NEW BEAM LINES FOR THE PRODUCTION OF RADIOISOTOPES AT ITHEMBA LABS

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Abstract

At iThemba LABS (previously the National Accelerator Centre) proton beams, accelerated in a K=200 separated sector cyclotron with a K=8 solid-pole injector cyclotron, to an energy of 66 MeV, are utilized for the production of radionuclides and neutron therapy. Proton therapy is done at an energy of 200 MeV. Low intensity beams of light and heavy ions as well as polarized protons, pre-accelerated in a second injector cyclotron with a K-value of eleven, are available for nuclear physics research. New beam lines are being planned and are under construction to extend the facilities for the production of radioisotopes. The design and construction of these extensions are discussed.

INTRODUCTION

At iThemba LABS [1, 2] the cyclotrons are operated on a 24 hours per day and 7 days per week schedule. In spite of this it remains difficult to meet the beam time requirements of the different disciplines. The cyclotrons are therefore being upgraded [3] to increase the intensity of the 66 MeV proton beam for radioisotope production, which has up to now been done in only one beam line. A vertical beam line for this purpose is presently under construction and plans for beam splitting in the existing horizontal beam line are underway to irradiate more than one target at a time.

VERTICAL BEAM LINE FOR HIGH-INTENSITY BEAMS

Fig. 1 shows a three-dimensional assembly drawing of the vertical beam line. The beam is directed away from the horizontal line with a 90° bending magnet with zero degree entrance and exit angles, and passes through two quadrupole magnets and two H-type sweeper magnets, which sweep the beam in a circular pattern with a radius of 10 mm over the target at a rate of 3 kHz. The sweeper magnets are mounted with their pole gaps perpendicular to each other and are driven by two AC sources with 90° phase difference between them. Downstream from the sweeper magnets are a steering magnet and a diagnostic vacuum chamber, containing a harp, a phase probe for non-destructive beam current measurement and a Faraday cup. The beam diverges from the focal point in front of the bending magnet and is focused to a full width of 20 mm in both directions on the target, which has a diameter of 40 mm. In the quadrupoles the maximum beam width is 50 mm for the expected emittance of 25 π mm mrad and energy spread of 6.5×10^{-3}.

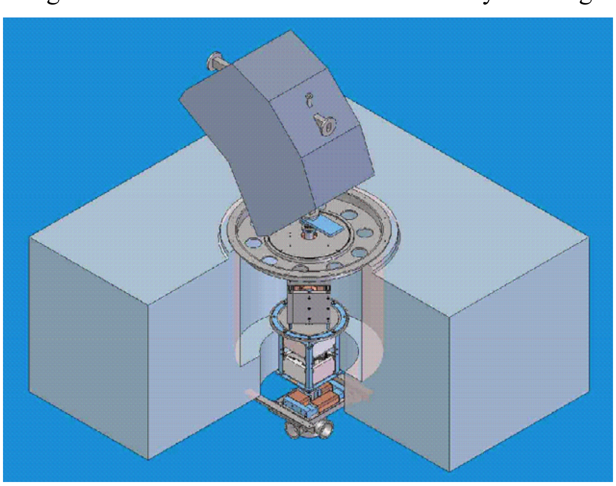

Figure 1: 3D drawing of the vertical beam line showing the bending magnet, two quadrupole magnets, two sweeper magnets, a steering magnet and the diagnostic chamber.

THE SWEEPER MAGNETS

The Yoke and Poles

The main parameters of the magnets are summarised in Table 1. Low-loss ferrite material was selected and acquired as four yoke and two pole pieces, per magnet, from Ceramic Magnetics Inc. [4]. Because of the large pole gap and the low flux density, magnet steel laminations would also have been suitable as far as the penetration depth is concerned [5], but the power loss would be too high for cooling of the yoke and pole pieces by convection of the ambient air only. The top and bottom pole pieces of each magnet were glued to the corresponding yoke pieces in order to assemble each magnet from only 4 separate pieces, by pressing them together in a stainless-steel frame with some insulating sections to prevent eddy currents, due to electromagnetic forces induced by the stray magnetic field, from flowing in the frame.

The gaps between yoke and pole pieces and also the shortest distance, of 15 mm, from a coil winding to magnetic material, are much larger than it would have been for a DC magnet, to limit the magnetic field strength in the windings and the consequent heating due to eddy currents.

