Betatron Core Slow Extraction at CNAO

Dr. Luciano Falbo

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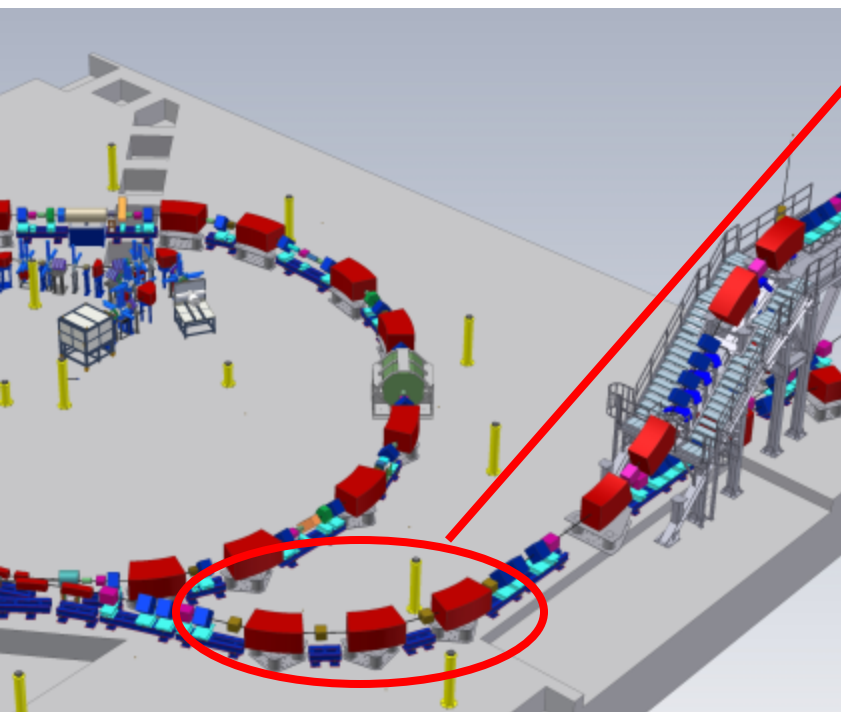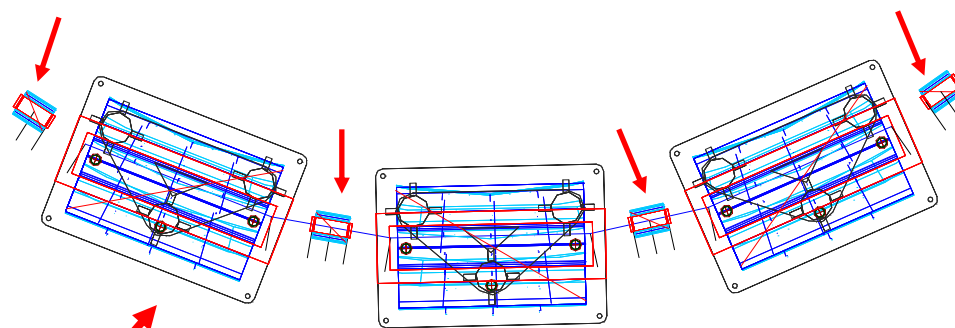Centro Nazionale di Adroterapia Oncologica

CNAO Machine

CNAO is the only Italian facility for cancer treatment with protons (60-250 MeV) and carbon ions (120-400 MeV/u). The first patient was treated with protons in 2011. Now it treats about 50 patients per day.

RFQ+IH

2 ECR sources

77.6 m ring

Three treatment rooms: two equipped with a horizontal line and one equipped with a horizontal and a vertical line

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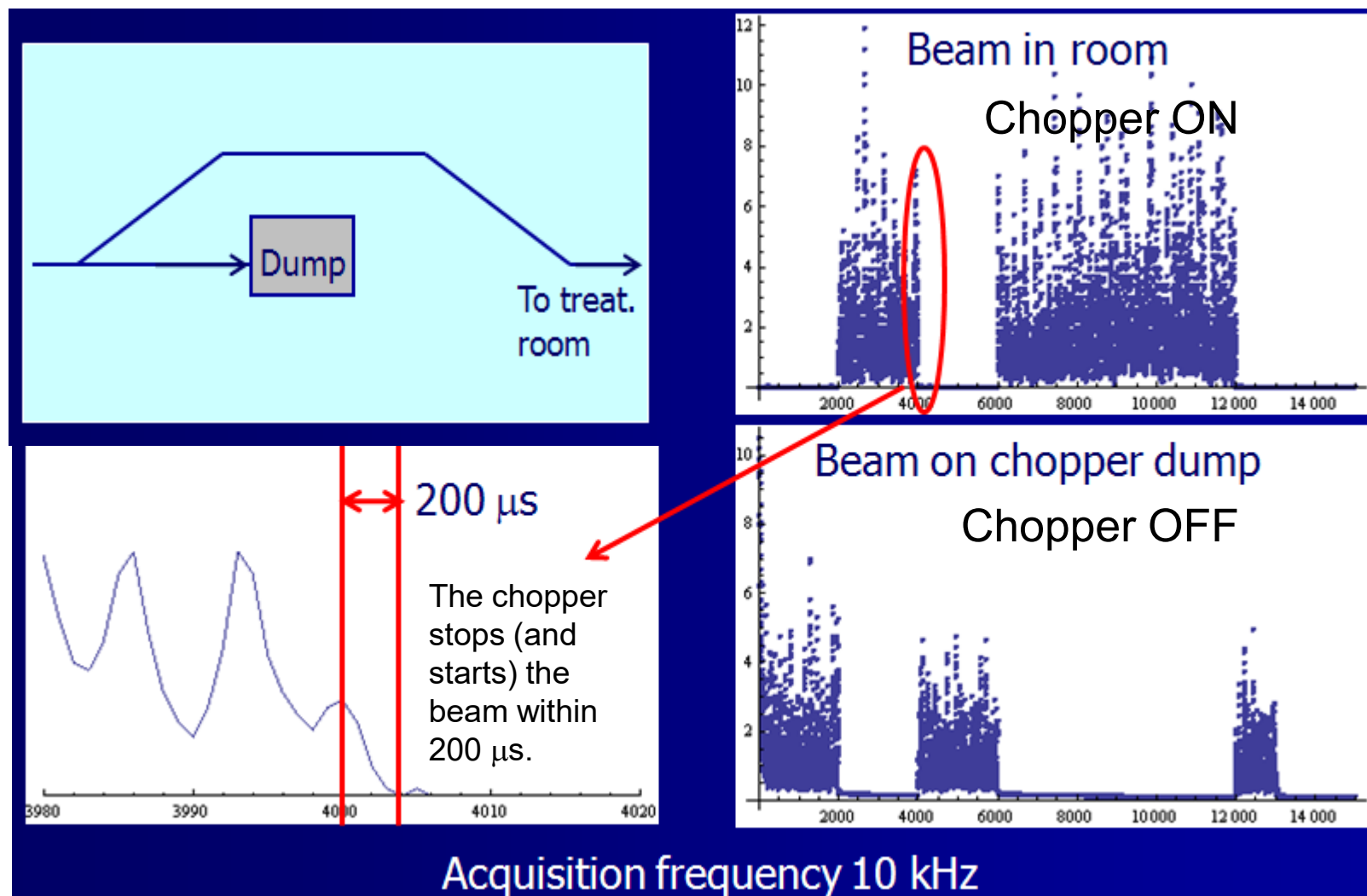
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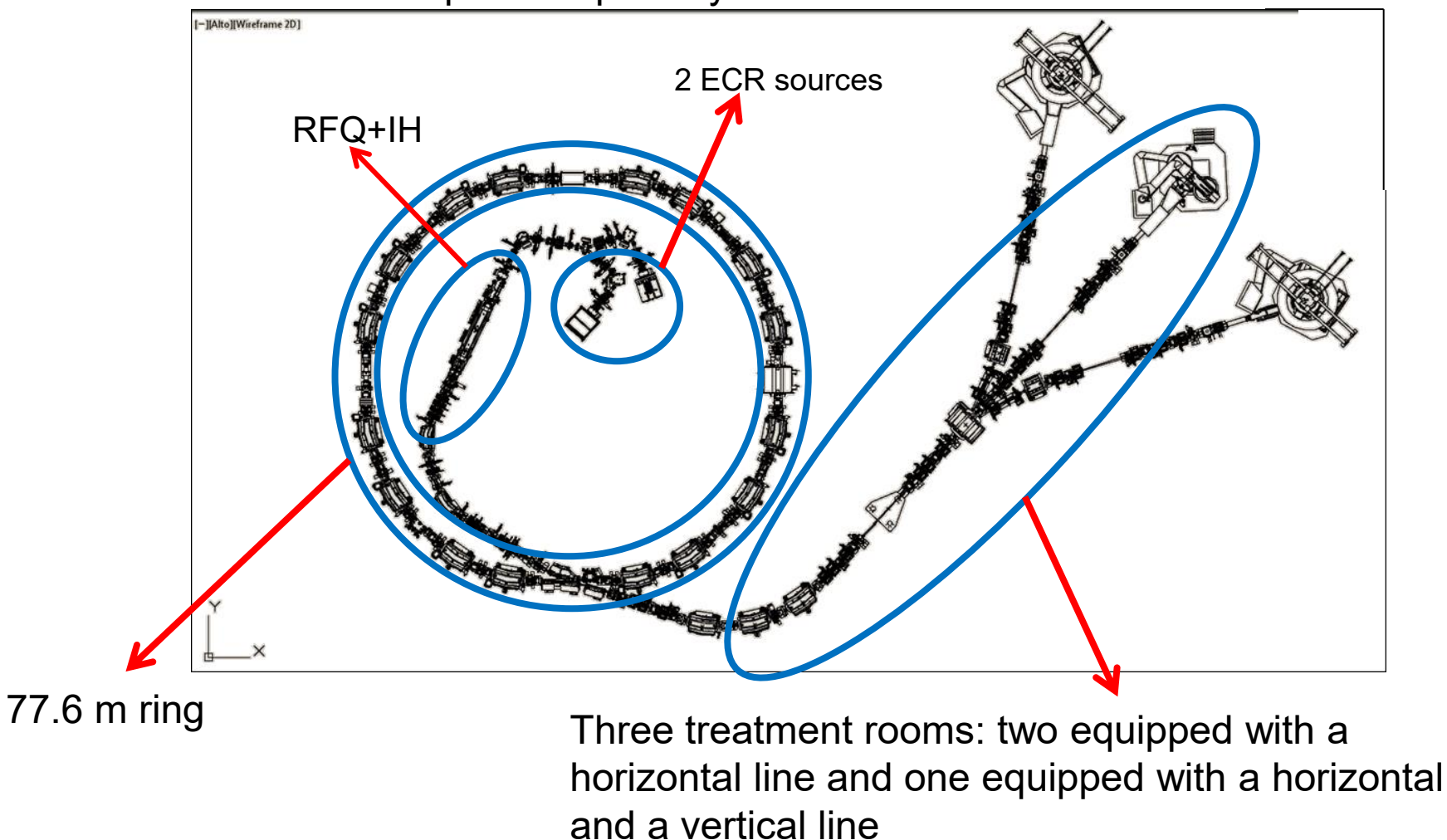
HEBT Chopper

