

Exploratory energy deposition studies in the superconducting dipole magnet of the carbon-ion gantry for the National Center for Oncological Hadrontherapy

G. Tosetti^{*,†}*CNAO National Center for Oncological Hadrontherapy, Pavia, Italy
and Politecnico di Milano, Milan, Italy*A. Mereghetti[‡] and M. G. Pullia[§]*CNAO National Center for Oncological Hadrontherapy, Pavia, Italy*

(Received 6 February 2025; accepted 7 January 2026; published 13 February 2026)

In the context of the HITRIplus project and EuroSIG international collaboration, a carbon-ion gantry is being designed for possible installation at the National Center for Oncological Hadrontherapy (CNAO), Pavia, Italy. The design is based on superconducting (SC) magnet technology for the dipoles, in order to reduce gantry dimensions and weight. Unlike normal-conducting magnets, SC magnets are sensitive to local beam losses, which can lead to local energy deposition and potential quenches, thus inducing considerable gantry downtime. This contribution presents exploratory studies of energy deposition in the SC dipole magnets currently foreseen for the gantry. The studies are carried out by means of Monte Carlo simulations, using the FLUKA code to characterize ruling factors such as beam spot size and impact angle. In this exploratory phase, simulations were carried out assuming simplified beam impact conditions.

DOI: [10.1103/b78n-rkyb](https://doi.org/10.1103/b78n-rkyb)

I. INTRODUCTION

Hadrontherapy [1] is an advanced method of cancer treatment where tumors are irradiated with charged hadron beams. Compared to conventional radiotherapy, carried out by means of photons or electrons, hadrontherapy is characterized by a dose delivery more conformal to the tumor volume, with improved sparing of surrounding healthy tissues. Therefore, hadrontherapy can be recommended in case of radio-resistant tumors or for tumors located near radio-sensitive tissues.

The National Center for Oncological Hadrontherapy (CNAO) [2] is a hadrontherapy center located in Pavia, Italy. CNAO offers treatments in three rooms, each equipped with a horizontal beam line; additionally, one of the rooms is also equipped with a vertical beam line. Beam acceleration at CNAO is attained by means of a synchrotron. Currently, the center deploys proton and

carbon-ion beams clinically, with ranges of 30 to 320 mm in the case of protons, and 30 to 270 mm in the case of carbon ions; the corresponding beam kinetic energy ranges are 62 to 227 MeV and 115 to 400 MeV/u for protons and carbon-ion beams, respectively.

In the context of the HITRIplus project [3] and EuroSIG international collaboration [4,5], a carbon-ion gantry is being designed for first installation at CNAO. A gantry is a complex mechanical structure that allows the rotation of a transfer beam line around the patient, drastically increasing the number of irradiation directions available for treatment planning. The current design [6–9] foresees superconducting (SC) magnet technology to reduce dimensions and weight of the structure, and hence its footprint on the installation site.

SC magnets are subject to quenches, i.e., the sudden transition from the SC state to the normal-conducting state of the magnet. If a quench occurs, the high current circulating in the magnet must be extracted, in order not to permanently damage the coils; moreover, recovery from a quench is a lengthy process, leading to considerable downtime of the gantry beam line. If too intense, beam losses reaching the magnet coils can induce a quench; in fact, beam particles and their secondaries arising from nuclear interactions with the magnet material deposit their energy while traveling through the coil, with the consequent increase of temperature. Therefore, it is important to assess at the design phase whether hadrontherapy beams

^{*}Present address: CNRS–LPC CAEN Laboratoire de Physique Corpusculaire de Caen, Caen, France.

[†]Contact author: tosetti@lpc.caen.in2p3.fr

[‡]Contact author: alessio.mereghetti@cnao.it

[§]Contact author: marco.pullia@cnao.it

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

accelerated at CNAO can be of concern for the gantry SC magnets, such that mitigation actions can be conceived and embedded in the gantry design.

This contribution presents exploratory energy deposition studies for the SC dipole magnet of the gantry. The energy deposition density is estimated by means of Monte Carlo simulations, using the FLUKA code [10,11], in an adiabatic approach, i.e., assuming that all the energy deposited locally contributes to the local temperature variation, ignoring thermal diffusion processes. Since at the time of writing the gantry design is still in a conceptual design phase, the study focuses on characterizing the factors ruling patterns of energy deposition density in a generic scenario rather than on precisely estimating energy deposition density values in specific scenarios of beam losses. The scenario considered throughout the studies envisages the loss of the entire beam extracted from the CNAO synchrotron on the SC dipole; even though such a scenario is unrealistic, it allows estimation of the order of magnitude of beam-induced energy deposition density values and assessment of whether beam losses can be of concern for quench protection, even if the estimates are extremely conservative, as shown later. Moreover, since there are no similar studies at hadrontherapy beam energies, it is important to characterize the simplest but most conservative scenario in order to show how more realistic assumptions, to be taken in more advanced studies, lead to more relaxed energy deposition density values. More realistic loss scenarios can be simulated only once beam loss patterns in beam lines are known, but at present there are no studies characterizing beam loss patterns in hadrontherapy beam lines, neither in terms of measurements (e.g., with beam loss monitors) nor in terms of estimations by means of methods such as beam dynamics simulations. In fact, the former would imply the use of specific monitors, which are not present in any hadrontherapy facility [12]; the latter are quite complex, since beam extraction from a hadrontherapy synchrotron takes place in a resonant way (hence a very nonlinear process), and they are usually performed for purposes such as spill quality optimization and ripple control, rather than for identifying beam loss patterns. In addition, a design of the beam line connecting the gantry to the CNAO synchrotron is not yet available at the time of writing, making the estimate of the beam loss pattern very arbitrary.

Section II gives an overview of the design of the gantry and of the superconducting dipole magnet considered for the studies. Afterward, Sec. III briefly describes the simulation setup and presents the estimates of energy deposition density. As done in the literature [13–15], energy deposition density estimates obtained with Monte Carlo codes are then compared to the quench limit, i.e., the estimated value of energy deposition density at which a quench takes place. Finally, Sec. IV reports the conclusions drawn.

II. OVERVIEW OF GANTRY DESIGN

The current layout of the C-ion gantry is shown in Fig. 1. The design is based on SC dipoles bending the beam by 45° and generating a magnetic field of up to 4 T (for carbon ions at the maximum energy of 430 MeV/u), with the aim of optimizing gantry dimensions and therefore weight. Another basic design characteristic is the presence of the scanning system downstream of the final bending section [16]; while such a choice implies a challenging design of the scanning magnets, it allows dealing with only one model of dipoles for the whole gantry by eliminating the need for dipoles of increasing aperture.

The SC dipole magnet is being designed by INFN LASA [18]. It is a $\cos\theta$ -dipole magnet with a Rutherford type cable made of 36 strands of Nb–Ti. The challenge of the design is twofold: on the one hand, the high magnetic field of up to 4 T and the requested magnet aperture of 80 mm imply a large stored magnetic energy; on the other hand, the large bending angle of 45° and small bending radius of 1.65 m make the winding of a $\cos\theta$ -dipole magnet extremely complex. In addition, the requested ramp rate of 0.4 T/m is quite demanding in terms of ac losses. The maximum current (i.e., for the 4 T magnetic field) is 2770 A and the operational temperature is 5 K.

