CONCEPTUAL DESIGN FOR A HIGH INTENSITY (5 mA) INDUSTRIAL CYCLOTRON

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SUMMARY

We propose a preliminary design for a 40 MeV fixed energy proton cyclotron with a maximum intensity of 5 mA. Special emphasis is put on a simple and reliable design, and on low operating costs. The proposed cyclotron has four separated sectors and is basically similar to the S.I.N. injector II. However for this energy, acceptable betatron frequencies are obtained up to the maximum intensity with 36 deg. rather than 26 deg. sector angle. Two 45 deg. dees provide an average energy gain of 1 MeV/turn, with two flat-topping cavities. The main acceleration frequency is 30 MHz (flat-topping at 90 MHz) allowing the use of inexpensive RF power amplifiers. The electrostatic deflector includes a low-interception septum, made of carbon fiber wires. The beam is injected from a high brightness, miniature E.C.R. source, located at the center and biased at 100 kV.

INTRODUCTION

High intensities of medium energy (40 MeV) protons may be necessary for efficient production of radioisotopes, or to produce a high flux of high energy neutrons, simulating 14 MeV neutrons produced in future fusion applications. For those high beam intensities (1 mA) linear accelerators have traditionally been used. Their main drawback is a large energy consumption, resulting in high operating costs. Recent progress in cyclotron intensities, specially at Triumf and SIN, has changed this situation. The new SIN injector, presently being commissioned, should be able to accelerate 72 MeV protons with intensities of 2 mA or more. Following this pioneering work, we propose the design of a 40 MeV , 5 mA, separated sector cyclotron, designed as a robust, industrial machine for large scale applications. Special emphasis is put on the reduction of the operating costs. The power consumption is 650 kW at low beam intensity, increasing to 990 kW for a 200 kW beam extracted. Such a total efficiency of 20% is probably unique in cyclotron history. The proposed cyclotron is specifically designed for unattended "free-wheel" operation and, thanks to very specific design features, should require a minimal manpower for maintenance. The automatic operation does not rely on a central computer. Instead, the intelligence is distributed, relying on hard-wired feedback systems, process controllers and microprocessors. Beam sharing is foreseen as an integral part of the system.

BEAM DYNAMICS AND POLE ANGLE

The study of the dynamics of high intensity beams in a cyclotron must include several space charge induced effects. Transverse space charge effects reduce the focusing forces. The beam envelopes become larger and the betatron frequencies are lowered, possibly driving the beam into dangerous resonances. Longitudinal space charge effects cause an abnormal energy-phase dependence in the beam, increasing the energy dispersion. This last effect can usually be reduced by a careful choice of the phase of the beam with respect to the accelerating and flat-topping RF systems . High intensity problems in cyclotrons have been carefully reviewed by W. Joho (1). In this study, we have generally used the formulas developed by Joho to account for those space charge effects. There is however, an essential difference between the design of the SIN injector II and this industrial cyclotron since the role of an injector cyclotron puts very strict requirements on the extracted beam quality (i.e. : emittance, phase width, energy dispersion). While in an industrial cyclotron the only constraint is to produce essentially 100% beam acceleration and extraction. The use of a larger emittance and phase width significantly decreases space charge associated problems. To compute the intensity-dependent values of the betatron frequencies ν_r and ν_z , a special computer code was developed. The zero-intensity ν_r and ν_z were derived from the orbit transport matrix at each turn, including gap, fringe field and relativistic effects. Transverse space charge effects were calculated using the Joho formulae (1). In a four sectors cyclotron of this design we are concerned by the following resonances :

$$\nu_z = 1$$
$$\nu_r = 1$$
$$\nu_r = \nu_z$$
$$\nu_r + 2\nu_z = 4$$
$$2\nu_r + \nu_z = 4$$