The HEBT line is equipped with a safety system: the HEBT chopper. It is made up of 4 fast magnets interlaced with three dipoles that allow to fast turn on/off the beam.

it is used to control the dose delivered to the patient and to synchronize irradiation with breathing.

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Chopped beam

Dump

To treat. room

Beam in room

Chopper ON

200 μs

The chopper stops (and starts) the beam within 200 μs.

Beam on chopper dump

Chopper OFF

Acquisition frequency 10 kHz

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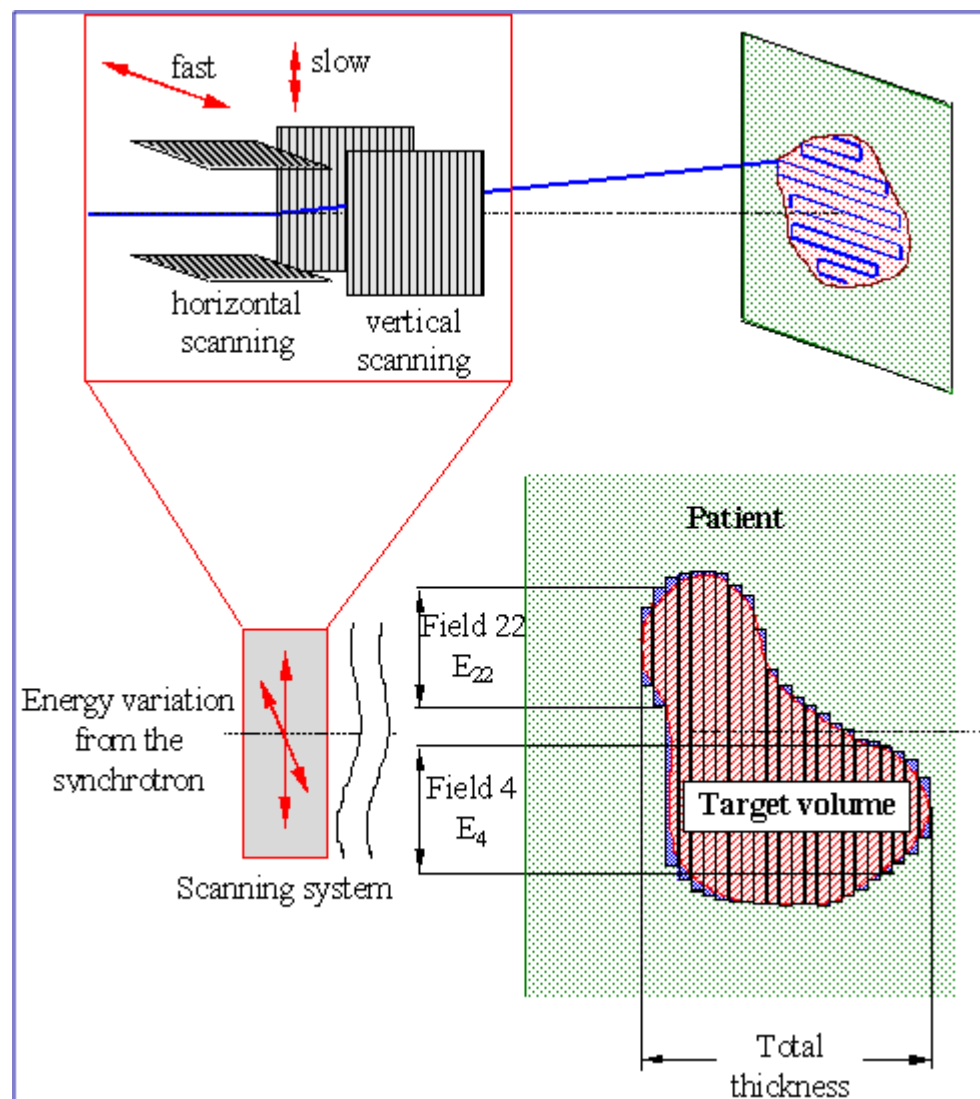Sistema Sanitario Regione Lombardia

Active systems

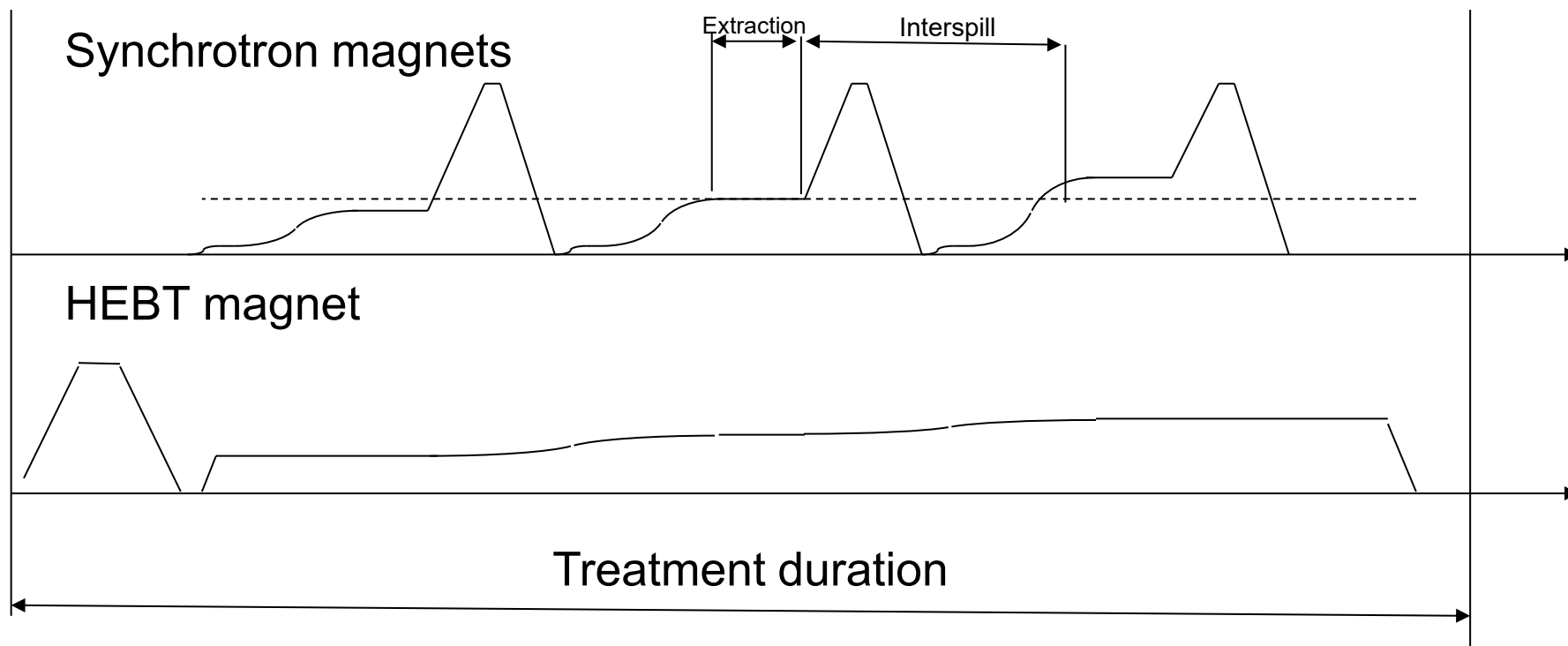The dose is delivered to the patient by an active system.
The irradiation of the tumor is performed dividing the target in slices along the beam directions (each slice corresponds to a different energy of the extracted beam). Each slice is divided in the transverse plane in several spots called voxels.
The depth is regulated changing the energy from the machine while two fast magnets move the beam among the voxels.
Two Ionization chambers measure the delivered dose in order to control the scanning magnets and the HEBT Chopper.

