DOE-BES Perspectives on High Magnetic Field Science

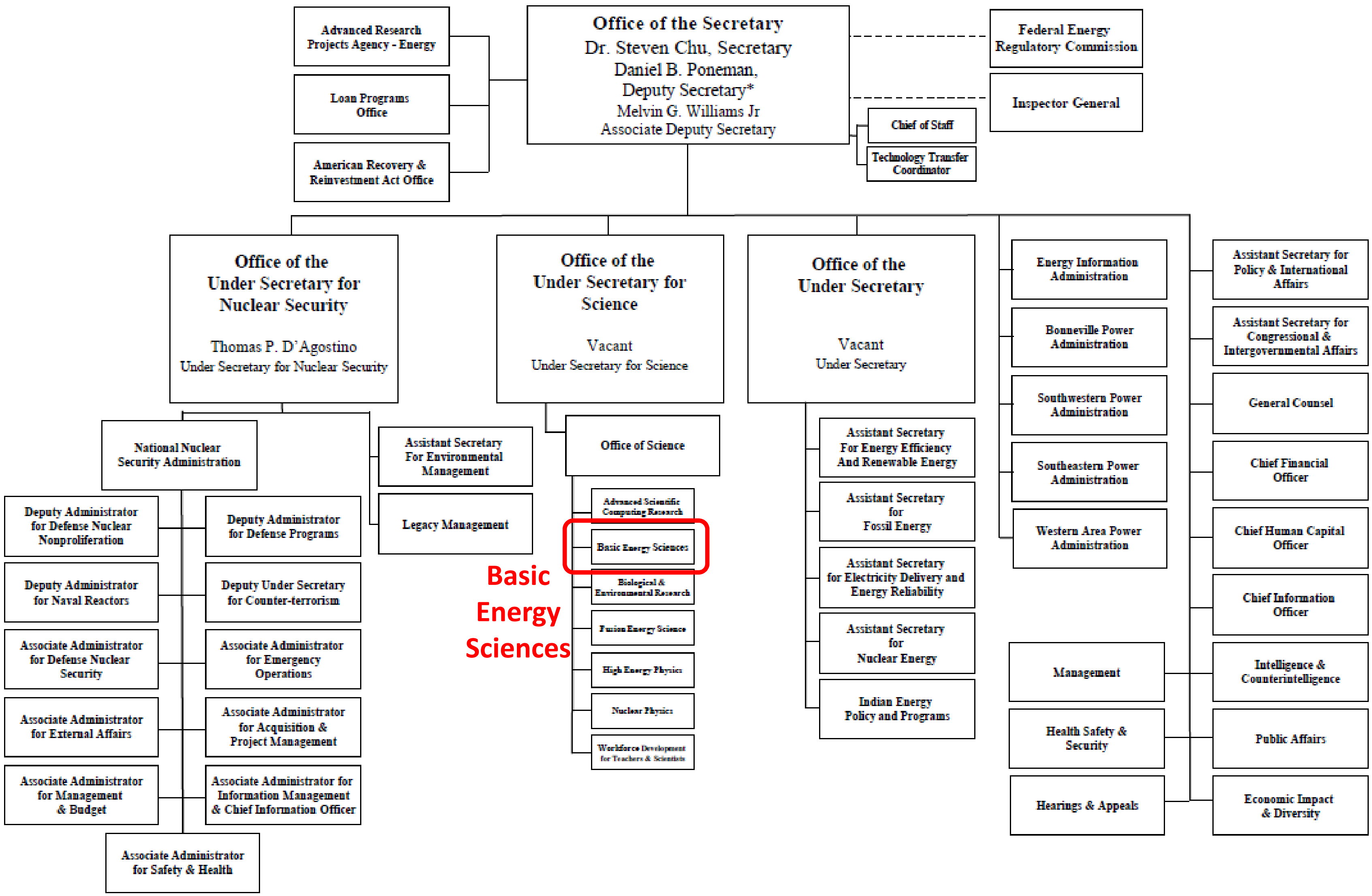
The National Academies
March 12, 2012

Andy Schwartz
Office of Basic Energy Sciences
Department of Energy

Outline

- DOE and Basic Energy Sciences (BES)
- Facilities
- High Field Science Highlights
- Beamline and Instrumentation Partnerships

Department of Energy



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Wanda Smith, Administrative Specialist

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- Margie Davis, Financial Management

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- Kerry Gorey, Program Support Specialist
- Robin Hayes, Program Manager
- Natalia Melcer, Program Manager
- Katie Perine, Program Analyst / BESAC
- Ken Rivera, Laboratory Infrastructure / ES&H

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Teresa Crockett, Program Analyst
Vacant

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  - Biomolecular Materials — Mike Markowitz
  - Synthesis and Processing Science — Bonnie Gersten
  - Technology Coordination Program Management — Craig Henderson, John Vetrano
- **Condensed Matter and Materials Physics** — Jim Horwitz; Marsophia Agnant, P.A.
  - Experimental Condensed Matter Physics — Andy Schwartz
  - Theoretical Condensed Matter Physics — Jim Davenport
  - Physical Behavior of Materials — Refik Kortan
  - Mechanical Behavior and Radiation Effects — John Vetrano
- **Scattering and Instrumentation Sciences** — Helen Kerch; Cheryl Howard, P.A.
  - X-ray Scattering — Lane Wilson
  - Neutron Scattering — Thiyaga P. Thiyagarajan
  - Electron and Scanning Probe Microscopies — Jane Zhu
  - Experimental Program to Stimulate Competitive Research (DOE EPSCoR) — Tim Fitzsimmons

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Linda Cerrone, Program Support Specialist
Rocio Meneses, Program Assistant

- **Operations**
  - X-ray and Neutron Scattering Facilities — Peter Lee, Vacant, ◆ James Murphy, BNL
  - NSRCs and EBMCs* — Mihal Gross, ☆ Tof Carim
  - Accelerator and Detector Research — Eliane Lessner
  - Facilities Coordination; Metrics; Assessment — Van Nguyen
- **Construction**
  - National Synchrotron Light Source-II — Phil Kraushaar
  - Facilities Upgrades and Major Items of Equipment (MIE) Projects — Joe May, Phil Kraushaar

* Nanoscale Science Research Centers and Electron-beam Microcharacterization Centers

Chemical Sciences, Geosciences, and Biosciences Division

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Michaelene Kyler-Leon, Program Assistant

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  - Gas Phase Chemical Physics — Wade Sisk
  - Condensed Phase and Interfacial Molecular Science — Gregory Fiechtner
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- **Photochemistry and Biochemistry** — Rich Greene; Sharron Watson, P.A.
  - Solar Photochemistry — Mark Spitler, ◆ Margaret Ryan, PNNL
  - Photosynthetic Systems — Gail McLean
  - Physical Biosciences — Robert Stack
  - Fuels from Sunlight Energy Innovation Hub — Carol Bessel
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  - Catalysis Science — Paul Maupin, Raul Miranda, ◆ Jan Hrbek, BNL
  - Separations and Analysis — Larry Rahn
  - Heavy Element Chemistry — Philip Wilk
  - Geosciences — Nick Woodward
  - Technology Office Coordination — Marvin Singer

