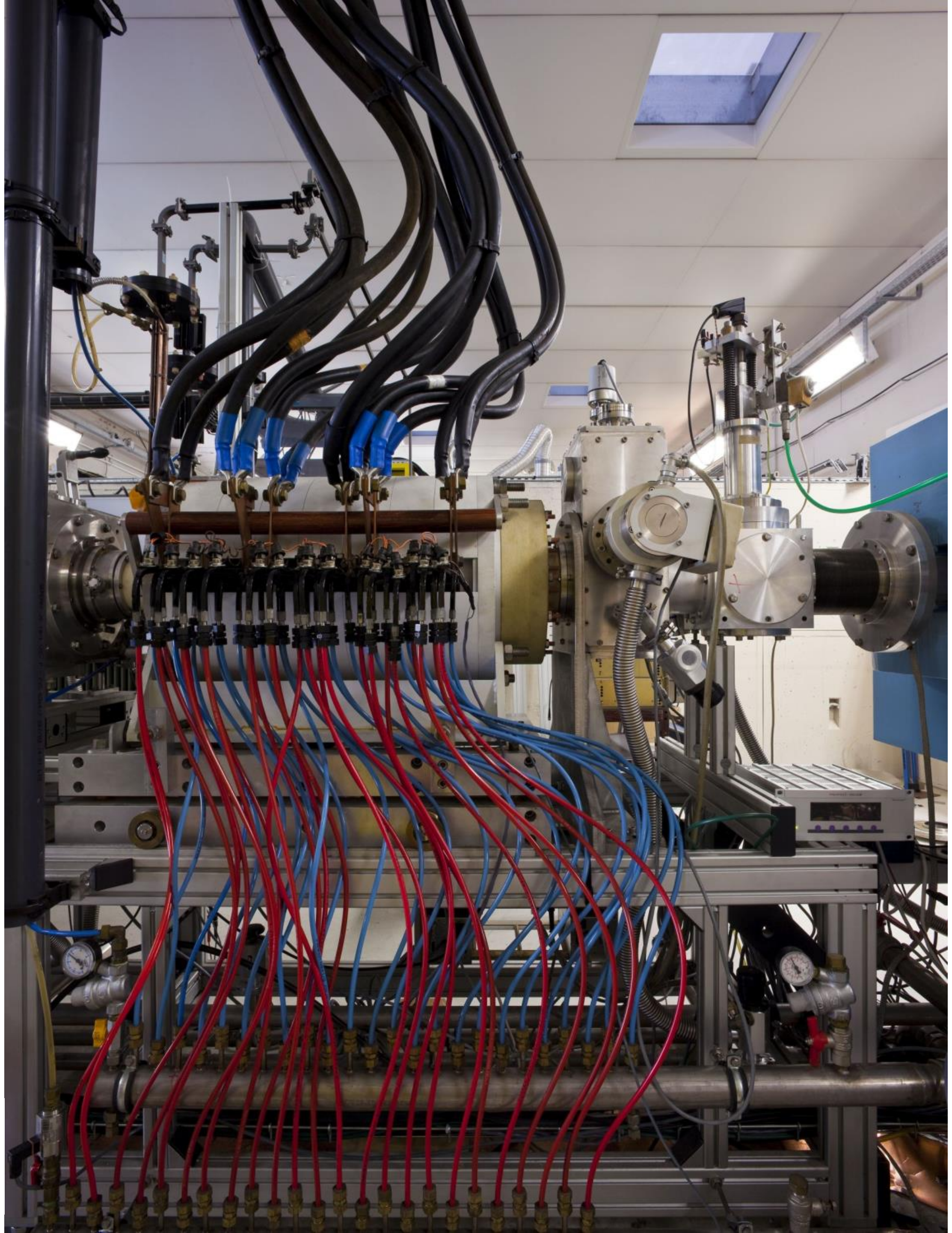
ECR charge breeding
of radioactive ion beams

J. Angot - LPSC
P. Chauveau - GANIL

Workshop on R&D for new ISOL beams at SPIRAL 1 and ALTO
Caen – March 12, 2025

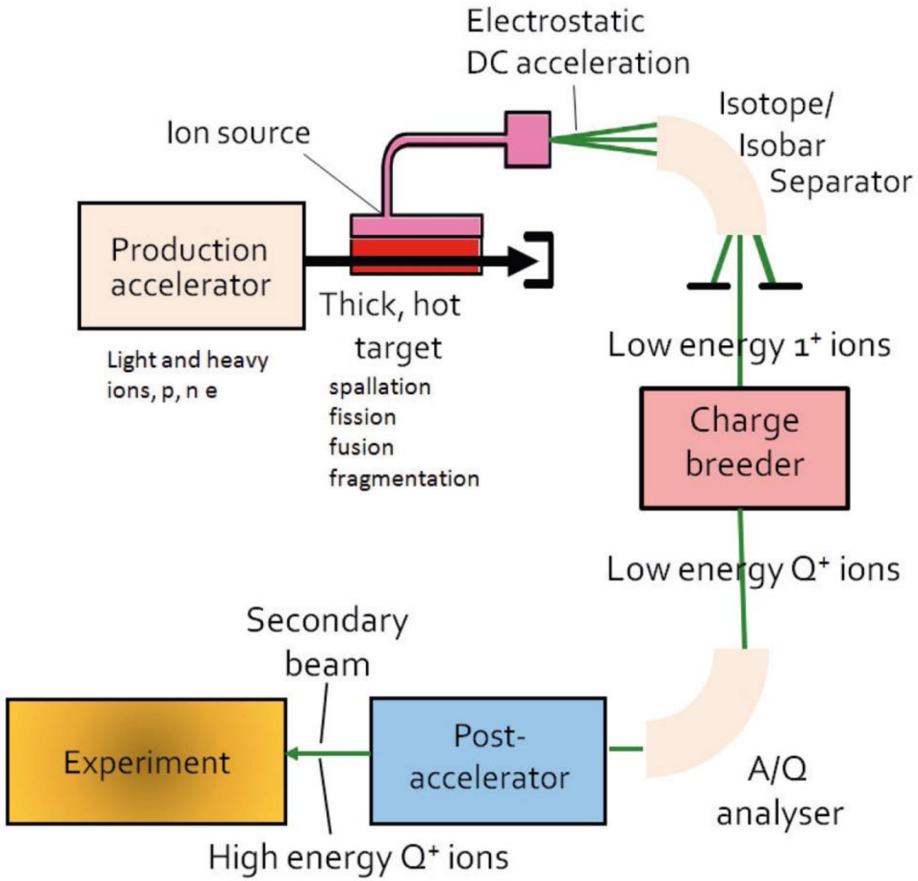


Outline

- Introduction
- Electron Cyclotron Resonance technics
- ECR CB : R&D
- ECR CB : short term plans
- Conclusion

