Sources d'ions et accélérateurs

le programme de développement au SSI

Résumé

Une fois démarrés, les accélérateurs d'ions, que ce soit des cyclotrons, des synchrotronsou même de simple plate-forme haute tension, peuvent voir leurs performances décuplées uniquement par l'introduction de nouvelles sources d'ions. C'est ceci qui est à l'origine du dynamisme et de l'intérêt pour le développement de nouvelles machines.

Le Service des Sources d'Ions étant principalement engagé dans la mise au point de sources d'ions lourd (masse supérieure à celle de hydrogéne), nous rappellerons les principaux procédés de production des ions et tout particulièrement les principes de base des sources de types ECR (pour Electron Cyclotron Resonance).

Nous nous efforcerons de montrer en quoi la mise au point des systèmes d'augmentation en charge des faisceaux (Charge breeding) initialement développé pour le projet PIAFE permettent l'amélioriation de presque tout les projets d'accélération en ligne des faisceaux secondaires. Nous mettrons aussi en lien les différent schéma d'injection des ions lourds au CERN avec les différentes approches concernant la production de faisceaux pulsés d'ions Pb.

Sources d'ions et accélérateurs

le programme de développement au SSI

1. **Introduction** : *Sources d'ions et accélérateurs*
2. **Les sources ECR** : *les principes*
3. **Sources ECR et faisceaux secondaires** : *production en ligne et charge breeding*
4. **Sources ECR et synchrotrons** : *optimisation faisceaux pulsés / continus*
5. **Prospectives** : *PHOENIX "Booster 18 GHz"*
   A-PHOENIX HTS 28 – 40 GHz

Sources d'ions et accélérateurs

Ion : « non - neutral atom »

positive ions
negative ions
light ions
heavy ions
multicharged ions

Source : flux of ions

continuous
pulsed
low current
high current
high brigthness
low brightness
efficiency

ION BEAMS

An ***energy****, generally per mass unit*

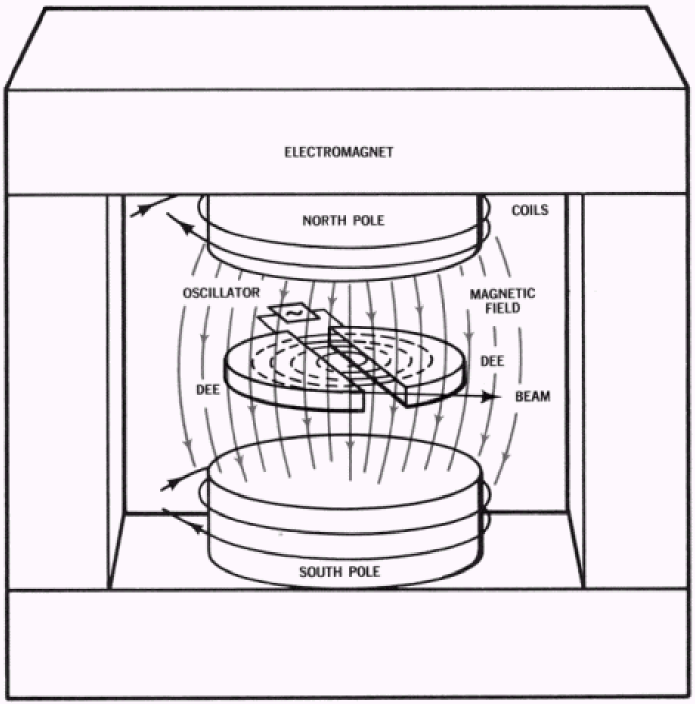
An ***intensity****, generally particules/second*

A ***transversal emittance****, generally the intrinsic transversal energy spread and the size of the beam*

A ***longitudinal emittance****, generally the intrinsic longitudinal energy spread and the time structure*

Sources d'ions et accélérateurs

Sources d'ions et cyclotrons



The cyclotron is caracterised by the parameter K defined by

$$W_n^{max} = K\left(\frac{q}{A}\right)^2$$

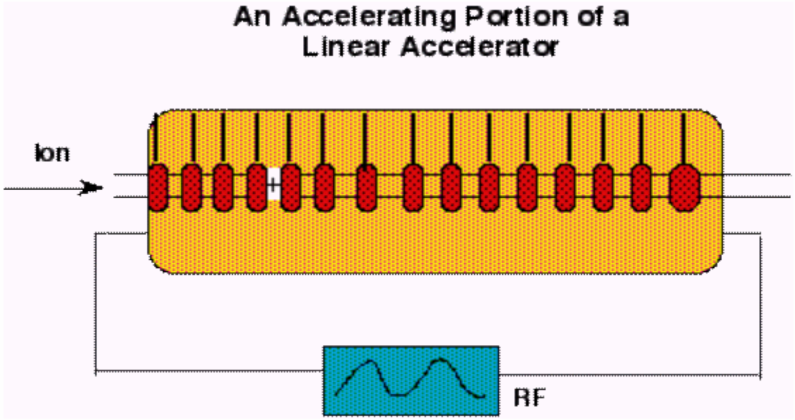
where W_n^{max} is the maximum energy per nucleon achievable, q the number of charge of the ion and A the number of mass of the ions.

The expression of K is : $K = \dfrac{R^2 B_{max}^2}{2m_n}$ where B_{max} is the maximal induction, R the mean radius of the extraction trajectory et m_n the mass of the nucleon

Ex. : "88 inch" Berkeley cyclotron, 40 years old, accelerate Bi^{46+} up to 6 Mev/uma.

Sources d'ions et accélérateurs

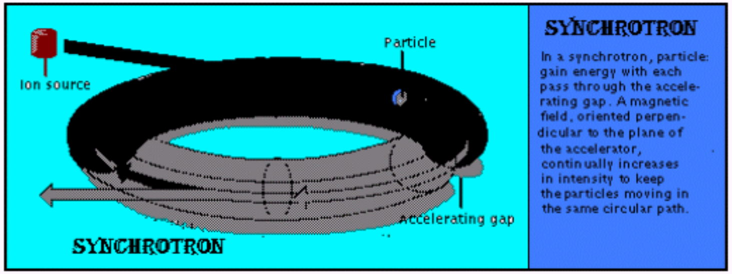
Sources d’ions et accélerateurs linéaires



For a linear accelerator, the energy is $W_n^{max} \propto (q/A)$ where W_n^{max} is the maximum energy per nucleon achievable, so the number of accelerator gap, so the length of the machine , so the price!

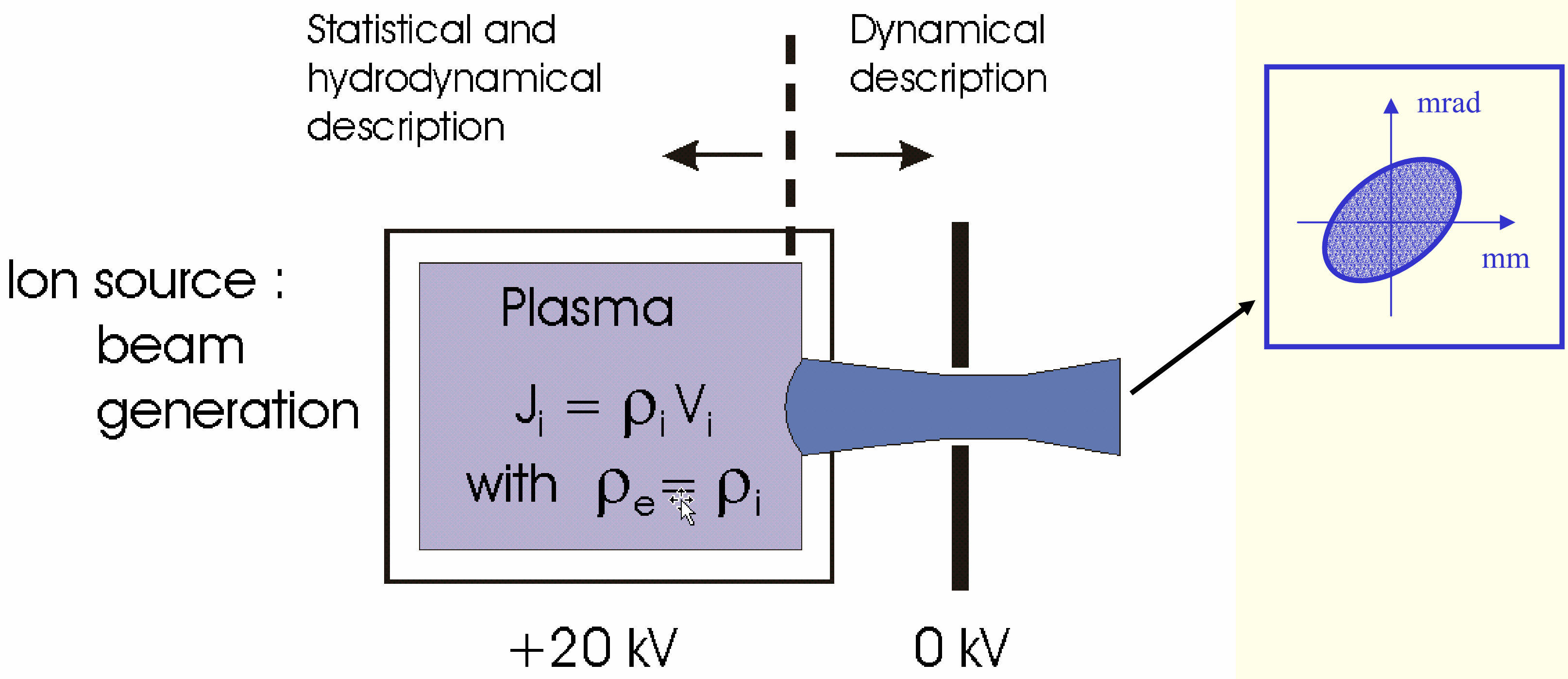
Synchrotron are fundamentaly cyclic accelerator , a bunch of particule is injected, followed by the accelerating time.

So the ion source must deliver a pulsed beam with a miximum intensity during some µs every second !



Sources d'ions et accélérateurs : *plasma and ion beam generation*

A plasma is called quasineutral if the number of positive charges per unit volume equals the negative charge density

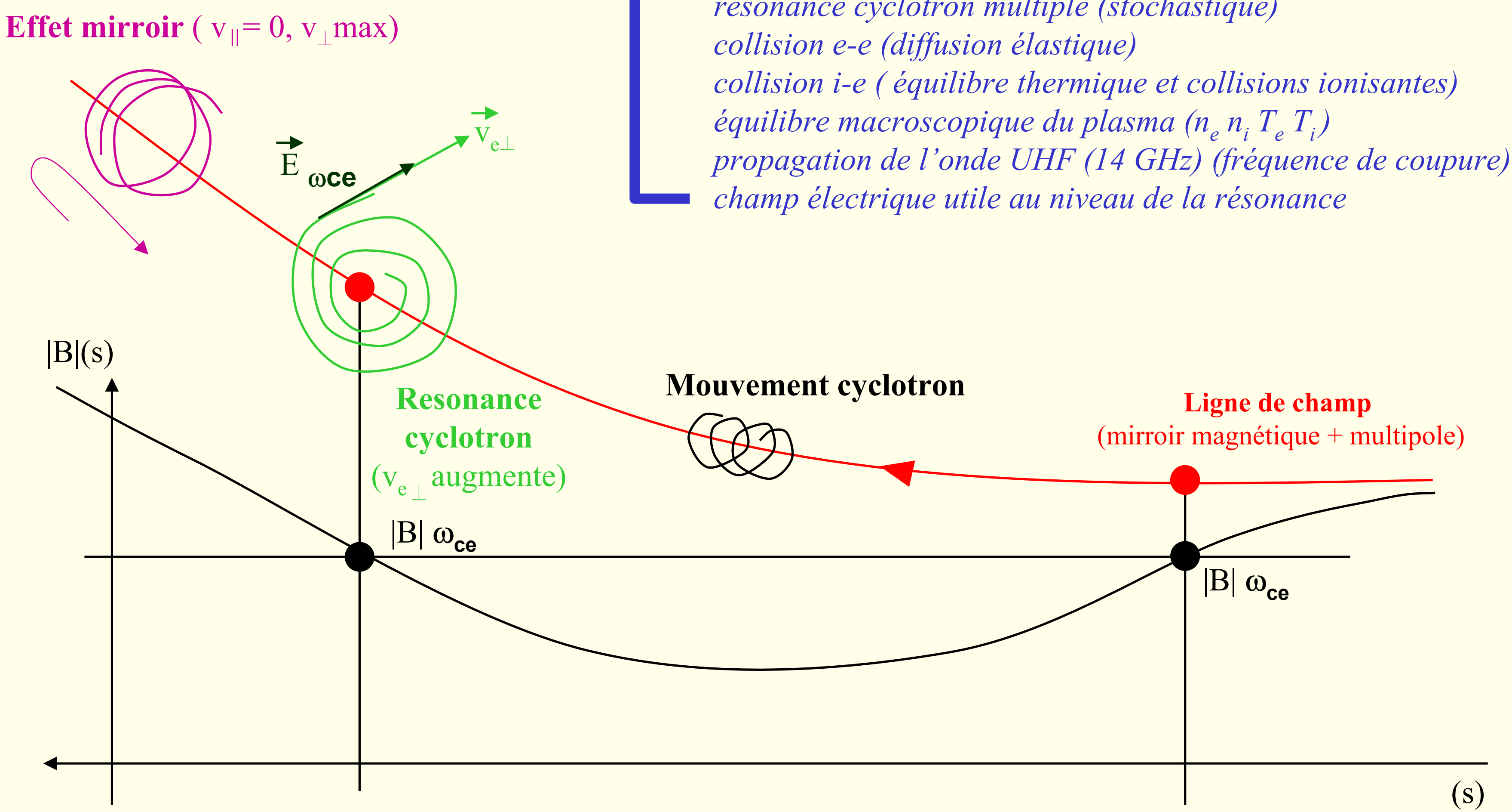


The ion current is determined only by ion temperature, ion density and area of extraction opening

