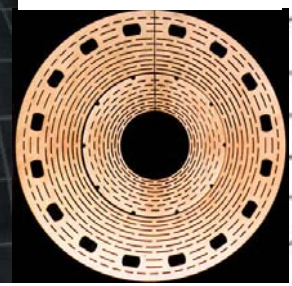
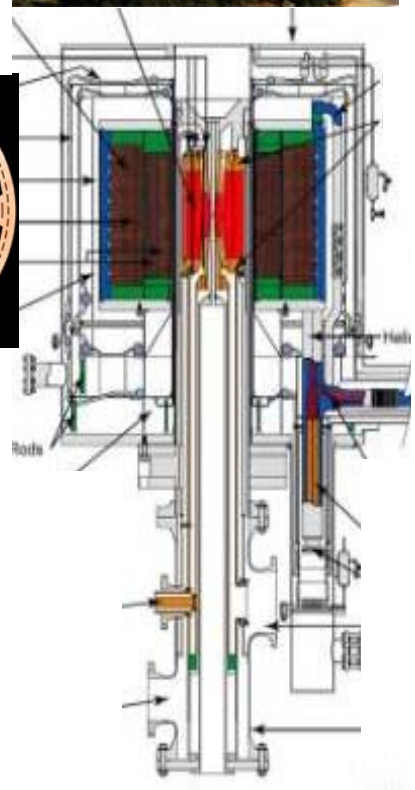
To request magnet time: www.magnet.fsu.edu

National High Magnetic Field Laboratory

Florida State University

33T Florida Bitter Magnet

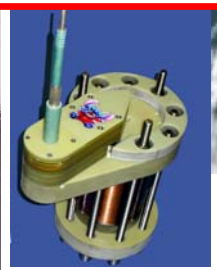




45T Hybrid Magnet

Los Alamos National Laboratory

65T Pulse Magnet
15mm bore



University of Florida

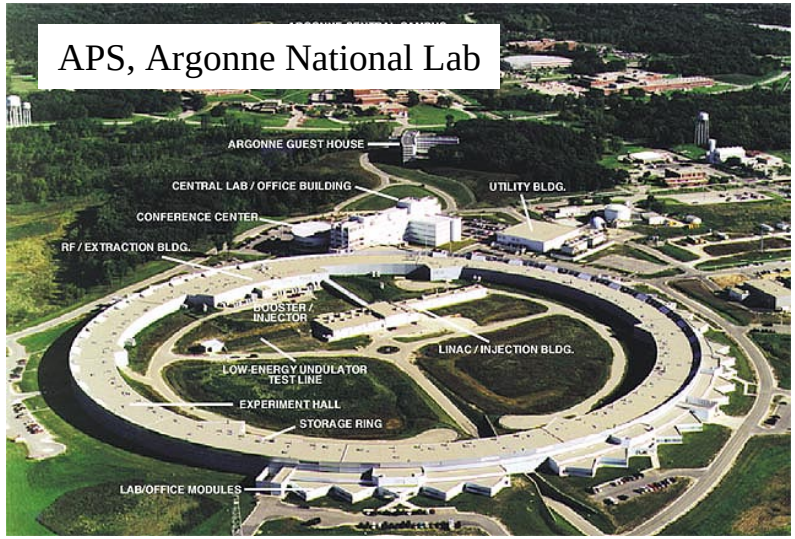
Advanced Magnetic Resonance Imaging and Spectroscopy Facility

11.4T MRI Magnet
400mm warm bore

High B/T Facility
17T, 6wks at 1mK

Magnets at Light Sources: Synchrotrons and Free-Electron Lasers

0.1–100 nm	X-ray/VUV photons
100 psec	pulse widths
1-10 MHz	pulse rep rate
1–10 micron	focused beam diameter
10^8	photons per pulse



COPPER MICROCOIL
(50 micron I.D.
150 micron O.D.
30 micron tall)

CLAIMS of 40T, 1Hz
10 nanosec pulse length
and "relatively simple"
to operate
BUT NO DATA

Might be able to design…
30T with 1kHz rep rate
few nanosecond pulse length
Only using 0.1% of X-rays

X-ray Free Electron Lasers	
10-100 fsec	pulse widths
10Hz -10kHz	pulse rep rate
10^{12}	photons per pulse

SINGLE-TURN COIL
10 mm I.D. 200T, 90% sample survival
5 mm I.D. 340T and sample goes away
1 microsec pulse length
and "relatively simple" to operate
PUBLISHED DATA

BEFORE

AFTER
1 microsec

Magnets at Neutron Sources and X-ray Sources

SPLIT-GAP MAGNETS

15-20 T/0.5 Hz	symmetric, pulsed		(KEK, Japan)
15 T/17.6*T	symmetric,	SC	(HMI, Germany)
14.5 T/17.1*T	symmetric,	SC	(HMI, Germany)
13T	asymmetric,	SC	(ILL, France)
11.5 T	symmetric,	SC	(NIST, USA)
11 T	asymmetric,	SC	(LANSCE, USA)
10 T	asymmetric,	SC	(JAERI, Japan)
9 T	symmetric,	SC	(NIST, USA)
7.5 T	symmetric,	SC	(ISIS, England)
7 T	asymmetric,	SC	(NIST, USA)
7 T	asymmetric,	SC	(HFIR, USA)

** increased field at the cost of sample volume, achieved with Nd pole pieces inserted into the gap*

SINGLE-SCATTERING-ANGLE MAGNET

(a conical holes for incoming and scattered neutrons)

20-25 T/0.5 Hz symmetric, pulsed (KEK, Japan)

VERTICAL MAGNETIC FIELD

(open angle in equatorial plane)

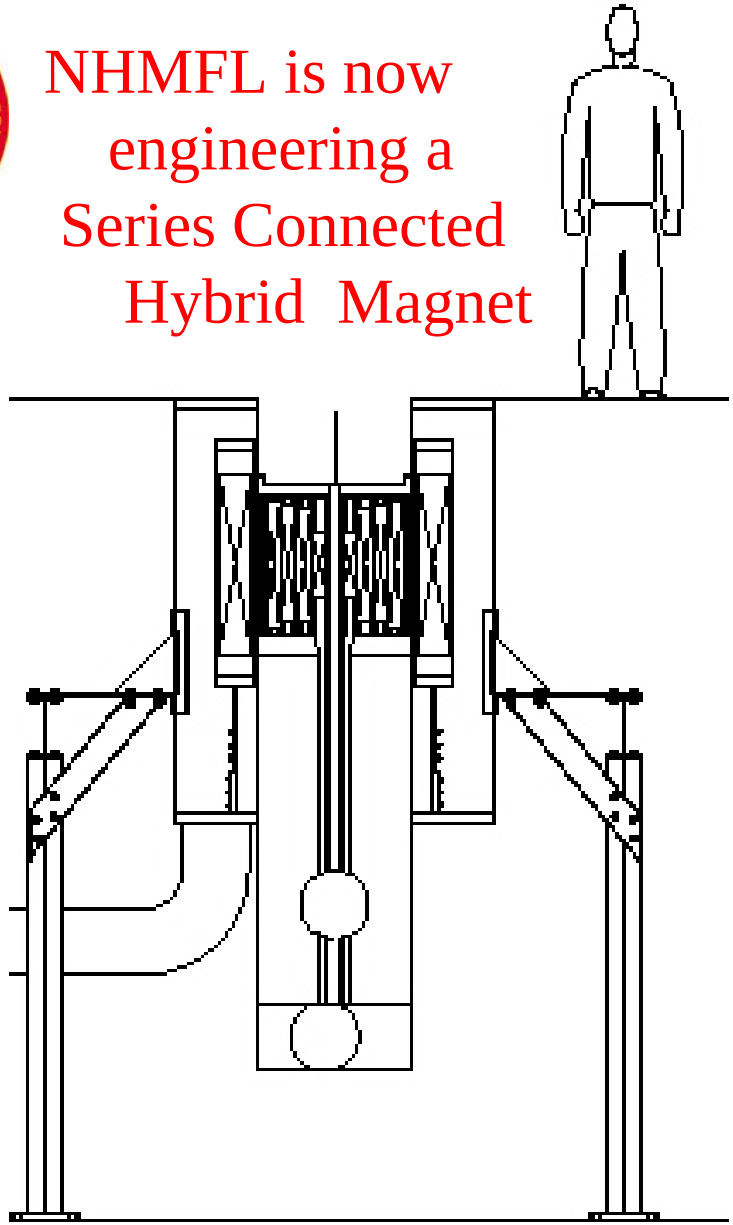
13 T	4x45°	(NSLS, BNL, USA)
13 T	4x45°	(APS, ANL, USA)
13 T		(SSRL, SLAC, USA)
13 T	4x45°	(ALS, LBL, USA)
10 T		(ESRF, Grenoble, France)

HORIZONTAL

10 T 6*10 mm (NSLS, BNL, USA)

There is an enormous scientific opportunity to the first neutron and X-ray facilities to integrate powered magnets into a beamline.

NHMFL is now engineering a Series Connected Hybrid Magnet



Connect a 20kA Resistive Magnet in series with a Superconducting Outsert Magnet

Magnet specifications

10 MW power consumption
35 T central field
40 mm clear bore
~ 1 ppm in 10mm DSV homogeneity

For experiments requiring
- high homogeneity
- high temporal stability
- long times at peak field

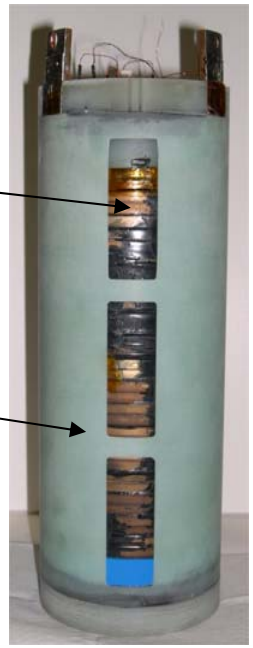
Engineering advantages
Reduced engineering for fault protection
~ 1/3 power of all-resistive magnet
Fits standard resistive-magnet cell

WHY PROPOSE A HYBRID MAGNET?

