DEVELOPMENTS IN THE DESIGN OF PROTON AND ION ACCELERATORS FOR MEDICAL USE

P.J. Bryant, CERN, Geneva, Switzerland

Abstract

Accelerators and medicine have been close companions since cyclotrons first made biological studies with particle beams possible in the 1930s. Later improvements, such as H-minus (H^-) extraction, made cyclotrons the foremost, commercially-available producer of medical isotopes. Although the world's first hospital-based proton treatment centre, Loma Linda, uses a synchrotron, the cyclotron is now also establishing a dominance in proton centres using passive beam spreading. However, two trends indicate a slightly different direction. The first is towards light ions and the second is towards 'pencil' beam scanning with active energy control. Together, these point to a new generation of synchrotrons with slow-beam-extraction systems that allow time for on-line dosimetry and provide very smooth spills. There are several variants for the slow extraction including the use of a betatron core and rf knockout. There are also methods for improving the spill quality such as rf channelling buckets and rf noise. The use of a synchrotron has the consequence of unequal emittances in the extracted beam, which affects the design of extraction lines, the rotational optics of gantries and the passive and active scanning systems.

1 CYCLOTRONS

Lawrence's first cyclotron worked early in 1932 [1]. Although this machine was conceived for the high-energy physics community, experiments were already underway by the end of the 1930s for the treatment of cancer by neutrons [2]. However, the cyclotron first dominated world markets in radionuclide production [3]. Here, the important development of H^- cyclotrons, after an initial setback, made it possible to reach much higher intensities and to extract with low losses by stripping. The commercially-built CYCLONE 30 (Fig. 1), which appeared in the late 1980s, became a de facto world standard. This machine uses extraction by stripping, the "deep valley" magnet design and a multi-cusp H^- source mounted externally, which allows a high-quality vacuum to be maintained within the cyclotron.

In general, the cyclotron owes its success to its robust and compact design, a quasi-continuous beam and adequate intensity. The same qualities are now establishing the cyclotron in proton therapy centres that use passive spreading (i.e. multiple Coulomb scattering) for the beam delivery. The first fully-commercial, in-hospital installation is now nearing completion at the Massachusetts General Hospital [4]. The merit of using protons for therapy by exploiting their Bragg peak behaviour was first suggested by R. Wilson in 1946 [5].

Another line of development is super-conducting cyclotrons that are sufficiently compact to be mounted directly on a gantry and to be turned around the patient. This has been successfully applied to a neutron therapy unit in the Harper-Grace Hospital in Detroit [6]. In the field of beam delivery based on a cyclotron, a voxel (volume-pixel) treatment system with a compact gantry is being developed at PSI, Villigen [7].

Figure 1: CYCLONE 30 cyclotron (courtesy of IBA).

2 SYNCHROTRONS

Although cyclotrons are well established in proton therapy, the world's first hospital-based proton therapy centre, Loma Linda [8], uses a synchrotron. The accelerator equipment for this facility was built with the help of Fermilab and was opened in 1990. A return to synchrotrons now seems possible with the recent trends towards the use of light ions (usually carbon) and high-precision raster scanning, as currently being demonstrated at GSI, Darmstadt [9]. In raster scanning, the tumour is treated in a series of slices of decreasing range. Once a slice has been 'painted' by a magnetically-steered 'pencil' beam, the energy is lowered to reduce the depth of the Bragg peak and 'painting' is repeated on the next slice. The advantage of raster scanning is that it can irradiate complex, and even re-entrant shapes while sparing the surrounding tissue. The conjunction of light ions and raster scanning is advantageous, since ions are less affected by multiple scattering in the patient's body and hence small spot sizes can be produced more accurately than for protons.

