



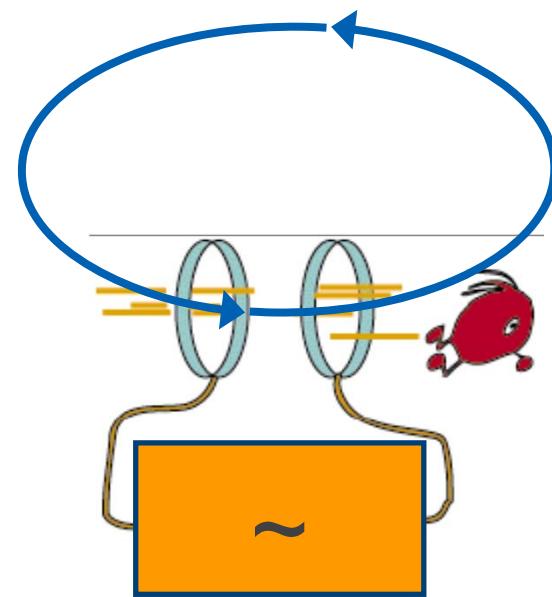
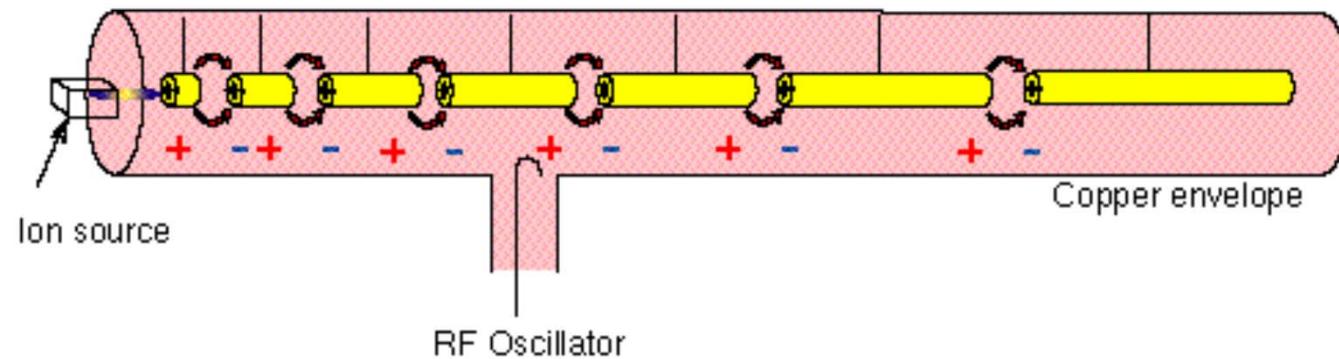
# Accelerators for hadrontherapy

M. Pullia

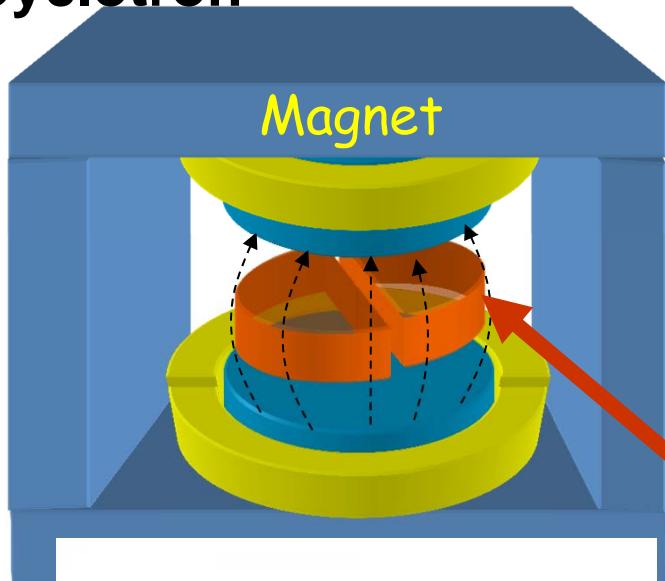
Giornatedi studio sui rivelatori, Cogne 2019

fondazione **CNAO**  
Centro Nazionale di Adroterapia Oncologica

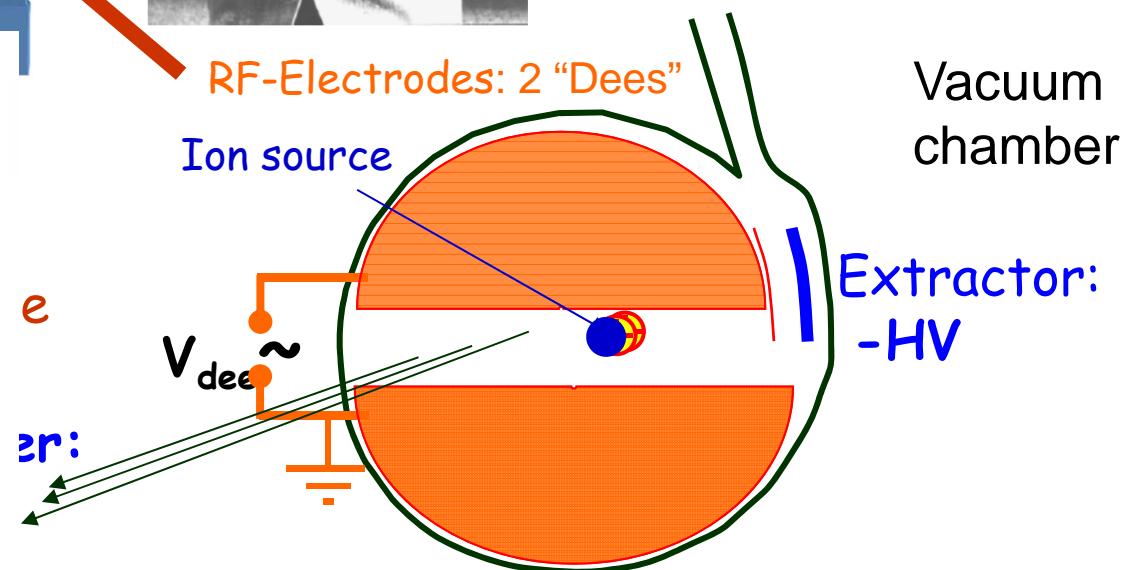
## RF accelerators (also circular)



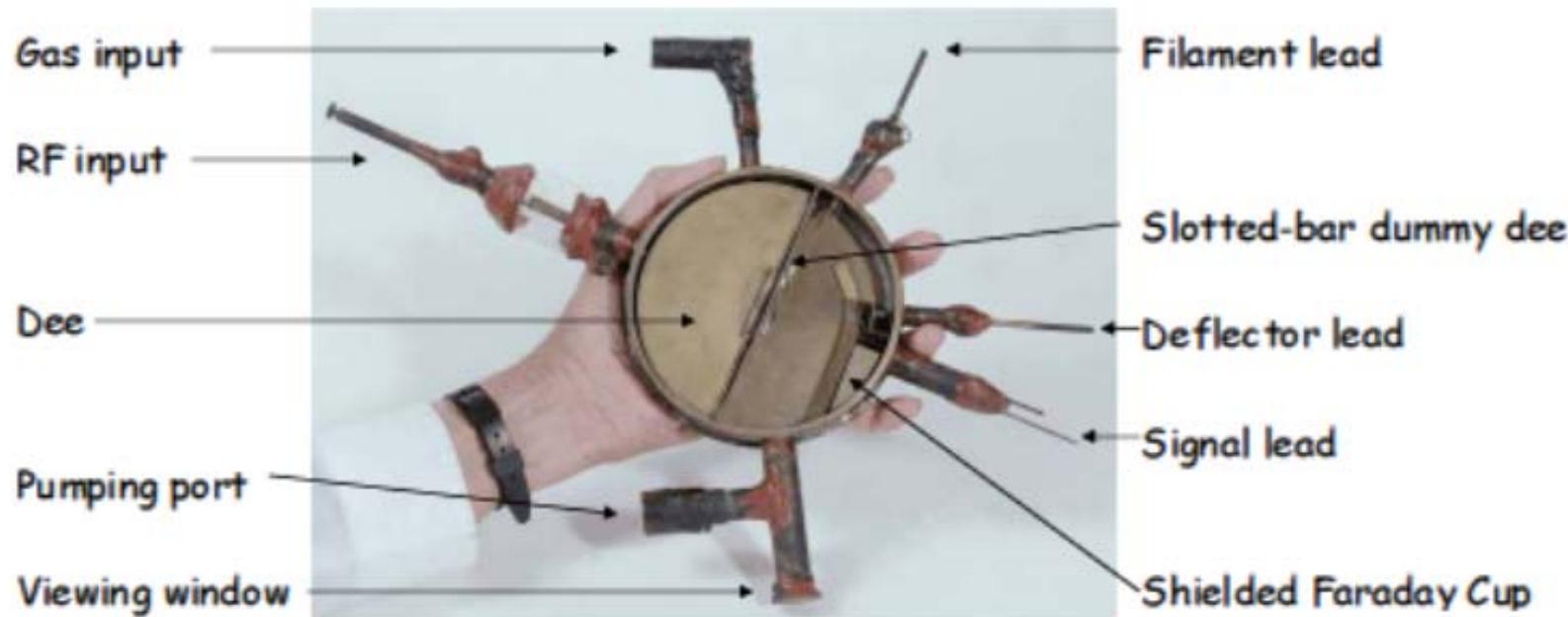
# Cyclotron



Ernest Lawrence  
(1901-1958)



## FIRST CYCLOTRON MODELS - Fall 1930



A new student, [Stanley Livingston](#), then took over, building a "4-inch" version in brass. Clear evidence of [magnetic field resonance](#) was found in November, and [in January 1931 they measured 80-keV protons](#).

Ions were produced from the residual gas by a heated filament at the centre. Note the liberally applied red sealing wax for vacuum tightness - and Glenn Seaborg's left hand.

(courtesy of G. Calabretta)

## Proton therapy cyclotron

### IBA PT subsystems : the Cyclone 235

The 230MeV cyclotron. WPE, Essen, 2010.



(Courtesy of IBA)

© IBA

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## Lorentz force

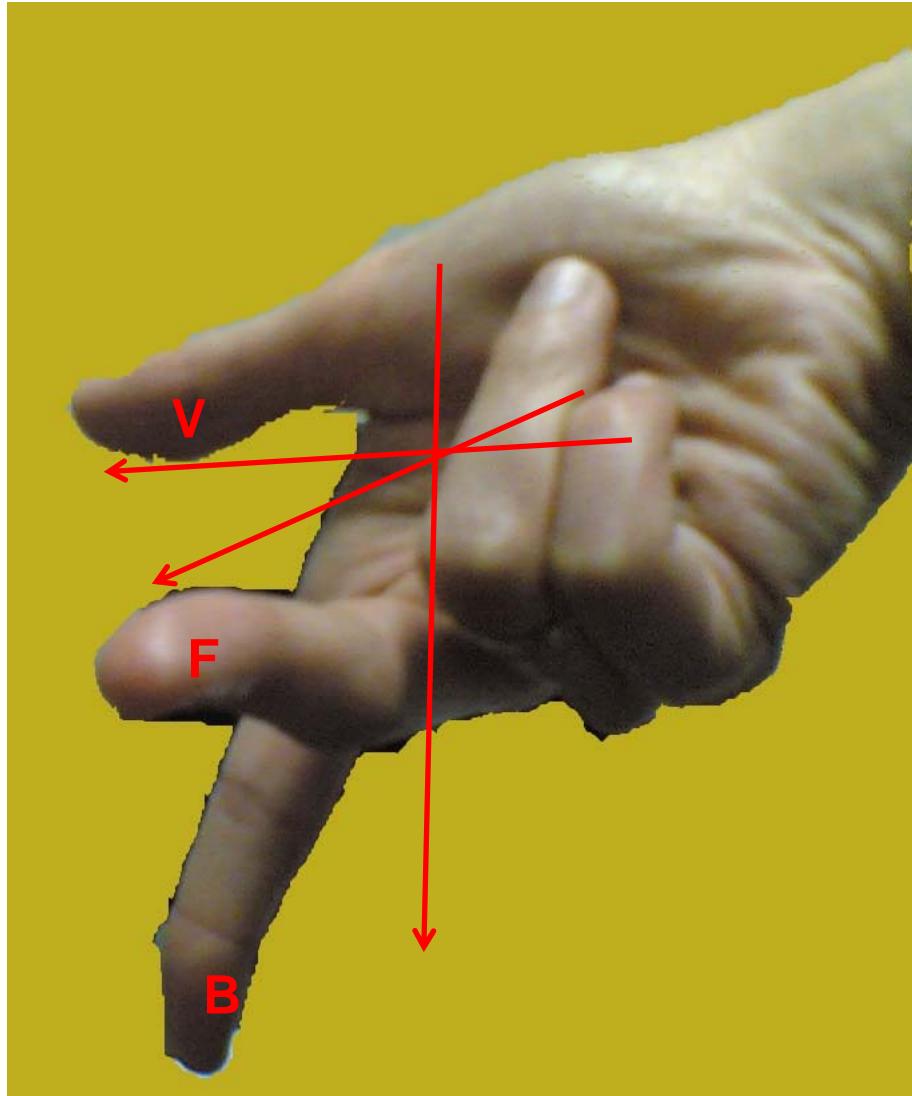
$$\vec{F} = q (\vec{E} + \vec{v} \times \vec{B})$$

↓      ↓      ↓      ↓      ↓  
 N      C      V/m    m/s    T

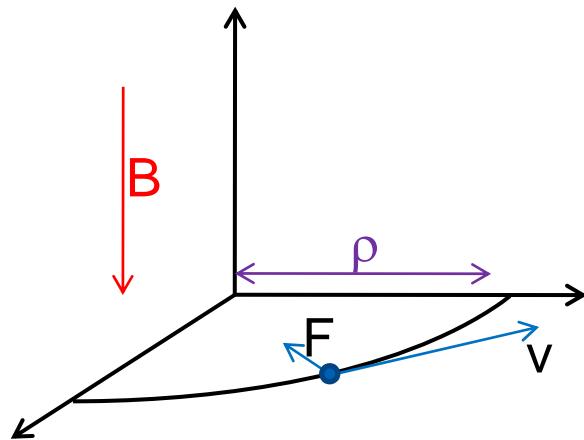
$E \sim 3 \text{ MV/m} = 3 \cdot 10^6 \text{ V/m}$   
 (dielectric rigidity of dry air)

$B \sim 1 \text{ T}$

$v < 3 \cdot 10^8 \text{ m/s}$



# Magnetic rigidity



$$F = q(E + v \times B)$$

$$qvB = \frac{mv^2}{\rho} \Rightarrow B\rho = \frac{p}{q}$$

## Practical units

$$0.2998 \ B [T] \rho [m] = p [\text{GeV}/c]/q [e]$$



“Zero comma c”

## Easy way

$$\gamma = \frac{m_0 c^2 + K}{m_0 c^2} \quad \beta = \sqrt{1 - \frac{1}{\gamma^2}}$$

$$p = m v = \gamma m_0 c \frac{v}{c} = \gamma \beta m_0 c = \gamma \beta m_0 c^2 / c \quad \text{GeV/c}$$

$$B \rho = \frac{1}{0.2998} \frac{p}{q} \quad \text{T m}$$

# 100 MeV proton

Proton	100 MeV	<b>Gamma</b>	<b>Beta</b>	<b>Betagamma</b>	<b>Momentum</b>	<b>Magnetic_Rigidity</b>
		1.106581	0.428199	0.473836619	0.444579577	1.482957842

$\uparrow$   
 $(938+100)/938$

# Cyclotron frequency

T	gamma	beta	bg	p [Mev/amu]	Brho		B	rho	T	f_cyc
1	1.001	0.046	0.046	43.174	0.145		1	0.145	6.57E-08	15.2E+6

T	gamma	beta	bg	p [Mev/amu]	Brho		B	rho	T	f_cyc
10	1.011	0.145	0.147	136.857	0.460		1	0.46	6.63E-08	15.1E+6

T	gamma	beta	bg	p [Mev/amu]	Brho		B	rho	T	f_cyc
100	1.107	0.430	0.476	443.056	1.489		1	1.489	7.26E-08	13.8E+6

## Limit of the classical, weak focusing cyclotron

The revolution frequency decreases when the particle begins to be relativistic ( $\gamma > 1$ )

$$m = \gamma m_0 = \frac{m_0}{\sqrt{1 - \beta^2}} \quad , \quad \beta = \frac{v}{c}$$

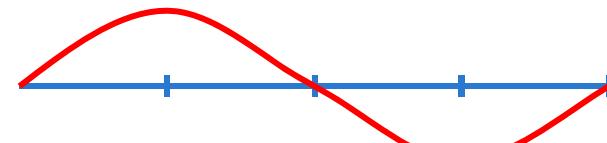
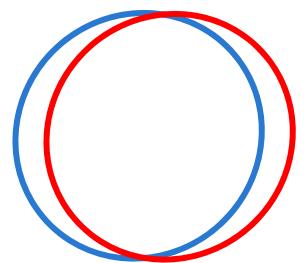
$$\omega_{rev} = \frac{QB(r)}{\gamma(r)m_0}$$

$\omega_{rev}$  constant if  $B(r) = \gamma(r)B_0$

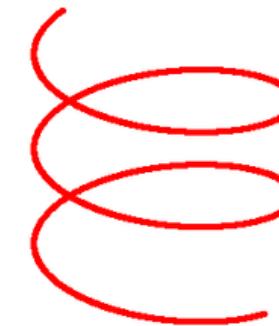
To keep synchronization,  $B(r)$  shall increase like  $\gamma(r)$

(courtesy of G. Calabretta)

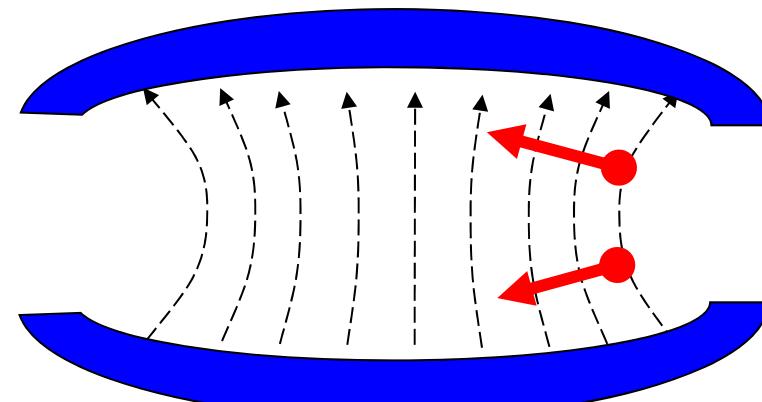
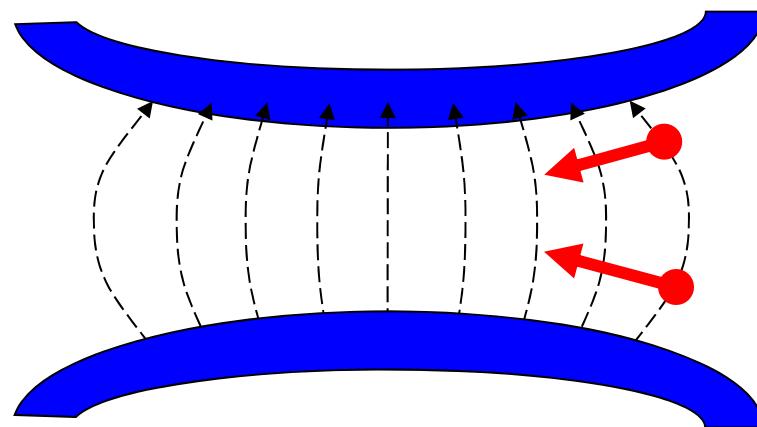
## Vertical focusing



Intrinsic  
Radial focusing

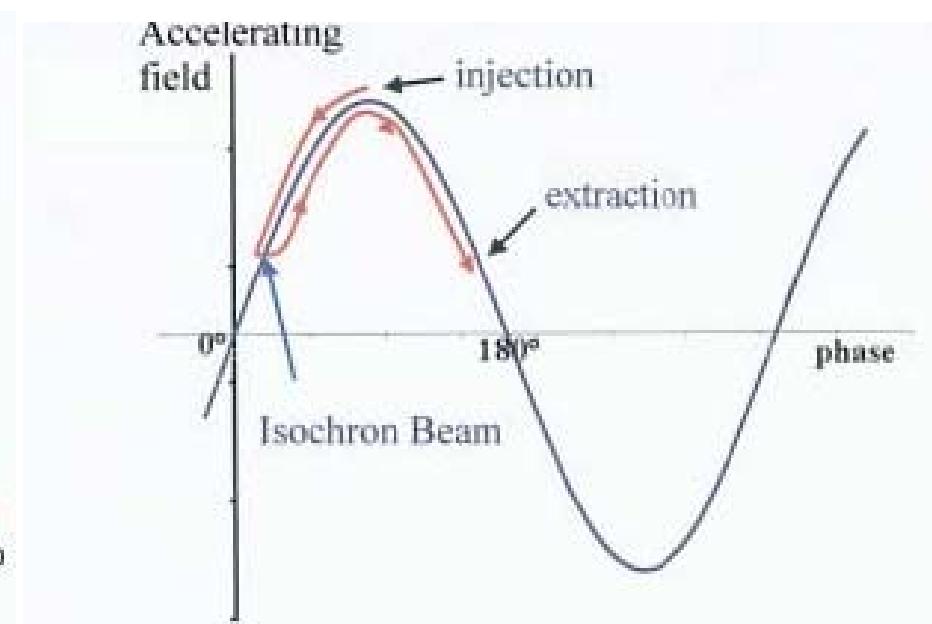
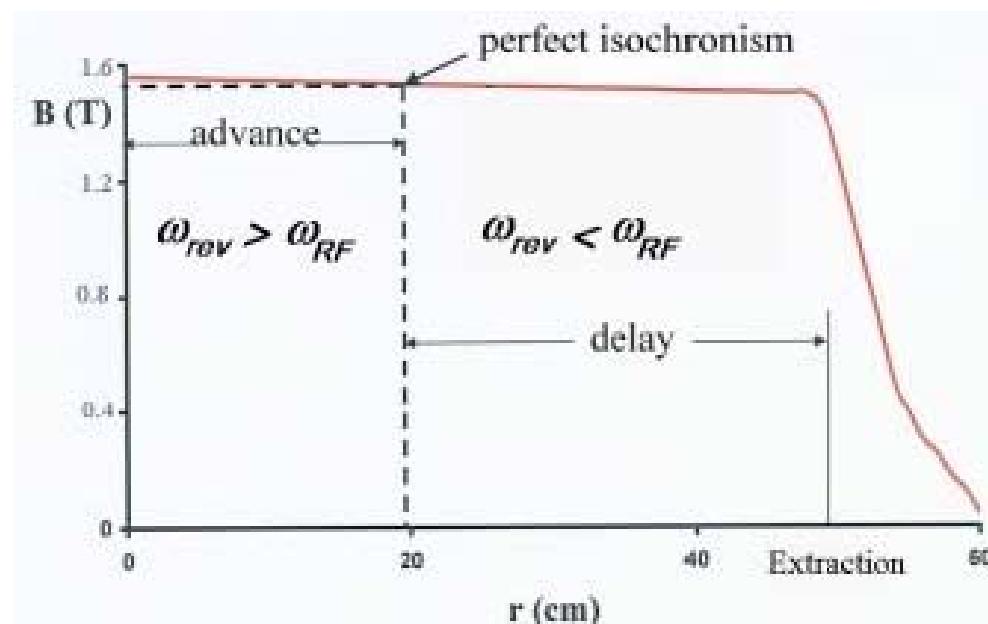


Conflicting requirement with radial B increase



# Limit of the classical, weak focussing cyclotron

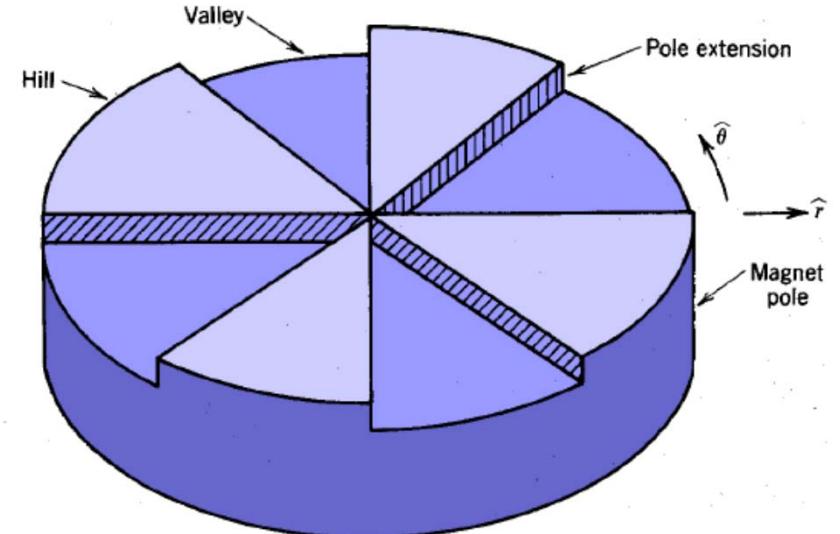
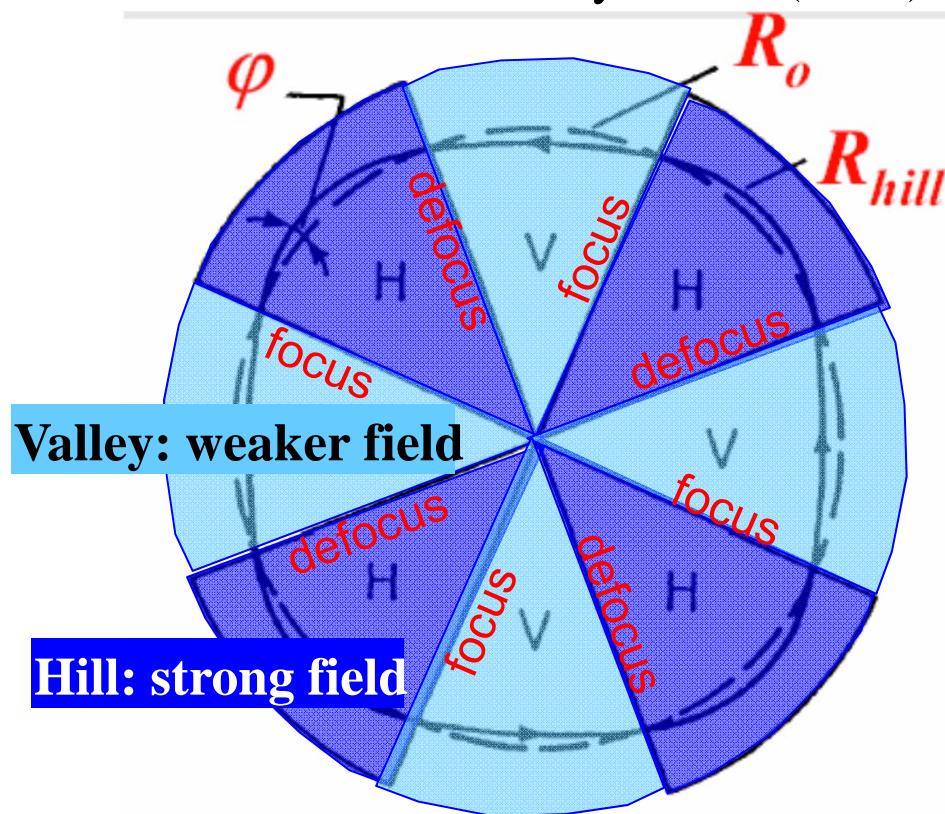
Isochronism only at a given value of R.  
 Choose the value at about 1/3 of extraction radius



(courtesy of G. Calabretta)

## Azimuthal focusing

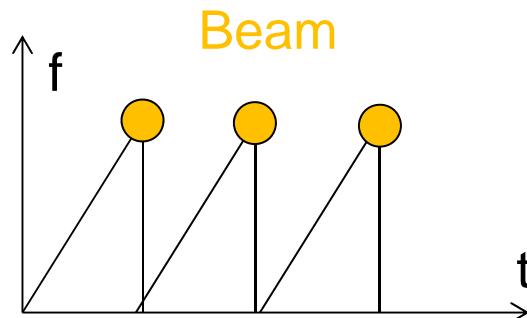
Thomas-Cyclotron (1938)



# Synchrocyclotron

Vary the RF frequency to keep the synchronism

The beam is **no more continuous**. There is a beam pulse for each RF frequency sweep.

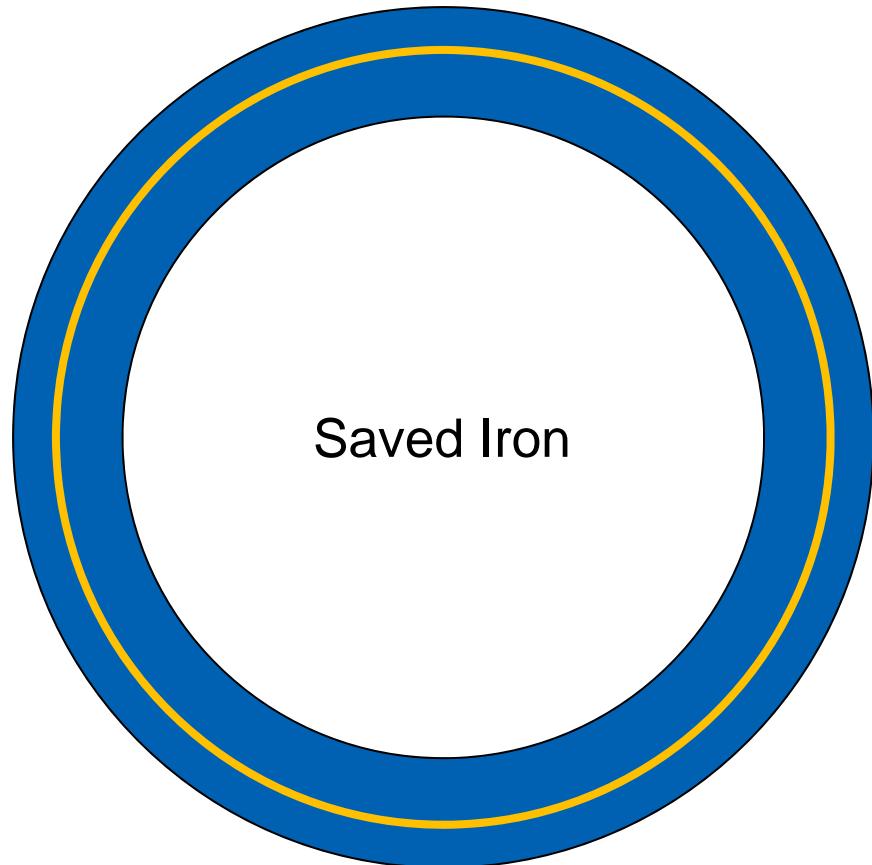
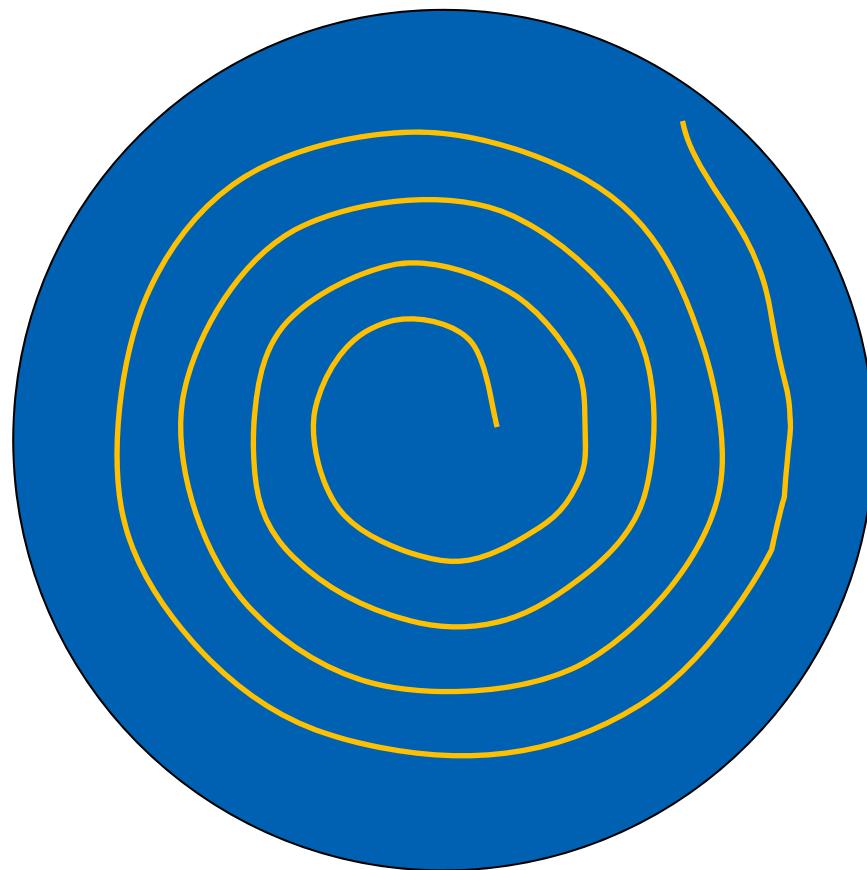


Deuteron ions to 190MeV  
and He<sup>2+</sup> ions to 380MeV

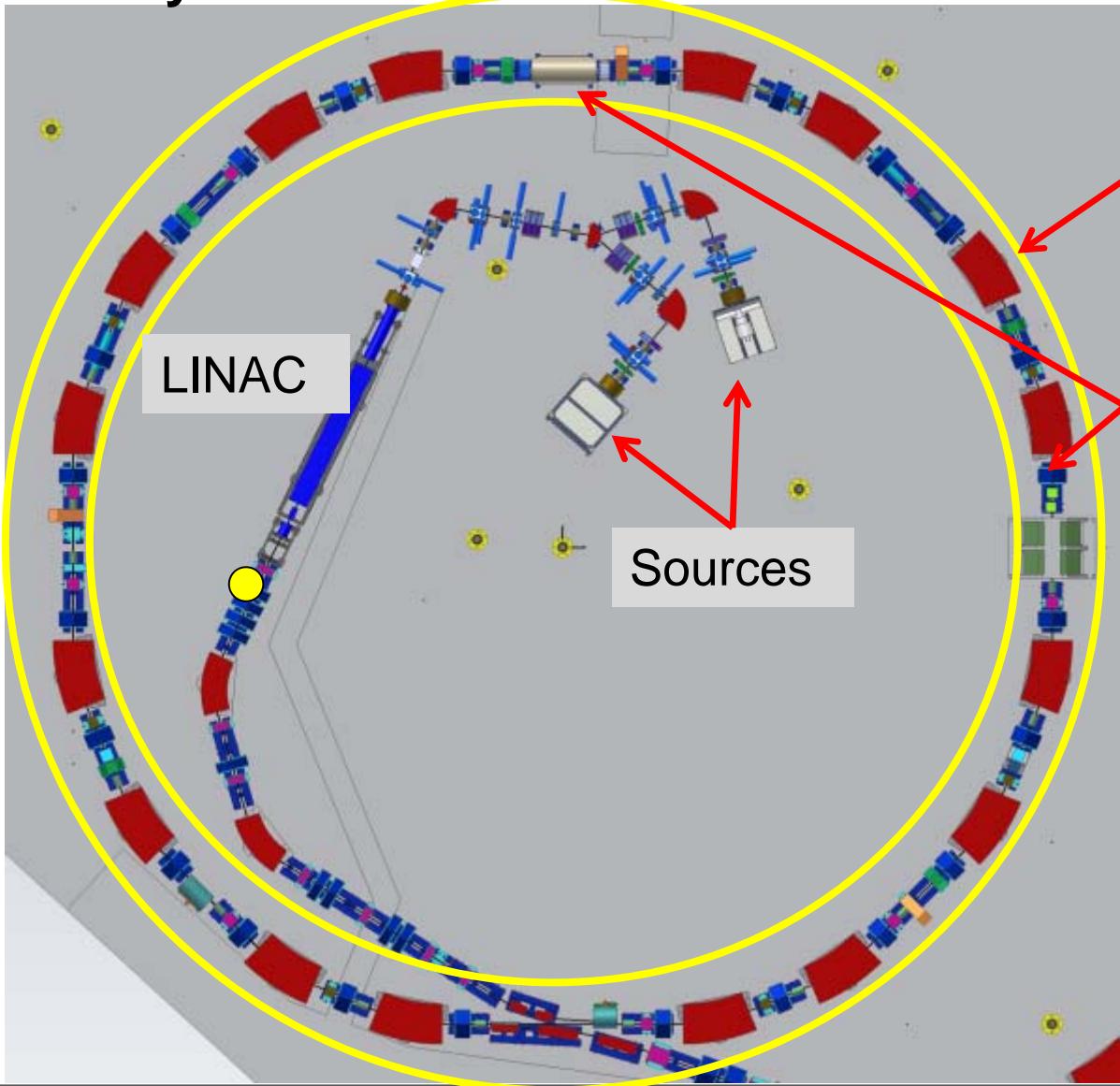


**Sincrociclotrone di Berkeley**

## Synchrotron vs cyclotron



## The Synchrotron



Dipoles (bending)

Quadrupoles  
(focussing,  
100 000 km!)

