Beam Diagnostics at CNAO

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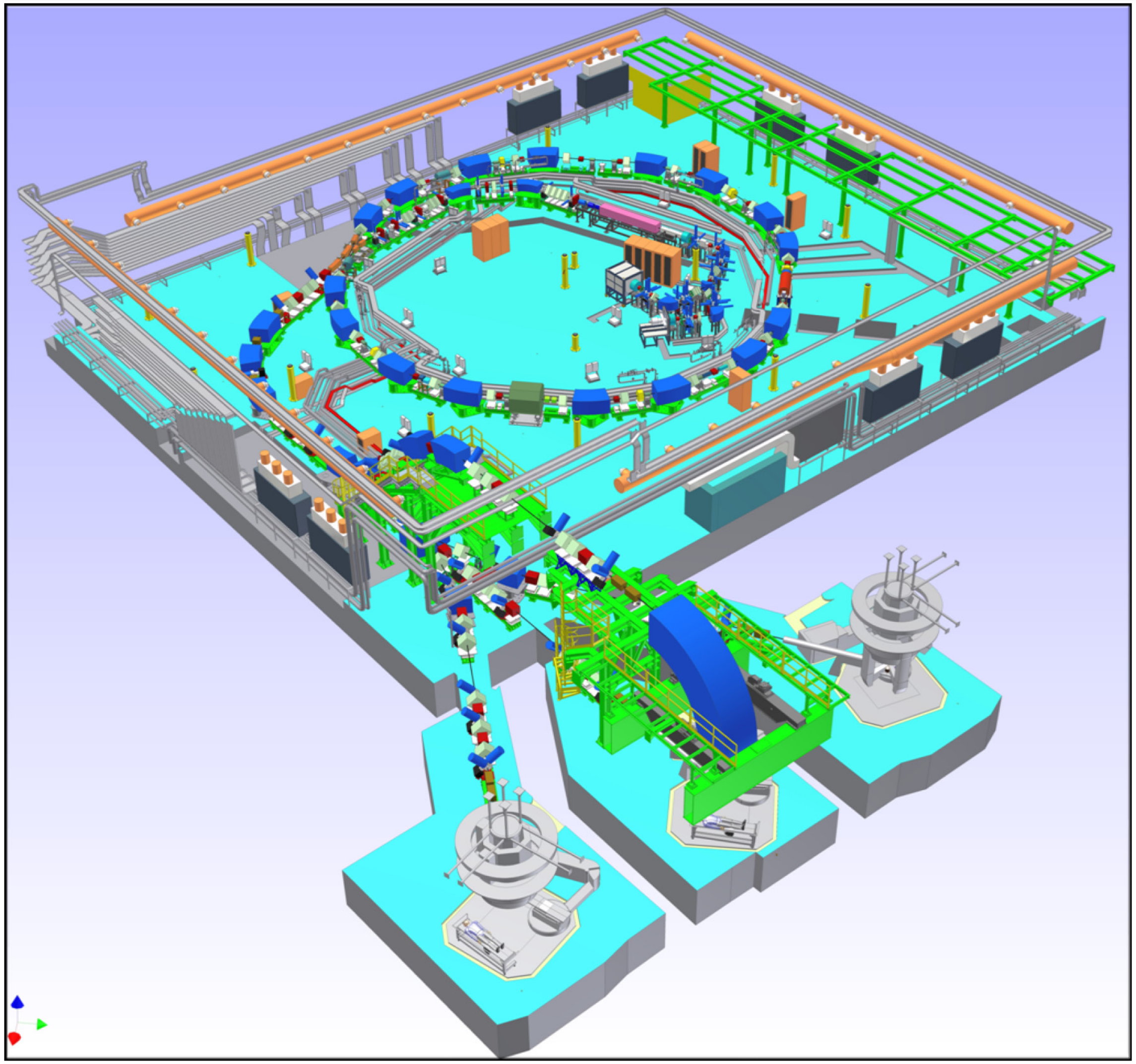
Present status of CNAO

- CNAO is the first Italian facility for deep tumor treatment with proton and carbon ions beam using active scanning.

- CNAO is going to treat patients with proton beams very soon.

- Machine commissioning with carbons ions is started.

CNAO highlights



- 2 DC ion, proton and carbon, ECR sources.
- Synchrotron circumference of about 78 m.
- 3 horizontal + 1 vertical treatment lines.
- 1 experimental line (in future).
- Active scanning.

Design Parameters I

Protons (< 10^{10} per spill)				
	LEBT (*)	MEBT	SYNC	HEBT
Energy [MeV/u]	0.008	7	7-250	60-250
Imax [A]	1.3×10^{-3} (0.43)	0.7×10^{-3}	5×10^{-3}	7×10^{-9}
Imin [A]	1.3×10^{-3} (0.43)	70×10^{-6}	0.12×10^{-3}	17×10^{-12}
$\varepsilon_{rms,geo}$ [π mm mrad]	35	1.9	0.67-4.2	0.67-1.43(V)
$\varepsilon_{tot,geo}$ [π mm mrad]	180	9.4	3.34-21.2	3.34-7.14 (V) 5.0 (H)
Magnetic rigidity [T m]	0.013 (0.039)	0.38	0.38-2.43	0.38-2.43
$(\Delta p/p)_{tot}$	±1.0‰	±(1.2-2.2)‰	±(1.2-3.4)‰	±(0.4-0.6)‰

* (H_3^+)

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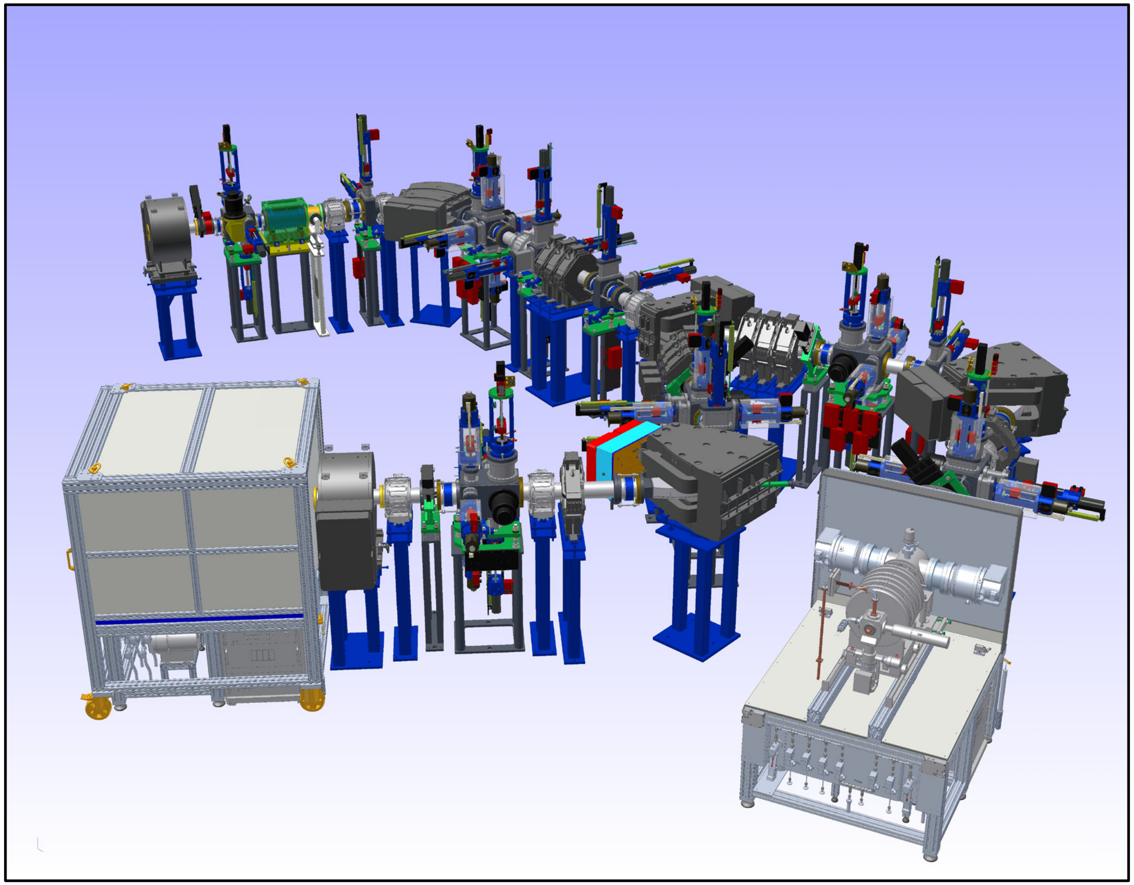
Design Parameters II

