

The SPIRAL2 accelerator at GANIL-Caen

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OUTLINE

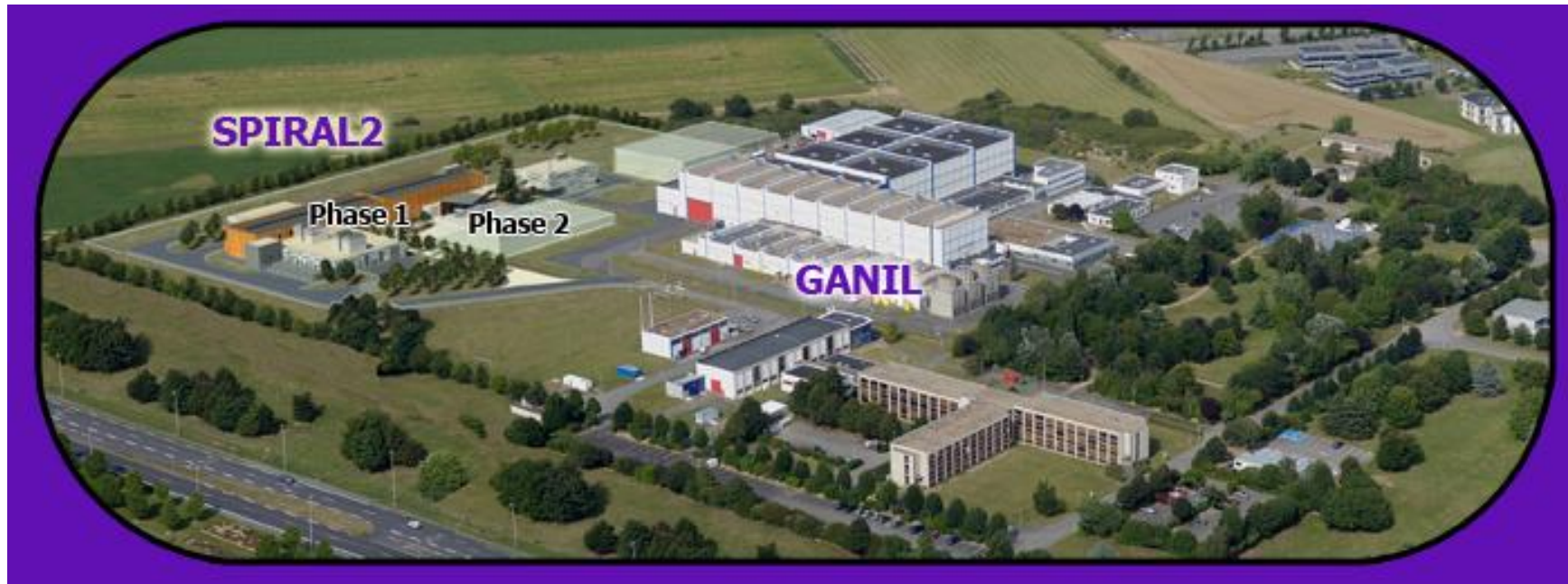
1. General description of SPIRAL-2 facility
2. Ion sources and low energy beam transport line (Lignes Basse-Energie)
3. The RFQ
4. The Medium Energy Beam Transport line (Ligne Moyenne-Energie)
5. The superconducting LINAC
6. The High Energy Beam Transport line (Ligne Haute Energie)

1. WHAT IS SPIRAL2

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

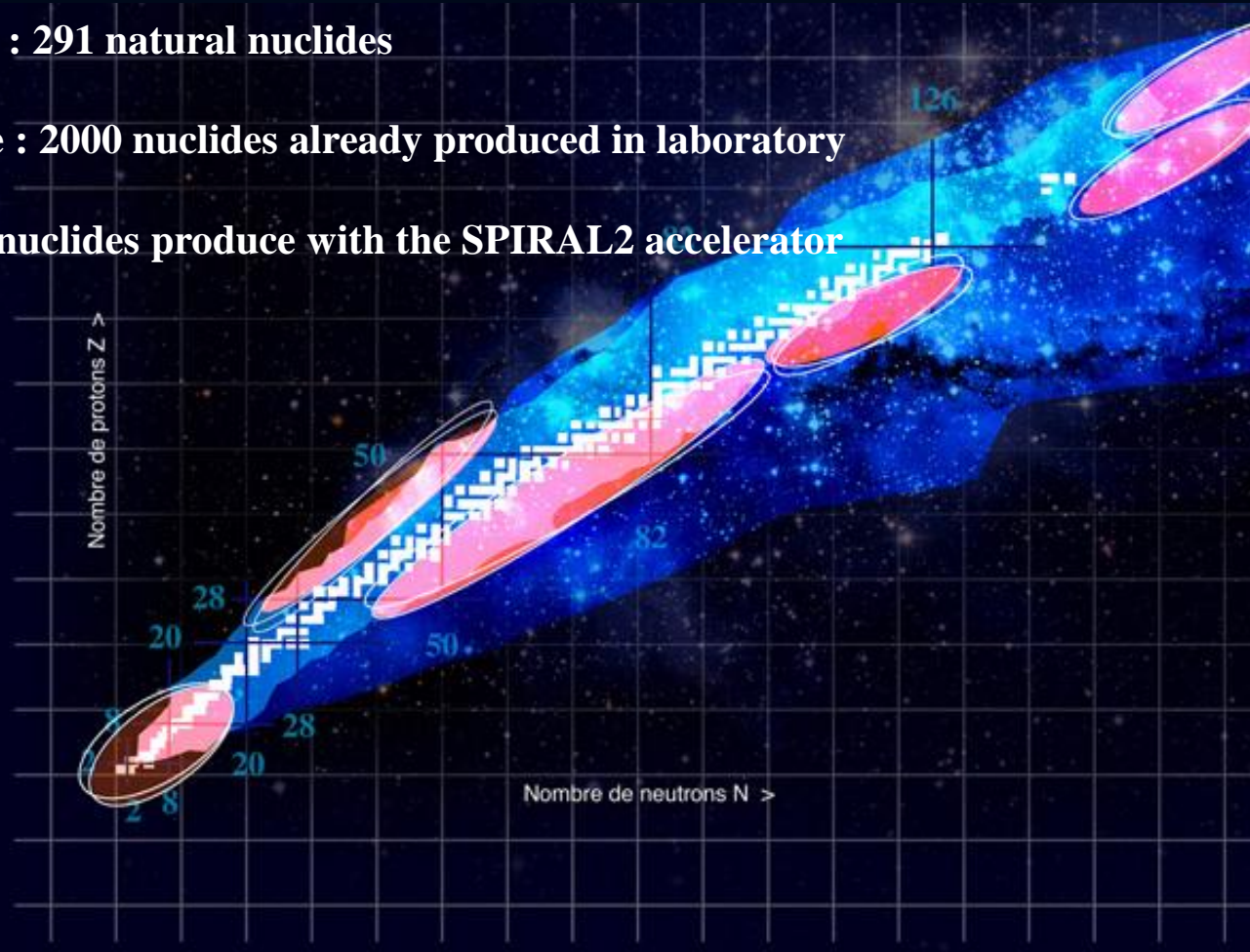
fundamental nuclear physics and interdisciplinary research

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

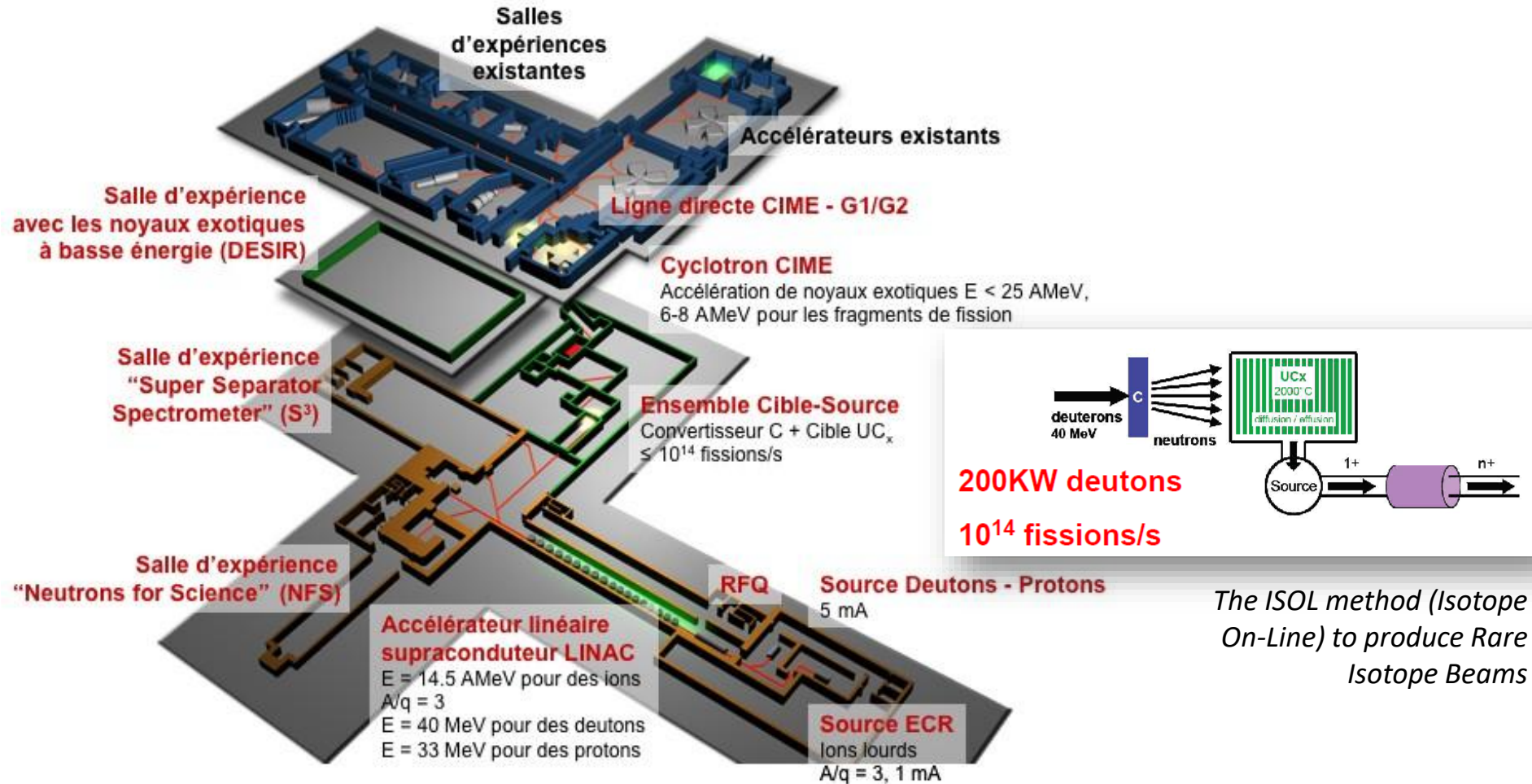


EXPLORATION OF TERRA INCOGNITA

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

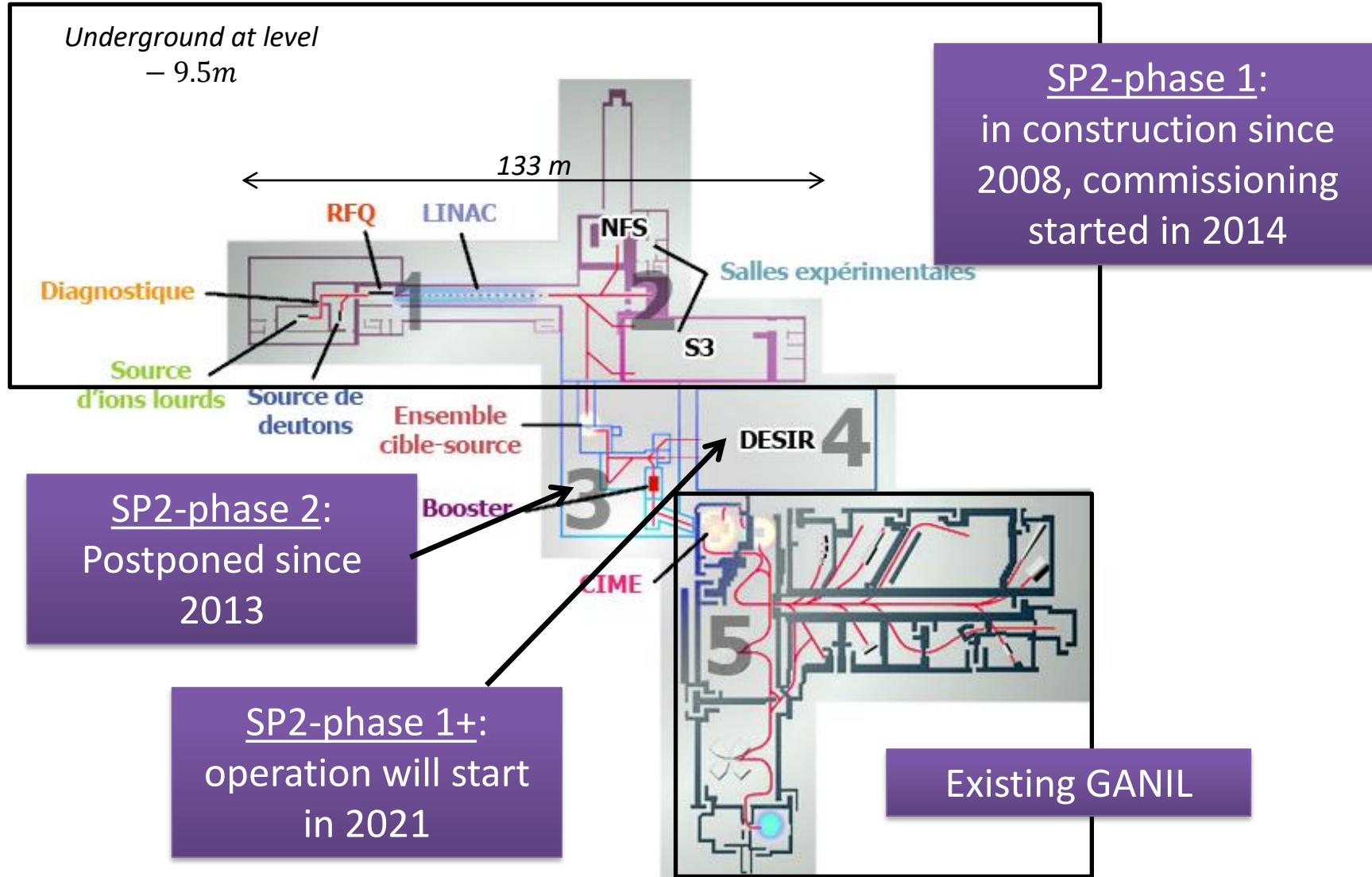


SPIRAL2 AT GANIL FACILITY

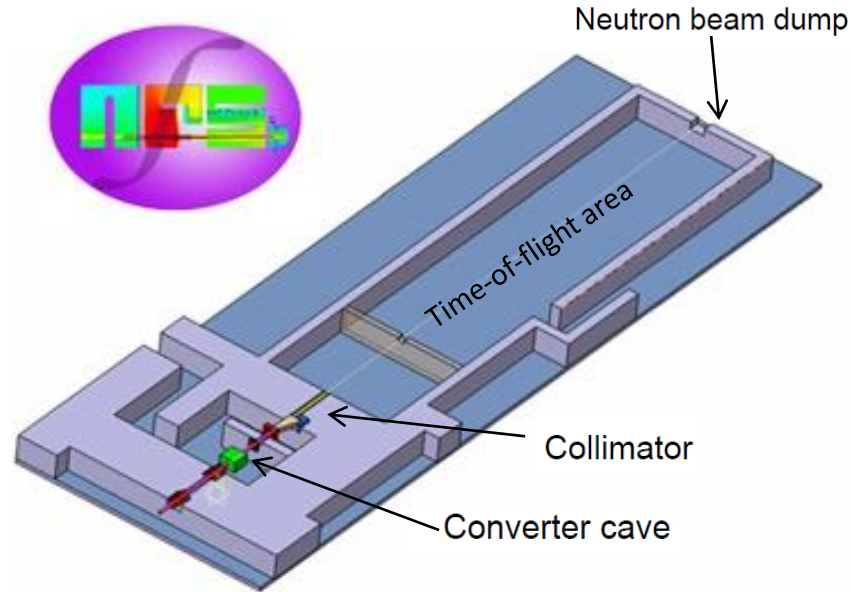


The ISOL method (Isotope On-Line) to produce Rare Isotope Beams

ORGANIZATION AND PHASE

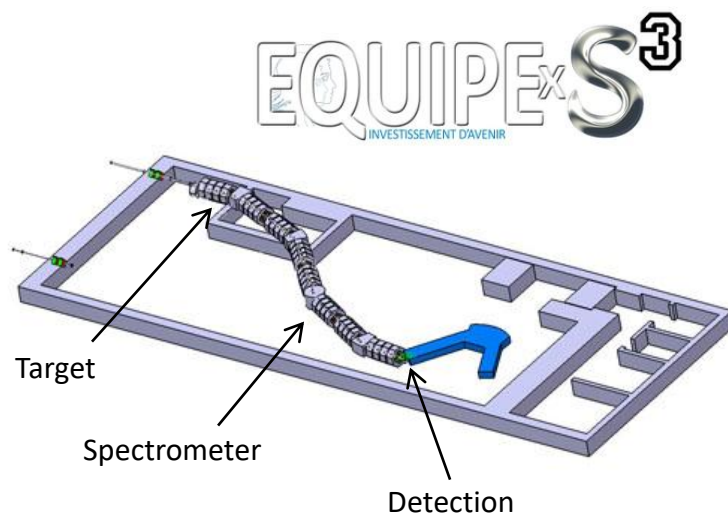


NEW EXPERIMENTAL AREAS



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

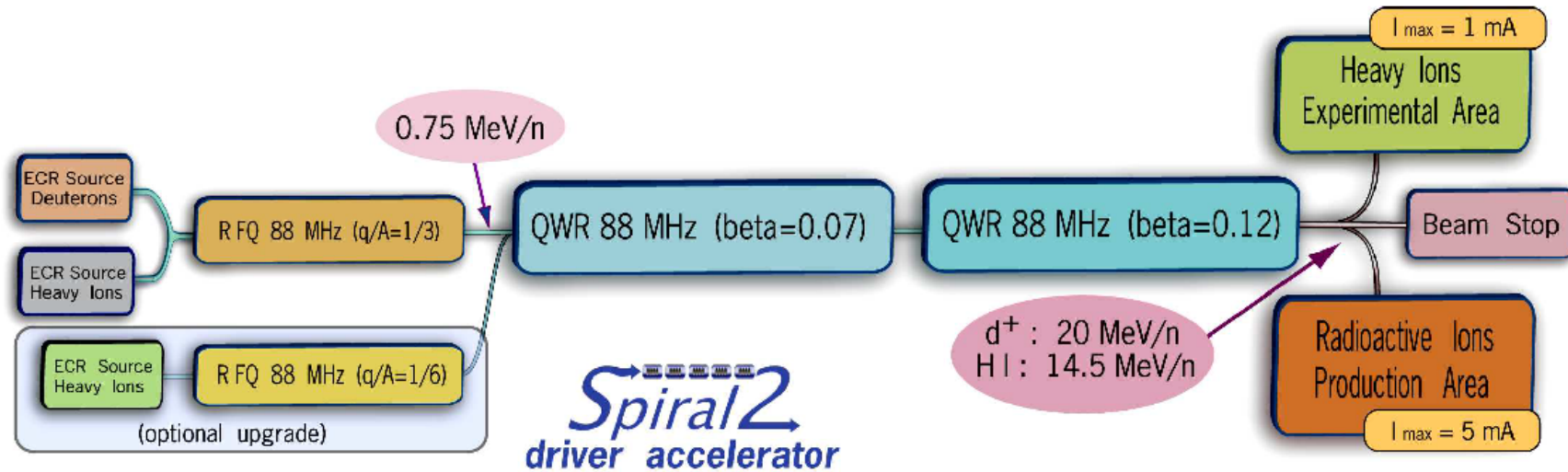
NFS (Neutrons For Science) are will use these neutrons for fundamental physics experiments and others applications (ex: cross sections measurements for next reactors generation, fusion ...)



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.

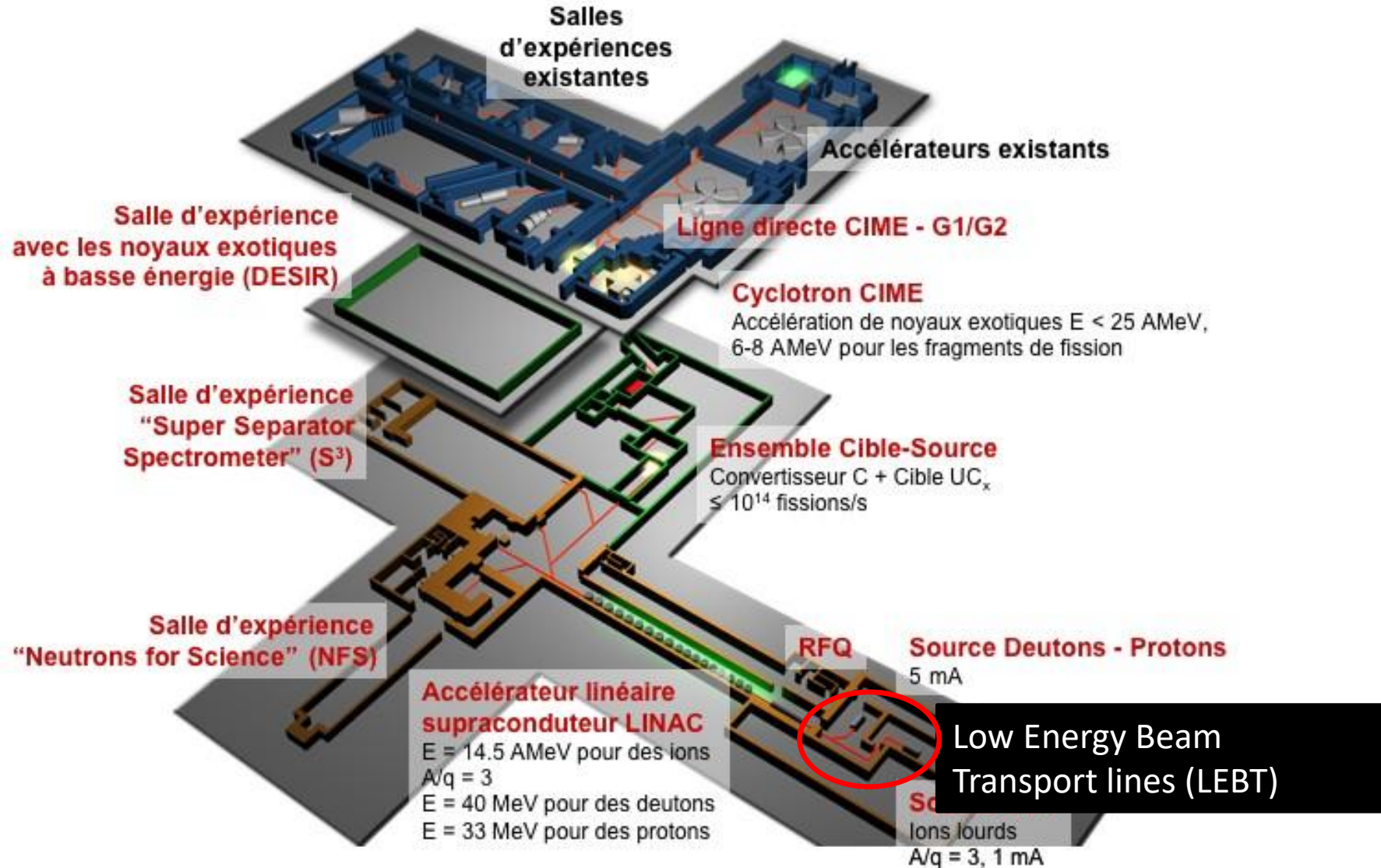
LINAC AND PRODUCED BEAMS



| Faisceau | p+ | D+ | ions | ions |
|-----------------------------|-----|-----|------|------|
| Q/A | 1 | 1/2 | 1/3 | 1/6 |
| I (mA) max. | 5 | 5 | 1 | 1 |
| W ₀ min. (Mev/A) | 2 | 2 | 2 | 2 |
| W ₀ 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 regroupuers |
| 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) |

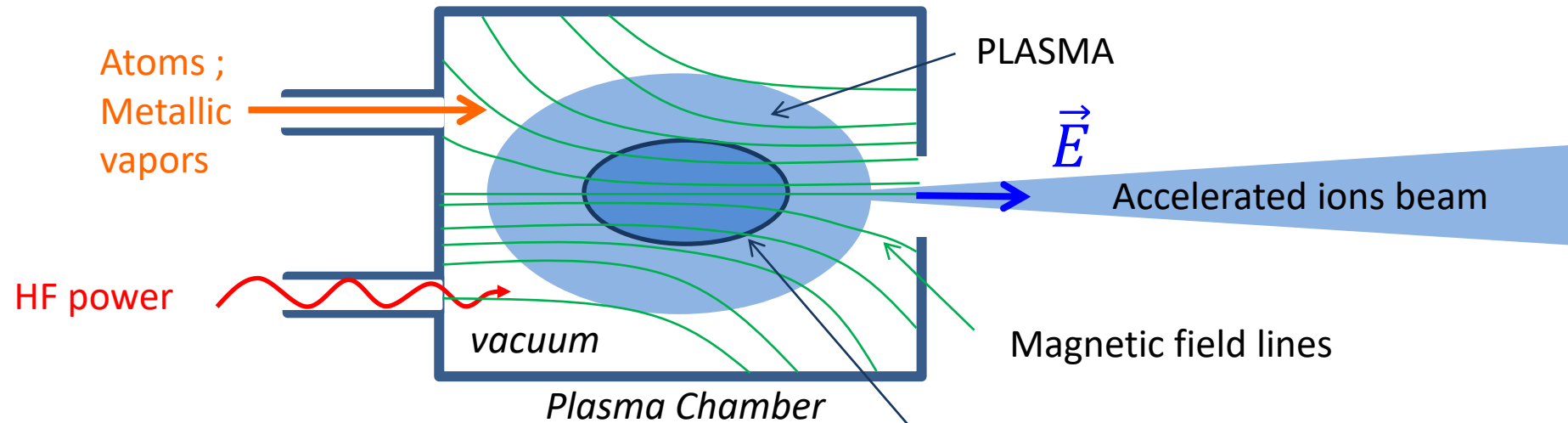
2. ION SOURCES AND LOW ENERGY BEAM LINES



LEBT = LBE (in French)

ECR ION SOURCES

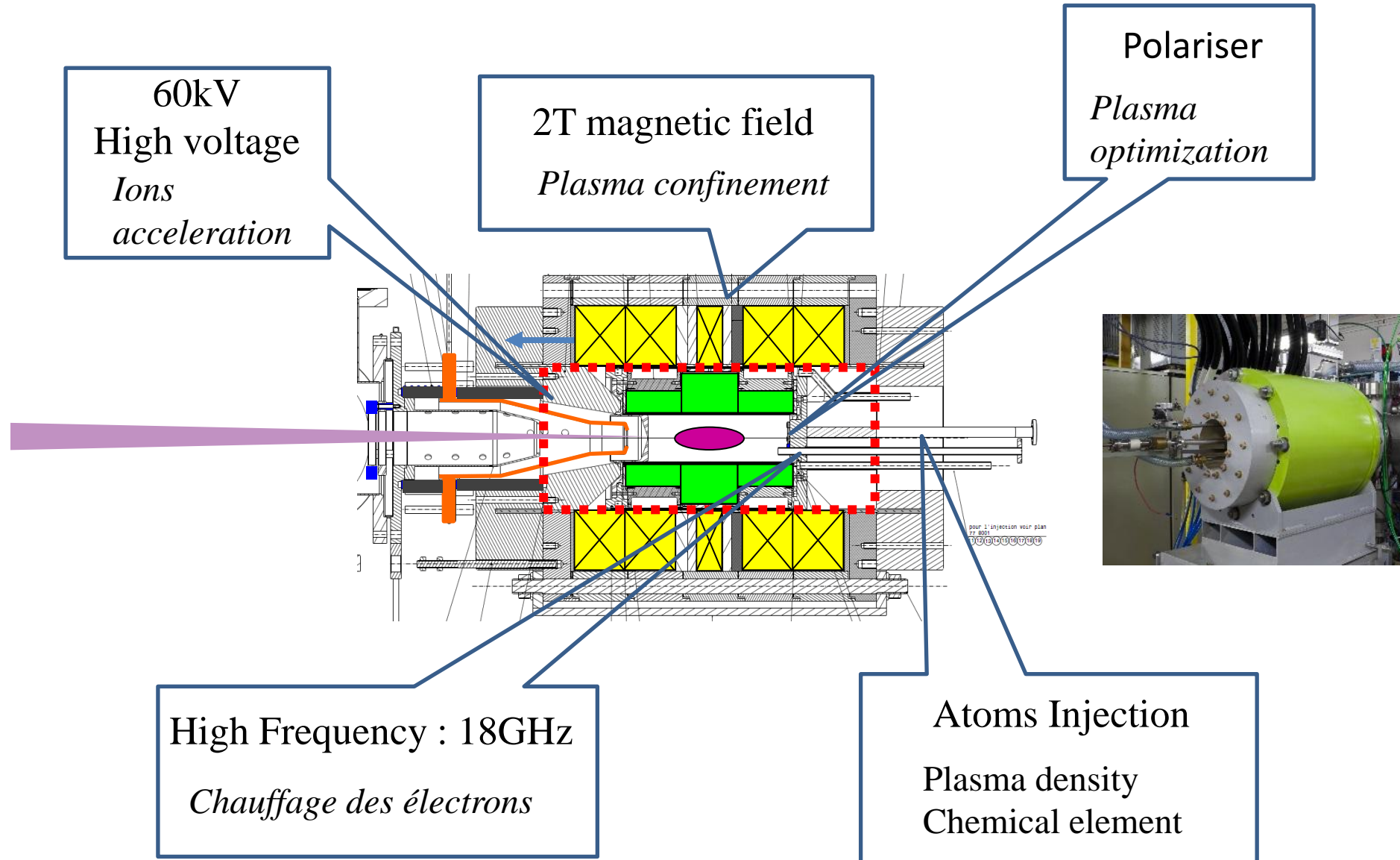
ECR = Electron Cyclotron Resonance



$$\omega_{RF} = \omega_{ce} = \frac{eB}{m_e} \text{ E ECR}$$

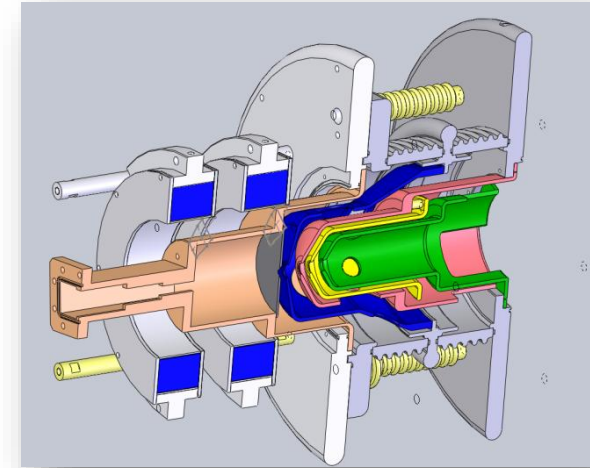
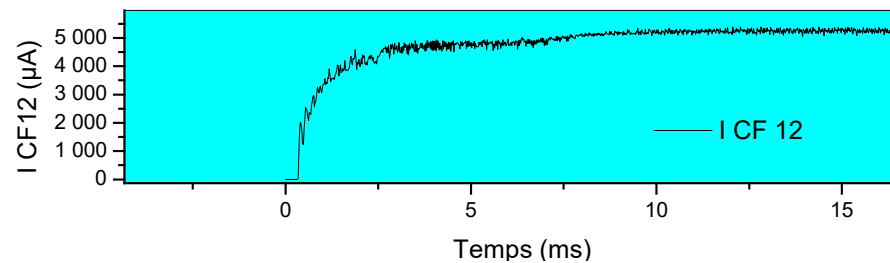
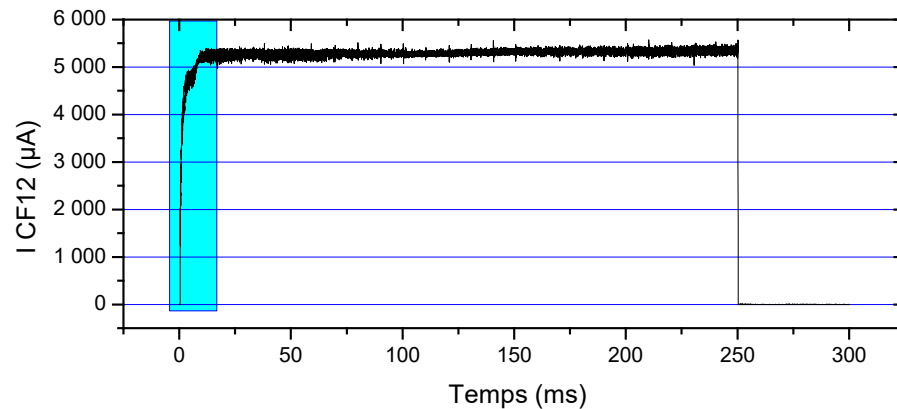
- Secondary vacuum (10^{-6} to 10^{-8} mbar)
- Magnetic confinement
- Hot electrons
- Cold ions
- Multi-ionization of ions
- Extraction of ions and acceleration (30-60kV)

SPIRAL2 Q/A=1/3 ION SOURCE



SPIRAL2 DEUTERON ION SOURCE

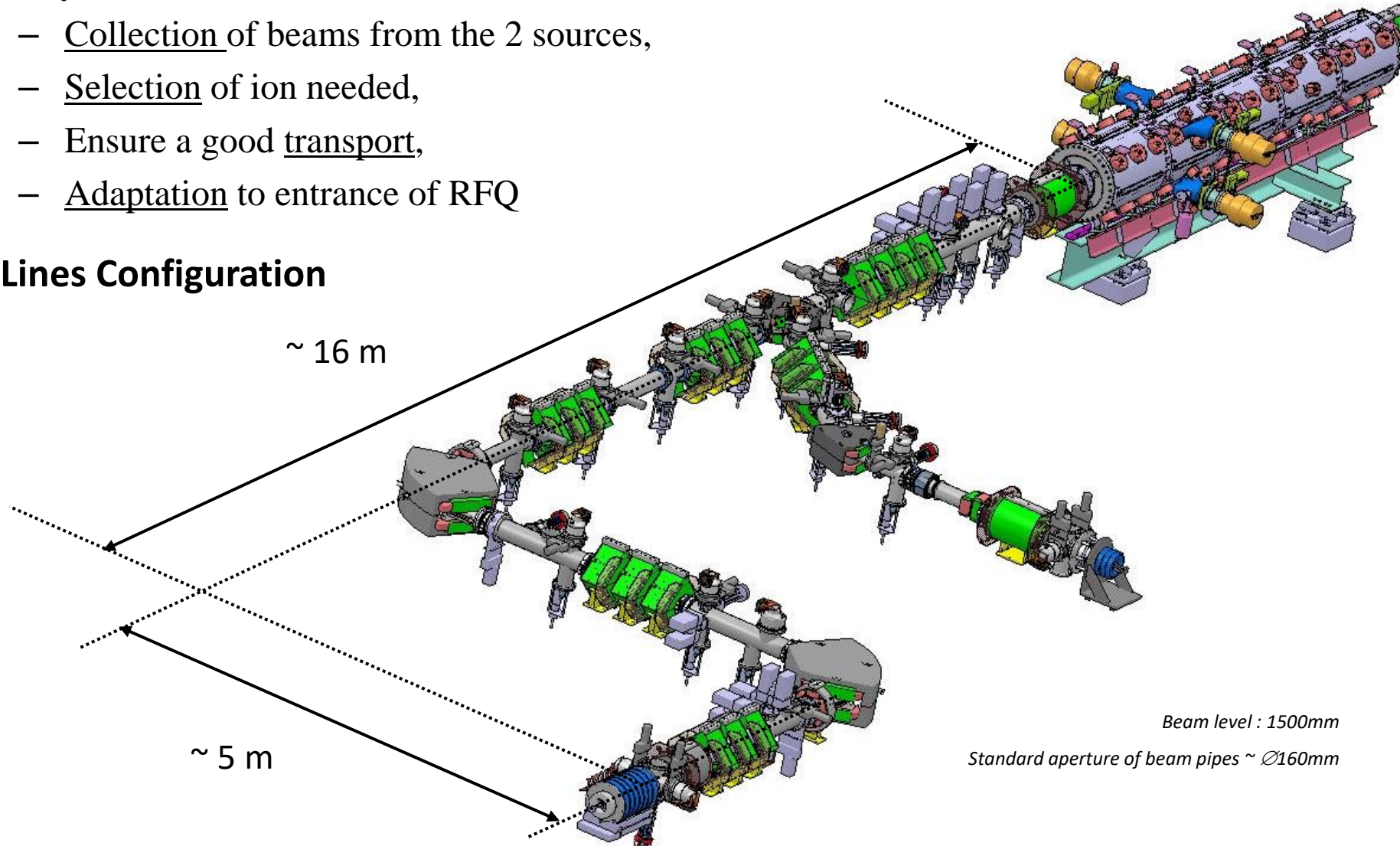
- Operational since 2009 (CEA-Saclay)
- 2kW 2.45GHz magnetron Pulsed or CW mode
- Up to 50kV bias potential
- 0,15 to 10mA Proton/Deuteron beams



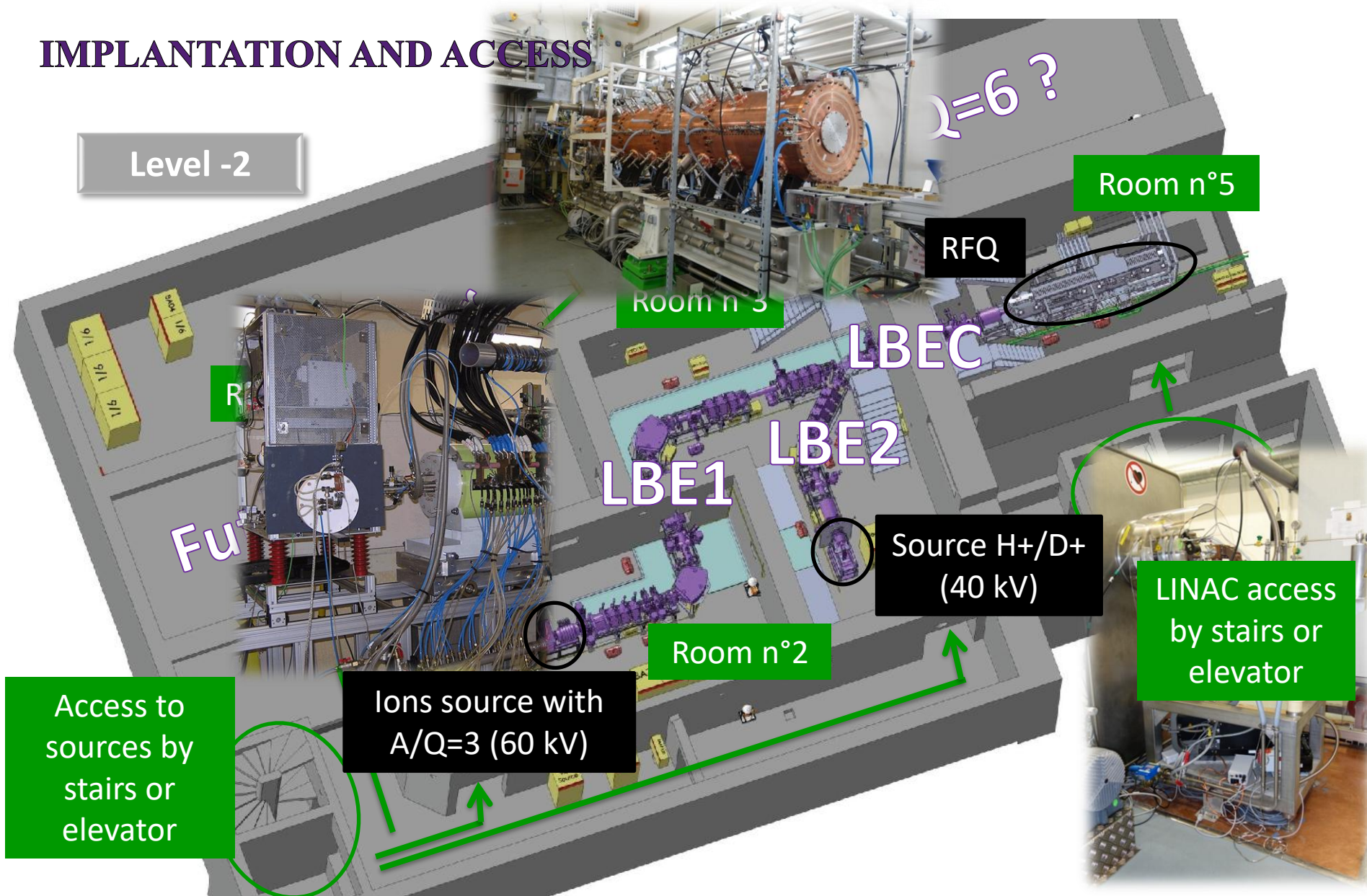
LEBT CONFIGURATION

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

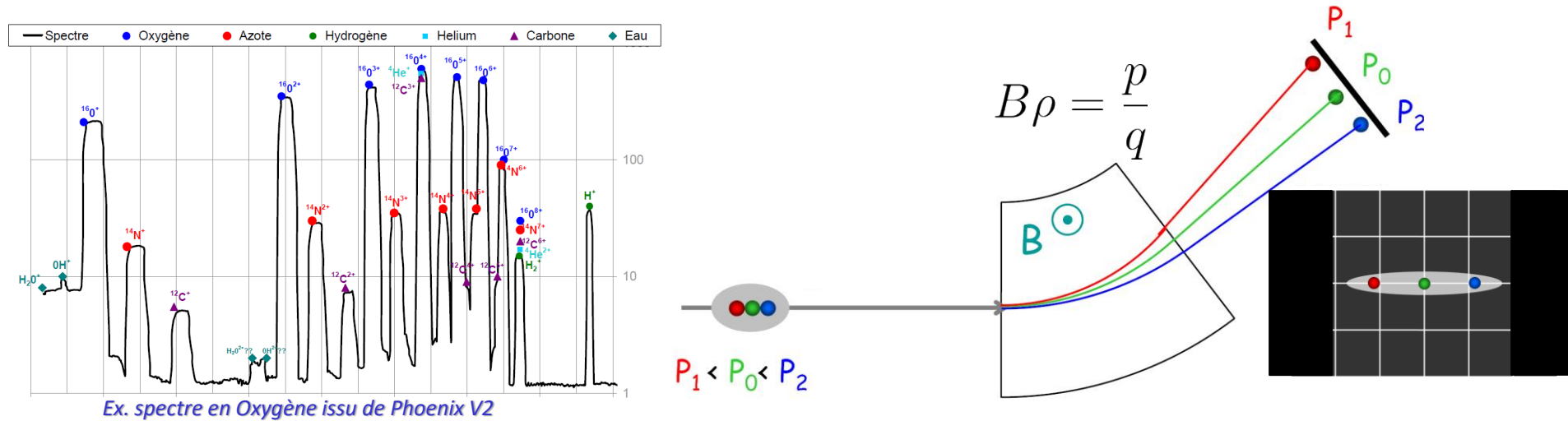
❖ Lines Configuration



IMPLANTATION AND ACCESS



IONS SELECTION COMING FROM SOURCE

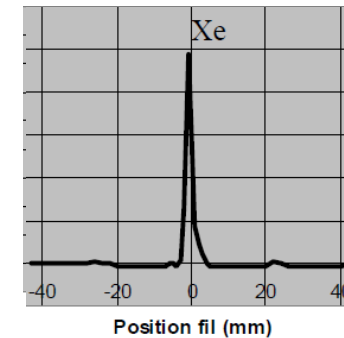


❖ **Protons/Deuterons (LBE2): simple magnetic separation**

- ✓ Dipole LBE2-D11 (with water cooled vacuum chambers)

