The Advanced Photon Source : An Introduction

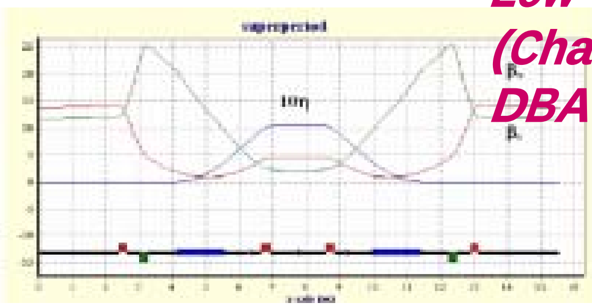
Argonne National Laboratory, a U.S. Department of Energy Office of Science laboratory,
is operated by The University of Chicago.
The Advanced Photon Source is funded by the U.S. Department of Energy,
Office of Science, Office of Basic Energy Sciences.

Third-Generation X-ray Sources

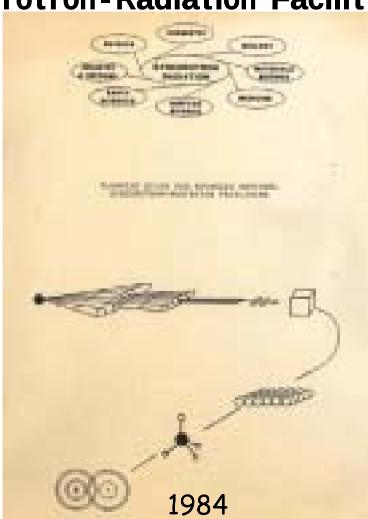
Chasman

Greene

Low Beam Emittance (Chaseman-Green or DBA Lattice)

