# THE SPIRAL2 ACCELERATOR AT GANIL-CAEN

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# OUTLINE

# 1. WHAT IS SPIRAL2

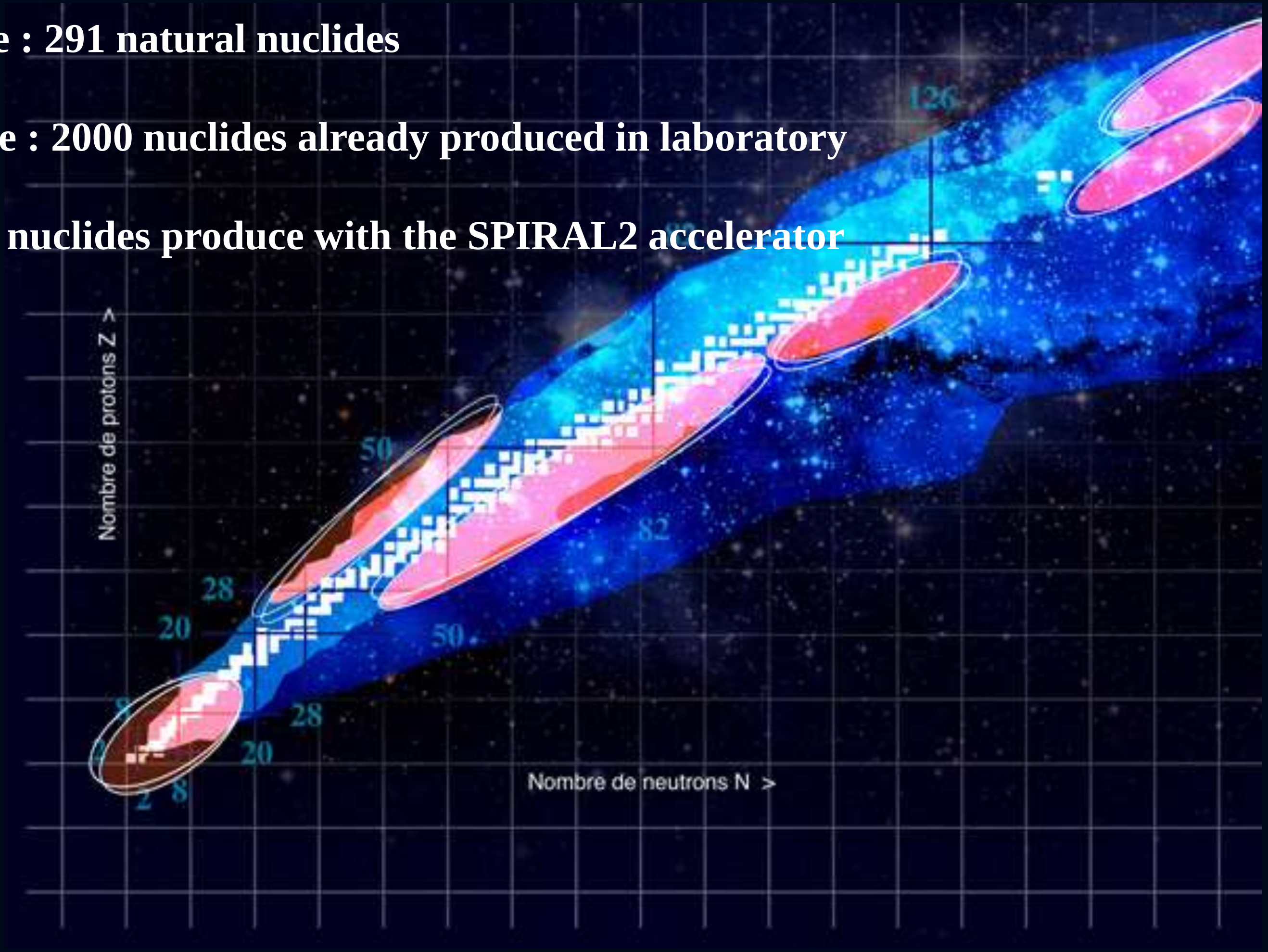
**SPIRAL2** (**Système de Production d'Ions RAdioactifs en Ligne de 2ème génération**) is a project of linear particles for studies in

fundamental nuclear physics and interdisciplinary research

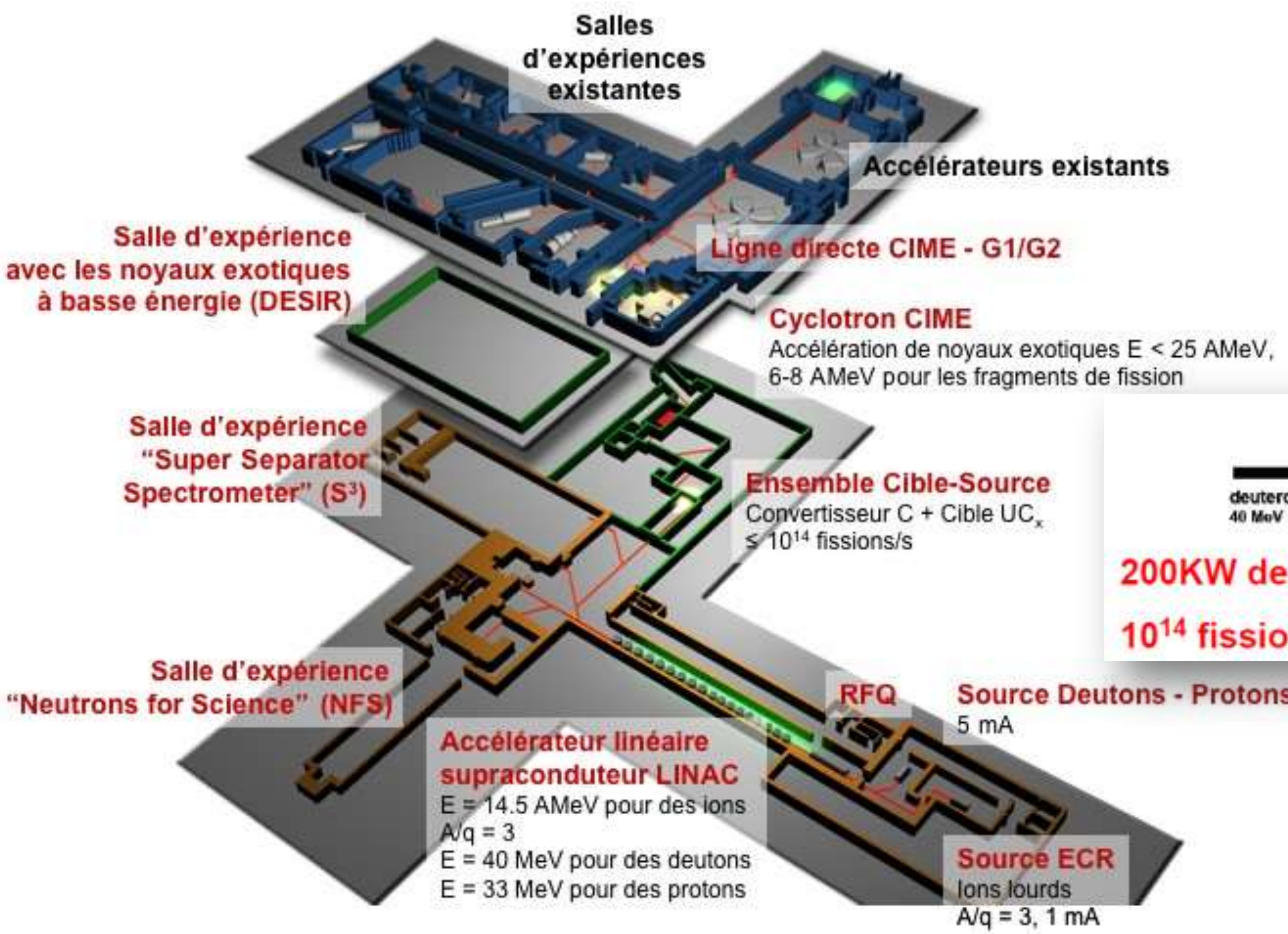
The facility, larger than existing facility at GANIL Caen will produce "exotic" ions beams

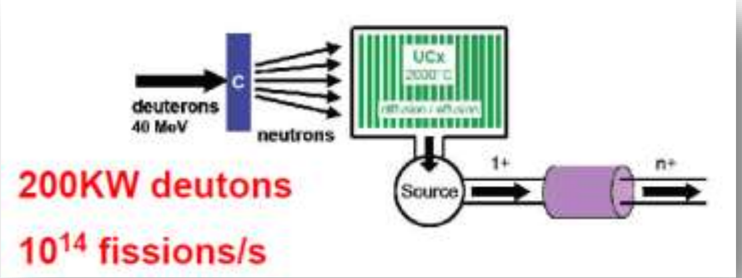
# EXPLORATION OF TERRA INCOGNITA

- **In white : 291 natural nuclides**
- **Sky blue : 2000 nuclides already produced in laboratory**
- **In red : nuclides produce with the SPIRAL2 accelerator**



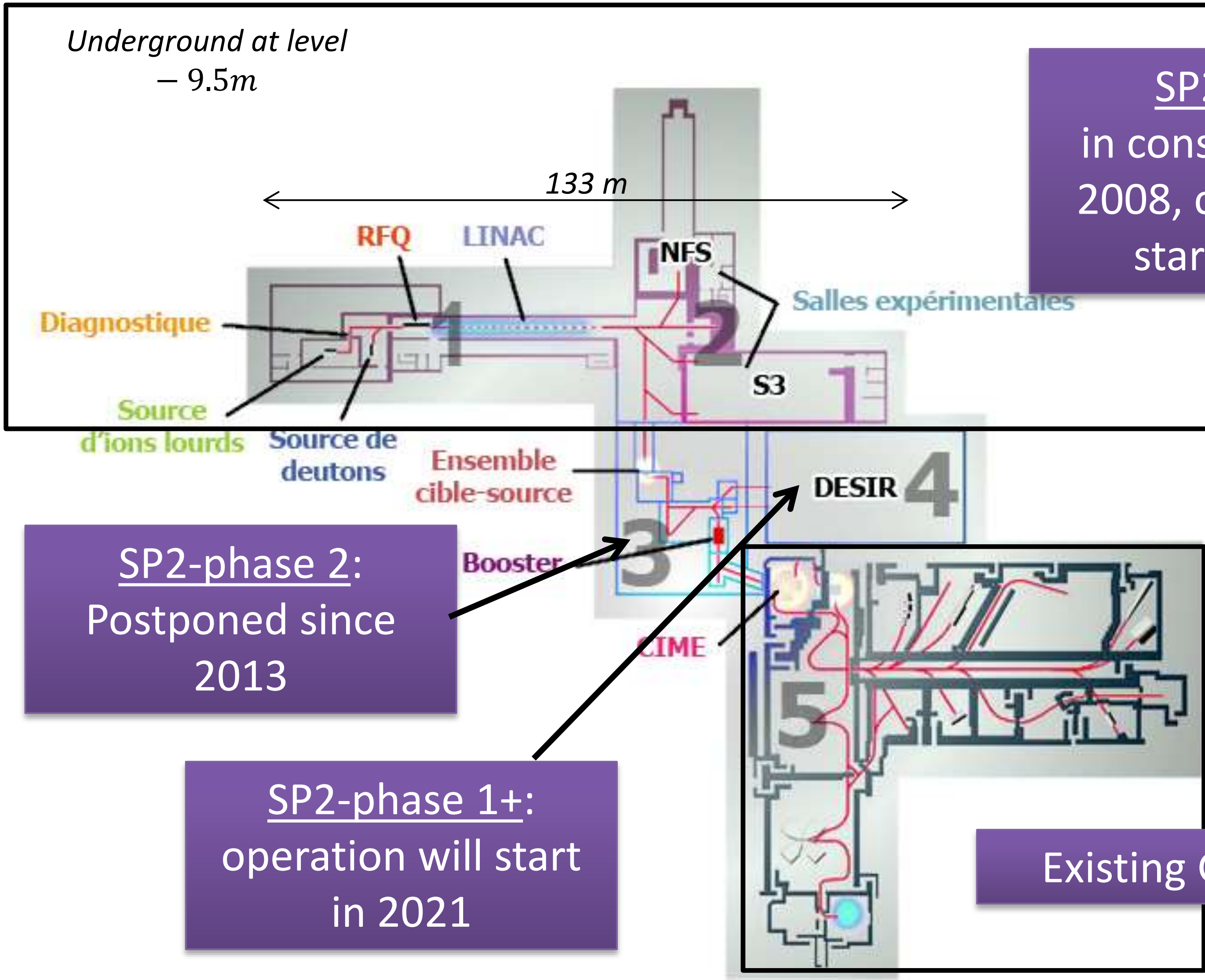
# SPIRAL2 AT GANIL FACILITY




*The ISOL method (Isotope On-Line) to produce Rare Isotope Beams*

# ORGANIZATION AND PHASE



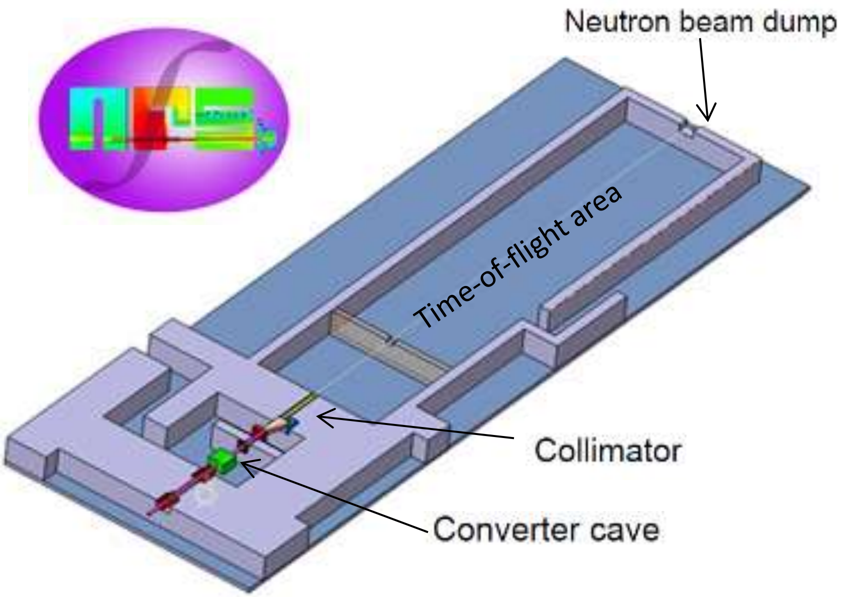

<u>SP2-phase 1</u>:
in construction since 2008, commissioning started in 2014

<u>SP2-phase 2</u>:
Postponed since 2013

<u>SP2-phase 1+</u>:
operation will start in 2021

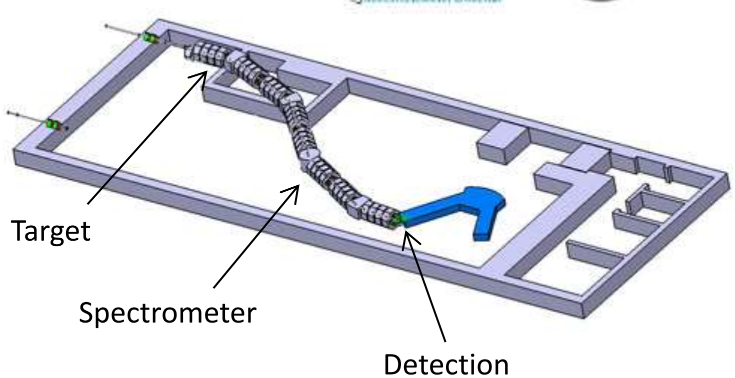
Existing GANIL

# NEW EXPERIMENTAL AREAS




Accelerated Protons and Deuterons by the SPIRAL2 linac can generate a neutrons source extremely intense

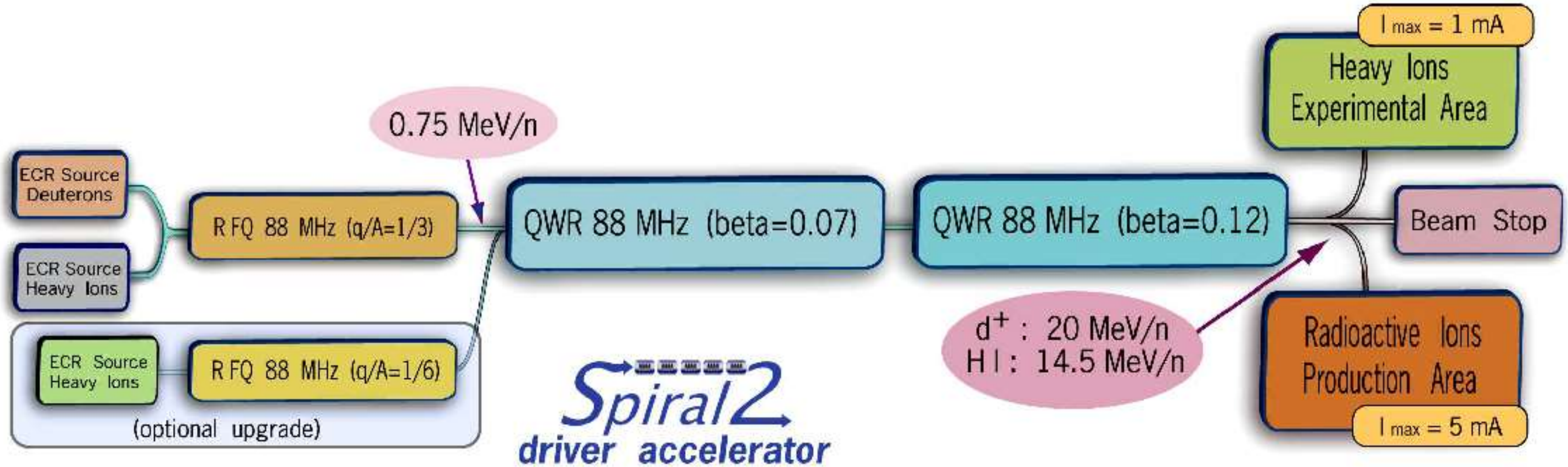
**NFS (Neutrons For Science)** are will use these neutrons for fundamental physics experiments and others applications (ex: cross sections measurements for next reactors generation, fusion …)




SPIRAL2 linac accelerate stable ions at very high intensity. By nuclear reactions, it will produce extremely rare isotopes like very heavy, super heavy elements or deficient neutrons nuclides.

**S3 (Super Séparateur Spectromètre)** is design for accept these high intensity and provide a precise separation degree in order to reject the contaminants and permit the identification of the interest nucleus.

# LINAC AND PRODUCED BEAMS



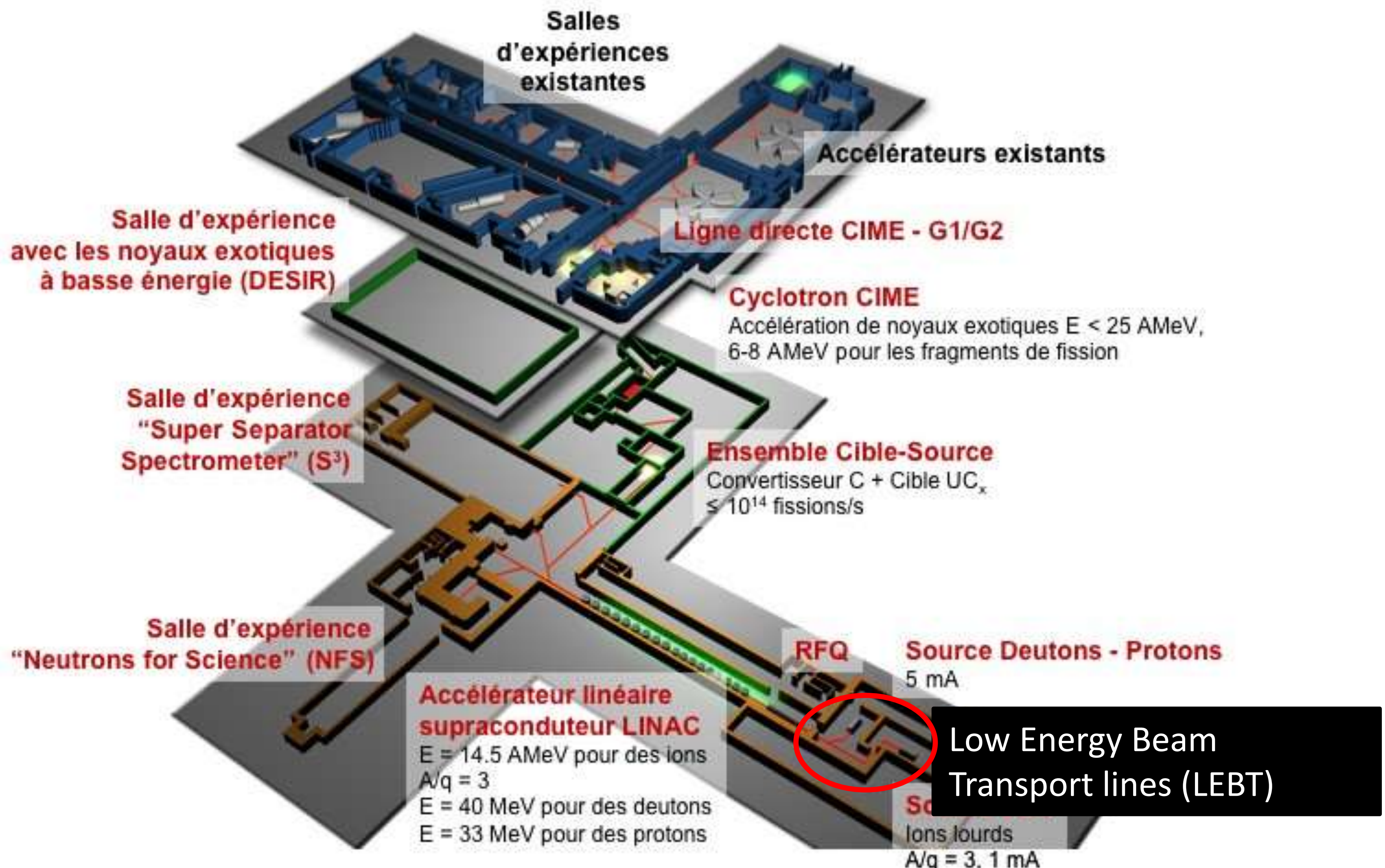

| Faisceau | p+ | D+ | ions | ions |
|---|---|---|---|---|
| Q/A | 1 | 1/2 | 1/3 | 1/6 |
| I (mA) max. | 5 | 5 | 1 | 1 |
| $W_o$ min. (Mev/A) | 2 | 2 | 2 | 2 |
| $W_o$ max. (Mev/A) | 33 | 20 | 14.5 | 8.5 |
| CW max. beam power (KW) | 165 | 200 | 44 | 48 |

**Longueur totale: 65 m (sans les lignes haute énergie)**

**$D^+$ : sourc ECR**
**Ions lourds: source ECR**
**Hacheur lent et rapide**
**RFQ (1/1, 1/2, 1/3) & 3 regroupeurs**

**12 QWR beta 0.07 (12 cryomodules)**
**14 QWR beta 0.12 (7 cryomodules)**
**Liquéfacteur Hélium 1 KW (4.2 K)**
**Q-poles chauds**
**30 amplificateurs RF état solide (10 & 20 KW)**

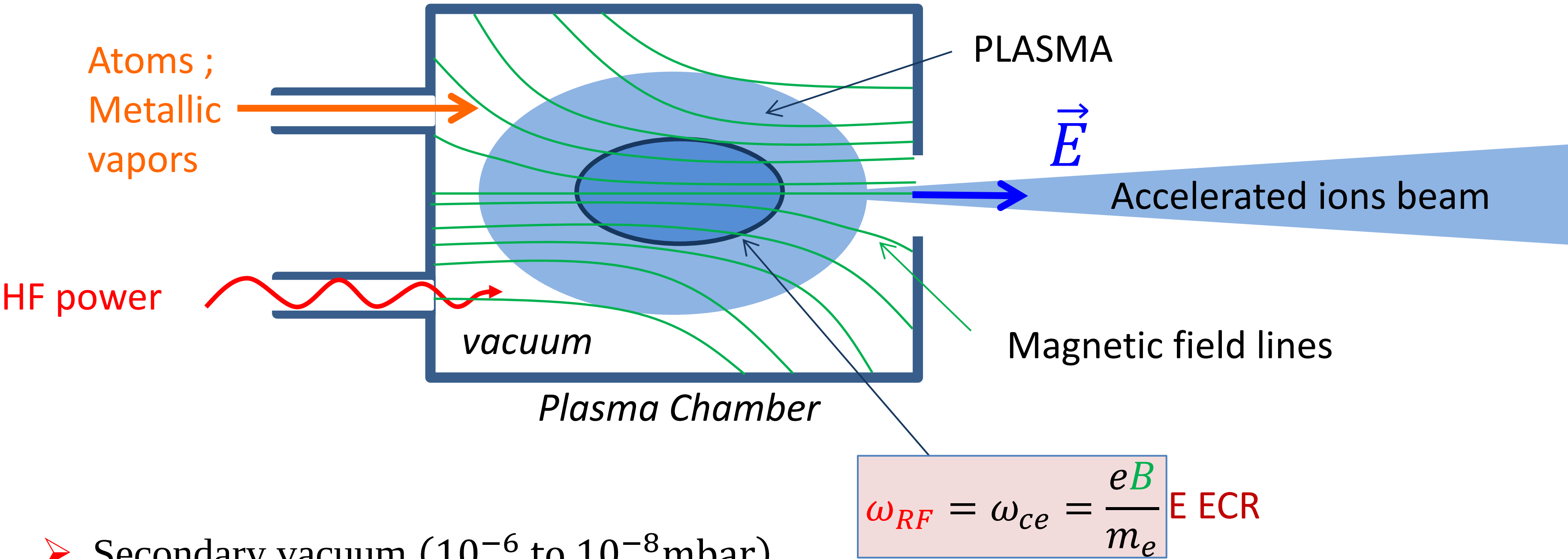
## 2. ION SOURCES AND LOW ENERGY BEAM LINES




LEBT = LBE (in French)

# ECR ION SOURCES

ECR = Electron Cyclotron Resonance



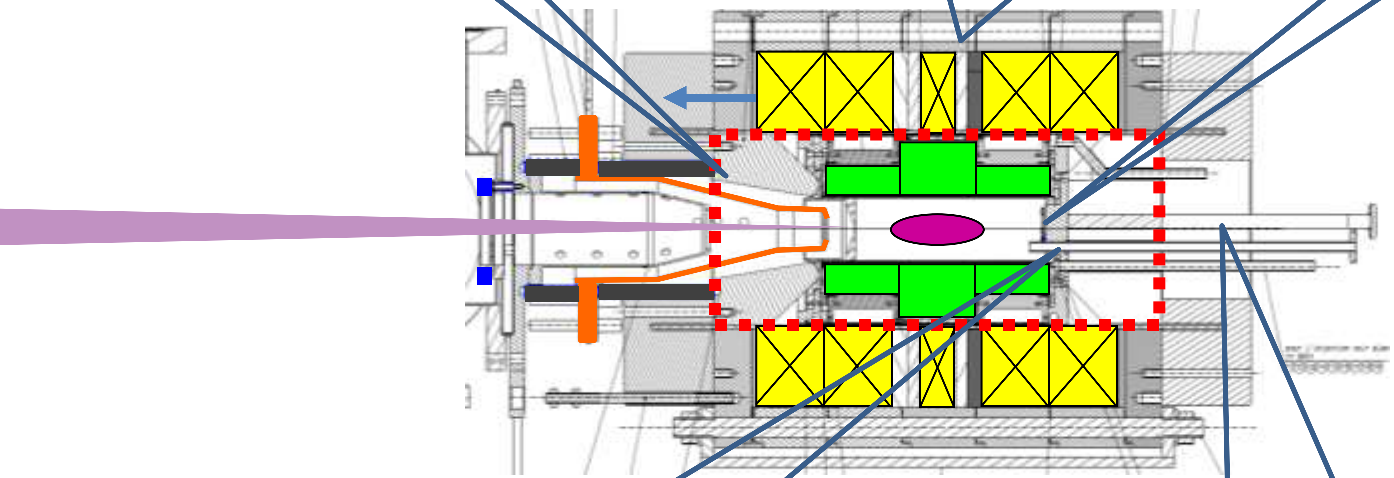

- Secondary vacuum ($10^{-6}$ to $10^{-8}$mbar)
- Magnetic confinement
- Hot electrons
- Cold ions
- Multi-ionization of ions
- Extraction of ions and acceleration (30-60kV)

# SPIRAL2 Q/A=1/3 ION SOURCE

60kV
High voltage
*Ions acceleration*

2T magnetic field
*Plasma confinement*

Polariser
*Plasma optimization*

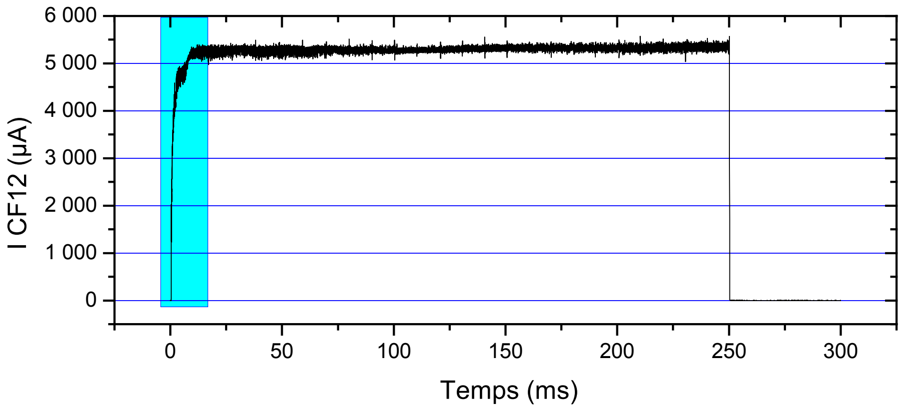


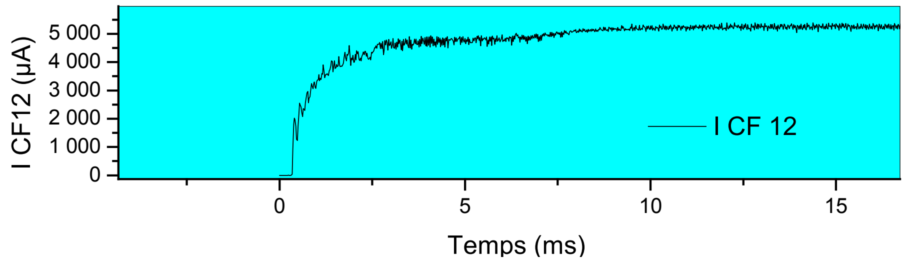
High Frequency : 18GHz
*Chauffage des électrons*

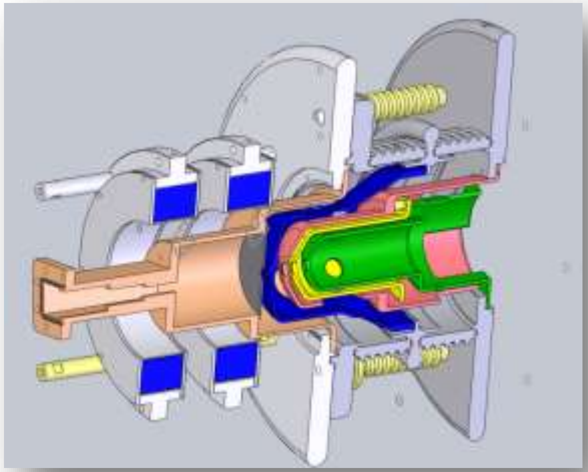
Atoms Injection
Plasma density
Chemical element

# SPIRAL2 DEUTERON ION SOURCE

- Operational since 2009 (CEA-Saclay)
- 2kW 2.45GHz magnetron Pulsed or CW mode
- Up to 50kV bias potential
- 0,15 to 10mA Proton/Deuteron beams



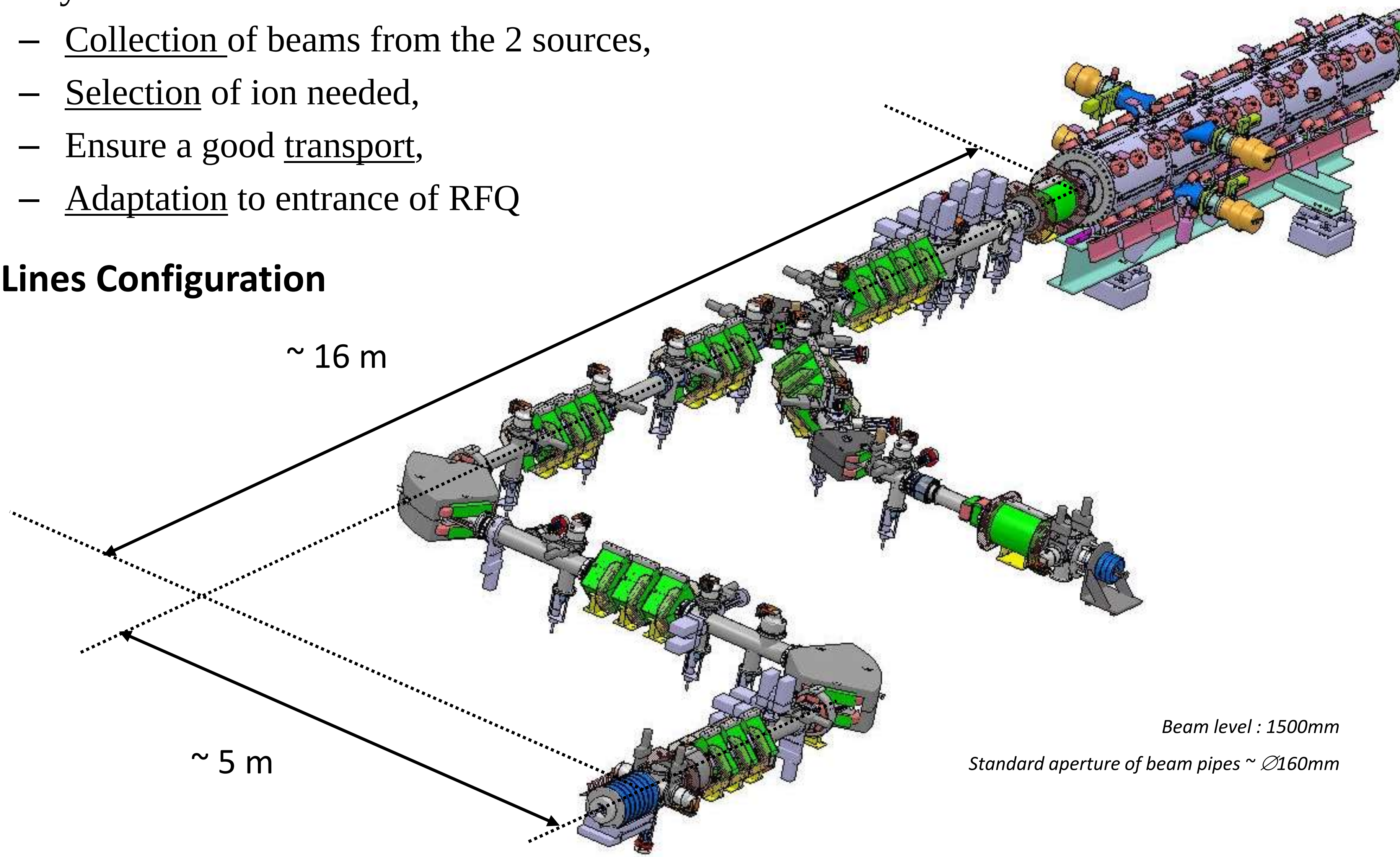



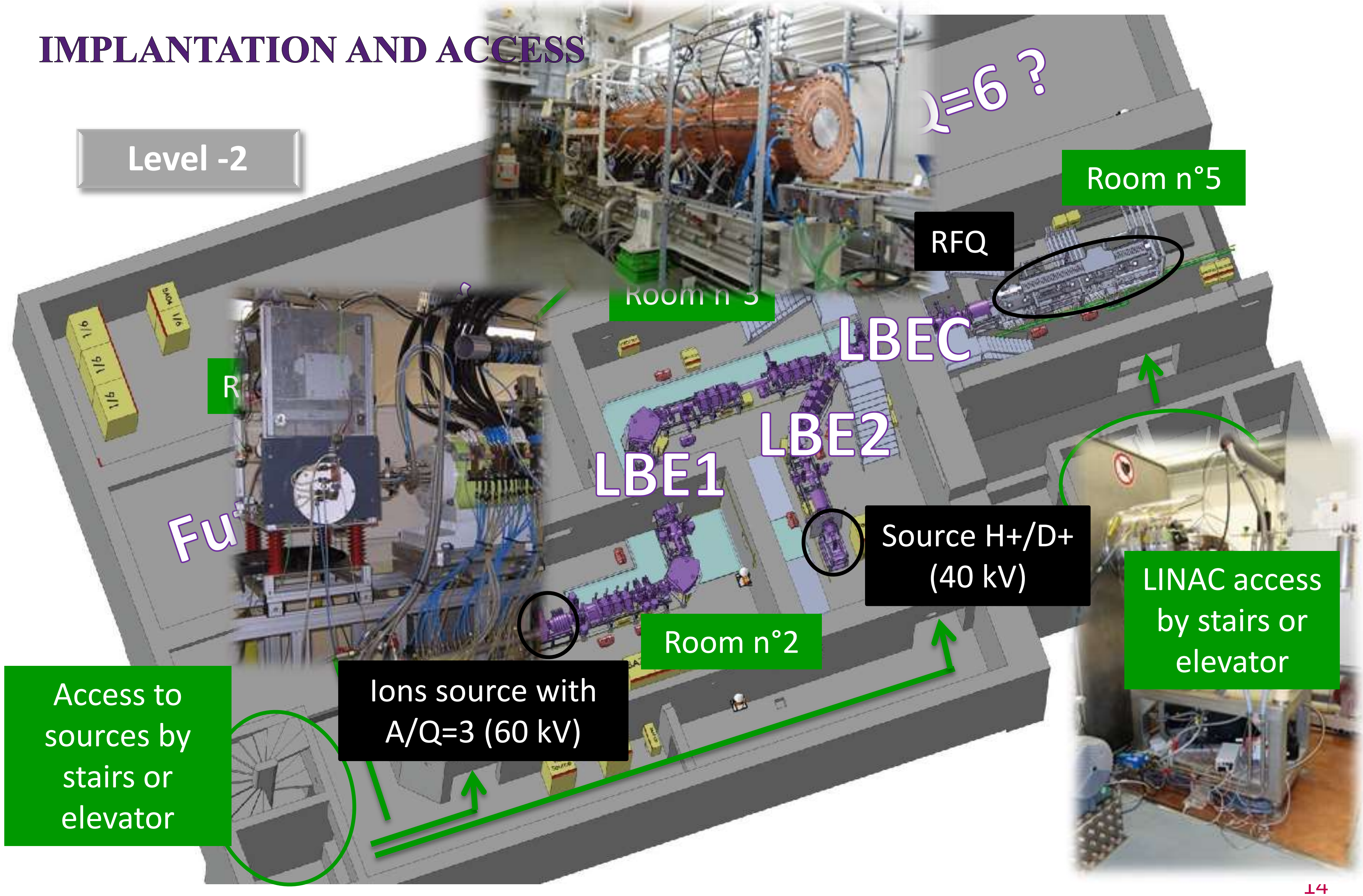
# LEBT CONFIGURATION

- Why LEBT ?
  - Collection of beams from the 2 sources,
  - Selection of ion needed,
  - Ensure a good transport,
  - Adaptation to entrance of RFQ

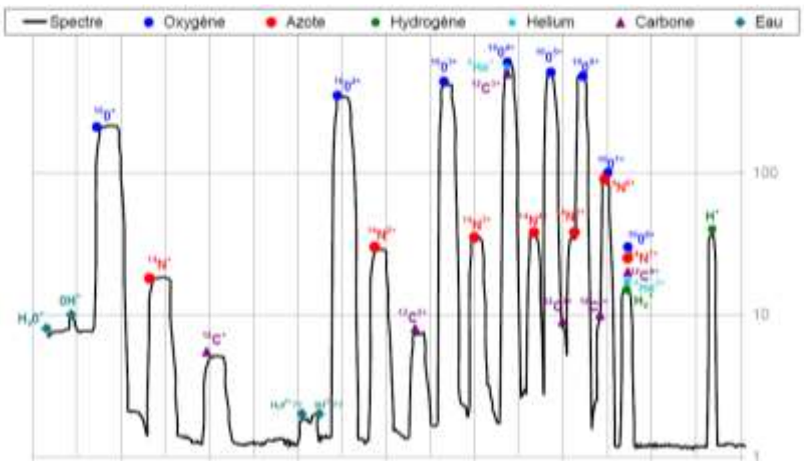
❖ **Lines Configuration**



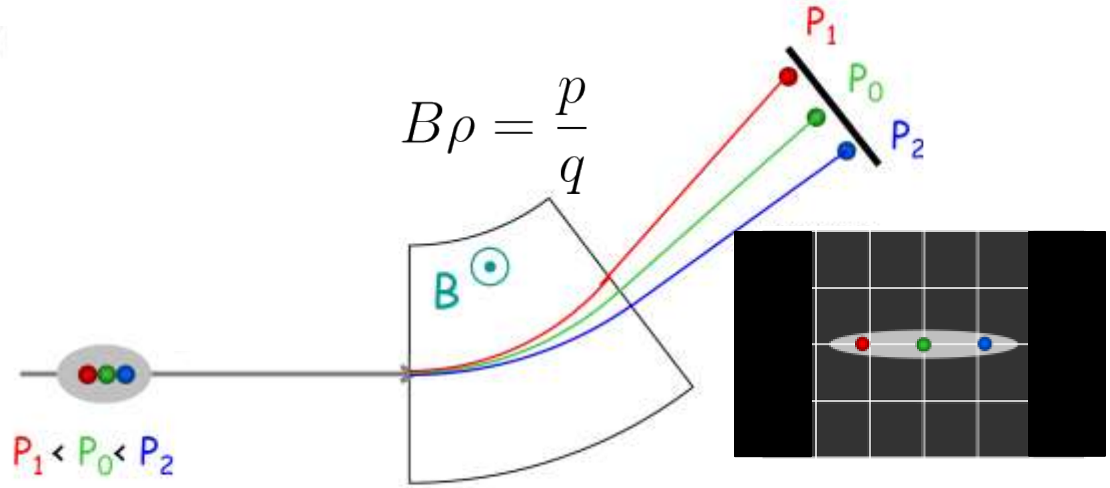
## IMPLANTATION AND ACCESS



# IONS SELECTION COMING FROM SOURCE

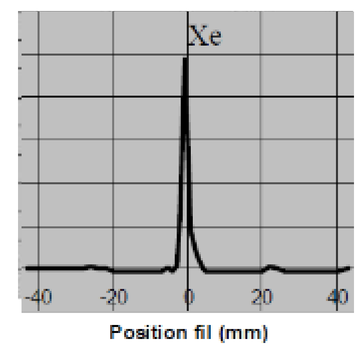



*Ex. spectre en Oxygène issu de Phoenix V2*




- **Protons/Deuterons (LBE2): simple magnetic separation**
  - ✓ Dipole LBE2-D11 (with water cooled vacuum chambers)

