Extraction Techniques for Medical Beams

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CAS, Erice, March 2017

Contents

Overview

- **The universal requirements for ‘medical beams’ are:**
  - Sufficient time for on-line dosimetry.
  - Control of the beam energy, distribution, shape and movement.
  - When something fails, a fast interlock to cut the beam off.

  A quick search of the literature shows that ‘medical beams’ include all the usual particles and machines.

- **Our theme is extraction, so we will try to classify the various possibilities accordingly.**
  - **‘Fast’** extraction (implying the beam is extracted at the same rate it is produced).
  - **‘Medium slow’** extraction (implying a half-integer resonant extraction).
  - **‘Slow’** extraction (implying a third-integer extraction).

- **There are two types of beam:**
  - A **‘spread-out’** beam (typically a uniform beam over 20 cm × 20 cm). This implies the use of a multi-fingered collimator to match the beam contour to the tumour.
  - A **‘pencil’** beam (implying voxel* scanning), which has the more challenging dosimetry and beam control requirements.

*** Voxel = Volume Pixel**

'Fast' extraction

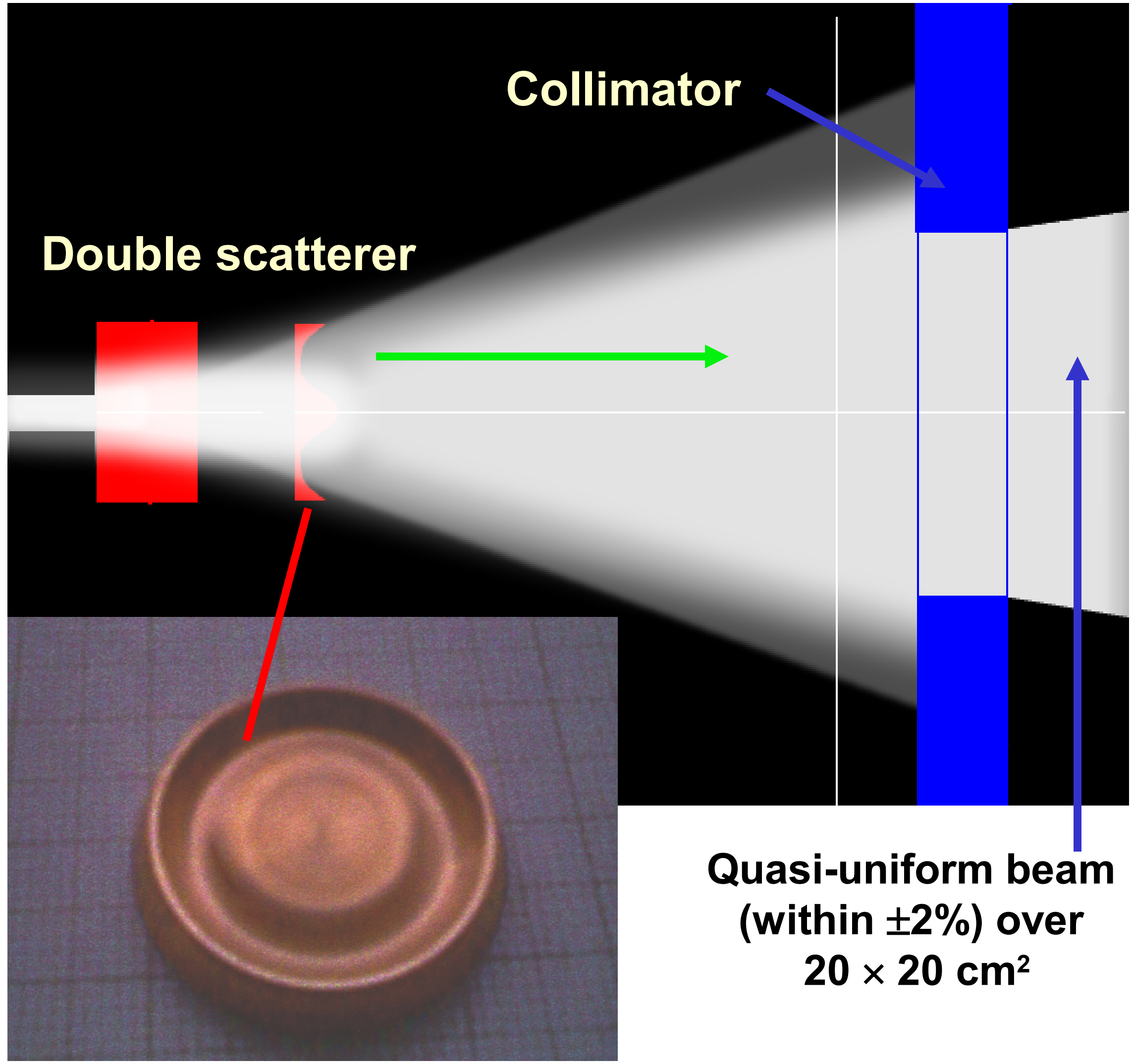
- **'Fast' extraction** concerns mainly X-ray machines, linacs and cyclotrons*, but proposals have been made to use synchrotrons in this way (S. Peggs).
- In order that the on-line dosimetry and the beam cut-off interlock have time to work, the machine beam intensity must be sufficiently low to provide an extended irradiation time.
  - **This regime is the only possible regime for X-ray machines. IMRT (Intensity Modulated Radio Therapy) is the modern variant. The beam has a large angular divergence from the source.**
  - **Cyclotrons are used to produce 'spread-out' proton beams (see next slide) that treat the whole tumour or whole lateral slices. This implies a single measurement of the dose which eases the specification of the on-line dosimetry system. Furthermore, the intensity loss in the scatterer system is ~60% and this loss is enhanced by additional absorbers and losses on a collimator. While being a rather 'dirty' mode of operation, it does help the requirement for an extended irradiation time.**

Note. Passive spreading (see next slide) is limited to cyclotrons and protons (heavier ions fission). There is a possibility of a purely optical spreading using non-linear optics, which has been demonstrated, but it is not used in practice.

* **Modern proton cyclotrons use H^- extraction, which replaces the old resonant extraction.**

Passive spreading for a 'spread-out' beam

- First scatterer significantly increases angular divergence.
- Second scatterer is shaped to scatter the dense centre to the edges while letting the edges pass largely unaffected.
- ~60% of the beam will be lost in the 2-stage scatterer.
- Scatterers will be a high *Z* material to favour scattering (copper).



‘Medium slow’ extraction

- ‘**Medium slow**’ **extraction** implies a synchrotron with a half-integer resonant extraction. The half-integer being a rather strong resonance ensures extraction in a few hundred micro-seconds.
- The principal example is the Loma Linda synchrotron in the world’s first hospital-based proton treatment centre opened in California in 1990. The accelerator design and equipment was carried out with the help of Fermilab and its Director Bob Wilson.
- In accordance with the rather fast ‘ slow’ extraction, Loma Linda uses passive spreading with protons, which is a logical choice.
- The proton synchrotron using the half-integer resonance with passive beam spreading and the unique ‘corkscrew’ gantries makes Loma Linda a centre like no other.

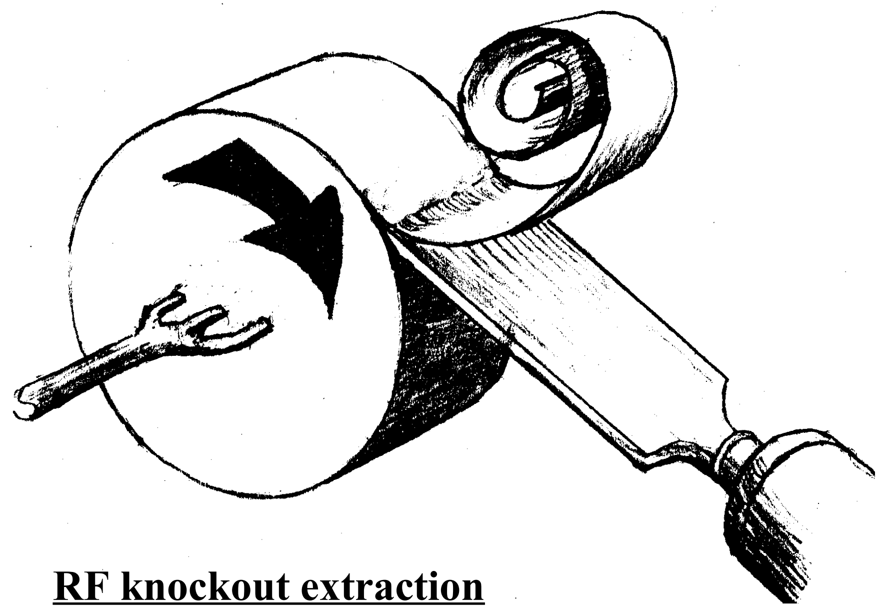
'Slow' extraction

- **'Slow' extraction** with a third-integer resonance is the preferred choice for a medical synchrotron using voxel scanning with a 'pencil' beam of hadrons* (i.e. makes use of the Bragg peak behaviour). This setup is not used with leptons.
- The spill time is controllable from about 1 to 10 seconds giving sufficient time for real-time dosimetry for each voxel.
- **'Slow' extraction is more sophisticated and there is a list of new topics to be taken into account:**
  - High sensitivity to ripple and changes in the lattice optics.
  - Very small horizontal emittance linked to a normal vertical emittance.
  - Different beam distributions in the two planes.
  - The need to match to a gantry that rotates between sessions.
  - The implementation of the beam cut-off interlock.
  - Finally, voxel scanning brings its own technical problems.