Vacuum

RF Cavity  
(acceleration)

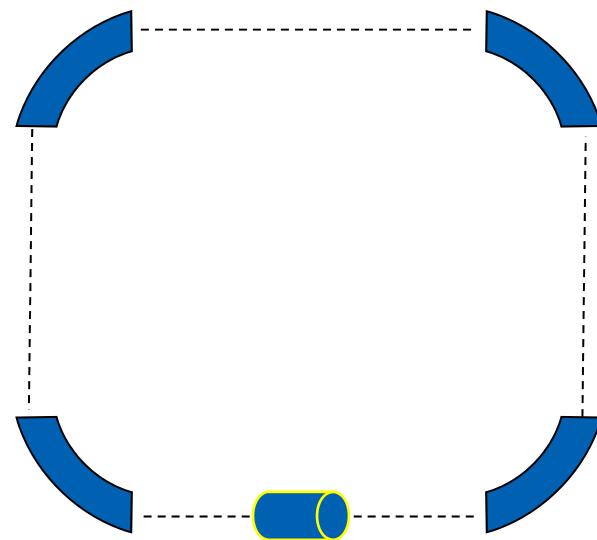
R fixed

E increases

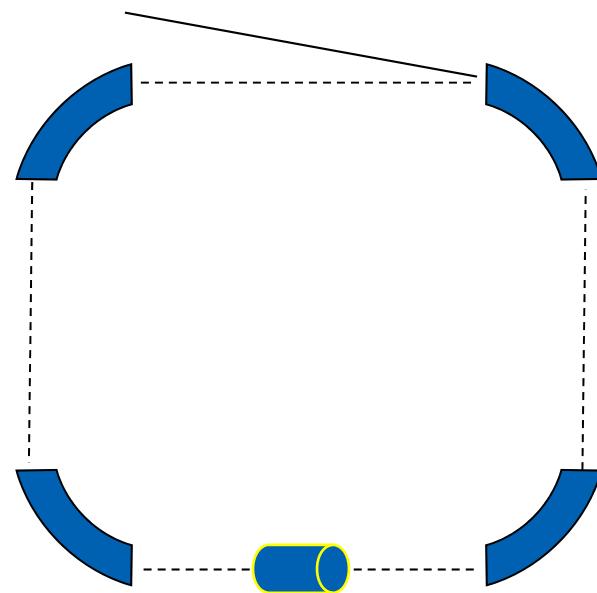
F increases

B increases

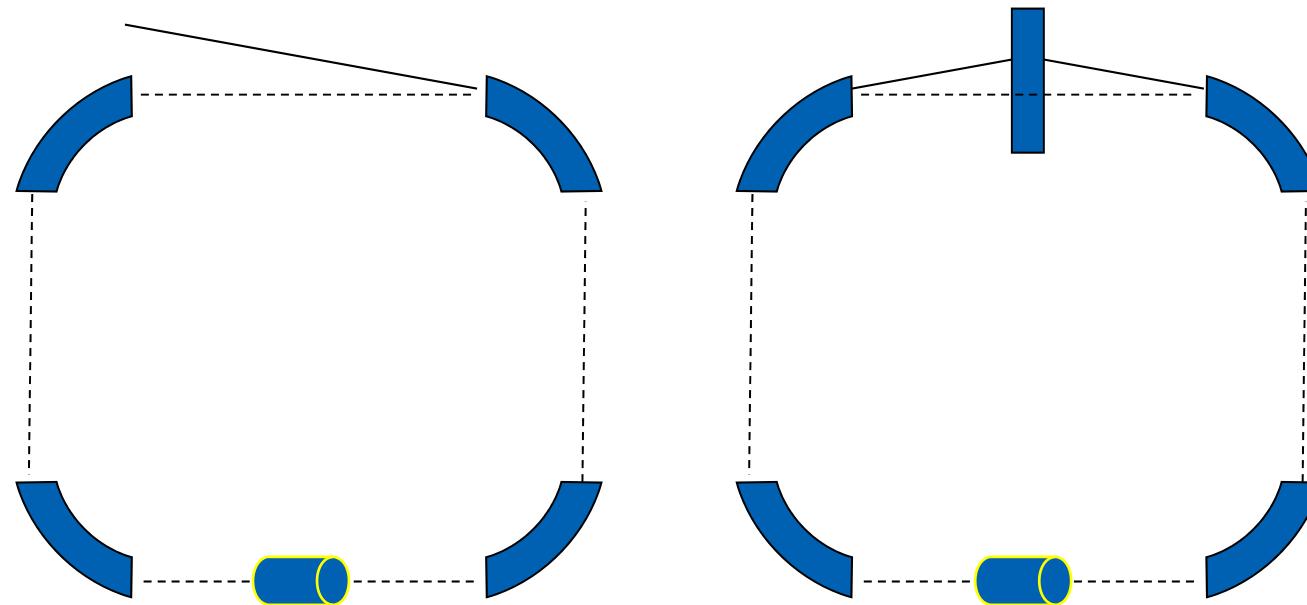
# Focusing



# Focusing



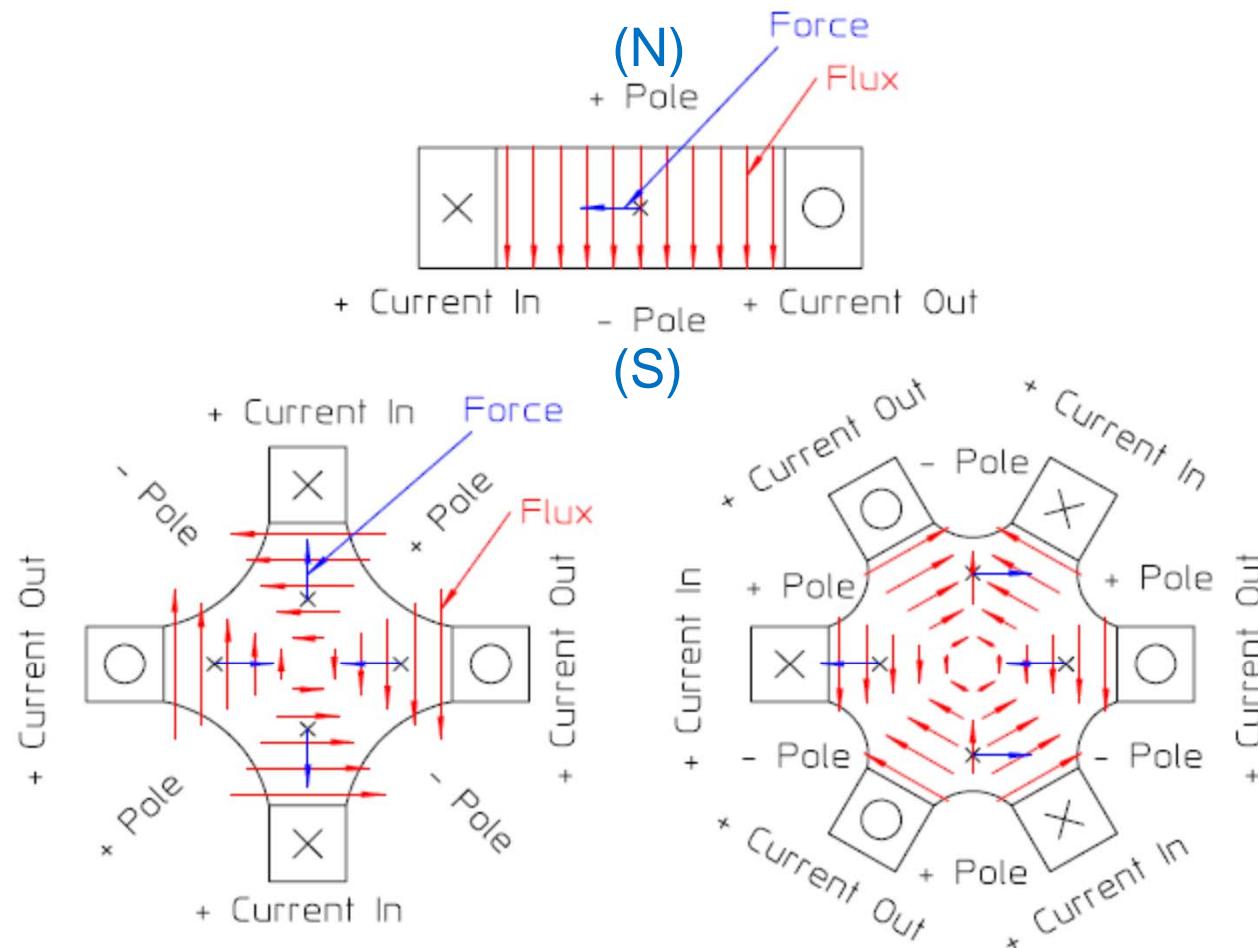
# Focusing



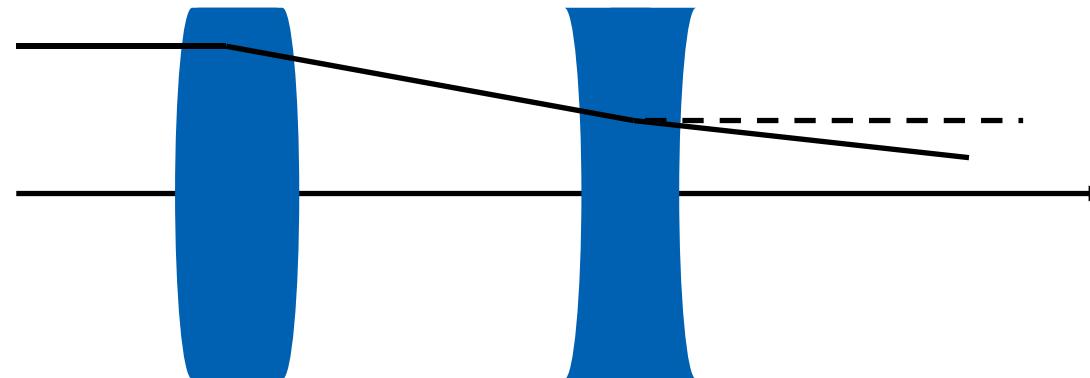
## Magnets and fields

- Dipoles to define the ideal path
- Quadrupoles to keep particles near the ideal path
- Sextupoles to correct Chromatic (momentum) effects

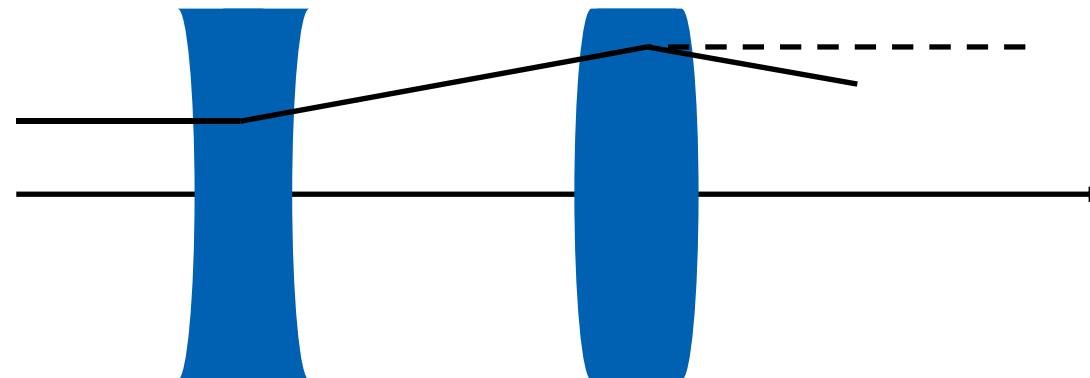
# Magnets and fields

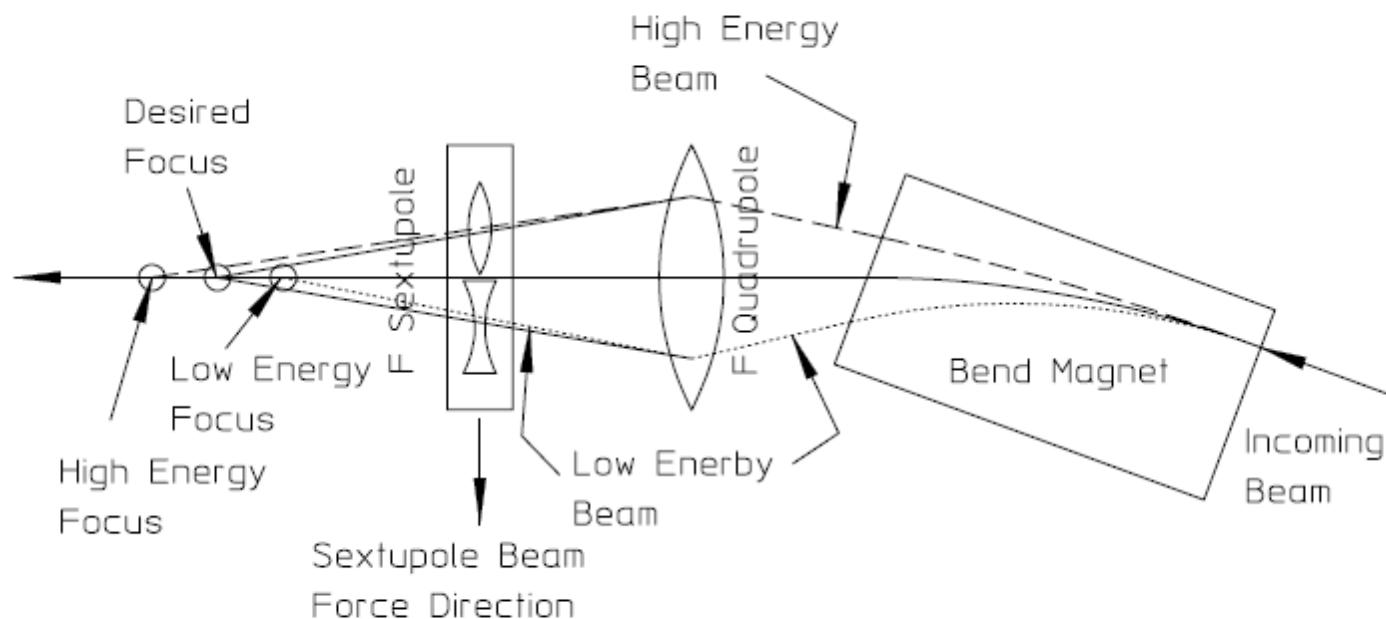


## Strong focusing

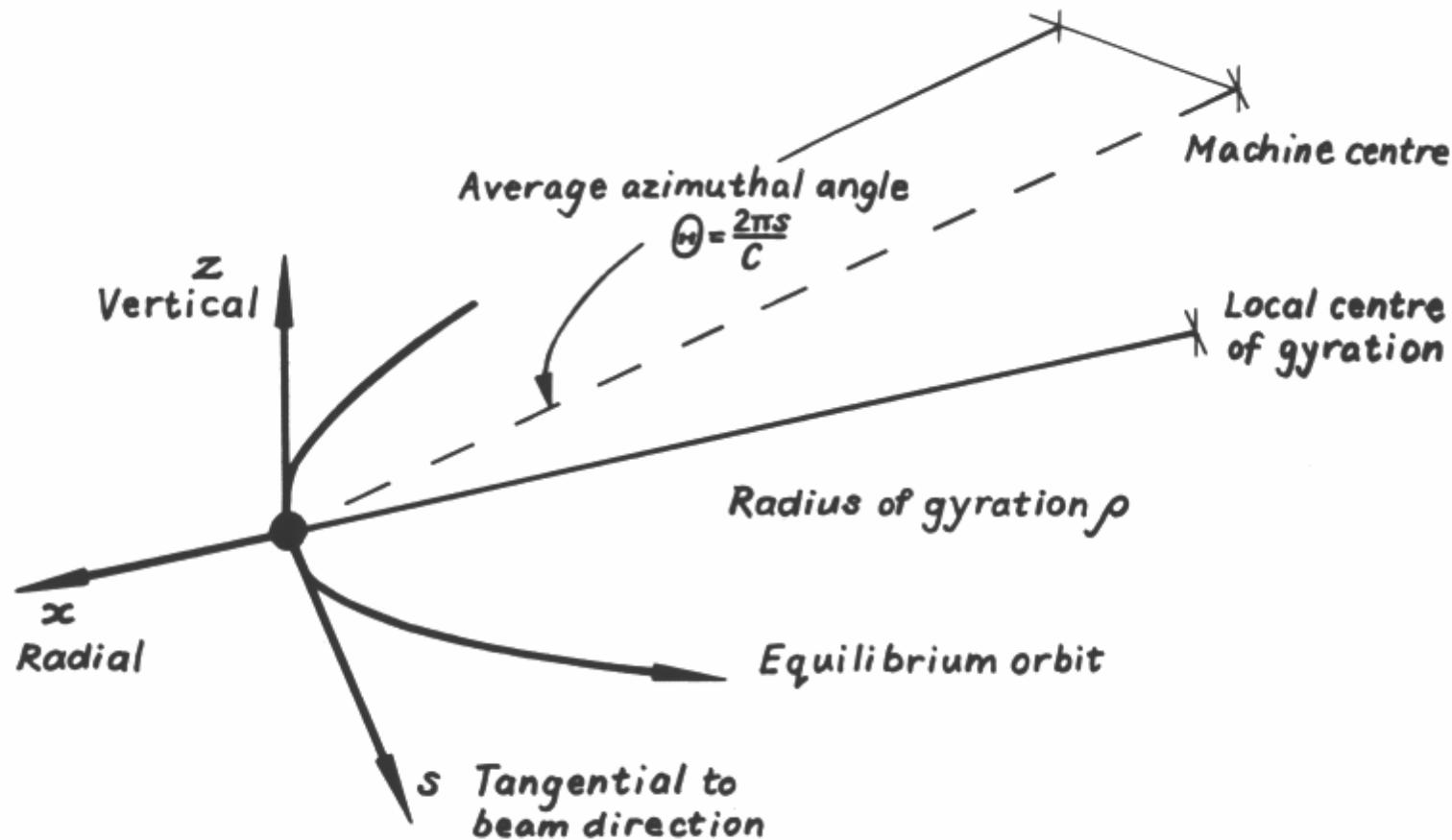


$$F \propto r$$





## Reference system



Motion described as displacement wrt reference particle

## Hill's equation and beta function

$$\frac{d^2y}{ds^2} + K_y(s)y = 0 \quad y = x \text{ or } z$$

$$y(s) = A \beta_y(s)^{1/2} \cos \left[ \int_0^s \frac{d\sigma}{\beta_y(\sigma)} + B \right]$$

$$\alpha_y(s) = -\frac{1}{2} \frac{d\beta_y}{ds} \quad \gamma_y(s) = \frac{1 + \alpha_y^2}{\beta_y}$$

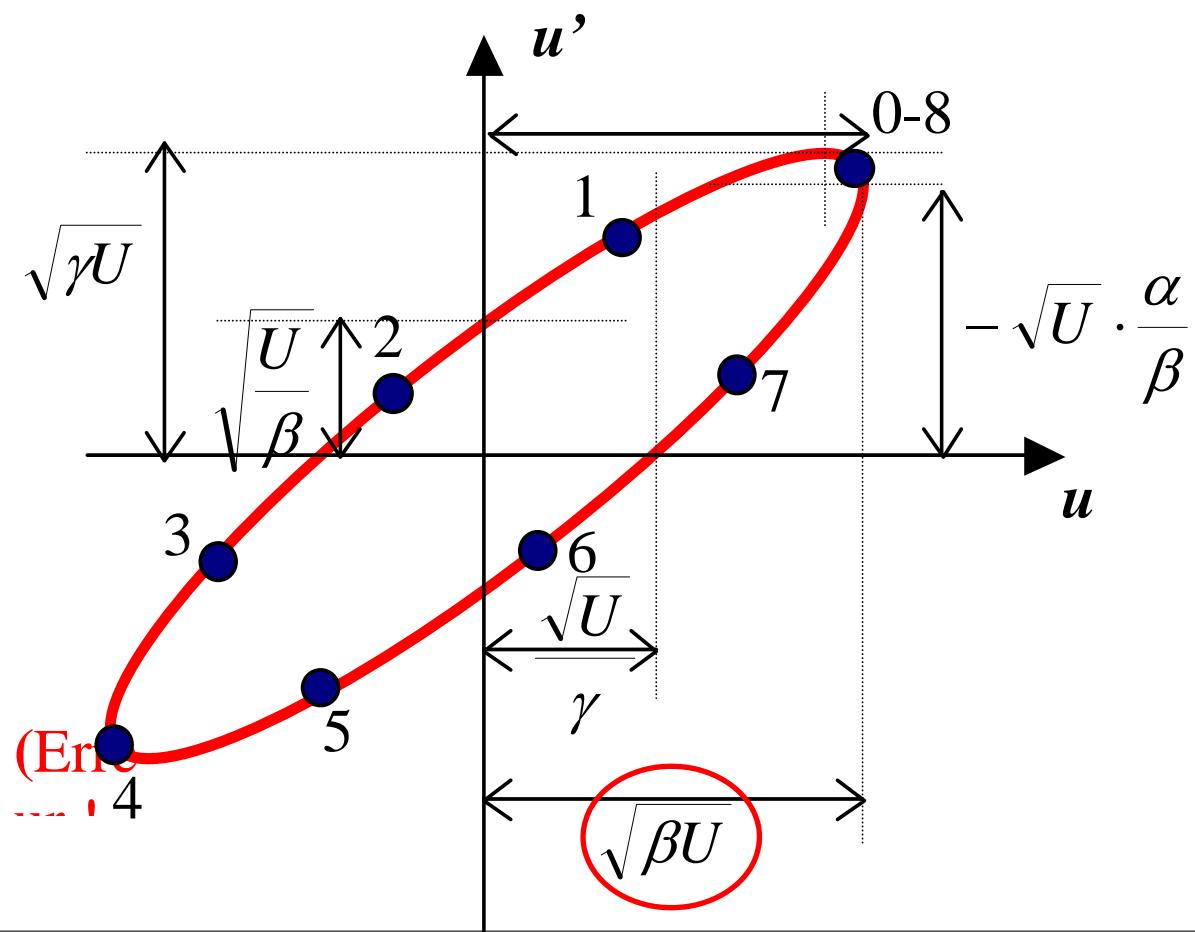
$$\mu_y(s) = \int_0^s \frac{1}{\beta_y(\sigma)} d\sigma$$

## Transfer matrix

$$\begin{pmatrix} y \\ y' \end{pmatrix}_2 = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \begin{pmatrix} y \\ y' \end{pmatrix}_1$$

$$\boldsymbol{M}(s_1 \rightarrow s_2) = \begin{pmatrix} \left(\frac{\beta_2}{\beta_1}\right)^{1/2} (\cos \Delta\mu + \alpha_1 \sin \Delta\mu) & (\beta_1 \beta_2)^{1/2} \sin \Delta\mu \\ -(\beta_1 \beta_2)^{-1/2} [(1 + \alpha_1 \alpha_2) \sin \Delta\mu + (\alpha_2 - \alpha_1) \cos \Delta\mu] & \left(\frac{\beta_1}{\beta_2}\right)^{1/2} (\cos \Delta\mu - \alpha_2 \sin \Delta\mu) \end{pmatrix}$$

$$\gamma \cdot u^2 + 2 \cdot \alpha \cdot u \cdot u' + \beta \cdot u'^2 = U$$



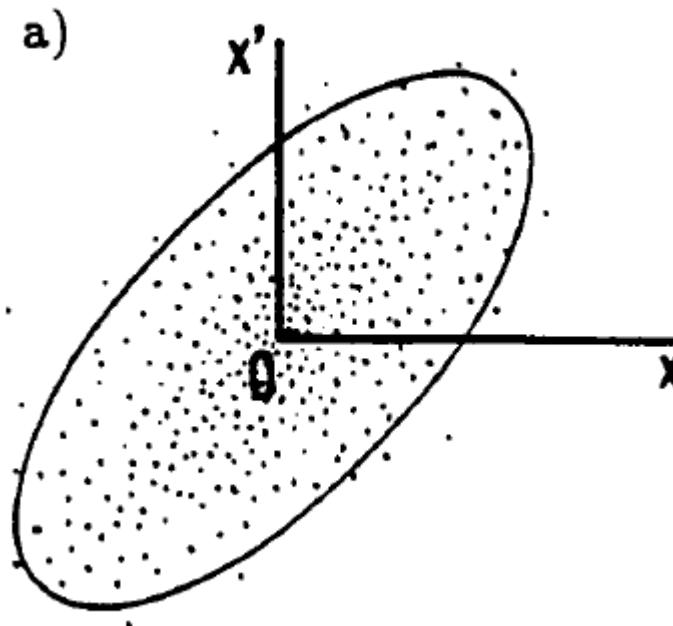
# Emittance

$$\gamma \cdot u^2 + 2 \alpha \cdot u \cdot u' + \beta \cdot u'^2 = \varepsilon$$

rms, 4 rms,  
90%, 95%, 99%

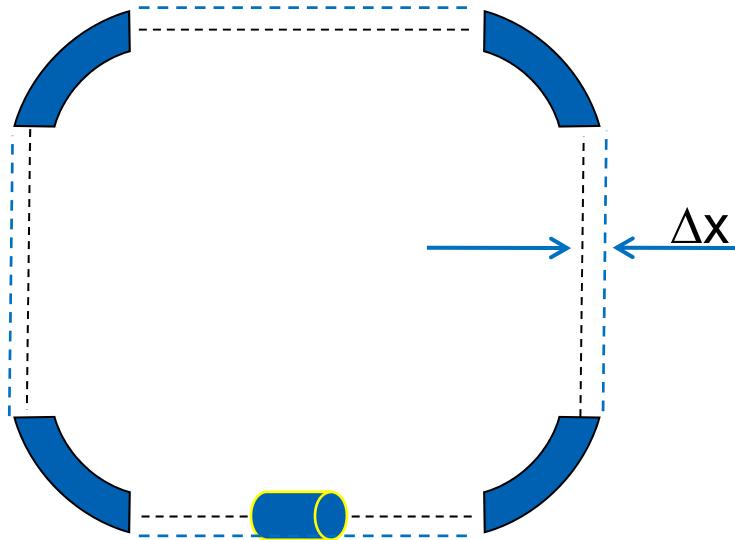
There are more  
emittance definitions  
than accelerator  
physicists...

