ILC Main Linac Superconducting Quadrupole

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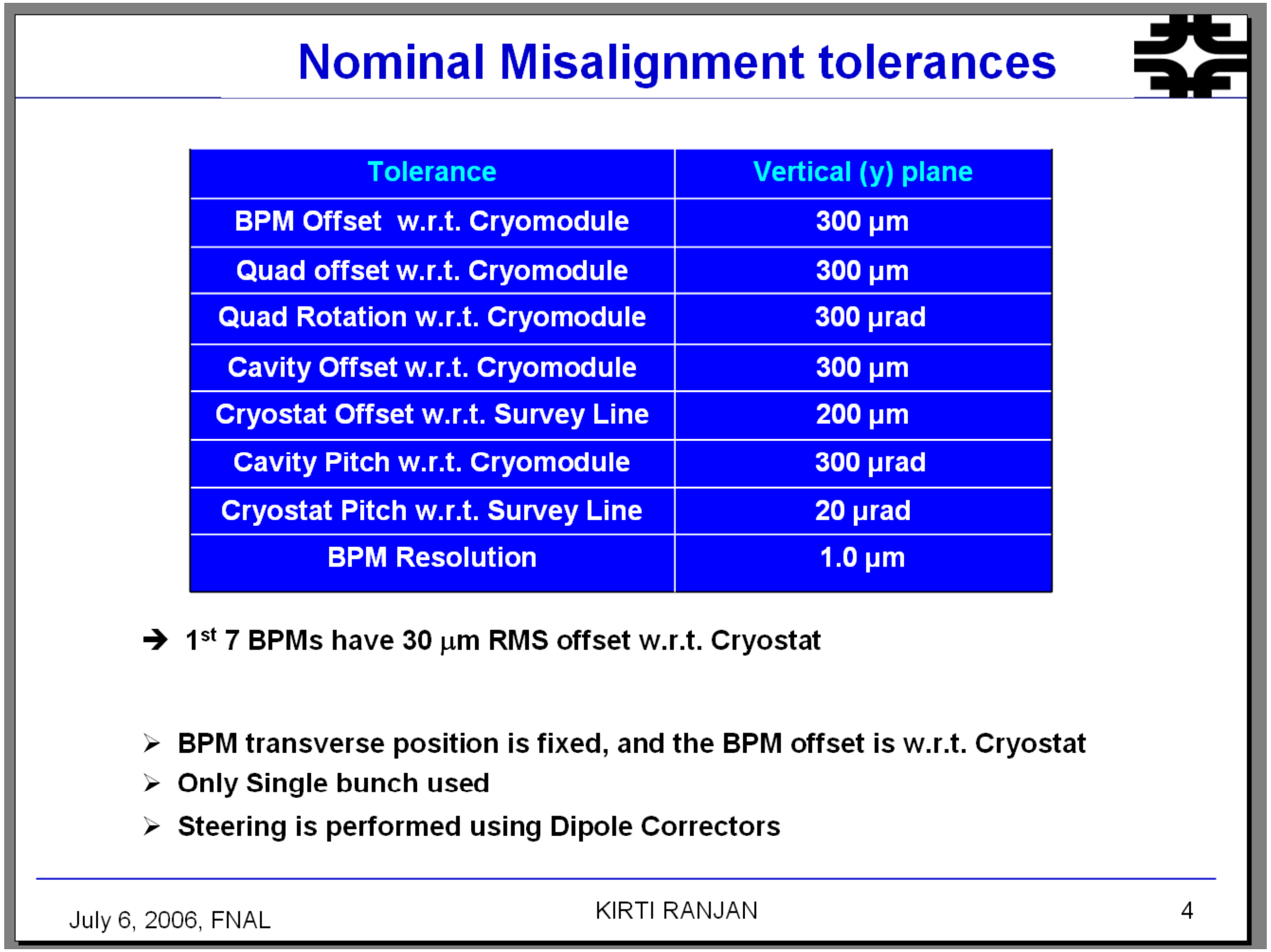
Outline

- Specification
- First Model Goals
- Quadrupole Concept
- Magnetic Design
- Quench Protection
- Mechanical Design
- Magnet Tests
- Quadrupole model status
- Quadrupole package R&D and EDR
- Summary

Quadrupole Specification

Integrated gradient, T	36
Aperture, mm	78
Effective length, mm	666
Peak gradient, T/m	54
Field non-linearity at 5 mm radius, %	0.05
Dipole trim coils	Vertical+Horizontal
Trim coils integrated strength, T-m	0.075
Quadrupole strength adjustment for BBA, %	-20
Magnetic center stability at BBA, um	5
Liquid Helium temperature, K	2
Quantity required	560

Quadrupole Misalignment Tolerances



Nominal Misalignment tolerances

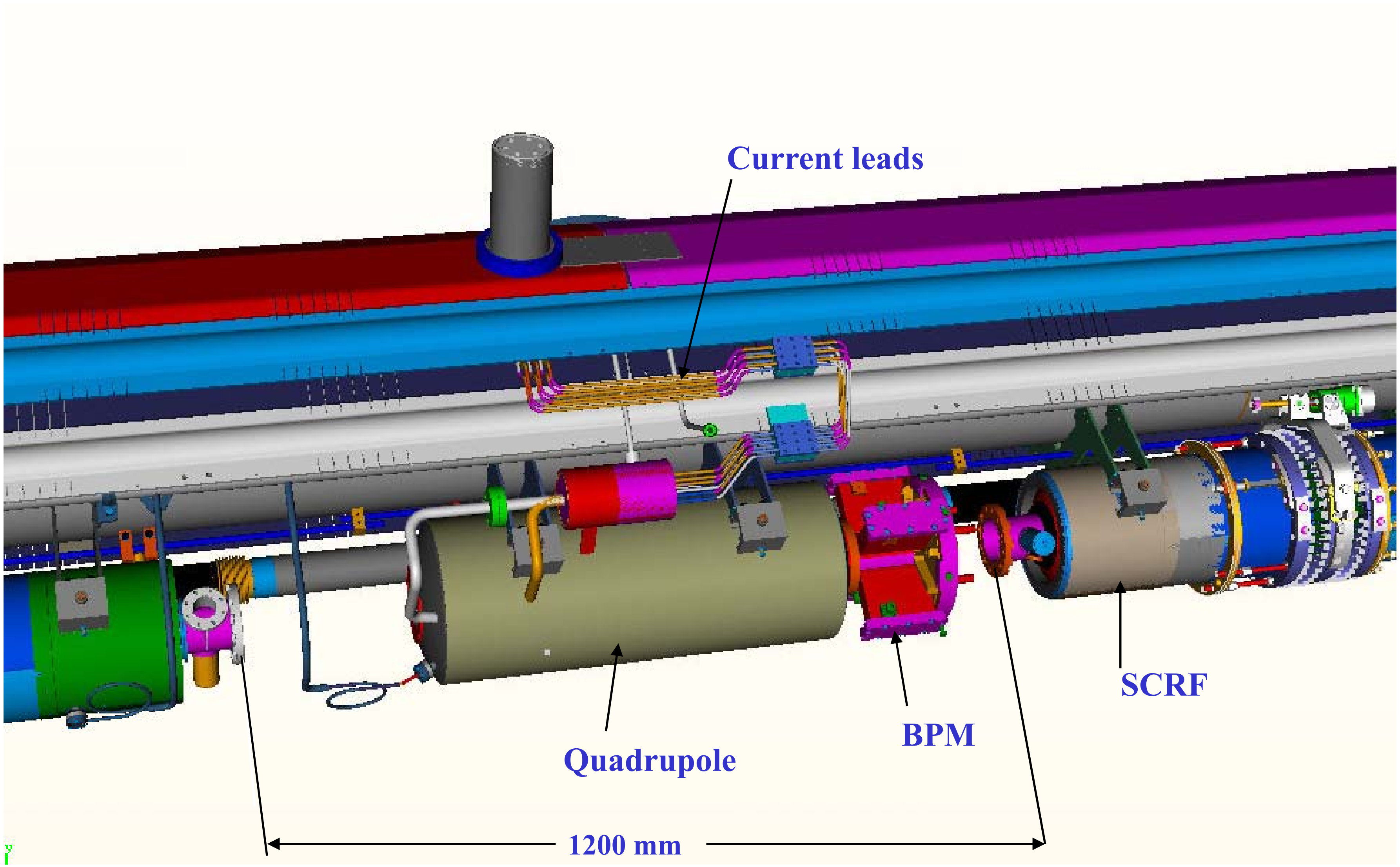
Tolerance	Vertical (y) plane
BPM Offset w.r.t. Cryomodule	300 µm
Quad offset w.r.t. Cryomodule	300 µm
Quad Rotation w.r.t. Cryomodule	300 µrad
Cavity Offset w.r.t. Cryomodule	300 µm
Cryostat Offset w.r.t. Survey Line	200 µm
Cavity Pitch w.r.t. Cryomodule	300 µrad
Cryostat Pitch w.r.t. Survey Line	20 µrad
BPM Resolution	1.0 µm

