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# Electromagnetic Design of the Superconducting Magnet for a Compact Heavy-Ion Synchrotron


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## Introduction

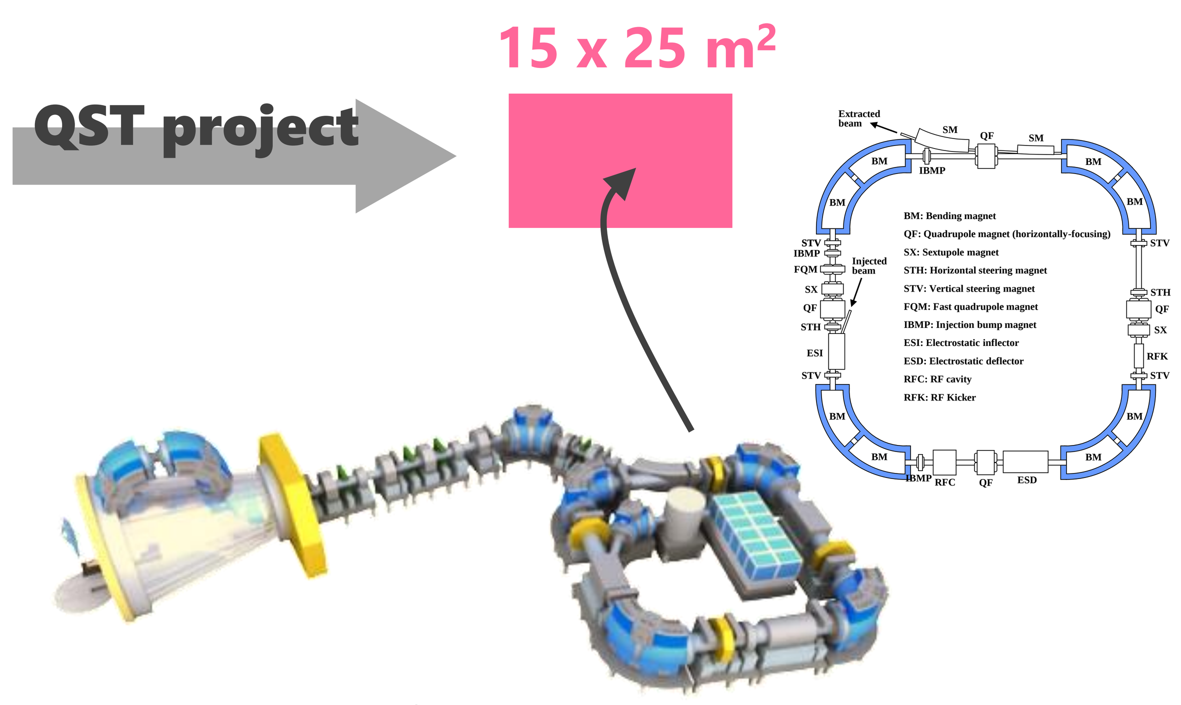
‣ Heavy-ion radiation therapy (HIRT) have advantages of a more localized dose delivery and a higher biological effect, compared to conventional X-ray therapy; however, the number of newly-constructed HIRT facilities was only three for the last three years (2018-2020).
→ One of the reasons is a huge introduction cost due to the large apparatus and building.

‣ National Institutes for Quantum Science and Technology (QST) has initiated a project to develop a compact and affordable HIRT system named "Quantum Scalpel".

Comventional HIRT system

**50 x 50 m²**

(footprint)



