

Building on TR-24 success: Advanced Cyclotron Systems Inc. launches a new cyclotron model

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Received: 1 October 2014 / Published online: 17 March 2015
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Abstract ACSI is designing a new 30 MeV cyclotron based on the TR-24. While minimizing changes from the proven TR-24, including maintaining the same outer dimensions, the energy of the cyclotron will be increased to 30 MeV, which will make it the most compact, non-superconducting, 30 MeV cyclotron design to date. Maximum beam current will match the TR-24 at 1 mA. With the size and footprint of a typical low energy PET cyclotron, this system will offer users a cost effective solution for a diversified facility capable of producing a wide spectrum of PET and SPECT radioisotopes for research and commercial distribution.

Keywords Cyclotron · Radioisotope production · Medical isotope · ^{99}Mo · $^{99\text{m}}\text{Tc}$ · Cyclotron energy

Introduction

In the last two decades, since the introduction of commercial negative ion cyclotrons, all commercial medical cyclotrons were divided into two distinct subcategories: low energy systems for the production of positron emitting radioisotopes, and high energy accelerators for production of single photon emitters. Low energy cyclotrons, typically capable of accelerating protons to a maximum energy of 10–19 MeV, offered users a method of cost-effective production of short-lived radioisotopes and became the foundation for the proliferation of positron emission tomography. Higher energy cyclotrons, typically 30 MeV,

continue to support conventional SPECT nuclear medicine. The high capital and operational cost of these 30 MeV accelerators and associated infrastructure were limiting factors in their market acceptance. Only about 30–40 systems were sold and commissioned worldwide since the 1990s. In 2010, Advanced Cyclotron System Inc. (ACSI) introduced a new, medium energy cyclotron model—the TR-24. Based on the small PET cyclotron platform, the TR-19, this cyclotron is the same size and requires the same infrastructure as a conventional PET cyclotron, but it offers significantly increased production capacity. The TR-24 has an energy range of 16–25 MeV, and beam currents over 750 μA , which makes it suitable for production of all PET and several SPECT radioisotopes. This cyclotron received a lot of interest due to its flexibility and cost effectiveness. 4 years into production, fifteen TR-24 systems have been sold worldwide, five of which are in Canada. However, there is still a significant global demand, two or three international tenders per year, for higher energy (30 MeV) cyclotrons. These tenders are often issued by institutes with the purpose to establish a multi-functional medical isotope production facility, to cover regional demand in both PET and SPECT radioisotopes.

One of the driving factors of TR-24 acceptance was the development of large scale $^{99\text{m}}\text{Tc}$ production using medium energy cyclotrons [1]. While offering a larger variety and flexibility for radioisotope production, the TR-24 still cannot be used for the production of ^{201}Tl and it generates significantly lower yields of some widely used SPECT radionuclides, in particular ^{123}I (Table 1).

The diversification of a facility's "isotope portfolio" very often plays a decisive role in the choice of the accelerator, especially for the emerging or regional markets, where accessibility and affordability of SPECT isotopes remains low. In anticipation of ^{99}Mo shortages in 2016 and

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Table 1 Comparison of theoretical saturated production yields for representative radioisotopes at 24, 28 and 30 MeV (IAEA recommended data)

Energy (MeV)	^{67}Ga (GBq/ μAh)	^{111}In (GBq/ μAh)	^{68}Ge (GBq/ μAh)	$^{123}\text{I}^{\text{a}}$ (GBq/ μAh)	$^{201}\text{Tl}^{\text{b}}$ (GBq/ μAh)	$^{99}\text{Mo}^{\text{c}}$ (GBq/ μAh)
24	22	22	16	1.3	–	–
28	30	28	21	1.1	0.05	0.05
30	34	30	23	0.6	0.06	0.06

^a ^{123}I cumulative yield at the end of the process, 4 h bombardment followed by 6.6 h decay [2]

^b ^{201}Tl cumulative yield at the end of process, 7.5 h bombardment, followed by ^{201}Pb extraction and 31.74 h decay [3]