➔ 1st 7 BPMs have 30 µm RMS offset w.r.t. Cryostat

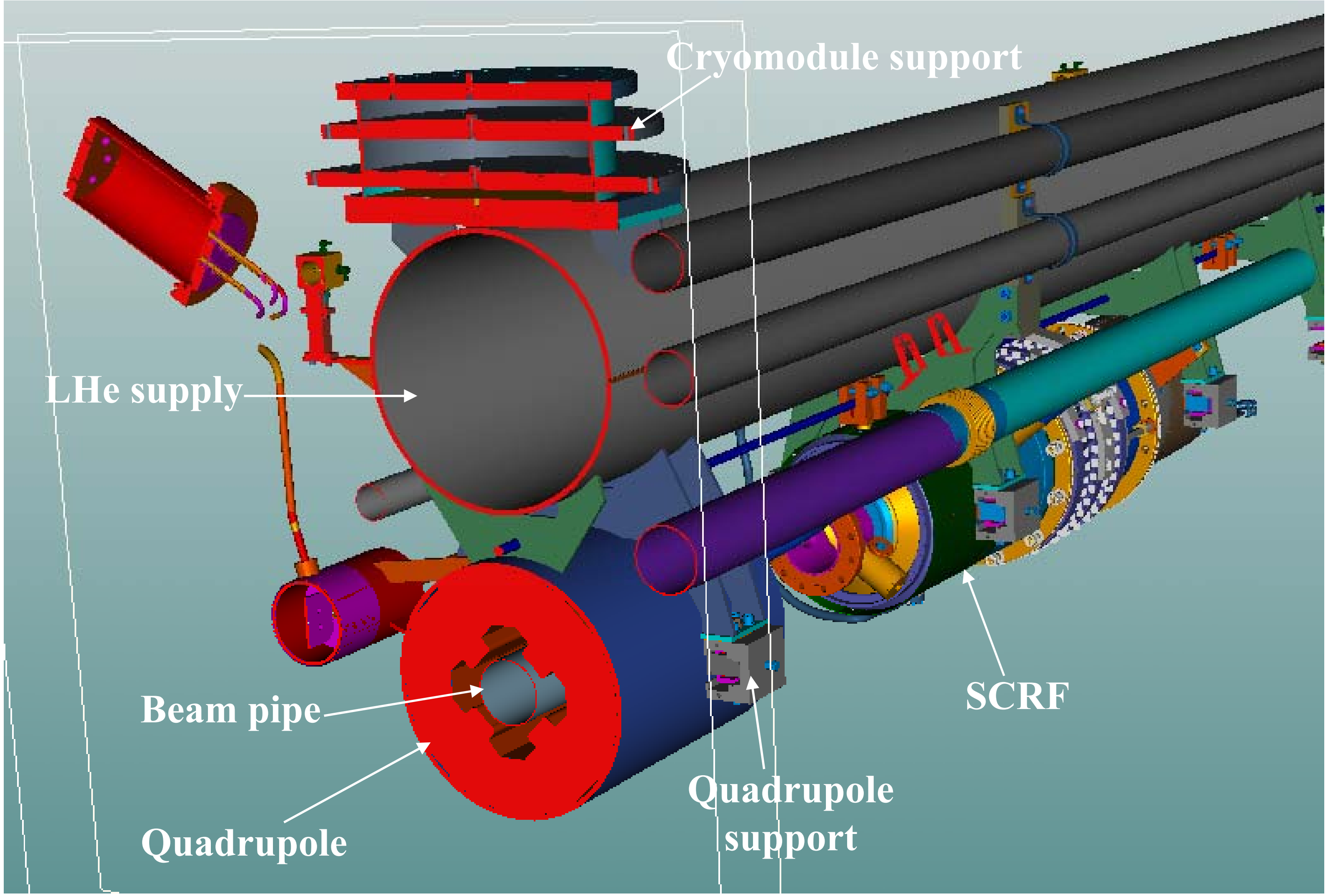
- BPM transverse position is fixed, and the BPM offset is w.r.t. Cryostat
- Only Single bunch used
- Steering is performed using Dipole Correctors

July 6, 2006, FNAL KIRTI RANJAN 4

Main Linac Cryomodule



Cryomodule cross-section



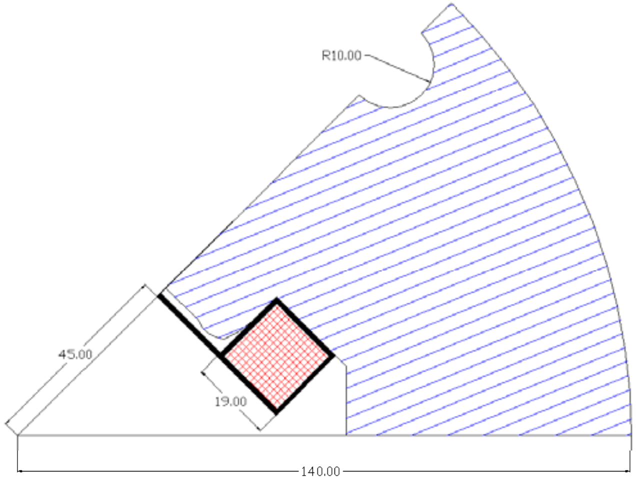
Quadrupole Model Goals

- Check quadrupole concept, magnetic and mechanical design
- Prove fabrication technology
- Measure the magnetic center stability at -20% gradient change with and without dipole shell type coils
- Investigate the acceptable (meet spec.) range of quadrupole integrated strength changes related to different beam energy levels
- Test quench protection system
- Test dipole correctors using trim coils
- Cold mass cost analysis

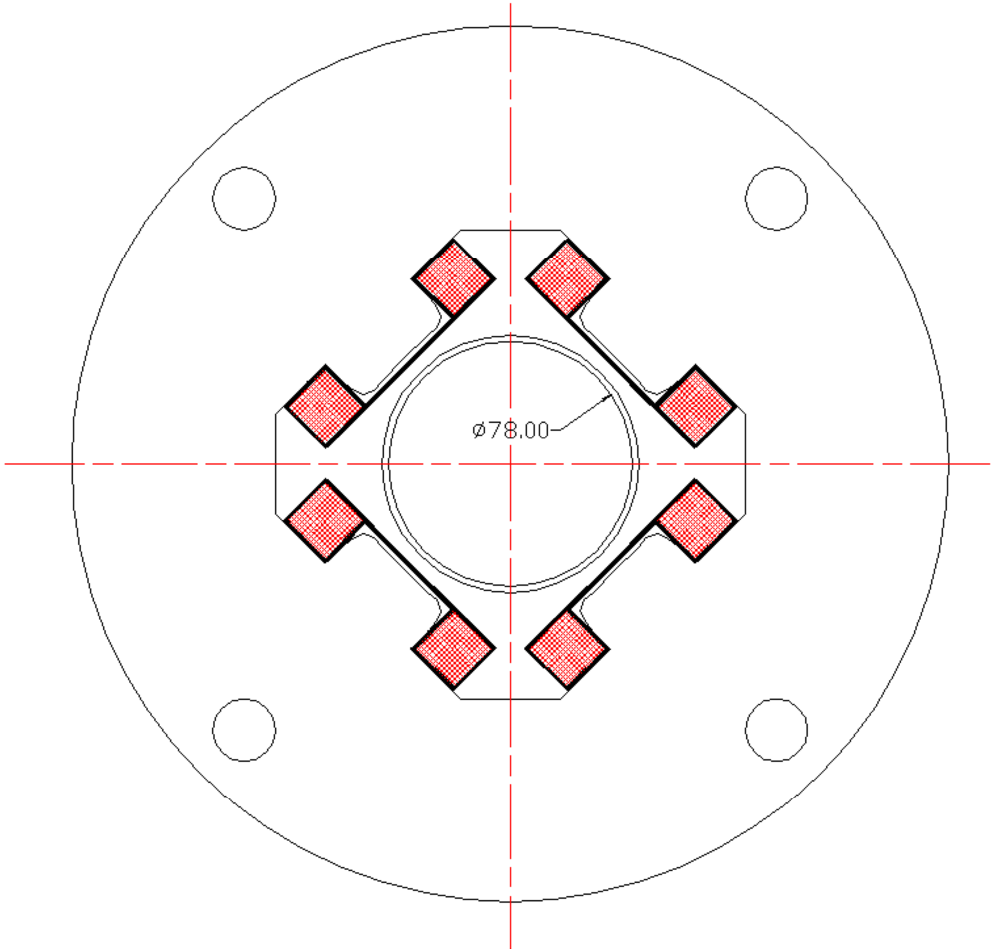
Experimental Model Concept

- Superferric quadrupole configuration with four racetrack coils and cold iron core
- Low peak current (100 A) to reduce heat load from current leads because each magnet powered separately
- NbTi with small filament size wire to reduce superconductor magnetization effects
- Coils wound into a stainless steel channel to provide mechanical rigidity and robast coil manufacturing technology
- Stainless steel structure around coil used as closed mold for coil epoxy vacuum impregnation
- Low carbon steel iron yoke is laminated to use stamping as more economic process
- All four poles and flux return combined in one solid lamination
- Racetrack coils and yoke configuration provide easy assemly/disassembly
- Yoke has magnetic shields at both ends to reduce fringe fields
- Two dipole shell type trim coils mounted on beam pipe outer surface
- Trim coils with beam pipe could be installed/removed
- Each main coil has heater which connected in series with others

