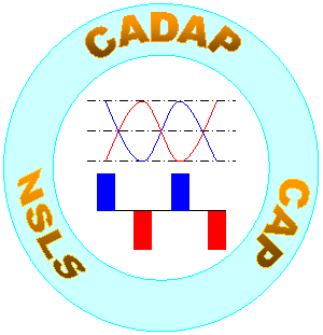


BNL-Accelerator Physics Seminar

Quench Protection

Issues in High Field Superconducting

Magnets

Linda Imbasciati

Acknowledgments:

- FNAL Technical Division: P. Bauer, G. Ambrosio, M. Lamm, A. Zlobin
- NHMFL Magnet Division: J.Miller, G. Miller
- LBNL Supercon Magnet: S. Caspi, L. Chiesa, D. Dietrich, P. Ferracin, S. Gourlay, A. Lietzke
- Technical University – Vienna: Prof. H. Kirchmayr

BNL, September 2003

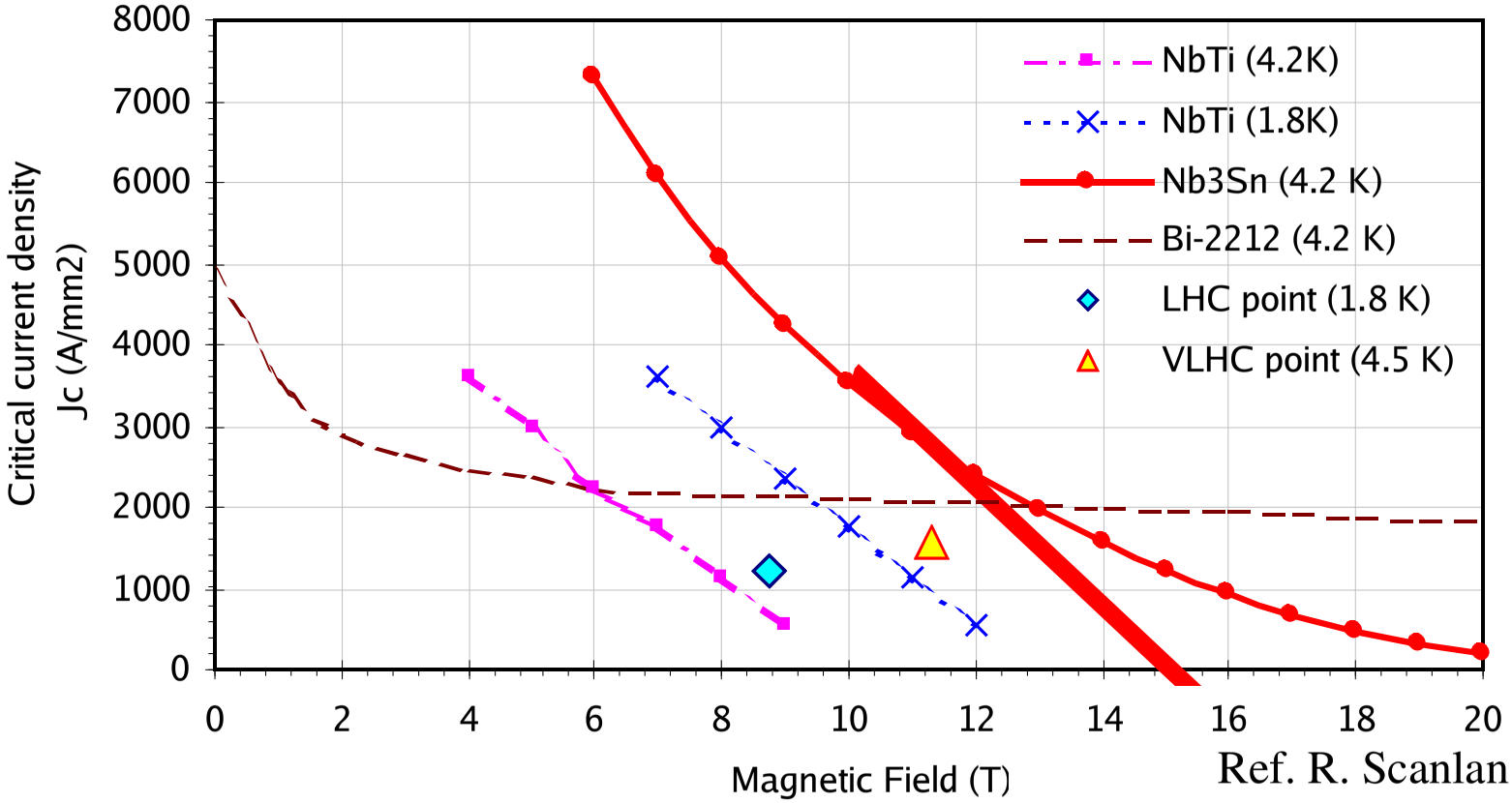
Outline

1. Introduction: high field Nb_3Sn magnets for future particle accelerators
2. Quench Protection Studies
    1. Simulations of the quench
    2. Peak temperature issue
3. Thermal Shock experiments
    1. Cable quench test and simulations
    2. Small Nb_3Sn magnet quench test

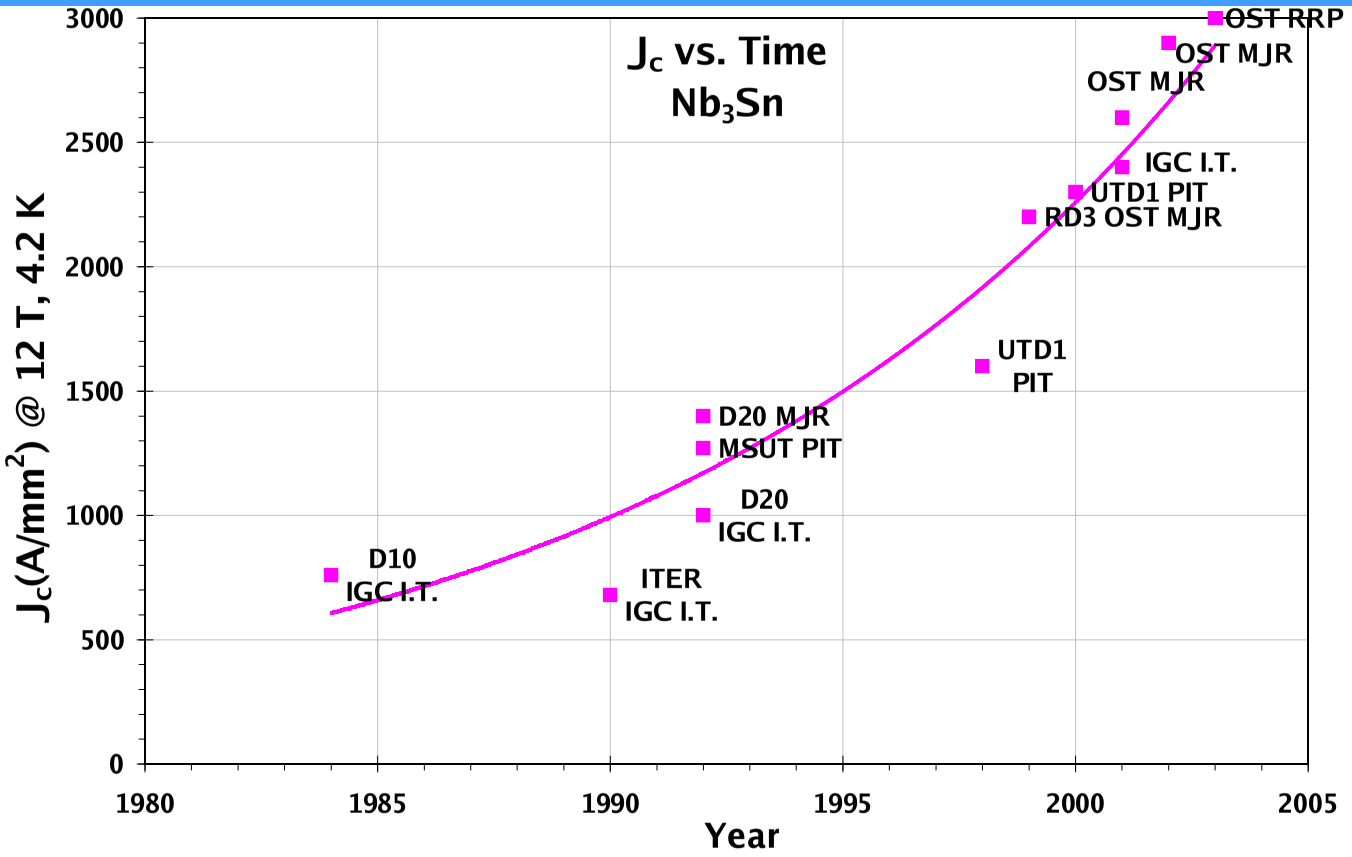
- Conclusions

Accelerator development

Accelerator		E (TeV)		R (km)	B_0 (T)	Magnet	cooling	Year	
Tevatron	Fermilab	2	c.m. p-p_{bar}	1	4.5	NbTi	LHe I	'83	Operating
HERA	DESY	0.9	p -target	1	5.5	"	"	'91	Prot.-elect.
RHIC	BNL	0.2	c.m.	0.6	3.5	"	"	'99	Heavy ions
SSC	SSCL	40	c.m. p-p	14	6.6	"	"	'93	Dismissed
LHC	CERN	14	"	4	8.3	"	He II, 1.9 K	2007	Scheduled
VLHC-1	Fermilab	40	"	35	2	superferric	LHe, 4.5 K	2015	HEPAP recc.
VLHC-2	"	175	"	"	10	Nb_3Sn	"	2030	?



Nb_3Sn Conductor Development



US/HEP Conductor Development Progress

Parameter	Goal	Progress
J_c (A/mm^2)	3000	2600-3000
D_{eff} (?m)	< 40	100-120 (MJR, IT); 50 PIT
Piece length (km)	> 10	0.25-1.5 (MJR); 0.25 -1 (high J_c IT)
Heat treatment (hr)	< 400	148
Cost ($/kA -m at 12 T)	< 1.50	5.5 (Int. Sn); 7.75 (MJR)

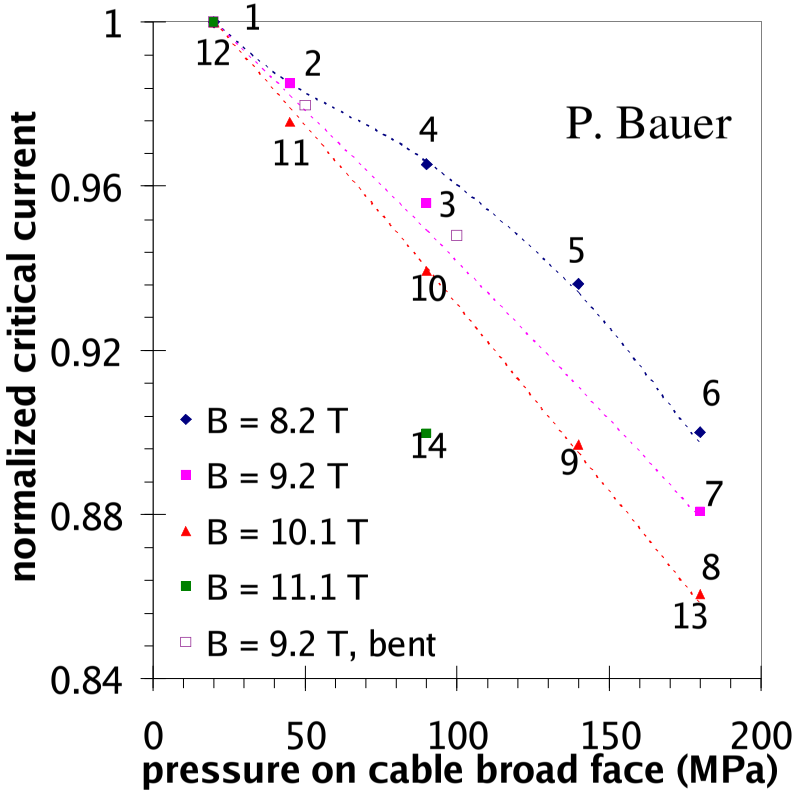
Nb_3Sn Strain Dependence

Nb_3Sn is a very brittle material after reaction:

- In composite strands, the maximum Ic corresponds to the minimum intrinsic strain
- Irreversible I_c degradation starts at ~0.5% tensile
- Irreversible I_c degradation starts at <-0.7% compressive

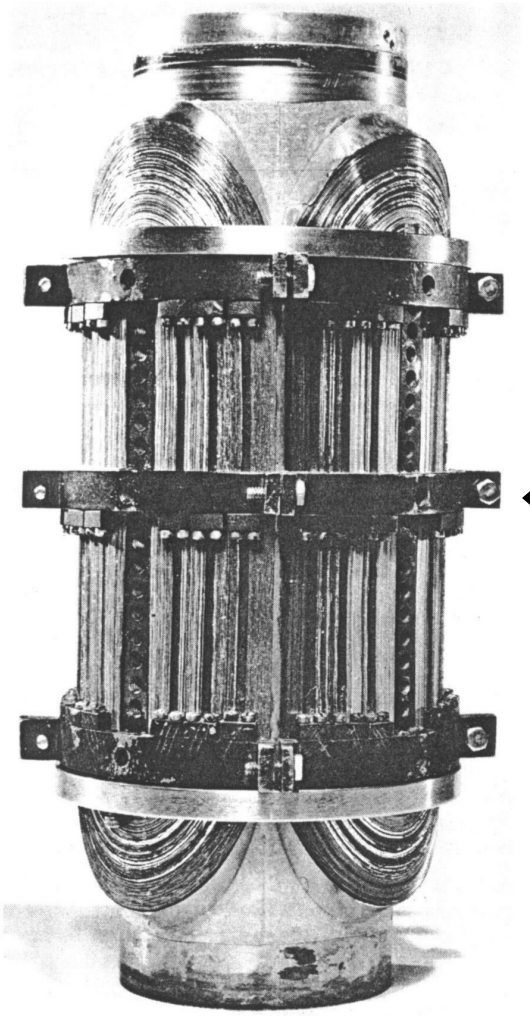
Strands: degradation of the critical parameters with applied strain

Cables: max. pressure on broad face for impregnated cables ~150 MPa



A. Den Ouden, thesis, Univ. of Twente

Nb_3Sn magnets history line



BNL Quadrupole

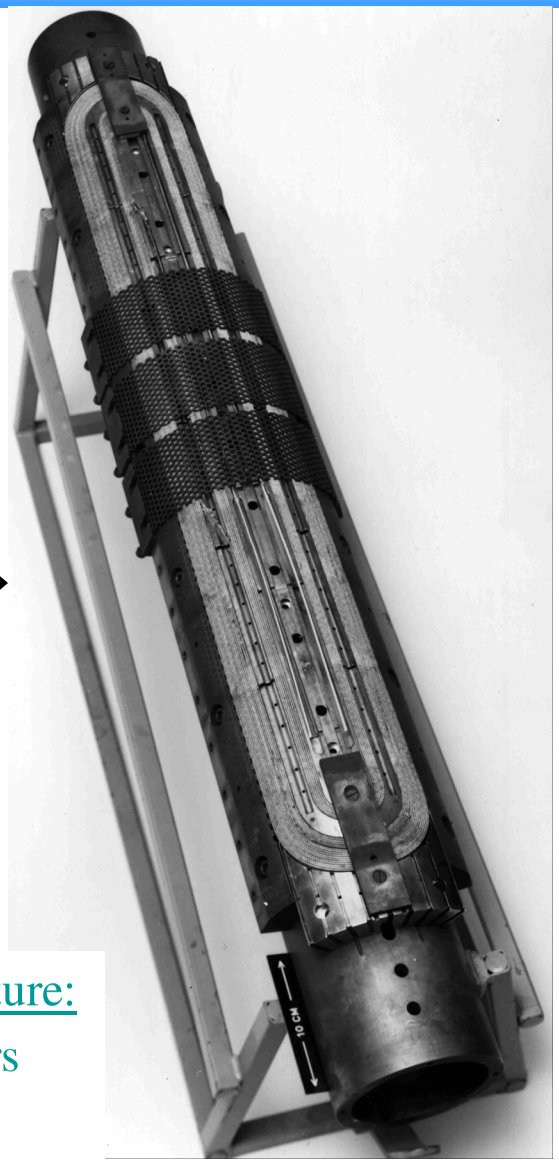
(W.B. Sampson, 1967)

- 3 T peak field
- Nb_3Sn tape 400 A/mm^2
- 7 cm bore
- 85 T/m field gradient

ELIN-CERN dipole

(S.Wenger, A.Asner, 1988)

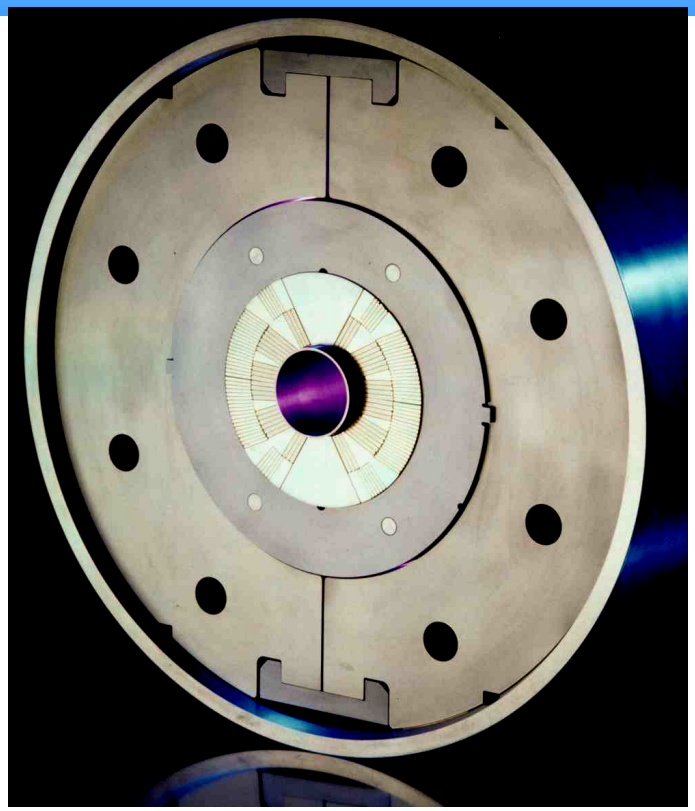
- mirror magnet: 10.2 T
- cos dipole: 9.45 T
- 5 cm bore



Mechanical structure:

- Aluminum collars
- Soft IronYoke
- Aluminum shell

Nb_3Sn magnets history line



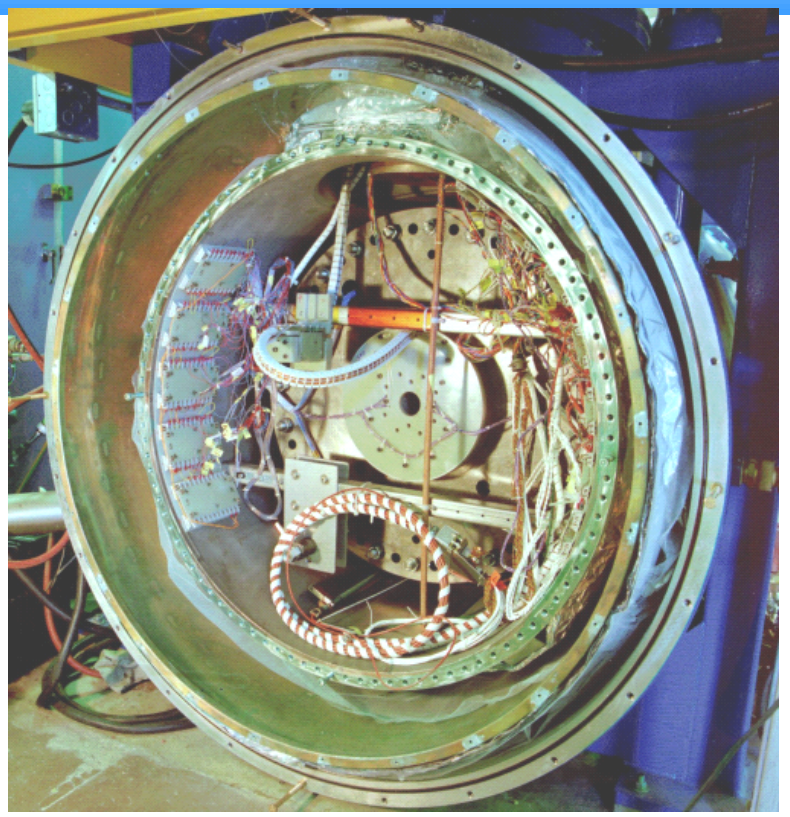
Twente Nb_3Sn dipole

(T.U. Twente, 1997)

