PERFORMANCE OF 75 T PROTOTYPE PULSED MAGNET

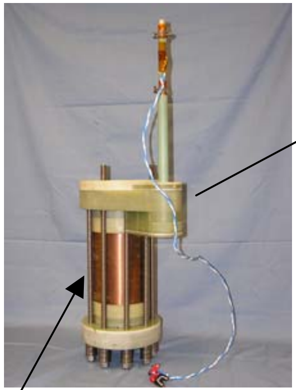
Charles A. Swenson, Andrew V. Gavrilin, Ke Han, Robert P. Walsh,
Kenneth W. Pickard, Edward Miller, Hans Schneider-Muntau
U.S. National High Magnetic Fields Laboratory, Tallahassee Florida

Dwight G. Rickel, Joseph S. Schillig, and James R. Sims
U.S. National High Magnetic Field Laboratory, Los Alamos New Mexico

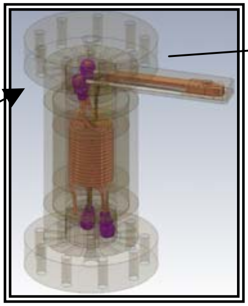
Presented on Sept 19, 2005
MT-19 Conference Genoa, Italy

75 T Magnet's Definition in Terms NSF Technology Development Path

65 T Prototypes

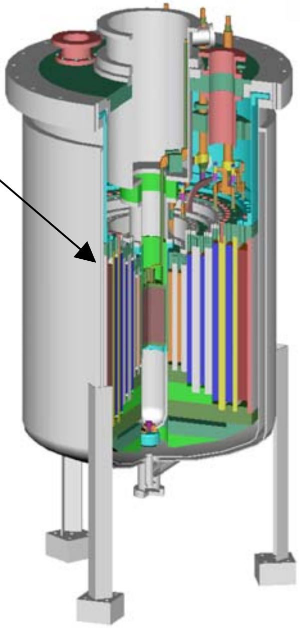


75 T Prototype



80 T Project

NSF Insert Technology



US-NHMFL 100 T Multi Shot Magnet

Joint US-DOE and US-NSF Project

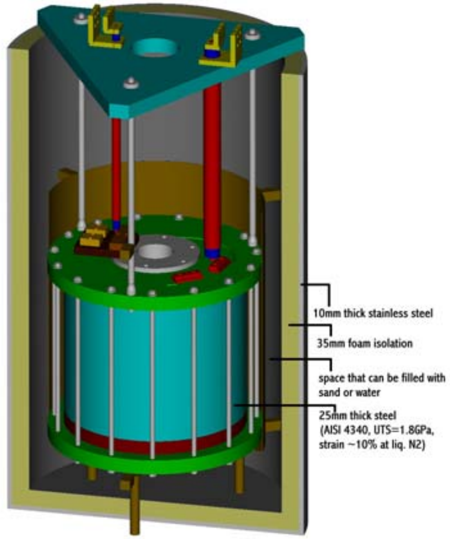
Goals of Development Path

- Develop reliable insert technology
- Support NSF user science program
- Explore limits of mono-coil technology
  - Efficient means to evaluate insert tech.
  - Baseline technology for future planning

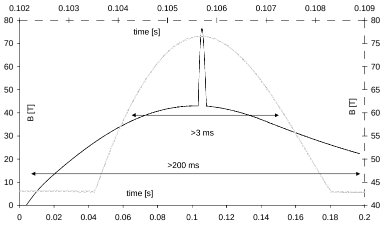
Global Efforts for High Field

Good Company
on
The Stony Path

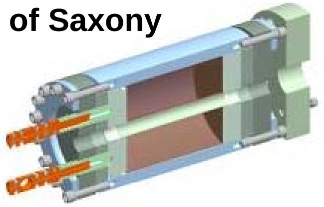
**European
ARMS
Program**

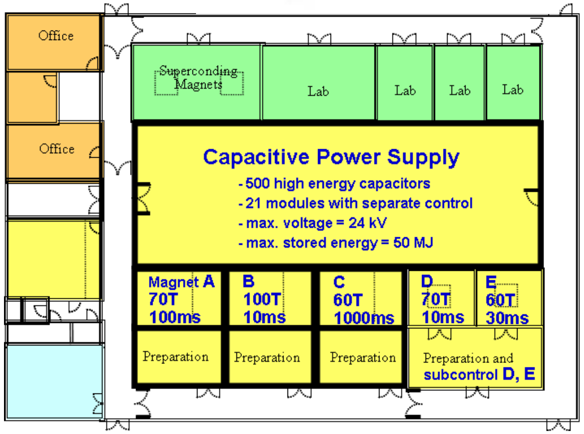


Advanced Hardware
Development & Testing



Dresden, Germany
**Free State
of Saxony**





Capacitive Power Supply

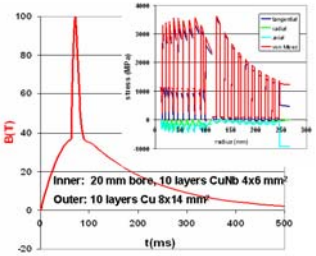
- 500 high energy capacitors
- 21 modules with separate control
- max. voltage = 24 kV
- max. stored energy = 50 MJ

Magnet A	B	C	D	E
70T	100T	60T	70T	60T
100ms	10ms	1000ms	10ms	30ms

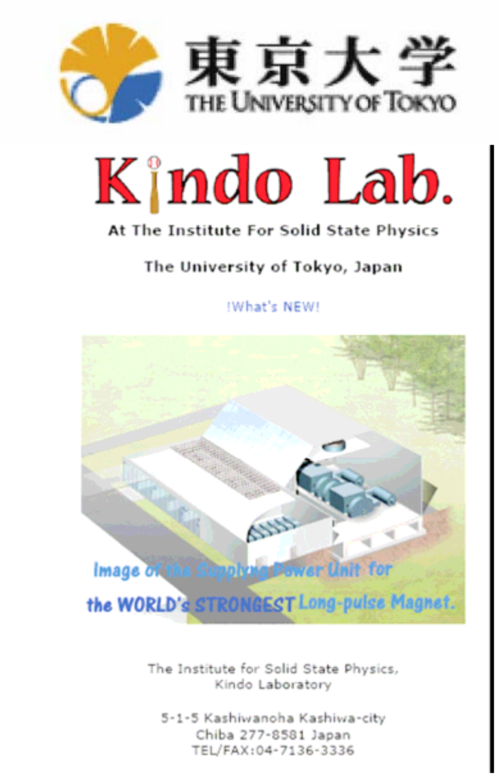
Preparation and subcontrol D, E

Funded!!! Begun
Hardware Development
Long Term Planning

100 T double coil magnet (43 MJ / 3 MJ)



Inner: 20 mm bore, 10 layers CuNb 4x6 mm^2
Outer: 10 layers Cu 8x14 mm^2



東京大学
THE UNIVERSITY OF TOKYO

Kindo Lab.

At The Institute For Solid State Physics

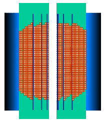
The University of Tokyo, Japan

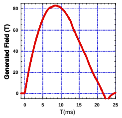
!What's NEW!

The Institute for Solid State Physics,
Kindo Laboratory

5-1-5 Kashiwanoha Kashiwa-city
Chiba 277-8581 Japan
TEL/FAX:04-7136-3336

Advanced Hardware Development
80- 82 T Class Magnets





Now Planning Generator
Driven 100 T Program

100 T Magnet System Overview

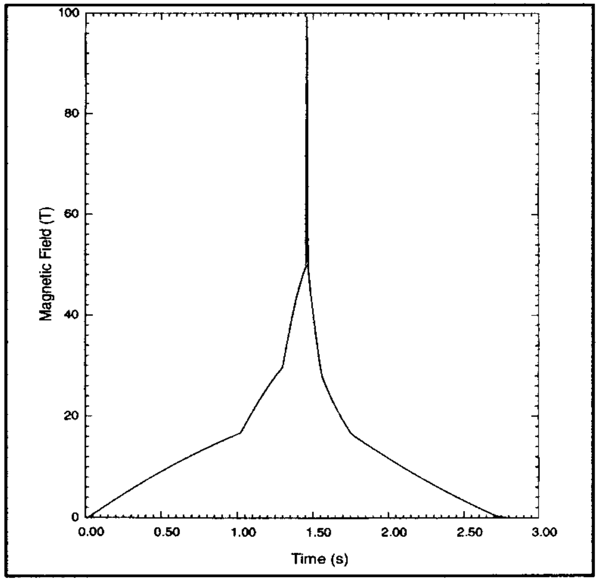
- Generator powered outer coil set (7 coils) produces a long pulse platform field to 44 T in a 225mm bore.

- Capacitor bank powered insert magnet produces a short pulse field to 56 T.

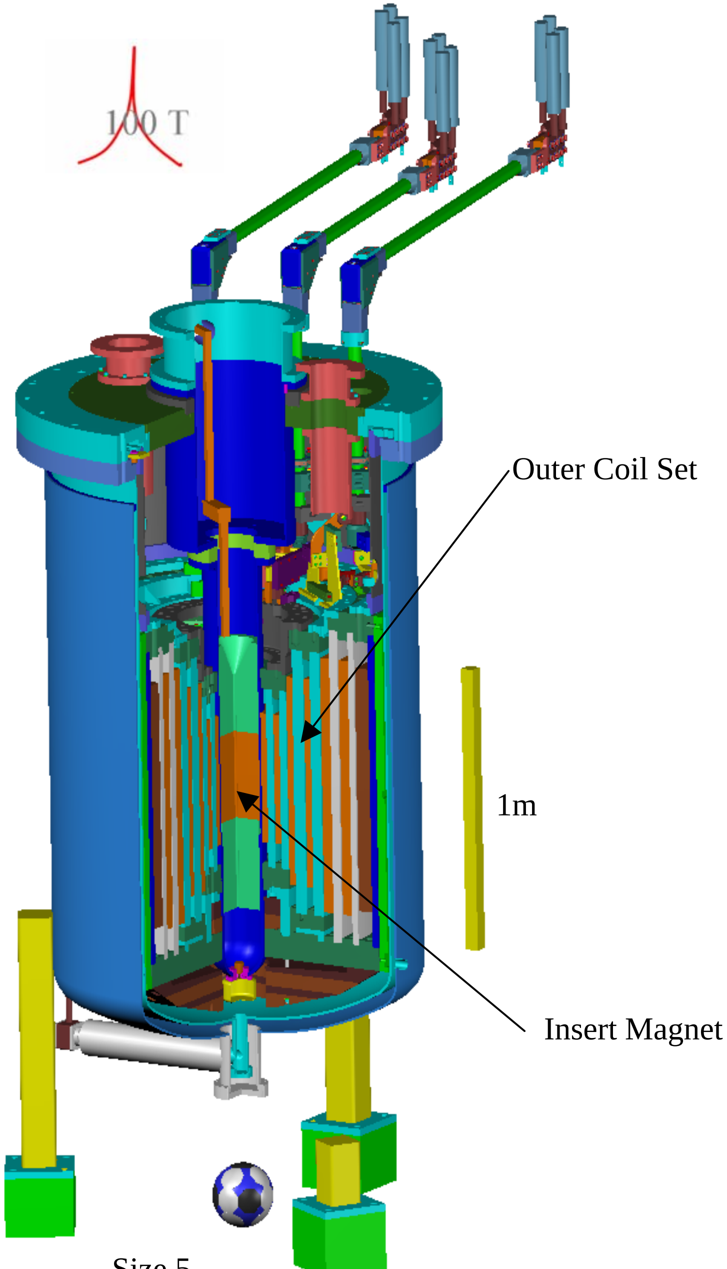
- Magnetic fields sum to produce up to 100 T non-destructively in a 15 mm bore.