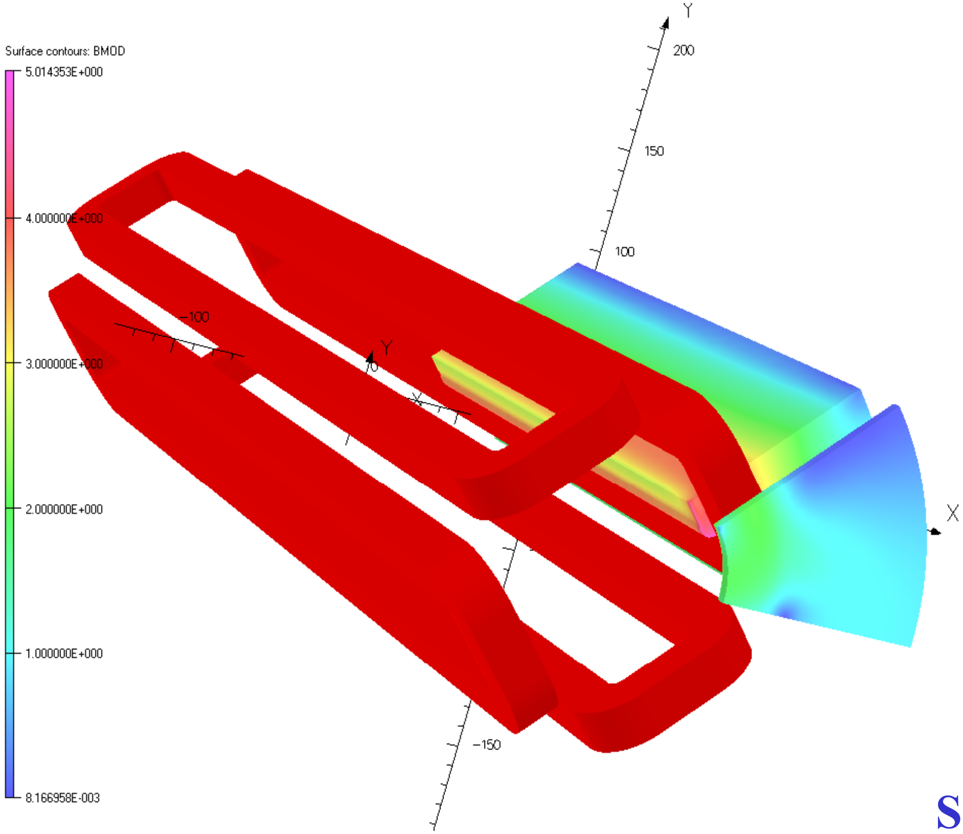
Quadrupole Cross-Section

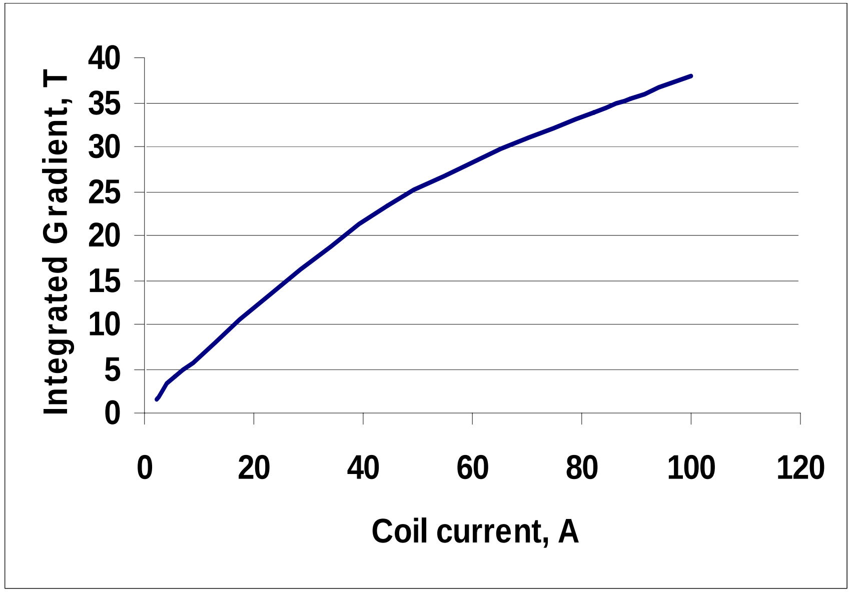


Cold mass diameter	280 mm
Cold mass length	680 mm
Pole length	600 mm
Peak current	100 A
Superconductor length	5 km
Yoke weight	250 kg