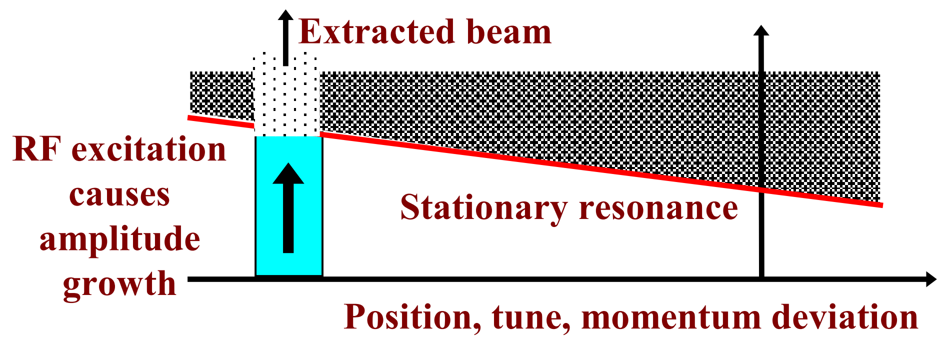
*** There are also 2 'spread-out' beam techniques that can be used with 'slow' extraction i.e. 'Wobbling' and 'Non-linear optical spreading'. These techniques are less demanding for the on-line dosimetry than voxel scanning.**

Descriptive view of ripple sensitivity (1)

- **Amplitude-driven, slow extraction** can be likened to the shaving action on a wood-turning lathe.
- The width of the shaving is equal to the width of the wood and is equivalent to the $\Delta p/p$.
- The thickness of the shaving is the horizontal emittance of the extracted beam. The X-section of the wood is the original beam emittance.
- **For ~1'000'000 turns, the shaving is extremely thin. The slightest vibration can cause the chisel to jump and chop the shaving.**

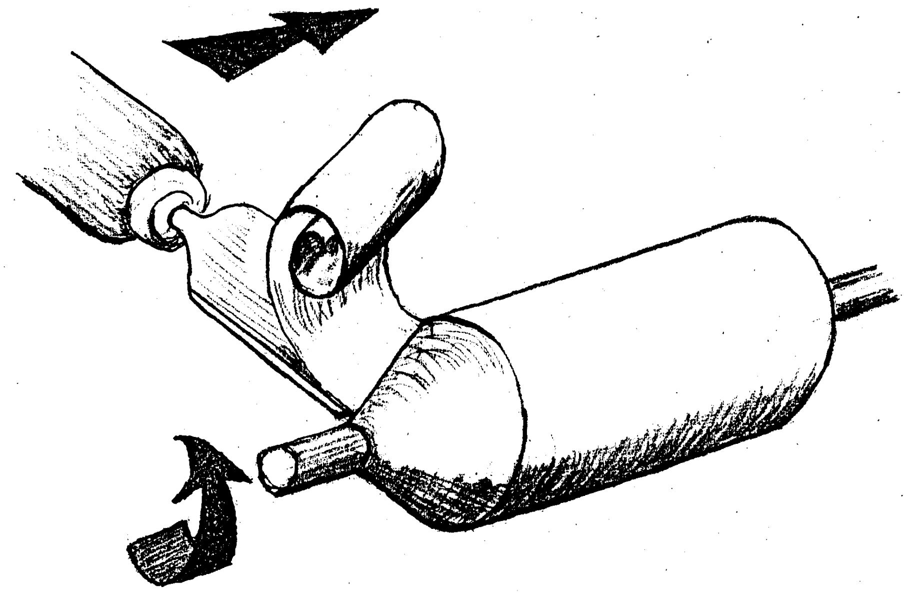


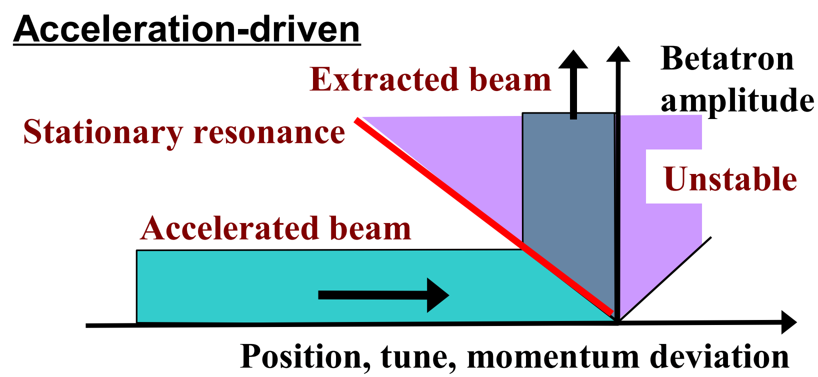
RF knockout extraction



Descriptive view of ripple sensitivity (2)

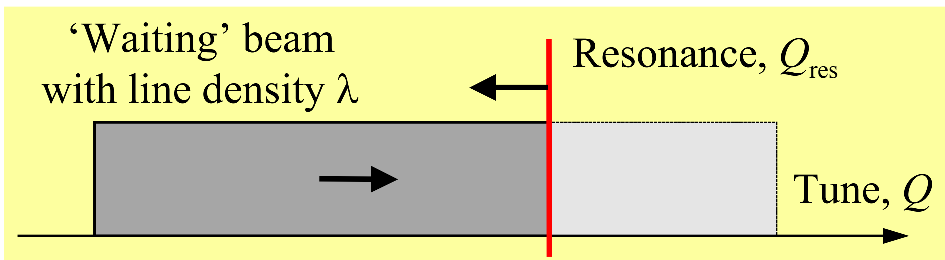
- **Acceleration-driven, slow extraction** can also be likened to the shaving action on a wood-turning lathe.
- The projected width of the shaving is equivalent to the extracted *Δp/p*. This is smaller than the width of the wood (i.e. the original beam *Δp/p*).
- The thickness of the shaving is the horizontal emittance of the extracted beam. The X-section of the wood is the original beam emittance.
- **For ~1'000'000 turns, the shaving is extremely thin. The slightest vibration can cause the chisel to jump and chop the shaving.**





Sensitivity to ripple (1)

- For a small medical synchrotron, the transit times typically vary from 100 turns up to 4000 turns. For simplicity, assume that most particles leave the machine within 2000 turns. For a revolution time of 0.5 μs, this represents a delay of 1 ms. **Thus, for 50 Hz, 100 Hz and 300 Hz ripples (common in power converters), it is reasonable to say that extraction is instantaneous.**
- Now consider the schematic model shown below, in which the 'waiting' beam is being consumed by a resonance. Whether the relative motion between the beam and the resonance is due to one partner, or both, is unimportant.



- The relative motion between the beam and resonance will be the sum of a constant velocity, $(\mathrm{d}Q/\mathrm{d}t) = \dot{Q}_0$

  plus a ripple term that may come from either the position of the beam via the main dipole field, or from the resonance via the tuning quadrupoles.