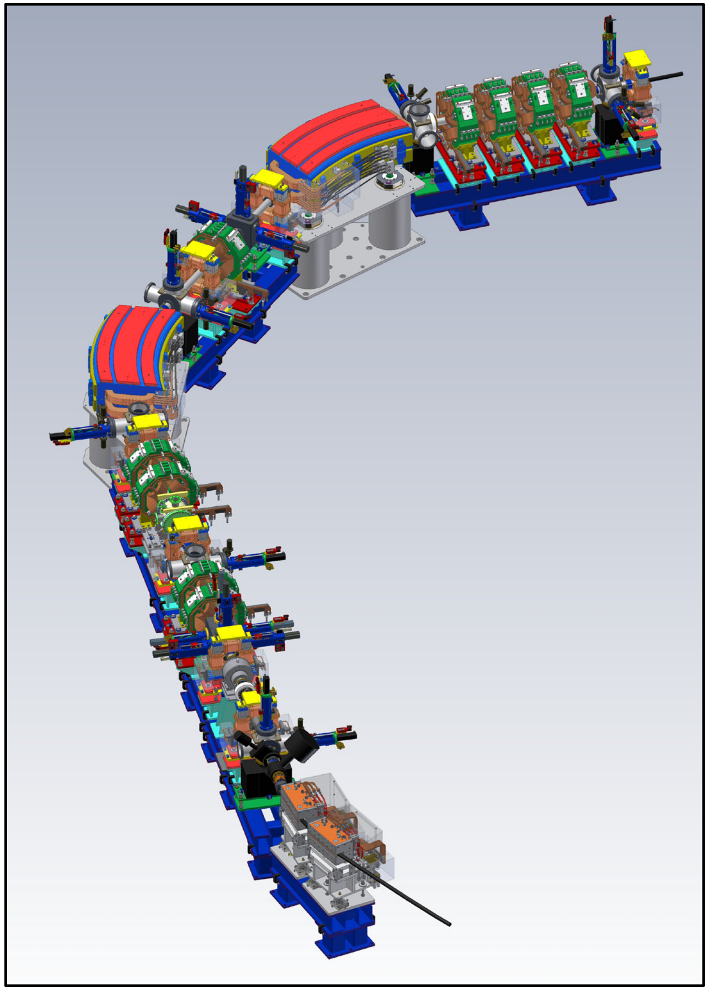
Carbon (< 4 10^8 per spill)				
	LEBT (C^{4+})	MEBT	SYNC	HEBT
Energy [MeV/u]	0.008	7	7-400	120-400
Imax [A]	0.16×10^{-3}	0.15×10^{-3}	1.5×10^{-3}	2×10^{-9}
Imin [A]	0.16×10^{-3}	15×10^{-6}	28×10^{-6}	4×10^{-12}
$\varepsilon_{rms,geo}$ [π mm mrad]	35	1.9	0.73-6.1	0.73-1.43(V)
$\varepsilon_{tot,geo}$ [π mm mrad]	180	9.4	3.66-30.4	3.66-7.14 (V) 5.0 (H)
Magnetic rigidity [T m]	0.039	0.76	0.76-6.34	3.25-6.34
$(\Delta p/p)_{tot}$	±1.0‰	±(1.2-2.0)‰	±(1.2-2.9)‰	±(0.4-0.6)‰

LEBT Beam Diagnostics



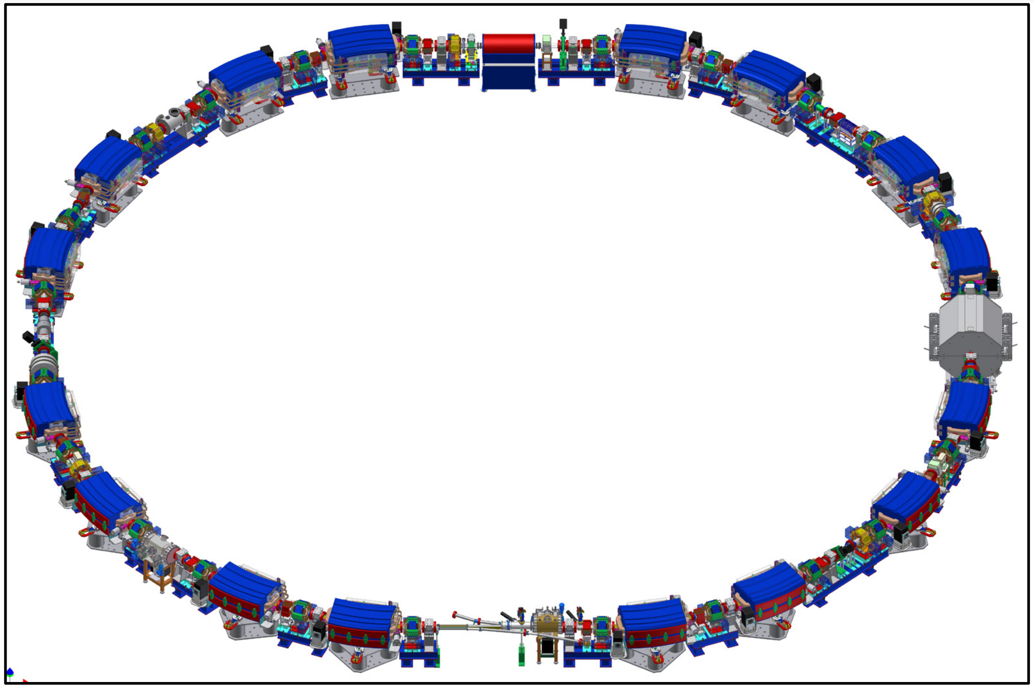
- Low energy beam (8keV/u).
- Continuous beam with intensity of few hundreds and total emittance of 180 π mm mrad.
- Compact tank (390mm) housing slits (H+V), wire scanners (H+V) and a faraday cup.
- Measurements of beam current, position and phase space distribution.

MEBT Beam Diagnostics



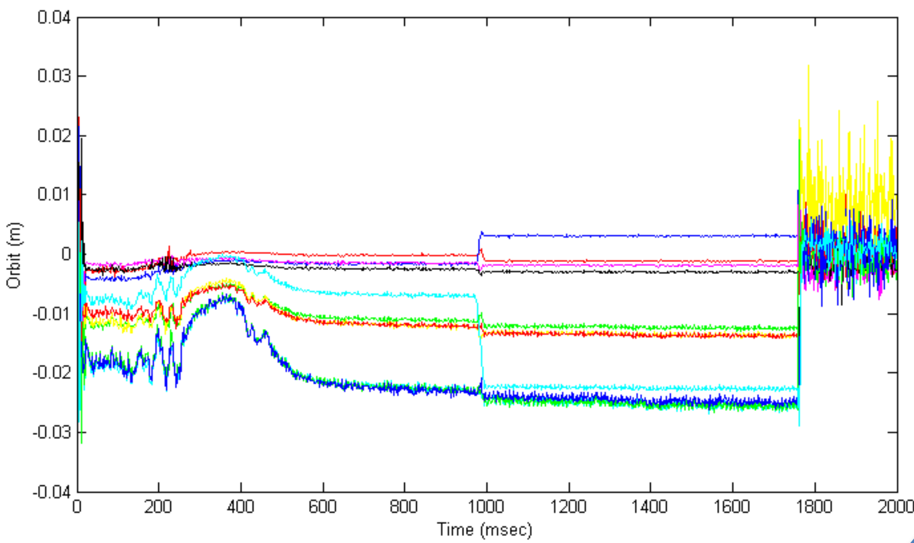
- At the end of the LEBT, the beam is chopped in order to be send beam to the LINAC only when it's required.
- The CNAO LINAC is composed by a RFQ followed by an IH-DTL working at 217MHz. The output beam energy is 7MeV/u.
- The MEBT instrumentation includes Faraday cups , fast current transformers for current measurement, phase probes for energy evaluation, a special pick-up for beam position and profile grids monitors.
- A couple of slits is present in the line for particles selection and diagnostic purposes.

Synchrotron Beam Diagnostics

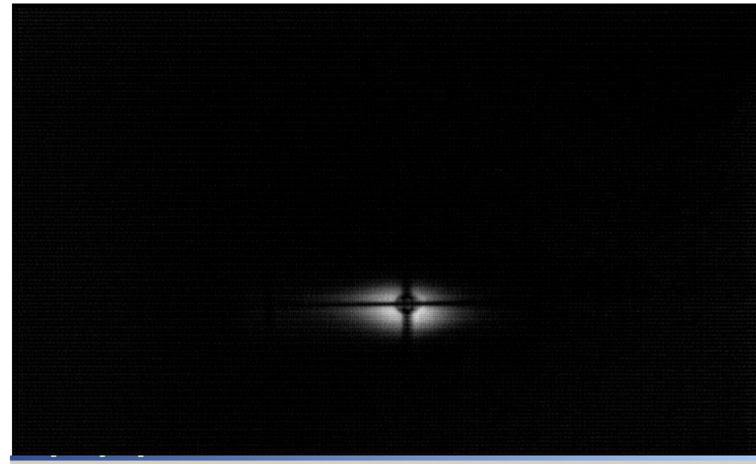


- A couple of luminescent screens measure the beam transverse distribution at the entrance to the ring and at the first turn end.
- Closed orbit measurement is made by using 11 horizontal and 9 vertical electrostatic pick-ups.
- The beam current intensity is measured with a DCCT.