Introduction

Principle of the Isotope Separation On Line method

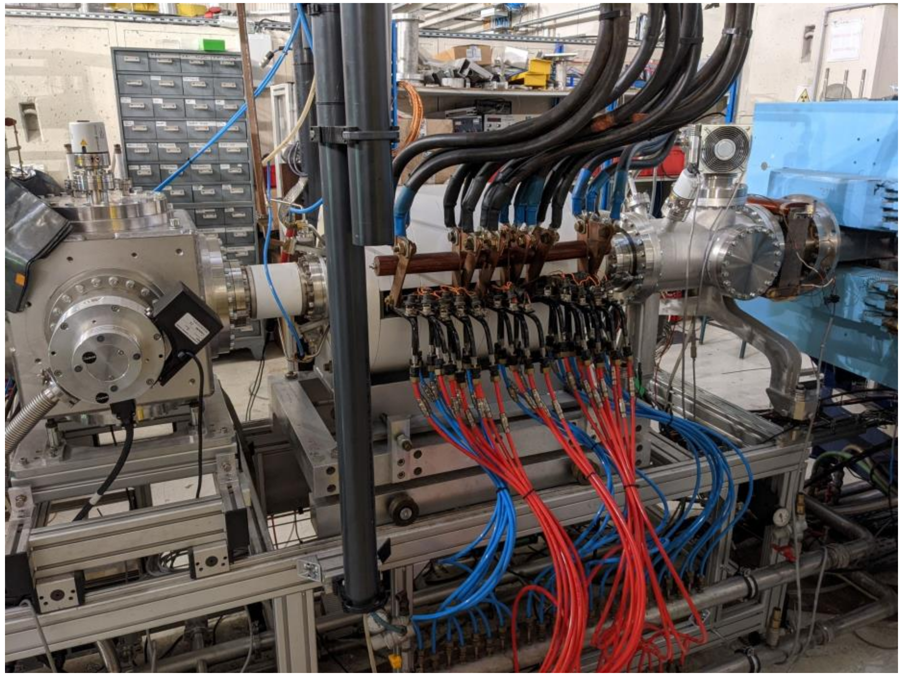


PHOENIX CB

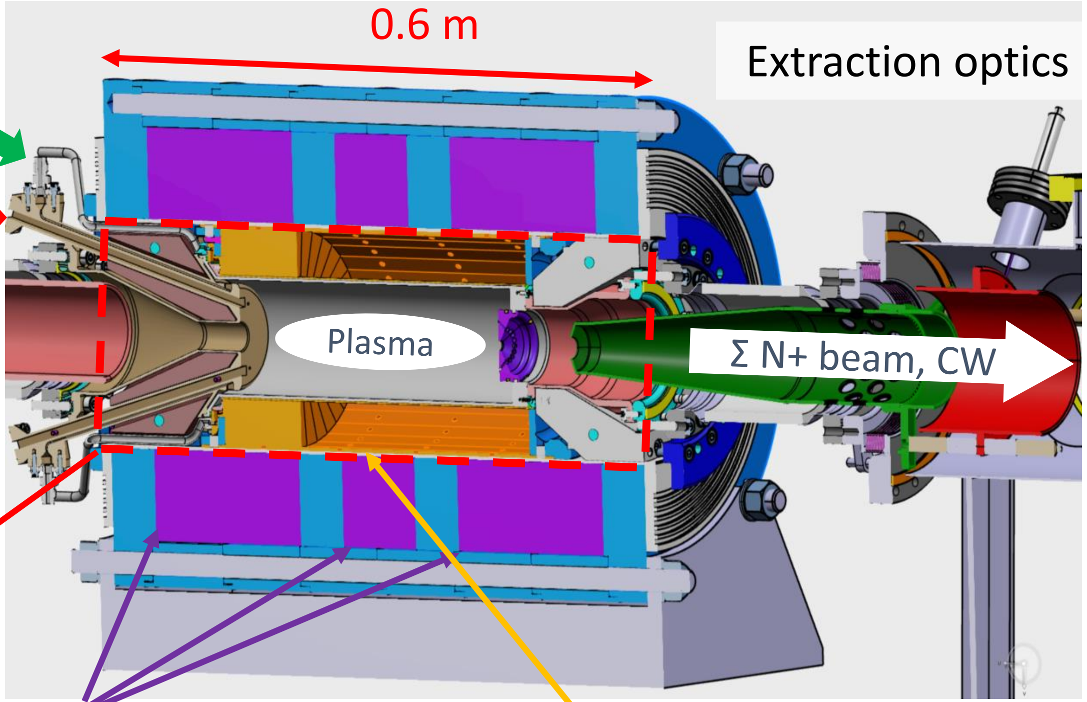
- PHOENIX CB, under development at LPSC since 2000

European context :

- ➢ 3 versions presently installed at GANIL, LNL and LPSC (R&D)



ECR technics

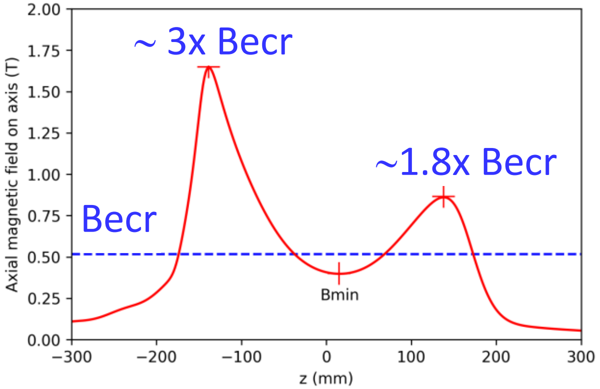


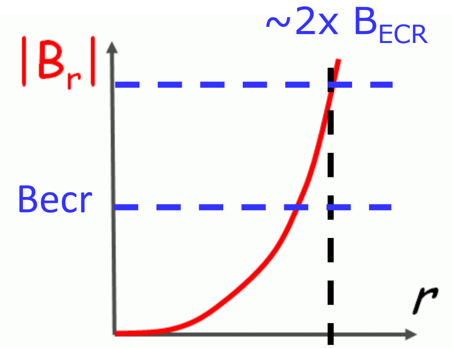
- Complex magnetic structure to trap the charged particles (magnetic mirror)
- Microwave injection to heat the electrons (electron cyclotron resonance)

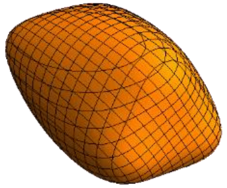
$$2\pi f_{RF} = \omega_{ecr} = \frac{eB}{m_e}$$

$$B_{ecr} \approx 0.52T \ @ \ f_{RF} = 14.5GHz$$

- Ionization by electron impact
- High charge state ionization through step by step process
- Limitation due to charge exchange with neutrals and deconfinement
- Extraction by electric field







To Increase the high charge state production :

- ↑ ne which scales with $\omega_{ecr}{}^2$
- ↓ residual pressure

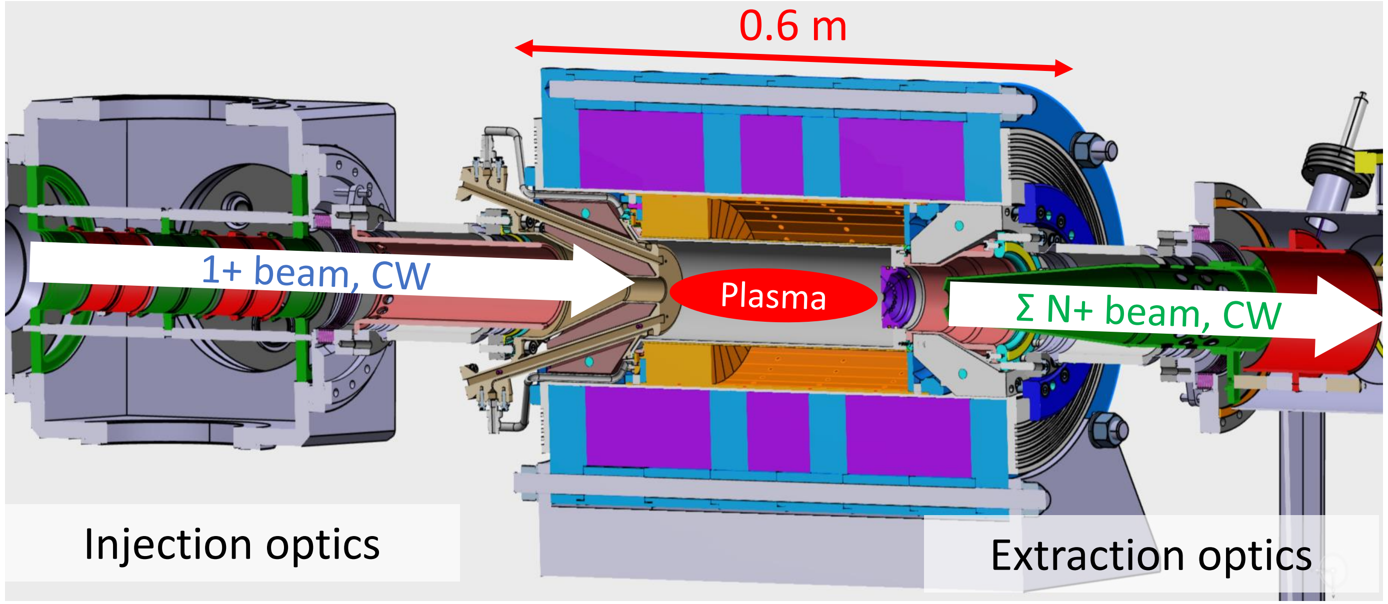
Increasing ω_{ecr} means increasing B field following ECR ion sources B field scaling laws = at the cost of increasing B field