❖ **Heavy Ions (LBE1): spectrometer like**

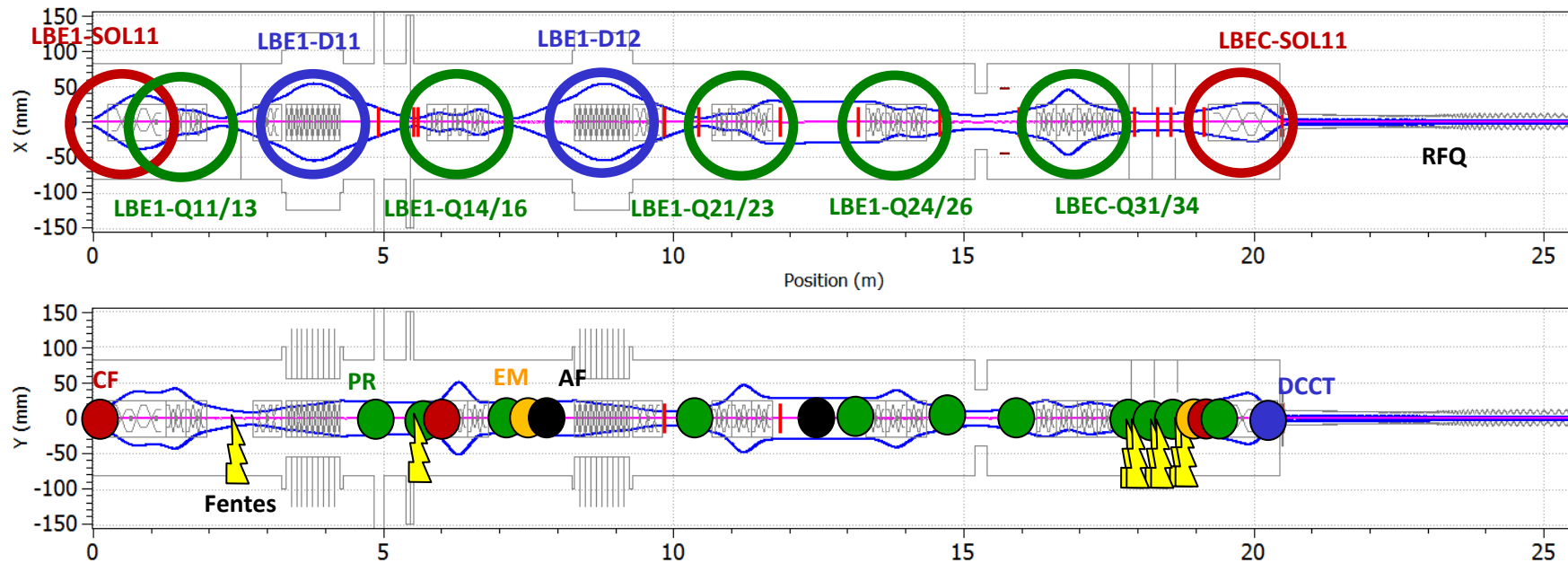
- ✓ Dipole LBE1-D11 (with water cooled vacuum chambers)
- ✓ Optical system Object / Image (resolving power better than 1/100)
- ✓ Selection slits (cooled)



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 $\sqrt{6}$ RMS, ~95%)

BEAM TRANSPORTATION UP TO RFQ

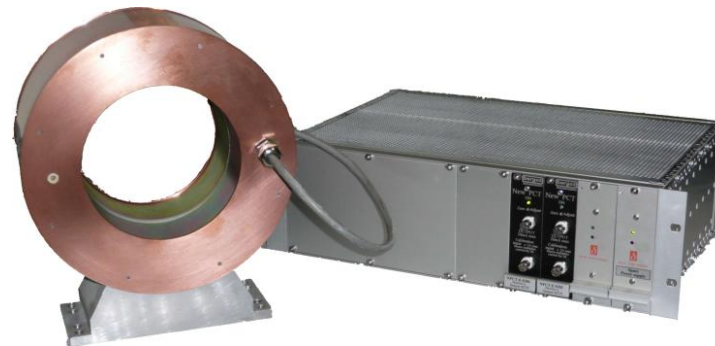


Faraday Cup

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

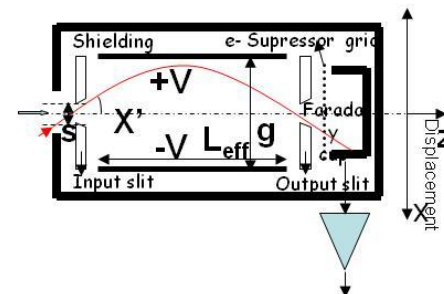
Profiler

Secondary emission monitor
 47 Tungsten wires ϕ 150 μ m
 Maximum beam size: 80 mm
 I_{max}: 0.1-1 mA cw



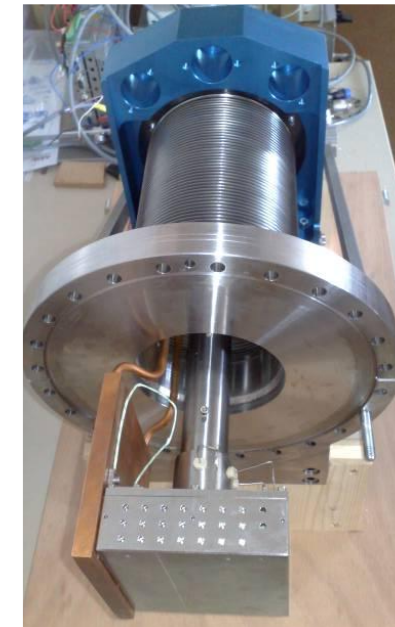
DCCT

Shielding : (μ -m \acute{e} tal + Armco + copper)
 B.W.: 0 – 10 kHz ; Noise: 1 μ A / Hz^{1/2}
 C.W. + Low Duty Factor Pulsed Mode Operation



Emittance-meter

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



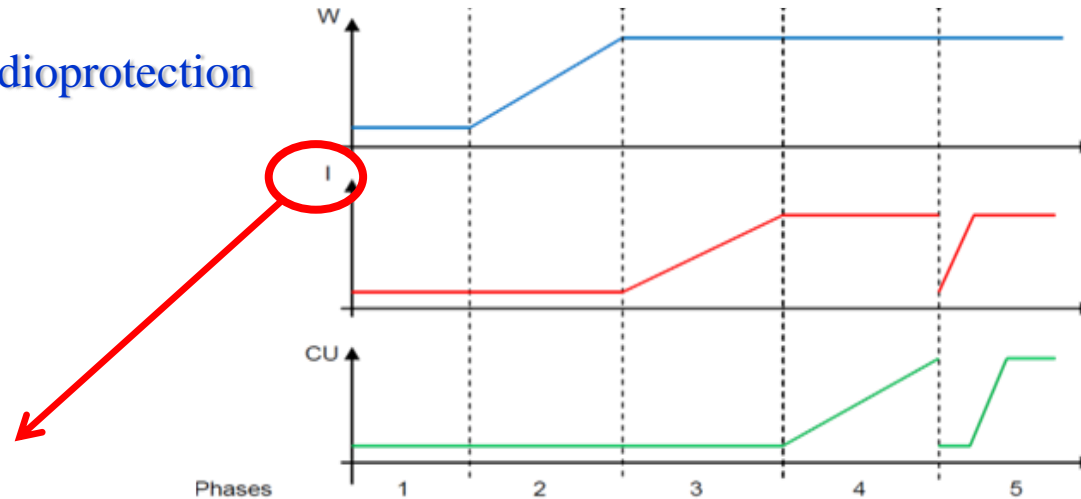
BEAM POWER CONTROL

❖ Crucial role for a high power machine

- ✓ Protection machine, safety, radioprotection
- ✓ Commissioning machine
- ✓ Power increasing on targets

❖ Control of the peak current

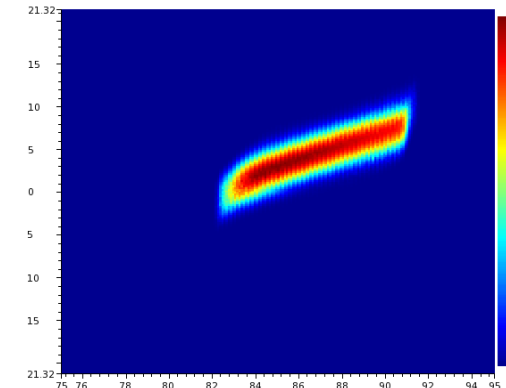
- ✓ From I_{\min} (typically 100 μA) to I_{\max} (6.5 mA)
- ✓ Controlled by a system to 3 slits in horizontal and vertical axis
- ✓ Coupling with definition of beam emittances: when $I \downarrow$, $\varepsilon \downarrow$



Phases of the power increasing during the commissioning



Software dedicated to emittances definition



Measurement of 50 μA Deuterons beam at Saclay

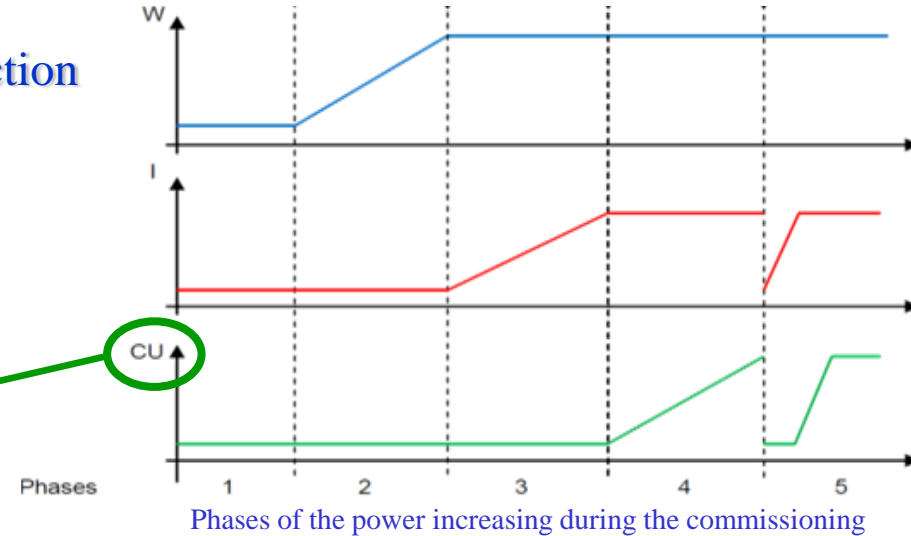
BEAM POWER CONTROL

❖ Crucial role for a high power machine

- ✓ Protection machine, safety, radioprotection
- ✓ Commissioning machine
- ✓ Power increasing on targets

❖ Control of duty cycle

- ✓ Using electrostatic : provide a pulsed beam
- ✓ V and f max : 10 kV, 1.5 kHz
- ✓ Duty cycle : typically for the first linac beams : 0.1% (500 μ s @2Hz)



Hacheur (chopper) electrodes



Beam profiler and associated "scraper"

PRODUCED BEAMS

➤ Type

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

➤ Energy

- ✓ Ions speed must be adapted to first modulations of RFQ

- ✓ Required source potential

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

$$\beta = 6.553 \cdot 10^{-3} \quad \Rightarrow \quad V_{source} = \frac{A}{q} \times 20 \text{ kV}$$

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

- ✓ LEBT beam energy

$$\Rightarrow W = A \times 20 \text{ keV}$$

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

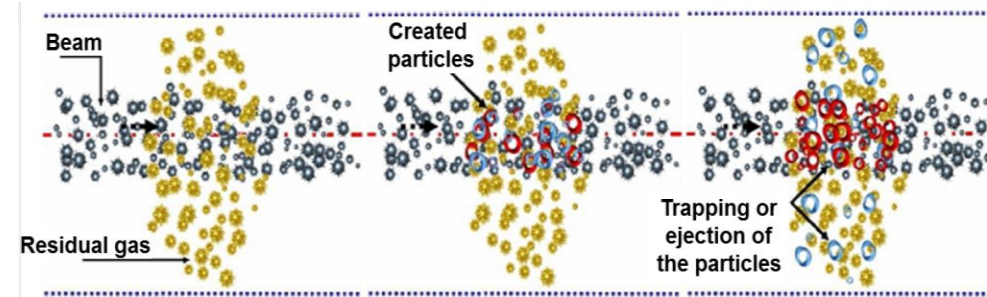
➤ Peak current

- ✓ 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. $^{16}\text{O}^{6+}$ 1.3 mA, $^{20}\text{Ne}^{7+}$ 0.4 mA, $^{40}\text{Ar}^{14+}$ 50 μA , $^{58}\text{Ni}^{19+}$ 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

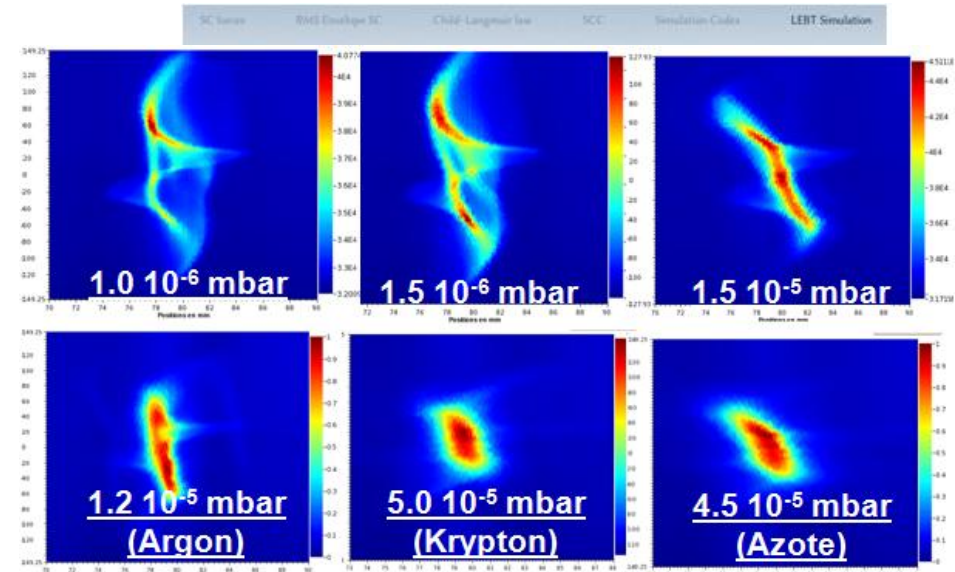
❖ Compensation phenomena

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



❖ Not well controlled aspects

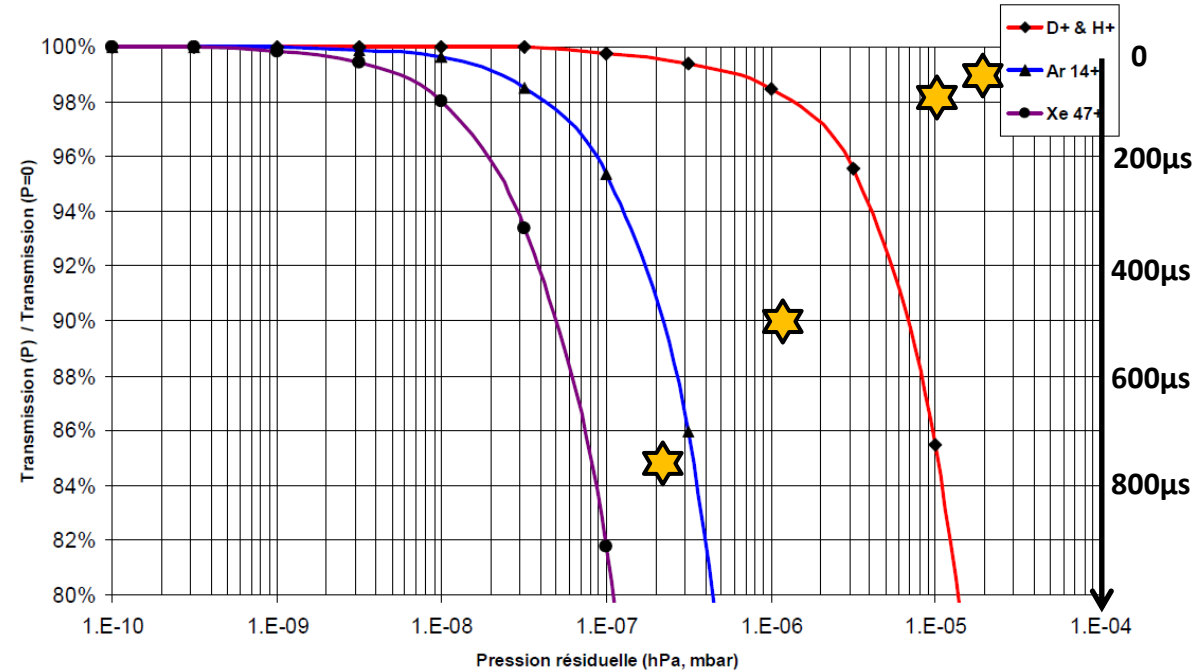
- ✓ Compensation level (close to 100%)
- ✓ Transients aspects in pulsed mode (the neutralization is not instantaneous)
- ✓ High contribution of the residual gaz nature (type) and pressure level



Emittance characterization of the SPIRAL2 beam (by Nicolas Chauvin)

VACUUM PRESSURE

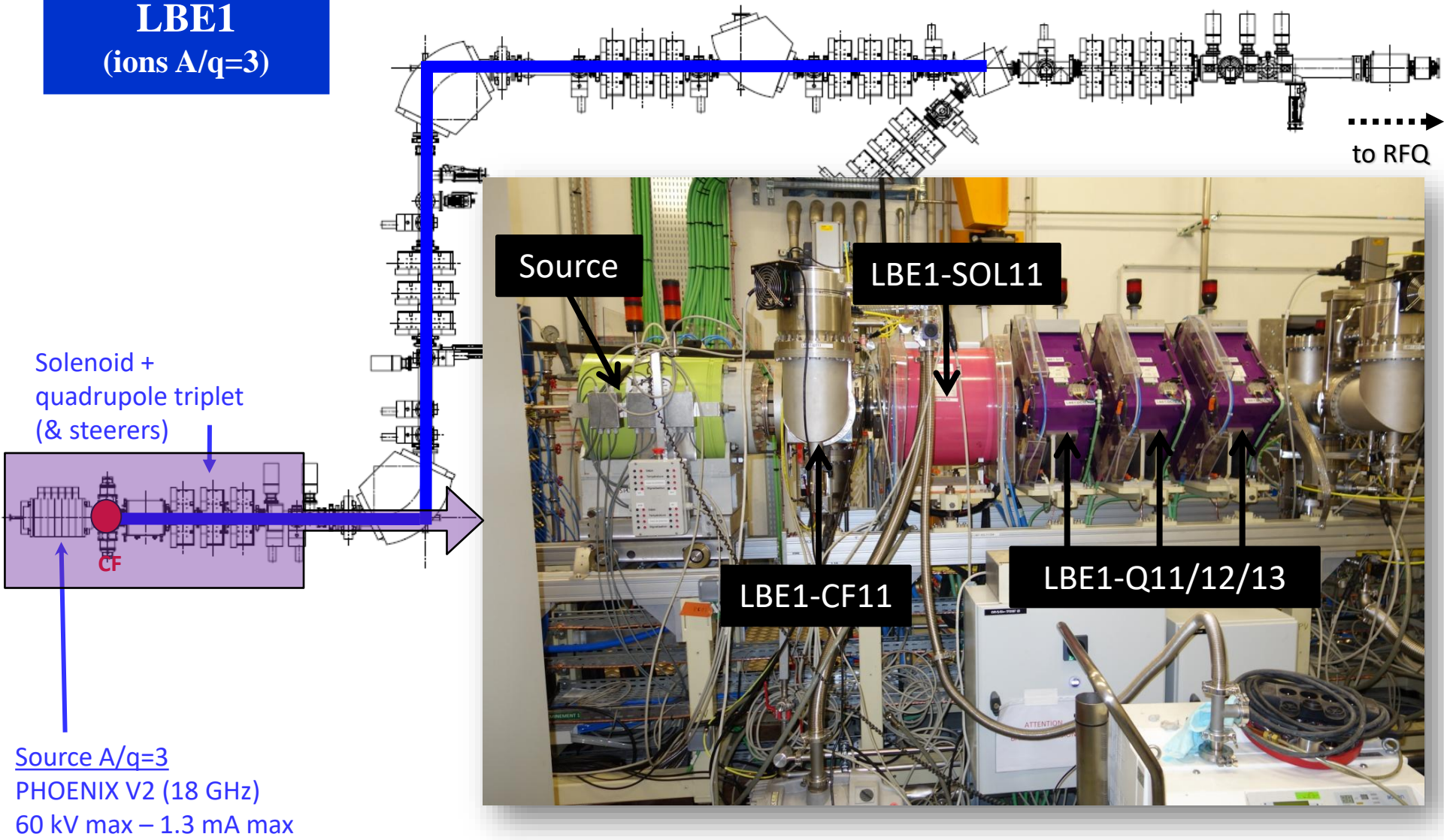
- ❖ Sufficiently good
in order to suppress losses by
electronic capture
- ❖ Not to good
For decrease the time of the
increasing of the compensation
(and ameliorate the emittances)



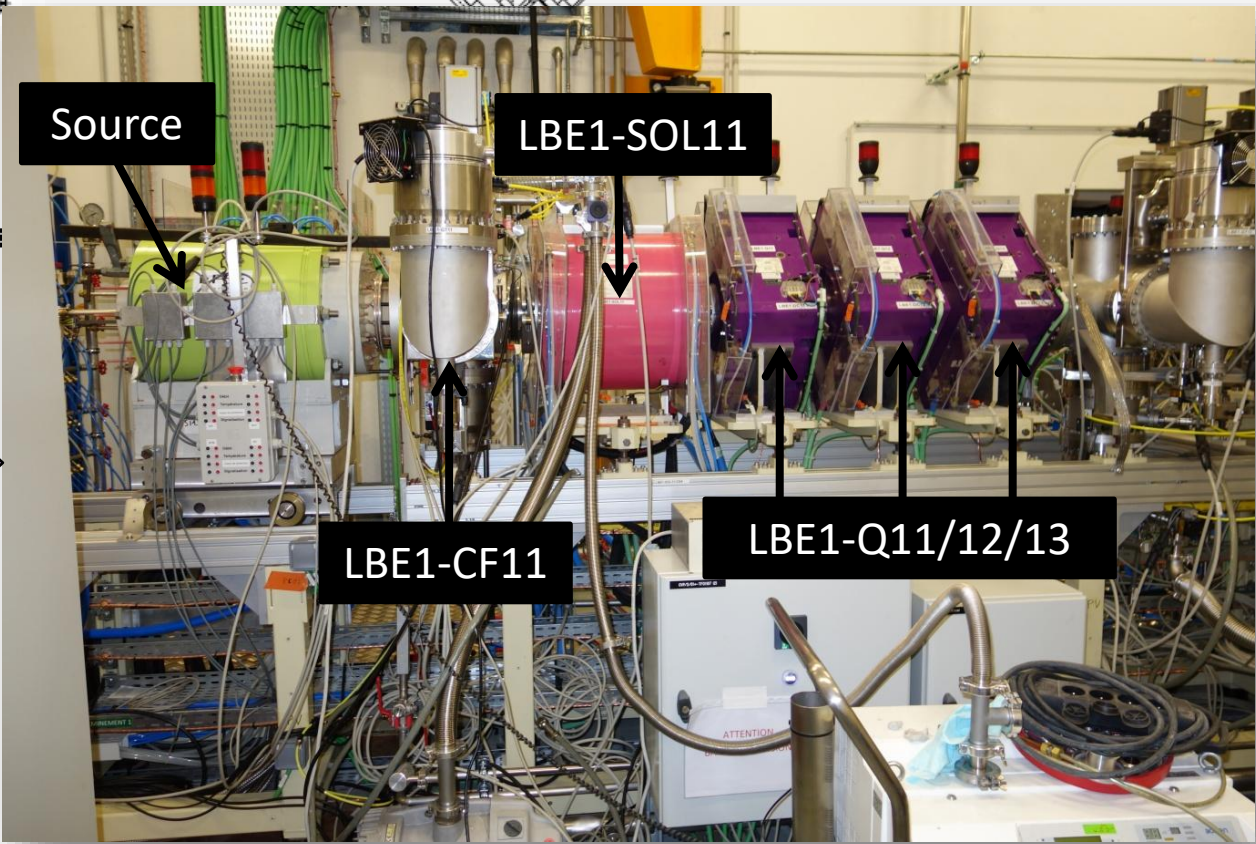
Transmission (calculation) and transients compensation (Deuterons case) as a function of the residual gas pressure

- 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

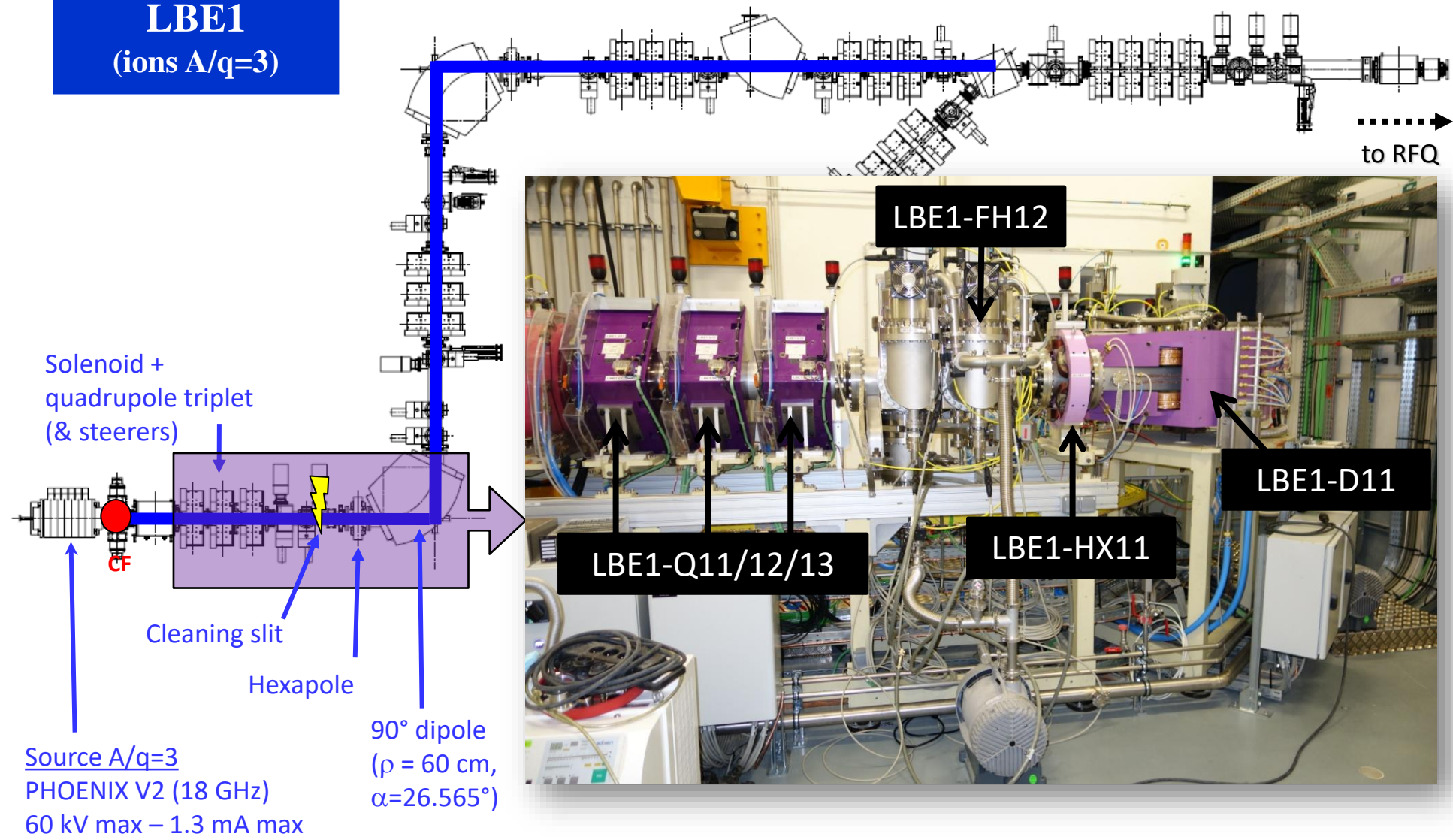
LBE1
(ions $A/q=3$)



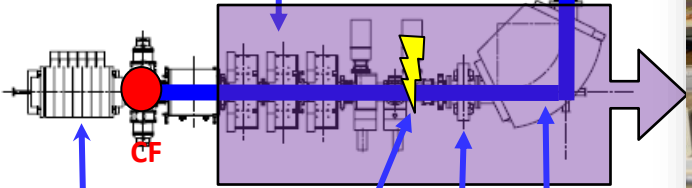
Source $A/q=3$
PHOENIX V2 (18 GHz)
60 kV max – 1.3 mA max



LBE1
(ions $A/q=3$)



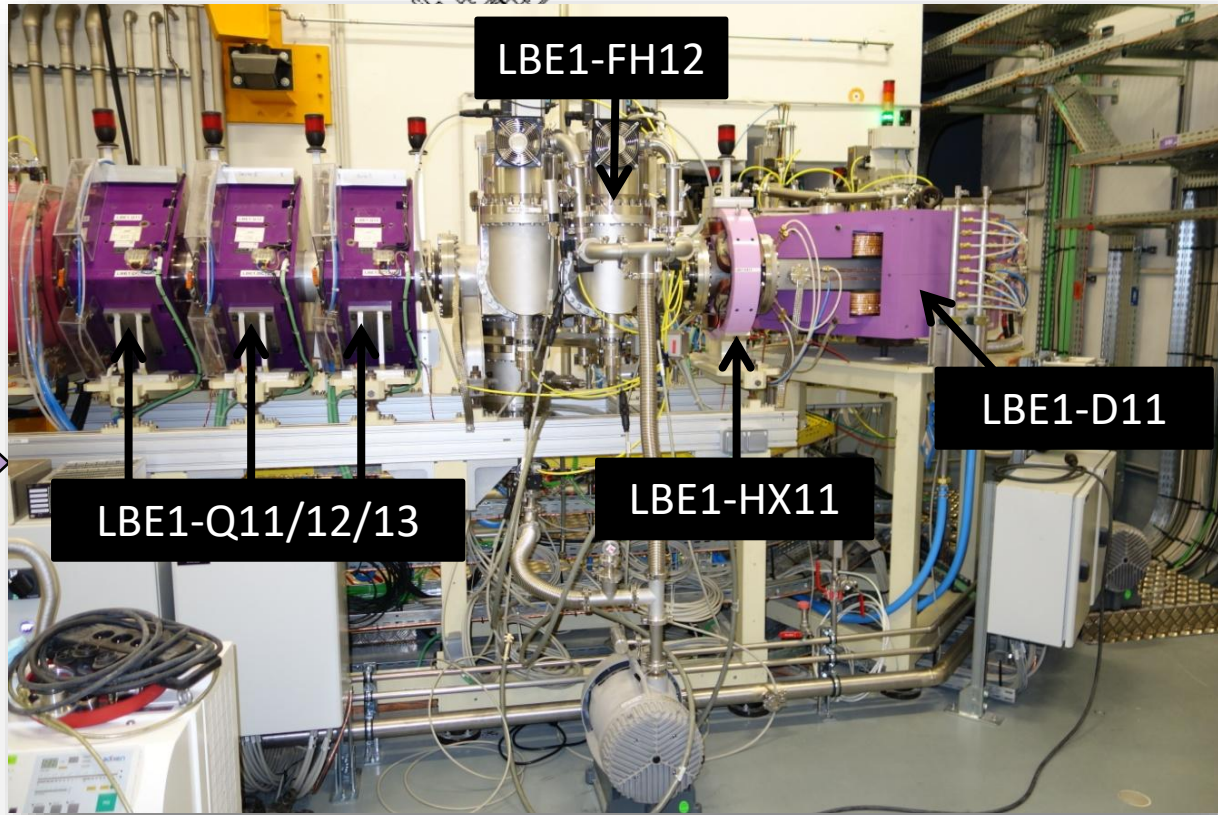
Solenoid +
quadrupole triplet
(& steerers)



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

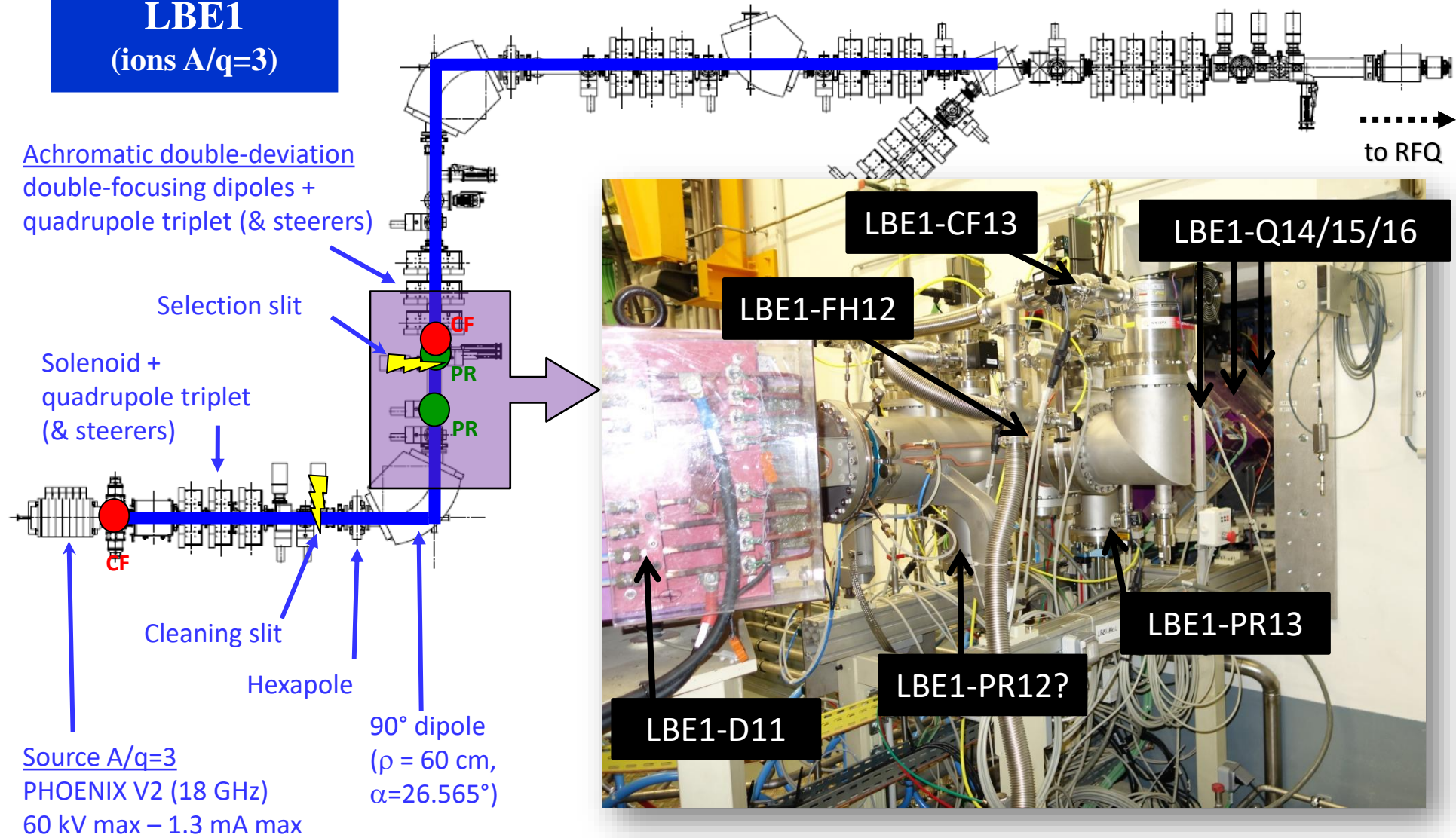
Cleaning slit
Hexapole

90° dipole
($\rho = 60$ cm,
 $\alpha=26.565^\circ$)



LBE1
(ions $A/q=3$)

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



Solenoid +
quadrupole triplet
(& steerers)

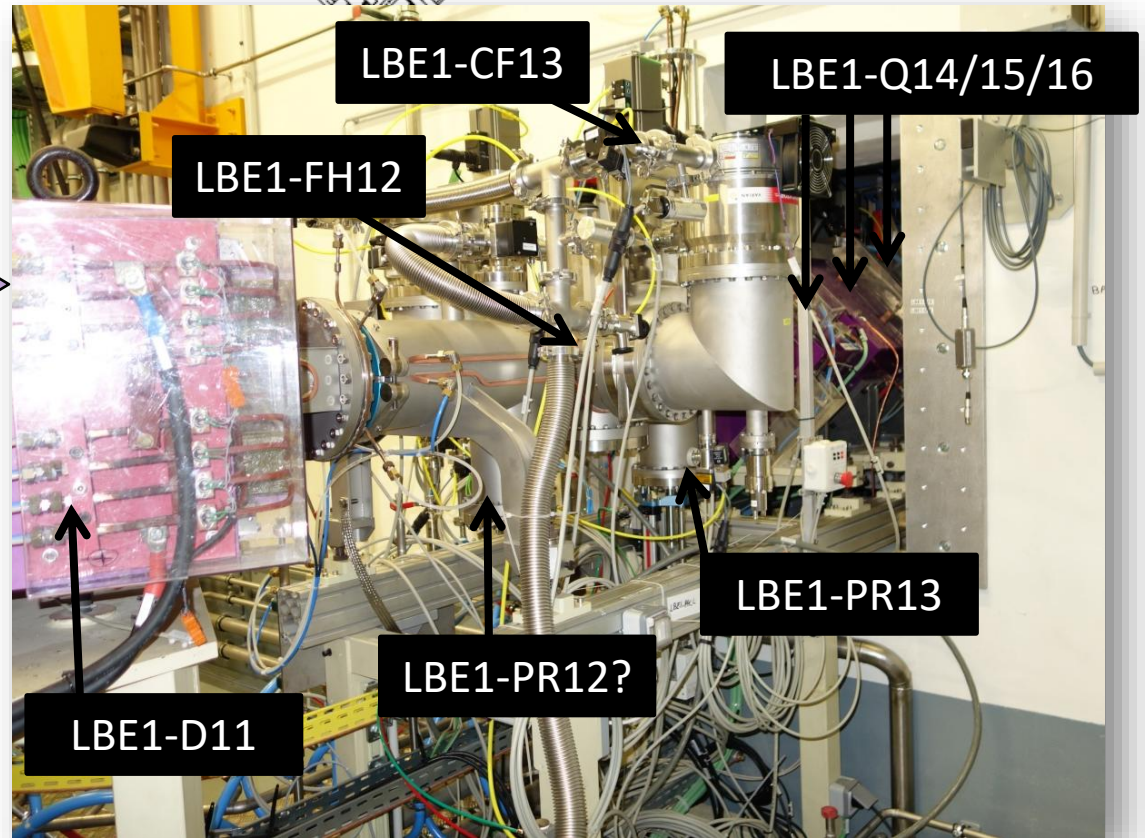
Selection slit

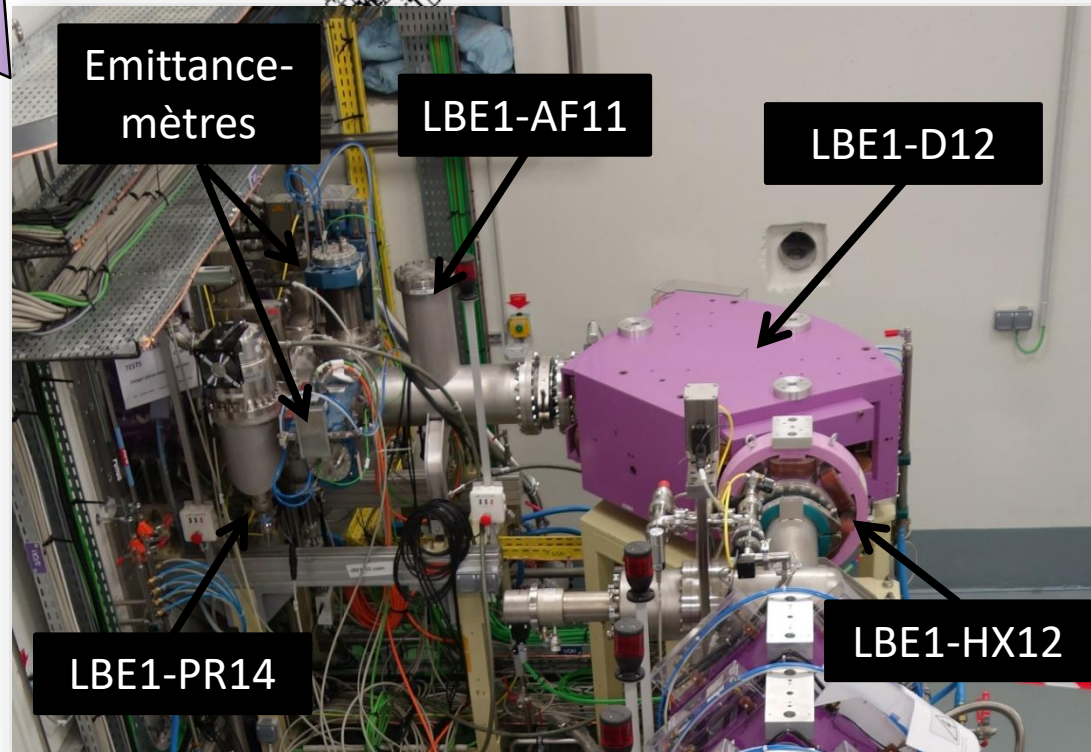
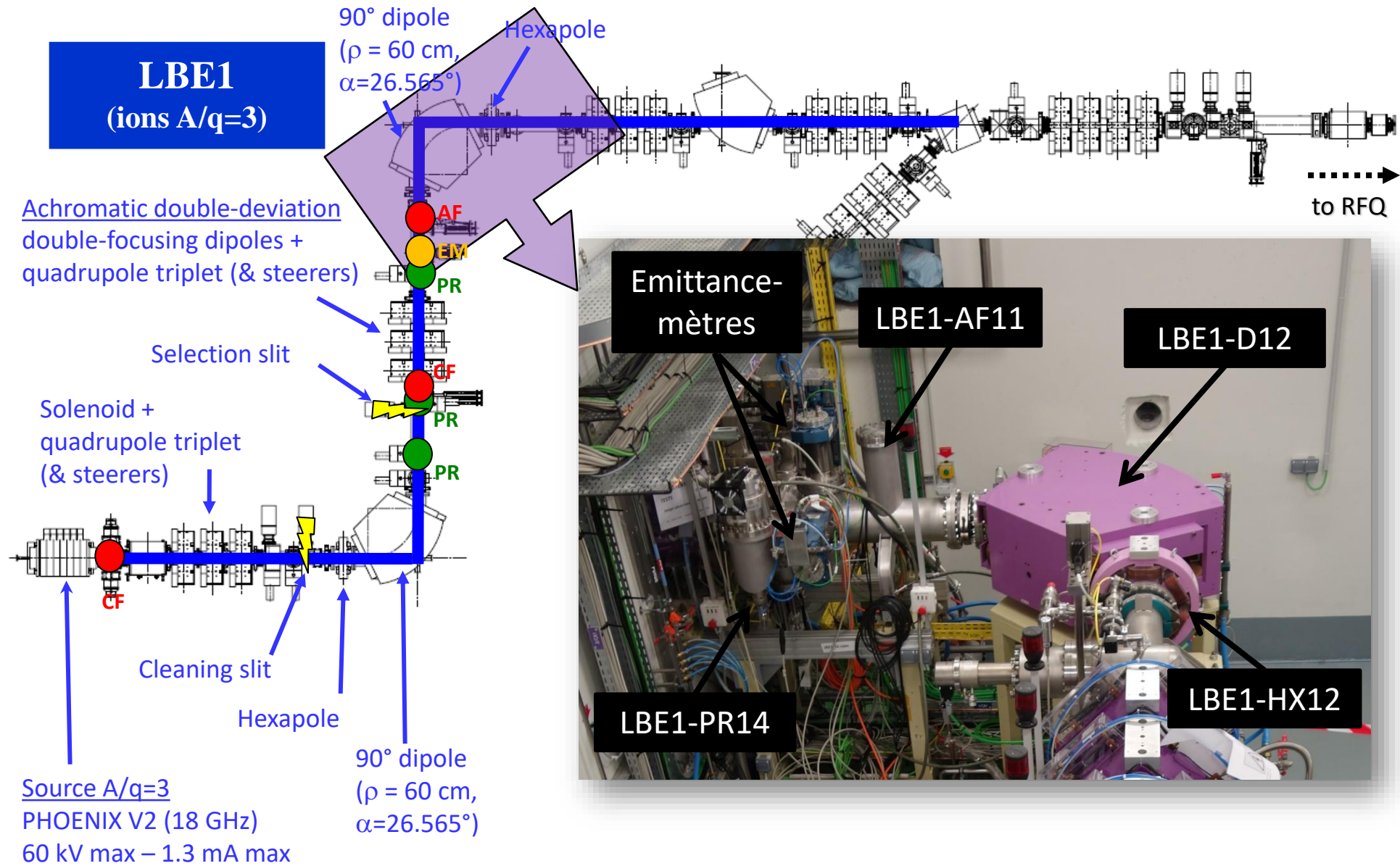
Cleaning slit