In order to prove the possibility to overcome all the challenges involved in the design of the SC dipole, INFN LASA decided to design and manufacture a demonstrator [17,19]. The design of the demonstrator differs from that of the gantry dipole in the bending angle, i.e., 30° instead of 45° , and the maximum ramp rate, i.e., 0.15 T/m instead of 0.4 T/m, because of the nonoptimized strand and cable available. Figure 2 shows a 3D rendering of the current SIG demonstrator.

In the present work, the quench limit is assumed to be the pure enthalpy margin of a single strand at maximum current and field for 0.1 ms heating time, i.e., 10 mJ cm^3 [20]; this is a conservative assumption, since the quench limit increases by decreasing the magnetic field intensity and magnet current, hence relaxing the margin to the quench. It should be noted that for the same magnet current and

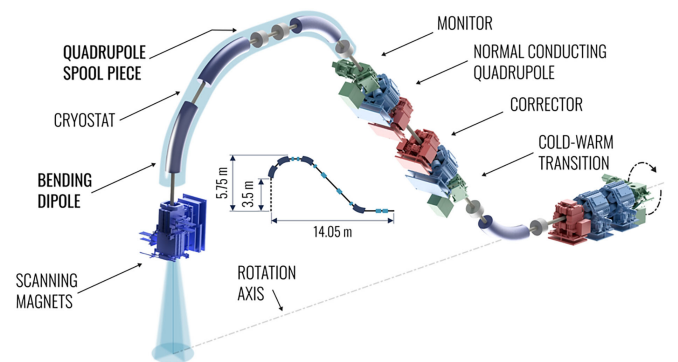


FIG. 1. 3D rendering [17] of the current layout of the carbon-ion gantry under study.

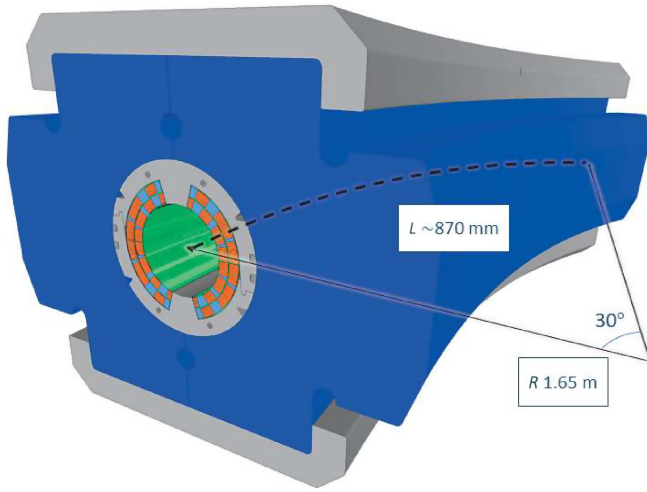


FIG. 2. 3D rendering of the SIG demonstrator dipole [17,19].

operating temperature, the quench limit is not the same for all the layers and blocks of the SC coils. In fact, if the local value of magnetic field in the SC coils (see Fig. 3) is taken into account [21], the quench limit ranges between 7.14 mJ cm^{-3} (where the maximum field value is found) and 20.6 mJ cm^{-3} (where the minimum field value is found) in the first layer of SC coils at maximum current. For comparison, when the magnet is operated at minimum field (i.e., in case of protons of minimum extraction energy), the quench limit ranges between 35.0 and 38.6 mJ cm^{-3} .

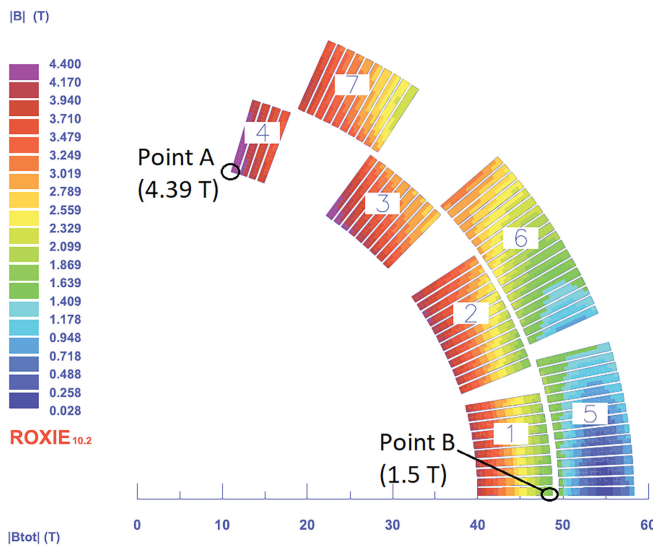


FIG. 3. 2D map [17,19] of magnetic field intensity in the two layers of SC cable of the SIG demonstrator dipole at maximum current. The points with the maximum (point A) and minimum (point B) value of the field in the first layer of SC coils are indicated.

III. ENERGY DEPOSITION SIMULATIONS

Monte Carlo simulations have been carried out with the FLUKA code. In order to compare results against the quench limit, results are normalized to a full beam extraction from the CNAO synchrotron, nominally 1×10^{10} protons and 4×10^8 carbon ions per extraction, taking place in 1 s [22].

Section III A reports results for a central, front face, full beam impact on a cylindrical target of homogeneous material; all the materials composing the SIG demonstrator are simulated individually. Section III B presents results obtained using the cross section of the SIG demonstrator, considering a beam impact on the inside of the magnet aperture with both straight (Sec. III B 1) and curved (Sec. III B 2) magnet geometries, while Sec. III B 3 shows a comparison of results between the two geometries.

A. Energy deposition in homogeneous material

The results presented here have been obtained considering the impact of the full beam onto a target of homogeneous material. Protons and carbon ions with energies corresponding to the extremes of the clinical operation at CNAO were simulated, i.e., 62 and 230 MeV for protons, and 115 and 400 MeV/u for C ions; no energy spread was considered. The beams are given a Gaussian distribution along both the horizontal (x) and vertical (y) axes, each with a full width at half maximum (FWHM) of 5 mm; this value is comparable to those foreseen by the current gantry optics [7,9]; no beam divergence was considered. The target is cylindrical, with the same radius and length, i.e., 24 cm; the dimensions have been chosen such that the target stops all primary particles (thick target). The beam hits the target normal to the cylinder base, at its center. Each material composing the SIG demonstrator was considered. In particular, for the SC coils, copper and niobium–titanium, i.e., the components of the SC material, have been considered either separately or together to form the material named “strand” (the ratio NbTi:Cu is 1:1.75); in addition, the “cable” material, which considers the strand material together with the cable insulation and stainless steel inlet [17,19], was considered as well. Energy deposition results are evaluated by means of a cylindrical mesh covering the entire target, with only one angular bin (profiting from the cylindrical symmetry of the beam), a radial step of 0.3 mm (corresponding to a tenth of the FWHM), and a longitudinal step of $50 \mu\text{m}$. Such a refined mesh allows proper capture of the steep gradients in the energy deposition distribution that will be seen in metallic materials at minimum beam energies.