- Coils are resistive, are cooled to 77 K and operate adiabaticall during the pulse

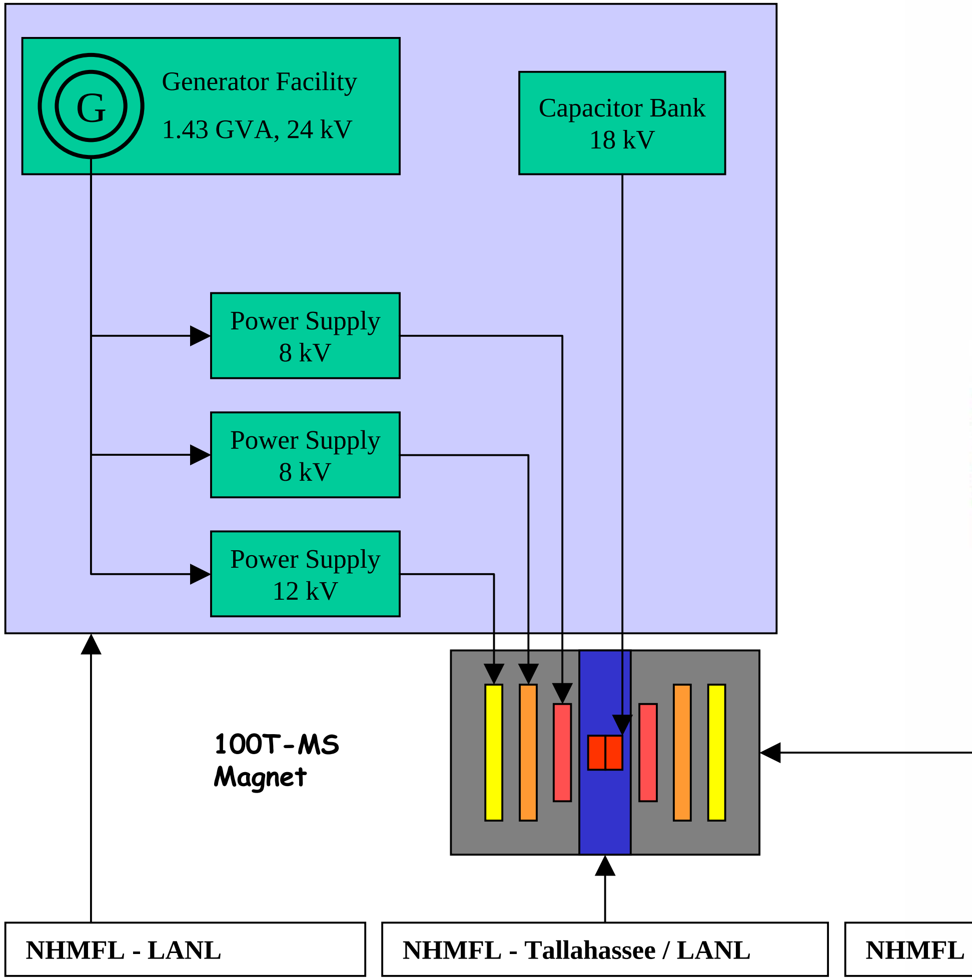
- Coils/magnets are nested solenoids and are heavily reinforced to withstand the very high magnetic loads



100T MS Magnet System Pulse Shape



100T-MS Power Supply System Overview



Generator Facility
1.43 GVA, 24 kV

Capacitor Bank
18 kV

Power Supply
8 kV

Power Supply
8 kV

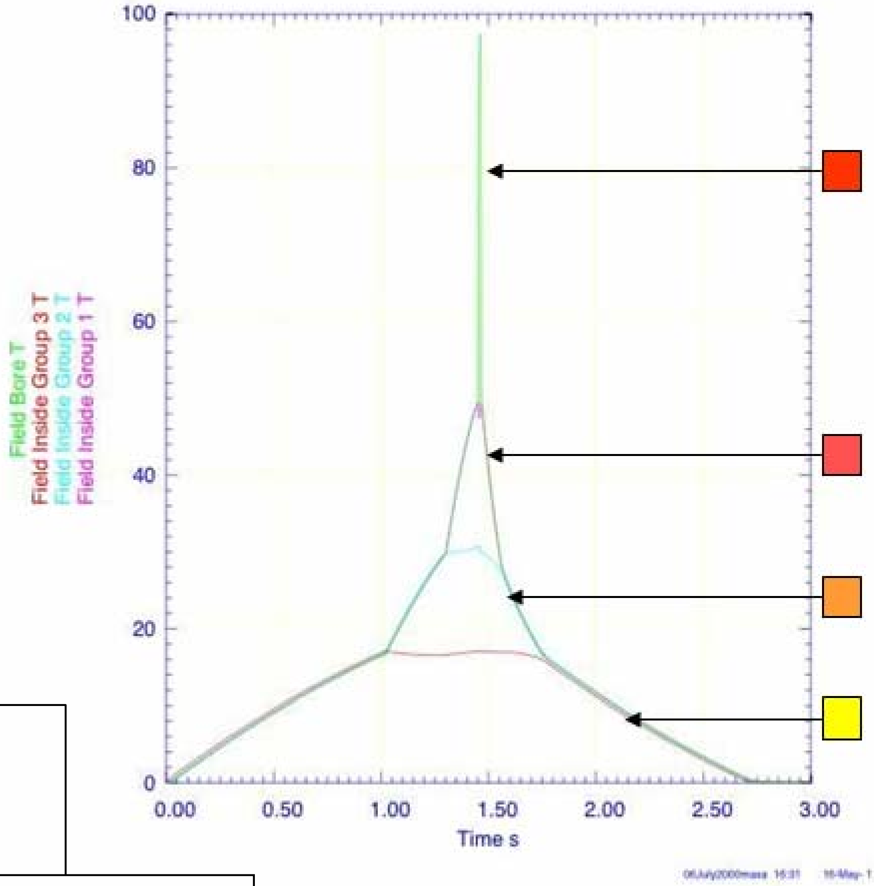
Power Supply
12 kV

100T-MS
Magnet

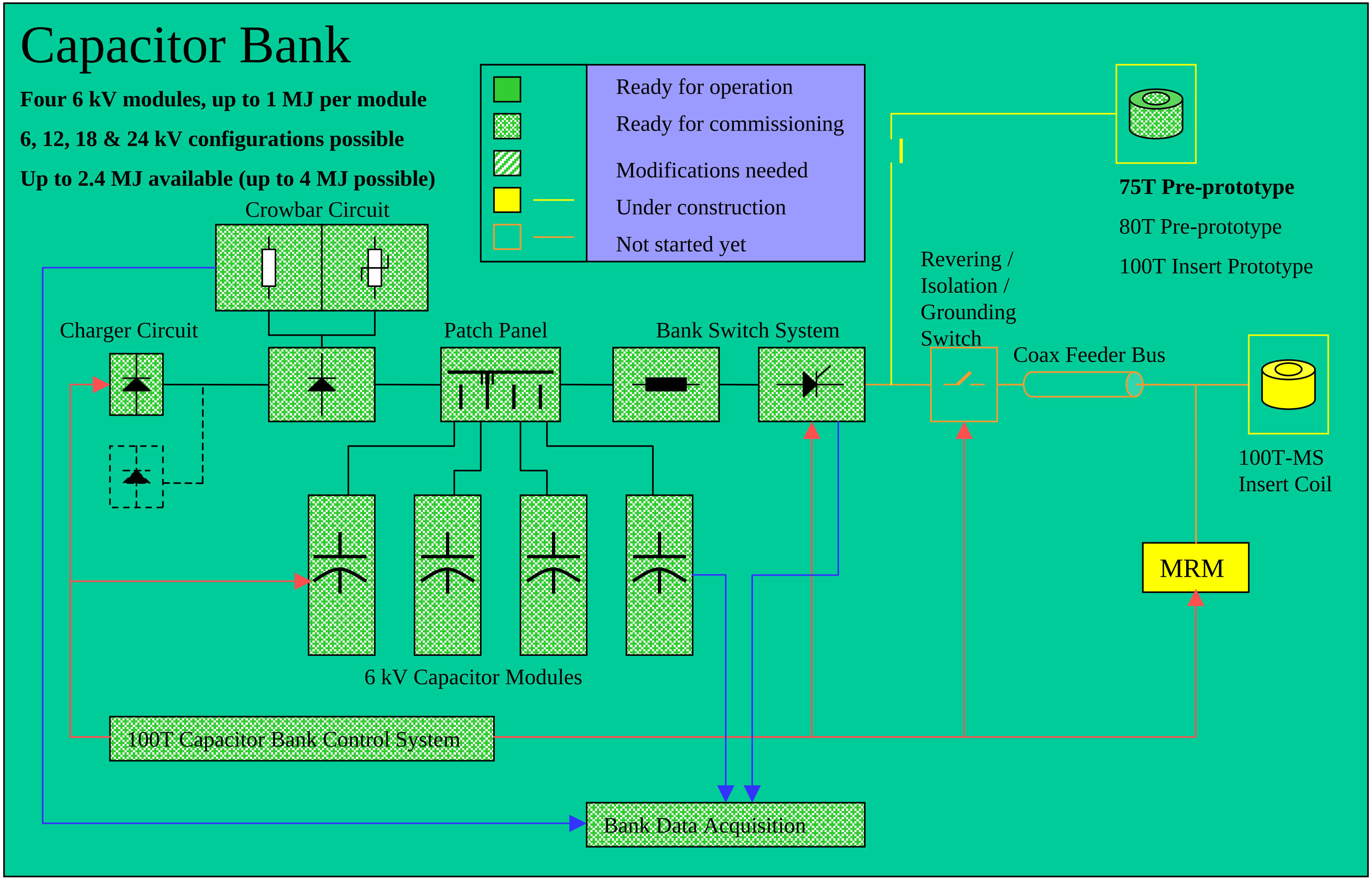
NHMFL - LANL

NHMFL - Tallahassee / LANL

NHMFL - LANL



Capacitor Bank for Insert & Mono Coil Program



Capacitor Bank

Four 6 kV modules, up to 1 MJ per module

6, 12, 18 & 24 kV configurations possible

Up to 2.4 MJ available (up to 4 MJ possible)

🟩	Ready for operation
▩	Ready for commissioning
▨	Modifications needed
🟨	Under construction
☐	Not started yet

75T Configuration

18kV, 3 modules
15.2 mF
(45.6mF/module)
16 caps/module

90T Insert Specifications *1st Production Insert 95 T Rating*

Coil Parameter	Attribute
Conductor	Bochvar CuNb 3.0 x 5.8 mm
Insulator	Kapton + Zylon Serving
Metal Reinforcement	2.5 GPa MP35N Alloy
Fiber reinforcement	5.0 GPa Zylon
Number of Layers	8
Turns per Layer	27
Bore	15.5 mm
Height	~ 300 mm Flange to Flange
Outside Diameter	199.5 mm
Outsert Field	43 T
Insert Field	50 T
Max Current	36.7 KA
Inductance	0.828 mH @ 20 Hz
Pulse Shape	Rise Time ~5.2 ms Decay Time ~ 8 ms
Cooling Time	~ 45 min between pulses

Insert reinforcement structure with zylon removed to illustrate metal placement

NHMFL Pulsed-Field Science Facility

User Facility Capacitor Bank

Present Configuration
1.4 MJ, 10 kV, 32 mF
4 mF/module

NHMFL Upgrade in Process
4.0 MJ, 16 kV, 32 mF
4 mF/module

Cell #4

65 T User

Cell #3

65 T User

Cell #2

50 T Mid-Pulse

Cell #1

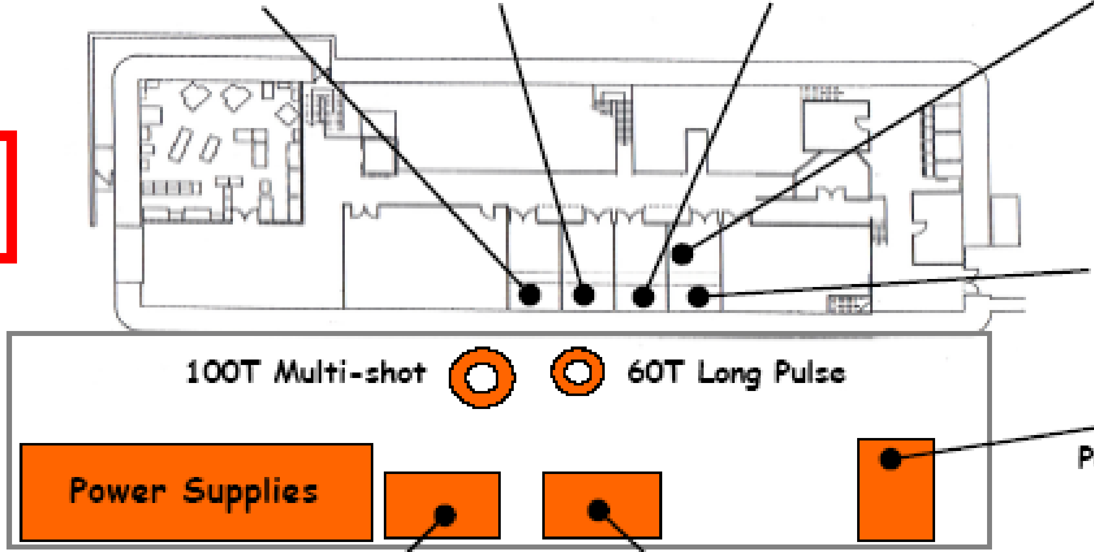
50 T Mid-Pulse

Cell #1

50 T Short-Pulse

Experimental Hall

High-Energy Experimental Hall



RPM Power Supply & Model Magnet

100 T Capacitor Bank
Now Operational

18kV, 3 modules
15.2 mF
(45.6mF/module)
16 caps/module

100 T Small Coil Program:
75 T Prototype

NHMFL – Pulsed Fields Community

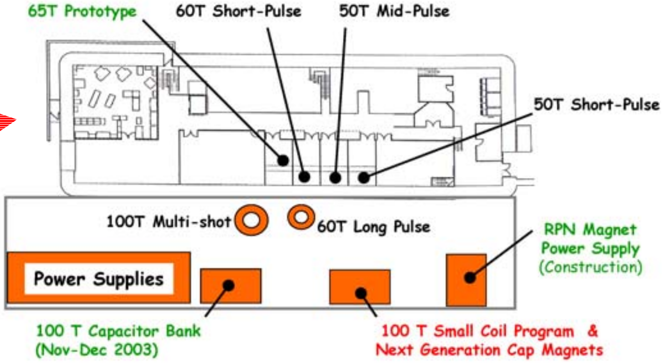
NHMFL MS&T
Capacitor Driven Pulsed Magnet Technology

