ACTIVATION OF A 250 MEV SC-CYCLOTRON FOR PROTON THERAPY

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Abstract

Beam losses in dedicated 230-250 MeV cyclotrons for proton therapy cause radioactivity in machine parts. A systematic study has been performed of the activation of PSI's 250 MeV SC-cyclotron for proton therapy. Since the start of the cyclotron operation dose rate measurements have been made as a function of time at several locations in and around the cyclotron. Gamma ray spectra have been measured of selected iron inserts in the pole and of copper disks in the liner of the RF system. The isotopic composition of the activation has been derived and compared with activations calculated with Monte Carlo calculations (MCNPX). The data and beam history of the cyclotron allow predictions of the dose rate during service activities shortly after beam interruption as well as after a specified period of operation.

INTRODUCTION

Dedicated Cyclotrons of 230-250 MeV have been used at proton therapy facilities since ~12 years [1]. Beam losses during the acceleration and extraction cause build up of radioactivity in the cyclotron, having consequences for accessibility, service and decommissioning. At the Center of Proton Therapy at PSI a dedicated 250 MeV SC-cyclotron [2,3] is in operation since 2007. Although the cyclotron is compact, the design has been optimized to achieve an extraction efficiency of 80%, which is achieved routinely at PSI.

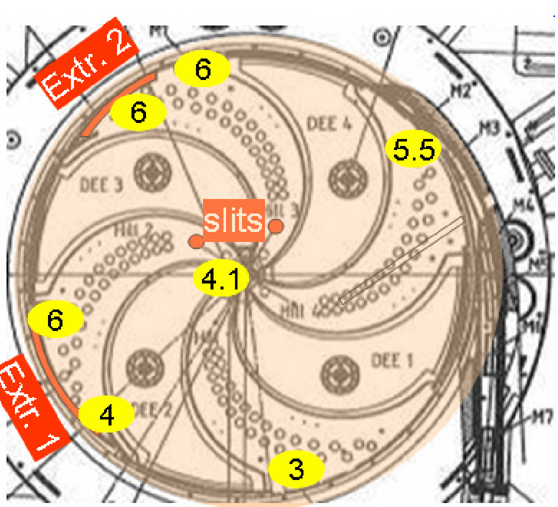

Figure 1: Dose rates (mSv/h) at different locations in the cyclotron, 10 cm from the surfaces, measured in 2010. The two phase slits and the two electrostatic extraction channels are indicated. The beam direction is clock wise.

The 20% beam loss at extraction will result in activation of the cyclotron. The other source of activation is the set of phase slits at 20 cm radius. Depending on the beam emittance from the source, 20-80% of the 11 MeV protons are intercepted by these slits. The here created neutrons and scattered protons thus also cause activation. The (tungsten) slits themselves (~6 mSv/h at 10 cm, 1 h after beam stop) can be retracted into the pole and therefore hardly contribute to the dose to the service staff. In order to estimate the activity and dose rates during future service tasks and at decommissioning of the cyclotron after many years of operation, a systematic study is going on since the first beam has been extracted.

METHODS AND MATERIALS

At every service activity that needs opening of the cyclotron, the dose rate is measured routinely with a standard dosimeter at several locations in the cyclotron, see fig.1. The measurements are performed at 10 cm distance from the surfaces and, as an indication for the dose to service staff, in between the pole caps in their open position.

At three occasions, dose rates at several locations have been measured as a function of time during 48 hours after beam switch off, using Genitron GammaTRACERs. The first time was in 2006 during the commissioning phase of the cyclotron, just after an acceptance test at which a beam with an intensity of 500 nA was extracted during 1 hour. The integral of all extracted beam until the moment of the measurement was only 2 µAh. The other two measurements have been done at service weekends, scheduled since the start of the patient treatment program. In 2010 an isotopic analysis has been made of the activation produced in iron inserts in the pole and in copper disks in the liner covering the pole. Gamma spectra from these samples have been measured in a calibrated HPGe setup at the Radiation Safety and Security Department at PSI. The spectra have been analysed automatically, yielding absolute activities of the gamma-ray emitting isotopes in each sample, at the reference moment in time: 1 hour after switching the beam off. The sample locations have been selected at different proton energies (radii).

A Monte Carlo calculation has been made with MCNPX 2.5.0 [4] to calculate the activity of created isotopes. A very simple model was used: 1 m^3 of iron or copper was hit by 10^6 protons of 50, 100 and 200 MeV or 10^6 neutrons of 6, 10, 50,100 and 200 MeV. The data generated by MCNPX have been processed with CINDER'90 [5,6] to obtain the activation at different moments in time, assuming a certain beam history.

RESULTS AND DISCUSSION

Dose Rate inside the Cyclotron

Figure 1 shows the top view of the lower cyclotron pole with the dose rates measured 50 minutes after stopping the beam in August 2010. The beam integral at that moment was 805 µAh. The dose rate at the exit of extraction channel Extr1 is higher than at the entrance. Also the dose rates at Extr2 and at the entrance of the channel through the SC-coil are relatively high (6 mSv/h), although beam measurements with foil burns have clearly shown that no beam is lost at these locations and that the beam leaves Extr1 without touching the septum or cathode. Therefore these dose rates must be caused by scattered protons and neutrons created in the first septum. These are forward peaked and will cause activation downstream. The relatively low dose rate of 3 mSv/h at 45° in front of Extr1 supports this assumption.