The Coils

To limit the losses due to eddy currents, the coils have to be made from a conductor with a small diameter, since the power dissipation in a round conductor is proportional to the square of the radius as well as the cross-sectional area of the conductor [6]. A thin water-cooled conductor implies a high pressure drop per meter, and, for the fixed available water pressure of 1.3 MPa, several cooling loops (which could eventually become clogged or develop leaks) per coil. The magnets are furthermore situated in an inaccessible and highly radioactive area where it is difficult to perform maintenance work. It was therefore decided to use air-cooled coils.

Table 1: Parameters of the 3 kHz sweeper magnets

Ferrite material for yoke and poles	MN 60LL
Magnetic flux density in pole gap (T)	0.038
Magnet length (mm)	200
Effective length (mm)	276
Pole gap (mm)	102
Pole width (mm)	100
Pole length (mm)	103
Thickness of yoke pieces (mm)	35
Gap between pole and yoke (mm)	103
Power dissipation in poles and yoke (W)	~ 90
Number of windings per pole (9 layers)	135
Peak current (A)	12
Peak voltage per coil (kV)	5.8
Gap between coil layers (mm)	3
Gap between windings (mm)	1
Diameter of coil conductor, consisting of 10 twisted Ø 0.5 mm poly- urethane-insulated copper wires (Ø mm)	2
Effective resistance per coil (Ω)	2
Inductance of two coils in series (H)	0.051
Power dissipation in coils (W)	200

To limit the power dissipation in the air-cooled coil, the conductor has been made up from several thin insulated wires, twisted together with a pitch of 30 mm to prevent circular currents due to the time-varying magnetic field enclosed by the individual wires, which are connected at their end points, since for a fixed conductor cross-sectional area the power loss per meter is inversely proportional to the number of wires. Because of the skin effect the thin twisted wires also ensure a more homogeneous current distribution, but this is not a very important consideration in the present case. Apart from the large gaps between the coils and the ferrite material, the magnetic field in the conductor has been limited further by spacing the coil layers and windings sufficiently far apart, which is also a prerequisite to prevent sparking and to allow air flow for cooling of the windings. A further reason for proper spacing between adjacent turns and layers is to ensure that the resonance frequency of the coil with its stray capacitance is far above the operating frequency, since the aim is to resonate the coils with series capacitors to provide a load resistance suitable for a commercial audio amplifier, without using matching transformers between the magnets and amplifiers. The effective resistance of the coil near its resonance frequency is too high for this.

The coil formers are made from polypropylene with 2 mm wide and 10 mm long regularly spaced openings for forced airflow. Eight mm wide nylon strips, spaced at 30 mm intervals and fixed through holes in the coil frame, provide insulation between adjacent coil layers.

The Series Capacitors

Each coil is connected in series with a capacitor bank, with a capacitance of approximately 110 nF, consisting of a combination of series and parallel capacitors to obtain the required voltage-holding and current-carrying capability. The two coils of a magnet with their capacitor banks are connected in series to the power supply. By using two capacitor banks per magnet, one for each coil, the maximum voltage to ground and also across the coils and capacitor banks is limited to below 6 kV. A resistor chain is connected across each capacitor bank. At resonance the two coils of a magnet, connected in series with each other, and also in series with two capacitor banks, have a resistance of 5.2 Ω, which presents a suitable load resistance for a commercial power audio amplifier.

Low-loss polypropylene capacitors with $\tan \delta < 6\times10^{-4}$ at 3 kHz and a small temperature coefficient of 200 parts per million per degree Celsius have been selected. The individual capacitors are all specified for a DC operating voltage of 1250 V and an AC voltage of 500 V at 3 kHz. The capacitor banks can withstand DC and AC voltages at 3 kHz of 26.25 kV and 10.5 kV, respectively. Since the Q-value of the coils, including ferrite losses, is approximately 200, the resonance frequency of the coils and capacitors has to remain stable within a few Hz to ensure long-term amplitude stability without temperature stabilization of the capacitor banks or continual frequency adjustment.

The capacitors for the two magnets are mounted on printed-circuit boards in two Elma racks with insulating supports for the boards and an insulating lining. The capacitors are situated at a distance of about 4 m from the magnets to which they are connected by eight RG 213/U coaxial cables to make them more accessible for inspection. Because of the cable capacitance there is a 0.37 % difference in the currents through the two coils of a magnet.