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Treatment execution

Synchrotron magnets

Extraction   Interspill

HEBT magnet

Treatment duration

0 sec<Extraction<4 sec
1.8sec<Interspill<2.2 sec for protons
2.1sec<Interspill<2.5 sec for carbon ions
Treatment duration dependent on tumour size (1 min-50 min)

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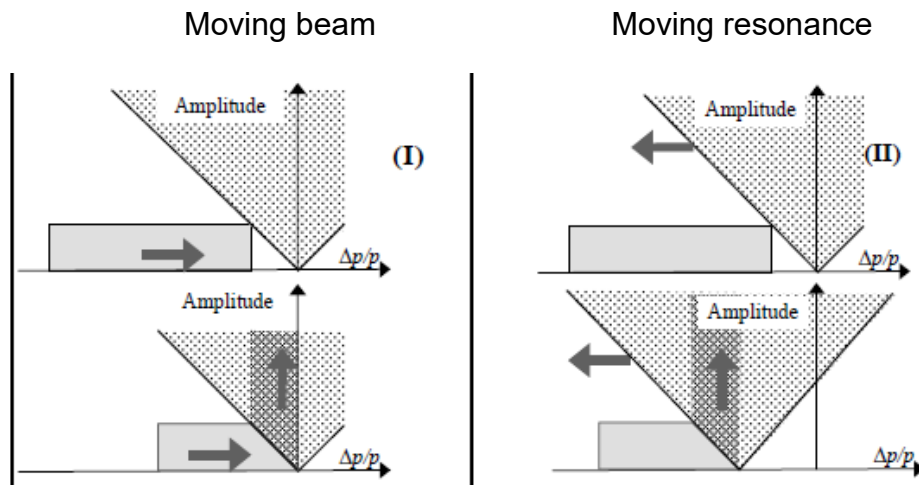
Resonant slow extraction

The extraction is realized by a third order resonance mechanism:
The machine tune is near 1.666 and a resonance sextupole feeds this resonance creating an unstable region. When beam enters this unstable region it can be captured by an electrostatic septum for the extraction.
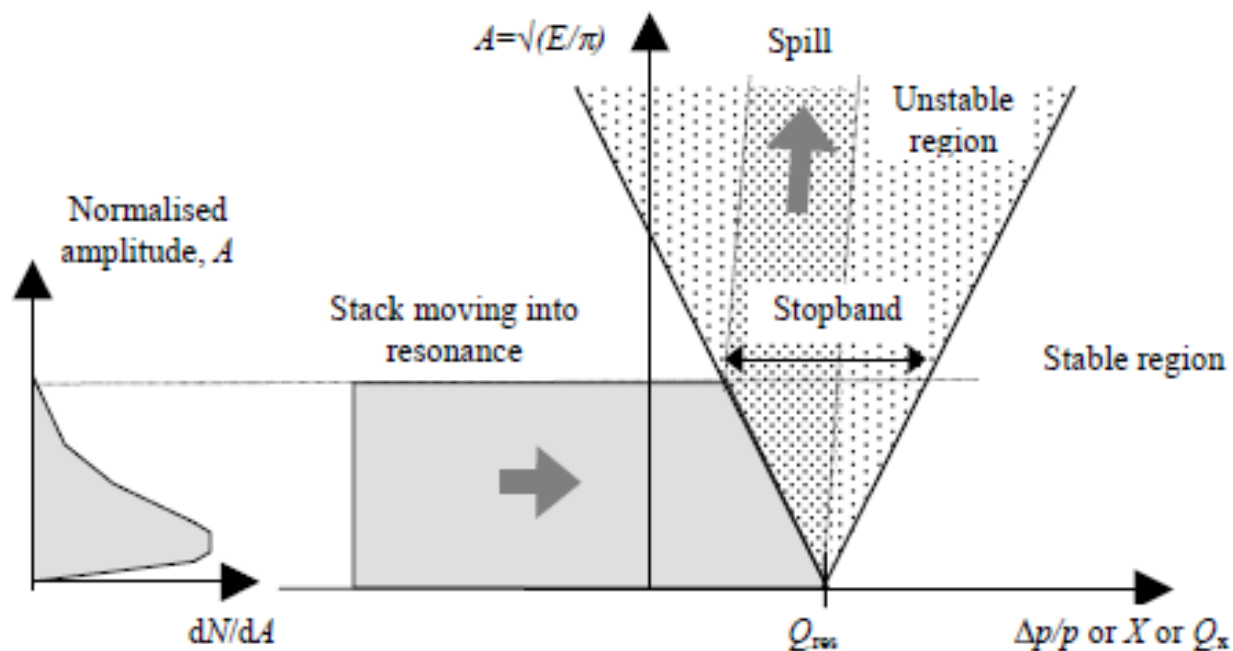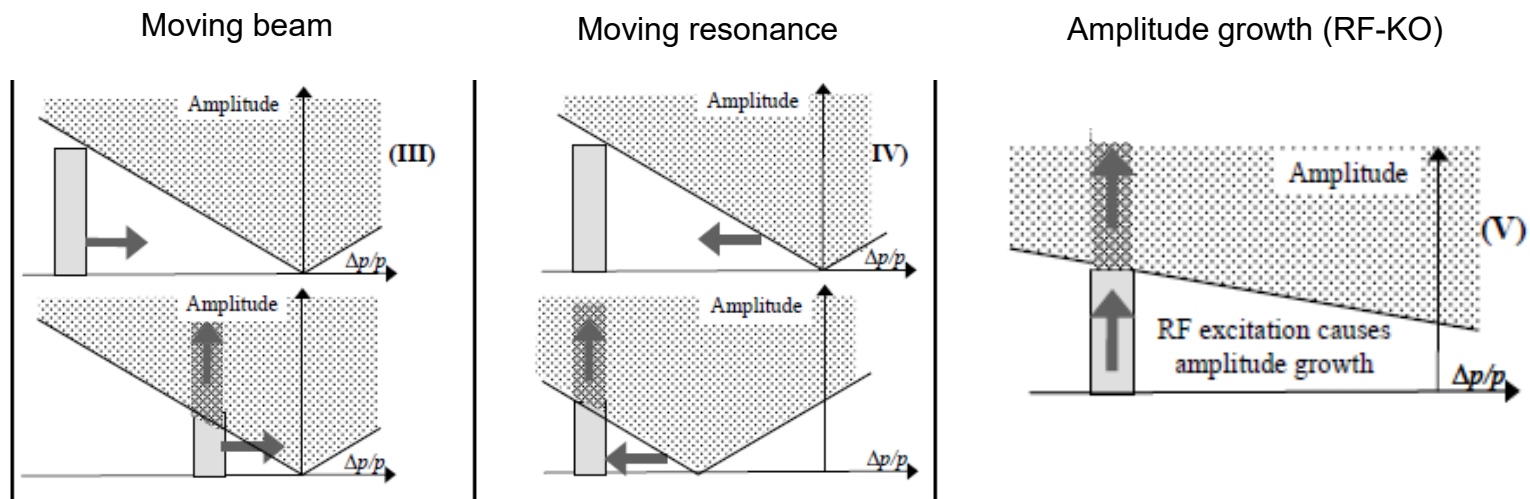

Steinbach diagram shows beam and resonance in the amplitude-momentum space

Extraction methods
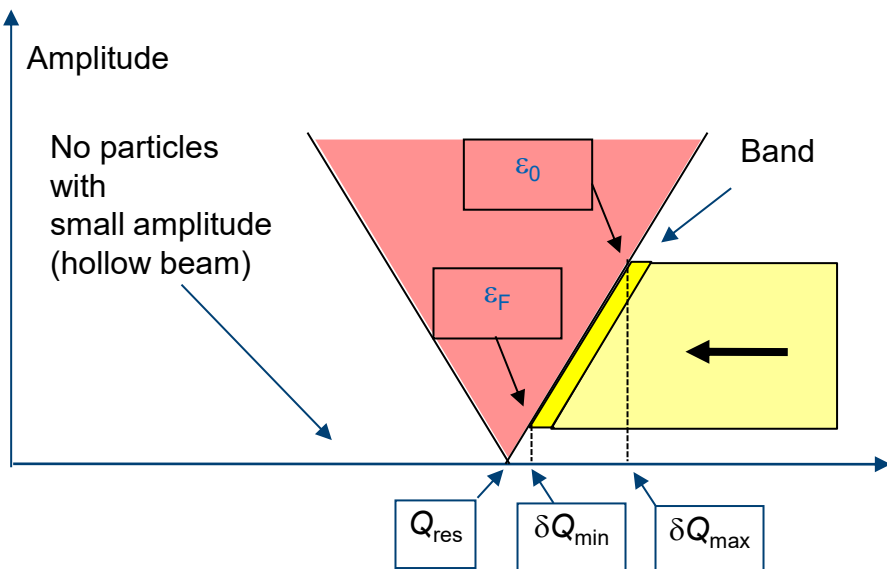

Momentum selection

Amplitude selection

Resonant slow extraction

The scheme adopted at CNAO is the «Momentum selection moving beam» scheme

The waiting beam has small emittance and large momentum spread
The extracted beam has small momentum spread.

