

Adroterapia: l'applicazione delle tecnologie degli acceleratori alla cura dei tumori

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Parte III

Corso di Formazione - Dipartimento di Fisica
"Sapienza" Università di Roma
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Schema del Corso

Parte I:

razionale dell'adroterapia

la realizzazione del Centro Nazionale di Adroterapia Oncologica (CNAO)

Parte II:

i centri di adroterapia nel mondo

viaggio alla scoperta del CNAO e delle tecnologie degli acceleratori

Parte III:

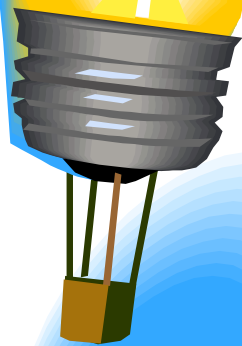
viaggio alla scoperta del CNAO e delle tecnologie degli acceleratori

Parte IV:

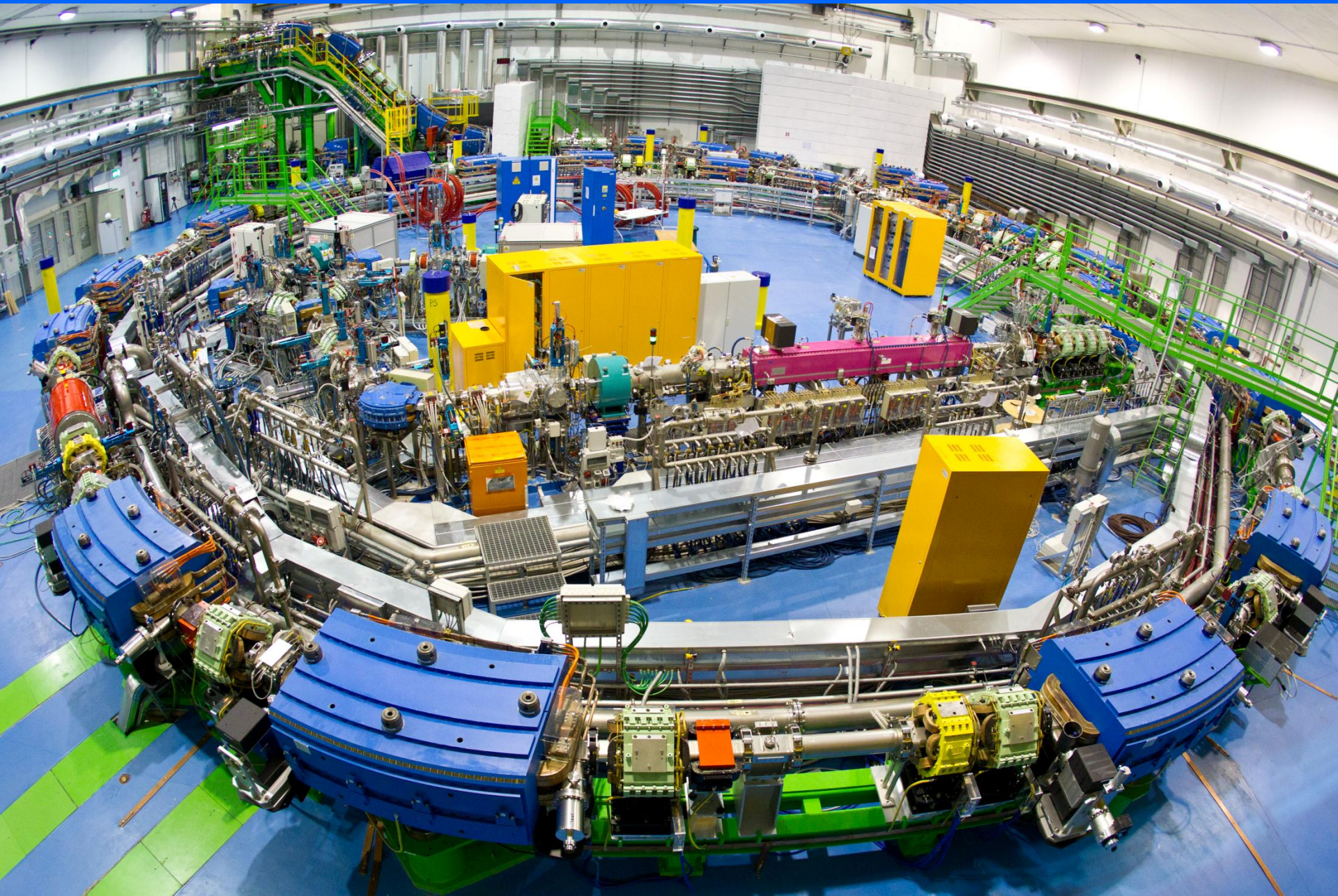
le tecnologie e i sistemi a contatto con i pazienti

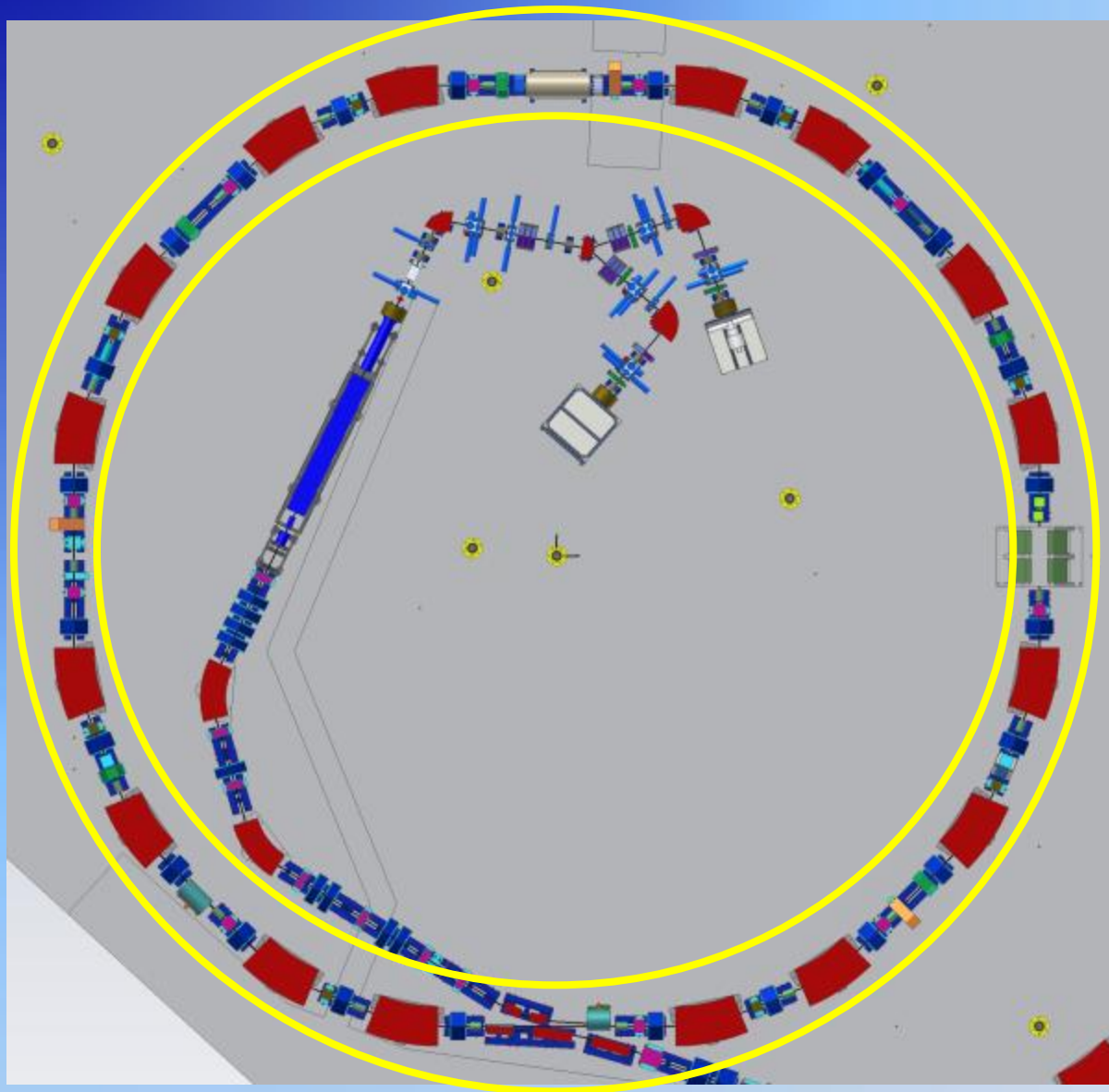
la sperimentazione clinica e i risultati sui pazienti

***Viaggio
alla scoperta
del CNAO***



Il sincrotrone





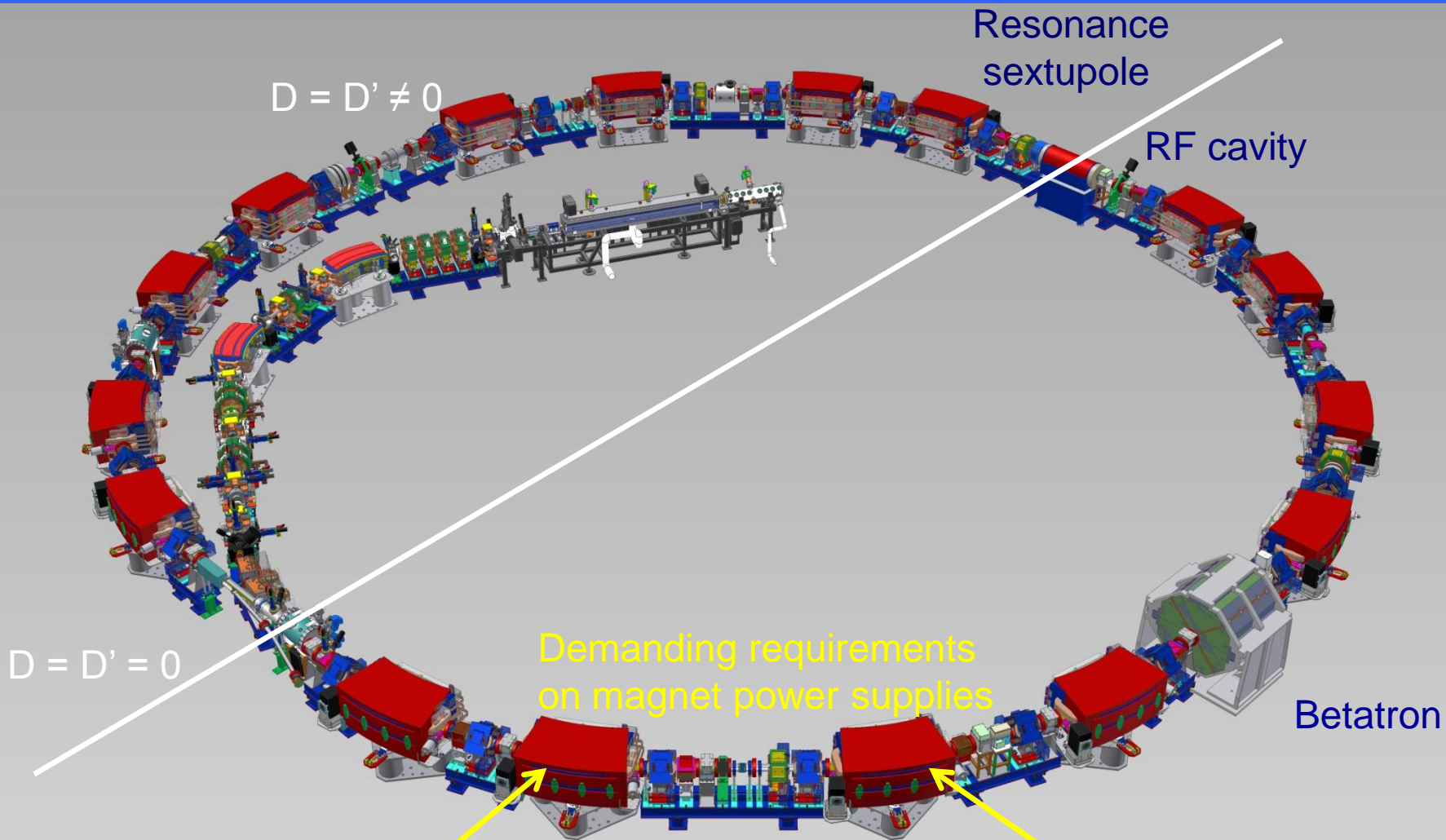
Synchrotron

7-250 MeV p
7-400 MeV/u C

$I \sim 0.1-5 \text{ mA (p)}$
 $I \sim 0.03-1.5 \text{ mA (C)}$

Slow extraction

Betatron core



	P inj	P – 60 MeV	P – 250 MeV	C6 inj	C6+ – 120 MeV	C6+- 400 MeV
B_p (T m)	0.4	1.1	2.4	0.8	3.3	6.4

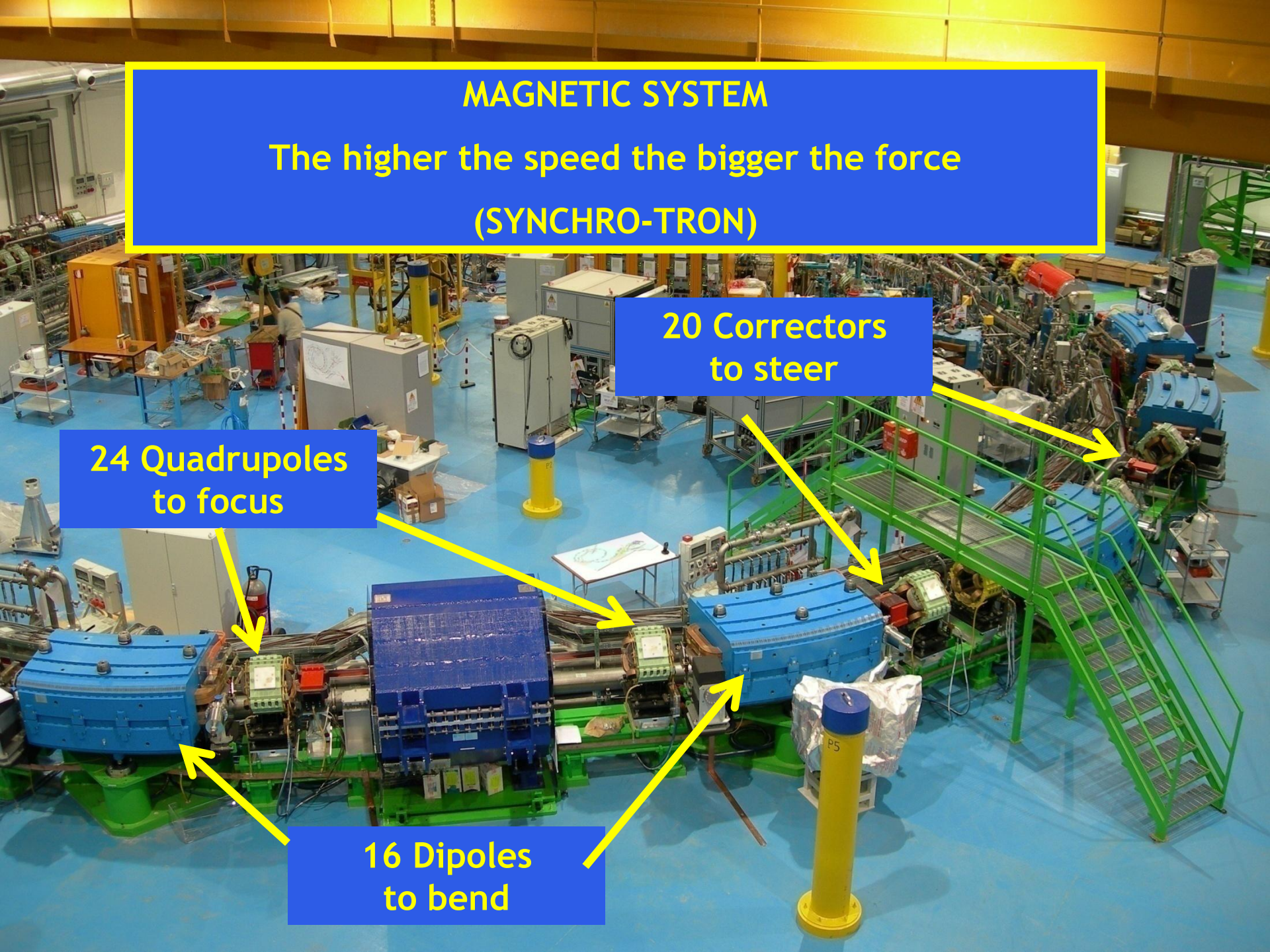
MAGNETIC SYSTEM

The higher the speed the bigger the force
(SYNCHRO-TRON)

20 Correctors
to steer

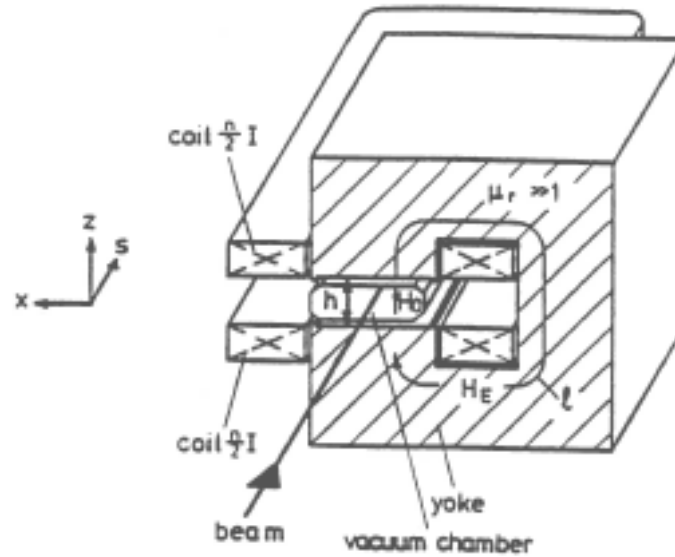
24 Quadrupoles
to focus

16 Dipoles
to bend



DIPOLI

Curvano la traiettoria



Campo magnetico verticale:

$$B_x = 0$$

componenti nel nostro
sistema di riferimento

$$B_y = B_o$$

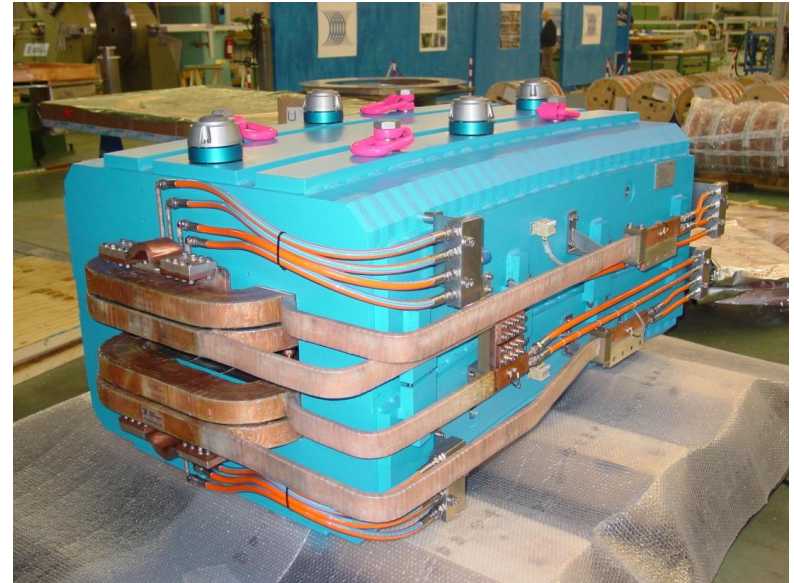
$$B_z = 0$$

$$B_o = \frac{\mu_0 n I}{h}$$

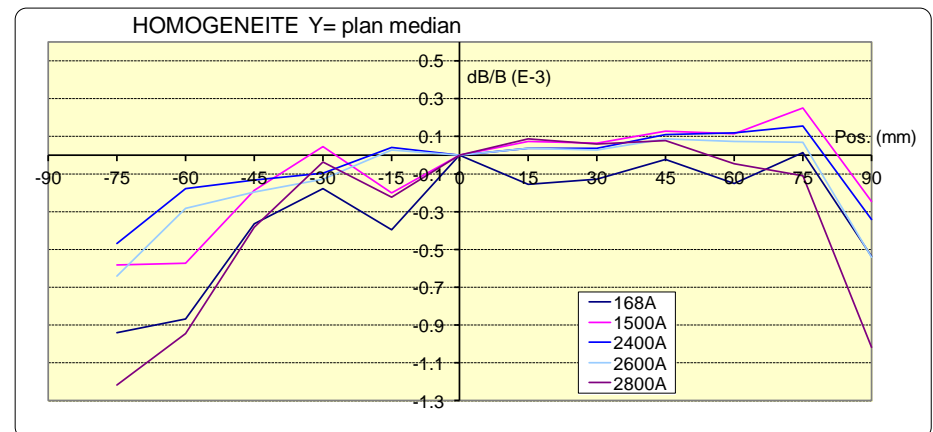
$$\frac{1}{\rho} \left[m^{-1} \right] = 0.3 \frac{B_o \left[T \right]}{p \left[GeV/c \right]}$$

16 + 1 Dipoles

Design parameter	Units	Value
Bending angle	[deg]	22.5
Entry Edge Angle	[deg]	11.25
Exit Edge Angle	[deg]	11.25
Bending radius	[m]	4.231
Gap	[mm]	71.6
Magnetic length	[m]	1.677
Resistance	[mΩ]	4.34
Inductance	[mH]	11.71
Cooling		Water
Nominal Current	[A]	2800
Nominal field	[T]	1.4492
Good field region	[mm]	±60 (hor); ±28 (vert)
Field Quality	$\Delta BL/BL$	$\pm 2 \cdot 10^{-4}$

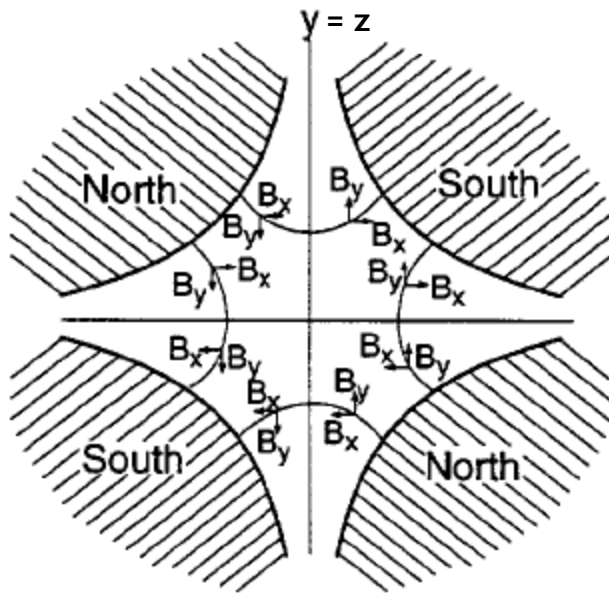


*Measured Integrated Field
Homogeneity at Different Currents*

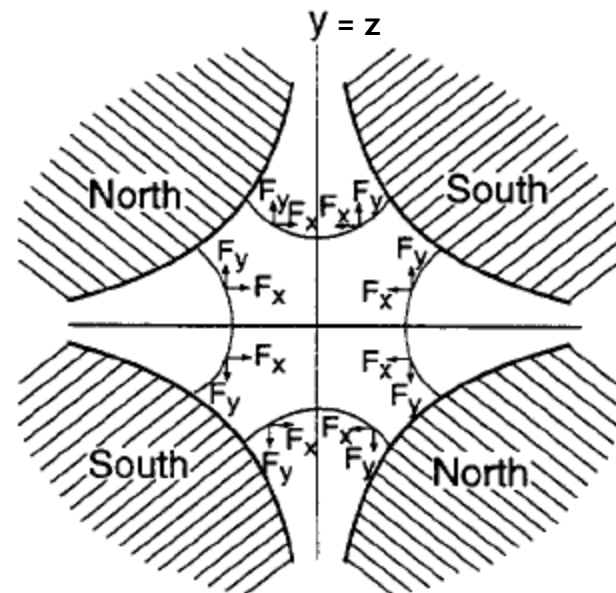


QUADRUPOLI

focheggiano le traiettorie
fuori asse



campo magnetico



forze sulle particelle

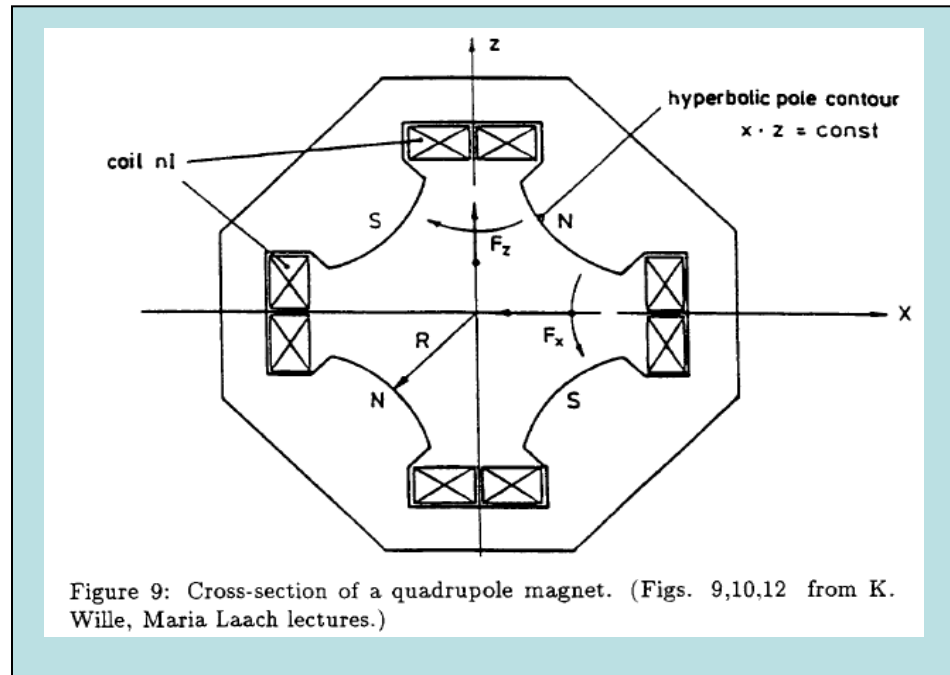
Quadrupoli

Componenti del campo magnetico nel nostro sistema di riferimento:

$$B_z = -g \cdot x$$

$$B_x = -g \cdot z$$

$$B_s = 0$$



g [T/m] = cte = *gradiente del campo magnetico*

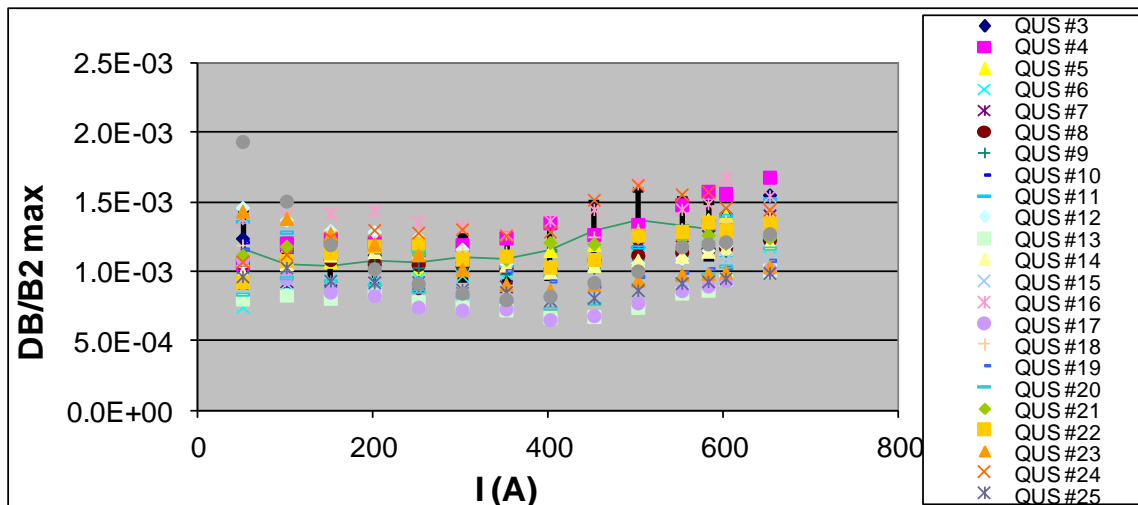
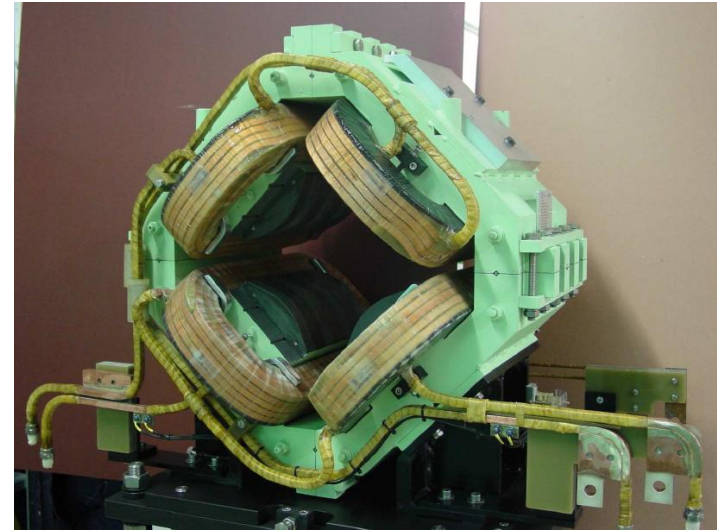
$$k$$
 [m⁻²] = 0.3 $\frac{g$ [T/m]}{p [GeV/c]

Forza del quadrupolo

24 Quadrupoles

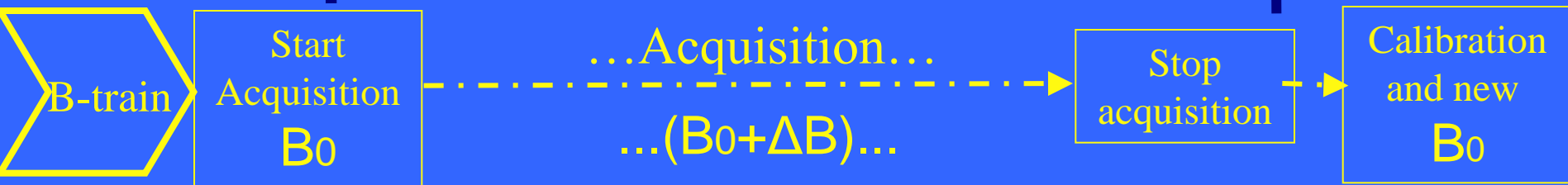
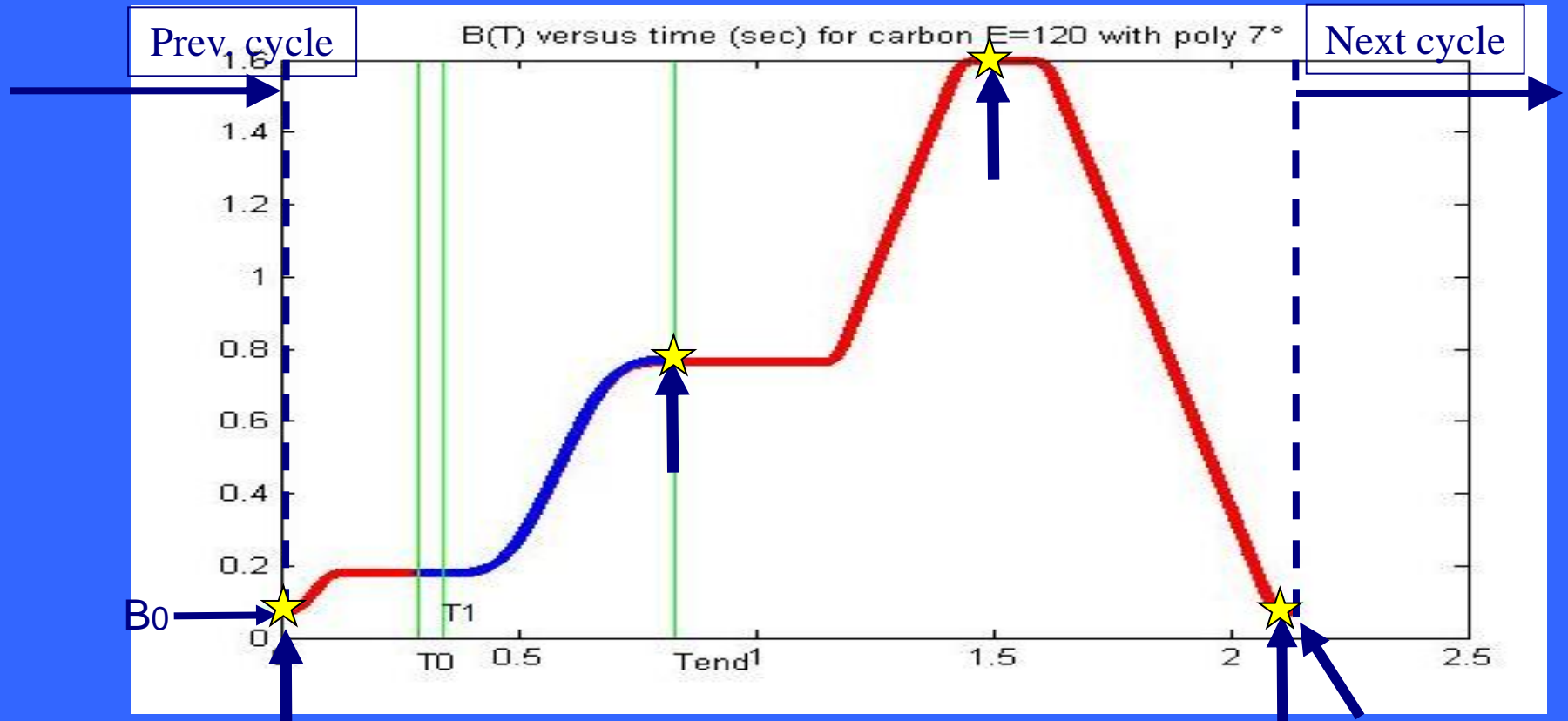
3 Families

<i>Design parameter</i>	<i>Units</i>	<i>Value</i>
Bore Radius	[mm]	85
Magnetic length	[m]	0.345
Inductance	[mH]	4.6
Resistance	[mΩ]	18.8
Cooling		Water
Nominal Current	[A]	580
Nominal Gradient	[T/m]	4.0
Good field region	[mm]	±60 (hor); ±30 (vert)
Field Quality	$\Delta BL/BL$	$\pm 5 \cdot 10^{-3}$



Measured Integrated Gradient Homogeneity at Different Current

Ciclo magnetico (B-Train)



Requested dipole magnetic field precision: 0.1 Gauss at 300kHz

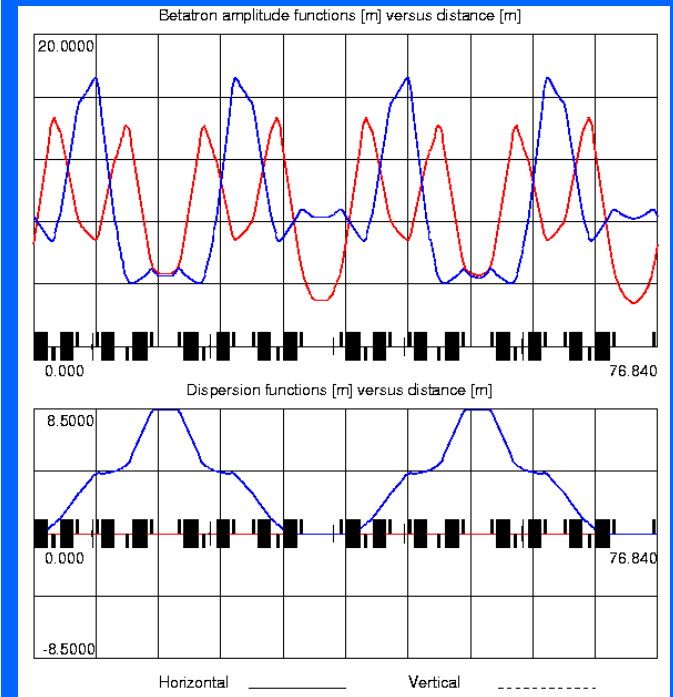
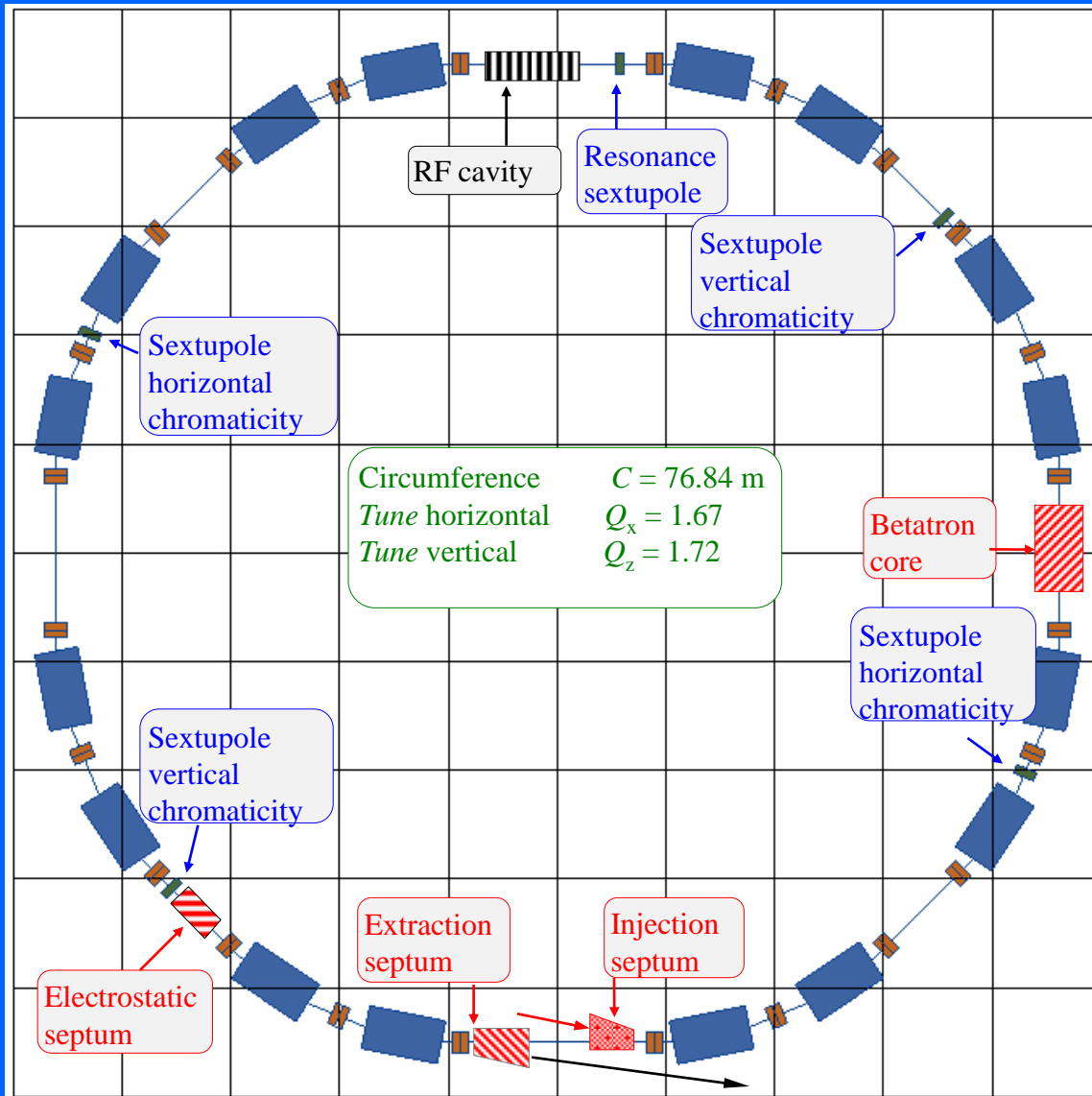
The synchrotron lattice

“PIMMS-like”

16 dipoles in series

24 quadrupoles (3 families)

5 sextupoles (3 families)



Ottica del sincrotrone

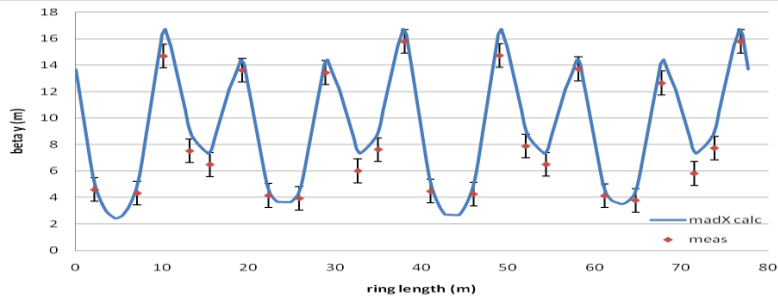
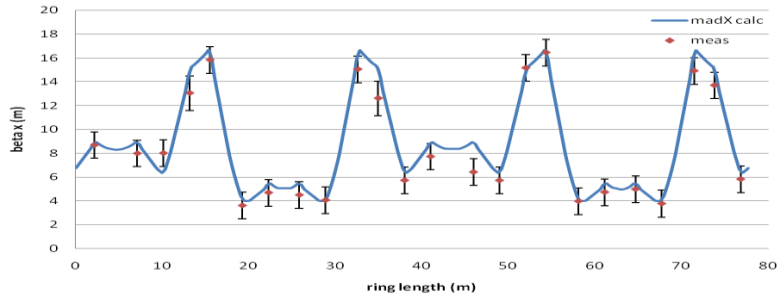
Based on PIMMS

- 2 Superperiods
- 2 Closed dispersion bumps
- 1 Dipole Family
- 3 Quadrupole Families
- 3 Sextupole Families