5 TESLA HIGH-Tc INSERT in 20 TESLA BACKGROUND

Bi-2212 conductor, reinforced with ZrO_2 - coated stainless steel tape

Thin-wall G-10 shell with circumferential openings at 120° for LHe cooling



A-unit (shown above) and B-unit: each a stack of 17 Bi-2212 double pancakes

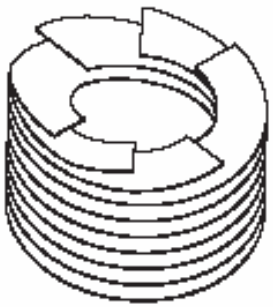
Complete 5 Tesla Insert with layer-wound C-unit

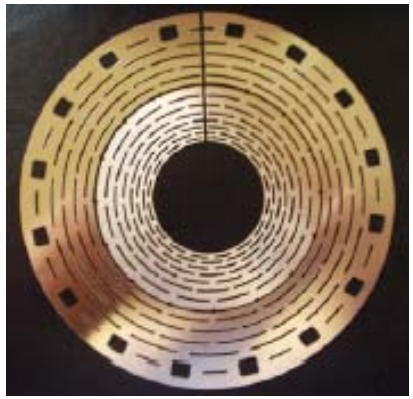
H.W. Weijers, U.P. Trociewitz, F. Trillaud, A. Mbaruku, P.V.S.S Sastry, Y.S. Hascicek, J. Schwartz, K. Marken, M. Meinesz, H. Miao, IEEE Trans. Appl. Supercond. 13, 1396 (2003)

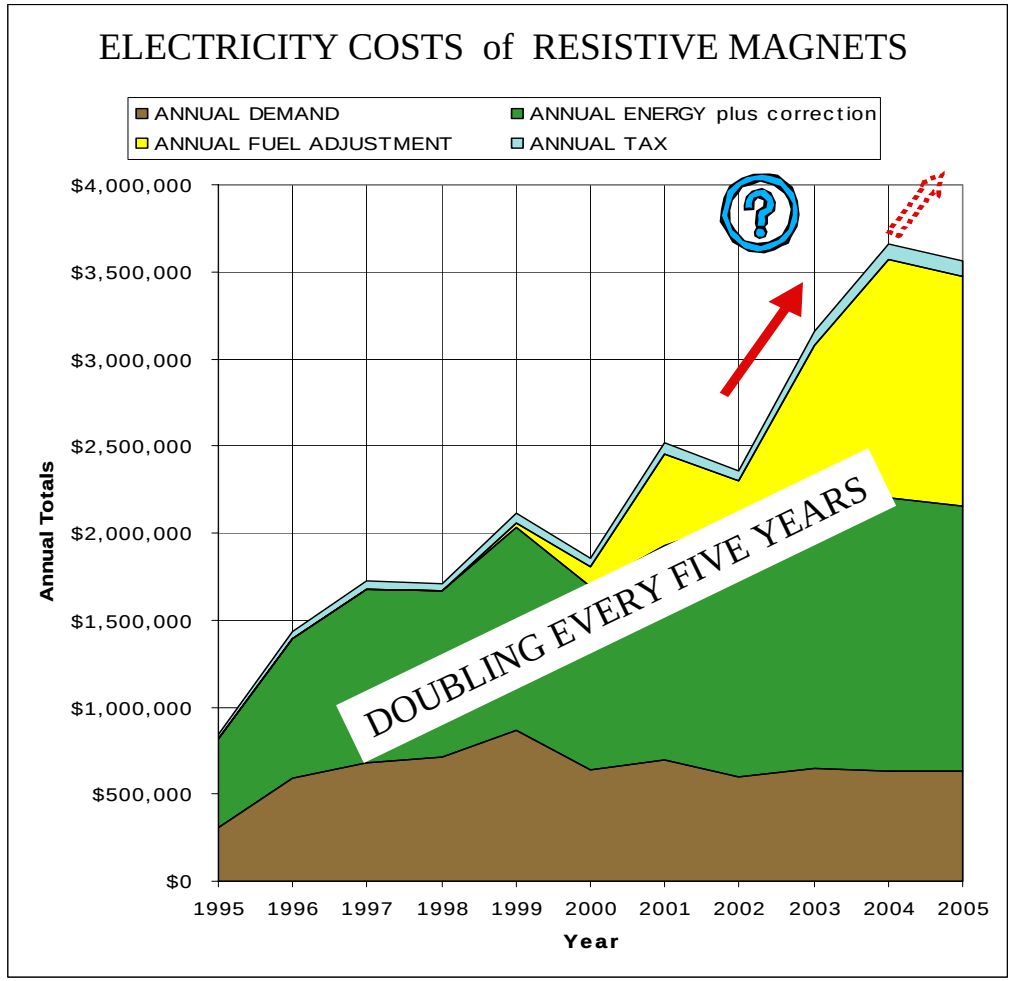
"Development of a 5 T HTS insert magnet as part of 25 T Class Magnets"

For applications at the APS, superconducting magnets would be a research project that would yield 17T-22T DC magnetic fields

WHY PROPOSE A HYBRID MAGNET?





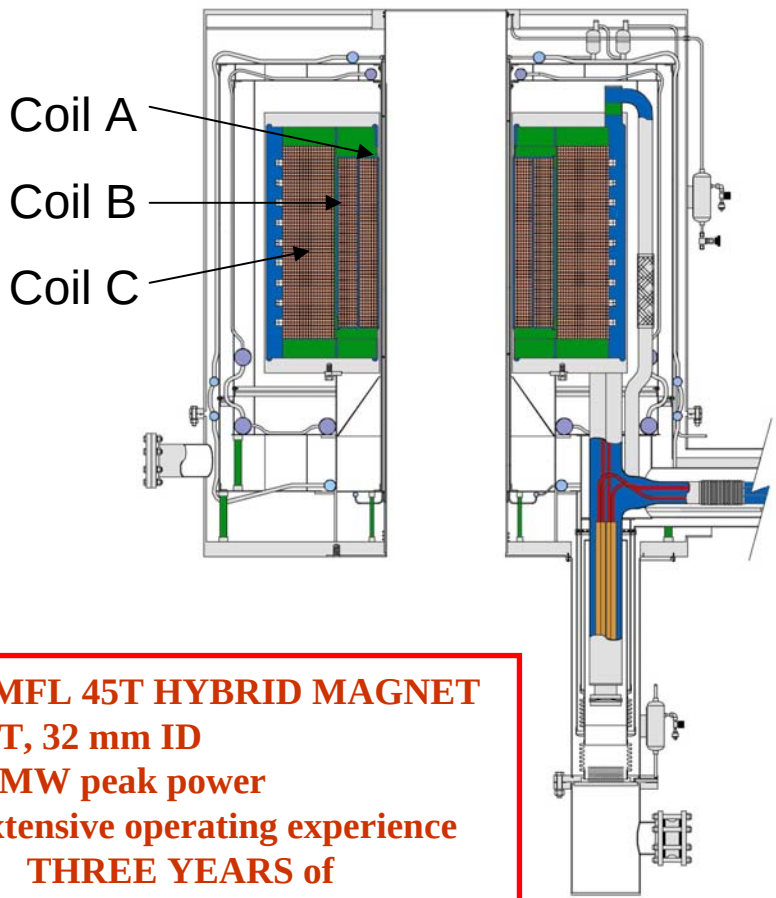


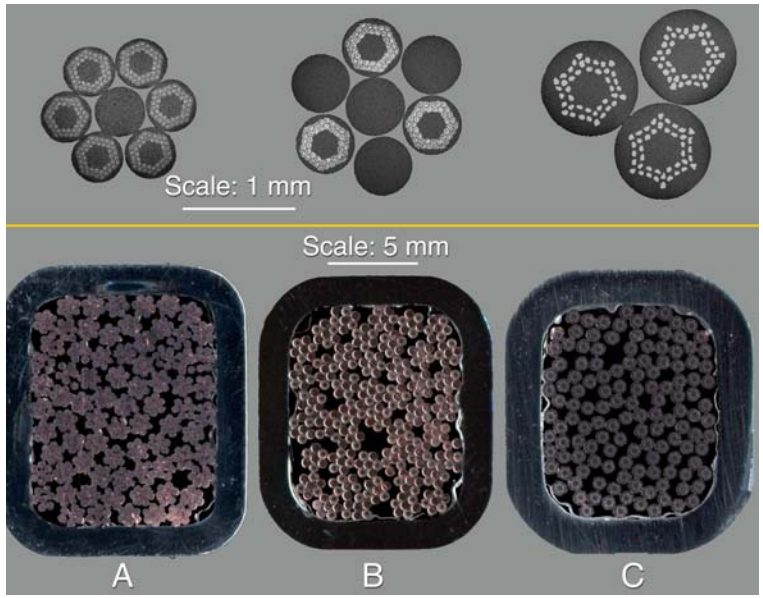
Actual costs at the NHMFL…
40MW power supply
Operated 16 hours a day
5 days a week
50 weeks a year
Average use over the operating time is only 17% of full 40MW capacity, due to users sweeping magnetic field, rather than sitting at full power.

…details of NHMFL contract with City of Tallahassee Power and Light are available upon request.

FLORIDA-BITTER RESISTIVE MAGNET
33T, 32 mm ID, 20MW peak power
Extensive operating experience
A DECADE of PUBLISHED DATA

NHMFL 45T HYBRID : MARRYING NHMFL SUPERCONDUCTING and RESISTIVE TECHNOLOGIES





Cu/Nb_3Sn Cu/Nb_3Sn Cu/NbTi

NHMFL 45T HYBRID MAGNET
45T, 32 mm ID
30MW peak power
Extensive operating experience
THREE YEARS of PUBLISHED DATA

CABLE-in-CONDUIT

Circulates superfluid liquid-He inside the conductor

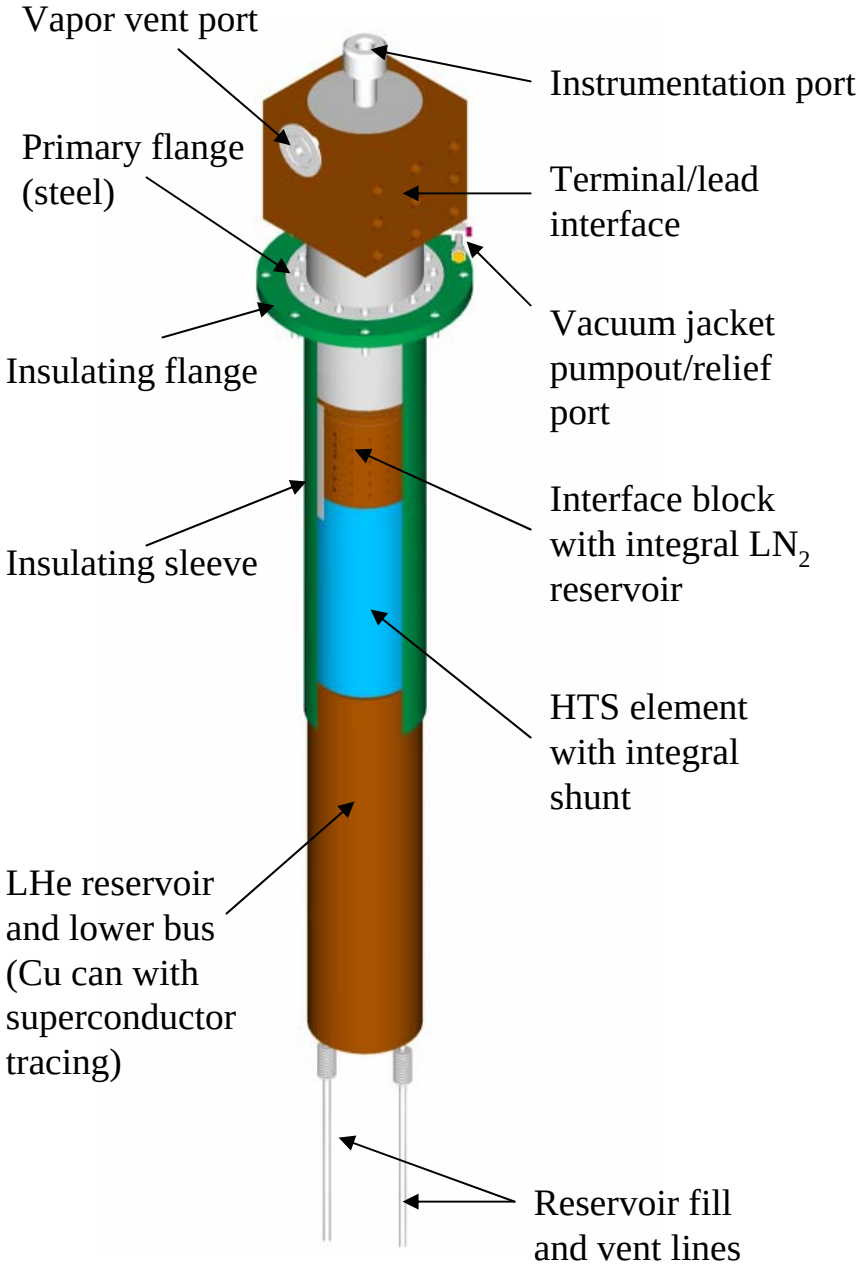
- Greater cooling of conductor
- Greater stability against quenches
- **ABILITY TO SCALE CONDUCTOR TO LARGER CROSS-SECTIONS**