Amplitude

No particles
with
small amplitude
(hollow beam)

ε_0

ε_F

Band

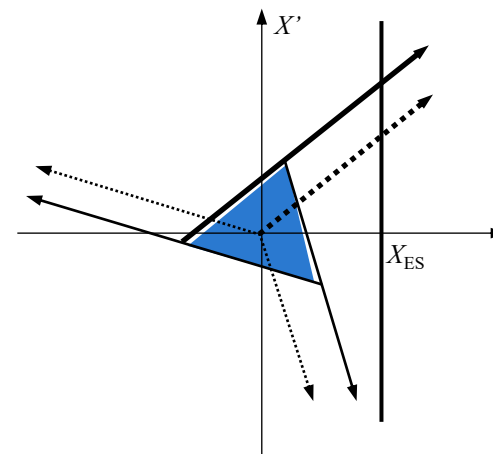Q_{res} δQ_{min} δQ_{max}

Lattice parameters are constant during the spill
Extraction takes place from a range of emittances and
this smoothes the spill
Hardt condition can be applied
A front-end acceleration mechanism can be added
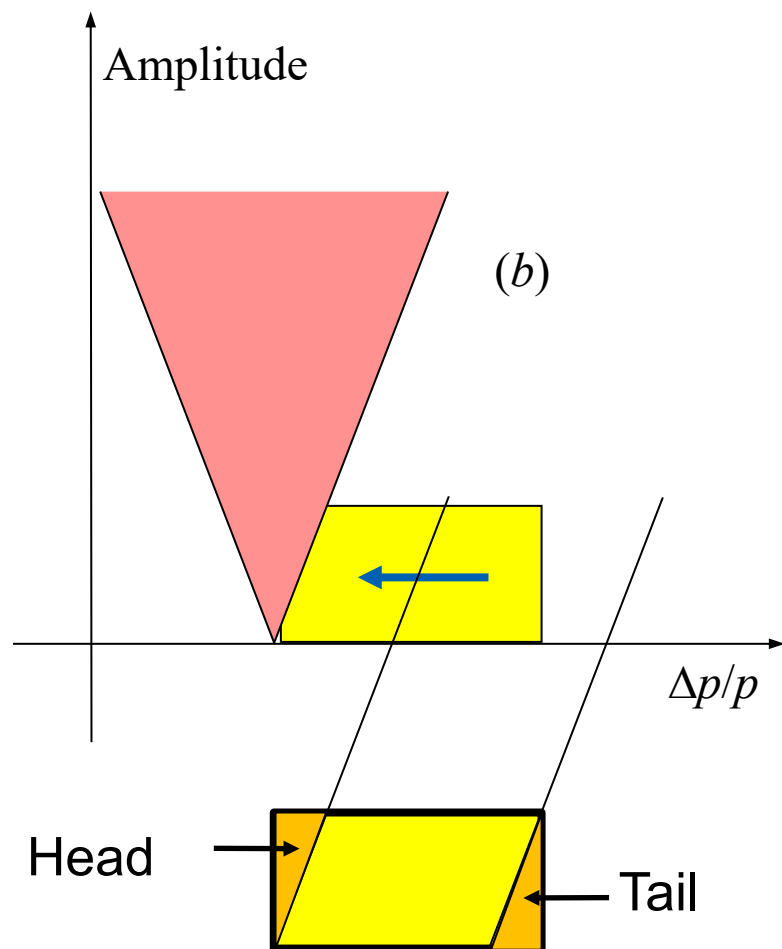Extraction separatrix and spiral step constant during
extraction.
Band profile, high frequency ripple tolerant.

$$dQ = \sqrt{\frac{ES^2}{48\pi^2\sqrt{3}}}$$

$$S = \frac{1}{2}\beta_x^{3/2}\frac{l_s}{B\rho}\frac{d^2B_z}{dx^2}\bigg|_0 = \frac{1}{2}\beta_x^{3/2}l_s K$$

X'

X_{ES}

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Head and tail of extraction

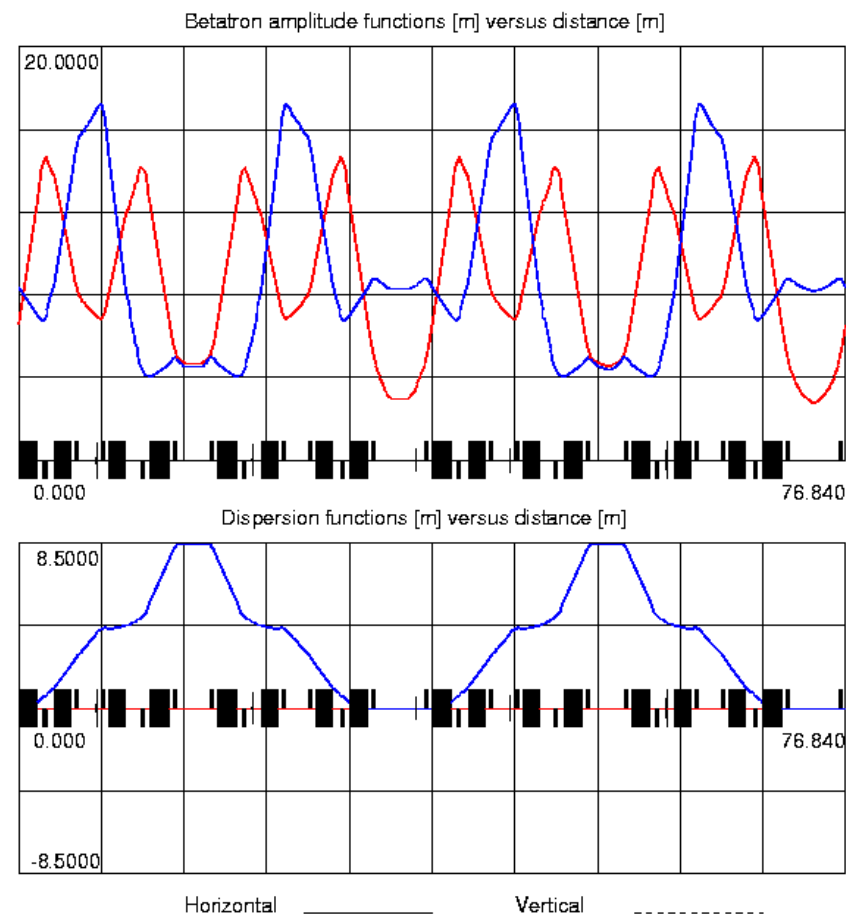
(b)

Amplitude

$\Delta p/p$

Head

Tail

The head and the tail of the beam can't irradiate the patient because beam size and position are different than during the center of the spill.
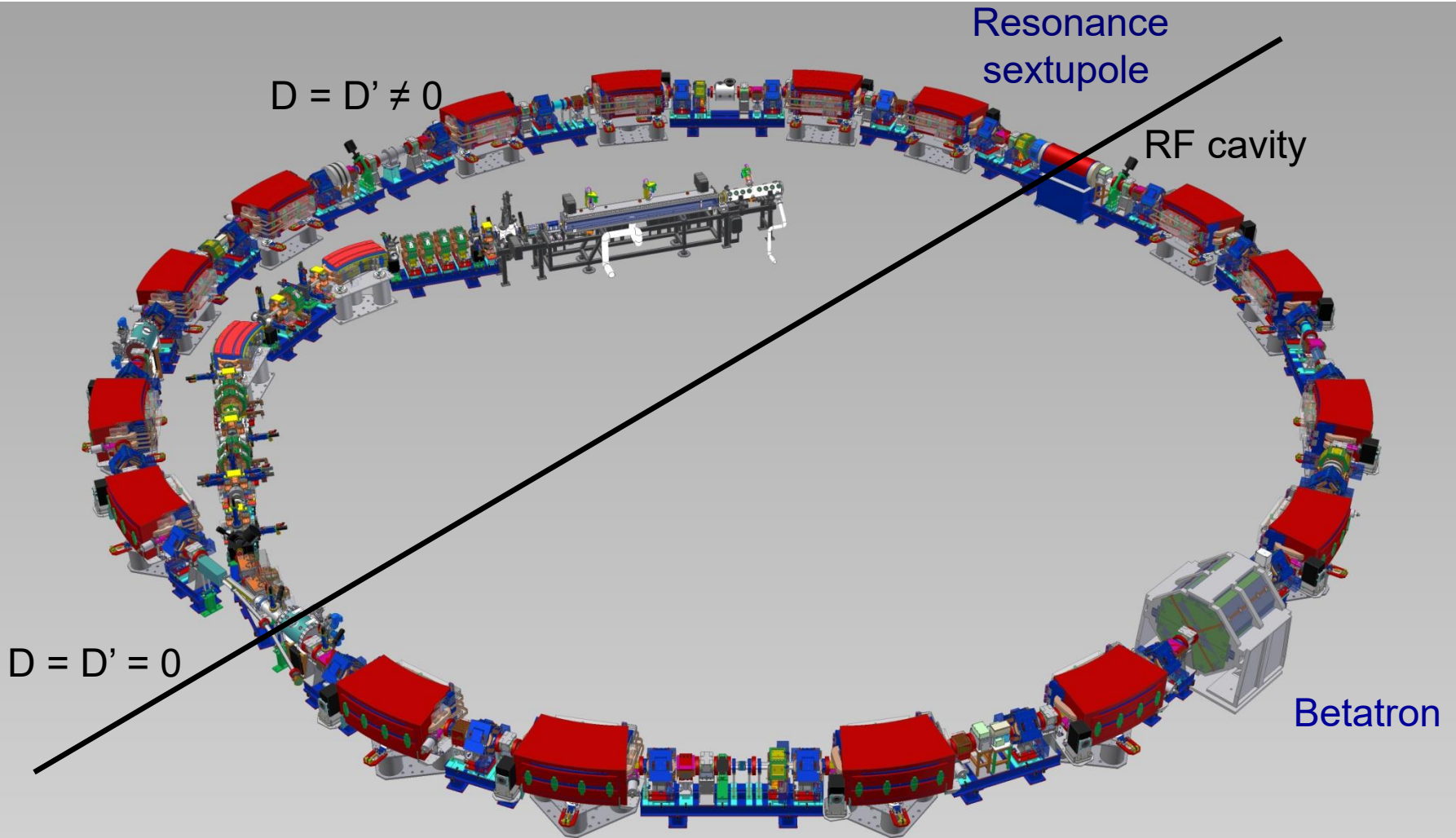So by the use of the HEBT chopper the head and the tail of the beam are sent to the HEBT dump.