Sensitivity to ripple (2)

- Let the ripple have the form,

$$Q_r = \delta Q \sin(\omega t); \text{ so that } \dot{Q}_r = \omega \delta Q \cos(\omega t)$$

- The flux of particles entering the resonance from a 'waiting' beam with a line density of λ will be,

$$\phi = \frac{\mathrm{d}N}{\mathrm{d}t} = \lambda\left(\dot{Q}_0 + \dot{Q}_r\right) = \lambda\left(\dot{Q}_0 + \omega\delta Q \cos(\omega t)\right)$$

- The irregularities of the spill can be quantified by a **Duty Factor, *F***, which has the advantage of being analytic in form, but its name is an unfortunate accident of history.

$$F = \frac{\langle \phi \rangle^2}{\langle \phi^2 \rangle}, \text{ over time, } T_{\text{spill}}$$

- In this case,

$$F = \frac{\left\{ \frac{1}{T_s} \int_{T_s} \lambda \left[\dot{Q}_0 + \omega\delta Q \cos(\omega t) \right] \mathrm{d}t \right\}^2}{\frac{1}{T_s} \int_{T_s} \lambda^2 \left[\dot{Q}_0 + \omega\delta Q \cos(\omega t) \right]^2 \mathrm{d}t}$$

so that

$$F = \frac{1}{1 + \frac{1}{2} \frac{(\omega\delta Q)^2}{\dot{Q}_0^2}}$$

Sensitivity to ripple (3)

- The above is valid for ripple up to 1 kHz and assumes that $\dot{Q}_0 > \omega\delta Q$.
- If $\dot{Q}_0 \le \omega\delta Q$, the resonance plunges periodically into the beam chopping the spill into a series of spikes. The critical ripple leading to a 'chopped' spill is given by,

$$(\omega\delta Q)_{\mathrm{critical}} = \dot{Q}_0$$

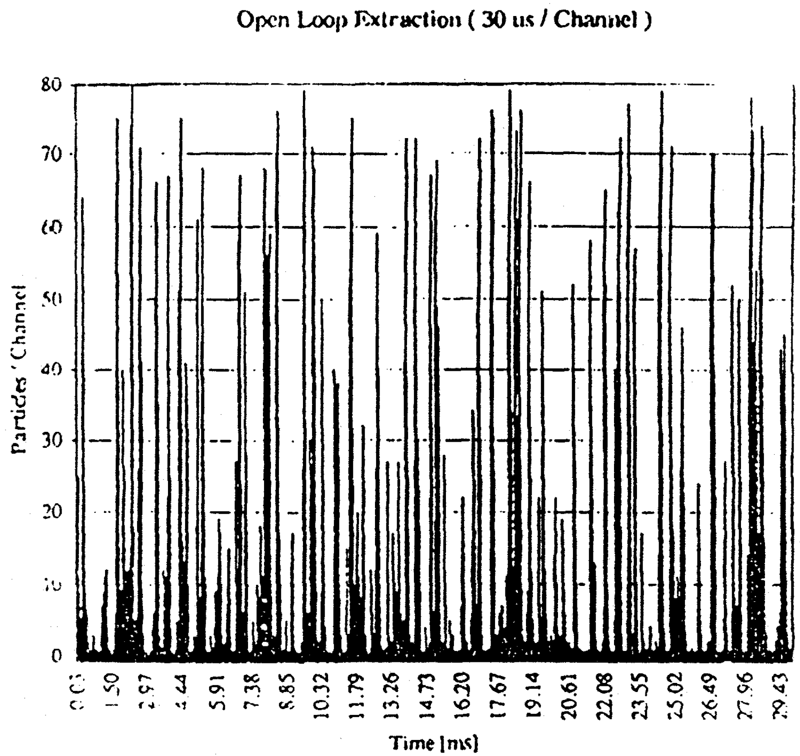
Let Q_{res} = 1.666, the tune shift to consume the beam ΔQ = 0.01 and T_{spill} = 1 s.
The average tune speed will be dQ_0/dt = 0.01
For small changes the relation of the tune ripple to the current ripple will be $\Delta Q/Q \approx \Delta I/I$.
The levels of ripple at which 'chopping' starts are shown below.

Ripple amplitudes	that 'chop' the spill
Frequency [Hz]	$(\delta Q/Q_{res})_{critical} = \Delta I/I$
50	$\geq 2 \times 10^{-5}$
100	$\geq 2 \times 10^{-5}$
300	$\geq 3.2 \times 10^{-6}$
1000	$\geq 9.6 \times 10^{-7}$
10'000*	$\geq 6.8 \times 10^{-8}$
100'000*	$\geq 6.8 \times 10^{-9}$

*** Modified formula**

Sensitivity to ripple (4)

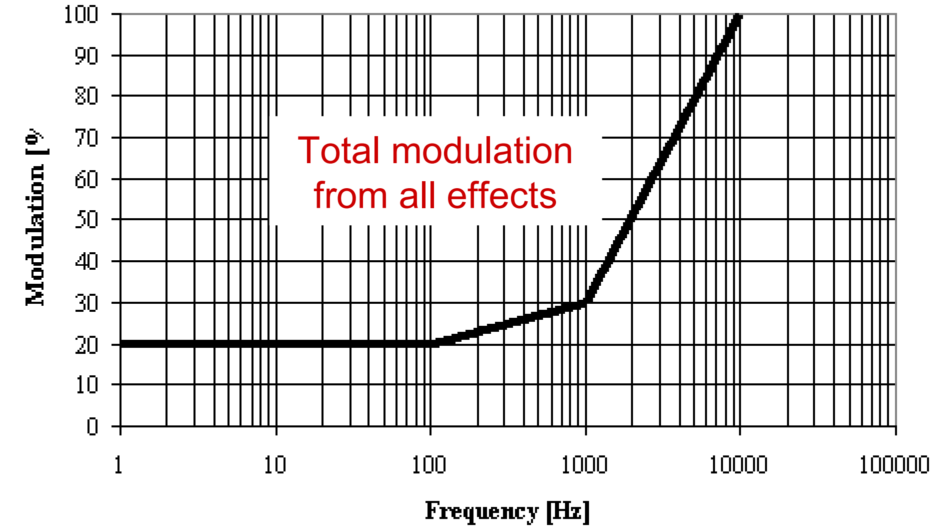
- For therapy with carbon ions, the spill rates are typically between 5×10^6 ion/s and 5×10^8 ion/s. Thus the lowest spill rate at the top frequency in the previous table is close to the regime of Poisson statistics.
- How a spill appears to the observer depends strongly on the sampling rate.
- The spill shown opposite is measured in 30 μs bins and the expected average spill rate was 15 ion per bin. The modulation exceeds that expected for Poisson statistics. The spike structure indicates strong over modulation (chopping) in the kHz frequency range.

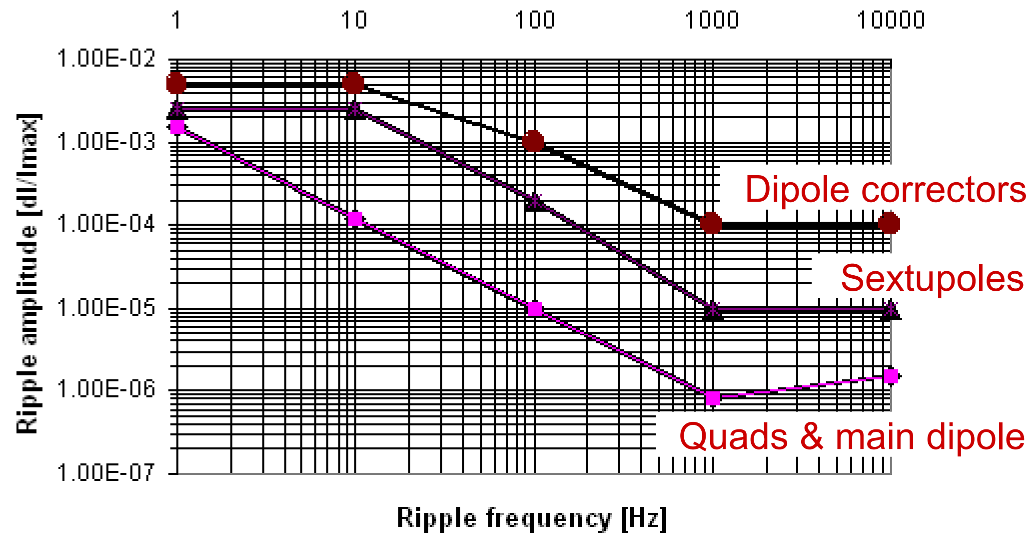


Slow extracted spill (Courtesy of GSI Darmstadt)

Sensitivity to ripple (5)

- A reasonable sampling frequency for hadron therapy is 10 kHz.
- Nominally, the 'dwell' time to irradiate a voxel would be 5 ms equivalent to 50 measurement bins at 10 kHz aiming at ± 2% accuracy.
- Ripple above 10 kHz becomes invisible to the measuring system.
- The top graph shows the specification for the maximum allowable ripple in the spill of the PIMMS project.
- The effect of ripple in the spill and the practical difficulties of reducing that ripple are maximum around 1kHz.
- The bottom graph shows how the top graph was interpreted for various power converters in PIMMS.



