MAGNET SYSTEM FOR PET CYCLOTRON BASED ON PERMANENT MAGNETS

E. Antokhin, BINP, Novosibirsk, Russia
T. Fujisawa, M. Kumada, T. Matsumoto, S. Wakasa, NIRS, Chiba, Japan

Abstract

The number of positron emission tomography (PET) centers based on proton cyclotron is rapidly growing nowadays worldwide. It actually requests for simple, reliable and cheap proton cyclotron of energy 10-20 MeV to be designed for mass installations. Normally the magnet system for PET cyclotron is made with iron and copper coils. Although the some optimization of conventional warm" magnet is possible, the another approach could be the magnet system based on permanent magnet, aiming the cost saving due to no needs of electric power during cyclotron life time. The permanent magnet system for 10 MeV PET cyclotron was designed, manufactured and measured. The present paper describes the cyclotron permanent magnet system as well as beam trajectory analysis in measured magnetic fields and RF system design..

INTRODUCTON

It is well known the fact that cyclotrons for positron emission tomography (PET) are used in world wide and the method to build them is well established. Nevertheless, there is growing demand for increasing number of PET centers applying cyclotrons

So the task to minimize cost for manufacturing and operation of PET cyclotrons is still actual. The magnets of conventional PET cyclotron have been electromagnets. The one possible way to make such cyclotrons cheaper and the operation easier is to use a permanent magnet (PM) material as magnetic field source instead of cupper coils.

This approach should save electric power, but provides additional difficulties coming from using PM material. Because magnets made with PM material are not so widely used in accelerator technology ([1]-[4]) it is also worthwhile and interesting to see whether the magnet made of PM is applied to a cyclotron or the other accelerator. The present paper describes the design, manufacturing, and test of PM for PET cyclotron.

MAGNET SYSTEM

Requirements for PM cyclotron magnet

Demand to use PM material on a cyclotron magnet imposes many additional requirements compared with electromagnet both for magnetic and mechanical structures. Magnetic circuit applied to PM cyclotron magnet for PET should provide following:

- Compact magnet system, allowing to reach 10 MeV proton energy, that means optimal choice of average magnetic field and pole radius.
- Minimum use of PM material
- Enough big focusing by hill/valley sectors
- Conventional installation of simple RF system and vertical installation of ion source.

To minimize weight and size of magnet system the average magnetic field value has to be high, limited by iron saturation.

To satisfy condition 1) the average magnetic field value was chosen as 1.4 T provided of 2.3 T and 0.5 T of hill and valley region fields correspondently. Such big difference of hill and valley field values provides enough focusing for beam. The classical 4 sectors (45 degree) configuration of hill and valley regions was applied, that allows using typical RF system with its convenient installation.

As hill gap providing enough beam intensity was chosen as 20 mm and then corresponding valley gap is 100 mm. The parameters of cyclotron magnet are summarized in Table 1.

Magnetic design

From the general Maxwell equations one can easily derive as follows

$$B_g = \sqrt{(B_m \cdot \mu \cdot H_m) \cdot \frac{V_m}{V_g}} \quad (1)$$

where V_m and V_g are PM material volume and volume of working gap respectively, B_m and H_m are magnetic induction and field inside PM material, μ is permeability of the vacuum

As we see B_g depends on choice B_m and H_m (or working point of PM material), which are defined by dimensions (area and thickness) of PM volume. The product $(B_m \times H_m)$ has a maximum at $B_m = H_m = B_r/2$, where B_r is remanence field of PM.

Table 1: Parameters of PM cyclotron magnet.

Average field (T)	1.4
Hill/Valley field (T)	2.3/0.5
PM magnetization (T)	1.23
Hill/Valley gap (mm)	20/100
Sector angle (deg.)	45
Pole diameter (mm)	750
PM weight (kg)	900

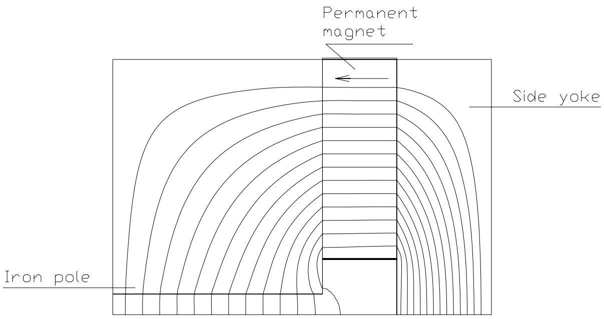

Figure 1: PM cyclotron magnet cross-section (1/4 part is shown)

