OPERATIONAL EXPERIENCE AT THE INTENSITY LIMIT IN COMPACT CYCLOTRONS

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Abstract

Compact cyclotrons are a cost-efficient choice for medical radioisotope production since negative hydrogen ions can be used at energies well below 100 MeV. The stripping extraction technique allows quite large circulating currents without the need for separated turns. Space charge limits are in the range of 1 to 2 mA, but operating for long periods at these levels is a challenge for many reasons, among them being the sputtering of metal surfaces where unaccepted beam is deposited. These limits and others observed during our 22 years of 24 hours/365 days of quasi continuous operation of TR30 cyclotrons will be explored.

INTRODUCTION

TR30s are compact, low energy, high current H- cyclotrons originally designed and developed by TRIUMF and Advanced Cyclotron Systems Inc. (ACSI) [1]. They are four sector machines with two 45^0 Dees in opposite valleys. Due to their external ion source, and thus low tank pressure, the beam gas stripping is minimal. This combined with negligible electromagnetic stripping results in no beam losses between 1 MeV and the maximum energy. Extraction is done above 15 MeV by passing and stripping H- beam through graphite foils located at the desired energy, making this process very simple and efficient. Dual extraction with two carousels is performed on regular basis. The first TR30 (TR30-1) was commissioned in 1990 [2] and was initially producing 500µA extracted proton beams at energies up to 30 MeV. In 1995, after an upgrade program [3, 4], this cyclotron's capabilities were increased to 1 mA at 30 MeV. In 2002 another TR30 (TR30-2) was build and installed by ACSI at TRIUMF site. Both these machines are used by TRIUMF and NORDION for medical radioisotope production. Several other TR30s were built and installed by ACSI at different locations and are intensively used for same applications [5].

Our more than 22 years operational and maintenance experience with TR30-1 and 10 years with TR30-2, along with the nature of our production schedule (24 hours/365 days), have helped us to evaluate the long term performance stability of these cyclotrons. Both beam intensity and uptime are critical parameters in estimating the limits of our machines and we are evaluating the cyclotron output and performance in terms of charge delivered (mAh). Both factors have to be considered concurrently in order to assess the long term performances of our cyclotrons. Operating these machines for long periods at mA level is a challenge. Fundamental intensity limits were considered by R. Baartman in [6] and will be also presented in another paper in these Proceedings.

CYCLOTRONS SUBSYSTEMS

We are detailing here the failures and lifetimes of several components and how these are affecting our cyclotrons performances based on accumulated statistical data.

Ion Source and Injection Line

The beam levels extracted out of our ion sources are dependent on our production demands. We are running between 2 mA and 10 mA, with an estimated average of 6mA extracted H- beams. At this level the filament lifetime is about 35 days. A filament change takes about 5 hours (cool-down, filament replacement, pumping down and filament conditioning) and is the type of maintenance that is scheduled without affecting production. A new filament is not altering the cyclotron output, other than the downtime.

The components in the Injection Line that have a relatively high rate of failure are the inflector and the buncher. We have experienced about 10 TR30-1 inflector failures in the past 10 years and a similar rate in TR30-2. They usually fail before affecting the injected beam intensity, and maintenance and recovery takes about 4 days (cool-down, replacement, vacuum recovery, inflectors conditioning and tuning and tank RF conditioning). Figure 1 shows a TR30-2 deteriorated inflector, as opposed to a new inflector in Fig. 2. TR30-2 buncher is failing at a rate of about once every 3 years and is preceded by beam amplitude deterioration. TR30-1 buncher has a more robust design and a low rate of failure. Beam amplitude is recovered in about 2 days after a buncher repair. Gradual physical deterioration of ion source components and especially the extraction optics combined with limited accessibility due to the nature of our application affects the overall beam transmission.

Extraction Foils

There is typical beam deterioration during the lifetime of an individual foil, due to its physical depreciation. As a result, the beam size is growing along the beam lines, and eventually, cannot be compensated with beam lines and injection line optics tunes. A foil change will be necessary. Figure 3 shows a 5 foils carousel ready to be installed, while Fig. 4 shows a used set of foils. Every new foil needs additional beam tuning. To estimate the foils lifetime we considered our statistics on 2325 foils

Figure 1: TR30-2 eroded inflector.

