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DIAGNOSTICS FOR MEDICAL ACCELERATORS

Medical Accelerators versus Experimental Accelerators /1

Medical machines are similar to LINAC, Cyclotron, Synchrotron used for low energy physics experiments, but...

- ◎ **Patient Safety** -> strict control to avoid over-dose to patient
- ◎ **Treatment Quality** -> dose distribution over cancer volume has to respect treatment planning requirements rigidly

Medical Accelerators versus Experimental Accelerators /2

- ◎ **Dose&Beam Delivery** -> the medical machine requires a “brain” (called *Nozzle*) receiving treatment planning details from the Medical World and controlling Machine Side, depending on the delivered dose
- ◎ **Diagnostics** -> beam diagnostics for medical machine is basically the same used for experimental machine, but its goals and control can be significantly different

Medical Accelerators Overview /1

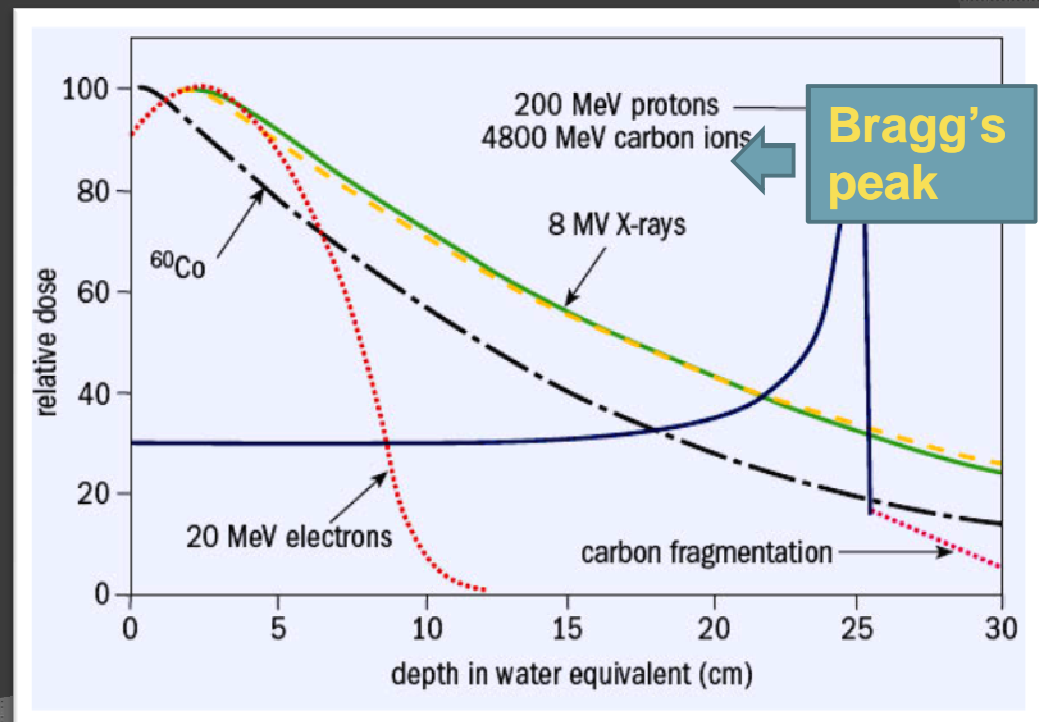
- ◎ **General Requirements:** compact size, cost kept down, easy to use and to maintain, reliable, efficient
- ◎ **@ Medical Centres:**
 - **LINAC:** compact size/ easy to use/ dedicated to conventional radiotherapy/ not suitable to accelerate hadrons up to hadrontherapy energies (prototypes of LINAC for hadrontherapy exist, but still not commercial)

Medical Accelerators Overview /2

- **Cyclotron:** compact size/ easy to use/ continuous beam/ high intensity, small intensity ripples/ fixed energy (passive modulators must be changed to modify energy), not negligible energy spread/ maximum energy not enough for C-ion treatments
- **Synchrotron:** large size/ elaborate operation but flexible machine/ wide intensity range suitable for treatments (1Gy/min in 1 litre), despite risk of significant ripples/ wide energy range with small energy spread/ suitable for C-ion treatments

Synchrotron for Hadrontherapy /1

- Hadrons release energy in the matter making Bragg's peak, differently from the other particles
- Hadrontherapy key-point is the ability of killing diseased cells selectively, minimizing damages in the all around region
- In this scenario, beam position accuracy at patient level becomes mandatory not to save 'bad' cells -> **Dose Uniformity [+2.5%]**

