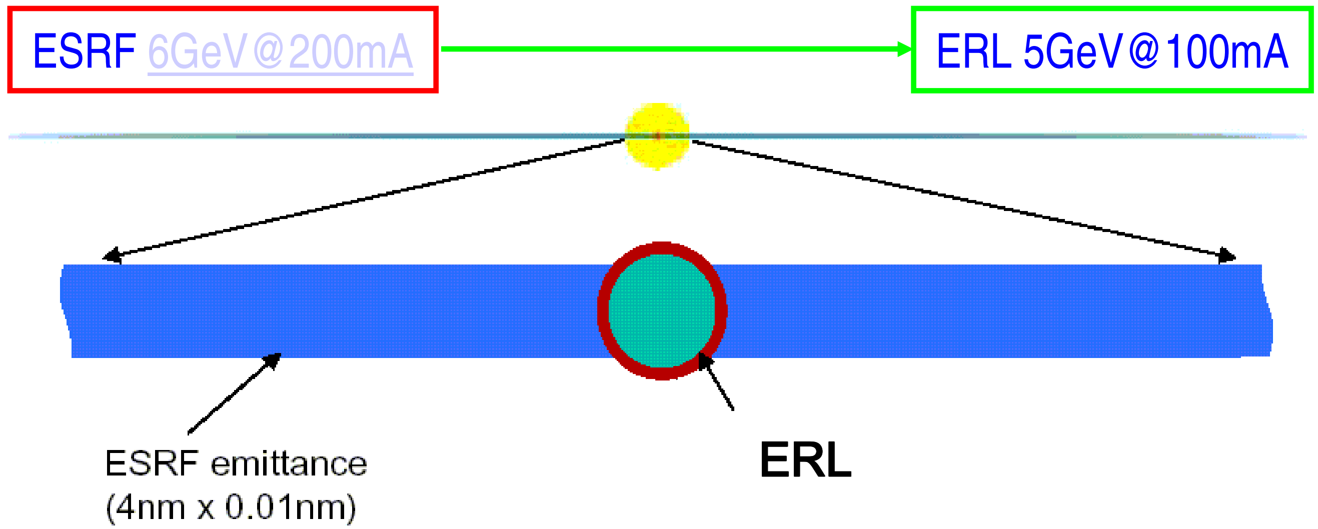
Emittance Excitation

CHESS & LEPP

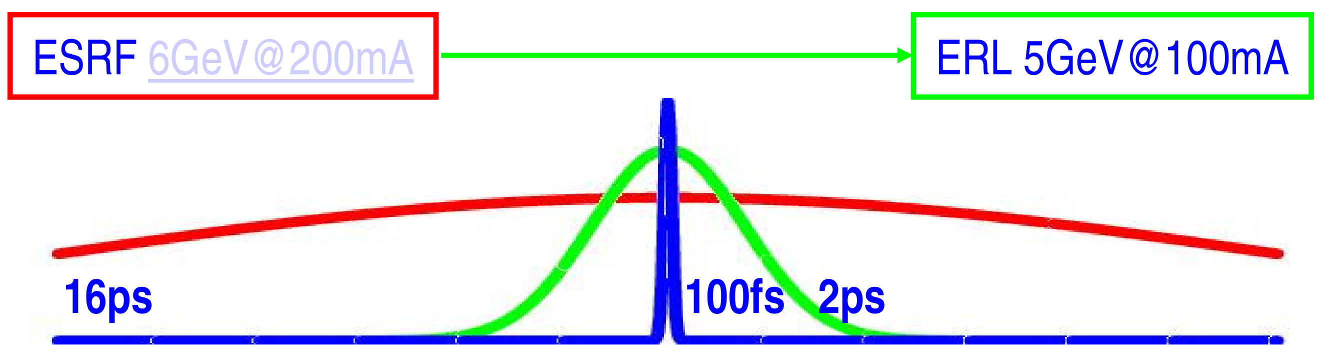


How good are ERL beam goals?

Transverse emittance reduction:



Bunch-legth reduction:



Smaller Beams and more Coherence

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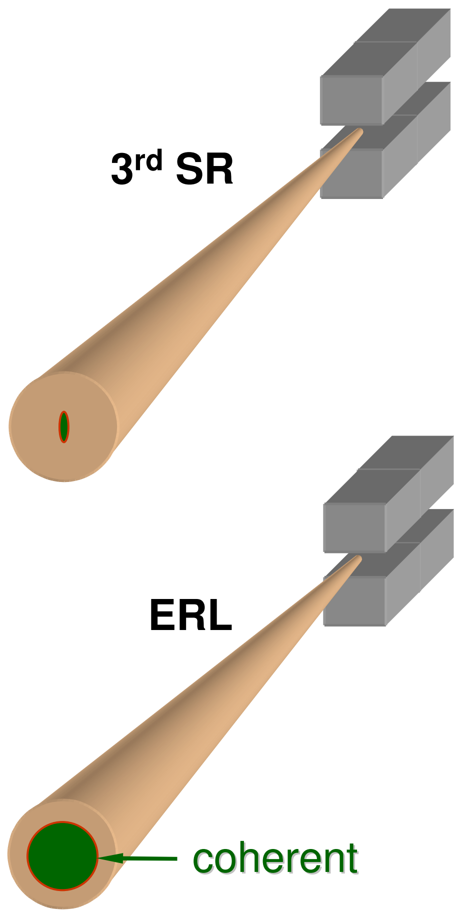
- Coherent x-ray diffraction imaging
- It would, in principle, allow atomic resolution imaging on non-crystalline materials.
- This type of experiments is completely limited by coherent flux.



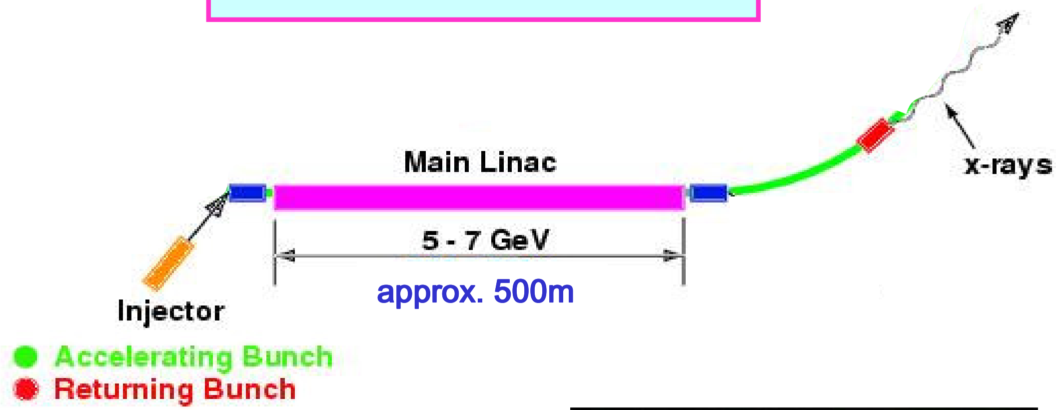
Factor 100 more coherent flux for ERL for same x-rays, or provide coherence for harder x-rays

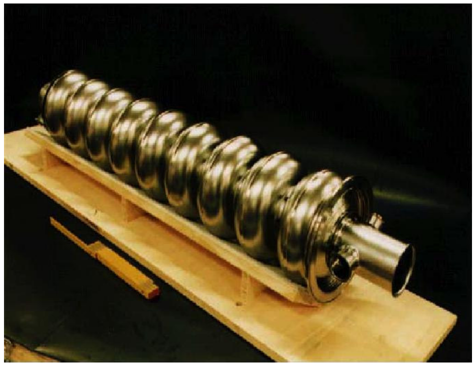
Principle of an X-ray ERL

CHESS & LEPP

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

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

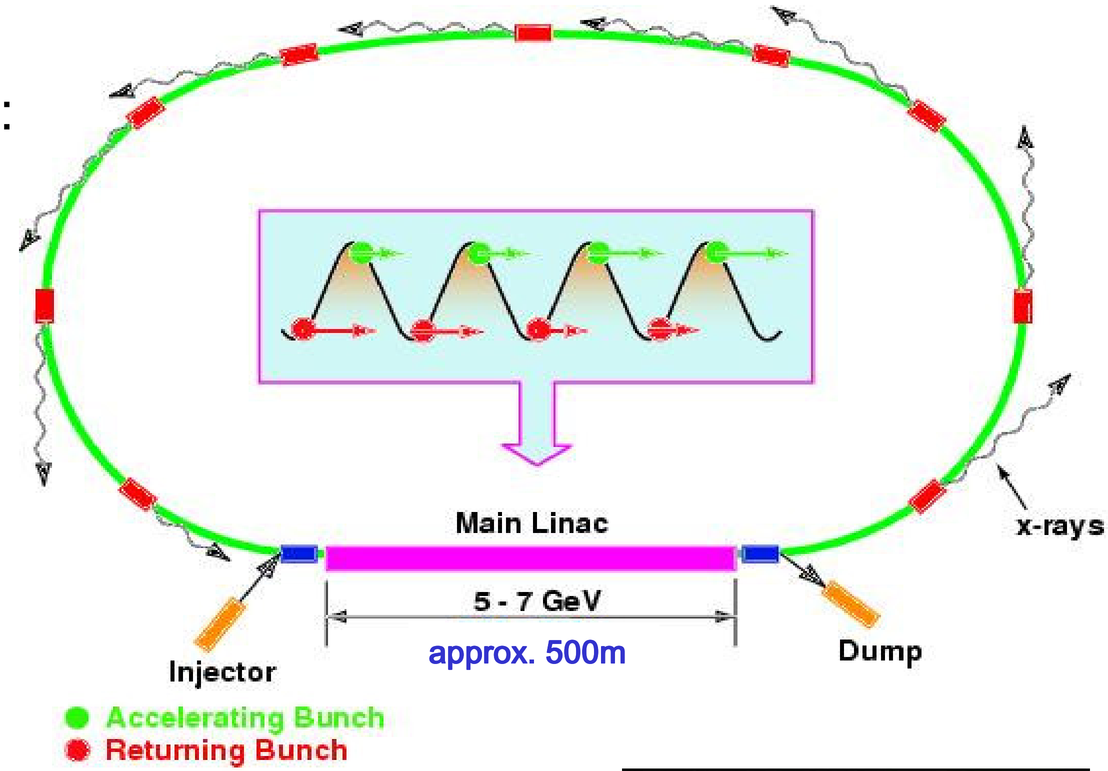




Principle of an X-ray ERL

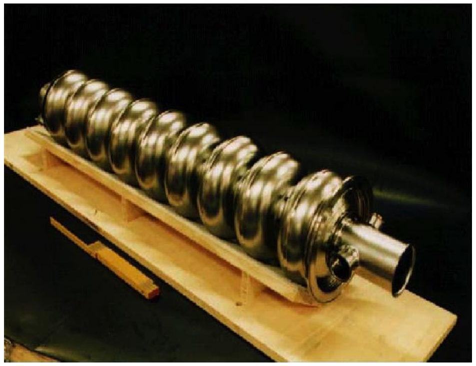
CHESS & LEPP

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



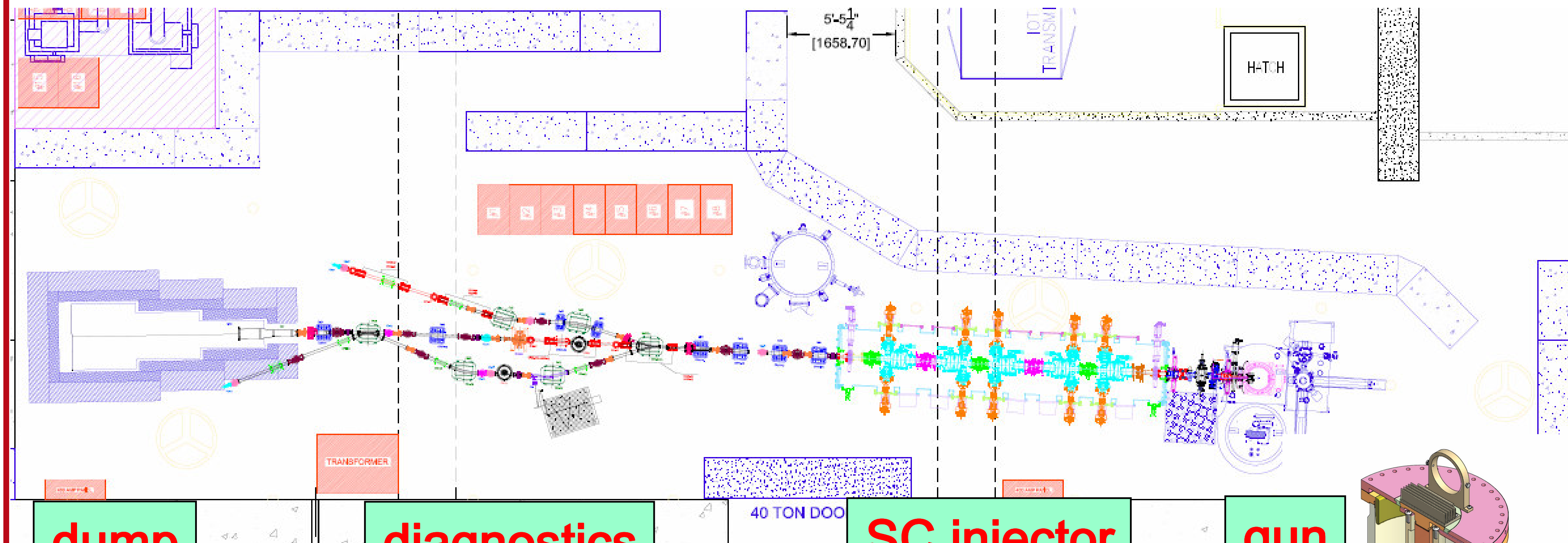
Challenges:

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



Injector prototype: Verification of beam acceleration

CHESS & LEPP

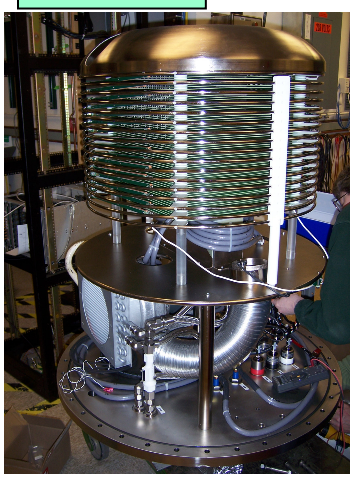


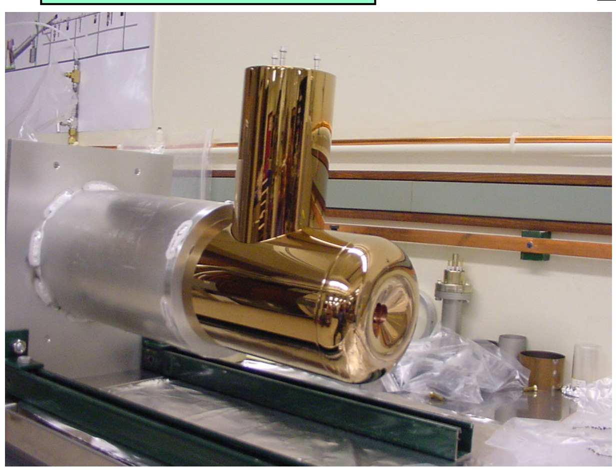
dump

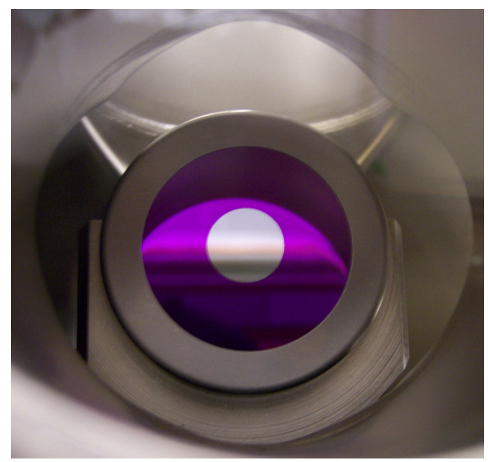
diagnostics

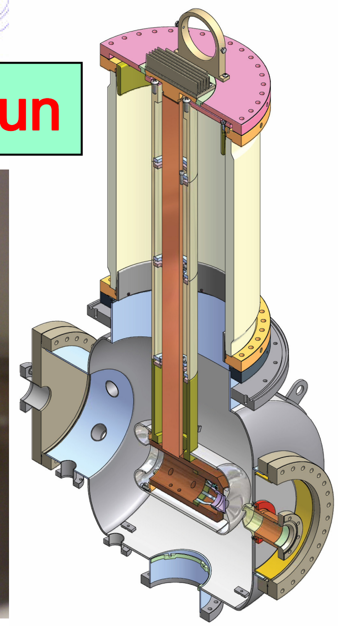
SC injector

gun



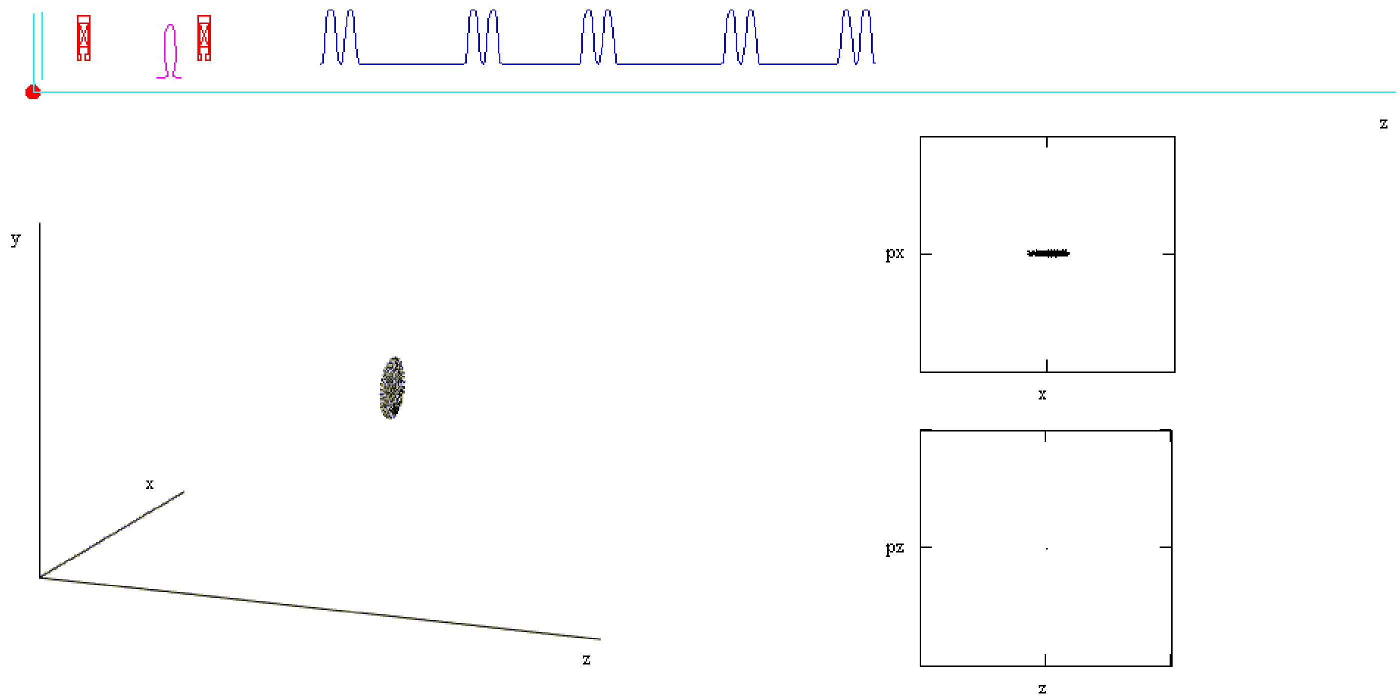




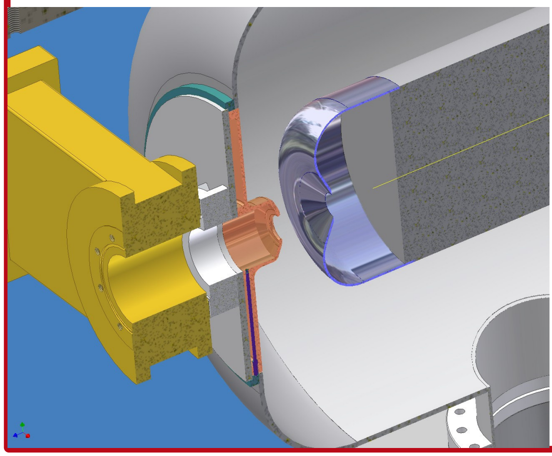


The injector: round beam optimization

CHESS & LEPP



courtesy Ivan Bazarov

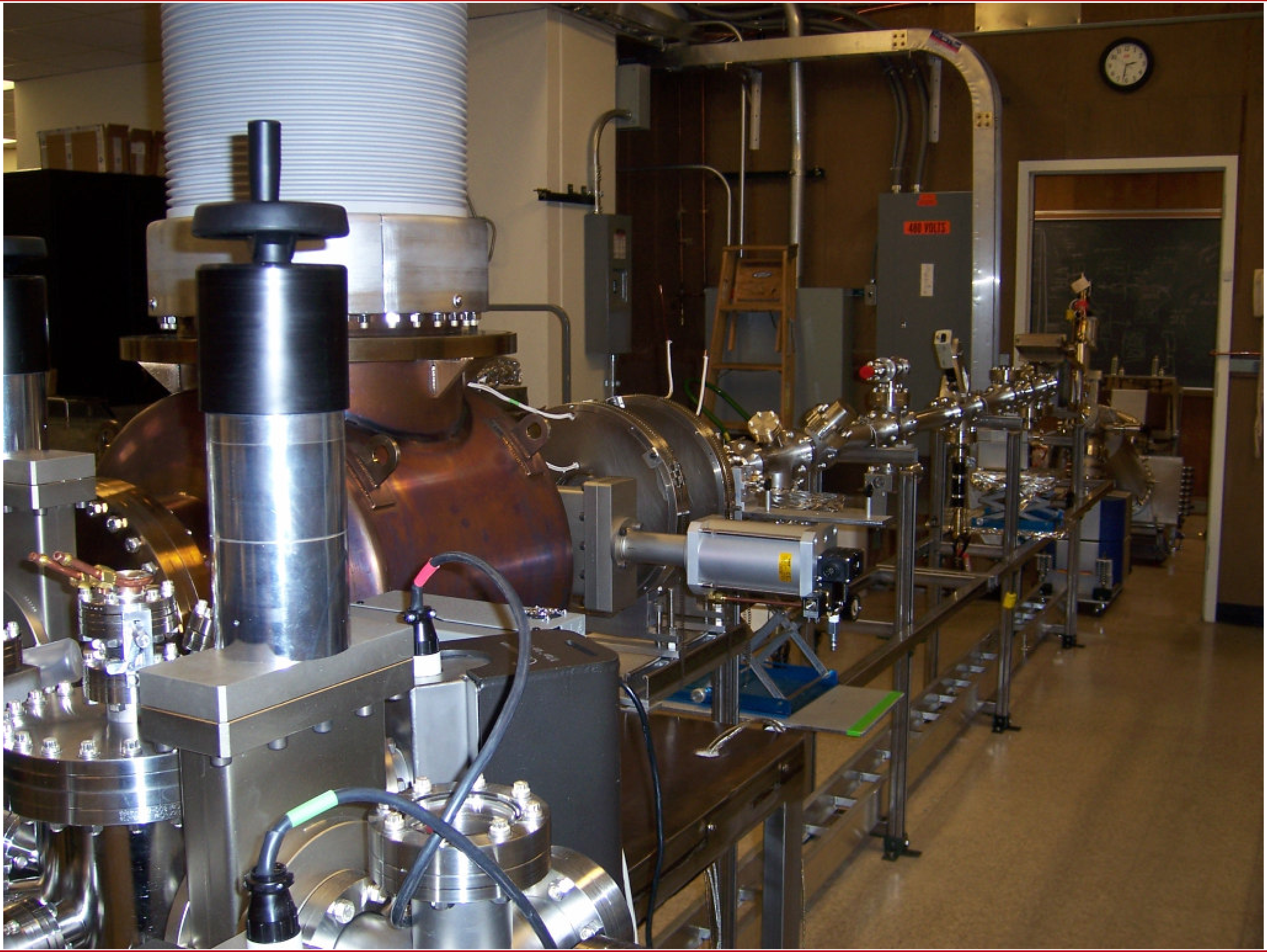


DC source for high current & low emittances

- 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

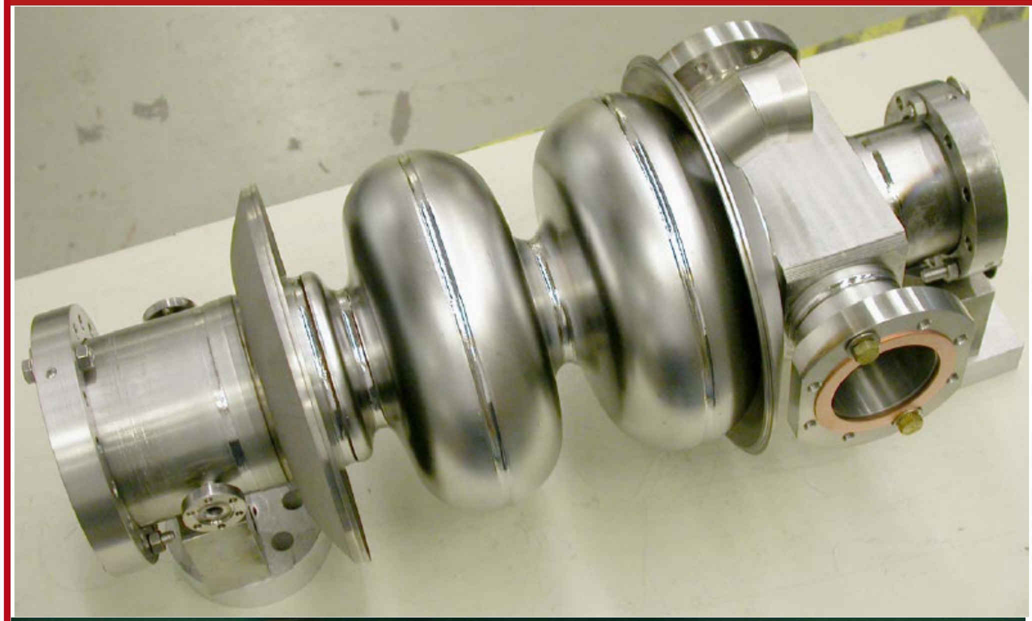
Gun prototype: well advanced

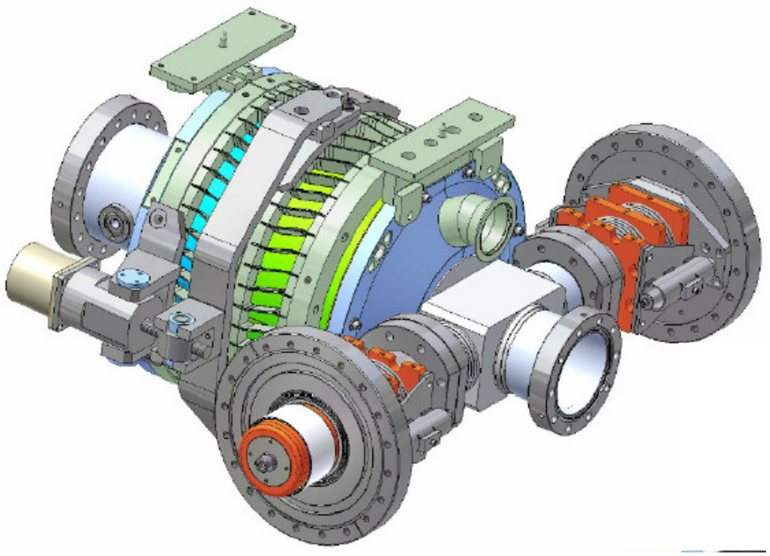
CHESS & LEPP



ERL accelerator R&D and construction

CHESS & LEPP

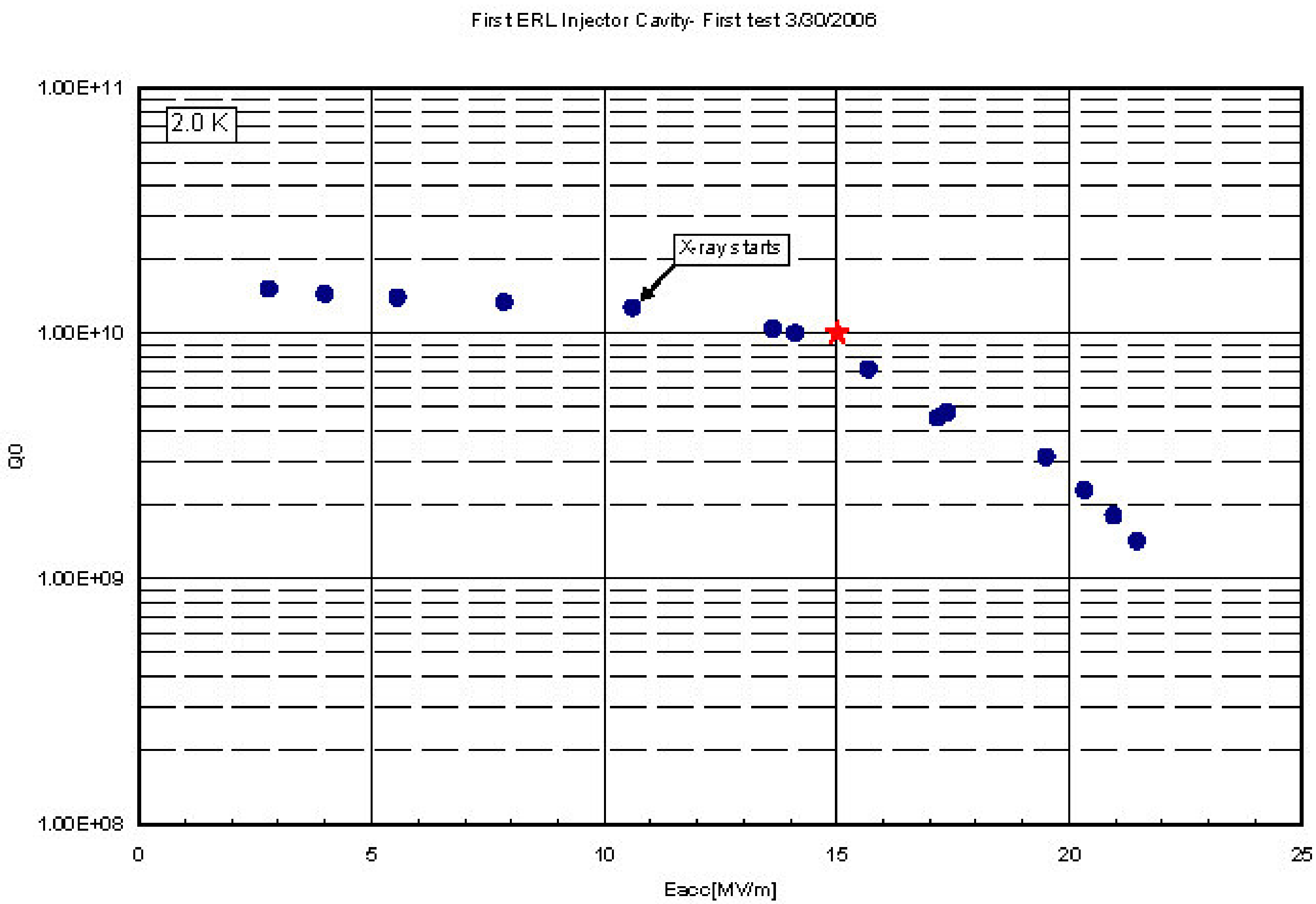




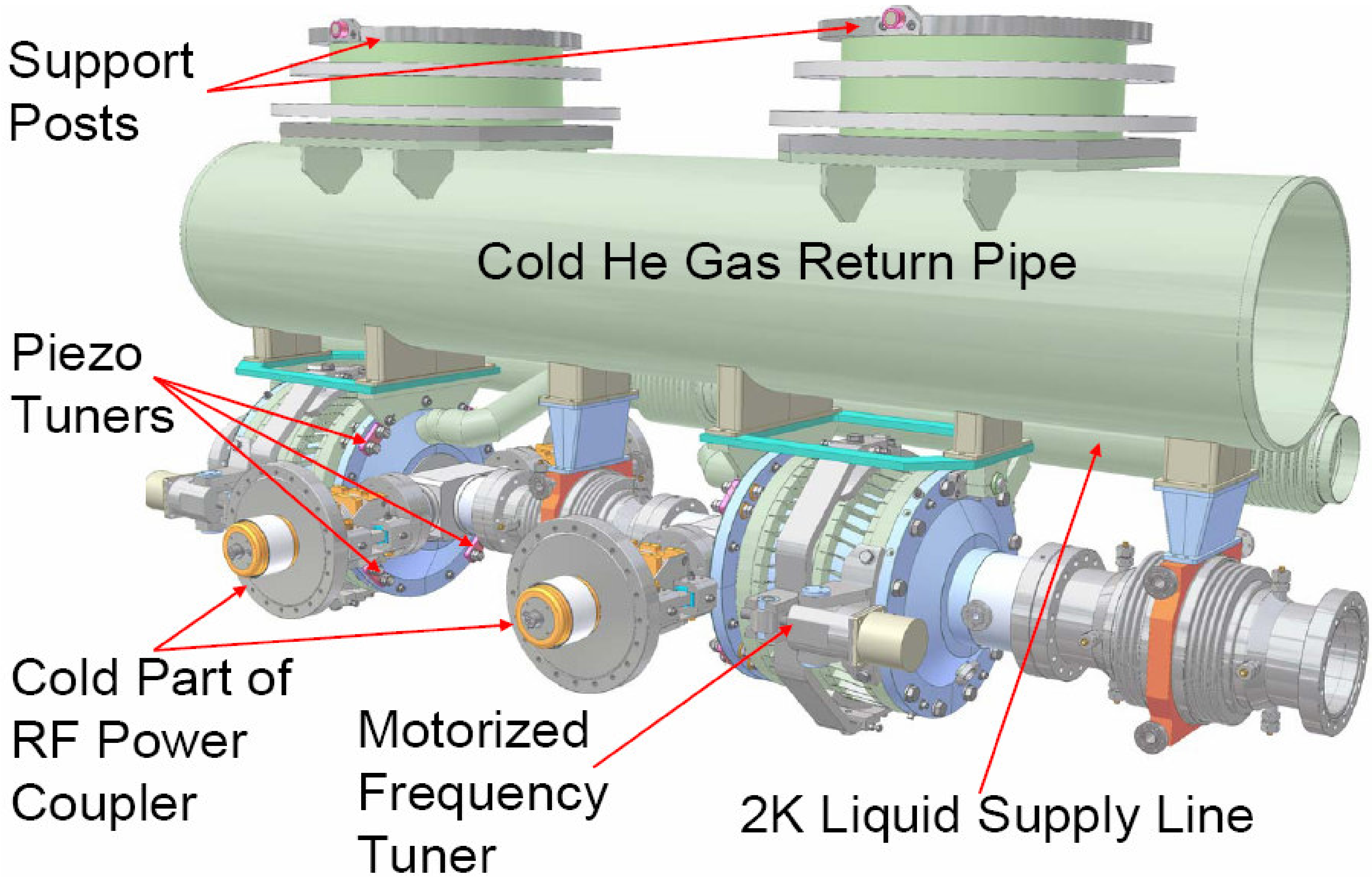
Superconducting Cavities, high power input coupler, and high precision frequency tuners are all developed and build at Cornell (with outside collaborators)