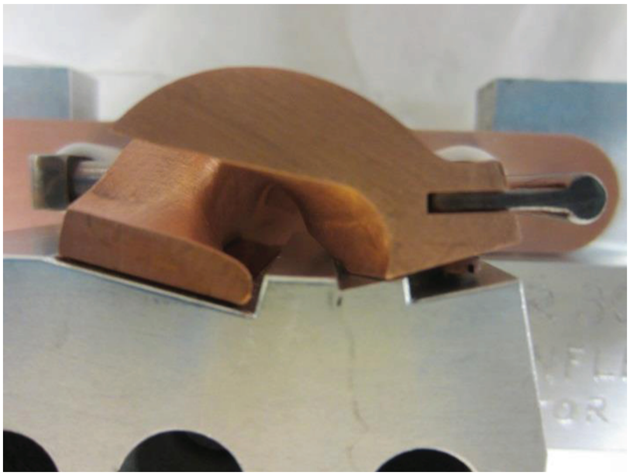

Figure 2: New inflector.

provided by our regular supplier, over a period of 5 years. There is an average of 23 carousels changes in one year on every beam line. TR30s are dual beam cyclotrons, and changing both carousels at one vault access is not always possible. As we regularly run different beam intensities for different targets, it might be interesting to underline that our experience doesn't show differences in foils lifetime (measured in total charge in µAh) when running different beam levels. The numbers are also comparable between the two cyclotrons. The differences come from the beam instability on the foil, either scheduled by production demand or inadvertent. The overall average lifetime considering all 4 beam lines is about 15 mAh. It takes about 5 hours to complete the job and recover after a carousel change, with most of the time spent on cool-down, tank vacuum recovery and RF conditioning. Figure 5 shows the tank vacuum recovery after a carousel change and Dees Voltage during RF conditioning. From our experience a couple of hours of RF conditioning after a carousel change helps a lot in maintaining a stable RF during runs. Foils and carousel changes represent an average of about 3% reduction in cyclotron uptime for a 5 foils carousel and is also a factor that limits target beam intensity.

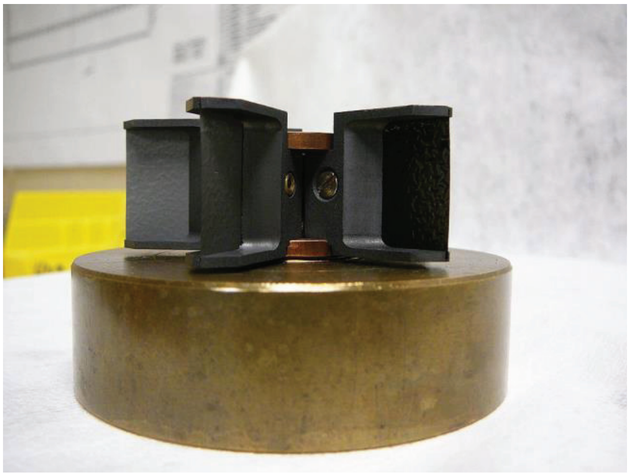

Figure 3: New extraction foils before carousel installation.

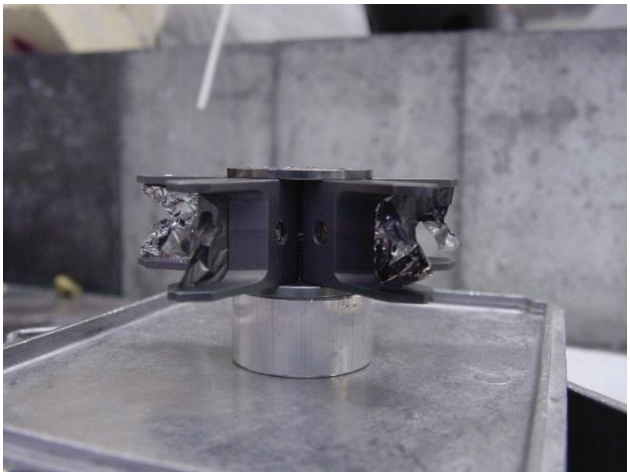

Figure 4: Used foils on extraction carousel.

RF Components

The RF components failure and maintenance contribution to the downtime of our TR30s is about a quarter of the total downtime and is reducing the cyclotrons' uptime by roughly 3%. Their impact to our cyclotrons charge output is mostly limited to downtime, with some effect on the beam intensity, though. RF tubes failures are most of the time predictable and replacements are generally scheduled without affecting production. Other RF components are failing without notice and affect the uptime, both in the RF amplifiers (high voltage capacitors, RF drivers), and RF components inside the tank (couplers, finger stock etc.). After 20 years of virtual continuous running we have been experiencing a pick in TR 30-1 RF components failures inside the tank. The Dees and the RF liners developed water leaks and cracks in several soldered parts. In 2009 a Dee water cooling line developed a leak and eventually we needed to replace both Dees assemblies. Based on our experience with our machines and input from similar equipment we consider that the TR 30s' Dees lifetime is about 20 years. The recovery time after the failure of the components inside the tank has to include long periods (days) of RF conditioning.