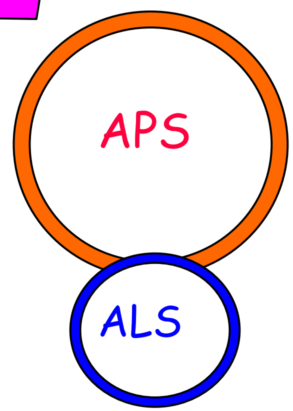


Planning Study for Advanced National Synchrotron-Radiation Facilities

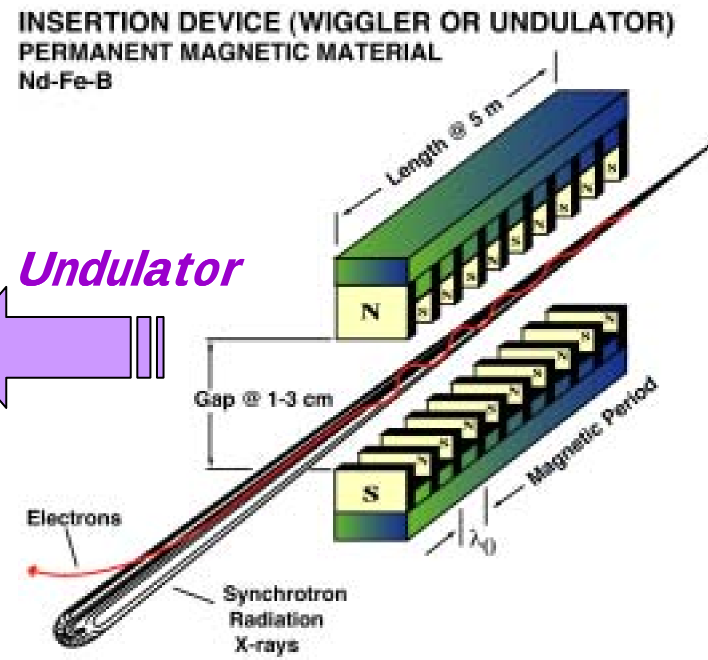


Cochairs:P. Eisenberger
M. Knotek

Scientific Drivers



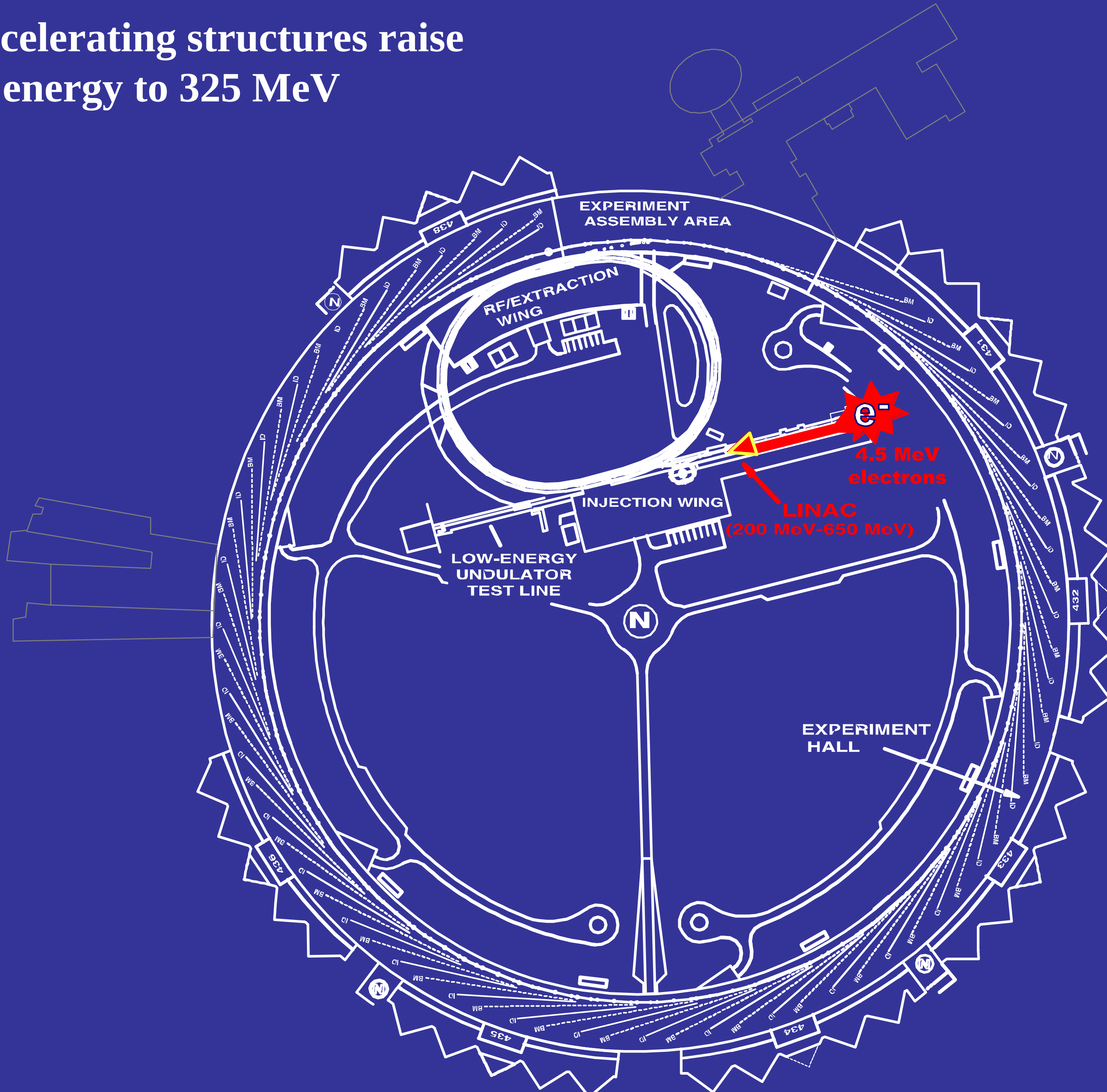
Undulator



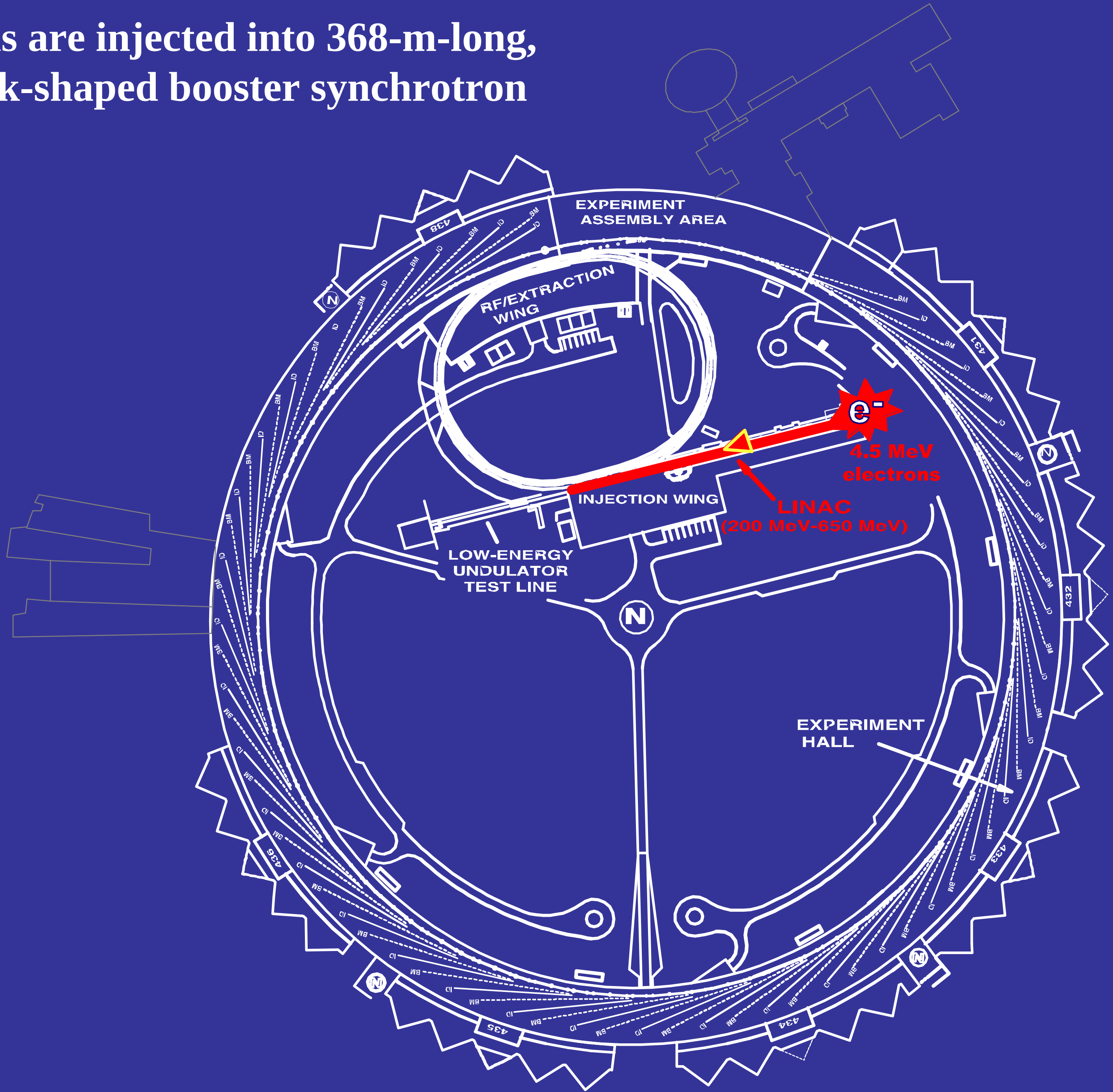
Third Generation Facilities

K. Halbach
N. Vinokurov

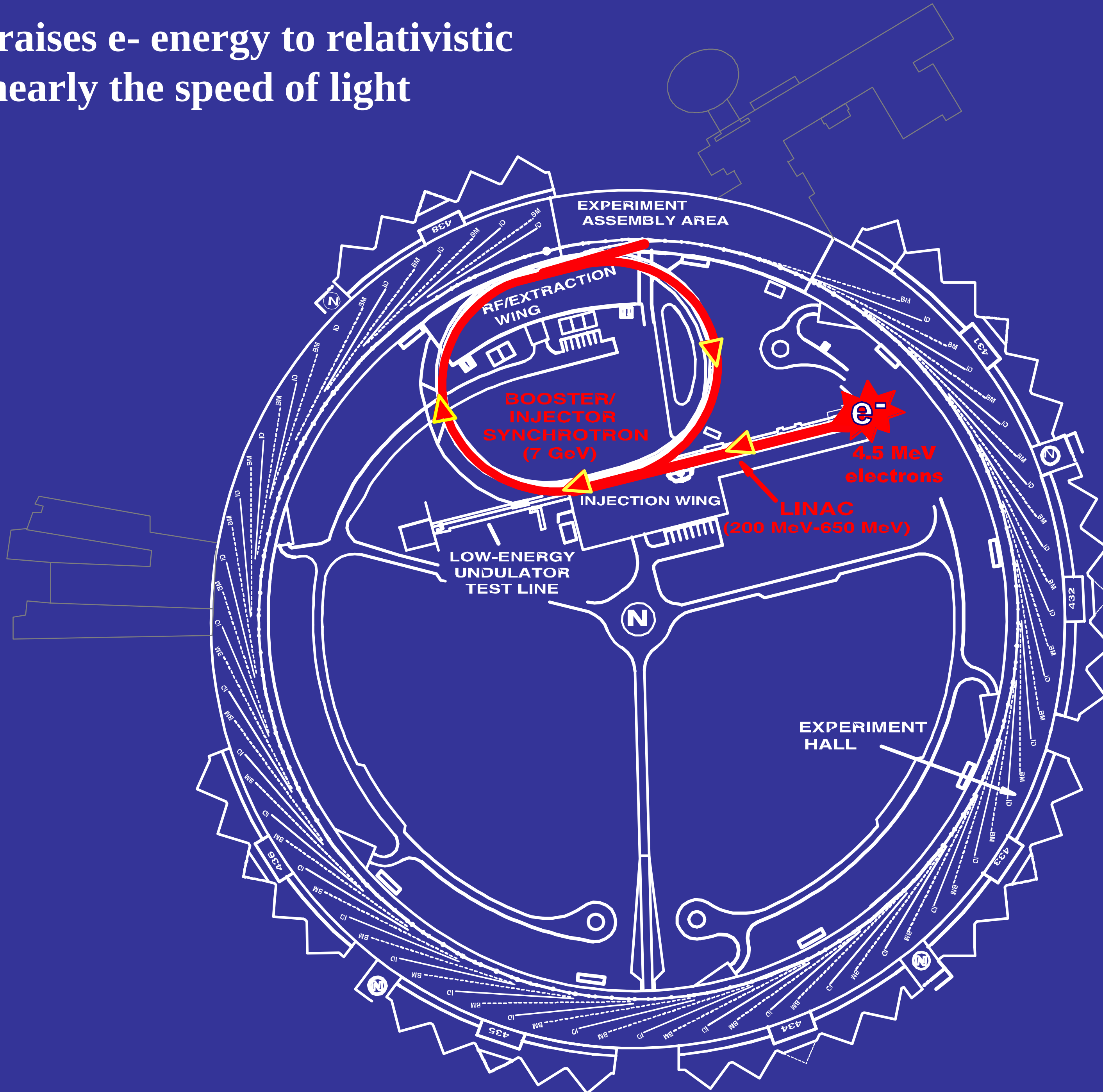
Linac accelerating structures raise electron energy to 325 MeV



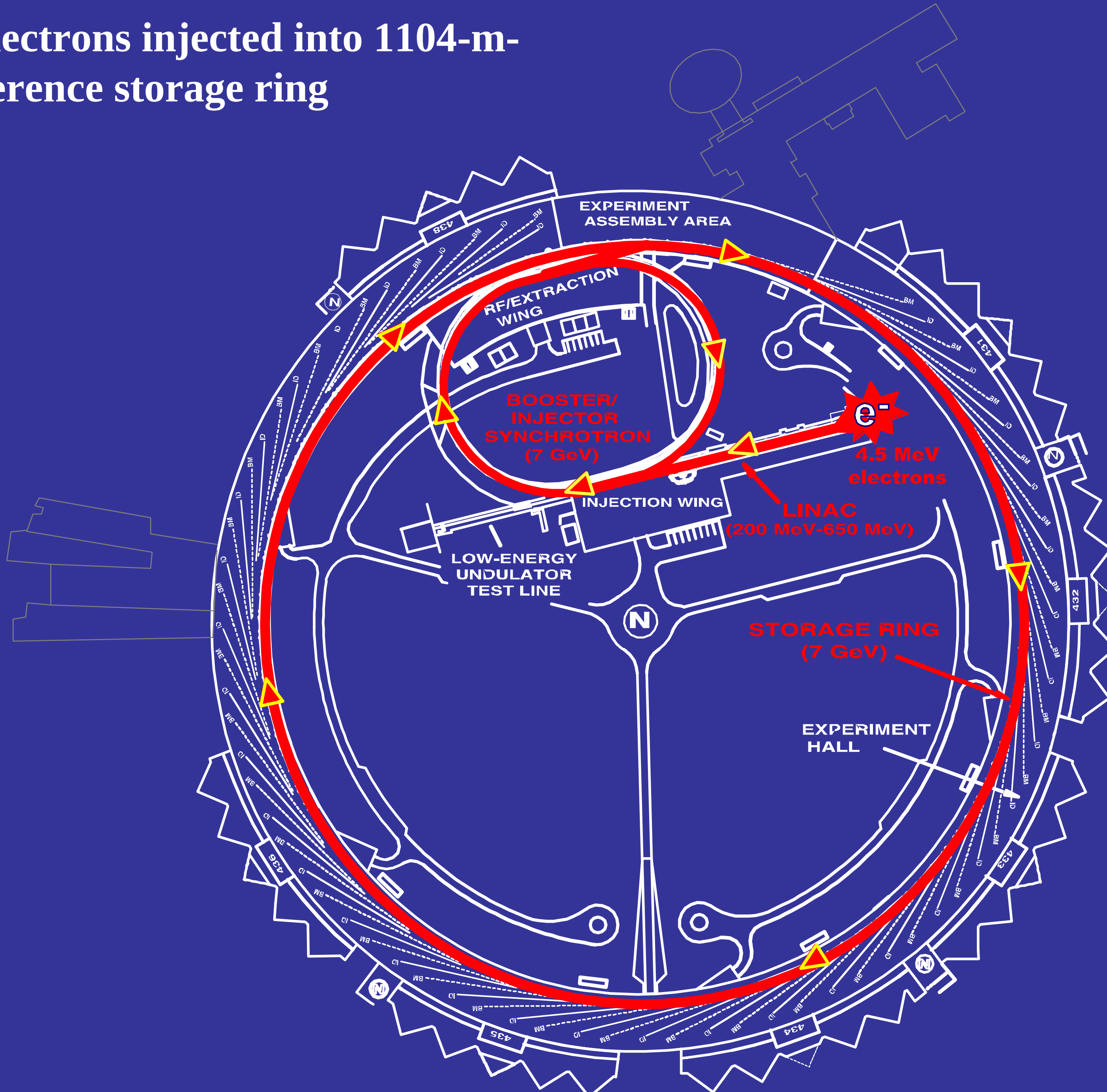
Electrons are injected into 368-m-long, racetrack-shaped booster synchrotron



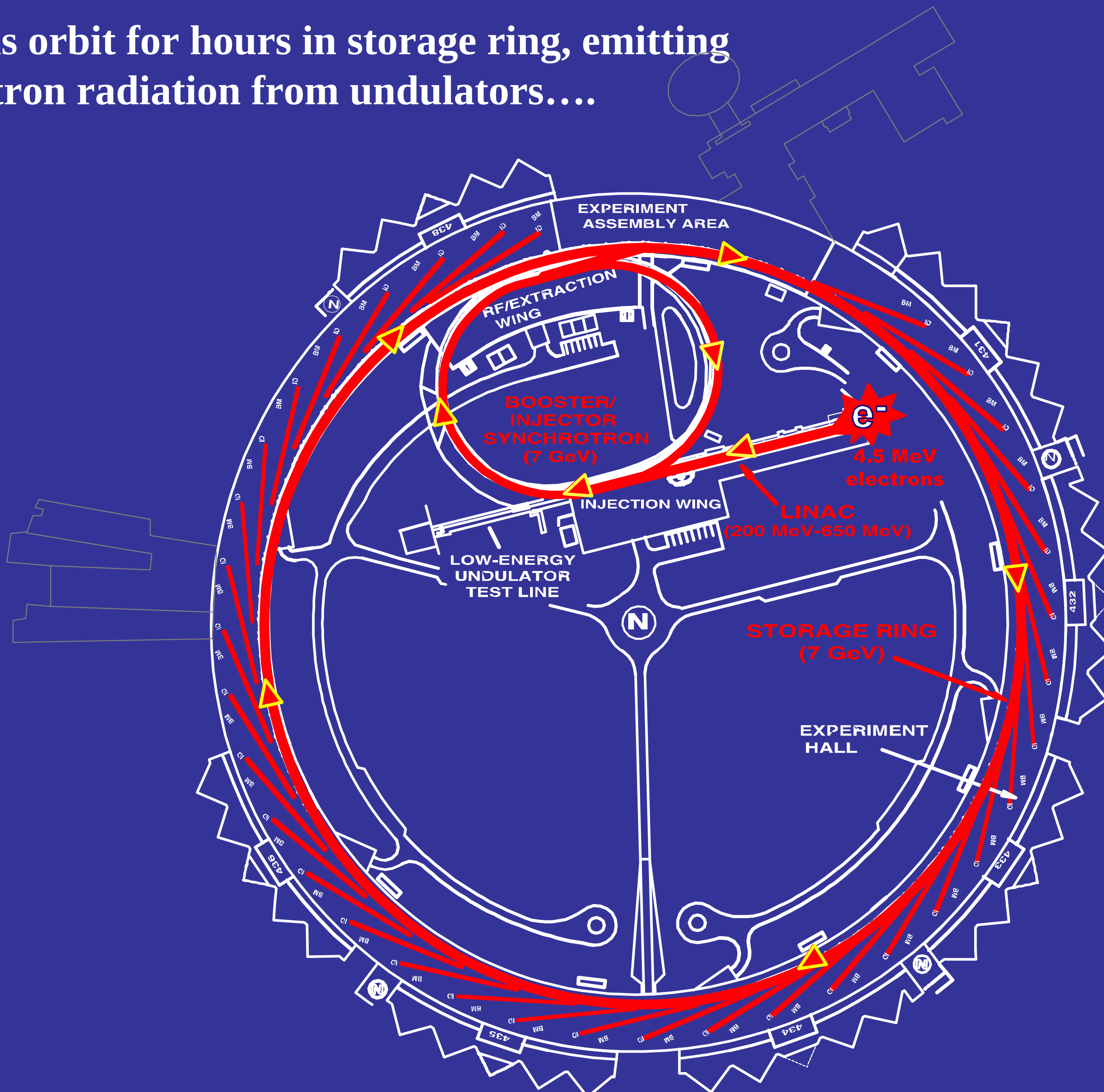
Booster raises e- energy to relativistic
7 GeV -nearly the speed of light