$$B_{inj} \approx 1.6T \ @ \ f_{RF} = 14.5GHz$$

$$B_{inj} \approx 3.0T \ @ \ f_{RF} = 28GHz$$

ECR CB : PHOENIX CB

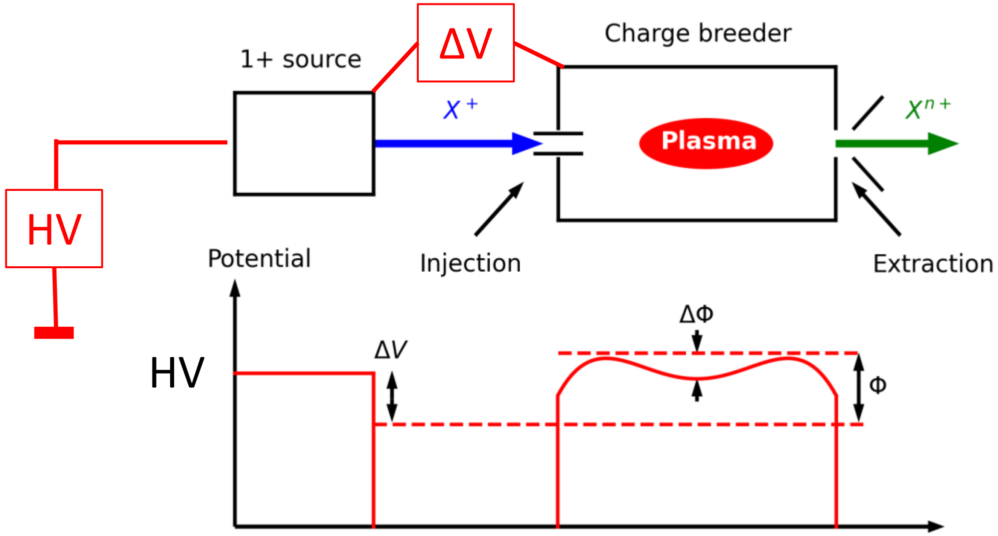
Modified min-B ECR ion source

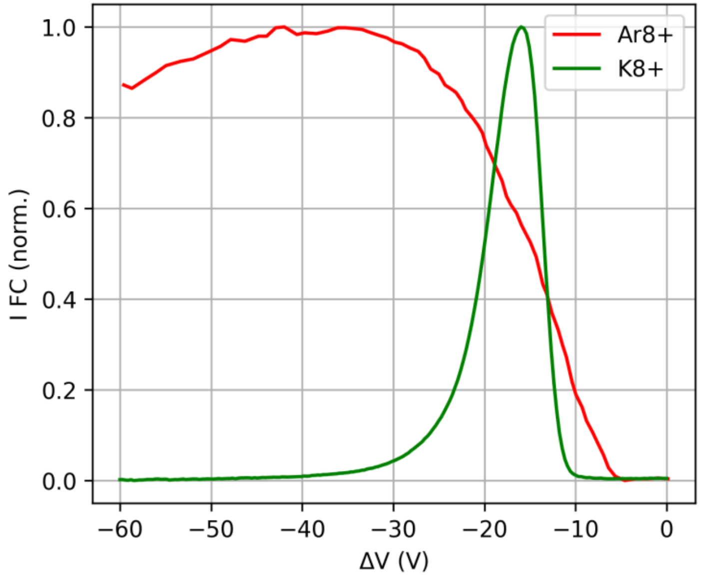


14.5GHz – 600W
Room temperature coils
Permanent magnet hexapole (1T at wall)
Binj : 1.7T Bext : 0.9T
HV: 20 – 40kV
CW or pulse mode

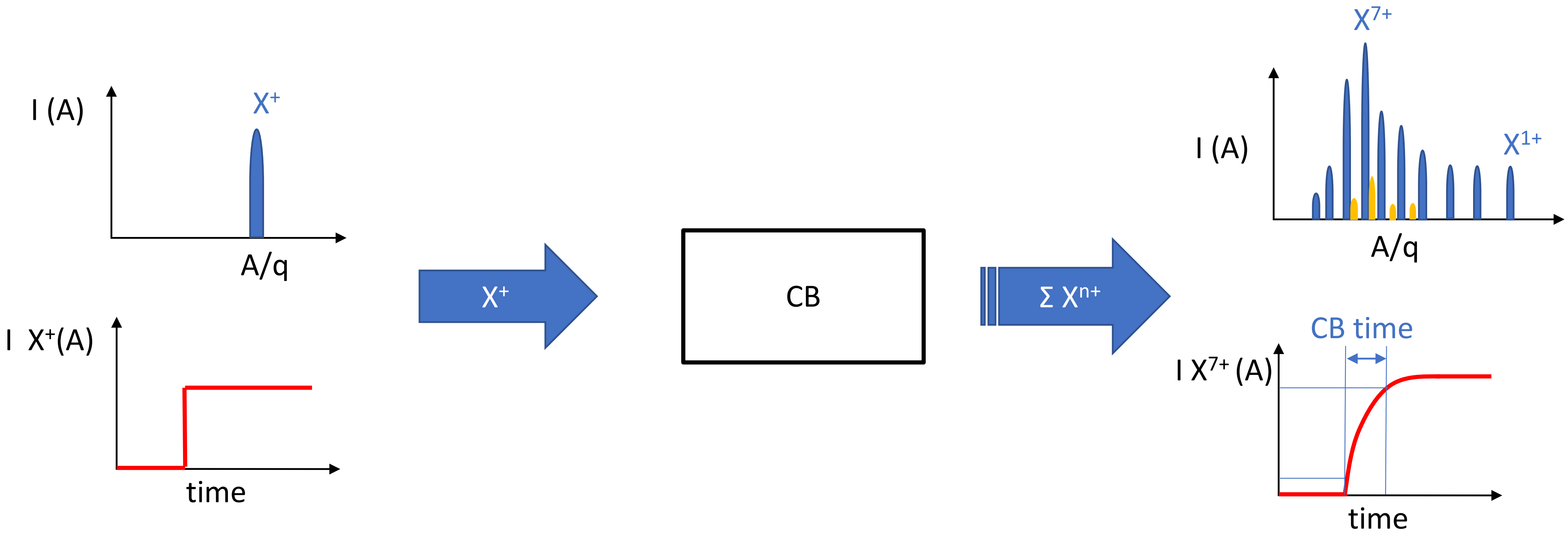
Capture process :

- Slowing down by CB potential and plasma potential
- Capture by potential dip or Coulomb collisions
- Multi ionization by electron impact





ECR CB : characteristics



Performances

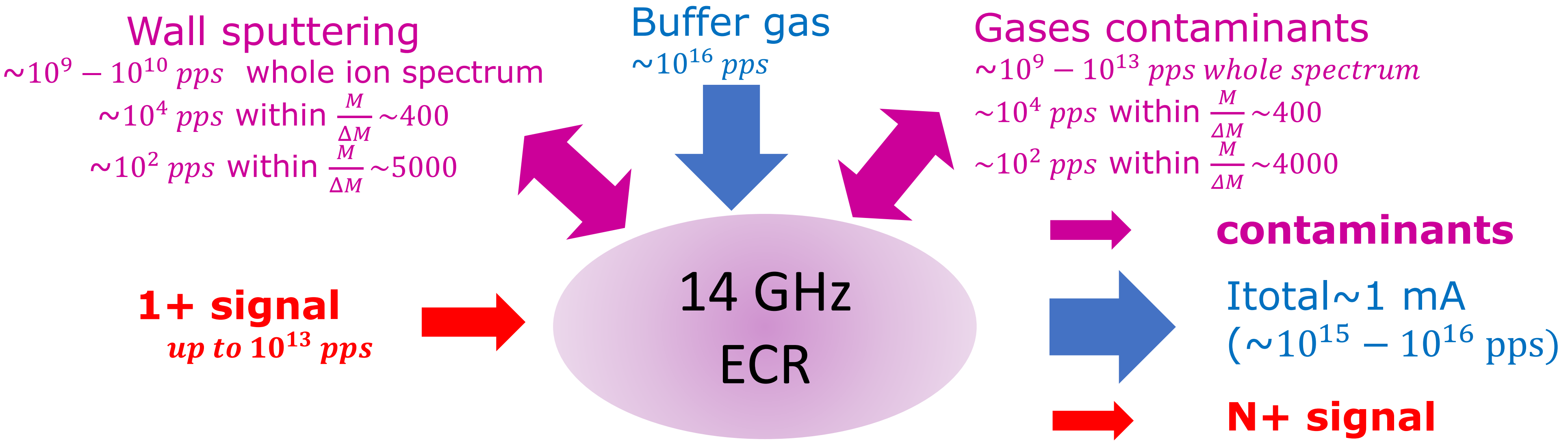
- Efficiency : $\eta = \frac{i(X^{q+})}{q * i(X^{+})}$
- Process Time
- Beam purity
- Beam quality