LEGEND

◆ Detailee (from DOE laboratories)
☆ On Detail to OSTP
P.A. Program Assistant

February 2012

Posted 21FEB12

Facilities

DOE Basic Energy Sciences User Facilities

Unique research facilities *and* scientific expertise for ultra high-resolution characterization, synthesis, fabrication, theory, and modeling of advanced materials

- **Available to all researchers *at no cost* for non-proprietary research, regardless of affiliation, nationality, or source of research support**
- **Access based on external peer merit review of brief proposals**
- **Coordinated access to co-located facilities to accelerate research cycles**
- **Collaboration with facility scientists an optional potential benefit**
- **Instrument and technique workshops offered periodically**
- **A variety of on-line, on-site, and hands-on training available**
- **Proprietary research may be performed on a full-cost recovery basis**

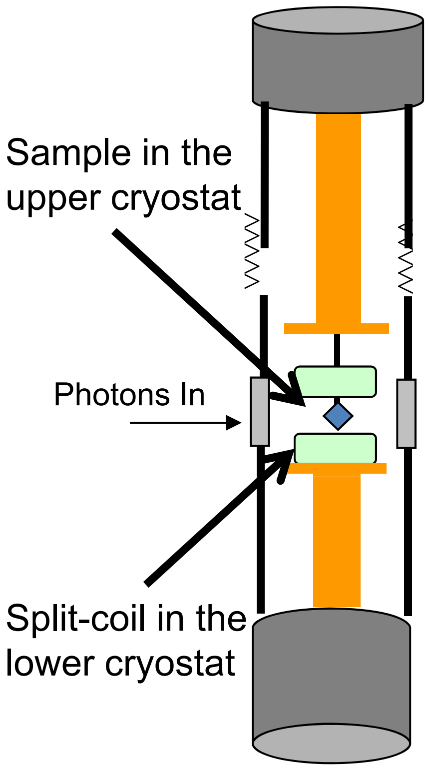
- **Nanoscale Science Research Centers**
  - *Center for Functional Nanomaterials (BNL)*
  - *Center for Integrated Nanotechnologies (SNL & LANL)*
  - *Center for Nanophase Materials Sciences (ORNL)*
  - *Center for Nanoscale Materials (ANL)*
  - *Molecular Foundry (LBNL)*
- **Electron-Beam Microcharacterization Centers**
  - *Electron Microscopy Center for Materials Research (ANL)*
  - *National Center for Electron Microscopy (LBNL)*
  - *Shared Research Equipment Program (ORNL)*
- **Light sources**
  - *Advanced Light Source (LBNL)*
  - *Advanced Photon Source (ANL)*
  - *Linac Coherent Light Source (SLAC)*
  - *National Synchrotron Light Source (BNL)*
    National Synchrotron Light Source II under construction
  - *Stanford Synchrotron Radiation Laboratory (SLAC)*
- **Neutron sources**
  - *High Flux Isotope Reactor (ORNL)*
  - *Manuel Lujan, Jr. Neutron Scattering Center (LANL)*
  - *Spallation Neutron Source (ORNL)*

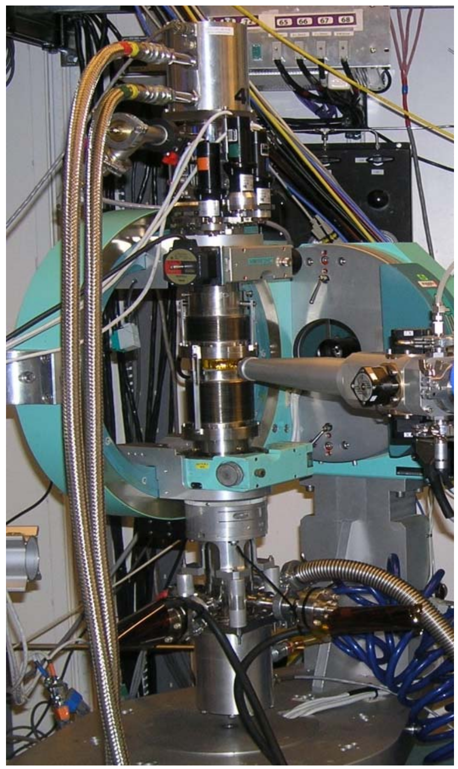
U.S. DEPARTMENT OF ENERGY

http://www.science.doe.gov/bes/suf/user-facilities

Instrumentation Development: High Field X-ray Scattering at APS

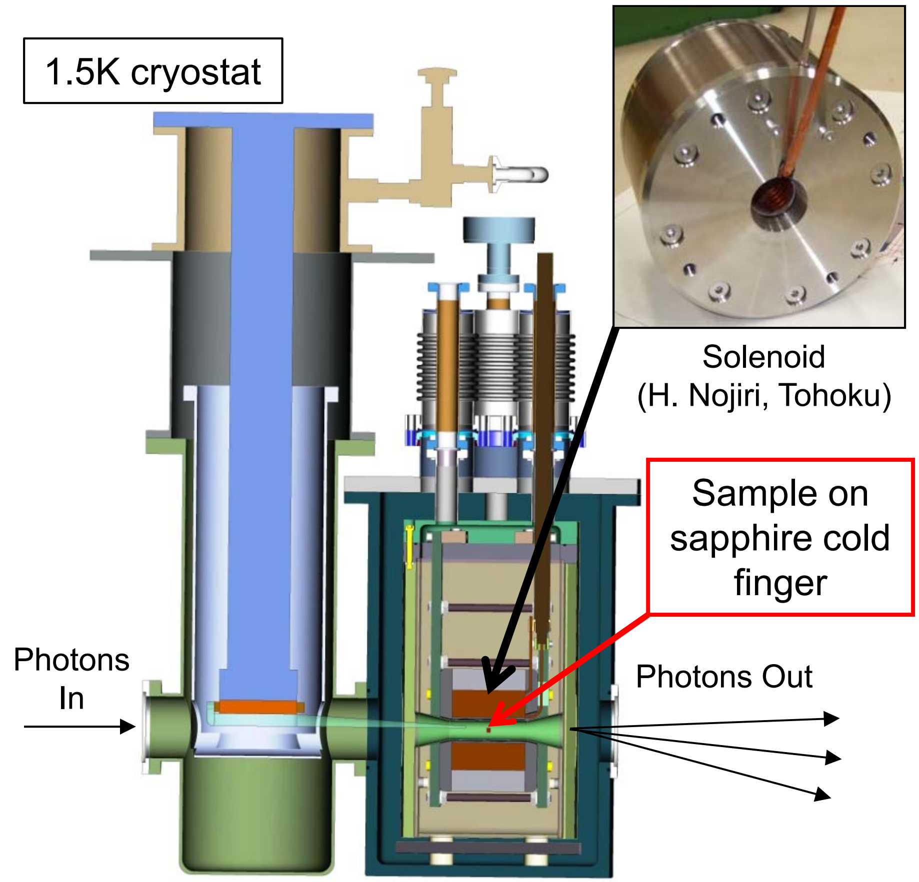
30T pulsed split-pair dual-cryostat magnet