Résonance cyclotronique électronique: ω_{ce}

Les mouvements de l'électron *:*

mouvement cyclotron simple
mouvement cyclotron dans le gradient (miroir magnétique)
résonance cyclotron simple (passage unique)
résonance cyclotron multiple (stochastique)
collision e-e (diffusion élastique)
collision i-e (équilibre thermique et collisions ionisantes)
équilibre macroscopique du plasma (n_e n_i T_e T_i)
propagation de l'onde UHF (14 GHz) (fréquence de coupure)
champ électrique utile au niveau de la résonance



Multicharged ion production : *Ionization equilibrium*

Balance equation of the density n_i of ions in the charge state i :

$$\frac{\partial n_i}{\partial t} = \sum_{j_{min}}^{i-1} n_e n_j \langle \sigma_{j\to i}^{ioni} v_e \rangle + n_o n_{i+1} \langle \sigma_{i+1\to i}^{exc} v_i \rangle$$

$$- n_o n_i \langle \sigma_{i\to i+1}^{exc} v_i \rangle - \sum_{j=i+1}^{j_{max}} n_e n_j \langle \sigma_{j\to i}^{ioni} v_e \rangle - \frac{n_i}{\tau_i}$$

Parametric model with n_e, $f(v_e)$, τ_i and n_0 arbitrary

n_e : electronic density

$f(v_e)$: electronic speed distribution

τ_i : ionic diffusion time

n_0 : neutral density

with $\tau_i = K_{diff} z_i^2$ (or more sophisticated description of ionic plasma diffusion process)

ionisation cross section:

$$\sigma_i^{ioni} = A_i^{ioni} \log(E_e / E_i^{ioni}) / E_i^{ioni} E_e$$

charge exchange cross section:

$$\sigma_{i,i-1}^{exc} = A^{exc} i / (E_0^{ioni})^3$$

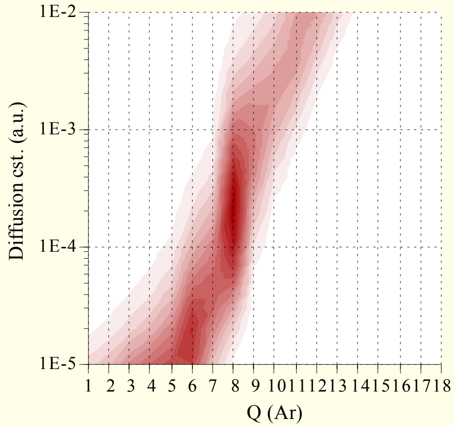
with : A_i^{ioni} : ionisation constant

E_i^{ioni} : ionisation potential of state i

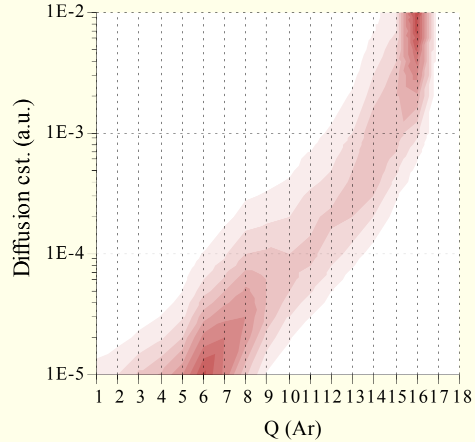
E_e: electronic energy

isn Grenoble

Multicharged ion production : *ionization equilibrium*

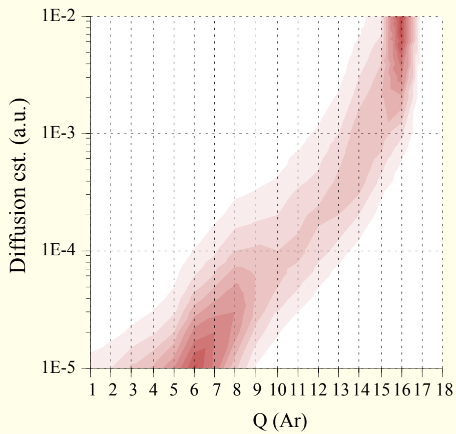


Te = 100 eV (maxwellian)

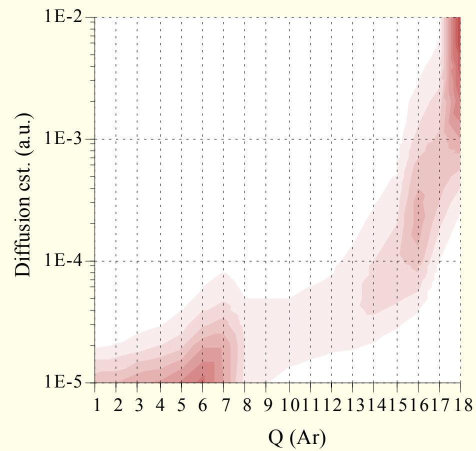


Te = 300 eV (maxwellian)

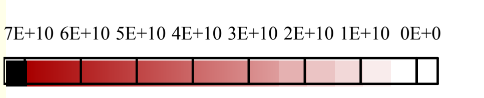
Density (cm-3) charge state distribution of Argon as a function of the confinement time of ions and for maxwellian distribution of electronic energy



Te = 1000 eV (maxwellian)



Te = 10000 eV (maxwellian)



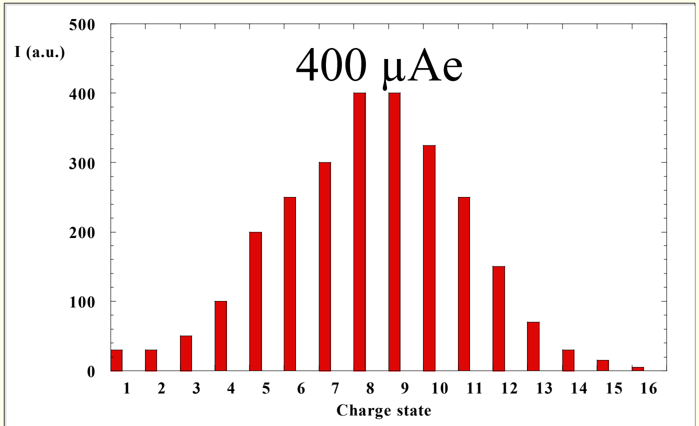
Ionisation Potential

Ar^{0} ≈ 15 eV Ar^{7+} ≈ 140 eV
Ar^{8+} ≈ 450 eV Ar^{15+} ≈ 1000 eV
Ar^{16+} ≈ 4400 eV

High current / high charge state optimization

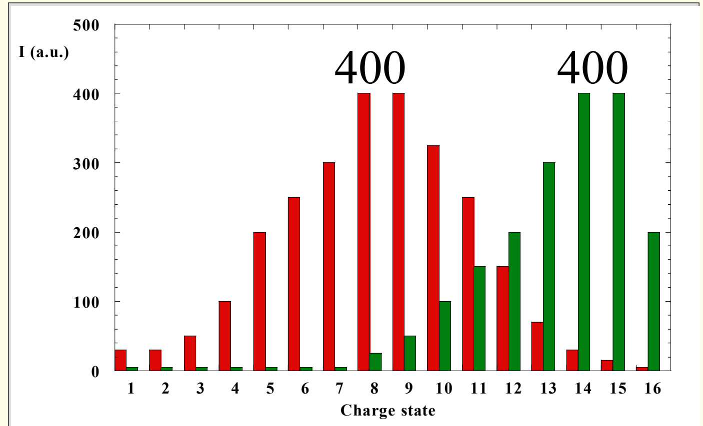
$J_i \propto n_e/\tau_i$

$\langle Z \rangle \propto n_e\tau_i$



ECR4 14.5 GHz / CERN

1-5 mAe/cm^2 $n_e\,\tau_i$ n_e/τ_i



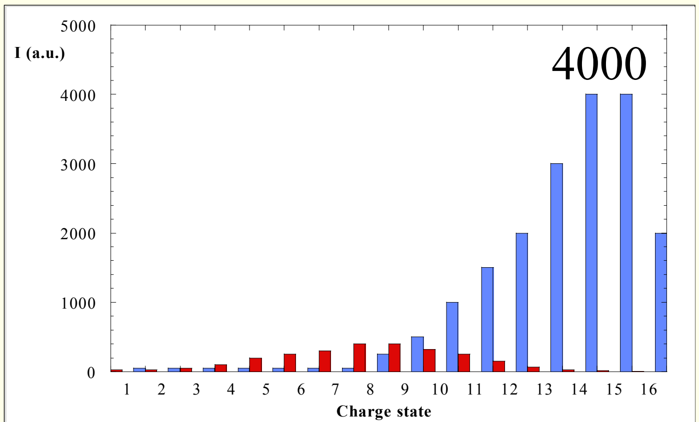
$n_e(\times 3)\ \tau_i(\times 3)$: 1-5 mAe/cm^2

$n_e\tau_i\,(\times 10)$ $n_e/\tau_i = C^{st}$

?

