PERFORMANCE OF THE HARPER HOSPITAL CYCLOTRON; EFFECT OF PULSED RADIO FREQUENCY*

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ABSTRACT

In the years 1984-1990, the National Superconducting Cyclotron Laboratory constructed and tested a K100 superconducting cyclotron to provide neutrons for cancer therapy; this cyclotron was installed in the Gershenson Radiation Oncology Center of Detroit's Harper Hospital in July 1990 and is now in routine use providing intense neutron beams for radiation therapy. In the process of starting up the cyclotron, a 1 in 5 pulsed operation mode was introduced to limit the beam current to levels required by target power limits – this pulsed mode easily provides beam currents at the 10 microamp design level (corresponding to approximately 1 rad/sec at the system isocenter and 2 minute treatment times). Moreover, radio frequency power used by the system is reduced to about one fourth of its unpulsed level, and cyclotron operation is exceedingly stable; this pulsed mode has therefore been adopted as the standard operating mode for the cyclotron. In the pulsed mode, beam power during the pulse is comparable to the resistive power loss in the rf cavity, and interesting new accelerator physics phenomena show up in the instantaneous time dependance of the beam during the 2 millisecond "beam-on" pulses.

1. INTRODUCTION

The K100 superconducting cyclotron for neutron therapy has been described in a number of earlier papers[1] including a report at the last Cyclotron Conference.[2] At the time of the report at the previous Conference, the cyclotron had just started up, and reliable measurements of beam current were not available. Operation was also severely handicapped by the absence of shielding which caused radiation protection trips to occur almost immediately. In following months shielding was installed around the cyclotron and beam current monitors were calibrated.

In the first months of operation with this improved configuration, beam currents were low compared to the specification and changes in the ion source and in the central region were introduced to correct this difficulty. The most important changes were: 1) reducing the clearance between ion source and dee to 3 mm, 2) reprogramming the central region slit system to correspond to a dee voltage of 33 kv rather than the 40 originally contemplated, and 3) changing the design of the cathode assembly in the ion source. With these changes, beam currents shifted from being too low to being too large – currents of 50 microamps were common and Beryllium targets melted on two occasions (overcurrent interlocks were enforced by a computer control system which had a two second cycle time – too slow to fully protect the target – much faster hard wired interlocks have since been installed). Efforts to achieve a smoothly adjustable operating current by turning down the rf voltage or by turning down the ion source arc current were overly sensitive and/or unstable and a circuit for lowering beam current by operating in a pulsed rf mode was next introduced. This last change was strikingly successful in both its current control aspect and in several unexpected other aspects – operation overall became extremely stable, rf power levels dropped to approximately one quarter of the unpulsed level, and tuning and other parameters were much less sensitive to thermal shifts. Given this ensemble of very helpful improvements, the pulsing circuit was adopted as a permanent part of the cyclotron system and operation since that time has been extremely smooth and reliable.

2. ACCELERATOR DESCRIPTION

The neutron therapy cyclotron, as described at the previous conference,[2] has the unusual feature of rotating on a full 360 degree vertical arc relative to a patient positioned at the center of this arc. If the patient is positioned to put the tumor at the center of this arc, the "isocenter" of the system, the neutron beam from every cyclotron orientation intersects the tumor whereas surrounding normal tissue is significantly exposed only when it is on the side of the patient facing the cyclotron and is therefore protected (when all treatment directions are summed) relative to the lethal doses administered at the tumor site.

The rotation system for the cyclotron consists of two large (4.27 m dia) steel rings which support the cyclotron and an opposing counterweight; these rings are supported by, and turn, on four large roller assemblies as indicated schematically in Fig. 1 and photographically in Fig. 2, (with H. Blosser and W. Powers standing on the cyclotron). On July 9, 1990 the cyclotron and support ring system were taken by motor-truck to Detroit and installed in an already prepared room in the Gershenson Radiation Oncology Center of Harper Hospital. Figure 3 is a photo showing the cyclotron as it was being lowered into the therapy room and Fig. 4 is a photo showing the cyclotron as it now appears to a patient entering the treatment room.

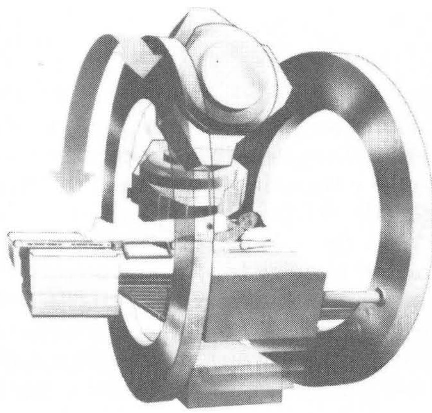

Figure 1. Schematic view of the Harper Hospital neutron therapy system showing the cyclotron mounted between two large rings which move it on a veritcal arc about the patient.

