An Energy Recovery Linac X-Ray Source at Cornell University

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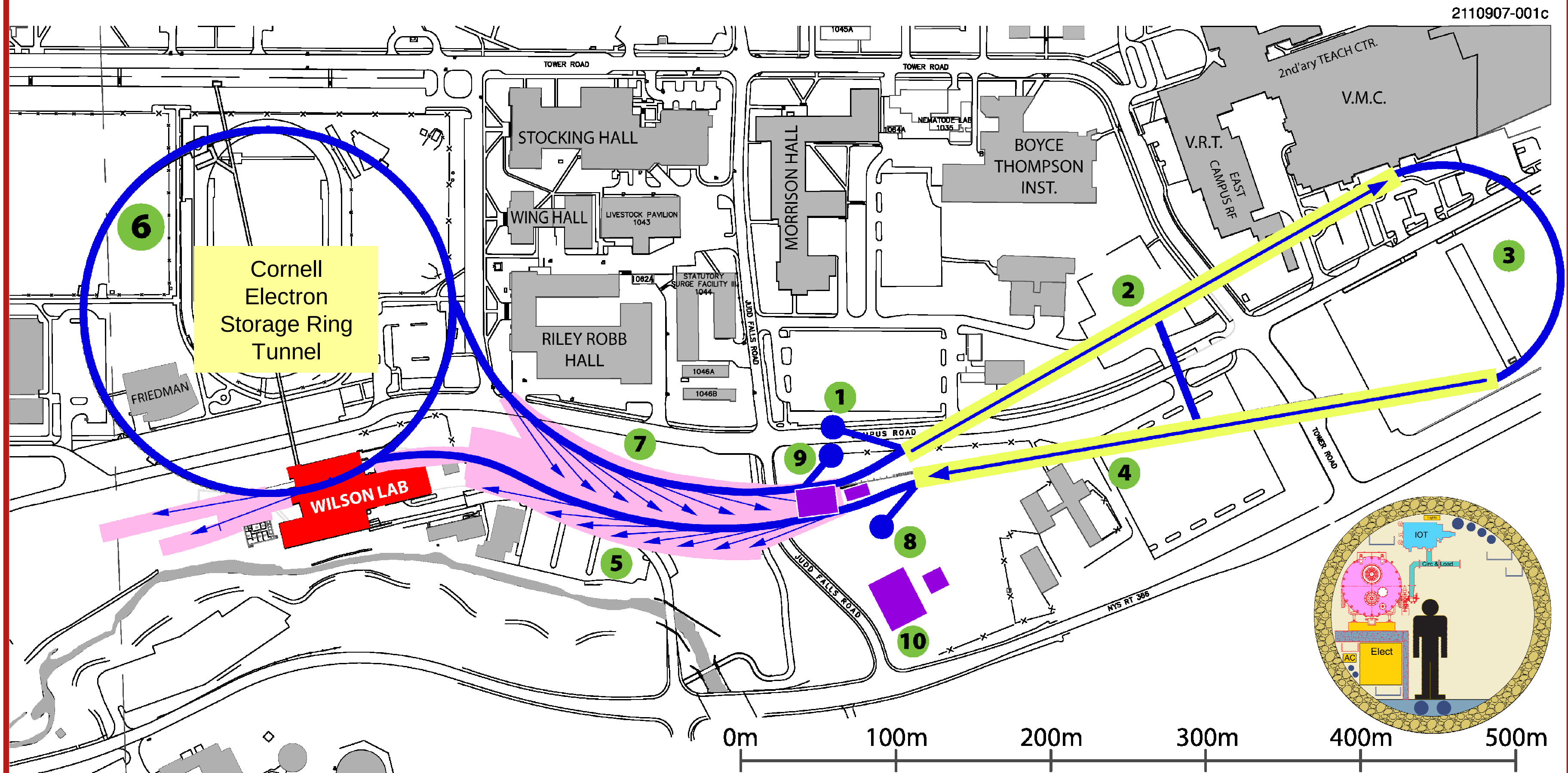
Georg H. Hoffstaetter
Cornell Physics Dep. / CLASSE



An Energy Recovery Linac X-Ray Source at Cornell University

- Hosted by the Research Division, this forum aims to inform staff members about the exciting and interesting research taking place across the division.

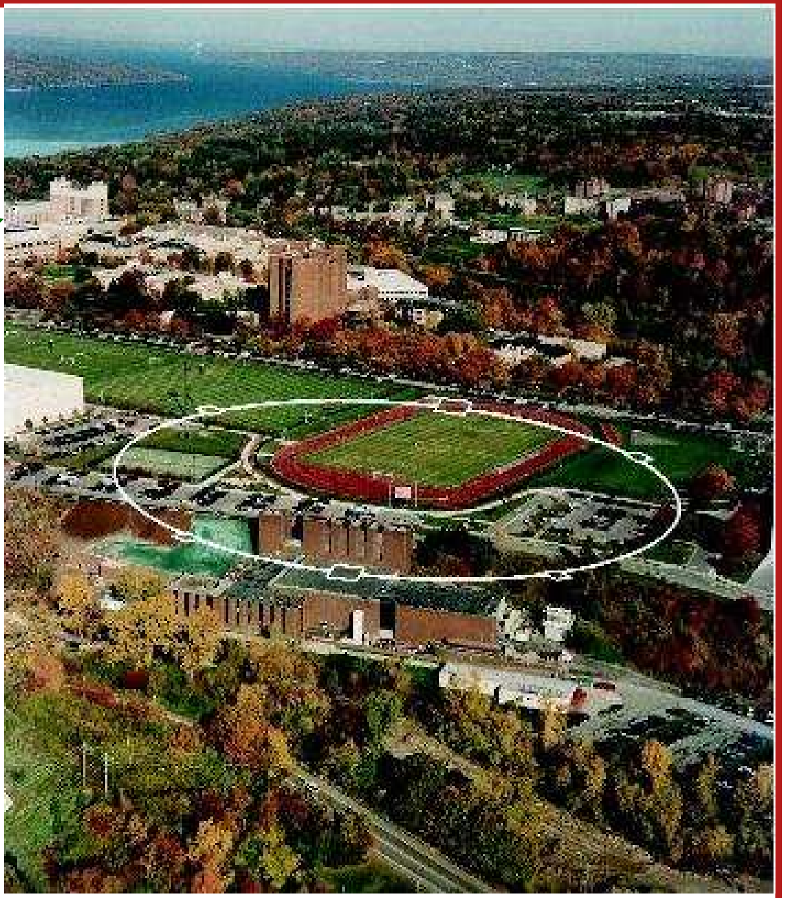
RSVP to the Office of the Vice Provost for

AN ENERGY RECOVERY LINAC X-RAY SOURCE AT CORNELL UNIVERSITY

The Energy Recovery Linacs (ERLs) can enhance the science potential of x-ray sources dramatically. Professor Hoffstaetter will present plans to make Cornell the first site for such an innovative science facility and provide examples of how the ERL works as well as the types of science it will impact. Cornell is in a unique position to tackle the many research topics the ERL presents and to construct and operate such a world-class research facility on campus, as indicated on the map below.

Forefront Accelerator R&D 1934 - present

Boyes McDaniel with Cyclotron



Forefront Accelerator R&D 1934 - present

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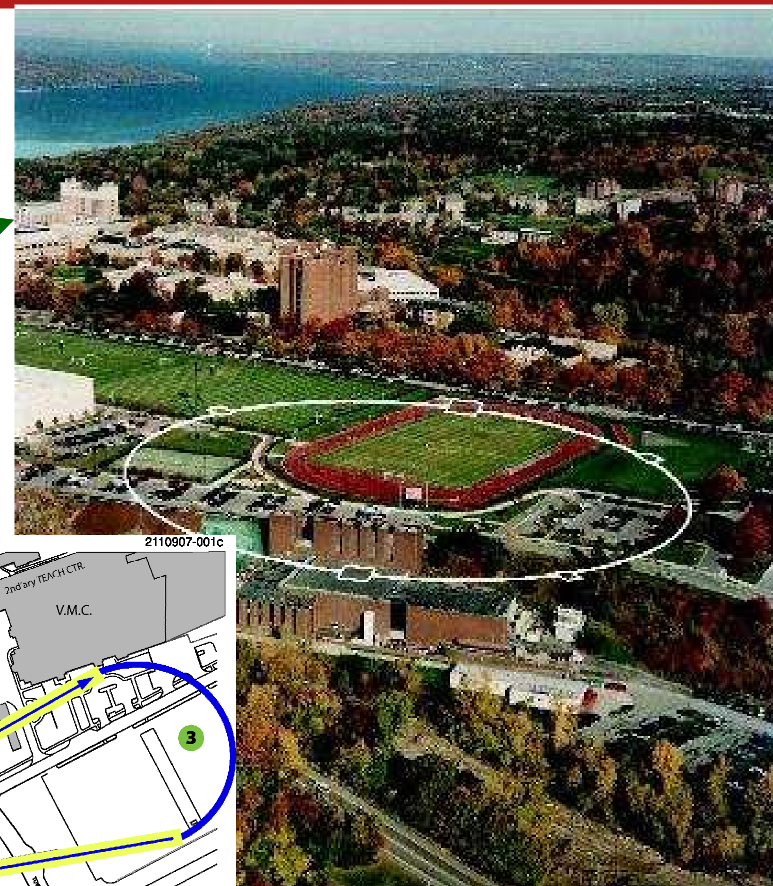

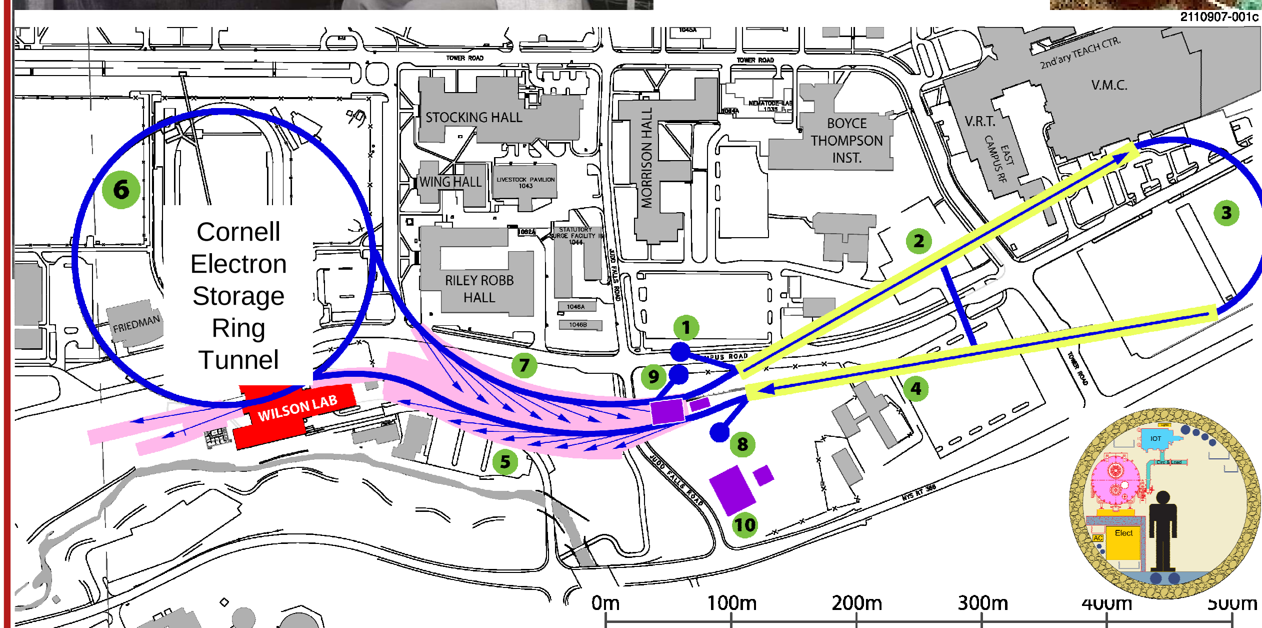

Forefront Accelerator R&D 1934 - present

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CLASSE at Cornell University has had a long history of forefront accelerator development for lepton accelerators.

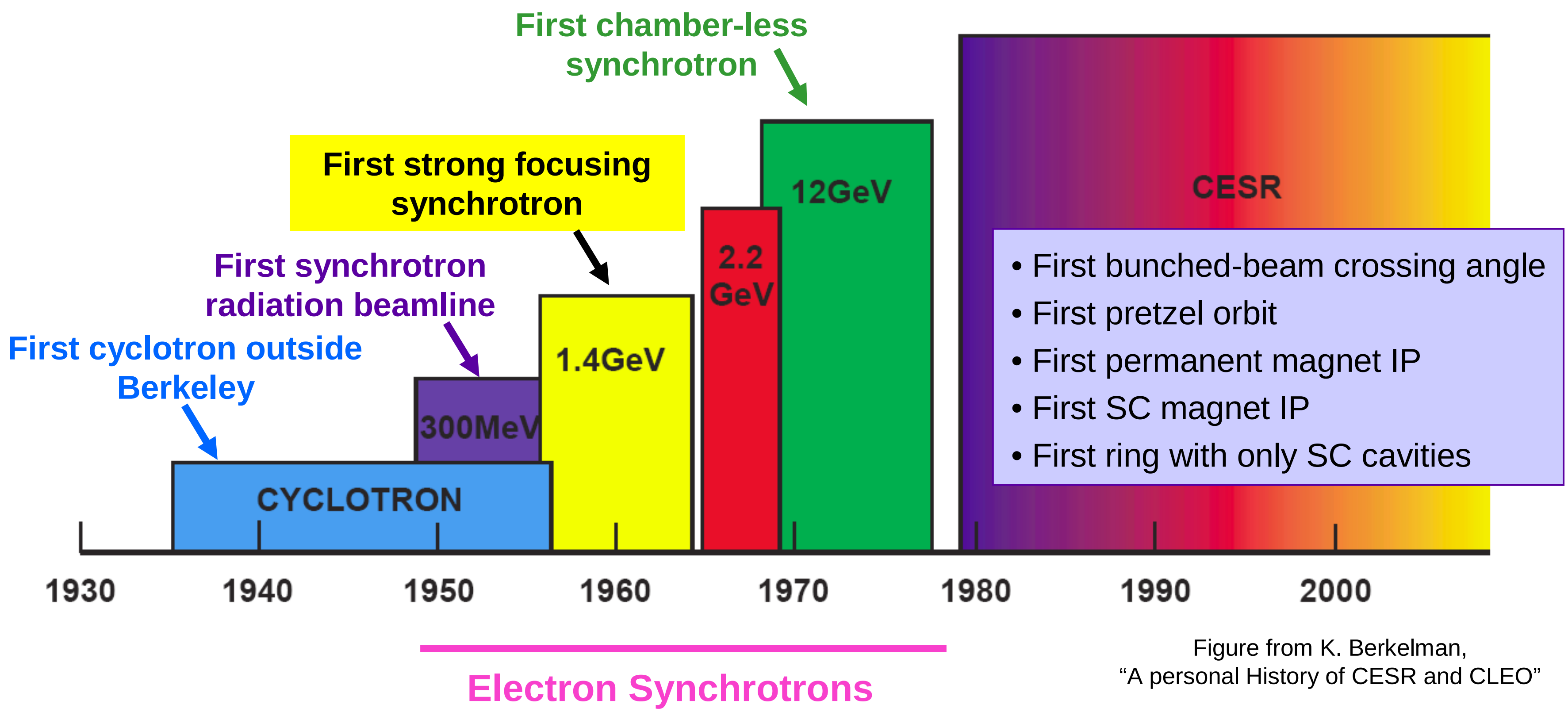

Figure from K. Berkelman,
“A personal History of CESR and CLEO”

Storage ring technology 1979 - present

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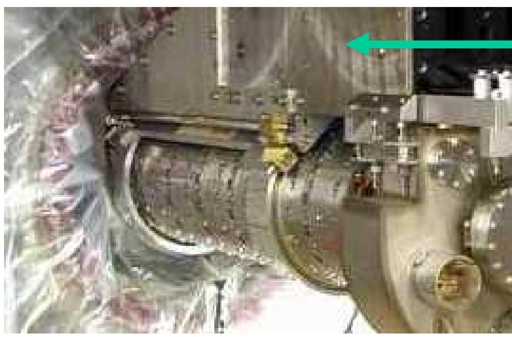
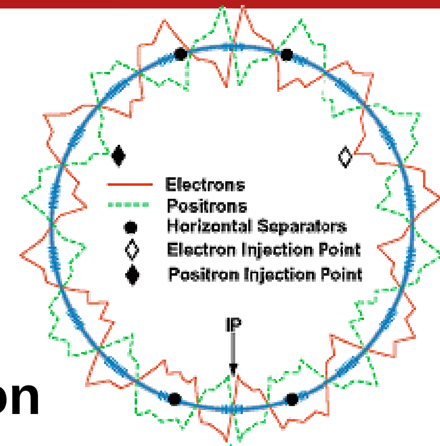


1979: First impedance controller storage ring

1983: First multiple-bunch collisions (Pretzel orbits)

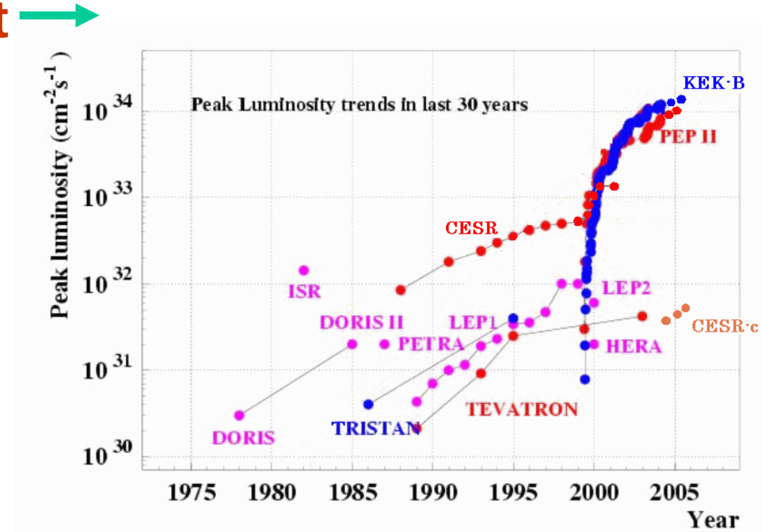


1986: First "Micro-beta" collision point with permanent magnets

1994: First crossing angle for bunched beams

1990-2000: Highest luminosity collider

2003: First wiggler dominated collider



Magnet Construction & Measurement

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High quality SC wiggler magnets for heavy radiation damping in CESR – build in house

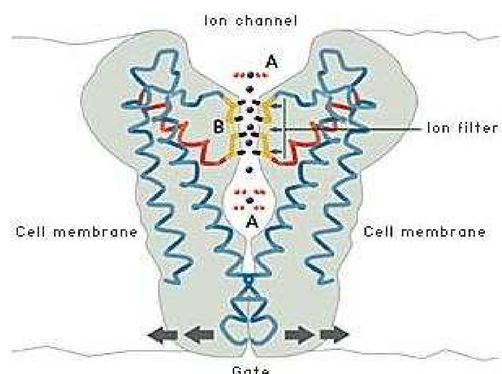
Compensating SC solenoids for CESR (8 months design to completion) - managed

Synchrotron Radiation @ Cornell

- 1947: 1st detection of synchrotron light at General Electrics. Soon advised by D.H.Tomboulian (Cornell University)
- 1952: 1st accurate measurement of synchrotron radiation power by Dale Corson with the Cornell 300MeV synchrotron.
- 1953: 1st measurement of the synchrotron radiation spectrum by Paul Hartman with the Cornell 300MeV synchrotron.
- Worlds 1st synchrotron radiation beam line (Cornell 230MeV synch.)
- 1961: 1st measurement of radiation polarization by Peter Joos with the Cornell 1.1GeV synchrotron.
- 1978: X-Ray facility CHESS is being build at CESR
- 2003: 1st Nobel prize with CESR data goes to R.MacKinnon

Dale Corson

Cornell's 8th president



Roderick MacKinnon

Can X-ray beams be improved ?

