1. NHMFL High B/T Facility Growth, Plans (NS)
2. Condensed Matter Theory (Vision, Challenges at High B) (Ingersent)
3. Scanning Probe Microscopy (Biswas)
4. Semiconductor Optics (Stanton)
5. Beyond the Quantum Limit (Maslov)
6. Transverse Thermoelectrics (Hershfield)
7. Materials Processing (Meisel)
8. Biophysics (Meisel)
9. Search for Axions (NS)
THREE STATIONS for USERS

I. High Cooling Capacity (8 nW)
   Bay 3:  B=15/16.5T, $T_{\text{min}} \sim 0.4$ mK,
   homogeneity $1.6 \times 10^{-5}$ /cm,
   $8 \text{ nW} \Rightarrow t > 6 \text{ wks} @ 1$ mK

II. Medium Cooling Capacity (1 nW)
   Bay 2:  B=8T, $T_{\text{min}} \sim 0.04$ mK,
   homog. $\sim 10^{-4}$ /cm
   t > 2 wks @ 0.1 mK

III. Fast Turn-around Facility
   10 T/10 mK -- fast turnaround
   test samples & cell design

❖ Capabilities
   magnetic susceptibility, resistivity, 
   high sensitivity NMR/NQR to 1100MHz, 
   ultrasound, transport, heat capacity, 
   dielectric susceptibility

❖ Time constants can be very long at mK
❖ Users work with staff for optimum design and automated data acq
European Microkelvin Collaboration
(Helsinki, Lancaster, London, ENS-Paris, Leiden, Heidelberg)
IoPCS, China (Li Lu)
Magnet System: 2 Magnets + Compensation coil

- Heat Switch
- Zero Field Space
- Top Load Access
- PrNi5
- PrNi5 ~ nW cooling power
- Compensation coils
- Thermal Link

18/20 T Magnet
15.5/16.5 T (current)

Designed as an integral system
NHMFL High B/T Facility  

**Growth, Plans**

**STATS.**

Housed in MicroKelvin Building

-- uses two thirds of infrastructure

Four dedicated personnel

2 funded by NHMFL (scientist, postdoc.)

(oversight 4 faculty -- have other grants/projects)

Experiments require very long time (6 - 9 months)

must have dedicated on site staff to run user experiments

Typically: 4-6 experiments/yr

2-3 new proposals/yr (last 3 years... 1 new user /yr)

![Growth Graph]

**USER Requests/Needs**

1. Higher B, seldom lower T
   
   need high B > 25 T

2. Shorter wait time
   
   --- currently 7 – 9 months

3. Update aging equipment

---

5/16/2014  

Sullivan Strategic Planning UF 4-24-2014
Need for Higher B --- currently limited to 16.5 T
--- work with magnet development group for specially designed HTC magnet (ultra-quiet environment)

Science Examples:
1. Very low T, high B phase diagram solid $^3$He unexplored
2. Spin polarized Fermi fluids
   Non-linear dynamics at high B, very low T not understood (D. Lee et al.)
• **Exploit available low temperature environment**  
  – develop devices operating at low T and thus with very low noise T.

**Examples:**

1. RF Amplifiers for enhanced NMR sensitivity (*Huan et al.*)
2. Magnetometer readout (AF range, same principle as (1)
3. Tunnel Diode oscillators (unique low power configuration for very low T app.)  
   contactless conductivity, magnetic susceptibility
4. SQUID technologies (need field compensated region).

**Needs people & budget** (past relied on occasional students)  
Need dedicated person

- Re-entrant RF cavity VHF NMR  
  660 MHz, 1.5 mK sample T
Reducing Queue

Open Bay 1 to NHMFL Users

- Need additional staff
  --- dedicated Staff Scientist plus Post-Doctoral
  $240k annual

- Equipment upgrade
  ($^3$He pumps, power supplies)
  $220k$ one time

Goal: reduce queue for access to magnet time to less than 4 months
Condensed Matter Theory at UF

James Dufty  Statistical mechanics, non-equilibrium
Selman Hershfield  Electron transport, quantum dots
Peter Hirschfeld  Superconductivity, strong correlations
Kevin Ingersent  Strong correlations, nanophysics
Pradeep Kumar  Magnetism & superconductivity
Dmitrii Maslov  Electron transport theory
Khandker Muttalib  Electron transport/ disorder
Sergei Obukhov  Statistical mechanics of polymers
Christopher Stanton  Ultrafast optics, semiconductors
Themes