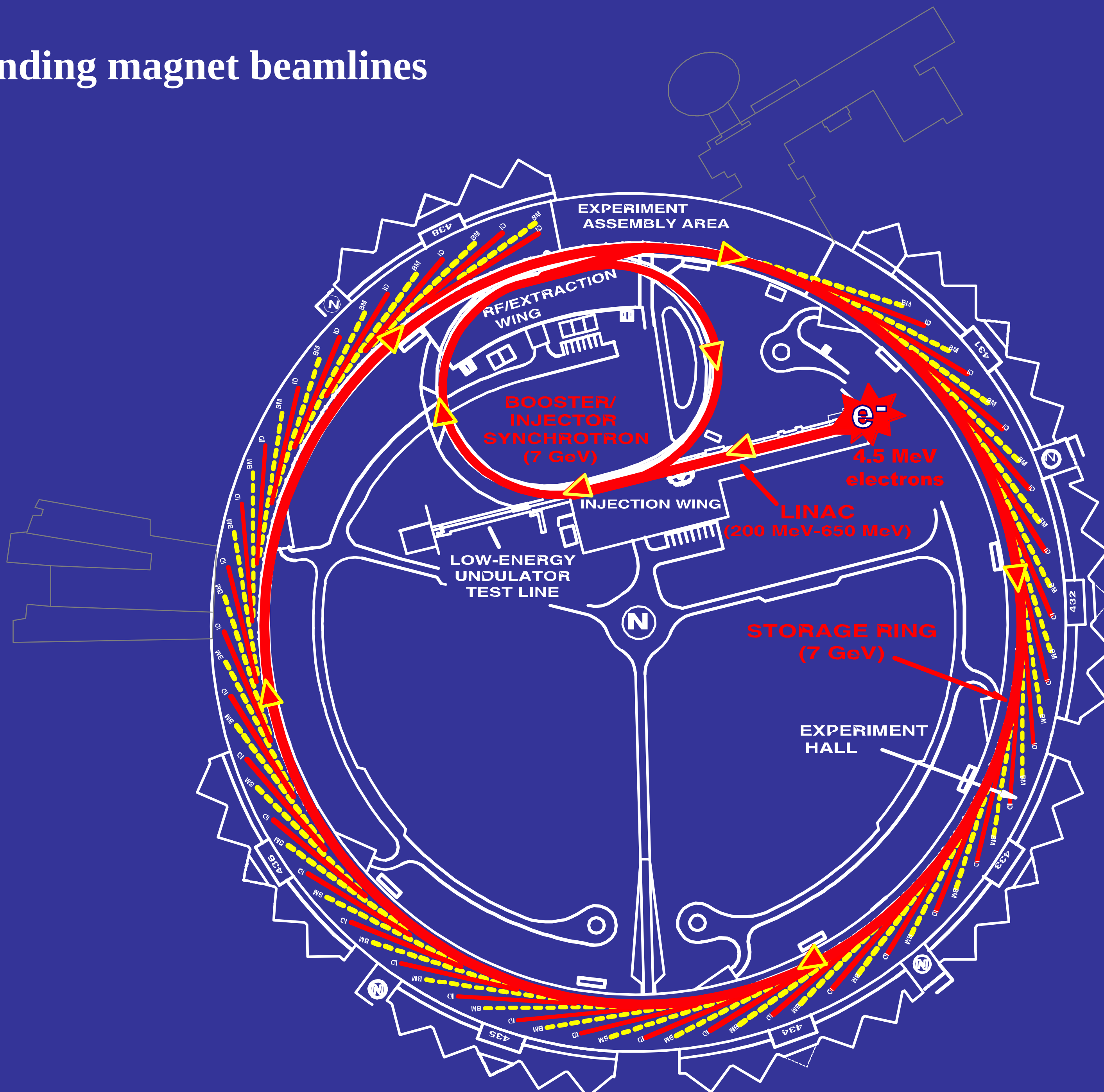
7 GeV electrons injected into 1104-m-circumference storage ring



Electrons orbit for hours in storage ring, emitting synchrotron radiation from undulators….



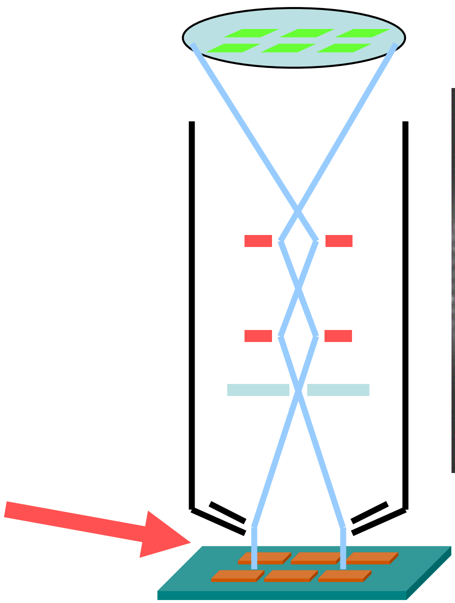
… and bending magnet beamlines

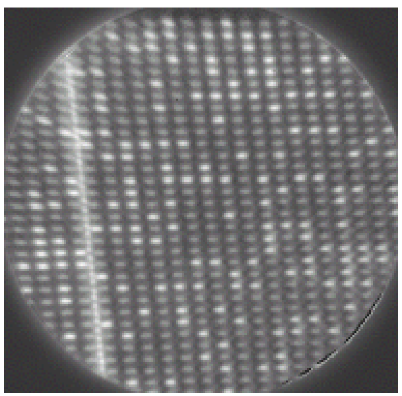


Polarization-dependent spectroscopy

Helicity dependent X-ray emission provides information concerning spin polarized density of bulk occupied states

Photoemission Microscopy





Spatial resolution target of 2 nm

- Magnetic contrast:
  - Domain imaging
  - Ground states in nanoscale systems
  - Interactions in particle arrays
  - Finite size effects
- Chemical contrast
  - Self-assembled systems
  - Segregation
  - Local electronic structure
  - Buried layers (~5 nm)
- Soft x-ray advantages:
  - High magnetic contrast
  - Access to TM, RE, semiconductors

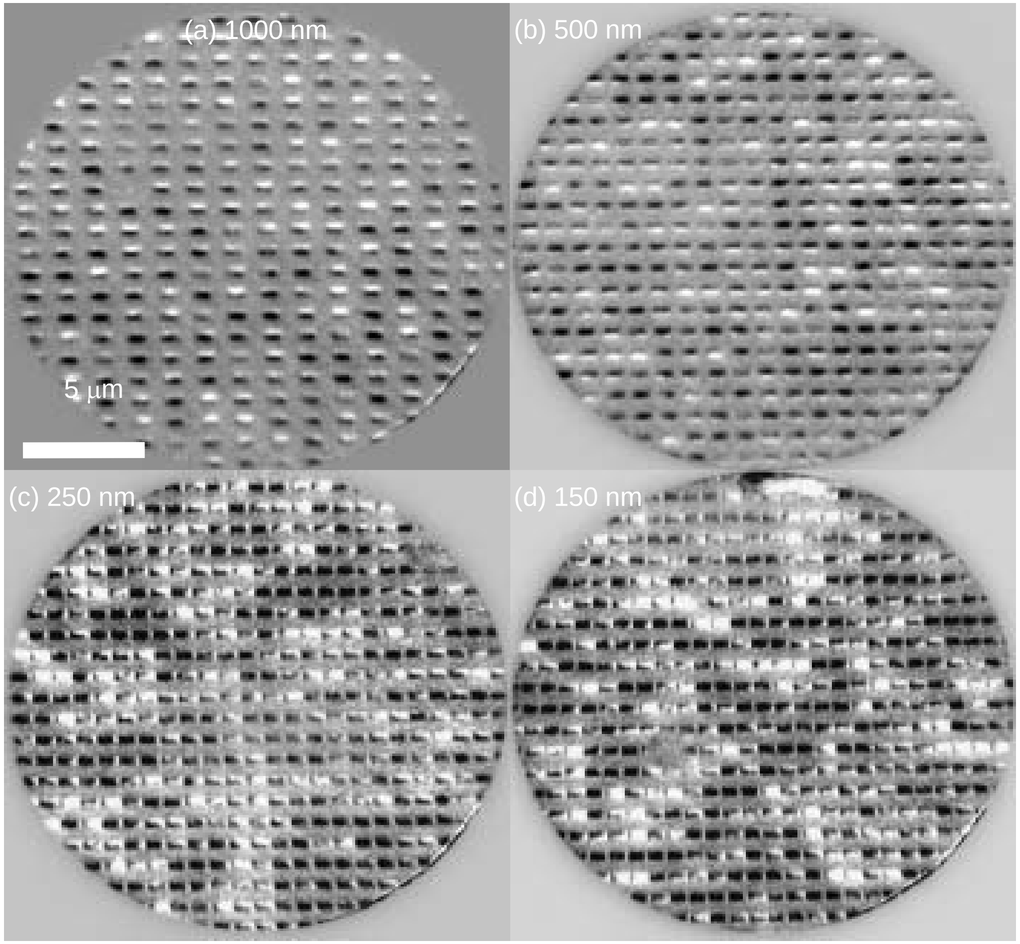


Figure 1. Magnetic PEEM images of the 500×1000 nm series of Co dots

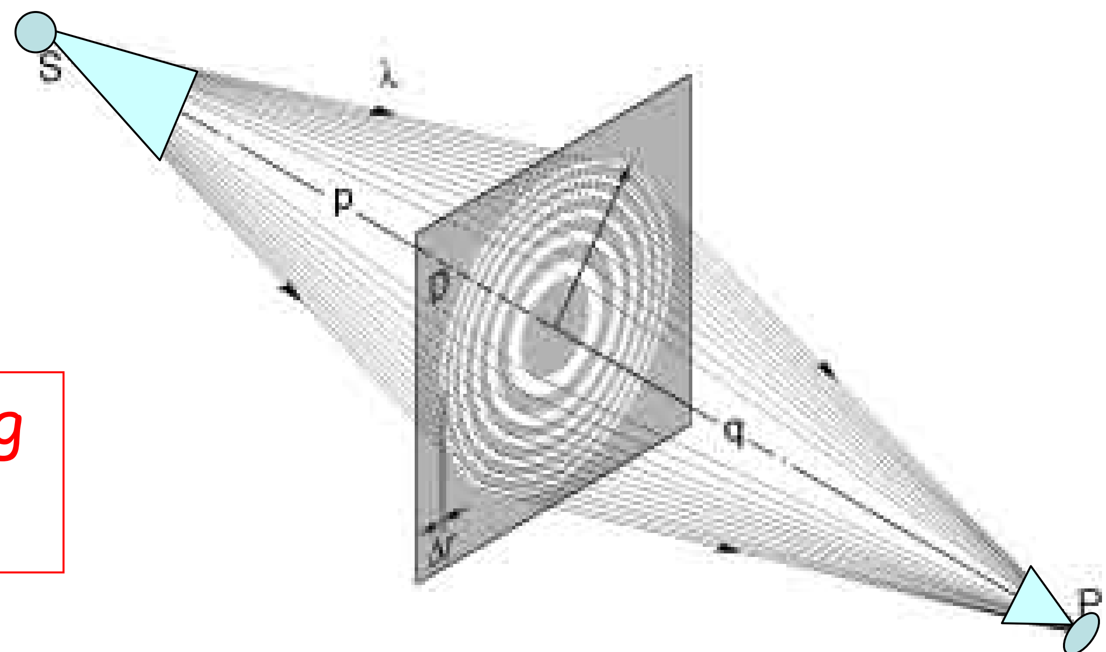
Observe magnetic images, within single dots and correlations among dots, as the spacing changes

Nano-Focusing of X-ray Beams

Brilliance = Radiated Power /0.1%BW / Unit Area / Unit Solid Angle at the Source

Brilliance is a conserved quantity in perfect optical systems

Useful in designing beamlines and synchrotron radiation experiments which involve focusing to small areas.