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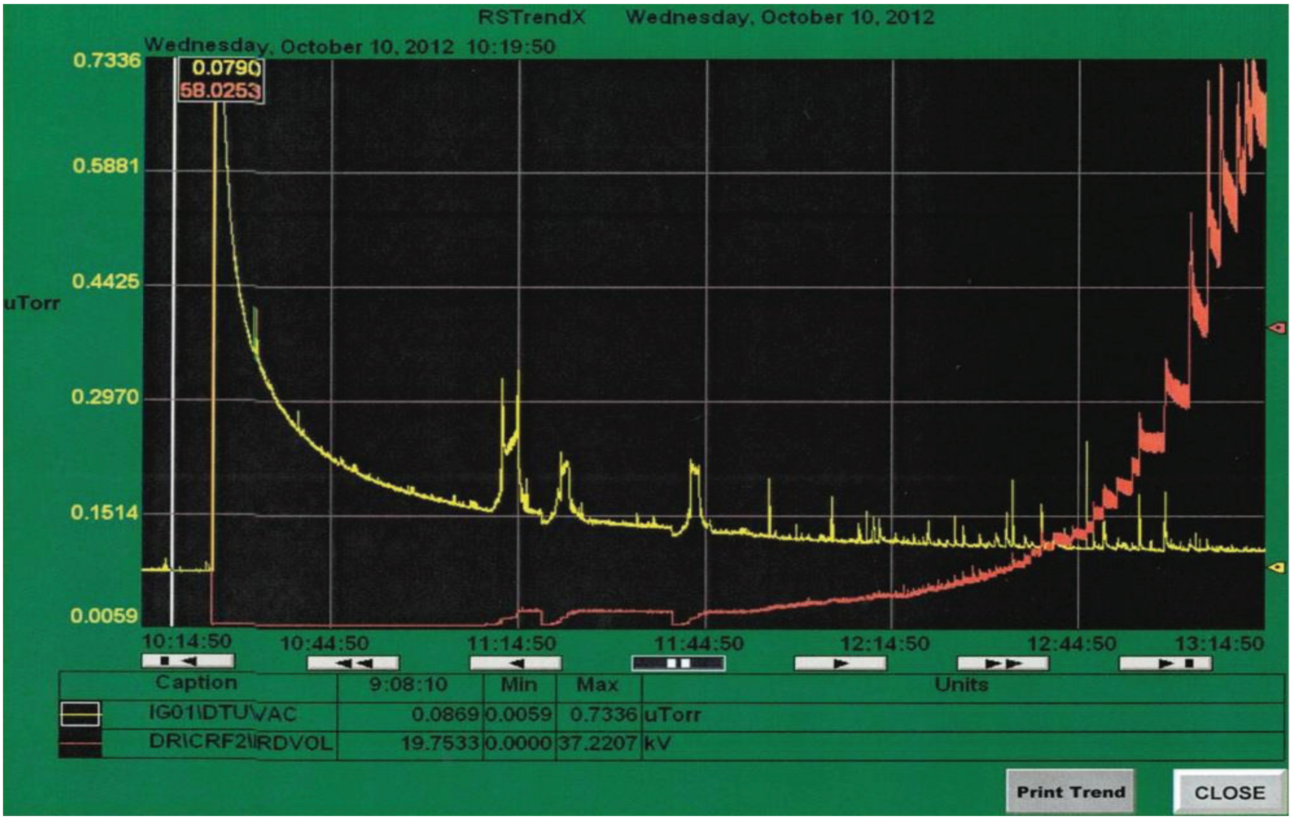

	Caption	9:08:10	Min	Max	Units
🟨	IG01\DTU\VAC	0.0869	0.0059	0.7336	uTorr
🟥	DR\CRF2\RDVOL	19.7533	0.0000	37.2207	kV

Figure 5: Tank pressure recovery after a carousel change (in yellow) and Dees voltage during RF conditioning.

They are followed by periods of limited beam intensity due to frequent RF sparks.

Diagnostics

We have several beam diagnostics in the cyclotron and along the beam lines. Most of the failures are occurring at the 1 MeV measuring probes with an average frequency of once every 16 months. This current probe is water cooled, totally intercepting and usually seeing about 1mA beam during the injection line tunings. It moves in and out the beam at the 5th turn. Fixing it requires tank access, and a few days of recovery time is typical, as RF conditioning is necessary. There is no beam amplitude limitation before and after the repair.

Centre Region

The average accelerated current is limited by the phase acceptance of the existing TR30 cyclotrons. Other limitations are resulting from space charge effects, both transverse and longitudinal [6]. These limits are becoming more evident when beams around and above 1mA are accelerated. Approximately 10 mA or higher DC beams have to be produced by the ion source in these cases and we observe an overall transmission deterioration at these levels. Almost all the beam produced but not accelerated ends on different parts of the Centre Region. Figure 6 shows part of the first turn and the inner wall of the central post after about two years of nearly continuous operation and Fig. 7 shows the same part after ten years. Sputtering of the metal surfaces is evident and has detrimental consequences in that area and eventually is affecting beam amplitude and stability (including RF). Accessibility for maintenance is limited by beam requirements in a 24/7, 365 days type of operation as well as by the high radiation fields inside the cyclotron and restricted physical space. Slight misalignments are possible and they are going to further contribute to overall transmission deterioration.