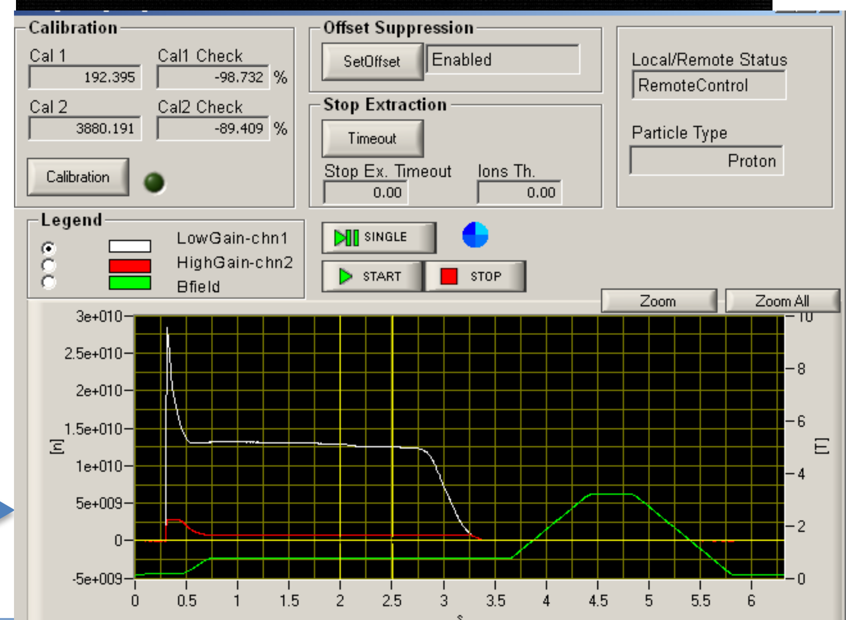
Synchrotron Beam Diagnostics



Orbit measurement in time



First turn



DCCT (and other signals) on a scope

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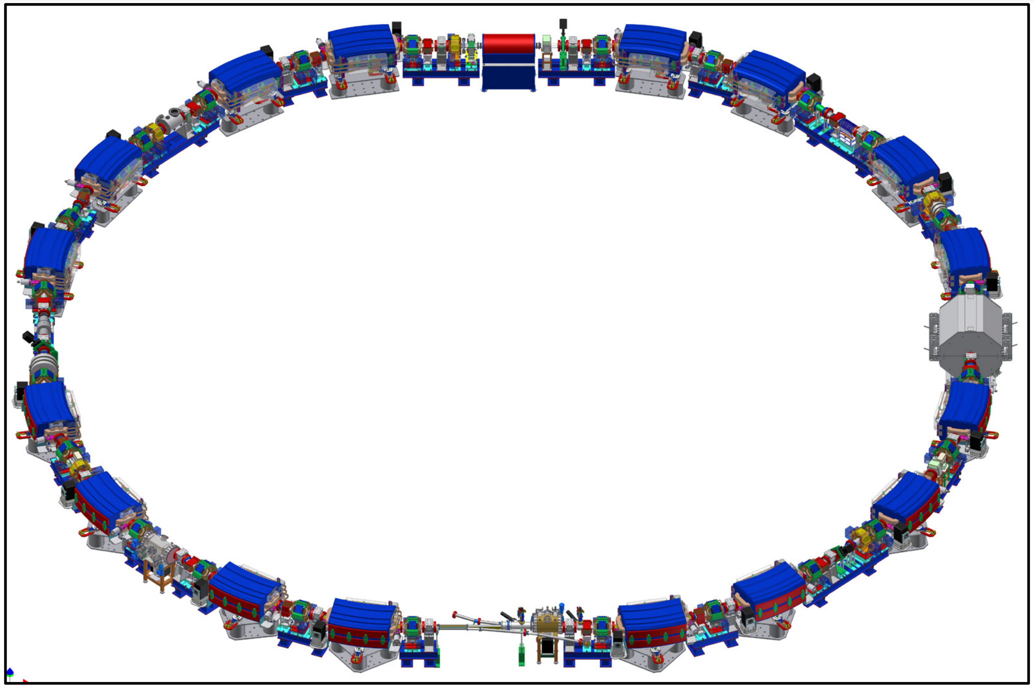
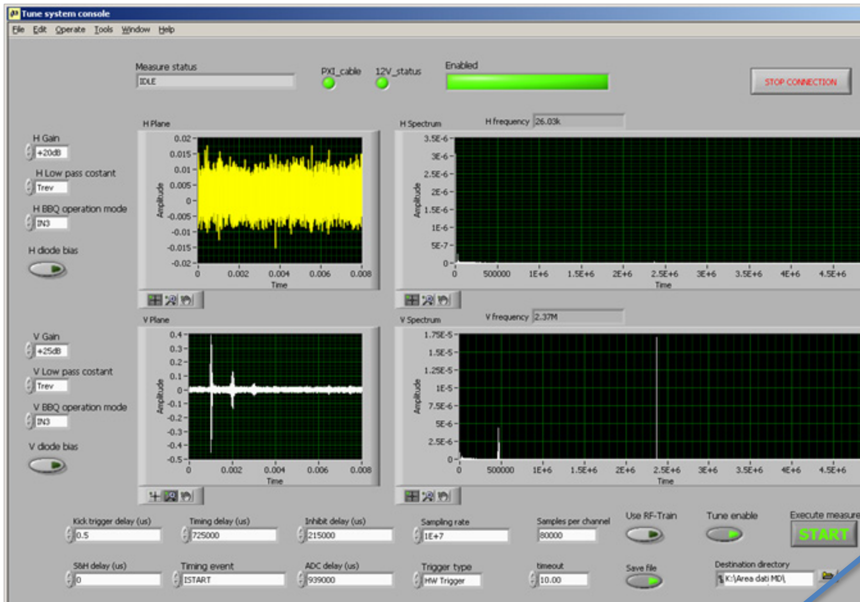
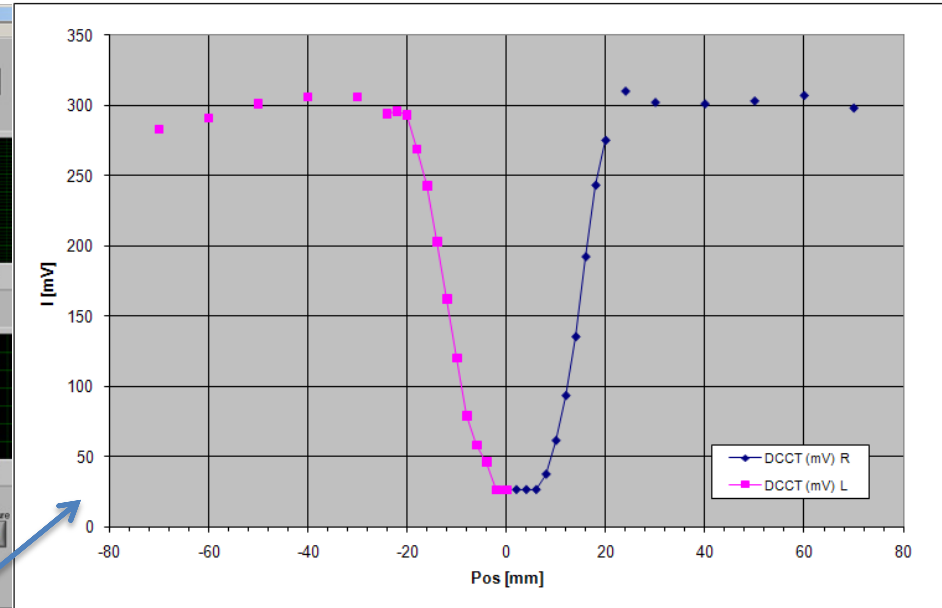
Synchrotron Beam Diagnostics

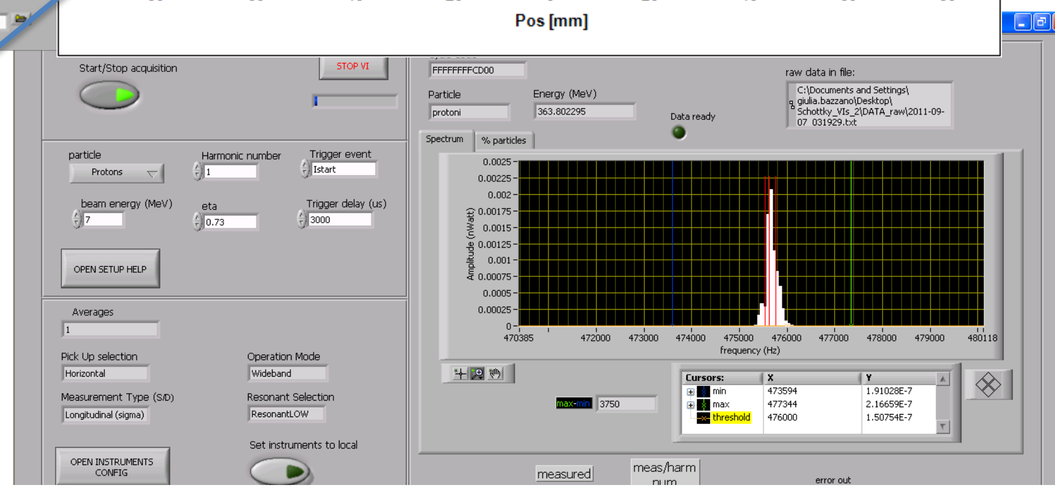


- A couple of Schottky PUs provides information on the beam frequency distribution.
- Horizontal and vertical scrapers are present to suppress beam halo (and used for profile measurement as well).
- Tune is measured in both planes using two fast kicker-magnets and a dedicated electronics that measures the resulting beam oscillation on the pick-ups.

