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RF SYSTEM FOR "TARN II"

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Abstract

An rf acceleration system for the INS heavy-ion synchrotron proposal is being developed. The rf characteristics of full-size ferrite toroids have been measured in a test cavity to study tunable frequencies of an rf cavity. It is estimated from the measurement on the ferrite material TDK SY-6 that a single-gap rf cavity based upon two ferrite-loaded quarter-wave coaxial resonators with four turns each of main and supplementary bias windings will give frequencies of 0.71-7.02 MHz for adiabatic capture and of 0.86-8.00 MHz for synchronous capture. RF acceleration parameters and design features of the rf cavity are presented.

RF acceleration parameters

A heavy-ion synchrotron at INS, TARN II [1], is planned to accumulate and accelerate ions from the INS SF cyclotron [2] and from a heavy-ion linac. A wide range in tunable frequencies of the TARN II rf cavity is required because various kinds of ions are injected at low energies from the two kinds of injectors.

The lowest injection energy is desired to be about 3 MeV/u to save a construction cost of the linac. The highest acceleration energy has been fixed at 1.3 GeV for protons. Because an average radius of the ring has been designed at 12.4 m and the rf cavity has been chosen to operate in the harmonic number of 2, the tunable frequencies of 0.61-7.02 MHz (the factor of 11.6) are desired in the case of adiabatic capture of ions with the energy of 3 MeV/u.

Synchronous capture of ions from the SF cyclotron will be made at frequencies of 7.32-8.00 MHz; the frequency of 7.32 MHz is the lowest of rf acceleration frequencies of the SF cyclotron. Adiabatic capture is further made in the harmonic number of 2 after completion of the synchronous capture. Because the average radius of the TARN II ring is 17 times as large as the extraction radius of the SF cyclotron, the tunable frequencies of 0.86-8.00 MHz (the factor of 9.3) are desired in the case of the synchronous capture.

The maximum rf voltage of the rf cavity is estimated to be 6 kV on condition that $^{40}Ar^{14+}$ beam is injected at the energy of 3 MeV/u with the momentum spread of +- 0.4 % and is accelerated in the repetition frequency of 0.5 Hz.

If incremental permeability of a ferrite can be varied by a factor larger than 220, the whole range of frequencies of 0.61-8.00 MHz (the factor of 13.2) will be achieved by a single rf cavity. However, it is known from the measurement on the ferrite material TDK SY-6 described later that the permeability is variable by the factor of 150; so that frequencies of the rf cavity are estimated to be tunable by the factor of 11.0.

Final rf acceleration parameters should be decided by actual rf characteristics of the rf cavity under construction. For the present, we propose from the measurement on the ferrite that the adiabatic capture and the synchronous capture are performed in different frequency range: we will properly change components of the rf cavity to adjust tunable frequencies. The proposed frequency range is 0.71-7.02 MHz for the adiabatic capture and 0.86-8.00 MHz for the synchronous capture. In the case of the adiabatic capture, therefore, the lowest injection energy will be raised up to 3.5 MeV/u instead of 3 MeV/u.

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Ferrite choice and measurement

Candidates for ferrite materials with high remanent permeability commercially available for the requirements for the TARN II rf cavity seem to be the ferrite materials TDK SY-6 and TDK SY-7. The remanent permeability of SY-6 is smaller than that of SY-7, but the rf loss of the former is lower than that of the latter. Curie temperature of ferrites with high remanent permeability is considerably low: for example, it is 90° C of SY-6. Moreover, the permeability varies with working temperature. We prefer the TDK SY-6 because of its low rf loss to avoid a change of the permeability due to temperature rise by the rf loss.

A ferrite test-cavity based upon a ferrite-loaded half-wave coaxial resonator is used for measurement on rf characteristics of a pair of full-size ferrite toroids with the outer diameter of 500 mm, the inner diameter of 320 mm and the thickness of 25 mm. The rf characteristics such as permeability and an rf loss are measured as a function of the dc bias field. The measurement has been done at low rf fields. The test cavity was useful at frequencies below 5 MHz when the fundamental resonance at the remanent state was tuned at 0.5 MHz. The rf characteristics of the ferrite necessary for the rf cavity design have been based upon data from both of the full-size toroids and the small-size toroids.

A value of the remanent permeability is based upon the full-size toroids. Three kinds of full-size toroids which were sintered at different conditions by the supplier were tested. The average remanent permeability of them is about 950. A value of the permeability at high bias fields is based upon the small-size toroids; it is 6 at the bias field of 2 kA/m.

The incremental permeability is considered to be variable by the factor of 150 for the rf cavity design. The previous design of the rf cavity [3] was based upon the factor of 230; it was obtained from the remanent permeability of 1400 of small-size toroids which were made on an experimental basis by the supplier before.

A value of μQf product is obtained from the measured rf loss. The product of the small-size toroids varies in the range of $(1.5\text{-}4.0)\times10^9$ depending on operation frequencies. The product at the remanent state of full-size toroids measured by the test cavity is slightly smaller than that of the small-size toroids.