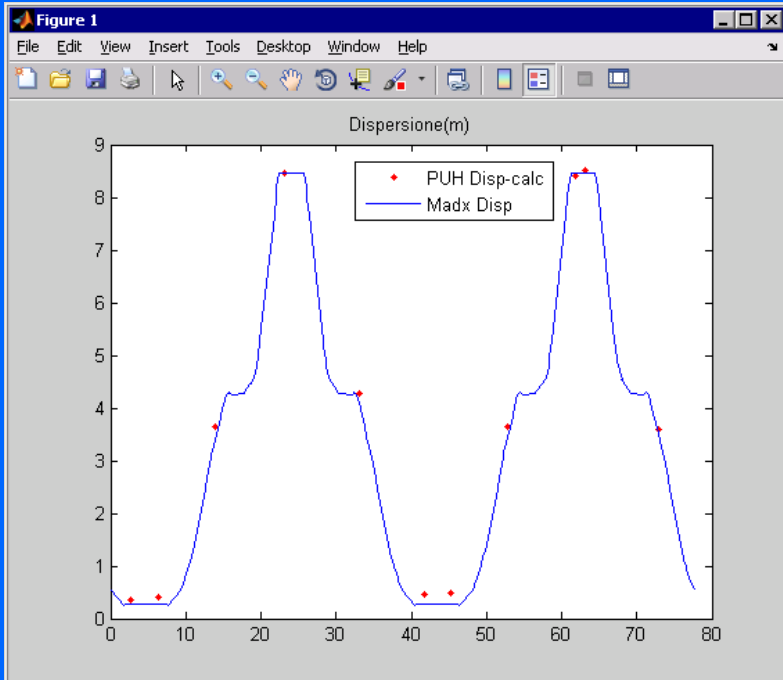
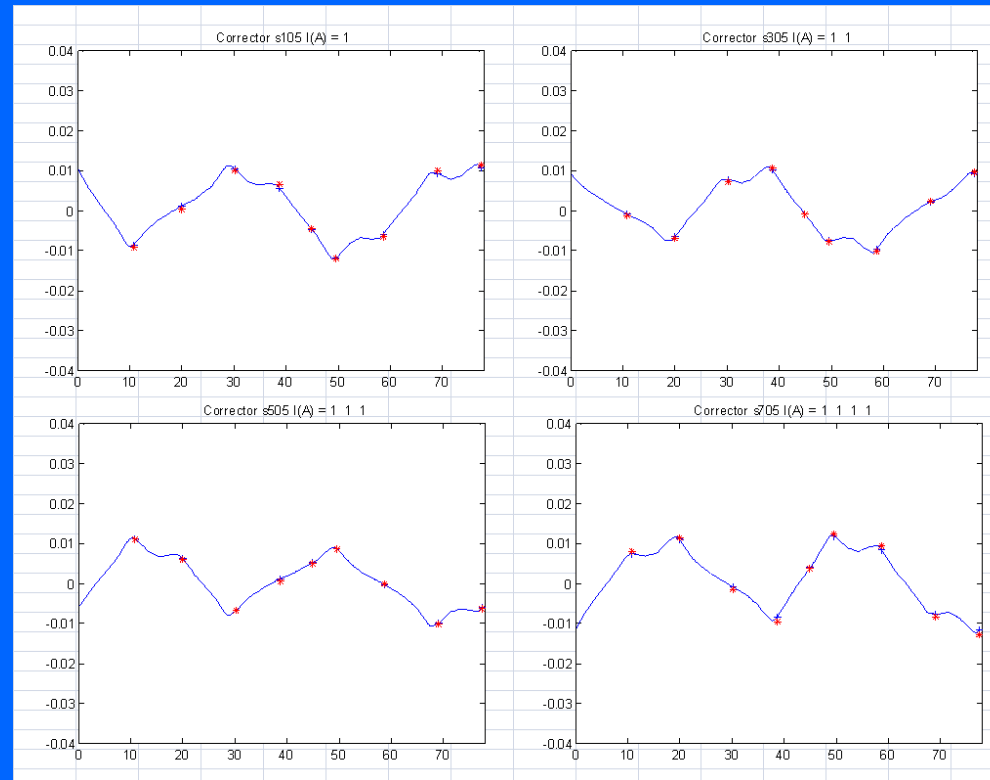
C	78 m
Qx	1.6666 - 1.67
Qy	1.72

Betas and dispersion

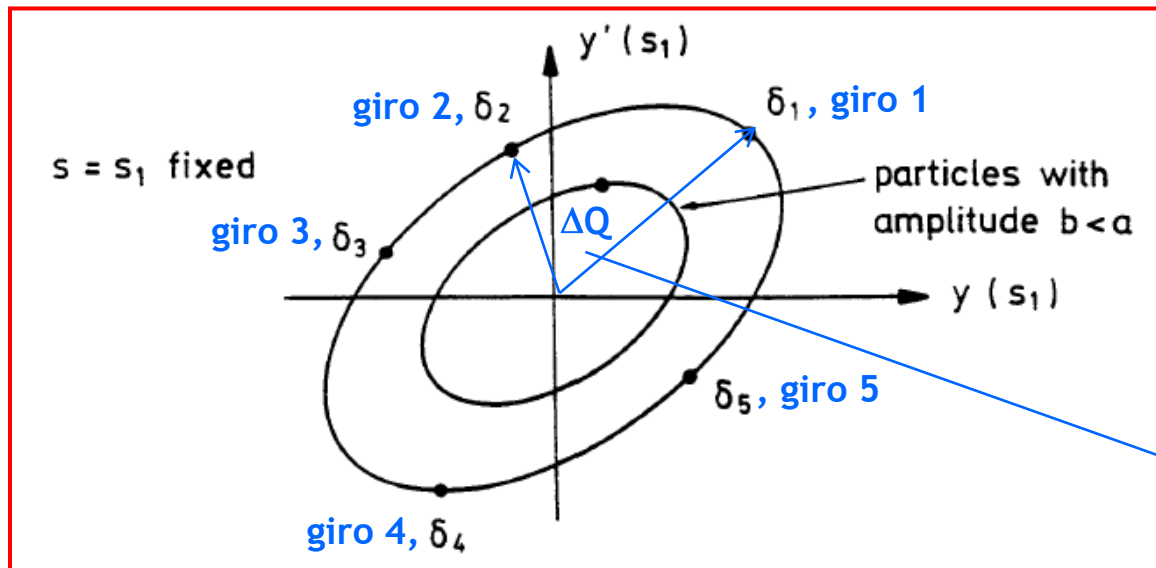
Optics measurements
fit with simulations



Response matrix



Spazio delle fasi di una particella



Parte decimale
del tune

*Area dell'ellisse =
invariante del moto_*

a energia costante

*L'area dell'ellisse che contiene tutte le particelle del fascio è
l'emittanza*

Le unità di misura dell'emittanza sono
m rad
(dimensione * divergenza)

Dimensione del fascio

Quanto misura il pacchetto di protoni o ioni carbonio all'interno della camera da vuoto?

La dimensione trasversa del fascio è

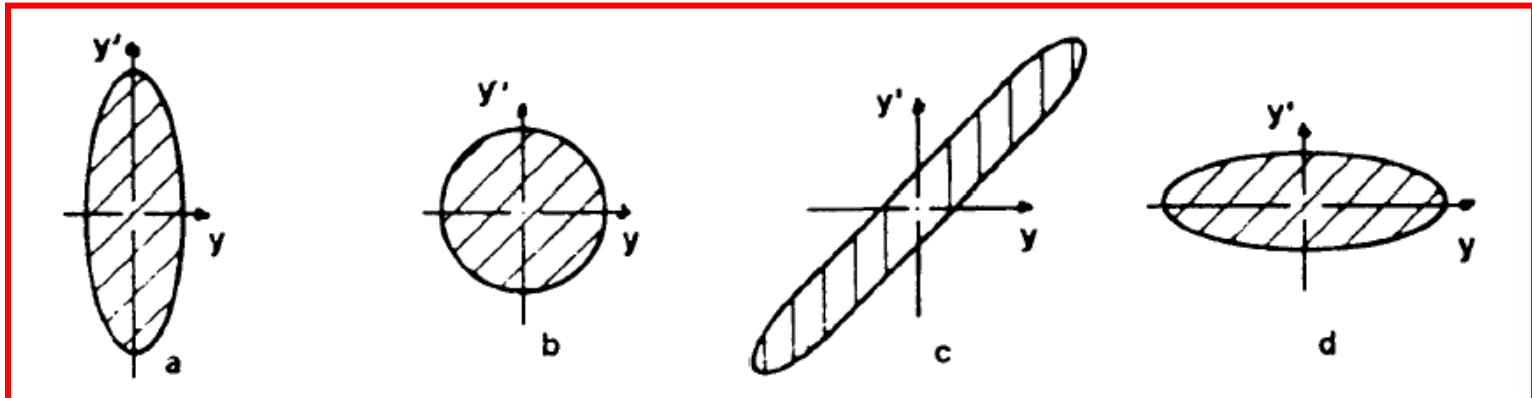
$$\sigma(s) = \sqrt{\epsilon\beta(s)}$$

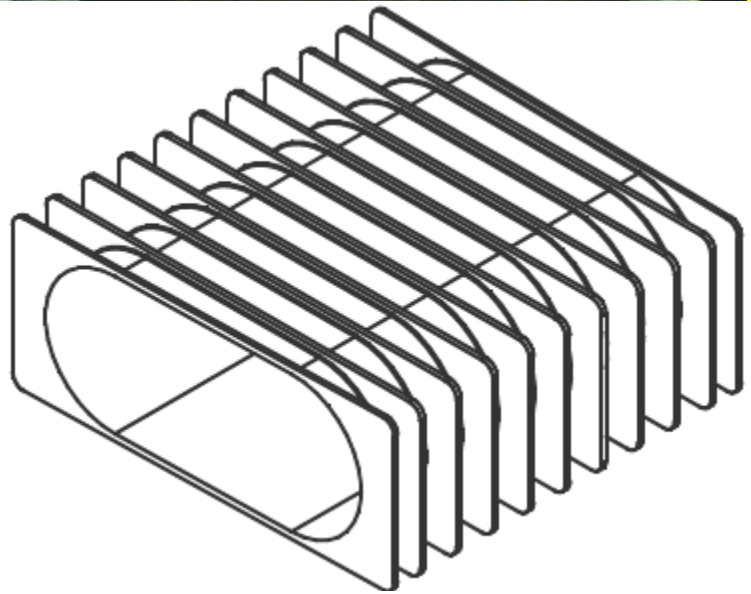
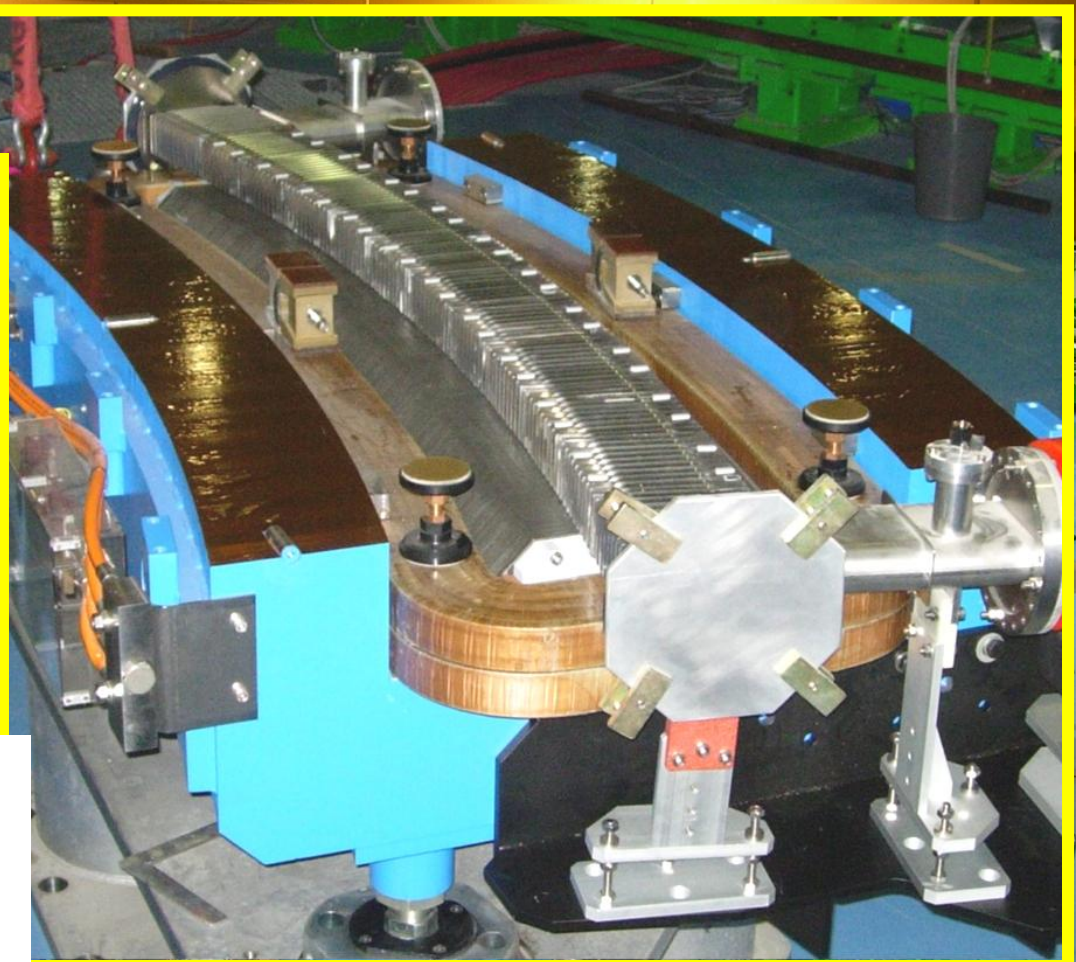
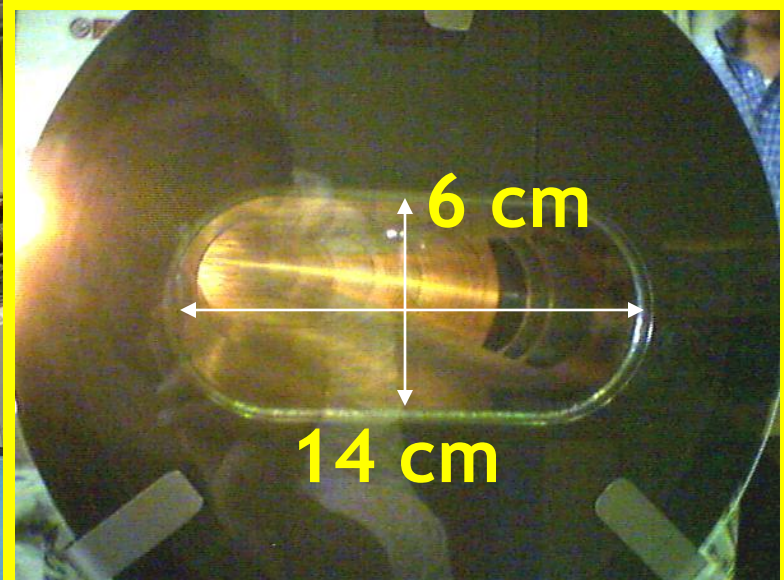
emittanza

beta

*L'emittanza si conserva qualunque sia la forza magnetica che agisce sulla particella:
Teorema di Liouville*

Spazio delle fasi in diversi punti dell'acceleratore





spessore= 0.3 mm !

Vacuum system
Particles travel through steel pipes in which an extremely low pressure is created (one thousand billions time less than atmospheric pressure)

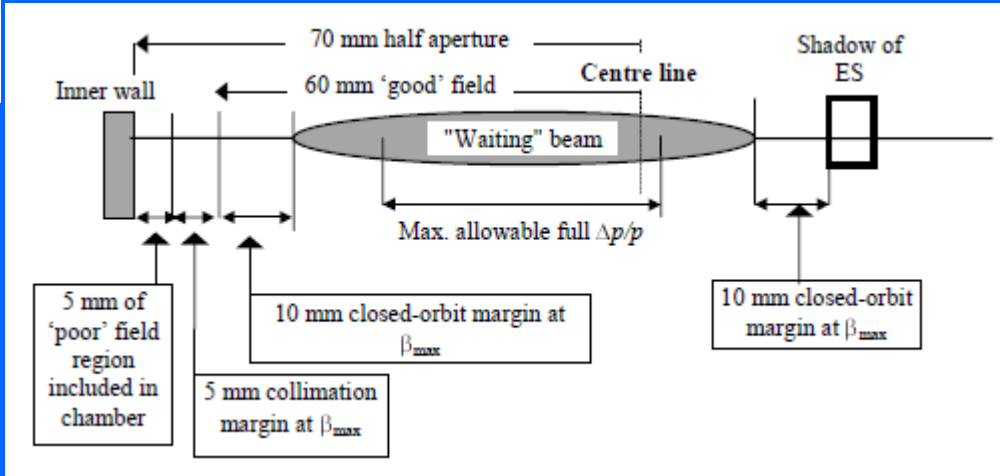
$$\text{Chamber aperture} = \pm \left[\underbrace{n \sqrt{\beta E_{\sigma} / \pi}}_{\text{Betatron envelope}} + \underbrace{0.5 D (\Delta p / p)_{\text{Full}}}_{\text{Momentum envelope}} + \text{Closed orbit} + \underbrace{\text{Collimator margin}}_{\text{POOR-field region}} \right]$$

GOOD-field region

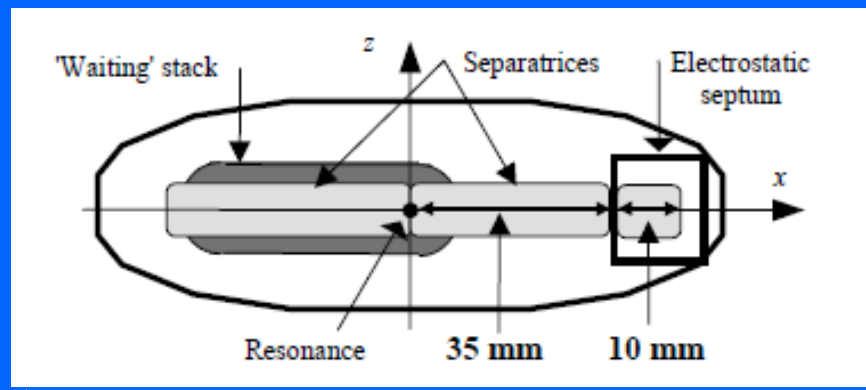
$$\text{Separatrix aperture} = \pm \left[\underbrace{\text{Separatrices} + \text{Closed orbit}}_{\text{Based on tracking}} \right]$$

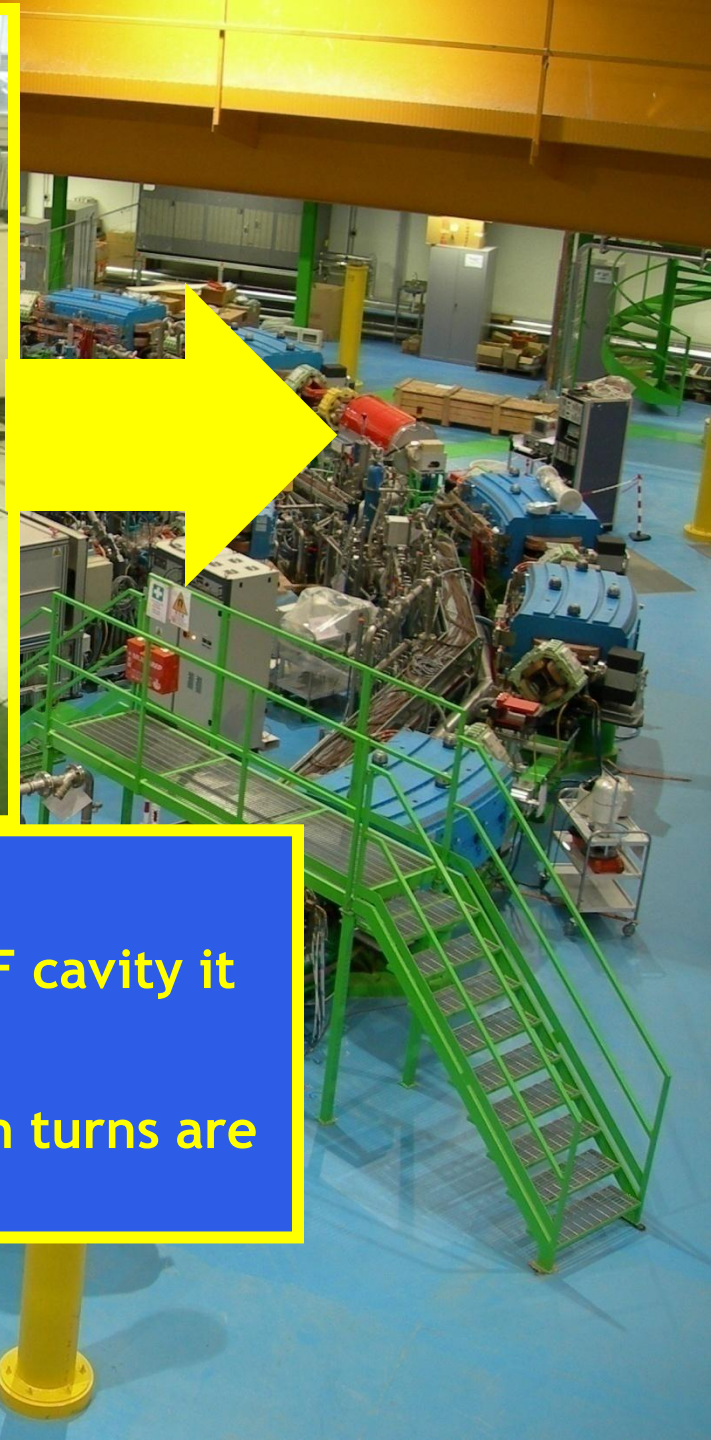
GOOD-field region

Apertura in un sincrotrone medicale



Nominal chambers, apertures and 'good' field regions		
Parameter	Horizontal	Vertical
Chambers:		
Outside dipoles	144 (± 72) mm	78 (± 39) mm
Inside dipoles	special	special
Physical aperture:		
Outside dipoles	140 (± 70) mm	74 (± 37) mm
Inside dipoles	140 (± 70) mm	64 (± 32) mm
'Good' field regions:		
At injection		
Outside dipoles	120 (± 60) mm	60 (± 30) mm
Inside dipoles	120 (± 60) mm	56 (± 28) mm
At top field		
Outside dipoles	same as low field	22 (± 11) mm
Inside dipoles	same as low field	20 (± 10) mm





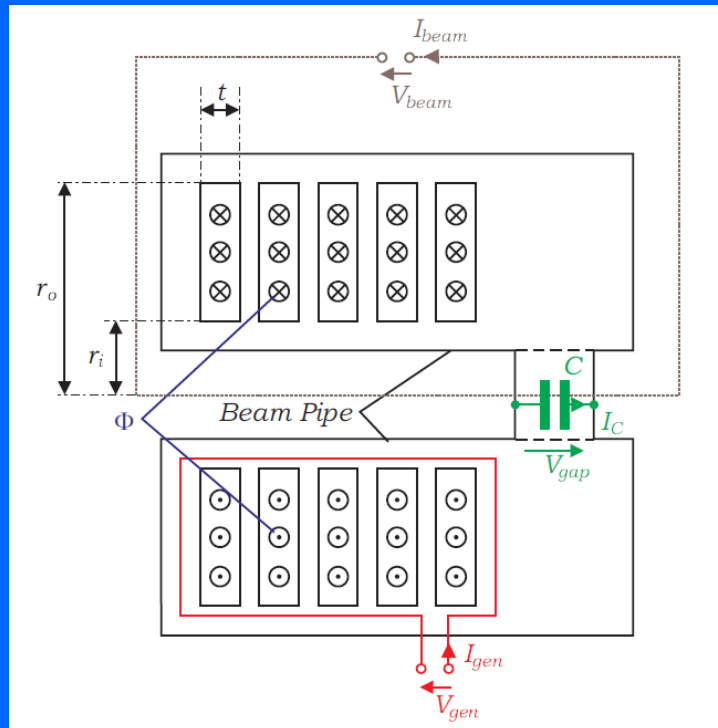
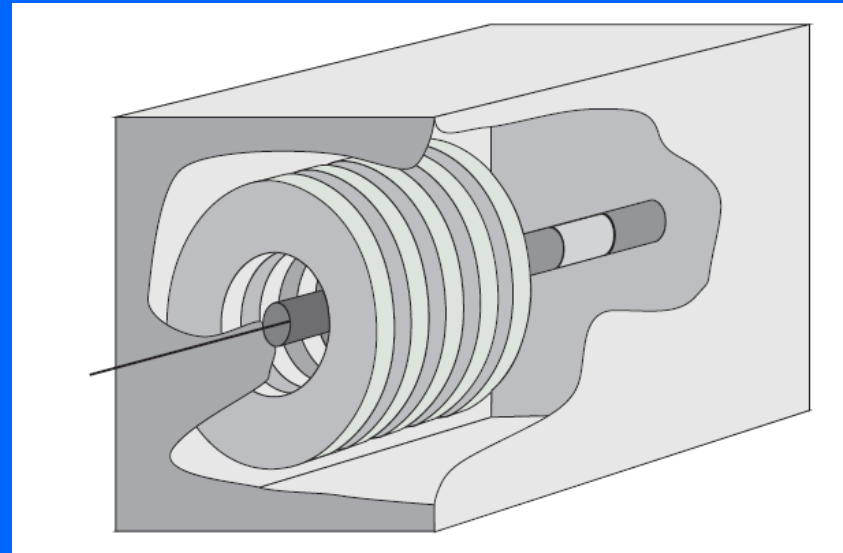
RF CAVITY

Each time the beam passes through the RF cavity it receives a push.

To reach the requested energy one million turns are necessary

Cavità a radiofrequenza (RF)

Sincrotroni per particelle debolmente relativistiche e particolari anelli di accumulazione richiedono cavità RF di frequenza bassa (< 10 MHz). A queste frequenze le dimensioni dei risuonatori convenzionali risultano eccessive ed incompatibili con le normali esigenze di compattezza dell'acceleratore.



Inoltre l'operazione dei sincrotroni debolmente relativistici richiede una variazione continua della frequenza RF durante la rampa di energia per seguire l'aumento della frequenza di rivoluzione associato all'aumento della velocità delle particelle.

L'uso di cavità caricate con dischi di ferrite viene incontro ad entrambe le esigenze. La permeabilità magnetica μ dei nuclei presenta valori elevati e modificabili tramite correnti di bias. La frequenza di risonanza della struttura risulta quindi bassa e controllabile entro range molto ampi (anche > 10).

Resonator 1/2

- Cavities working in a wide range of frequencies are of two types: broadband cavities or tunable cavities. Both of them are obtained by resonators filled with ferrite or ferrite-like materials.
- The solution adopted at CNAO is a tunable cavity obtained filling a coaxial resonator with VITROVAC 6025, a ferrite-like amorphous material Co-based with a broadband frequency response produced by VACUUMSCHMELZE.

VITROVAC features:

Low dependence of μ on temperature

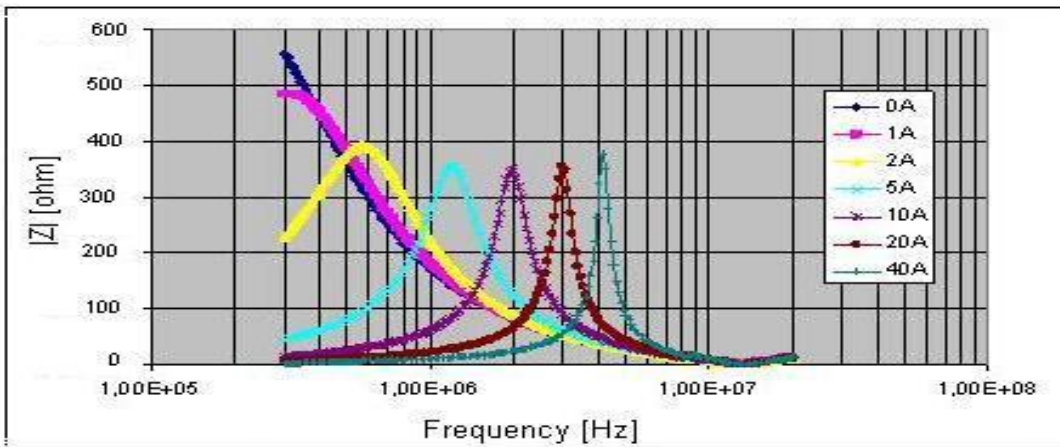
High permeability

High figure of merit μQ_f

High magnetic sensibility

Resonator 2/2

- Cavity response has always the bell-shaped frequency response of a resonator but it has the effective trend of a resonator only increasing the polarization current.
- The bell-shaped form of the impedance allows to cut superior harmonics on the gap. Thanks to vitrovac features the polarization is NO challenging and needs few amperes (about 10 A at 3 MHz).
- Thanks to the characteristics of Vitrovac, cavity is compact: the length is only 1.376 m



Q

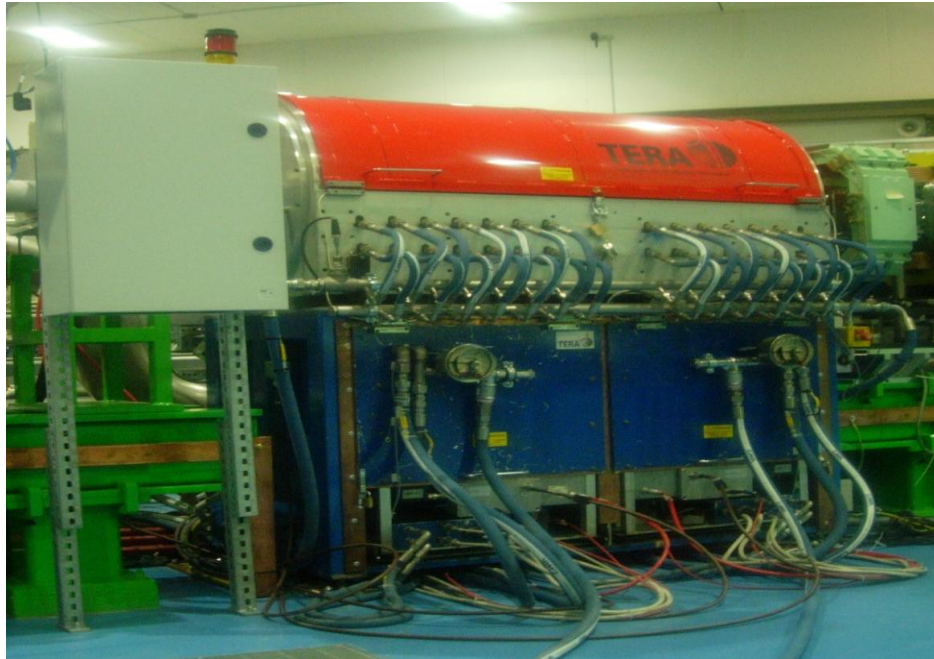
1-5

Rshunt

400 ohm

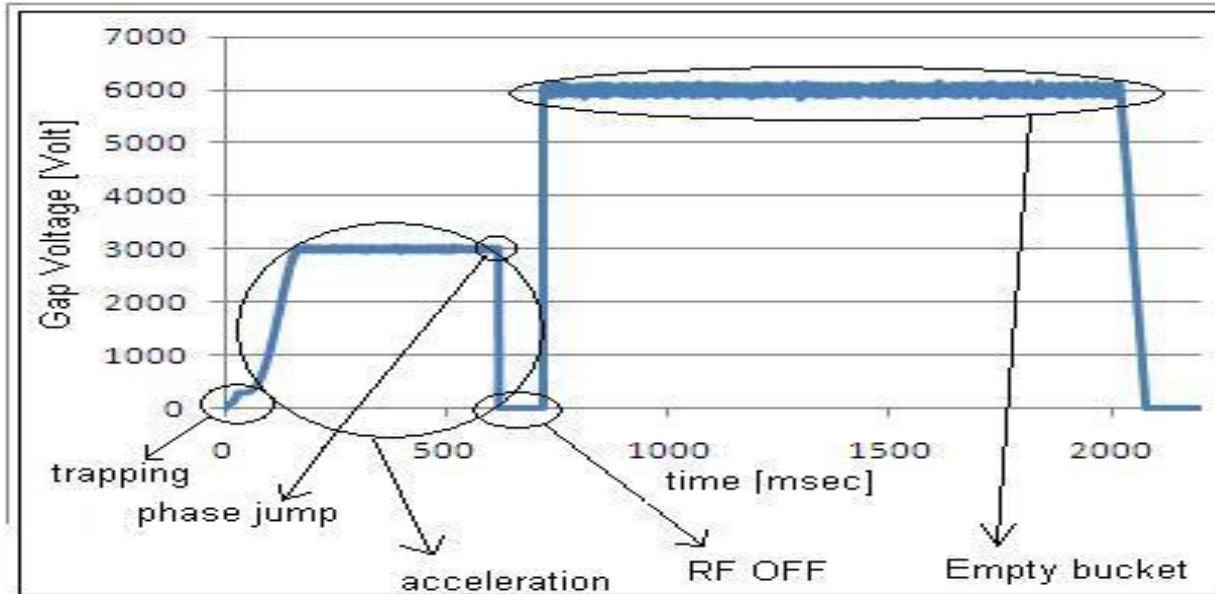
Synchrotron RF system

- The main feature of a low energy hadron synchrotron is that when accelerating beam, the revolution frequency of the beam changes significantly. As a consequence the acceleration in the ring must be obtained by RF cavities able to change the frequency in a wide range from hundreds of kHz to MHz with moderate voltages. In CNAO case the cavity accelerates at the first harmonic number of the beam so the frequency must go from 460 kHz to 3 MHz.
- As it will be shown, the RF system features depend not only on the beam acceleration method but are influenced from the injection and extraction techniques: RF appears as a fundamental tool in the management of the features of the beam delivered to the patient.



CNAO RF cavity cycle 1/2

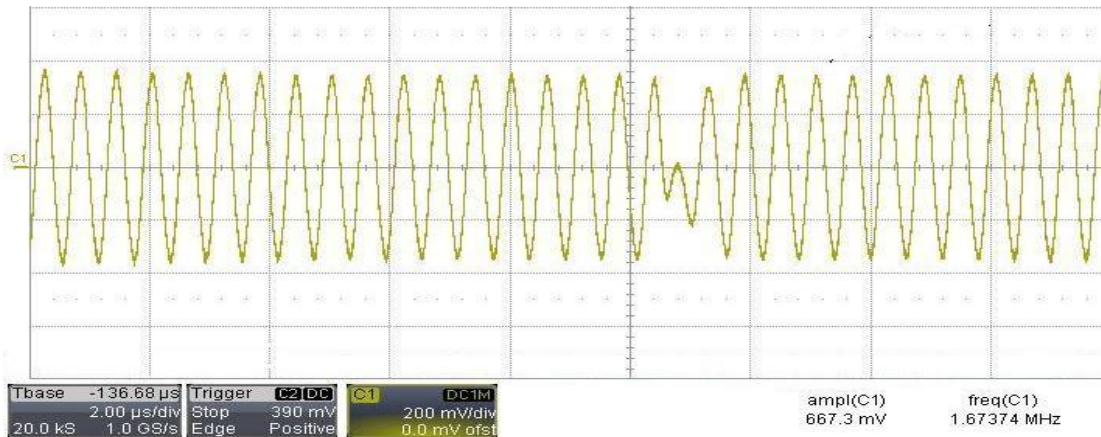
- The following picture shows the cavity gap voltage during a 1 sec extraction proton cycle. The different phases are illustrated: trapping, acceleration, phase jump, RFOff, empty bucket channelling (EB).



- Beam is injected in synchrotron through a multi-turn injection mechanism: beam is not bunched and no synchronism is necessary but RF must increase its voltage with an adiabatic law to reduce losses and preserve longitudinal emittance.
- RF voltage goes from 25 V to 6000 V and this implies that the voltage control loop must have enough resolution and must be as precise as possible to guarantee the required trend. An error of 1 V can be accepted.

CNAO RF cavity cycle 2/2

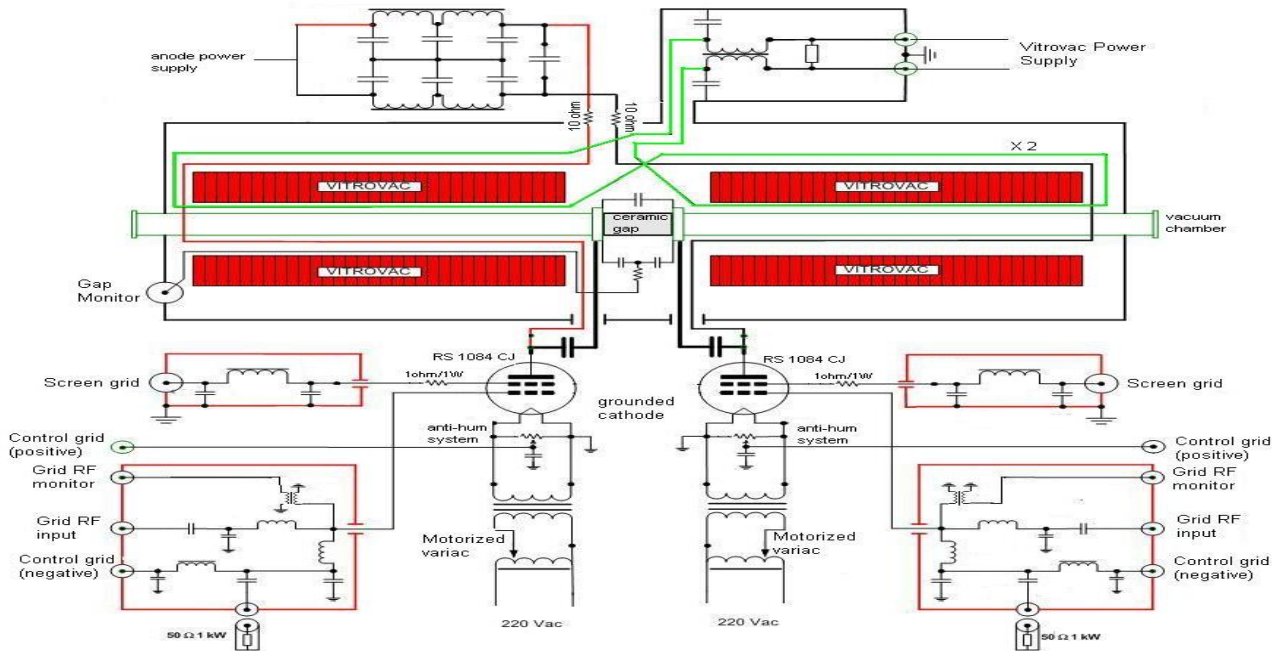
- After acceleration and before debunching RF phase must change of 180 degrees. This technique is mandatory to manipulate beam energy distribution: without it the extraction of the beam is not uniform in terms of intensity during the spill and the spill has not a unique position but it changes during extraction.
- Phase jump and RF OFF must be sudden: any further ringing disturbs beam distribution



- During extraction RF must be switched on at a fixed voltage and frequency: this technique is fundamental to reduce (a factor of 8) the ripple spill due to power supplies ripple: the frequency is near (some kHz) the extraction frequency and must be adjusted depending on the energy. The voltage must be about 8 kV peak. This represents the main stress in terms of power for the amplifier.

Amplifier

The RF power is obtained by a push-pull amplifier realized by two 70 kW tetrodes.



INSTALLED POWER

Tetrode type	RS1084CJ
Tetrode working point	Class B
Control grid voltage	-180 V
Screen grid voltage	900 V
Anode DC Voltage	11 kV
Max Anode DC current	6 A
Max power per tetrode	25 kW
Max Screen grid power	180 W
Max RF voltage gap	10 kV
Max RF grid input	500 W

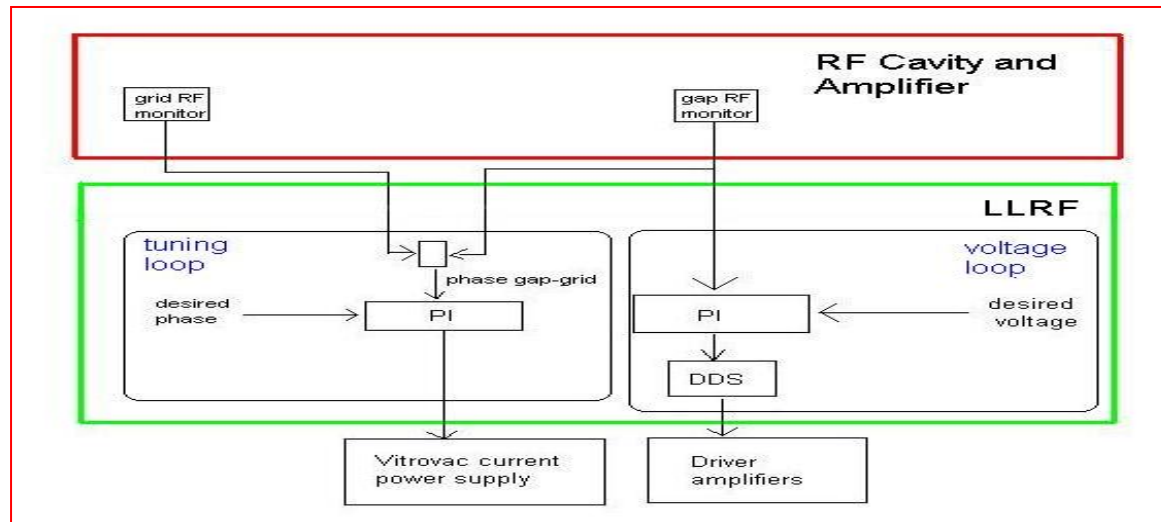
Cavity Control

The control of the cavity is realized by a digital LLRF exploiting FPGA and DSP technologies.