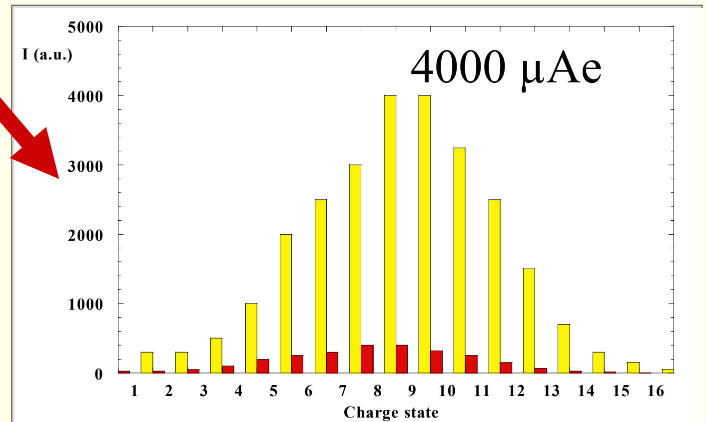
J_i

P_{UHF}



$n_e(\times 10)\ \ \tau_i\, C^{st}$: 10-50 mAe/cm^2

$n_e\,\tau_i\,(\times 10)$ $n_e/\tau_i\,(\times 10)$

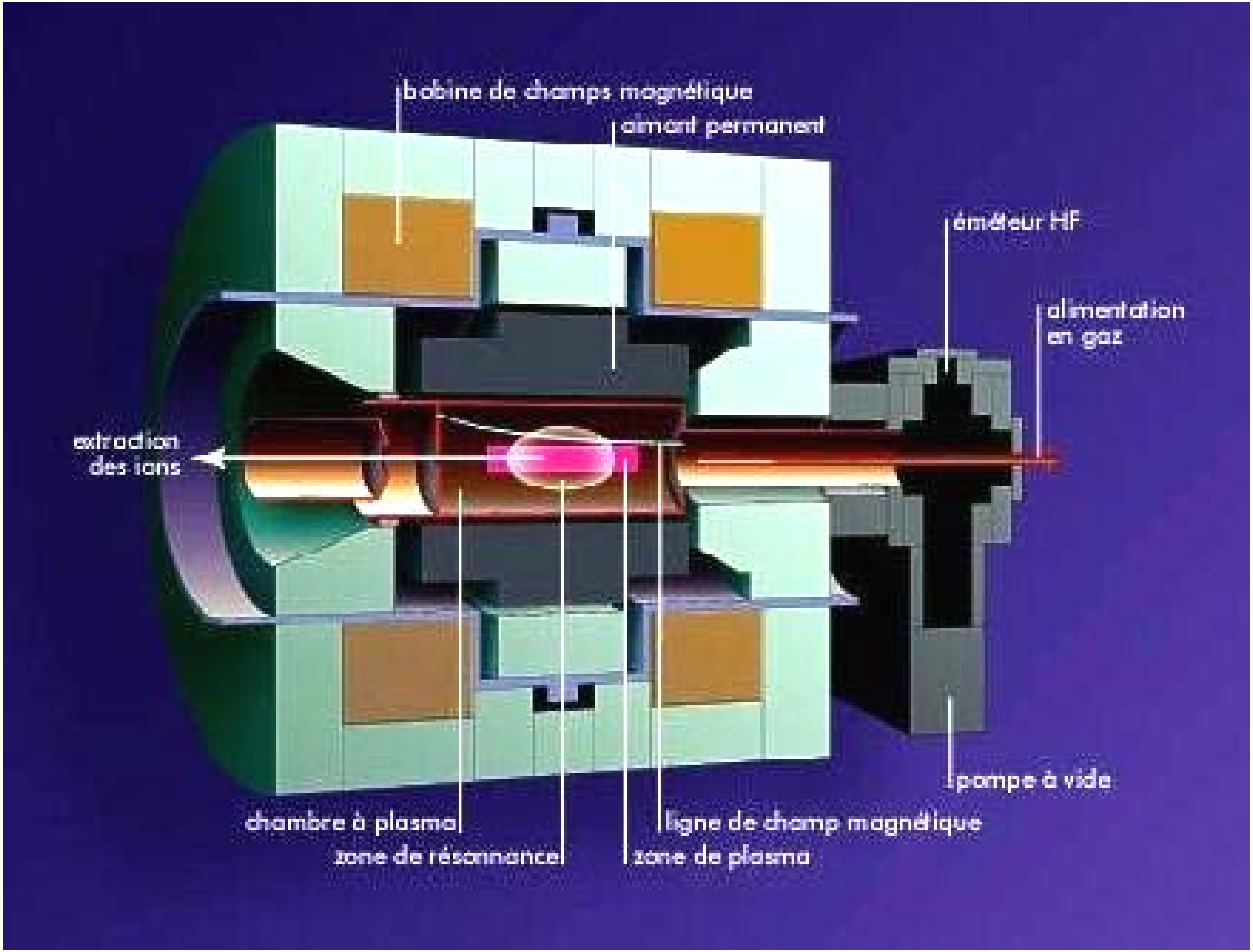


$n_e(\times 3)\ \tau_i(\div 3)$ 10-50 mAe/cm^2

$n_e\tau_i = C^{st}$ $n_e/\tau_i\,(\times 10)$

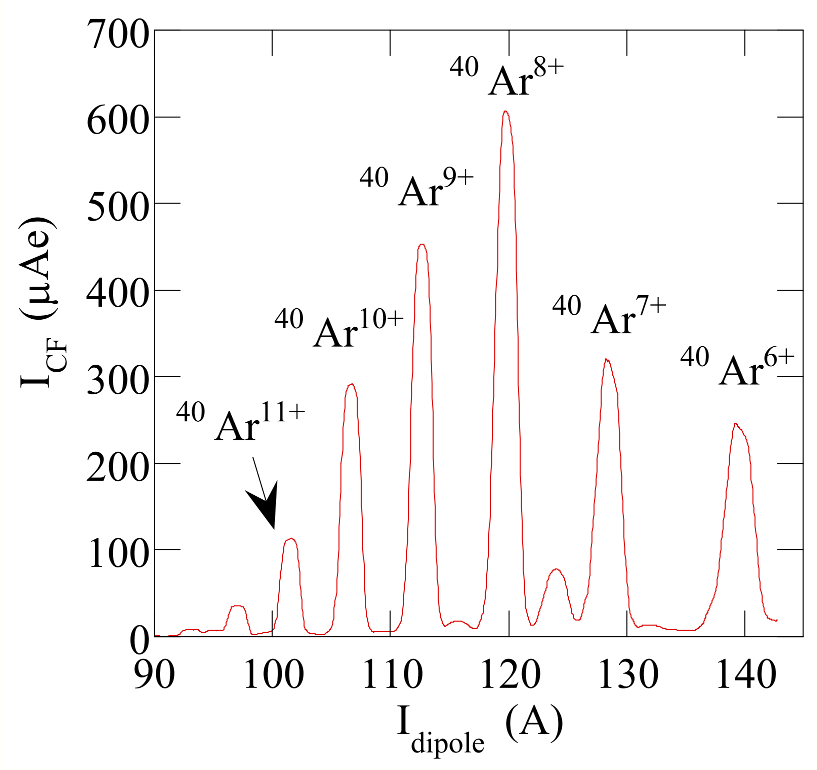
Electron Cyclotron Resonance Ion Source

Plasma Chamber
Φ 70 mm
L 200 mm

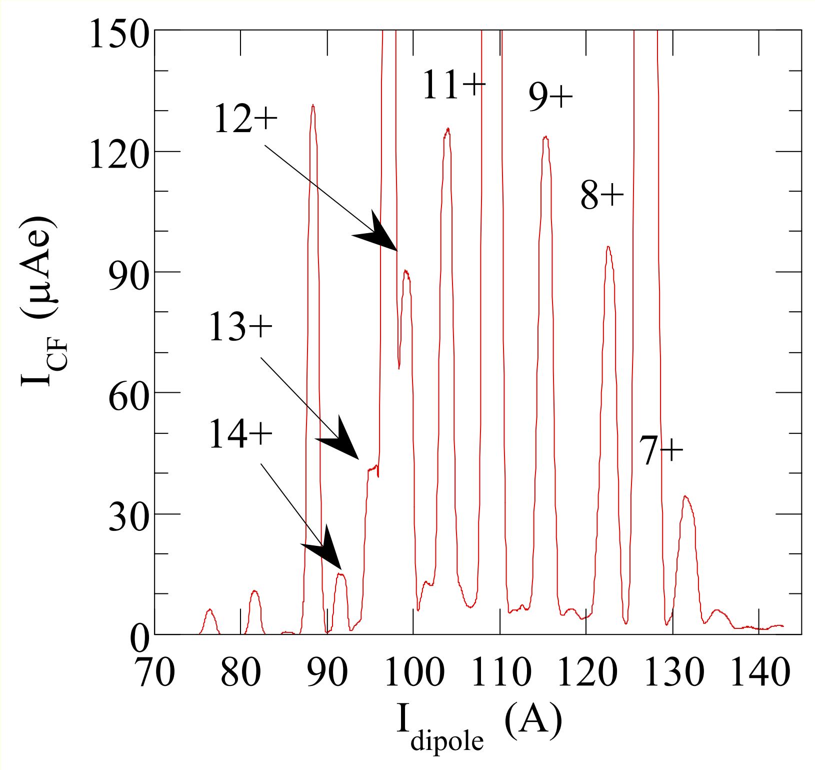


Source
Φ 500 mm
L 700 mm

Electron Cyclotron Resonance Ion Source : *typical spectrum*



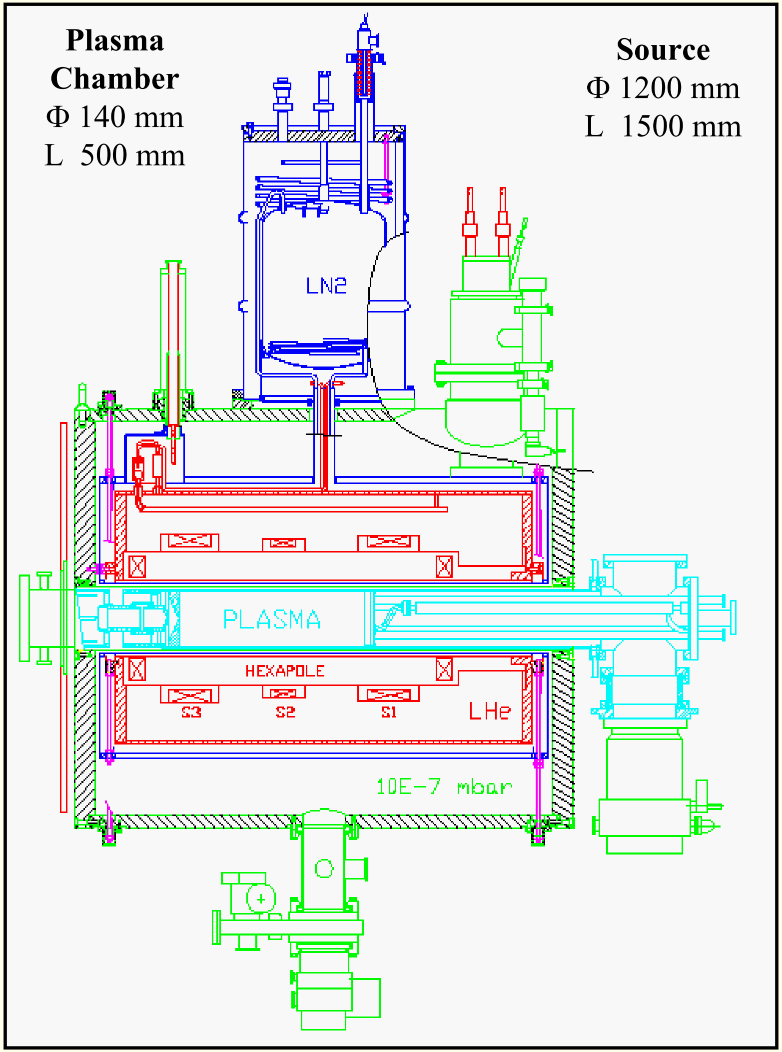
Ar $^{8+}$ tuning

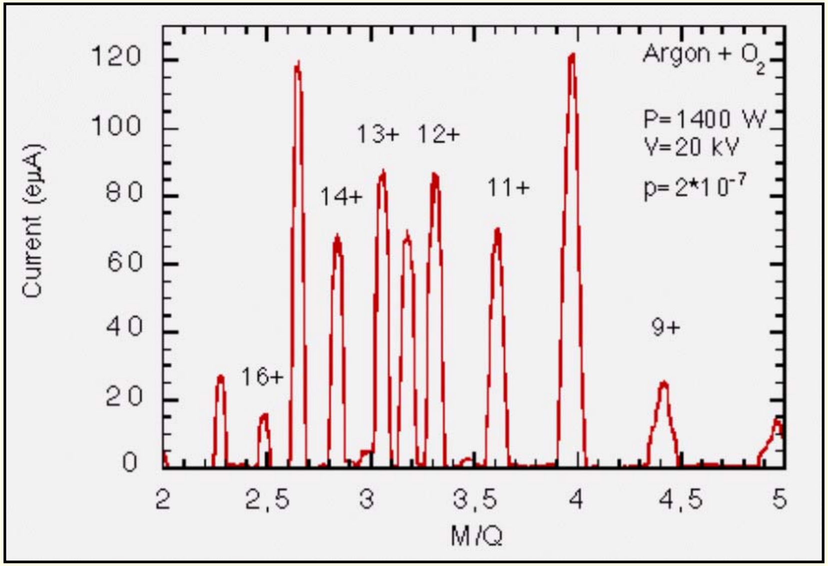


Ar $^{14+}$ tuning

ECR4-M 14.5 GHz / GANIL / 25 KV

Electron Cyclotron Resonance Ion Source : *Source supraconductrice CENG/LNS Catane*





Pour :

> sources compactes sur très fortes charges Ar > 14+

Contre :

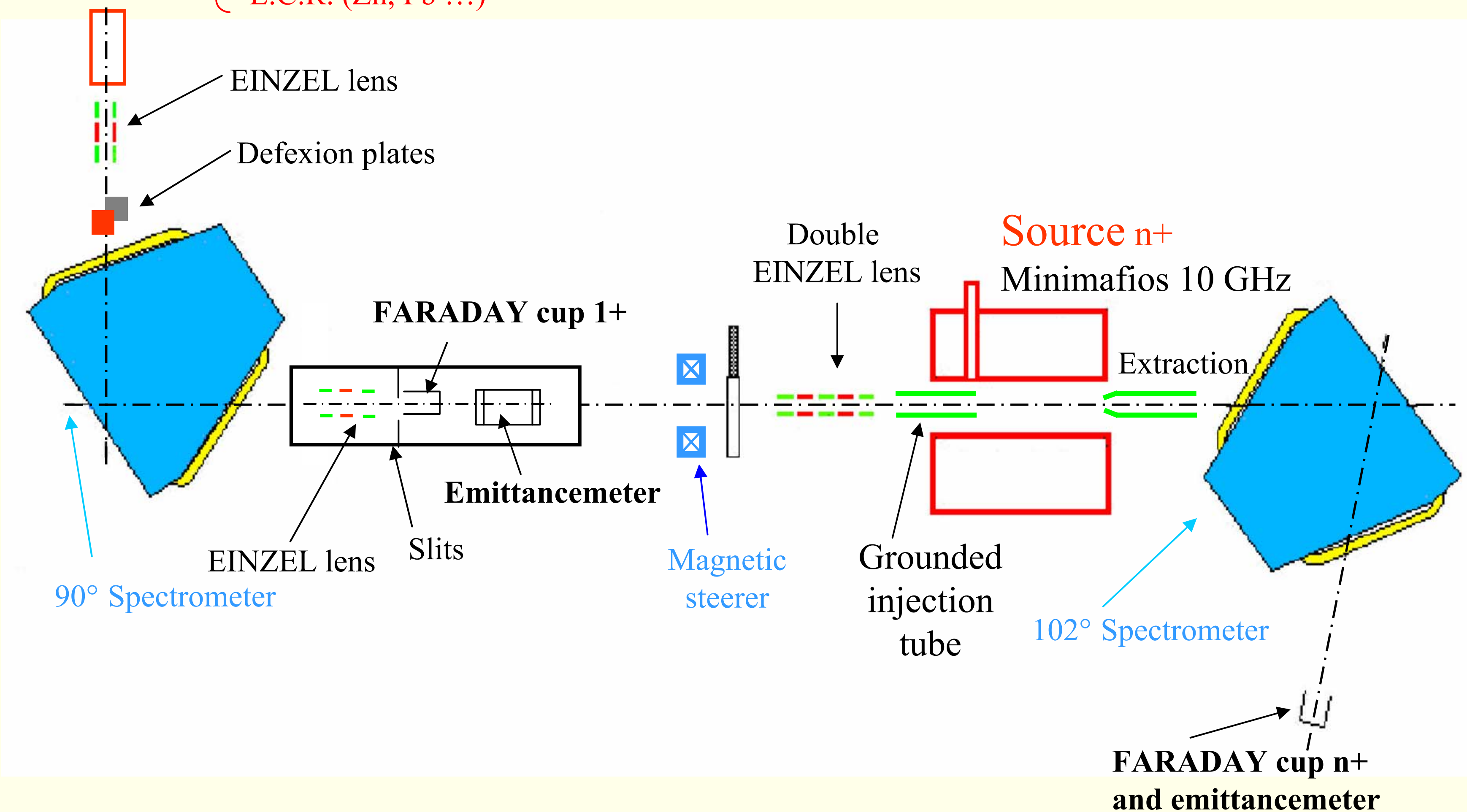
< sources compactes sur charges moyennes ou faibles Ar < 14+

Compromis fort courant ?