-11 T field

- 5 cm bore

- PIT conductor from SMI



D20 Nb_3Sn dipole at LBNL

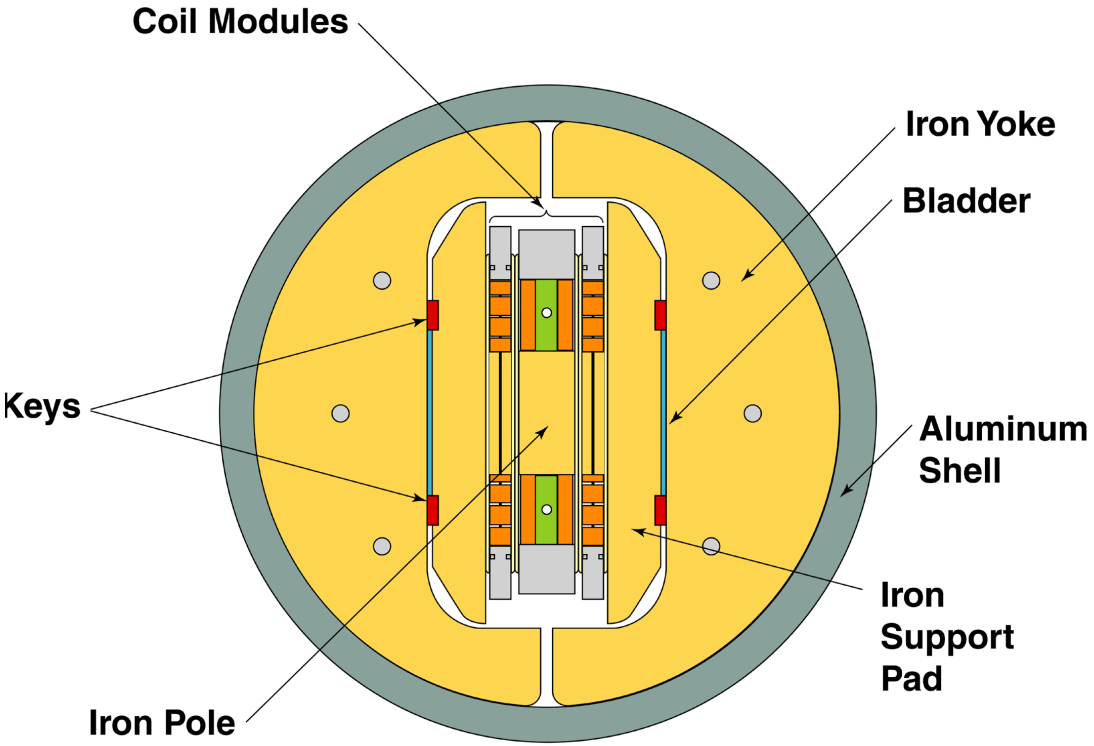
(R.Scanlan, Supercon Group, 1998)

- 12.8 T at 4.4 K

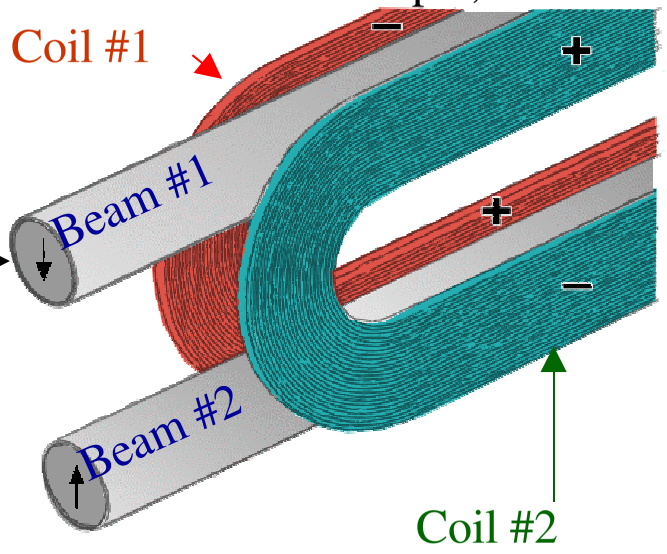
- 13.5 T at 1.8 K

- 5 cm bore

World Record Dipole Field



Ramesh Gupta, BNL



RD-3 Nb_3Sn dipole at LBNL

(S.Gourlay, Supercon Group, 2001)

- 14.7 T at 4.2 K
- coil gap = 25 mm
- 3 double-pancake coils
- MJR conductor

$F_x = 12$ MN/m @ 14.7 T

RD3 Design Features

– "Racetrack" coils

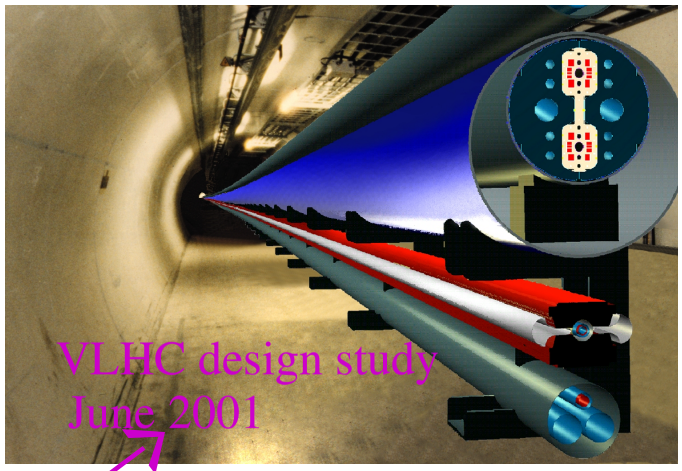
– Common coil design

- Intrinsic dual-bore
- Large bend radii

- Reusable structure with bladder system

Future accelerator projects

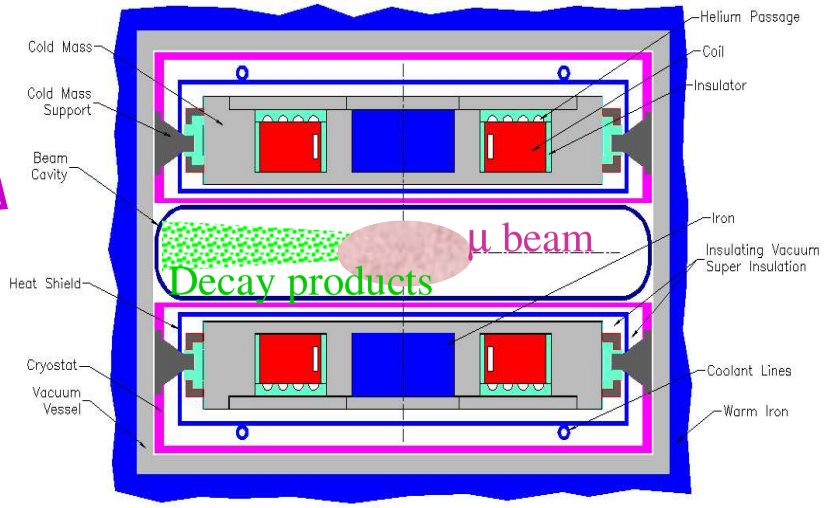
- LHC upgrade
  - Luminosity upgrade
    - Quadrupoles at IR
    - Separation dipoles at IR
  - Energy Upgrade: arc magnets



- Tesla: quad for final focus
- Very Large Hadron Collider (VLHC)
- Muon Collider, factory

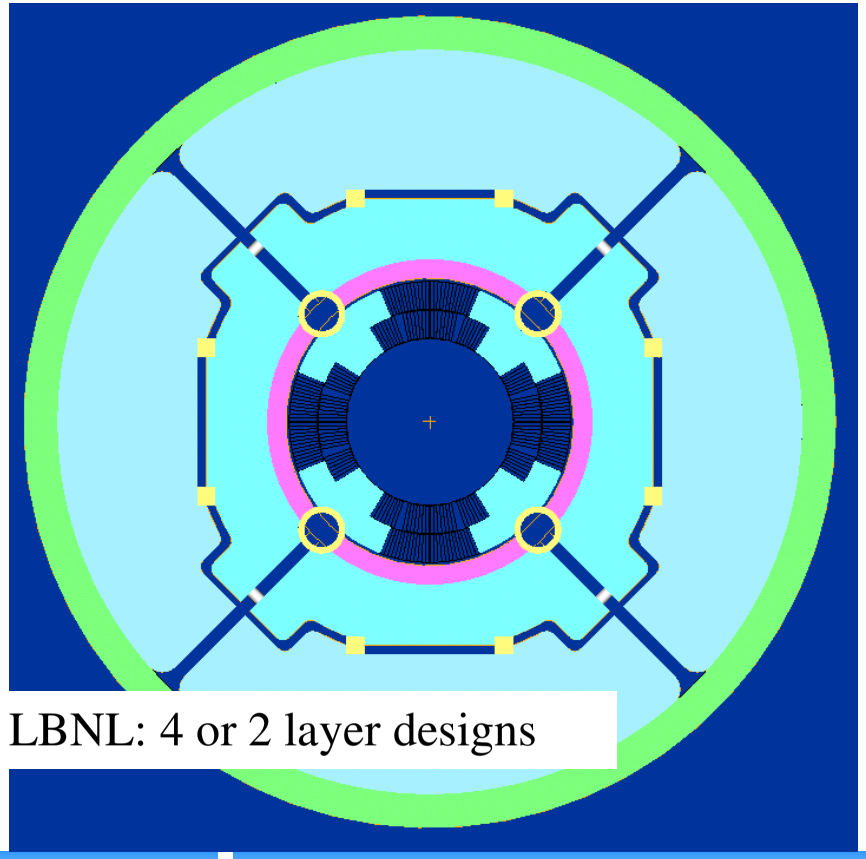
(high T margin for high radiation doses)

- …

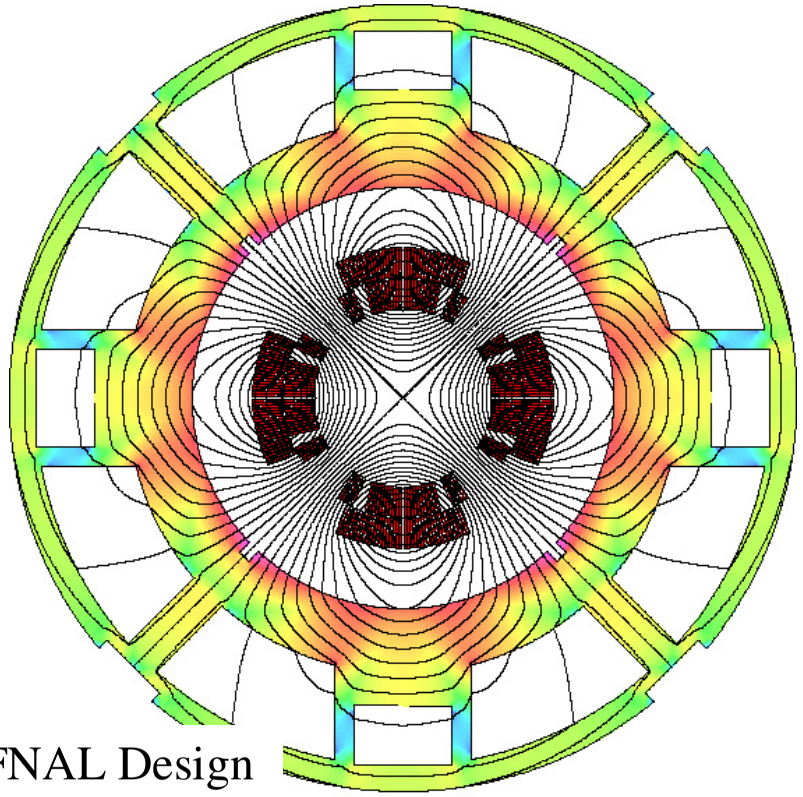


2nd Generation IR Quads for LHC

- LHC Upgrade proposal, x2 Luminosity by reducing β* by 1/2
- replace NbTi IR quads with Nb_3Sn Magnets (US National Labs)
  - use existing footprint (size, PS, cryogenics)
  - 90 mm aperture, 250 T/m gradient



LBNL: 4 or 2 layer designs

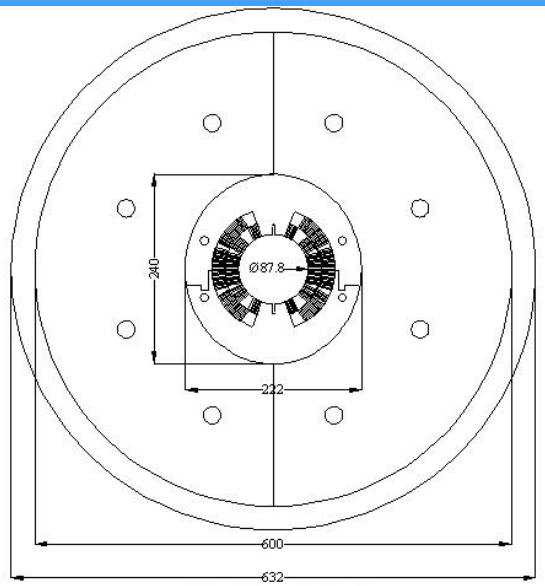


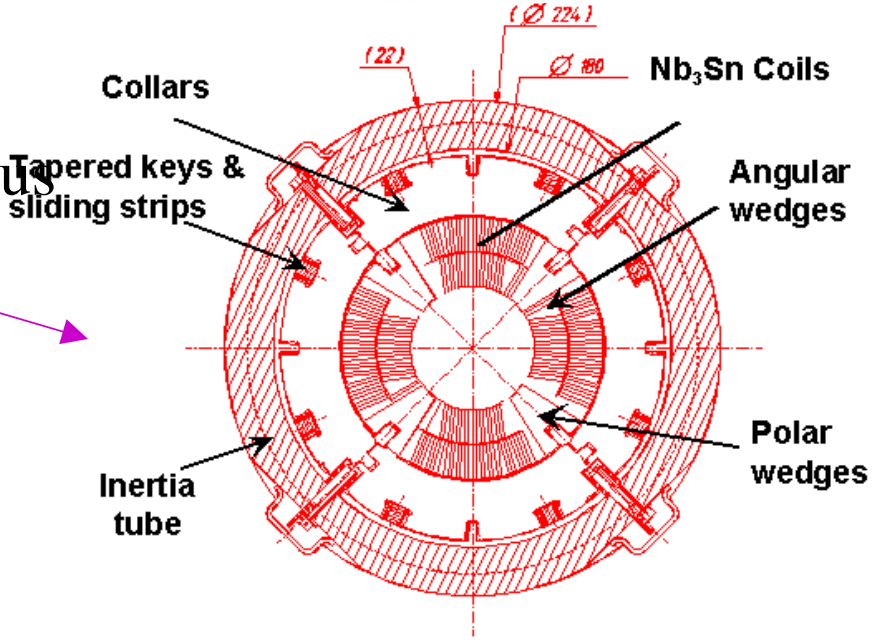
FNAL Design

Other Nb_3Sn LHC Upgrade Magnets

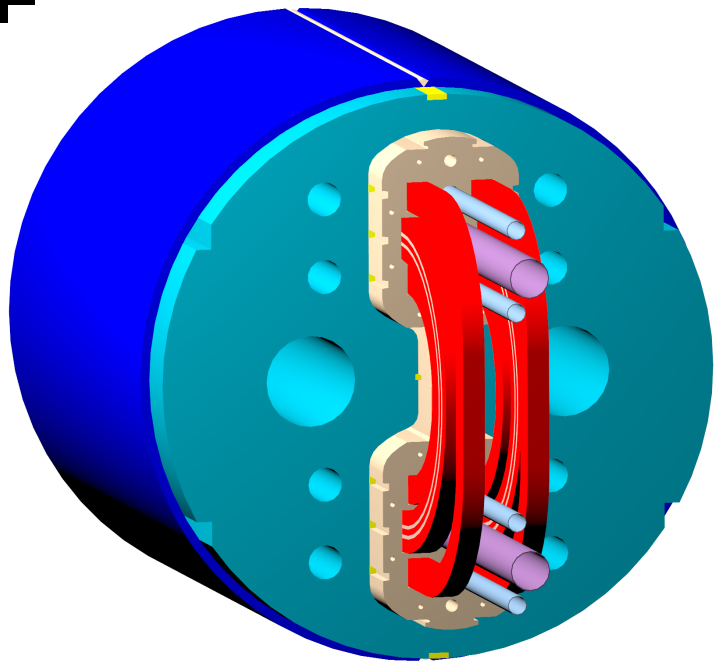
Possible upgrade for the LHC luminosity:

- Beam separator dipole D1
  - BNL design:
  - 15 T B_{ss},
  - Aperture: H: ~90 mm, V: 20 mm
  - TU of Twente and CERN
  - 10 T dipole magnet at 4.4 K, 88 mm bore
- Quadrupole for TESLA final focus
  - CEA/Saclay Nb_3Sn:
  - 211 T/m in 56 mm bore

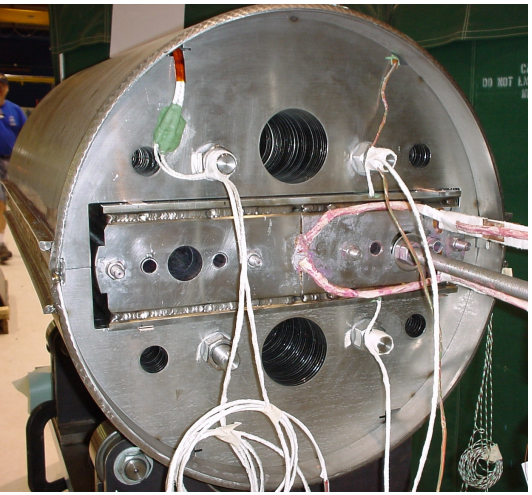




FNAL Common Coil



- Single-layer => Low inductance
- React-and-Wind => Low cost
- Mechanical design
  - Block type stress management
  - Precise conductor position
  - Small coil displacements
  - 10 mm thick skin



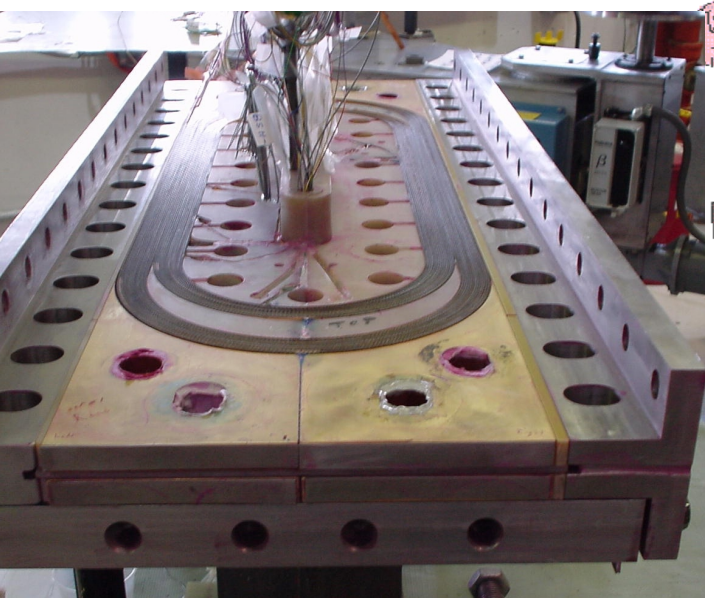
1st model just tested

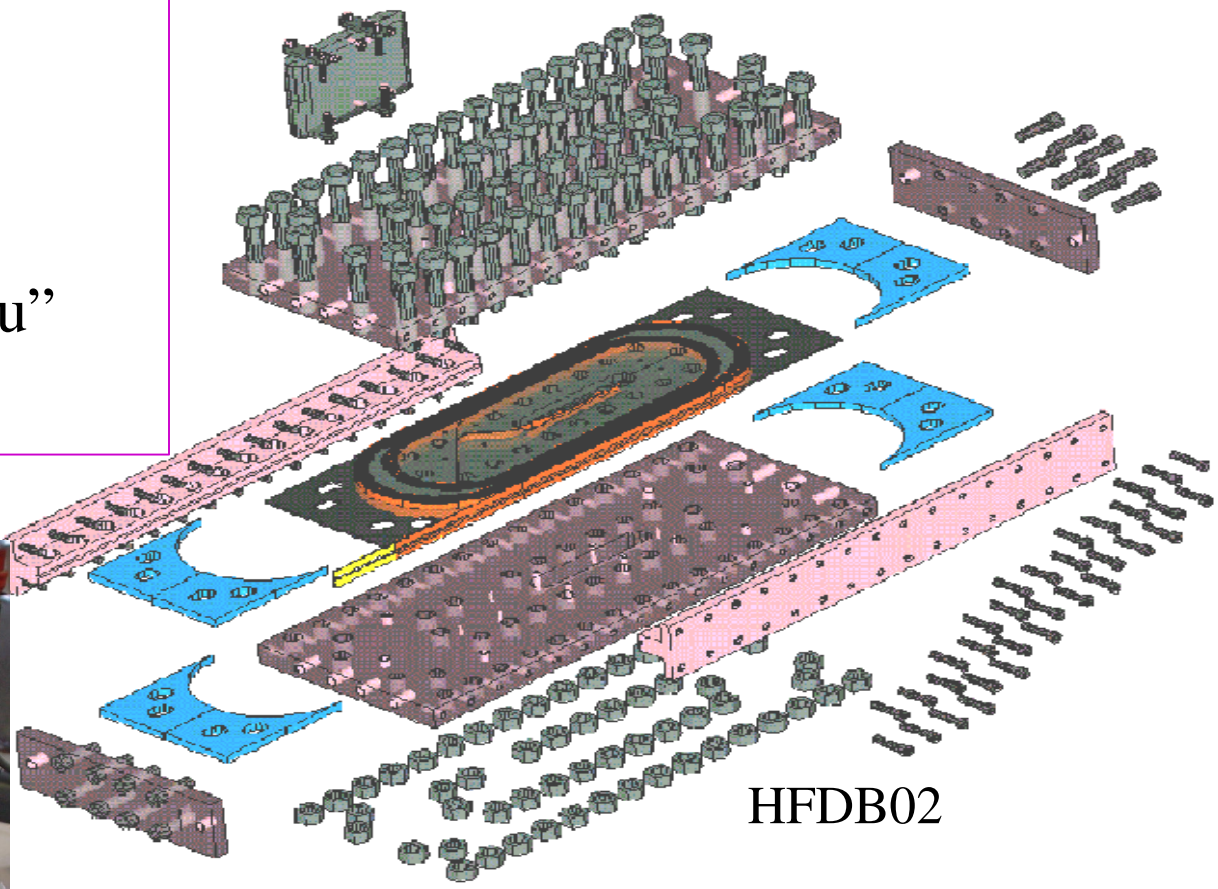
Bridge-reinforced collars

Racetrack Magnet

R&D magnet

- React&Wind
- Insulation study
- Impregnation “in situ”
- Quench studies



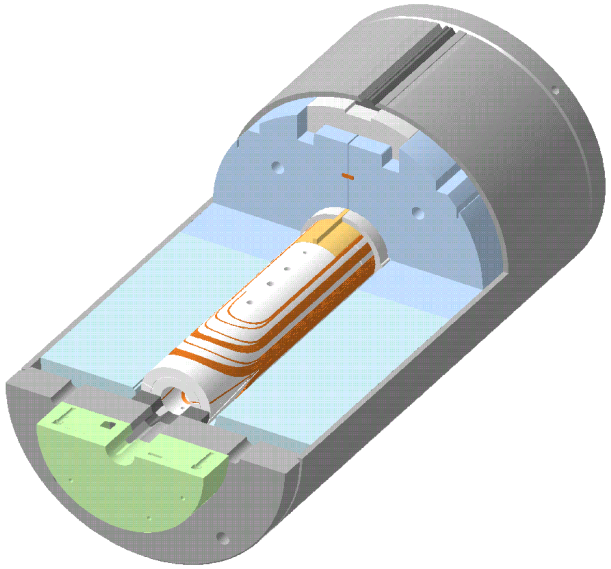


Test results

1- Conductor instabilities: current 60% SS

2&3- ~70% at faster current ramps

FNAL Cos Magnet



- Ceramic Insulation with Ceramic Binder
- No Interlayer Splice
- Spacers instead of Collars
- Coil pre-stress provided by both aluminum clamps and Skin