Materials in the ultra-quantum limit: Typically reached through a small effective Fermi energy due to
• Low carrier density (semiconductors, semimetals)
• Strong correlations (heavy fermions)
• …

Extreme realization: Quantum critical matter where $E_F \rightarrow 0$
• Extreme sensitivity can provide new functionalities
• Instabilities near underlying QCPs yield new states (e.g., cuprate superconductors)
• Magnetic field tuning is often the cleanest way to access a QCP
Themes

Topological States

• This area has its origin in the quantum Hall effect (so high B), but took off with focus on band-structure effects in zero field.
• Still a hot topic (see NHMFL 2014 Theory Winter School).
• Interest is now evolving toward areas where high fields may be more important:
  ◦ connections with superconductivity (e.g., Majorana modes in vortex cores)
  ◦ topological states made possible by strong correlation (e.g., SmB$_6$)
• Also connects to broader interests in spin-orbit coupling.
Relevant Future Projects

Peter Hirschfeld

• Magnetic field response of superconductors with small Fermi energy.
• Combined pressure and field dependence of critical temperature in unconventional superconductors (with James Hamlin, MPI workshop).
• Interplay of superconductivity, spin-orbit coupling and magnetism in correlated heterostructures, e.g., LAO/STO.

Kevin Ingersent

• Unconventional heavy-fermion quantum criticality – field-driven or probed via high-field measurements.
• Interplay of Kondo correlation, spin-orbit coupling and magnetism in heterostructures.
Scanning Probe Microscopy in High Magnetic Fields

- SPMs such as Scanning Tunneling Microscopes and Atomic Force Microscopes are powerful techniques for the study of materials and nanostructures

- Addition of a high magnetic field capability will open heretofore unexplored avenues such as:
  1. The local density of states of superconductors at low temperatures and high magnetic fields (which could perhaps exceed their upper critical fields)
  2. Magnetic field driven changes in structures of multiferroic materials such as BiFeO$_3$
  3. Surface studies of magnetostrictive materials for device applications
  4. Magnetic field driven phase transitions in materials such as charge ordered oxides and heavy fermion materials
Some areas of interest

Scanning tunneling spectra taken at different temperatures on BSCCO (Pasupathy et al., Science 320, 196 (2008)). The transition from SC to normal state can be studied as a function of B as opposed to T with an STM in high magnetic fields similar to the point contact data on PCCO shown below (Yun et al., arXiv:0712.1614):

Piezoelectric force microscopy image of BiFeO3 showing the polarization domains (Zhao et al., Nature Materials 5, 823 (2006)). Behavior of such domains in high magnetic fields could reveal critical information about the origin of multiferroism in BiFeO3 and related materials.
Feasibility of project at the NHMFL

- The availability of world leading high magnetic field technology
- Recent developments in high magnetic fields (~30 T) using superconductors as opposed to resistive magnets
- Existing technology and expertise at the NHMFL on low noise electronics and low mechanical vibration environments
Feasibility of project at the NHMFL

- Existing scanning probe microscope designs can conform to the requirements of the new NHMFL magnets e.g. the heart of the SPMs, the coarse approach mechanism, is usually made of non-magnetic materials such as MACOR and can be designed to fit the constraints of the magnet boresize.

A 1.5 inch diameter coarse approach mechanism for a low temperature STM (http://www.phys.ufl.edu/~amlan/ltstm.html). Such a mechanism could be reduced in size to fit the high magnetic field bores.
Semiconductor Optics in High Magnetic Fields
C. J. Stanton

Optics + High Magnetic Fields is a powerful tool for probing semiconductor nanostructures.

Provides information on:
1. Conduction and Valence Band Electronic States.
2. Spin-splitting.
3. Effects of Quantum Confinement
4. Effects of Dimensionality
5. Effects of Strain.
6. Compare different growth techniques. (MBE vs. MOVPE).

Experimental Techniques:
2. Magneto-absorption
3. Magnetic Circular Dichroism (MCD)
4. Optically Pumped NMR (OPNMR)

Time Resolved Optical Techniques provide further information on:
1. Carrier Dynamics
2. Spin Dynamics
3. Many-body interactions.