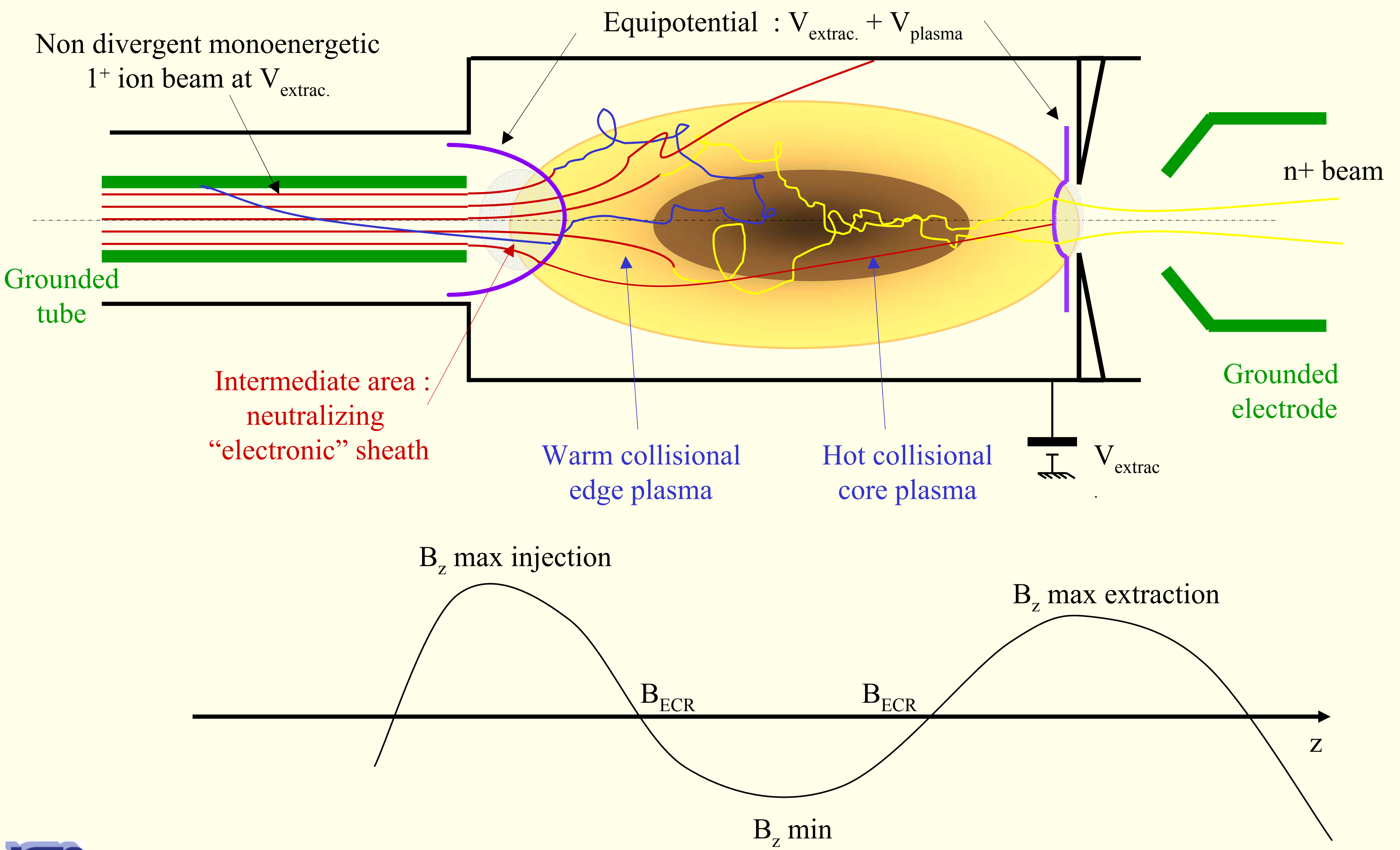
Coût environ 10 fois supérieure

Experimental setup for the 1+/n+ charge breeding

1+ Source
- Thermoionic (Rb)
- Hollow Cathode (Zn)
- E.C.R. (Zn, Pb …)



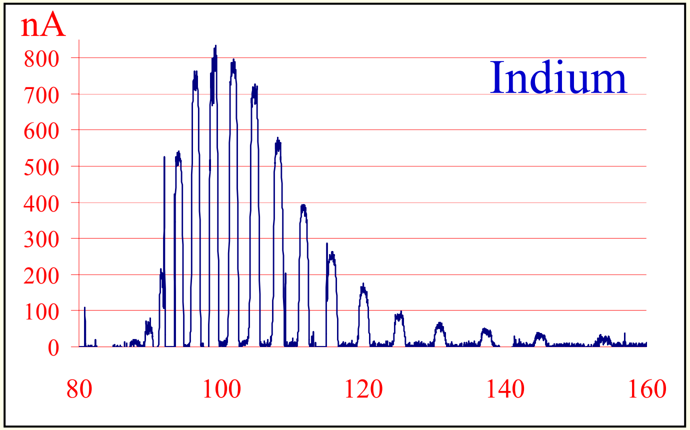
1+ / n+ transformation with an ECRIS for multicharged ions



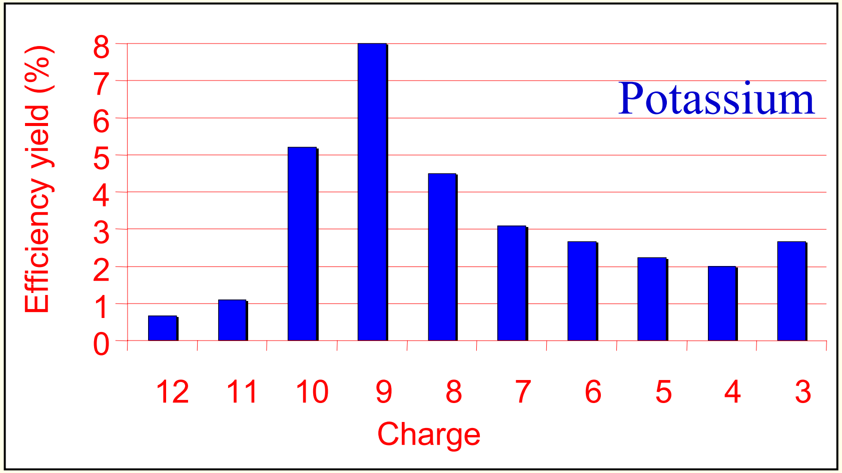
Experimental setup for the 1+/n+ charge breeding

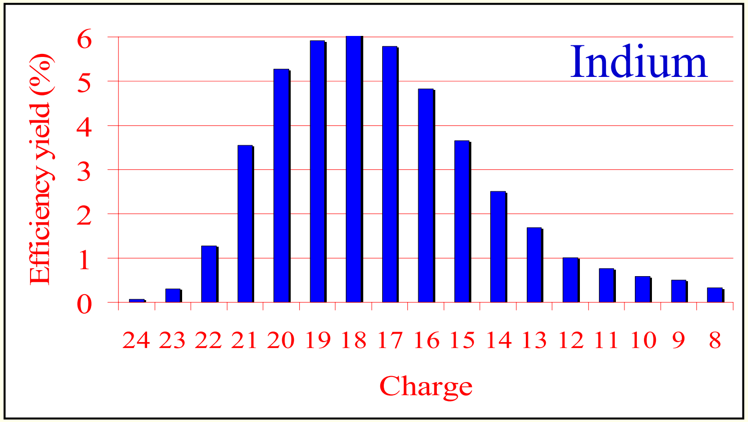
Efficiency yields

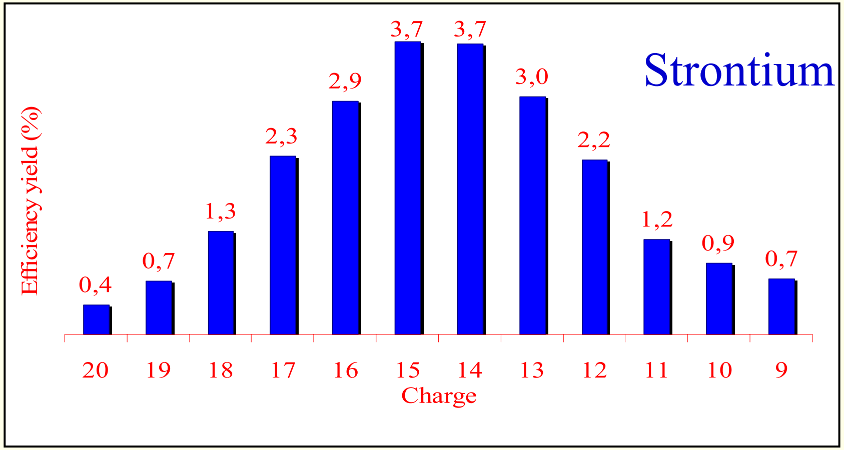
Delta I measurement



I Spectrometer



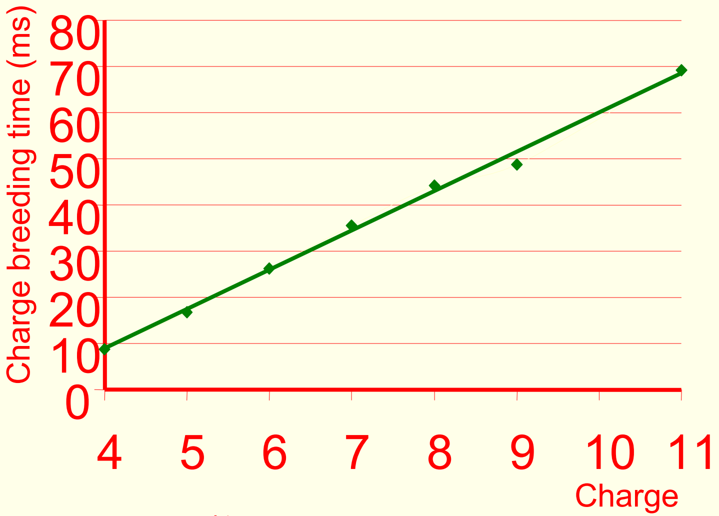


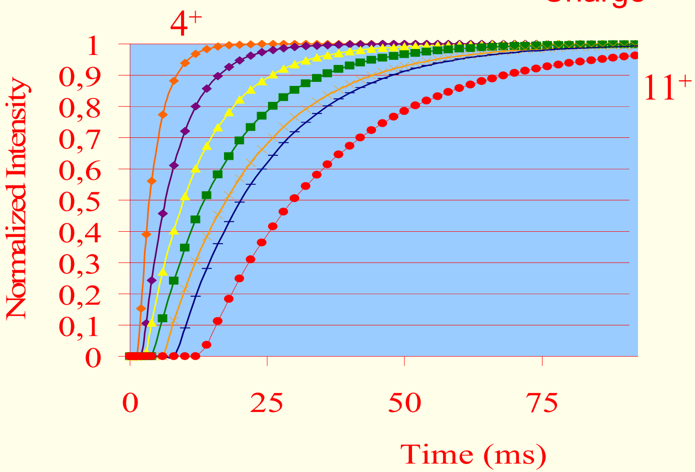


CSD efficiency yield

Experimental result with the 1+/n+ charge breeding

Charge breeding time τ_{cbt} with ^{39}K

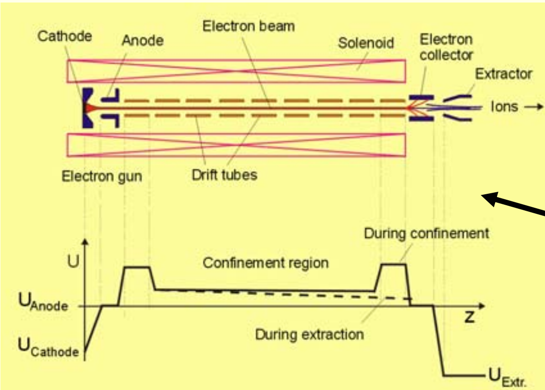


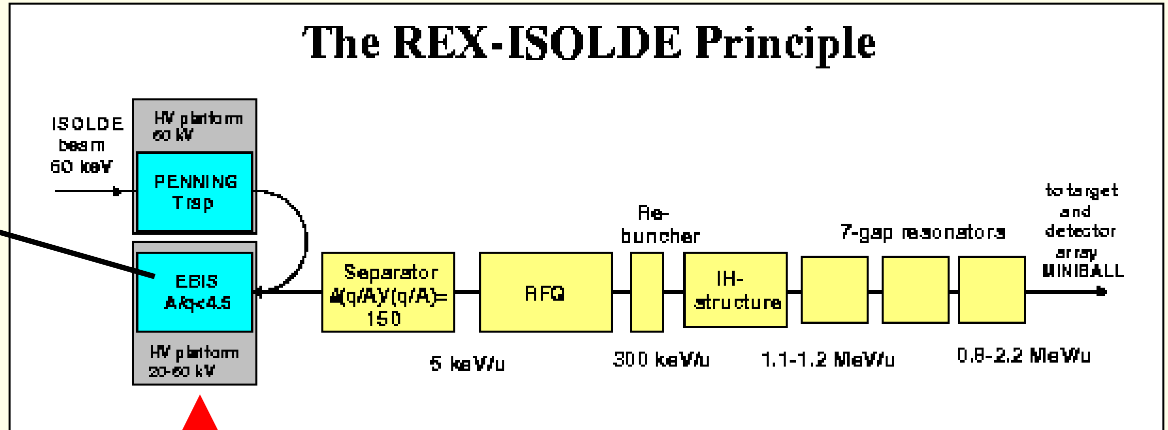


Produced elements

Element	1+ Intensity (nA)	n+ Charge	Yield (%)
^{20}Ne	1000	4	7.5
^{23}Na	660	6	1.3
^{39}K	280	6	6.5
^{64}Zn	42	10	2.8
^{69}Ga	460	11	2
^{85}Rb	90	13	5
^{88}Sr	470	14	3.7
^{90}Y	178	14	3.3
^{109}Ag	175	17	3
^{115}In	130	18	3.3
^{120}Sn	167	19	4.1
^{208}Pb	700 (2+)	25	6.8

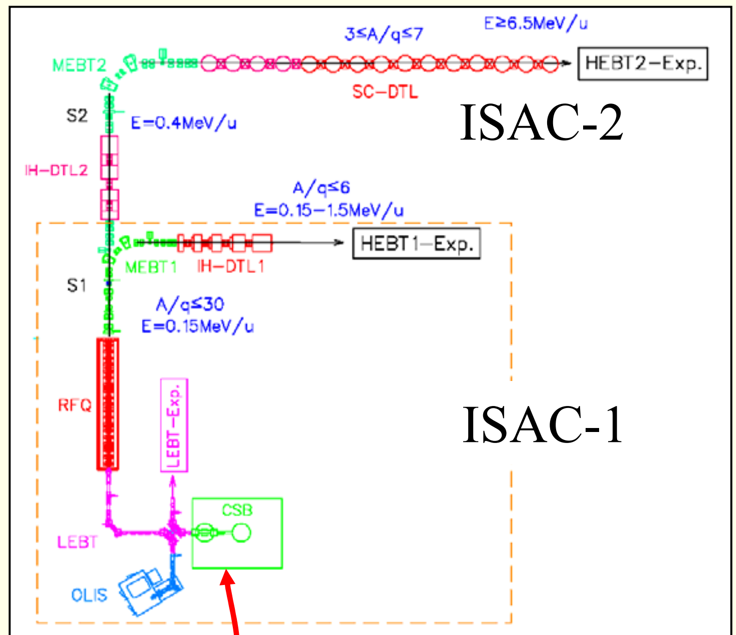
The EBIS charge breeder/stripper versus the ECRIS one