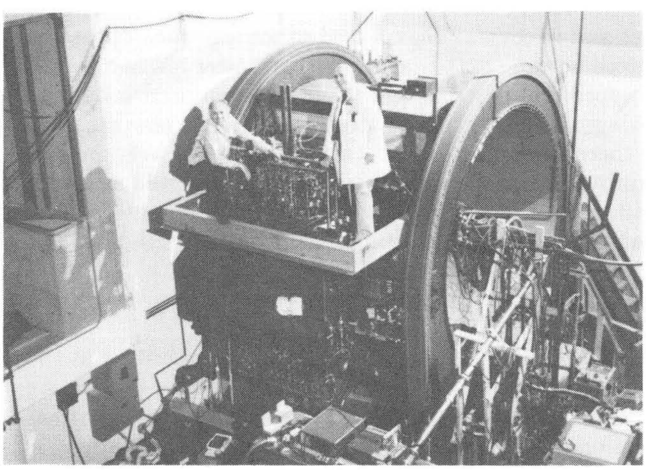

Figure 2. View of the Harper cyclotron and support ring system at NSCL with H. Blosser (left) and W. Powers.

In routine operation, the cyclotron is filled with liquid helium early each morning and the magnet is ramped to its operating current. Filaments in the final stage tube of the rf amplifier are also turned on at this point and, like the magnet, are left on for the day. Ion source arc current and rf drive are turned on and off at the beginning and end of each treatment, the pair of systems being used to provide turn-off redundancy.

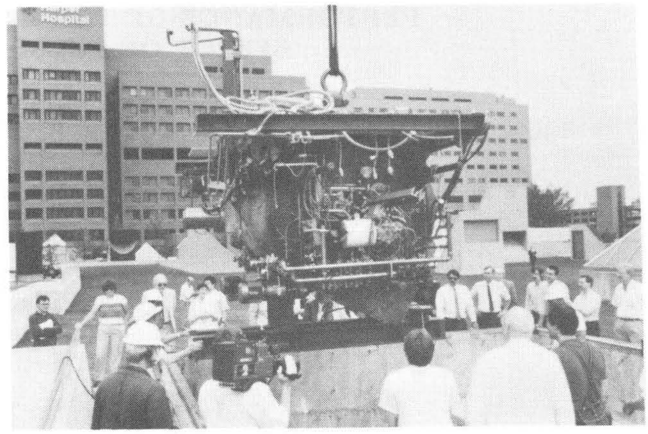

Figure 3. View of the K100 cyclotron being lowered through the roof of the Harper Hospital Oncology Center.

At present (June 1992) an accelerator technician or a physicist is usually present during a treatment run and also customarily starts up the machine at the beginning of each day. A typical treatment run consists of aligning the patient relative to markers established in the treatment planning sequence, checking and closing radiation areas, pre-setting the dose monitor system to turn off the cyclotron when the stipulated dose has been delivered (or when the time interval allowed for the treatment has expired), and setting a keyed interlock which enables the cyclotron to turn on. The cyclotron beam is then brought on by pressing "ion source on" and "rf on" buttons in sequence (normally no other control action is required to activate the beam). When the stipulated dose has been delivered (or when the preset time has elapsed) the source and rf are turned off by a "treatment complete" interlock and cannot again be turned on until the dose control system is reset and the key control again activated to authorize further operation.

Since normal cyclotron beam turn-on has been found to consist of simply pressing the "on" buttons for source and rf, modifications to the control system are in process to have the key switch on the therapy console automatically initiate the "on" condition in the ion source and rf circuits; the therapy technician will then be in complete control of the treatment in the same fashion as is customary on X-ray units and the cyclotron technician or physicists will only be summoned in the event of difficulty. A major virtue of this operating mode (associated with the operating stability provided by the pulsed rf) is that a cyclotron operator is clearly not needed which is an important saving in operating costs.