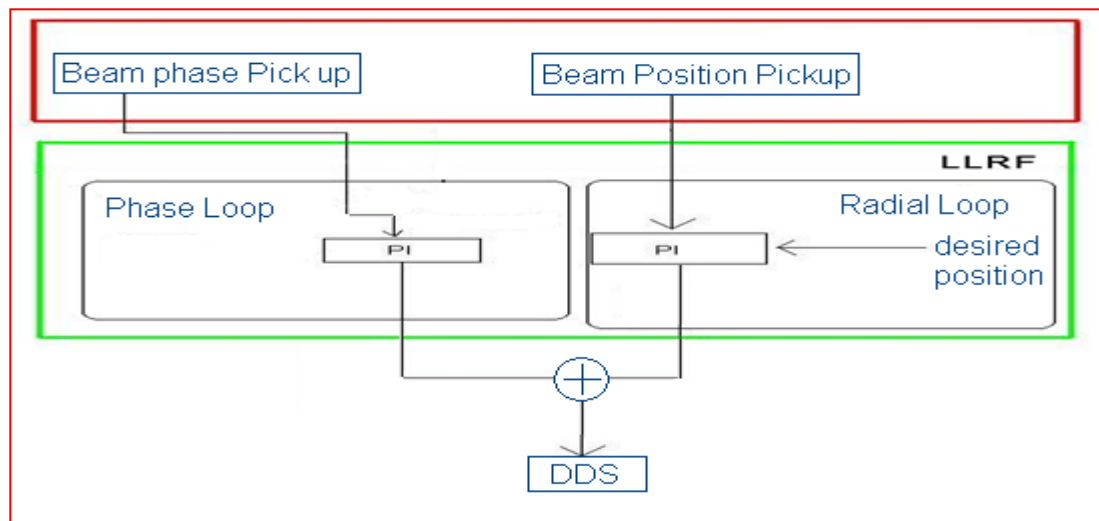
A tuning loop and a voltage loop (servo loops) control RF cavity voltage.

A phase loop and a radial loop (beam loops) control the frequency according to beam behaviour.

Servo Loops

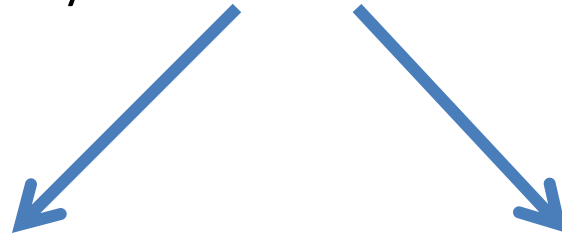


Beam Loops



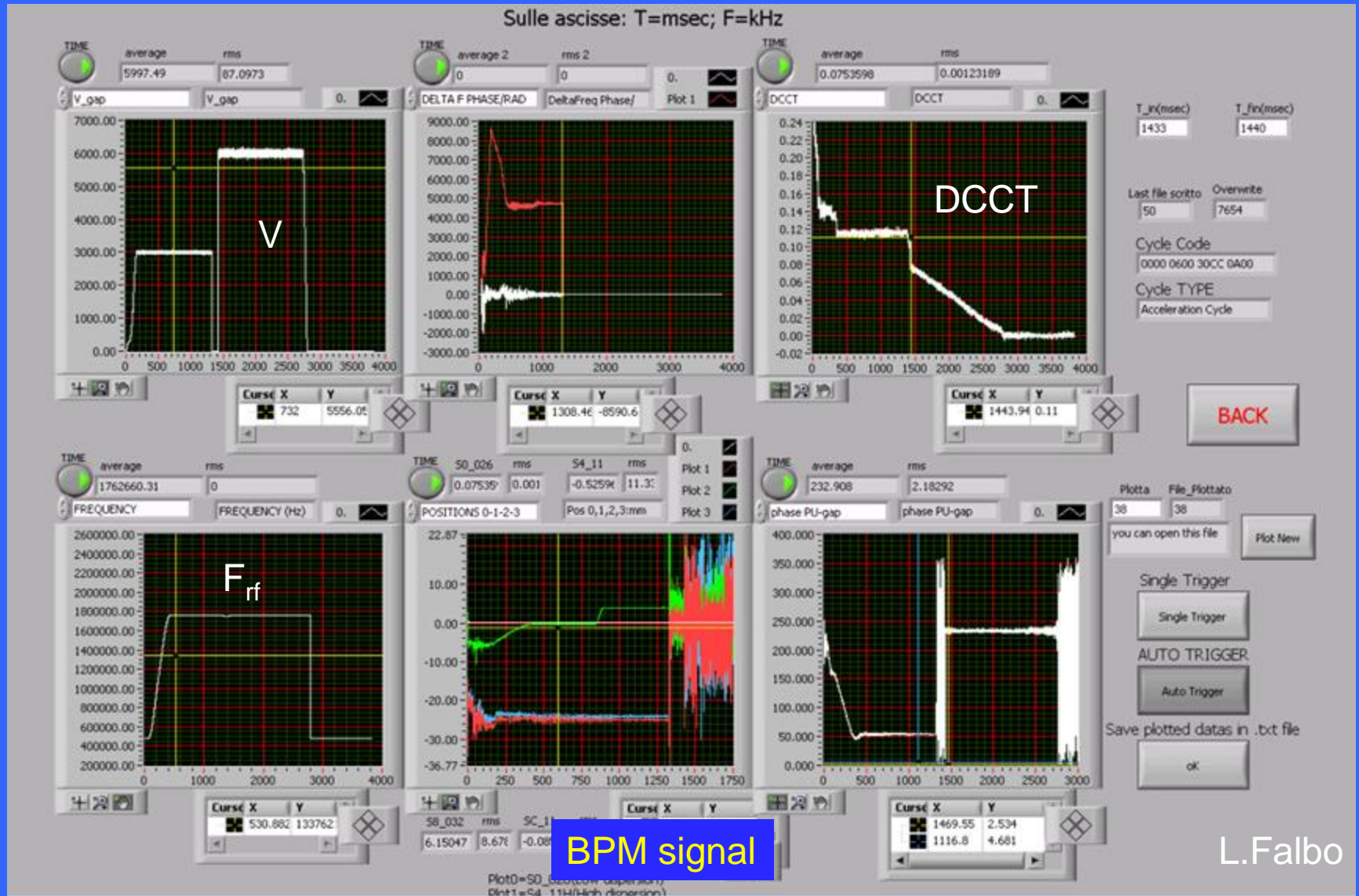
Beam Control

- The ring design forces the beam to pass not in the center of the vacuum chamber: the dispersion function is adjusted so that, thanks to a dp/p , beam orbit is negative in lots of regions reaching also -35 mm.
- The position different from zero is not only due to transmission problems: Considering the resonant extraction mechanism, the position in the dispersive regions is a free parameter to be adjusted in optimising extraction.
- The first two points explain the mandatory necessity of beam loops able to adjust the programmed frequency in feedback with beam position.



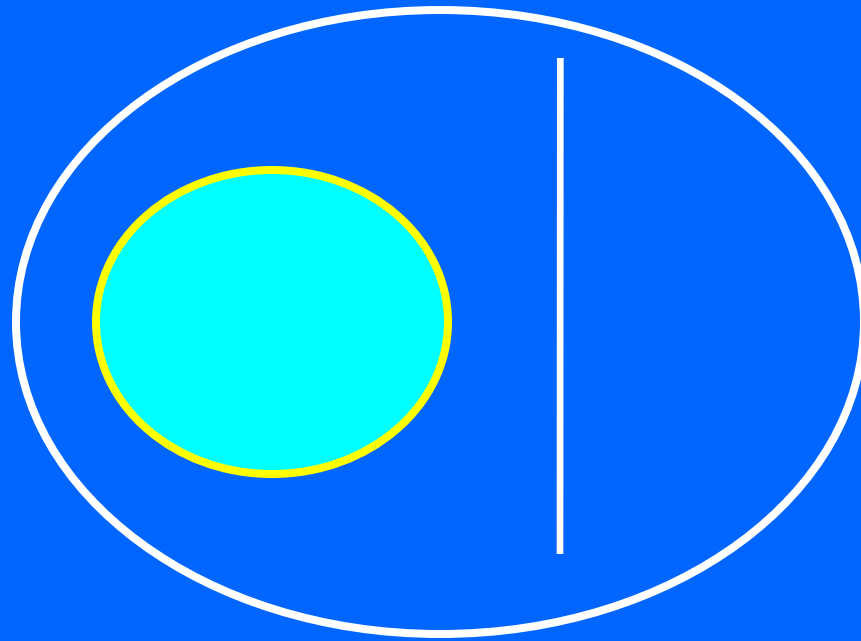
Phase Loop using beam pickup to damp synchrotron oscillations (>factor of 20): AC loop (10 Hz,5 kHz) that is based on the phase between beam and RF.

Radial Loop using Beam Pick up position to act on frequency as a PI in order to set radial position with a precision < 0.2mm

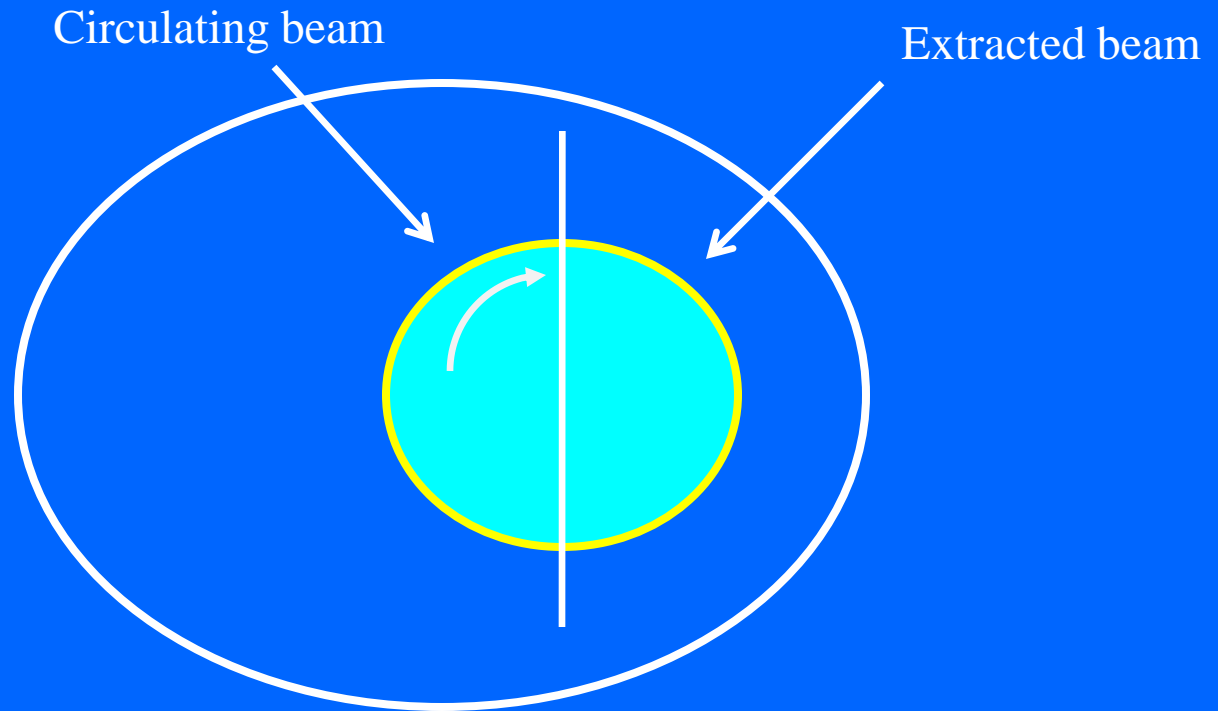


- Extraction is the reciprocal of injection...
- Single turn extraction
- “Multi turn” extraction
- Manymanymany turns extraction
- Extraction happens at higher energies!

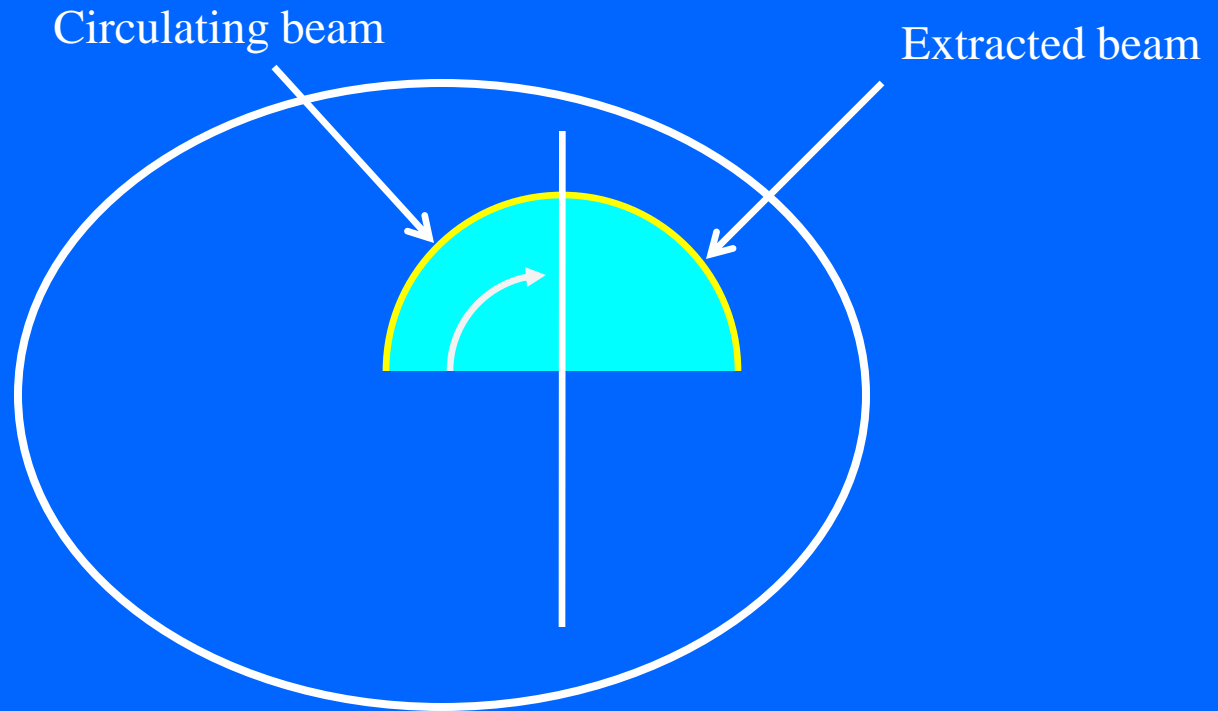
“Multi turn” extraction



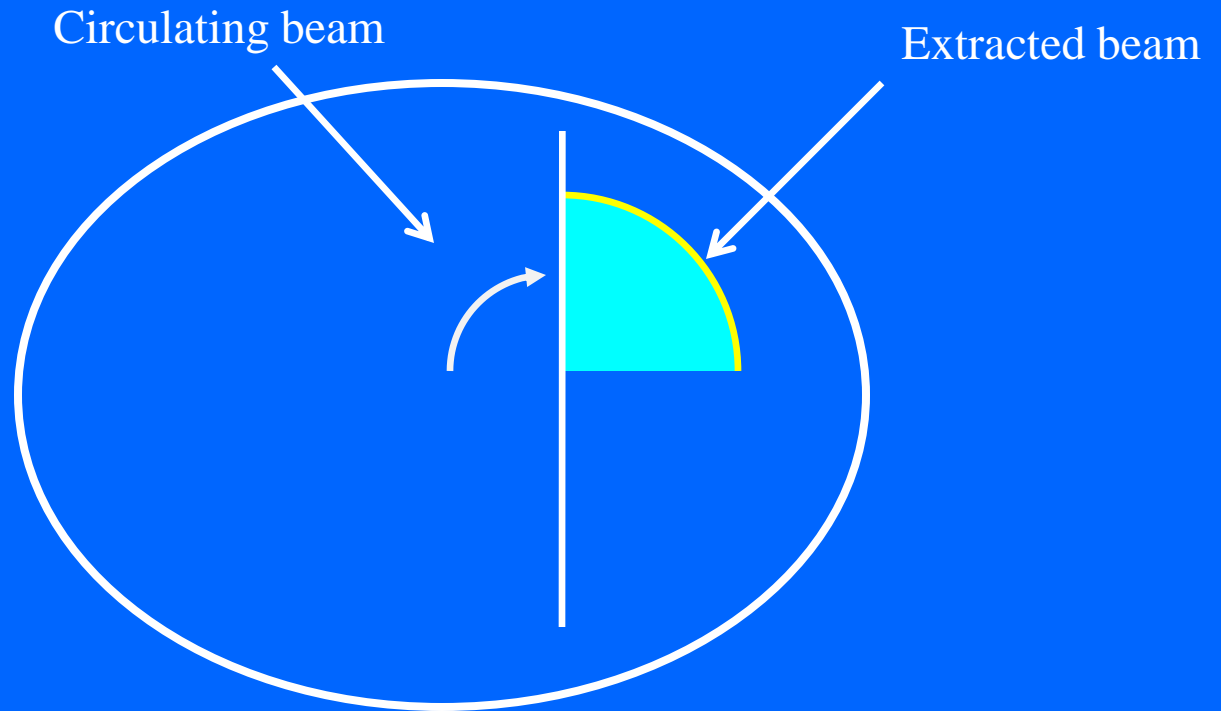
“Multi turn” extraction



“Multi turn” extraction



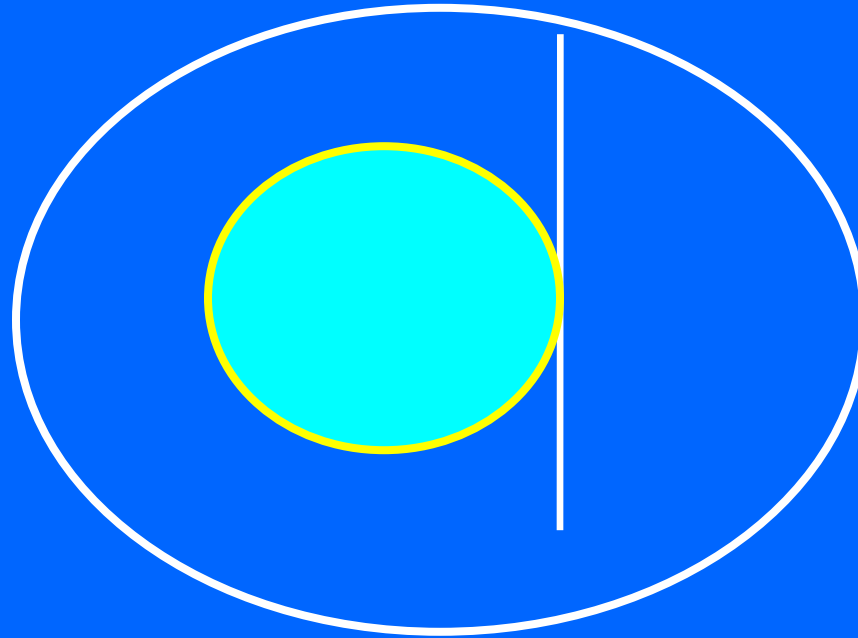
“Multi turn” extraction



Resonant extraction

- What if I want to extract over 10^6 turns?

The entire beam would be lost on the septum



I have to move quickly only a small part of the beam!

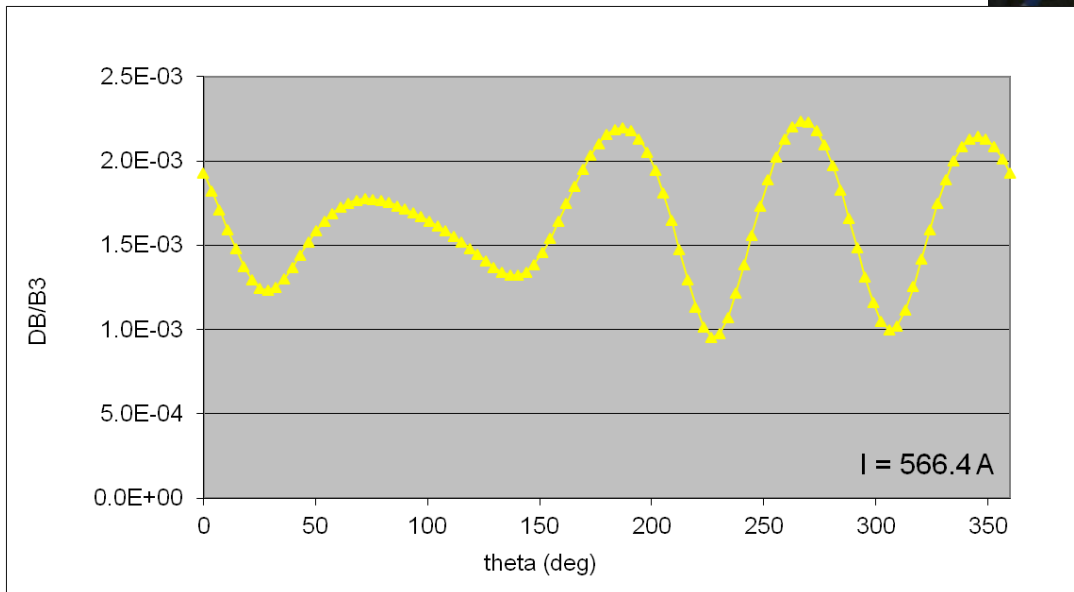
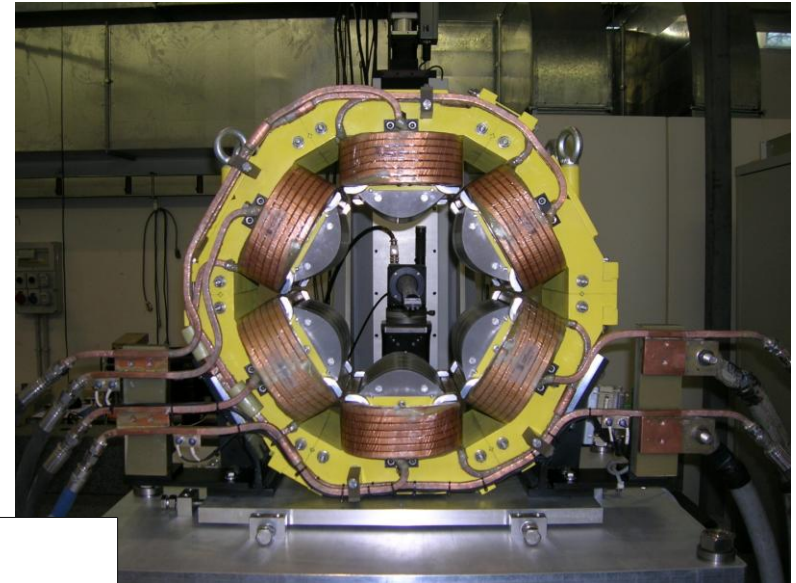
L. Badano, M. Benedikt, P.J. Bryant, M. Crescenti, P. Holy, P. Knaus, A. Meier, M. Pullia e S. Rossi, *Proton-Ion Medical Machine Study (PIMMS) - Part I*, CERN/PS 99-010 DI (1999).

L. Badano, M. Benedikt, P.J. Bryant, M. Crescenti, P. Holy, P. Knaus, A. Meier, M. Pullia e S. Rossi, *Proton-Ion Medical Machine Study (PIMMS) - Part II*, CERN/PS 2000-007 (DR).

1 Resonance Sextupole

(+4 sestupoli di cromaticità)

<i>Design parameter</i>	<i>Units</i>	<i>Value</i>
Bore Radius	[mm]	100
Magnetic length	[m]	258
Inductance	[mH]	2.69
Resistance	[mΩ]	24.4
Cooling		Water
Nominal Current	[A]	566.4
Nominal Gradient	[T/m ²]	59.6
Good field region	[mm]	±60 (hor); ±30 (vert)
Field Quality	$\Delta BL/BL$	$\pm 2.5 \cdot 10^{-3}$



*Measured Integrated Gradient
Homogeneity at Nominal Current*

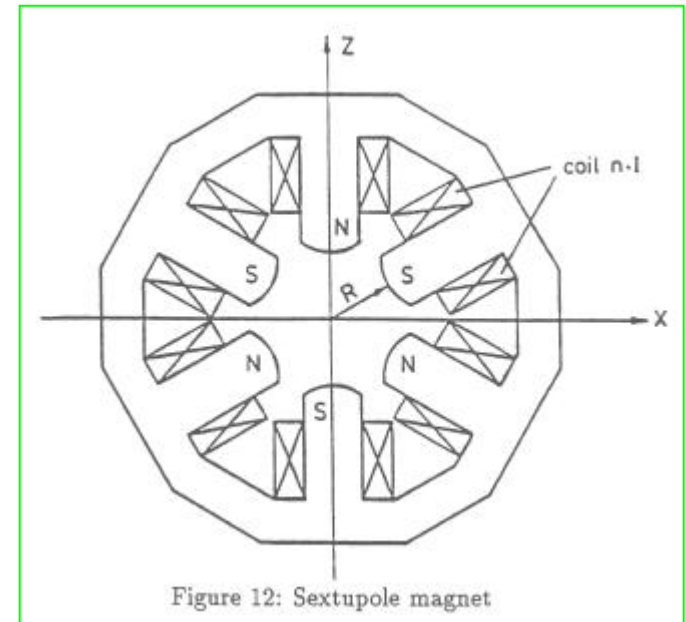
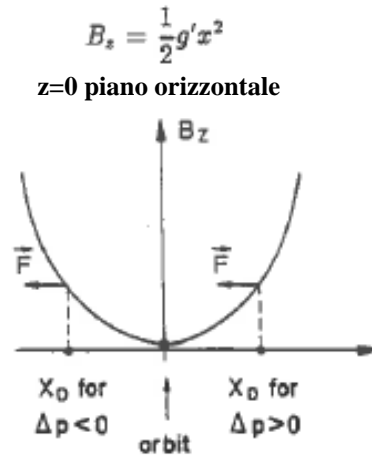
Sestupoli

Componenti del campo magnetico nel nostro sistema di riferimento:

$$B_z = \frac{1}{2} g' (x^2 - z^2)$$

$$B_x = g' x \cdot z$$

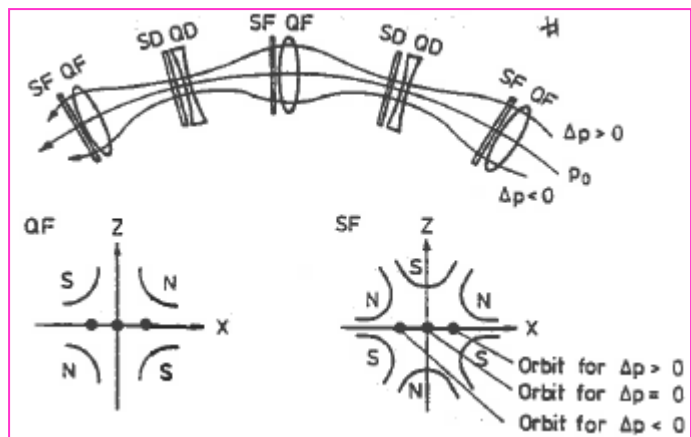
$$B_s = 0$$



$$g' \text{ [T/m}^2] = 6\mu_0 n I / R^3$$

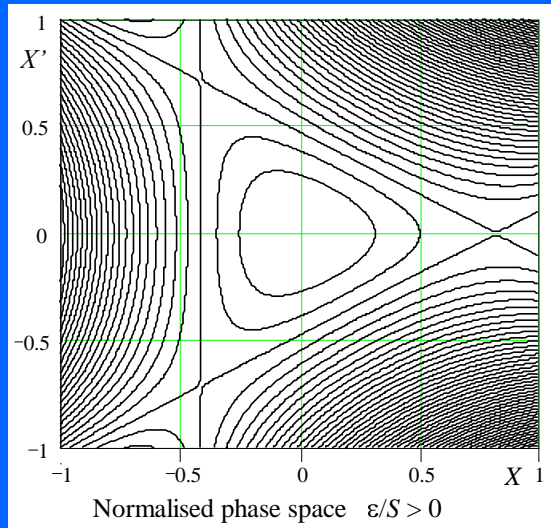
Forza del sestupolo

$$m \text{ [m}^{-3}] = 0.3 \frac{g' \text{ [T/m}^2]}{p \text{ [GeV/c]}}$$



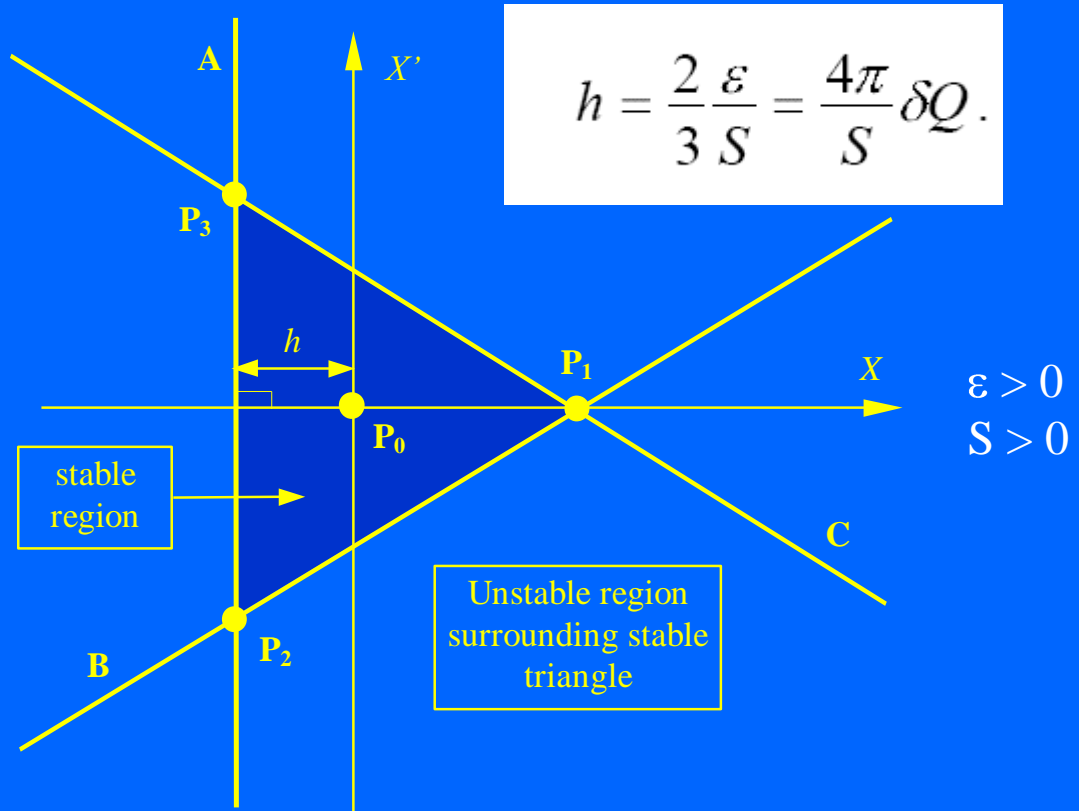
Sestupolo come quadrupolo posizione-dipendente

“Accensione” del sestupolo “deforma” lo spazio delle fasi (tune vicino al terzo di intero)



Le traiettorie nello spazio delle fasi normalizzate sono descritte dall'Hamiltoniano di Kobayashi le cui mappe sono rappresentate in figura

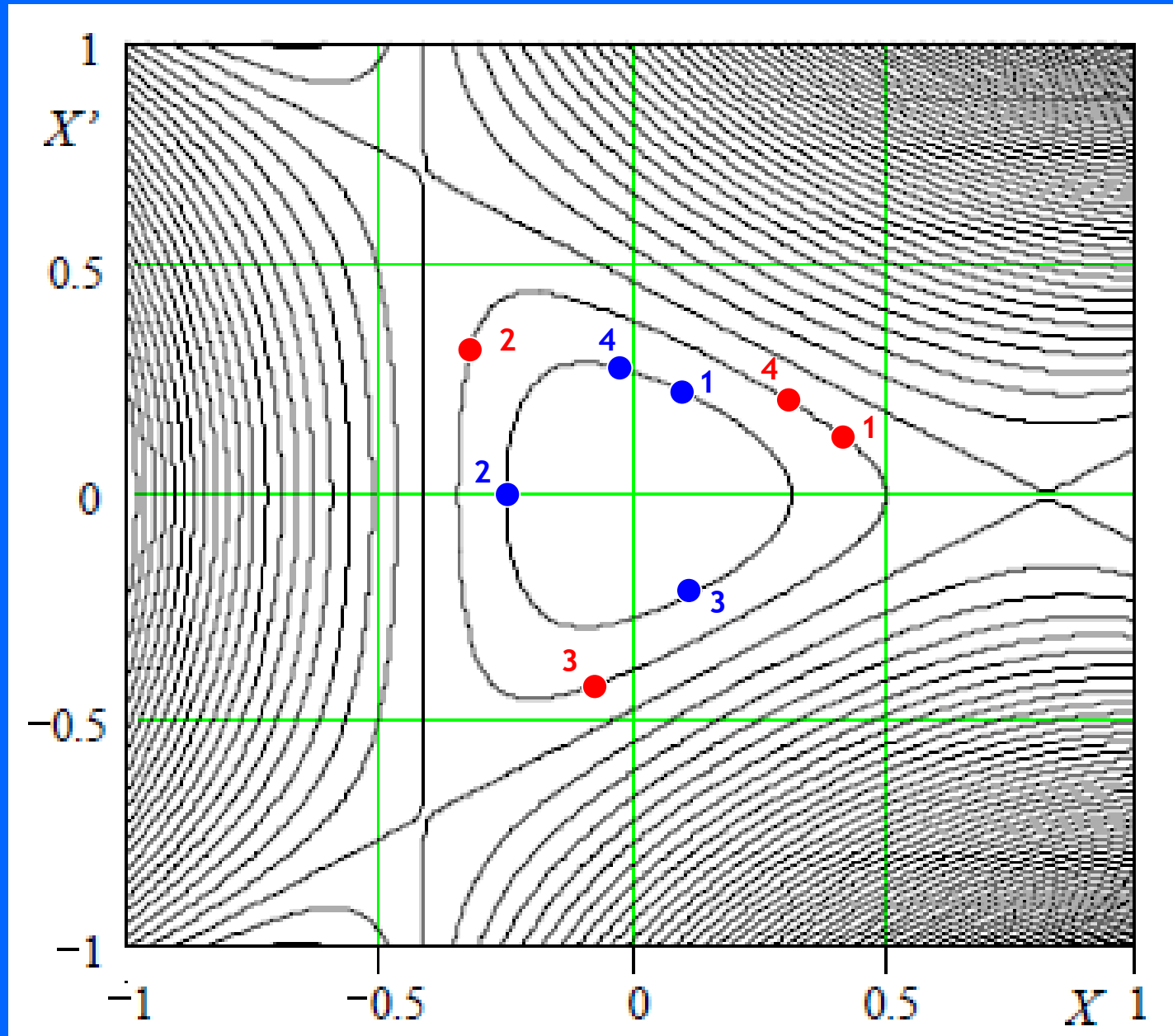
$$\longrightarrow H = \frac{\varepsilon}{2} (X^2 + X'^2) + \frac{S}{4} (XX'^2 - X^3)$$



$$h = \frac{2\varepsilon}{3S} = \frac{4\pi}{S} \delta Q.$$

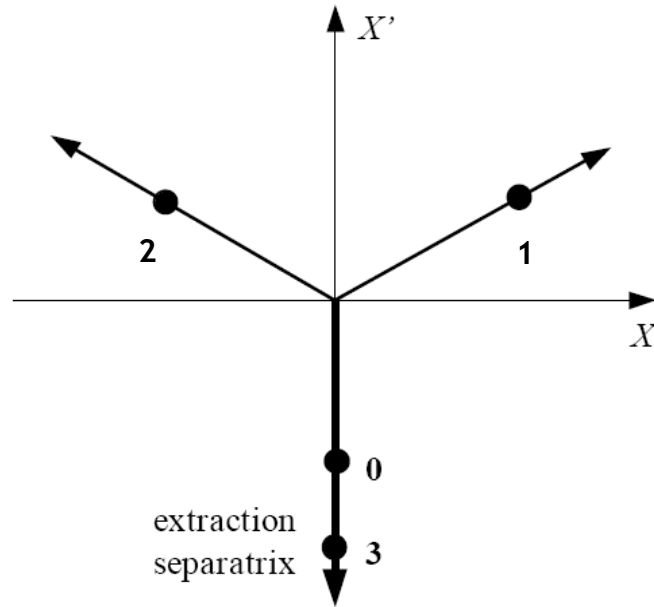
$$\text{Area (acceptance) of stable triangle} = 3\sqrt{3}h^2 = \frac{48\sqrt{3}\pi}{S^2} (\delta Q)^2 \pi$$

I movimenti delle particelle "lontane" dalla risonanza



I “salti” delle particelle in risonanza

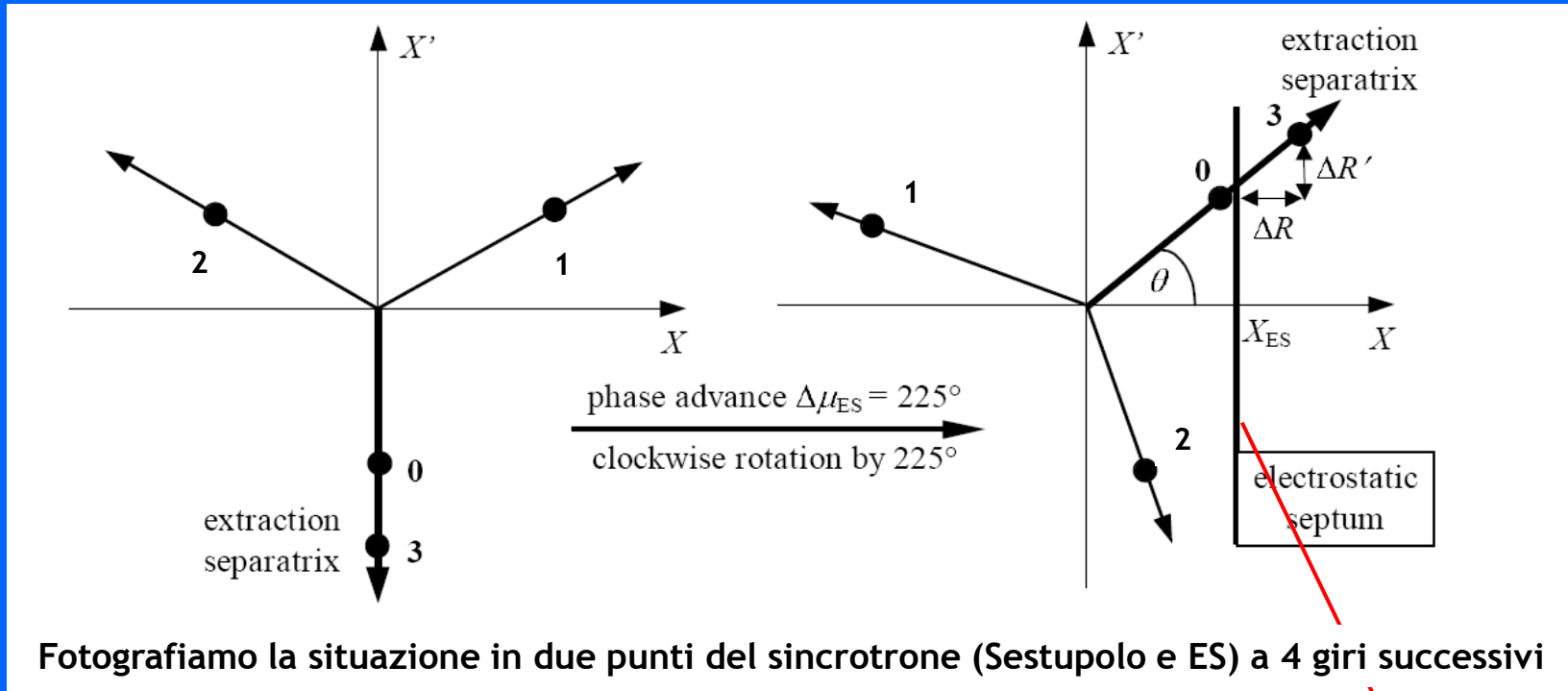
Consideriamo una particella al limite della stabilità: $\delta Q = 0$
(il triangolo centrale diventa un punto e la particella si muove lungo le separatrici)



Fotografiamo la situazione al Sestupolo
a 4 giri successivi

I "salti" delle particelle in risonanza

Consideriamo una particella al limite della stabilità: $\delta Q = 0$
 (il triangolo centrale diventa un punto e la particella si muove lungo le separatrici)



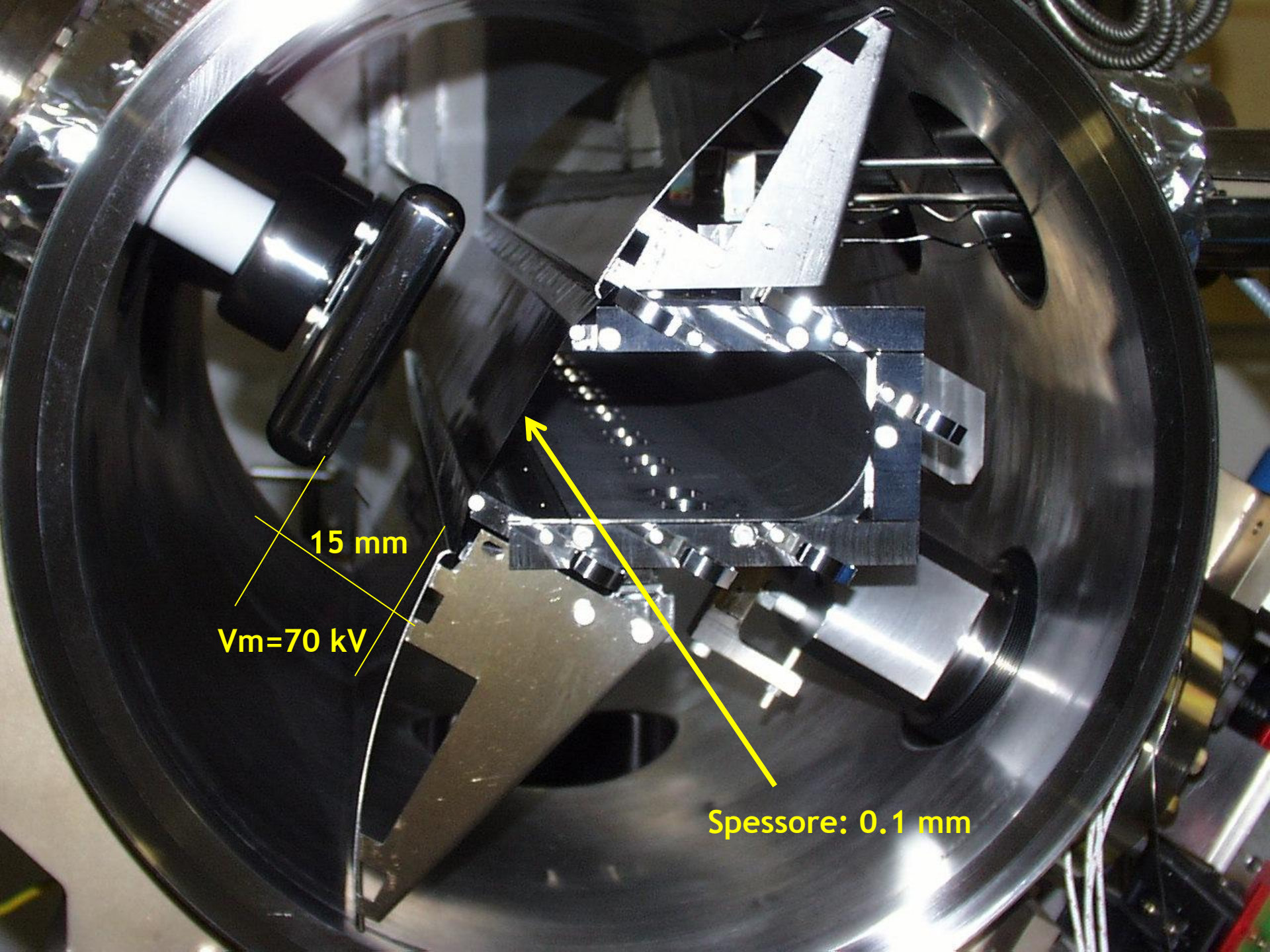
**Setto elettrostatico sottile per ridurre perdite di fascio:
 $t = 0.1 \text{ mm}$**

$$\Delta R = \Delta A_{\text{last}} \cos \mathcal{G} = \frac{3}{4} |S| \frac{1}{\cos \mathcal{G}} X_{ES}^2,$$

$$\Delta R' = \Delta A_{\text{last}} \sin \mathcal{G} = \frac{3}{4} |S| \frac{\tan \mathcal{G}}{\cos \mathcal{G}} X_{ES}^2.$$