Synchrotron Optics

2 Superperiods
2 Closed dispersion bumps
1 Dipole Family
3 Quadrupole Families
3 Sextupole Families (two family to Adjust chromaticity and one for the resonance)
Horizontal chromaticity at extraction -4

Betatron amplitude functions [m] versus distance [m]

Dispersion functions [m] versus distance [m]

Horizontal _____   Vertical - - - - - - - - - -

Synchrotron details

Resonance sextupole

RF cavity

$D = D' \neq 0$

$D = D' = 0$

Betatron
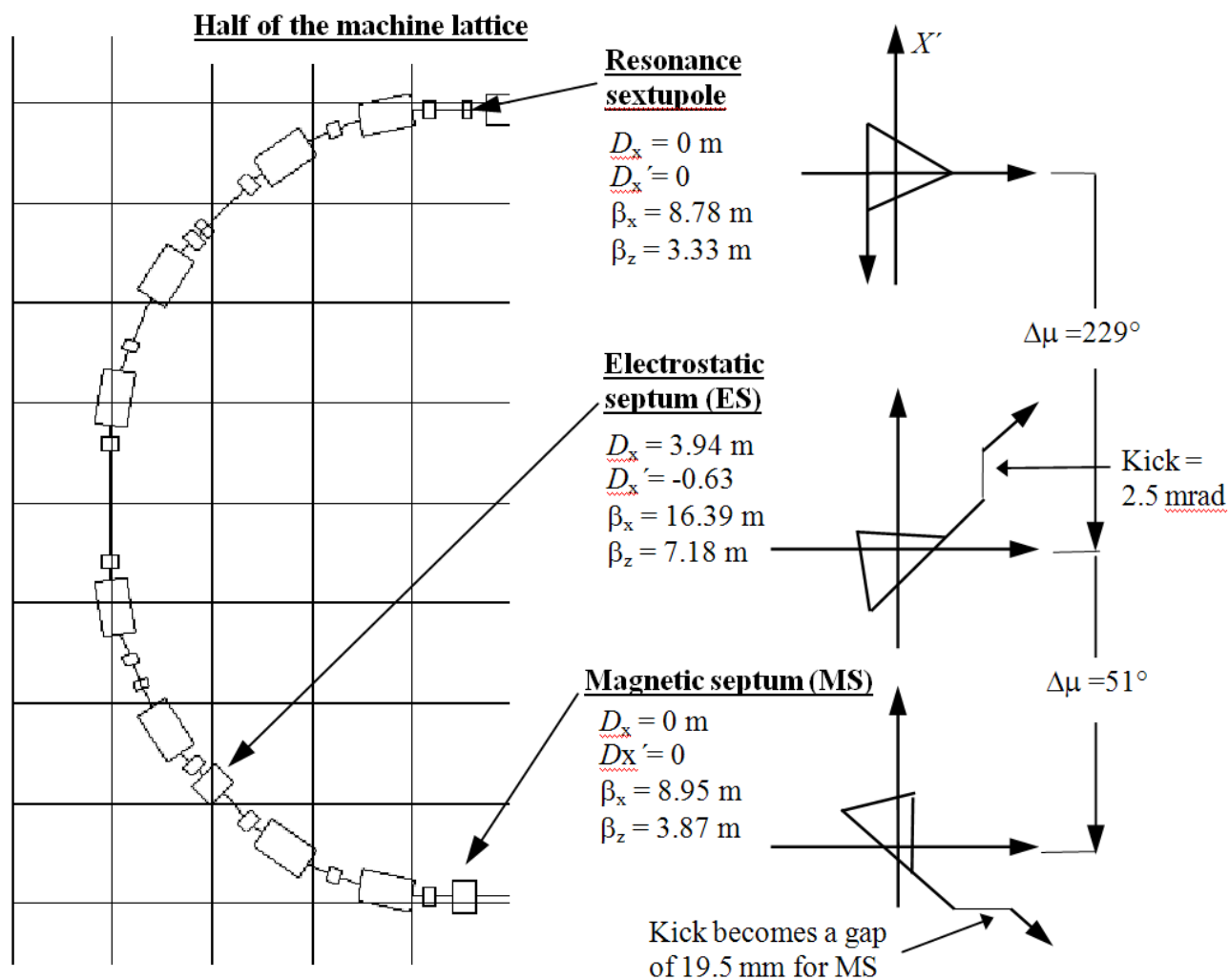
Extraction setup at CNAO

Figure 3 *Extraction configuration*
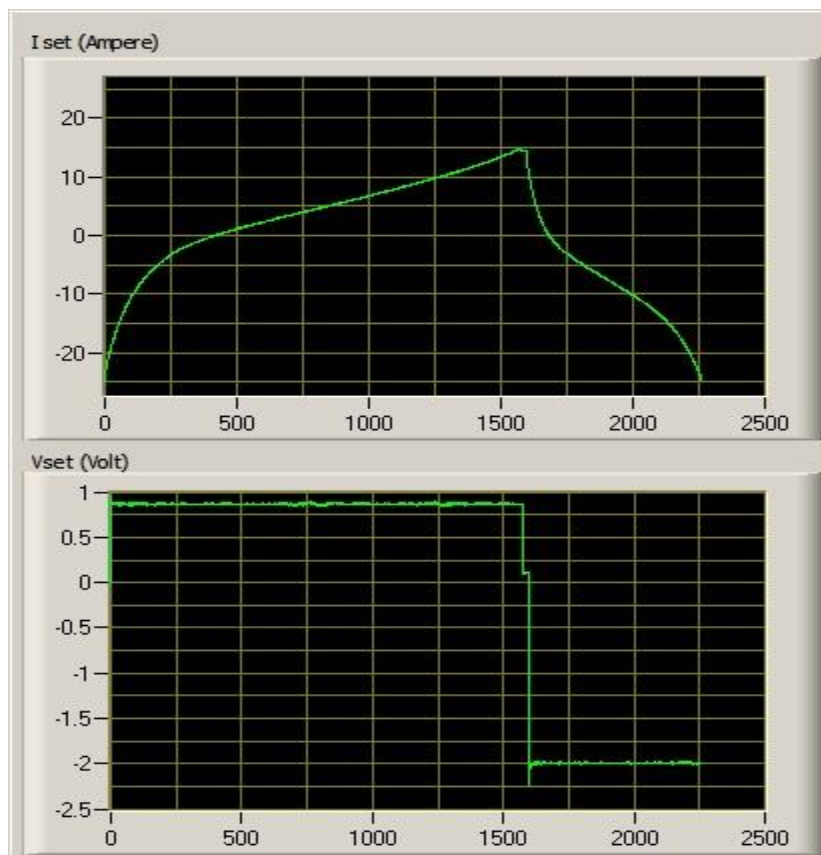
Betatron core 1/2

At CNAO the element used to accelerate the beam into the resonance is a betatron core.