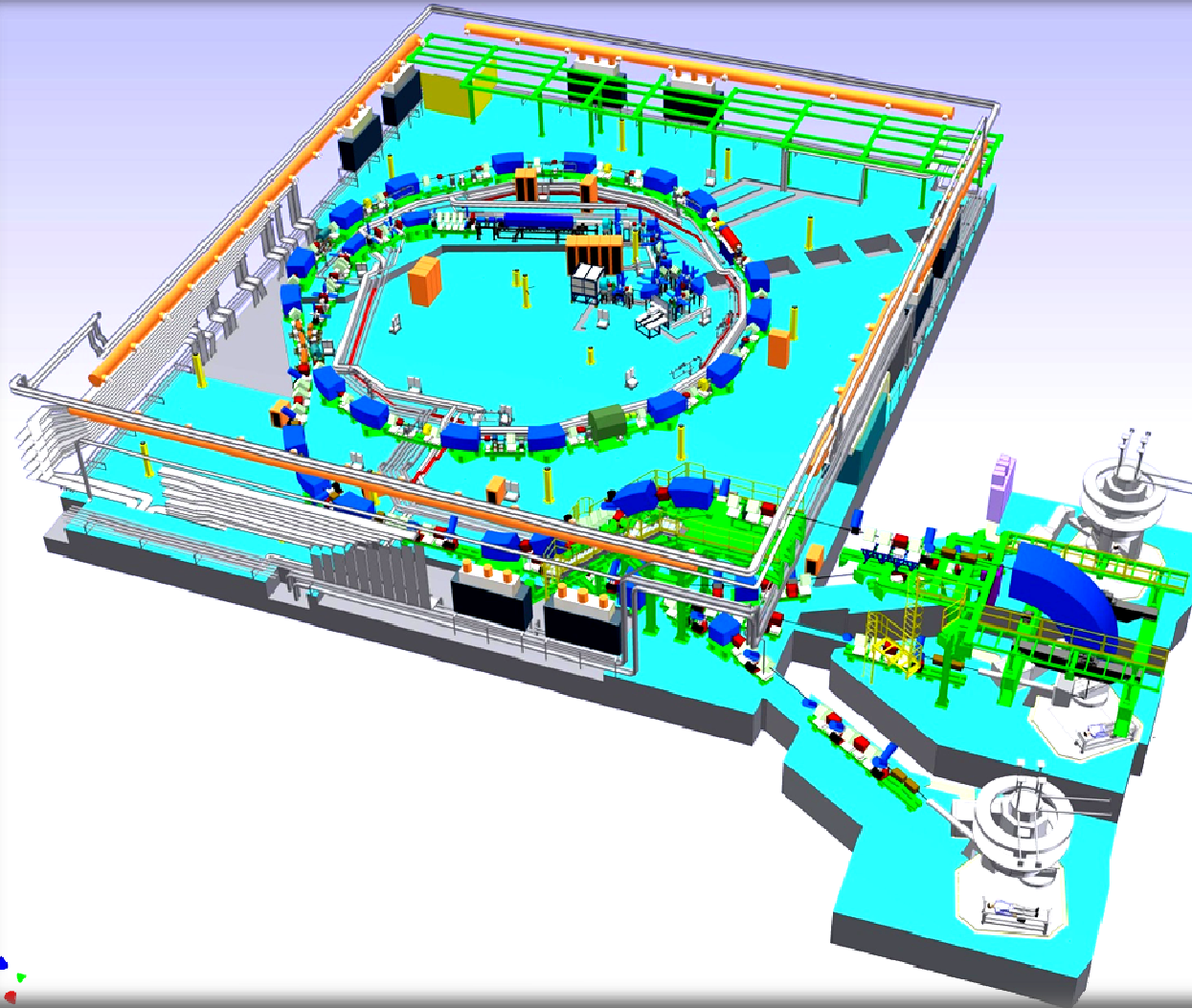


Synchrotron for Hadrontherapy /2

- Wide Energy Range (@ CNAO: source 8keV/u, after LINAC 7MeV/u, extraction 60-250MeV for protons, 120-400MeV/u for C6+ ions, energy resolution 1mm step equivalent)
- Wide Intensity Range (@ CNAO, one nominal spill contains $1\text{E}+10$ protons or $4\text{E}+08$ C6+ ions reducible of a factor 100, without emittance increasing)
- Cycle-based Machine: beam parameters change quickly (1-2 sec), depending on treatment requirements

-> Different detector principles must be used

CNAO Layout



- 2 DC sources (protons and C⁶⁺ ions)
- synchrotron circumference 76.84m
- 3 horiz + 1 vert treatment lines
- 1 experimental line (for future)
- protons extracted at 60-250MeV
- C-ions extracted at 120-400MeV/u
- bar-of-charge for narrow beam in the horizontal plane
- active scanning
- first patient in few months

Monitors Requirements /1

(peculiar for Medical Machine)

- ◎ **Fast Setting Up and Debugging** [patients should not wait, for comfort & cost] -> don't forget Beam Instrumentation at design time
- ◎ **Monitors should not perturb beam** -> non (or low) interceptive monitors only can be used during treatments [if we add/ remove targets on beam path, we change Bragg's peak depth]
- ◎ **Dose Delivery System** -> system dedicated to measure the dose delivered to the patient

Monitors Requirements /2

(peculiar for Medical Machine)

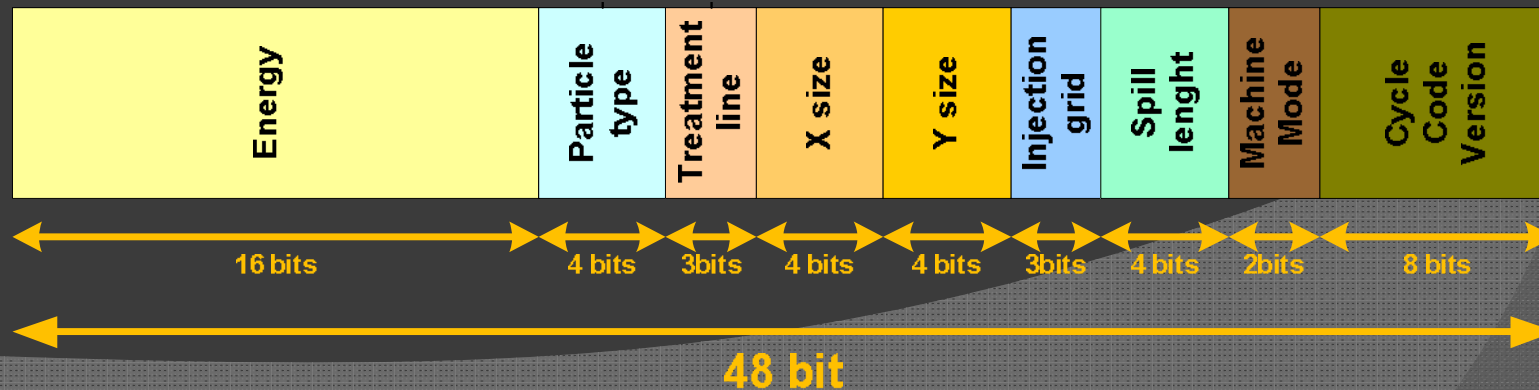
In particular, to guarantee treatment quality (@ CNAO):