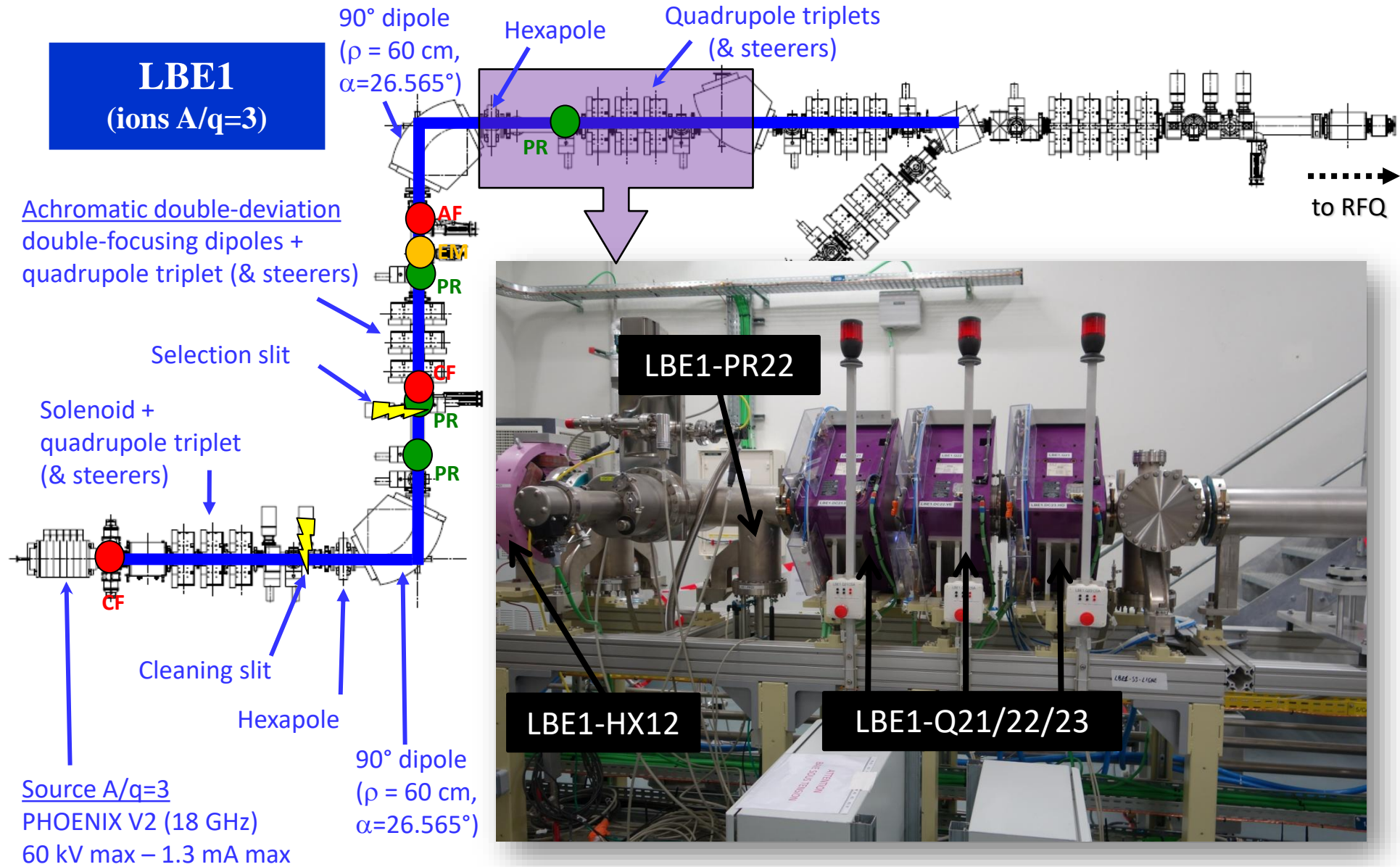
Hexapole

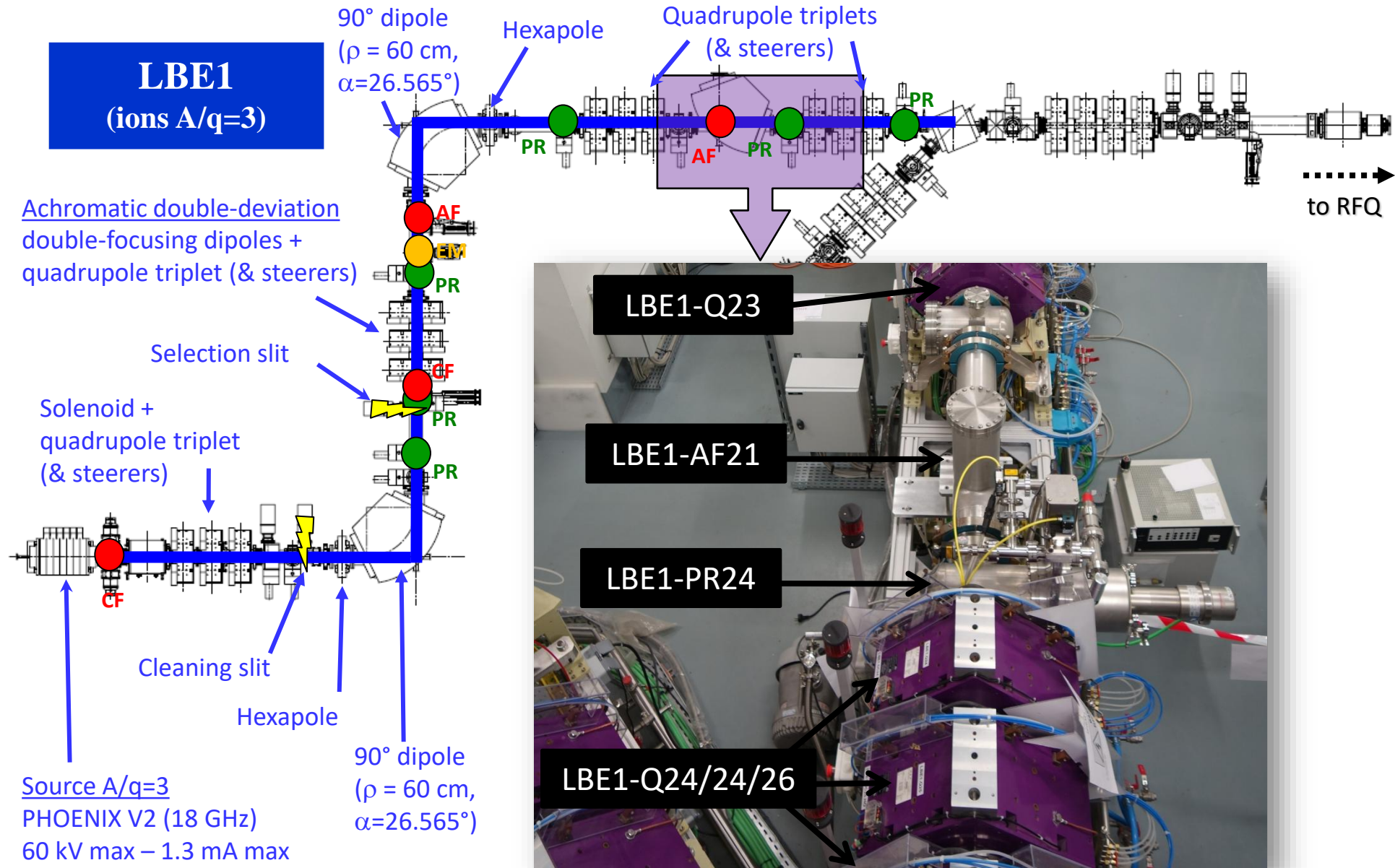
90° dipole
($\rho = 60 \text{ cm}$,
 $\alpha = 26.565^\circ$)

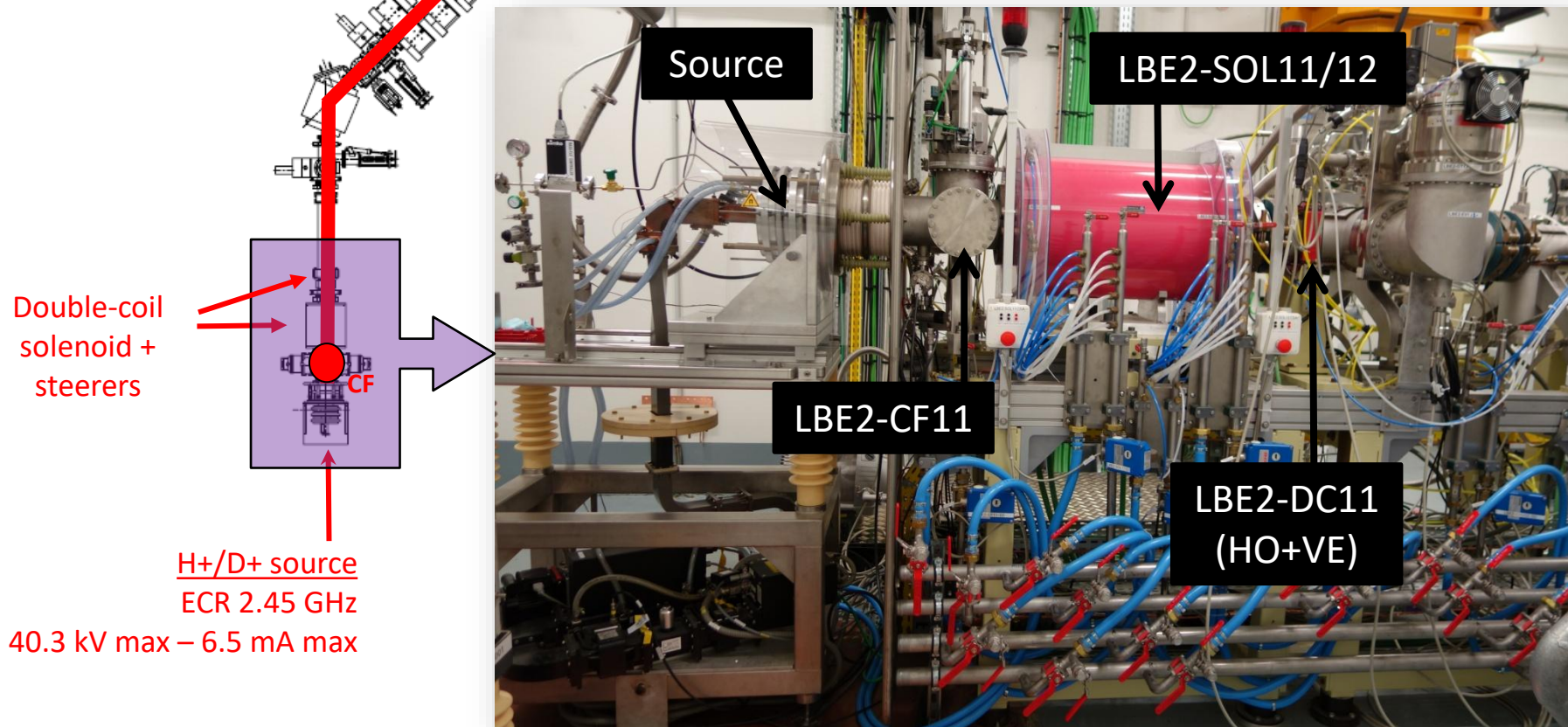
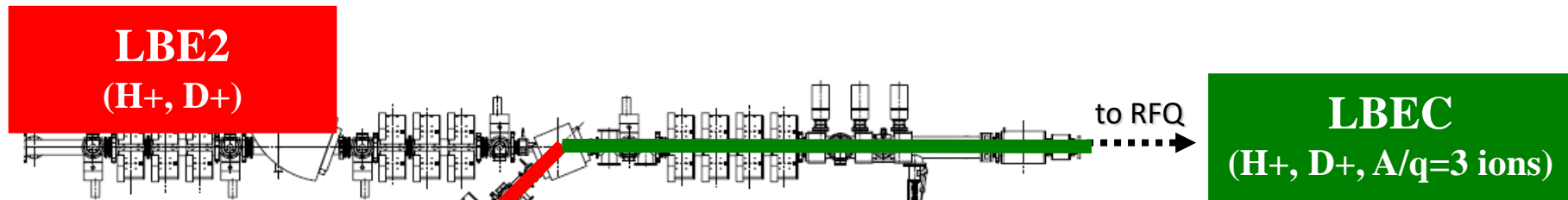
Source $A/q=3$
PHOENIX V2 (18 GHz)
60 kV max – 1.3 mA max

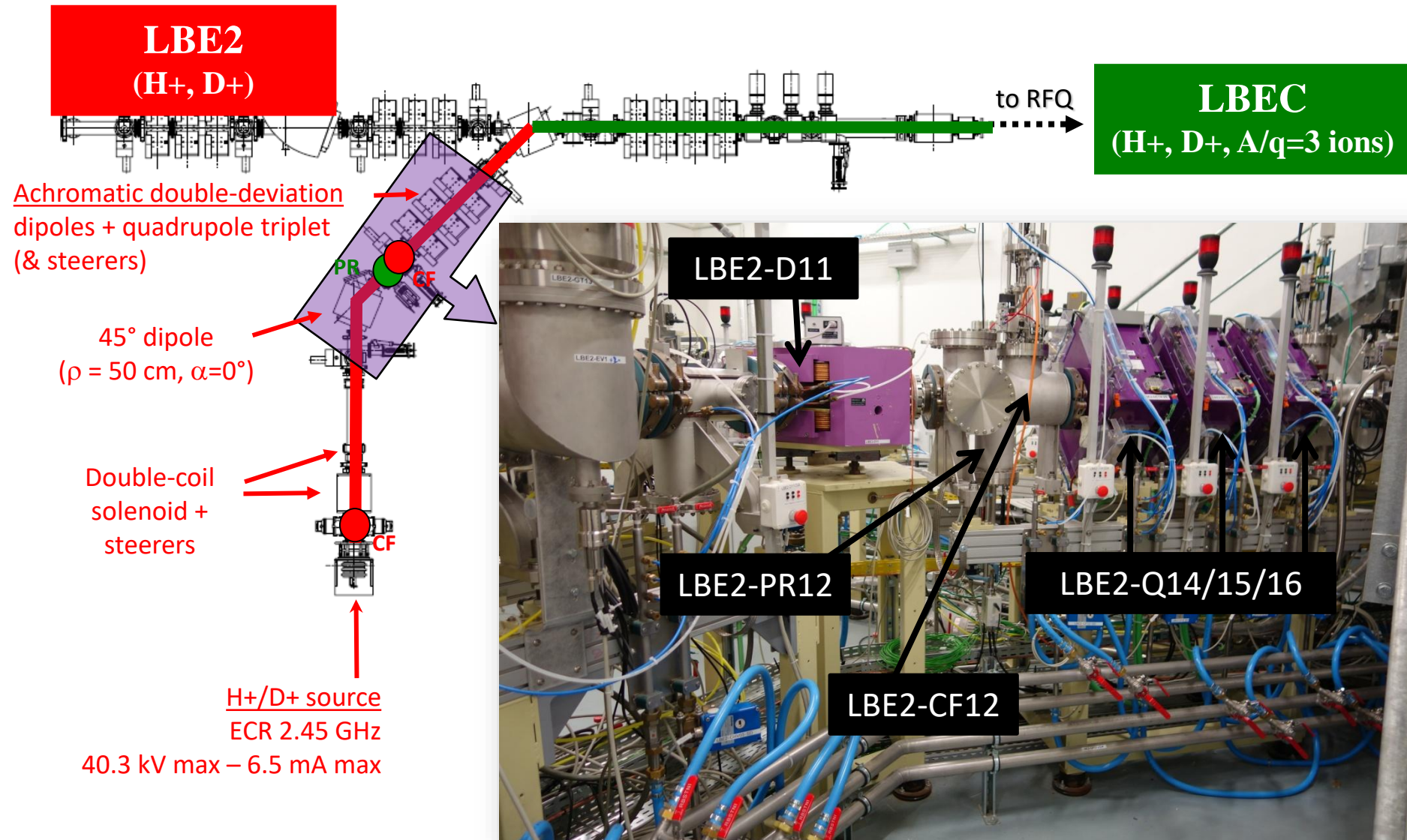


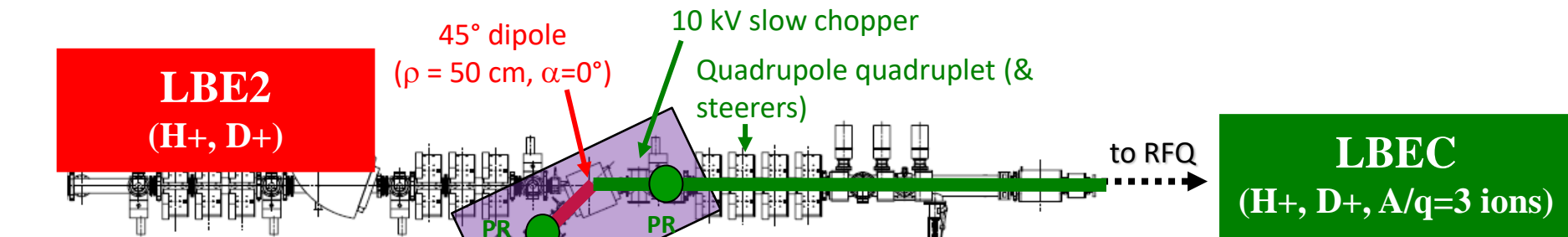












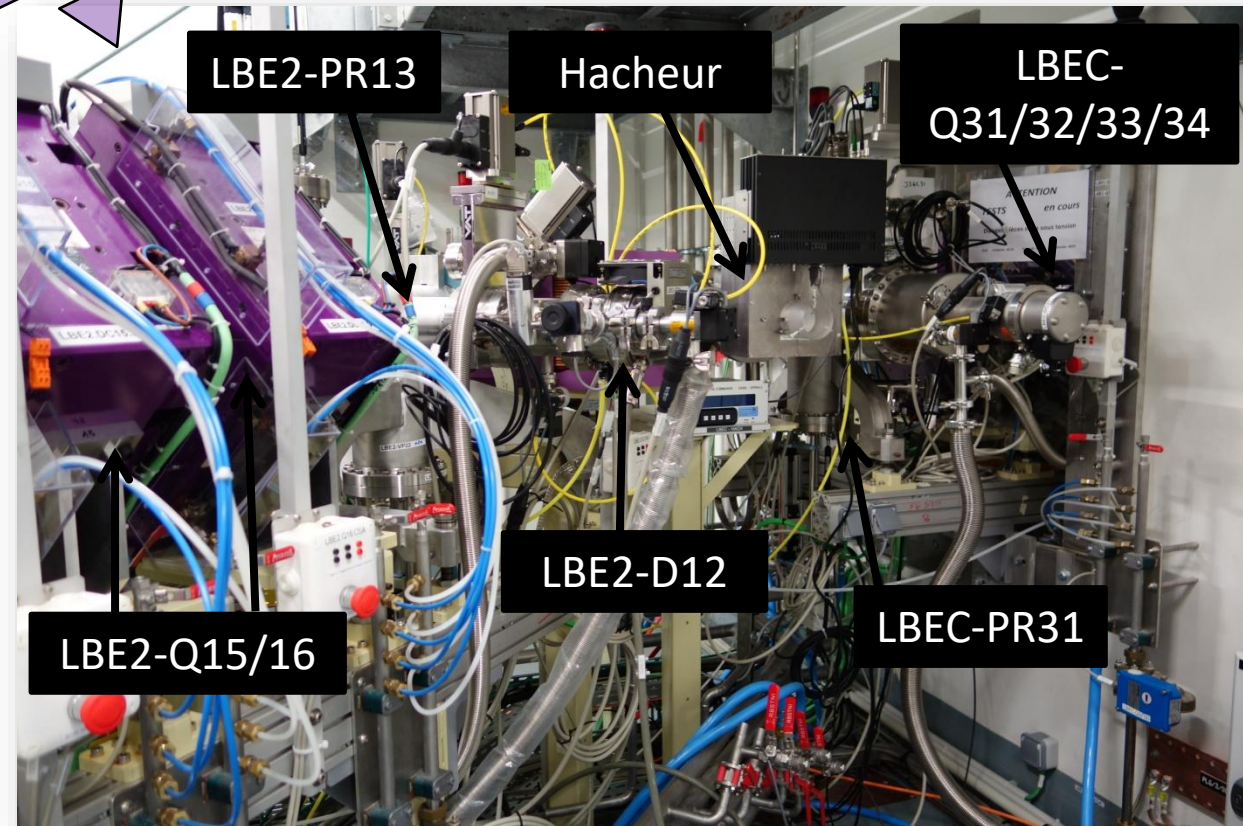
Achromatic double-deviation
dipoles + quadrupole triplet
(& steerers)

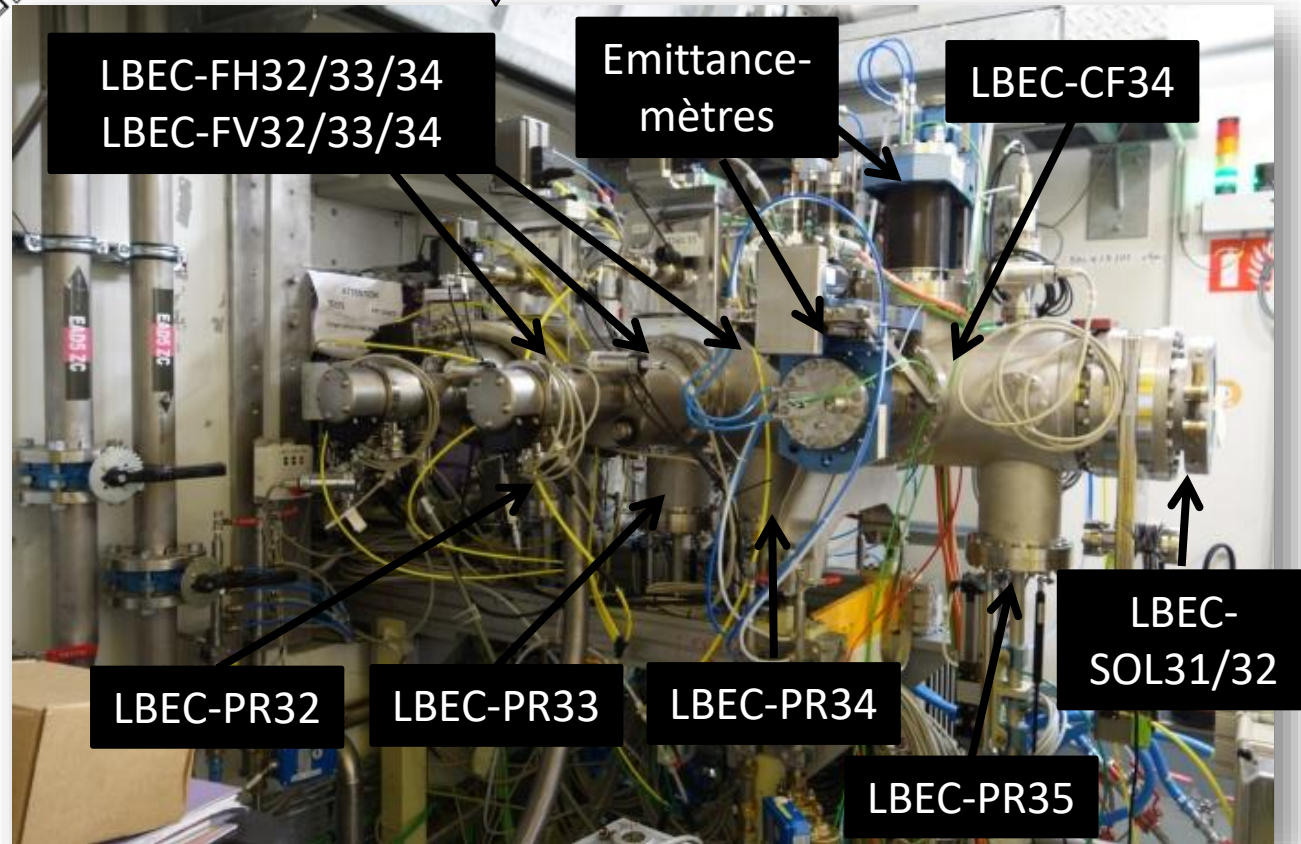
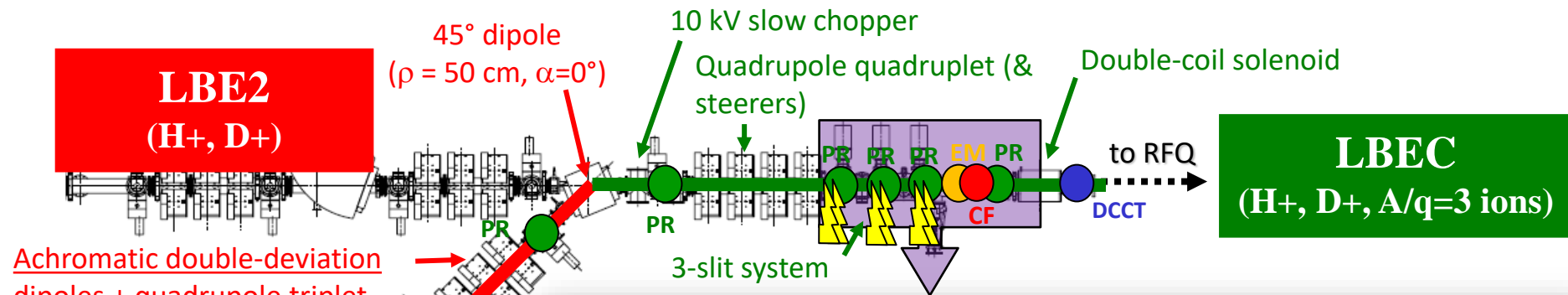
45° dipole
($\rho = 50 \text{ cm}, \alpha=0^\circ$)

Double-coil
solenoid +
steerers

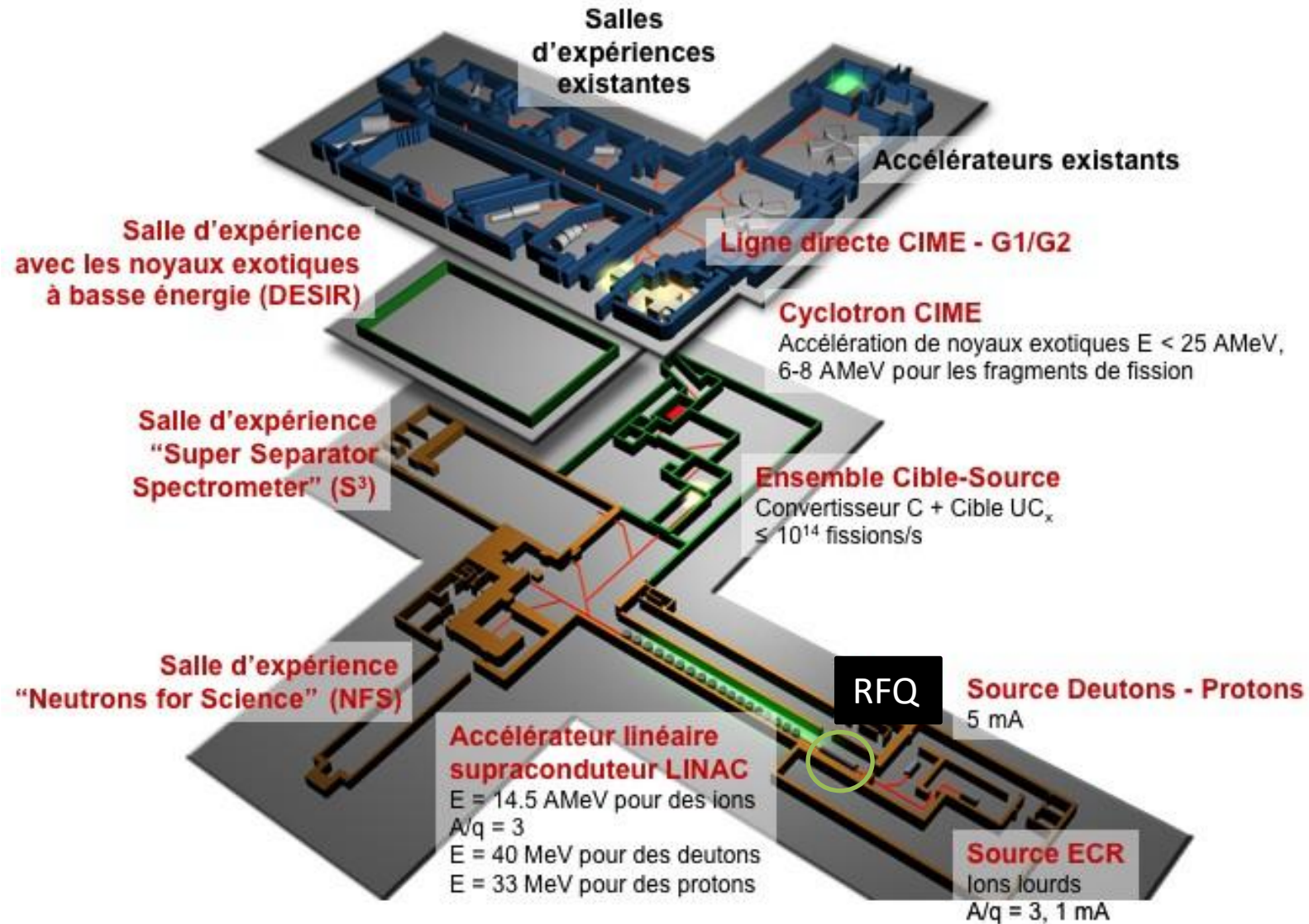
H+/D+ source
ECR 2.45 GHz

40.3 kV max – 6.5 mA max

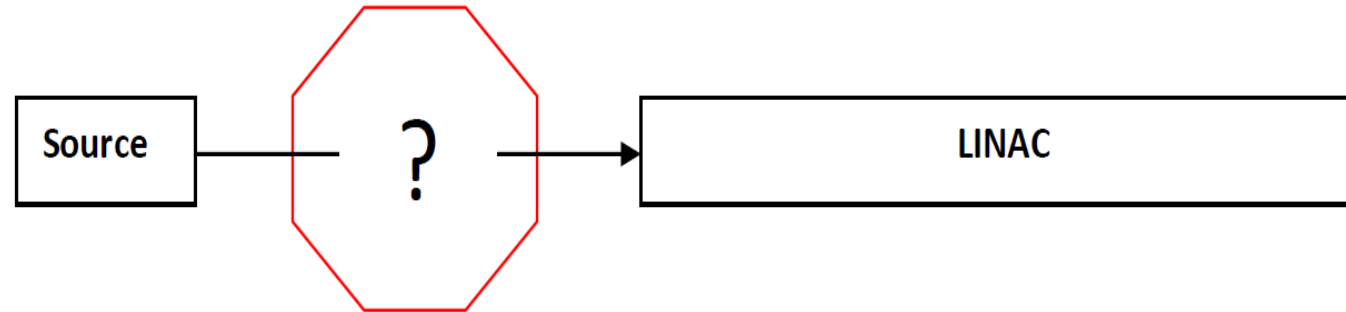




3. THE SPIRAL2 RFQ



WHY A RFQ IS NEEDED ?



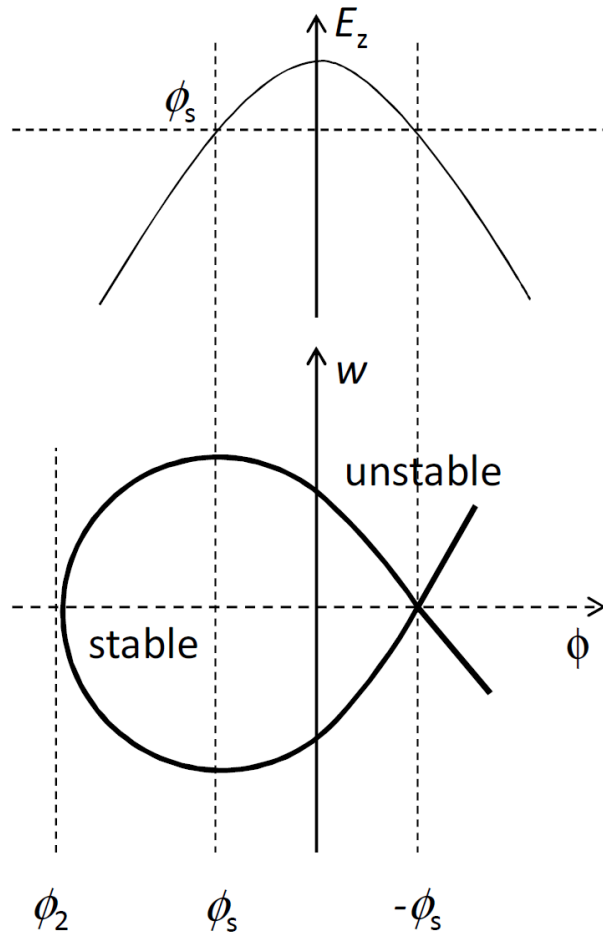
What we have to put between the source and the LINAC for :

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

#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 $\sim 3 \Phi_s$ (acceleration)



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

Numerical application :

$$\Phi_s = -30^\circ \Rightarrow \text{efficiency} = 3 \times 30 / 360 = 25 \%$$

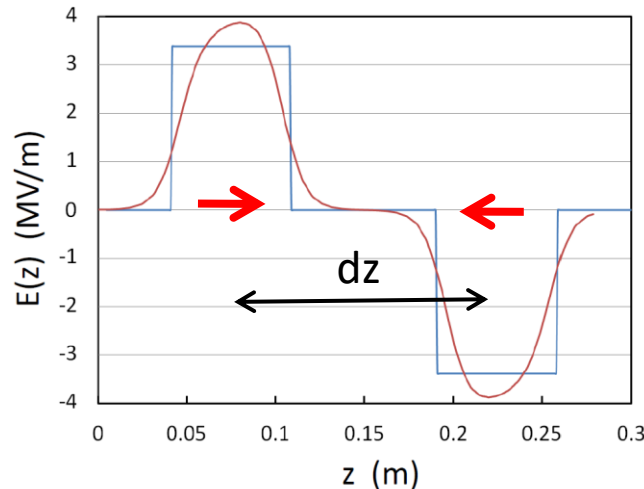
75% of particles are lost if no bunches

#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



$$dT = \frac{T_{rf}}{2}$$

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

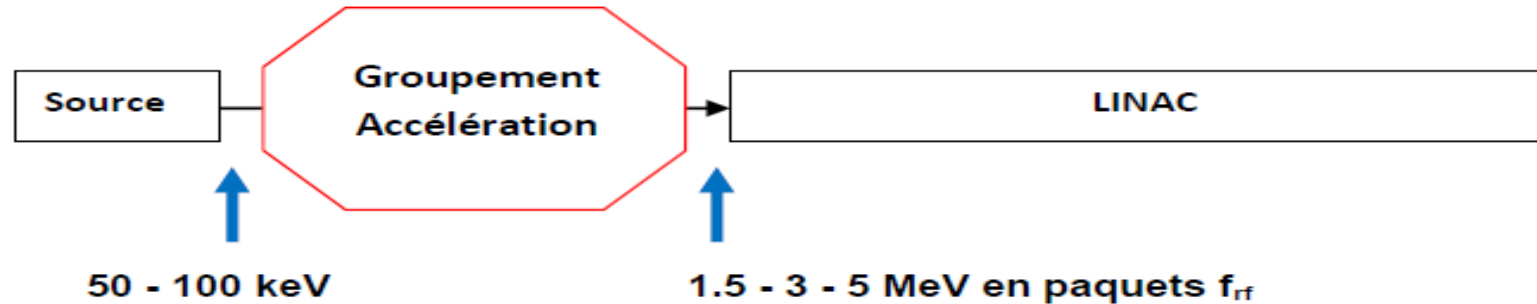
$$\beta = \frac{2 dz}{c T_{rf}} = \frac{2 dz}{\lambda_{rf}}$$

Numerical application :

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

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

IDEAL SYSTEM BETWEEN SOURCE AND LINAC



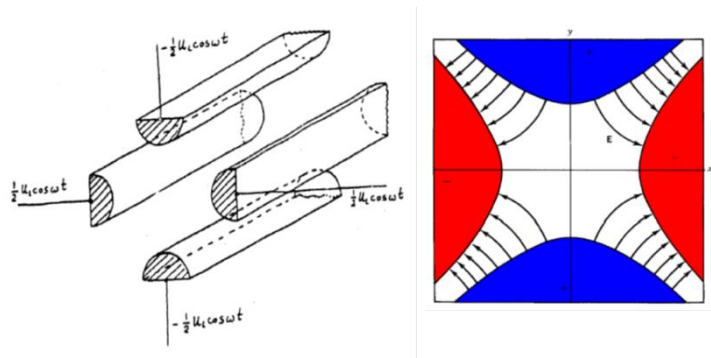
- 1- Efficient bunching at the RF frequency
⇒ Set of “bunching cavities” at f_{rf} (adiabatic bunching, $\rho > 95\%$)
- 2- Acceleration at high energy ($V_{acc} > 1 MV$)
⇒ Set of “accelerating cavities” at f_{rf} (LINAC)
- 3- Radial focalization in order to don't lose particles
- 1- + -2- = RF structure => Radio-Frequency Quadrupole (RFQ)**

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

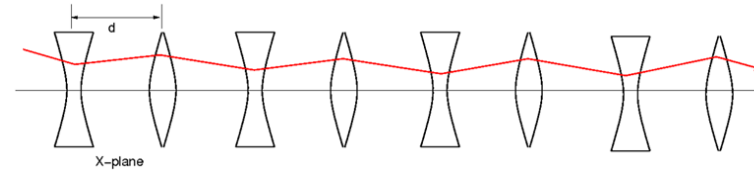
At Los Alamos : R.H. Stokes, **K.R. Crandall**, J.E. Stovall, and D.A. Swenson, “ RF Quadrupole beam dynamics”, PAC79

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

FEW ASPECTS OF RFQ

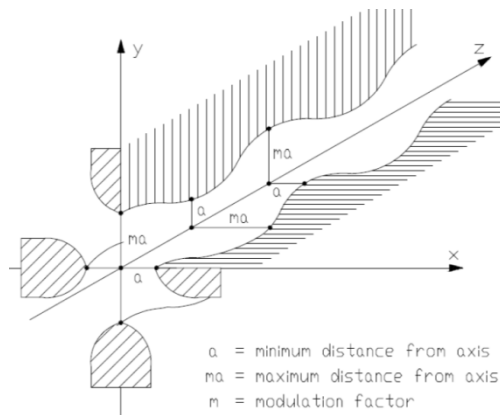


The electric field oscillate at the RF frequency
 \Rightarrow Transport of the particles in a series of focusing and defocusing quadrupoles



Alternating focusing

No E_z longitudinal component \Rightarrow No acceleration



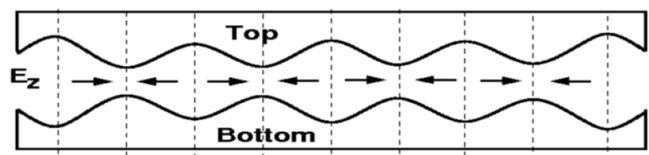
Electrodes modulation des électrodes in order to create a longitudinal component $E_z(z)$

\Rightarrow Continuous series of “cavities”

\Rightarrow Radial focusing

+ Progressive bunching of the beam

+ Acceleration of bunches



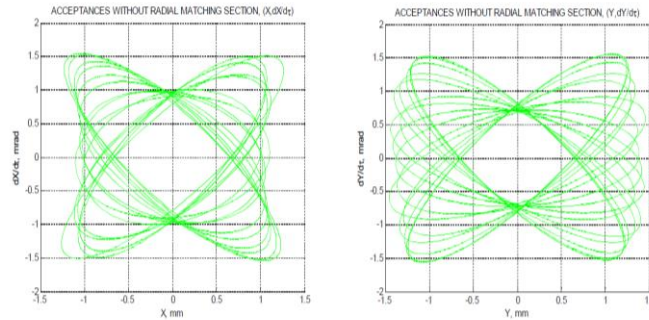
5 SECTIONS OF THE RFQ (1/5)