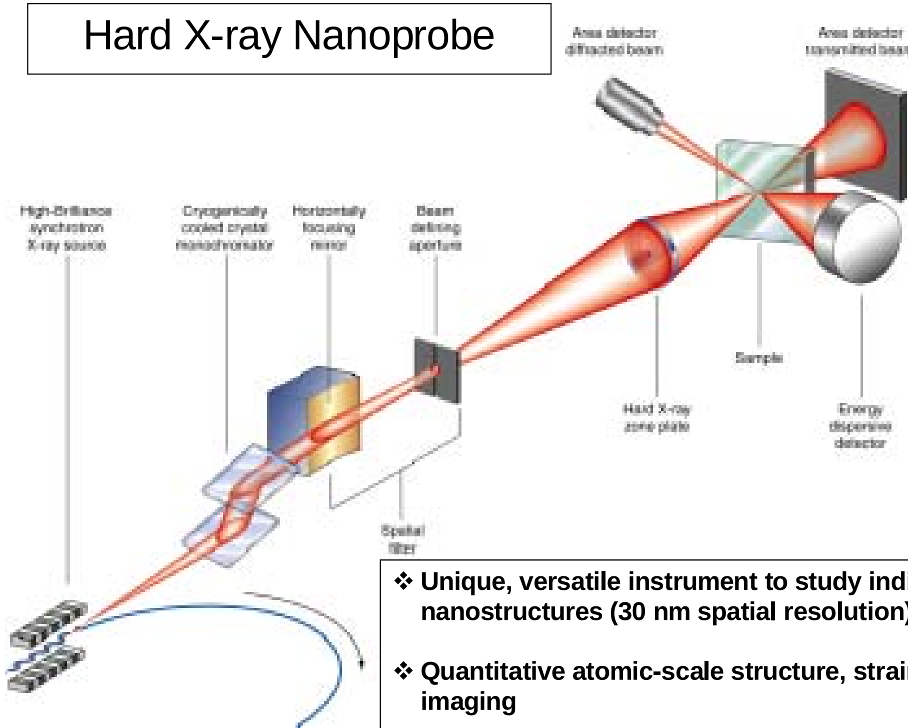
Zone Plates as Focusing Elements

Routine Focal Size at APS: 10 keV → 100 nm
1 keV → 50 nm

Tools for Nanoscience

- Hard x-ray nanoprobe
  - Scan real and reciprocal space in nanovolumes
- Adaptive optics with feedback
- Multi-parameter "smart" scans

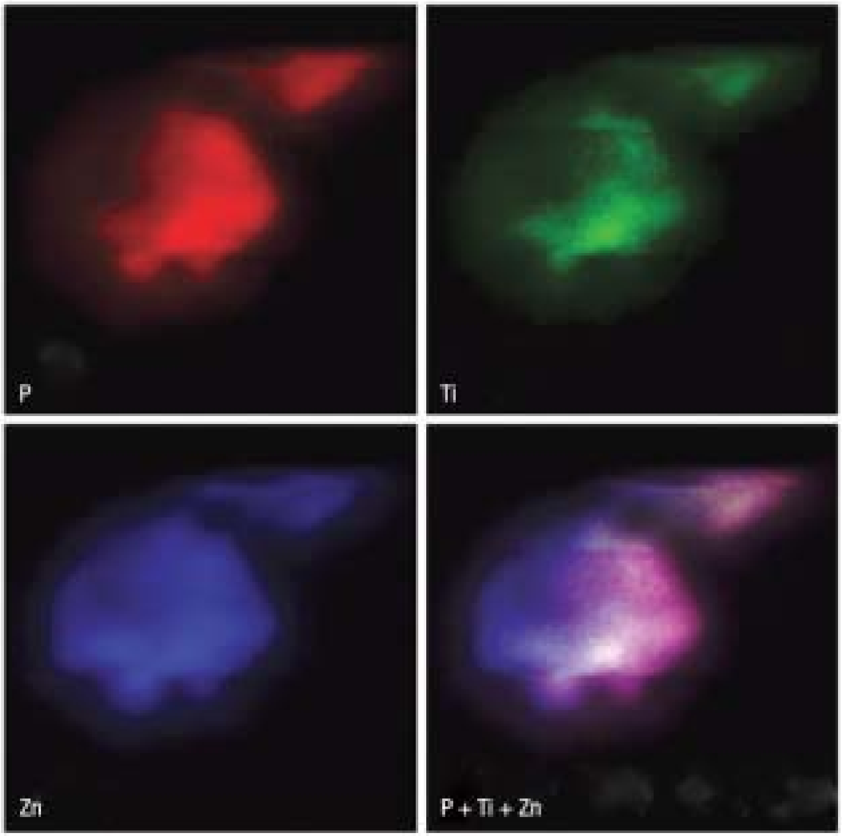
Hard X-ray Nanoprobe



- ❖ **Unique, versatile instrument to study individual nanostructures (30 nm spatial resolution)**
- ❖ **Quantitative atomic-scale structure, strain, orientation imaging**
- ❖ **Sensitive trace element and chemical state analysis**
- ❖ **Ability to penetrate overlayers, environments, fields**

High-resolution elemental maps of a 21 μm x 21 μm area of a single nucleus containing $3.6x10^{6}$ nanoparticles

TiO2-DNA nanocomposites were synthesized in an attempt to develop them into nanodevices that would be able to enter cells and function in vivo and in situ.
The nanocomposites are introduced into cells using standard transfection methods and translocated into the cell nuclei.
X-ray micro-fluorescence is crucial in quantifying the success rate of transfection and revealing the intracellular distribution of the nano-composites.

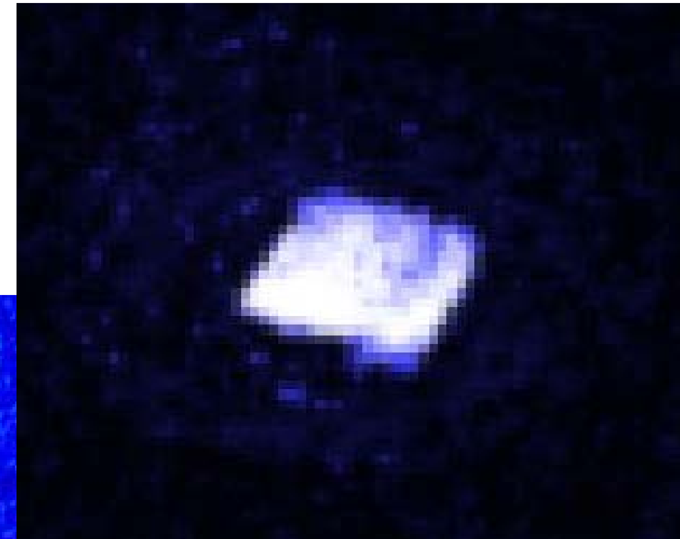


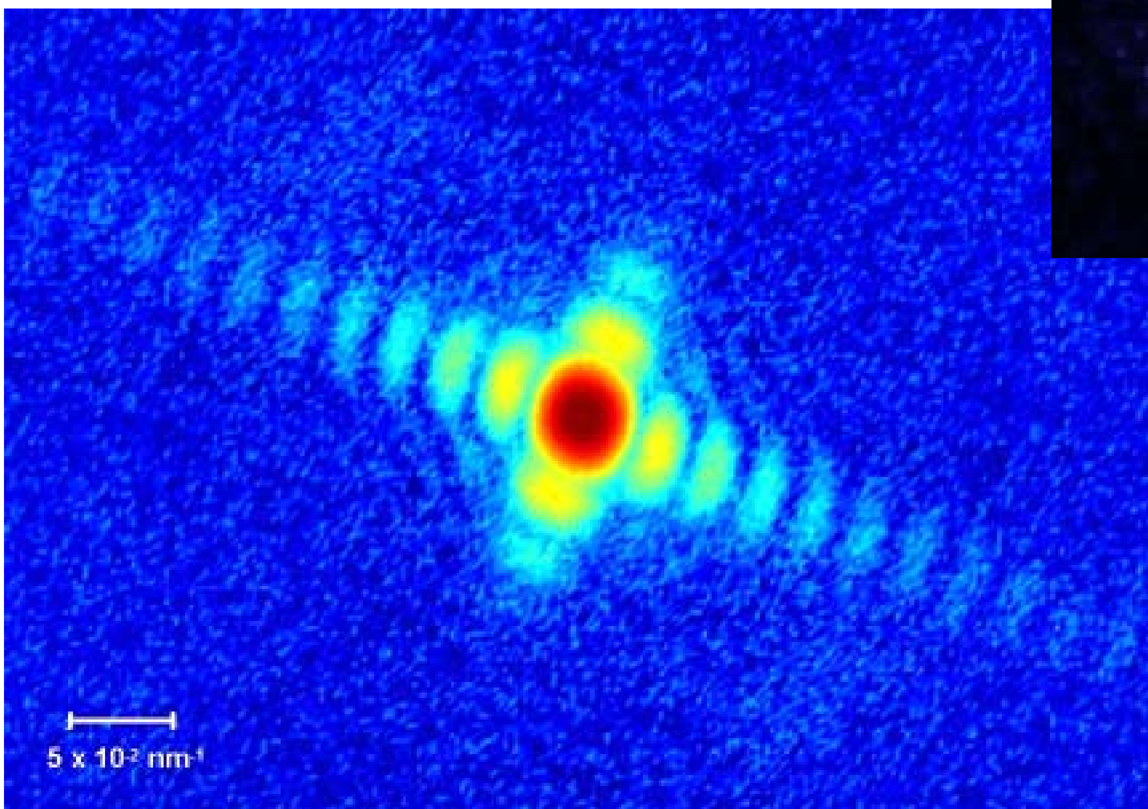
T Paunesku, T Rajh, G Wiederrecht, J Maser,
S Vogt, N Stojicevic, N. Protic, B Lai, J Oryhon, M Thurnauer,
G Woloschak, *Nature Materials* ***2*** *(2003) 343-346*

Coherent XRD from a cubic silver single nanocrystal

Transverse coherent flux from APS Undulator A: $F_c \sim 10^{11}$ ph/s/0.1%BW

Measure single nanocrystal diffraction pattern.





Observe 5 - 10 high contrast fringes.

Results agree with 2D calculations of projections of a nanocube.