*** A long list here: details in the next pages ***

- ◎ **Minimize Intensity Ripples:** [magnets] debuncher, betatron – [operation] slow extraction – [diagnostic] Chopper Faraday Cup, Current Transformer, Beam Qualification Monitors (intensity), Servo-Spill
- ◎ **Qualify Beam Size and Intensity:** Beam Qualification Monitors intensity&position (before sending beam to patient), NOZZLE (control of scanning magnets)

Diagnostics Control /1

- CNAO synchrotron works with a cycle about 2sec long
- It means that every 2sec a message is sent by the Timing System to all the subsystems (magnets, diagnostics, ...) providing beam parameters (particles type, energy, intensity,...) needed for the next machine cycle



Diagnostics Control /2

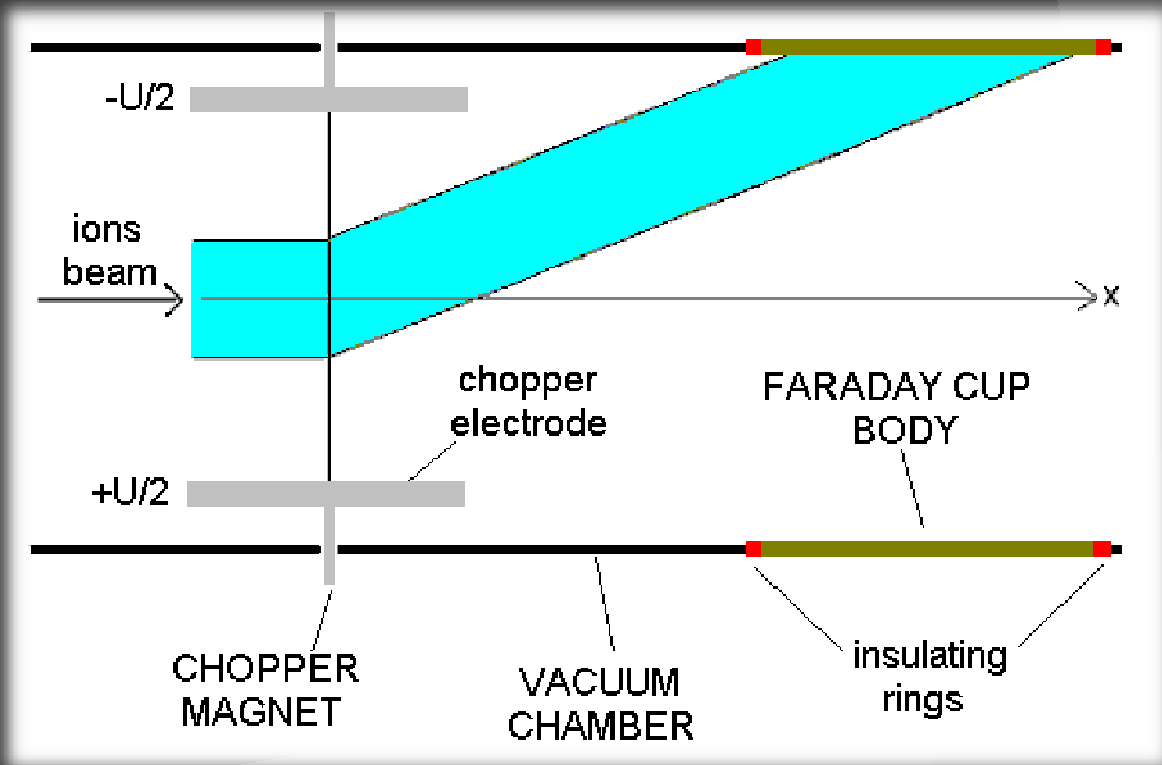
- Next cycle can start only if all the subsystems have sent back their right acknowledge
- Monitors setting (amplifier gain, slits position, expected parameters to qualify the beam...) changes automatically depending on the new beam parameters: in few ms machine configuration can change drastically (using the Timing message)
- The list of cycles to be executed is fixed by the treatment planning *of course*

Monitors in details

- ⦿ Let's go into details for some monitors used to improve beam quality, in position, dimension and intensity uniformity
- ⦿ We refer to CNAO experience. Some monitors are available on the market, others are home-made and are aiming to satisfy peculiar needs of CNAO machine

Chopper Faraday Cup /1

- Source beam is DC. Before entering LINAC, beam has to be bunched
- Chopper is a magnet deflecting particles towards vacuum chamber, to make bunched a continuous beam (@ CNAO injection line: beam against vacuum chamber for more than 95% time)



Chopper Faraday Cup /2

● The Chopper Faraday Cup (CFC) aims to detect source current stability and ripples with 10kHz bandwidth. 1% resolution for the minimum beam current (C-ions, 0.15mA) requires 1.5uA absolute resolution