Phoenix 14 GHz
« Daresbury »

Fabriquées par Pantechnik
sous contrat ISN/Pantechnik (CROP)



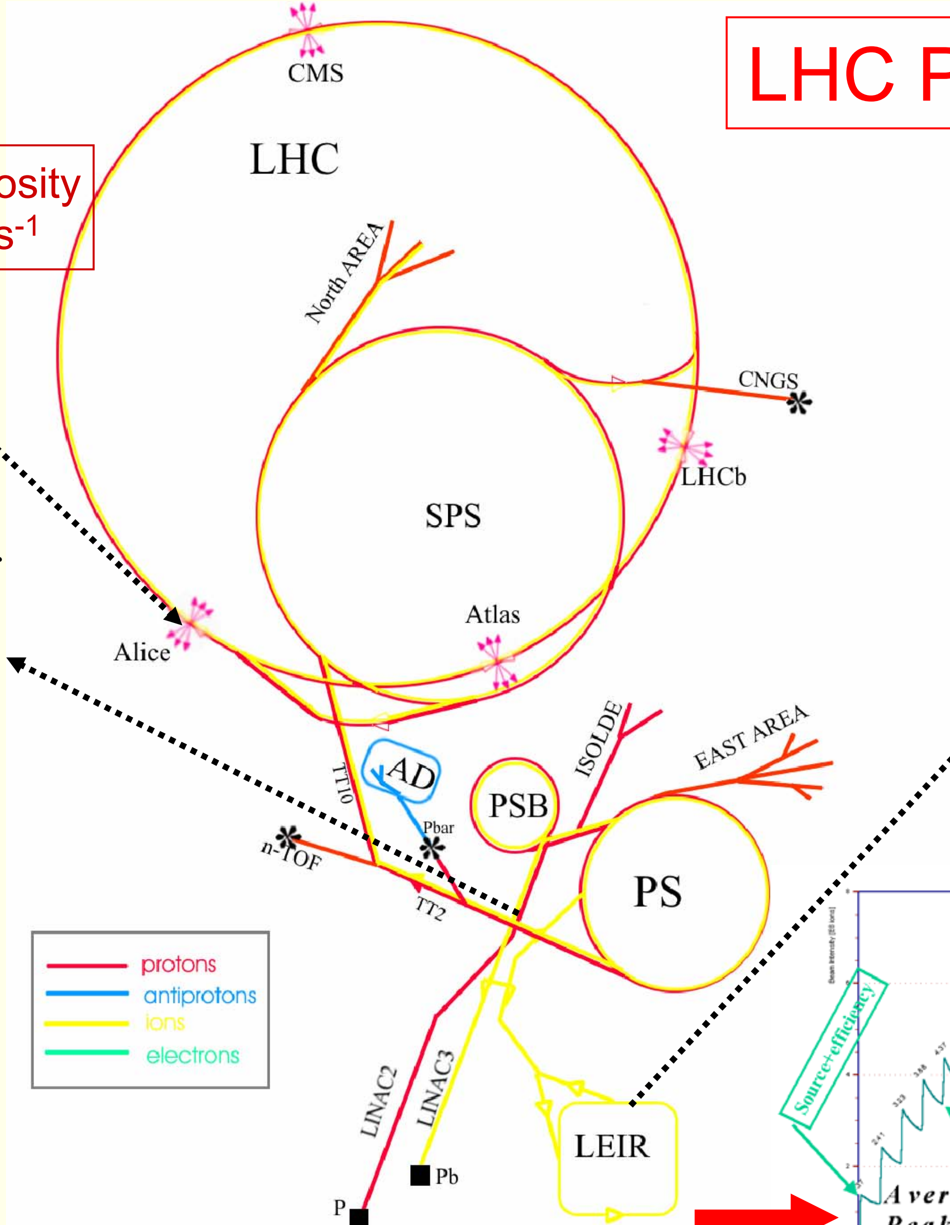
Phoenix 14 GHz
Triumf

LHC Pb and ion source

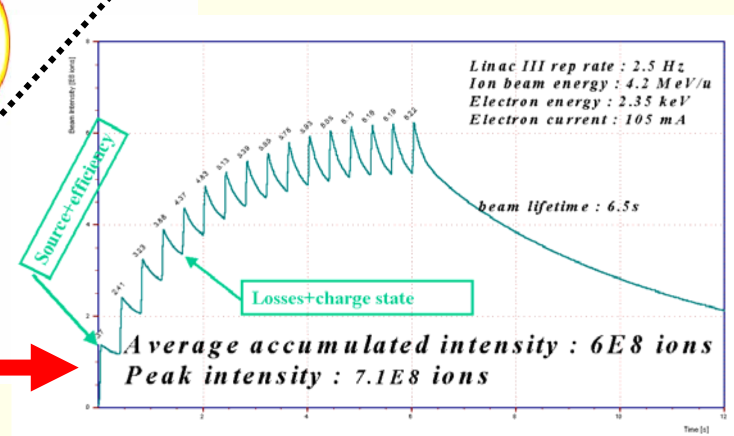
LHC Pb luminosity
7 10^{27} cm^{-2} s^{-1}

Voie directe
vers le booster

6 mA
5.5 µs
~ 10^8 ions/bunch



Voie d'accumulation
dans LEIR



0.25 mA / 450 µs

PHOENIX strategy to produce High Multi Charged Ion beams

28 GHz RF Gyrotron → $n_e \times 4$ with respect to 14.5 GHz ECRIS

\+

medium magnetic confinement → Plasma leakage INCREASED

\+

High RF Power Density (8 kW/litre) → n_e is maintained to High density

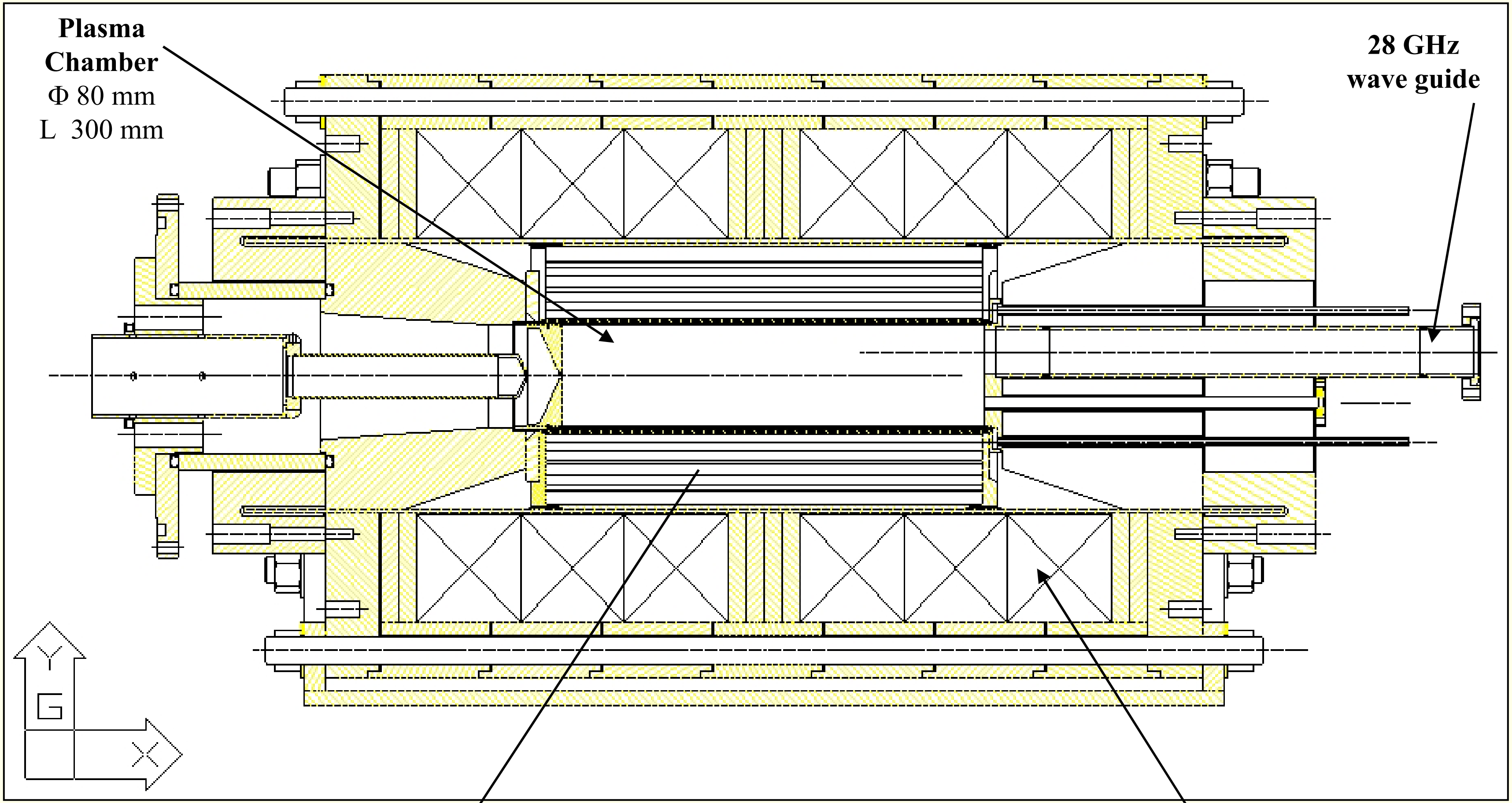
=

High Current Multicharged Ion Production

$n_e \times 4$ with respect to 14.5 GHz ECRIS + Plasma leakage INCREASED → **High Current**
n_e/τ_i ~ maximum
(current density)

n_e is maintained to High density → **Multi Charged Ion Production**
with $n_e\tau_i$ ~ C^{st}

