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CONCEPTUAL DESIGN OF TR100+: AN INNOVATIVE SUPERCONDUCTING CYCLOTRON FOR COMMERCIAL ISOTOPES PRODUCTION*

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Abstract

Utilizing dedicated cyclotrons to produce medical isotopes is an arising technology in hospitals across Canada. An excellent example is that in Jan. 2015, the CycloMed99 team, led by TRIUMF, demonstrated a breakthrough in producing the world's most highly used medical isotope, Tc-99 m, on existing medical cyclotrons. Now we propose to design an innovative H_2^+ superconducting cyclotron TR100+ for the production of commercially valuable radioisotopes. This project will be aiming at proton energy of 70 – 150 MeV and proton current of ~800 µA, since (i) cyclotron in this energy range is not developed world-wide; (ii) in this energy range numerous highly interested and increasingly demanded radionuclides can be produced, e.g. Sr-82 and Ac-225. Our machine shall be designed to accelerate H_2^+, by injection from external ion source and extraction by stripping. This shall allow to extract proton beam of variable energies with very high extraction efficiency, thus allow to reduce activation caused by beam losses. The basic parameters of our machine and simulations of stripping extraction will be presented in this paper.

OVERVIEW

There are two main types of commercial medical cyclotrons [1]: (i) those for medical isotope production, and (ii) those for proton therapy. The former are typically high-current low-energy (1 mA, 7 – 30 MeV) H^- machines, while the latter are low-current high-energy (1 µA, 200 – 400 MeV) proton machines. There are several well-established vendors [1] in each of these markets: ACSI, GE, Varian, IBA, Siemens, Sumitomo and Still River; and emerging players such as BEST and CIAE (China). From this overview it becomes apparent that 7 – 30 MeV and 200 – 250 MeV medical cyclotrons are well covered in the market by multiple strong players.

However, contrastingly, the 70 – 150 MeV range is not well represented; there being only few outliers at 70 and 100 MeV: the Best Cyclotrons 70P (in Legnaro, Italy) [2], the IBA C70 (in Nantes, France) [3], and CYCIAE-100 in Beijing [4]. All these are accelerating H^- to extract protons by stripping, in which a dominant factor limiting the beam intensity is the beam losses due to the electromagnetic stripping of the second electron during acceleration. To reduce activation of the accelerator system, caused by the resulting beam spills, the losses have to be kept low. This requires the magnetic field to be lower, the higher the machine energy, which in turn leads to the larger magnet size. Since the cost of the cyclotron rises with magnet size, the commercial H^- cyclotron balances acceptable losses versus size, ending up at a compromised energy of ~70 MeV [5].

Another option is to use protons directly, without stripping. But this extraction method requires well separated turns, which is achieved with a large radius of the machine and a high accelerating voltage, making the cyclotron very expensive. Proton machines for the therapy (up to ~1 µA extraction) can hardly reach an extraction efficiency above 80% [6, 7]. If they were for high current, they would not be able to run, because too much beam would get lost at extraction, exacerbating the neutron production and machine activation problem.

To overcome these limitations and reliably deliver high current (≥500 µA) proton beam on target, we intend to accelerate H_2^+, two protons bound by a single electron, with a binding energy much larger than the H^- case. This implies that a much higher magnetic field can be used in a compact cyclotron with significantly reduced magnet size and consequently lower costs.

In this energy range up to 150 MeV, numerous highly interested and increasingly demanded radio-nuclides can be produced, either as parent nuclei for generator use, or directly as an active pharmaceutical ingredient. For example, the two isotopes Actinium-225 and Bismuth-213 are anticipated to drive radiopharmaceutical developments for the researches of cancers (Melanoma, Prostate and Pancreatic) conducted at BCCA in Canada, and to expand in the world leading radionuclide imaging program. Another example, the isotope Strontium-82 (Sr-82) is used exclusively to manufacture the generators of Rubidium-82, which is the most convenient Position Emission Tomography (PET) agent in myocardial perfusion imaging. Over the last years, the demand for the Sr-82 from pharmaceutical industry has been growing, and such a demand is anticipated to continue to grow for the next 20 years. Other commercially relevant medical isotopes that can be produced from proton beams in the energy range 70 – 150 MeV include At-211, Ti-45 and Ra-223. With additional development, access to isotopes such as Ra-224, Pb-212 and Bi-212 will be possible. To date, virtually all Sr-82 is produced at large research facilities which are primarily used for scientific researches, and in most cases is partially subsidized. Using dedicated cyclotrons to produce medical isotopes is an arising technology in hospitals across the world.