ECR CB characteristics :

- Operate in CW or pulsed mode
- Robust instrument
- High 1+ flux acceptance > 10^{13} pps

ECR CB : beam purity

Orders of magnitude



- **Signal** to **noise** ratio is a key parameter for ECRIS CB at low RIB intensity:

T. Thuillier
ECRIS 2018 workshop

	Signal (pps)	10^3	10^4	10^5	10^6	10^7
For $\frac{M}{\Delta M} \sim 300$	Signal/Noise	0.01	0.1	1	10	100
	N+ RIB fraction	0.9%	9%	50%	91%	99%
For $\frac{M}{\Delta M} \sim 6000$	Signal/Noise	1	10	100	1000	10000
	N+ RIB fraction	50%	91%	99%	99.9%	99.99%

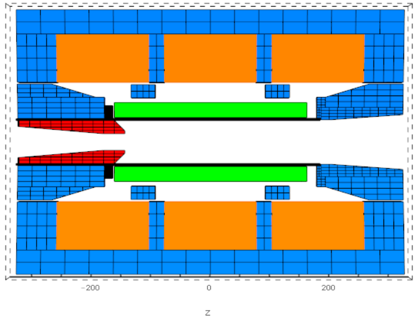
Considering the RI species to be produced, a fine analysis can be done to determine the possible contaminants, select the appropriate charge state and estimate the contamination yield

ECR CB R&D

- LPSC – GANIL collaboration on ECR CB performances in the frame of the« ions radioactifs » IN2P3 master – project
  2015 - 2025

- GANIL - LPSC – LNL collaboration for the contaminants reduction (in particular LPSC – LNL research collaboration agreement)
  2017 - 2024

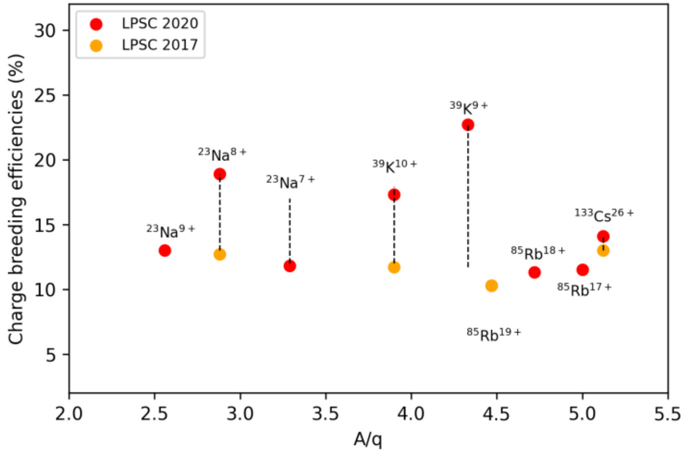
ECR CB R&D - LPSC

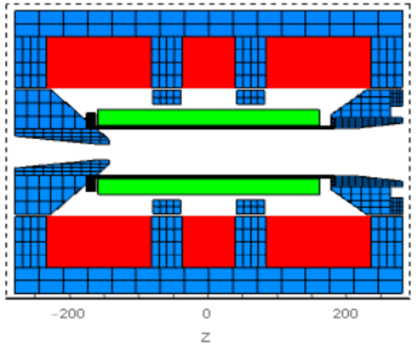


6 coils configuration

- ➢ Enhance 1+ beam capture
- ➢ Efficiency increase with better confinement
- ✓ Optimisation of injection optics
- ✓ Reinforced injection B_{inj} 1.2 → 1.6T:
- ✓ Optimisation of axial field profile (rings pos., coils tuning)

2018-2022

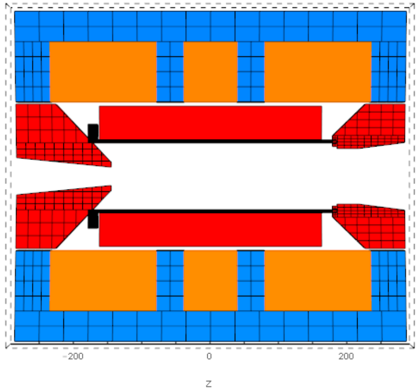




5 coils configuration

- ➢ Ease the tuning and stabilize the plasma
- ➢ Study CB contamination issue
- ✓ Improve the axial magnetic field profile
- ✓ Decrease the cross talk between the coils
- ❖ Plasma chamber failure in early 2024

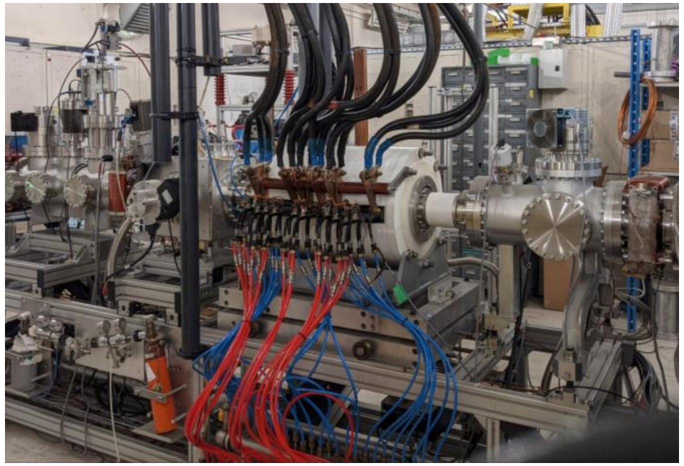
2023 - 2024



Large diameter configuration 72 → 100mm

- ➢ increase high charge state production
- ➢ decrease the density of contaminants
- ✓ Increase the plasma volume
- ✓ sealing exclusively with metal gaskets
- ✓ 18GHz operation, two frequency heating
- ❖ Qualification under progress

Since 2024



ECR CB R&D - GANIL

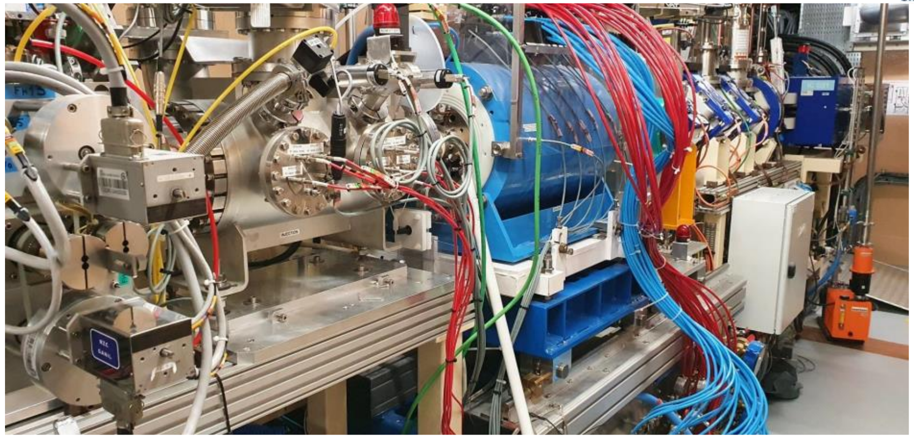
SPIRAL1 CB modified by GANIL and qualified at LPSC in 2015

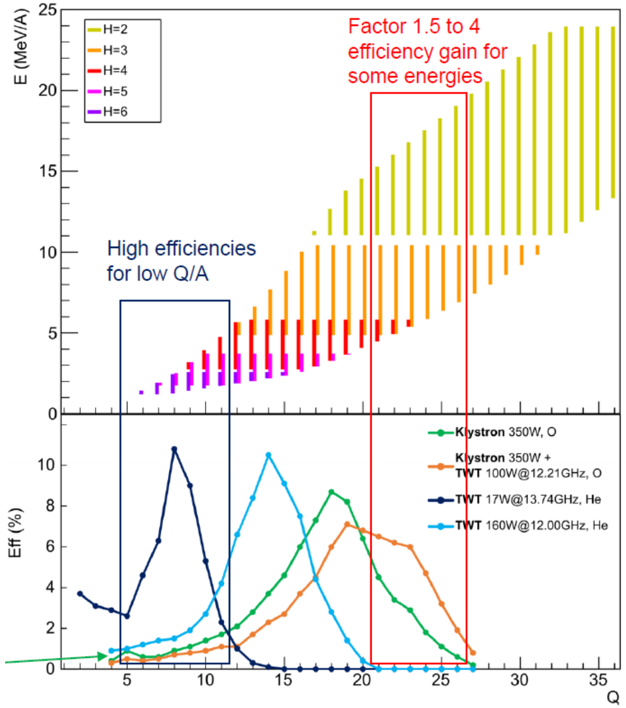
Optimisation of the CB configuration to enhance the CB efficiency
- Plasma electrode location
- Reinforced injection B_{inj} 1.2 $\rightarrow$ 1.45T
- Axial B field
- Support gas (He, H_2)