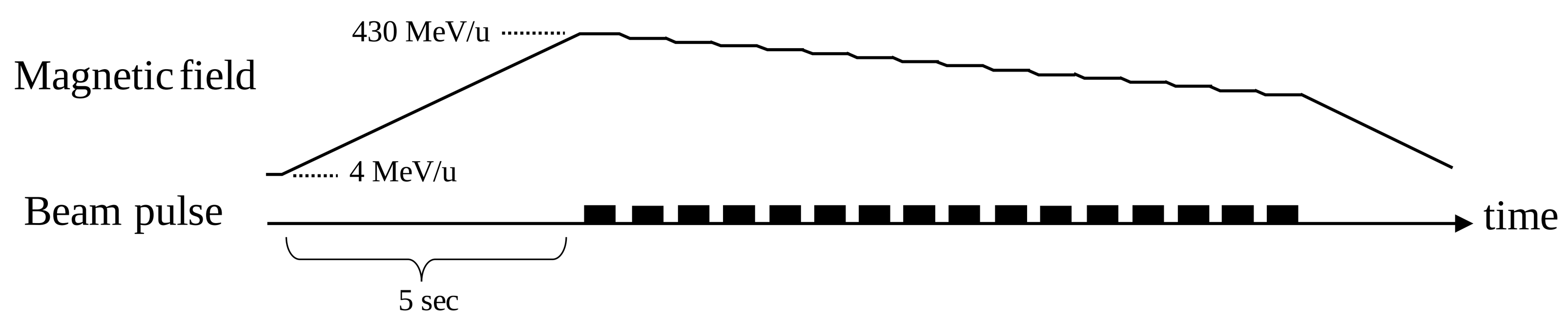

**New generation HIRT system**

‣ In this presentation, a concept design of the superconducting magnet applied for the compact HIRT synchrotron is reported.

‣ Main features of the synchrotron are
- circumference: about 29 m
- four 90-degree sectors; consists of two 45-degree bending equipped with curved dipole and quadrupole coils
- injecting 4 MeV/u ion beam
- accelerating until 430 MeV/u in 5 sec duration
- extracting while gradually decelerating

| Specifications of the superconducting magnet | |
|---|---|
| Central field | 0.3–3.5 T |
| Central field gradient | 0.1–1.5 T/m |
| Ramp rate | 0.64 T/s |
| Operation temperature | 4.2 K |
| Magnetic length | 1.49 m |
| Curvature radius | 1.89 m |
| Field quality | $2.5\times10^{-4}$ (injection)<br>$3.5\times10^{-4}$ (top energy) |
| Field gradient quality | $1.0\times10^{-3}$ |