Figure 4 shows the longitudinal profile of the peak energy deposition, i.e., the largest value of the map of energy deposition found at a specific longitudinal position along the axis of the cylinder as a function of the longitudinal position. It should be noted that in order to see the typical profile of a Bragg peak, the longitudinal

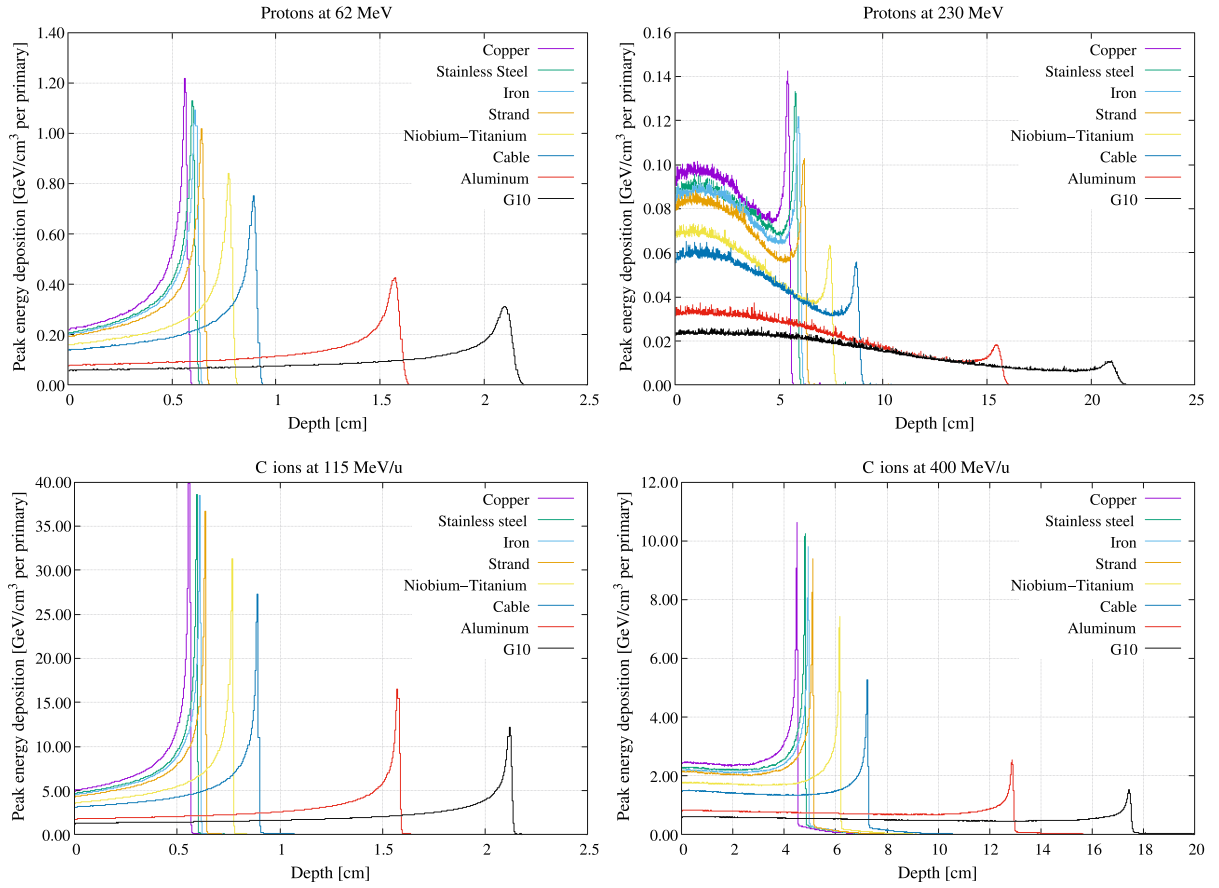


FIG. 4. Longitudinal profiles of peak energy deposition in a thick target of homogeneous material for proton beams (upper frames) and carbon-ion beams (lower frames), at minimum (left frames) and maximum (right frames) beam kinetic energies. Results for a central beam impact and different materials are shown.

profile of the total energy deposition should be considered, i.e., the integral of the map of energy deposition found at a specific longitudinal position. As expected, the materials with the highest density consistently exhibit the most pronounced peak, independently of the particle used or its energy. As it can be seen, carbon ions at minimum energy lead to the largest values of energy deposition, whereas protons of maximum energy lead to the smallest.

Table I reports the maximum values of energy deposition shown in Fig. 4 for a selection of materials, converted in mJ cm^{-3} by considering the nominal beam extraction intensities reported in Sec. III. As it can be seen, all values exceed the assumed quench limit of 10 mJ cm^{-3} (see Sec. II). In the following sections, strand is conservatively chosen as the cable material over the material named “cable” (which is more complete in composition since it also considers the insulation layers and the stainless steel inlet), due to its higher density and average atomic number. Copper and Nb–Ti materials are discarded since each of them omits one of the main components of the superconductor.

The dependence of the maximum energy deposited on the beam spot size has been characterized by simulating

different beam FWHMs for a target made of strand. Simulations have been performed only for the maximum beam kinetic energies, which maximize the particle range in the material, and hence, the impact of beam particle scattering and straggling. Results are shown in Fig. 5. As it can be seen, the maximum energy deposition found in depth scales fairly well with the beam spot size only for

TABLE I. Maximum values of energy deposition density in a thick target of homogeneous material for a central full beam impact. Values are shown only for selected materials, in case of carbon ions (second column) and protons (third column), at minimum (left) and maximum (right) beam energies. Values are given for a full beam extraction, taking into account the nominal beam intensities reported in Sec. III.

Material	Maximum energy deposition (mJ cm^{-3})	
	C ions	Protons
Cu	2560—685	1952—224
Strand	2368—602	1632—166
Nb–Ti	1984—480	1344—104
Cable	1768—339	1184—91

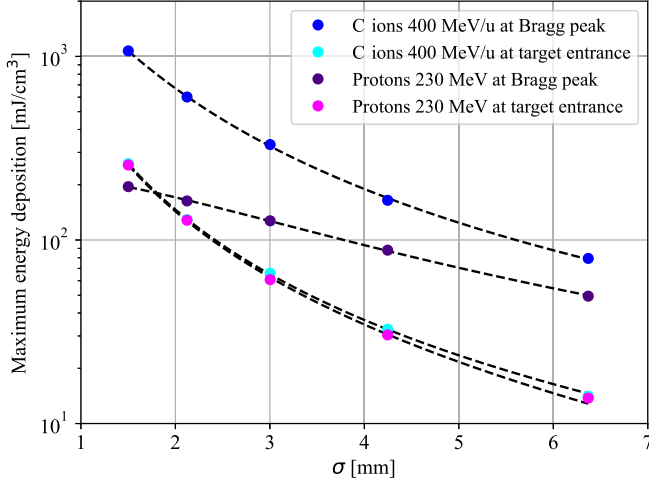


FIG. 5. Comparison of maximum energy deposition values and values at entrance in a thick target of strand material for a central full beam impact as a function of the beam spot size. A round beam is considered in case of carbon ions and protons at maximum beam energies; the nominal beam intensities reported in Sec. III are considered. Points represent simulation results, whereas dashed lines indicate fits through data following Eq. (1).

carbon ions, whereas it is not the case for protons; in fact, these suffer from scattering and straggling way more than carbon ions. On the contrary, in the proximity of the entrance surface, scaling with the spot size is valid for both particle species, and data can be fitted with the equation:

$$E_{\max} = \frac{A}{\pi\sigma^2 - b} + c, \quad (1)$$

where A , b , and c are the fitting parameters. While A is the most intuitive fitting parameter, b and c do not actually carry a specific physics meaning and they are used only for numerical reasons; indeed, their values are always close to 0, except for the case of protons at the Bragg peak. It should be noted that b prevents $E_{\max}$ from going to infinity when σ tends to 0, and c prevents $E_{\max}$ from going to 0 when σ tends to infinity. The beam dimensions considered are consistent with current values foreseen by the optics studies of the CNAO gantry.