100T Insert
Technology

FOCUS

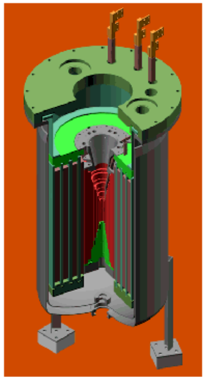
The development of the Pulsed Field Facility For Scientific Research

NHMFL Pulsed Science Field Facility



LANL Design Engineering Group

NSF 60 T
Long Pulse



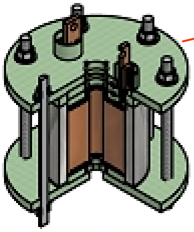
DOE-NSF 100 T
Multi-Shot Magnet
Outsert Coil Assembly

NHMFL Pulsed Magnet Hardware Developments

65 T Project
(2003-2005)

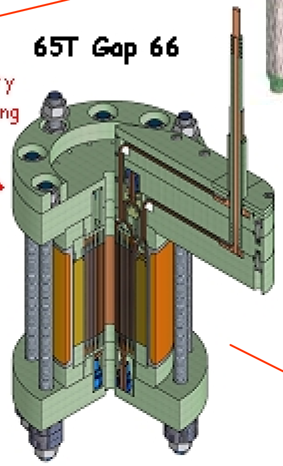
60T ZMD

E = 0.5 MJ

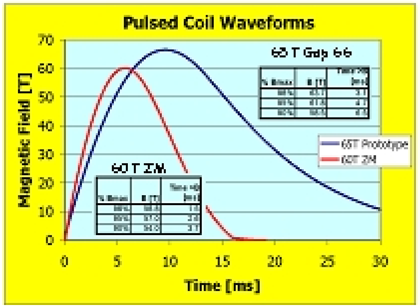


Reliability Engineering

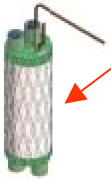
65T Gap 66



Energy = 1.3 MJ



Poly-Layer Assembly Process Development



Insert Prototype Operation

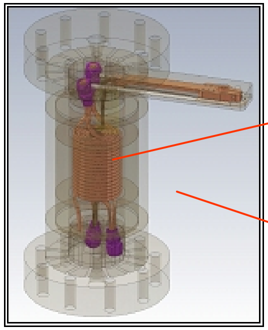
65 T Project Accomplishments:

- •Accumulated > 3642 science pulses on four magnets (Two assemblies are in operation)
- •Accumulated ~ 1800 full field science shots
- •Proven insert design template for CuNb work with 75T prototypes
- •Developed production capability for poly layer assembly process.

---

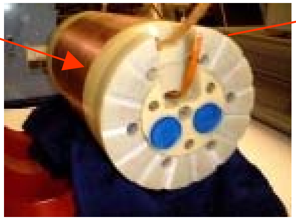
75 T Project
(2004-2005)

Design Concept

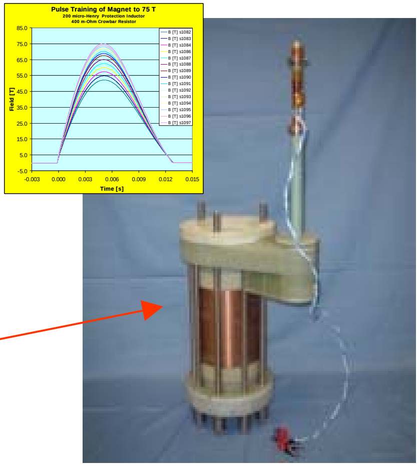


Insert Prototype CuNb Conductor

Nested Coils



75 T Prototype Assembly

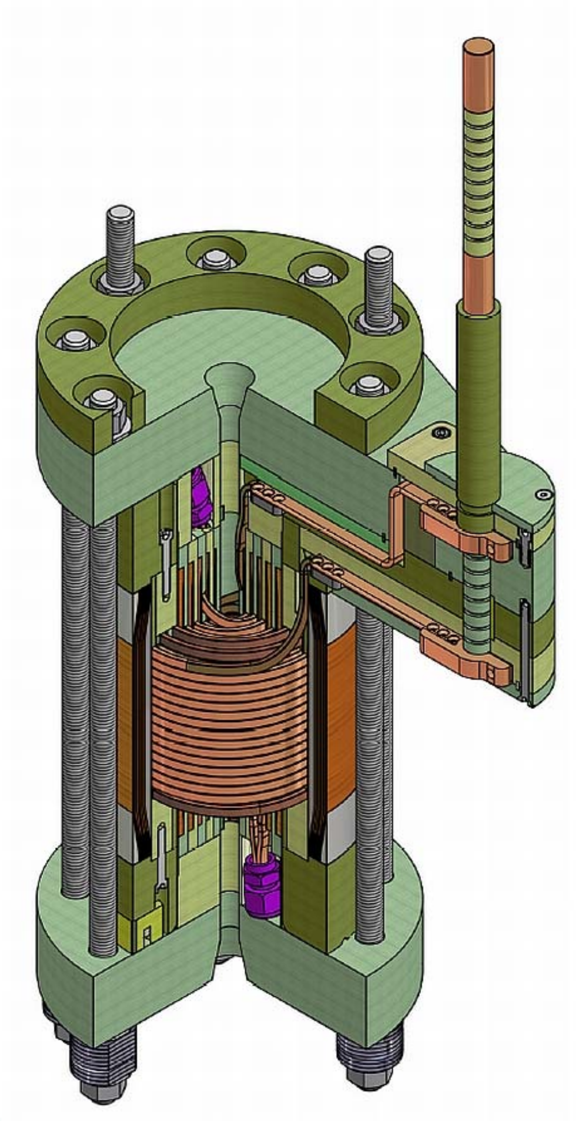


75 T Project Accomplishments:

- •Operational test of Bochvar CuNb wire
- •Refine Poly-Layer Assembly Process
- •Validated operation at 100 T stress levels
- •Accumulated > 120 pulses > 70 Tesla
- •Accumulated ~ 12 pulses at 75 Tesla

Started Testing Nov. 2004

NHMFL 75 T Prototype Magnet

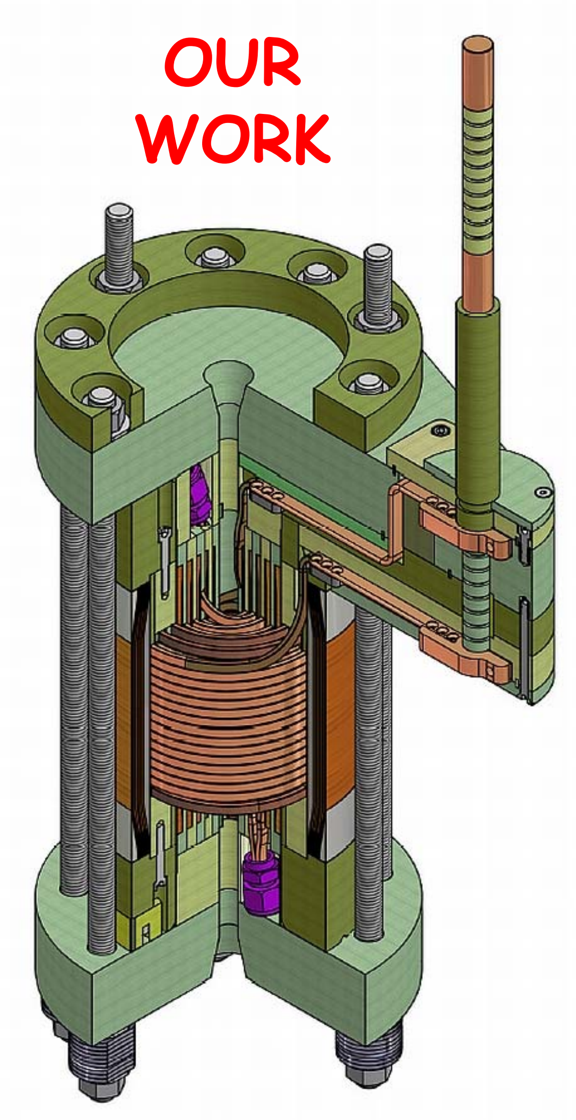


Qualitative Technical Description

- Nested two coil assembly
- Coils are connected in series
- Uses novel materials technology
  - Conductor: Cu-Nb nano-composite
  - Reinforcement: Hybrid metal organic composite
    - Zylon fiber reinforcement
    - MP35N nickel-cobalt superalloy
  - Materials specifications “discovered” fatigue
- Used novel engineering structures and design principals
  - Coaxial lead structure
  - Free supported leads to relieve strain
  - Poly-layer assembly process for inner coil
    - There are no transitions
    - Every layer has a mechanical joint
  - Cooling gap between coils
  - Magnetic centering on assembly
  - Distributed internal reinforcement
    - Factor in fatigue & thermal properties

NHMFL 75 T Prototype Magnet

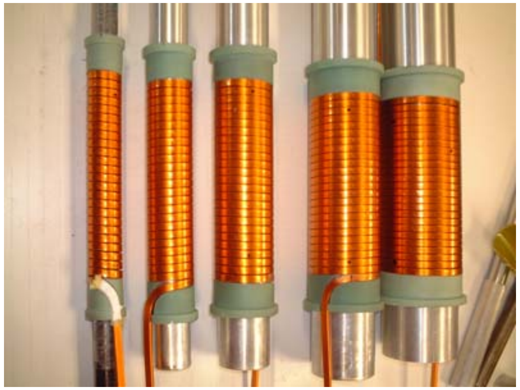
OUR WORK

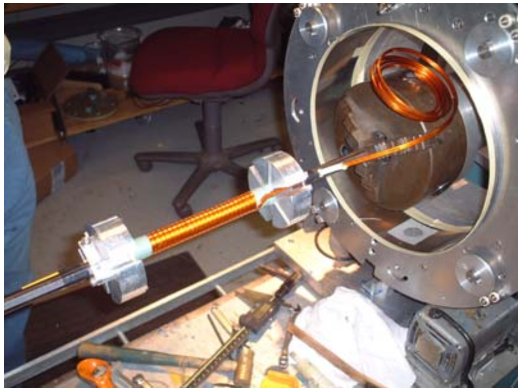


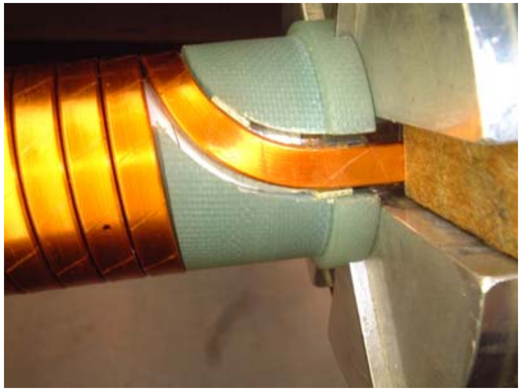
Qualitative Technical Description

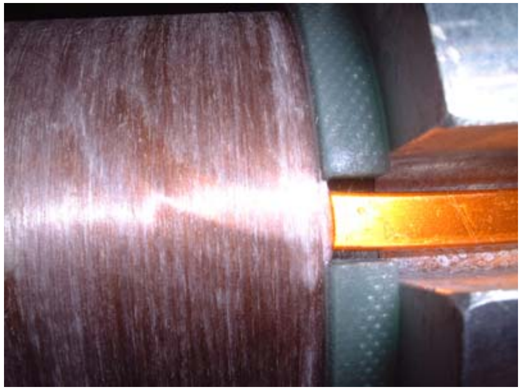
- Nested two coil assembly
- Coils are connected in series
- Uses novel materials technology
  - Conductor: Cu-Nb nano-composite
  - Reinforcement: Hybrid metal organic composite
    - Zylon fiber reinforcement
    - MP35N nickel-cobalt superalloy
    - Materials specifications “discovered” fatigue
- Used novel engineering structures and design principals
  - Coaxial lead structure
  - Free supported leads to relieve strain
  - Poly-layer assembly process for inner coil
    - There are no transitions
    - Every layer has a mechanical joint
  - Cooling gap between coils
  - Magnetic centering on assembly
  - Distributed internal reinforcement
    - Factor in fatigue & thermal properties

