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

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Parte II

Corso di Formazione - Dipartimento di Fisica
"Sapienza" Università di Roma
9 Luglio 2013

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:

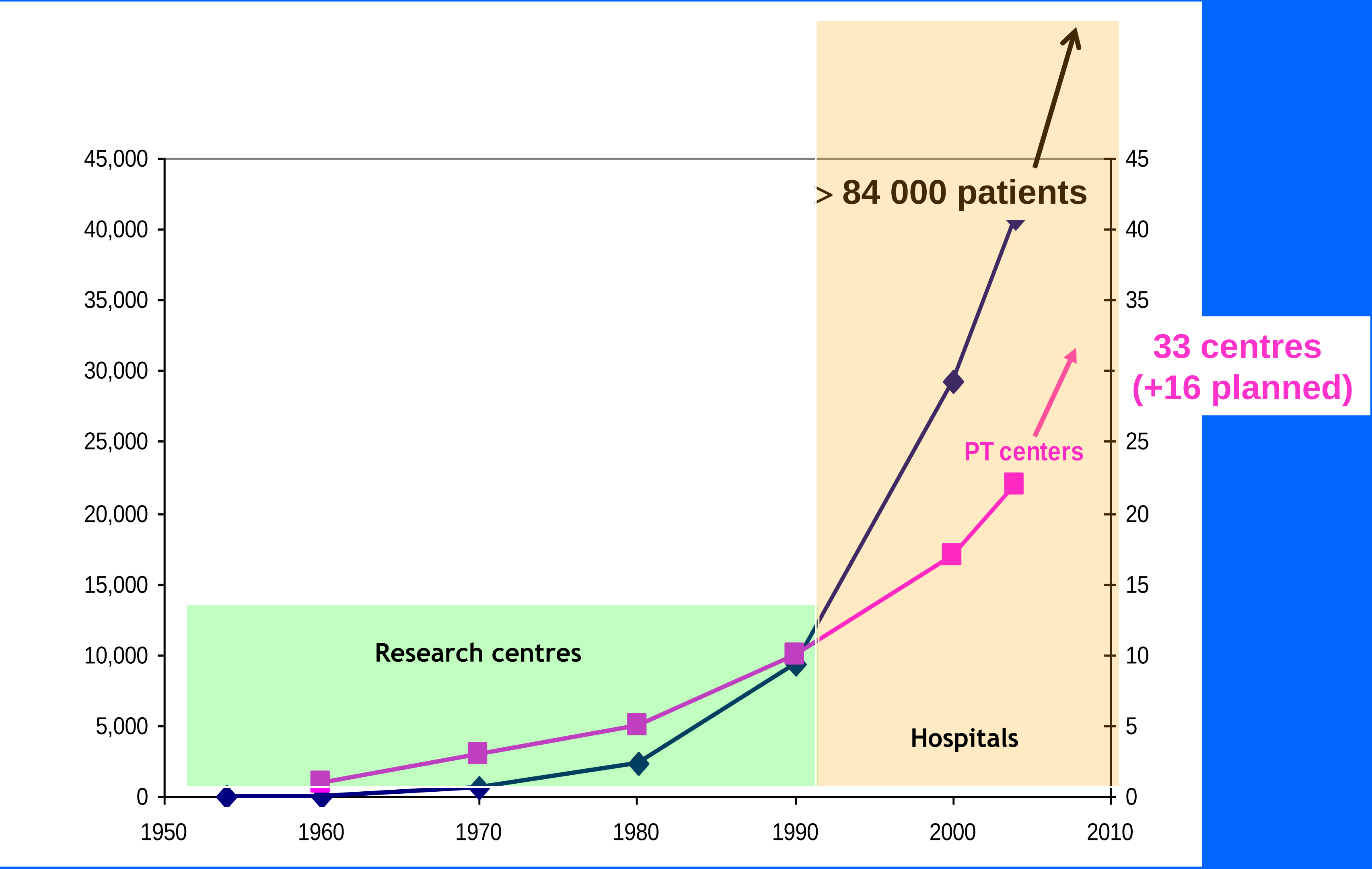
viaggio alla scoperta del CNAO e delle tecnologie degli acceleratori

Parte IV:

le tecnologie e i sistemi a contatto con i pazienti

la sperimentazione clinica e i risultati sui pazienti

Protontherapy is booming (www.ptcog.psi.ch)

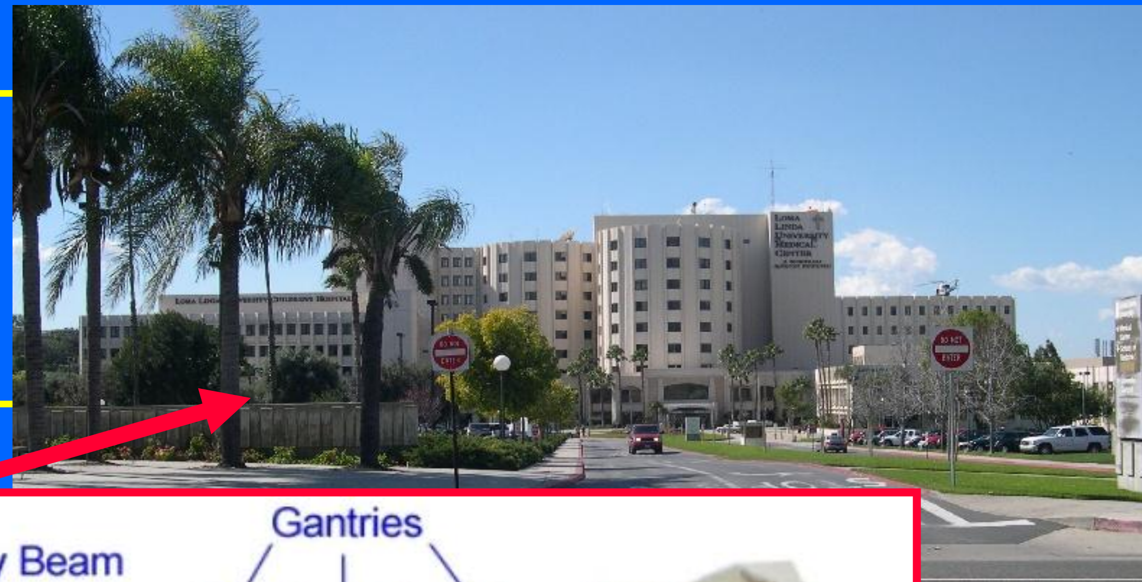


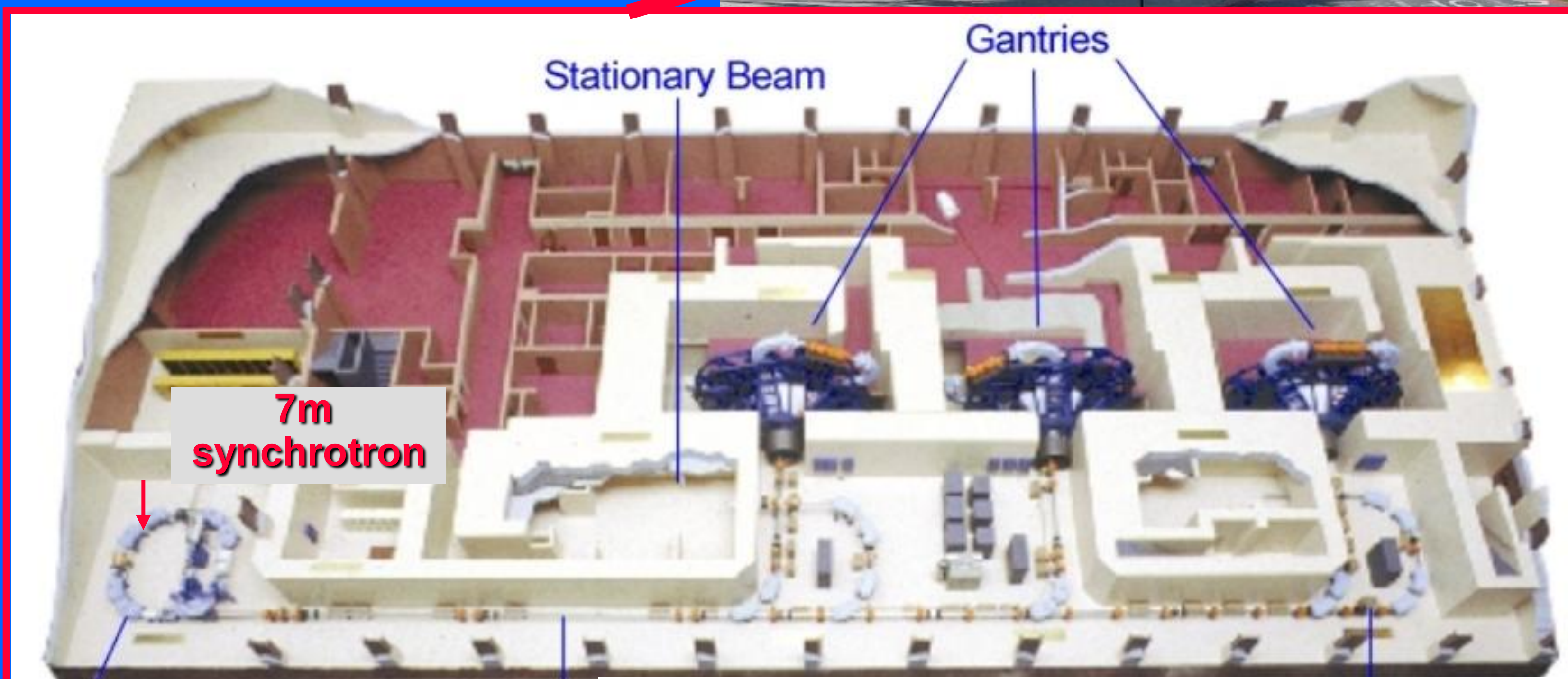
Carbon Ions: > 9000 patients; 6 centres (+2 planned)

Loma Linda University Medical Center: first patient 1992

First hospital based protontherapy centre (1992)

2012:160 sessions/d





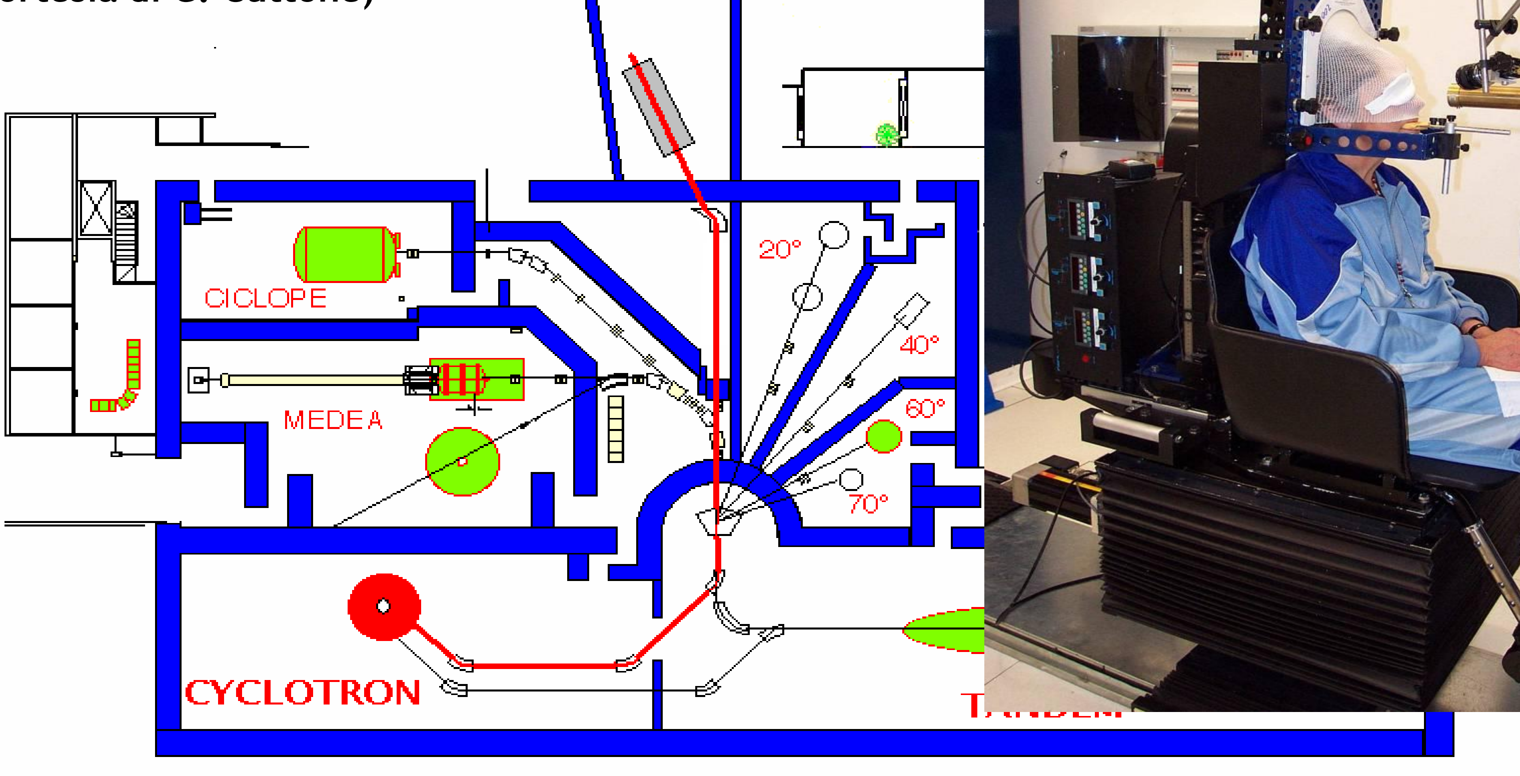
Optivus Ltd. commercialises this centre

Centro CATANA ai LNS dell'INFN

Primo trattamento con protoni da 62 MeV nel 2002

250 pazienti affetti da melanomi oculari

(Cortesia di G. Cuttone)



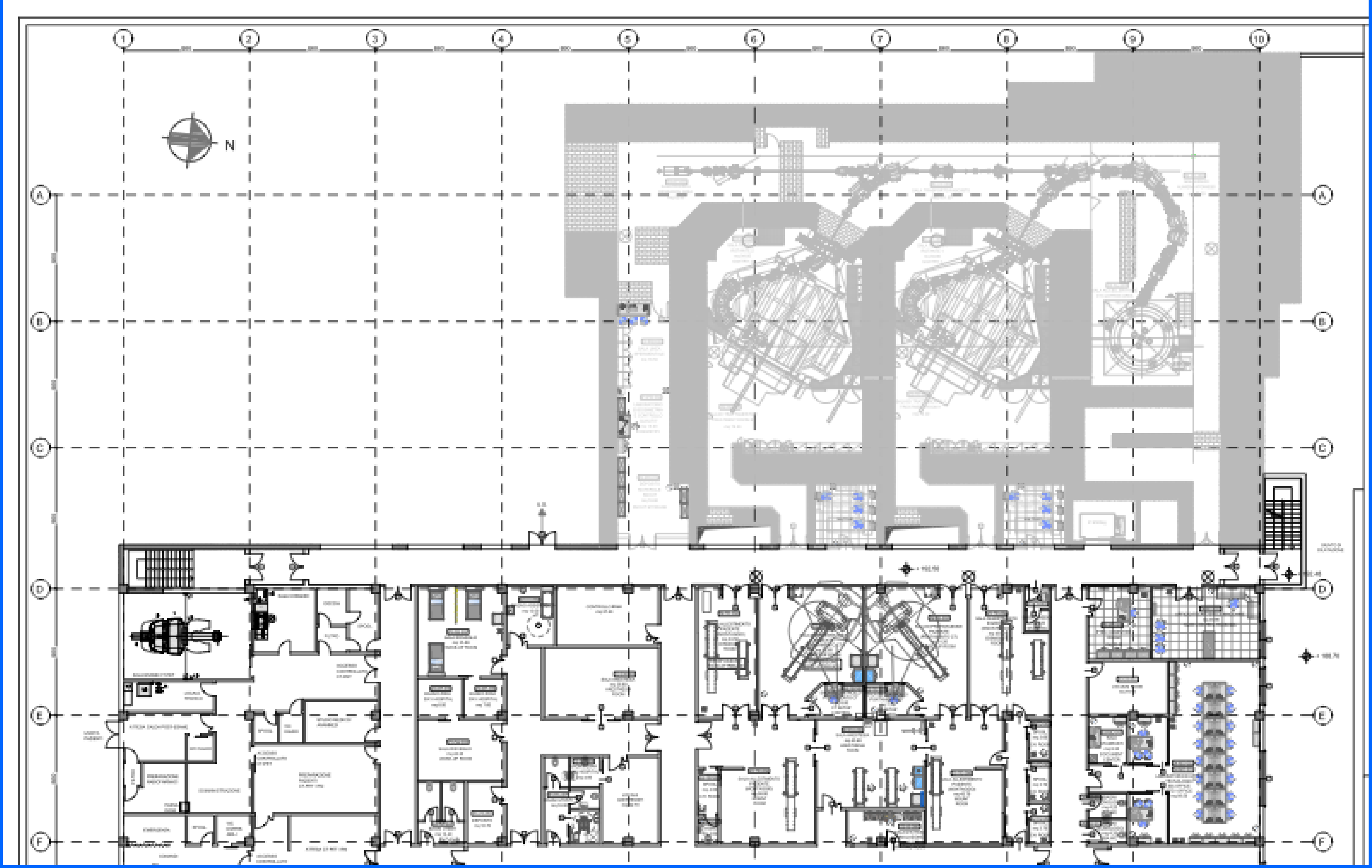
Progetto ATreP di Trento

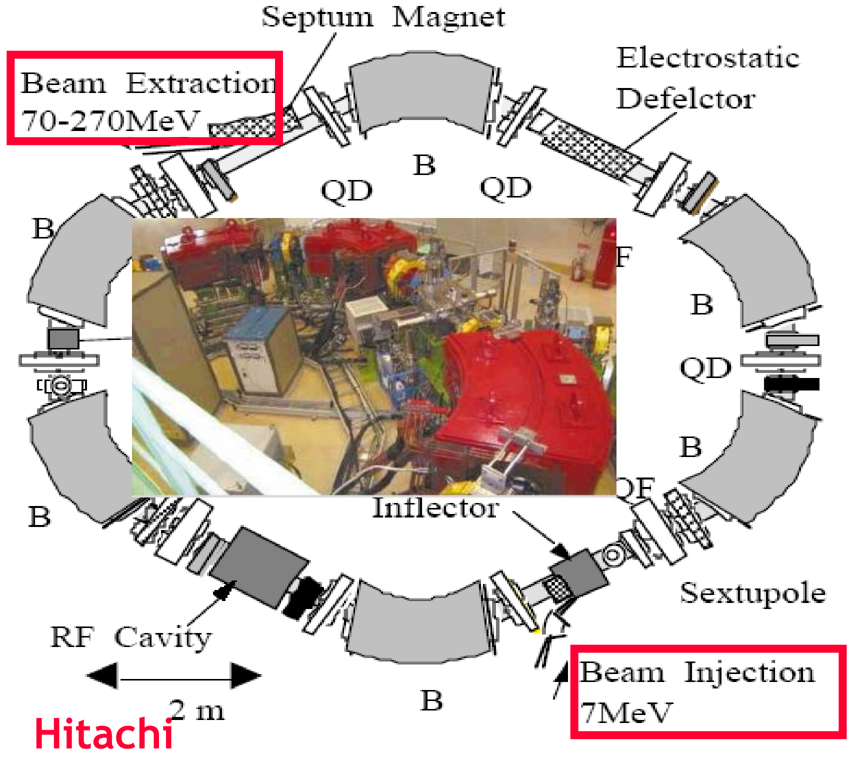
Centro di protonterapia

Ciclotrone IBA

2 sale con gantry e 1 sala a fascio fisso

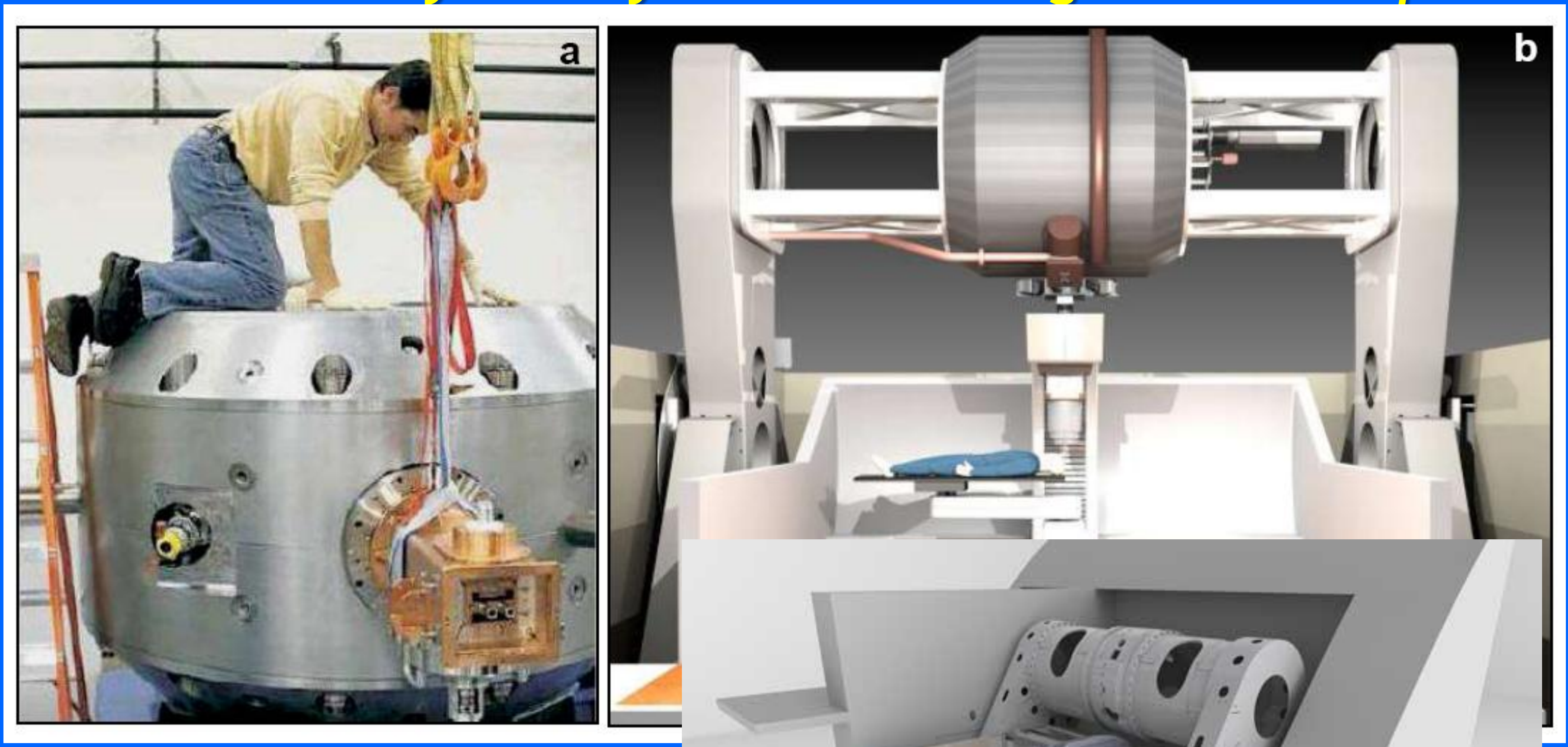
Fascio da ciclotrone per fine 2013





Protontherapy: a market exists …

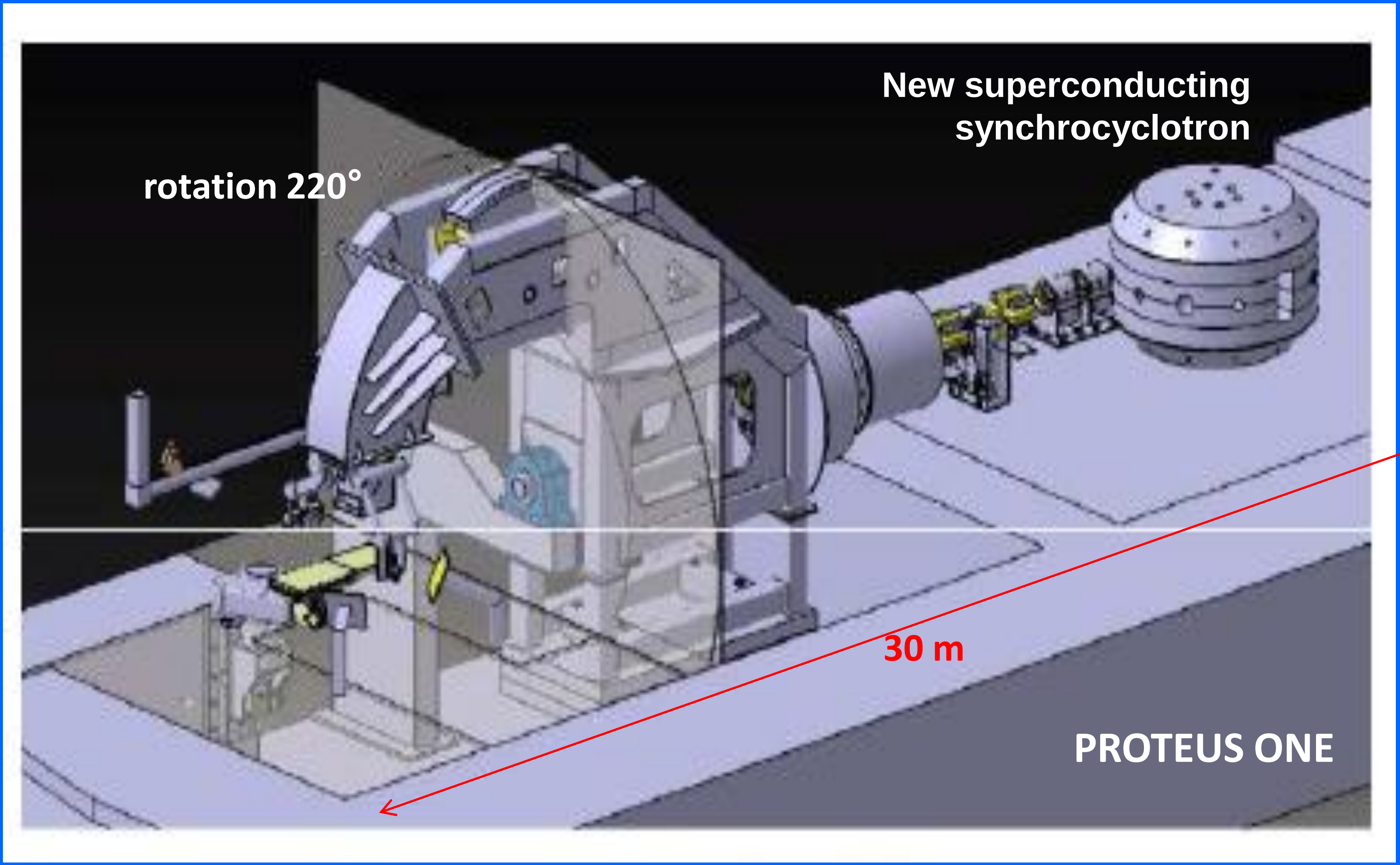
Coming up: single room facility
250 MeV synchrocyclotron rotating around the patient



MEVION S250

Superconducting SC
Diameter 1.8 m

Single room facility by IBA



Carbon Ion facilities

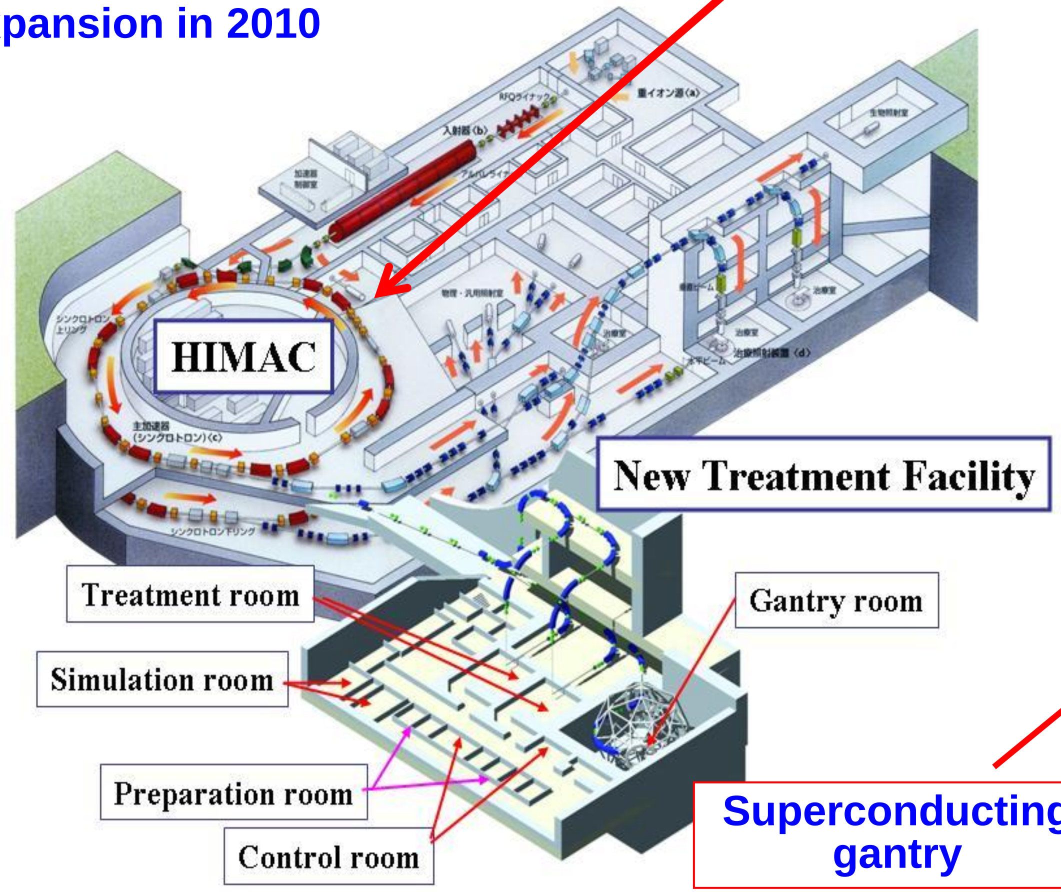
HIMAC

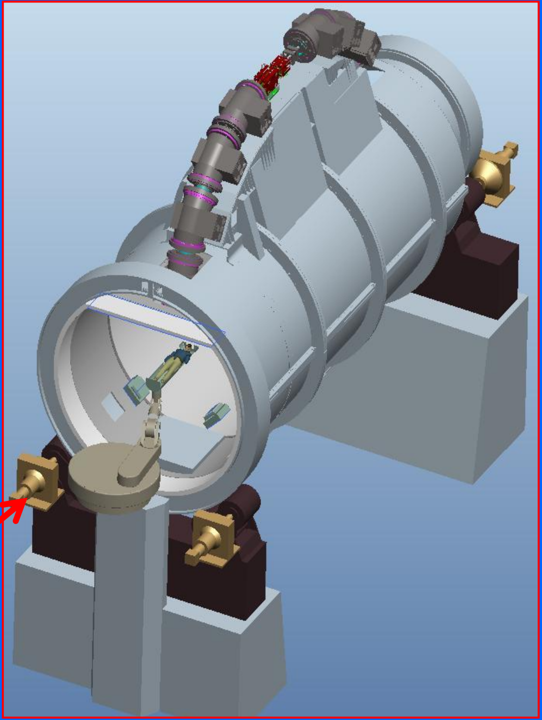
Heavy Ion Medical Accelerator in Chiba

(First patient in 1995)

