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Design study of an ultra-compact superconducting cyclotron for isotope production

V. Smirnov [a,*], S. Vorozhtsov [a], J. Vincent [b]

[a] Joint Institute for Nuclear Research, Dubna, Russia
[b] Ionetix Corporation, Lansing, MI 48911, USA

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ABSTRACT

A 12.5 MeV, 25 μA, proton compact superconducting cyclotron for medical isotope production has been designed and is currently in fabrication. The machine is initially aimed at producing ^{13}N ammonia for Positron Emission Tomography (PET) cardiology applications. With an ultra-compact size and cost-effective price point, this system will offer clinicians unprecedented access to the preferred radio-pharmaceutical isotope for cardiac PET imaging. A systems approach that carefully balanced the subsystem requirements coupled to precise beam dynamics calculations was followed. The system is designed to irradiate a liquid target internal to the cyclotron and to minimize the need for radiation shielding. The main parameters of the cyclotron, its design, and principal steps of the development work are presented here.

1. Introduction

A 12.5 MeV, 25 μA, proton compact superconducting cyclotron for medical isotope production has been designed and is currently in fabrication. The machine is initially aimed at producing ^{13}N ammonia for myocardial perfusion positron emission tomography (PET) studies applied to the detection of coronary artery disease. The "ION-12SC" [1] cyclotron features a cryogen free magnet small enough to operate within a standard medical space similar to that utilized by a typical PET scanner. ^{13}N ammonia is produced in a liquid target internal to the cyclotron. Usability, reliability and compact size with a cost-effective price are the key requirements of the design.

To allow for efficient mass production, installation and operation by a trained non-technical staff, the cyclotron design and operation must be kept simple. To provide for high reliability and operating efficiency, the requirements for each subsystem must be kept modest and well within physical limits. The machine design philosophy has to be one of robustness optimizing low sensitivity to perturbations versus high performance. The basic design arrived at achieved the following key points.

- To keep the machine size small and simple, a compact cryogen-free superconducting magnet featuring a patented cold steel design was applied such that the magnetic yoke is in thermal contact with the superconducting coils [2].
- The final energy radius of 115 mm was arrived at as a qualitative compromise between machine size and required peak RF voltages.
- The RF system consists of a simple conventional ~175° dee operating in the 1st harmonic mode and applying a peak voltage of ≤20 kV.
- The ion source consists of a cold cathode PIG source that is positioned to center the starting beam.
- Beam quality such as brightness and timing is not an issue for this application.
- No extraction system is needed since an internal target will be used. Some turn separation is needed to minimise losses on the target window frame.

The conceptual design is shown in Fig. 1.

State of the art detailed 3D calculations were performed. The electromagnetic fields of the structural elements were calculated using the Tosca\Opera3D program [3]. The SNOP program [4] was used to determine particle tracing in the in full 3D fields of the magnet and RF system. The main parameters of the cyclotron are listed in Table 1.

2. Magnetic system

The magnet design must set the average field profile to maintain isochronism and provide the required flutter to maintain

* Corresponding author. Tel.: +74962162160; fax: +74962166666.
E-mail address: vsmirnov@jinr.ru (V. Smirnov).

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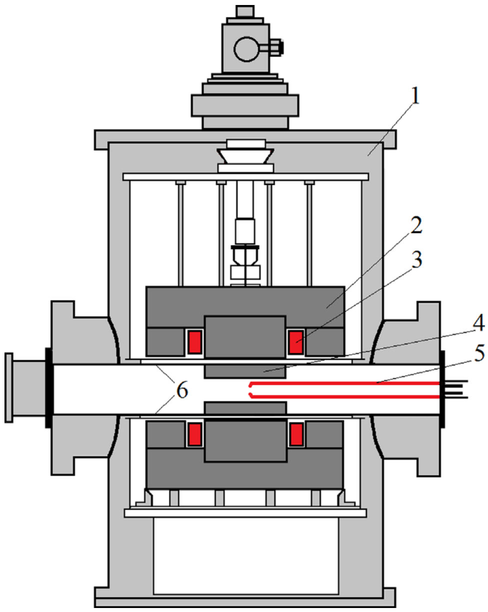

Fig. 1. Schematic presentation of the magnet structure (not to scale): 1—outer cryostat, 2—yoke, 3—superconducting coil, 4—warm spiral poles, 5—dee, 6—warm bore.