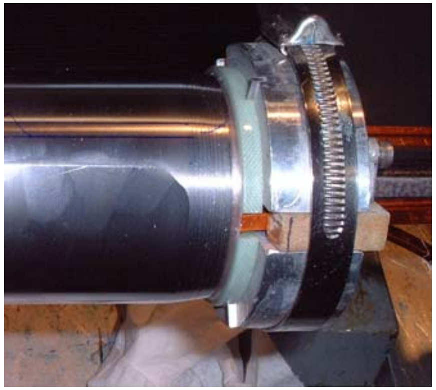
Poly-Layer Assembly Process

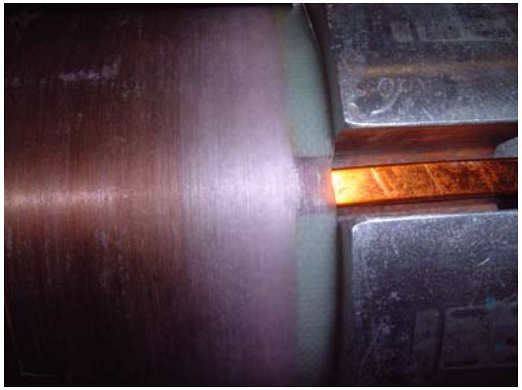

Layer Helix Coils


Winding Mandrel

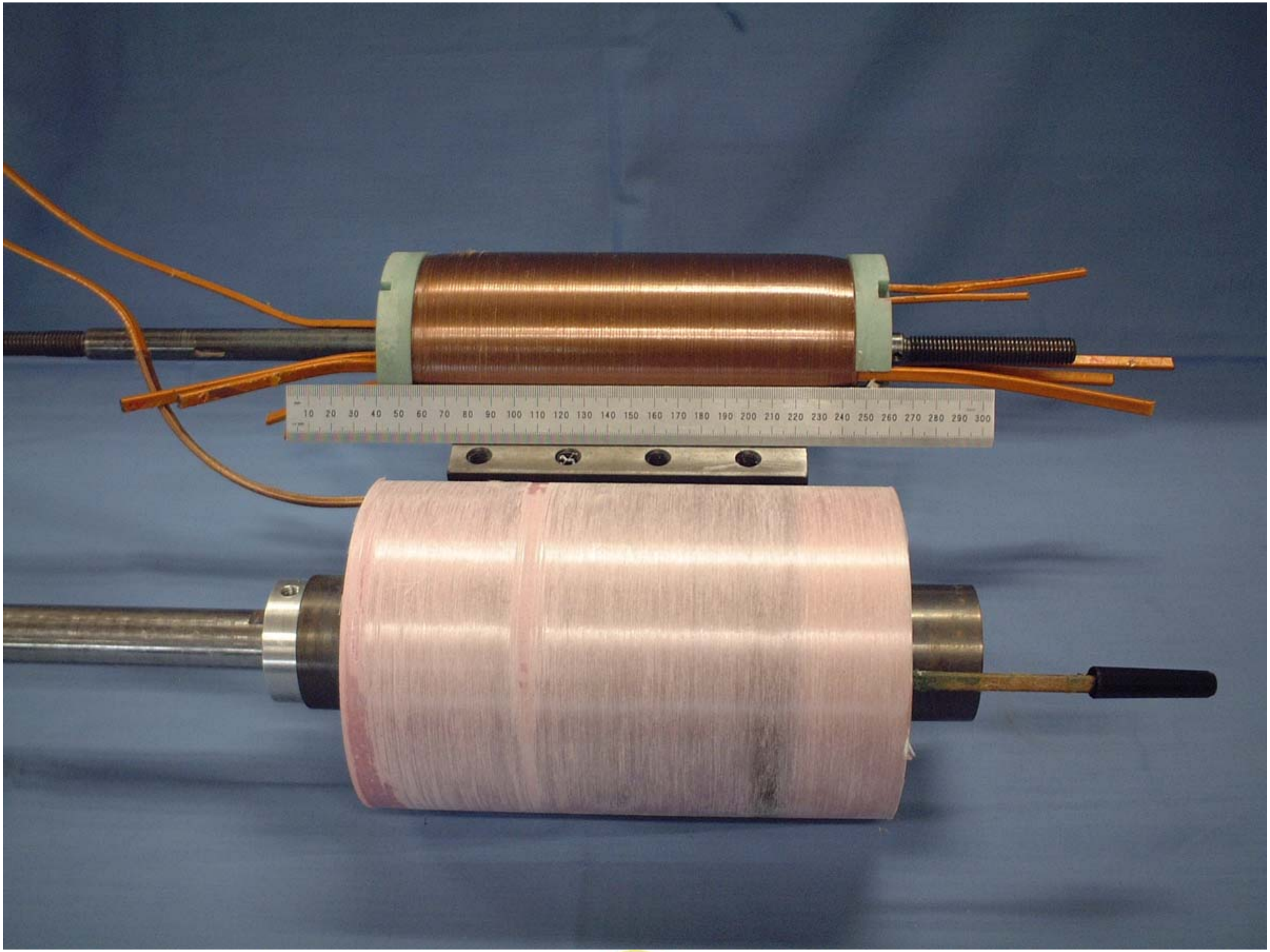

Detail End Spool

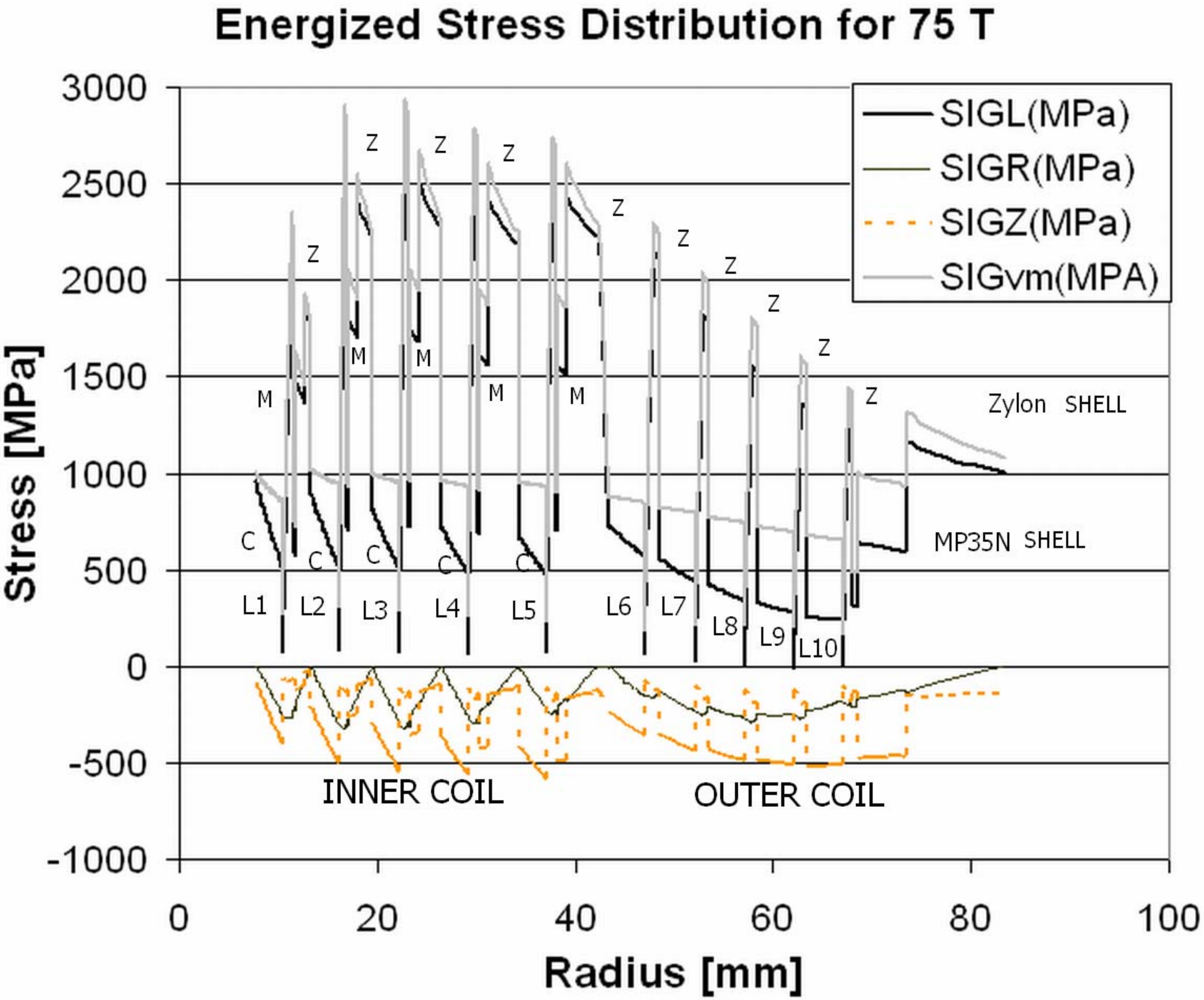

Zylon & S2 Interlayer


MP35N Sheet


Primary Zylon Reinforcement

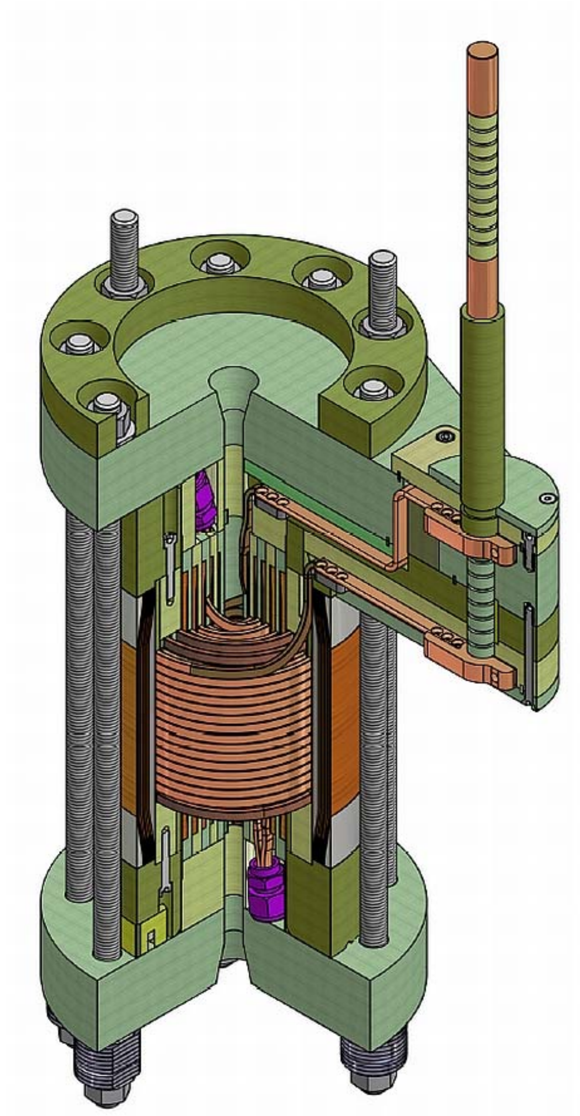
75 T Inner and Outer Coils



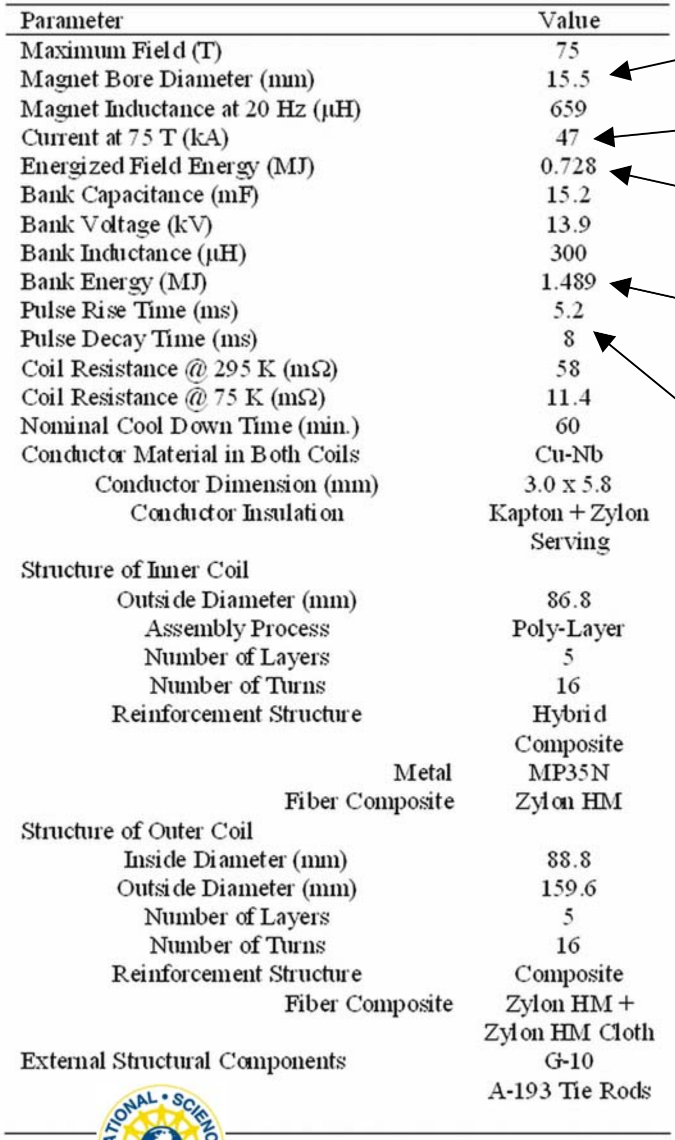


Energized mid-plane stress distribution for 75 T prototype. Layers are designated with the notation L1 – L10. The Cu-Nb conductor is designated by the letter C. Zylon reinforcement regions are designated by the symbol Z. The letter M designates MP35N metal reinforcement. Each layer in the inner coil is fully reinforced by a hybrid structure comprised by an MP35N sheet wrapped shell and a high-density zylon fiber composite.