- Narrower and less divergent beams
- More coherent beams
- Shorter pulses

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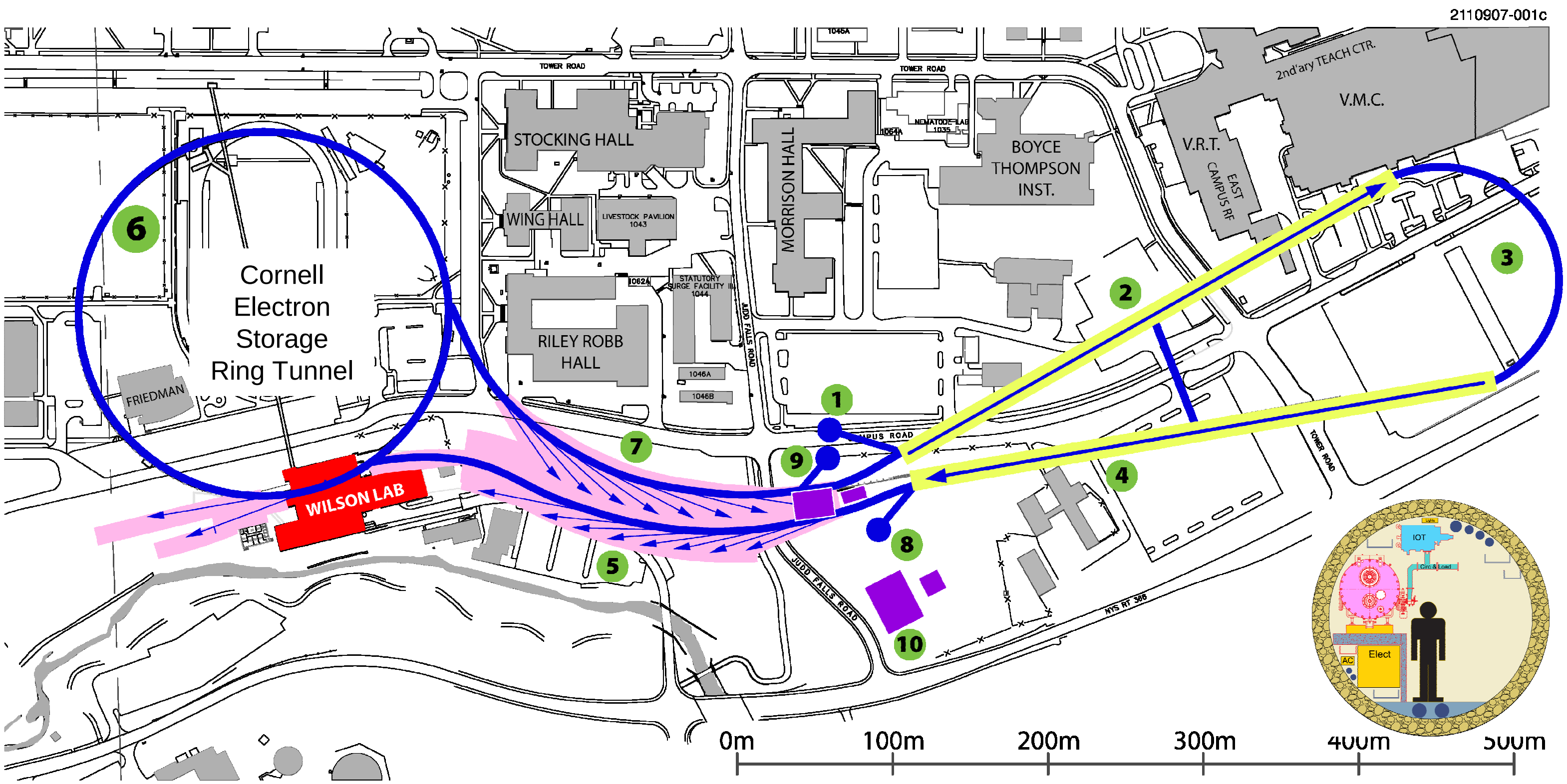
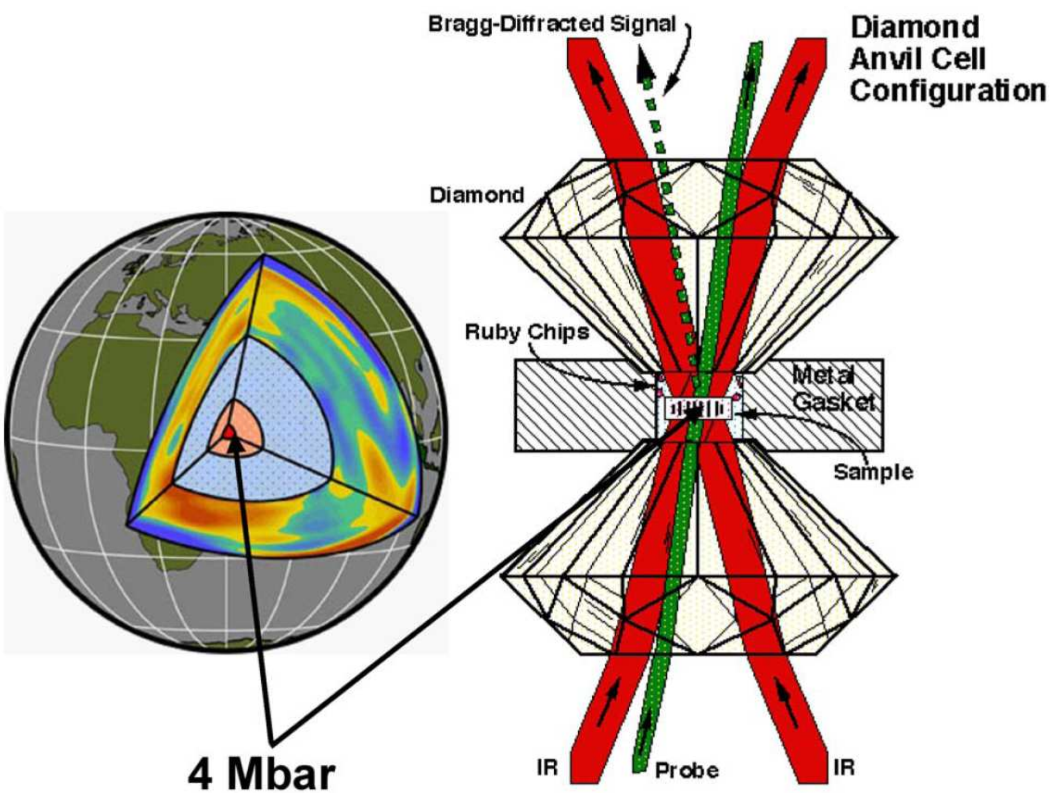
} all of the above



What goes on deep inside the earth and planets ?

LASSE

- HP experiments for µm samples are brightness-limited. Time resolved experiments for plasticity, rheology measurements,
  phase transitions, etc. are especially photon starved.
- Higher P ⇒ smaller samples.
- No ideal pressurization
  ⇒ need to scan sample.
- Peak-to-background critical.
- ERL will greatly extend
- pressures and
  samples that can be studied and add dynamic information.
- Cornell has very strong HP tradition:
  - First center of the earth pressures: at CHESS
  - Britchman Award winners: Basset, Ruoff, Ashcroft

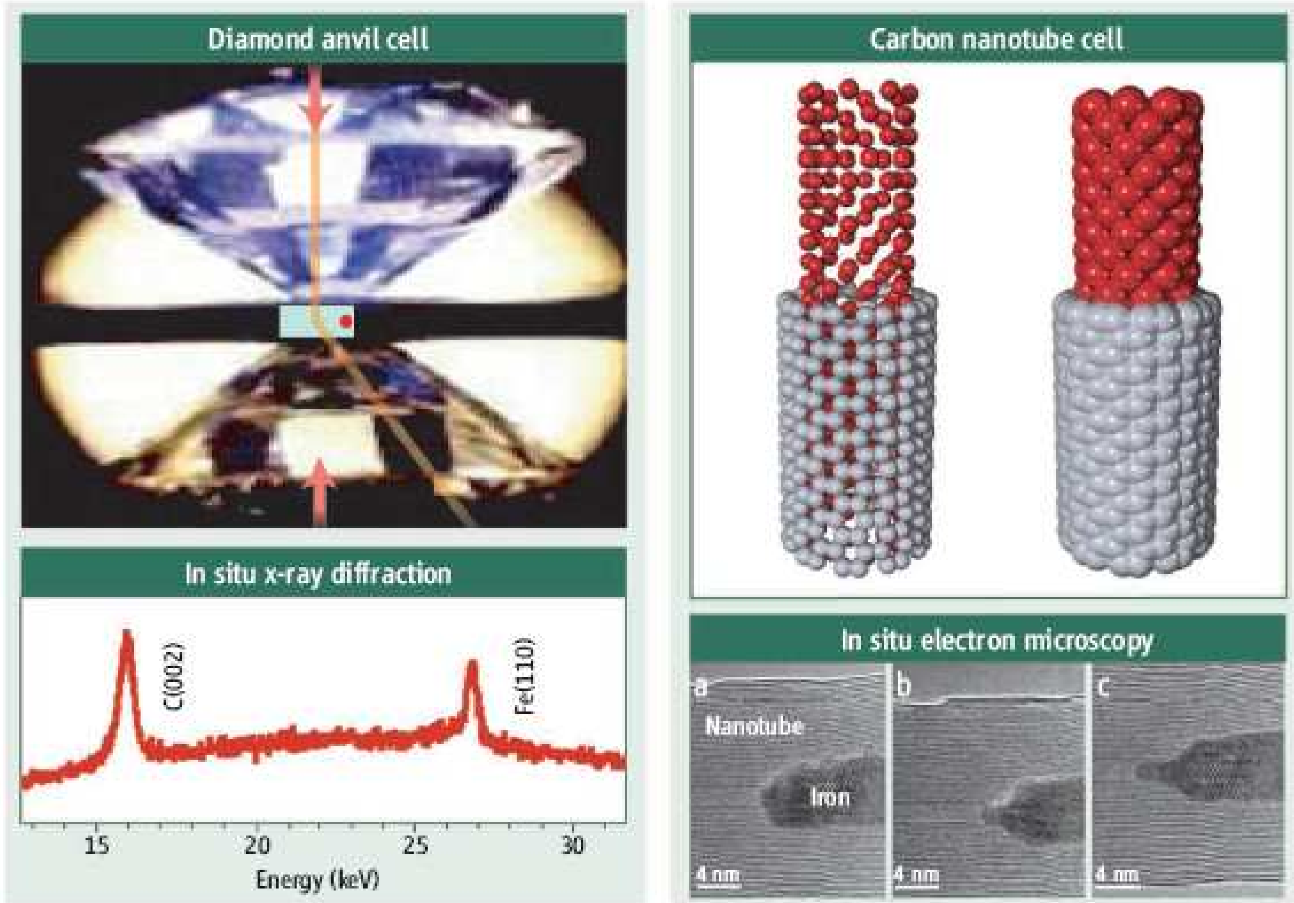


Now: 200Mph/s/µm
ERL: 100Tph/s/µm

High pressure in carbon nanotubes

Up to 1600GPa with multi-wall nanotubes.

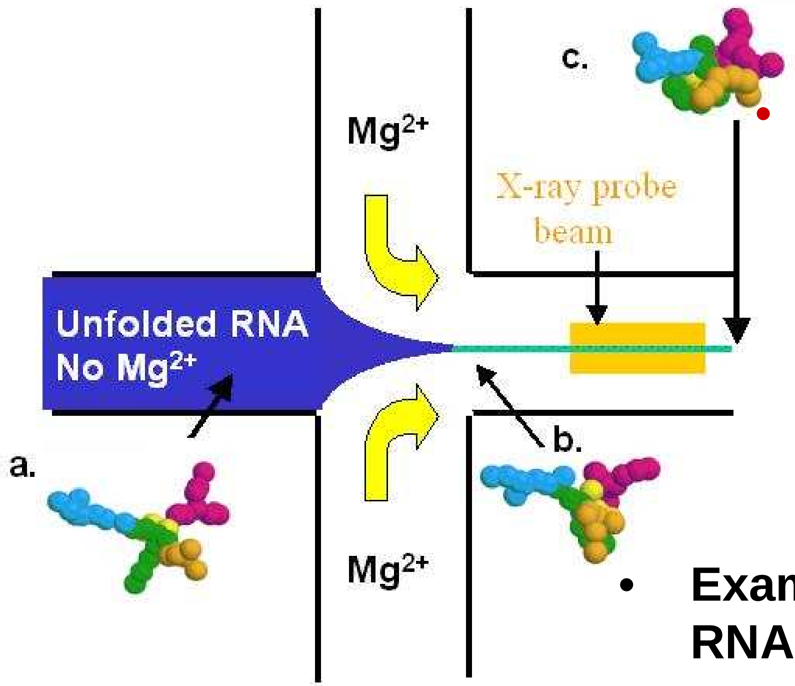
Less C Absorption:
Soft x-ray usable



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.

Can we understand the dynamics of macromolecules in solution ?



Thanks to Lois Pollack

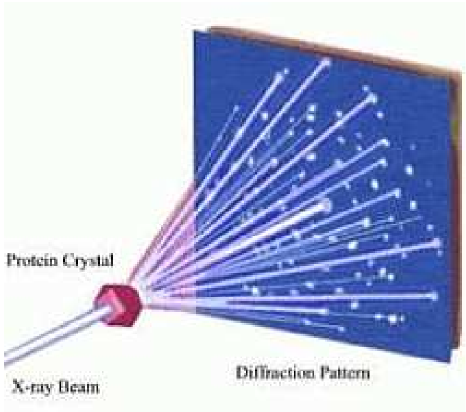
Cornell Univ.

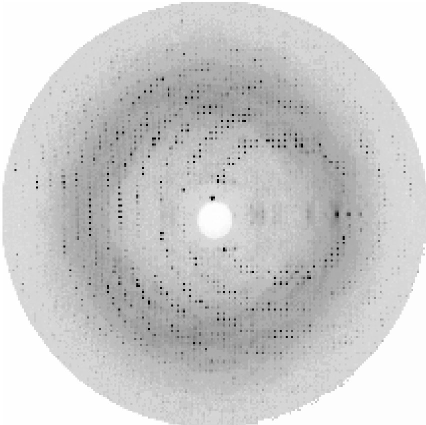
- **Data acquisition entirely limited by source brilliance. The ERL will extend time scales from present milliseconds to microseconds.**

- **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.**

Exemple for protein folding: Bovine Spongiforme Encephalopathie – Mad Cow D.

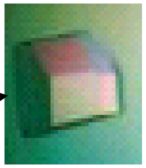
Smaller crystals from hard to crystallize materials



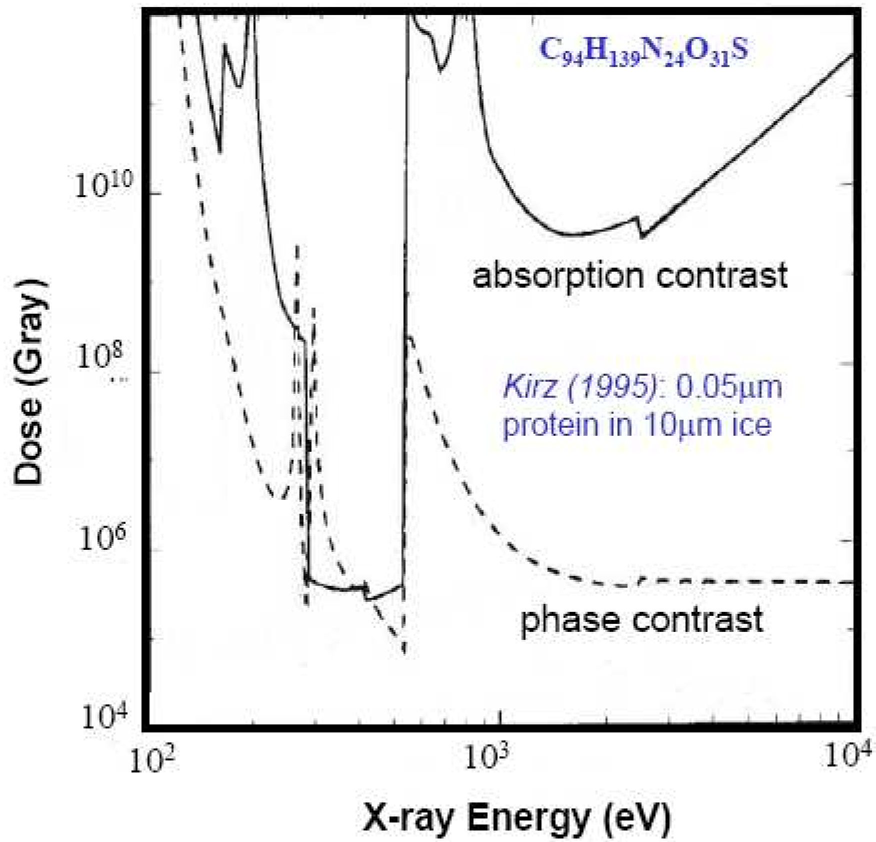


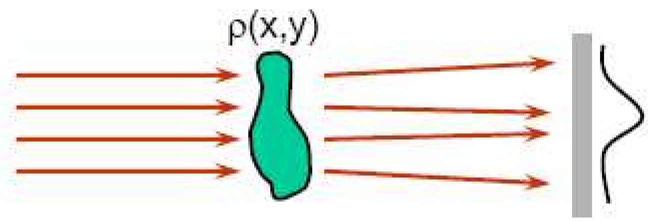
ERL enables new crystallographic method

1. Obtaining good crystals is rate limiting. Easier to obtain microcrystals.
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.



Coherent beams from ERLs: Phase contrast imaging





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

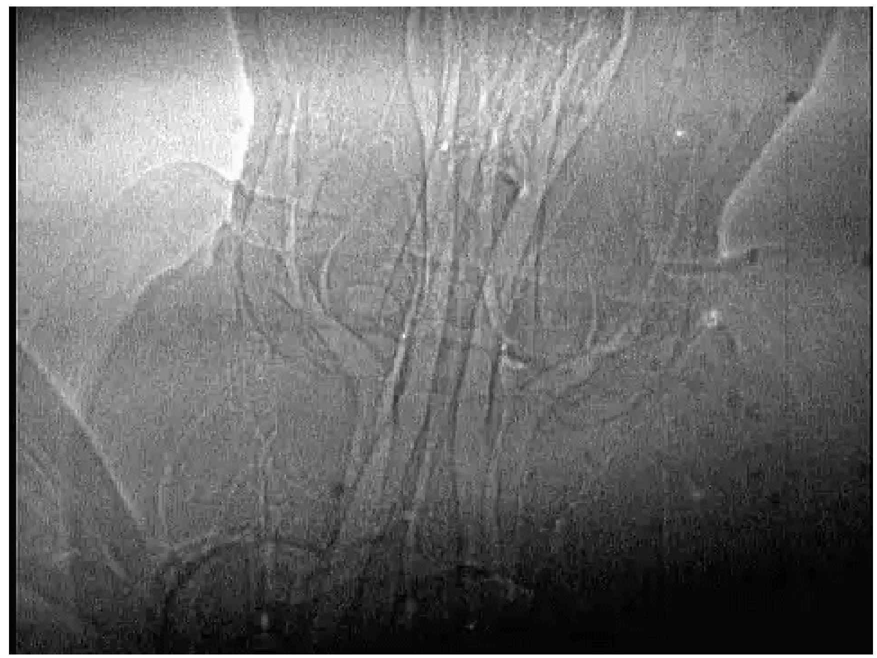
Real-time insect breathing

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.

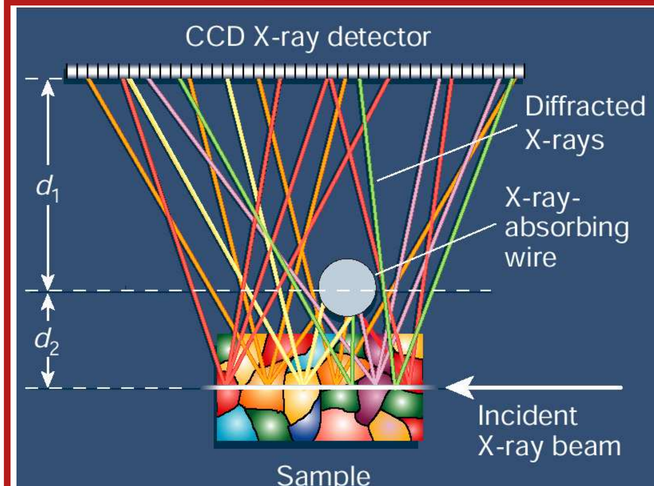
Science (2003) 299, 598-599.