A bias response of the ferrite has been measured by a lumped circuit instead of the test cavity. A true bias response of the ferrite itself is not measured by the test cavity because it has a closed loop which is formed by connection of inner and outer conductors due to the half-wave resonator. The measured value of the bias response of the full-size toroids at the remanent state is less than 0.2 msec, which is comparable with that of the small-size toroids.

RF cavity

Ferrite materials capable of widely variable permeability required for an rf cavity of a heavy-ion synchrotron have a high rf loss; so that a load impedance of a final rf power amplifier is low. One of great difficulties on the rf cavity of the heavy-ion synchrotron is considered that the load impedance is too low to match an internal resistance of a final power tube.

A value of the load impedance depends on an arrangement of the rf cavity: two single-gap rf cavities in series or a single-gap rf cavity. The single-gap rf cavity is capable of a high load impedance compared with the two single-gap rf cavities in series. Therefore, we prefer the single-gap rf cavity although bias windings separated from inner and outer conductors make a structure of the rf cavity complicated and make a bias current response slow.

The TARN II single-gap rf cavity consists of two ferrite-loaded quarter-wave coaxial resonators. The two resonators are excited in push-pull mode with four "figure of eight" bias windings. Figure 1 shows the rf cavity under construction and Table 1 shows a summary of the rf cavity.

An inner diameter of the toroid is fixed by spaces associated with a beam aperture of 200 mm: the spaces for beam pipes, heater and heat insulator for vacuum baking, high voltage isolation and bus bars for bias windings. An outer diameter and a thickness are fixed mainly by manufacturing condition of it.

The product of an induced rf magnetic field in ferrites and a frequency, $B_{rf}f$, is in proportion to an rf voltage of the rf cavity. When the product exceeds a certain threshold, an instability known as the Q-loss effect [4] occurs. We have assumed that the product should be less than 10 mT·MHz. This condition leads to the use of 24 toroids for each quarter-wave resonator with some margins because of the maximum rf voltage of 6 kV.

The rf loss in the ferrite toroids is evaluated to be 20 kW at the frequency of 8 MHz and the rf voltage of 6 kV. The temperature rise due to the rf loss should be depressed with water-cooling copper plates inserted between adjacent toroids. The temperature rise is estimated to be lower than 10° C by the total water-flow of 60 l/min through all the cooling plates.

Table 1. Summary of the TARN II rf cavity

Frequency range	0.71 - 7.02 MHz for adiabatic capture
	0.86 - 8.00 MHz for synchronous capture
Harmonic number	2
Peak rf voltage	6 kV maximum
Cavity length	2.55 m
Beam aperture	200 mm in diameter
Resonance mode	push-pull mode of two ferrite-loaded quarter-wave coaxial resonators
Ferrite material	TDK SY-6
Permeability	950 at remanent state
	6 at dc bias field of 2 kA/m
μQf product	1.5×10^9 at 8 MHz
Bias response	faster than 0.2 msec
Curie temperature	90° C
Toroid dimensions	500 x 320 x 25 mm^3
Number of toroids	24 x 2
$B_{rf}f$ product	10 mT·MHz at rf voltage of 6 kV
Total rf loss	20 kW at 8 MHz and 6 kV
RF loss density	160 mW/cm^3 at 8 MHz and 6 kV
Shunt impedance	480 ohms/resonator at 8 MHz
Bias windings	Main and supplementary windings with four turns each in symmetric "figure of eight" configuration
Main bias current	1000 A maximum
Suppl. bias current	100 A opposite to main current
No. of cooling plates	25 x 2
Total water flow	60 l/min
Temperature rise	lower than 10° C
Baking temperature	350° C

We have equipped with two kinds of bias windings in parallel: main and supplementary windings. Full use of the whole range in the variable permeability of the TDK SY-6 is desired for tunable frequencies as wide as possible. The permeability changes largely at low bias fields, but a setting precision of a dc power supply is poor at a low dc current. If a single dc power supply is used for a bias current, it is difficult to control low frequencies precisely. The supplementary windings are excited by a constant but reverse dc current opposite to the main current to improve this. The sum of the two currents gives the net bias current. Because the main current can start from a non-zero value which is well stabilized, the fine control of low frequencies is expected.

In the design of the rf cavity, the following subjects [5,6] have been carefully taken into account.