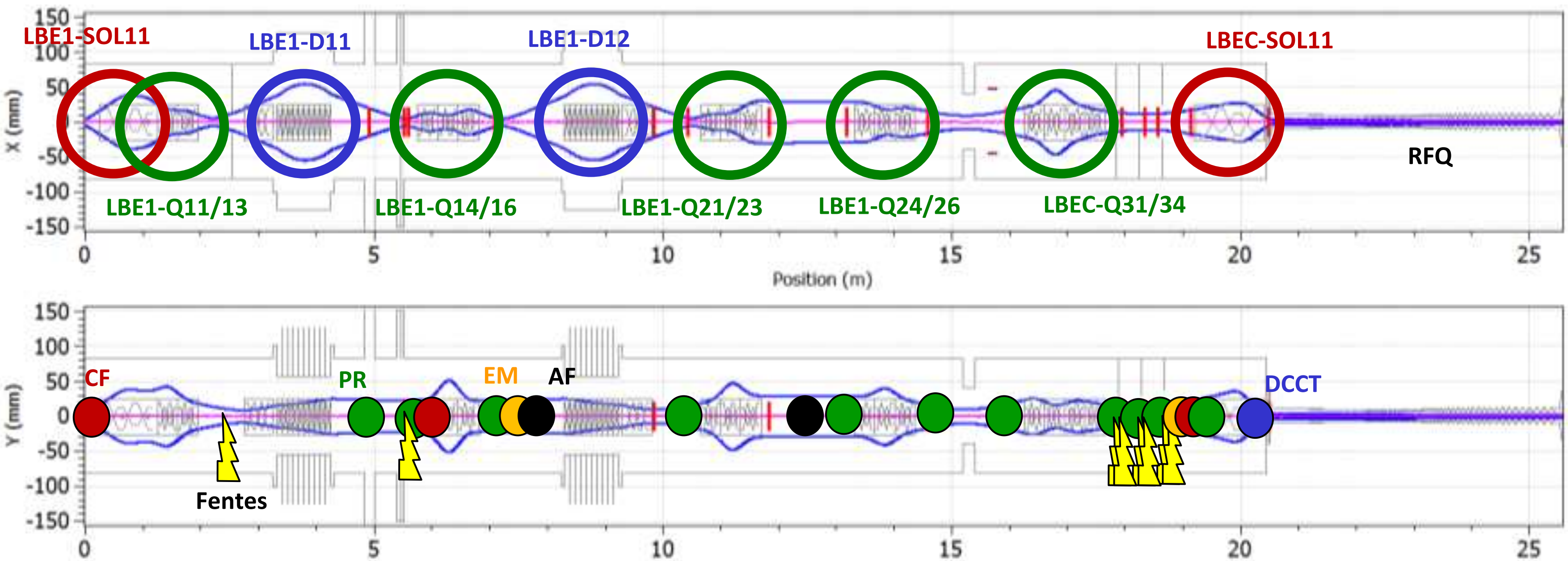
- **Heavy Ions (LBE1): spectrometer like**
  - ✓ Dipole LBE1-D11 (with water cooled vacuum chambers)
  - ✓ Optical system Object / Image (resolving power better than 1/100)
  - ✓ Selection slits (cooled)




Beam profile measurement on LBE1-PR13

# BEAM TRANSPORTATION UP TO RFQ

- Transmission optimization and emittance preservation
- Give a stable and well adapted beam to RFQ entrance
- Magnetic transport : dipoles, solenoids, quadrupoles…
- Key role of beam instrumentation (diagnostics, slits …)




Ex. beam transport in **LBE1+LBEC+RFQ** (envelopes at √6 RMS, ~95%)

# BEAM TRANSPORTATION UP TO RFQ

## Profiler

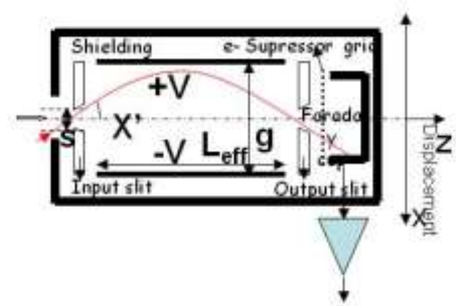
Secondary emission monitor
47 Tungsten wires ø 150 µm
Maximum beam size: 80 mm
Imax: 0.1-1 mA cw

## DCCT

Shielding : (µ-métal + Armco + copper)
B.W.: 0 – 10 kHz ; Noise: 1 µA / Hz ½
C.W. + Low Duty Factor Pulsed Mode Operation

## Emittance-meter

Allison scanner
Max. diameter beam: 80 mm
Max measurable angle: ± 100mrad
H.V. max: 2.8 kV
Max Beam power: 300 W



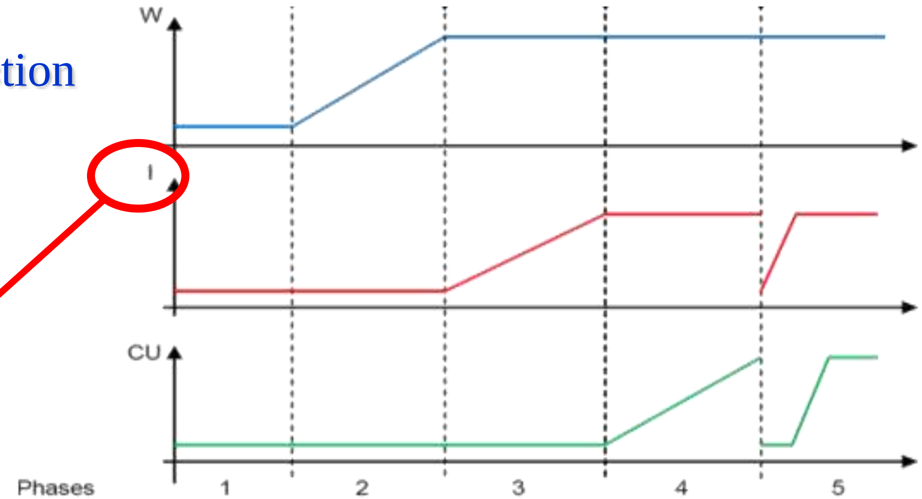

## Faraday Cup

Water cooled
P max: 1,2 kW ( 250°)
P density max: 2120 W/Cm²

# BEAM POWER CONTROL

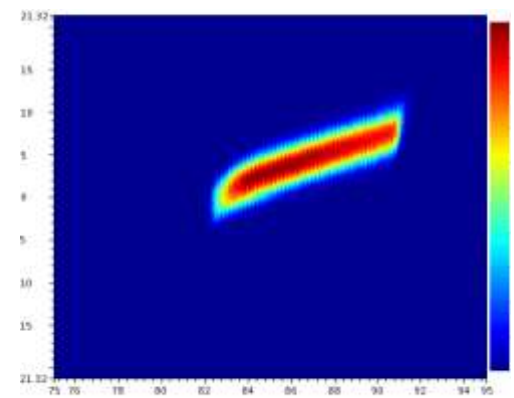
- **Crucial role for a high power machine**
  - ✓ Protection machine, safety, radioprotection
  - ✓ Commissioning machine
  - ✓ Power increasing on targets

- **Control of the peak current**
  - ✓ From $I_{min}$ (typically 100 µA) to $I_{max}$ (6.5 mA)
  - ✓ Controled by a system to 3 slits in horizontal and vertical axis
  - ✓ Coupling with definition of beam emittances: when I ↓, ε ↓



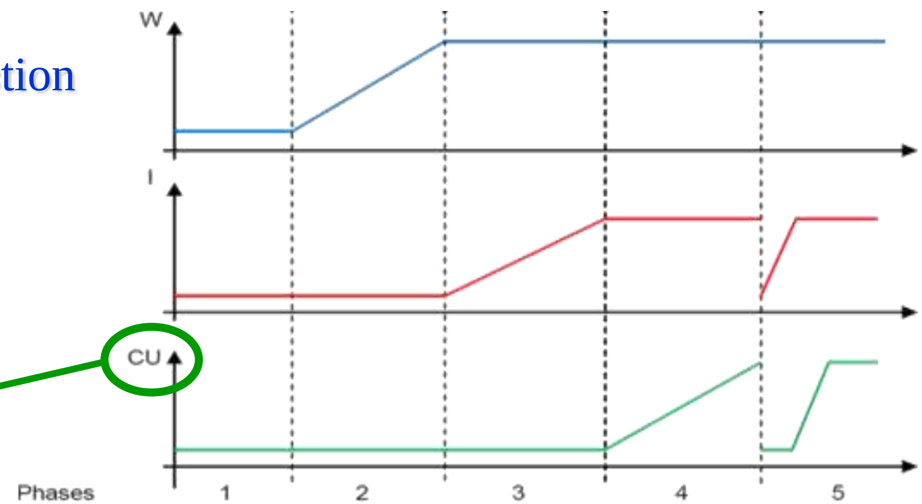
Phases of the power increasing during the commissioning


Software dedicated to emittances definition


Measurement of 50µA Deuterons beam at Saclay

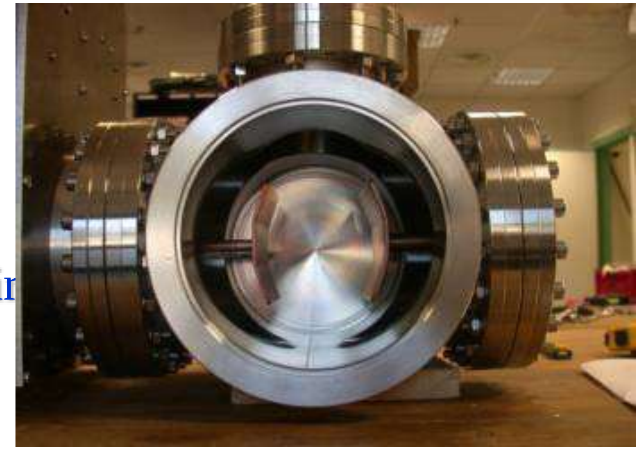
# BEAM POWER CONTROL

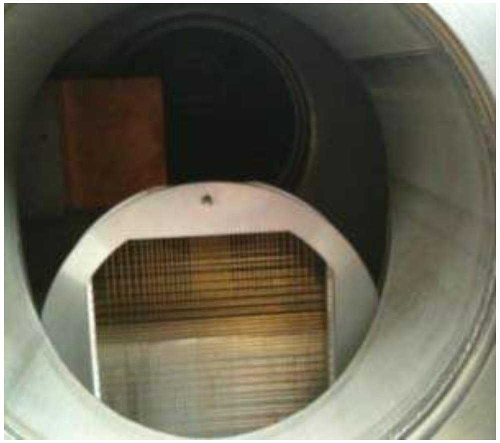
- ❖ **Crucial role for a high power machine**
  - ✓ Protection machine, safety, radioprotection
  - ✓ Commissioning machine
  - ✓ Power increasing on targets



Phases of the power increasing during the commissioning

- ❖ **Control of duty cycle**
  - ✓ Using electrostatic : provide a pulsed beam
  - ✓ V and f max : 10 kV, 1.5 kHz
  - ✓ Duty cycle : typically for the fir linac beams : 0.1% (500µs @2Hz)


Hacheur (chopper) electrodes


Beam profiler and associated “scrapper”

## PRODUCED BEAMS

- Type
  - LBE1+LBEC: heavy ions with A/q = 3 max *(ex: $^{12}C^{4+}$, $^{16}O^{6+}$, $^{20}Ne^{7+}$, $^{40}Ar^{14+}$, $^{58}Ni^{19+}$)*
  - LBE2+LBEC: Deuterons, Protons, $H_2^+$

- **Energy**
  - ✓ Ions speed must be adapted to first modulations of RFQ
  - ✓ Required source potential

$$W = qV_{source} = (\gamma - 1)\, m_0 c^2 \approx \frac{1}{2} m_0 v^2 \quad \Rightarrow V_{source} \approx \frac{m_0 c^2}{2q}\beta^2$$

$$\beta = 6.553.10^{-3} \quad \boxed{\Rightarrow V_{source} = \frac{A}{q} \times 20kV}$$

Ex. Protons: 20.15 kV, Deuterons: 40.27 kV, $^{16}O^{6+}$: 53.31 kV, $^{12}O^{4+}$: 59.99 kV

  - ✓ LEBT beam energy

$$\Rightarrow W = A \times 20keV$$

## EMITTANCES AND PEAK CURRENT

- Emittances
  - Transverses: 0.1 à 0.3 π.mm.mrad (Normalized RMS emittance)
    200 à 500 π.mm.mrad (Marginal emittance not normalized)
  - Longitudinal: Continuous beam

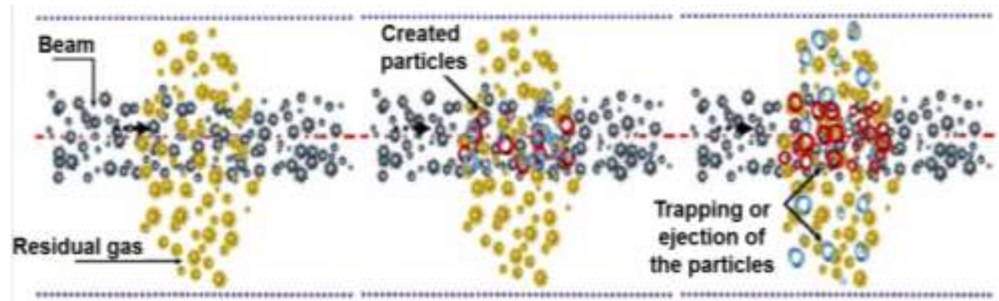
- **Peak current**

  - ✓ Protons, deuterons : more than 6.5 mA for obtain 5 mA max in the LINAC
  - ✓ Heavy ions : 1.3 mA (if possible) for obtain 1 mA max in the LINAC
    *Ex.* $^{16}O^{6+}$ *1.3 mA,* $^{20}Ne^{7+}$ *0.4 mA,* $^{40}Ar^{14+}$ *50 μA,* $^{58}Ni^{19+}$ *20 μA*
  - ✓ At these low energy at relatively high current, Coulomb repulsion contribute on the beam (ie: this is the charge space)
  - ✓ In a magnetic transport line, these forces are compensate :
    => beam tuning depend slowly to the current level (first tuning using the $B\rho$ scaling is possible ☺)

# SPACE CHARGES COMPENSATION

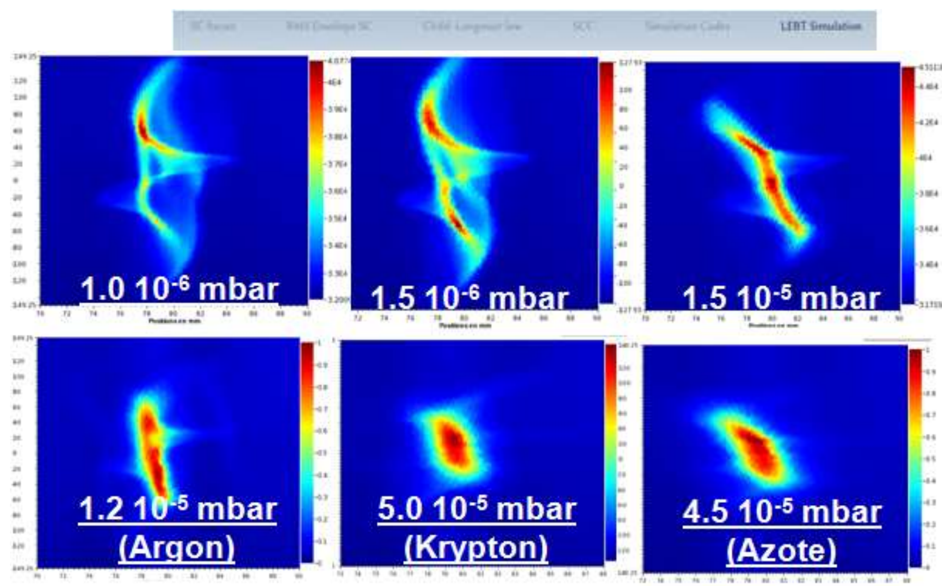
## ❖ Compensation phenomena

- ✓ Residual gas ionisation
- ✓ Electron trapping by the beam (@potential positif)
- ✓ Neutralization of space charges forces




## ❖ Not well controlled aspects

- ✓ Compensation level (close to 100%)
- ✓ Transients aspects in pulsed mode (the neutralization is not instantaneous)
- ✓ High contribution of the residual gaz nature (type) and pressure level



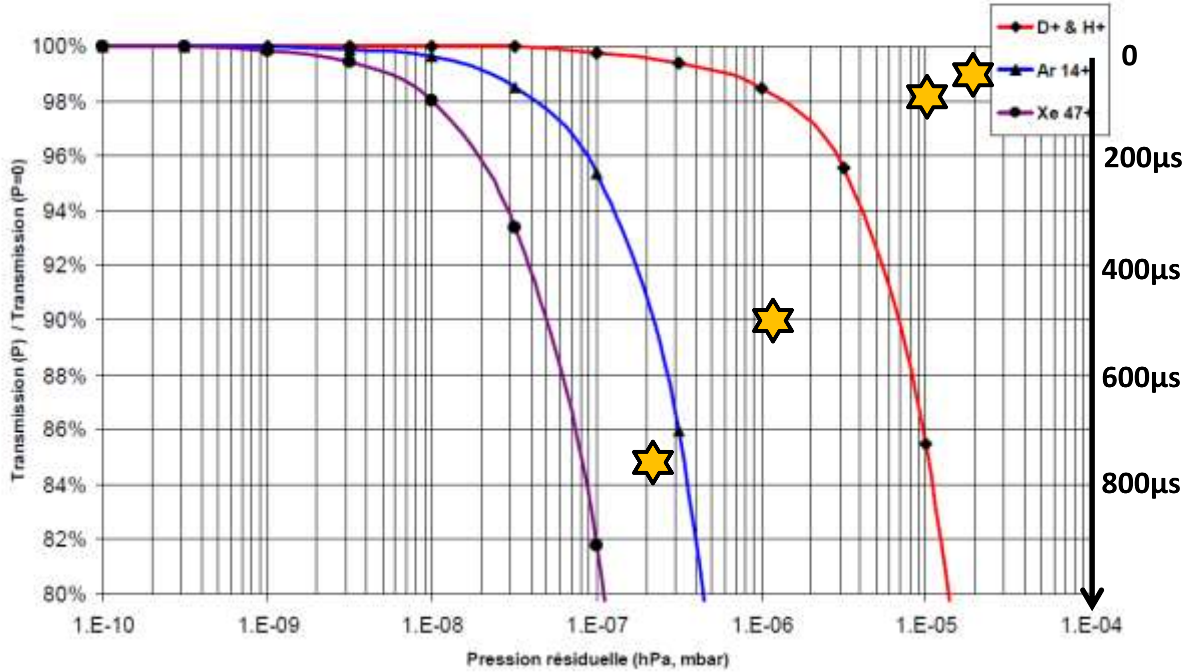

Emittances measurement at the RFQ SPIRAL2 entrance (by N. Chauvin)

Calculation of the transcient compensation (by D. Uriot)

# VACUUM PRESSURE

- **Sufficiently good**
  in order to suppress losses by electronic capture

- **Not to good**
  For decrease the time of the increasing of the compensation (and ameliorate the emittances)

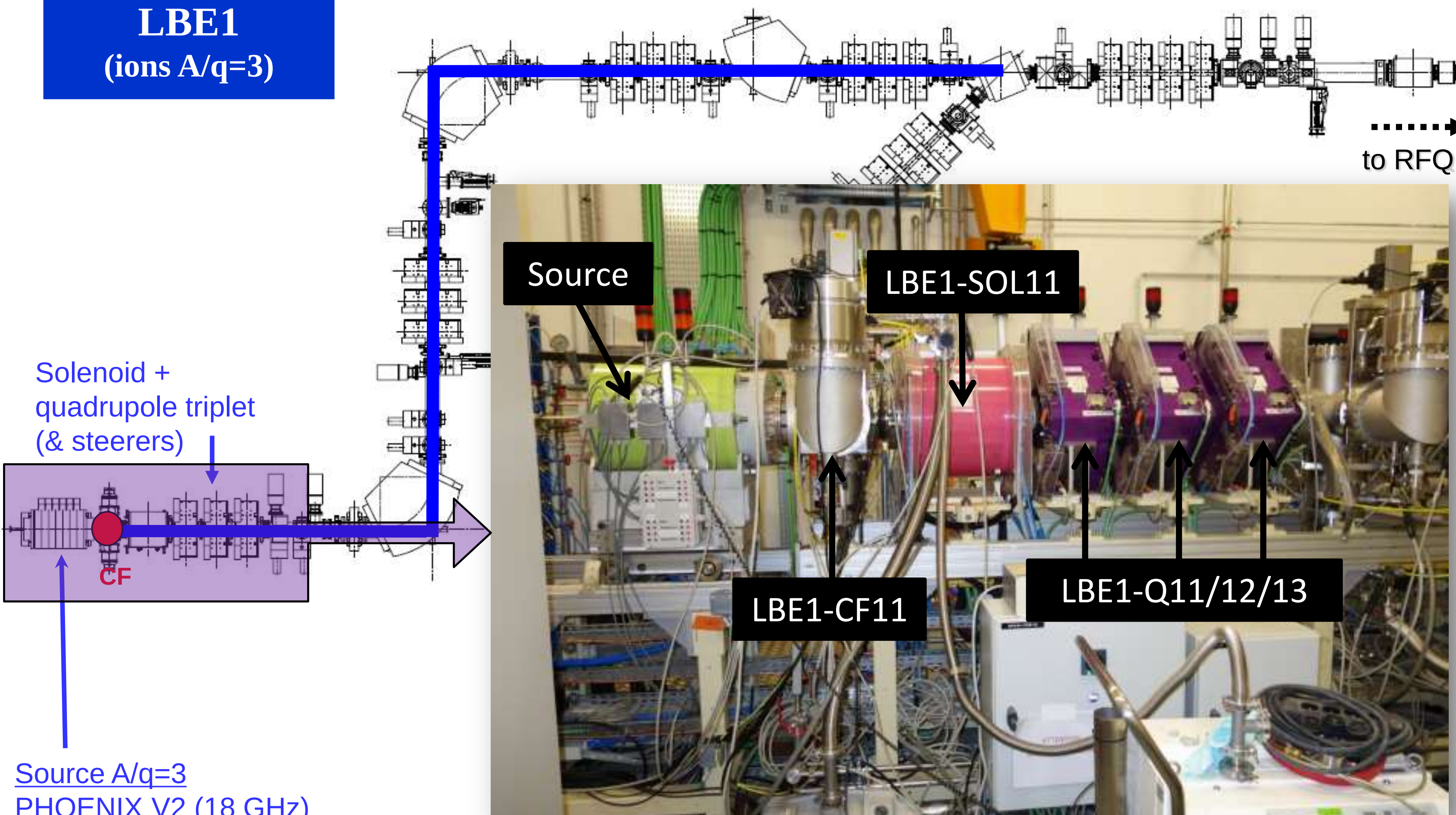



Transmission (calculation) and transients compensation (Deuterons case) as a function of the residual gas pressure

- Vacuum level have to be carefully choose
  - Between $10^{-6}$ and few $10^{-5}$ mbar for Protons/Deuterons particles
  - Between $10^{-8}$ and few $10^{-7}$ mbar for working with heavy ions

# LBE1 DESCRIPTION (1/6)

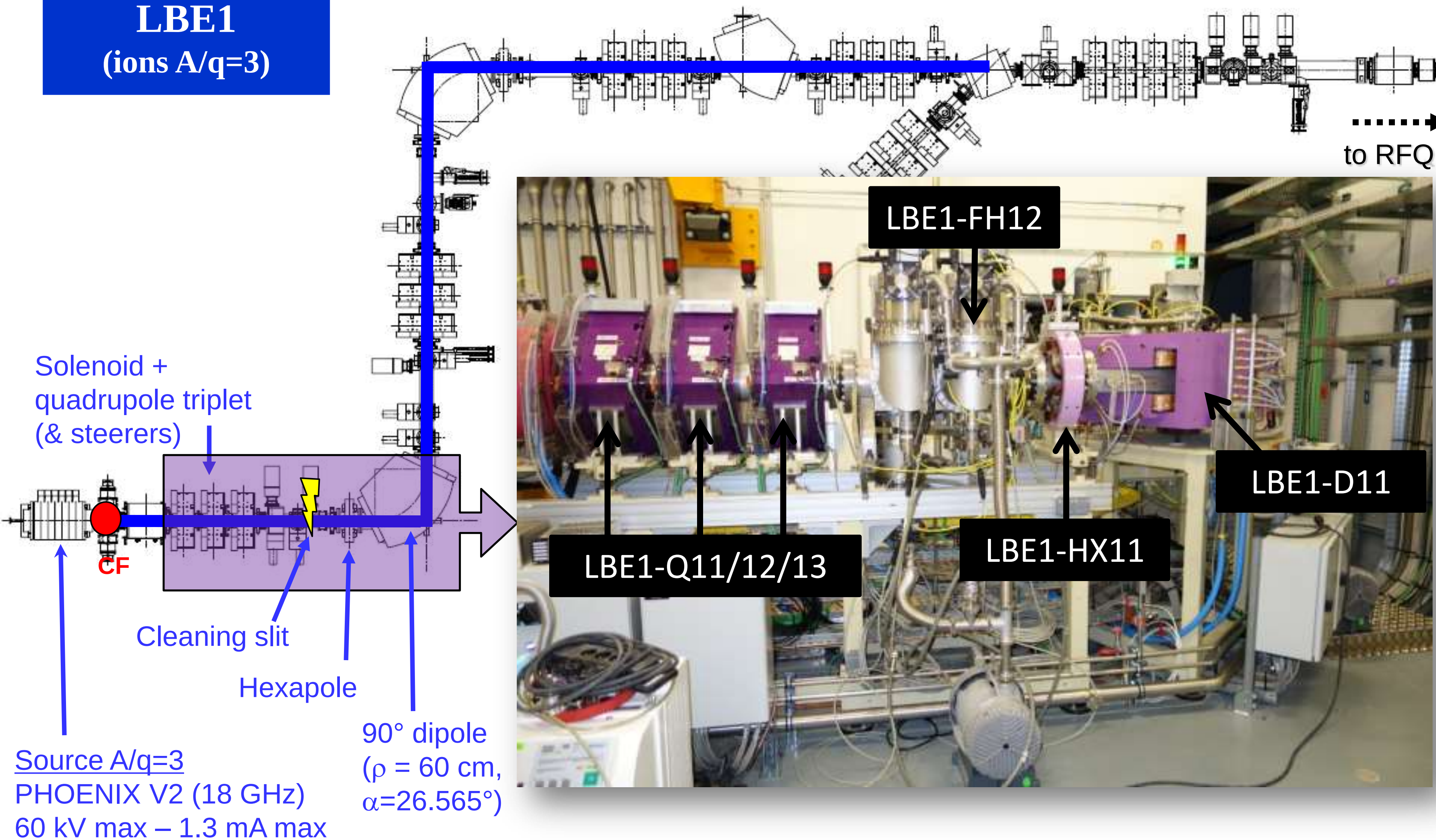
**LBE1**
**(ions A/q=3)**




Source A/q=3
PHOENIX V2 (18 GHz)
60 kV max – 1.3 mA max

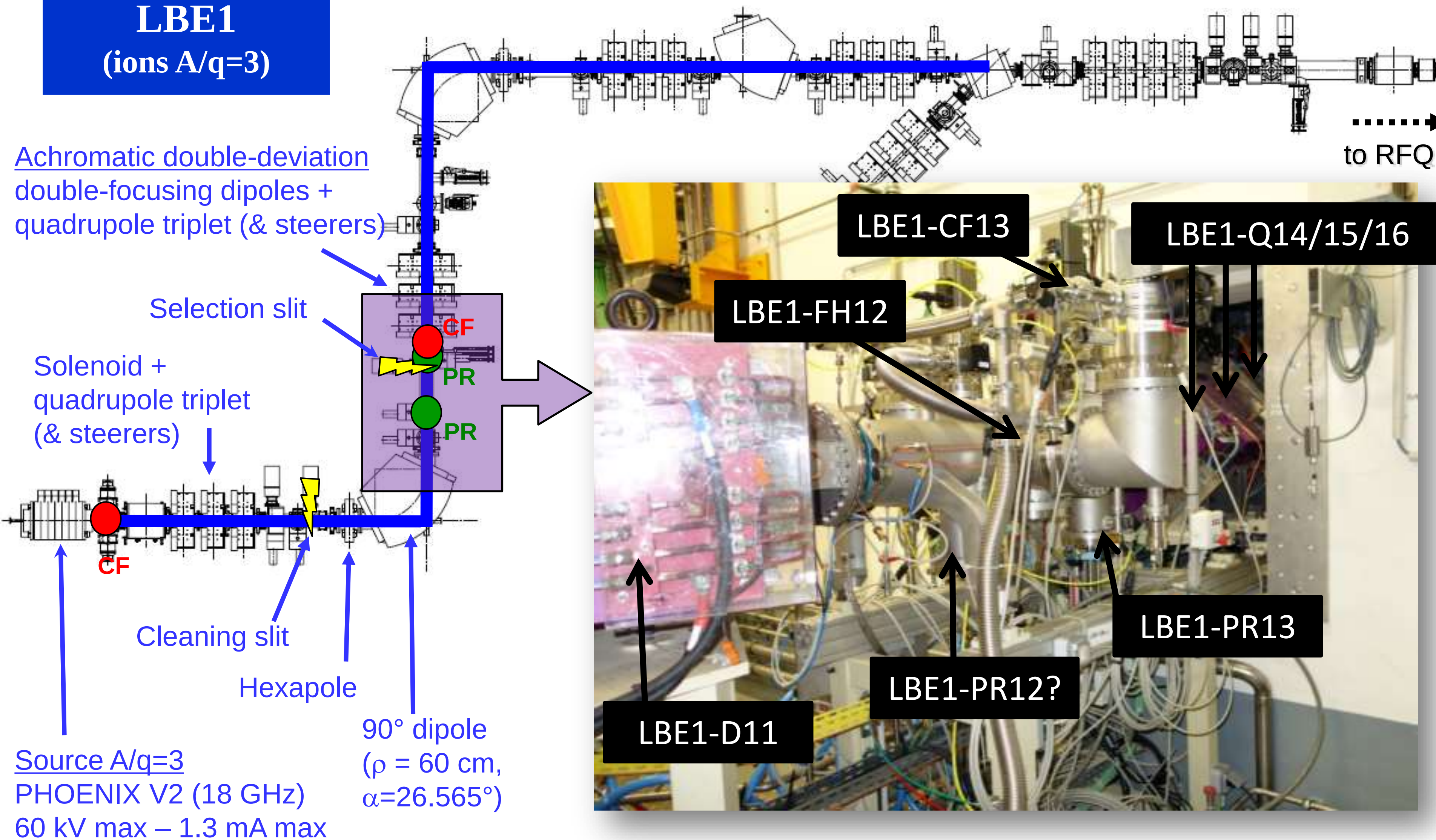
# LBE1 DESCRIPTION (2/6)