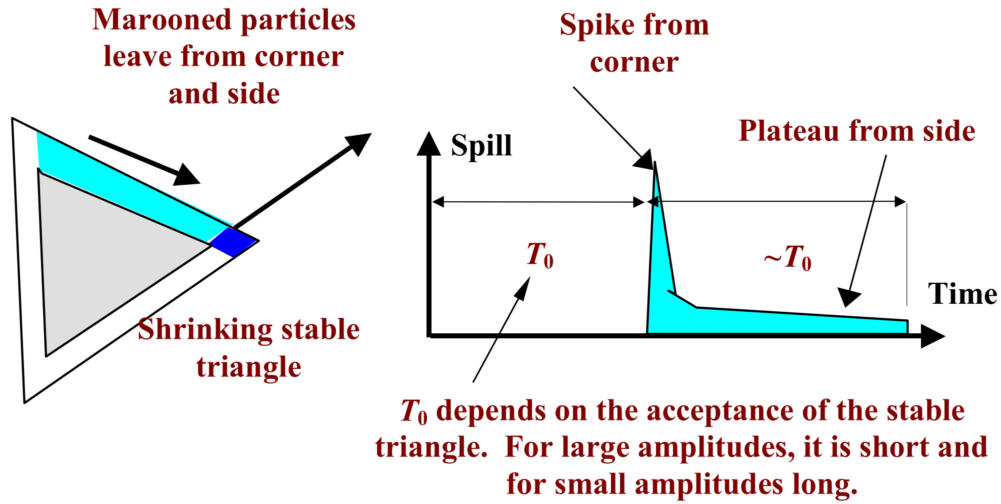


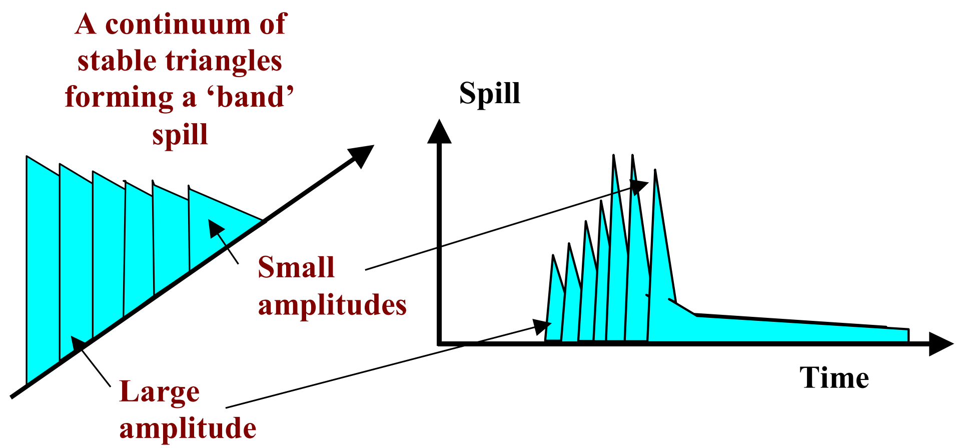
Handling ripple

- The precision of the dosimetry can always be improved by lowering the machine intensity and increasing the ‘dwell’ time on each voxel to ensure patient safety.
- **However, we must do as much as possible to avoid this at the design stage, because it increases the irradiation time and hence patient discomfort, and it reduces patient throughput affecting the business model.**
- **The first step** is to invest as much as possible in the specification of the power converters. Conventional power converters are controlled via a DAC and the setting precision is determined by the number of bits in the DAC.
  - A **12-bit DAC** (1 in 4096 $\cong 2.4\times10^{-4}$) is commonplace,
  - The **16-bit DAC** (1 in 65’536 $\cong 1.5\times10^{-5}$) was developed during the 1970s at the CERN-ISR [J. Pett, Digital-Analogue Converter 16-bit, ISR 6034] and is now available commercially.
  - An **18-bit DAC** (1 in 262’144 $\cong 3.8\times10^{-6}$) is more of a development device than a commercial reality.
  - **Note the DAC is only an indication of the ripple, which will vary with frequency. It does determine how smoothly the beam can be moved.**
- **The second step** is to look for techniques that combat the ripple.
- **The third step** is to look for design features that reduce the effect of ripple.

‘Intrinsic smoothing’

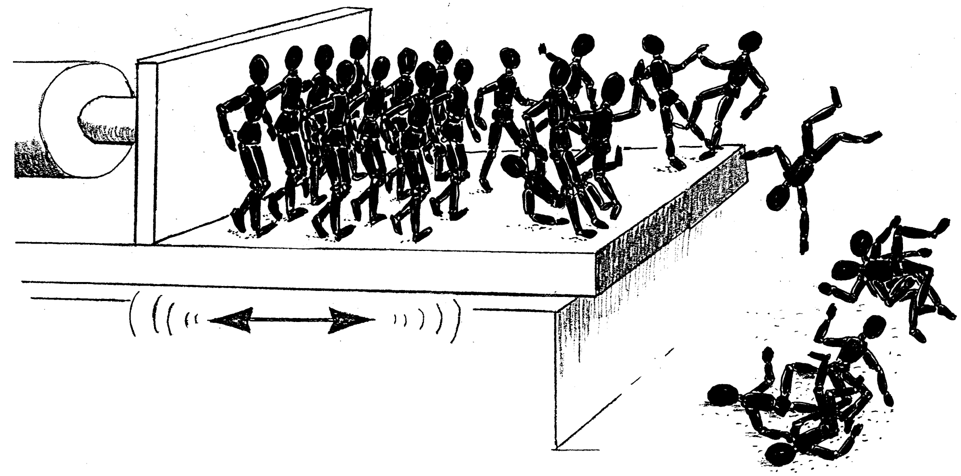
- Referring back to the ‘strip’ and ‘band’ spills of the previous lecture.
- Elementary ‘strip spill’
  - This occurs in an RF, amplitude-driven extraction.
  - ~50% leave in a spike from the corner and
  - ~50% leave from the side, more or less evenly over the spill.
- ‘Band spill’
  - As occurs in the acceleration-driven extraction of PIMMS.
  - **Spikes are spread out, lowering the high-frequency (kHz) component. Known as Intrinsic Smoothing.**

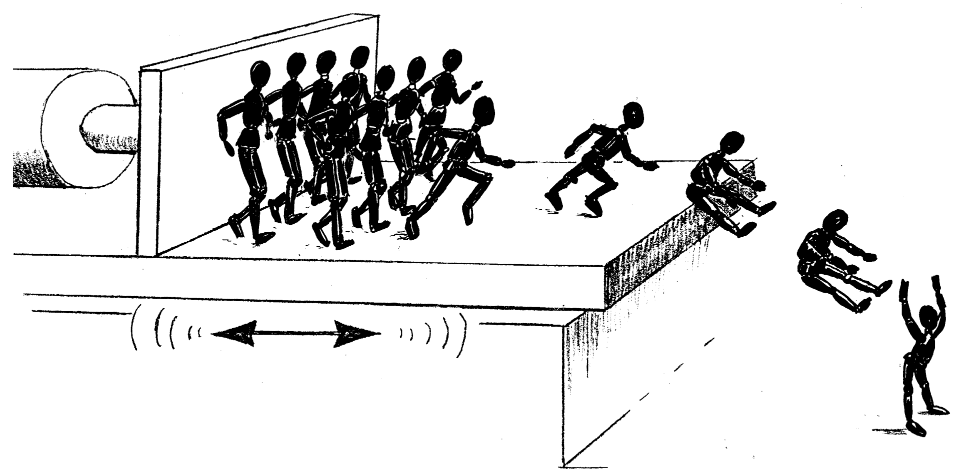




‘Front-end’ acceleration

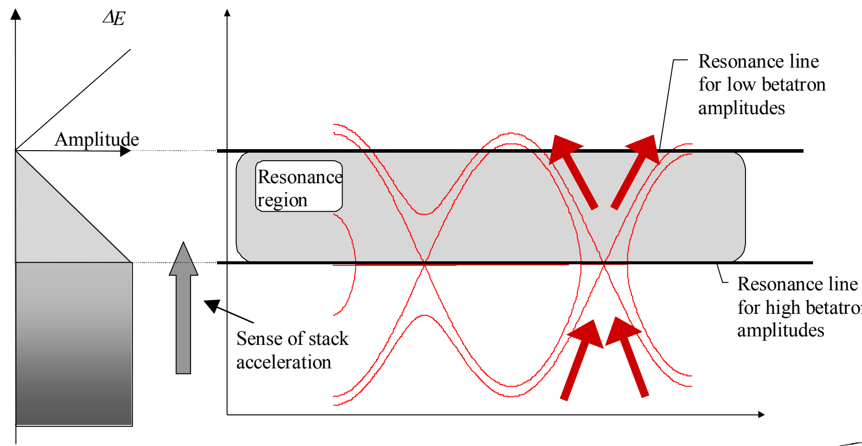
- The spill can be desensitized to ripple by increasing the beam velocity as it enters the resonance, so that it is well above the velocity modulation caused by the ripple.
- The top picture shows the ‘beam’ advancing at the speed of the betatron core and being dominated by the ripple.
- In the lower picture, the ‘beam’ speeds up just before the resonance, so that the ripple becomes less influential.
- **This is called ‘Front-end’ acceleration and can be done by ‘empty-bucket’ channeling (see next slide) or by RF noise.**

