Superconducting magnets

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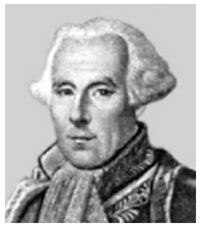
CONTENTS

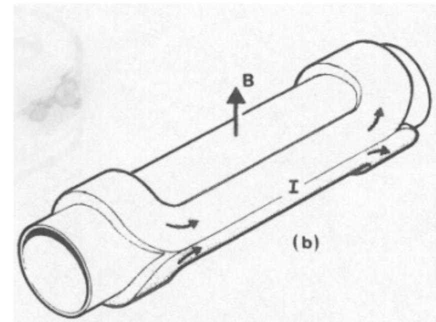
- Basics of electromagnet design
- Superconducting materials
  - Current density versus magnetic field
- Aperture versus field or gradient
  - Simple approximated expressions for dipoles and quadrupoles
- What is available

BASICS OF ELECTROMAGNET DESIGN

- Electromagnets: magnetic field is generated by currents according to Biot-Savart law



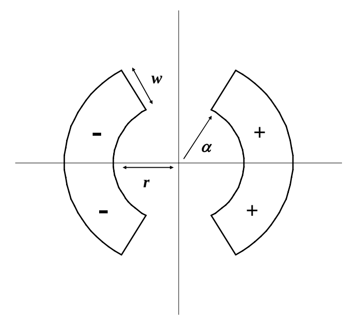
  - Field is proportional to current density
  - Field is inverse proportional to distance



Artist view of a dipole, from M. N. Wilson « Superconducting Magnets »

- Example 1. Dipole configuration (60° sector coil)
  - Field proportional to coil width
  - Field independent of aperture

$$B_1 = -4\frac{j\mu_0}{2\pi}\int_0^{\pi/3}\int_r^{r+w}\frac{\cos\theta}{\rho}\rho d\rho d\theta = -\frac{\sqrt{3}\mu_0}{\pi}jw$$

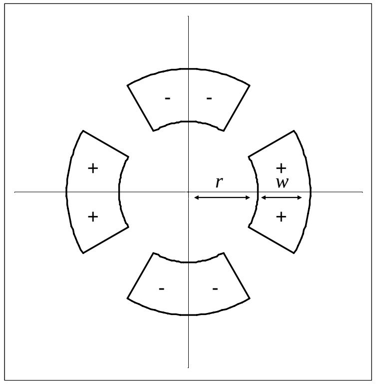


Cross-section of a dipole based on 60° sector coils

- Example II. Quadrupole configuration

$$G = -8\frac{j\mu_0}{2\pi}\int_0^{\alpha}\int_r^{r+w}\frac{\cos 2\theta}{\rho^2}\rho d\rho d\theta = -\frac{\sqrt{3}\mu_0}{\pi} j \ln\left(1+\frac{w}{r}\right)$$

  - Gradient proportional to j
  - Gradient depends on *w/r*



Cross-section of a quad based on 30º sector coils

BASICS OF ELECTROMAGNET DESIGN

- The current density is the key parameter
  - Resistive magnets: water cooled copper or aluminum cable – current densities of from 5 A/mm^2 to 100 A/mm^2 (with special cooling)
  - Superconducting magnets: current densities of ~500 A/mm^2 →
    - They can be much smaller and have much lower operational costs (only power consumption is to keep them cold)
  - but one disadvantage
    - Superconducting state is destroyed by magnetic field (Nb-Ti: ~ 13 T, Nb_3Sn: ~ 25 T)
    - The field in the coil is ~central field (dipole or solenoid) or ~gradient ×aperture radius (quadrupole)
    - Superconducting magnets are limited by the conductor *j* vs *B* property (critical surface)
  - This limitation is not present in resistive magnets
    - Very high field solenoids have to use resistive cables – superconductors used in the low field regions to make them more compact and economic

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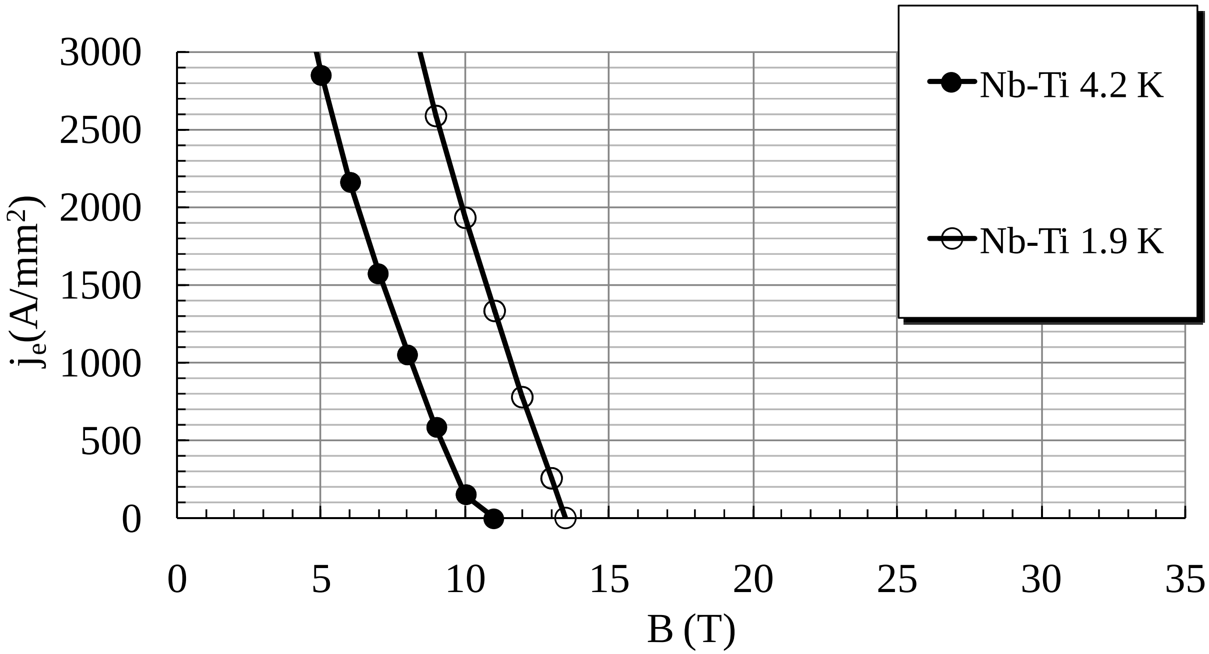
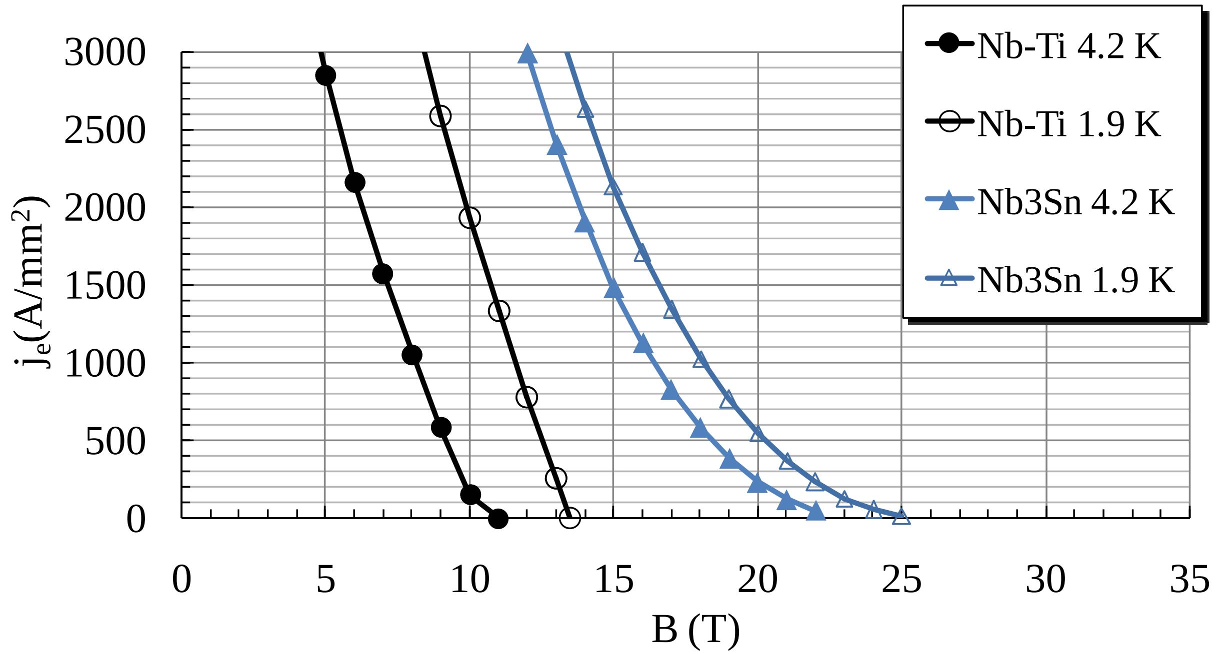
SUPERCONDUCTING MATERIALS

