A LIGHT, SUPERCONDUCTING H^- CYCLOTRON FOR MEDICAL DIAGNOSTICS AND NEUTRON RADIOGRAPHY

Martin F Finlan*, Marcel Kruip and Martin N Wilson
Oxford Instruments Ltd, Osney Mead, Oxford OX2 0DX, England
*Amersham International PLC, Amersham Laboratories, Amersham,
Buckinghamshire, HP7 9LL, England

Summary

Oxford Instruments, working in close collaboration with Amersham International are developing a compact, lightweight, low radiation field superconducting cyclotron. The combination of superconductivity, H^- acceleration and no internal yoke as such makes this possible. It is intended for use as a generator of short half lived isotopes for use in hospitals for PET and other imaging procedures, for use in industrial PET imaging, and as a neutron generator for neutron radiography. With a weight of 2000 kg, it is transportable and comparitively easy to handle and is capable in the 17 MeV version of generating 1.8 10^{12} neutrons/second for neutron radiography.

Introduction

Conventional isochronous cyclotrons have an iron yoke which facilitates the creation of the magnetic field on the median plane, reducing the electrical power consumption. Shaped ridges on the surface, in conjunction with orbit and harmonic coils, provide flutter for focussing and also the isochronous field shape. Superconducting cyclotrons have mainly followed the same design path, with the resistive copper windings replaced by superconducting windings. The realisation that full magnetic efficiency is not required for the low energy cyclotrons needed for isotope production led us to investigate the possibility of producing an isochronous field shape without iron, and adequate flutter with iron pieces only ie no conventional return yoke.
Computer generated field plot data demonstrated that it is possible to produce an isochronous field without iron for proton and H^- machines with energies up to at least 60 MeV, and to get a good focussing field shape with iron pole pieces inside superconducting solenoids. It was also clear that the superconducting windings were easily realisable with conventional Oxford magnet technology such as was being used routinely and successfully in the NMR imaging magnet field. A consequent advantage is the ability to use efficient, small RF cavities to give lower copper losses.

Particle

An assessment of the isotopes needed for PET imaging suggested that low energy proton beams would produce the four major isotopes in sufficient quantities (see table 1), and that protons would also be the best particle for neutron production for radiography[1]. By not having to accelerate other particles the machine design is simpler and therefore cheaper and more reliable. These are of course essential properties for a machine designed to be used in routine clinical diagnostic procedures.

Experience at Amersham with the modified CP-42 H^- cyclotron has shown that near 200 micro-amp beams of protons can be routinely extracted for over 100 hours per week for isotope production, with peak currents in the 300 micro-amp region at proton energies to over 42 MeV. H^- was therefore chosen as the particle for the superconducting cyclotrons.

Stripping

Assessment of the beam current losses in the CP-42 suggested that the superconducting machine would have a considerably improved performance. Lorentz stripping was calculated using the Scherk & Stinson [1,2] formulae to be negligible for the parameters chosen (less than .0001% overall for the 12 MeV version). Gas stripping was calculated to be less than 0.1% overall for an operating pressure of 10^{-7} torr, of which less than 0.02% leads to neutron production, ie equivalent to a current of 20 nano-amps for a 100 micro-amp beam. Neutron production from the beam baffle would then produce a maximum flux one metre from the beam baffle of 10 neutrons cm^{-2} sec^{-1}. This flux is easily attenuated to the undesignated area level of 1.7 n cm^{-2} sec^{-1} by a few cm of borated polythene. Even at a pressure of 10^{-6} torr, gas stripping leading to neutron production is less than 0.2%, needing about 15 radial cm of borated polythene to maintain undesignated area external radiation fields.
The solenoid shape of the proposed superconducting cyclotron will allow actual working pressures in the ion circulating region to be much lower by direct pumping than for a compact machine with a yoke in which the conductance to the vacuum pumps is much lower. It was this consideration also which led to the use of an external ion source, which can inject down the field lines of the solenoid bore via a differentially pumped chamber to minimise the amount of hydrogen which is introduced to the median plane.

Energy.

With these advantages in mind, Oxford and Amersham have studied designs having proton output energies of up to 40 MeV, but have concentrated on the 12 MeV machine for short half-lived isotope production for PET imaging (e.g. carbon-11, nitrogen-13, oxygen-15 and fluorine-18) and for neutron radiography, and the 17 MeV machine for PET imaging, high output neutron radiography and isotope production. The choice of 12 MeV for the PET cyclotron is a compromise between a high energy to maximise the isotope production rate and a low energy to minimise cyclotron neutron production, stray magnetic field and size. The easily attainable current level of about 100 micro-amp external beam gives rise to little or no neutron activity from the cyclotron and the external magnetic field one gauss contour surface can be as little as 3 metres away from the machine.