NHMFL High Tc Current Lead

- Highly efficient
- Highly stable
- Rugged
- Safe
- Easily commercialized

HIGH Tc LEAD

Allows high current through superconducting coil and reduced helium losses due to Joule heating

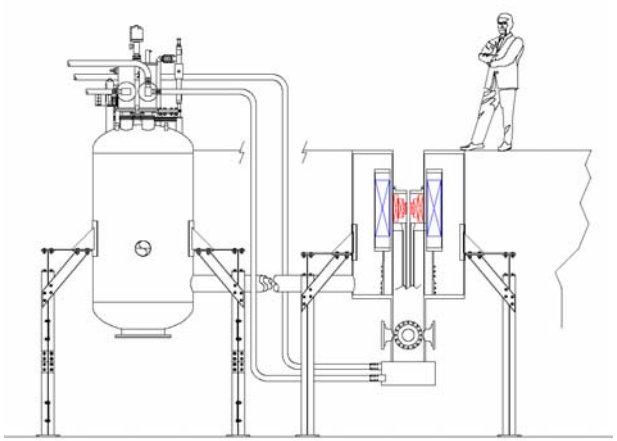


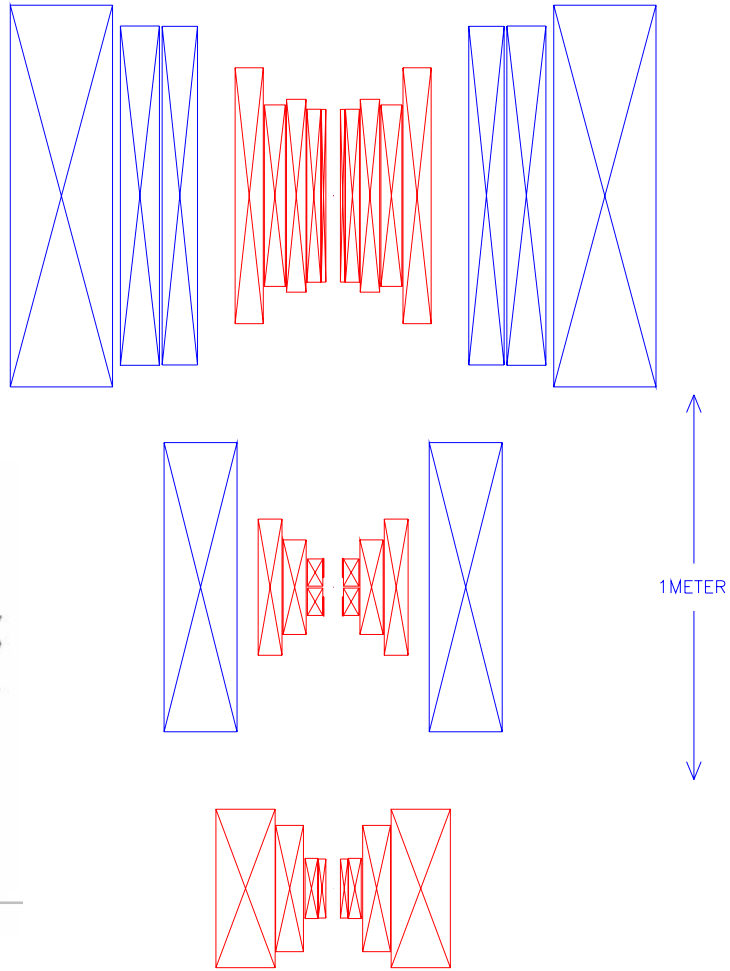
Cable-in-Conduit and High-Tc Current Leads enable a Series-Connected Hybrid design

Connect a 20kA Resistive Magnet

in series with

Superconducting Outsert Magnet





45-T Hybrid
32-mm bore
30 MW

SCH
35 T, High Homo
40-mm bore
10 MW

33-T All-Resistive
32-mm bore
20 MW

Comparison of General Features

Feature	45-T Hybrid	Series-Connected Hybrid
Maximum on-axis field – combined system, normal operation	45 T	37 T (35 T, high-homo.)
On-axis field contribution by the resistive insert	31 T	22.3 T
On-axis field contribution by the superconducting outsert	14 T	14.7 T
Winding-pack current density	44 A/mm^2 (max of 3 coils)	63 A/mm^2
Winding-envelope current density	37 A/mm^2	63 A/mm^2
Outsert stored energy	100 MJ	27 MJ
Total cold mass of the superconducting outsert (outsert windings, magnet vessel, in-vessel supports, buses, and cryogenic current leads)	14 t	2.7 t
Operating current	67 kA, insert 10 kA, outsert	20 kA, both
Insert power	4 supplies, 30 MW	1 supply, 10 MW
Superconductor choices	Nb_3Sn and NbTi, CICC, 3 grades, size and composition	Nb_3Sn, CICC, 3 grades, composition only

Note that the stored energy of the Series Connected Hybrid is about 1/4 that of the 45-T Hybrid
Cold mass is about 1/5 of the 45-T Hybrid
– both indicate significantly reduced cost relative to the 45-T Hybrid.

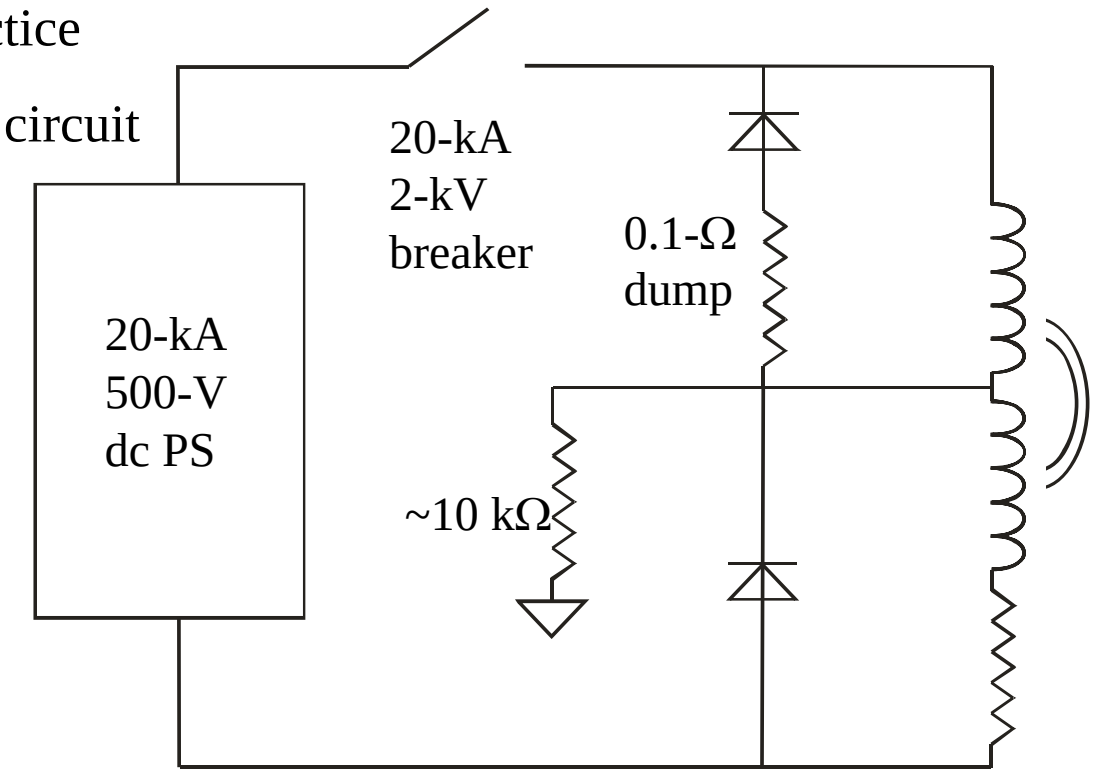
Resistive Magnet Insert Options for the benchmark design

Warm bore [mm]	Total on-axis field* [T] Homogeneity	Field contribution from insert [T]	Field contribution from outsert [T]	Comments
40	35 10^{-6} over 10 mm dsv	20.35	14.65	Cost-optimized outsert design for achieving 35 T and high homogeneity using an insert of 54 mm wet bore. Shims on the insert bore tube.
32	40 10^{-3} over 10 mm dsv	25.35	14.65	Same outsert as above. Standard insert and bore tube.
50	36 10^{-3} over 10 mm dsv	21.35	14.65	Same outsert as above. Standard insert and bore tube.
100	27 $20 \cdot 10^{-6}$ over 50 mm dsv.	12.35	14.65	Same outsert as above. Standard insert and bore tube.

Retain considerable flexibility to reconfigure resistive insert.

Why a single power-supply?