Z. Islam et al., Rev. Sci. Instrum. **80**, 113902 (2009)

30T solenoid for single-crystal diffraction



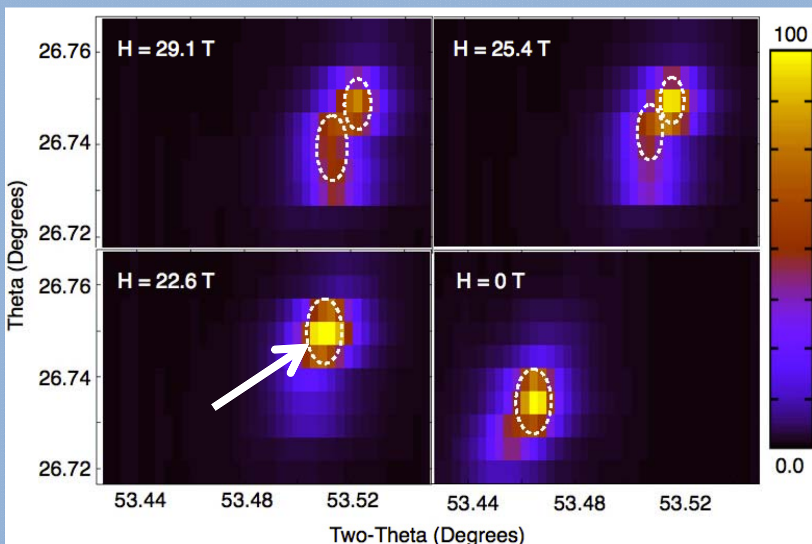
Z. Islam et al., Rev. Sci. Instrum. **83**, 035101 (2012)
J. P. C. Ruff et al., Phys. Rev. B **85**, 024104 (2011)

X-ray diffraction studies in pulsed magnetic fields

Magneto-elastics of a spin liquid (split-pair w/ 1D strip detector)

E X A M P L E

$TbTi_2O_7$ spin liquid

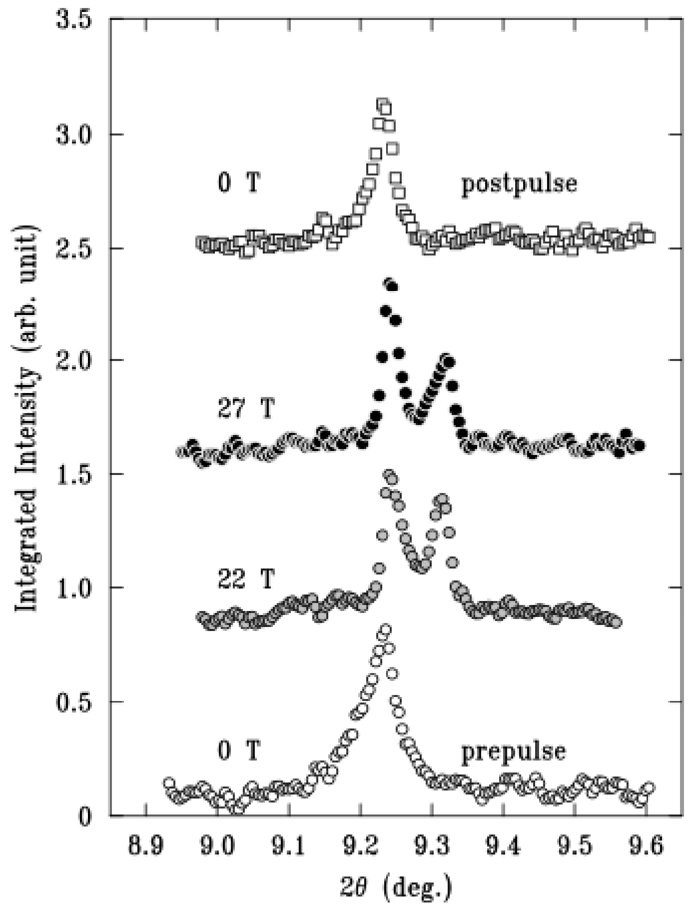


Material has no magnetic order down to ~70mK. Magneto-striction observed below 25T and structural transition above 25T.

J. Ruff et al., Phys. Rev. Lett. **105**, 077203 (2010)

Z. Islam et al., Rev. Sci. Instrum. **83**, 013113 (2012)

Jahn-Teller effects in $TbVO_4$ (Solenoid w/ 2D image plate)

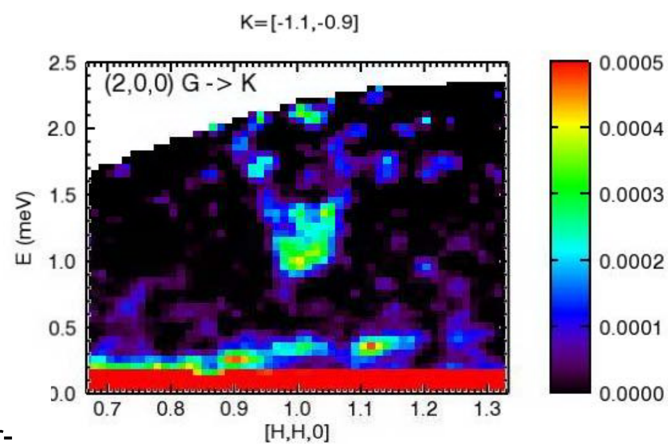


Z. Islam et al., Rev. Sci. Instrum. **83**, 035101 (2012)

SNS User-Science at 16 Tesla with "Fat SAM"

The large magnet nick-named "Fat SAM" is shown above leaving the Bruker manufacturing facility in 2010. It was developed through a collaboration between the SNS and the Swiss neutron facility (PSI).

- The Spallation Neutron Source has a new large, portable magnet that provides a world-leading combination of high-field strength and stray-field suppression
- The 16 Tesla magnet is called Fat SAM (Shielded Asymmetric/symmetric Magnet)
- Researchers, armed with the combination of CNCS (Cold Neutron Chopper Spectrometer) and Fat SAM, are currently investigating quantum magnetic behaviors in advanced materials. Surprisingly large magnetic excitations were recently observed in a new class of kagome quantum antiferromagnets.

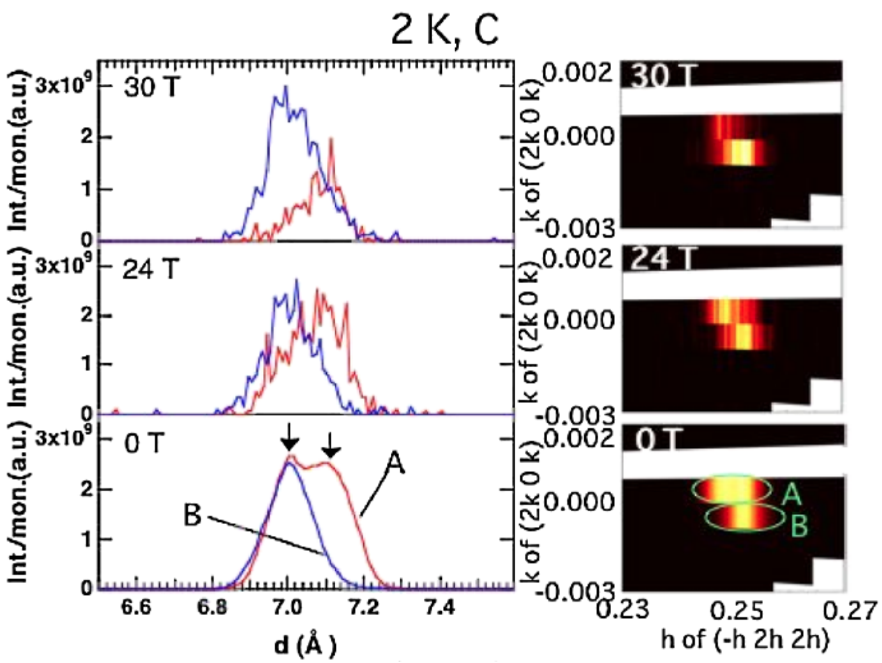


A neutron scattering spectrum obtained at high magnetic field (16 T) on the CNCS instrument shows a gapped excitation of about 1 meV, which challenges theoretical predictions.