Since $V_g \approx L_g \cdot \pi \cdot R^2$ for case of cyclotron magnet (where R is pole radius, L_g is gap hight) we can rewrite (1) for non relativistic particle as

$$(B_g \cdot R)^2 = (B_m \cdot \mu \cdot H_m) \cdot \frac{V_m}{L_g \cdot \pi} \propto energy\ \ of\ \ particle \qquad (2)$$

Note that required volume of PM material depends only on particle energy, magnet gap and PM working point and doesn't depend on pole radius or average magnetic field value. For given magnet gap required PM weight to achieve 10 MeV proton energy should be about 1 ton. In order to achieve big values of average and hill magnetic field (1.4 T and 2.3 T respectively) the magnetic circuit has to provide a concentration of magnetic flux from PM blocks for magnet working gap. The schematic drawing of used such magnetic structure is shown in figure 1, [5].

After the basic analytical estimations were done the 3D evaluation of design, taking into account the fragmentation for hill/valley poles and various fridge fields, was performed.

Pole radius finally was found out to be 375 mm as corresponding average magnetic field 1.4 T for 10 MeV proton energy.

Mechanical design

Mechanical design has to provide following functions for realization of PM cyclotron:

- Possibility of assembling/disassembling of accelerator, providing its commissioning and routine operation.
- Possibility of pole shape correction for isochronous regime.

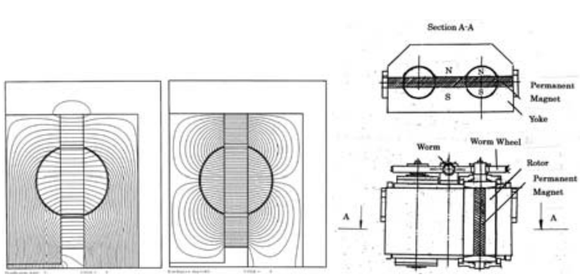

Figure 2: Principle of Flux Engine and its drawing.

The one possible way to satisfy these requirements is to make zero value magnetic field inside magnet gap of magnet with special device called "Flux Engine" (FE). The magnet applying FE consists of fixed part (stator) and moveable part (rotor), containing equal volumes of PM material. Rotation of rotor for 180 deg. allows canceling magnetic field inside working gap. The principle is illustrated in Fig. 2.

The resulting torque of FE was 1800 N-m. That value was determined from computer simulations and testing of especially designed 1/6 scale model of real FE. Rotational driving mechanism of the rotor is done through worm located between two worm wheels. A pair of worm wheels is rotated by another worm wheel implemented at the center (figure 2). Two rotors can be rotated for same amount of angle by a single motor.

Figure 3 presents the whole magnet system view.

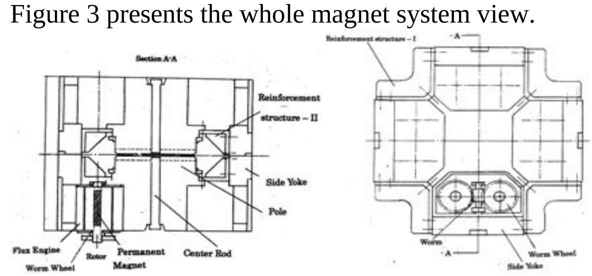

Figure 3: PM cyclotron magnet view.

AVERAGE FIELD MEASUREMENTS

Before starting the measurements possibility of full scale magnet disassembling and adjustment was checked by residual magnetic field measurement (at opposite rotor PM magnetization location). That residual field was found as 560 Gauss as maximum, allowing easy magnet disassembling/assembling.

After first trial magnetic field measurement (with flat magnet gap structure) disagreement with calculation was found as the calculation average field value is 5 % higher than measured one. The reason of that disagreement was not exactly determined, so to reach the designed average field value the valley gap height was reduced from 100 mm to 70 mm, allowing still standard RF cavity installation.

The maximum average field was measured then as 1.38 T, that corresponds the designed target value.

Average magnetic field distribution adjustment process is shown in figure 4 (last measurement is 5th step). Both cutting pole and shimming was applied to reach isochronous field. The resulting magnetic field strength is close to designed value and its shape is nearly isochronous as it follows from trajectory simulations.

