High Field Studies at the Advanced Photon Source: Current Status and Future Plans

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X-Ray Science Division

Advanced Photon Source

ESRF, November 16, 2006

Acknowledgements

V. Kirykhin - Rutgers University

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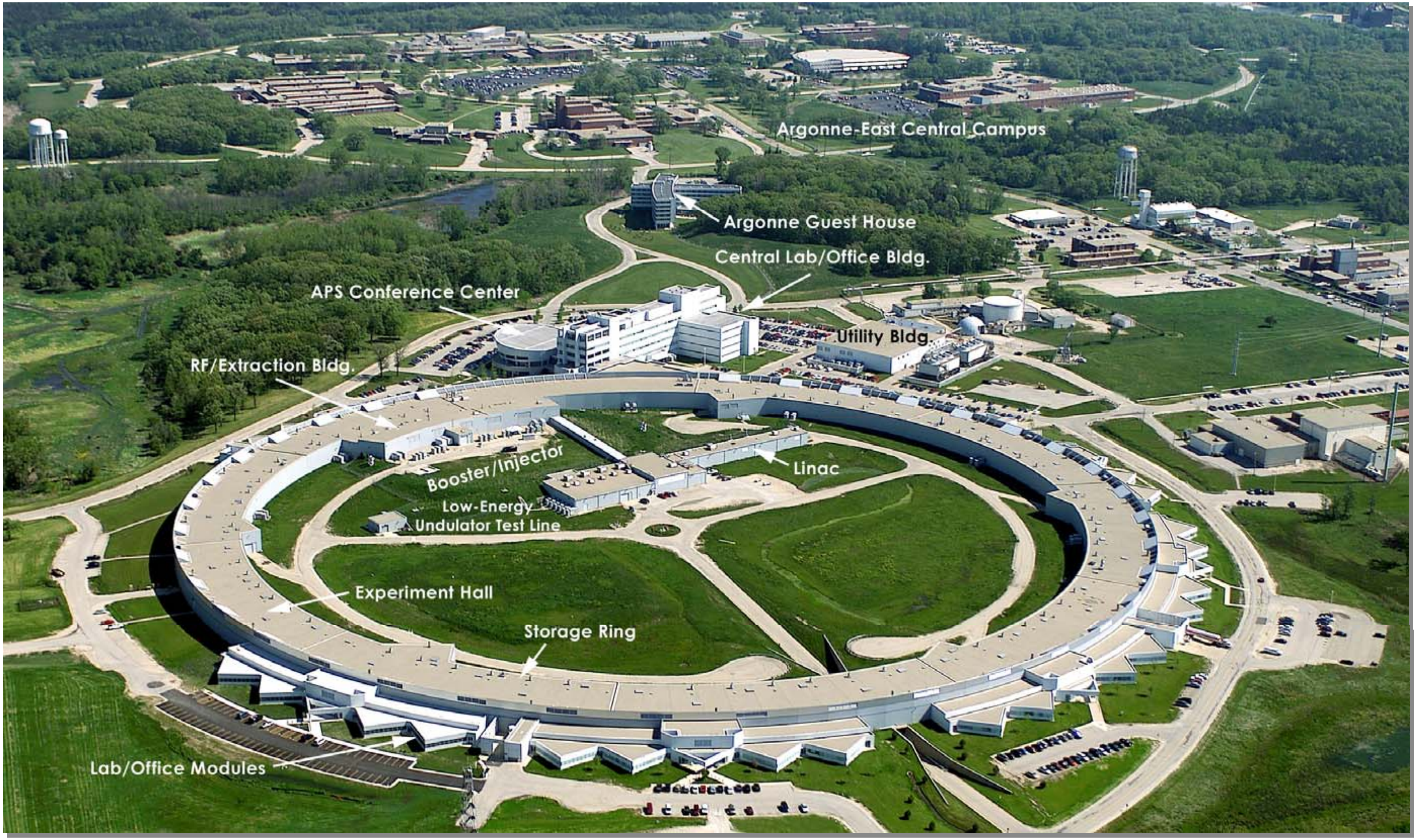
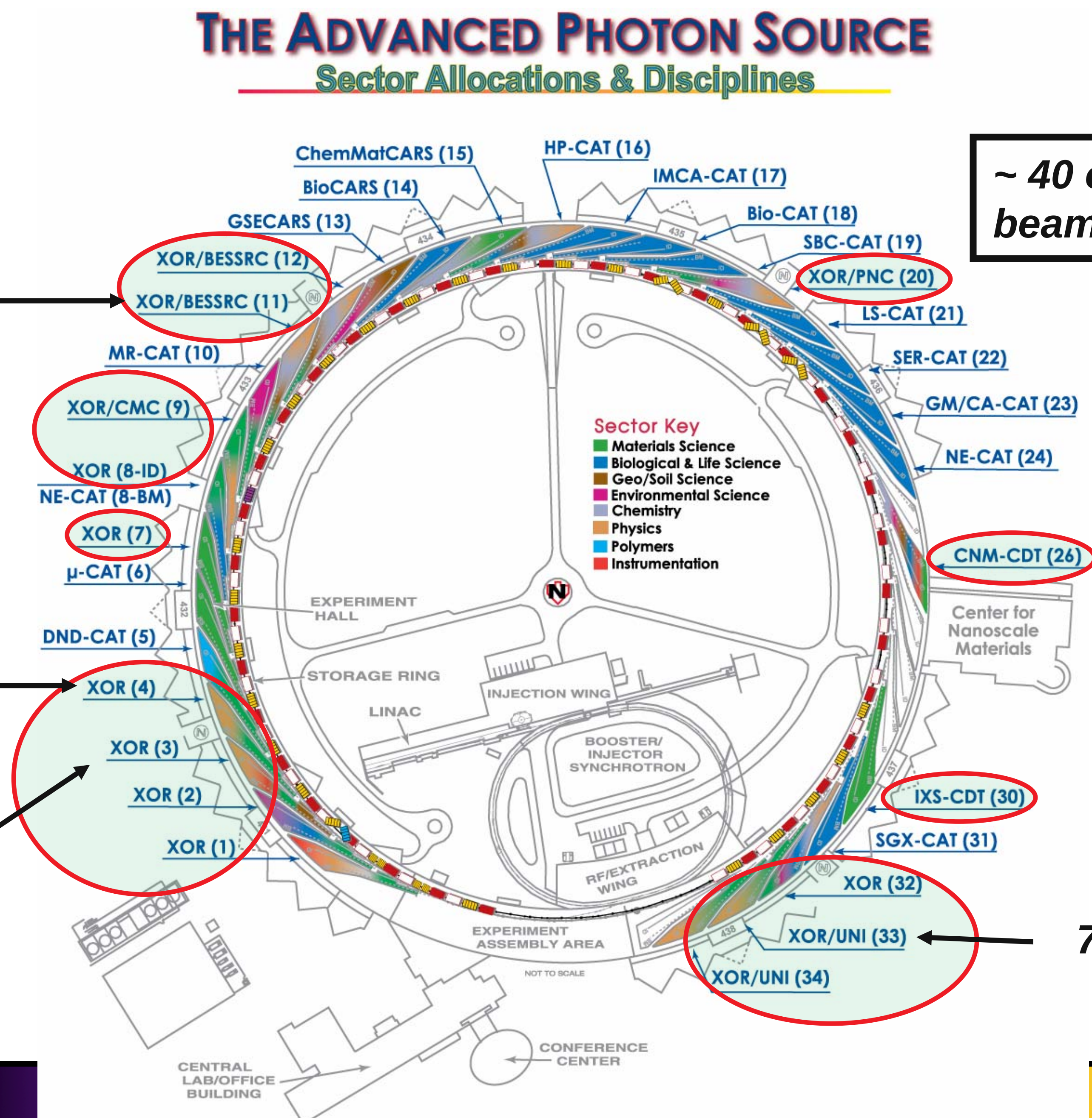
Z. Islam, J. C. Lang and Y. Ren - Advanced Photon Source