### Operation patter of synchrotron




## Design of the superconducting magnet

### – 2D coil design –

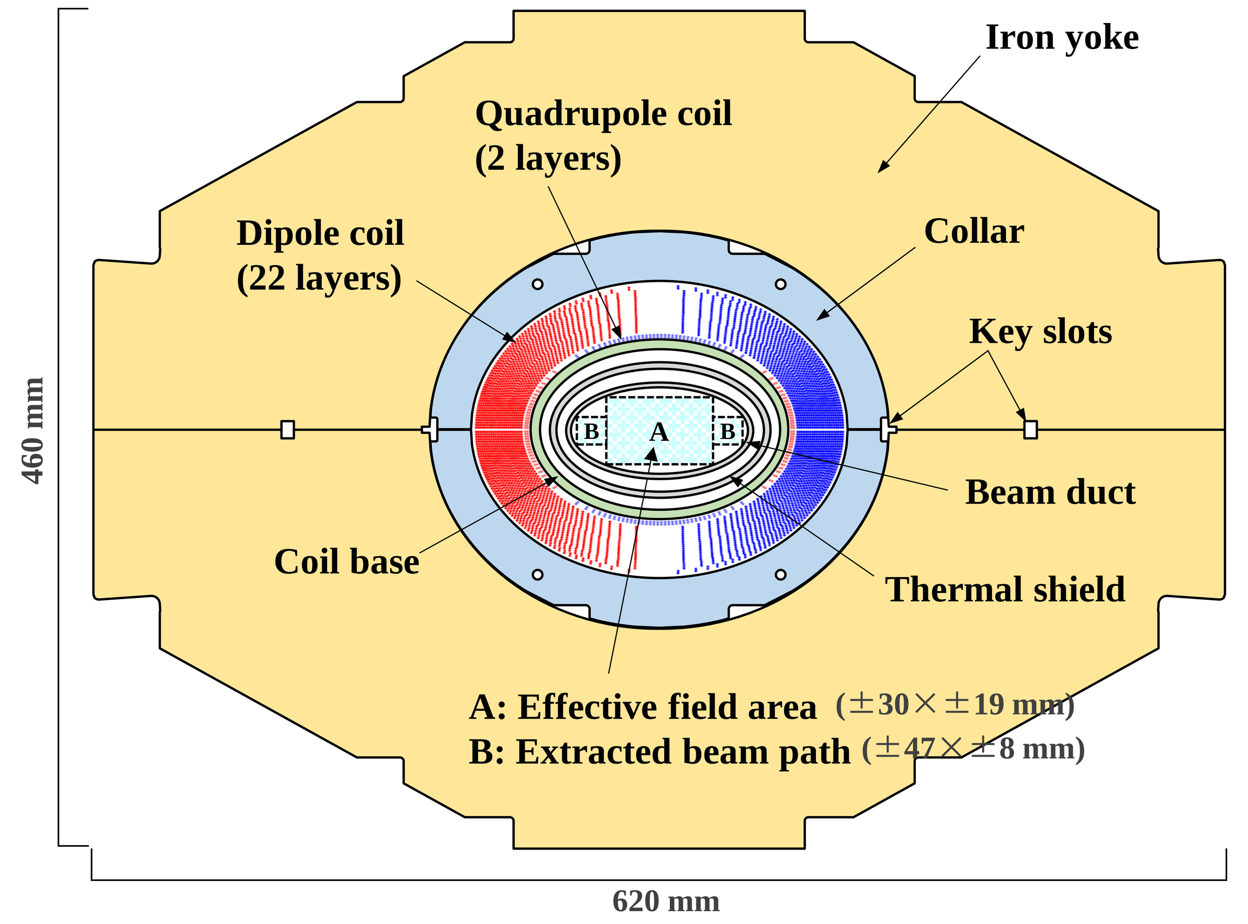
‣ Curved coils are wound on a FRP mandrel with the 1 mm diameter NbTi wires.

| Main features of the superconducting wire | |
|---|---|
| Diameter | $\phi$1.1 mm (with insulation) |
| Cu:CuNi:NbTi | 1.43:1.40:1.00 |
| Filament diameter | 2.4 μm |
| Number of filaments | 33600 |
| Twist pitch | 10 mm |
| Critical current | 492 A (5 T, 4.2 K)<br>399 A (6 T, 4.2 K)<br>305 A (7 T, 4.2 K) |
| RRR | 166 (0 T), 82 (2 T), 63 (3 T) |

‣ Inner shape of the coil was determined to the ellipse with 144 mm (hori.) and 100 mm (vert.) considering the space for the thermal shield, the thickness of the beam duct and mandrel.
‣ Inner radius of the iron yoke was set to 125 mm (hori.) and 109 mm (vert.) for the field quality in the applied field range.

| Coil parameters of the superconducting magnet | | |
|---|---|---|
| Item | Dipole | Quadrupole |
| Number of turns/pole | 1070 | 36 |
| Number of layers | 22 | 2 |
| Nominal current | 265 A (3.5 T) | 123 A (1.5 T/m) |
| Self-inductance | 5.51 H | 8.39 mH |
| Stored energy | 193 kJ | 0.06 kJ |

### Cross section of the superconducting magnet




### – 3D design –

‣ Calculation in three-dimension is carried out by using OPERA-3D code with the consideration of the nonlinearity of permeability.
‣ Multipole filed components generated due to the curved shape of the magnet were compensated by the wire displacements on each outer 2-layers of the dipole and quadrupole coils.