Model test results

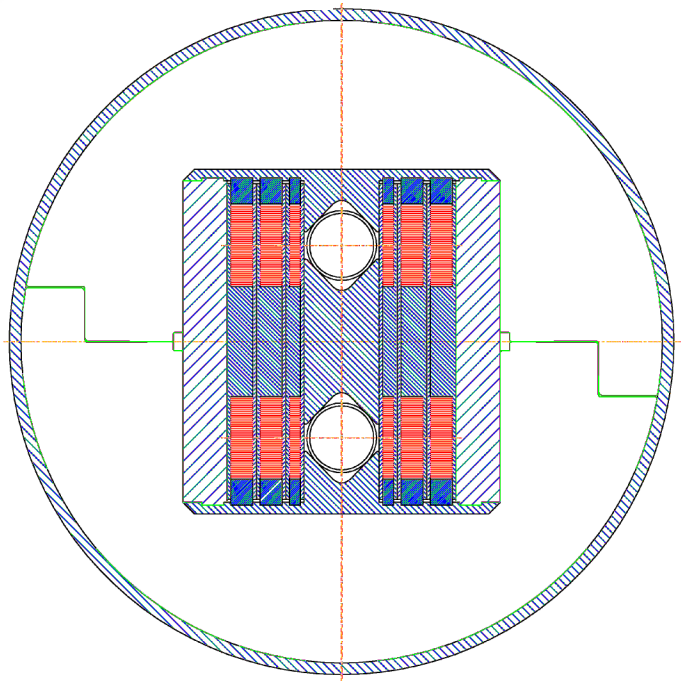
- Quench problems in splices
- Field Harmonics ~1 unit
- Low Hysteresis with passive correctors
- Low AC loss with cable SS core

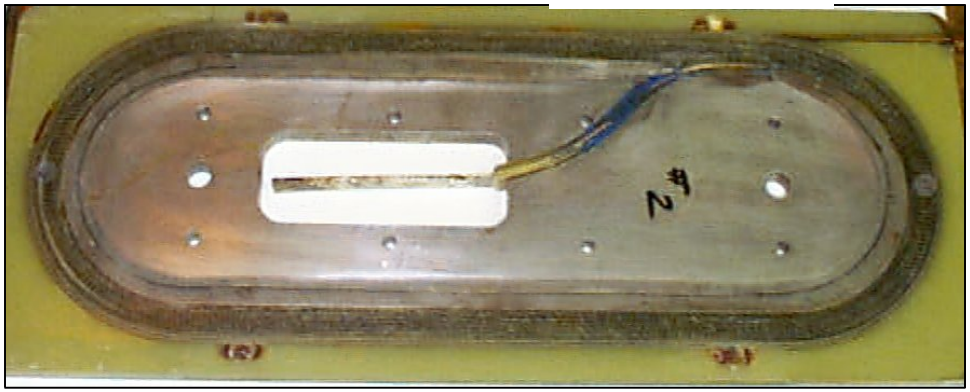
BNL High Field Magnet Program

BROOKHAVEN NATIONAL LABORATORY

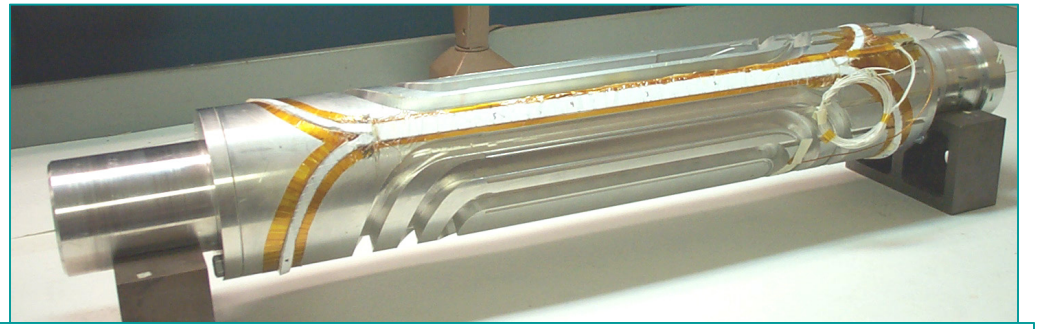
Common Coil and React&Wind

10 turn coil





BNL 92% SS with NB_3Sn ITER Conductor



12.5 T background field for insert tests

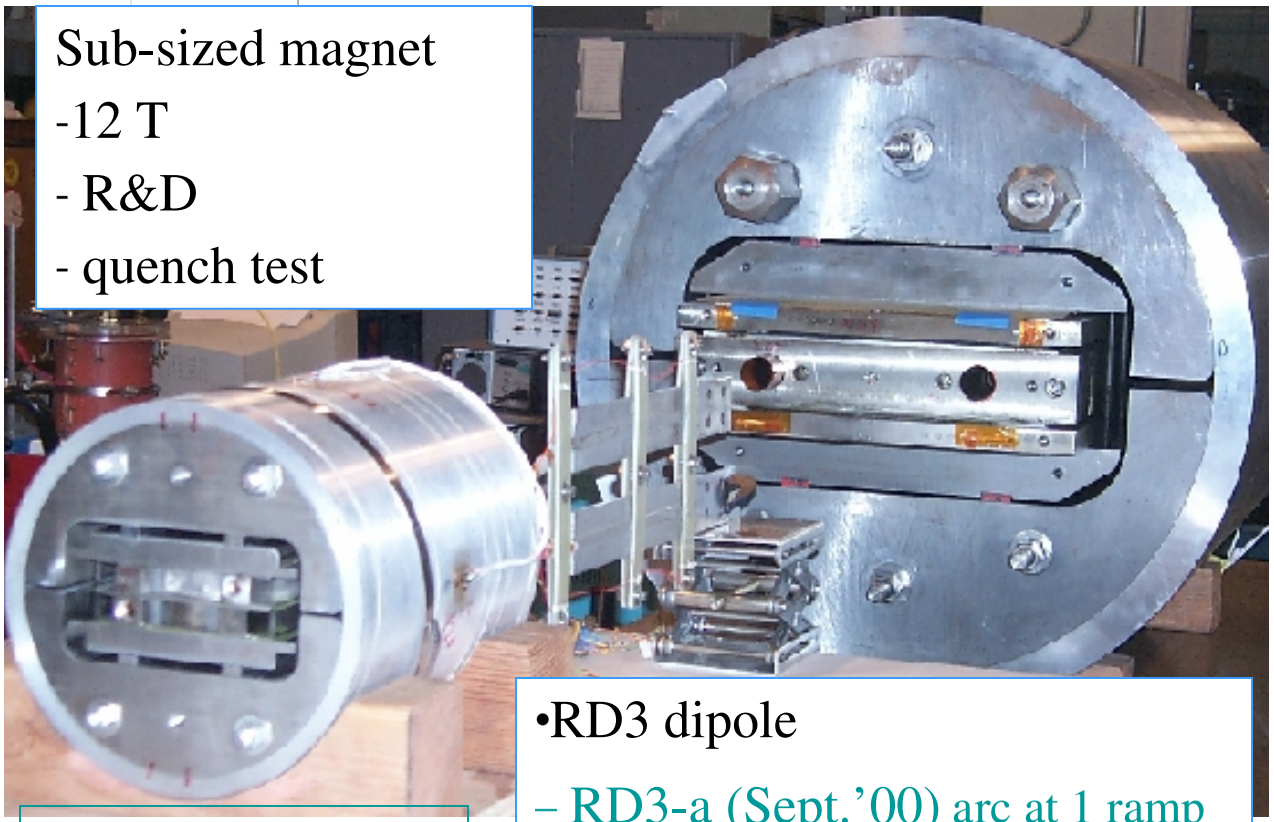
–2-Layer Nb_3Sn outer

– inner HTS layer

- Slots machined in aluminum tube (no helix)
- Nb_3Sn ITER conductor
- short-sample limit of the conductor, 820 A
- ~2.5 T peak field at conductor

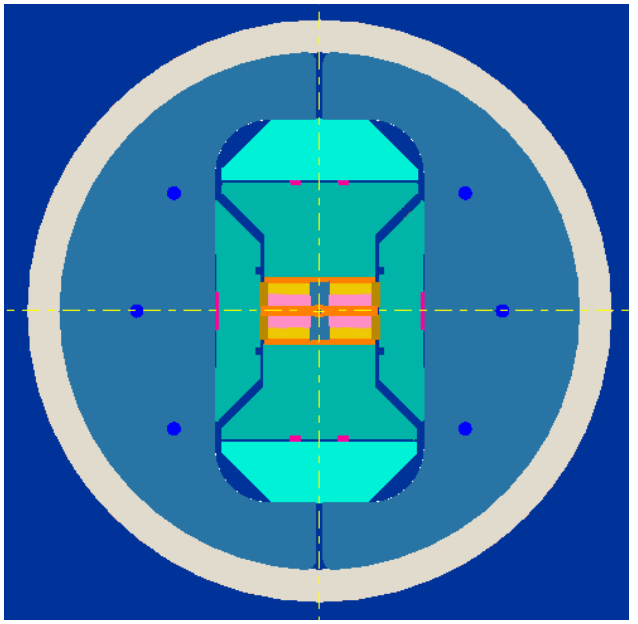
LBNL HFM Program

Sub-sized magnet
-12 T
- R&D
- quench test



HD Magnet

- Two double-pancake coil
- Horizontal orientation
- single aperture
- 15 -16 T



•RD3 dipole

– RD3-a (Sept.'00) arc at 1 ramp

– RD3-b: High-field magnet record

– RD3-c: High-field and accelerator quality PAC03

SM test results:

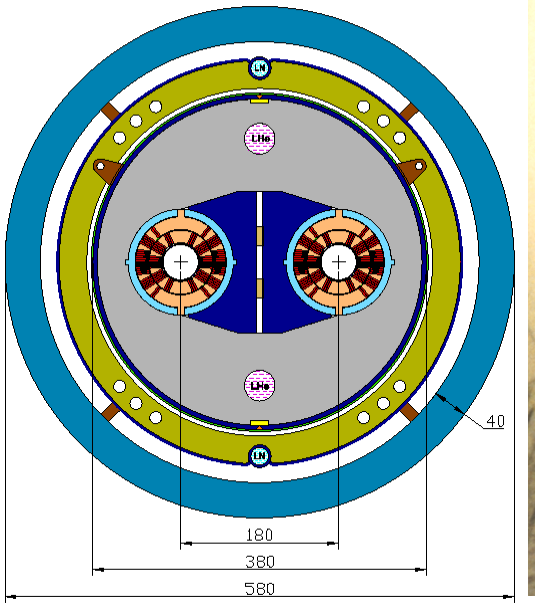
-All Nb_3Sn standard cable went to SS

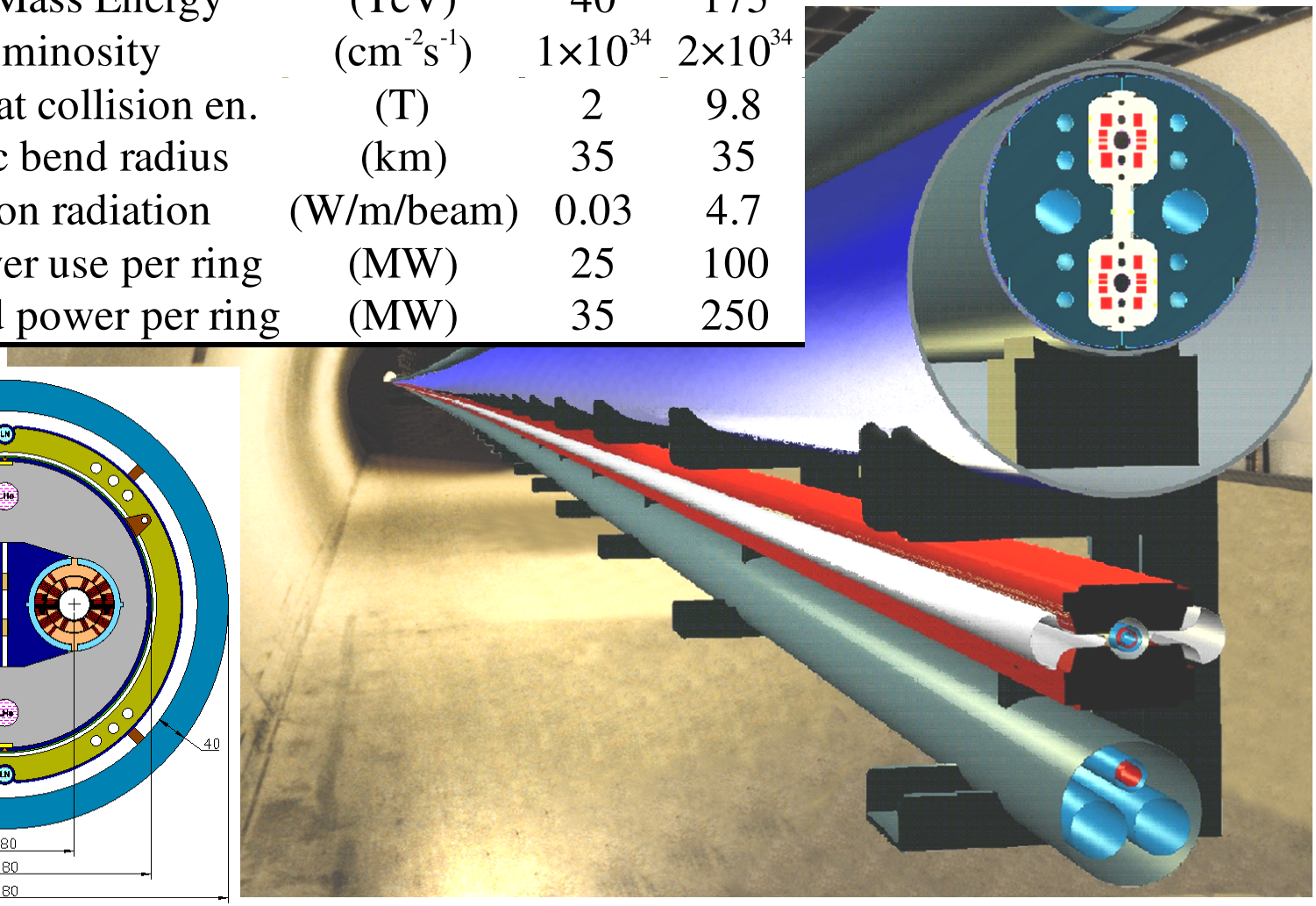
- problems with mixed strand cable and HTS

VLHC Design Study

		Stage 1	Stage 2
Total Circumference	(km)	233	233
Center-of-Mass Energy	(TeV)	40	175
Peak luminosity	($cm^{-2}s^{-1}$)	1×10^{34}	2×10^{34}
Dipole field at collision en.	(T)	2	9.8
Average arc bend radius	(km)	35	35
Synchrotron radiation	(W/m/beam)	0.03	4.7
Average power use per ring	(MW)	25	100
Total installed power per ring	(MW)	35	250

Very Large Hadron Collider





VLHC FNAL magnets

Magnet parameters and comparison with LHC main dipole magnets

	Com. Coil	cos□	LHC dipole
Bore Field/Peak Field (T)	10/11.3	10/10.5	8.3
Operating Current - I_o (kA)	23.5	21.3	11.8
Inductance (mH/m)	2×1.5	2×1.07	2×3.7
Stored Energy (kJ/m)	2×414	2×243	2×245
Length (m)	16	16	14.5
Cable Cross Section (mm^2)	31	29.3	24/28
Cu/non Cu	1.05	1.2	1.6/1.9
J_{Cu} (A/mm^2)	1987	1734	709

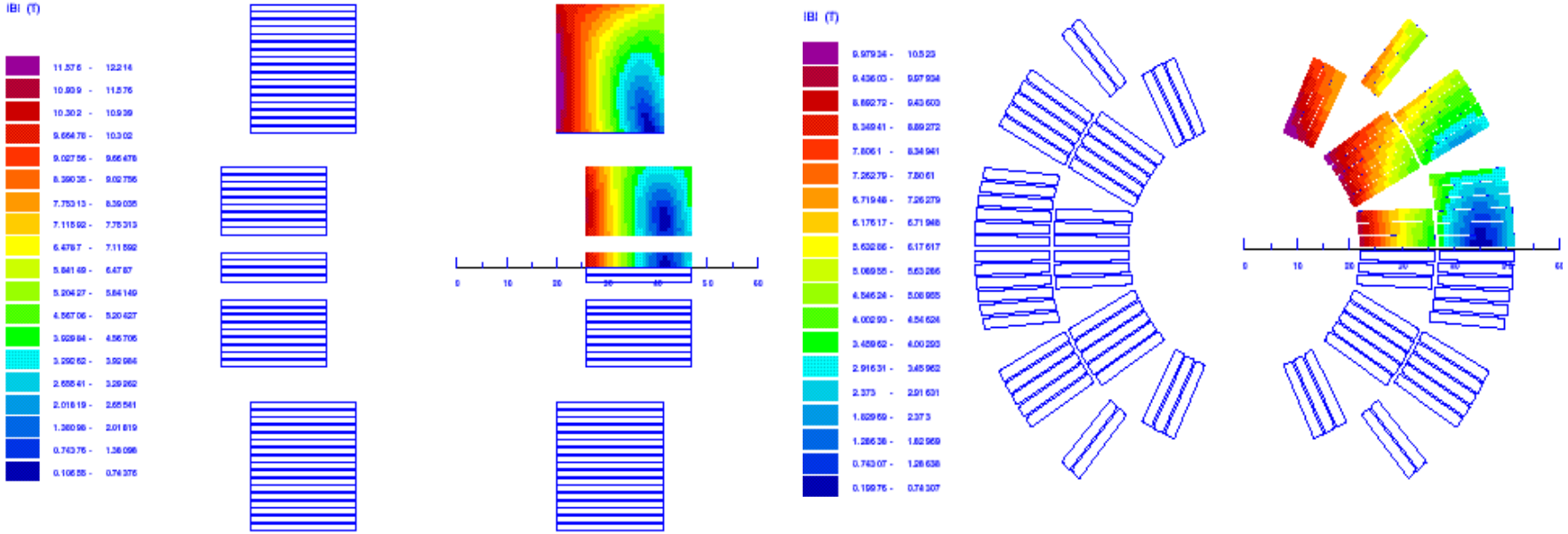
With no active protection

Power/volume = J_{Cu}^2 =

$\cong 6 \cdot 10^{-10} \Omega m \cdot 10^{18} A^2/m^4 =$

= 600 MW/m^3 melts

metals in a few sec!