Maximum Spiral step

Maximum Spiral pitch



15 mm
 $V_m = 70 \text{ kV}$

Spessore: 0.1 mm

Dal setto elettrostatico (ES) al setto magnetico (MS) per imboccare il canale di estrazione

L'angolo di deflessione del setto elettrostatico (2.5 mrad) crea la spaziatura per entrare nel setto magnetico di piccolo spessore (circa 2 cm)

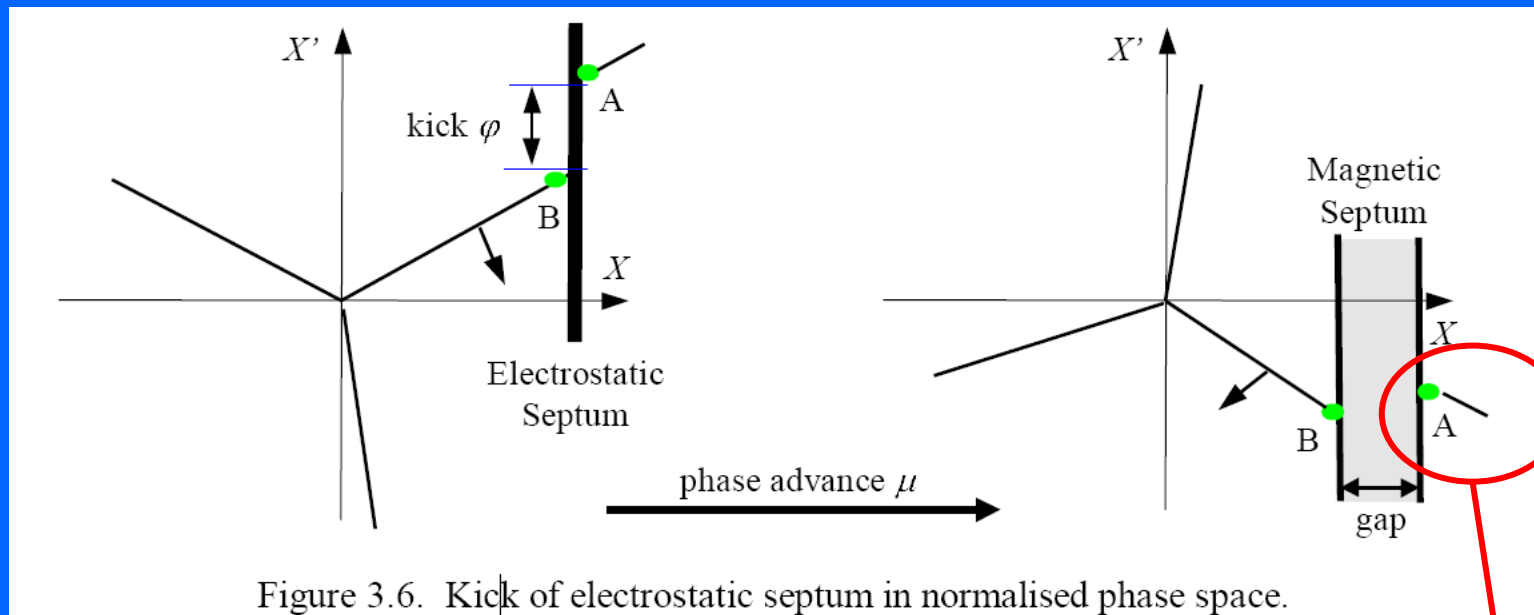
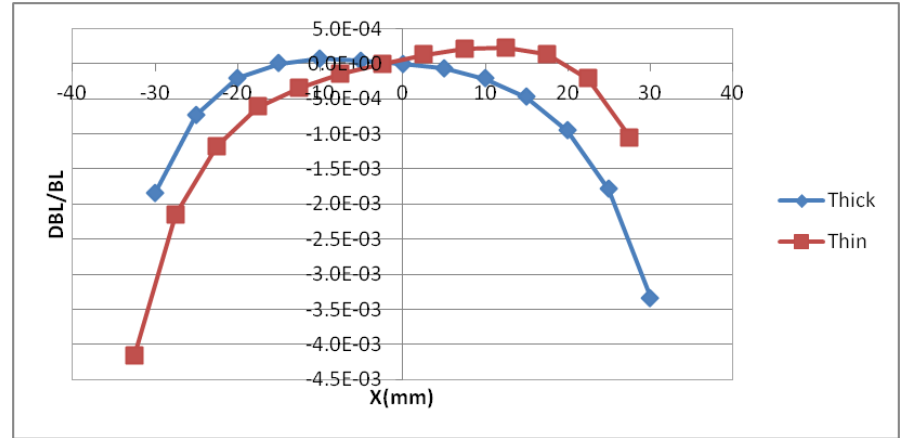
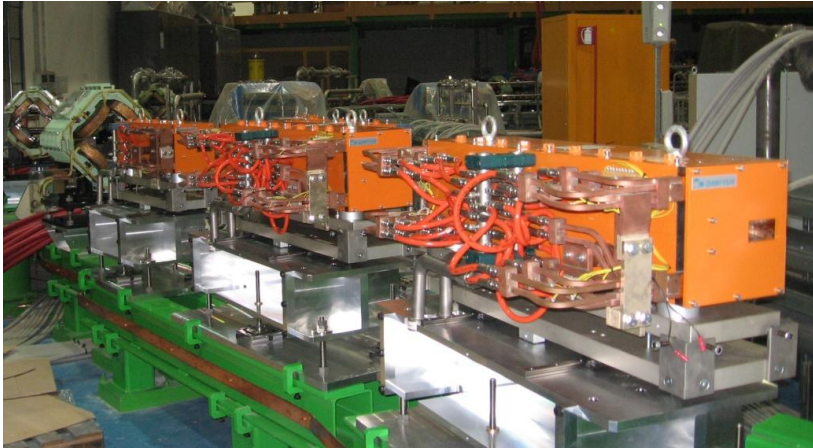


Figure 3.6. Kick of electrostatic septum in normalised phase space.

Avanzamento di fase ideale tra ES e MS: 90°
Ossia massima conversione di angolo in spostamento

Porzione di fascio estratta:
“barra di carica”

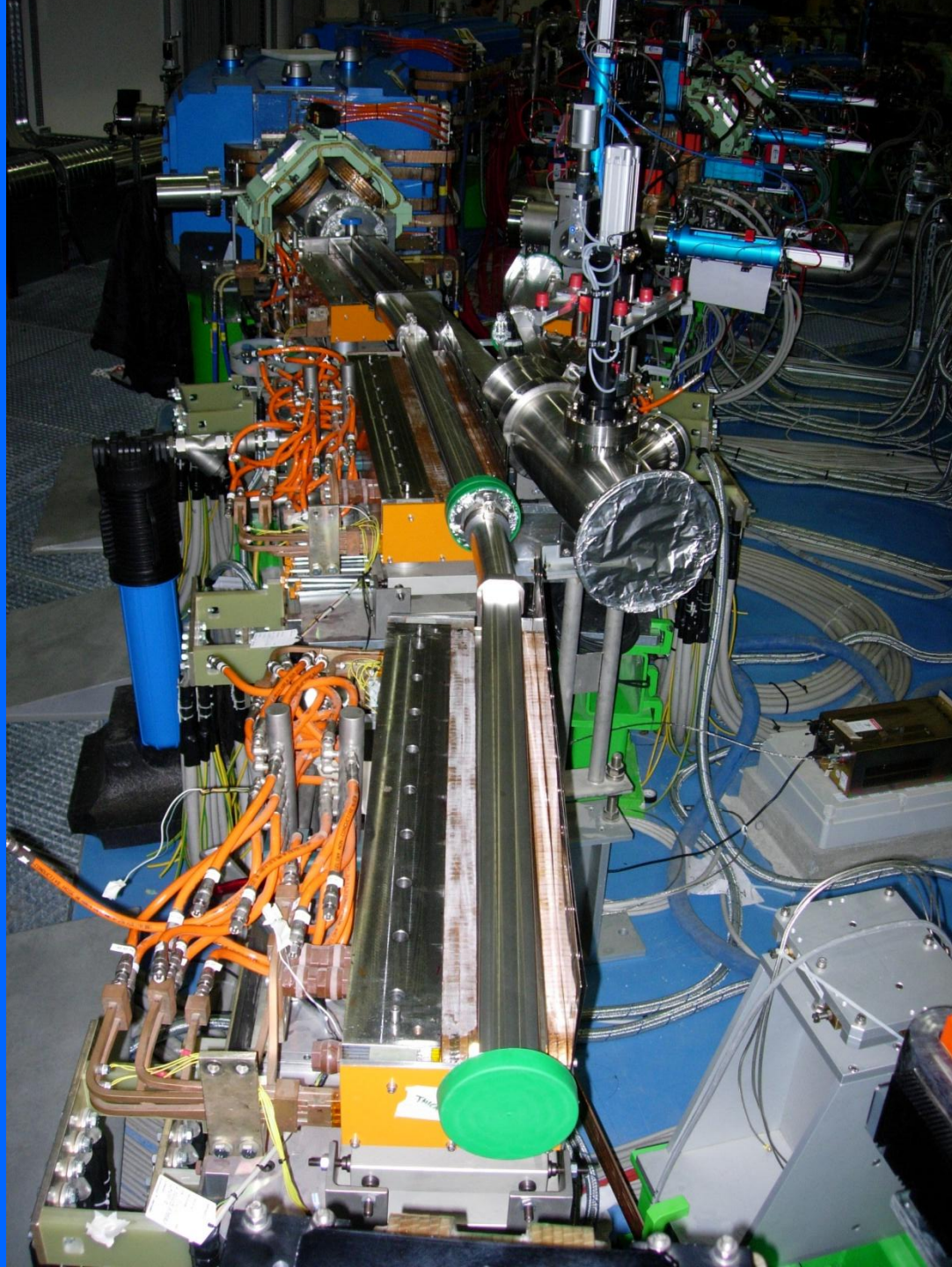
Extraction Septa: 2 Thick, 1 Thin



Measured Integrated Field Homogeneity at Nominal Current and $Y=0$

<i>Design parameter(Thin)</i>	<i>Units</i>	<i>Value</i>
Deflection angle	[mrad]	50
Gap aperture	[mm]	80 (hor) x 40 (vert)
Magnetic length	[m]	0.650
Resistance	[mΩ]	0.89
Inductance	[μH]	29.6
Cooling		Water
Nominal Current	[A]	3881
Nominal field	[T]	0.488
Good field region	[mm]	31 (hor) x 26 (vert)
Field Quality	$\Delta BL/BL$	$\pm 1 \cdot 10^{-2}$

<i>Design parameter (Thick)</i>	<i>Units</i>	<i>Value</i>
Deflection angle	[mrad]	150
Gap aperture	[mm]	75 (hor) x 40 (vert)
Magnetic length	[m]	0.975
Resistance	[mΩ]	2.9
Inductance	[μH]	150
Cooling		Water
Nominal Current	[A]	3881
Nominal field	[T]	0.975
Good field region	[mm]	49 (hor) x 30 (vert)
Field Quality	$\Delta BL/BL$	$\pm 1 \cdot 10^{-2}$



Extraction setup at CNAO

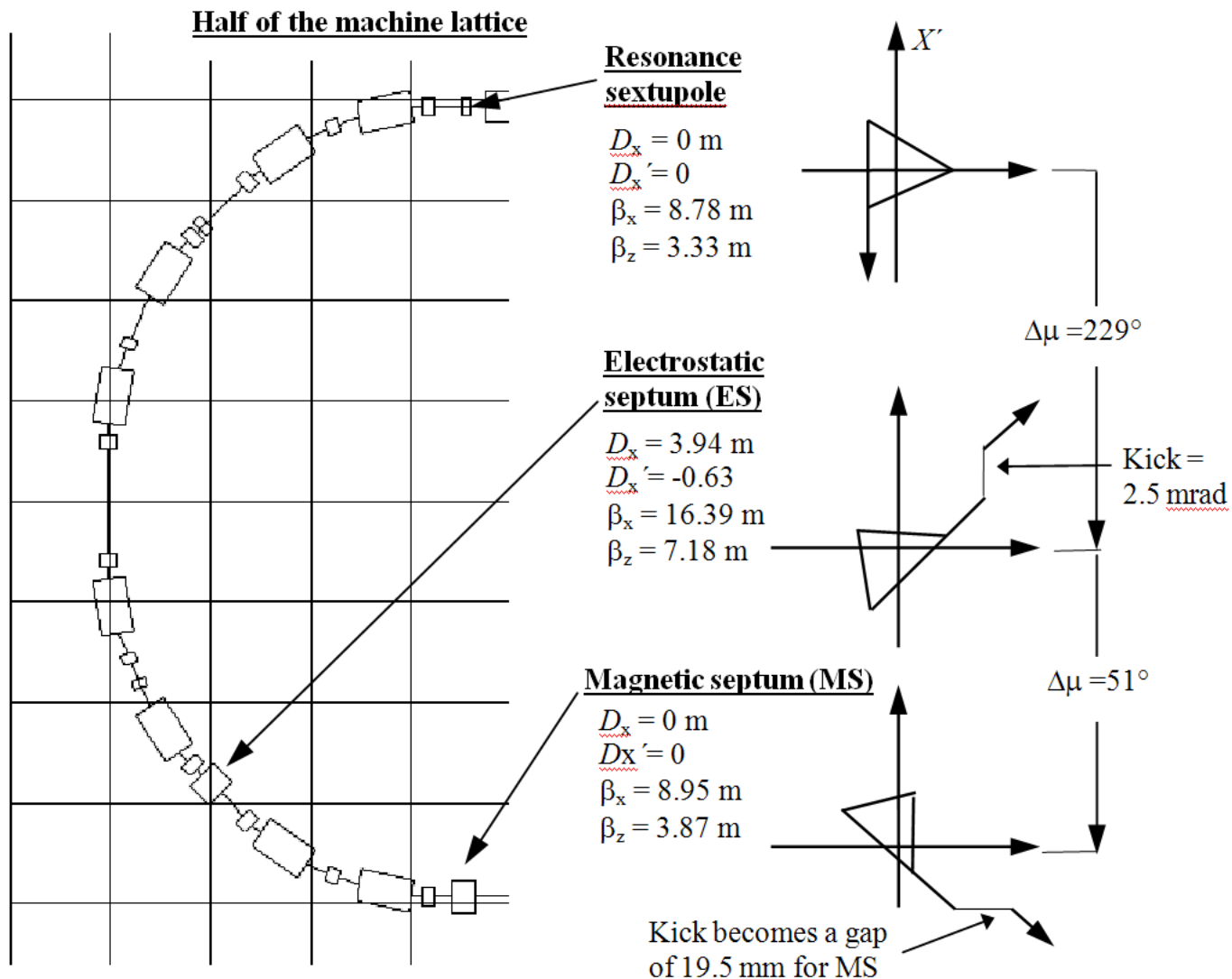
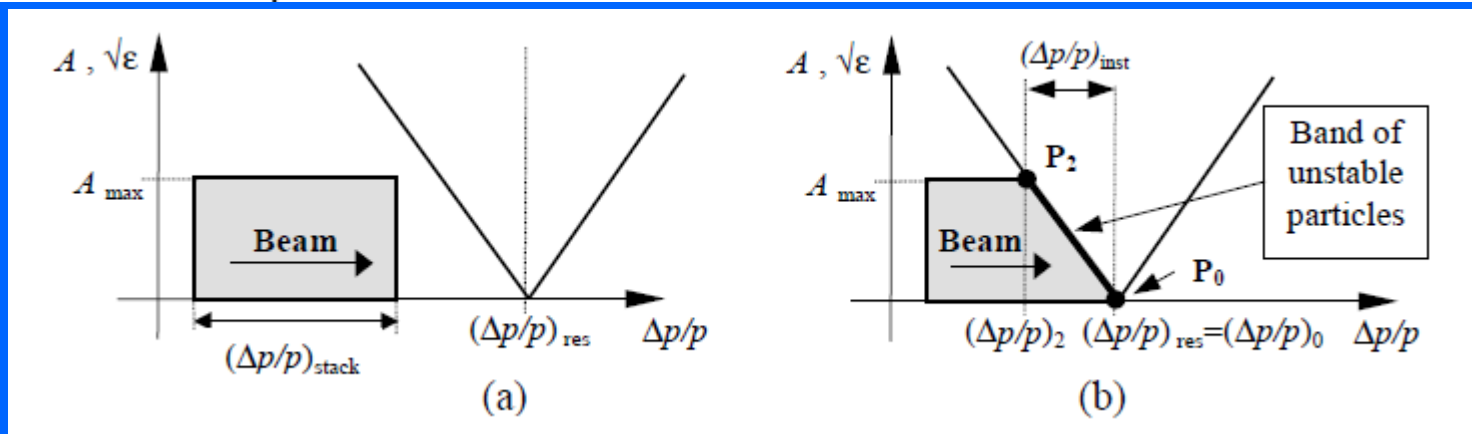
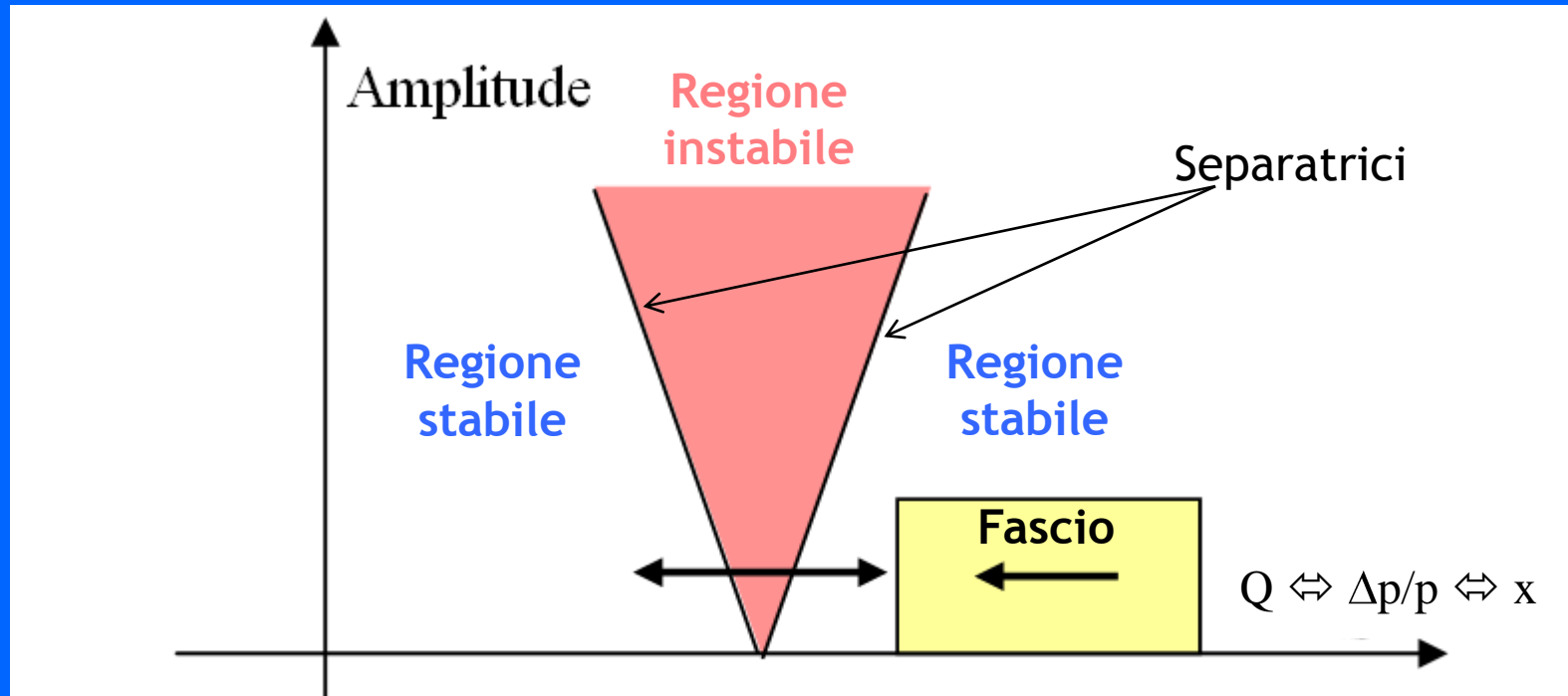


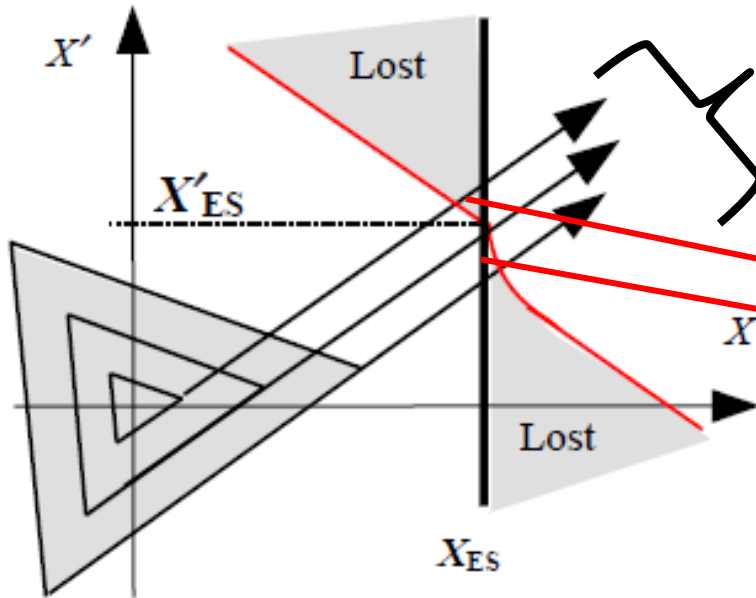
Figure 3 Extraction configuration

Come “spingere” il fascio nella risonanza: il diagramma di Steinbach

In questo spazio i lati del triangolo diventano linee di risonanza, confini tra regione instabile e regione stabile.

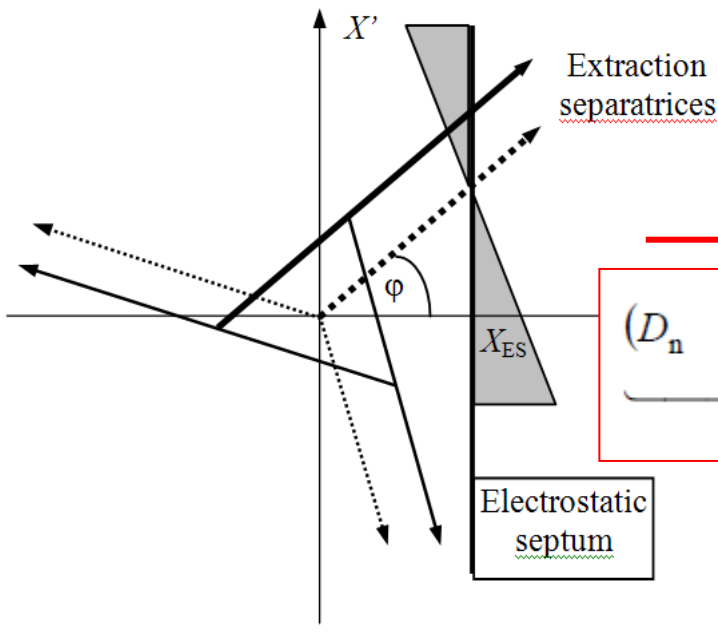


Ridurre le perdite di fascio all'estrazione: la condizione di Hardt



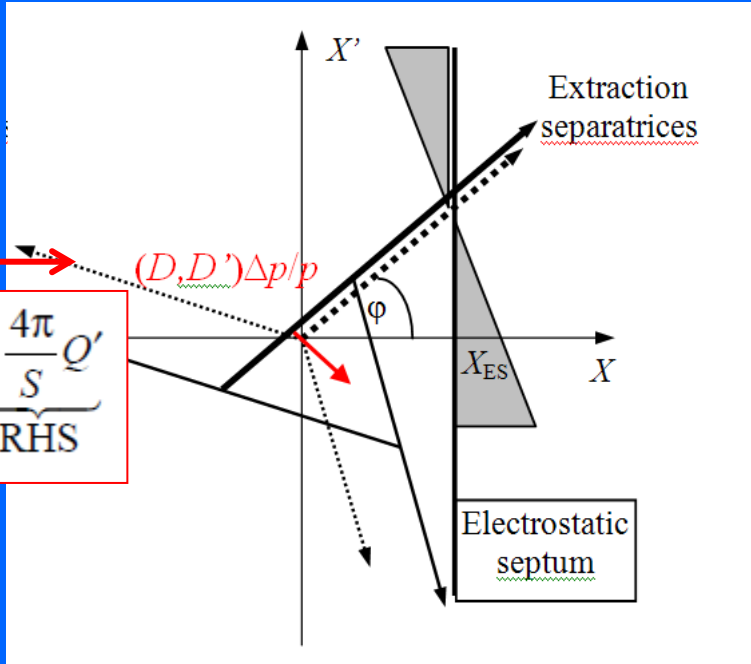
Separatrici non allineate

Perdite di fascio sulle pareti del setto elettrostatico



HARDT

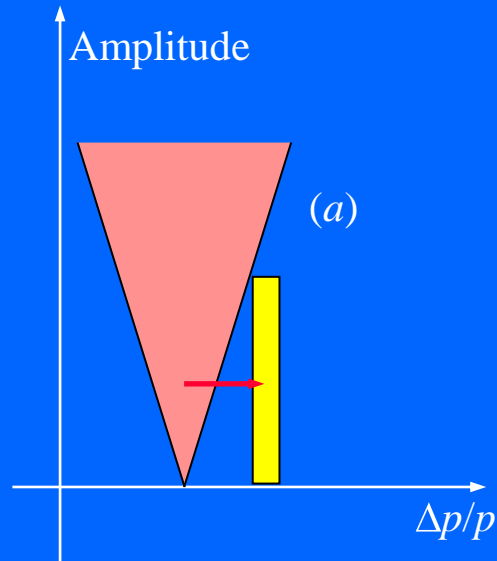
$$\underbrace{(D_n \quad D'_n)}_{\text{LHS}} \begin{pmatrix} \cos(\alpha - \Delta\mu) \\ \sin(\alpha - \Delta\mu) \end{pmatrix} = \underbrace{-\frac{4\pi}{S} Q'}_{\text{RHS}}$$



$(D, D')\Delta p/p$

Schemi a confronto

Amplitude selection

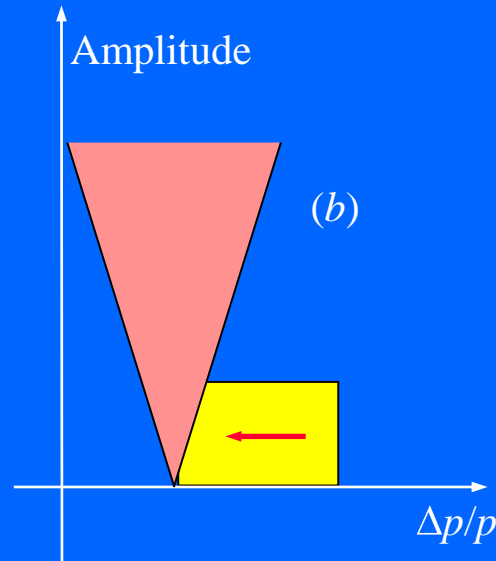


Separatrici e spiral step variano durante l'estrazione.

No Hardt condition.

Strip: alta sensibilità al ripple.

Amplitude-momentum selection

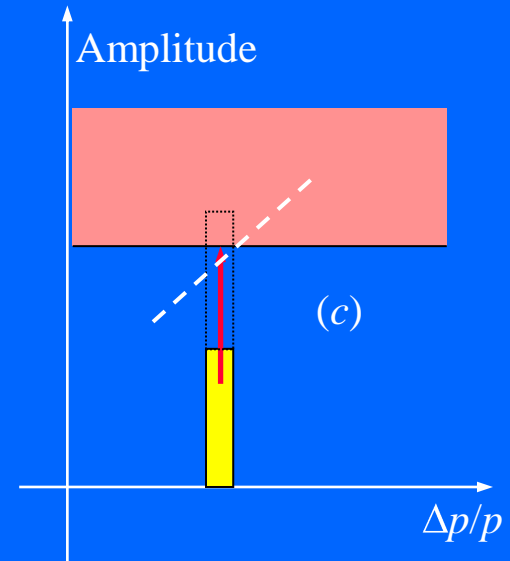


Separatrici e spiral step costanti durante l'estrazione.

Hardt condition possibile.

Banda: sensibilità ridotta al ripple.

RF-KO



Separatrici e spiral step costanti durante l'estrazione.

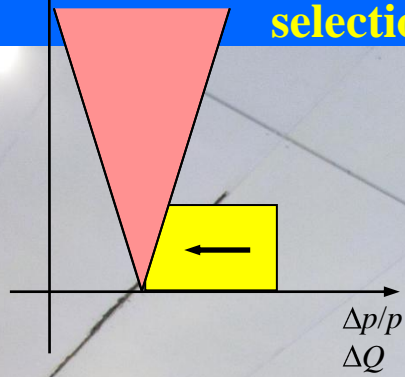
Hardt condition possibile.

Strip: alta sensibilità al ripple.

Amplitude

Amplitude-momentum selection

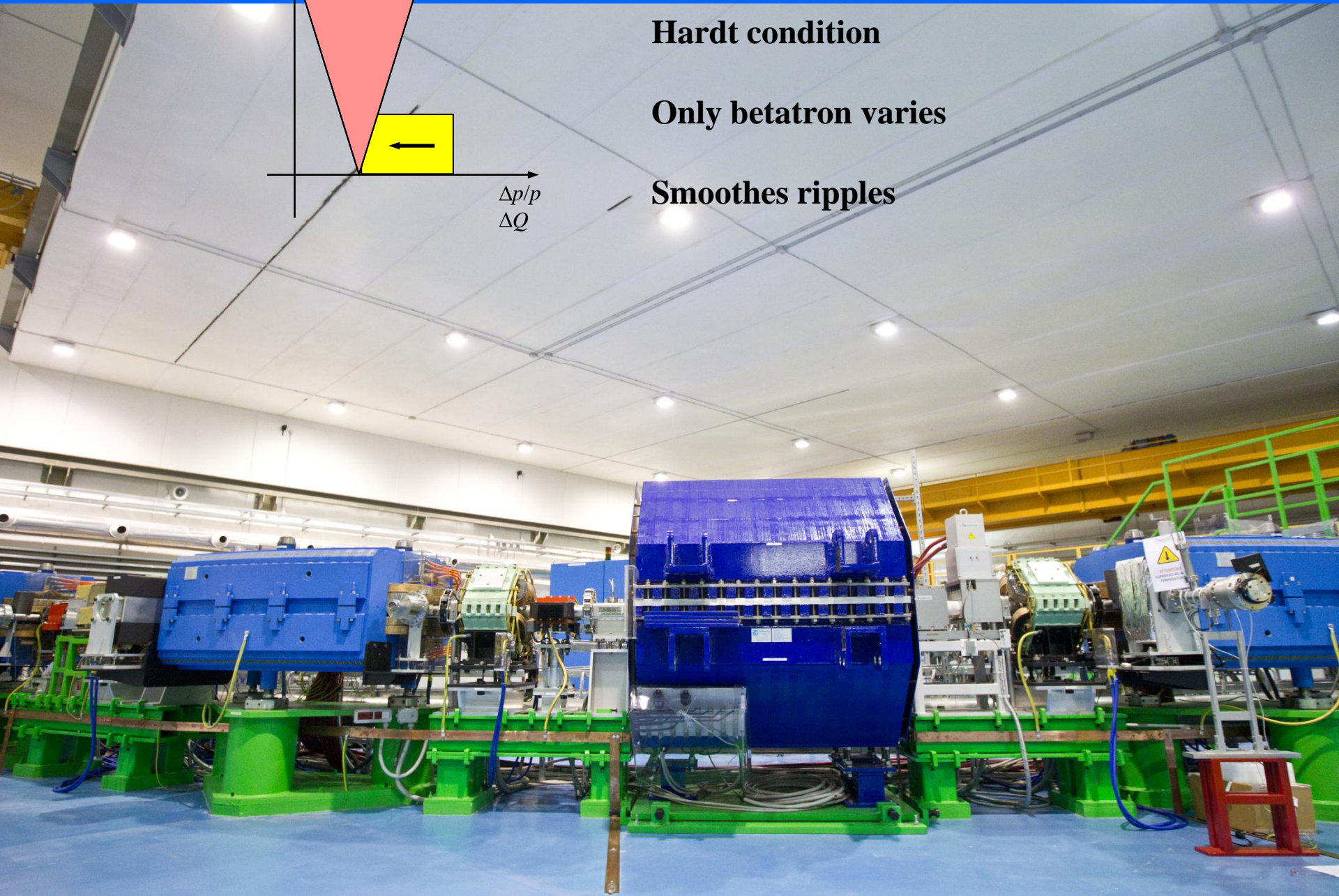
The betatron core



Hardt condition

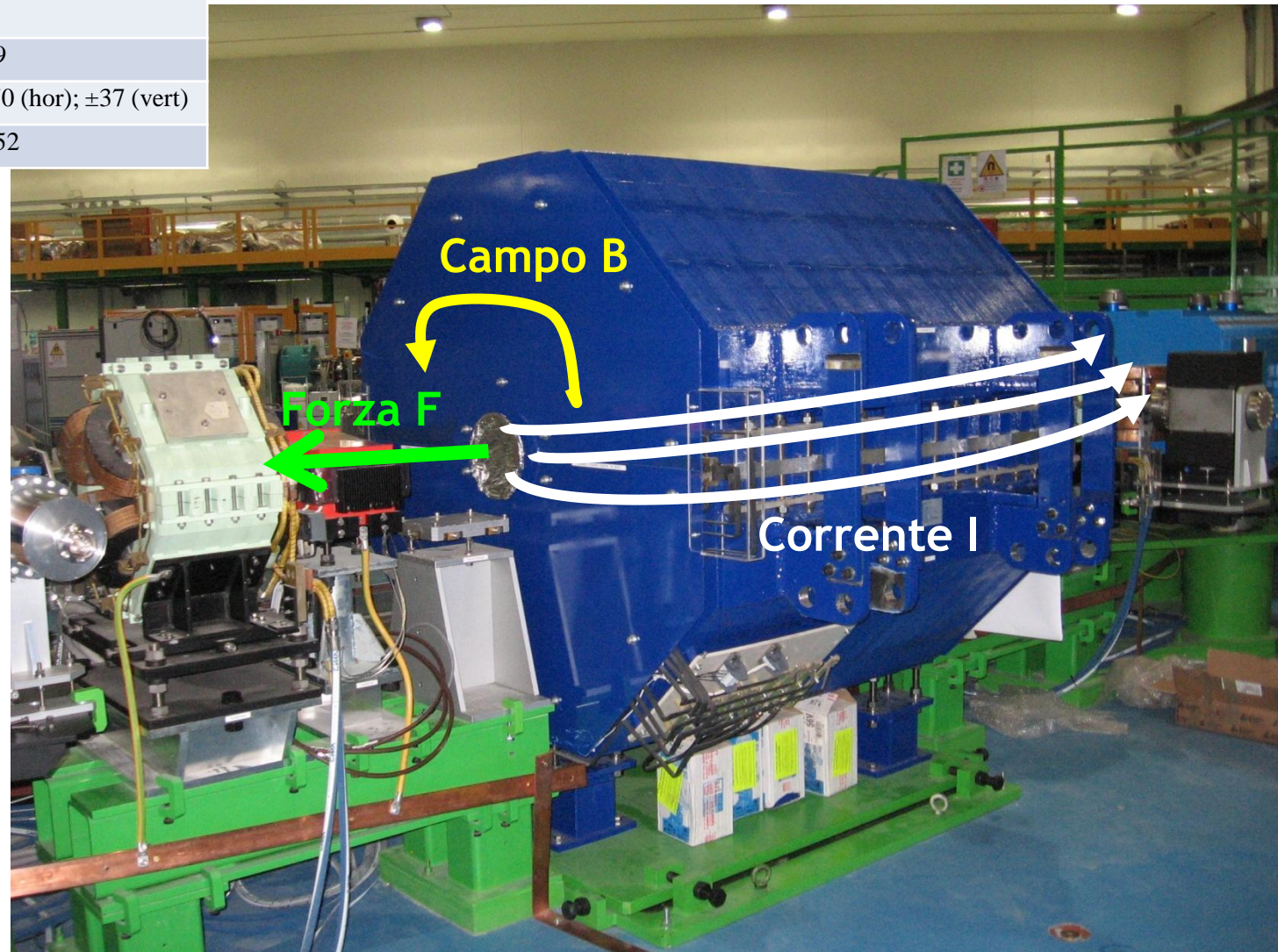
Only betatron varies

Smooths ripples



Betatron Core

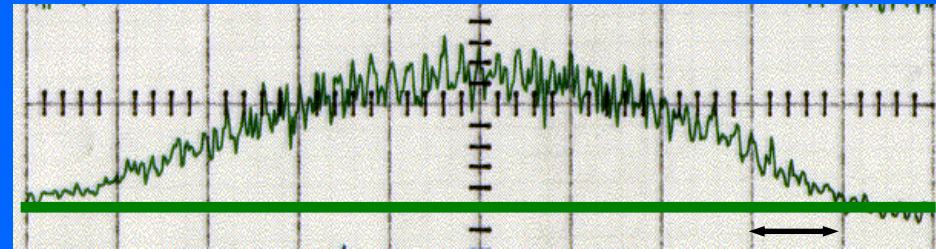
Design parameter	Units	Value
Weight	[tons]	25.3
Length	[m]	1.56
Resistance	[m Ω]	43.5
Fringe Field in GFR	[T]	$<1.0 \cdot 10^{-4}$
Cooling		Air
Nominal Current	[A]	70
Flux Across Core	[Wb]	2.9
Good field region	[mm]	± 70 (hor); ± 37 (vert)
Field in the core	[T]	1.52



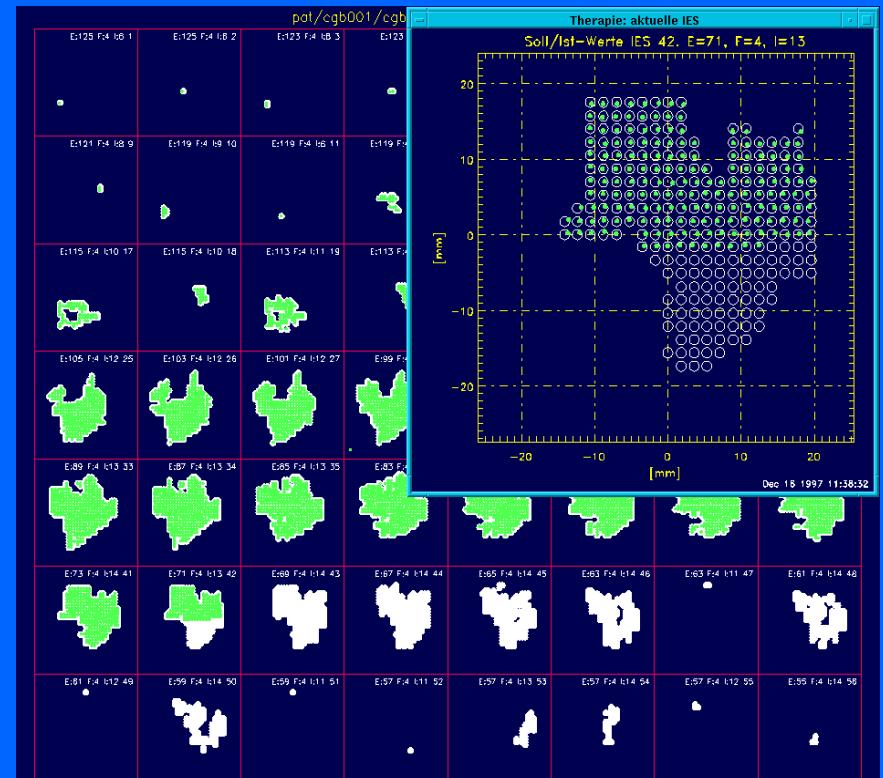
Betrone spinge il fascio nella risonanza