Commercial superconducting (SC) cyclotrons are becoming ever more compact due to the introduction of successive

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generations of conductor technology for the magnet windings. The application of superconducting design has two evident advantages [6]. Firstly, the superconducting coils allow the machine to have extremely good reproducibility and linearity in the magnetic field with respect to the changes in the coil current, because the field-shaping iron and yoke get completely saturated in a strong field (> 2 T) of the coils; there is barely hysteresis effect. The magnetic field is dominated by the coil current. Secondly, the power consumption is at least 10 times less, and the machine's total weight is 2 times lighter than any normal-conducting cyclotron [7, 8] of identical energy. However, compactness is not necessarily a virtue. There should be a cost optimum in a design for a medical isotope production machine that adopts more mature and (comparatively) lower field conductor technology.

Since 20 years ago the idea of H_2^+ cyclotron was initially proposed [9, 10], there were not many studies devoted on this until the SCENT project [11], the IsoDAR and DAEδALUS Projects [12, 13] were brought up. The former is for an extraction energy of 260 MeV for proton therapy, while the latter is for energy up to 800 MeV/n for neutrino physics research. Although none of these machines has been built yet, it's conceived that the H_2^+ cyclotron will come into the market within the next few years because of its advantages.

BASIC DESIGN CONCEPT

The scale of our machine is set by the proton energy (up to 150 MeV), the superconducting magnet technology, the high-current (up to 2 mA) H_2^+ external ion source, the stripping of H_2^+ to extract protons (up to 800 µA), and the multiple external production targets, etc. A conceptual design was carried out for the superconducting cyclotron. It's a 4 sector compact machine of 3.8 m diameter, 2.0 m height, and 4 deep-valleys. The two opposite valleys accommodate rf cavities and the other two house diagnostic elements. Two RF cavities operating in 4th harmonic at a fixed frequency of ~97 MHz, accelerate the H_2^+ with a maximum dee voltage of 120 kV. Table 1 summarizes the main parameters of the cyclotron.

Table 1: TR100+ Main Parameters

Parameters	**Values**
Particle accelerated	H_2^+
Injection energy (keV/n)	25
Extraction energy (MeV/n)	100−150
Number of sector	4
Pole radius (cm)	106.5
Hill gap (cm)	4.5
Mean magnetic field (T)	3.1−3.7
Max. magnetic field (T)	4.5
Injection scheme	Axial + external ion source
Extraction	*p* by stripping extraction
Coils	2 superconductors
Max. current density (A/mm^2)	46
Number of cavities	2
RF harmonic number	4
RF frequency (MHz)	~97

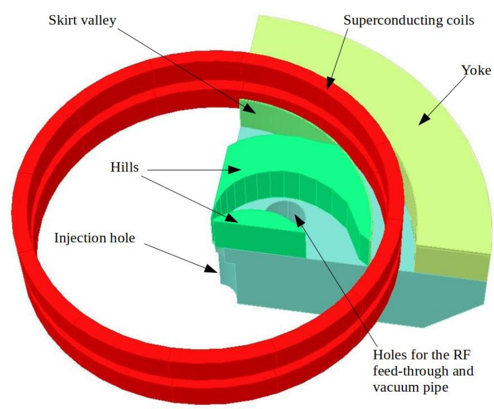

Figure 1: 1/8 OPERA model of the main magnet, mainly composed of the pole with spiral sector, skirt valley, yoke and superconducting coil (illustrated in various colors). The skirt valley serves to compensate for the isochronous field in the extraction region as well as to create a positive field gradient in the valley for the beam extraction.

MAGNETIC FIELD DESIGN

The magnet was modelled with OPERA-3D (see Fig. 1). Using the deep-valley concept, the poles are shaped to achieve an adequate axial focusing and good isochronism, by azimuthal profiling of the sectors as well as by grooving and shimming of the sectors. The sector's azimuthal width varies from ~ 40° in the center to ~ 46° at outmost edge, while the spiral angle changes from ~ 20° to ~ 70° at maximum. The pole gap maintains at ~4.5 cm. The magnet is energized by a pair of superconducting coils, symmetrically placed above and below the median plane. These coils operate at current density of 46 Amp/mm^2, creating an average magnetic field of 3.1 T in the centre, up to 3.7 T at radius of ~1.0 m.

Figure 2 shows the contour of the magnetic flux density in the median plane. The field isochronism is better than $\pm 5 \times 10^{-4}$ over the acceleration region (see Fig. 3). The phase excursion is less than ±30° throughout, assuming a peak energy gain of 0.4 MeV per turn (see Fig. 4).