➤ **Section 1 – Radial adaptation at the entrance** (“Radial Matching section”)

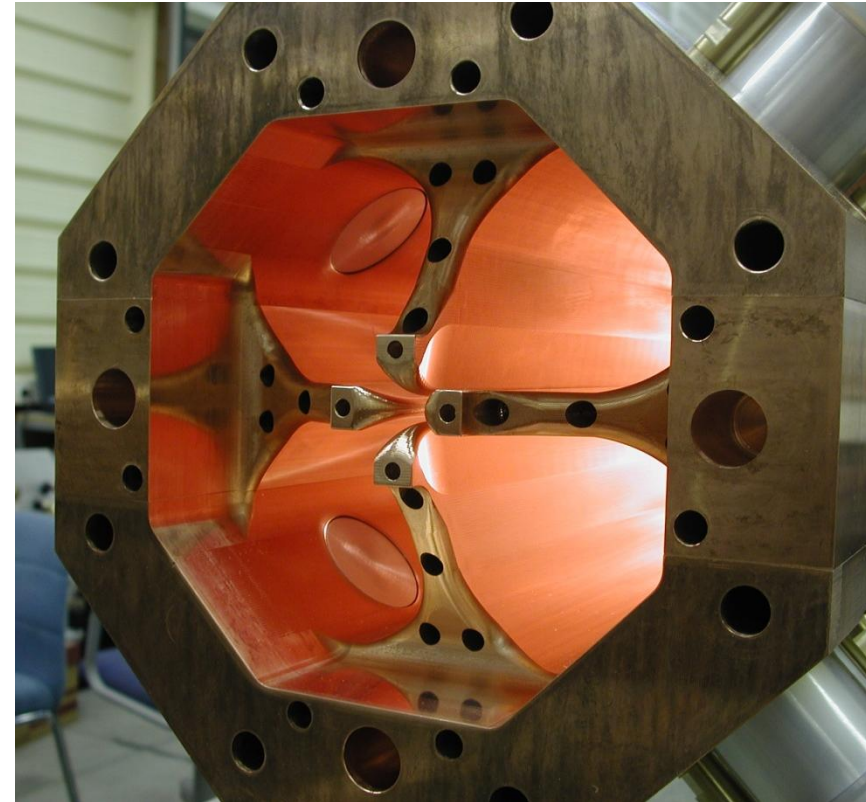
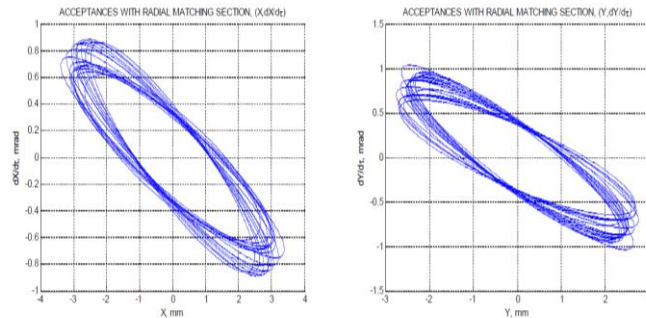
Make a beam with small dimensions ($r_{max} \sim 5 \text{ mm}$)

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

Acceptances without radial adaptation



Acceptances with radial adaptation



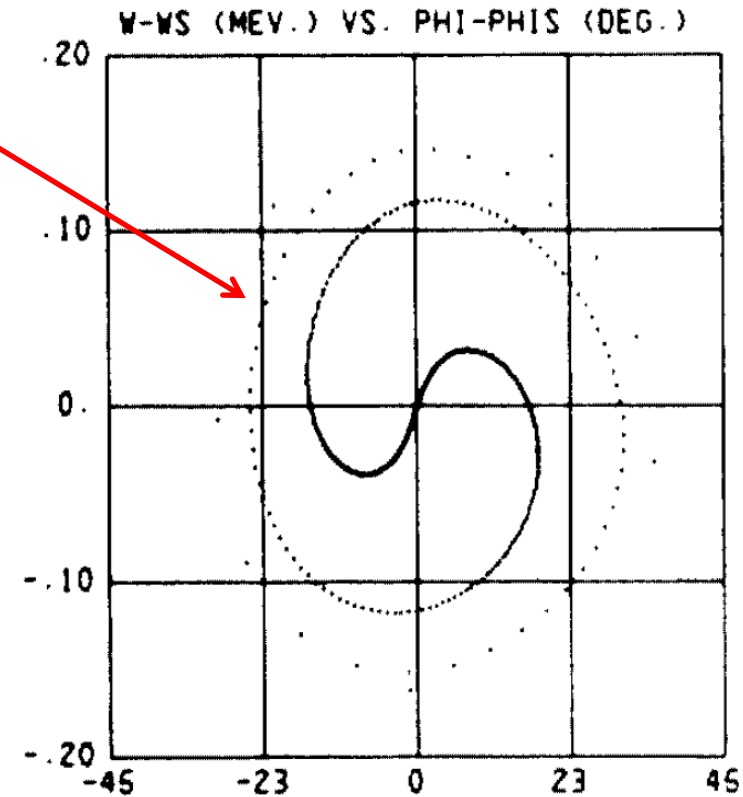
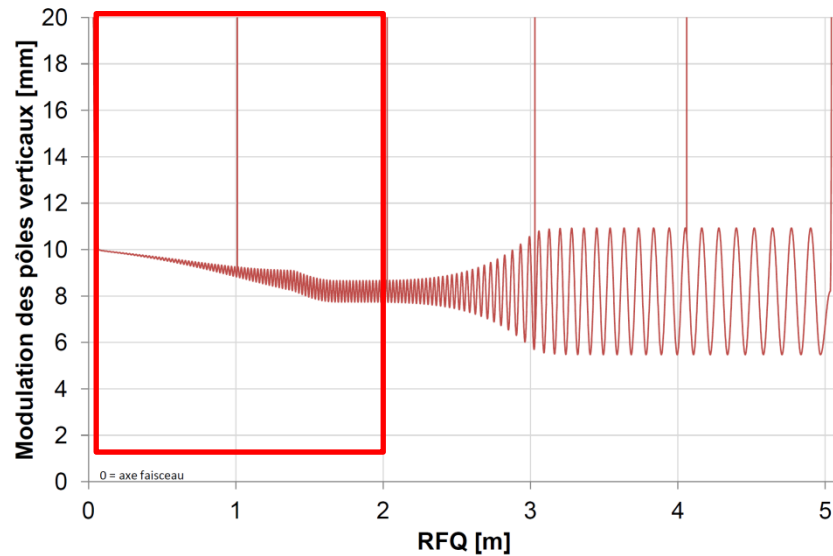
5 SECTIONS OF THE RFQ (2/5)

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

Almost no acceleration ($\Phi_s \sim -90^\circ$)

Very slow increasing of the modulation for start the adiabatic bunching

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

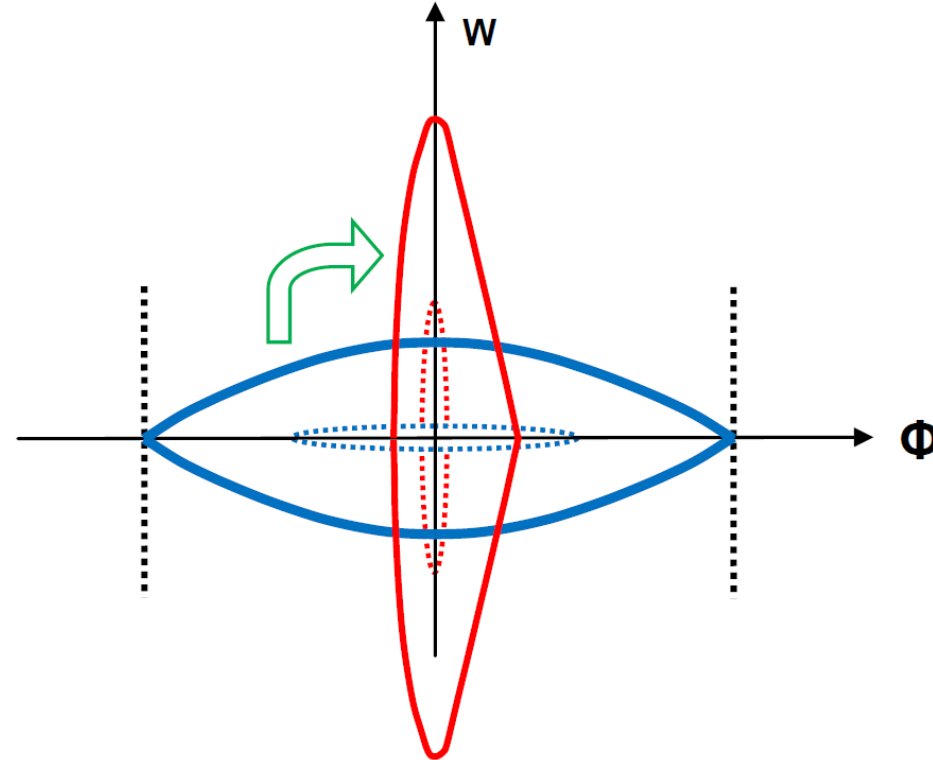
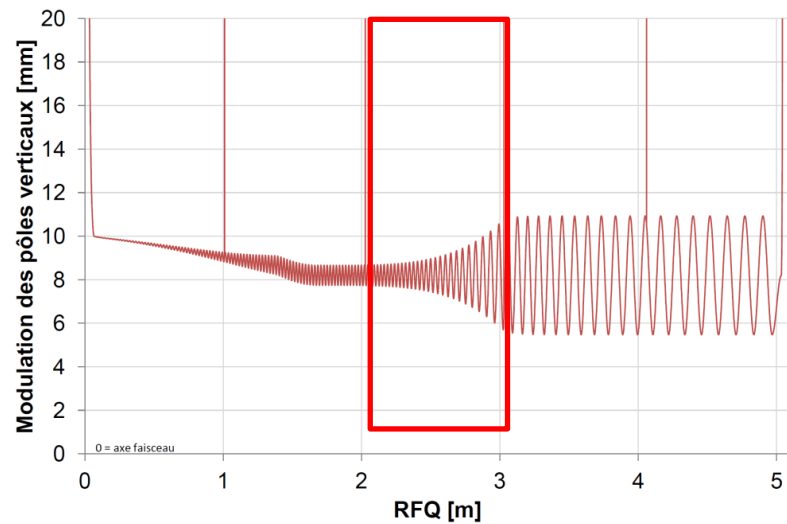


5 SECTIONS OF THE RFQ (3/5)

➤ Section 3 – Adiabatic bunching or “Gentle buncher section”

Progressive acceleration until nominal acceleration rate

Progressive variation of phase Φ_s ($-90^\circ \Rightarrow -30^\circ$) and modulation (1.1 \Rightarrow 2.0)

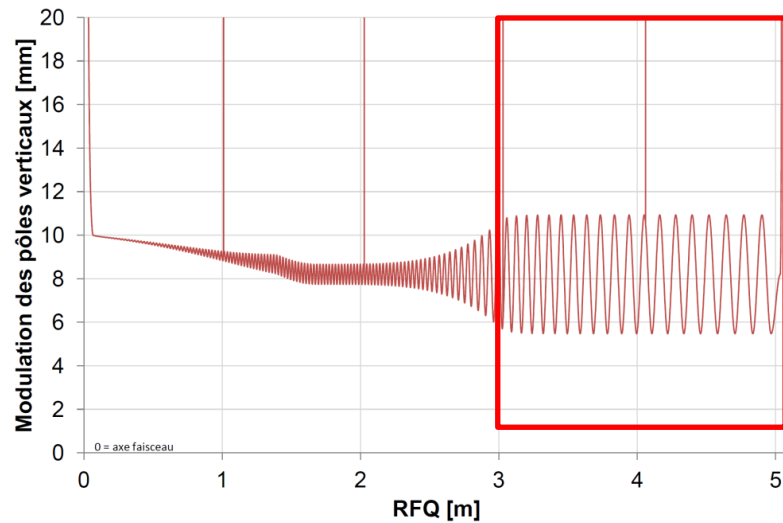


5 SECTIONS OF THE RFQ (4/5)

➤ Section 4 – Acceleration or “accelerating section”

Constant parameter for the maximum accelerating rate

$$\Phi_s = -30^\circ, \text{ modulation} = 2, V = V_{max}$$



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)

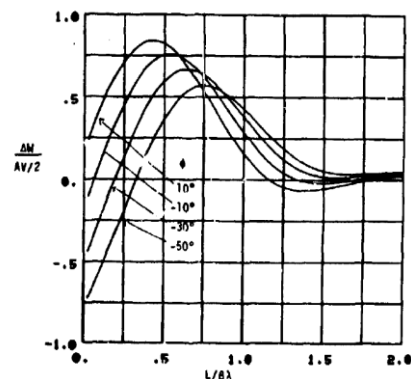
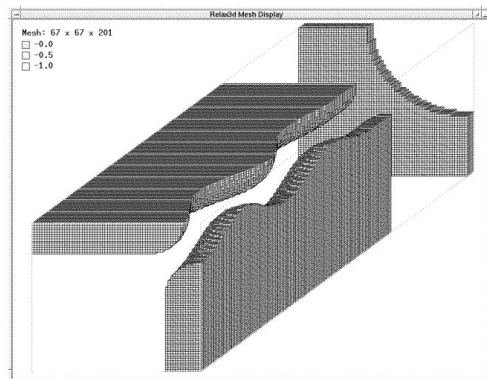
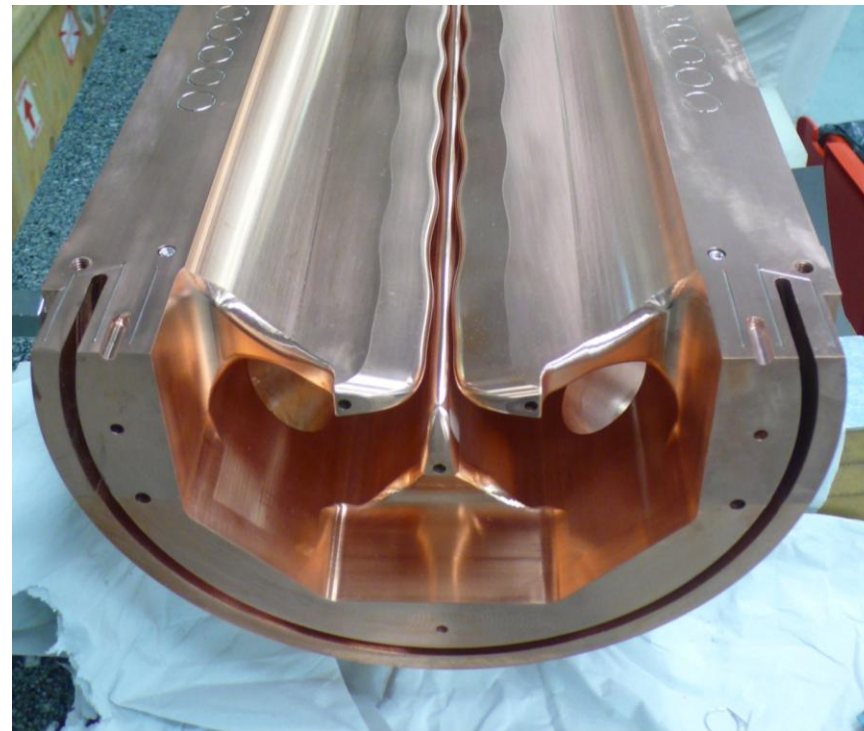
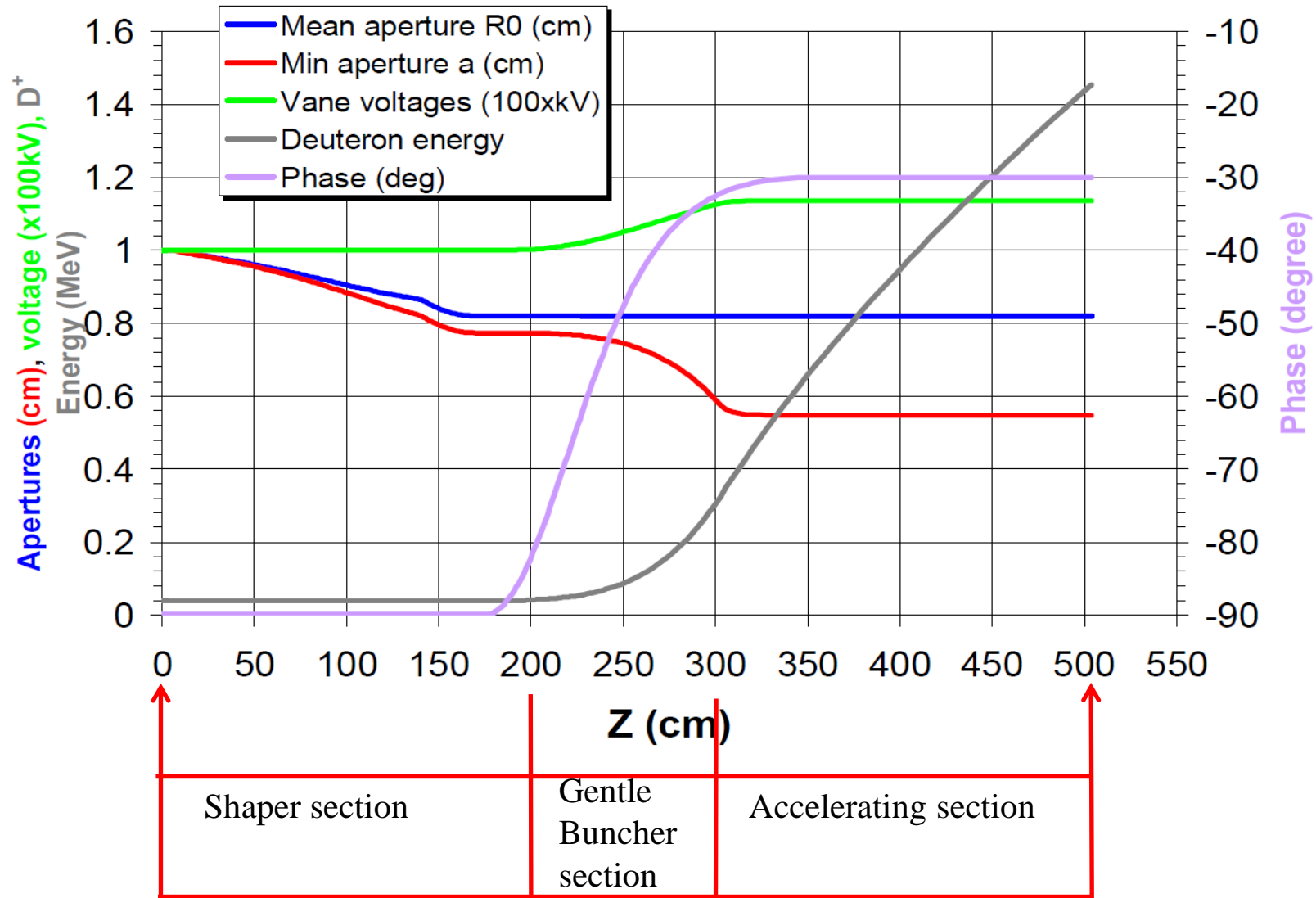


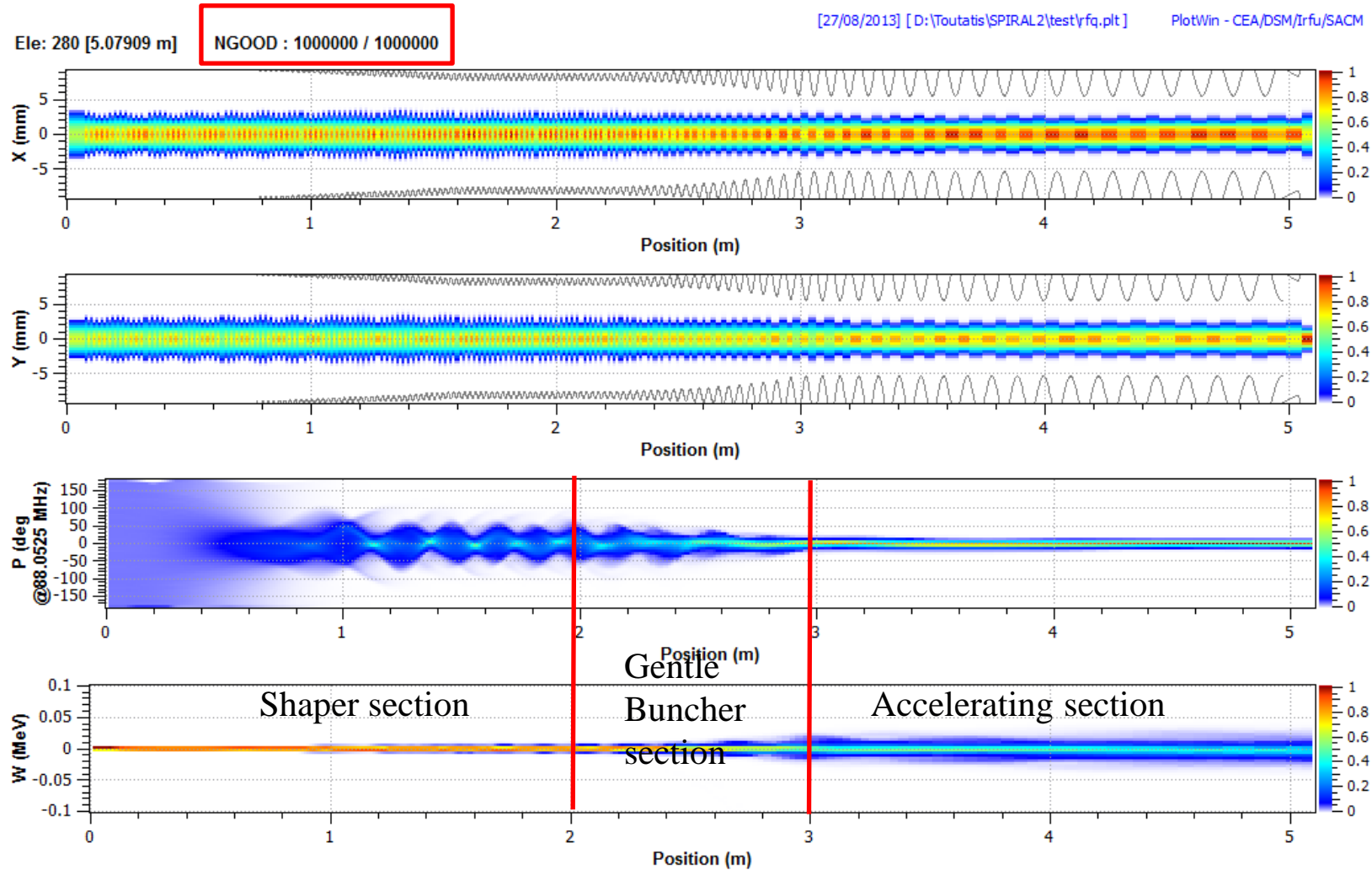
Fig. 3. Change in energy of a particle in the fringe region as a function of fringe length L plotted for several initial phases ϕ , assuming potential function from eq. (7).



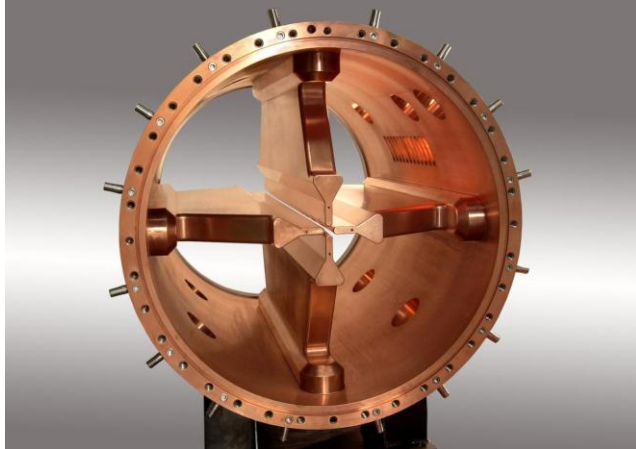
PARAMETERS OF THE SPIRAL2 RFQ



BEAM CALCULATION OF THE SPIRAL2 RFQ



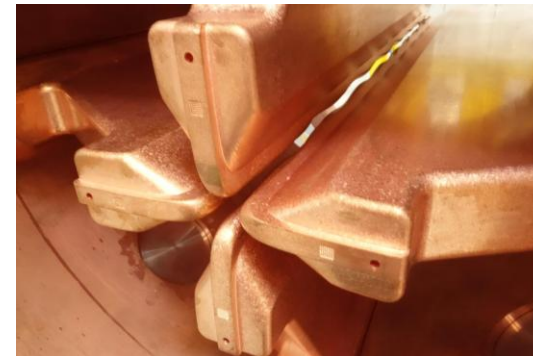
FROM PROTOTYPE TO OPERATION



Prototype

Careful attention must be taken :

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

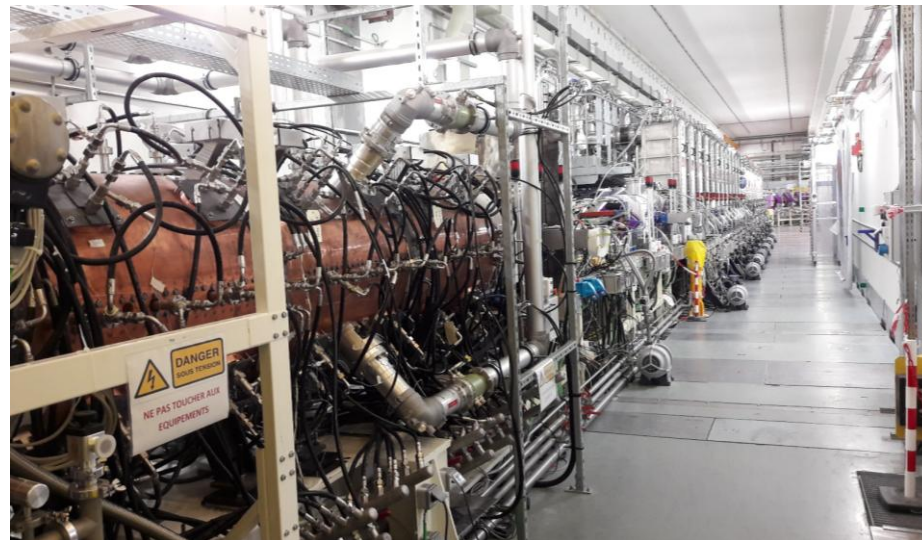
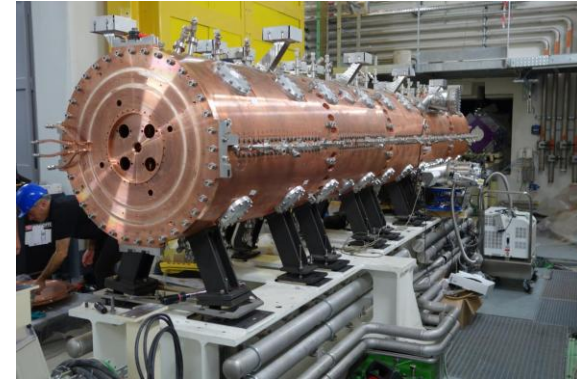


Final RFQ : Assembling



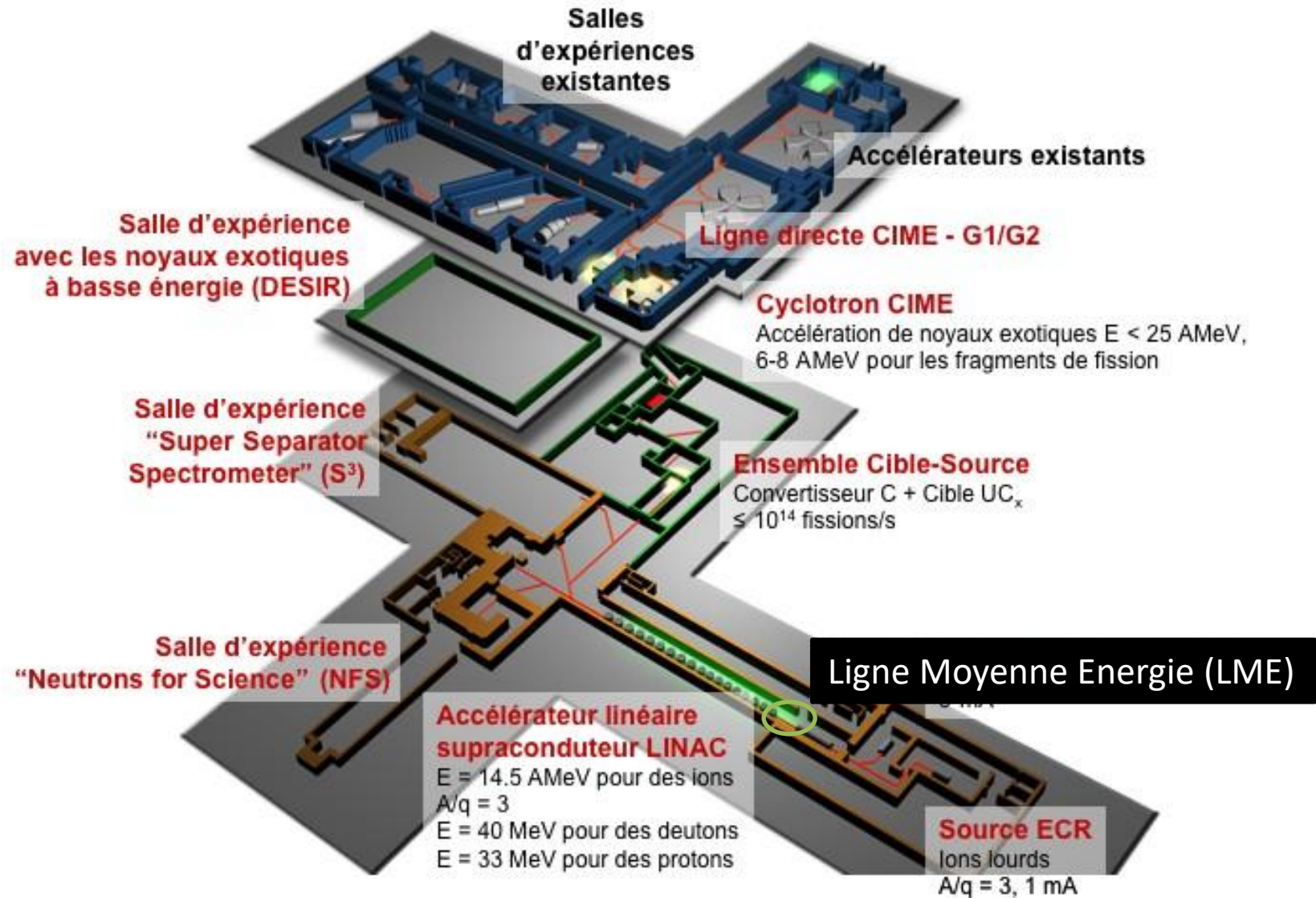
FROM PROTOTYPE TO OPERATION

On site ...



Ready for beam !

4. THE MEDIUM ENERGY BEAM TRANSPORT (MEBT)



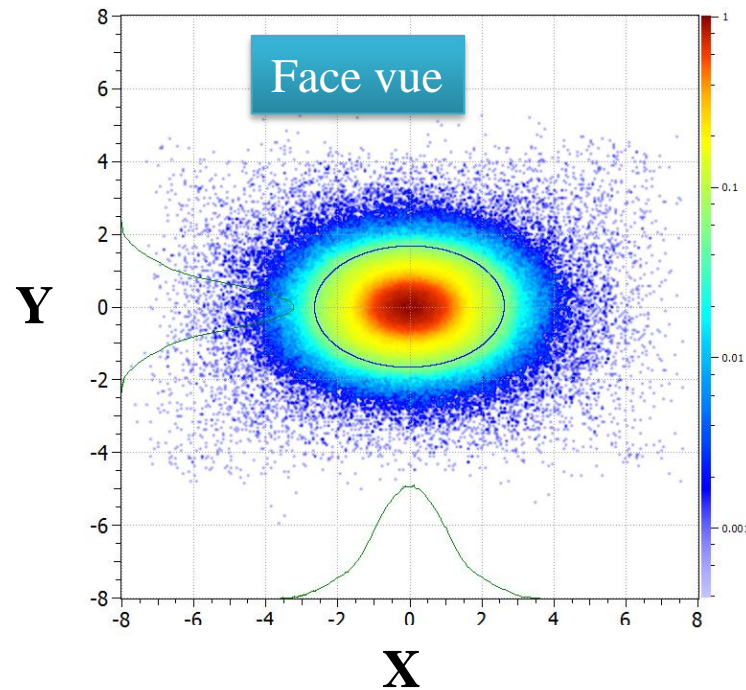
BEAM CHARACTERISTICS AFTER THE RFQ

RFQ exit:

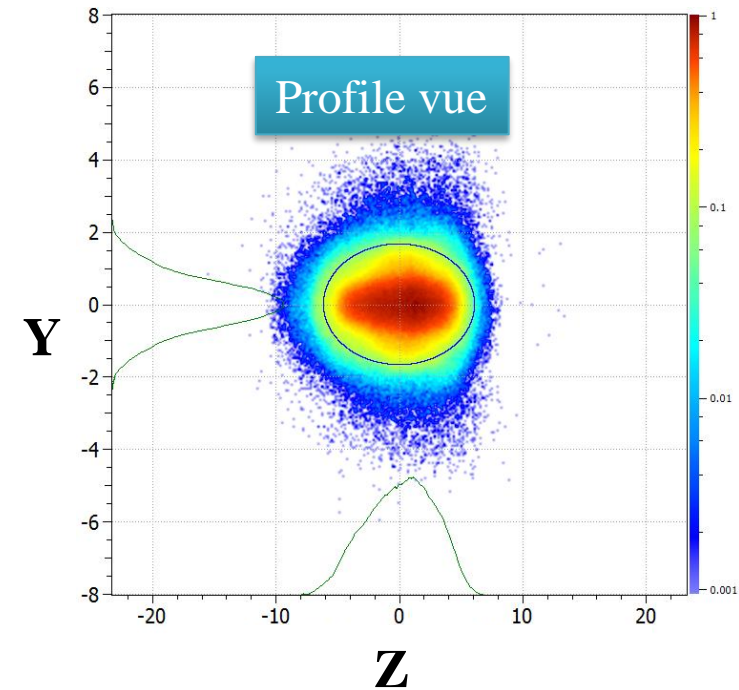
- Beam : bunched (**88 MHz**)
- Speed : $\beta = 0.04$
- Current : **100 μA to 5 mA**
- Power : up to **7 kW**
- Particles : **Protons, Deuterons, heavy ions**
- Mass/charge ratio A/q : **1 to 7**
- Energy : **0.75 MeV/A**
- Duty cycle : **0.1% à 100%**



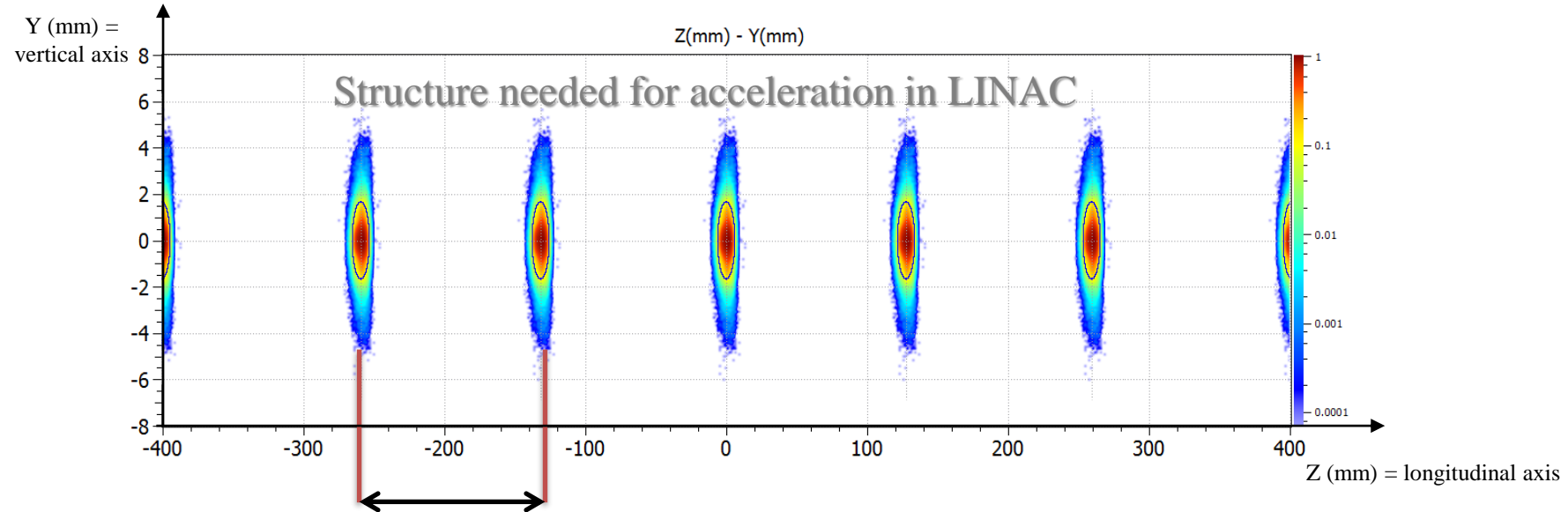
Z is the beam direction (longitudinal axis)



Example:
Deuterons
at 5 mA



BEAM CHARACTERISTICS : TIME STRUCTURE



Bunch frequency : 88 MHz ($\Rightarrow 88 \times 10^6$ pulse/sec) \Rightarrow time between pulses = 12 ns or 130 mm or 360°

The duty cycle is the ratio over 1 sec when the beam is On

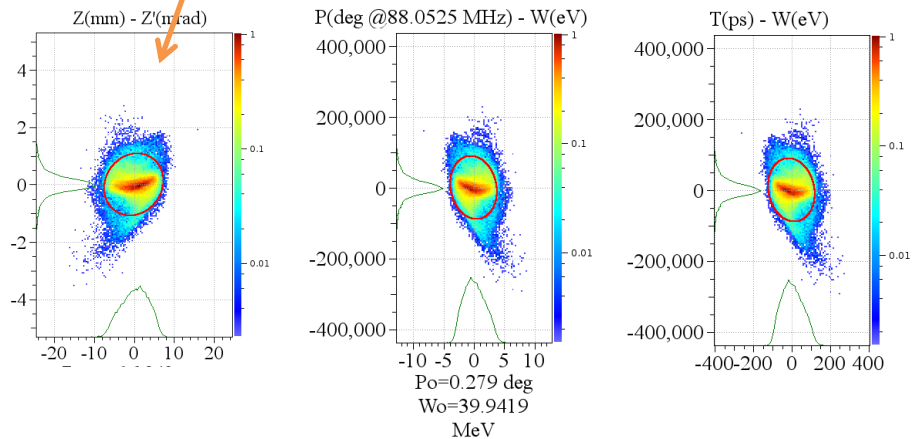
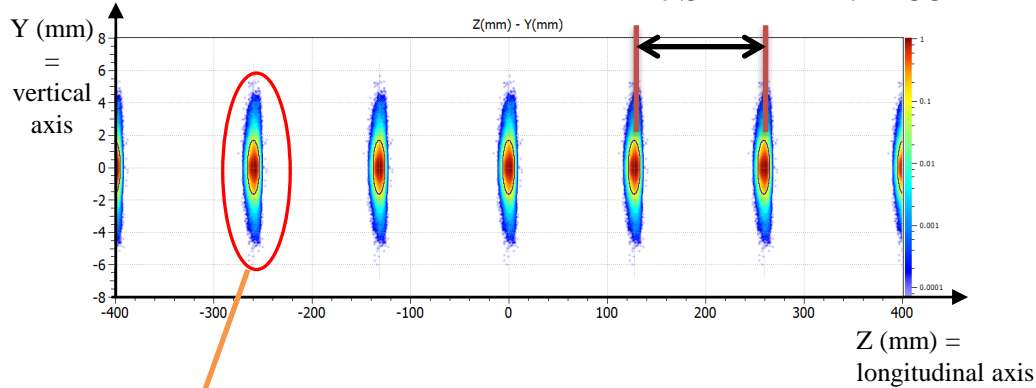


At Spiral2 the duty cycle : 0.1% to 100%, macro pulse length 1 ms to 1 s

88000 pulses

RELATION IN THE LONGITUDINAL PLANE

At SPIRAL2 : $f=88 \text{ MHz} \Rightarrow T=12\text{ns}$ or 130 mm or 360°



Beam is known by :

\bar{E} , charge q and frequency f in Hz

Bunch length is define by quantities :

- σ_z (m),
- σ_ϕ (degrés) (phase length)
- σ_T (s) (time length)

We have :

$$\sigma_z (m) = \frac{\sigma_\phi (degrés) \times \beta \lambda}{360} \text{ with } \lambda = \frac{c(m/s)}{f}$$

$$\sigma_z (m) = \frac{\sigma_\phi \times \beta c(m/s)}{360 \times f} \text{ and } \sigma_T (s) = \frac{\sigma_\phi (^\circ)}{360 \times f}$$

And standard deviation in energy σ_E is the

longitudinal divergence : $\sigma_{z'} (rad) = \frac{\sigma_E (MeV)}{\bar{E} \times \gamma (\gamma + 1)}$

$$\sigma_a \text{ is the standard deviation} = \sqrt{\frac{1}{n} \sum_{i=1}^n (a_i - \bar{a})^2}$$

where a is an uniform law

Ex :

deuterons
beam at
40 MeV

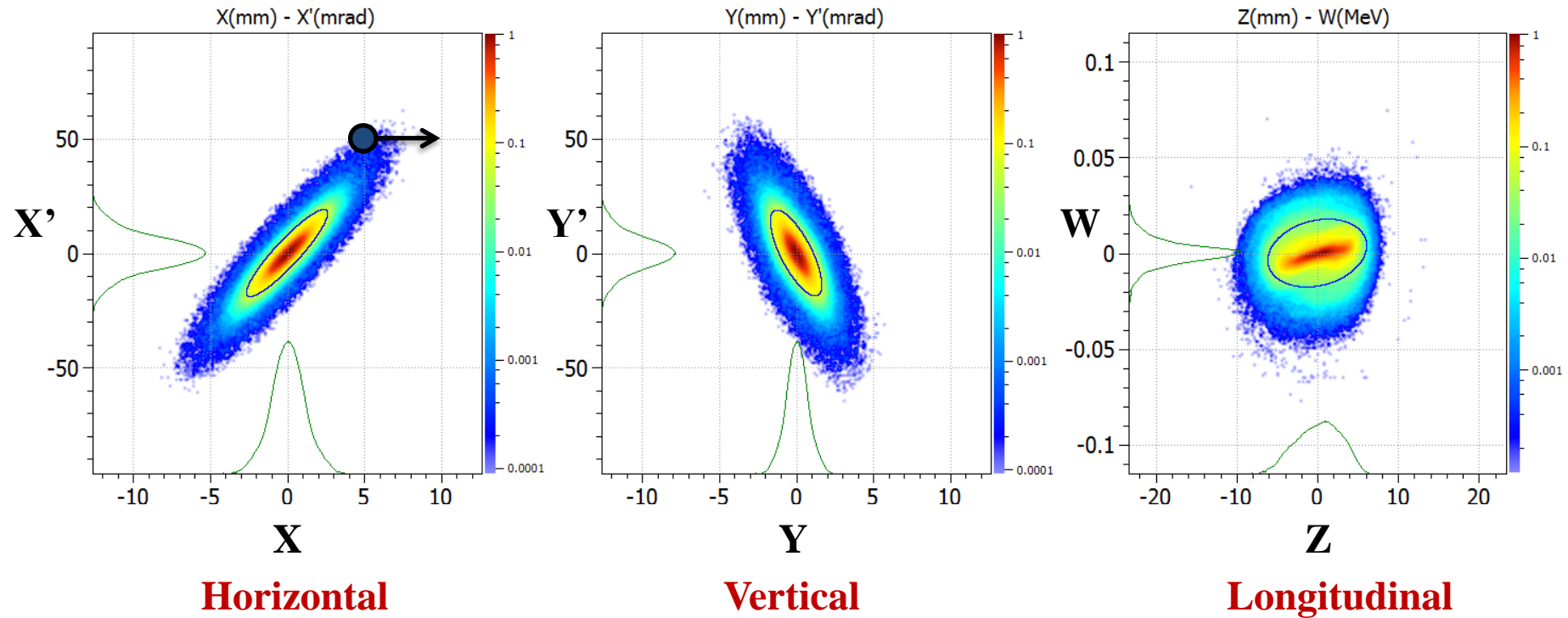
Beta = 0.203144975 Gamma = 1.021295366
Mo = 1875.61340548 MeV