2 synchrotrons 800 MeV/u, therapy and nuclear physics

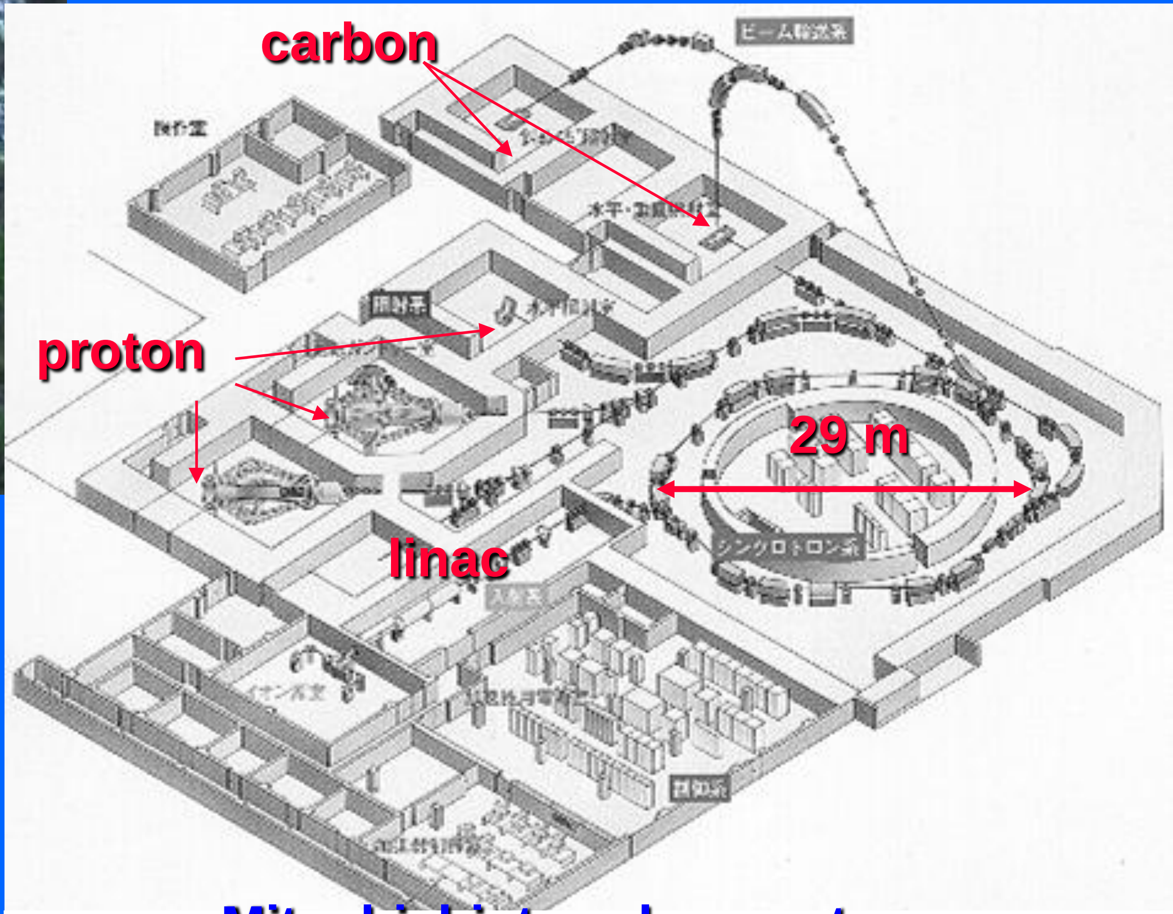
Expansion in 2010





Superconducting gantry

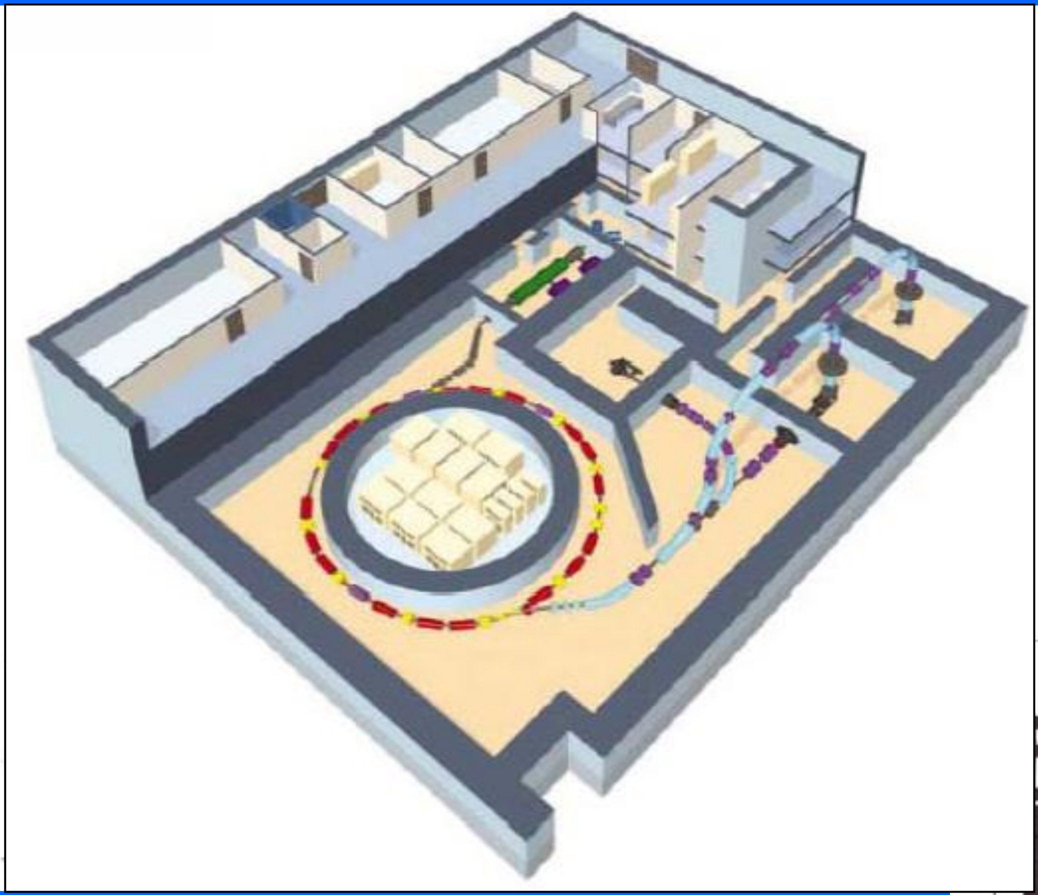
The Hyogo 'dual' Centre

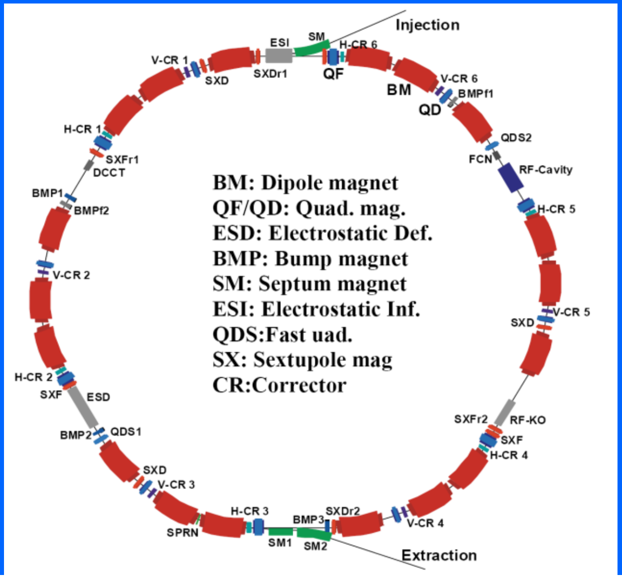


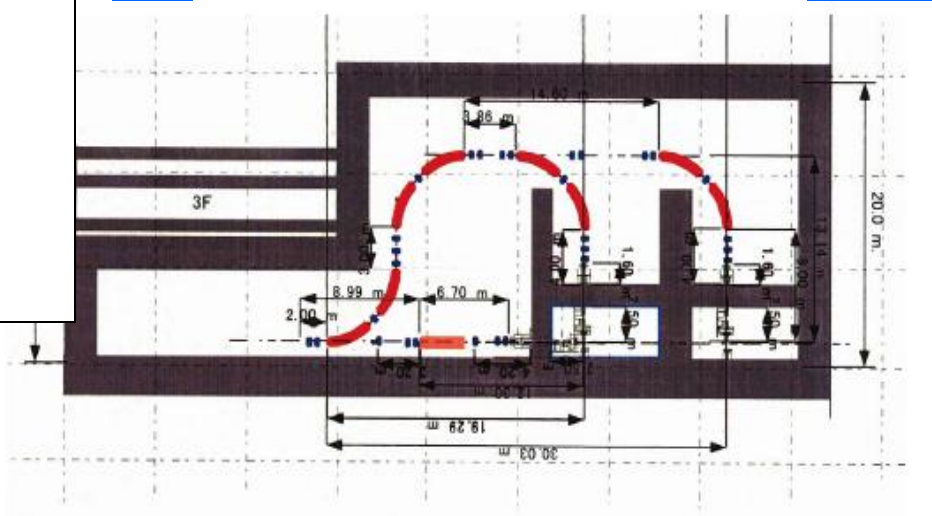
Mitsubishi: turn-key system

500 carbon patients

The Gunma University centre



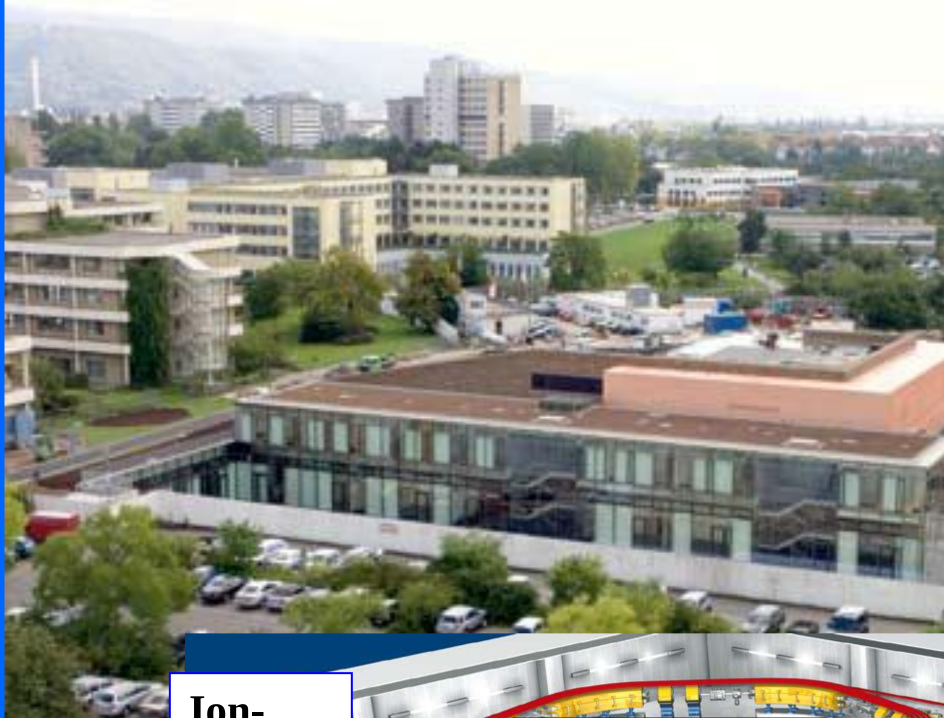




R&D = NIRS + KEK + RIKEN

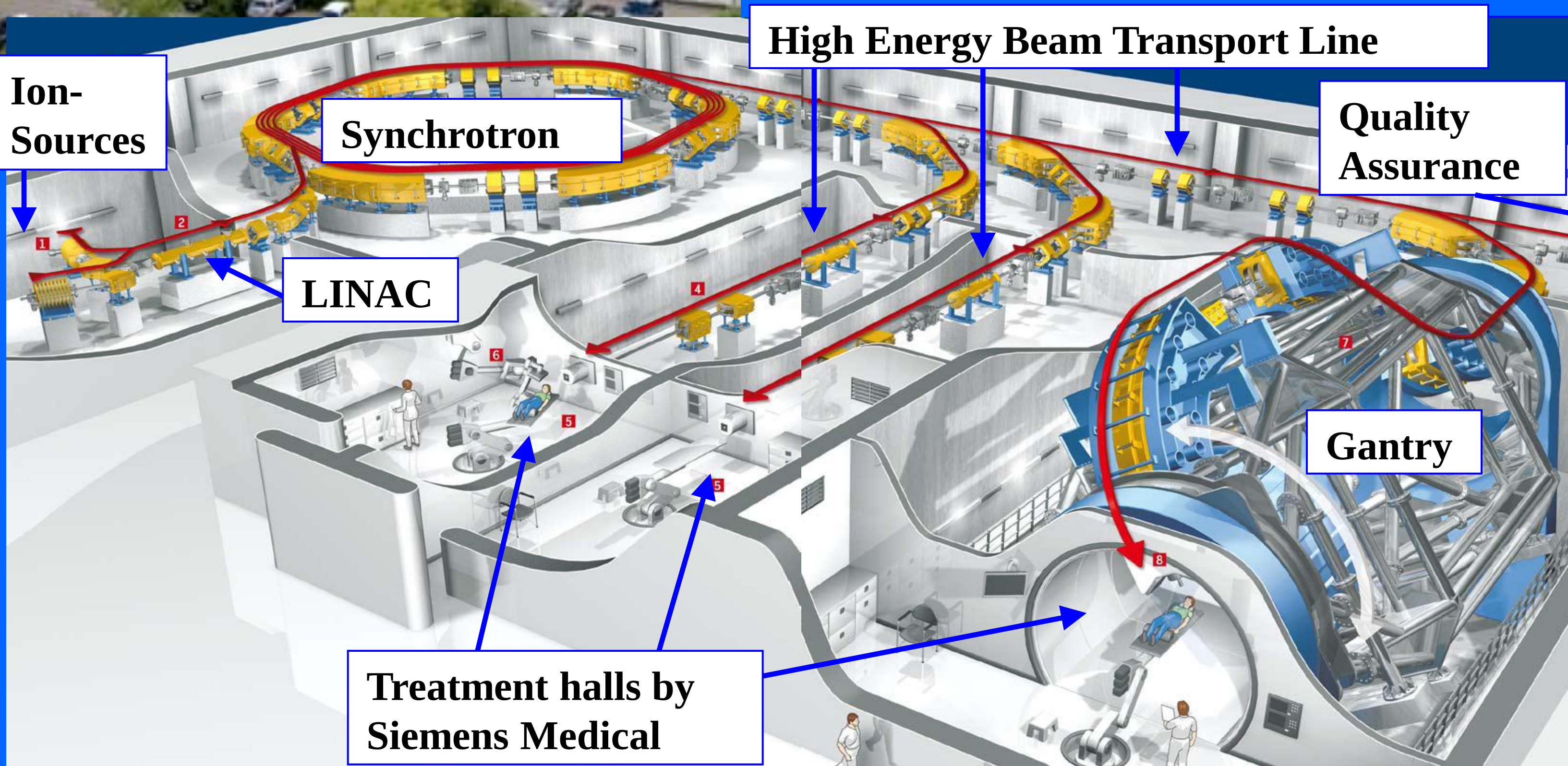
Construction: Mitsubishi

HIT - Heidelberg



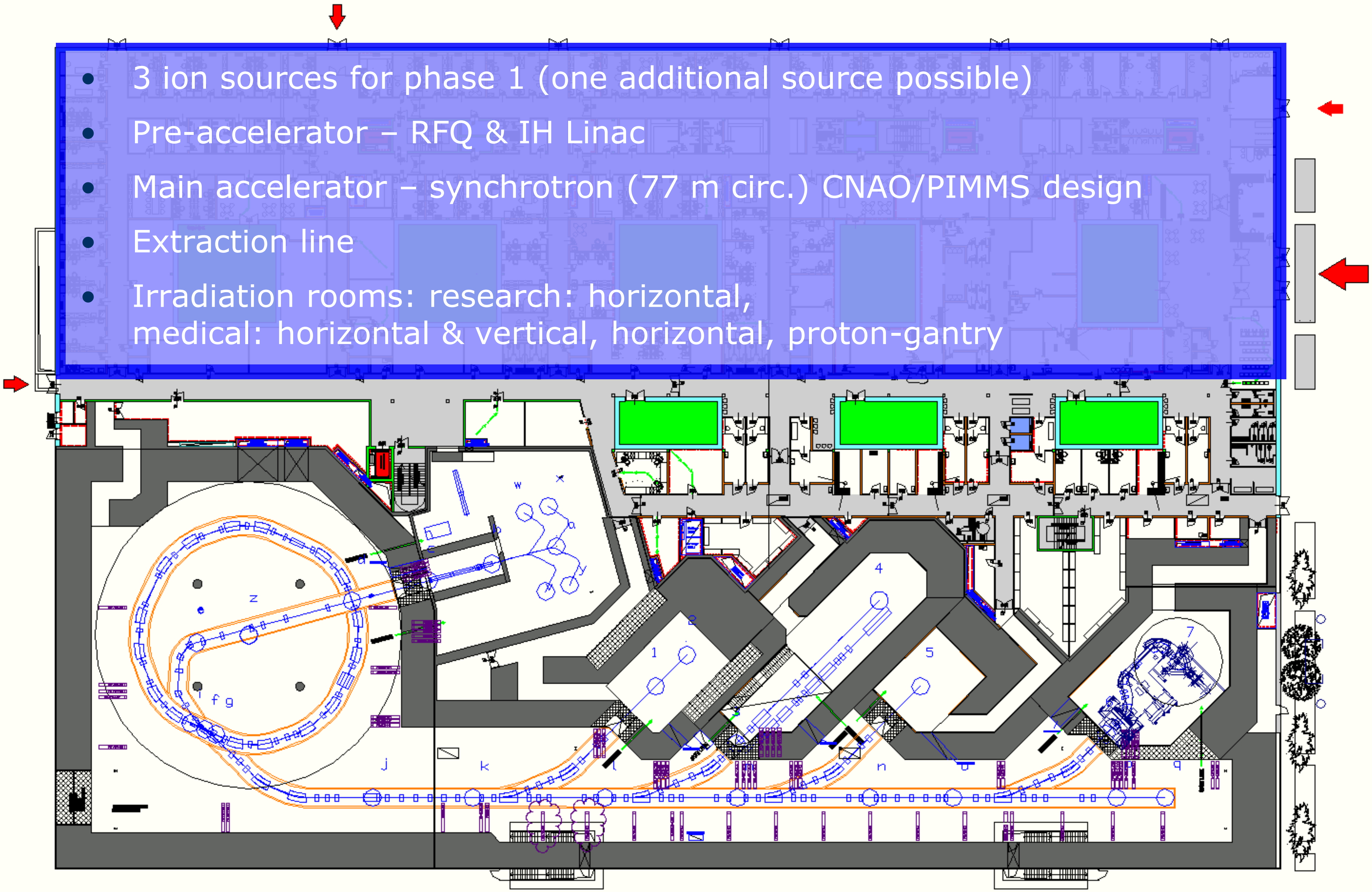
First patient: end 2009

So far about 1.000 patients

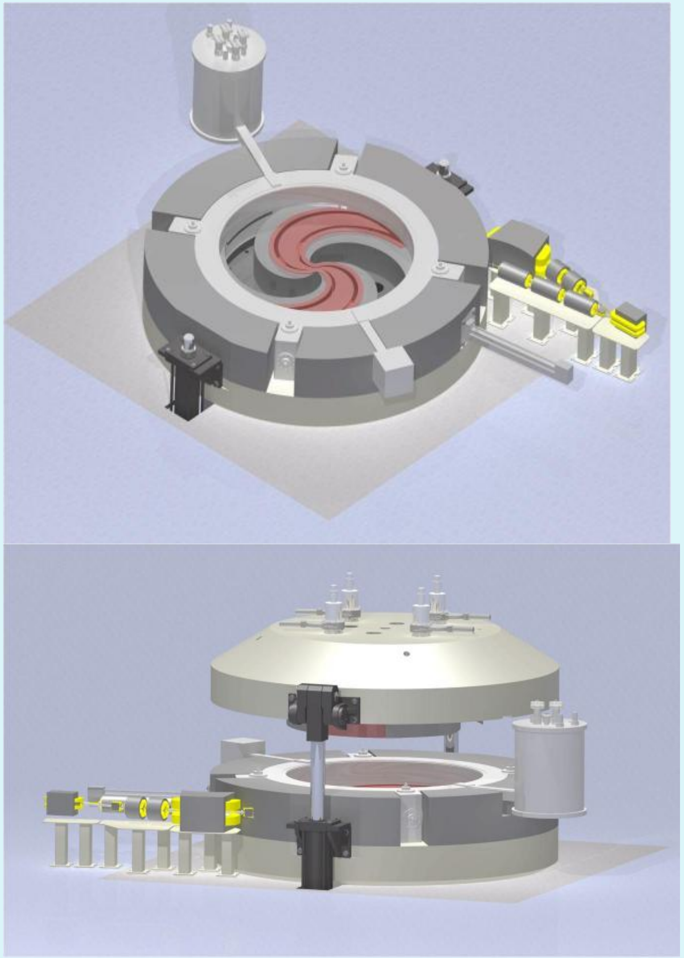


Med-Austron (based on CNAO/INFN/CERN design + DDS)

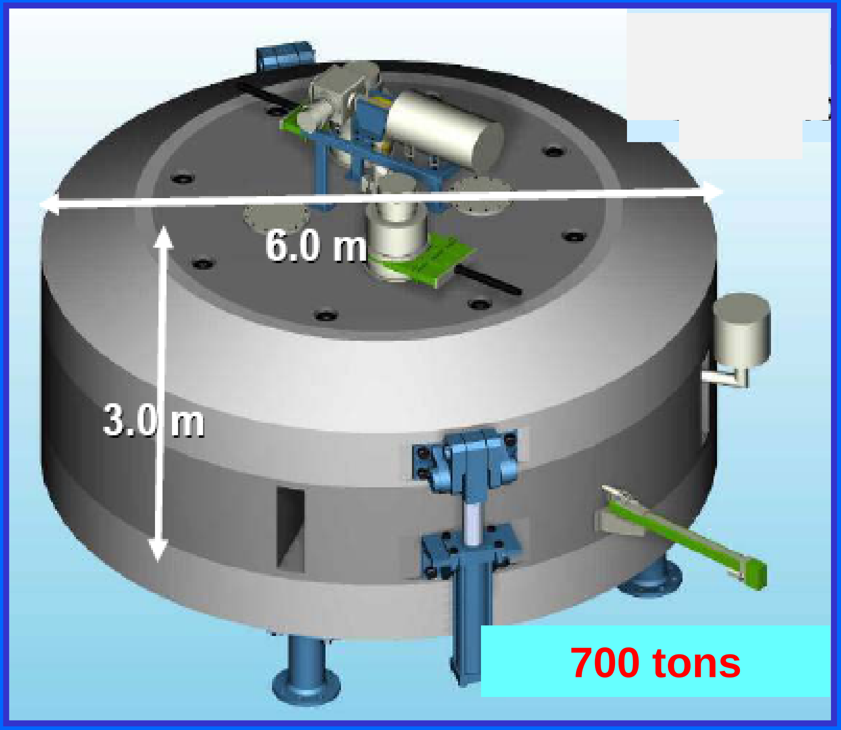
- 3 ion sources for phase 1 (one additional source possible)
- Pre-accelerator – RFQ & IH Linac
- Main accelerator – synchrotron (77 m circ.) CNAO/PIMMS design
- Extraction line
- Irradiation rooms: research: horizontal,
  medical: horizontal & vertical, horizontal, proton-gantry



New medical accelerators (?): IBA Superconducting cyclotron



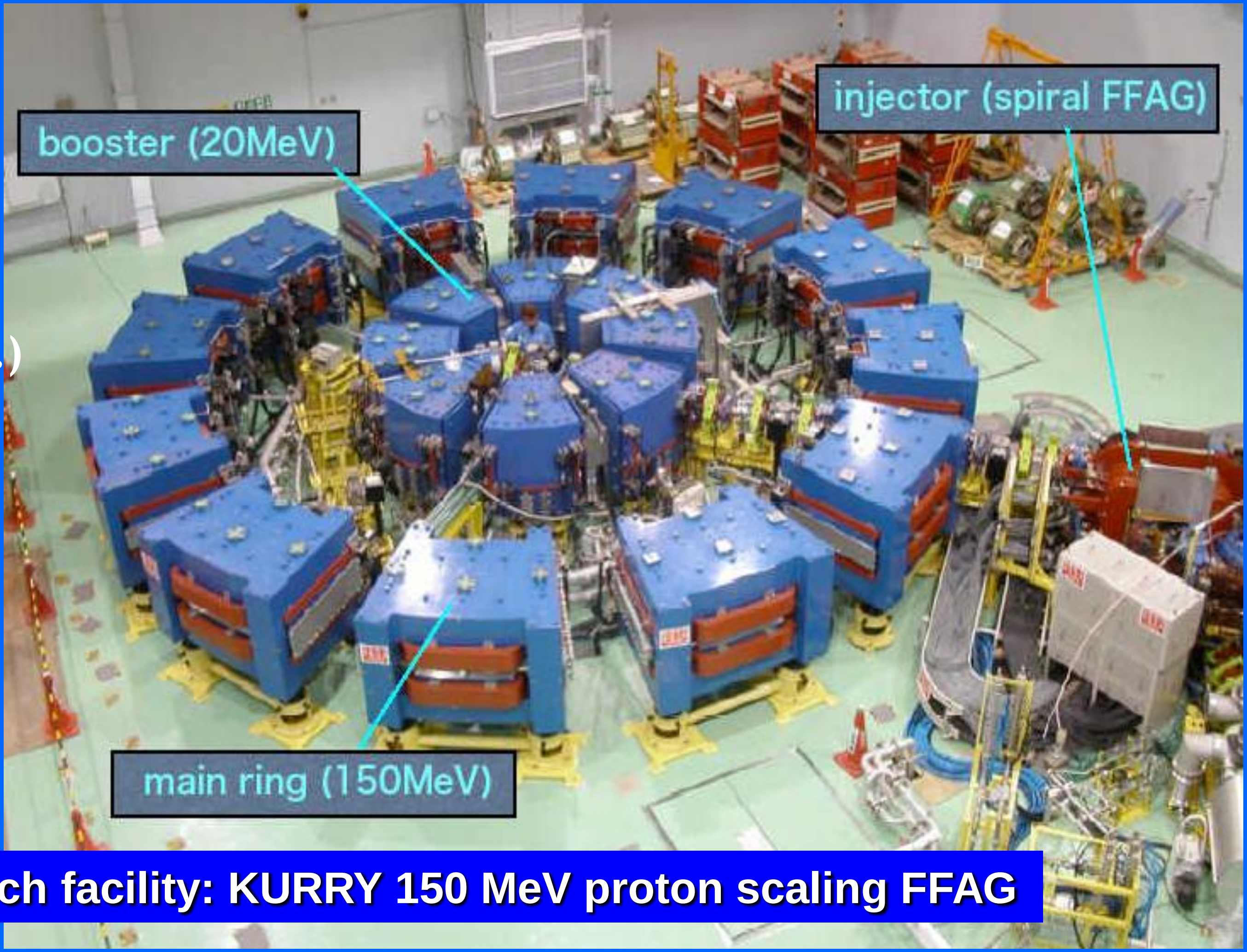
IBA C400 Cyclotron :
400MeV/u carbon , 265 MeV p
(B_c = 4.5 T)



New medical accelerators (?): FFAG

(original idea dates back to 1950's)

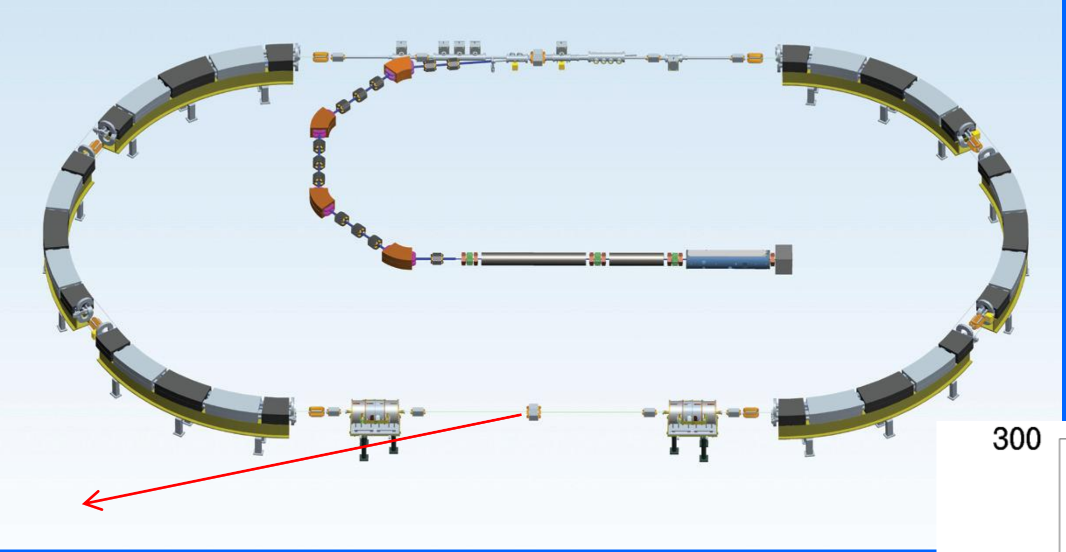
+ Simplicity of fixed field
+ Potential for fast (ms) variable energy
+ Rapid cycling (200 Hz, repainting)
- High intensities
- Multistage accelerators
- Complicated magnets
- Complicated RF cavity
- Dense lattice (ext. diff.)



Only existing reasearch facility: KURRY 150 MeV proton scaling FFAG

New medical accelerators (?): BNL fast cycling synchrotron

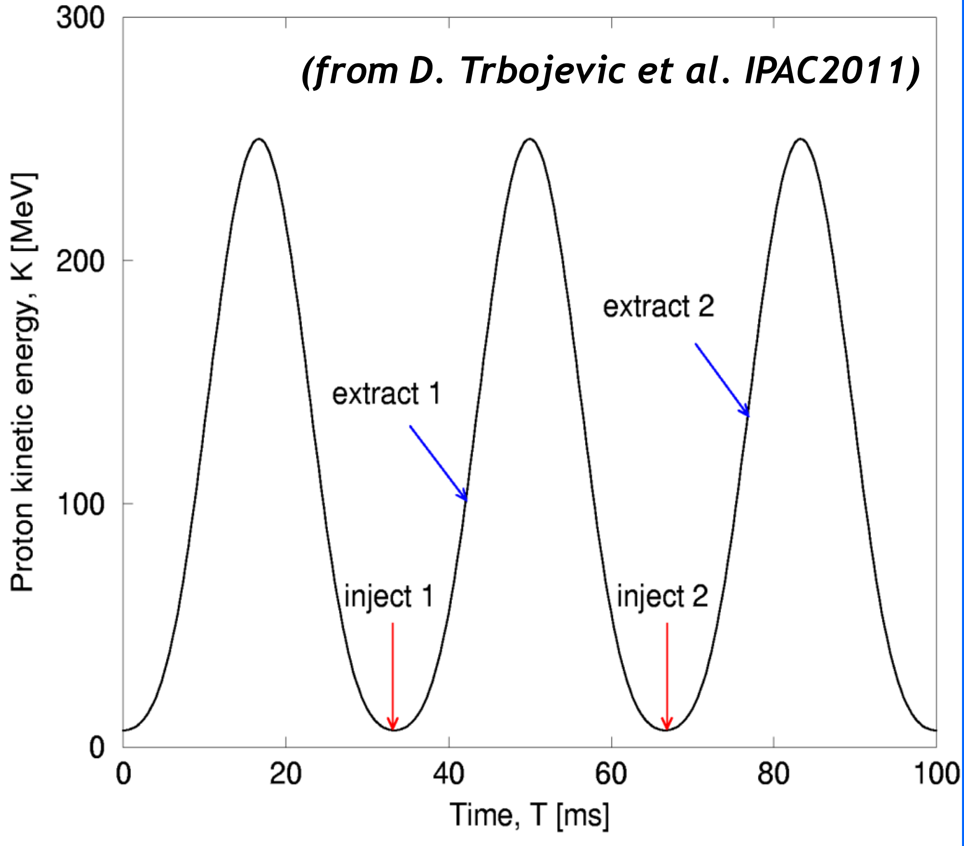
(first publication 1999's, S. Peggs et al.)



Injection linac at 8 MeV/u

Racetrack, FODO in the arcs, D=0 ss

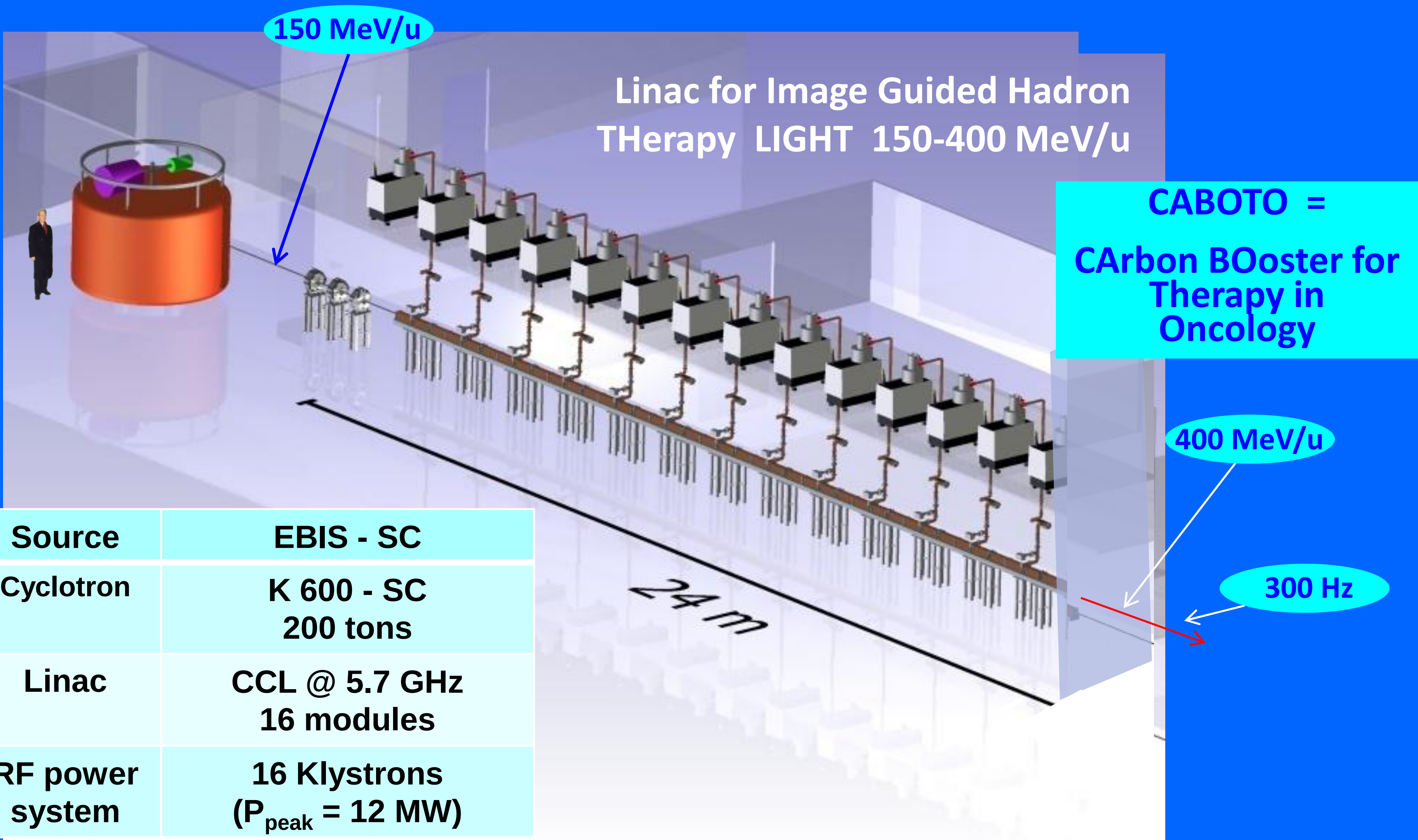
Fast inj+extr, C = 60 m



30 Hz repetition rate (repainting?)

Fast energy change

New medical accelerators (?): TERA cyclinac for C-ions

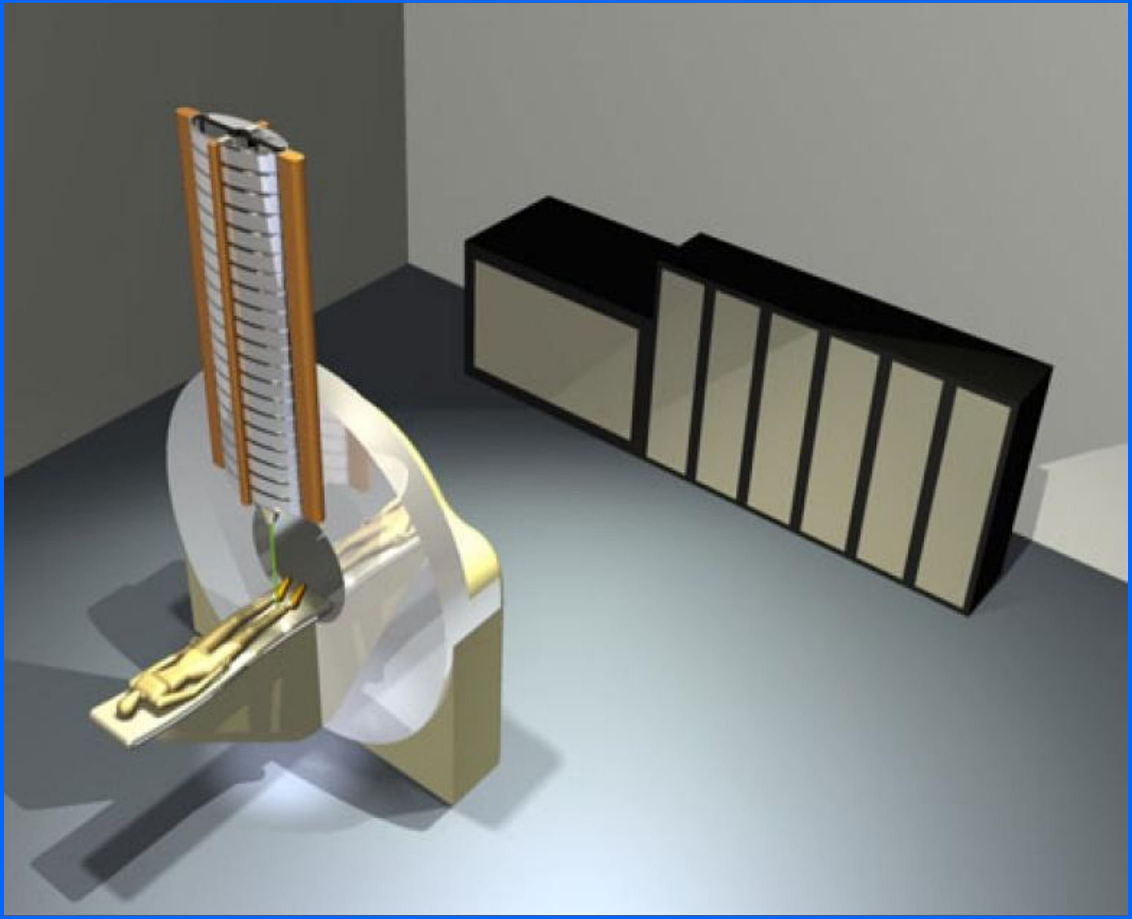


Source	EBIS - SC
Cyclotron	K 600 - SC 200 tons
Linac	CCL @ 5.7 GHz 16 modules
RF power system	16 Klystrons (P_{peak} = 12 MW)

Energy is adjusted in 2 ms in the full range by changing the power pulses sent to the accelerating modules

Charge in the spot is adjusted every 2 ms with the computer controlled source

New medical accelerators (?): Dielectric Wall Accelerator (DWA)

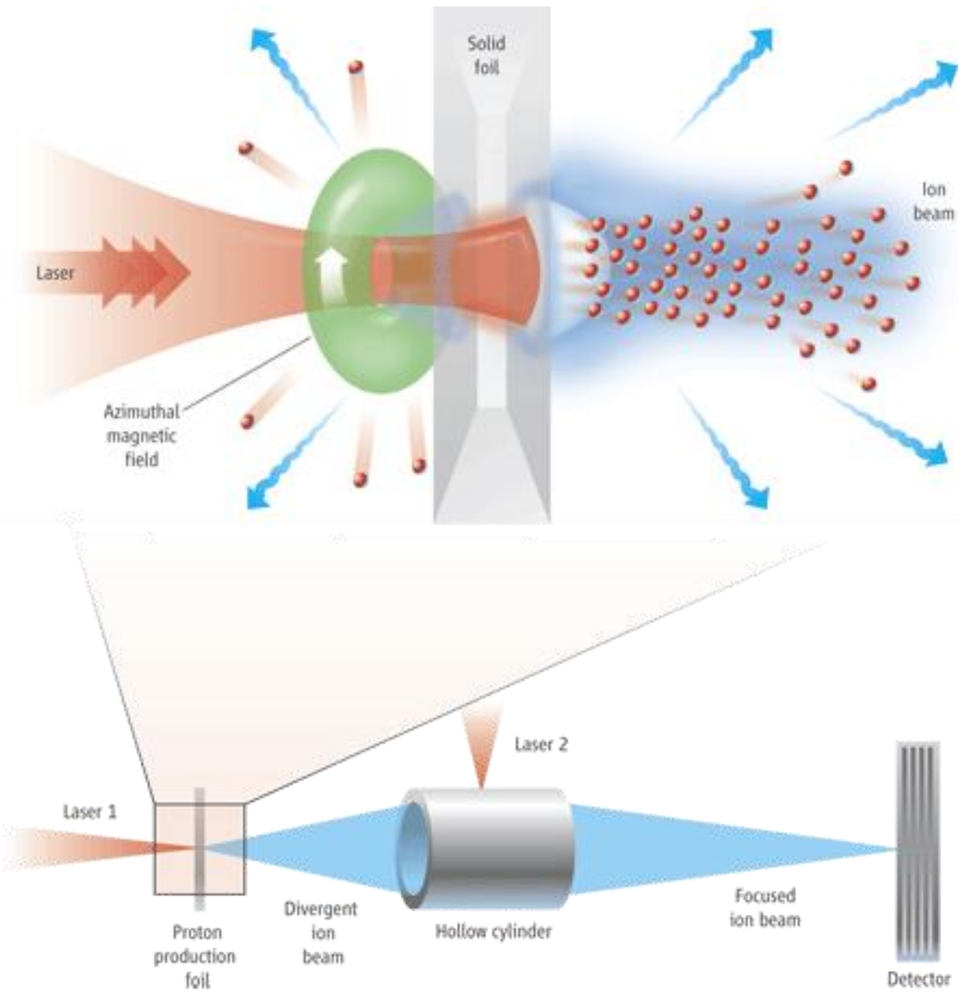


Pulsed High-Voltage accelerators (G. Caporaso et al)

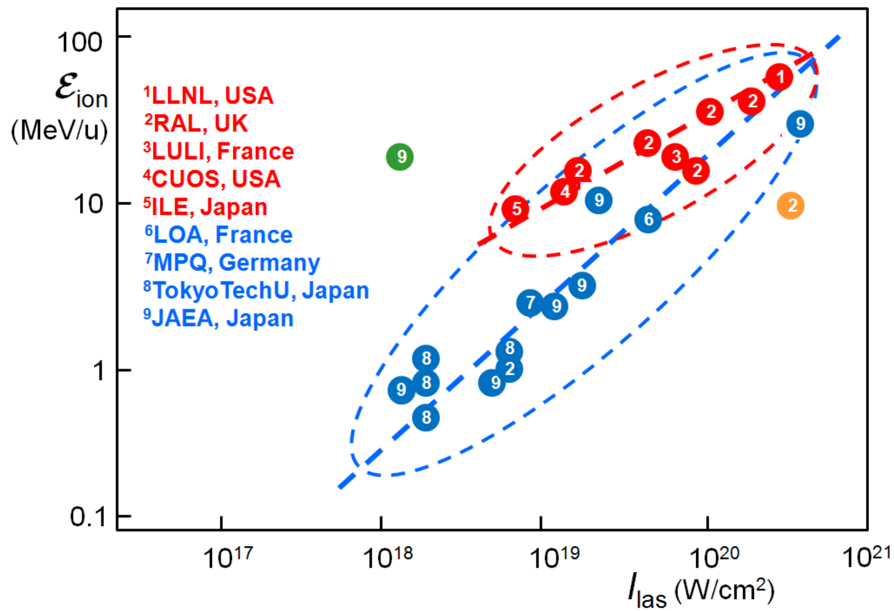
built in collaboration with Tomotherapy – Madison (T. Mackie)

Far into the future

New medical accelerators (?): laser-driven particle accelerators



Toncian et al., *Science* 2006

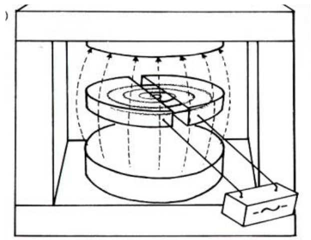


courtesy of S.D.Kraft & G. Kraft

The accelerators used today in hadrontherapy are "circular"

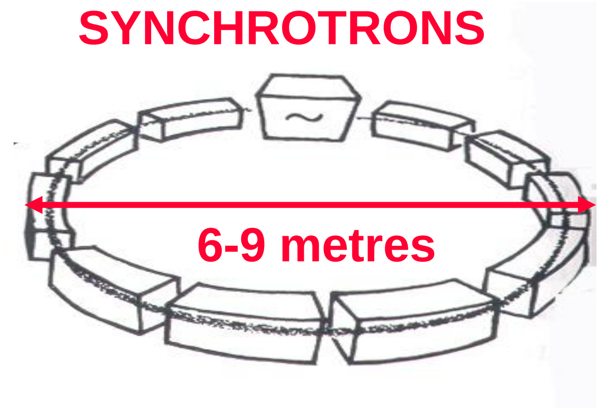
Teletherapy with protons (200-250 MeV)

CYCLOTRONS (*) (Normal or SC)



4-5 metres

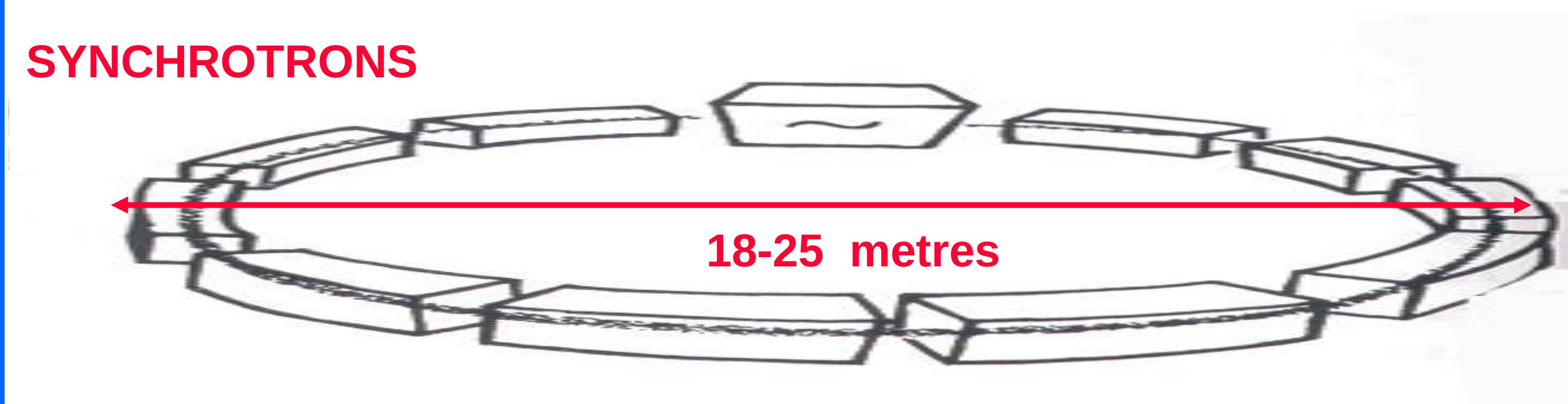
SYNCHROTRONS



(*) also synchrocyclotrons

Teletherapy with carbon ions (4800 MeV = 400 MeV/u)

SYNCHROTRONS



Equazione fondamentale

per descrivere il movimento di una particella in un acceleratore

Il moto di una particella carica è modificato dai campi elettromagnetici

$$\frac{d\vec{p}}{dt} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

$\vec{E} = campo\ elettrico$

$\vec{B} = campo\ magnetico$

$\vec{p} = m\vec{v} = momento$

$m = m_o\gamma = massa$

$\vec{v} = velocità$

$q = carica$

$$\beta = \frac{v}{c}$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

→ *particella relativistica*

Campi elettrici

$$\vec{\mathbf{F}} = m_o \vec{\mathbf{a}} = q\vec{\mathbf{E}}$$

Accelerazione:

aumento di velocità
+ aumento di energia

con le cavità a radiofrequenza

Campi magnetici

$$p = m_o \gamma v = qB\rho$$

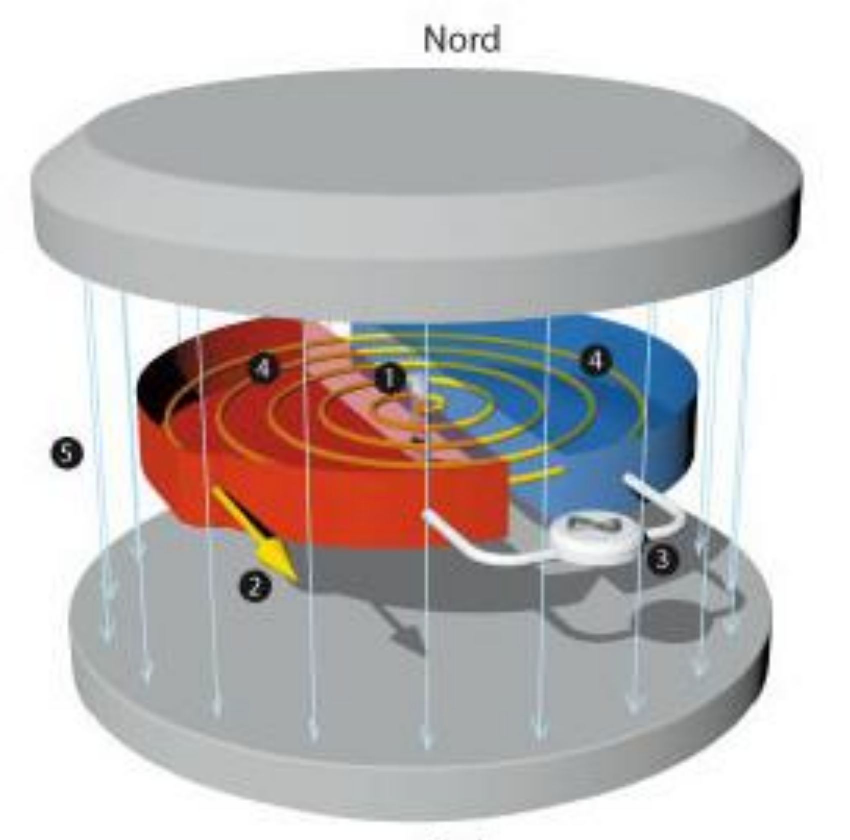
Curvatura:

se campo B uniforme
→ ρ aumenta con p: ciclotroni

se p e B "sincroni"
→ ρ costante: sincrotroni

Stato di carica q è importante

Cyclotron



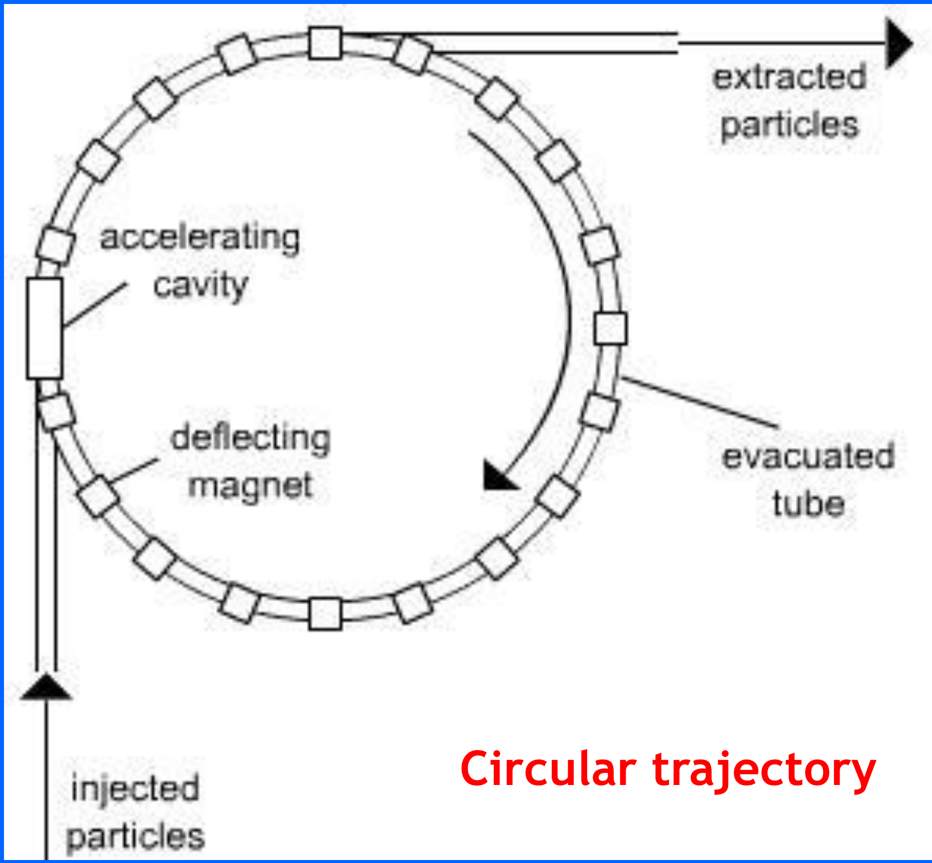
Spiral trajectory

B = constant

Dynamic law: $\omega_{rev} = \frac{qB}{m}$

Fixed frequency, high intensities

Synchrotron



Circular trajectory

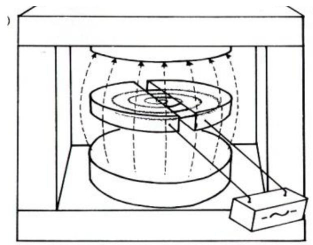
ρ = constant

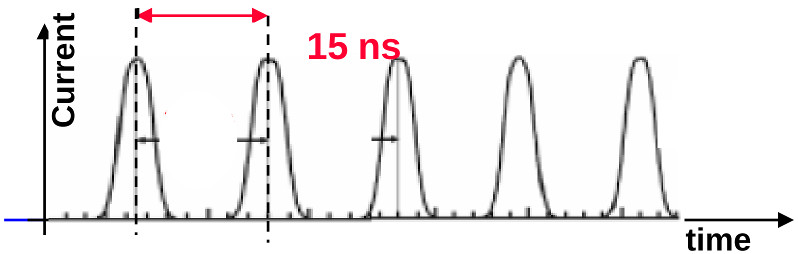
Dynamic law: $p = qB\rho$

Energy increases with B

The time structures of the beams are very different

CYCLOTRONS (Normal or SC)