3D Quadrupole Magnetic Design

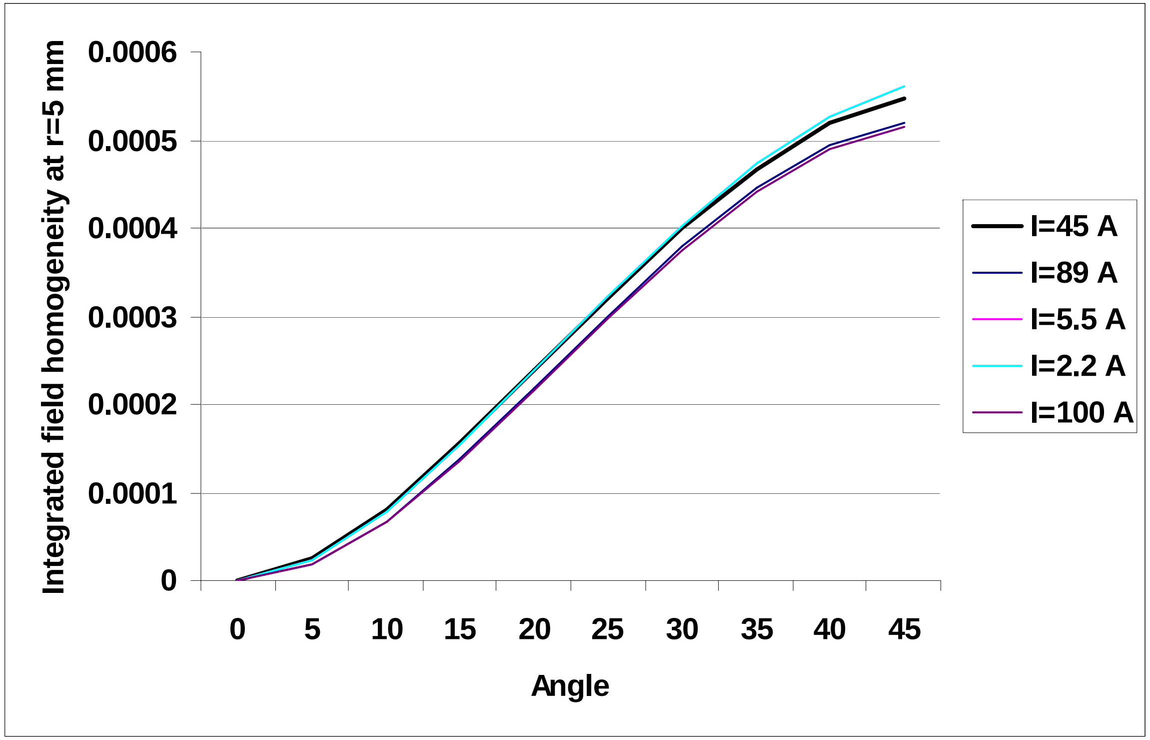




Specified peak integrated gradient 36 T at 93 A of total current/coil

Maximum flux density 5 T at pole ends and 100 A current

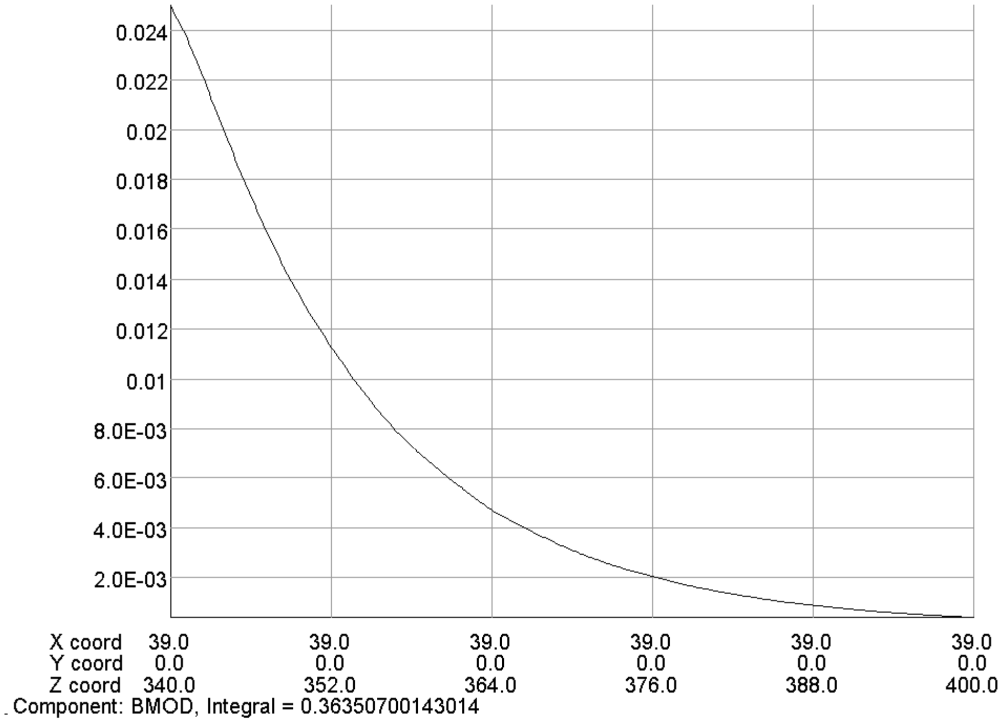
3D Integrated Field Quality



1. There are less than 1 unit changes in integrated field homogeneity at radius 5 mm because of iron saturation effects.

2. Total allowed high order harmonics less than 5.5 units at R=5mm and caused by magnet ends.

Quadrupole Fringe Field along Z-axis



Magnet end plate provides effective shielding up to several Gauss of magnetic field at distance 60 mm from magnet end (400 mm from magnet center). Z=340 mm magnet end.

Superconductor Choice

- Superconductor type NbTi – well known technology and cost efficient at specified fields
- Small filament size < 5 um achievable to reduce superconductor magnetization effects
- Diameter 0.3-0.5 mm for currents <=100 A to reduce heat load from current leads and cables from power supply
- Cu:Sc ratio ~ 1.5-2 to provide safe quench protection
- RRR 50-100 to improve superconductor stability and quench parameters
- Efficient electrical insulation: polyimide, formvar, etc

Superconductor Magnetization Effects

Quadrupole critical parameters

- Magnetic center stability must be 5 µm at -20% strength change
- Low fringing fields:

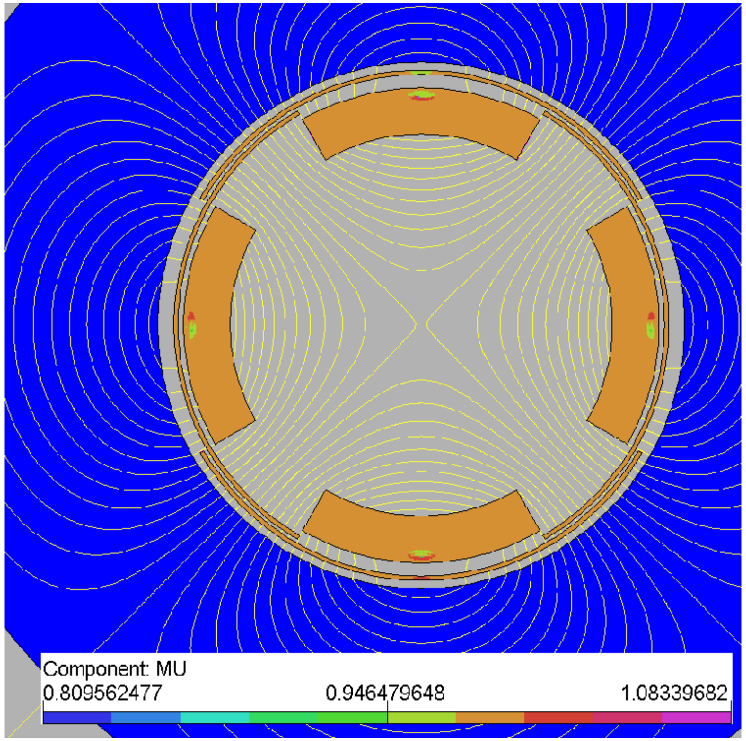
  1 µT during SCRF cooling down

  10 µT during SCRF operation

- Possible issues:

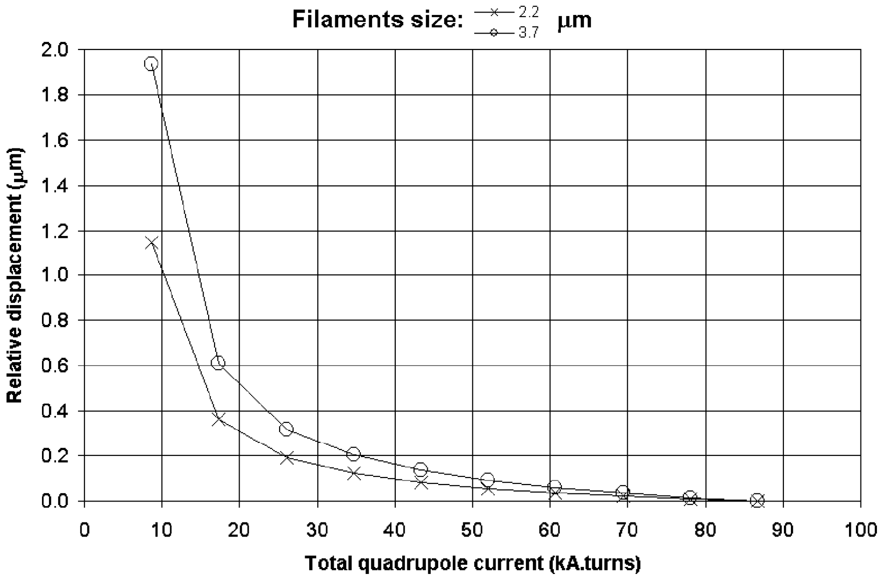
  - magnetic center motion (SC magnetization, Lorentz forces, mechanics, iron saturation and hysteresis, etc)

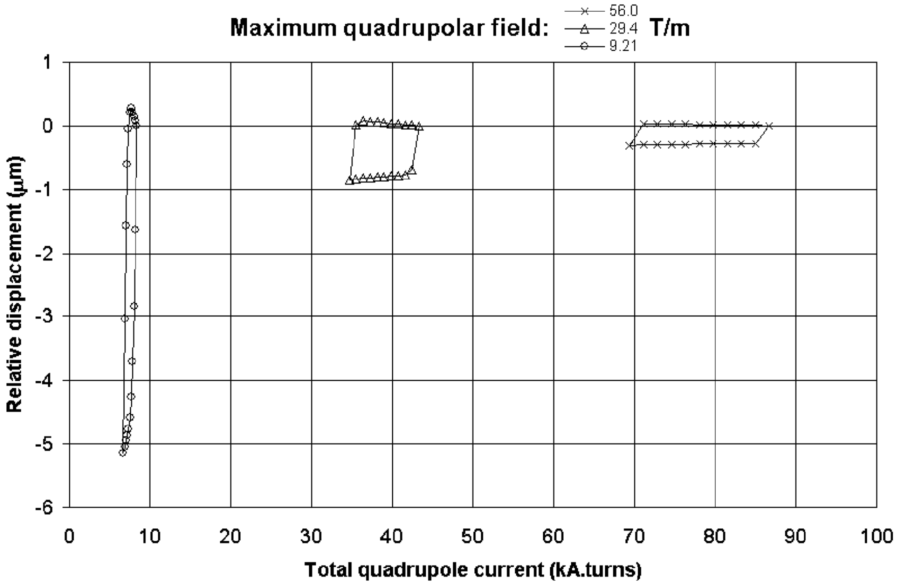
  - fringing field trapped in SCRF at cooling down and operation substantially reduces Q - SCRF quality factor



Calculated 2-4 µm magnetic center displacement in shell type quadrupole with dipole correctors placed between quadrupole coils and yoke because of NbTi superconductor magnetization