PHOENIX 28 GHz

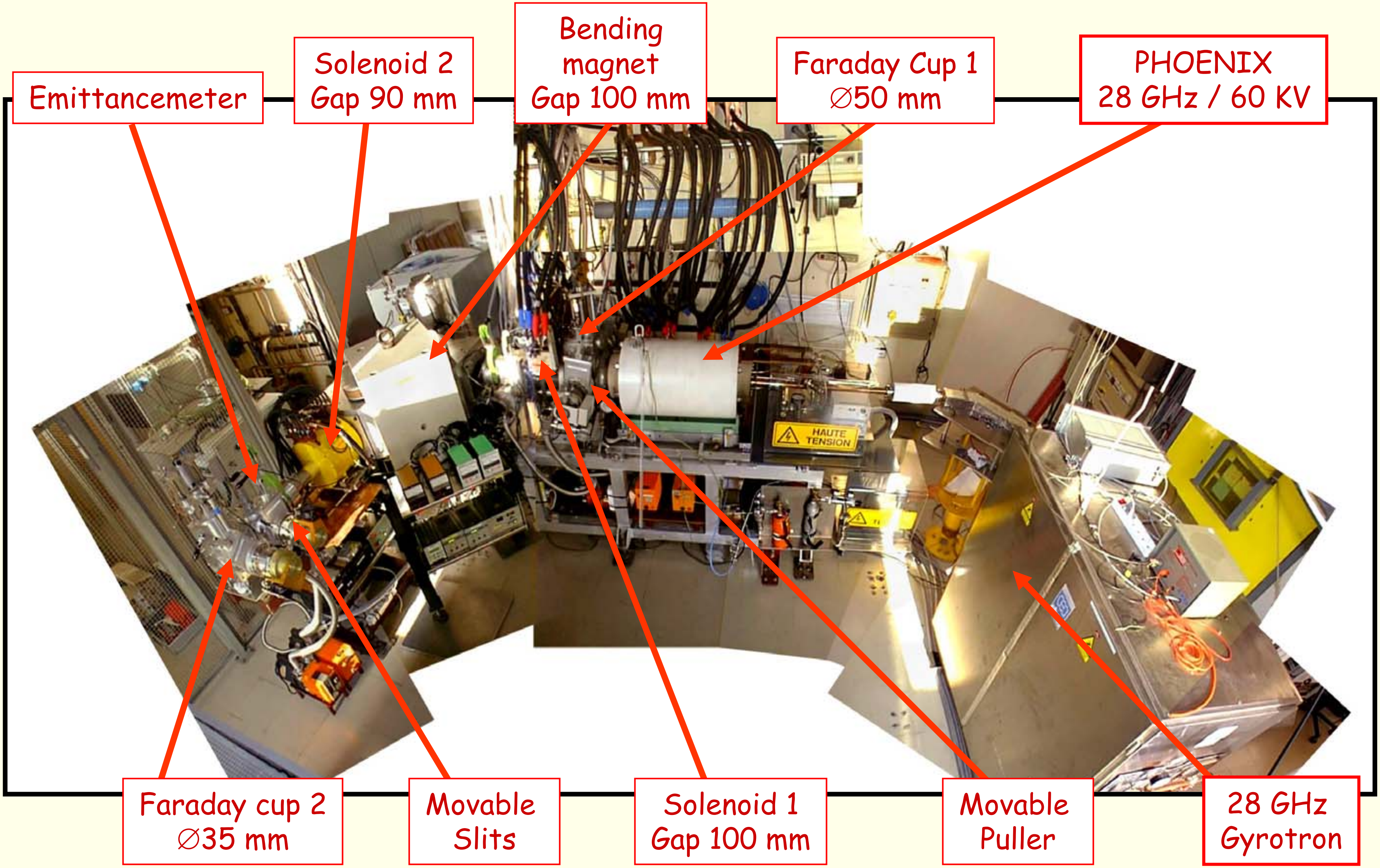


Hexapole
FeNdB

Source
Φ 500 mm
L ~ 800 mm

Coils
3 ×[2 Coils × [55 V × 1300 A]] = 214 KW

PHOENIX 28 GHz : *60 KV high current beam line*

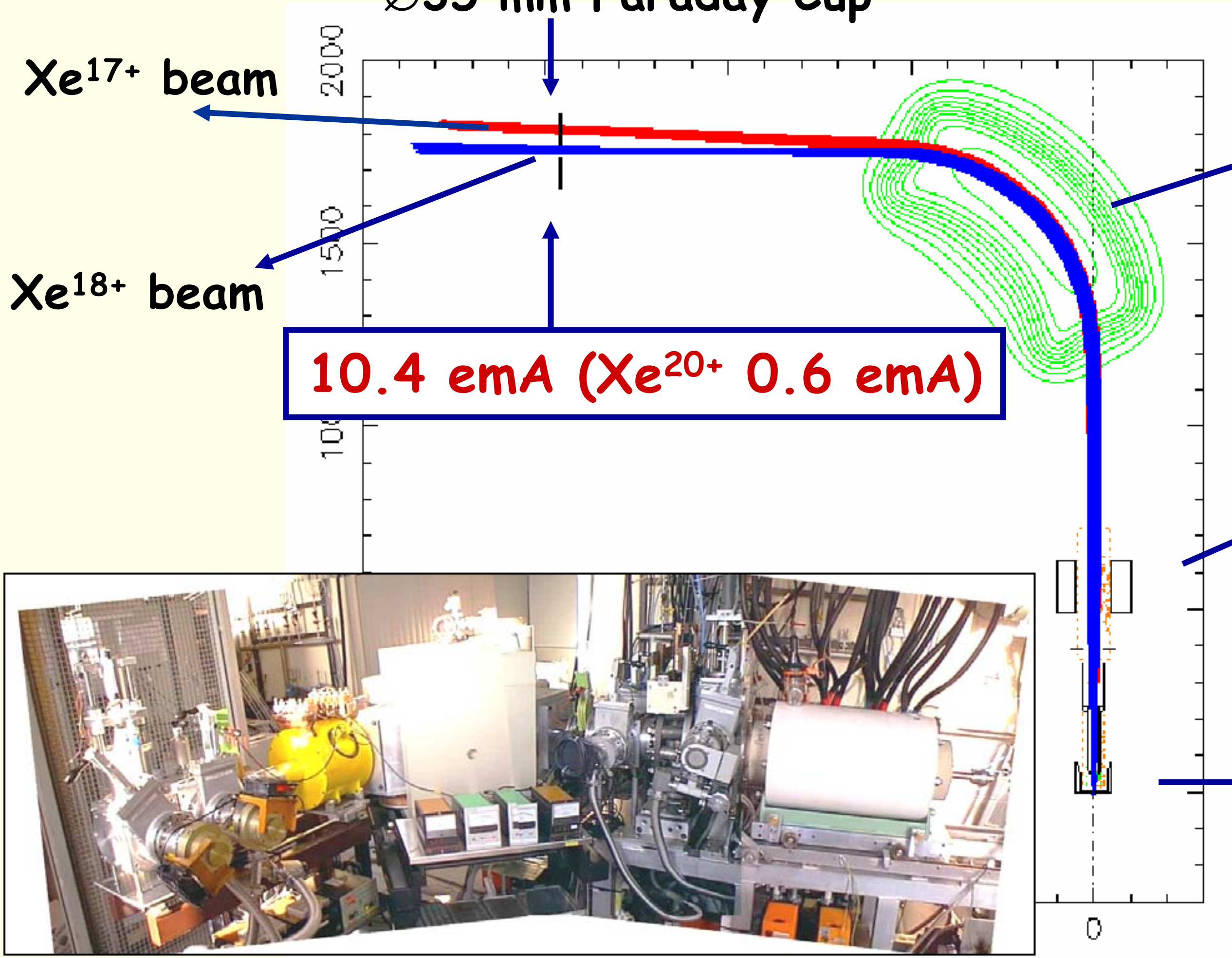


PHOENIX 28 GHz : high current extraction (Xenon)

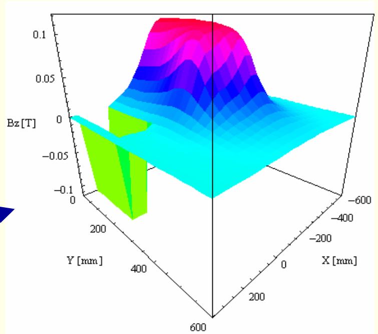
∅35 mm Faraday Cup

Xe^{17+} beam

Xe^{18+} beam



10.4 emA (Xe^{20+} 0.6 emA)



3D field map of the 90° Bending magnet

3D field map of the solenoid

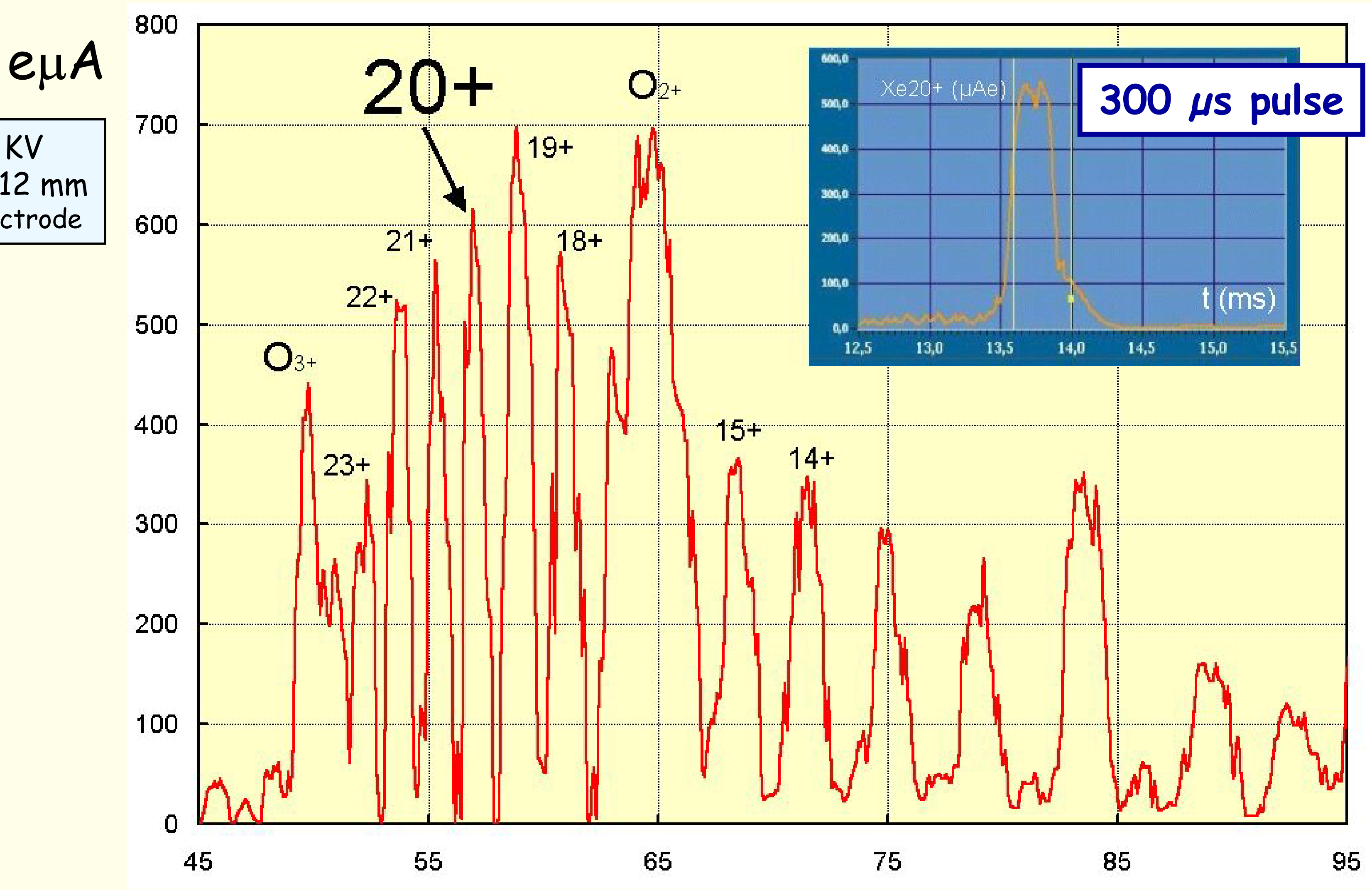
12.5 emA (I_{FC1})

3D source extraction field and magnetic fringe field of the source

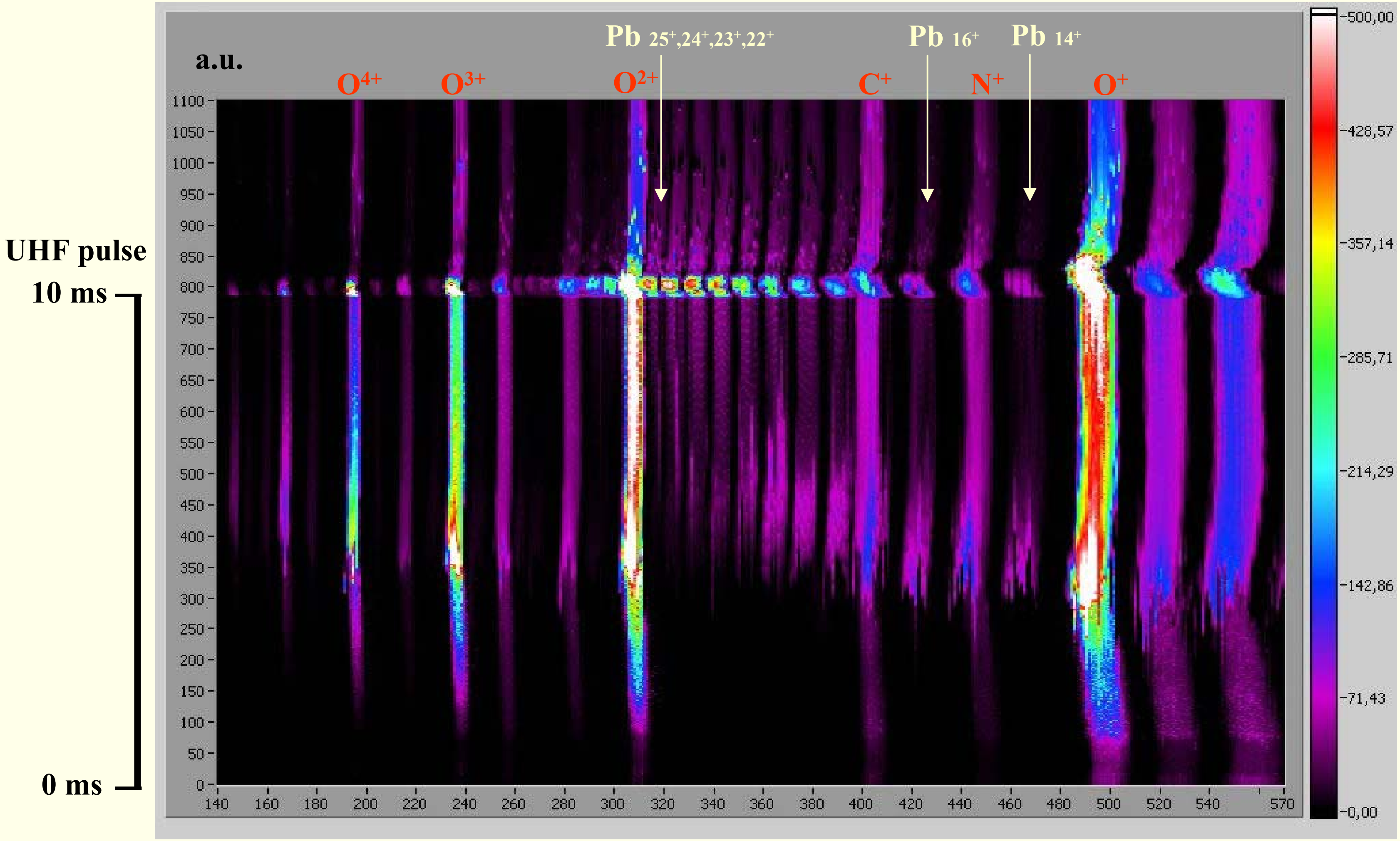
15 emA (I_{HV})