According to optics, the beam spot in the gantry is not round but elliptical. Figure 6 shows longitudinal profiles of the peak energy deposition when the beam spot is made elliptical while keeping the same rms area. Protons and carbon ions at maximum kinetic energies have been considered, impinging on a strand target. The legends report the dimension of the smaller axis of the ellipse. The figure shows that the peak energy deposition at the entrance is almost the same for each case, no matter the actual spot shape. On the contrary, as the beam particle travels through the material, the energy deposition is diluted as the spot elongates; as it can be seen, the case of the round beam turns out to be the most conservative.

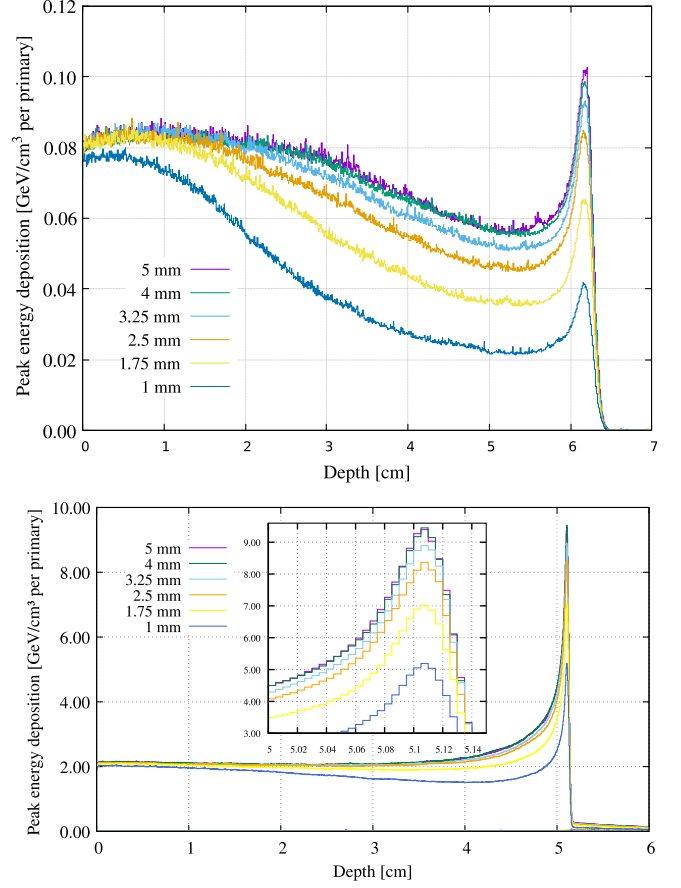


FIG. 6. Longitudinal profiles of peak energy deposition in the strand material for proton beams (upper frame) and carbon-ion beams (lower frame) at maximum kinetic energy. An enlarged view of the Bragg peak region has been inserted in the lower frame to show more clearly the effect on energy deposition density by an increasingly elongated beam spot. The curve for a central full beam impact for a round beam with a horizontal and vertical FWHM of 5 mm is compared to those for elliptical beams of same rms area; the legend reports the size of the smaller axis of the ellipse.

B. Energy deposition in actual magnet geometry

The results presented here have been obtained considering the impact of the entire beam extracted from the CNAO synchrotron onto the cross section of the SIG demonstrator, shown in the left frame of Fig. 7; the FLUKA geometry model of the cross section is shown in the right frame of Fig. 7. The two SC coils, i.e., the inner and outer coils, are each simulated as a single region of strand material, without implementing all Rutherford cables. The insulation layers are explicitly modeled and filled with the G10 plastic material; they are located radially on the inside and outside of each coil. The collar and the yoke are implemented as indicated in the SIG Conceptual Design Report (CDR) [19], i.e., made of aluminum and iron, respectively. Vacuum is present both in the opening of the magnet (aperture) and outside of the yoke. A 2 mm

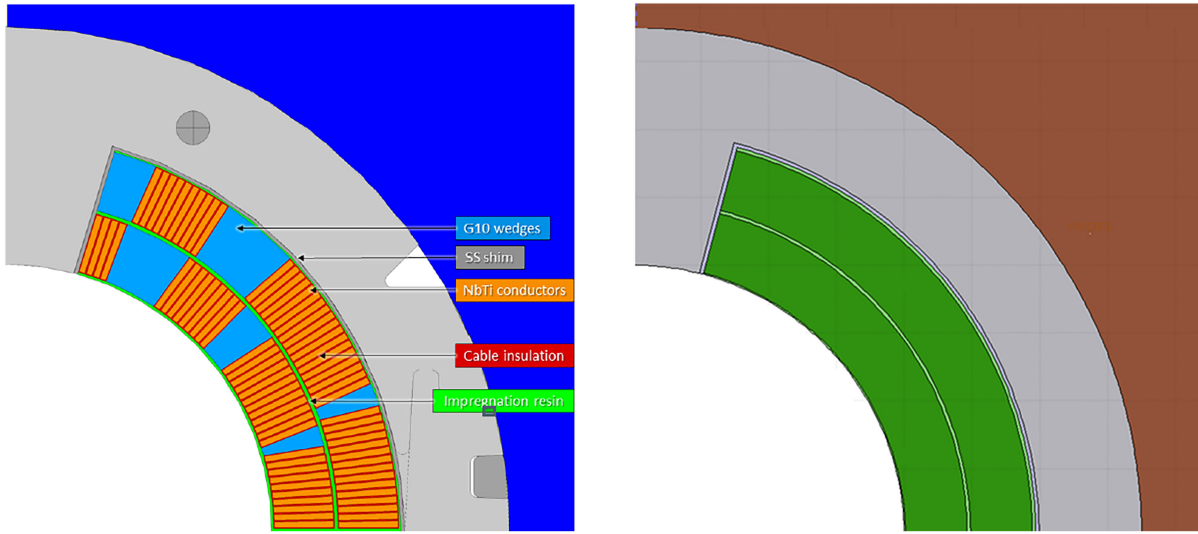


FIG. 7. Cross section of the SIG demonstrator from the design [17,19] (left frame) and as implemented in FLUKA (right frame), without the vacuum chamber.

vacuum chamber, made of stainless steel (specifically, AISI 316L), is implemented in the geometry to assess its shielding effects; the vacuum chamber is not in contact with the magnet aperture.