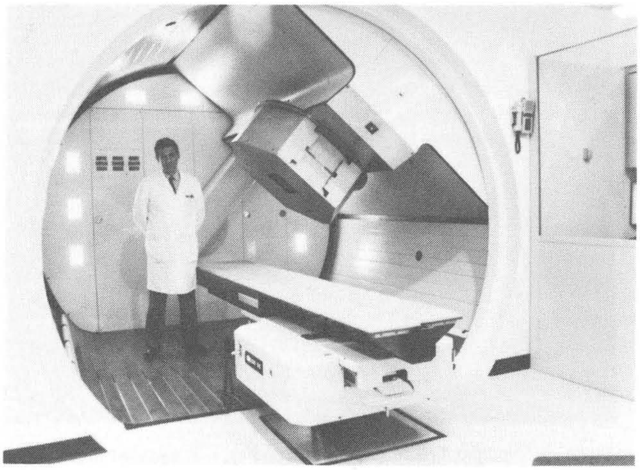

Figure 4. The Harper Cyclotron as it appears to a patient arriving for therapy. The large object above the patient table is the neutron collimator consisting of 12,000 adjustable 3 mm dia. Tungsten rods.

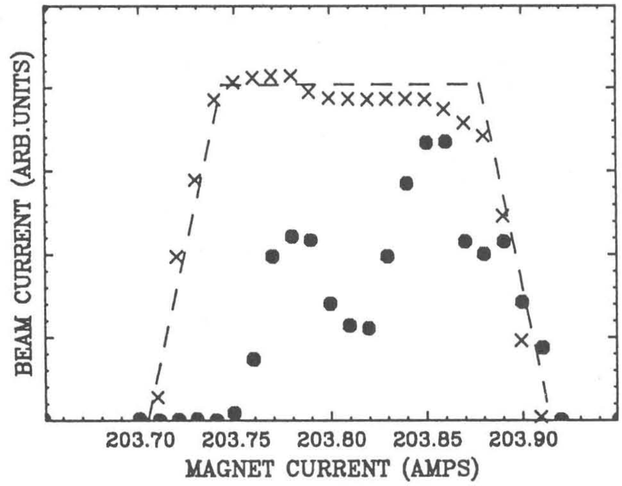

Figure 5. Plot of target current vs. magnet current with target at 286 millimeter for the x data and 298 millimeters for the circle data. The dashed line is the expected 286 millimeter curve.

3. BEAM CHARACTERISTICS WITH PULSED RF

The first hint of unusual beam phenomena associated with the rf pulsing mode came from magnet tuning curves, i.e. graphs of beam current vs. magnet current. Figure 5 shows two such curves, one with the main target at a radius of 286 mm, the other with the target at 298 mm. (The nominal full energy target radius is 305 mm.) The 286 mm curve has the dominantly trapezoidal shape which one expects from such tuning curves, the flat top of the curve indicating the "phase window" available for deviations from isochronism with the given rf voltage and the linear edge indicating the "phase width" of the beam relative to the rf. (The curve provides the data to compute the phase of the beam relative to the rf at any magnetic field setting using the formalism of Garren and Smith.[3]) In contrast with the 286 mm curve, the 298 mm results show strong "pathological features", i.e. peaks, valleys, plateaus, etc. – structure which should not be possible if a single ion species is being accelerated in a normal cyclotron.

A number of possible explanations of the strange 298 mm pattern have been considered. One hypothesis for explaining the strange struture is that the beam consists of several Q/A components, a situation which is easily possible at Q/A = 1/2; radiation monitors, however, showed no change in neutron production per microcoulomb at various points on the 298 curve, indicating that the entire structure was dominantly due to deuterons, any other ion being at least x5 less effective than the deuteron in neutrons per microcoulomb. The relatively sudden appearance of the structure in a radius interval of only 12 mm is also quanitatively inconsistent with Q/A groups seperating due to differences in phase slip. A number of other beam dynamics explanations have also been explored but no phenomena in reasonable correspondence with the Fig. 5 data has come up.

Searching for other measureable aspects of the pulsed beam brought up the idea of looking at the time dependance of the beam on the target, which turned out to be quite surprising. Figure 6, for example, shows a pair of scope traces on a 2 milli-sec/cm scale, the upper trace giving the rf on a dee stem pickup loop and the lower giving the beam current on the target. The rf trace shows the programmed 2 milli-sec "on", 8 milli-sec "off" pattern of the pulsing, whereas the lower trace shows for each rf pulse the surprising pattern of a large target current component at the beginning of the rf pulse, followed by an interval of zero current, followed by a second, smaller target current pulse. The instantaneous current in the target pusles is quite large; the time average beam on this run was 12μa, indicating that the large peak is at about 170μa. Beam power in this time interval is then about 8 kw, a level of the same order as the nominal 25 kw rf drive provided by the main power amplifier.