17 MeV was chosen as the proton energy for high level neutron production on a beryllium target using an extracted current of 200 micro-amps. The choice was a compromise between higher energies and lower currents, and lower energies with higher currents. Although the cyclotron should be capable of much higher current output, it seemed prudent to limit the current to a level which is easy on target and on the cyclotron .This current thus gives an output of 1.8 10^{13} neutrons/second for extracted currents of about 200 micro-amps, which is higher than any other portable neutron source [1] .The cyclotron so described can weigh as little as 1250 kg for 17 MeV proton production.

The magnet.

The mean magnetic field can be made to be in the 5 tesla region,but has been chosen to be only about 3 tesla for the 17MeV cyclotron both to minimise Lorentz stripping and to make the centre region geometry more tractable. Even at this field, the 17 MeV extraction radius is only 20cm. The peak field corresponding to this mean field is 3.6 Tesla, resulting in a Lorentz stripping loss of less than 0.4% overall, mostly in the energy region above 14 MeV. This corresponds to a neutron flux at about a metre from the neutral beam baffle of 400 neutrons cm^{-2} second.
The peak field value was chosen to give a flutter which ensured axial focussing at the higher energies. It is one of the virtues of the yokeless superconducting design that such high flutter is achievable.
The 12 MeV field level is 2.5 tesla mean, resulting in 3.2 tesla peak to give enough flutter for good axial focussing with straight edged sectors (fig 3). The RF cavity design is thus much simplified. Lorentz stripping is negligible and with an extraction radius of only 20 cm the machine is still acceptably small and light.

Ion injection

The H^- ions are produced in Ehler type sources operating in the magnetic field of the superconducting solenoid, with differential pumping to limit the hydrogen input to the machine vacuum. An ECR source is also being investigated for higher energy efficiencies.
After extraction from the source, the beam is deflected through right angles to travel axially down the magnetic field lines towards the median plane where an inflector bends it back again to form the first orbit. Both gridded and helical inflectors are being studied. Currents of more than 2 mA have been put through both types of structure, more than adequate for our purpose.

The RF system

The RF resonant cavities are calculated to consume only 6 kW power for the 12 Mev cyclotron and 8 kW for the 17 MeV cyclotron. A solid state amplifier is located at the cyclotron, driving the cavities in phase with trimmers for each cavity to maintain the correct phase relationship and relative dee voltages A remote master oscillator drives the amplifier. With this shape of cyclotron, multipactoring is not expected to be a problem.

The neutral beam baffle.

A feature of H^- cyclotrons is the flux of neutral hydrogen which emanates from the median plane via gas and Lorentz stripping. This is minimal for this type of superconducting cyclotron, but is nevertheless intercepted by a proprietary neutral beam baffle which minimises the neutron output and the resultant activation due to the energetic H^- flux.

The Compact Superconducting Cyclotron

Figure 1 presents an artists impression of the 17 MeV cyclotron, and Fig. 2 shows a cross section of the same machine. Referring to Figures 1 and 2, the axially directed magnetic field needed to constrain the particle orbits is induced by four solenoids split equally above and below the median plane. Design of the magnet follows fairly standard Oxford lines and indeed is very similar to an existing product for NMR spectroscopy and imaging. The magnet coils will be immersed in a liquid helium tank, forming part of a fairly conventional vacumm insulated cryostat,with double radiation shields to intercept any thermal radiation coming from room temperature sources. These shields will be cooled by a small closed cycle cooler of the kind commonly used in cryo-pumps.

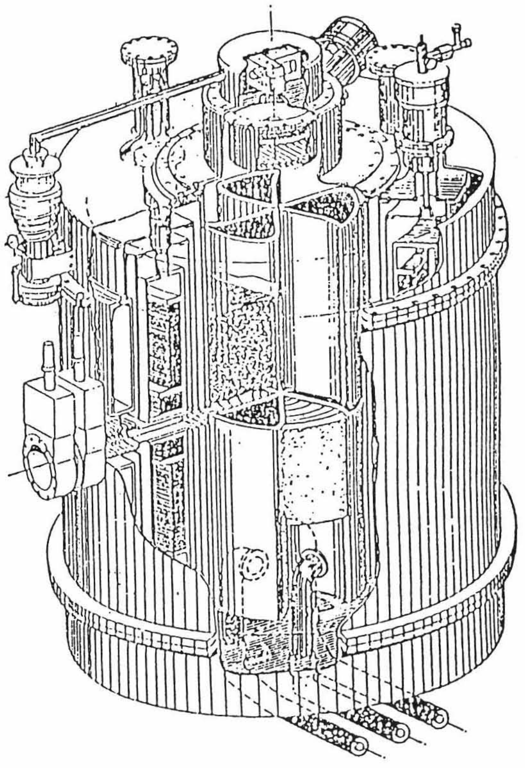

Fig 1: Artist's impression of the cyclotron.