Injection optimisation
- 1+ Optic beam injection simulation/optimisation
- Blind tuning for radioactive ions
- Molecular experiments
- Capture simulations

Plasma heating studies to increase global efficiency at different final energy
- Single frequency tuning for low charge states
- Double frequency heating for high charge states

Radioactive Beams :
- 2019 : 38K1+/8+ @9MeV/u
- 2021 : 47K1+/10+ @7.7MeV/u
- 2021 : 42Cl1+/9+ @ Identification station





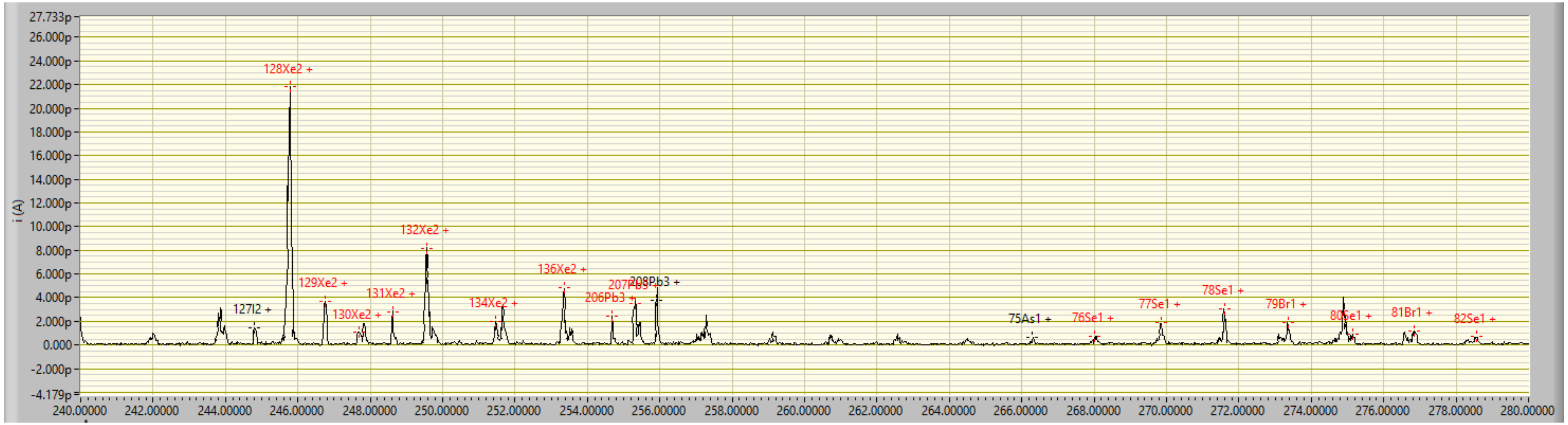
^{84}Kr

Maunoury, ECRIS2022 talk

ECR CB R&D – purity issue

Enhancement of the 1+N+ beam line diagnostics to measure the purity

- Upgrade of the beamline (UHV vacuum sealing, improvement of surface conditions)
- Improved the spectrometer (command resolution, Hall probe with temperature compensation)
- Developed instruments : channeltron detectors to improve sensitivity
- Developed an analysis program to identify the species



Dipole Bfield (mT)

Identified contaminants with different origin :

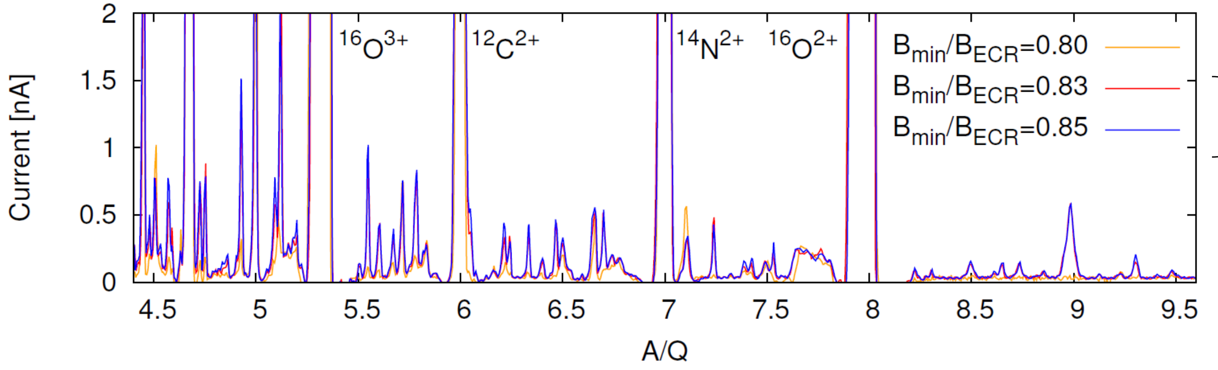
- Sputtering : Zn, Fe, Al, Ni, Br, Ag..
- Air pollution : As, Pb, S, C..
- Residual vacuum : Ne, Xe..
- Cleaning products : Cl, C..
- Previously injected elements : Na, K …

- ➢ CB venting : not with air, with noble gas
- ➢ Venting injecting the gas into the plasma chamber
- ➢ Improve the vacuum sealing (now 10^{-8}mbar res. vacuum)
- ➢ Enhance the parts cleaning
- ➢ Use pure mono-isotopic liners in front of the plasma
- ➢ Keep the CB clean (inject only the necessary species)

ECR CB R&D – purity issue

Plasma stability : ECR plasma instability comparative experiments demonstrated the increase of impurities coming from the wall sputtering (SS 316L plasma chamber and AUG plasma electrode)