Synchrotron Beam Diagnostics





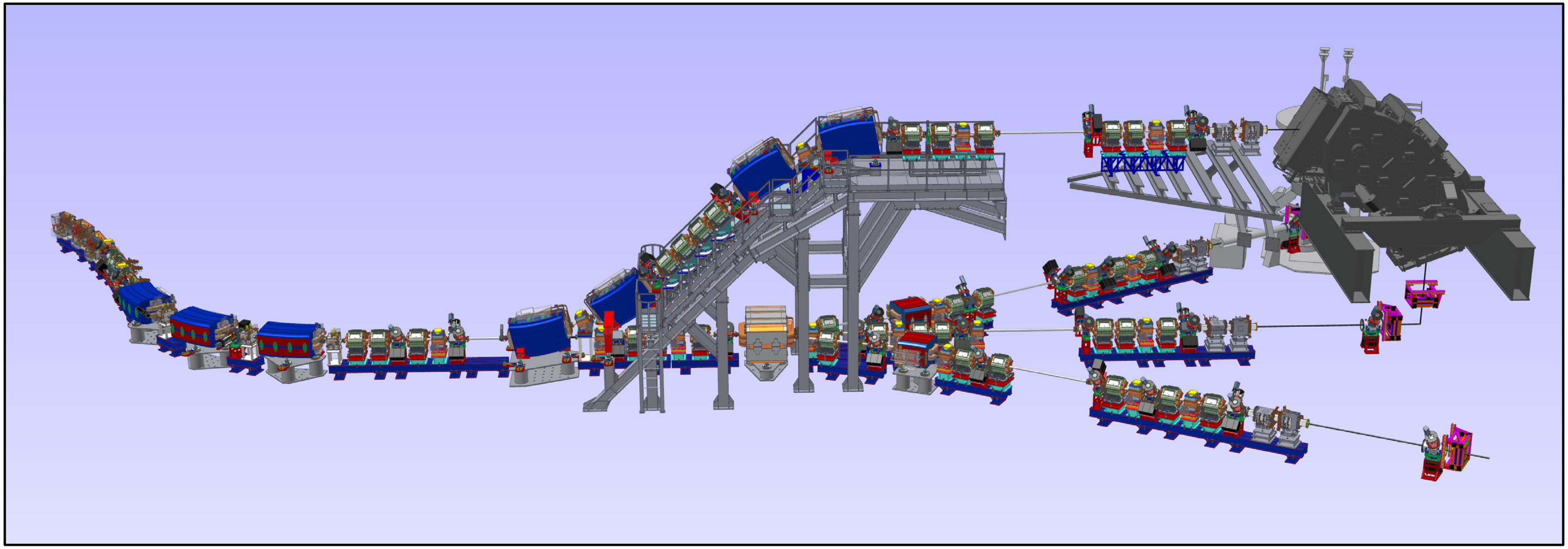


Tune measurement

Profile with scraper

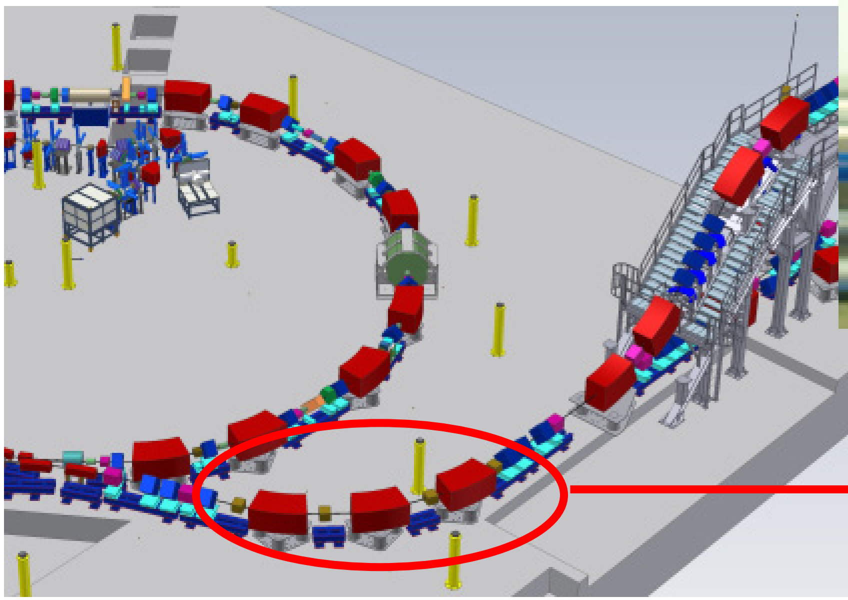
Schottky scan at injection

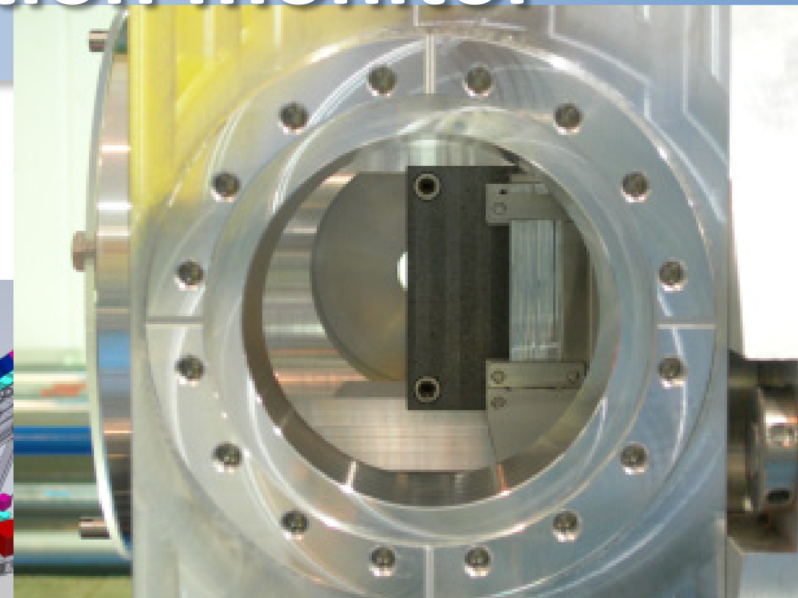
HEBT Beam Diagnostics

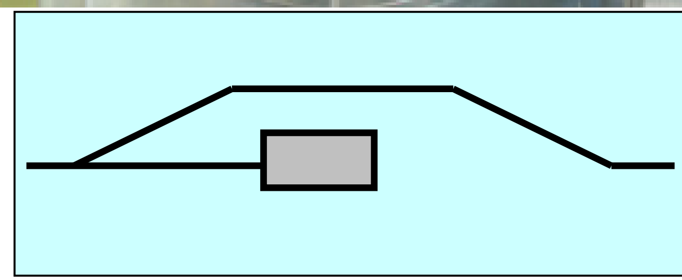


- Beam is extracted to the treatment rooms over a large energy range (60-250MeV /120-400 MeV/u) and over a large current range ($4 \cdot 10^6$ to 10^{10} pps).
- The extraction lines are equipped with scintillating fibre harps coupled to CCD camera (achievable spatial resolution is 1 mm) measuring beam: profile, position and intensity.

Qualification monitor







- ❖ A profile monitor (QPM: made of scintillating fibres harps) and a fast intensity monitor (QIM: made of a scintillator coupled to a Photo-Multiplier) measure relevant beam quantities before sending it to the patient.

Recent Results

- ❖ The beta functions measurements.
- ❖ Septum shadow monitor.
- ❖ The extracted beam servo spill using the air core quadrupole.