- Animal functions
- Biomechanics
- Internal movements
- New findings



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

Can we improve polycrystalline materials

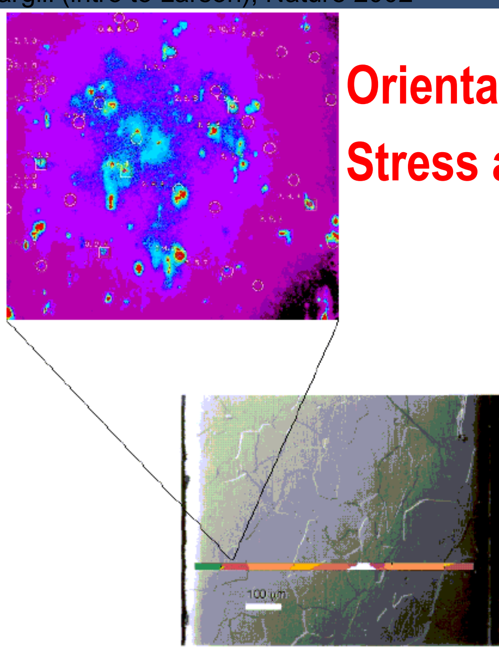


Cargill (intro to Larson), Nature 2002

Differential-Aperture X-ray Microscopy (DAXM)

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

ERL: smaller area

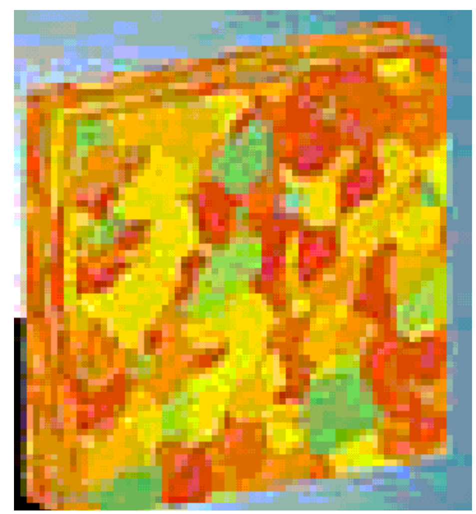


Orientation of crystals and

Stress and strain in crystals

Ben Larson (2000), ERL science workshop, Cornelll

3-D Studies of Structure

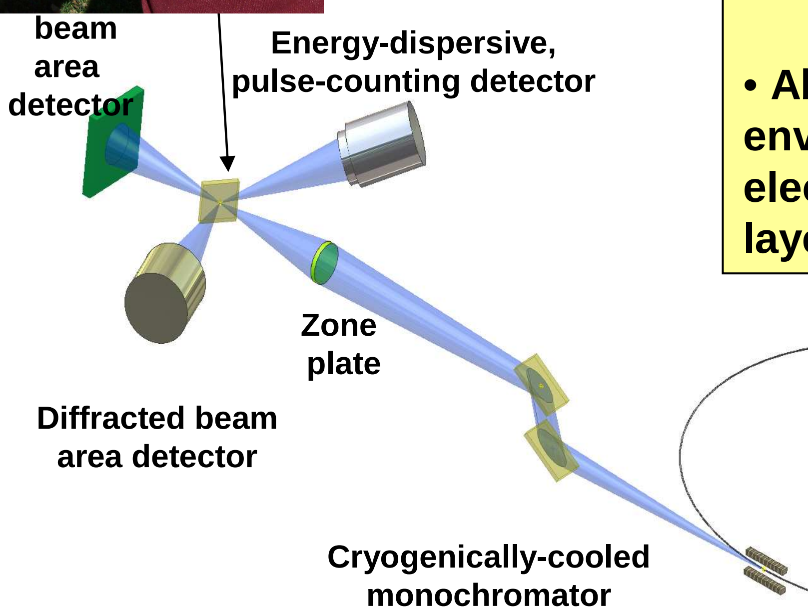


Unprecedented nano beams

Storage ring:

nanobeam flux limited by source size, shape, and divergence.

- **Increase fluorescent trace element sensitivity from present 10^{-19} g to single atom (10^{-24} g)**
- **Sensitive to chemical state via XAFS at at ultra-low concentrations**
- **Ability to penetrate thick layers, nasty gas environments, etc. (as opposed to EM), electrodes used in under-potential deposition of layers, etc.**



1nm X 1nm beam size
Complementary to e-microscopes

Smaller Beams and more Coherence

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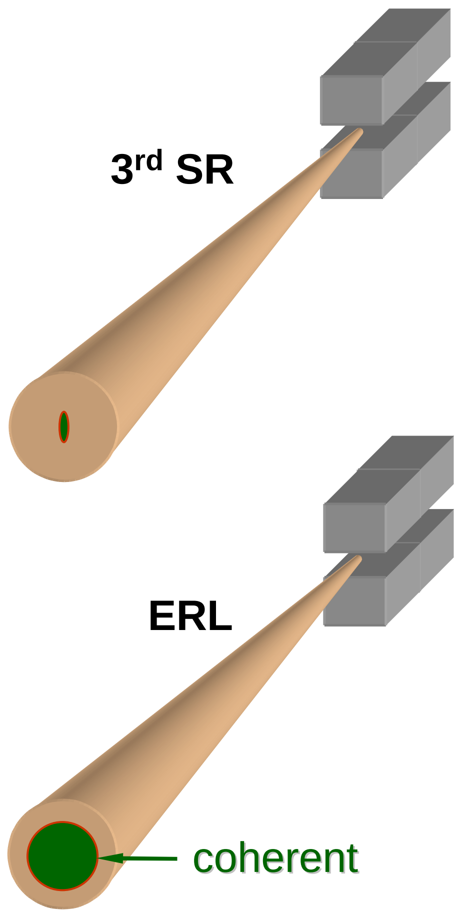
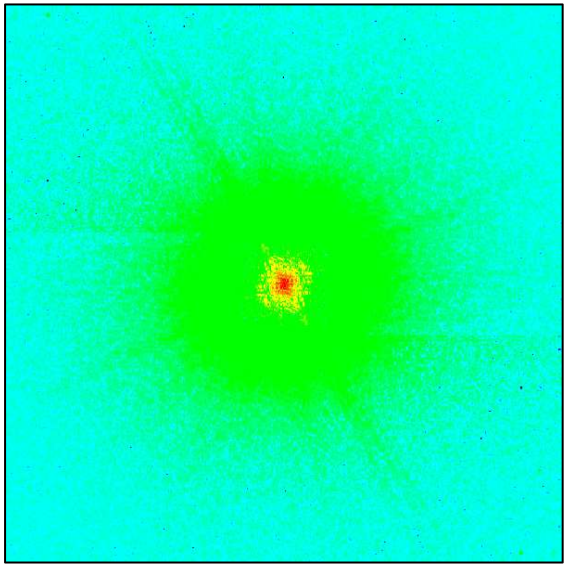
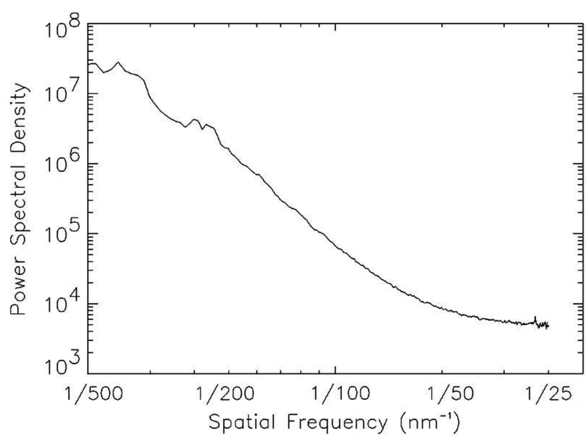
- Coherent x-ray diffraction imaging
- It would, in principle, allow atomic resolution imaging on non-crystalline materials.
- This type of experiments is completely limited by coherent flux.



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

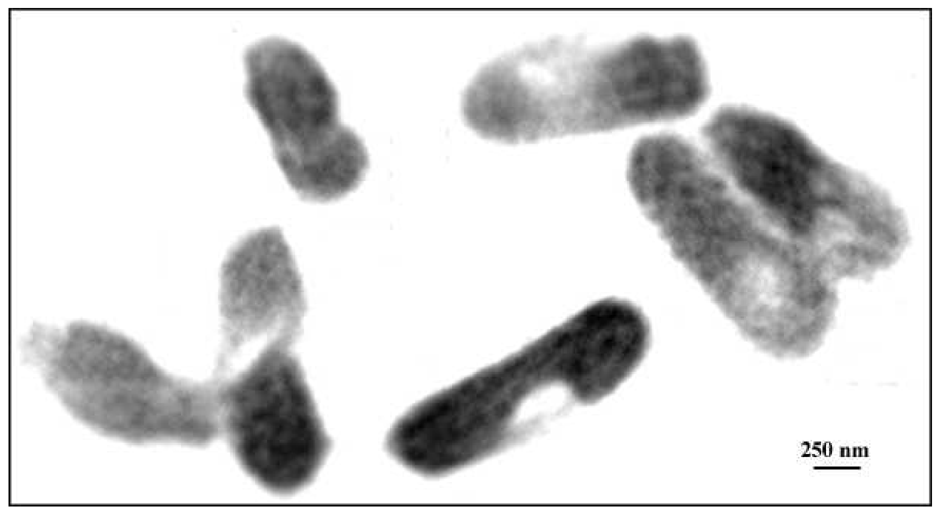
Coherent imaging





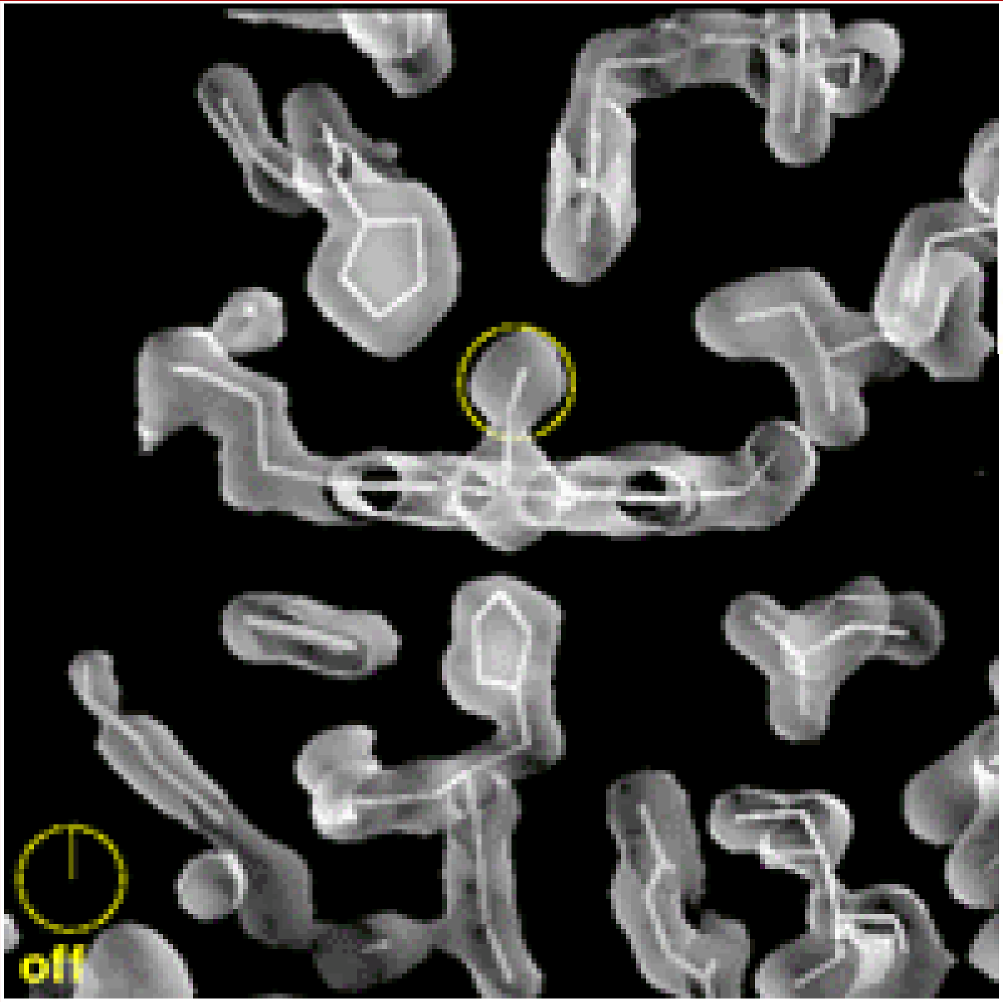
Miao et al., *Proc. Nat. Acad. Sci.* (2003)

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 ~ $8x10^6$ Gray
Diffraction image to ~30nm resolution

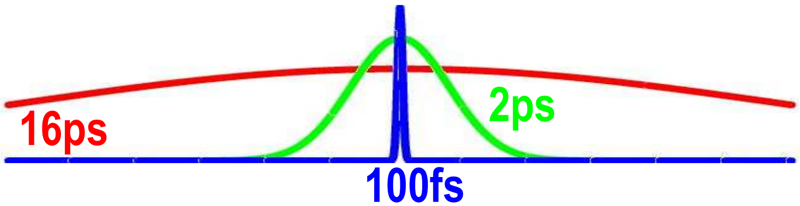


ERL: Diffraction image to sub nm resolution

Time resolved x-ray analysis



ESRF 5GeV@100mA

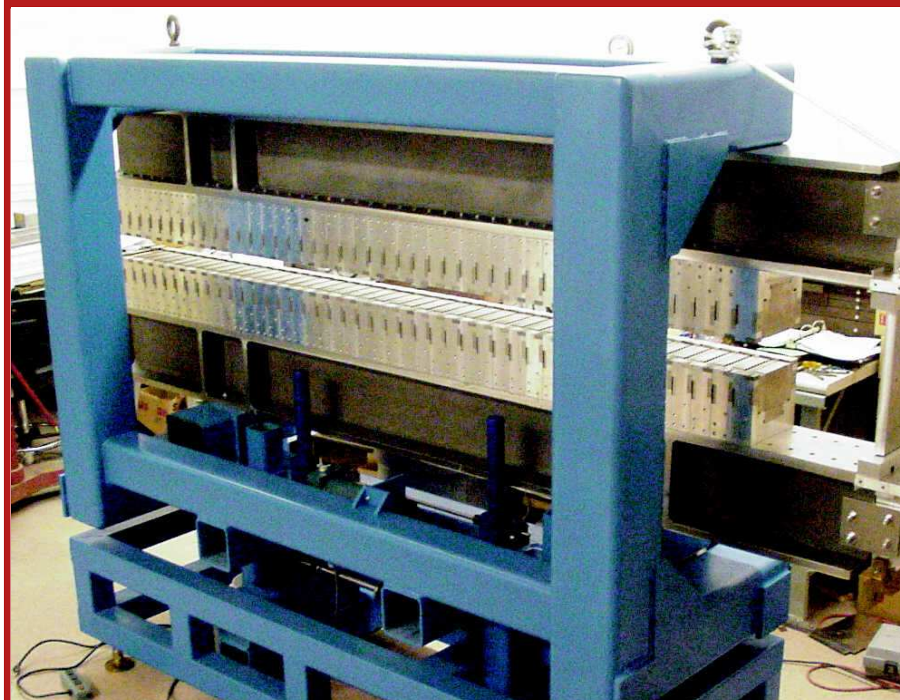


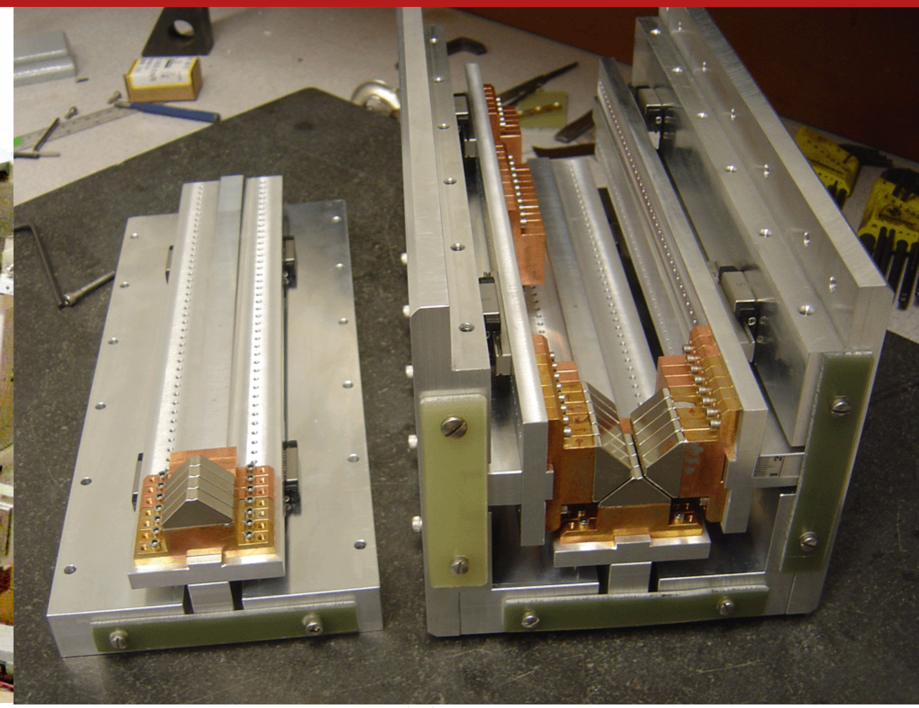
ERL 5GeV@100mA

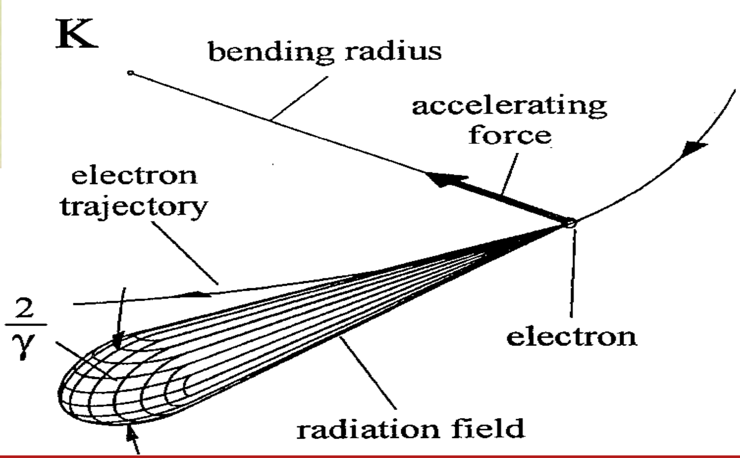
Phil Anfinrud

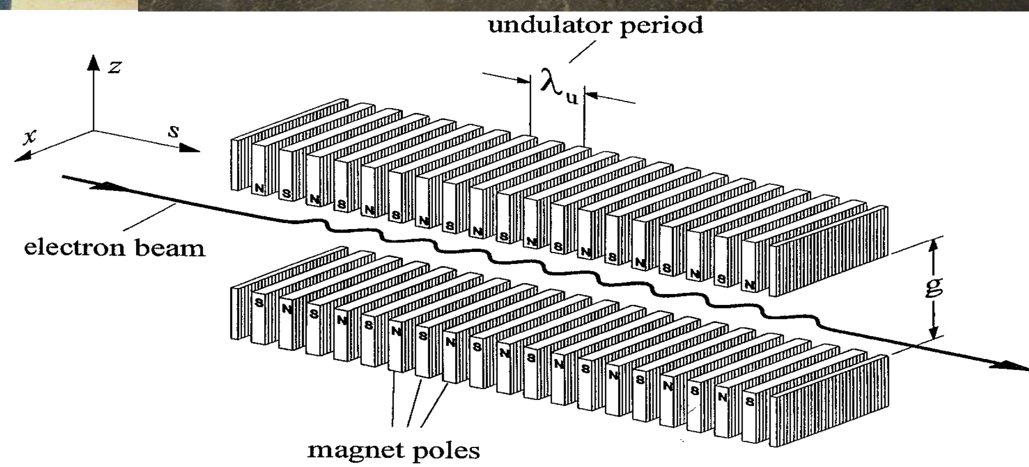
- Time resolution to improve from 10s of ps to 0.1ps