**LBE1**
**(ions A/q=3)**

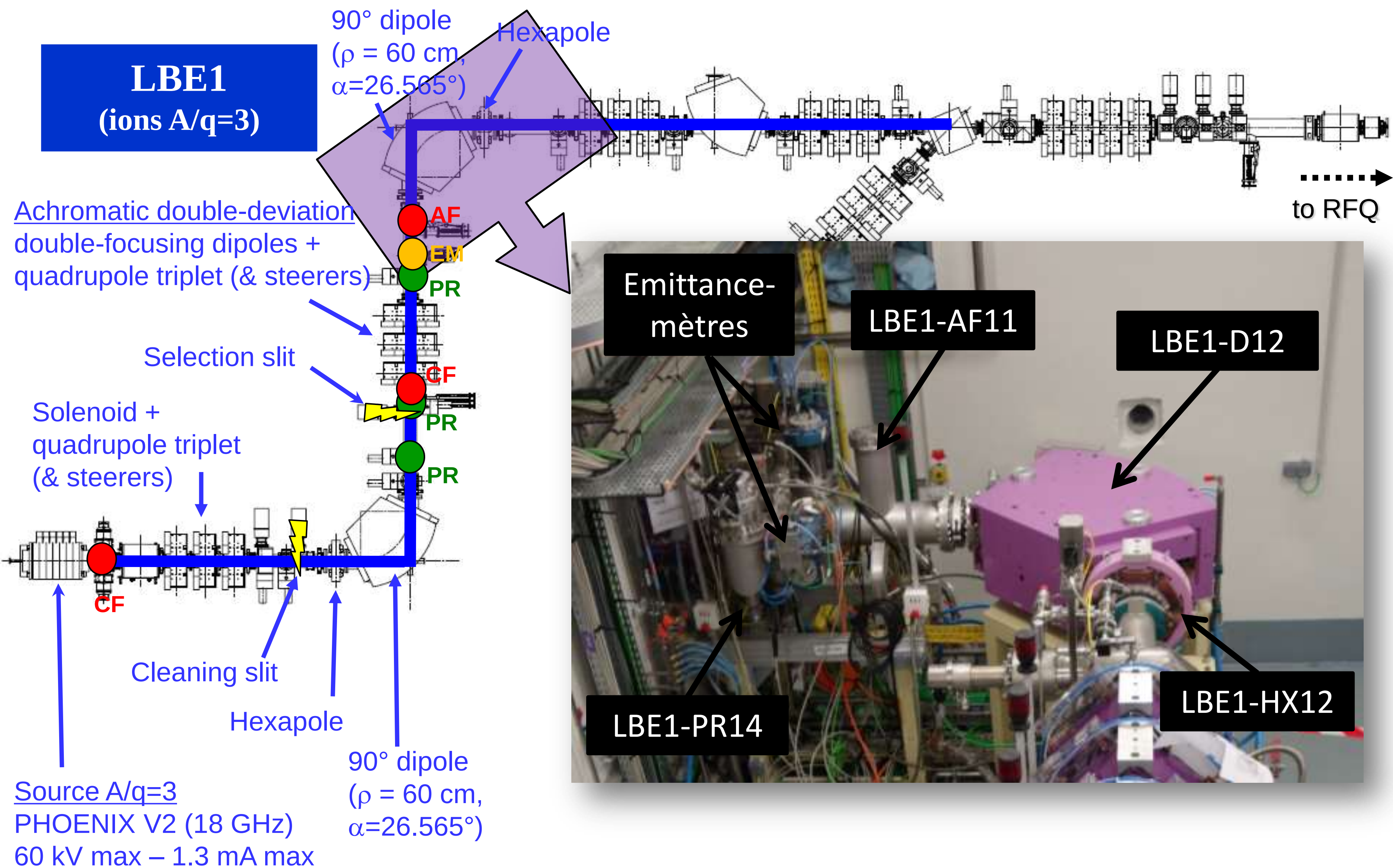


# LBE1 DESCRIPTION (3/6)

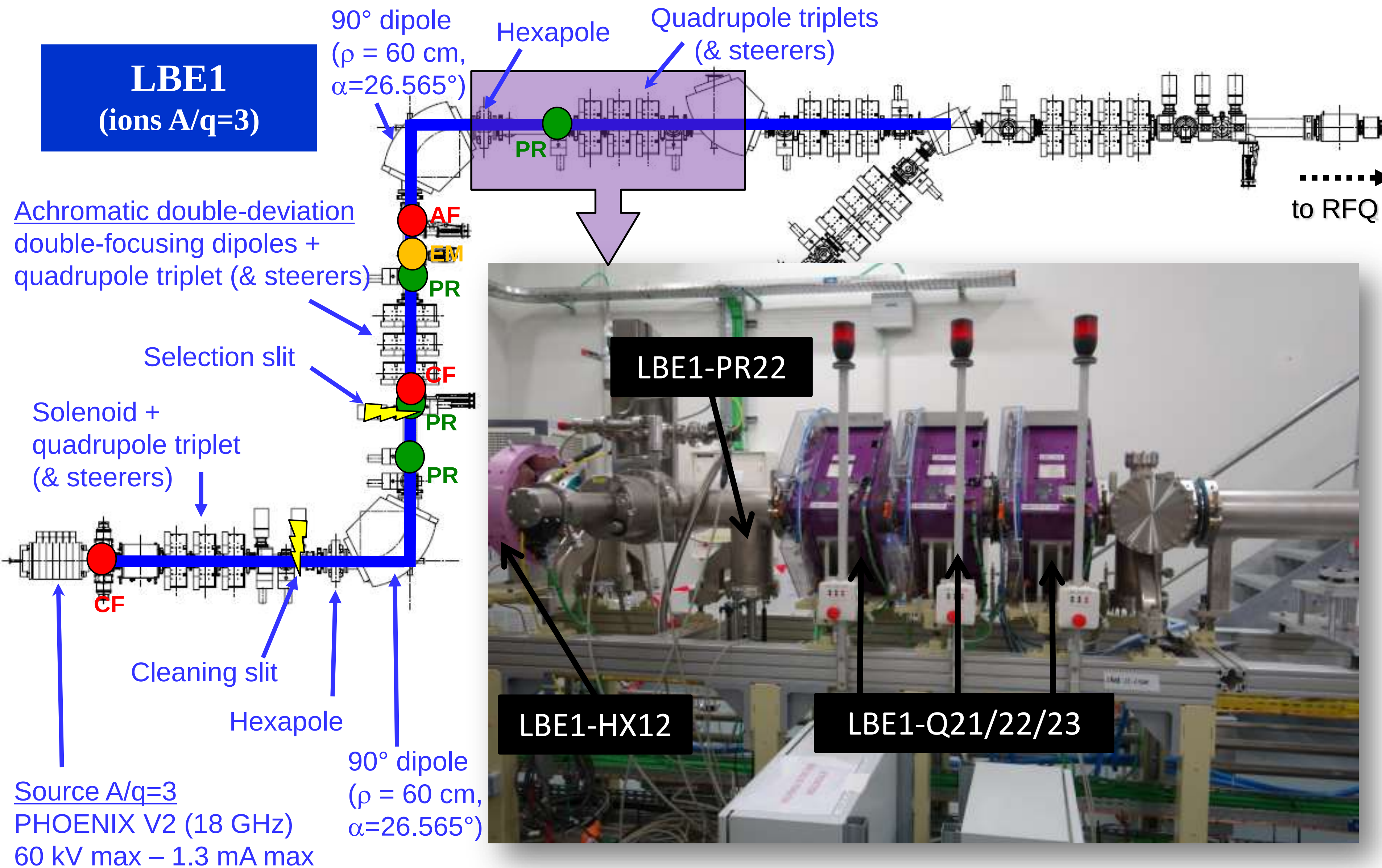
**LBE1**
**(ions A/q=3)**



# LBE1 DESCRIPTION (4/6)

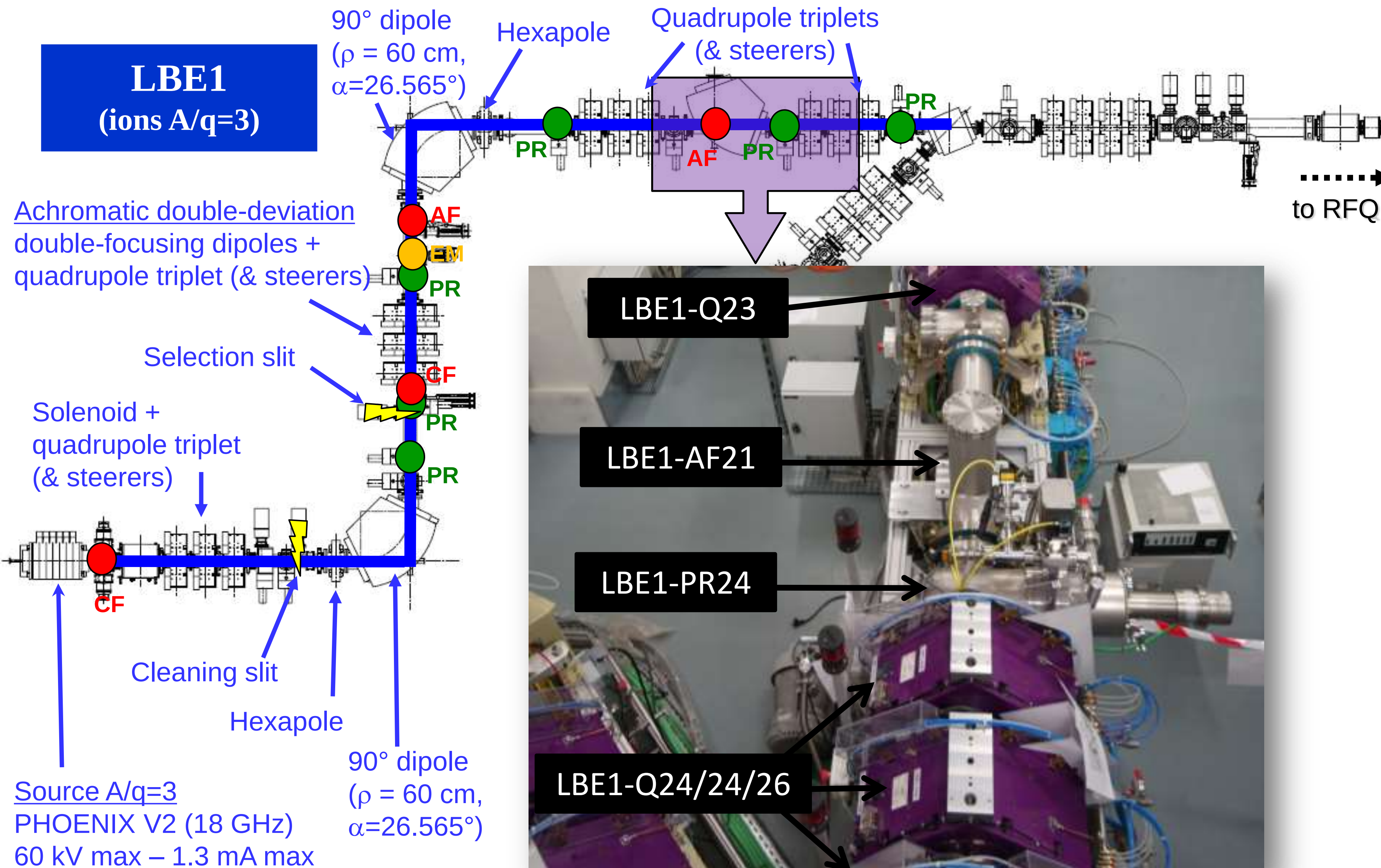


# LBE1 DESCRIPTION (5/6)

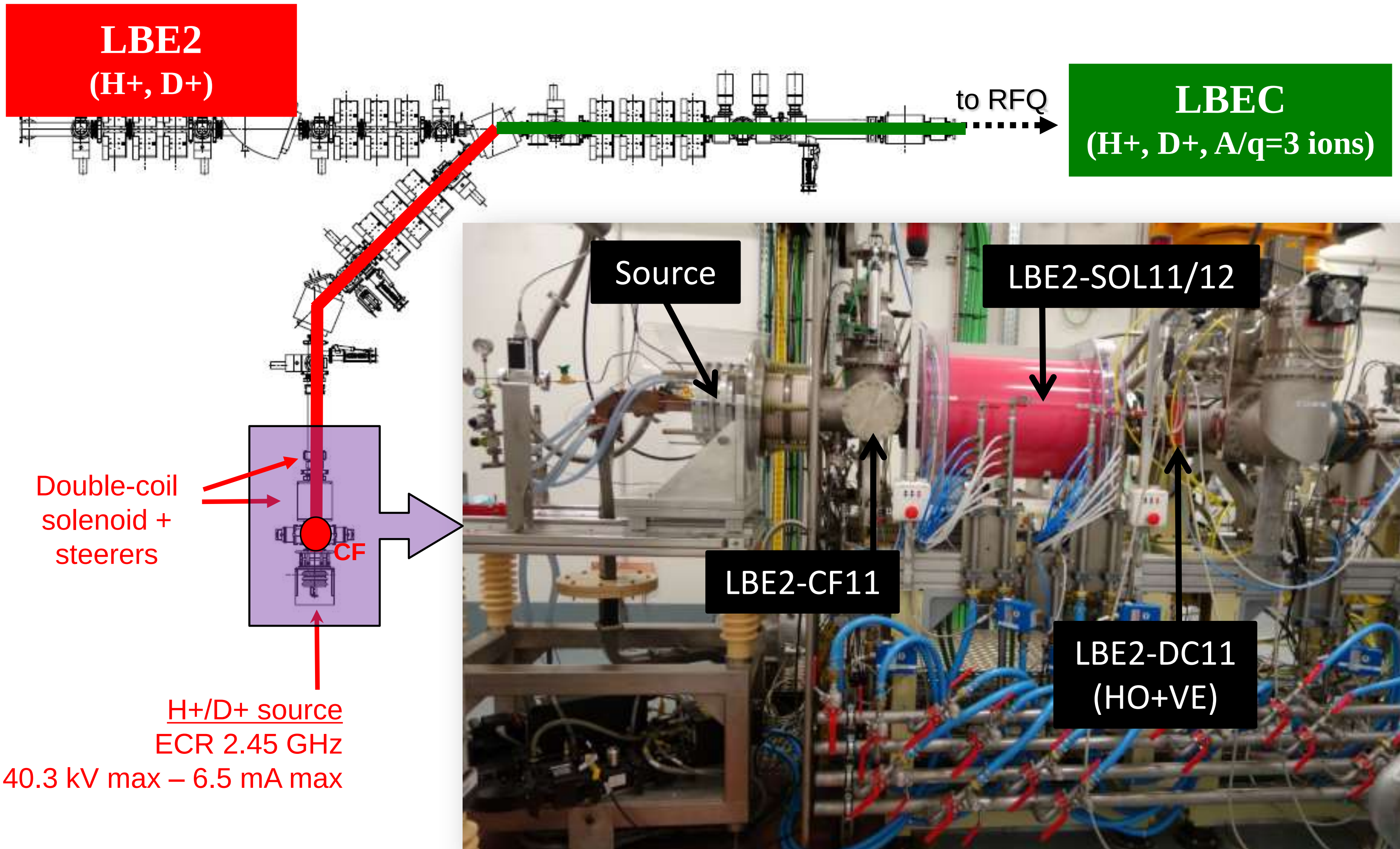


# LBE1 DESCRIPTION (6/6)

**LBE1**
**(ions A/q=3)**

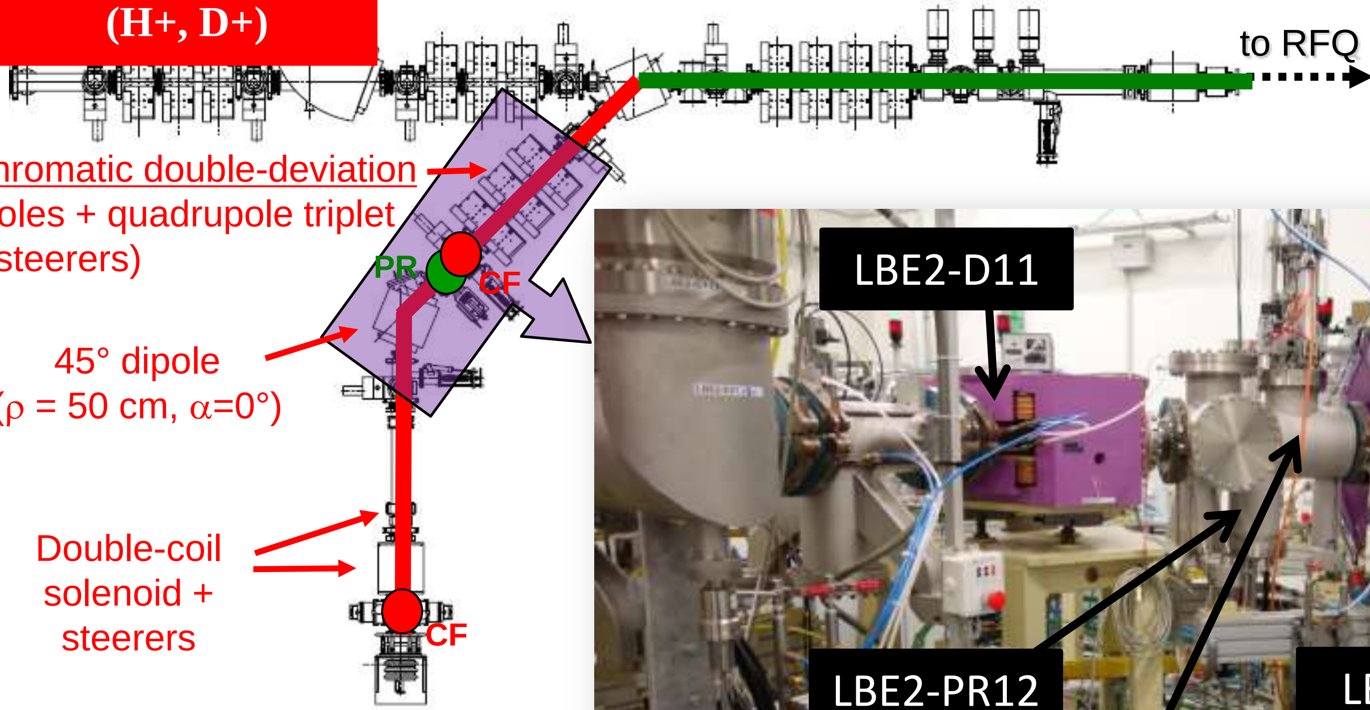


# LBE2 + LBEC DESCRIPTION (1/4)



# LBE2 + LBEC DESCRIPTION (2/4)

**LBE2**
**(H+, D+)**



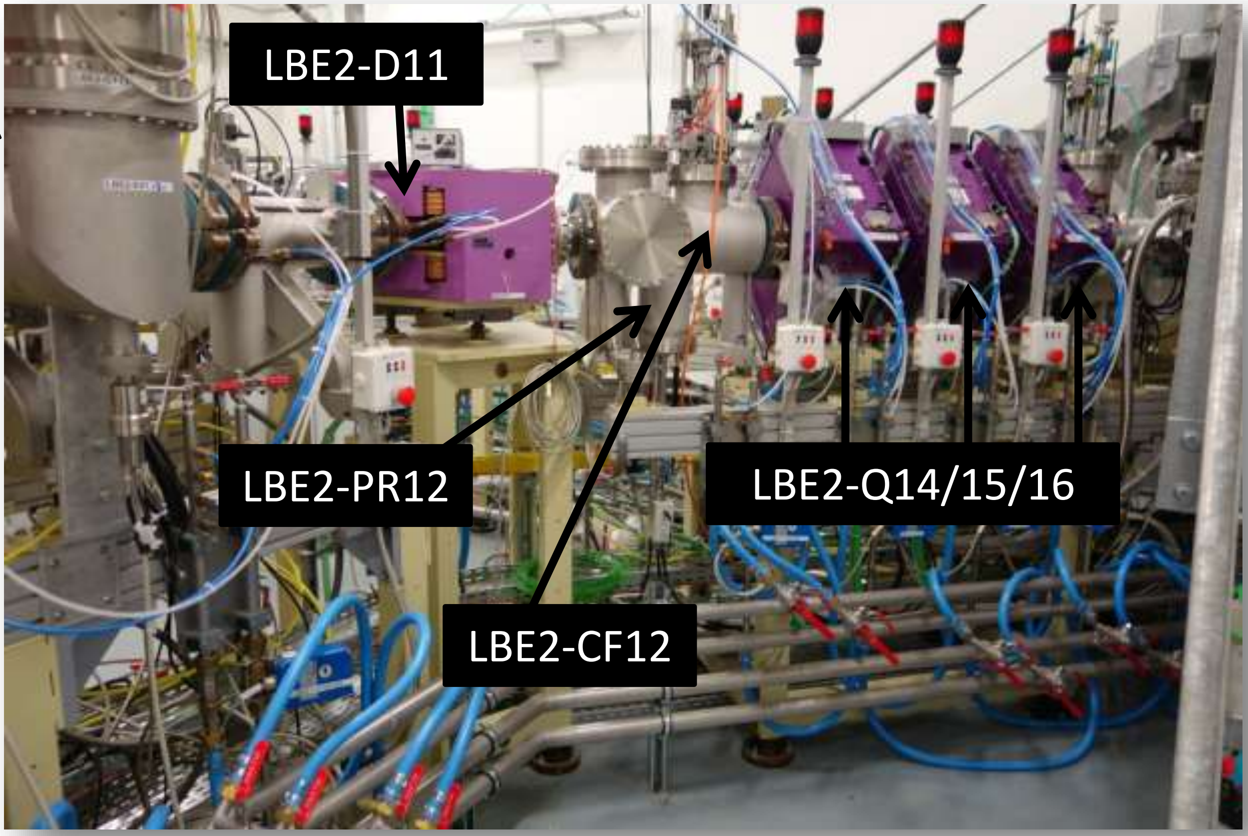

**LBEC**
**(H+, D+, A/q=3 ions)**

Achromatic double-deviation dipoles + quadrupole triplet (& steerers)

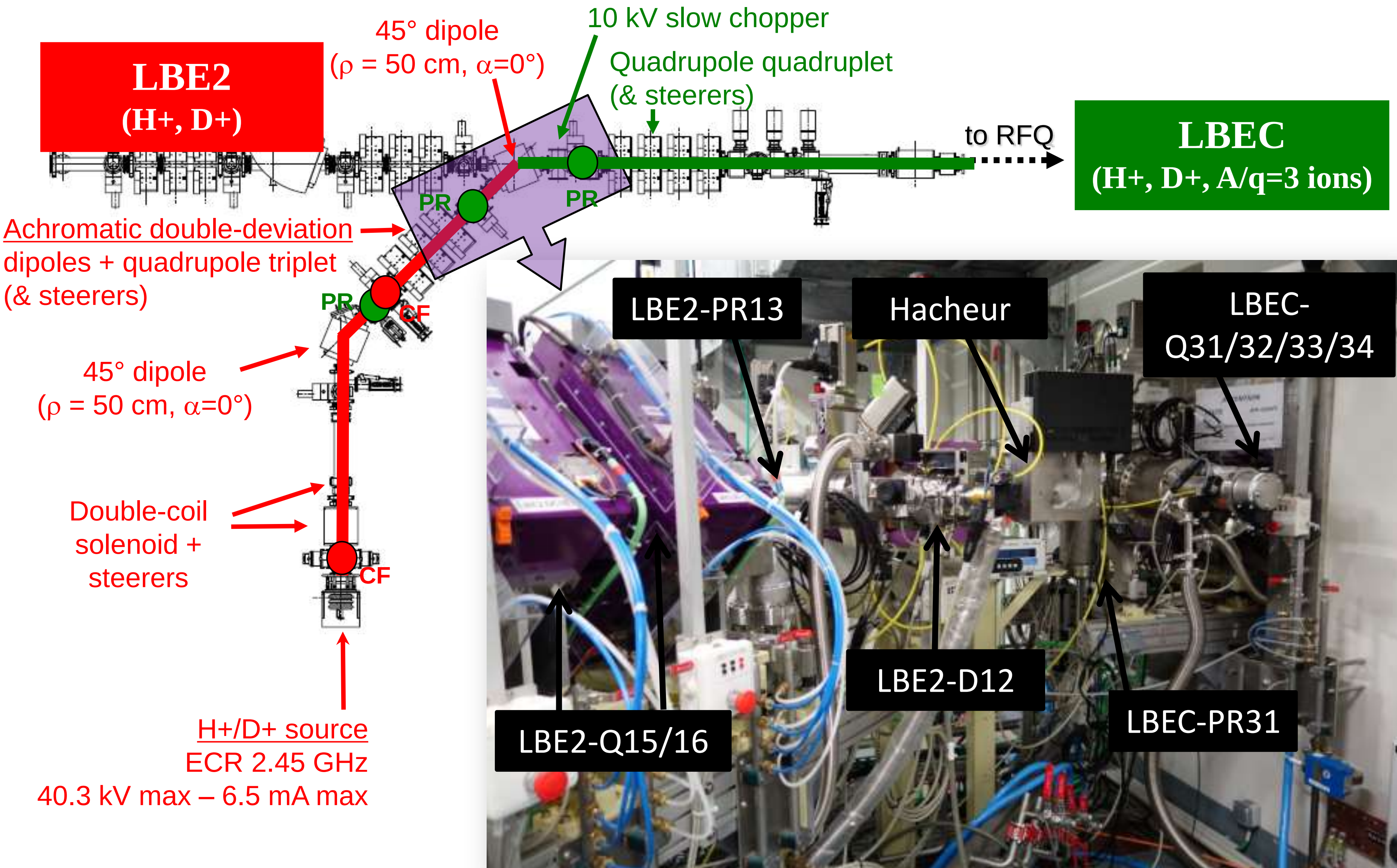
45° dipole
($\rho$ = 50 cm, $\alpha$=0°)

Double-coil solenoid + steerers

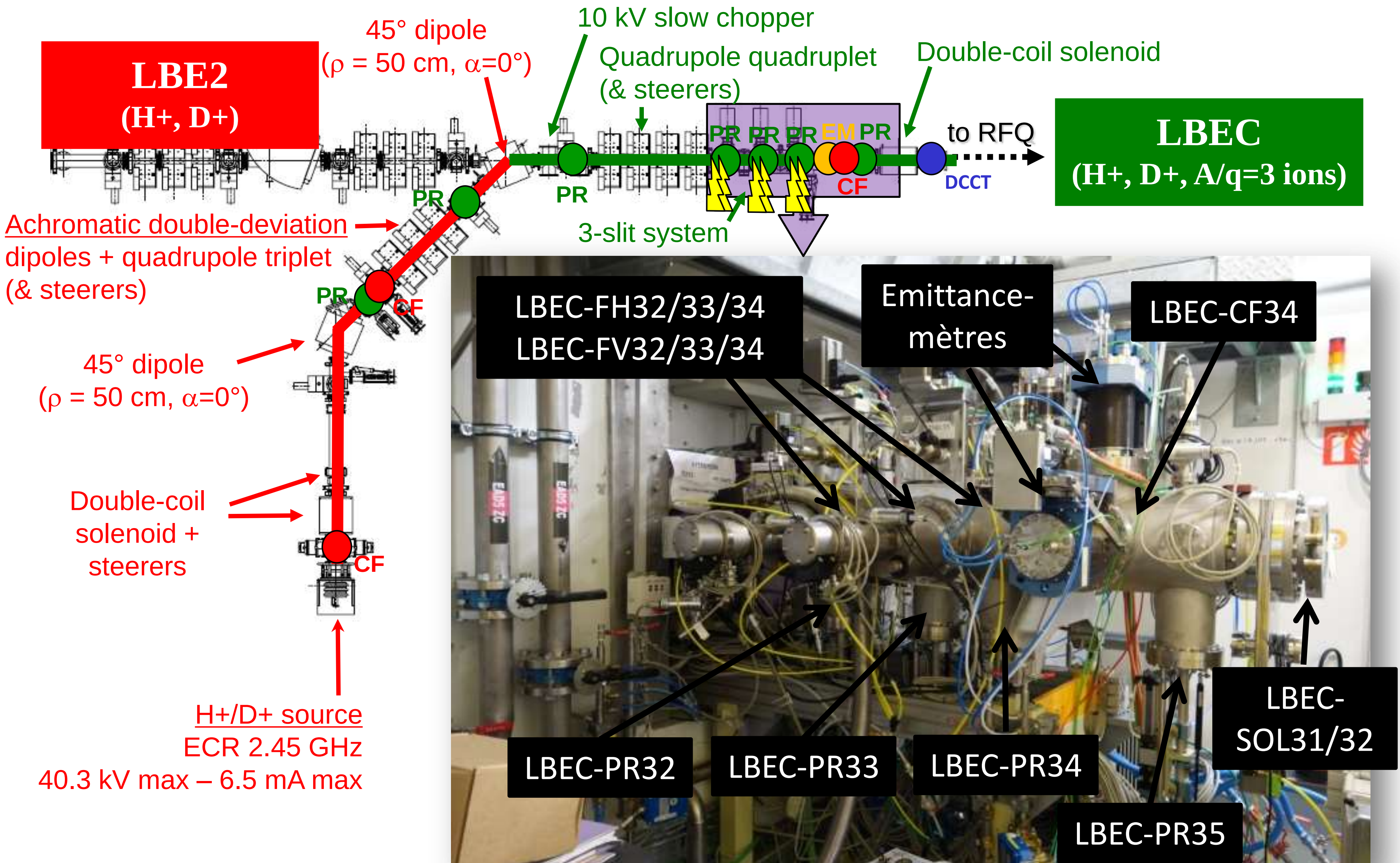
H+/D+ source
ECR 2.45 GHz
40.3 kV max – 6.5 mA max



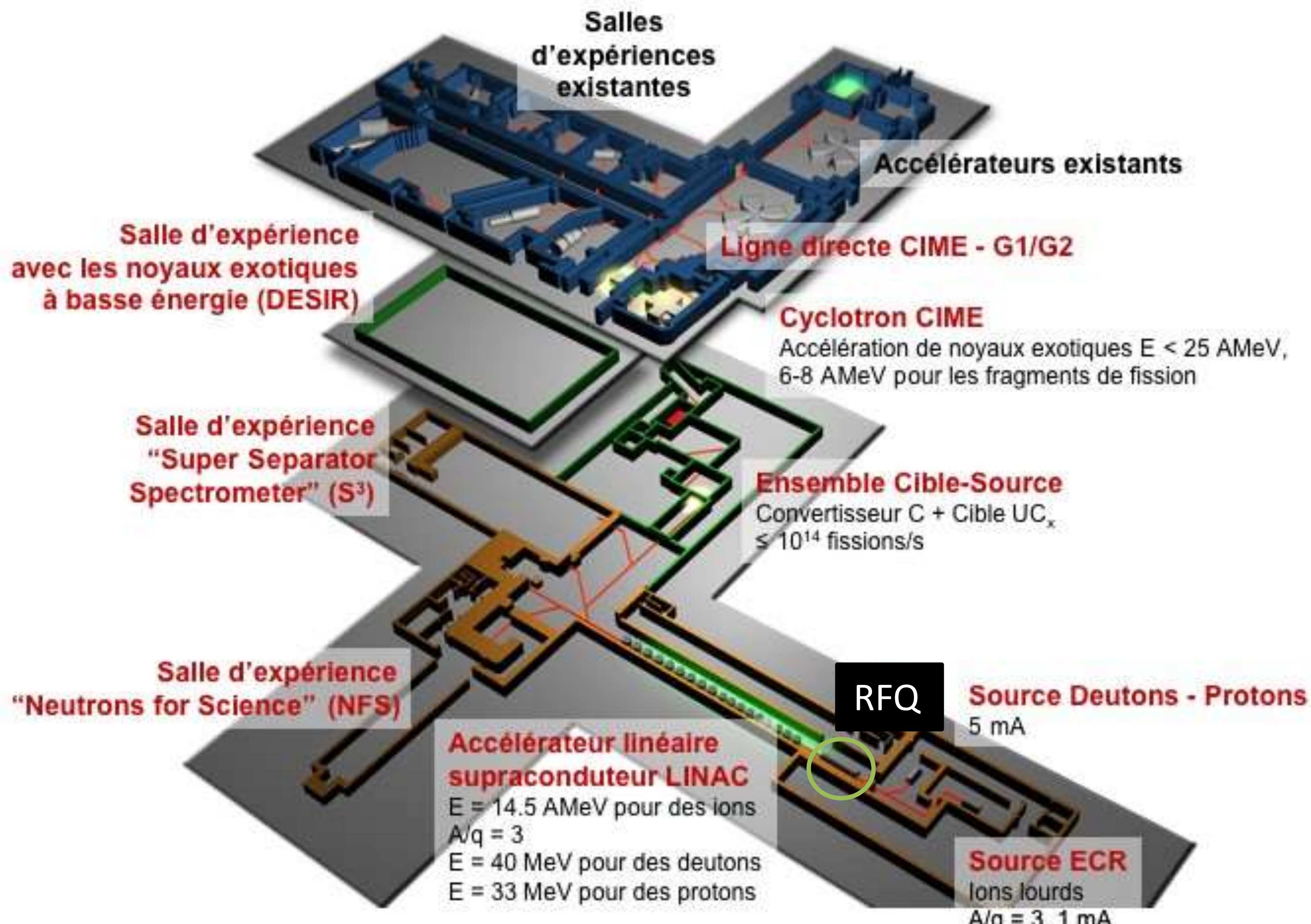
# LBE2 + LBEC DESCRIPTION (3/4)



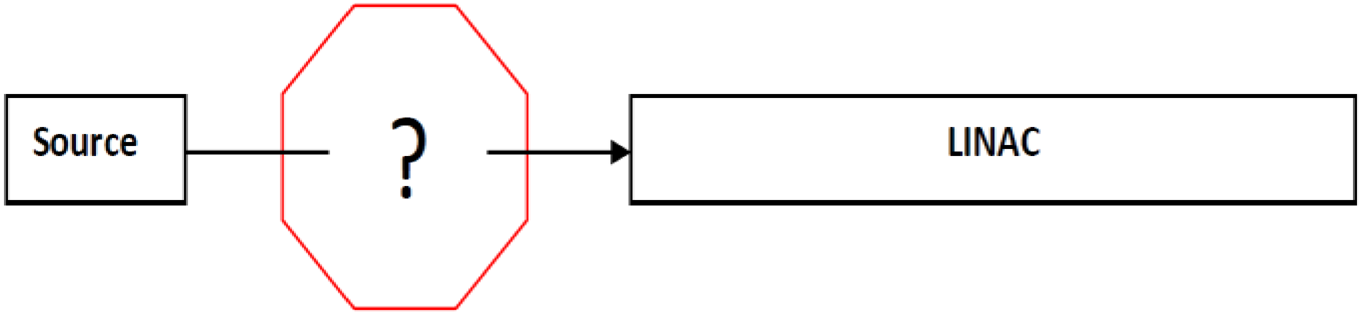
# LBE2 + LBEC DESCRIPTION (4/4)



## 3. THE SPIRAL2 RFQ



## WHY A RFQ IS NEEDED ?



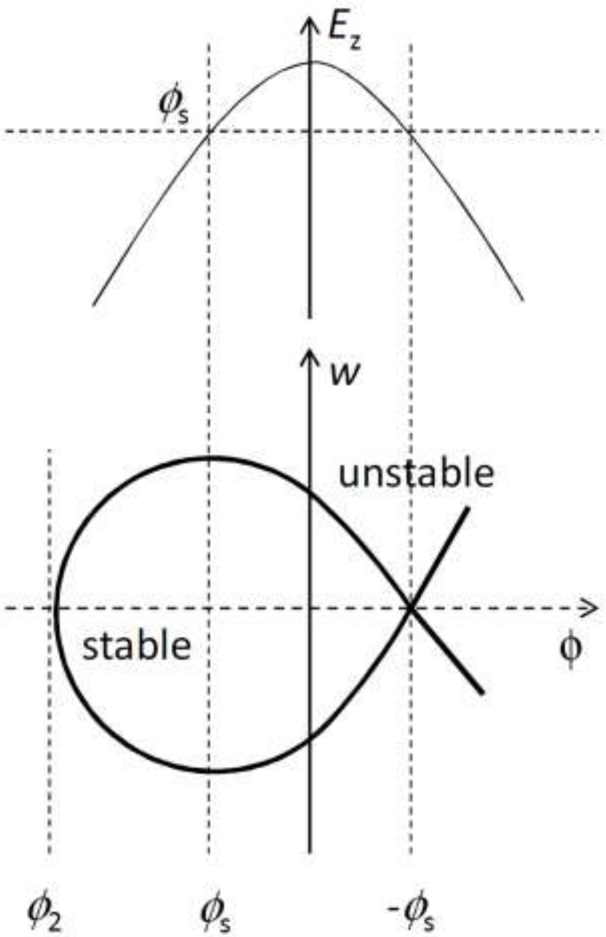

**What we have to put between the source and the LINAC for :**

#1 : obtain a good transmission of the LINAC ($I_{LINAC} = I_{Source}$)

#2 : obtain a good efficiency of the LINAC (energy gain per cavity)

**?**

# #1 : A GOOD TRANSMISSION OF THE LINAC




**Production of ions by the source is a continuous beam**

**LINAC need particles bunches**

**Phase acceptance ~ 3 $\Phi_s$** (acceleration)

↓

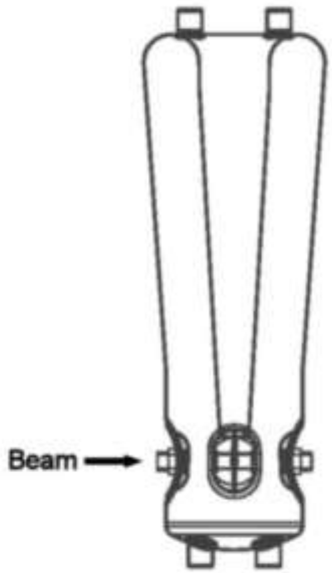
**Continuous beam produce by the source have to be regroup in bunches ($f_{rf}$)**

Numerical application :

$\Phi_s = -30°$ => efficiency = $3 x 30 / 360 = 25$ %

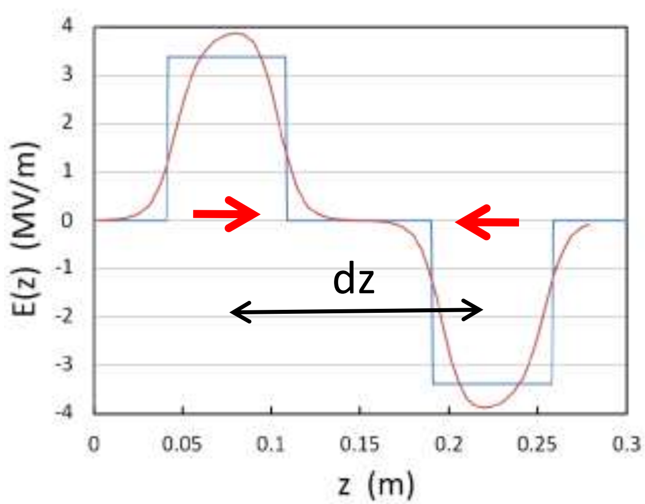
75% of particles are lost if no bunches

## #2 : A GOOD ACCELERATION IN THE LINAC




Particles must be in synchronism with the accelerating field in order to have a maximum energy gain per cavity.

Ions speed is imposed by the geometry and the frequency of the LINAC cavities



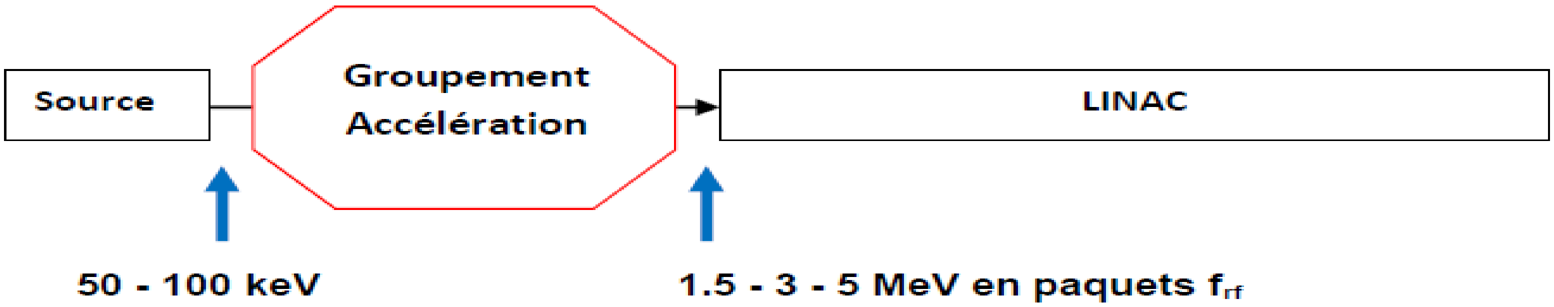

$$dT = \frac{T_{rf}}{2} \qquad dT = \frac{dz}{v} = \frac{dz}{\beta c} \qquad \beta = \frac{2\,dz}{c\,T_{rf}} = \frac{2\,dz}{\lambda_{rf}}$$

Numerical application :

$88\ MHz \Rightarrow \lambda_{rf} = 3.4\ m \qquad dz = 10\ cm$

$\beta = 0.06 \Rightarrow$ $\boldsymbol{W\ Protons = 1.6\ MeV}$

# IDEAL SYSTEM BETWEEN SOURCE AND LINAC




-1- Efficient bunching at the RF frequency
$\Rightarrow$ Set of "bunching cavities" at $f_{rf}$ (adiabatic bunching, $\rho > 95\%$)

-2- Acceleration at high energy ($V_{acc} > 1\ MV$)
$\Rightarrow$ Set of "accelerating cavities" at $f_{rf}$ (LINAC)

-3- Radial focalization in order to don't lose particles

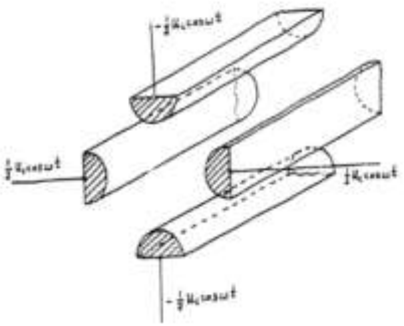
**-1- + -2- = RF structure => Radio-Frequency Quadrupole (RFQ)**

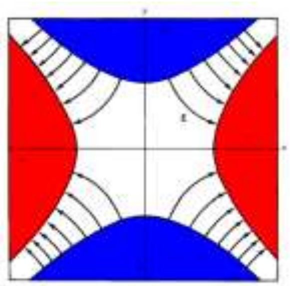
First publication : I.M. Kapchinskiy, V.S. Tepliakov, Prib. Tekh. Eksp. 2, 19-22 (1970)

At Los Alamos : R.H. Stokes, **K.R. Crandall**, J.E. Stovall, and D.A. Swenson, " RF Quadrupole beam dynamics", PAC79

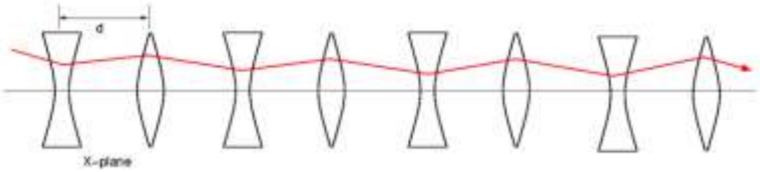
In Europe (LNS-Saclay) : J-L. Laclare, M. Olivier et all, design in 1982 => 1st beam in 1984

# FEW ASPECTS OF RFQ

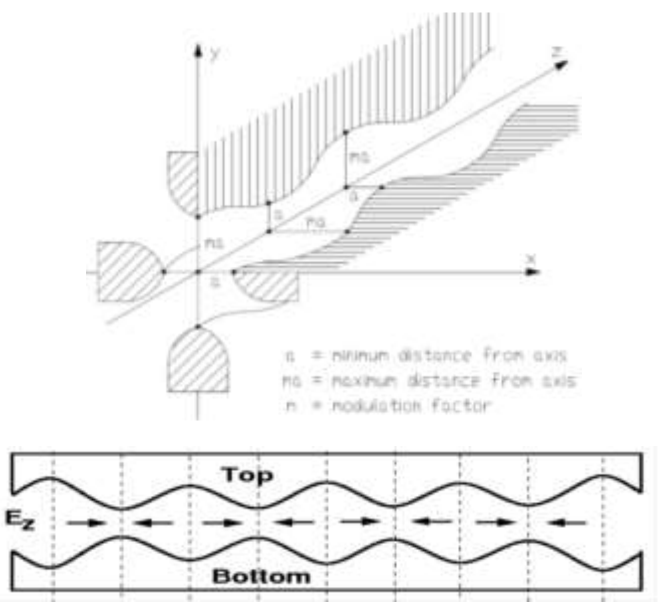




The electric field oscillate at the RF frequency
⇒Transport of the particles in a series of focusing and defocusing quadrupoles




**Alternating focusing**
No $E_z$ longitudinal component ⇒ No acceleration




Electrodes modulation des électrodes in order to create a longitudinal component $E_z(z)$

⇒ Continuous series of “cavities”

⇒ Radial focusing

+ Progressive bunching of the beam

+ Acceleration of bunches

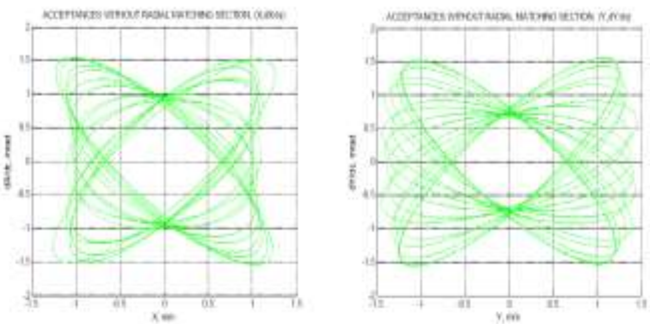
# 5 SECTIONS OF THE RFQ (1/5)

- **Section 1 – Radial adaptation at the entrance** ("Radial Matching section")

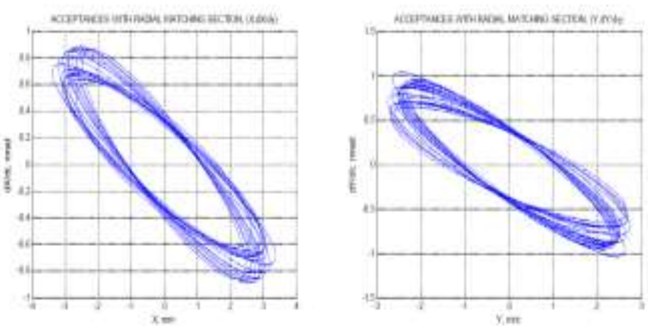
Make a beam with small dimensions ($r_{max} \sim 5\ mm$)

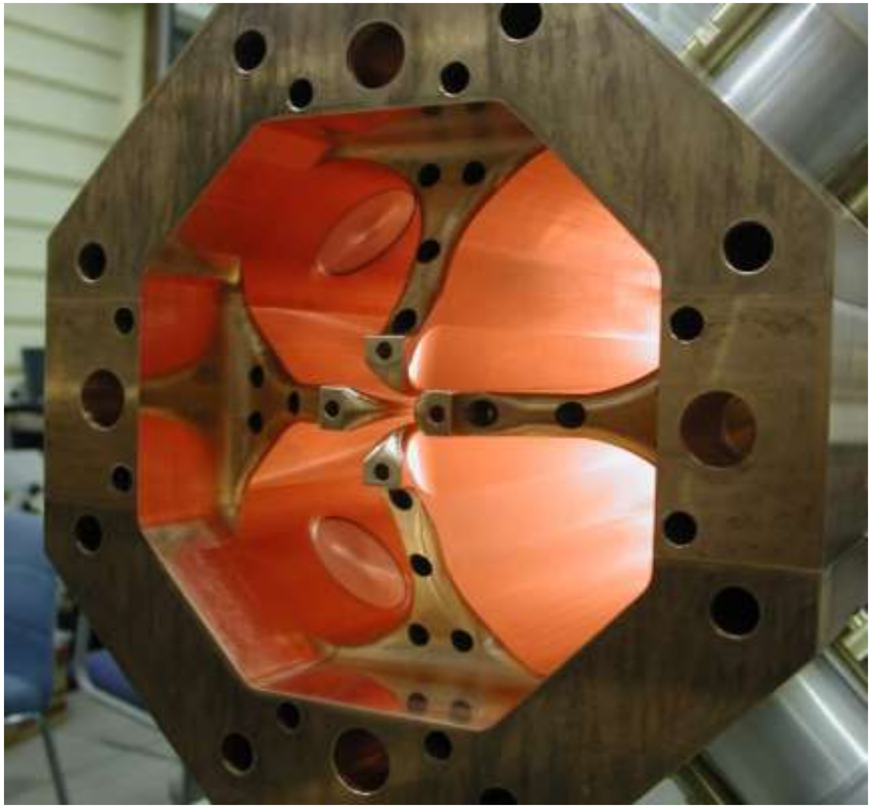
Progressive adaptation of the beam at the RF focalisation (as a function of time)

Acceptances without radial adaptation



Acceptances with radial adaptation





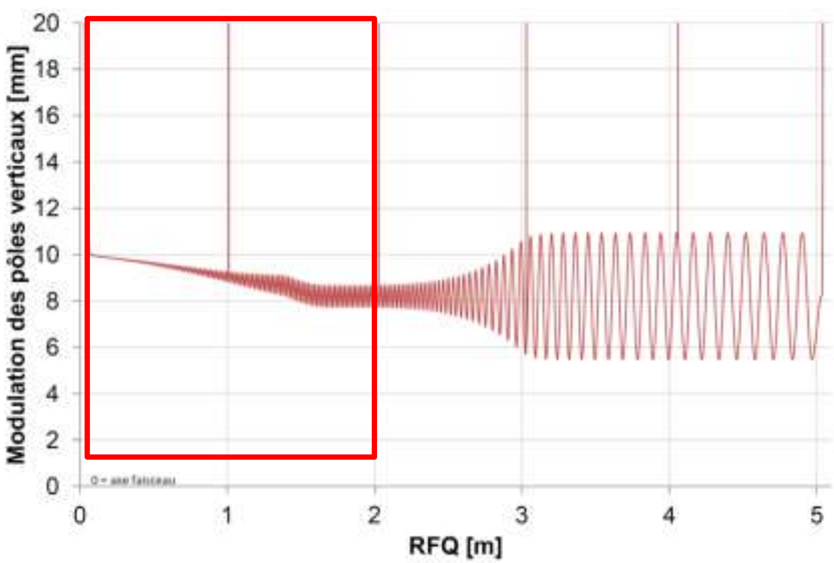
# 5 SECTIONS OF THE RFQ (2/5)

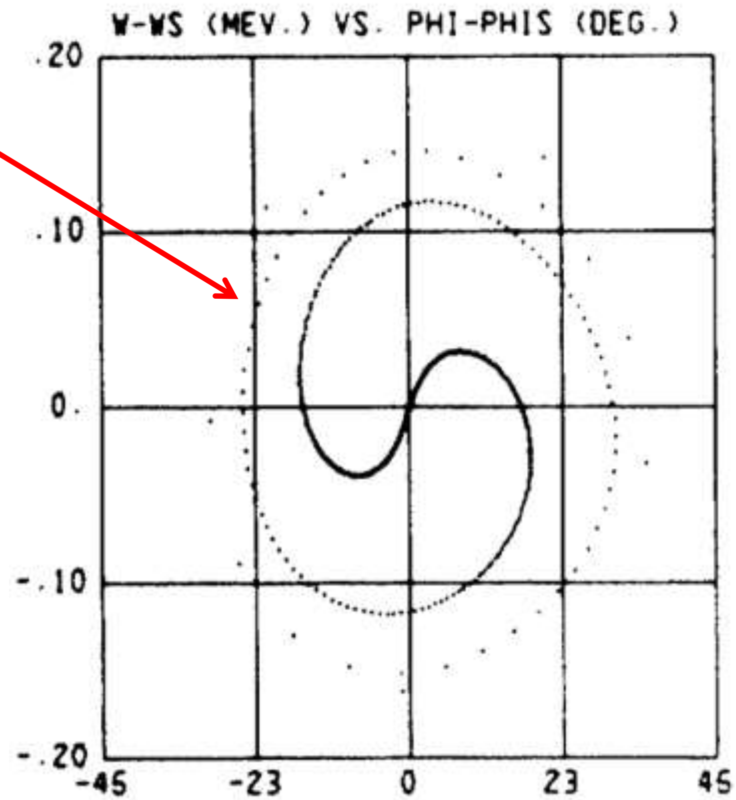
- **Section 2 – Shaper section « Mise en forme des paquets »**

Almost no acceleration ($\Phi s \sim -90°$)