Geometrical vs normalized  
emittance



$$\text{Ellipse area} = \pi \varepsilon$$

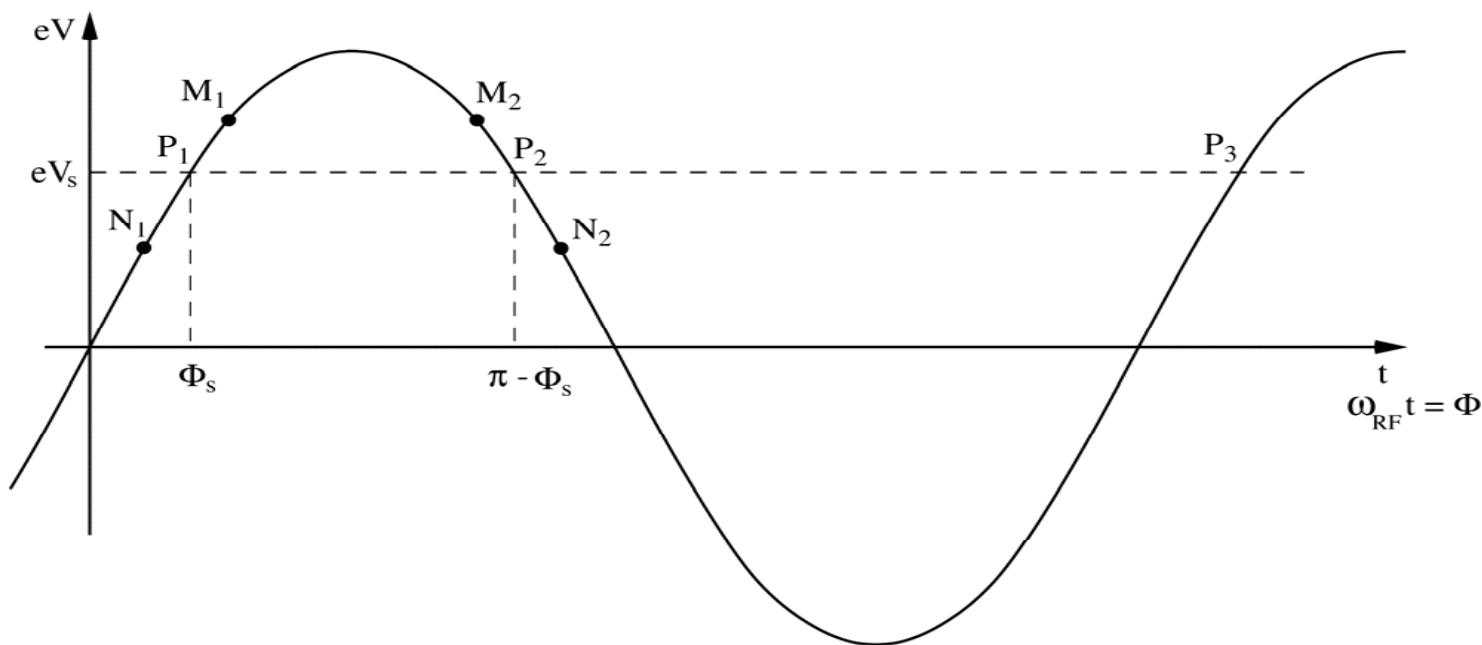
## Dispersion function



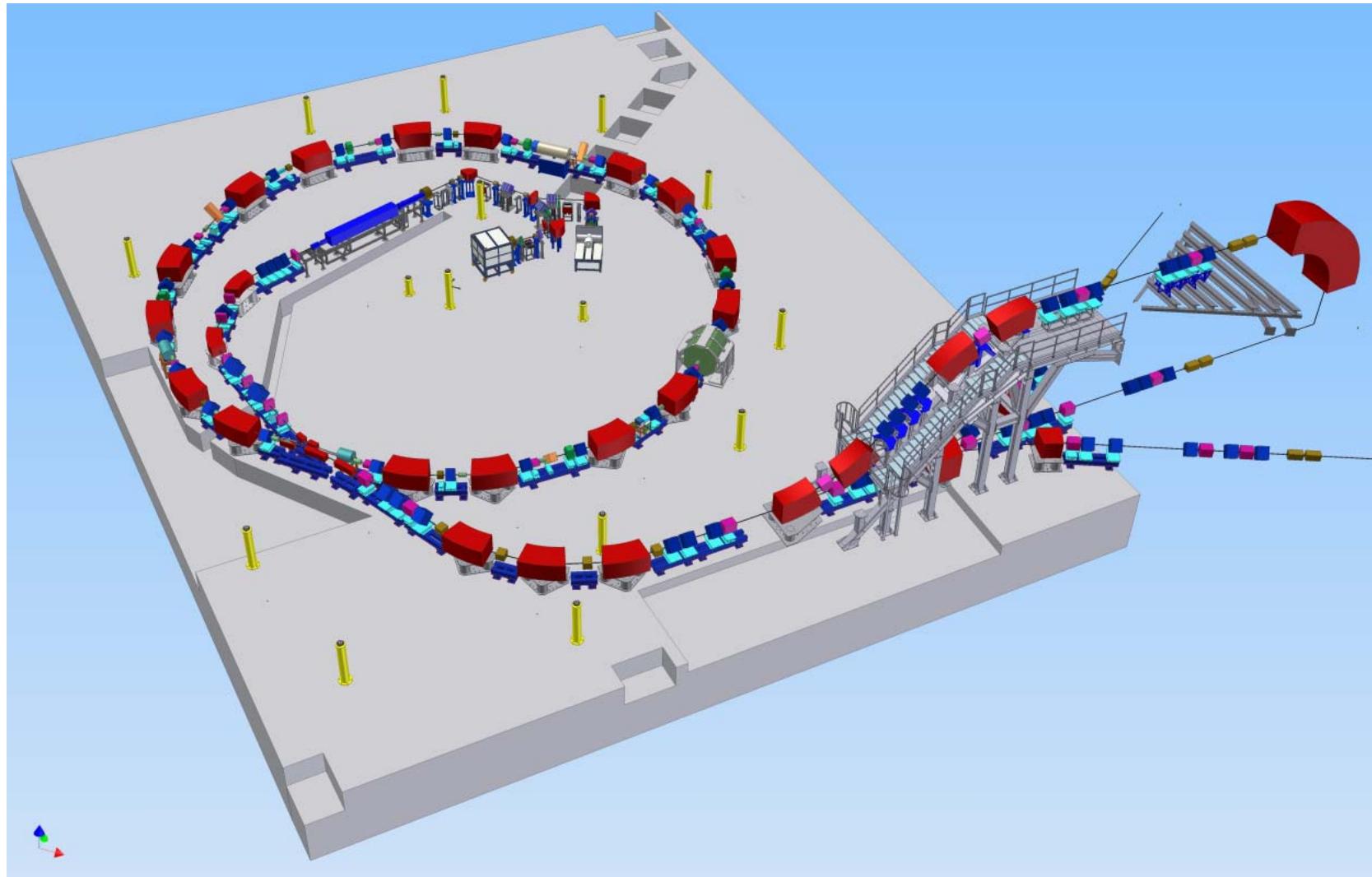
A particle with different energy moves along a different path

$$\Delta x = D \Delta p/p$$
$$\Delta x' = D' \Delta p/p$$

# Phase stability



# The CNAO accelerator and lines



# Design Parameters I

<b>Protons (<math>10^{10}</math>/spill)</b>				
	LEBT (*)	MEBT	SYNC	HEBT
Energy [MeV/u]	0.008	7	7-250	<b>60-250</b>
Imax [A]	$1.3 \times 10^{-3}$ (0.65, 0.45)	$0.7 \times 10^{-3}$	$5 \times 10^{-3}$	<b><math>7 \times 10^{-9}</math></b>
Imin [A]	$1.3 \times 10^{-3}$ (0.65, 0.45)	$70 \times 10^{-6}$	$0.12 \times 10^{-3}$	$17 \times 10^{-12}$
$\varepsilon_{\text{rms,geo}}$ [ $\pi$ mm mrad]	45	1.9	0.67-4.2	0.67-1.43(V)
$\varepsilon_{90,\text{geo}}$ [ $\pi$ mm mrad]	180	9.4	3.34-21.2	3.34-7.14 (V) 5.0 (H)
Magnetic rigidity [T m]	0.013 (0.026)	0.38	0.38-2.43	0.38-2.43
$(\Delta p/p)_{\text{tot}}$	$\pm 1.0\%$	$\pm(1.2-2.2)\%$	$\pm(1.2-3.4)\%$	$\pm(0.4-0.6)\%$

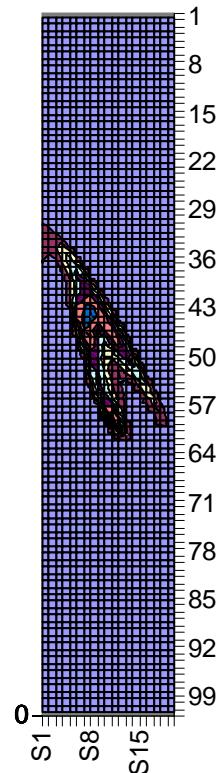
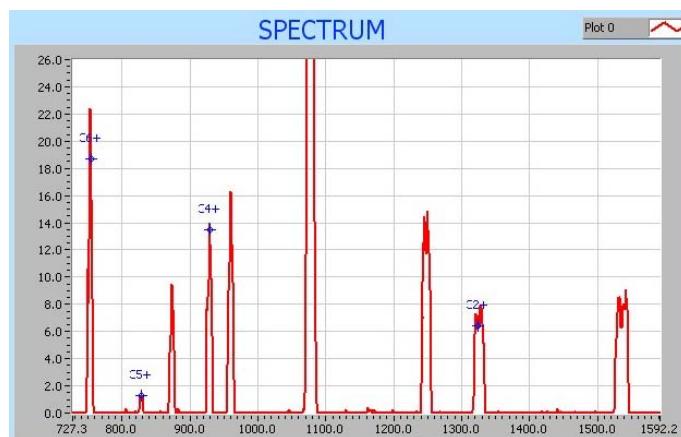
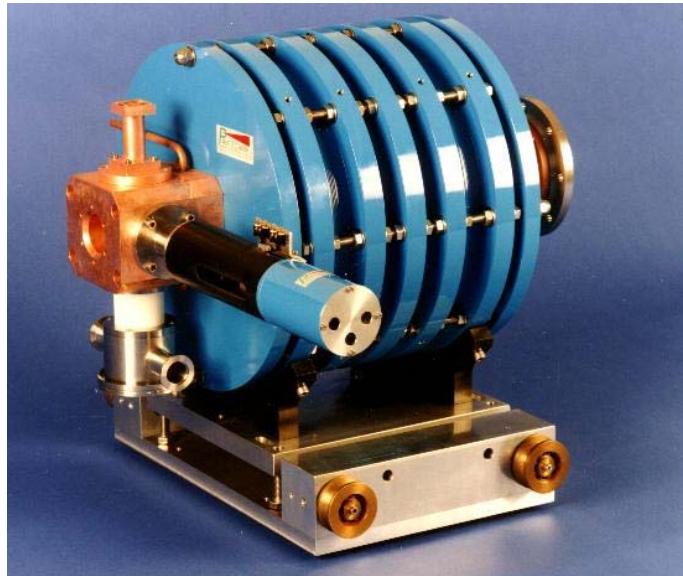
\* ( $H_2^+$ ,  $H_3^+$ )

# Design Parameters II

<b>Carbon (<math>4 \cdot 10^8</math> C/spill)</b>				
	LEBT (C <sup>4+</sup> )	MEBT	SYNC	HEBT
Energy [MeV/u]	0.008	7	7-400	<b>120-400</b>
Imax [A]	$0.15 \times 10^{-3}$	$0.15 \times 10^{-3}$	$1.5 \times 10^{-3}$	<b><math>2 \times 10^{-9}</math></b>
Imin [A]	$0.15 \times 10^{-3}$	$15 \times 10^{-6}$	$28 \times 10^{-6}$	$4 \times 10^{-12}$
$\varepsilon_{\text{rms,geo}}$ [ $\pi$ mm mrad]	45	1.9	0.73-6.1	0.73-1.43(V)
$\varepsilon_{90,\text{geo}}$ [ $\pi$ 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
$(\Delta p/p)_{\text{tot}}$	$\pm 1.0\%$	$\pm (1.2-2.0)\%$	$\pm (1.2-2.9)\%$	$\pm (0.4-0.6)\%$

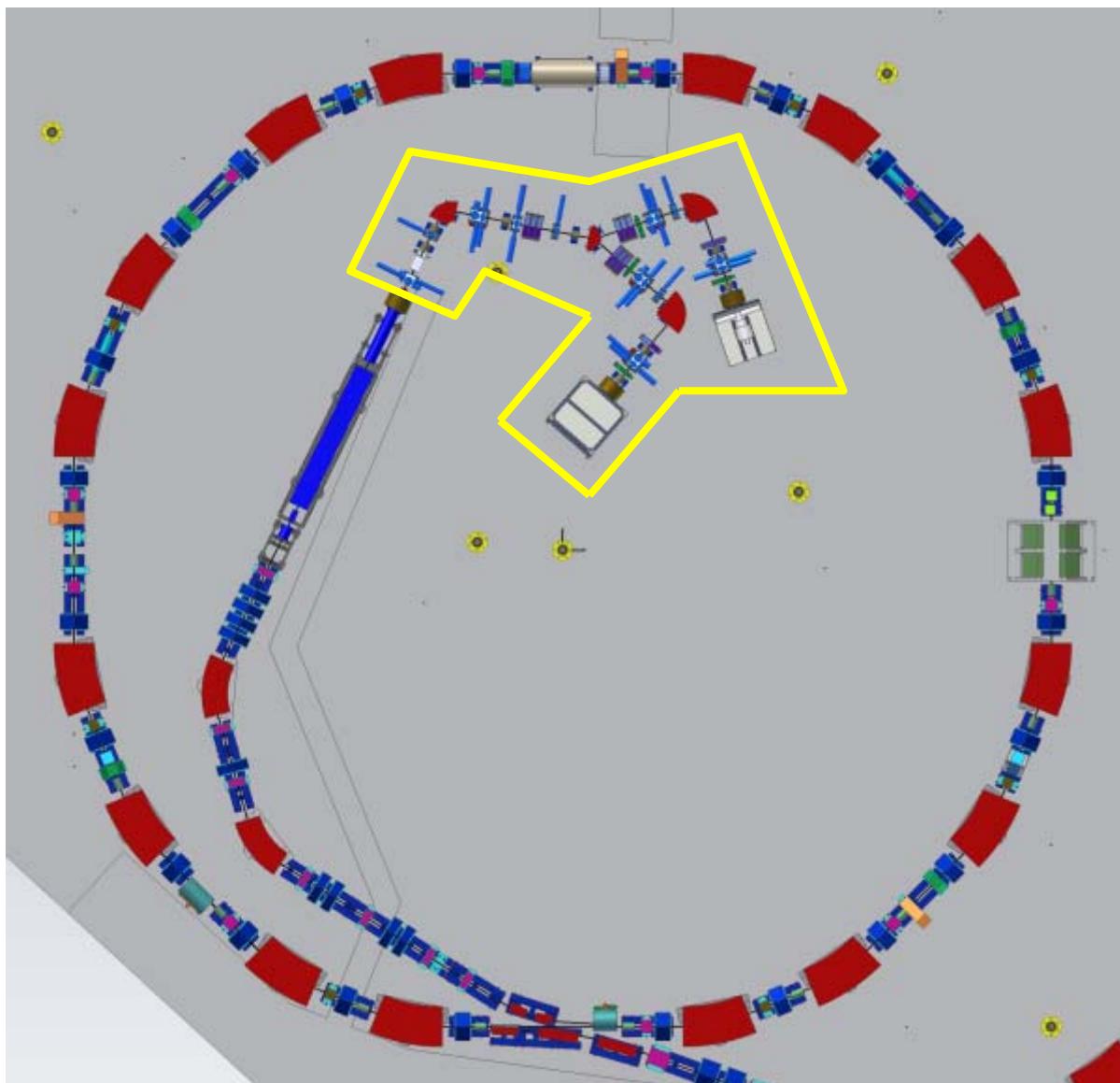
## Sources

ECR, always on



$$I_{\text{tot}} = 250 \mu\text{A}$$

$$I_{180\pi} = 85\% I_{\text{tot}}$$



**LEBT**

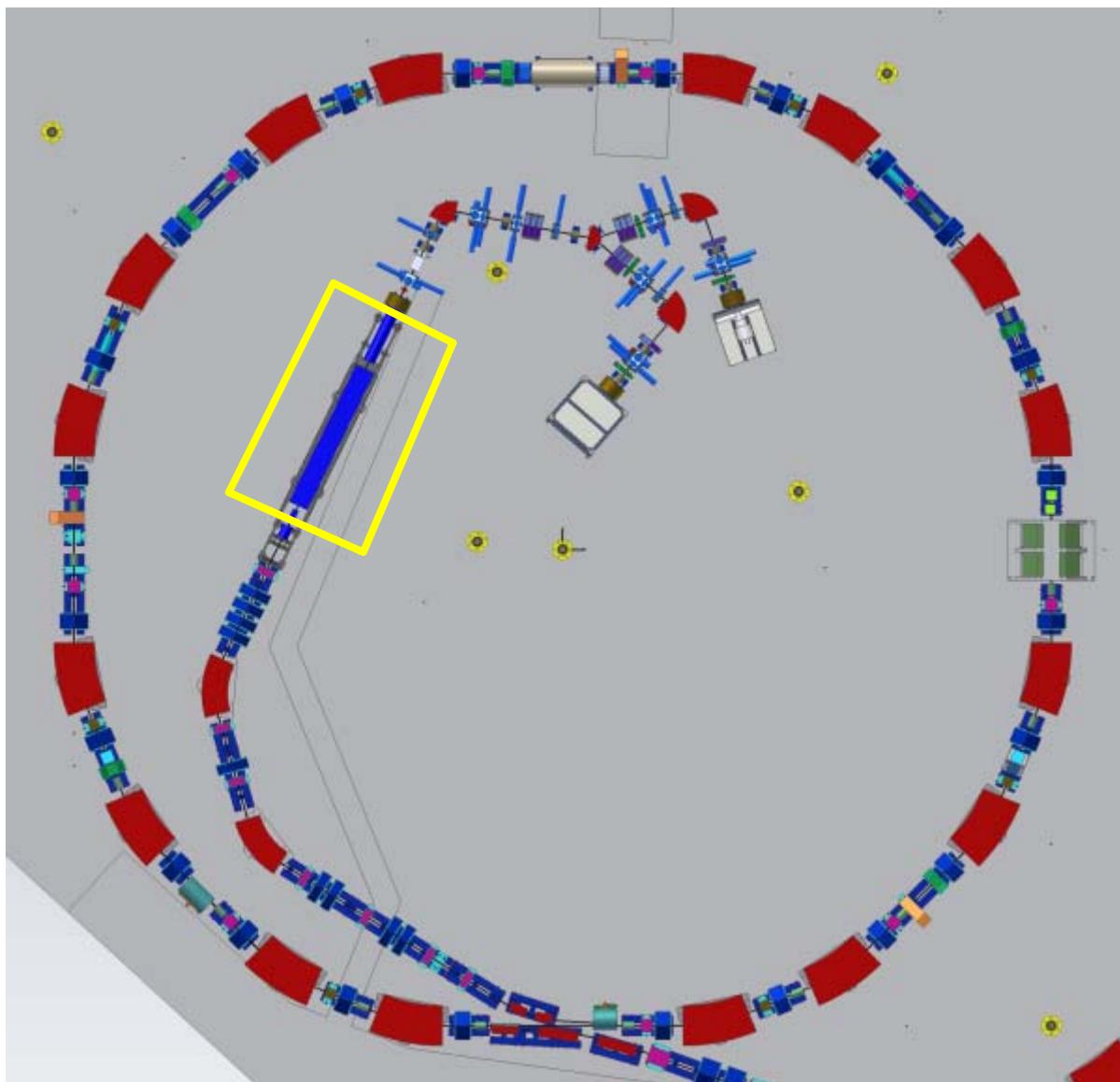
**0.008 MeV/u H<sup>3+</sup>**  
**0.008 MeV/u C<sup>4+</sup>**

**I ~ 0.7 mA (H<sup>3+</sup>)**  
**I ~ 0.2 mA (C<sup>4+</sup>)**

**Two sources**

**Continuous beam**

**LEBT Chopper**



**RFQ-LINAC**

**217 MHz**

**RFQ**

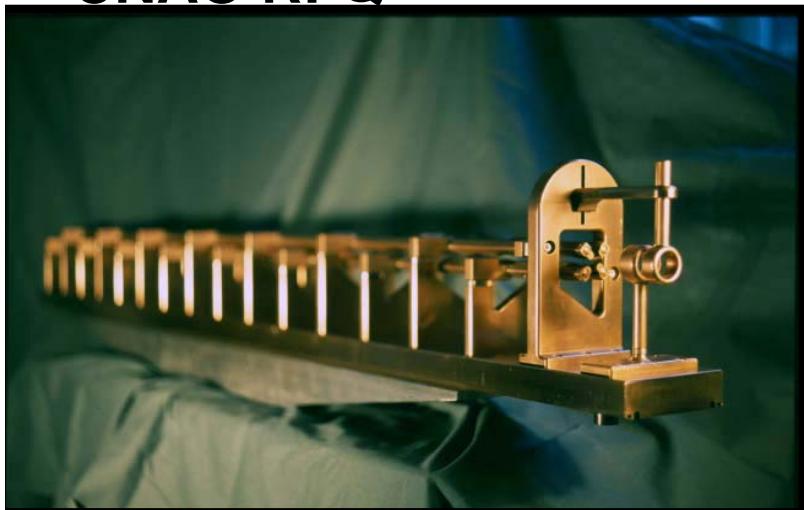
**0.008-0.4 MeV/u H<sup>3+</sup>**  
**0.008-0.4 MeV/u C<sup>4+</sup>**

**LINAC**

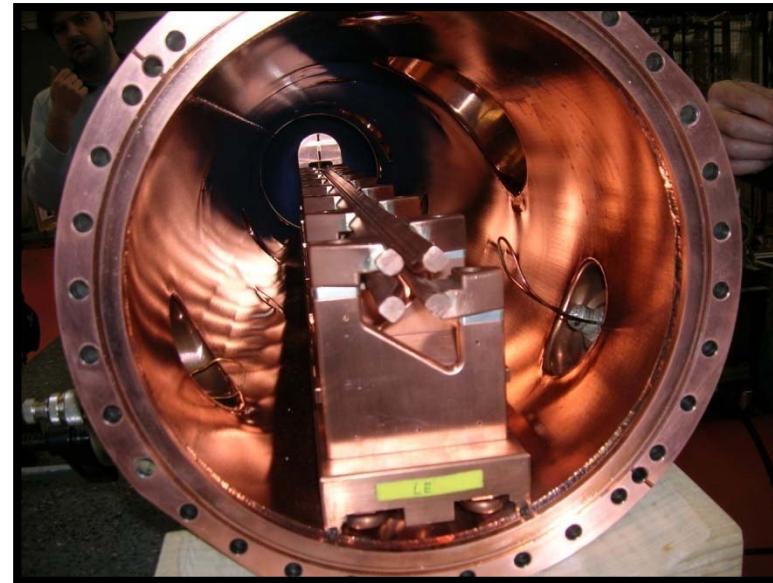
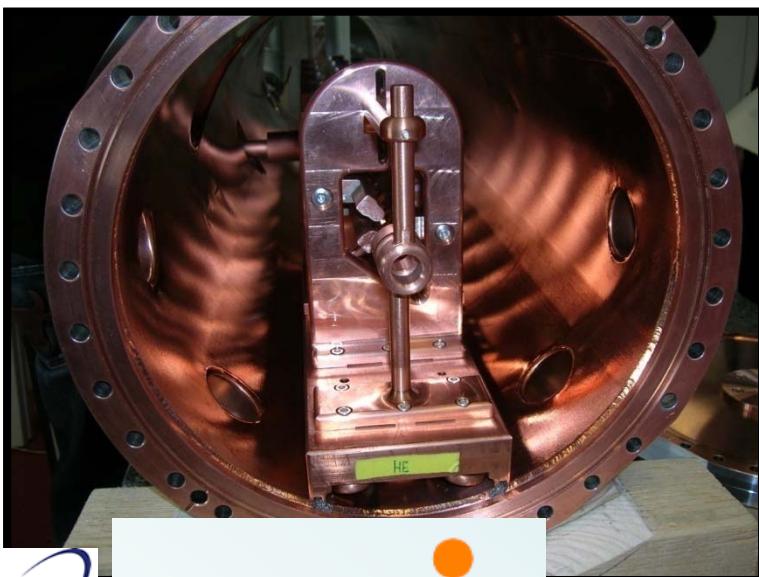
**0.4-7 MeV/u H<sup>3+</sup>**  
**0.4-7 MeV/u C<sup>4+</sup>**

**Pulse for temperature**

## CNAO RFQ



Struttura interna



Ingresso ioni

217 MHz

Four-rod like type  
Energy range = 8 – 400 keV/u  
Electrode length = 1.35 m,  
Electrode voltage = 70 kV  
RF power loss (pulse): about 100 kW  
Low duty cycle: around 0.1%

Uscita ioni

# LINAC

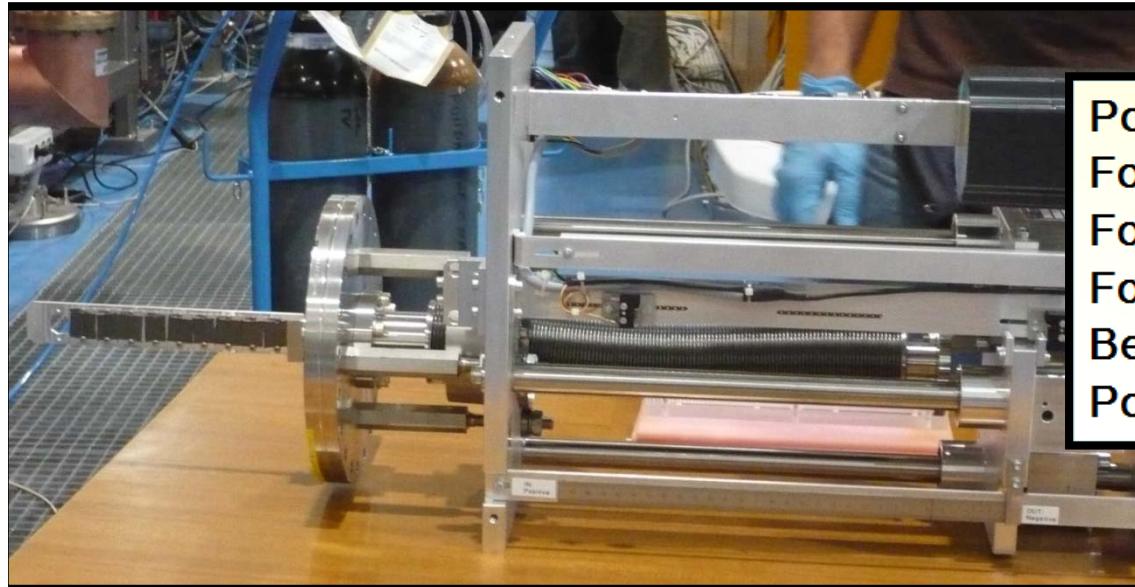


**3 Integrated magnetic triplet lenses**  
**56 Accelerating gaps**

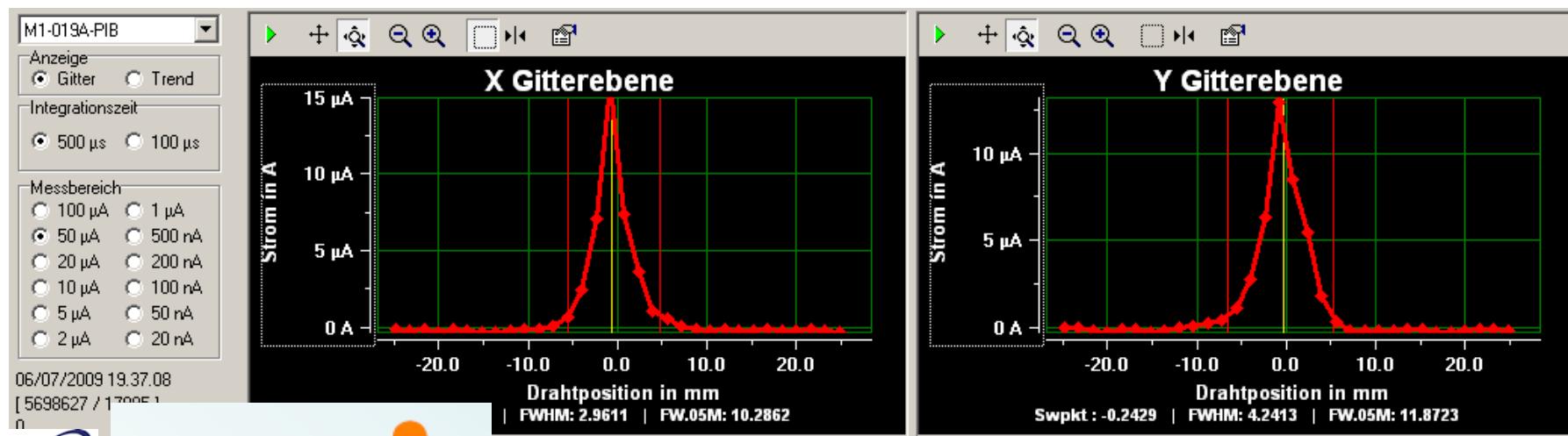
<b>Energy range</b>	<b>0.4 – 7 MeV/u</b>
<b>Tank length</b>	<b>3.77 m</b>
<b>Inner tank height</b>	<b>0.34 m</b>
<b>Inner tank width</b>	<b>0.26 m</b>
<b>Drift tube aperture diam.</b>	<b>12 – 16 mm</b>
<b>RF power loss (pulse)</b>	<b>≈ 1 MW</b>
<b>Averaged eff. volt. gain</b>	<b>5.3 MV/m</b>

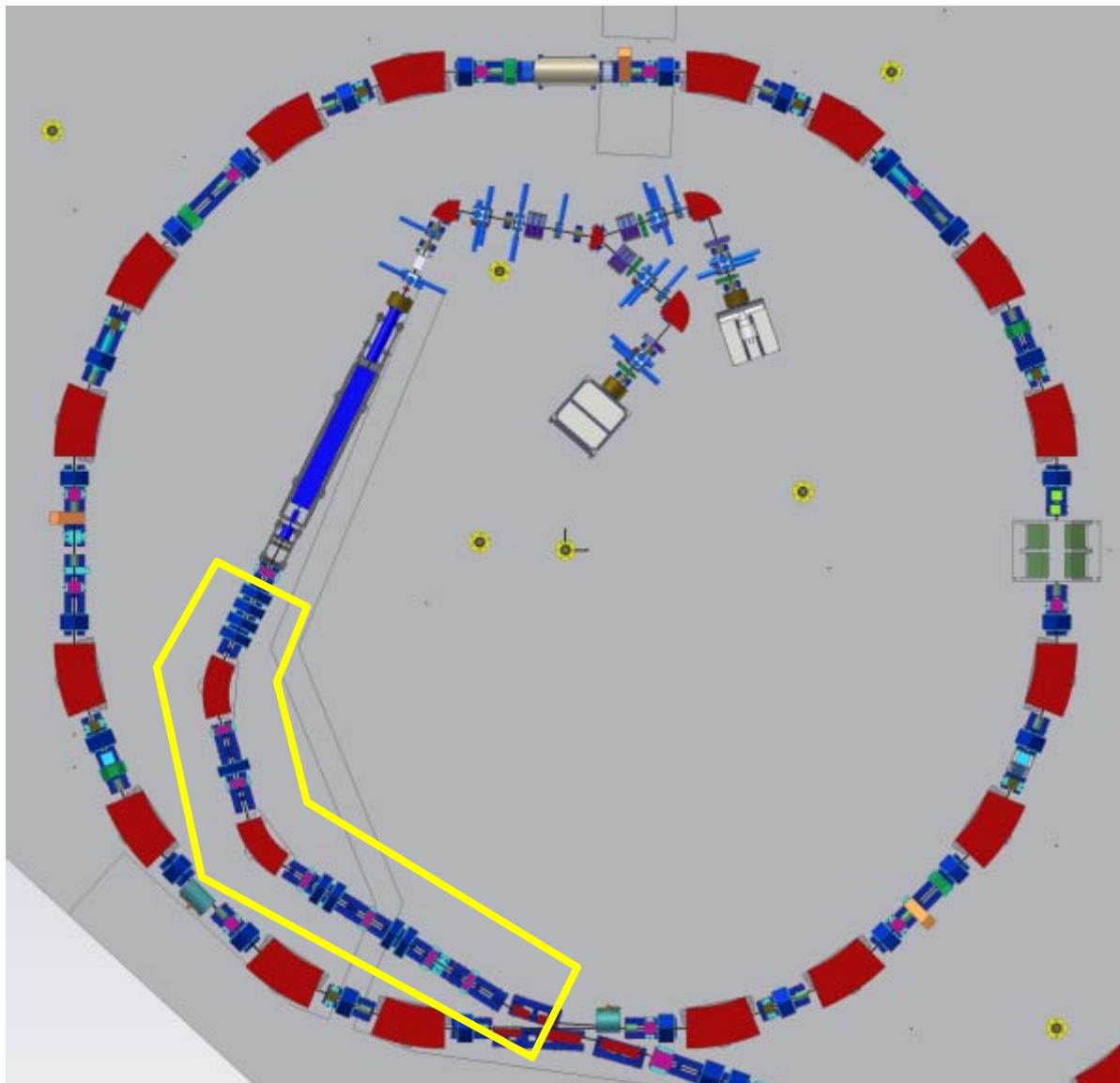


## Carbon foils



Positions:	10
Foil material:	Carbon
Foil thickness:	100-200 $\mu\text{g}/\text{cm}^2$
Foil diameter:	15 mm
Beam diameter:	5 mm
Position accuracy:	$\pm 0,5 \text{ mm}$





**MEBT**

**7 MeV p  
7 MeV/u C<sup>6+</sup>**

**I ~ 0.7 mA (p)  
I ~ 0.15 mA (C<sup>6+</sup>)**

**(x,x')<sub>Inj</sub>**

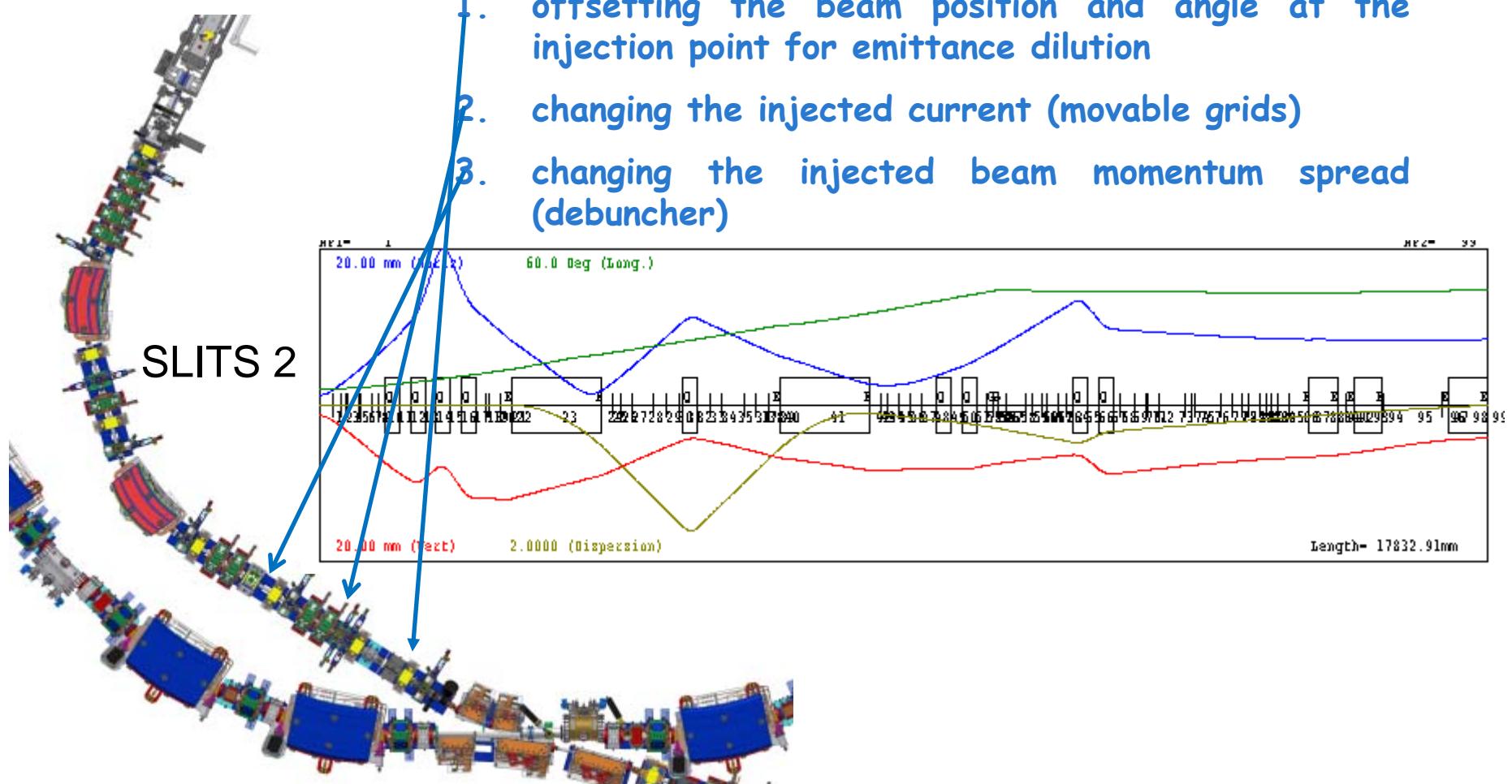
**Stripping foil**

**Current selection**

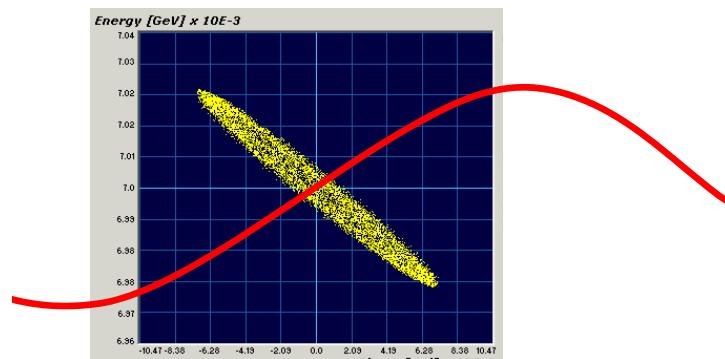
**Debuncher**

**Emittance dilution**

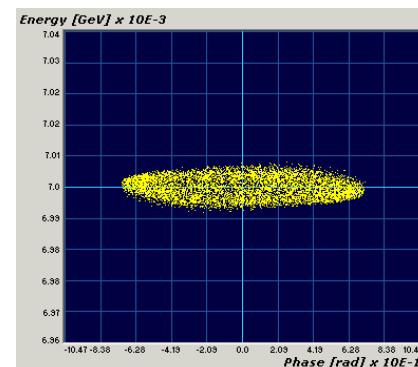
## MEBT Layout



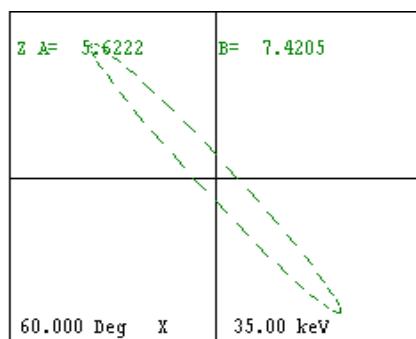
# Debuncher



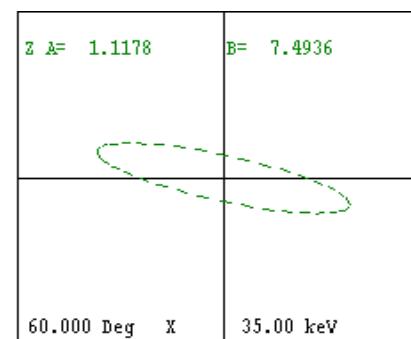
*PATH computation of the beam ( $P = 0.75$  mA) in the longitudinal phase space before the debuncher*