The optimized magnetic field provides a vertical tune rapidly reaching above 0.2 and not crossing the coupling resonance $\nu_r - \nu_z = 1$. See Fig. 5.

EXTRACTION STUDIES

We extract protons by stripping of H_2^+. Placing the stripper properly (on the hill) can't only pull the protons to the outside of cyclotron in a decent path, but also deliver different energy protons to the same cross-over point in one turn. As an example, Fig. 2 shows the extraction trajectories of 140 and 150 MeV/n protons, where the radial distance is greater than 5.5 cm from the machine centre. Further studies (involving the centre region modelling) are needed to find out whether or not this is sufficient for the proton beam to get around

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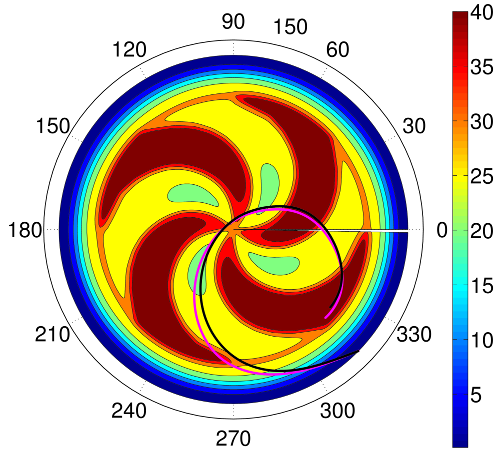

Figure 2: The contour of $B_z(r,\theta)$ in the median plane, and the extraction trajectories of 150 MeV (magenta) and 140 MeV (black) protons after being stripped. Both trajectories arrive at the same location where the field falls off to zero. The maximum field strength is ~45 kG on the hill.

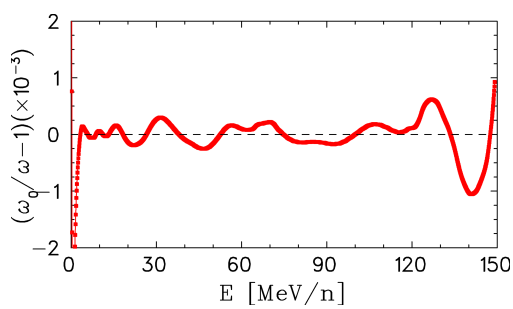

Figure 3: The isochronism parameter $(\omega_0/\omega - 1)$ vs. energy, where ω_0 and ω are resp. the nominal rf angular frequency and the revolution angular frequency of particle along the SEO in the modeled magnetic field map.

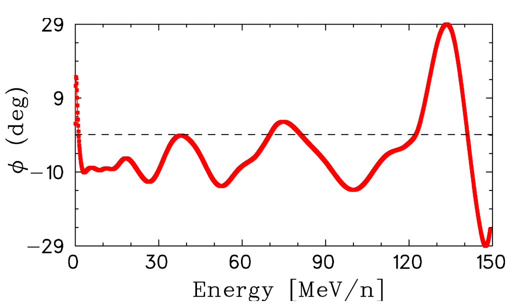

Figure 4: The rf phase vs. energy, showing that the excursion stays within ±30° over the entire energy range, assuming a peak energy gain of 0.4 MeV per turn.

the centre posts. Other lower extraction energies could be delivered from the other extraction ports.

Multi-particle simulation was done to calculate the extraction envelope, assuming a circulating emittance of 0.54 π.mm.mrad (4rms, normalized). Before entering the fringe field, the beam radial size is smaller than 0.25 cm while the axial size is smaller than 1.25 cm (2rms), well within the pole gap. However, after entering the fringe field,

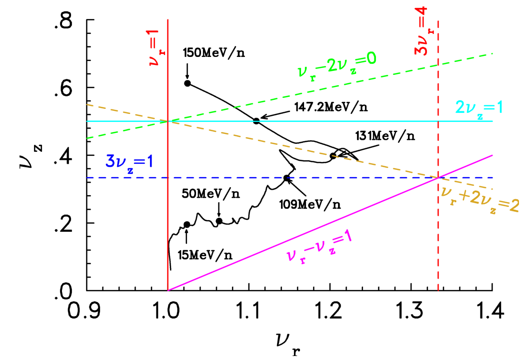

Figure 5: The tune diagram. Note that the coupling resonance $\nu_r - \nu_z = 1$ is preferably avoided; however the half-integer resonance $2\nu_z = 1$ occurs at ~147.2 MeV/n.

the radial size gets defocused continuously while the axial size gets over-focused (see Fig. 6). This suggests that magnetic channels need to be configured to compensate for these.