PHOENIX 28 GHz : afterglow control with Lead

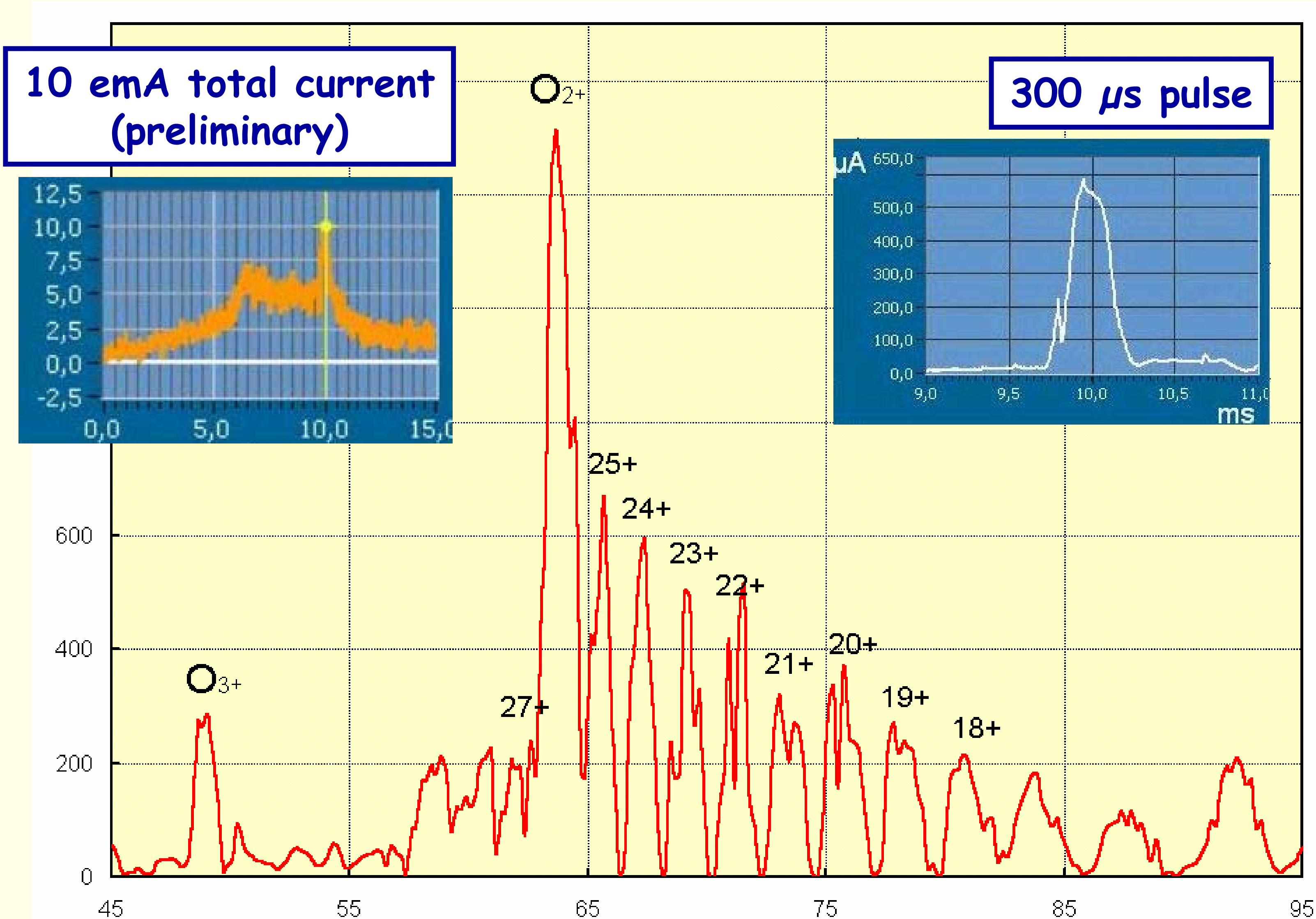
- 55 KV
- ∅ 12 mm electrode



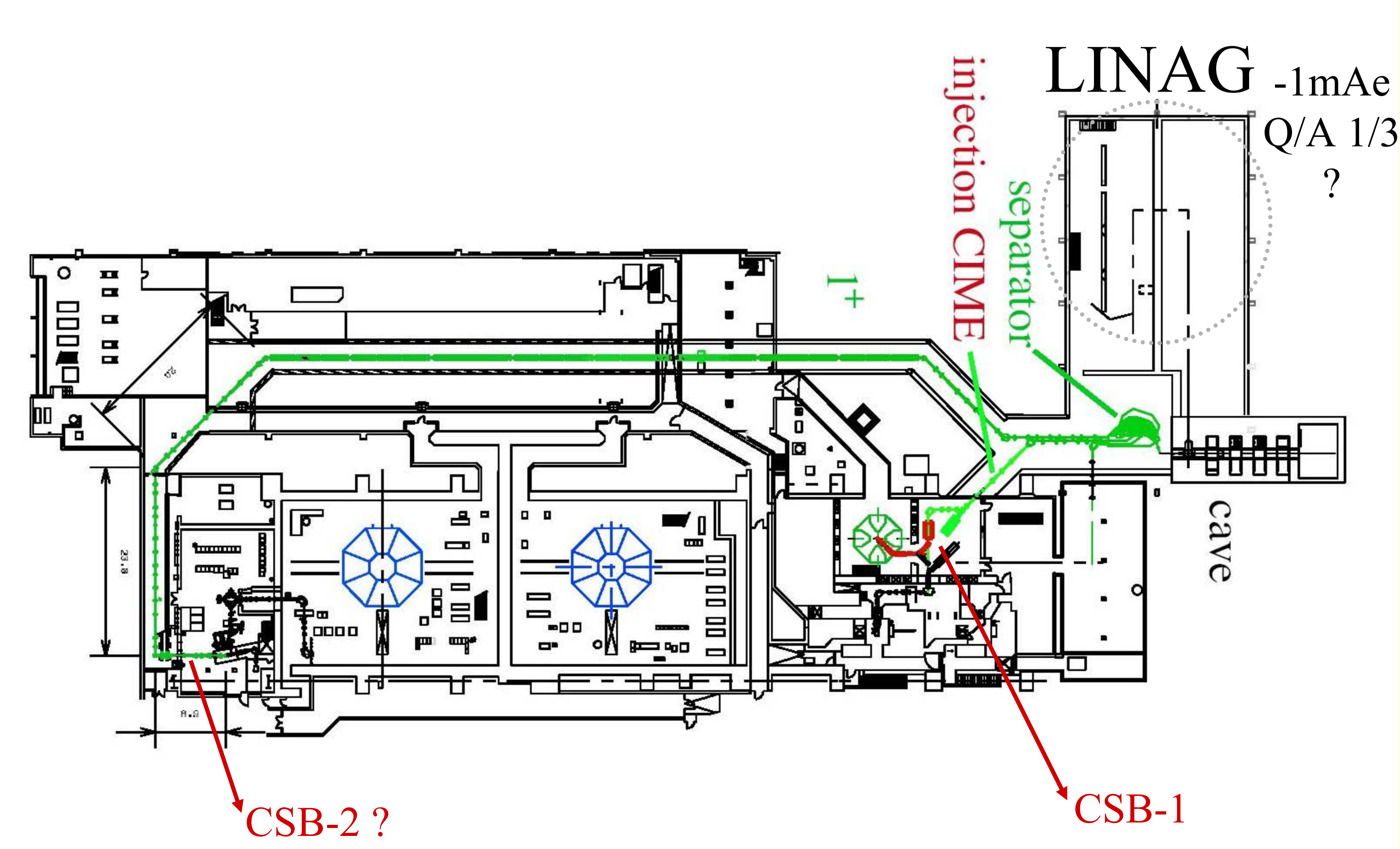
PHOENIX 28 GHz : afterglow control with Lead



PHOENIX 28 GHz : high current extraction (Lead)



Sources ECR et faisceaux secondaires



A-PHOENIX : 2T / 18-40 GHz HTS ECR source

A CW and pulsed compact ECRIS

- An upgraded version of the PHOENIX 28 GHz source

1. *Very compact high field machine for high current production*
2. *Development of a new coil technology for accelerator*
3. *Upgrade of the UHF coupling efficiency*
4. *Upgrade of the confinement for high current and/or high charge state optimization*
5. *Higher B_r for lower UHF Power*
6. *Higher $|B|$ for higher Z*
7. *Multi frequency CW functionning at 18 and 28 GHz*
8. *Pulsed operation at 40 GHz*
9. *Possible application at CERN, GSI, GANIL/LINAG, INFN-LNL, HMI…*

A-PHOENIX : 2T / 18-40 GHz HTS source
20 K compact multipurpose coil for accelerator application

New very compact 20 K cryostat (Φ_{int} 160 mm)
(down to 18 mm between the cold coil and the room temperature vessel)

Prototype coil (tested for 90 A/mm²)

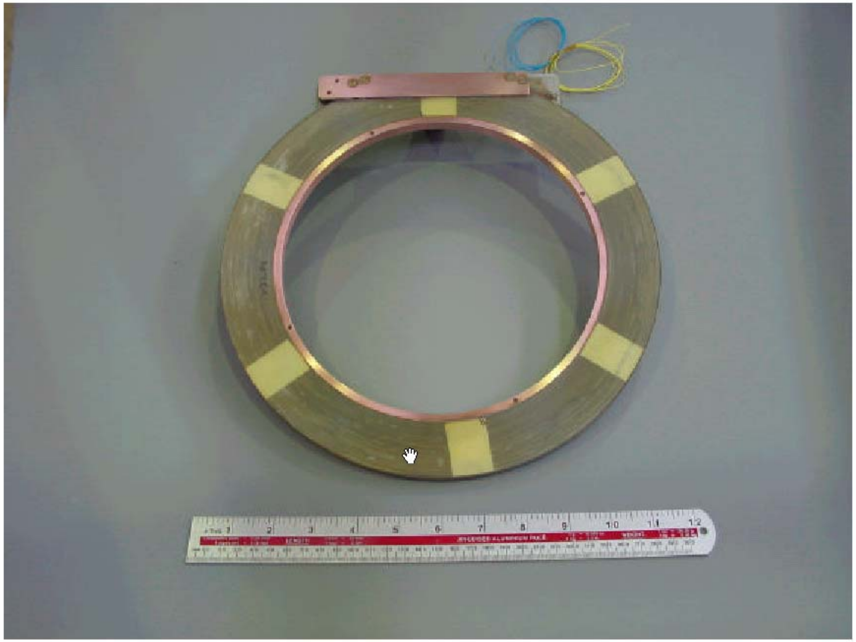
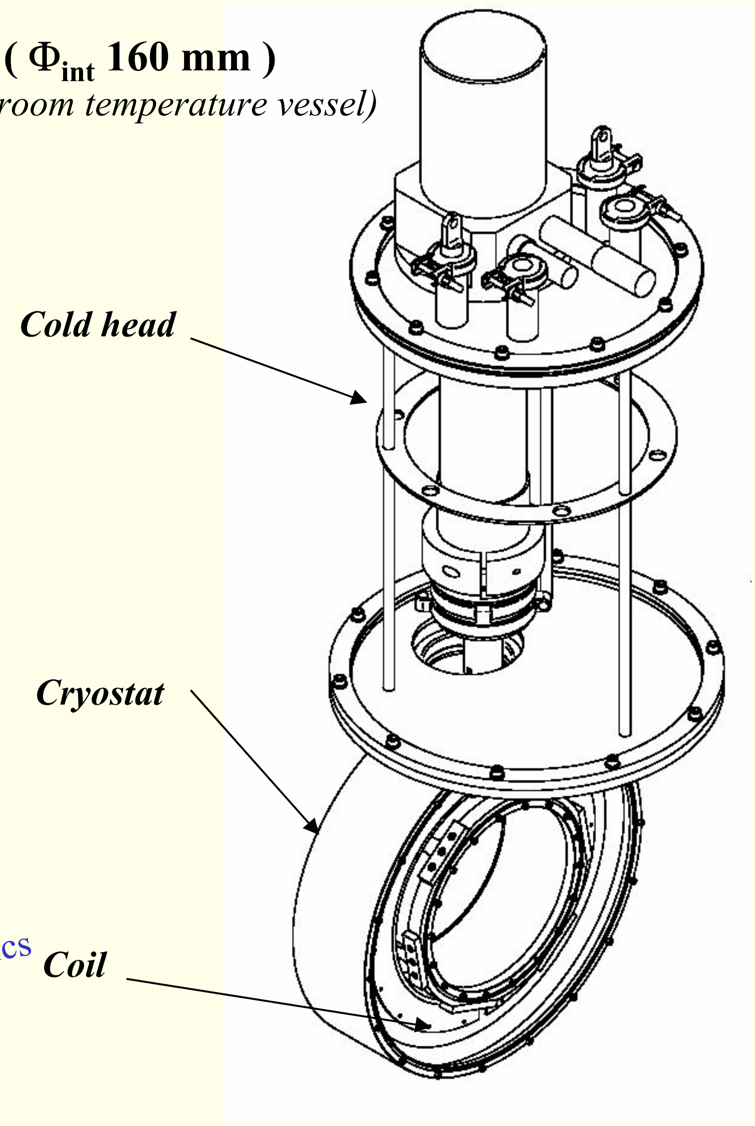
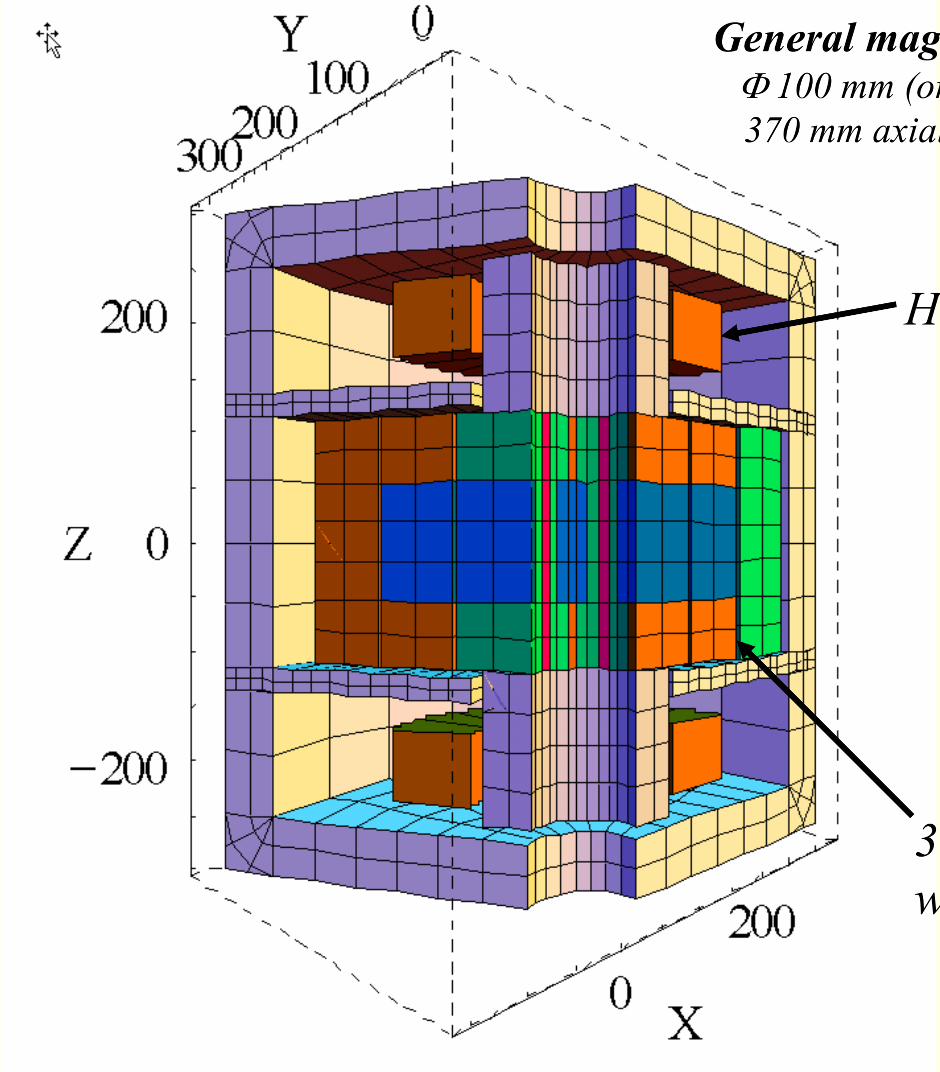