UNICAT

I. Robinson, F. Pfeiffer, I Vartanyants, Y Sun, Y Xia, *Opt. Express* **11** 2329 - 2334 (2003)

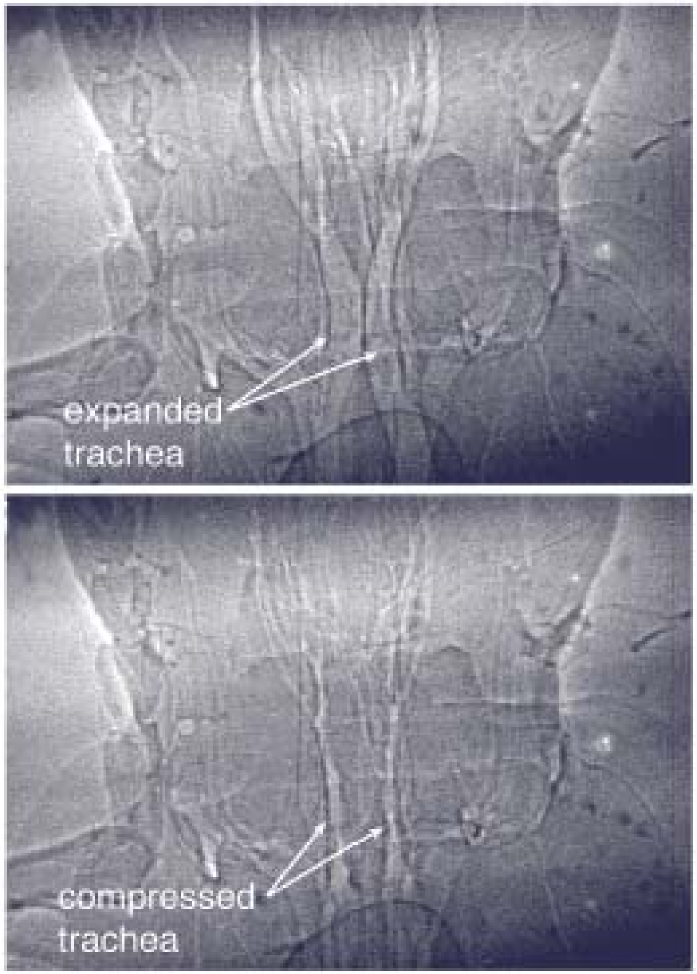
Studies of insect respiration using phase-enhanced, time-resolved x-ray imaging

X-ray phase-contrast images taken in real time of living and breathing insects show how they breathe.

Before these studies, it was thought that insects breathe through passive gas diffusion or changes in internal pressure.

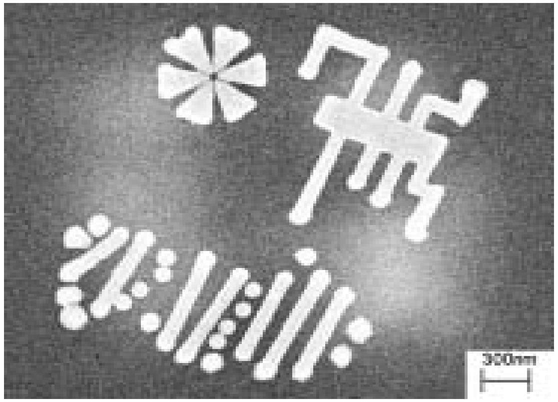
The tracheae were inflated at rest and then were squeezed.

This technique is now being used to study beetles, insects and fish in real time.

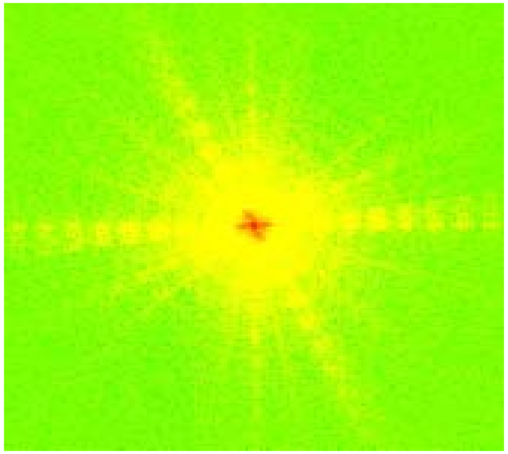


MW Westneat, O Betz, RW Blob, K Fezzaa, WJ Cooper, W-K Lee, *Science* **299** (2003) 558 - 560

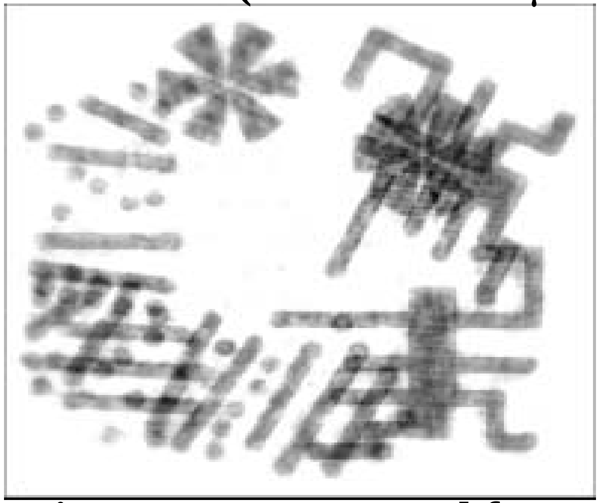
Coherent X-ray Diffractive Imaging



(a) **A SEM image of a double-layered sample made of Ni (~2.7 x 2.5 x 1 μm^3)**



(*b*) A coherent diffraction pattern from (*a*) (the resolution at the edge is 8 nm)



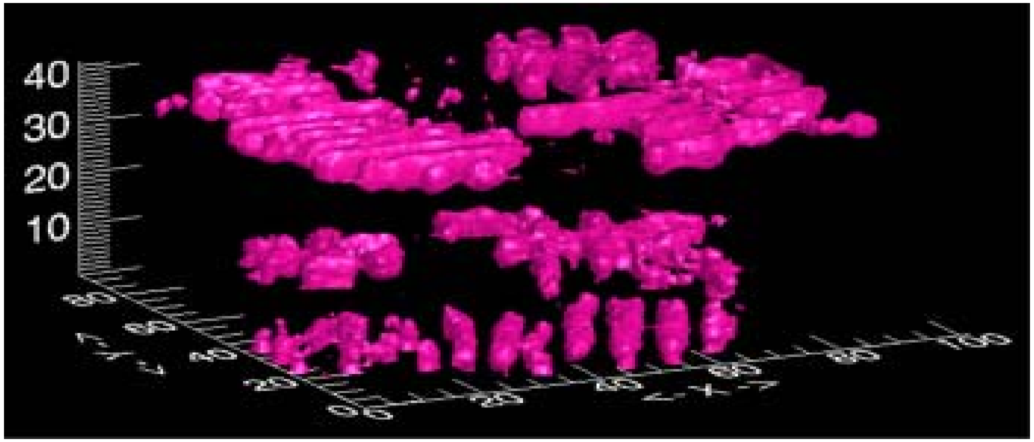
(c)* An image reconstructed from *(b)

J Miao, T Ishikawa, B Johnson, EH Anderson, B Lai, KO Hodgson
Phys. Rev. Lett. 89, 088303 (2002).