Those two last additive resonances, driven by the main harmonic of the field, could cause a severe degradation of the beam quality. Using this computer code the influence of the sector angle was studied. For such a cyclotron, 30 deg. sectors would seem a desirable value. However, as shown in fig. 1, the beam would be driven into the $\nu_r+2\nu_z=4$ resonance by space charge forces. Increasing the sector angle to 32 or 34 deg. as shown on fig. 2 brings the first half of the acceleration in the $\nu_r=\nu_z$ zone. Finally, best beam behavior is obtained for 26 or 36 deg. angle as shown on fig. 3,4. Not surprisingly, 26 deg. is used for the SIN injector II and 36 deg. is the sector angle of the Indiana cyclotron. For those angles, beam currents up to 5 mA (35 deg. phase width, i.e. 50 mA peak) do not induce major focusing problems.

FIG 1

α = 30°

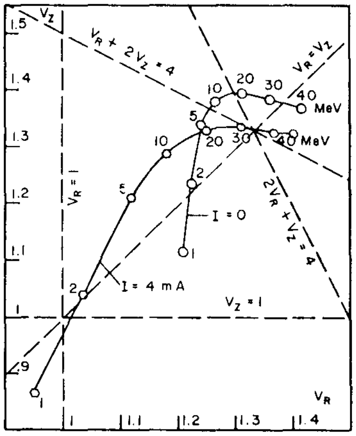


FIG 2

α = 34°

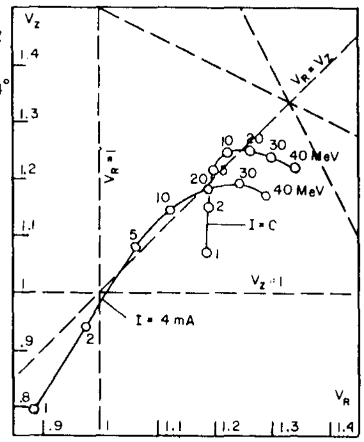


FIG 3

α = 26°

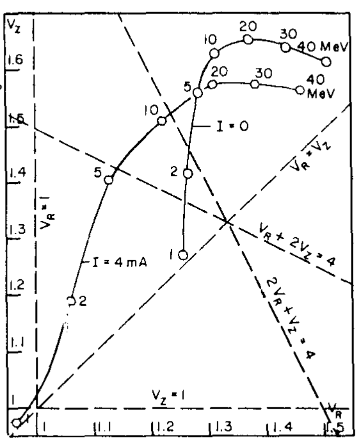
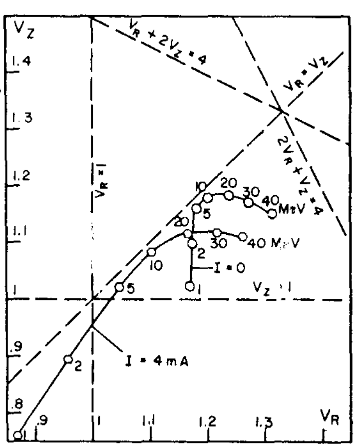


FIG 4

α = 36°



MAIN PARAMETERS

The main parameters of the proposed cyclotron are illustrated in table 1.