Superconductor magnetization effects





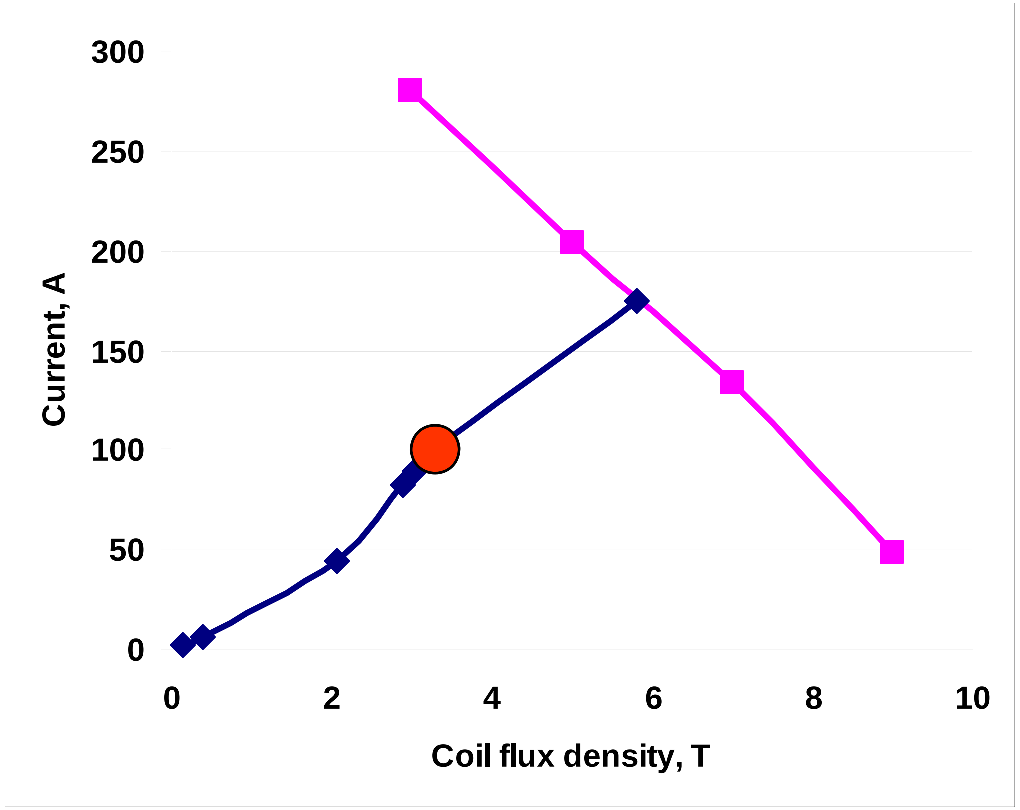
Magnetic center displacement at zero shell corrector current

Magnetic center displacement at zero shell corrector current and -20% gradient change

Racetrack corrector has low 2D magnetization effects

3D effects (end effects) should be investigated

Quadrupole Load Line



Icoil/Ic = 100 A/175 A = 57 % of short sample limit

Quench Protection

Magnet protection system

1. Quench detection system with detection time 30 ms or better
2. External dump resistor 10 Ohm to limit max voltage to 1 kV
3. Heaters for each coil with effective response time 100 ms or better

Quench adiabatic propagation velocity v=27 m/s

Inductance range L=3.9H - 7.9 H

Dump resistor 17 Ohm/m

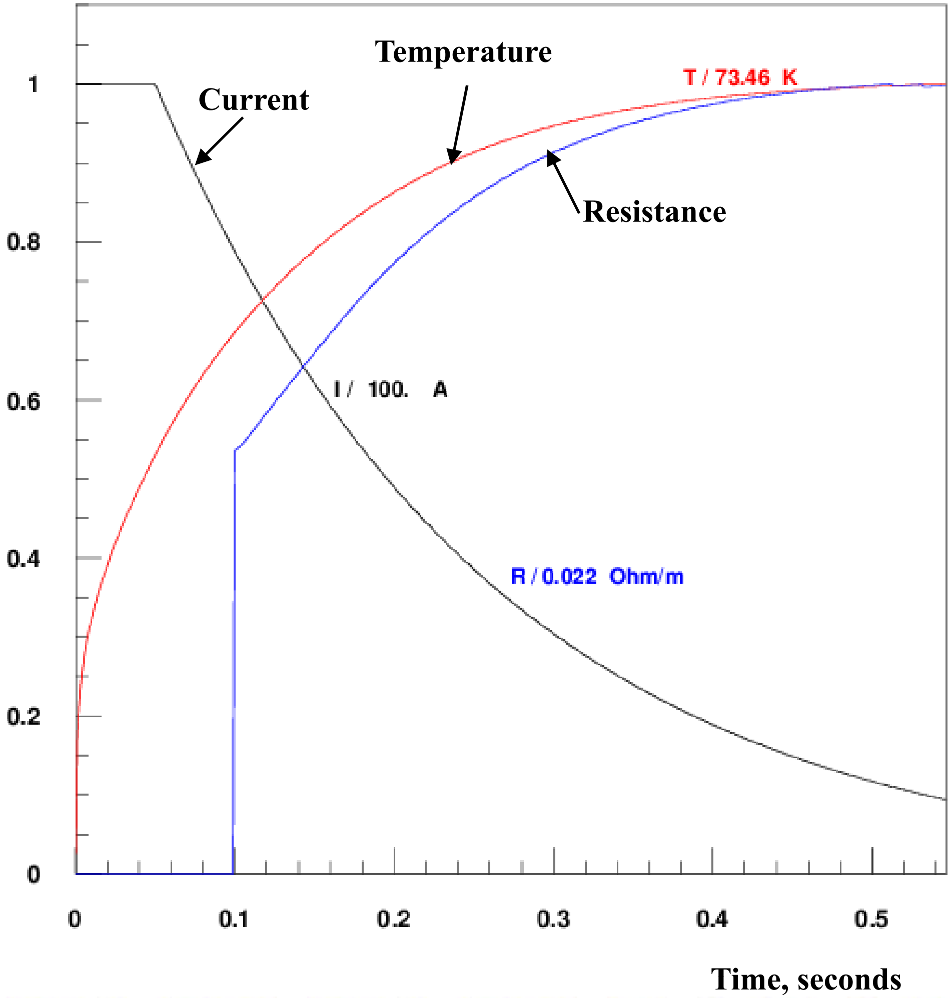
Initial current 100 A

Quench detection and switch to dump resistor after 50 ms

Heater response 100 ms

Maximum temperature 74 K, 0.5 s after the quench

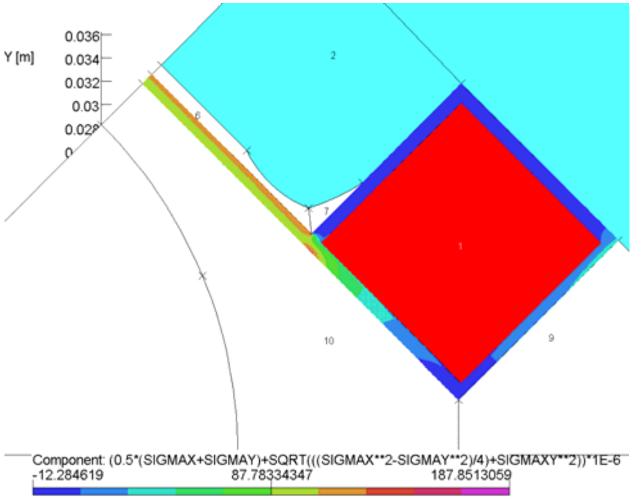
Magnetic field energy 40 kJ



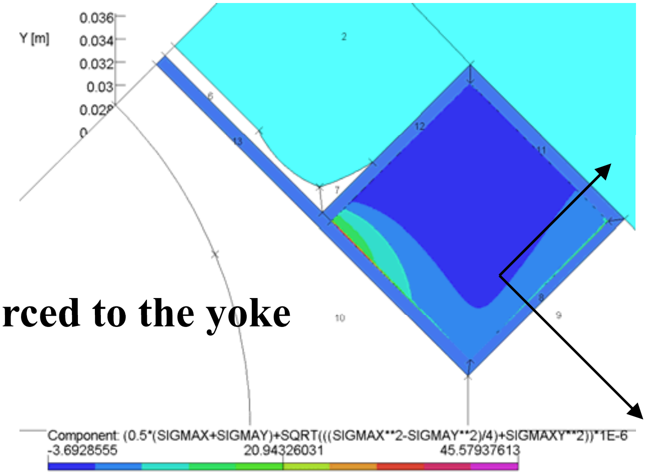
Mechanical Stress Analysis

Stainless steel coil support structure

Lorentz forces at 100 A :	Fx=133 kN/m
	Fy=-34.4 kN/m
Support structure max stress	120 MPa
Coil max stress	45 MPa
Coil displacements	11-19 um
Coil Young modulus	40 GPa