Very slow increasing of the modulation for start the adiabatic bunching

Particles of group at the center of the bucket
Good emittance / little halo



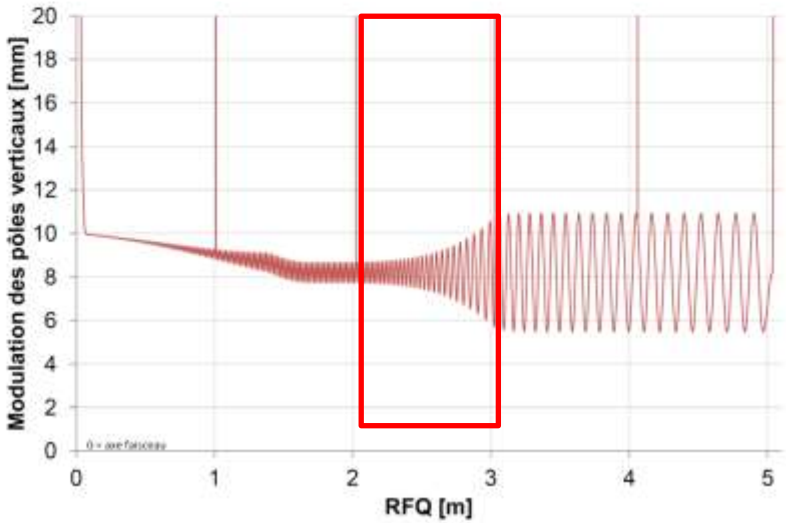



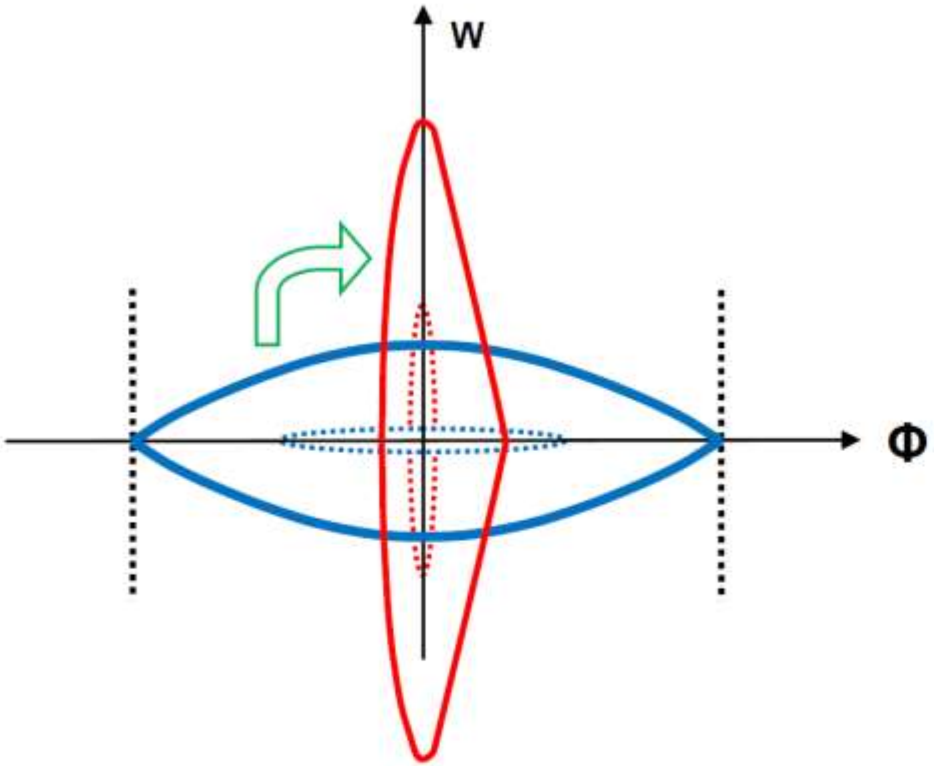
# 5 SECTIONS OF THE RFQ (3/5)

➢ **Section 3 – Adiabatic bunching or "Gentle buncher section"**

Progressive acceleration until nominal acceleration rate

Progressive variation of phase $\Phi_s$ $(-90° \Rightarrow -30°)$ and modulation (1.1 => 2.0)



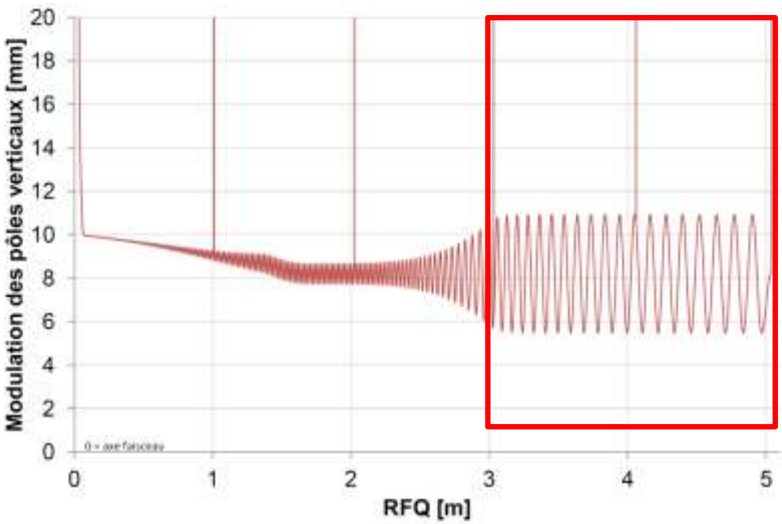



# 5 SECTIONS OF THE RFQ (4/5)

- **Section 4 – Acceleration or "accelerating section"**

Constant parameter for the maximum accelerating rate

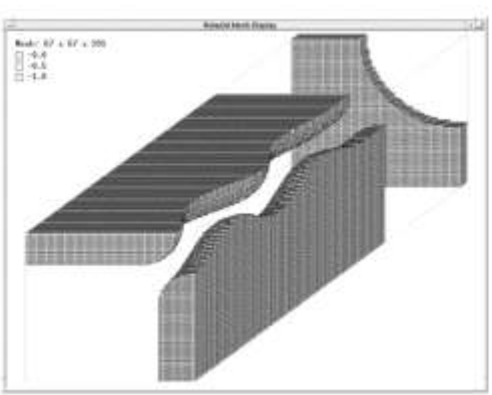
$\Phi_s = -30°, modulation = 2,\ V = V_{max}$




# 5 SECTIONS OF THE RFQ (5/5)

- **Section 5 – Exit matching section**

Taking into account of the fringed fields (champ de fuite) at the exit of the RFQ (radial and longitudinal effects)



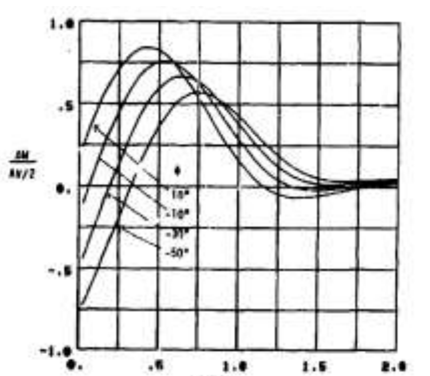
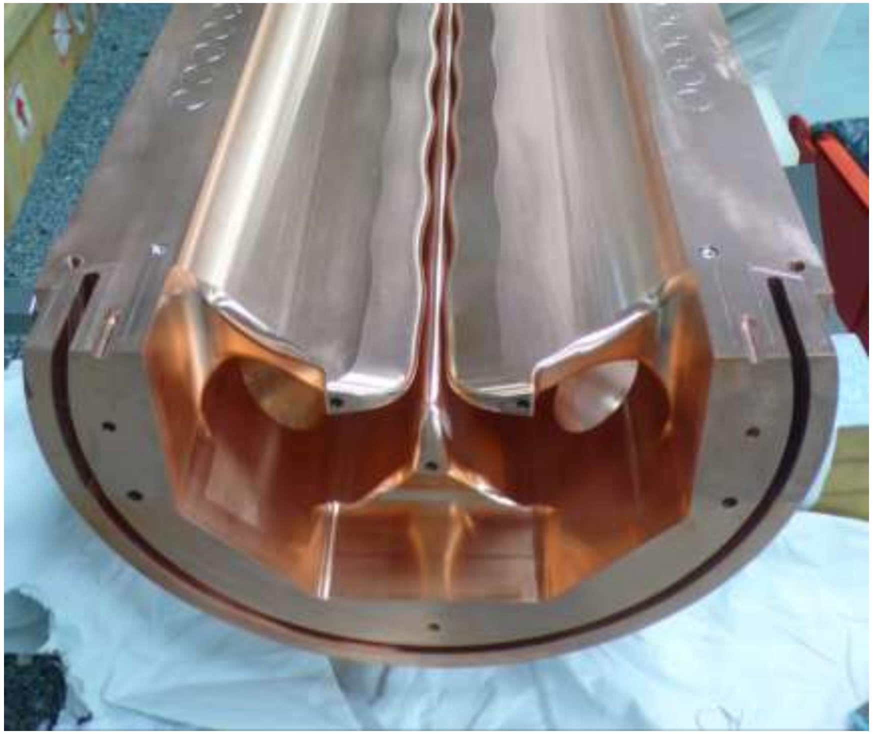
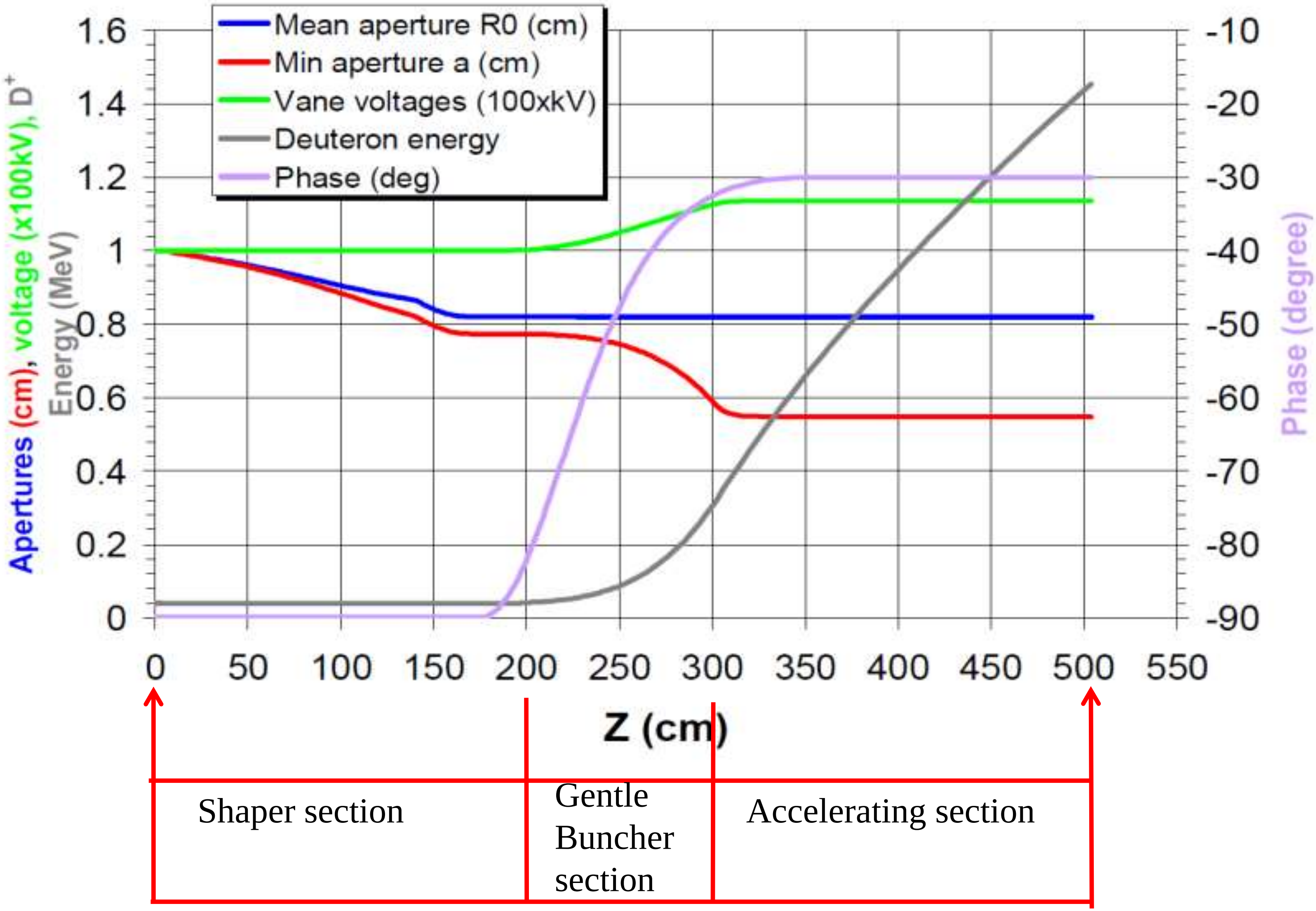


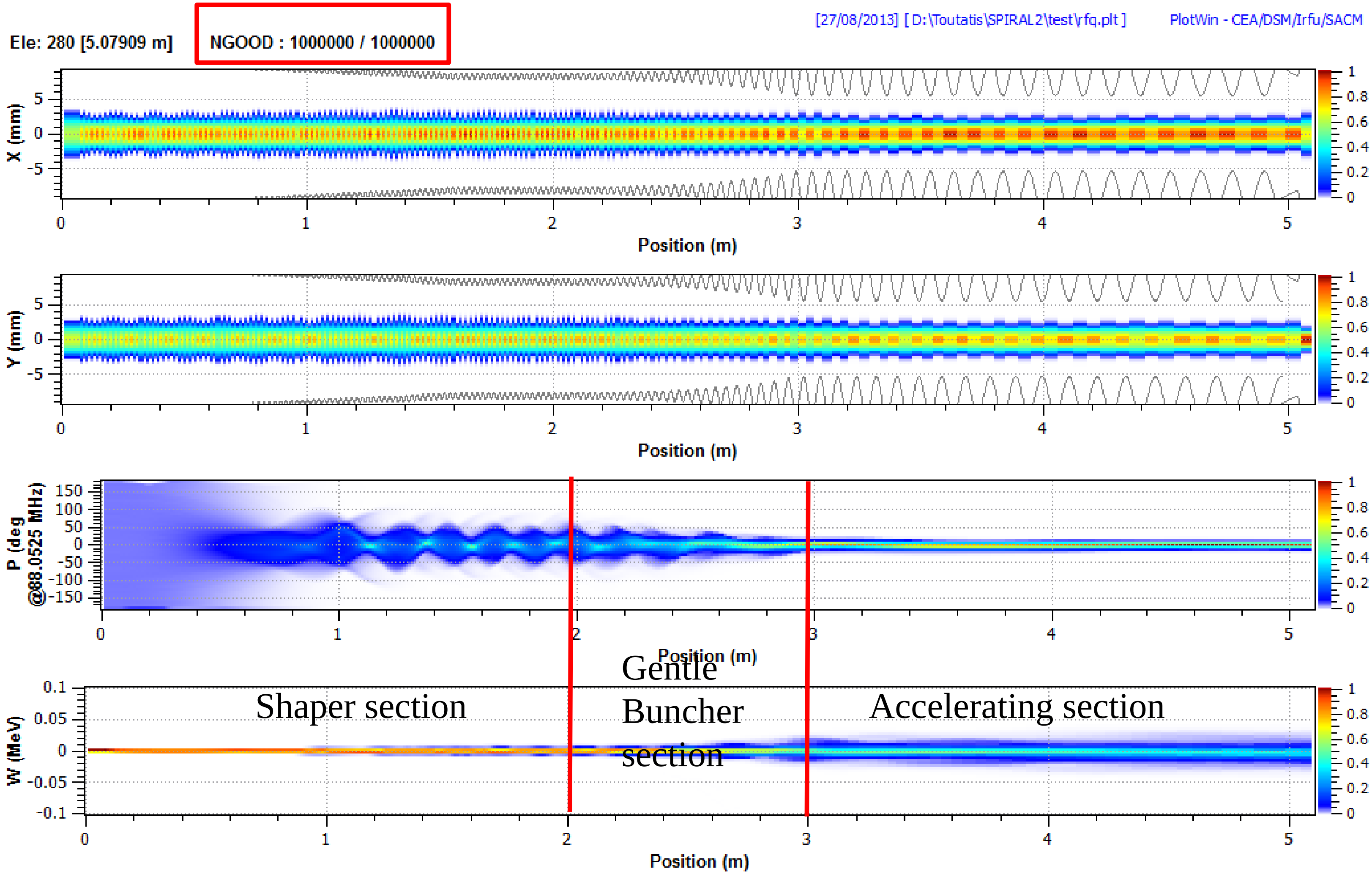

Fig. 3. Change in energy of a particle in the fringe region as a function of fringe length L plotted for several initial phases φ, assuming potential function from eq. (7).



# PARAMETERS OF THE SPIRAL2 RFQ



# BEAM CALCULATION OF THE SPIRAL2 RFQ

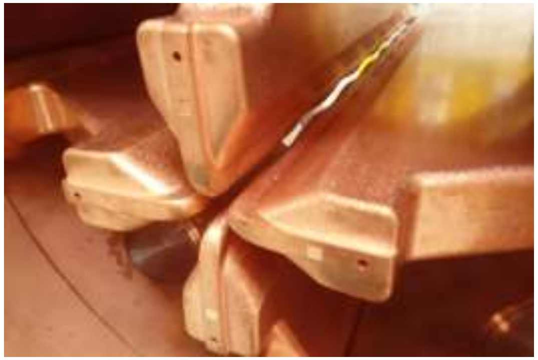


# FROM PROTOTYPE TO OPERATION

**Prototype**

Careful attention must be taken :

- To obtain tension law and the good frequency
- Cooling
- Manufacturing tolerances ($\pm 65\mu m$) and assembly ($\pm 100\mu m$)



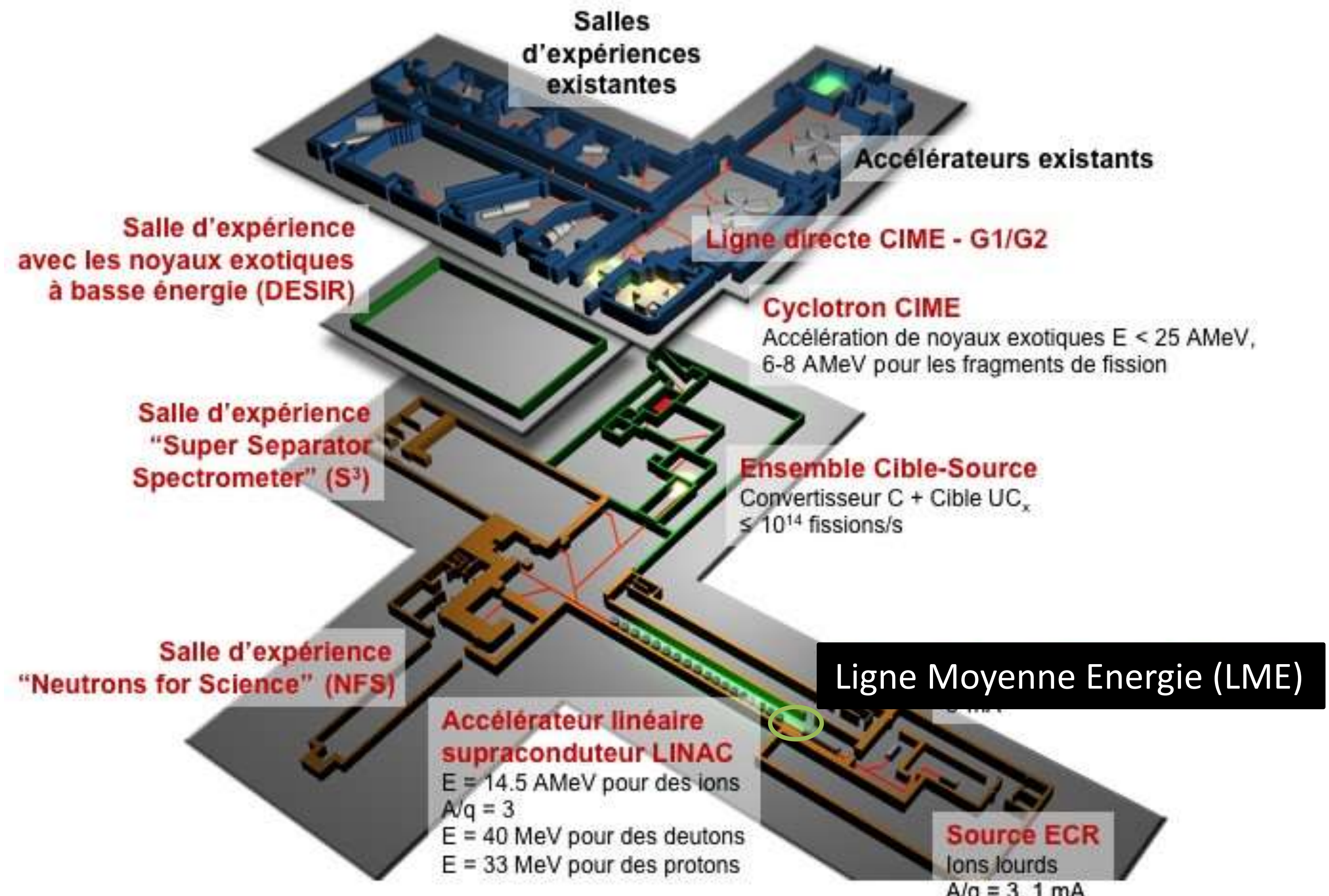
**Final RFQ :** Assembling

# FROM PROTOTYPE TO OPERATION

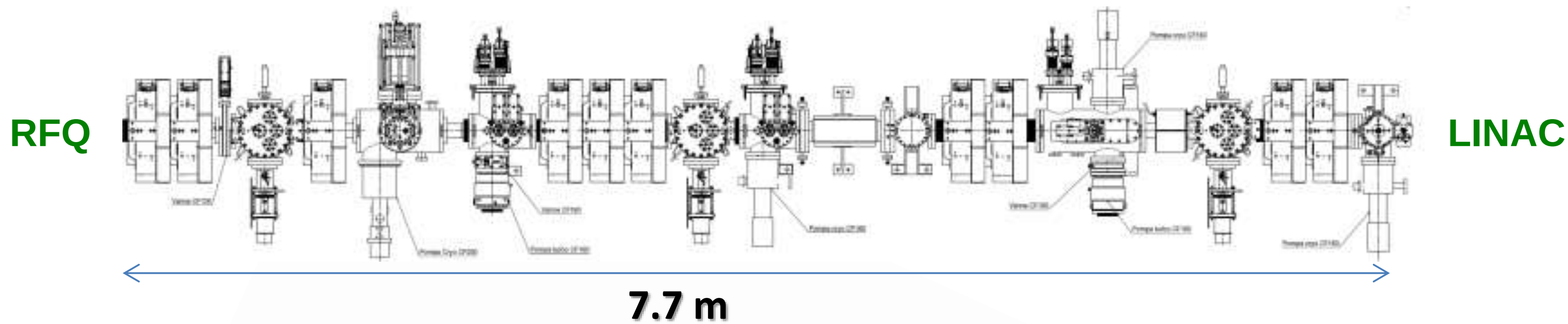
**On site …**

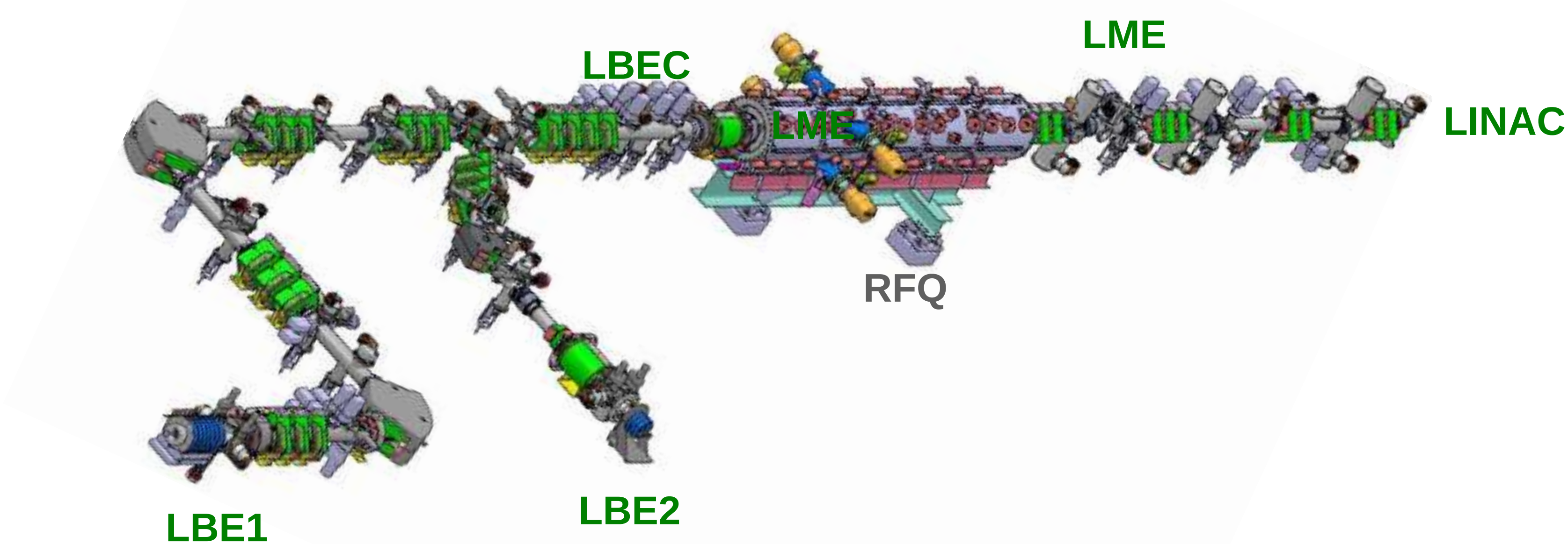
**Ready for beam !**

# 4. THE MEDIUM ENERGY BEAM TRANSPORT (MEBT)



## GENERAL VIEW OF THE MEBT



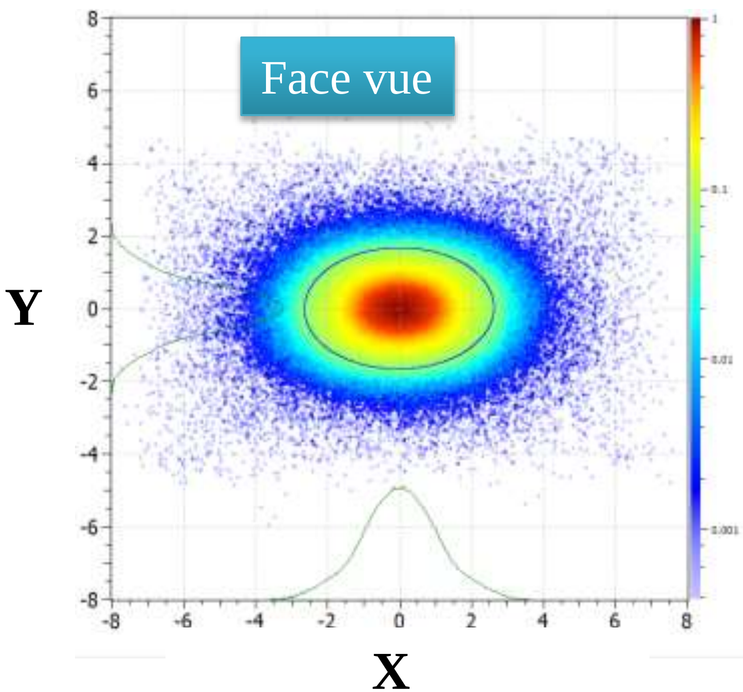



## BEAM CHARACTERISTICS AFTER THE RFQ

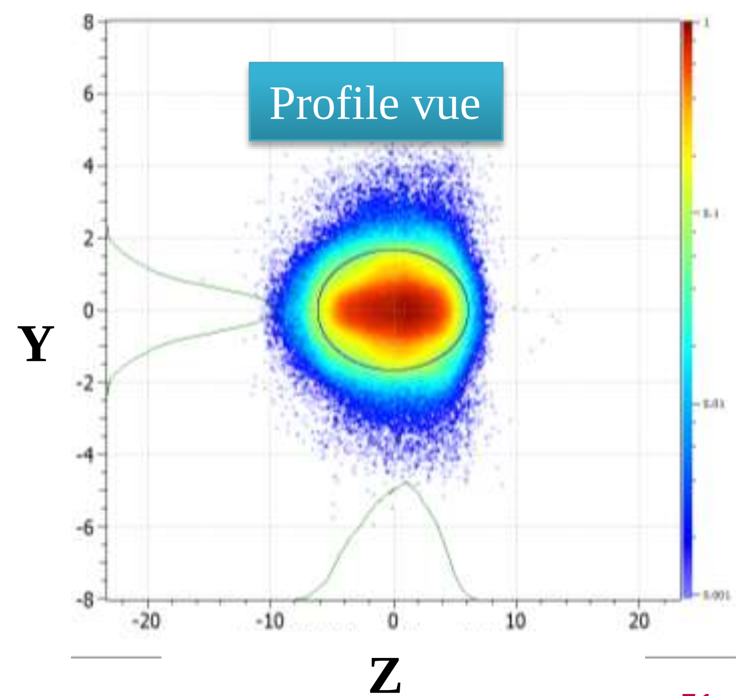
### RFQ exit:

- Beam : bunched **(88 MHz)**
- Speed : $\boldsymbol{\beta = 0.04}$
- Current : **100** µ$\boldsymbol{A}$ to **5** $\boldsymbol{mA}$
- Power : up to **7 kW**
- Particles : **Protons, Deuterons, heavy ions**
- Mass/charge ratio A/q : **1** to **7**
- Energy : **0.75 MeV/A**
- Duty cycle : **0.1% à 100%**

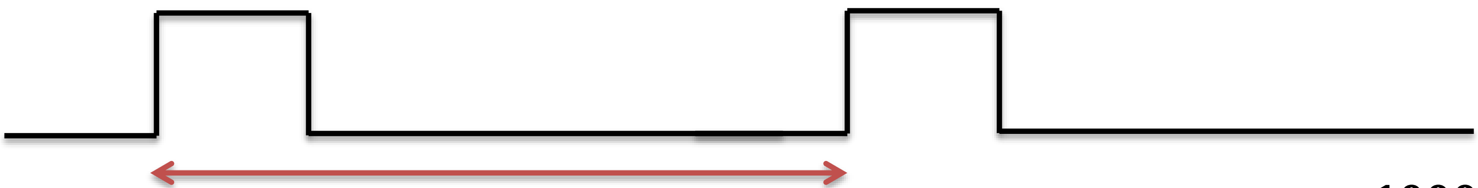
**Z is the beam direction (longitudinal axis)**




Example:
Deuterons
at 5 mA

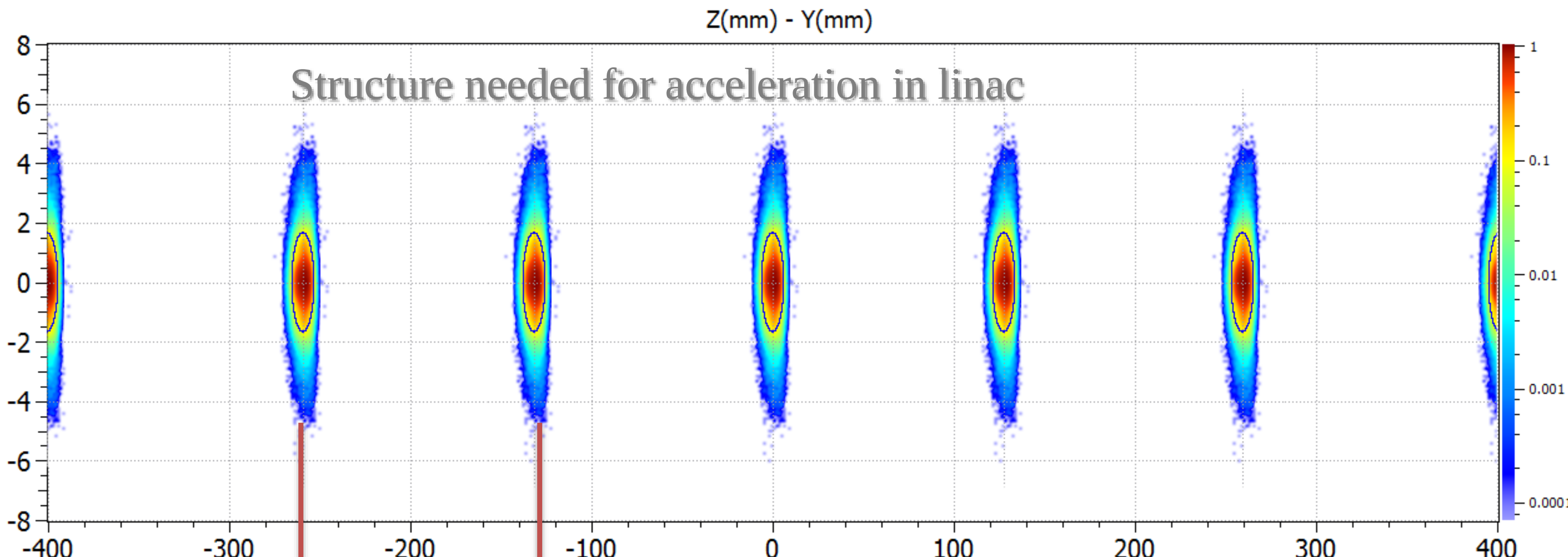


## BEAM CHARACTERISTICS : TIME STRUCTURE



**~10000 bunches**

**Duty cycle : 0.1% to 100%, pulse length 0.1ms to 1s**

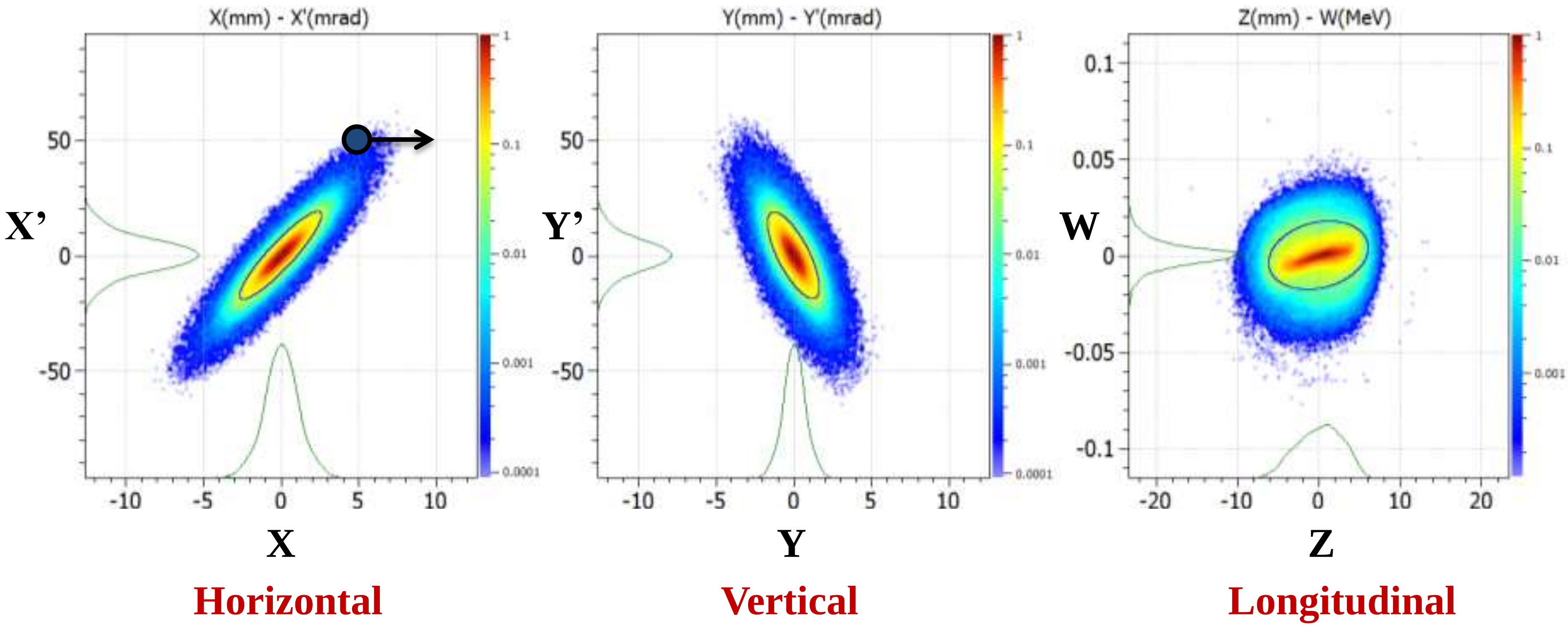



130 mm or 12 ns or 360°

Bunch frequency : 88 MHz

# BEAM CHARACTERISTICS : PHASE SPACE

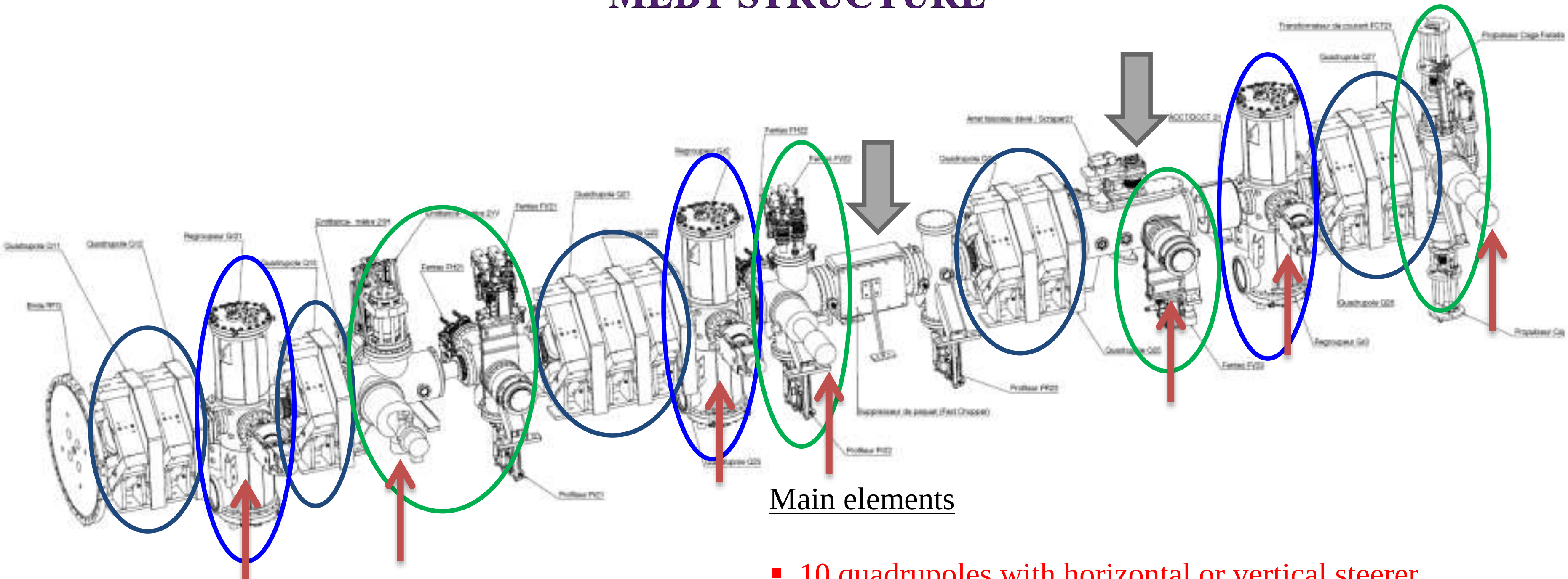
Phase spaces, emittances: ε




**Large transverse divergence + space charge**

**Example** : One particle with 5 mm, 50 mrad → after z=10cm, position is **10 mm**

## MEBT STRUCTURE



**Focusing devices**

**Acceleration**

**Diagnostics**

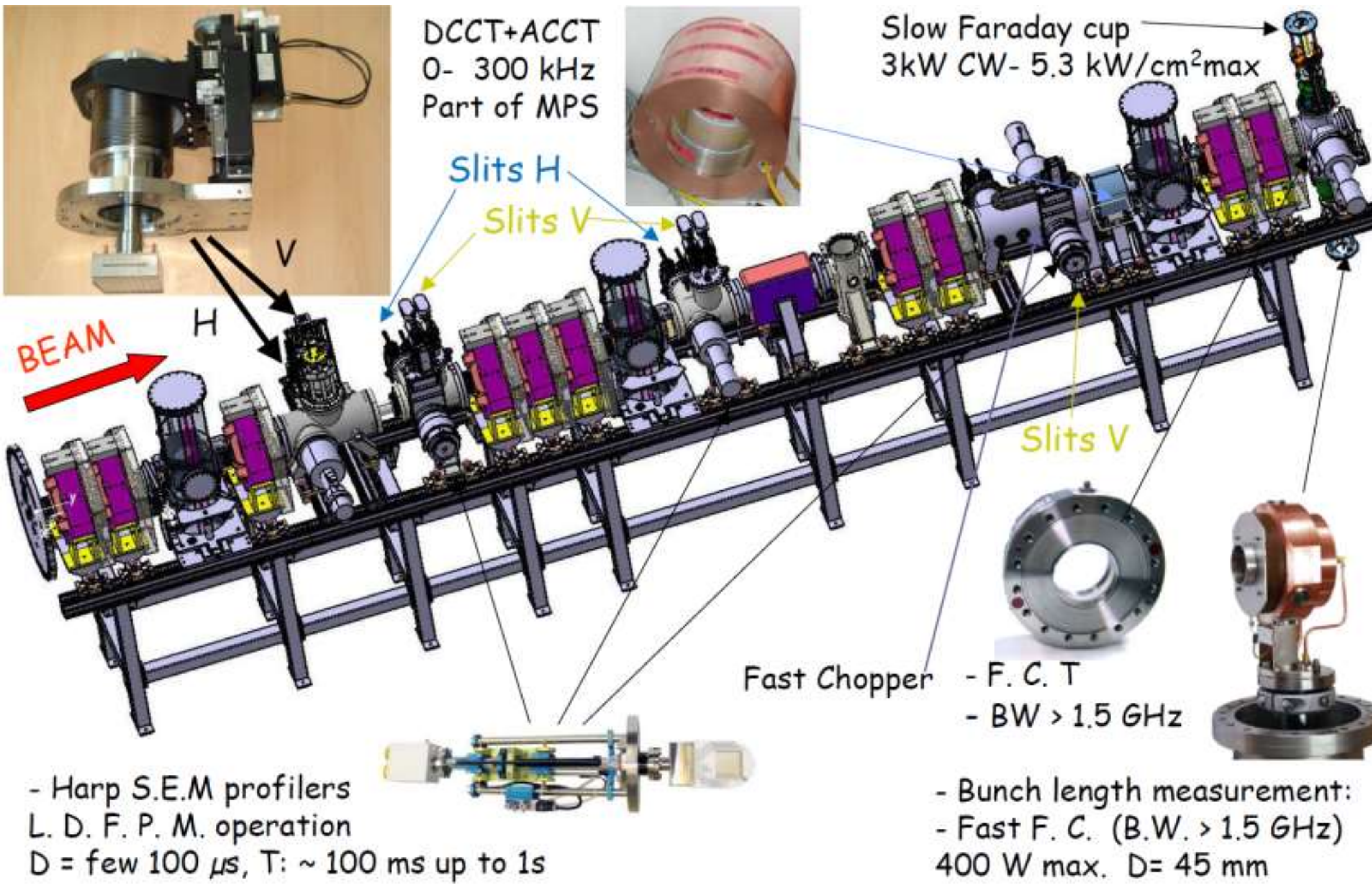
**Pumping device**

**Bunch selector**

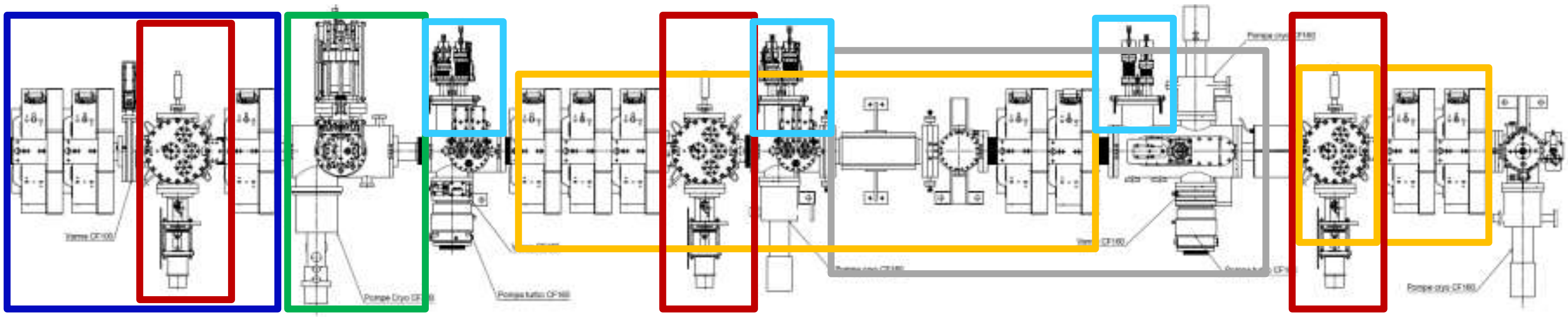
Main elements

- 10 quadrupoles with horizontal or vertical steerer
- 3 rebuncher
- 3 sets of vertical and horizontal slits
- 3 sets of beam profilers (vertical and horizontal)
- 1 device for transverse emittance measurement
- 1 DCCT (beam current)
- 1 rapid Faraday cup
- 1 FCT (current and phase extension measurement)
- 7 location for pumping system
- Electromagnetic dipole
- Beam stopper
- Rapid chopper (bunch suppressor)