Table 1
Main cyclotron parameters.

Parameter	Value
Cyclotron type	Compact, Isochronous
Accelerated particle	Proton
Injection type	Internal PIG source
Central magnetic field	4.5 T
RF system	Single 175° dee
Operation RF harmonic	1
RF frequency	68 MHz
Peak dee voltage	$\leq$20 kV
Final energy	12.5 MeV
Beam intensity	$>$25 μA
Final radius	115 mm
Cyclotron diameter	870 mm
Cyclotron height	1253 mm
Cyclotron weight	1570 kg
Magnet (iron+coils) weight	900 kg

focus. The design requirements resulted in the following criteria and conditions.

- A warm bore through the magnet provides the mounting surfaces for the warm iron sectored poles and must maintain a minimum 30 mm vertical gap to accommodate the ion source, RF resonator, internal target, and other equipment as is needed (see Fig. 1).
- There must be a minimum of 17 mm thermodynamic barrier between the outer surfaces of the warm bore and sectored poles to the cold steel.
- The cold steel yoke is to be manufactured of AISI 1008 steel.
- The SC coils are wet wound with Ecobond 24 resin using Supercon NbTi 54S43 1 mm insulated diameter wire.
- The coil current density is limited to 150 A/mm^2 to reduce the forces and coil fields to conservative values for the wire specified.
- A 1.5 W cryocooler is used to bring the coil temperatures below 4.5 K through proprietary linkages.
- The vertical coil forces are consistently directed away from the median plane into and supported by the surrounding magnet yoke and vary from a high value of ~140 kN during the ramp to the operating value of 20 kN.
- The force on the warm iron poles is ~20 kN directed away from the cyclotron median plane.

The *B–H* curve of the magnet yoke was modeled as steel-08 produced by the Izhora factory in St. Petersburg, Russia. The *B–H* curve for this steel was measured by CERN in Switzerland up to 1.96 T for the CMS experiment (LHC, CERN) [5]. This curve was reasonably

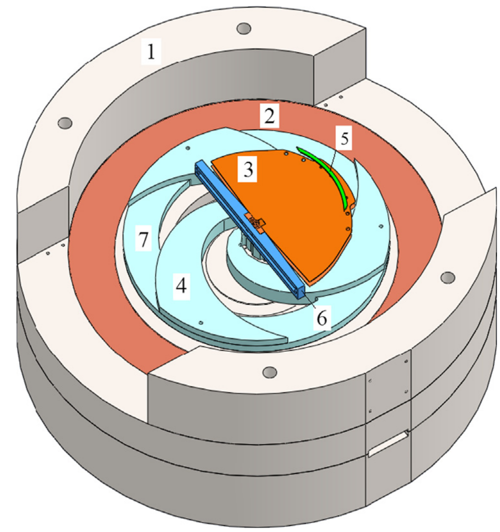

Fig. 2. Cyclotron mechanical model: 1—yoke, 2—superconducting coil, 3—dee, 4—spiral shim, 5–1st harmonic shim, 6—dummy dee, 7—valley shim.

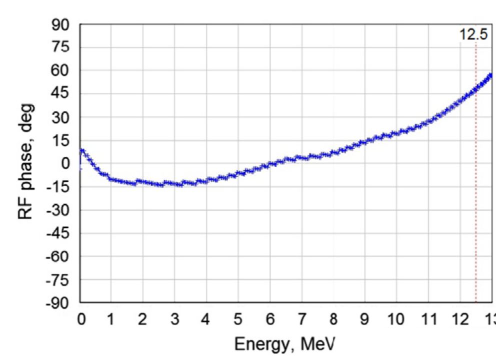

Fig. 3. Beam RF phase excursion.

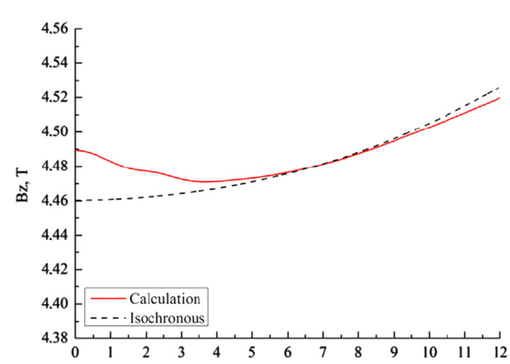

Fig. 4. Mean magnetic field vs. radius.