First vertical test

CHESS & LEPP

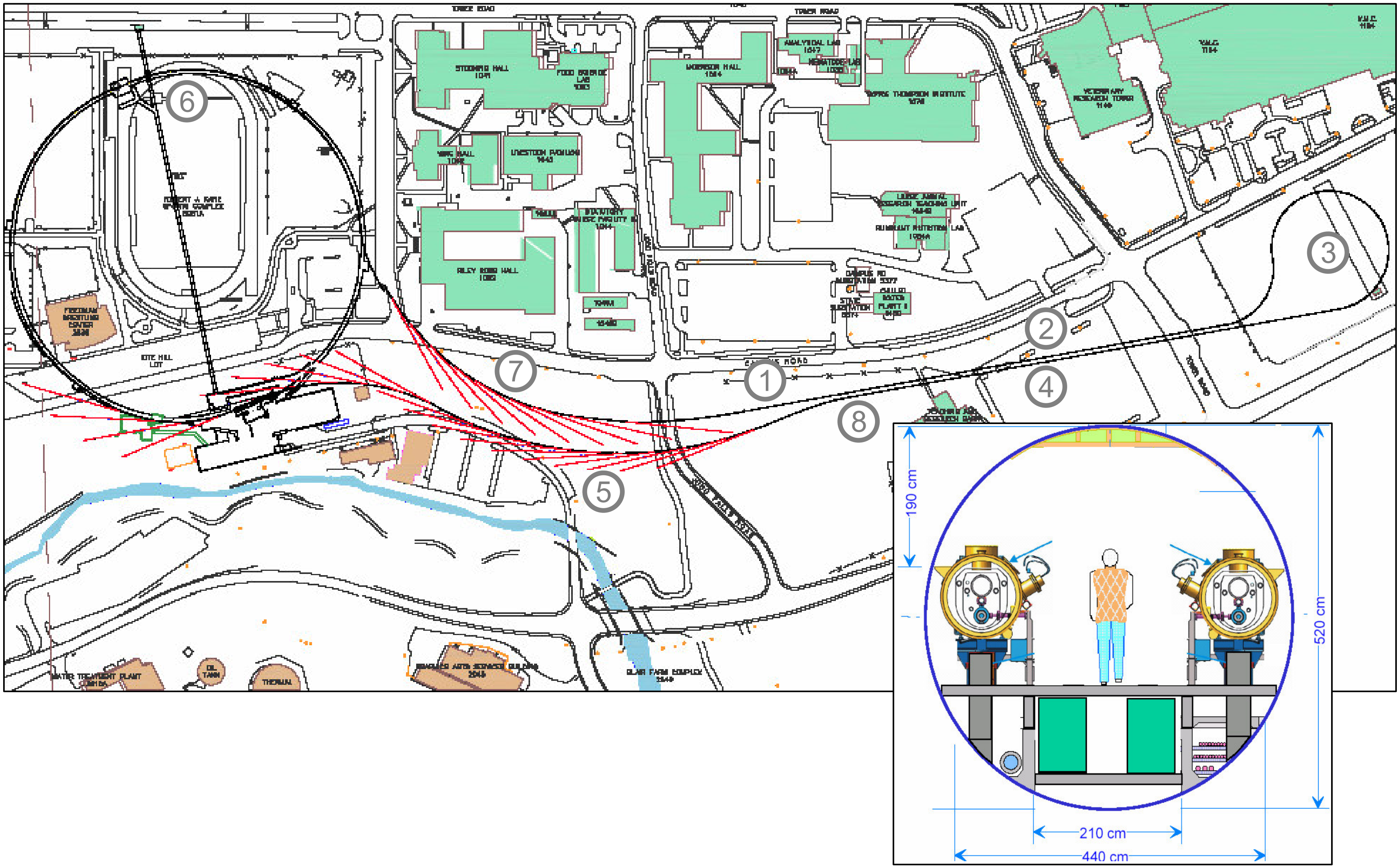


Assembly of the injector accelerator



ERL@CESR design version 1.3

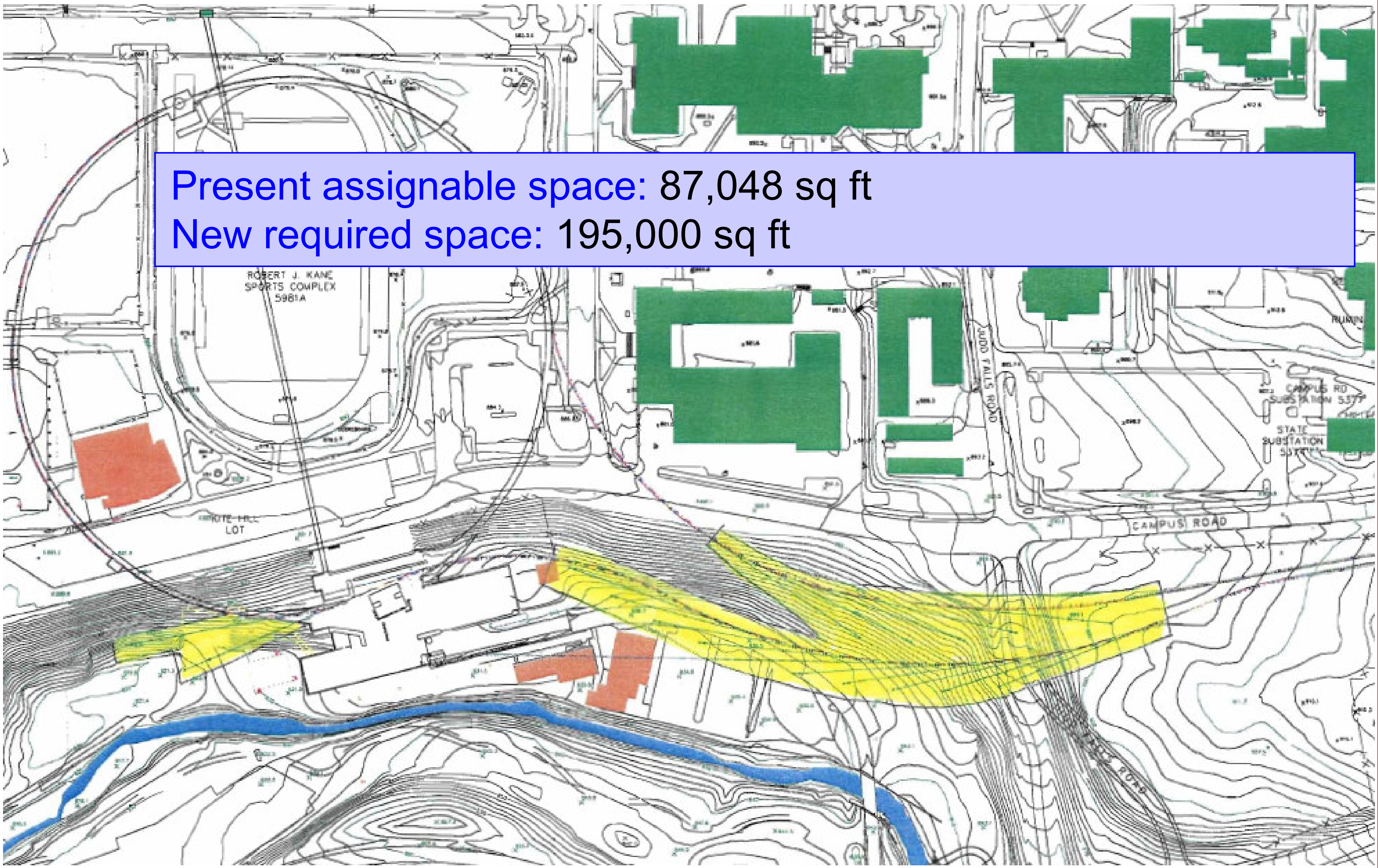
CHESS & LEPP



Space requirements

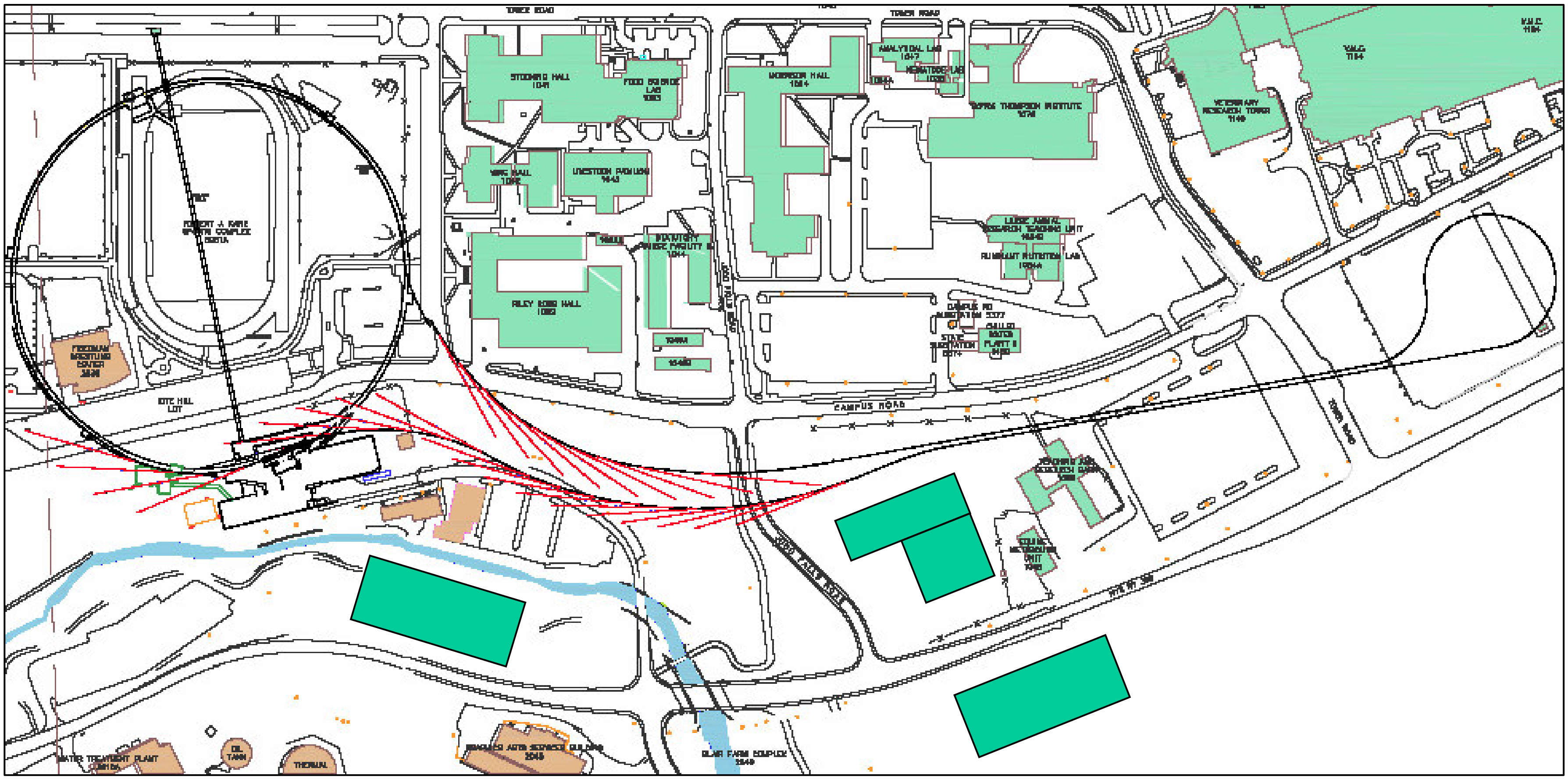
CHESS & LEPP

Present assignable space: 87,048 sq ft
New required space: 195,000 sq ft



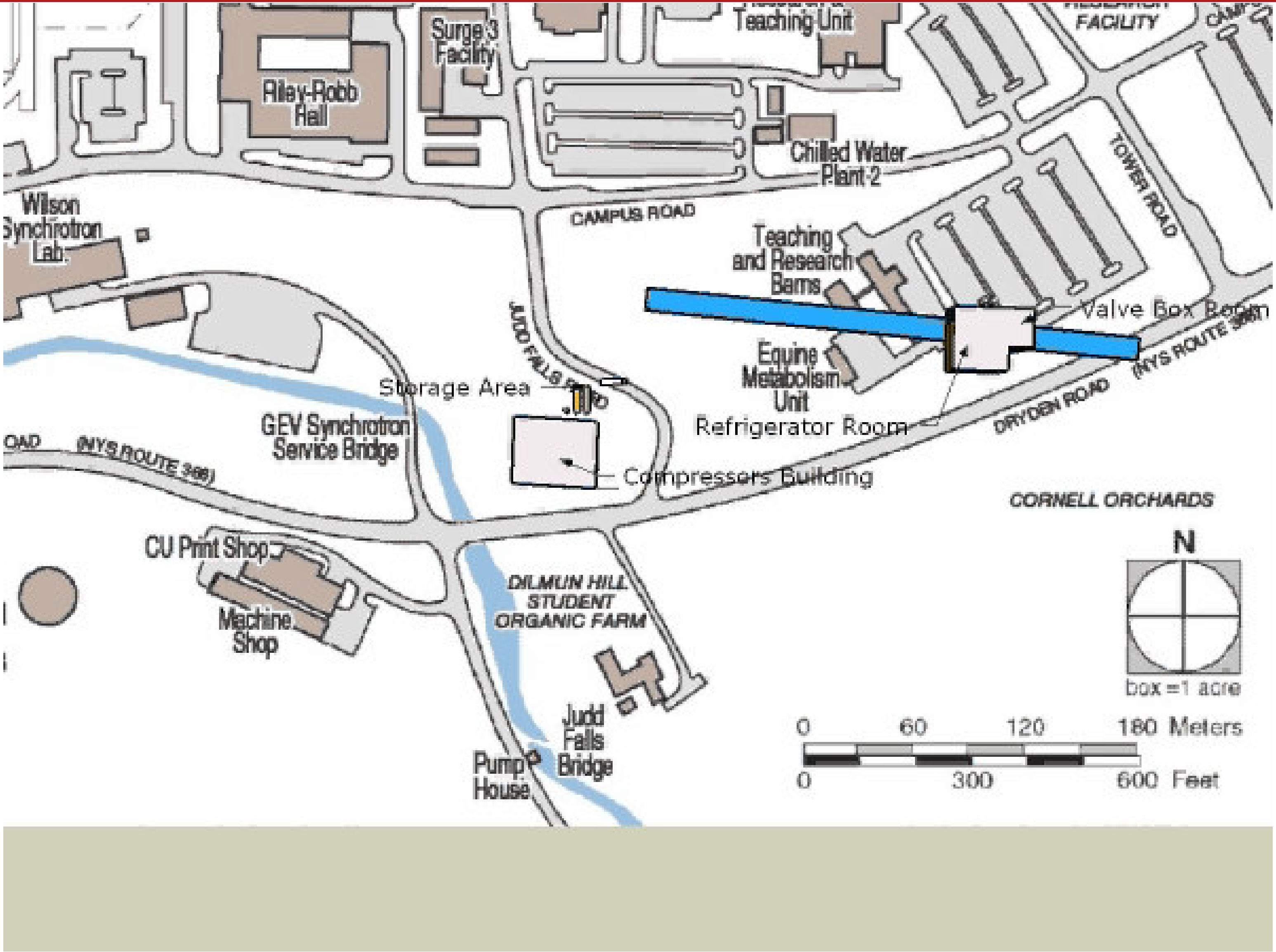
Cryogenic building

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



Cryogenic building

CHESS & LEPP

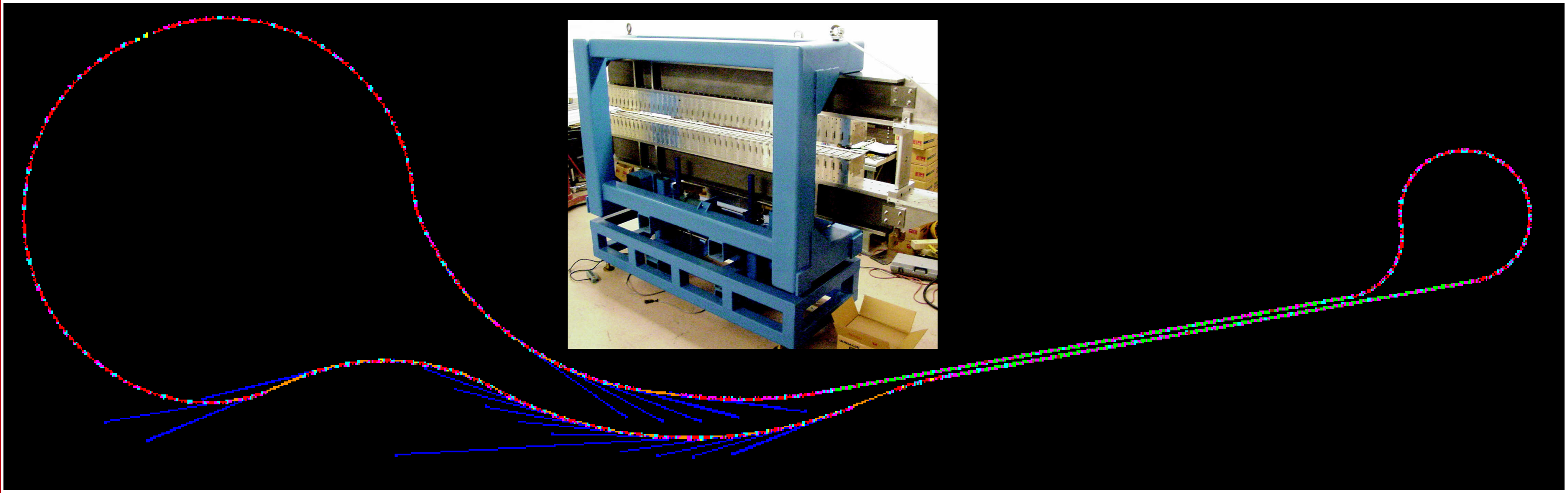


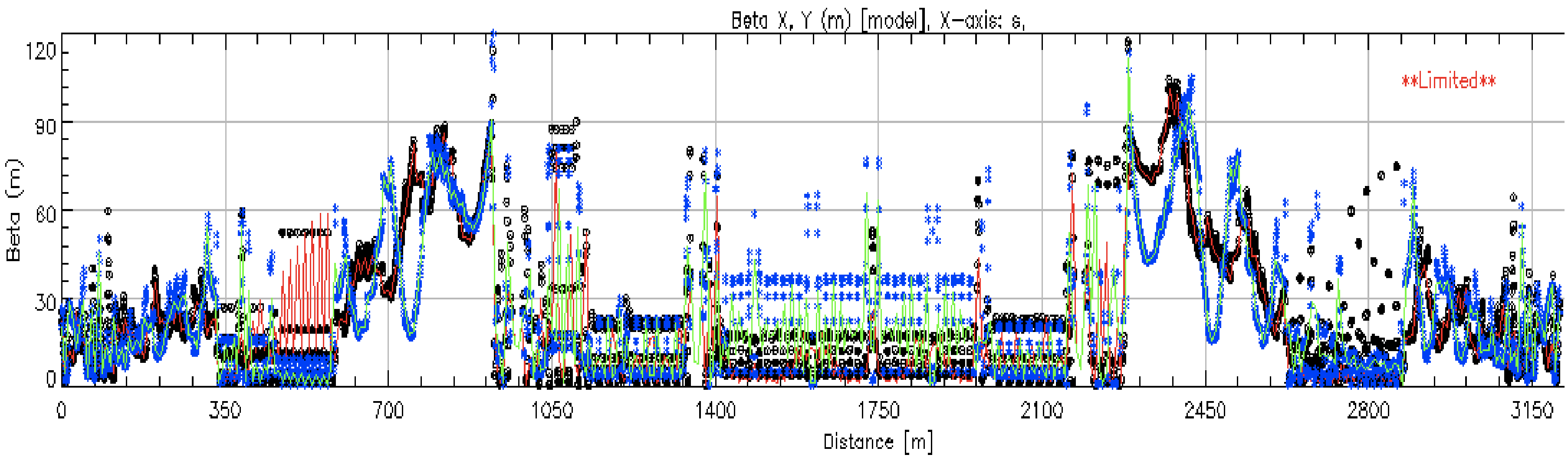