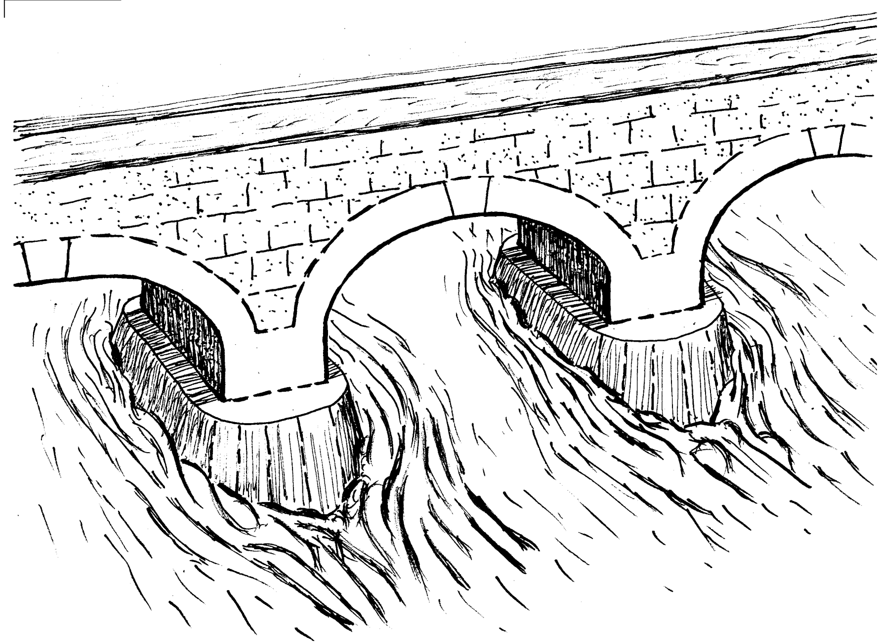




‘Empty-bucket’ channeling

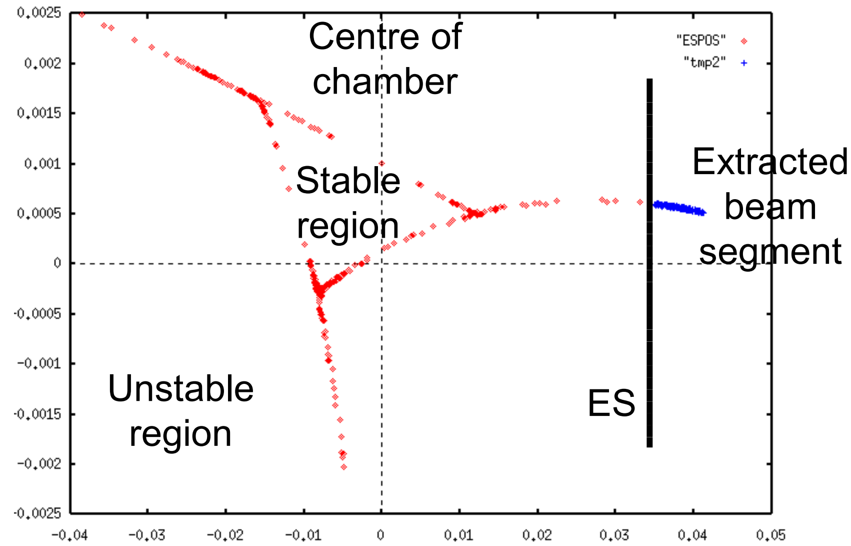
- The betatron core slowly accelerates the beam into the resonance (upwards in the diagram).
- The empty RF buckets are nearly stationary. If they were to be filled, they would accelerate their beam in the opposite sense to the betatron core.
- **When the slowly moving beam meets the empty buckets, it has to stream round the buckets through a narrow phase-space gap at a much higher speed to maintain the flow.**
- The beam enters the resonance quickly and is extracted.

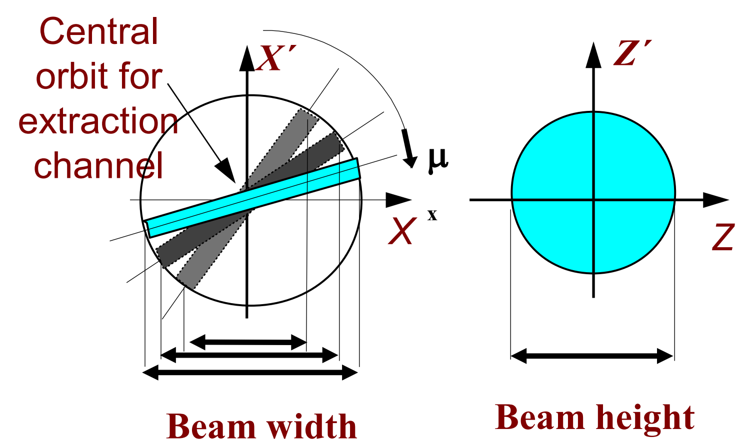




The small horizontal emittance

- A mono-energetic extracted beam segment is typically 10 mm long and 0.1 mrad wide.
- For the acceleration-driven extraction there is a continuum of segments of different momenta. If the Hardt Condition is applied these segments are all superimposed.
- The small horizontal emittance is often obscured by dispersion, optical mismatch, ripple or drift moving the beam spot.
- As the precision of the extraction is improved, the true shape of the segment becomes clear.
- **This is sometimes thought of as a disadvantage, but it can be used to control the beam width at the patient.**



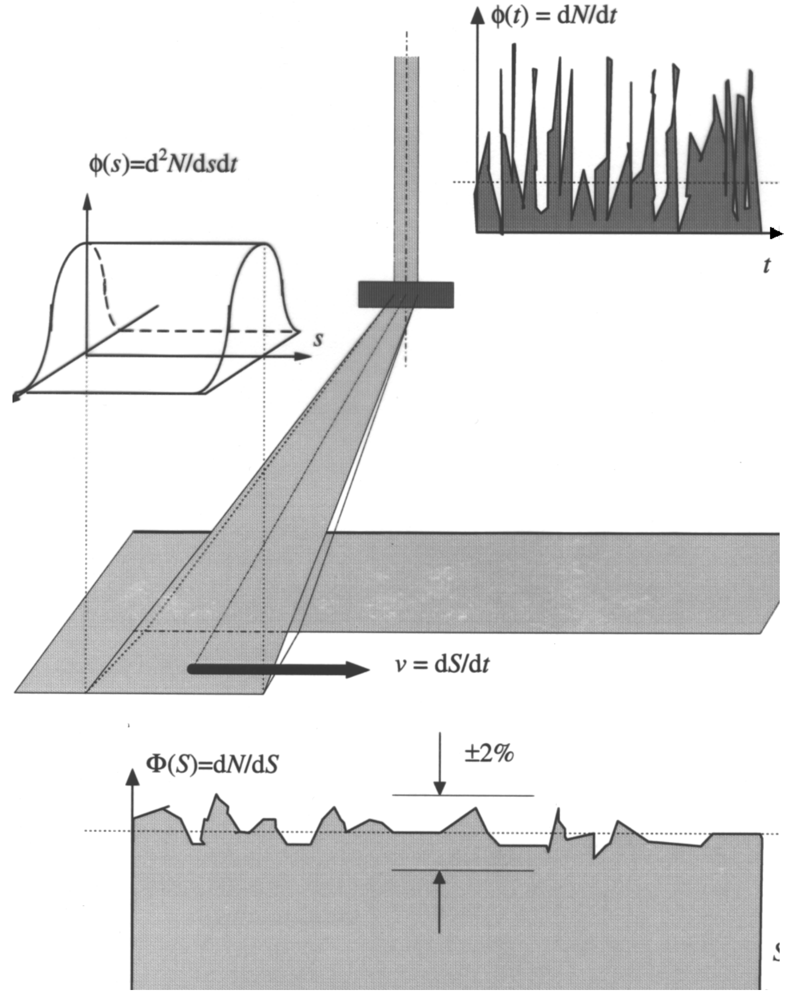


Eddy-current smoothing

- Normally, we try to avoid eddying currents in accelerators;
  - To reduce field distortion during ramping.
  - To reduce resistive losses during ramping.
- However, during a slow extraction we would like;
  - Very stable conditions in the 1000 Hz region for the main lattice elements.
  - Very smooth ramping of the betatron core, if this is used to feed the resonance.
- Adjusting the lamination thickness of the magnet elements can be of help. **This is a compromise - some resistive losses and distortion during ramping for some field smoothing on the extraction flat top.**
- It is also important to check the main dipole design for any unwanted eddy current circuits via straps between the end plates for example.