Radiation production with undulators





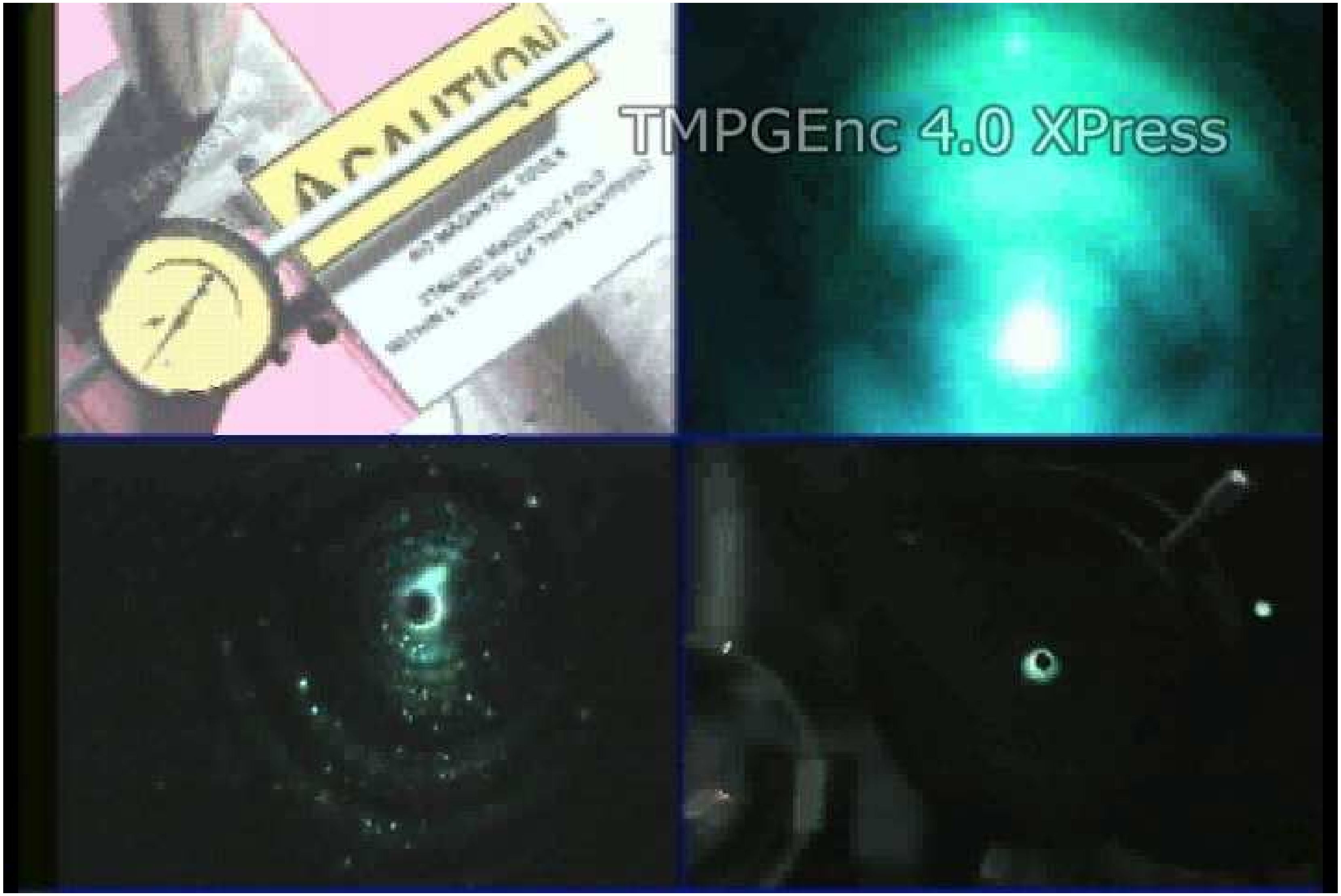




Lasing at JLAB with the ERL-FEL

Wiggler gap

High Reflector



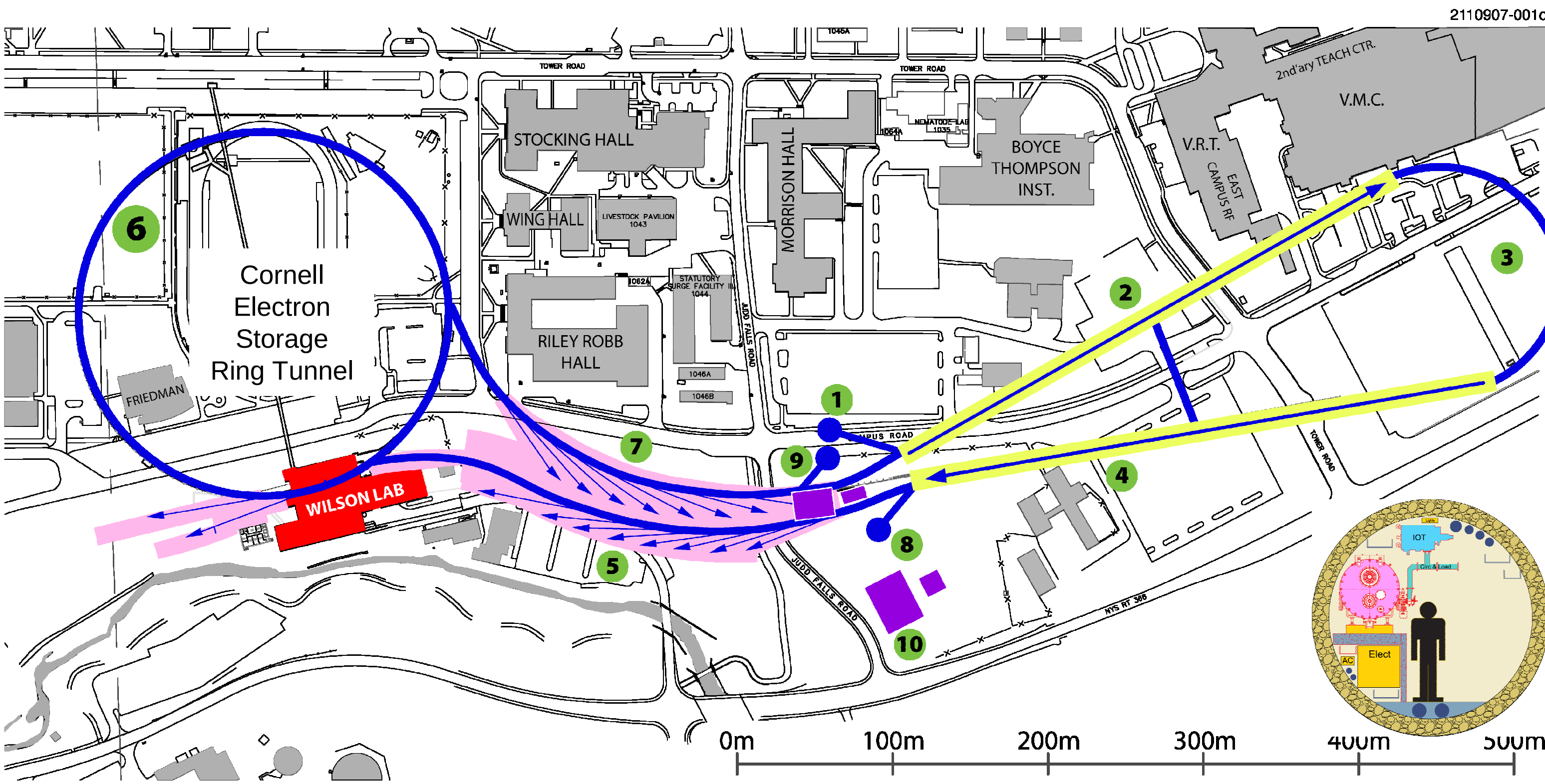
Hole Outcoupler

Beam in control room

Electron beams for improved X-ray beams

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

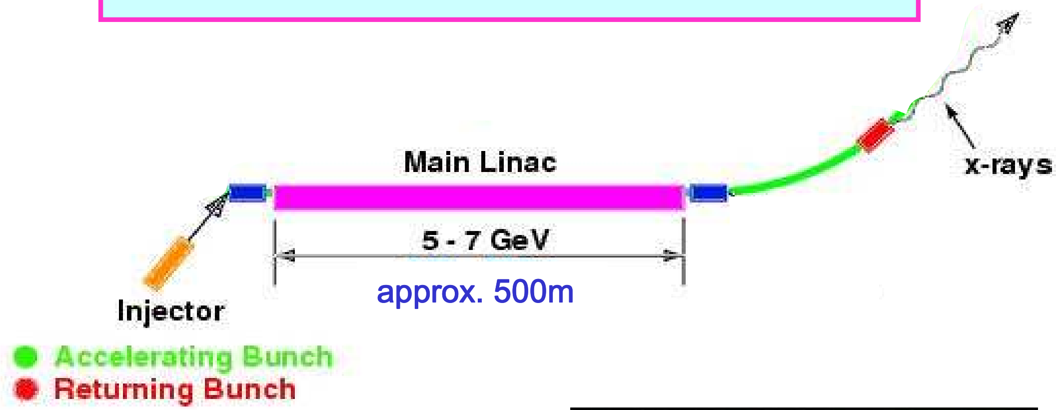
} all of the above



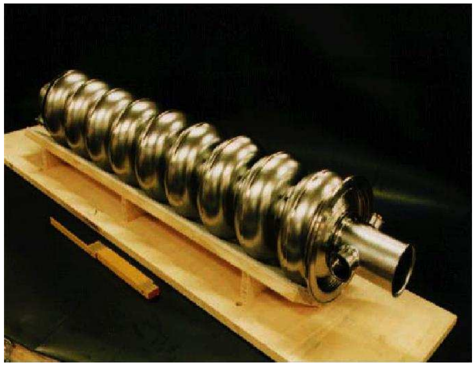
Principle of an X-ray ERL

Narrow beams in rings widen up after many hundreds of turns.

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

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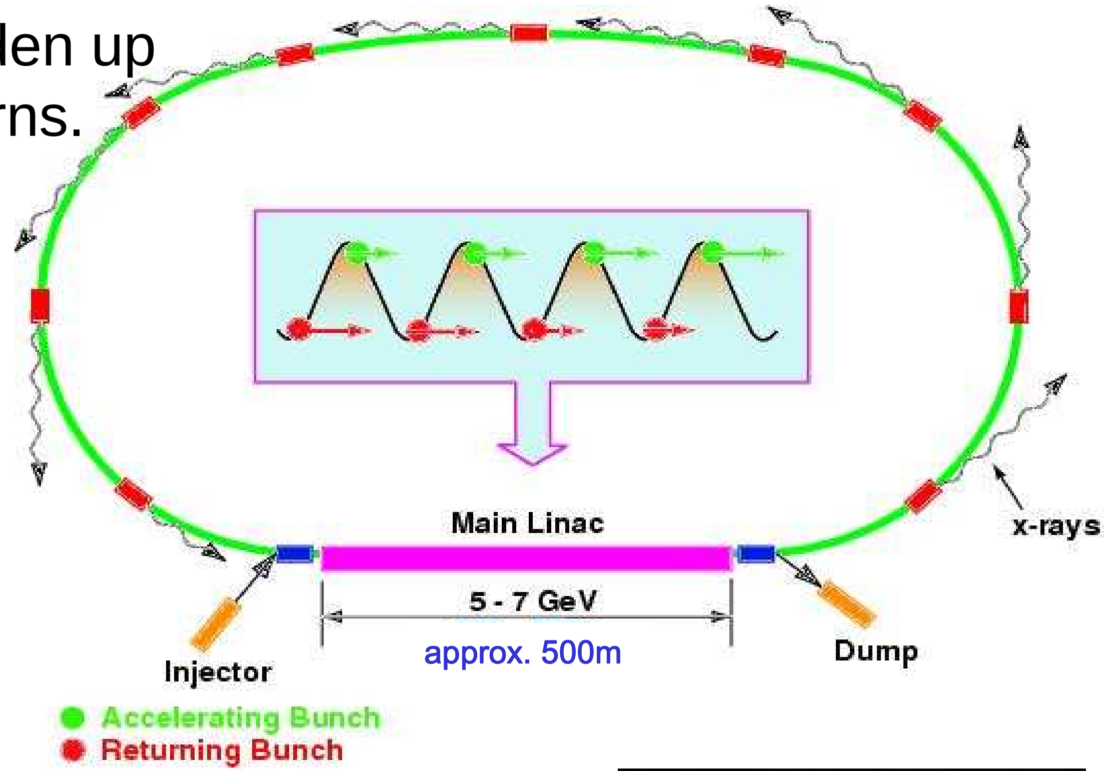
Principle of an X-ray ERL

Narrow beams in rings widen up after many hundreds of turns.

Widening is limited during one turn



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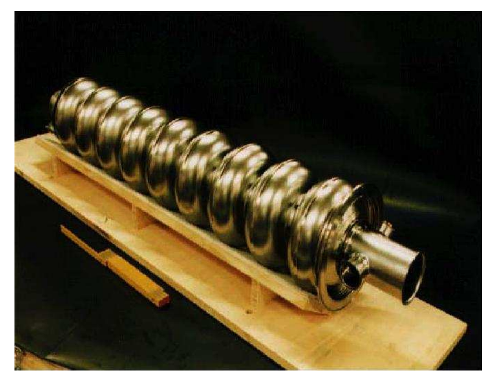
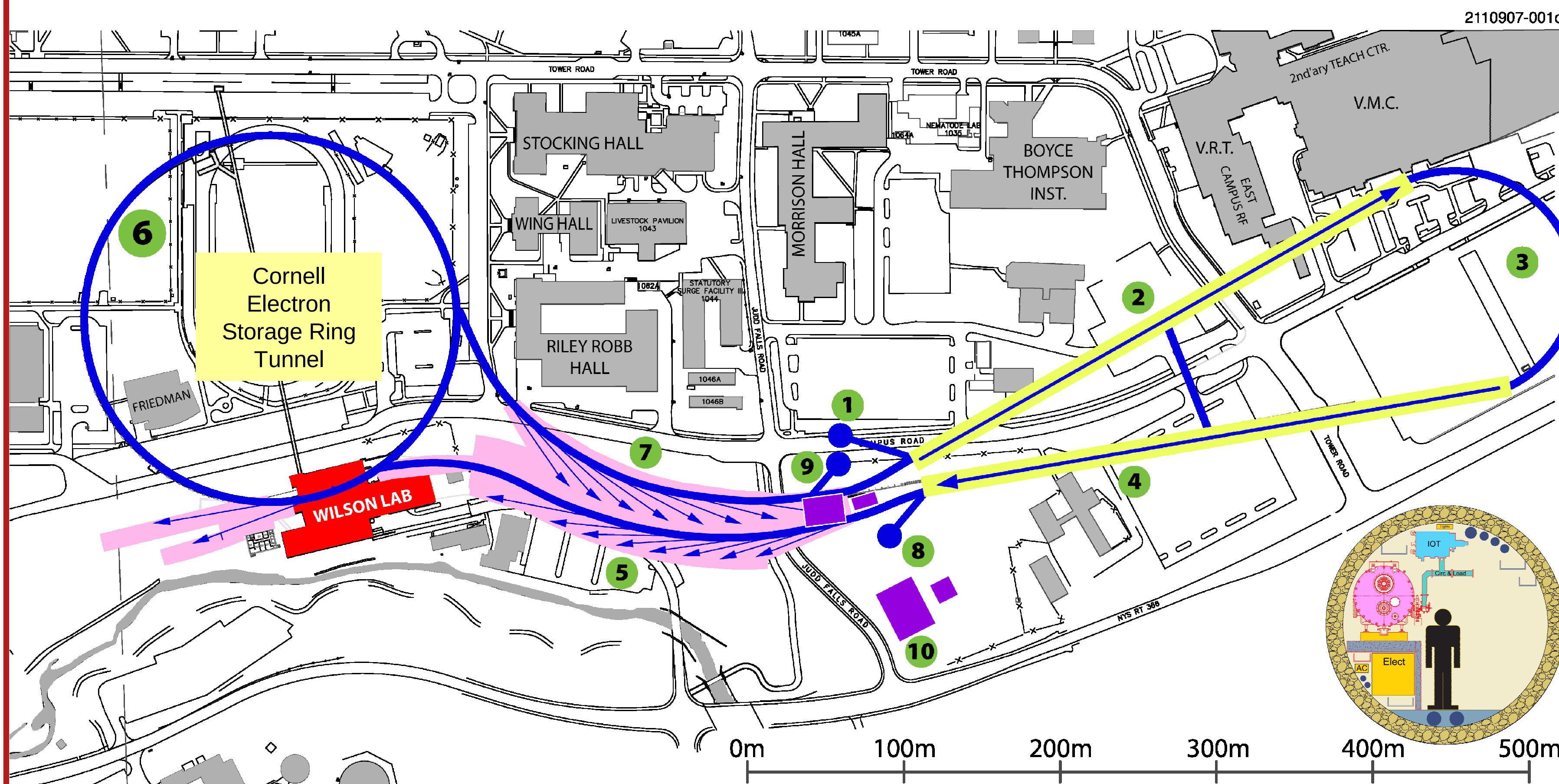


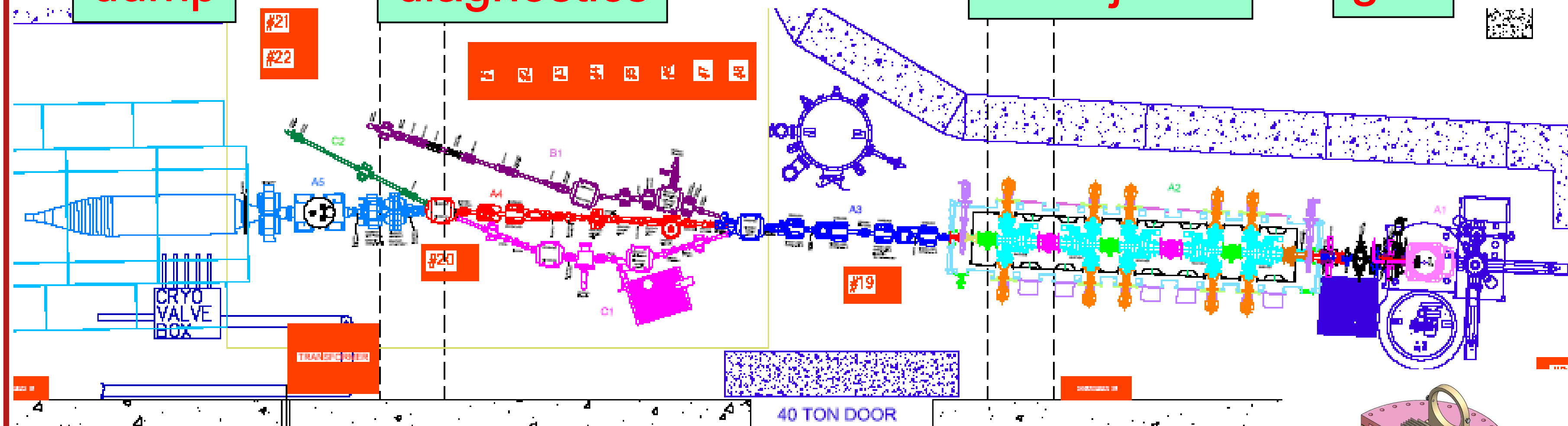
5GeV ERL extension to CESR



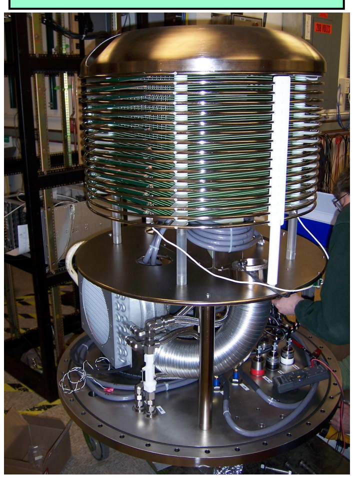
Conceptual building design

Cornell Injector prototype: Verification of beam production

dump | diagnostics | SC injector | gun



Power sup.