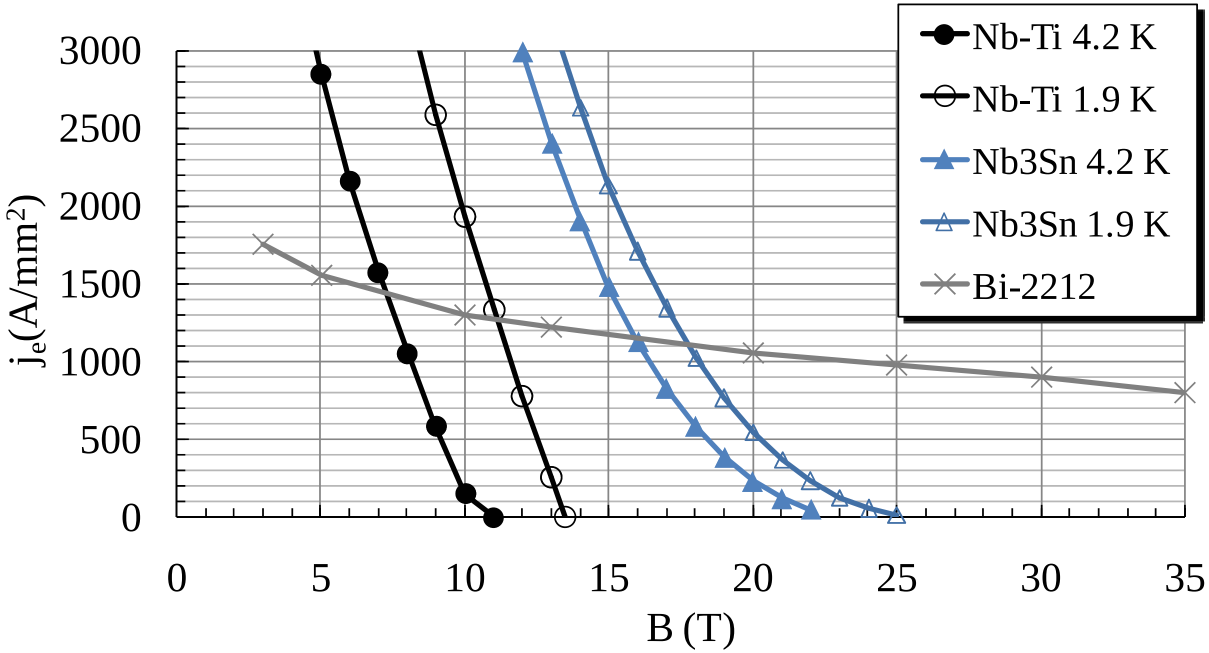


- Nb-Ti is the workhorse for 4 to 10 T
  - Can reach ~2500 A/mm^2 at 6 T and 4.2 K or at 9 T and 1.9 K
  - Well known industrial process, good mechanical properties
  - Thousands of accelerator magnets have been built
  - 10 T field in the coil is the practical limit at 1.9 K

SUPERCONDUCTING MATERIALS



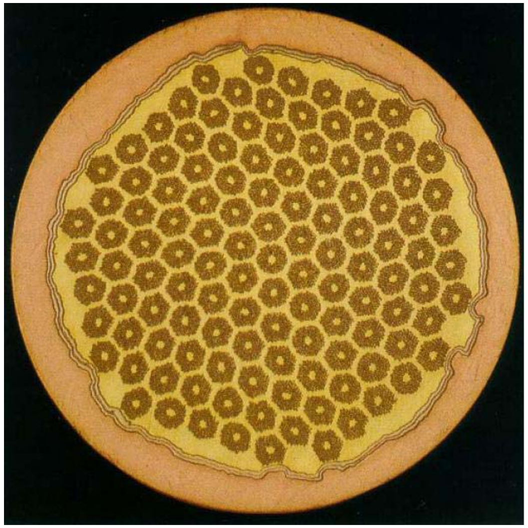
- Nb_3Sn: towards 20 T
  - Can reach up to ~3000 A/mm^2 at 12 T and 4.2 K
  - Complex industrial process, higher cost, brittle and strain sensitive
  - ~25 short models for accelerator magnets have been built
  - ~20 T field in the coil is the practical limit at 1.9 K



- HTS materials: dreaming 40 T
  - Current density is low, but very little dependence on the magnetic field
  - Used in solenoids, used in power lines – no accelerator magnets or models have been built – small racetracks have been built

SUPERCONDUCTING MATERIALS

- The above quoted current densities cannot be reached in the coil
  - Bulk superconductor is unstable
  - Superconductor is in thin filaments (twisted) surrounded by copper
  - Strands make cables (twisted), and one has voids and insulation
- In general a cable has 1/3 of superconductor



Superconductor filaments inside a strand

Strands assembeld in a Rutherford cable

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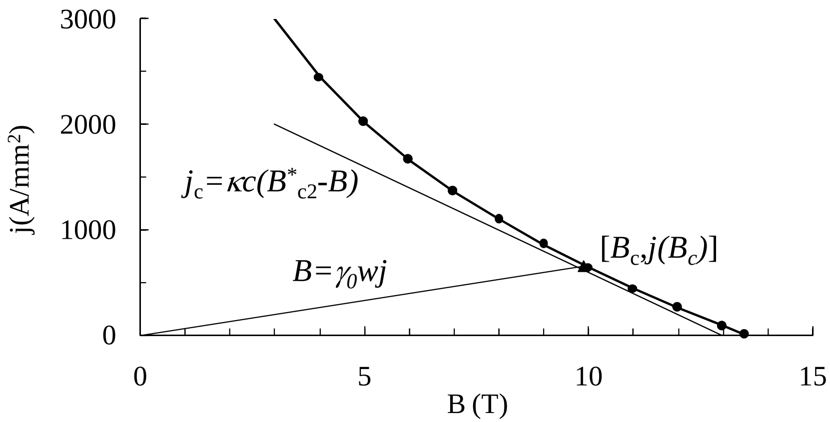
DIPOLES

- Why at 1.9 K Nb-Ti critical field is 13 T and we can get only 10 T?

$$B = j\gamma = wj\gamma_0$$

$$B_p = \lambda B = \lambda\gamma j$$

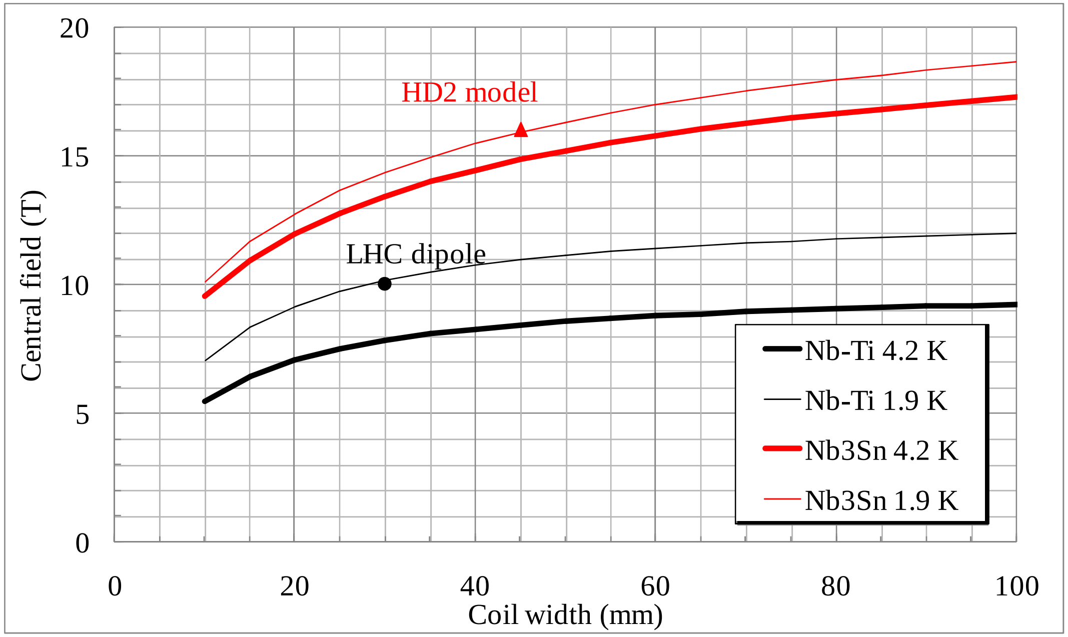
$$B_{ss} = \frac{\kappa c B^*_{c2}}{1+\lambda\kappa c\gamma}\gamma = B^*_{c2}\frac{aw}{1+aw}$$



- There is a saturation for large coil widths
  - For thin coils, doubling the coil width one doubles the field
  - For thick coils, doubling the coil width one has little gain
  - Ex. Nb-Ti at 1.9 K: doubling from 30 mm thick to 60 mm one increases the field only from 10 T to 11 T

DIPOLES

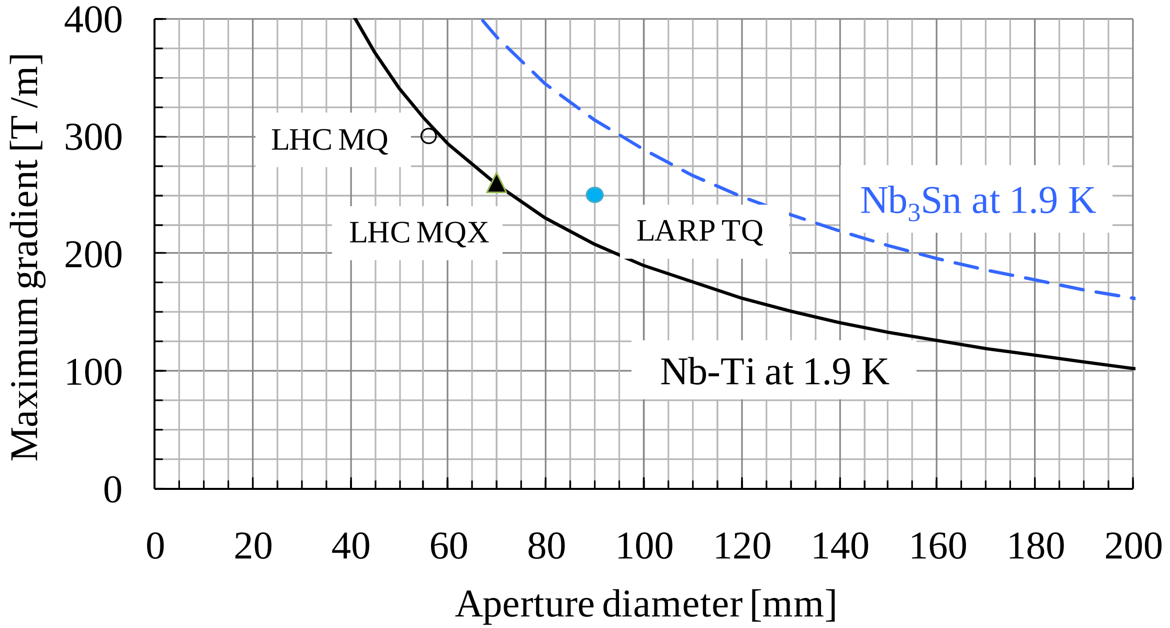
- In dipoles the field depends on the coil width *w* and on the critical surface – little dependence on aperture radius *r*