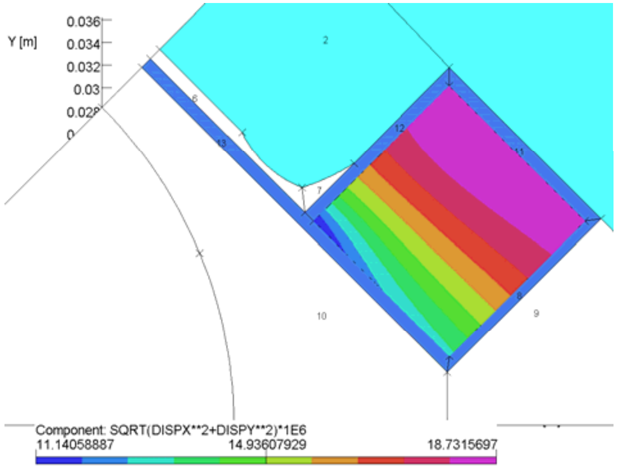


Support principal stresses



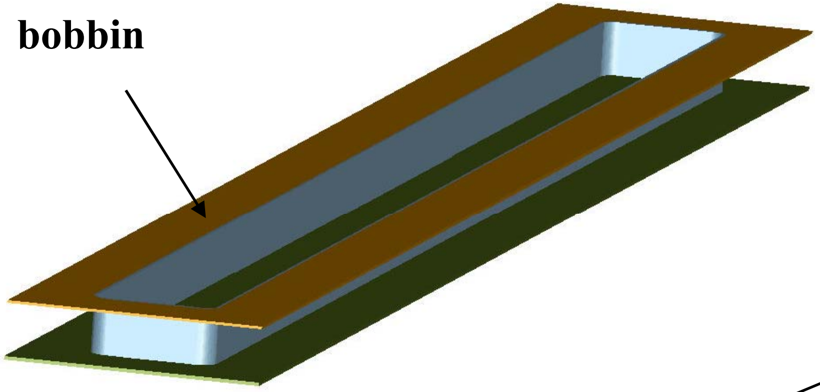
Coil forced to the yoke

Coil principal stresses

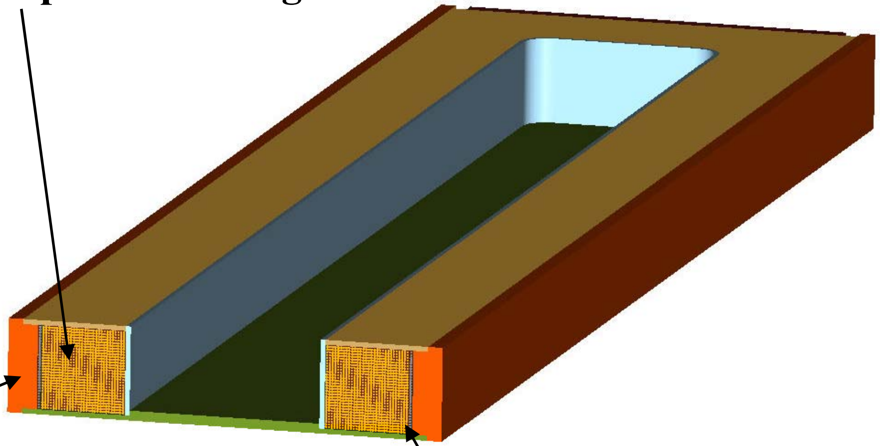


Coil displacements

Quadrupole Coil Design



Coil bobbin



Coil assembly

Coil bobbin used as mandrel for superconducting coil winding

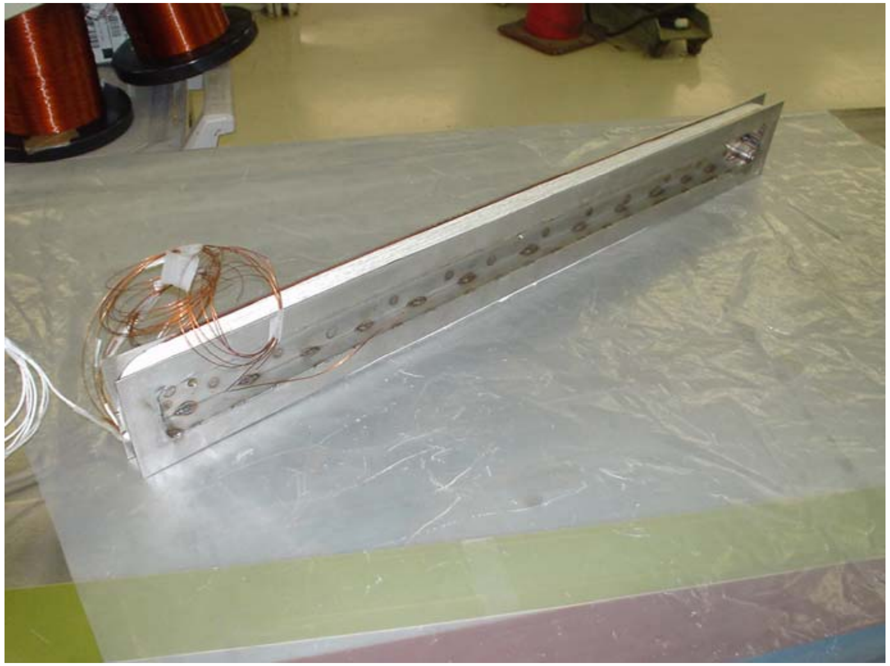
Kapton film used as ground insulation between bobbin and wires

Bobbin and outer collar structure forms closed mold for epoxy vacuum impregnation

Easy assemble coil structure with an iron yoke

Coil attached to the pole on both ends

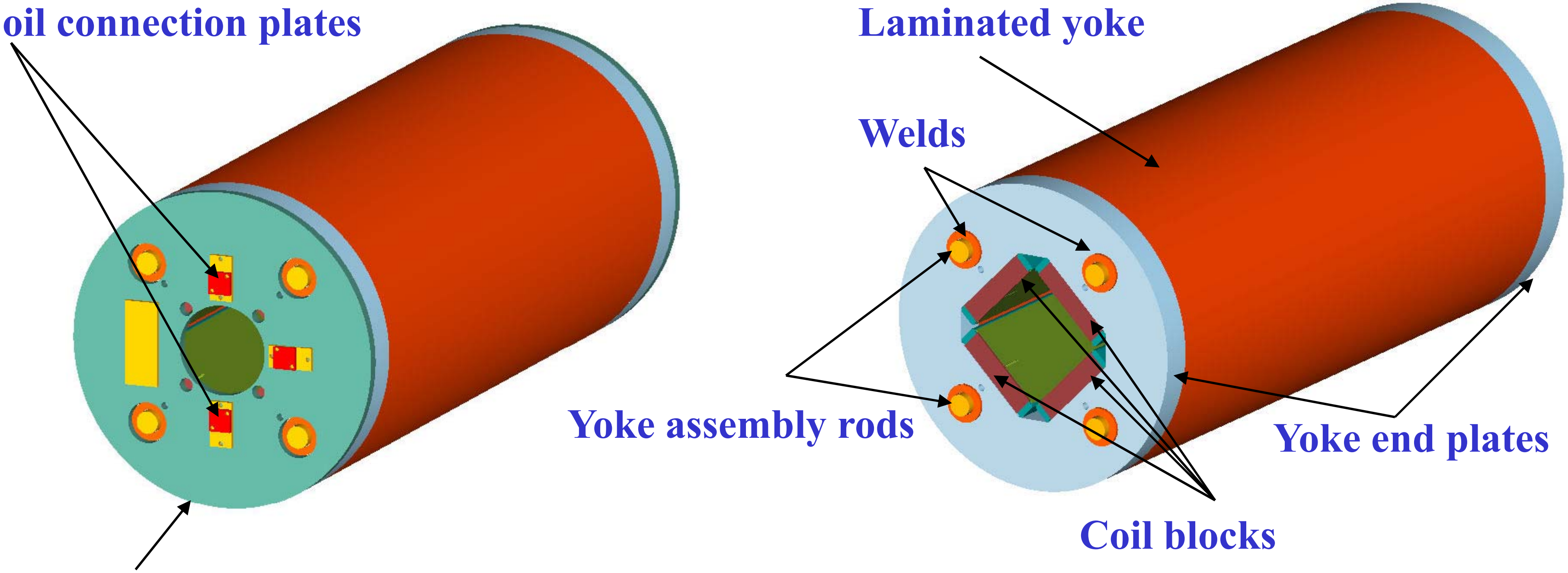
Superconducting coil fabrication



SC Coil after winding

SC Coil after collar welding and epoxy impregnation (ready to install)