EXRACTED BEAM

We tested the limits of the extracted beam with the present optics along the beam lines. The maximum level transported on target was 800 µA and the limitation came from the beam spills along the beam lines and on target collimators. We need about 950 µA of total beam to be able to put 800 µA on target. An increase from 600 µA to 800 µA on target resulted in doubling the currents on the horizontal collimators (from 23 µA to 46 µA). All the attempts to reduce the beam losses along the beam line down to acceptable values were not successful. We assume this is due to extracted beam quality at higher intensities.

CYCLOTRONS AVAILABILITY

Table 1 shows both cyclotrons availabilities for several years and the overall averages for the periods since we have analyzed these data. We define availability as the ratio between the sum of beam running hours and standby hours to the total hours in a year (24x365). The time left consists of downtime and maintenance hours for all the cyclotron's subsystems including the target stations. The averages are 70% for TR30-1 (for the last 13 years) and 75% for TR30-2 (for the last 9 years). If we subtract the downtimes due to the target stations failures and add it to running hours the availability will increase to about 75% and 80%, respectively. The difference in availabilities between the two cyclotrons could be explained by the nature of our application, and the fact that we change the targets more often on TR30-1. This higher frequency is affecting the beam lines, and in some degree the tank pressures, resulting in more frequent RF conditioning in TR30-1. Our target stations are subsystems specific to our applications only. TR30-1 drops in availability in 2010 and 2011 are due to the cooling water leak in the Dees, after more than 20 years of operation, and the consecutive replacement work.

Table 1: Cyclotrons Availability

Year	TR03-1 [%]	Tr30-2 [%]
2000	66	
2001	71	
2002	76	
2003	72	
2004	83	68
2005	91	76
2005	73	78
2007	69	70
2008	64	81
2009	64	75
2010	56	79
2011	55	78
2012	66	70
Average	70	75

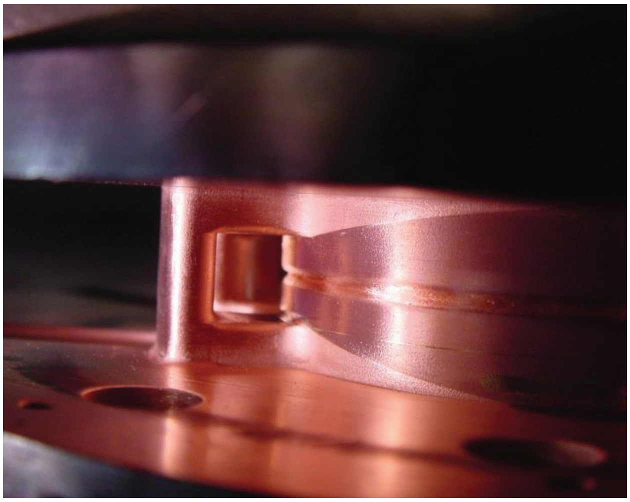

Figure 6: Centre Region post after 2 years of almost continuous beam.

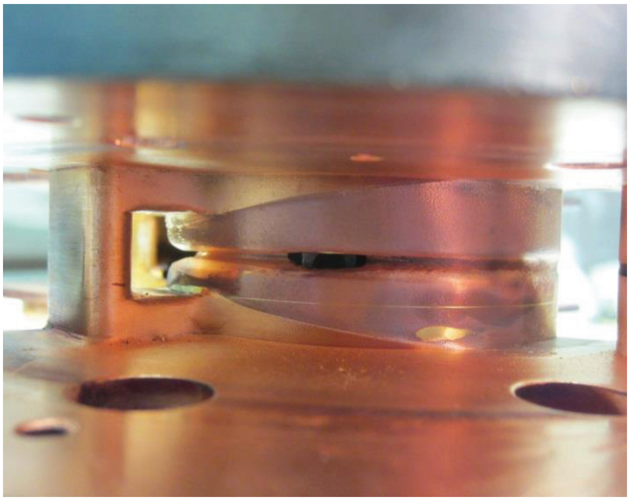

Figure 7: Centre Region post after 10 years of almost continuous beam.

CONCLUSIONS

We have looked at TR30s cyclotrons output and performance in terms of dose (mAh) and found a number of practical limitations in both current amplitudes and machine availability, when they are running close to the space charge limits and in a 24/7/365 type of operation. Some of these limits are possible to surmount with improvement in design, manufacturing and maintenance. Some are limits inherent to this type of cyclotron and a fundamental approach to its concept is necessary to be able to produce beams beyond 1.5 to 2 mA in long term applications.

ACKNOWLEDGMENT

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