The Audio Amplifiers

Two audio power amplifiers with a peak power output of 1.8 kW each, are connected via a pair of shielded wires to the capacitor banks. The power output from the amplifiers is much higher than required, but the amplifiers are specified in terms of peak power output and in the present application the load characteristics are also very different from what the amplifiers are intended for. Furthermore the exact load resistance was not known before the amplifiers were bought. It was therefore decided to be on the safe side, especially since reliability is of importance for the production of radioisotopes and the amplifiers are relatively inexpensive.

The Beam Pipe

A ceramic, Al_2O_3, beam pipe with a conducting layer on the inside, which allows penetration of the magnetic field, but prevents charge accumulation, is used. The power dissipation due to eddy currents in the conducting layer is proportional to the third power of the radius and the thickness of the layer [7]. For a power dissipation of less than 30 W at 3 kHz in the tube with an inner diameter of 86 mm the surface resistance of the layer has to be more than 3 Ω per square. The power dissipation in each of the stainless steel flanges on the tube, at a distance of 40 mm from coils, is 30 W. The power dissipation in the mild steel plate, which forms part of the support structure above the top magnet, is 28 W. Beam current intercepted by the layer is used in the interlocking system to protect the tube.

SPLIT BEAM LINES FOR RADIONUCLIDE PRODUCTION

The layout of the beam lines for operation with split beams is shown in Fig. 2. A 800 mm long electrostatic channel, operating with a negative deflector voltage of 70 kV across a 30 mm gap, will be used to deflect about a third of the beam away from the existing beam line. Two thirds of the beam will then be used in the vertical beam line while the deflected beam will be diverted around the 90° vertical bending magnet before it is directed to the vault that is presently used for radionuclide production. The relatively low voltage and field strength of the electrostatic channel have been chosen because the electrodes are not situated in a strong magnetic field, as is usually the case in a cyclotron. To minimise beam losses in the septum it is important that the beam should be diverging at the entrance to the channel. The expected beam loss for a 400 μA total beam current is 2.2 μA. The quadrupole magnet, directly after the electrostatic channel, is planned for adjusting the beam height in the following septum magnet that deflects the beam through 20°. The entrance of the septum magnet is 2 m down stream from the entrance of the electrostatic channel and is similar to one of the magnetic extraction channels of the separated sector cyclotron. At the entrance of the septum magnet the beam separation is 35 mm. The deflected beam is focused by three quadrupole magnets to a double waist in the switcher magnet, with zero degree entrance and exit angles.

CONCLUSIONS

Several projects for improving the facilities for production of radioisotopes are in progress. The flat-topping systems, buncher, beam stop and vertical beam line are scheduled for completion by the end of 2004. Operation with split beams is planned for 2006.

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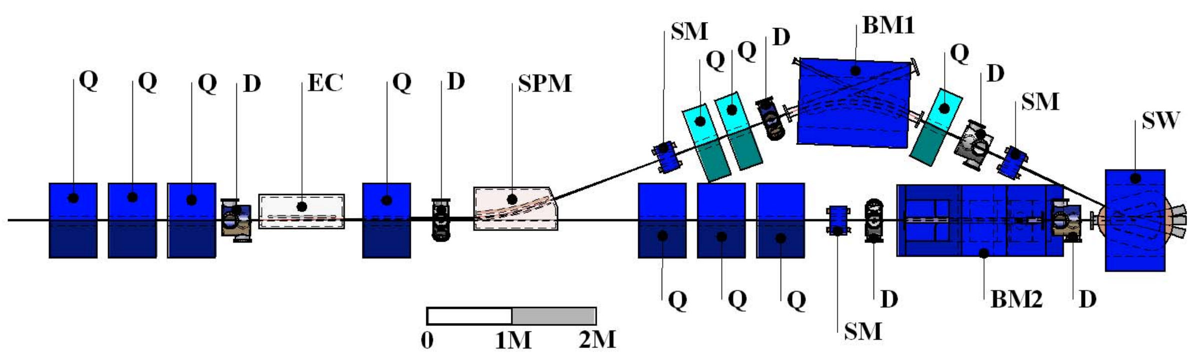

Figure 2: Layout of the planned beam lines for supplying two targets for radionuclide production simultaneously with beam. The main components are the electrostatic channel EC, the septum magnet SPM, the bending magnet BM1and the existing switcher magnet SW. The bending magnet BM2 deflects the beam downward into the vertical beam line. Q, SM and D designate quadrupole magnets, steering magnets and diagnostic vacuum chambers, respectively.