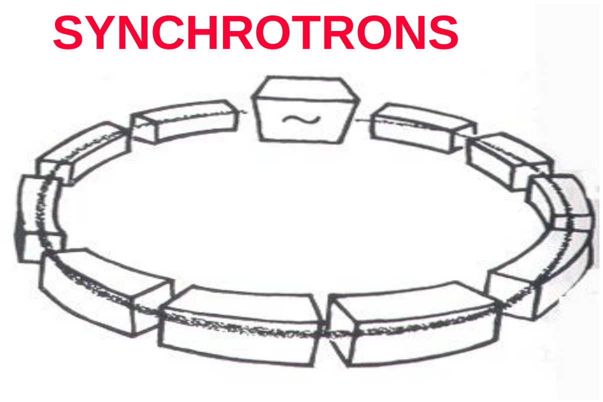


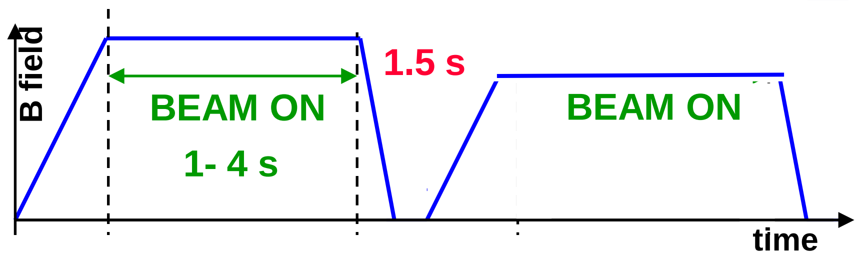


Pulsed beam always present (I ~ 50 μA)

Fixed energy

SYNCHROTRONS

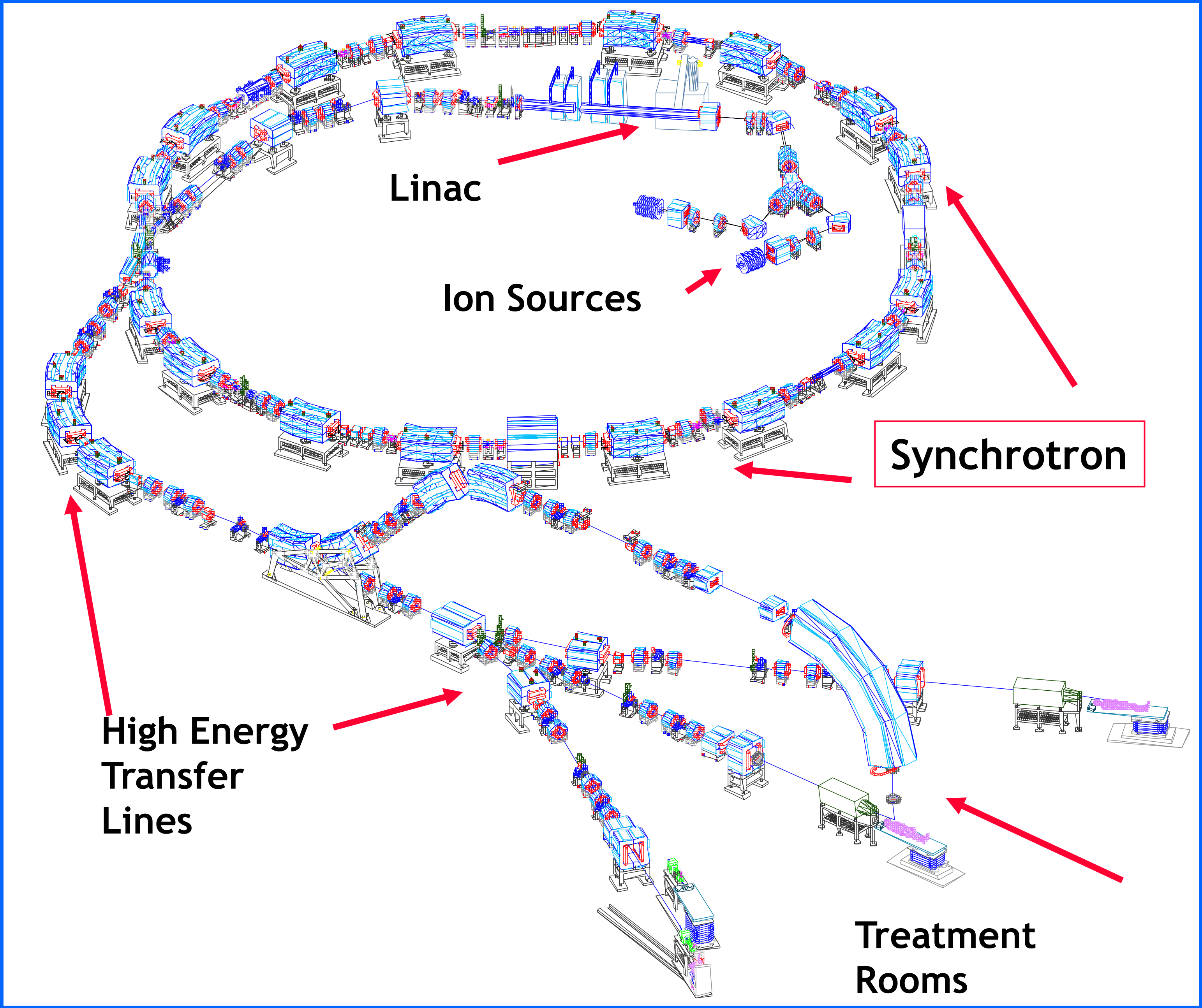




Cycling beam has 1 second gaps (I few nA)

Variable energy

Hospital based: safety, efficiency, reliability, maintainability



Starting point… THE PATIENT
Hospital based: safety, efficiency, reliability, maintainability

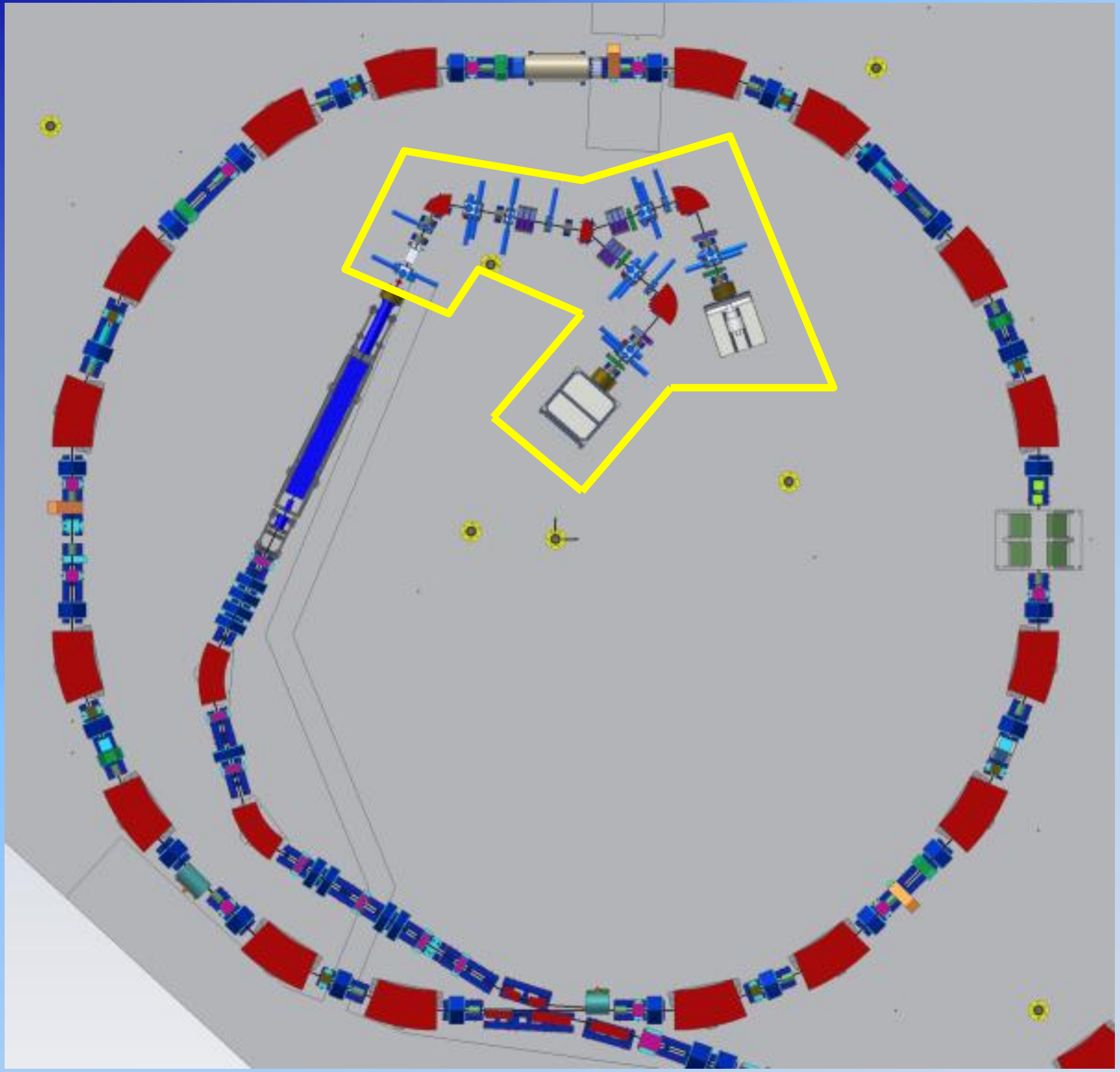
1	Beam particle species	p, He^{2+}, Li^{3+}, Be^{4+}, B^{5+}, C^{6+}, O^{8+}
2	Beam particle switching time	≤ 10 min
3	Beam range	1.0 g/cm^2 to 27 g/cm^2 in one treatment room 3.1 g/cm^2 to 27 g/cm^2 in two treatment rooms Up to 20 g/cm^2 for O^{8+} ions
4	Bragg peak modulation steps	0.1 g/cm^2
5	Range adjustment	0.1 g/cm^2
6	Adjustment/modulation accuracy	≤± 0.025 g/cm^2
7	Average dose rate	2 Gy/min (for treatment volumes of 1000 cm^3)
8	Delivery dose precision	≤± 2.5%
9	Beam axis height (above floor)	150 cm (head and neck beam line) 120 cm (elsewhere)
10	Beam size[1]	4 to 10 mm FWHM for each direction independently
11	Beam size step[1]	1 mm
12	Beam size accuracy[1]	≤± 0.25 mm
13	Beam position step[1]	0.8 mm
14	Beam position accuracy[1]	≤± 0.2 mm
15	Field size[1]	5 mm to 34 mm (diameter for ocular treatments) 2×2 cm^2 to 20×20 cm^2 (for H and V fixed beams)
16	Field position accuracy[1]	≤± 0.5 mm
17	Field dimensions step[1]	1 mm
18	Field size accuracy[1]	≤± 0.5 mm

(Basic specifications of CNAO facility)

Le sorgenti

e

La LEBT



LEBT

0.008 MeV/u H^{3+}
0.008 MeV/u C^{4+}

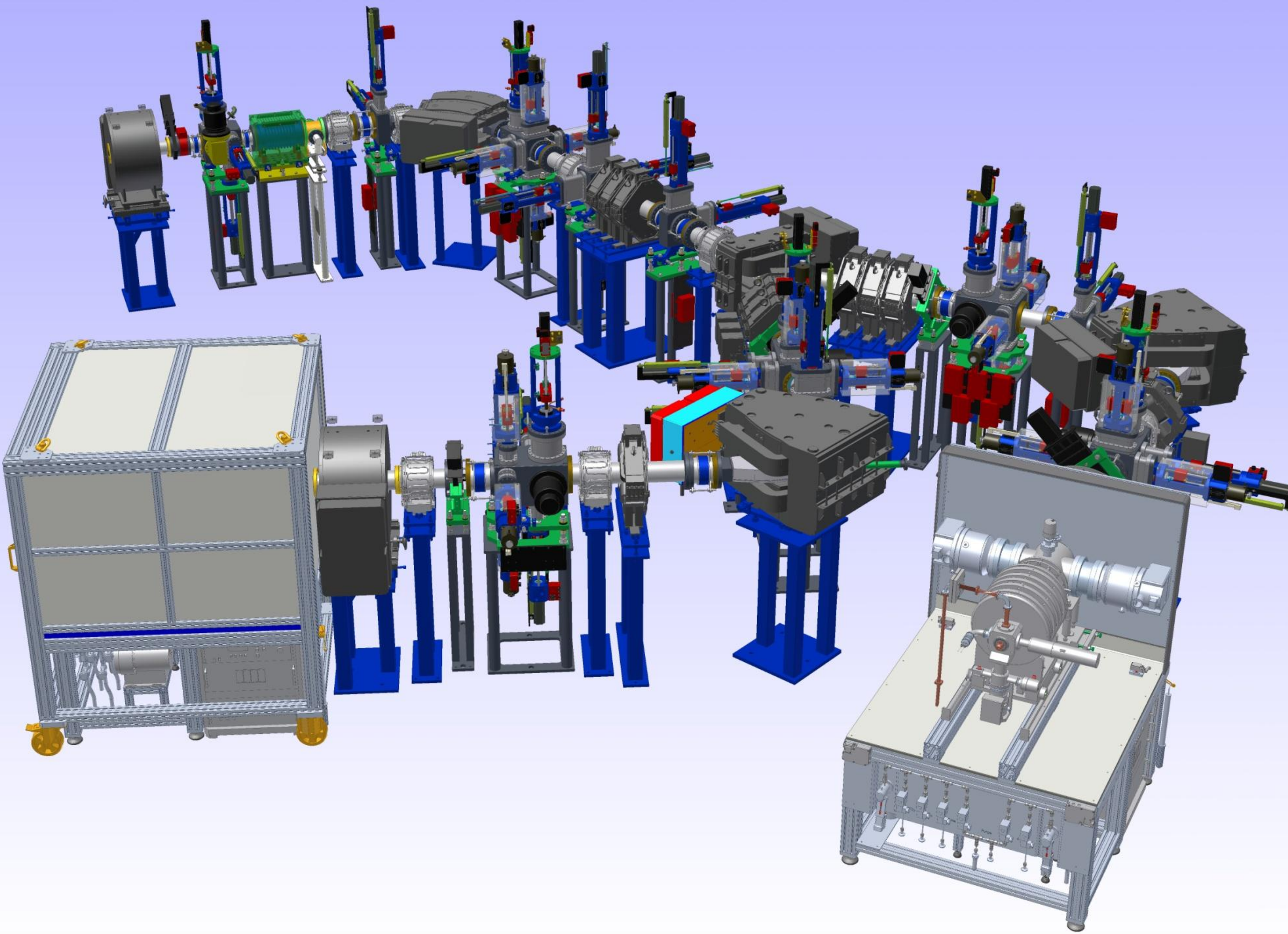
I ~ 0.5 mA (H^{3+})
I ~ 0.2 mA (C^{4+})

Two ECR sources

Continuous beam

LEBT Chopper

LEBT



Ion Sources

The ion sources are used for accelerators, in industry for the treatment of surfaces (plasma etching, coating, etc..), for ion implantation or for the disposal of waste.

The objective of the ion sources is to produce a beam of particles that can be injected into the accelerators with adequate characteristics to optimize the acceleration process, minimizing the losses of the beam inside the machine and maximizing the overall reliability.

The characteristics which must have a source to operate as an injector of a Cyclotron, a Synchrotron, or a Linac are:

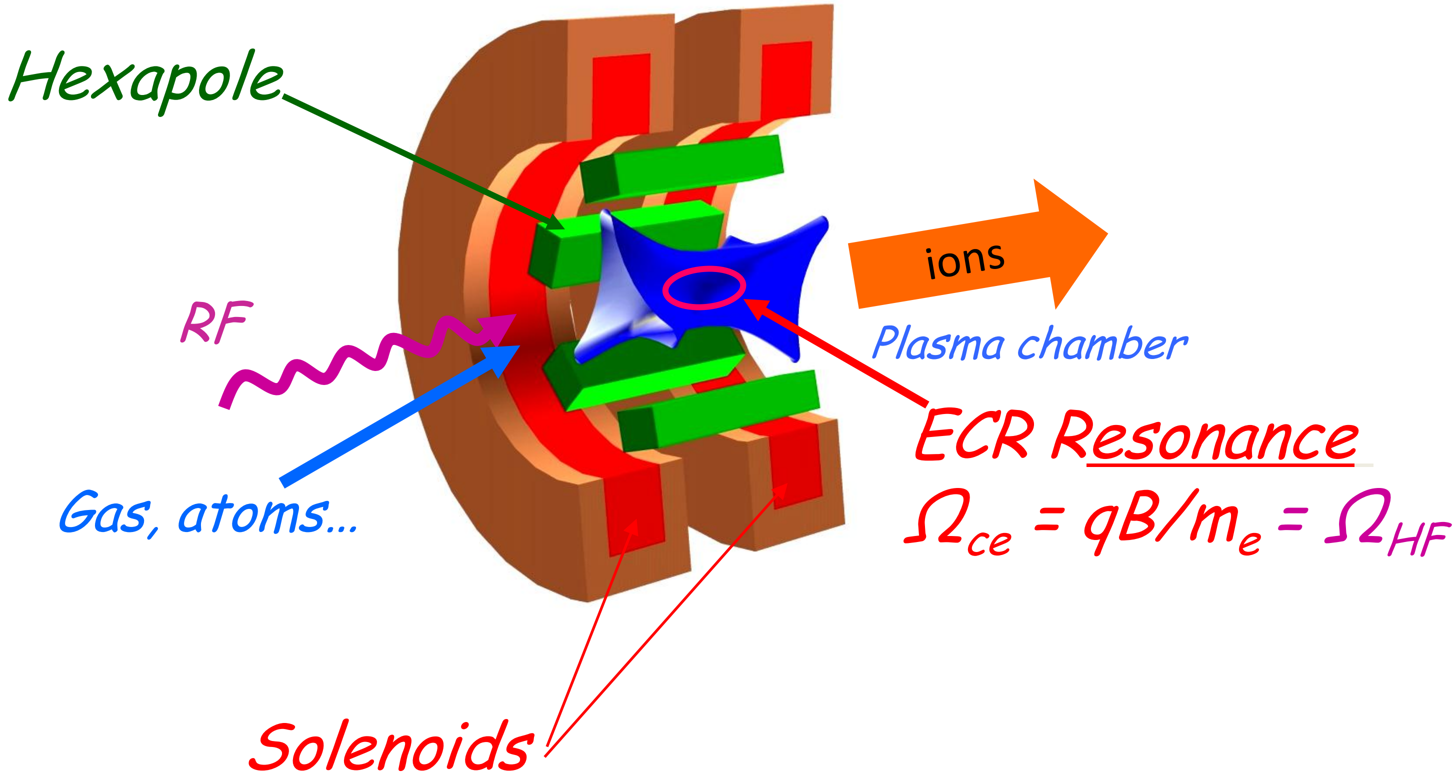
- Great stability
- Production of intense beams of higher charge states.
- Small emittance both transverse and longitudinal.
- Ability to operate for long periods without maintenance.

Types of Ion Sources

The universal ion source does not exist, but there is the best source for producing a special beam.

- Single charge state Sources: PIG, Duoplasmatron, MDIS
- Very high charge state Sources: EBIS
- Sources close to "universal" application: ECRIS

ECR
(Electron Cyclotron Resonance)



The ECRIS are able to produce ions with a high state of charge by providing a plasma for interaction between a microwave field and the free electrons present in a gas, i.e. realizing a plasma ECR.

ECRIS

Advantages

- High currents of high charge state
- High reliability and long life
- Continuous and pulsed beams
- Any beams

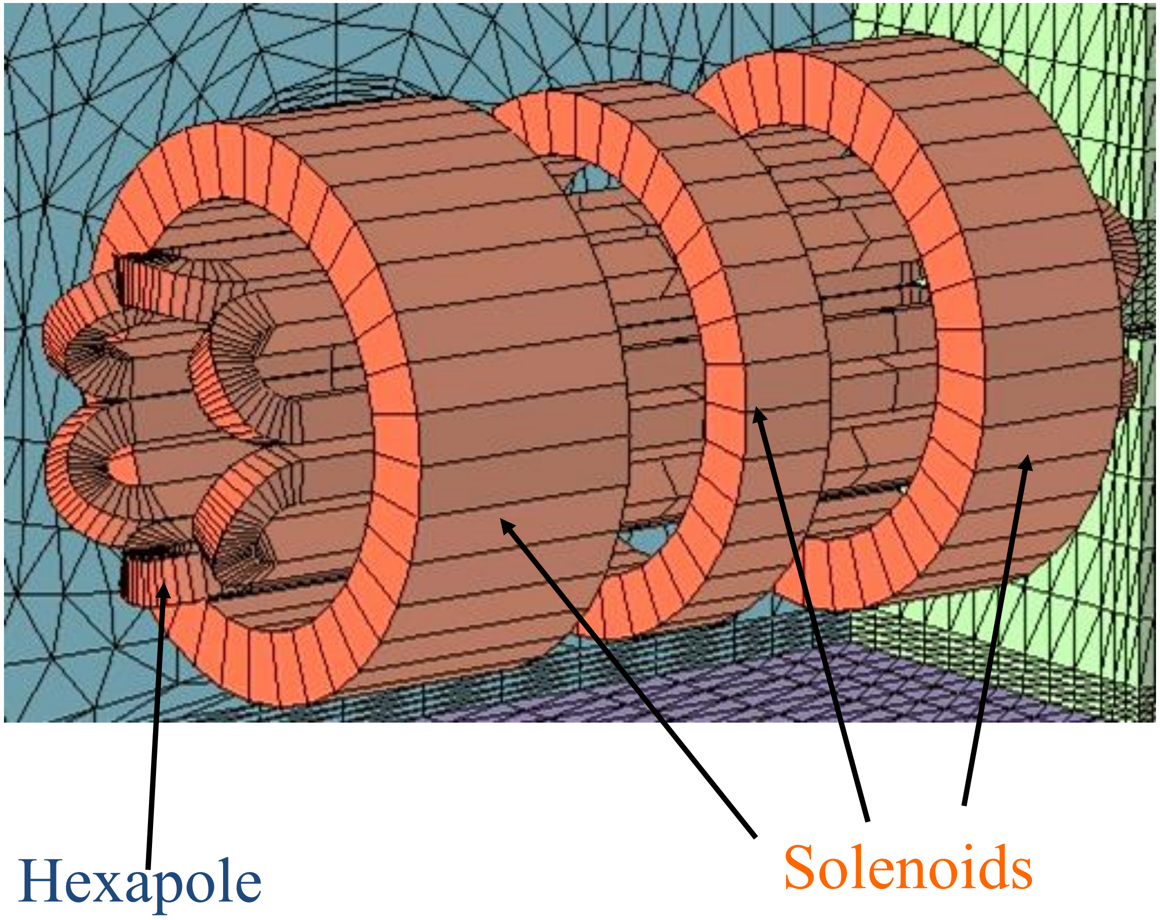
Disadvantages

- High power consumption if is not used permanent magnets (CNAO choice) or superconducting coils
- Expensive technology
- Long conditioning time for the high charge states

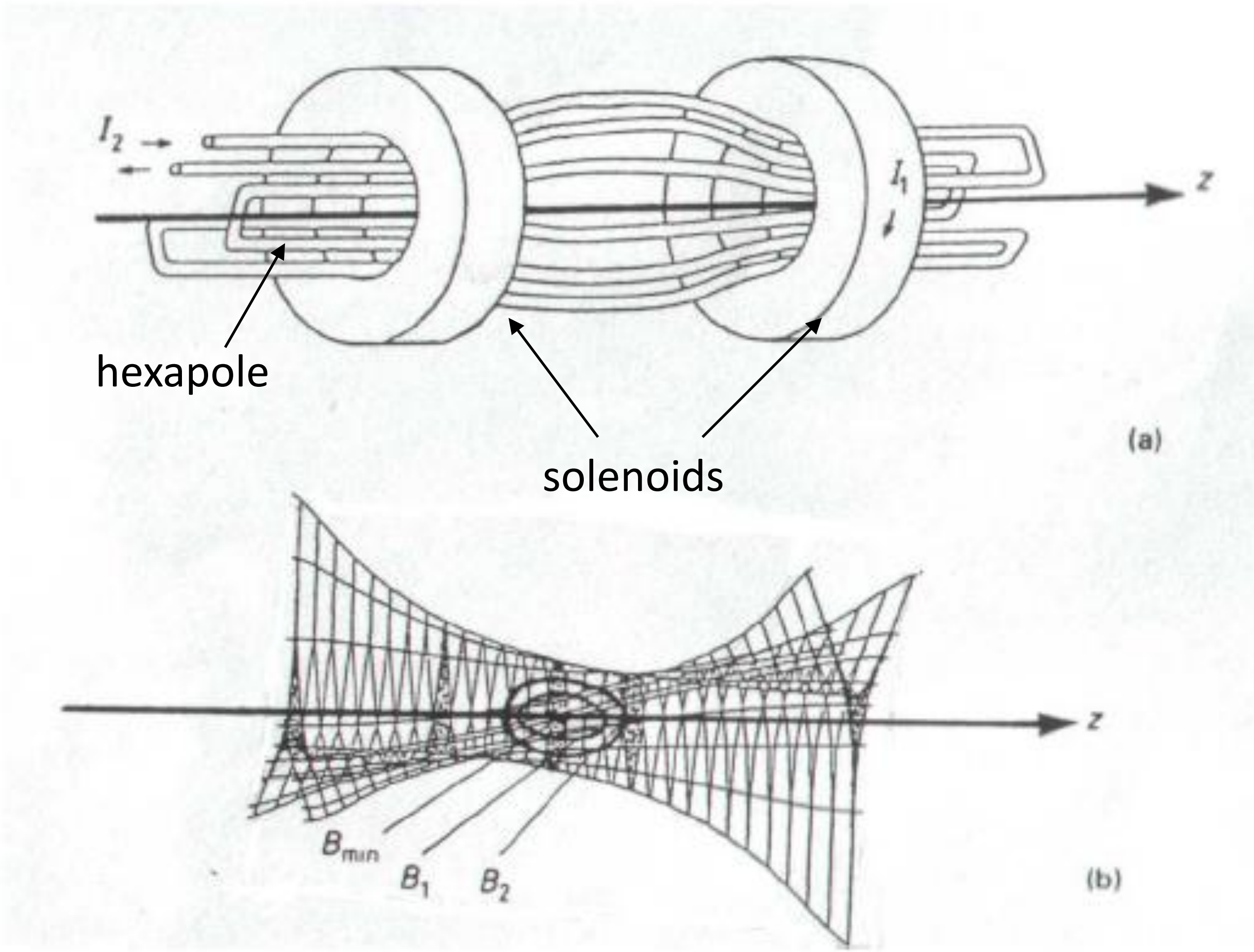
B-min magnetic system
(Multi Mirrors)

The solenoids generate a magnetic field called the Simple Mirror weak in the central region of the chamber, stronger in the peripheral regions (axial field).

The hexapole generates a field that increases going from the center towards the periphery in a direction transverse to the axis of the plasma chamber (radial field).



B-min magnetic configuration

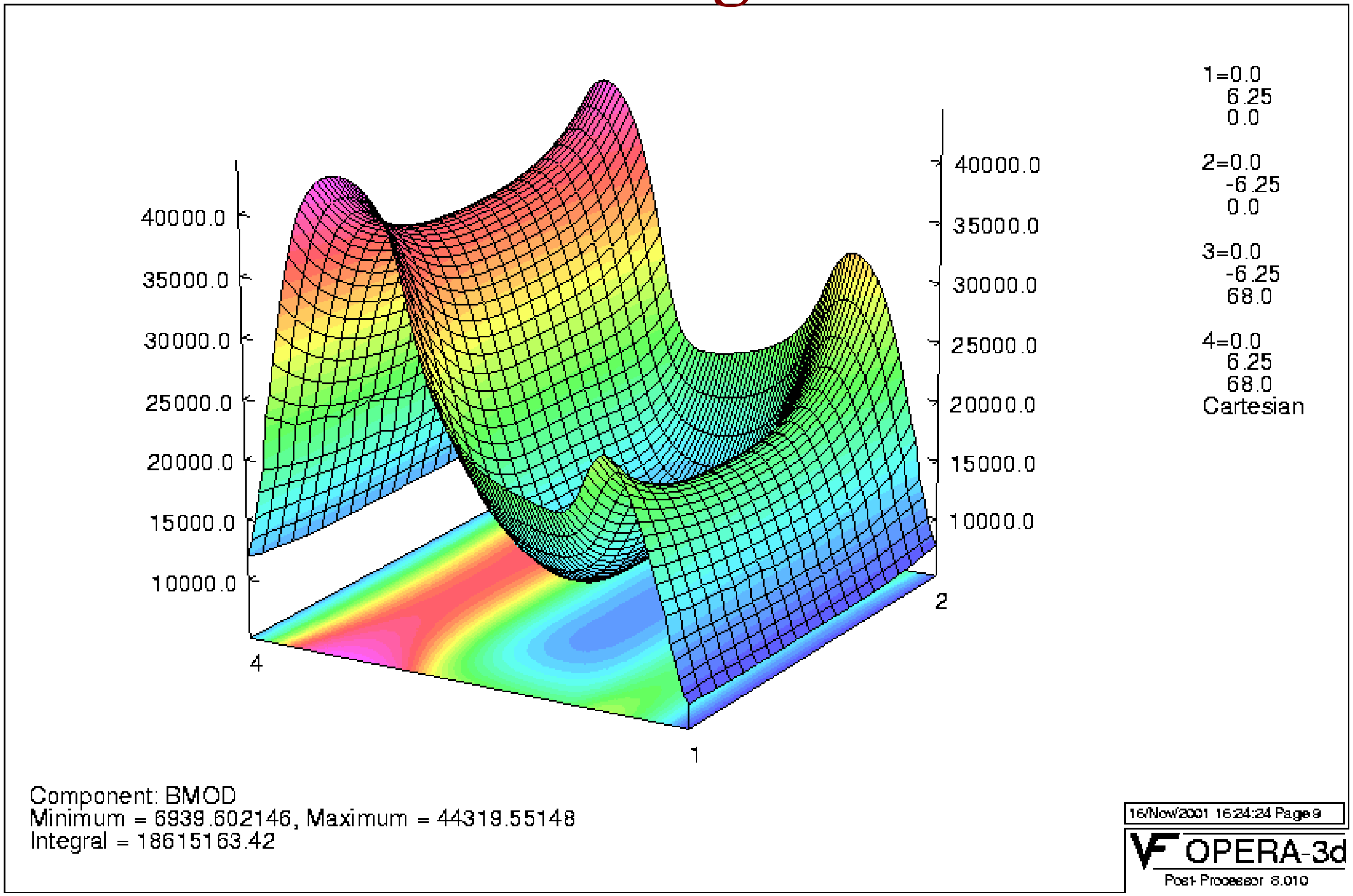


In this case there are closed surfaces of constant B (egg-shaped).

The stability of the confinement is guaranteed, in the case in which the plasma is generated by means of em waves and thanks to the resonance ECR, only if

$$B_{max} > 2\ B_{ECR}$$

Magnetic field



- High-B Mode concept,

Ciavola & Gammino, 1990

$$\begin{cases} B_{inj} \approx 3B_{ECR} \text{ or more if possible} \\ B_{rad} \geq 2B_{ECR} \\ B_{ext} \leq B_{rad} \end{cases}$$

The plasma ECR

A Gas under normal conditions of temperature and pressure has a small number of free electrons.

→ Magnetic field →

Few free electrons spiraling around the lines of force of the magnetic field with frequency

$\omega_c = eB/m$

↓

A circularly polarized electromagnetic wave transfers energy to the electron by the resonance ECR:

$\omega_{RF} = \omega_c$

←

The electrons collide with the gas atoms and form a plasma

The angular frequency of this cyclotron motion is $\omega_c = eB/m$

The resonance condition is met when $\omega_{rf} = \omega_c$

Considering relativistic speeds $B_{ECR}(T) = 357\ f_{rf}(GHz)$

At CNAO: f_{rf} = 14,5 GHz B_{ECR} = 0,5 T

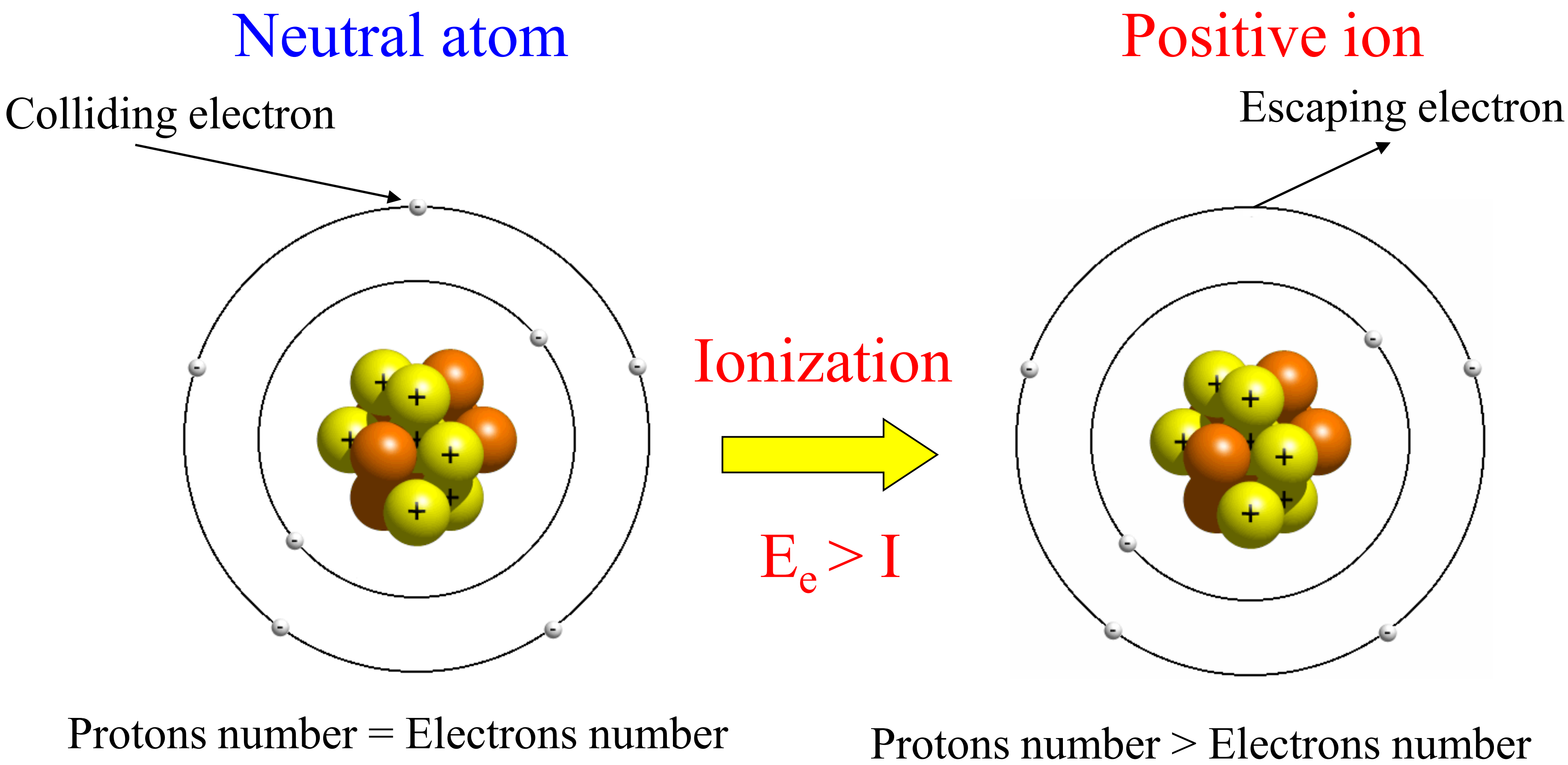
PLASMAS

In physics and chemistry, plasma is a state of matter similar to a gas in which a certain portion of the particles are ionized. In the universe, plasma is the most common state of matter, most of which is in the rarefied intergalactic plasma (particularly intracluster medium) and in stars.

Heating a gas may ionize its molecules or atoms (reduce or increase the number of electrons in them), thus turning it into a plasma, which contains charged particles: positive ions and negative electrons or ions. Ionization can be induced by other means, such as strong electromagnetic field applied with a laser or microwave generator at positive ions and negative electrons or ions.

The presence of a non-negligible number of charge carriers makes the plasma electrically conductive so that it responds strongly to electromagnetic fields. Plasma, therefore, has properties quite unlike those of solids, liquids, or gases and is considered a distinct state of matter.