Since in this simulation scenario the beam impacts the magnet aperture with an angle and the beam has a finite range in the magnet materials, a “cutoff angle” (θ_{cut}) can be defined, i.e., the angle at which the beam is fully stopped inside a single layer of material:

$$\sin \theta_{\text{cut}} = \frac{t}{R}, \quad (2)$$

where t is the thickness of the material and R is the particle range in that material. Table II lists the cutoff angles for stainless steel, G10, and strand materials, considering the thicknesses of the vacuum chamber, the innermost insulation layer, and the inner coil, respectively. The beam ranges are derived from the longitudinal profiles of the peak energy deposition shown in Fig. 4. It should be noted that the strand layer is capable of fully stopping the primary

beam particles at minimum extraction energy, no matter the ion species.

For consistency with the simulations presented in the previous section (Sec. III A), a Gaussian beam with a FWHM of 5 mm is always considered on both the x and y axes; the beam impacts the magnet at different angles on the horizontal (i.e., x - z) plane from the inside of the aperture, as in the case of a beam loss taking place in the magnet. Simulations are performed only for C ions at minimum energy, since they present the highest values of energy deposition (see Fig. 4 and Table I). The scoring mesh is cylindrical, with a longitudinal step of 50 μm , an angular step comparable to the midsize of the bare cable (i.e., ~ 1 mm), and a radial step of 30 μm .

Results obtained simulating a straight magnet geometry are shown in Sec. III B 1, whereas those obtained with a curved geometry linearly segmented are shown in Sec. III B 2.

1. Straight magnet geometry

Figure 8 shows the longitudinal profile of the peak energy deposition in the inner coil; the beam impacts the magnet aperture from the inside, without going through the vacuum chamber. The impact point is on the horizontal midplane of the magnet, at the longitudinal midpoint. Two sets of impact angles have been considered: the smaller angles are multiples of 13 mrad, i.e., the angle above which the $\pm 3\sigma$ beam envelope fully impacts the magnet aperture along its entire length (“full illumination” angle); the case of an impact angle of 6.5 mrad has been considered as well, even though a portion of the beam does not hit the magnet. The larger angles have been chosen for gradually approaching the case of the homogeneous target (see Sec. III A). Values of energy deposition in the outer coil are not shown,

TABLE II. Cutoff angles for the specified thicknesses (second column) of selected materials, in case of carbon ions (third column) and protons (fourth column), at minimum (left) and maximum (right) beam energies. An empty cell indicates that the beam is stopped by the material layer, no matter the impact angle.

Material	Thickness (mm)	Cutoff angle (mrad)	
		C ions	Protons
Stainless steel	2	340—42	318—33
G10	0.2	9.3—1.1	9.2—0.9
Strand	9.1	176	141

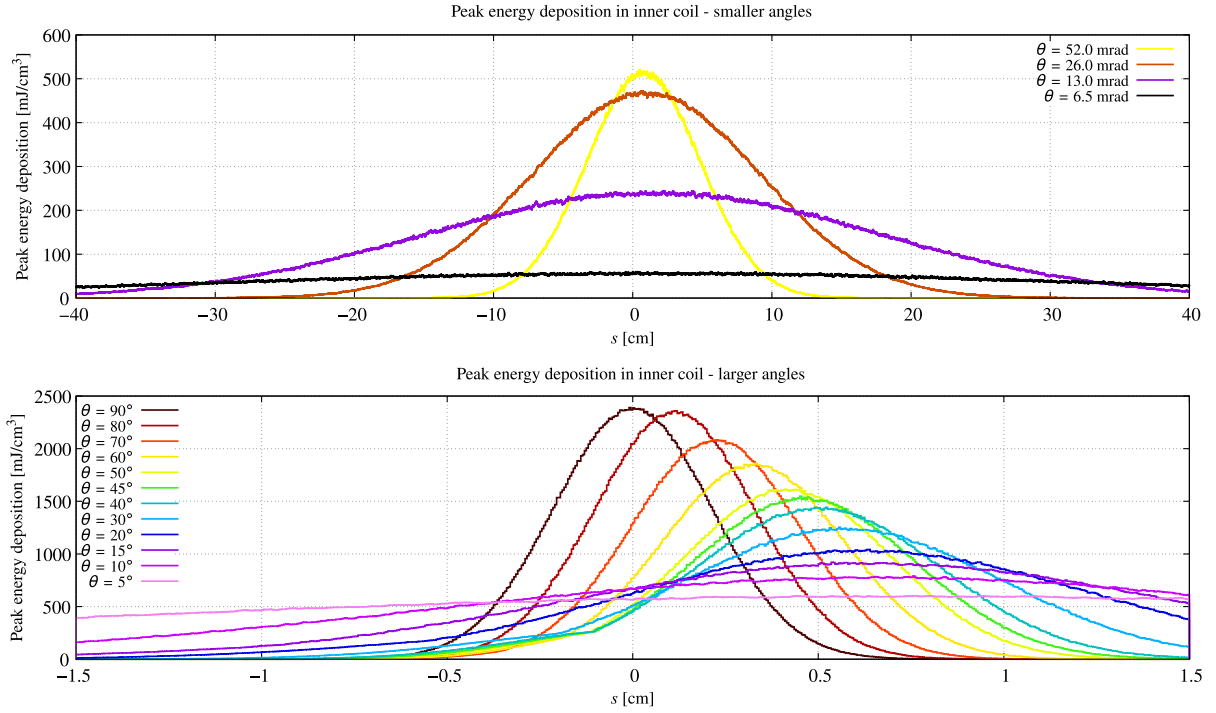


FIG. 8. Longitudinal profile of peak energy deposition in the inner coil of the main dipole magnet (straight magnet geometry) of the C-ions gantry in case of carbon ions at minimum extraction energy, for low impact angles (upper plot) and large impact angles (lower plot). The beam hits the magnet from the inside of the aperture (no vacuum chamber). Please bear in mind the different horizontal scales.

since the beam fully stops inside the inner coil (see Table II for the cutoff angles).

As it can be seen, the longitudinal profile of the peak energy deposition broadens for impact angles increasingly grazing. This behavior is expected: a lower impact angle results in a proportionally larger beam spot size at the impact point, which broadens the longitudinal distribution of peak energy deposition and hence lowers the maximum value. In addition, the maximum energy value shifts farther from the longitudinal midpoint, since beam particles are directed more longitudinally.