Beta Function Measurements

- Beta function (β_Q) measurement, at the synchrotron quadrupoles level, is obtained by a small static variation of the quadrupole strength (Δk) and by measuring the consequent tune shift ΔQ according to :

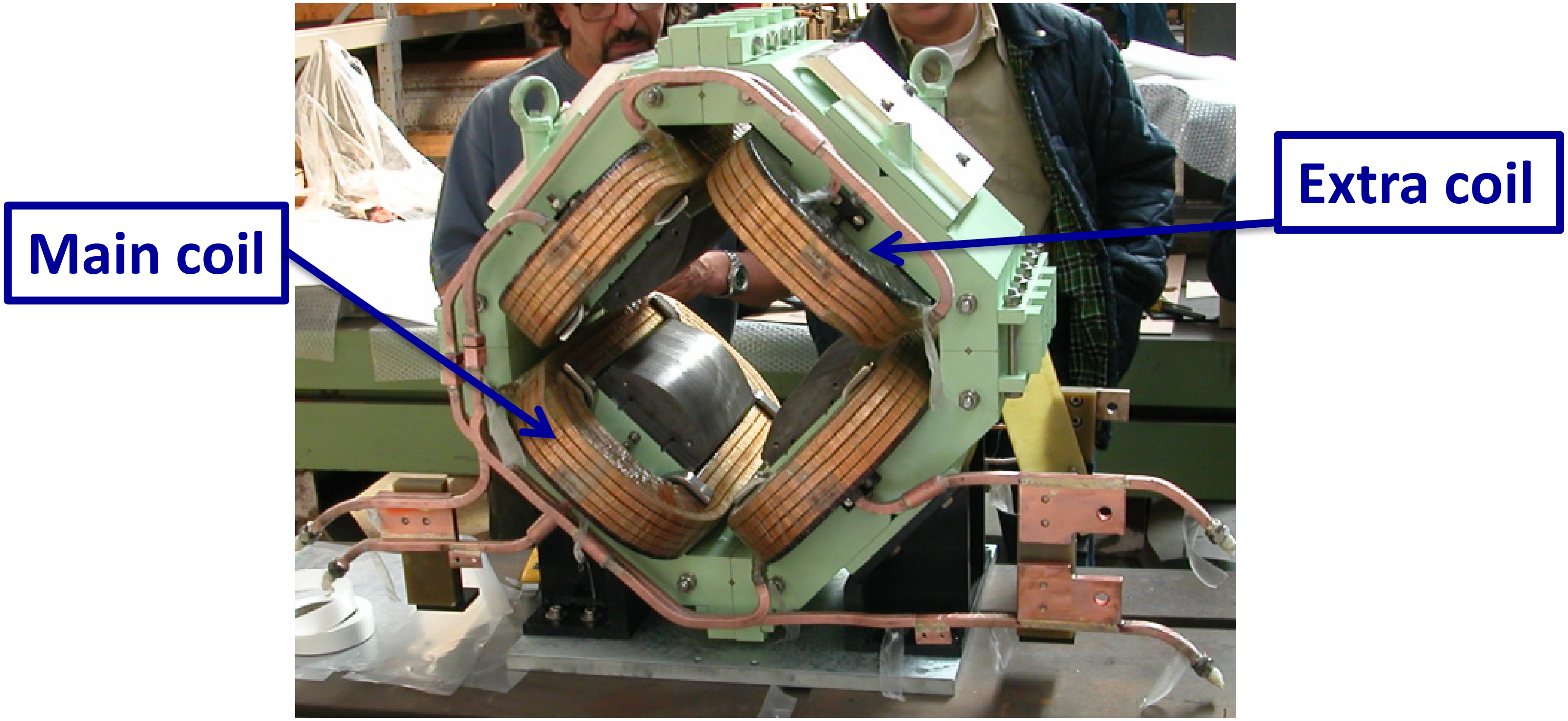
$$\beta_Q = \frac{4\pi}{\Delta k \cdot L_q} \Delta Q$$

Where L_q is the quadrupole magnetic length.

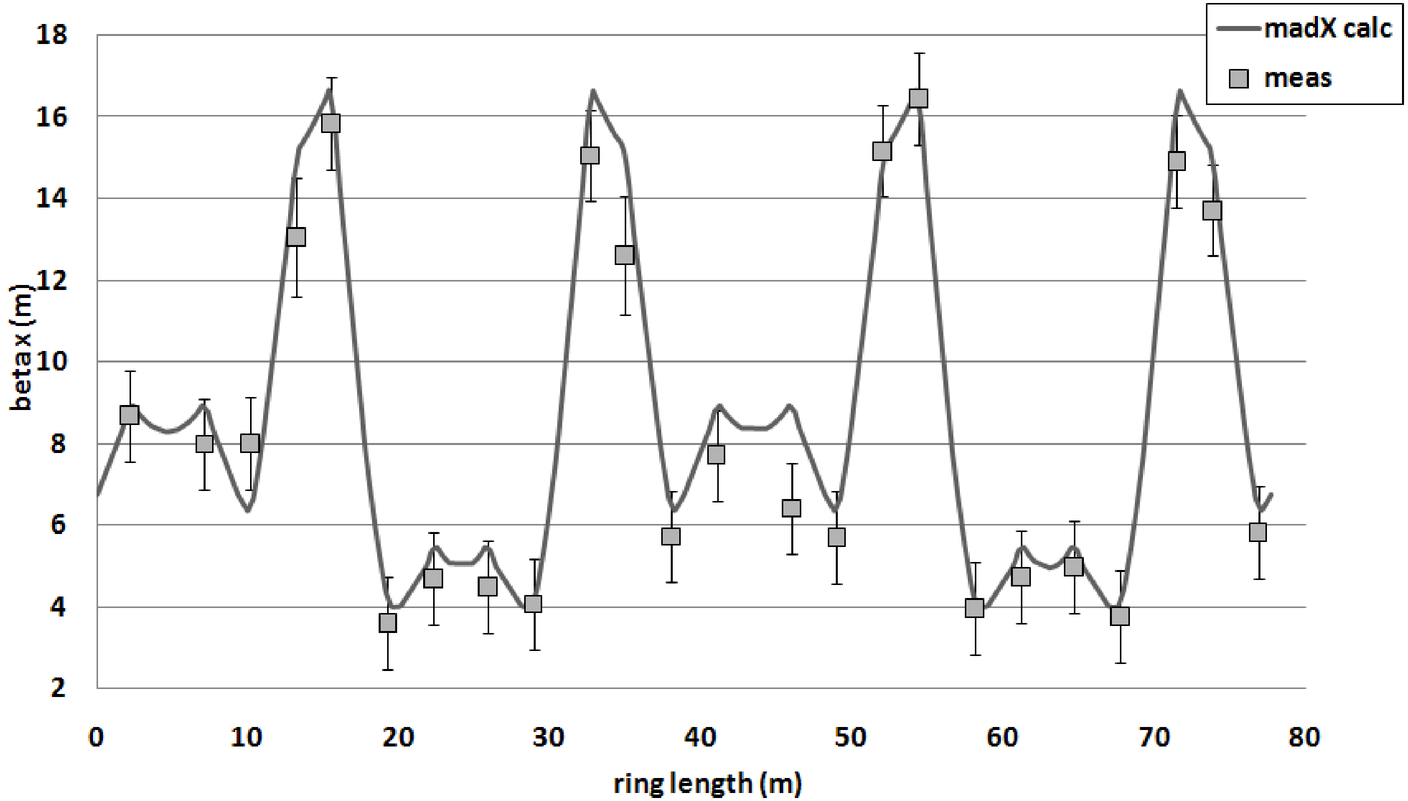
- The Tune measurement is based on the direct diode detection principle (developed at CERN).

Beta Function Measurements

Quadrupoles have been designed with an extra coil to permit single quadrupole variation for diagnostic measurements and special "extraction gymnastics".