Common Quench Protection Strategy

1- Quench detection ASAP

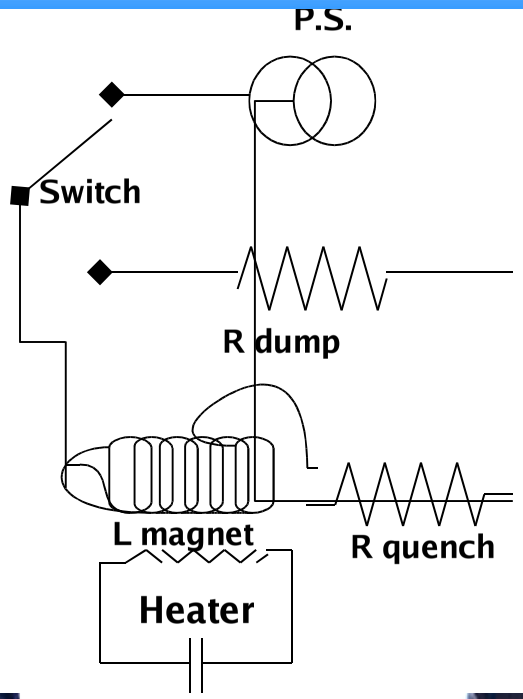
- Voltage taps detecting resistive growth
- Noise rejection with bridge circuit
- Signal processing (software)

2- Current disconnection and extraction

- PS ramp-down
- Extract stored energy into an external dump resistor

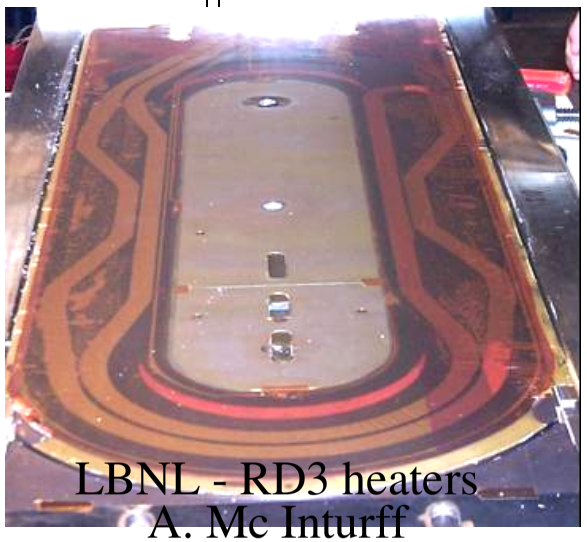
$V_{max} = I_0 \cdot R_{Dump}$; R_{Dump} chosen to have $V_{max} < 1$ kV

=> R_{Dump} is fixed with the current, not with L



3- Spread energy into the winding

- Natural quench propagation – only for small magnets
- Quench heaters
- "Quench-back" (quench induced by fast current decay)

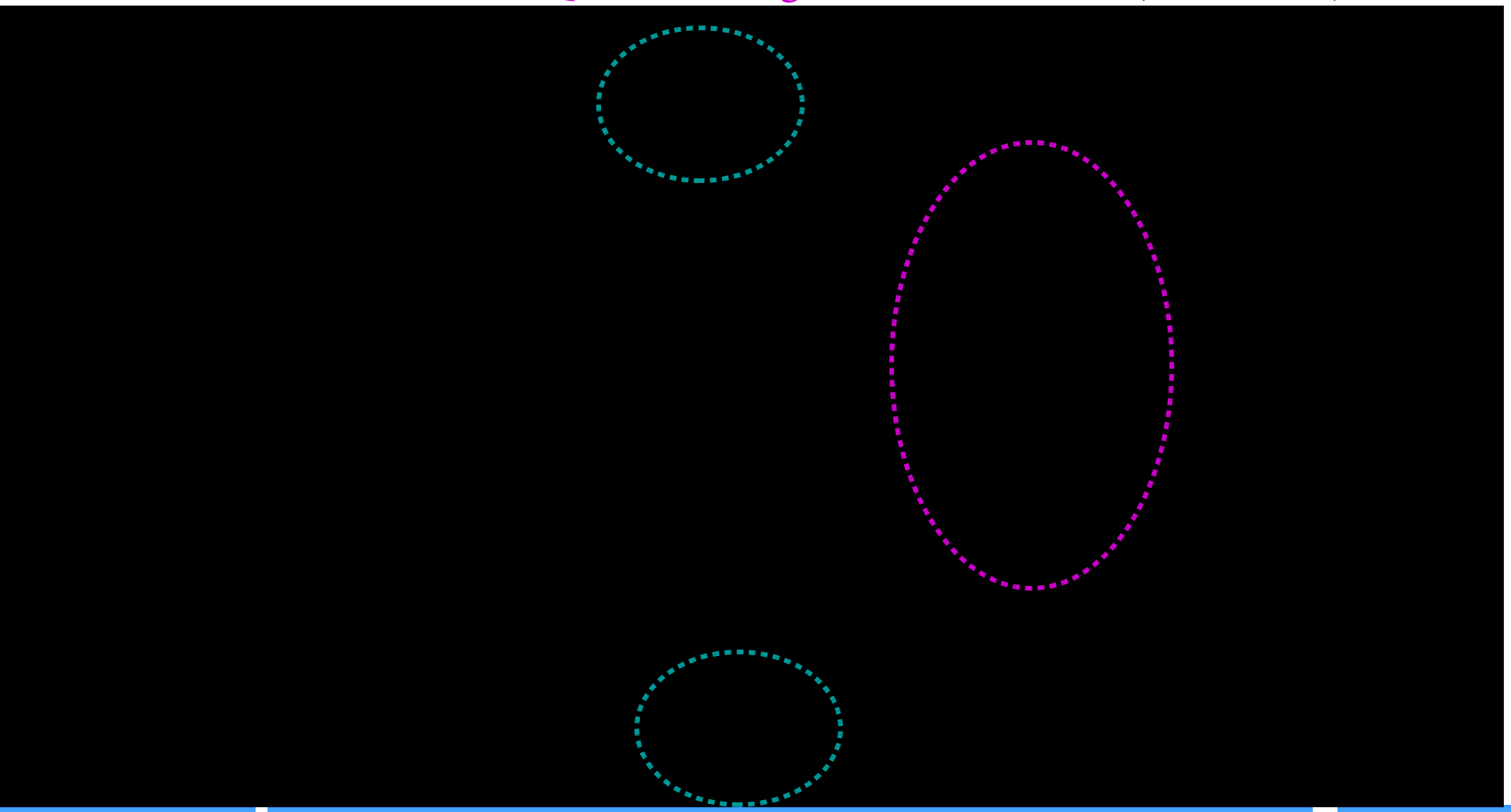


LBNL - RD3 heaters
A. Mc Inturff

Quench protection in a string

Bypassing the quenching magnet (through external thyristors or cold diodes)

2. Two current circuit: 1- Magnet string + dump resistors ($\tau \sim 100$ sec)
   2- Quenched magnet + diode ($\tau \sim 100$ ms)



Hot Spot Temperature

Adiabatic heat balance equation

$$\tilde{n}(T)\,J(t)^2\,dt = c_P(T)\,dT$$

Joule heating per unit volume

Temperature rise

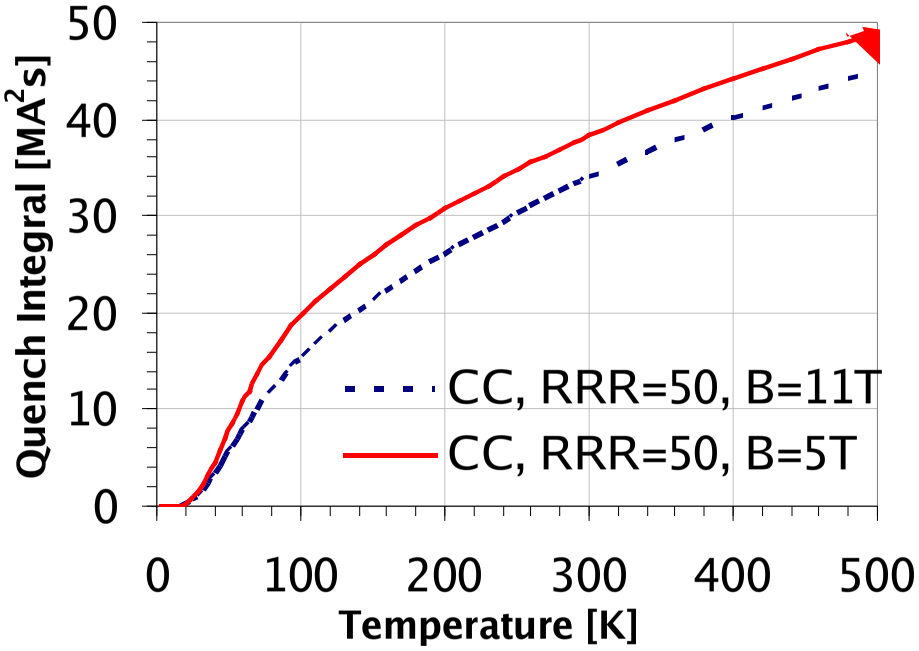
Definition:

The *QI* is the square current integrated in time [MIIts = MA^2s]

$$QI(T_{peak}) = \int_0^{t} I^2(t)\,dt = A^2 \int_{To}^{Tpeak} \frac{c_P(T)}{\tilde{n}(T)}\,dT$$

Current decay

Material properties



Magnets with the same coil composition, refer to the same MIIts curve, a way to predict the hot spot temperature.

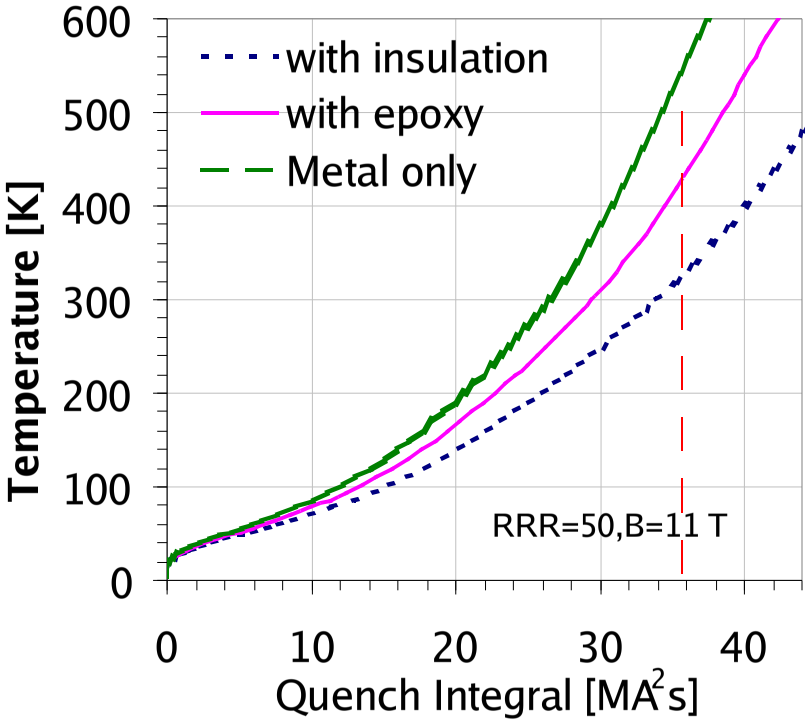
To reduce T_{peak}:

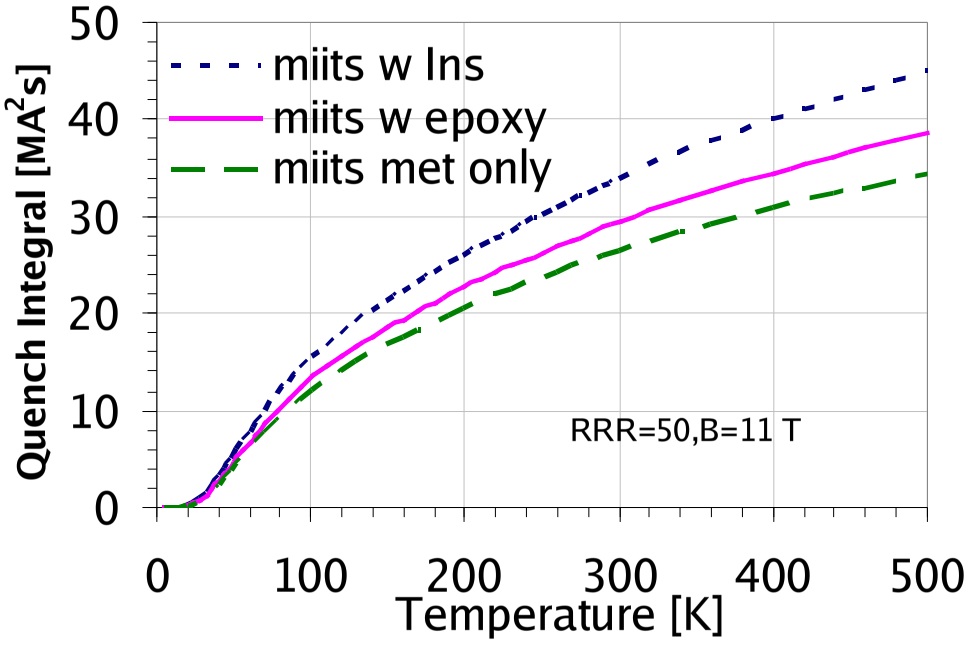
- Decrease J (larger cable, more copper)
- Lower resistivity
- Fast current ramp down (early quench detection and fast heater action)

Hot Spot Temperature

- Adiabatic equation (no heat exchange with Helium, no heat conduction) => conservative peak temperature estimation
- The insulation can absorb heat (~ as LHe for NbTi magnets)
- Heat diffusion into 0.1 mm insulation

Diffusivity Material	D (m^2/s) at 4 K	D (m^2/s) at 300 K	?t (ms) at 4 K	?t (ms) at 300 K
G10	$9 \cdot 10^{-5}$	$3 \cdot 10^{-7}$	0.1	33
Epoxy	$6 \cdot 10^{-5}$	10^{-6}	0.2	10



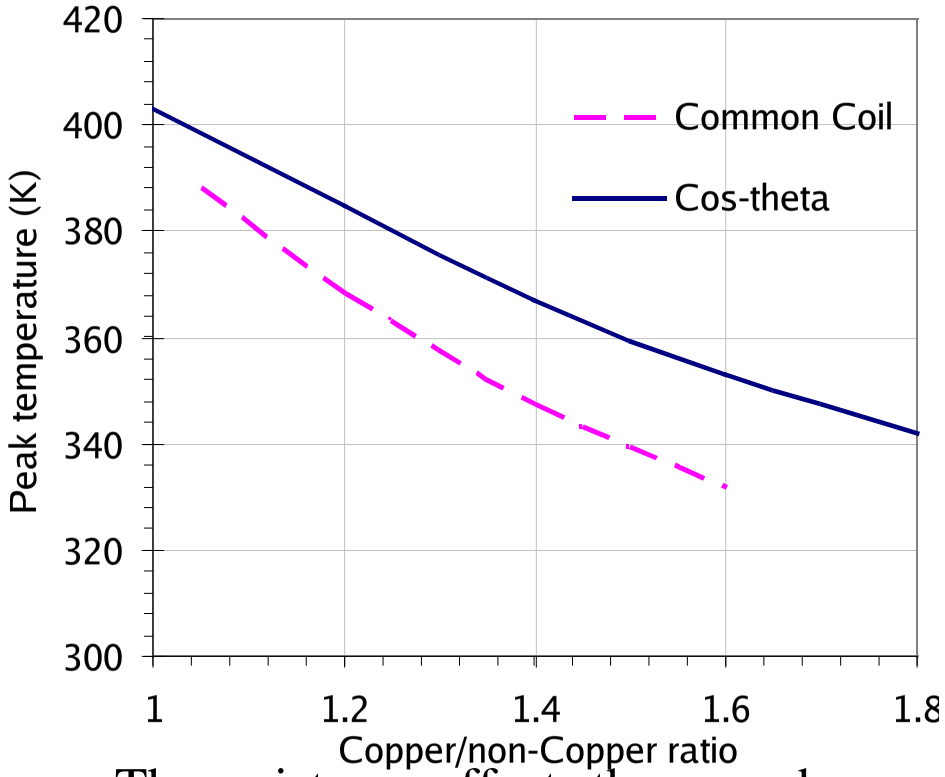


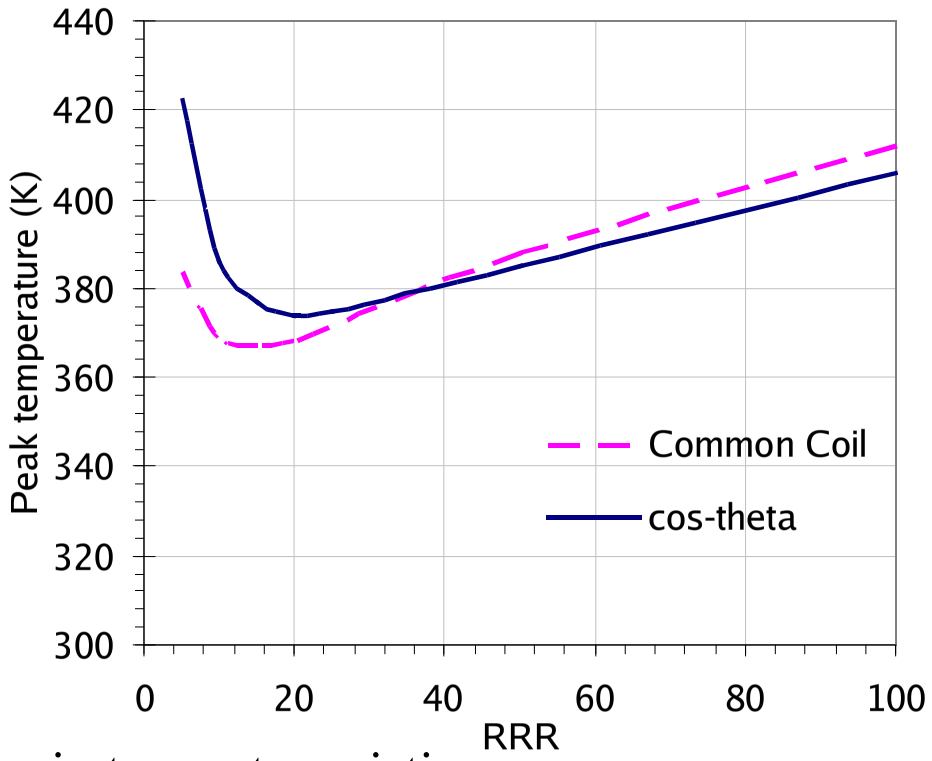
Quench Simulations

1. with numerical codes (QLASA + Quenchpro)
   - VLHC-2 magnets
   - Protection requirements
2. Analytical model
   1. Generic Nb_3Sn accelerator magnet
   2. Peak temperature trends varying several parameters
3. FE model
   1. Cable quench experiment
   2. Detailed temperature distribution (T gradients)

VLHC Quench Protection

Conductor parameters: copper content and RRR





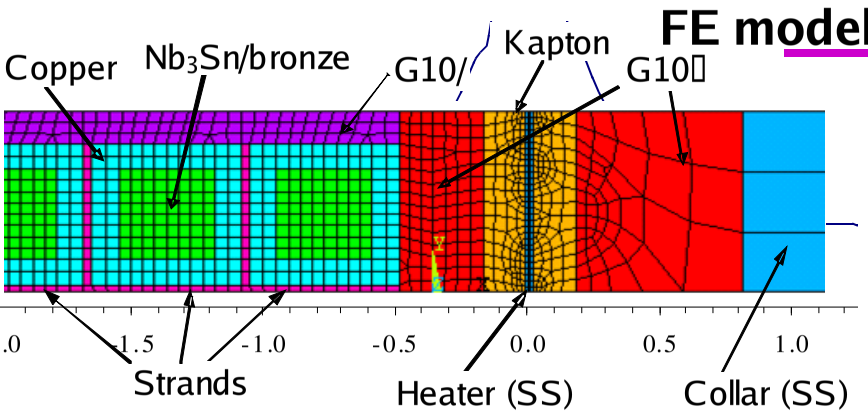
The resistance affects the quench process in two antagonistic ways:

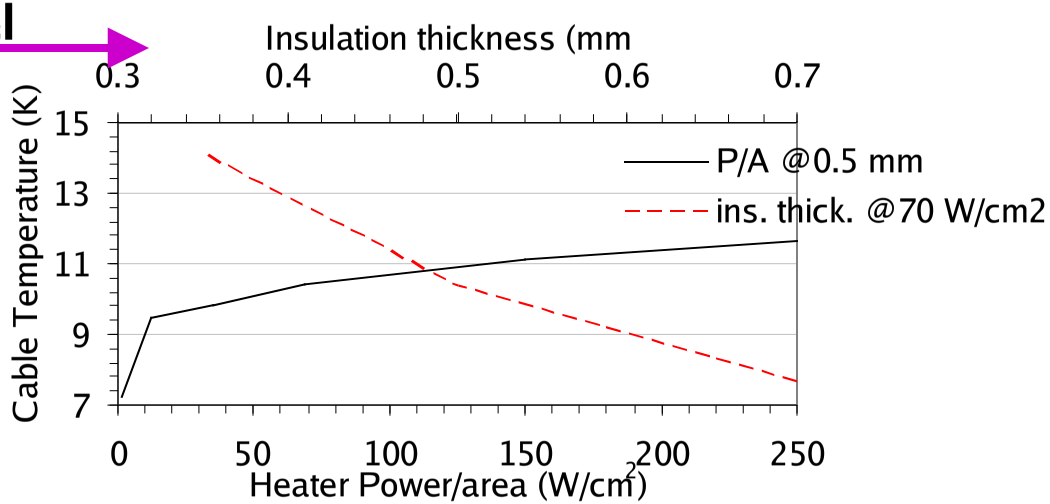
1- the lower the resistance the lower the heat generation at the hot spot;

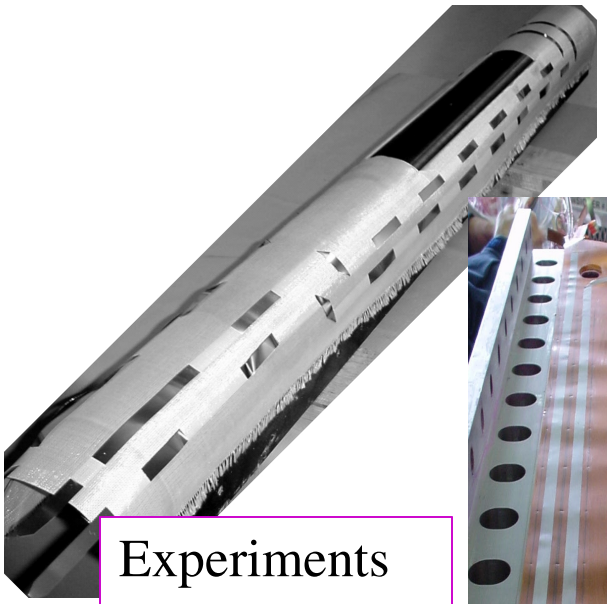
2- the lower the overall resistance of the magnet, the longer the decay time.

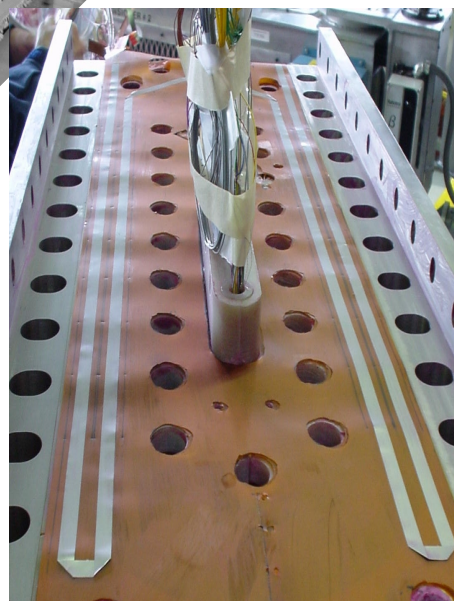
=> We need an active protection system: heater efficiency !