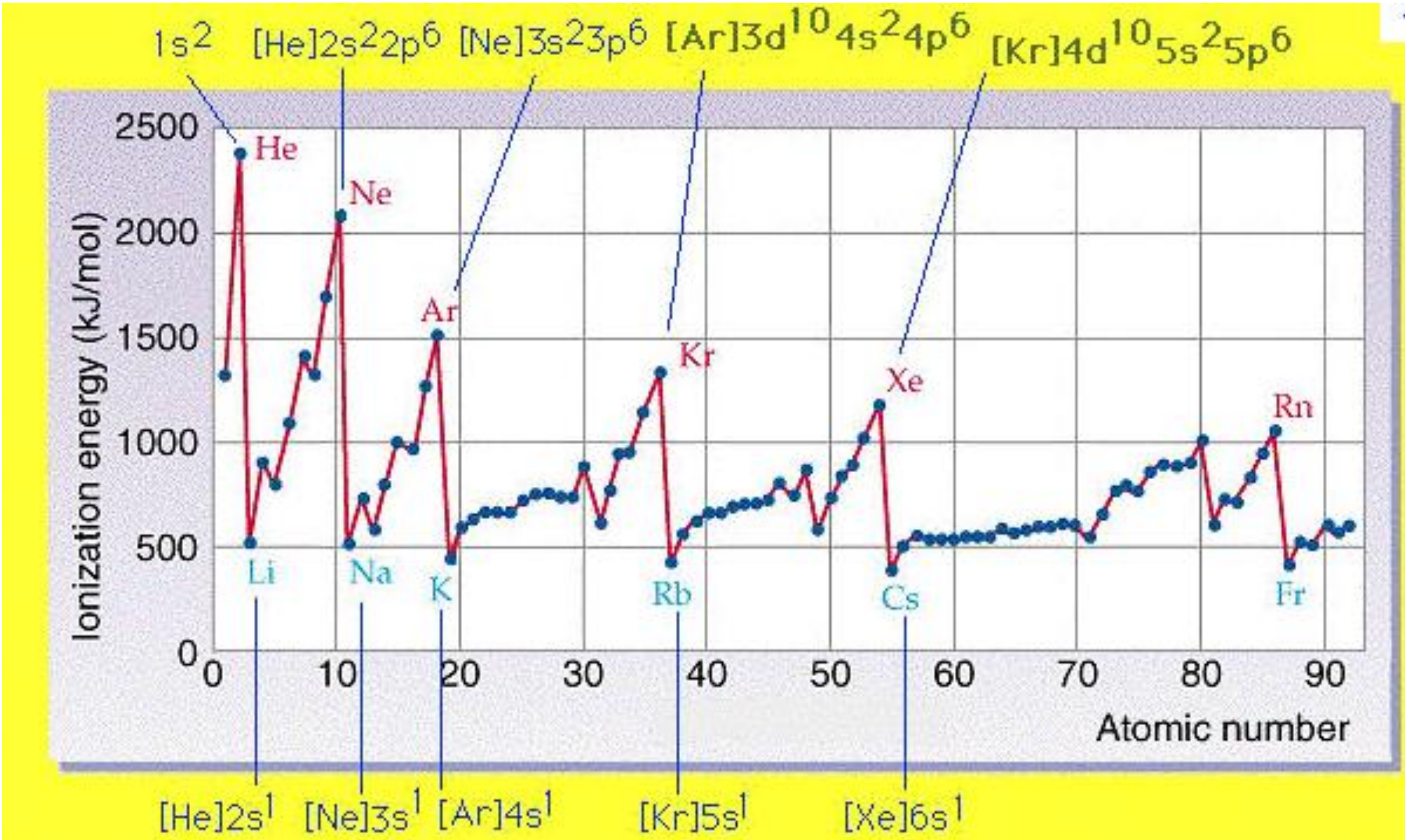
Ionization



The process it's possible when the Energy of the electrons is higher of the Ionization potential of neutral atoms

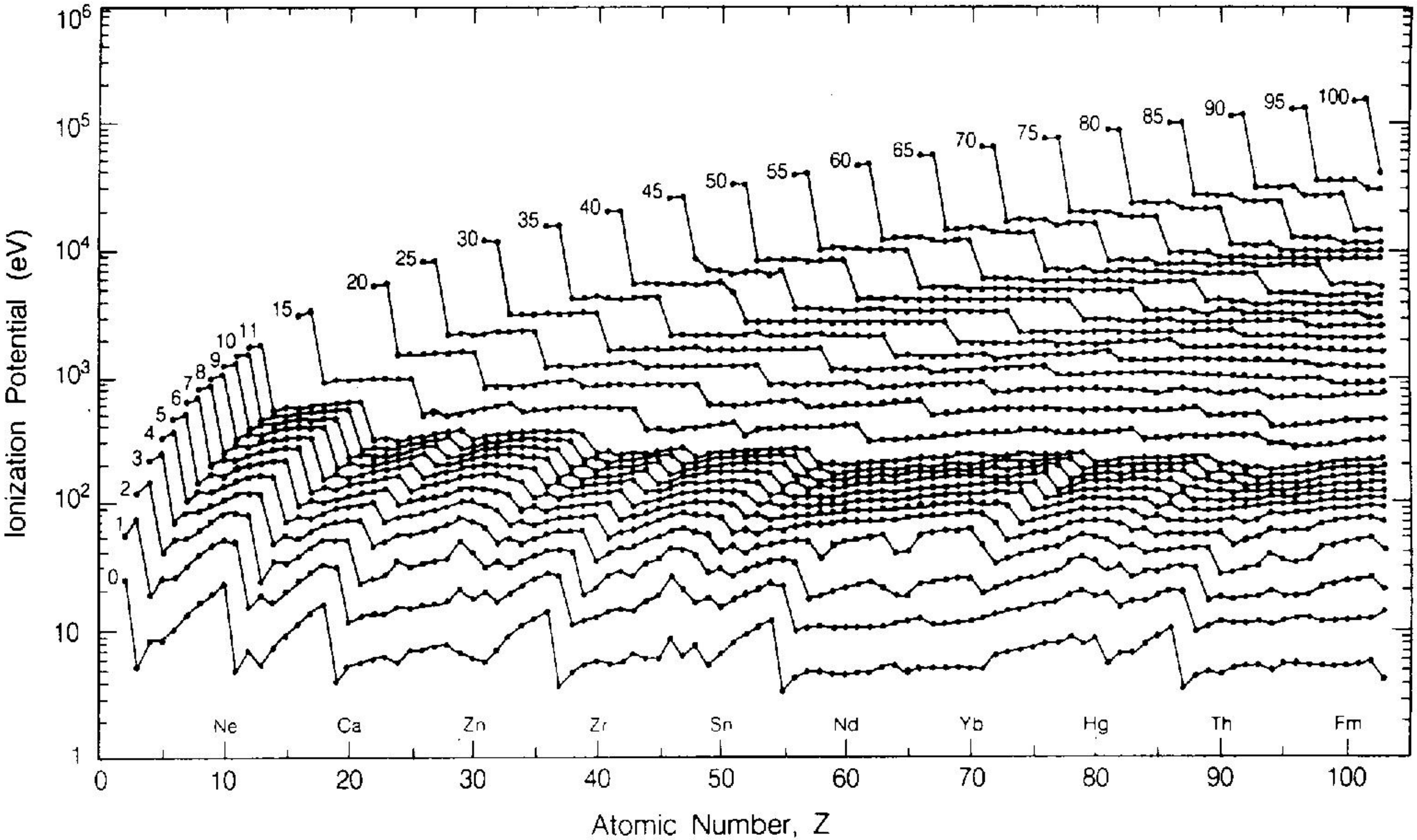
Ionization energies versus atomic number

$1\ eV \simeq 100\ kJ \cdot mol^{-1}$



The periodicity is a direct result of the electronic configuration of the elements

Ionization potential



The increase of the energy of electrons in the plasma increase the charge state

How to achieve high intensity and high charge states?

The increase in
electron density

↓

increases the beam current
extracted from the source

↓

The increase in the
ion confinement time

↓

more ions are confined,
more ionizing collisions
are able to undergo
Increase the maximum
achievable charge state
from the source

↓

Increase of the quality factor Q given by the product between the electron density and the confinement time

$$Q = n_e \tau_i$$

Important parameters

- The maximization of the Quality factor

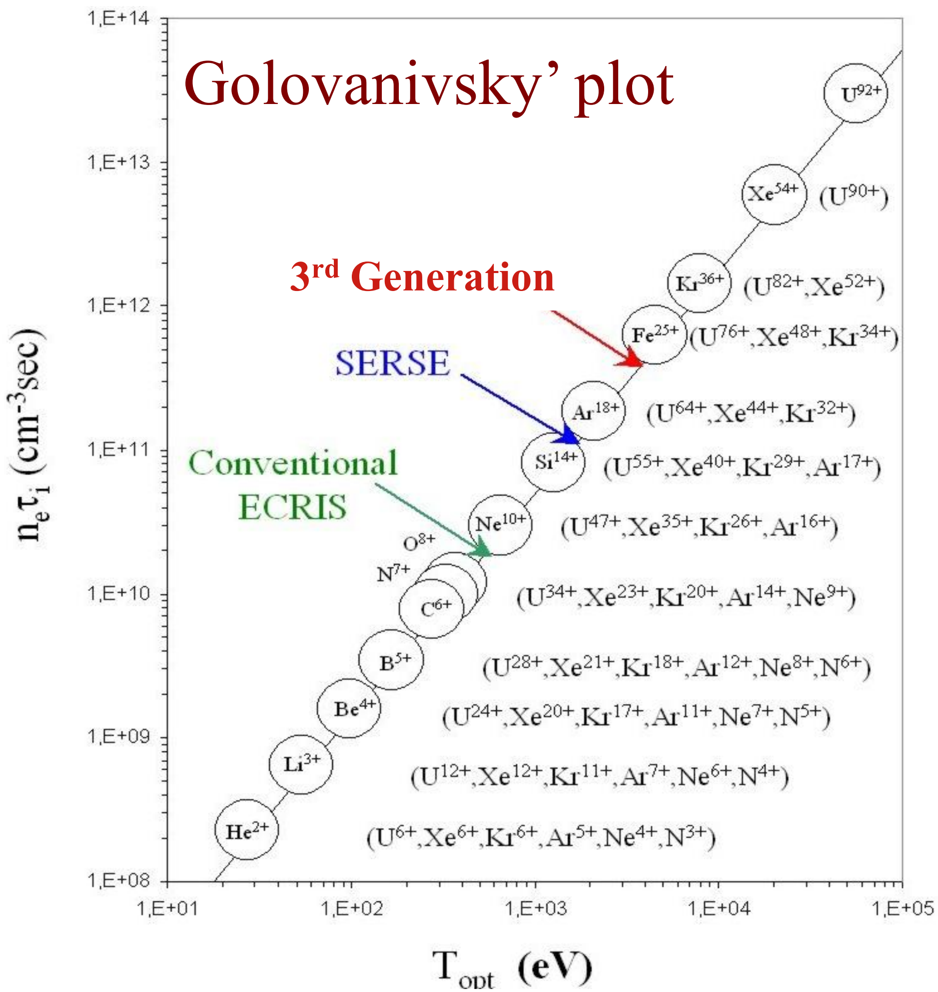
$$Q = n_e \tau_i$$

- Reduction of the neutral fraction

$$\frac{n_0}{n_e} \leq f\left(T_e, A, z\right)$$

- Increasing of the Electronic Temperature T_e

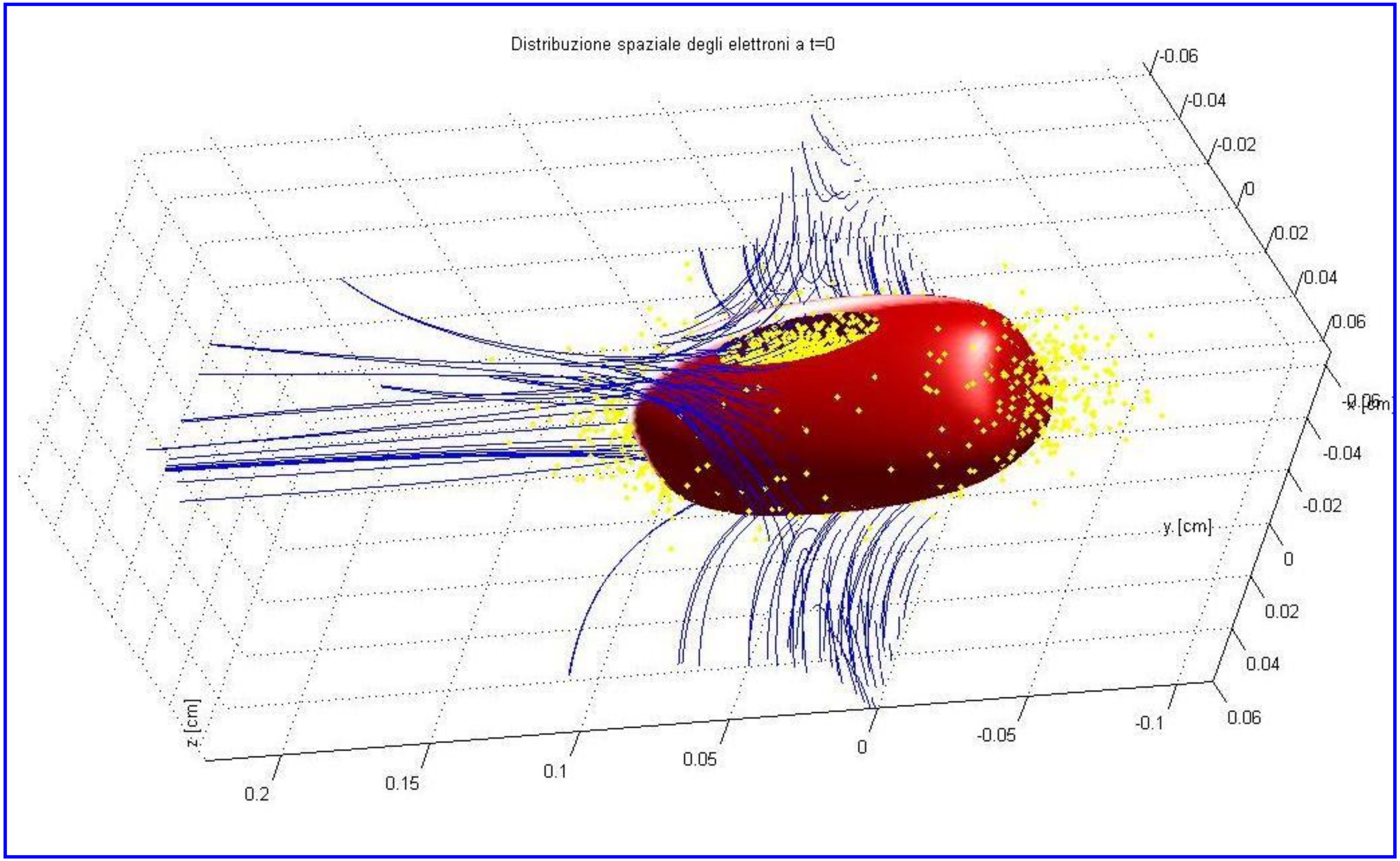
$$\frac{n_i}{n_n} = 2.4\ x\ 10^{21}\,\frac{T^{3/2}}{n_e}\,e^{-U_i/_{KT}}$$



The Golovanivsky' plot shows the obtainable ion charge states for different values of electron temperature and quality factors $n_e\ \tau_i$

For fully stripped light ions: $n_e \tau_i \cong 10^{10}\ cm^{-3}\sec \quad T_e^{opt} = 0.5\,keV$

Electron Distribution and Resonance Surface



ECR SUPERNANOGAN

Ion sources produced by Pantechnik in collaboration with: INFN-LNS

O1 and O2 sources inside the Synchrotron ring

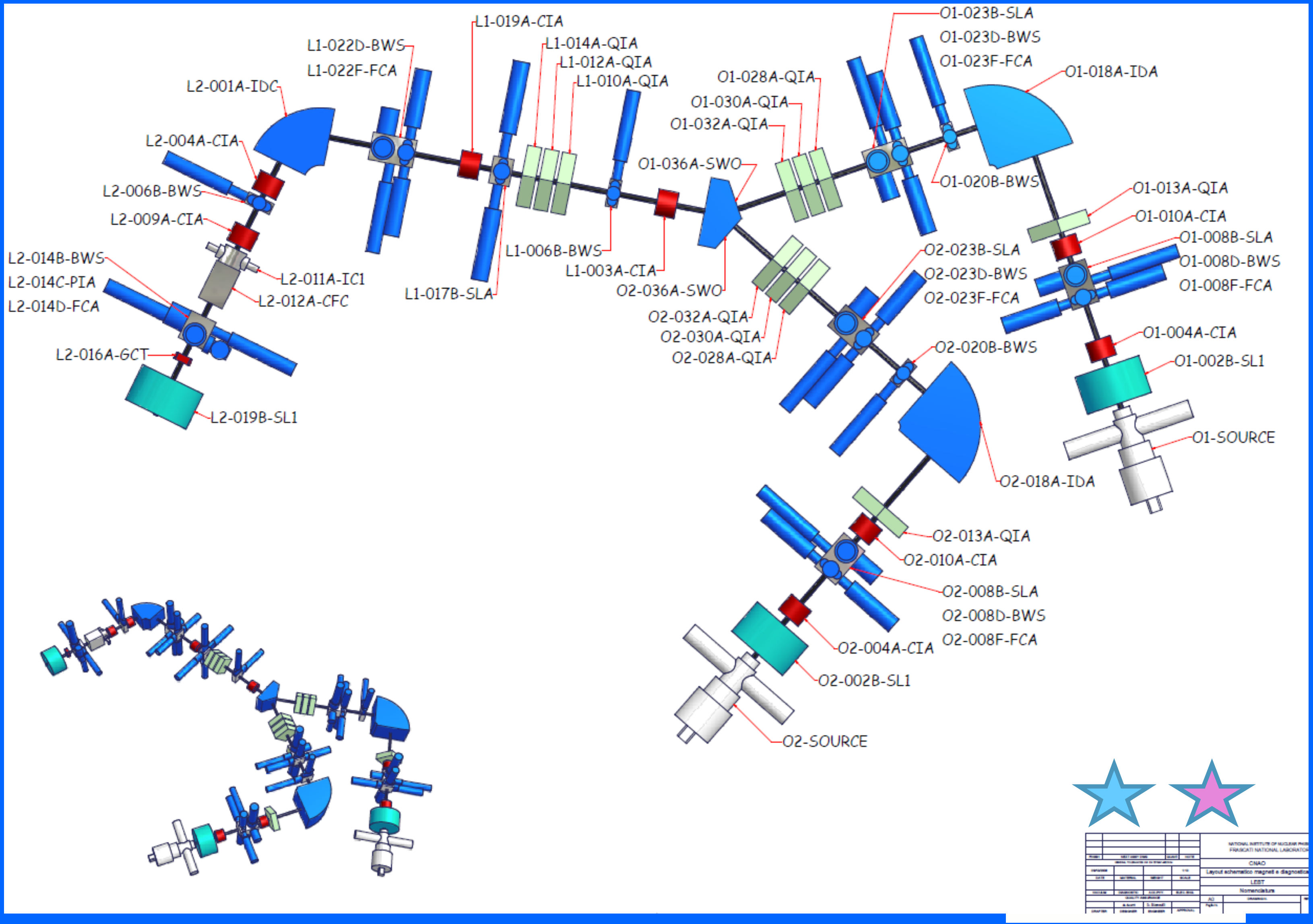
Significant improvements have been provided by INFN-LNS: frequency tuning effect, gas control, extractor reliability, etc.

ECR SUPERNANOGAN

Measured performances

Ions	Current (request) [μA]	Current (avail.) [μA]	After improvements by INFN-LNS [μA]	Emittance (request) π mm.mrad	Emittance (new extractor) π mm.mrad	Stability [99,8%]
C^{4+}	200	200	250	0.75	0.56	36 h
H_2^+	1000	1000		0.75	0.42	2 h
H_3^+	700	600	1000	0.75	0.67	8 h
He^+	500	500		0.75	0.60	2 h

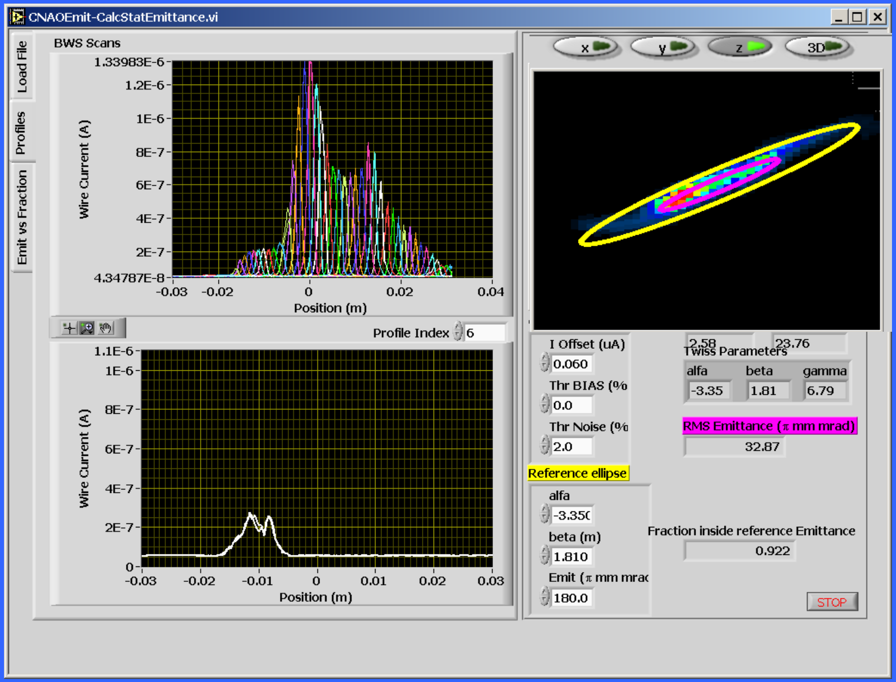
LEBT commissiong:LEBT layout



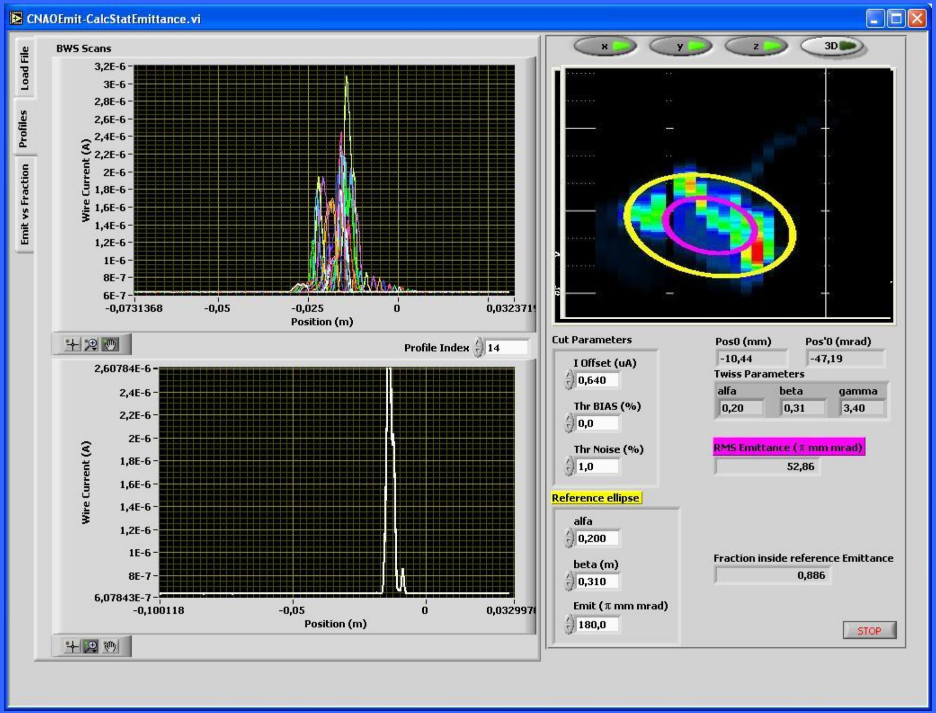
Sources currents and emittances

H_3^+, 1.0mA
(design =700 mA)

Emittance measured after spectrometer



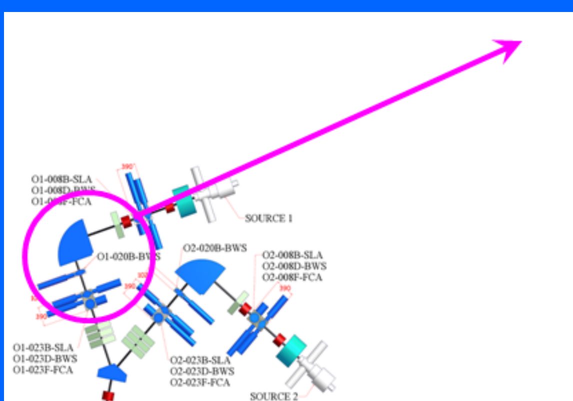
C^{4+}, 250 μA
(design = 200 μA)

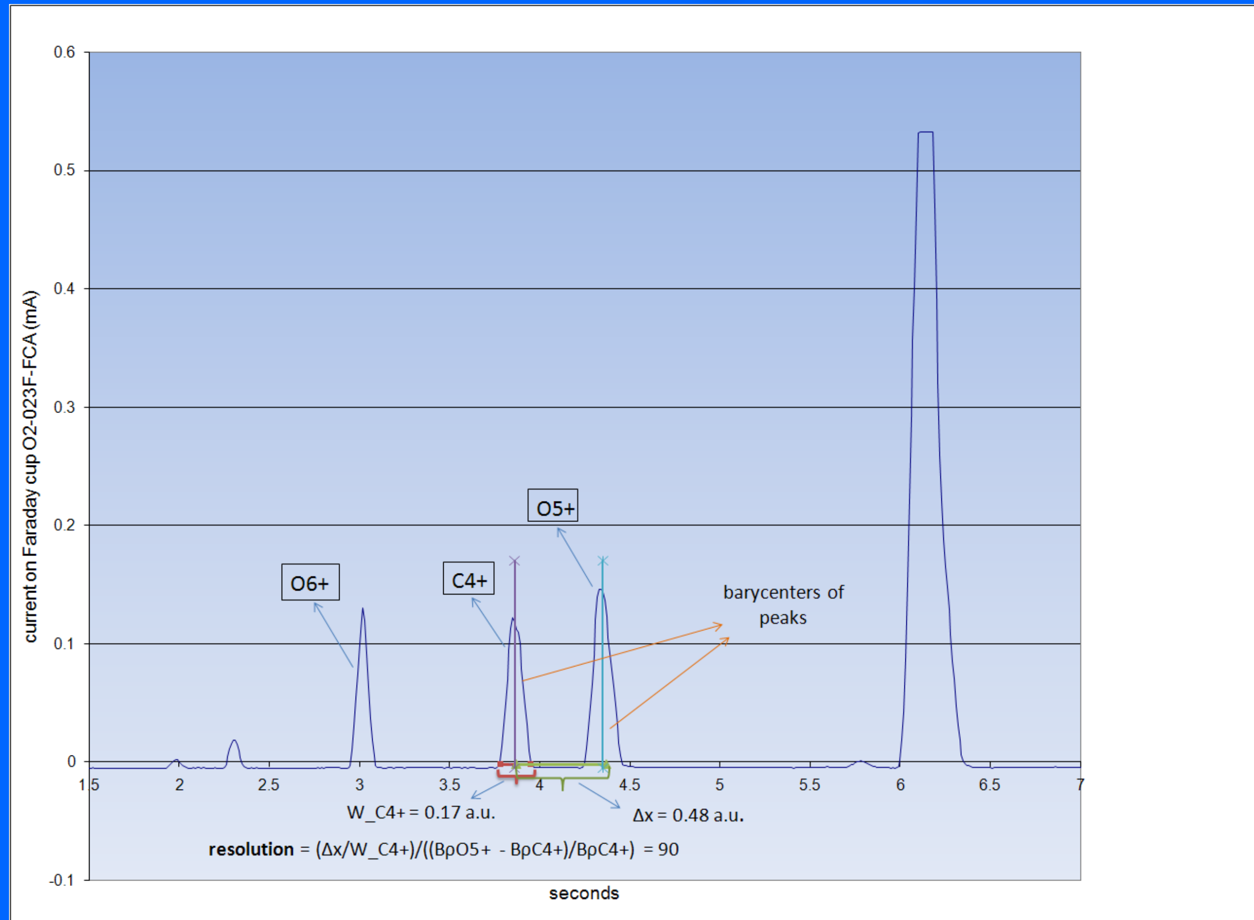


Species selection

$$R = \frac{\left(\frac{\Delta x}{W}\right)}{\left(\frac{(B\rho_{O^{5+}} - B\rho_{C^{4+}})}{B\rho_{C^{4+}}}\right)}$$

Minimum resolution to separate C4+ from O5+: R≈30





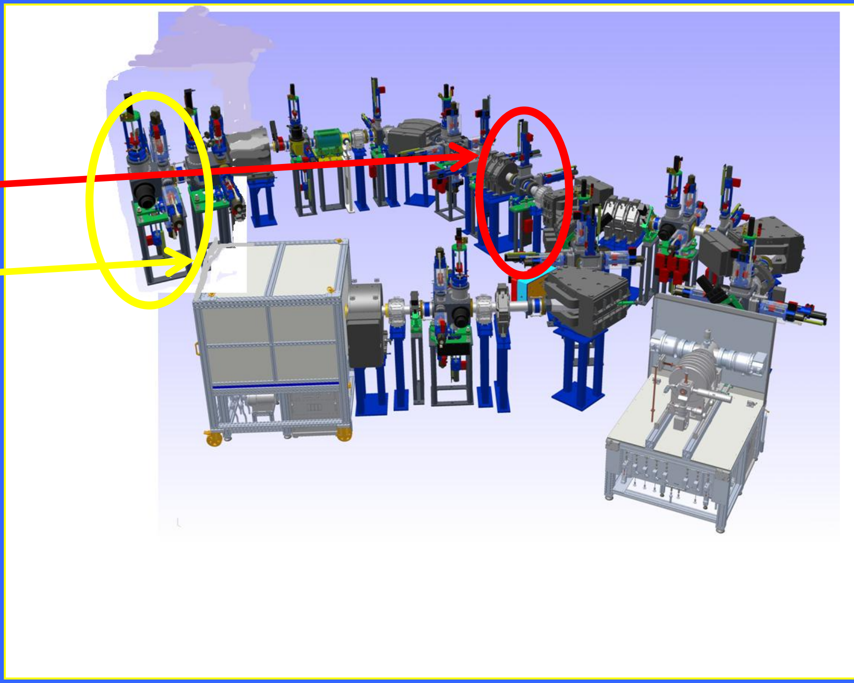
Measured R≈90

Measurement performed with a fixed gap of slits (2mm).

Thanks to the good resolution different species could be selected and transported along the LEBT

LEBT commissioning

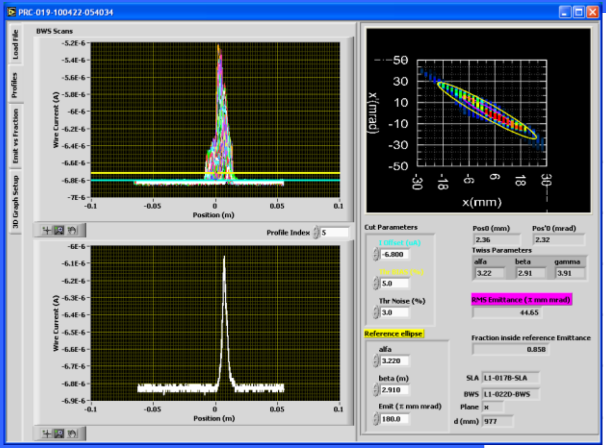
Diagnostic tanks containing
slits, wirescanners, faraday cups
Along the line + TB0

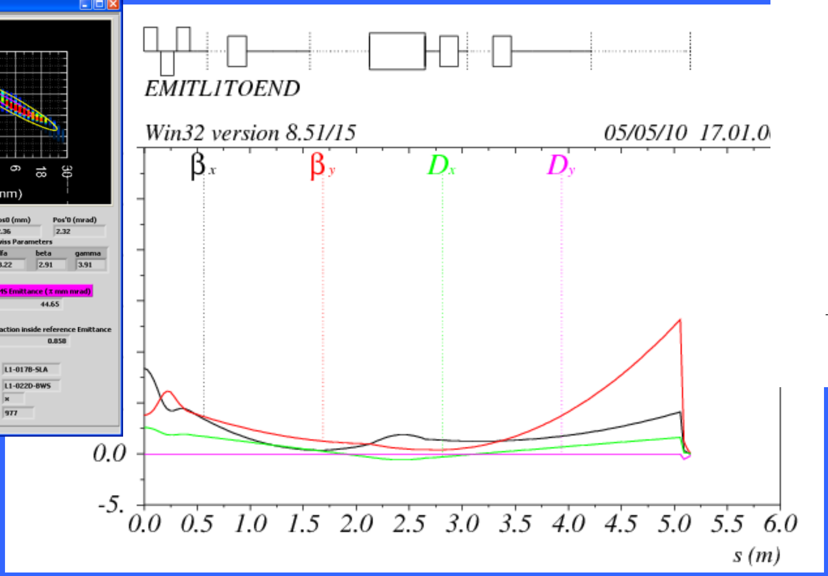


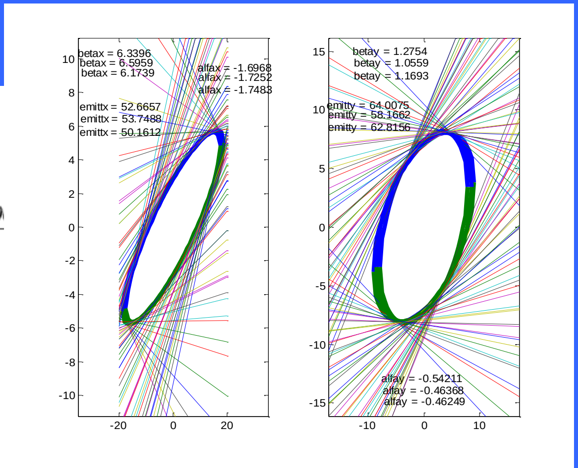
Emittance and Twiss Parameters measurements

- With tank diagnostics
- With Quad scans
- Model Agreement better than ± 10%

Transmission efficiency up to 97%



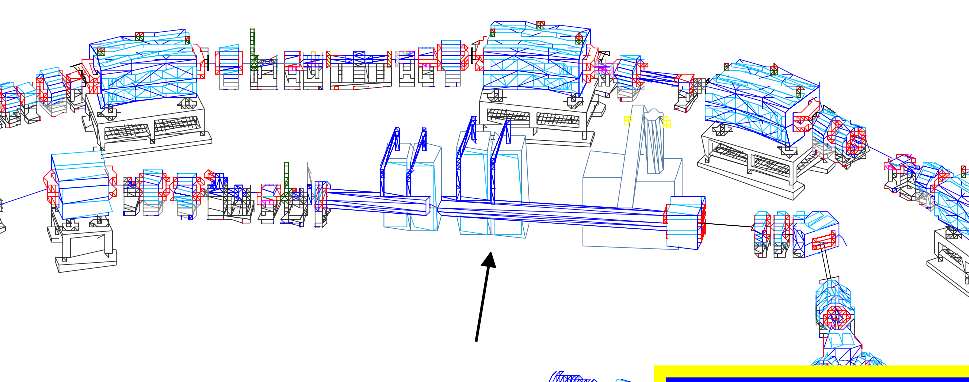




Il Linac

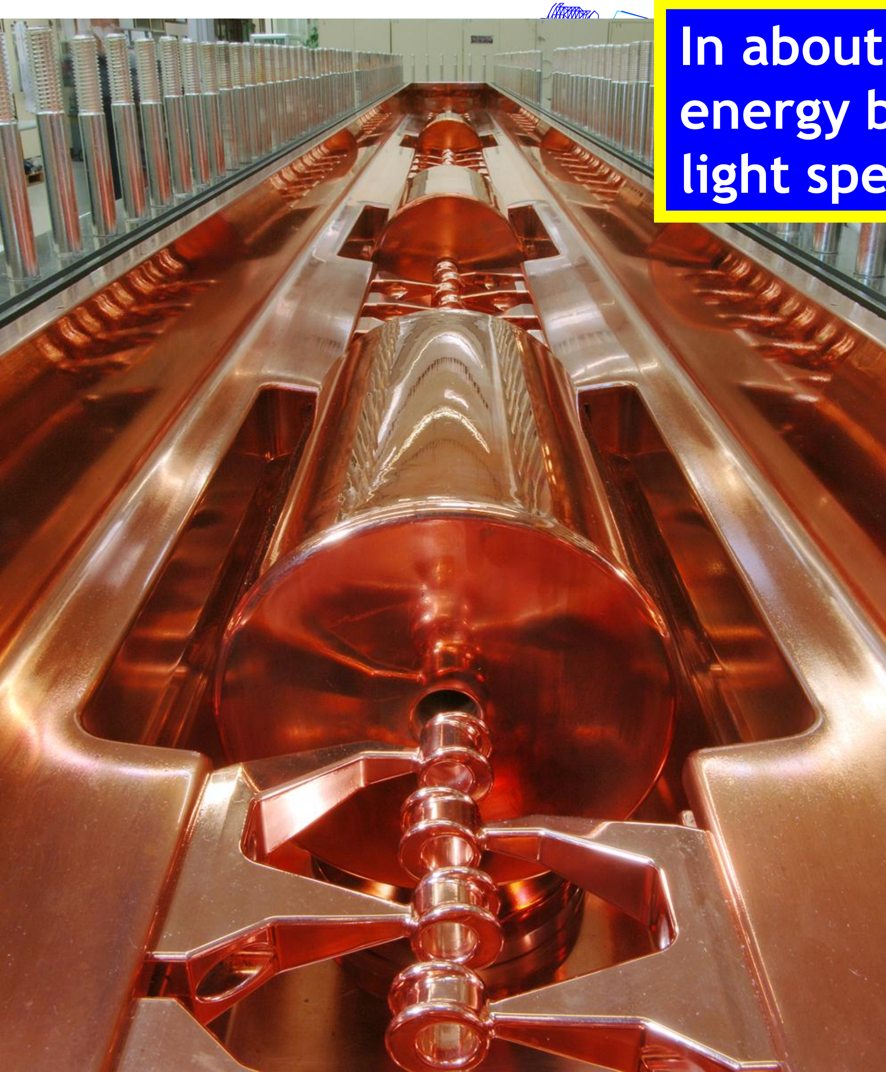
e

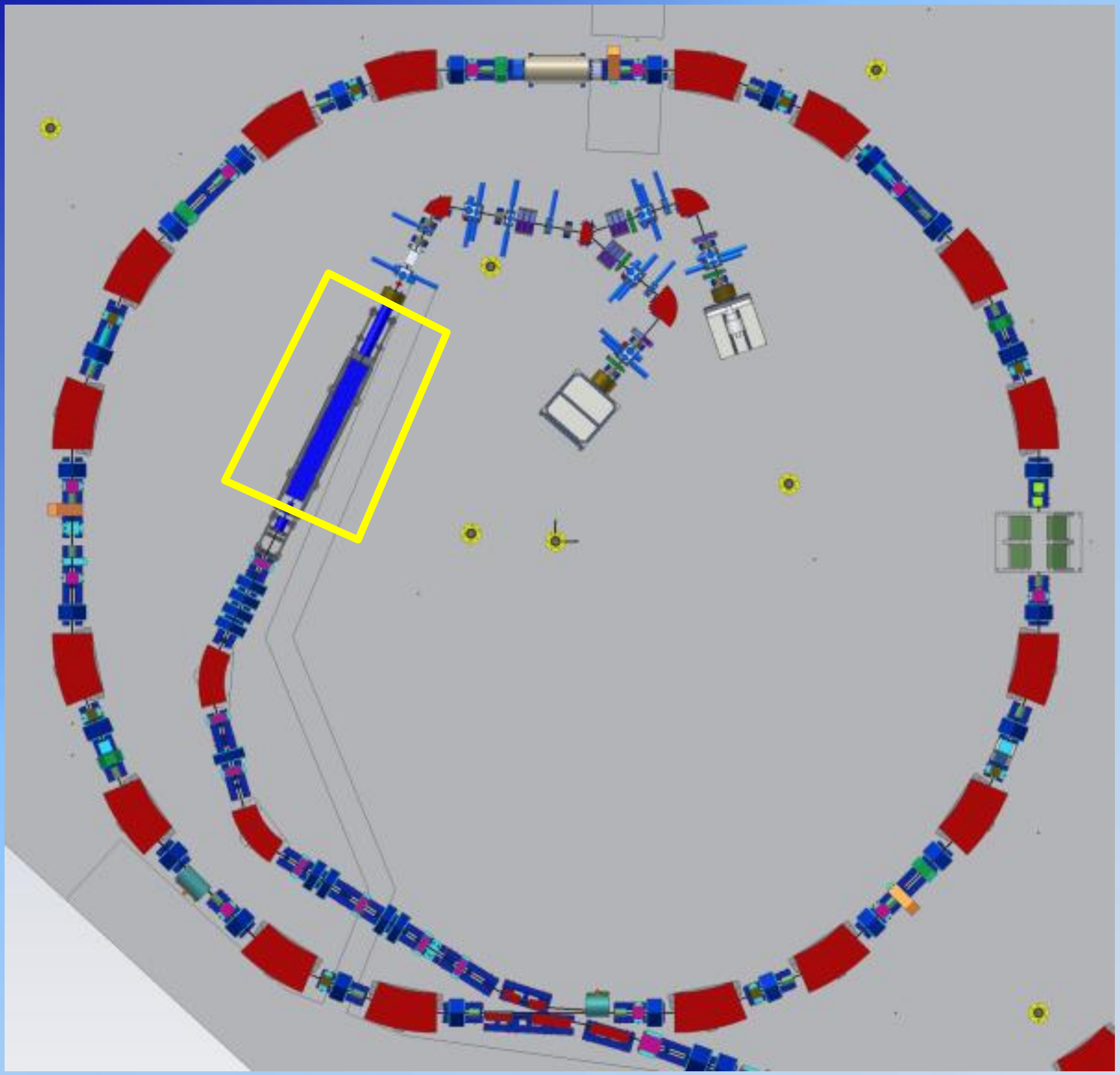
La MEBT



The Linear accelerator for ions

In about 6 meters the beam increases the energy by a factor 1000 - to reach 1/10th of light speed... 30'000 km/sec





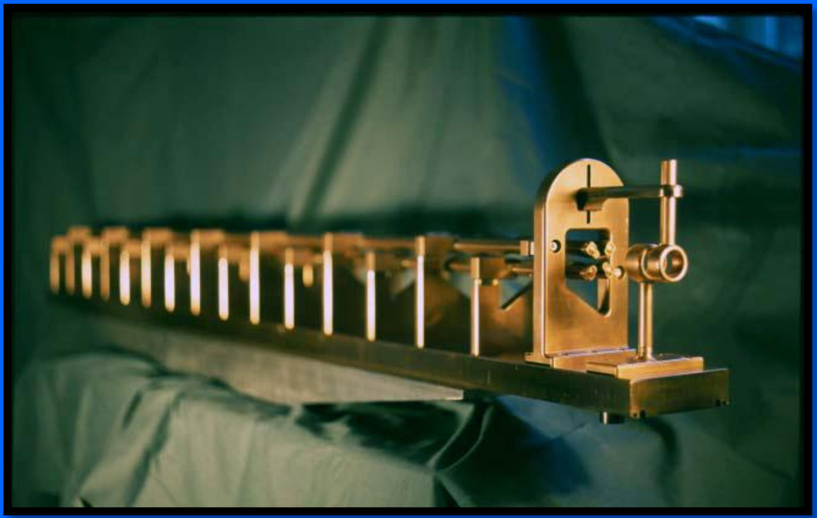
Linac=RFQ+IH

217 MHz

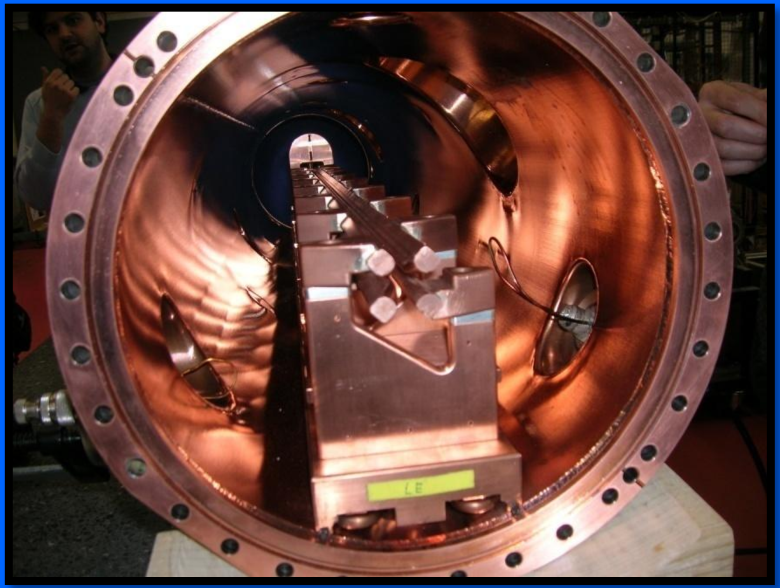
RFQ
0.008-0.4 MeV/u H^{3+}
0.008-0.4 MeV/u C^{4+}

IH
0.4-7 MeV/u H^{3+}
0.4-7 MeV/u C^{4+}

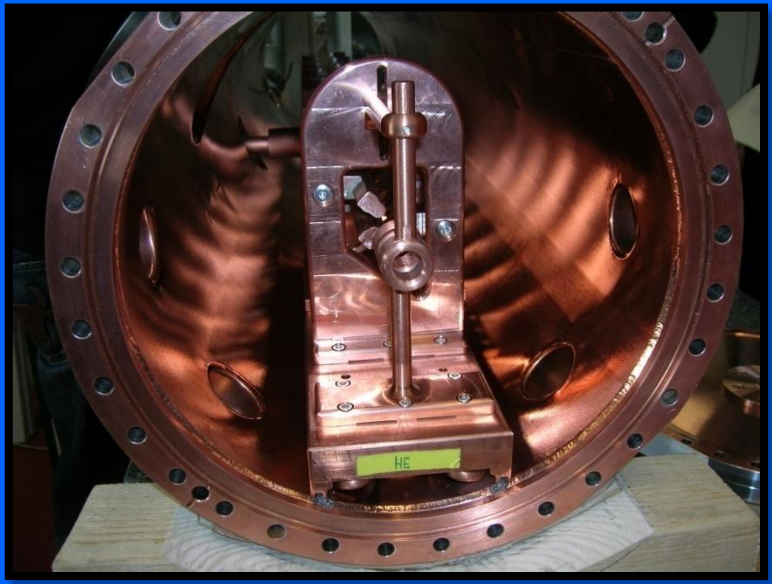
CNAO RFQ



Struttura interna



Ingresso ioni



Uscita ioni

Four-rods like type

Energy range = 8 – 400 keV/u

Electrode length = 1.35 m,

Electrode voltage = 70 kV

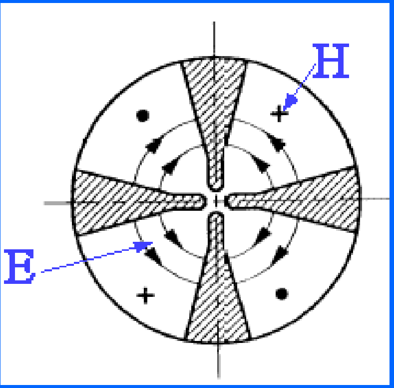
RF power loss (pulse): about 100 kW

Low duty cycle: around 0.1%

Gli ***RFQ*** (detti anche "***four vanes structures***") sono utilizzati per la prima accelerazione di protoni e ioni ($\beta \approx 0.01$). L'idea è quella di utilizzare strutture aventi un campo elettrico che simultaneamente focalizza e accelera le particelle del fascio. Per far questo si utilizzano strutture risonanti del tipo mostrato in figura. In prossimità dell'asse, il ***campo elettrico*** ***quadrupolare*** consente una ***focalizzazione trasversa*** del fascio. La ***modulazione*** pseudo-sinusoidale del ***profilo degli elettrodi***, d'altra parte, consente di avere una componente di campo lungo z che ***accelera il fascio***.