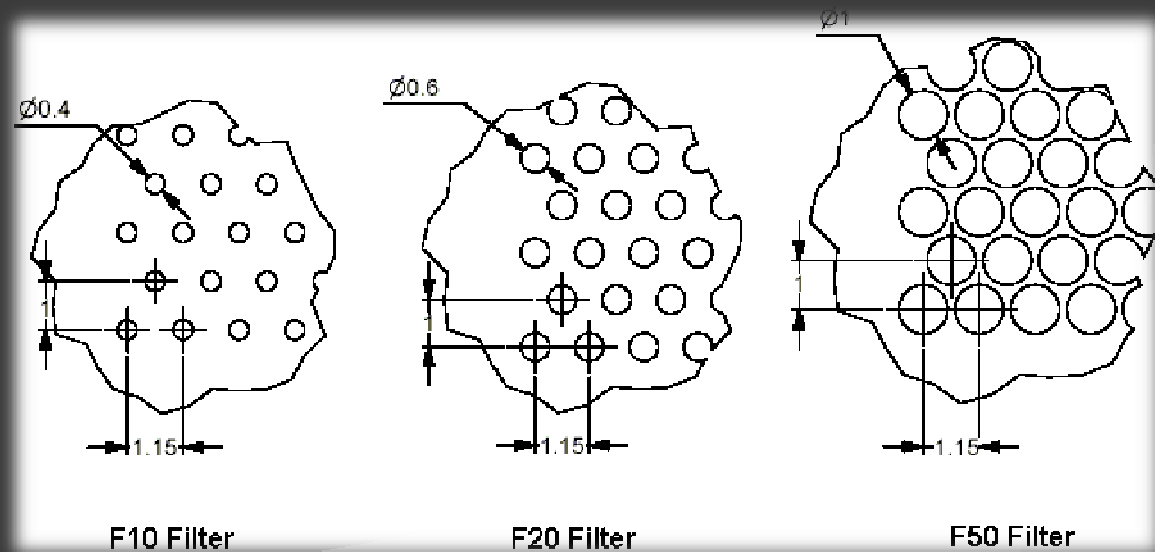
● CFC High Voltage switched ON/ OFF when Chopper OFF/ ON, not to perturb beam entering LINAC

-> Beam uniformity is a key-point for medical machine, in particular for hadrontherapy

H3+ Current Intensity at Chopper	0.70mA
C4+ Current Intensity at Chopper	0.15mA
Beam Current Stability	±1.5%
Beam Current Ripples	<±2%
Beam Energy	8keV/u
Beam before the Chopper	continuous
Beam after the Chopper	100usec pulse at 0.5Hz
LEBT Vacuum Pressure	10 ⁻⁶ -10 ⁻⁸ torr

Degrader

- The machine is prepared for 'nominal' intensities, that can be reduced according to treatment planning requirements
- At CNAO we use a Degrader made of 3 pepper-pot metal plates, reducing intensities down to 10% of nominal value, without affecting beam emittance

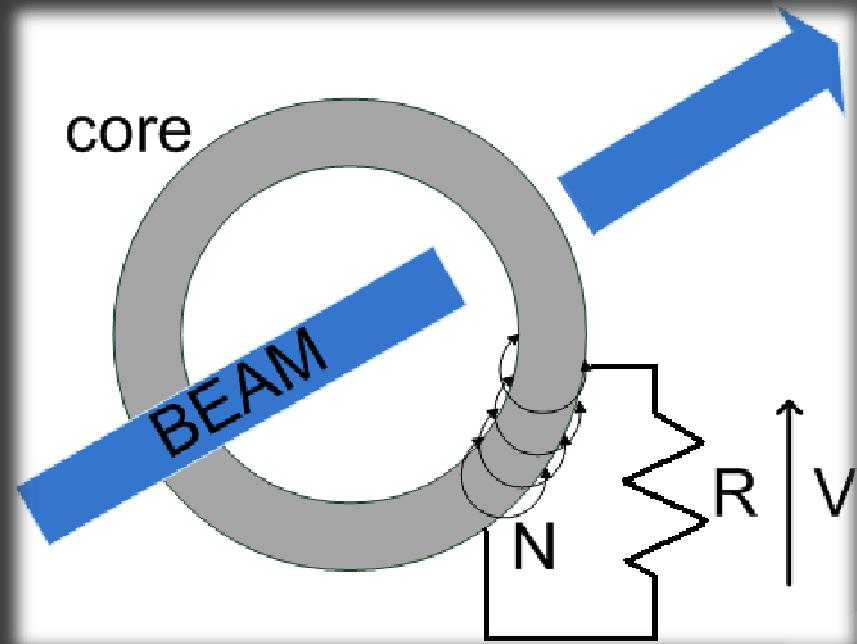


Current Transformers

- Charge flow measurement: beam current changes during acceleration / beam charge *hopefully* remains constant
- Non-interceptive intensity measurement, for continuous (DC) and pulsed (AC) beams

