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Magnetic alignment and mechanical analysis of superconducting bending section for proton therapy

Ciro Calzolaio[1], Stéphane Sanfilippo[1], Jacobus Maarten Schippers[1], **F. Trillaud**[2]

[2]: Paul Scherrer Institute, Forschungsstrasse 111, 5232 Villigen, Switzerland

[1]: Instituto de Ingeniería, Universidad Nacional Autónoma de México, CDMX, 04510, México

Abstract--The last bending section of a proton therapy beam line is mounted on a rotating gantry to target the cancerous cells of the patients from all possible angles. Such capability is necessary to deposit the appropriate amount of radiation dose to the tumor and to spare the surrounding healthy tissue. In the following work, a magnet configuration employing combined function magnets is presented. It includes two conventional electromagnets and three superconducting magnets operated at 4.2 K mounted on a rotatory gantry. For such assembly, an alignment procedure is carried out to guarantee a large beam momentum acceptance. Furthermore, 3D mechanical Finite Element analysis was conducted to check that the structural support of the superconducting magnets and their thermal shields could handle their weigh as well as the momentum due to the rotation.

Alignment procedure (6 steps):

1-The magnets are positioned as if the protons travel along the geometric axis of the magnets. No stray field between magnets and a perfect straight trajectory are assumed in the drift spaces

2-Only the SC-DQS magnet is switched on. Several protons at energies in the range of ± 10 % of the reference kinetic energy (185 MeV) are shot. At the end of the bending section, the exit angle is estimated for all the protons. A search algorithm sorts out the protons exiting the bending section with a zero degree angle. The dipole field produced by the SC-DQS magnets is adjusted according to:

$$\rho B = \frac{\sqrt{E_k^2 + 2E_0E_k}}{cq}$$

E_k: kinetic energy, E_0: rest energy, c: light speed, q: proton charge, ρ: bending radius, B: bending field

3-The SC-QS magnets (switched off) are moved along their axis perpendicular to the proton beam trajectory

4-The positions of the Q magnets are adjusted according to the trajectory of the proton beam at the reference kinetic energy

5-Due to the stray field of the SC-DQS magnets, the SC-QS magnetic axis is further displaced. To correct this displacement, a reference particle is shot through the bending section. The distance between the SC-QS magnetic axis and the reference particle trajectory is calculated and the SC-QS magnets are adjusted following step 3). Step 5) is iterated as the 3D magnetic field map slightly changes due to the presence of iron.

6-Finally, all the magnets are switched on. A reference particle is shot anew. The distance between the reference particle trajectory and the positions of the magnetic axis of the SC-QS magnets and the Q magnets are calculated. If discrepancies larger than 0.5 mm are found, the position of the Q magnets is corrected by repeating steps 4) and 5)