Contacts: L. Santodonato, SE group leader; G. Ehlers, CNCS Lead Instrument Scientist; L. DeBeer-Schmitt, SNS SE Lead

SNS: 30 Tesla Magnet Reveals High-field Magnetic phases of $MnWO_4$

Pulsed magnet, pulsed neutrons combined in pioneering experiment



The commensurate peak in $MnWO_4$ observed at several field conditions. Left: Scattering weight shift to shorter d spacing as the field increases is interpreted as field manipulation of a long-period noncollinear spiral structure. The color plot on the right is the same reflection shown in reciprocal lattice units in the plane of interest.

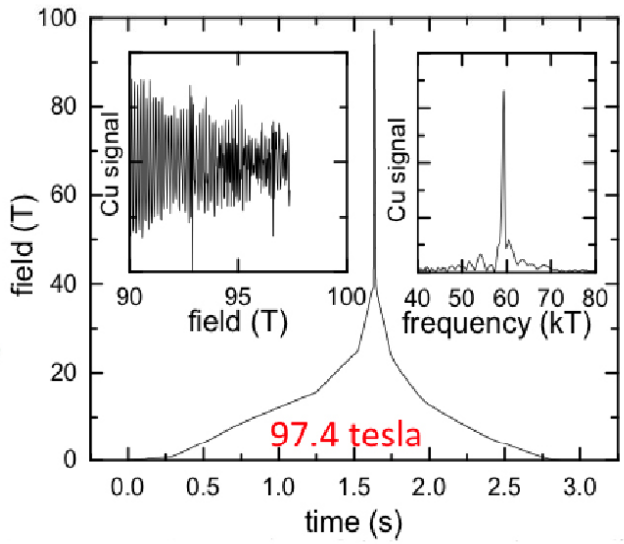
- The pulsed neutron beam at SNS and pulsed 30 T magnetic fields were combined to elucidate the high-field phases of multiferroic $MnWO_4$.
- The peak shape and splitting of the commensurate reflection in the high-field phases in $MnWO_4$ were observed for the first time.
- This is the first study demonstrating 30 T magnetic fields with pulsed neutrons.
- The technique is being developed for use on other instruments and for the general user program.
- Multiferroic materials, which have both electric and magnetic order, might be used in a variety of technological applications.

Slide courtesy of ORNL

H. Nojiri, et al., "Neutron Laue diffraction study on the magnetic phase diagram of multiferroic $MnWO_4$ under pulsed high magnetic fields," *Phys. Rev. Lett.* **106**, 237202 (2011).

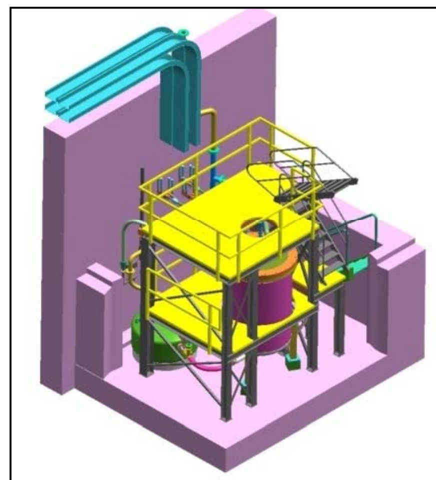
100 Tesla magnet at Los Alamos National Lab

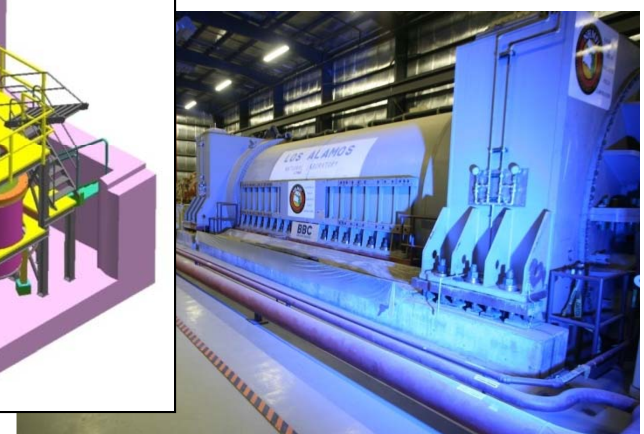
New High Magnetic Field Record



97.4 tesla was confirmed via magneto quantum oscillations in polycrystalline copper.

- World record: strongest magnetic field produced by a ***nondestructive*** magnet
- Achieved a record field of 97.4-tesla in August 2011.
- Provides an unprecedented tool to study fundamental properties of materials and understand the physics of structurally complex systems at a quantum level.





LANL's 1.43 GW generator can safely deliver a 600 MJ electrical pulse, a key capability giving the US a lead in high magnetic field generation capability

- NHMFL-PFF, a national user facility, now provides the unique capability for magnetic pulses of 95 tesla.
- Record puts LANL within reach of a magnet capable of repeatably achieving 100 tesla, a goal long sought by scientists.