## MEBT DIAGNOSTICS



# MEBT FUNCTIONS



**The 6 main functions of the MEBT :**

**1 – Provide focusing and maintain the beam bunched at the RFQ exit**

**2 – Ensure a possible upgrade of the accelerator with future A/Q=6 beam line**

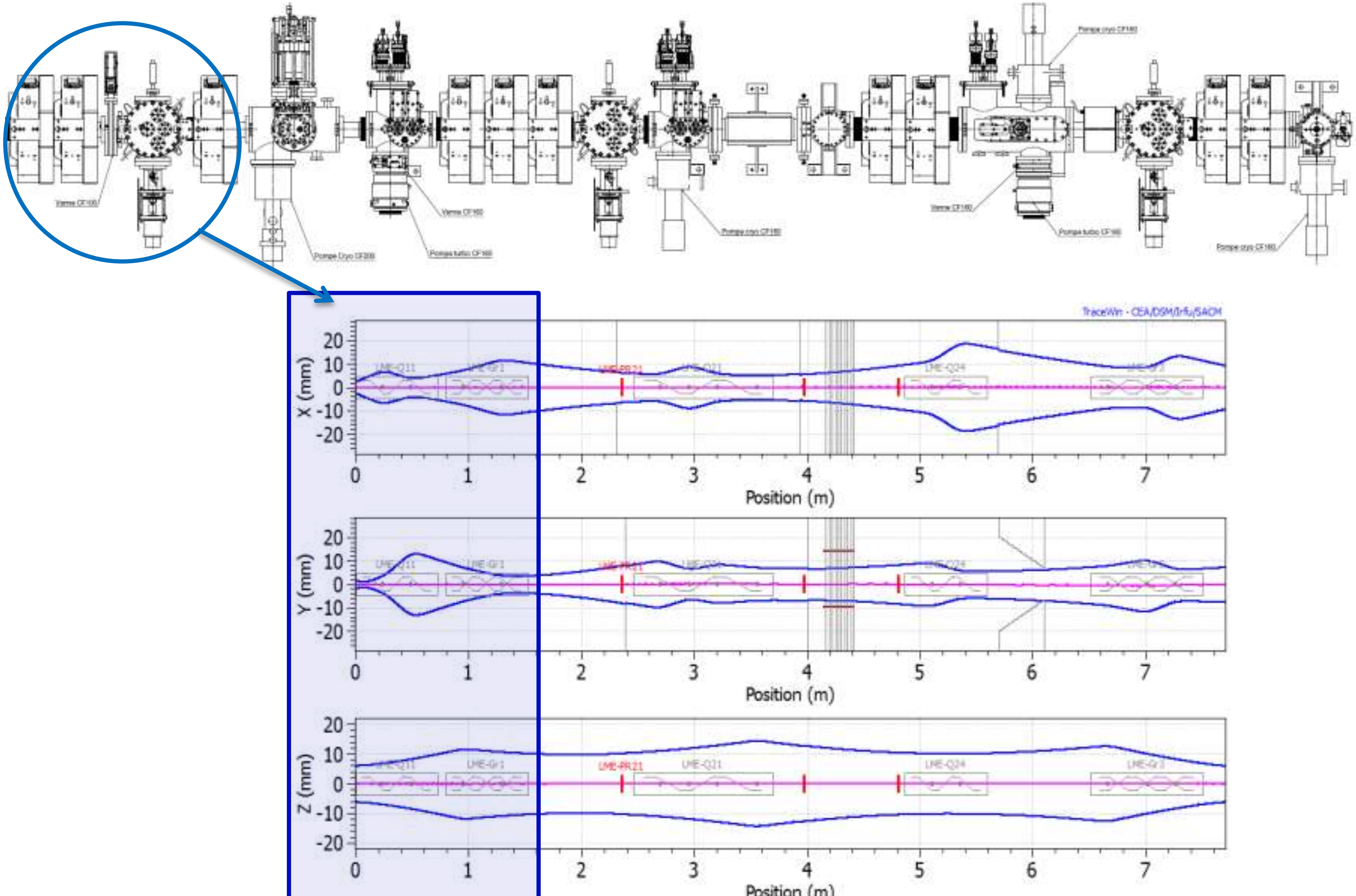
**3 – Maintain beam bunched for the LINAC**

**4 – Cleaning the beam**

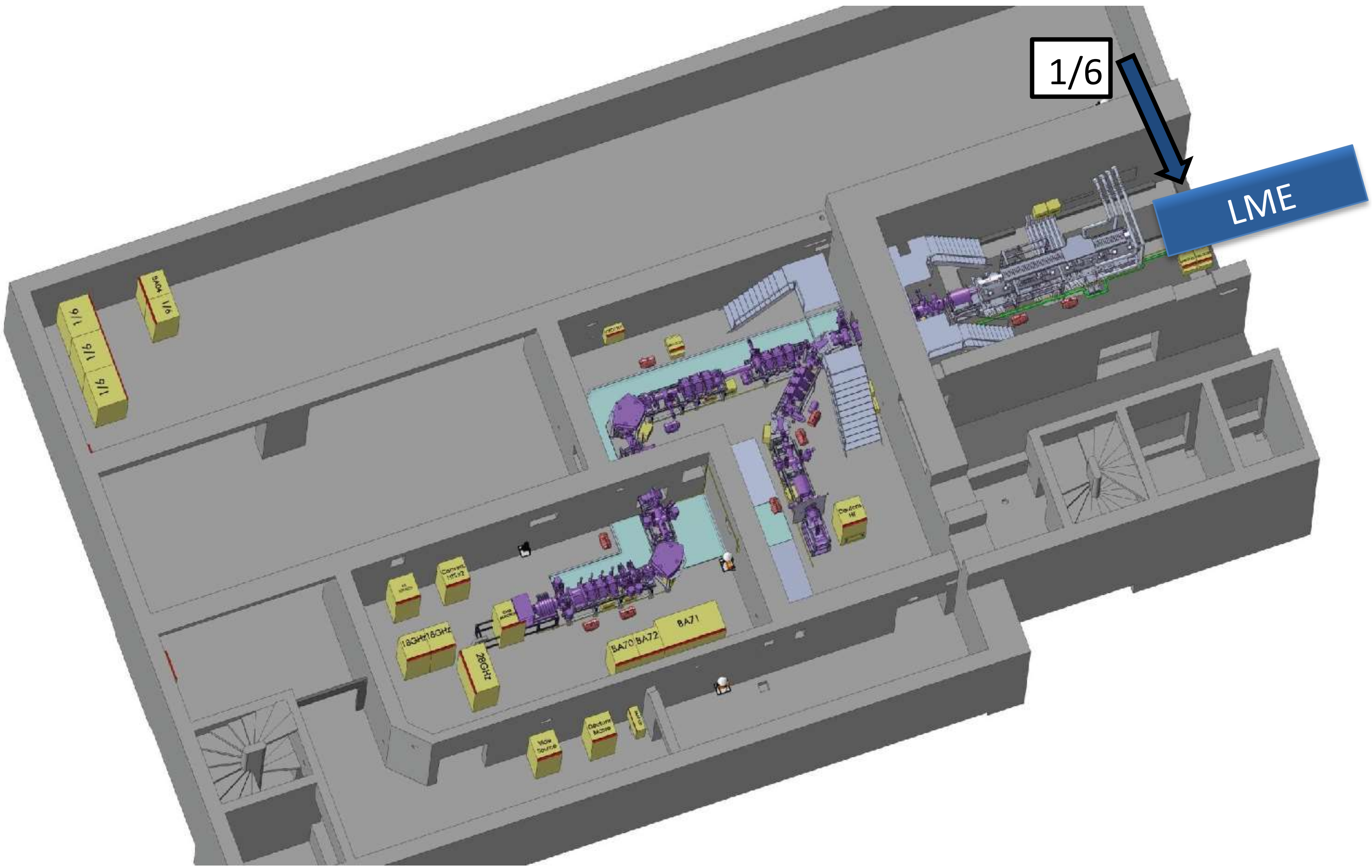
**5 – Provide bunch selection**

**6 – Beam matching for the LINAC**

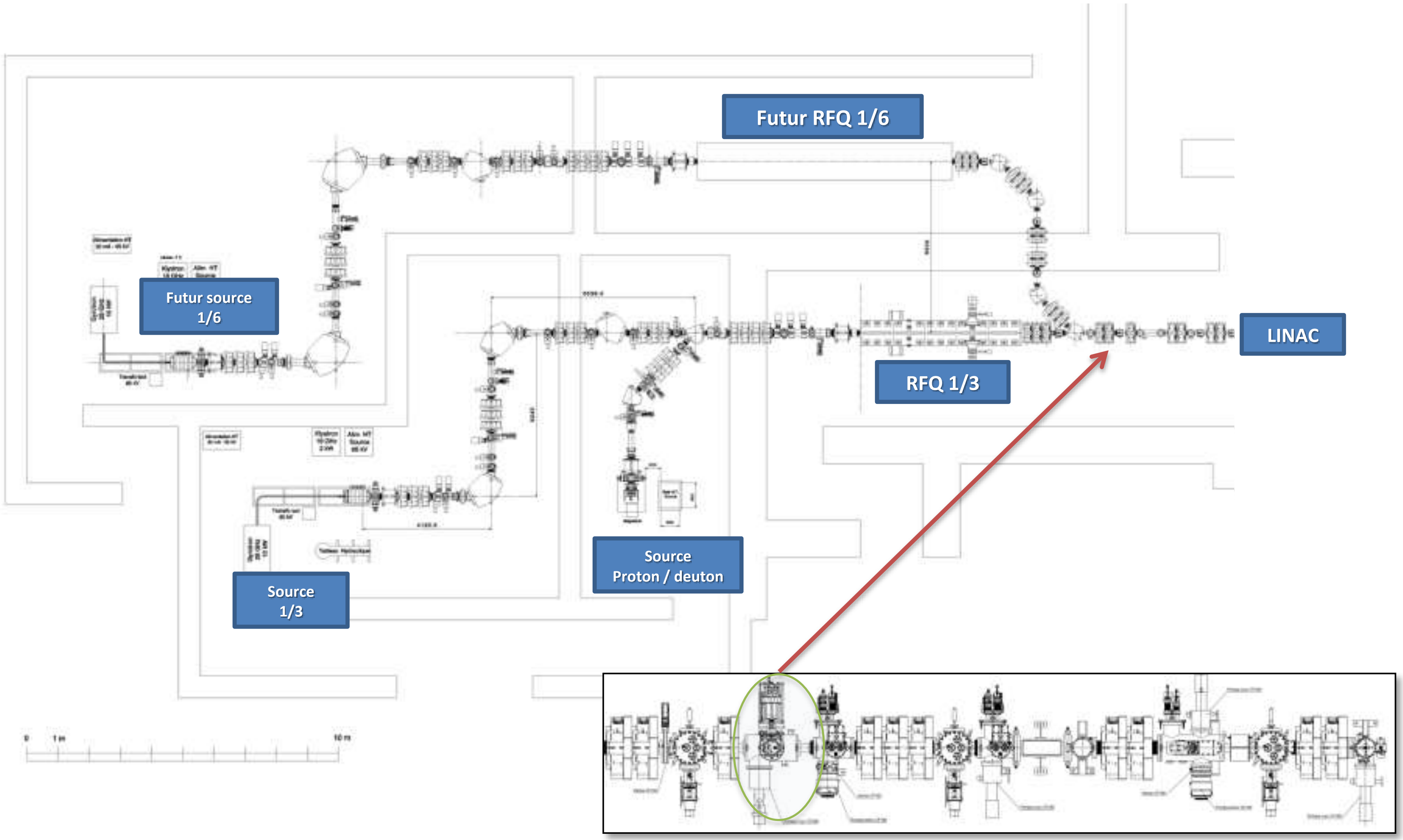
# 1 - GET THE BEAM FROM THE RFQ



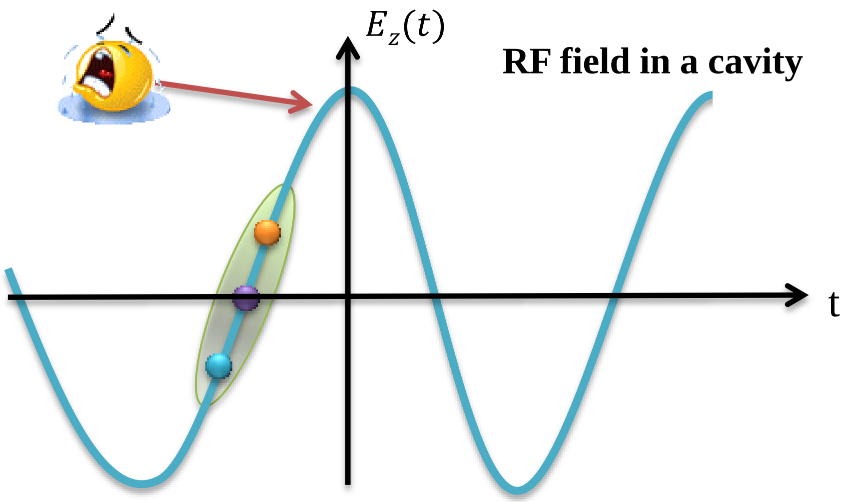
# 2 - UPGRADE OF THE ACCELERATOR WITH FUTURE A/Q=6 BEAM LINE



# 2 - UPGRADE OF THE ACCELERATOR WITH FUTURE A/Q=6 BEAM LINE



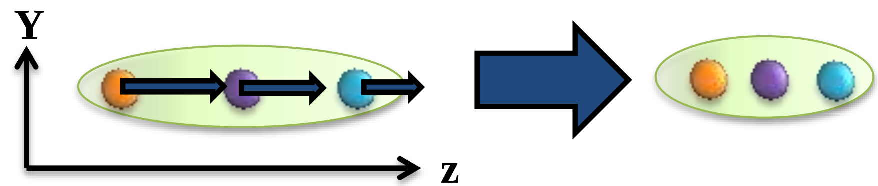
# 3 - MAINTAIN BEAM BUNCHED FOR THE LINAC



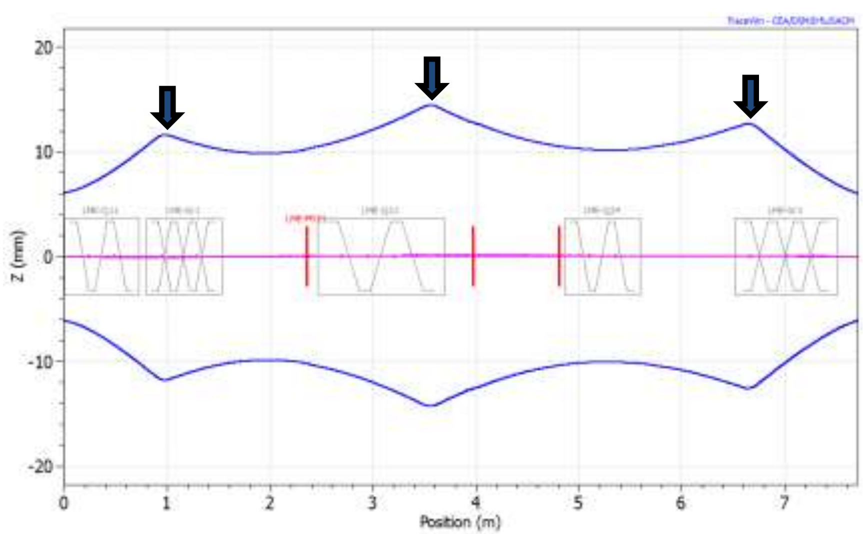

## RF buncher principle

Staying in the linear part of the accelerating field

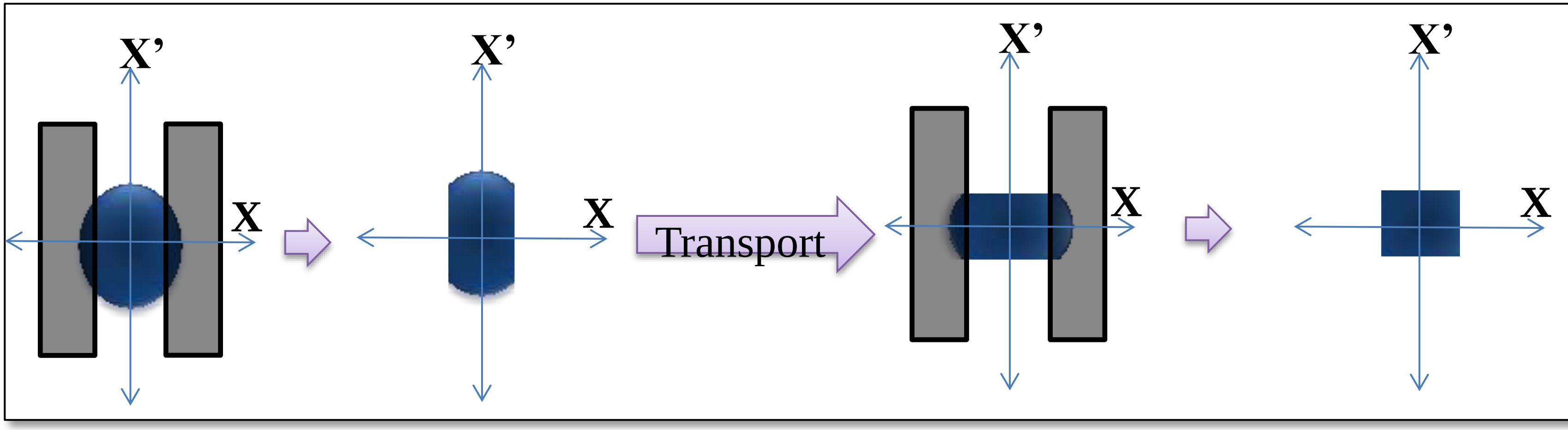
- For E=0 : speed is constant
- Arrive in advance, particle is slowing-down
- Arrive late, particle is accelerate

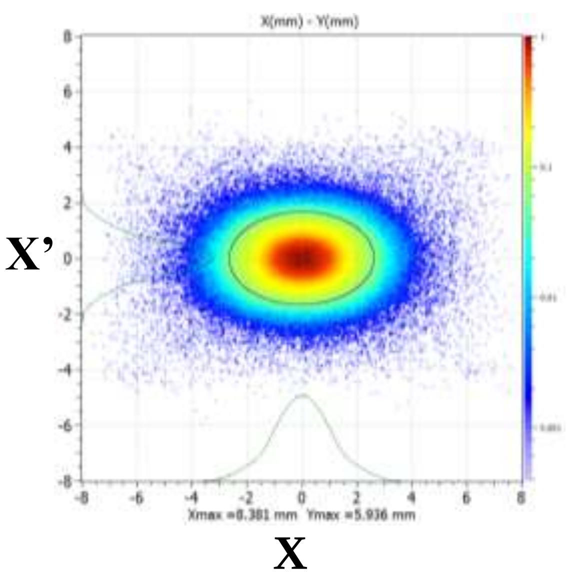


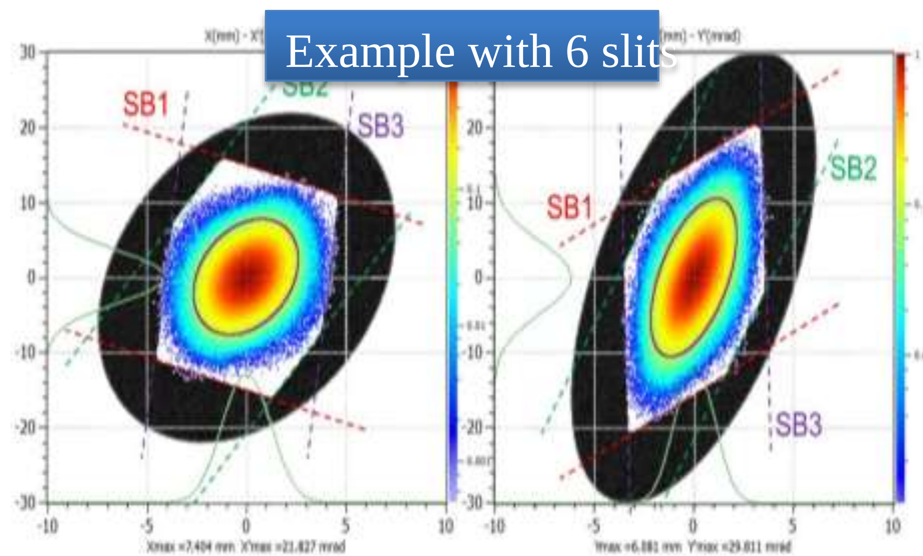

Bunch length in mm
(eq to time)



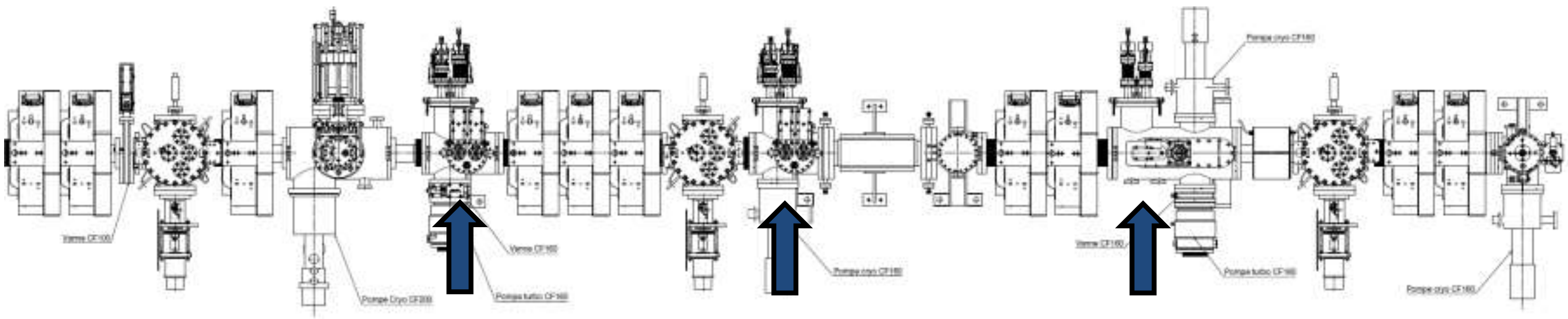
# 4 - CLEANING THE BEAM



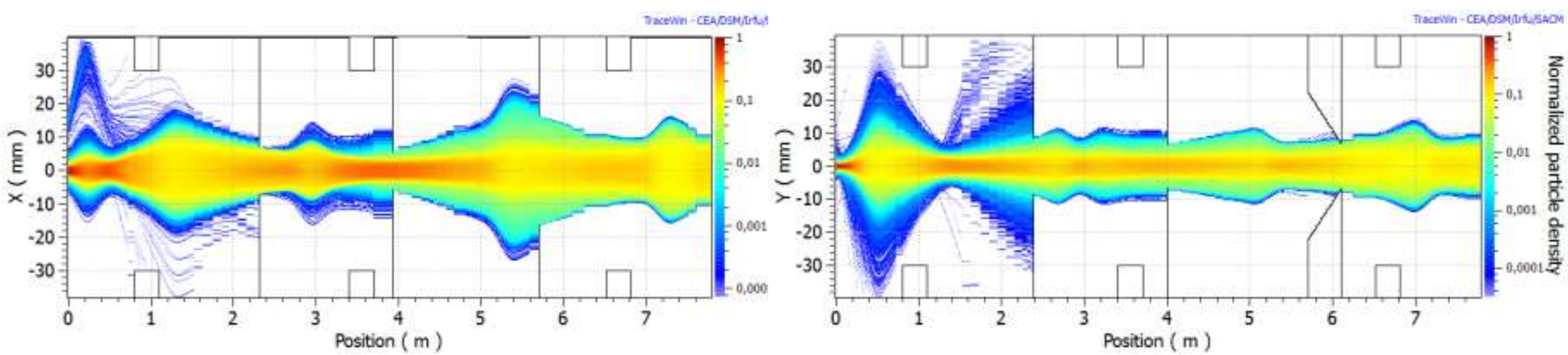



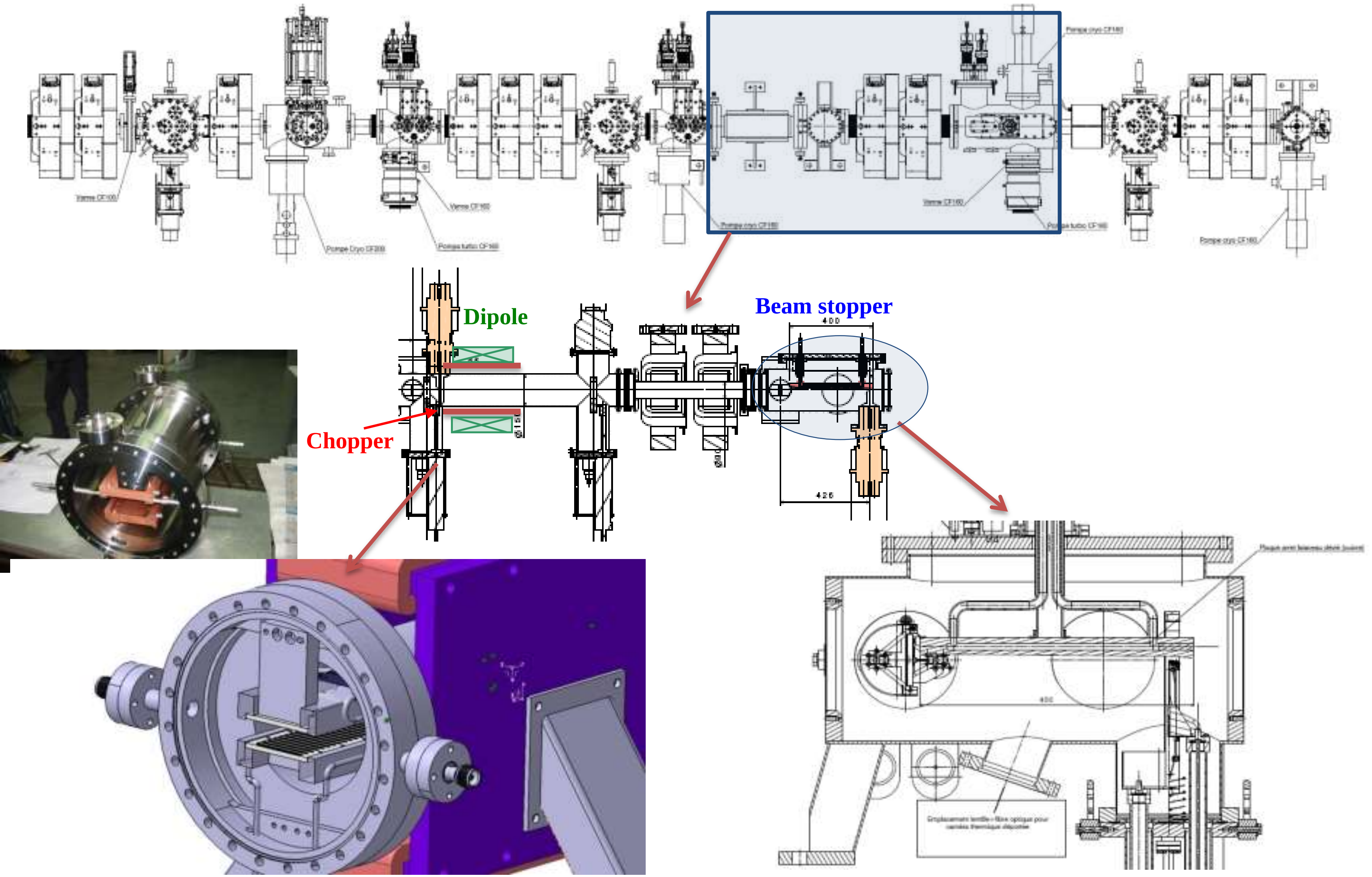
## 4 - CLEANING THE BEAM



- Adjustment of the cleaning slits using the various beam intensity diagnostics (DCCT, FCT and Faraday cup).
- Dissipate power on each slits do not exceed 150 W.
- 1W lost in the LINAC cost ~1kW in cryogenic consumption + structures activation

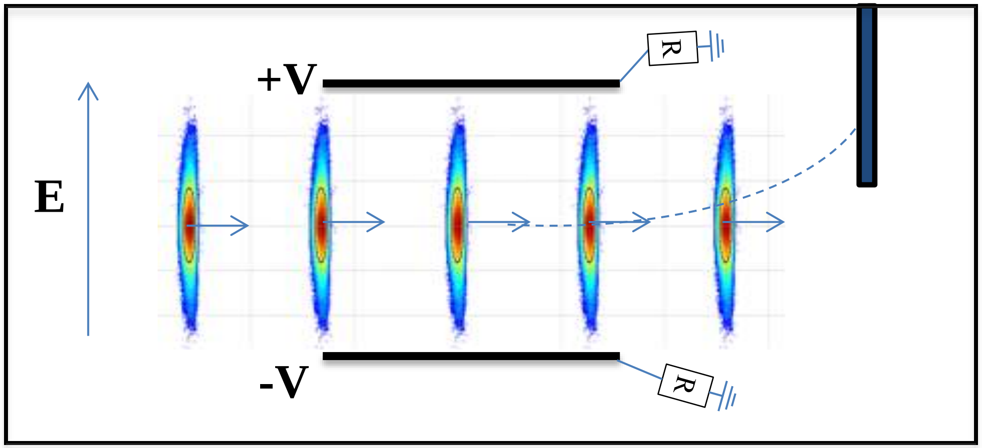


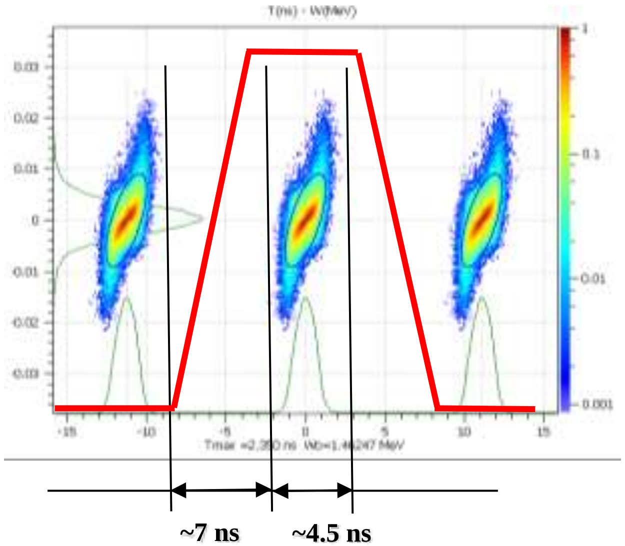
## 5 - PROVIDE BUNCH SELECTION



# 5 - PROVIDE BUNCH SELECTION

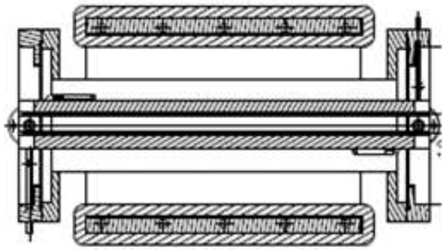
Needed for physics experiments : keep 1 bunch over 1000 or 10000



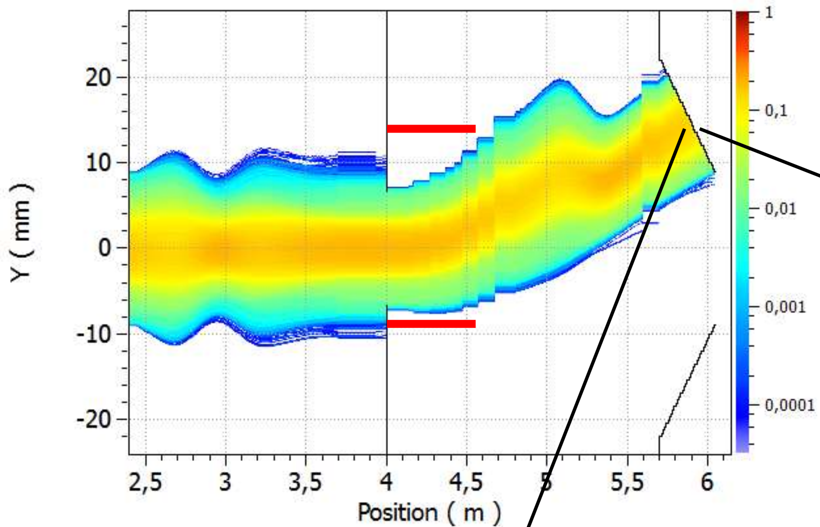




Need a device to carry out this feature :

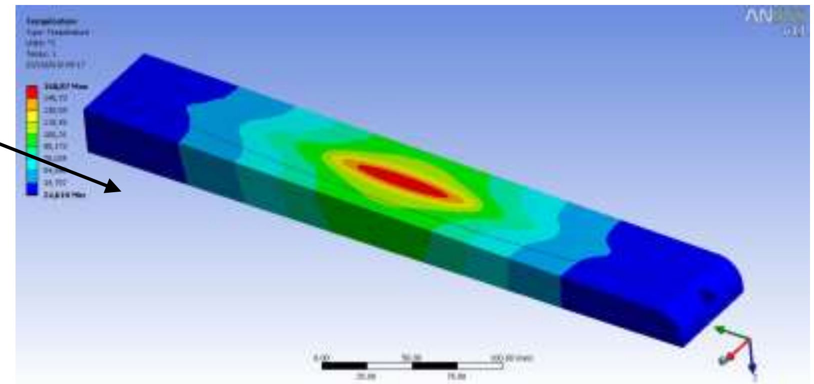
- Rise time : 7 ns
- Phase speed : beam, 4% de c
- Use a magnetic dipole and electric field switch in order to realize the 999/1000 suppression bunches

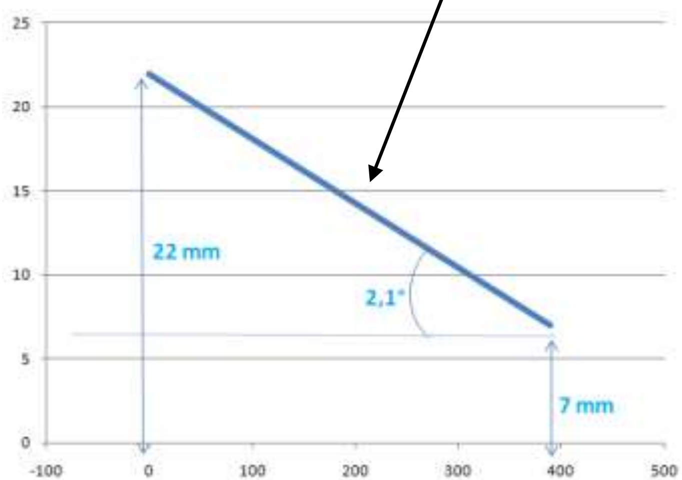


# 5 - PROVIDE BUNCH SELECTION

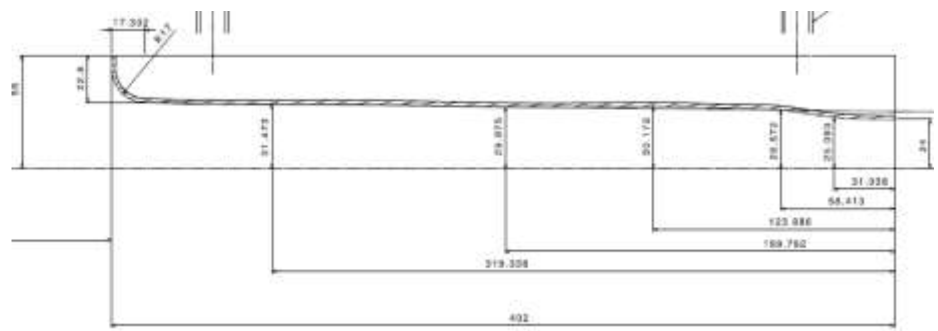



Beam power deposition : 7kW






Controlled using thermocouples



## 6 - BEAM MATCHING FOR THE LINAC

- **The LINAC is a focusing channel almost quasi periodic.**
- **We can adapt the channel to the beam or adapt the beam to the channel.**
- **At Spiral2, the second method have been choose. This is the most simple way for variable currents and also because there is various beams to accelerate.**

**Postulate**

- **Beam is considered adapt in a periodic channel if beam parameters are identical at the entry and at the exit of a period (~section of acceleration)**
- **It exist for One set (q/A, current, ε) only one beam at the entrance which valid the first condition**

A beam is 3 dimensions (**X, Y , Z**) & 3 divergences (**X', Y', Z'**)

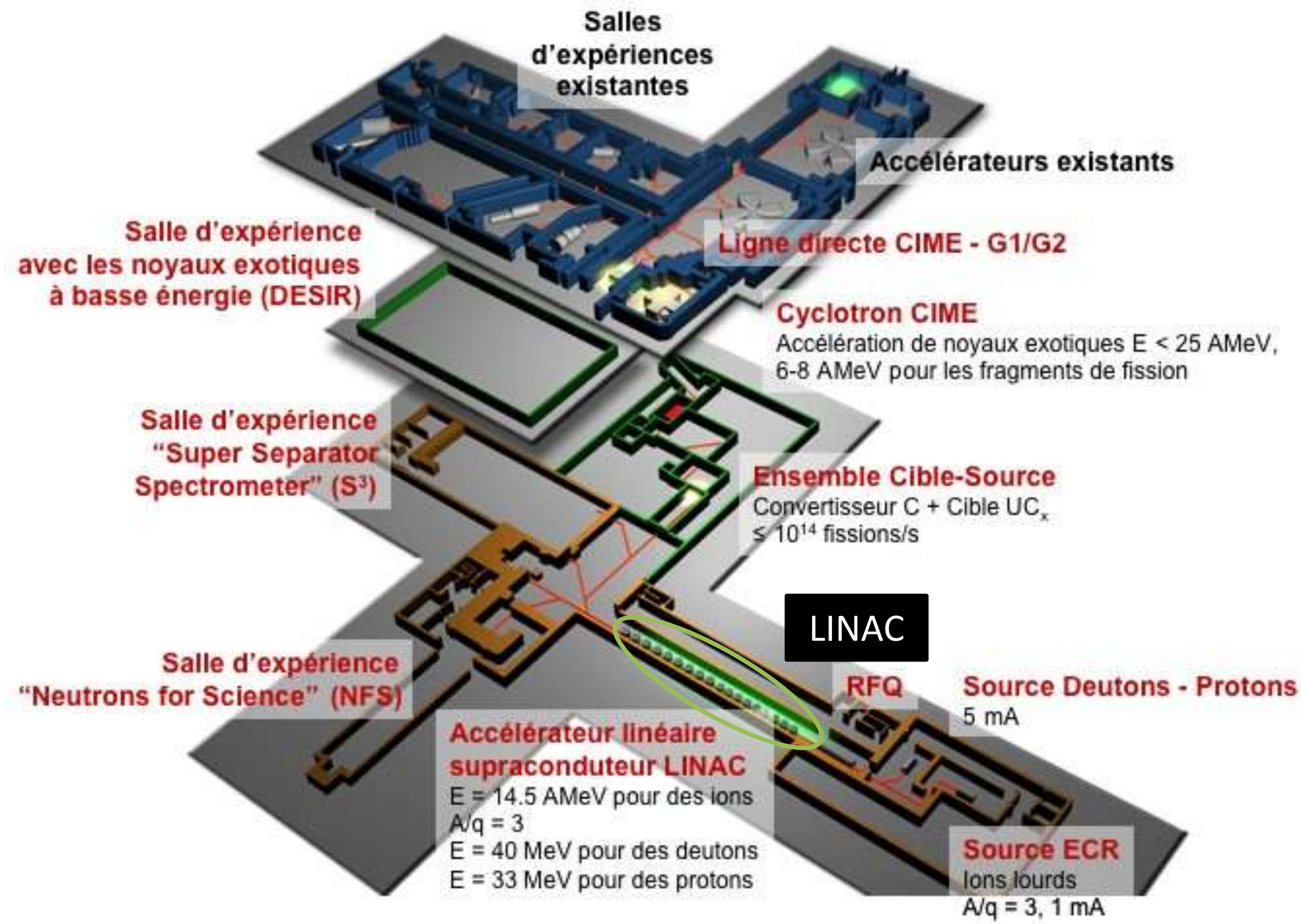
⇒ 6 parameters → 6 independent tuning

⇒ 4 quadrupoles and 2 re-bunchers of the MEBT will provide the adapted beam for the LINAC.