Quench Heater Studies

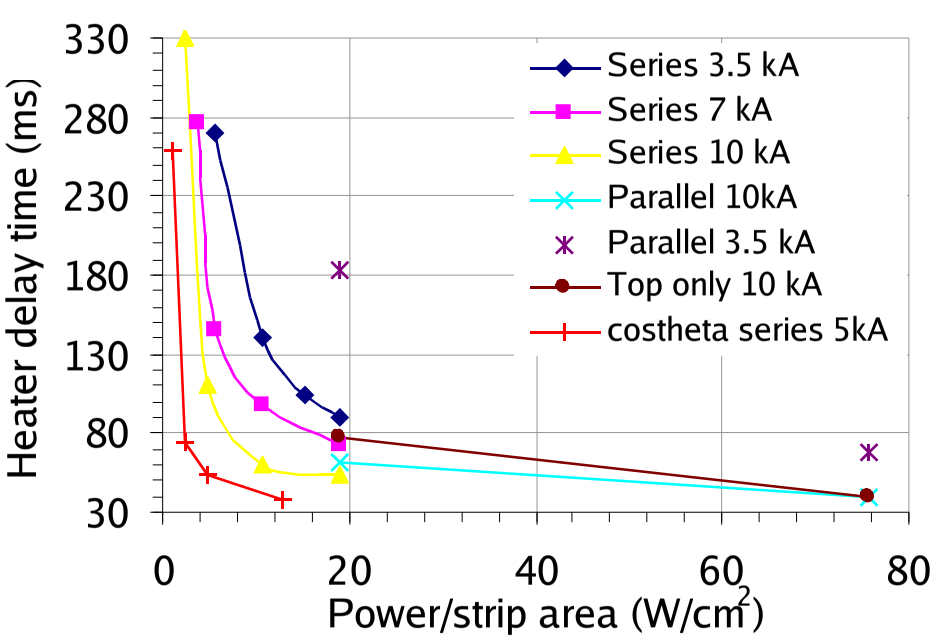






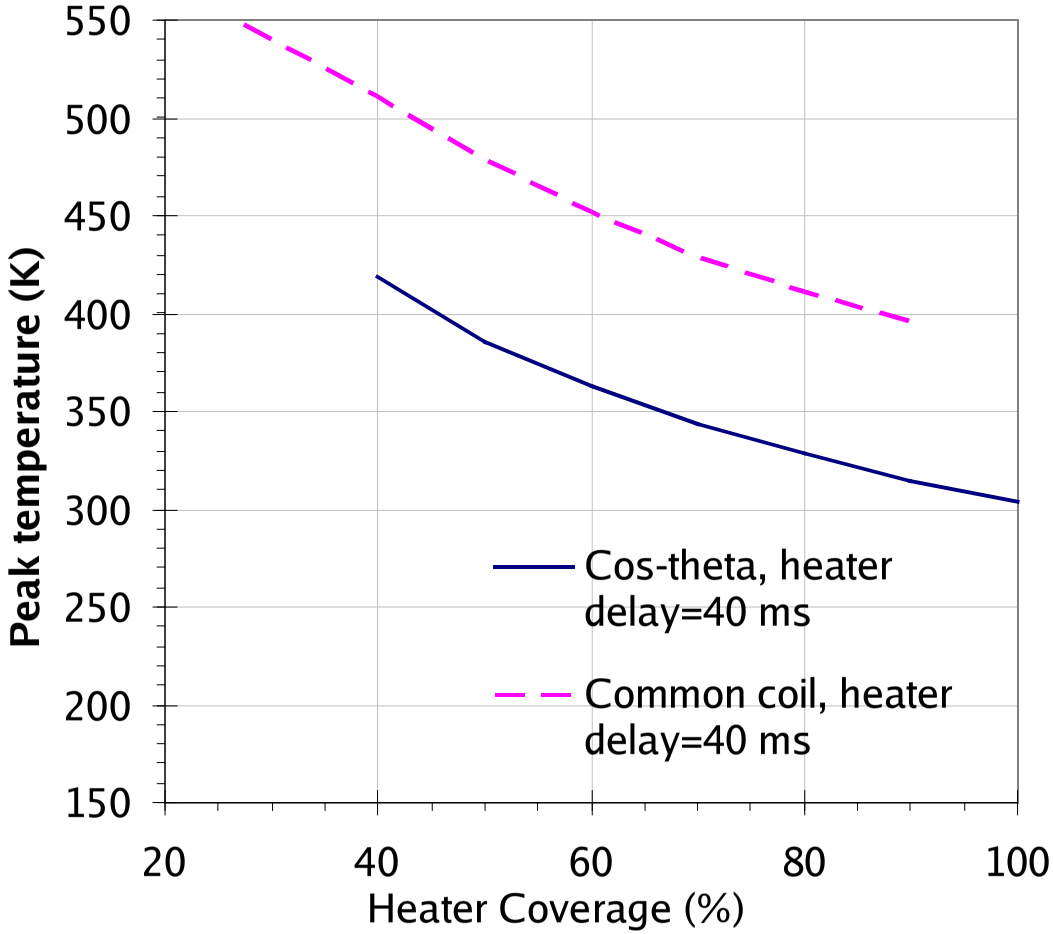


Experiments on cos and racetrack magnets



VLHC Quench Protection

Quench heaters efficiency affects the most T_{peak} and V after the quench



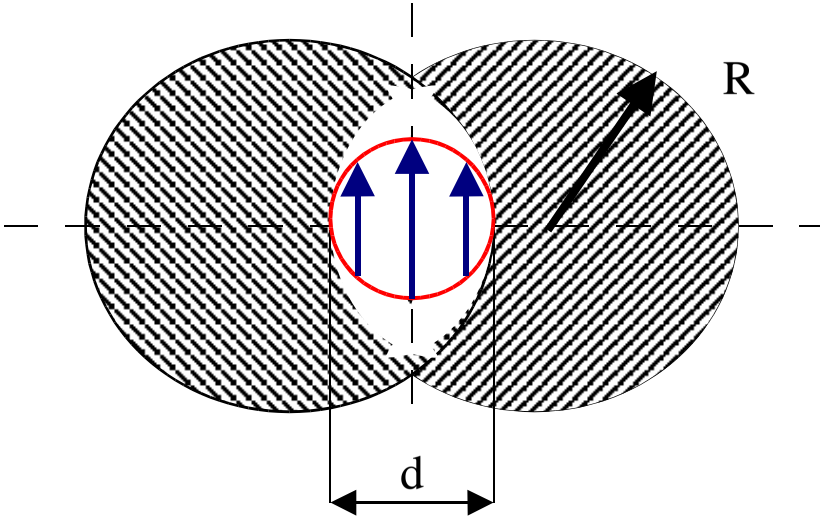
Voltage :

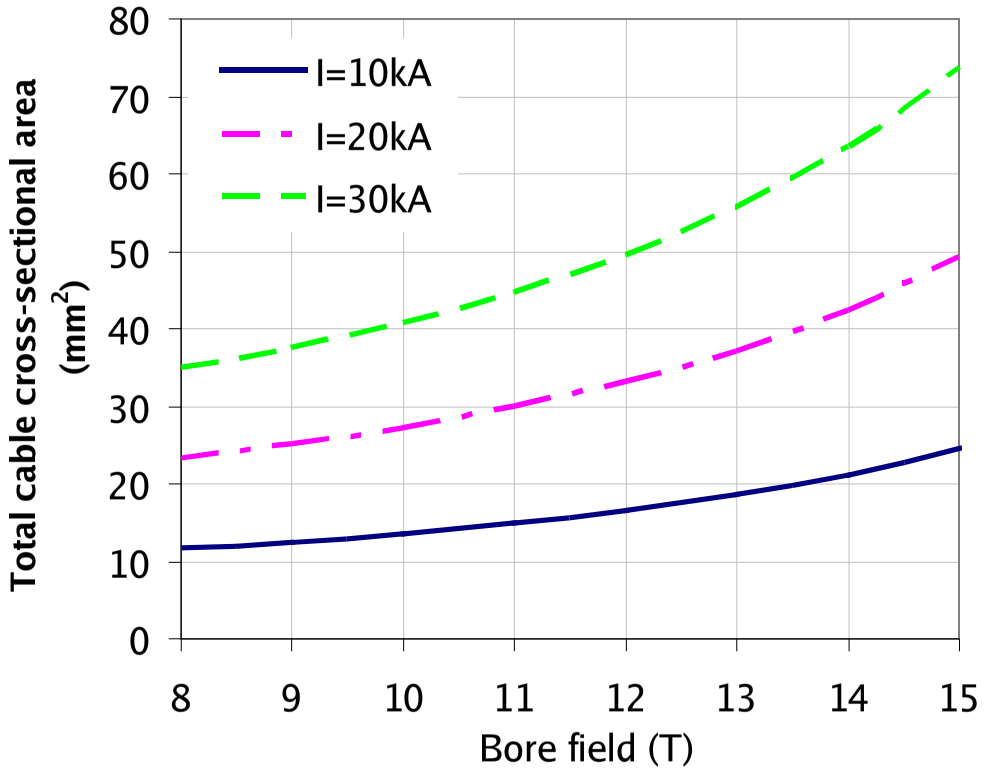
For V_{max} < 1 kV, the cos /common coil magnets require 50/70% heater coverage.
V depends also on the symmetry of the heater strips.
Heater failure has to be avoided, to avoid high T, V and high thermal stress.

General HFM Quench Study

An analytical calculation of trends, varying magnet parameters, such as …

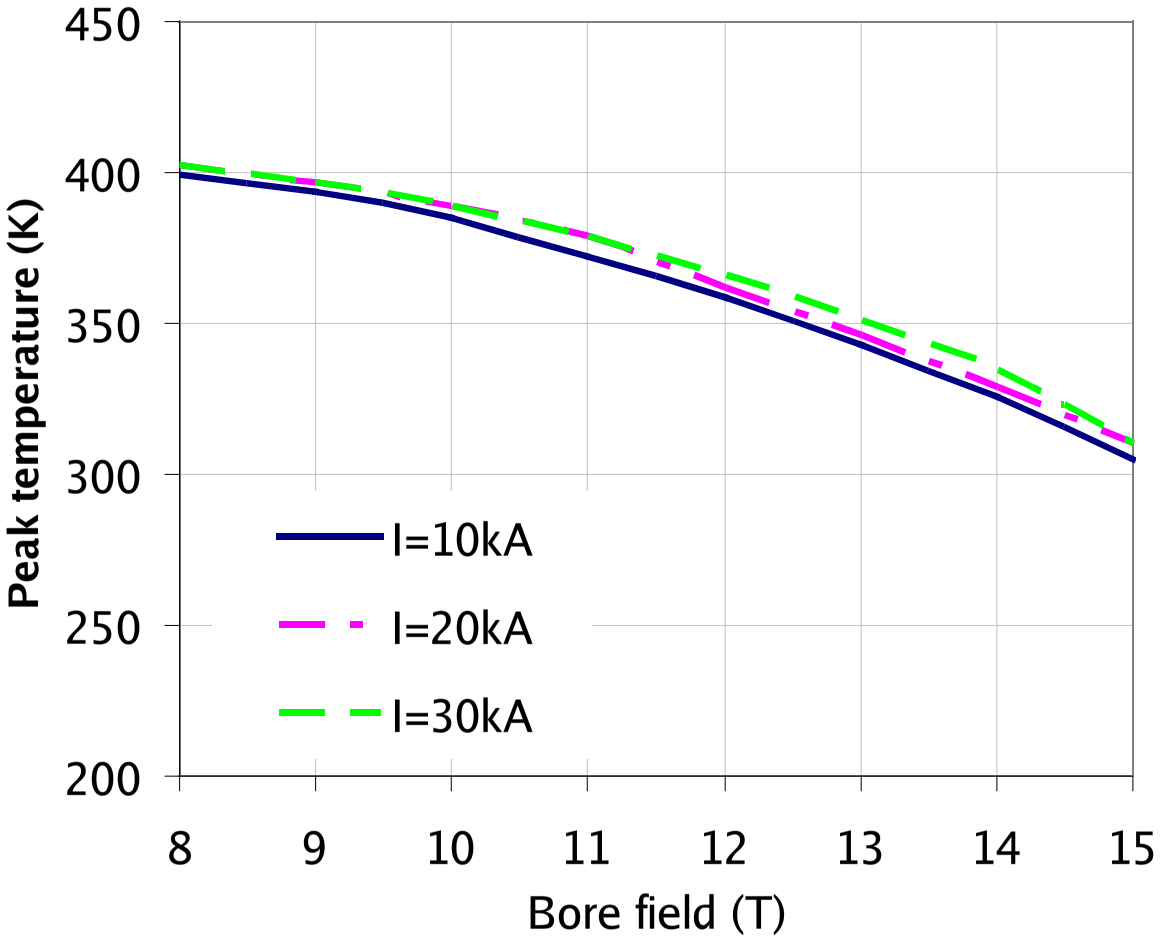
… *when fixed*	*Value*	*Unit*
Bore field	10	T
Oper. current	20	kA
Total delay time	30	ms
Bore diameter	40	mm
J_{CU}	2	kA/mm^2
J_c at 12 T	3	kA/mm^2
Magnet length	15	m
Heater coverage	50	% area





Peak Temperature Trends

Increasing the field and keeping all the other parameters fixed (I, J_{CU},…)



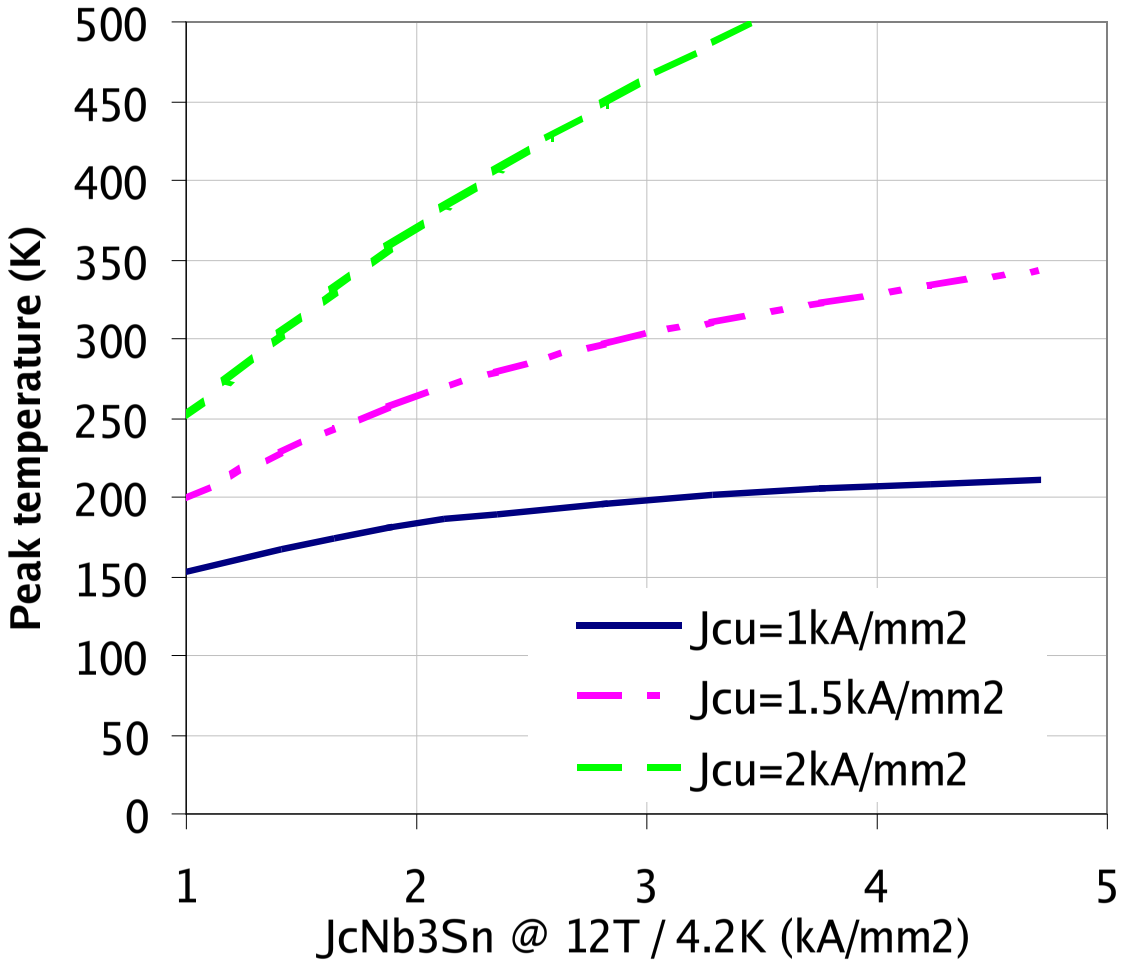
1- T_{peak} does NOT depend on the current

2- T_{peak} does NOT increase with field

- Increase number of turns and cable size
- Increase both total stored energy and coil volume

Peak Temperature Trends

- T_{peak} increase steeply with J_{CU}
- T_{peak} increase with J_c, (especially at high J_{cu})

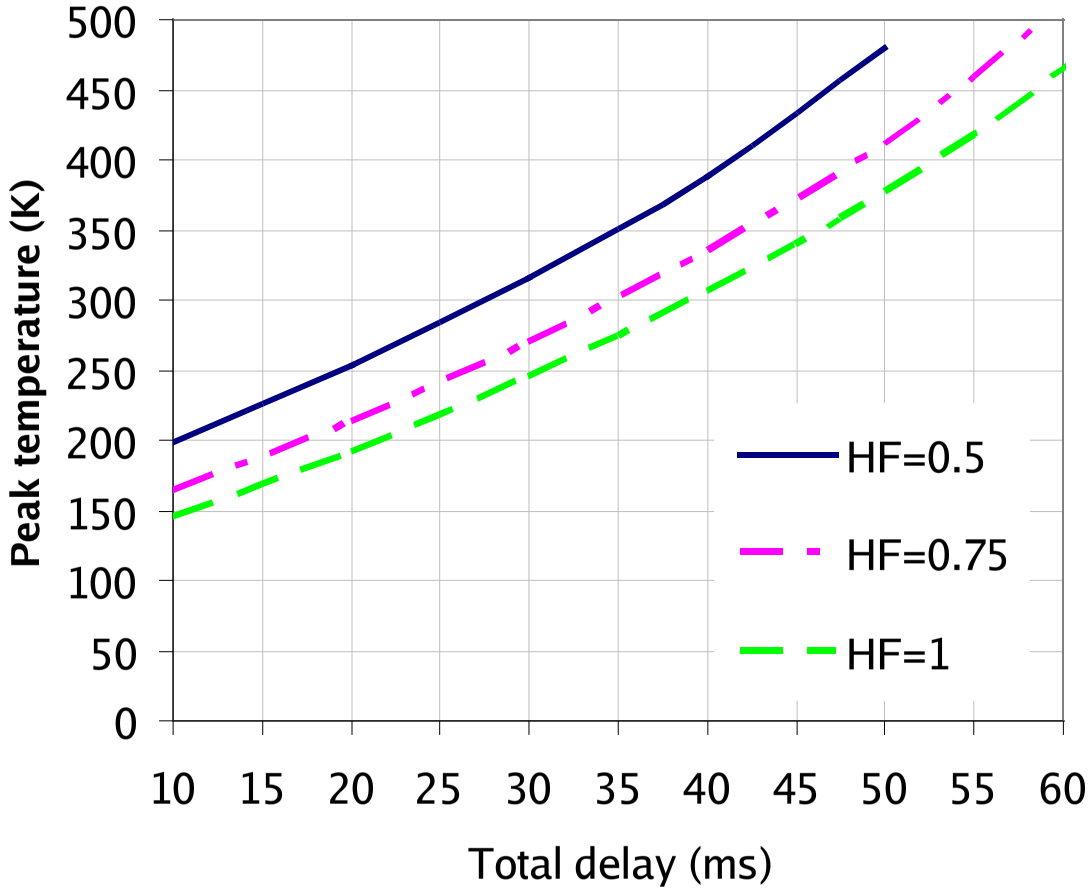


T_{peak} increase with J_c
- because of the loss of c_P
- reduced inductance (less turns), partly counteracts the c_P loss

Peak Temperature Trends

Heater efficiency:

- 10 ms increase in time delay results in a ~25% increase in T_{peak}
- Heater coverage > 50% conflicts with redundancy!



Quench Simulations results

- High peak Temperatures in long magnets (300-400 K)
- High temperature gradients
- High thermal stresses

=> Peak temperature limit?