Sigma_Z [rms] = 3.3051 mm
Sigma_Z' [rms] = 0.4838 mrad
Sigma_Time [rms] = 54.2704 ps
Sigma_Energy [rms] = 39889.0181 eV
Sigma_Phase [rms] = 1.7203 deg
Sigma_Energy [rms] = 39889.0181 eV

dz = -0.535191 mm
dz' = 0 mrad
dP = 0.278565 deg
dT = 8.78784 ps
dW = 0 eV

BEAM CHARACTERISTICS : PHASE SPACE

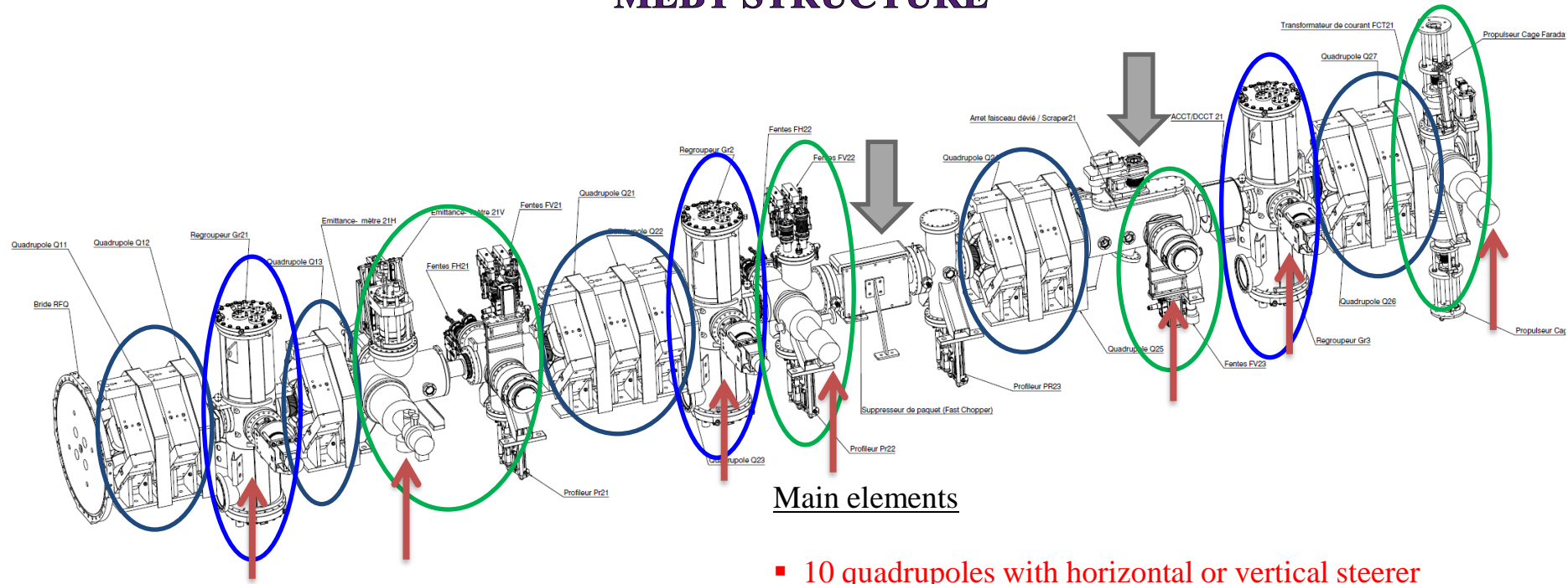
Phase spaces, emittances: ε



Large transverse divergence + space charge

Example : One particle with 5 mm, 50 mrad \rightarrow after $z=10\text{cm}$, position is **10 mm**

MEBT STRUCTURE



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)

Focusing devices

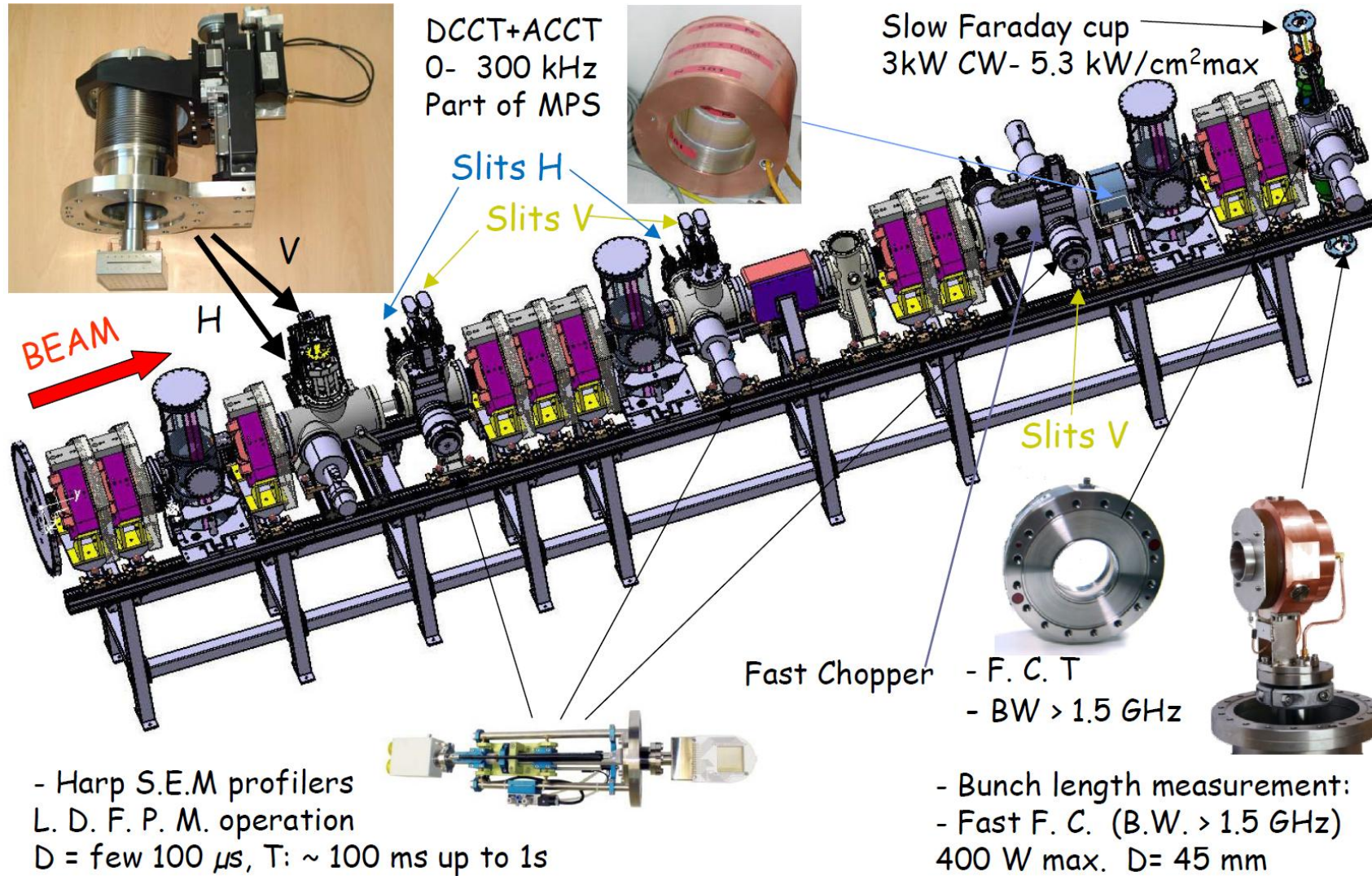
Acceleration

Diagnostics

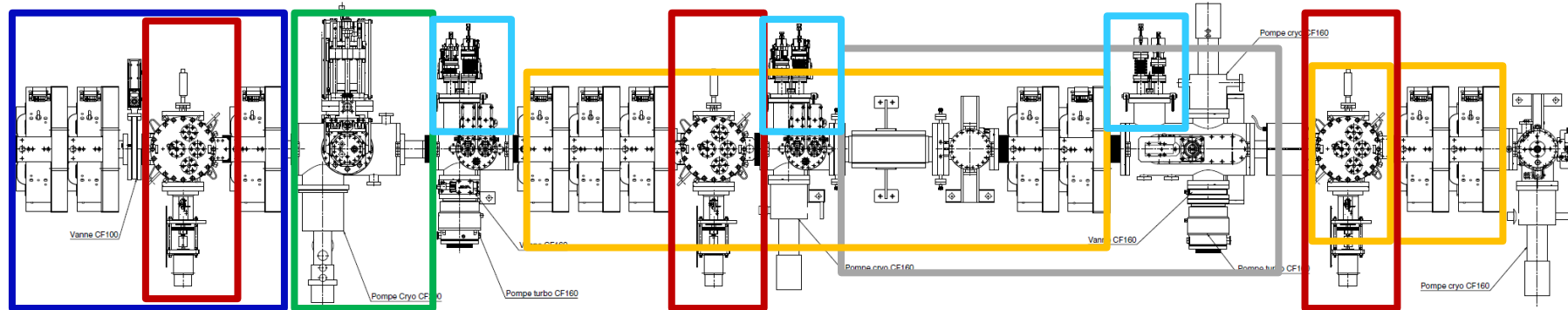
Pumping device

Bunch selector

MEBT DIAGNOSTICS



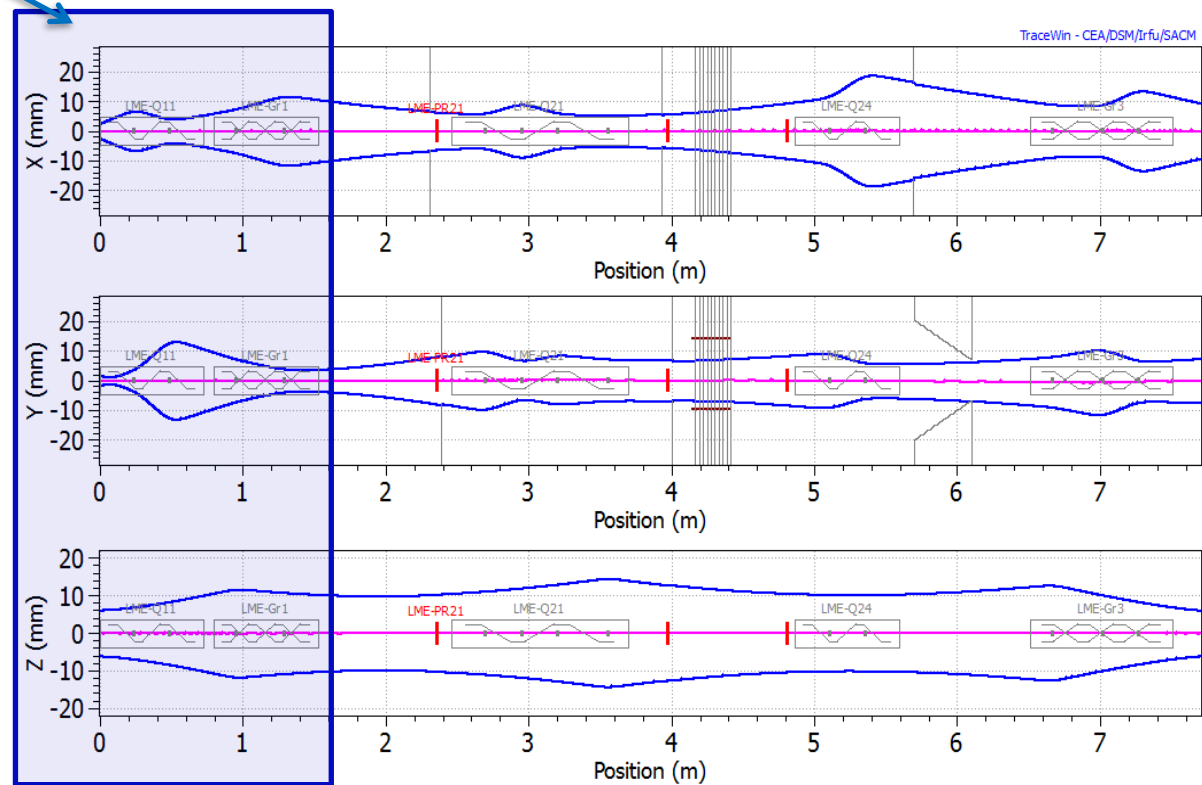
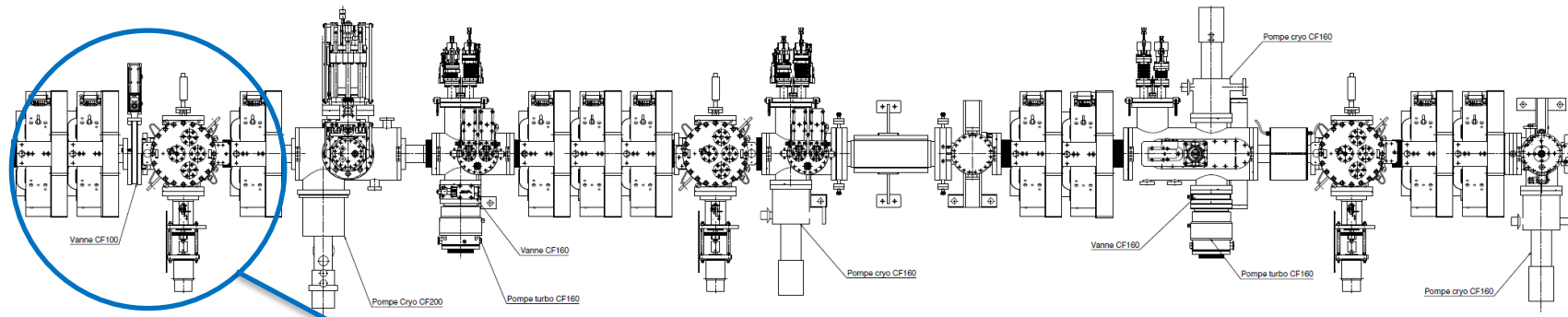
MEBT FUNCTIONS



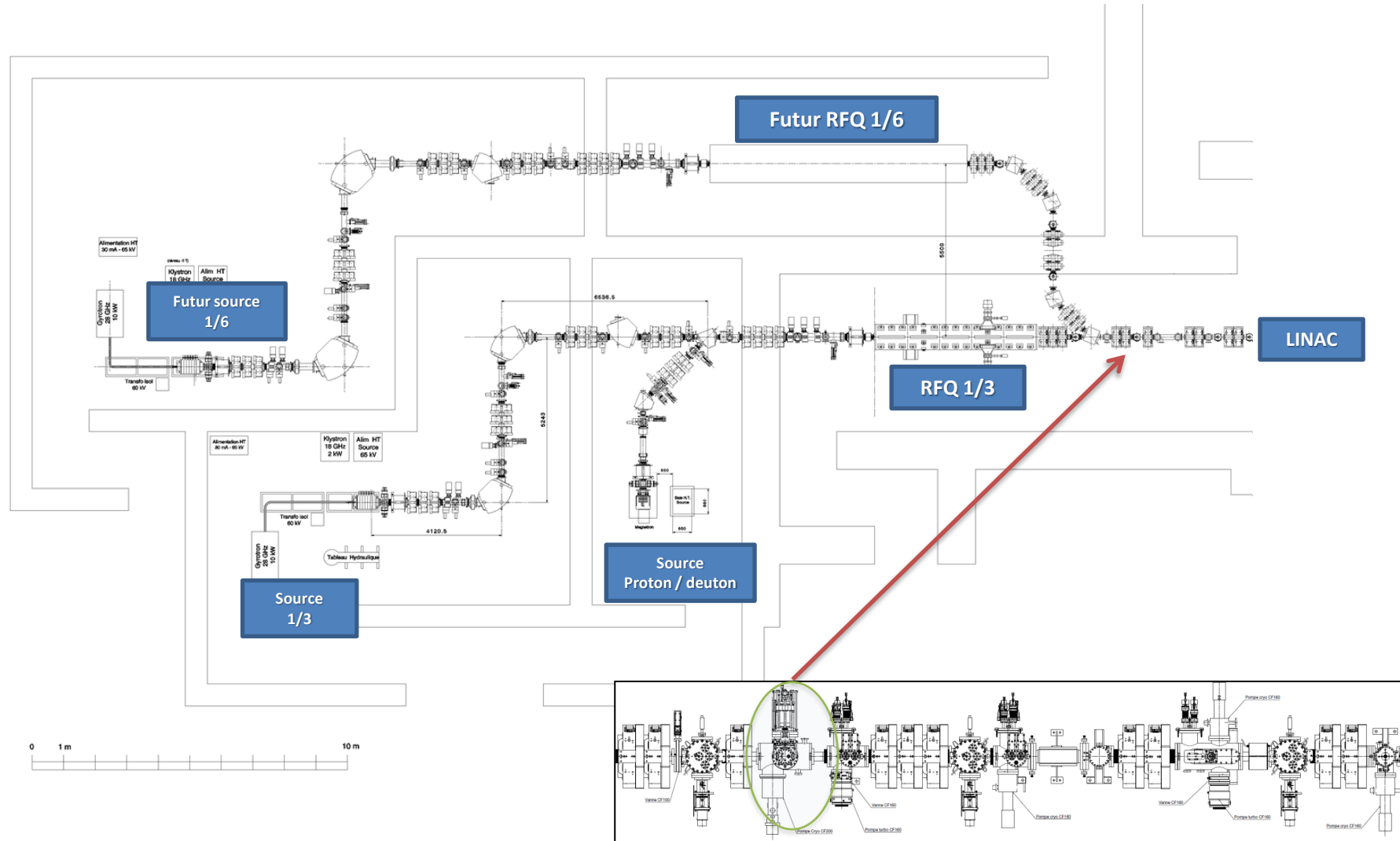
The 6 main functions of the MEBT :

- 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

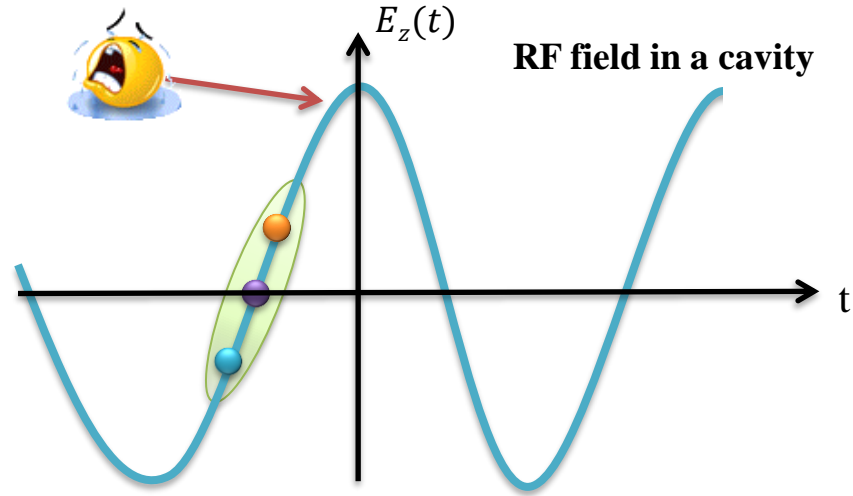


2 - UPGRADE OF THE ACCELERATOR WITH FUTURE A/Q=6 BEAM LINE



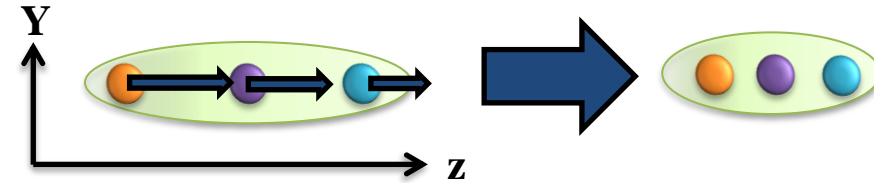
3 - MAINTAIN BEAM BUNCHED FOR THE LINAC

RF buncher principle

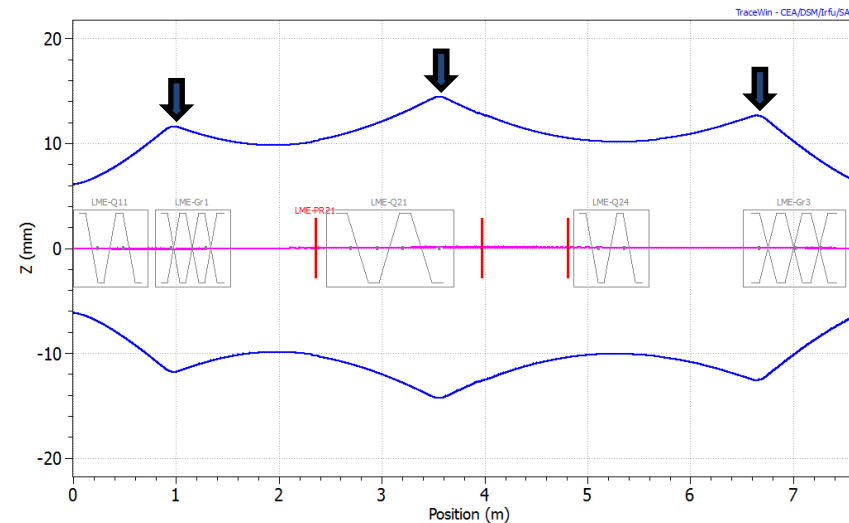


Staying in the linear part of the accelerating field

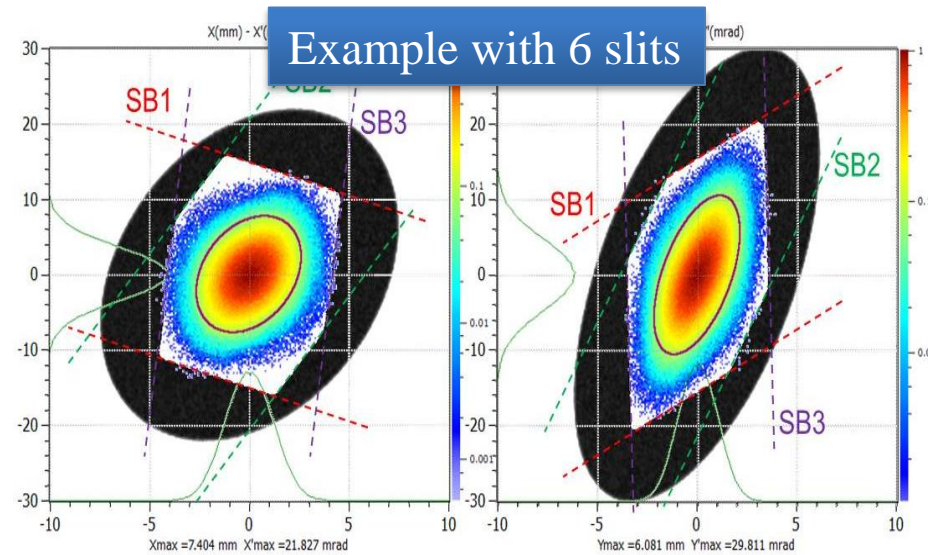
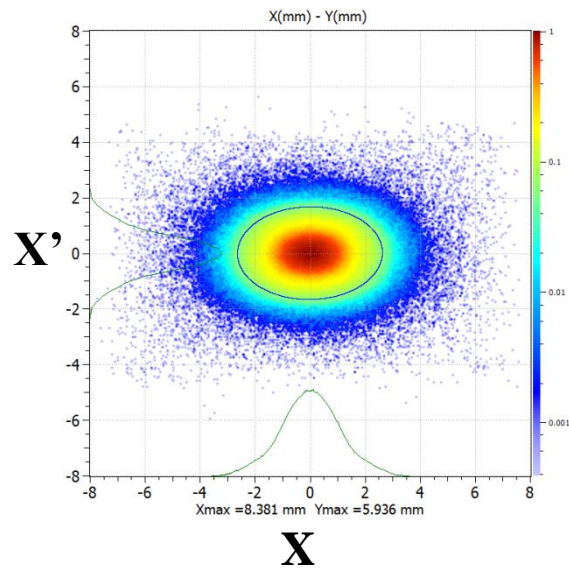
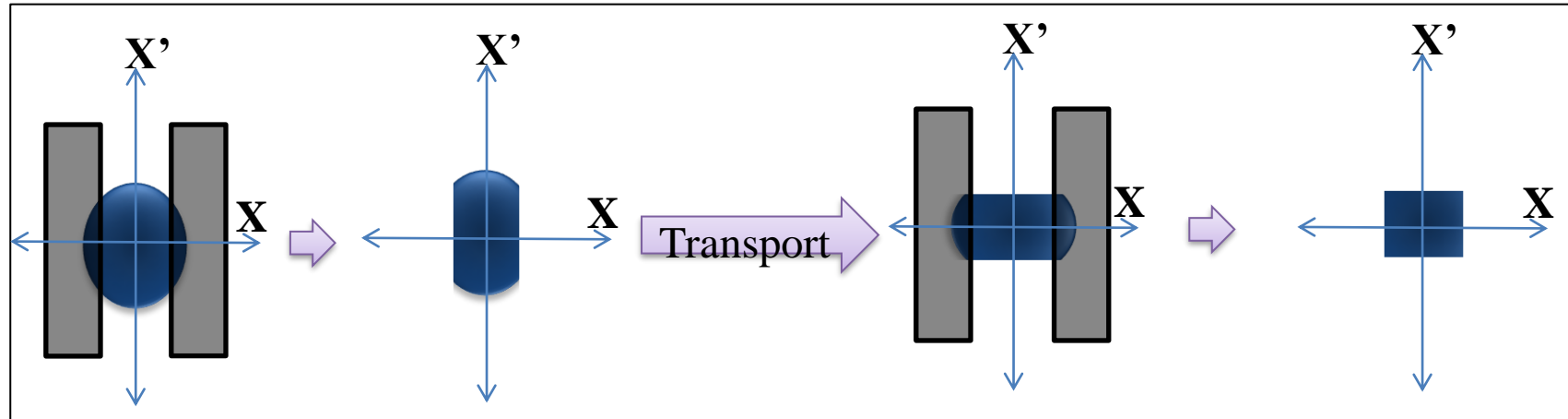
- For $E=0$: speed is constant
- Arrive in advance, particle is slowing-down
- Arrive late, particle is accelerate



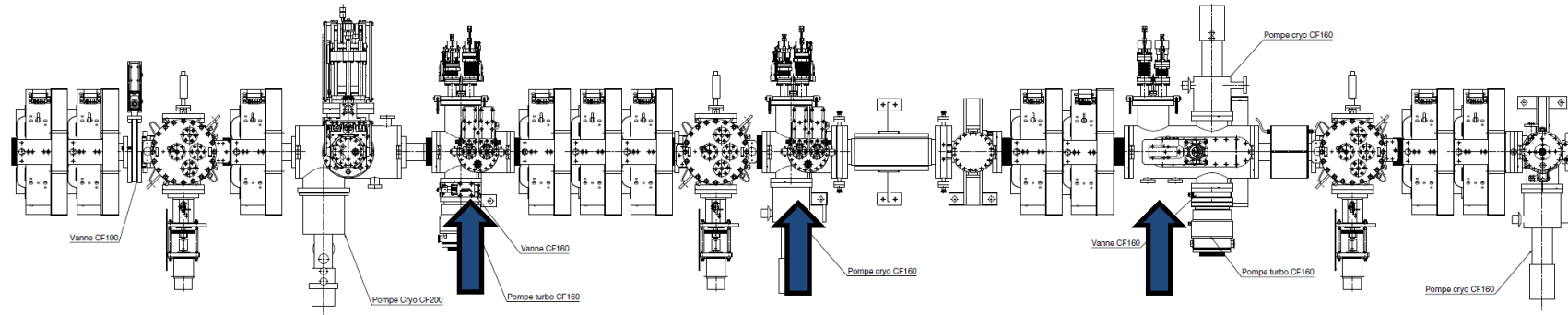
Bunch length in mm
(eq to time)



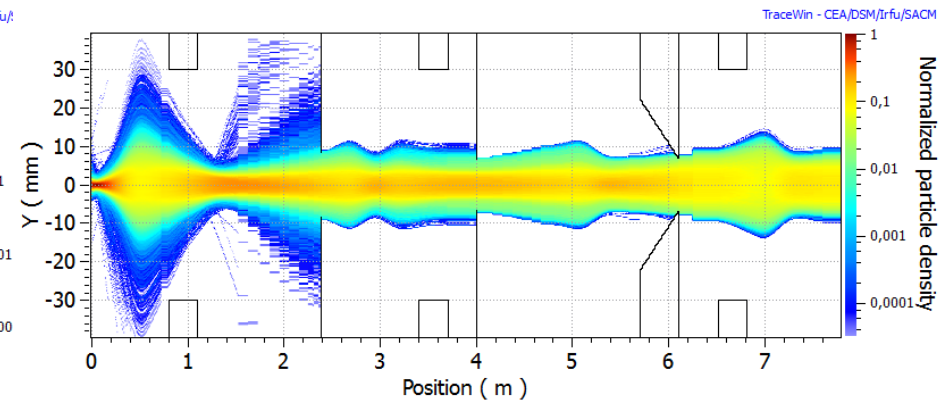
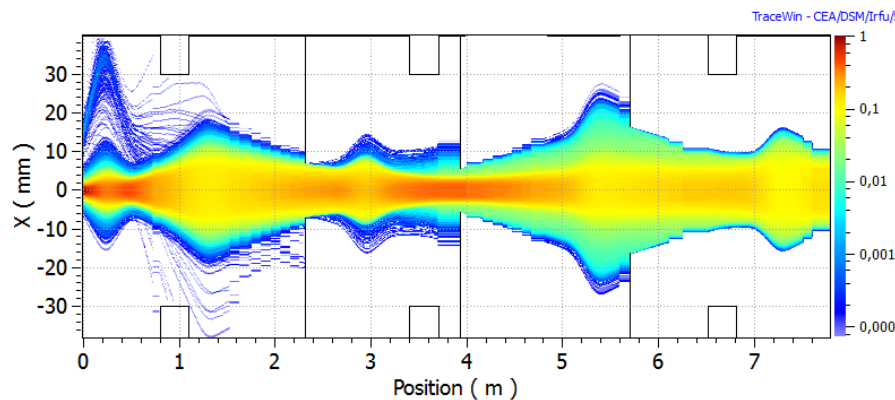
4 - CLEANING THE BEAM



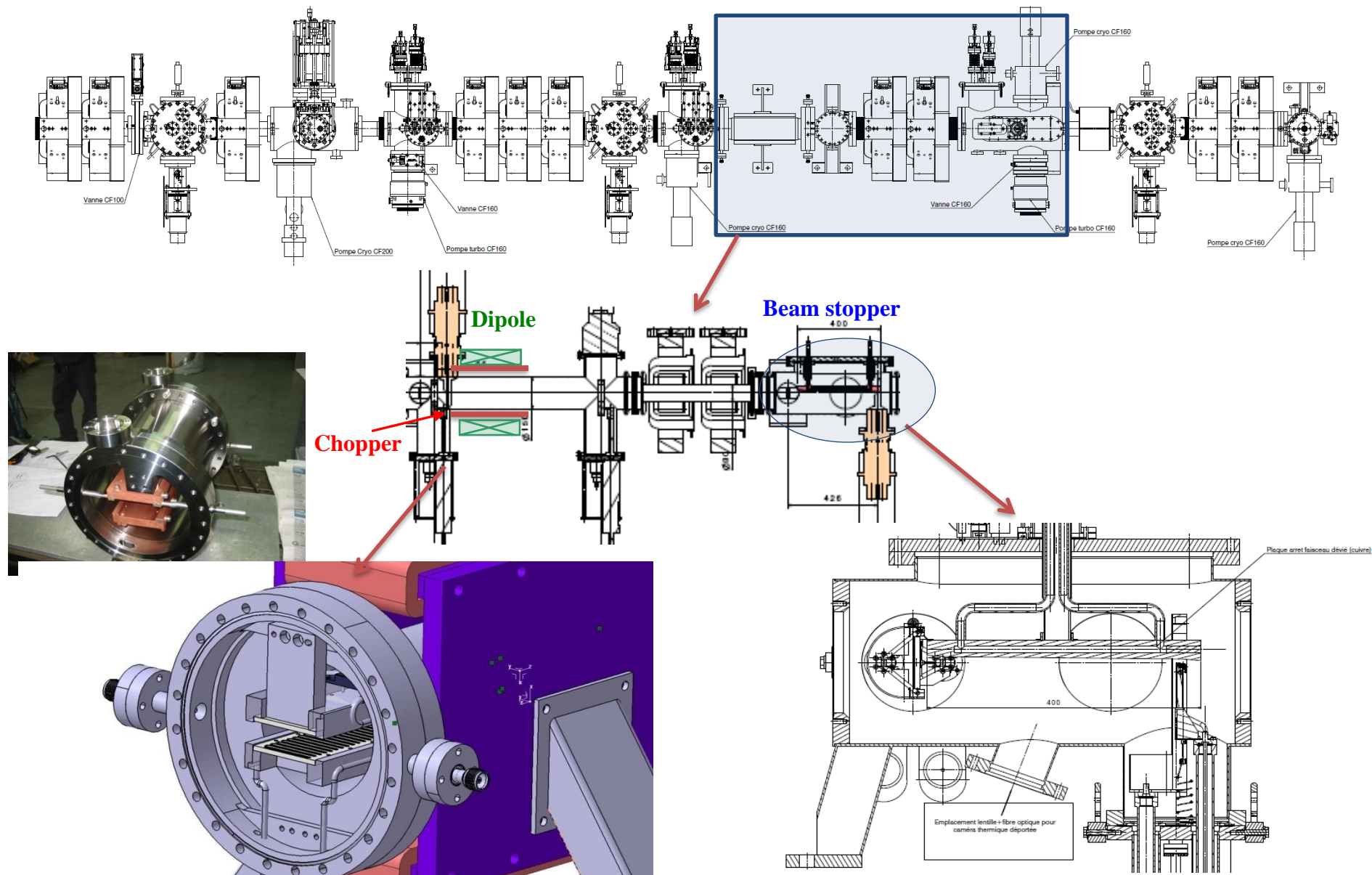
4 - CLEANING THE BEAM



- 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

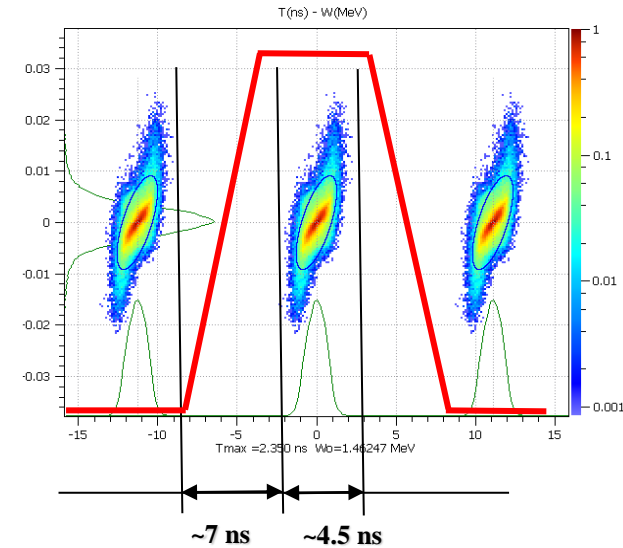
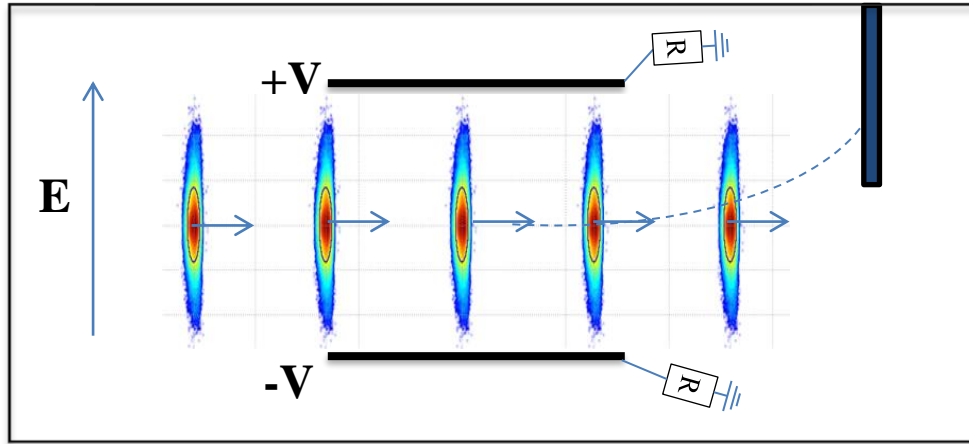


5 - PROVIDE BUNCH SELECTION



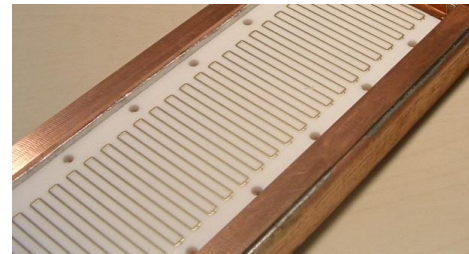
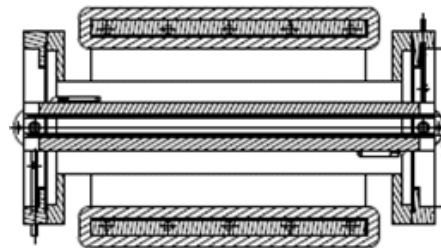
5 - PROVIDE BUNCH SELECTION

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

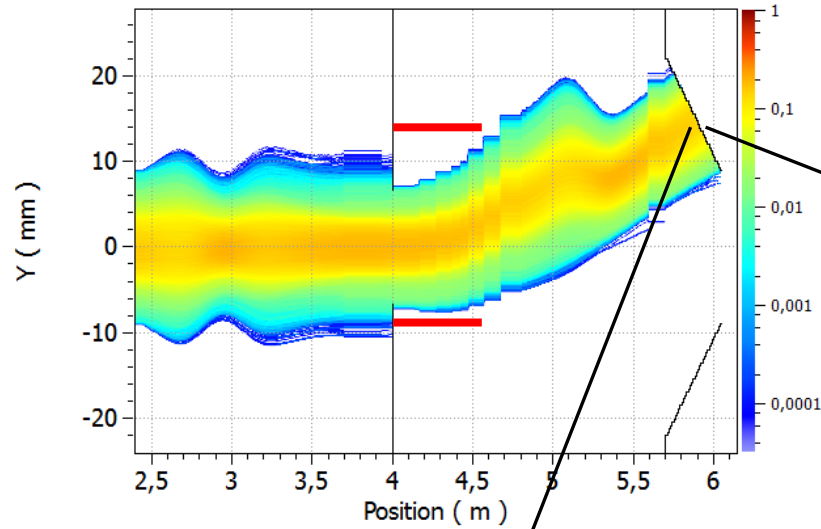


Need a device to carry out this feature :

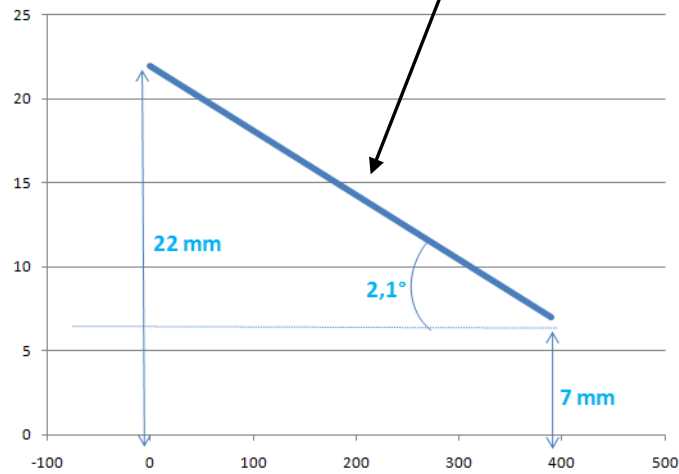
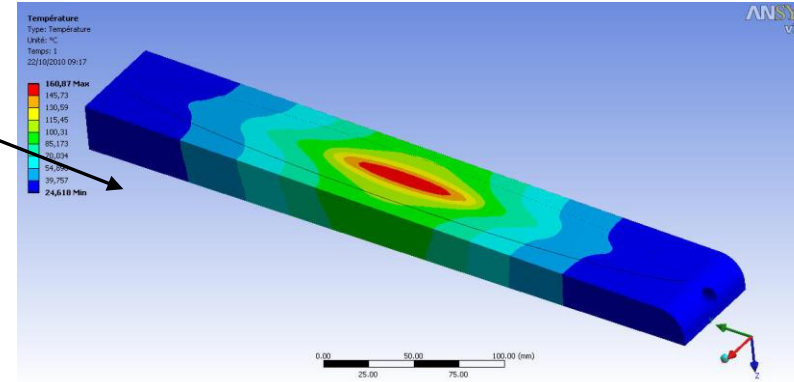
- Rise time : 7 ns
- Phase speed : beam, 4% de c
- Use a magnetic dipole and electric field switch in order to realize the 999/1000 suppression bunches



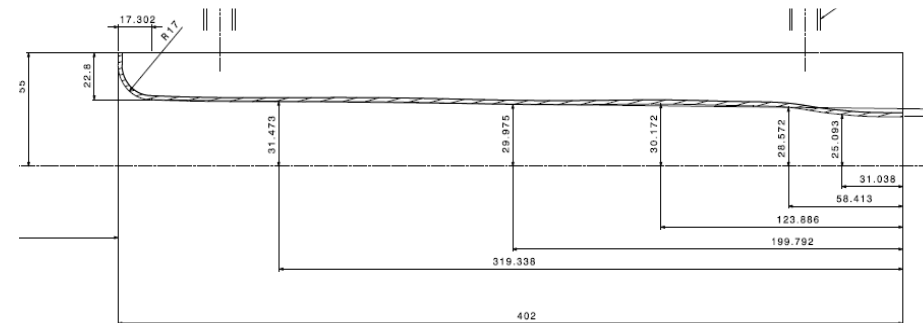
5 - PROVIDE BUNCH SELECTION



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')