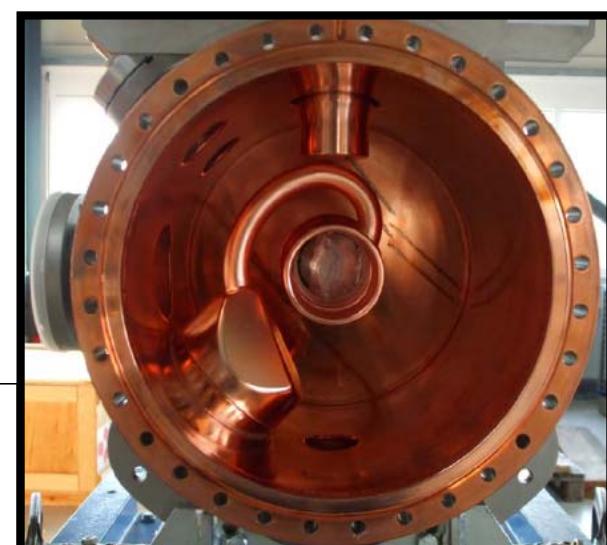
*PATH computation of the beam ( $P = 0.75$  mA) in the longitudinal phase space after the debuncher*



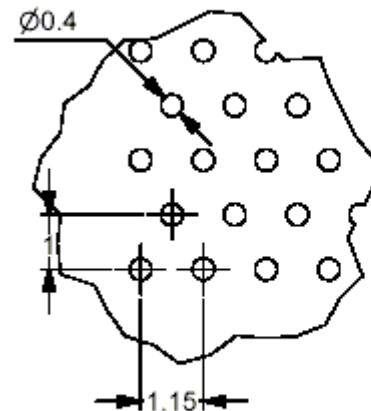
*TRACE 3D computation of the beam ( $P = 0.75$  mA) in the longitudinal phase space before the debuncher*  
Page 44 Accelerators for hadrontherapy



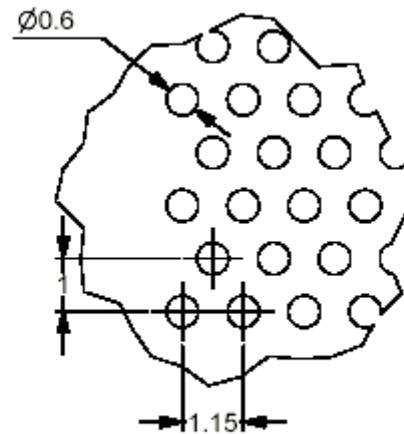
*TRACE 3D computation of the beam ( $P = 0.75$  mA) in the longitudinal phase space after the debuncher*



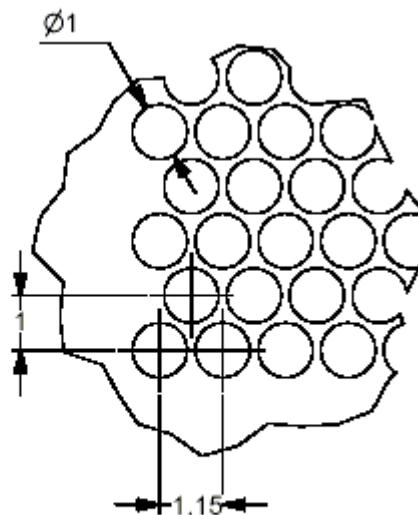
## Intensity degrader



F10 Filter



F20 Filter

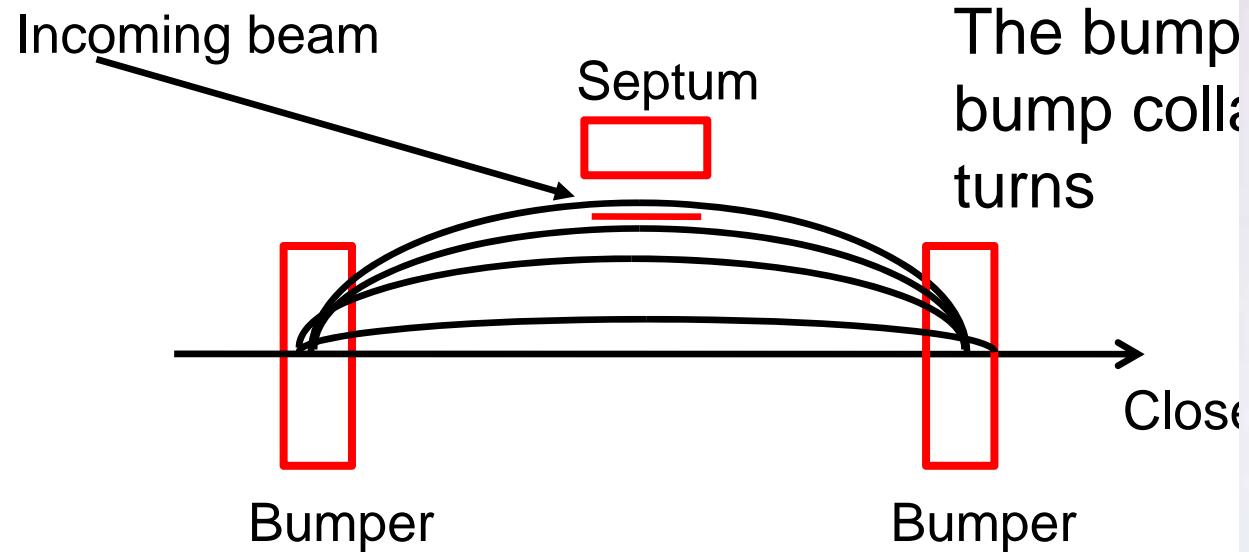


F50 Filter



4 transmission levels: 100%, 50%, 20%, 10%  
Keep overall emittance unchanged

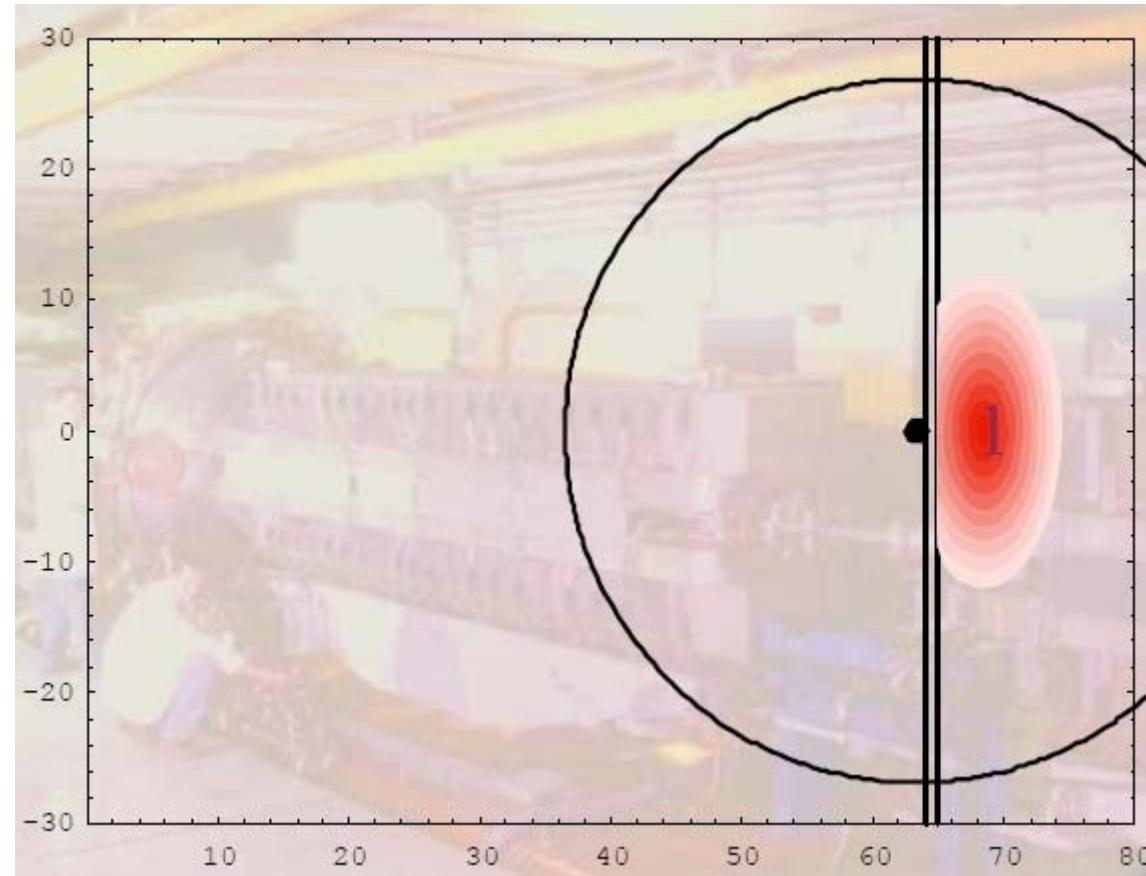
## Multiturn injection



The bump  
bump colla  
turns

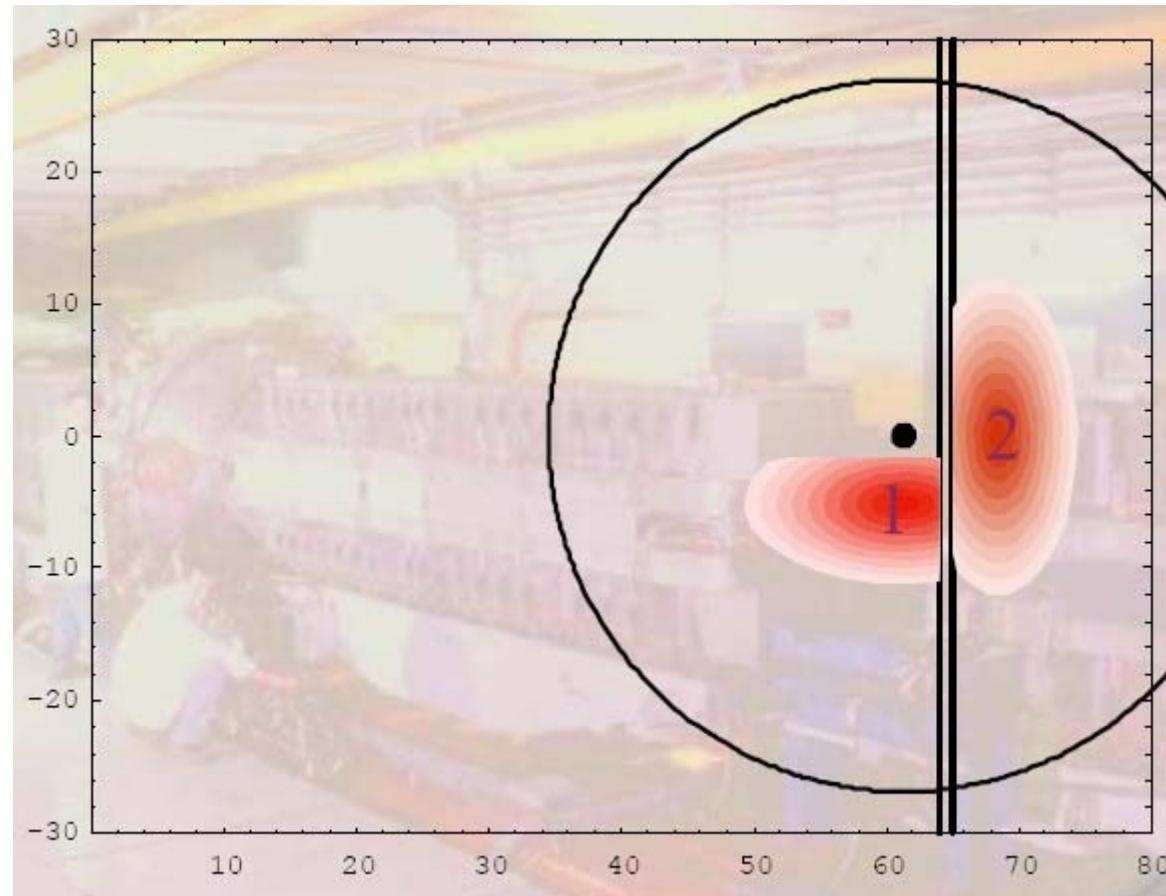


## An animated view (courtesy of R. Steerenberg)

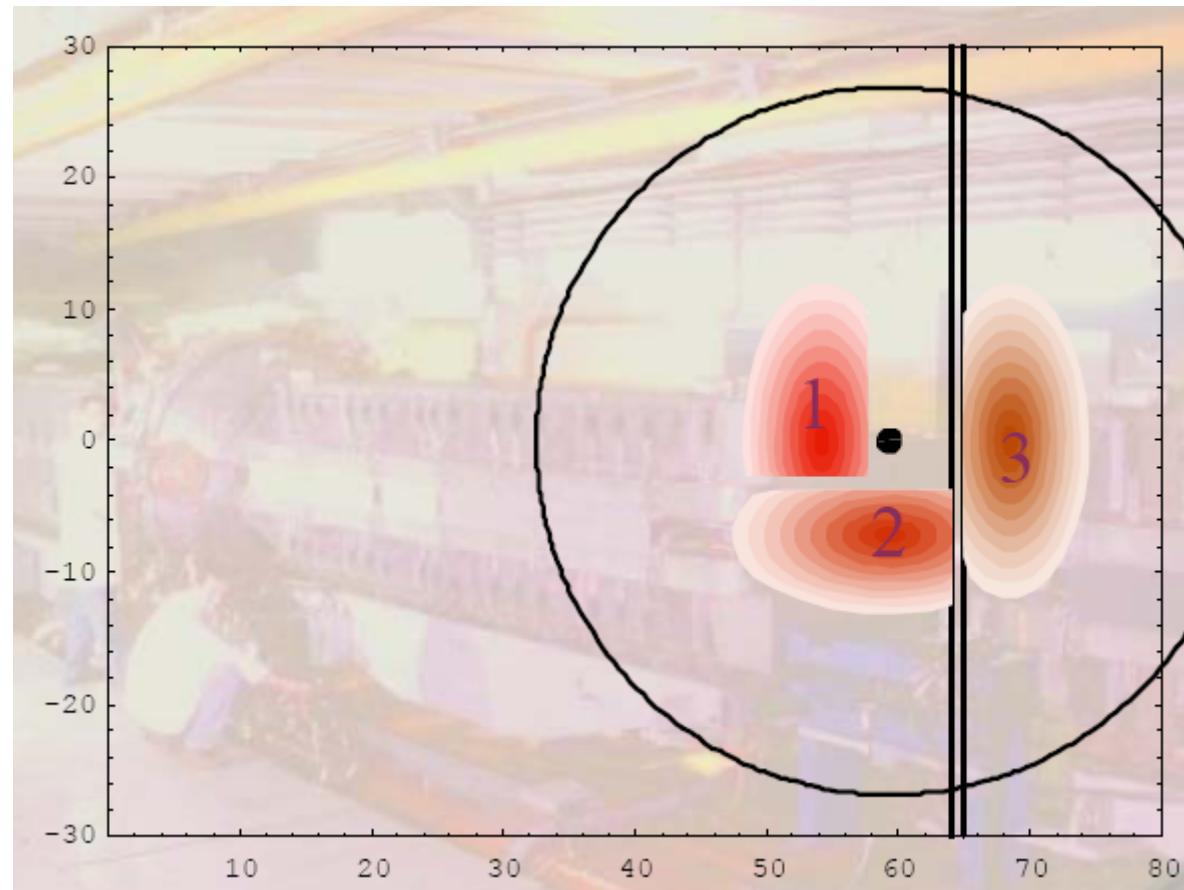


Emittance in the synchrotron larger than in injector

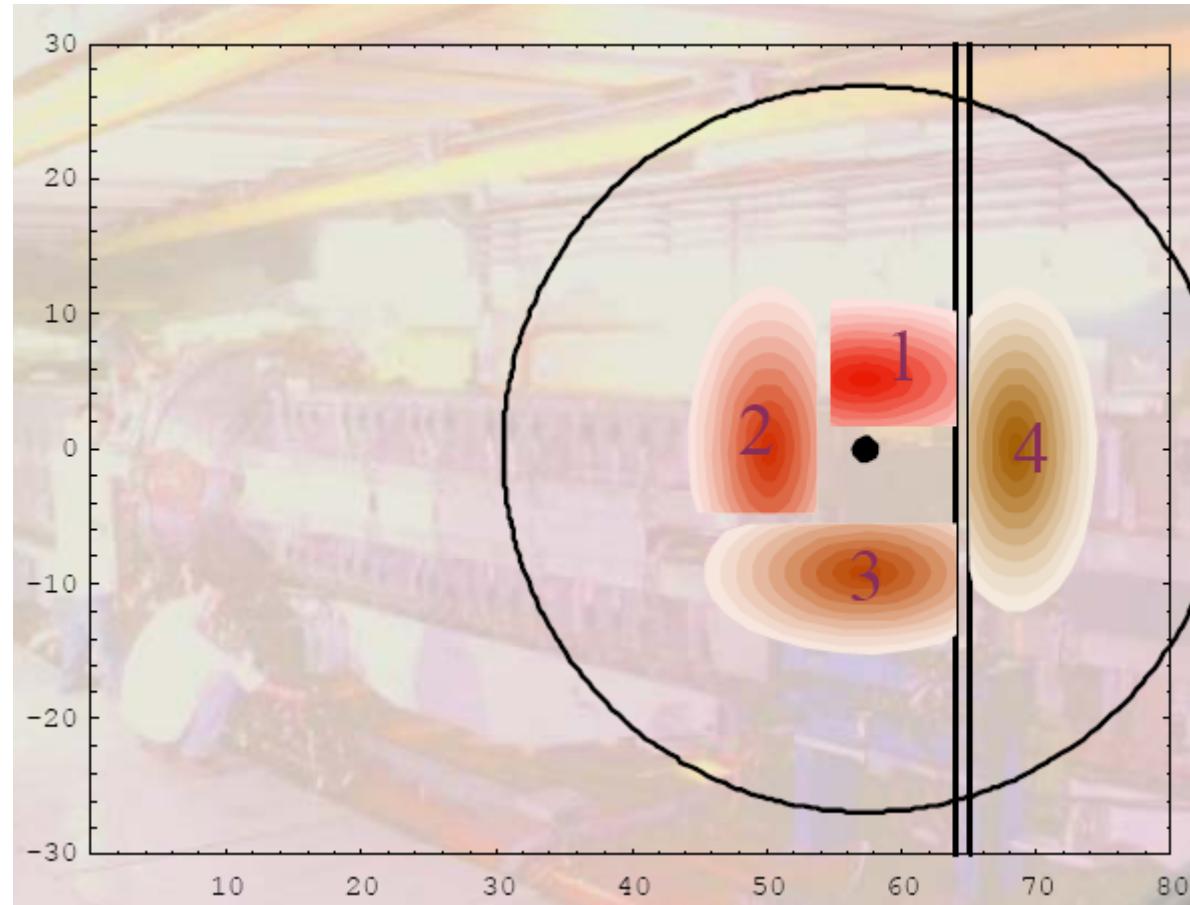
## An animated view (courtesy of R. Steerenberg)



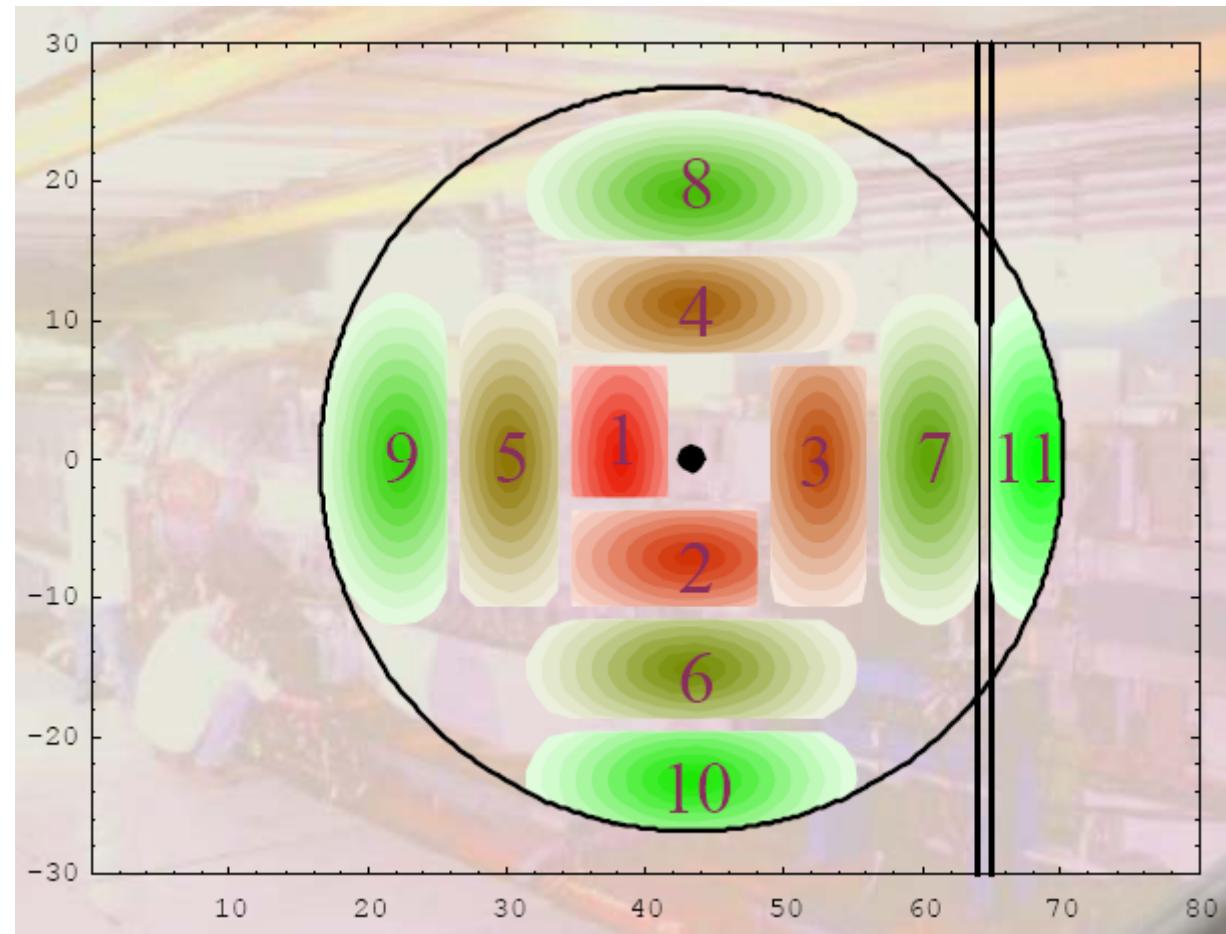
## An animated view (courtesy of R. Steerenberg)



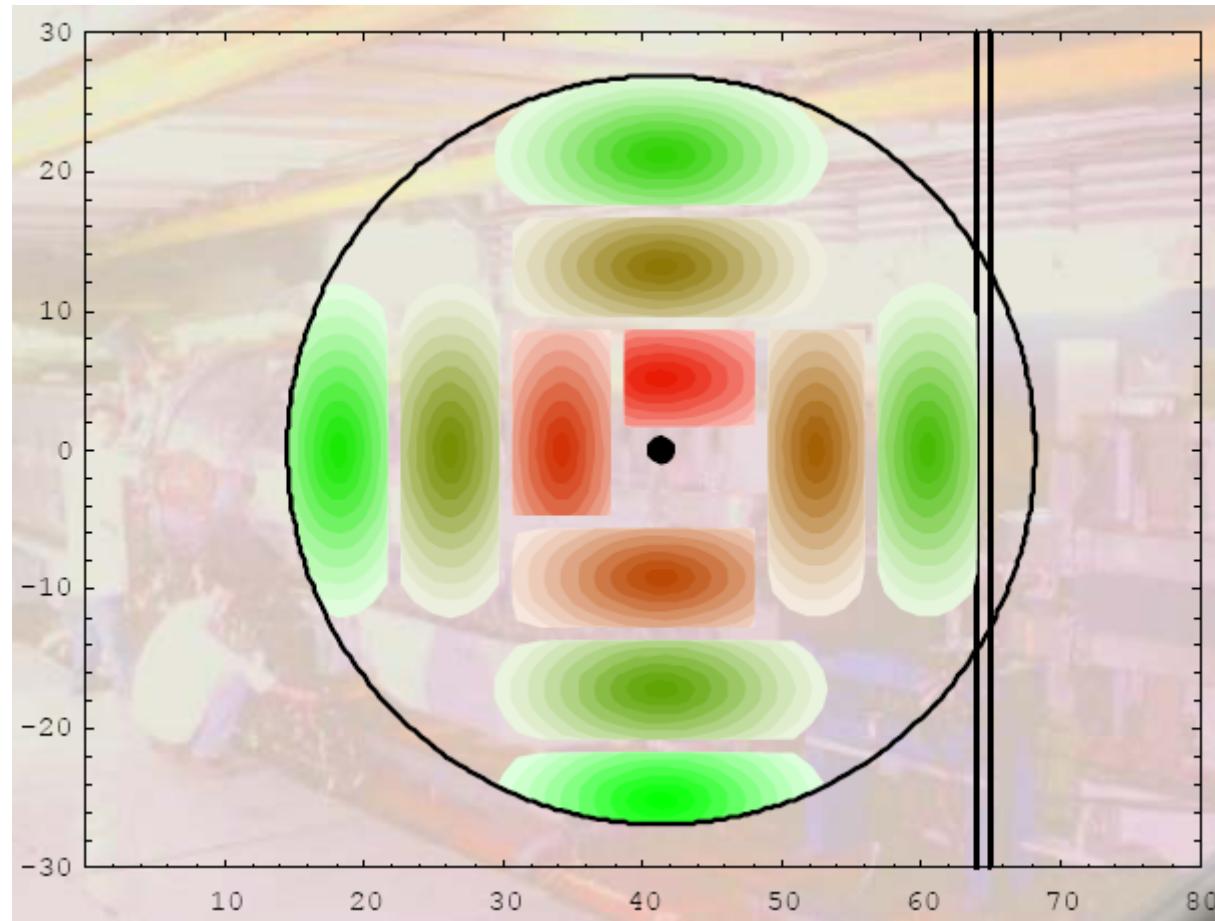
## An animated view (courtesy of R. Steerenberg)



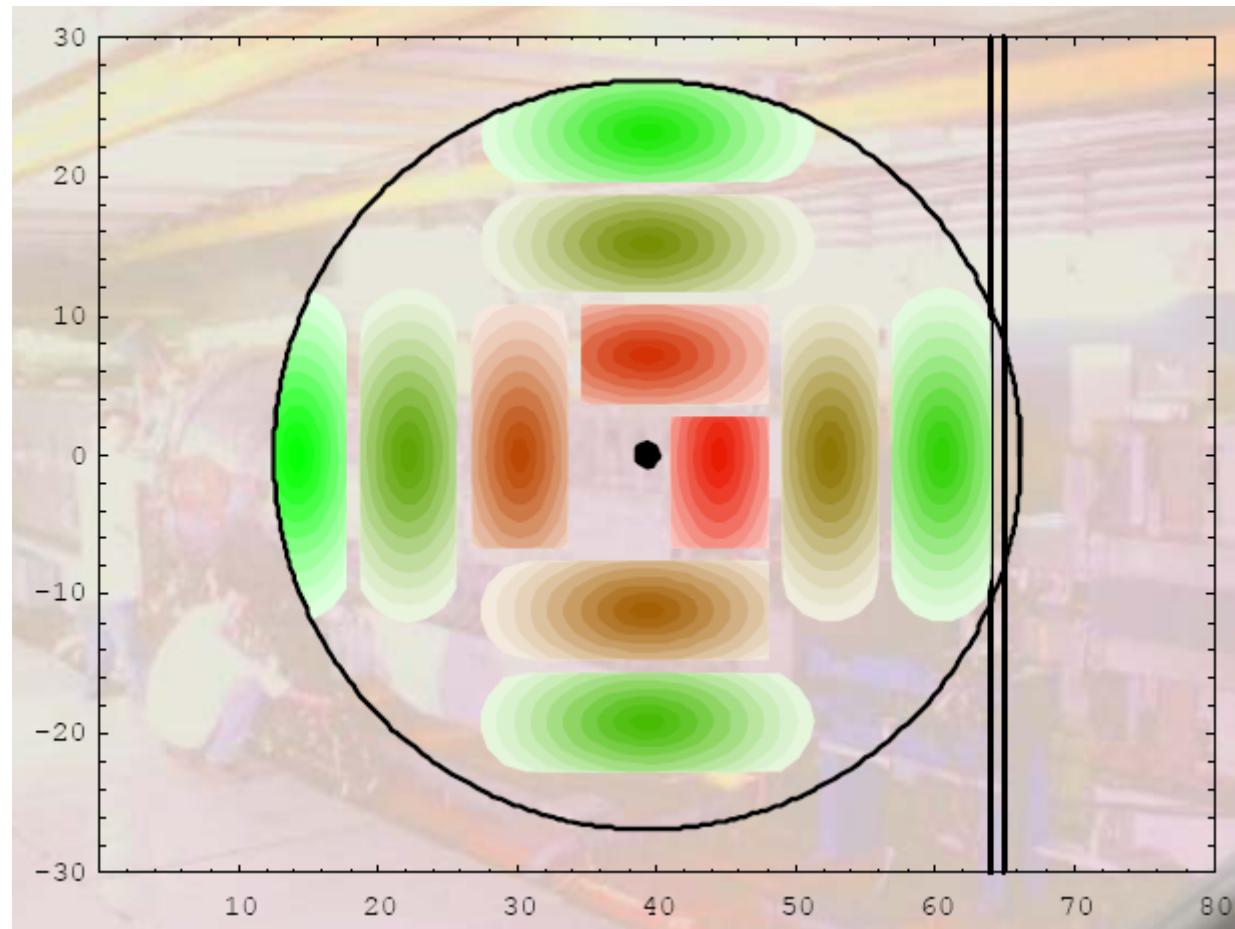
## An animated view (courtesy of R. Steerenberg)