It consists in a toroidal magnet placed around the beam orbit with a diameter of about 1.6 m and a length of about 1.5 m. Inside the magnet there are two coils; a variable current in the coils creates a variable flux of magnetic field resulting in a DC voltage along the beam path.
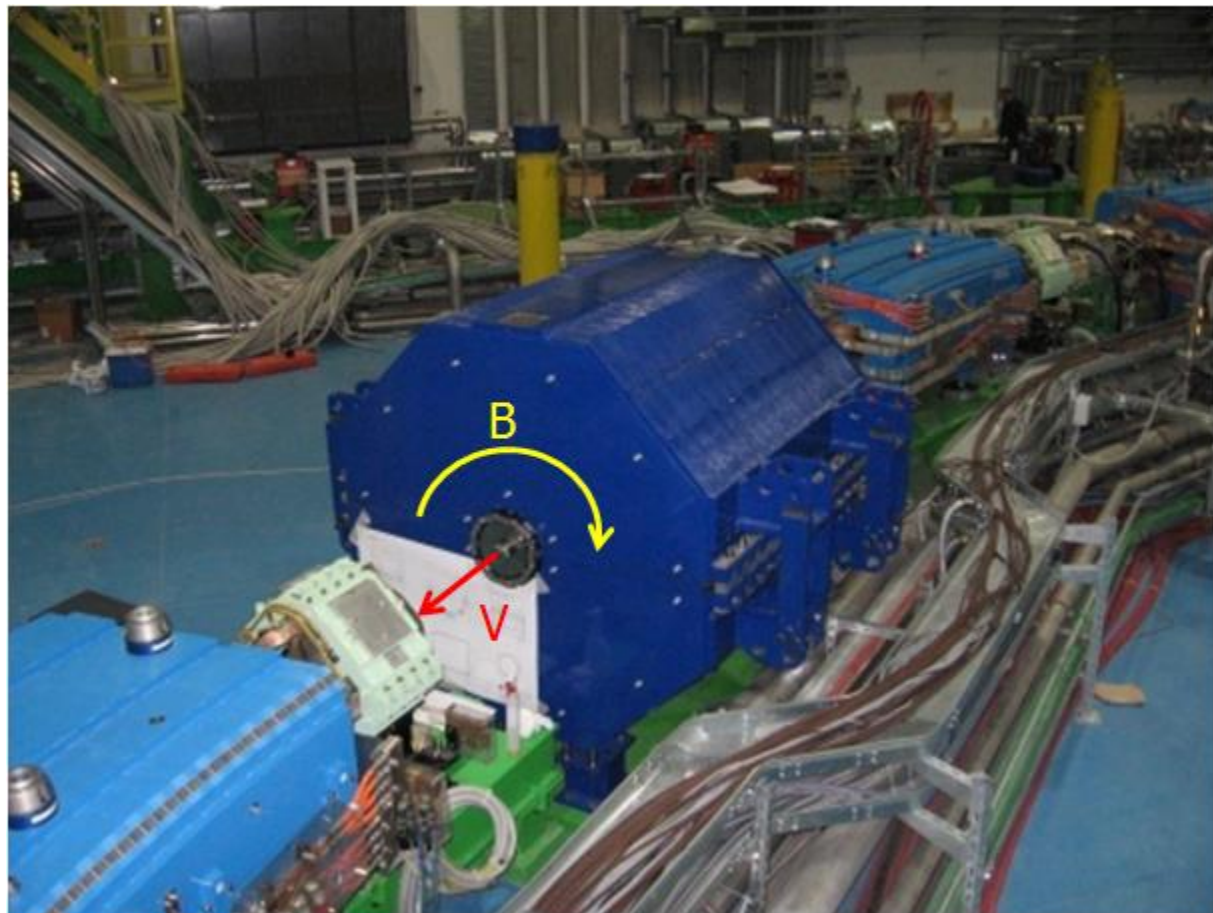
Betatron core 2/2

A sensing coil inside the magnet gives a feedback signal used to control the bipolar power supply that drives the coils, obtaining the needed accelerating voltage.

Typical current ramp needed to extract beam in 1.5 sec with a FEM of about 0.86 Volt; the shape of the current is due to the nonlinear magnetic properties of the betatron core.

Particle dynamics under the betatron FEM 1/2

When betatron core is on, every turn each particle receives an energy kick given by

$$\Delta E = \frac{Z}{A} V$$

Where Z is the atomica number, A the mass number and V the betatron FEM

Relativistic formulas give us the momentum spread kick due to betatron FEM, useful to understand the process in a steinbach diagram.

$$\frac{\Delta p}{p} = \frac{1}{\beta^2 E} \frac{Z}{A} VFT$$

Considering that the total momentum spread of the beam is fixed the previous equation relates The FEM with the extraction time T, by the beam frequency F, the relativistic beta and beam energy

Particle dynamics under the betatron FEM 2/2

Measurements confirm the proportionality between the FEM and the extraction time
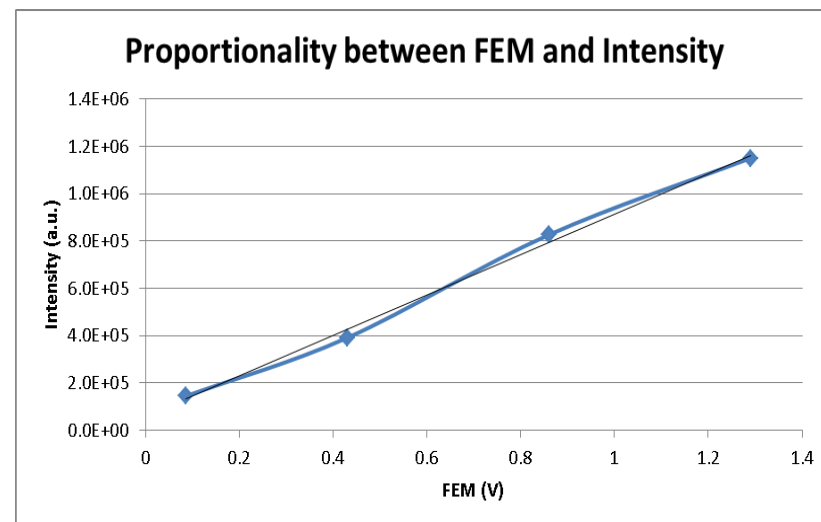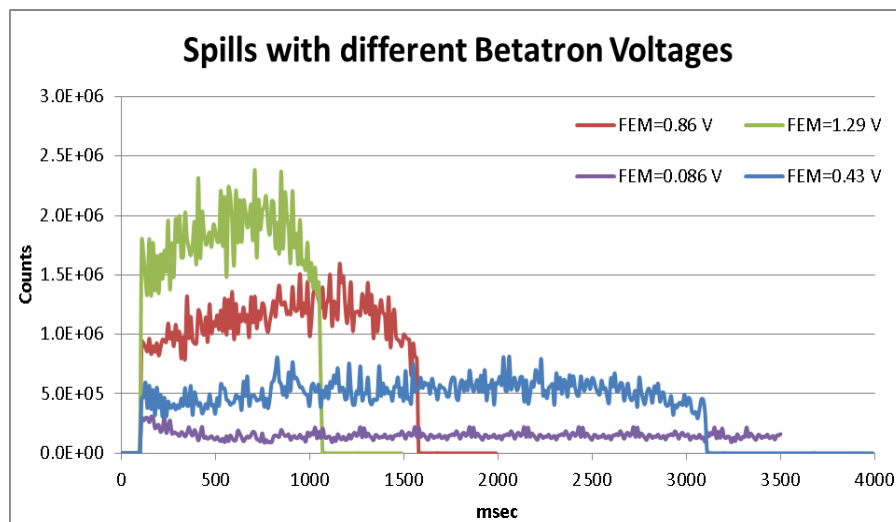
Spill time profile with four different Betatron voltages

FEM versus spill intensity with four different voltages

Empty Sweeping Bucket and Betatron Extraction

During the extraction RF cavity is switched on to perform a gym called
Empty sweeping Bucket. A bucket far from beam energy is created and moved
At a high frequency near the beam. This technique is mandatory to decrease
Ripple spill due to synchrotron power supplies ripple.
The presence of the bucket influence particle longitudinal beam dynamics and
can cause also beam losses and beam extraction; however if the RF
parameters are correctly set, the linear relationship between betatron force and
time extraction is maintained.
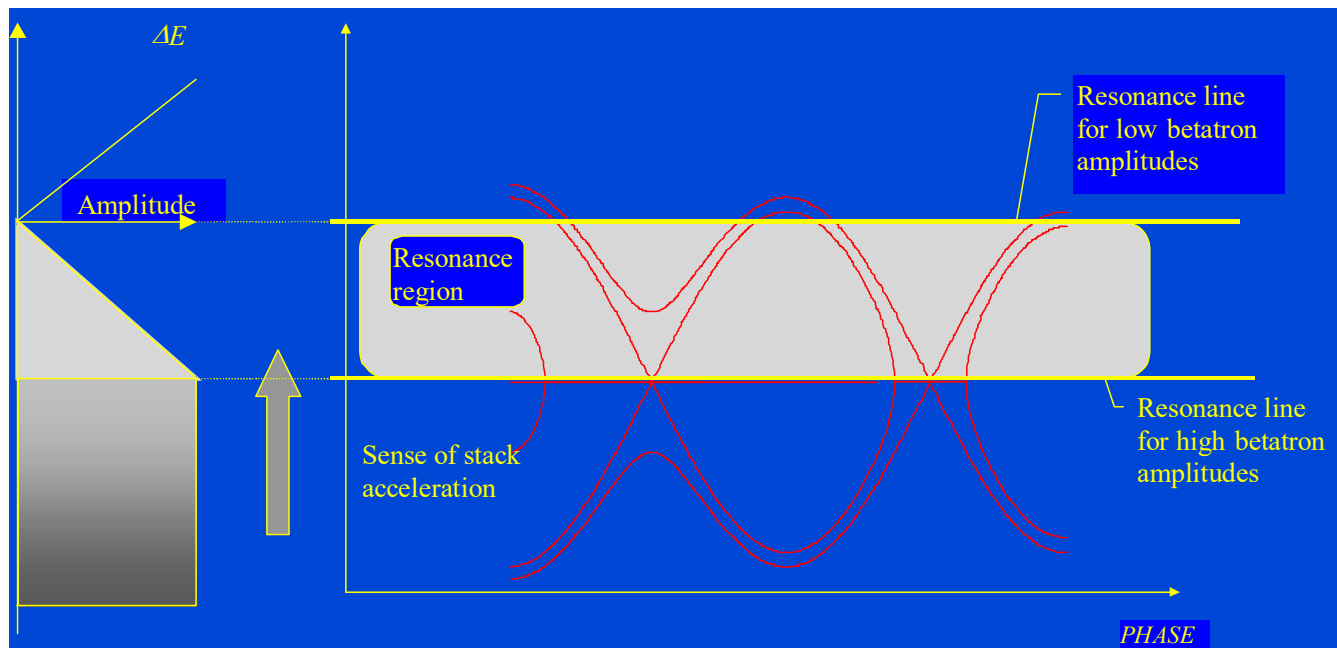
Intensity regulation 1/2