- At 20 kA, CICC dimensions still practical for winding outserts
- With 20-kA HTS leads, the cryogenic load actually reduced relative to the 45-T Hybrid
- 2 PSs in series would impose significantly higher turn-to-turn voltages than current practice
- Single breaker protection circuit

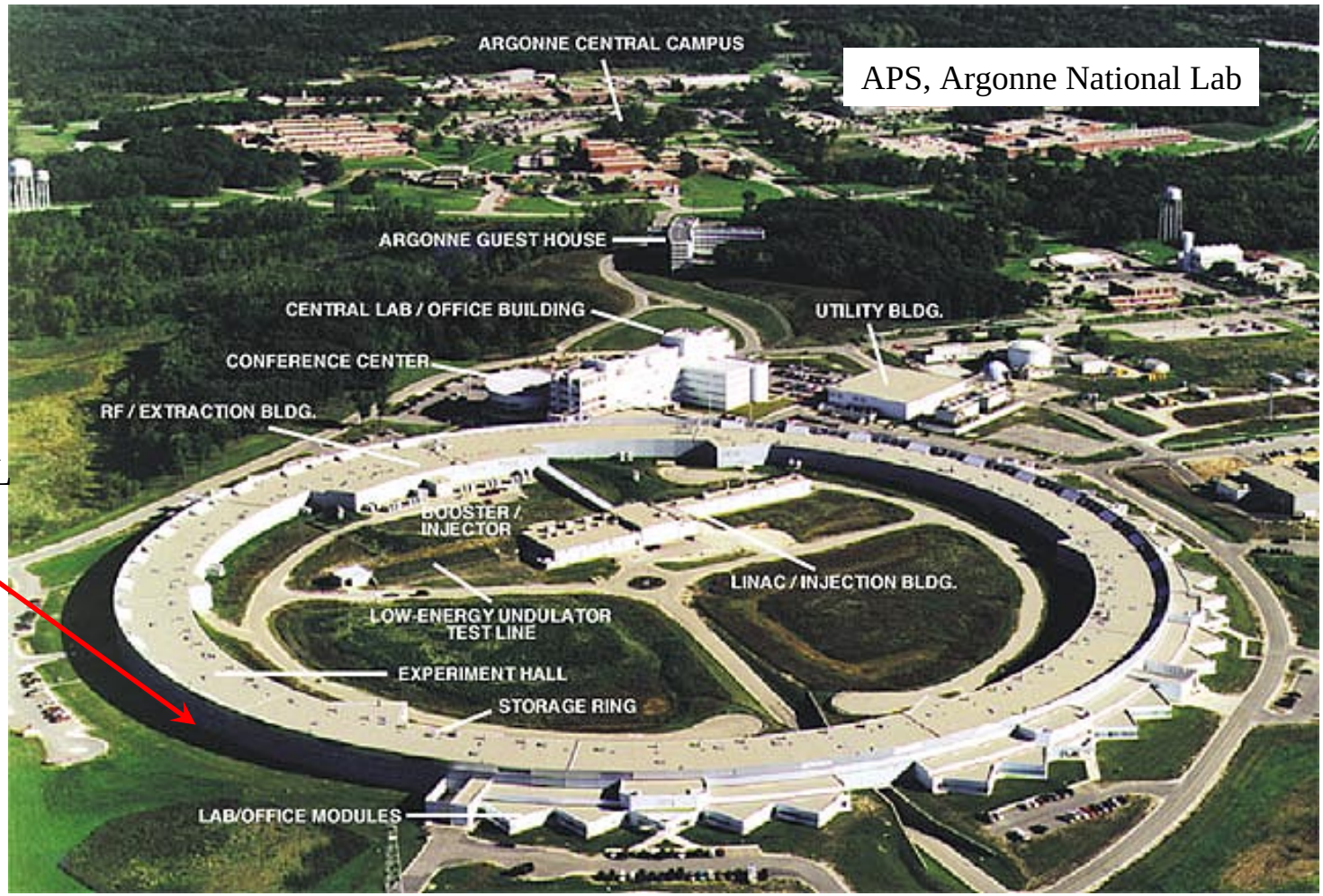


To request magnet time: www.magnet.fsu.edu

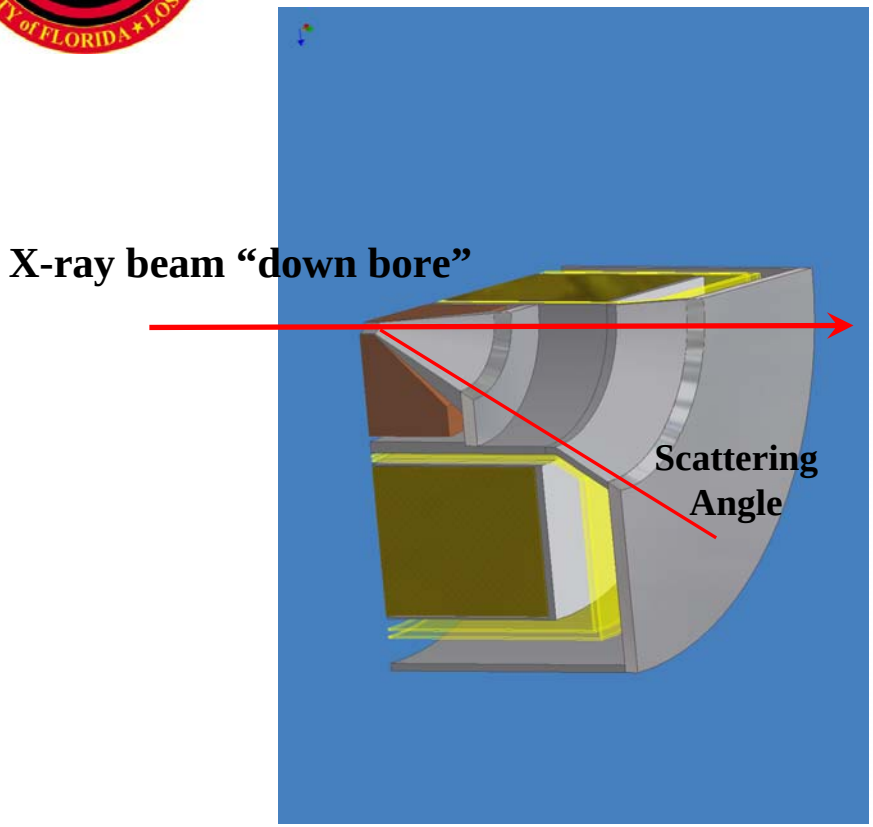
Magnet Beamline at the APS

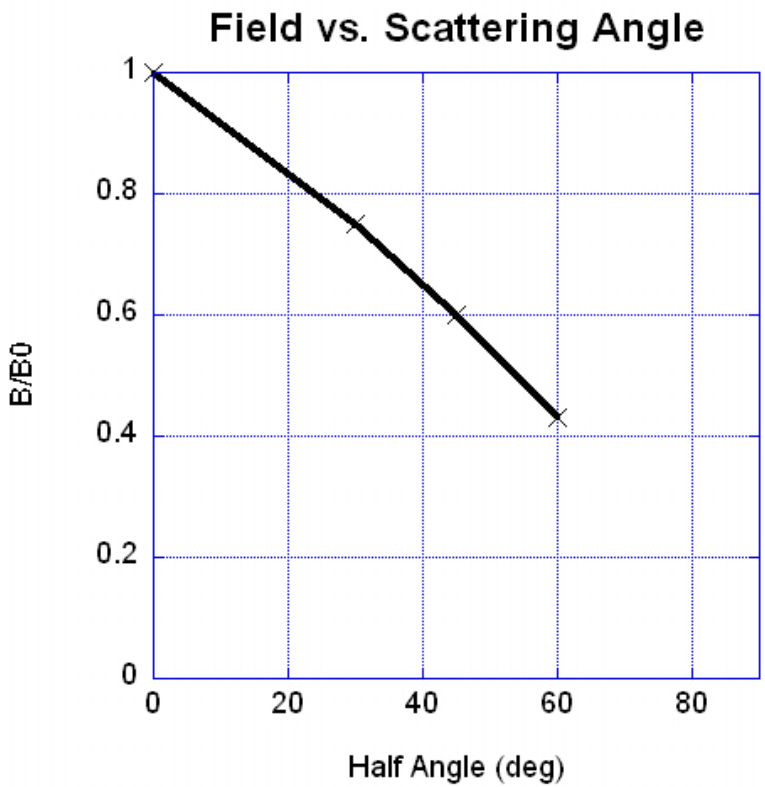
A fourth branch of the NHMFL at the APS

Possible location for APS/NHMFL DC magnet beam line(s).



Magnet Beamline at the APS: "Down-Bore" Magnet

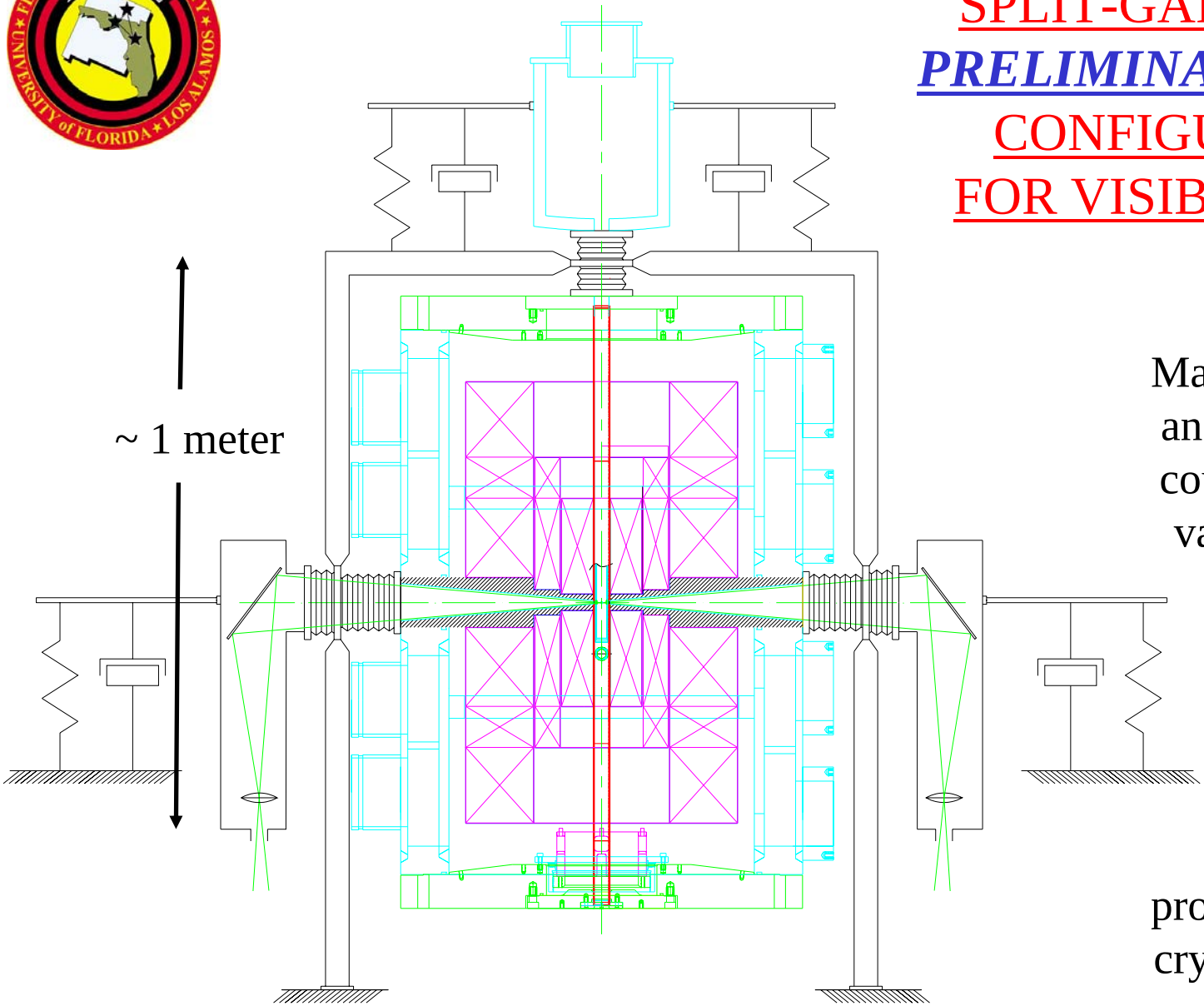




As the field for a 32 mm 10-MW SCH with a straight bore is ~ 40 T, the plot indicates the field w/ a 30 degree half angle might be as high as 30 T. Previously, HJSM & Eyssa performed a similar study for HMI and stated the field with 30 degree scattering angle would be around 23 T. This 7 T discrepancy provides some indication of how much speculation is incorporated in this plot.