Cathode

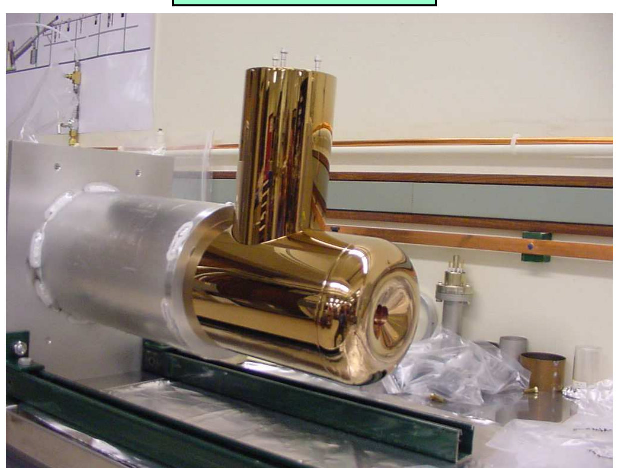
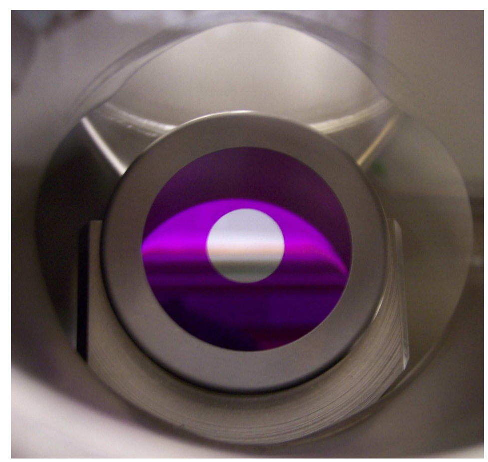
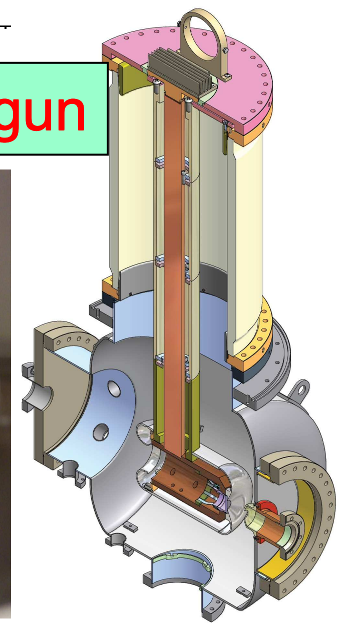


Photo emitter



gun



Cornell Injector prototype: 3D

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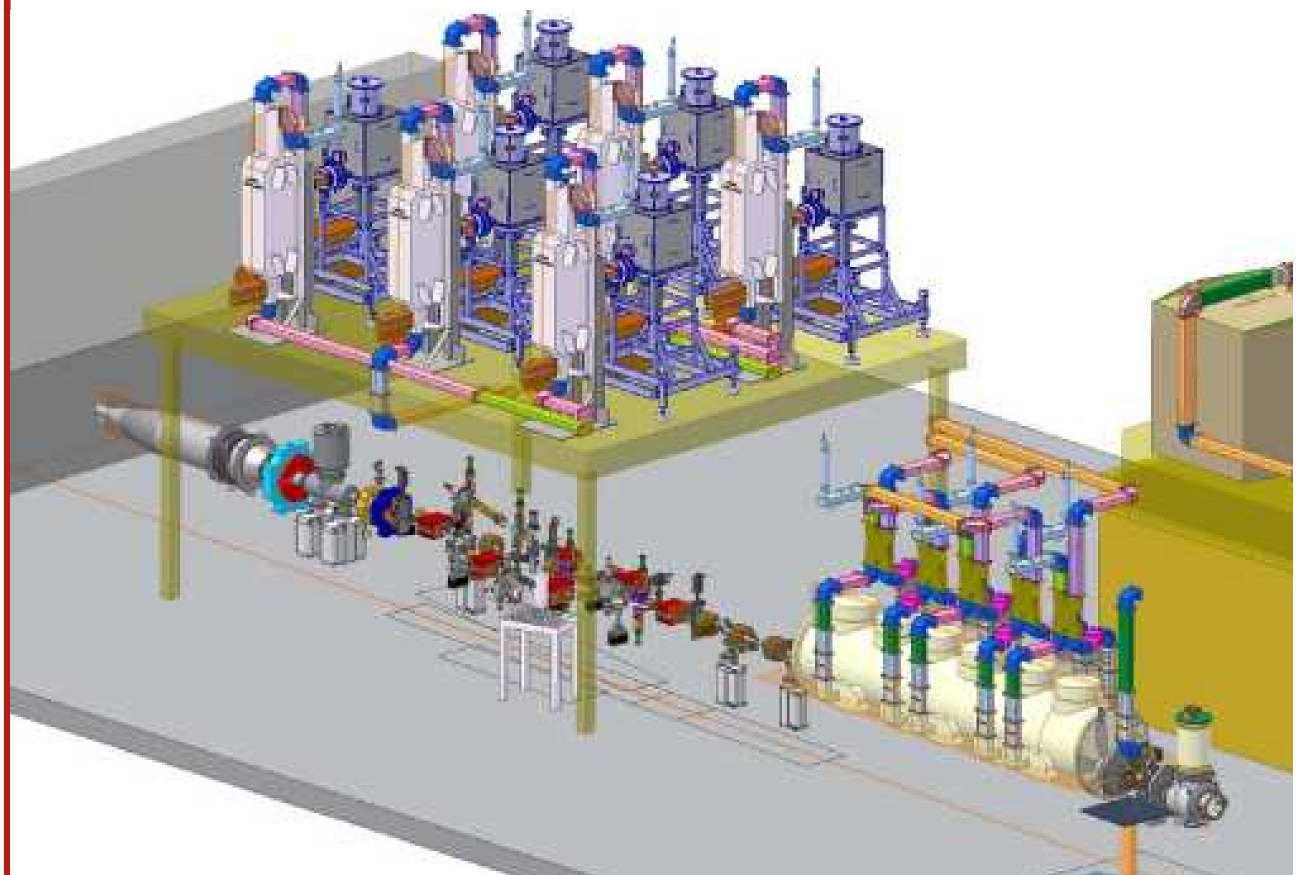


<u>Parameters</u>:

100 mA avg current (5 MeV)

33 mA avg current (15 MeV)

77 pC / bunch at 1.3 GHz

< 1 mm emittance

< 1-2 ps bunch length

<u>Demonstrate:</u>

Cathode longevity

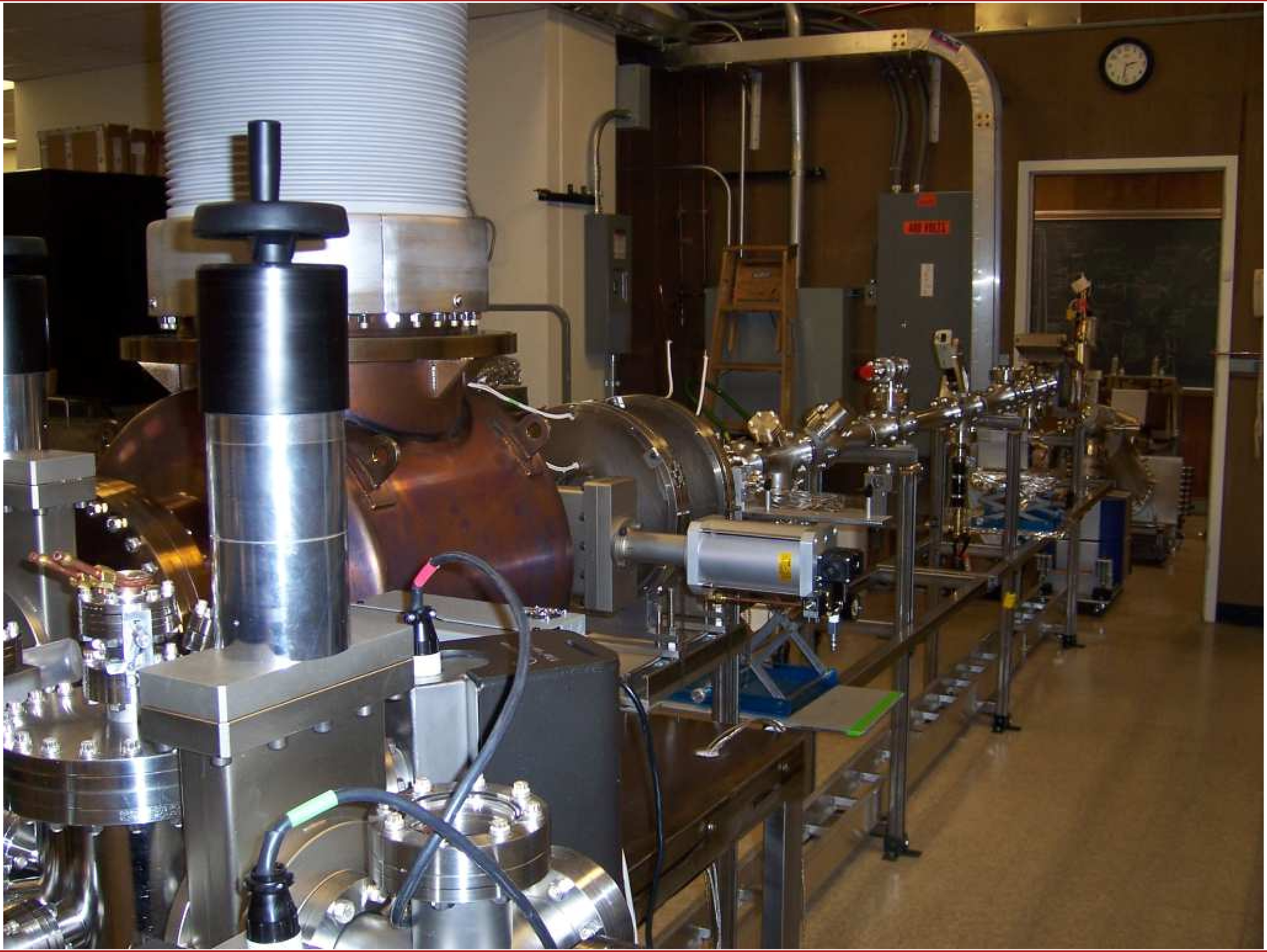
Low emittance

RF controls

Parameter sensitivity

reliability

Gun prototype: well advanced



Emittance Measurement System

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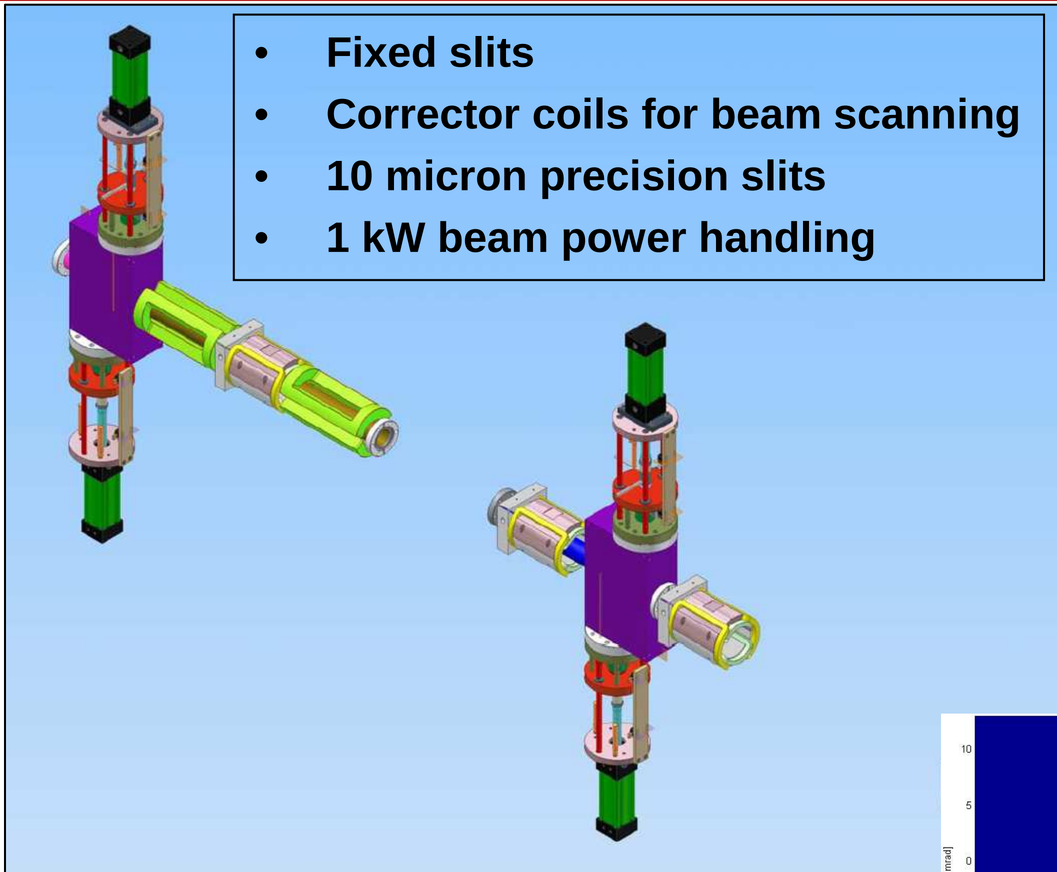
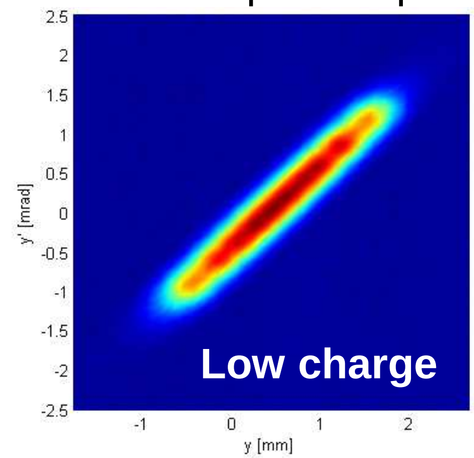


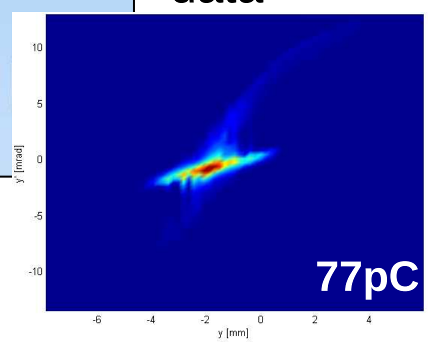
- Fixed slits
- Corrector coils for beam scanning
- 10 micron precision slits
- 1 kW beam power handling

Measured phase space

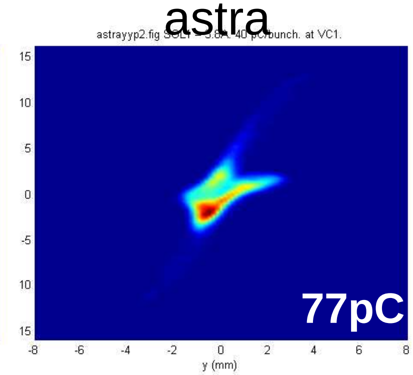


Courtesy Ivan Bazarov

data



astra



Highest current: 25mA
Highest voltage: 430kV
Highest bunch charge: 80pC
Highest Q.E.: 14%

Good agreement with Astra calculation for a misaligned solenoid.

Prototype SC linear accelerator

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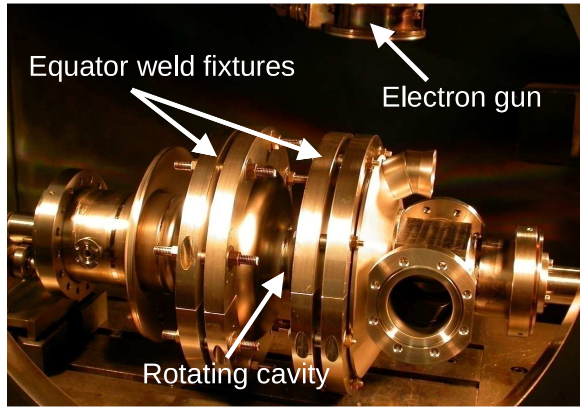
Transport from Newman Lab to Wilson Lab

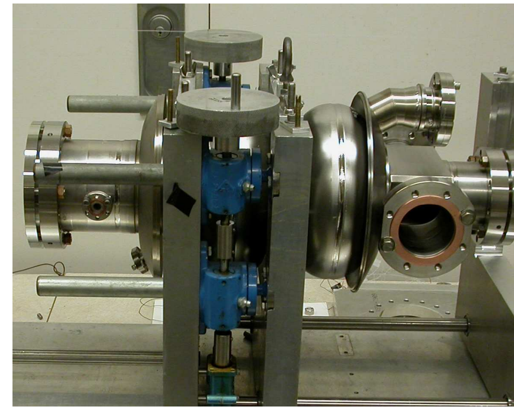
Cavity Production at Newman Lab

Pressed Nb cups for cavities

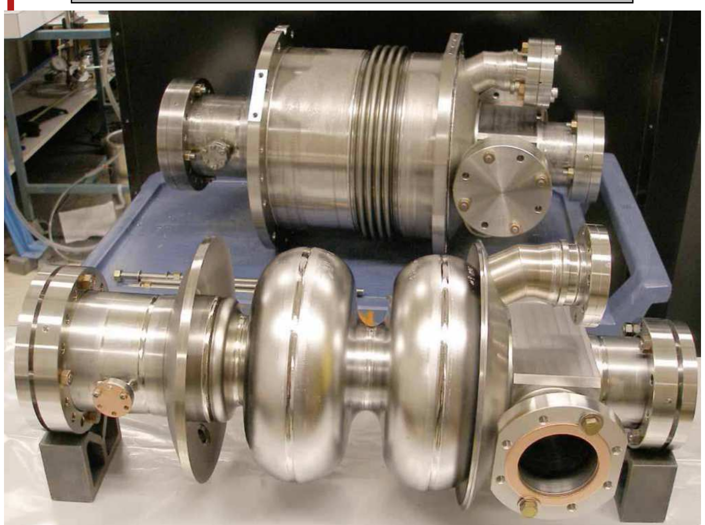
E-beam welding of cavity



Tuning of cavity

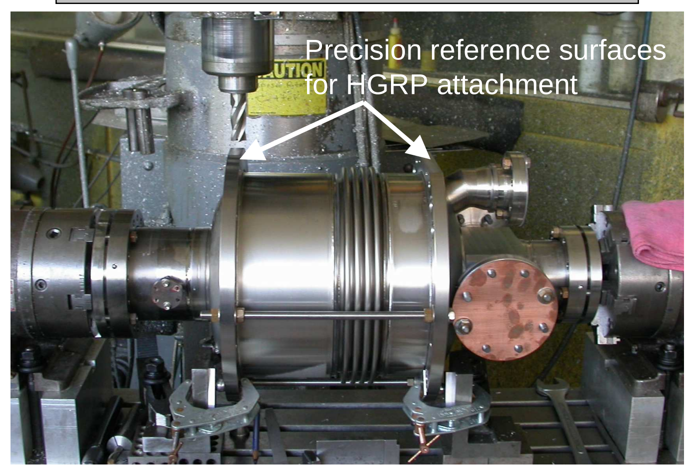


Cavities with and w/o He vessel



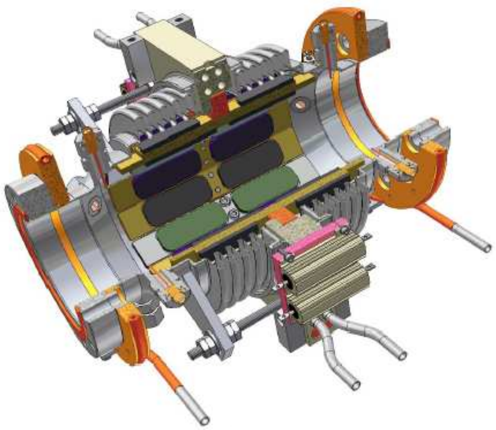
BCP cavity etch

Final machining of He vessel



HOM absorbers a la Cornell

From design

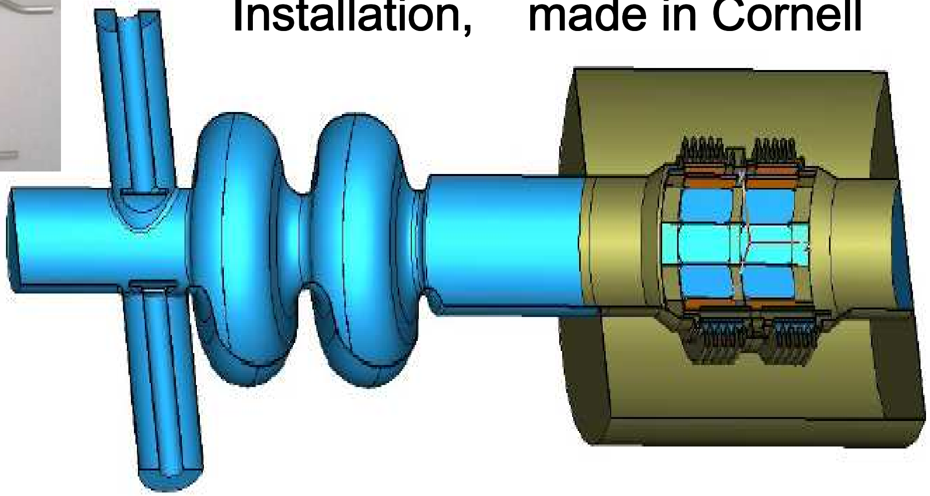


to production and

The Cornell-type HOM absorbers:

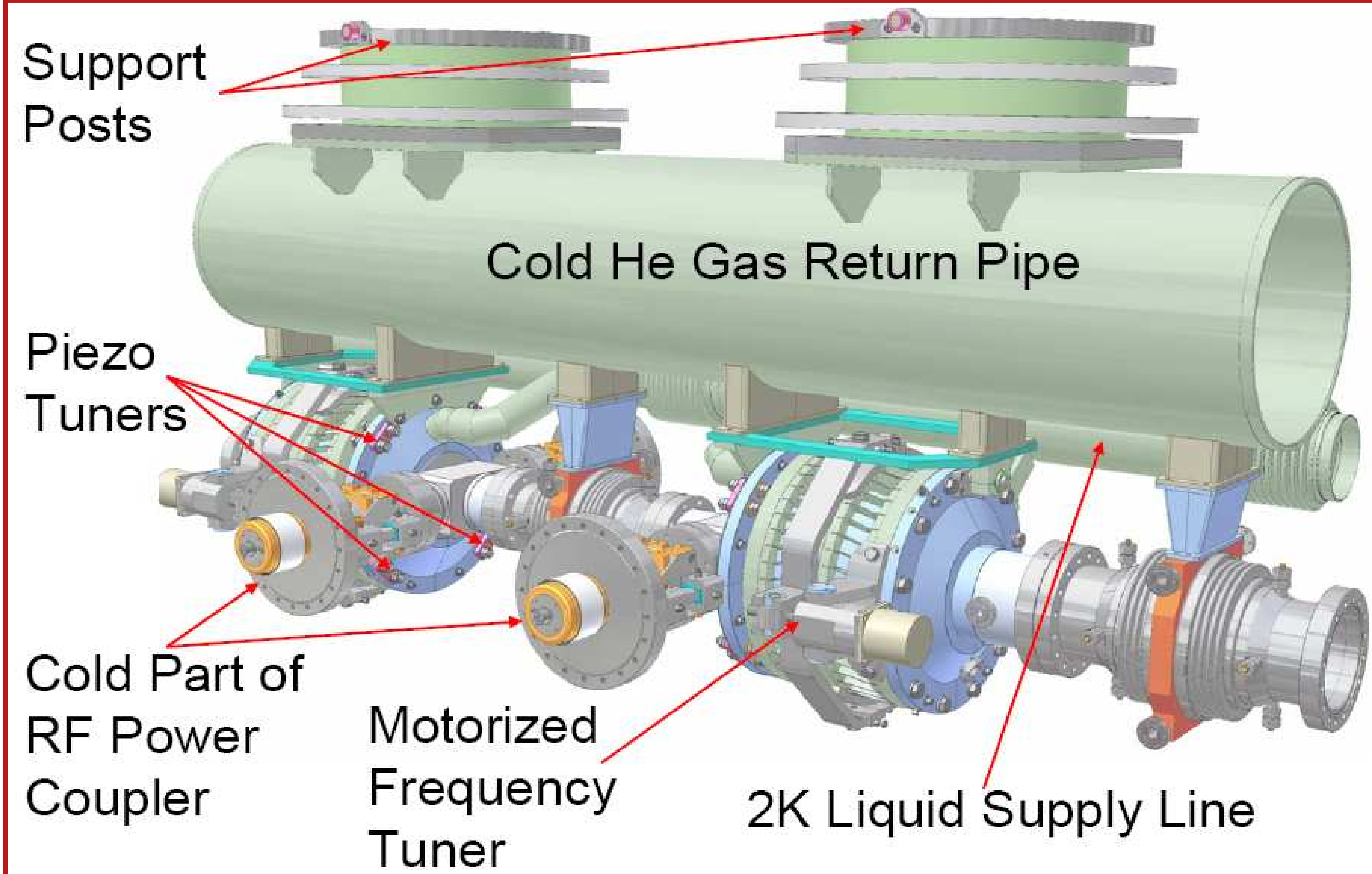
- first developed for CESR
- adopted internationally
- Refined for the ERL

Installation, made in Cornell

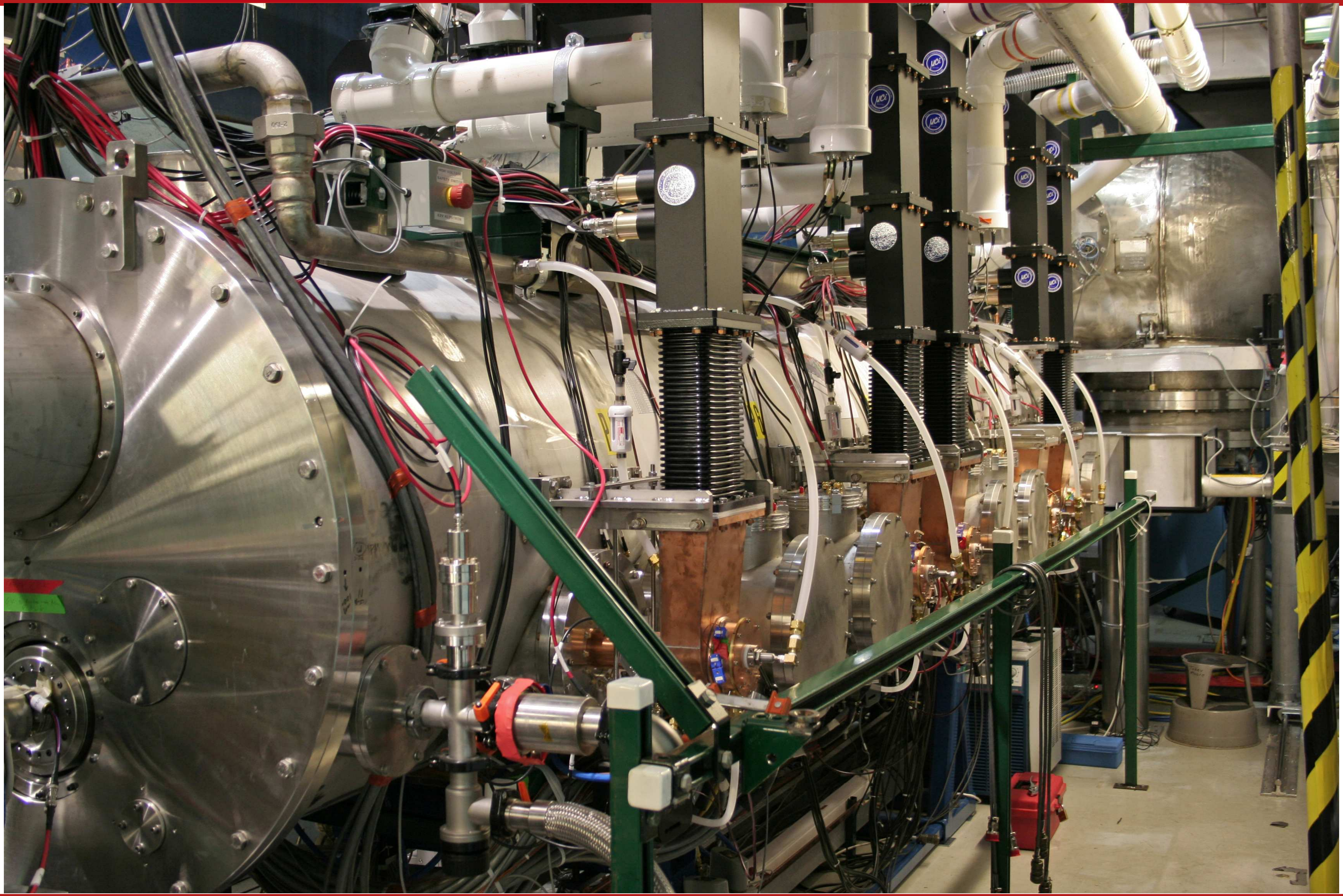


HOM absorbers quickly reduce unwanted field components.

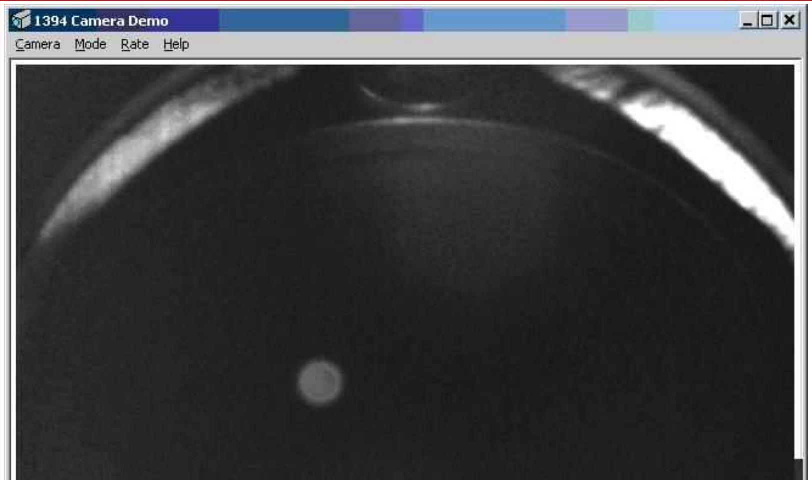
Assembly of the injector accelerator



Assembly of the injector accelerator

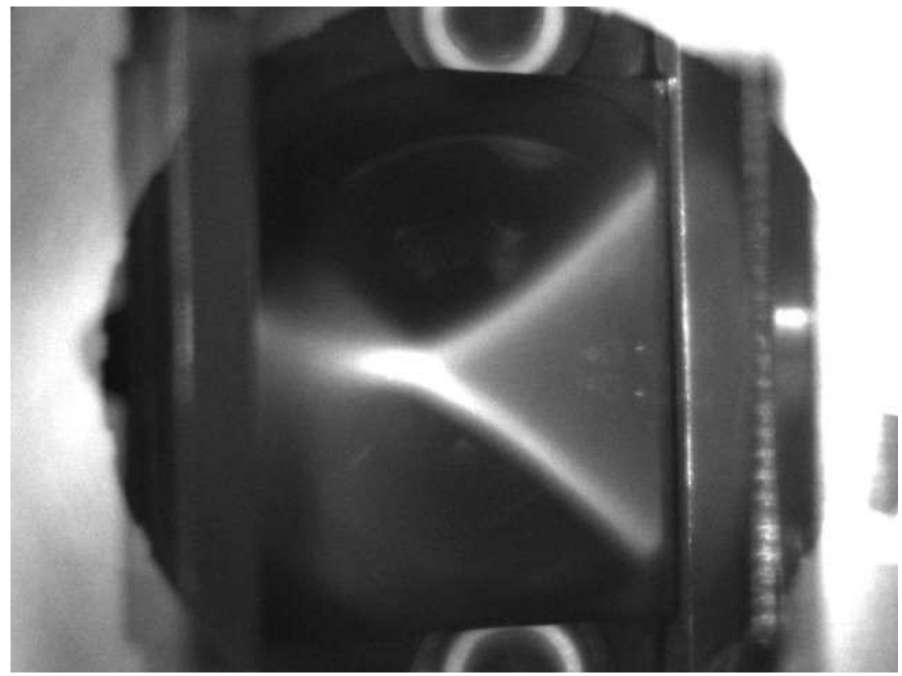


Cornell Injector prototype: First beam



Beam on viewer after the gun – July 7, 2008

Accelerated beam on a viewer in A4 (straight ahead), first RF cavity on – July 8, 2008



Avoiding beam growth during acceleration i.e. by Ion focusing

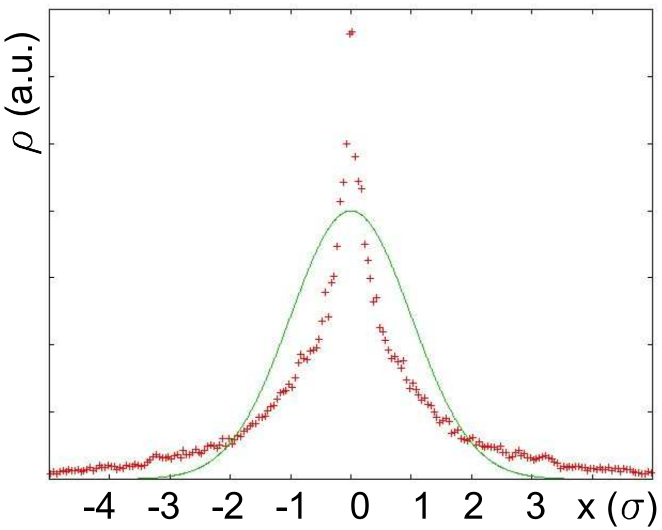
- Ion are quickly produced due to high beam density

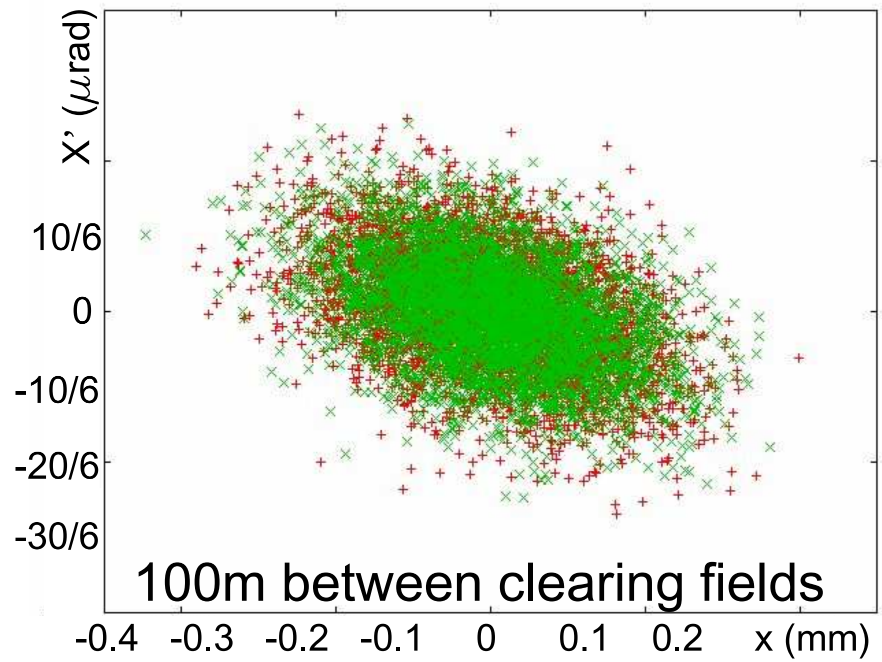
Ion	σ_{col}, 10MeV	σ_{col}, 5GeV	τ_{col}, 5GeV
H_2	$2.0 \cdot 10^{-23}\mathrm{m}^2$	$3.1 \cdot 10^{-23}\mathrm{m}^2$	5.6s
CO	$1.0 \cdot 10^{-22}\mathrm{m}^2$	$1.9 \cdot 10^{-22}\mathrm{m}^2$	92.7s
CH_4	$1.2 \cdot 10^{-22}\mathrm{m}^2$	$2.0 \cdot 10^{-22}\mathrm{m}^2$	85.2s

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

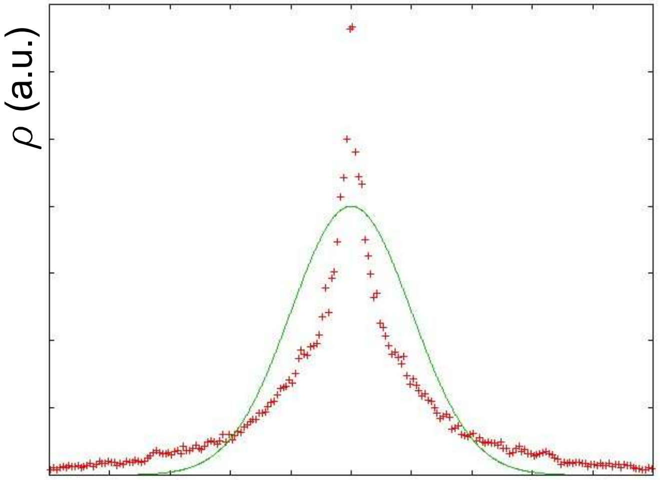
- Conventional ion clearing techniques:
  1) Long clearing gaps have transient RF effects in the ERL [2ms every 7ms].
  2) Short gaps have transient effects in injector and gun and produce more beam harmonics that excite HOMs [0.4 ms every 7ms].
  3) DC fields of about 150kV/m have to be applied to appropriate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