Collaborations:
1. Jun Kono Group. Rice University
2. Mike Santos Group. University of Oklahoma
5. Russ Bower Group. University of Florida

NHMFL Collaborators:
1. Steve McGill
2. Yong-Jie Wang
3. Young-Dahl Jho
4. Scott Crooker
5. Arneil Reyes
6. Phil Kuhns
Spin-Split bands in Semiconductors

**DMS = Host Semiconductor + Magnetic Impurities**

Examples: CdMnTe (II-VI), InMnAs (III-V)

- DMS Large g-factors Spin Polarized Electrons and Holes

**Spintronics**

Large g-factor comes from alignment of spins of magnetic ions.

Exchange interaction of Mn ions and electrons/holes enhances spin splitting.

- How accurately can we measure spin-split band structure?
  - Cyclotron Resonance, Magneto-absorption, Optically Pumped NMR

- How accurately can we calculate spin-split band structure?
  - Needed for device modeling.

**Systems:** InMnAs (CB, VB), InSb (CB, VB), GaAs (VB)

- g \( \square \) 100
- g \( \square \) - 50
- g \( \square \) - 0.5
High Field Cyclotron Resonance

- Megagauss Laboratory, Univ. of Tokyo
- High B fields needed due to low mobilities in doped samples.
- Narrow Gap, Dilute Magnetic Semiconductors: InMnAs, InMnSb

- NHMFL - Los Alamos: Graphene
Simulation of CR Spectra

8-band $k \cdot p$ method; $J_{pd}$ and finite $k_z$ effects are included + Fermi’s golden rule

InMnAs

High Field CR can be used to investigate small band splittings and changes with doping.
**CR in Graphene**

\[ H = \hbar c^* \mathbf{\sigma} \cdot \left( \frac{h \nabla}{i} + \frac{e A_B}{\hbar c} \right) \Rightarrow E_{n,\pm} = \pm \gamma \sqrt{n} \]

where \[ \gamma = \frac{\sqrt{2} c^* h}{l_B}, \quad n = 0, 1, 2, K \]

Unusual results for Graphene:

1. \[ E_{n,\pm} : \sqrt{n}, \quad n = 0, 1, 2, \ldots \]
2. There is an \( n=0 \) Landau Level.
3. \[ E : \sqrt{B} \]
4. Get both e-active, and h-active CR.

\[ \Psi_{n,\pm}(x, y) : \begin{pmatrix} \Phi_{n-1,k} \\ \pm i \Phi_{n,k} \end{pmatrix} \]
In the annealed sample, CR is seen for both e-active and h-active!

Can accurately measure Fermi level (non-contact).
InSb – Narrow Gap

$g_{el} \sim -50$

Conduction Bands

Valence Bands

Santos Group - Oklahoma

VB to CB Magneto-absorption

7.4 T

6 T

a) experiment

b) theory – (unstrained)

unstrained

---

Santos Group - Oklahoma
InSb – Narrow Gap

g_{el} \sim -50

VB to CB Magneto-absorption

Conduction Band spin-splitting

Strained

Santos Group - Oklahoma
Optically Pumped NMR (OPNMR)

OPNMR measures **transfer of electron spin to nuclei**.

Signal depends on the **sign** of the polarization.

\[ P = \frac{n_{\uparrow} - n_{\downarrow}}{n_{\uparrow} + n_{\downarrow}} \]

*PCCP* Physical Chemistry Chemical Physics

**PCCP, 11, 7031 (2009)**

**lh transitions dominate structure.**

OPNMR is sensitive to Spin Polarization.

Hayes Group, Wash. U.
Separation of Spin-Up and Spin-Down Absorption

Spin-split valence bands GaAs

\[ \alpha : n_{\uparrow} + n_{\downarrow} \]

\[ P = \frac{(n_{\uparrow} - n_{\downarrow})}{(n_{\uparrow} + n_{\downarrow})} \]

Left circularly polarized absorption at the magnetic field of 7T
Change magnetism by changing the **radial position** of the Mn ion in the dot. This changes the sp-d exchange interaction between electrons and holes in the dot and the Mn ions.