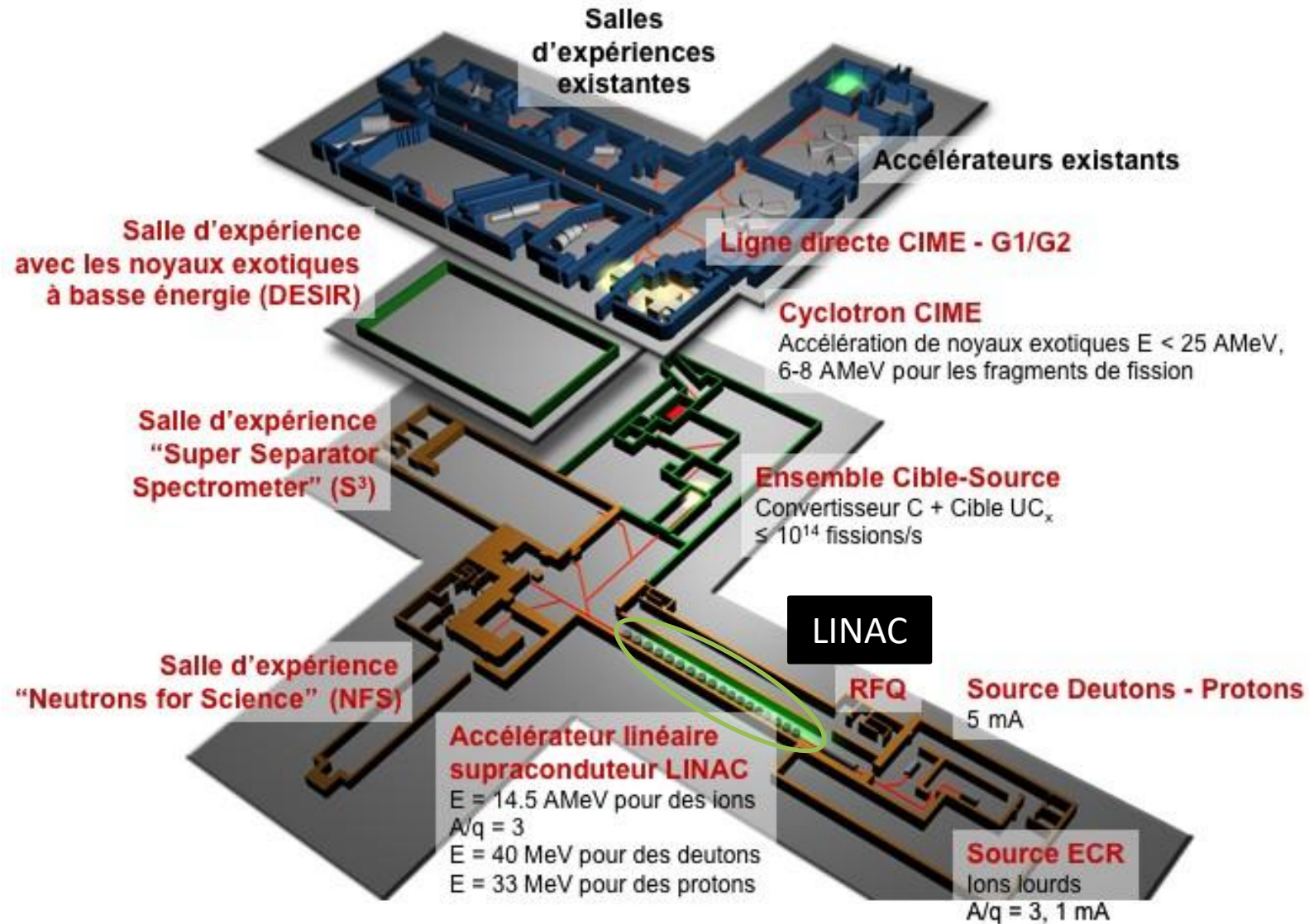
⇒ 6 parameters → 6 independent tuning

⇒ 4 quadrupoles and 2 re-bunchers of the MEFT 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

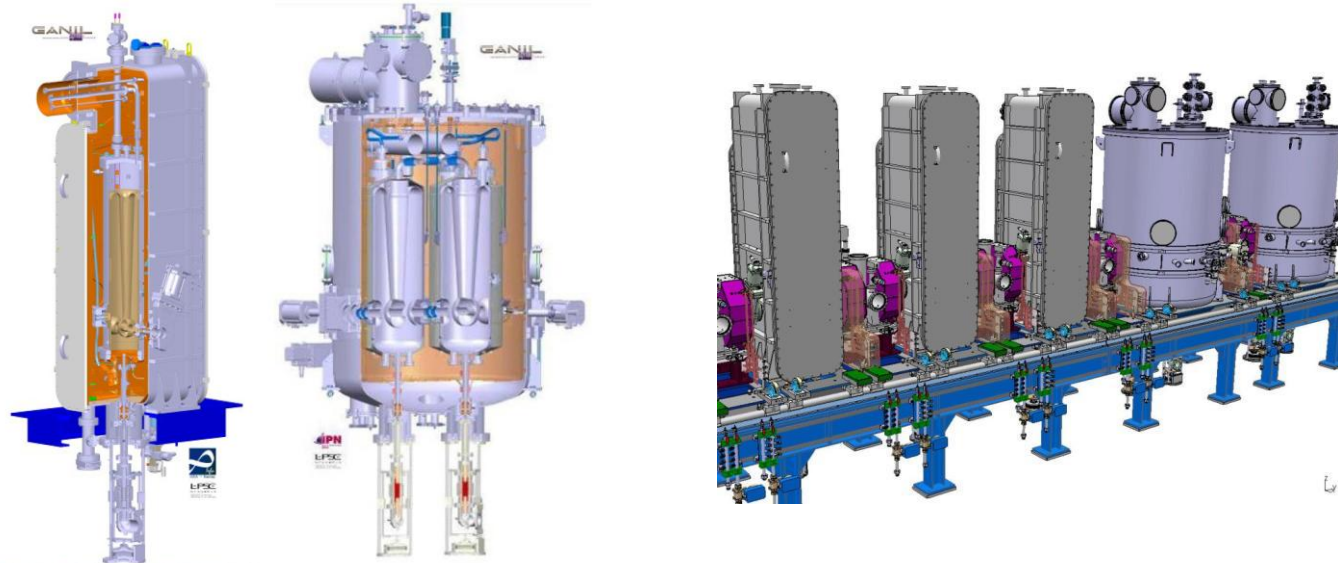
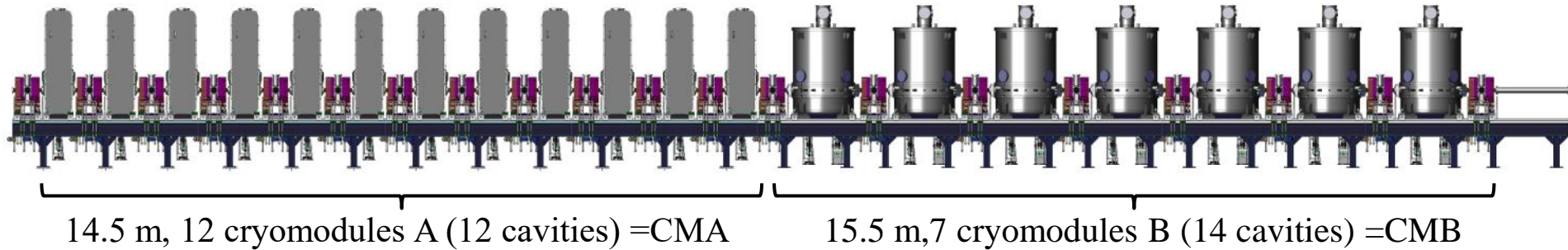


THE SPIRAL2 LINAC

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

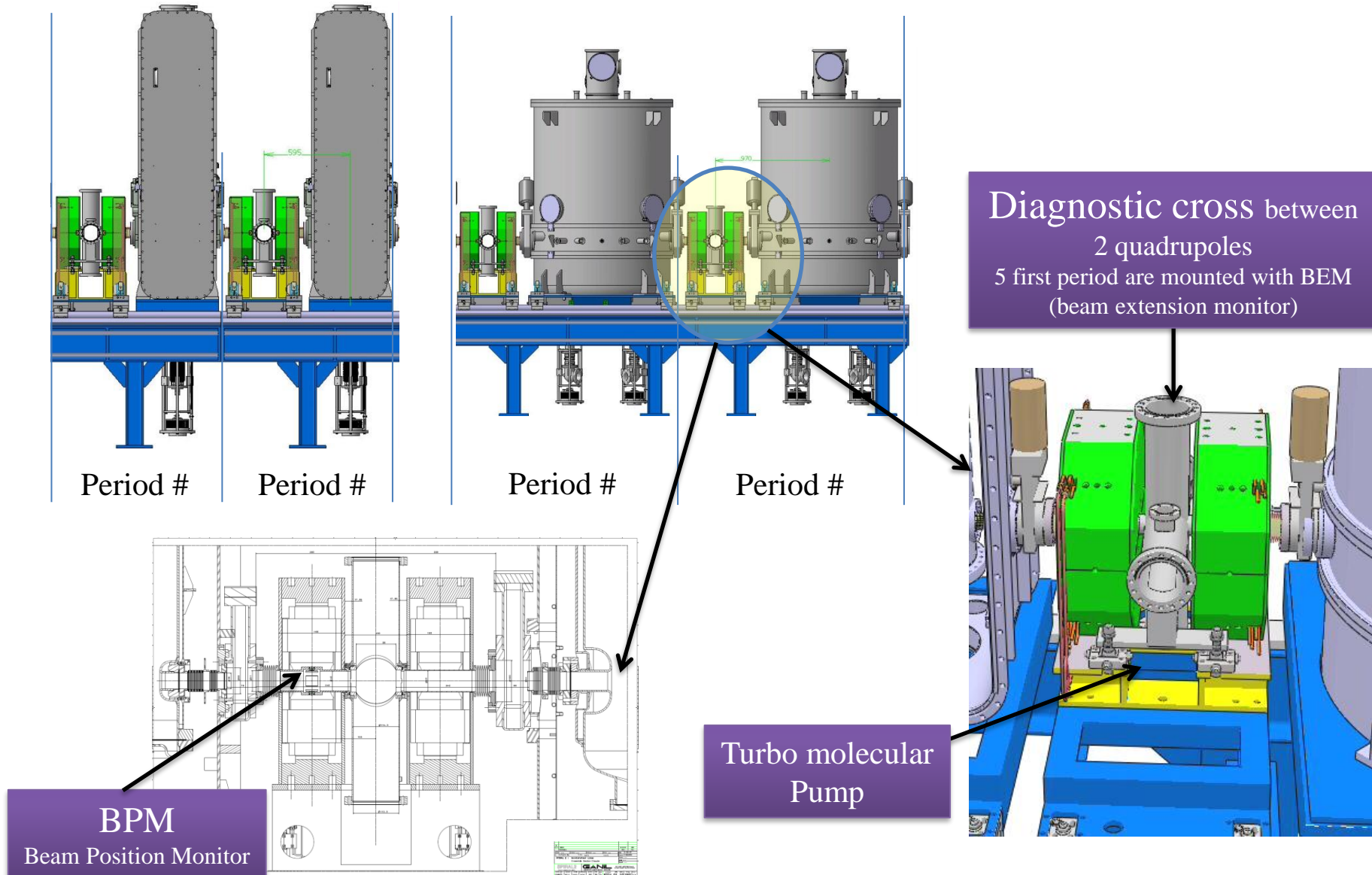
High intensity :

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

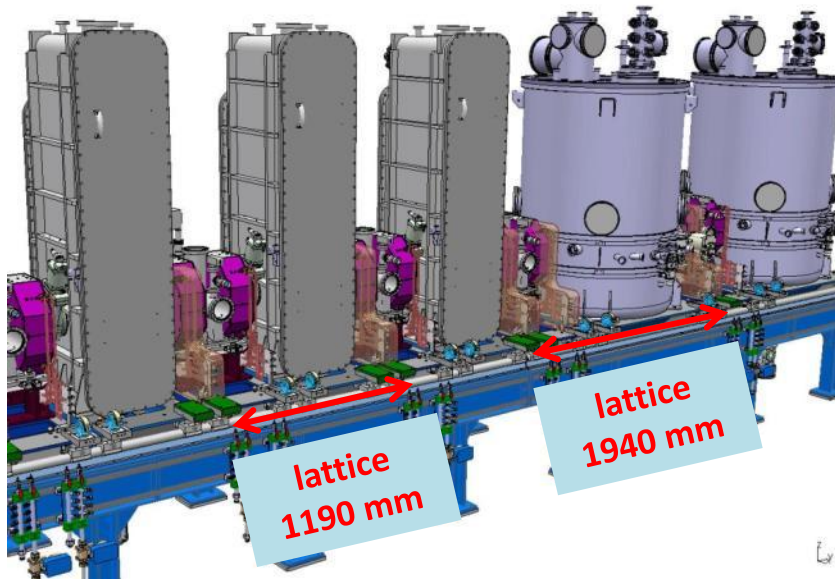


THE SPIRAL2 ACCELERATOR AT GANIL-CAEN

PERIOD OF THE LINAC



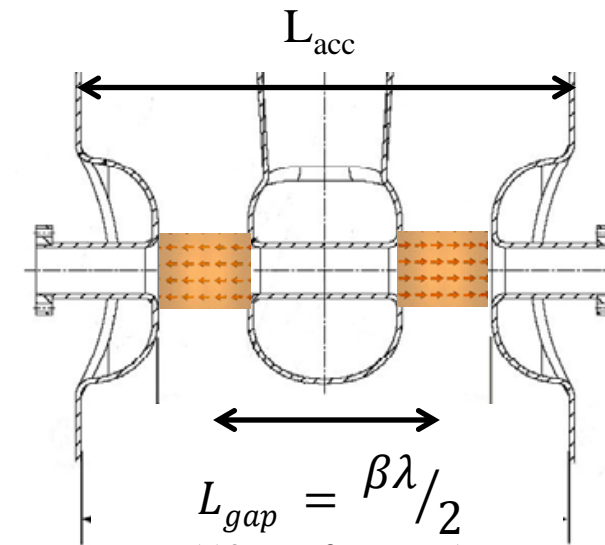
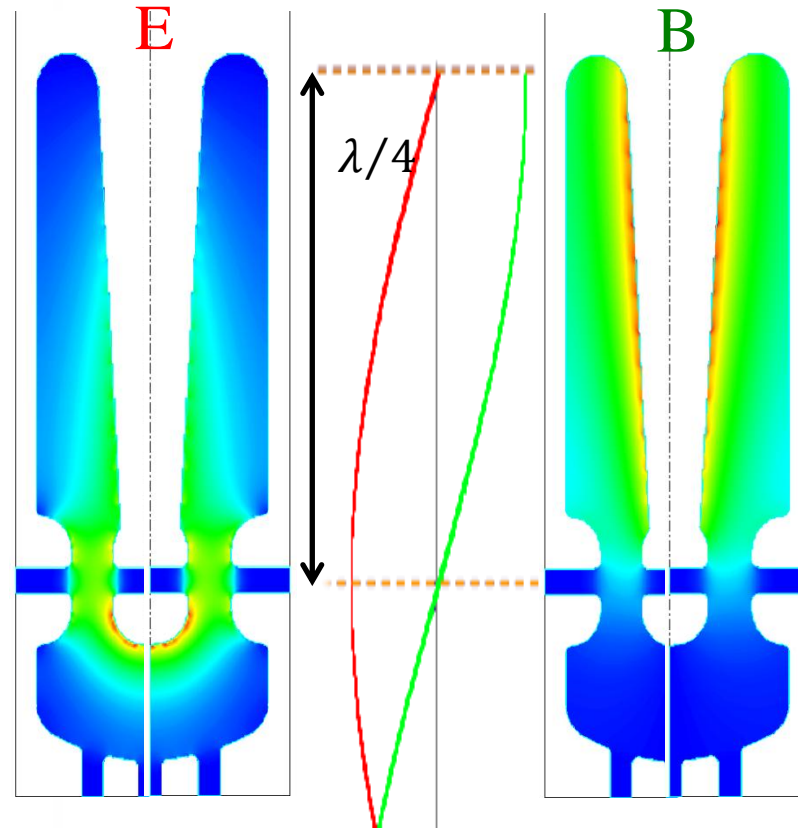
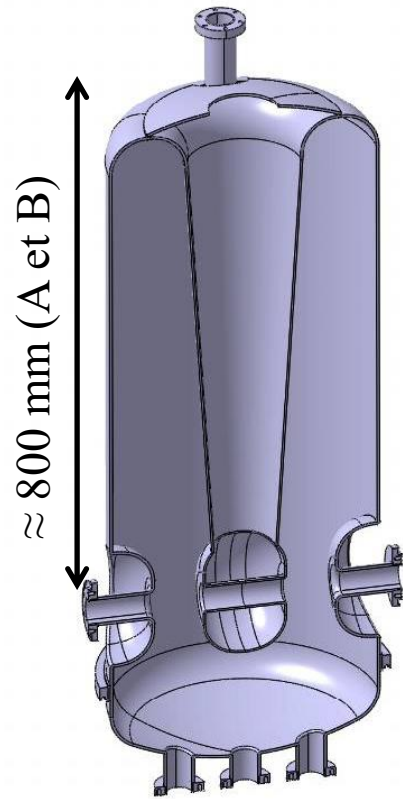
CHARACTERISTICS OF THE SPIRAL2 CAVITIES



| 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 |
| β_{optimum} | 0.07 | 0.12 |
| $E_{\text{peak}}/E_{\text{acc}}$ | 5.36 | 4.76 |
| $B_{\text{peak}}/E_{\text{acc}}$ (mT/MV/m) | 8.70 | 9.35 |
| L_{acc} [m] | 0.24 | 0.40 |
| V_{acc} at 6.5 MV/m & β_{opt} (MV) | 1.55 | 2.66 |
| G [Ω] | 22 | 37 |
| r/Q [Ω] | 600 | 515 |
| Q_0 ($P_{\text{cav}}=10\text{W}$ @ 6.5 MV/m) | $3.5 \cdot 10^8$ | $1,4 \cdot 10^9$ |

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

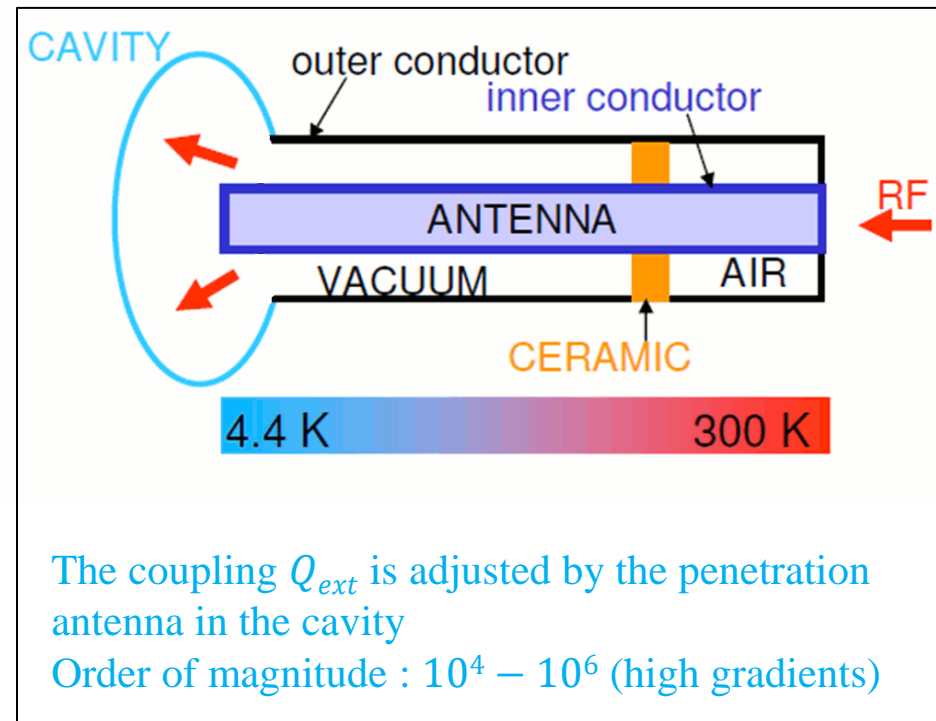
P_{ext} : supplied power to the cavity (10kW)

⇒ Q_{ext} fixed by the cavity parameters and the beam

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

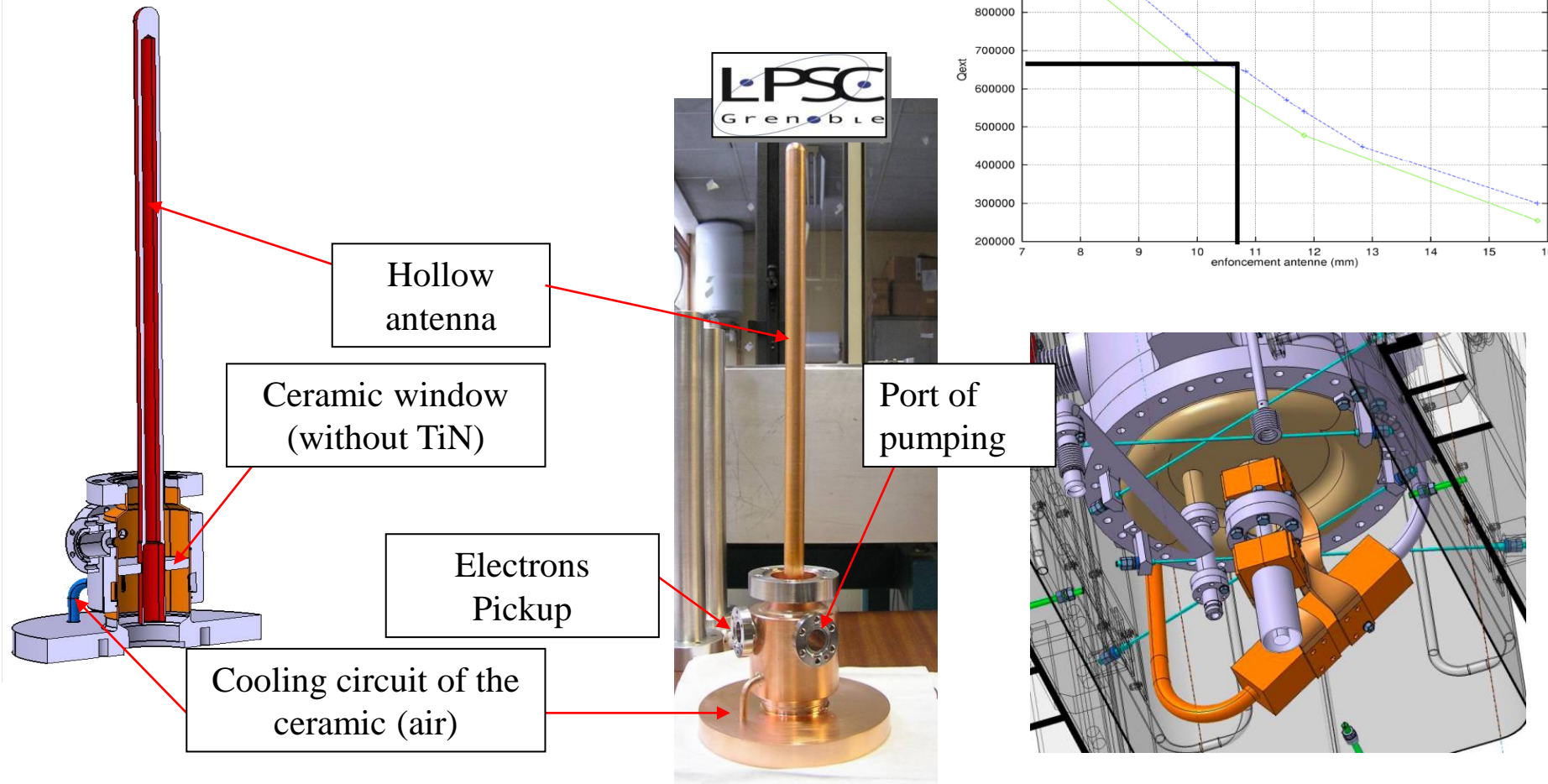
V_{acc} : acceleration potential of the cavity

I_b, Φ_S : beam current and synchronism phase

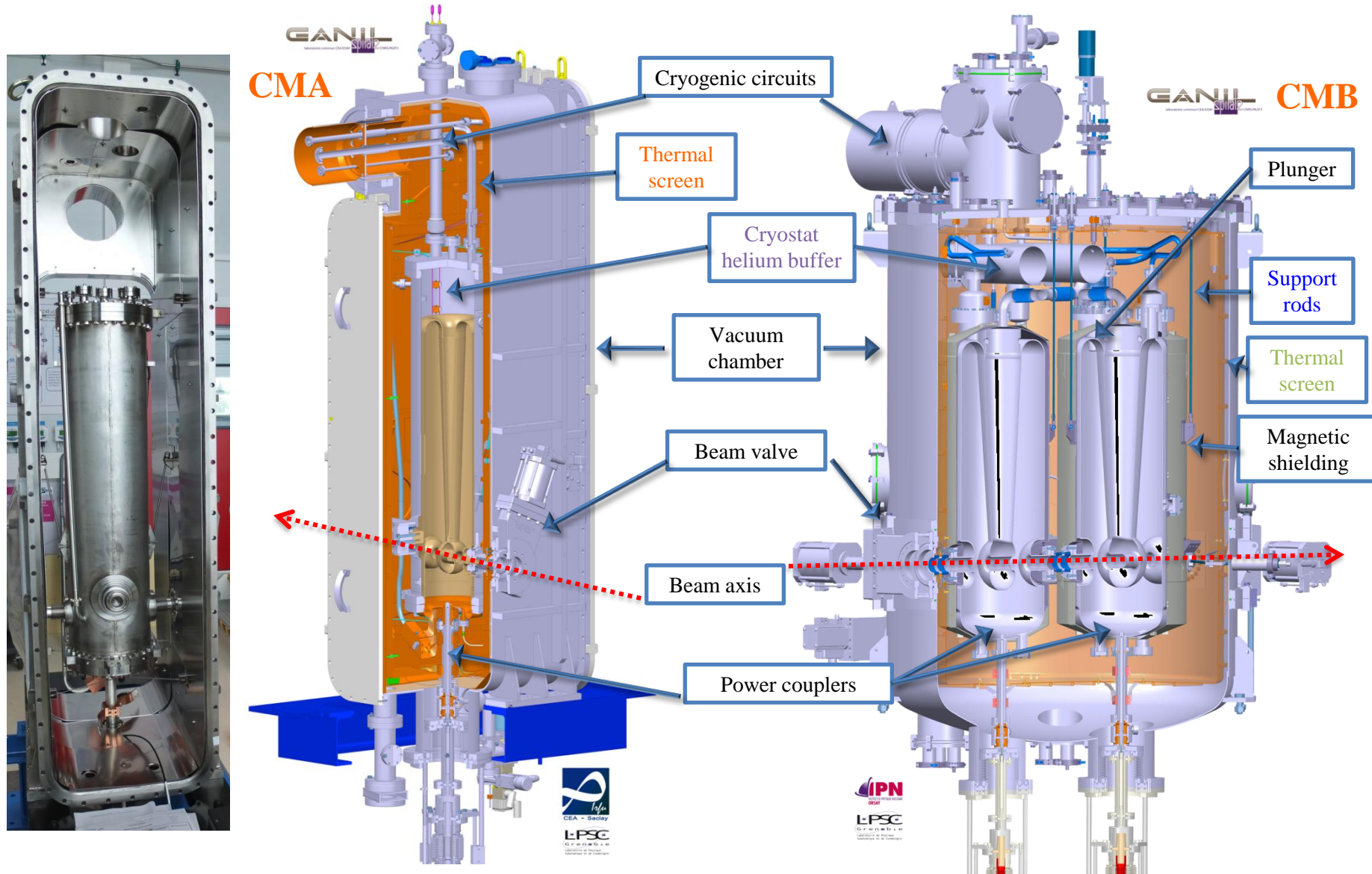


POWER COUPLER OF CAVITY

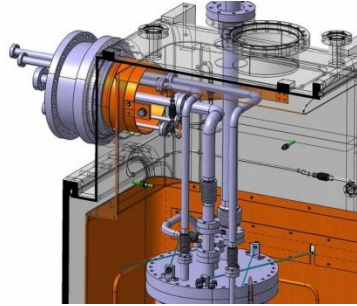
- Same design for both types of cavities
- $Q_{ext} = 6.5 \cdot 10^5$ (CMA) and $Q_{ext} = 1.0 \cdot 10^6$ (CMB), are obtained by ajustement of the antenna penetration



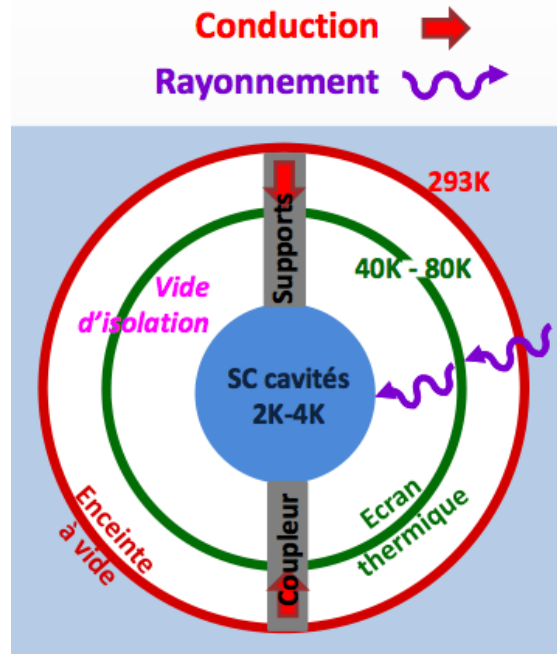
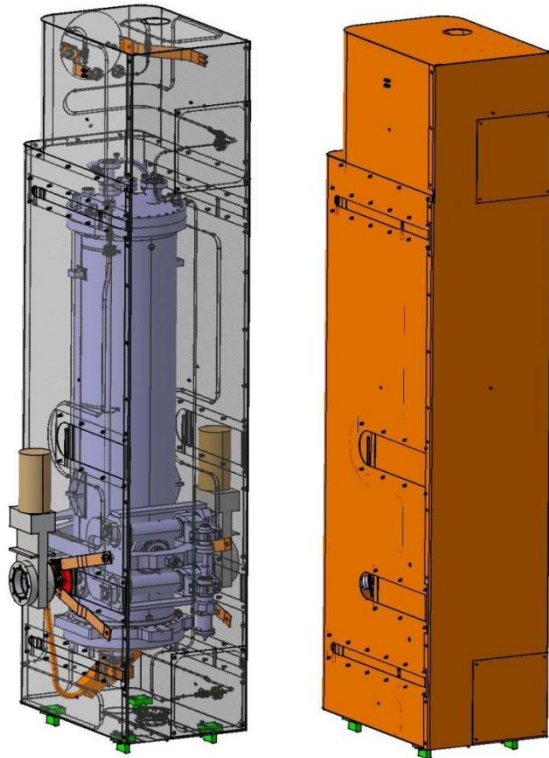
CRYO-MODULE : CMA / CMB



CRYO-MODULE A : CMA

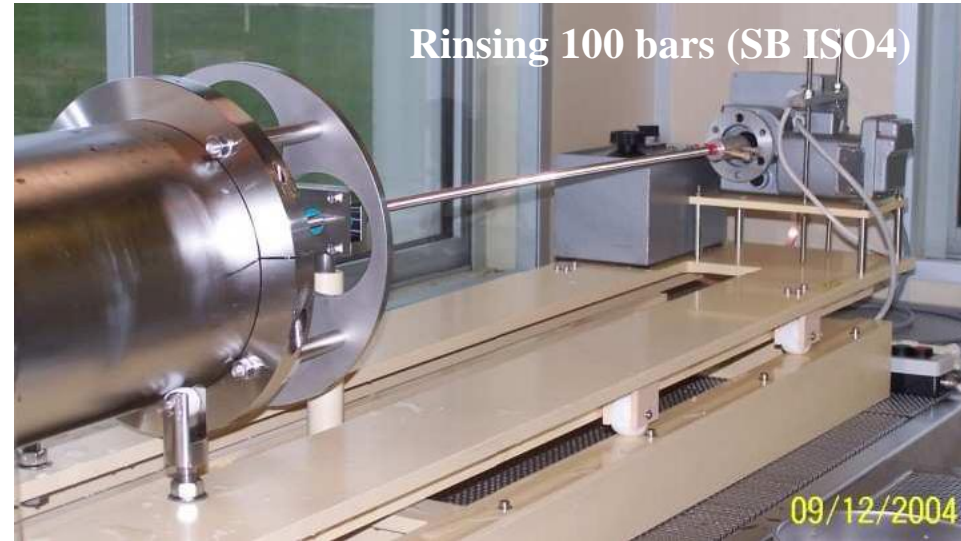


- Separated vacuum chamber - cavity
- Static losses $< 11 W$
- $P_{CAV} < 10 W/cavity$ ($E_{acc} 6.5 MV/m$)



CAVITIES : CHEMICAL PREPARATION
HPR (HIGH PRESSURE REACTORS)

Chemical attack : $150\mu\text{m}$



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

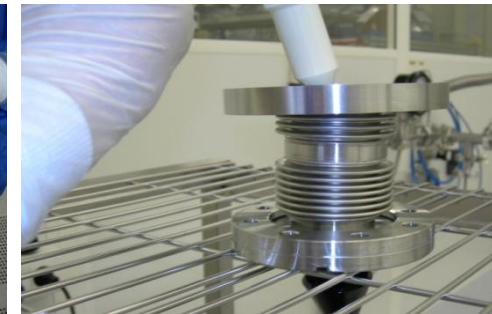
Assembling
of coupler on
the cavity



Cavity implantation
in the vacuum
chamber in the clean
room

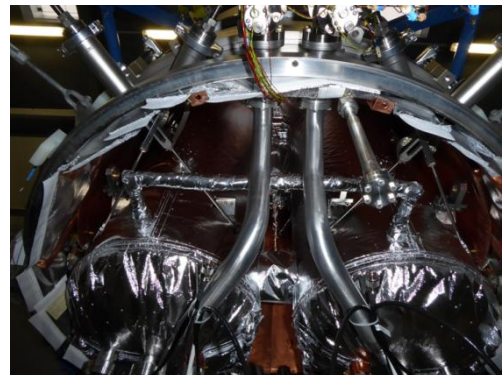
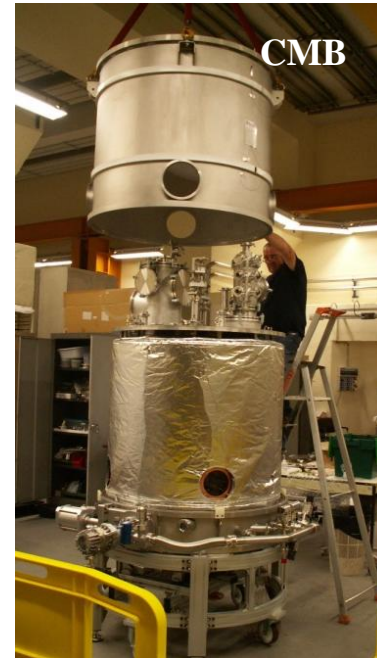


Systematic counting
of dusts of the
piece mounting on
cavities



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



Protection weather in Normandy

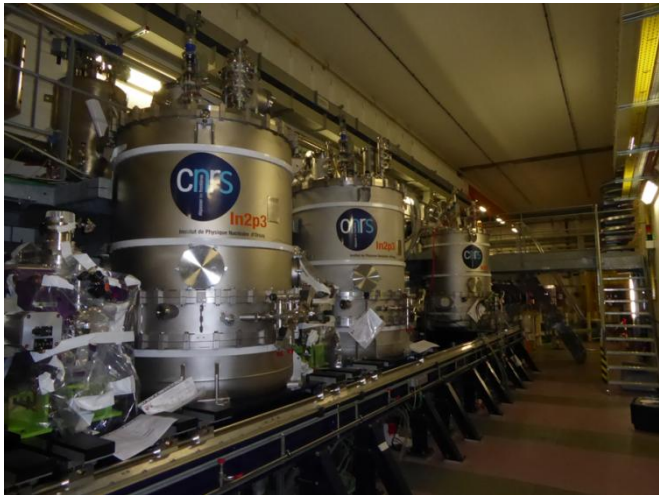


Sensors of shocks

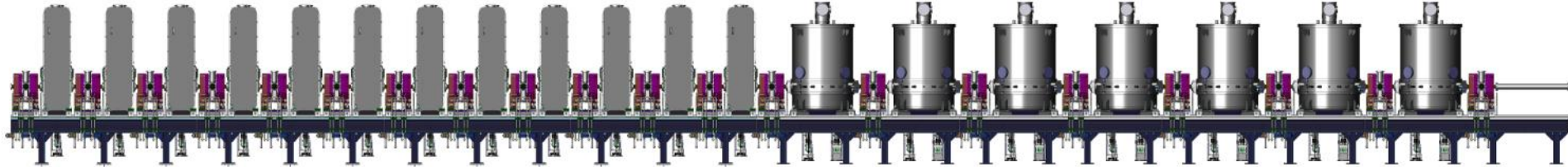


Spring mounting

CRYO-MODULE – ON SITE AT SPIRAL2



BEAM TUNING STEPS – INCREASE THE POWER



- ❑ Phase #1: Channel definition :
 - Transverse focusing → **Without beam**
 - Field law and synchronism phase of cavities

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

- ❑ 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 μ A | 200 μ s | 1 Hz | 10 pA | 0.4 mW / 0.4 W |
| #3 | 5 mA | 200 μ s | 1 Hz | 1 μ A | 40 mW / 40 W |
| #4 | 5 mA | CW | | 5 mA | 200 W / 200 kW |

BEAM TUNING STEPS – PHASE #1



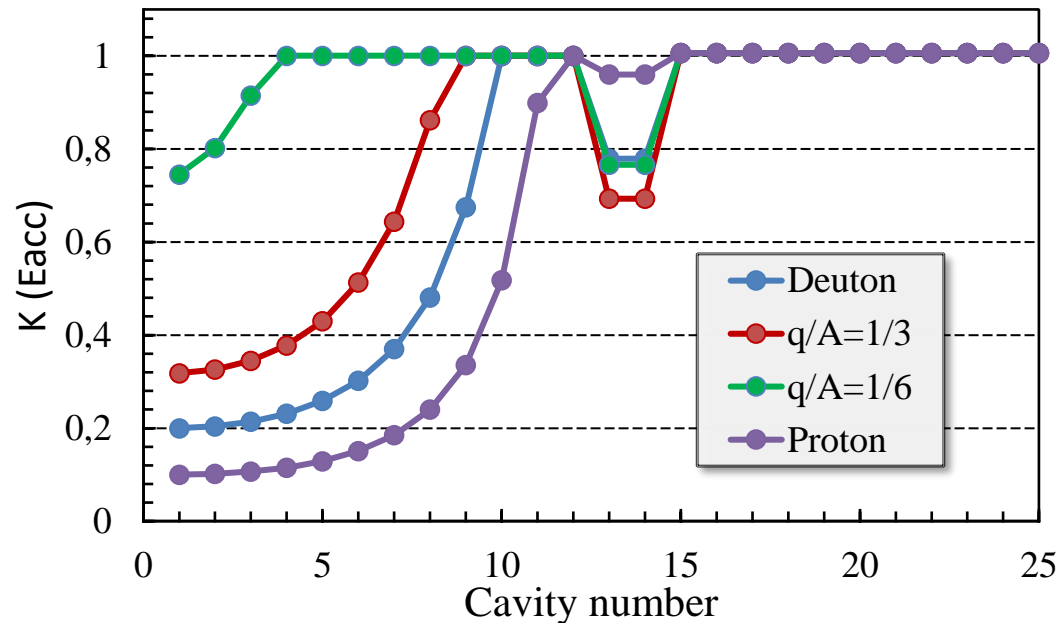
- ☐ Quadrupoles gradients calculation in order to create continuous transverse focusing.
- ☐ Synchronism phases and cavities accelerating field calculation
 - Continuous longitudinal focusing
 - Check if desired acceleration is sufficient
 - Maximization of the longitudinal acceptance



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

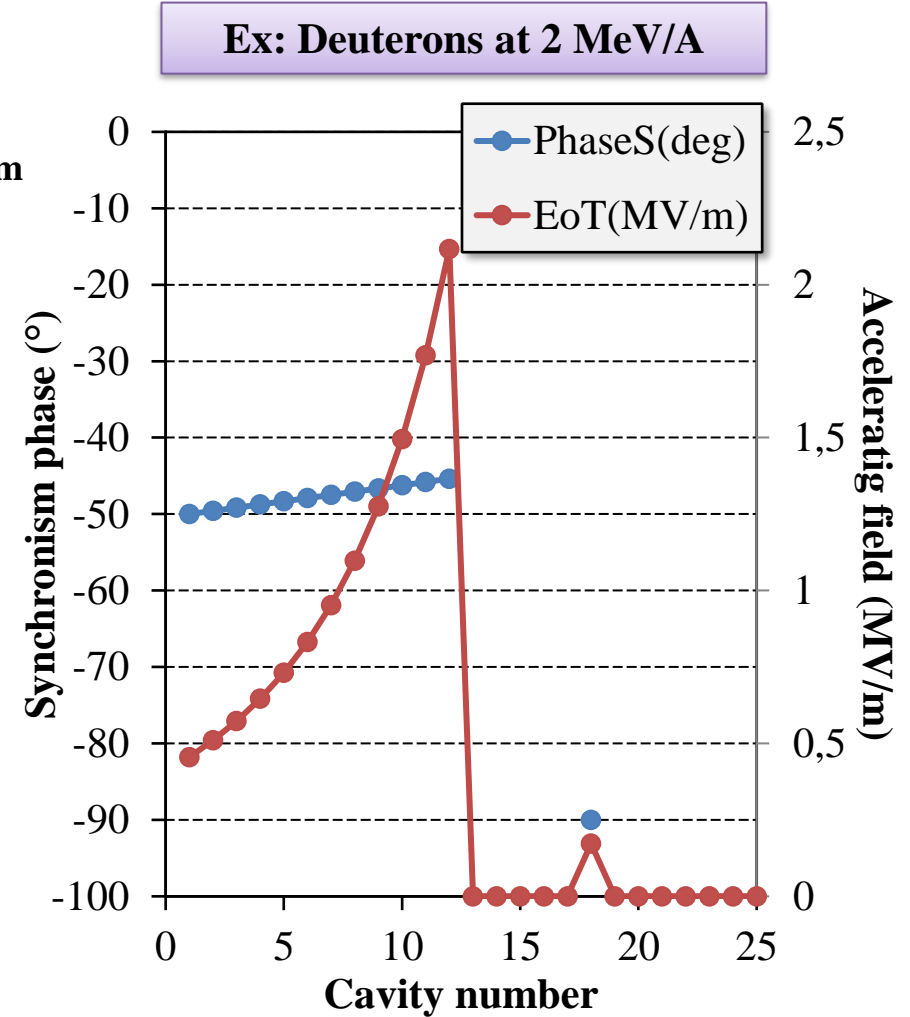
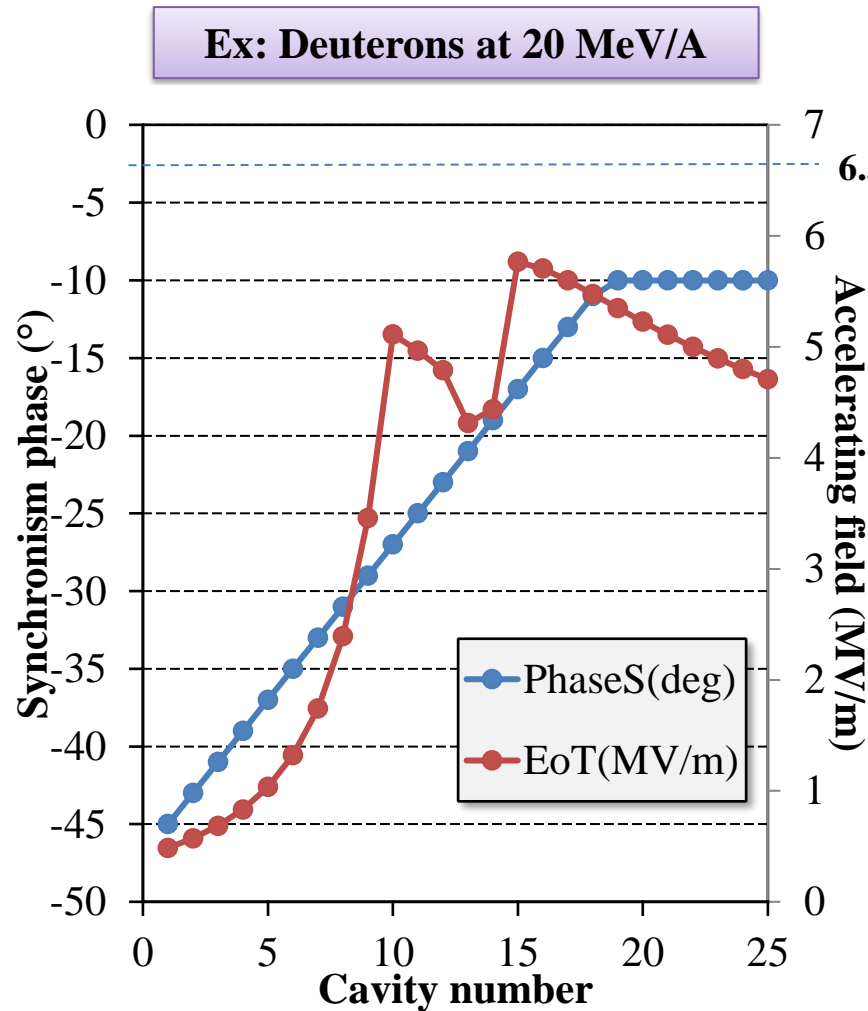