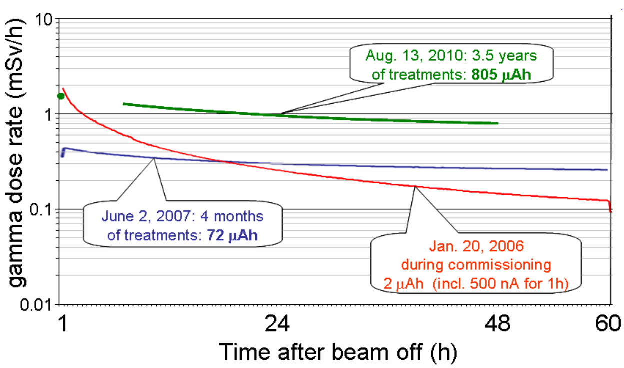

Figure 2: Dose rate in between the pole caps, after switching the beam off.

The measured dose rates in between the open pole caps as a function of time, are shown in figure 2. Contrary to the rather constant dose rates measured in 2007 and 2010, the measurement during the cyclotron commissioning in 2006 shows a strong contribution of isotopes with a short half life. This is due to both the low activity accumulated during the preceding beam history (2 µAh) and to the high extracted beam intensity during one hour just before opening the cyclotron. In normal operation, however, the beam intensity averaged over the day is 20-40 nA, yielding much lower contributions of short living isotopes.

Observed Isotopes in Iron and Copper

The distribution of measured gamma emitting isotopes 1 h after beam switch off, is shown in figure 3. Apart from the strong Cu^{64} and Cu^{61} contributions, the distribution of the isotope types is broader in copper than in iron. In iron the $Mn^{52,54,56}$ isotopes dominate the distribution. The total specific dose rate at 10 cm, calculated from the specific activities, is larger from copper (180 nSv/h.g) than for iron (74 nSv/h.g). In copper more than 90% of the dose rate is due to the decay of Cu^{64} (~70%) and Cu^{61} (~20%), with half life of 12 h and 3.4 h respectively. Most of the isotopes in iron and copper have a half life time of less than 100 days. Exceptions are Mn^{54} (312 d) in iron, Zn^{65} (243 d) in copper and Co^{60} (5 y) in both iron and copper. All isotopes show an increase of specific activity with the radial location of the sample. This correlates with the higher beam density and the higher energy of the protons and eventually created neutrons at large radius.

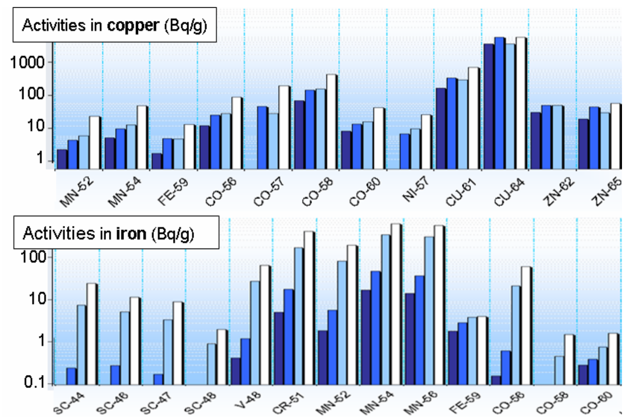

Figure 3: Measured specific activities of the most important isotopes in copper (top) and iron (bottom). The different bars at each isotope reflect the sample locations in the cyclotron: the brighter the line colour, the larger the radius of the location in the cyclotron.

Calculation of the Activation of Iron and Copper

From the MCNPX calculations with protons or neutrons at the different energies, the amount of the isotopes created in copper and in iron has been calculated. From these results the relative activity per isotope has been calculated at the reference moment. The calculations also yield isotopes that do not emit (measurable) gamma rays. The obtained distributions (fig. 4) look very similar to the measured data in figure 3.

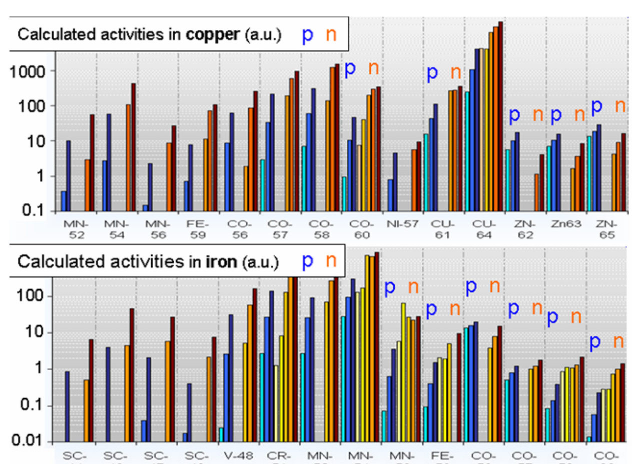

Figure 4: Calculated specific activities (a.u.) of the most important isotopes in copper (top) and iron (bottom). The colours of the different bars at each isotope reflect the incident particle (blue: p, red: n). Darker colours indicate higher energy.