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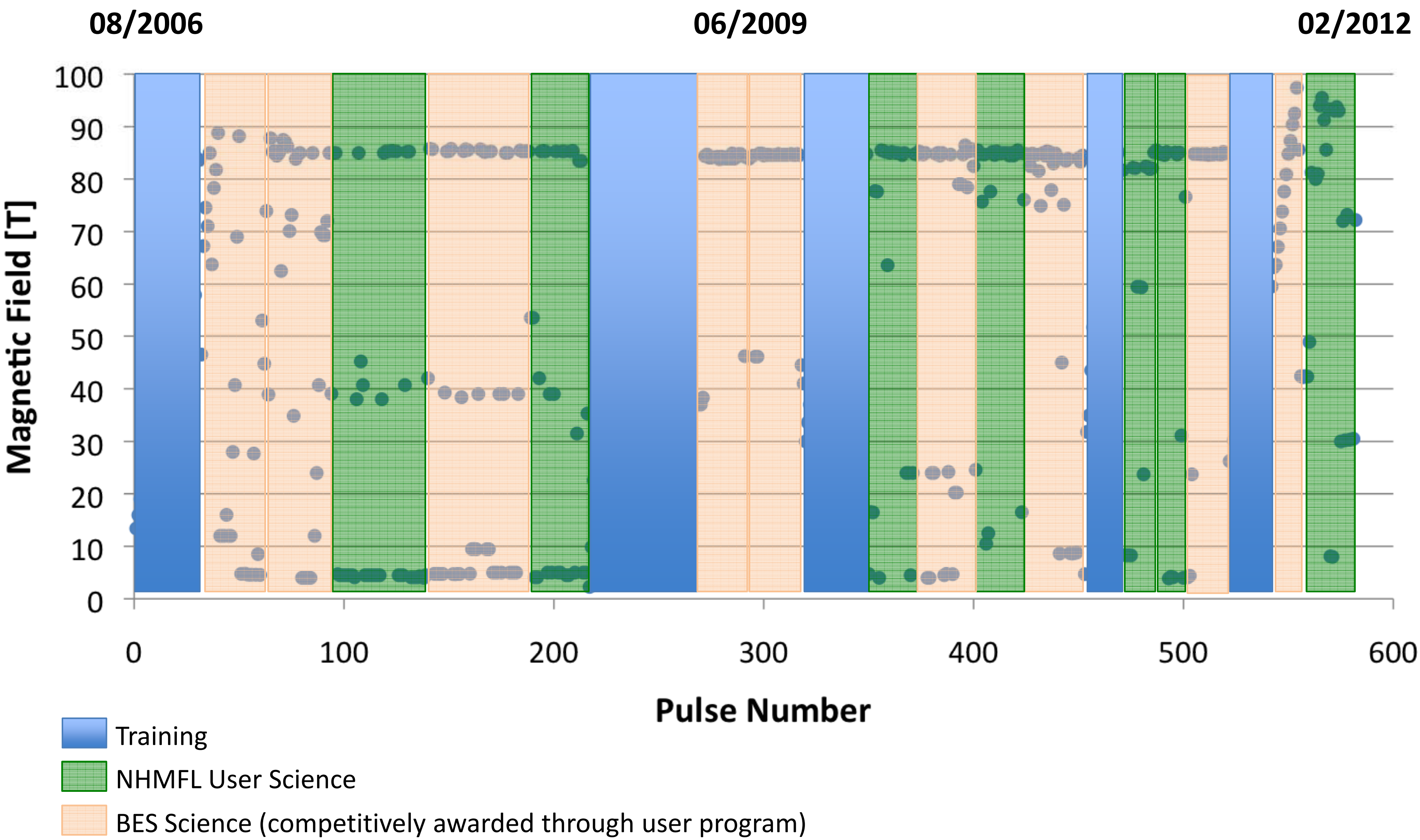
BES Support:
- Magnet R&D from approx. 1996-2006
- High field science project from 2006 to present

100T Magnet – Multi-shot Pulse History
Enabling a robust science program



Science Highlights

100 Tesla Science*

*Supported by DOE's Office of Basic Energy Sciences

MPA-CMMS

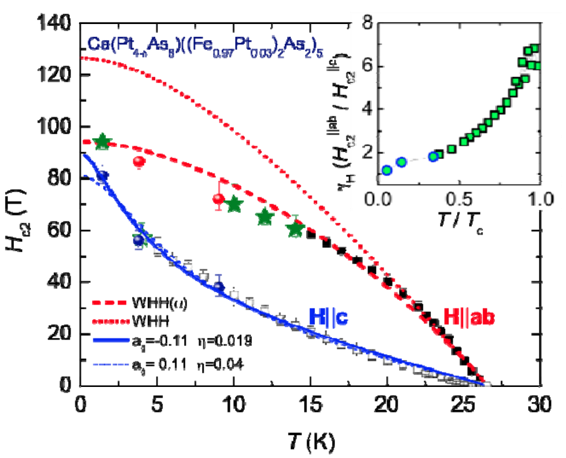
Los Alamos National Laboratory

Anisotropic H_{c2} up to 92 T and the signature of multiband superconductivity in $Ca_{10}(Pt_4As_8)((Fe_{1-x}Pt_x)_2As_2)_5$

E. Mun, N. Ni, J. M. Allred, R. J. Cava, O. Ayala, R. D. McDonald, N. Harrison, and V. S. Zapf

PRB rapid comm. **85**, 100502 (**2012**)

Magnetic fields to 100 T are an indispensible tool for studying the newly-discovered iron-based family of high-T_c superconductors. Unlike the cuprates, the iron-based superconductors appear to have upper critical fields that are unexpectedly isotropic at low temperatures — a fact that may be related to the Fermi surface topology and will likely prove useful in eventual superconducting wire applications. Until now, the isotropy of the upper critical field had only been measured in the most three-dimensional 122 sub-family of pnictide superconductors. By extending the field to 90 T, we were able to demonstrate the isotropy in the upper critical field as a more general property of pnictide superconductors.

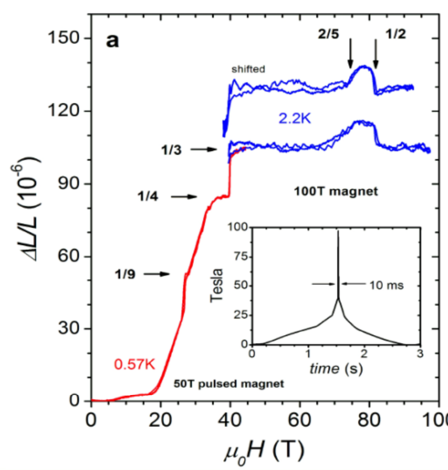


Magnetostriction and magnetic texture up to 1/2 saturation in the quantum magnet $SrCu_2(BO3)_2$

M. Jaime, R. Daou, S. A. Crooker, F. Weickert, A. Uchida, A.Feiguin, C. D. Batista, H. A. Dabkowska and B. D. Gaulin

Proc.Nat.Aced.Sci. USA (under review **2012**)

Frustrated quantum magnets are paradigmatic examples in which competing interactions lead to exotic states, such as spin liquids, spin supersolids and complex magnetic textures. $SrCu_2(BO_3)_2$ has been known for some time to exhibit a rich spectrum of magnetization plateaux related to the formation of stripe-like magnetic textures in applied fields. The structure of these plateaux is still highly controversial due to the intrinsic complexity associated with competing length scales. Using magnetic fields extending to 97.4 T, we found new magnetic textures in $SrCu_2(BO_3)_2$ via magnetostriction and magnetocaloric measurements. Notably, the data reveals marked lattice responses at 82 T and at 73.6 T, attributed to the long-predicted ½-saturation plateau, and to a new 2/5 plateau. The stability of these new magnetic textures is confirmed by a controlled density matrix renormalization group approach.

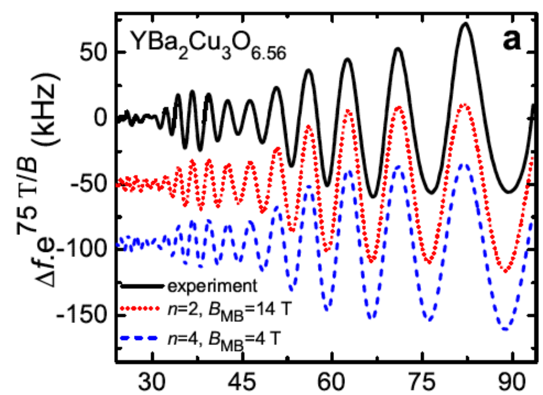


Quantum oscillations from nodal bilayer magnetic breakdown in the underdoped high temperature superconductor $YBa_2Cu_3O_{6+x}$

S. E. Sebastian, N. Harrison, R. Liang, D. A. Bonn, W. N. Hardy, C. H. Mielke, and G. G. Lonzarich

PRL (under review **2012**)

We performed quantum oscillation measurements in the underdoped cuprate $YBa_2Cu_3O_{6.56}$ in magnetic fields over a significantly large range in magnetic field extending from ~24 to 94 T, enabling three well-spaced low frequencies at ~440 T, 532 T, and 620 T to be clearly resolved. We find that a small nodal bilayer coupling that splits a nodal pocket into bonding and antibonding orbits yields a sequence of frequencies and accompanying beat pattern similar to that observed experimentally on invoking magnetic breakdown tunneling at the nodes. The relative amplitudes of the multiple frequencies observed experimentally in quantum oscillation measurements are shown to be reproduced using a value of nodal bilayer gap quantitatively consistent with that measured in photoemission experiments in the underdoped regime.