Synchrotrons are better suited than cyclotrons to the acceleration of the higher-rigidity ions and to the delivery of well-focused beams of a precise, controllable energy, as needed for raster scanning. To meet the requirements of raster scanning and to respect the prescribed dose to ±2.5% requires a continuous on-line intensity measurement and beam control. The synchrotron therefore operates with a third-integer, slow-extraction scheme that dilates the spill time to about 1 s to facilitate on-line dosimetry. Typically, operation would be 'ramp and hold' with a minimum cycle rate of about 0.5 Hz. This allows synchronisation with breathing if required. Some 60 spills of 4×10^8 carbon ions each at the patient, or 60 spills of 10^{10} protons each would comprise a single treatment (known as a 'fraction') with a treatment time of about 2 min. The beam spot should be variable between 4 and 10 mm full width at half height and have a positional stability and precision of a few tenths of a millimetre. For carbon ions the synchrotron would be ~75 m in circumference and would produce ions of ~400 MeV/u, whereas for protons these figures would be ~45 m and ~220 MeV.

Such a machine needs to be precise in all respects, but *especially it needs a smooth spill*. This is so important that it becomes the overriding design criterion and will be the main topic in the following sections. A poor spill quality makes it necessary to lower the spill intensity and the scanning speed, so that the spill imperfections can be corrected by the on-line scanning system.

3 RESONANT EXTRACTION

Resonant extraction schemes fall into three categories schematically shown in Fig. 2.

• *Quadrupole-driven extraction (classic).* Selects large through to small betatron amplitudes by moving the resonance.

• *Acceleration-driven extraction.* Selects particles with a fixed betatron amplitude-momentum relation by moving the beam into a stationary resonance.

• *RF knockout extraction* [10]. Selects constant betatron amplitude by blowing the beam up onto a stationary resonance.

All these schemes share three fundamental features:

• Losses on the extraction septum
• A sensitivity to tune ripple that is legendary, and
• A small emittance in the plane of extraction.

Some loss on the extraction septum is inevitable due to the continuity of the extraction separatrix, but the degree of loss depends on how the extraction is set up.

An analysis of the tune ripple will quickly indicate the need for ripple specifications tighter than 1 in 10^6 at kHz frequencies. The same analysis will also show that relief can be obtained by increasing the tune speed (dQ/dt) with which the particles enter the resonance. A scheme for achieving this will be presented in Section 6.3.

The emittance in the plane of extraction can be estimated by equating the beam's phase-space volume (transverse × longitudinal emittances) in the ring and in the spill. The momentum spreads will be of the same order, but the extracted transverse emittance will suffer a strong reduction by the ratio of the revolution time to the spill time (~10^6). Coupling from the vertical emittance in the sextupoles will increase this value and dispersion effects, closed-orbit changes and ripple, will hide it, but the true extracted emittance will still be very small.

The following sections will be devoted to reviewing the design measures that can be taken to:

• Control the extraction losses,
• De-sensitise the machine to ripple, and finally to
• Accommodate the transverse emittance asymmetry.

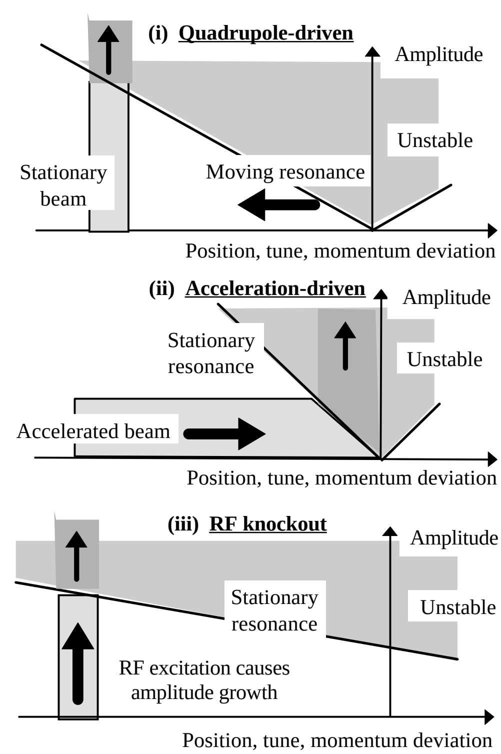

Figure 2: Slow-extraction schemes.