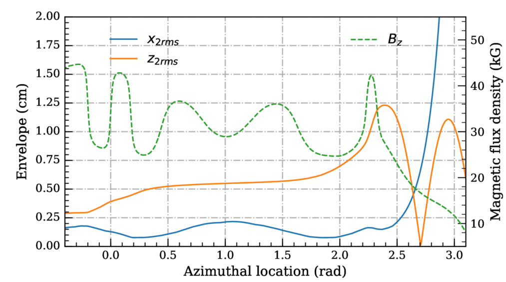

Figure 6: The axial (orange, solid) and radial (blue, solid) beam sizes (2rms) of 150 MeV protons. Also shown is the magnetic field strength along the extraction trajectory (green, dash).

INTENSITY LIMITATION

The acceleration process of H_2^+ in a compact cyclotron is similar to that of H^-: in both cases the space charge effects are strongest on the first turns. The intensity limit is due both to the vertical space charge tune shift and to the longitudinal space charge effect. Both effects give similar upper limits in the TR30 case [14]. The measurements for the TR30 demonatrated 1.0 mA beam current accepted under 5 mA injected dc beam. For the TR100+, we simply scale the expected current limit of H_2^+ using the formula (7) given in [14]:

$$\hat{I}_{max(vert)} = \beta \left(\frac{\nu_{z0} b_{max}}{R_\infty}\right)^2 \frac{I_0}{4}\,. \quad (1)$$

For the TR100+, we have $R_\infty \simeq 2.0$ m and I_0 twice as large as for the TR30. We assume $\nu_{z0} \sim 0.1$ and the same values of β as well as of the vertical aperture. These give ~ 40% of the space charge limit of TR30, that is, 400 μA H_2^+ expected from the cyclotron. This means 800 μA protons after stripping. However, this requires twice higher injection energy of H_2^+, that is, 50 keV. Also, to gain enough radius on the first 2 turns, it requires to maintain the energy twice as large on these turns because $\beta = \sqrt{2E/mc^2}$. So the rf voltage has to be twice as high.

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BEAM LOSSES

We concentrate on two types of H_2^+ beam loss: electromagnetic dissociation (Lorentz stripping) and interactions with residual gas. The binding energy of the last electron is 2.75 eV, ~ 3.6 times larger than the binding energy in the H^- case. This bind can be dissociated by the electric field, generated from the motion of the ion in the magnetic field. The equivalent electric field in the rest frame of the ion is represented as

$$E = 3\beta\gamma B\,, \tag{2}$$

where B is the static magnetic field in Tesla, β and γ are relativistic factors of ion motion, and the electric field is given in MV/cm. At 150 MeV/n in a magnetic field of 3.5 Tesla, the electric field is 2.1 MeV/cm. The H_2^+ survival issue is complicated by the large number of stable vibrational states [15]. In terms of the calculations performed by Hiskes [16], ions in a vibrational state $\nu > 16$ will dissociate during acceleration; roughly 2% of the beam would be lost into the vacuum chamber.

The circulating ions can lose their orbital electron as they travel along the acceleration path due to interactions with the residual gas. The fractional beam particles which survive is given by [17]

$$\frac{N}{N_0} = \exp\left(-3.35\times 10^{16}\int \sigma_L(E)\,P\,dL\right)\,, \tag{3}$$

where P is the vacuum pressure in torr (3.35×10^{16} is the number of molecules/cm^3/torr), and L is the path length in cm. The cross section of electron loss is

$$\sigma_L(E) = 4\pi a_0^2\left(\frac{V_0}{V}\right)^2\frac{Z_t^2+Z_t}{Z_i}\,, \tag{4}$$

where V is the ion velocity, while V_0 and a_0 are the characteristic Bohr velocity and radius. Z_t and Z_i are the atomic number of the residual gas and of the incident ion respectively. We estimated the beam losses along the acceleration path. To achieve an amount of loss below 1.0% during the acceleraion, the vacuum has to be better than 1.0×10^{-7} torr.

CONCLUSION

An initial design was carried out to evaluate the feasibility of building a superconduting cyclotron to accelerate H_2^+ beam up to 150 MeV/n, by stripping extraction to deliver protons of 800 μA. The design goal seems to be feasible with the present technology. Next, the centre region and injection line will be studied. Further optimizations of the spiral shape of the sector and of the coils are needed to provide a better vertical focusing and to lower magnetic forces, taking into account the design of rf cavities to be operated at high voltage and high power. Moreover, some physics questions need to be answered about the vibrational state population of the beam coming from ion source.

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