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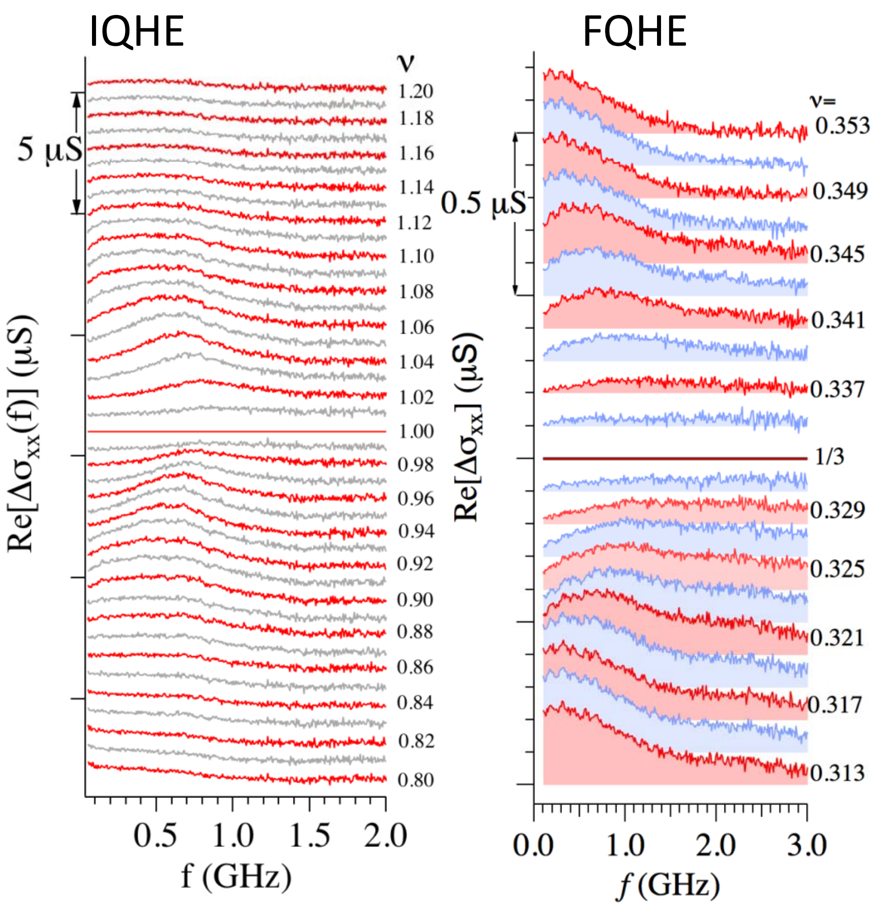
Evidence for solid of fractionally charged particles in high magnetic field

diagonal conductivity $\Delta\sigma_{xx}=\sigma_{xx}(\nu)-\sigma_{xx}(\nu=1/3)$



Spectra taken within the Landau filling (ν) ranges of the quantum Hall effects for the same sample near ν=1 (integer) and ν=1/3 (fractional). Offset for clarity.

An RF or microwave resonance is a signature of a *disorder-pinned* Wigner solid, understood as a pinning mode.

Pinning modes: long known at high magnetic field termination of fractional quantum Hall effect (QHE) series, were later found near integer QHE.

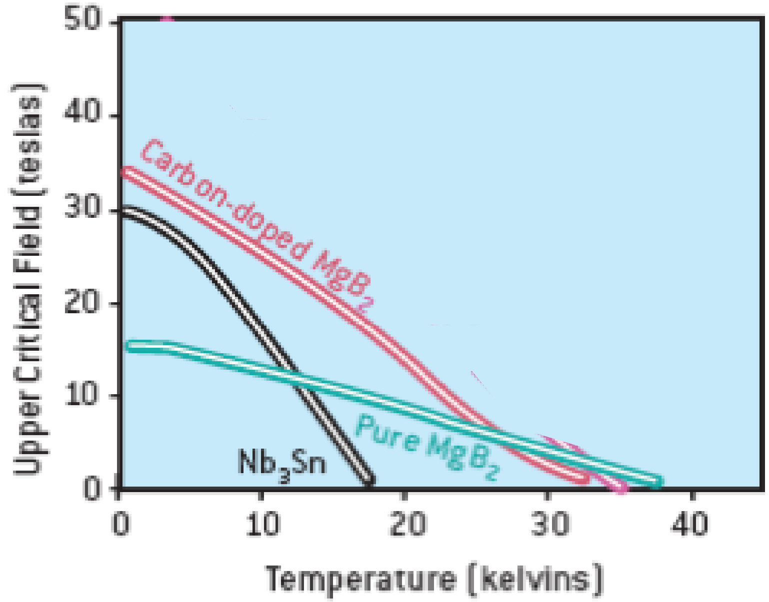
This work shows a pinning mode resonance within fractional QHE, indicating fractionally charged excitations can solidify.

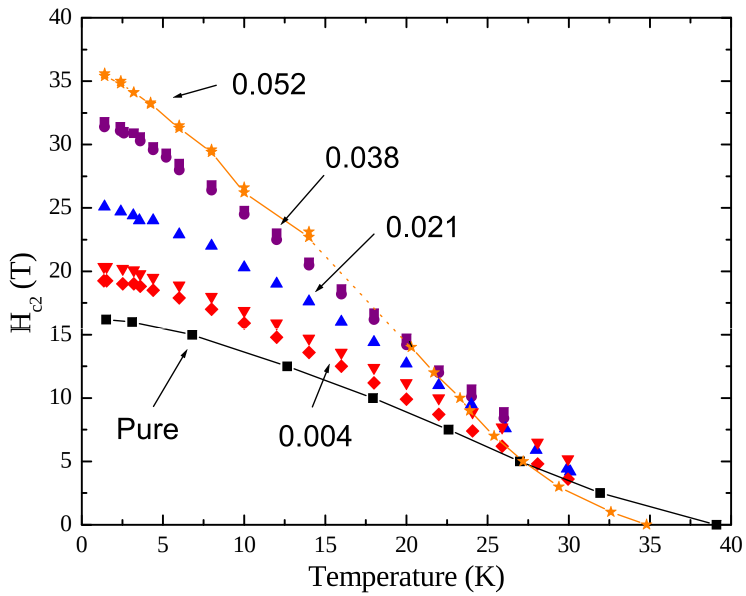
Han Zhu, et al.,"Observation of a Pinning Mode in a Wigner Solid with ν =1/3 Fractional Quantum Hall Excitations," Phys. Rev. Lett. **105** , 126803 (2010).