Arial View of the Advanced Photon Source





~ 40 operational beamlines

7 T

4 T

7 T

(11 T)

7 T

7 T

Argonne NATIONAL LABORATORY

Dedicated High Magnetic Field Facilities

Current Status:

- ***SPring8:*** ***15 T***
- ***ESRF:*** ***10T***
- ***APS:*** ***4T***

First Meeting in Tallahassee on May 3, 1999

NHMFL - Technology

Jack Crow
Hans Schneider-Muntau
Steve Van Sciver
Yehia Eyssa
Mark Bird
Liang Li
Denis Markiewicz

NHMFL - Science

Jim Brooks
Zach Fisk
Gang Cao
Elbio Dagotto
Bob Schrieffer
Lev Gorkov
Vladimir Dobrosavljevic

APS - Science & Technology

Gopal Shenoy
Denny Mills
Jonathan Lang
Efim Gluskin
George Srajer
Myron Salamon/UIUC

Scattering Cross Section

Nonresonant:

$$f = f^{charge} + f^{magnetic} = \rho(Q)\ \hat{\varepsilon}' \cdot \hat{\varepsilon} + i r_o \left(\frac{\hbar\omega}{m_e c^2}\right)\left[\frac{1}{2}\vec{L}(Q)\cdot\vec{A} + \vec{S}(Q)\cdot\vec{B}\right]$$

$$I_{non-res} \propto \frac{\sin(\theta)}{\sin(2\theta)}\{\underbrace{S_y^{\,2}\sin^2(2\theta)}_{\sigma->\sigma} + \underbrace{4\sin^4(\theta)\left((S_z\sin(\theta)) + (L_x + S_x)\cos(\theta)\right)^2}_{\sigma->\pi}\}$$

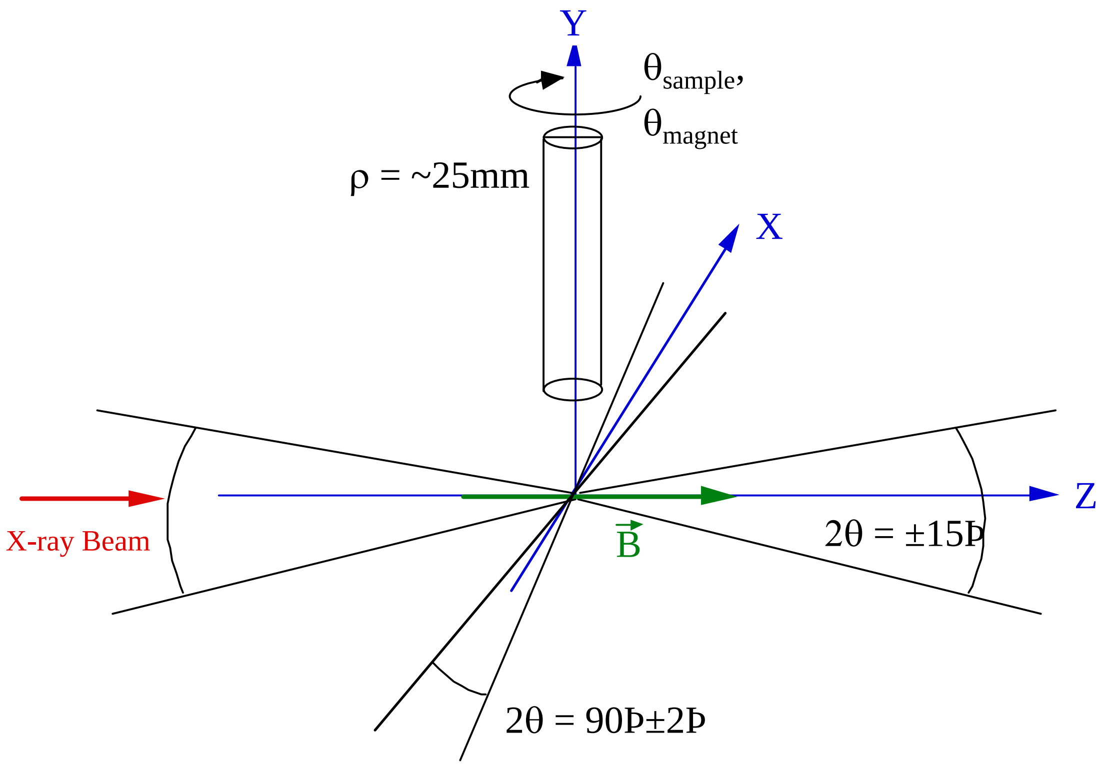
Resonant (dipole only):

$$f^{res} = F^0\left(\hat{\varepsilon}_f \cdot \hat{\varepsilon}_i\right) - iF^1\left(\hat{\varepsilon}_f \times \hat{\varepsilon}_i\right)\bullet \hat{m}_n + F^2\left(\hat{\varepsilon}_f \cdot \hat{m}_n\right)\left(\hat{\varepsilon}_i \cdot \hat{m}_n\right)$$

Magnetic Field Parallel to the Beam Direction

Applications:

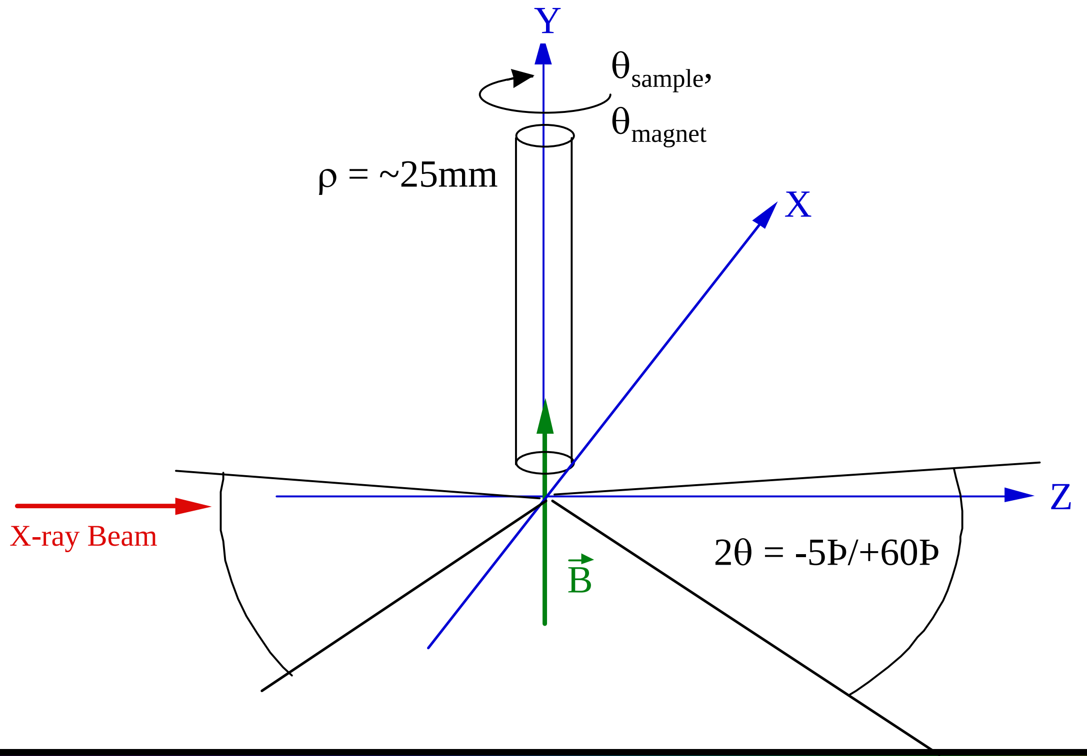
- Dichroism in absorption or fluorescence
- Small angle scattering



Magnetic Field Perpendicular to the Beam Direction

Applications:

- Diffraction
- Resonant and non-resonant scattering



Many Workshops Followed

Here is the subset:

- ***High Magnetic Field and Synchrotron Radiation***
  September 13, 2001, ESRF - Grenoble

- ***Big Light Workshop***
  May 6-7, 2004, NHMFL - Tallahassee

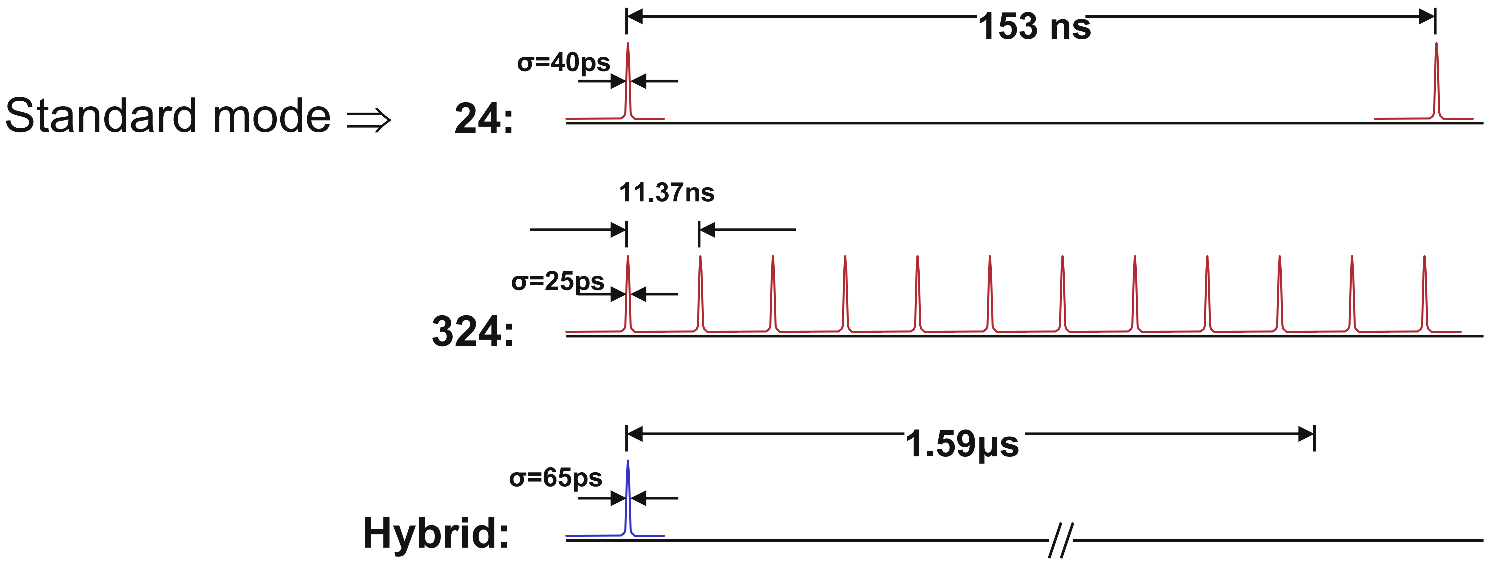
- ***Science Opportunities Using X-rays and Neutrons***
  May 10-12, 2005, NHMFL - Tallahassee

- ***High Field and APS Upgrade***
  June 8-9, 2006, APS - Argonne National Laboratory

Magnet Choice

- ***DC Magnetic Field: 30-40 T***
- ***Field Perpendicular to Beam Direction***

Timing Structure at the APS



Science Drivers

Superconductors:

- competing phases in the cuprates
- *S*=1/2 triangular lattice Na_xCoO_2

Frustrated magnets:

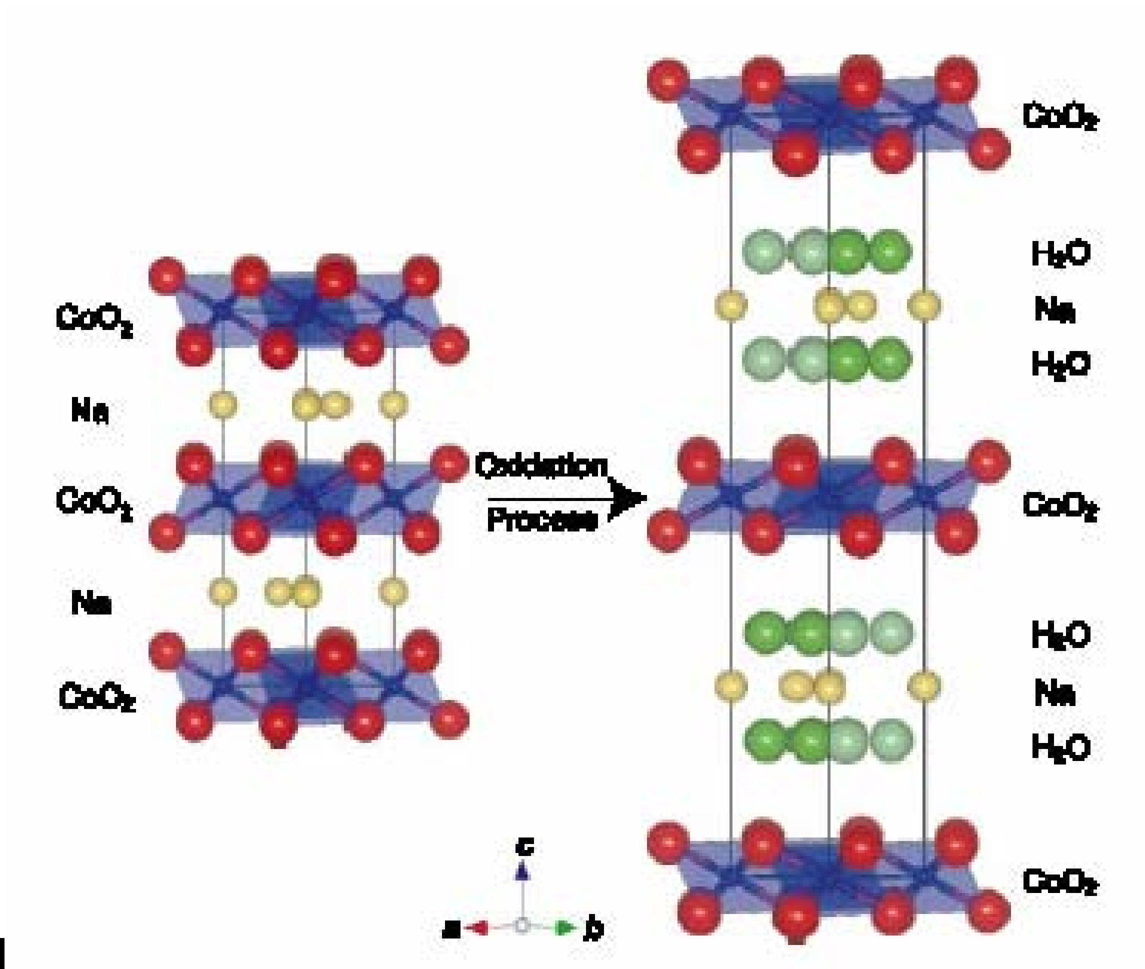
- spin-Peierls-like phases
- multiferroics

Other examples:

- hidden order
- Bose condensation of magnons

Novel superconductor $Na_{0.3}CoO_2 + 1.3H_2O$

Powder sample with $T_c \approx 4.5$ K

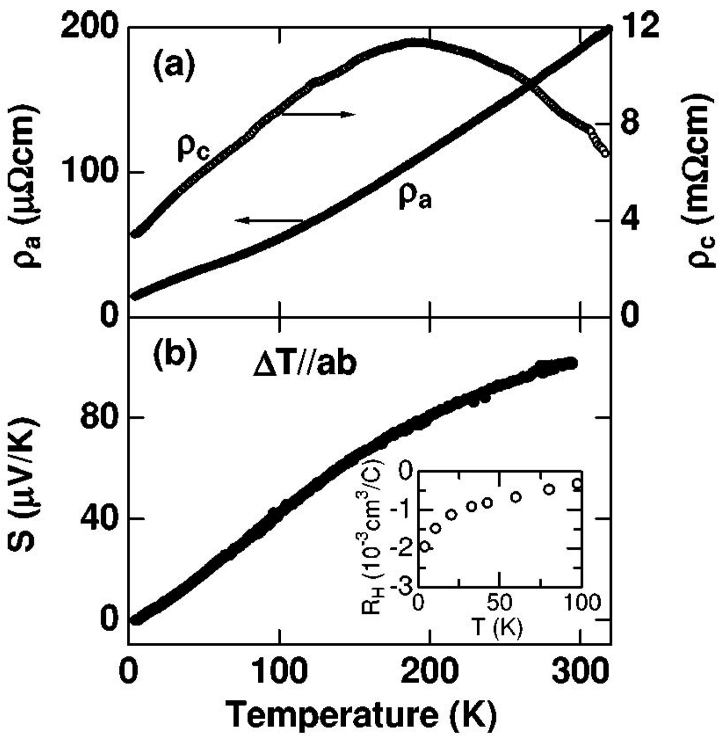


1) De-intercalate Na
$Na_{0.75}CoO_2 \rightarrow Na_{0.3}CoO_2$

2) Add water
$\rightarrow Na_{0.3}CoO_2 + 1.3H_2O$

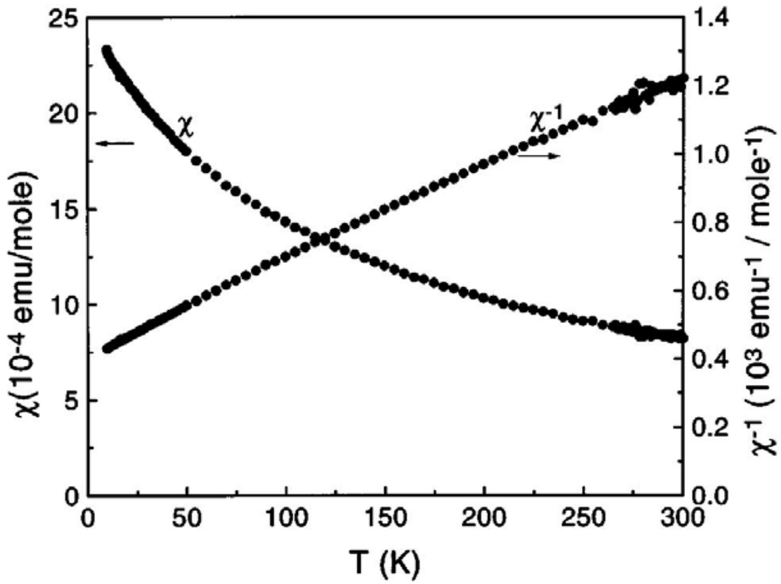
Takada *et al.*, Nature **422**, 53, 2003