The rf trace in Fig. 6 shows a considerable "droop" with time and the possibility that the beam was passing first inside and then outside of some central region obstruction came to mind as a possible cause of the observed double peak structure. This hypothesis however had difficulty with another observed aspect of the phenomena, namely that very small changes in either the dee fine tuner or in the magnetic field would cause the time structure to shift relative to the rf pulse as indicated in Figs. 7 and 8. (The horizontal scale has been expanded in these Figs. relative to the scale for Fig. 6 to better show the pulse.) Changes in the magnet current of a few parts in 10,000 were sufficient to shift the pulses from

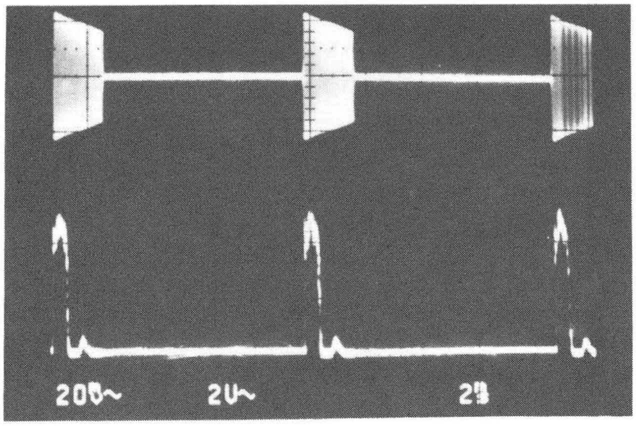

Figure 6. Dual beam scope trace from an rf pickup loop (top) and from the full energy target (bottom) showing three 2 millisecond 100 Herz pulses on a 2 ms/cm time scale. Time average beam $12\mu a$.

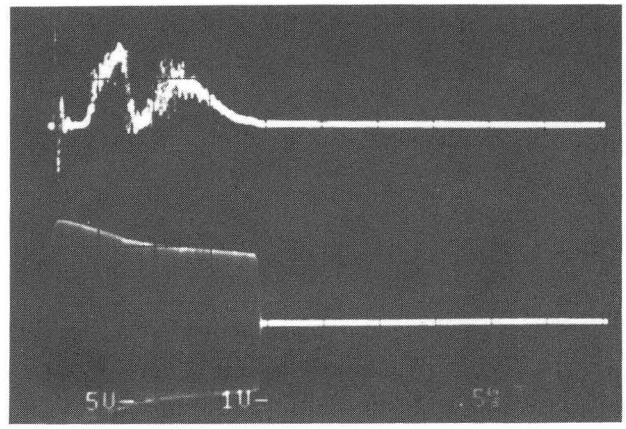

Figure 8. Scope trace similar to Fig. 7 except a further adjustment of the dee fine tuner has moved the first target current peak away from the origin and changed the time average beam current to $8.4\mu a$.

the Fig. 6 pattern to that of Figs. 7 or 8 and it seems quite unlikely that the transverse phase space could be so sharp that such a time shift could happen due to the microscopic movement of the early turns caused by a 1 in 10,000 magnetic field shift. Two other aspects of the observations are difficult to reconcile with this hypothesis namely: 1) raising and lowering the rf voltage changed the amplitude of the pulses, but did not cause their time position to shift and 2) the sharp on/off/on structure shown in Figs. 7 and 8 never appears on a plunging target at 200 mm radius, whereas it would be expected to show on this target in the same way if the phenomena is due to some aspect of the cyclotron's central region.

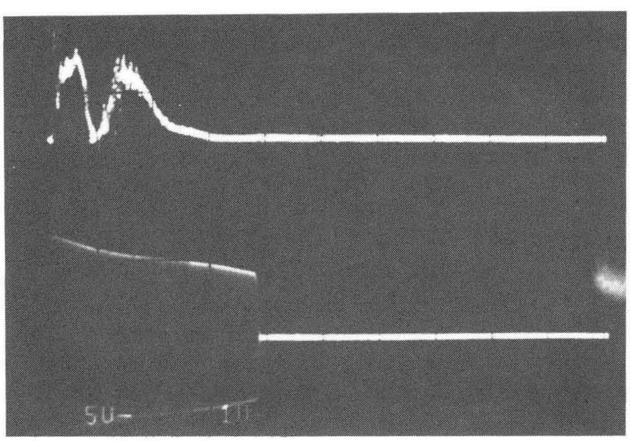

Figure 7. Target current and dee volts on an expanded time scale (0.5 ms/cm) with the dee fine tuner shifted slightly relative to Fig. 6 and with the target trace on the upper scale. This setting reduced the beam current to $9.2\mu a$ and changed the two target current peaks to approximately equal magnitude.