The Reconstructed 3D structure

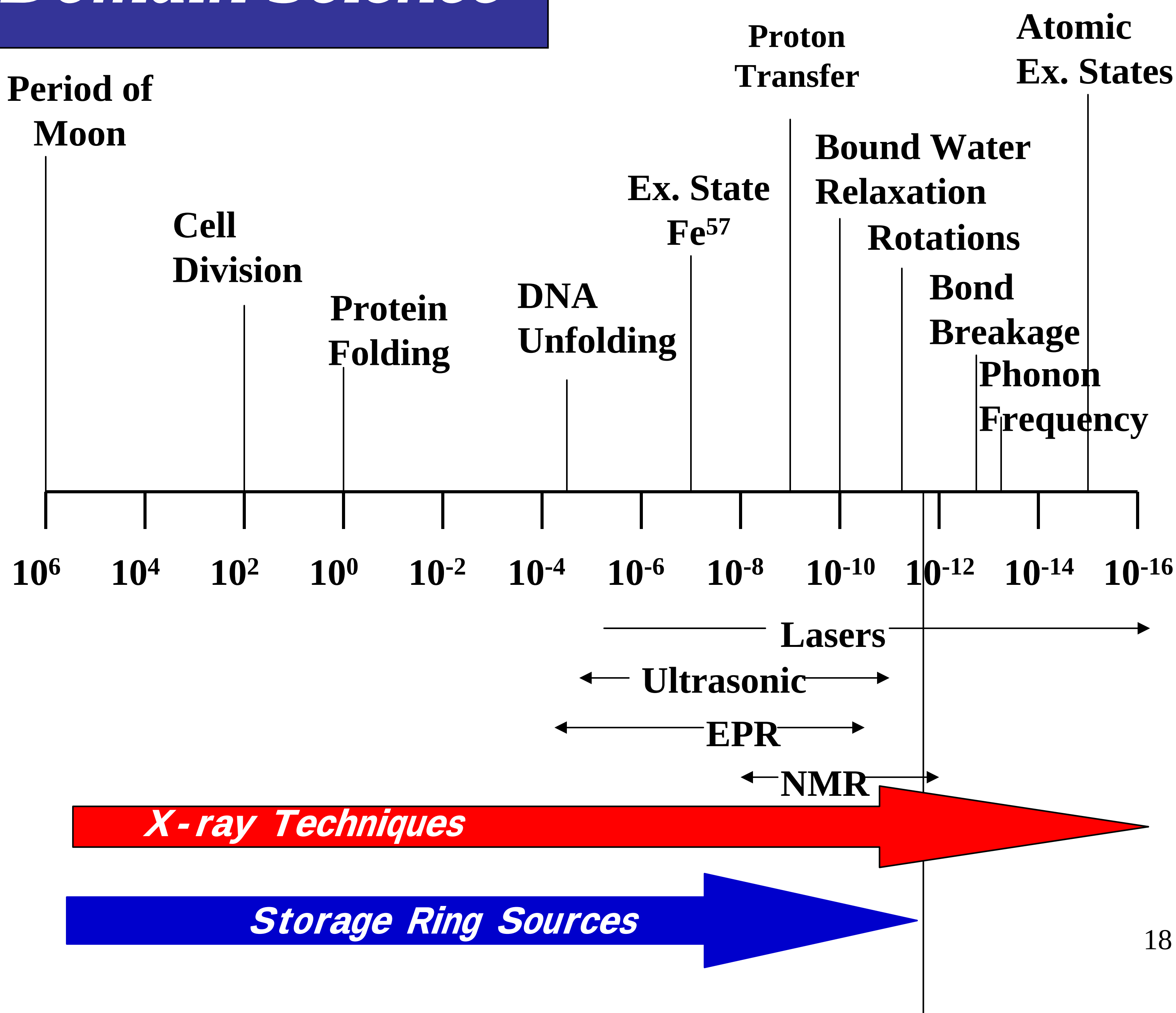
The reconstructed top pattern

The reconstructed bottom pattern

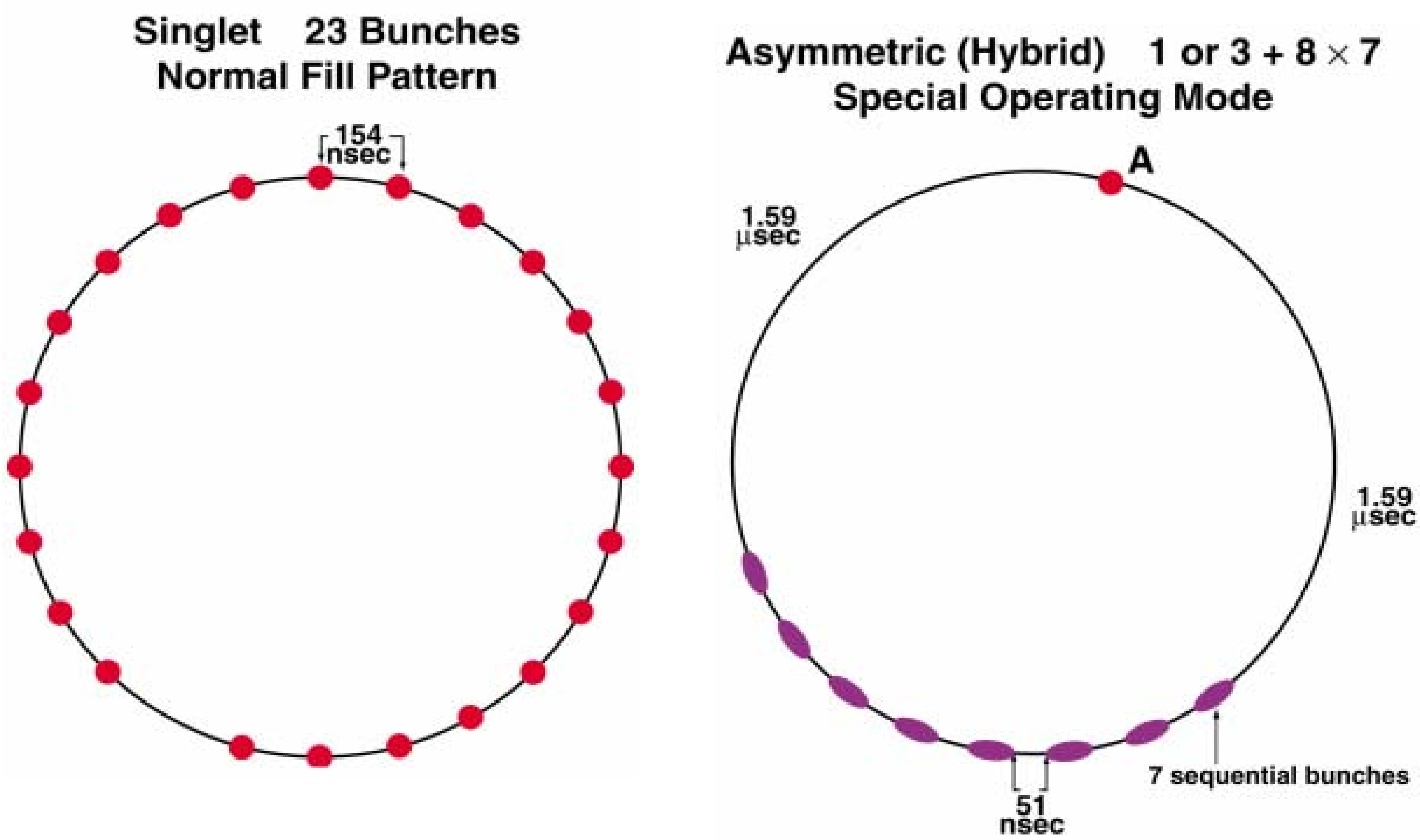


An iso-surface rendering of the reconstructed 3D structure

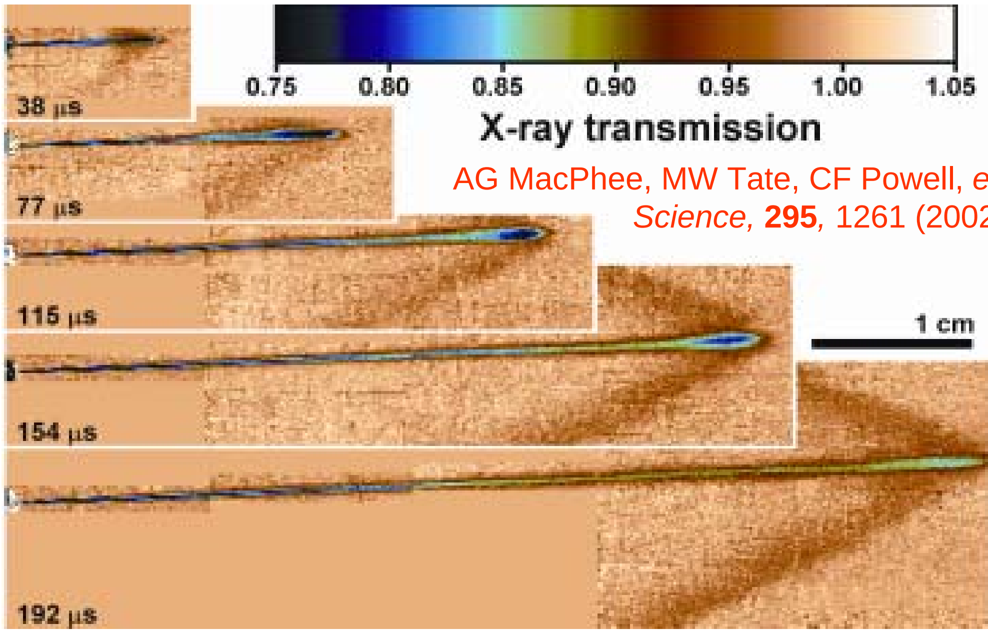
Time Domain Science



Typical Bunch Filling Patterns at APS

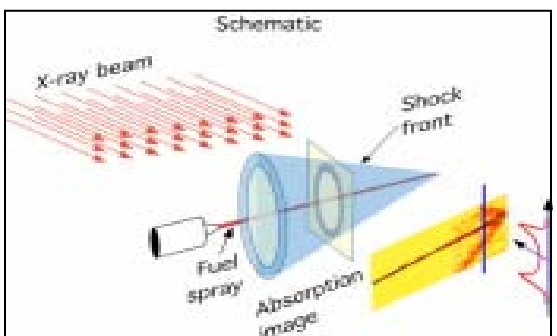


Shock waves generated by a supersonic liquid jet



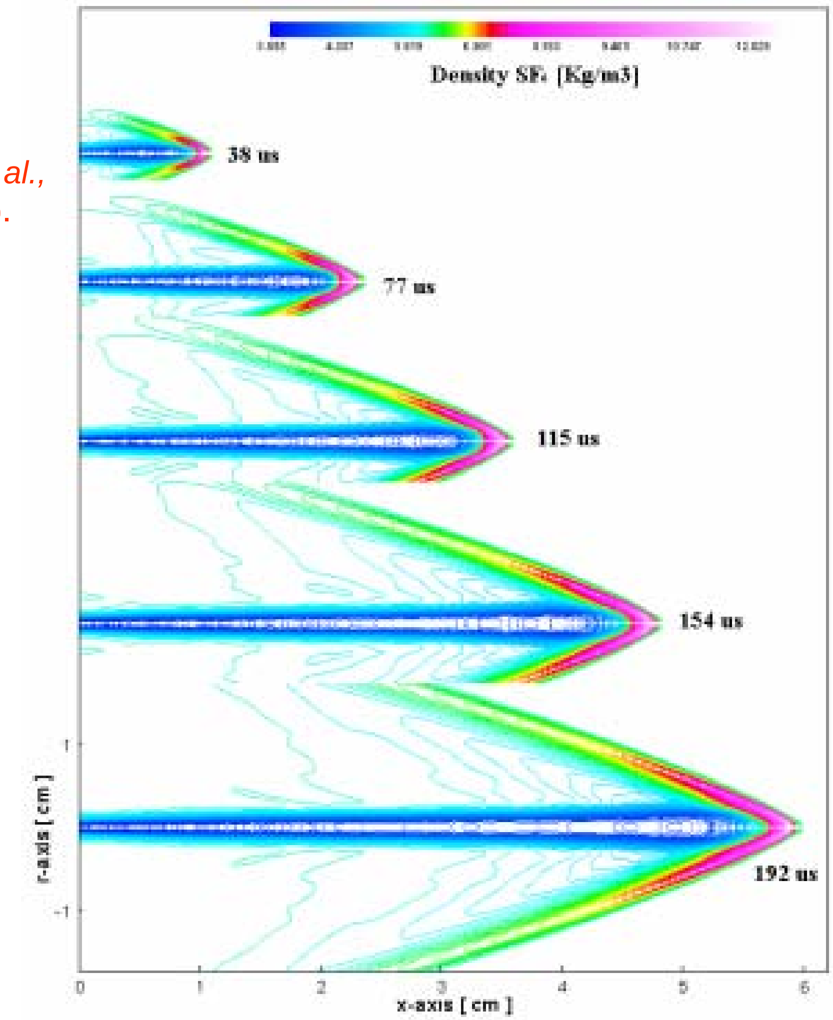
AG MacPhee, MW Tate, CF Powell, *et al.*, *Science*, **295**, 1261 (2002).

- ✓ Supersonic liquid jet can generate shock waves
- ✓ X-radiographs yield characteristics of the shock waves
- ✓ The shock waves can be quantitatively simulated



Key Collaborators

- J. Wang's group APS
- S. Gruner's group Cornell U.
- M.-c. Lai's group Wayne State U.