Can tune the spin-splitting and g-factors in these materials.
Effective g factors vs Mn Doping Radius

Effective g factors calculated for 1, 2 and 4 Mn impurity atoms

$$\Delta E = 2 J g \mu_B B$$

$J = 3/2$ for HH

$J = 1/2$ for CB, LH

25 A CdS core

25 A ZnS shell
\[ \omega_c = \frac{eB}{mc}; \quad R_c = \frac{v_F}{\omega_c}; \quad I_B = \sqrt{\frac{\hbar c}{eB}} \]
\[ \omega_c \tau \sim \frac{l}{R_c} \]

Classical magnetoresistance, dHvA-ShdH

\[ \frac{\phi_c}{k_B T} \]

Ultra-quantum limit and beyond

\[ \frac{\phi_c}{E_F} \sim k_F^2 \frac{2}{B} \]

\[ L_\phi \text{ (phase breaking length)} \]

Phase-coherent phenomena
Life beyond the (ultra-quantum) limit:
field-induced phases

$$\frac{\phi_c}{E_F} \sim k_F^2 |B| E_F > 1$$
Abstract
It is shown that a strong magnetic field applied to a bulk metal induces a Luttinger-liquid phase. This phase is characterized by the zero-bias anomaly in tunneling: the tunneling conductance scales as a power law of voltage or temperature. The tunneling exponent increases with the magnetic field as $B \ln B$. 
Bi @ T=25 mK

Bompadre, Biagini, Maslov, and Hebard, Phys. Rev. B64, 073103
Signatures of Electron Fractionalization in Ultraquantum Bismuth

Kamran Behnia,¹ Luis Balicas,² Yakov Kopelevich³

SCIENCE  VOL 317  21 SEPTEMBER 2007  1729

\[ B \parallel \text{trigonal} \]
\[ I \parallel \text{bisectrix} \]
\[ T=0.44 \text{ K} \]
Two Phase Transitions Induced by a Magnetic Field in Graphite

Benoît Fauqué, David LeBoeuf, Baptiste Vignolle, Marc Nardone, Cyril Proust, and Kamran Behnia

1LPEM (UPMC-CNRS), Ecole Supérieure de Physique et de Chimie Industrielles, 75005 Paris, France
2Laboratoire National des Champs Magnétiques Intenses (CNRS-INSU-UJF-UPS), 31400 Toulouse, France

(Received 2 April 2013; published 25 June 2013)
3D Quantum Hall Effect in Hole-Doped Graphite

**Energy levels of bulk graphite (meV) in a 20 T field along the c-axis**


**Figure 2**: Dependence of carrier density on Br intercalation time extracted from Hall (bottom curve) and optical (top curve) measurements.
\[ \omega_c \tau \sim \frac{l}{R_c} > 1 \]

\[ \frac{\omega_c}{k_B T} > 1 \]

Classical magnetoresistance, dHvA-ShdH
How boring classical magnetoresistance can be?
\[ \rho(B) = \rho(0)(1 + \omega_c^2 \tau^2(\tau)) \propto \frac{1}{\tau(T)} + B^2 \tau(T) \]

phonons: \( 1/\tau \propto T \Rightarrow B^2 / T \) scaling

Fermi liquids? \( 1 / \tau \propto T^2 \) Has anyone seen \( B^2 / T^2 \) scaling of \( \rho \)?

Non-Fermi liquids Shorter times \( \Rightarrow \) stronger fields!

Wiedemann-Franz law (or its violation): much better seen for transverse components

\[ L_{xy} = \kappa_{xy} / T \sigma_{xy} \]
Do we understand the “tale of two times” in the cuprates?

\[ \rho \propto \frac{1}{\tau} \propto T \]

\[ \cot \theta = \frac{\sigma_{xx}}{\sigma_{xy}} \propto \frac{1}{\tau} \]

**FIG. 9.** Inverse Hall angle \((\cot \Theta_H)\) calculated from the data in Figs. 3 and 7. The gradient of the \(T^2\) plot decreases as \(\delta\) is increased. As in Fig. 7 the solid lines show data for two single crystals of YBa\(_2\)Cu\(_3\)O\(_{7-\delta}\).
Why linear magnetoresistance is so ubiquitous?

Graphite
Graphene
Topological insulators...

Bi @ T=25 mK

Bompadre, Biagini, Maslov, and Hebard, Phys. Rev. B64, 073103
Why parallel magnetoresistance is so strong?