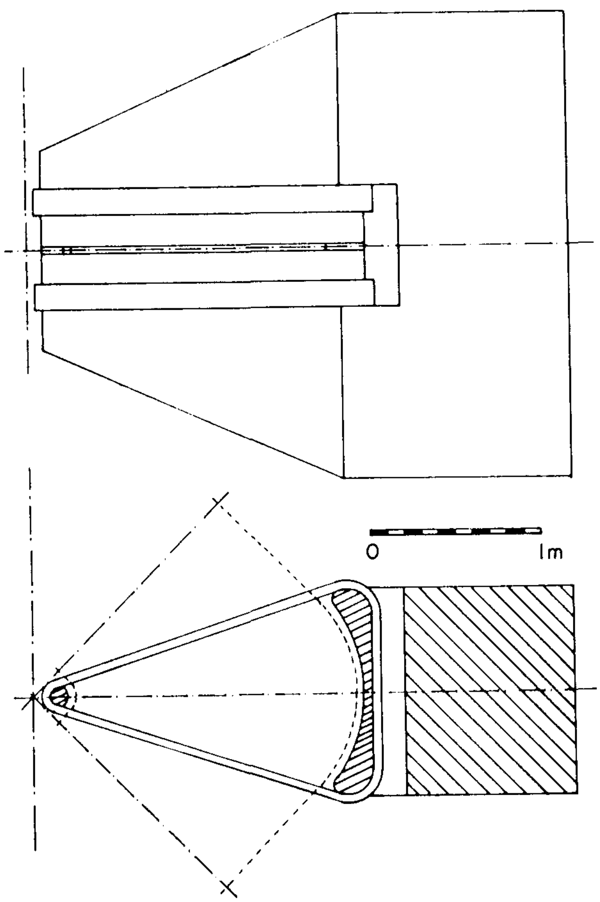
TABLE 1

Beam		
Energy (fixed)	40	MeV
Maximum average intensity	5	mA
Maximum beam power	200	kW
Phase width	35	deg.
Energy dispersion (extr.)	400	keV
Normalized emittance	1.88	mm.mrad
Emittance at injection	132.	mm.mrad
Emittance at extraction	6.9	mm.mrad
Average beam size	4x4	mm
Extraction radius	125	cm
Magnet System		
Number of sectors	4	
Sector angle	36	deg.
Field	12	kG
Magnet gap	3.5	cm
Outer pole radius	195	cm
Coil power (4 sectors)	95	kW
Trim-coils power (5 pairs)	10	kW
Main Acceleration RF System		
No of dees	2	
Energy gain per turn	1	MeV
Angle of dee	45	deg.
Harmonic number	4	
Frequency (fixed)	30	MHz
Dee voltage	270	kV
RF power (cavity losses)	2x75	kW
RF power (beam acceleration)	2x100	kW
Flat Topping RF System		
Angle of dee	15	deg.
Harmonic number	12	
Frequency (fixed)	90	Mc/s
Dee voltage	30	kV
RF power (cavity losses)	2x25	kW
RF power (beam deceleration)	-2x12	kW
Beam Injection		
Source	compact ECR	
Bias voltage	100	kV
Proton intensity (dc)	75	mA

MAGNET DESIGN

The sector magnet design is illustrated in fig. 5. Two spacers, made of watercooled aluminum, guarantee an exact pole parallelism. The pole-spacers assembly constitute a tight vacuum chamber element. The weight of a complete sector is approximately 45 tons and required coil power is 18.75 kW per sector, or 24 kW including power supply losses. The main coils are connected in series for the 4 sectors. In addition each sector has a pair of low-power correction coils for fine tuning and harmonic control. In each sector, a N.M.R. probe is installed inside the external spacer. The isochronism is obtained, at the desired field only, by a careful shimming of the sector poles. To make the final minor corrections , 5 sets of low-power trim coils are installed inside the dees.