AC-Beam Transformer

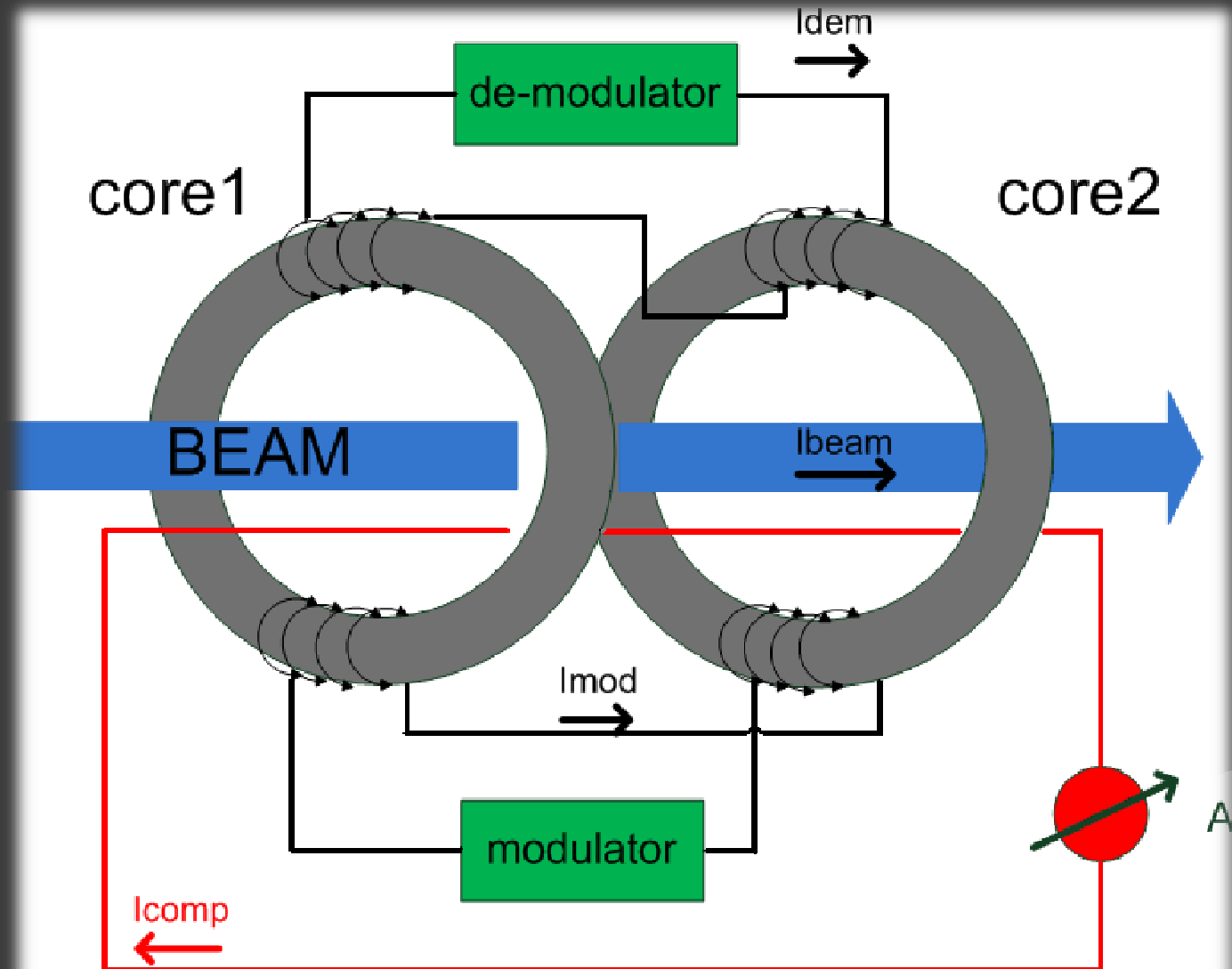
- For bunched beam (up to few ms long batches)
- Beam acts as a primary winding
- Beam current is read from the secondary winding
- $\tau_{\text{Droop}} [\text{sec}] = \text{Winding Inductance} [\text{H}] / \text{Read-Out Resistance} [\Omega]$
After 1 τ_{Droop} , signal is exponentially reduced of $1/e$



DC-Beam Transformer /1

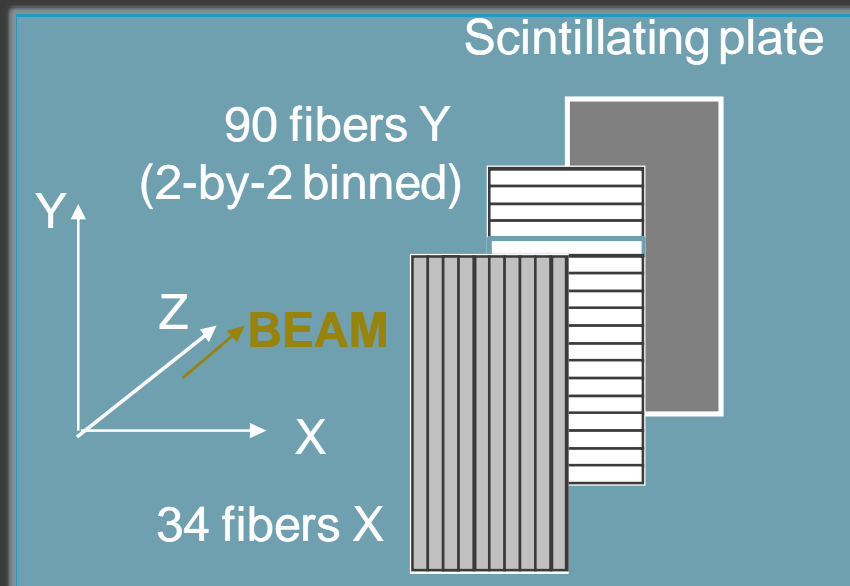
- For continuous beams (either DC-component of bunched beams)
- Use of two 'identical' cores
- Beam current measured through the magnetic field induced by the beam in the core
- Blind to fast current variations