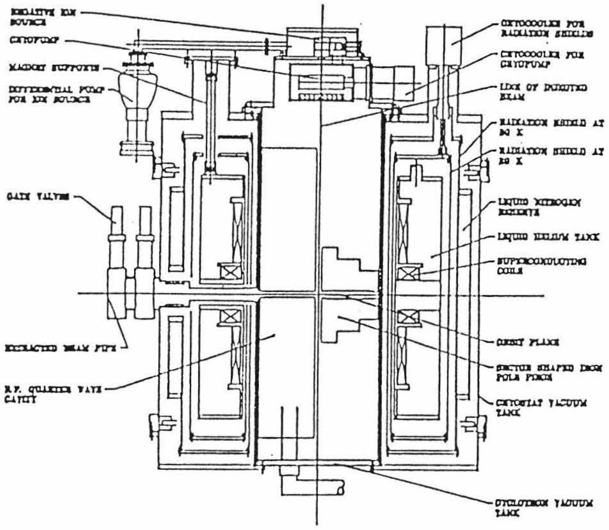

Fig 2: Cross section of the cyclotron.

The main cyclotron vacuum tank will be situated within the magnet cryostat bore and will be separate from the cryostat vacuum. Vacumm pumping will be either cryopumping mounted on top of the vacuum tank, or diffusion pumping from underneath. In either case, there will be separate pumping of the external ion source by a small diffusion pump. The sector shaped iron pole pieces are shown in the form of three pairs located symmetrically above and below the median plane, having spiral or straight sides as appropriate. The heat leakage to the liquid helium is low enough for the NMR superconducting magnets to cause them to require topping up at only three monthly intervals. It is expected that the 12 MeV cyclotron will be comparable, although the portable 17 MeV machine will be topped up at monthly intervals.

Also in three pairs are the RF cavities located between the iron sectors. These are designed to resonate at three times the particles orbit frequency, so that the energy gain per turn is about 150 keV for a cavity peak voltage of 30 kV.

The control system requirements for both energies are minimal. After setting the power level of the magnet and putting it in the permanent magnet mode, no further control or power input is needed. The RF system is servo-controlled to constant voltage and frequency. Output current level is specified by the ion source current and inflector parameters. These and the vacuum system parameters are monitored by a micro-driven proprietary interface crate.

The PET cyclotron

The PET cyclotron energy has been limited to 12 MeV to minimise the shielding requirements for the cyclotron and to make it easier to limit the stray magnetic field to be lower than 0.1 milli-tesla in the region of the imaging equipment. The cyclotron body is enclosed in an iron cylinder of radial extent about 10 cm, which serves to duct the bulk of the stray field lines back to the solenoid core and also provides fast neutron moderation.

The magnetic field level for this machine has been set at 2.5 tesla mean to simplify the RF cavity design by allowing straight sided sectors, ie no spiral. Parameters are shown in table 2 and figure 3. Currents in the region of 100 micro-amps are expected to generate enough isotopes for PET diagnostic purposes and will be well within the machine capability.

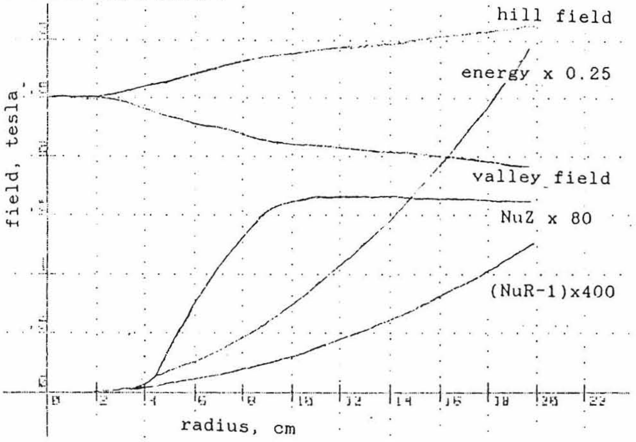

Fig 3: Hill field, valley field, energy, NuR and Nu
as a function of radius.

Table 1

Yields of PET isotopes from 100 micro-amps 12 MeV protons

Reaction	Half life	Yield mCi
15N(p,n)15O	2 min	84 mci/sec
13C(p,n)13N	10 min	16 Ci (20 minute irradiation)
11B(p,n)11C	20 min	7 Ci (40 min irradiation)
18O(p,n)18F	110 min	15 Ci (60 min irradiation)

It is assumed that enriched targets are used, and that there are no losses by evaporation or in processing. Target systems will vary in the amount of produced isotope which is available to the user.