FIG. 5 : SECTOR MAGNET



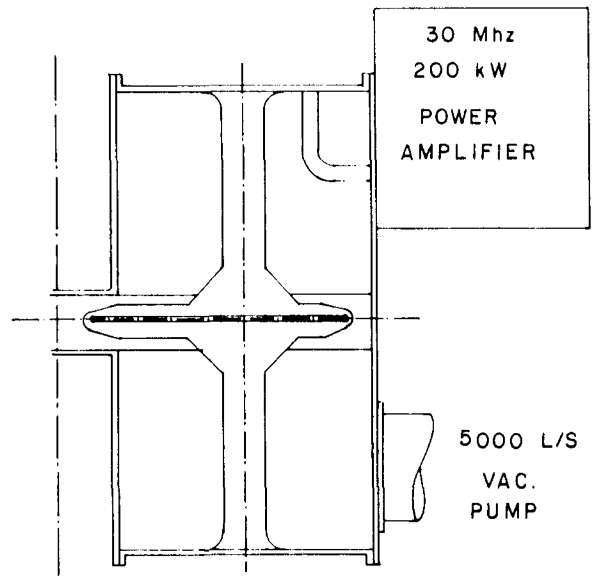
RF SYSTEMS

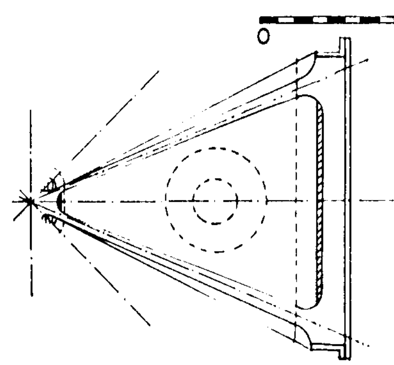
Main cavities design
The 2 low capacity 45 deg. dees are supported at the center of a half-wavelength vertical resonator. Unlike SIN injector II, a radial gradient of dee voltage was found unnecessary. This choice allows the use of classical cylindrical coaxial lines, resulting in a very low RF power. The final amplifier stages are located on the cavity with a direct inductive coupling. This configuration avoids any intensity dependent tuning of the main RF system. The variable load presented by the beam acceleration appears simply as a variable dc plate current of the final amplifier tube. The amplifier remains always close to optimum energy efficiency. The design of the cavity is illustrated in fig. 6

Flat topping cavities design
2 Flat topping cavities decelerate the beam and therefore gain energy from the beam. If the energy gain from the beam becomes much larger than the energy delivered by the power amplifier, accurate phase and amplitude control becomes impossible. Quite a low Q is therefore necessary in a flat topping cavity so that, even at maximum beam current, 50% of the dissipated power is still provided by the amplifier. To keep a reasonable dee voltage distribution versus radius, the 15 deg. dees are supported at the center of a half wavelength stripline (flat line) type resonator. Here also, the final amplifiers are directly coupled to the cavity.

Low level systems
The 2 main and 2 flat top cavities are driven from a common master oscillator via frequency multipliers, amplitude and phase regulating circuits. Fine tuning of the cavities is done by small trimming capacitors, adjusted to get 180 deg. phase difference between grid and plate of the final amplifier tube. Calculation shows that stabilities of 0.1% for amplitude and 0.5 deg. for phase are required. Such requirements are well within the possibilities of existing circuits. Start-up, recovery after a spark and tuning of the RF systems are entirely automatic.

FIG. 6 R.F. CAVITY





EXTRACTION

To limit the activation of the cyclotron, two conditions should be met :
a) The extraction efficiency should be essentially 100%. This requires well separated turns.
b) The septum material should produce only short life-time isotopes, and the amount of septum material in the beam should be minimal.
The first condition is met if the turn separation at extraction (20 mm) is much larger than the radial width of the beam. This width is due to the radial emittance of the beam (3.5 mm for E=6.9 mm.mrad. and vr=1.3) and to the energy dispersion (7.4 mm for dE=400 keV).
To meet the septum specifications, we

propose a large gap (15 mm), low field (80 kV/cm), electrostatic deflector. The septum is a grid made from thin (0.05 mm) carbon fibers, spaced every two millimeters. This results in a low effective density structure with high power dissipation by radiation and producing only short lifetime radioisotopes. The high voltage electrode is made of watercooled aluminum. The electrostatic deflector is located in a straight section, simplifying the mechanical design.

After the electrostatic deflector, the beam enters a 15 kG, 45 deg. C-magnet of conventional design.

INJECTION

For this application, a high intensity low emittance proton source is necessary. Recently, small high brightness proton sources using the Electron Cyclotron Resonance (E.C.R.) have been built (2). Such sources uses permanent magnets and a closed magnetic circuit, and are therefore quite insensitive to external magnetic fields. We plan to install such a source, biased at 100 kV, in the median plane of the cyclotron, at the center.