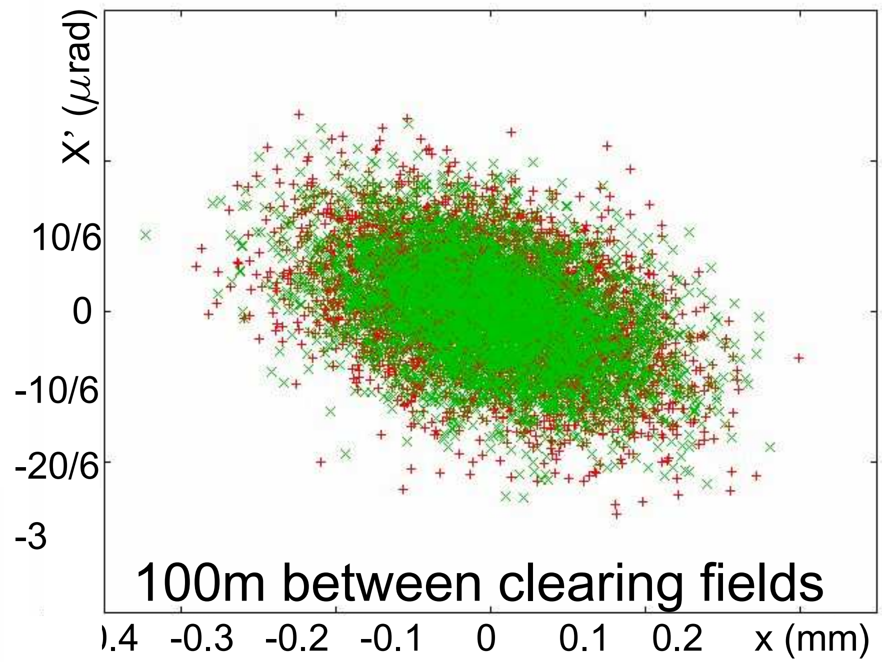
Ions in an ERL beam

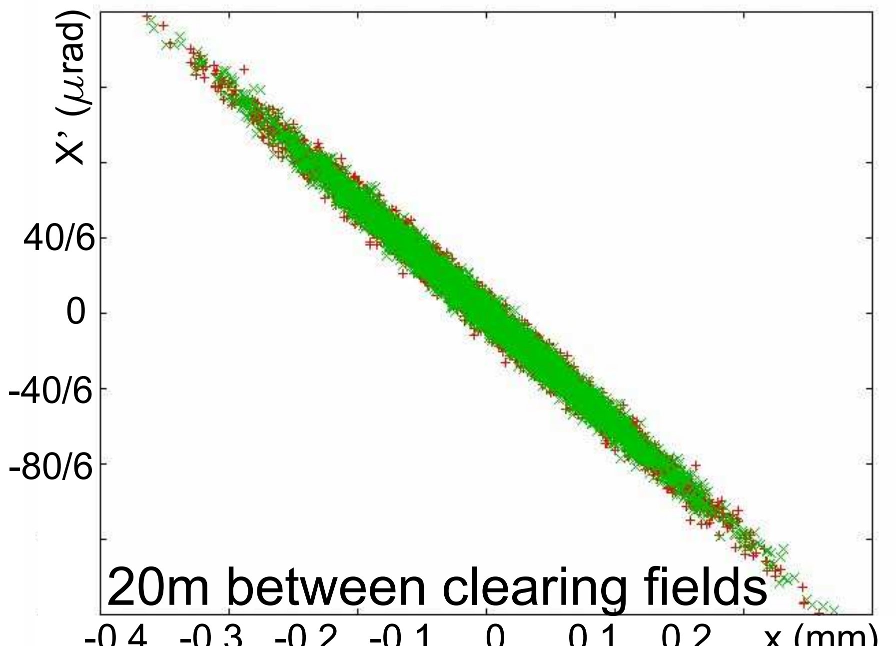




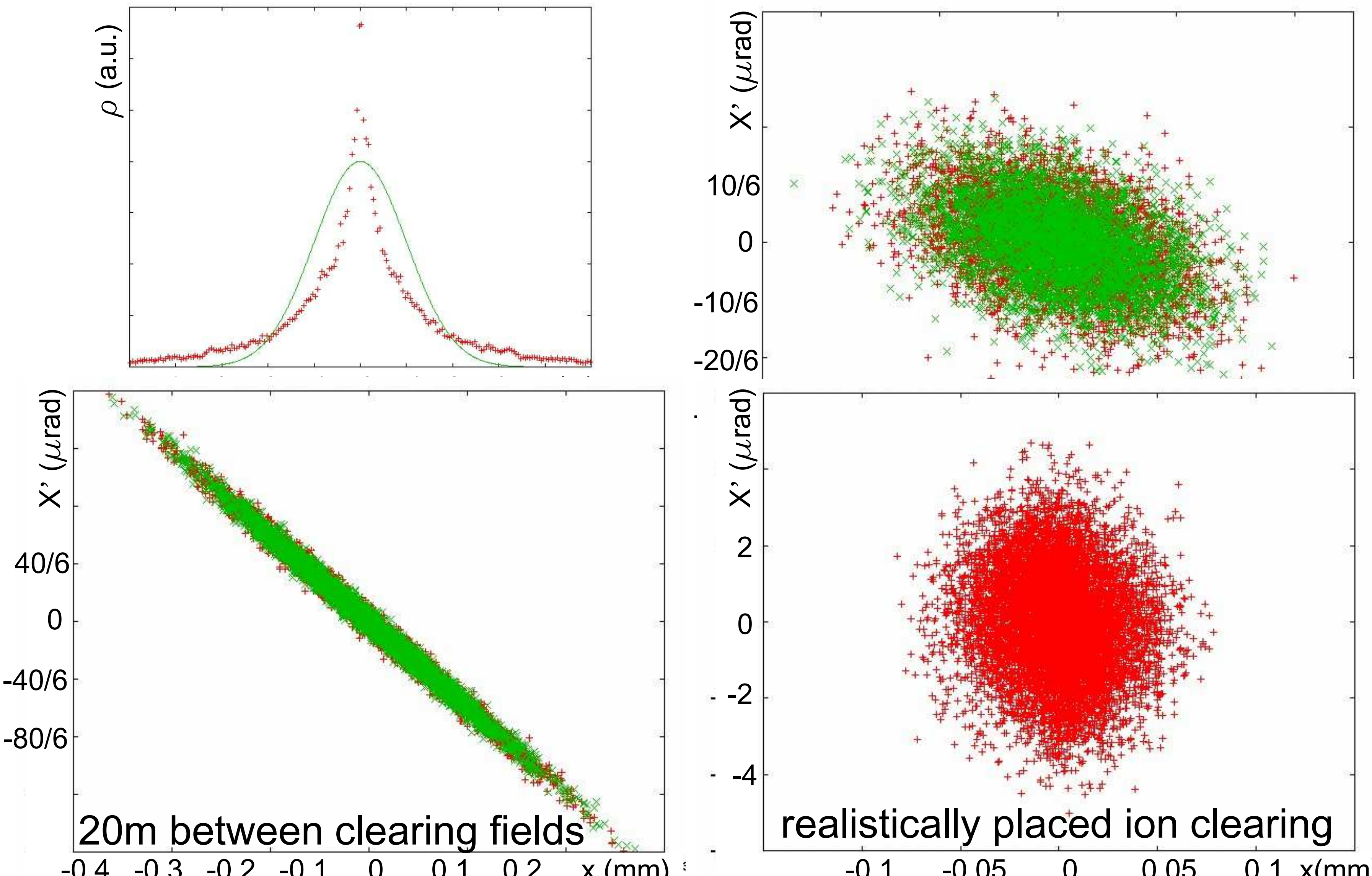
Ions in an ERL beam



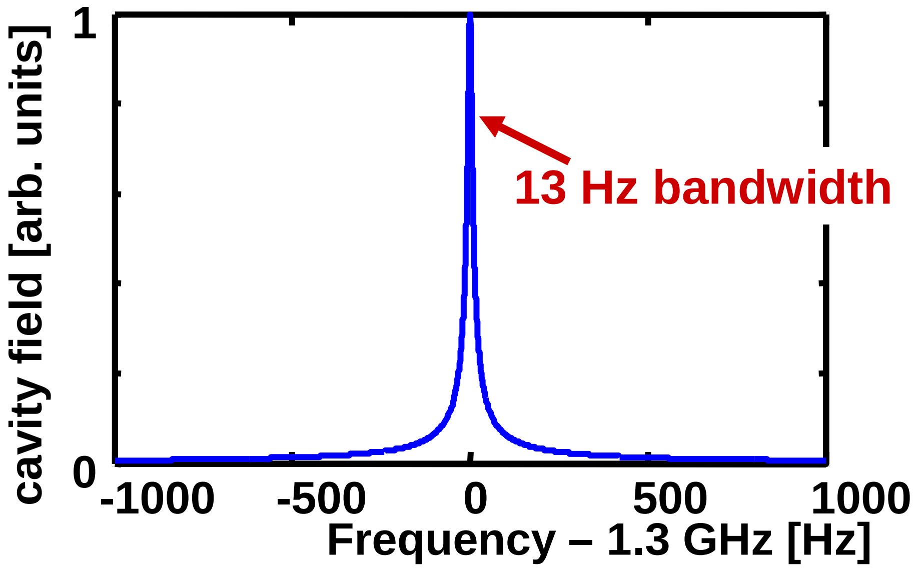


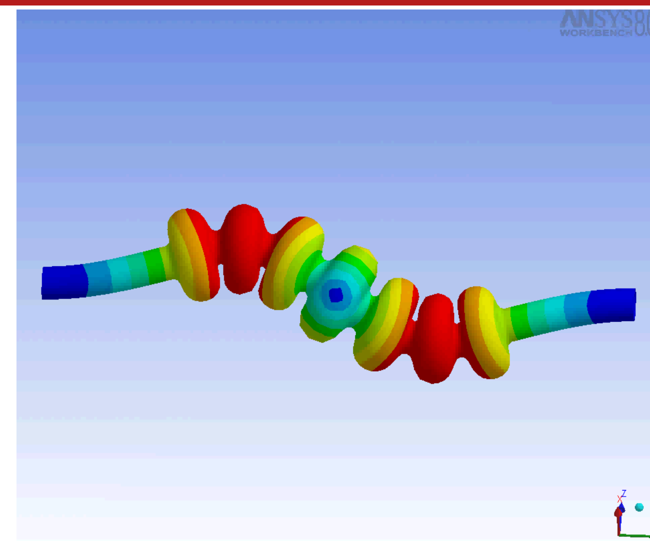


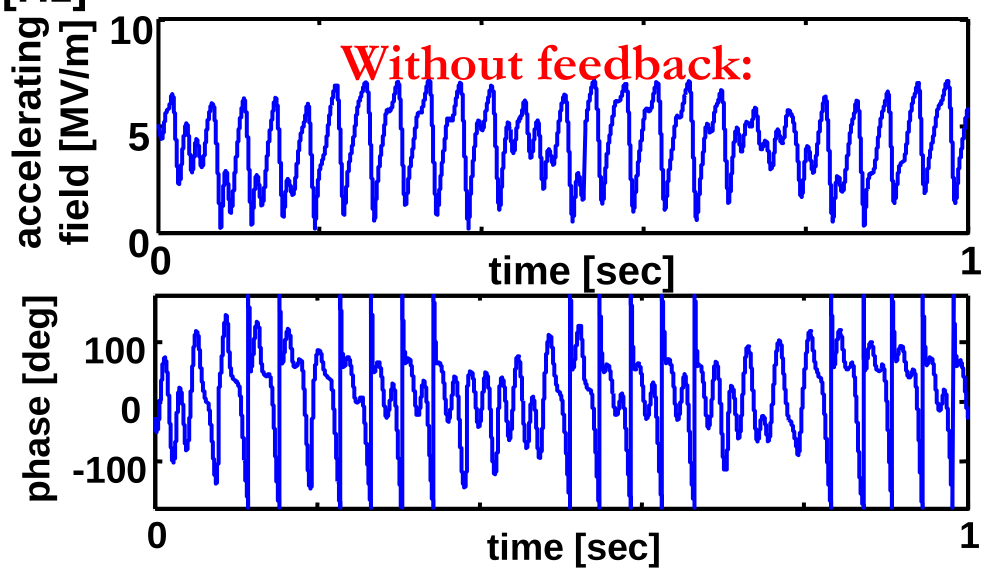
Ions in an ERL beam



Cavity control for SC linacs (ERL & ILC)



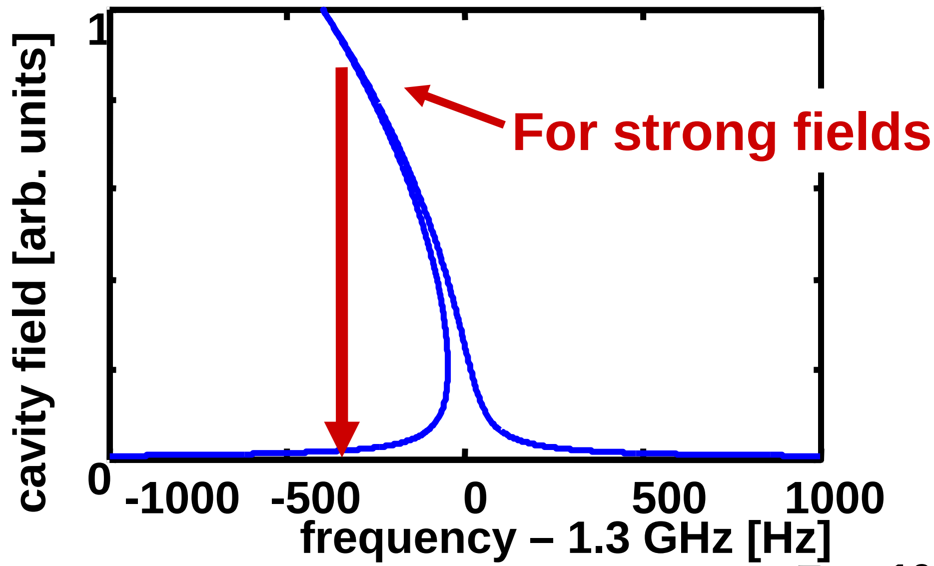


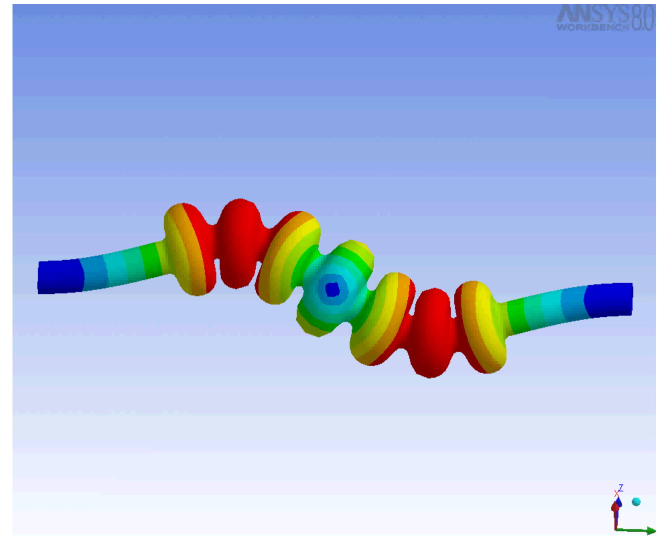


- Run cavity with lowest possible bandwidth for ERL.
- But frequency stabilization becomes very critical.

Cavity control for SC linacs (ERL & ILC)

CLASSE





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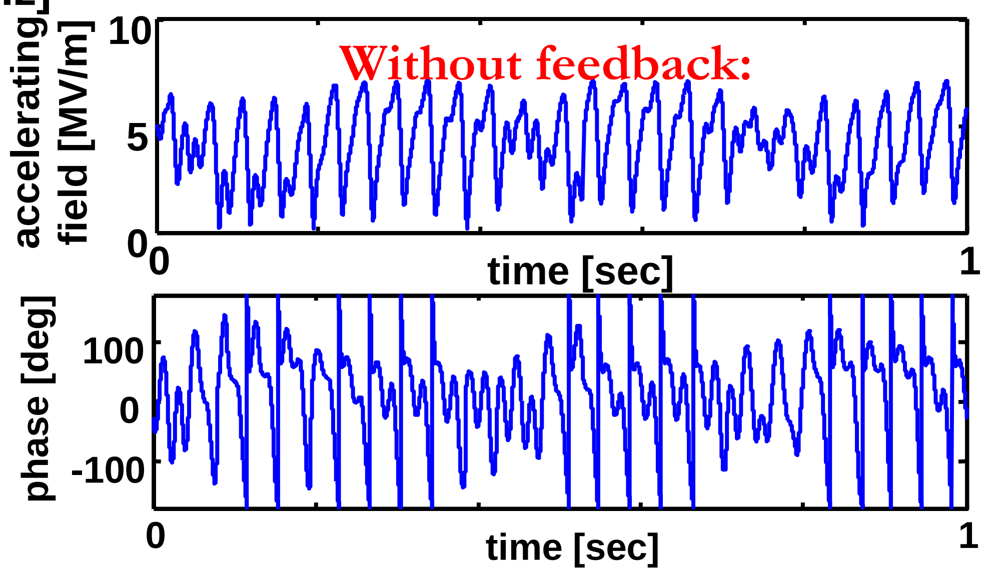

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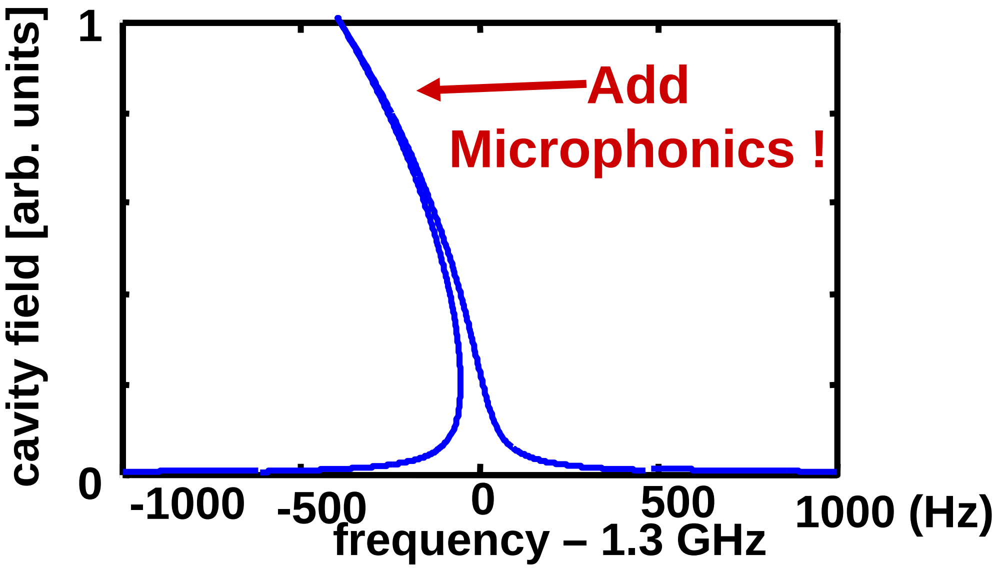

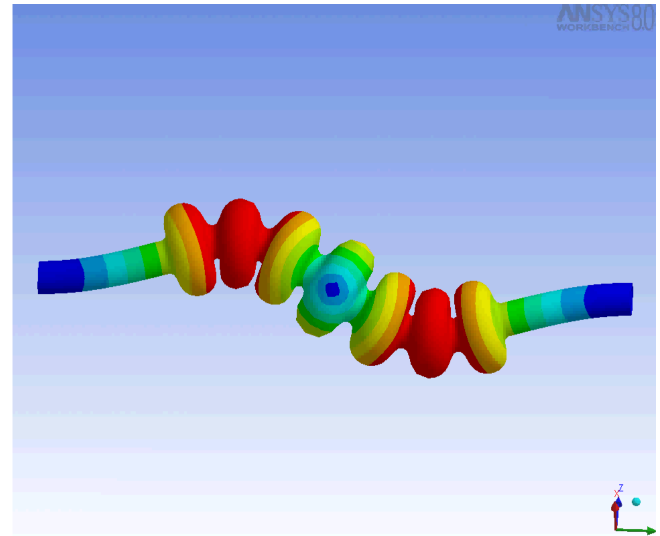

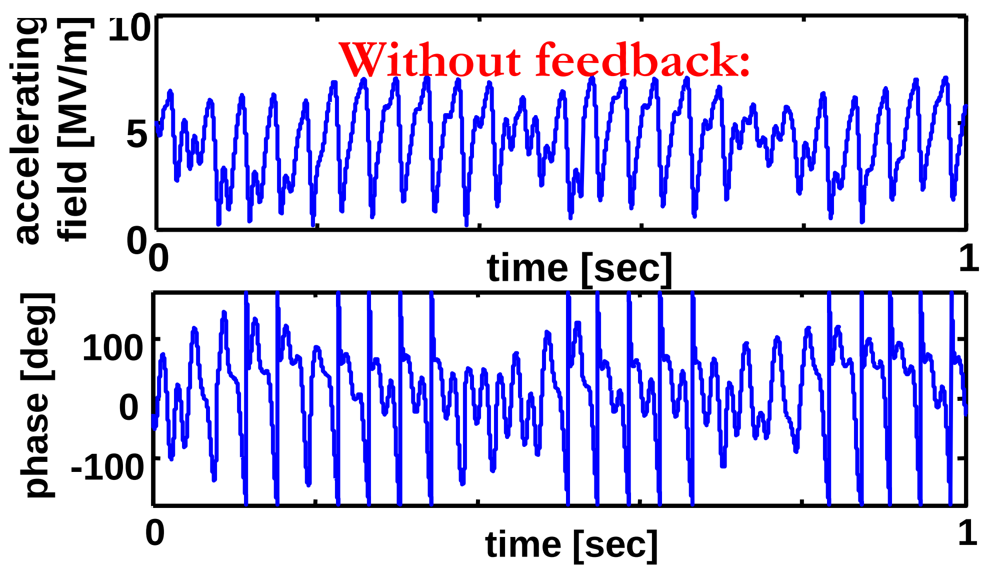

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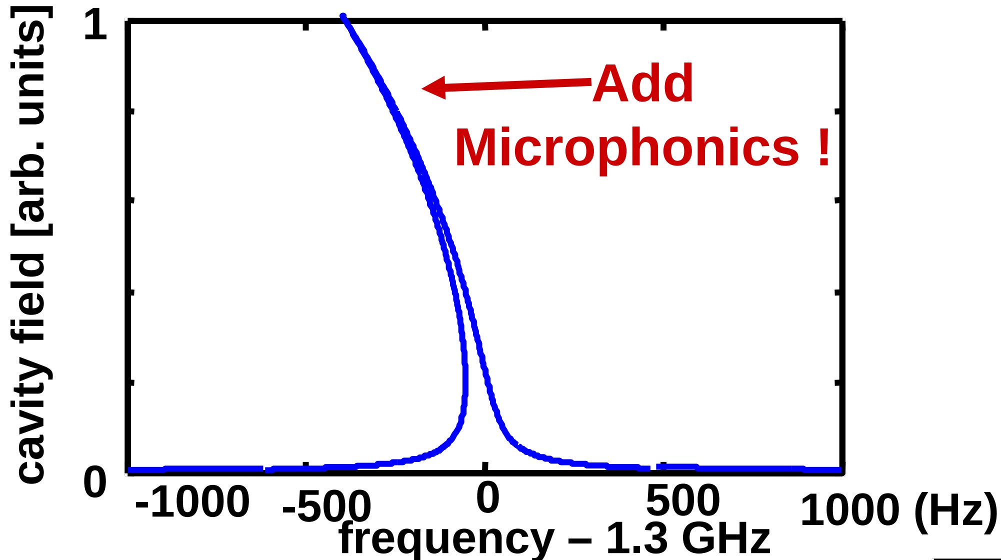