Beam distributions and scanning

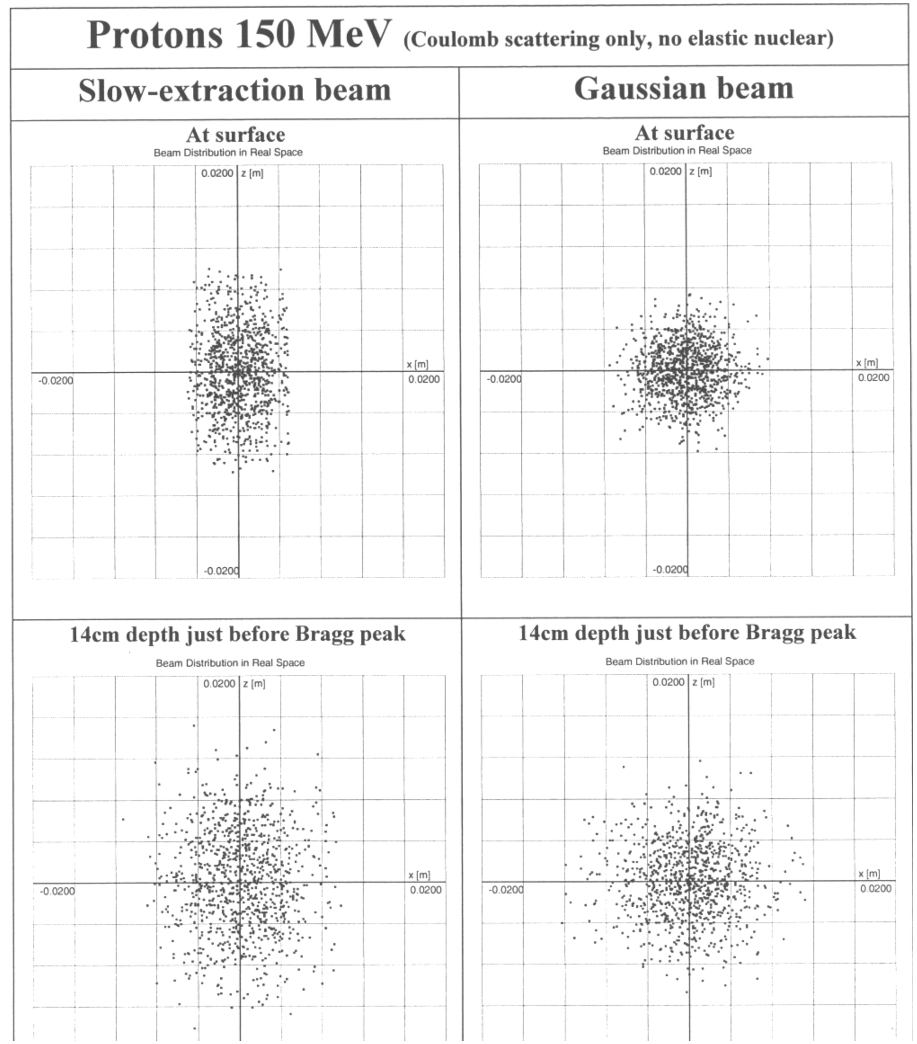
- The beam distributions are near-uniform over a narrow rectangle in the horizontal phase space and near-gaussian in the vertical phase space .
- For voxel scanning, overlapping gaussian spots gives a smooth deposition of beam, whereas overlapping rectangles gives 'hot/cold' ridges.
- The immediate choices are :
  - To scan with the gaussian distribution aligned to the 'slow' scanning direction, since errors are more likely to build up over time between rows.
  - To take mini-steps (1/5th of the voxel width) in the 'fast' scanning direction along the row.
- The figure shows a precise hard-edge beam spot. In practice, the spot is sufficiently diffuse to significantly reduce the above problems. The 1/5th stepping also helps the dosimetry.



Coulomb scattering (1)

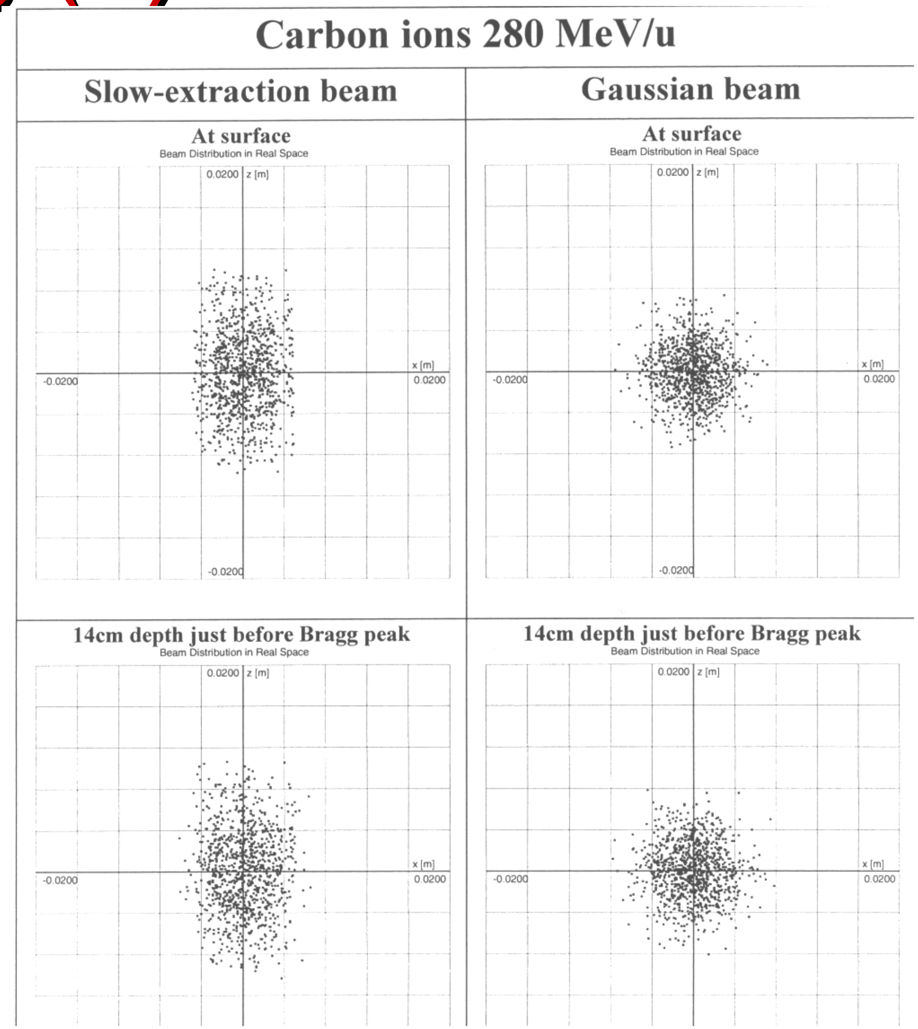
A comment on the blowup of the sharp edges of the rectangular beam distribution in the horizontal phase space and the gaussian edge in vertical phase space.

- 150 MeV protons penetrate tissue by 14-15 cm.
- Note the degradation of the sharp edge of the slow-extracted beam.