Since the time to stop the beam is not zero, some particles will arrive to the patient after the nozzle has decided that the irradiation has finished

HEBT Chopper reaction time

Required dose on the patient

Overdose on the patient
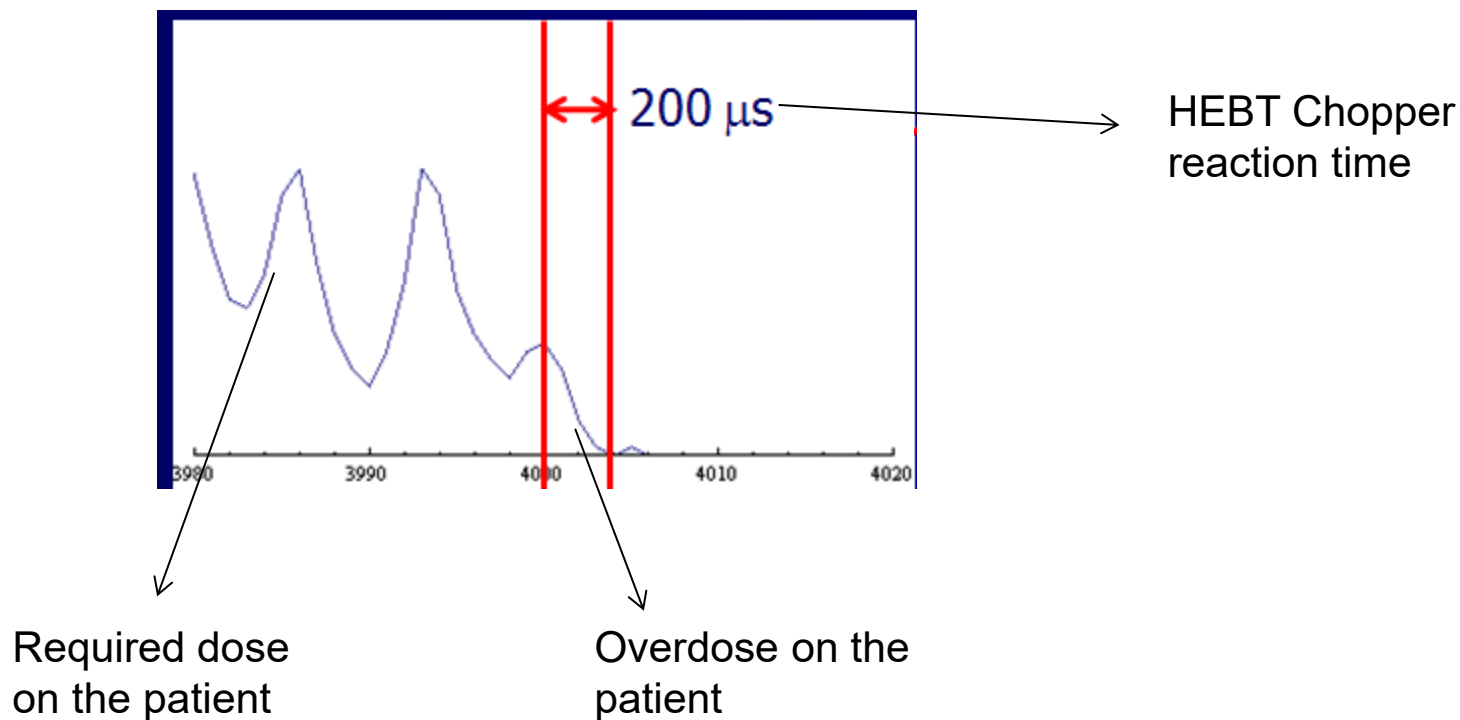
Intensity regulation 2/2

The voxels of each slice require a different dose depending on the tumor size. For a good treatment the overdose must be smaller than 2.5% of the dose required by each voxel.

For each slice, the average extracted current must be related to the current of the voxel which requires the smallest dose.

It is needed to find a way to extract cycle per cycle a different fraction of the nominal current.

Degraders 1/3

A strategy to decrease beam intensity is the use of a mechanical filter (degrader)
This idea has been implemented at CNAO and was exploited for some years by
using three degraders installed in the medium Energy beam line
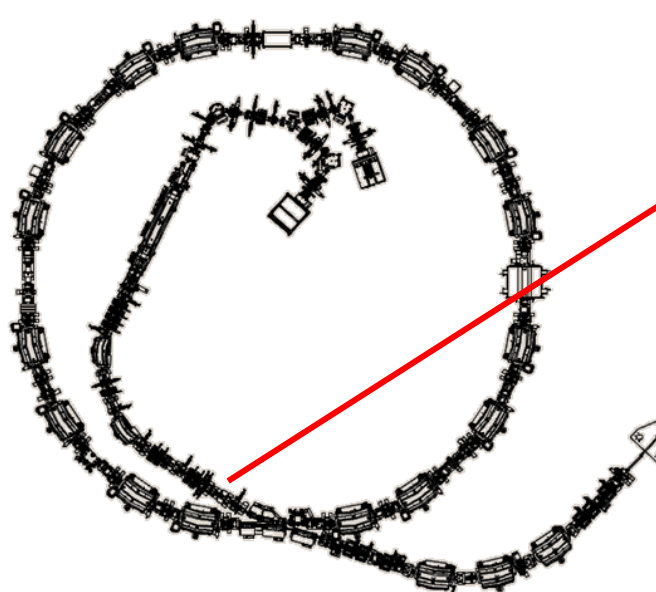
3 degraders
10% transparency
20% transparency
50% transparency

Degraders 2/3

The use of degraders has some disadvantages:

- The degraders are moved cycle per cycle (about every 3 sec), so the moving system needs an accurate maintenance
- The movement of the degraders needs about 1 sec and this time lengthens the time between two spills.
- Only 4 reduction factors can be obtained
- To guarantee that the extracted current has the right value the nominal current must be stable enough, and this is not always true in particular after maintenances on the sources or the LINAC.
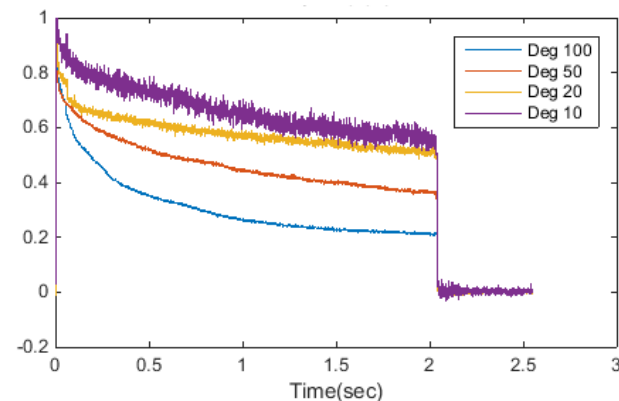
Degraders 3/3

- Since at the injection energy the space charge tune shifts are relevant, reducing the injected charge in the synchrotron changes the space charge effects : this can lead to different emittances and then different beam characteristics of the extracted beam
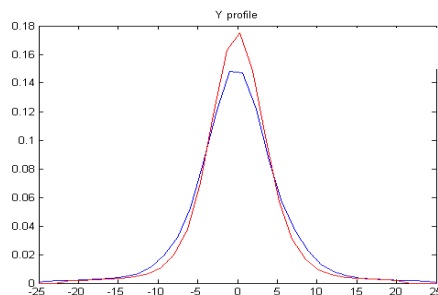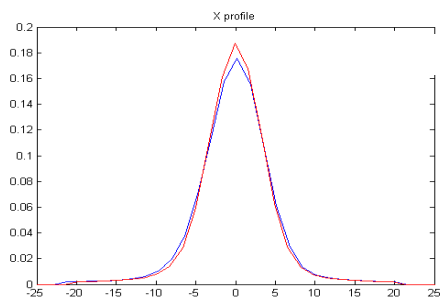
Horizontal and vertical profile of extracted beam with and without a 20% degrader

— 20% degrader
— Without degrader

Particles stored in the ring (normalized to the maximum value) versus time with different degraders

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Dynamic betatron method

A solution of all the disadvantages due to the degraders is the so called dynamic betatron extraction. The idea is to exploit the linearity between FEM betatron and extracted intensity.
For each machine cycle the betatron will accelerate beam with a FEM given by

$$V = \frac{N}{N_{max}} V_{max} R$$

Where

V_{max} is the FEM to extract beam at the maximum intensity

N_{max} is the accelerated current corresponding to the maximum extracted intensity

N is the current accelerated in the current machine cycle

R is the ratio between the extracted intensity required by the current slice and the maximum extracted intensity

Dynamic betatron method advantages

With the dynamic betatron method
- There are no mechanical elements and the intensity modulation is obtained by the same device used for extraction
- There is no limit in the number of reduction factors
- To guarantee that the extracted current has the right value the nominal current must be stable enough, and this is not always true in particular after maintenances on the sources or the LINAC.
- The extracted beam has always the same characteristics
- The extracted current will be independent on instabilities of the accelerated current (usually due to injector instabilities)
- It is possible to reduce the number of acceleration cycles to irradiate the same slice. For example if the machine usually accelerates N particles per cycle, it is possible to irradiate a slice needing N particles at half intensity with only one cycle (with a degrader you would need two cycles).The comparison of 50 treatments with degraders and with dynamic betatron showed a time reduction of about 30% !!!!