4 CONTROLLING LOSSES

In a quadrupole-driven extraction, the stable, phase-space triangles shrink during the extraction. The momentum spread is usually small, so the physics can be adequately represented by a single triangle as shown in Fig. 3 in normalised phase space (X, X'). The important point is that the separatrix moves as the extraction proceeds, leading to variable losses on the septum where it cuts the separatrix. This loss cannot be eradicated, but it can be reduced to an absolute minimum, by using the acceleration-driven extraction in which the beam is moved instead of the resonance and by applying the Hardt condition [11]. The beam can be moved by a betatron core [12] or stochastic noise [13].

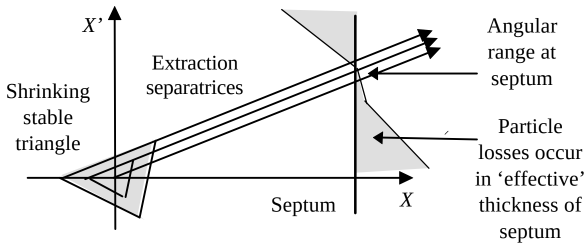

Figure 3: Movement of the extraction separatrix.

The Hardt condition aligns the extraction separatrices for all momenta along the resonance line that is 'cutting' the beam (see Fig. 4). Thus, all particles are made to leave the machine on the same path and the septum can be aligned for minimum loss. The condition is derived by removing the momentum dependence from the general equation for a separatrix.

$$D_n \cos\alpha + D'_n \sin\alpha = -\frac{4\pi}{S} Q' \qquad (1)$$

where (D_n, D'_n) is the normalised dispersion function at the septum, α is the anticlockwise angle from the X-axis to the perpendicular to the extraction separatrix, Q' is the chromaticity and S is the sextupole strength. Effectively, the Hardt condition moves the stable triangles along the direction of the dispersion vector by varying the chromaticity. It is more convenient if the beam has a small transverse emittance and a wide momentum spread. Since medical machines work below transition, the chromaticity should be negative to ensure the transverse stability of the "waiting" beam. Extraction is then best made to the outside of the ring and the "waiting" beam placed to the inside. These choices limit the application of the Hardt condition to positions where the extraction septum has $D_n > 0$ and $D'_n < 0$, as in the second half of a dispersion bump.

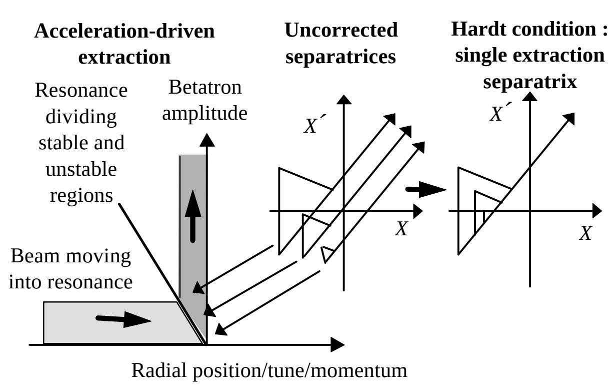

Figure 4: The Hardt condition.

The mathematically trivial solution of (1) of zero dispersion and zero chromaticity leads to a Hardt condition suitable for the rf knockout extraction.

5 CONTROLLING RIPPLE

In the following sections, it will be assumed that the Hardt condition is applied and that the beam is therefore 'fed' into a stationary resonance.

5.1 Betatron core

A good method for accelerating a beam of small emittance and large momentum spread into the resonance is a betatron core [12]. This technique has the important advantage that it maintains all transverse optical parameters (and hence power converters) in the machine constant. The 'stepping' from the digital to analogue converters (DAC) for elements correcting closed orbits or lattice functions can be particularly disruptive to spills. With the betatron core, the only system that changes is the power converter for the core itself. Since this is a single unit, special care can be taken with its design and that of its DAC. The betatron core is a high inductance device and is intrinsically smooth in its operation.