NHMFL 75 T Prototype Magnet



Quantitative Technical Description



Parameter	Value
Maximum Field (T)	75
Magnet Bore Diameter (mm)	15.5
Magnet Inductance at 20 Hz (μH)	659
Current at 75 T (kA)	47
Energized Field Energy (MJ)	0.728
Bank Capacitance (mF)	15.2
Bank Voltage (kV)	13.9
Bank Inductance (μH)	300
Bank Energy (MJ)	1.489
Pulse Rise Time (ms)	5.2
Pulse Decay Time (ms)	8
Coil Resistance @ 295 K (mΩ)	58
Coil Resistance @ 75 K (mΩ)	11.4
Nominal Cool Down Time (min.)	60
Conductor Material in Both Coils	Cu-Nb
Conductor Dimension (mm)	3.0 x 5.8
Conductor Insulation	Kapton + Zylon Serving
Structure of Inner Coil	
Outside Diameter (mm)	86.8
Assembly Process	Poly-Layer
Number of Layers	5
Number of Turns	16
Reinforcement Structure	Hybrid Composite
Metal	MP35N
Fiber Composite	Zylon HM
Structure of Outer Coil	
Inside Diameter (mm)	88.8
Outside Diameter (mm)	159.6
Number of Layers	5
Number of Turns	16
Reinforcement Structure	Composite
Fiber Composite	Zylon HM + Zylon HM Cloth
External Structural Components	G-10 A-193 Tie Rods

Bore [mm]

Current [kA]

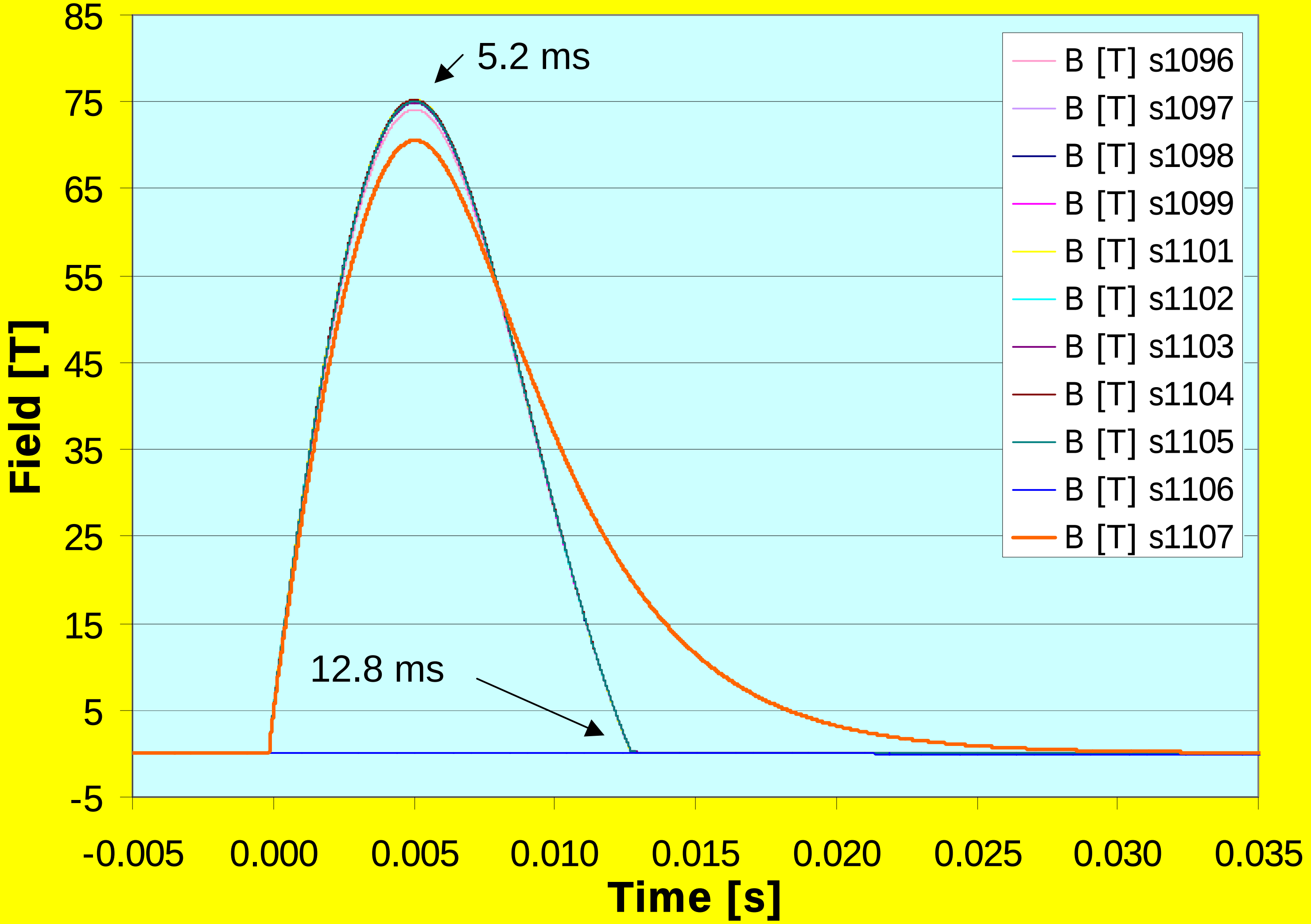
Field Energy [MJ]

Bank Energy [MJ]

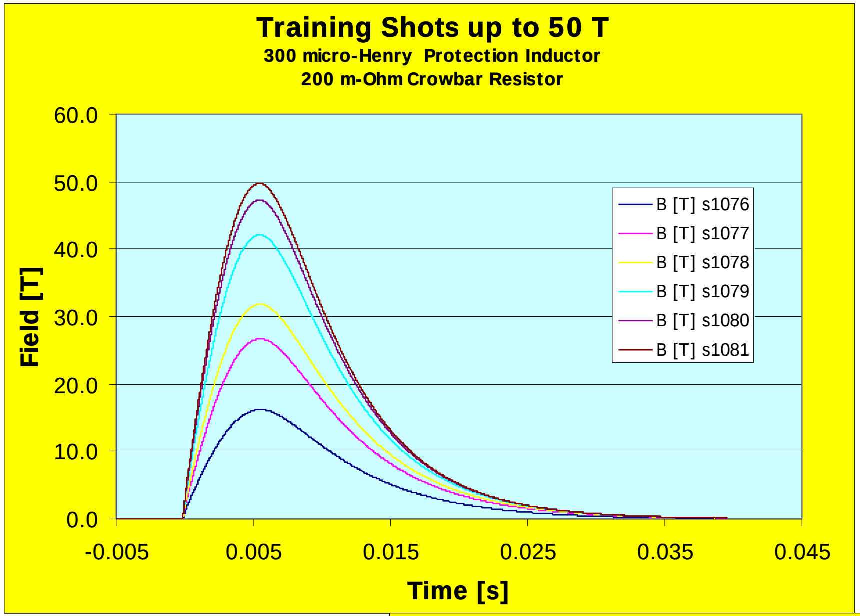
Time Constants [ms]

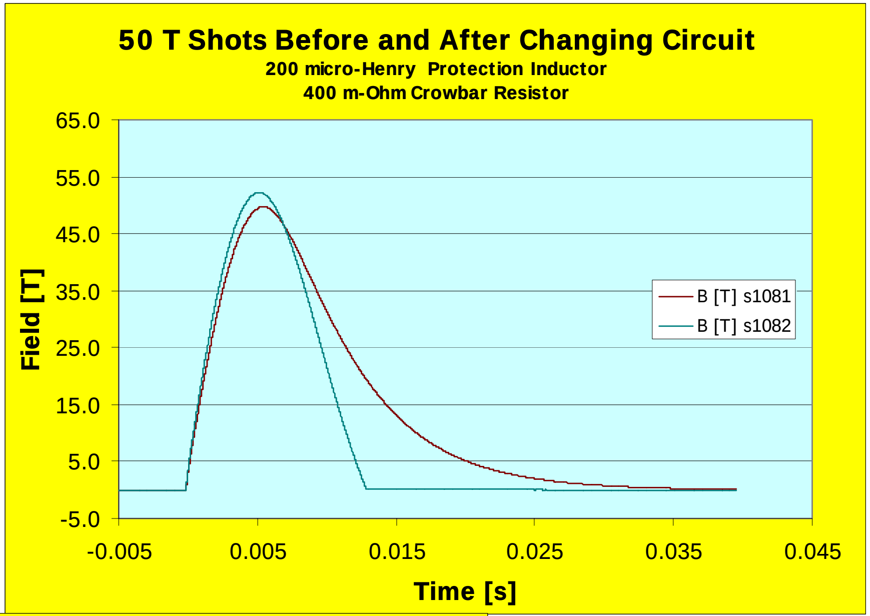
75T Magnet Waveforms

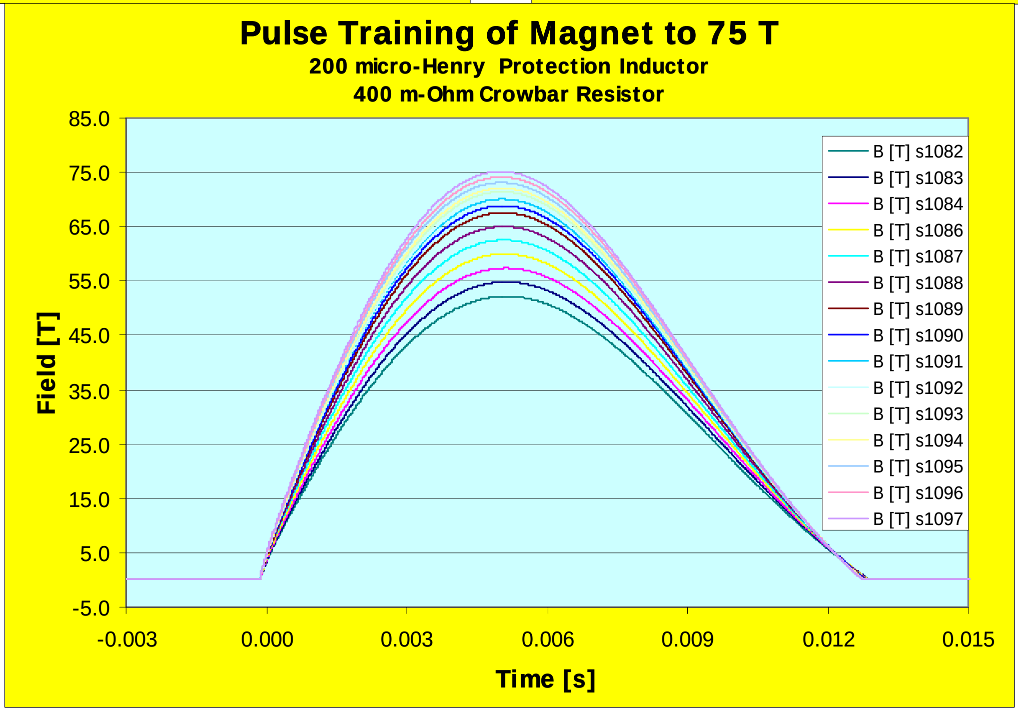
200 micro-Henry Protection Inductor
400 m-Ohm Crowbar Resistor @ B > 70 T
200 m-Ohm Crowbar Resistor @ B < 70 T