Synopsis: What would Lorentz say?
Necessary and sufficient condition for longitudinal magnetoresistance

Band structure: few % (up to 10%)
Graphite: enormous parallel magnetoresistance ($B$ along $I$ along $c$-axi)
Have we seen any marked deviations from the Lifshitz-Kosevich formula near quantum critical points?
Phase coherent phenomena
Have we seen any signatures of phase coherence in strongly correlated materials?
Claim: all we know about electron-electron interactions in “good” metals comes from phase-coherent effects: weak (anti) localization and Altshuler-Aronov effect. In bad metals, we are still measuring the “Drude” conductivity

\[ L_\phi = \sqrt{D \tau_\phi} \propto 1 / \sqrt{T} \]

Challenge: shorter phase-breaking lengths \( \rightarrow \) stronger fields
Challenge: universal conductance fluctuations in bad metals

What a mesoscopic sample of a bad metal would show?
Challenge: high-temperature weak localization

Common wisdom: weak localization is a low temperature phenomenon.

Electron–impurity scattering forms a trajectory. Electron-electron interaction breaks the phase

$$\delta \sigma : -\frac{e^2}{h} \ln \frac{\tau_\phi}{\tau}$$
Classical bosons: $N_{ph} \sim \frac{T}{\omega}$

$\rho = \text{const: defects}$

$\rho \propto T$: phonons above the Debye temperature

$\rho = AT^2 + CT^5$
Scattering on phonons in the classical regime ($T > T_D$) is elastic.

Momentum relaxation: fast.

Energy and phase relaxation: slow (energy diffusion).

Typical $k$ of phonons: $k \sim k_D \sim k_F$

$$\tau \sim T^{-1}$$

$$\delta \sigma : -\frac{e^2}{h} \ln \frac{\tau \phi}{\tau} \sim -\frac{2}{3} \frac{e^2}{h} \ln \frac{T}{T_D}$$

$$L_\phi = \sqrt{D \tau \phi} \sim l_B$$

Quantum magnetoresistance at high $T$ the same as at low $T$

On the absolute scale, $L_\phi$ is short!

Introduction

Selman Hershey, University of Florida

Transverse Thermoelectrics

However, they estimate that power densities as high as 10 kW can be achieved in a 1 m³ volume.

To date they have only created a 1 cm long such tube, which produces 1.3 W and 10°C thermal reservoirs.

The idea is that by partially converting into electrical energy, the tube could be used as an annoucement Dl9ram of a thermoelectric conversion tube in which energy from a car's internal combustion engine ends up losses in a waste heat (7). The goal of this four-year project is to develop a thermoelectric prototype that can increase the fuel economy of a vehicle by 5%. These have been used to recover heat from automobile's [6] as much as 75% of the energy generated by a thermoelectricity to recover heat from automobile's [6] as much as 75% of the energy generated by a vehicle's internal combustion engine.

Recently, people are also very interested in using thermoelectric devices to harness waste or excess heat. At the APS March meeting in 2014, there was a presentation about efforts at General Motors to harness waste or excess heat. The silicon diodes measured in the quantum limit in graphene [5] has also been measured in the quantum limit in graphene [5] has also been measured in the quantum limit in graphene [5].

There are many examples of interesting thermoelectric phenomena in magnetic fields. For example, the quantum Hall effect has been measured in graphene [5]. The Quantum Hall effect is a quantum mechanical effect that occurs in two-dimensional systems of quantum Hall effect [2,3]. The Quantum Hall effect is a quantum mechanical effect that occurs in two-dimensional systems of quantum Hall effect [2,3].

The study of thermoelectric phenomena at high magnetic fields has been an important part of the basic science studies at the NHMFL. As an example, if a thermal gradient is applied perpendicular to a magnetic field, then an electric field will develop perpendicular to the both important parallel and the magnetic field. This is the first quantum-thermal conversion effect usually referred to as the Hall effect. It was discovered while studying the Hall effect in disordered systems.
ideal place to study transverse thermoelectric devices.

Thus, the NHMF is the thermal generator and the resulting current are in perpendicular directions. The Neumann Effect is an example of transverse thermoelectric effect. The materials are easy to make. The Neumann Effect is in contrast to a large magnetic field transverse thermoelectric

![Figure 2: A transverse thermoelectric device created by laying two different materials](image)

reduces the performance of this device by a factor of 10. A traditional longitudinal device experiencing the same flow and current conditions produces a lower efficiency by a factor of 10. A transverse device will often increase the area by a factor of 10 than increases the efficiency. As the transverse device takes the difference of the heat flow and current condition area, it provides the area to range between the hot and cold regions and the transverse element. A combination of these devices is critical because of the need to only allow current between these two states. The power output is not only proportional to the efficiency, but also in the conductive area between the hot and cold regions.