- Identification help : discriminate wall sputtered vs gaseous elements

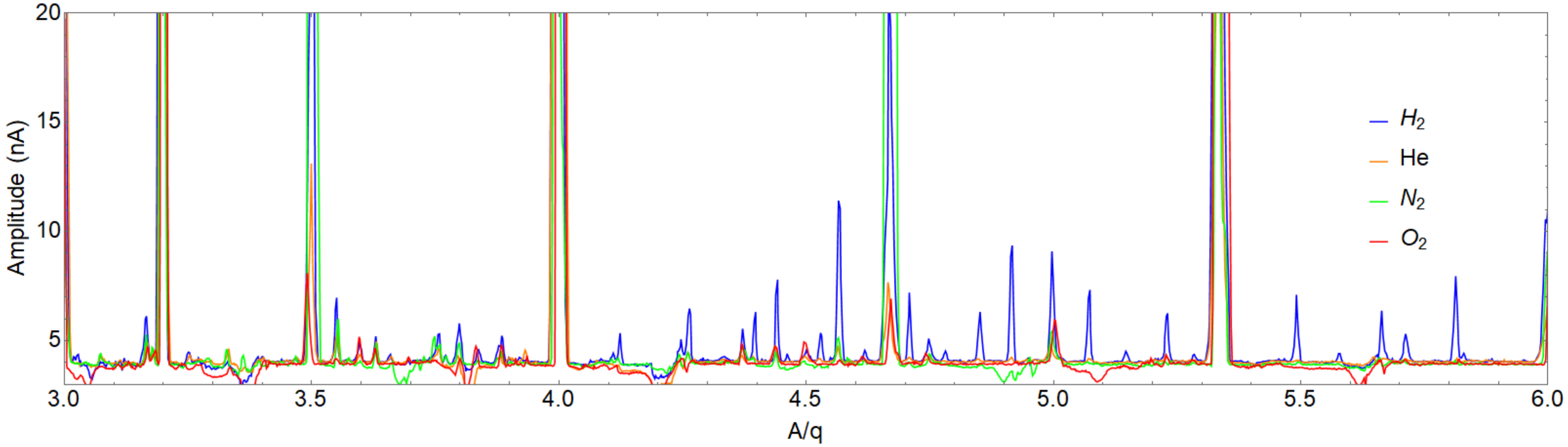


Stable Oxygen plasma

Unstable regime increases the contaminants yield

O. Tarvainen et al.
https://doi.org/10.1063/1.5053348

Support gas species : CB operated at 600W



Hydrogen highly increases the contaminants yield

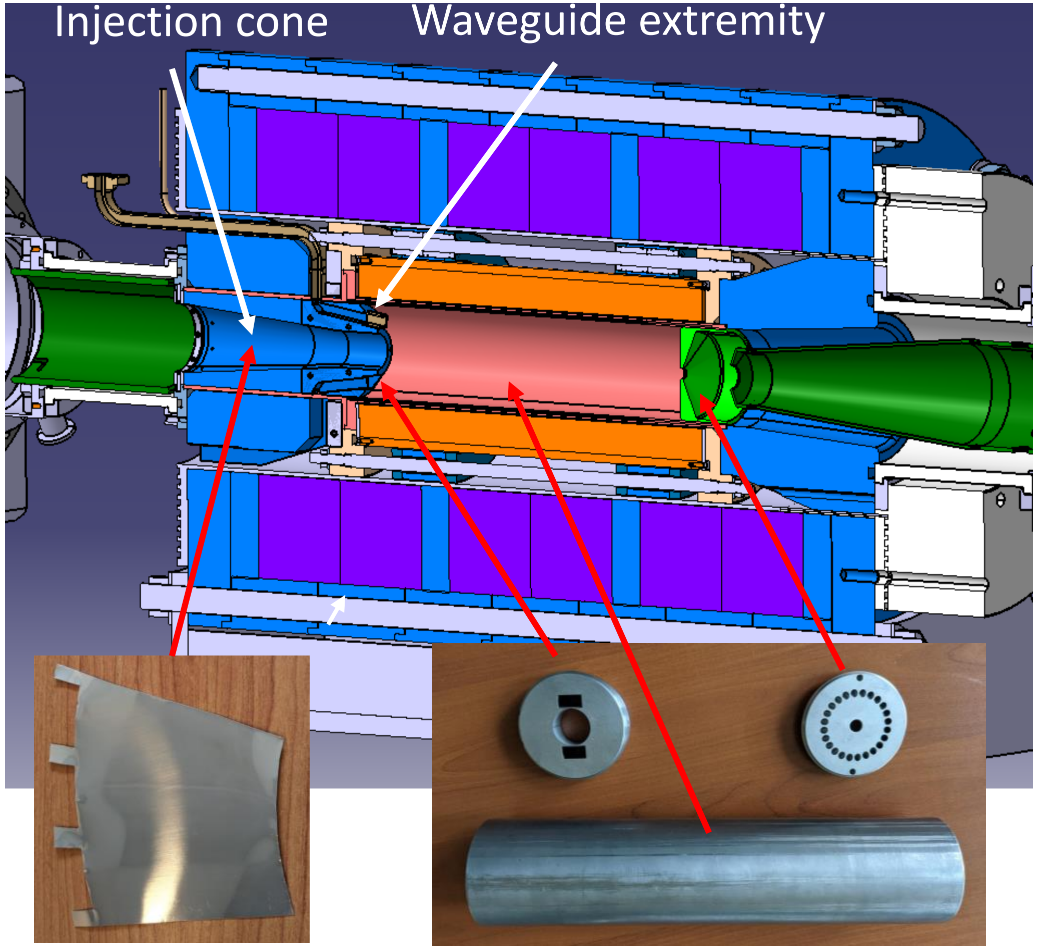
J. Angot talk
NACB workshop 2020, remote

During the CB conditioning phase : operate the CB in unstable regime with H_2 as support gas for cleaning
In operation : operate the CB in very stable regime if possible with He (lowers efficiency)

ECR CB R&D : purity issue

Liners experiments:

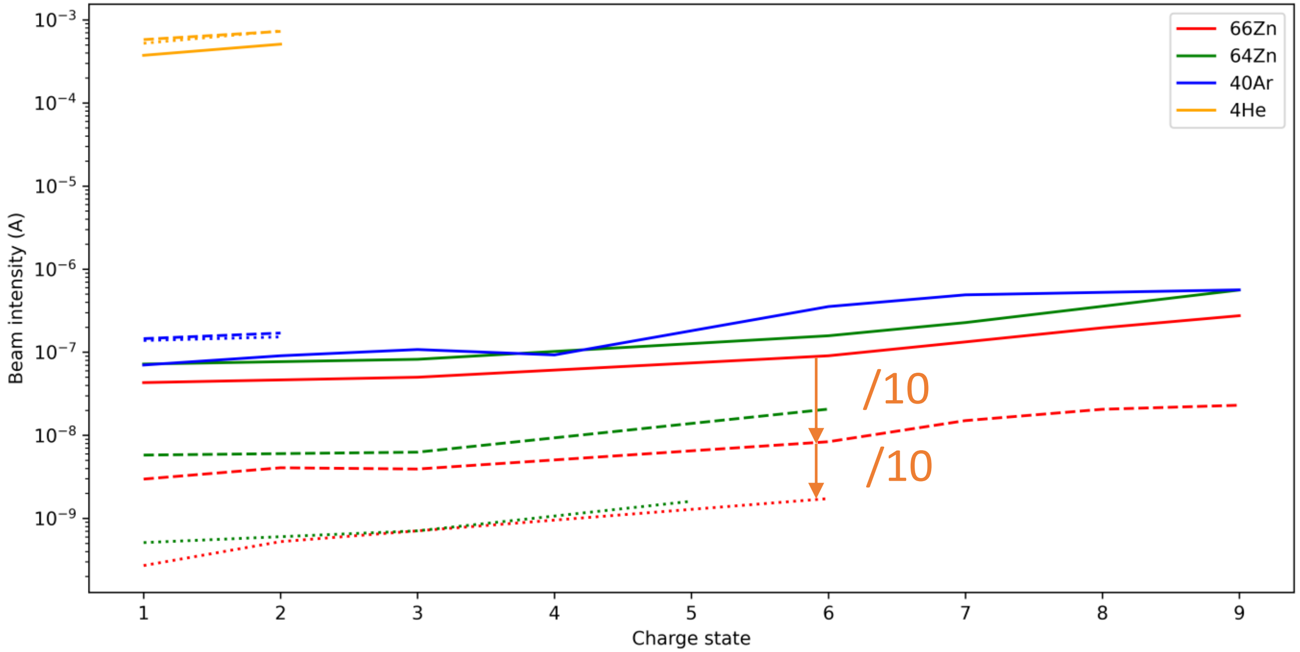
- CB operated as a source with He as support gas, 550W
- CB tuned to produce 400µA He^{2+}



Solid: Nb Liner

Dashed : Nb Liner + Ta on injection cone

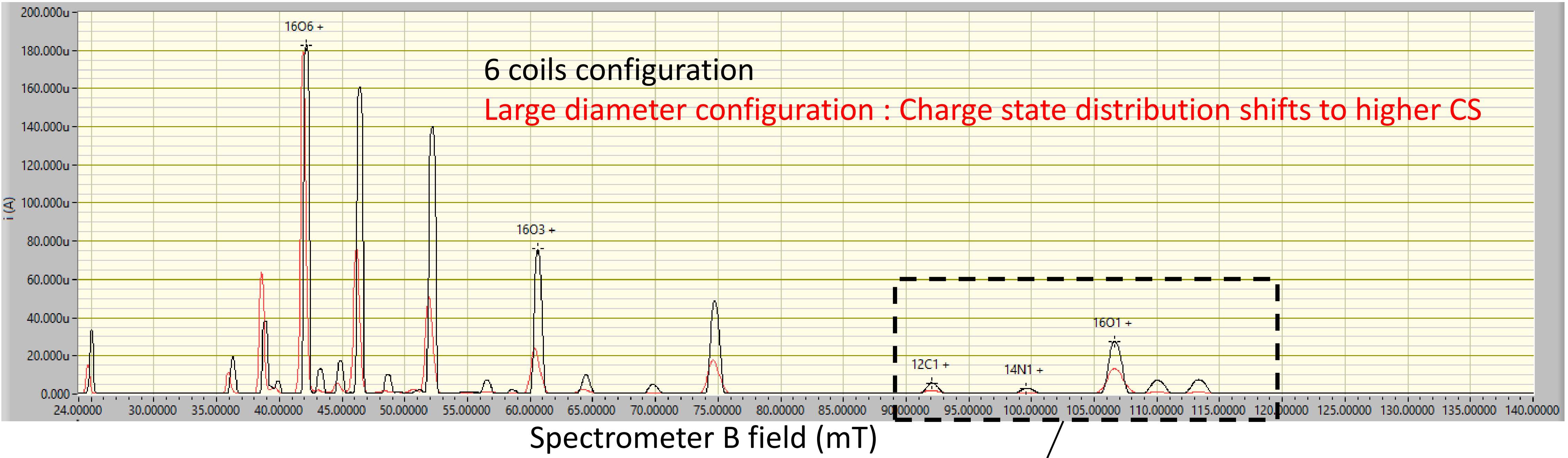
Dotted : Nb liner + Ta on injection cone and waveguide extremity