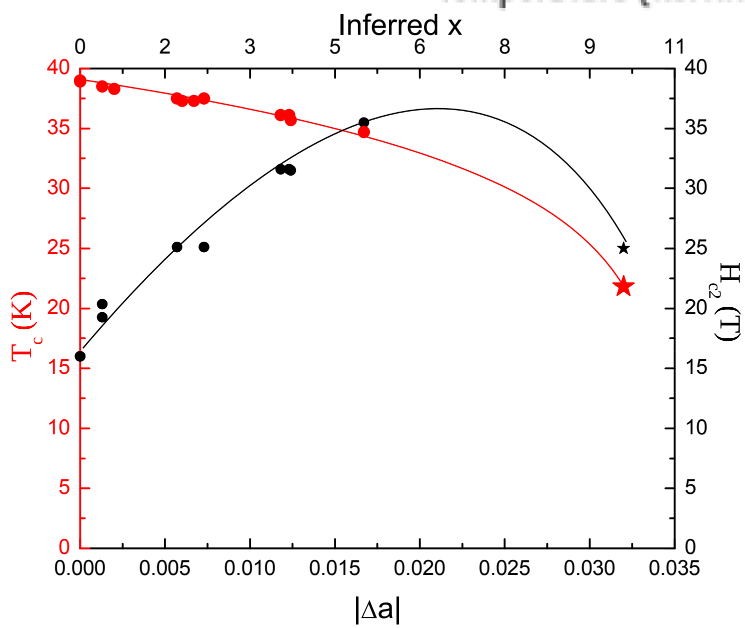
Optimizing MgB_2

High purity MgB_2 has a rather low $H_{c2}(T)$ curve. High field studies of $Mg(B_{1-x}C_x)_2$ at the NHMFL in Tallahassee revealed….

tuning of T_c and H_{c2} with light carbon doping makes MgB_2 superior to Nb_3Sn (in H-T space).

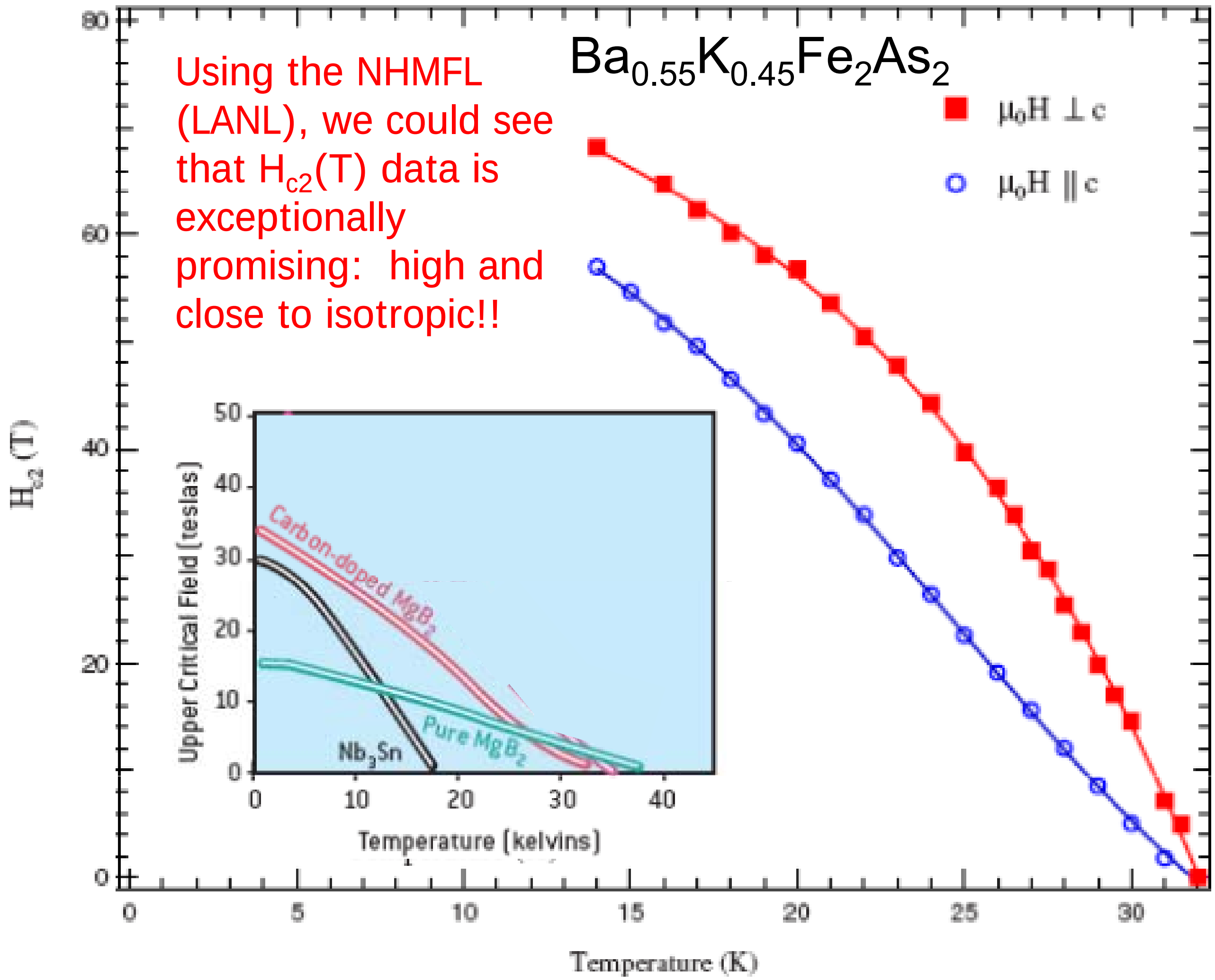






Slide courtesy of Ames Lab

Upper critical field of pnictide superconductor



Phys. Rev. B **78**, 220505(R) (2008)

U.S. DEPARTMENT OF ENERGY

Slide courtesy of Ames Lab

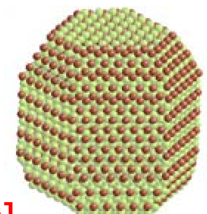
Semiconductor quantum dots in high magnetic fields:
A long track record of BES-NHMFL collaboration…

BES program on Semiconductor Nanocrystal Quantum Dots

PI: Victor Klimov (Chemistry Division, Los Alamos) ⟺ *Co-I: Scott Crooker (NHMFL-Los Alamos)*

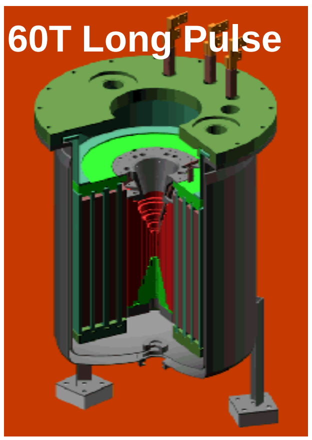
Collaboration enables optical spectroscopy of colloidal semiconductor nanocrystals…

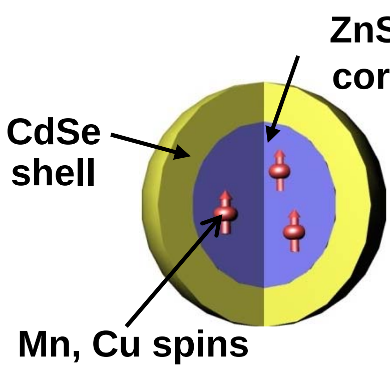
…in ultrahigh magnetic fields…

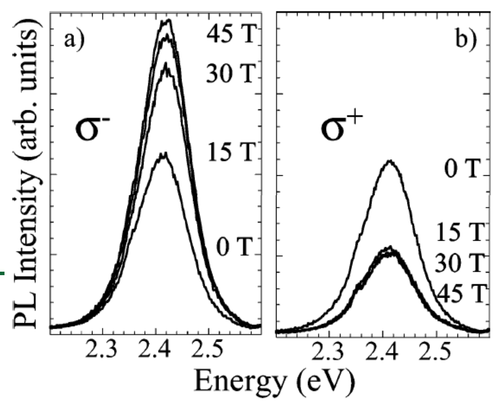


…& milli-Kelvin temperatures

e.g., Spectroscopy of magnetically-doped nanocrystals [Phys. Rev. Lett (2011)] [Nature Materials (2009)]