  - Nb-Ti: 30 mm coil gives about 10 T (LHC)
  - Nb_3Sn: 45 mm coil gives about 16 T (HD2 model)

QUADRUPOLES

- In quadrupoles for each aperture there is a maximal reachable gradient, obtained for a finite coil width



  - Nb-Ti: 35 mm aperture radius, 260 T/m (LHC MQXA and MQXB)
  - Nb_3Sn: 45 mm aperture radius, 260 T/m (TQ LARP models)

MAGNET LENGTH

- In principle, very long magnets can be built
  - No limitations from the superconducting technology
  - The limitation comes from the tooling, and related cost problems
- For Nb-Ti, magnets with lengths in the range of 10-15 m have been built
- For Nb_3Sn, only 1-m long models have been built
  - A 3.4 m long quadrupole is being built by the LARP program

A stack of LHC dipoles seen from the satellite

A 15m truck unloading a 27 tons LHC dipole

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  - Simple approximated expressions for dipoles, quads and solenoids
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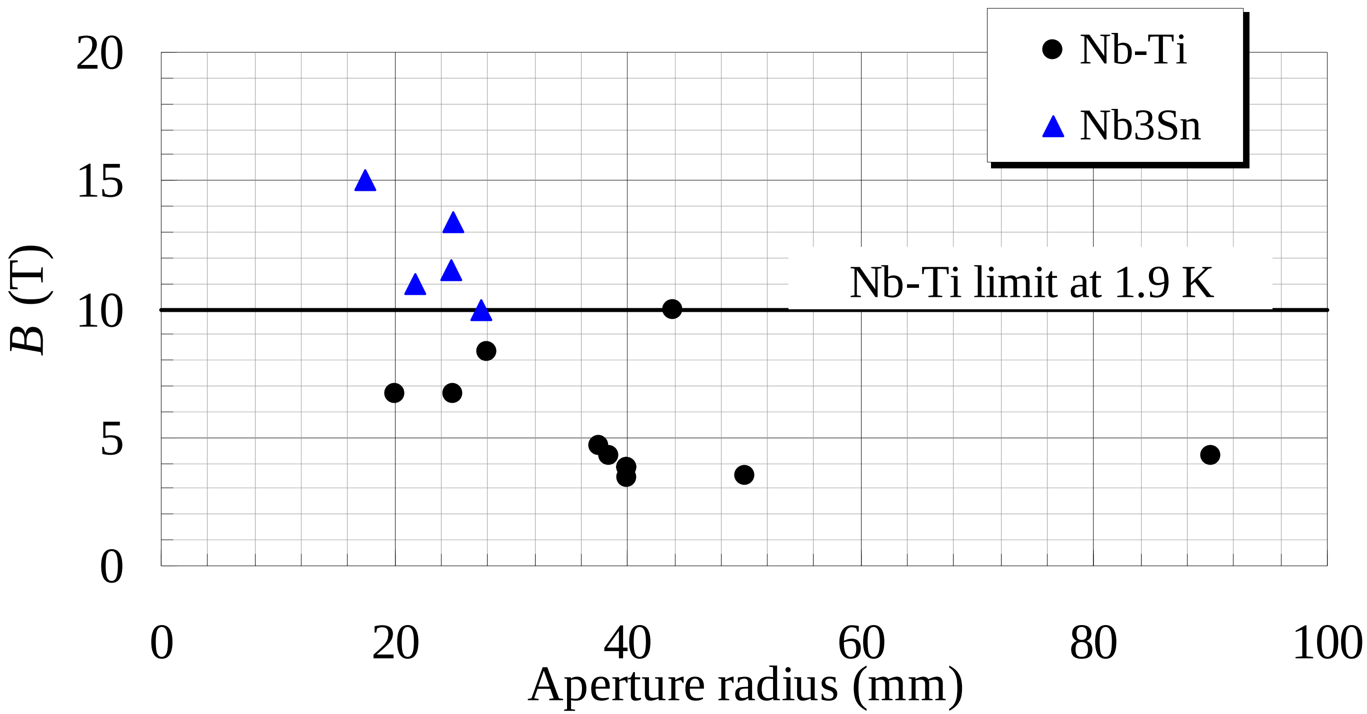
WHAT IS AVAILABLE: DIPOLES



- Note1: short sample field is given for Nb3Sn, operational (about 80%) is given for Nb-Ti

WHAT IS AVAILABLE: DIPOLES

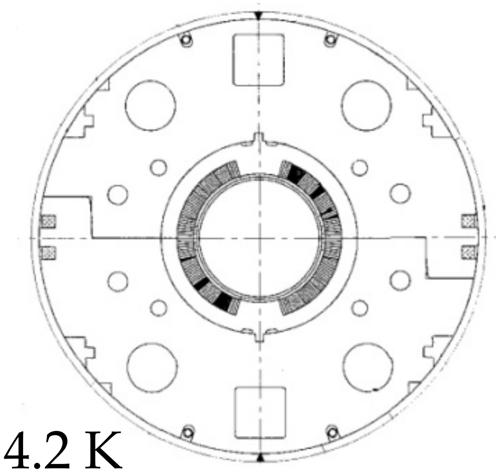
	Aperture		Field (T)						
	r (mm)	diam (mm)	Operational	Short sample	L (m)	Units	Temp. (K)	Material	Comments
LHC MB	28.0	56.0	8.3	9.7	14.3	1248	1.9	Nb-Ti	Twin aperture
LHC MBX	40.0	80.0	3.8		9.5	5	1.9	Nb-Ti	
LHC MBRC	40.0	80.0	3.8		9.5	8	4.5	Nb-Ti	Twin aperture
LHC MBRS	40.0	80.0	3.8		9.5	4	4.5	Nb-Ti	
LHC MBRB	40.0	80.0	3.8		9.5	4	4.5	Nb-Ti	Twin aperture
RHIC MB	40.0	80.0	3.5	5.2	9.5	360	4.5	Nb-Ti	
RHIC D0	50.0	100.0	3.5		3.6	24	4.5	Nb-Ti	
RHIC DX	90.0	180.0	4.3		3.7	12	4.5	Nb-Ti	
HERA MB	37.5	75.0	4.7	6.4	8.8	416	4.5	Nb-Ti	
SSC MB	20.0	40.0	6.7	7.4	1.5	about 10	4.5	Nb-Ti	
SSC MB	25.0	50.0	6.7	7.4	1.5	about 10	4.5	Nb-Ti	
Tevatron MB	38.5	77.0	4.3		6.4	774	4.5	Nb-Ti	
CERN Fresca	43.9	87.8	10.0	10.2	1.0	1	1.9	Nb-Ti	
CERN Elin	27.5	55.0		10.0	1.0	1	*4.2*	Nb_3Sn	
MSUT	25.0	49.9		11.5	1.0	1	4.2	Nb_3Sn	
LBL D20	25.0	50.0		13.4	1.0	1	4.35	Nb_3Sn	
FNAL HFDA	21.8	43.5		11.0	1.0	6	4.2	Nb_3Sn	
LBL HD2	17.5	35.0		15.0	1.0	1	4.2	Nb_3Sn	

- Note1: short sample is an approximate estimate
- Note2: some magnets come with different lengths