5.2 Intrinsic smoothing

The Hardt condition has the fortuitous advantage of applying smoothing to the spill by mixing all betatron amplitudes in the extraction process. When a 'strip' of particles become marooned outside the stable triangle by the action of the betatron core, they are trapped in the resonance for several hundred turns before being released into the spill. When this occurs, approximately half of the particles are concentrated in a spike and the other half are spread out in a flat tail. The delay between entering the resonance and emerging in the spike depends upon the initial betatron amplitude. The length of the tail is about equal to the delay [14, 15] (see Fig. 5).

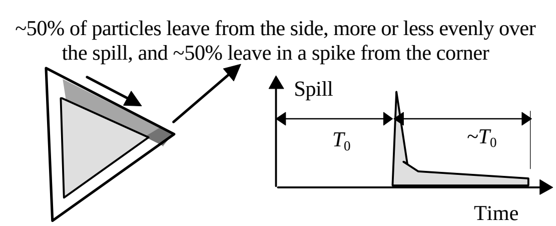

Figure 5: An elementary 'strip' spill.

The Hardt condition ensures that a mixture of all betatron amplitudes (and hence transit times) enters the resonance throughout the spill, which has the effect of spreading the spikes that would otherwise all appear coherently with the power converter ripple. This has the useful feature of being effective at kHz frequencies that are difficult to treat by feedback systems and other means.

By referring back to Fig. 2, it can be seen that *only the acceleration-driven extraction has this advantage*. The quadrupole-driven extraction starts with short transit times at large amplitudes and then moves to the longer transit times at small amplitudes. The rf-knockout extraction always has large amplitudes and short transit times, which means maximum response to ripple. This can be used to advantage for switching the beam on and off rapidly at the level of the resonance for breathing synchronisation and with a passive/wobbling beam spreading system that is less critical for the on-line dosimetry than raster scanning [16].

5.3 Channelling rf bucket

One way of making the spill less sensitive to a relative tune motion between the beam and the resonance is to make the particles enter the resonance with a velocity that is much in excess of the ripple velocity. The technique for doing this is to create a region between the beam and the resonance where the particle velocity is higher, but the density is lower so that the flux is constant. This can be done by stochastic noise or by an empty channelling rf bucket [17,18]. The later is more easily applied on the time scale of a 1 s spill and no new equipment is needed since the main rf cavity can be used. The action of the cavity is based on a technique known as phase-displacement acceleration. All particles in the beam are accelerated by the betatron core and, at the same time, the rf cavity is set so that it would decelerate particles by the same amount if they were trapped inside the bucket. The beam, however, is outside the rf bucket and the influence of the cavity is only felt as the revolution frequency of the particles approaches that of the cavity. Close to the cavity, the particles are compressed into a narrower and narrower region of phase space and have to move rapidly around the bucket, which remains empty. This can be visualised by thinking of a river flowing past the piers of a bridge. The narrower the space allowed between the piers, the greater the river’s velocity (see Fig. 6).

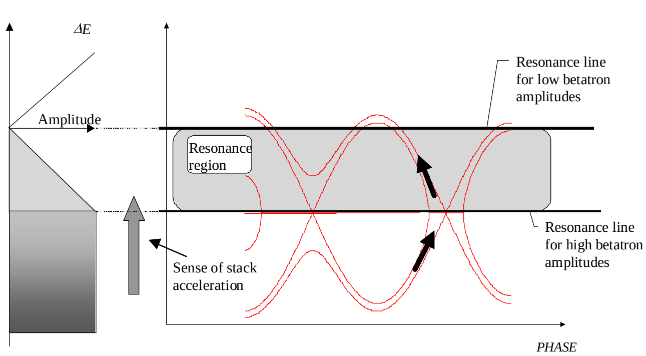

Figure 6: RF channelling.