Prototype Training to 75 T


Training Shots up to 50 T
300 micro-Henry Protection Inductor
200 m-Ohm Crowbar Resistor

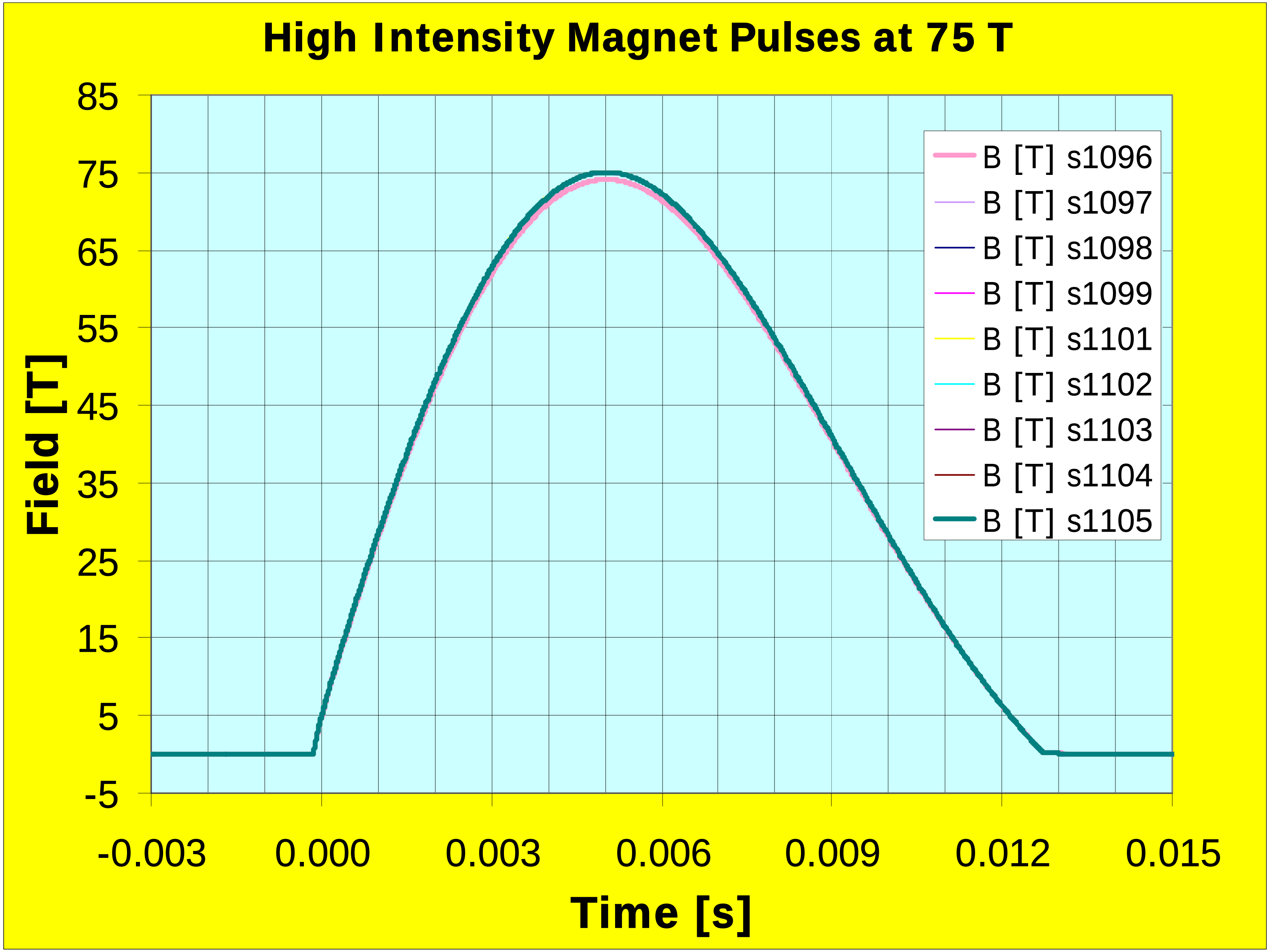

50 T Shots Before and After Changing Circuit
200 micro-Henry Protection Inductor
400 m-Ohm Crowbar Resistor


Pulse Training of Magnet to 75 T
200 micro-Henry Protection Inductor
400 m-Ohm Crowbar Resistor

Design voltage calculation was within 50 V using Eyssa’s code.

Geometric Tolerances are Key

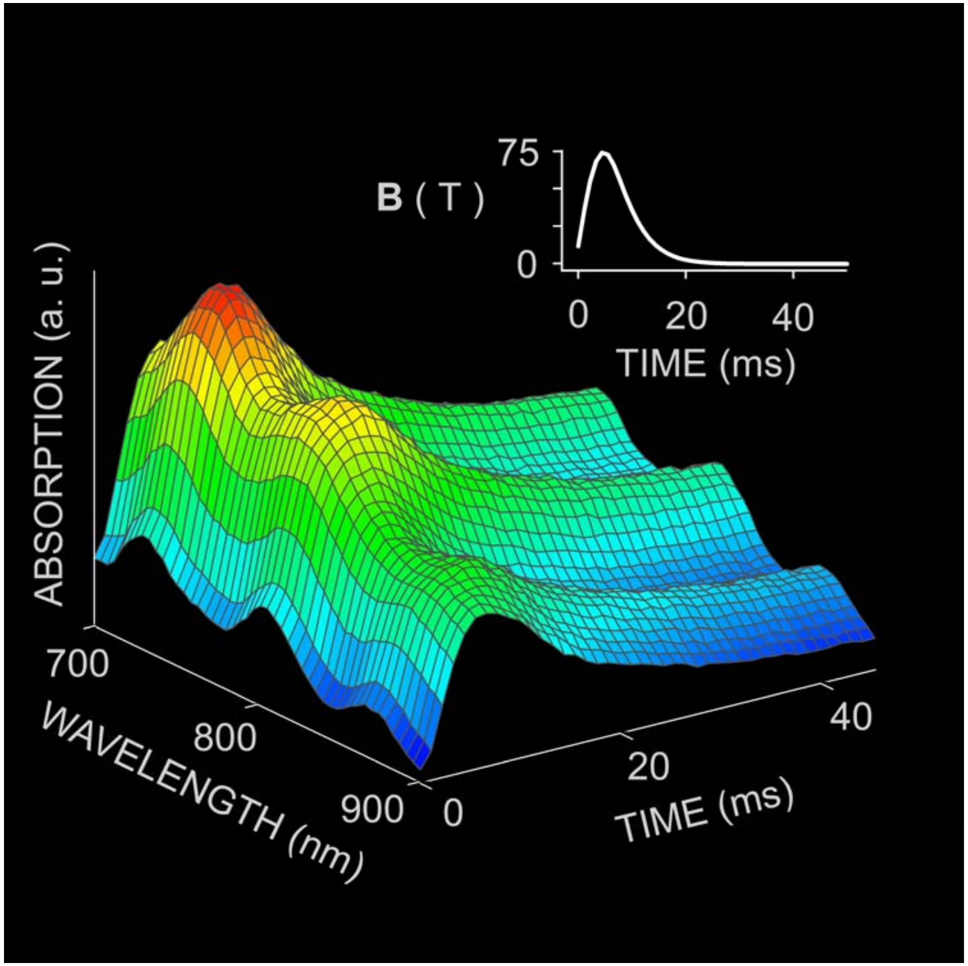
Initial Operation at 75 T



Pulsed Science in 75 T

Graduate student Sasa Zaric, from Prof. Jun Kono's research group at Rice University, worked with NHMFL-LANL scientist Scott Crooker to measure polarization-dependent optical absorption in single-walled carbon nanotubes in magnetic fields up to 75 T. These high-quality carbon nanotubes, prepared by Prof. Richard Smalley's research group (also at Rice University), are individually suspended by micelles in an aqueous solution, which allows them to rotate freely and orient in large magnetic fields via their anisotropic magnetic properties. Magnetic flux through the bore of aligned individual nanotubes alters the band structure of the nanotube itself through an exotic manifestation of the Aharonov-Bohm effect. This non-intuitive quantum effect is predicted to monotonically decrease the band gap of semiconducting nanotubes with increasing magnetic field, ultimately transforming them into metallic nanotubes at magnetic fields of order 2000 Tesla (for tube diameters ~ 1 nm). In 75 Tesla, the observed broadening and splitting of the interband absorption peaks in semiconducting nanotubes signals the onset of this Aharonov-Bohm effect, and quantitative measurements allow direct comparison with existing theories for this effect.

This work is part of a scientific collaboration between Rice University, the NHMFL, and the High Magnetic Field Laboratory in Toulouse, France. This work represents a continuation of Zaric and Kono's previous studies, published in Science earlier this year, of carbon nanotube absorptionand emission in the 45 T Hybrid magnet.



Optical absorption of magnetically-aligned carbon nanotubes to 75 Tesla. Peaks in the spectra correspond to particular helicities of nanotubes.

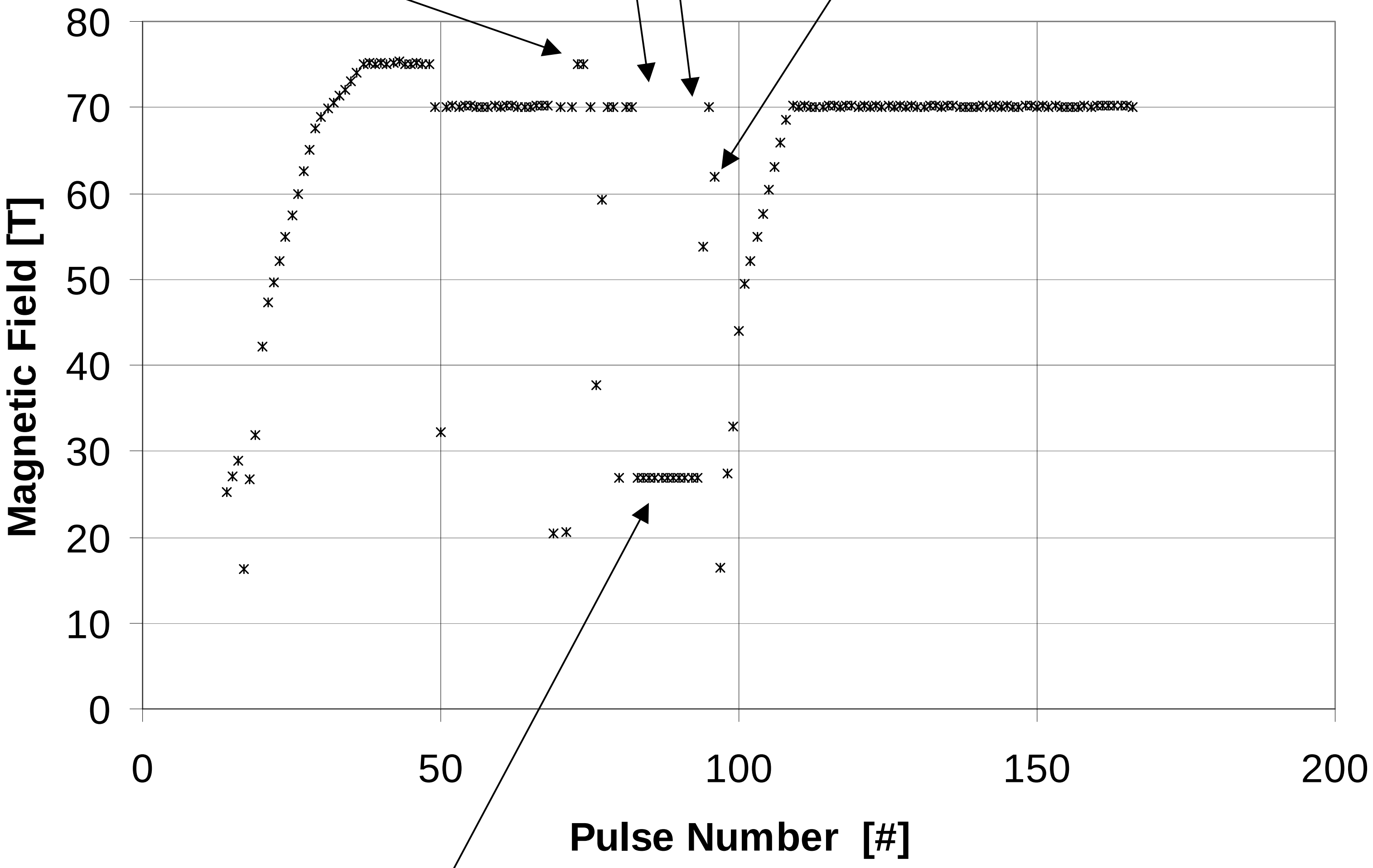
The Stony Path

Operations Record for 75 T Prototype

Optics Work

Noise Detected

Fault!