The temperature coefficient of gap magnetic field was measured as about -0.07%/^{0}C. Such coefficient is acceptable for normal work of cyclotron.

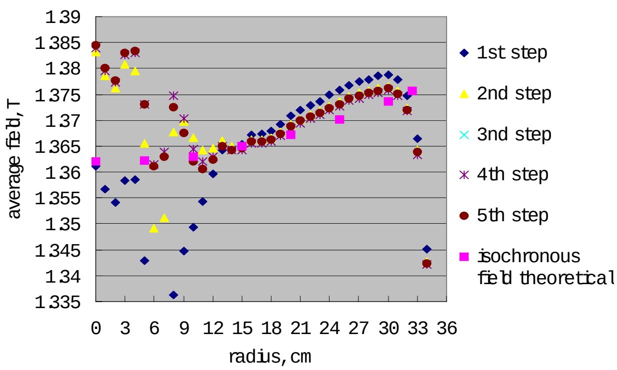

Figure 4: Series of average field measurements to reach isochronous field.

TRAJECTORY SIMULATION

The trajectory analysis was done for last field measurement for following conditions: RF frequency is 84.28 MHz, initial radius is 40 mm, initial energy is 130 keV, RF voltage is 30 kV. The result is presented in figure 5. The reached proton energy is 10.3 MeV.

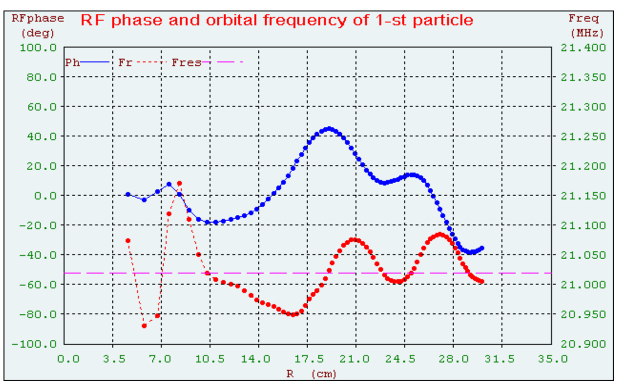

Figure 5: RF phase and orbital frequency.

Note that radial oscillations for this conditions and measured field is large enough as about 3 cm, that may lead to increasing axial oscillations through the nonlinear resonance Q_r-2·Q_z. The reason for increased radial oscillations is big first harmonic of magnetic field, which caused by non-symmetric structure of central part of cyclotron magnet following from necessity of ion source installation. The results for trajectory simulation for the same measured field, but with excluded from field map first harmonic, is shown in figure 6. The RF phase value is left practically the same as for previous case, but radial oscillations now does not exceed 3 mm and axial ones does not exceed 2 mm. Note that RF frequency corresponding that case is 84.316 MHz.

There can be two ways to reduce the influence of first harmonic of field, which are subject for further studing:

- to find more optimal initial conditions for starting acceleration, which provide isochronous phase acceleration with small radial oscillations.

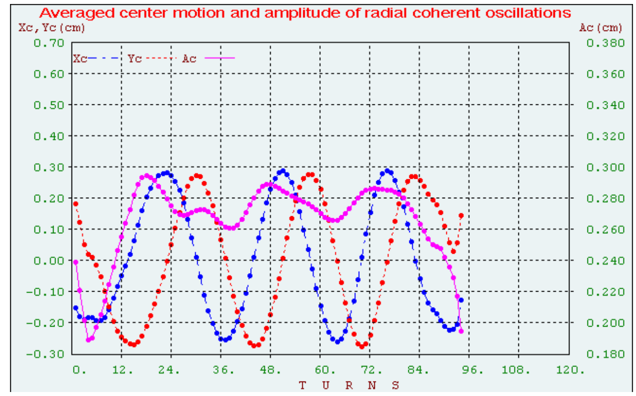

Figure 6: Radial oscillations and average center motion for measured field map without first harmonic.

- to make symmetric central magnet part by setup second hole on opposite side with respect to ion source hole.

CONCLUSION

A permanent cyclotron magnet of variable magnetic field from 2.3 Tesla peak field to practically zero field was designed and constructed for the first time. The using flux engine allows magnet disassembling and pole shape adjustment at switch off (zero) field mode. The reached average field distribution and proton energy correspond the designed value.

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