VLHC magnet	Cos?/Com.Coil
Cu/non-Cu (RRR=50)	1.2/1
Heater Coverage	50/100 %
QI @ 400 K	~42 MA^2s
QI @ 40 ms ($I=I_0$)	~20 MA^2s
Peak Temperature	~400 K
Bulk Temperature	~130 K
Max Volt to Ground	900/255 V
Current Decay Time	~100 ms

- 500 K: solder melting point
- 430 K: epoxy glass-transition
- Nb_3Sn conductor damage
- epoxy failures

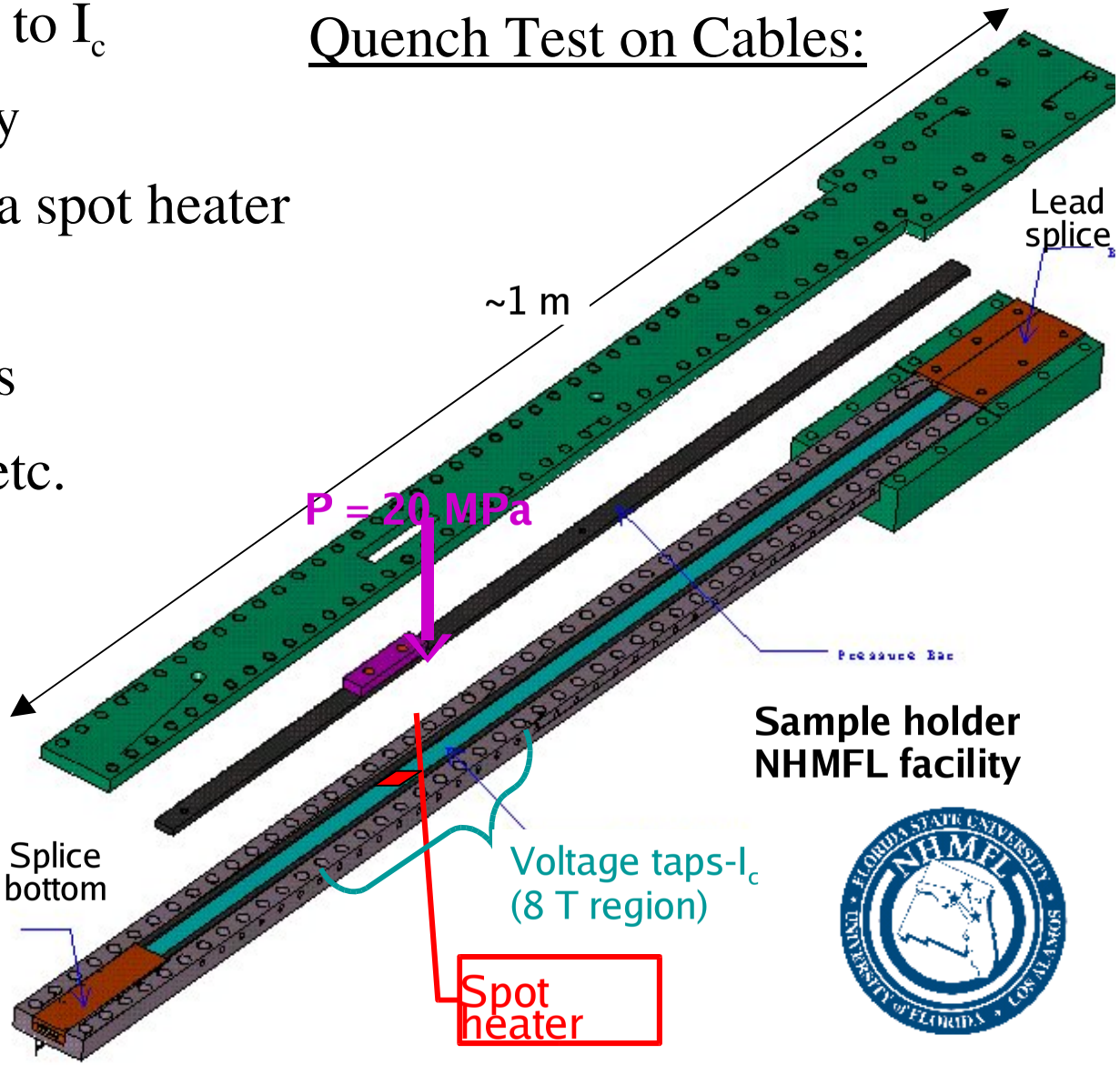
Research program:

- Theoretical studies
  - FE quench simulation
  - Mechanical analysis
- Experimental program
  - Cable quench experiment
  - Subscale Nb_3Sn magnet: "thermal shock test"

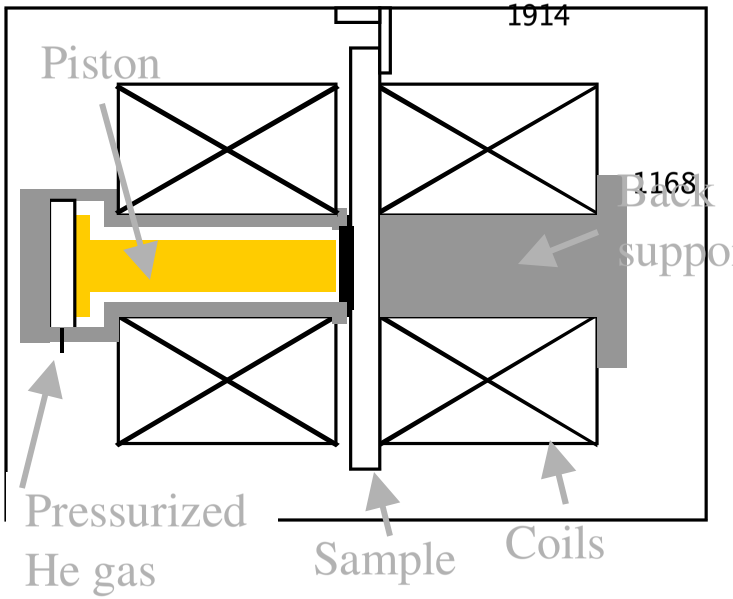
Concept of the experiment

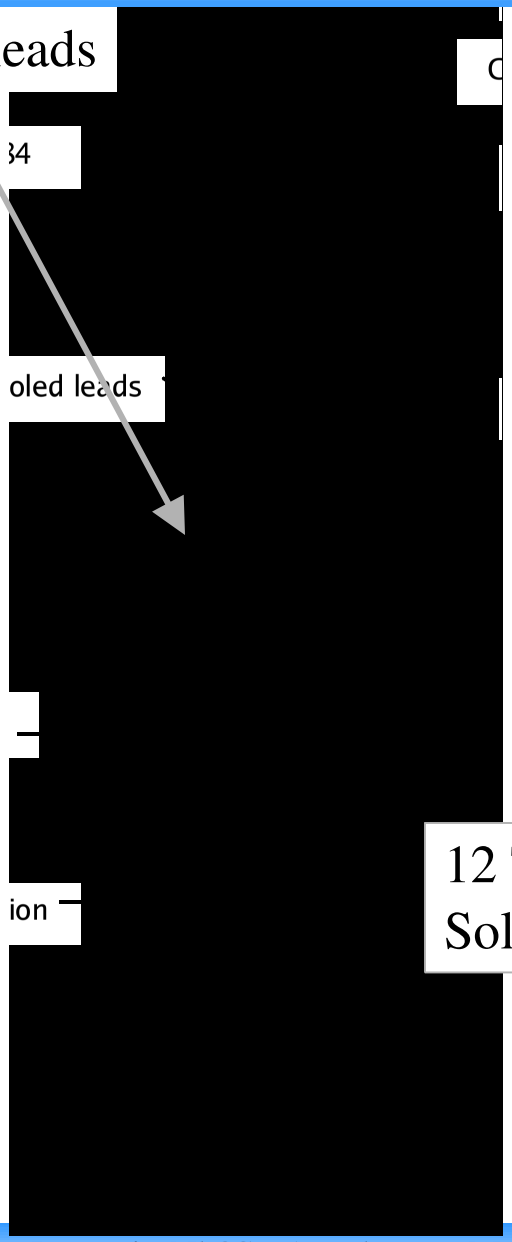
- Ramp the current close to I_c
- Set current switch delay
- Induce a quench using a spot heater
- Measure T via the R
- Repeat I_c measurements
- Increase delay time… etc.

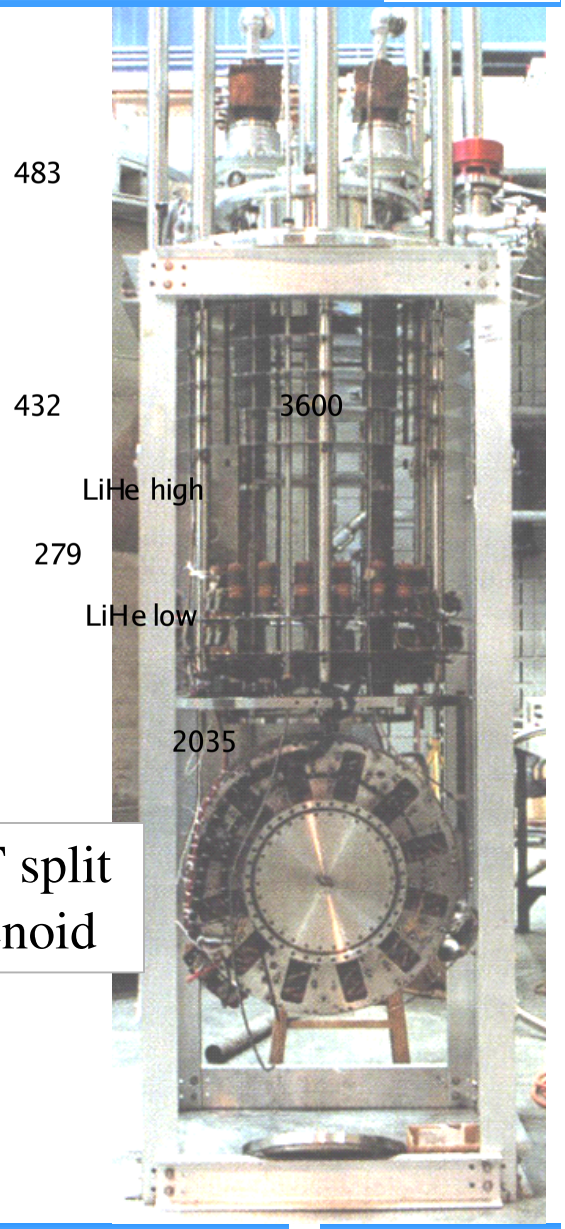
Samples: Rutherford cable:
- 41 strands, 0.7 mm-Ø
- ITER conductor (IGC-IT),
- Ic ~ 8 kA, at 8 T/4.2 K



Cable Test Facility



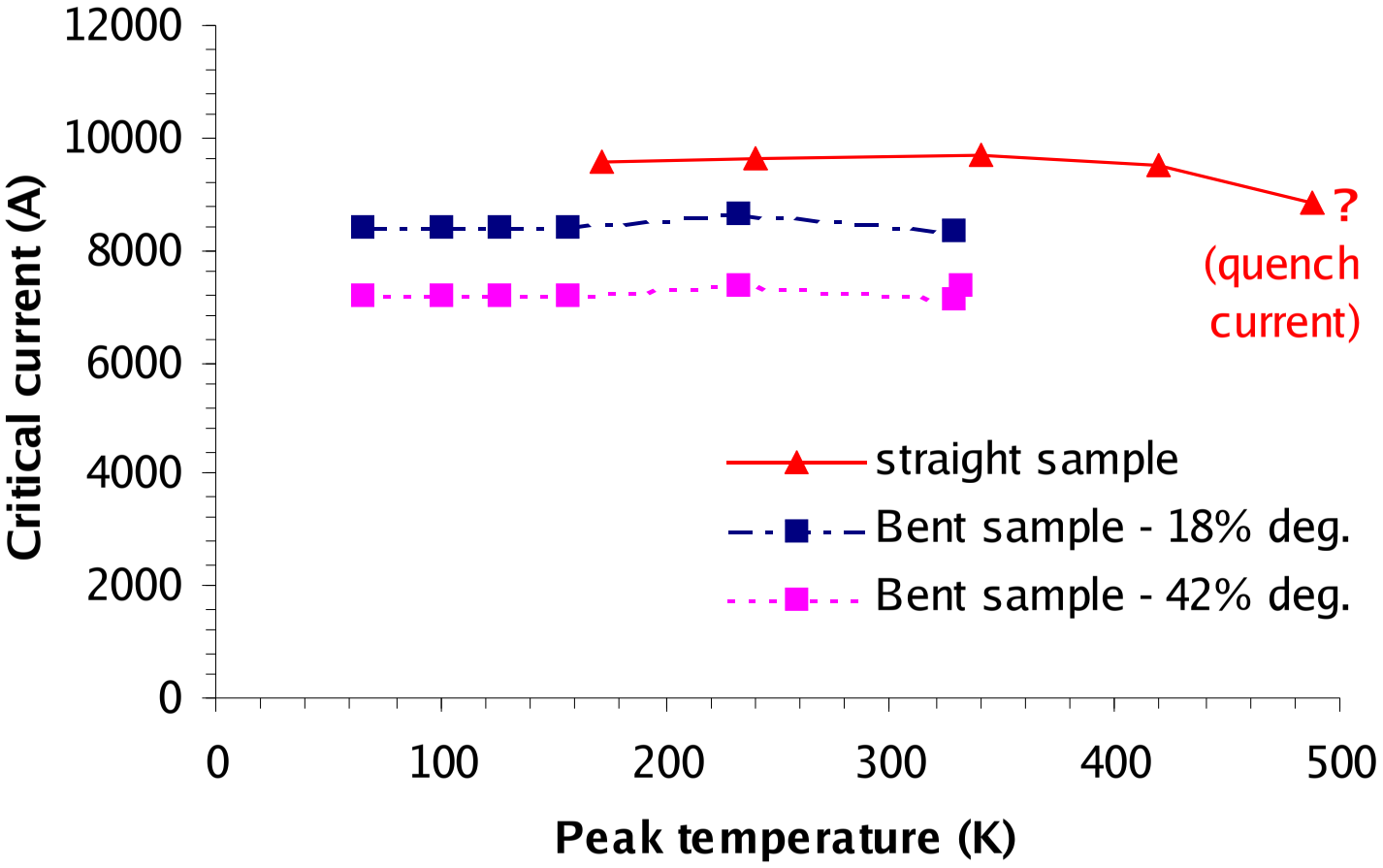


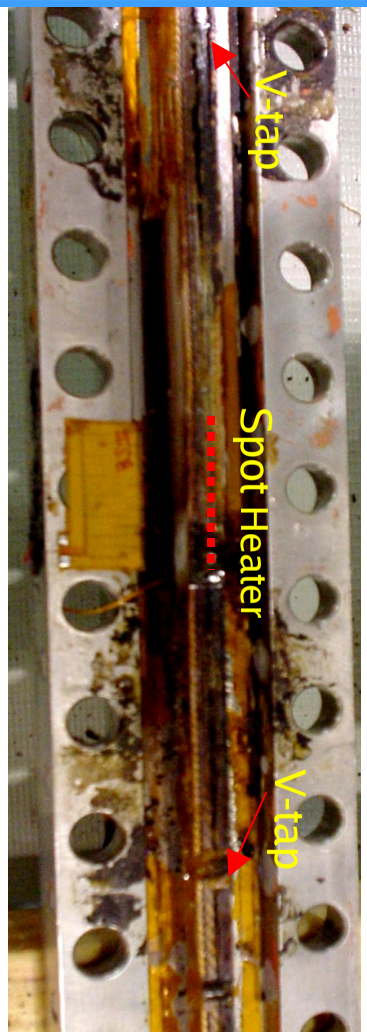


12 T split Solenoid

Experiment results

- No degradation up to ~ 400 K (straight sample)
- No degradation up to ~ 300 K (bent sample)

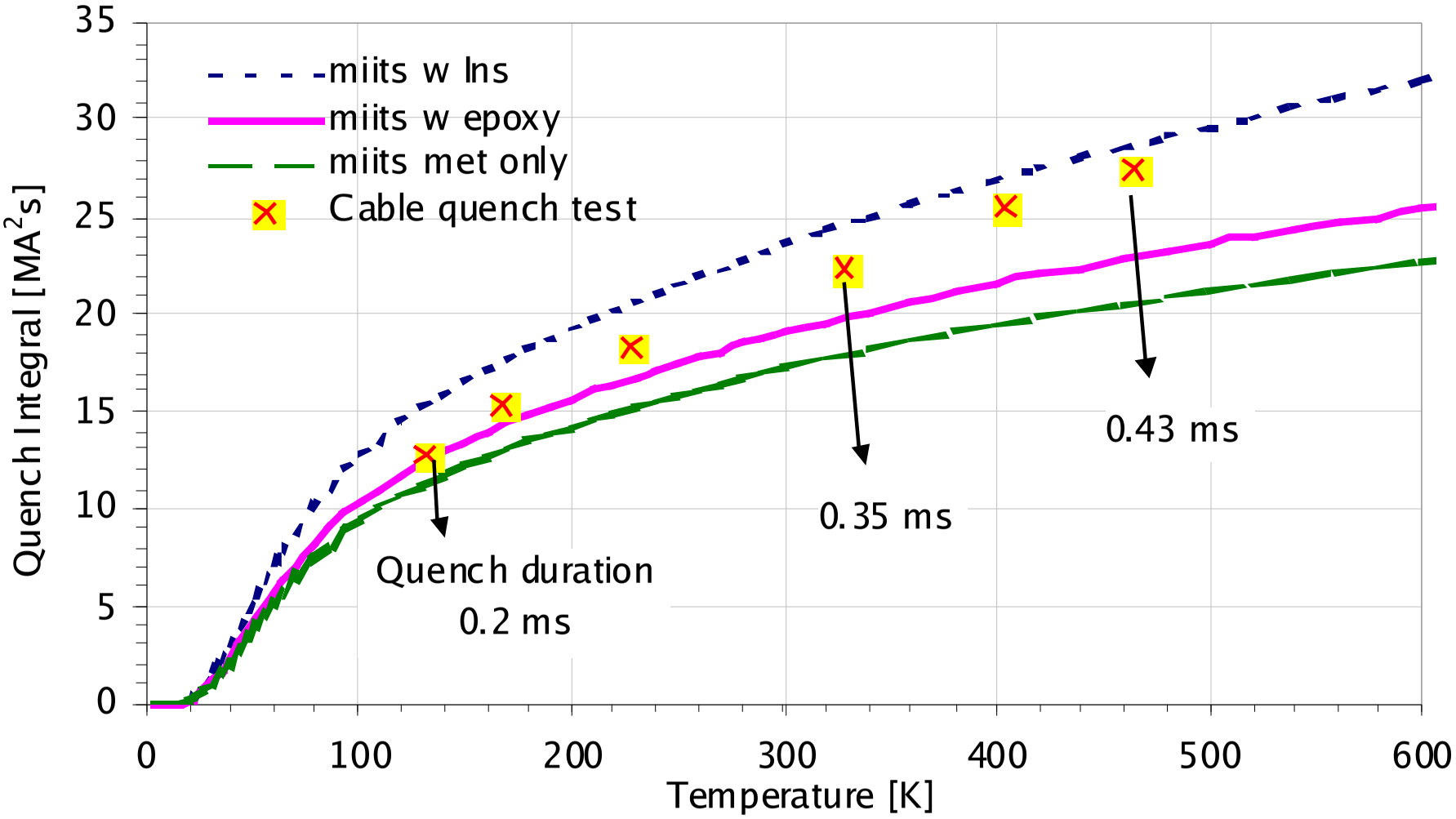




Burn marks on the sample that reached ~500 K

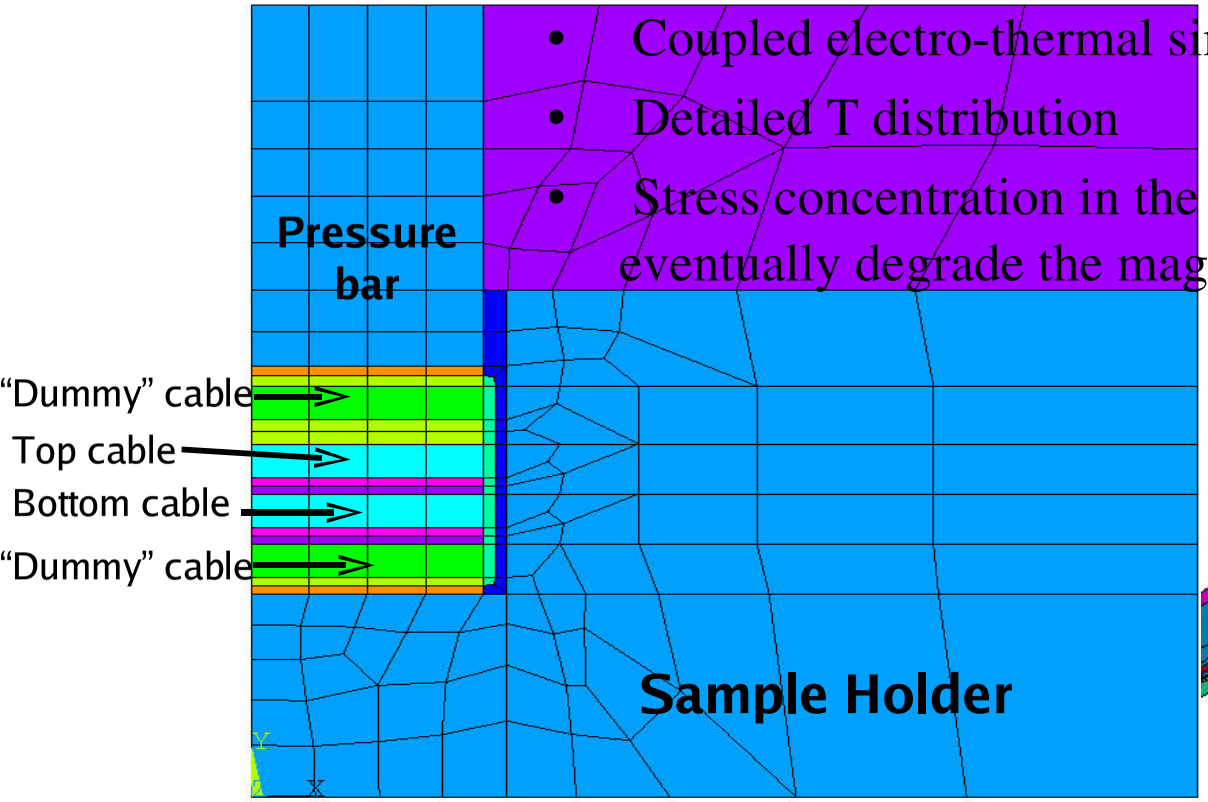
Adiabatic model

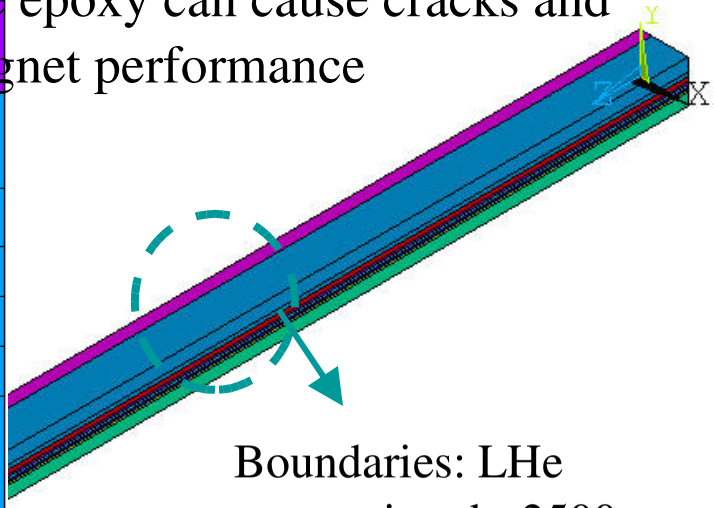
Quench Integral includes ~ 0.1 mm cable insulation