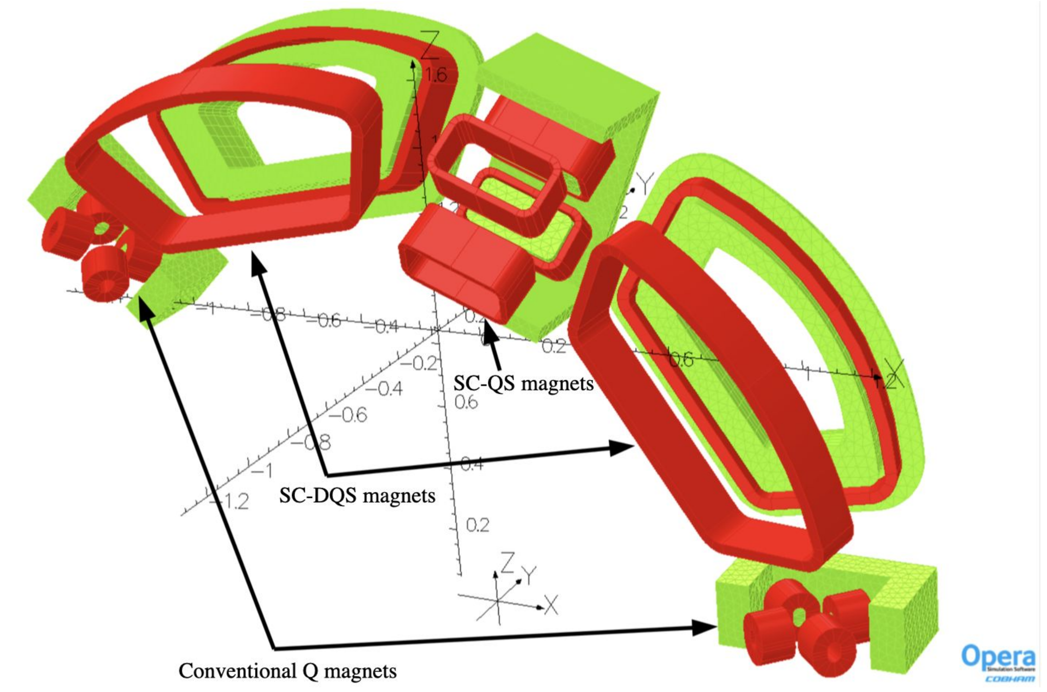

Fig. 1. Layout of the magnets held on the rotating gantry: conventional quadrupole magnets (Q), superconductor combined quadrupole and sextupole magnets (SC-QS) and combined dipole, quadrupole and sextupole magnets.

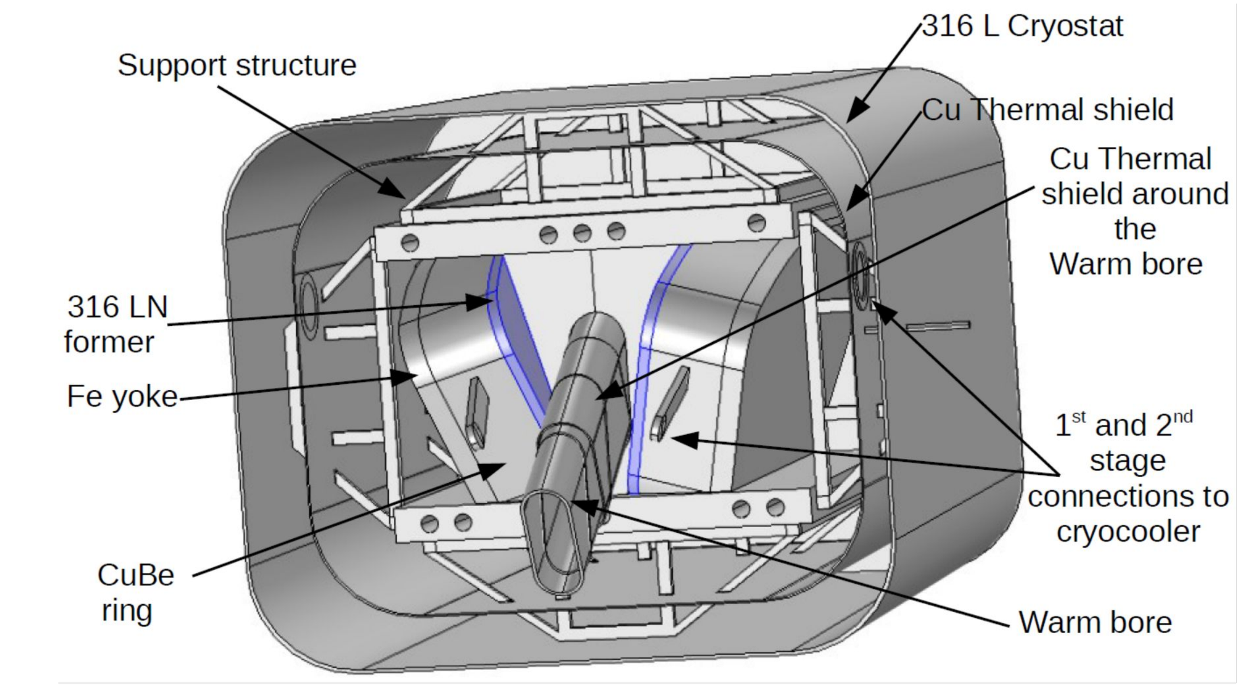

Fig. 2: SC-DQS magnet support including cryocooler anchoring points, thermal shield and the cryostat walls.