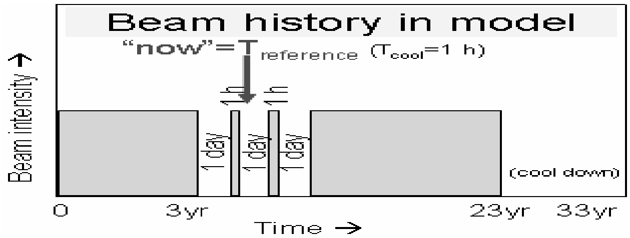

Figure 5: Beam intensity as a function of time, as used in the calculations of the activity.

In fig. 4 it can be seen that in most cases the activities created by protons are less than those created by neutrons. In general a larger specific activity is observed when higher energies (p or n) are used, which is consistent with the experimental observations.

ANALYSIS

Estimation of Future Activation

Despite the very coarse model and the lack of any energy spectrum usage, the close resemblance between the calculations and the measurements allows a normalization of the calculated distribution to the measured distribution. Separate scale factors have been calculated for iron and copper, each defined as the ratio between the integral of the calculated activity distribution and the integral of the measured activity distribution.

The thus obtained factors will also be used to scale the calculated distributions at later moments in time, given the assumed history of beam usage shown in figure 5. Figure 6 shows the remaining activity after a running period of 23 years with a continuously extracted 250 µAh per year, followed by a cool down time of 1, 10 and 100 years. The specific activity in copper is higher than that in iron. Fortunately the volume of the copper parts is smaller and easier to process than the big iron pole pieces.

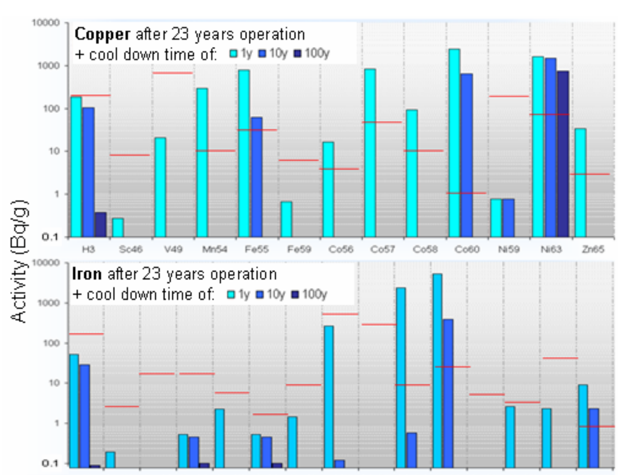

Figure 6: Calculated specific activities of the isotopes in copper (top) and iron (bottom) after 23 years of continuous operation, followed by a cool down time of 1, 10 and 100 years. The horizontal lines indicate the legal limits for non radio-active disposal.

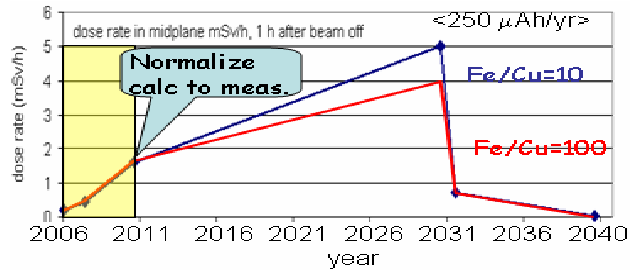

Figure 7: Estimated dose rate in the mid plane between open pole caps, based on the 2010 measurements and scaled calculated dose rates, assuming 250 µAh/y.

Scaled to the 2010 measurement of the dose rate at the mid plane between the poles (fig. 2), the calculated dose rates from iron and copper have been extrapolated into the future. In figure 7 the results are shown. Since the contribution to the total dose rate of iron with respect to the one of copper is not yet known, curves with different contribution (weight) ratios are shown. The total dose rate is estimated to rise from 1.5 mSv/h in 2010 to 4-5 mSv/h in 2030. Of course a more intensive beam usage will increase this value.

CONCLUSIONS

After 3 years of patient treatments the typical dose rate close to the pole has grown to 3-4 mSv/h, with local hot spots of 6 mSv/h. Already after a few months of daily patient treatments, the dose rate at the mid plane of the opened cyclotron is hardly decreasing shortly after beam off. Therefore waiting times until a few days will not help to limit the dose to the staff. The calculations and the measurements show that the activation increases with the radius in the cyclotron and that it is mainly due to activation by neutrons. A shift of the slits more into the cyclotron centre is expected to reduce the rise in dose rate. The calculation model, although very crude, indicates good qualitative agreement with the measurements of the isotopic content of the iron and the copper. By scaling the calculations to the measurement results, a prediction can be been made of the isotopic content, activity and dose rate at any moment in the future; a method that could be employed at other cyclotrons as well.

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