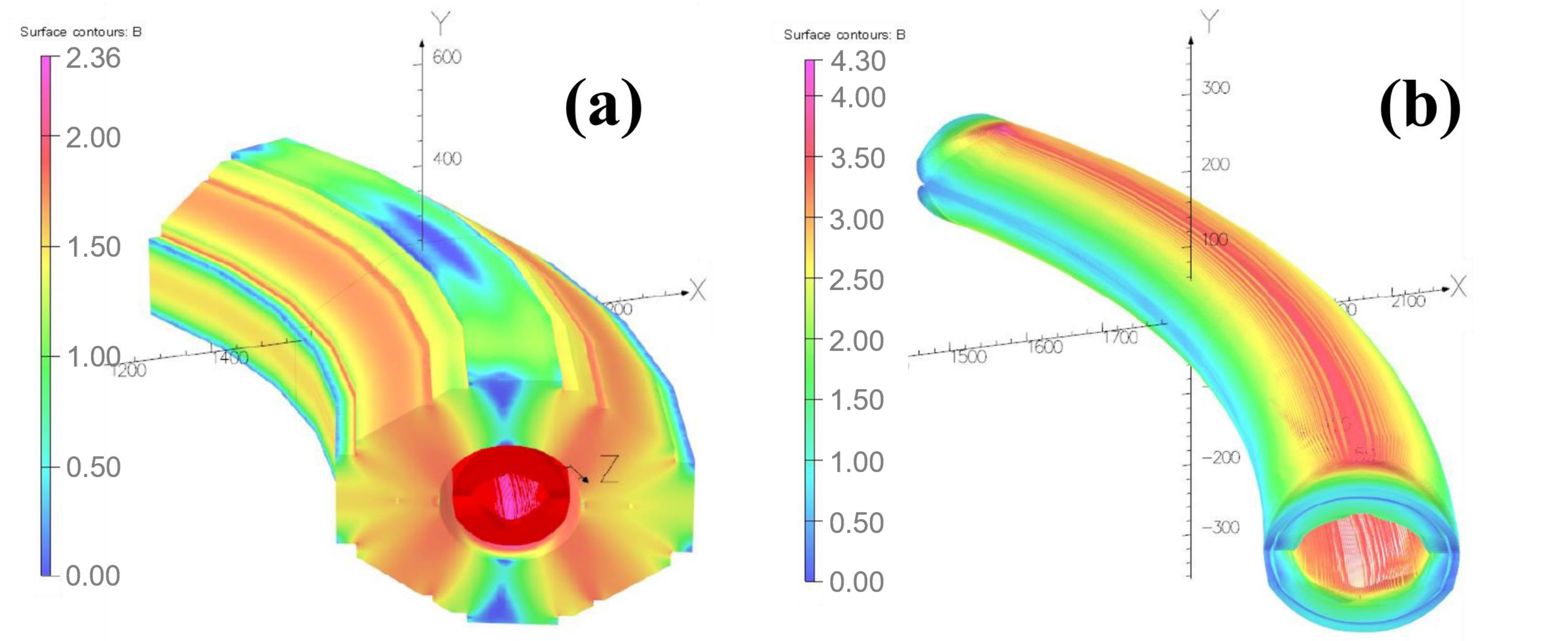
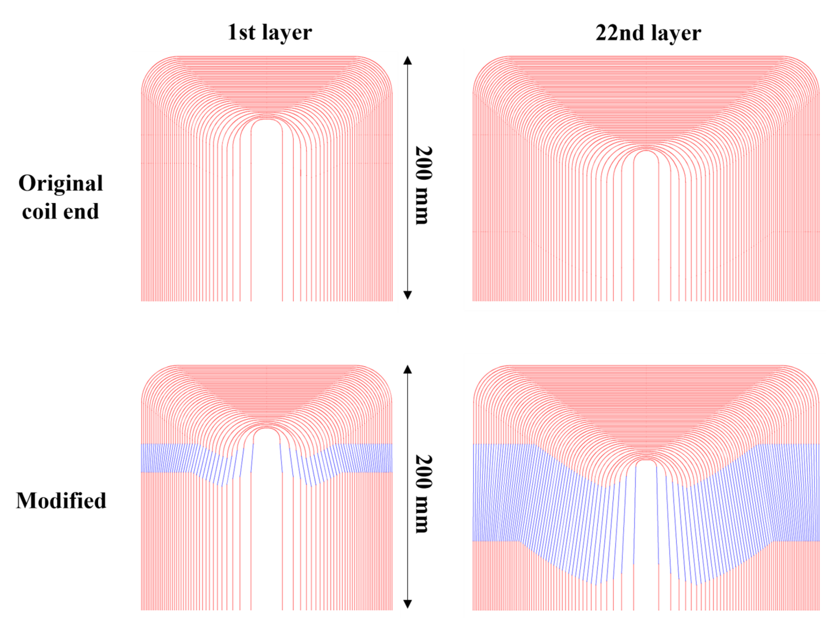