The coils are reasonably well understood at this point. The main uncertainties are the housing, fault forces, structure, etc.
A few man-months on the design of such a system is required before publicly distributing firm field projections in Teslas.

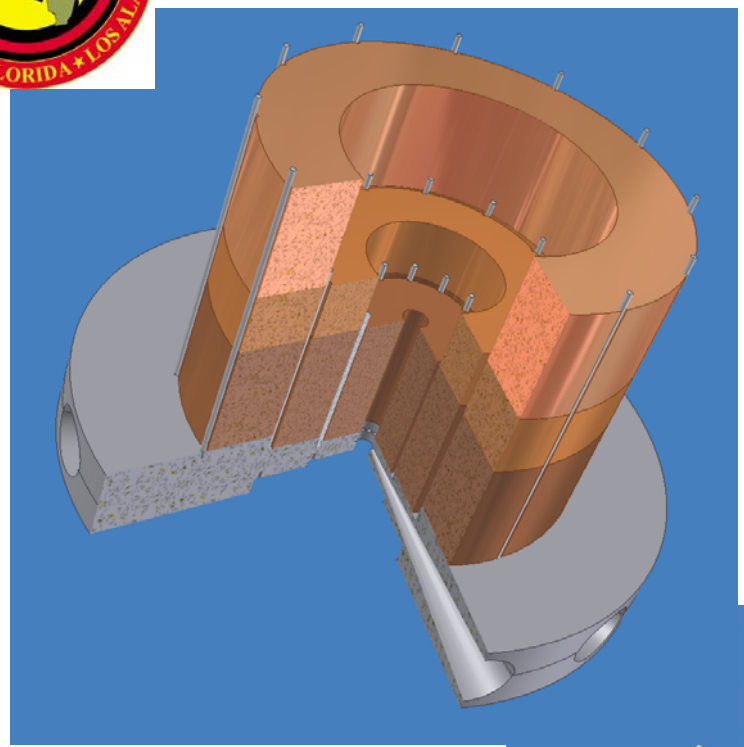
SPLIT-GAP MAGNET ***PRELIMINARY*** SYSTEM CONFIGURATION FOR VISIBLE OPTICS

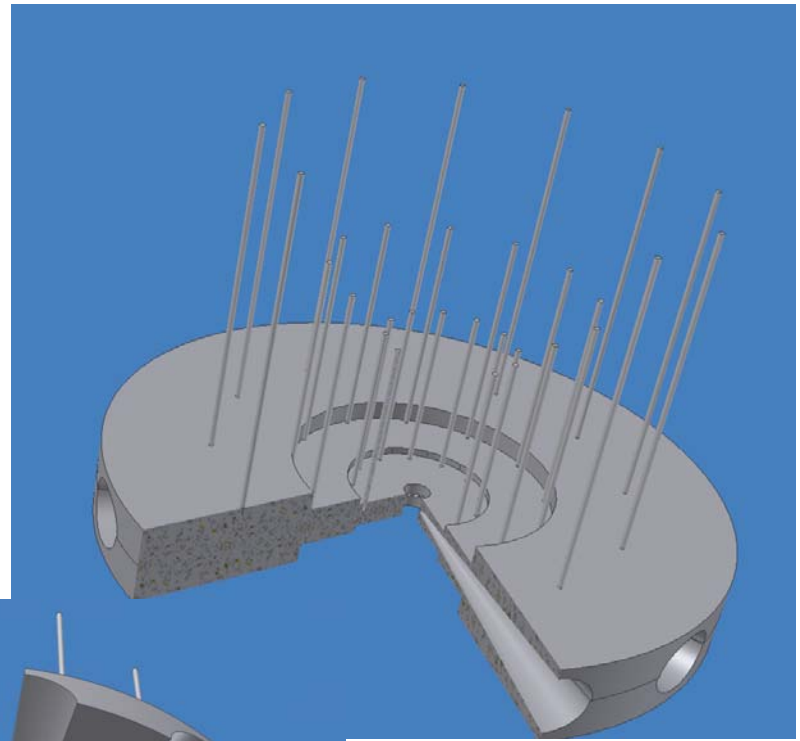


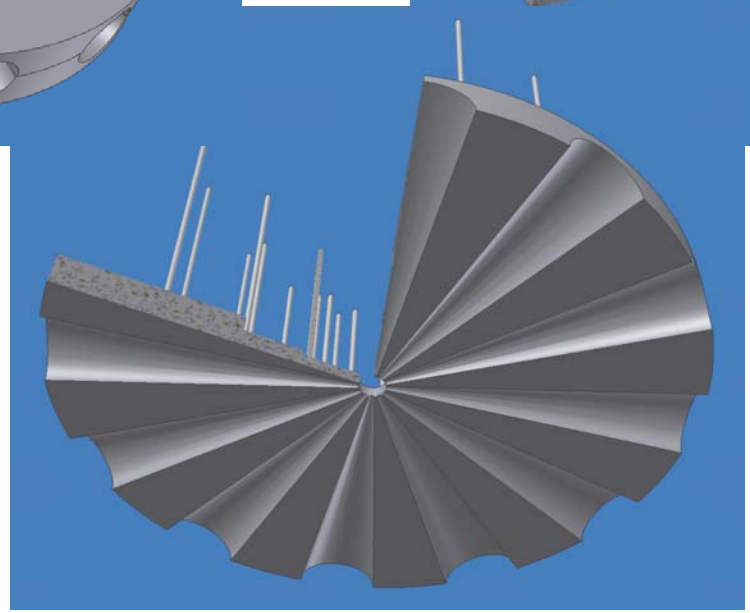
Magnet housing bore and scattering space could provide rough vacuum for optics.

Insert dewar to provide high vacuum cryogenic insulation.

SPLIT OPTICS MAGNET
PRELIMINARY HALF ASSEMBLY



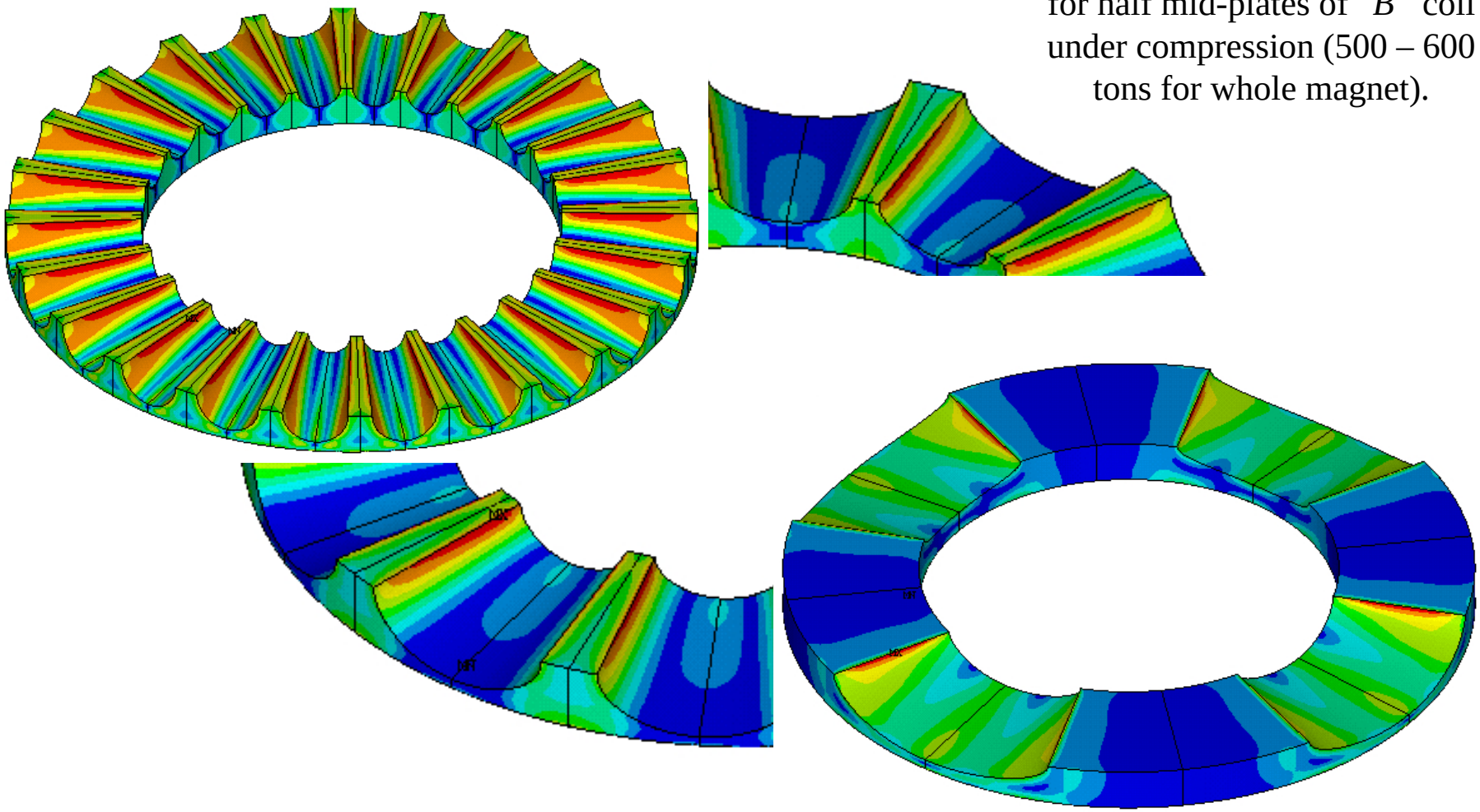




SPLIT OPTICS MAGNET
PRELIMINARY MID-PLATE DESIGN

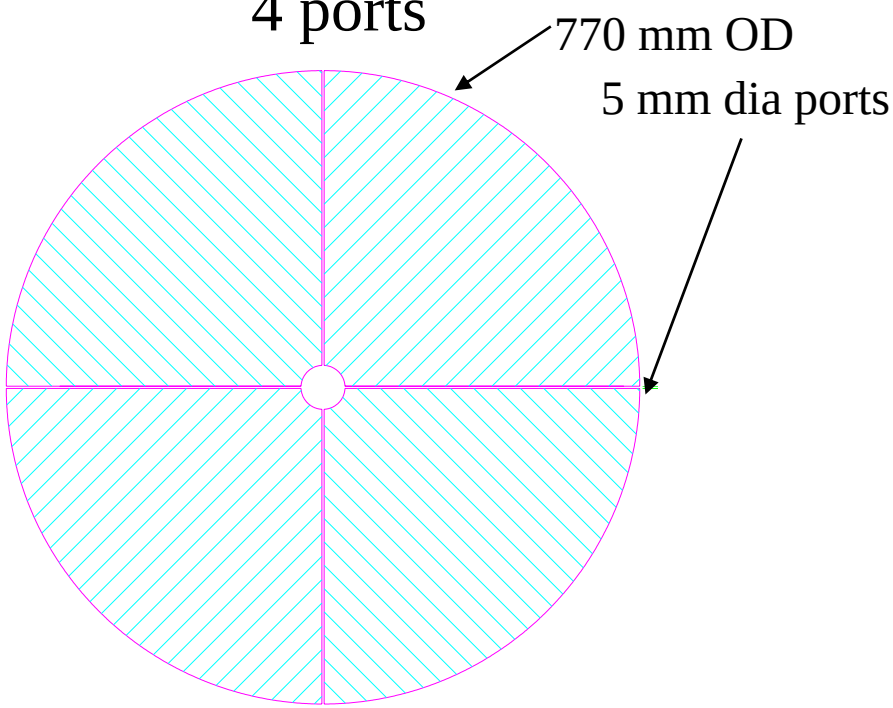
Stress Contours

for half mid-plates of "*B*" coil under compression (500 – 600 tons for whole magnet).