- ☐ For each particle species and energies, calculation have to be reproduce independently to the beam current



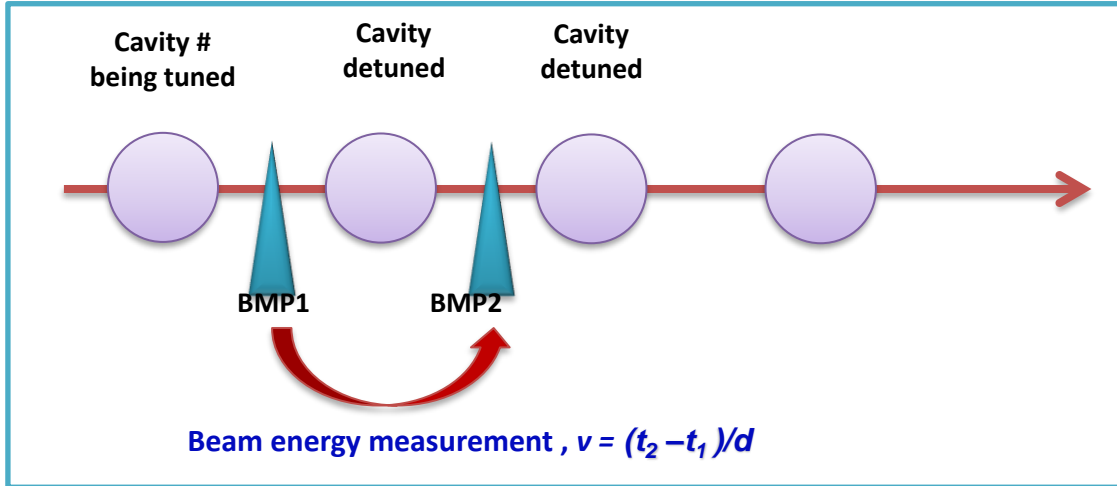
Optimized machine for ions to A/q=5

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



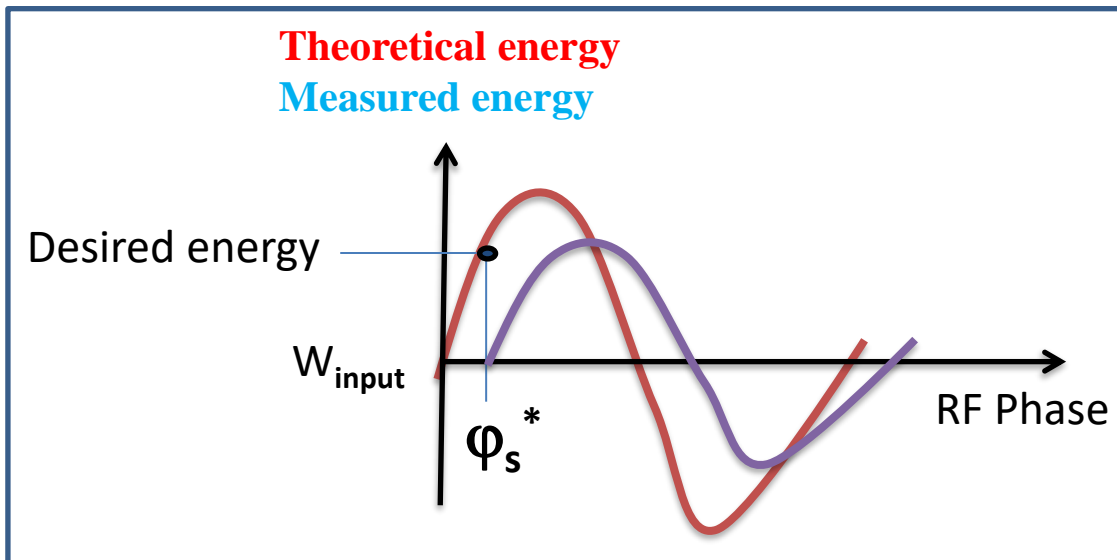
More difficult

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

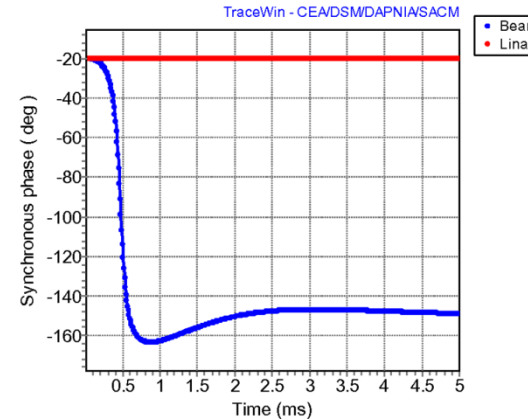
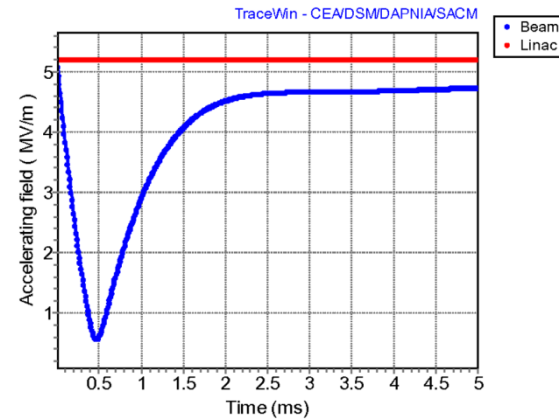


Need new adjustments

- Steerers
- Quadrupoles

BEAM TUNING STEPS – PHASE #2 : BEAM LOADING

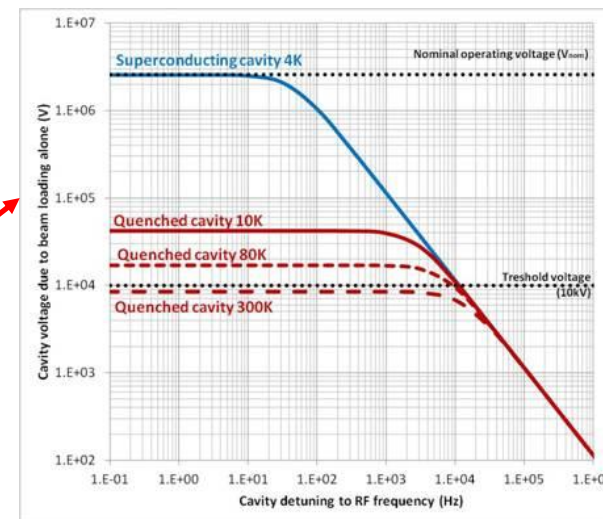
Beam is decelerated in a switched-off cavity by the potential induced by the “beam loading”.



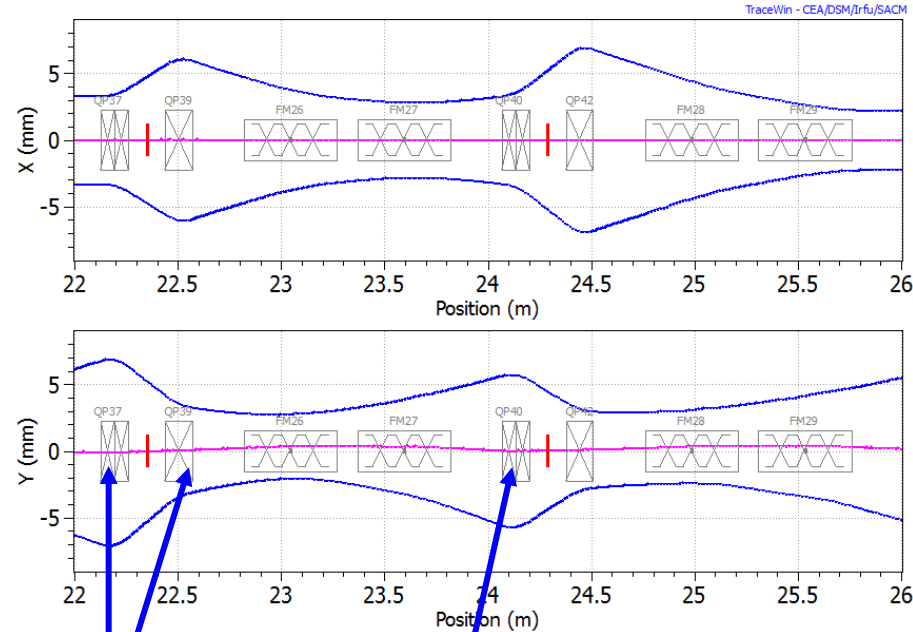
→ A switched-off cavity for any reason must be detunes in frequency

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

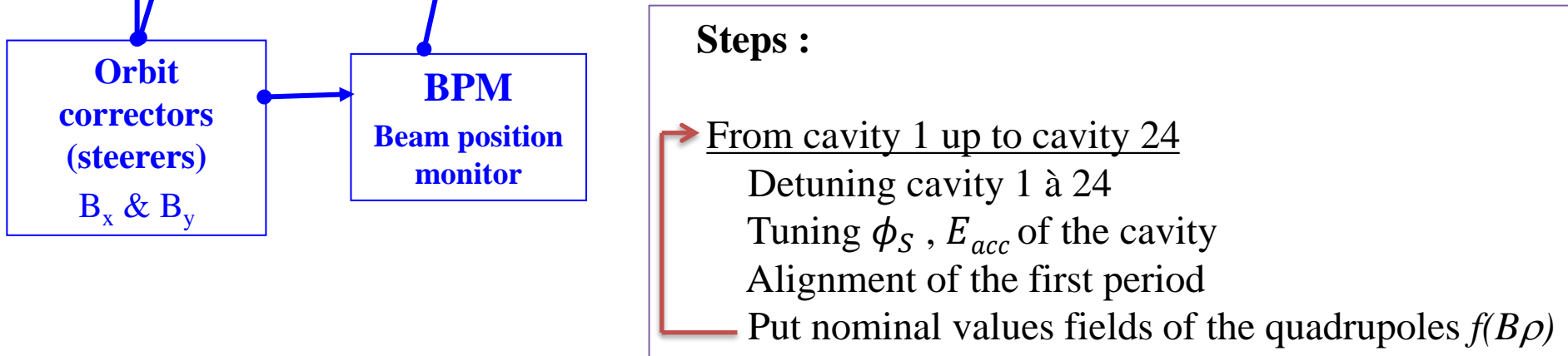
Induced potential by the beam loading at 5 mA



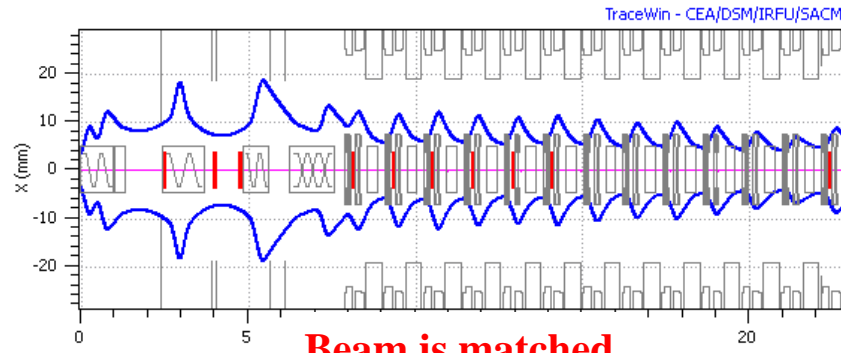
BEAM TUNING STEPS – PHASE #2 : TRANSVERSE POSITION



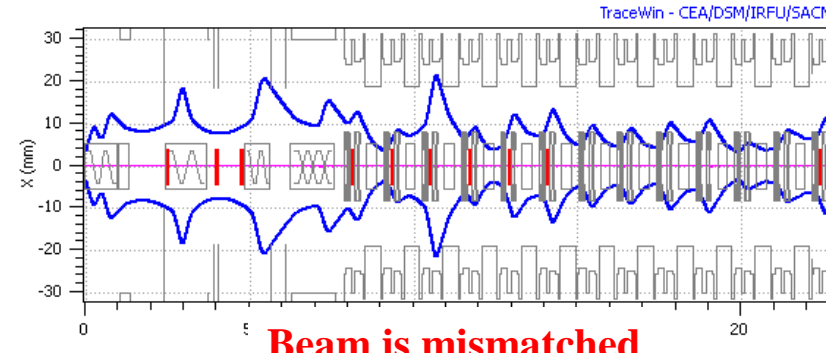
- Compensation of the misalignments
- Compensation of the cavities steering



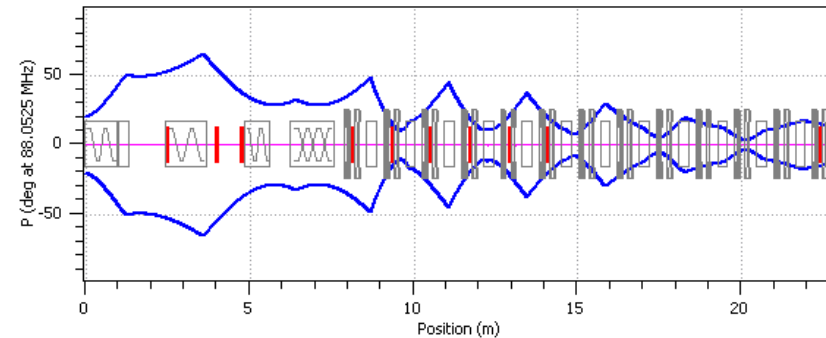
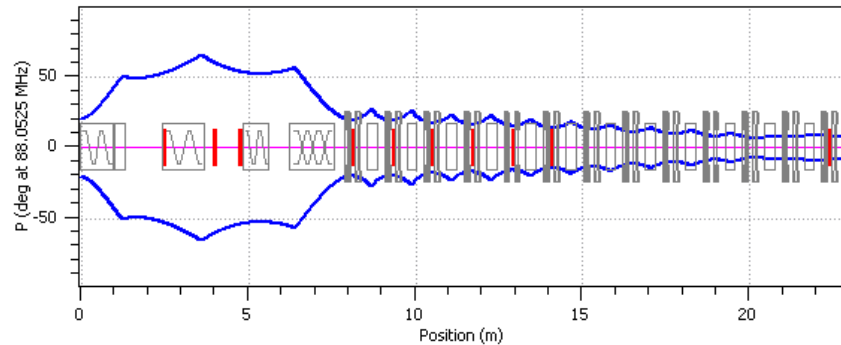
BEAM TUNING STEPS – PHASE #3 : MATCHING-MISMATCHING



Beam is matched



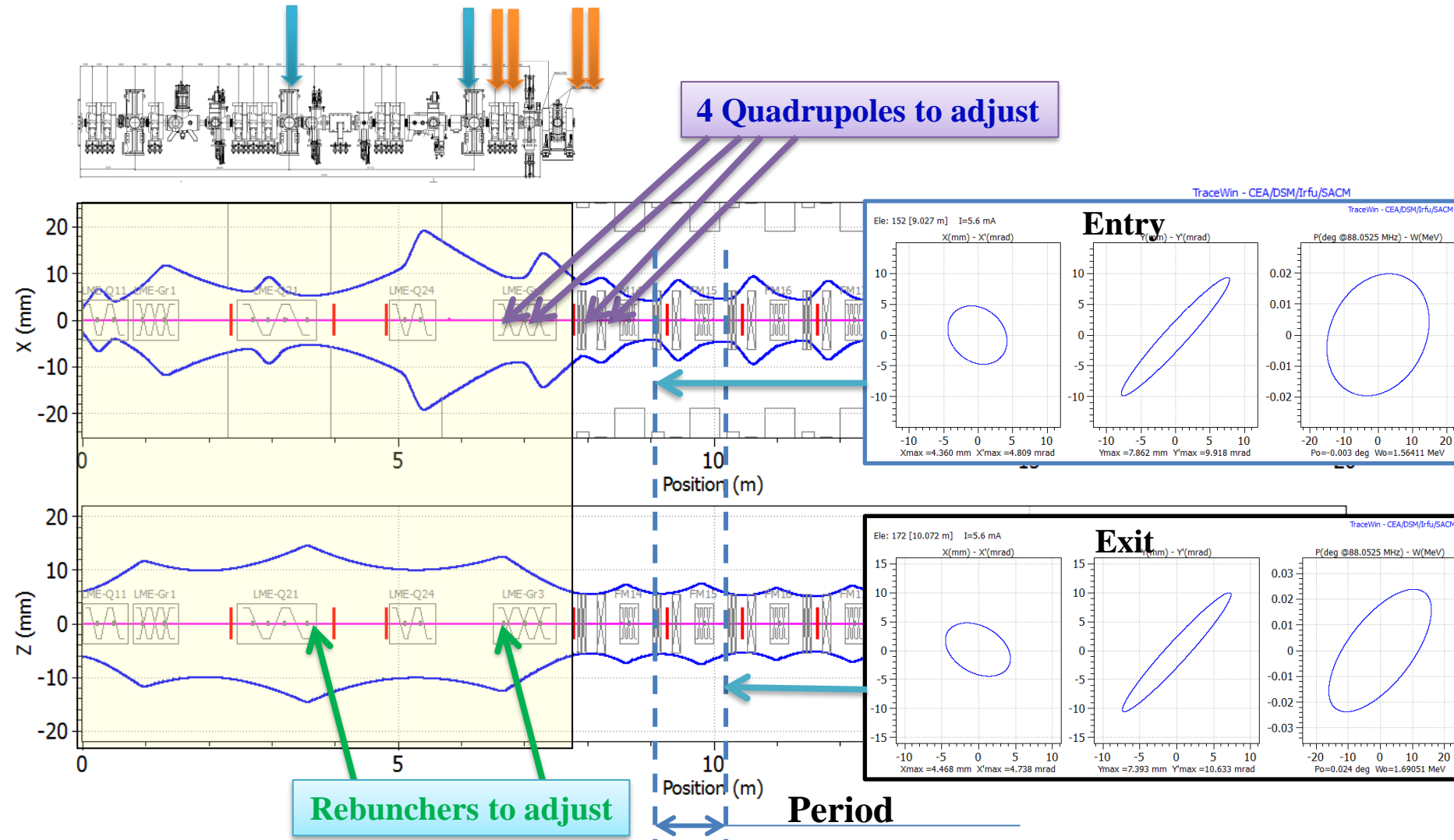
Beam is mismatched



Effect of the mismatching :

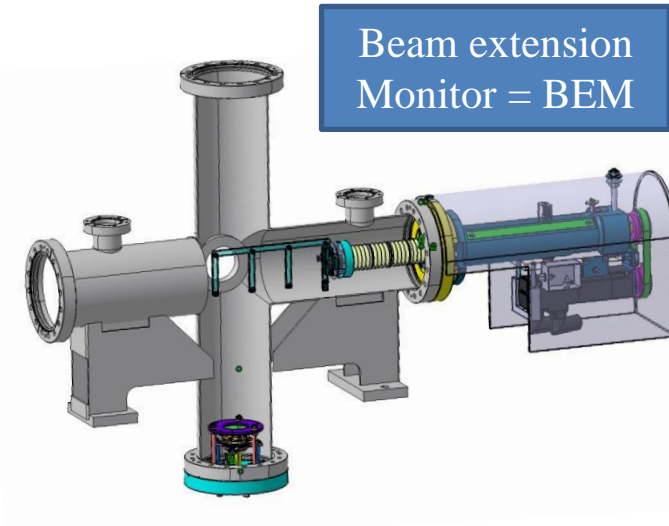
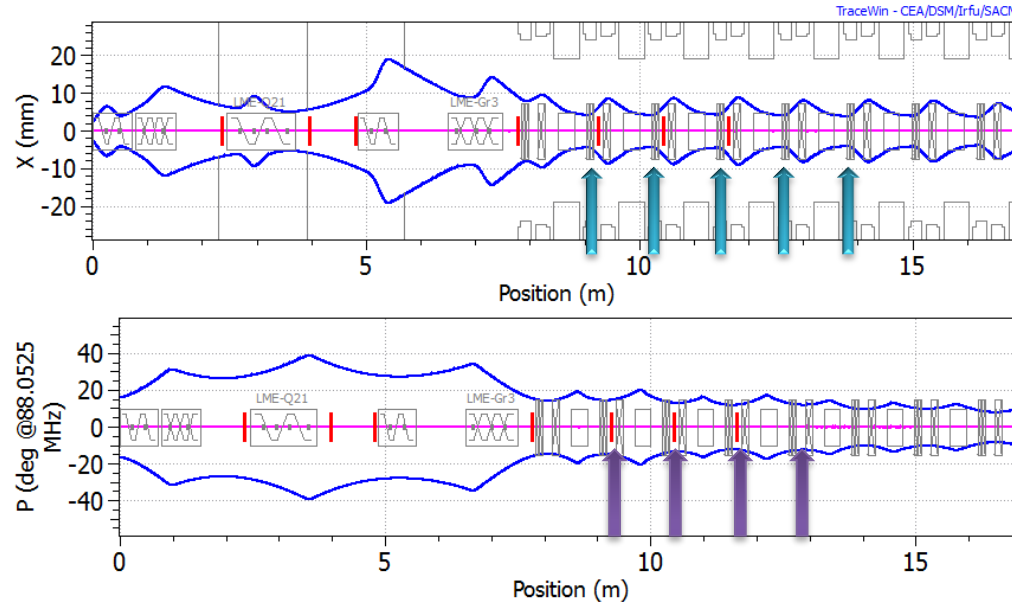
- Emittances growth
- Halo formation
- Beam losses
- Decrease of the performances for the physics experiments

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 σ_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

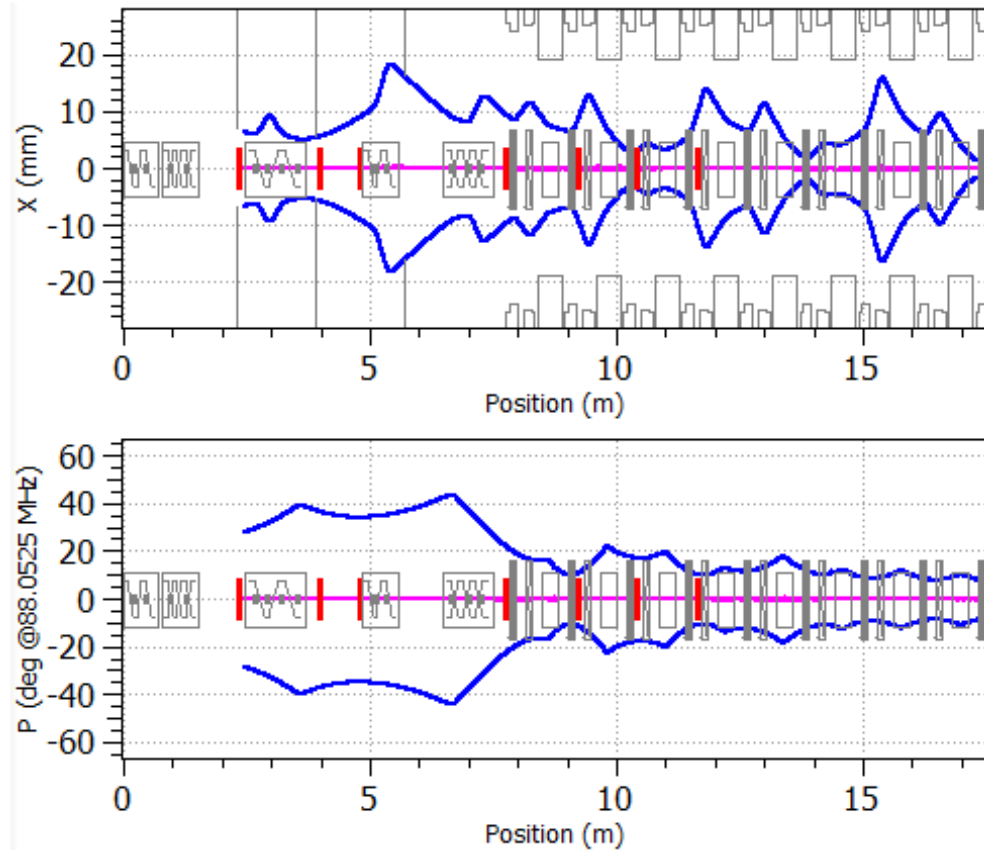
Quadrupolar momentum of BPM : $Q \approx \frac{X_C^2}{R^2} + \frac{\sigma_x^2 - \sigma_y^2}{R^2} + \dots$

- ✓ 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 φ_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

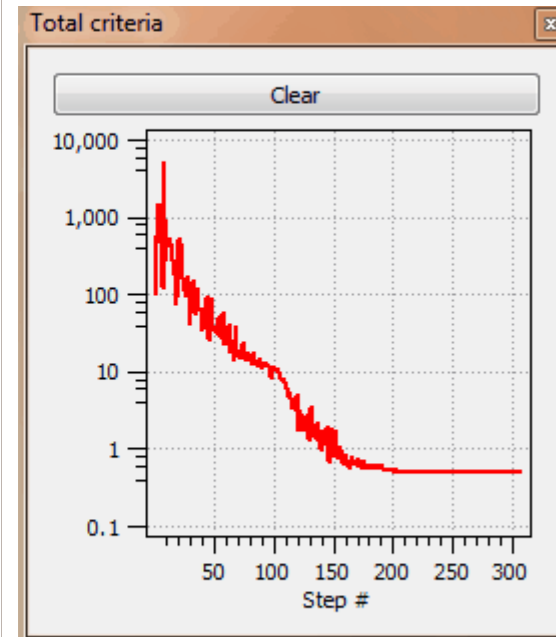
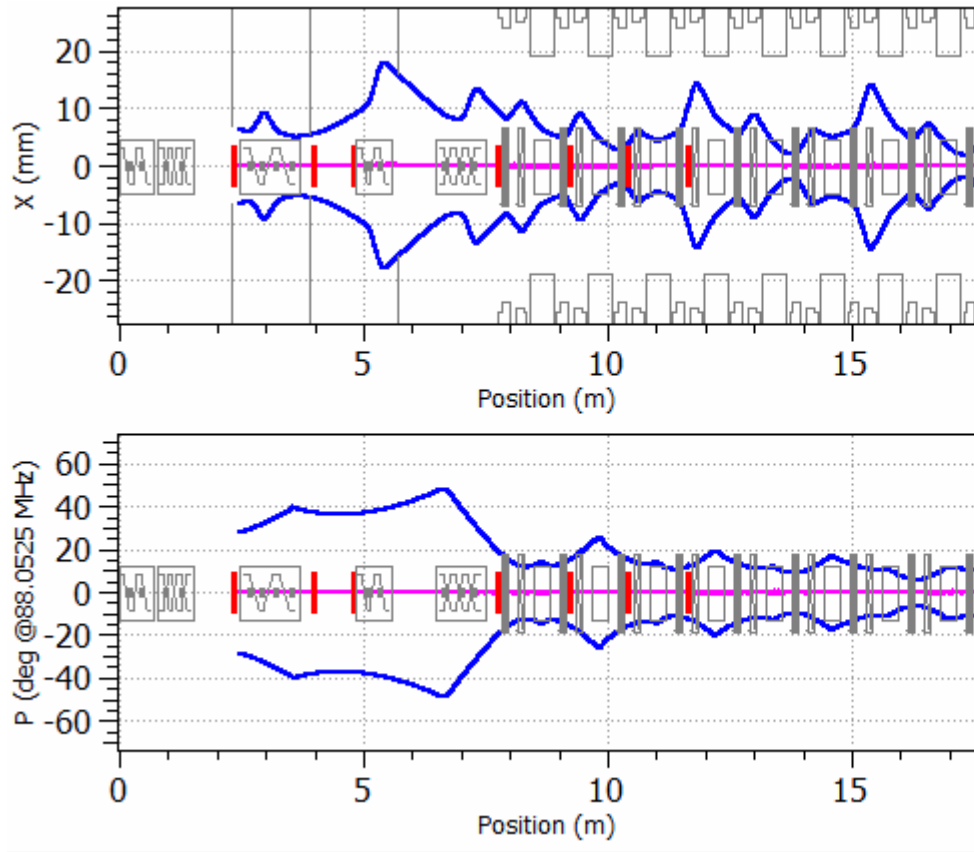


Probable situation of a
initial tuning of the LINAC

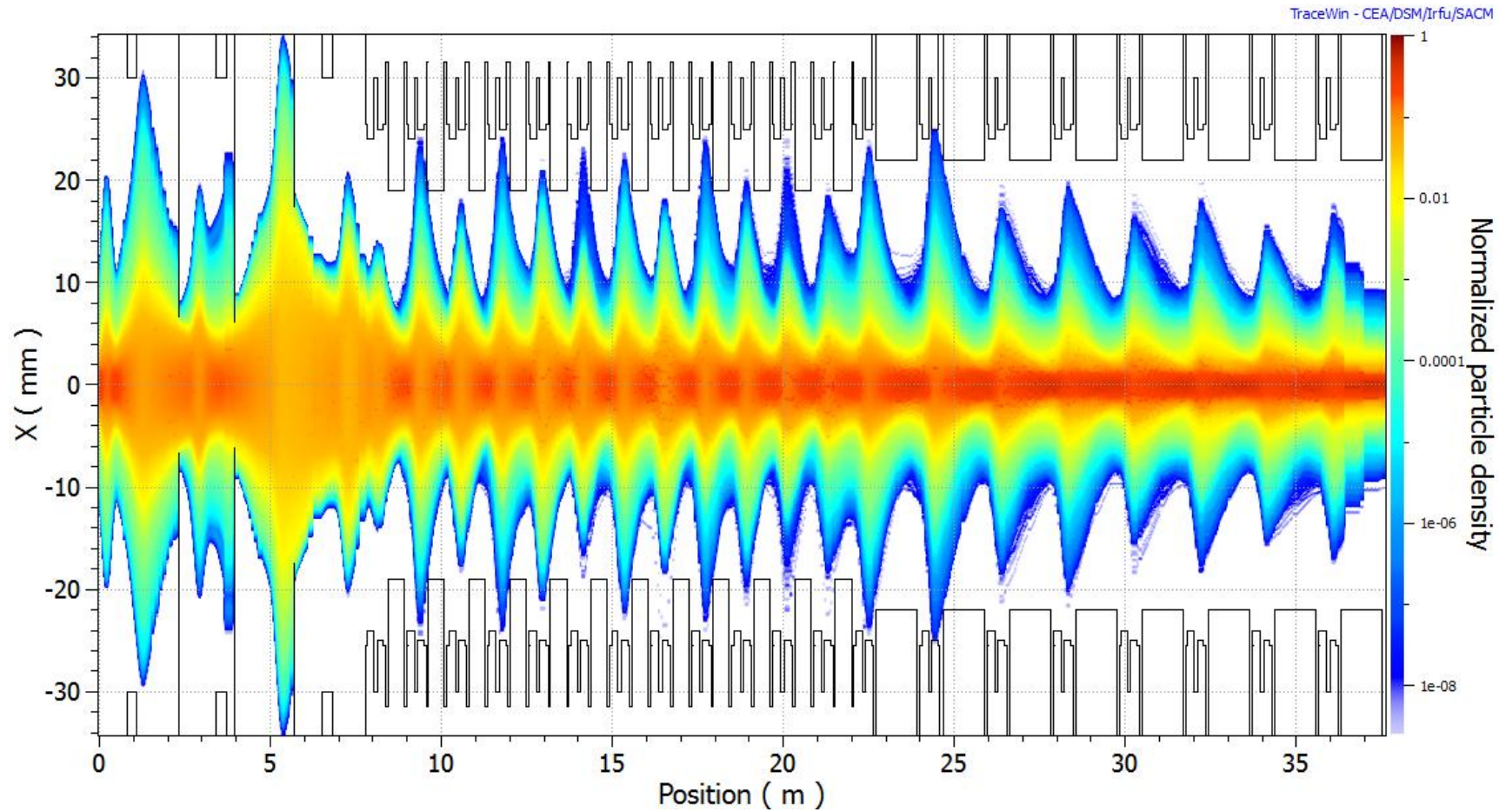
Iterative process

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

BEAM TUNING STEPS – PHASE #3 : LINAC MATCHING

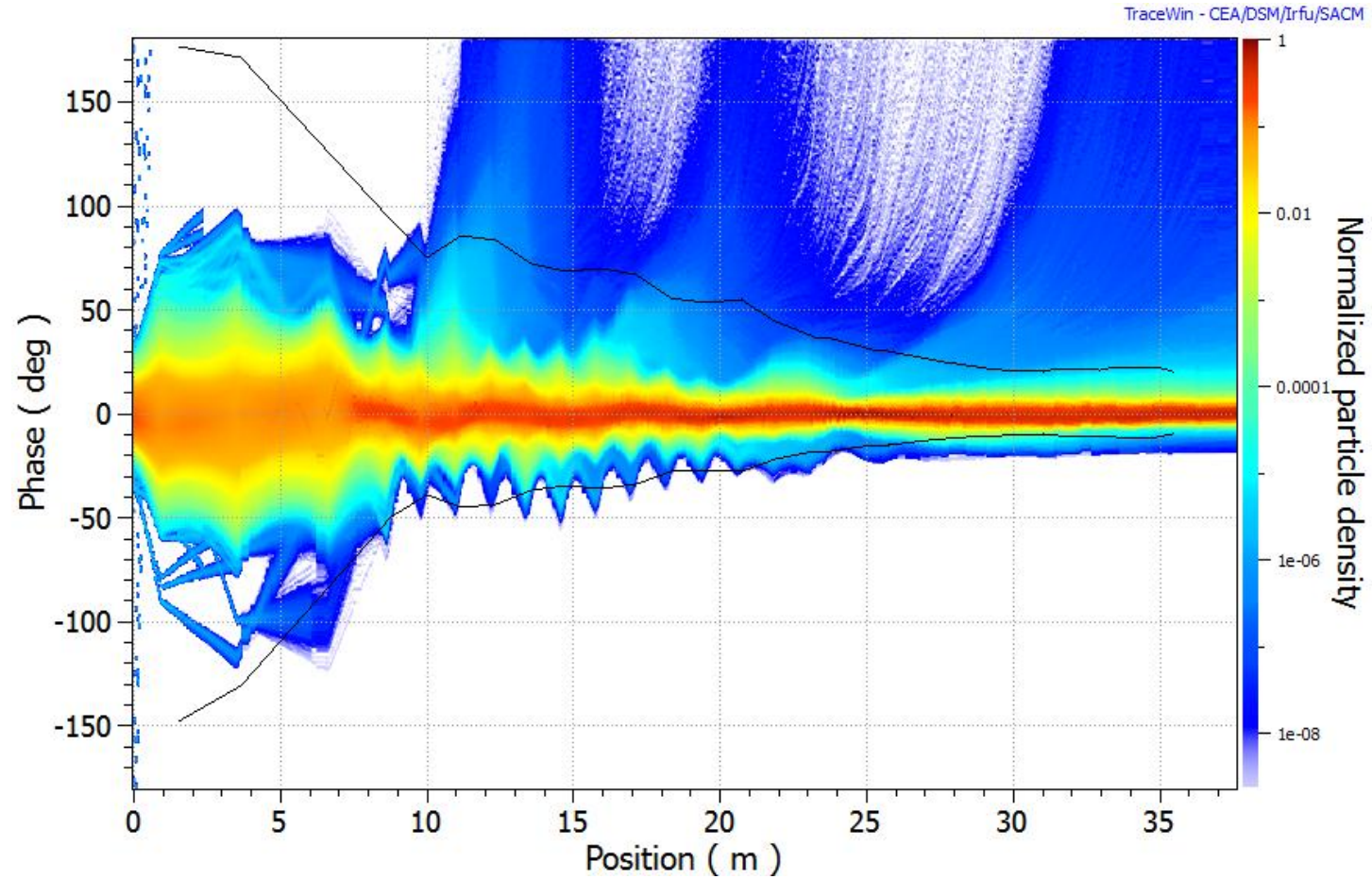


ASPECTS OF THE LOSSES – TRANSVERSE BEAM PROFILES



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

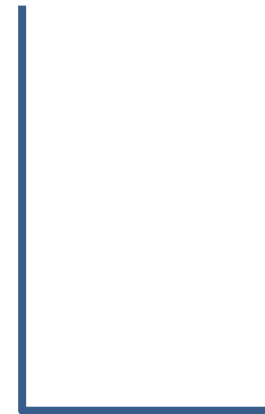
BEAM POWER ?

Deuterons beam : 40 MeV, 5 mA = 200 kW

1 kg of Copper

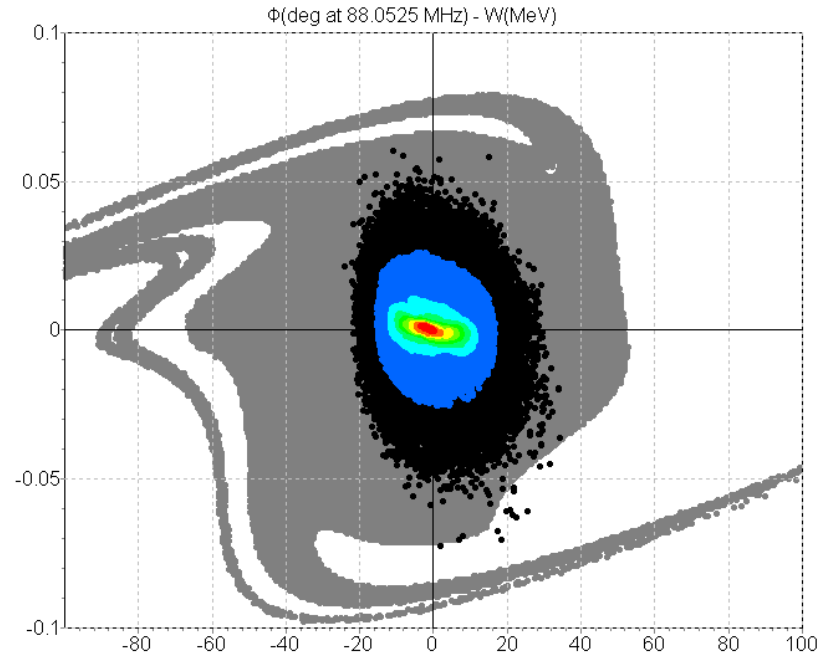


Melted in 3 seconds !