^c Cross sections and yields simulated using Nuclear Model Code EMIPRE-II

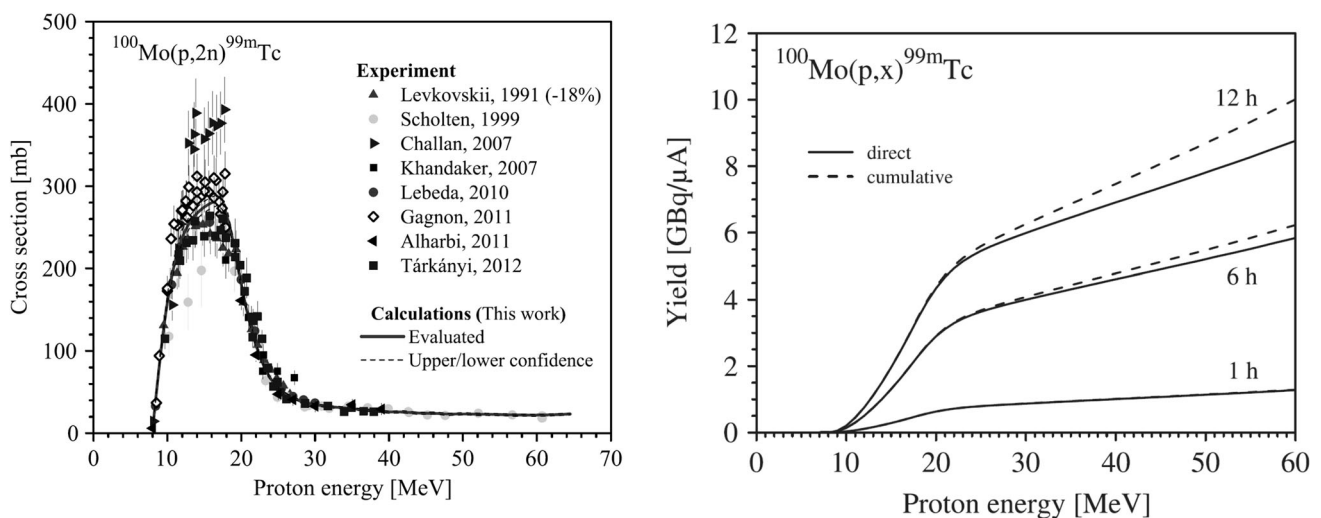


Fig. 1 Cross section data for $^{100}\text{Mo}(p,2n)^{99\text{m}}\text{Tc}$ nuclear reaction and integral yield of $^{99\text{m}}\text{Tc}$ as a function of energy at beam current of 1 μA and different irradiation times [3]

beyond, the considerations for using cyclotrons for direct production of $^{99\text{m}}\text{Tc}$ via $^{100}\text{Mo}(p,2n)^{99\text{m}}\text{Tc}$ and ^{99}Mo via $^{100}\text{Mo}(p,x)^{99}\text{Mo}$ reactions respectively play a significant role in justification for higher energy accelerator facilities. While for the direct production of $^{99\text{m}}\text{Tc}$ beam energy must be limited to 24 MeV due to co-production of other Tc radionuclidic impurities, and the production rate of $^{99\text{m}}\text{Tc}$ no longer increases as rapidly above 23 MeV (Fig. 1), the production rate of ^{99}Mo continues to rise as energy increases. The yield of ^{99}Mo more than doubles at 30 MeV, compared to 24 MeV, and approximately 600 Gbq of ^{99}Mo can be produced in a 24 h irradiation at 500 μA (Fig. 2). At this production rate, a 30 MeV cyclotron facility can generate 1250 Gbq of ^{99}Mo in a single, 60 h irradiation. While this level of production cannot significantly contribute to global supply of ^{99}Mo , it can meet the needs of smaller local markets. Cyclotron produced ^{99}Mo can be used as generator of $^{99\text{m}}\text{Tc}$ immediately after target processing, which takes approximately 1 h, and sufficient decay time for $^{99\text{m}}\text{Tc}$ growth, typically 6–24 h.

