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Design and test of a NbTi prototype coil for a low beta section

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Abstract. The design of superconducting quadrupoles for a proton and antiproton low beta section and the test of a prototype coil are presented. Previous studies [1,2] show that high gradient and short quadrupole magnets are required for a compact low beta section in order to allow the insertion of such a magnetic system with minor changes of the lattice [3]; each quadrupole is 400 mm long and has to provide a magnetic induction gradient of 60 T/m. A beam pipe of at least 120 mm diameter is required to avoid beam loss during injection and before the beam cooling. The magnetic design of the superconducting magnets for the low beta section is presented, together with a detailed discussion of the quench protection design. Two prototype coils were produced and one of them was tested. A detailed description of the test setup and a full discussion of the results will be presented.

1. Introduction
A low beta section to inject a proton or antiproton beam into an accumulation cell [4] having a low impact on the lattice has been investigated [1]. A proton energy range up to 3.7 GeV has been considered [2]. In order to reduce the impact of the insertion of the low beta section, high gradient and short superconducting quadrupole can be used to design a compact assembly of two magnets each side of the target region. Each quadrupole has a magnetic length of 400 mm and a gradient of 60 T/m, giving an integrated gradient of 24 T. The maximum beam envelope diameter is 114 mm so that the reference radius is 57 mm.

2. Superconducting magnets
The superconducting magnets for the low beta section are an assembly of four NbTi racetrack coils (figure 1). Each coil is 443 mm long and has a cross section of 39 mm x 65 mm; the distance between facing coils is 140 mm. The quadrupole has an iron shield 30 mm thick with an inner radius of 180 mm, the shielding reduces the fringe filed in the radial direction and does not affect the field in the quadrupole. The NbTi wire by SUPERCON Inc. has an (insulated) outer diameter of 1.17 mm and a copper over superconductor ratio of 1.3. The loadline of the magnet together with the engineering critical line of the NbTi wire is plotted in figure 2; the engineering critical line is calculated reducing the wire performance of 20% assuming a 0.8 filling factor in coil windings [5]. The working point is

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set at 80% of the critical point on the loadline. Maximum field on coils at the working point is 6.88 T and the maximum radial magnetic field at the reference radius is 3.37 T (see also figure 1). The radial gradient at the center of the magnet is then 59.2 T/m, whereas the integrated gradient over a line parallel to z axis at the reference radius (57 mm) is 23.4 T; the latter includes the fringe field.

![Figure 1](image1.png)

**Figure 1.** Field on coils (Bmod) and radial field (Br) at the center of the magnet (z=0); the radial field is plotted up to 57 mm radius.

![Figure 2](image2.png)

**Figure 2.** Load line of the superconducting coil and critical line of the VSF/SSCI NbTi wire. The latter is calculated using data by SUPERCON Inc. considering an 80% filling factor. The critical point, the calculated working point for 20% safety margin and the measured quench (QUENCH) point are plotted on the load line.

![Figure 3](image3.png)

**Figure 3.** Adiabatic maximum temperature versus the ICD ($\beta_e^2 dt$) for the VSF/SSCI wire.

![Figure 4](image4.png)

**Figure 4.** Maximum temperature (top) and voltage and current (bottom) versus time calculated by quench program by Cobham plc.

2.1. Quench protection

The engineering current density at the working point is 210 A/mm$^2$, the wire current is 285 A and the energy stored for a single coil is 30 kJ. The inductance is thus 0.75 H. Two quench calculations have
been performed: the first in the adiabatic case [6] and a full finite elements model (FEM) quench simulation. The adiabatic maximum temperature as a function of the integrated current density (ICD) in the coil for the VSF/SCSI wire is plotted in figure 3; the calculated maximum temperature is about 130 K since the ICD is $8.3 \cdot 10^{16} \text{A} \cdot \text{s} \cdot \text{m}^{-4}$ considering a shunt resistance of 7 $\Omega$ and a maximum voltage of 1 kV. The coil temperature for the FEM simulation, together with the voltage over the coil and the current versus time are plotted in figure 4. Maximum temperature is about 45 K and maximum voltage is below 450 V. In the simulation, a reaction time of 100 ms and a shunt resistance of 0.5 $\Omega$ are considered.

3. Cold mass design of the Prototype coil test

Two prototype coils were produced by ALSTOM; the G10 pole and case of the coil was designed and machined at Forschungzentrum Juelich (FZJ). One of the coils encased in the G10 support is visible in figure 5: the two NbTi wires to connect the coil are also visible. The cold mass assembly is plotted in figure 6. The design of the cold mass assembly considered two load cases: the cooldown from room temperature to 4 K and the Lorentz force. The latter were calculated up to a current density of 225 A/mm², 7% higher than the nominal working point, splitting the coil in 12 sections. The calculation by ANSYS showed that the cold mass assembly can work with a safety margin higher than 1.4 and requires the use of AL AW5083-H321. Both the G10 support and the aluminium case have to be machined with a 50 $\mu$m tolerance. The G10 support guarantees high electrical insulation, high mechanical resistance, no eddy currents and low thermal expansion coefficient.

![Figure 5. Cold mass of the single coil test during assembly. The G10 support of the coil, the aluminium case body, its end cap and the Al wedges are visible.](image)

![Figure 6. Drawing of the cold mass assembly: all the parts in Figure 5 and the aluminium tie rods which provide the required pre-stress are plotted.](image)

4. Results

The cold assembly during the commissioning of the cold test is visible in figure 7. One prototype coil has been housed in a standard top access cryostat and cooled down to 4 K; the cooldown lasted about two days in order to avoid damages of the coil due to cooling speed. A quench protection system having a 10 ms reaction time and a 0.5 $\Omega$ shunt resistance together with a slow control system to control the current supplied (up to 400 A) and the current leads temperature were used. The coil was successfully loaded up to 200 A with a ramping speed up to 30 A/s and then up to 282 A with a ramping speed of 16 A/s (see figure 8). The limits of current in the first case and ramping speed in the latter are due to power supply system limitation. The coil survived different quenches due to heat leak disturbance.
by current leads and it did not suffer any damage after the quench during the higher current test at 282 A. A full training of the coil could not be performed due to the amount of liquid helium available for the tests; the first current induced quench is 99% of the nominal current. Both the maximum current simulations and mechanical design are validated since the full assembly and in particular the superconducting have not suffered any damage. The presented NbTi racetrack coils can be used to assemble superconducting quadrupoles for a compact low beta section.

**Figure 7.** Cold mass (see figures 5, 6) installed on the top flange of the cryostat

**Figure 8.** Measured Current ramp up to 282 A. The nominal working point current is 285 A.

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