Fig. 3D images of the magnetic-flux densities of the (a) iron yoke and (b) coil at the central field and gradient of 3.5 T and 1.5 T/m.

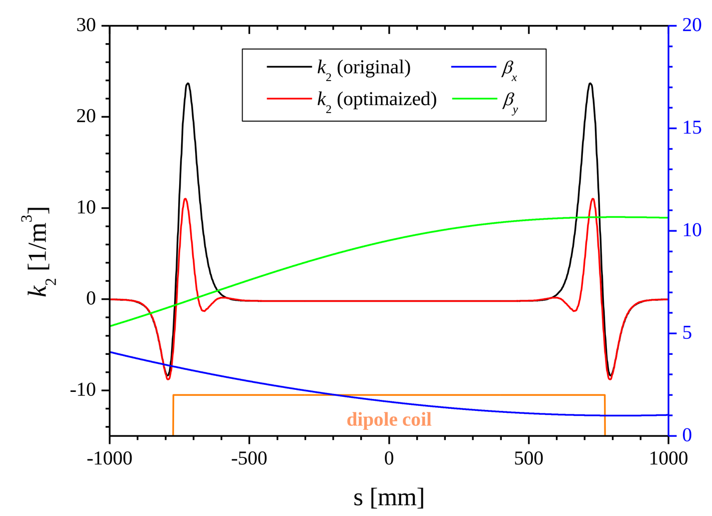
‣ Maximum field in the superconducting wires is 4.3 T, which corresponds to the operation point of 71% on the load line.
‣ Relative field errors were evaluated at the reference radius of 30 mm, and it was verified that the field and gradient qualities meet the synchrotron requirements.

| Relative field errors at the reference radius | | | | | |
|---|---|---|---|---|---|
| $B_1$ | 0.30 | 1.50 | 2.50 | 3.50 | [T] |
| $B_3 / B_1$ | −1.07 | −1.51 | −1.27 | 3.35 | [$10^{-4}$] |
| $B_5 / B_1$ | −0.08 | −0.04 | −0.05 | −0.16 | [$10^{-4}$] |
| $B_7 / B_1$ | −0.01 | −0.01 | −0.01 | −0.01 | [$10^{-4}$] |
| $B_9 / B_1$ | 0.01 | 0.01 | 0.02 | 0.02 | [$10^{-4}$] |
| $B_2 / R_{ref}$ | 0.13 | 0.64 | 1.07 | 1.5 | [T/m] |
| $B_4 / B_2$ | −3.61 | −3.02 | −1.44 | 1.68 | [$10^{-4}$] |
| $B_6 / B_2$ | 2.14 | 1.98 | 1.97 | 2.25 | [$10^{-4}$] |
| $B_8 / B_2$ | −0.04 | 0.00 | 0.01 | 0.02 | [$10^{-4}$] |
| $B_{10} / B_2$ | −0.40 | −0.40 | −0.40 | −0.40 | [$10^{-4}$] |

### Dipole coil-end design




‣ Winding pattern of the dipole coil-ends was optimized to prevent the linear coupling resonance from being excited.
‣ Integrated sextupole considering the beta function could be reduced to less than 0.1% of the original.




## Summary

‣ Design study of the superconducting magnet was carried out for the heavy-ion therapy synchrotron. The
‣ Bending magnet with 3.5 T central field and 1.5 T/m field gradient has been designed while achieving the required quality.
‣ Although contributions of the persistent, coupling and eddy currents have not been treated in this study, they will be verified in the next design step.