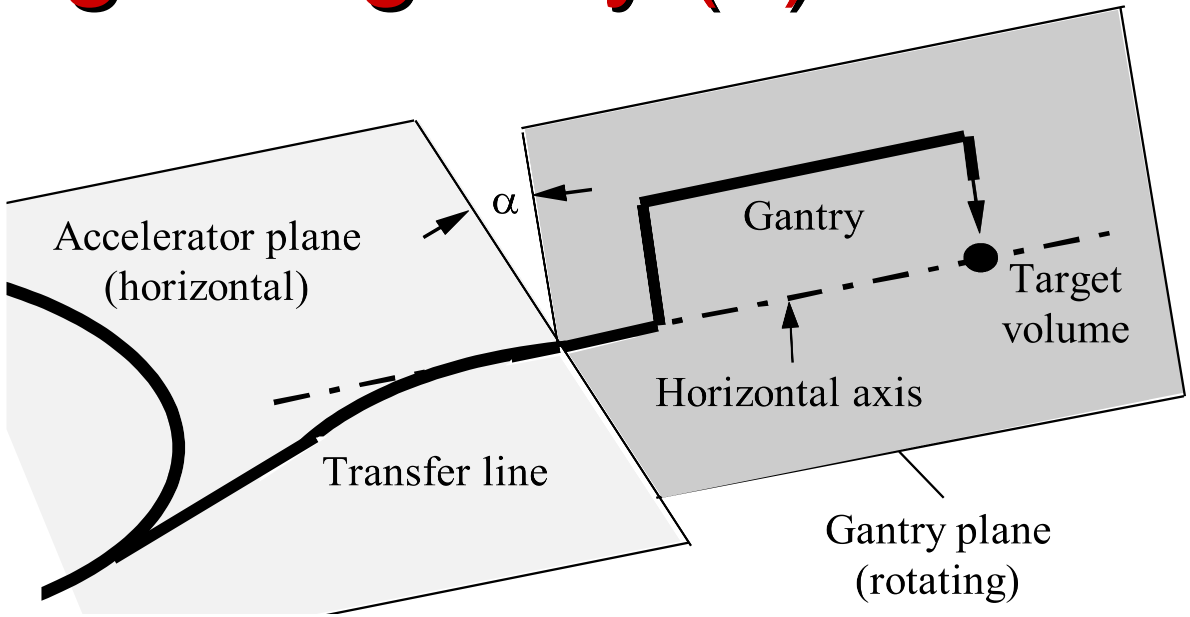


Coulomb scattering (2)

- 280 MeV/u carbon ions also penetrate tissue by 14-15 cm.
- Note the reduced degradation of the sharp edge of the carbon-ion beam compared to the case of the proton beam.

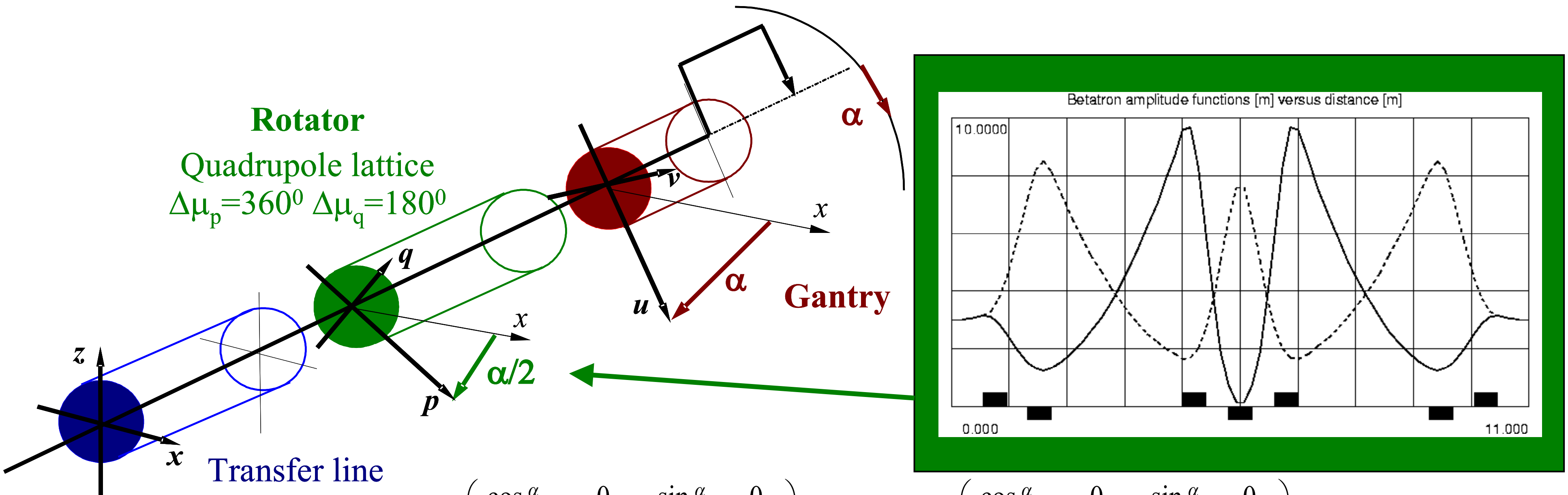


Matching to a gantry (1)



- **For medical applications any dependency of beam size or beam distribution on gantry angle must be avoided.**
  - **For cyclotron beams being used for passive spreading**. A symmetric beam with identical particle distributions and identical optical functions in both phase spaces at rotation point works well.
  - **For slow extracted beams with the properties described earlier,** we need a more sophisticated approach.

Matching to a gantry (2)



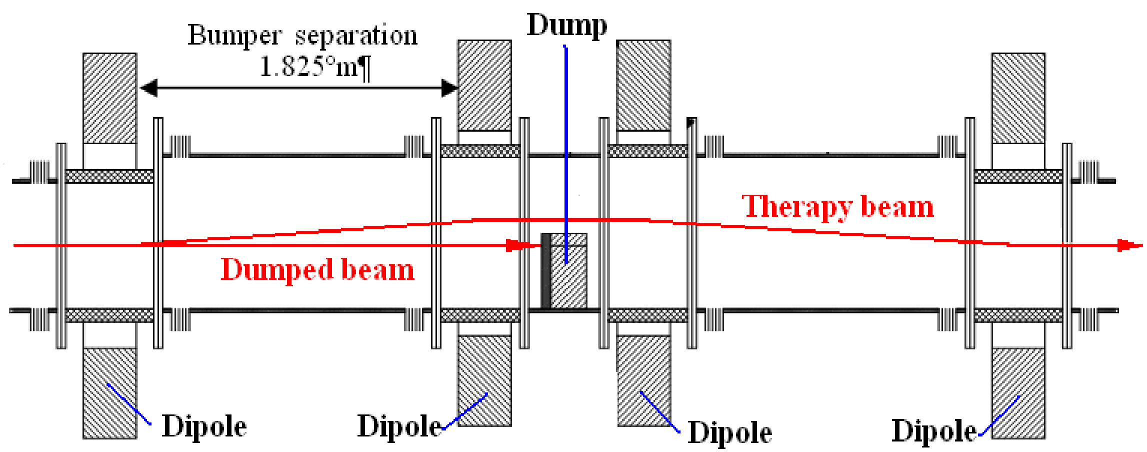
$$M_0 = \begin{pmatrix} \cos\frac{\alpha}{2} & 0 & \sin\frac{\alpha}{2} & 0 \\ 0 & \cos\frac{\alpha}{2} & 0 & \sin\frac{\alpha}{2} \\ -\sin\frac{\alpha}{2} & 0 & \cos\frac{\alpha}{2} & 0 \\ 0 & -\sin\frac{\alpha}{2} & 0 & \cos\frac{\alpha}{2} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} \cos\frac{\alpha}{2} & 0 & \sin\frac{\alpha}{2} & 0 \\ 0 & \cos\frac{\alpha}{2} & 0 & \sin\frac{\alpha}{2} \\ -\sin\frac{\alpha}{2} & 0 & \cos\frac{\alpha}{2} & 0 \\ 0 & -\sin\frac{\alpha}{2} & 0 & \cos\frac{\alpha}{2} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

- Maps the beam 1:1 to the gantry independent of the angle.
- This is the rotator solution and it maps the dispersion function and the Twiss functions rigorously to the gantry coordinate system.