Quadrupole cold mass



Coil connection plates

Laminated yoke

Welds

Yoke assembly rods

Yoke end plates

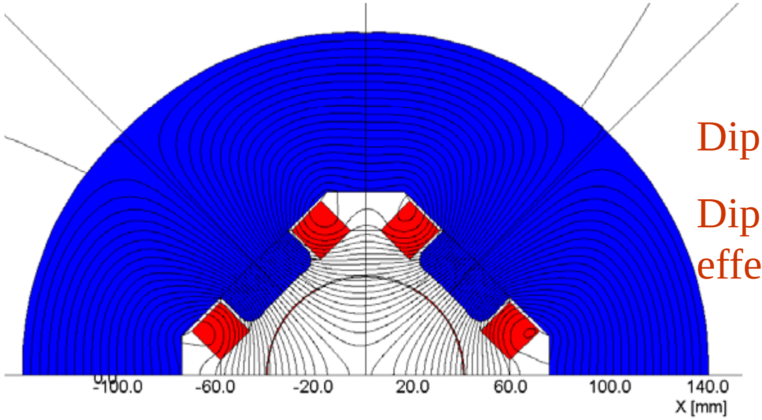
Coil blocks

End shield

Cold mass: Length 680 mm

Outer diameter 280 mm

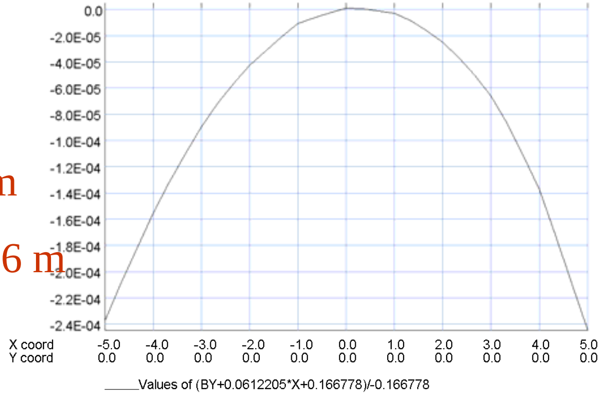
Dipole Correctors



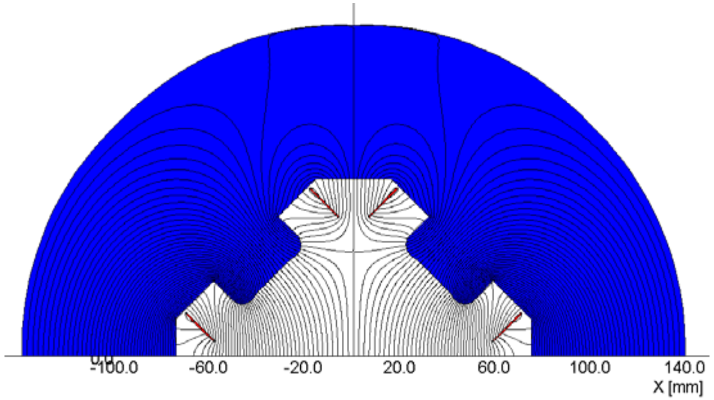
Shell type dipole field homogeneity

Dipole integrated field 0.075T-m

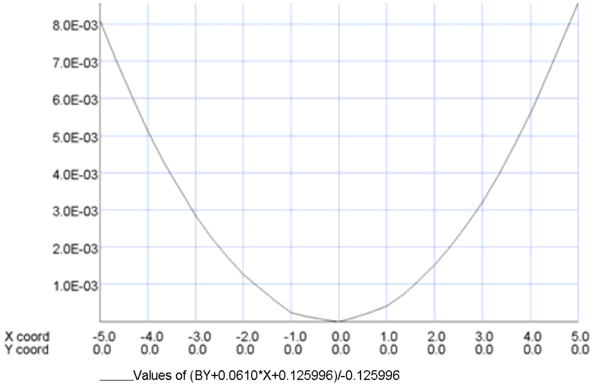
Dipole center field 0.125T at 0.6 m effective length



Shell type dipole field homogeneity at 61 T/m gradient and 0.166 T vertical dipole field



Racetrack type dipole field at zero quadrupole field



Racetrack type dipole field homogeneity at 61 T/m gradient and 0.125 T vertical dipole field

Magnet Tests

1. Quadrupole test using VMTF (Stand busy with LARP model tests)

   Field measurements by rotational coils. All probes and systems exist. This is the quickest way. There should be pair current leads for quadrupole and two pairs for dipole correctors.

2. Quadrupole test using Stand 3

   Field measurements using flat board dipole coils. Needs probes and stand upgrade. Stand is good for test quadrupole general parameters: currents, training, correctors, etc.

3. Quadrupole test at 4.2K using Tevatron test stand. Needs cryostat. Main advantage is possibility to use stretch wire technique. Cryostat from Low-Beta Quadrupole may be an option.

4. Tests using Stand 4. Main advantage is possibility for tests at 2 K LHe temperature with stretch wire technique.

Questions for Magnet Tests

1. **Quadrupole magnetic center stability during -20% gradient decrease. Should be measured at different gradient levels in range of gradients of 2-100%.**
2. **Magnetic center stability as in 1. at different trim coils currents.**
3. **Long term magnetic center stability at DC current for different field levels.**
4. **Field quality at 5 mm reference radius for strait section and whole length at different quadrupole and trim coils currents.**
5. **Fringing field at some distance (~100mm) from magnet end**
6. **Peak current at quench.**
7. **Efficiency of quench protection system.**
8. **Coil maximum temperature after the quench.**
9. **Quadrupole cooling down time and time recovery after the quench.**
10. **Effective RRR.**
11. **Residual magnetic field at zero currents.**

Quadrupole model status

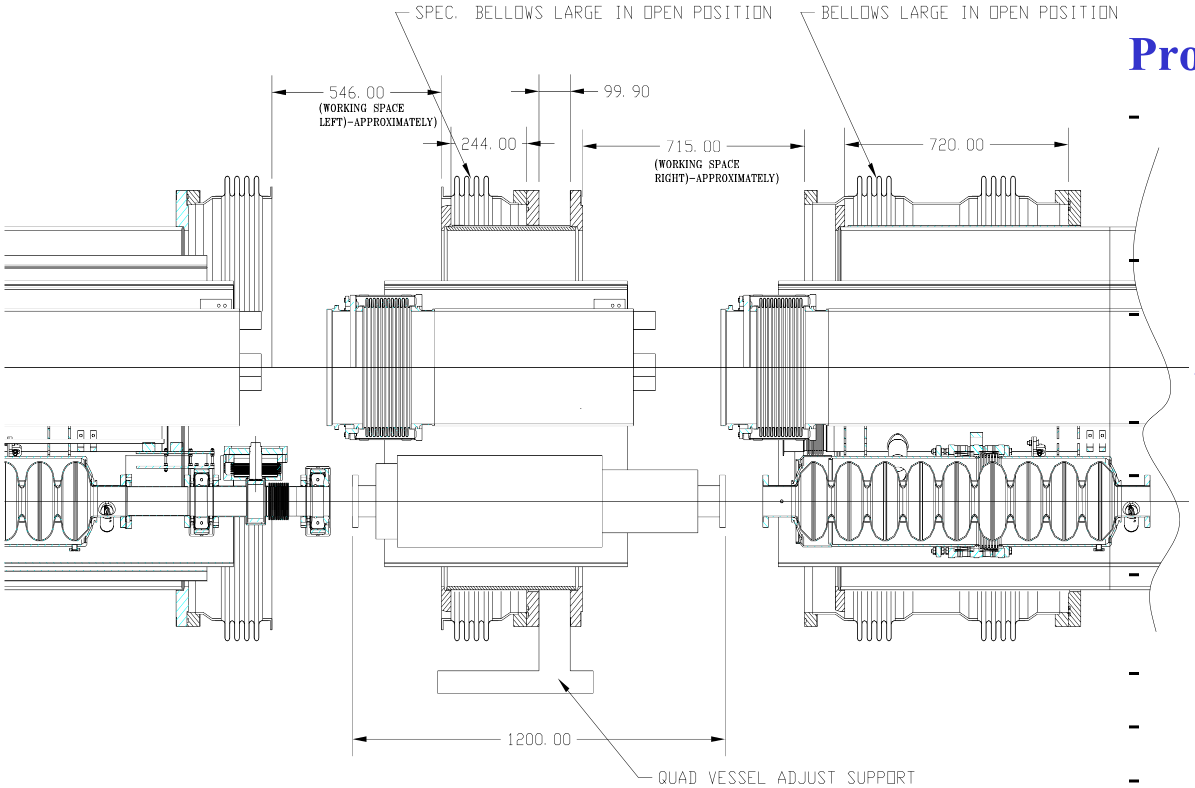
- **The ILC ML Quadrupole cold mass is designed.**
- **The first quadrupole model fabrication is in progress.**
- **In proposed magnet configuration special attention paid on providing better magnetic center stability. For that used very small filament size superconductor, superferric yoke configuration, racetrack coils in stainless steel container.**
- **Two options of correction coils under consideration: racetrack or shell types trim coils**
- **Magnetic and mechanical analysis were performed. Magnet pole, coil geometry optimized for better integrated field quality. End shields designed to reduce fringing fields.**
- **Proposed quench protection scenario with external dump resistor and coil heaters.**
- **Proposed cost effective magnet manufacturing technique based on FNAL experience.**

Nevertheless it should be noted:

This is an experimental magnet and designed to be flexible for various modifications: coil change, yoke disassembly, removable correction coils, etc.

Nobody at that time investigated a superconducting quadrupole center stability with micron accuracy.