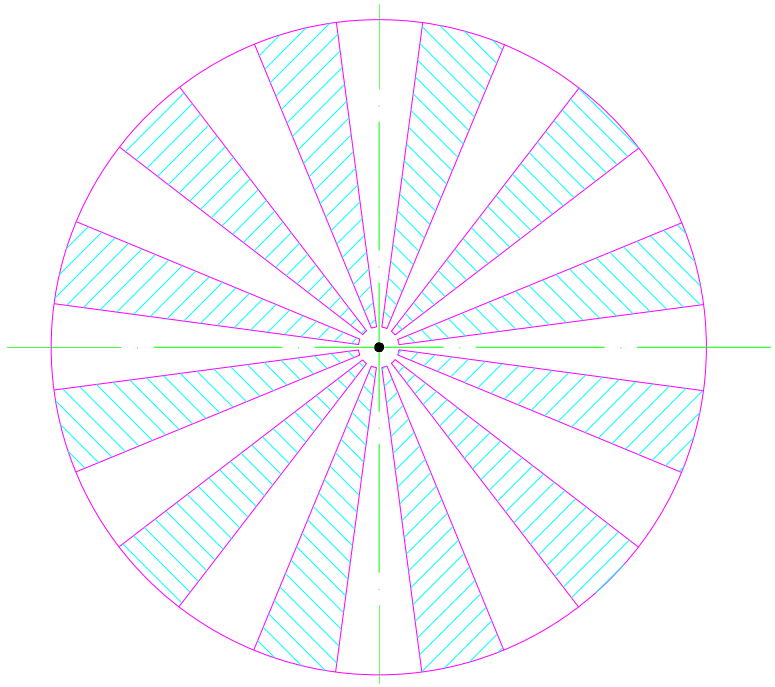
SPLIT OPTICS MAGNET
PRELIMINARY MID-PLANE COMPARISON

Grenoble, 18 T
4 ports



0.4° vertical take-off angle
(f = 72)

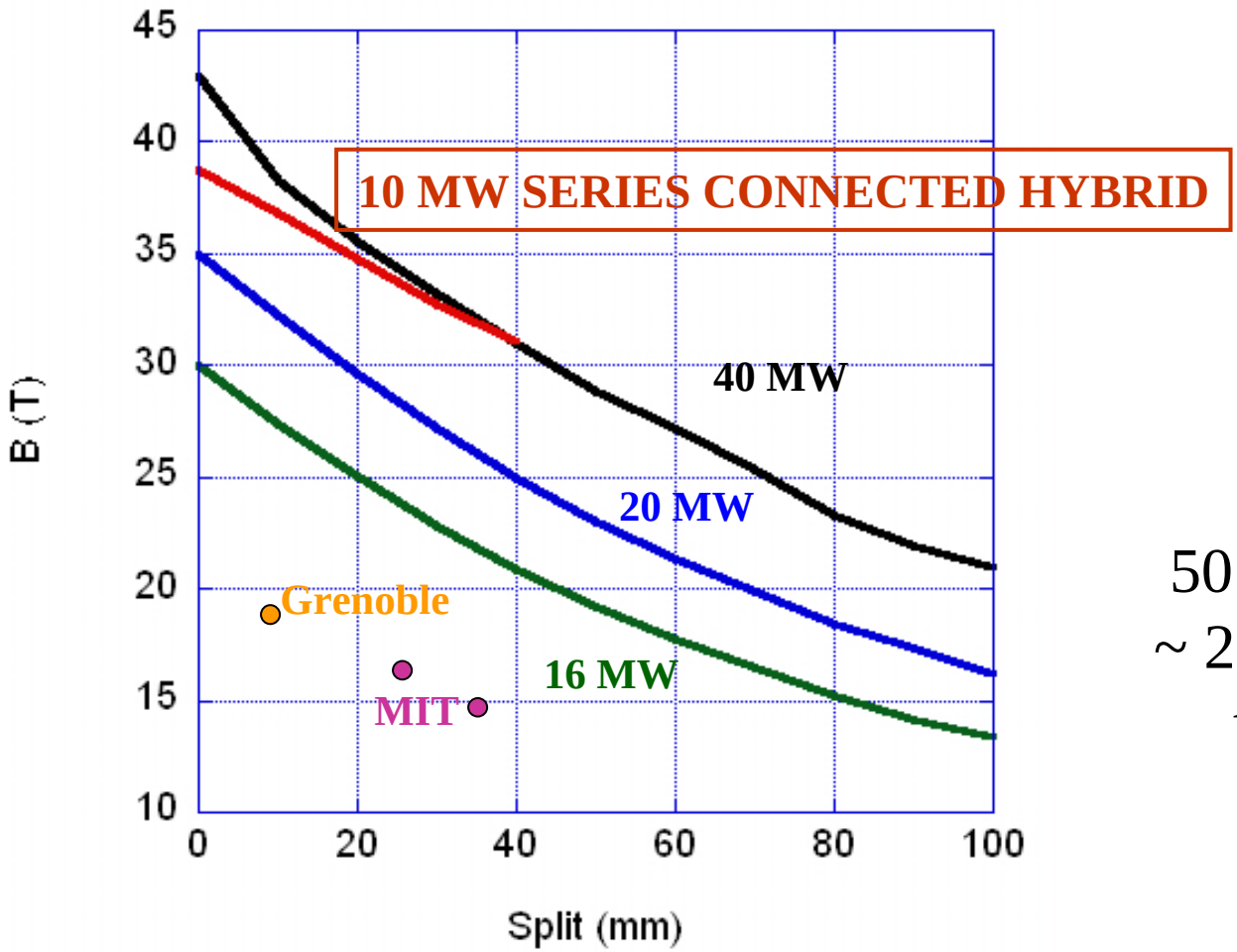
Tallahassee, 29 T?
40mm gap, 12 ports



5.7° vertical take-off angle
(f = 5.0)

SPLIT-GAP MAGNET SUMMARY

Attainable field is critically dependent on space required for gap-side bus-bars, cooling, structure, # of coils, etc!

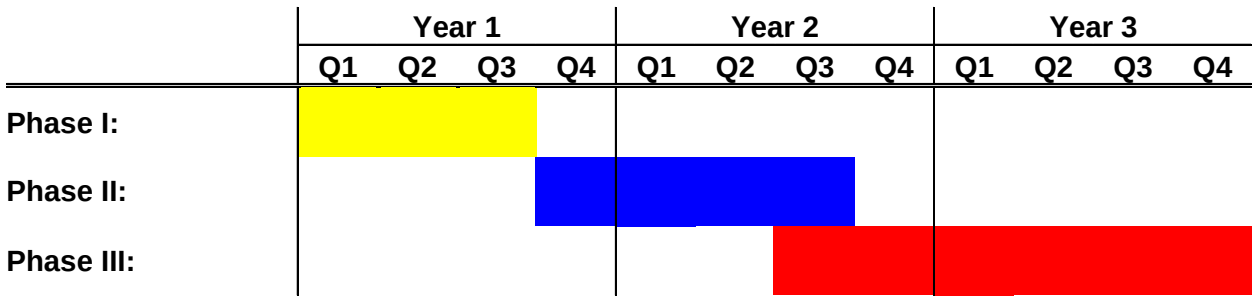


50 mm bore
~ 2 T less field
than 32 mm bore

Magnet Beamline at the APS

Proposed project phases

- Phase I – Conceptual design, detailed project planning, refined cost projections
- Phase II – Engineering design, R&D on enabling technologies, long-lead procurements
- Phase III – Fabrication, assembly, commissioning



Magnet Beamline at the APS

DC Power-System Costs

(2005 estimates based upon 1992 actuals from NHMFL power supply)

	1992 k$ @ 34 MW	2005 k$ @ 40 MW
DC Power System Total		**20700**
12kV Switch Gear	1500	2600
AC Power Distribution	900	1600
Harmonics Filter	300	500
DC Power Supply & Bus System	6800	11700
Control System	2500	4300

	1992 k$ @ 22 MW	2005 k$ @ 40 MW
Cooling System Total		**15800**
Deionized Water System	1600	4300
Chilled Water System	2800	7500
Cooling Tower	800	2100
Other (well, waste-water, etc.)	700	1900
Building for technical infrastructure		**1500**
Engineering and contractor's fees		**5600**
Grand Total (40 MW system)		**43600**
Unit Cost	**1.1 $/W**	

- Costs compiled by H.-J. Schneider-Muntau, August 19, 2004
- Projection from a study at Hahn-Meitner Institute gave very similar projection for a 40 MW unit when infrastructure and engineering fees are normalized.

Magnet Beamline at the APS

Series-Connected Hybrid Magnet Costs

	1st Magnet	2nd Magnet	
Resistive Insert (including spare)	**1200**	**1200**	Each unit similar difficulty. Split-gap maybe more difficult
Superconducting Outsert	**2650**	**2045**	Significant savings on engineering and manufacturing development. Minor savings on extended production of conductor and repeat processing.
Engineering, design, & dev.	850	425	
Conductor	1400	1260	
Winding, heat-treatment, VPI	400	360	
Cryostat	**550**	**550**	Potential savings on 2nd cryostat eliminated by complication of radial access.
Refrigerator & installation	**1600**	**320**	Single refrigerator can serve both facilities. More lines required.
Power/protection circuit	**400**	**360**	Duplicate hardware, less engineering
System integration, test & remed.	**450**	**405**	Same task 2nd time.
Total	**6850**	**4880**	

Cost projection by J.R. Miller based on a pre-conceptual design with a 10 MW insert and a 15 T outsert. Cost algorithms developed from 45T Hybrid experience and updated for current year.