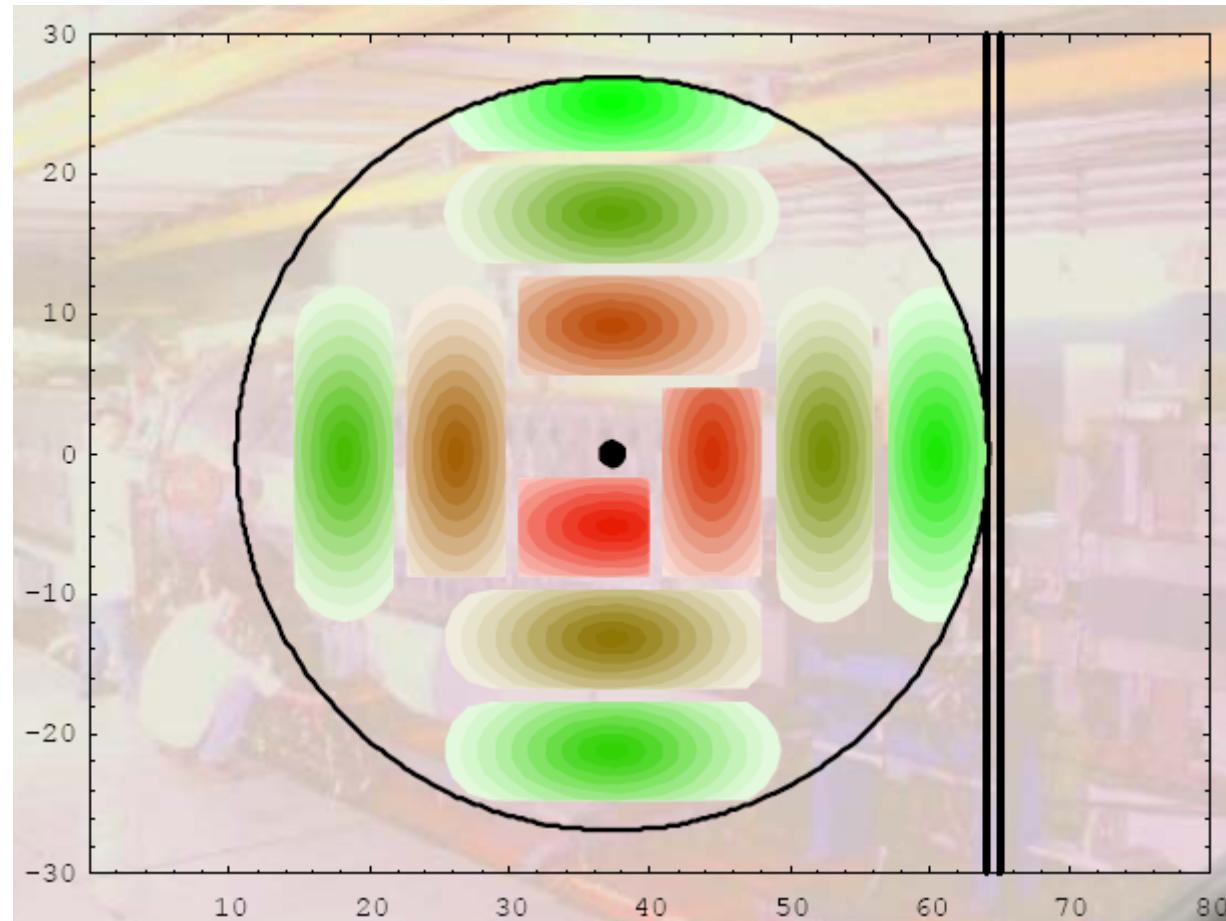
## An animated view (courtesy of R. Steerenberg)



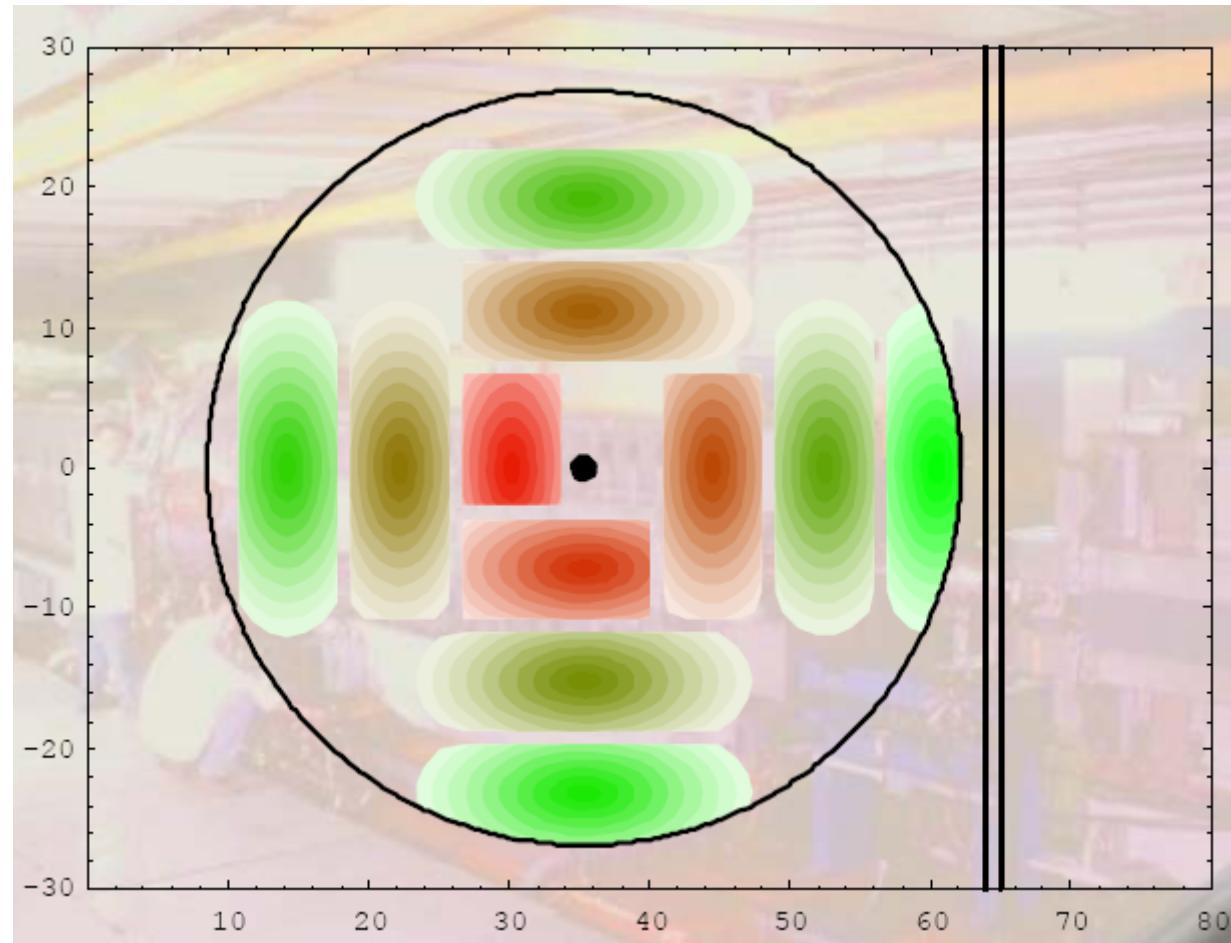
## An animated view (courtesy of R. Steerenberg)

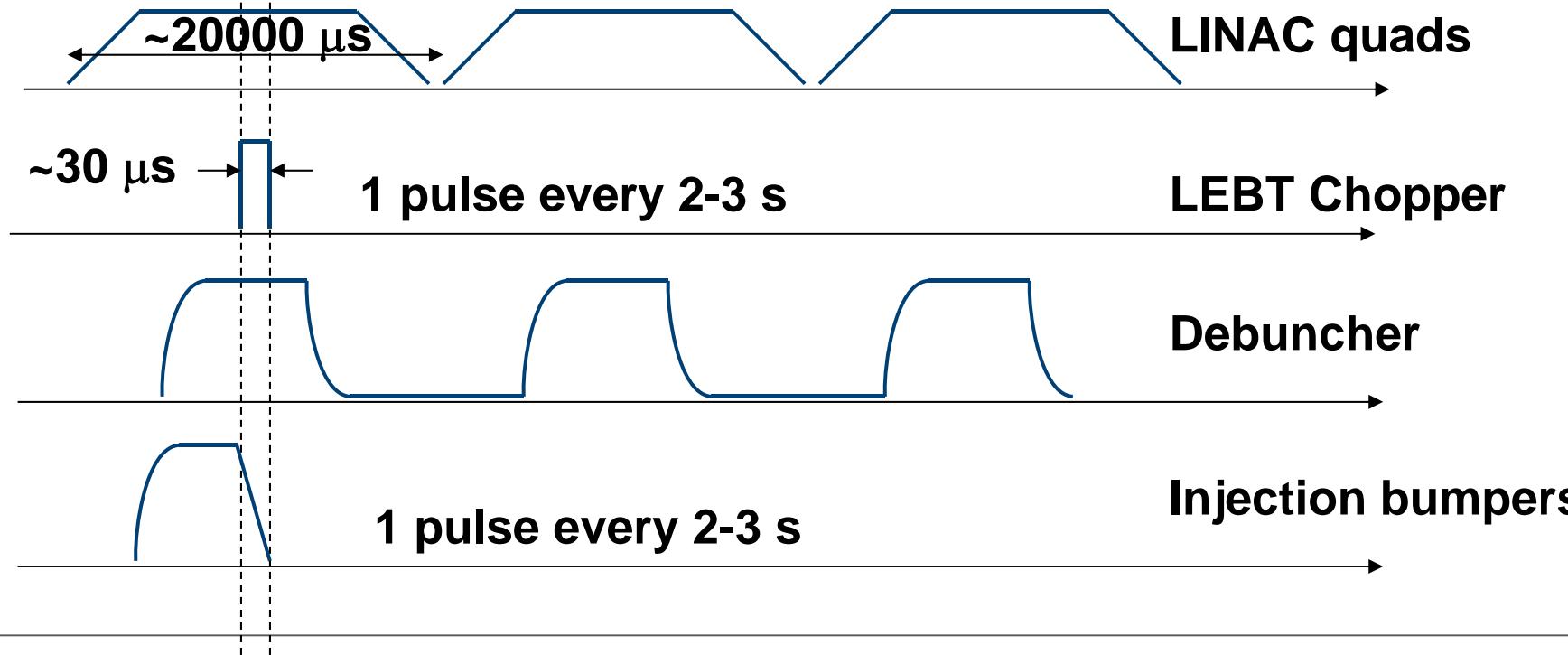
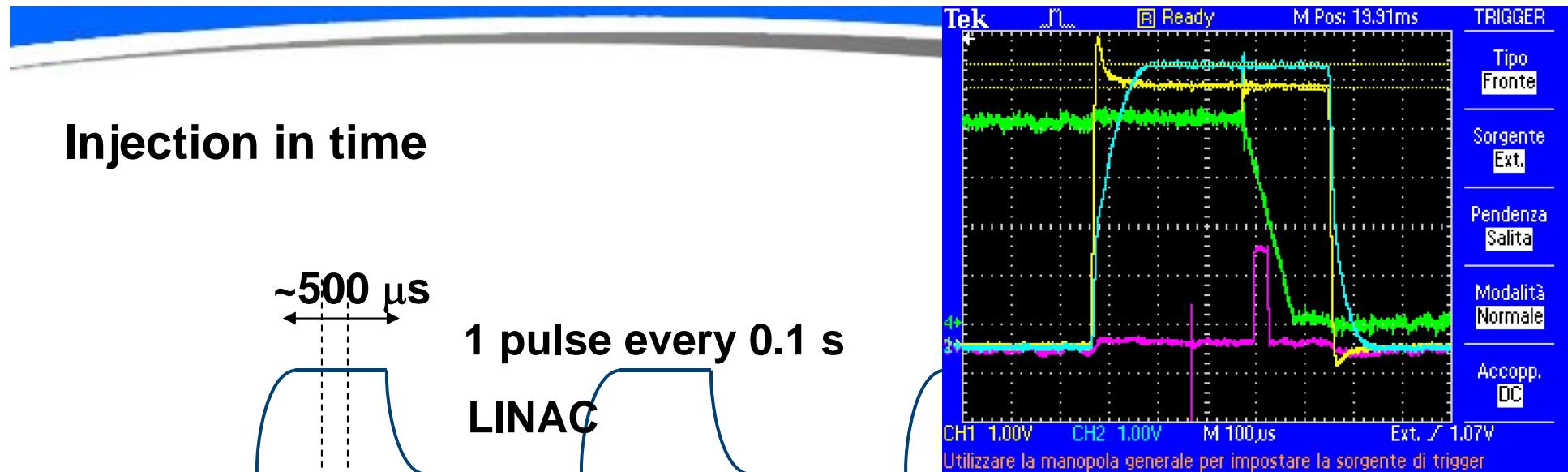


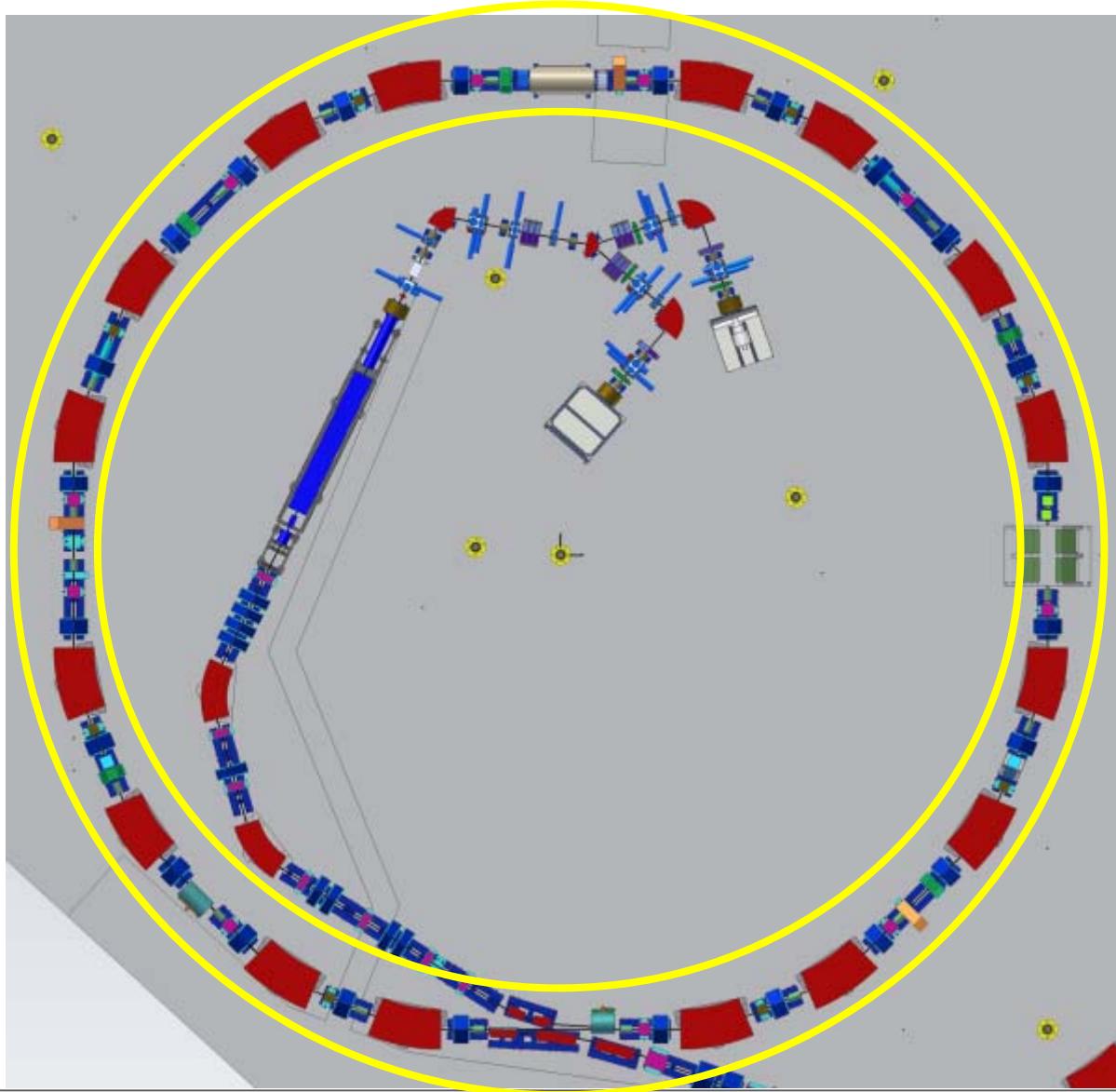
## An animated view (courtesy of R. Steerenberg)



## An animated view (courtesy of R. Steerenberg)







## Synchrotron

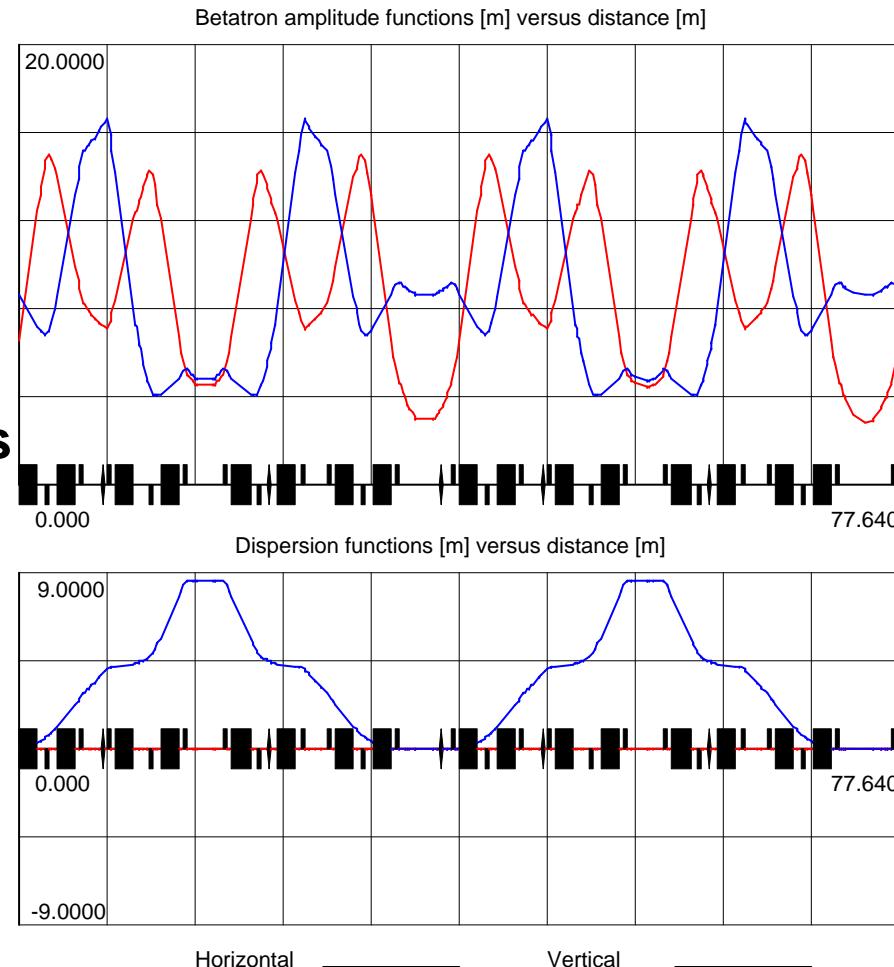
**7-250 MeV p  
7-400 MeV/u C**

**$I \sim 0.1\text{-}6 \text{ mA (p)}$   
 $I \sim 0.03\text{-}1.5 \text{ mA (C)}$**

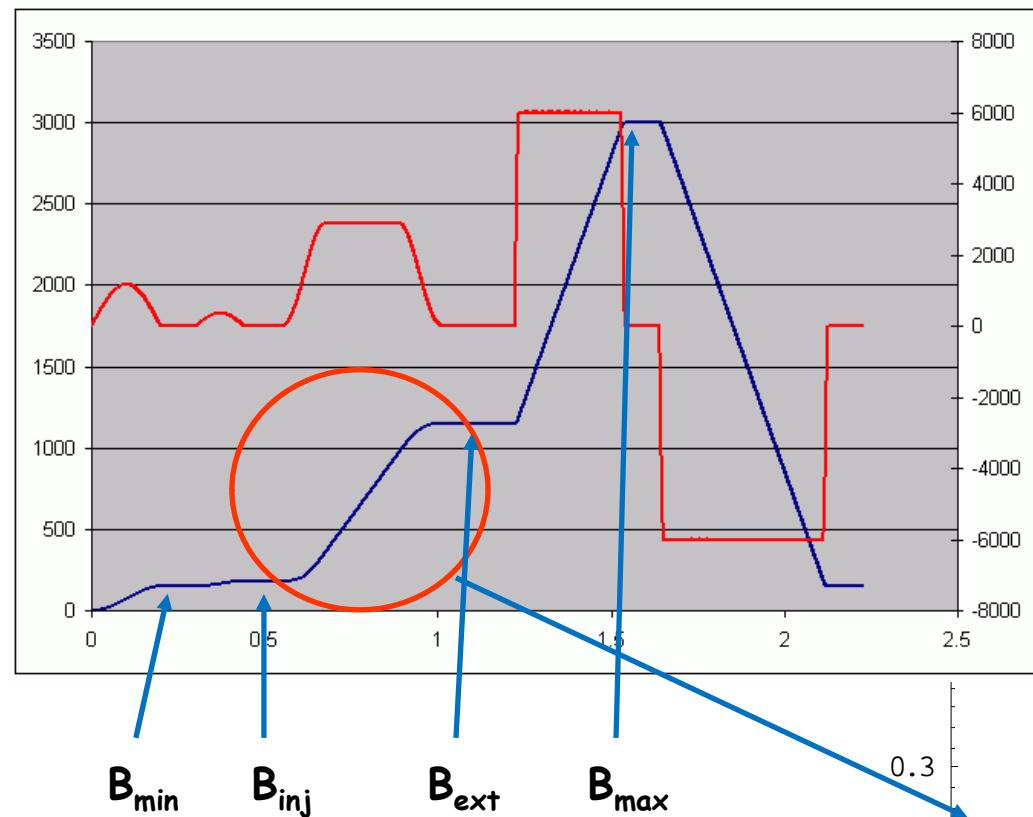
## Slow extraction

# Synchrotron optics

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

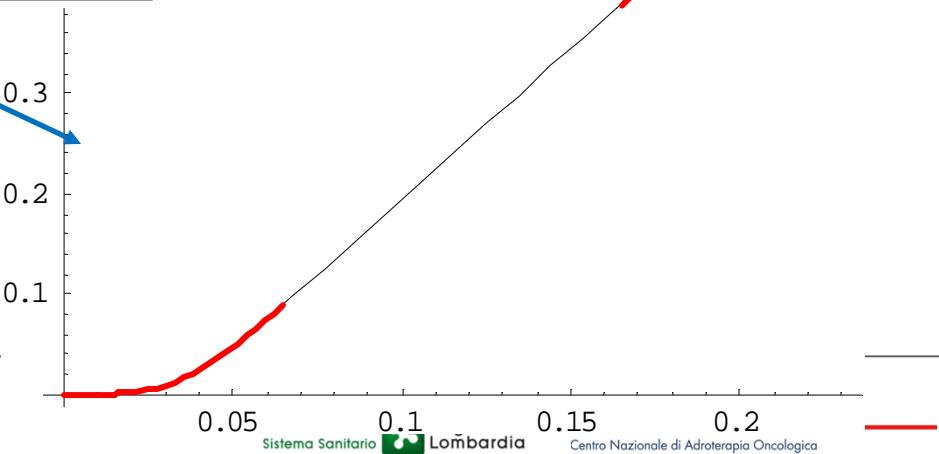


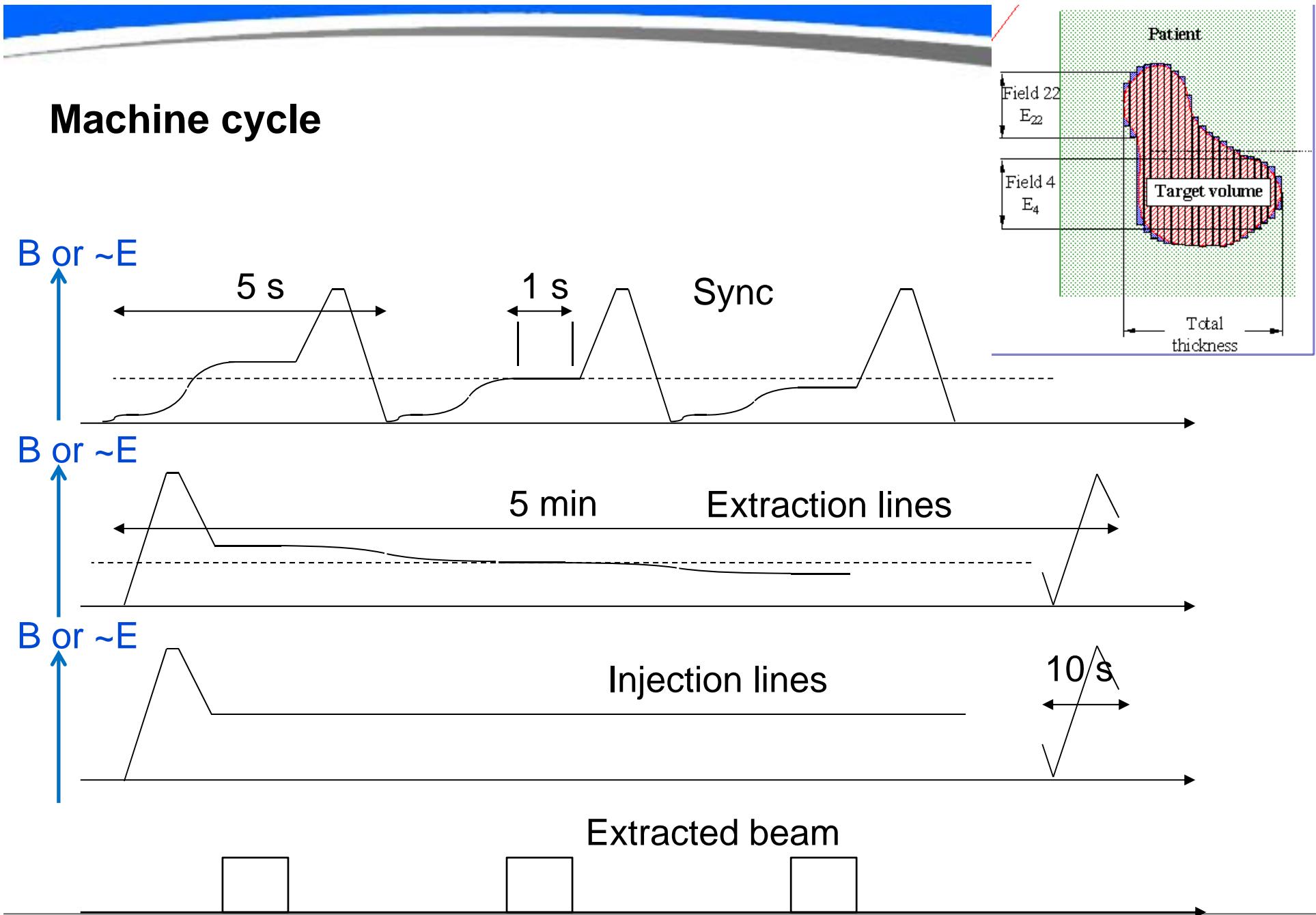
## Magnets' cycle



Hysteresis cycle for  
repeatability

Fixed ramps connected  
by linear ramps





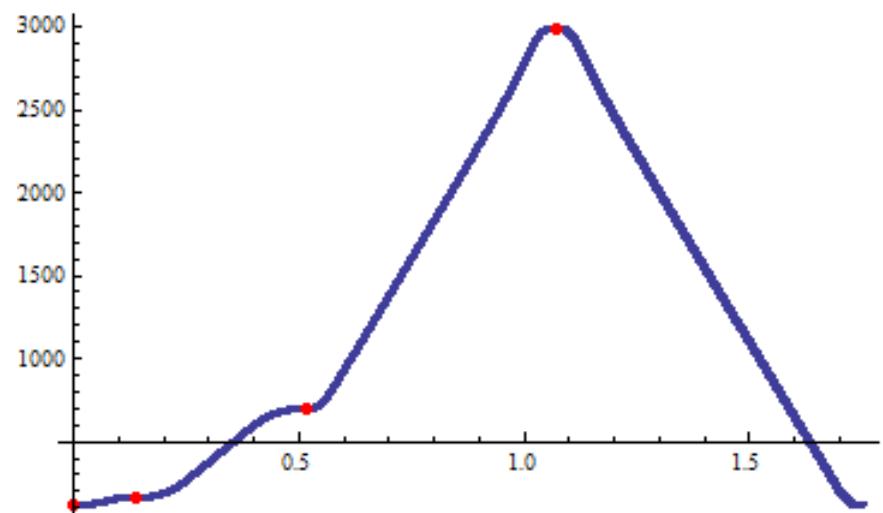
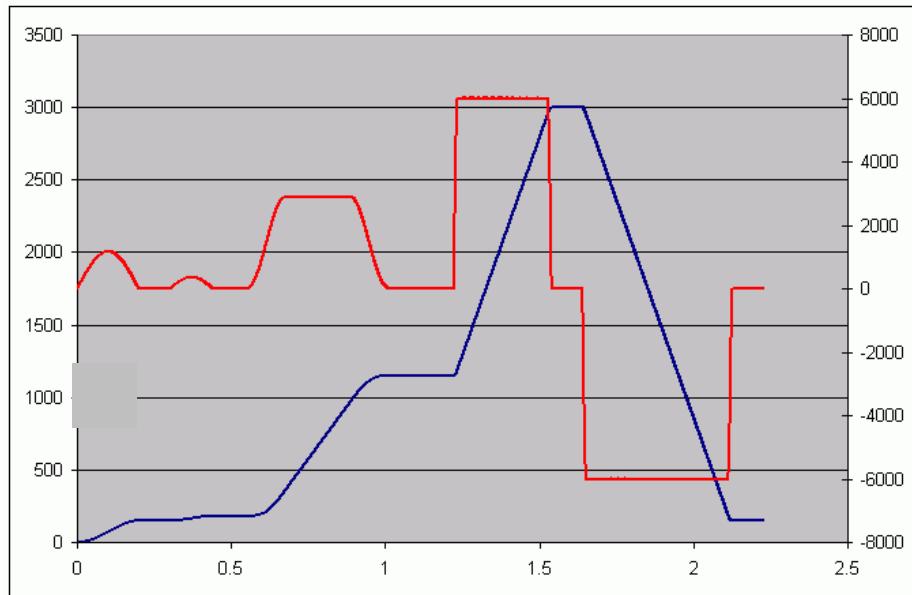
## Control system

Energy changes every 5s ...maybe...