Advantages of ERL@CESR

- Operation of CESR and ERL test simultaneously.
- Use all of the CESR tunnel.
- Lots of space for undulators.
- Space for future upgrades, like an FEL.
- No basements of existing buildings to worry about.
- Only one tunnel for two linacs.
- Example character for other existing light sources.

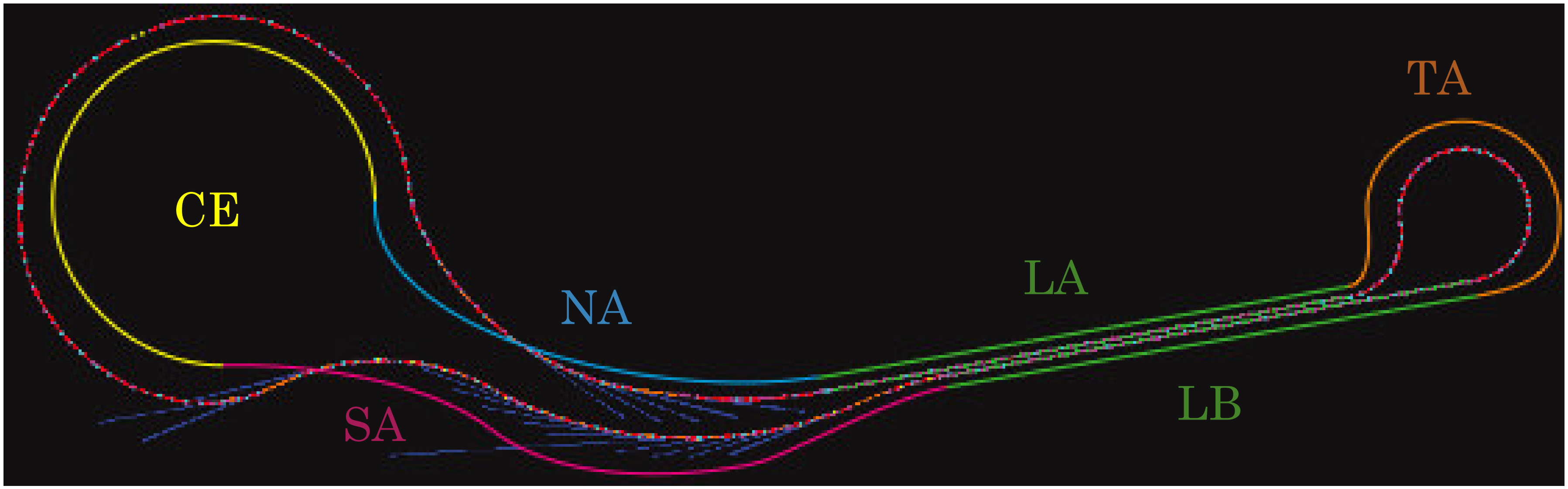
Linear Optics (A – high brilliance)

CHESS & LEPP



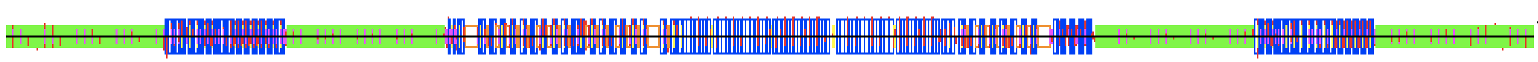


Incoherent Synchrotron Radiation (ISR)



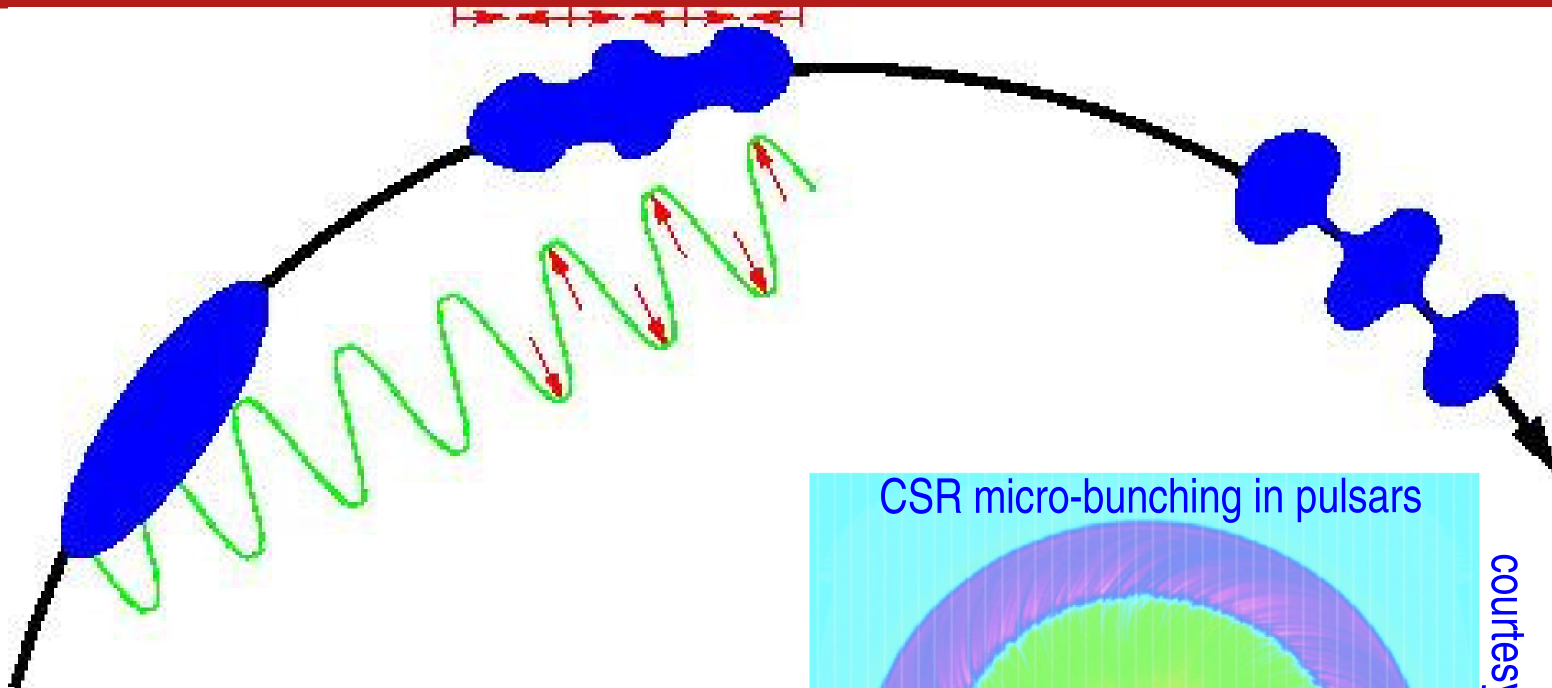
TS.SE.SSNAM#S.DDD#DC”
MA.SA.CELLB05.Qua03a