Sample Holder FE Model

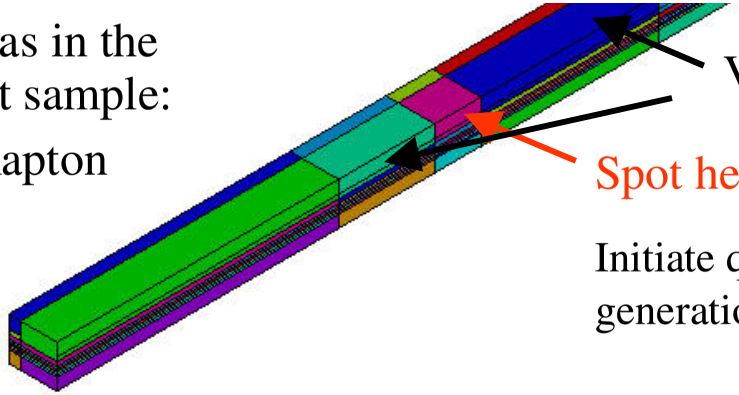
- Coupled electro-thermal simulation of the quench
- Detailed T distribution
- Stress concentration in the epoxy can cause cracks and eventually degrade the magnet performance





Boundaries: LHe convection; h=2500

Insulation as in the straight sample:
= G10 + Kapton

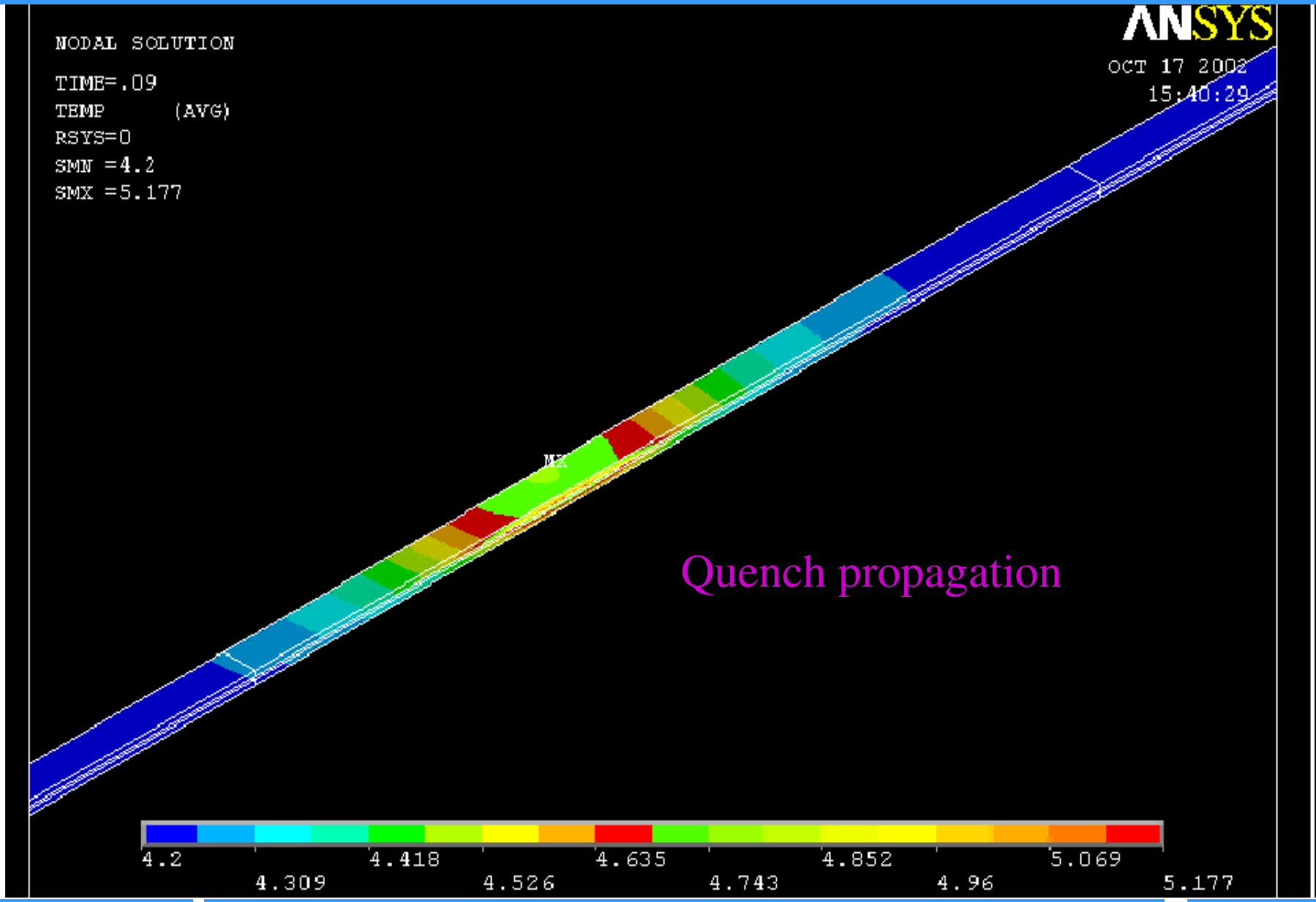


V tap regions

Spot heater region:

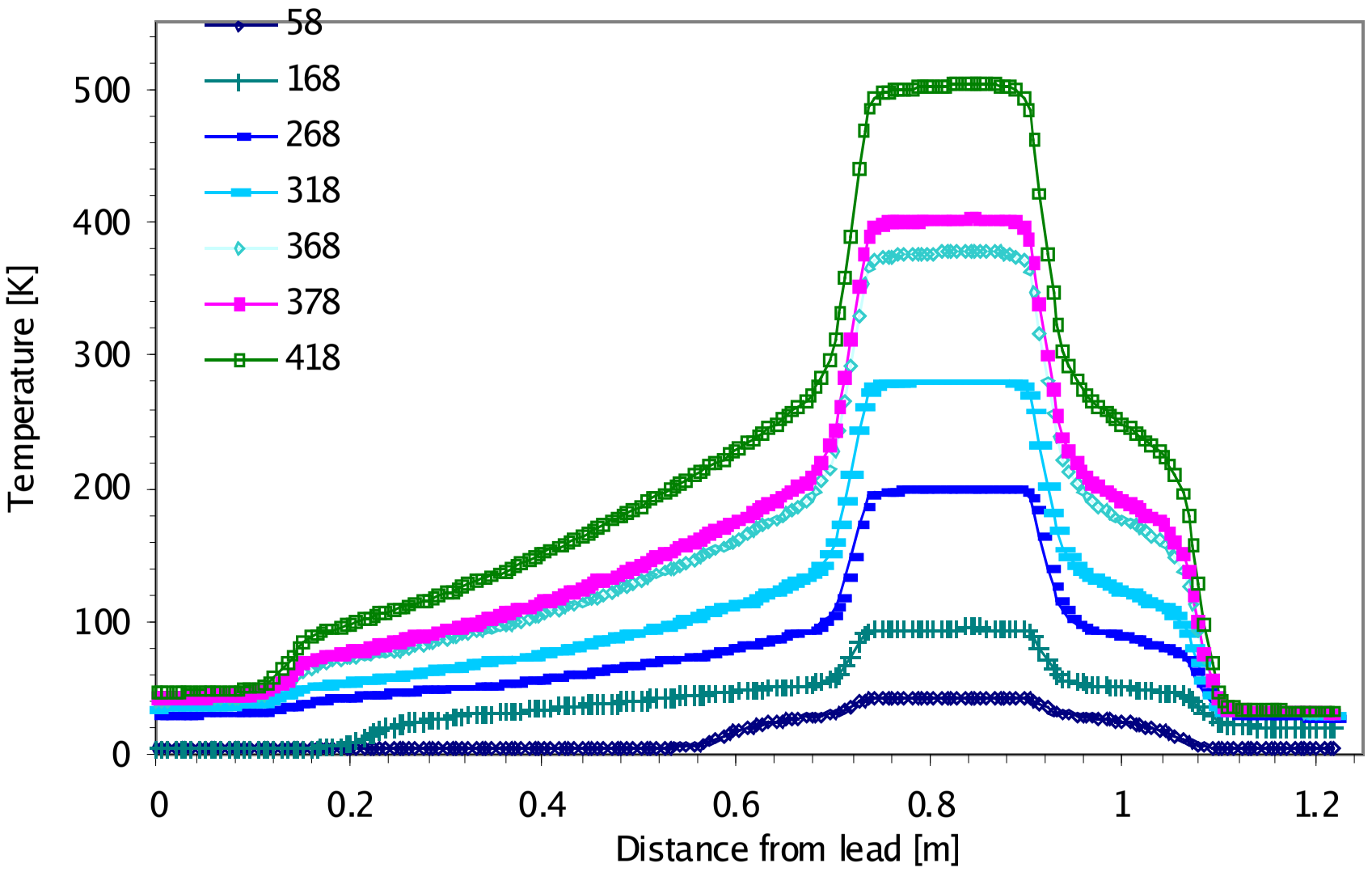
Initiate quench with heat generation in heater

FE Quench Simulation

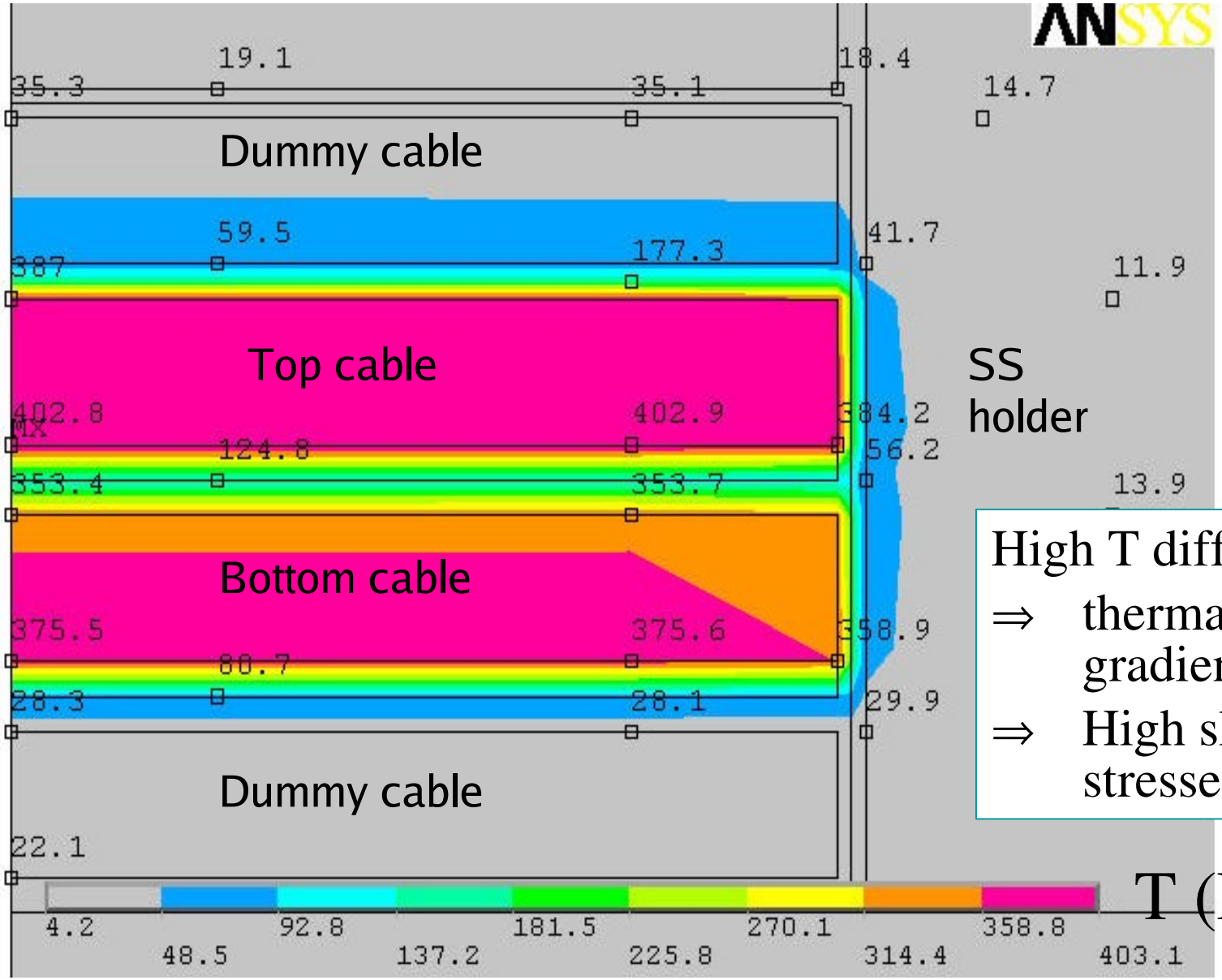


FE Quench Simulation

T profile at different times (ms) after the quench start



FE model results



High T differences

⇒ thermal gradients

⇒ High shear stresses

Stress Analysis

Total strain contributions at $T_{peak} = 400$ K :

- Pre-compression of Nb_3Sn filaments $\varepsilon_{int} = -0.14\%$
  - due to different thermal contraction of the materials inside the strand
    (from $T_{reac} = 650$ºC to 4.2 K is $\varepsilon_m = -0.28$ %)
  - at 400 K ~50 % of ε_m (estimated by thermal contraction coefficients, bronze/SC area, and elasticity moduli)
- Thermal expansion strain $\varepsilon_{therm} = -0.46$ % (Stress = 167 MPa)
  - With ANSYS T profile $\varepsilon_{therm} = -0.22$ %

⇒ Total intrinsic strain ε_{tot}

- Applied Pressure (piston) $_y = 20$ MPa

Main	x	y	z
ε_{tot}	-0.6	-0.06	-0.36
ó	-102	-20	-60

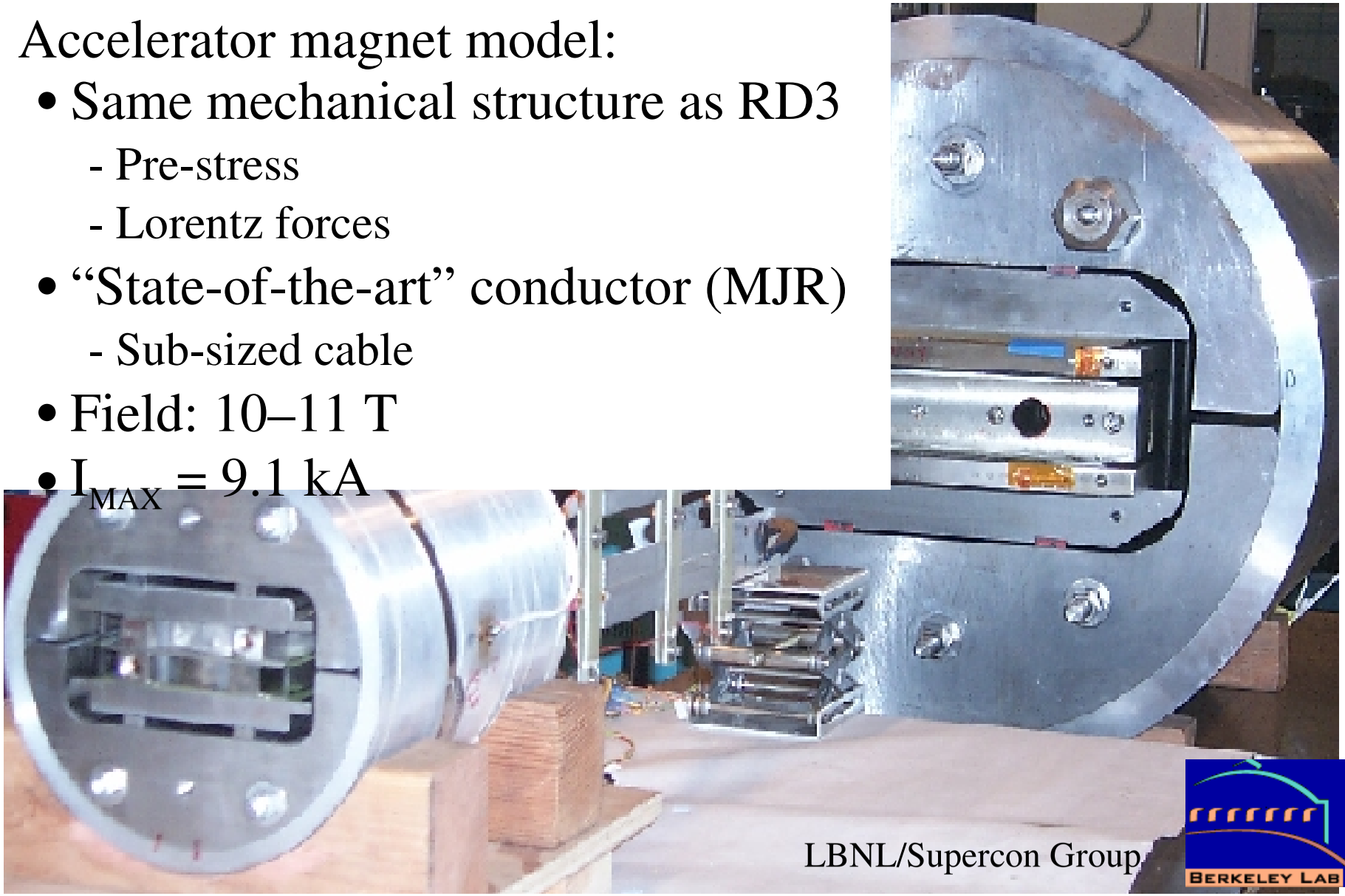
Shear	σ_y=20 MPa	
ã2	0.55	%
ô2	41	MPa

Neglected other applied strains
- Pre-stress
- Lorentz forces
- Bending strain (for React&Wind)

Sub-sized Nb_3Sn Magnet

Accelerator magnet model:

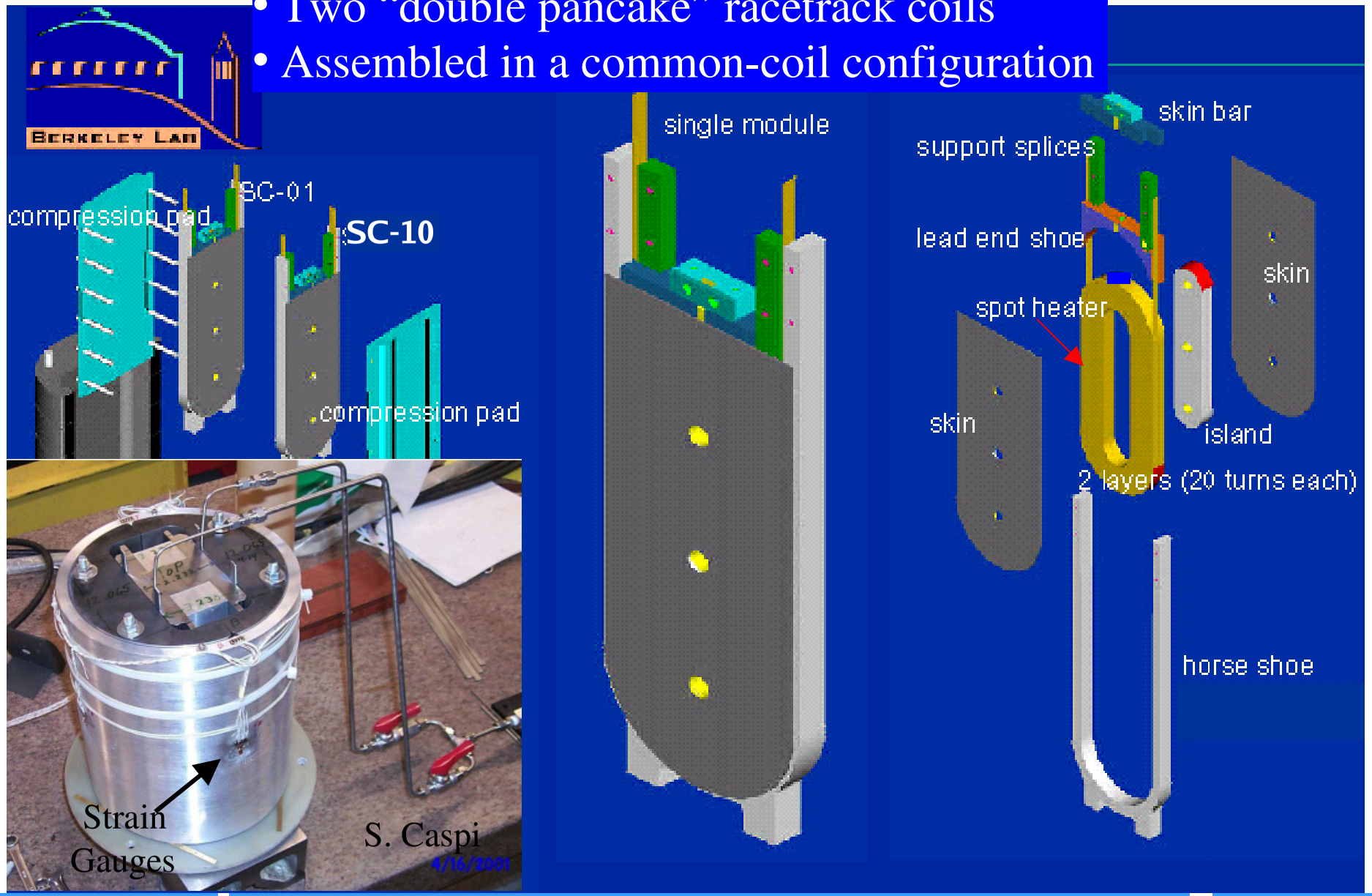
- Same mechanical structure as RD3
  - Pre-stress
  - Lorentz forces
- "State-of-the-art" conductor (MJR)
  - Sub-sized cable
- Field: 10–11 T
- I_{MAX} = 9.1 kA