**Difficulty :** **the space charge introduce coupling between X, Y, Z dimensions**

**⇒In space charge condition, matching of the 3 planes (X, Y, Z) must be done at the same time.**

# 5. THE SUPRA-CONDUCTING LINAC

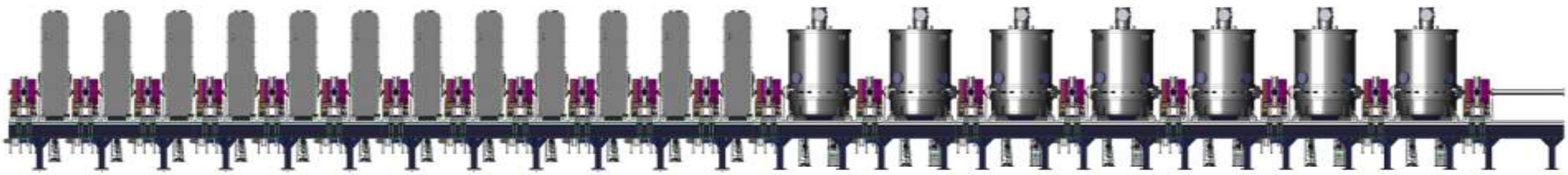


# THE SPIRAL2 LINAC

Need to accelerate : Protons to A/q=7 ions
Variable energy : from 2 MeV/A to 33 MeV/A
⇒ **Cavities with independent phase**

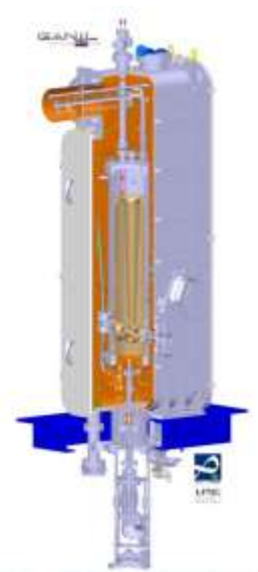
**High intensity :**

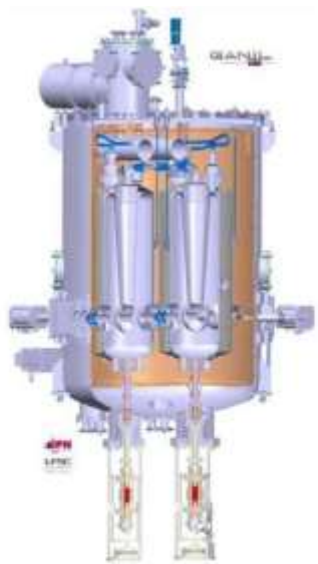
- Short cryomodules
- Periodic and continuous structure
- Repartition of diagnostics : fair and square

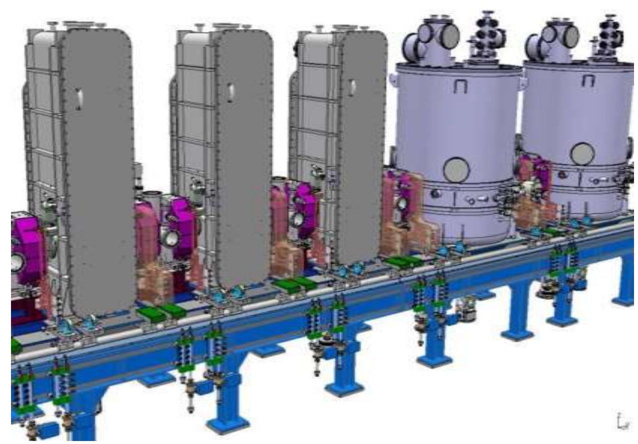


14.5 m, 12 cryomodules A (12 cavities) =CMA

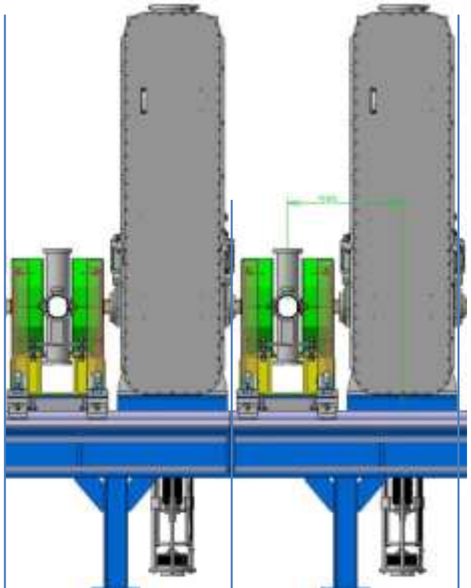
15.5 m,7 cryomodules B (14 cavities) =CMB



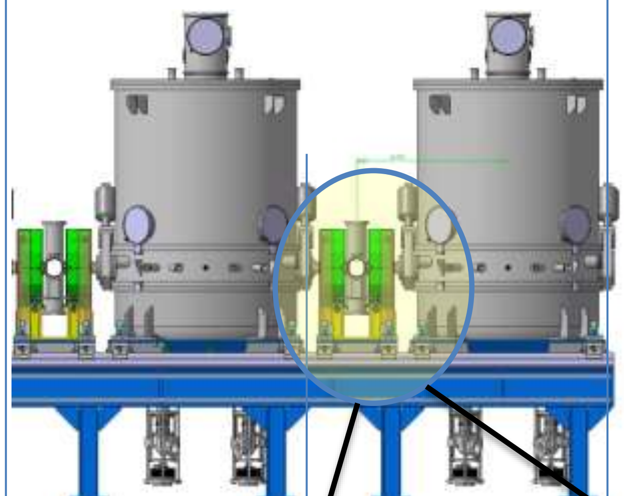




# PERIOD OF THE LINAC

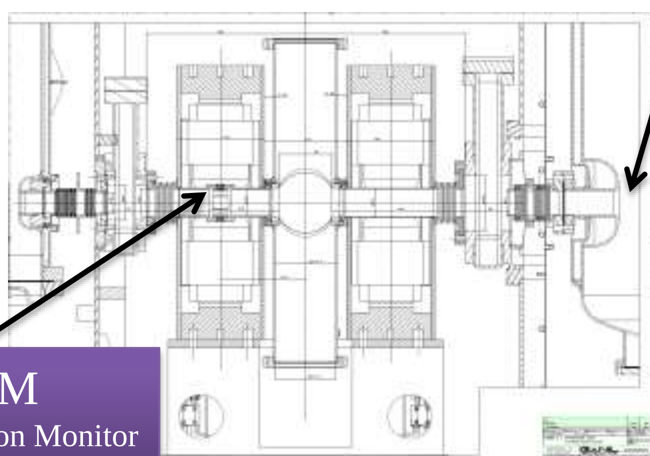


Period # | Period #

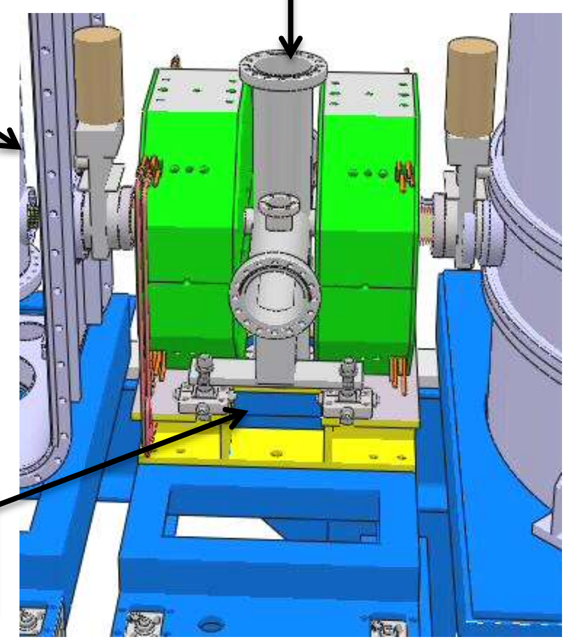


Period # | Period #

**Diagnostic cross** between 2 quadrupoles
5 first period are mounted with BEM (beam extension monitor)

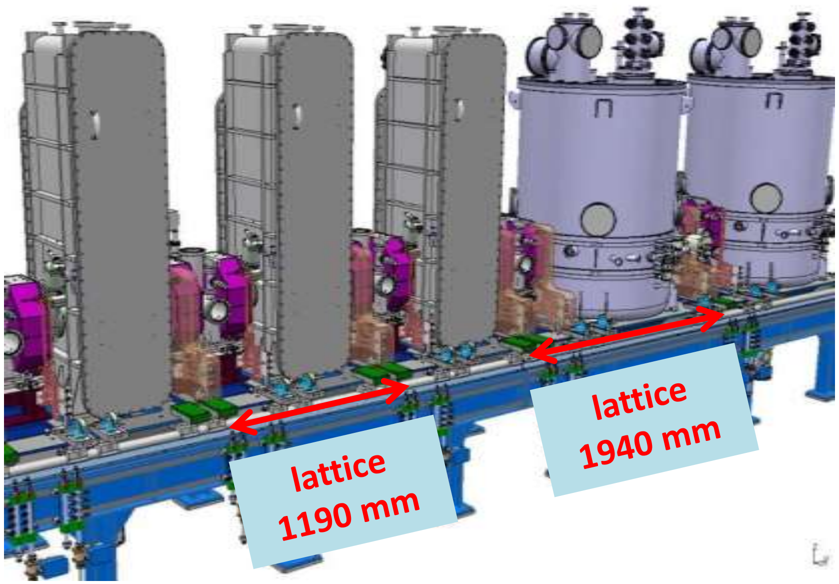


**BPM**
Beam Position Monitor



**Turbo molecular Pump**

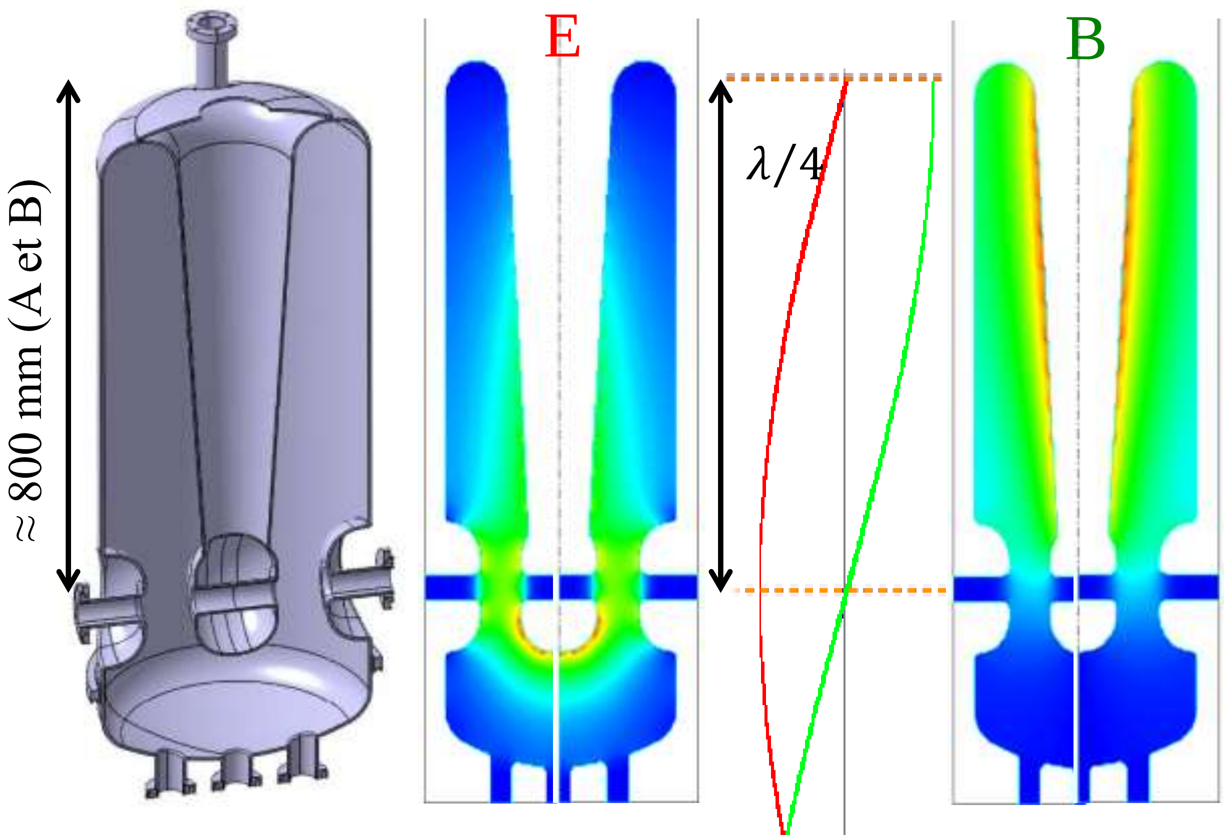
# CHARACTERISTICS OF THE SPIRAL2 CAVITIES

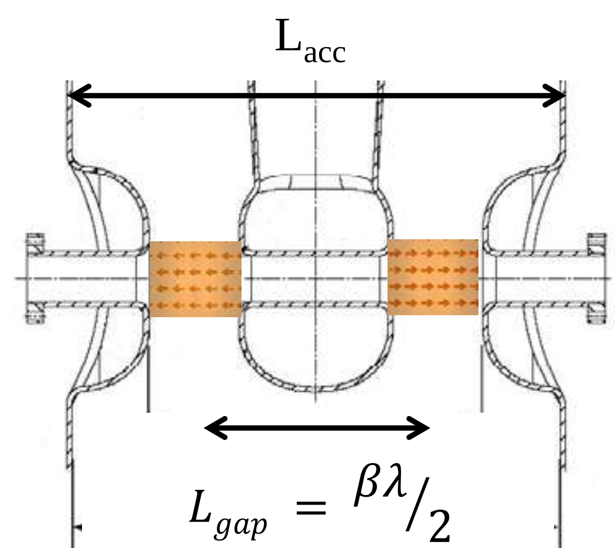



| Cavity | A | B |
|---|---|---|
| Number of cavity | 12 | 14 |
| ∅ cavity diameter (mm) | 238 | 380 |
| ∅ Beam pipe diameter (mm) | 38 | 44 |
| f [MHz] | 88.05 | 88.05 |
| $\beta_{optimum}$ | 0.07 | 0.12 |
| $E_{peak}/E_{acc}$ | 5.36 | 4.76 |
| $B_{peak}/E_{acc}$ (mT/MV/m) | 8.70 | 9.35 |
| $L_{acc}$ [m] | 0.24 | 0.40 |
| $V_{acc}$ at 6.5 MV/m & $\beta_{opt}$(MV) | 1.55 | 2.66 |
| G [Ω] | 22 | 37 |
| r/Q [Ω] | 600 | 515 |
| $Q_0$ ($P_{cav}$=10W @ 6.5 MV/m) | $3.5\ 10^8$ | $1,4\ 10^9$ |

# FIELD DISTRIBUTION IN CAVITY

Cavity A and B: quarter of wave




110 mm for type A
190 mm for type B

# POWER COUPLER OF CAVITY

Power coupler function :

- Transmission of the RF power of the RF source to the beam
- Ensure the thermic transition between ambient temperature (300 K) to the cavity temperature (few K)
- Establish a barrier between cavity vacuum and outside

Definition of an external coupling coefficient $Q_{ext}$ :

$$Q_{ext} = \frac{\omega W}{P_{ext}} = Q_0 \frac{P_{CAV}}{P_{ext}}$$

$W$ : energy RF stored in the cavity

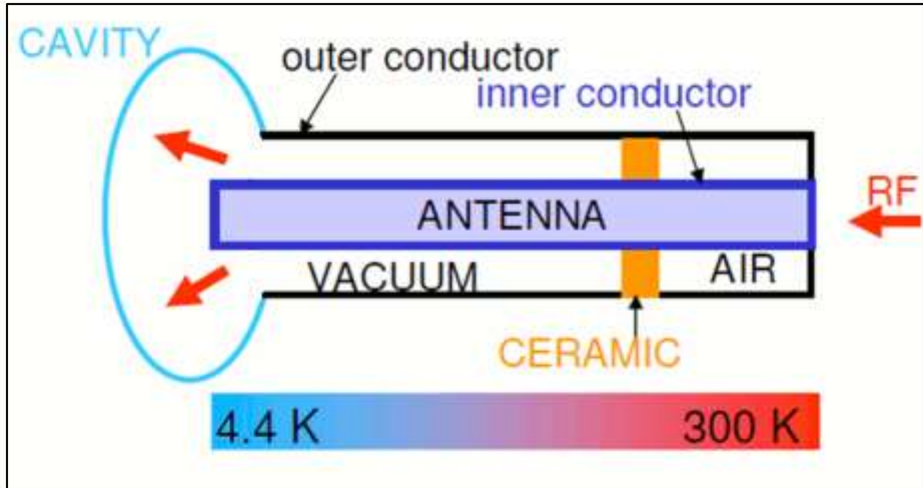
$P_{ext}$ : supplied power to the cavity (10kW)

$\Rightarrow Q_{ext}$ fixed by the cavity parameters and the beam

$$Q_{ext} = \frac{V_{acc}}{\left(r/Q\right) I_b \cos \Phi_S}$$

$V_{acc}$ : acceleration potential of the cavity

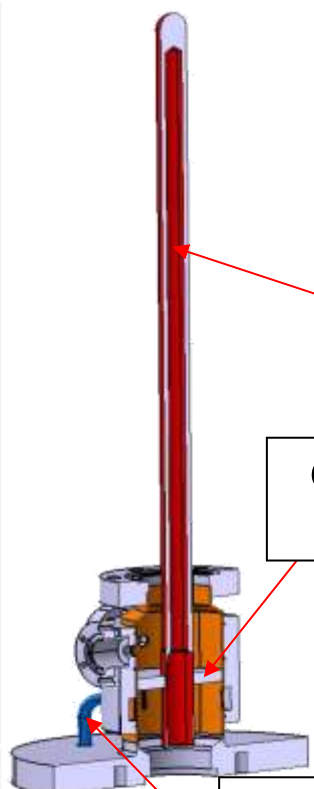
$I_b$ , $\Phi_S$ : beam current and synchronism phase




The coupling $Q_{ext}$ is adjusted by the penetration antenna in the cavity
Order of magnitude : $10^4 - 10^6$ (high gradients)

## POWER COUPLER OF CAVITY

- Same design for both types of cavities
- $Q_{ext} = 6.5\ 10^5$ (CMA) and $Q_{ext} = 1.0\ 10^6$ (CMB), are obtained by ajustement of the antenna penetration



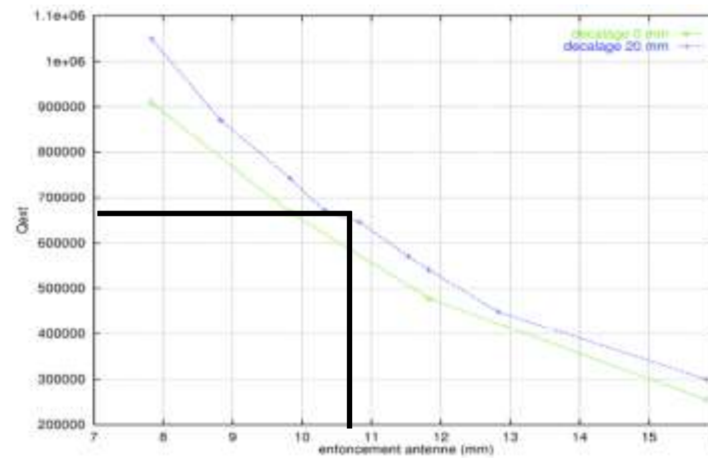

Hollow antenna

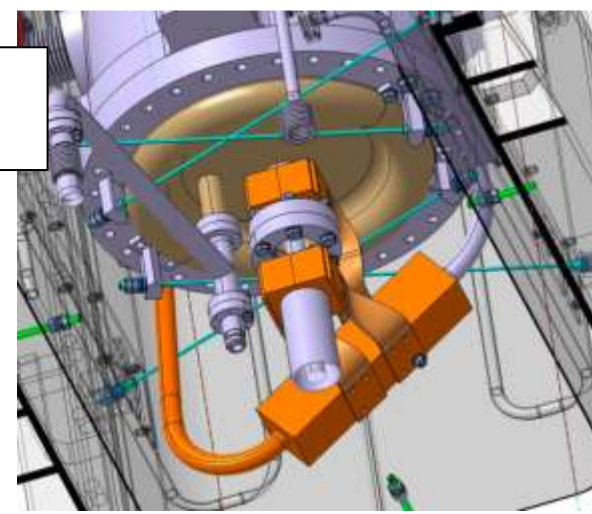
Ceramic window (without TiN)

Electrons Pickup

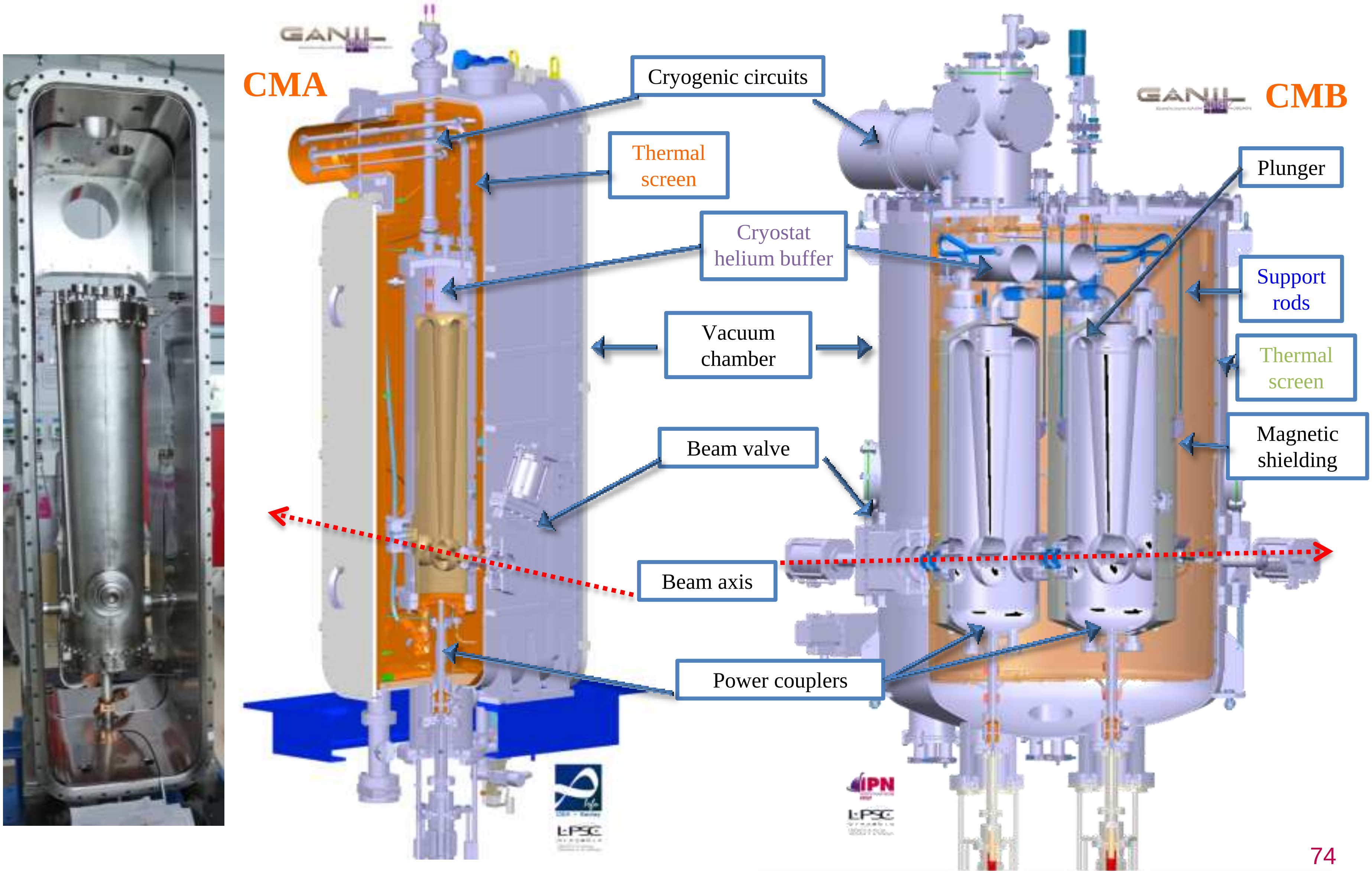
Port of pumping

Cooling circuit of the ceramic (air)

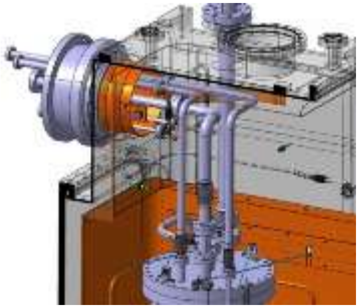


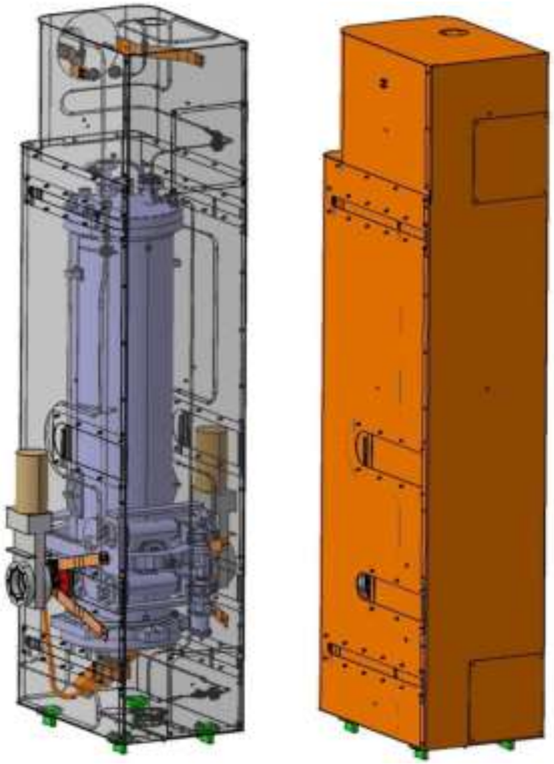
# CRYO-MODULE : CMA / CMB

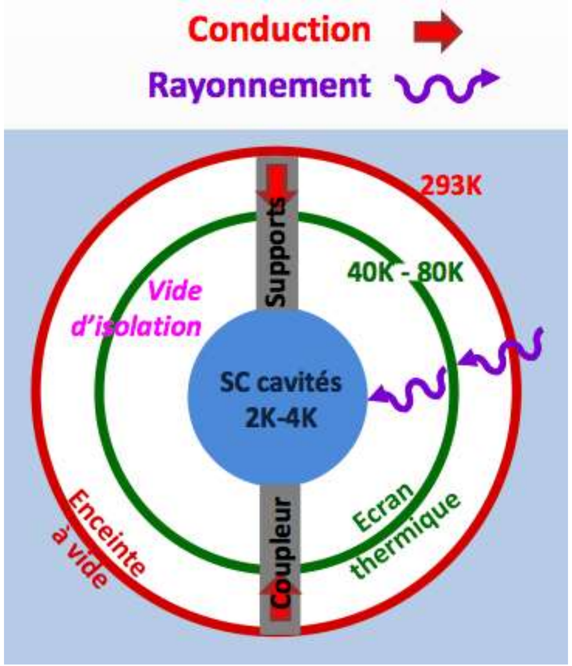


# CRYO-MODULE A : CMA



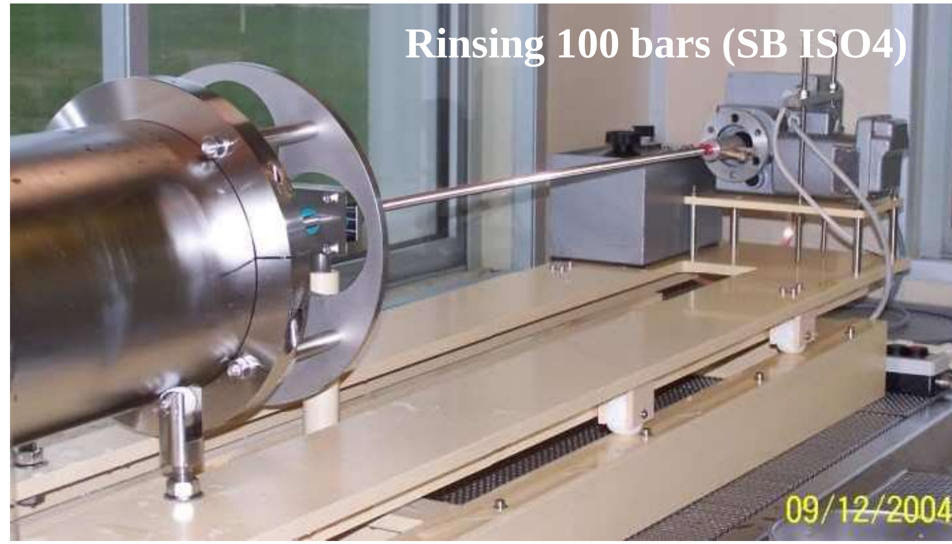
- Separated vacuum chamber - cavity
- Static losses $< 11\ W$
- $P_{CAV} < 10\ W/cavity\ (E_{acc}\ 6.5\ MV/m)$





## CAVITIES : CHEMICAL PREPARATION
### HPR (HIGH PRESSURE REACTORS)

Chemical attack : $150 \mu m$

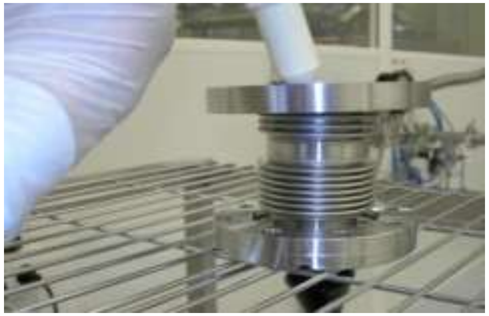




# CRYO-MODULE A (CMA) – ASSEMBLY IN CLEAN ROOM

Assembling of coupler on the cavity

Cavity implantation in the vacuum chamber in the clean room

Systematic counting of dusts of the piece mounting on cavities

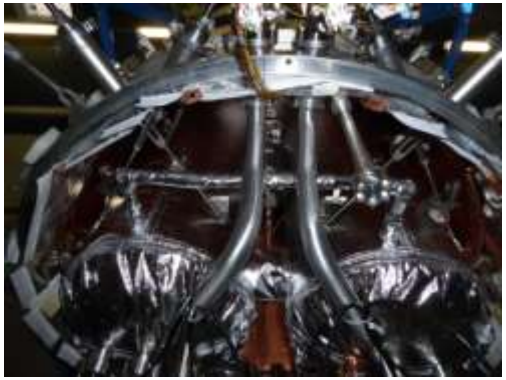


# CRYO-MODULE A (CMA)
# ASSEMBLY OUTSIDE THE CLEAN ROOM

Next steps of the assembly are done outside the cleaning room







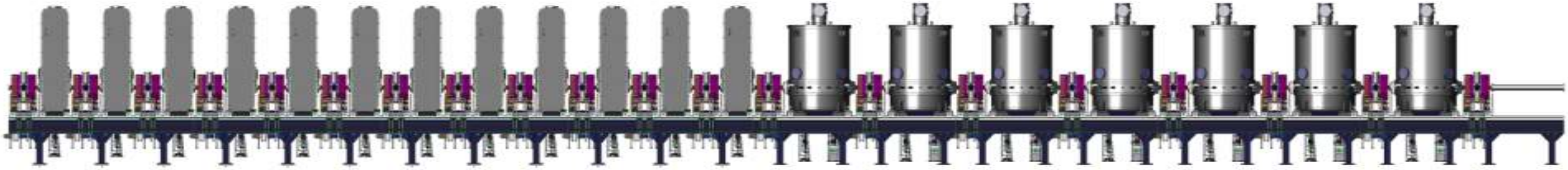
Bottom view of the CMB open

## CRYO-MODULE – TRANSPORTATION ON SITE



## CRYO-MODULE – ON SITE AT SPIRAL2

# BEAM TUNING STEPS – INCREASE THE POWER



- Phase #1: Channel definition :
  - Transverse focusing
  - Field law and synchronism phase of cavities

→ **Without beam**

- Phase #2: Tuning of the structure (at 1st order) :
  - Transverse position
  - Field and phase of cavities

→ **Minimum power**

- Phase #3: Beam tuning (2nd order) :
  - Transverses and longitudinal sizes

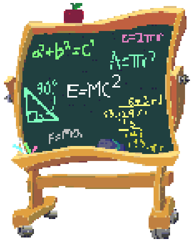
→ **Minimum power at nominal current**

- Phase #4: Power increasing :
  - Power increase with the increasing of the duty cycle

Example : Deuterons beam

| Phase | Peak current | Pulse length | Frequency | Average current | Average power (40 keV / 40 MeV) |
|---|---|---|---|---|---|
| #2 | 50 µA | 200 µs | 1 Hz | 10 pA | 0.4 mW / 0.4 W |
| #3 | 5 mA | 200 µs | 1 Hz | 1 µA | 40 mW / 40 W |
| #4 | 5 mA | CW | | 5 mA | 200 W / 200 kW |

# BEAM TUNING STEPS – PHASE #1

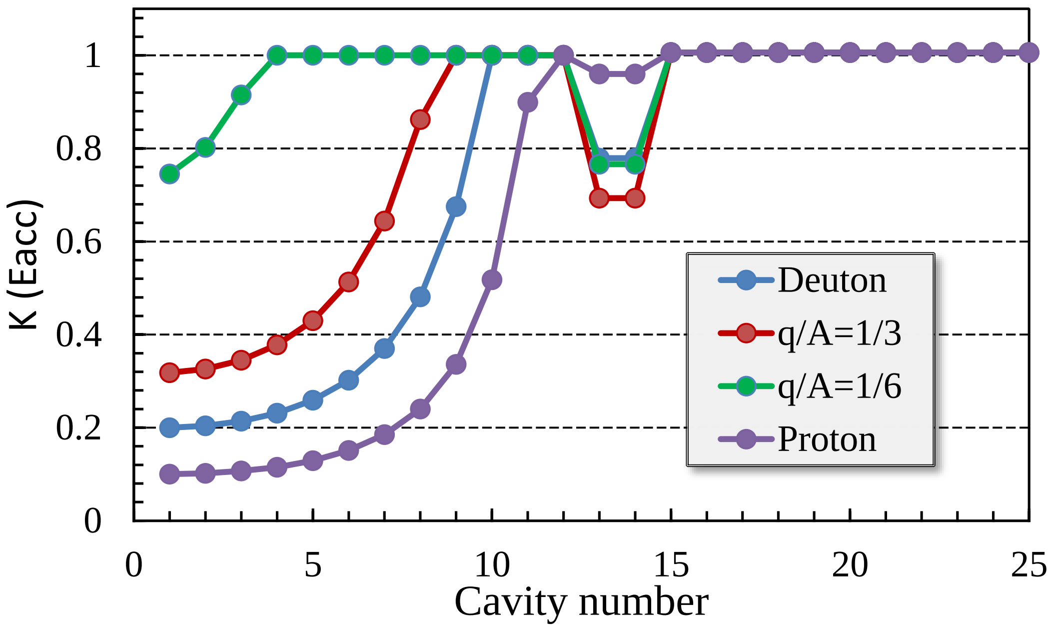


❑ Quadrupoles gradients calculation in order to create continuous transverse focusing.

❑ Synchronism phases and cavities accelerating field calculation
→ Continuous longitudinal focusing
→ Check if desired acceleration is sufficient
→ Maximization of the longitudinal acceptance

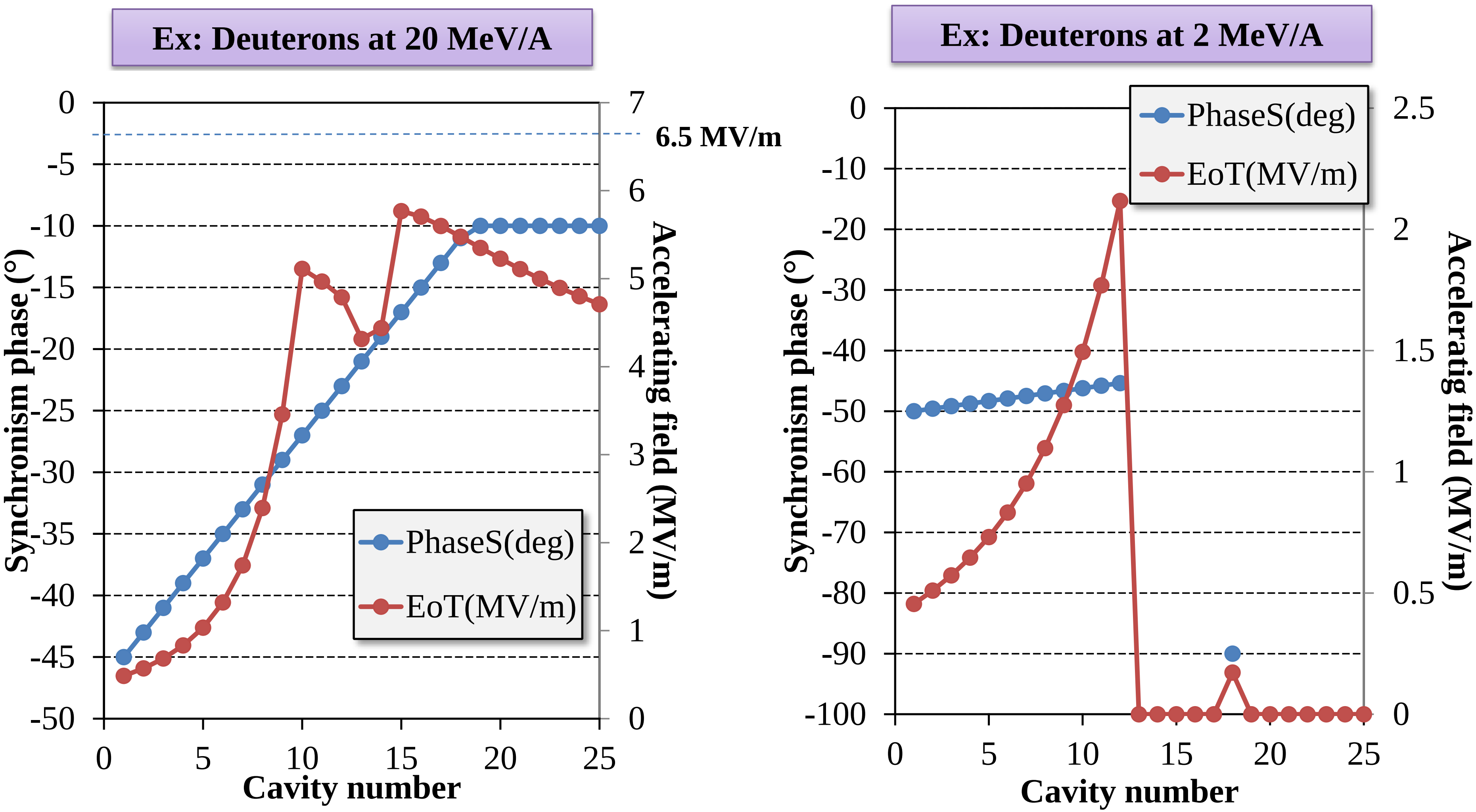
❑ In practice : very hard because everything is coupled and machine stability impose rules. We use simulation tools which give optimization of these calculations.