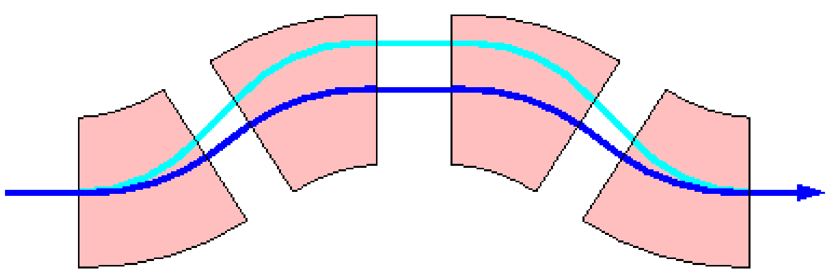
LB
TA
LA
NA
CE
SA
LB
TA
LA



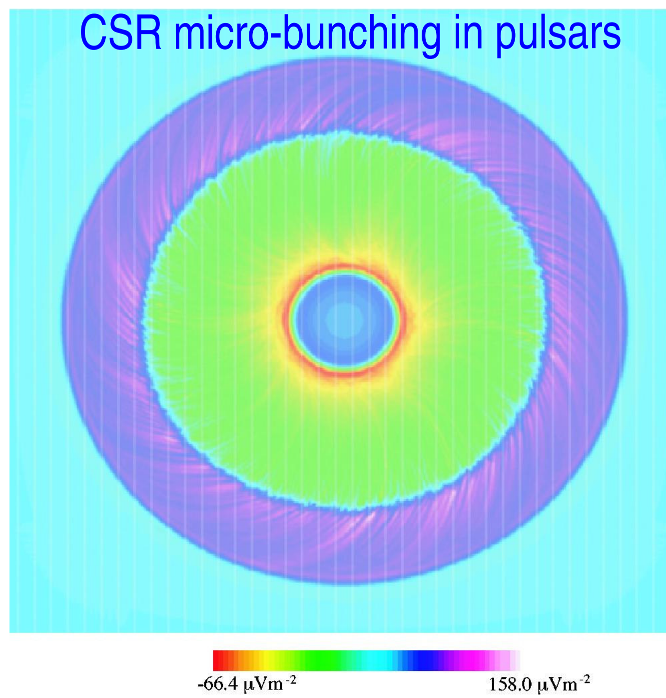
Coherent Synchrotron Radiation

CHESS & LEPP





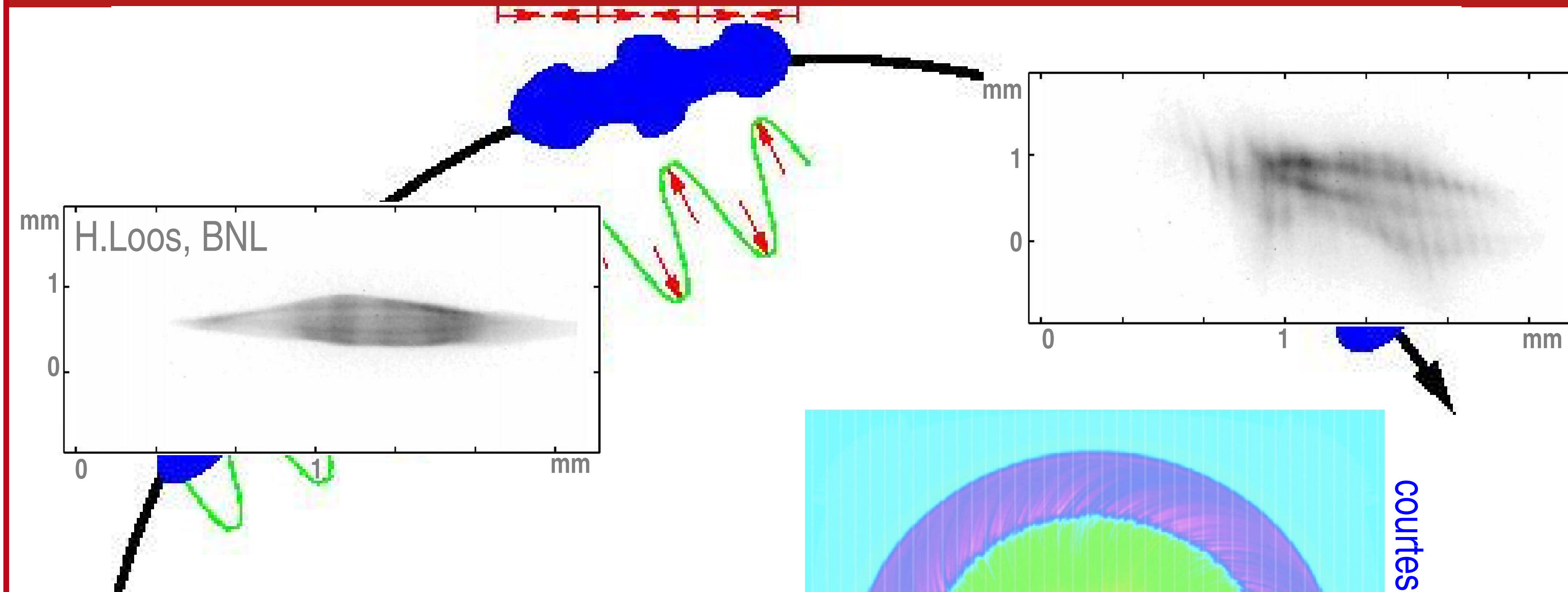
Bunch compressor in an ERL

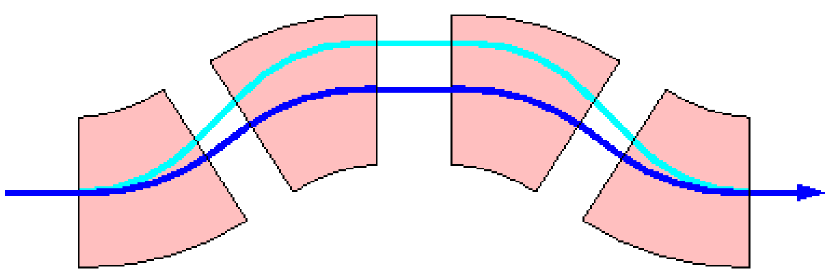


courtesy Bjoern Schmekel

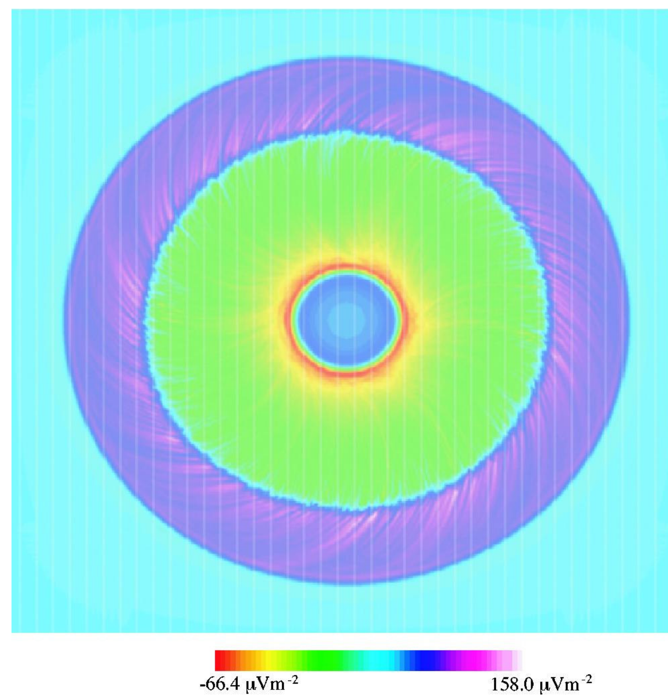
Coherent Synchrotron Radiation

CHESS & LEPP





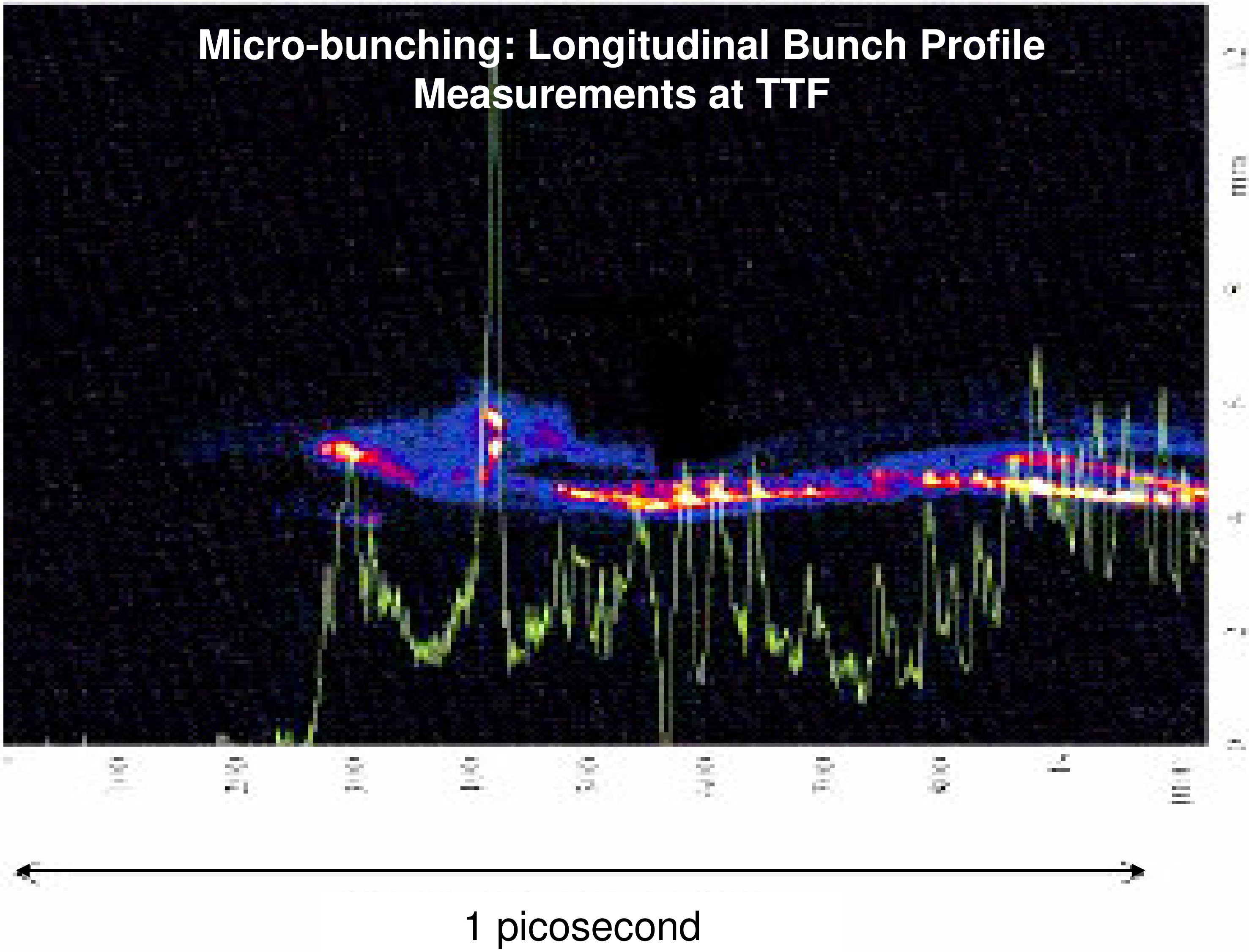
Bunch compressor in an ERL



courtesy Bjoern Schmekel

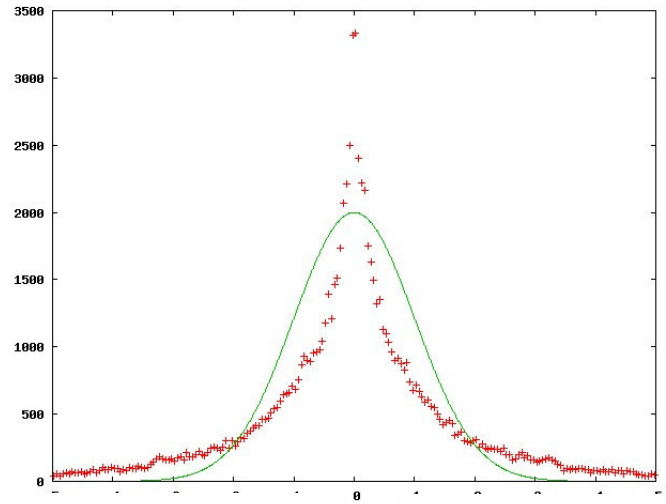
Microbunching due to CSR

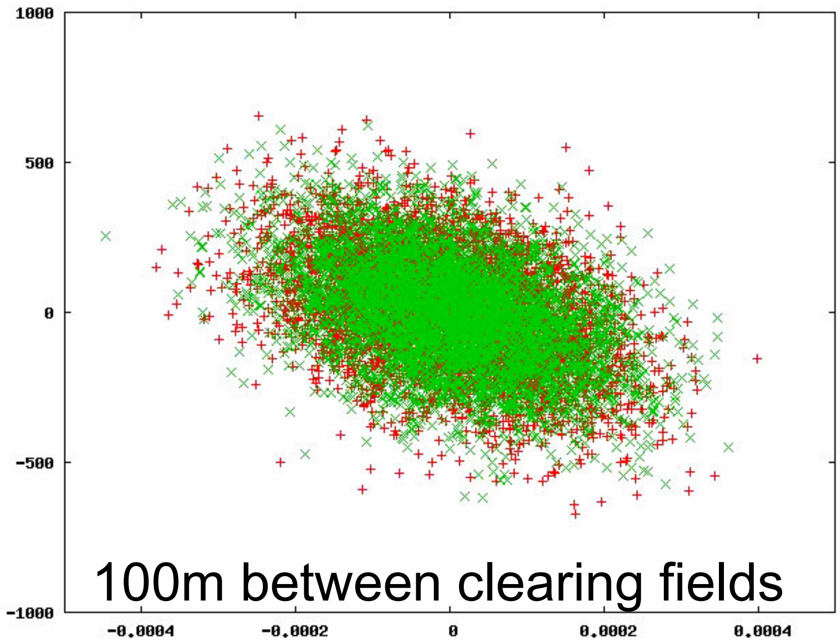
CHESS & LEPP



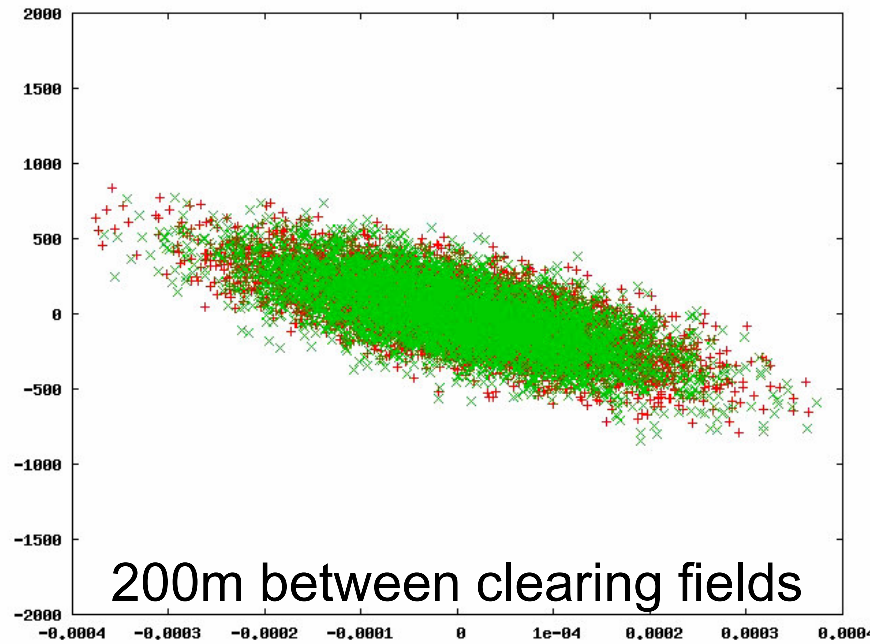
Ions in an ERL beam

CHESS & LEPP





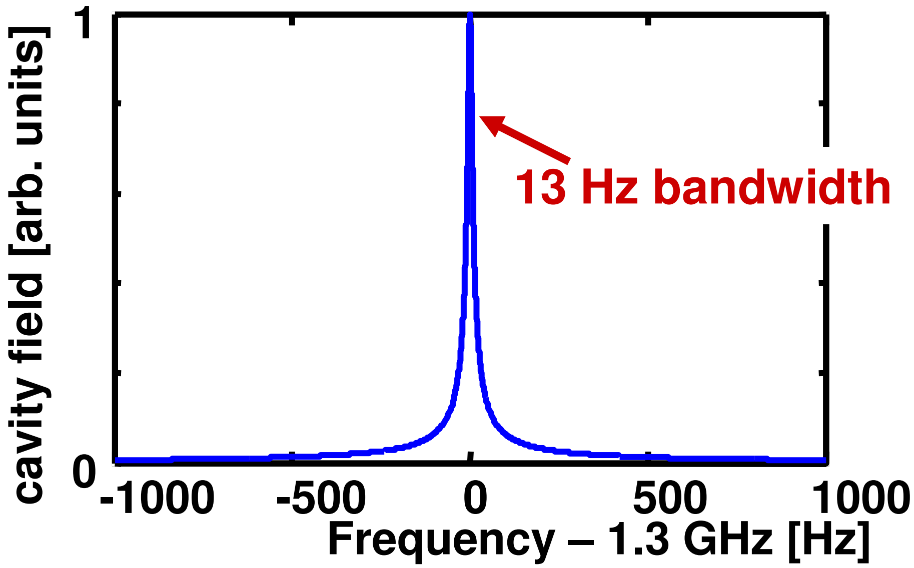
100m between clearing fields

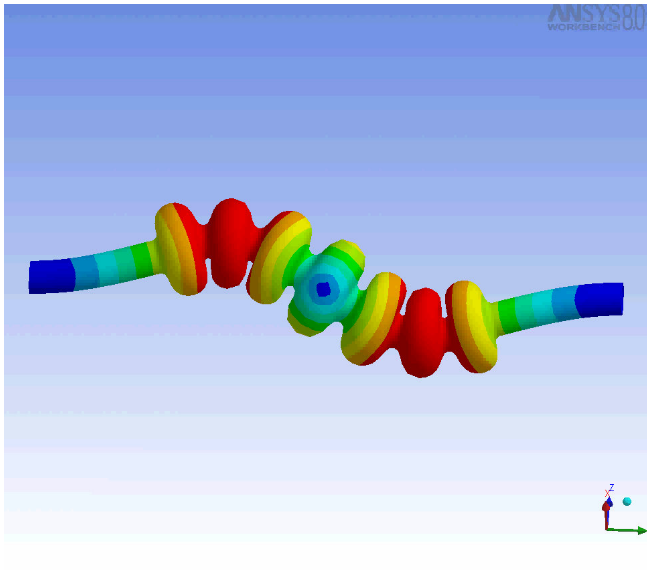


200m between clearing fields

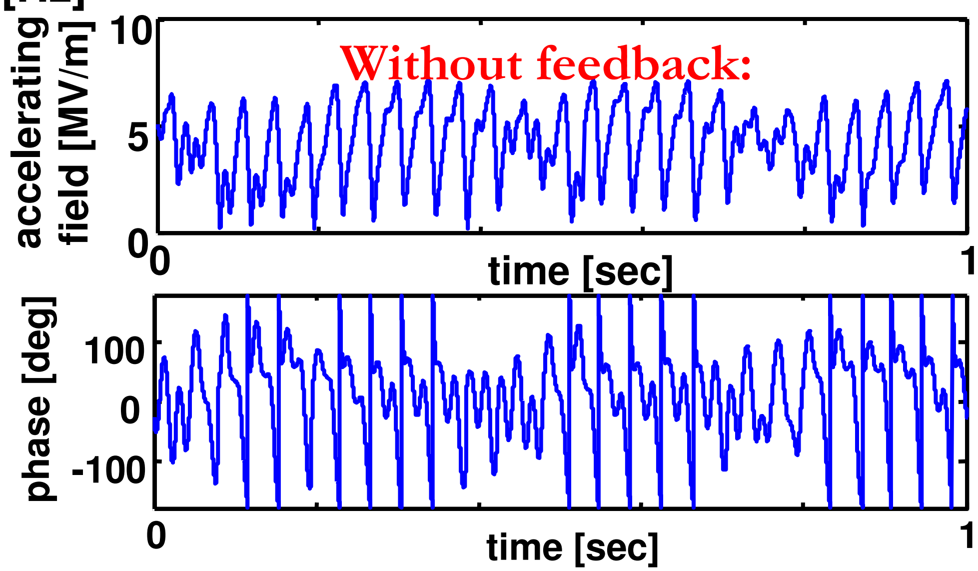
Cavity control for SC linacs (ERL & ILC)