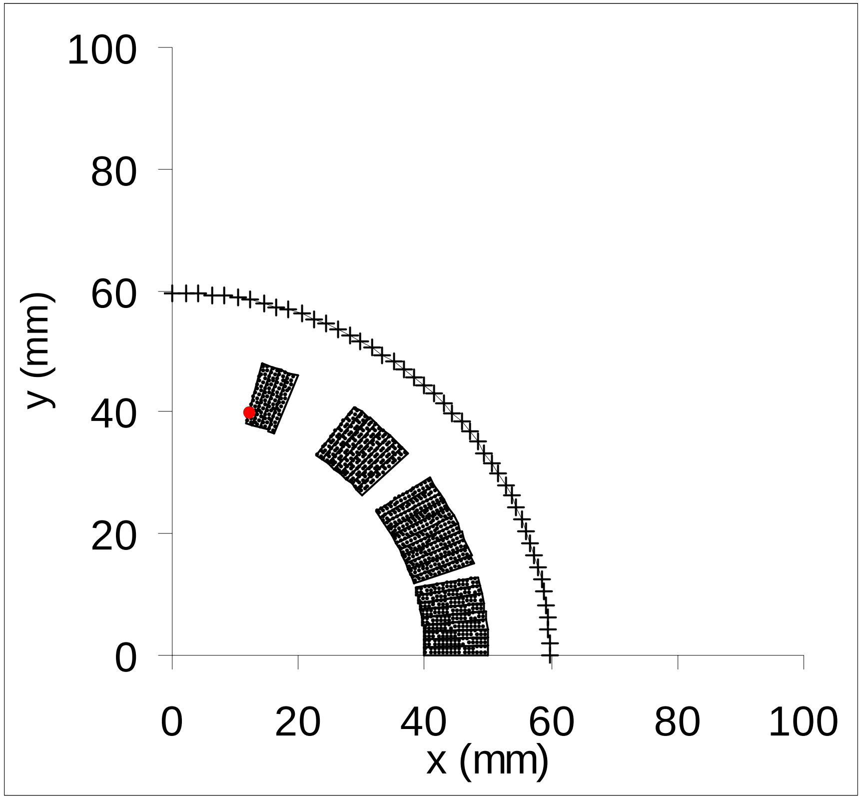
WHAT IS AVAILABLE: DIPOLES

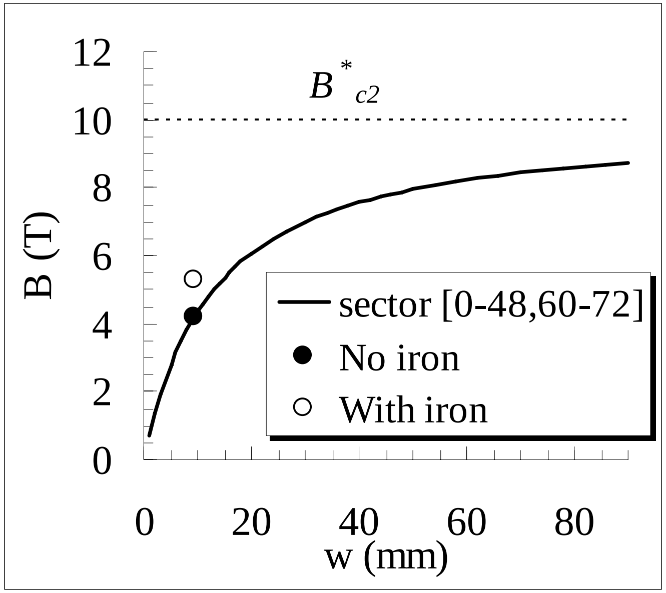
RHIC MB: 40 mm aperture, ~5 T, 9.5 m long

- Main dipole of the RHIC
- 296 magnets built in 04/94 – 01/96



- Nb-Ti, 4.2 K

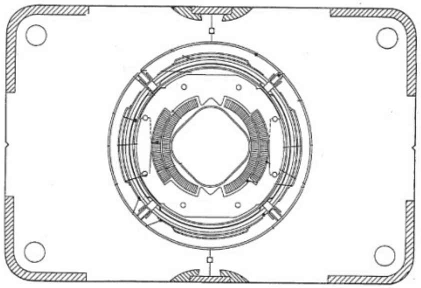




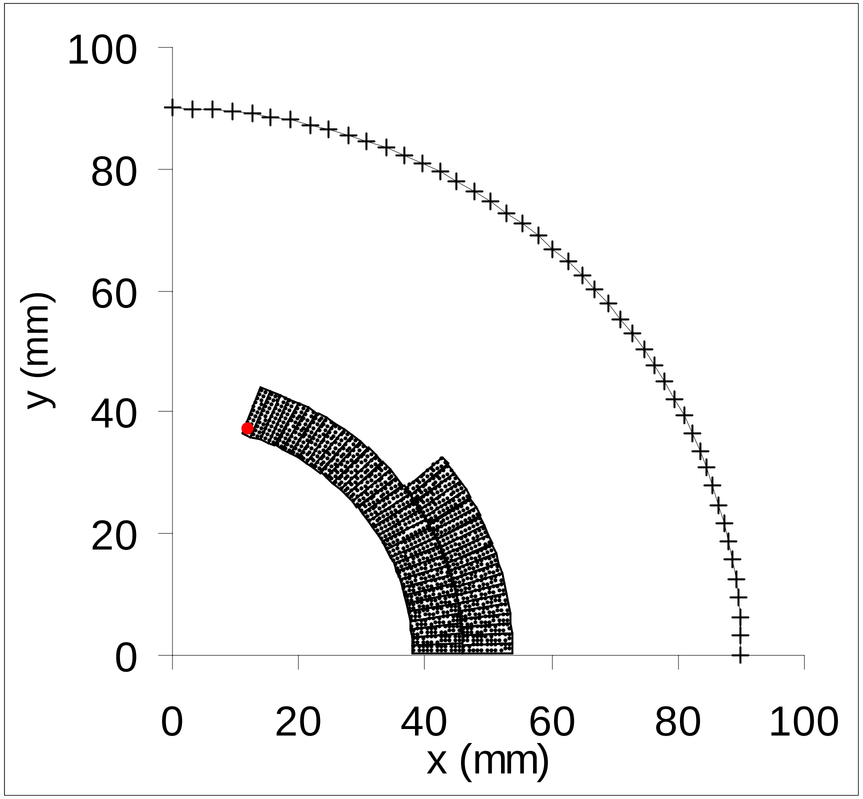
WHAT IS AVAILABLE: DIPOLES

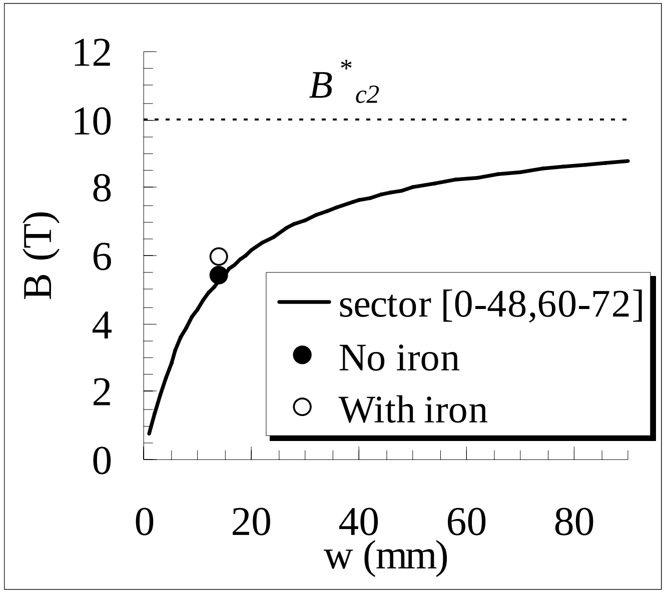
Tevatron MB: ~40 mm aperture, ~6 T, 6.4 m long

- Main dipole of the Tevatron
- 774 magnets built in ~1980



- Nb-Ti, 4.2 K

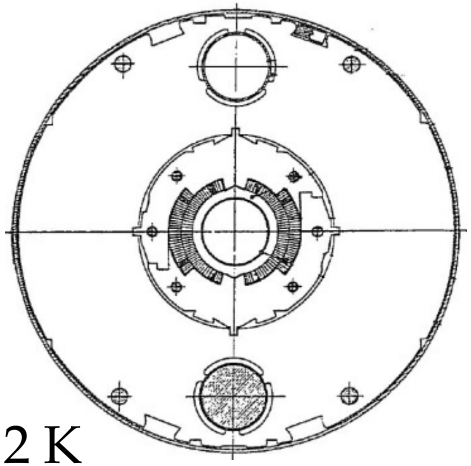


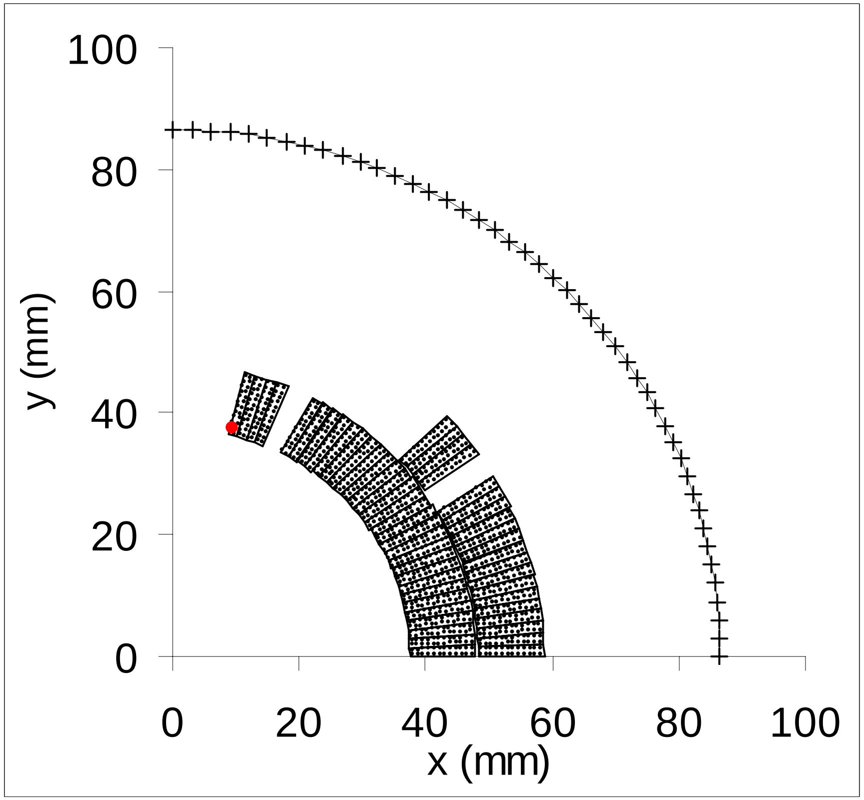


WHAT IS AVAILABLE: DIPOLES

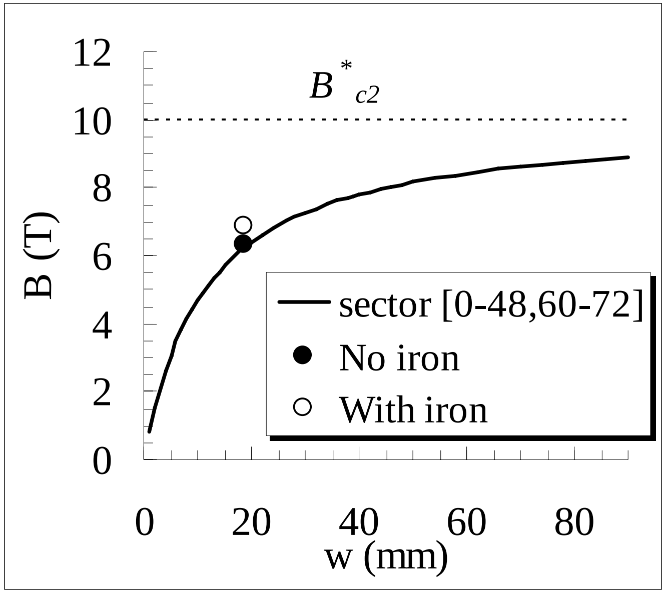
HERA MB: ~40 mm aperture, ~6.5 T, 9 m long