1. The bias windings are wound in a symmetric "figure of eight" configuration [7]. This configuration gives a wide space at the acceleration gap.
2. Wide bus bars for the main windings are used to decrease their own self-inductance. The supplementary windings are connected to the main ones by large capacitances of bypass capacitors.
3. Capacitors adjusting frequencies of the fundamental resonance are connected in the bridge between acceleration electrodes. This arrangement does not change frequencies of spurious resonances which excite the two quarter-wave resonators in same phase.
4. The ferrite-loaded rf filters on input lines of the bias windings are equipped inside the rf cavity to decrease the rf voltage on them. The arrangement of the four bias windings are suitable for the filter installation.
5. The main windings are connected to each other at their ends by proper capacitors to raise frequencies of spurious resonances. Spaces for this purpose are prepared at both ends of the rf cavity.
6. A short rf feeder between final rf power amplifiers and the rf cavity is desired to decrease its self-inductance. A large hole at the mid-bottom of the rf cavity makes it possible; the wide space due to the symmetric "figure of eight" configuration of the bias windings is also helpful for this purpose.
7. Baking of the inner conductors for ultra-high vacuum will be made at the temperature of 350° C by mineral-insulated heaters. To avoid heating of the ferrite toroids, each inner conductor is fixed by five thin stainless-steel supports at its end and the heater is covered by heat insulators. Forced air cooling inside the rf cavity and the water cooling of the copper plates are also helpful for protection of the toroids against heating.

Construction of the TARN II rf cavity will be completed in a middle of this year. Construction of equippments such as final rf power amplifiers and low level rf system will be started after tests on the rf cavity at low rf level. Further studies on the proposed regulation and control system [8] is being continued.

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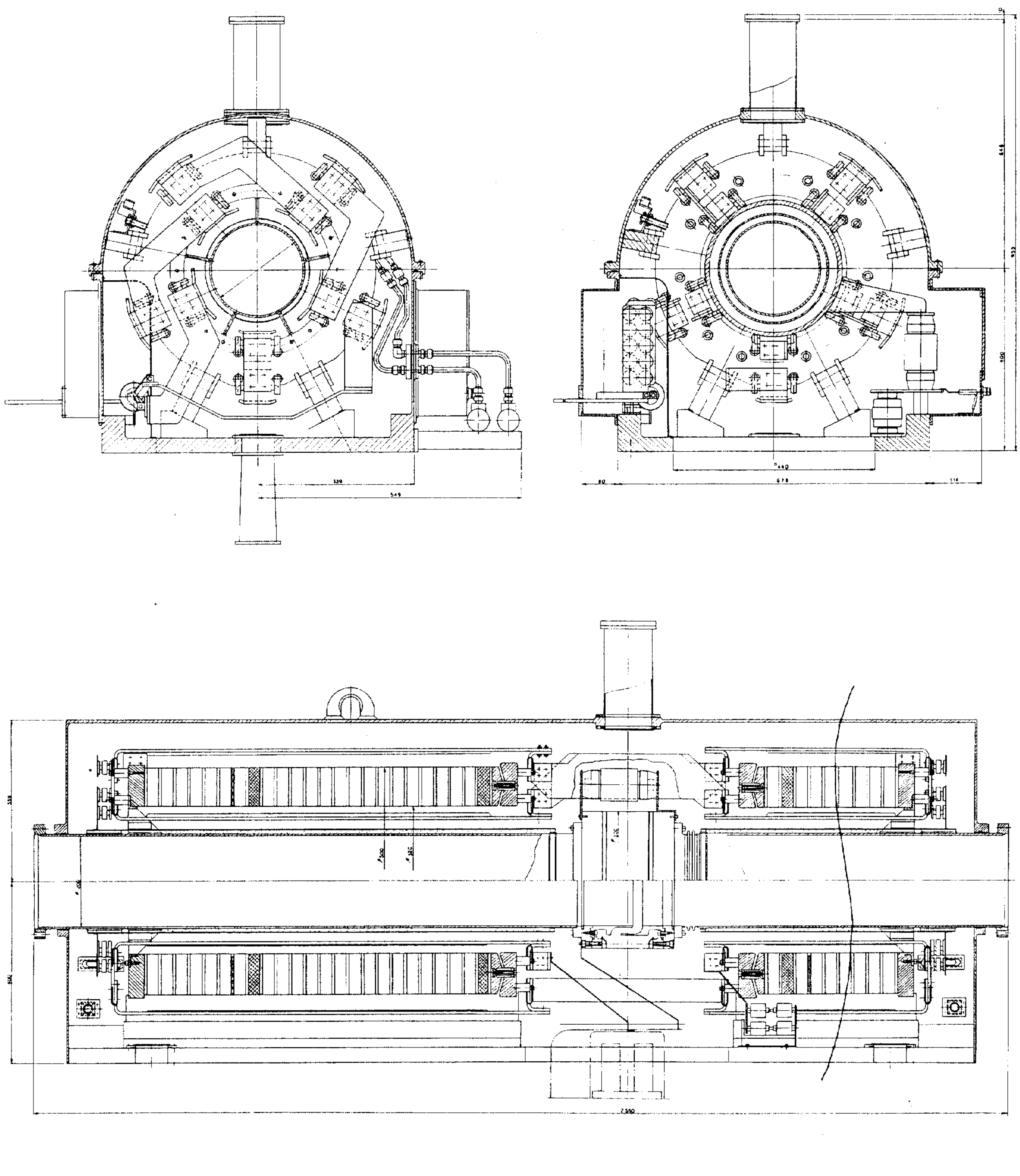

Fig. 1. Cross-section of the TARN II rf cavity