Figure 9 shows the maximum values of energy deposition (i.e., the largest values found in the longitudinal profiles of the peak energy deposition, and hence the highest values in the entire coil). The case without beam pipe is given by the red points. The black line shows the scaling of the maximum energy deposition found for the perpendicular impact (i.e., with a 90° impact angle) with $\sin \theta$ as indicated in the legend. The red points roughly follow the trend of the black line, although there are visible discrepancies due to geometric reasons. In the range between 600 and 1400 mrad, simulations predict a lower maximum value than that obtained with the analytical formula. The analytical formula assumes a perpendicular impact (with an appropriately enlarged spot size), whereby all energy deposition events by δ radiation, which typically occur transversely to the path of the beam hadrons, overlap perfectly among neighboring beam particles, especially

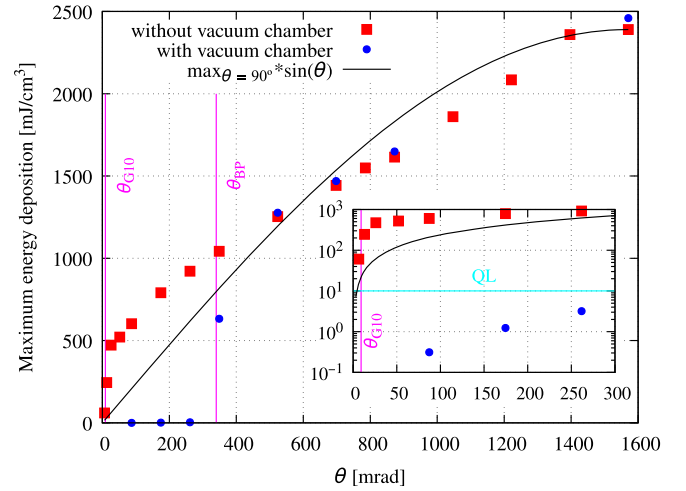


FIG. 9. Maximum energy deposition in the inner coil of the main dipole magnet (straight magnet geometry) of the C-ions gantry in case of carbon ions at minimum extraction energy. Values obtained in presence of the beam pipe (blue dots) are compared to values in absence of the beam pipe (red dots) as shown in the longitudinal profiles in Fig. 8. The black line shows the scaling of the maximum energy deposition found for the perpendicular impact with $\sin \theta$. The magenta lines show the cutoff angles of the insulation layer (G10) and of the beam pipe (BP). The smaller frame is an enlarged view of the range between 0 and 300 mrad; the cyan line indicates the assumed quench limit. Please bear in mind the logarithmic scale of the vertical axis in the enlarged view plot.

near the Bragg peak; this is not the case for oblique impact angle. In the range between 26 and 600 mrad, simulations predict a higher maximum value than that obtained with the analytical formula: in these cases, the impact angle is such that energy deposition values in the Bragg peak region of a given beam particle also overlap with energy deposition values in the plateau region of neighboring beam particles. Finally, for impact angles smaller than 26 mrad, the red points show a trend completely different from that of the analytical formula, because the impact angle approaches the cutoff angle of the G10 insulation layer. The presence of the pipe (blue points) is very important at angles smaller than the cutoff angle of the stainless steel vacuum chamber, which is 340 mrad for the considered beam (see Table II), because it lowers the possibility of quenching; in any case, impact angles close to the cutoff angle still lead to energy deposition values much higher than the quench limit, indicating that some margin to the cutoff angle must be taken. On the contrary, at impact angles larger than the cutoff angle, the presence of the pipe becomes irrelevant, as expected.

2. Curved magnet geometry

Figure 10 shows the FLUKA geometry of the curved dipole cut through the magnet midplane; the assumed curvature radius and bending angle are 1.65 m and 45°, respectively. The geometry has been built programmatically as a sequence of short linear segments by means of a Python [23] script based on the pyFLUKAgeo package [24], a Python library capable of manipulating FLUKA geometries in a programmatic way. Indeed, the geometry is not based on a torus but it is linearized in 45 straight cells (one at each degree), each replicating the SIG demonstrator cross section; a dedicated copy of the scoring mesh is superimposed to each cell. The longitudinal position of the center of each cell is given by

$$L_i = (i + 0.5) \times L_c, \quad (3)$$

where

$$L_c = 2R \sin \frac{\theta}{2}, \quad (4)$$

where R is the curvature radius (i.e., 1.65 m), θ is the partition angle (i.e., 1°), L_c is the length of each cell, and i is the index number of the cell (i.e., 0, 1, ..., 44).

As for the simulations carried out in the straight magnet geometry (see Sec. III B 1), a beam of C ions at 115 MeV/u was considered, with a FWHM of 5 mm on both axes, and without any divergence; the beam hits the dipole aperture always on the midplane. The impact on both sides of the aperture was simulated (see Fig. 10) shooting the beam from the upstream (entrance) face: to hit

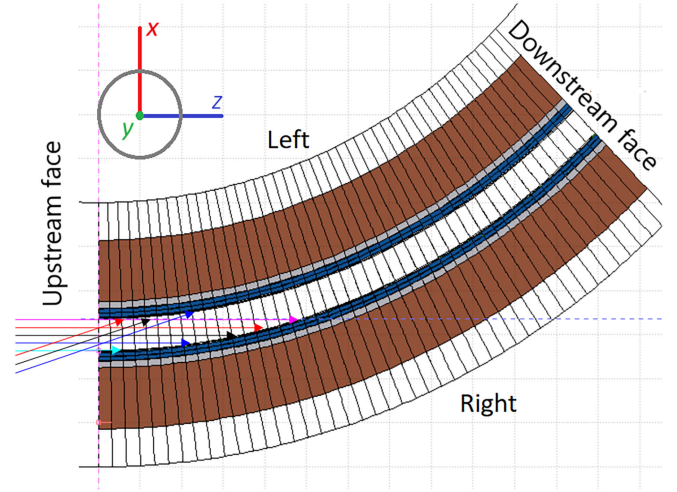


FIG. 10. Schematics of the beam impact conditions simulated with the curved geometry model of the main dipole magnet of the C-ions gantry. The geometry is not a toroidal one but it has been approximated by 45 straight segments. The arrows depict the beam direction; colors will be used to disentangle the simulated cases. The orientation of the FLUKA reference system is shown in the upper left corner.

the right side of the magnet aperture, the beam is parallel to the FLUKA z axis; to hit the left side, the beam is given an angle such that the left side of the aperture can be hit tangentially by the beam when shooting the beam from the rightmost transverse position of the magnet aperture on the upstream face (i.e., 17.5° or 305 mrad). Different transverse positions at the magnet entrance (upstream face, see Fig. 10) have been considered, such that every cell that can be hit (more or less at the longitudinal center) from the upstream face was simulated. These starting conditions will turn into different local impact angles.

Figure 11 shows the longitudinal profiles of the peak energy deposition in the inner coil in a selection of the considered cases: -3.5 , -1.75 , 0 , 1.75 , and 3.5 cm along the FLUKA x axis for the impacts on the right of the aperture; -1.75 , 0 , and 1.95 cm for the impacts on the left of the aperture. Few artifacts are visible at the boundaries between the cells because the scoring meshes are slightly longer than the cells; hence, meshes of neighboring cells overlap for tiny fractions (sub-mm), but with the wrong angles. The horizontal axis is the s coordinate, i.e., the cumulative linear position along the longitudinal axes of the meshes. The longitudinal profiles are spaced according to the different starting positions, which lead to different hit longitudinal positions. For the cases of beam hitting the right side of the aperture, the peak gets sharper and more intense as the curvature angle increases, since the local impact angle increases; the opposite happens for the cases of beam hitting on the left side of the aperture, since the local impact angle decreases.