Unpredictable sequence of cycles

Unpredictable cycle duration (breath synchronization)

Event driven ramps



## Control system

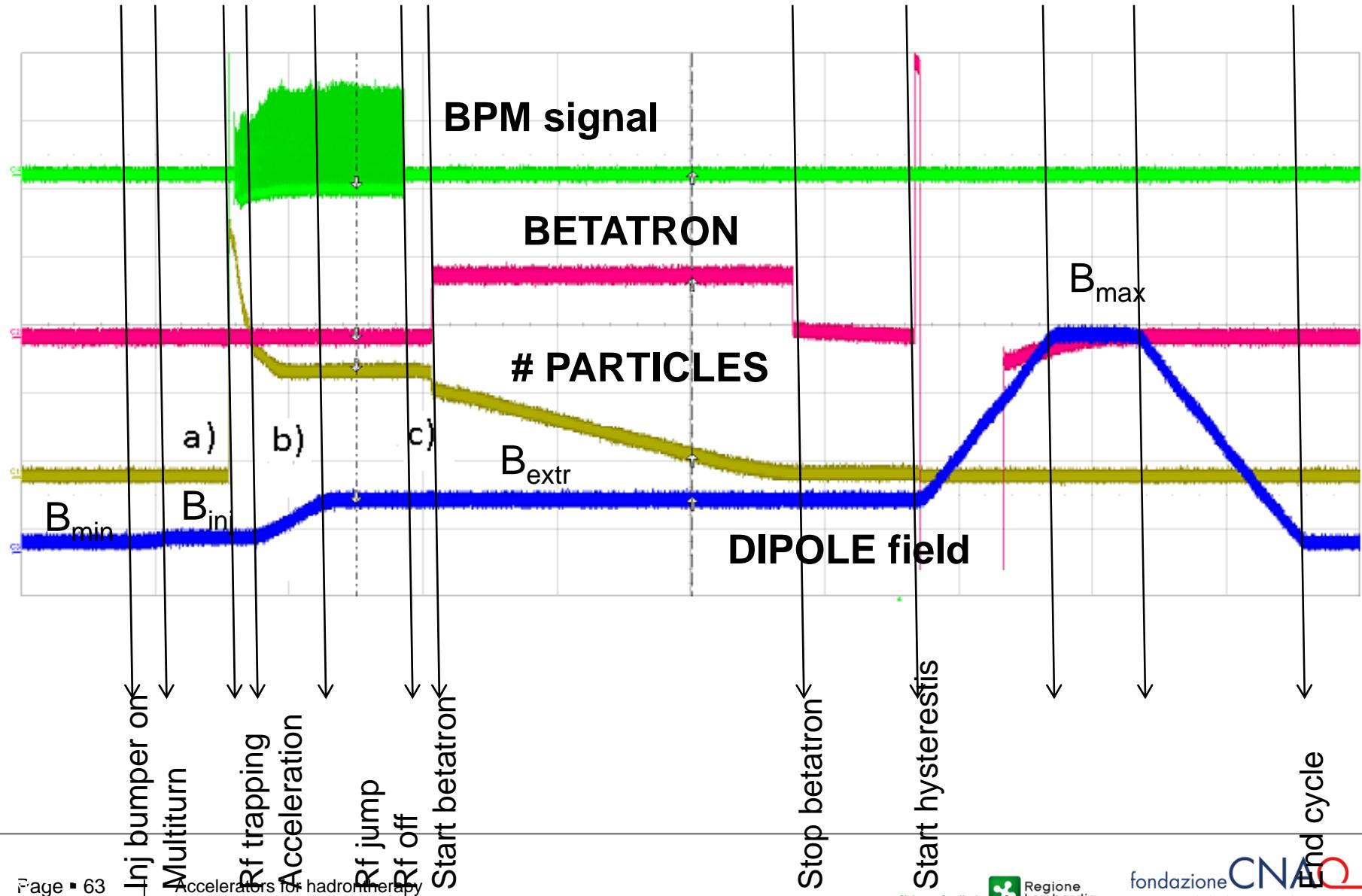
Distributed intelligence



Chiamare lo schema

Ezio Gribaudo 2011

# Machine Cycle



## Extraction

- We need to distribute the beam on the tumor
- The beam in the machine is a “bunch” shorter than  $1 \mu\text{s}$  ( $0.000001 \text{ s}$ )
- It's like we had an apple to distribute on a trail 10 m long

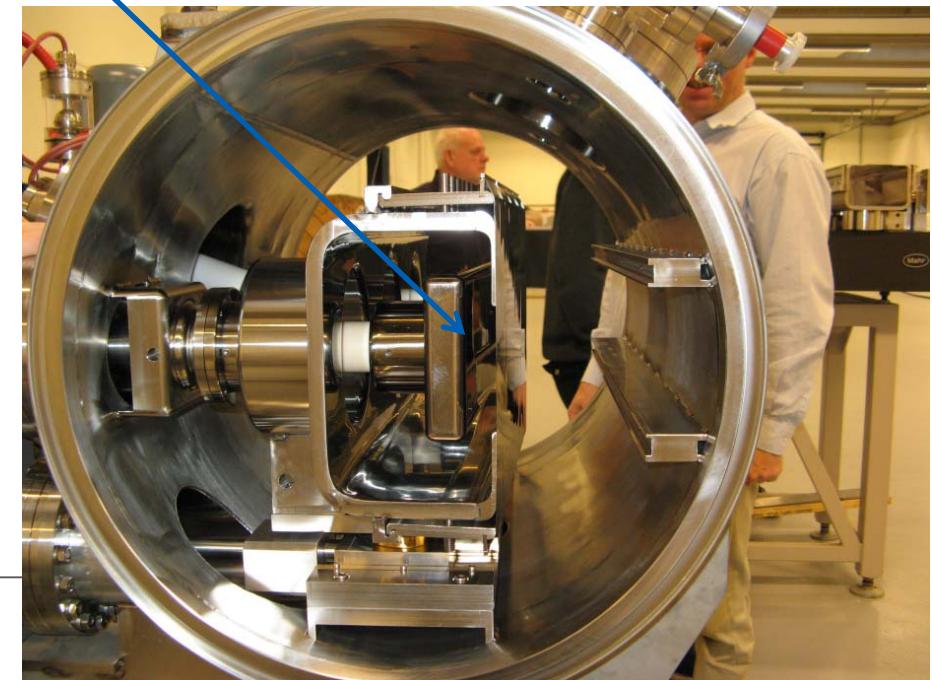
## Extraction

- We have to ‘peel’ the beam (using a resonant process)



Beam

Electrostatic septum  
(with the help of a resonance)



# Extraction possibilities at CNAO

Betatron core

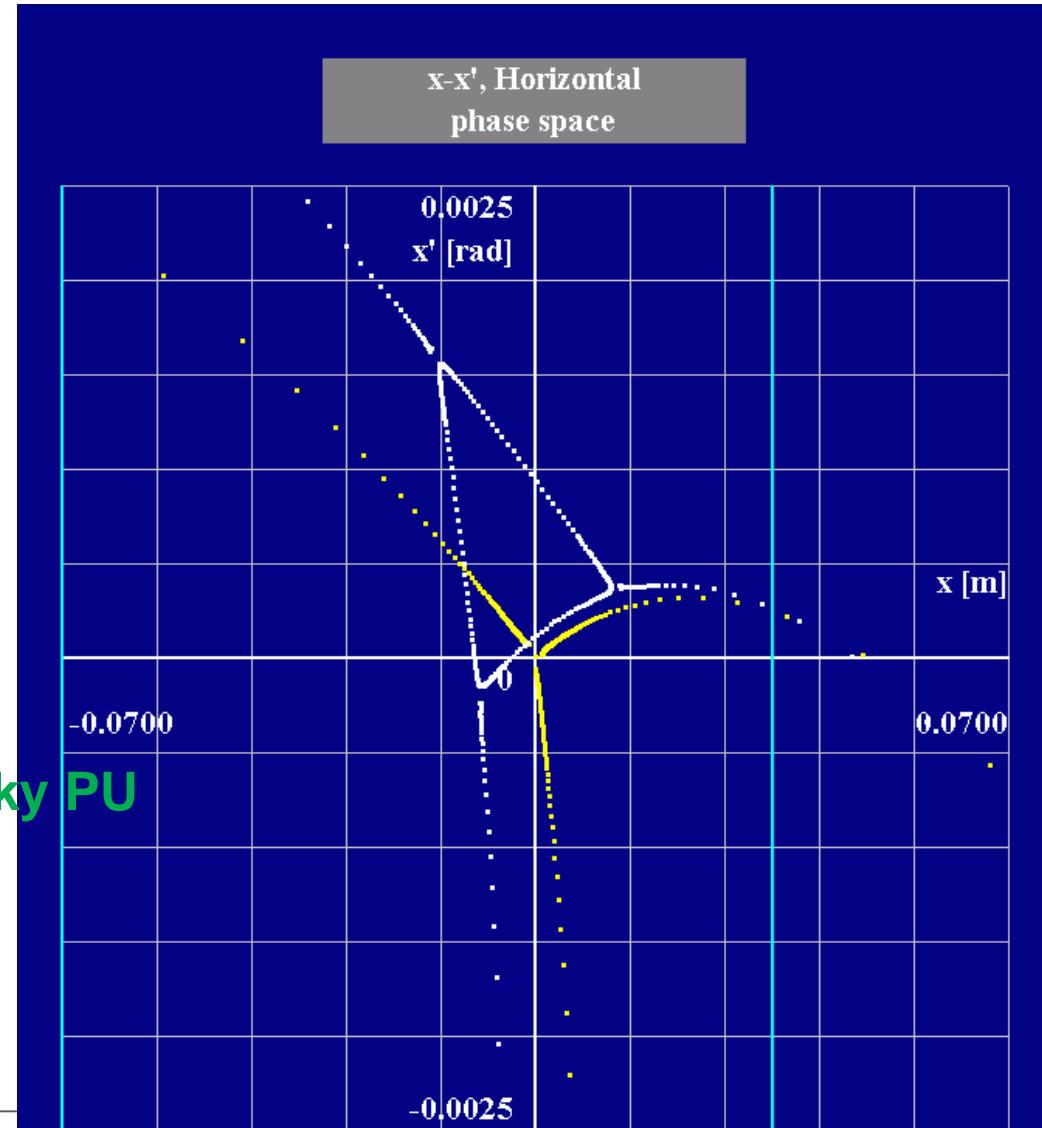
Empty bucket

Air core quadrupole

RF-KO in progress

Beam shaping with Schottky PU

Additional quad winding

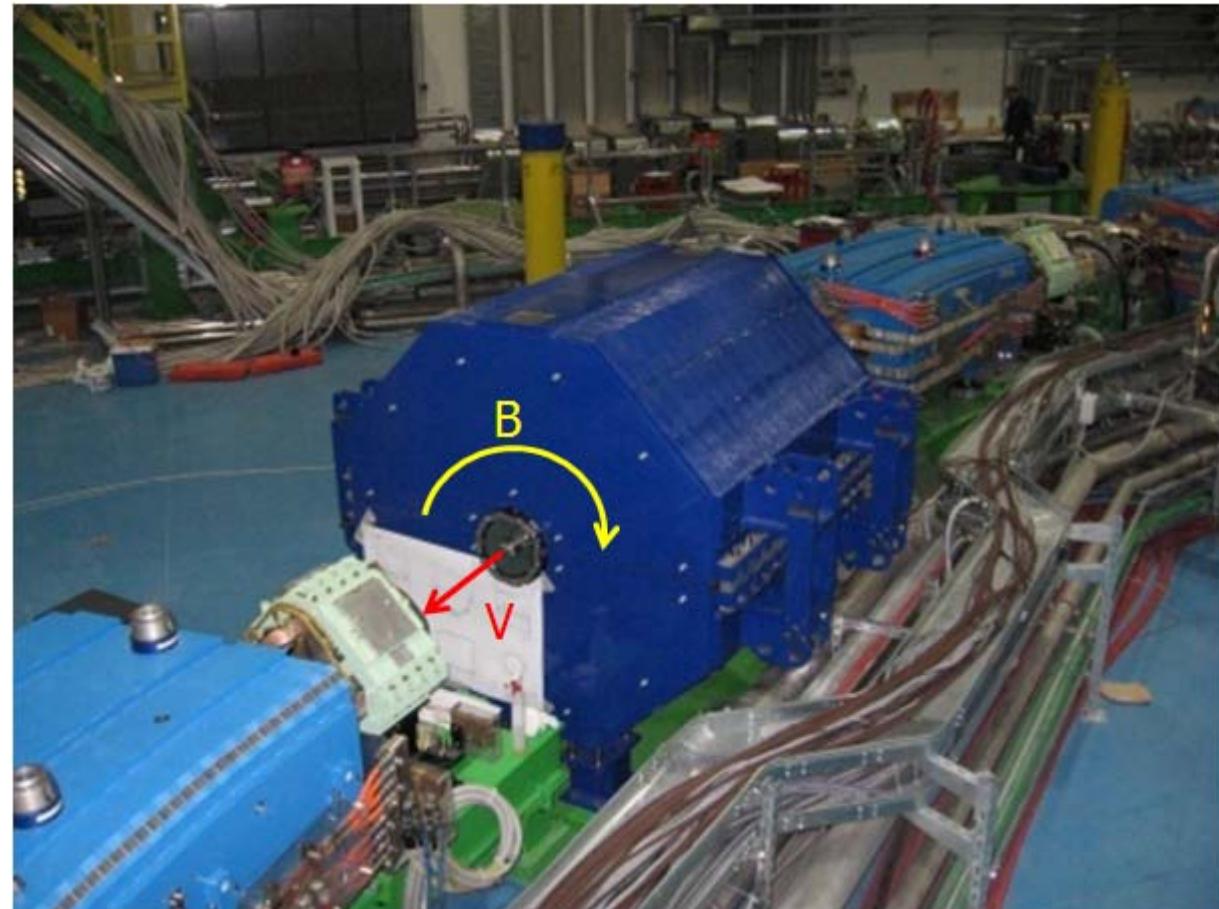


## Betatron core

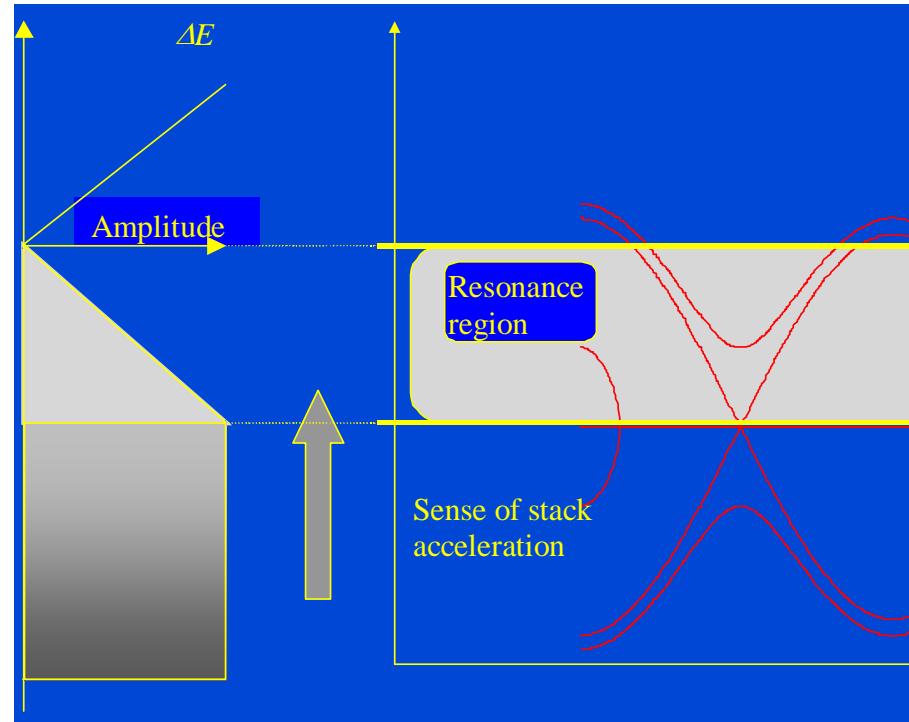
Pushes the beam  
against the  
resonance

$$\Delta\Phi = 2.46 \text{ Wb}$$

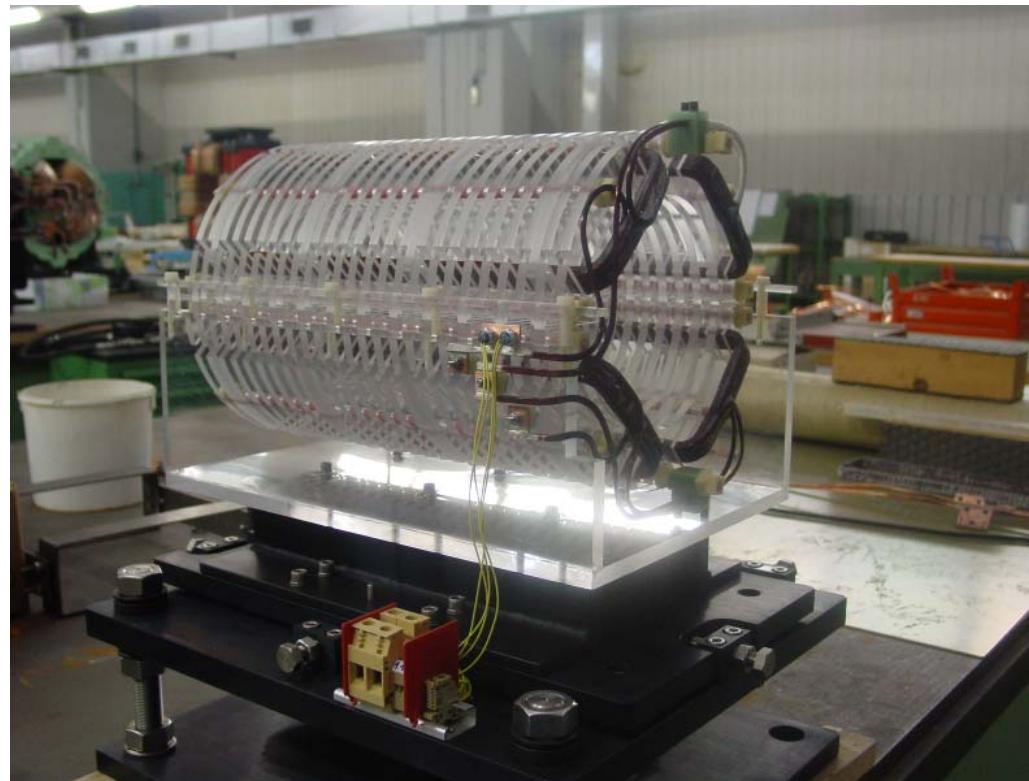
Magnetic screen  
needed



# Empty bucket

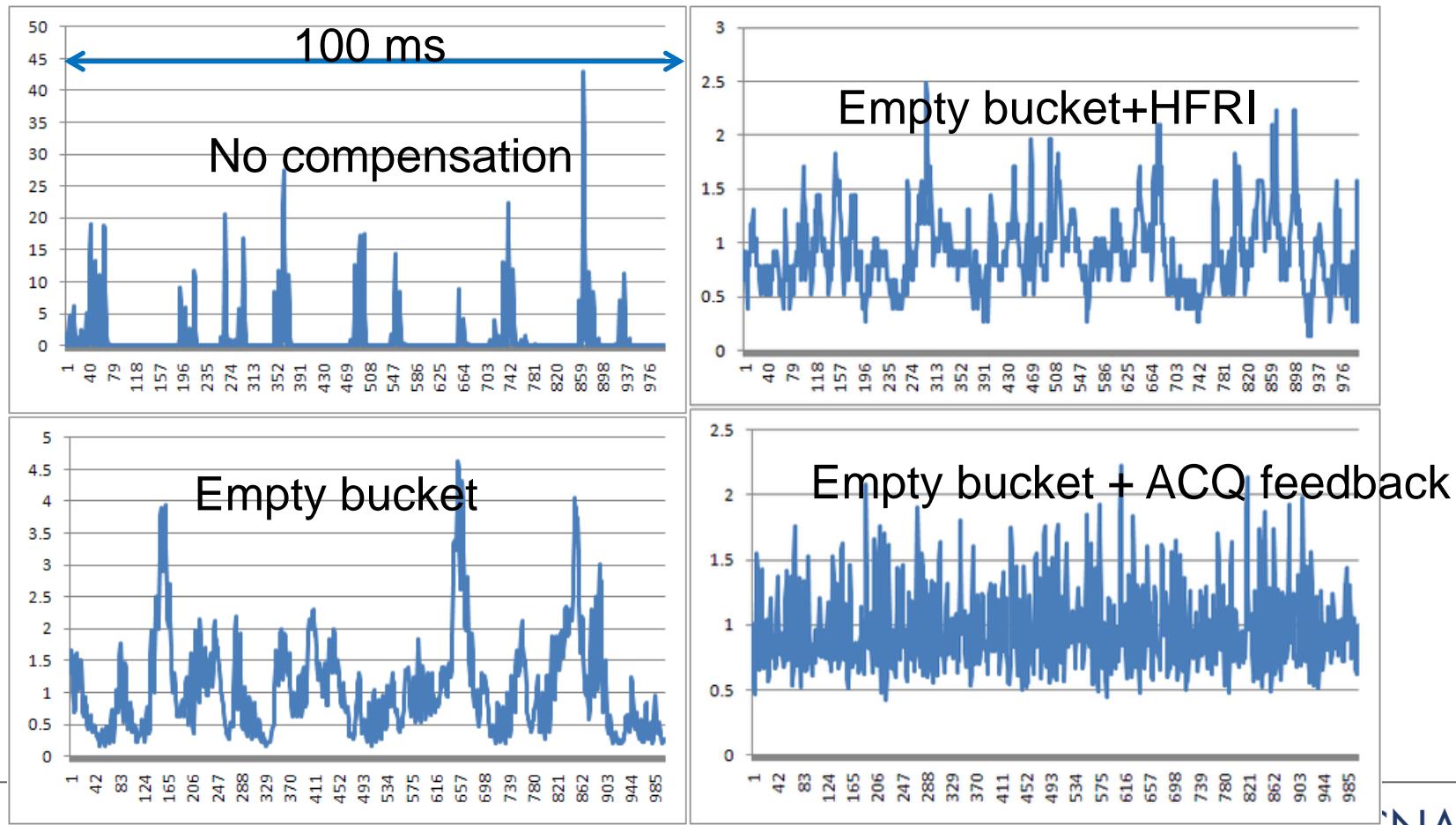


## Air core quadrupole



# Ripple compensation

Integration time 100 us (10 kHz data)

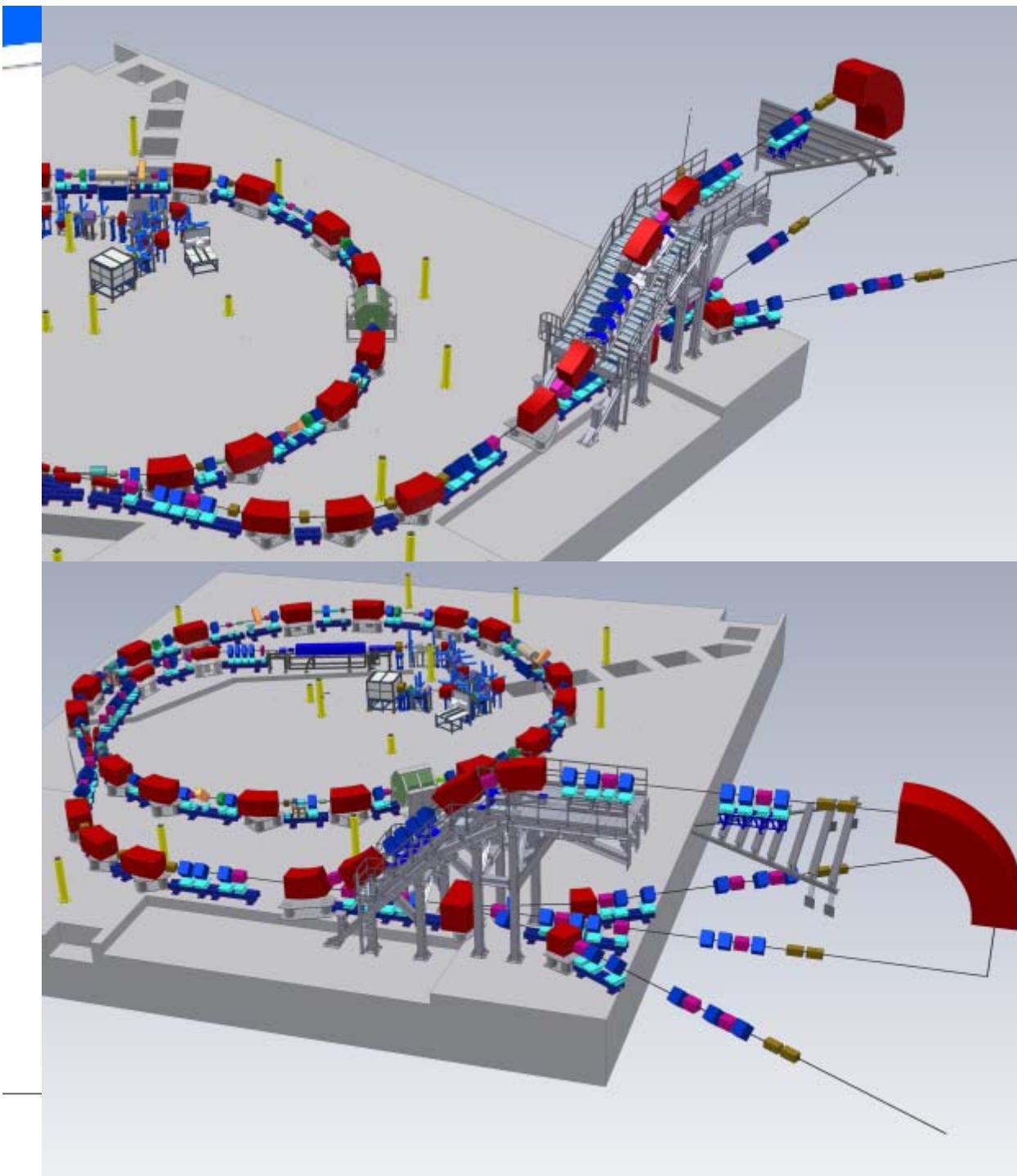


## HEBT

**60-250 MeV p  
120-400 MeV/u C  
 $10^{10}$  p/spill (~2nA)  
 $4 \cdot 10^8$  C/spill (~0.4nA)**

**different settings for**

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

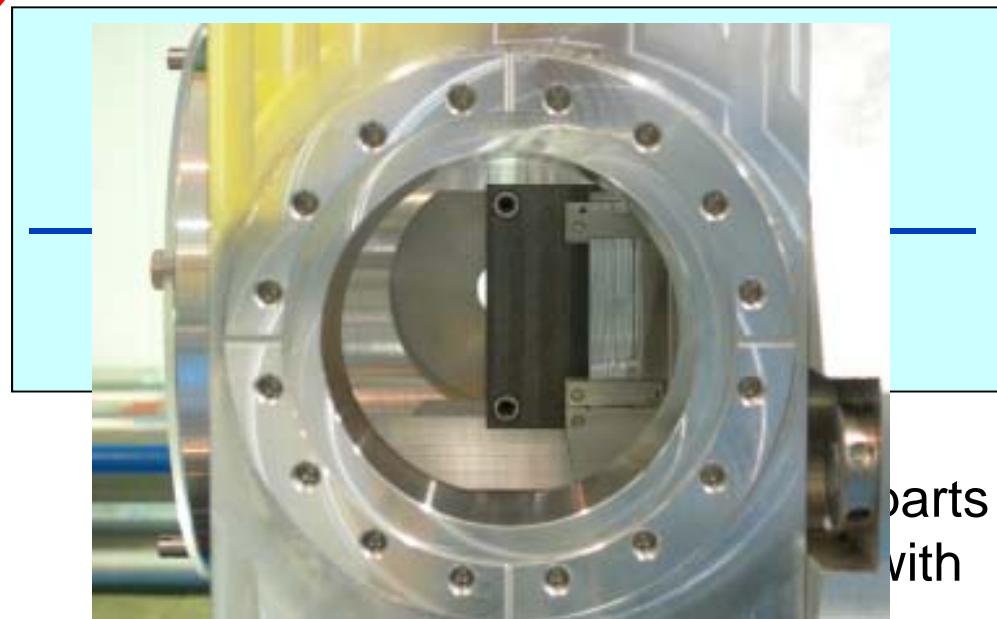
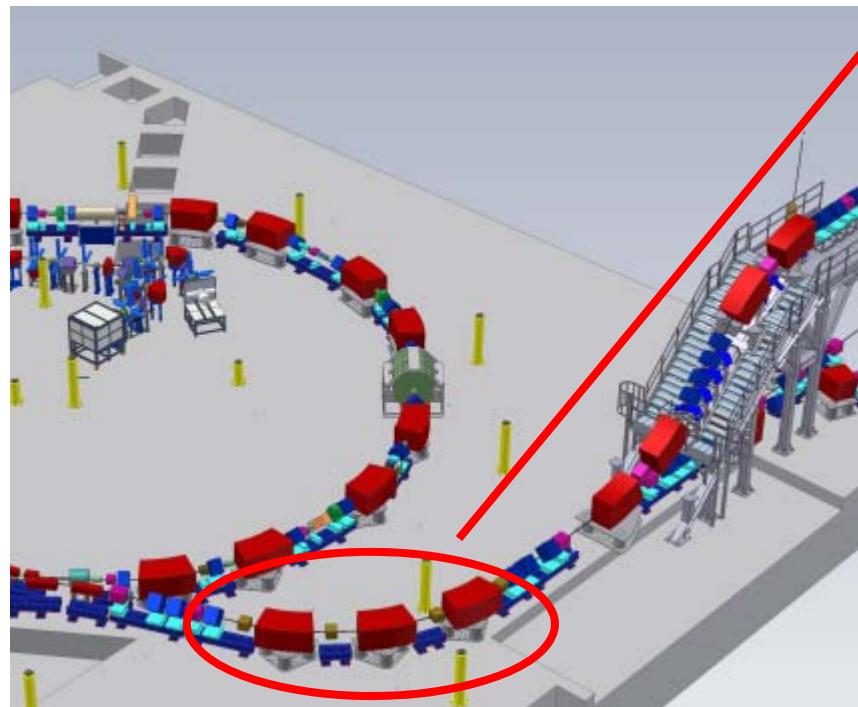
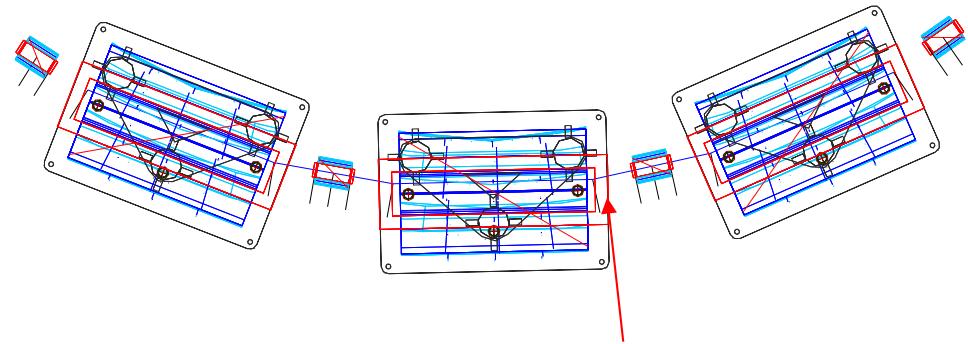


# Chopper

Fast turn on/off for the beam

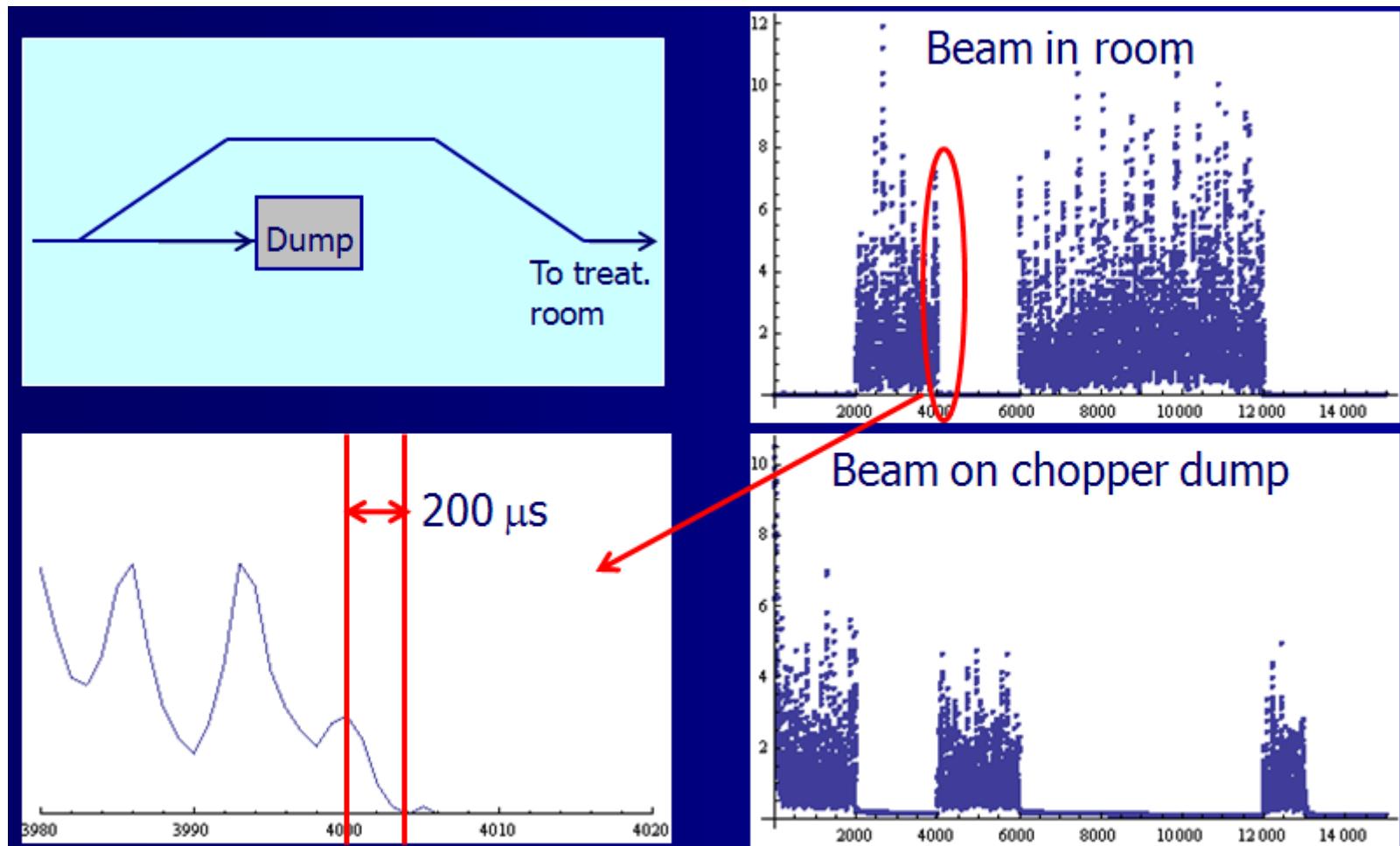
Intrinsically safe

Allows beam qualification



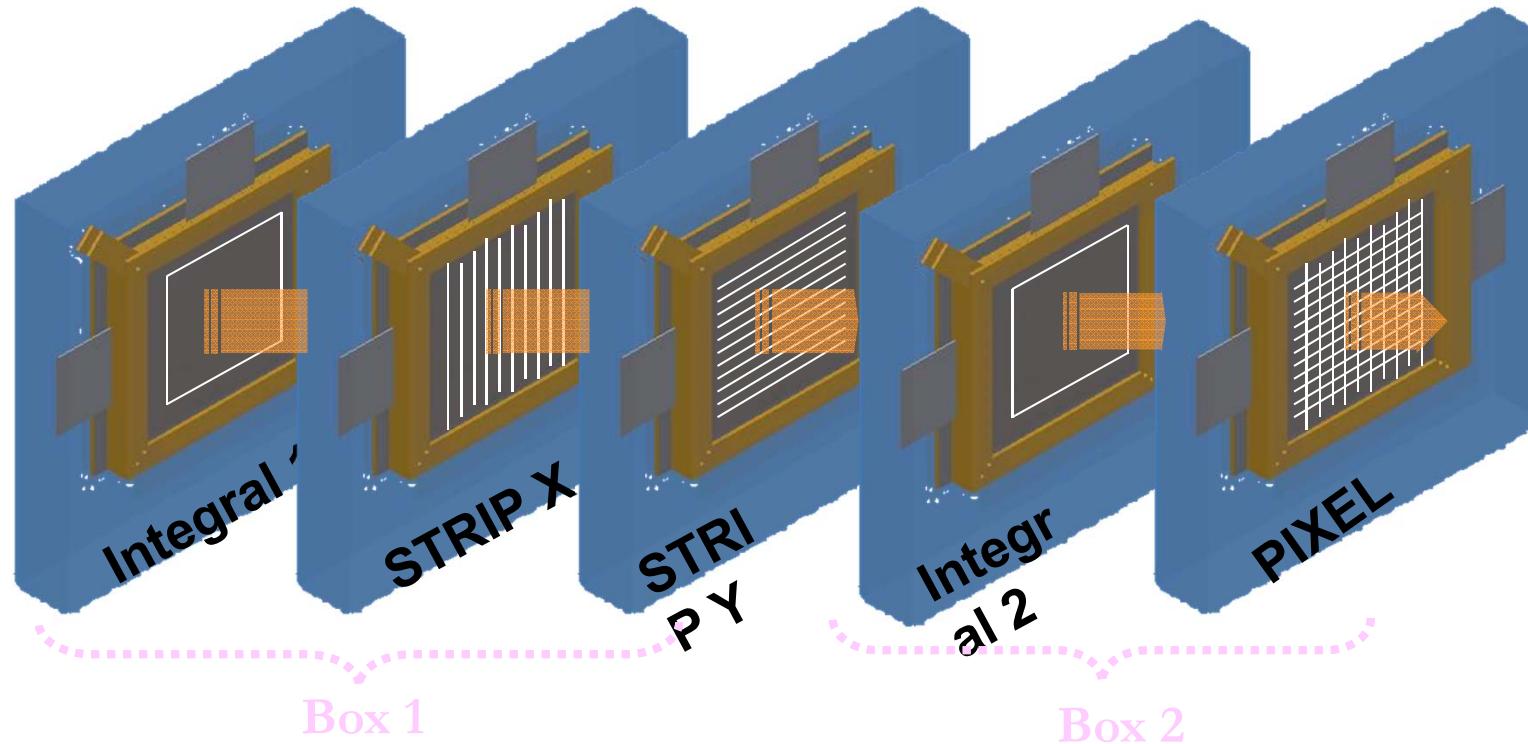
parts  
with  
breathing.