Figure 4: Finished prototype coil



Etudiées par Pantechnik sous contrat
Pantechnik / NSC (New Dehli) / Space Cryomagnetics

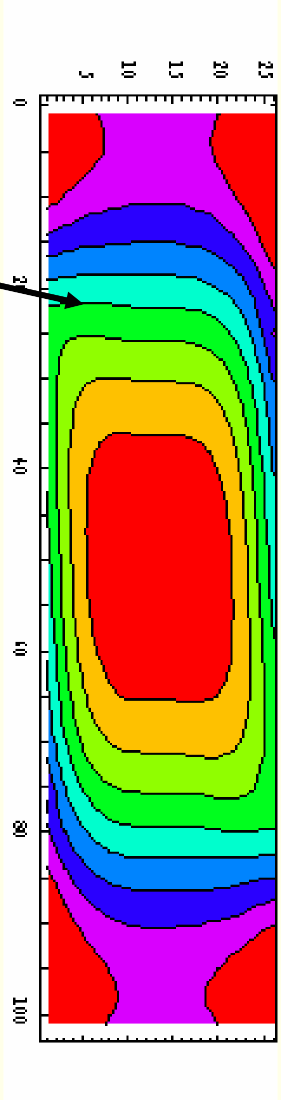
A-PHOENIX : 2T / 18-40 GHz HTS source
magnetic structure



General magnetic structure

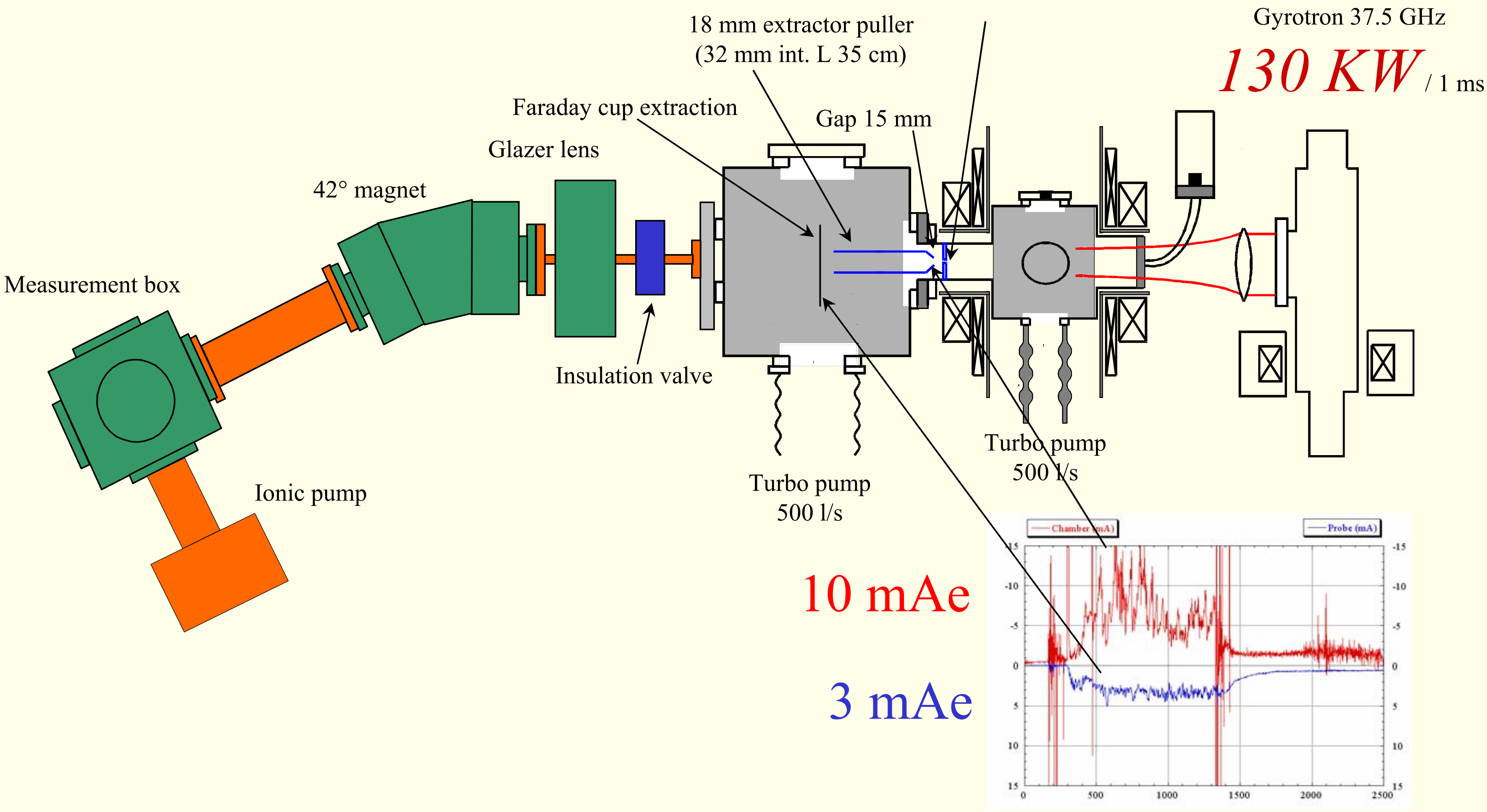
Φ 100 mm (or less) hexapole

370 mm axial mirror system



Simple M irror I on S ource 37 GHz

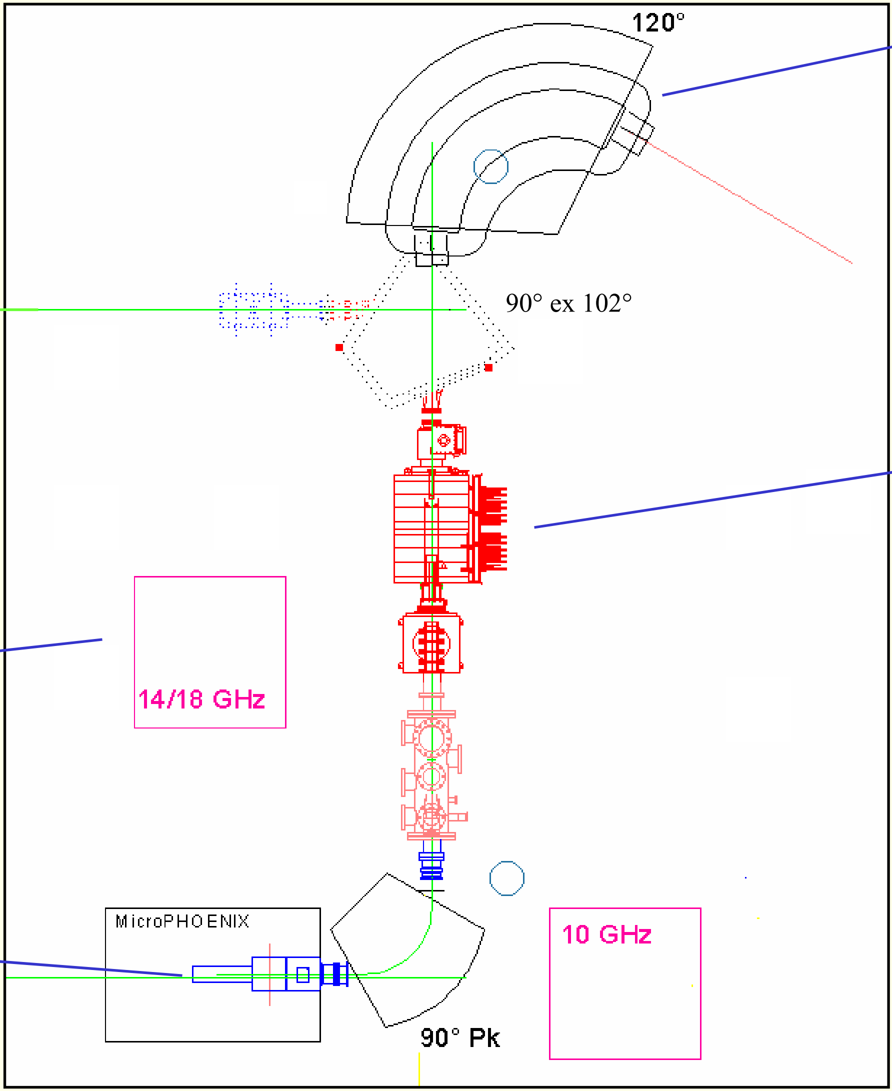
Ø 1 mm extraction hole and no hexapole



ISN / Grenoble

IAP / Nizhny Novgorod

Upgrading of the charge breeding system



Aimant 120° « de Lyon »
R=1000 pour le controle des impuretés et la séparation des très fortes charges

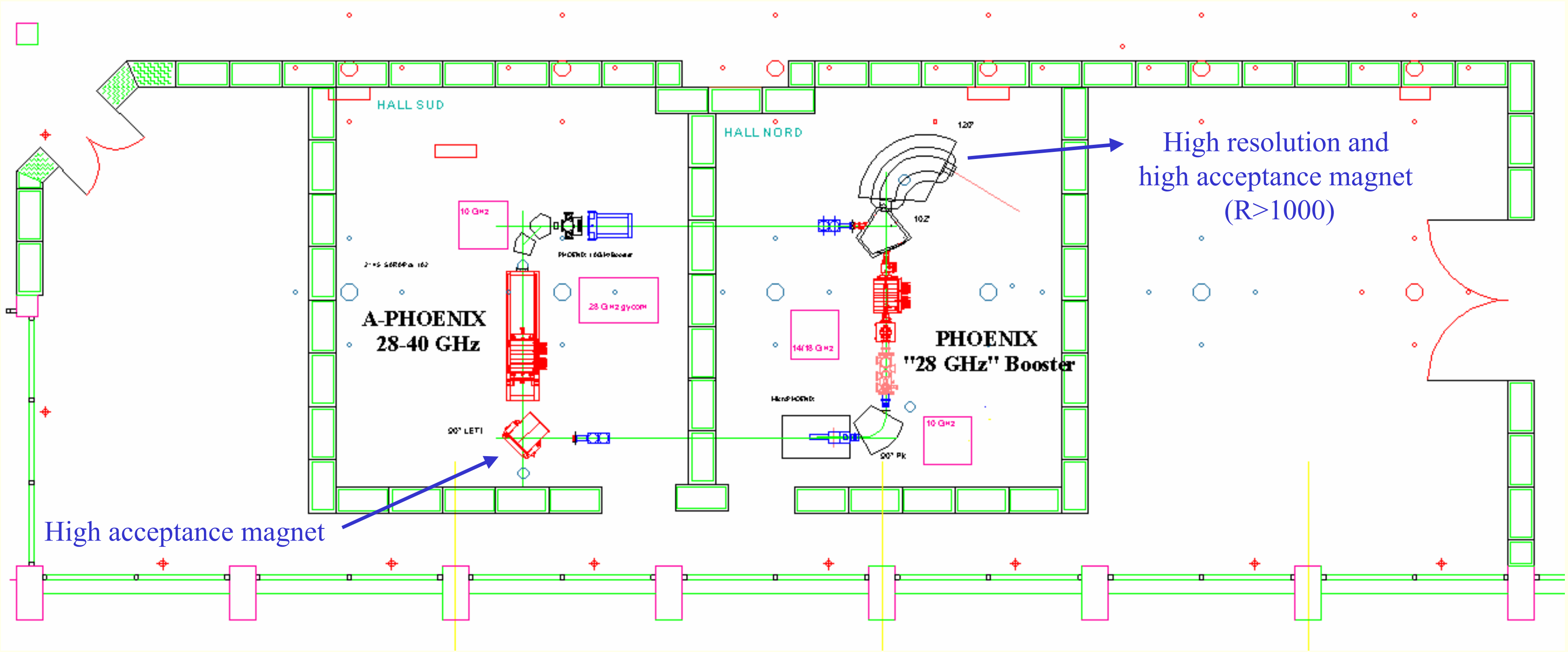
Injection possible dans A-PHOENIX ?
Accumulation ?
Purification ?

PHOENIX 28 GHz devient PHOENIX 18 GHz Booster
Augmentation du <Z>
Augmentation du |B|
Contrôle de la largeur de distribution
Contrôle du temps d'ionisation

Nouvel émetteur
18 GHz

Nouvel injecteur
Mono /multichargés
Hautes / basses intensités
MicroPHOENIX

Test benches at the new ISN/SSI laboratory : new sources and new beam lines
An open laboratory with 4 beam lines for ion source development



SSI "ring" : *4 beam lines with possible retro-injection system*

for the study of the generalisation of the charge breeding / retro injection process on any ECR sources (metallic ion production, multicharged ion accumulation, very high charge state ion production)