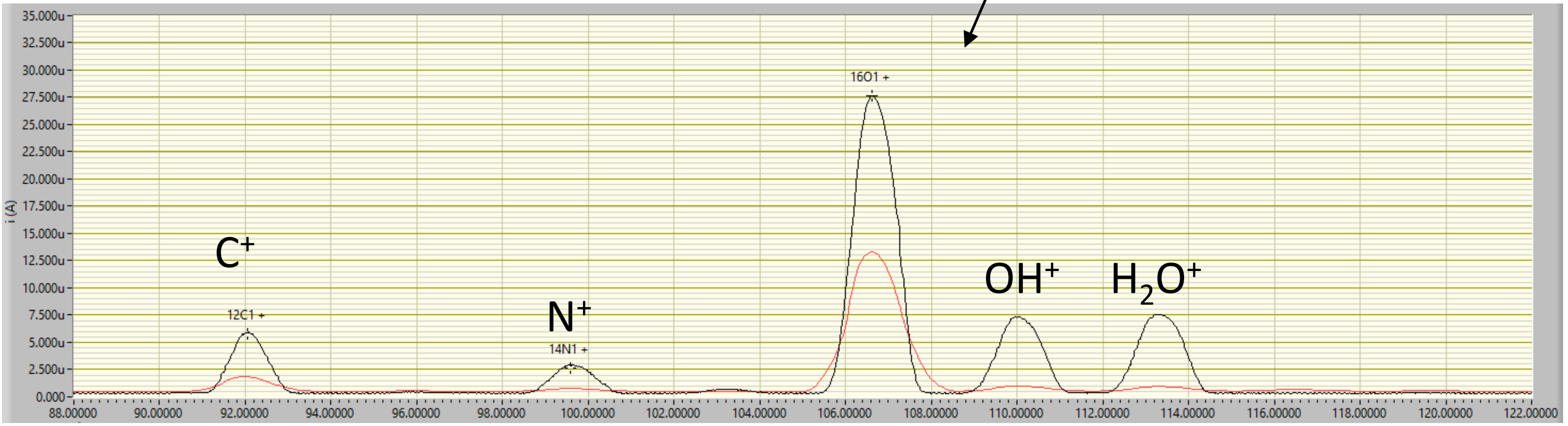


- Unexpected surfaces identified as source of contaminants by sputtering
  - ➢ Necessary to cover them with Nb liners
- CB operation with Nb liners OK (source mode)

ECR CB R&D : purity issue

Large diameter configuration : Oxygen plasma at 500W





Great reduction of contaminants , factor >2

ECR CB R&D

R&D on ECR CB by GANIL and LPSC lead to improve the performances :

- Efficiency increase now ranging 10 – 15 % for all the masses
- CB time unchanged 15 – 30 ms/q
- Better understanding of purity issue

ECR CB short term plans

Proposition of a new IN2P3 project to improve the beam purity (+ enhance high charge state production ?)
Starting in 01/2026

- Optimize the magnetic configuration to reduce the sputtering into the plasma chamber (studies)
- Use of ultra pure mono isotopic liners, improve the initial surface finish
- Improve residual vacuum
- Make support gas decontamination

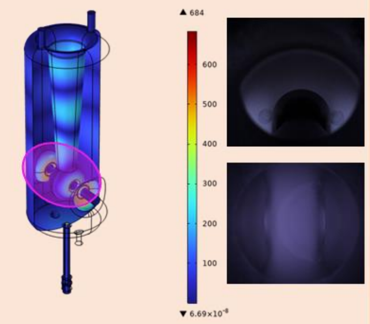
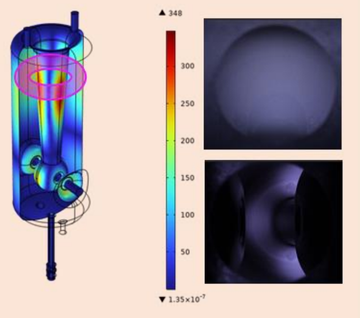
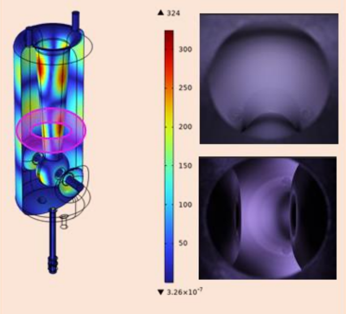
- Develop online technics to reduce contamination, to be applied before RI production :
  - ➢ Plasma cleaning of internal surfaces
  - ➢ Coating of the surfaces : Atomic layer Deposition of ultra pure Al_2O_3 (Argonne National laboratory idea)

- Adapt these technics to the GANIL CB

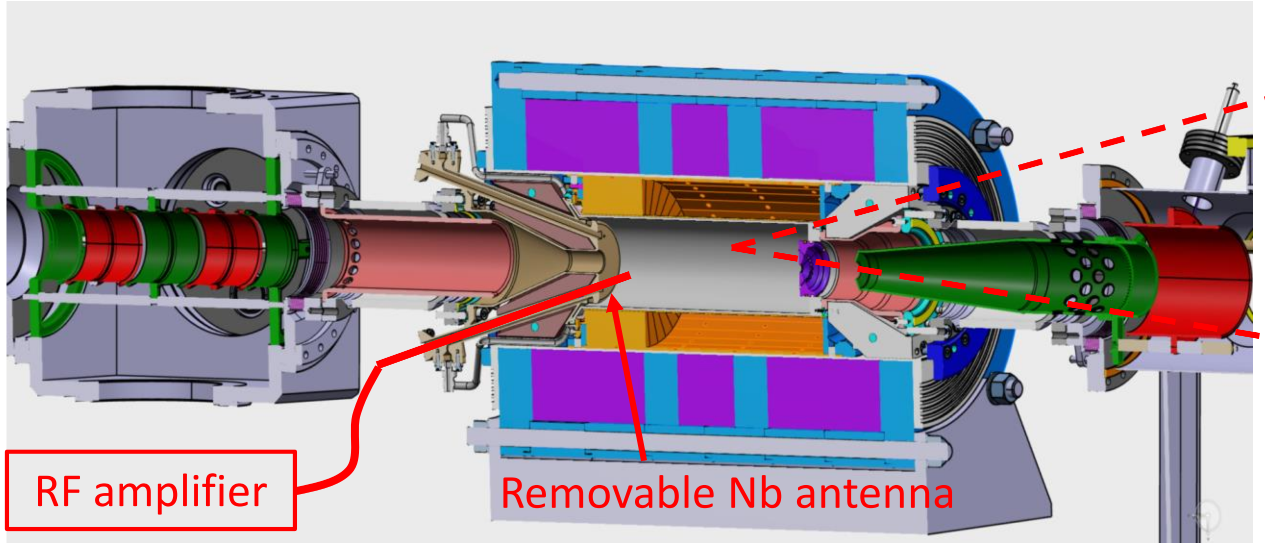
ECR CB short term plans

Plasma cleaning : benefit from the RF accelerator cavities cleaning technics (DECAP project)

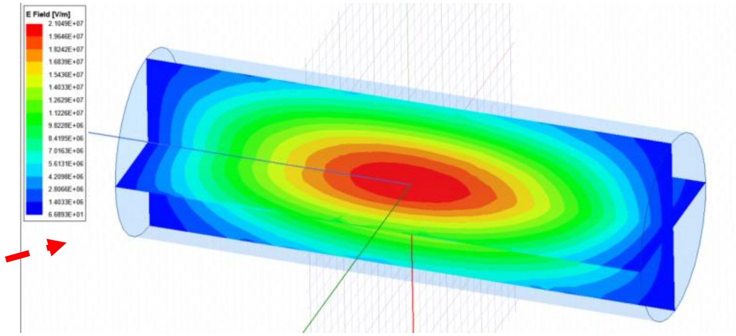
- Use high purity Nb liners
- Ignite a plasma using the cavity resonant frequencies, at high pressure with mixed gas species (Ar/O_2)
- Change the coils tuning, coils polarity, resonant mode … to treat a maximum surface
- Cleaning by ion bombardment to detach the contaminants and pumping of atoms or molecules (chemical reactions)