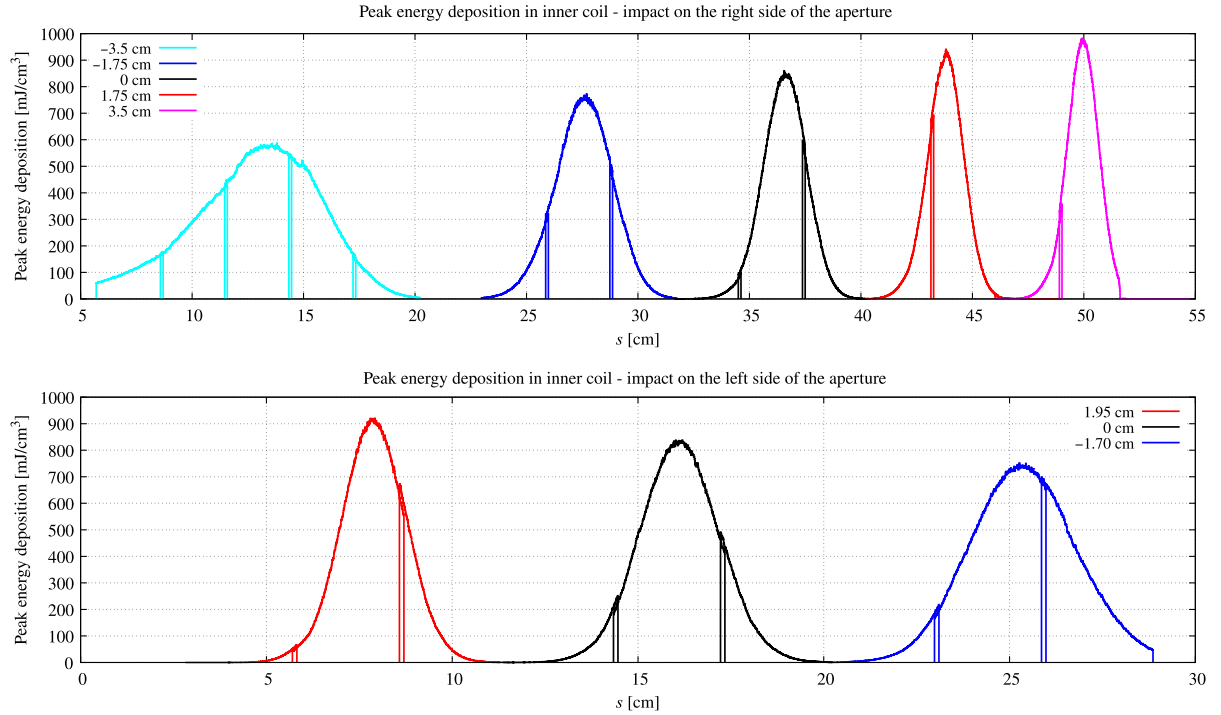


FIG. 11. Longitudinal profile of peak energy deposition in the inner coil of the main dipole magnet (curved magnet geometry) of the C-ions gantry for carbon ions at minimum extraction energy, in case of impact on the right side of the magnet aperture (upper plot) and on the left side of the magnet aperture (lower plot). Colors refer to those of the arrows in Fig. 10. The beam hits the magnet from the inside of the aperture (no vacuum chamber). Please bear in mind the different horizontal scales.

3. Comparison

Figure 12 reports the maximum energy deposition for C ions at 115 MeV/u obtained with the curved magnet geometry when hitting the magnet aperture on the right side (red points) and on the left side (blue points); values from all simulated cases (and not only the subset in Fig. 11) are shown. For comparison, values obtained in straight magnet geometry are shown as black points (the same already shown in Fig. 9). As it can be seen, results for the curved magnet geometry (red and blue points) are consistent with those from the straight magnet geometry, provided that the impact angle at the center of the hit point is considered.

IV. CONCLUSIONS

In the framework of the HITRI^{plus} project and of the EuroSIG international collaboration, a superconducting gantry for carbon-ion beams is being designed for first installation at CNAO, Pavia, Italy. This contribution presents estimates of beam-induced energy deposition density in the superconducting dipole magnets of the gantry obtained with the FLUKA Monte Carlo code. Simulations considered the full impact of the nominal beam extracted from the CNAO synchrotron on a single dipole magnet in adiabatic hypothesis, leading to conservative estimates. Furthermore, no specific scenario

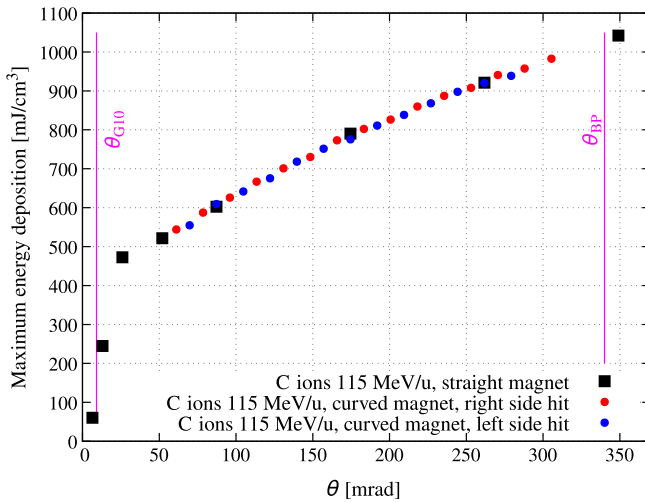


FIG. 12. Maximum energy deposition in the inner coil of the main dipole magnet of the C-ions gantry for carbon ions at minimum extraction energy. Values obtained with the curved magnet geometry (red and blue points, for beam hits on the right and on the left side of the aperture, respectively) are compared to those obtained with the straight magnet geometry (black points, see Fig. 9). The magenta lines show the cutoff angles of the insulation layer (G10) and of the beam pipe (BP).

of beam losses based on optics studies or operational experience was considered, because of the high degree of complexity of the former for these exploratory simulations and the lack of suitable monitors for the latter.

In the simplified case of a central beam impact onto a thick target of homogeneous material, maximum values of energy deposition in the superconducting coils are one to two orders of magnitude larger than the assumed quench limit, no matter the beam species and beam extraction energy. C ions at minimum extraction energy (i.e., 115 MeV/u) lead to maximum energy deposition values, both per single ion and per single extraction, i.e., when considering nominal beam intensities. As expected, values of energy deposition scale fairly well with the spot area unless scattering of beam particles becomes dominant, as it happens for protons at maximum extraction energy at the location of the Bragg peak. Similarly, the eccentricity of the beam spot has a minor impact on energy deposition values unless very large eccentricity values are reached, as seen for carbon ions at maximum extraction energy.

Simulations with the actual cross section of the SIG demonstrator were carried out considering both a straight and a curved magnet geometry; an impinging beam of C ions at minimum extraction energy was considered, keeping constant the beam spot size but varying the impact angle. Results with these geometries confirm that lowering the impact angle (i.e., toward grazing impacts) results in a decrease in energy deposition due to the elongation of the beam footprint on the impacted surface. Nevertheless, hadrontherapy beams can be of concern for magnet quench in case of impact even with an angle of some tens of mrad; on the other hand, a vacuum chamber of a couple of mm substantially shields the magnet against direct beam losses with an angle of up to few tens of mrad.