- Main dipole of the HERA
- 416 magnets built in ~1985/87





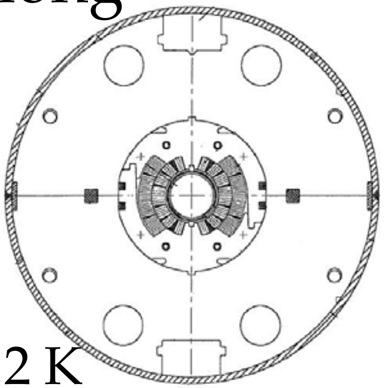
- Nb-Ti, 4.2 K

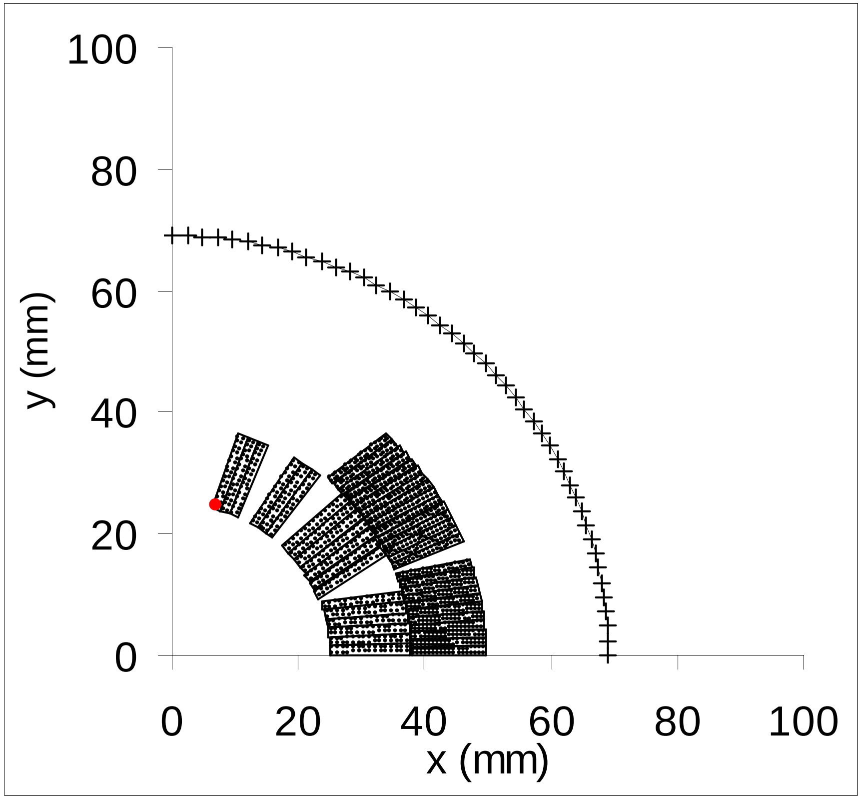


WHAT IS AVAILABLE: DIPOLES

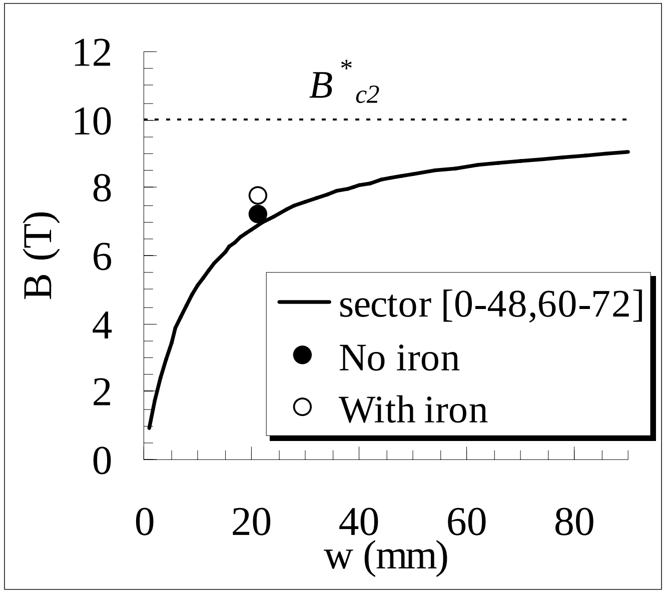
SSC MB model: ~25 mm aperture, ~7.5 T, 1.5 m long

- Main dipole of the ill-fated SSC
- 18 prototypes built in ~1990-5





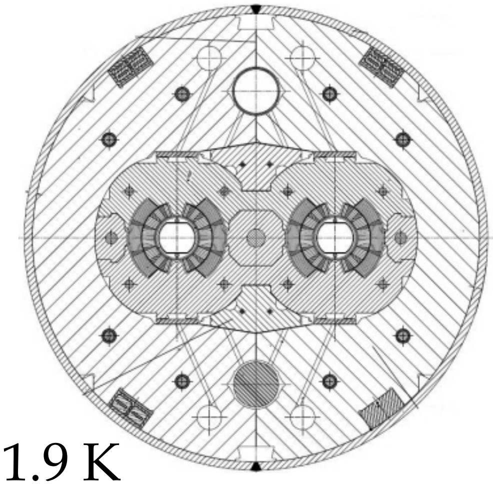
- Nb-Ti, 4.2 K



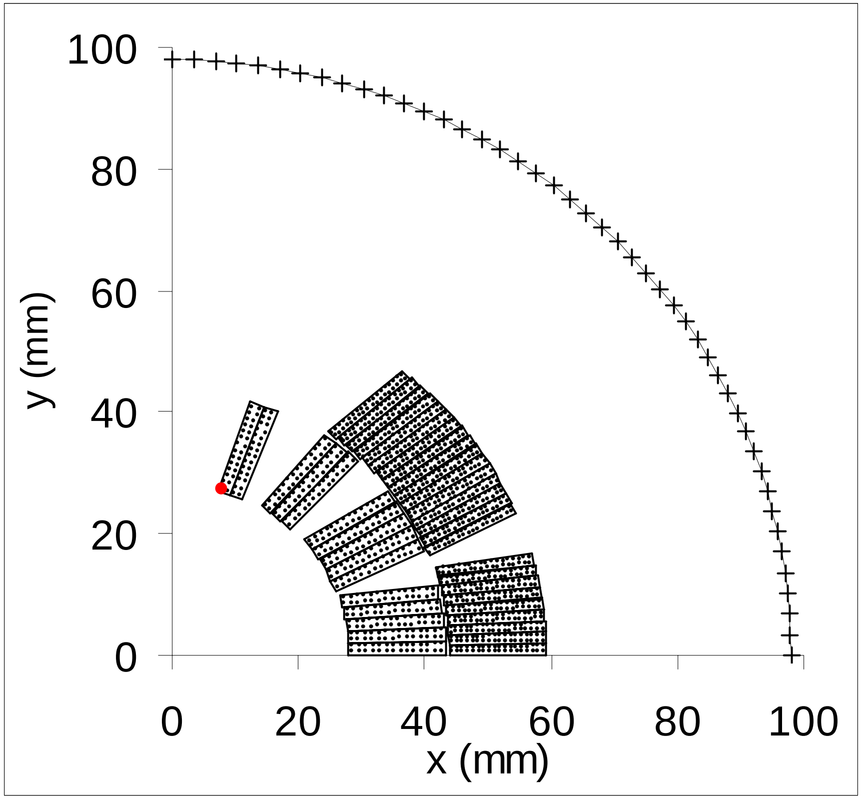
WHAT IS AVAILABLE: DIPOLES

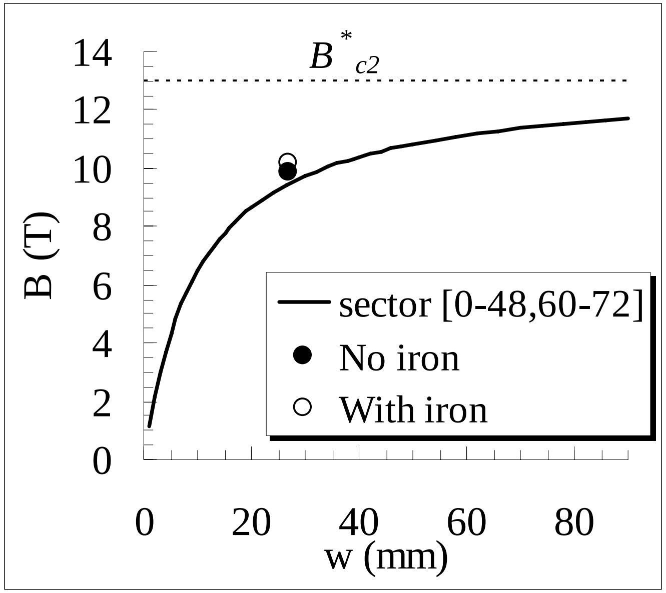
LHC MB: ~30 mm aperture, ~10 T, 14 m long