The injection scheme will be similar to that of the SIN injector. The dc beam from the source will be injected along the axis of a sector magnet. In this sector a magnetic cone is provided to align and focus the trajectory on the 500 keV equilibrium orbit.

To compensate the misalignment of equilibrium orbits occurring at the gaps when the energy gain is large compared to the total energy (called GABA effect at SIN), we propose to introduce a lateral offset of the sectors along the main dee axis. This would allow the smooth connection of the equilibrium orbits of successive half-turns, reducing acceleration-induced radial oscillations. The necessary offset decreases with radius, from 3.56 cm at the first half turn,to 1.1 cm at extraction. This correction gives a very slight spiral shape, the spiral angle decreasing with radius.

To add a low-frequency macro-structure to the beam, deflecting plates are installed inside the dee at the very first half turn. The plates deflect the beam horizontally onto the phase slits. The effect of this deflection is equivalent to a reduction in phase acceptance. This low frequency macrostructure will be used for :

a) Beam development: Using a low duty factor,space charge effects can be investigated with a low average current.

b) Intensity variation: Using the duty factor, it is possible to adjust the beam intensity without changing space charge dependent tuning.

c) Beam sharing: Fast switching of beam transport magnets is done during beam-off periods. Using different duty factors on alternate pulses, an independent control of intensity on each beam line is possible.

BEAM DIAGNOSTICS

Except for a beam stopper on the first turn, all beam diagnostics are non intercepting. The diagnostics may be divided into three groups :

-phase probes
-beam profile monitors
-radiation monitors

The phase probes are of the capacitive type. They are installed inside the main dees. Their azimuthal extent is 5 deg.. Radially, 5 probes are foreseen. Each one looks at 8 of the 40 turns. The phase probes provide a measurement, not only of the phase but also of the beam intensity, after calibration against the interceptive stopper.

The non-interceptive radial beam profile monitors use secondary electrons produced by the beam on the residual gas. Those secondary electrons are accelerated by a homogeneous electric field orthogonal to the beam (i.e. vertical), and collected on a grid structure with 2 mm resolution, extending continuously from the first to the last turn. Two such radial profile monitors are located on opposed radii, between the sector magnets and the flat-topping cavities. The associated electronics amplify and multiplex the different wire currents. A microprocessor displays the profiles, computes for each turn the radius, the beam width and the centering. If critical beam parameters fall outside limits, the beam is interrupted by the fast deflector on the first turn.

Radiation monitors, located at different symmetric places on the cyclotron, allow detection of any beam loss with a good sensitivity. At preset levels of losses, the beam is interrupted by the fast deflector.

Those redundant beam diagnostics should provide a faster beam turn-off in case of malfunction than a human operator could. This feature, as well as the distributed intelligence in other subsystems of the cyclotron, should allow a safe unattended operation, up to the highest beam intensities. An operator should only be required for :

- beam tuning and development
- malfunction diagnosis and cure
- non-standard operation,overriding system interlocks.

CONCLUSIONS

We have shown that a 40 MeV, 5 mA proton cyclotron could be built. Such a cyclotron would be economical to operate, require small operating staff, and give reliable beam with low down-time. The possibility to achieve beam sharing, with individual control of the intensity on each line, would greatly enhance the attractiveness of the machine for such applications as neutron therapy. All the techniques involved in the construction are well within the present "state of the art", and have individually been tested in similar applications. Although extremely high beam intensities are expected, the activation of such a cyclotron would probably be lower than that of presently operating cyclotrons for isotope production.

REFERENCES

(1) W.Joho 9th Int. Cyclotron Conf. Proc. (Caen,1981) pp.337-347
(2) J.Ishikawa et al. Proc. of Int. Ion Engineering Conf. (Kyoto,1983) pp.379-384