❑ For each particle species and energies, calculation have to be reproduce independently to the beam current



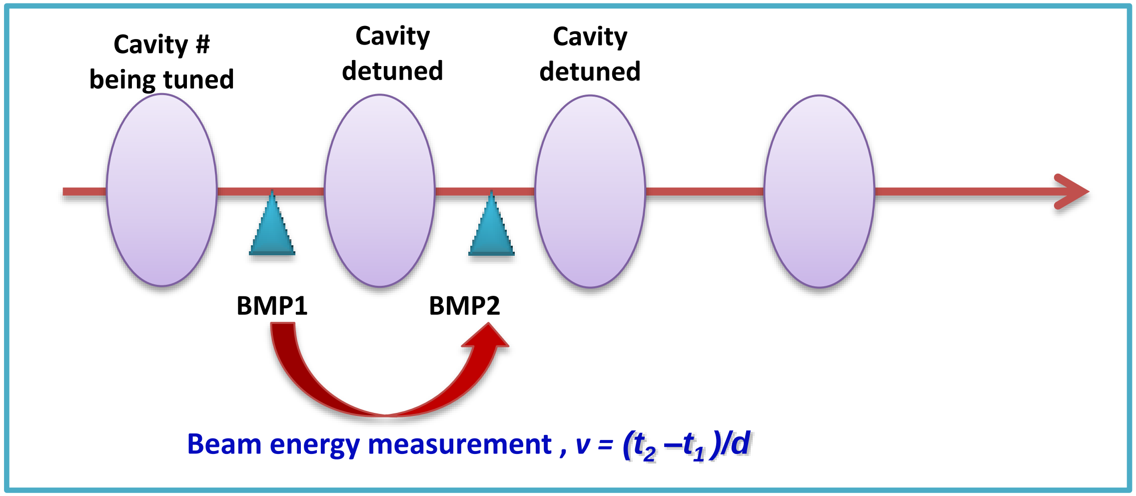

Optimized machine for ions to A/q=5

# BEAM TUNING STEPS – PHASE #2 : PHASE AND RF FIELD



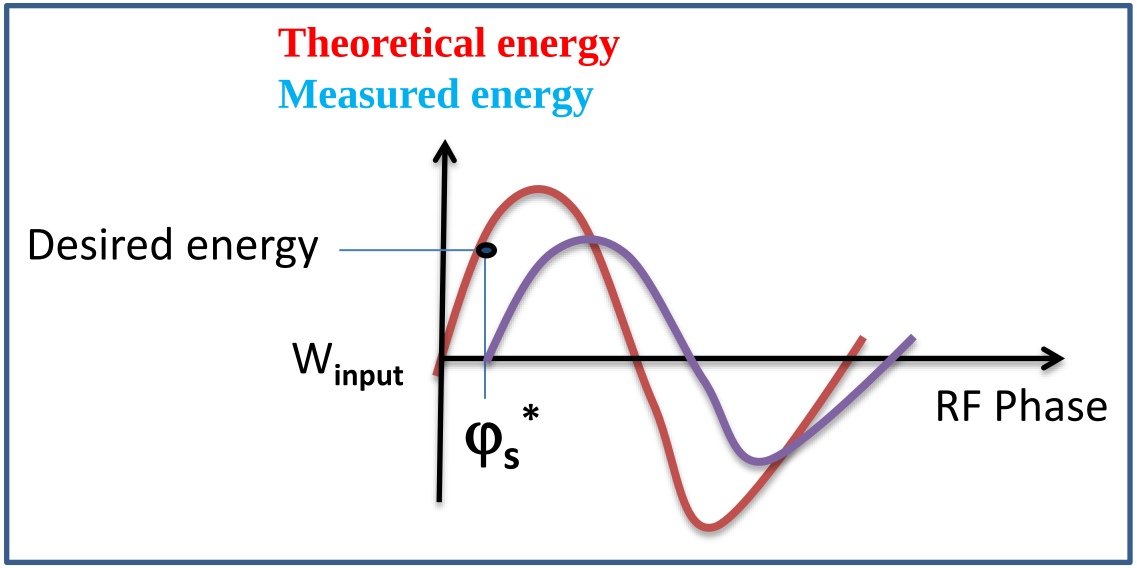

More difficult

# BEAM TUNING STEPS – PHASE #2 : PHASE AND RF FIELD




## Hypothesis:

- Calculation done using field-maps are correct
- Time of Flight measurements are sufficiently precise
- Beam loading suppress by the cavities detuning
- The beam is bunched correctly

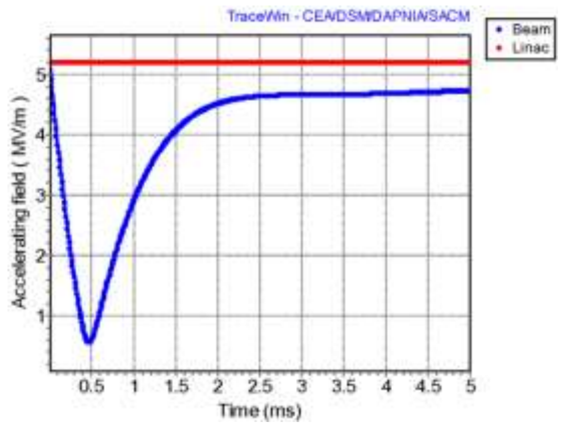


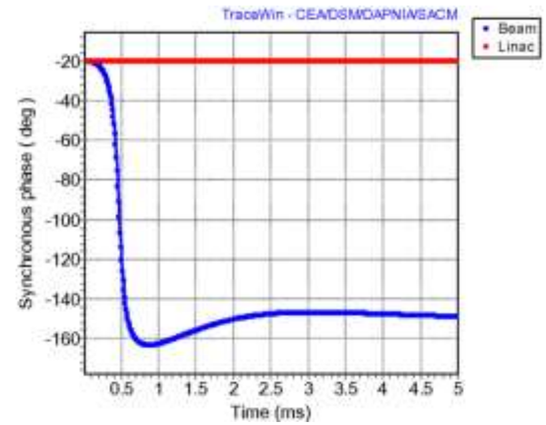

## Need new adjustments

- Steerers
- Quadrupoles

## BEAM TUNING STEPS – PHASE #2 : BEAM LOADING

**Beam is decelerated in a switched-off cavity by the potential induced by the "beam loading".**

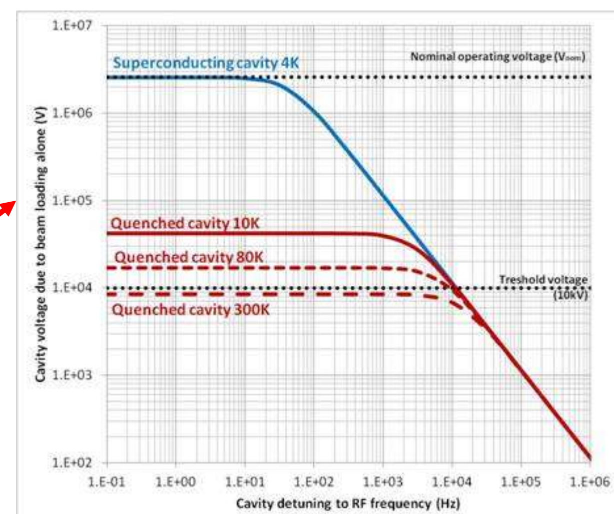


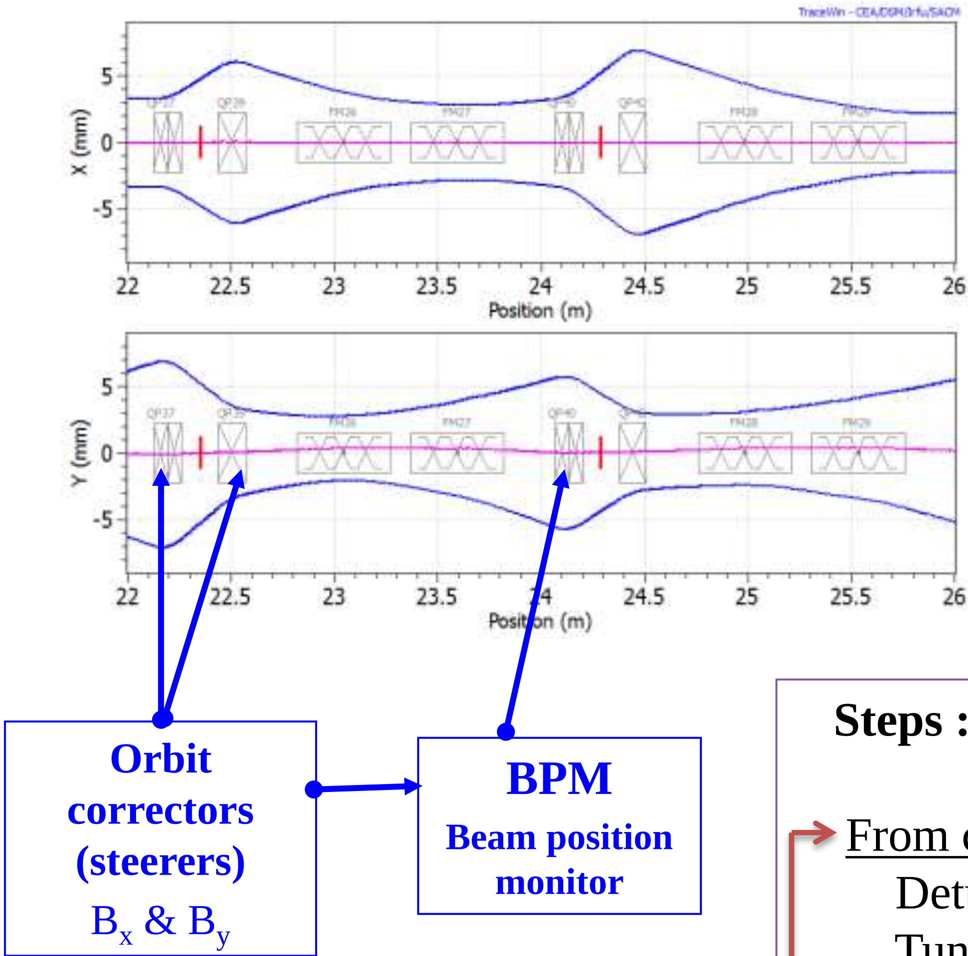

**→ A switched-off cavity for any reason must be detunes in frequency**

Precision Time Of Flight : $\frac{\Delta E}{E} = \mathbf{2.10^{-3}}$

Induced potential by the beam loading at 5 mA



## BEAM TUNING STEPS – PHASE #2 : TRANSVERSE POSITION




- Compensation of the misalignments
- Compensation of the cavities steering

**Steps :**

From cavity 1 up to cavity 24

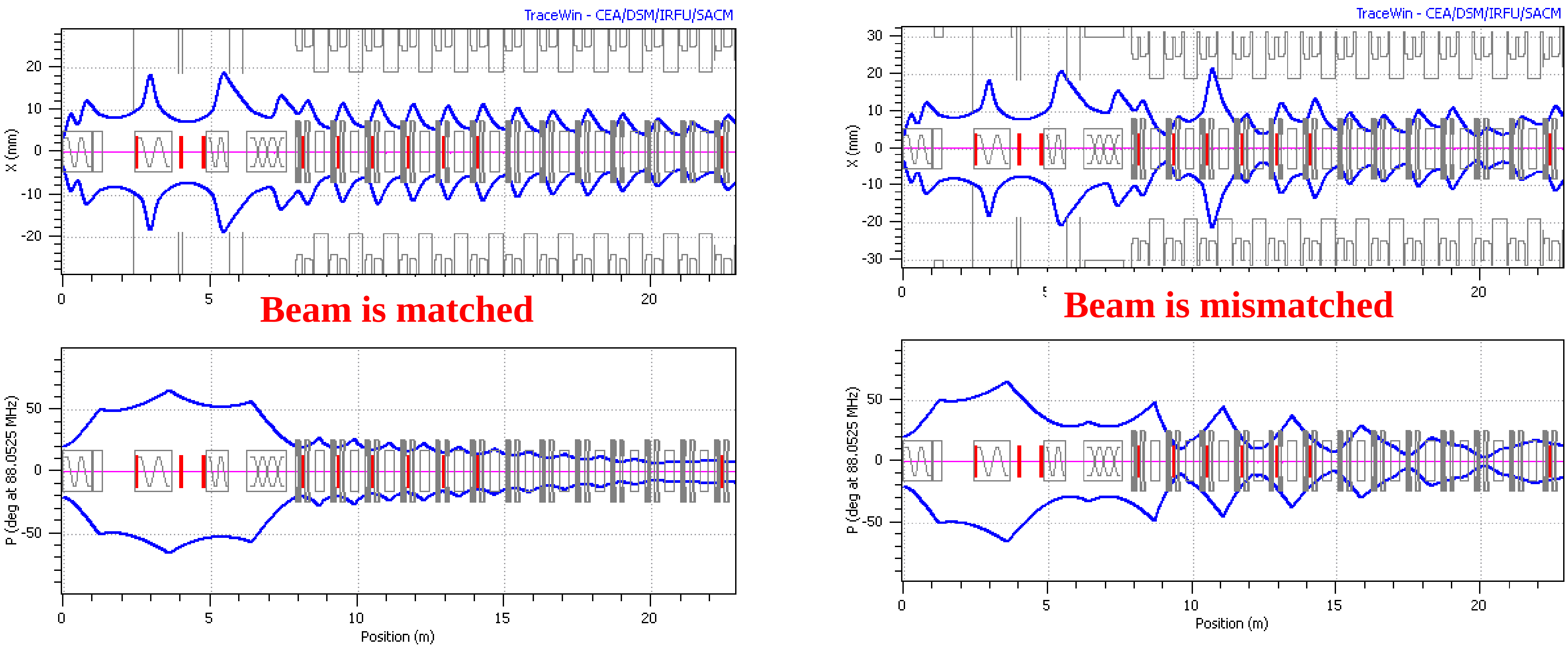
Detuning cavity 1 à 24

Tuning $\phi_S$ , $E_{acc}$ of the cavity

Alignment of the first period

Put nominal values fields of the quadrupoles *f(Bρ)*

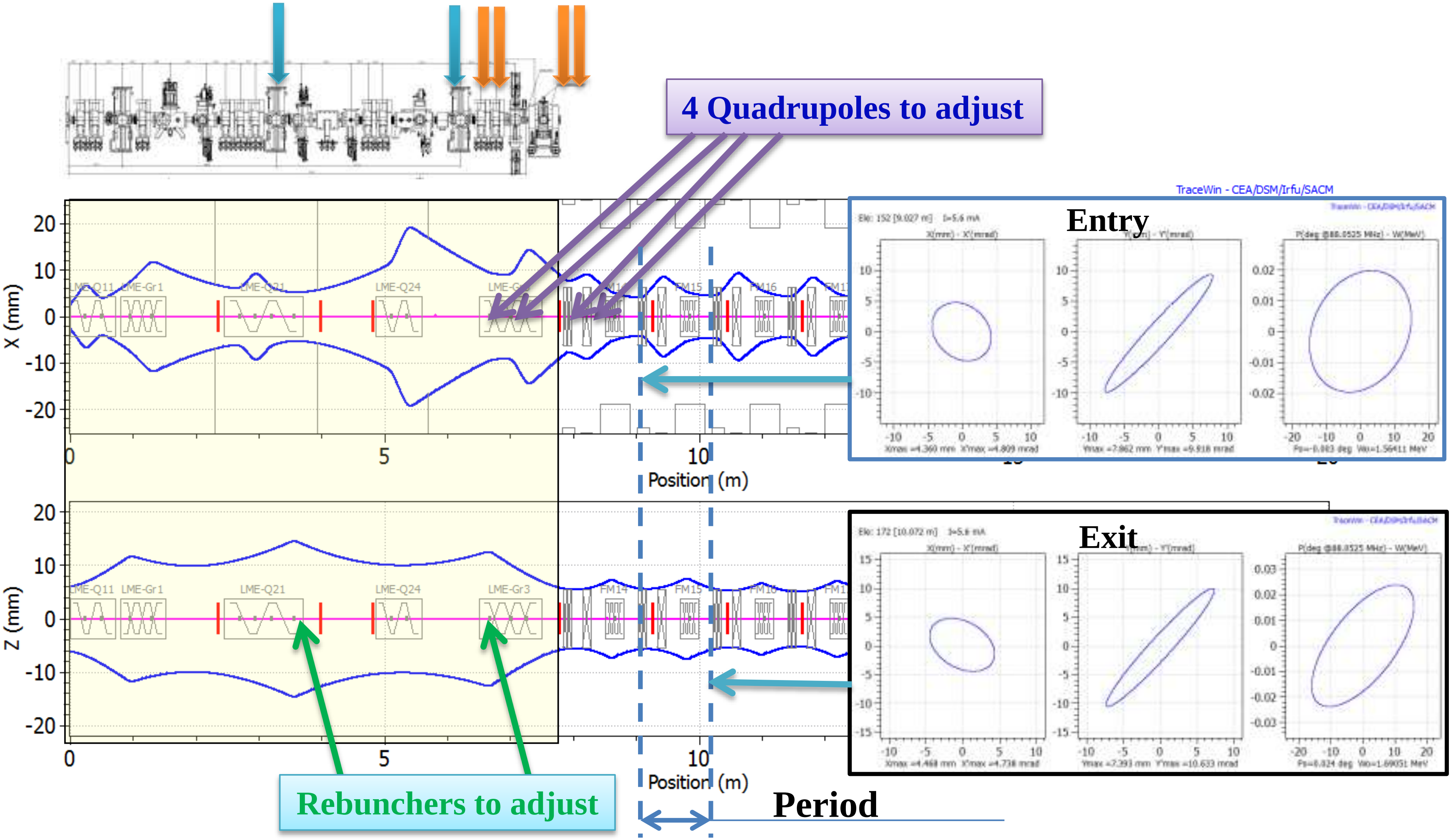
## BEAM TUNING STEPS – PHASE #3 : MATCHING-MISMATCHING




**Effect of the mismatching :**

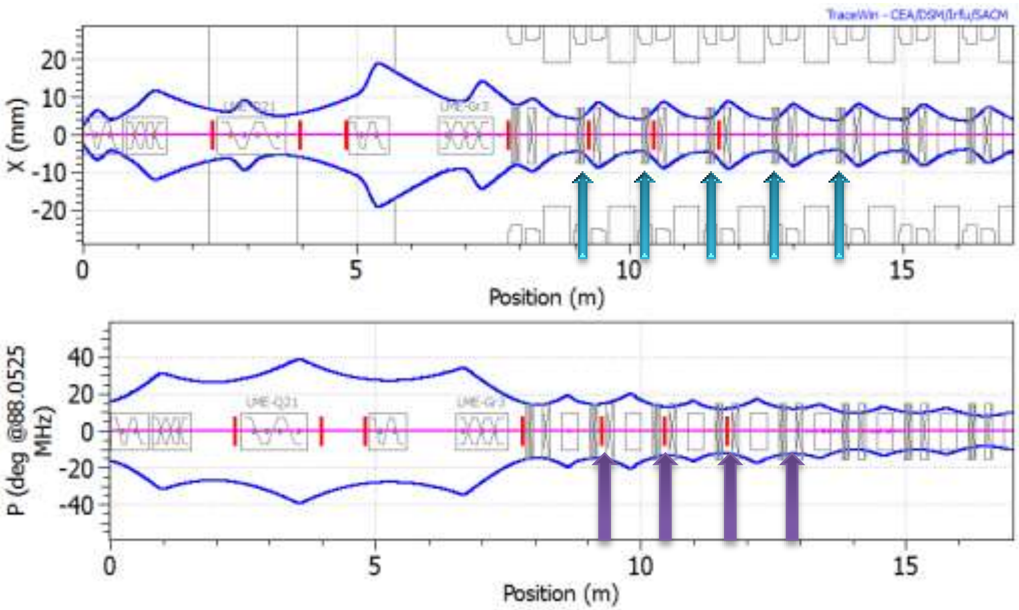
→ Emittances growth
→ Halo formation
→ Beam losses
→ Decrease of the performances for the physics experiments

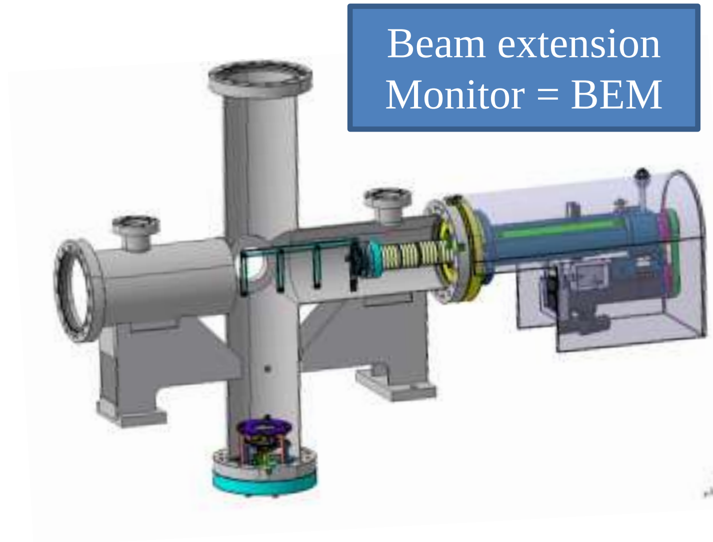
# BEAM TUNING STEPS – PHASE #3 : THEORETICAL ASPECTS




**Get close beam at the entrance and at the exit of the period**

## BEAM TUNING STEPS – PHASE #3 : METHODOLOGY




- Tuning of the last LME quadrupole double (LME-Q26, LME-Q27), first quadrupole doublet of LINAC (LINA-Q01 & LINA-Q02) and 2 rebunchers of the LME (LME-GR2 et LME-GR3)
- Criteria : sizes $(\sigma_X{}^2 - \sigma_Y{}^2, \sigma_z)$ are constant at each period
- Measurement to $\sigma_X{}^2 - \sigma_Y{}^2$ over 5 periods (from 2 to 7) using the Beam Position Monitors (BPM)
- Measurement to $\sigma_z$ over 4 periods (from 2 to 6) using the Beam Extension Monitors (BEM)
- This method isn't based on the direct beam sizes but on discrepancies over One period

  ⇒ Suppression of the uncertainties on emittances, systematic errors of the diagnostics

# BEAM TUNING STEPS – PHASE #3 : BEAM POSITION MONITOR

Current induction on the 4th electrodes when the beam pass through

**Dipolar momentum of BPM :** $D \approx \frac{X_C}{R}$

- ✓ Size coupling negligible

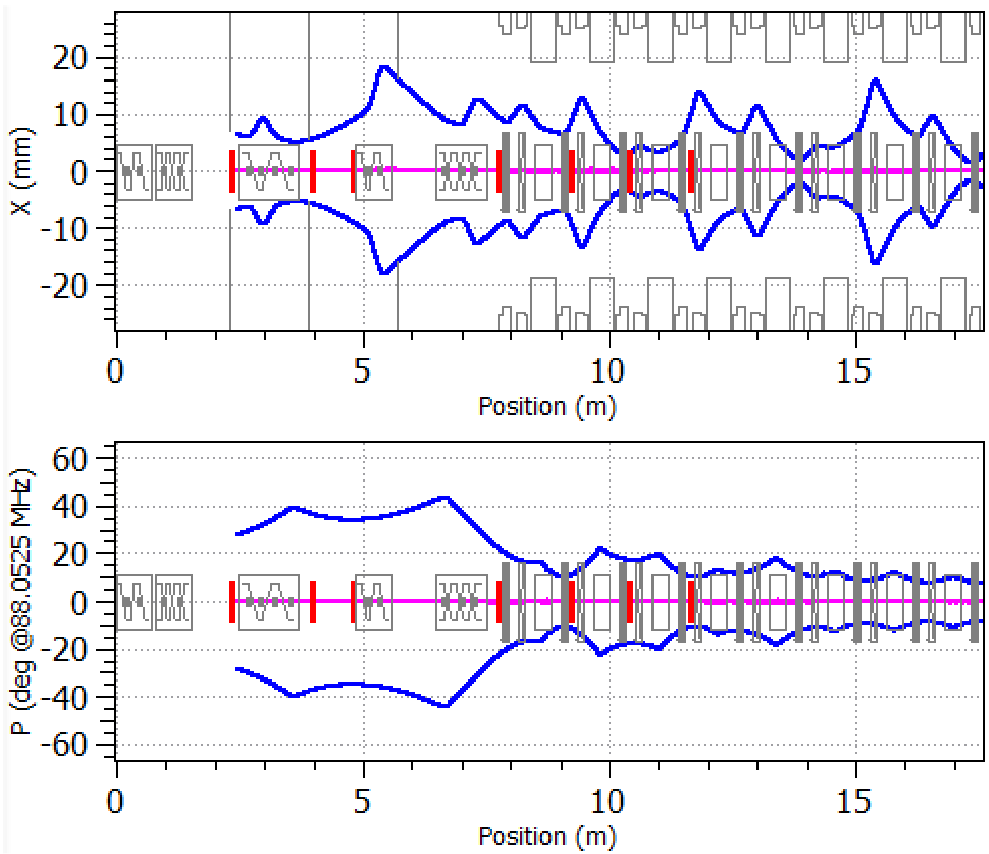
**Quadrupolar momentum of BPM :** $Q \approx \frac{{X_C}^2}{R^2} + \frac{{\sigma_x}^2 - {\sigma_y}^2}{R^2} + \cdots$

- ✓ Coupling with the slow position (1/10)
- ✓ Amplitude signal at same order than dipolar momentum

## Crucial diagnostic

- ➢ Phase measurement : Using time of flight technic, dedicated to cavities tuning, $E_{acc}$ et $\varphi_s$
- ➢ Position measurement : beam alignment along LINAC
- ➢ Quadrupolar momentum measurement : transverse matching of the beam in the LINAC

## BEAM TUNING STEPS – PHASE #3 : LINAC MATCHING

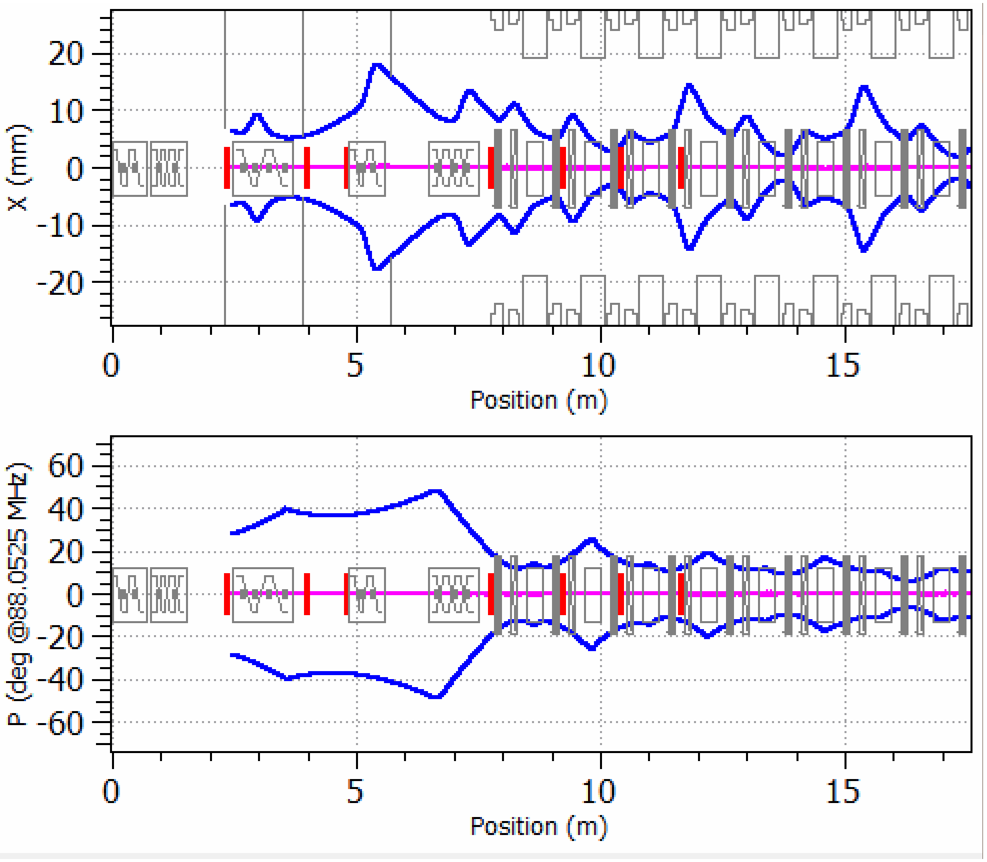


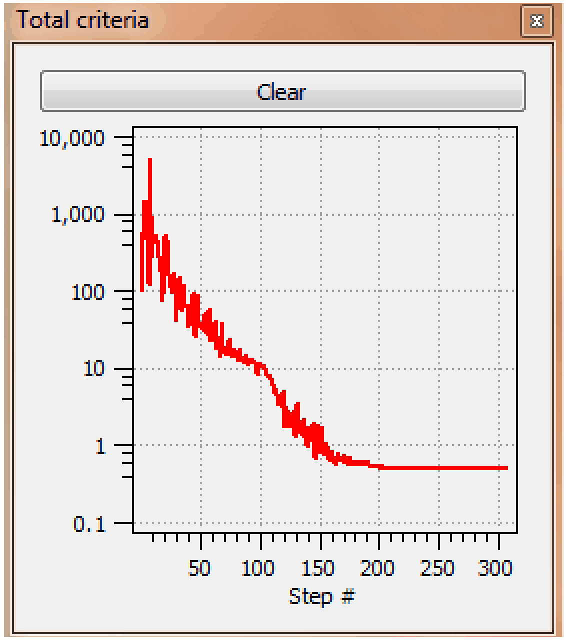

Probable situation of a initial tuning of the LINAC

**Iterative process**

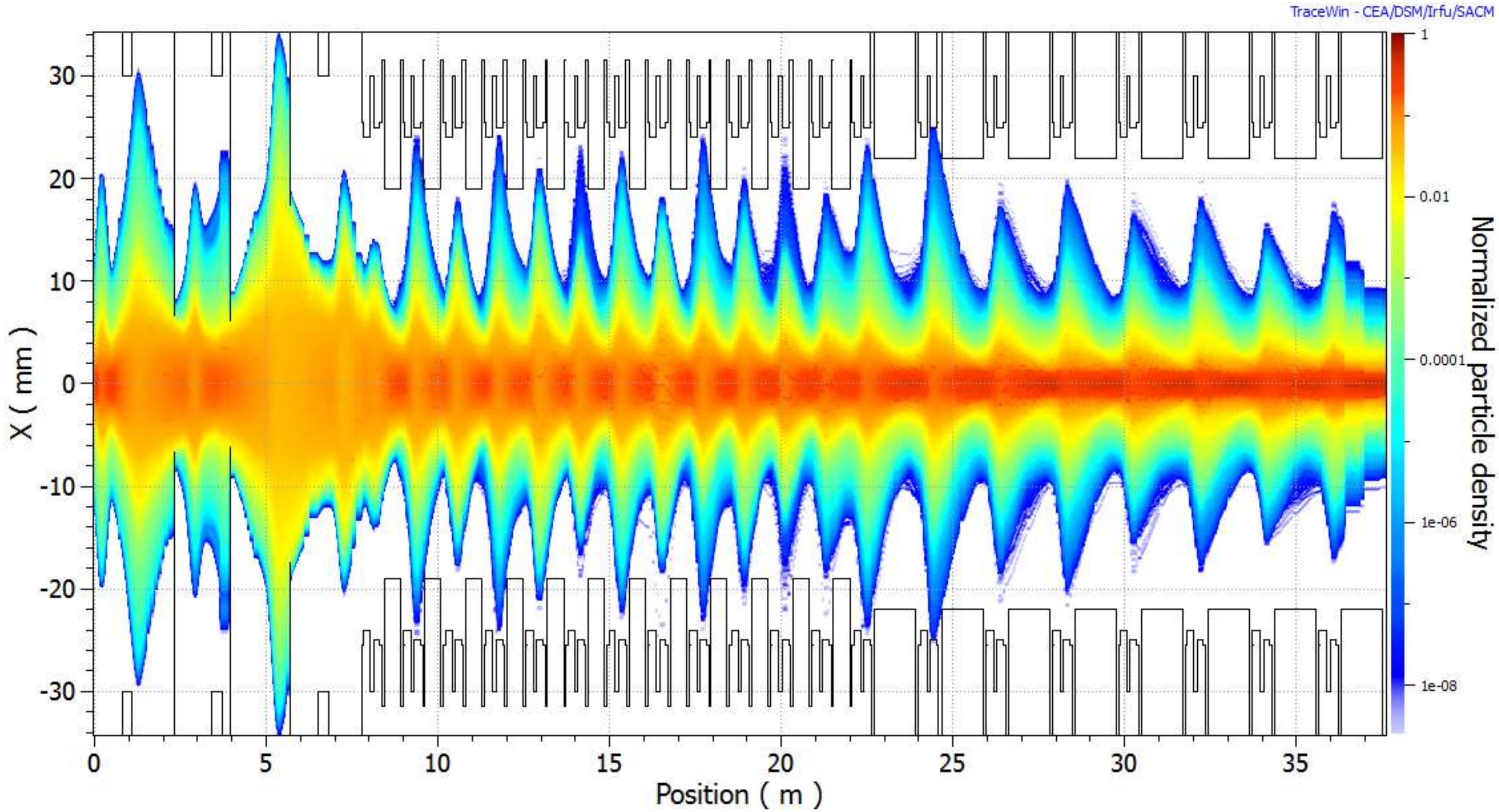
- Apply values to elements which have to be adjust
- Measurement of sizes $\sigma_x{}^2 - \sigma_y{}^2$
- Measurement of bunch length $\sigma_z$
- Calculation of a general criteria
- Determination of the new values set

# BEAM TUNING STEPS – PHASE #3 : LINAC MATCHING



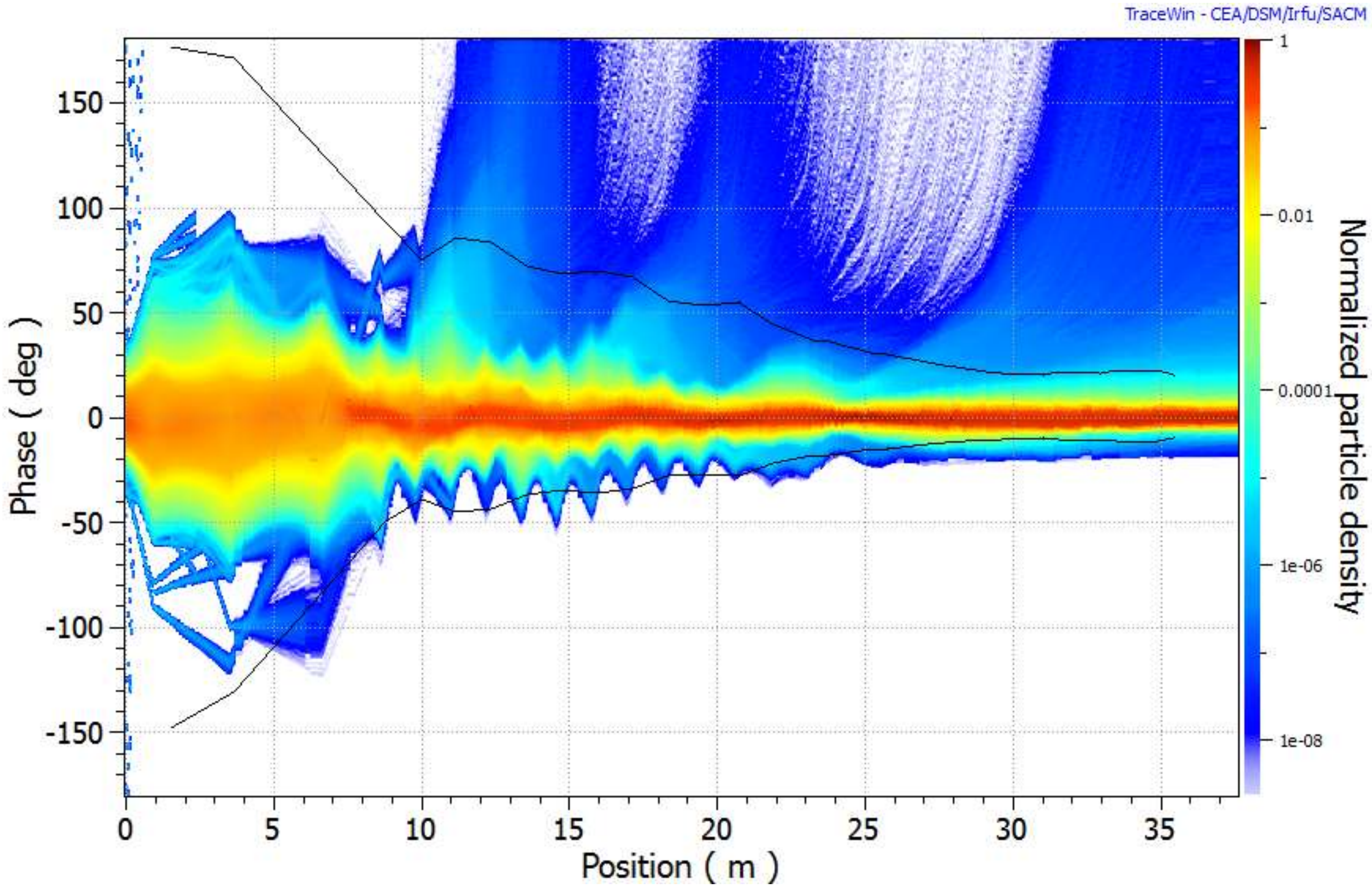



## ASPECTS OF THE LOSSES – TRANSVERSE BEAM PROFILES




Calculation for 400.000.000 particles

## ASPECTS OF THE LOSSES – LONGITUDINAL BEAM PROFILE



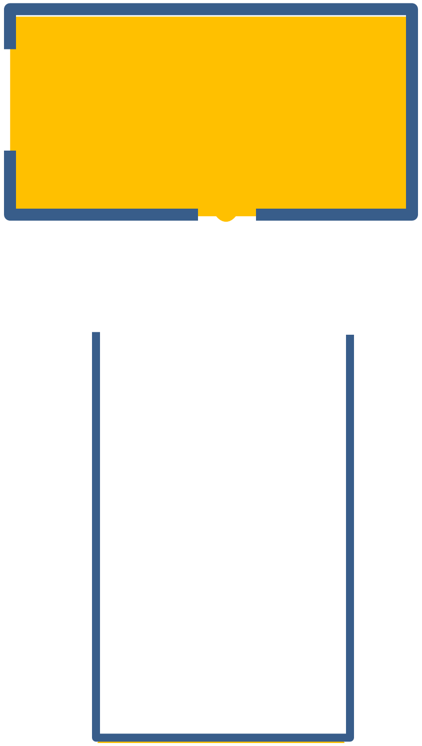

Calculation for 400.000.000 particles

## ASPECTS OF THE LOSSES – BEAM POWER

### BEAM POWER ?

Deuterons beam : 40 MeV, 5 mA = 200 kW

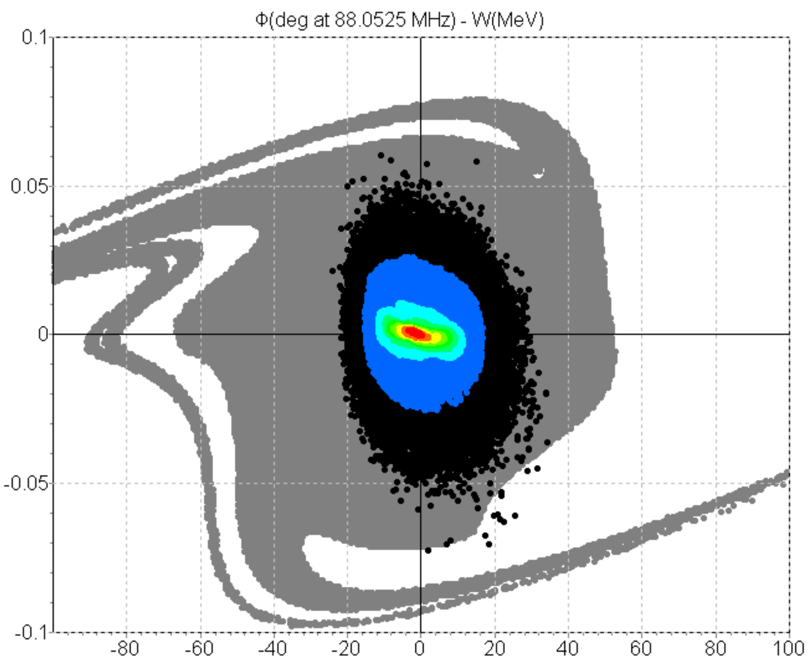
1 kg of Copper



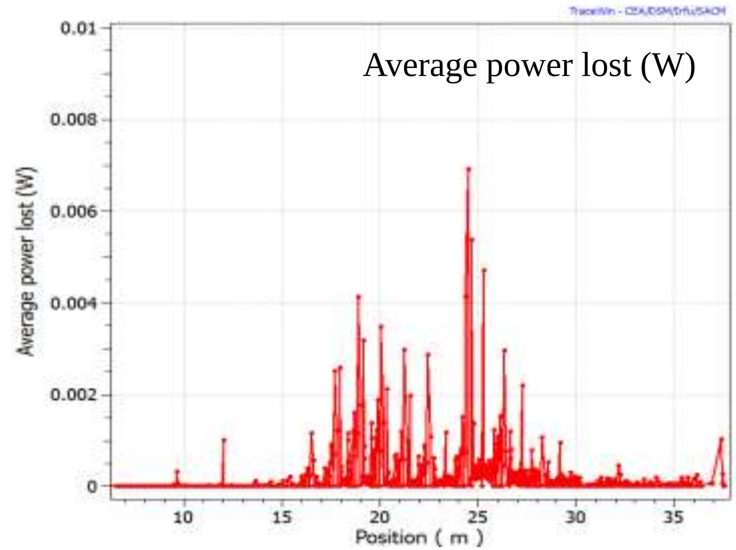
**Melted in 3 seconds !**

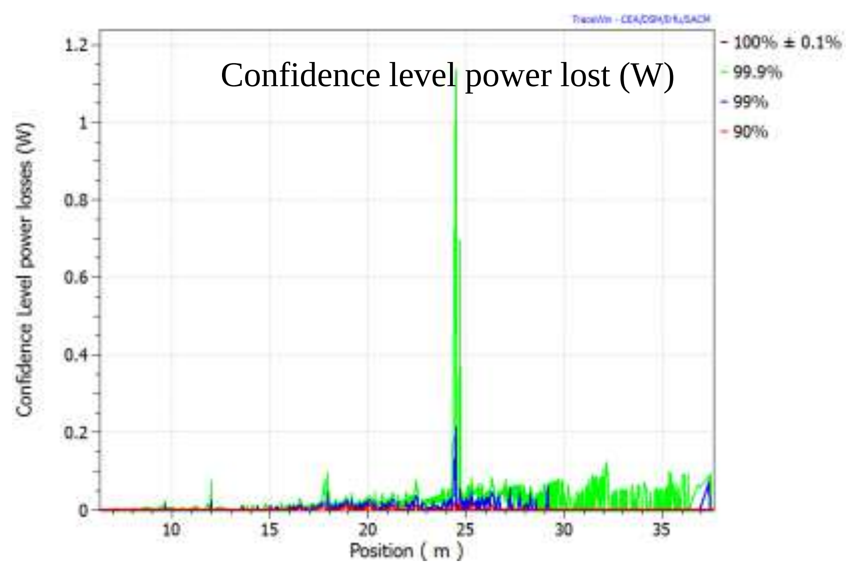
# ASPECTS OF THE LOSSES

Longitudinal acceptance (Deuterons)




Losses : statistic results



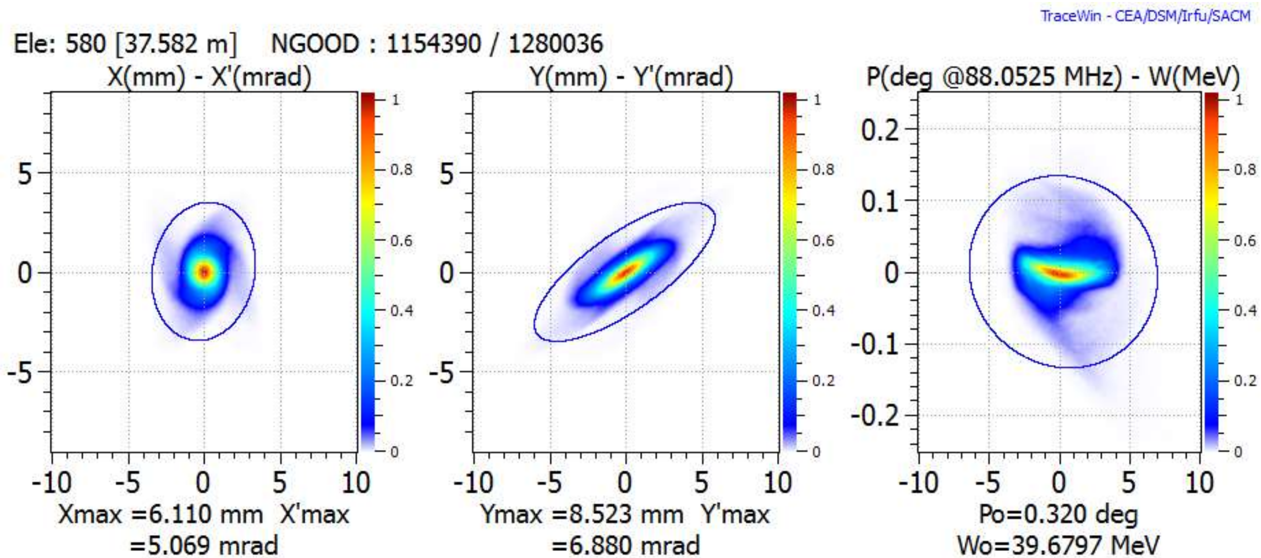




Losses control : Using the beam loss monitor

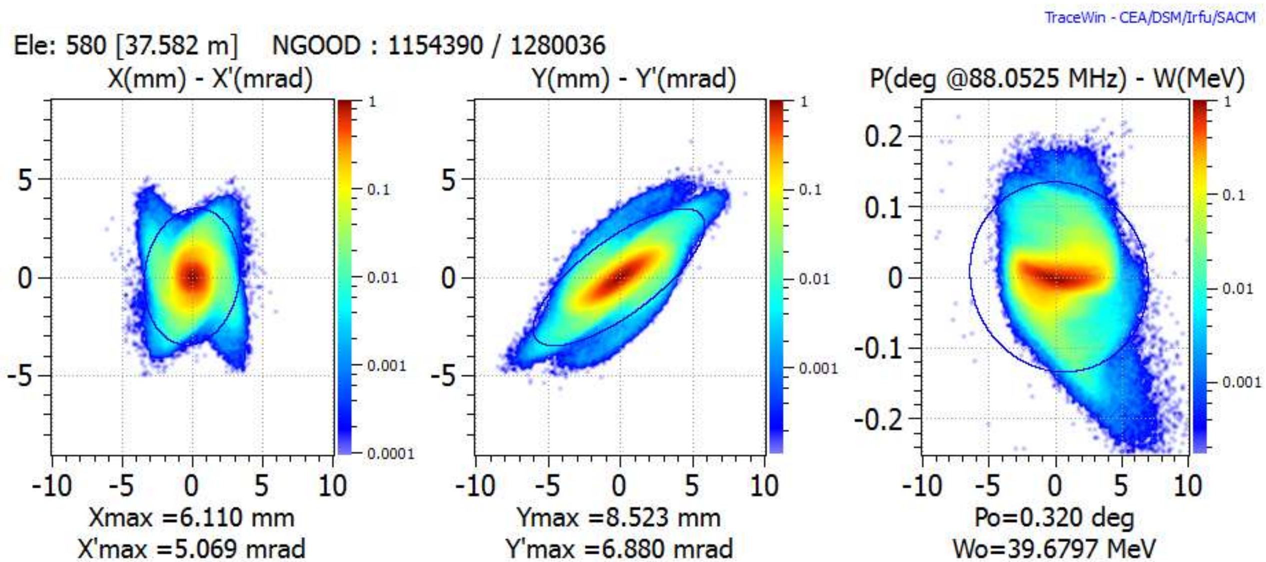
Losses minimization : Increase the acceptance