The presented studies show that values of energy deposition in the superconducting coils strongly depend on the size and angle of the impacting beam. Therefore, in order to improve results, it is important to consider the beam transfer line connecting the gantry to the upstream synchrotron and estimate beam loss distributions in the gantry, e.g., using single particle tracking codes in the case of more specific beam loss scenarios. These simulations are quite complex, as beam extraction from the CNAO synchrotron proceeds with a resonant mode, a highly dynamic and nonlinear process; in addition, the beam line connecting the gantry to the CNAO synchrotron should be designed.

Another way of improving results is a more systematic evaluation of the role of the beam pipe, e.g., by scanning through beam energies the cutoff angle and the maximum impact angle by which the beam pipe effectively shields the SC coils. At the same time, the estimate of the margin to quench could be improved by comparing bin by bin the map of energy deposition values with that of enthalpy limits calculated from the map of magnetic field (as done, e.g., in

Sec. II). Similarly, the FLUKA geometry could be made even more realistic, e.g., by implementing the entire gantry geometry and including magnetic fields.

ACKNOWLEDGMENTS

The authors would like to thank S. Savazzi and E. Felcini from CNAO and M. Prioli from INFN LASA for fruitful and inspiring discussions.

DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

-
- [1] M. Durante, R. Orecchia, and J. S. Loeffler, Charged-particle therapy in cancer: clinical uses and future perspectives, *Nat. Rev. Clin. Oncol.* **14**, 483 (2017).
 - [2] CNAO website, <https://fondazionecnao.it/>.
 - [3] HITRIplus website, <https://www.hitriplus.eu/>.
 - [4] L. Rossi *et al.*, A European Collaboration to investigate superconducting magnets for next generation heavy ion therapy, *IEEE Trans. Appl. Supercond.* **32**, 4400207 (2022).
 - [5] M. Pullia, E. Felcini, E. Benedetto, L. Dassa, E. De Matteis, M. Donetti, G. Frisella, M. Karppinen, C. Kurfurst, S. Mariotto, A. Mereghetti, A. Mirandola, A. Pella, D. Perini, L. Piacentini, M. Pivi, M. Prioli, A. Ratkus, L. Rossi, and M. Vretenar, Gantries for carbon ions, *Health Technol.* **14**, 973 (2024).
 - [6] M. G. Pullia *et al.*, Explorative studies of an innovative superconducting gantry, *J. Phys. Conf. Ser.* **2420**, 012099 (2023).
 - [7] E. Felcini, G. Frisella, A. Mereghetti, M. G. Pullia, S. Savazzi, M. T. F. Pivi, and E. Benedetto, Beam optics studies for a novel gantry for hadron therapy, *J. Phys. Conf. Ser.* **2420**, 012098 (2023).
 - [8] S. Savazzi, E. Felcini, M. G. Pullia, and A. Mereghetti, Carbon ion gantry layout and optics solutions, Technical Report No. NIMMS Note–2022-007, CERN, 2022.
 - [9] S. Savazzi, L. Piacentini, E. Felcini, R. Filippini, L. Dassa, M. Pivi, and M. G. Pullia, Gantry design, Technical/Deliverable Report No. M7.2, HITRIplus, 2024.
 - [10] A. Ferrari, P. R. Sala, A. Fassò, and J. Ranft, *FLUKA: A Multi-particle Transport Code (Program Version 2005)*, CERN Yellow Reports: Monographs (CERN, Geneva, 2005), [10.5170/CERN-2005-010](https://arxiv.org/abs/10.5170/CERN-2005-010).
 - [11] FLUKA Collaboration, The FLUKA code: Overview and new developments, *EPJ Nucl. Sci. Technol.* **10**, 16 (2024).
 - [12] Hadrontherapy centers are equipped with monitors for radiation protection purposes, designed to monitor loss intensities via induced radioactivity, therefore do not have temporal or spatial resolution sufficient for energy deposition studies.
 - [13] A. Ciccotelli, R. B. Appleby, F. Cerutti, K. Buffet, F. Butin, G. Corti, L. S. Esposito, R. Garcia Alia, M. Karacson, G. Lerner, M. Wehrle, and D. Prelipcean, Energy deposition studies for the Upgrade II of LHCb at the CERN Large

- Hadron Collider, *Phys. Rev. Accel. Beams* **27**, 061003 (2024).
- [14] N. Fuster-Martínez, R. Bruce, F. Cerutti, R. De Maria, P. D. Hermes, A. Lechner, A. Mereghetti, J. Molson, S. Redaelli, E. Skordis, A. Abramov, and L. Nevay, Simulations of heavy-ion halo collimation at the CERN Large Hadron Collider: Benchmark with measurements and cleaning performance evaluation, *Phys. Rev. Accel. Beams* **23**, 111002 (2020).
- [15] N. V. Mokhov, I. L. Rakhno, I. S. Tropin, F. Cerutti, L. S. Esposito, and A. Lechner, Energy deposition studies for the high-luminosity Large Hadron Collider inner triplet magnets, *Phys. Rev. ST Accel. Beams* **18**, 051001 (2015).
- [16] E. Felcini, P. Schwarz, and M. Pullia, Magnetic design of downstream scanning magnets for a novel hadrontherapy gantry, *Phys. Rev. Accel. Beams* **28**, 032401 (2025).
- [17] M. Prioli, E. Bianchi, A. G. Calroni, R. Cereseto, S. Farinon, A. Gagno, F. Levi, S. Mariotto, A. Pampaloni, L. Rossi, C. Santini, R. U. Valente, E. Felcini, G. Frisella, A. Mereghetti, S. Savazzi, M. G. Pullia, E. O. Kavoura, I. Georgiadis, and C. Kokkinos, Conceptual design report of the superconducting ion gantry (SIG) dipole demonstrator magnet, Technical Report No. INFN-24-02-MI, INFN, 2024, [10.15161/oar.it/211921](https://oar.it/211921).
- [18] INFN LASA website, <https://homelasa.mi.infn.it/>.
- [19] E. De Matteis, A. Ballarino, D. Barna, A. Carloni, A. Echeandia, G. Kirby, T. Lecrevisse, J. Lucas, S. Mariotto, J. van Nugteren, M. Prioli, L. Rossi, C. Senatore, M. Sorbi, S. Sorti, M. Statera, F. Toral, and R. U. Valente, Conceptual design of an HTS canted cosine theta dipole magnet for research and hadron therapy accelerators, *IEEE Trans. Appl. Supercond.* **34**, 4402505 (2024).
- [20] D. Fazioli, Analisi di stabilità termica di un magnete superconduttore per adroterapia, Master's thesis, Università di Bologna, 2021–2022.
- [21] E. Felcini (Private communication).
- [22] L. Badano, M. Benedikt, P. J. Bryant, M. Crescenti, P. Holy, A. T. Maier, M. Pullia, S. Rossi, and P. Knaus (CERN-TERA Foundation-MedAustron Oncology-2000 Collaboration), Proton-ion medical machine study (PIMMS), 1, Report No. CERN-PS-99-010-DI, CERN, 2000, <https://cds.cern.ch/record/2858081>.
- [23] Python documentation website, <https://docs.python.org/3/>.
- [24] Repository of the pyFLUKAgeo, <https://github.com/CNAO/pyFLUKAgeo/>.