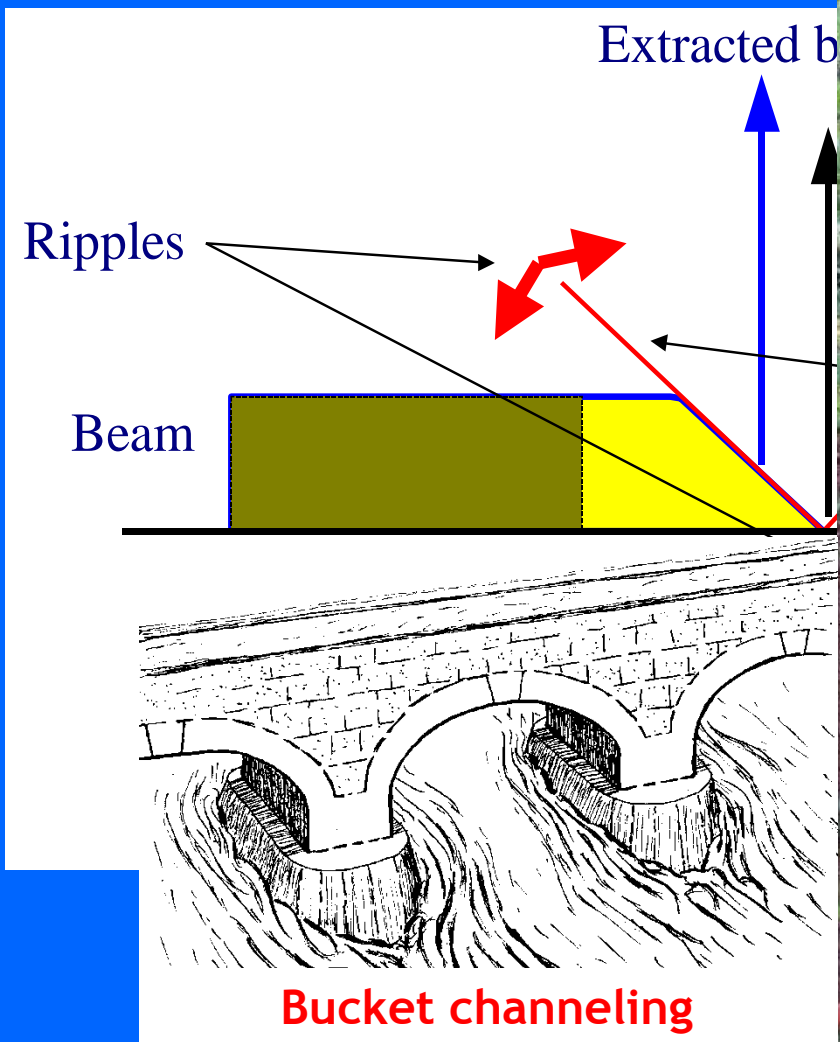
Intensity ripple ($\Delta I/I$) $\leq \pm 20\%$ at 2 kHz
(extraction with a betatron core - PIMMS)



50 ms

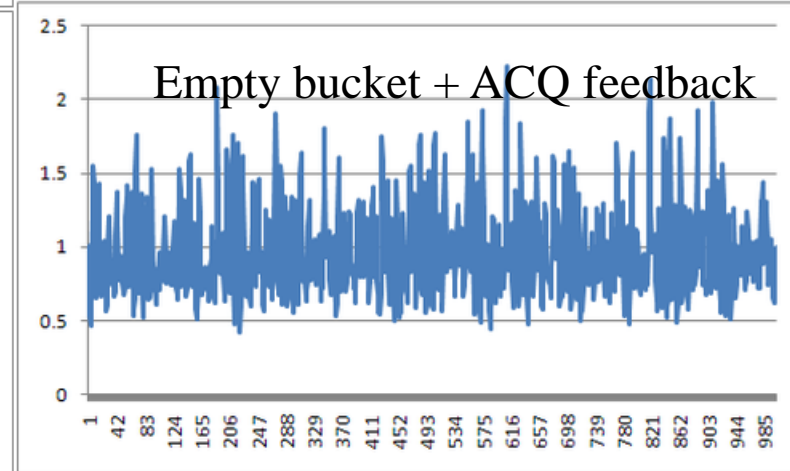
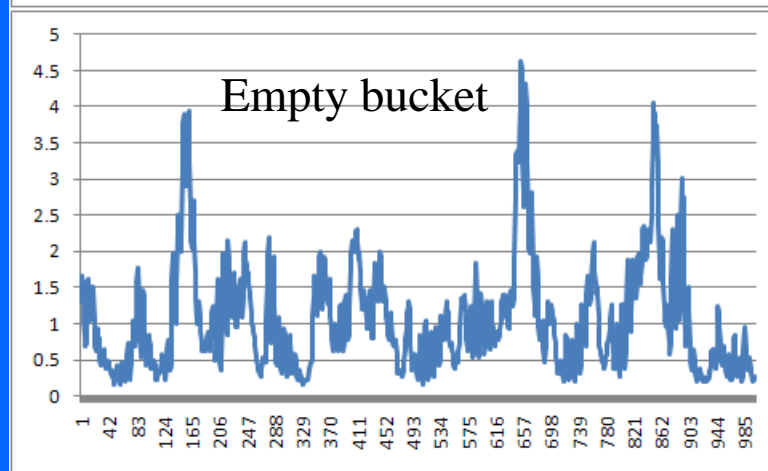
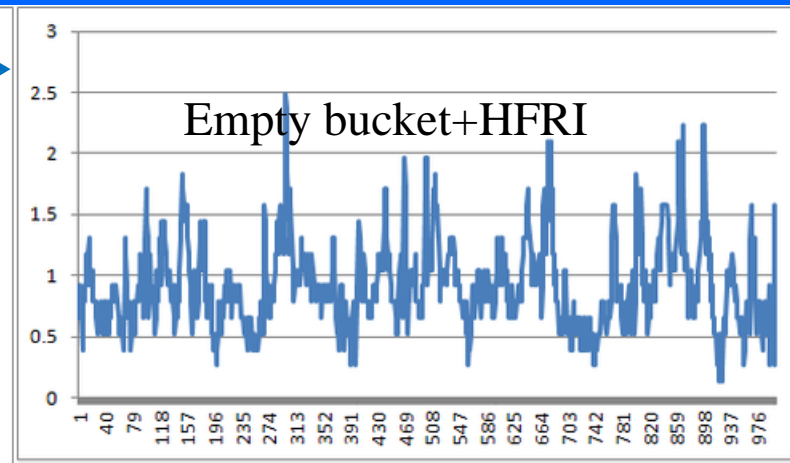
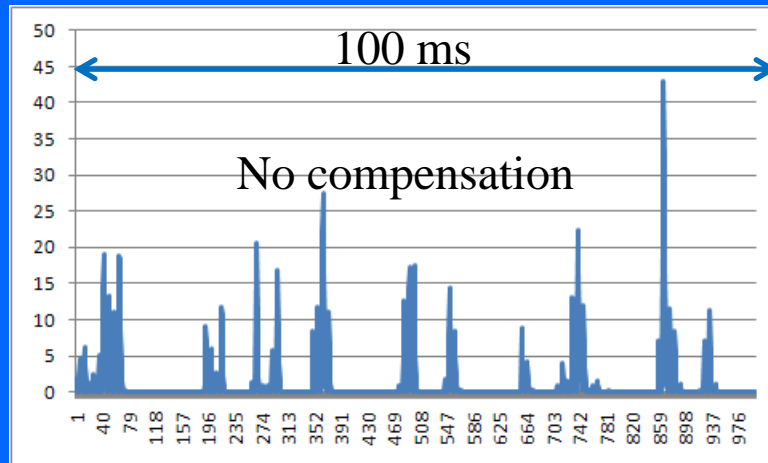


Empty bucket: come rendere estrazione insensibile al ripple

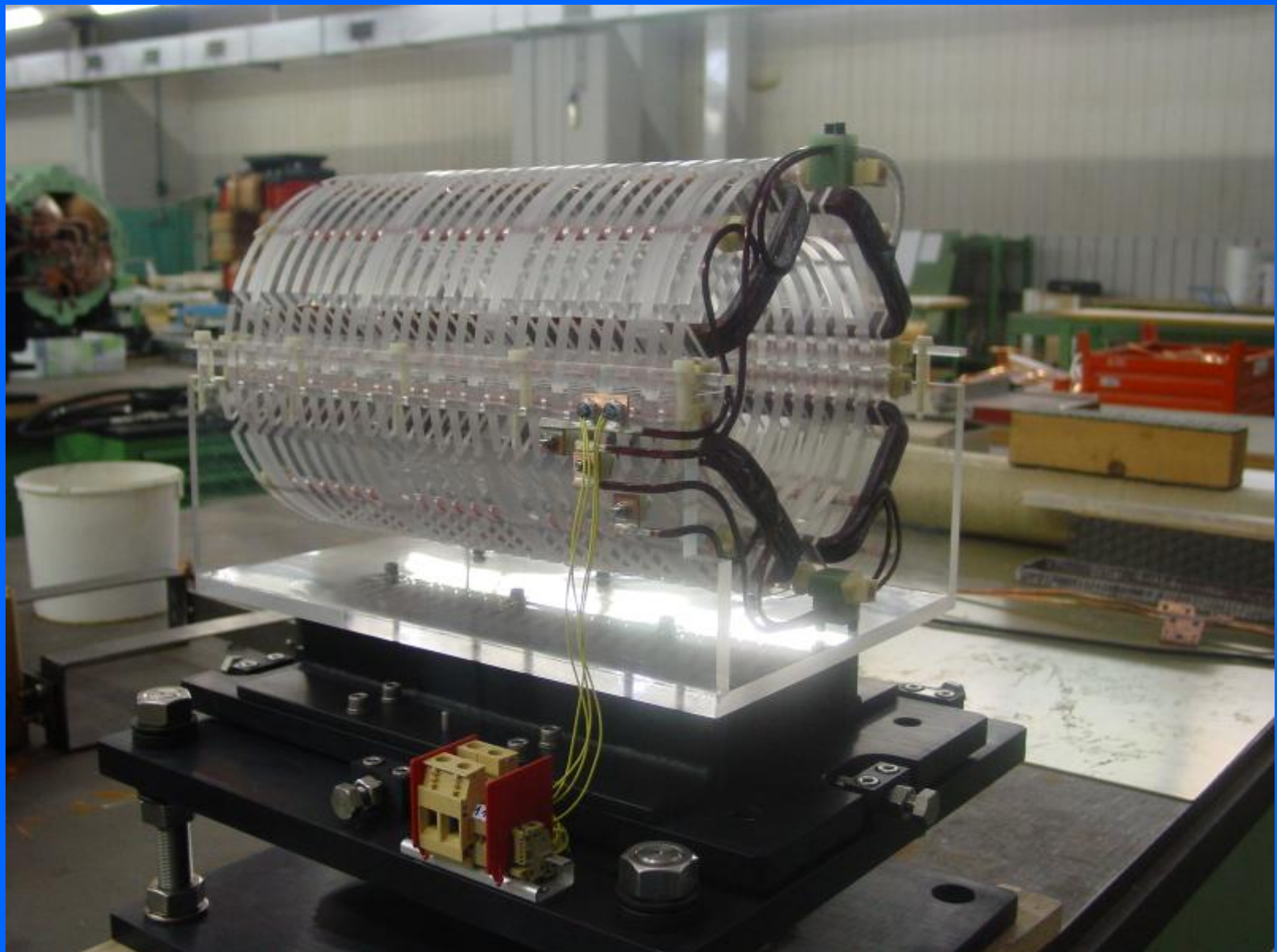


Metodi per compensare il ripple

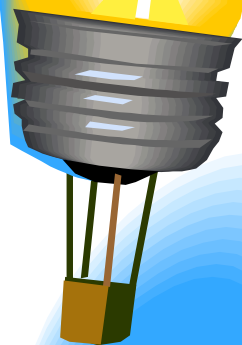
Sampling frequency 10 kHz



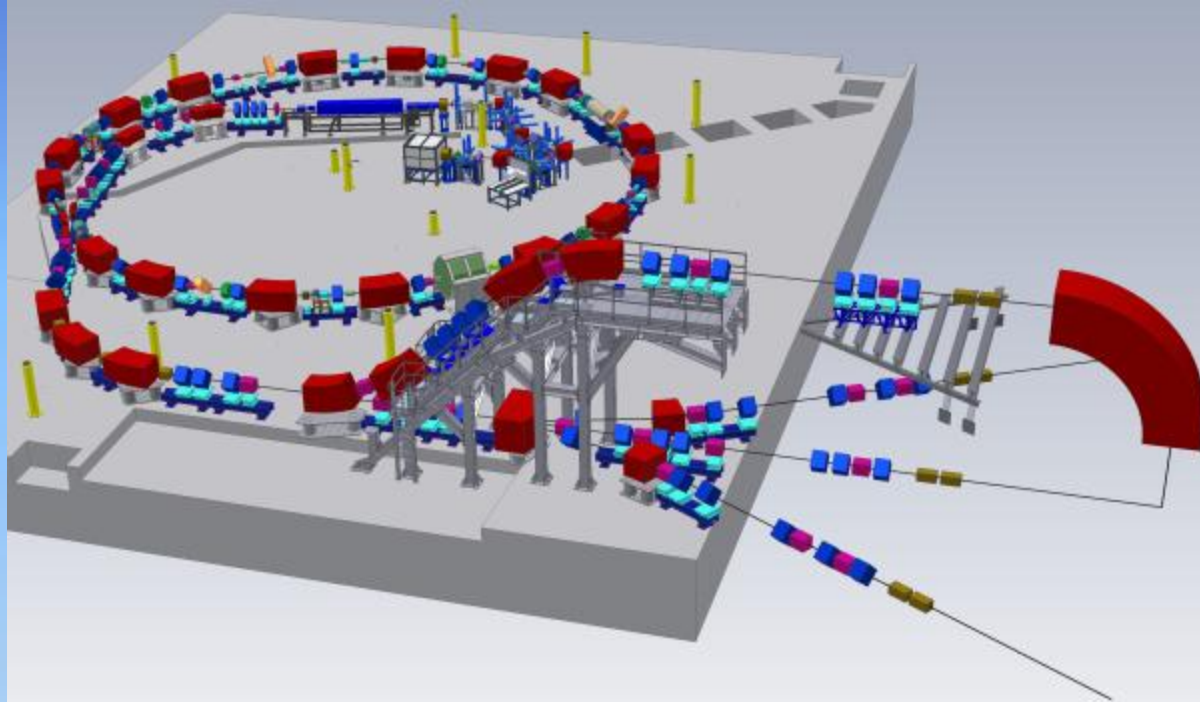
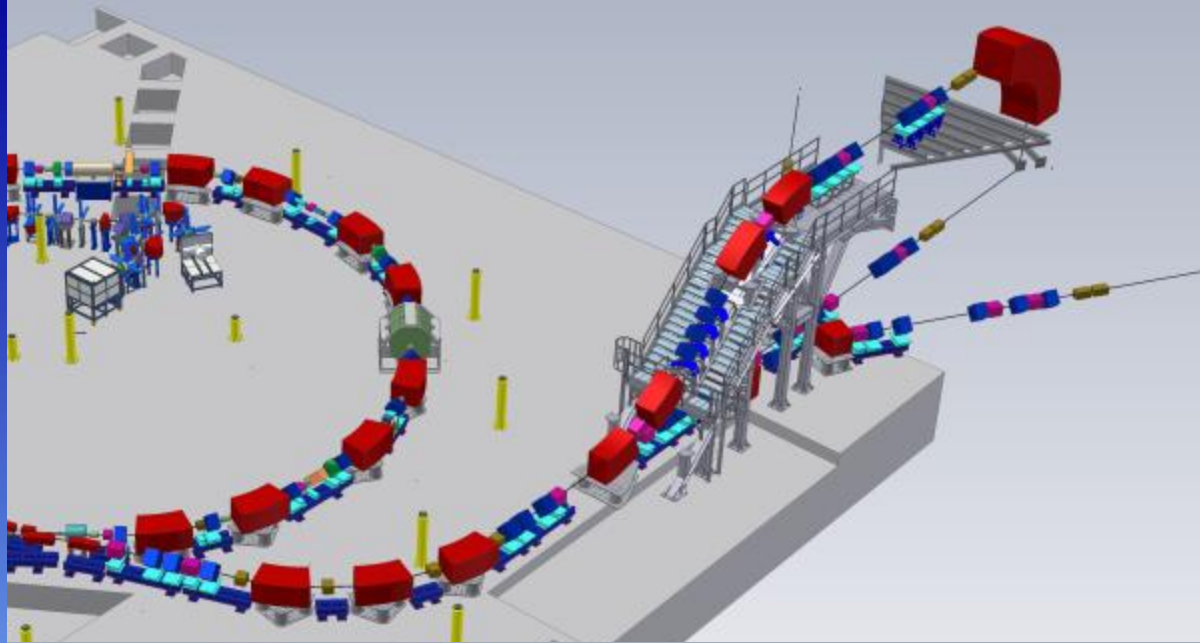
*Quadrupolo ad "aria"
per compensare il ripple*



***Viaggio
alla scoperta
del CNAO***



Le linee di estrazione
HEBT



HEBT

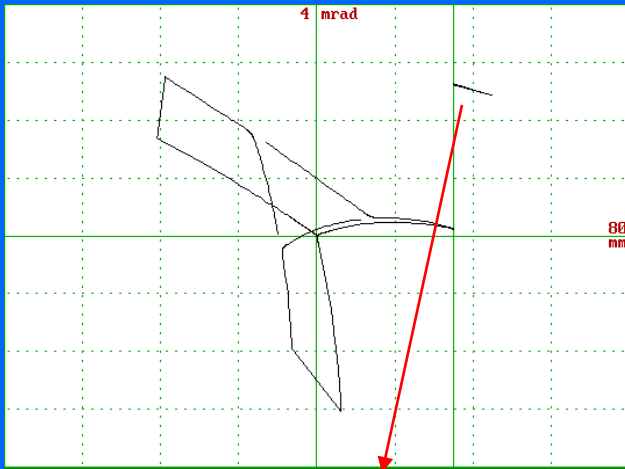
60-250 MeV p
120-400 MeV/u C

10^{10} p/spill (~ 2 nA)
 $4 \cdot 10^8$ C/spill (~ 0.4 nA)

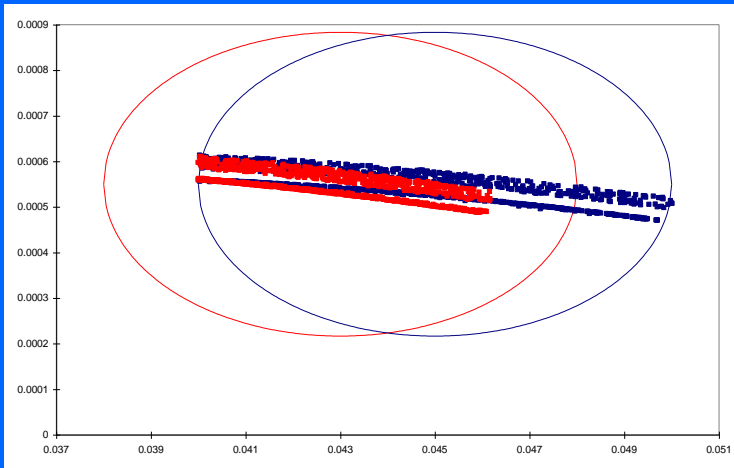
different settings for

- Treatment Line
- Horizontal beam size
- Vertical beam size
- Extraction energy

Extracted beam



Twiss functions at entry (ES in ring)		
$\beta_x = 5 \text{ m}$	$\alpha_x = 0$	'Free' parameter.
$E_x = 5\pi \text{ mm mrad}$		'Unfilled' ellipse - 'free'.
$\beta_z = 7.16 \text{ m}$	$\alpha_z = -0.18$	Values from ring.
$E_{z,\text{RMS}} = 0.7324 \text{ to } 1.4286 \pi \text{ mm mrad}$ $E_{z,\text{RMS}} = 0.6679 \text{ to } 1.4286 \pi \text{ mm mrad}$		Carbon range from ring. Proton range from ring.
$D_x = 2.095 \text{ m}$	$D'_x = -0.0393$	Determined by extraction.
$D_z = 0$	$D'_z = 0$	



Twiss functions at exit (all beam exits)		
$\beta_x = 7.2 \text{ m}$	$\alpha_x = 0$	According to medical specifications and earlier choice of 'free' parameters.
$\beta_z = 2 \text{ to } 27 \text{ m}$	$\alpha_z = 0$	
$D_x = 0$	$D'_x = 0$	
$D_z = 0$	$D'_z = 0$	

Beam at HEBT entrance

Instance [System1:H2-009B-SFH] - Running User [user]

Standard Tools

Official Name: H2-009B-SFH v 2.0.0

Lock | Unlock

CNAO-LV1-05_user_VI

Inhibit

Cycle Prog: 5754904

Cycle Code: 00002C0002880E11

ErrorCode: 0

ErrorString:

Actuator Settings

SetActuator | In/Out Status: In

Calibration

SetCalib. | Calib. In Progress

Max: 1 n | Current: 0 n

Istant [ms]: 200 | Export

Acquisition Settings

SetAcq.Par.

Start Event: Start Betatron | Exposure Time: 20 ms

Start Delay: 0 ms | Gain: 0.00

Number Images: 40 | Rate: 20.000 Hz

Information

Serial Number: 460231-0

Camera Status: 1

Saturation:

ONESHOT

START | STOP

Advanced...

X Graph

XCenter	XCenter Rms	Integral
3 mm	4 mm	758209.110
XCenter Avg	XCenter Avg Rms	Tot. Integral
6 mm	2 mm	13352739.307

Y Graph

YCenter	YCenter Rms	Integral
0 mm	4 mm	845177.835
YCenter Avg	YCenter Avg Rms	Tot. Integral
0 mm	0 mm	14899675.347

Bar of charge

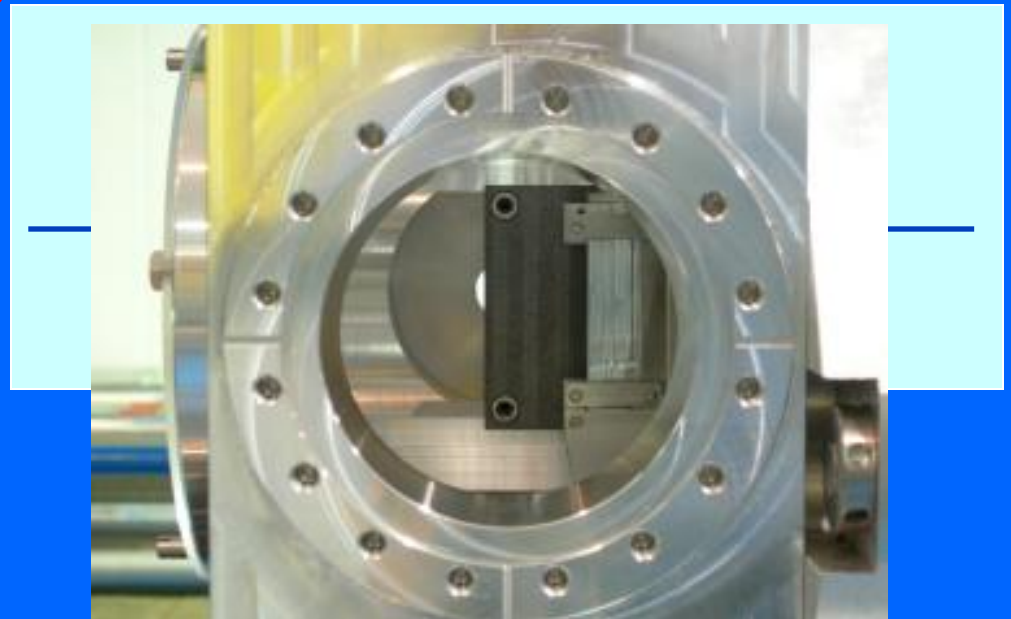
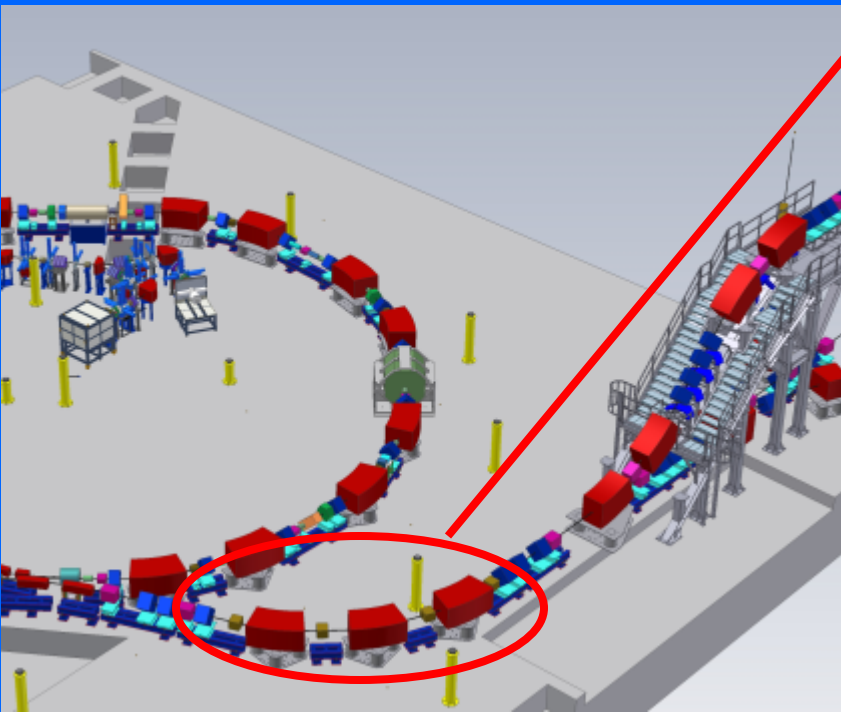
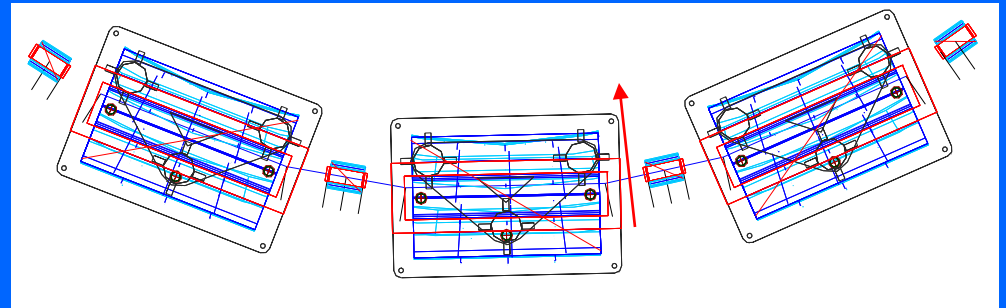


Chopper

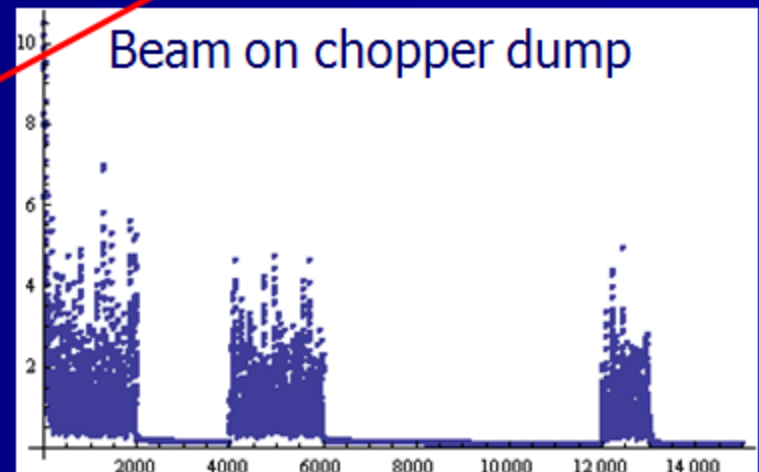
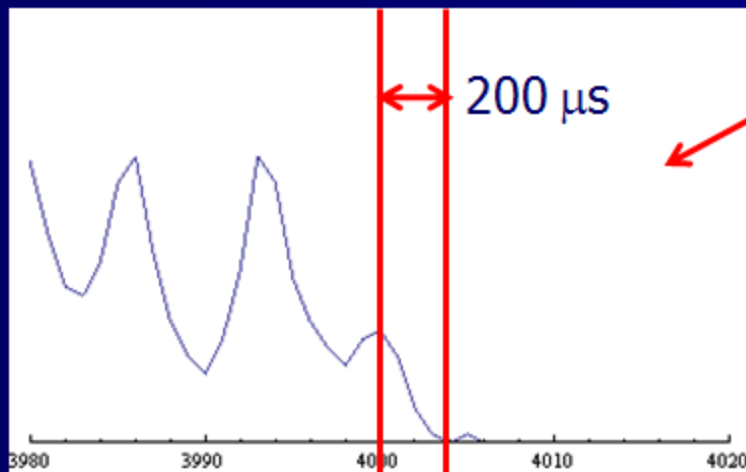
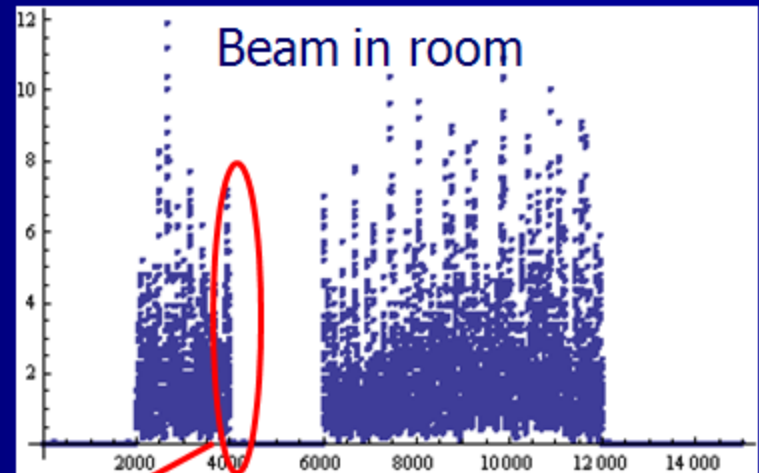
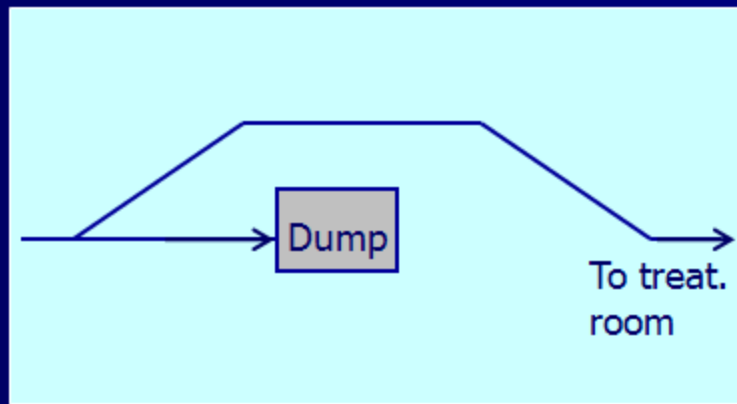
Fast turn on/off for the beam

Intrinsically safe

Allows beam qualification



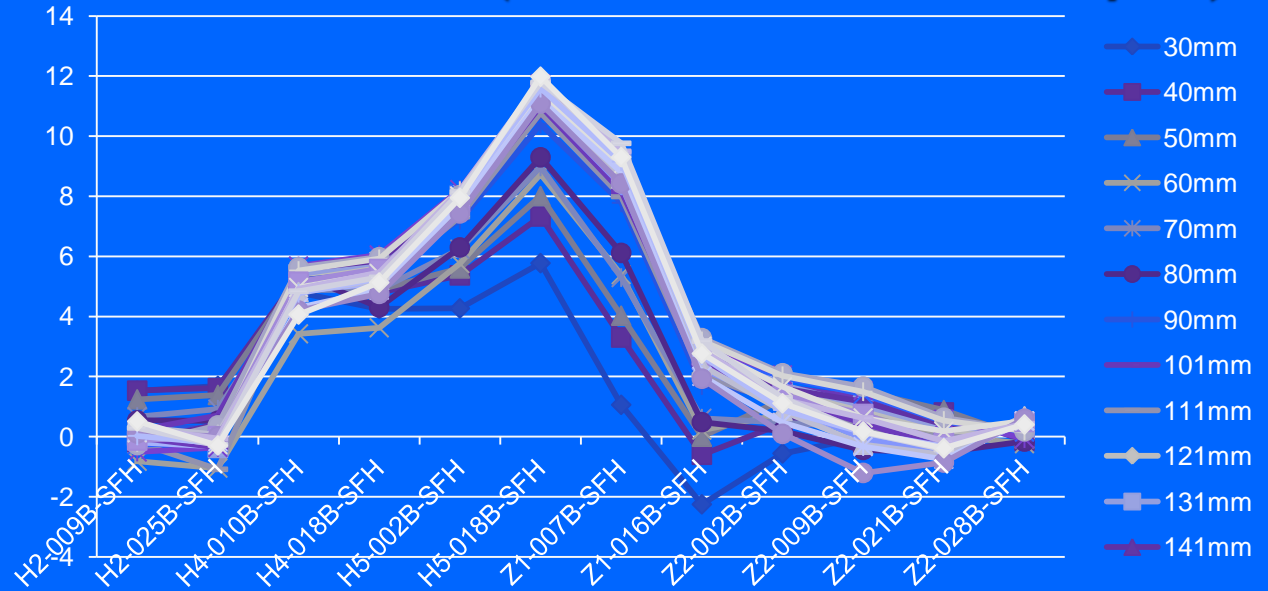
Chopped beam



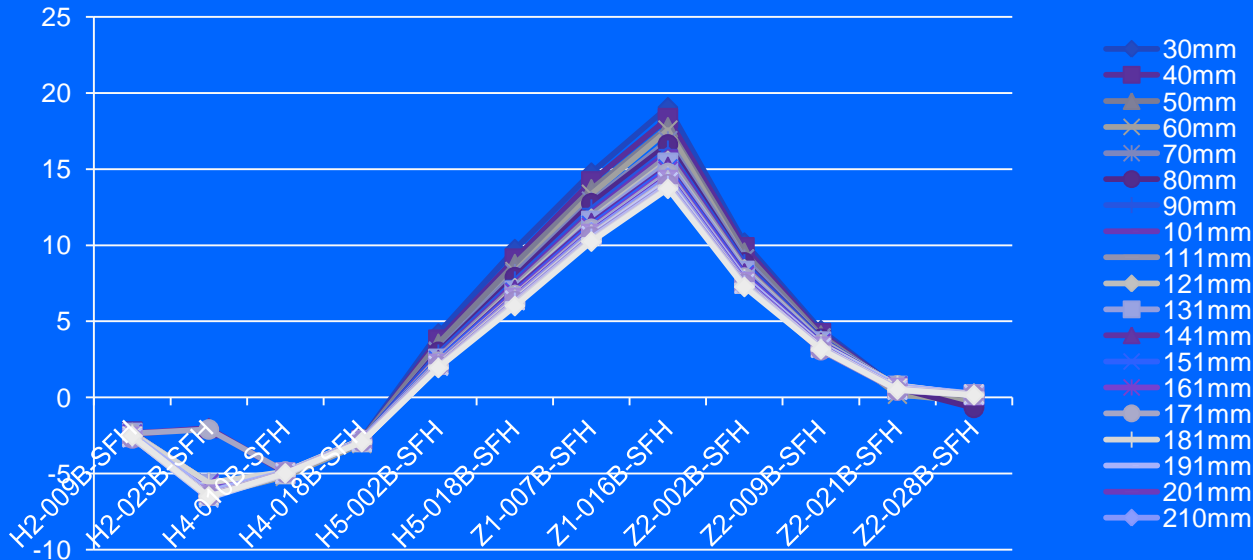
Acquisition frequency 10 kHz

P Trajectories along HEBT as a function of energy (measured in mm-depth)

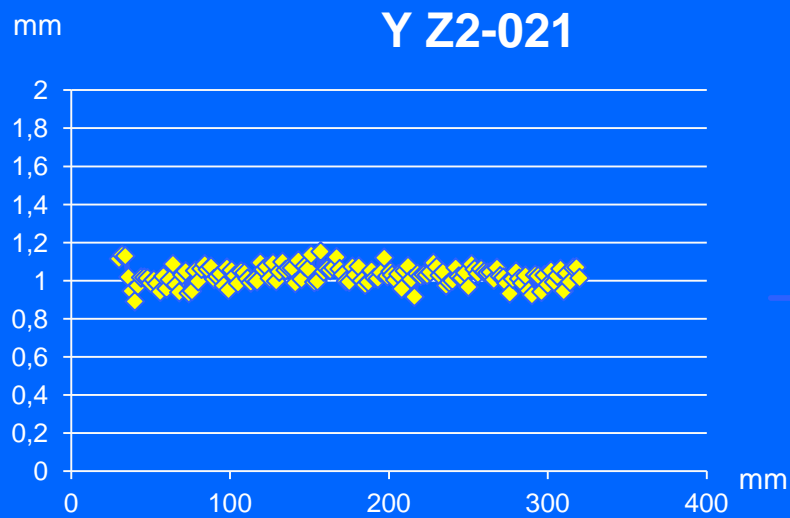
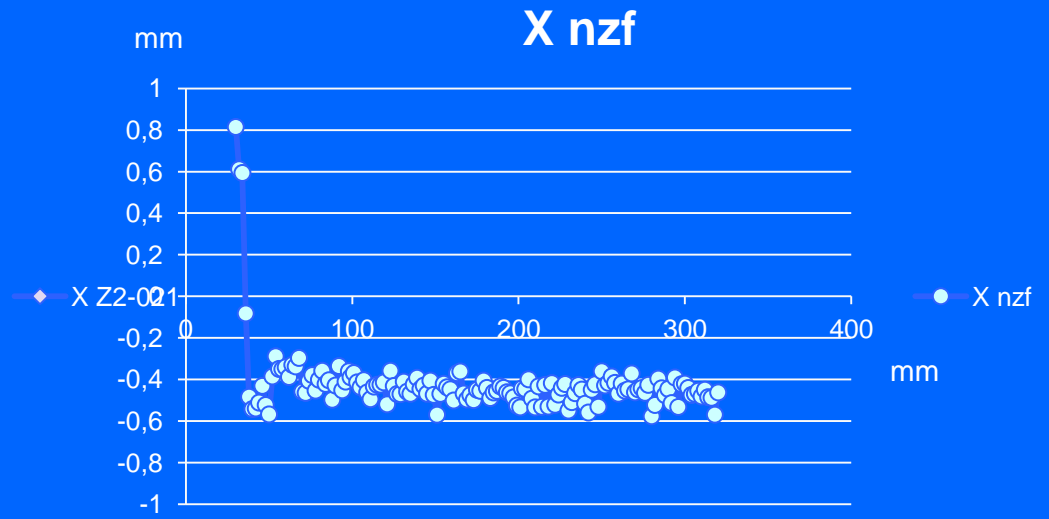
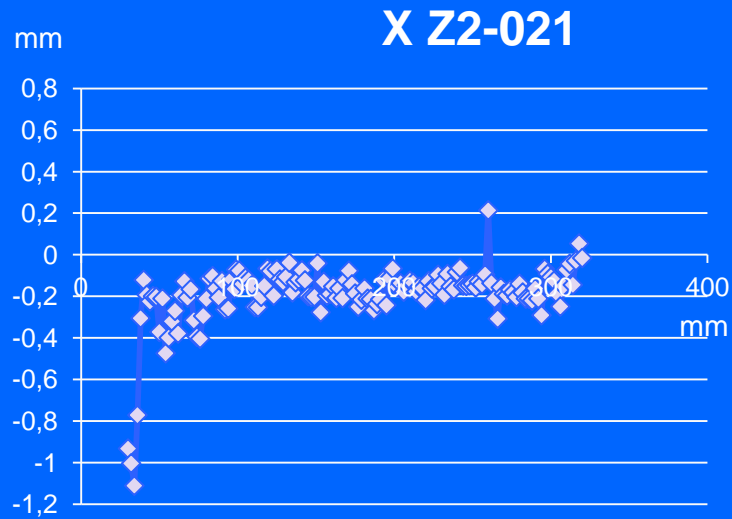
Horizontal