- Main dipole of the LHC – twin aperture
- 1276 magnets built in 2001-06



- Nb-Ti, 1.9 K

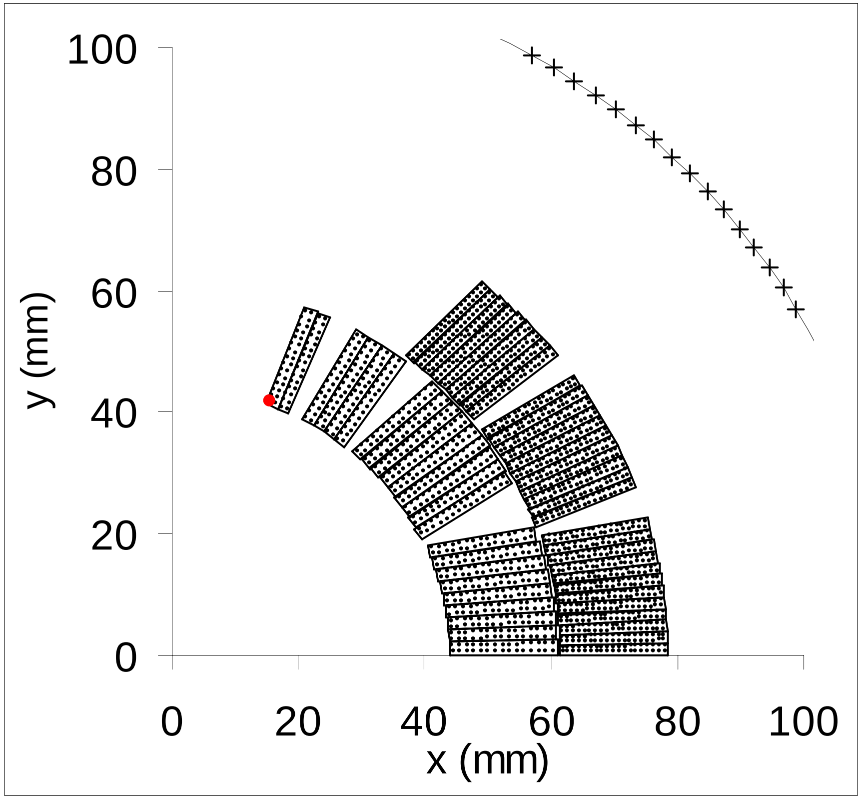




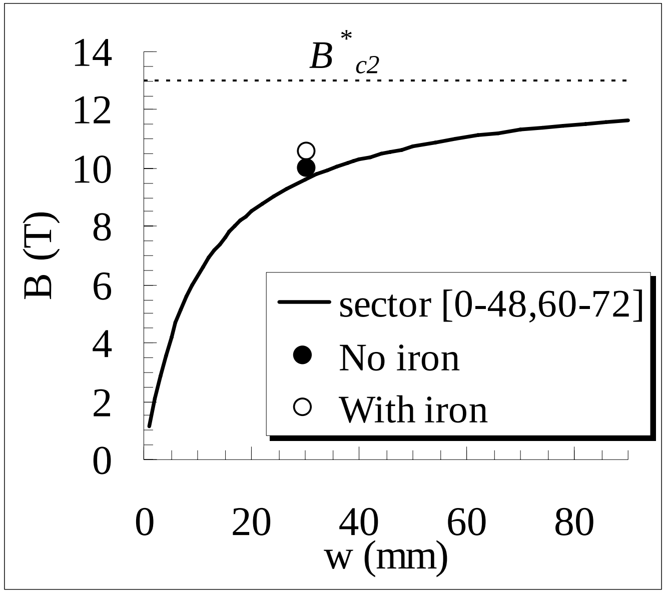
WHAT IS AVAILABLE: DIPOLES

FRESCA test station: ~45 mm aperture, ~10.5 T, 1 m long

- Dipole for cable test station at CERN
- 1 magnet built in 2001



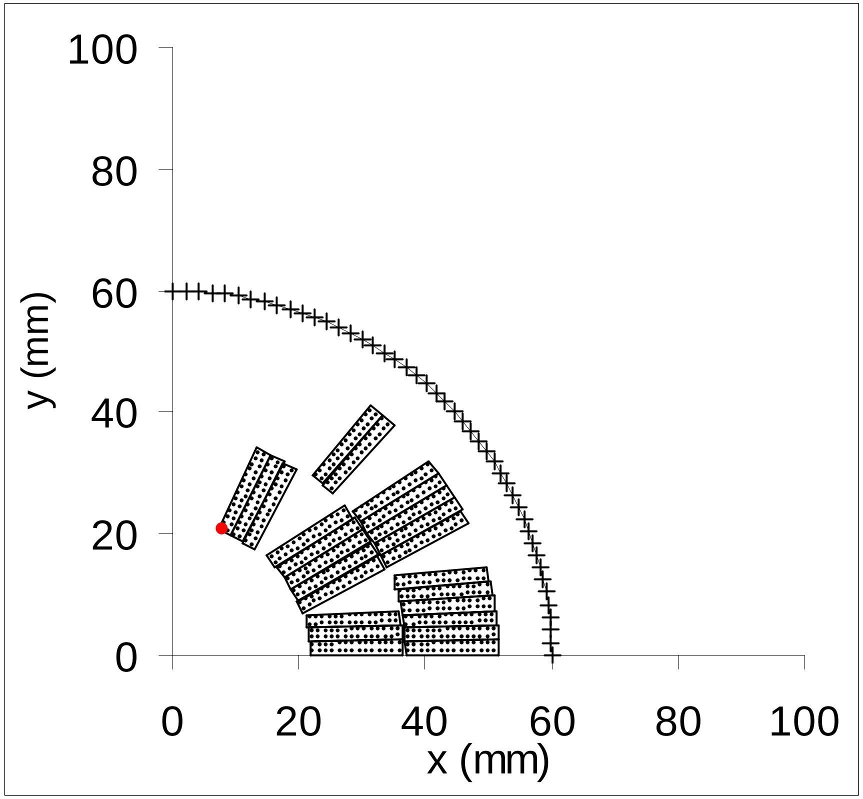
- Nb-Ti, 1.9 K



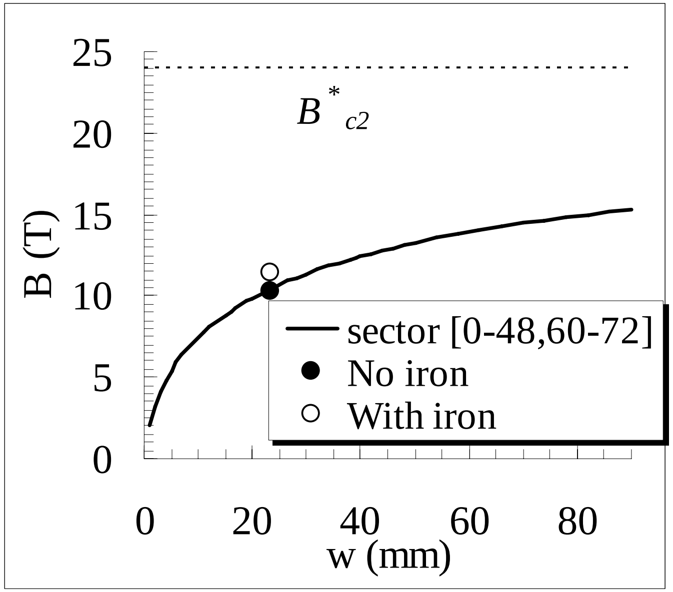
WHAT IS AVAILABLE: DIPOLES

HFDA02-07 dipole models: ~20 mm aperture, ~11 T, 1m long

- Nb_3Sn model built at FNAL
- 6 models built in 2000-2004

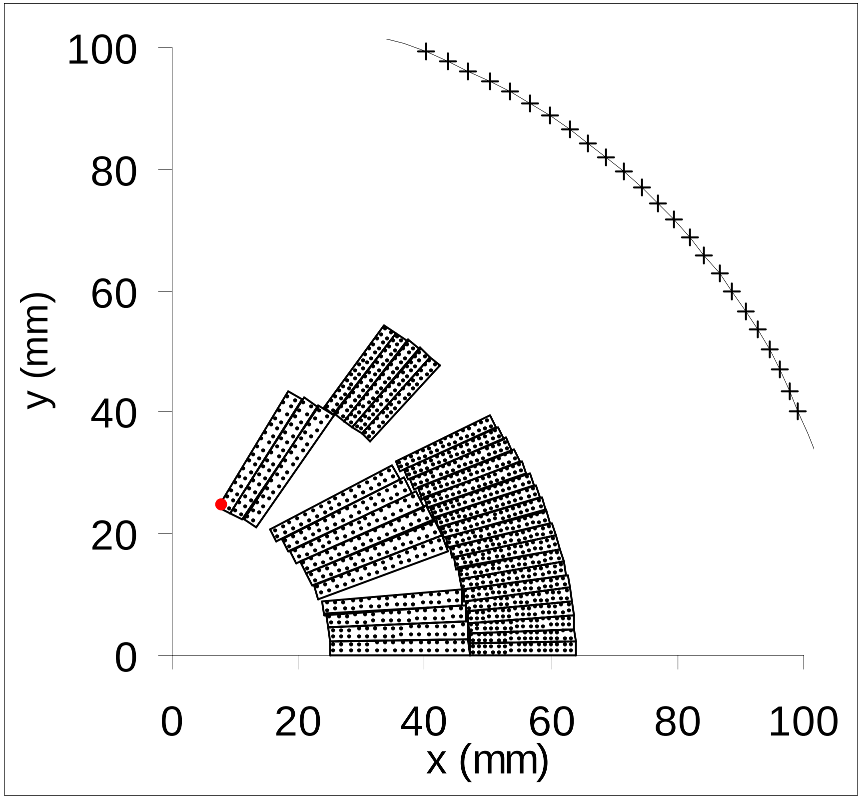


- Nb_3Sn, 4.2 K

