MAGNET SYSTEM DESIGN

HITRI plus
Heavy Ion Therapy Research Integration

www.hitriplus.eu

DECADES OF EXPERIENCE IN ACCELERATOR DESIGN, CONSTRUCTION AND OPERATION. EXPERTISE AND KNOW-HOW OF MAGNET SYSTEM DESIGN

DESCRIPTION

Various alternatives for the design of the demonstration magnet were examined and the most promising option was selected based on technical and financial aspects as well as a range of magnet parameters that are optimal for use in both the synchrotron and the gantry.

It was concluded that the choice of a CCT magnet based on Nb-Ti is the most promising alternative and will be used for the demonstrator.

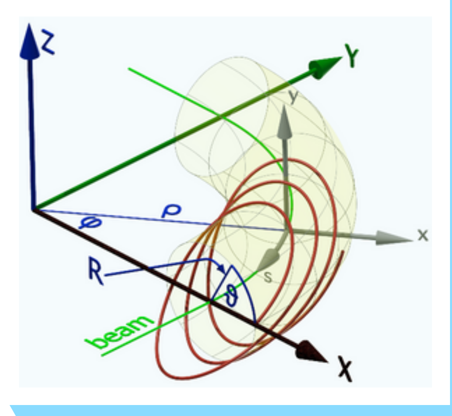
Nb-Ti based CCT design for the demonstrator magnet is chosen, optimizing parameters for use in both synchrotron and gantry - over Cos-Theta.

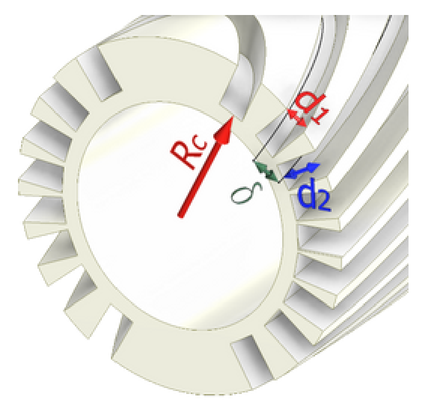
Simultaneously, research for the Future Circular Collider (FCC) led to a septum magnet concept and wax impregnation techniques, influencing HITRIplus activities.

The selected parameters (in conjunction with the I.FAST and TERA-NIMMS-SIGRUM project) are summarized in the table and will be the aim of the demonstrator.

The curved CCT design is a key challenge. Design parameters include a magnetic rigidity of $B\rho$=6.6 T m, bending radius ρ =1650 mm, and magnetic field B0 = 4 T. Financially, the conductor cost is 8 Euros/m, considerably less than Rutherford cabling. Mechanics are expected to be cost-effective. Operating temperature ranges from 4.7 K to 5 K using a cryocooler. Power supply requirements include a voltage range of 20 V, supporting a max current of 2 kA, and a maximum ramp rate of 150 A/s. Power consumption is manageable with a single cryocooler.

Geometry of the curved CCT magnet, which will be constructed





Parameters	Values	unit
Geometry	Straight, combined	-
Central magnetic field B	4	T
dB/dt	0.4	T/s
Magnetic and physical length	0.8 and 1 m	m
Bore diameter	80	mm
Operation temperature	4.7 ÷ 10	K
Iron	Iron Shield + support	-
Loadline margin (@4.7 K)	25	%

Table: The selected parameters.

CHALLENGE

A CCT magnet is an accelerator magnet that combines the magnetic fields generated by interleaved and tilted solenoids in opposite directions. Each layer of the magnet has a specific current distribution that generates a pure harmonic field, as well as a magnetic field that can be neutralised by a corresponding layer with an opposite tilt. To ensure the structural integrity of the magnet, the windings are arranged within the ribs and spars of a supporting mandrel. This design allows the Lorentz forces generated by each turn of the windings to be intercepted and conducted so that no stresses can accumulate. While straight CCT magnets are a proven concept, proving the feasibility of a curved magnet design is a challenge.

CCT magnets offer a promising alternative to traditional Cos-Theta magnets for accelerators due to simpler construction and fewer components, reducing costs. The curved design of CCT magnets enables a more compact and flexible accelerator, enhancing energy efficiency and reducing operating expenses.

Despite their potential, successful prototypes of curved CCT magnets are yet to be realized.

SOLUTION

HITRIplus will construct and test a groundbreaking curved CCT demonstrator magnet. The superconducting Nb-Ti winding, twisted in six strands around copper, will be encased in an iron yoke with braided polyester insulation. The support structure, a hollow curved tube, will be made from pre-preg material. The curved mandrel and windings are likely to be of Aluminum - Bronze. This first-of-its-kind magnet aims to demonstrate the feasibility of a curved CCT design with a central field of 4 T, a ramp rate of 0.4 T/s, and a compact bore diameter of 80 mm.