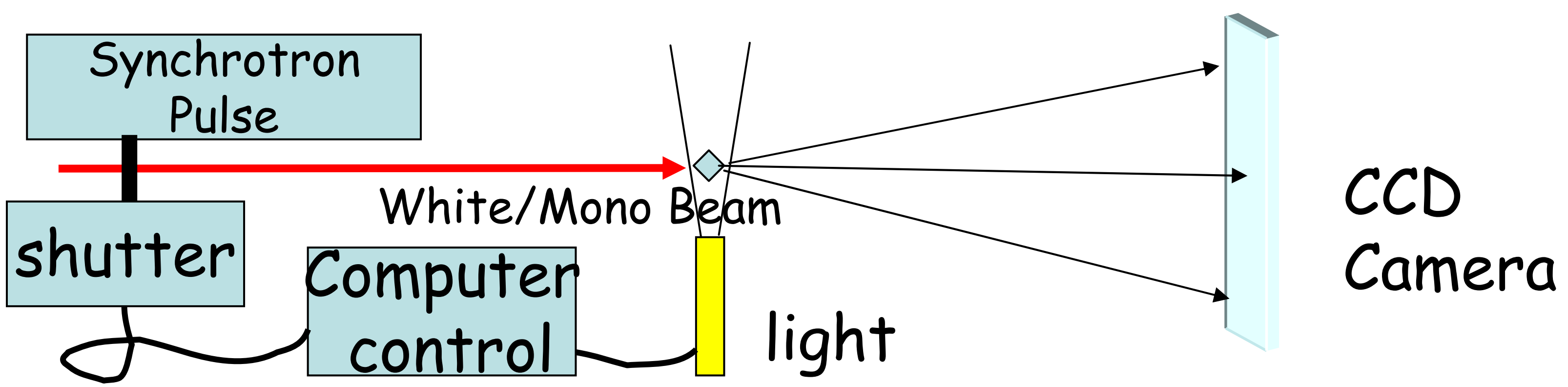


- ✓ Two phases: liquid particle and ambient gas
- ✓ Discrete particle tracking

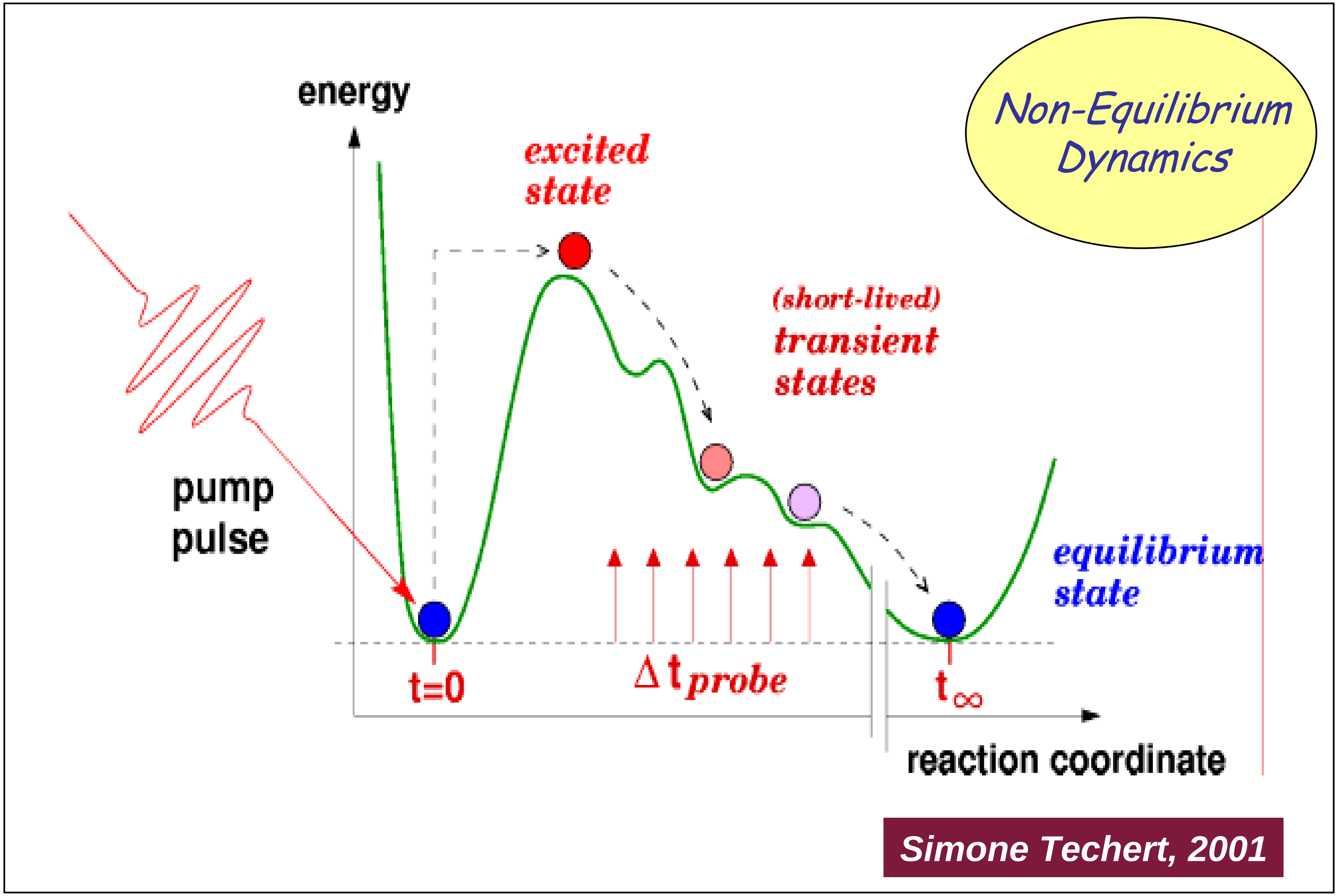
Time-resolved Crystallography/Spectroscopy

If a reaction can be initiated in a crystal, simultaneously throughout the crystal, then Laue photography or x-ray spectroscopy can capture the structural changes or charge transfers at the *100 ps* (10^{-10} *s*) to *ms* (10^{-3} *s*) timescale.

Light-initiated reactions can be studied using the Laue method.



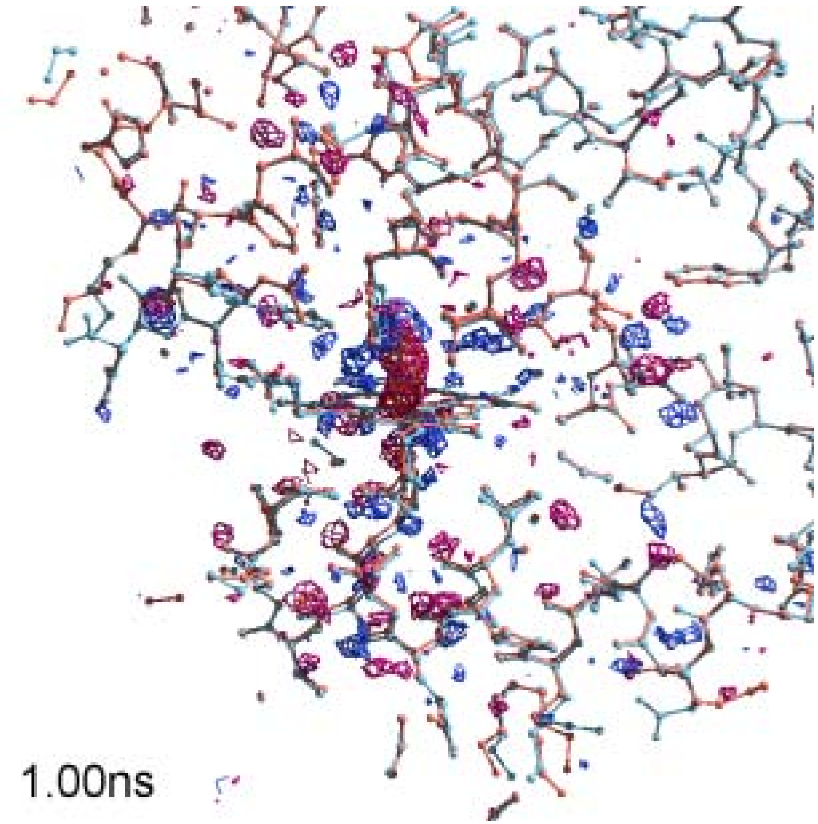
Making a movie of chemical reactions



Protein Conformational Relaxation and Ligand Migration in Myoglobin: A Nanosecond to Millisecond Molecular Movie from Time-Resolved Laue X-ray Diffraction.

$F(Q,t)$

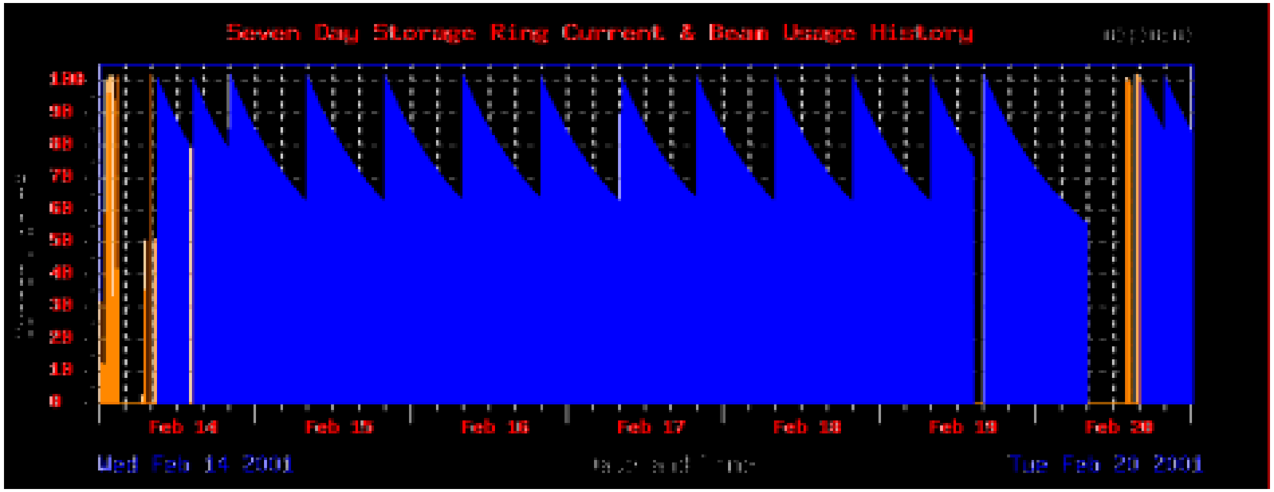
CO ligand is photo-dissociated by a 7.5 ns laser pulse, and the subsequent structural changes are probed by 150 ps X-ray pulses at 14 laser/X-ray delay times



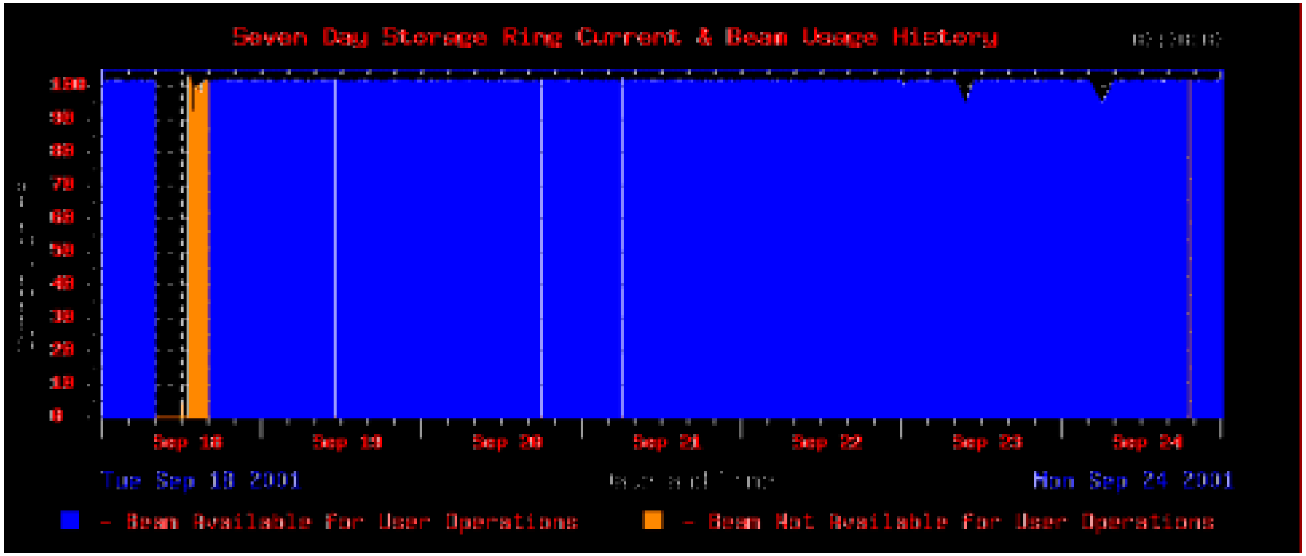
V Srajer, Z Ren, TY Teng, M Schmidt, T Ursby, D Bourgeois, C Pradervand, W Schildkamp, M Wulff, K Moffat, *Biochemistry* **40**: 13802-13815 (2001)