DC-Beam Transformer /2



Beam Qualification /1

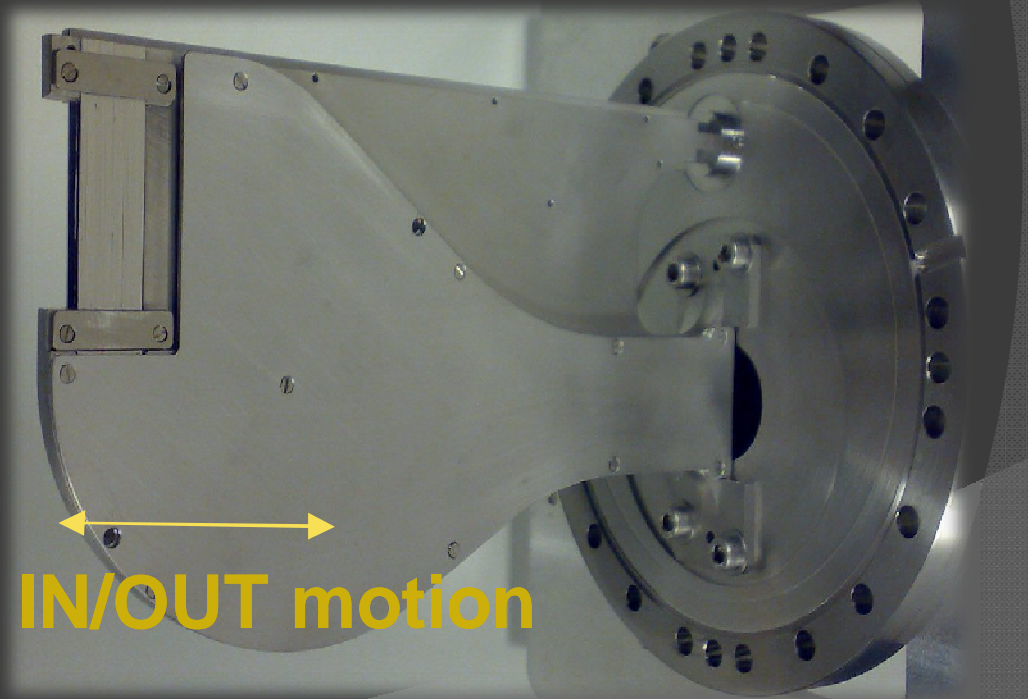
- ◉ Beam size, position (QPM) and intensity (QIM) quality checked before sending beam to patient or during treatment suspensions:
 - Avoid treatment interruption
 - Improve treatment quality



- ◉ QPM+QIM placed in front of extraction line dump. During first 100ms of each spill, beam is dumped and qualified. If qualification result is positive, beam is sent to treatment room

Beam Qualification /2

- Qualification measurements cannot take more than 100ms: number of treatments per day must be maximized
- Automatic beam qualification:
 - Cycle-Code dependent
 - Algorithm to be commissioned