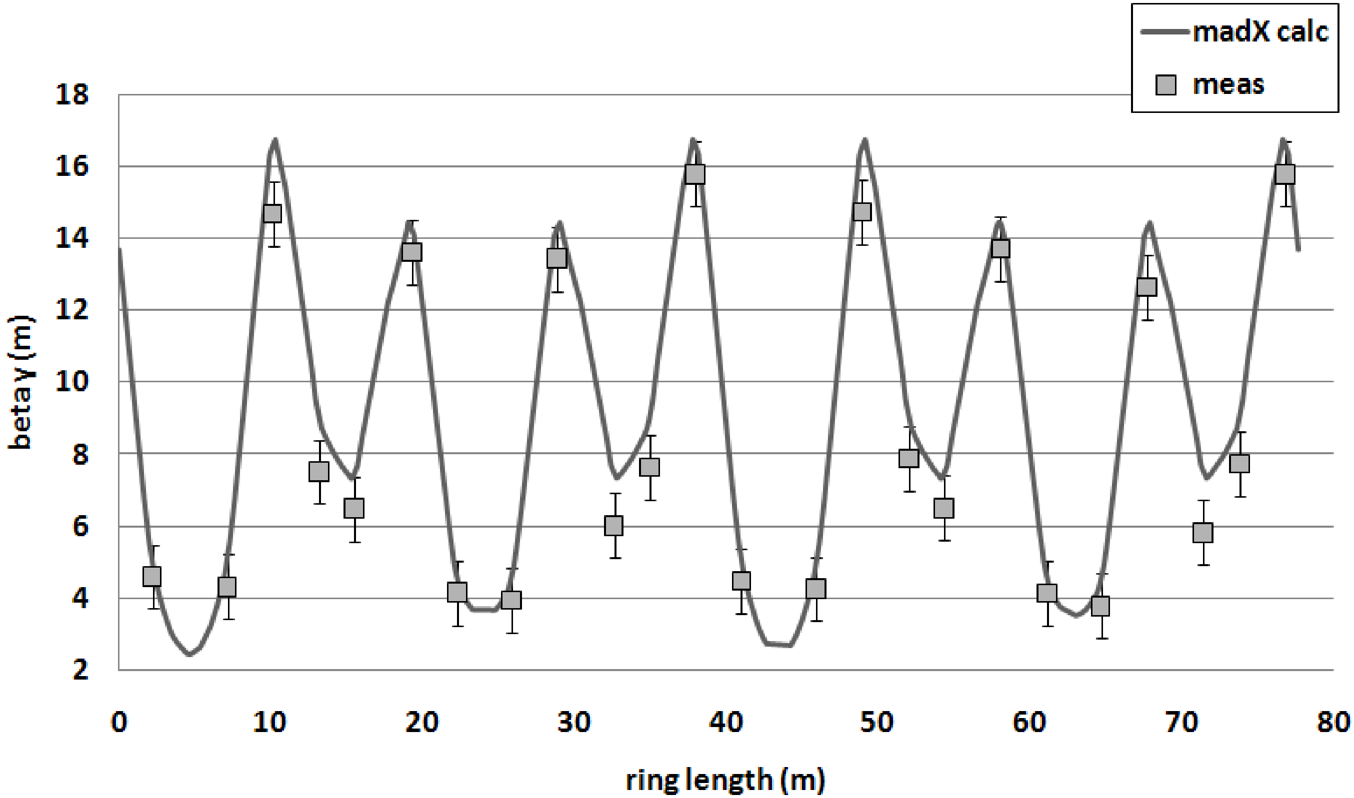


Beta Function Measurements



- Horizontal beta function measurement at extraction
- The measurement uncertainty is ±1m

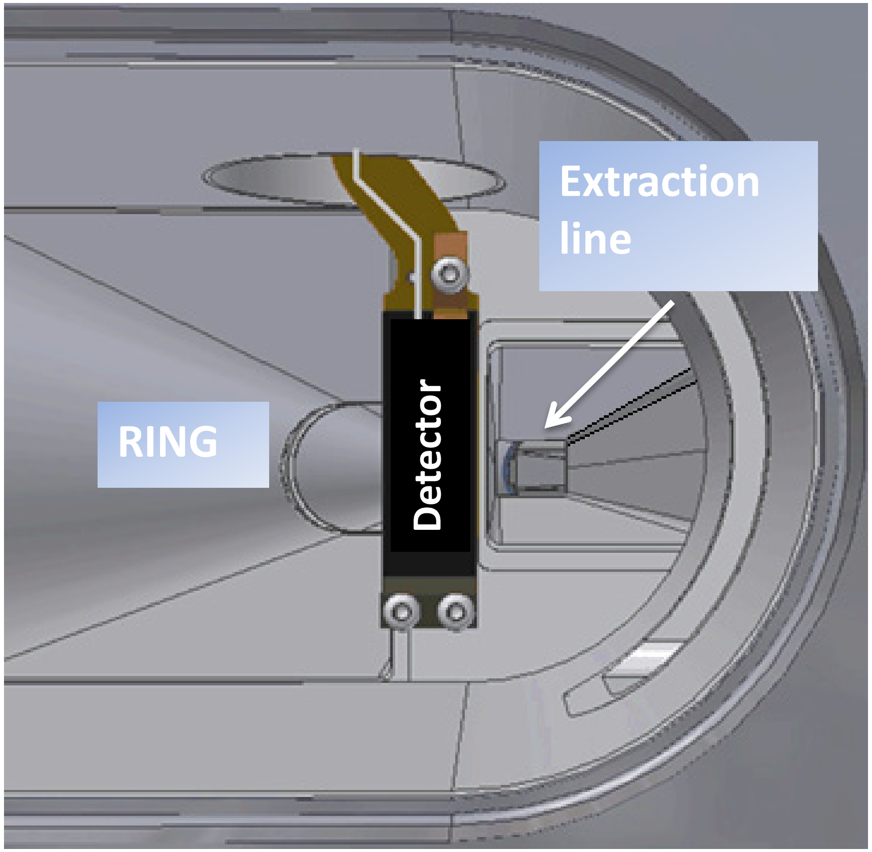
Beta Function Measurements



- Vertical beta function measurement at extraction
- The measurement uncertainty is ±1m

Septum Shadow Monitor

- The detector has been installed to position with precision the gap between circulating and extracted beam at the septum.
- It is installed exactly upstream the magnetic extraction septum coil.
- The sensor prototype has been designed and built at the "Institut de Microtechnique", Switzerland following CNAO specifications.



Detector installation at extraction septum

Septum Shadow Monitor

- The detector (Fig. a) is made of an amorphous silicon (a-Si:H) PIN diode.
- The sensor thickness is 5 µm, deposited on 500 µm glass (Fig. b).
- Top and bottom are metallized with Al.

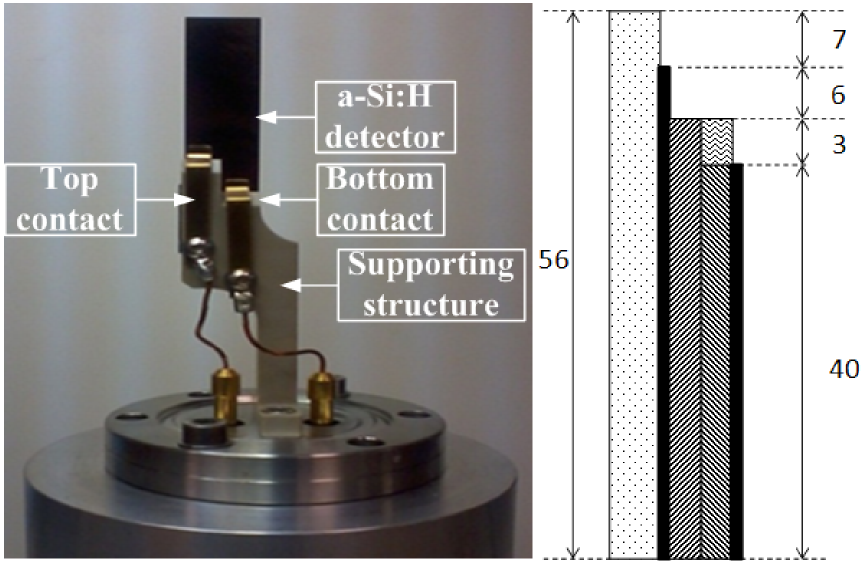


Fig. a Fig. b

All dimensions in mm (drawing not in scale)

Legenda:

glass
a-Si:H intrinsic
metallization
p-doping
n-doping

a-Si:H detector and its mechanics (Fig. a), detector cross section layout (Fig. b)

Septum Shadow Monitor

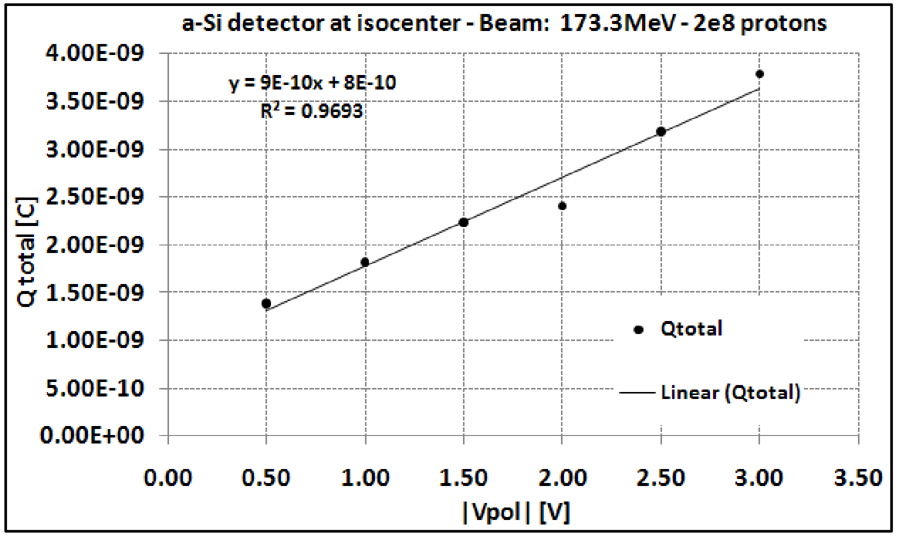


Fig.1 Total charge collected versus diode reverse voltage.