Another conjecture as to the origin of the pulsing phenomena is that the beam is exciting an unusual rf mode which could actually be at a much higher frequency. (The beam pulse is quite narrow in time, as indicated by the edges of the 286 mm trapezoid in Fig. 6, and its Fourier components thus include strong harmonics well into the Ghz range.) A survey of possible higher modes was made in the computer using a transmission line representation of the cyclotron resonator. Several modes showed up in the computer search near harmonics of the main frequency and with waveforms such as push-pull-pull, etc. which would be expected to mainly disturb the beam at large radii. Noting these results, actual modes in the cyclotron were checked experimentally by coupling a frequency synthesizer into the main rf drive line of the cyclotron (replacing the main power amplifier) and using a spectrum analyzer to observe the response in a dee stem pick up loop. Table I gives a partial presentation of the wealth of peaks found in this search, with "height" (of the line on the spectrum analyzer) as an indication of the coupling effectiveness and/or the "Q" of the particular mode. The right hand column of Table I shows an expanded search in the vicinity of the second, fourth, fifth, and ninth harmonics of the main rf drive frequency (210, 420, 525 and 945 Mhz). A relatively weak mode shows at 420 Mhz i.e. at the exact fourth harmonic frequency to within measurement error, and stronger modes occur nearby at 439 and 442 Mhz. Similarly near the fifth harmonic, several modes which the beam could excite are found near the harmonic frequency, and likewise for the ninth harmonic.

These higher order modes if excited could deaccellerate the beam by simply absorbing energy from the beam or could throw the beam off center in the case of push-pull-pull configurations or could disturb the axial motion in the circumstance of modes which are anti-symmetric relative to the median plane. Many of the higher or-

Table 1. Harper cyclotron rf modes (exicted through coupler). "Height" on 10db/cm scale. "Fine Scan" near 2, 4, 5, and 9th harmonics of 105 Mhz.

	Course Scan		Fine Scan	
mode	freq. Mhz	height (cm)	freq. Mhz	height (cm)
1	105	5.6	207.8	1.0
2	146	3.6	227.1	1.1
3	158	3.6		
4	177	2.6	420	1.1
5	207	2.4	439.44	4.4
6	219	3.0	442.11	4.6
7	229	2.1		
8	240	3.9	508.75	3.1
9	271	3.0	513.0	2.0
10	355	3.6	525	2.0
11	365	4.2	529	3.6
12	386	4.6	542	4.2
13	439	4.2		
14	453	3.5	941	2.0
15	465	4.0	942	2.8
16	482	5.7	943.06	2.0
	peaks above 3.5 only		944	1.6
17	511	4.0	944.5	1.6
18	536	4.8	945.0	2.0
19	619	3.6	945.37	2.4
20	923	3.7	946.8	1.1
21	938	3.3		
22	943	4.0		

der modes have a voltage null near or at the center of the cyclotron and peak at the outer edges of the dee (like a half-wave open ended line); such modes would be preferentially excited by the large radius beam and be consistent with the pulsing phenomena not appearing on the 200 mm target. The sensitivity of the pulse pattern to small changes in the magnetic field and to fine tuning of the rf cavity are also plausibly consistent with this explanation, the shift with magnetic field shifting the beam rotation frequency slightly and possibly moving the frequency across the response curve of a very high Q mode, and the shift with fine tuning possibly preferentially shifting the mode frequency of a higher order mode so that the mode sweeps through the beam rotation frequency.

An experiment to directly observe a possible higher order mode was attempted with a null result, namely to introduce a special triggering circuit for the spectrum analyzer which would trigger the analyzer at any desired point in the beam pulse structure. If a higher order mode appeared in correlation with triggering at null points of the beam current, the higher mode hypothesis would have been strongly supported. The experiment, however, showed no such modes detectable above the background. This could mean that the dee stem pick up loop to which the analyzer was coupled was at a null current point of the desired mode, and a second search with a capacitive pick up probe near a dee would give a very different view of possible modes, but this is rather difficult to implement from the hardware aspect, the necessary changes leading to excessive interference with the ongoing medical program. It then seems likely to the authors that the interesting time structure of the Harper cyclotron beam is due to excitation of higher modes in the cavity by the beam, but experiments to fully confirm this hypothesis are not likely at the present time.

4. SUMMARY

The superconducting K100 medical cyclotron is in routine use for treatment of cancer patients and performs with superb stability and reliability. Control systems are being modified so that the cyclotron can be turned on and off with a key switch on the therapy console with no operator present at the cyclotron console. An interesting time dependence of the beam structure is perhaps due to excitation of higher order modes by the very intense beam which is circulating in the cyclotron during the pulses. This hypothesis has not been rigorously confirmed.

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*Work supported by Harper Hospital. Use of NSCL facilities through National Science Foundation and Michigan State University approval.