Quadrupole package between cryomodules



Pros:

- Cryomodules and Quadrupoles having different specs and performance are decoupled
- Cryomodules could be identical
- Manufacturing, assembly and test lines are independent
- Independent design, prototyping and tests
- Could be different (higher) temperature and lower corresponding cryoload
- Lower influence of fringing fields from magnets and current leads
- Feed boxes decoupled from Cryomodule
- Lower quadrupole vibrations
- Higher accuracy of quadrupole positioning
- Easy mechanical position adjustment and long term space stability
- Easy replacement
- Lower fabrication and assembly cost

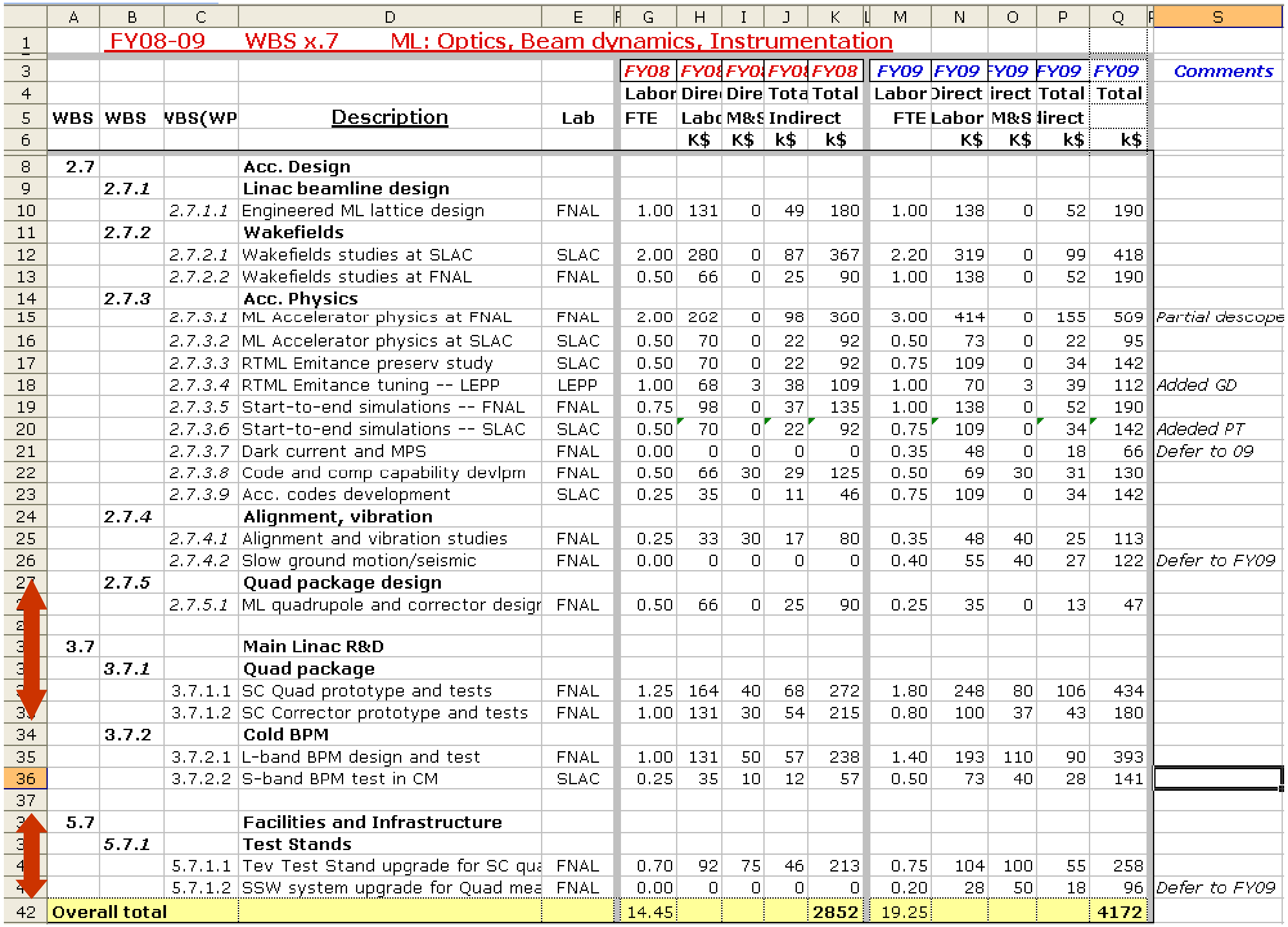
Cons:

- More connections and higher tunnel installation cost

Quadrupole package R&D and EDR goals

- Design and fabricate the quadrupole models of high and low gradient versions acceptable also for RTML
- Upgrade Stand 4 for quadrupole tests at 2 K using stretch wire technique
- On the base of test results:
  - prove the quadrupole design, manufacturing technology and performance
  - make decision about combined or stand alone correctors
- Design and build the quadrupole package placed between cryomodules
- Design and built for Main Linac quadrupole package:
  - current leads
  - power supplies
  - quench detection system
  - instrumentation system
- Test the stand alone package magnetic and mechanical performance
- Assemble and test the ML Quadrupole package prototype
- Write Quadrupole package EDR section including full set of drawings, test results and cost estimation

Quadrupole package WBS



	A	B	C	D	E	G	H	I	J	K	M	N	O	P	Q	S
1		FY08-09		WBS x.7 ML: Optics, Beam dynamics, Instrumentation												
3						FY08	FY08	FY0	FY08	FY08	FY09	FY09	FY09	FY09	FY09	Comments
4						Labor	Dire	Dire	Tota	Total	Labor	Direct	irect	Total	Total	
5	WBS	WBS	VBS(WP	Description	Lab	FTE	Labo	M&S	Indirect		FTE	Labor	M&S	lirect		
6							K$	K$	k$	k$		K$	K$	k$	k$	
8	2.7			**Acc. Design**												
9		2.7.1		**Linac beamline design**												
10			2.7.1.1	Engineered ML lattice design	FNAL	1.00	131	0	49	180	1.00	138	0	52	190	
11		2.7.2		**Wakefields**												
12			2.7.2.1	Wakefields studies at SLAC	SLAC	2.00	280	0	87	367	2.20	319	0	99	418	
13			2.7.2.2	Wakefields studies at FNAL	FNAL	0.50	66	0	25	90	1.00	138	0	52	190	
14		2.7.3		**Acc. Physics**												
15			2.7.3.1	ML Accelerator physics at FNAL	FNAL	2.00	262	0	98	360	3.00	414	0	155	569	Partial descope
16			2.7.3.2	ML Accelerator physics at SLAC	SLAC	0.50	70	0	22	92	0.50	73	0	22	95	
17			2.7.3.3	RTML Emitance preserv study	SLAC	0.50	70	0	22	92	0.75	109	0	34	142	
18			2.7.3.4	RTML Emitance tuning -- LEPP	LEPP	1.00	68	3	38	109	1.00	70	3	39	112	Added GD
19			2.7.3.5	Start-to-end simulations -- FNAL	FNAL	0.75	98	0	37	135	1.00	138	0	52	190	
20			2.7.3.6	Start-to-end simulations -- SLAC	SLAC	0.50	70	0	22	92	0.75	109	0	34	142	Adeded PT
21			2.7.3.7	Dark current and MPS	FNAL	0.00	0	0	0	0	0.35	48	0	18	66	Defer to 09
22			2.7.3.8	Code and comp capability devlpm	FNAL	0.50	66	30	29	125	0.50	69	30	31	130	
23			2.7.3.9	Acc. codes development	SLAC	0.25	35	0	11	46	0.75	109	0	34	142	
24		2.7.4		**Alignment, vibration**												
25			2.7.4.1	Alignment and vibration studies	FNAL	0.25	33	30	17	80	0.35	48	40	25	113	
26			2.7.4.2	Slow ground motion/seismic	FNAL	0.00	0	0	0	0	0.40	55	40	27	122	Defer to FY09
27		2.7.5		**Quad package design**												
			2.7.5.1	ML quadrupole and corrector desigr	FNAL	0.50	66	0	25	90	0.25	35	0	13	47	
2																
3	3.7			**Main Linac R&D**												
3		3.7.1		**Quad package**												
			3.7.1.1	SC Quad prototype and tests	FNAL	1.25	164	40	68	272	1.80	248	80	106	434	
3			3.7.1.2	SC Corrector prototype and tests	FNAL	1.00	131	30	54	215	0.80	100	37	43	180	
34		3.7.2		**Cold BPM**												
35			3.7.2.1	L-band BPM design and test	FNAL	1.00	131	50	57	238	1.40	193	110	90	393	
36			3.7.2.2	S-band BPM test in CM	SLAC	0.25	35	10	12	57	0.50	73	40	28	141	
37																
3	5.7			**Facilities and Infrastructure**												
3		5.7.1		**Test Stands**												
4			5.7.1.1	Tev Test Stand upgrade for SC qua	FNAL	0.70	92	75	46	213	0.75	104	100	55	258	
4			5.7.1.2	SSW system upgrade for Quad mea	FNAL	0.00	0	0	0	0	0.20	28	50	18	96	Defer to FY09
42	**Overall total**					14.45				**2852**	19.25				**4172**	