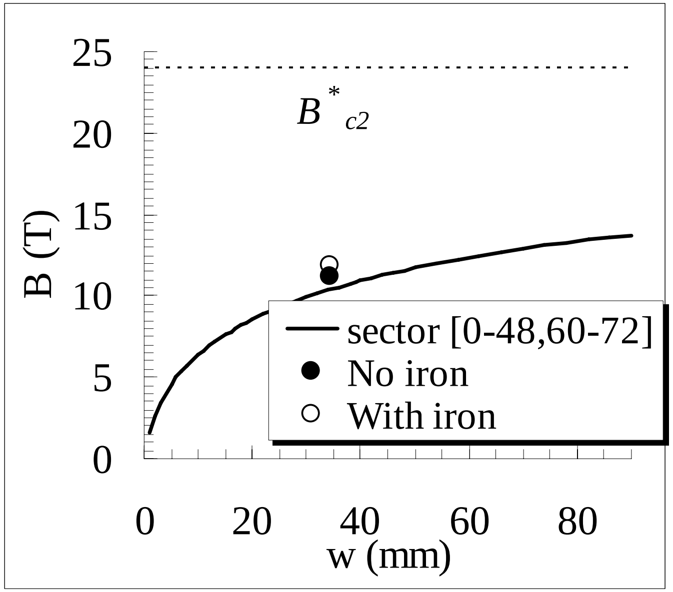


MSUT dipole model: ~25 mm aperture, ~11.5 T, 1 m long

- Nb_3Sn model built at Twente University (NL)
- 1 model built in 1995



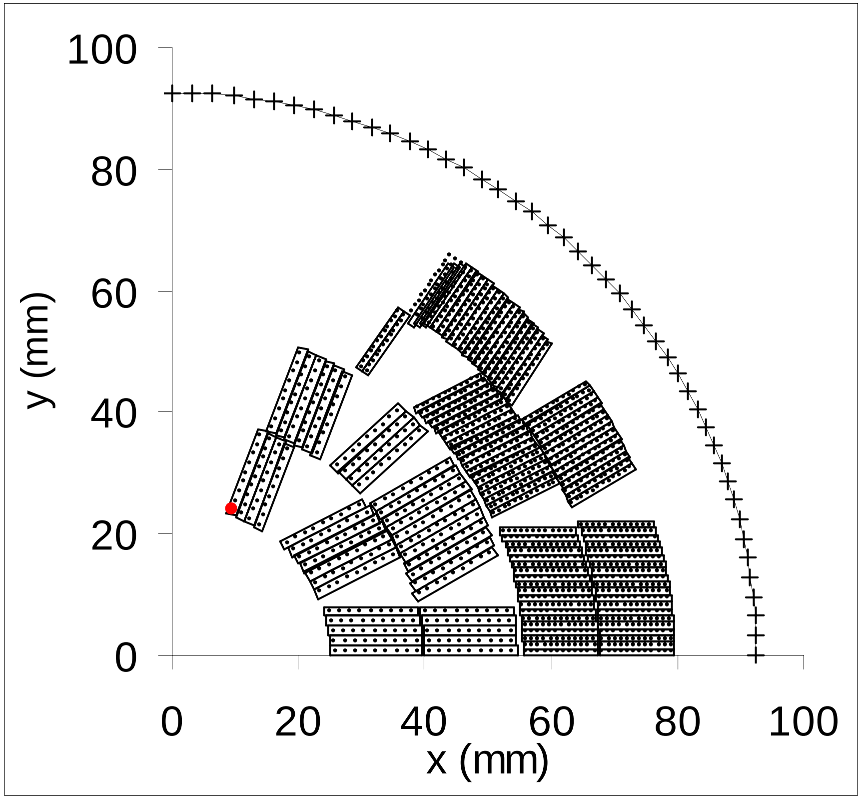
- Nb_3Sn, 4.2 K



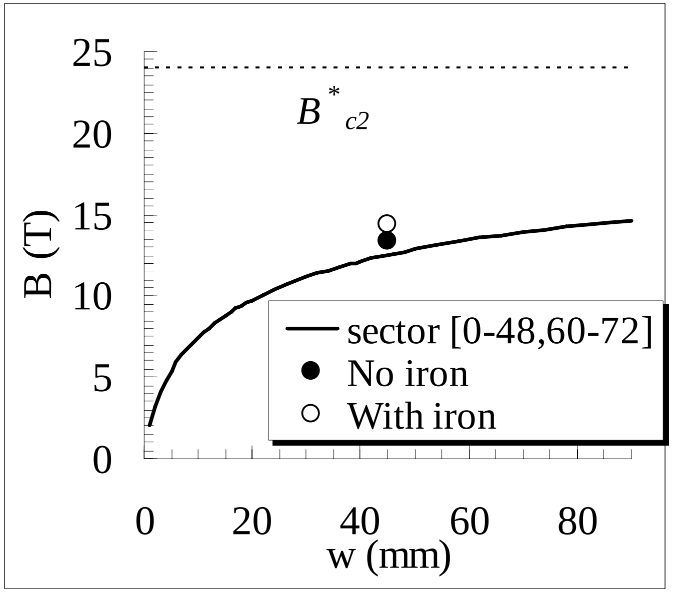
WHAT IS AVAILABLE: DIPOLES

D20 dipole model: ~25 mm aperture, ~15 T, 1 m long

- Nb_3Sn model built at LBNL (USA)
- 1 model built in 1994, reached 13.4 T, present world record



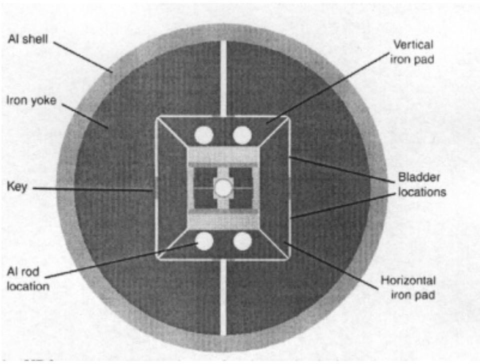
- Nb_3Sn, 4.2 K

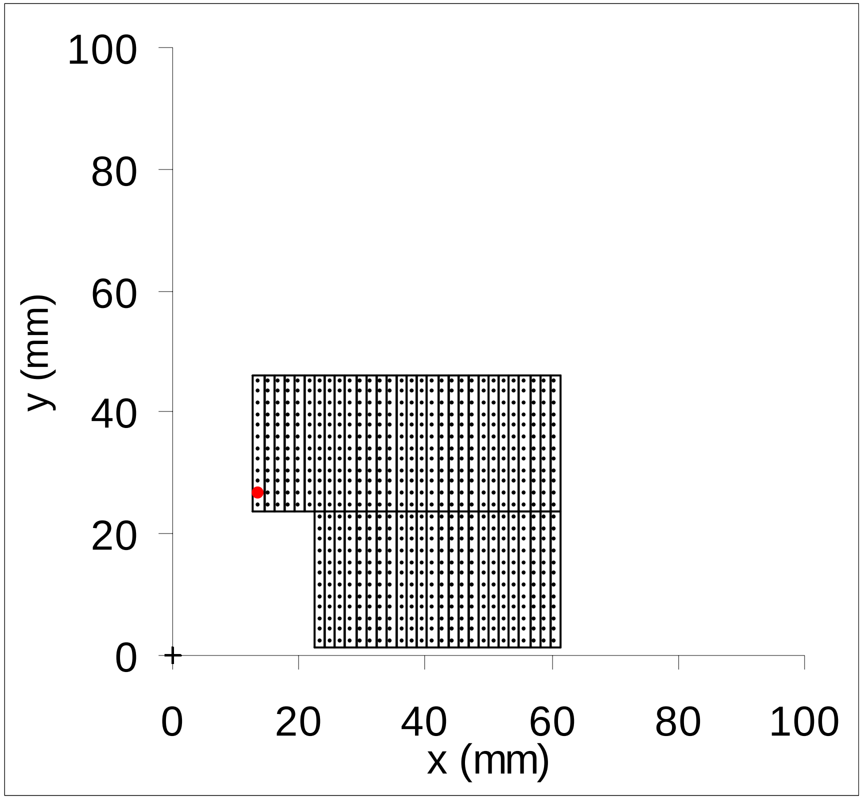


WHAT IS AVAILABLE: DIPOLES

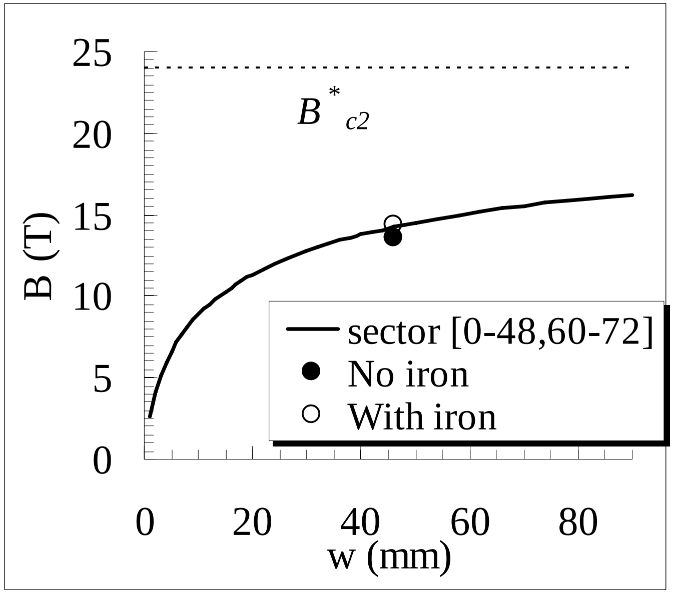
HD2 model: ~20 mm aperture, ~16 T, 1 m long