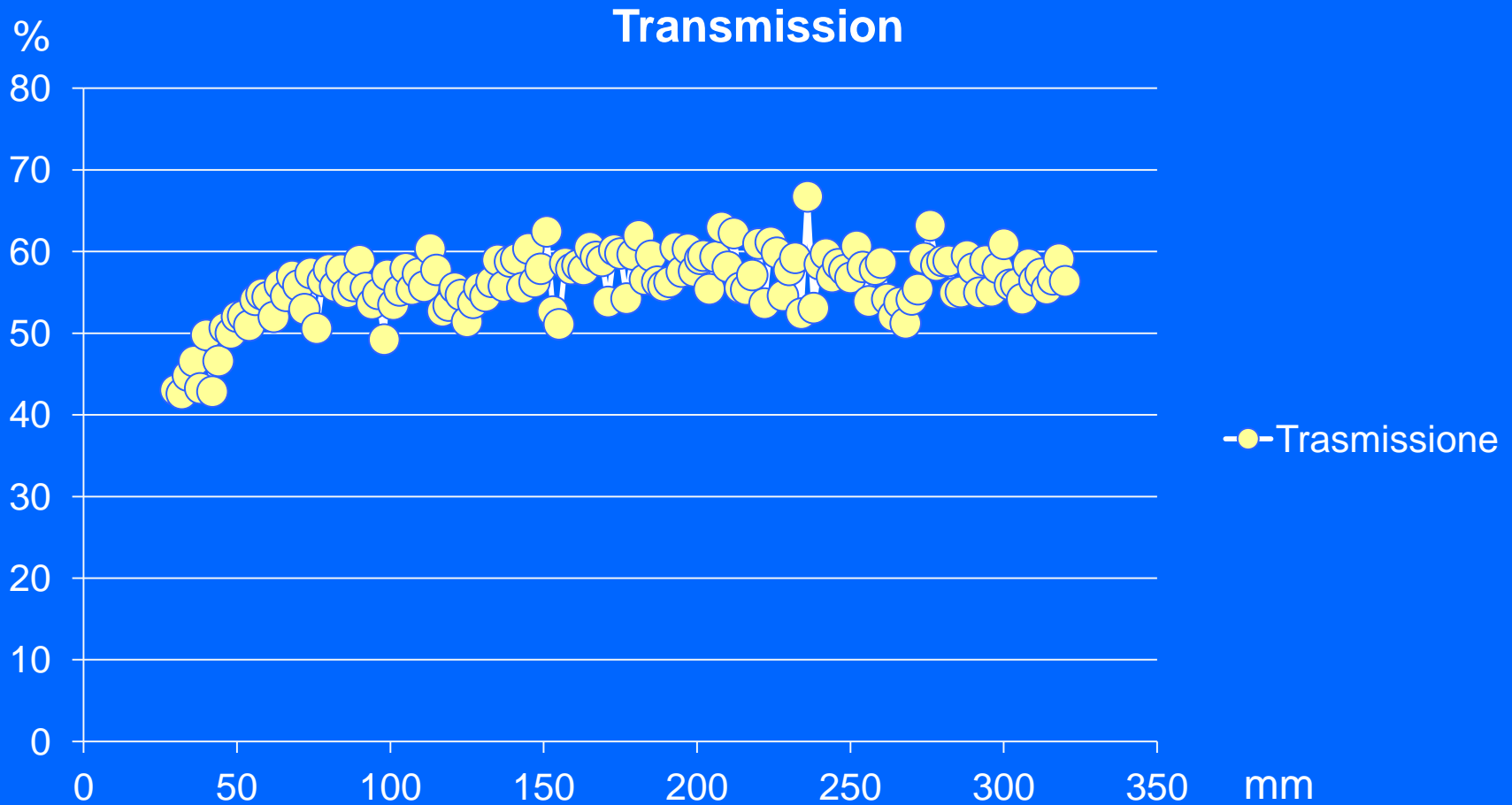
Vertical



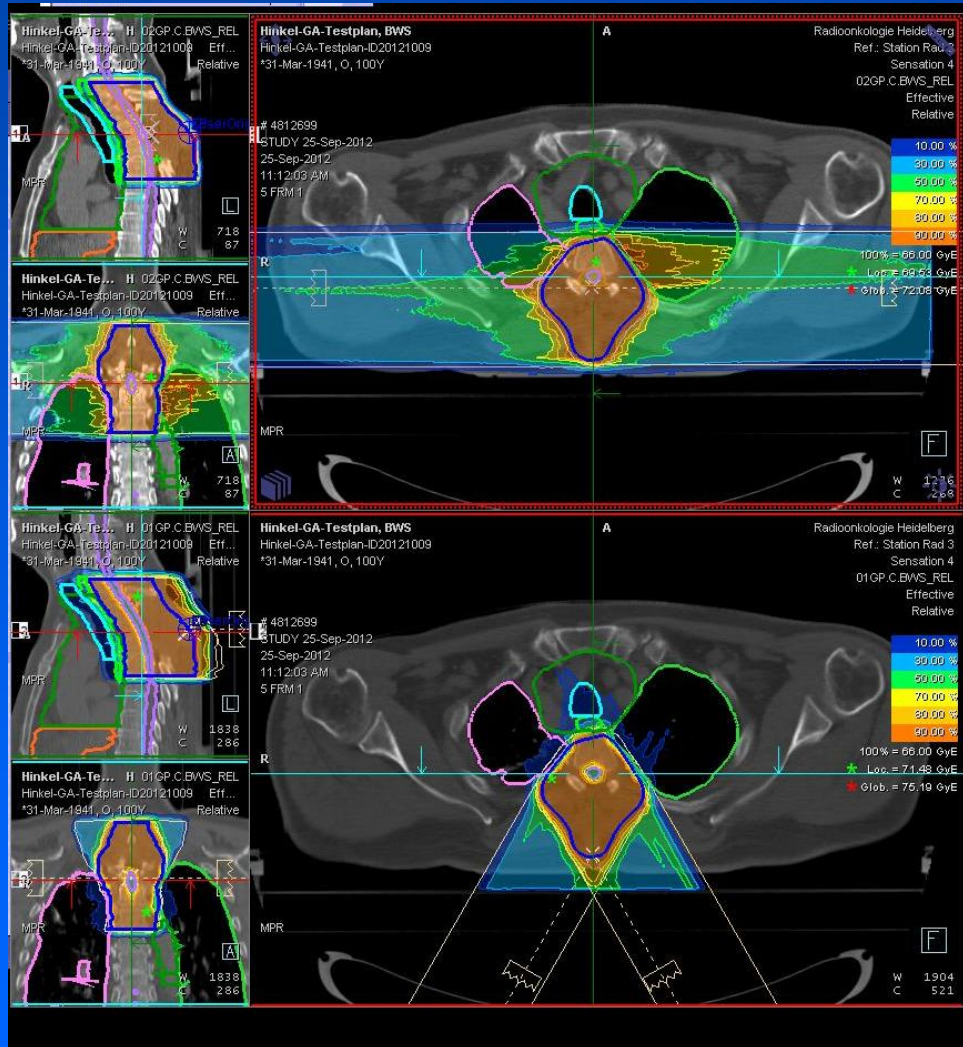
Beam (p) position in last monitor and nozzle as a function of the energy (after final steering)



Proton transmission from accelerated to isocenter as a function of the energy



Gantries / Challenges



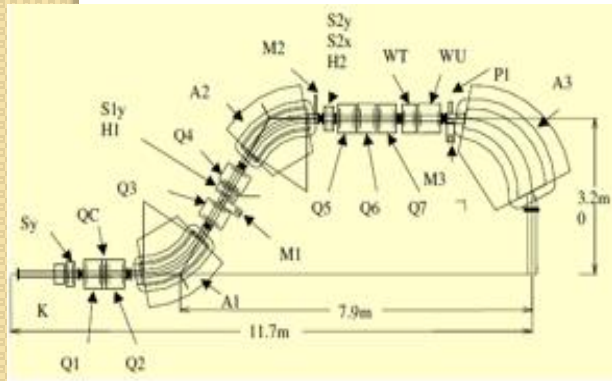
Fixbeam horizontal

**with Gantry:
relevant sparing of
Normal tissue**

(Courtesy of T. Haberer)

Comparison of dimensions

Conventional RT

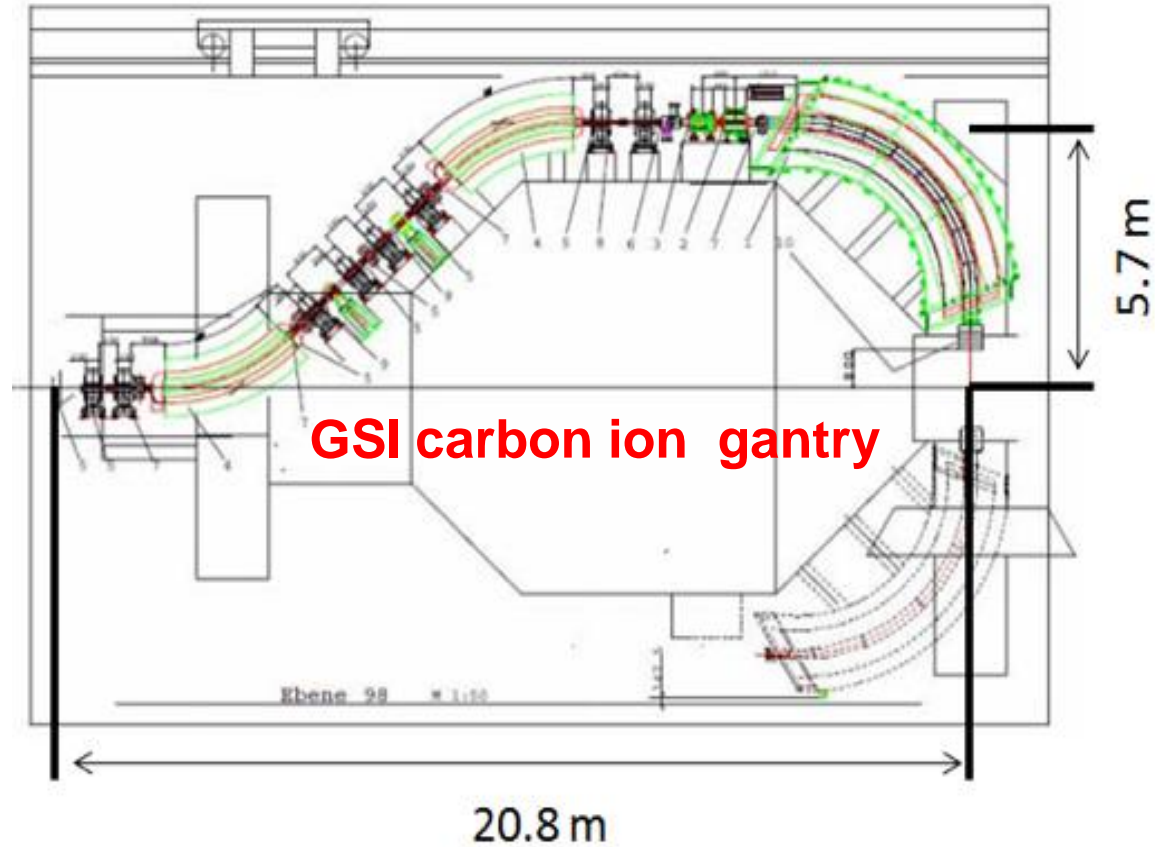


Proton Gantry
 $Br < 2.4 Tm$

PSI proton gantry

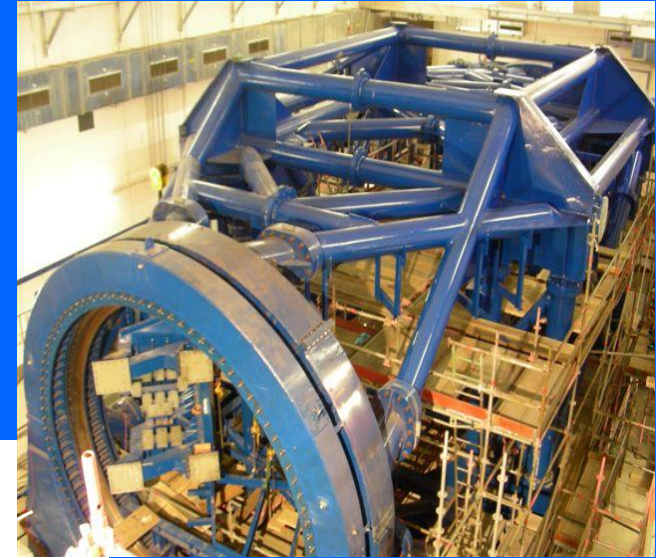
(Courtesy M. Pullia)

Carbon Ion Gantry
 $Br < 6.4 Tm$

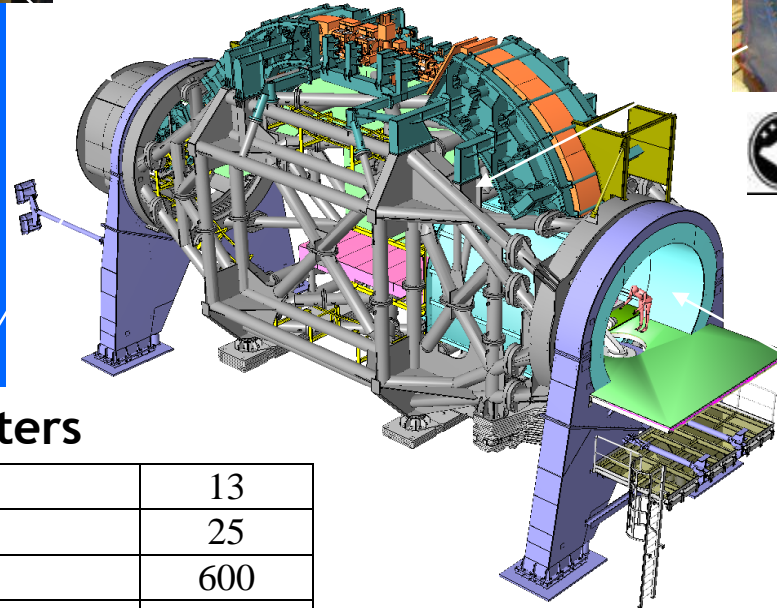


Heidelberg ion gantry: unique in the World!

First patient October 19th, 2012

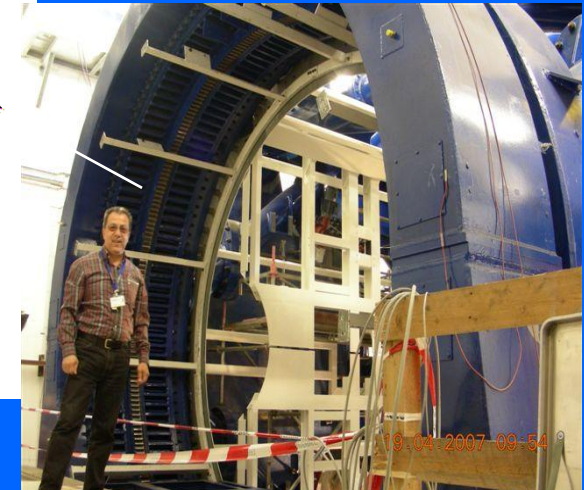


(Courtesy T. Haberer)

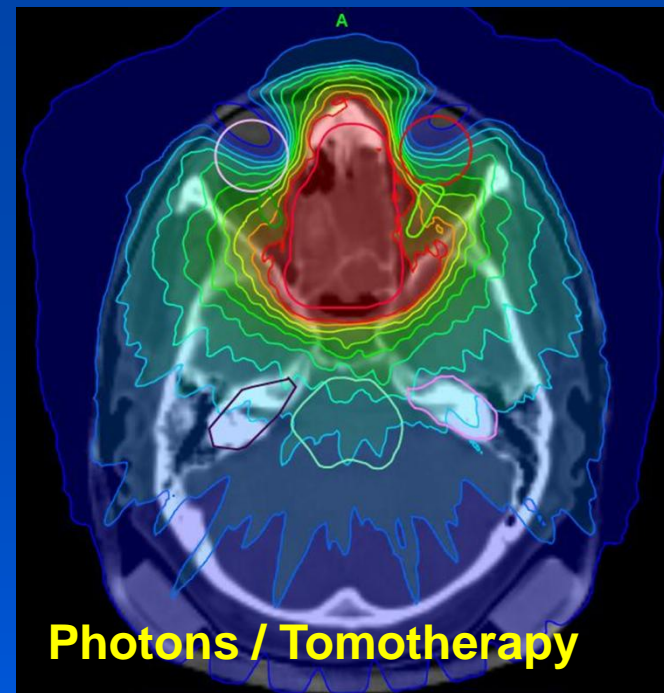
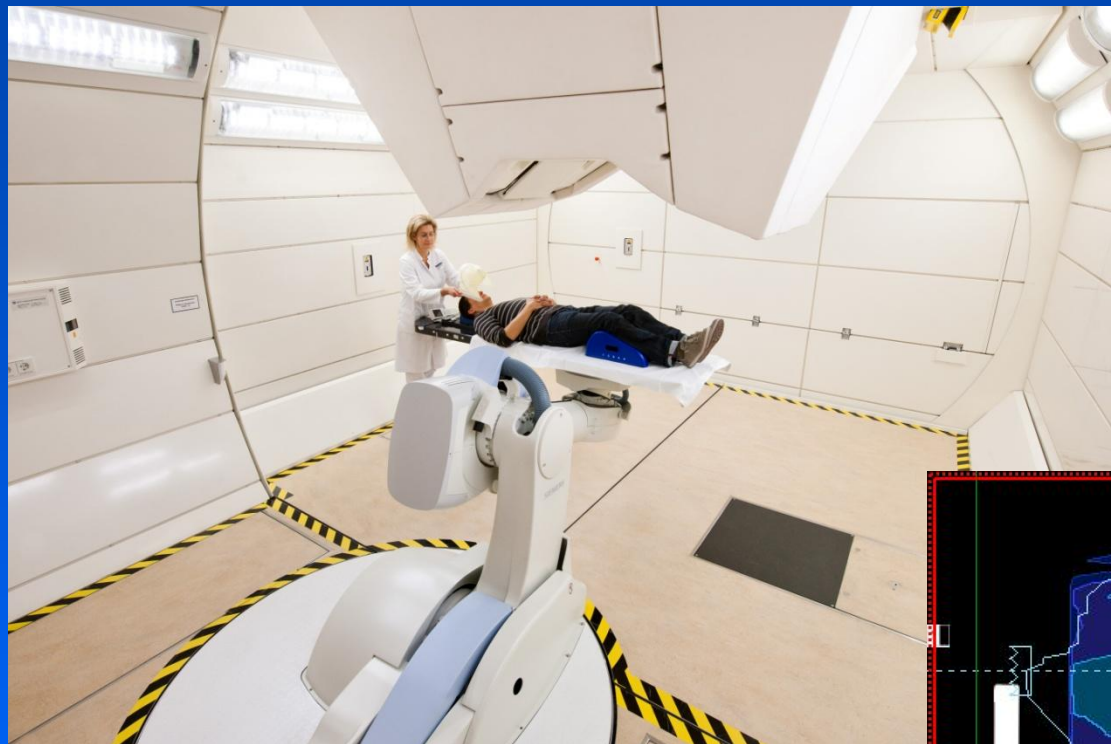


Main Parameters

Diameter [m]	13
Length [m]	25
Overall weight [t]	600
Maximum power [kW]	600
Rotational weight [t]	420
Maximum allowed deformation [mm]	0,5

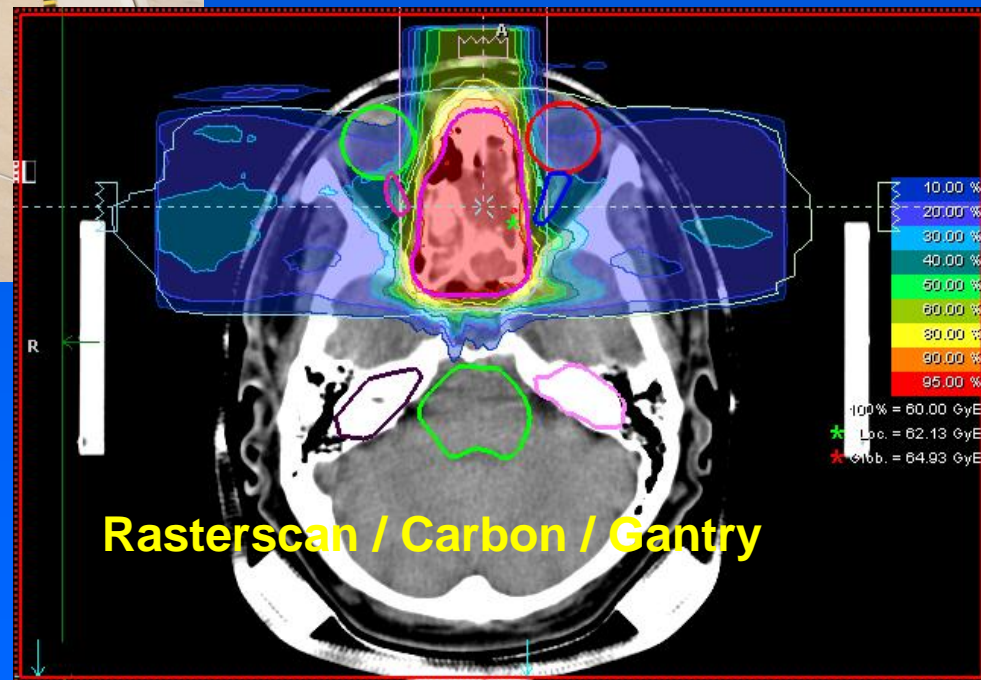


1st treatment at the HIT's world-wide only scanning ion gantry



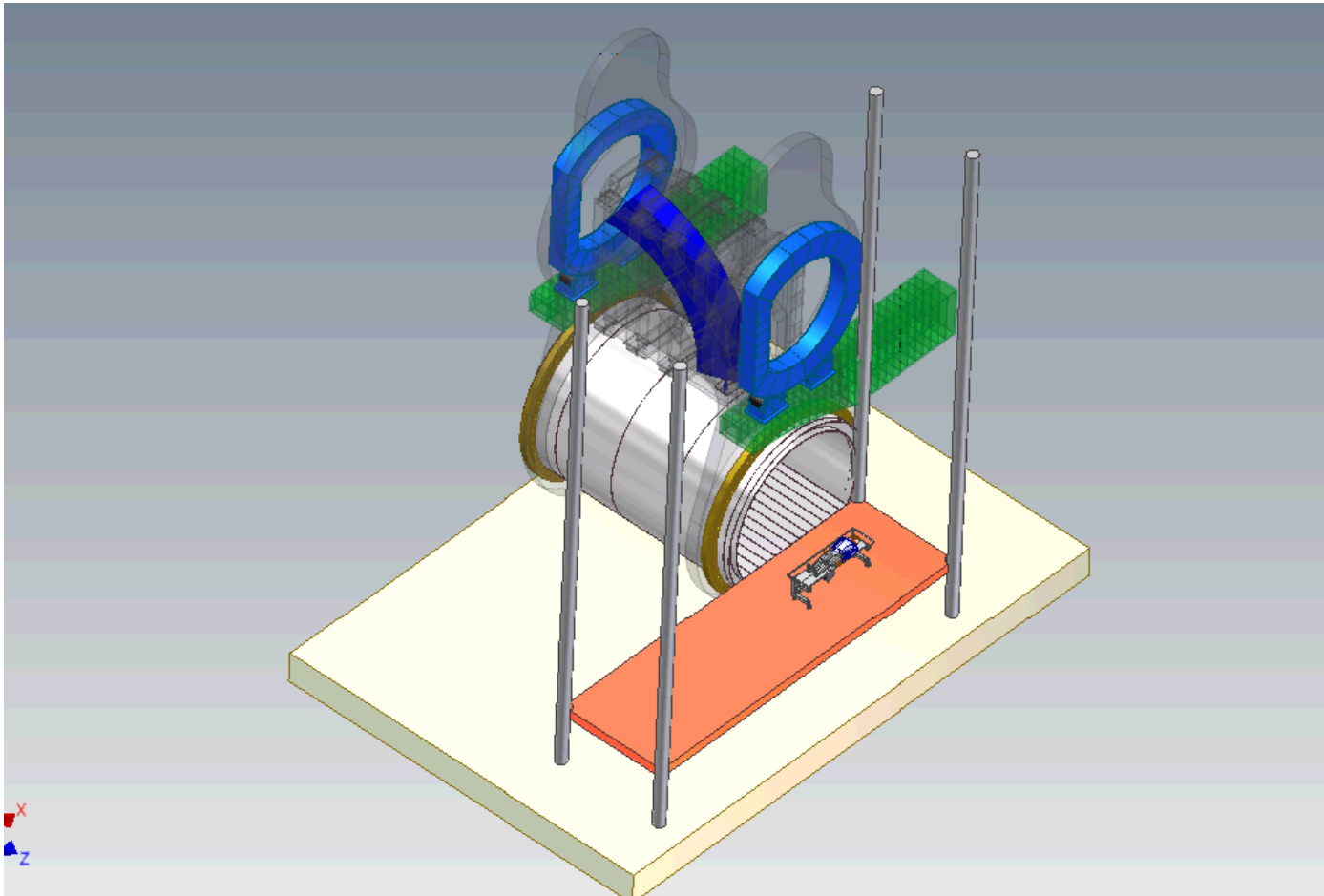
*October 19th, 2012
oligo-astrocytoma*

(Courtesy of T. Haberer)



Novel gantry for carbon ions

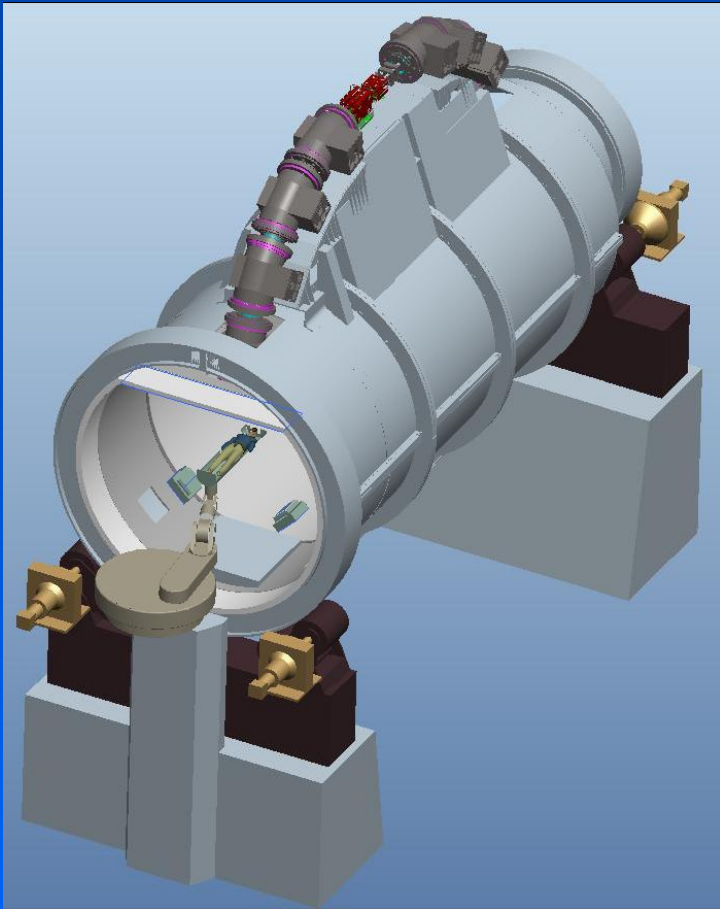
The ULICE WP6 collaboration realized a conceptual design of a **mobile isocenter gantry**,



Rationale for the choice

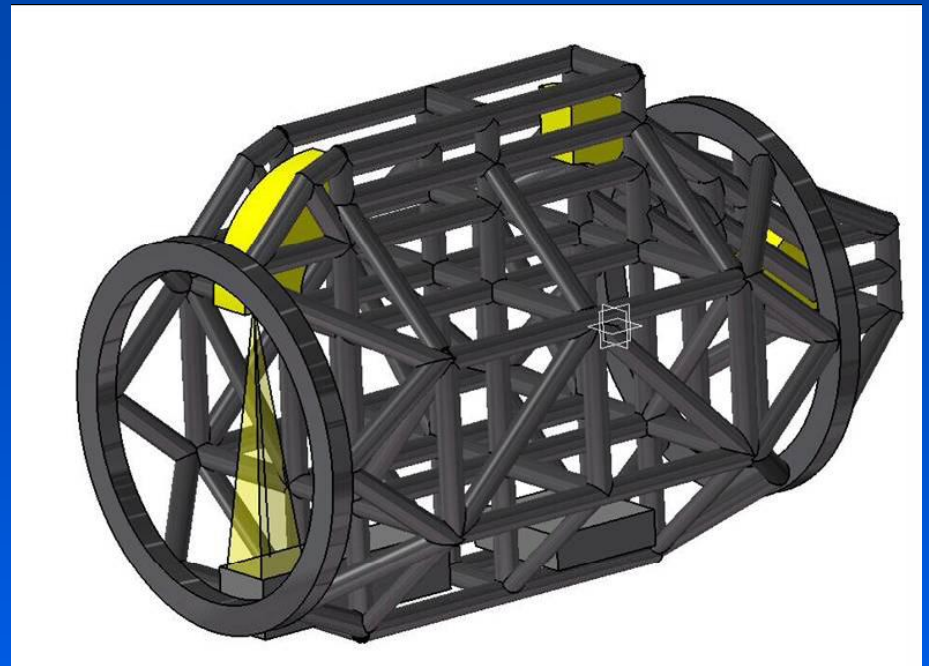
- Innovative layout
- Cheaper and simplified mechanical structure
- Less magnets in the gantry line
- Total weight reduced as well as deformations
- Well known magnet technology
- Layout scalable to SC magnets

Design of Superconducting Gantries



**NIRS / HIMAC (J): 200 to,
Radius: 5.5 m, L: 13m, 3 T**

(Courtesy of T. Haberer)



**CEA (F) and IBA (B)): 210
to, Radius: 4m, Length:
13m, B_{\max} (90°-Dipole): 5.39 T
(NbTi)**

*Use of cryocoolers foreseen
→ Long recovery time in
case of quenches!*

HIMAC superconducting gantry is in construction

Combined function magnets:
bending and focusing (BM1 ~ BM6)

Scanning magnets at
the middle point

Combined function magnets (BM9 ~ BM10)

- > square irradiation field
- > parallel beams

Flux monitor
Position monitor

Iso-center

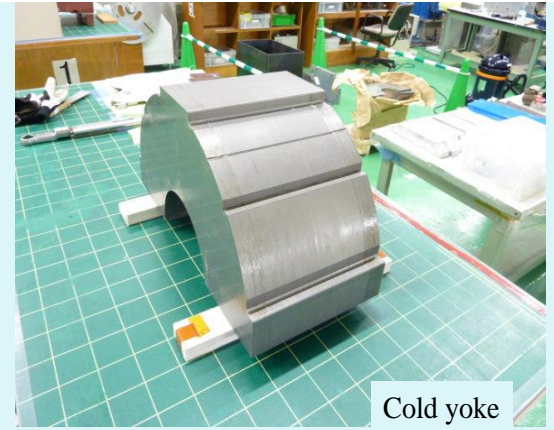
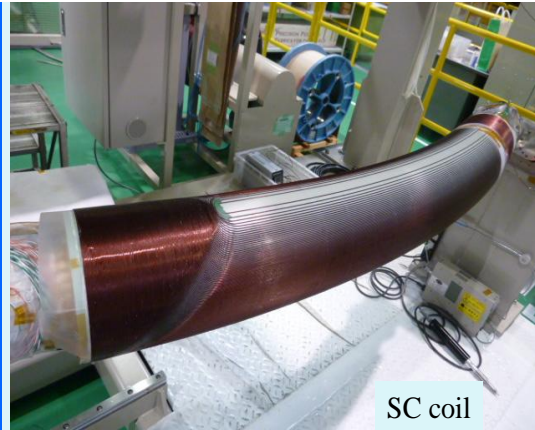
5450.0

13000.0

(Courtesy T. Murakami)

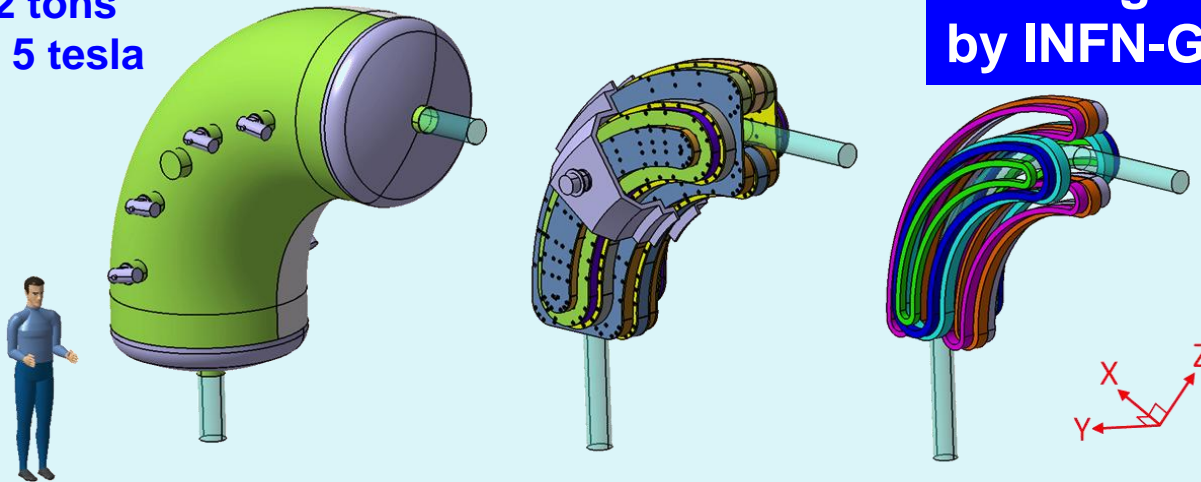
$B_{max} = 2.88 \text{ T}$
 $G_{max} = 9.0 \text{ T/m}$

B and G changing vs cycle



Project in progress by CEA (France) in collaboration with IBA

12.2 tons
B = 5 tesla

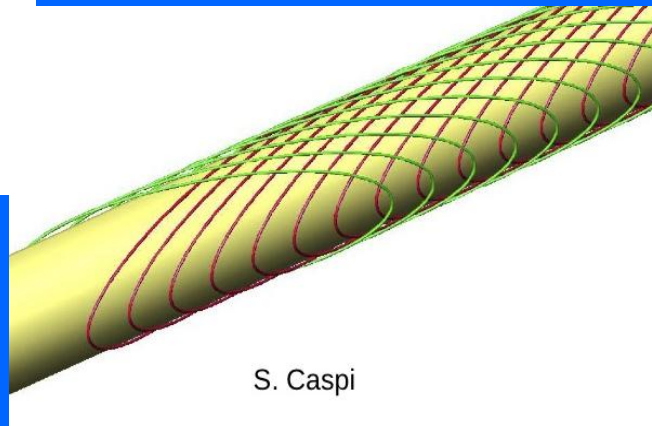


90° magnet following a design by INFN-Genoa and TERA

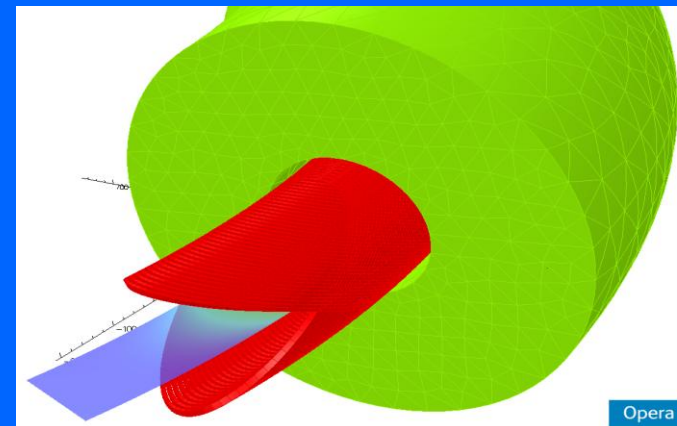
Project in progress at LBL - Berkeley

Two layer helical wires on a straight cylinder give a dipole field

(S. Caspi et al.)



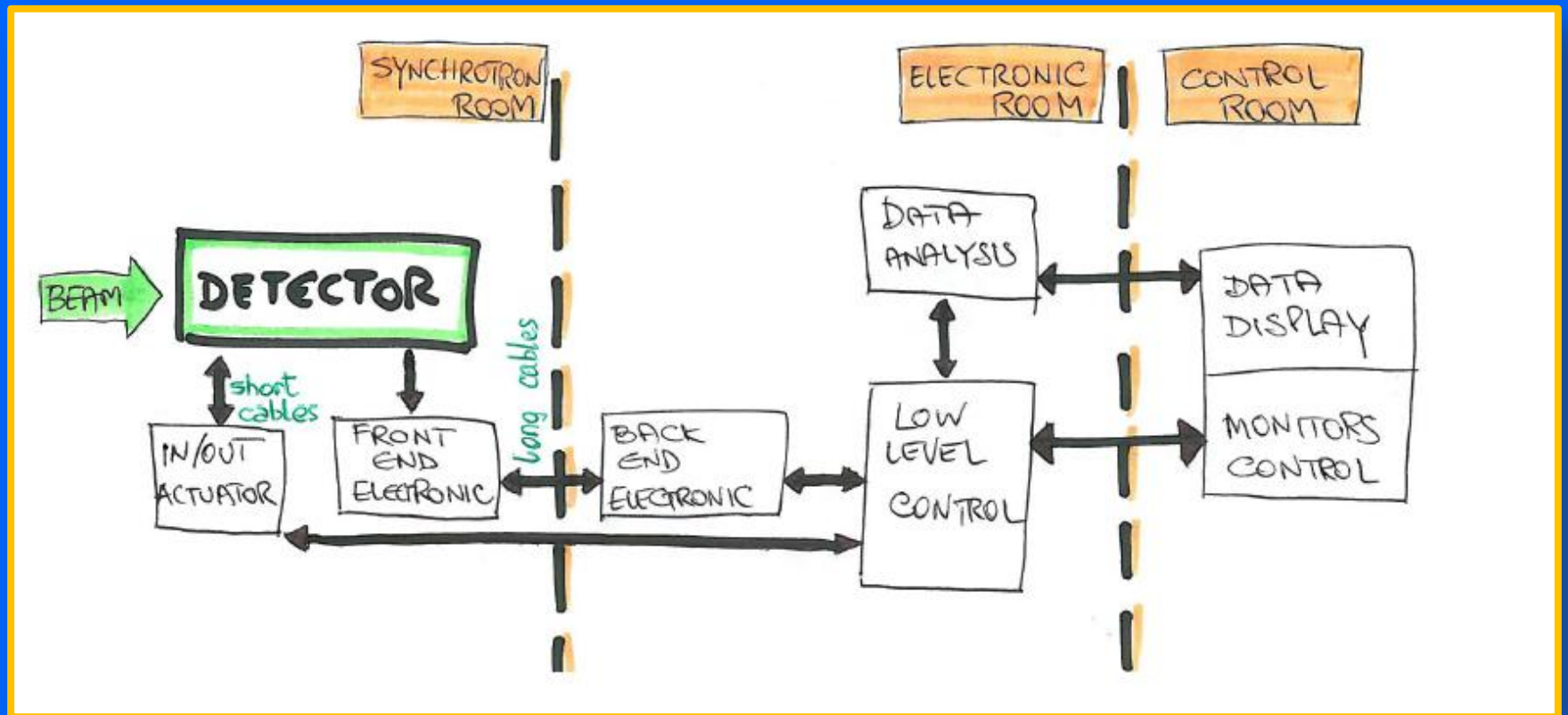
S. Caspi



Opera

ISSUES: field quality for scanning beams;
changing fields (energy) for active scanning

Rivelatori di fascio: Layout



Requisiti Rivelatori

(tipici per macchine medicali)

- ◉ **Distribuzione dei monitor adeguata in numero e tipologia** -> è indispensabile per poter avere una comprensione rapida ed efficace dello stato del fascio e poter intervenire prontamente in caso di guasti. E' necessario minimizzare le interruzioni di fascio terapeutico (per comfort dei pazienti e economia della macchina)
- ◉ **Poco intercettivi** -> durante il trattamento non è permesso l'uso di rivelatori che disturbano il fascio in distribuzione o energia (cambiare l'energia del fascio primario, vuol dire alterare la profondità del picco di Bragg e quindi del trattamento). Durante le fasi di qualifica del fascio pre-trattamento è permesso l'uso di rivelatori intercettivi / distruttivi.

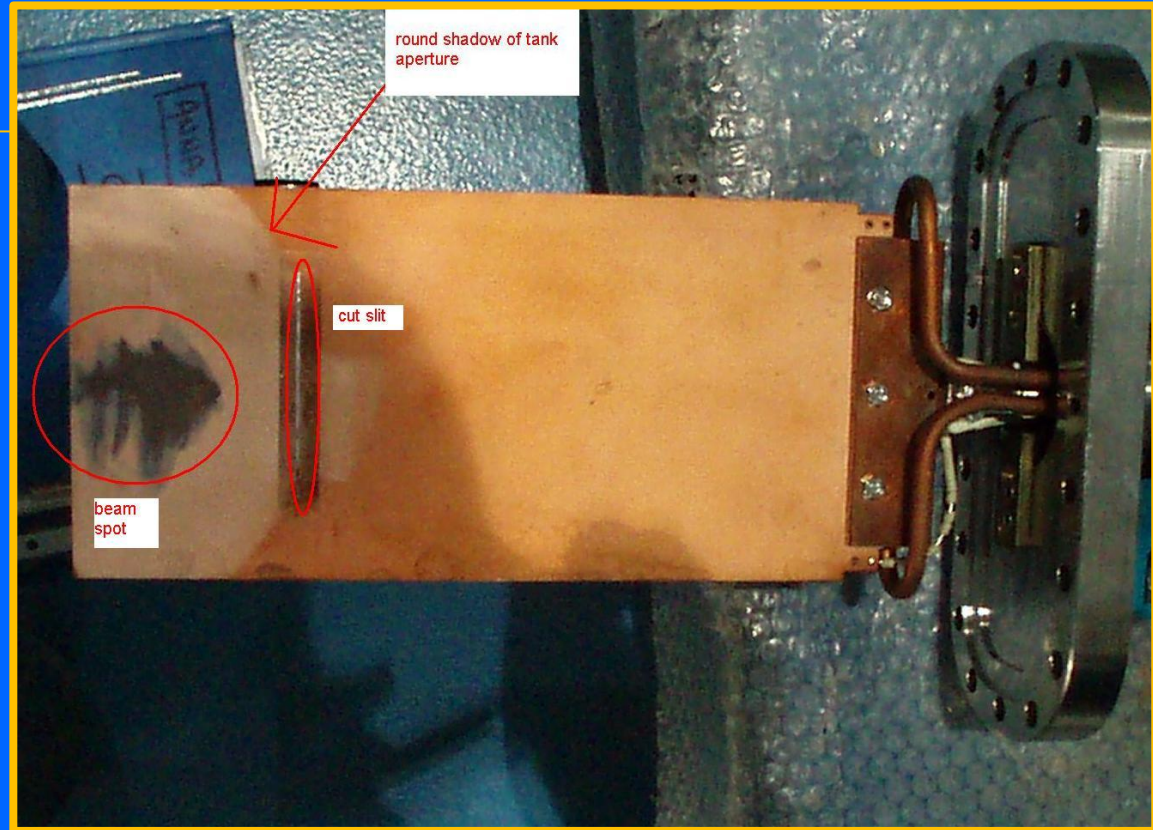
Rivelatori: overview

- ⦿ Andiamo a vedere in dettaglio il funzionamento e le caratteristiche dei rivelatori usati più comunemente
- ⦿ Descriviamo i monitor installati al CNAO. Alcuni di questi monitor sono disponibili sul mercato e molto diffusi negli acceleratori con fascio simili; altri sono rivelatori peculiari, sviluppati all'interno del CNAO stesso, per soddisfare esigenze particolari della nostra macchina.