In traditional thermoelectric, heat flow and current flowing through the material is perpendicular to one another, which means that one would need a much hotter and colder region to generate any power. In a car, for application power output is the most important parameter as the Cameron limit is reached, and current or thermal gradient may produce zero power. In contrast, the NHMF can provide high power outputs faster and more efficiently, as there are some theoretical models which approximate the practice one in a number of real-world examples. These are some theoretical models which appear to be beneficial to the developer. As the transverse device is in the same direction, the thermal gradient and the current carry the current.

In a transverse thermoelectric, heat flow and current flowing through the material is parallel to one another. This means that one would need a more efficient field to generate more power. In contrast, the NHMF can provide high power outputs faster and more efficiently, as there are some theoretical models which approximate the practice one in a number of real-world examples. These are some theoretical models which appear to be beneficial to the developer. As the transverse device is in the same direction, the thermal gradient and the current carry the current.

Creating transverse thermoelectric devices is a challenging task. However, a very important connection because of the challenge to create transverse thermoelectric devices.

Relevance for the NHMF
These have still not been optimized for use in a magnetic field. A discussion of the advantages of using transverse thermoelectric coolers (Finnis and Hauser) contains a brief review of transverse thermoelectric coolers. There is an excellent review article by Albert T. K. Miller that transverse thermoelectric cooling device. Here, I discuss models predicting the possibility for cooling large amounts of refrigerant at low temperature. Key models are provided, showing the potential for transverse thermoelectric cooling. These materials can work at cryogenic temperatures, because of their simplicity they can also in principle be made quite small.

Another potential application of transverse thermoelectric is for cooking. These materials can work at cryogenic temperatures, because of their simplicity they can also in principle be made quite small.

How the thermoelectric material is wound around the cylinder depends on the geometry for a transverse thermoelectric generator in a magnetic field. The hot and cold material is wound around the cylinder, shown below. The current flow around the wire with the direction determined by how the thermoelectric generator is connected. In the case of the generator, there is a large current cost for the magnetic field. A large current cost for the magnetic field is the cost of electricity. Much of the electricity used to create an axo magnetic field. However, the use of other potential benefits for the NHEC.

**Figure 3:** Geometry for a transverse thermoelectric generator in a magnetic field. The hot and cold material is wound around the cylinder. The current flow around the wire with the direction determined by how the thermoelectric generator is connected. In the case of the generator, there is a large current cost for the magnetic field. A large current cost for the magnetic field is the cost of electricity. Much of the electricity used to create an axo magnetic field. However, the use of other potential benefits for the NHEC.

**Additional benefits**

References:


“New Thrusts”: Materials Processing in High Magnetic Fields and Gradients
(comments by Mark Meisel, UF, who did not present any slides at the time

DOE ERFC  (Energy Frontier Research Center) Proposal submitted and pening.
“The Center for Extreme Magnetic Field Science”
PI: Ian Baker, Dartmouth College
CoPI: Gerald M. Ludtka, ORNL, and his group has a webpage:
(http://web.ornl.gov/sci/physical_sciences_directorate/mst/mpg/AP_magnetic.shtml

UF Part:
Michele Manuel, UF MSE, http://www.mse.ufl.edu/people/mse-faculty/michele-manuel/
Jennifer Andrew, UF MSE, http://www.mse.ufl.edu/people/mse-faculty/jennifer-andrew/
(Jennifer Andrew was in attendance for this discussion.)
Mark Meisel, UF Physics and NHMFL (only NHMFL person involved as Co-PI)

Comment: “Materials Processing” in US, Japan, and Europe should be considered for PPHMF-2015 as the next generation of HTC magnets are being planned.
“Biophysics/Bioengineering Discussion
(comments by Mark Meisel, UF, who did not present any slides at the time

UF Physics:
Steve Hagen is only full-time, funded faculty member in biological physics. 
http://www.phys.ufl.edu/~hagen/

Steve was in Europe, but his thoughts about thinking beyond the present confines involved improved central facilities, as communicated by Meisel. Joanna Long commented that such facilities were located near the AMRIS site. The issue of having more access to a confocal microscope was picked by Carlos Rinaldi, UF BME, http://www.bme.ufl.edu/people/rinaldi_carlos, who was present. Carlos has the idea of adding nonstandard adaptors to a confocal microscopic for imaging magnetic nanoparticles. Also attending was Jon Dobson, UF BME, http://www.bme.ufl.edu/people/dobson_jon

Ultimately, the point was made that these needs may not be directly related to making next generation high magnetic fields available to users. However, these points serve as points of conversation. The conversation involved the microscopy facilities at NHMFL.