Gli RFQ, introdotti da circa 20 anni, consentono di interfacciare la sorgente col Linac provvedendo al ***focheggiamento***, alla ***prima accelerazione*** ed al "***bunching***" del fascio con efficienza di cattura elevatissima.

Nella figura a lato sono rappresentate qualitativamente le linee di forza del capo elettrico e magnetico del modo risonante (***pseudo TE_{210}***) in una generica sezione trasversa.



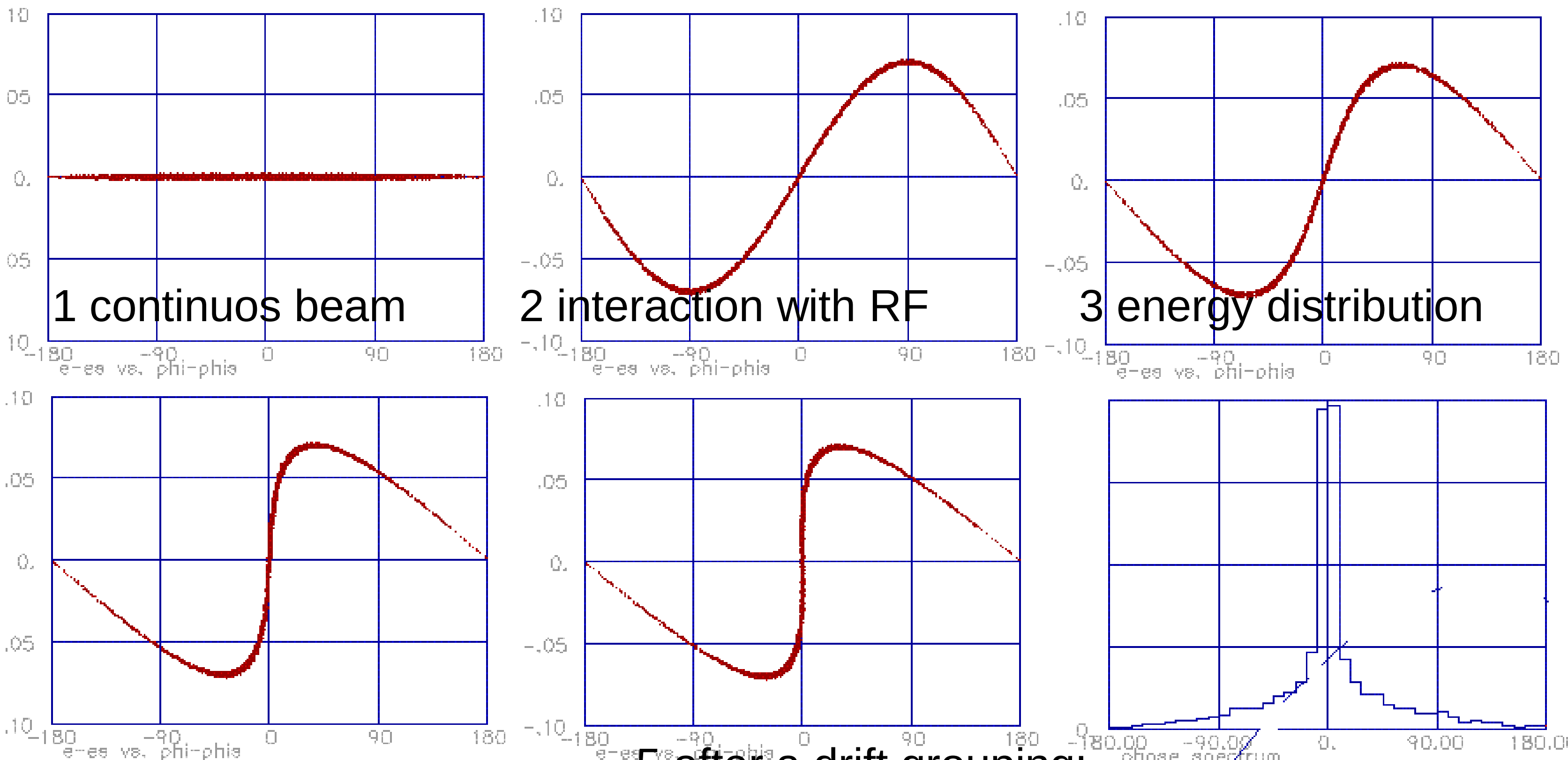
Bunching

Preparation to acceleration:

- generate a velocity spread inside the beam
- let the beam distribute itself around the particle with the average velocity

(Courtesy A. Lombardi)

Discrete Bunching



1 continuos beam

2 interaction with RF

3 energy distribution

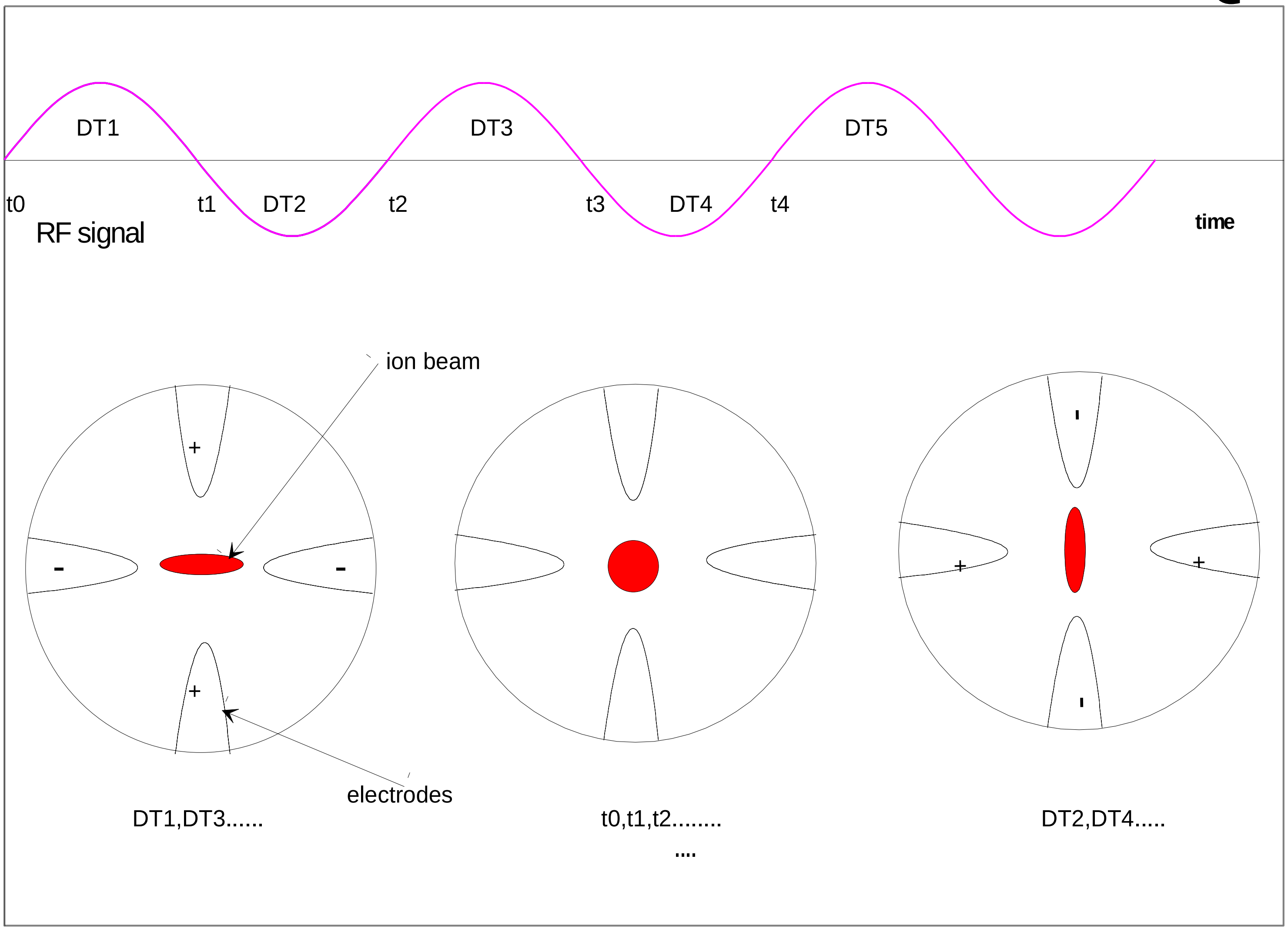
4 earlier particles are slowed down, later particles are accelerated

5.after a drift grouping: around the “central” particle

6 distribution of the particles

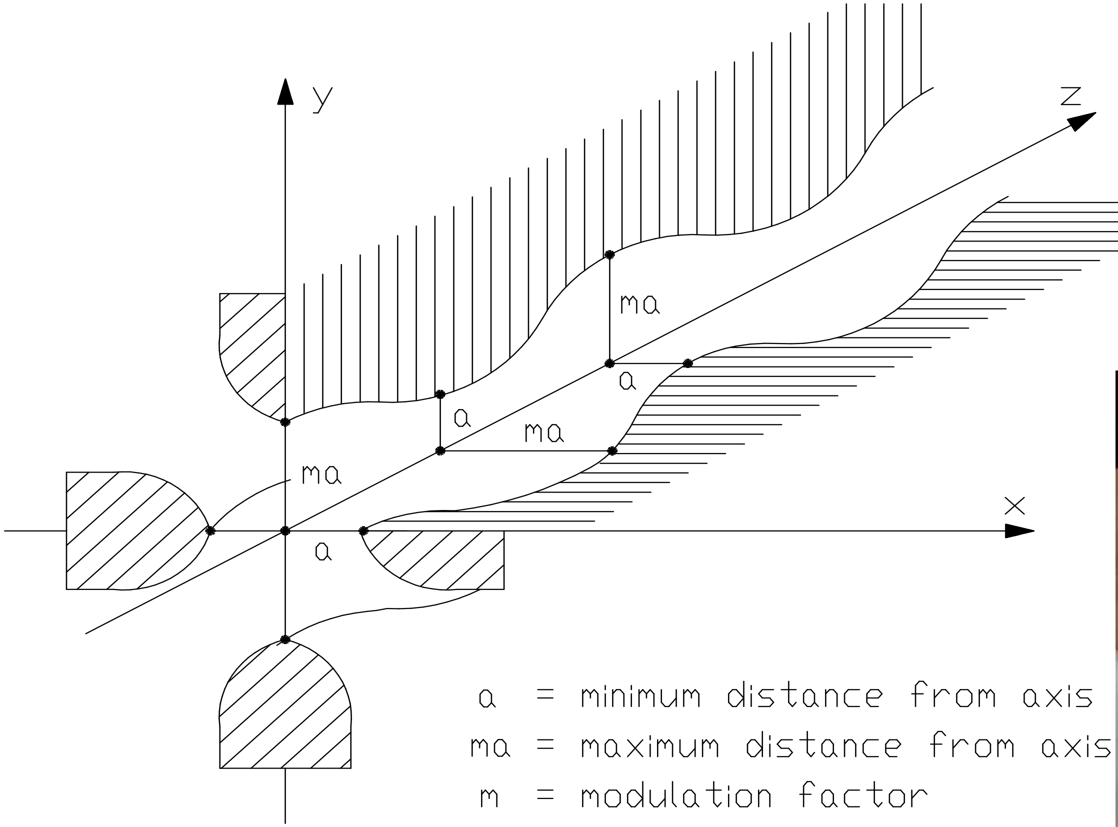
(Courtesy A. Lombardi)

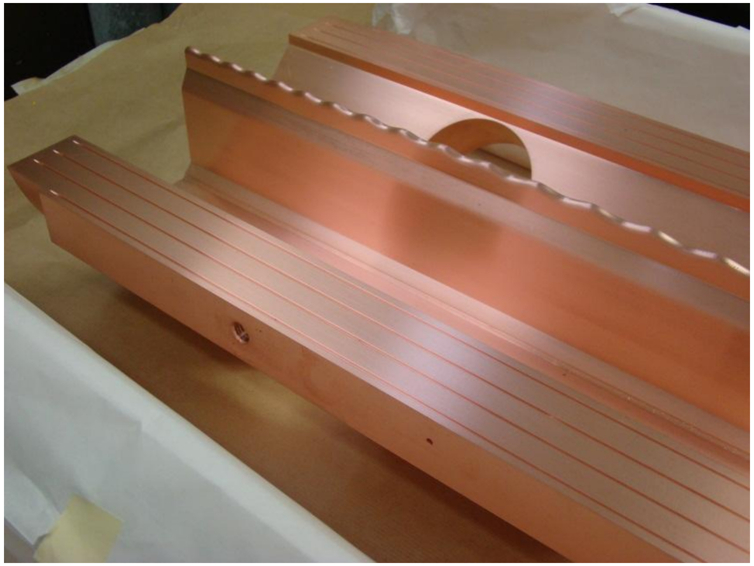
transverse field in an RFQ



(Courtesy A. Lombardi)

acceleration in RFQ

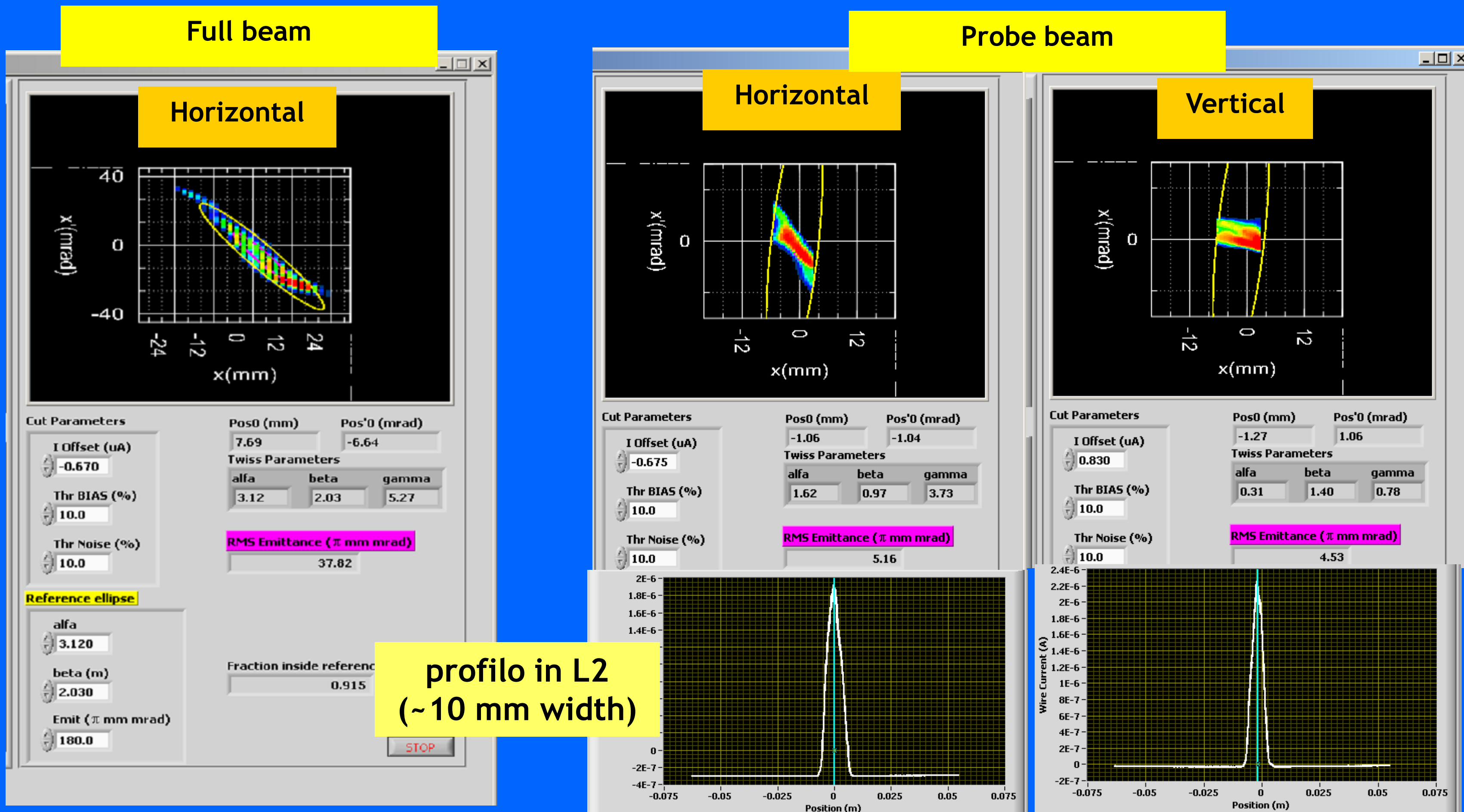




longitudinal modulation on the electrodes creates a longitudinal component in the TE mode

(Courtesy A. Lombardi)

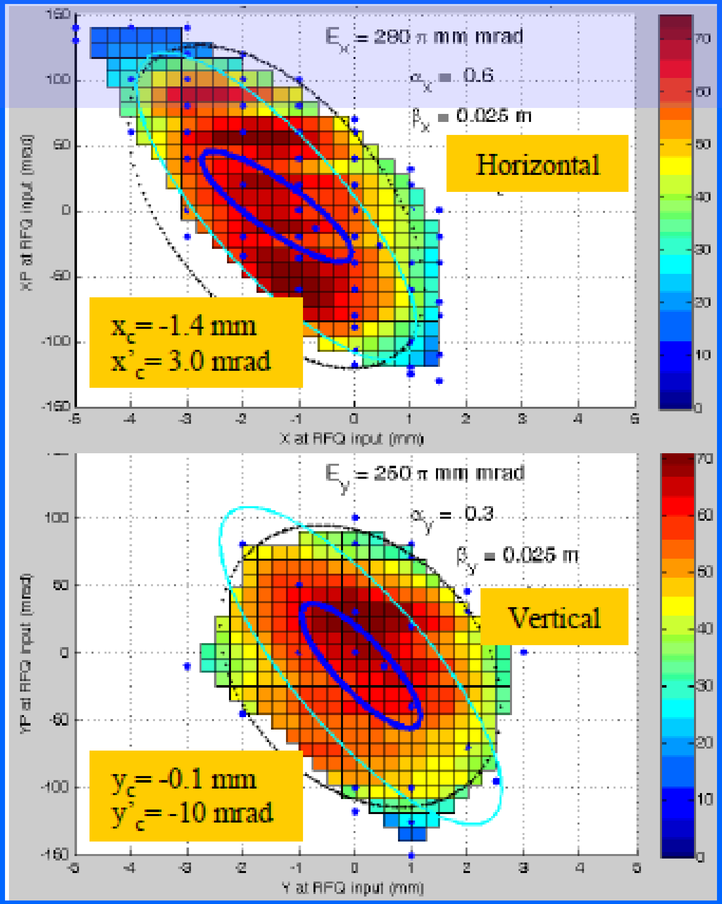
H_3^+ : "full beam" and "probe beam" Emittances in L1-017 and profile in L2



Preparazione del "probe beam": Fascio ottimizzato in L2. Le slitte vengono chiuse quanto basta per selezionare un fascio di intensità di ~100 μA.

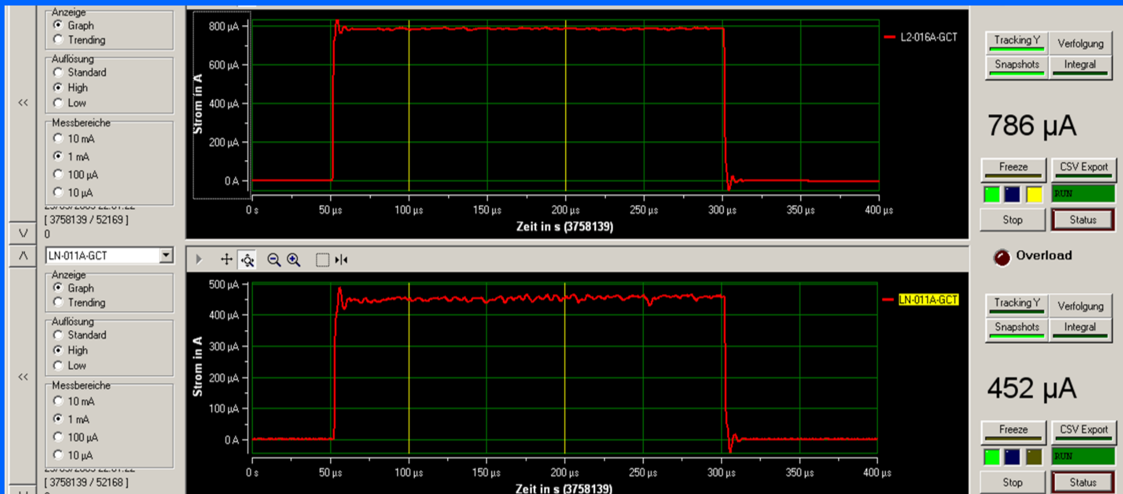
Misure di accettanza dell'RFQ

- Scansione sull'accettanza dell'RFQ usando gli steerer della LEBT
- Le coordinate nello spazio delle fasi all'iniezione nell'RFQ sono state misurate durante il commissioning della LEBT con TB0



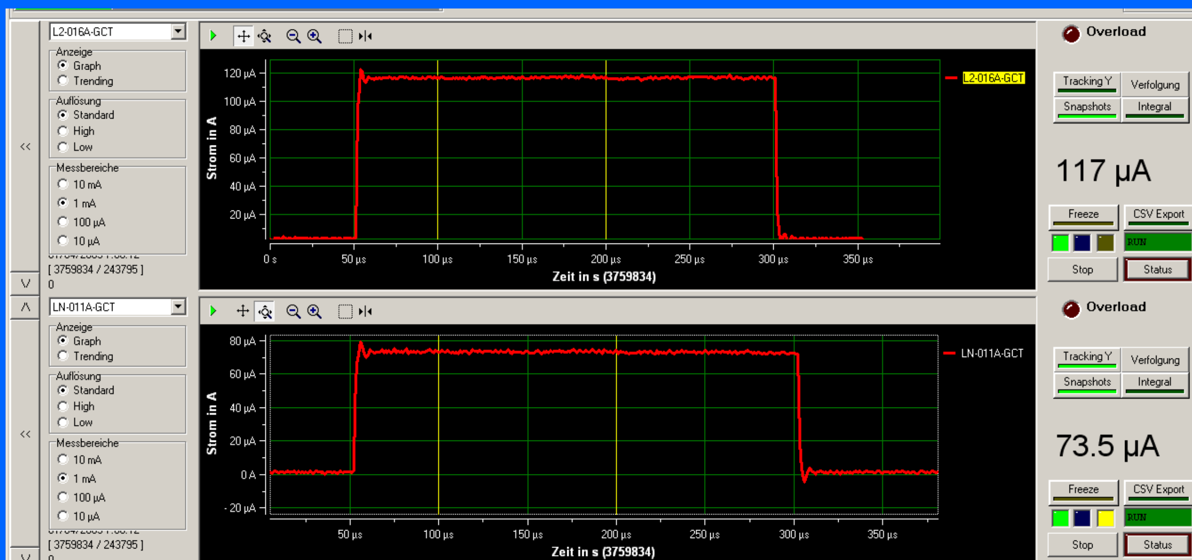
- Ellisse blu: H3+ probe beam @ 8 keV/u
- Ellisse azzurra: accettanza dell'RFQ matchata con un'emittanza di 180 pi mm mrad
- Ellisse nera: accettanza al 90% che fitta coi dati sperimentali

Commissioning RFQ
Corrente di fascio prima e dopo l'RFQ



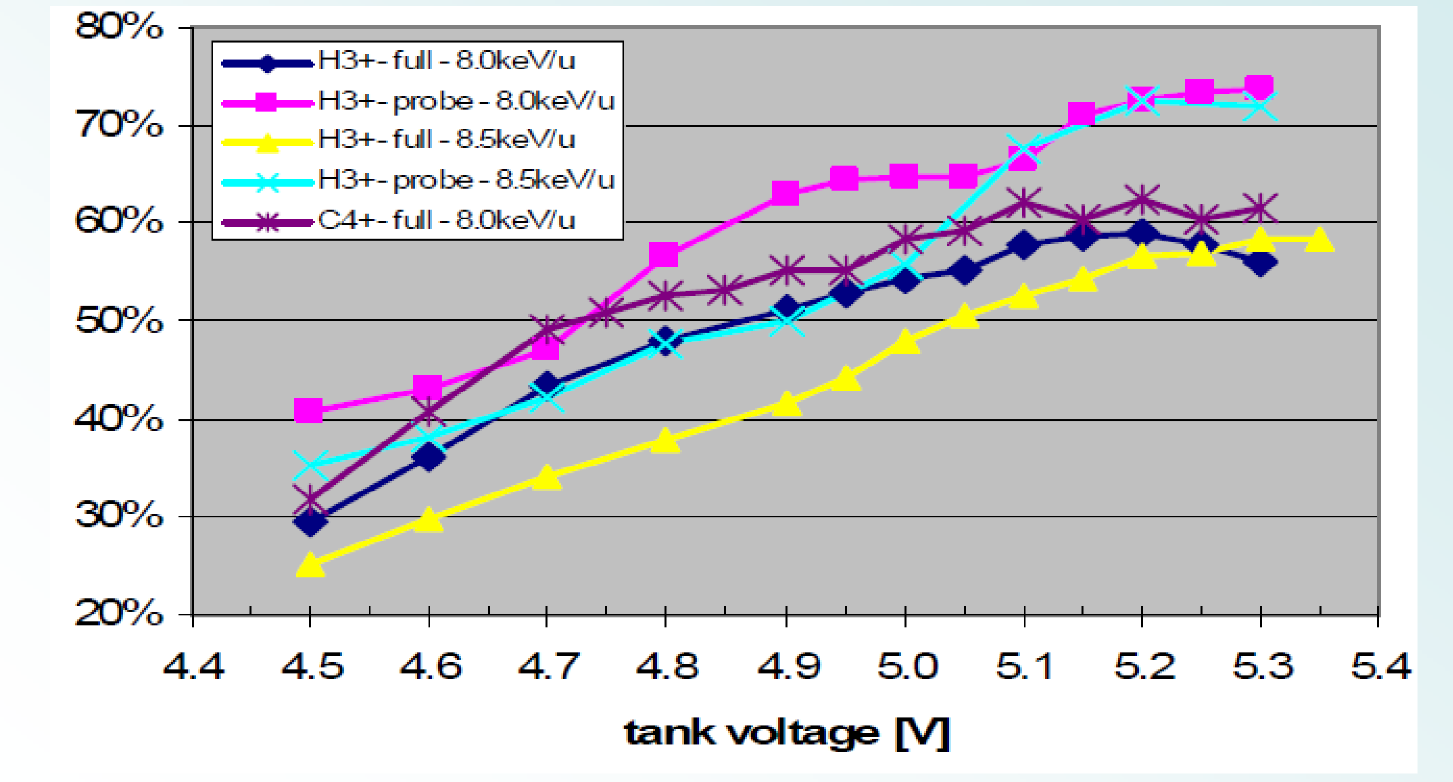
***Risultati H_3^+ @ 8 keV/u*:**
Correnti in entrambi gli ACTs (L2-016A-GCT e in TB2) @ V_{Tank} = 5.1 Volt

Risultati C_4^+ @ 8 keV/u
Correnti in entrambi gli ACTs (L2-016A-GCT e in TB2)



RFQ Transmission

Misurando la corrente prima e dopo l'RFQ



Risultati H3+ full beam: **Trasmissione ~57 % al punto di lavoro = 5.1 Volt (195 kW)**
Steering accettabile in entrambi i piani

Risultati C4+ full beam : **Trasmissione ~60 % al punto di lavoro = 5.1 Volt (195 kW)**
Steering accettabile in entrambi i piani

Tra RFQ e IH

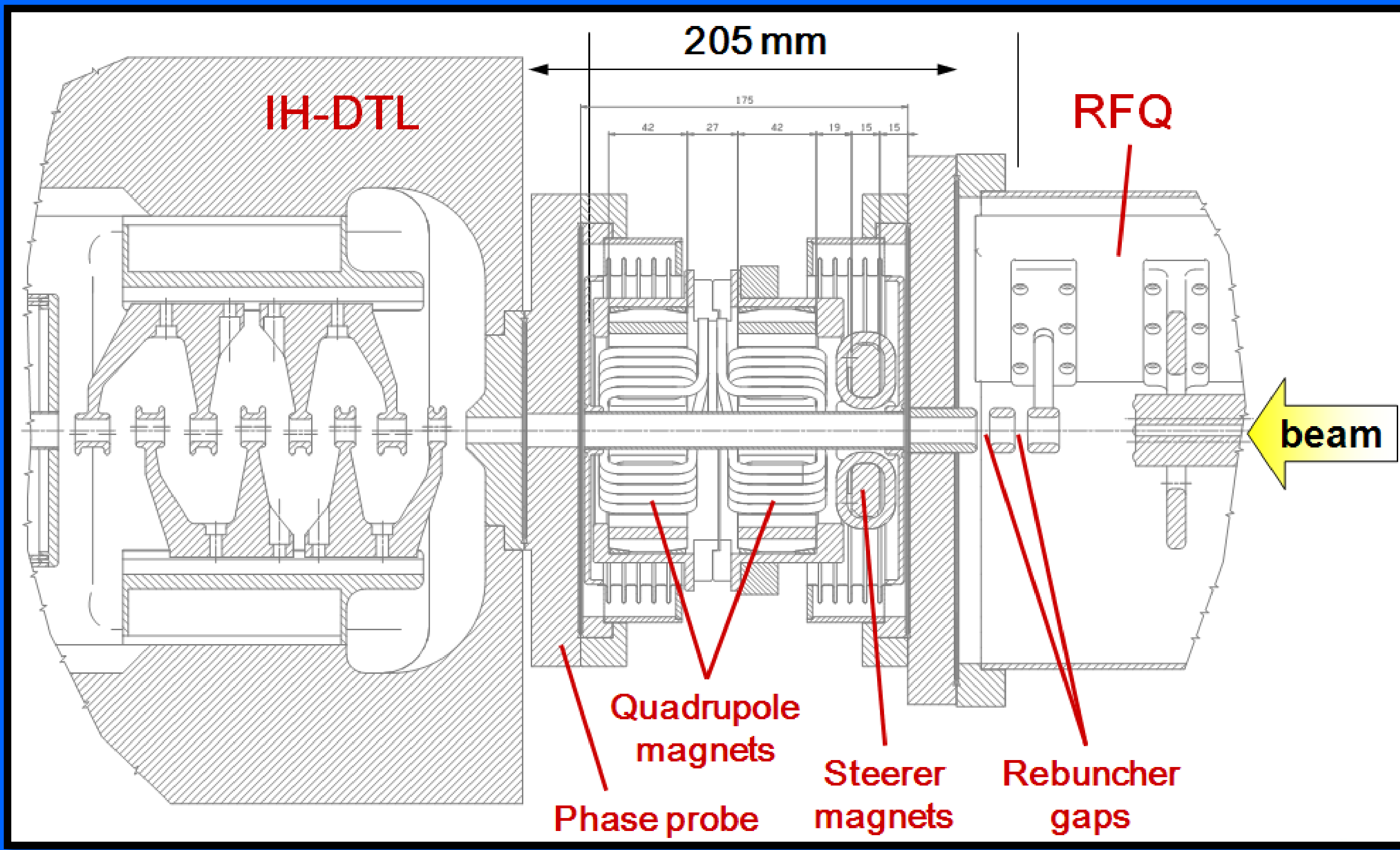
L'RFQ è adatto per trasporto e accelerazione alle basse energie per le sue buone proprietà di focheggiamento. Per energie più alte l'efficienza cala e le strutture con drift tubes diventano più adatte.

- I drift tubes sono usati anche come "rebuncher" dopo l'RFQ per migliorare il "matching" del fascio all'accettanza della struttura longitudinale seguente. Una soluzione comune è una cavità di tipo buncher tra l'RFQ e la struttura DTL.

- Nel caso CNAO/Heidelberg è stato sviluppato un nuovo modello: un drift tube è montato direttamente alla fine dell'RFQ (ma comunque dentro la cavità) formando così un'unità buncher.

Tra RFQ e IH: Inter Matching Section

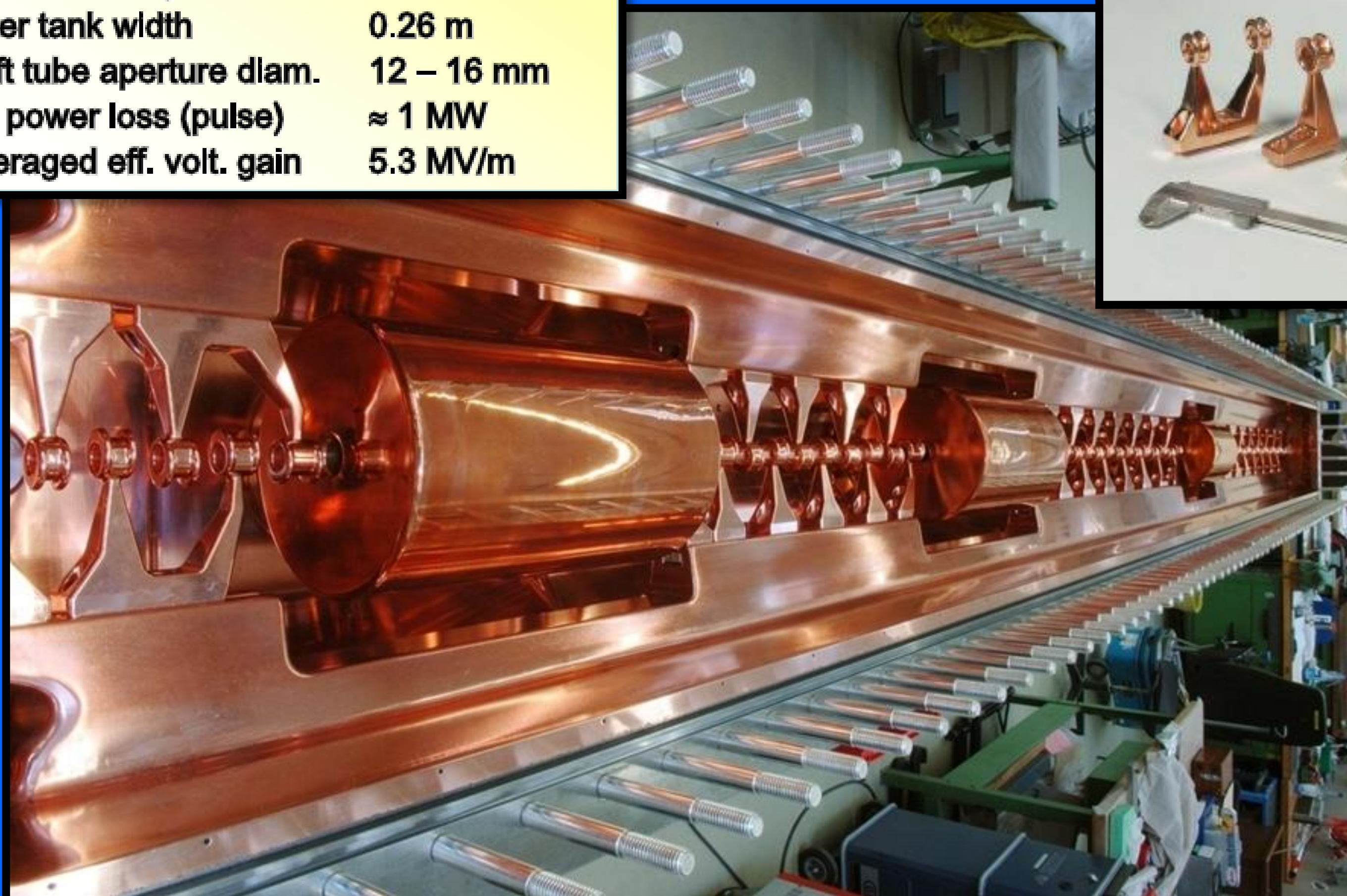
Per focheggiare il fascio in entrambi i piani trasversi di fase e per correggere le piccole deviazioni angolari del fascio all'uscita dell'RFQ, viene flangiata al tank dell'RFQ un'unità magnetica costituita da un xy-steerer a da un doppietto (QD).