## Chopped beam



# CNAO Beam delivery system

# Beam delivery – scanning control



## 1 Integral chamber:

- Beam Intensity  
measure every  $1\ \mu\text{s}$

## 2 Strip chambers (X and Y):

- Beam position measure  
every  $100\ \mu\text{s}$ , with  $100\ \mu\text{m}$   
of precision

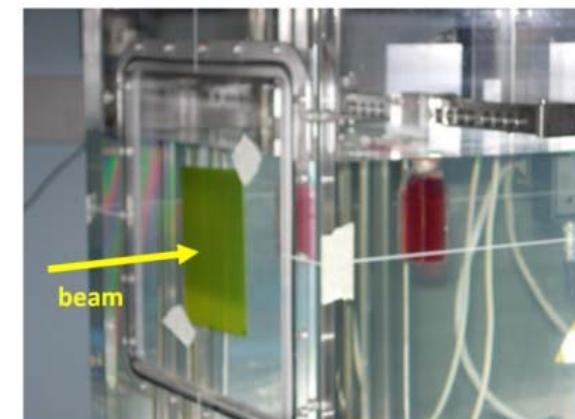
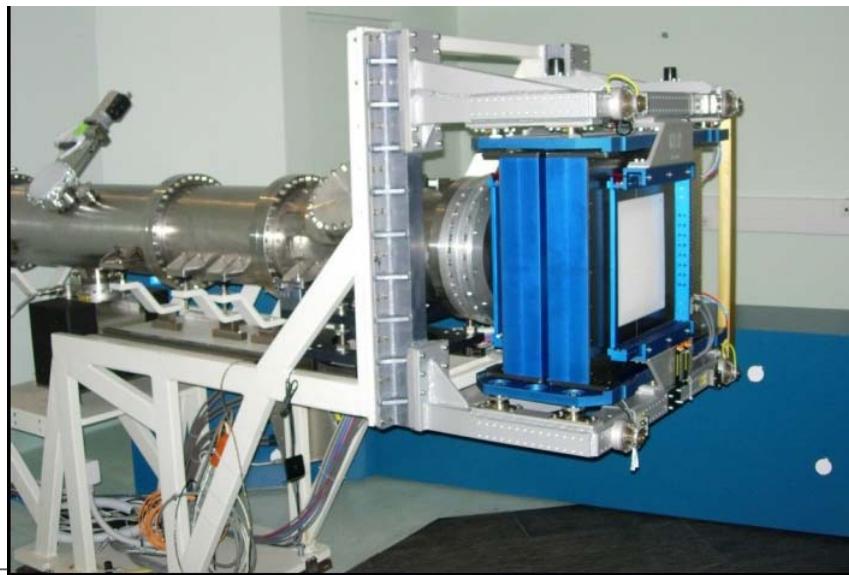
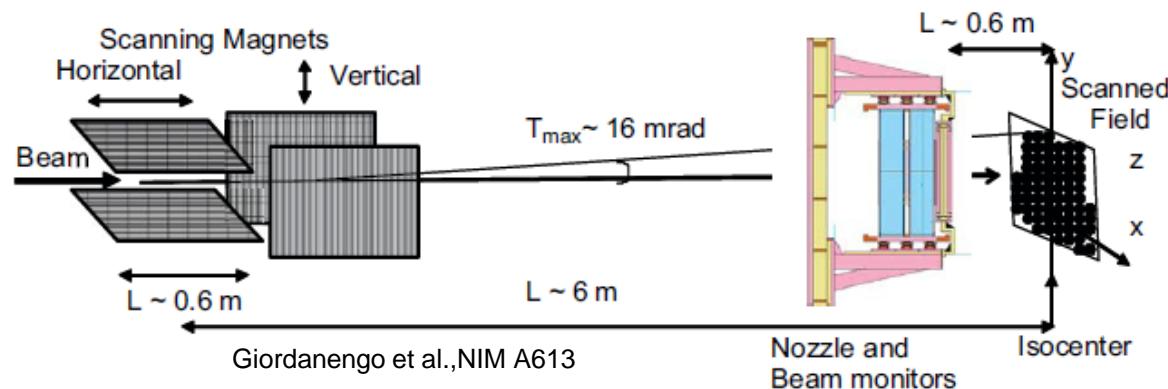
## 1 Integral chamber:

- Beam Intensity measure  
every  $1\ \mu\text{s}$

## 1 Pixel chamber:

- Beam position and dimension  
measure every  $100\ \mu\text{s}/1\ \text{ms}$ ,  
with  $200\ \mu\text{m}$  of precision

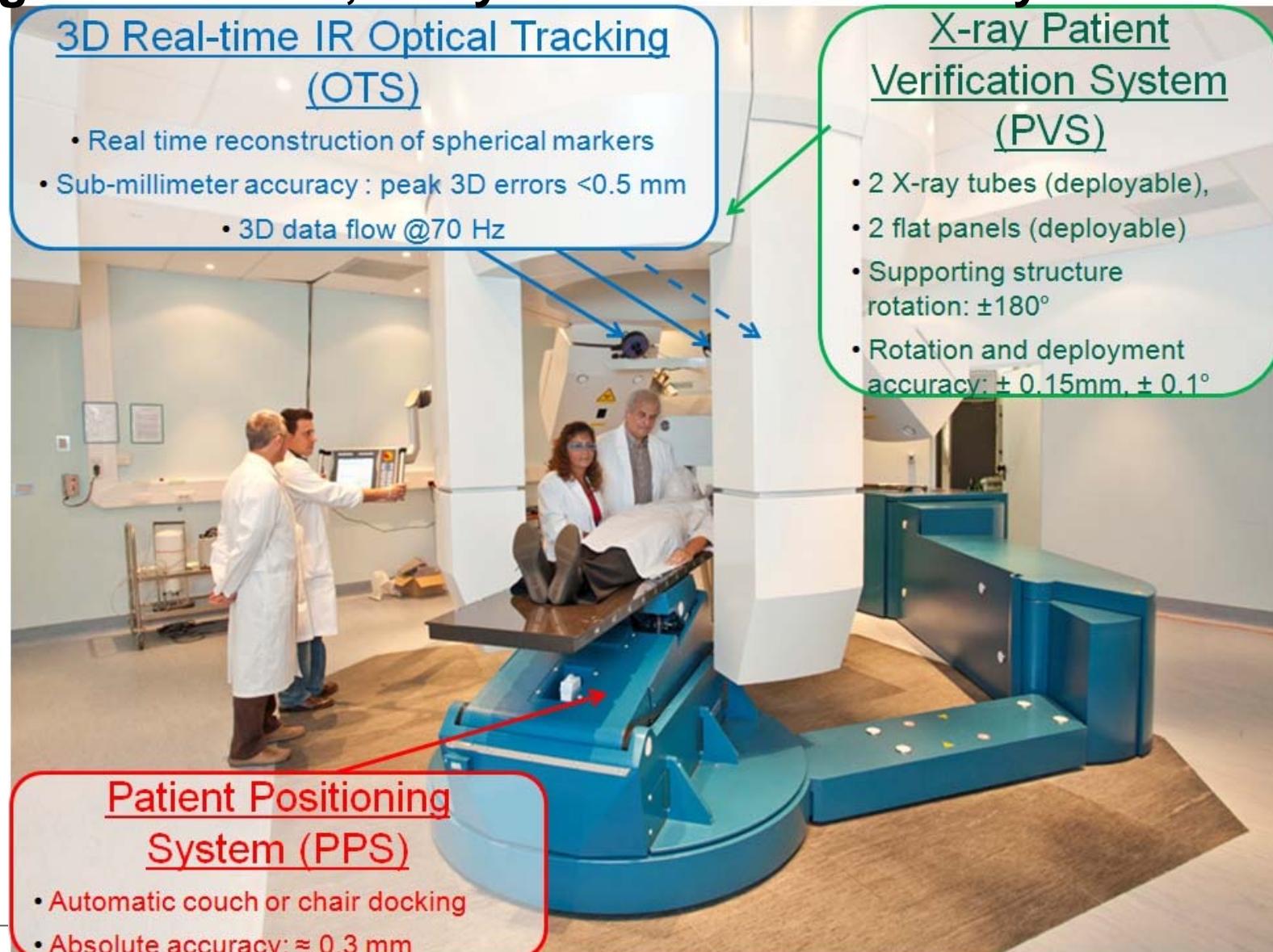
# Dose delivery



# Una volta fuori dall'acceleratore...

# Patient Positioning and Verification strategy at CNAO

## Integrated robotic, X-ray and IR localization system

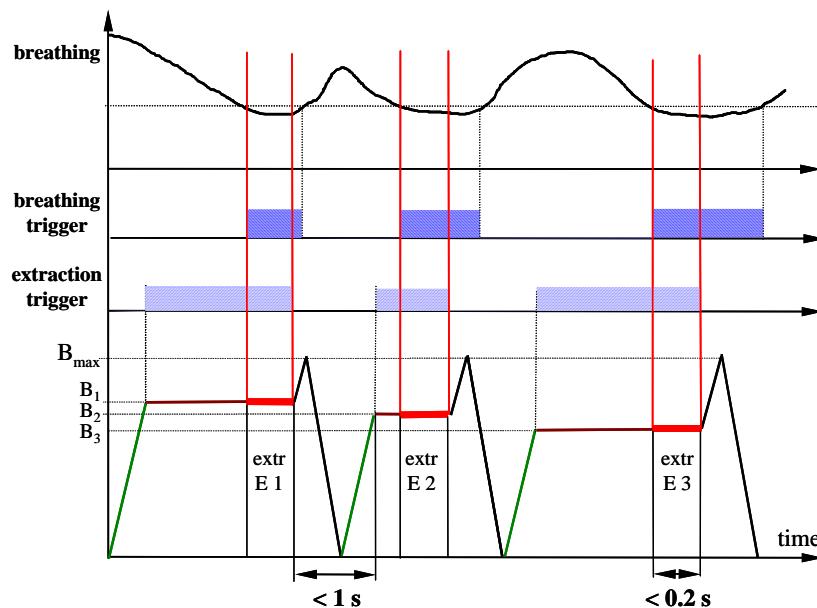


# Patient positioning



## Advanced techniques: breath synchronization

“Minimal” choice: breath synchronisation  
(already applied in Chiba, HIT and CNAO)



Interesting also for IMRT: lots of efforts and devices

External surrogates with correlation models  
X-rays  
Ultrasound, MRI  
Particle radiography

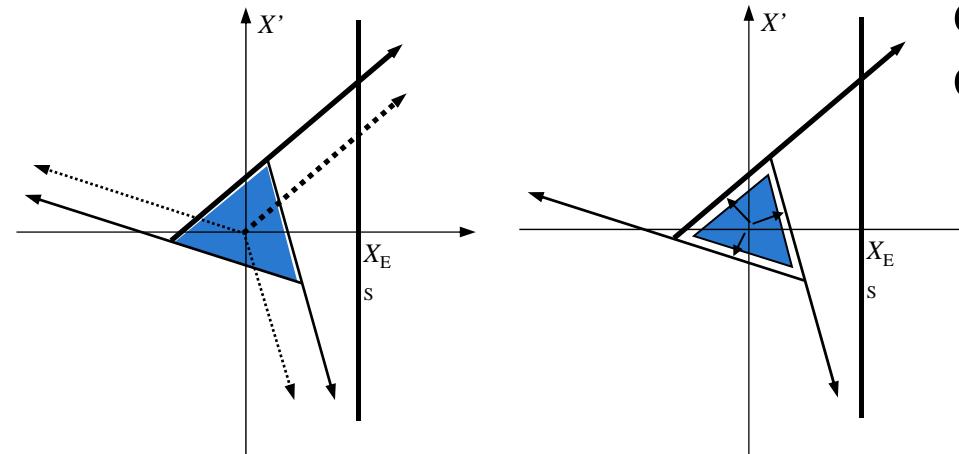
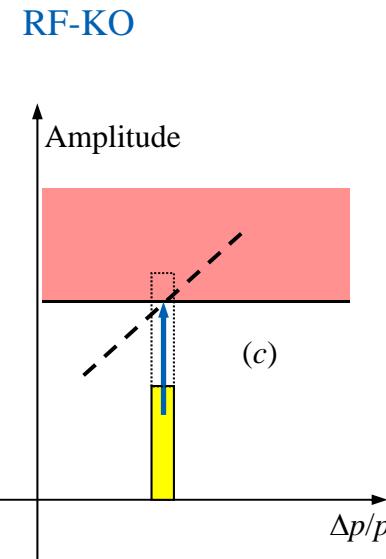
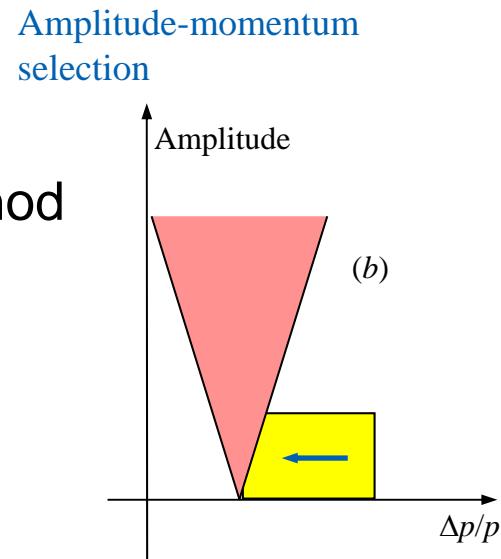


## Future and R&D



## Implementation of RFKO in addition to betatron

Standard method  
at CNAO

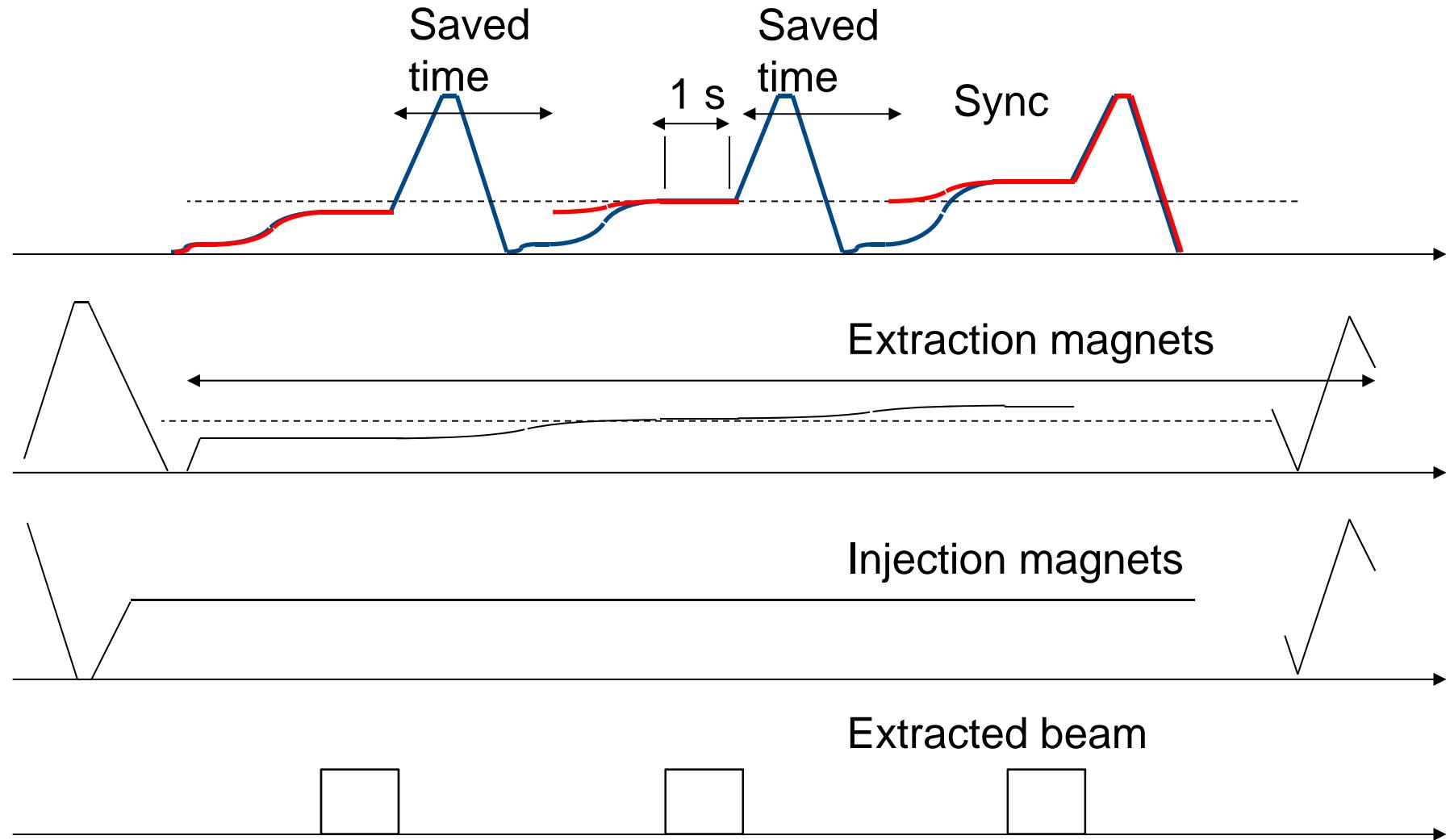


## RFKO implementation

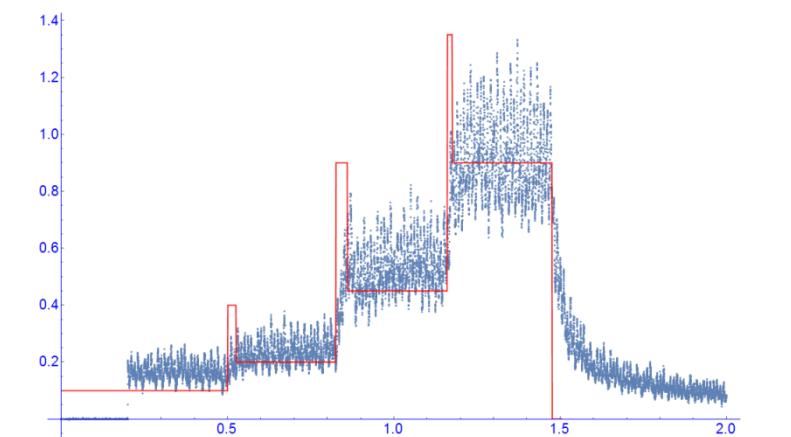
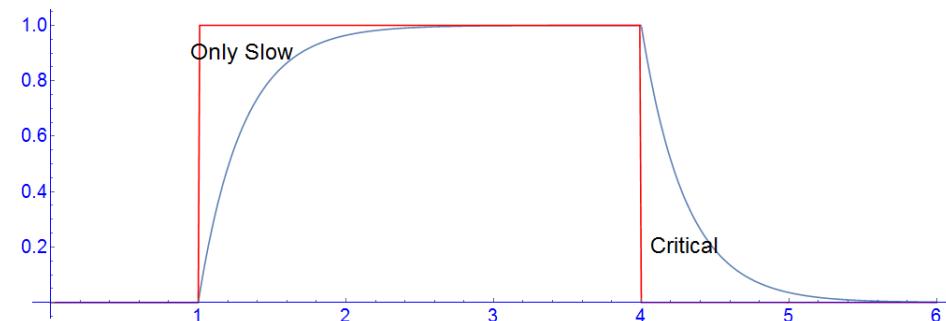
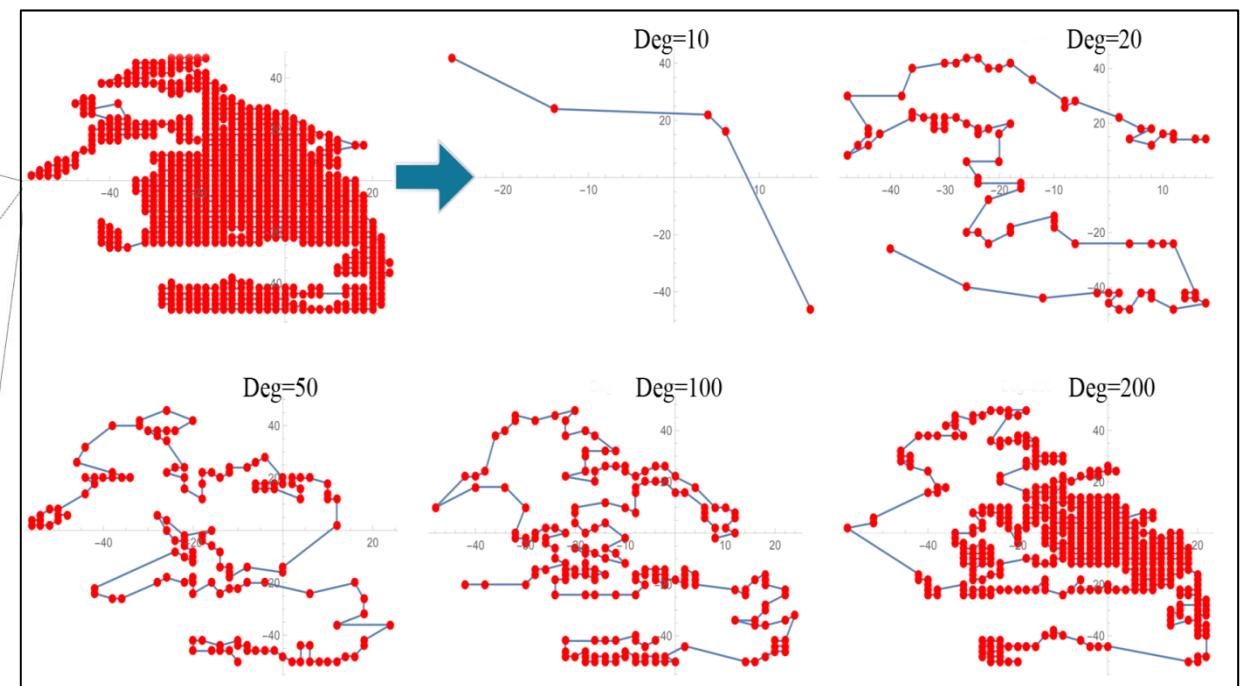
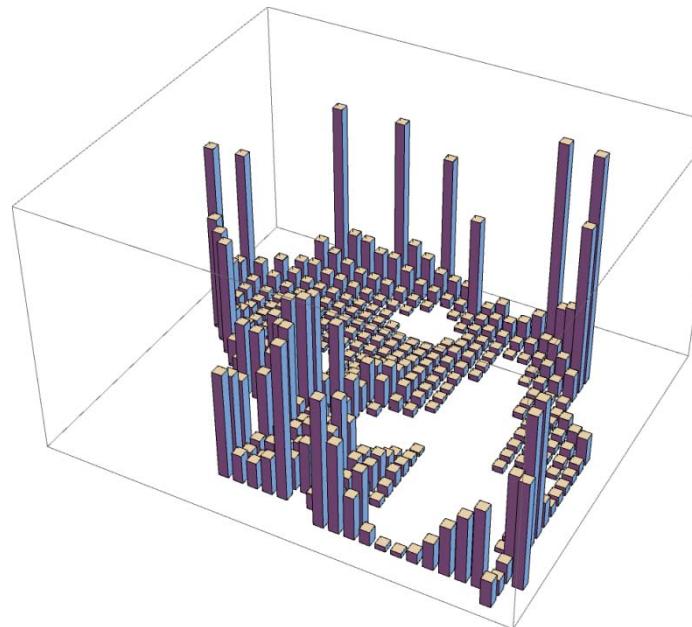
RFKO Kicker installed  
in the ring and cabled

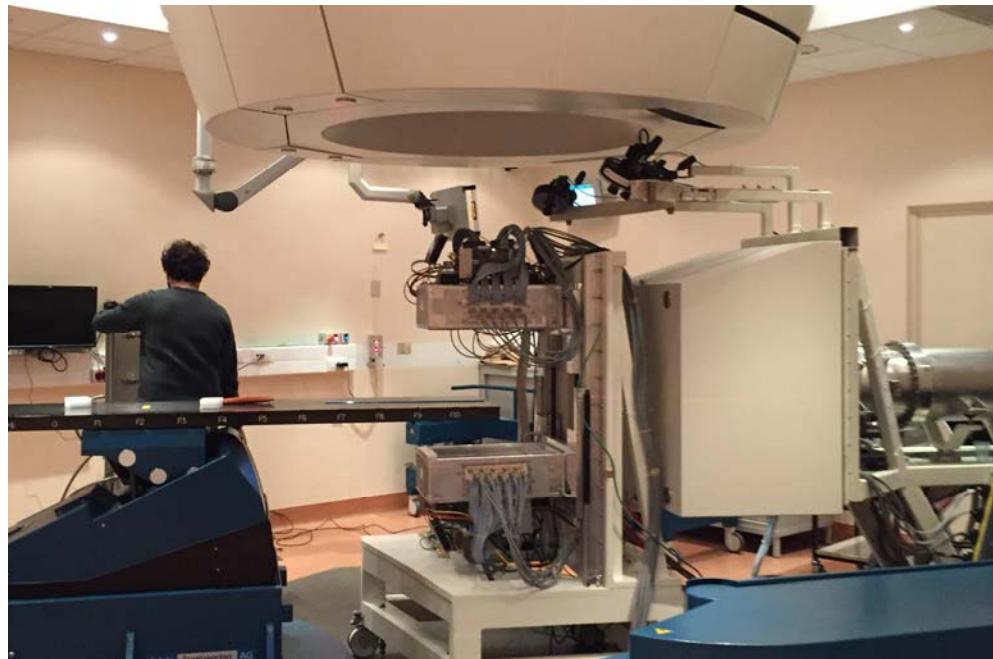


## Treatment execution with Multi Energy Extraction



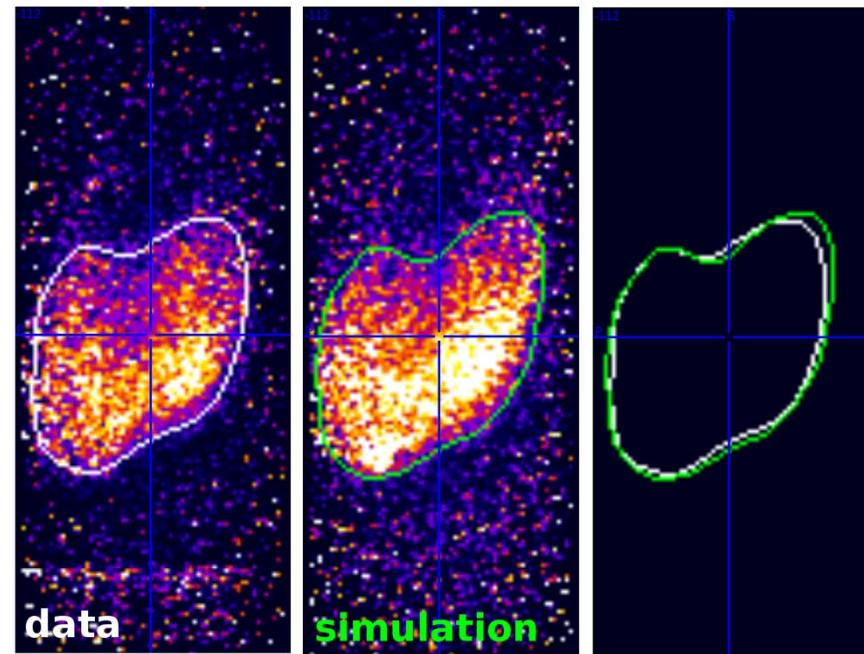
# Intensity Modulation



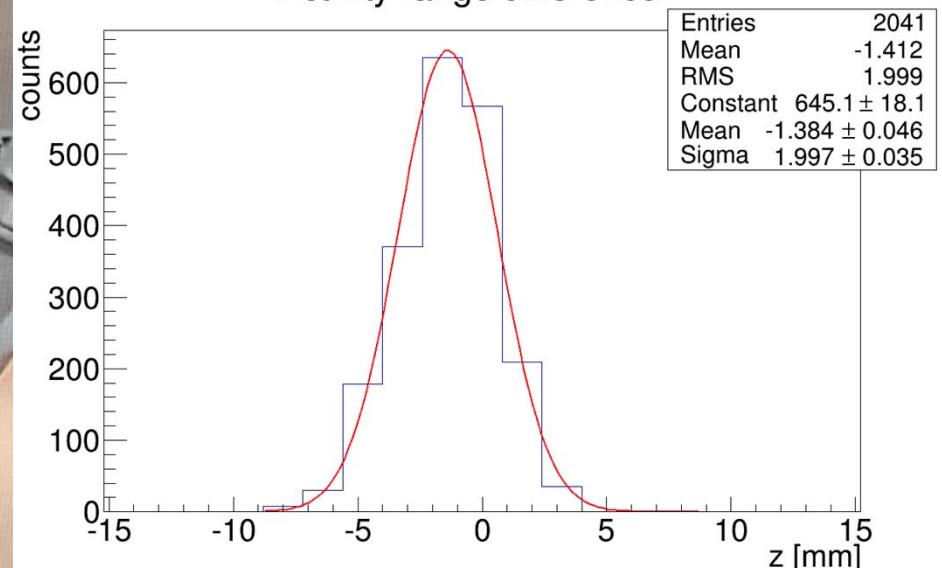


Patient - 01/12/2016  
Proton beam  
4 min treatment + 1min after

InSide

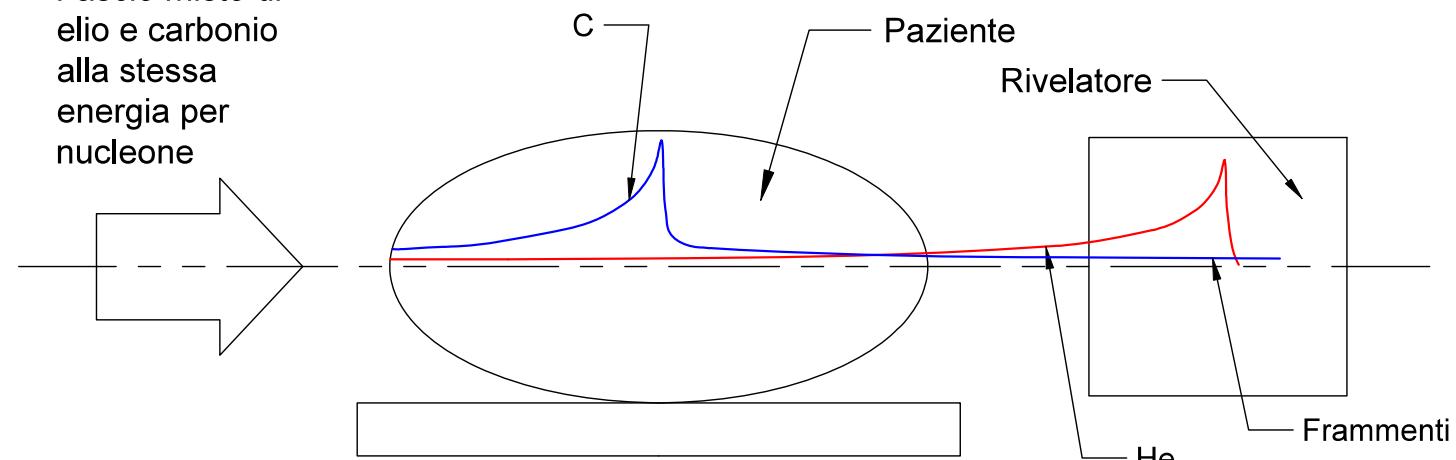


Activity range difference



# HeCheck

Fascio misto di elio e carbonio alla stessa energia per nucleone

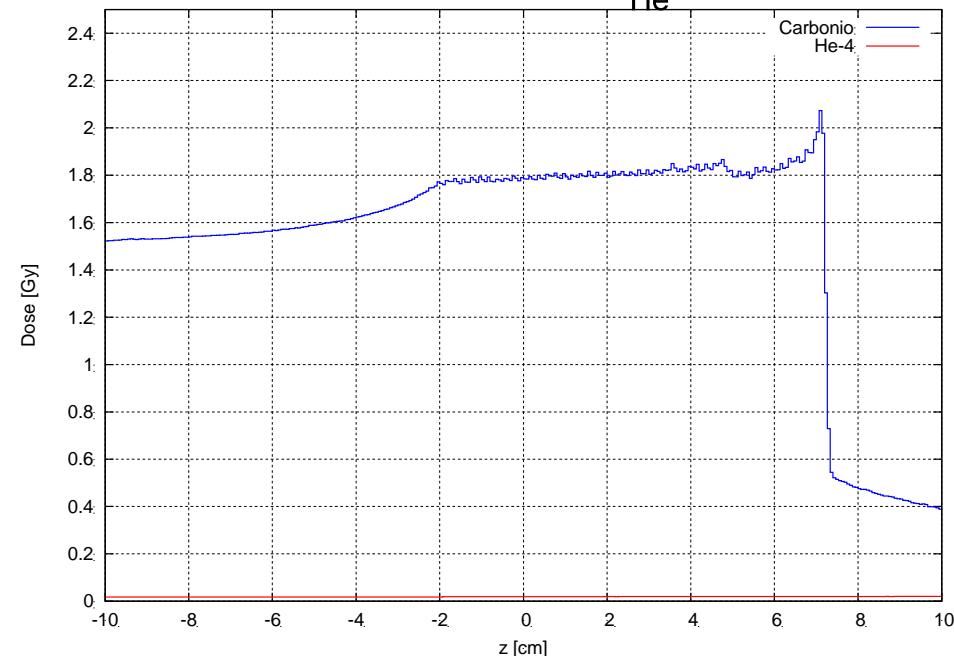


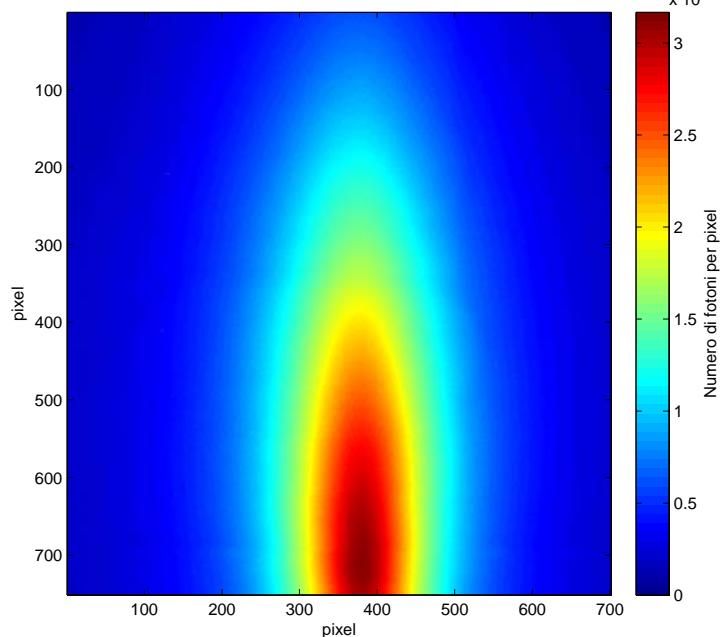
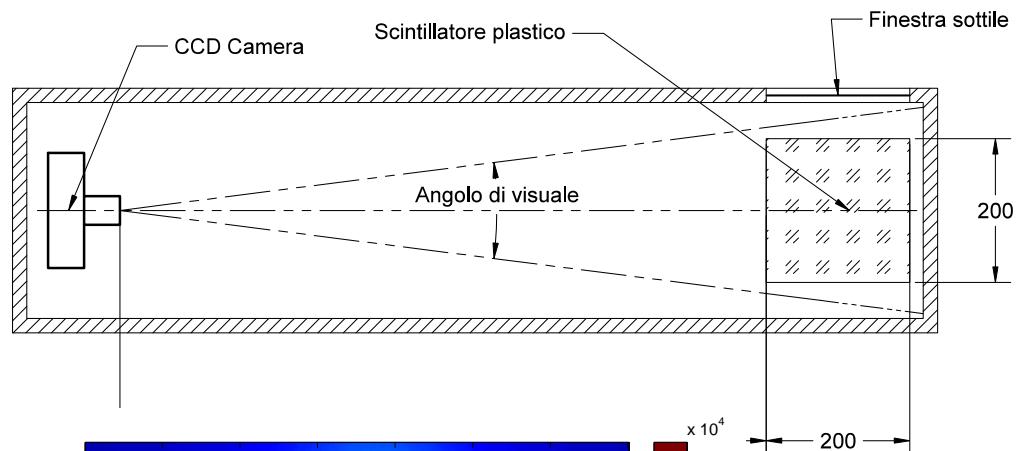
Proof of principle