Finally, when Alex Angerhofer was describing a nanoliter EPR coil assembly, the point was made that assembly facilities would be needed by eventual users.
SEARCH FOR AXIONS (COLD DARK MATTER) --- High B, Low T, ultra-quiet

Leading question(s) in Astrophysics/Cosmology today: \textit{origin and composition of dark matter and dark energy}

**Dark Matter** -- must be non-baryonic, cold (non-relativistic)

\textit{responsible for anomalous rotation curves of matter in galaxies, motions of galaxy clusters, lensing….}

**Axions** (originally postulated to solve strong CP problem in strong interactions)

\textit{born cold in early universe, should exist as halos around galaxies, mass \sim 10-1000 \mu eV}

\textit{-- possible to detect expected abundance in lab. experiments}

Milky Way axions can be detected by \textbf{Sikivie method}:

\textit{decay in a strong B field via Primakoff effect to microwave photons pioneered at UF and BNL, now at Seattle with multi-university collaborations}

\begin{itemize}
  \item microwave photon (Detect with high Q microwave cavity)
\end{itemize}

For $B = 7T$, $V = 500 \text{ L}$, $m \sim 2 \text{ GHz}$, all DM=axions, $Q \sim 10^5$

\begin{itemize}
  \item Power emitted \quad $P \sim 10^{-21} \text{ W}$
\end{itemize}
AXION Magnet: Search for Dark Matter

Potential MagLab Involvement
Develop higher-field, larger-volume persistent magnet

Existing Detector at U. of Wash.

Baffling
Bucking Magnet
SQUID
“1K”Pot
Microwave Cavity
Main Magnet
8 Tesla
600 mm Bore
13 ton

ADMX Achieved and Projected Sensitivity

Cavity Frequency (GHz)

ADMX Achieved and Projected Sensitivity

Axion Coupling $g_{aY}$ (GeV$^{-1}$)

Too Much Dark Matter
ADMX Published Limits
ADMX M1
ADMX M2
ADMX HF

Non RF-cavity Techniques

White Dwarf and Supernova Bounds

Axion Cold Dark Matter

Warm Dark Matter

“Hadronic” Coupling

Minimum Coupling

Axion Mass (μeV)

4/25/2014 Sullivan Strategic Planning  UF  4-24-2014

ADMX, U. Wash, UF, LLNL, Berkeley

High Q Cu cavity

Superheterodyne receiver


**FUTURE**

- Need High \( B^2V \)
  
  \( B \sim 25 \text{ T}, V \text{ same (500 l)}, \text{ improve sensitivity by factor of 12} \)
  
  must maintain ultra-quiet environment

- Lower noise \( T \), current limit is physical \( T \)
  
  need to cool with dil fridge (planned 2015 +)
  
  quantum noise limit \( \sim 50 \text{ mK} \) (close J. Clarke *et al.*)

---

**Solenoids Present & Future, Mark Bird 2014**

<table>
<thead>
<tr>
<th>( B^2V ) (T^2m^3)</th>
<th>( B^4 ) (kT^4)</th>
<th>Magnet</th>
<th>Application/ Technology</th>
<th>Location</th>
<th>Field (T)</th>
<th>Bore (m)</th>
<th>Len (m^3)</th>
<th>Energy (MJ)</th>
<th>Cost ($M)</th>
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<td>2660</td>
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<td>7</td>
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<td>Fusion/Ti Mono Ventilated</td>
<td>Cadarache</td>
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<td>160</td>
<td>20 T, 1m</td>
<td>Axion/HTS CIC</td>
<td>?</td>
<td>20</td>
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<td>2</td>
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<td>Cadarache</td>
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<td>MRI/Mono Pers</td>
<td>Minnesota</td>
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<td>8</td>
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<td>MRI/Mono Pers</td>
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</table>

CICC = Cable-In-Conduit Conductor
SRC = Stabilized Rutherford-Cable
Mono = Monolithic Conductor
Pers = persistent
Ti = NbTi, Sn = Nb\(_3\)Sn

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