Constant-Current or “Top-Up”Operation

Conventional Fill



Top-Up



APS is first facility to begin 'Top-Up' operation starting in 1999

Maximizing APS Brilliance

Lower Emittance

$\varepsilon_x \approx 5x\ 10^{-4}\ E^2\ \varphi^3$ nm-rad

4 nm.rad → 2 nm.rad

Increased Current

100 mA

↓

300 mA

Undulators

Length: 5 m

↓

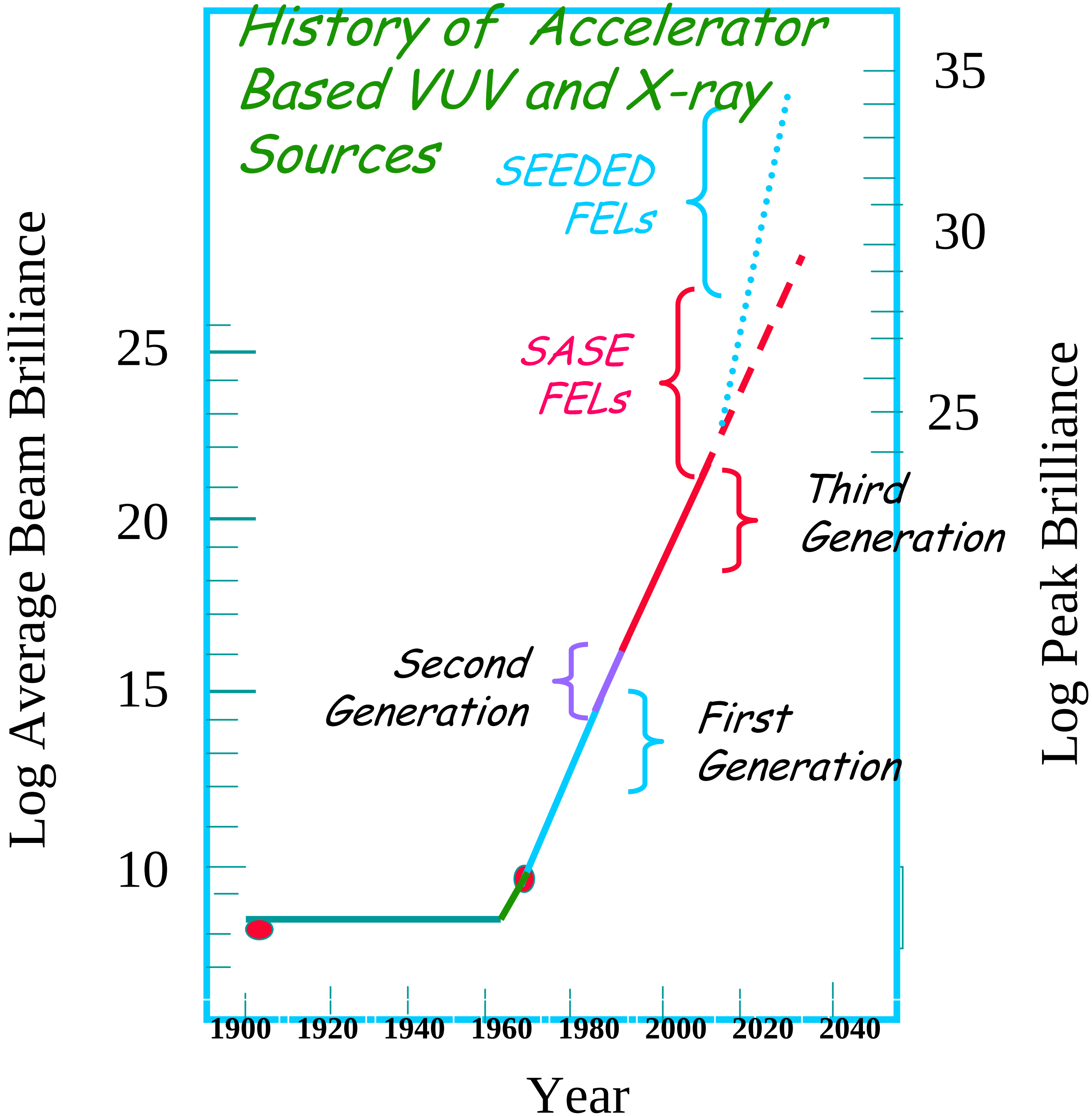
10 m

Type: Superconducting
Variable -Period

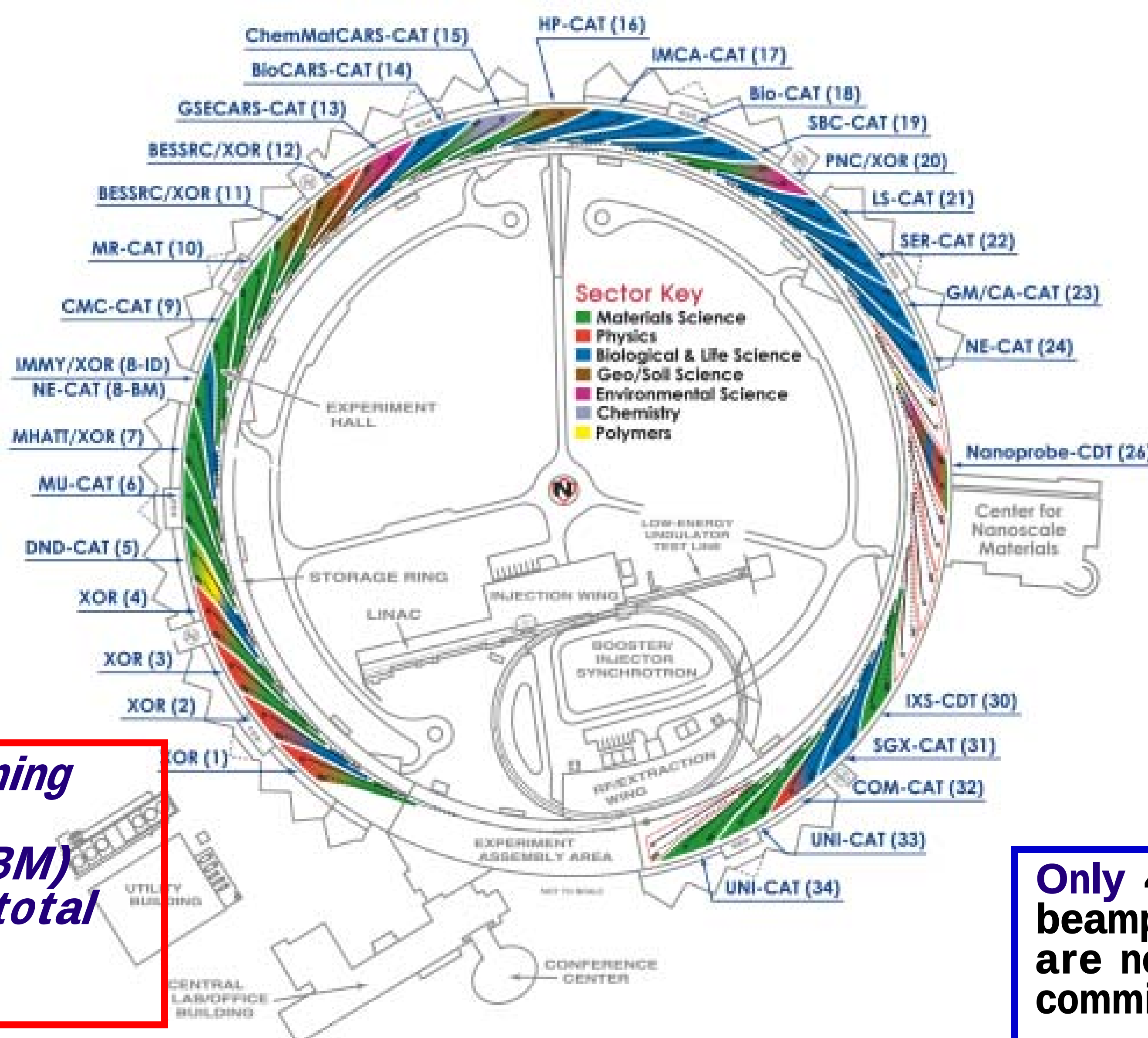
Ultimate Enhancement of APS:

Average Brightness: 10^{22-23} ph/s/0.1%BW/mm^2/mrad^2

Peak Brightness: 10^{24-25} ph/s/0.1%BW/mm^2/mrad^2

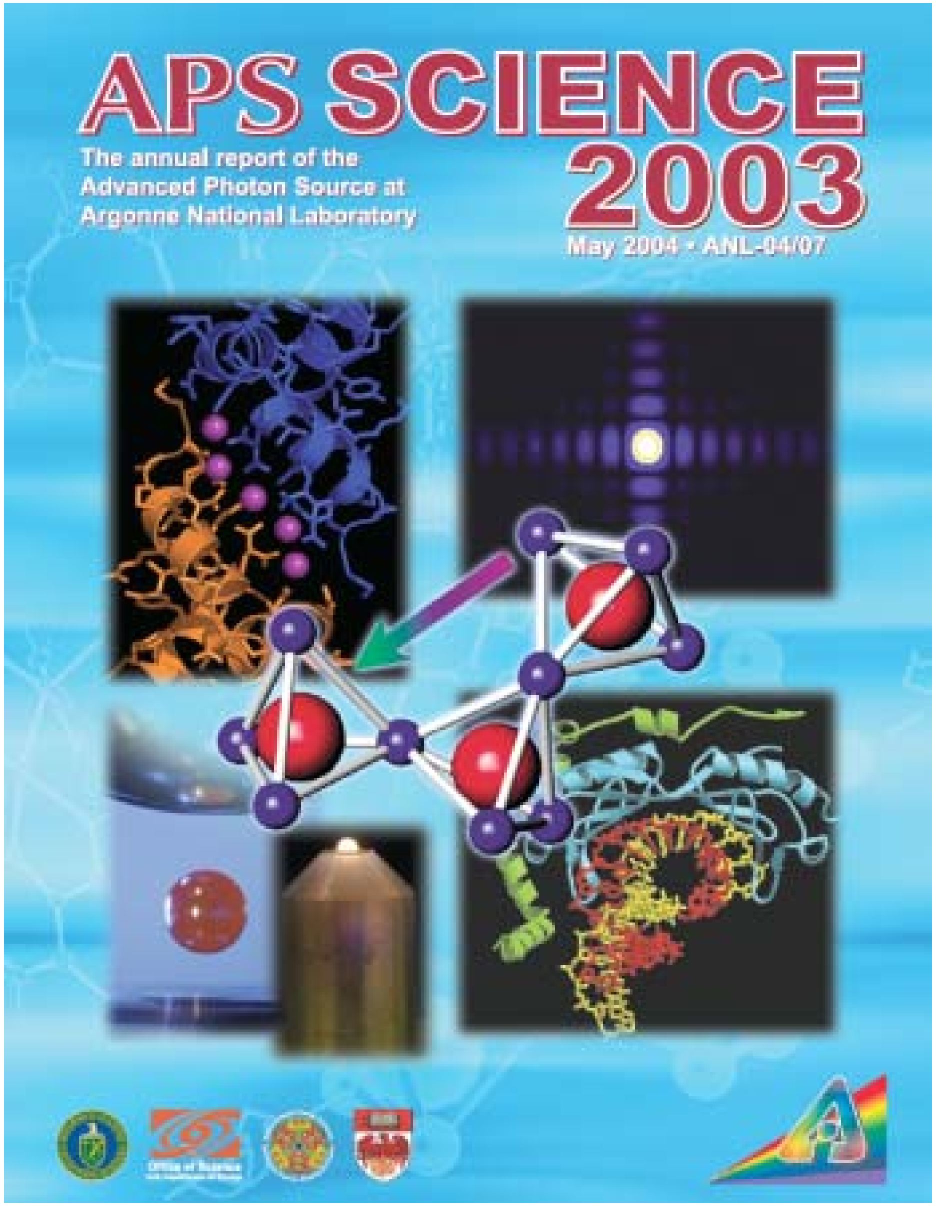

History of Accelerator Based VUV and X-ray Sources
SEEDED FELs
SASE FELs
Third Generation
Second Generation
First Generation
Log Average Beam Brilliance
10
15
20
25
Log Peak Brilliance
25
30
35
1900
1920
1940
1960
1980
2000
2020
2040
Year

APS Research Groups by Sectors and Disciplines



38 functioning beamports (25ID, 13BM) out of 68 total available

Only 4 ID beamports are not yet committed



For beamtime at the APS:
http://www.aps.anl.gov/aps/frame_beamtime.html