## PHASE SPACES AT THE EXIT OF THE LINAC

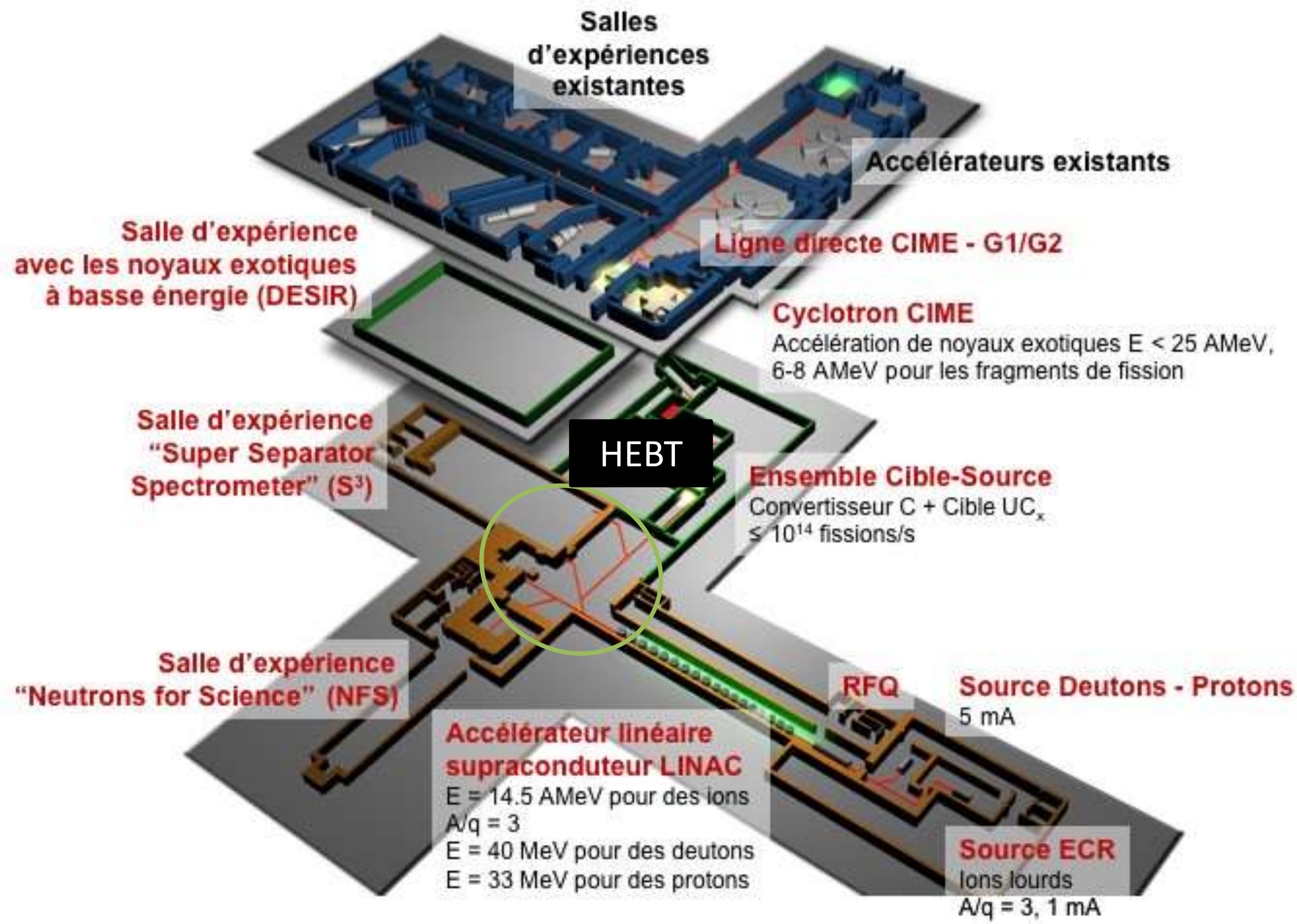
Linear scale



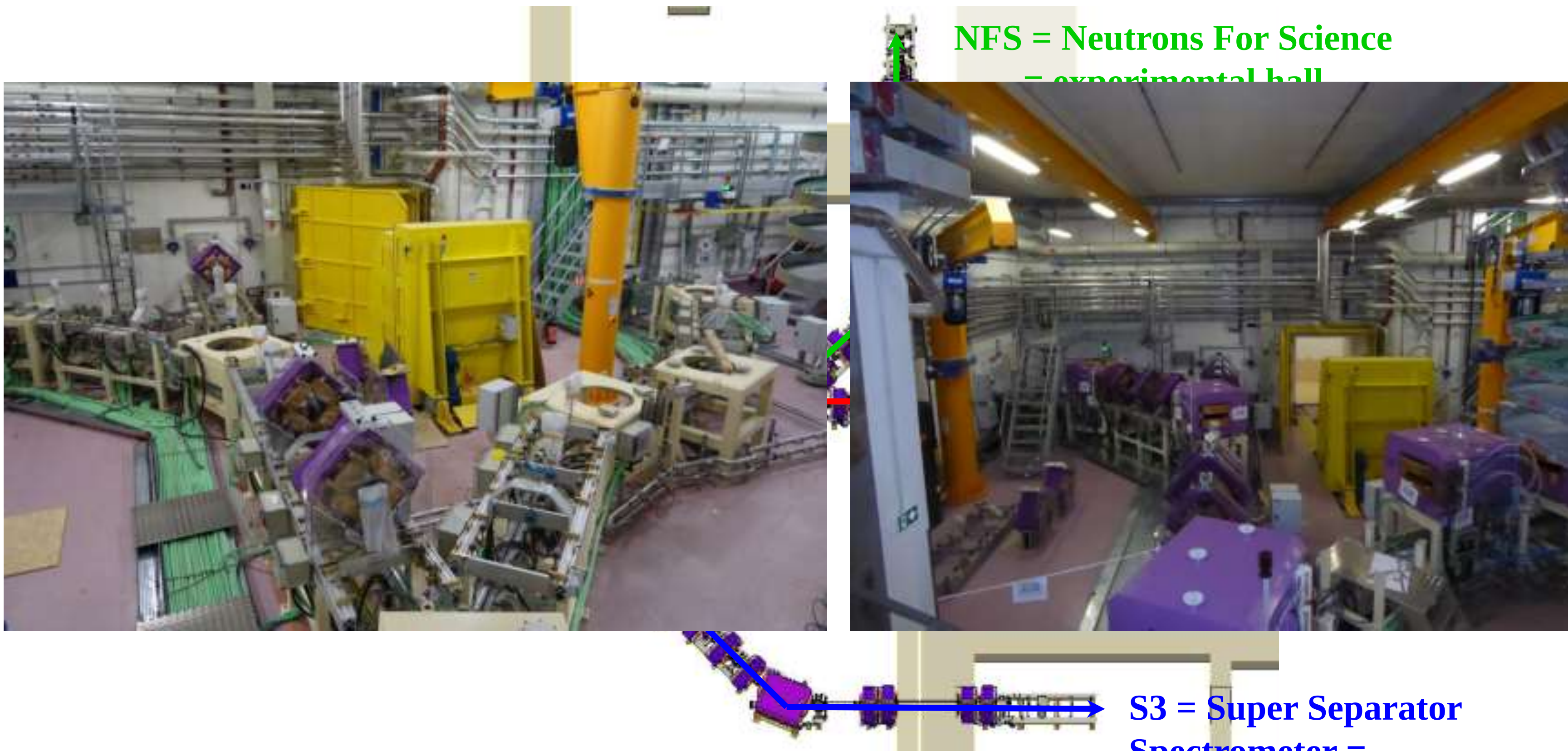

Logarithmic scale



# 6. THE HIGH ENERGY BEAM TRANSPORT LINES



# IMPLANTATION OF HEBT



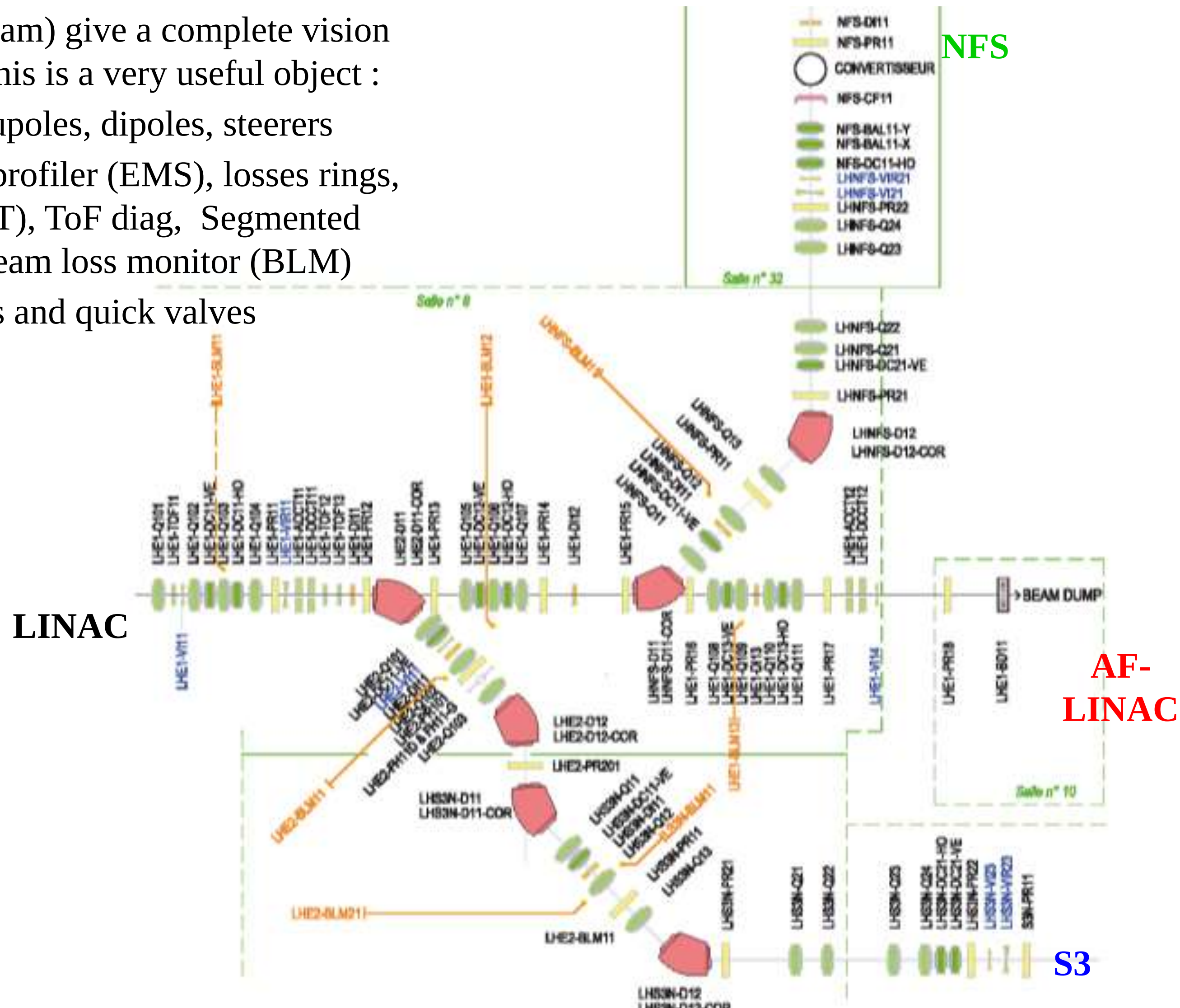

**3 lines (totale length = 54.5m) :**

- **LHE1** : from LINAC to Beam-dump. L=21.3m.
- **LHNFS** : from dipole LHNFS-D11 to neutrons converter. L=14m.
- **LHS3N** : from dipole LHE2-D11 to target area of Super Separator Spectrometer S3. L=19.2m.

# HEBT : NAME OF THE ELEMENTS

The synoptic (overview diagram) give a complete vision of the elements of the lines. This is a very useful object :

- ➢ Magnetic element : quadrupoles, dipoles, steerers
- ➢ Beam diagnostics : beam profiler (EMS), losses rings, current diag (ACCT-DCCT), ToF diag, Segmented collimator, beam-dump, beam loss monitor (BLM)
- ➢ Vacuum valves : isolations and quick valves

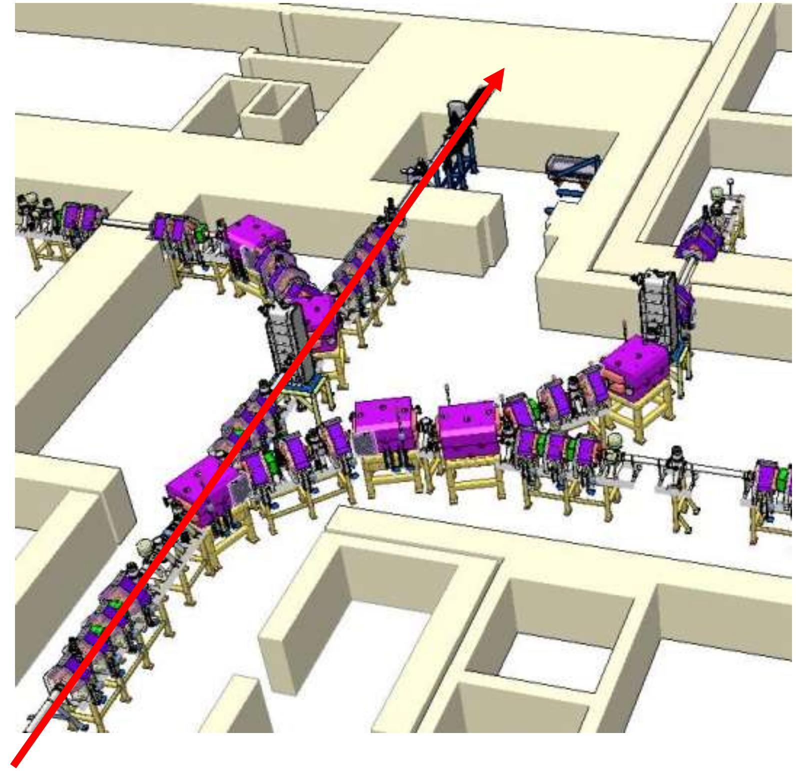


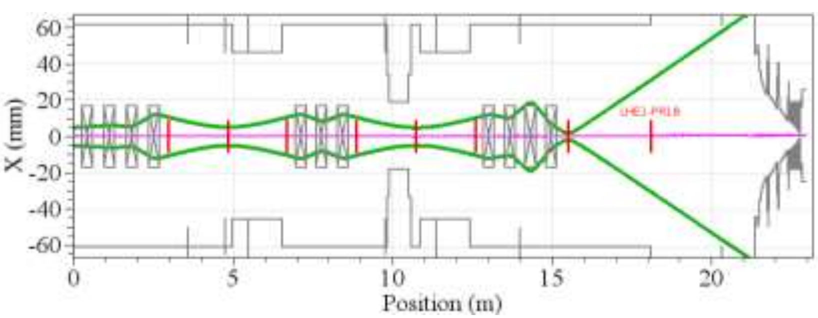
# TRANSPORT UP TO THE BEAM-DUMP

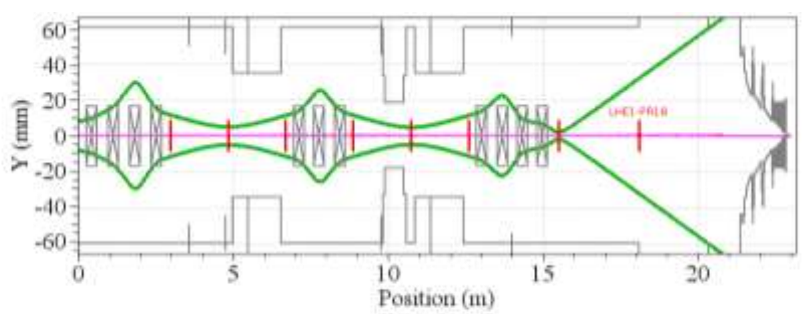
## From LINAC exit up to the beam-dump

### 3 sub sections :

- LINAC beam matching
  - 4 quadrupoles + One set of X – Y steerer
  - 2 EMS + 1 ToF + 1 ACCT-DCCT + 1 ring losses + 1 BLM
- One triplet
  - 3 quadrupoles + One set X – Y steerer
  - 2 EMS + 1 ring losses + 1 BLM
- beam matching to beam-dump
  - 4 quadrupoles + One set of X – Y steerer
  - 3 EMS + 1 ACCT-DCCT + 1 ring losses + 1 BLM
  - 1 segmented collimator or clover (4 current measurement)
  - 27 thermocouple sensors fixed on the beam-dump

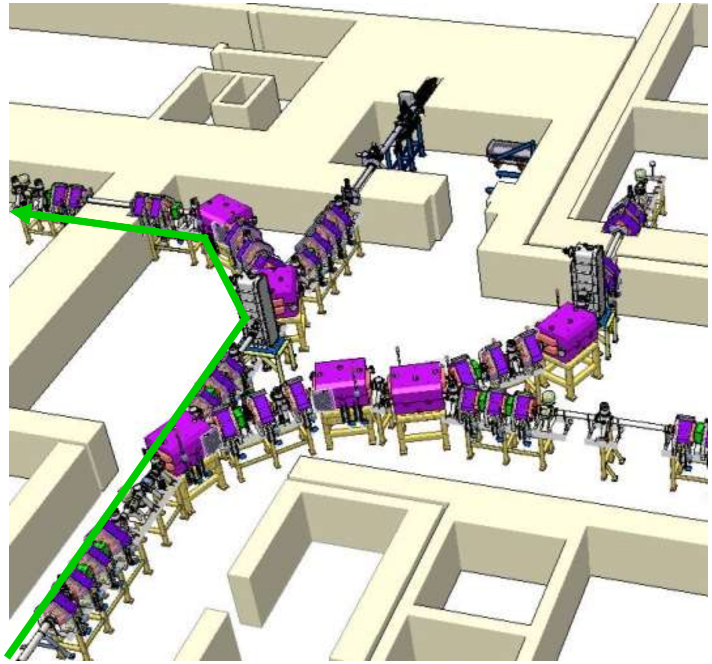




# TRANSPORT UP TO THE NFS EXP. AREA

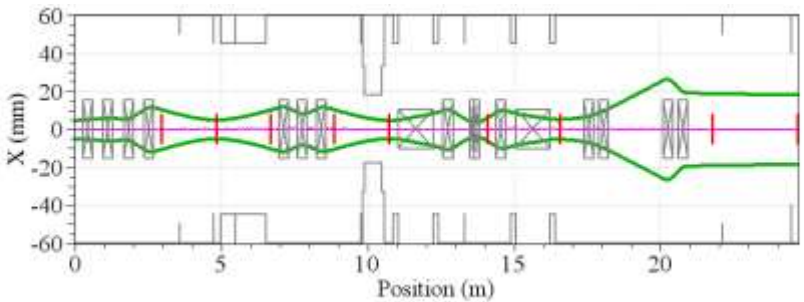
## From LINAC exit up to NFS : 4 sub sections

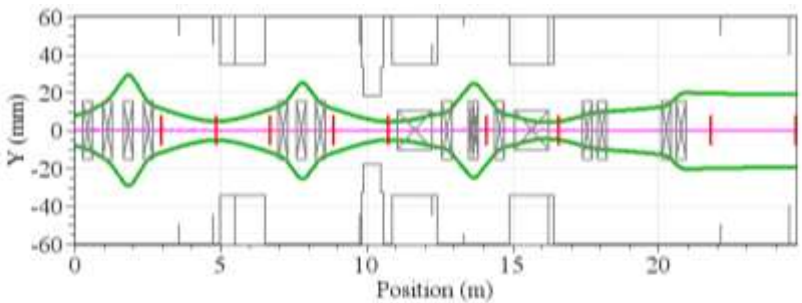


- LINAC beam matching
  - 4 quadrupoles + One set of X – Y steerer
  - 2 EMS + 1 ToF + 1 ACCT-DCCT + 1 ring losses + 1 BLM
- One triplet
  - 3 quadrupoles + One set X – Y steerer
  - 2 EMS + 1 ring losses + 1 BLM
- Left-left deflection
  - 2 dipoles + 3 quadrupoles + 1 steerer Y
  - 1 EMS + 1 ring losses + 1 BLM
- Matching to NFS + neutrons converter hall
  - 4 quadrupoles + 2 steerers Y + 1 steerer X
  - 3 EMS + 1 Faraday cup
  - 2 target points (irradiation and converter)

High limitation for NFS :

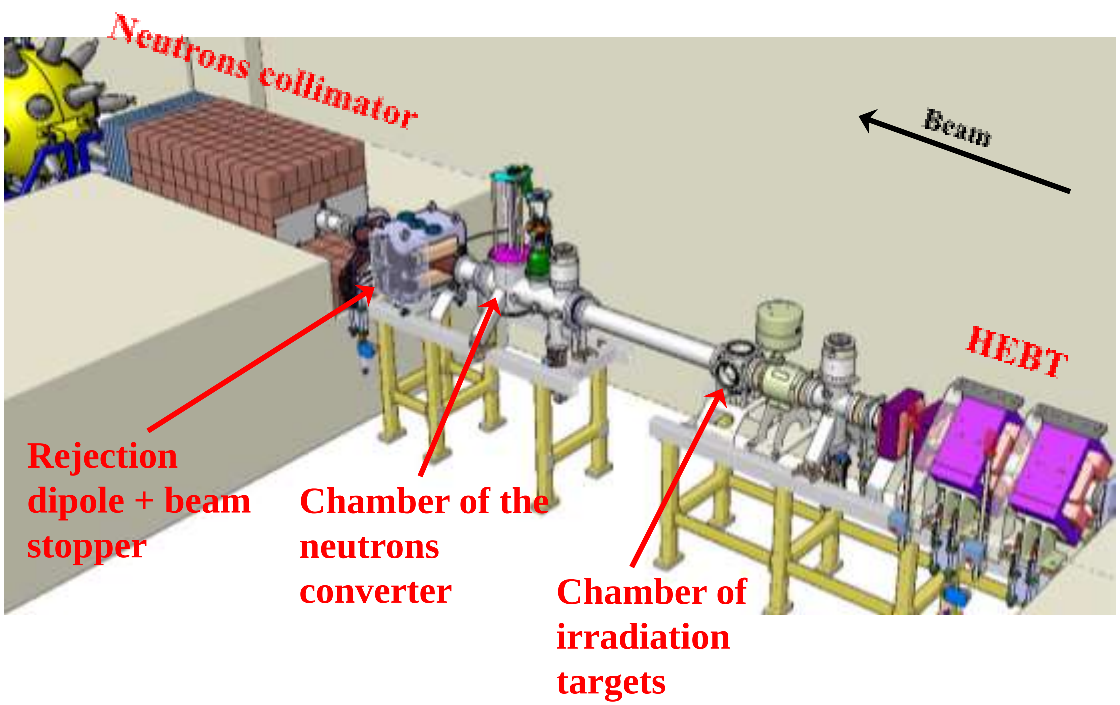
**$P_{max} = 2kW$ in Deuterons at 40MeV**

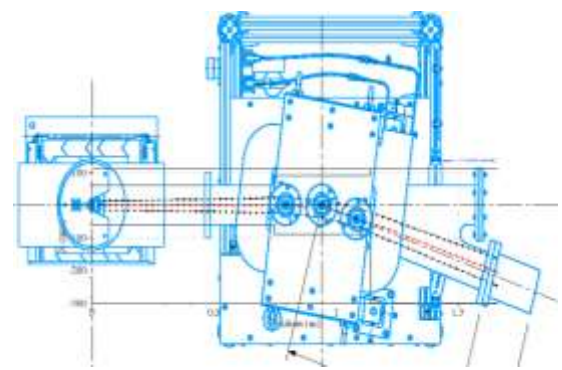


# FEW WORDS ABOUT NFS EXP. AREA

- NFS wil use ligth particles : Deuterons (40MeV) and Protons (10MeV-33MeV) : $\mathbf{0.4Tm < B\rho < 1.3Tm}$
- $P_{max} = 2kW$ ($I_{max} = 50\mu A$ Deuterons at 40MeV) using source peak current reduction (for irradiation experiments) or bunch suppressor of the MEBT (rate 1/100 or more)
- Beam sizes : 1 to 4mm RMS
- Need a bunched beam on neutrons converter for the neutrons time of flight experiments
- Primary beams are stopped in target or in a beam stopper

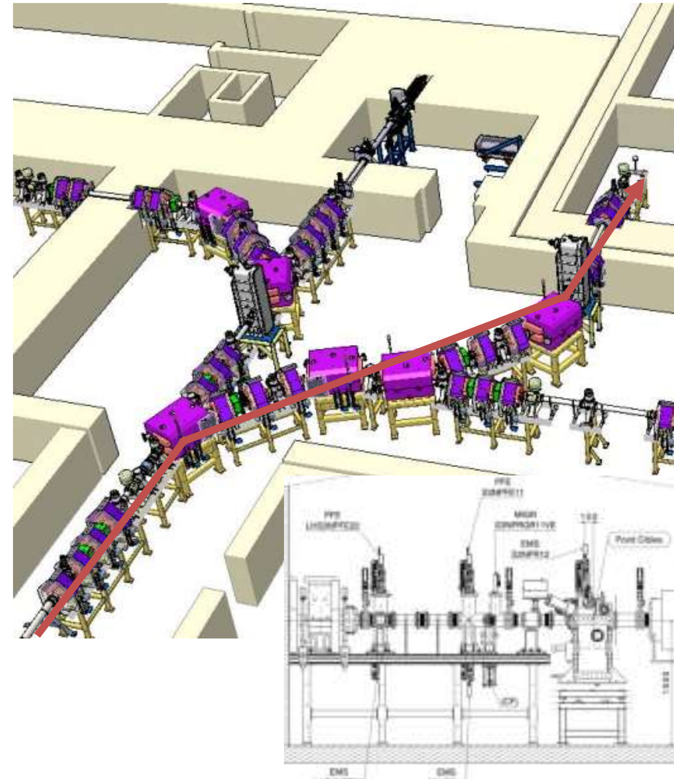


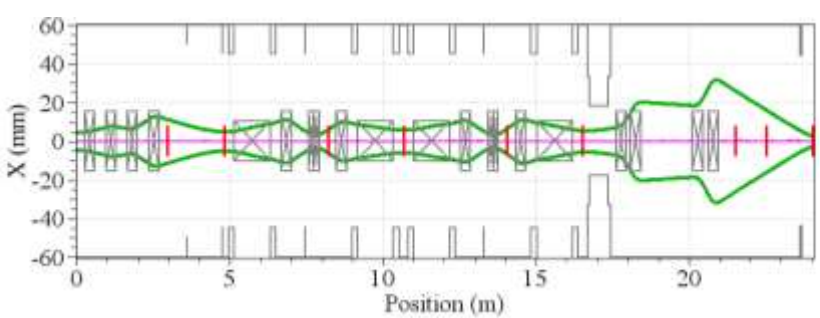
# TRANSPORT UP TO THE S3 EXP. AREA

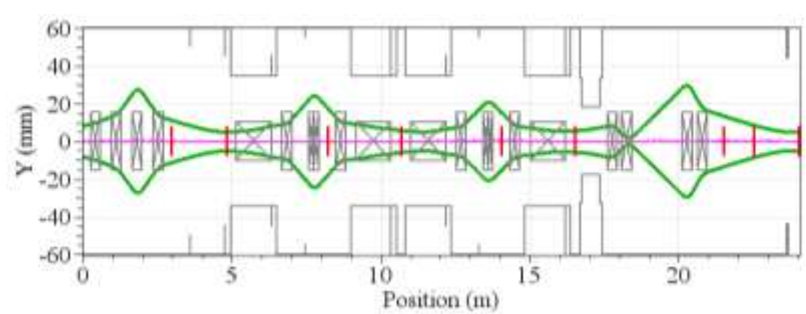
## From LINAC exit up to S3 : 4 sous-sections

- LINAC beam matching
  - 4 quadrupoles + One set of X – Y steerer
  - 2 EMS + 1 ToF + 1 ACCT-DCCT + 1 ring losses + 1 BLM
- Right-right deflection
  - 2 dipoles + 3 quadrupoles + 1 steerer Y
  - 2 EMS + 1 ring losses + 1 BLM
  - 1 jeu de fentes horizontal
- left-left deflection
  - 2 dipoles + 3 quadrupoles + 1 steerer Y
  - 1 EMS + 1 ring losses + 2 BLM
- Matching to + target room
  - 4 quadrupoles + 2 steerers Y + 1 steerer X
  - 4 EMS + 1 MIGR VE + 2 PFE + 1 Faraday cup



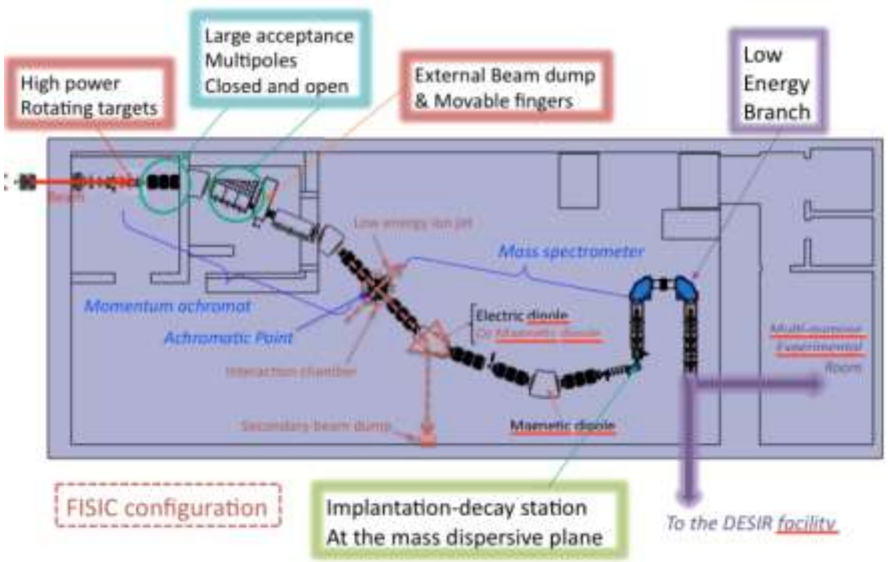
2 target modules (stables or actinides)

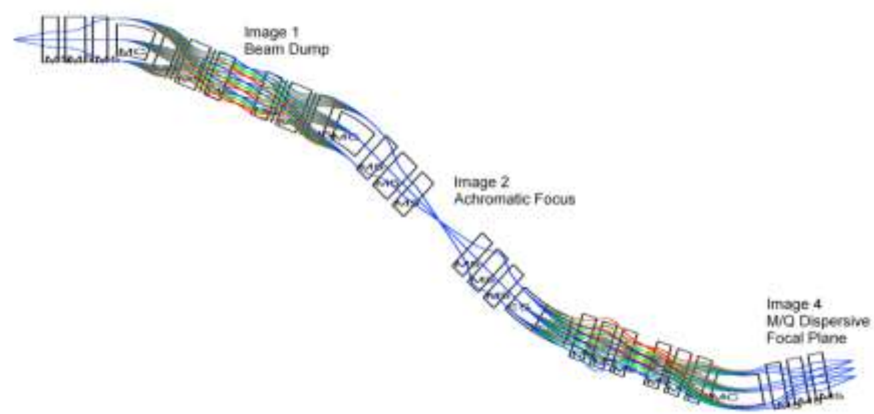


# FEW WORDS ABOUT S3 EXP. AREA

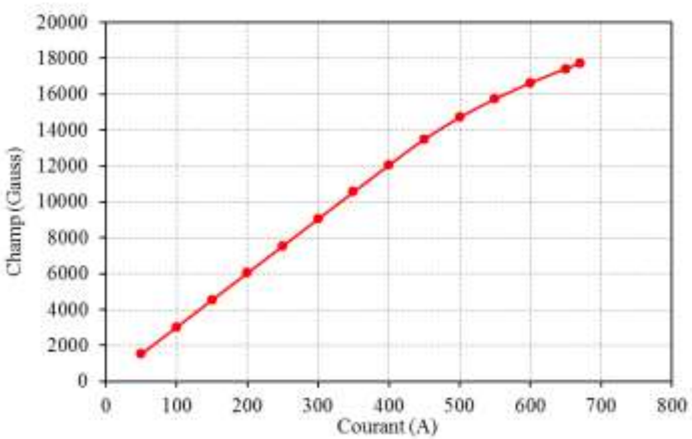
- S3 will use heavy ions with A/q=3 at energy from 2MeV/u up to 14.5MeV/u : $\mathbf{0.6}\boldsymbol{Tm} < \boldsymbol{B\rho} < \mathbf{1.65}\boldsymbol{Tm}$
- Beam sizes on targets : $\sigma_{x,y} = 0.5 \times 0.5$ to $2.5mm$ (Gaussian) or $\sigma_x = 0.5mm$ (Gaussian) $\times\ \Delta y = 10\ mm$
- Tuning of the primary beam will be very complex, completely linked to the S3 tuning.
- For super heavy nuclides experiments : Energy of the primary beam will be 5-6MeV/u. But S3 spectrometer need to be tune at 1MeV/u (energy of the products).



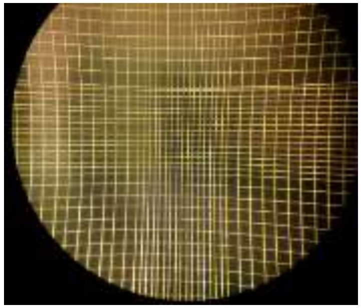
# MAGNETIC ELEMENTS AND CURRENT ALIMENTATION

- 2 types of quadrupoles :
  - Type 1 (G=13T/m, $I_{max}$=280A) : N=10
  - Type 2 (G=10T/m, $I_{max}$=370A) : N=18
- Steerer : $B_{max}$=245G, $I_{max}$=10A
  - 5 dedicated to horizontal plane
  - 10 dedicated to vertical plane
- 6 rectangular dipoles : $\theta = 45°, \rho = 1.5m$
  - $B_{max}$=1.68T, $I_{max}$=670A,
  - Gap=80mm, useful zone=60mm
  - Auxiliary coil : I=10A, V=15V
  - Connect to a commutation grid for the alimentation (safety aspects)
  - RMN field measurement of dipole



# HEBT BEAM DIAGNOSTICS

## Beam profilers (EMS) : formed by 2 grid of wires



- 16 EMS in HEBT and around NFS +S3 targets locations
- 2 types : 1mm step and variable steps between wires, $\phi_{wires} = 70\mu m$
- Need to use the slow beam chopper of the LEBT in order to modulate the beam intensity with its energy (risk of wires melting)

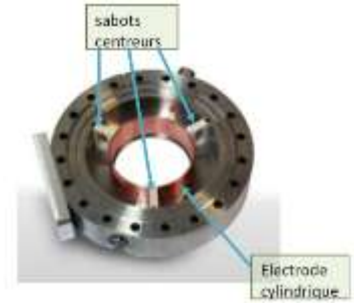
## Beam Loss Monitor (BLM) : 6 systems

- Device to control and monitor the beam losses in the HEBT structures
- locate around 1m to the beam line as clse as possible to the maximum of the transverse beam envelops in HEBT

# HEBT BEAM DIAGNOSTICS

## Beam energy using Time of Flight technic :

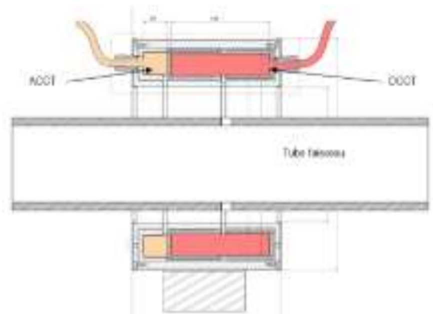
- Located after the LINAC in the matching section
- 2 pick-up devices at around 2m distances
- Use during beam tuning and optimization

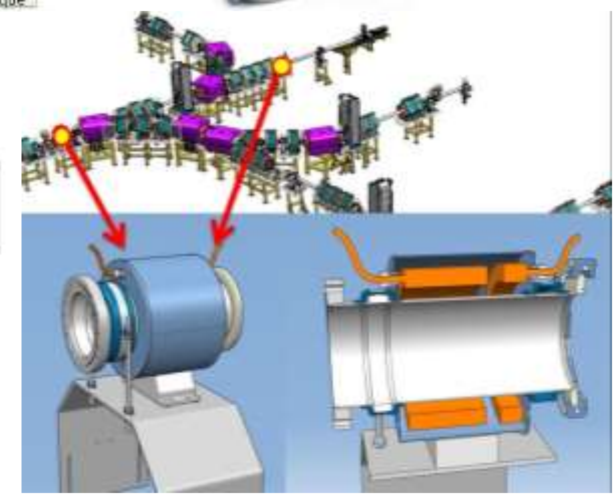




## Beam current measurement :

- 2 devices :
  - At the beginning of the HEBT
  - At the end of HEBT close to the beam-dump
- Measurement of total and transmission current
- Measurement of beam power $P = I \times E$



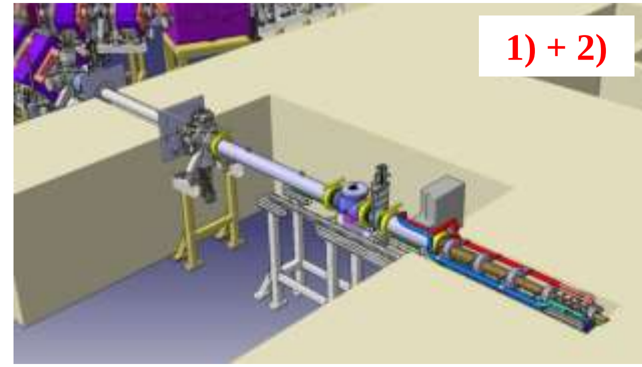


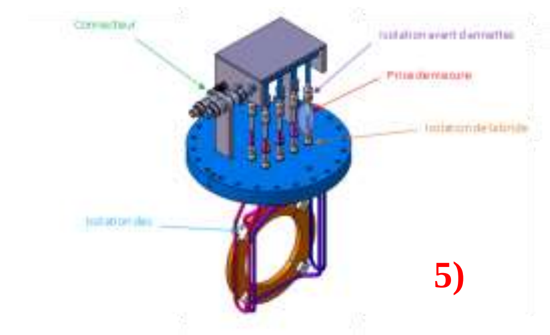
## Ring losses : DI

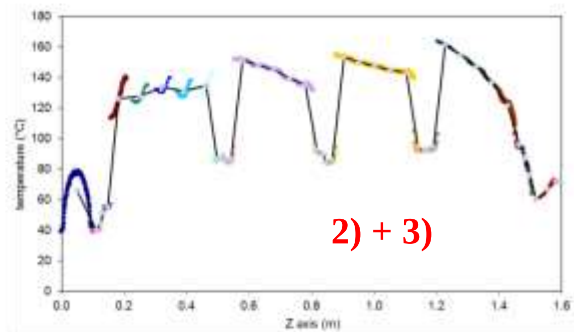
- Normal working condition $I = 0$
- Intercept beam ($I > 0$) in case of mismatching or misalignment
- 6 DI in HEBT (1 in each sub-sections except matching sections NFS et S3)
- Horizontal and vertical aperture of the ring depend to HEBT implantation
- For 10W losses = 250nA for Deuterons beam at 40MeV
- For $I > I_{threshold}$ on a ring, beam must be switched off

# THE SPIRAL2 BEAM-DUMP

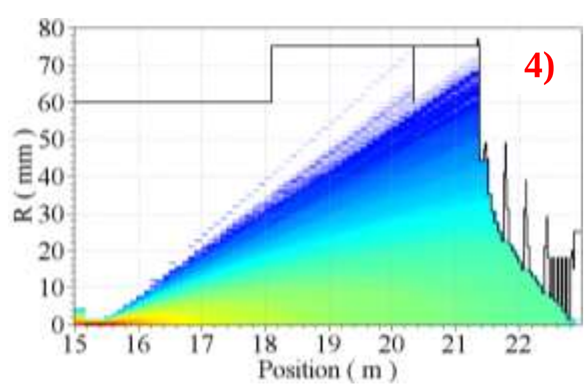
1) Using : tuning of the LINAC and HEBT, beam qualification at the beginning of experiment, beam retuning during experiment
2) Design to stop a Deuterons beam to 40MeV and 5mA (P=200kW)
3) Internal part see by the beam optimize to maximize a flat power deposition
4) Match a beam to $\sigma_x = \sigma_y = 14mm$ at beam-dump entry
5) Segmented collimator located 1m before the bean-dump (4 sectors in Copper). Small halo beam fraction interception for injection optimization of the beam in the beam-dump
6) Demineralized water cooling



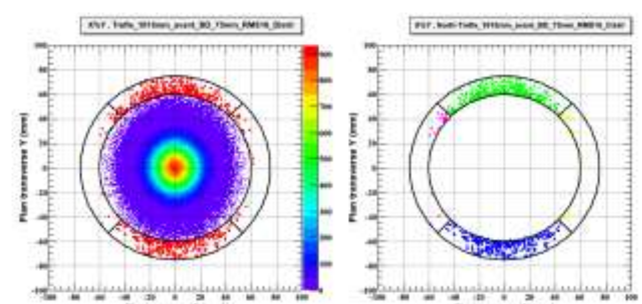








100nA (4W of intercept D)



# THANKS YOU FOR YOUR ATTENTION