$Na_{0.75}CoO_2$: Strange Metal



Terasaki et.al., PRB **56**, R12685 (1997)

Large thermopower

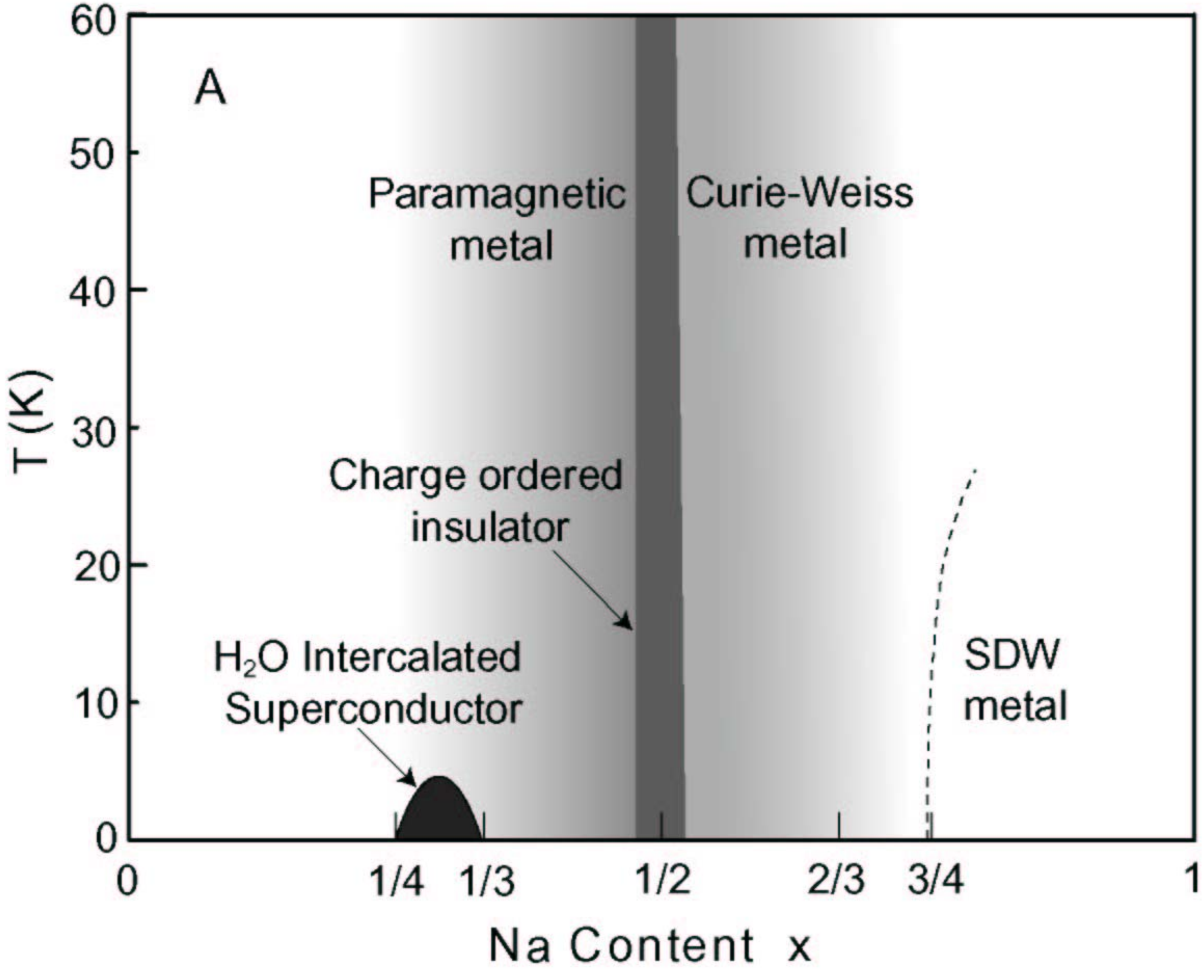


Ray et.al., PRB **59**, 9454 (1999)

Curie-Weiss magnetism (localized) coexists with metallic behavior (delocalized)

Proposed Phase Diagram

Foo, et.al., PRL **92**, 247001 (2004)

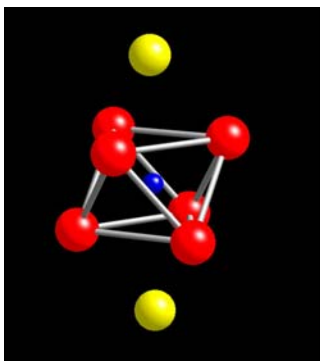


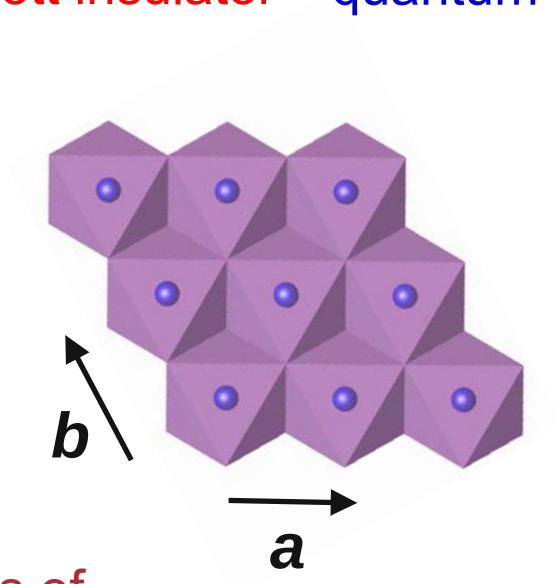
Rich Physics

The intriguing ingredients of Na_xCoO_2 + y H_2O

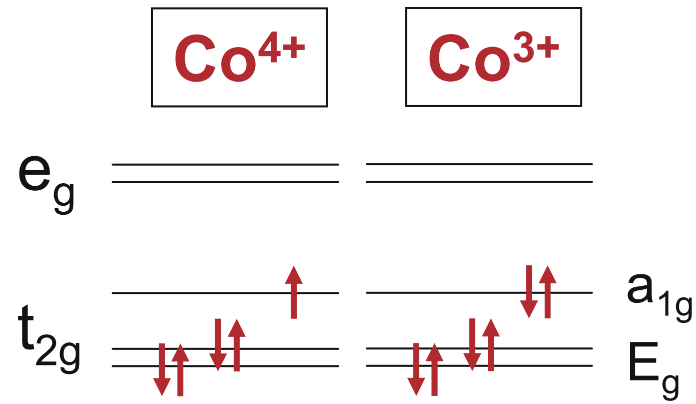
→ a doped S=1/2 triangular lattice

doped Mott insulator quantum frustrated





Stacked planes of CoO_6 octahedra



$S = 1/2$ $S = 0$

- exotic superconductivity
- strange magnetism (unhydrated)