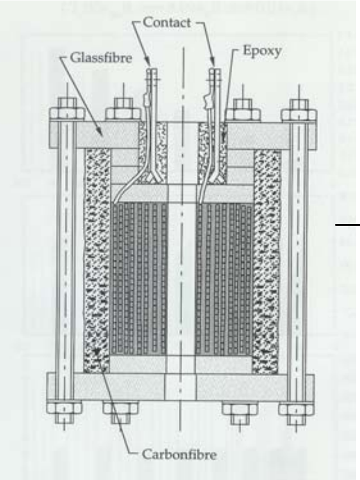
Cap Bank
Diagnostics

47 kA is challenging

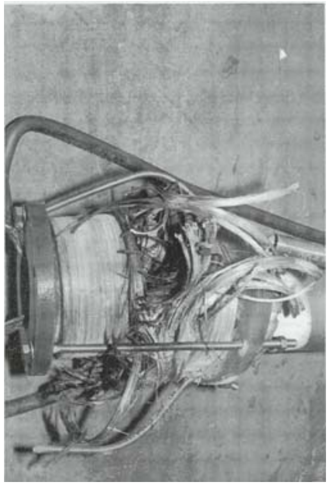
"Well, back to the old drawing board."

Another Measure of Progress

1994

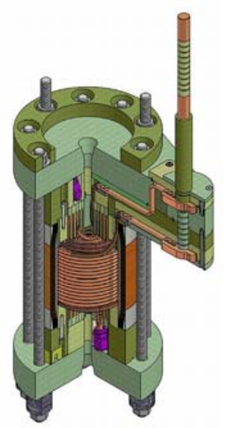


40-T Design

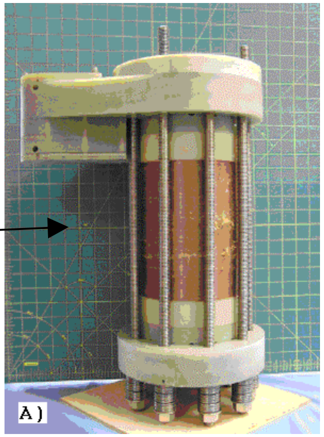


Electrical Fault

2005



75-T Design



Electrical Fault

Caveats

- Engineering does have its limits.
- Physical nature of processed materials determines what you can do.

Fault Observations Insert Coil

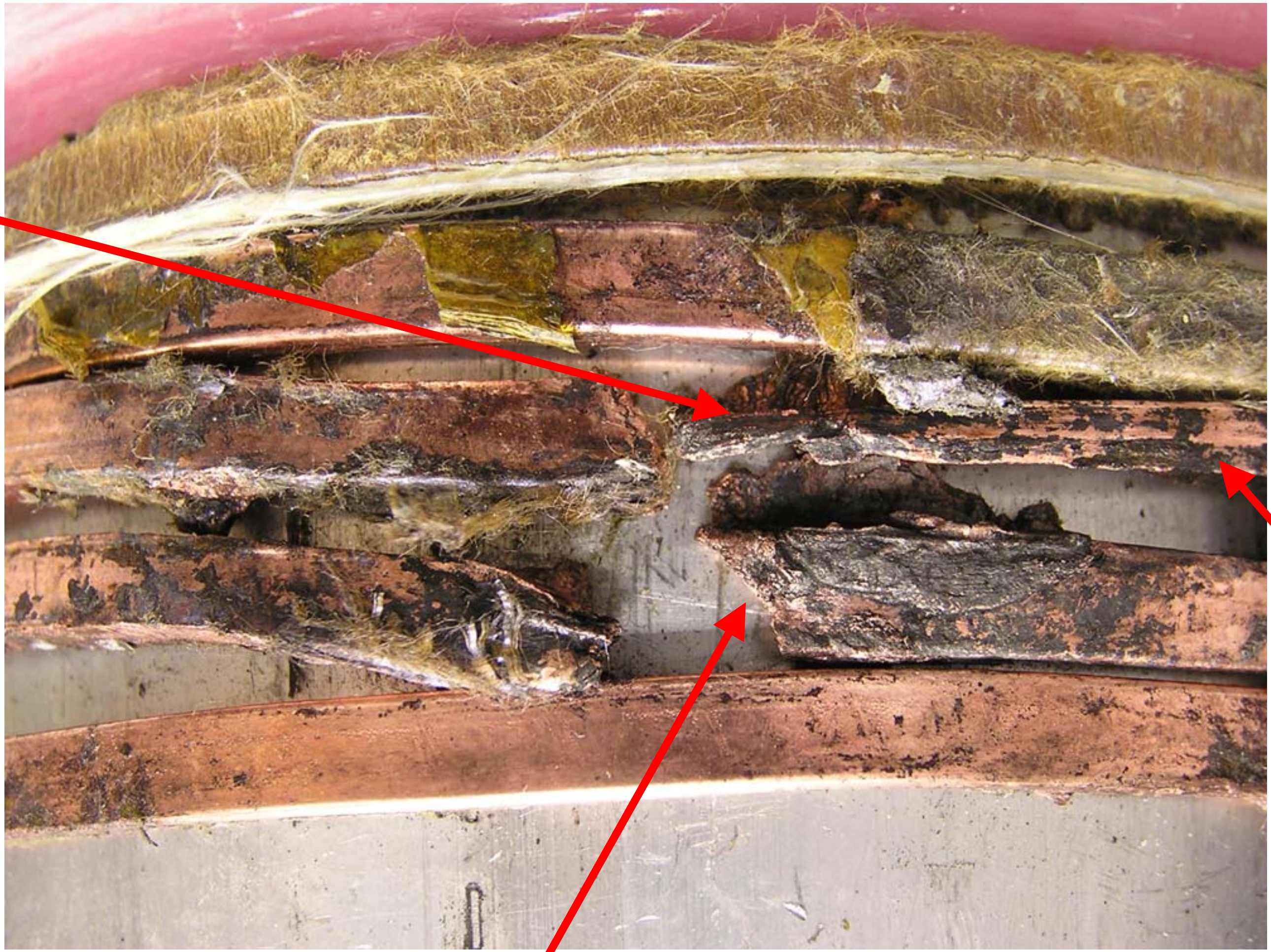
Extraction of 75 T Insert from outer coil assembly.

Detail image of damaged zylon on external surface of insert. The burn depth was ~ 0.2 mm to 0.3 mm in depth

Fault Observations Outer Coil

Burn damage present on the bore of the outer coil assembly.

Fault Observations Outer Coil



Magnetic Center

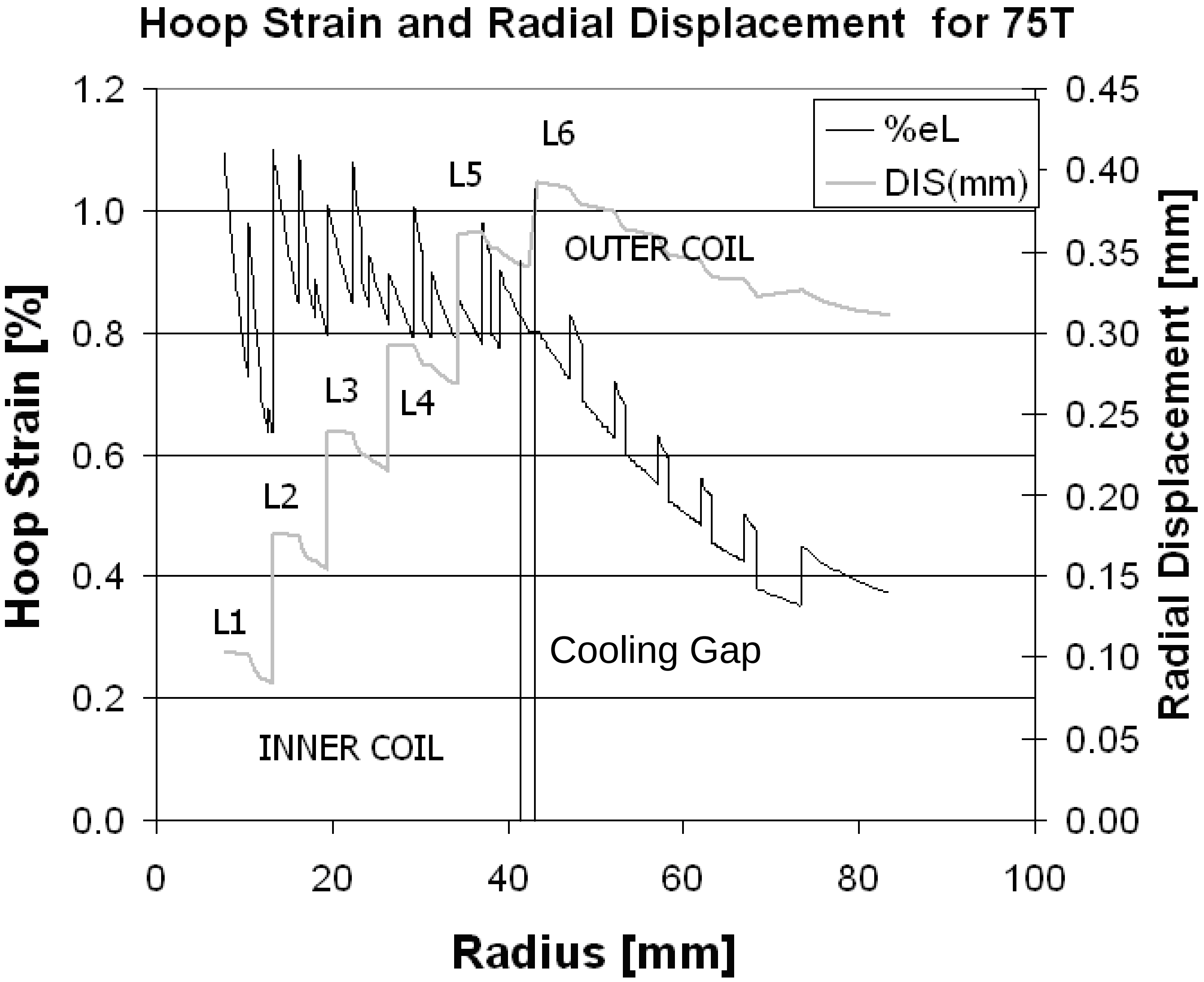
Primary Failure Turn

Extruded taper caused by Lorentz loading after Cu melted.

Secondary Shear Failure

Summary Observations of Fault

- Fault in turn 11 of first layer of outer coil
- Hypothesis
  - Wire defect initiating crack. (Catastrophic local Joule heating)
  - Arcing between turns creating defect (Catastrophic local Joule heating)
  - Possible cryo-delamination damage of epoxy matrix on inner bore
- Post failure mechanics
  - Turn continued to carry current
  - Extreme heat melted copper matrix in wire
  - Turn collapsed due to adjacent axial Lorentz loads.
  - Turn was extruded into cooling manifold between coils
  - Adjacent turn sheared due to additional axial stress
- Insert coil recoverable.


Hoop Strain and Radial Displacement for 75T

Note the radial displacements of L6 which is the fault layer. Conductor strain is below 0.8%. However the net radial displacement is large. The inner bore defines the outer wall of the LN cooling manifold.

Resulting actions on 75T & 80 T Projects

- Recover insert. Replace zylon reinforcement.
- Redesign 75 T outer coil for additional wire insulation of zylon serving.
- Review & redesign 80 T magnet design to minimize axial compression.
- Review selection of turn to turn filler materials.