CHESS & LEPP



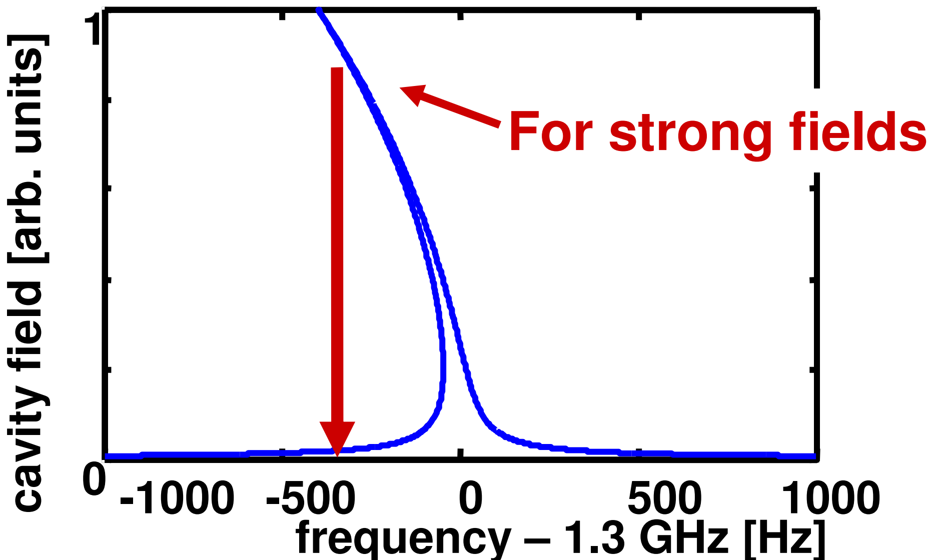


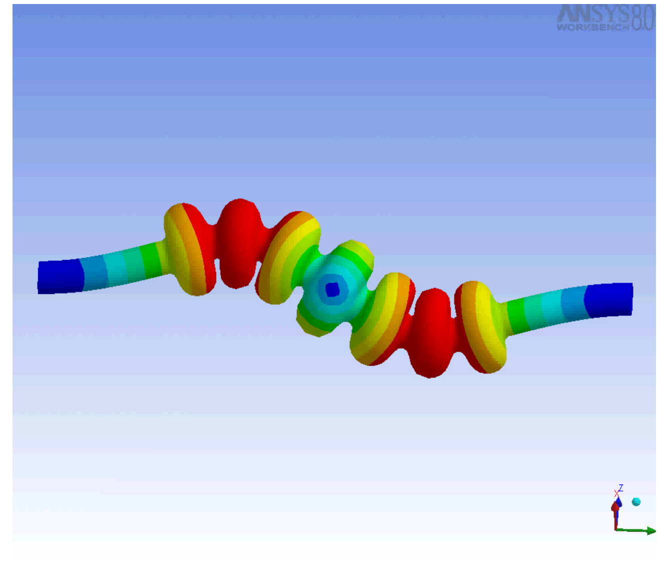
- Run cavity with lowest possible bandwidth for ERL.
- But frequency stabilization becomes very critical.



Cavity control for SC linacs (ERL & ILC)

CHESS & LEPP





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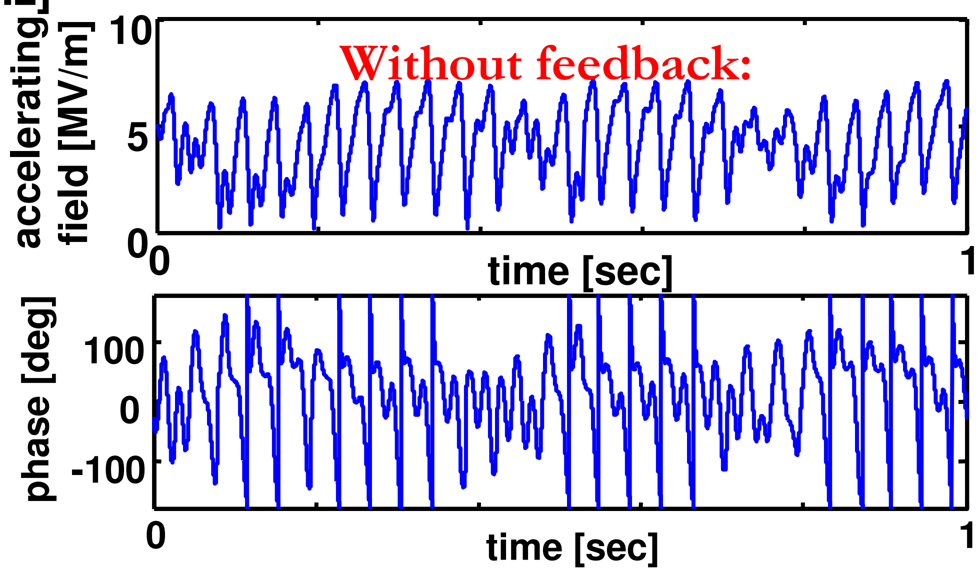
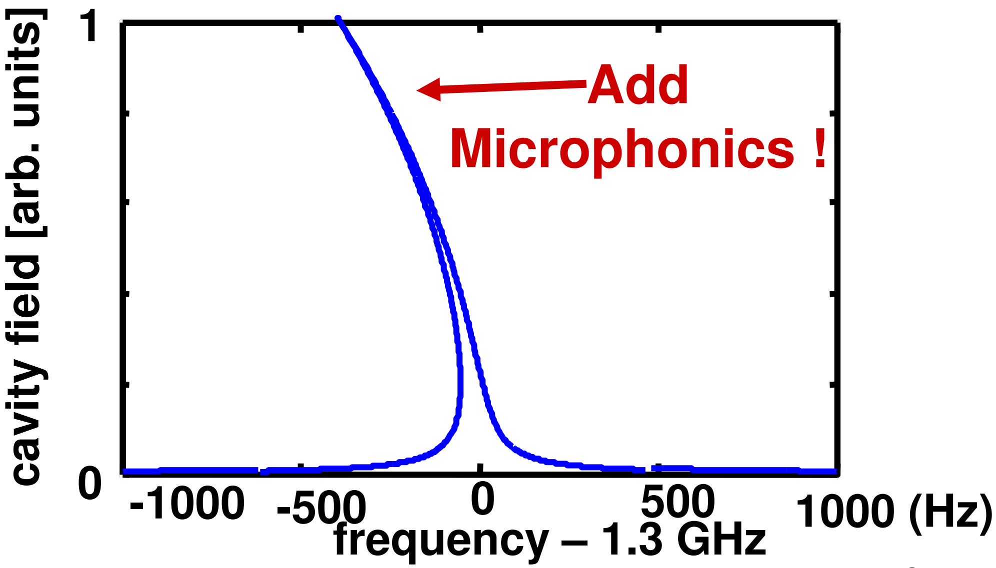
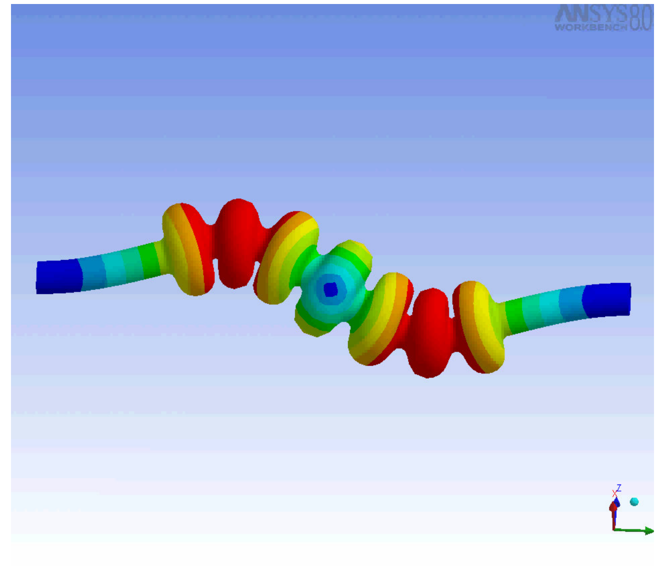


Cavity control for SC linacs (ERL & ILC)

CHESS & LEPP





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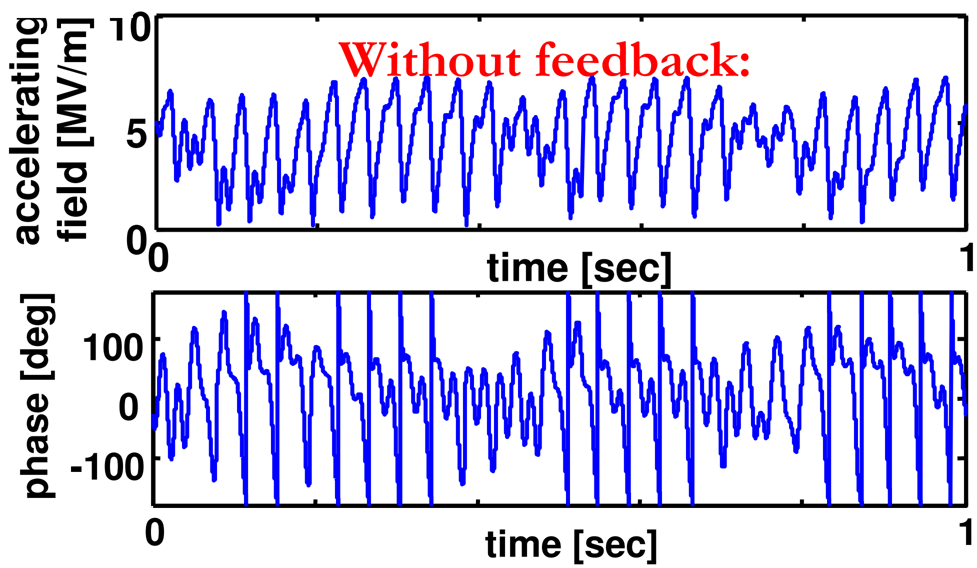
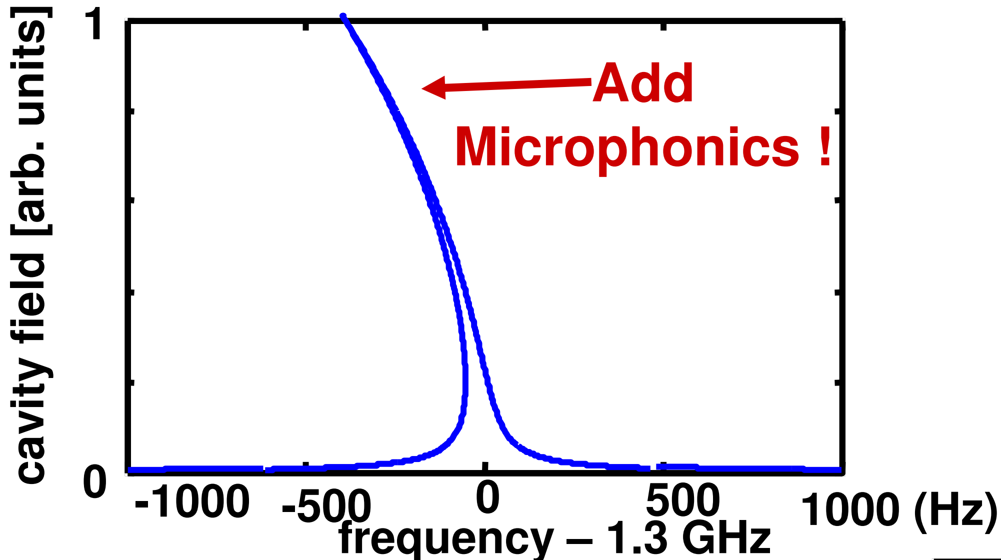
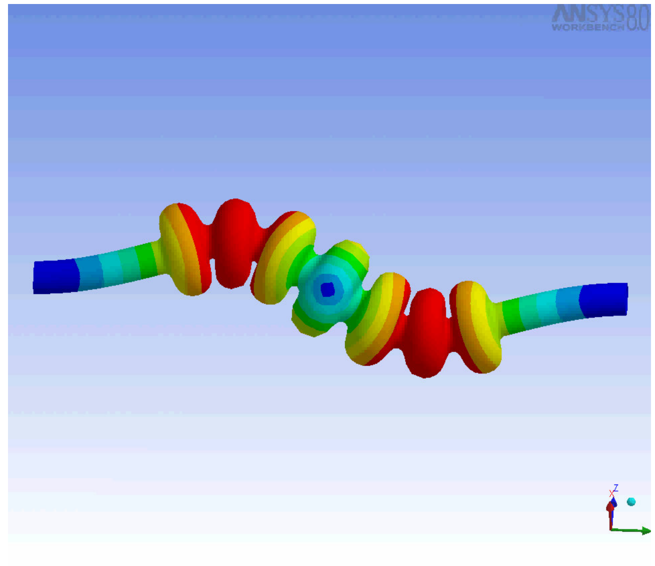


Cavity control for SC linacs (ERL & ILC)





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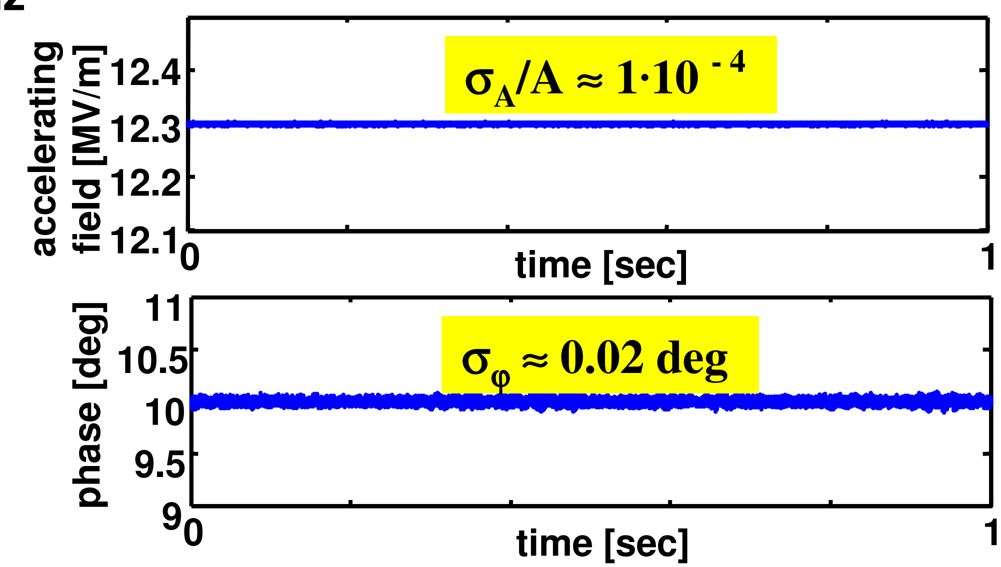
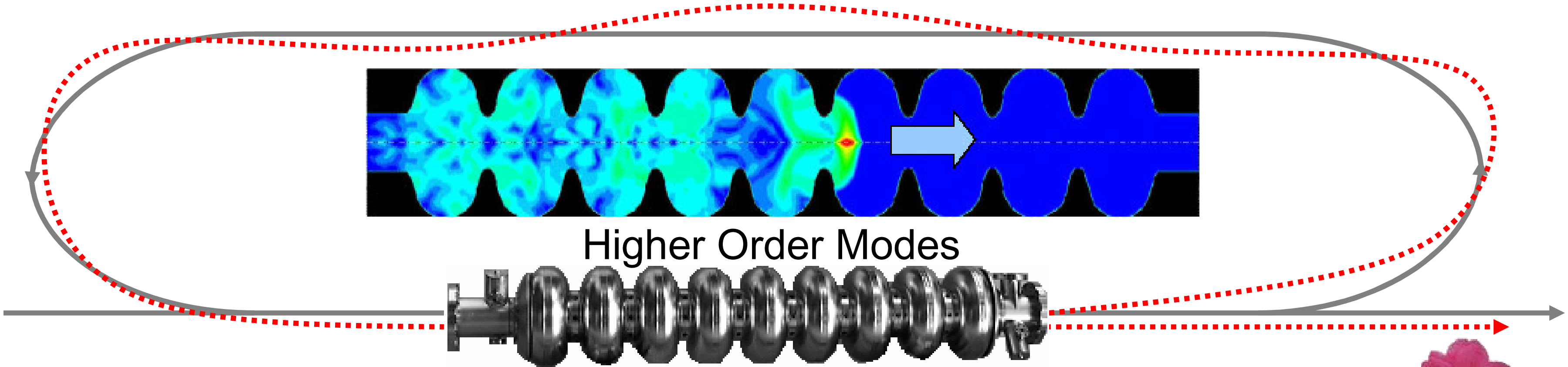