Driven by the above rationale we have evaluated the possibility of modifying the TR-24 cyclotron magnet to further increase beam energy while keeping the same overall external dimensions. According to our modeling, the maximum extracted proton energy can be increased to 30 MeV, which would make this new cyclotron a very compact and cost-effective 30 MeV cyclotron.

Cyclotron design considerations

In order to minimize design changes and risk, the new design deviates as little as possible from the proven TR-24 cyclotron. In particular, the RF frequency is unchanged at 85 MHz, and the main magnet and RF resonator geometry is unchanged up to the 24 MeV orbit radius. Beyond this radius, the main magnet parameters and cyclotron optics follow the TR-24 design, but extend to a larger radius to permit 30 MeV extraction. Design changes are limited to the main magnet pole, the energizing coils, the vacuum wall, and the RF resonators.

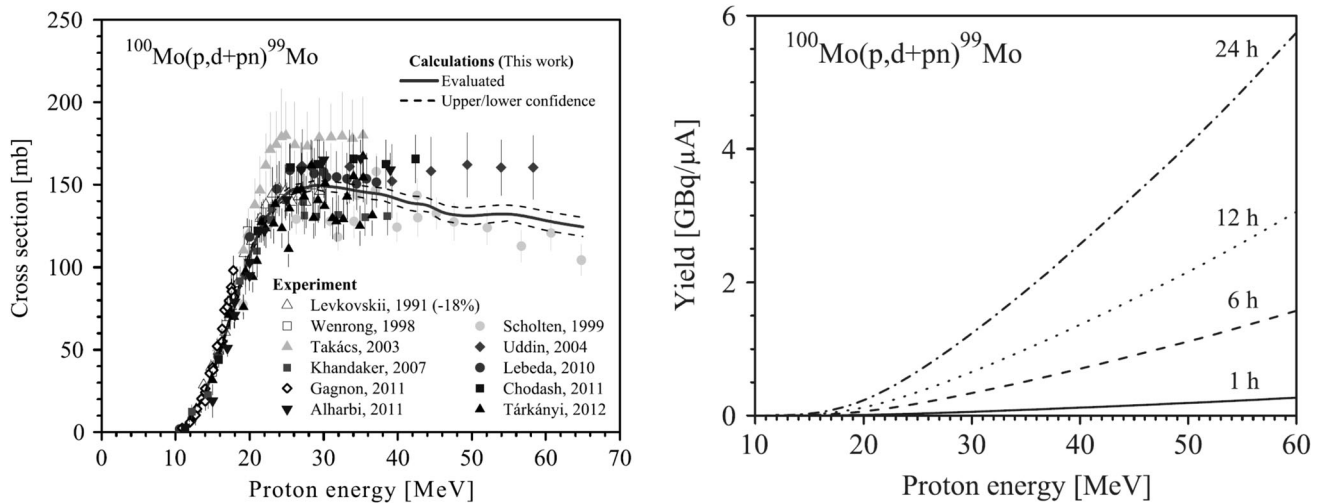


Fig. 2 Cross section data for the $^{100}\text{Mo}(p,d+pn)^{99}\text{Mo}$ nuclear reaction and integral yield of ^{99}Mo as a function of energy at a beam current of $1\ \mu\text{A}$ and different irradiation times [4]

Main magnet pole

Because the RF and cyclotron frequencies are to be kept constant, all increases in beam energy will come from increasing the size of the main magnet pole, and by allowing the cyclotron to accelerate beam to a larger radius within that pole size. Note that the TR-24 cyclotron can accelerate and extract beam up to 25 MeV before cyclotron transmission drops. In order to increase to 30 MeV, the final beam orbit radius must be increased 5 cm. This is accomplished by:

1. Increasing the pole radius.
2. Increasing the hill radius by reducing the vacuum wall ledge width.
3. Maintaining isochronous field towards the outer radii, by sculpting the hills towards the hill outer radius.

For the new cyclotron, the outer radius of the main magnet pole is increased from 600 to 619 mm. Increasing the pole radius, without changing the return yokes, is made possible by the more efficient use of the space between the pole steel and the return yokes, via optimization of the coils and the vacuum wall. The new coils are taller and narrower, and the vacuum wall overhangs the coils, to make better use of the space between the coils.