IH tank

3 Integrated magnetic triplet lenses
56 Accelerating gaps

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

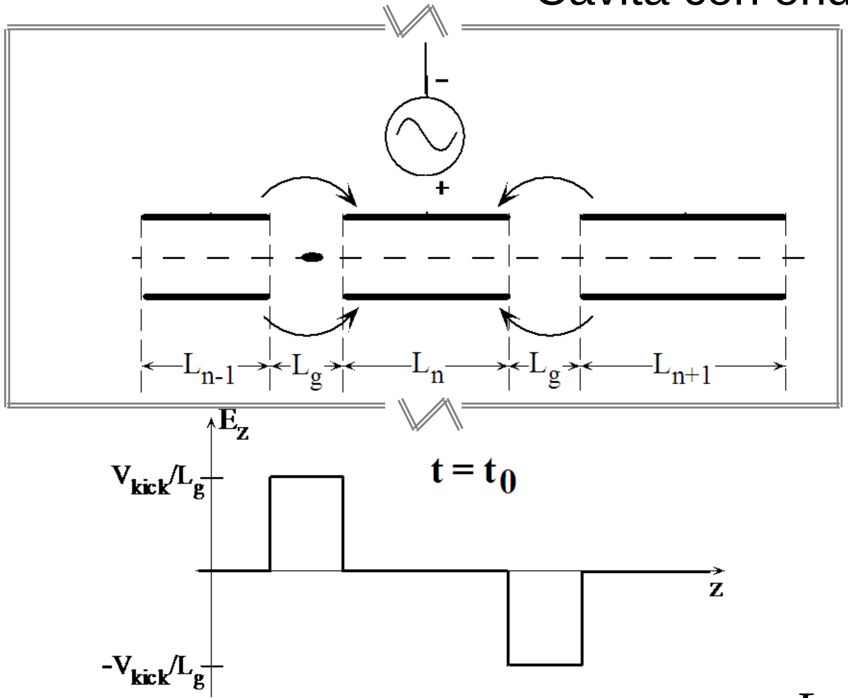


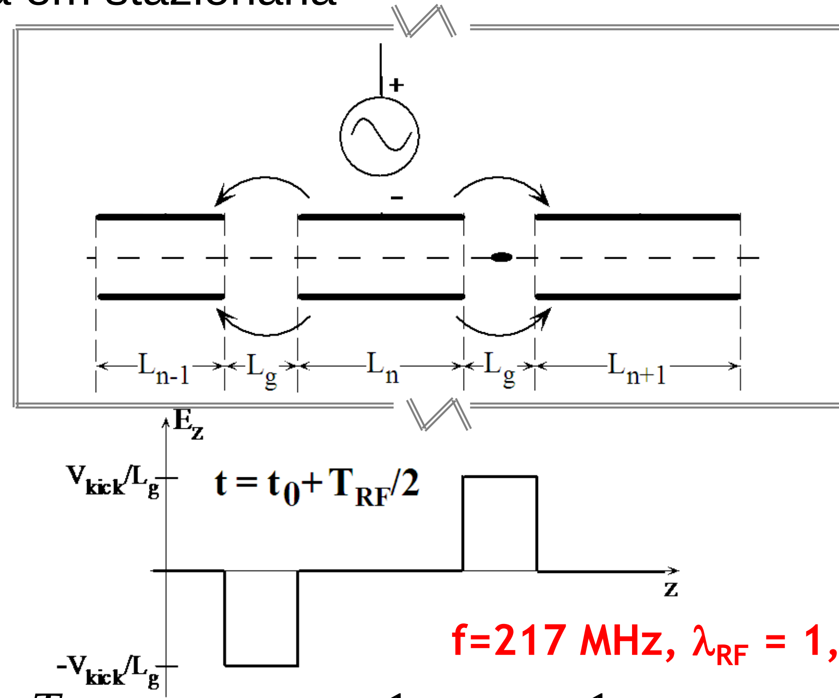
Synchronous particle

- Design a linac for one "test" particle. This is called the "synchronous" particle.
- The length of each accelerating element determines the time at which the synchronous particles enters/exits a cavity.
- For a given cavity length there is an optimum velocity (or beta) such that a particle traveling at this velocity goes through the cavity in half an RF period.
- In a synchronous machine EACH cell is different

(Courtesy A. Lombardi)

Cavità con onda em stazionaria

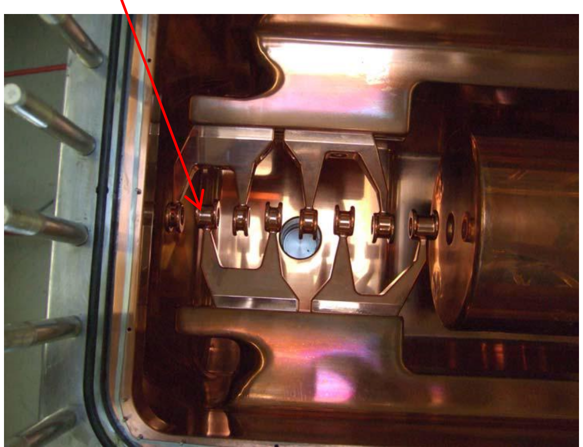


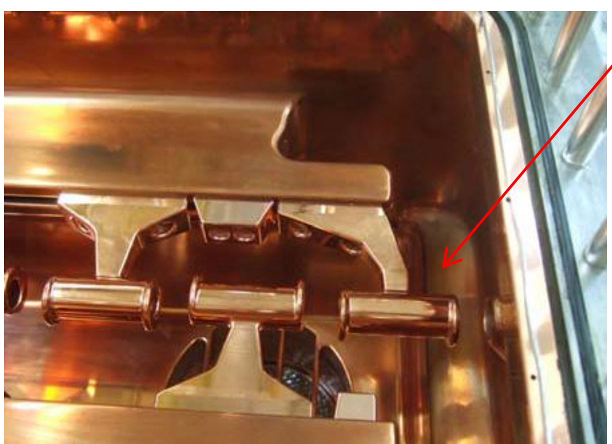


f=217 MHz, λ_{RF} = 1,38 m

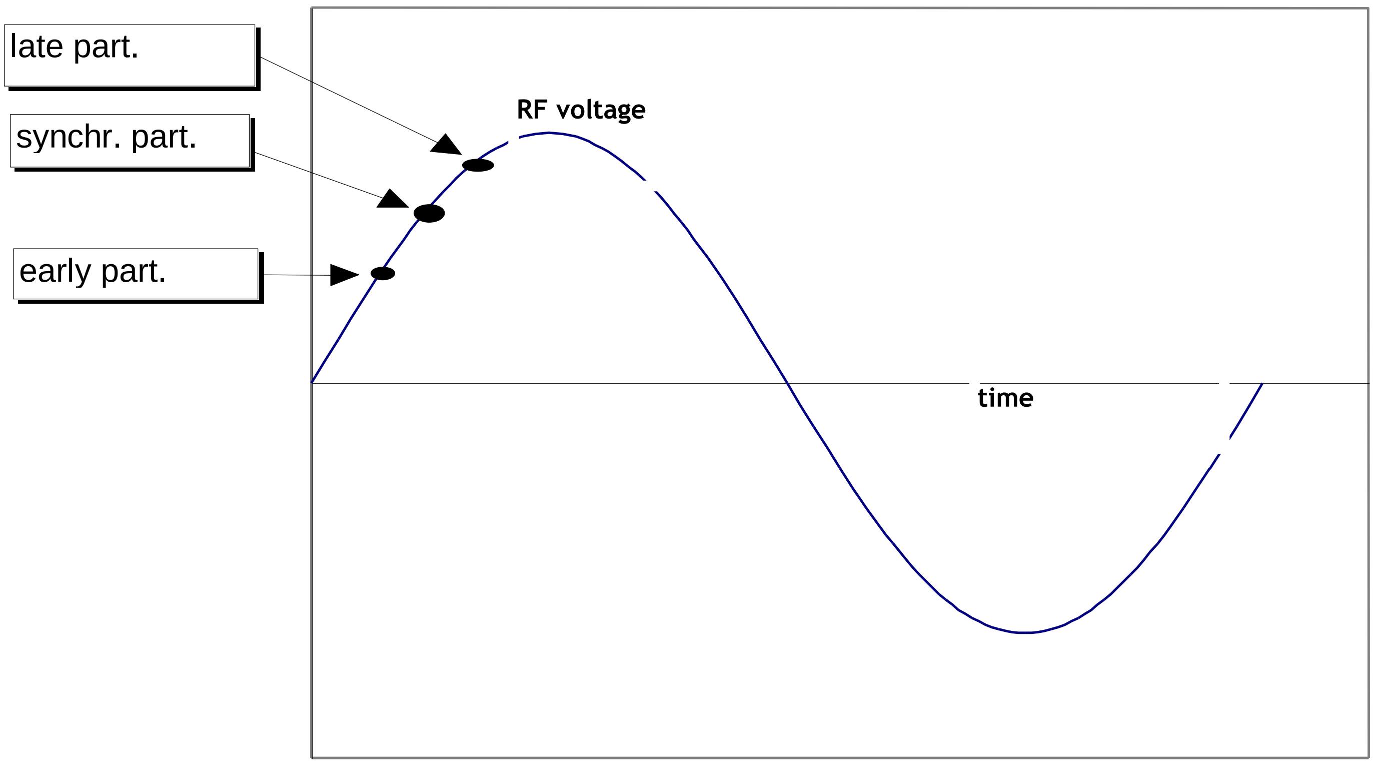
La lunghezza L_n del n-simo tubo di drift: $\frac{L_n}{v_n} = \frac{T_{RF}}{2}$ => $L_n = \frac{1}{2} v_n T_{RF} = \frac{1}{2} \beta_n \lambda_{RF}$

Ingresso IH: L_n=20 mm	$\beta_{0,4}$ = 0,03	$\beta_{7,0}$ = 0,12	Uscita IH: L_n=80 mm





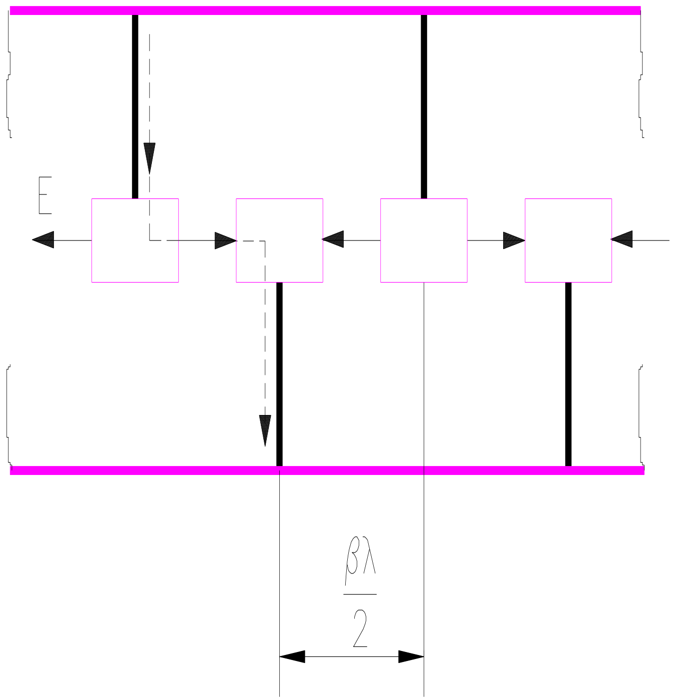
Supponiamo che la fase sincrona sia scelta in anticipo rispetto al picco ($\varphi_s \leq 0$). Una qualunque particella che attraversi il gap prima della fase sincrona avrà un kick più piccolo e guadagnerà meno velocità presentandosi in ritardo al gap successivo. Al contrario una particella che attraversi il gap dopo la fase sincrona avrà un kick più grande e guadagnerà più velocità presentandosi in anticipo al gap successivo.

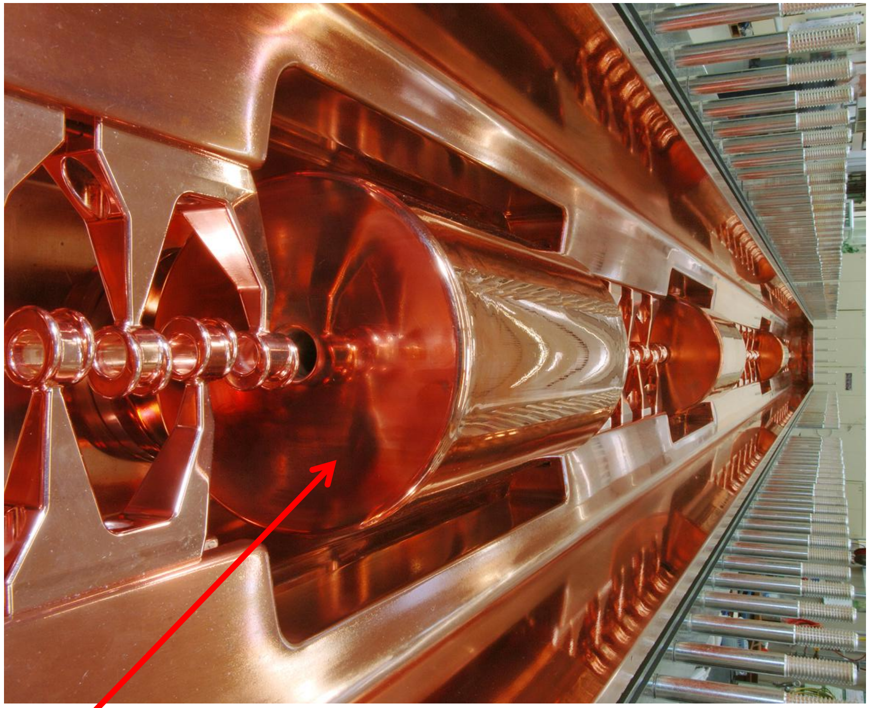


Quindi la scelta $\varphi_s \leq 0$ garantisce il ***focheggiamento longitudinale*** del fascio (***principio di stabilità di fase***, valido per ogni acceleratore lineare). La scelta opposta $\varphi_s \geq 0$ porta invece all'instabilità longitudinale.

Interdigital H structure

I=Interdigital: stem alternati come dita intrecciate
H: campo elettrico trasversale, “raddrizzato dagli stem”



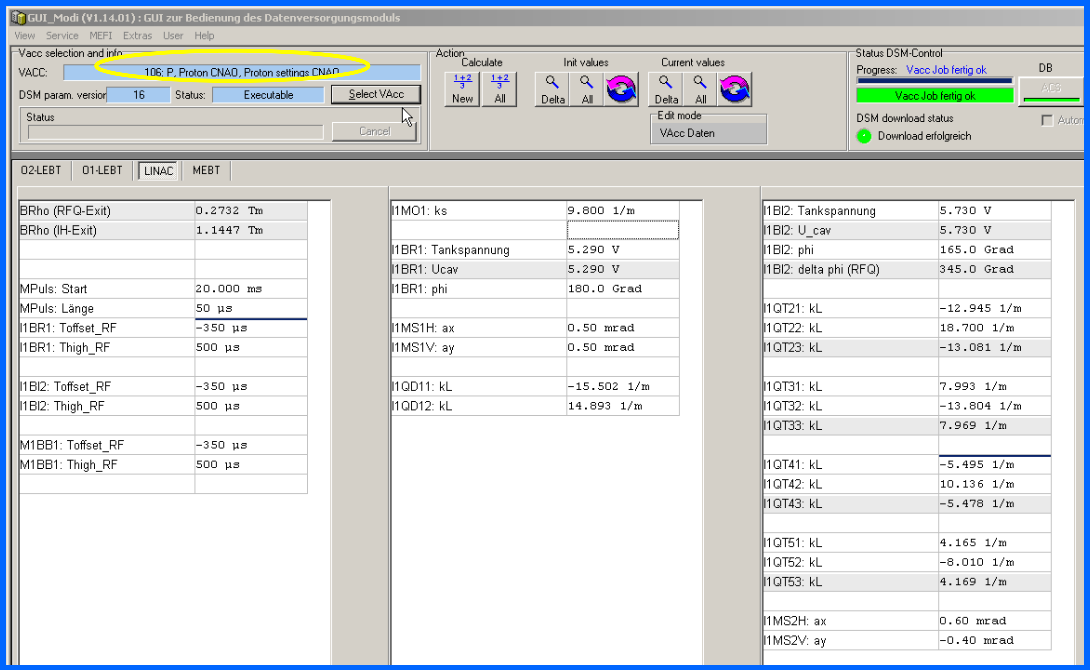


•stem on alternating side of the drift tube force a longitudinal field between the drift tubes

•focalisation is provided by quadrupole triplets places OUTSIDE the drift tubes

LCS = LINAC Control System

- VACC = Virtual Accelerator
- Serve per creare, accelerare e trasportare un fascio (includendo informazioni su: specie ionica, corrente magneti interni al LINAC, energia fascio, intensità, ecc.)
- I controlli per ogni specifico set-up sono salvati nella memoria delle DCU degli alimentatori e della dignostica

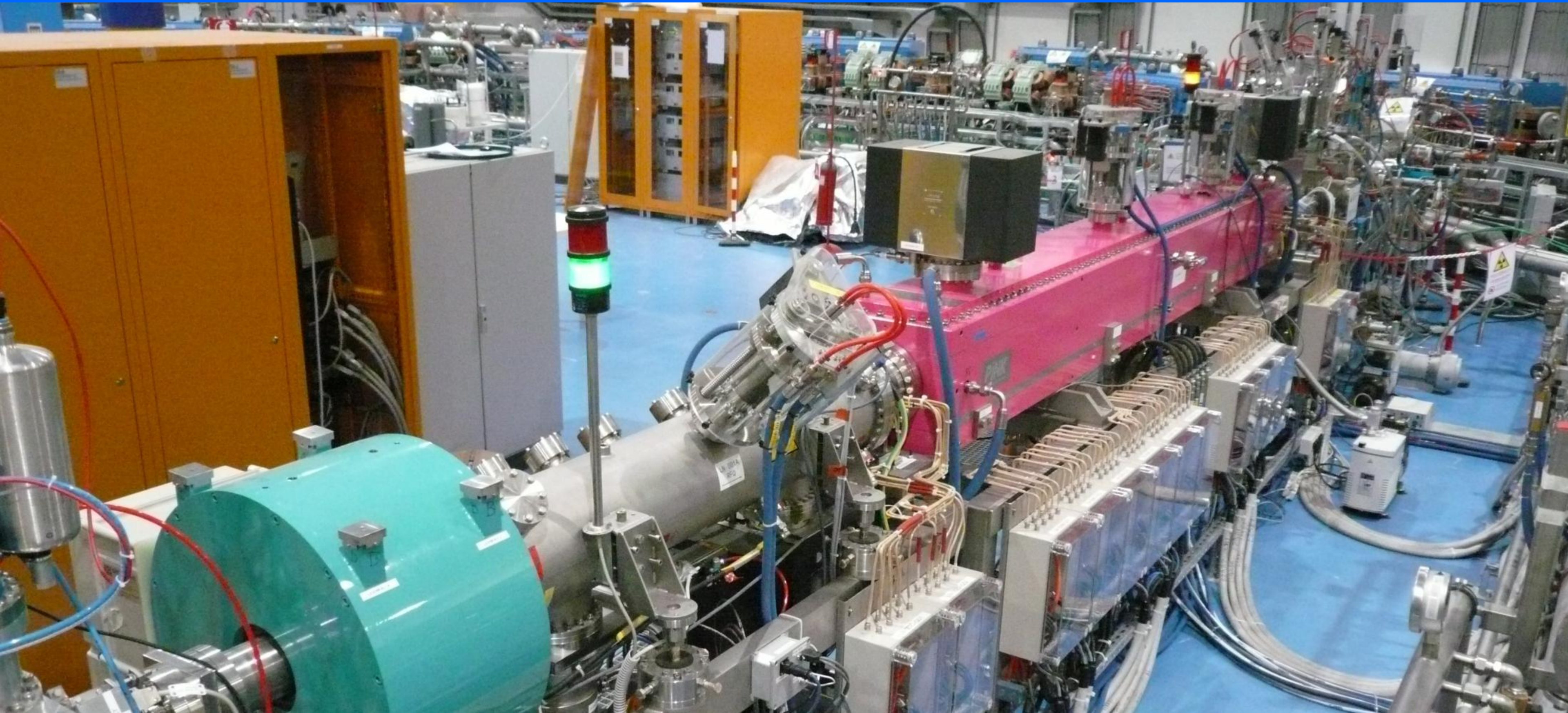


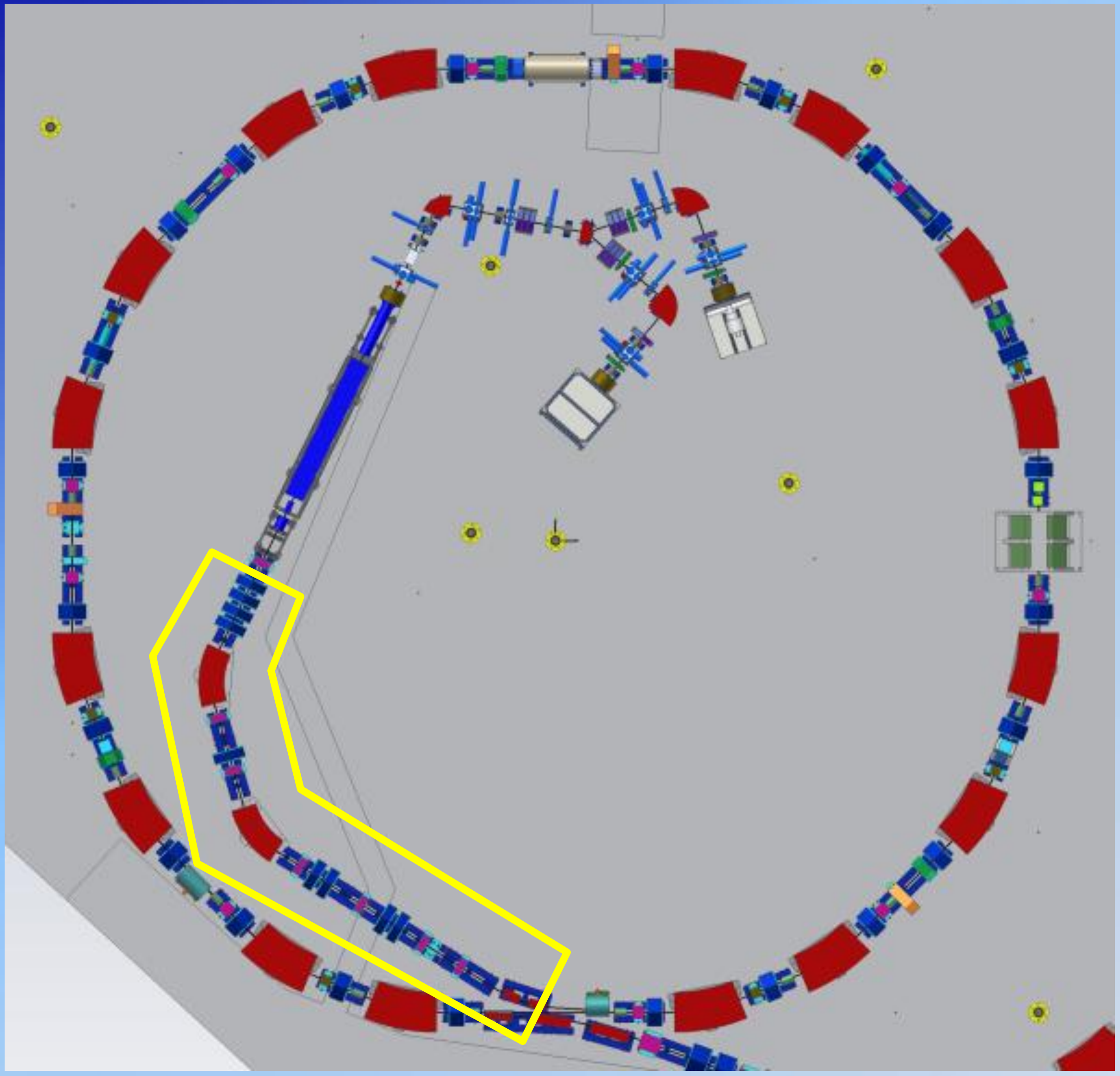
- Per chiedere un set up diverso dell'acceleratore basta solo il numero del set up (VACC) da mandare alle DCUs con i valori di tutti i magneti
- Ci sono poi interfacce diverse per controllare i valori attuati e per fare misure

Linac commissioning

Request at LINAC exit	measured	nominal
current for C6+ (7 MeV/u)	135 microA	120 microA
current for H+ (7 MeV)	1.2 mA	0.75 mA

Successfully commissioned in July 2009





MEBT

7 MeV p
7 MeV/u C^{6+}

I ~ 0.75 mA (p)
I ~ 0.12 mA (C^{6+})

Stripping foil

Current selection

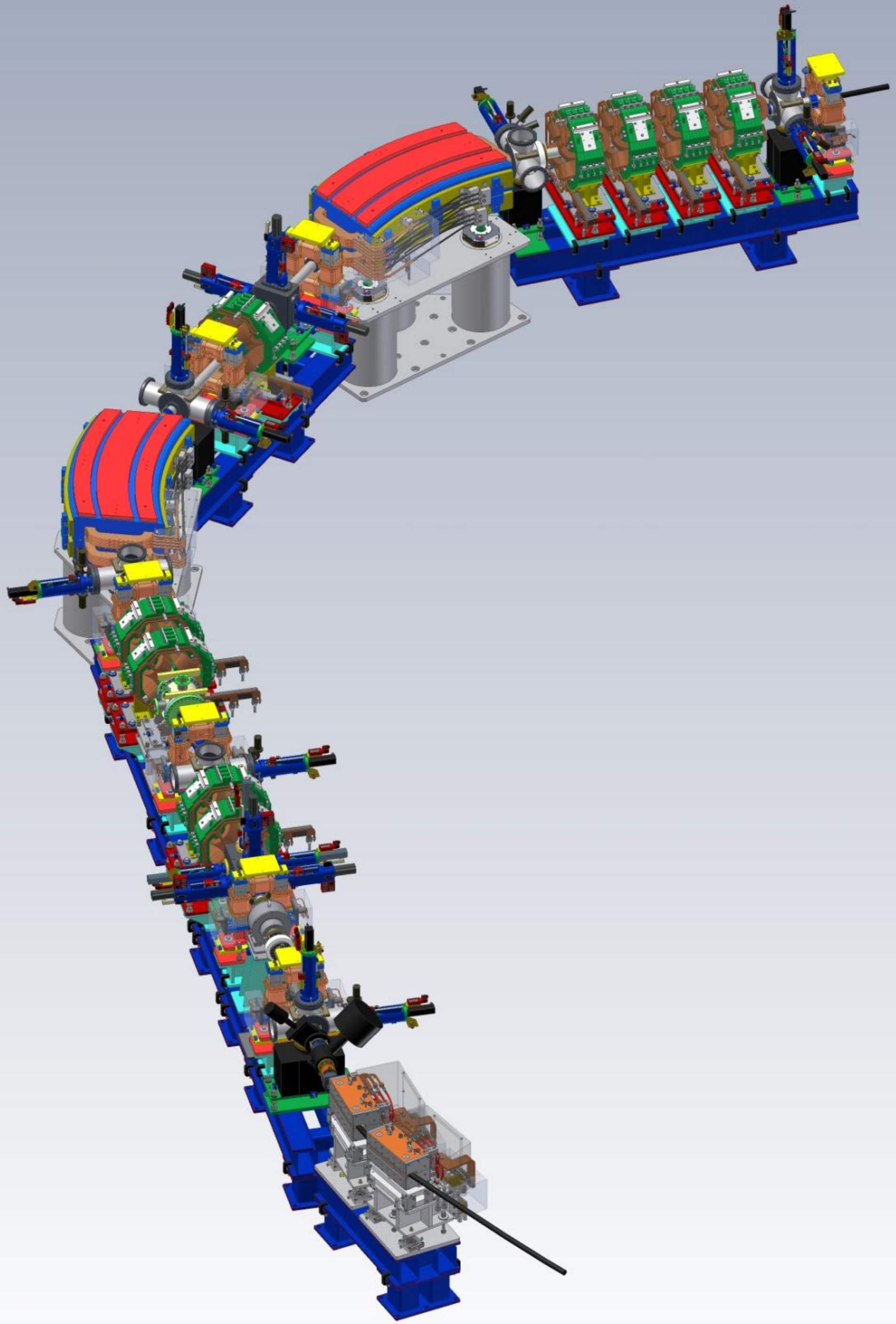
Debuncher

Emittance dilution

Match betas

$(x,x')_{Inj}$

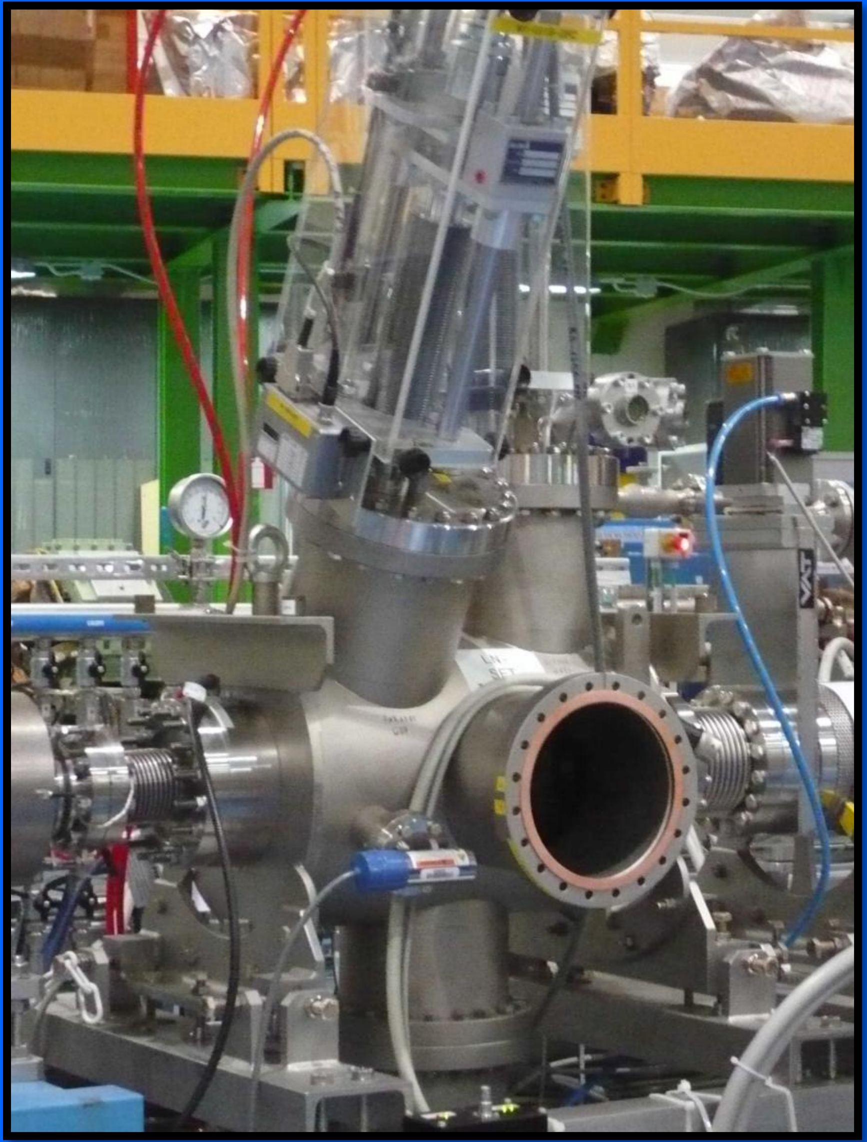
Layout MEBT



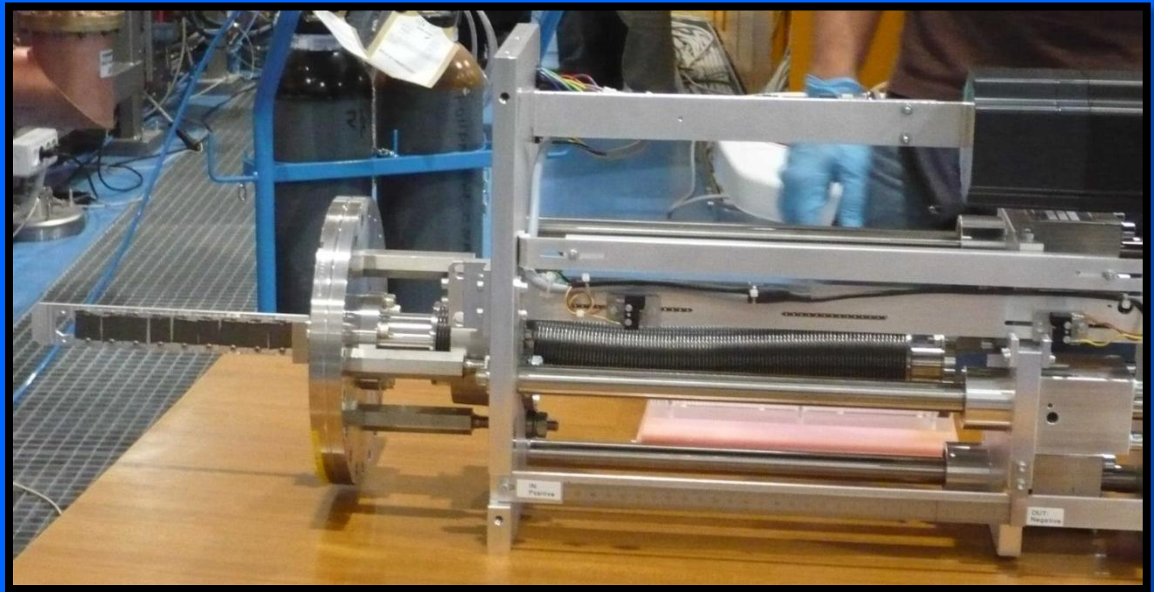
Stripper foil tank

Tutte le strutture RF sono disegnate per una frequenza di risonanza pari a 216.816 MHz e per rapporti massa su carica: A/q < 3 ($^{12}C^{4+}$, H^{3+}, $^{3}He^{+}$, $^{16}O^{6+}$).

Per togliere gli elettroni rimanenti prima di iniettare gli ioni nel sincrotrone, un sottile stripper foil di carbonio è posizionato a circa 1 m dopo il DTL.

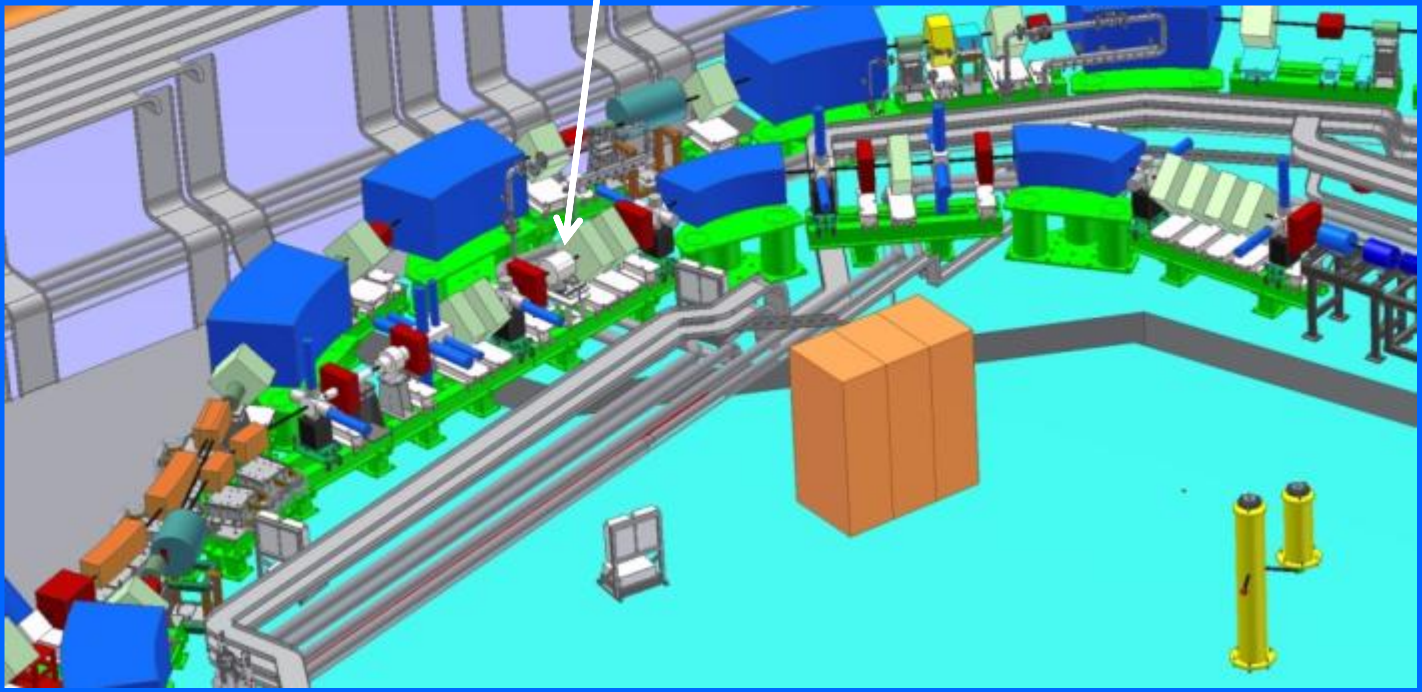


Carbon foils



Positions:	10
Foil material:	Carbon
Foil thickness:	100-200 µg/cm²
Foil diameter:	15 mm
Beam diameter:	5 mm
Position accuracy:	±0,5 mm

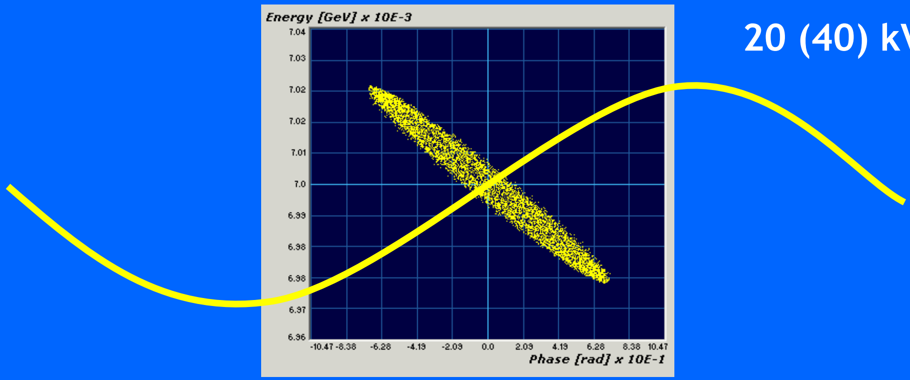
Debuncher to minimize the injected beam momentum spread



Il Debuncher

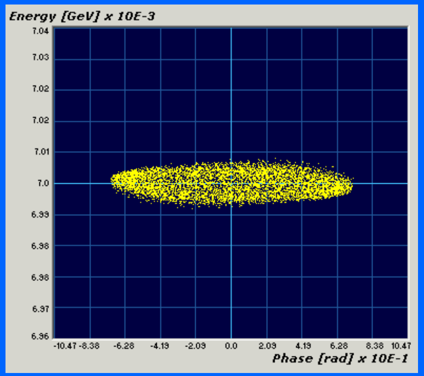
- È un acceleratore a 2 gap che riduce la dispersione in termini di momento (da 0.2% a 0.1%)
- La frequenza di risonanza è tunata da un RF plunger mobile montato in cima.

Debuncher

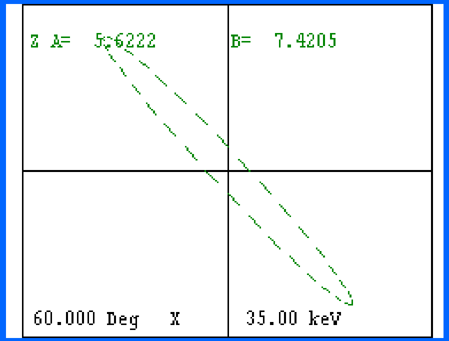


20 (40) kV/gap

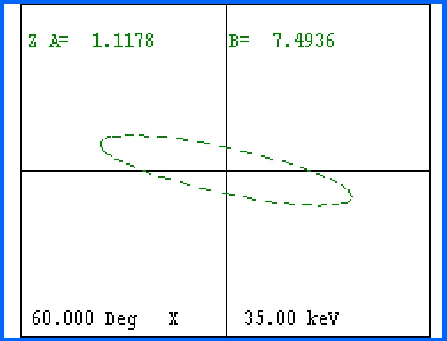
PATH computation of the beam (p 0.75 mA) in the longitudinal phase space before the debuncher



PATH computation of the beam (p 0.75 mA) in the longitudinal phase space after the debuncher



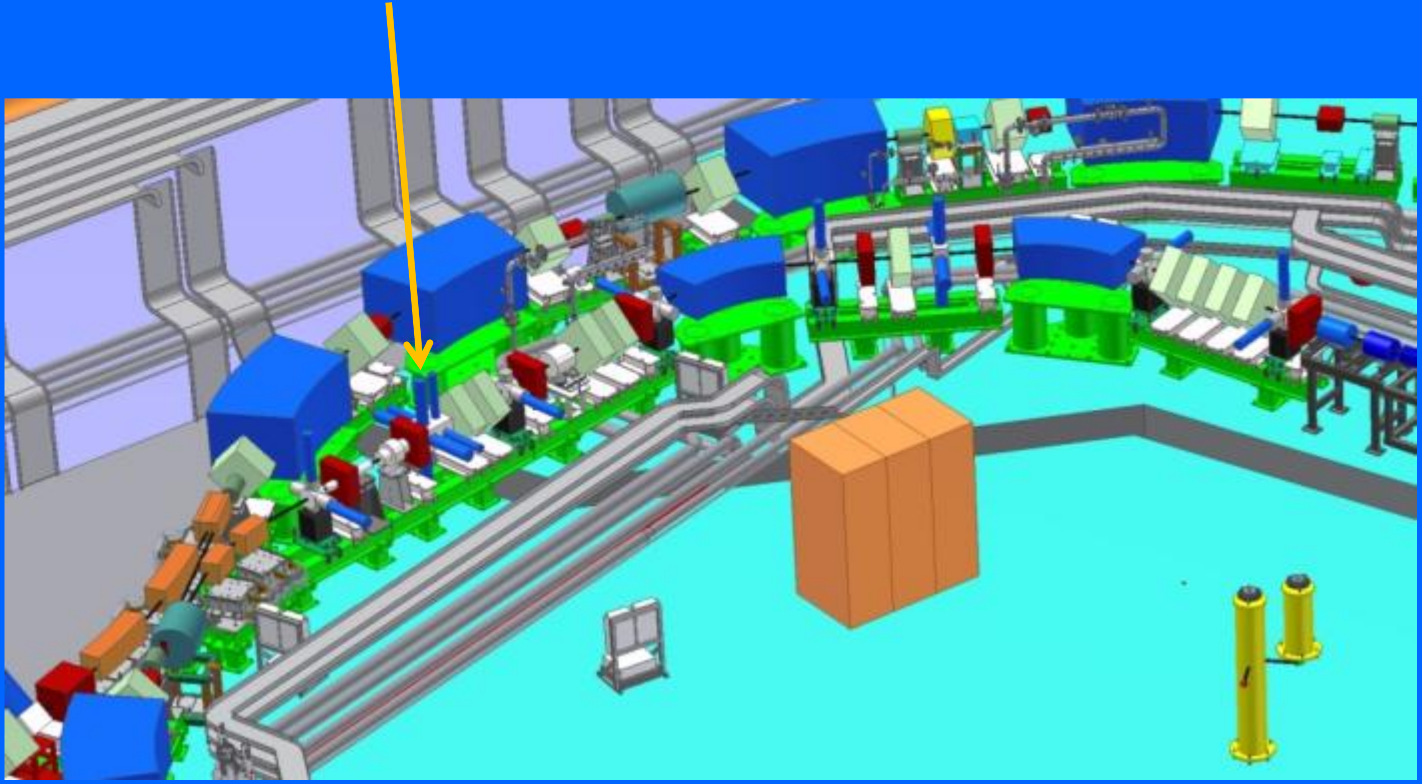
TRACE 3D computation of the beam (p 0.75 mA) in the longitudinal phase space before the debuncher



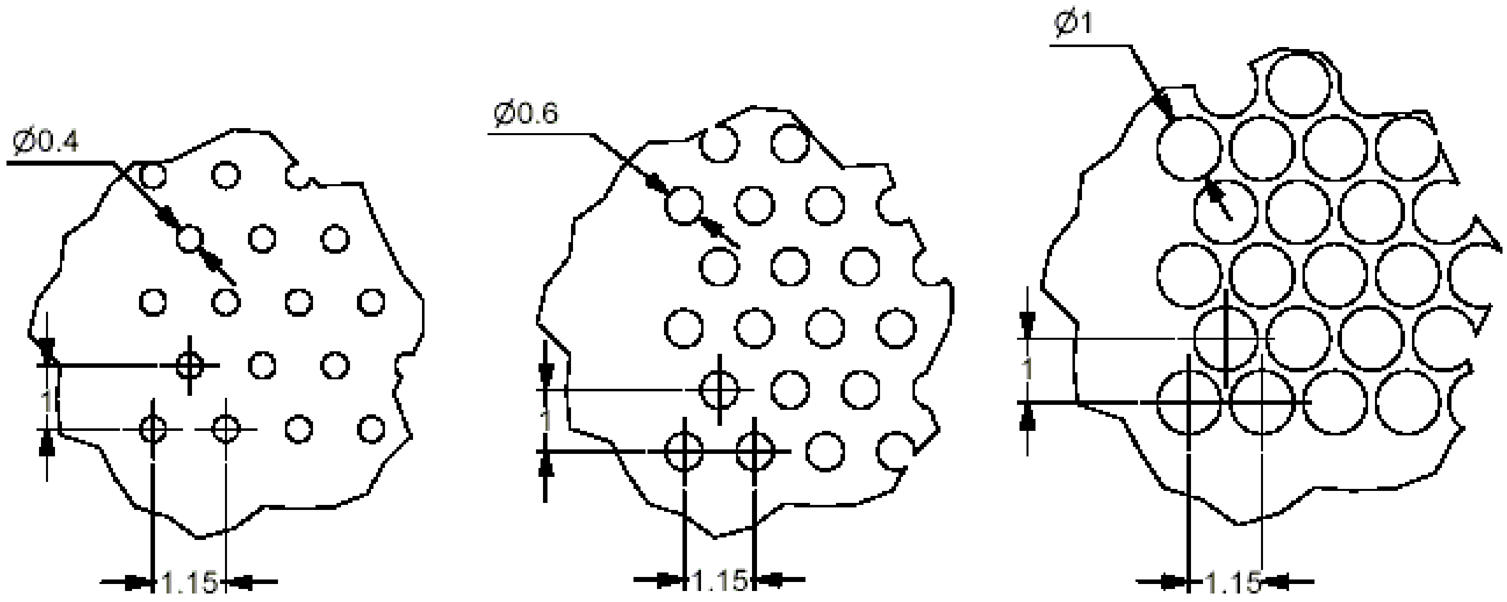
TRACE 3D computation of the beam (p 0.75 mA) in the longitudinal phase space after the debuncher