- Nb_3Sn model built LBNL
- 1 model built in 2008 (13.3 T reached)

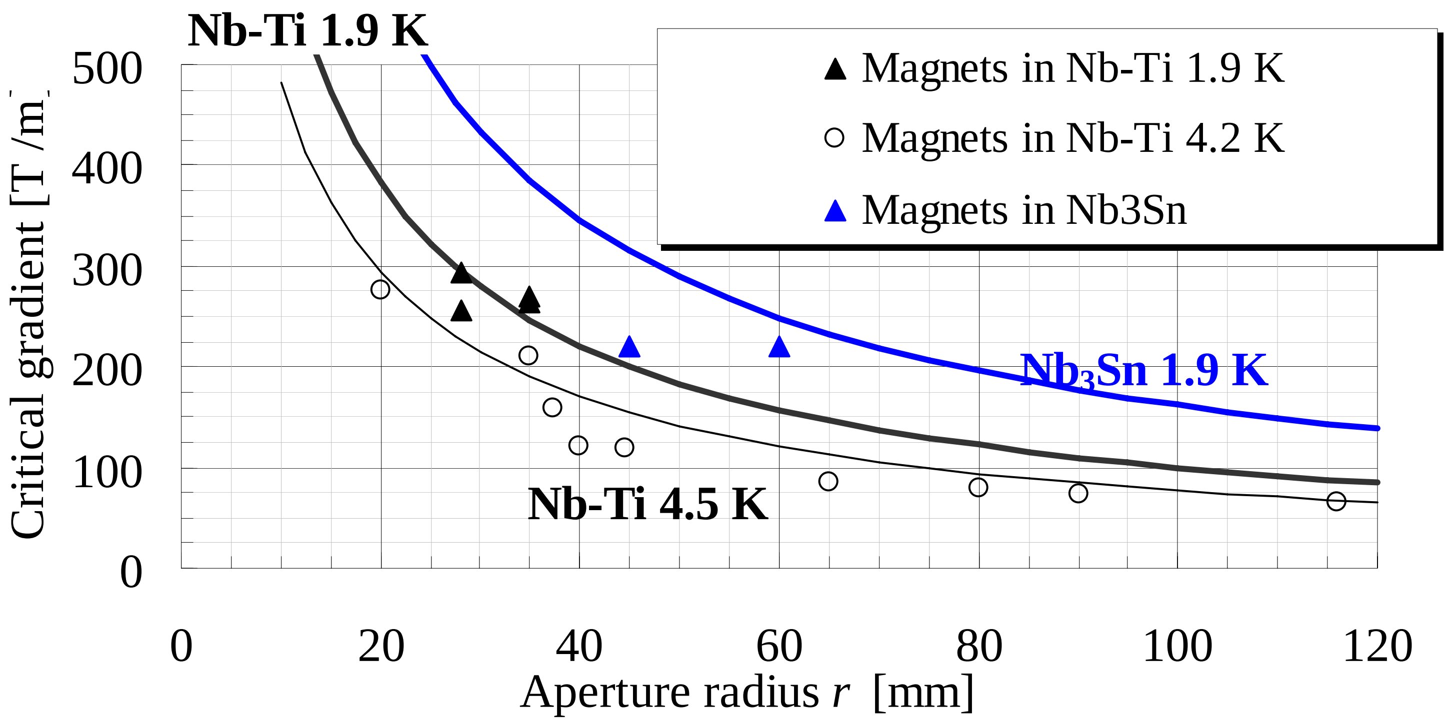




- Nb_3Sn, 4.2 K



WHAT IS AVAILABLE: QUADRUPOLES



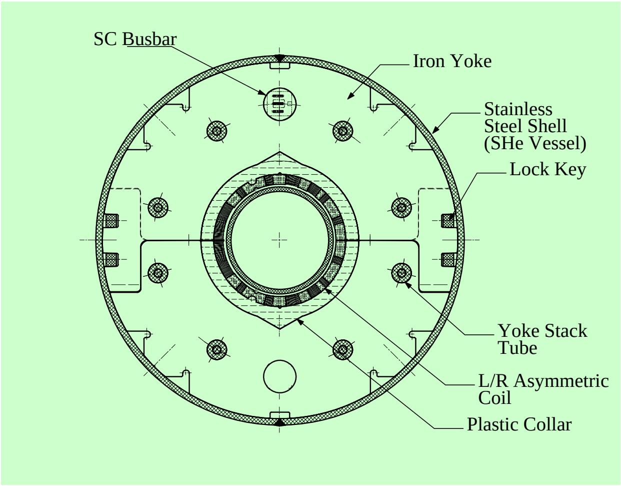
WHAT IS AVAILABLE: QUADRUPOLES

	Aperture		Gradient (T/m)						
	r (mm)	diam (mm)	Operational	Short sample	L (m)	Units	Temp. (K)	Material	Comments
LHC MQXA	35	70	215	265	6.4	18	1.9	Nb-Ti	
LHC MQXB	35	70	215	260	5.5	18	1.9	Nb-Ti	
LHC MQ	28	56	223	300	3.2	400	1.9	Nb-Ti	Twin aperture
LHC MQM	28	56	200	250	2.4-4.8	60	1.9	Nb-Ti	Twin aperture
LHC MQY	35	70	160	200	3.4	24	4.5	Nb-Ti	Twin aperture
RHIC MQ	40	80	71	110	1.13-1.83	420	4.3-4.6	Nb-Ti	
RHIC MQY	65	130	48	70	1.4-3.4	72	4.3-4.6	Nb-Ti	
Tevatron MQ	44.6	89.2	74		2.3	180	4.4	Nb-Ti	
Hera MQ	37.4	74.8	91	125	1.5-1.8	224	4.6	Nb-Ti	
SSC MQ	40	80	210	>260	5.0	a few	4.3	Nb-Ti	
LEP I MQC	90	180	36	55	2.0	8	4.3	Nb-Ti	
LEP II MQC	80	160	60	75	2.0	8	4.3	Nb-Ti	
ISR MQ	116	232	43		1.15-0.65	8	4.5	Nb-Ti	
LARP TQ	45	90	*200*	220	1	about 10	4.4	Nb3Sn	
LARP LQ	45	90	*200*	220	3.4	1	1.9	Nb3Sn	Foreseen 2009
LARP HQ	60	120	*120*	200 (220)	1	1	4.4 (1.9)	Nb3Sn	Foreseen 2009
LHC MQXC	60	120	120	150	10	16	1.9	Nb-Ti	Foreseen 2014

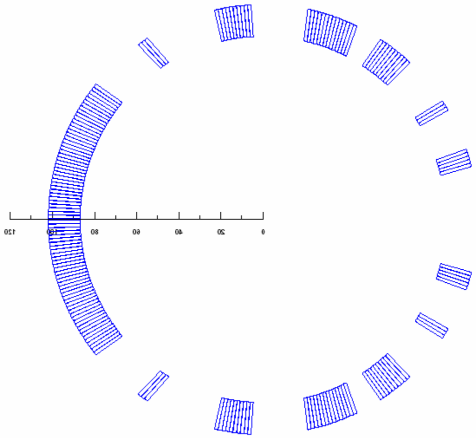
- Note1: short sample is approximate estimate
- Note2: some magnets come with different lengths

WHAT IS AVAILABLE: COMBINED FUNCTION

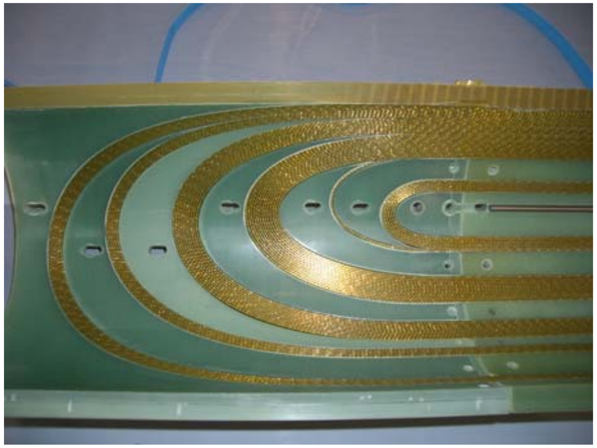
- In Japan combined functions superconducting magnets have been designed for a beam transfer line (JPARC) for neutrino experiment
  - These magnets give a dipole field (2.6 T) superimposed with and a quadrupole field (18.6 T/m) over a 180 mm aperture diameter
  - The transfer line has been successfully commissioned in 2009



JPARC magnet cross-section



JPARC magnet coil cross-section (Roxie view)



JPARC magnet coil end

CONCLUSIONS

- Nb-Ti gives fields up to 10 T, with lengths up to 15 m
- Nb_3Sn can give fields up to 16-20 T
  - 13.4 T present record
  - A lot of experience for 1 m long models, but no experience on long magnets
  - 3.4 m long being built and will be tested in 2009
- HTS could break the 20 T barrier
  - R&D needed, time scale of 10 years
- Apertures range: from 50 to 100 mm
  - Larger apertures are feasible in principle, but care should be taken for large electromagnetic forces
- Many magnets are available since accelerators have spare components