Scattering Studies in High Fields in Na_xCoO_2 + y H_2O

Open Questions:

1) Mechanism for superconductivity (x=0.3)
   - role of magnetic fluctuations ?
   - competing orders ?

neutrons and x-rays in field

2) Charge order (x=0.5, unhydrated)
   - Na order confirmed, but charge order in CoO_2 planes ?

x-rays in field

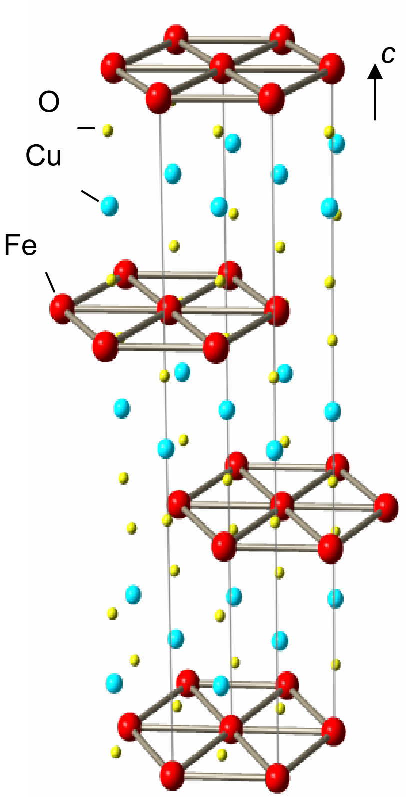
3) Magnetism (x ≈ 0.75, unhydrated)
   - unusual spin-density wave state
   - metamagnetic transition