Injected current selection

Intensity degrader



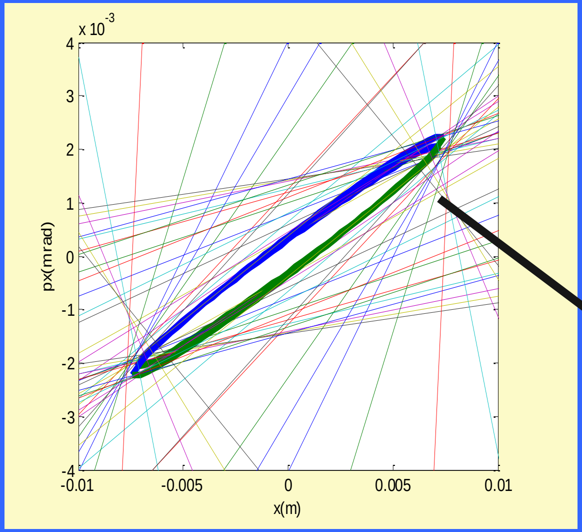
Intensity degrader

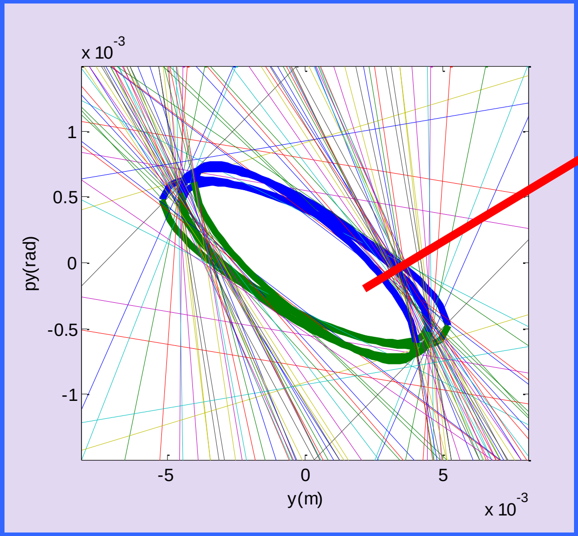


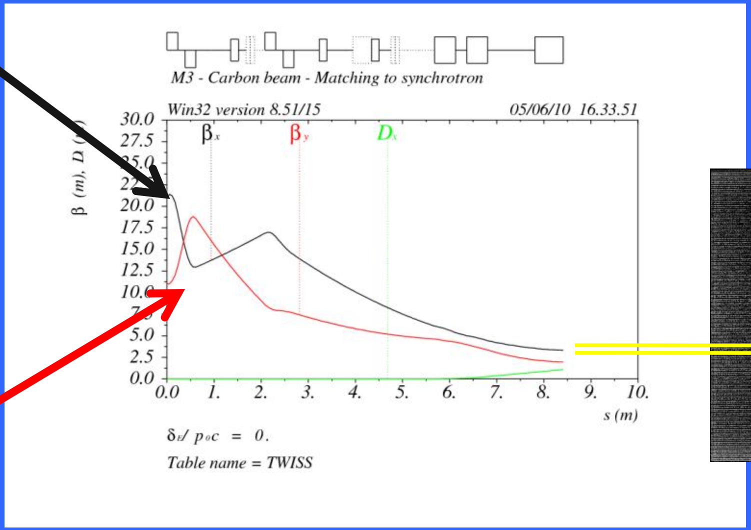
F10 Filter F20 Filter F50 Filter

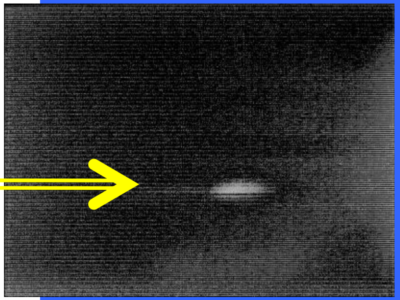
4 transmission levels: 100%, 50%, 20%, 10%
Keep overall emittance unchanged

Emittance measurements with Quad Scans used for beam optimisation at injection

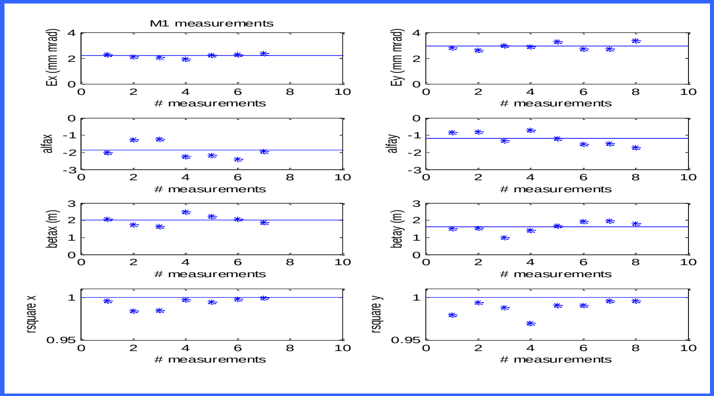








TVScreen in synchrotron



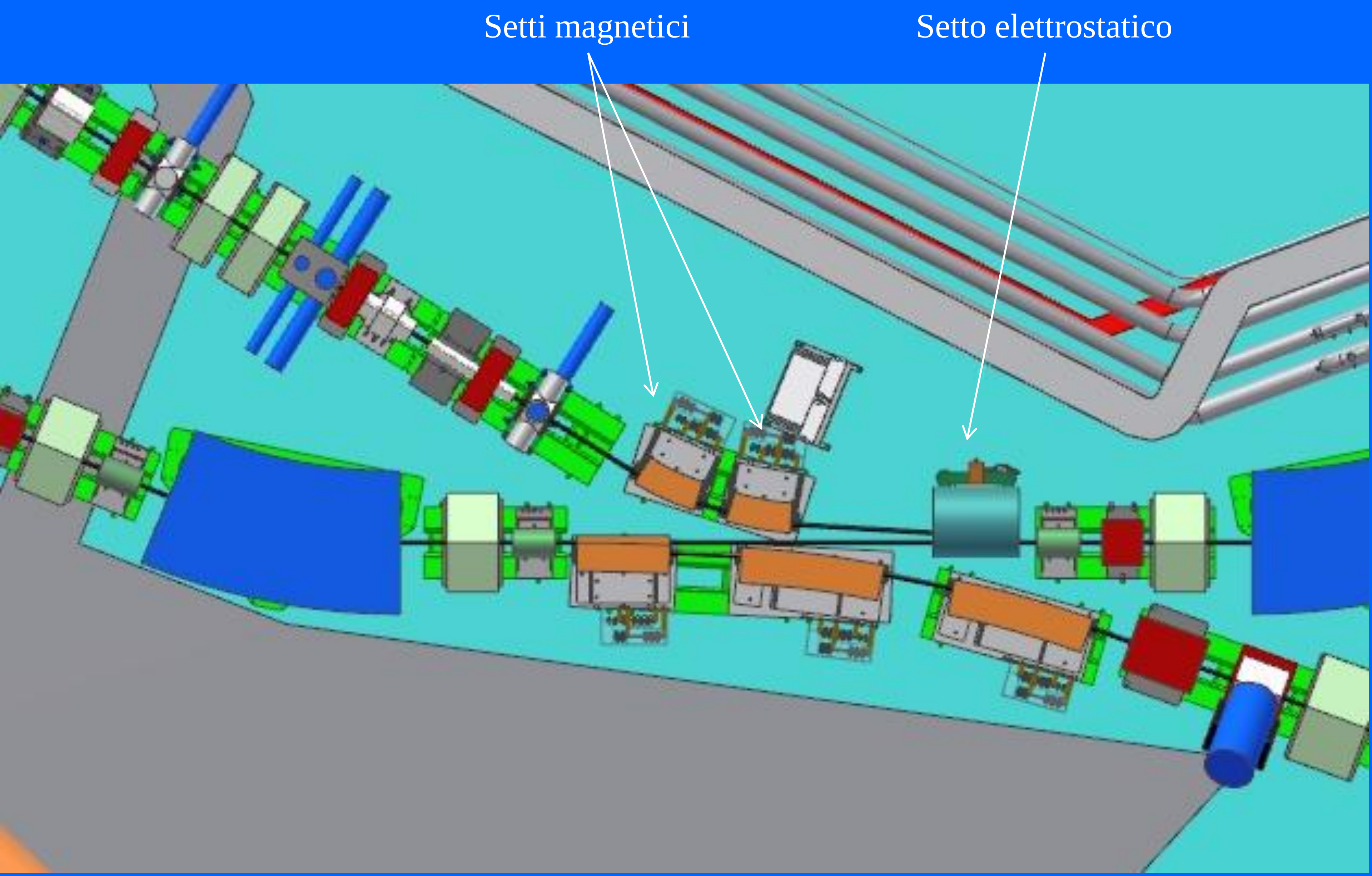
Different quad sets

Carbon beam
> 90 % transmission in MEBT

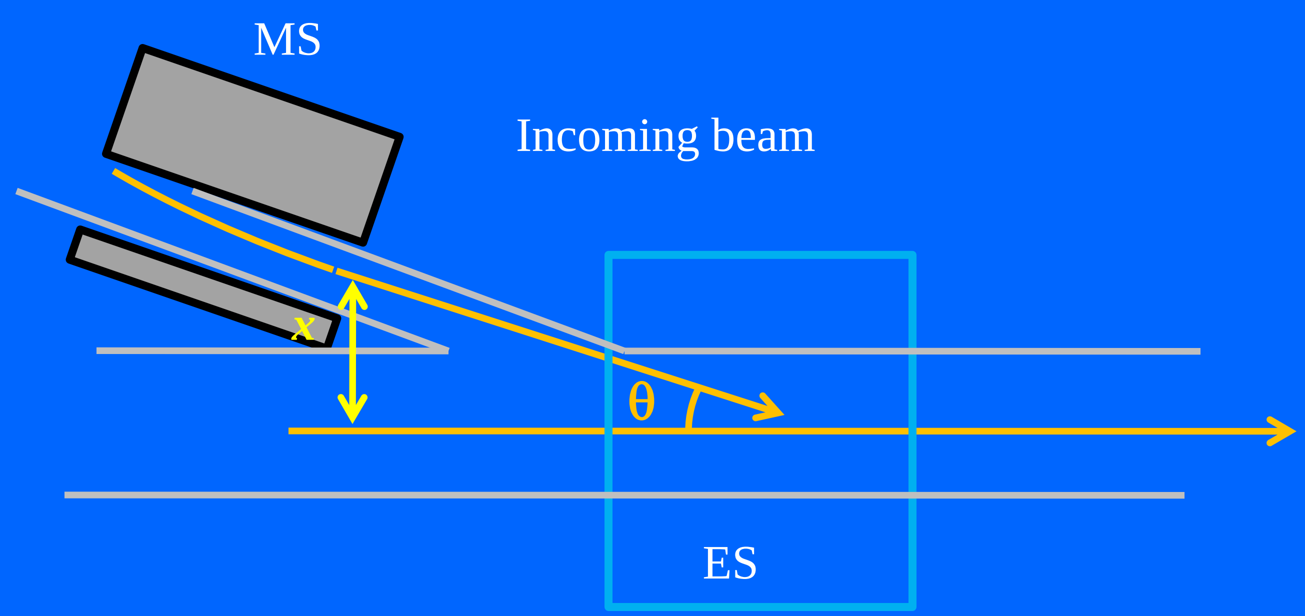
Dalla MEBT al sincrotrone

il processo di iniezione

Injection section layout



Position and angles

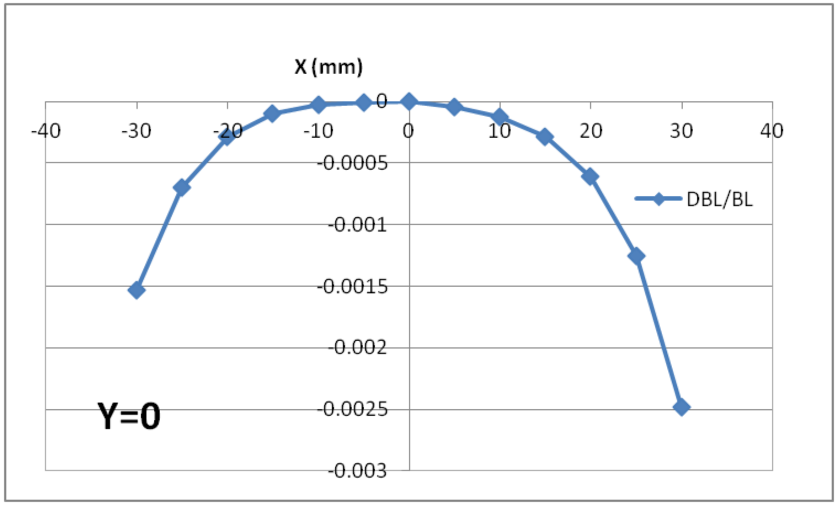


$$x = \sqrt{\beta_x}\left(\sqrt{\varepsilon_i} + \sqrt{\varepsilon_x}\right) + D_x\left(\left(\frac{\Delta p}{p}\right)_i + \left(\frac{\Delta p}{p}\right)_x\right) + x_{co} + x_s$$

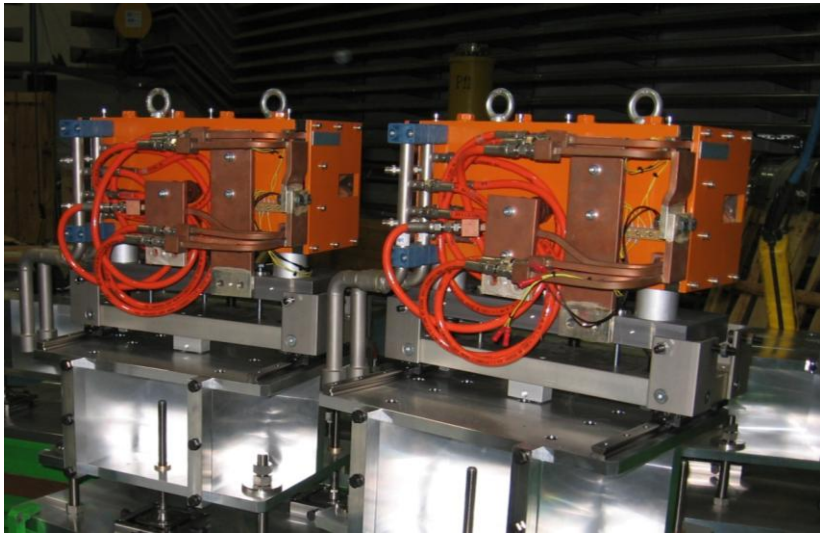
where $\pi\varepsilon_i$ and $\pi\varepsilon_x$ are the un-normalised horizontal emittances in the injected beam line and the ring respectively,
$(\Delta p / p)_i$ and $(\Delta p / p)_x$ are the momentum spread of the beam in the injection line and the ring respectively,
x_{co} is an allowance for closed-orbit deviations and clearances and
x_s is the effective thickness of the septum unit.

2 Injection Magnetic Septum

Design parameter	*Units*	*Value*
Deflection angle	[mrad]	250
Gap aperture	[mm]	80 (hor) ; 40 (vert)
Magnetic length	[m]	0.444
Resistance	[mΩ]	0.72
Inductance	[μH]	21.3
Cooling		Water
Nominal Current	[A]	3416
Nominal field	[T]	0.429
Good field region	[mm]	71 (hor); 40 (vert)
Field Quality	ΔBL/BL	$\pm 1\ 10^{-2}$

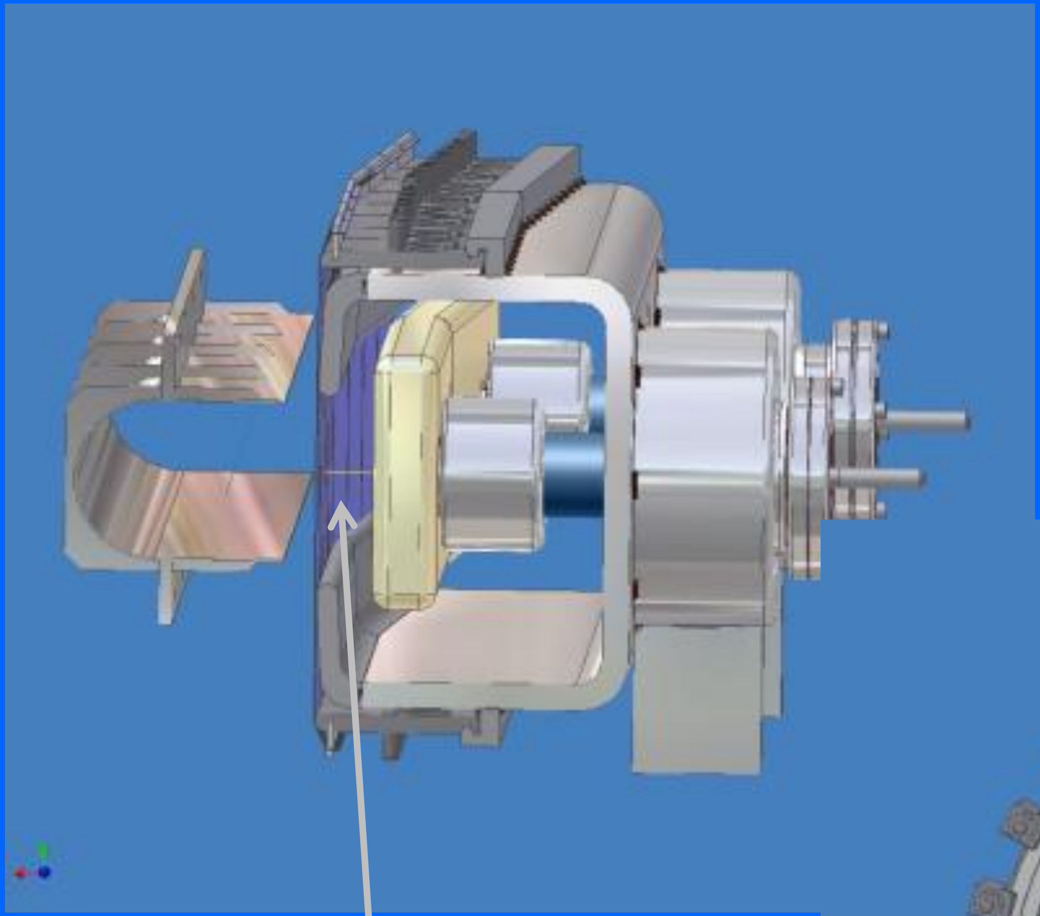


Measured Integrated Field Homogeneity at Nominal Current

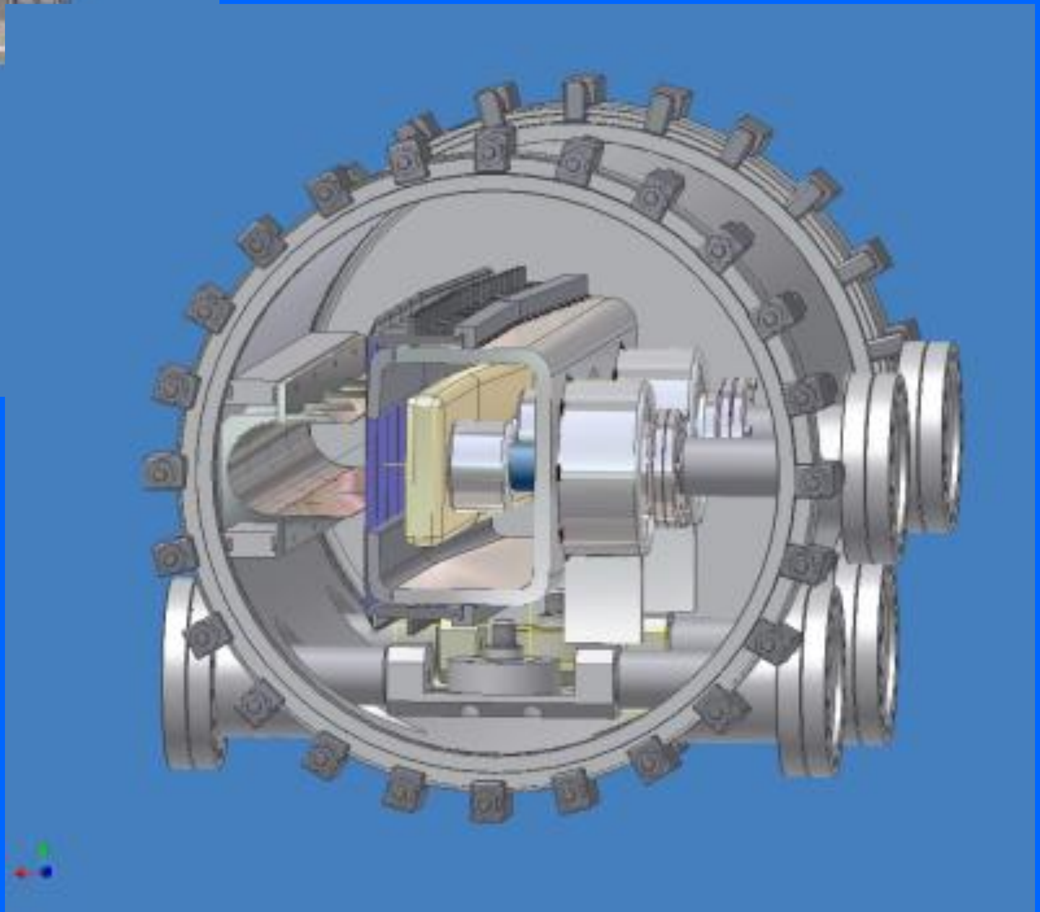


Electrostatic septum

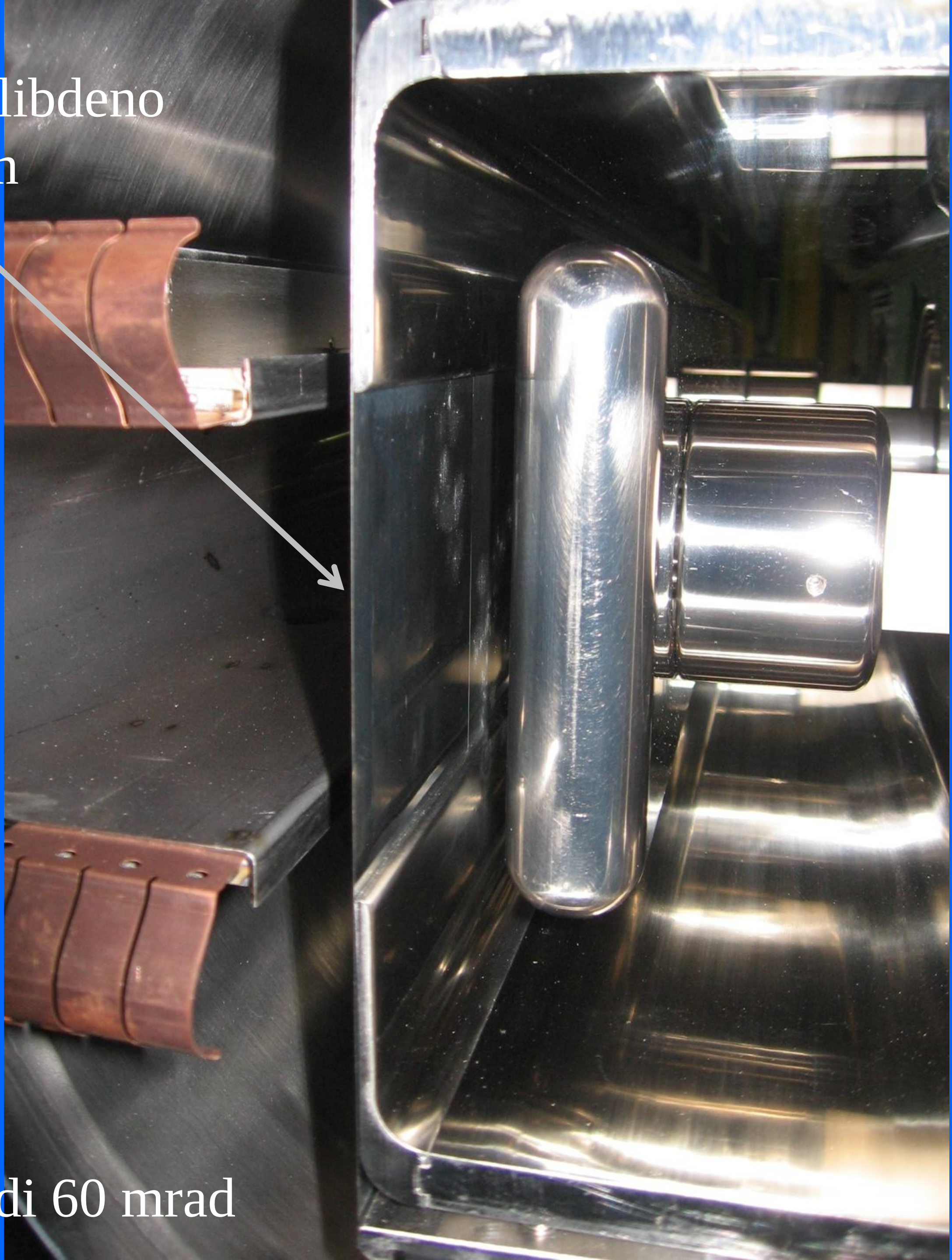
Thin, straight and aligned



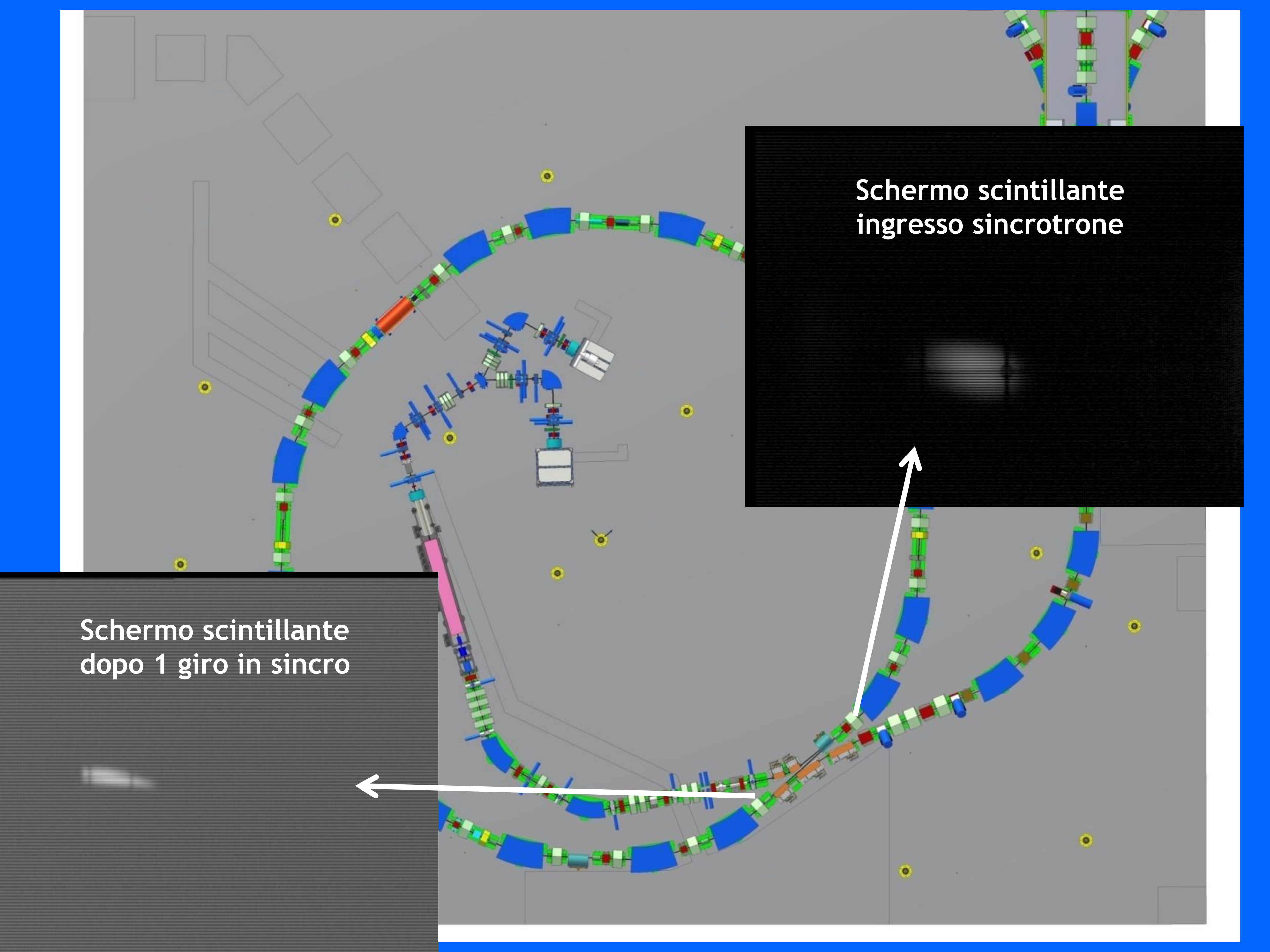
70 kV / 1.5 cm



Foglio di Molibdeno
0.1 mm

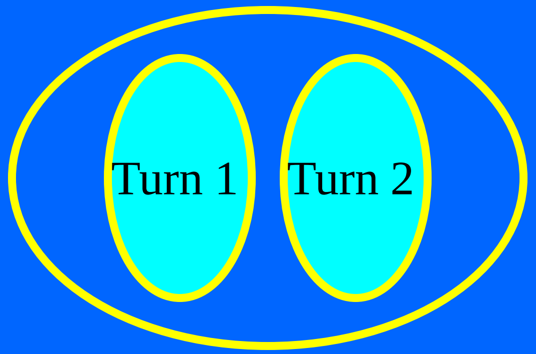


Deflessione di 60 mrad


Schermo scintillante
ingresso sincrotrone
Schermo scintillante
dopo 1 giro in sincro

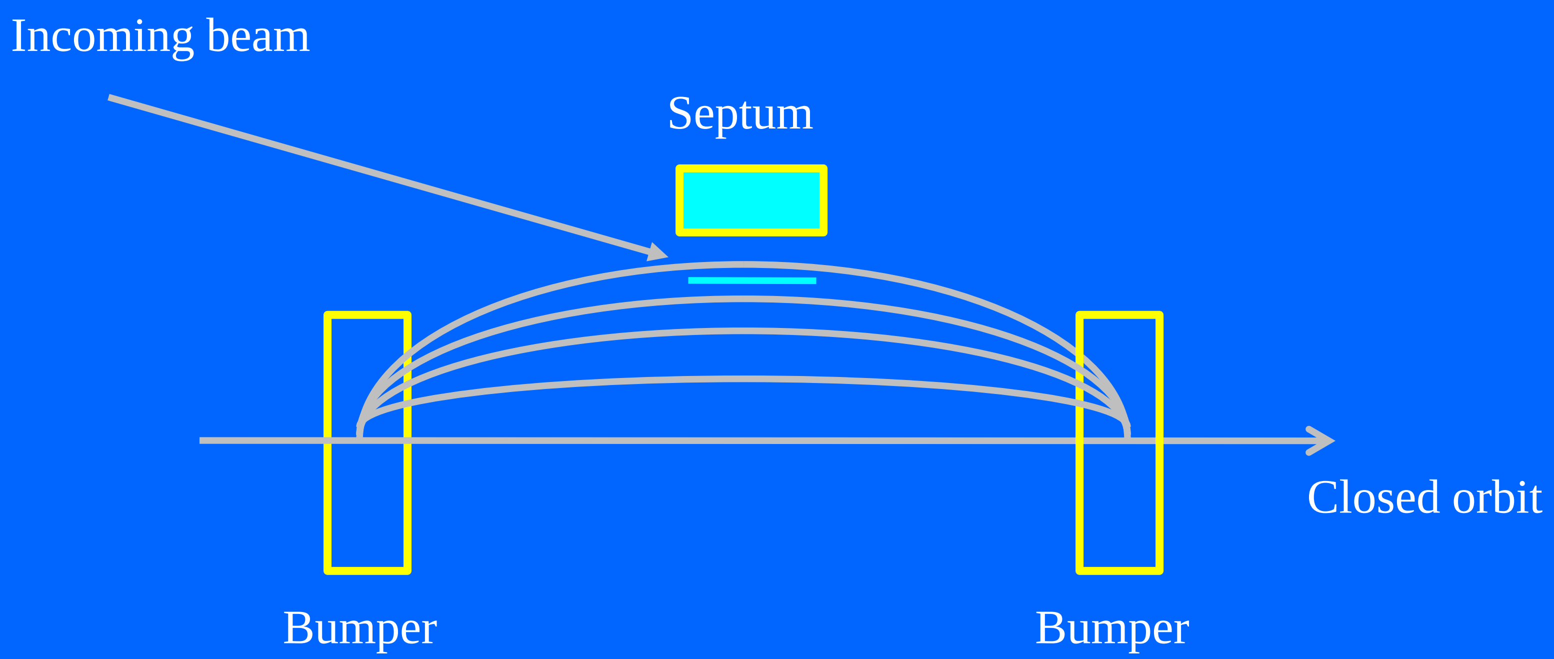
Multiturn Injection

- Sometimes the current is not enough... Then we want to insert charges for longer than one turn.
- We cannot beat Liouville, but we can stack beams one next to the other (increase emittance)



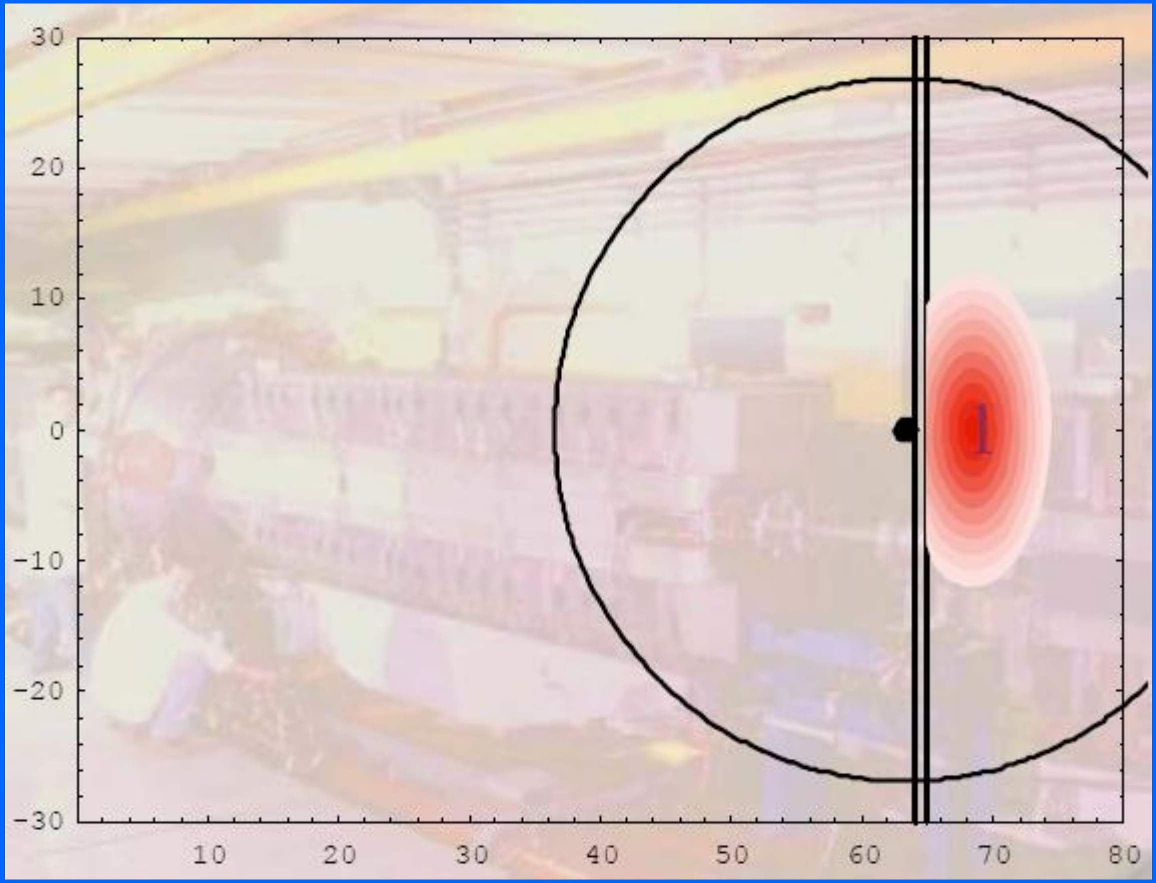
Multiturn injection

Create an orbit "bump"

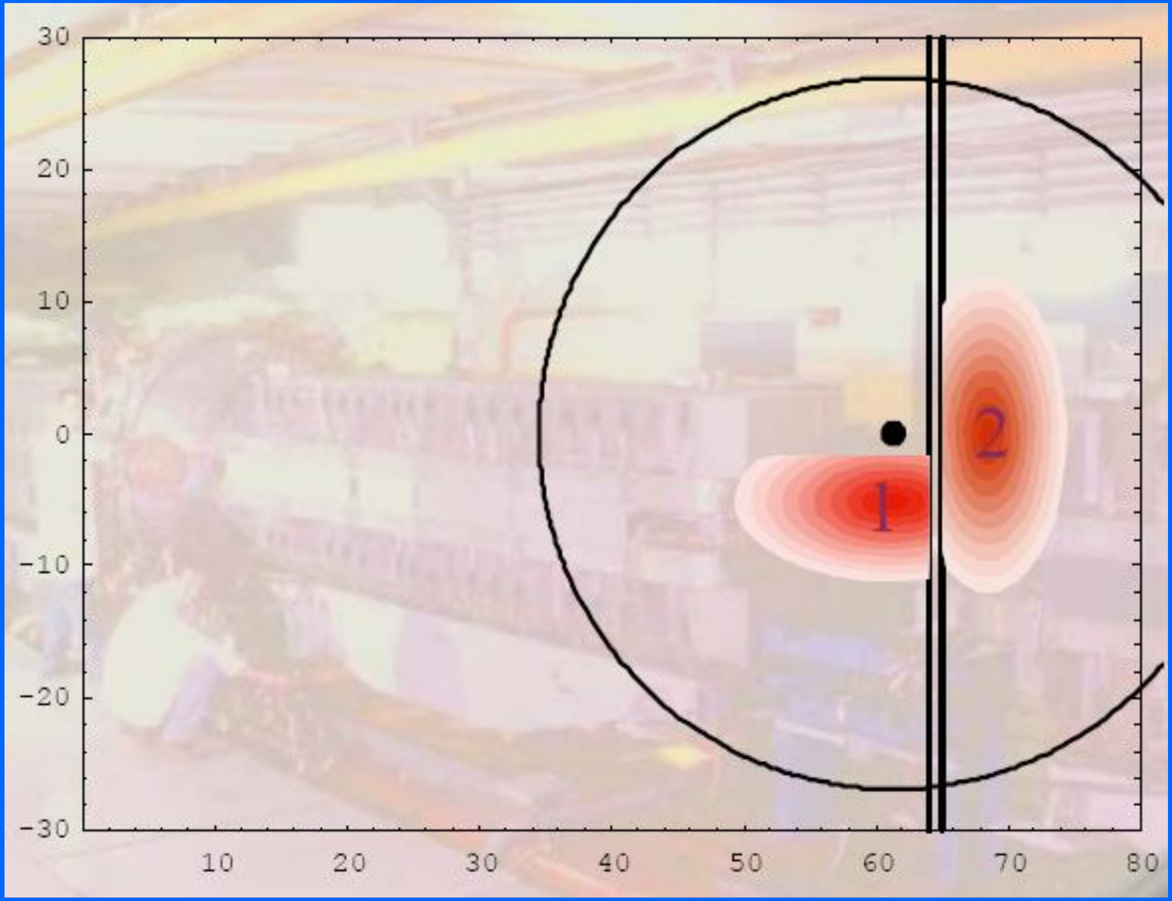


Generally there are 2, 3 or 4 bumpers.
The bump collapses in tens of turns

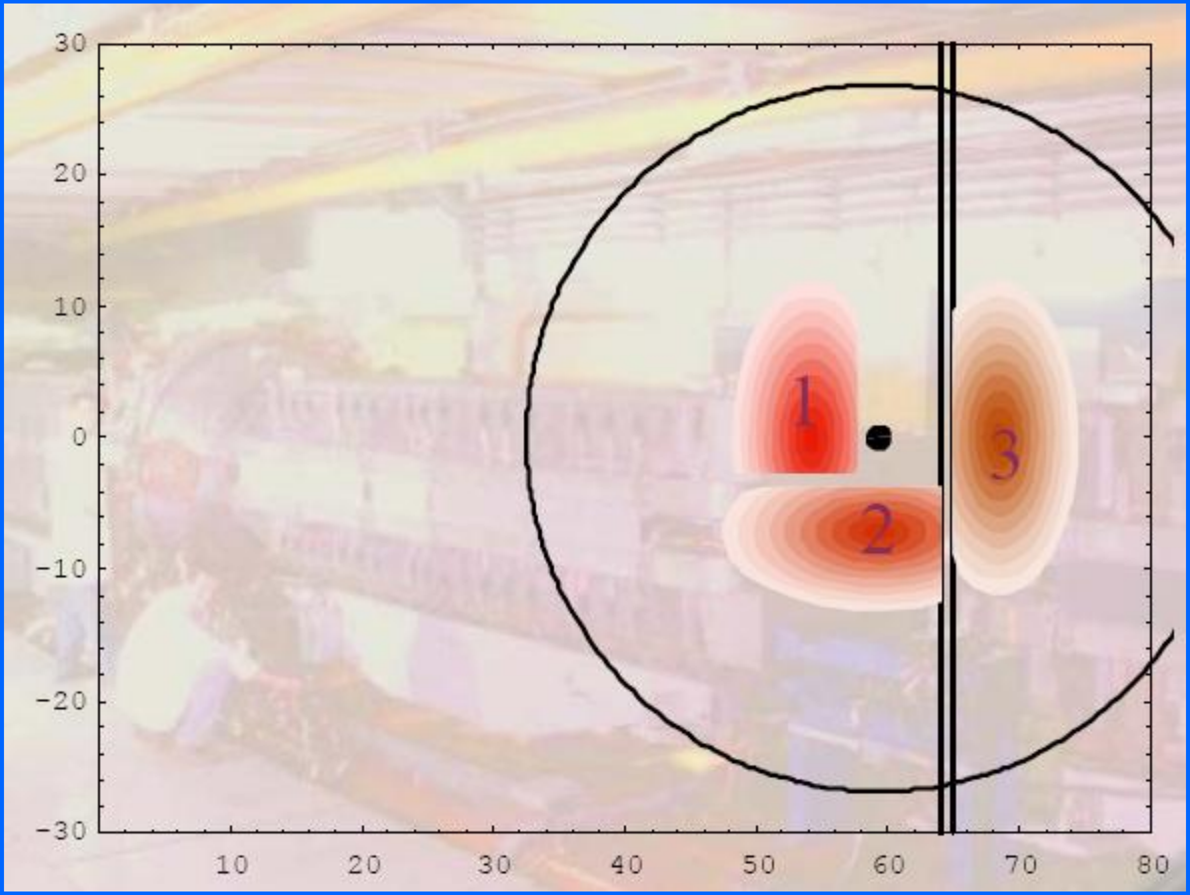
An animated view (courtesy of R. Steerenberg)