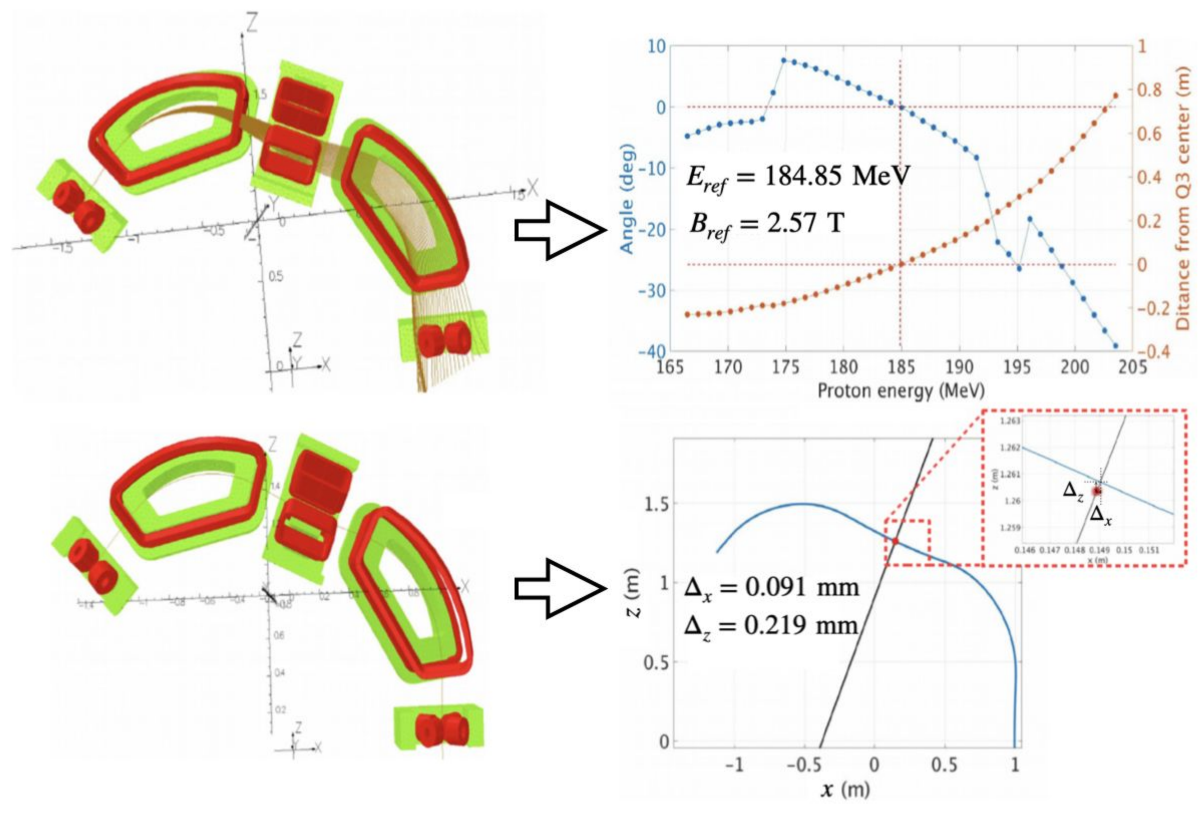

Fig. 3: Alignment procedure. Top row: protons with energies in the range of ± 10 % with respect to the nominal kinetic energy (185 MeV) are shot along the bending section. Bottom row: a reference particle at E_{ref} is shot along the bending section. Δx and Δz are the distances along the x and z axes between the SC-QS magnetic axis and the particle trajectory.