VALUE

- The demonstrator results will prove that it's feasible to construct a curved CCT with the selected parameters applicable in both an accelerator ring and a gantry
- The CCT magnets are promising mainly for the usage in accelerator rings for the bending and focusing of particle beams, contributing to a more compact size. Consequently, they offer several advancements, which could reduce costs of ion therapy treatments. The developments also offer implications for size reduction and increased efficiency of the facilities
- The coil of the CCT is stress managed (unlike Cos-Theta) which makes it robust, easy to construct and to configure
- The gantry magnets will be cryocooled for increased simplicity of installation, infrastructure and daily operation, not requiring any external helium supply. The demonstrator will be tested in a cryostat bath with further development goals of a dry magnet
- In industrial applications for which superconductive magnets are already used, curved CCT magnets offer a potential opportunity of constructing the machinery to become more compact

WAX IMPREGNATION METHOD FOR CCT MAGNETS

DESCRIPTION

Impregnating a CCT magnet with epoxy resin or wax is crucial for enhancing its mechanical and electrical performance, thermal stability, and durability.

In the magnet topology used for the CCT demonstrator, the mandrel and grooves for each turn are self-supporting even without wax or resin. However, for the CCT demonstrator, wax is suitable to prevent wire movement in the grooves, while other Itopologies might require the mechanical properties of epoxy.

Superconducting coils with epoxy often exhibit "training," needing multiple quenches before reaching the nominal current. Recent tests show wax as a better alternative in stress-managed coils. A wax-impregnated Nb3Sn cable reached the short-sample limit without a single quench. (test performed by the Paul Scherrer Institute).

In the SuShi septum project (Future Circular Collider), a wax-impregnated CCT magnet reached nominal current without a quench. The technique manages wax contraction and void formation. Applied to the HITRIplus magnet's test coil, it used 2x8 twisted ropes in 5.7x23 mm grooves on an aluminum-bronze mandrel. The impregnated winding, despite no overpressure, displayed solid consistency.

Removing ropes from the groove required significant force. The polyester braid crucially prevented large voids in case refill during freeze-out fails, acting as a wax retainer.

CHALLENGE

CCT magnets typically need to be impregnated with wax or epoxy resin, in order to provide insulation and mechanical support to the coils. Superconducting coils impregnated with epoxy resins show a training behaviour, requiring several quenches to reach the nominal current.

The CCT magnet has a complicated geometry which makes impregnation difficult. It has circular grooves where enclosed pockets can easily be created. The liquid wax can then become enclosed in the volume, contacting, freezing and creating a void.

The wax needs to be cooled down and impregnated in a way so that there's always a refilling channel available which remains open and doesn't freeze. The heating and cooling methodology needs to be synchronized. The temperature must be controlled at the point when the wax starts freezing and the refilling channel must never be blocked.

SOLUTION

Using the wax impregnating method, the formation of voids in the wax volume during freeze-out was prevented. Additionally, not a single quench was observed during the testing period.

A coil with wax impregnated winding can reach the desired limit without a single quench. Wax can be a better alternative to epoxies in stress-managed coils, by providing a mechanical support turn-by-turn.

VALUE

- Wax is a better alternative to epoxy for CCT impregnation when the coils are stress managed, as in the case of the HITRIplus CCT demonstrator where each turn and each cable is in a channel within a metallic supporting structure. The metallic walls intercept the Lorentz forces and there is no accumulation causing stress
- Wax (50 CHF for 10 kg) is cheaper by a factor of 10 compared to epoxy (2300 chf for a 5-gallon kit)
- It's beneficial from a risk management perspective. The method is reversible, so in case there is a problem in the coil, the wax can be heated and the coil can be removed and re-wound, sparing the costly mandrel. For resin impregnated coils, neither wire nor mandrel can be recuperated in case of a mistake
- Fast and simple, the time needed for impregnation and cool down of the wax is ca 4-5 hours. Setup for wax is also simpler, it will not harden unless cooled, making the process easy to control. For comparison epoxy has a curing protocol of ca 1 day, the temperature (120 °C) also needs to be controlled over time, overnight supervision may be needed
- Epoxy resins can release volatile organic compounds and other toxic fumes during the curing process, which can be harmful if inhaled in large amounts. Therefore, wax impregnation can be a safer and more environmentally friendly alternative for impregnating magnets
- Robust method, it's possible to top up insufficient wax volume. Mistakes are simple to repair
- Saves time and resources on the quench training. Quench is a source of risk and should be avoided when possible. It can take a lot of time to train a magnet in case of epoxy impregnation, however with wax the magnet can be switched on working instantly