The outer hill radius will be increased from 560 to 603 mm. This is accomplished by reducing the width of the ledge used to seal the vacuum wall to the pole, from 36 to 16 mm. The vacuum wall width itself will remain at 43 mm, but it will extend into the otherwise unused space between the main magnet coils.

Further, the area of the magnet poles and hills will be used more efficiently, by maintaining isochronous field

towards the outer radius of the hills. To achieve this, the hills will be sculpted so that the hill gap is closed towards the outer radius, reducing the edge effects to the outermost radii. The hill gap will be reduced to a minimum of 23 mm (full gap) at the outer radius of the hill. Note that most of this reduced hill gap occurs beyond the radius of the circulating beam.

Figure 3 below shows the larger sculpted hills and the larger poles of the new cyclotron design. The dashed lines indicate the outline of the original TR-24 magnet pole.

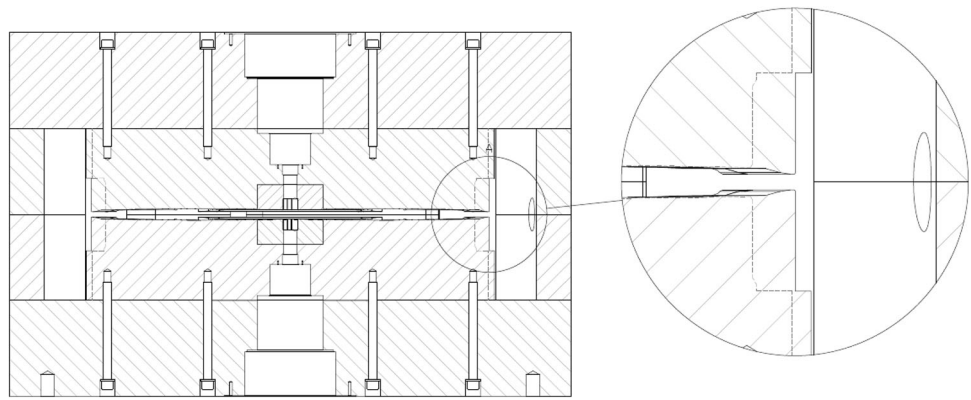
As with the TR-24 cyclotron, the valley field has been pushed relatively high in order to increase the average field, the cyclotron frequency, and maximum energy. In consequence, the flutter is low and the cyclotron tune is low. For this reason, the new cyclotron will remain below the Walkinshaw resonance, as was chosen for the TR-24.

The return yokes will not be changed from the TR-24 design. The increased flux from the larger poles will be handled without increasing the return yoke area. The field in the return yokes is increased to 18 kGauss, a reasonable value for a compact cyclotron.

Hill and valley angles will remain as per the TR-24 design. By maintaining a relatively large valley angle, 40° – 45° , the RF resonators can have a near optimal angle for efficiency and especially for high beam stability.

Main magnet coils

The space between the magnet pole and return yoke will be used more efficiently, principally by reducing the inside diameter of the magnet coils and increasing their height. As for all of the TR cyclotrons, direct water cooled hollow

Fig. 3 Modified magnet design

oxygen free high conductivity copper conductor will be used. For the new cyclotron, the conductor dimensions will be 14.8×12.3 mm with a 5.8 mm diameter cooling channel. As for the TR-24, each of the two coils will be composed of five pancakes, and each pancake of two 9-turn layers, for a total of 90 turns per coil. The coil width will be decreased by 15 mm and the inside radius will be increased by 19 mm. To recover some of the lost copper, the height of each coil will be increased by 11 mm. Main magnet power will increase to 22 kW.

Vacuum wall

The outer diameter of the hill will be increased further, by decreasing the width of the ledge used by the vacuum wall. The forged aluminum vacuum wall will retain its thickness, but will be moved outward and will overhang the coils. The TR-24 vacuum wall ledge width of 36 mm will be reduced to 16 mm.