BBU: Collective Instabilities

CHESS & LEPP

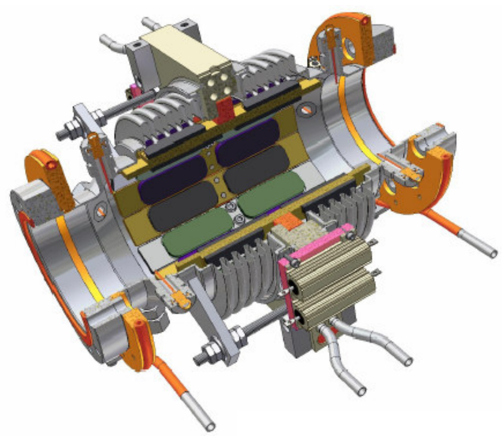


$$V_x(t) = T_{12}\,\frac{e}{c}\int_{-\infty}^{t} W_x(t-t')V_x(t'-t_r)I(t')dt'$$

- Similar instabilities would occur in the Linear Collider

HOM absorbers a la Cornell

From design

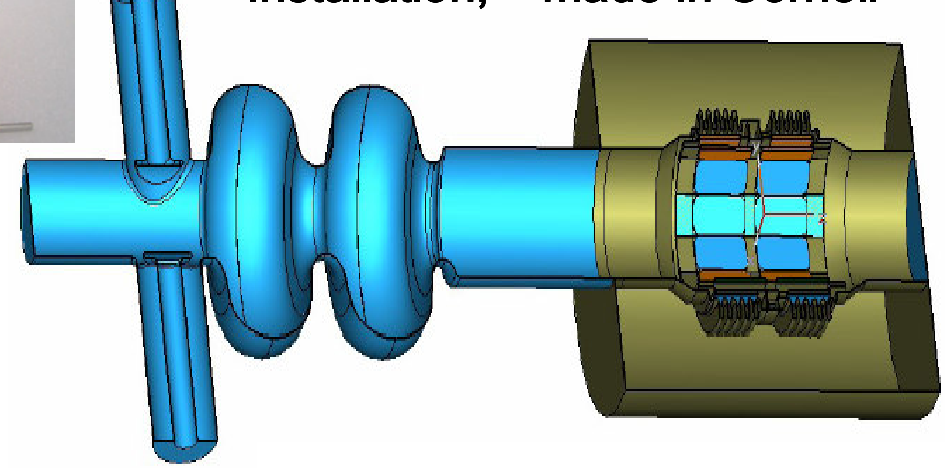


to production and

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.

ERL student projects

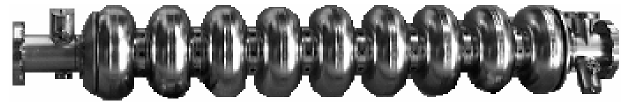
The ERL is a great chance for students to make real contributions:

- Accelerator layout and optimization (PhD student Chris Mayes)
- Beam stability and stabilization (PhD student Changsheng Song)
- Design of ion absorbers (PhD student Yi Xie)
- Beam disturbance by ions (HEP-PhD student Christian Spethmann)
- Couple kick beam dilution (Cornell undergrad Brandon Buckley)
- Characterization of optimal gun materials (Cornell undergrad Vaibav)
- Several other Cornell undergrads and REU students for injector controls, dump design, beam simulations, cavity design, …

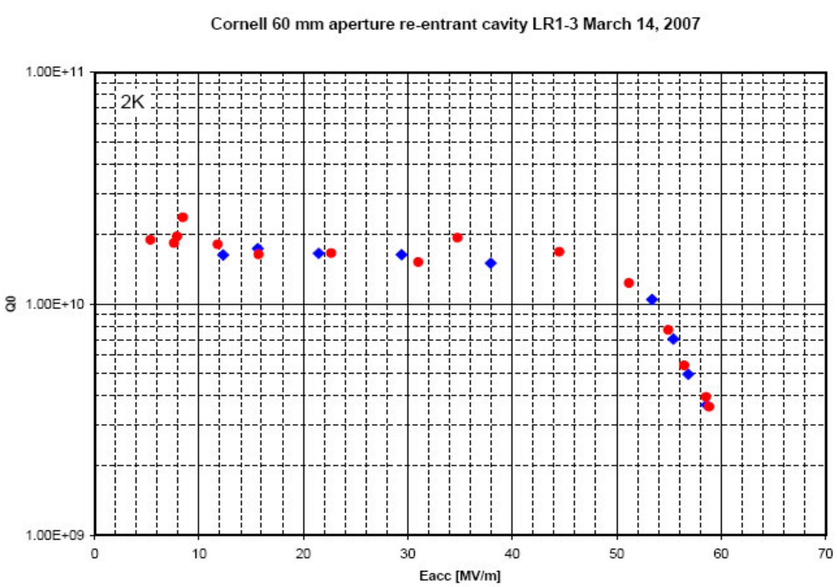
SRF & Solid State/Surface Physics

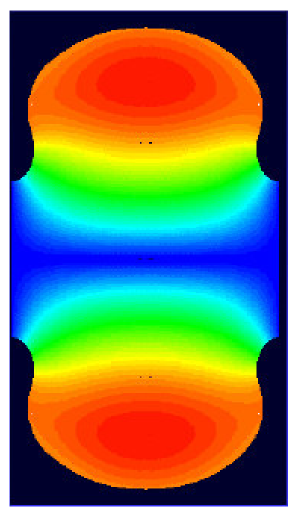
CHESS & LEPP

Research Subjects with Solid State Physics aspects:



- Higher gradients in solid niobium cavities (**ILC and ERL**)
- Understand the dependence on Q on field (**ILC and ERL**)
- Alternate materials for superconducting cavities, e.g. Nb_3Sn, Nb bonded to Cu, Nb on Cu,... (**ILC, ERL, Muon accelerator**)
- Improve breakdown characteristics of cavities to assure high duty factor operation (**main ERL and ILC**)





APS Upgrade Review

CHESS & LEPP

An "Outfield" ERL Option (G. Decker[1])

- Advantages
  - Linac points away from APS[2] to give straight-ahead FEL hall[3]
  - Beam goes first into new, emittance-preserving turn-around arc[4]
  - Avoids wetlands etc. by using narrow corridor for linac and return line
- Issues
  - Big and expensive
  - Turn-around should be *bigger* than shown
  - Beam goes wrong way around the APS in this sketch (readily fixed)
  - No space for really long undulators.

[1] G. Decker, "APS Upgrade External ERL Option," 9/27/06.
[2] M. Borland, "ERL Upgrade Options and Possible Performance," 9/18/06.
[3] M. Borland, "Can APS Compete with the Next Generation?", May 2002.
[4] M. Borland, OAG-TN-2006-031, 8/16/06.

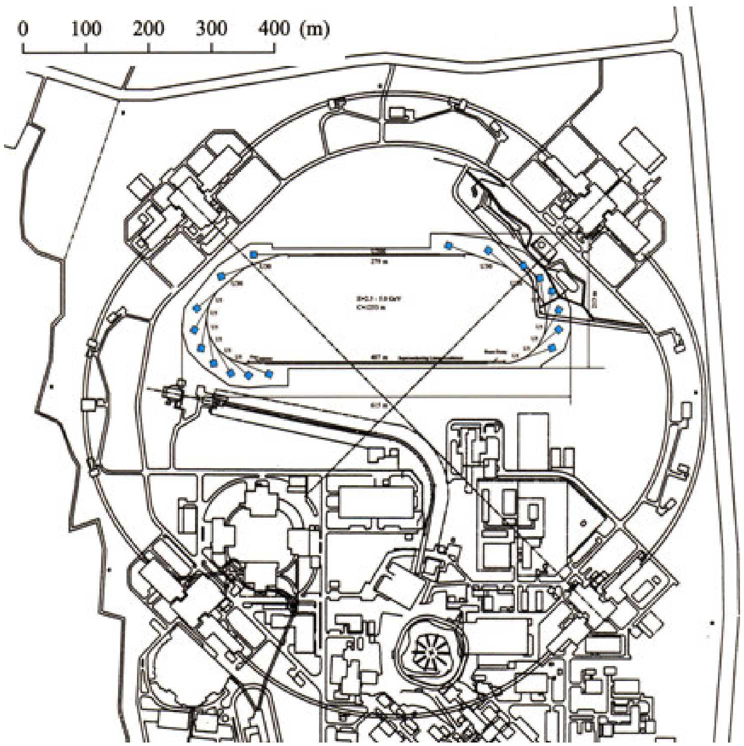
ERL Colleagues: KEK

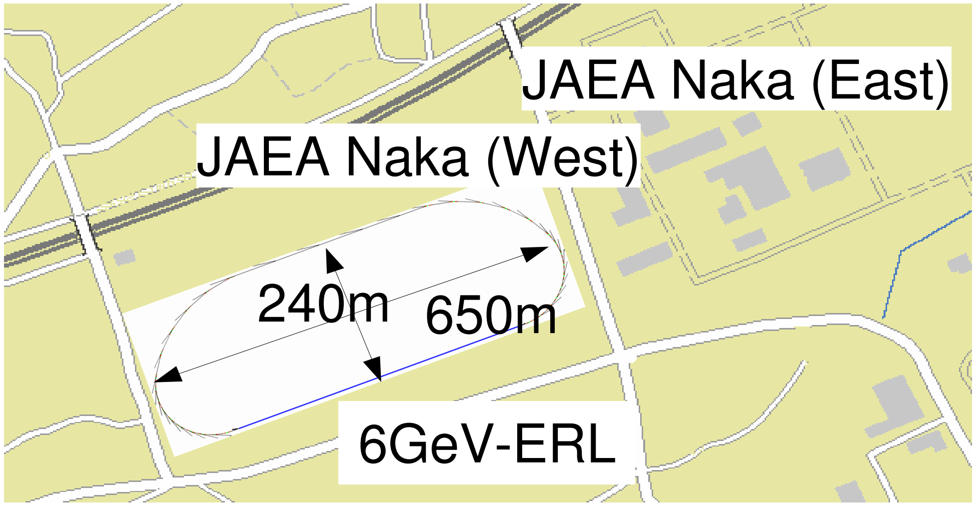
CHESS & LEPP

Two Japanese institutes, KEK and JAEA, proposed each own ERL-based synchrotron light source.

KEK 5GeV ERL at Tsukuba site

JAEA 6GeV ERL at Naka site

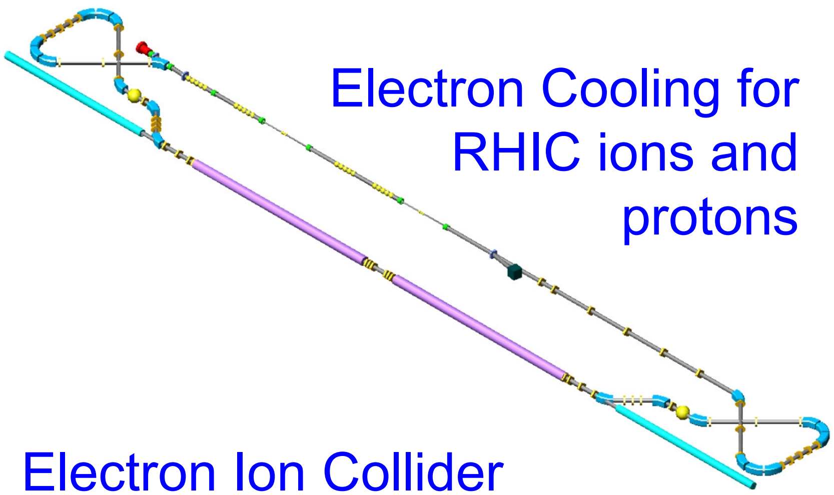




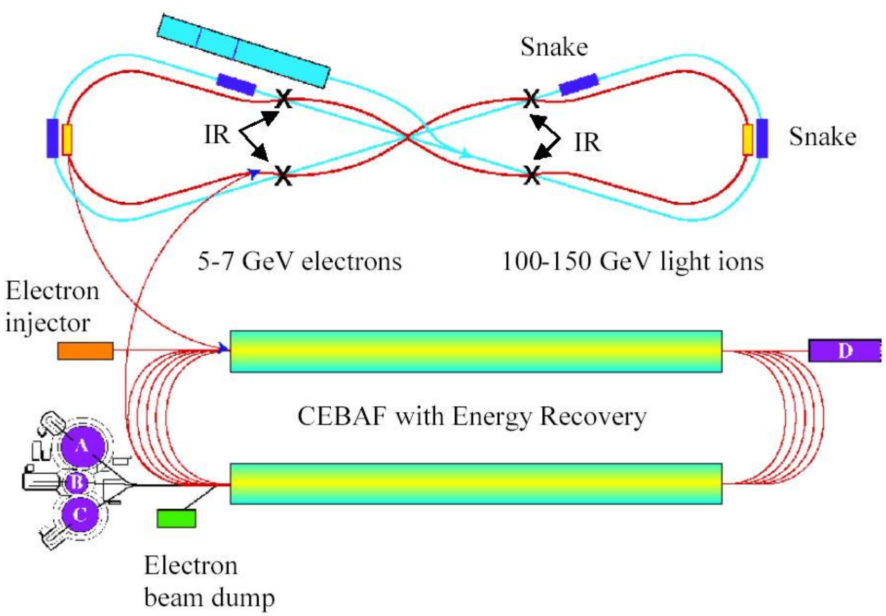
Non Light Source ERLs

CHESS & LEPP

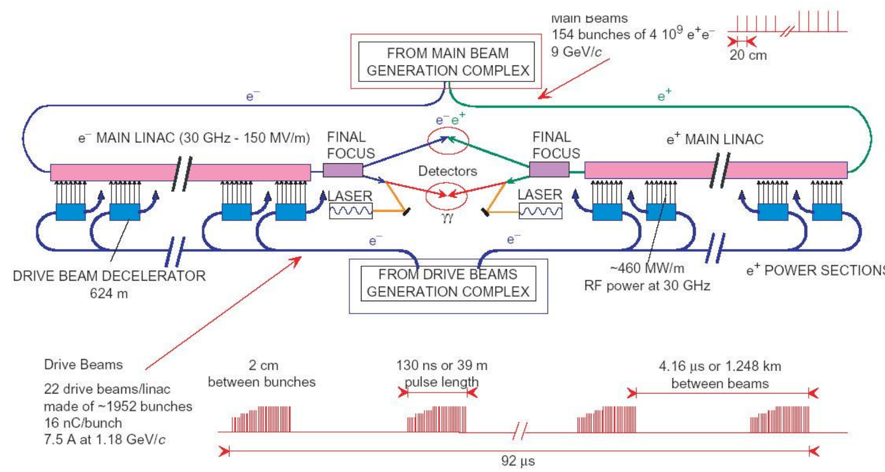
Electron Cooling for RHIC ions and protons