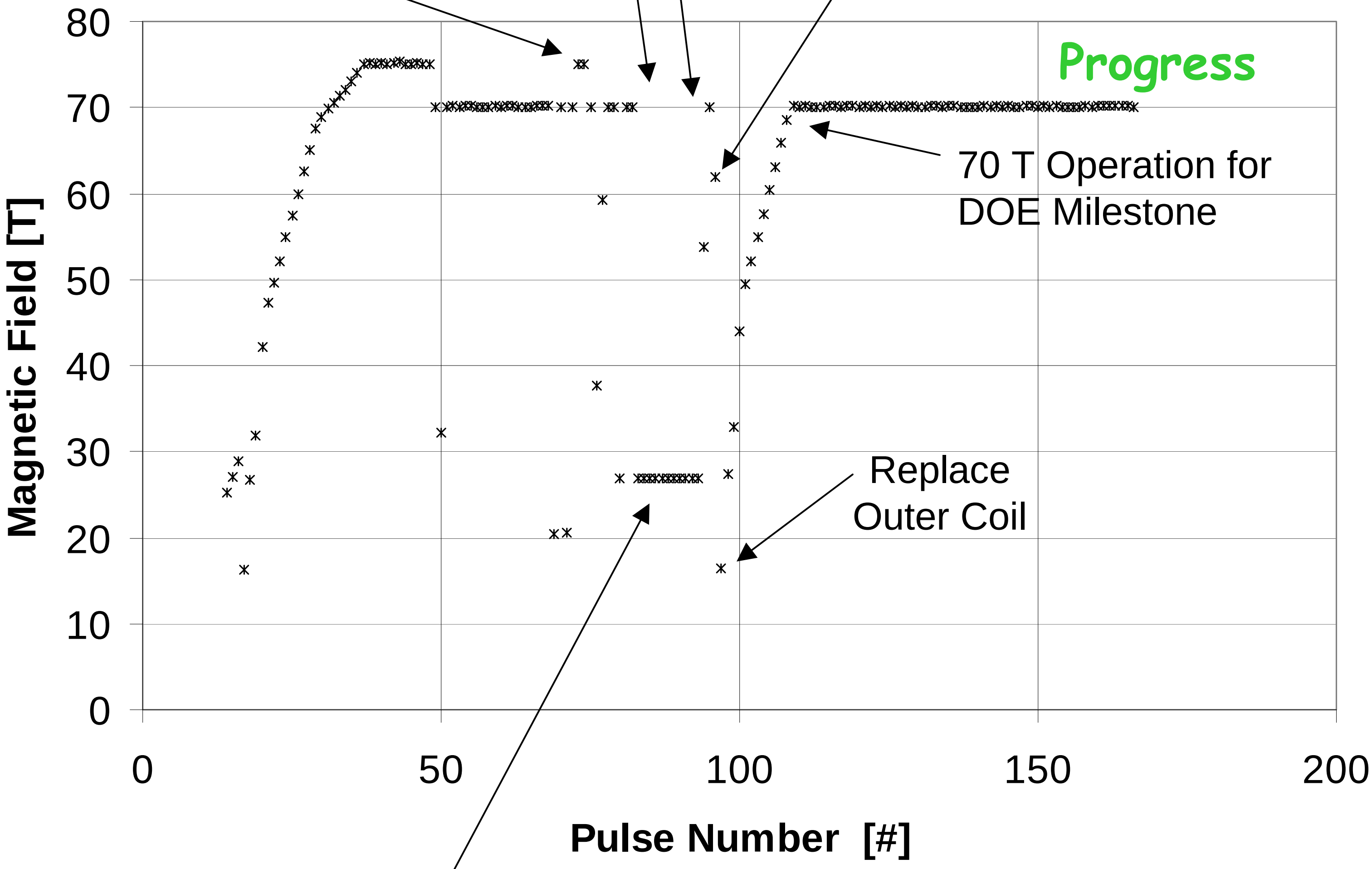
Example of zylon serving present on Cu-Nb conductor helix.

75 T Insert Recovery

Images of 75T magnet assembly during rebuild. The images are: A) The 75T prototype after electrical fault, B) The insert coil after extraction from the damaged outer coil, and C) The insert coil after minor rework and just prior to reassembly for use in another 75T magnet.

4 month
recovery
time!

Operations Record for 75 T Prototype



Optics Work

Noise Detected

Fault!

The Stony Path

Progress

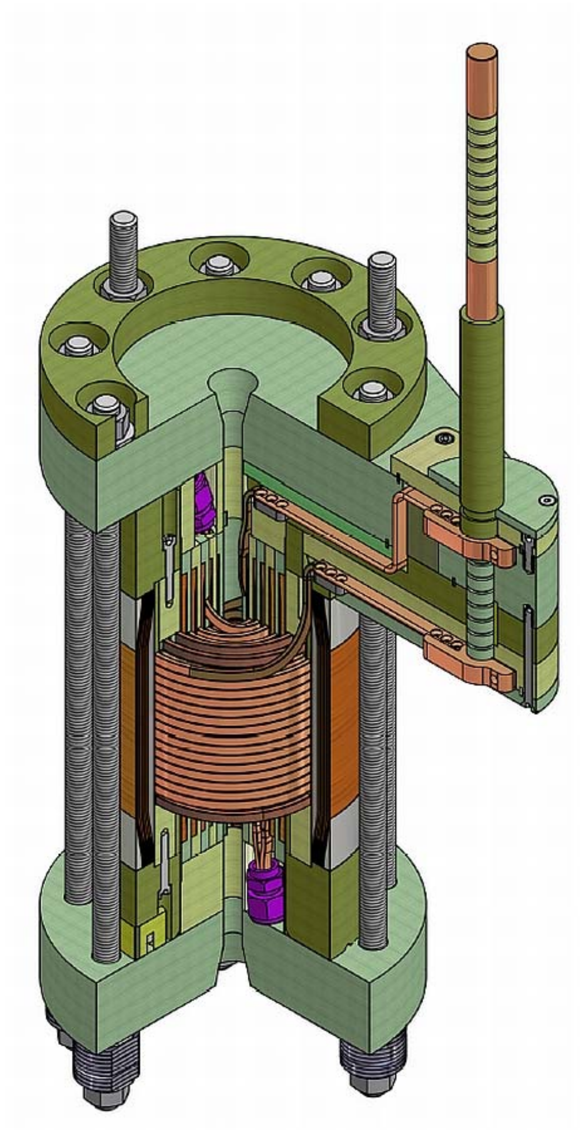
70 T Operation for DOE Milestone

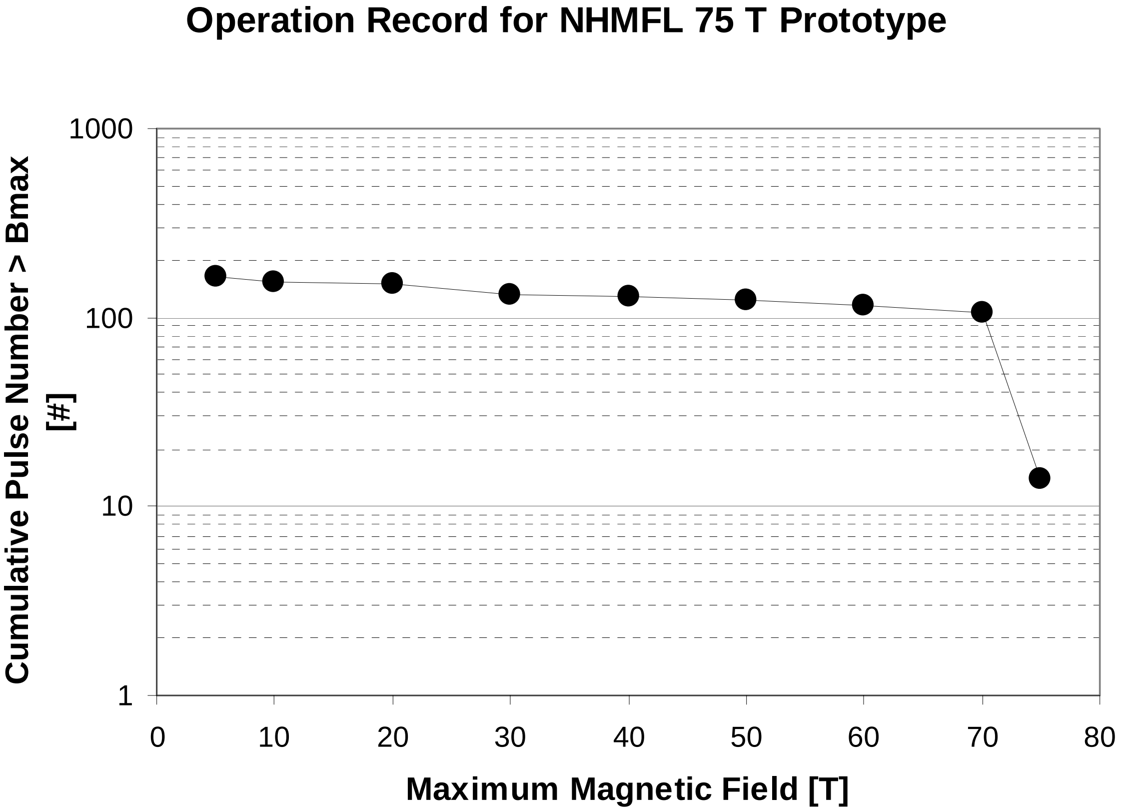
Replace Outer Coil

Cap Bank Diagnostics

47 kA is challenging

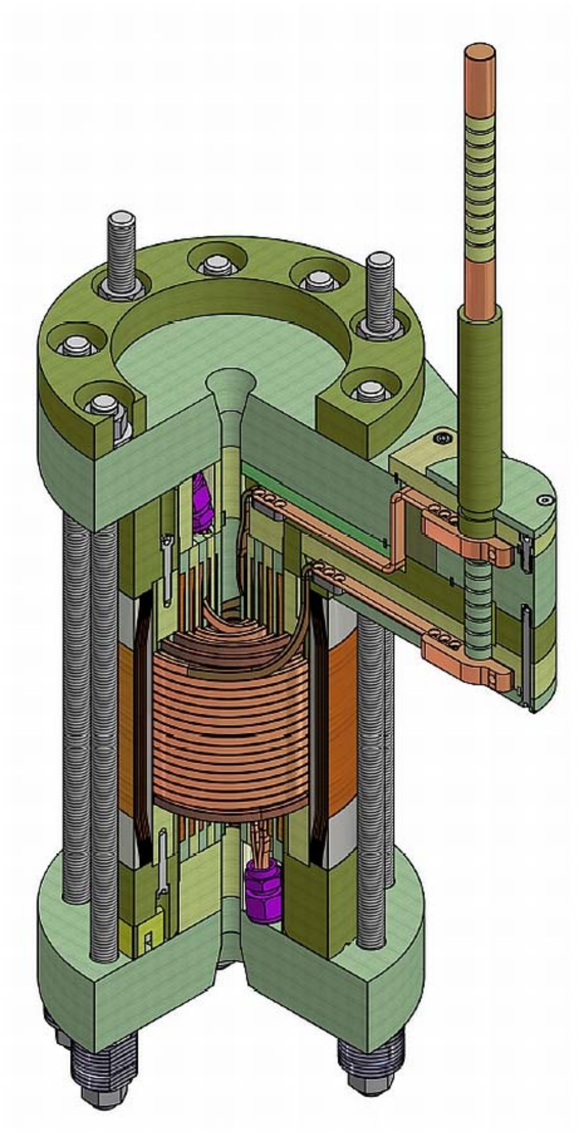
75T Pulse Performance





Operation Record for NHMFL 75 T Prototype

75 T Summary



- •Developed novel hardware design.
- •Developed & implemented new materials.
- •Demonstrated 75 T mono-coil technology.
- •Operated at intensities equivalent to 100 T.
- •Validated of Cu-Nb nano-composite.

Contributors to NHMFL 75 T Magnet

Individual	Institution	Function	Role in 75T work
John Miller	NHMFL	MS&T Director	Total support of technical work
Ed Miller	NHMFL	Technician	Winding - R&D
Ken Pickard	NHMFL	Technician	Fabrication & R&D
Andy Gavrilin	NHMFL	Analysis	Thermo-Mechanical Model
Scott T. Bole	NHMFL	Designer	Manager Eng. Group
H.J. Schneider-Muntau	NHMFL	Mentor	Mentor
Scott Marshall	NHMFL	Desinger	Magnet CAD
Steve Kenny	NHMFL	Designer	Zylon Serving Machine
Ke Han	NHMFL	Metallurgy	MP35N & Conductor
Bob Walsh	NHMFL	MS&T-MTS	Materials Characterization
Vince Toplosky	NHMFL	MS&T-MTS	Materials Testing
Joe King	NHMFL	Technician	Fabrication
Mark Collins	NHMFL	Machinist	Fabrication
Lee Windham	NHMFL	Purchasing	Procurement
Alex Lacerda	NHMFL*	NHMFL Deputy Director	Total support of 100T program
Dwight Rickel	NHMFL*	100T Project Leader	Magnet Testing +
Jim Sims	NHMFL*	100T Outsert Team Leader	Total Moral & Technical Support
Joe Shillig	NHMFL*	Cap Bank	Bank Designer
Pat Ruminer	NHMFL*	Technician	Magnet Integration
Mike Pacheco	NHMFL*	Technician	Operations Support
Alan Paris	NHMFL*	Technician	Cap Bank Assembly
Mike Gordon	NHMFL*	Technician	Cap Bank Controls
Alexander Shikov	Bochvar Institute	Deputy Director General Bochvar Institute VNIINM	Total support of R&D effort to producer Cu-Nb
Victor Pantsyrnyi	Bochvar Institute	Deputy Director Materials Division Bochvar Institute VNIINM	Cu-Nb Conductor R&D

NHMFL* NHMFL Pulsed Field Science Facility at Los Alamos National Laboratory