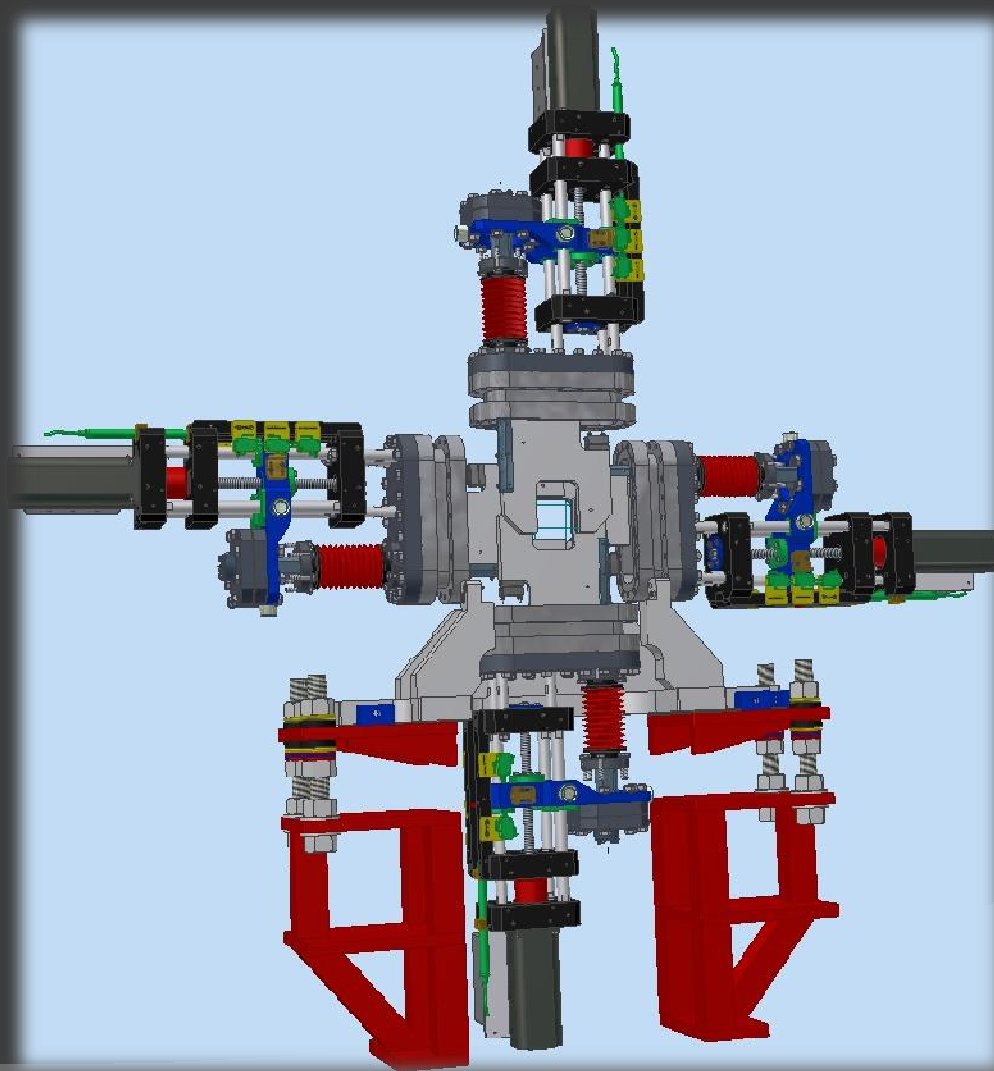
Servo-Spill Loop

- ⦿ Dose Delivery system monitors 'online' (1MHz – if statistics significant) the number of particles sent to patient BUT... if intensity ripples are “very high” it is not enough to protect the patient from over-dose
- ⦿ Machine detectors shall limit current intensity ripples to avoid voxel over-dose [from specifications, voxel dose peak < 4% voxel dose]
- ⦿ We foresee open/ closed loop (10kHz bandwidth) between a large bandwidth intensity monitor in the extraction line (or the Nozzle) and the air-core quadrupole in the synchrotron, for fast correction to intensity ripples
- ⦿ Intensity measurement perturbation on beam for patient must be minimized

Watch-Dog /1

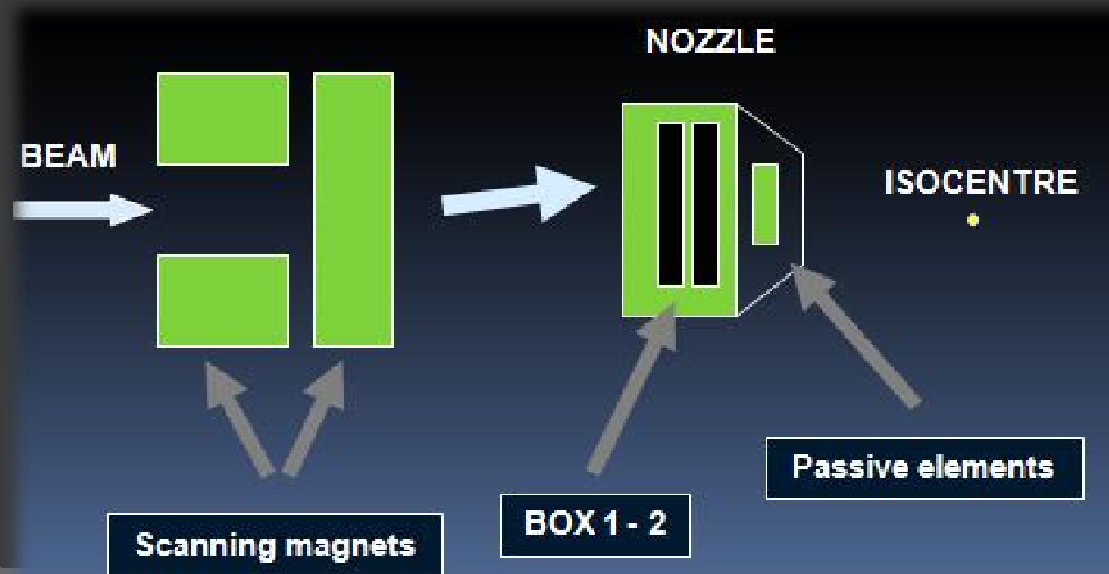
- At extraction lines end, the Nozzle controls scanning magnets power supplies so to direct the beam to the 'right' target
- Watch-Dog monitor aims to measure barycenter position at scanning magnets entrance, during treatment, so to check barycenter offset and its drift, during treatments (at 100Hz-300Hz)
- Extraction line correctors setting is changed consequently, in such a way to move beam barycenter to the center, if it is not
- To suppress beam position offset and drift is mandatory to avoid 'dose holes' at patients (-> **Dose Uniformity**)

Watch-Dog /2



Nozzle

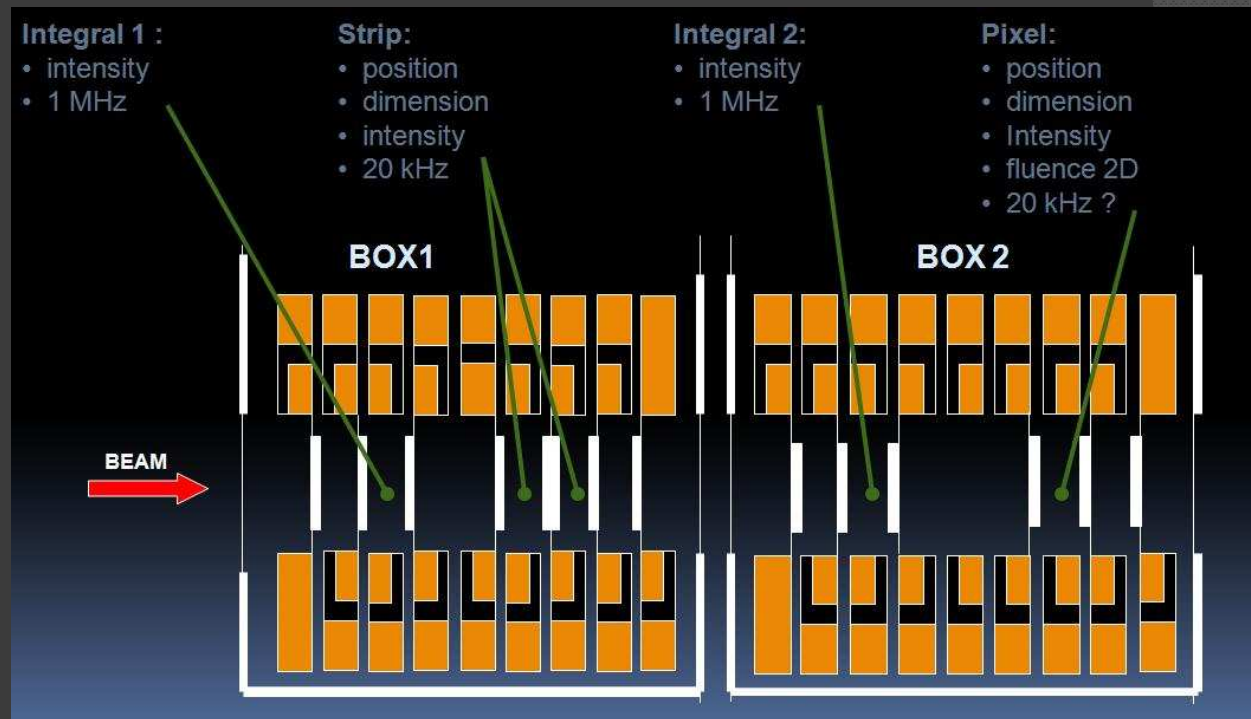
- ⦿ Nozzle is the usual name for **Beam Delivery** (beam steering to reach the right target position) and **Dose Delivery** (measuring the flow of particles going to the patient) systems
- ⦿ It acts as interface between accelerator and medical worlds