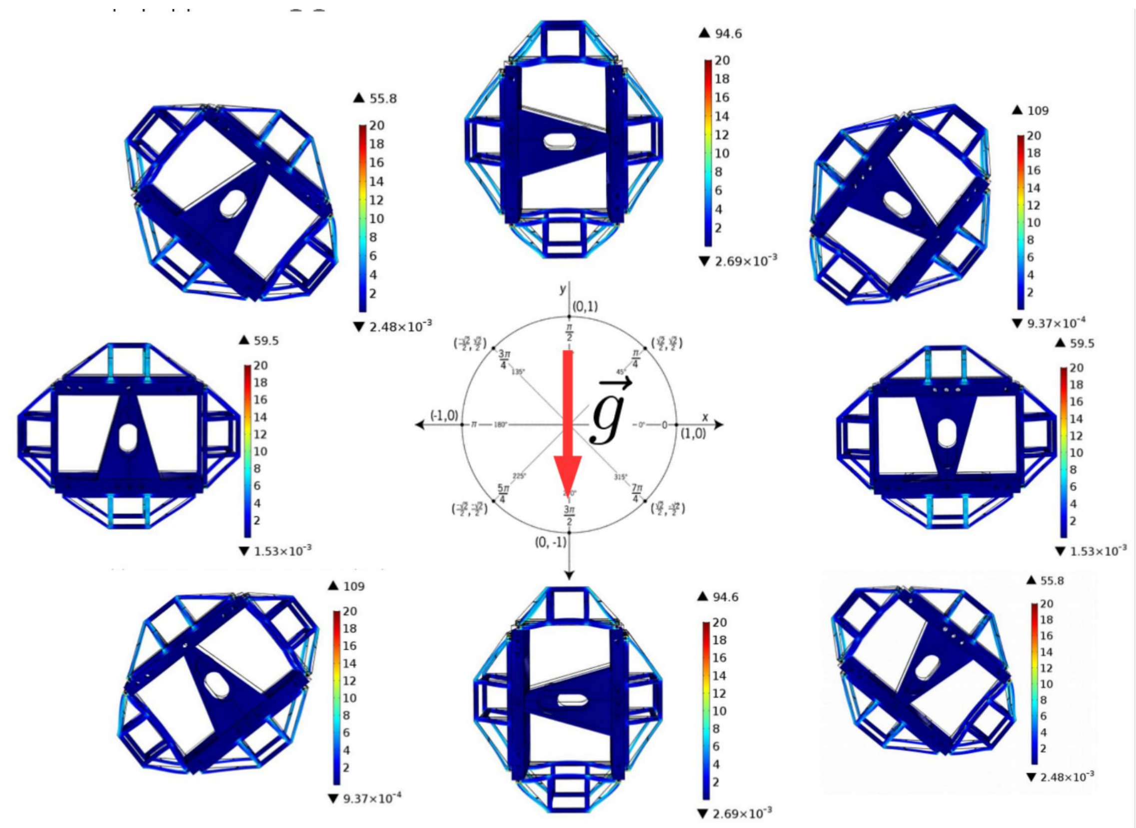

Fig. 4: Distribution of von Mises stresses in the magnet support structure over a full rotation.

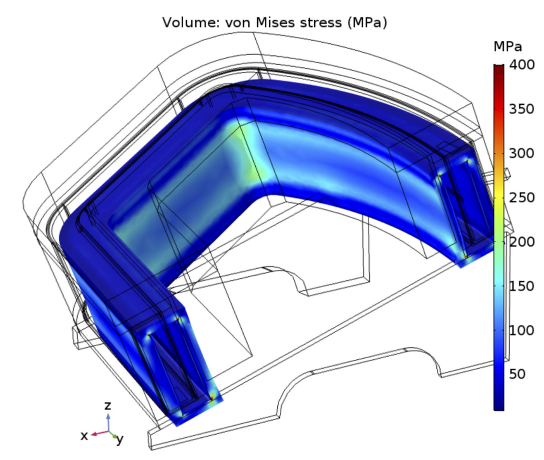

Fig. 5: Distribution of von Mises stresses in the 316LN coil casing.