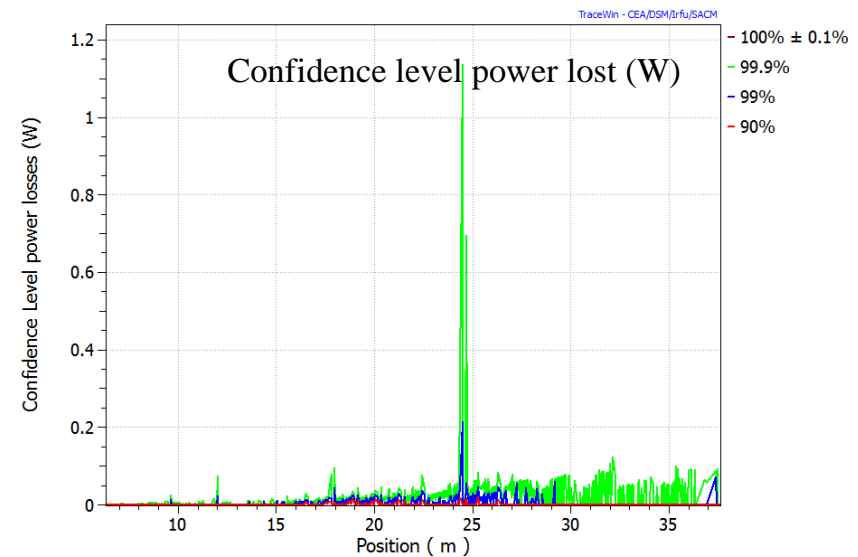
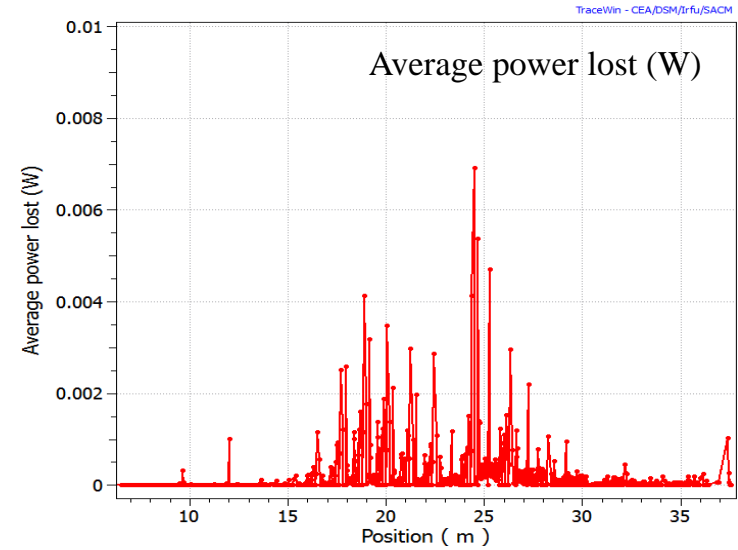
ASPECTS OF THE LOSSES

Longitudinal acceptance (Deuterons)



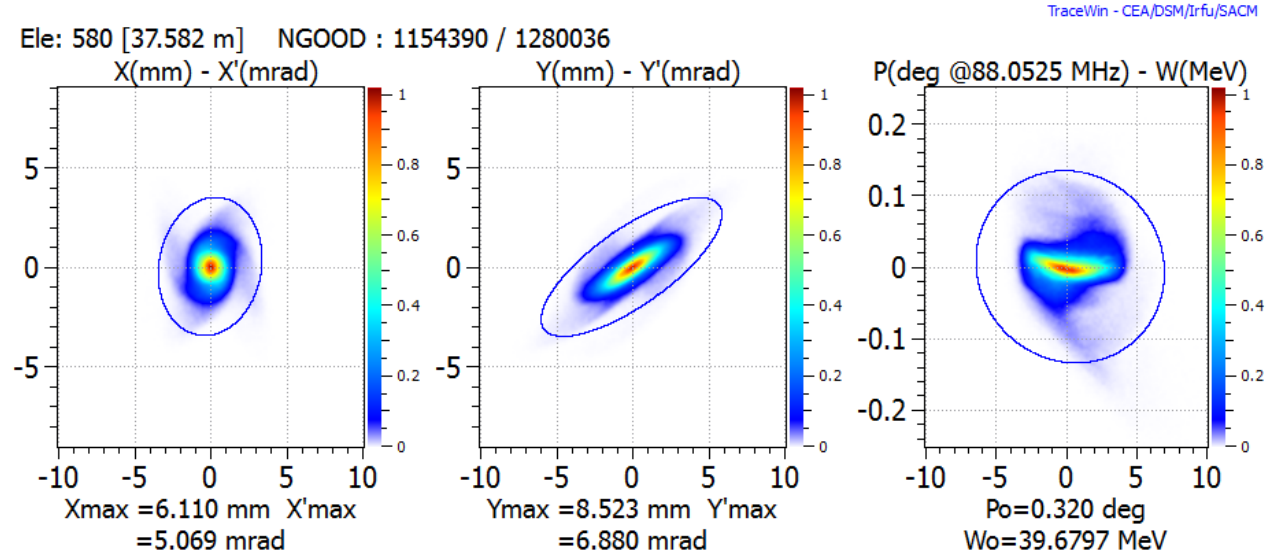
Losses control : Using the beam loss monitor
Losses minimization : Increase the acceptance

Losses : statistic results

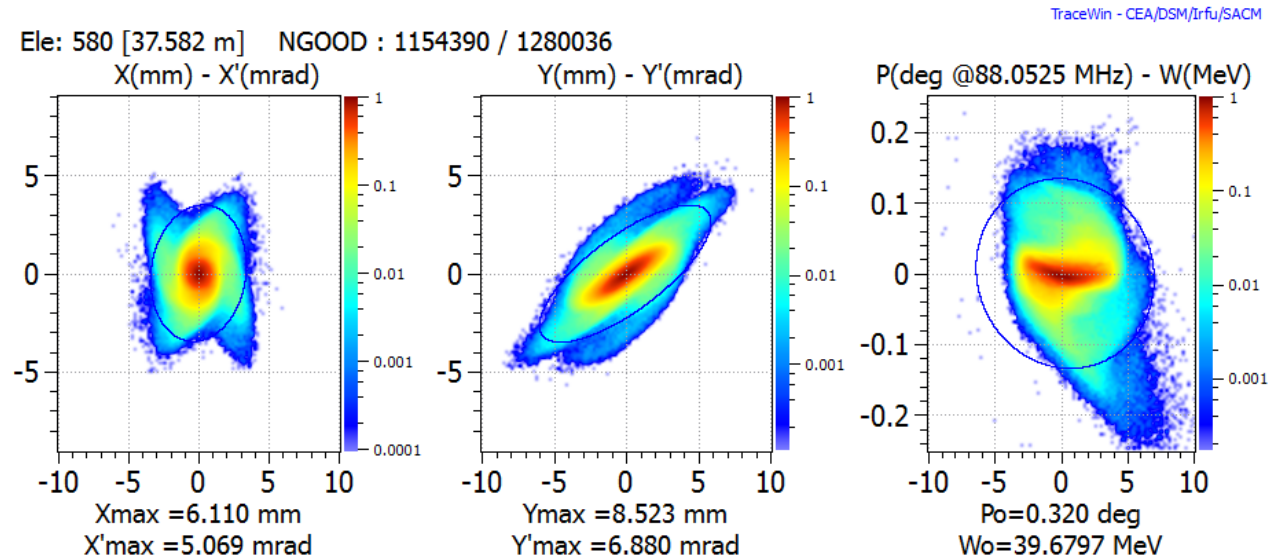


PHASE SPACES AT THE EXIT OF THE LINAC

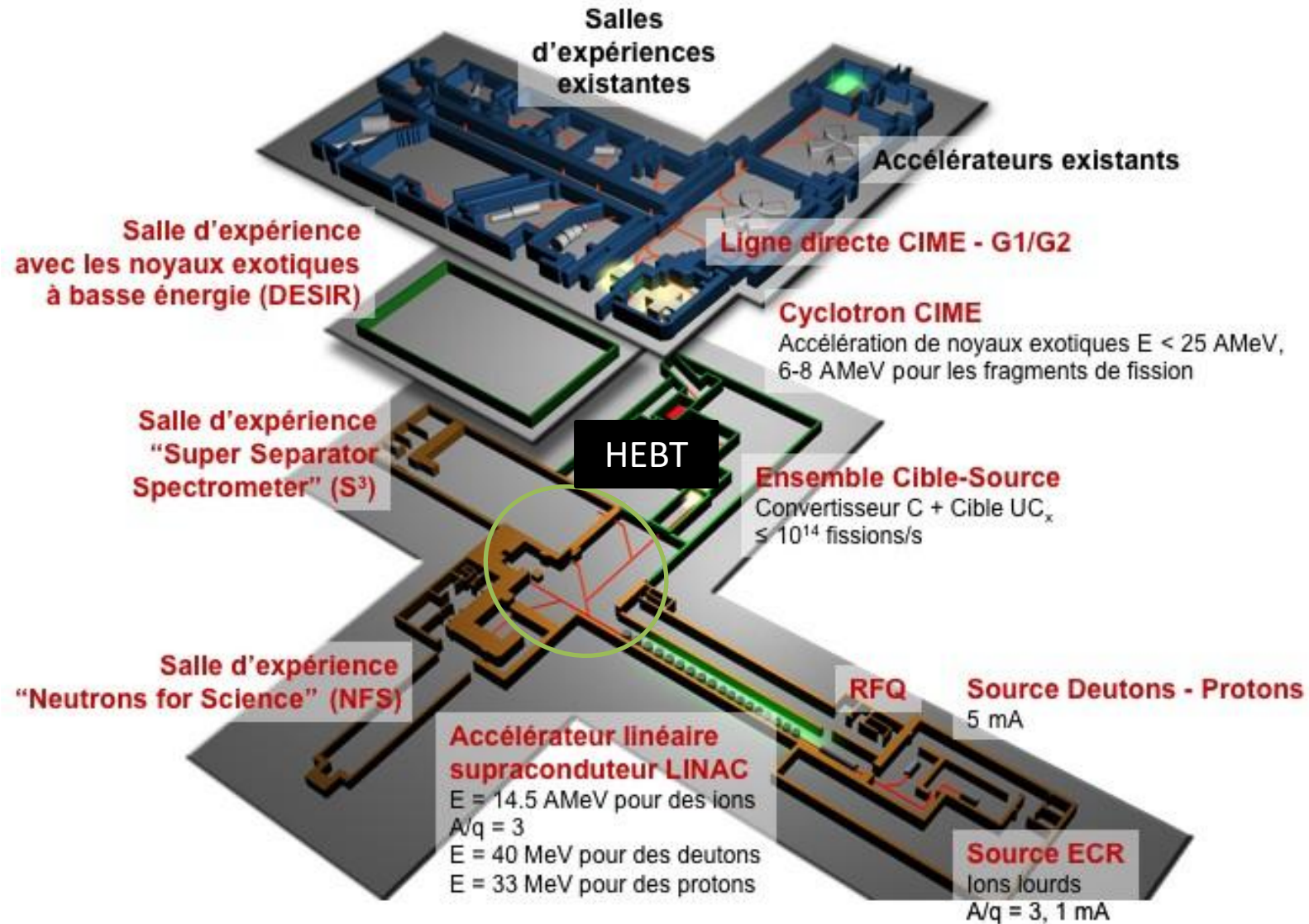
Linear scale



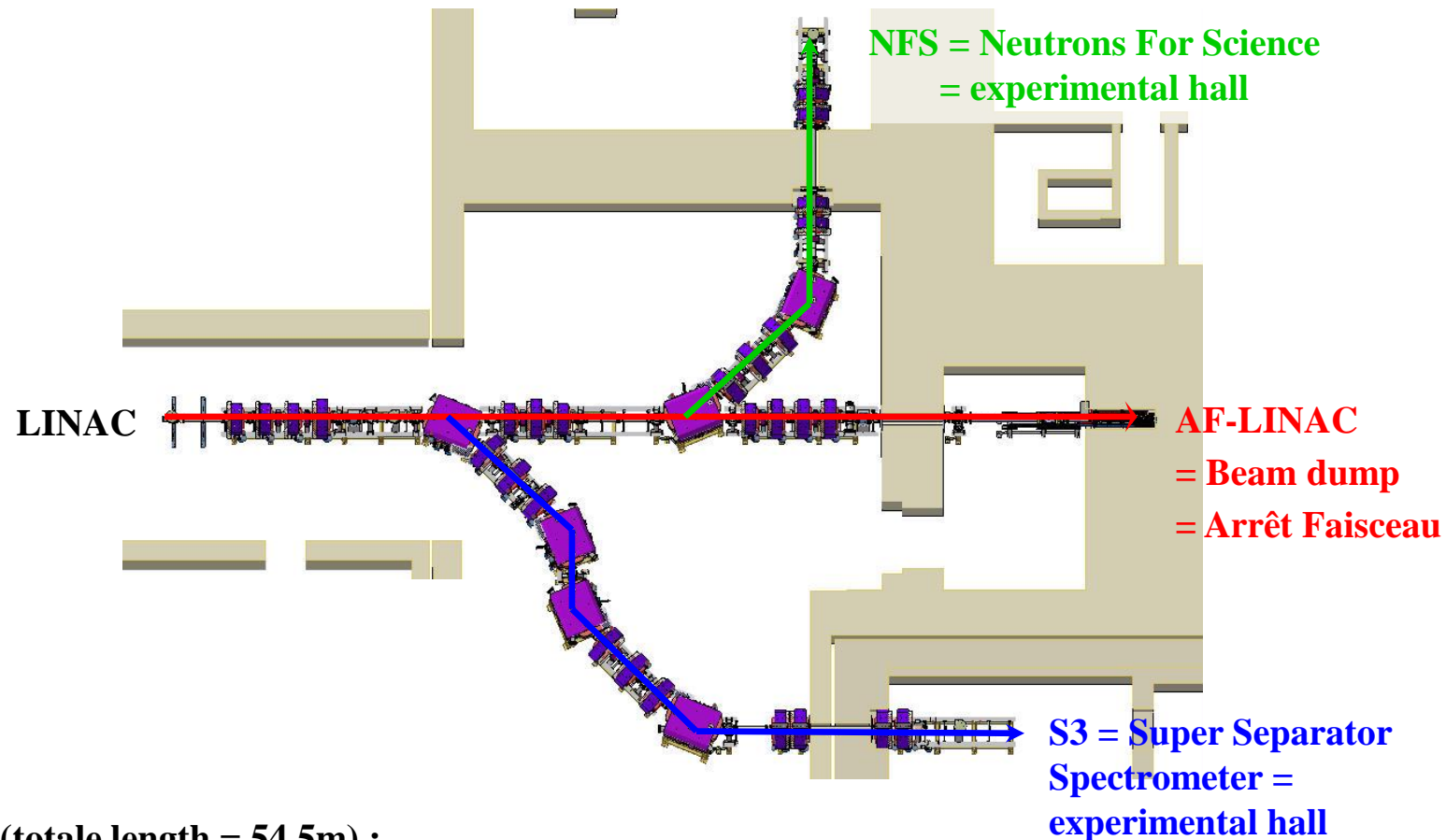
Logarithmic scale



6. THE HIGH ENERGY BEAM TRANSPORT LINES



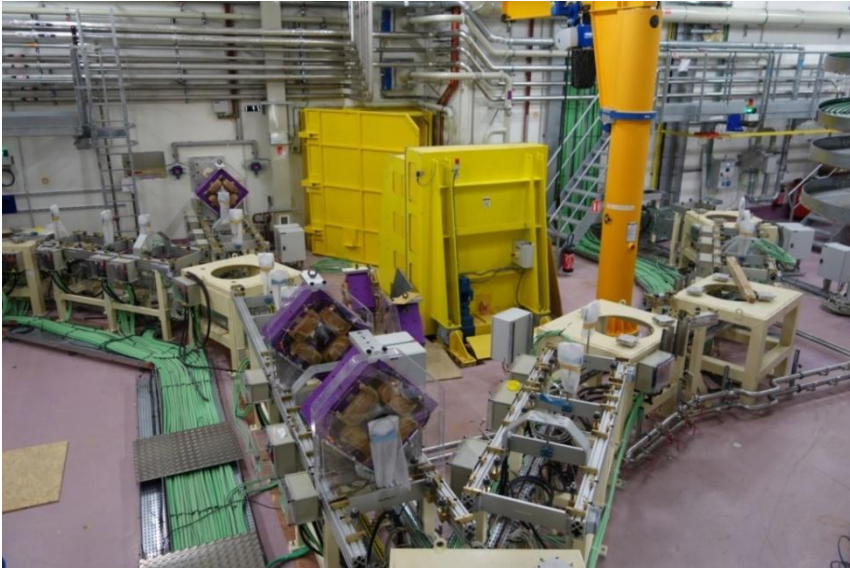
IMPLANTATION OF HEBT



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.

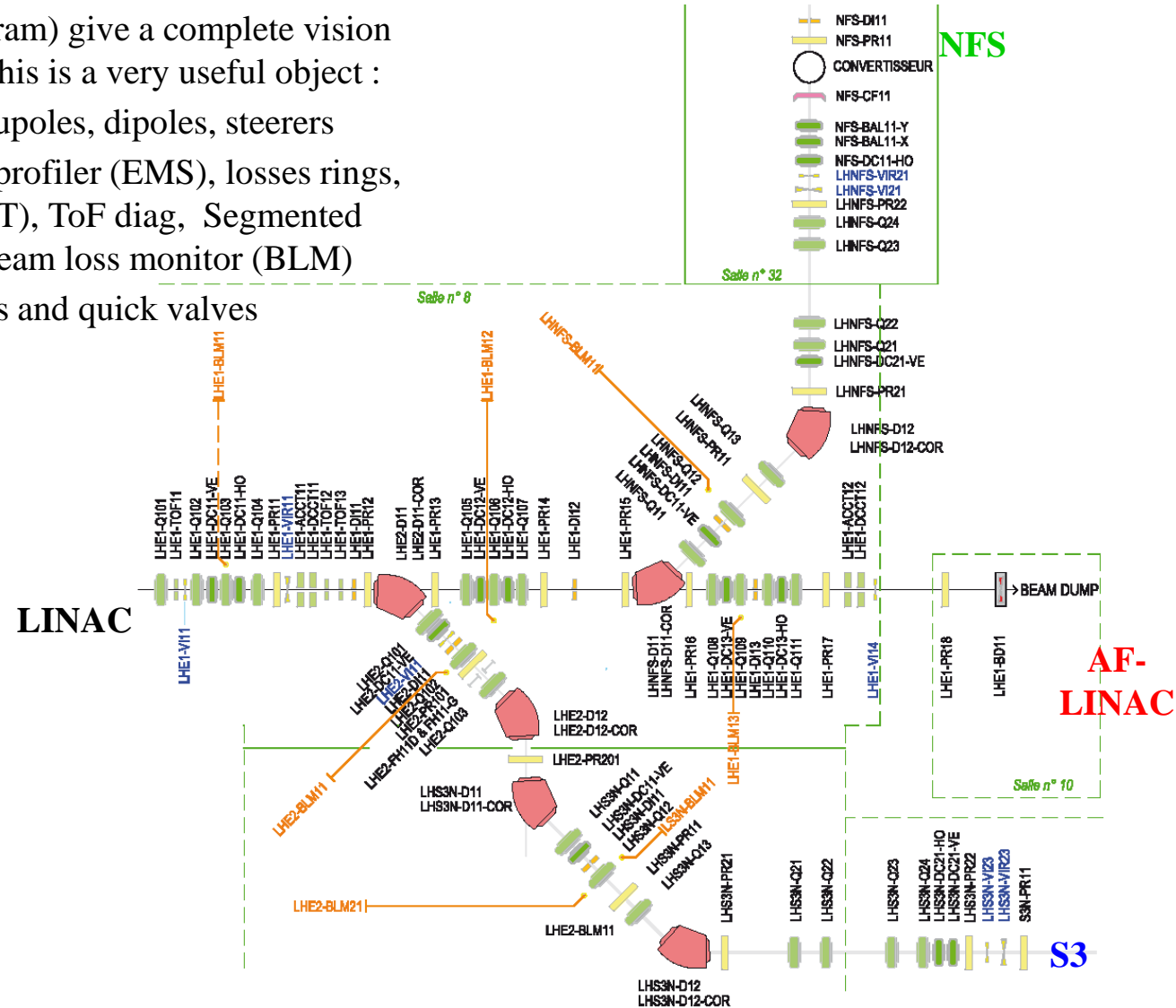
IMPLANTATION OF HEBT



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

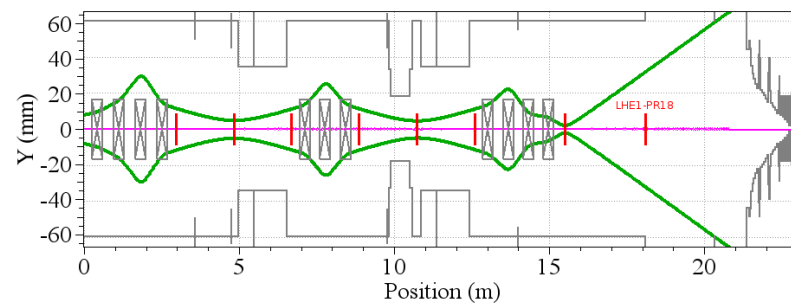
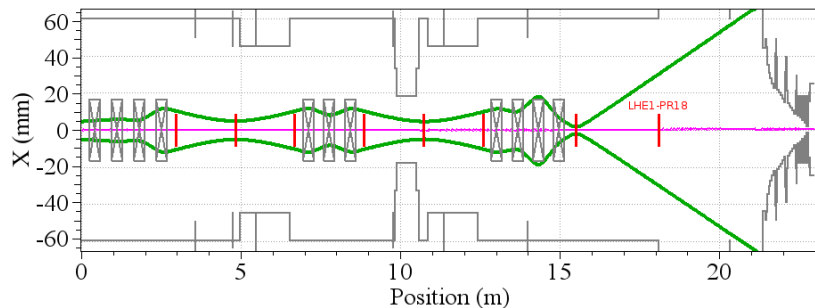
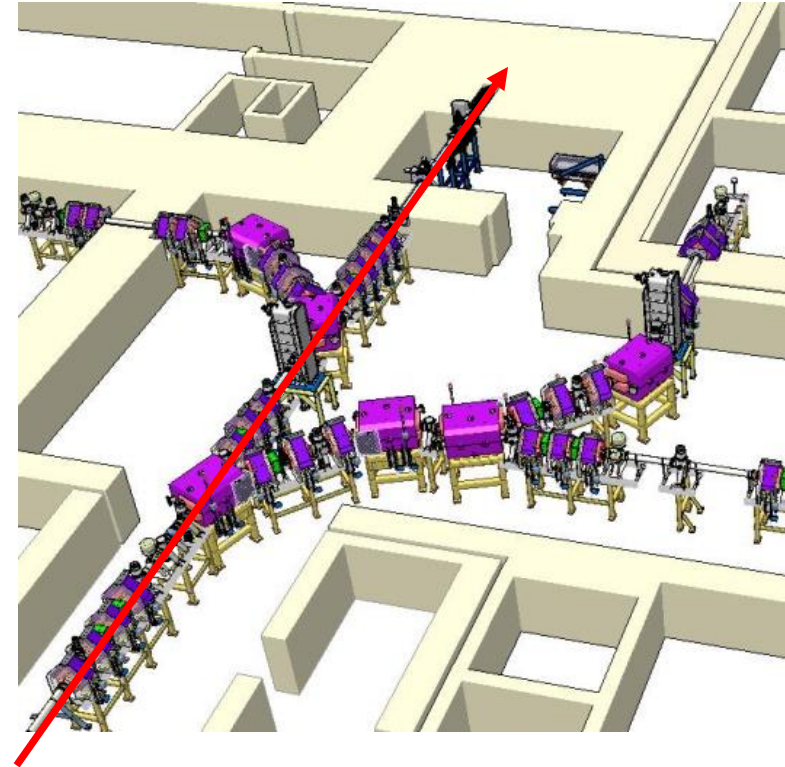


TRANSPORT UP TO THE BEAM-DUMP

From LINAC exit up to the beam-dump

3 sub sections :

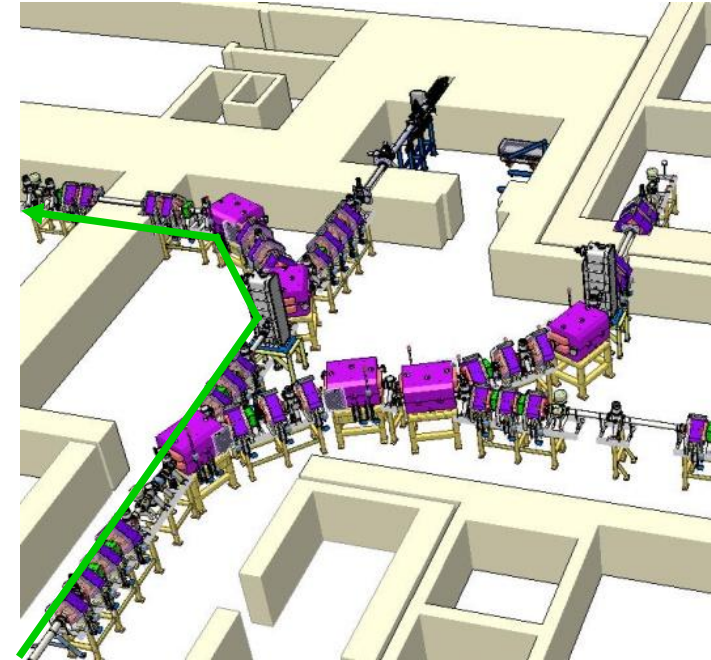
- LINAC beam matching
 - 4 quadrupoles + One set of X – Y steerer
 - 2 EMS + 1 ToF + 1 ACCT-DCCT + 1 ring losses + 1 BLM
- One triplet
 - 3 quadrupoles + One set X – Y steerer
 - 2 EMS + 1 ring losses + 1 BLM
- beam matching to beam-dump
 - 4 quadrupoles + One set of X – Y steerer
 - 3 EMS + 1 ACCT-DCCT + 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

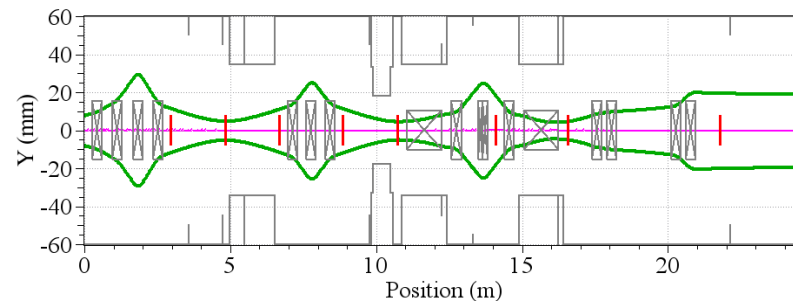
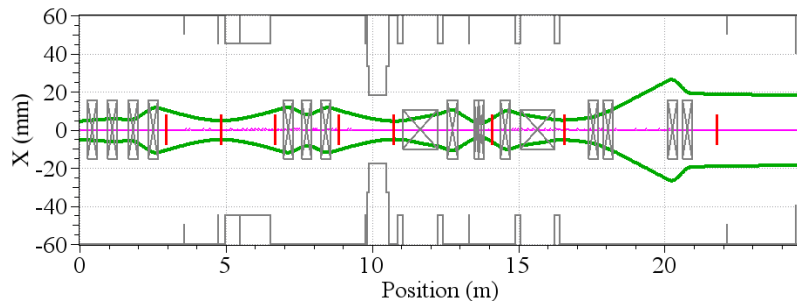
From LINAC exit up to NFS : 4 sub sections

- 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)



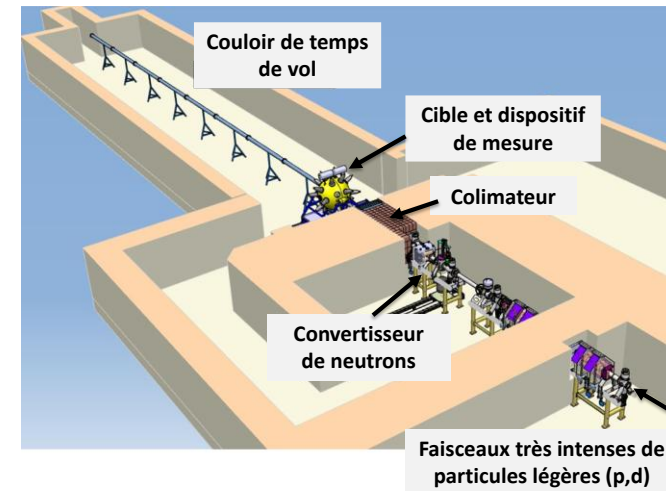
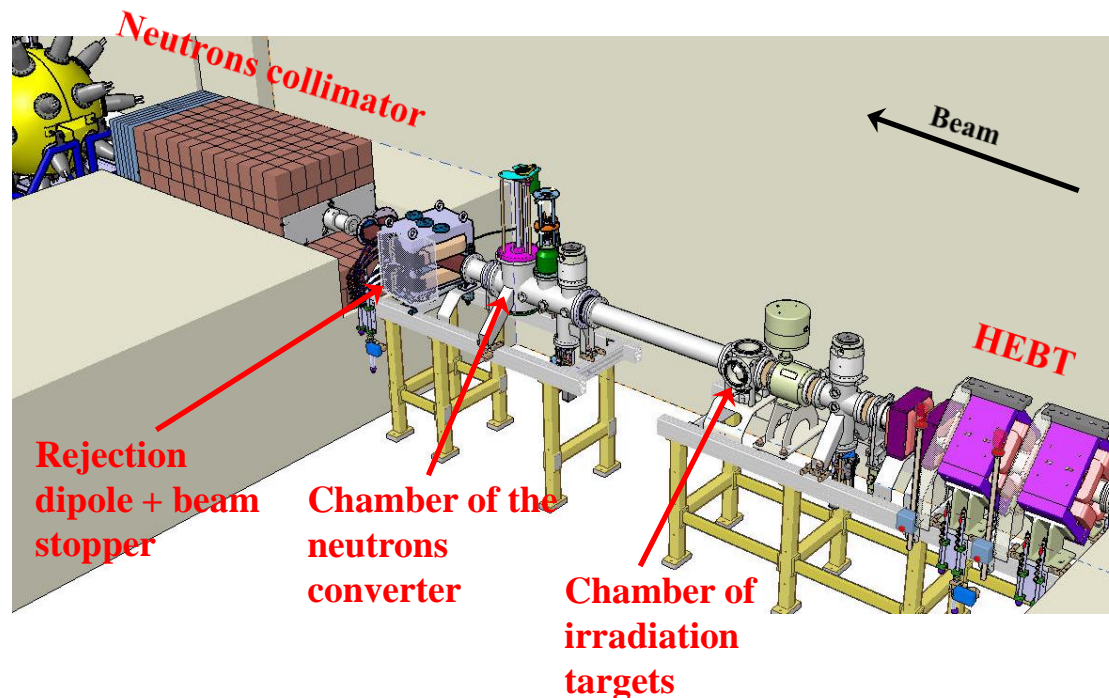
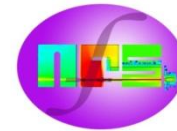
High limitation for NFS :

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



FEW WORDS ABOUT NFS EXP. AREA

- NFS will use light particles : Deuterons (40MeV) and Protons (10MeV-33MeV) : $0.4Tm < B\rho < 1.3Tm$
- $P_{max} = 2kW$ ($I_{max} = 50\mu A$ 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



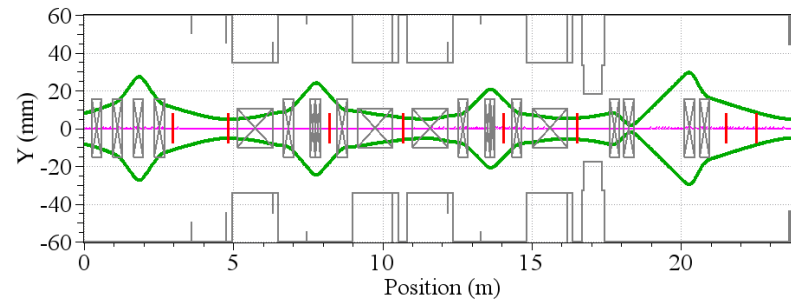
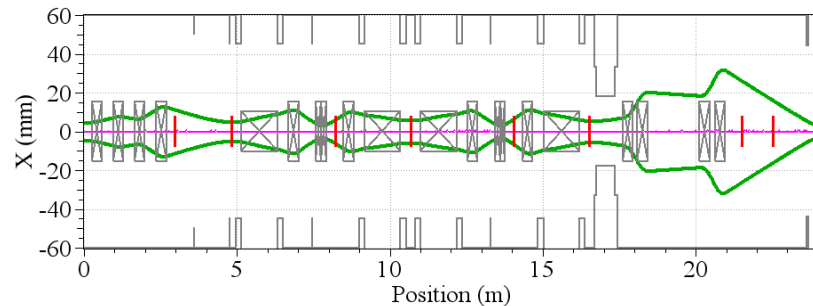
TRANSPORT UP TO THE S3 EXP. AREA

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

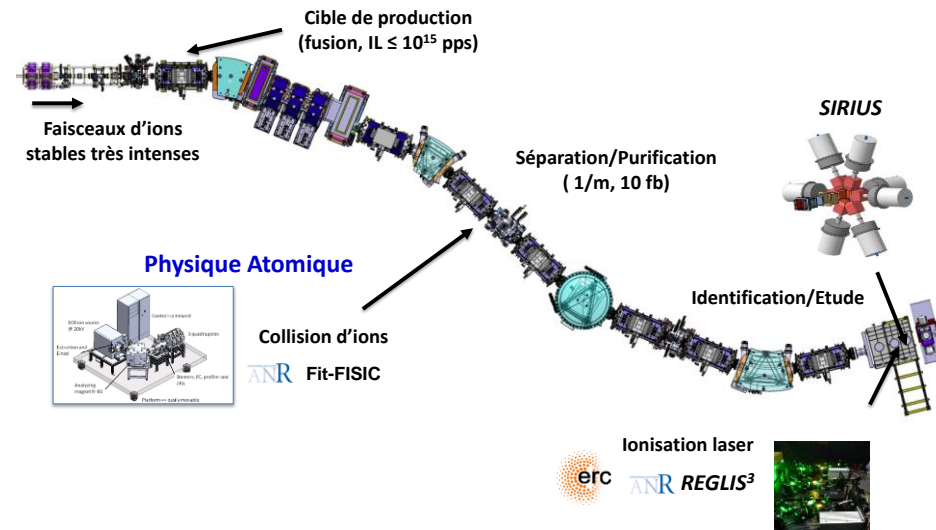


2 target modules (stables or actinides)



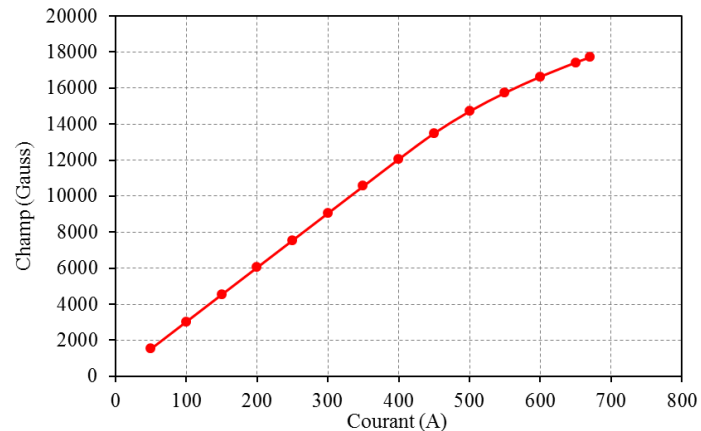
FEW WORDS ABOUT S3 EXP. AREA

- S3 will use heavy ions with $A/q=3$ at energy from 2MeV/u up to 14.5MeV/u : $0.6Tm < B\rho < 1.65Tm$
- 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

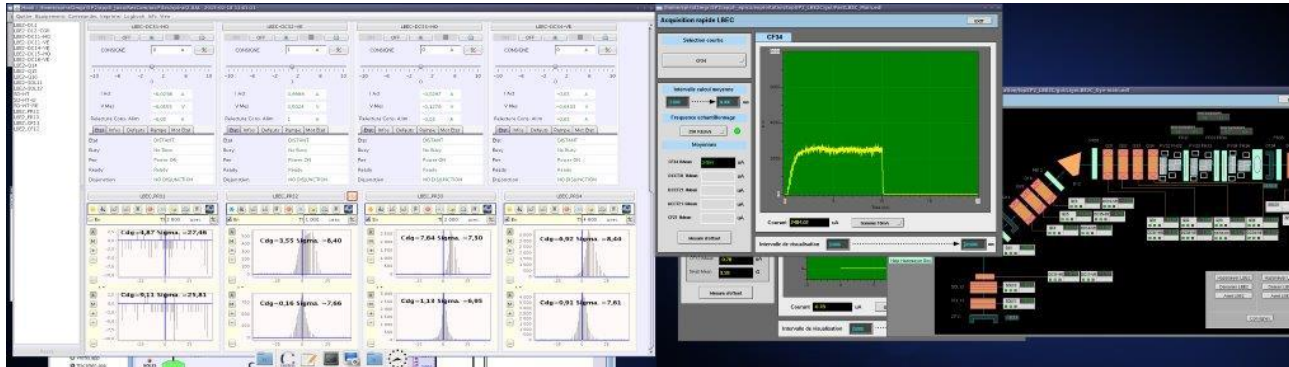
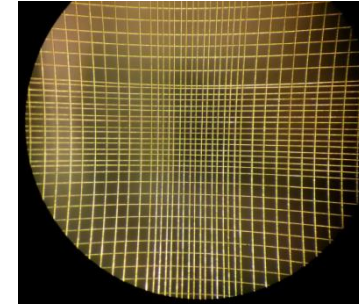
- 2 types of quadrupoles :
 - Type 1 ($G=13\text{T/m}$, $I_{\text{max}}=280\text{A}$) : $N=10$
 - Type 2 ($G=10\text{T/m}$, $I_{\text{max}}=370\text{A}$) : $N=18$
- Steerer : $B_{\text{max}}=245\text{G}$, $I_{\text{max}}=10\text{A}$
 - 5 dedicated to horizontal plane
 - 10 dedicated to vertical plane
- 6 rectangular dipoles : $\theta = 45^\circ$, $\rho = 1.5\text{m}$
 - $B_{\text{max}}=1.68\text{T}$, $I_{\text{max}}=670\text{A}$,
 - Gap=80mm, useful zone=60mm
 - Auxiliary coil : $I=10\text{A}$, $V=15\text{V}$
 - 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)



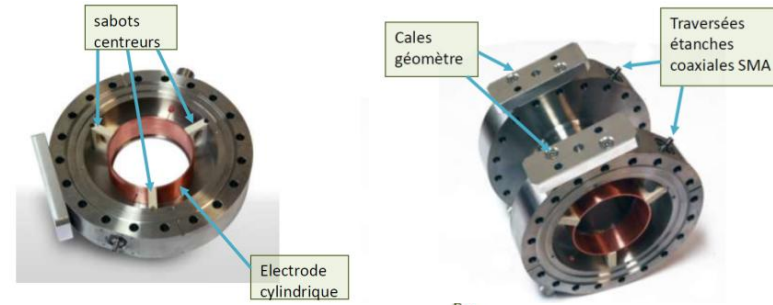
Beam Loss Monitor (BLM) : 6 systems

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

HEBT BEAM DIAGNOSTICS

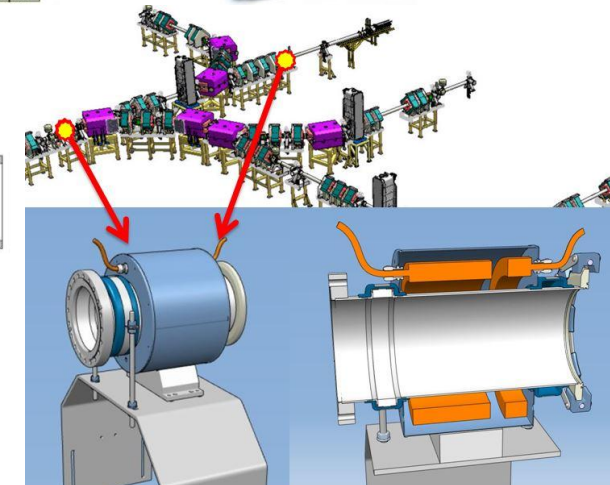
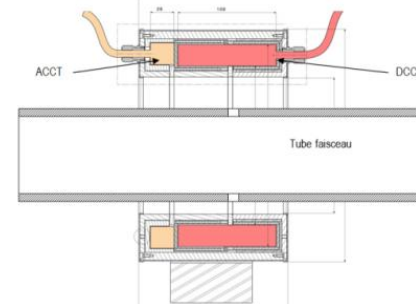
Beam energy using Time of Flight technic :

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



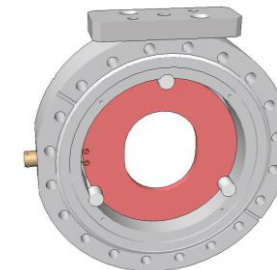
Beam current measurement :

- 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 $P = I \times E$



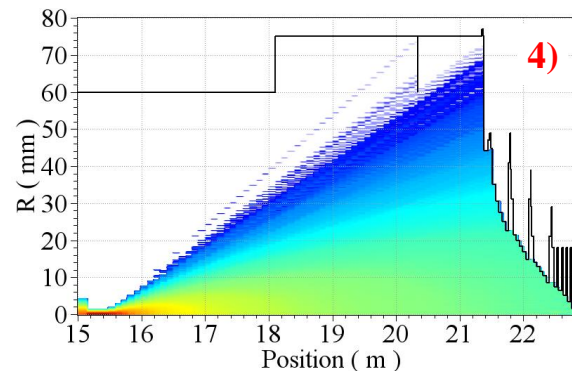
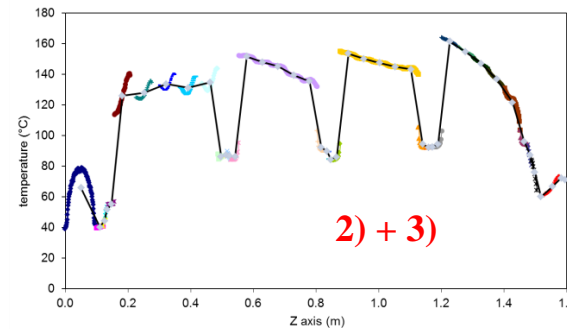
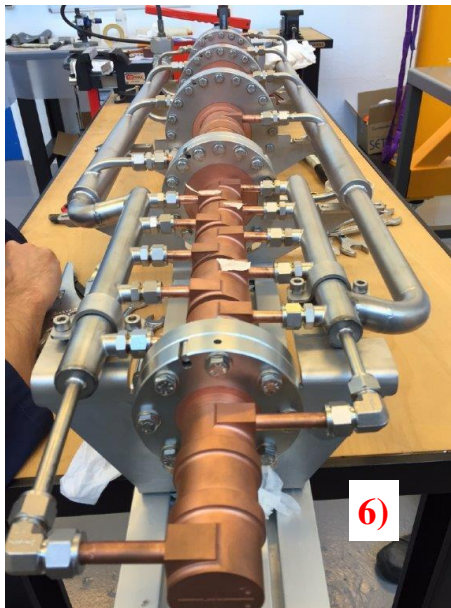
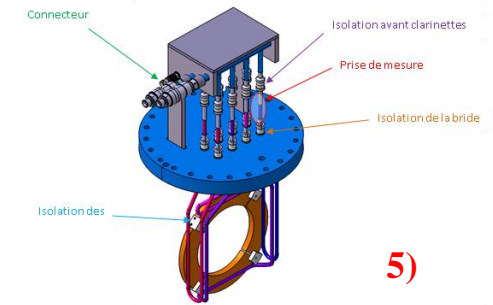
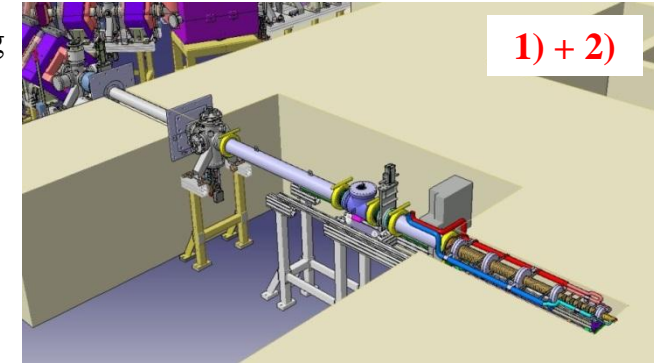
Ring losses : DI

- 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

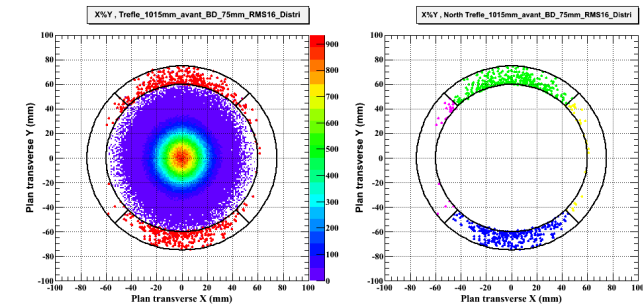


THE SPIRAL2 BEAM-DUMP

- 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 $\sigma_x = \sigma_y = 14\text{mm}$ at beam-dump entry
- 5) Segmented collimator located 1m before the beam-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