The sealing surface could have been further reduced, however at 16 mm, the ledge is still sufficient to allow a double O-ring seal, complete with pumping groove, for the lower sealing surface. This technique is preferred for this difficult to access seal, so that in the later life of the cyclotron, when the inner O-ring seal finally fails, a roughing pump can be used to reduce the leak rate several orders of magnitude, to maintain high vacuum. That will allow maintenance to be delayed, potentially for many months, until the next annual maintenance shut-down. The relatively accessible upper seal is made with a single larger cross-section O-ring, to better accommodate the range of gland depth which this seal needs to handle due to tolerance stack-up.

The vacuum ledge height will also be raised, to allow the flux density to remain high near the outer radius of the hills. This high-vacuum ledge height makes it convenient for the vacuum wall to overlap the coils.

The alternative was considered, where the coil height was increased further, allowing the coil inside radius to be

increased. However, the coil height is limited also due to the RF coupler and the extraction probe gate valves.

The RF coupler and extraction probe ports are modified slightly to maintain a minimum vacuum wall section modulus and moment of inertia. This will avoid any difficulties with distortion of the vacuum wall during fabrication and installation. The vacuum wall at the RF coupler and the extraction probe ports will be thickened above and below the mounting flanges to increase the rigidity. Further, the extraction port hole will be a milled rectangle instead of circular, to reduce the height of the hole.

RF resonators

The RF Resonators will be extended radially outward to beyond the 30 MeV orbit radius of 533 mm at the centre line of the RF valleys. The back of the TR-24 resonator will be extended 55 mm. The additional area of the resonator will add capacitance, but this will be substantially offset by pushing the valley liner deeper into the magnet valley. The remaining difference in capacitance will be compensated by shortening the dee stems. Base power required to achieve 50 kV without beam load will be marginally increased. More substantial power increases will be required to handle the larger beam load of $1 \text{ mA} \times 30 \text{ MeV} = 30 \text{ kW}$. The new cyclotron will use the high-powered versions of the TR-24 RF amplifier, which has ample capacity for the additional power. With full beam load, the RF tube will be running at about 55 % of its maximum power rating.

Principal design differences from the TR-24 are summarized in Table 2 below.

Results of modeling and simulations

The new magnet design is at an advanced stage. Magnet simulations are done using Vector Fields Tosca software. Beam optics is simulated using in-house software. The new

Table 2 Principal design modifications made to TR-24 cyclotron

Parameter	Original TR-24	After modification
Energy range, MeV	16–25	18–30
Hill radius, mm	560	603
Pole radius, mm	600	619
Hill gap, mm	30	30 (23 @ OD)
Magnet coil inside radius, mm	605	624
Magnet coil outside radius, mm	737	741
Conductor cross-section, mm	13.6 × 13.6 × Φ6.0	14.8 × 12.3 × Φ5.8
Main magnet operating power, KW	20	22
RF frequency, MHz	85	85
Vacuum wall thickness, mm	43	43
Vacuum wall ledge width, mm	36	16