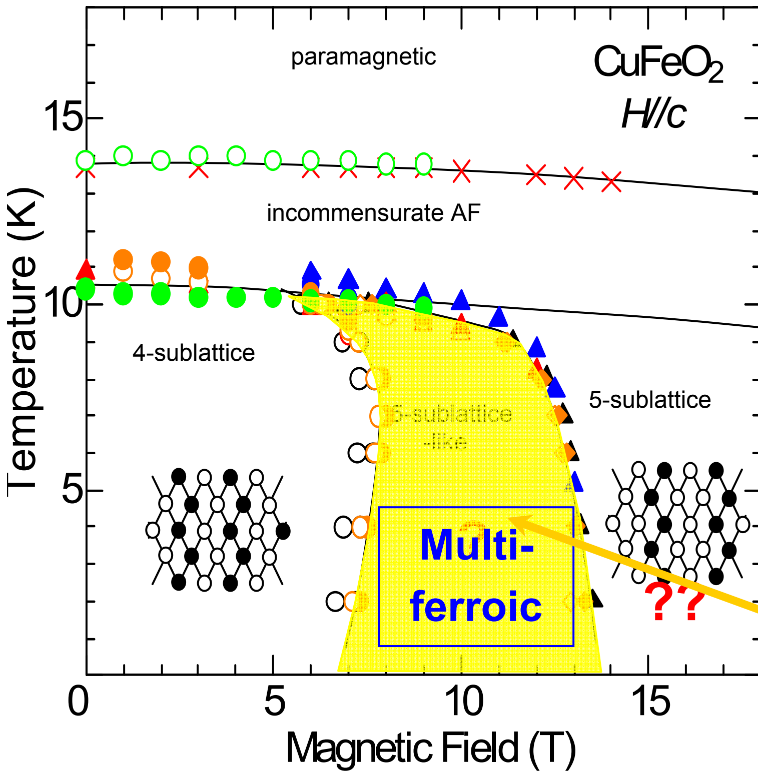
neutrons and x-rays in field

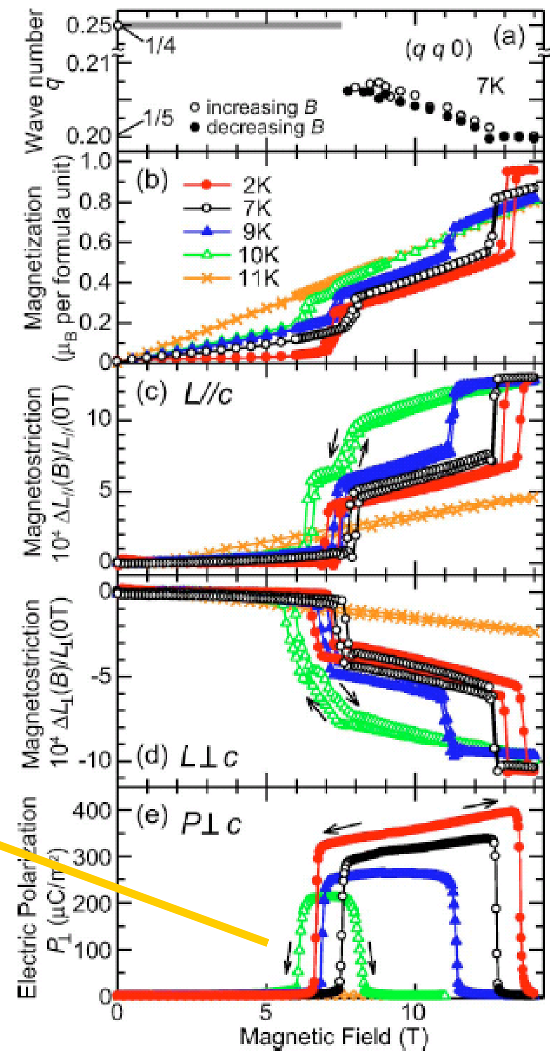
Y.S.Lee, MIT

Field-Driven Ferroelectricity in Multiferroics

An example: $CuFeO_2$



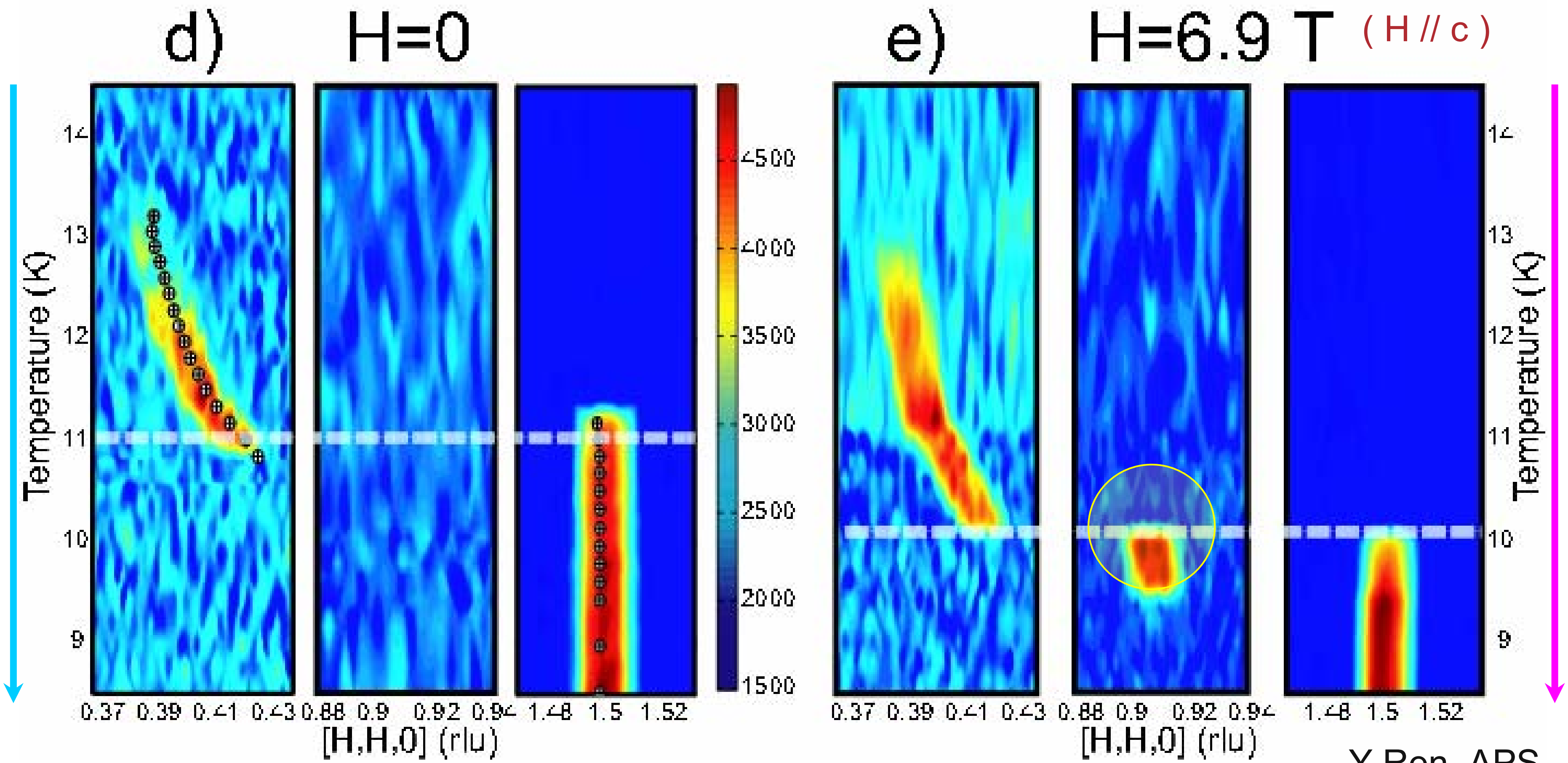




Kimura, Lashley & Ramirez, Phys. Rev. B (R) 2006

Spin-Lattice Interaction in $CuFeO_2$

An additional magnetic-field-induced incommensurate structural modulation, associated with the magneto-ferroelectricity, indicates that the lattice plays an important role in the multiferroic effect.



Y.Ren, APS

*National Research Council Report**

Committee on High Magnetic Field Science:

"New instruments for studying the ***neutron and x-ray*** scattering properties of materials in high magnetic fields should be developed in the United States"

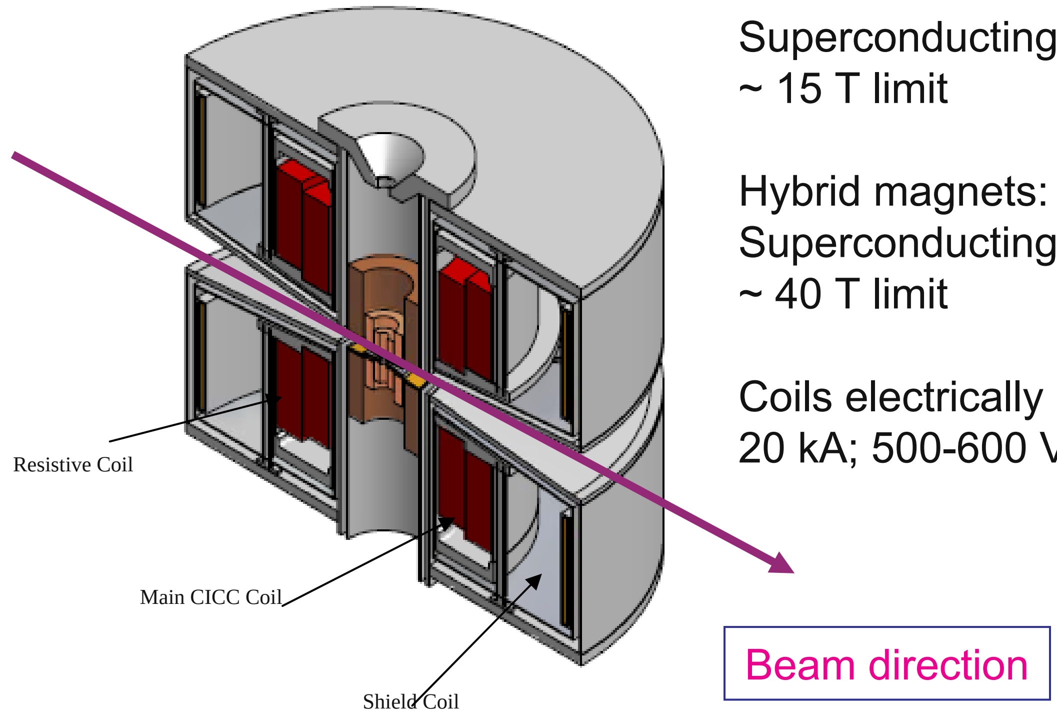
Workshop:

Science Opportunities Using X-rays and Neutrons

May 10-12, 2005, NHMFL - Tallahassee

*The National Academies Press, Washington (2005), http://books.nap.edu/catalog/11211.html

Magnet Technology Advances + Neutron Community



Superconducting magnets:
~ 15 T limit

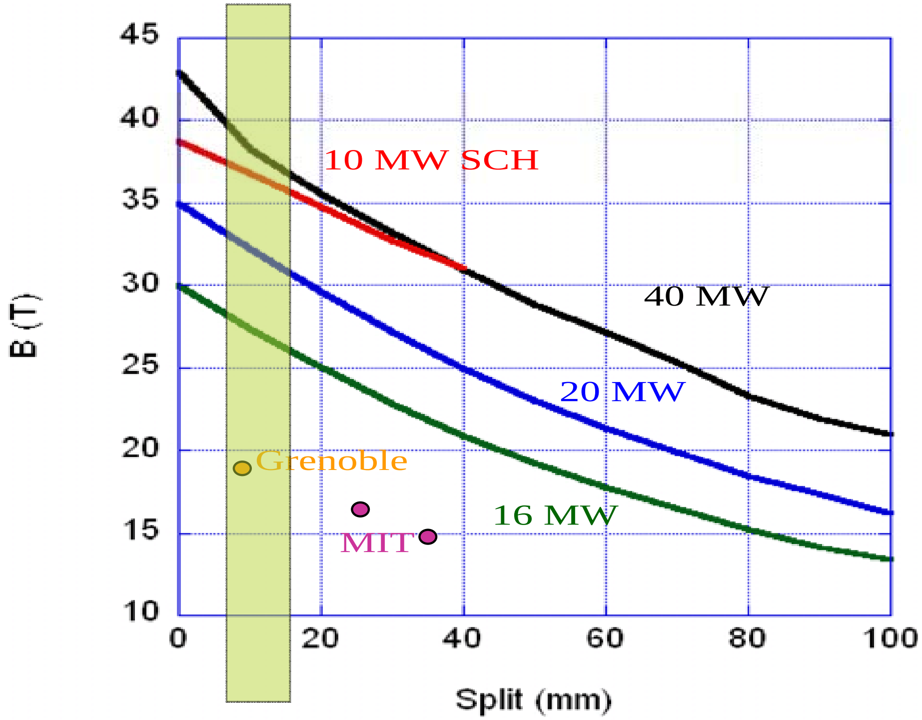
Hybrid magnets:
Superconducting +Resistive
~ 40 T limit

Coils electrically in series:
20 kA; 500-600 V

Section of the proposed split-coil, series-connected hybrid magnet

Courtesy: M.Bird, NHMFL

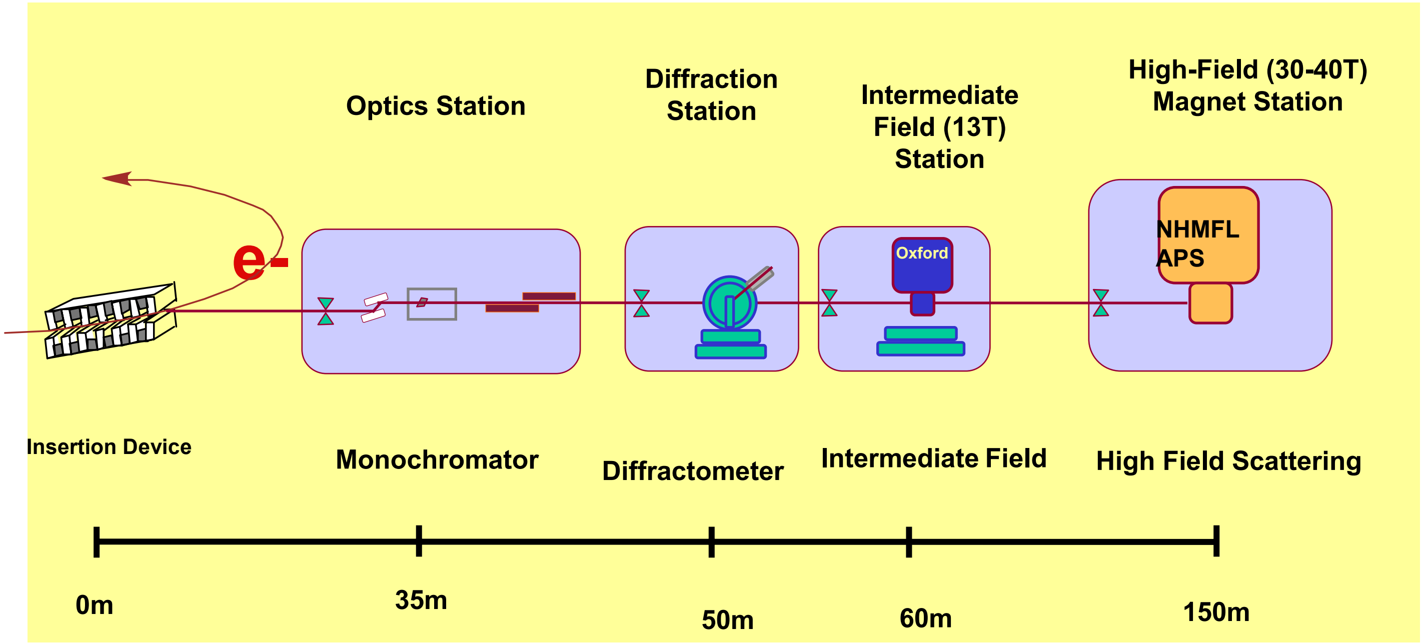
Field Strengths



Preliminary field vs. coil gap and power for resistive and SCH magnets of various power levels.

Courtesy: M.Bird, NHMFL

Proposed Beamline



APS Upgrade

Planning started in Summer 2006

Options being explored:

- **Small emittance ~ 1 nm rad**
- **APSx3**
- **ERL**

Proposal to be submitted next year

High magnetic field is one of the themes in the Upgrade

Conclusions

Partnership

Users	$\Rightarrow$	Science Drivers	$\Rightarrow$	Rutgers
Magnets	$\Rightarrow$	Design & Construction	$\Rightarrow$	NHMFL
Facility	$\Rightarrow$	Beamlines	$\Rightarrow$	XOR-4

Proposal to fund the conceptual and engineering design submitted on Oct. 13, 2006