Electron Ion Collider



CLIC-like drive beam ERL

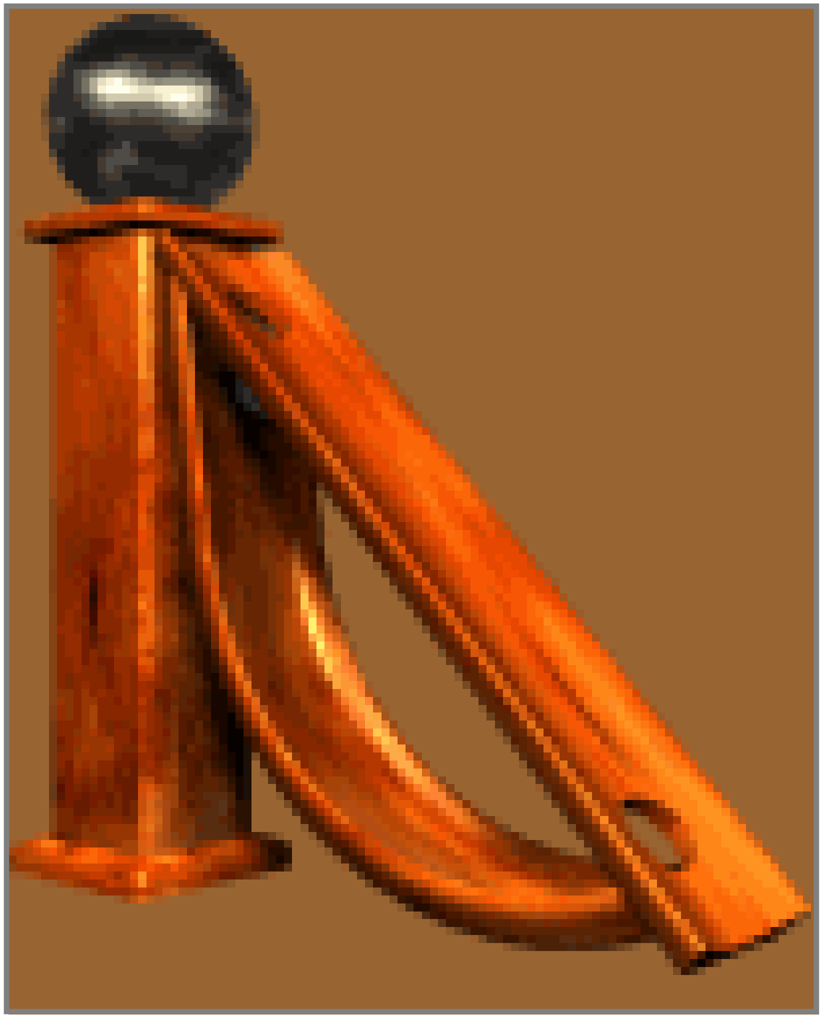


A low emittance RF source

Could save the electron damping ring in a LC

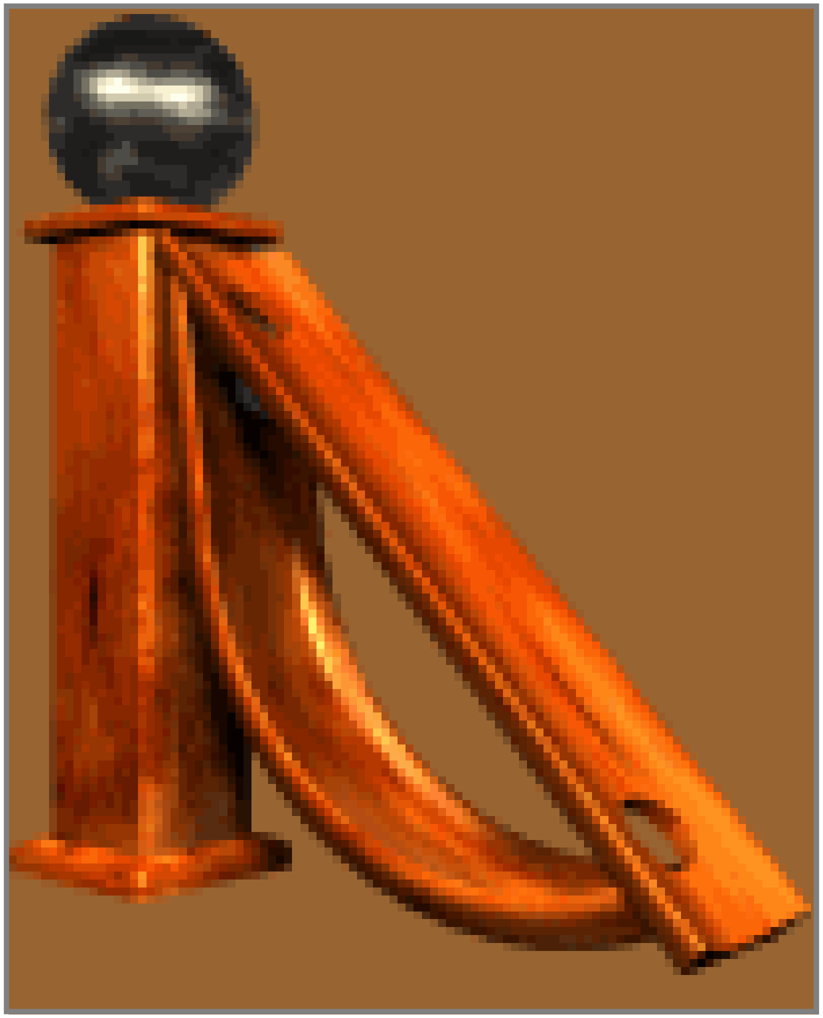
Accelerator Physics @ CESR

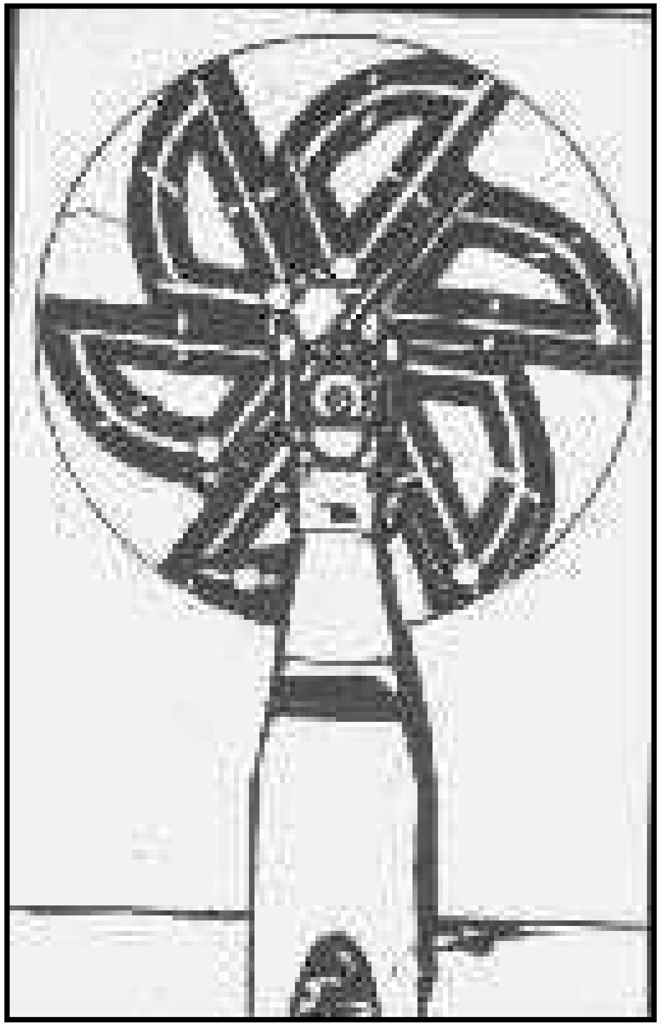
CHESS & LEPP



Accelerator Physics @ CESR

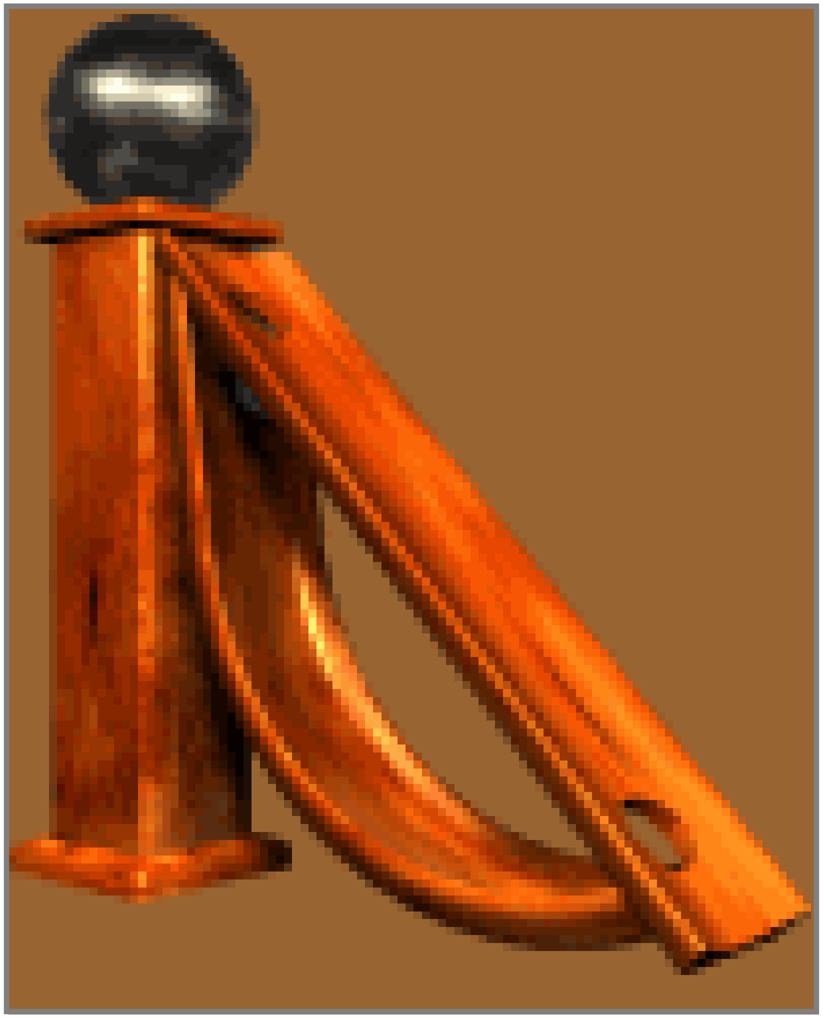
CHESS & LEPP

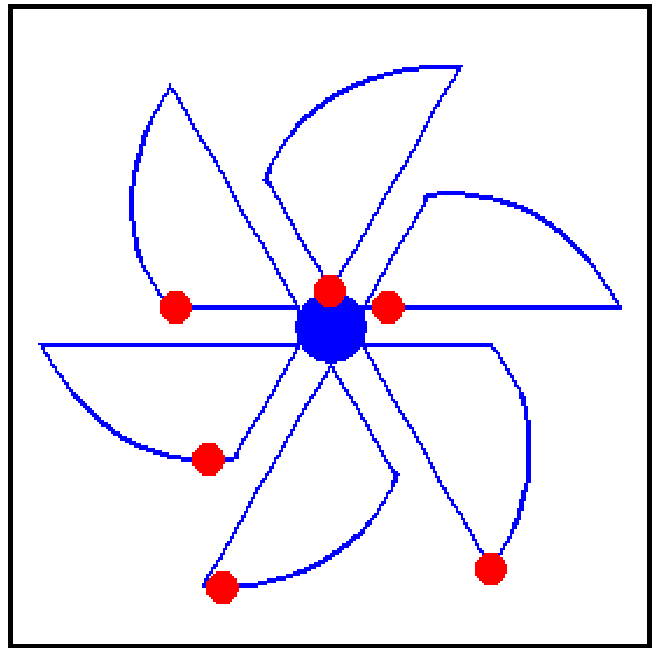


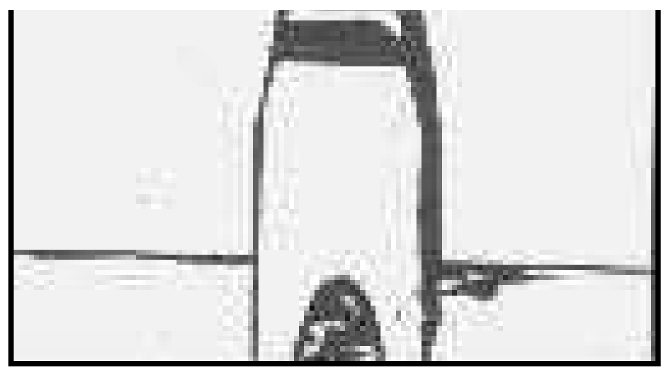


Accelerator Physics @ CESR

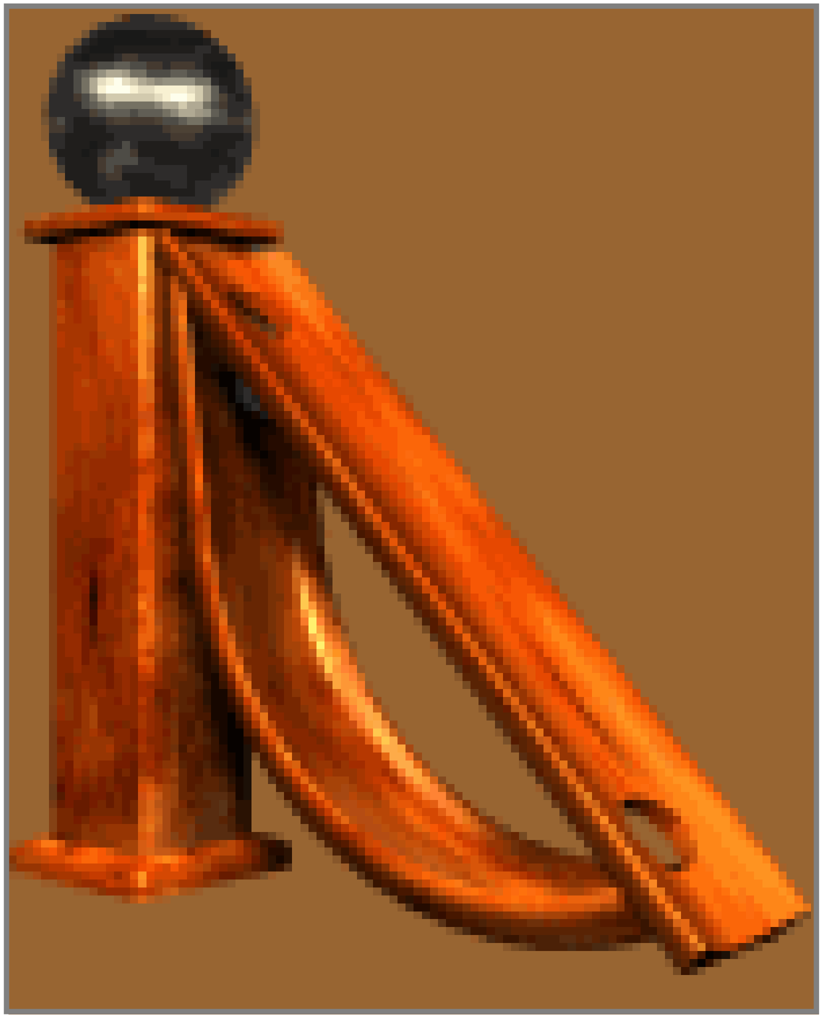
CHESS & LEPP

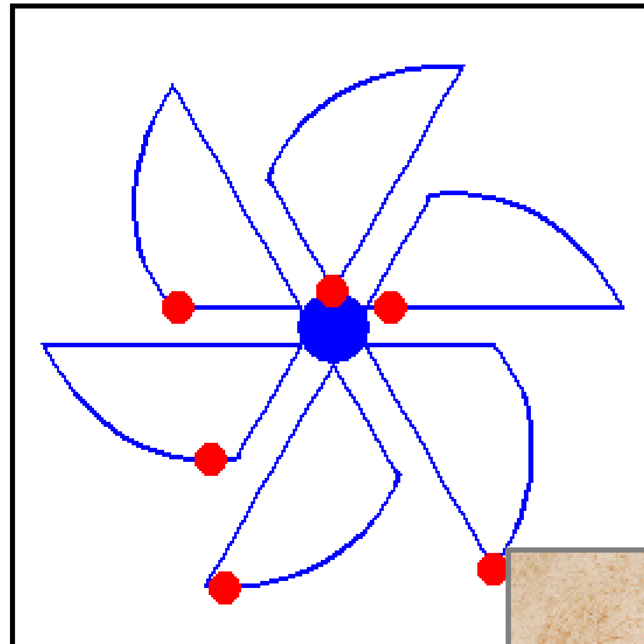


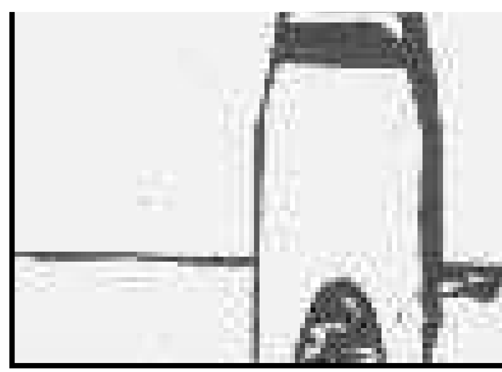




Accelerator Physics @ CESR







Leonardo da Vinci

(1452-1519)

ERL and FELs

- **ERLs deliver photons in lots of small buckets.**
- **XFELs deliver photons in a few big buckets.**

When delivered faster than thermal equilibration…

0.1 eV/atom

Threshold for permanent structural damage

↓

1 eV/atom

Most materials melt

↓

10 eV/atom

Ablation occurs

Assuming "average" element is carbon (85 barn /atom cross-section), LCLS will give 1eV/atom for beams 10-30 μm diameter.

Even more severe for higher Z or for European XFEL