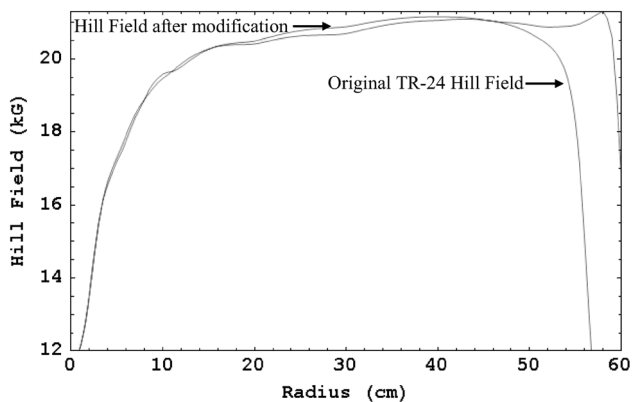


Fig. 4 Hill field versus radius

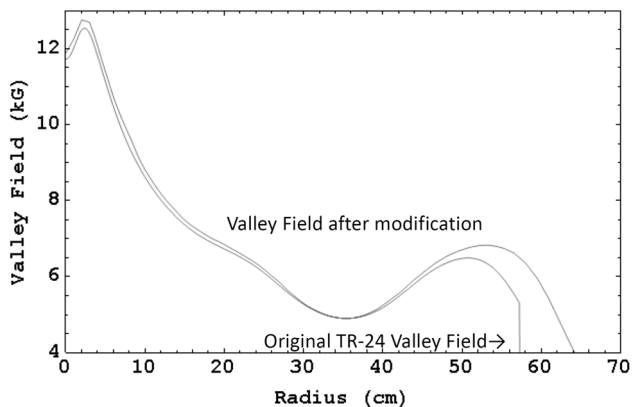


Fig. 5 Valley field versus radius

hill and valley fields, after the magnet modifications described above, are shown in Figs. 4 and 5, with the original TR-24 fields shown for comparison.

The extracted beam is currently being optimized by varying the azimuthal location of the extraction foil, in order to vary the trajectory of the extracted beam. The shape of the downstream hill edge is being adjusted to optimize the radial gradients over the range of extracted

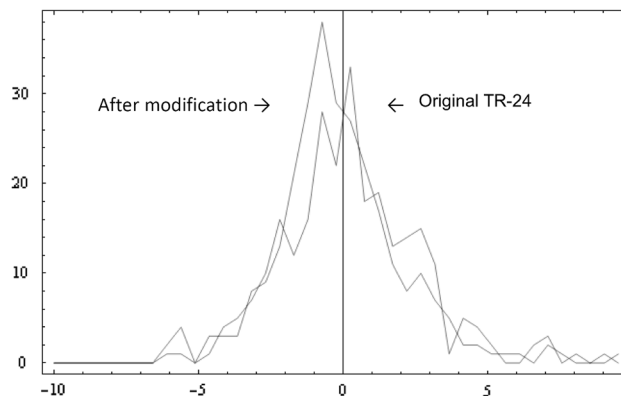


Fig. 6 X distribution on target at 24 MeV

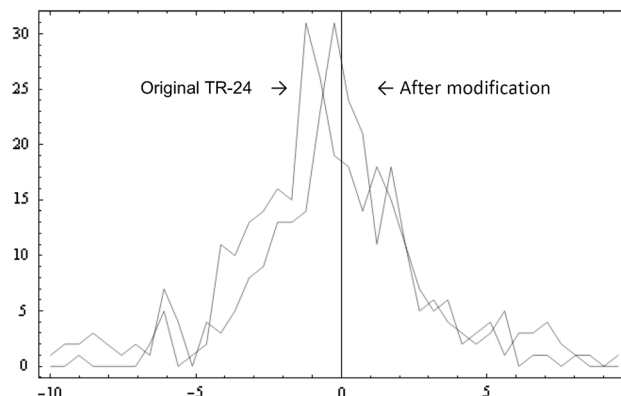


Fig. 7 Z distribution on target at 24 MeV

beam trajectories. While the downstream hill edge shape is optimized for extracted beam focus, the upstream hill edge is adjusted to maintain the isochronous condition for the circulating beam. Therefore the two hill edges are not mirror symmetric.

Figures 6 and 7 show the extracted beam distribution in X and Z at the location of a cyclotron mounted target selector. The jagged nature of the plot comes from the

relatively low number of particles used in the simulation. Final simulations will use larger numbers of particles, which will smooth the data and reduce the uncertainties.

Conclusions

A new compact 30 MeV cyclotron system has been designed and modeled. The new design is based on the proven TR-24 cyclotron platform and has the same magnet size and footprint as the TR-24 cyclotron. The higher beam energy is achieved by increasing the outside radius of the magnet poles, hills, and RF resonators, and by closing the hill gap towards the outside radius. These changes are facilitated by decreasing the width of the pole steel used by the vacuum wall and increasing the inside radius and height of the magnet coils. The size of the new magnet is $1.7 \times 1.7 \times 1.1$ m high and 20 tons, substantially smaller than for the alternative 30 MeV cyclotrons. Both the TR-30 and the Cyclone-30 have about twice the footprint area and at weigh about 50 tons [5].

With lower capital, infrastructure and operational costs, compared to larger 30 MeV cyclotrons, this system will

offer a cost-effective solution for production of a wide spectrum of PET and SPECT radioisotopes for research and commercial distribution.

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