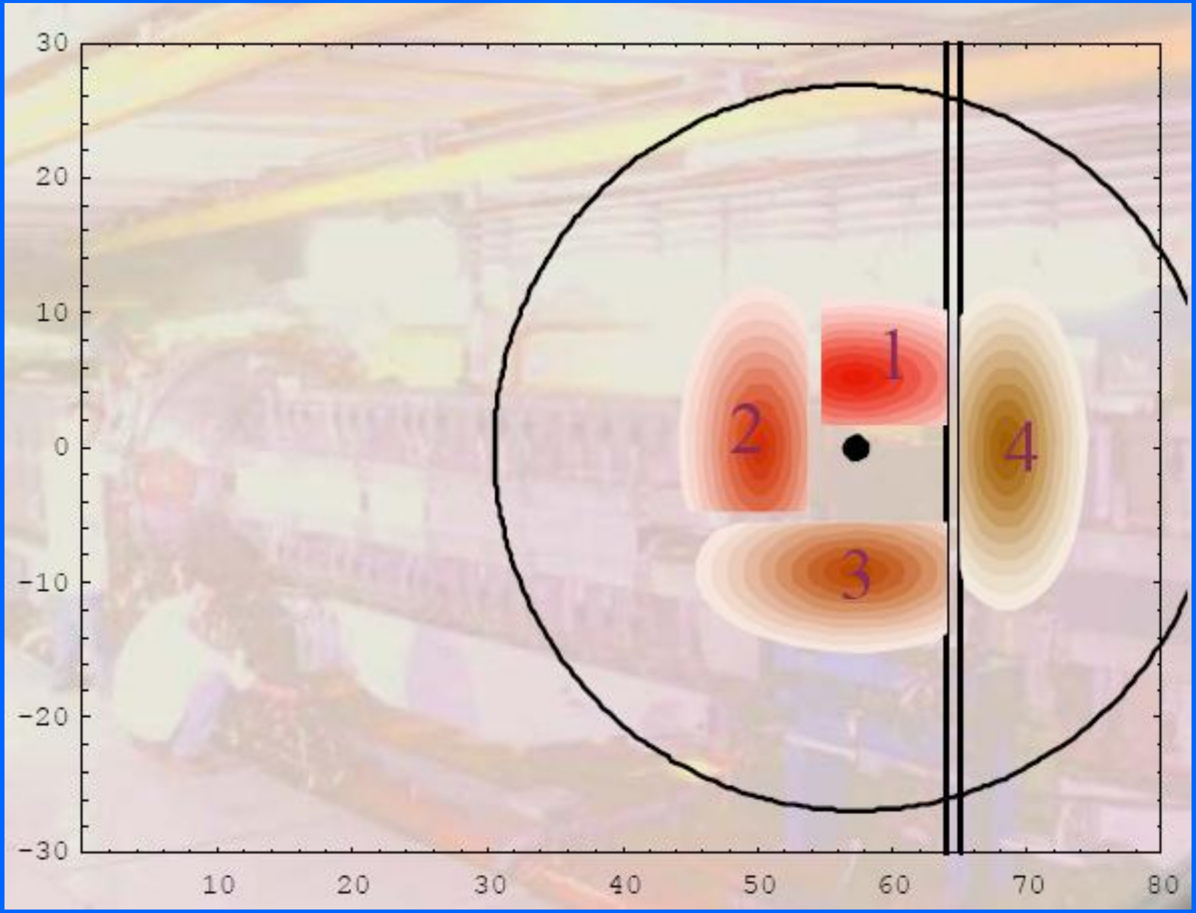
An animated view (courtesy of R. Steerenberg)



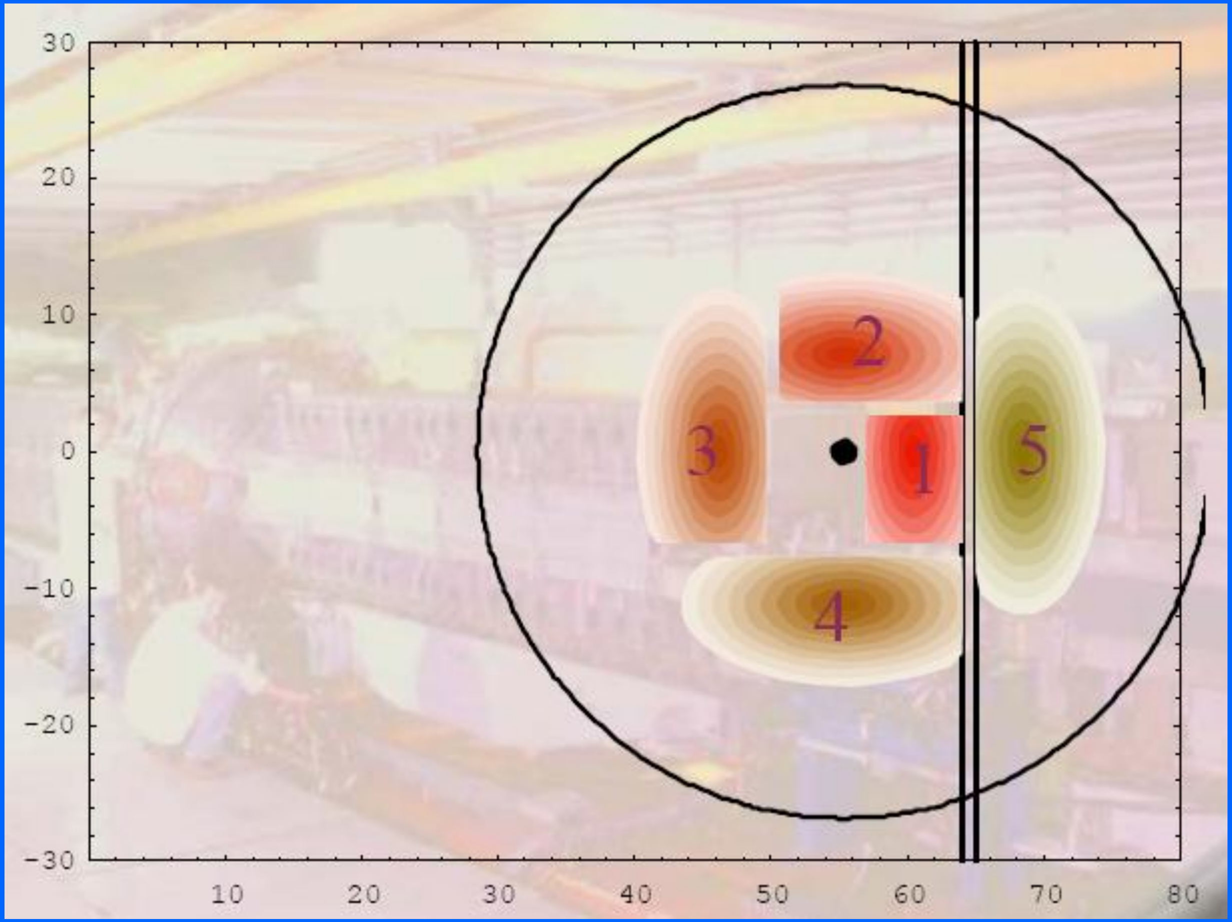
An animated view (courtesy of R. Steerenberg)



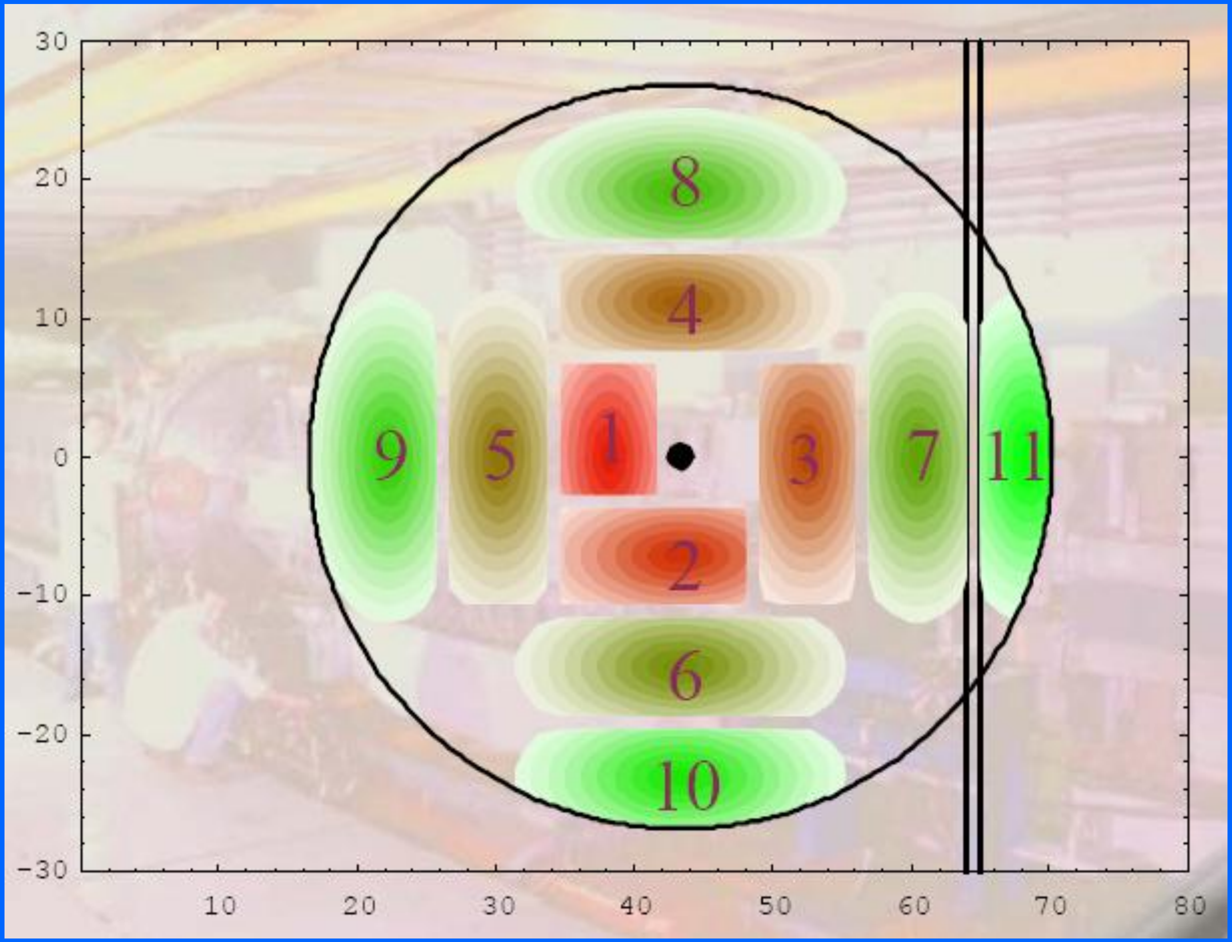
An animated view (courtesy of R. Steerenberg)



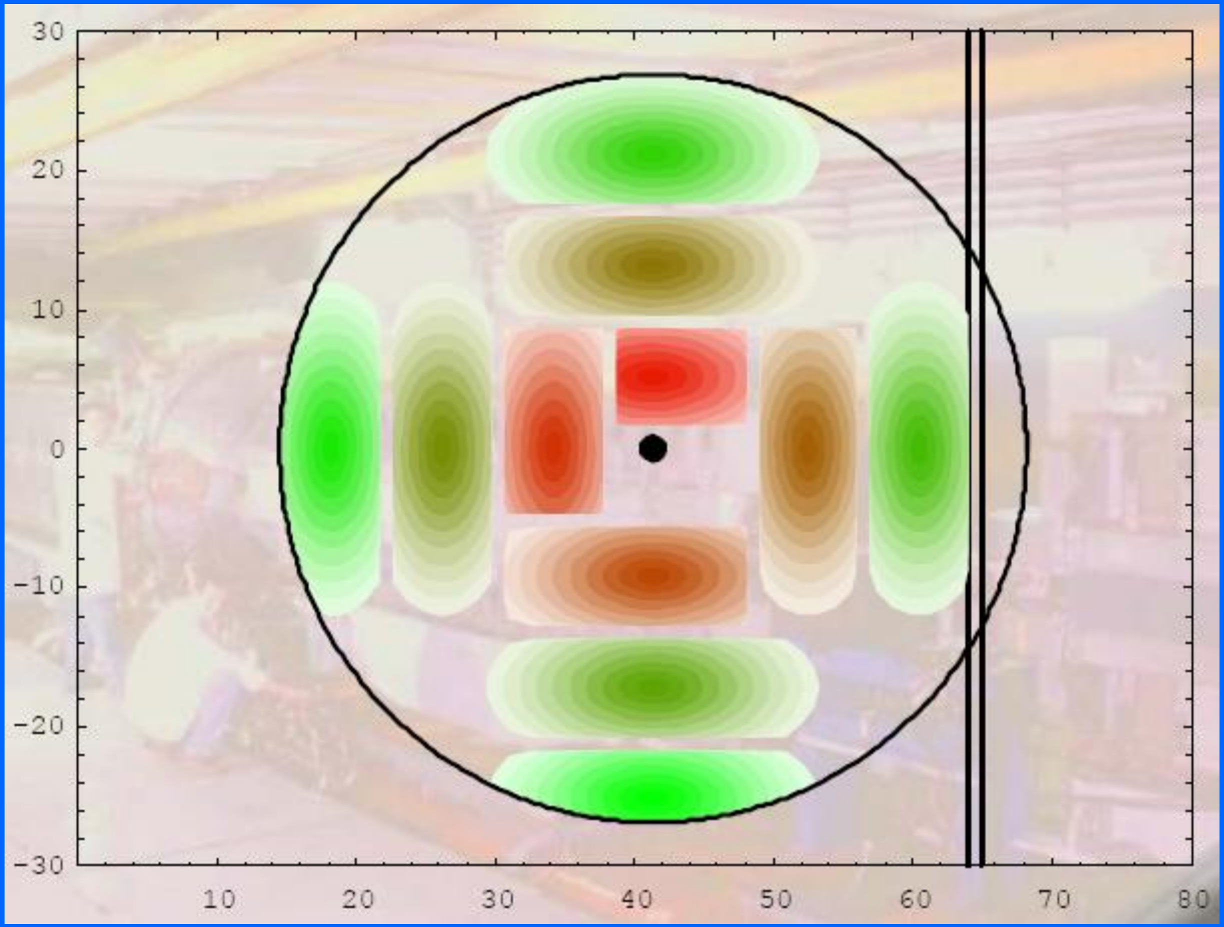
An animated view (courtesy of R. Steerenberg)



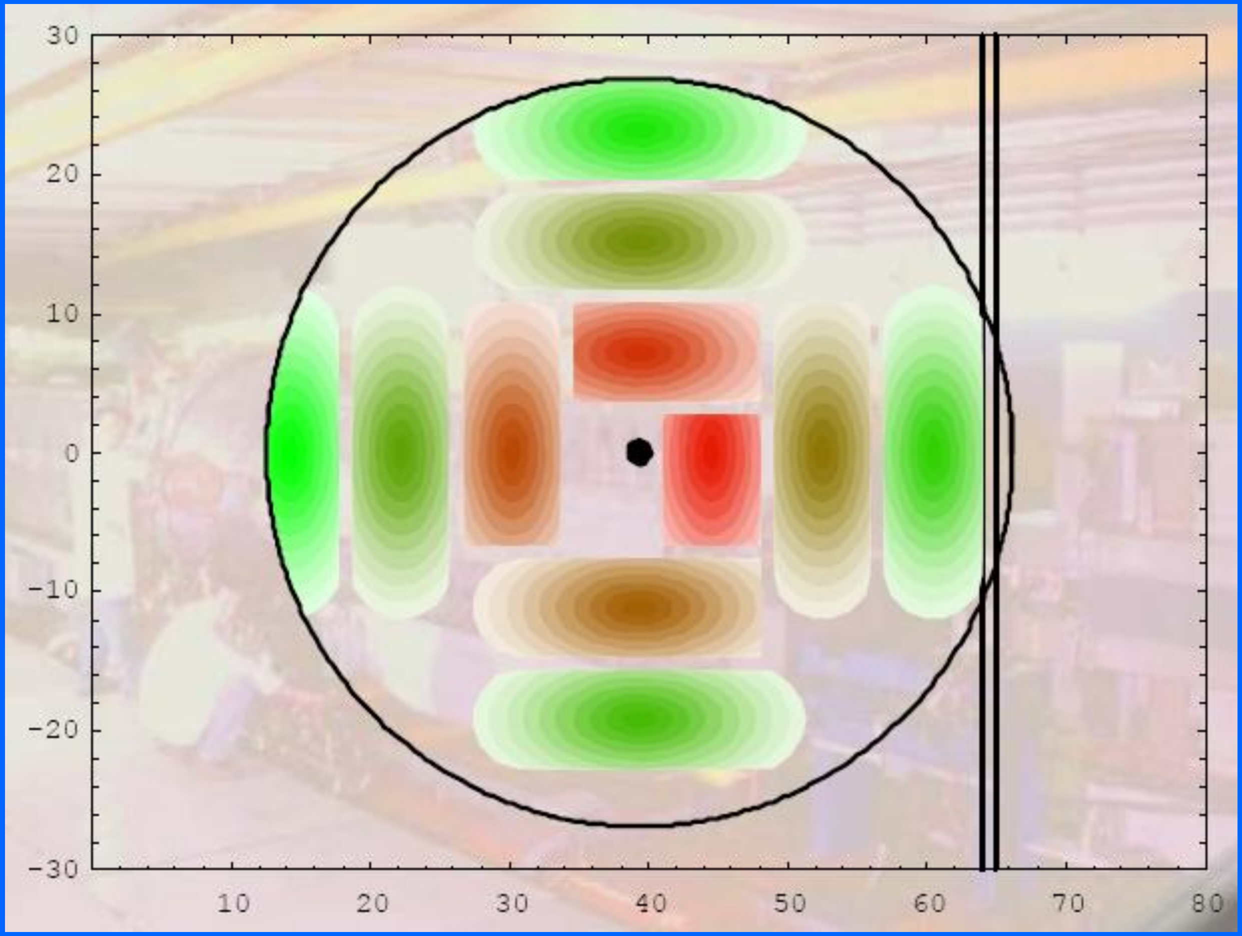
An animated view (courtesy of R. Steerenberg)



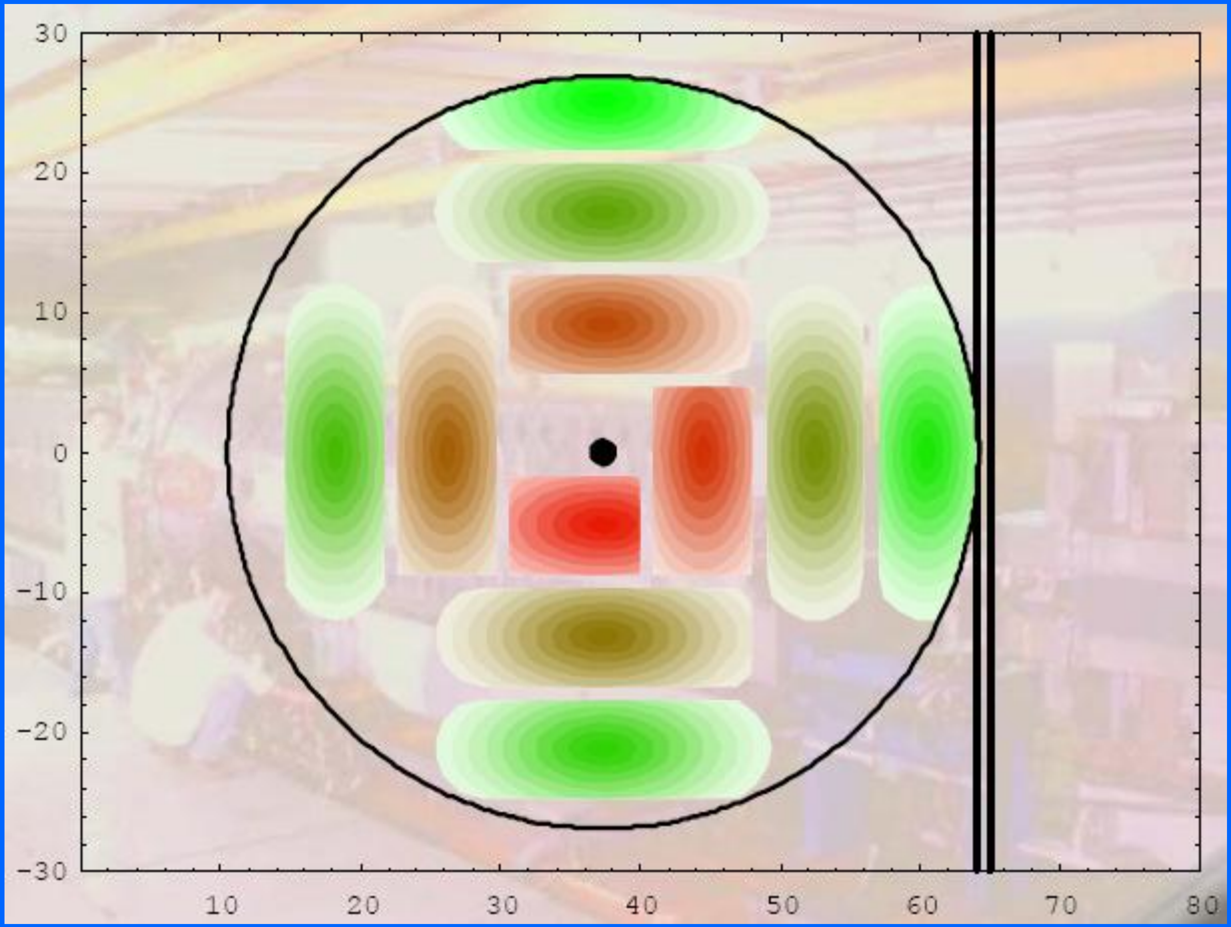
An animated view (courtesy of R. Steerenberg)



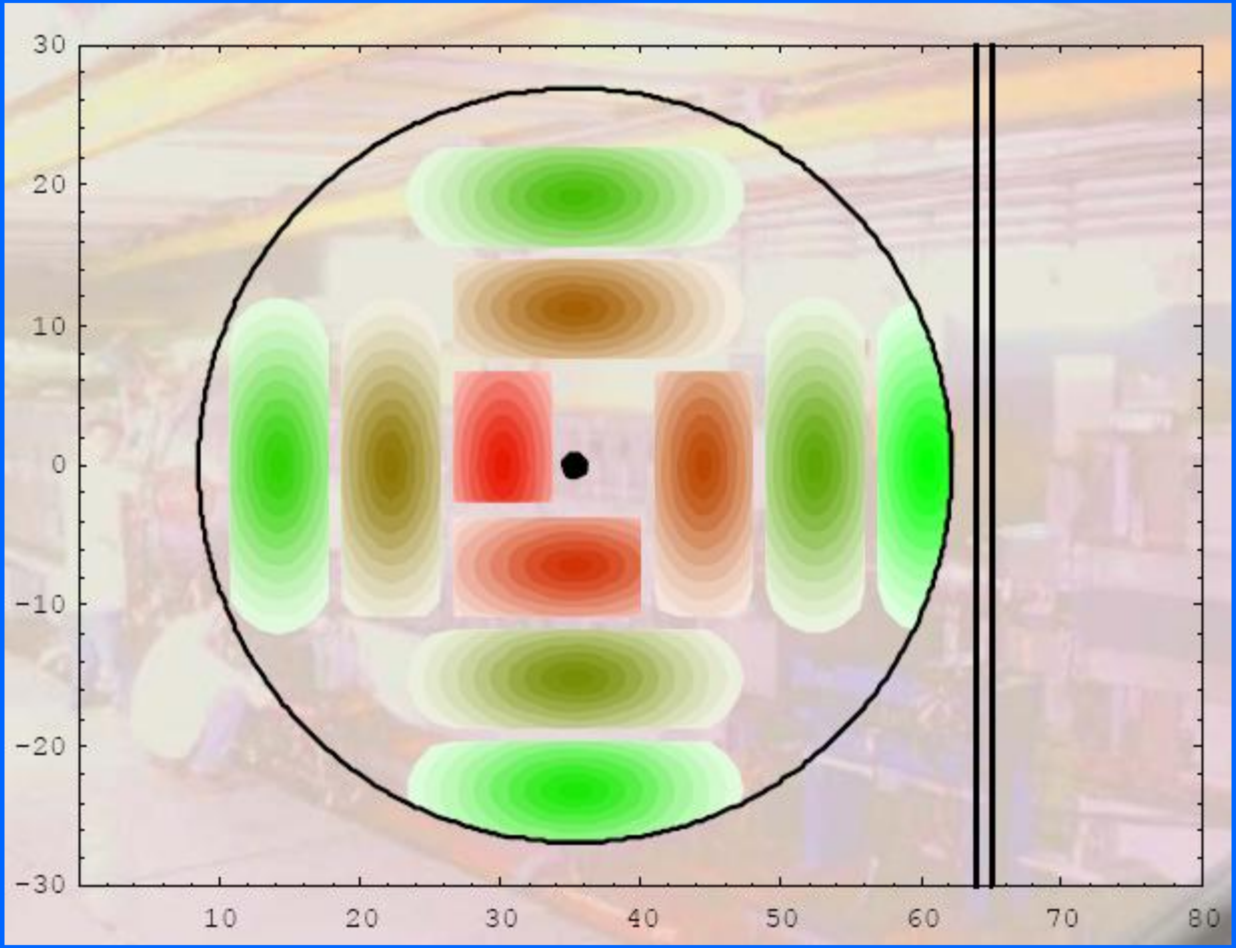
An animated view (courtesy of R. Steerenberg)



An animated view (courtesy of R. Steerenberg)



An animated view (courtesy of R. Steerenberg)

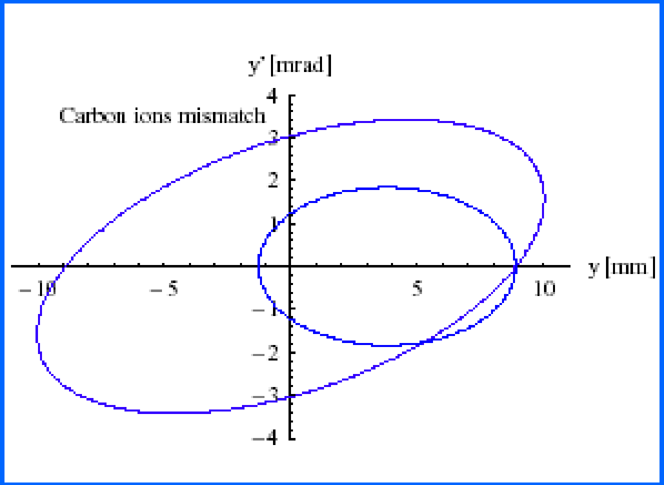


Injection

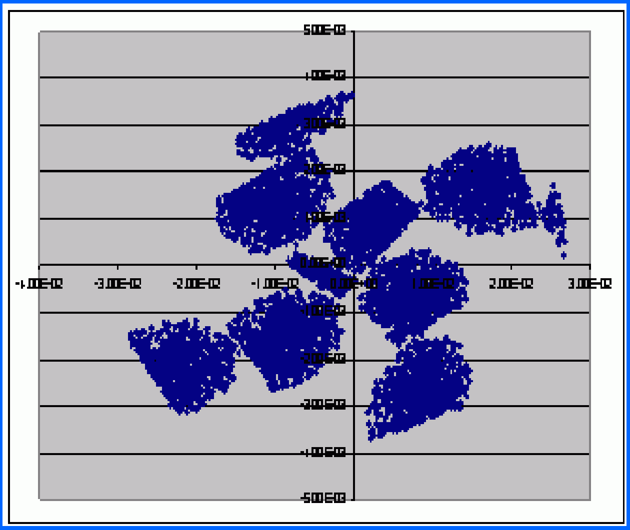
Protons = 1.9 (E_x/E_{linac}=2.3)

Carbon = 2.6 (E_x/E_{linac}=3.2)

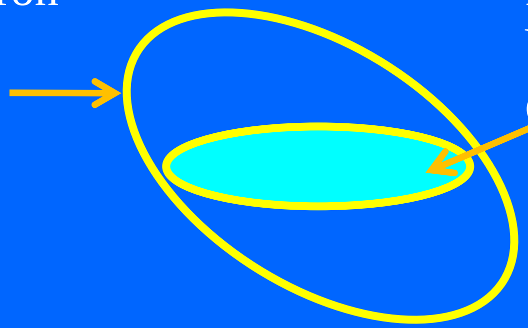
~30 μs bump duration

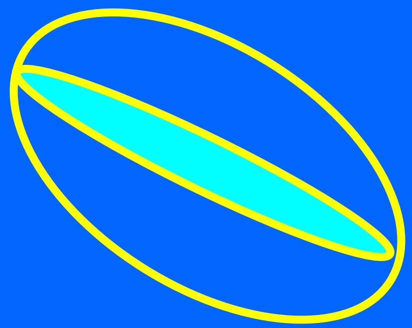


BDI BDI IMS

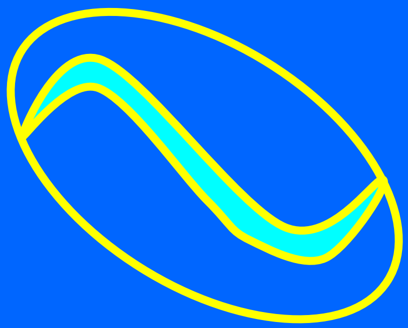


Beam matching at injection

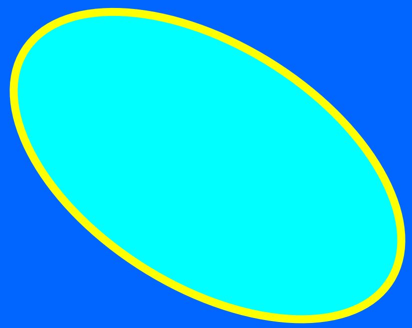




Initially just rotate
(emittance is conserved)

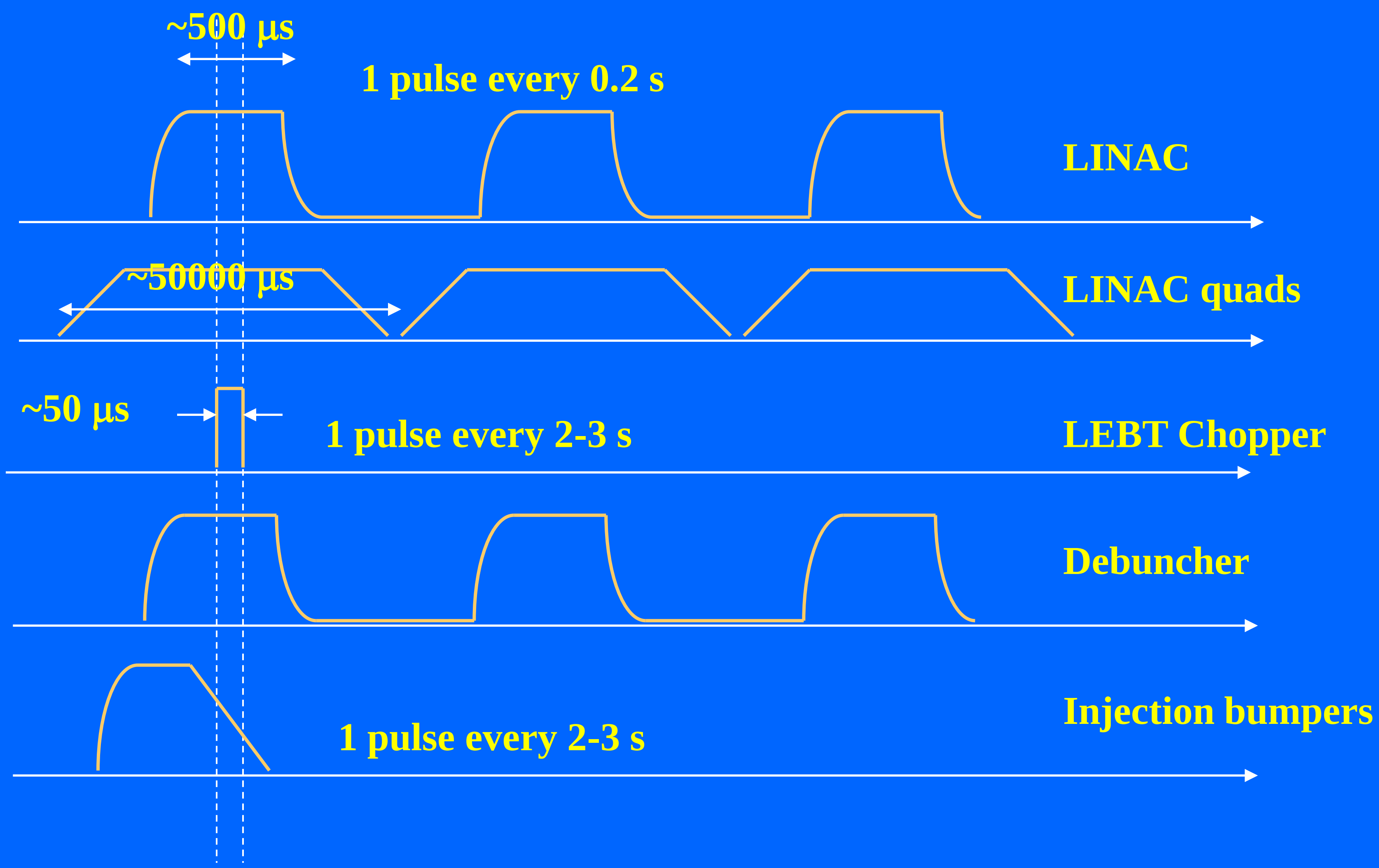


Nonlinearities distort beam ellipse.
Area is conserved

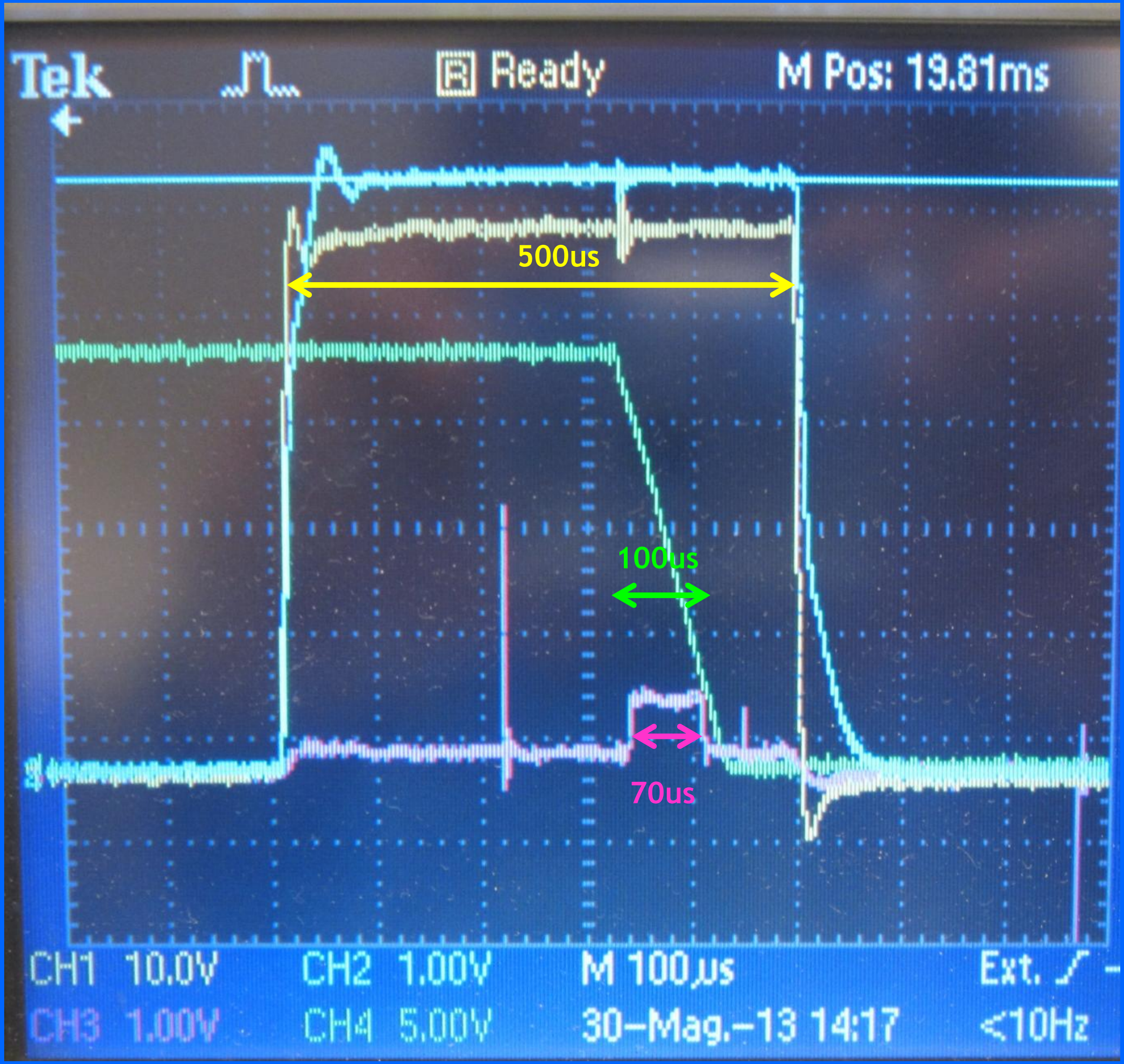


Filamentation is complete
Emittance has increased in practice

Injection in time



Timing dell'iniezione

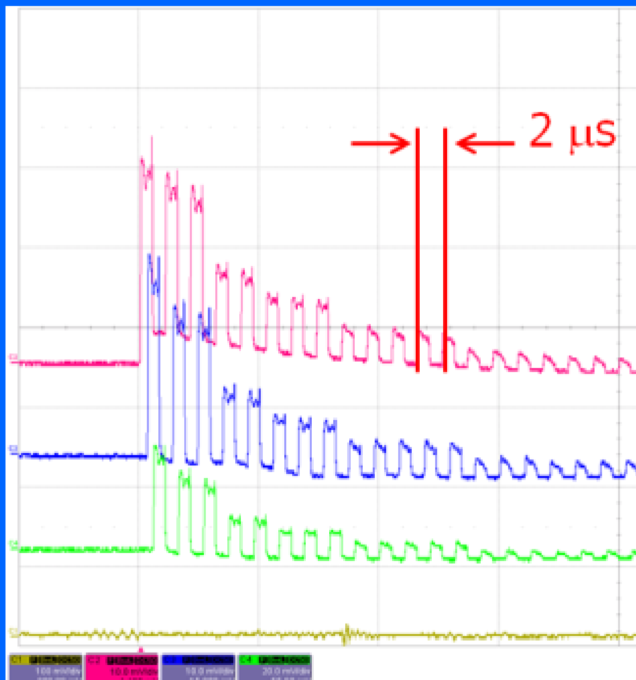


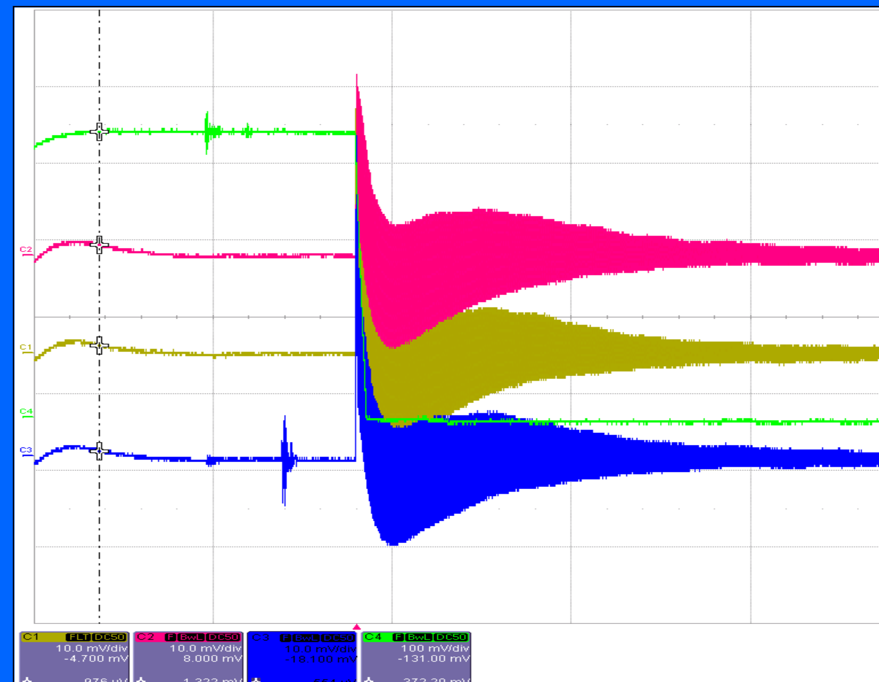
Impulso RF IH

Impulso RF RFQ

Impulso Injection Bumper

Impulso Chopper LEBT





Multiturn injection measured on three pick-ups without adiabatic trapping with 1μs beam (left) and 30μs beam.

Ringrazio il gruppo CNAO e in particolare:

U. Amaldi - generalità adroterapia
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M. Ciocca - dosimetria
A. Facoetti - radiobiologia
L. Falbo - cavità RF
M. Ferrarini - radioprotezione
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A. Parravicini - diagnostica
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