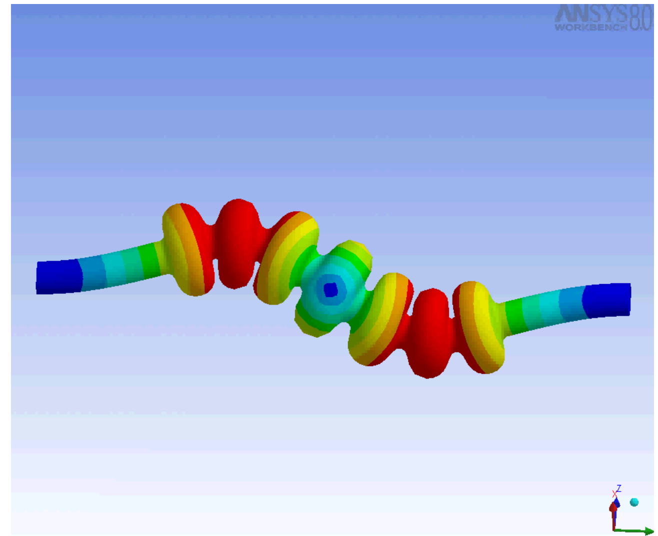

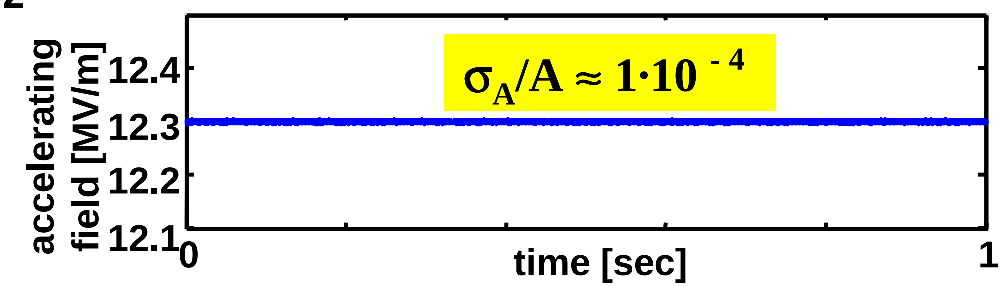

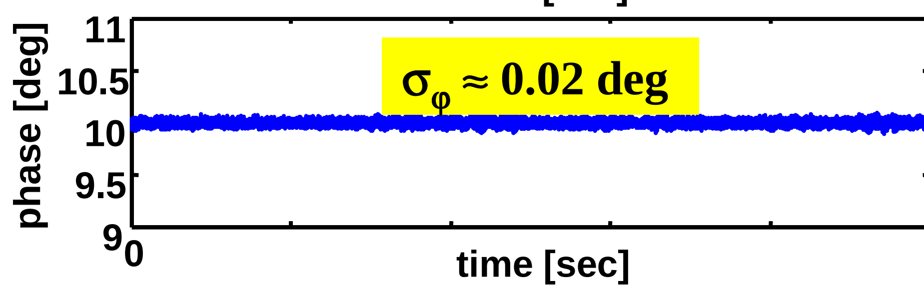

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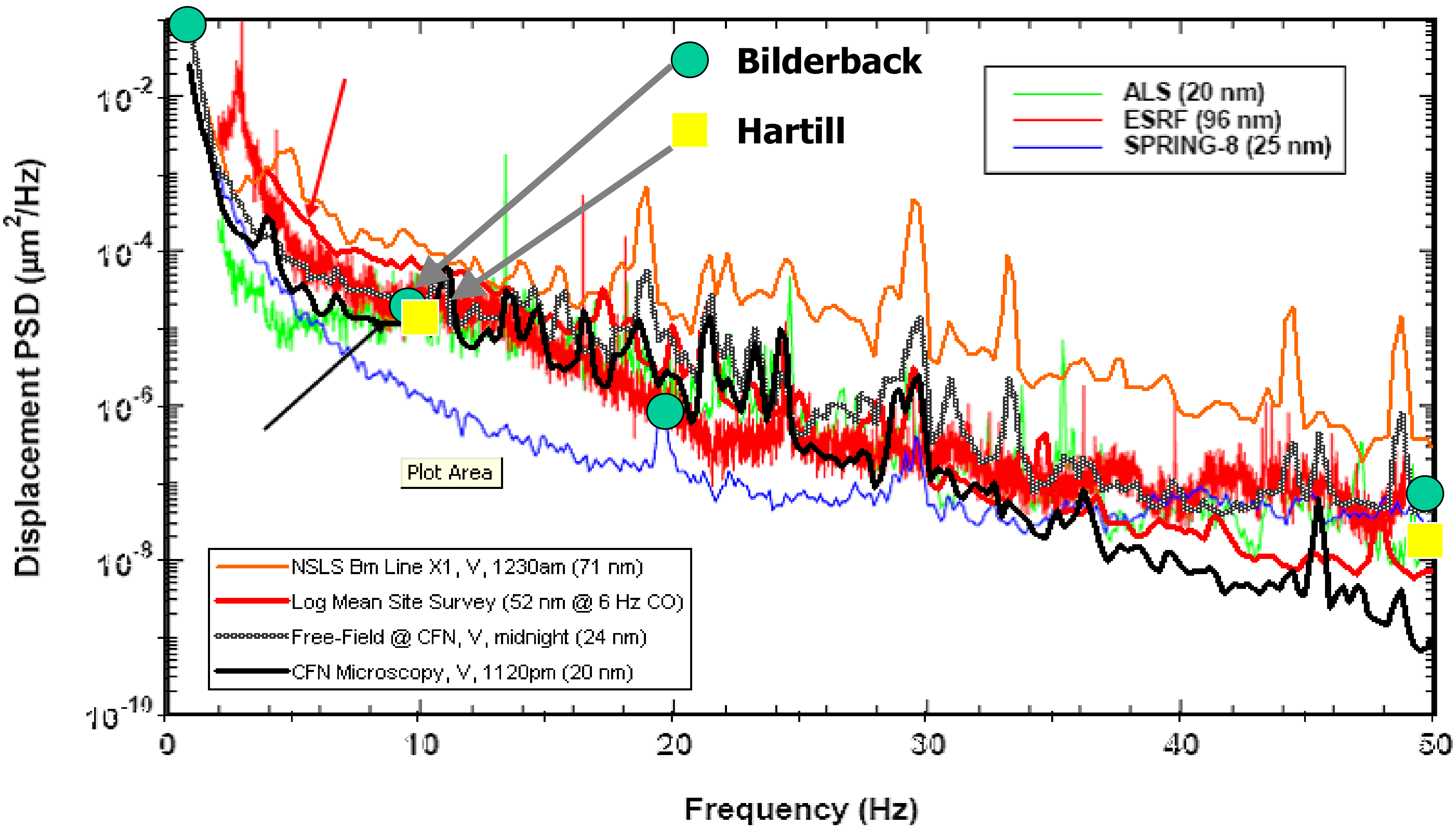
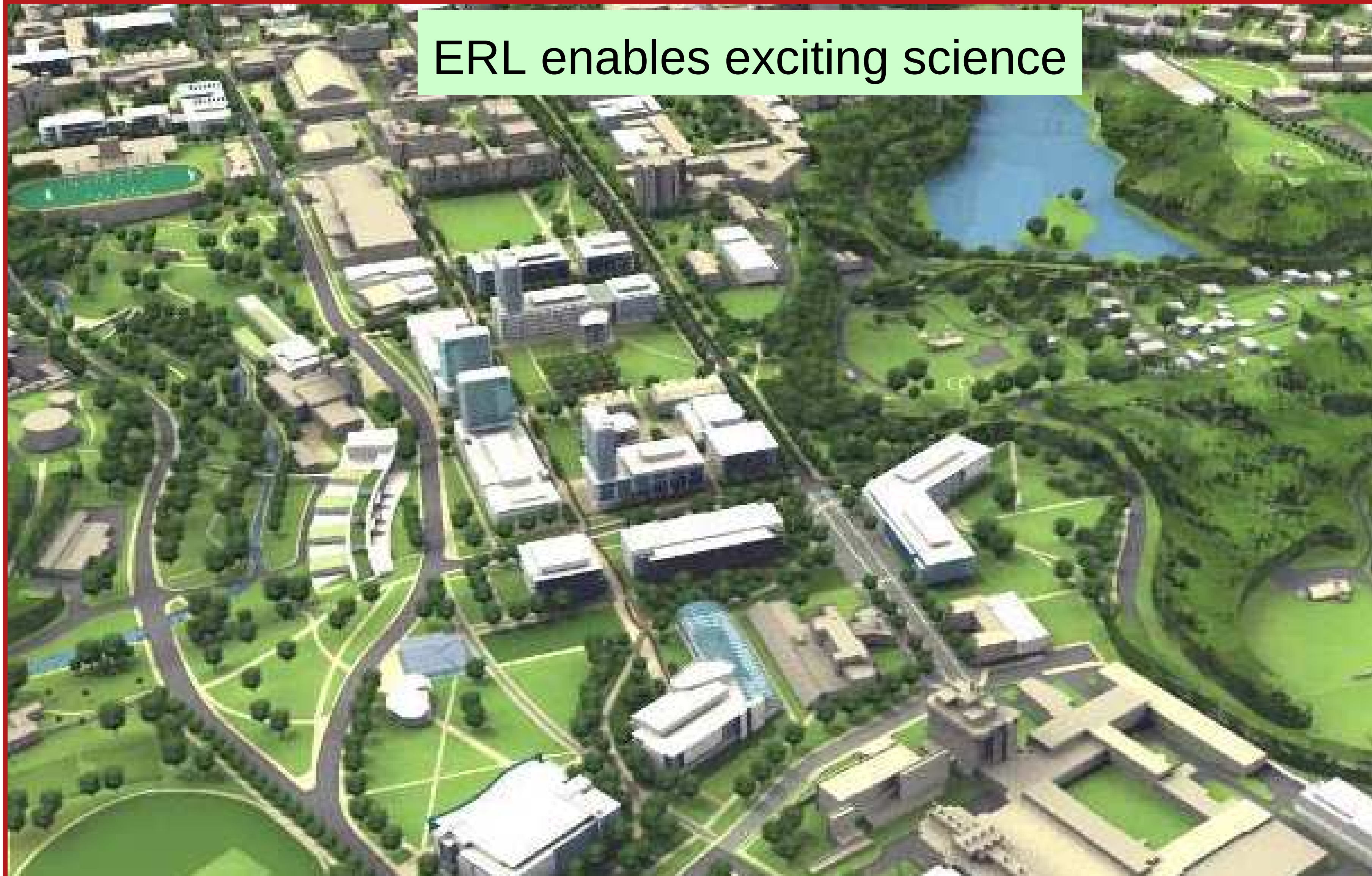
Vibration measurements



Toward the Future …



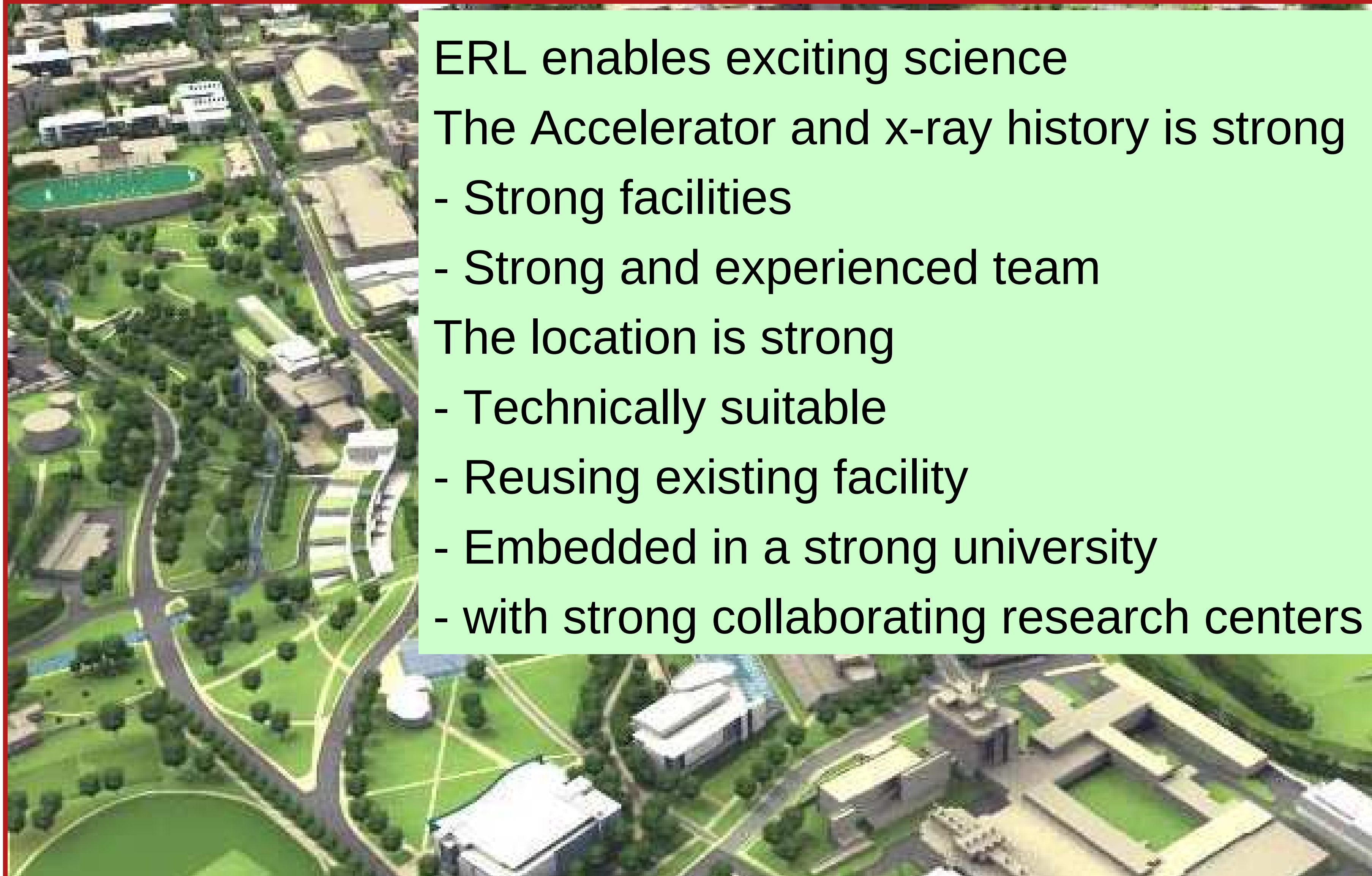
Toward the Future …

ERL enables exciting science

The Accelerator and x-ray history is strong

- Strong facilities
- Strong and experienced team

Toward the Future …



ERL enables exciting science

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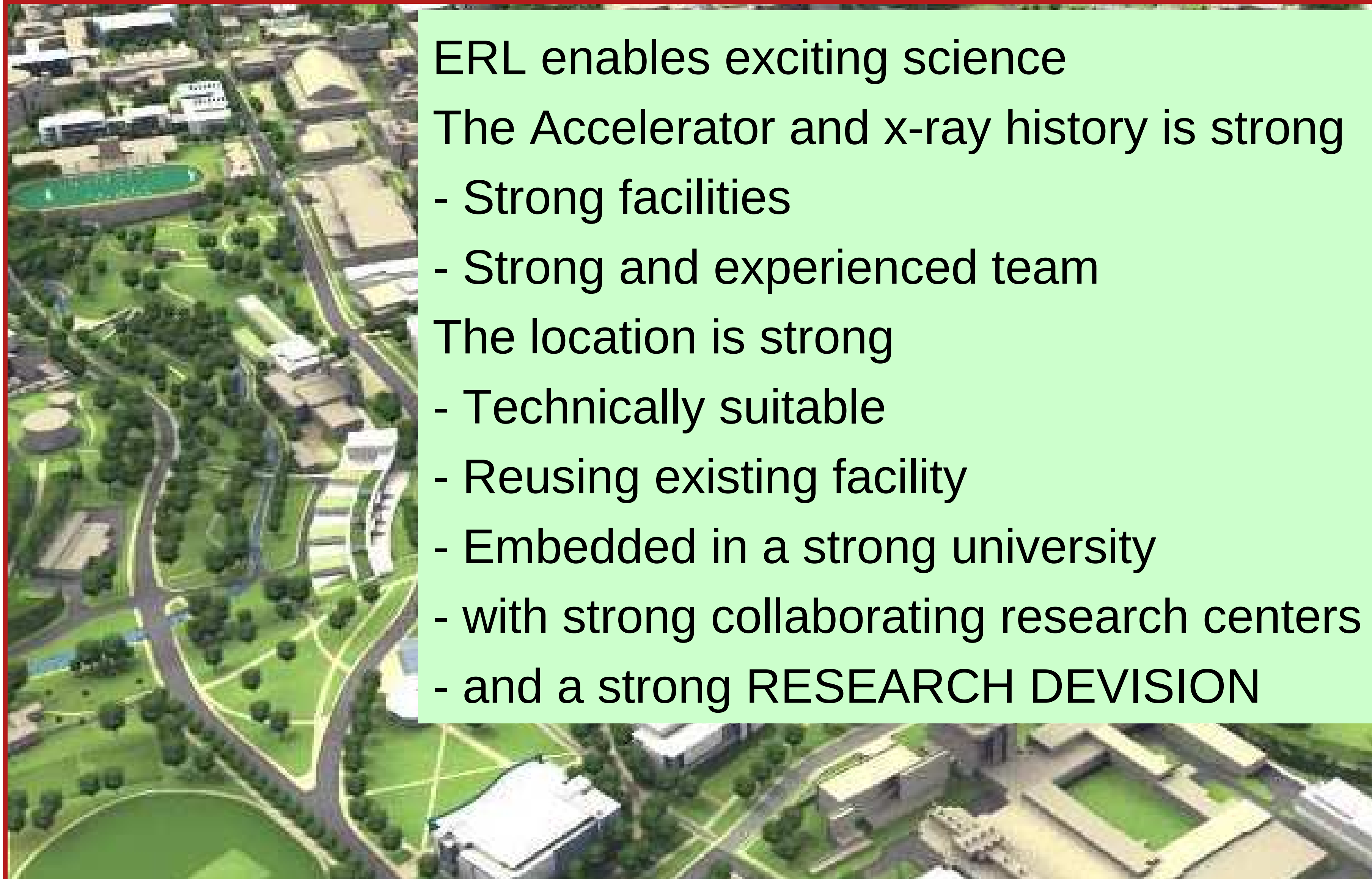
The location is strong

- Technically suitable
- Reusing existing facility
- Embedded in a strong university
- with strong collaborating research centers

Toward the Future …



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- and a strong RESEARCH DEVISION

The next ERL workshop is in Ithaca 1 year from now