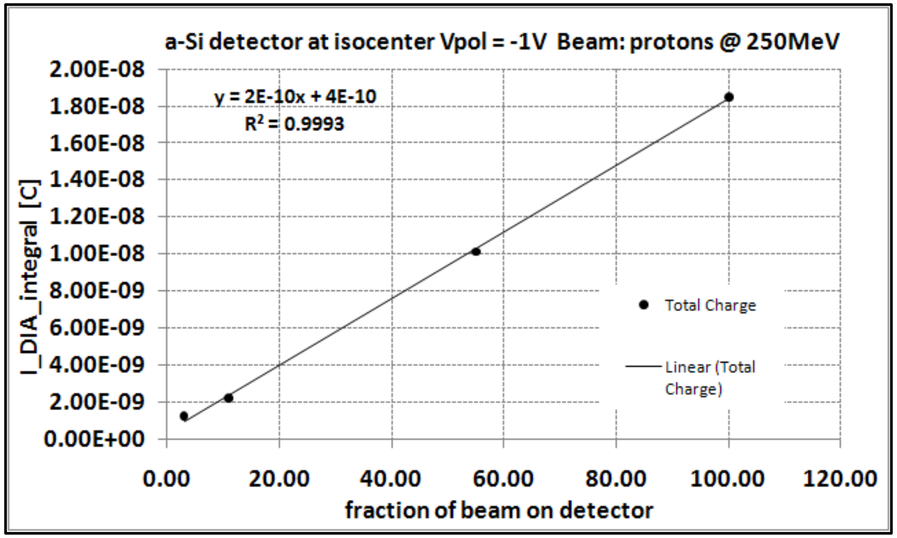
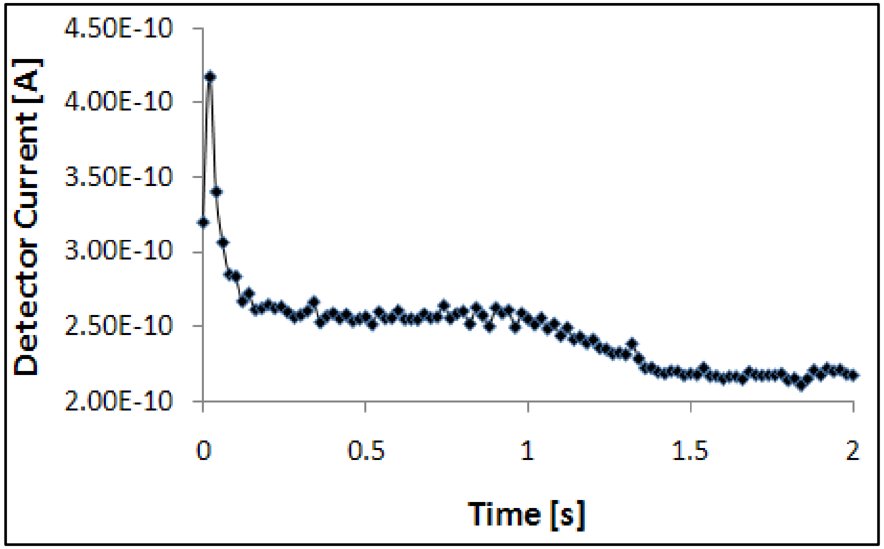


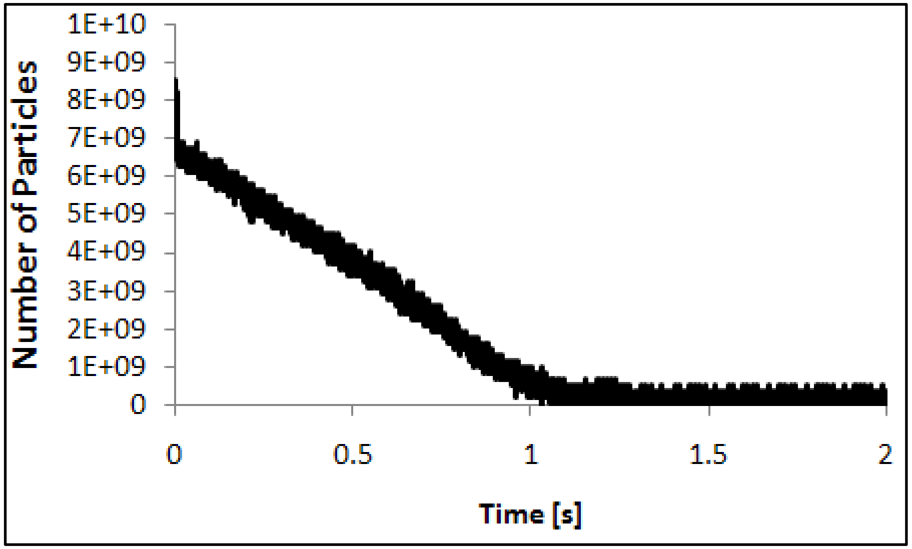
Fig. 2 Total charge collected versus number of protons: highest intensity about 2e9 protons.

- Calibrated on the extracted beam.
- It features good linearity at different polarization voltages and over a large range of impinging protons.

Septum Shadow Monitor



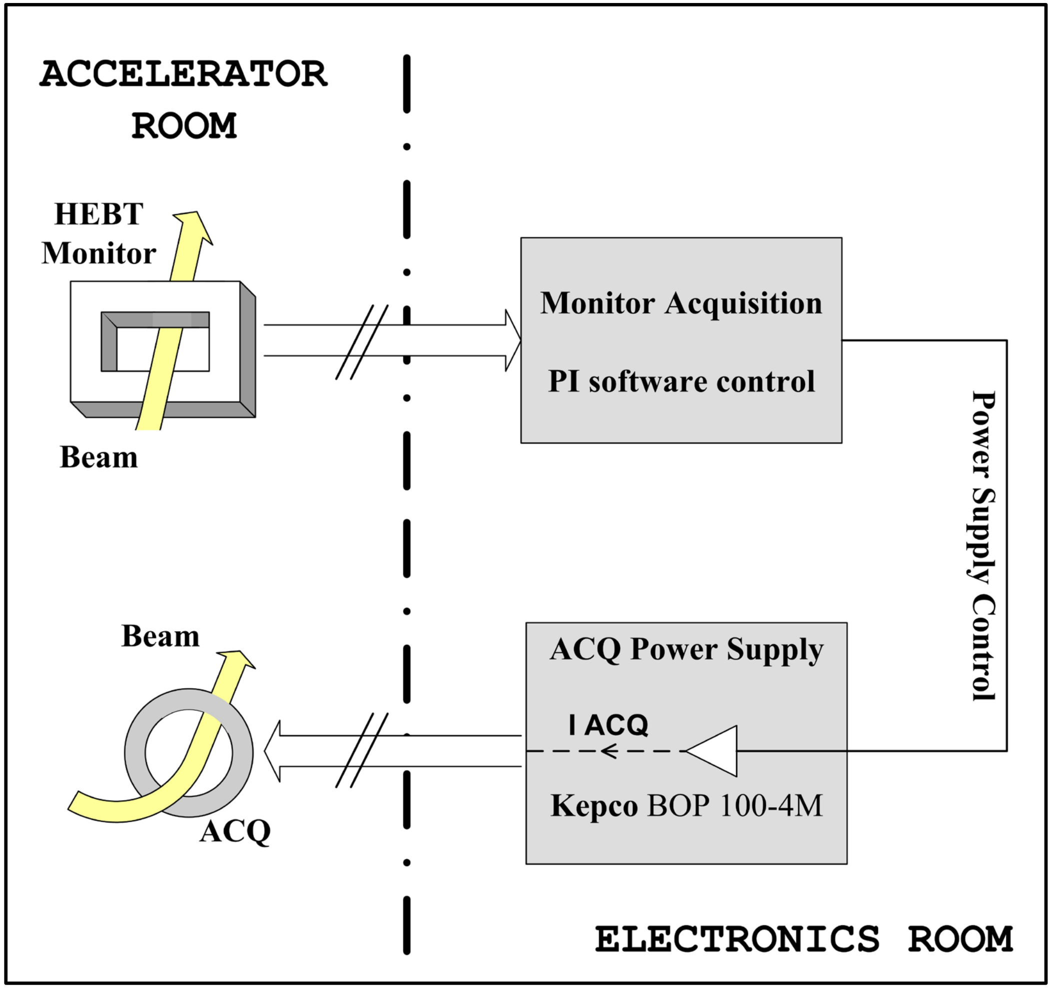
Signal on the SSM in its operative position. Estimated total number of particles collected ~ 1.3 e7.



Signal on the DCCT during extraction.

Servo-Spill on the ACQ

- Aim: Reduction of the extracted beam intensity ripple.
- The extracted beam is measured in the HEBT (QIM & Nozzle) and a PI control drives the air core quadrupole power supply closing the loop.