Slit

Meccanica

- Piatti orizzontali e verticali
- Rame, spessore 2-3mm (sufficiente a fermare il fascio in LEBT e MEBT)
- Movimentati da motori brushless, per un posizionamento rapido (fino a 100mm/sec) e accurato
- LEBT: bassa energia e fascio DC -> tanta potenza rilasciata nei piatti, sotto vuoto -> necessario raffreddamento ad acqua



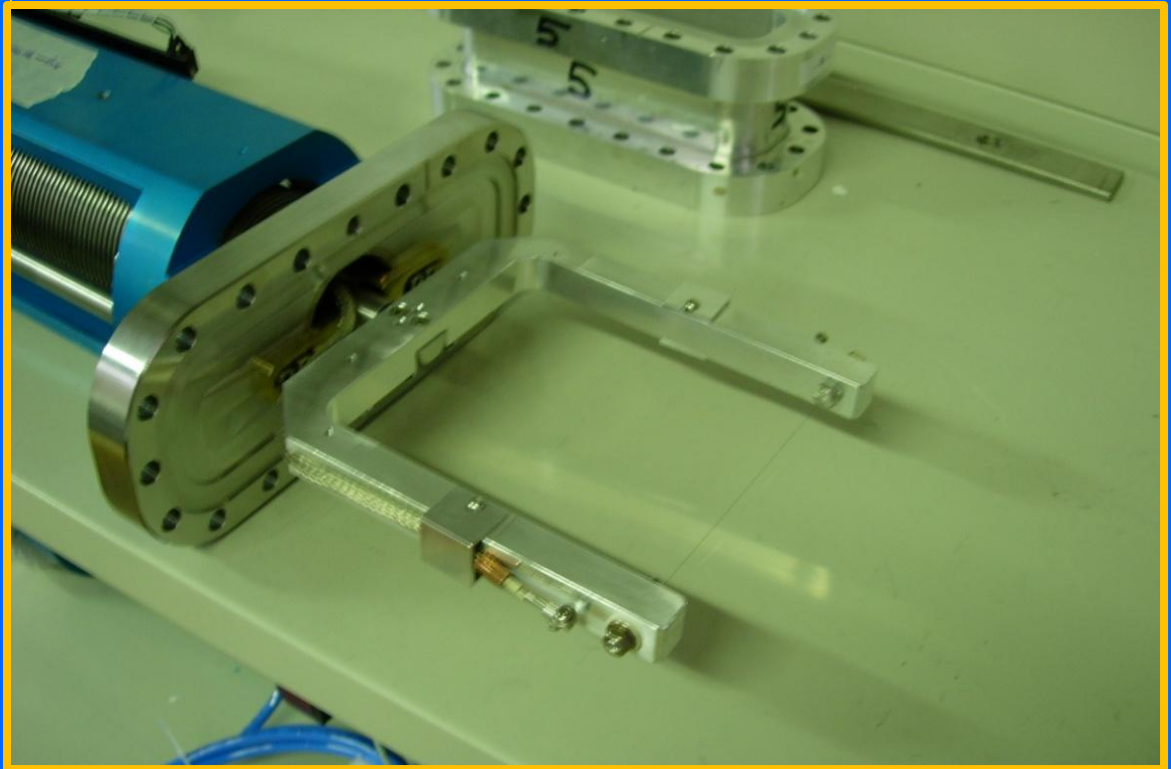
Finalità

- Soppressione degli aloni di fascio
- Selezione specie dopo lo spettrometro
- Misura di emittanza

Wire Scanner

Meccanica

- Fili con scansione orizzontale e verticale;
- Tungsteno; diametro 0.1mm;
- Movimentati da motori brushless, per un posizionamento rapido (fino a 200mm/sec) e accurato;
- Profilo ricostruito dal segnale di un solo filo, quindi non si pone il problema di equalizzare parecchi amplificatori (vedi MWPC e arpe), ma tempo di misura più lungo



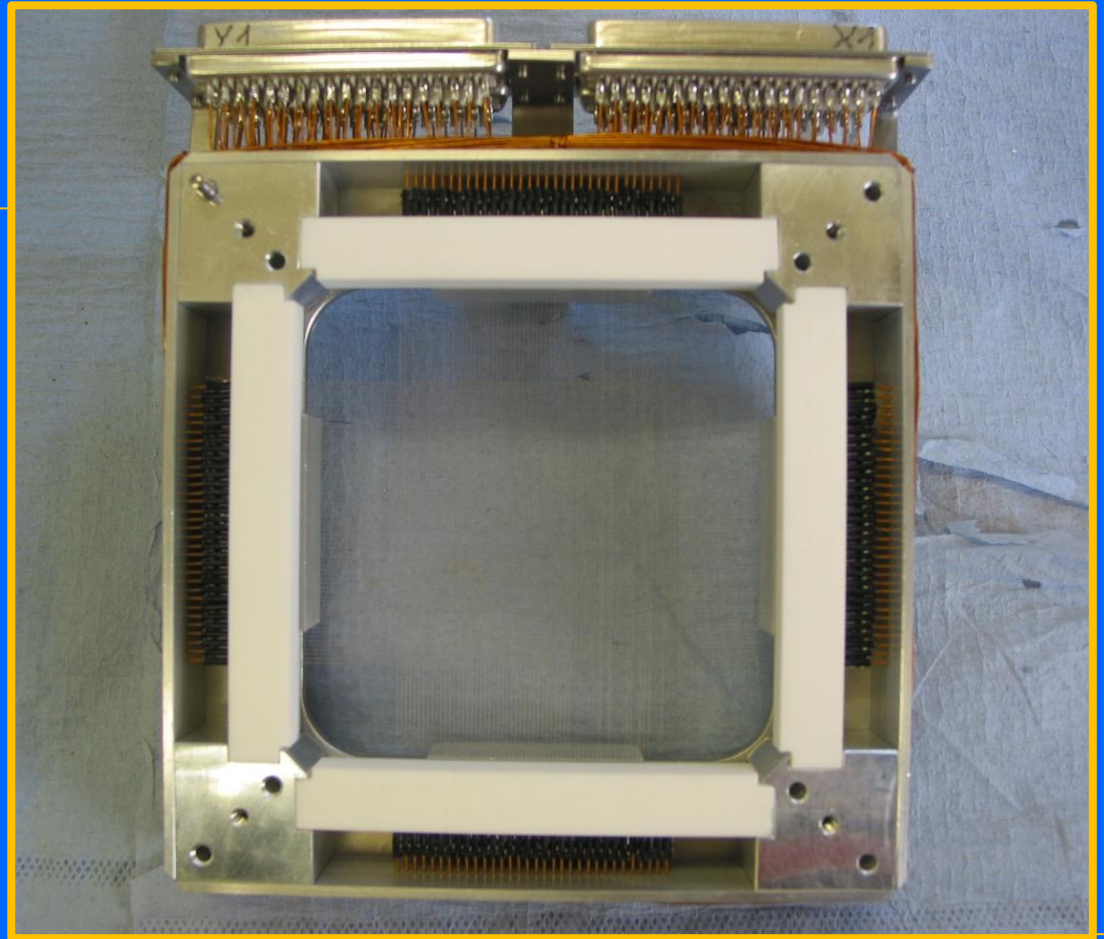
Finalità

- Profilo di fascio orizzontale e verticale (per fasci continui);
- Indicazione relativa dell'intensità del fascio.

Arpe

Meccanica

- Fili orizzontali e verticali;
- 32 o 64 fili per piano, ciascuno riletto da un amplificatore (-> serve procedura per equalizzare gli amplificatori);
- Misura molto rapida;
- Attenzione a emissione di secondari (prodotti da un filo e raccolti dai fili adiacenti);
- Movimentazione IN/OUT pneumatica.



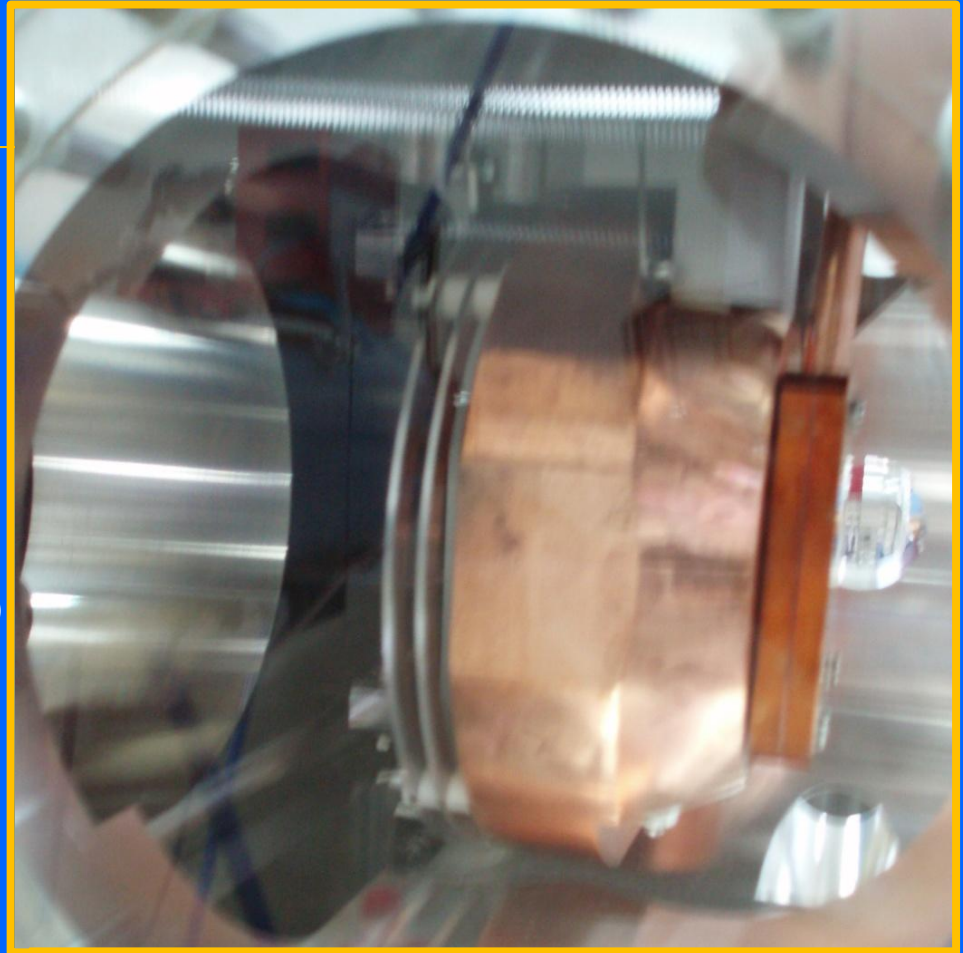
Finalità

- Misura di profili orizzontali e trasversali per fascio impulsato (e per fascio continuo se la potenza rilasciata non provoca surriscaldamento)

Faraday Cup

Meccanica

- 'Coppa' di rame di spessore sufficiente a fermare completamente il fascio primario;
- Raffreddamento ad acqua se potenza rilasciata dal fascio primario è elevata (raffreddate nella LEBT; non raffreddate nella MEBT);
- Un anello ('repeller') posto attorno alla coppa e polarizzato (nella LEBT/CNAO a -350V) serve per confinare nella coppa gli elettroni secondari che altrimenti fuggirebbero falsando la misura;
- Tra anello repeller e coppa, c'è un anello messo a terra, per evitare correnti di fuga dal repeller;
- Movimentazione IN/OUT pneumatica;
- Attenzione a fenomeni di sputtering (di rame) o ricoprimento di materiale isolante (carbonio) che rendono isolanti zone che devono essere conduttive e viceversa, danneggiando il funzionamento del rivelatore



Finalità

- Misura (distruttiva) di intensità di fascio continuo e impulsato;
- Beam stopper.

Current Transformer

➤ Misura del numero di ioni:

- La corrente di fascio cambia durante l'accelerazione;
- La carica totale del fascio (ossia, il numero di ioni) *hopefully* rimane costante;

➤ Trasformatori per fascio DC e AC sono profondamente diversi;

➤ E' necessario shielding magnetico.

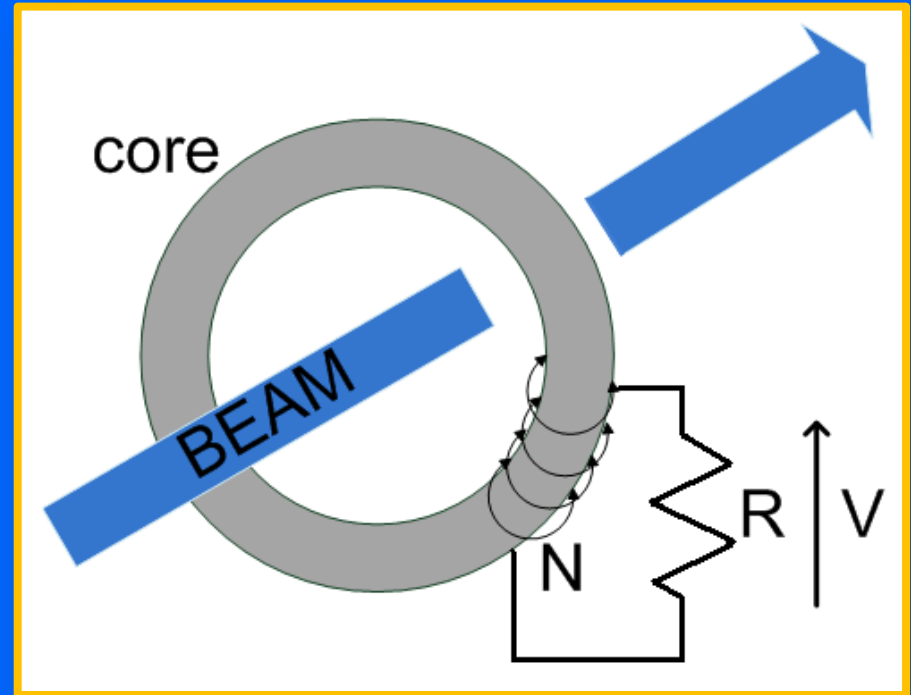


Goal

- Misura di intensità non intercettiva;
- Ottimizzazione di multi-iniezione e accelerazione;
- Monitoraggio continuo perdite di fascio.

AC-Beam Transformer

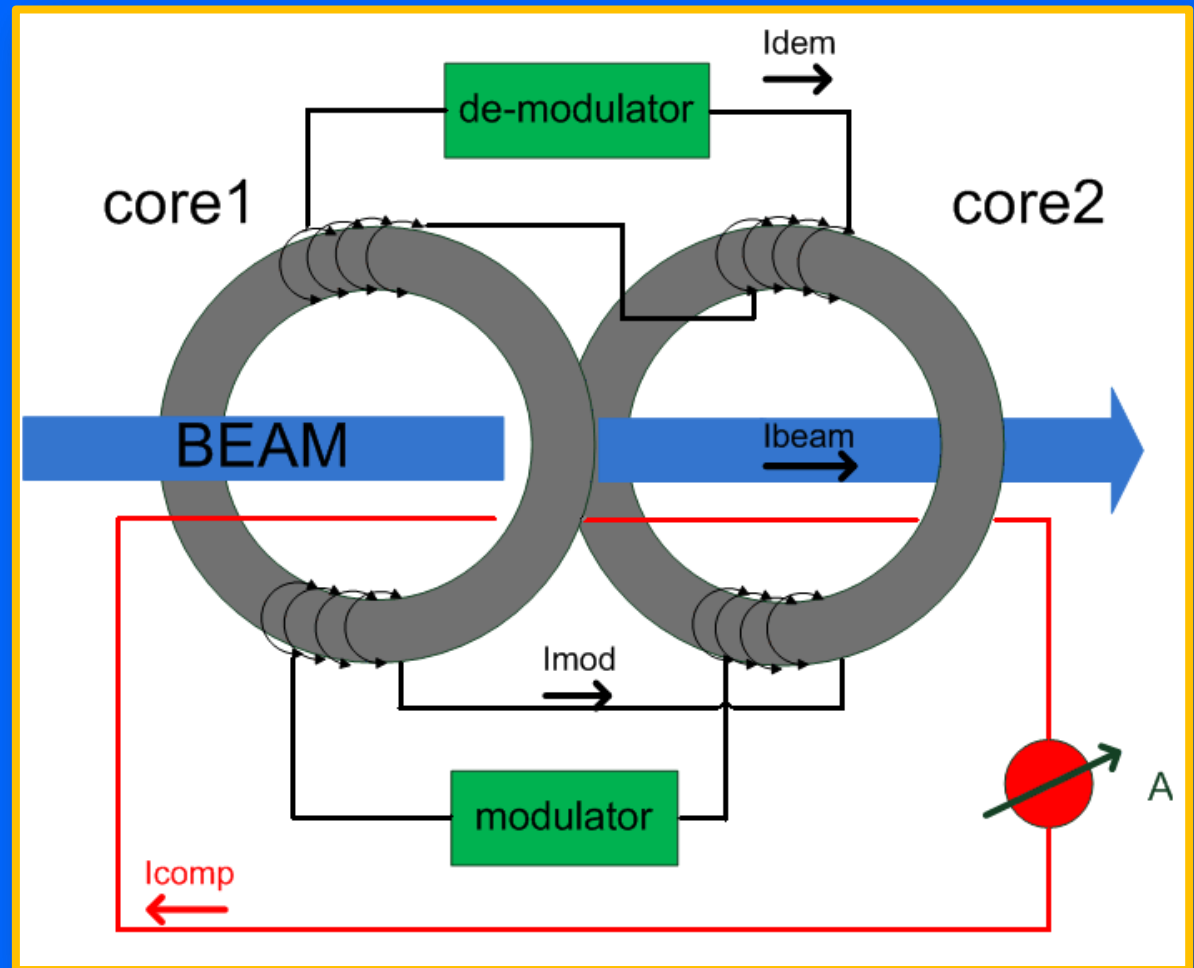
- Per fasci impulsati (lunghezza impulso fino a pochi msec)
- Il fascio funge da avvolgimento primario
- Corrente di fascio riletta da avvolgimento secondario



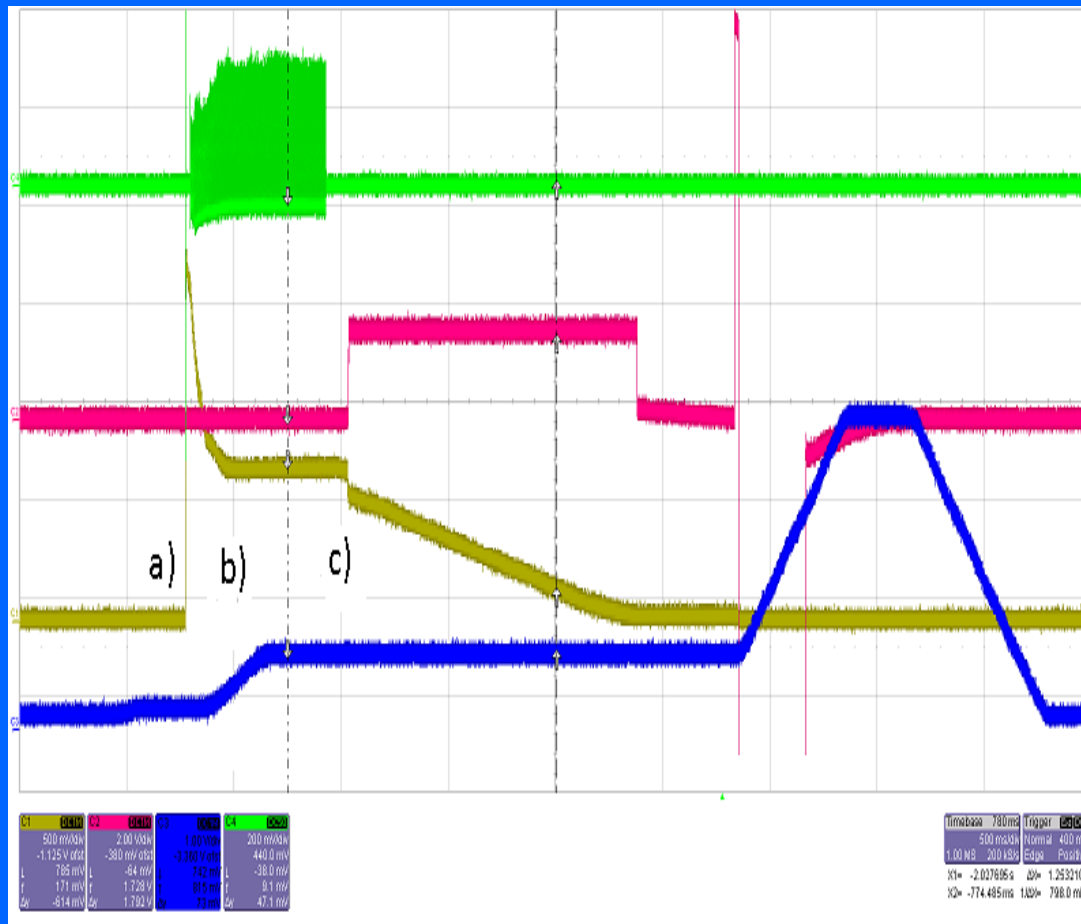
- $\tau_{\text{Droop}} [\text{sec}] = \text{Winding Inductance} [\text{H}] / \text{Read-Out Resistance} [\Omega]$
Dopo circa $1 \tau_{\text{Droop}}$, il segnale risulta ridotta di $1/e$.

DC-Beam Transformer

- Per fasci continui (o componente DC di fasci impulsati)
- Composto da due nuclei 'identici'
- La corrente di fascio viene misurata attraverso il campo magnetico indotto dal fascio sui nuclei
- Non vede variazione di corrente 'rapide'



... in sala controllo



Segnali mostrati in sala di controllo: **DCCT**, campo B, pickup, tensione del betatrone. Sono identificabili le fasi del ciclo del sincrotrone: a) iniezione, b) accelerazione, c) estrazione.

TV Screen

Meccanica

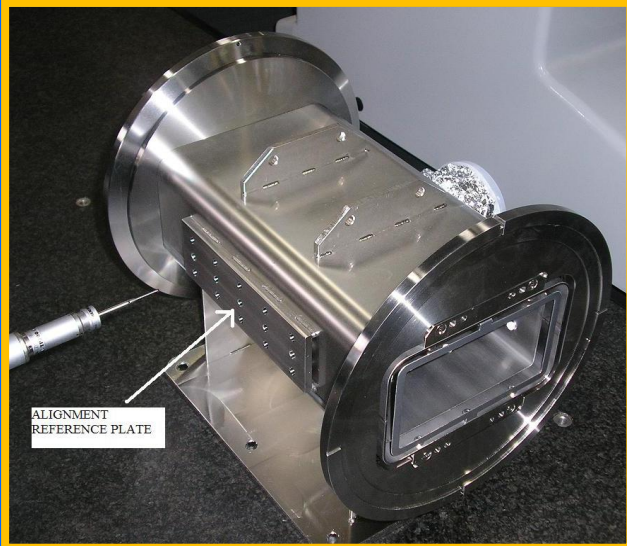
- Schermo di Zirconia osservato da una telecamera CCD;
- La telecamera può essere danneggiata dalle radiazioni;
- Usati a basse energie (iniezione, 7MeV/u) -> fascio fermato completamente dallo schermo -> rischio di surriscaldamento e accumulo di carica;
- Misura distruttiva (fascio a 7MeV/u completamente fermato dallo schermo).



Finalità

- Misura trasversa del profilo;
- Ottimizzazione di iniezione e primo giro in sincrotrone.

Pickup (Elettrostatico)



Principio

- Formato da due elettrodi, si comporta come condensatore, quando il fascio passa tra gli elettrodi;
- Lunghezza elettrodi deve essere \ll lunghezza impulso.

Meccanica

- Elettrodi di alluminio, lunghi 30cm;
- 11 PU orizz e 9 PU vert installati sul sincrotrone (vicino ai quadrupoli); 1 PU orizz + vert nella MEFT.

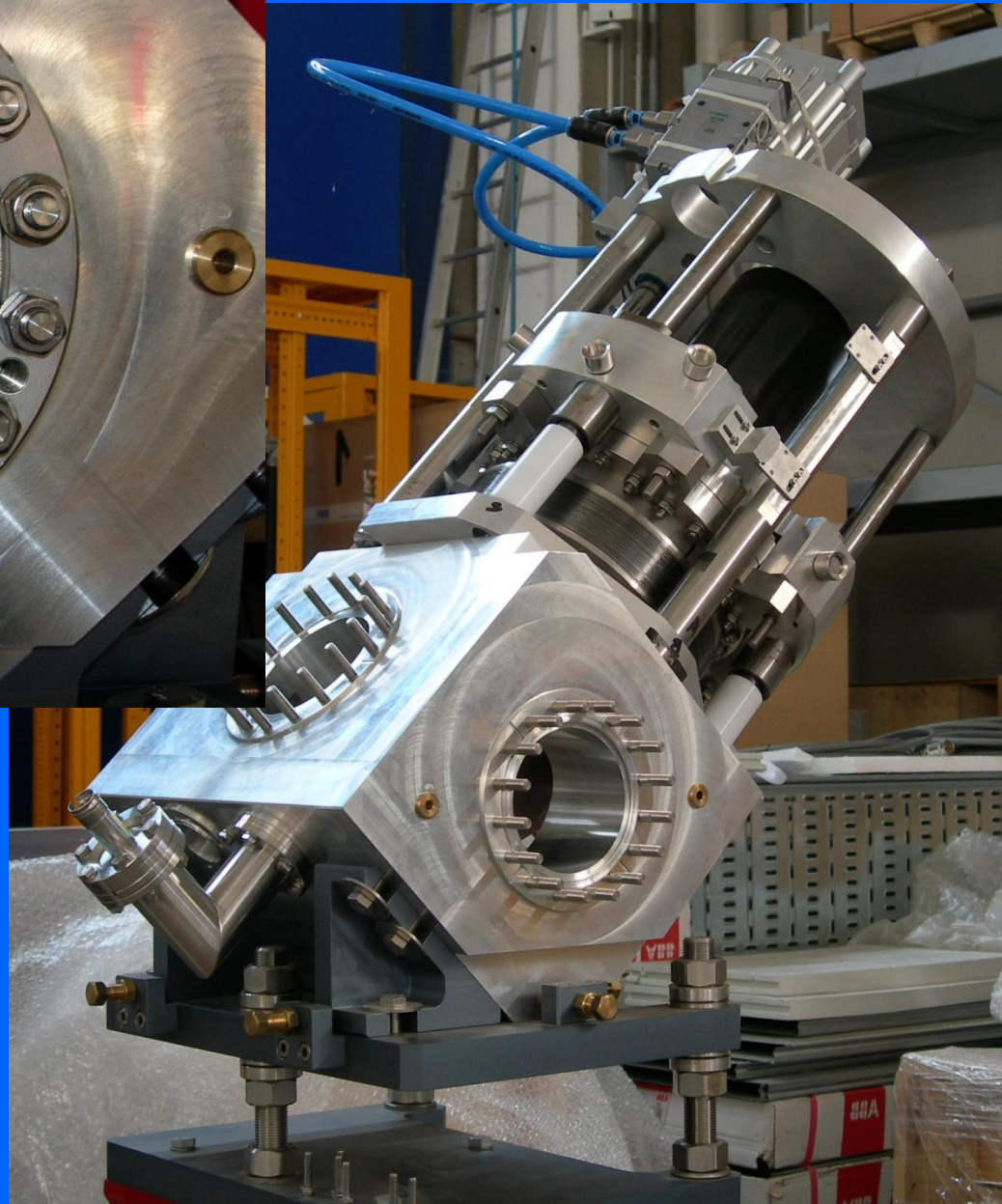
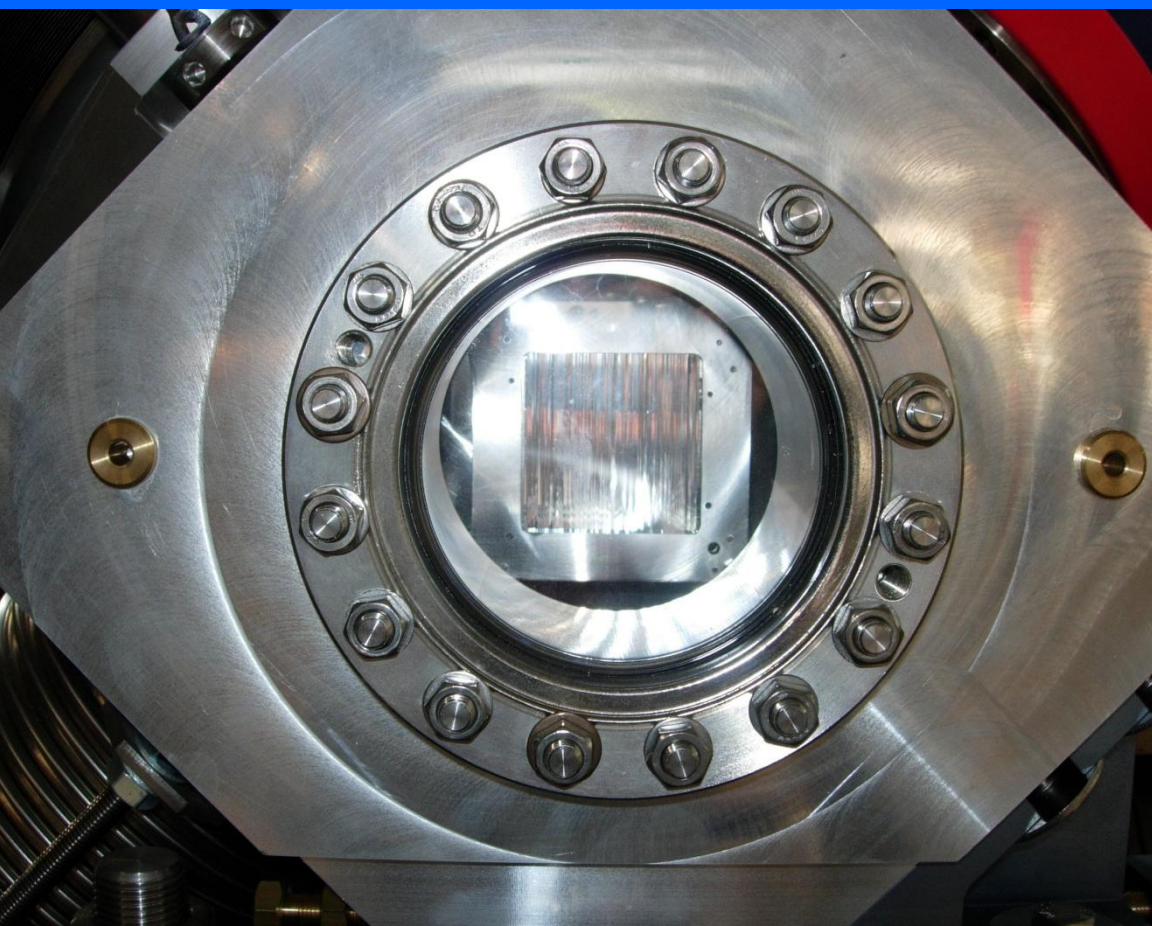
Finalità (per fascio impulsato)

- Posizione trasversa baricentro fascio;
- Profilo longitudinale;
- Misura di orbita chiusa;
- Stima intensità fascio (dal segnale somma dei due elettrodi);
- Controllo RF;
- Misura di Tune.

Misura di intensità e profili nella HEBT

- HEBT -> alta energia -> bassa interazione fascio - materia:
 - No problemi di surriscaldamento; ioni raramente fermati in un rivelatore;
 - Serve rivelatore ad alta sensibilità.
- Alta intensità -> elevato numero di interazioni:
 - Bisogna evitare pile-up e saturazione.
- **Scintillating Fibers Harps (SFH)**: arpe di fibre scintillanti; il fascio di fibre viene focalizzato su una telecamera o una barra di fotodiodi // elettronica semplice e compatta, software di acquisizione dati più elaborato;

SFH



...dalla sala controllo:

Instance [System1:T2-021B-SFH] - Running User [user]

Standard Tools

Official Name: T2-021B-SFH v. 3.1.0 (21/04/2011)

Lock Unlock

CNAO-LV1-07_user_VI

Inhibit

Cycle Prog: 42455714

Cycle Code: 0000240000CC0D00

ErrorCode: 0

ErrorString:

Actuator Settings

In/Out Status: In

SetActuator

Calibration

SetCalib.

Raw Data

Calib. In Progress

Max: 1 n Current: 0 n

Istant [ms]: 500 Export

Acquisition Settings

SetAcq.Par.

Start Event: Start Betatron Gain: 0.00

Start Delay: 0.000 ms Exposure Time: 1.0000 ms

Number Images: 35 Rate: 20.000 Hz

Binning: 8.000

Information

Serial Number: 460230-C

Camera Status: 1

Saturation

ONESHOT

START STOP

Advanced...

X Graph

42455711

Y-axis: 0 to 10000

X-axis: -31.29 to 30.47 mm

XCenter	XCenter Rms	Integral
4 mm	7 mm	100287.225

XCenter Avg	XCenter Avg Rms	Tot. Integral
2 mm	1 mm	1650177.311

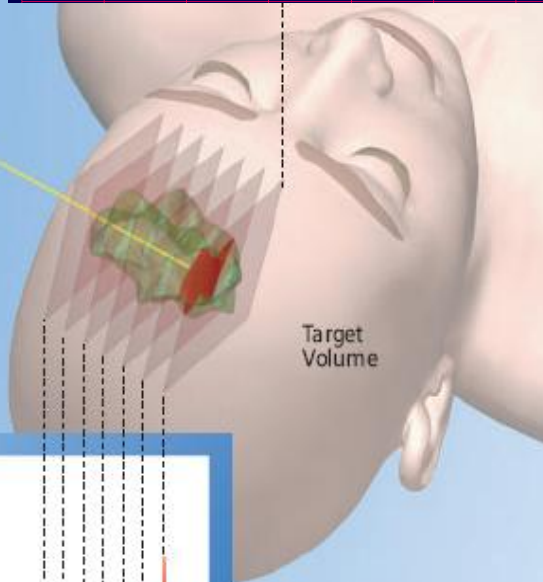
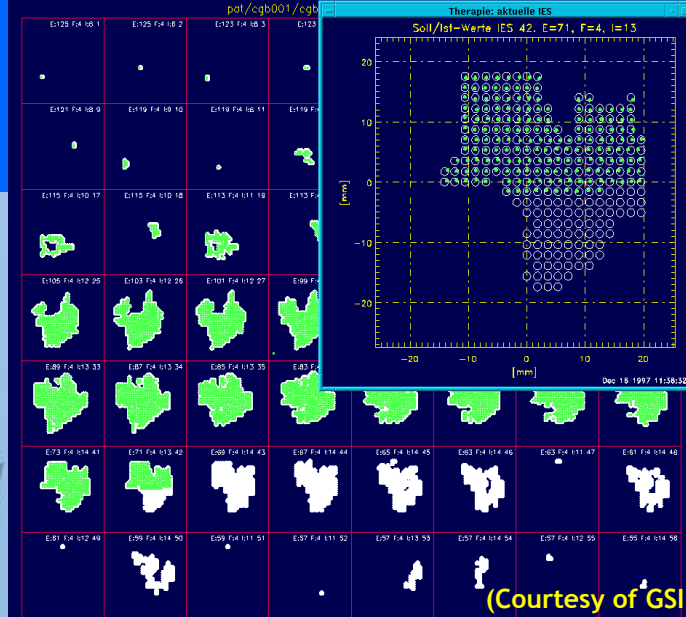
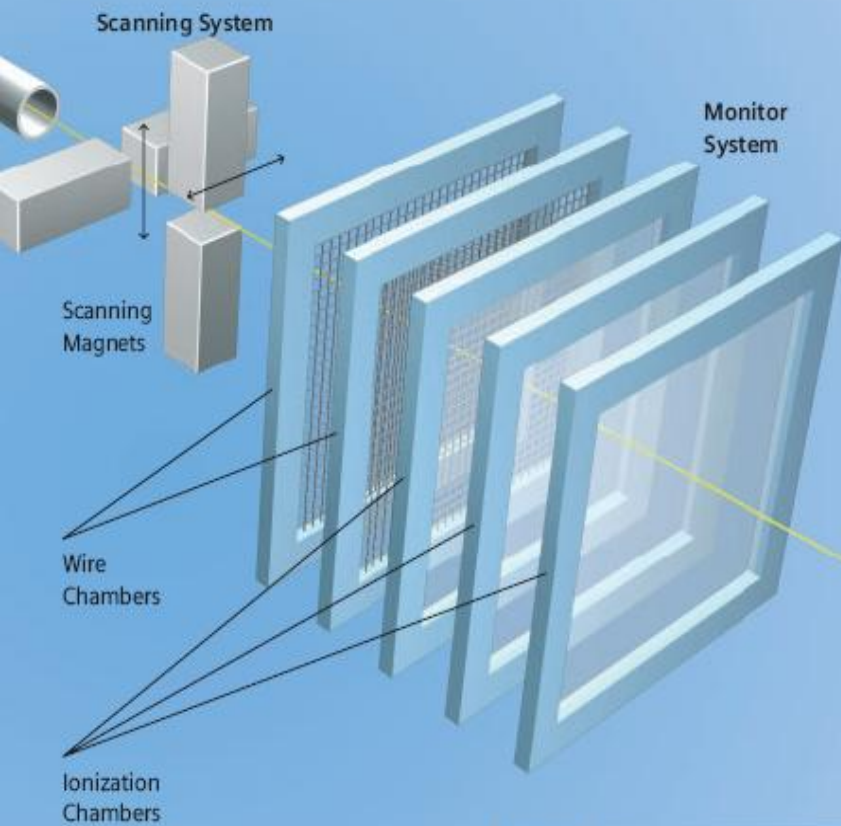
Y Graph

Y-axis: 0 to 20000

X-axis: -30.93 to 30.71 mm

YCenter	YCenter Rms	Integral
1 mm	7 mm	85089.610

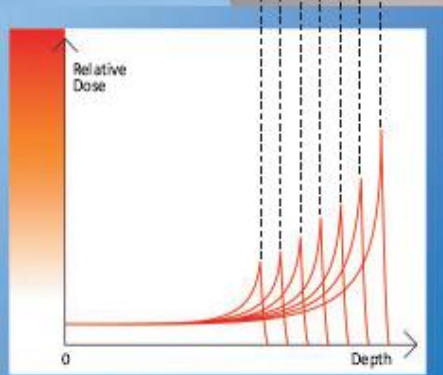
YCenter Avg	YCenter Avg Rms	Tot. Integral
0 mm	0 mm	1467739.520



Example:

Depth 5 cm:
Proton 80 MeV
Carbon 150 MeV/u

Depth 25 cm:
Proton 195 MeV
Carbon 380 MeV/u

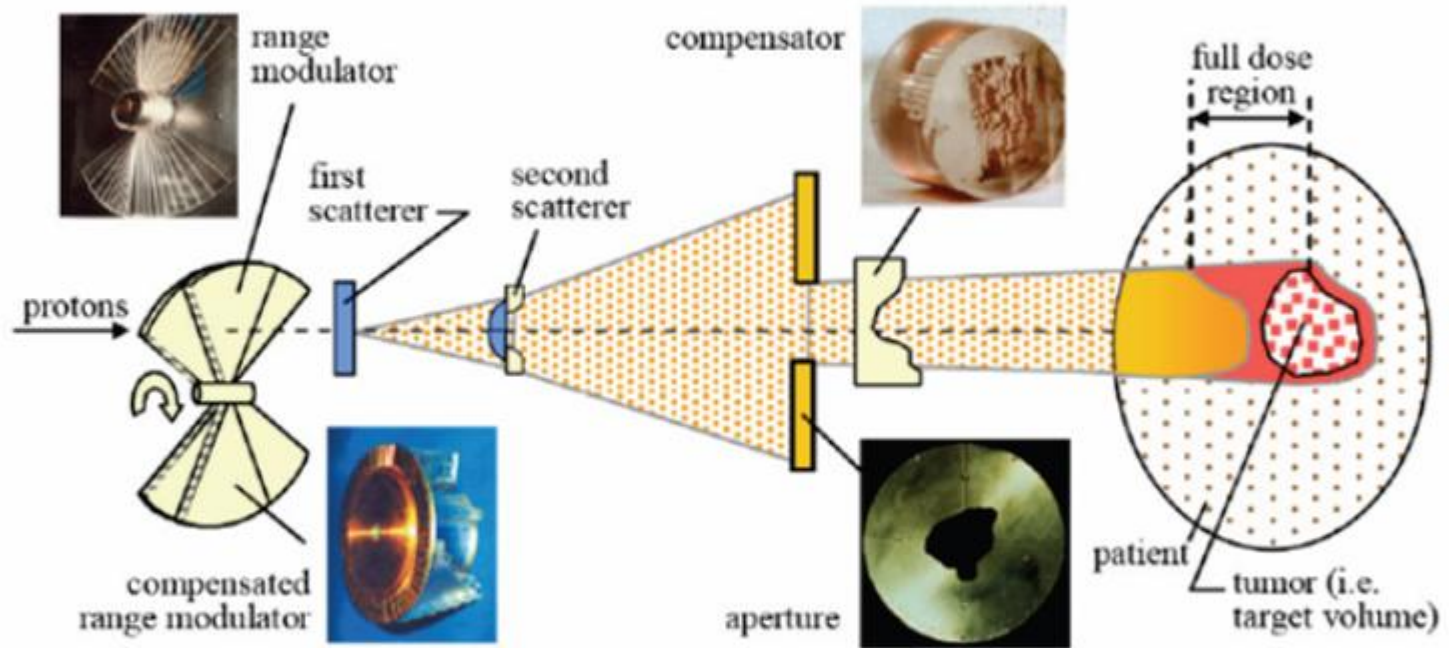


Irradiation technique active scanning

(Courtesy of Siemens Medical)