LBNL/Supercon Group

Magnet Assembly

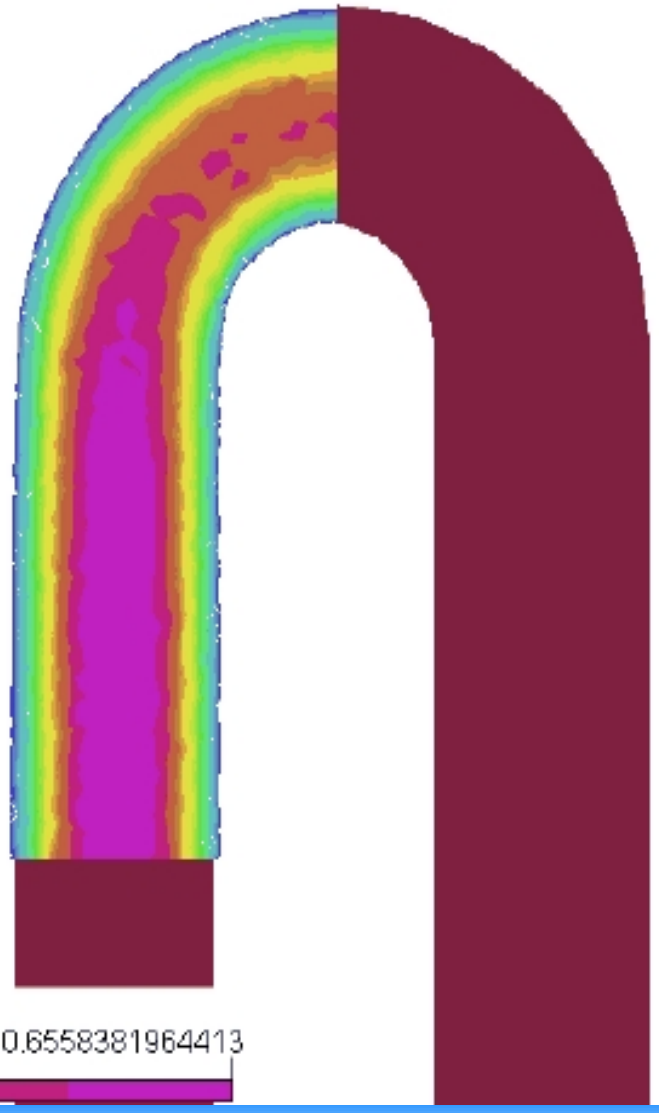
- Two "double pancake" racetrack coils
- Assembled in a common-coil configuration



Magnetic Field

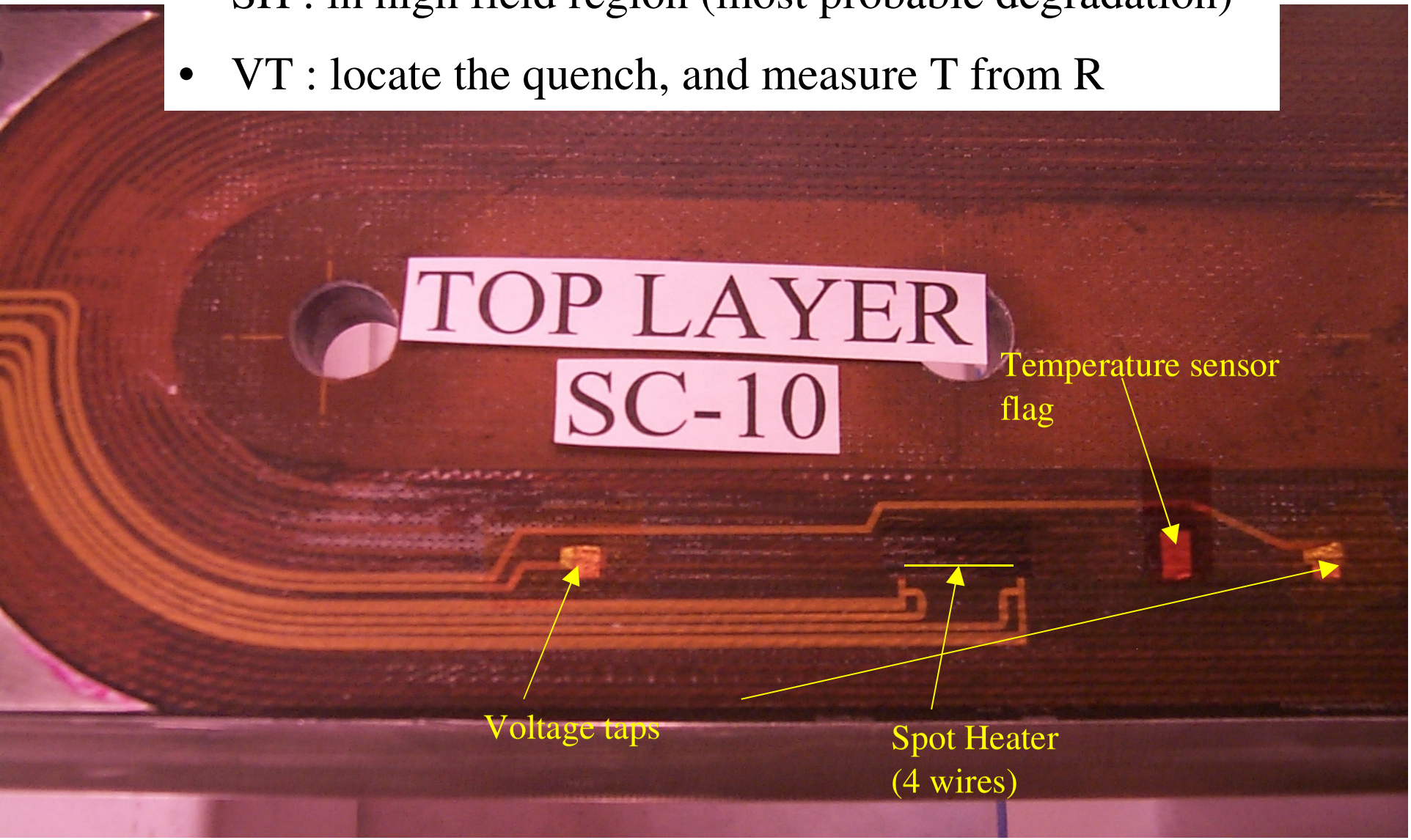
Conductor parameters

Parameters	Coil 1	Coil 10
N of strands	20	
Cable (mm)	8 x 1.3	
Strand d (mm)	0.7	
Insulation (mm)	0.15	
Cu:SC	0.87	1.5
J_C (A/mm^2)	2265	1763
Cu RRR	40.6	53.5

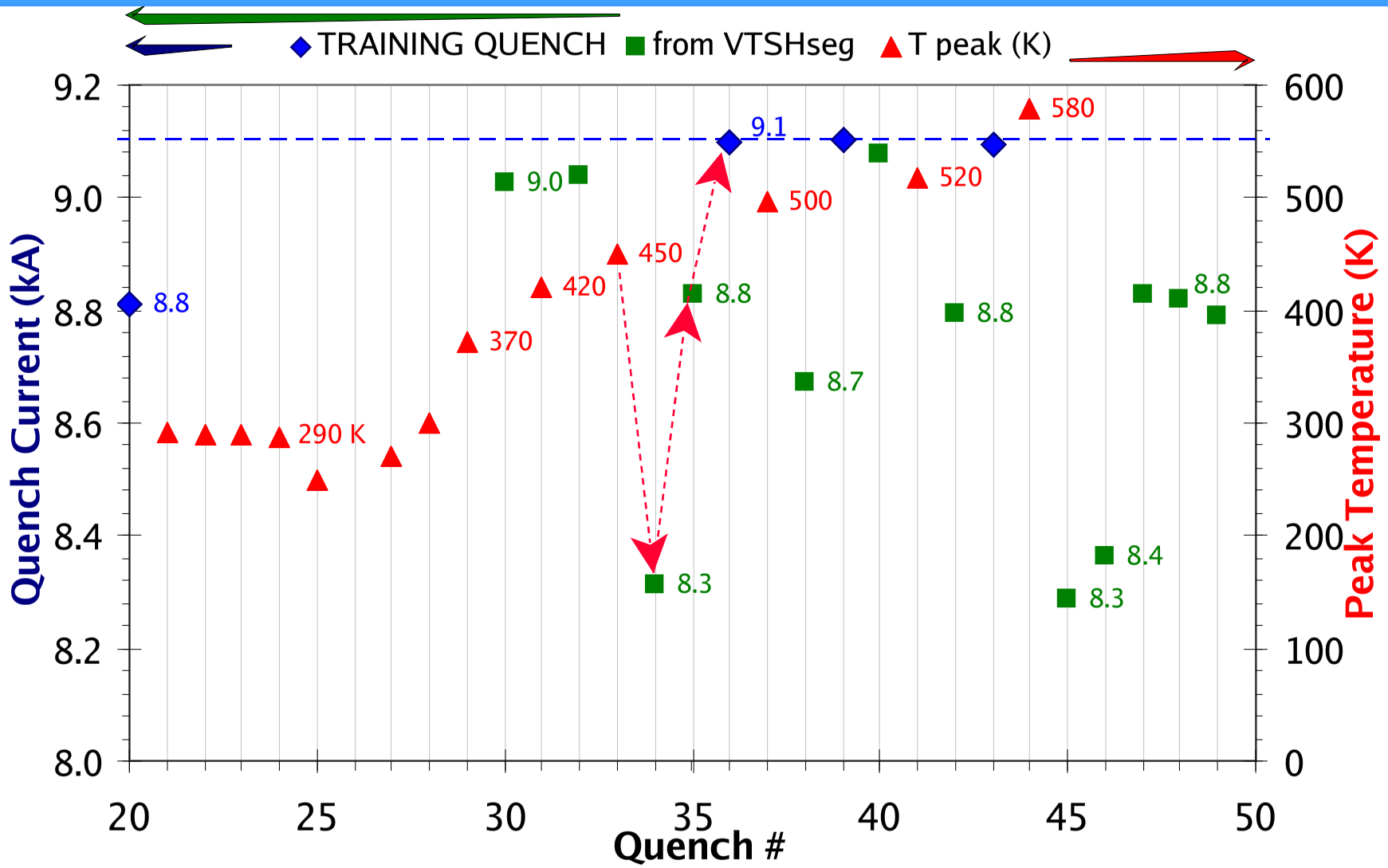


Experiment set up

- SH : in high field region (most probable degradation)
- VT : locate the quench, and measure T from R



Test Results



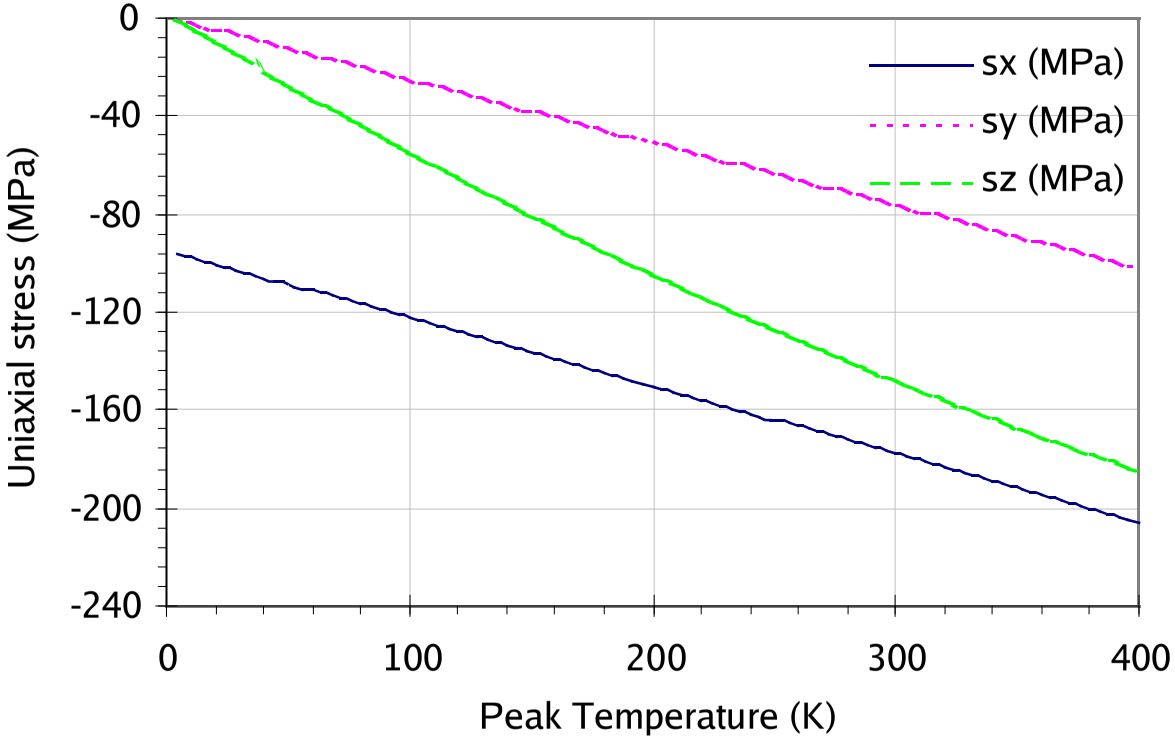
- Detraining after T > 430 K
- Signs of irreversible degradation (I/I_{max} ~ 3%) after T > 580 K

Stress analysis

Up to 400 K

- Stresses and strains below irreversible limits
- Shear stress ~ epoxy strength (~40 MPa)

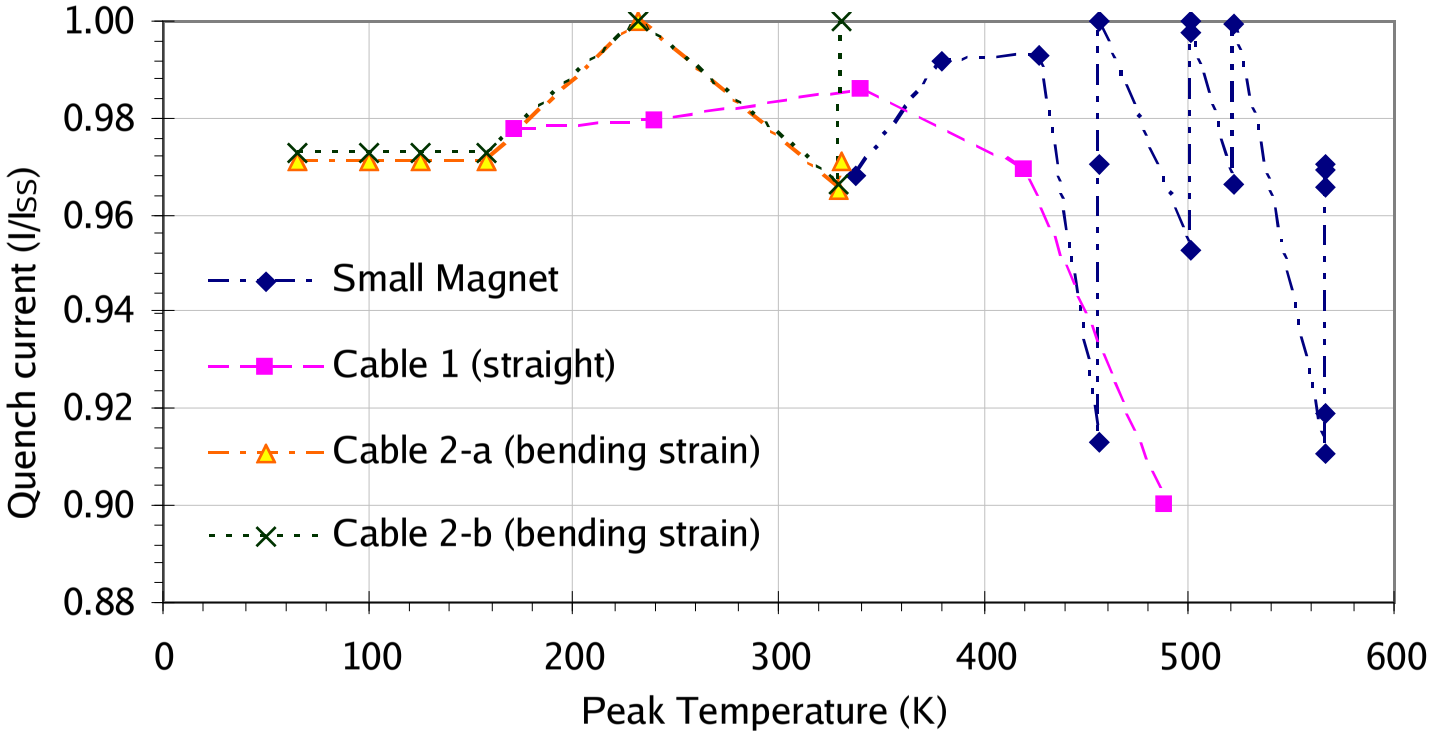
$$\sigma_x(T) = E_x(\varepsilon_{0x} - c_x(T - T_{bath})/2)$$
$$\sigma_y(T) = E_y c_y(T - T_{bath})/2$$
$$\sigma_z(T) = E_z(T) c_z(T - T_{bath})$$



	x	y	z
ε (%)	-0.21	-0.27	-0.42
ε_{tot} (%)	-0.36		-0.57
σ (MPa)	-206	-111	-169
τ (MPa)	$\tau_{x,y} = 47$	$\tau_{y,z} = 29$	$\tau_{x,z} = 18$
Irreversib.	σ=-150/-200 MPa	σ=-150/-200 MPa	ε_{tot}<-0.7%

Conclusions

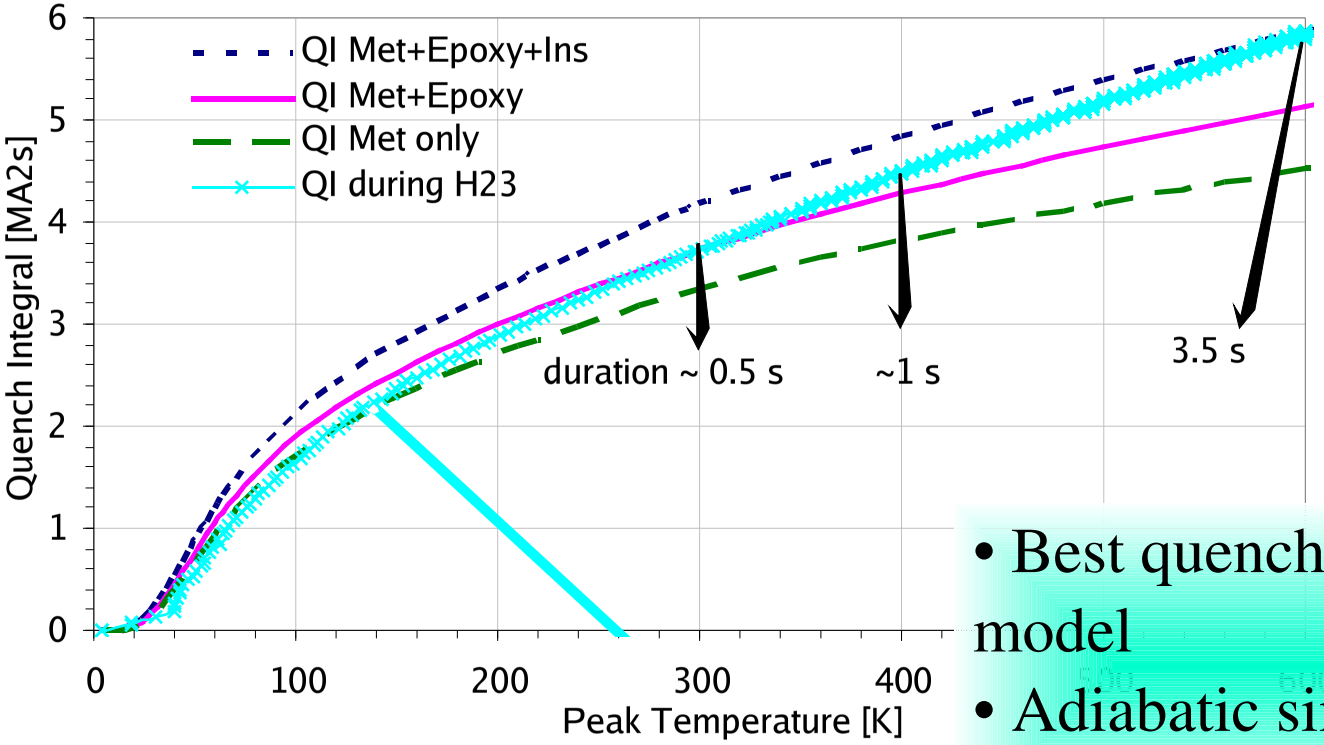
- "Thermal shock" experiments indicate that T_{peak} up to 400 K do not compromise the magnet performance, if the stresses and strains in the conductor remain below its limits.
- At about 430 K, the epoxy resin undergoes a reversible glass transition, which can temporary weaken the insulation.



Conclusions -2

Contribution of insulation to thermal balance during quench

- Measured *QI* agree with the insulated cable curve at ~ T ≥ 300 K, and with the pure metal curve at lower T
- Consistent with diffusivity times: more "adiabatic", (less insulating material participating in the process) at the beginning of the quench



- Best quench simulation: FE model
- Adiabatic simulations: epoxy + up to 0.1 mm insulation at high T.

Outlook

The quench on Nb_3Sn magnet studies may continue with

- FE analyses of the thermo-mechanical response of a magnet during quench (*MT-18*)
- Material R&D, including
  - strip heaters insulation (ex. sol-gel)
  - Coil mechanical limits including I_c degradation under pressure thin edge of the cable and shear strength
- Thermal shock tests on Nb_3Sn magnets with different designs