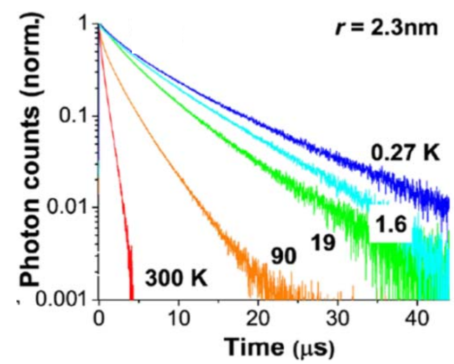


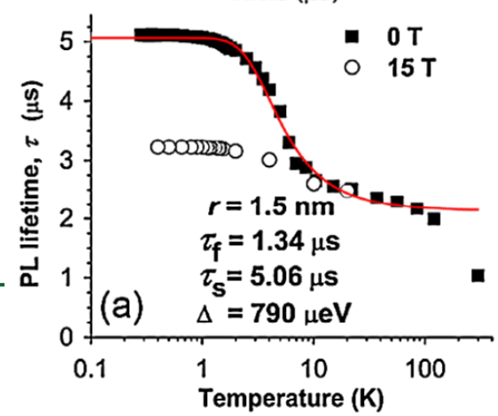




e.g., Revealing the exciton fine structure in PbSe nanocrystals via time-resolved optics

[Physical Review Letters (2010)]





Slide courtesy of LANL

BES Beamline and Instrumentation Partnerships

<u>Statement of Task</u>:

“How should the issue of providing magnetic fields to light sources and neutron facilities be handled?”

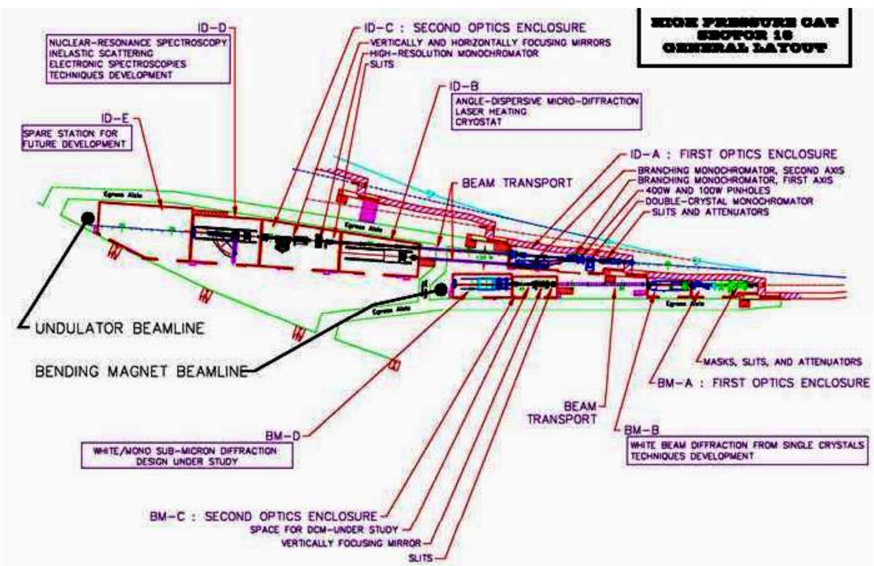
→ BES has a very successful history of partnerships at x-ray and neutron facilities.

DOE and Non-profit Partners

High Pressure Beamline (HPCAT) at APS

Beamline costs shared by BES, NNSA, and CIW Geophysical Lab.

High Pressure Research is poised to address long-standing issues in Condensed Matter Physics due to improved diamond cells, large volume presses and brighter x-ray and neutron sources.



- ***The High Pressure Collaborative Access Team (HPCAT) was established to advance cutting-edge, multidisciplinary, high-pressure science and technology using the Advanced Photon Source (APS) of Argonne National Laboratory.***
- ***The integrated HPCAT facility has established four operating beamlines.***
- ***An array of novel x-ray diffraction and spectroscopic techniques has been integrated with high pressure and extreme temperature instrumentation at HPCAT.***
- ***With a multidisciplinary approach and multi-institution collaborations, the high-pressure program at the HPCAT has enabeld myriad scientific breakthroughs in high-pressure physics, chemistry, materials, and Earth and planetary sciences.***

Federal Agency Partners

GeoSoilEnviroCARS (GSECARS)

- National user facility operated by University of Chicago
- Construction and operations supported primarily by DOE-Geosciences and NSF-Earth Sciences (recent undulator upgrade funded by DOE, NSF, and NASA)
- Sector consists of an insertion device (undulator) beamline (13-ID), a bending magnet beamline (13-BM), two support laboratories and office area.
- Four experimental stations (three can run simultaneously, soon to be four).
- 100% of beam time available to community through peer-reviewed General User Proposals
- Majority of the research - proposed largely by independently supported investigators - is conducted as collaborations with GSECARS staff

Advanced Photon Source at ANL

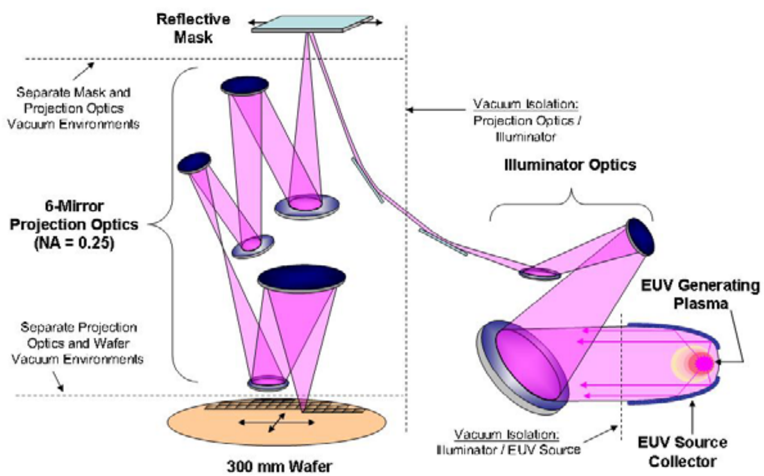
U.S. DEPARTMENT OF ENERGY

Slide courtesy of Steve Sutton, Center for Advanced Radiation Sources, University of Chicago

Industrial Partners

Synchrotron EUV Lithography facility at ALS provides advanced research on nanoscale manufacturing capability for semiconductor industry.

Impact:
Address materials development challenges for nanoscale manufacturing in 2015-2020.



Synchrotron Protein Crystallography at APS provides advanced analysis of protein structures in the drug discovery process.

Impact:
The beta-secretase inhibitor which is currently in Phase I clinical testing to determine its potential as a treatment for Alzheimer’s disease.

Thank you.