Beam cut-off

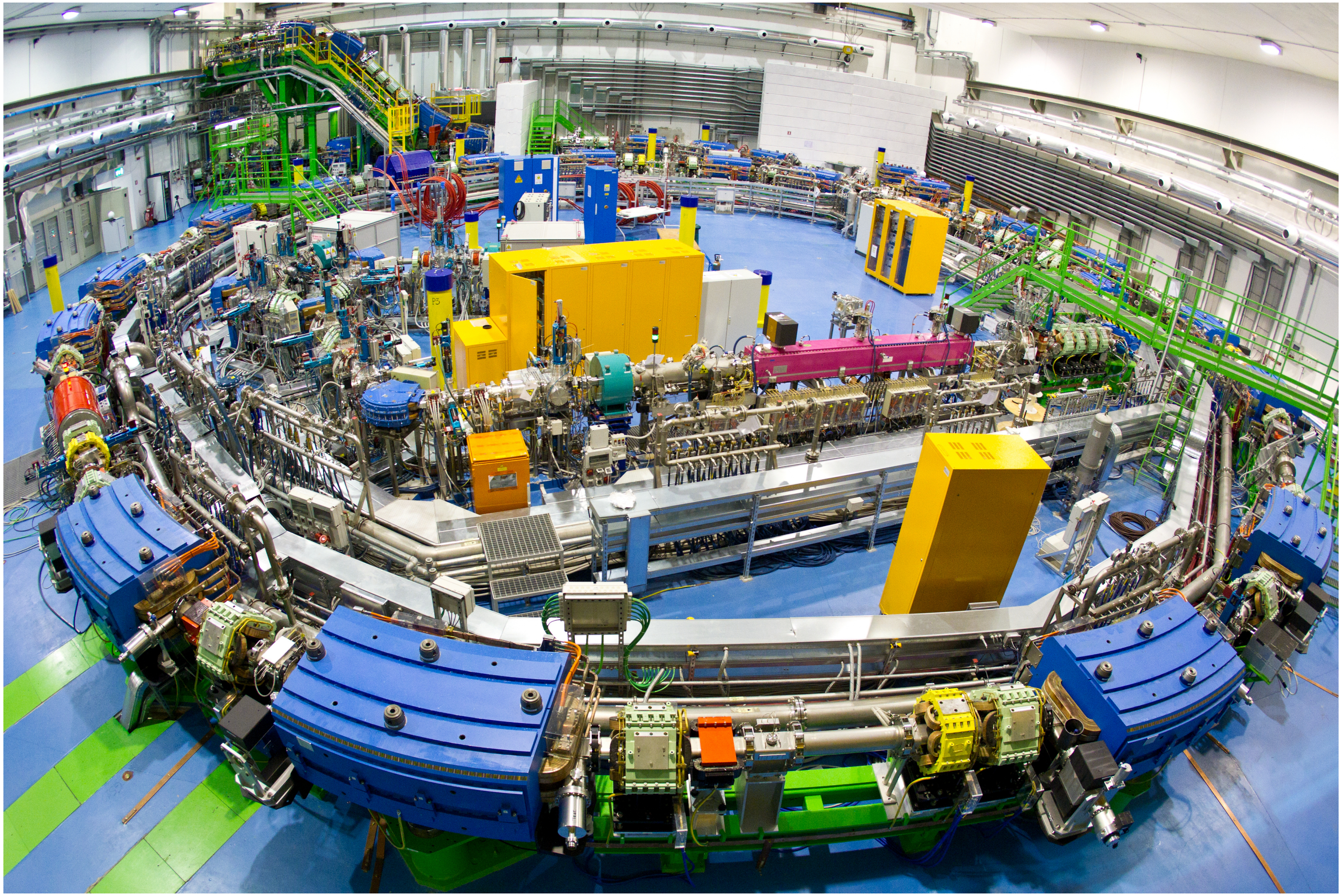
- **Amplitude-driven, slow extraction** has the advantage that the RF excitation driving the amplitude growth can be switched off quickly and since the extraction works only with large amplitude ions the transit time in the resonance is short making the overall switching time a few μs. However, some halo ions are left on the brink of instability.
- **Acceleration-driven, slow extraction** is slower to respond to being switched off. Not only is the betatron core slower than the RF, there are small amplitude ions trapped in the resonance that can take a few ms to transit.

In both cases, a second mechanism is needed. Place four identical ferrite dipoles powered in series in a straight section to excite a closed-orbit bump that holds the beam clear of a dump block. By switching off the dipoles, or in the event of a power failure, the beam drops onto the dump. The switching time < 200 μs.

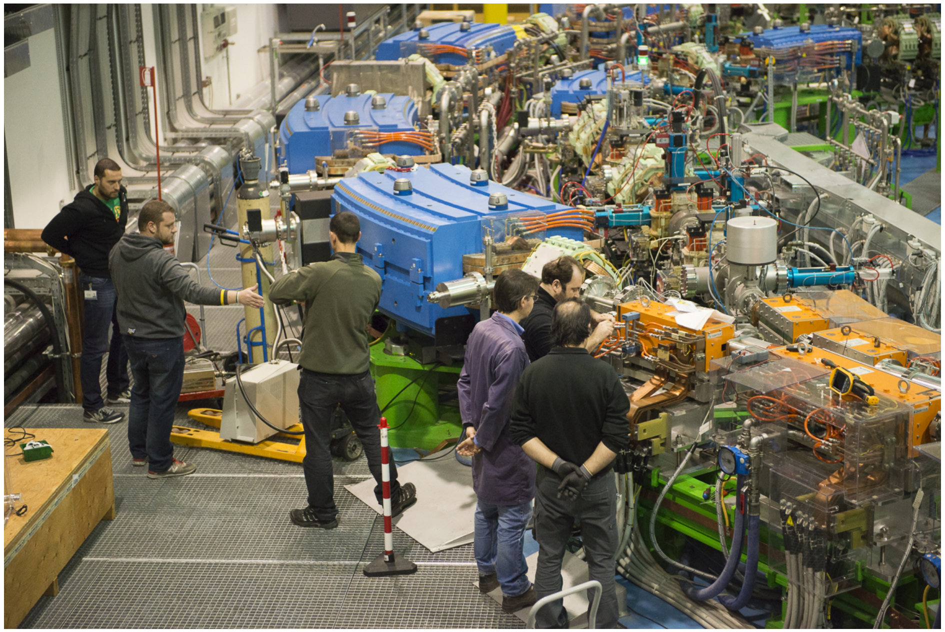


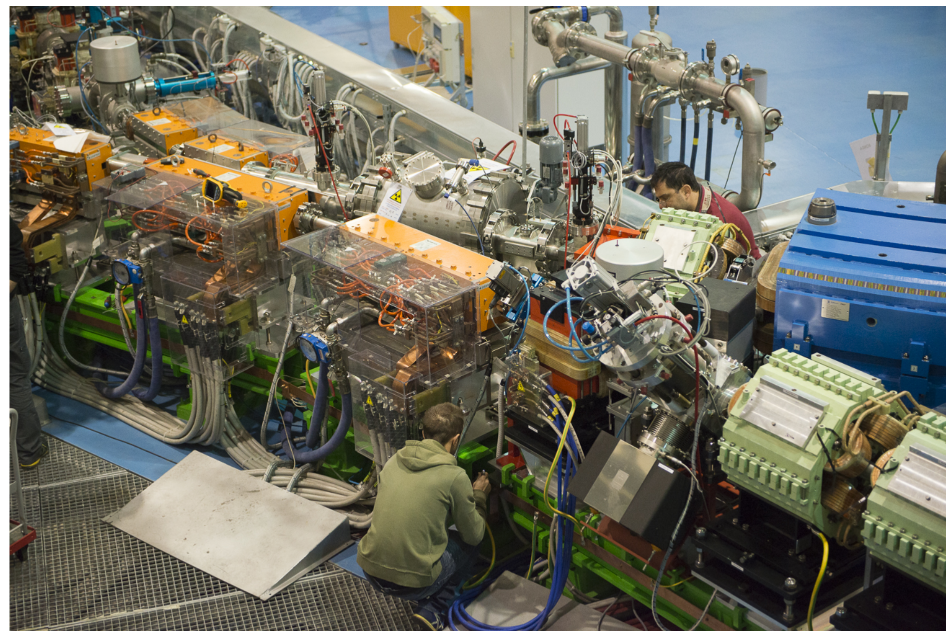
CNAO centre

CNAO ring



CNAO injection / extraction region





CNAO control room

CNAO treatment room

Thank you for your attention.

Choices

Leptons:				
	Photons	**Electrons**		
Hadrons:				
	Neutrons	**Protons**	**Alphas**	**Light ions**
Accelerators				
	X-ray tubes	**Linacs**	**Cyclotrons**	**Synchrotrons**
Extraction				
	Fast	**Slow by quadrupole**	**Slow by RF**	**Slow by betatron core**
Beam delivery				
	IMRT	**Passive spreading**	**Raster scanning**	**Gantry/Fixed**