Magnet Beamline at the APS

Total System Cost

OPTION 1: 10MW DC Power Supply and
One 30T Series-Connected Hybrid (SCH) Magnet
(down-bore or split-gap geometry)

- 10MW dc power system, complete: 11 M$
- 30T SCH magnet system, complete: 7 M$

Total: 18 M$

OPTION 2: Additional Cost
Second 30T Series-Connected Hybrid Magnet
(one each of down-bore and split-gap geometry)

- Extension of services from 10 MW supply
  (buswork, cooling water plumbing, controls): 1 M$
- Second 30T SCH magnet system, complete: 5 M$

Total additional: 6 M$

Total for Two Magnet Configuration: 24 M$

Magnet Beamline at the APS

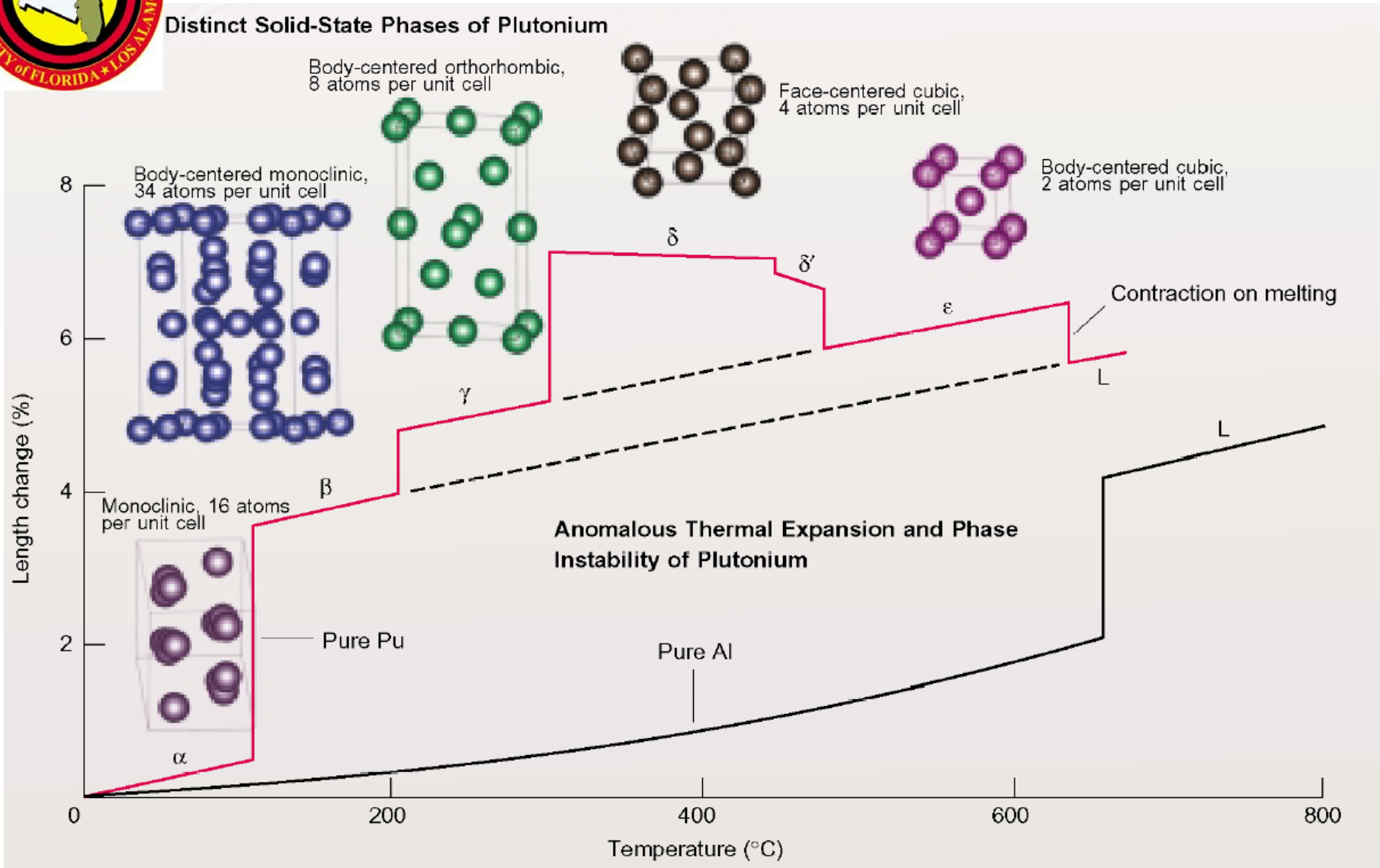
Annual Operating Costs

TO BE DEVELOPED…

FIVE-PERSON BEAMLINE TEAM
ANNUAL ELECTRICAL COSTS OF $1-2M

To request magnet time: www.magnet.fsu.edu

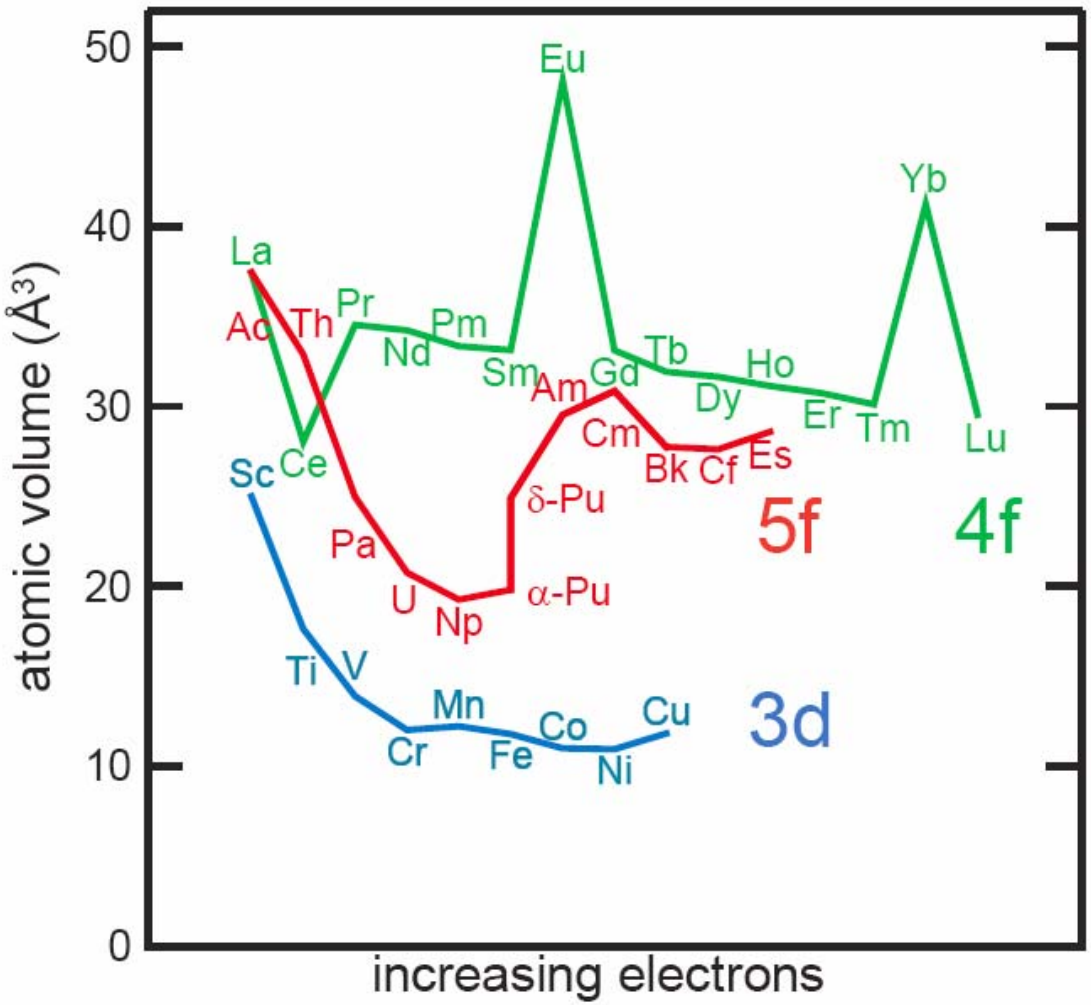
Plutonium: the most interesting element in the Periodic Table



δ-phase is stabilized to low temperatures by few percent Ce, Al, Ga etc.

Atomic volumes of the actinides and 3d and 4f metals

Pu straddles the itinerant/localized divide!