Future improvements 1/3

Simulations have been performed for an extraction method able to shorten the treatments.
The idea starts from the principle that each slice is made up of voxels needing a different dose.
If one irradiates first the voxels requiring less dose and then the one requiring more dose, one can extract beam at different intensities during the same slice.
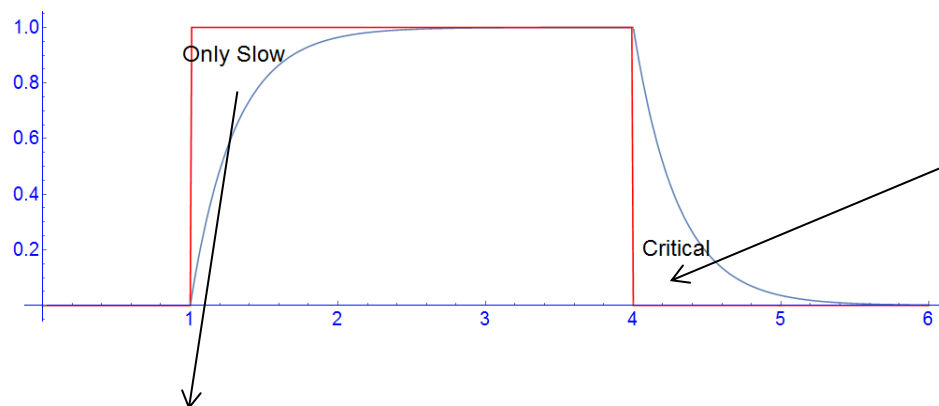This can be obtained just increasing the betatron FEM during the same extraction.
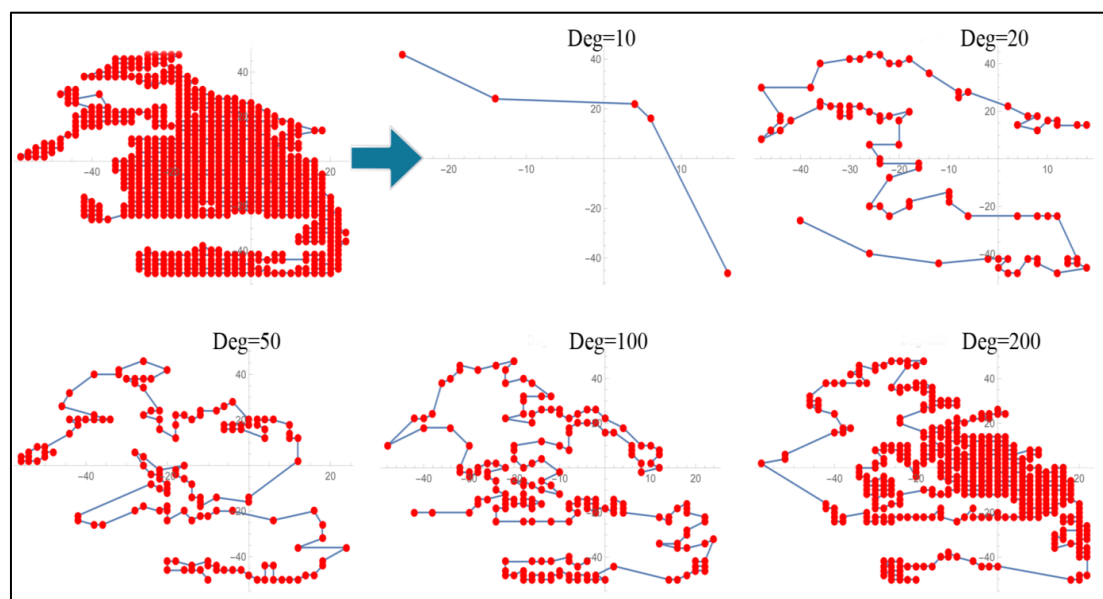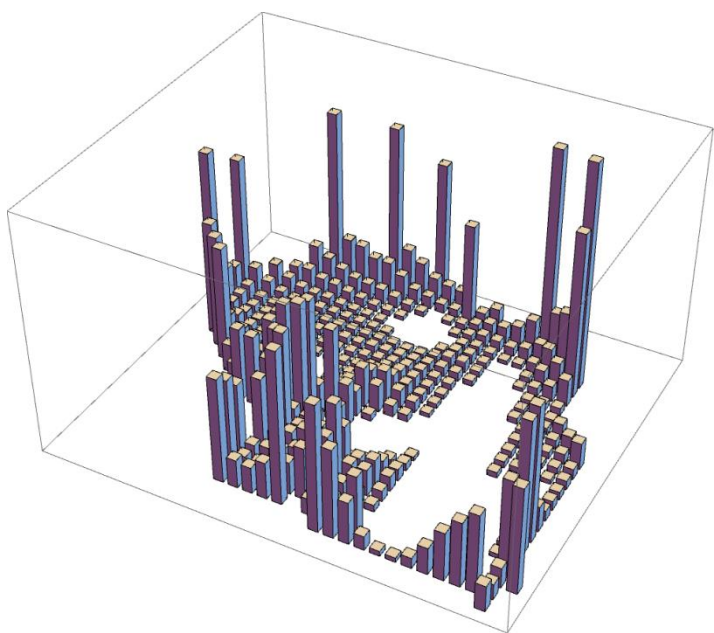
Dose required by the voxels of a slice

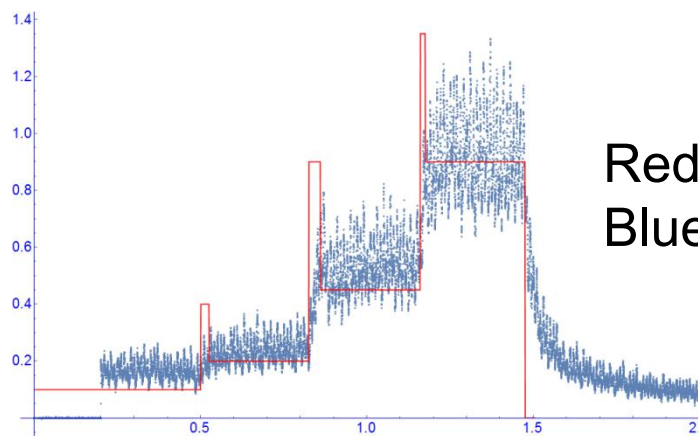The voxels of each slice must be re-arranged according the needed dose

Future improvements 2/3
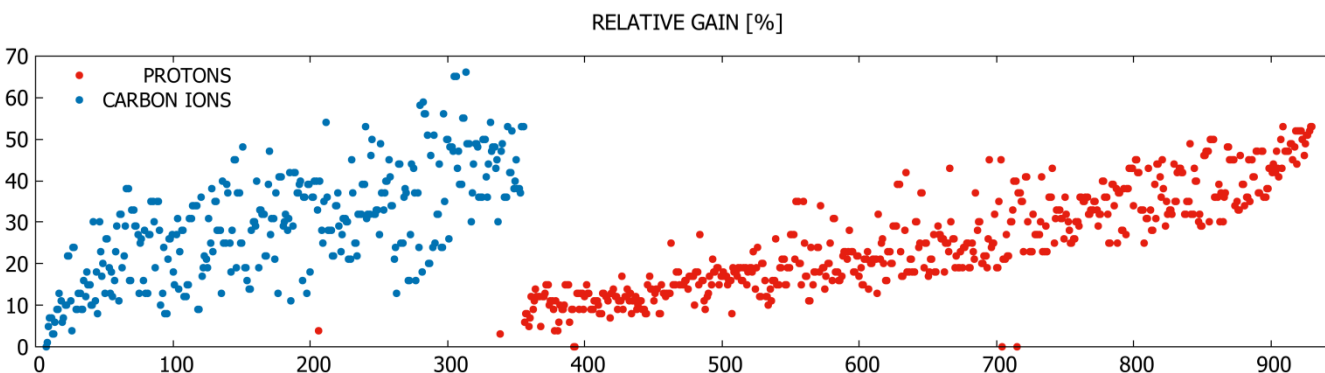
The betatron reaction time is about 25 msec

This overdose explains why the voxels must be re-arranged from the Minimum to the maximum dose: in this way it can be eliminated by the chopper

To avoid this the required FEM has an overshoot

Red: Betatron FEM
Blue: Extracted beam

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Future improvements 3/3
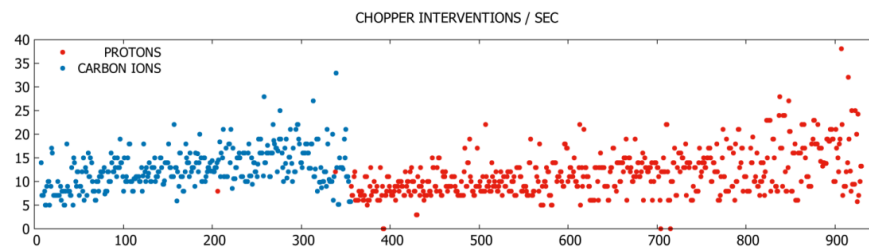

RELATIVE GAIN [%]

PROTONS
CARBON IONS

irradiation time is reduced of
25% for protons (max 53%)
28% for carbon ions (max 66%)

Drawback: **increment of chopper interventions**

Can be a parameter to discriminate among treatment plans candidate to intensity modulation.

CHOPPER INTERVENTIONS / SEC

PROTONS
CARBON IONS

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Thank you for your attention

"Physics is like sex: sure, it may give some practical results, but that's not why we do it. "

R. Feynmann

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