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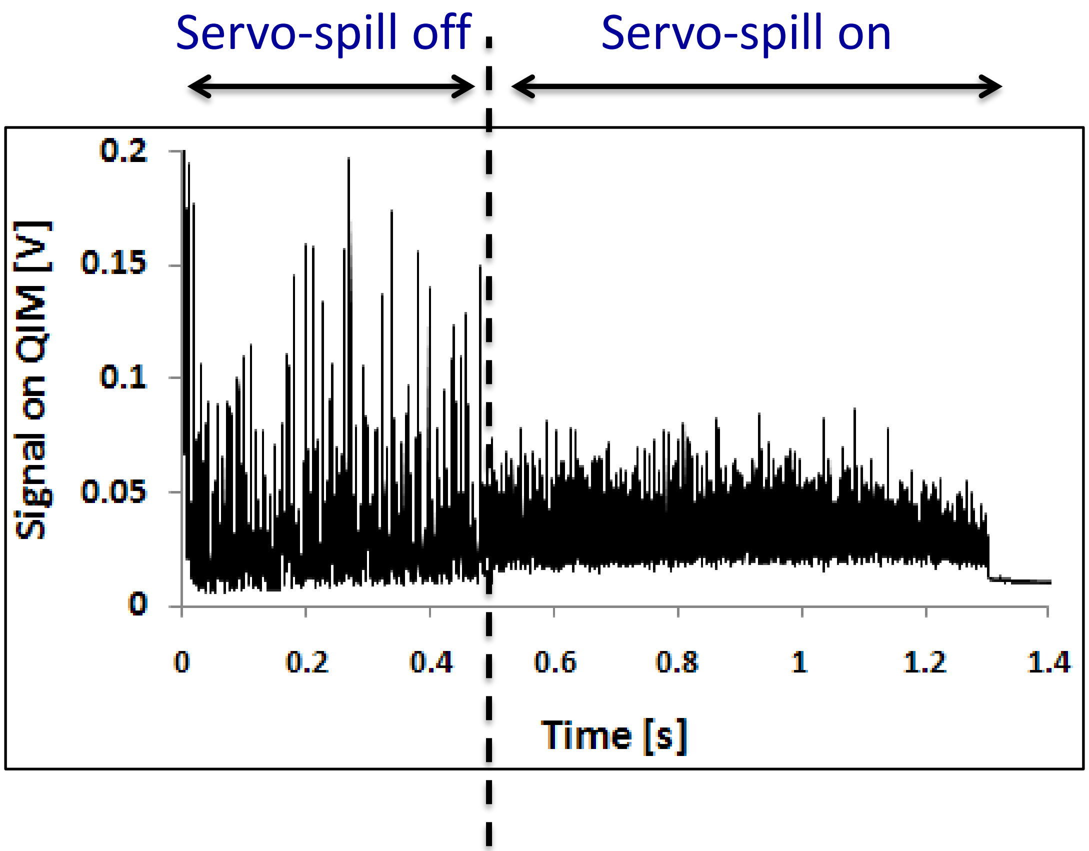
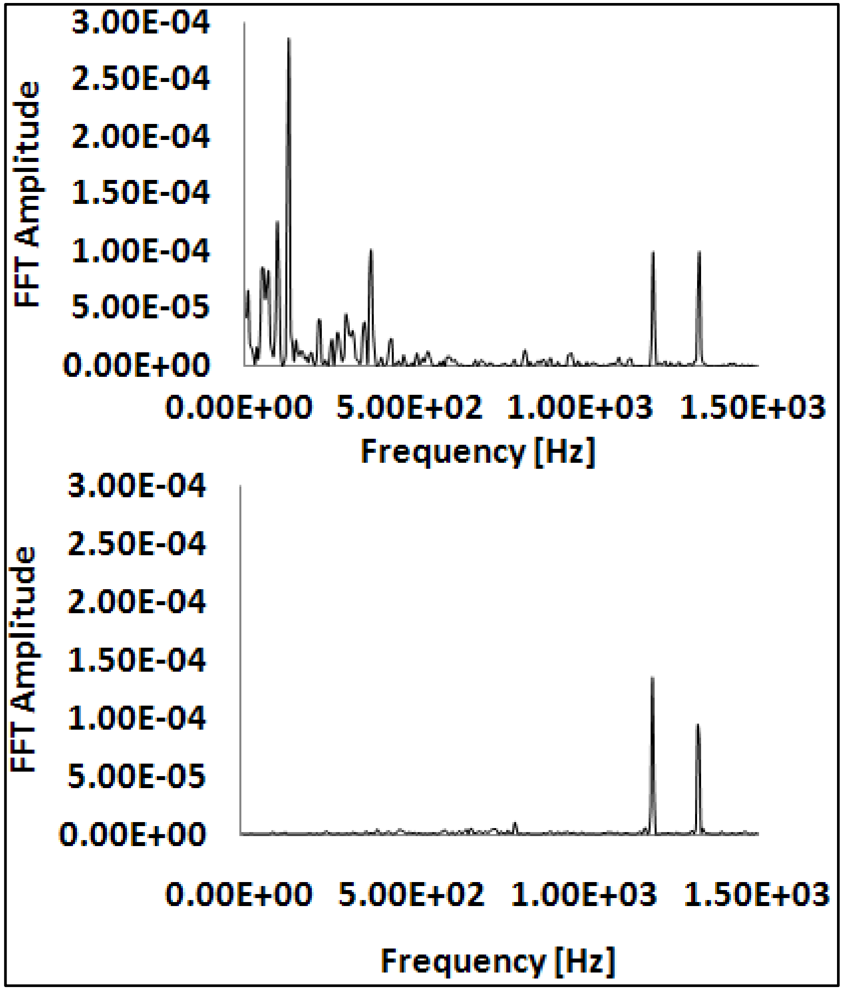
Servo-Spill on the ACQ

- Beam intensity signal on Qualification Intensity Monitor (QIM). Sampling frequency = 10 kHz.
- At t = 0.5s the servo spill is switched on and the beam intensity ripple is significantly reduced.



Servo-Spill on the ACQ

- FFT of the intensity signal on QIM without (on Top) and with servo-spill (on Bottom) .
- The use of servo-spill strongly reduces the low frequency components of the beam intensity ripple.



Conclusions

- CNAO is going to start patient treatment very soon and therapeutic beams have been produced and transported to treatment rooms.
- Beams have been successfully measured all along the accelerator complex.
- Ripple reduction techniques have been successfully put into operation.
- Commissioning of the accelerator with carbon ions is in progress.
- RD in beam diagnostics is always in progress and the implementation of new monitors is foreseen in the next future.

Acknowledgments

NATIONAL

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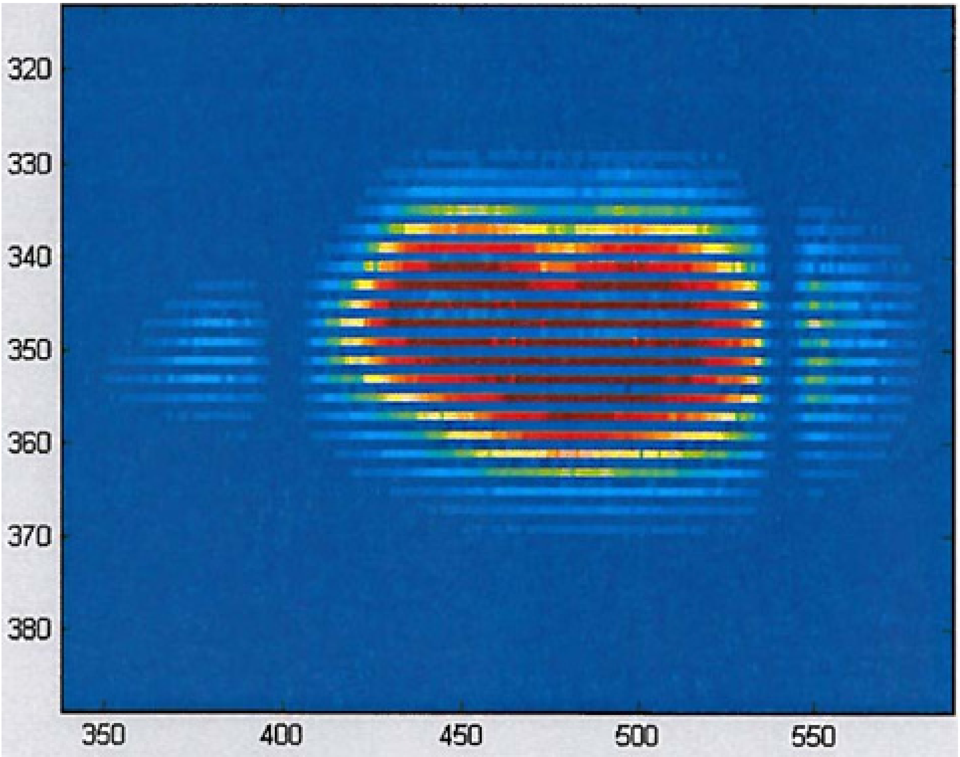

Thanks for your attention