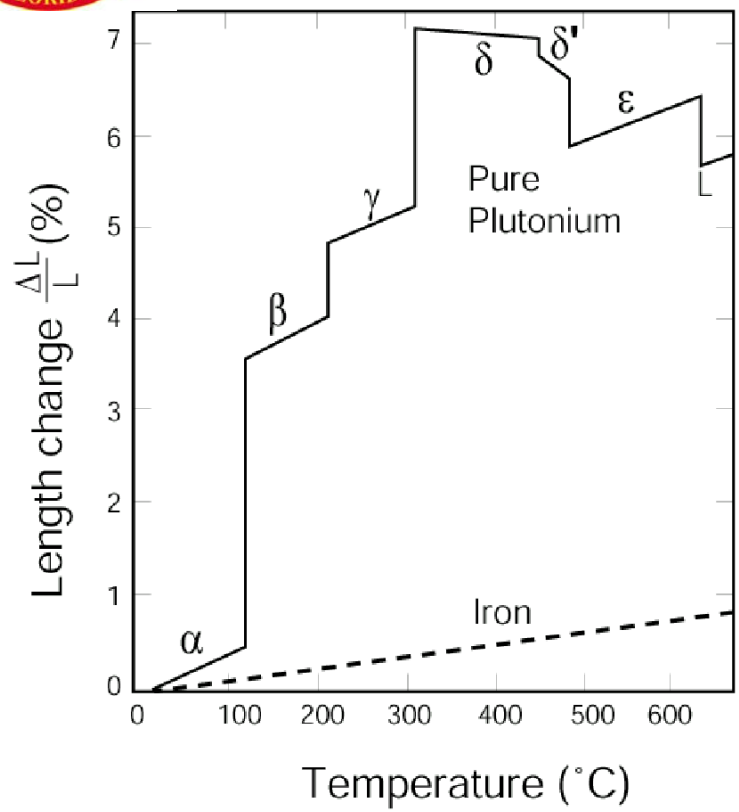


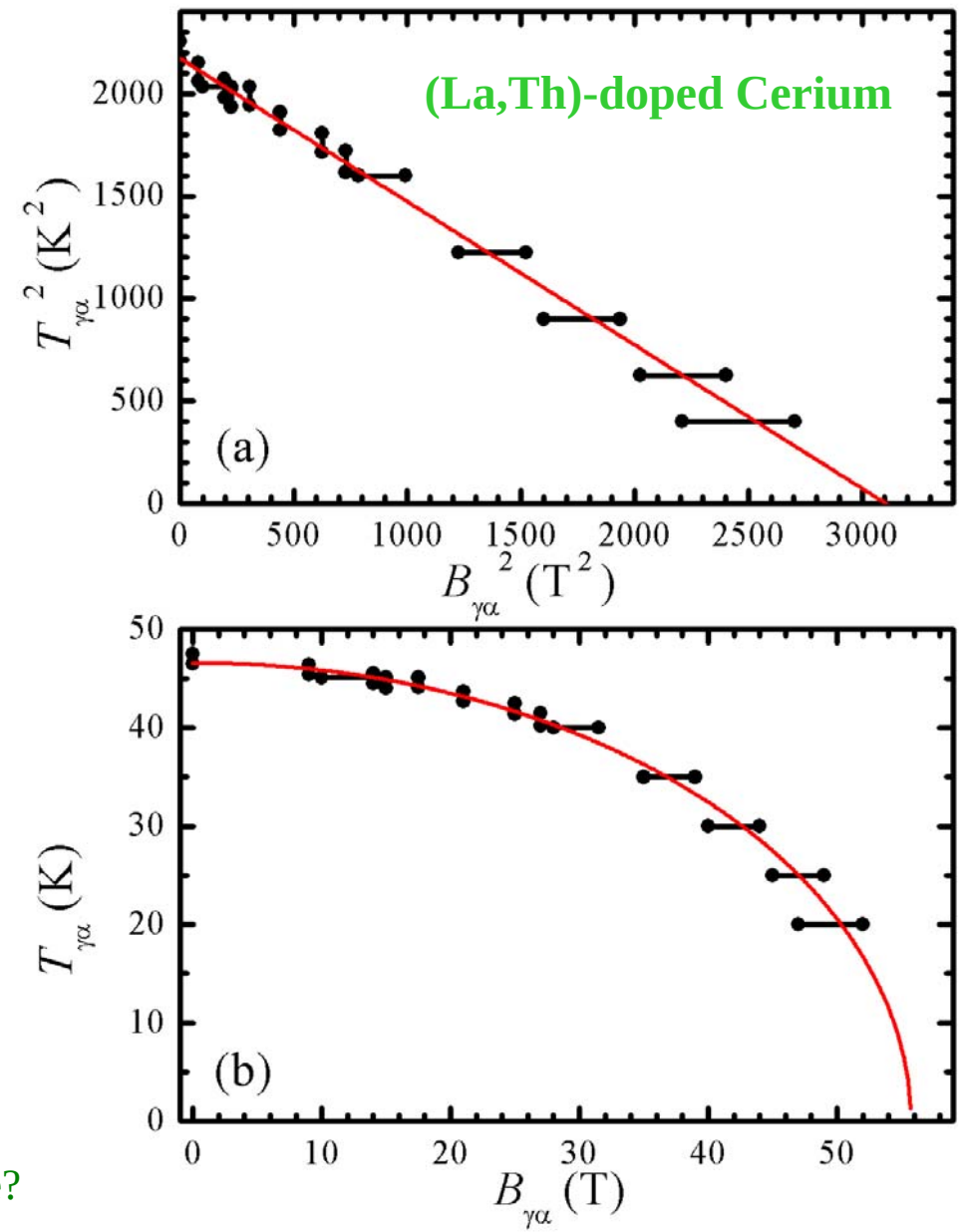
Late actinides (Am to Es) show little dependence on Z (as in magnetic 4f metals)
This, plus magnetic order in Cm and beyond suggests that
5f electrons are localized.

Abrupt jump in volume at Pu

Early actinides (Th to Np) show large drop in with Z (as 3d metals) as electrons contribute to cohesive energy.
This, plus absence of magnetism in Th to Np suggests that
5f electrons are itinerant.

Volume Collapse in Plutonium and Cerium





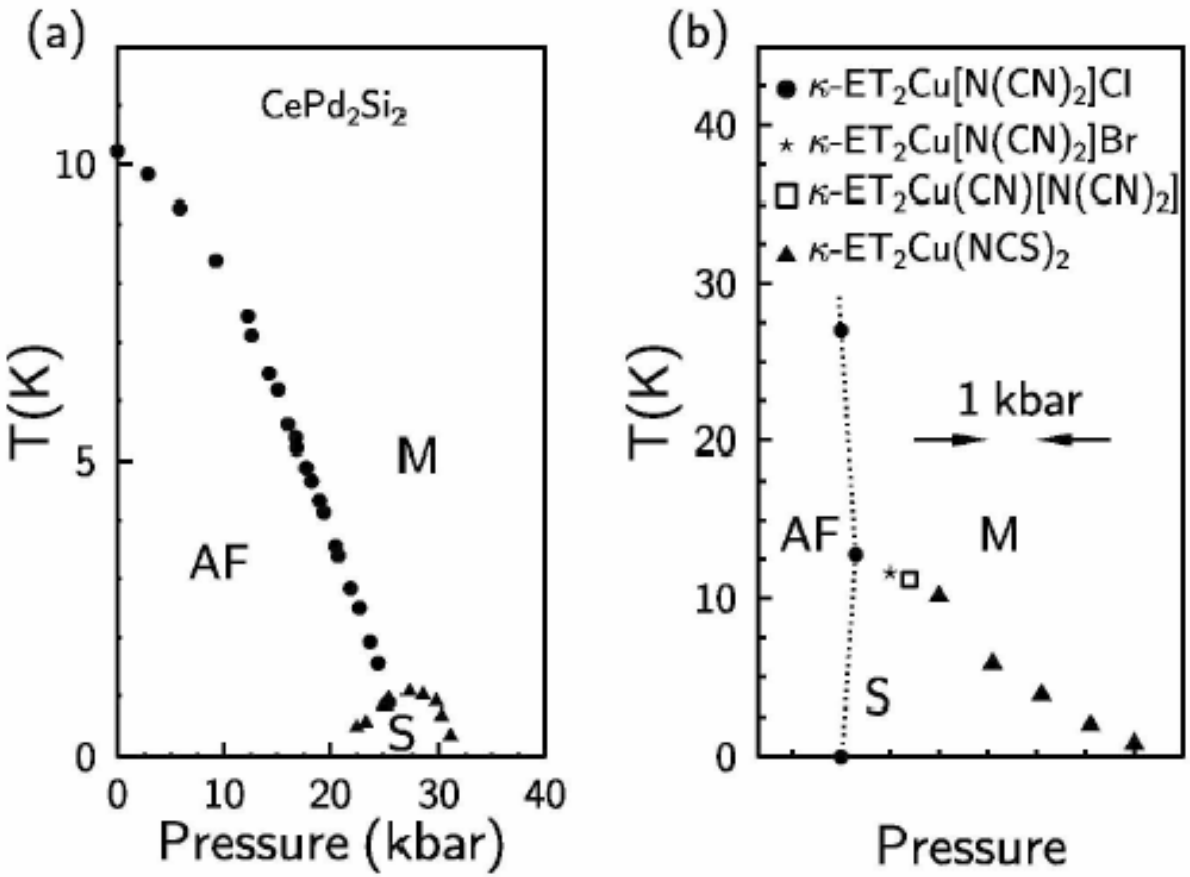
Both systems show volume collapses driven by f electrons.

Is there common physics?

Are field-induced phase transitions feasible?

[For recent summary of Ce, cond-mat/0403086 (K. Haule et al.) and refs therein.]

Similar Phase Diagrams: Heavy Fermions and Organics



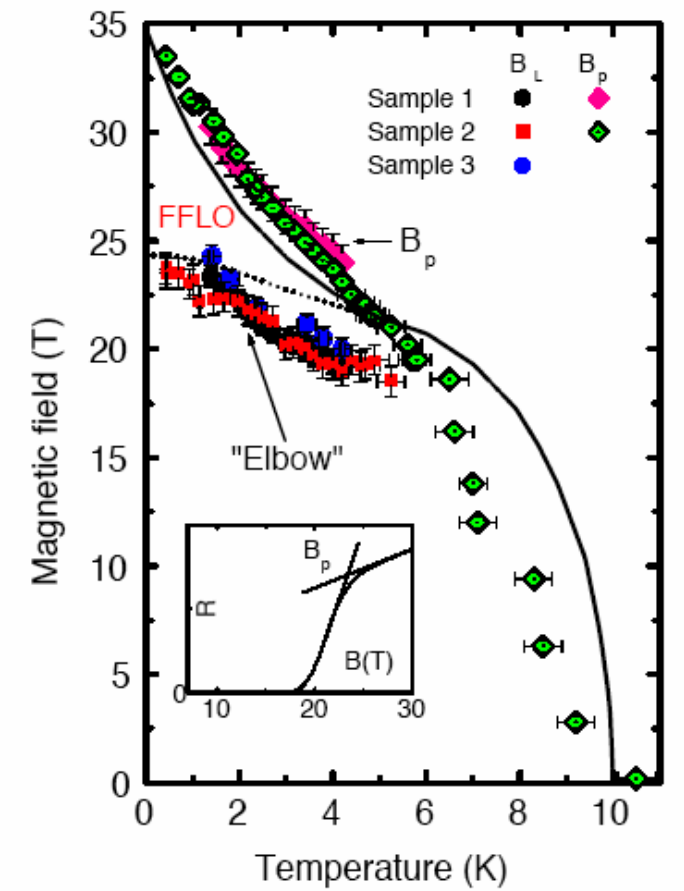
(a) $T-P$ phase diagram of $CePd_2Si_2$ (Mathur). (AF=antiferromag., S=supercon., M=metal)

[After Singleton, Rep. Progr. Physics (2000) and McKenzie, Com.Cond Mat.Phys.(1998).]

(b) $T-P$ phase diagram of κ-(BEDT-TTF)$_2$Cu(NCS)$_2$, κ-(BEDT-TTF)$_2$Cu[N(CN)$_2$]Br, κ-(BEDT-TTF)$_2$Cu(CN)[N(CN)$_2$] κ-(BEDT-TTF)$_2$Cu[N(CN)$_2$]Cl.

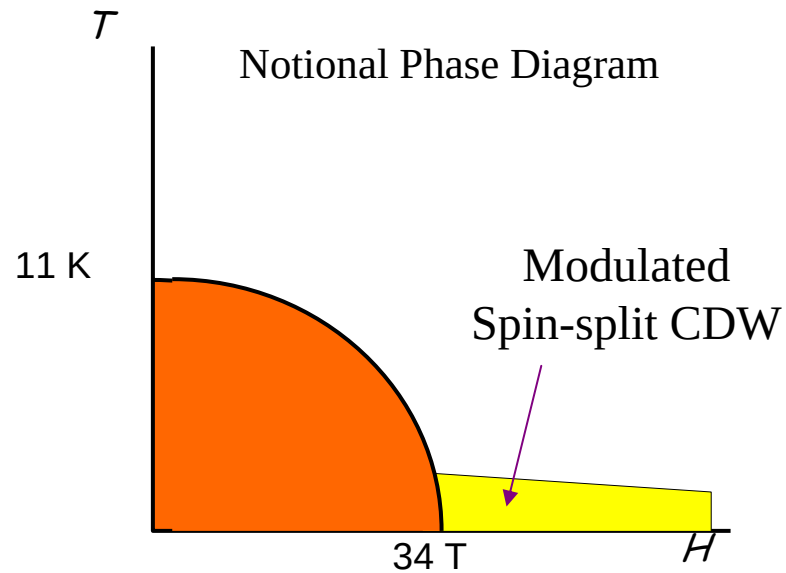
Modulated Collective States in High Magnetic Fields

Superconducting-phase modulated
Fulde-Ferrell-Larkin-Ovchinnikov
in κ-(BEDT-TTF)$_2$Cu(NCS)$_2$



Curves are theory (PRB **50**, 12760); measurement (points, JPCM **12**,L641).

Superposition of two Charge-Density Waves
with different wave vectors
Modulated CDW amplitude in (per)$_2$Au(mnt)$_2$



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