He 10% in number wrt C

1% in dose

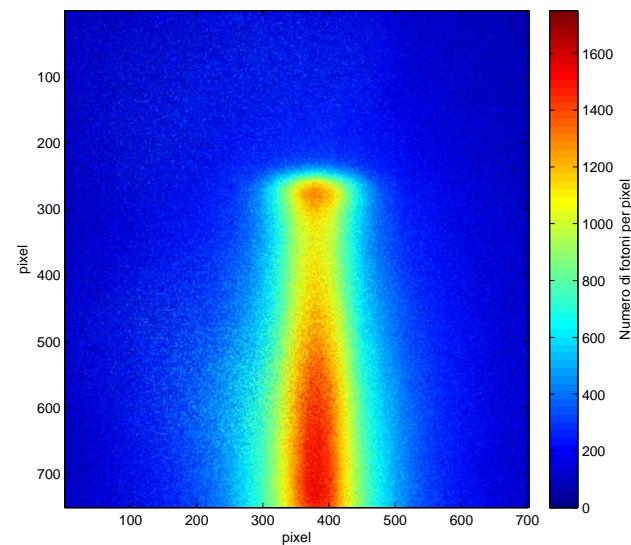
<https://doi.org/10.1002/mp.13219>



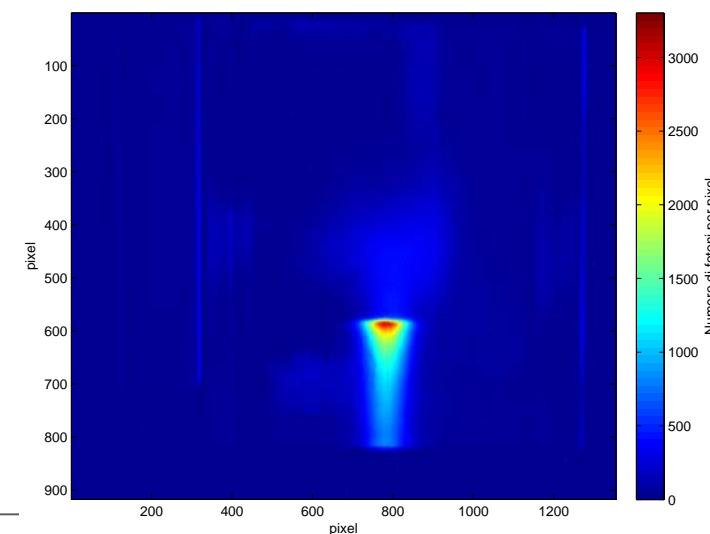


Frammenti da carbonio da 280 MeV/u e  $5 \times 10^7$  primari.

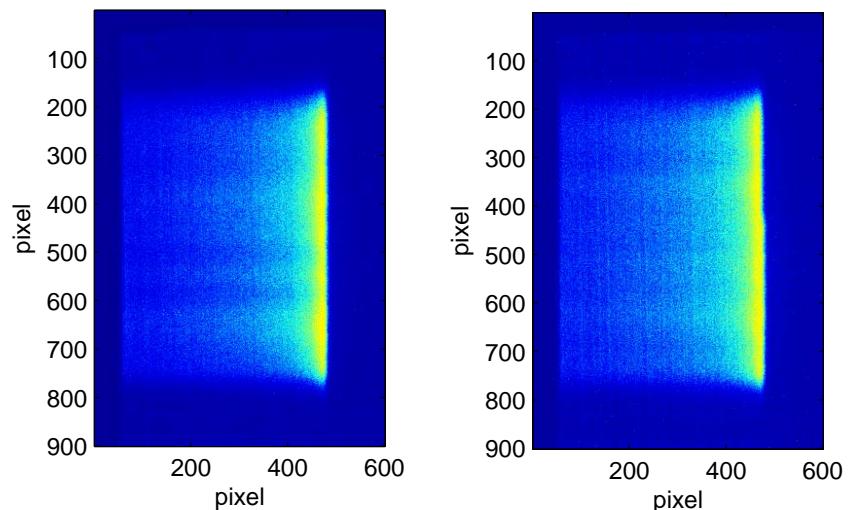
Protoni da 81 MeV e  $5 \times 10^5$  primari.



Protoni ( $5 \times 10^5$ ) da 226.5 MeV e carbonio ( $5 \times 10^6$ ) alla stessa energia per nucleone.

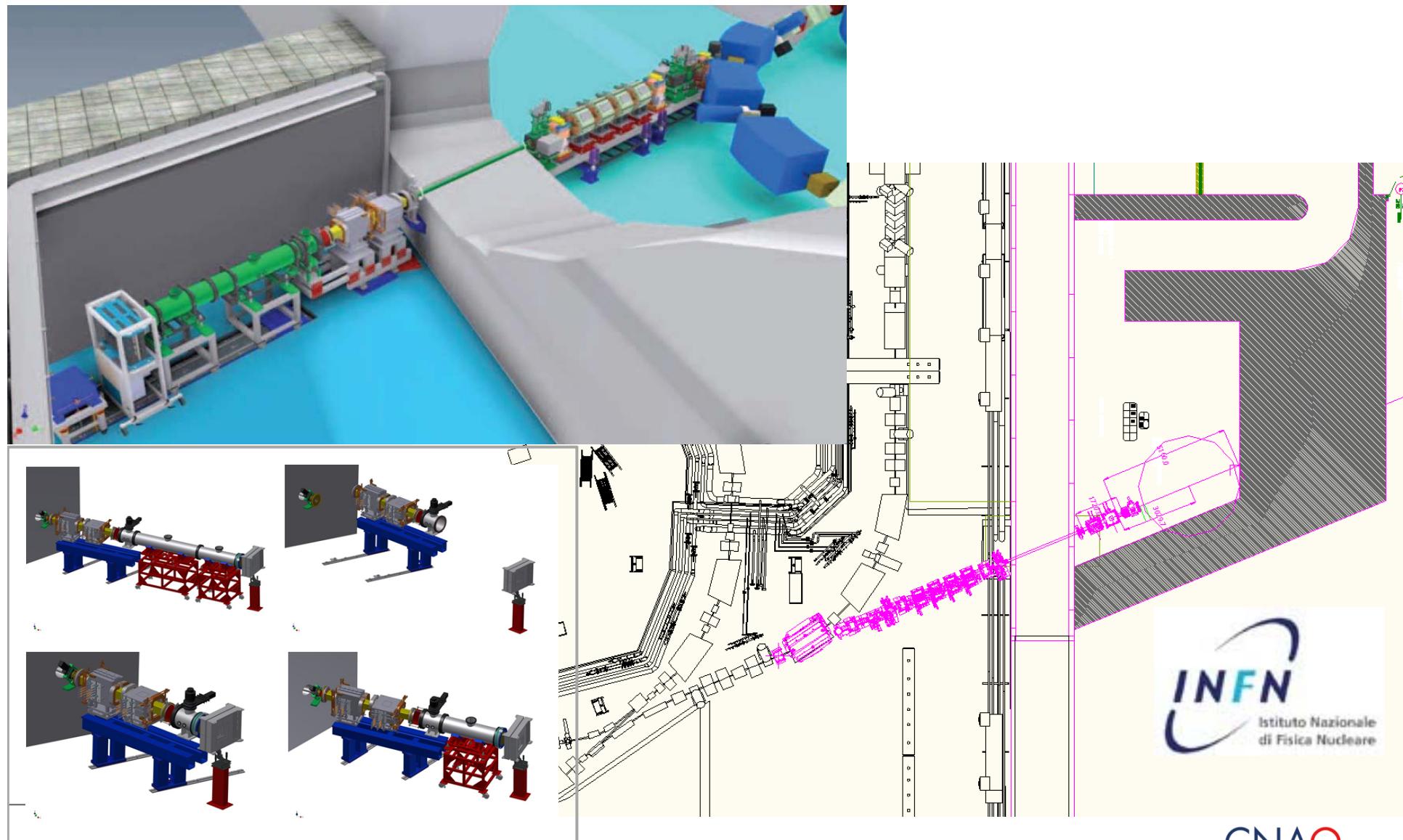


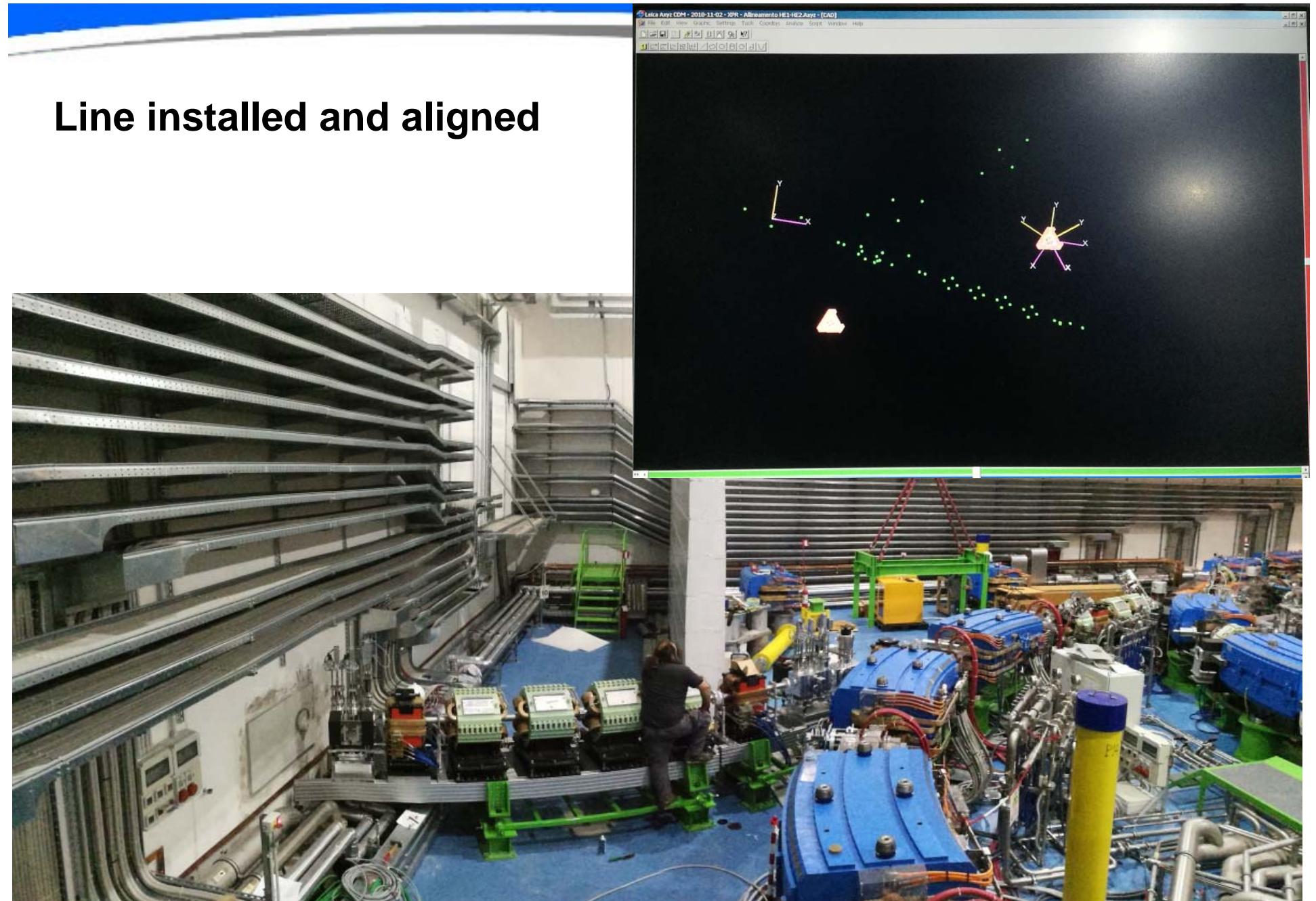
# Resolution < 1 mm



Posizione n°	Range misurato senza slab [mm]	Range misurato con slab da 1mm [mm]	Range misurato con slab da 2mm [mm]
1.	100.524	99.244	98.732
2.	100.524	99.244	98.476
3.	100.524	99.500	98.732
4.	100.524	99.244	98.732
5.	100.524	99.500	98.732
6.	100.524	99.500	98.732
7.	100.524	100.268	100.268
8.	100.524	100.268	100.780
9.	100.524	100.524	100.780
10.	100.524	100.268	100.780
11.	100.524	100.524	100.780
12.	100.524	100.268	100.780
13.	100.524	100.524	100.524
14.	100.524	100.268	100.524
15.	100.268	100.012	100.524

## Experimental room





# Experimental room – phase 2 – 3<sup>rd</sup> source

Additional ion species

Higher performances source

Ion	SUPERNANOGEN (14.5 GHz)	AISHa (18 GHz + TFH)
	[ $\mu$ A]	[ $\mu$ A]
H <sup>+</sup>	2000	4000
H <sup>2+</sup>	1200	2000
H <sup>3+</sup>	800	1000
<sup>3</sup> He <sup>+</sup> - <sup>4</sup> He <sup>+</sup>	800	2000
<sup>12</sup> C <sup>4+</sup>	200	800
<sup>6</sup> Li <sup>2+</sup>	//	600
<sup>18</sup> O <sup>6+</sup>	250	1000
<sup>16</sup> O <sup>6+</sup>	400	1200
<sup>21</sup> Ne <sup>7+</sup> - <sup>20</sup> Ne <sup>7+</sup>		

Present Layout

Source H<sub>3</sub><sup>+</sup>

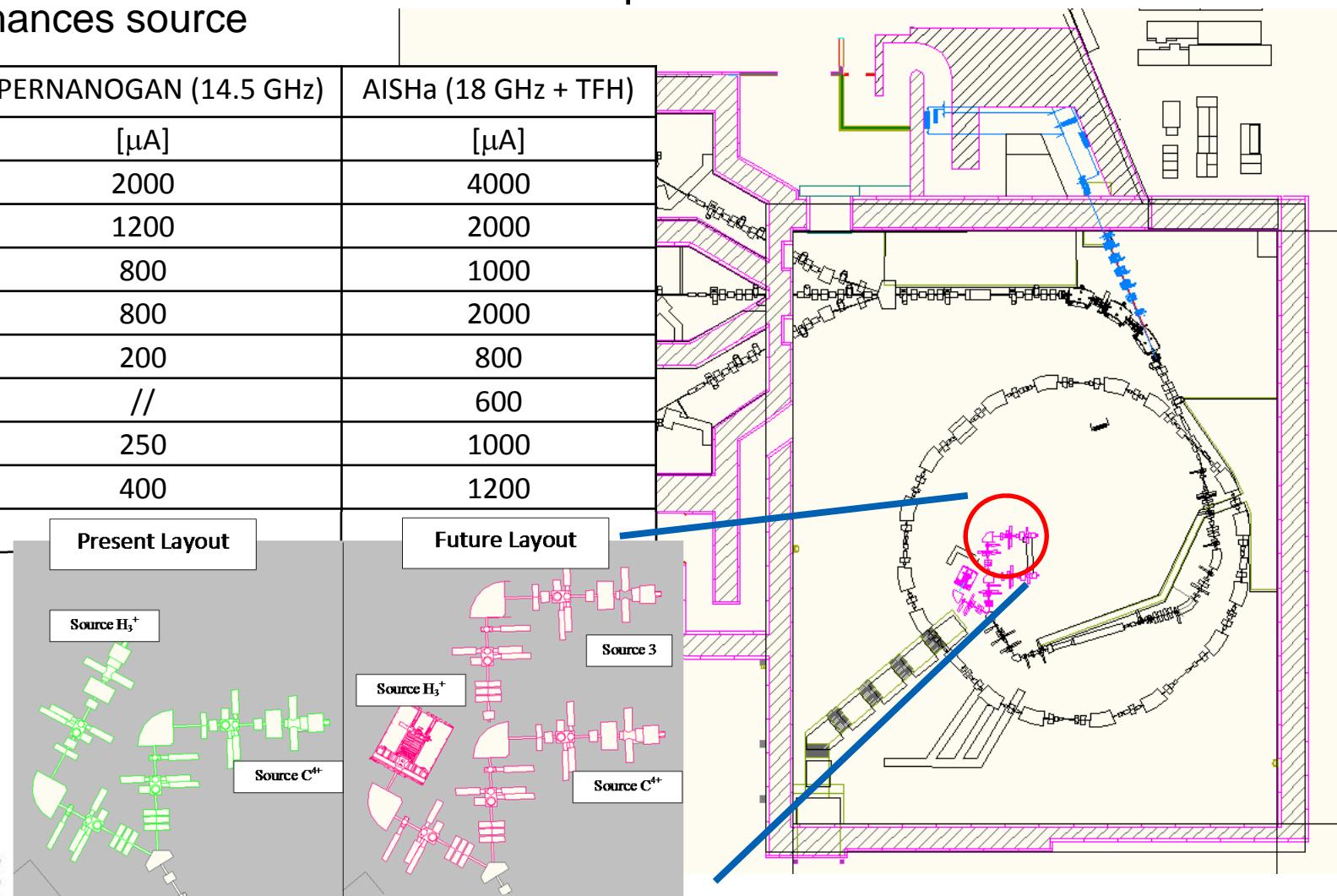
Source C<sup>4+</sup>

Future Layout

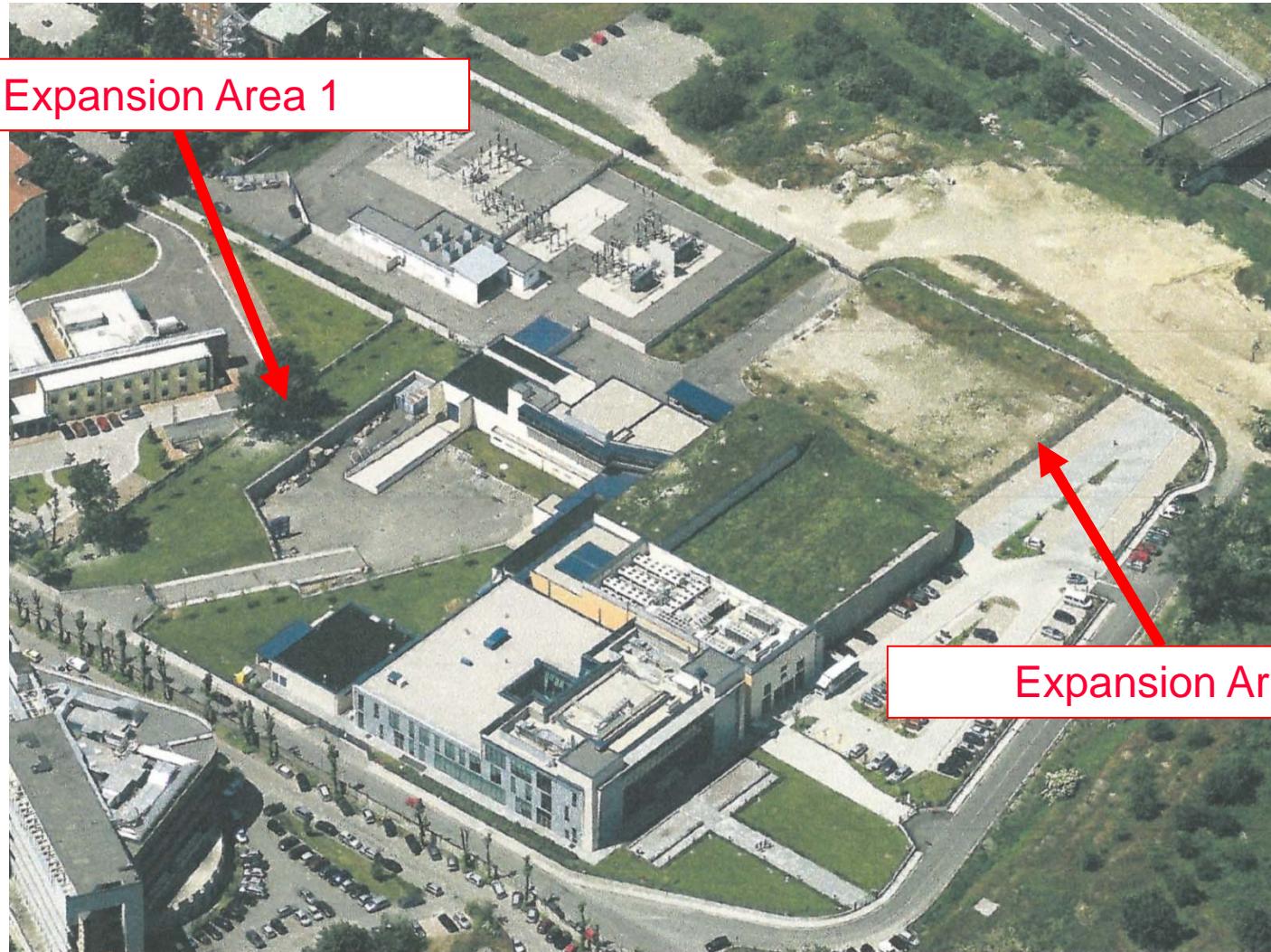
Source H<sub>3</sub><sup>+</sup>

Source 3

Source C<sup>4+</sup>

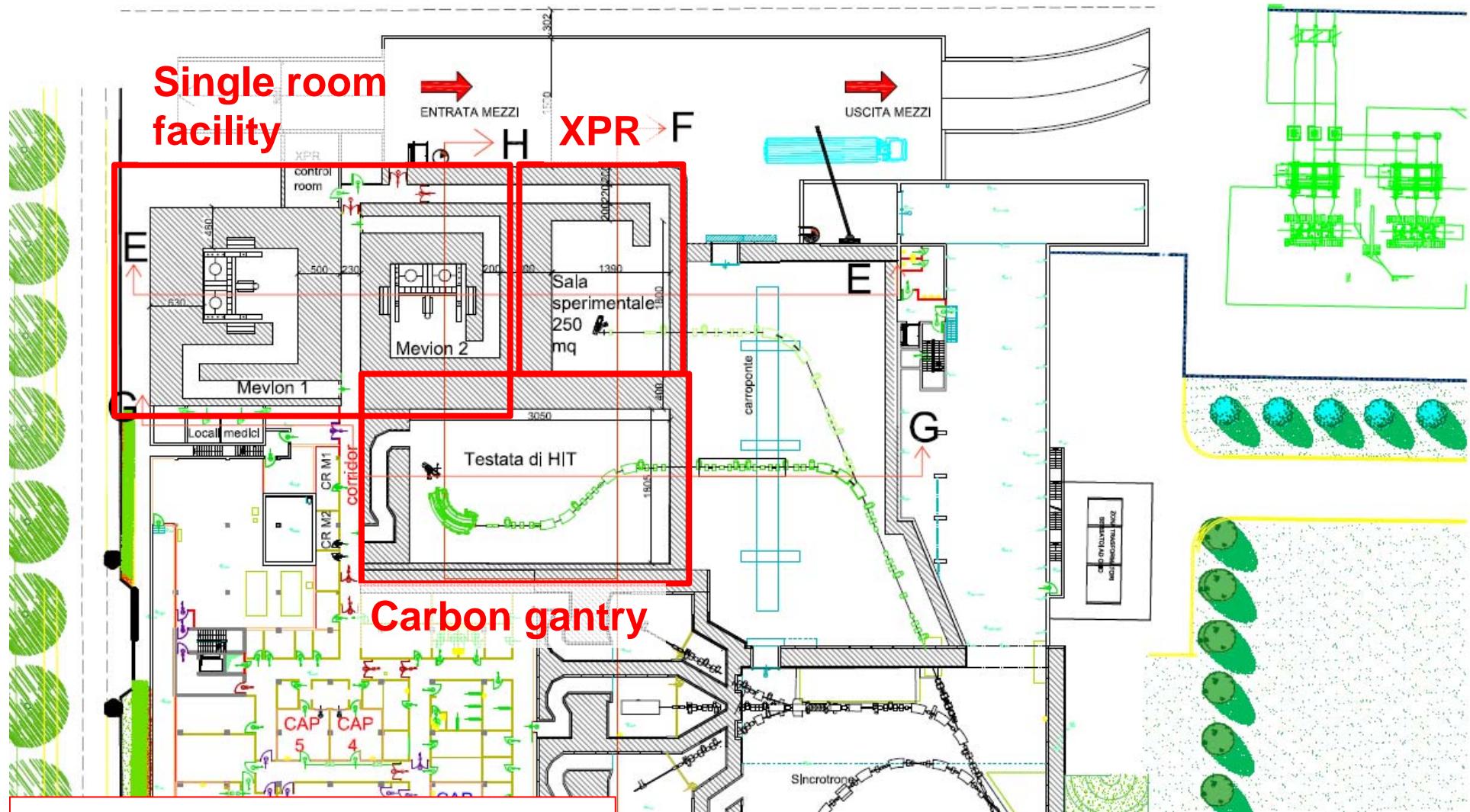


## View of the site



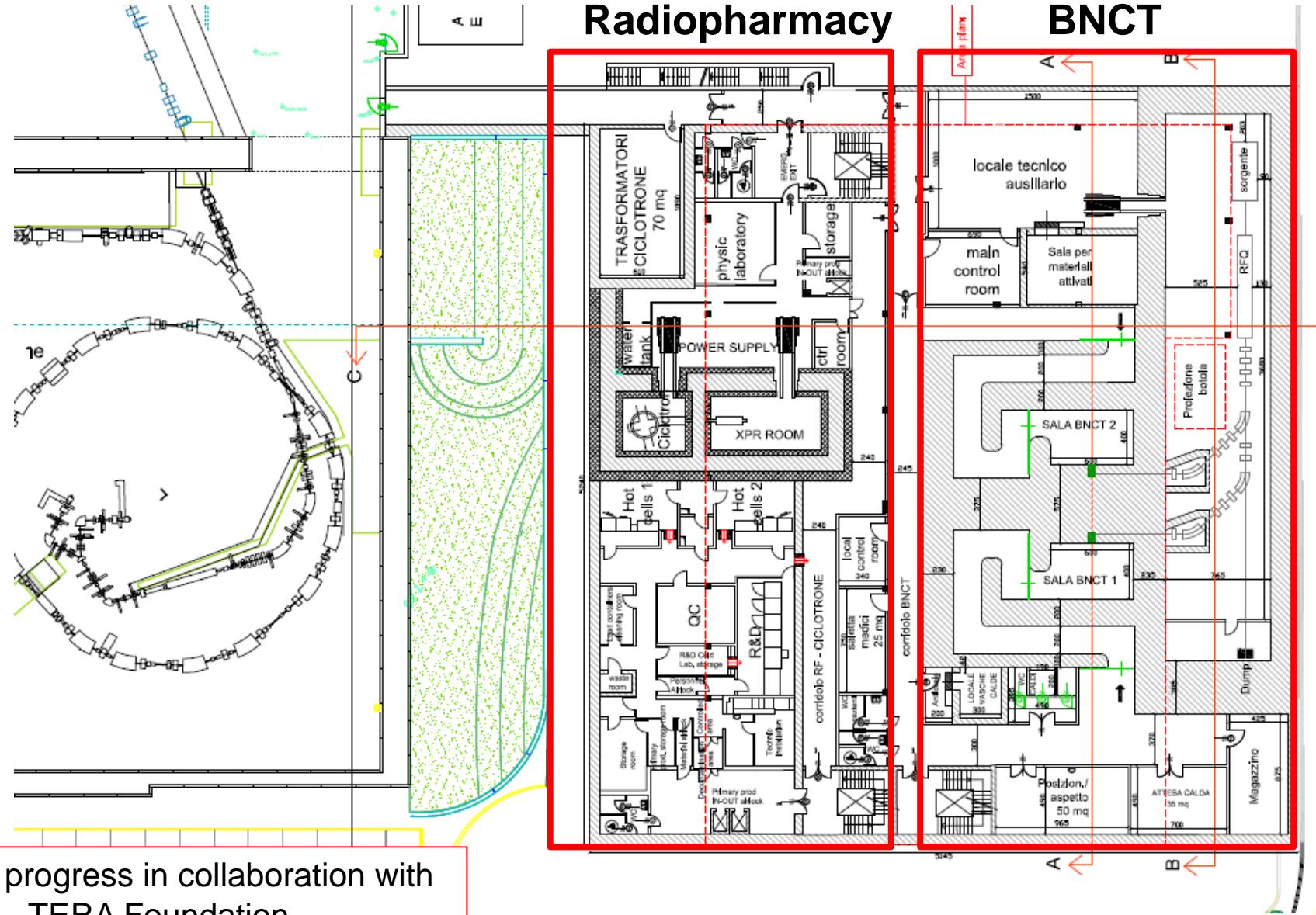
Copyright ©2008 Pictometry I

# Expansion Area 1



Work in progress in collaboration with  
TERA Foundation

## Expansion Area 2



**Research is a must** to keep CNAO up-to-date  
to stay always at the cutting edge



*The Centre technology needs to evolve and adapt according to the research outcome: it is not a static "black box" producing beam, it is an evolving entity*



# Thank you for your attention

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

R. Feynmann