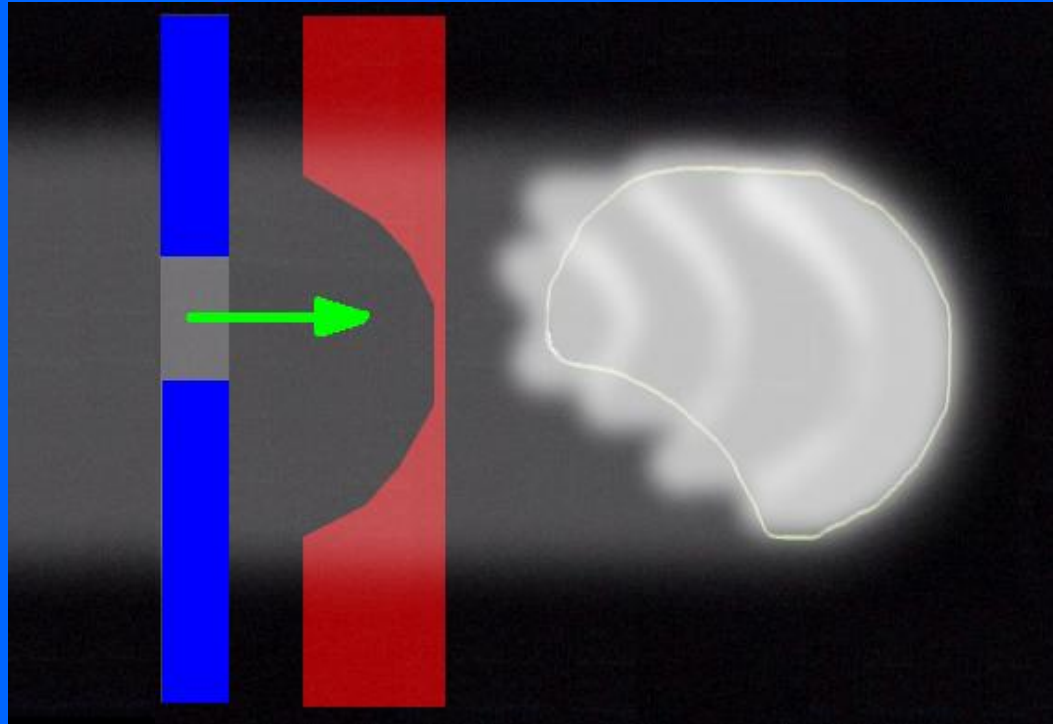
Passive Dose Delivery

Treatment nozzle for a passive scattering proton therapy beamline



© M. Goitein: Application of Physics in Radiation Oncology

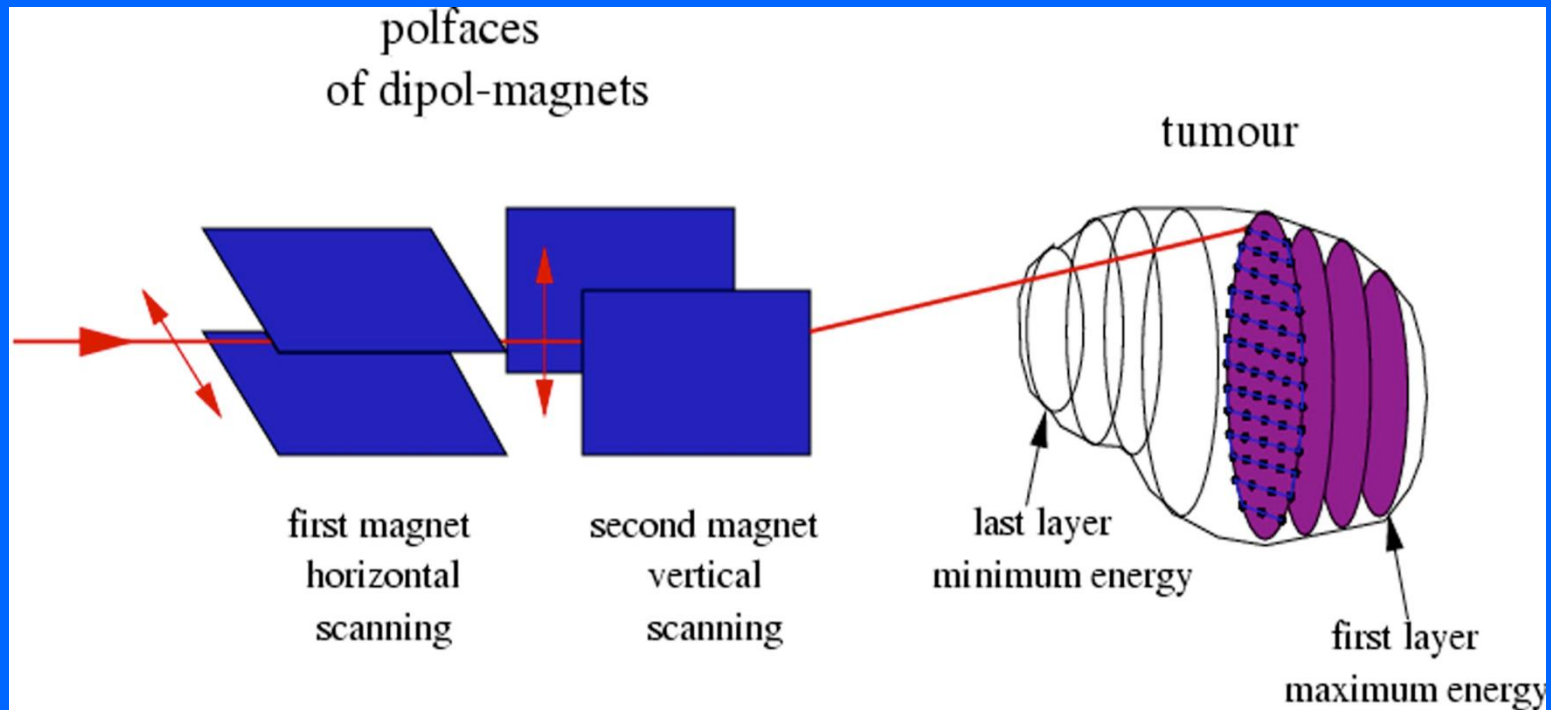
***Methods for imparting the dose with carbon ions:
layer stacking (NIRS+Japan)***



**Wobbling and multileaf collimator adapted
to transverse shape of each slice
(energy changed with synchrotron and range shifter)**

Conformation, components activation, secondary neutrons

Methods for imparting the dose with carbon ions: active scanning: “raster scanning” à la GSI (HIT+CNAO)



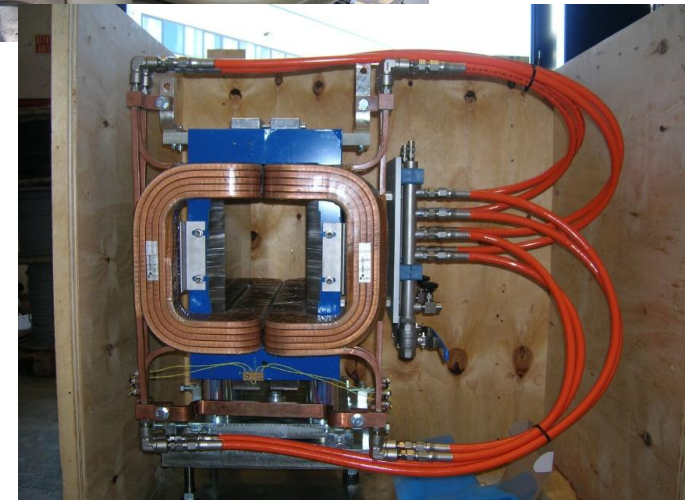
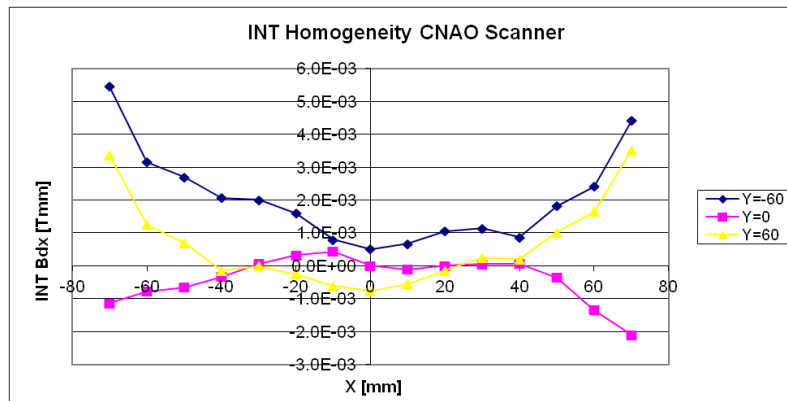
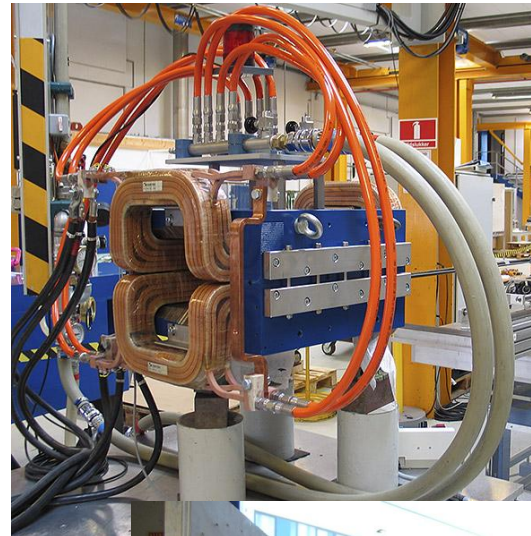
The synchrotron beam is moved
continuously

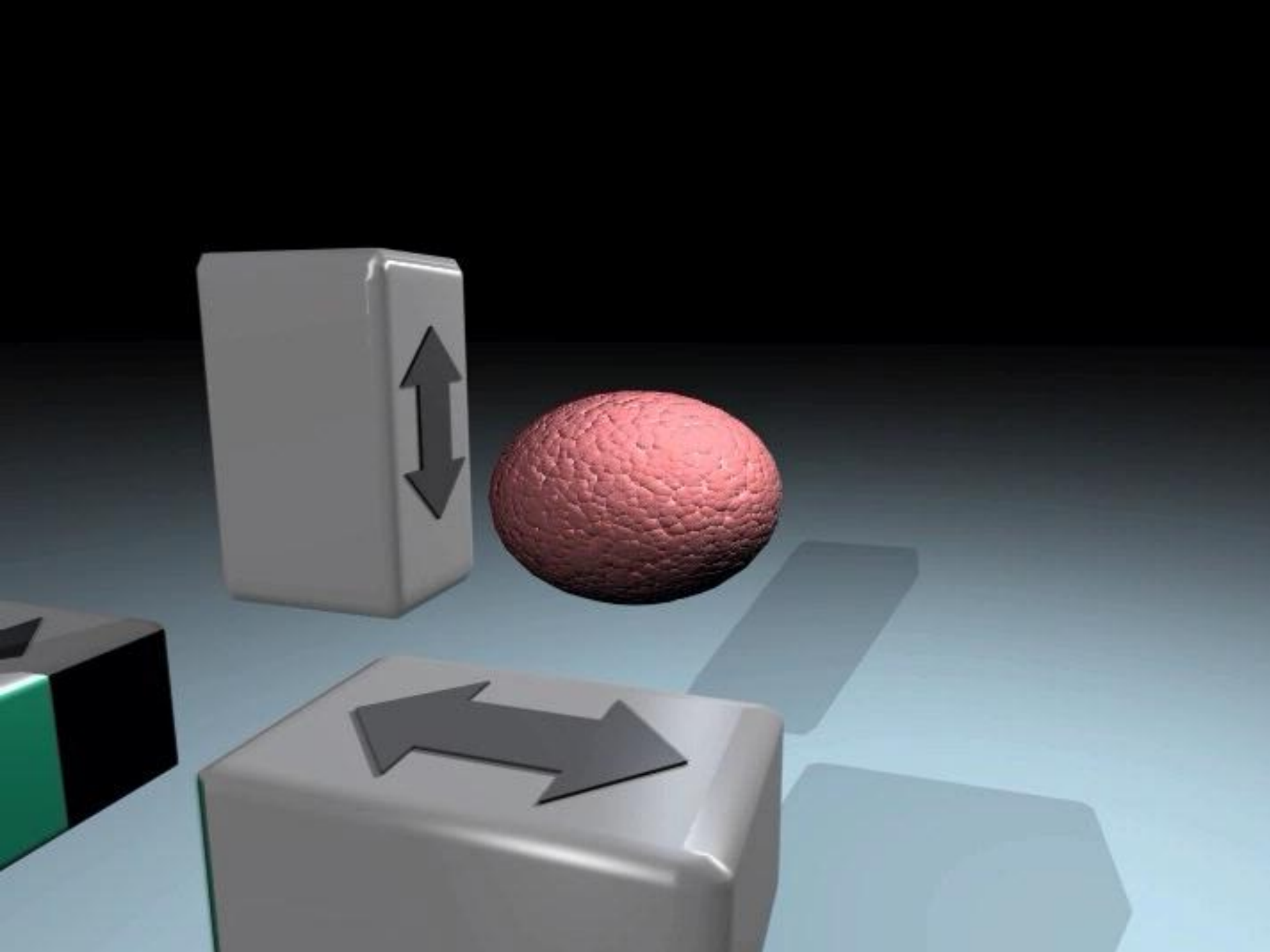
Energy changed with the synchrotron

NIRS decided recently to adopt the active scanning ←

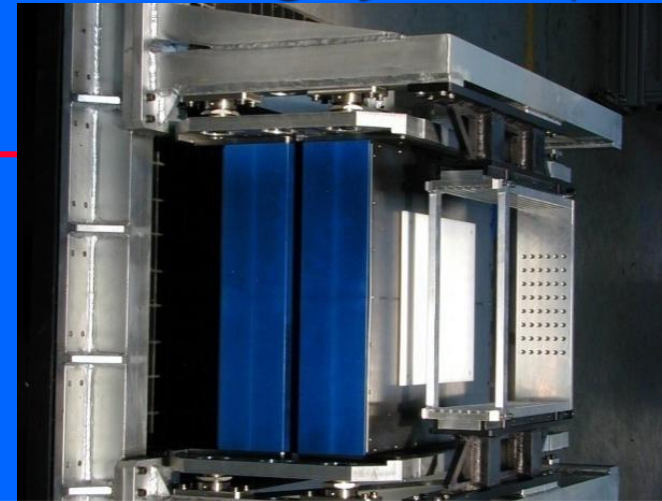
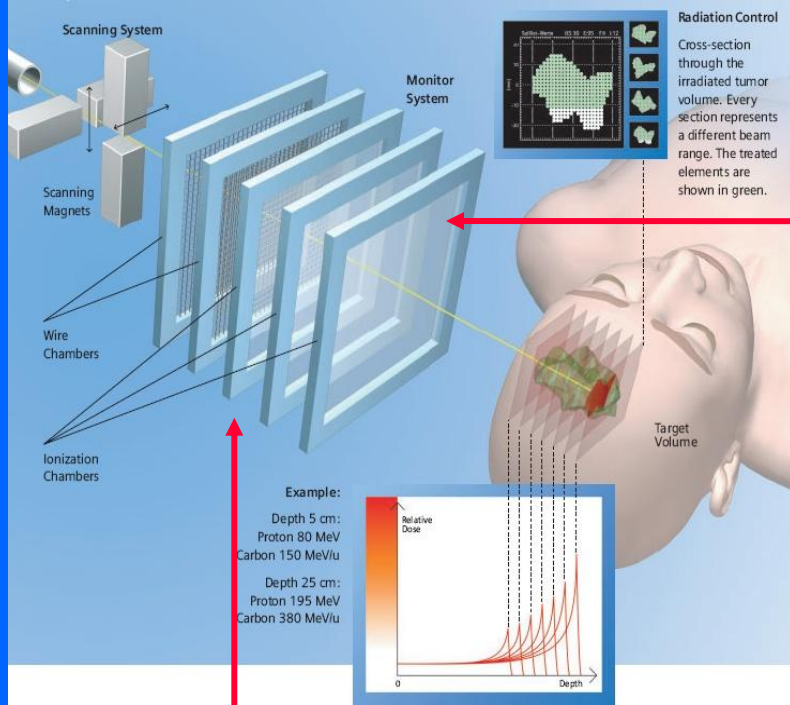
Scanning Magnets (4 Hor + 4 Vert)

<i>Design parameter</i>	<i>Units</i>	<i>Value</i>
Kick angle	[mrad]	27
dI/dt	[A/sec]	121256
Gap	[mm]	146
Magnetic length	[m]	550
Resistance	[mΩ]	24.9
Inductance	[mH]	4.4
Cooling		Water
Nominal Current	[A]	603.3
Nominal field	[T]	0.310
Good field region	[mm]	±60 (hor); ±60 (vert)
Field Quality	Δ BL/BL	$\pm 2 \cdot 10^{-3}$





Monitoring system (CNAO)



Double system of ICs:
(integral, stripX,Y) - (integral, pixel)

Two measures: Intensity, Position, Profile

Readout frequency: 1 MHz (integral),
10 kHz (strip, pixel)

Resolution: 0.1 mm strip, 0.2 mm pixel

Area: 20 x 20 cm²

Non uniformity < 1%

Short term stability < 0.3%

(NIMA 698 (2013) 202-207)

Issue: monitoring spots of C-ions at low intensity

Il fascio: dall'acceleratore al paziente attraverso il Dose Delivery

Il fascio per l'acceleratore

DD

Il fascio per il Paziente

- | | | |
|------------------------|---|-------------------------------------|
| • Energia | → | • Profondità (range nel tessuto) |
| • Dimensione/Emittanza | → | • Distribuzione di dose |
| • Forma | → | • Distribuzione di dose |
| • Intensità | → | • Rateo di dose |
| • Temporizzazione | → | • Movimento organi/radiobiologia... |

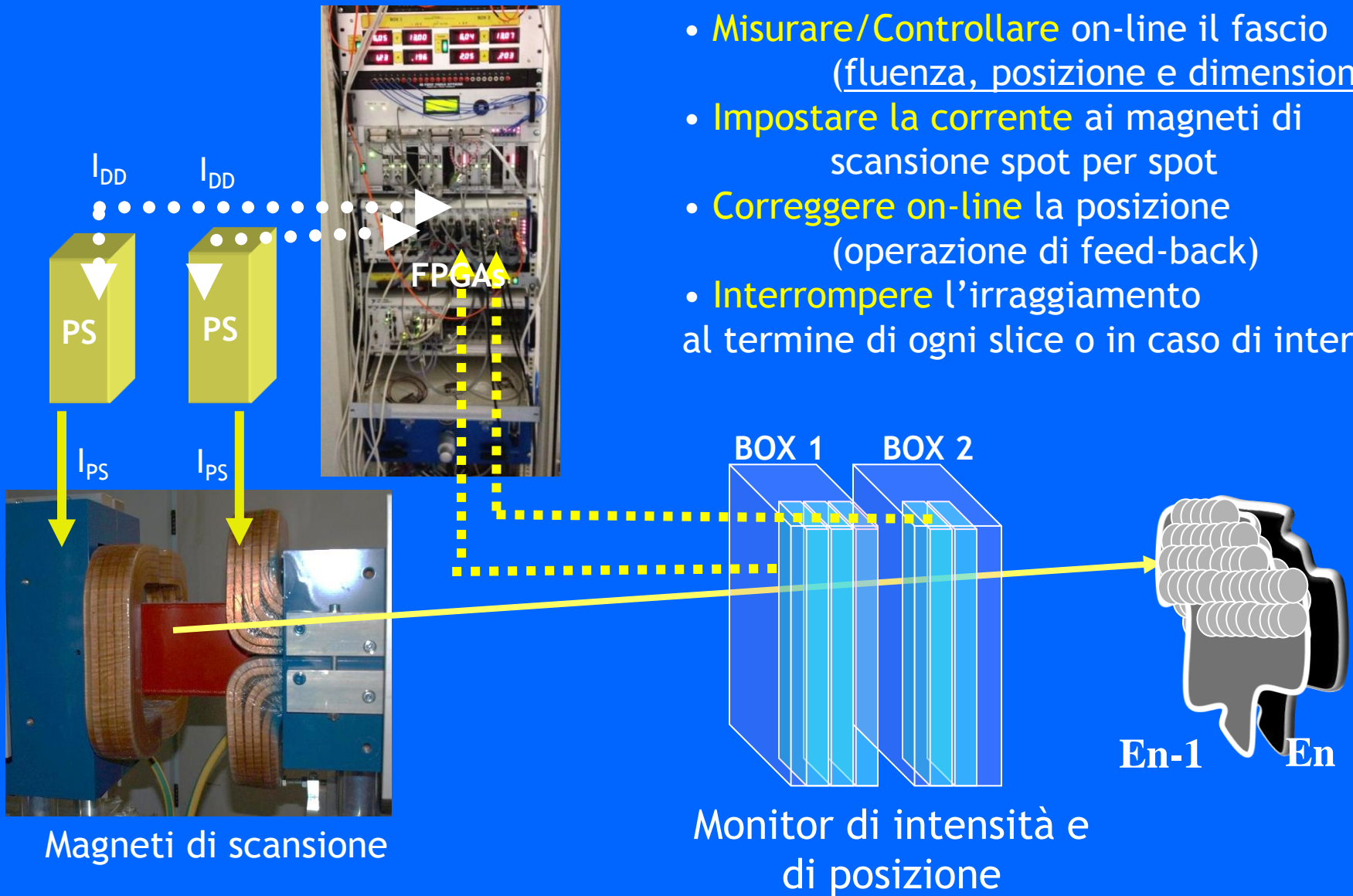
Le 5D del fascio → X, Y, profondità, tempo, specie

Il fascio per il Dose Delivery

- | | | |
|--------------------------|--------------------|--|
| • N_{spot} | sequenza di: | 10^4 - 10^5 spot (pencil beams) |
| • E_n | caratterizzati da: | energia, specie, |
| • N_p | | N di particelle, |
| • $(\Delta X, \Delta Y)$ | | posizione |
| • FWHM _{x,y} | | dimensione |
| | | distribuiti in: 10 ÷ 50 slice (energie-profondità) |

Durante l'irraggiamento il DDS deve:

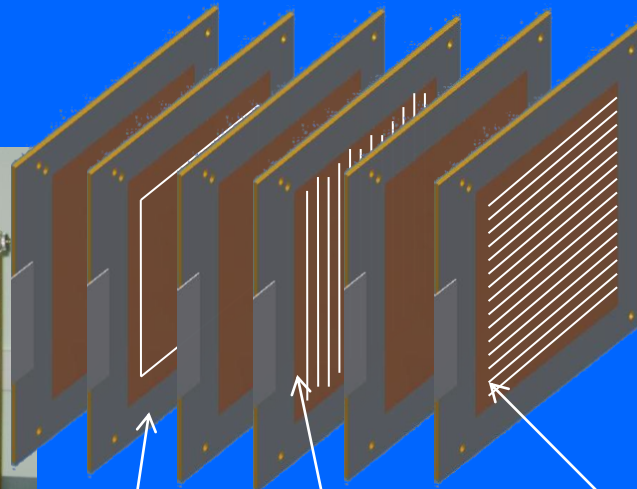
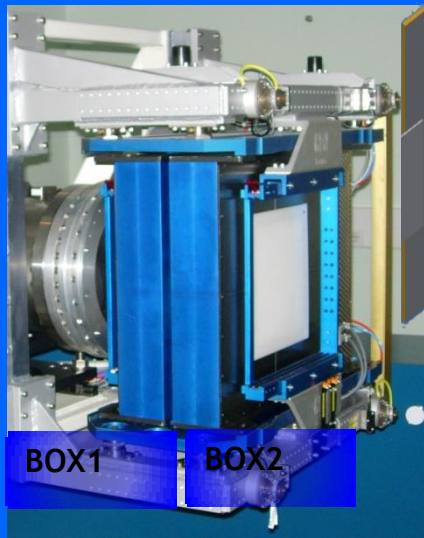
DD control system



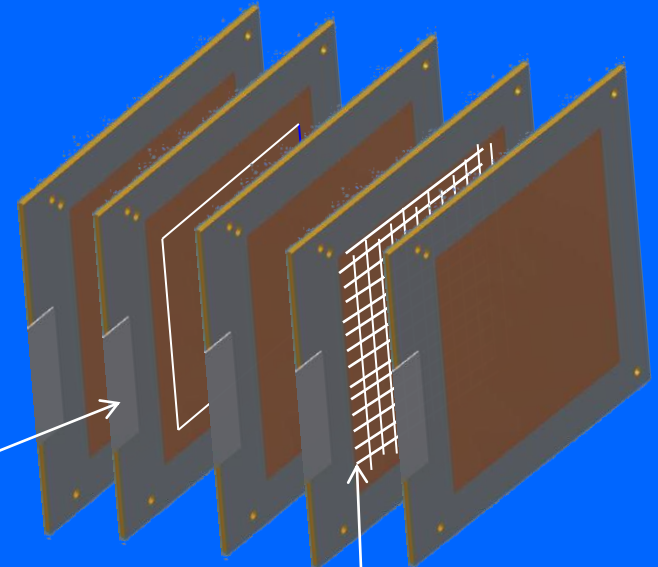
I monitor per il controllo on-line del fascio

- 5 camere a ionizzazione a gas (azoto)
- piatti piani paralleli e anodi segmentati
- trasparenti al fascio (0.9 mm waterEquiv)
- HV -400 V
- Gap 5 mm

1 cont = 200 fC



Elettrodi in BOX1



Elettrodi in BOX2

Bckgrd currents= ± 250 fA/channel

Sensitive area
 24×24 cm²

128 V strips

Strip X
pitch 1.65 mm

128 H strips

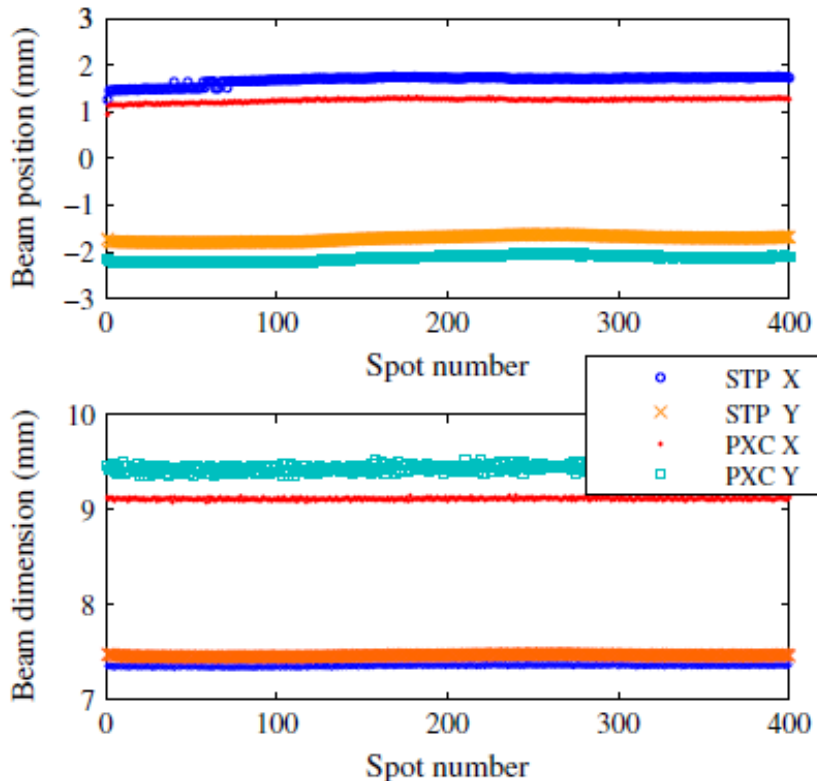
Strip Y
pitch 1.65 mm

1024 pixels

Pitch 6.6 mm

Caratteristiche dei rivelatori

Misura di posizione e dimensione del fascio



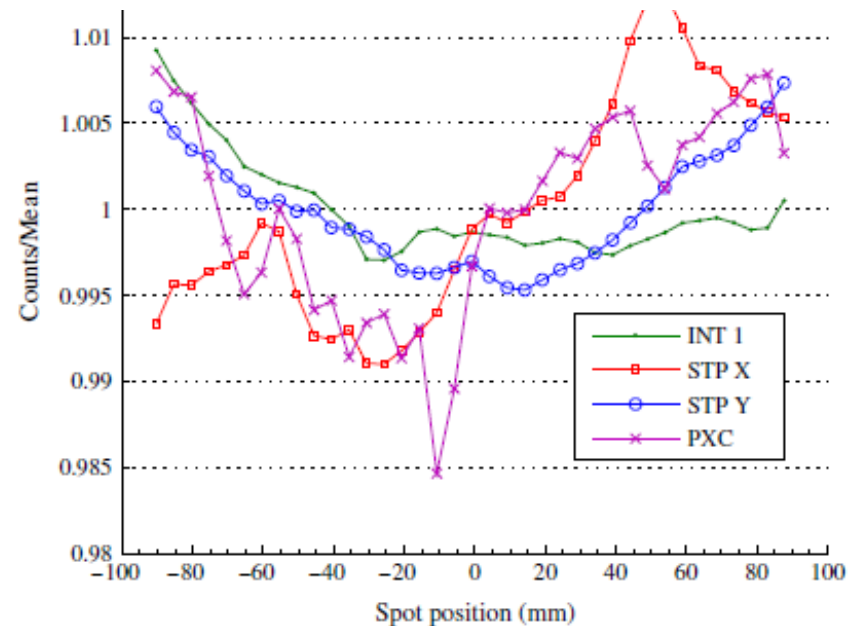
Risoluzione delle camere a strip e a pixel nella misura della posizione con $7E+7$ p/spot): 0.10 mm strip e 0.2 mm pixel

Giordanengo et al. NIM A 698 (2013) 202

Stabilità a breve termine nella misura della fluenza dei 5 rivelatori (su 400 spot consecutivi): Migliore del 0.3%

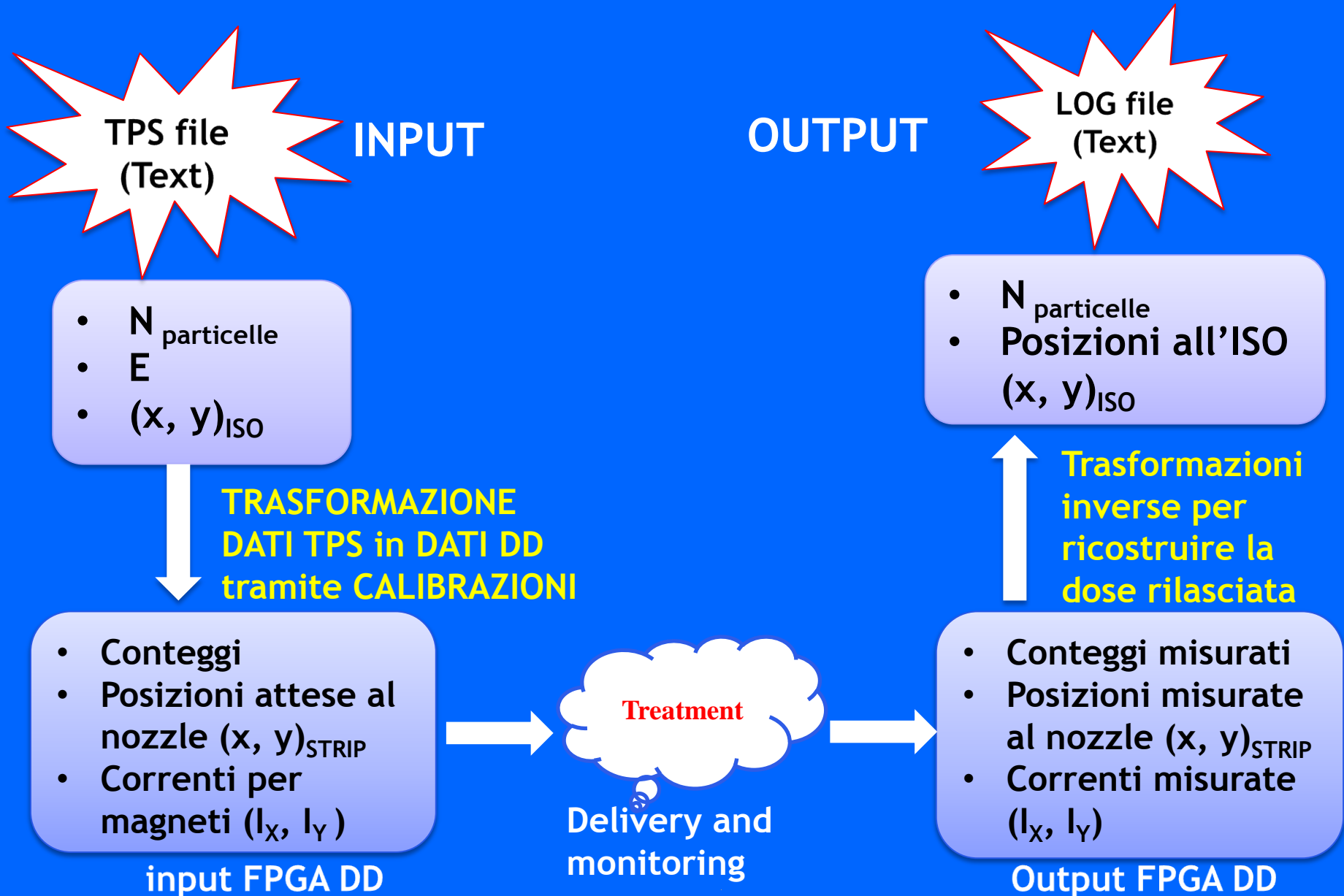
	INT1	INT2	STP X	STP Y	PXC
Max-min (%)	1.4	1.4	0.62	0.89	0.77
RMS (%)	0.30	0.29	0.11	0.14	0.12

Uniformità lungo l'asse X dei 5 rivelatori
Camera Integrata 1% (0.5% per campi piccoli)

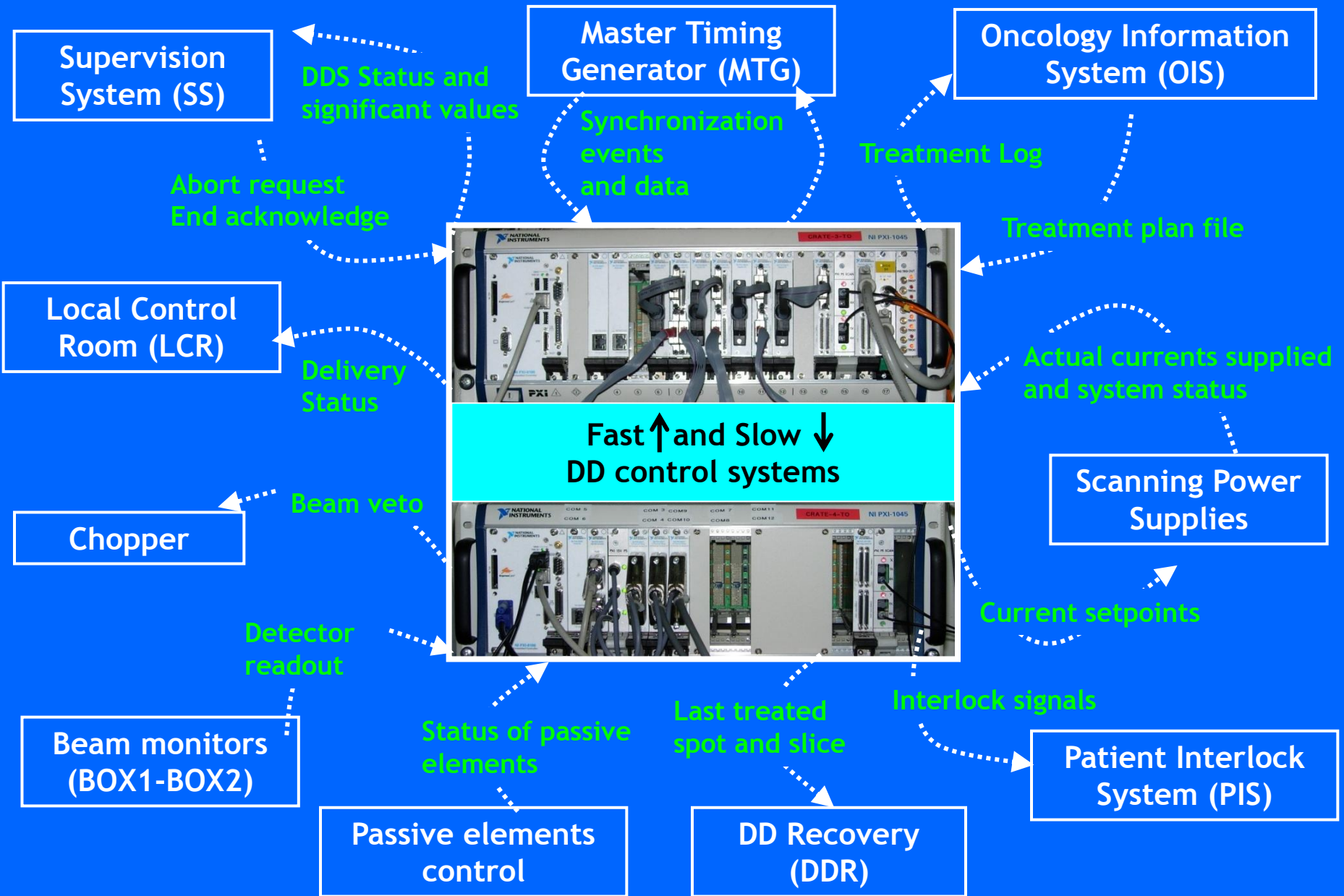


Media dei conteggi di ciascun punto normalizzati alla media delle 37 posizioni

INPUT e OUTPUT principali del DD per un trattamento



Sistemi che si interfacciano al Dose Delivery



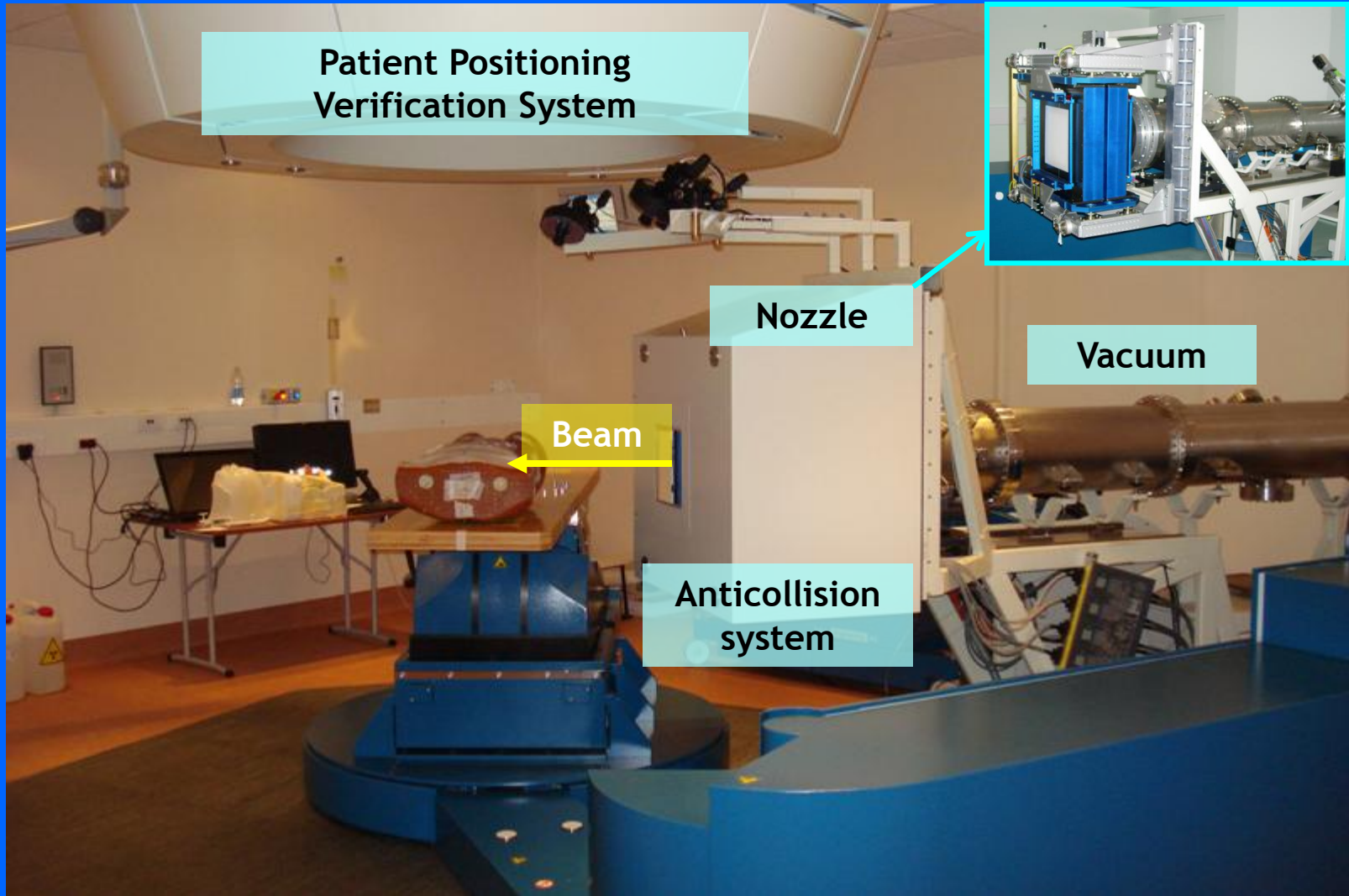
Condizioni di interlock e veto al chopper

Il Dose Delivery è connesso direttamente al chopper per interrompere l'irraggiamento in $< 200 \mu\text{s}$ in caso di:

- **errori in dose ($\text{Int1} \neq \text{Int2}$, $\Delta\text{counts} > 100$)**
- **errori in posizione ($\Delta x > 1 \text{ mm}$, $\Delta y > 1 \text{ mm}$)**
- **condizioni di interlock (HW e SW) del DD**
- **distanza tra spot $> 10 \text{ mm}$**

Il Dose Delivery prima dello spill *Controlla e Conferma* («AckCycle») che l'ENERGIA caricata è ESATTA, in caso contrario genera un Interlock e il trattamento si interrompe

Il nozzle con i monitor del DDS





CNAO is producing a CE marked Dose Delivery System for EBG - MedAustron

DATE 13th of June , 2012

CNAO – CENTRO NAZIONALE DI
ADROTERAPIA ONCOLOGICA

And

EBG MedAustron GmbH

DOSE DELIVERY SYSTEM DEVELOPMENT AND LICENSE AGREEMENT

U. Amaldi - generalità adroterapia
G. Baroni - posizionamento e verifica del paziente
E. Bressi e C. Biscari - ottica
L. Casalegno e M. Russo - IT
G. Ciavola - sorgenti
M. Ciocca - dosimetria
A. Facoetti - radiobiologia
L. Falbo - cavità RF
M. Ferrarini - radioprotezione
F. Gerardi - edifici e impianti
S. Giordanengo e M. Donetti - beam delivery
L. Lanzavecchia - sistema da vuoto
A. Parravicini - diagnostica
C. Priano - magneti
M. Pullia - ottica e iniezione ed estrazione
S. Vitulli - acceleratori lineari

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