5.4 Eddy currents

It is worthwhile checking the eddy current smoothing in the magnets and vacuum chamber in such a machine. The disruptive effects of eddy currents during the ramp must be limited, but it is counter productive to over-design with ultra-thin-walled chambers of high resistivity. If a quadrupole is used to drive the extraction, it is especially important to ensure that this unit will filter out kHz frequencies and not pass them on to the beam. Eddy currents and the intrinsic smoothing discussed in Section 5.2 are useful because they improve in efficiency with increasing frequency and their influence starts in the kHz region.

5.5 Feedback

Feedback on the resonance is adversely affected by the resonance transit time. Since this time varies from a few hundred turns to several thousand for different particles entering at the same instant, the feedback is limited in efficiency and best used only for the low-frequency shaping of the spill.

6 EMITTANCE ASYMMETRY

The unequal transverse emittances delivered by a slow extraction make it impossible to rely on the conventional methods used for matching gantries to cyclotrons where the beam emittances and the optics functions in the two planes are all assumed to be equal and the dispersion to be zero at the interface between the fixed line and the rotating gantry.

6.1 Rotator

With unequal emittances and lattice functions and non-zero dispersion, a device known as a *rotator* [19] can be used that links, one-to-one, the optics of the fixed machine directly to those of the gantry and makes this liaison completely independent of the rotation angle. The mathematics of the rotator is simple and rigorous, but the practical design has to be approached with some care [20].

It should be noted that in cyclotron-based installations the emittances are large in both planes, there is adequate intensity for collimation and the final beam delivery is made through thick scatterers, which mask any rotational effects in the gantry optics. Active scanning with a ‘pencil’ beam will be more demanding.

6.2 “Bar” of charge

The slow-extracted beam from a synchrotron is not only asymmetric in terms of emittance, it is also asymmetric in the shape of its “footprint” in phase space. In the vertical plane, the beam occupies the usual elliptical area, whereas, in the horizontal plane, it is a narrow “bar”, which is in fact a segment of the extraction separatrix and it appears as a near-rectangle, typically 10 mm long and 0.05 mrad wide. This "bar" must arrive at the patient with a known and controllable orientation, since this determines the spot size in that plane. The positive aspect of this behaviour is that it provides an independent "handle" on the control of the beam size in the horizontal plane. This introduces a new concept of controlling the beam size, not from the gantry, but from a betatron phase shifter set upstream in the transfer line.

6.3 Vertical beam size control

The vertical beam-size control can also be moved out of the gantry to a point closer to the accelerator. The technique that allows this to be done is the use of telescope modules with integer phase advances for the extraction line optics. Once the modules are all of this type, the vertical betatron amplitude function is simply handed with fixed magnification ratios from one module to the next until it arrives at the patient.

Moving the controls of the horizontal and vertical beam sizes upstream is a new philosophy that opens the way to providing just one set of optics controls for all gantries and fixed beam lines in a complex. At the same time, it reduces the number of optical constraints placed on the gantry design.

7 CONCLUSIONS

Interest in light-ion radiotherapy and the successful demonstration of raster scanning at GSI are pointing to a new generation of medical synchrotrons that use resonant slow-extraction. These will be high precision machines and, in particular, they will need to incorporate special features for ensuring a smooth beam spill. The characteristics of the slow-extracted beam will impose sophisticated designs on the extraction lines and gantries and the higher rigidity of the light ions will make them larger. While existing cyclotron-based centres are principally medical centres with accelerator equipment, the new generation of ion synchrotrons will be better described as medical centres with dedicated accelerator complexes. It begins to be reasonable to design separate buildings linked by tunnels that contain the rotators, leaving only the gantries installed in the medical part.

8 ACKNOWLEDGEMENTS

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