- ⦿ In case of active scanning (like CNAO) it controls scanning magnets

CNAO Nozzle /1

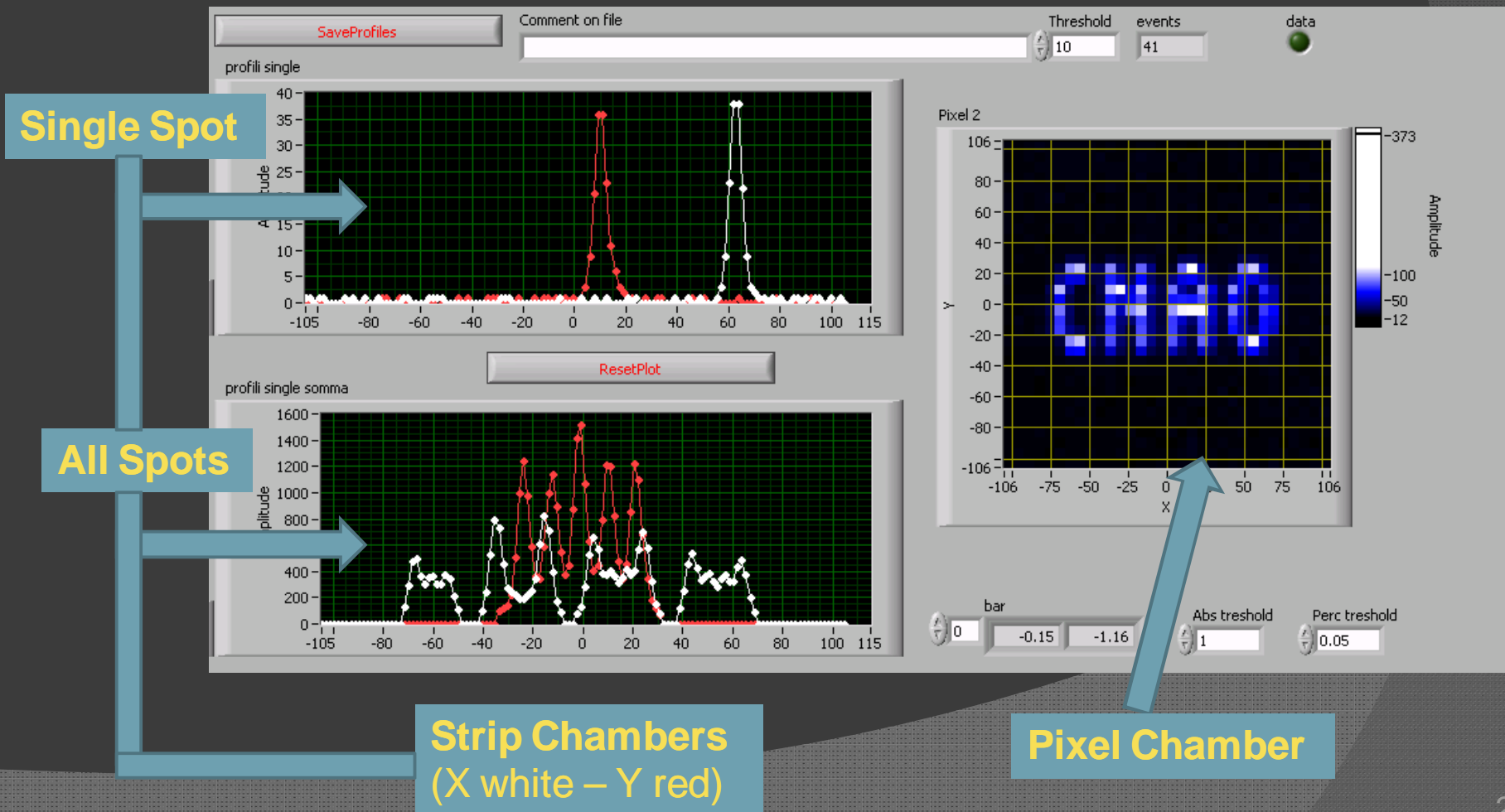
- CNAO Nozzle is made of BOX1 and BOX2, each one made of 2 ionization chambers (->direct measurement of the charge delivered to patient)
- Nozzle is globally < 1mm water-equivalent thick
- Each BOX measures intensity (@1MHz / 1 cnt=200fC ~ 8000 protons at 60MeV) and position (@ 10kHz / 50um accuracy)



CNAO Nozzle /2

To conclude...

...an example of scanning magnets control by the Nozzle



- Thanks for your attention -