Table 2

Parameters of the 12 MeV Cyclotron

External beam current	100 micro-amp for isotopes
Particle	H^-
Extraction	Stripper foil
Extraction radius	200 mm
Mean field	2.5 Tesla
Peak field	3.2 Tesla
orbit frequency	38 MHz
RF cavities	3 @ 60 deg
RF frequency	114 MHz
RF voltage	30 kV
RF power consumption	9 kW
Power consumption	17 kW
Energy gain/turn	150 keV (average)
Outer diameter	100 cm (of cryo-tank)

Table 3
Parameters of the 17 MeV Cyclotron

External beam current	50 micro-amp for isotopes 200 micro-amps for neutrons
Particle	H^-
Extraction	Stripper foil
Extraction radius	200 mm
Mean field	3.0 Tesla
Peak field	3.6 Tesla
orbit frequency	44 MHz
RF cavities	3 @ 60 deg
RF frequency	132 MHz
RF voltage	30 kV
Energy gain/turn	150 keV (average)
Overall diameter	115 cm
Overall height	176 cm
RF power consumption	13 kW
Total power consumption	20 kW
Cooling water	50 litres/min
Liquid helium usage	0.2 litres/hour
Liquid helium capacity	180 litres
Liquid helium endurance	37 days

Neutron Radiography Cyclotron

Neutron production is feasible with the 12 MeV cyclotron to give thermal neutron fluxes for radiography of about 8 10^{10} n cm^{-2} s^{-1} from a current of 200 micro-amps of protons on a beryllium target. For the higher neutron output needed for some applications, the cyclotron energy has been set at 17 MeV, an energy which allows a neutron yield of 1.8 10^{13} neutrons/second for a current of 200 micro-amps of protons on a beryllium target (Hawkesworth)[1]. The useful thermal flux is in the region of 1.8 10^{11} n cm^{-2} s^{-1}. The peak flutter of this machine is 1.3 tesla for a mean field of 3 tesla, no magnetic shield being needed. This cyclotron is intended to be transportable, with a cyclotron weight of 1250 kg and, with a polythene moderator weight of 750 kg, an overall weight of about 2 tonnes. Table 3 illustrates the parameters of this machine. Fig 4 shows the general arrangement for neutron production, described in more detail by Hawkesworth[1]. The extracted beam passes along a short beam pipe to a water cooled beryllium target. This target is surrounded by a sphere of high density polythene about one metre diameter which serves as moderator, reflector and fast neutron shield. The superconducting magnet will be kept permanently cold, being topped up with liquid helium every month. Liquid nitrogen is used in the outer radiation shield as a heat transfer medium and also to provide buffer storage of 'cold' against the unlikely eventuality of cooler failure. No topping up of liquid nitrogen will normally be required.

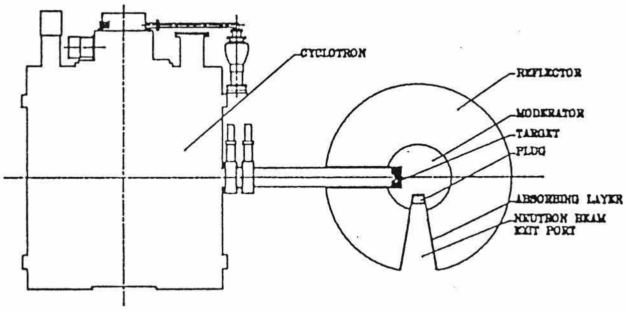

Fig 4: General arrangement of target and moderator.

The cyclotron is expected to weigh about 1250 kg and the polythene moderator will be about 750 kg, ie a total system weight of 2 tonnes. It thus becomes possible to envisage a very mobile and versatile installation for pointing the neutron beam in any direction, as sketched for example in Fig 5.

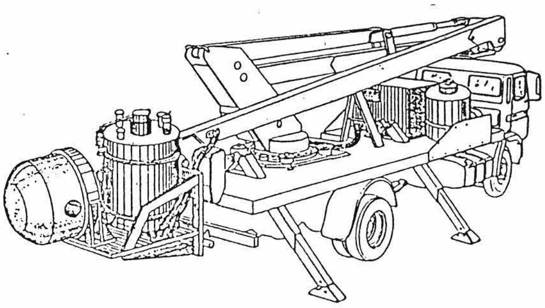

Fig 5: A possible mobile arrangement for the neutron source.

Maintenance

The cyclotrons are designed to need little maintenance and to be used by an unskilled operator. Ion source blocks and extractor foil blocks, each consisting of a number of heads, will be replaced at 1200 hour intervals. Liquid helium will be topped up every three months for the 12 MeV, each month for the 17MeV cyclotron.

References

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(4) Wright B T. Arch Math NaturVidenskab 54(2), 9(57)