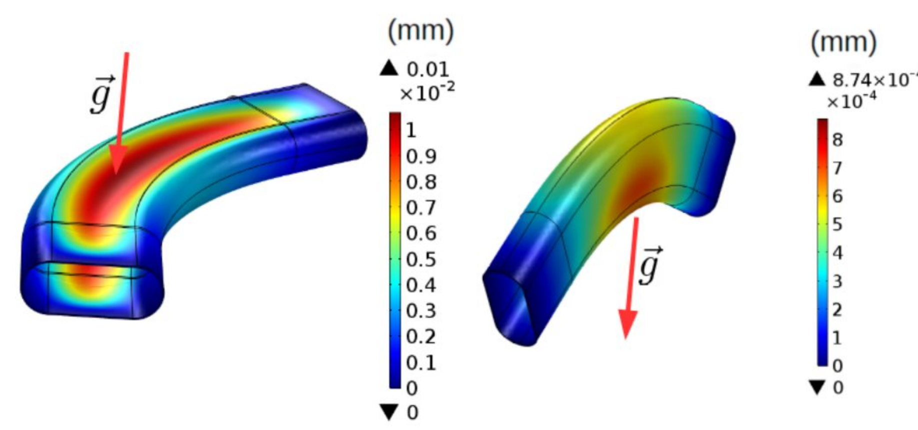

Fig. 6: Thermal shield deformation under its own weight. The plot on the left corresponds to the worst case scenario whereas the one on the right is the best case scenario.

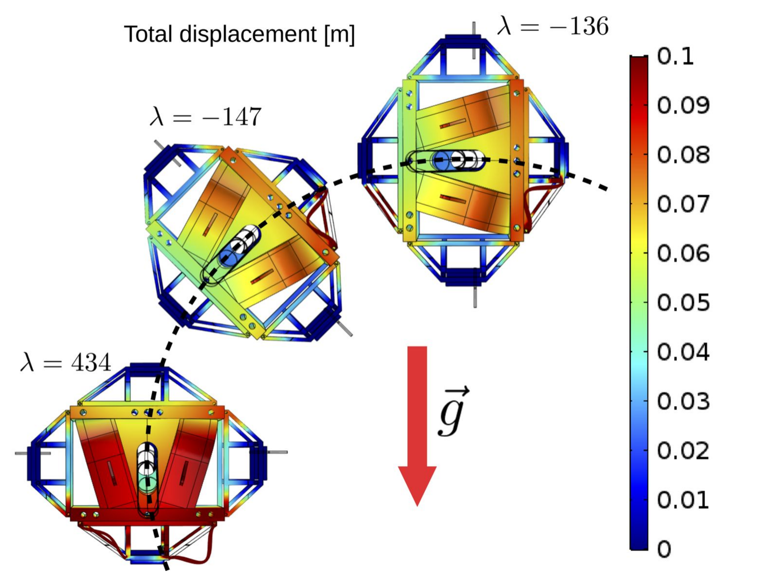

Fig. 7: Total displacement at the first critical buckling load.

Mechanical analysis:

1) *Analysis of the rotating structure supporting the SC-DQS magnets. This structure connects a magnet to its cryostat:*

The calculated peak stress, equal to 110 MPa, is located at the connection between the Ti-6Al-4V truss structure and the 316LN support (Fig. 4). It is a safe value of operation as the yield strength of Ti-6Al-4V around 4.2 K exceeds 1000 MPa and values between 860 MPa and 1000 MPa have been measured for the 316LN steel.

λ is the critical load factor, i.e. the load multiplier at which the structure becomes unstable. The absolute values of λ upon rotation are much larger than unity (Fig. 7). Therefore, the load that the structure can withstand is below the critical one.

2) *Buckling analysis of the support structure including the warm bore and the thermal shield:*

The simulations show a maximum deformation of 0.01 mm which wards off the danger of thermal bridges (Fig. 6).

3) *Analysis of the 316LN coil casing:*

The yield strength of 316LN equal to 750 MPa was not exceeded at 4.2 K thereby indicating that the 15 mm thickness of non-magnetic stainless steel is sufficient thick to handle the mechanical deformation of the coils (Fig. 5).

Conclusion:

An alignment procedure was developed to ensure the best focus of the proton beam through the bending section for a large beam momentum. The reference kinetic energy of the proton beam is 185 MeV. This procedure is composed of 6 steps combining the magnetic field produced by the magnets and the particles' trajectory. Besides this procedure, 3D mechanical analyses were conducted to guarantee that the main components surrounding the SC-DQS Nb_3Sn magnets (most critical magnets) do not interfere with the safety of the superconducting coils to ensure the safe and reliable operation of the SC-DQS magnets in the bending section.

References:

A.Gerbershagen, C. Calzolaio, D. Meer, S. Sanfilippo and M. Schippers, "The advantages and challenges of superconducting magnets in particle therapy," *Superconductor Science and Technology*, vol. 29, no. 8, p. 083001, 2016.