	Mode 11 – 683 MHz	Mode 16 – 767 MHz	Mode 19 – 857 MHz
COMSOL E-field surface plot Plasma location			

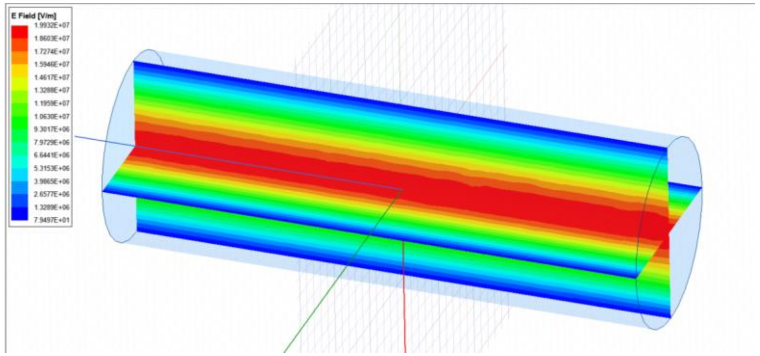
C. CHENEY project presentation, IJCLab



TE111 at 1.869GHz



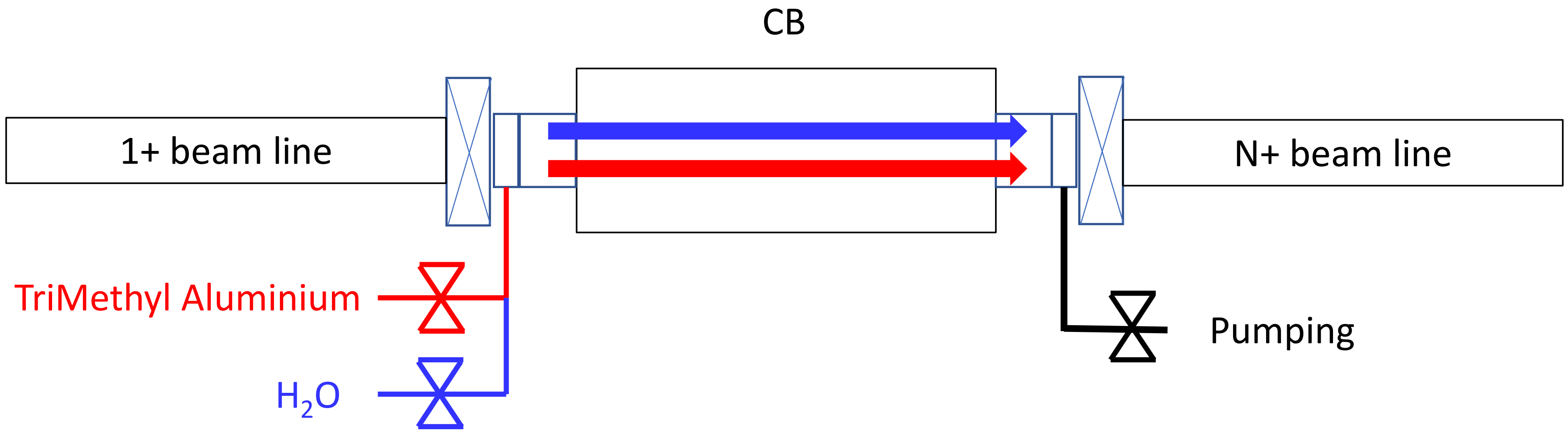
TM010 at 2.342GHz



ECR CB short term plans

Online surface coating by ALD (Argonne National Lab. original idea)

- Preliminary design by SIMaP Grenoble
- Layer by layer grow of ultra pure Al_2O_3 coating
- 2-3 days process to reach 100nm thickness



ECR CB short term plans

High charge state production

- Test the LPSC CB large diameter configuration at 18GHz
- Add double frequency heating

  (TWTA purchased by LPSC in the frame of the EQUIPEX+ PACIFICS project)

Conclusion

- R&D on ECR CB enabled increasing the PHOENIX CB performances
- Preliminary studies on beam purity allowed identifying ways to reduce contamination
- We will propose a new IN2P3 project to improve beam purity
- Interested in RI species to be produced at SPIRAL1 to analyse the different contaminants

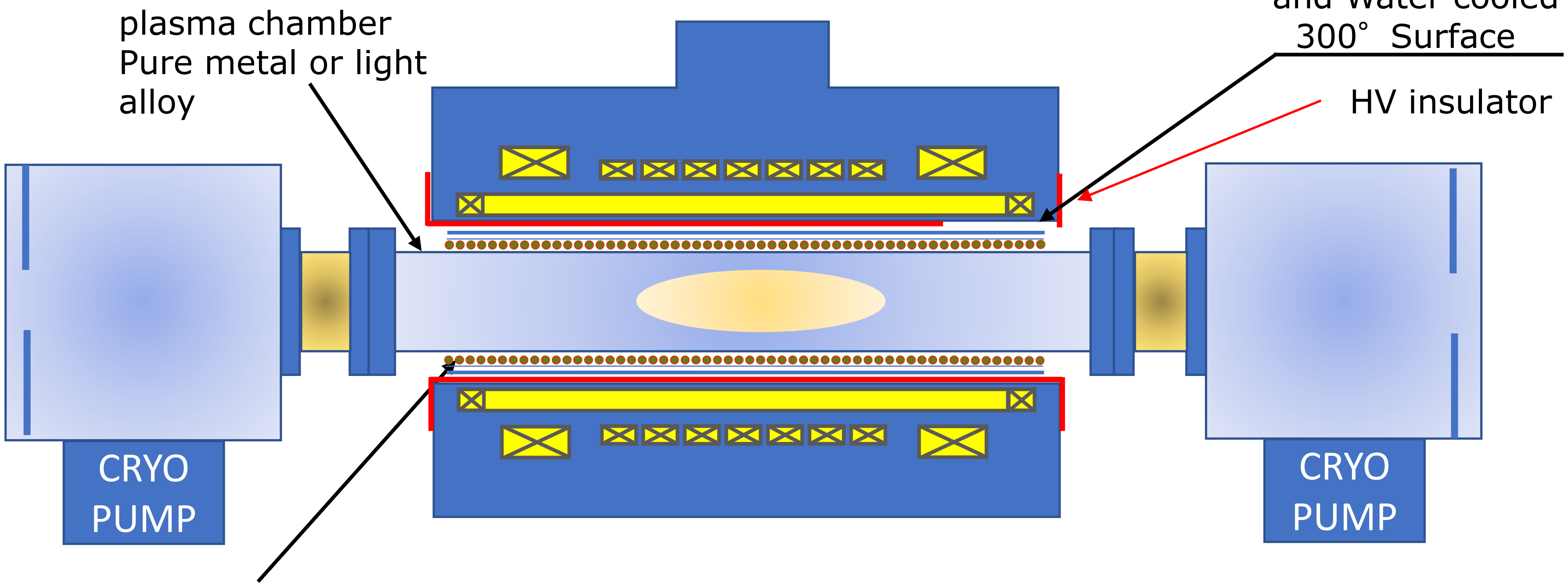
Thank you for your attention

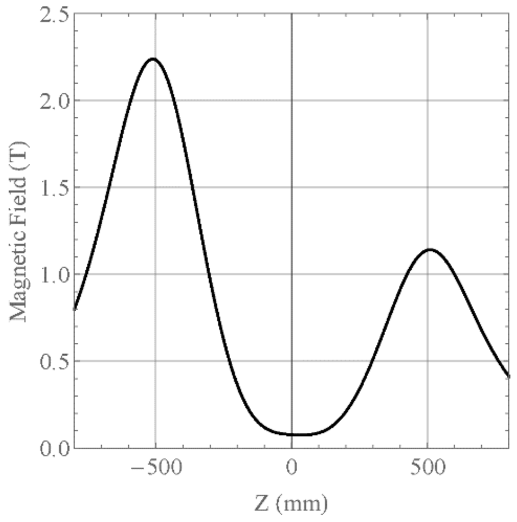
R&D on ECRIS CB

New concept of superconducting Charge Breeder

+20% efficiency, -40% CB Time, drastic reduction of contaminants

Flat Field ECR CB @ 14-18 GHz, NbTi@4 K





Plasma chamber:
Ø200 mm
L~1000 mm
ECR Zone ~500 mm

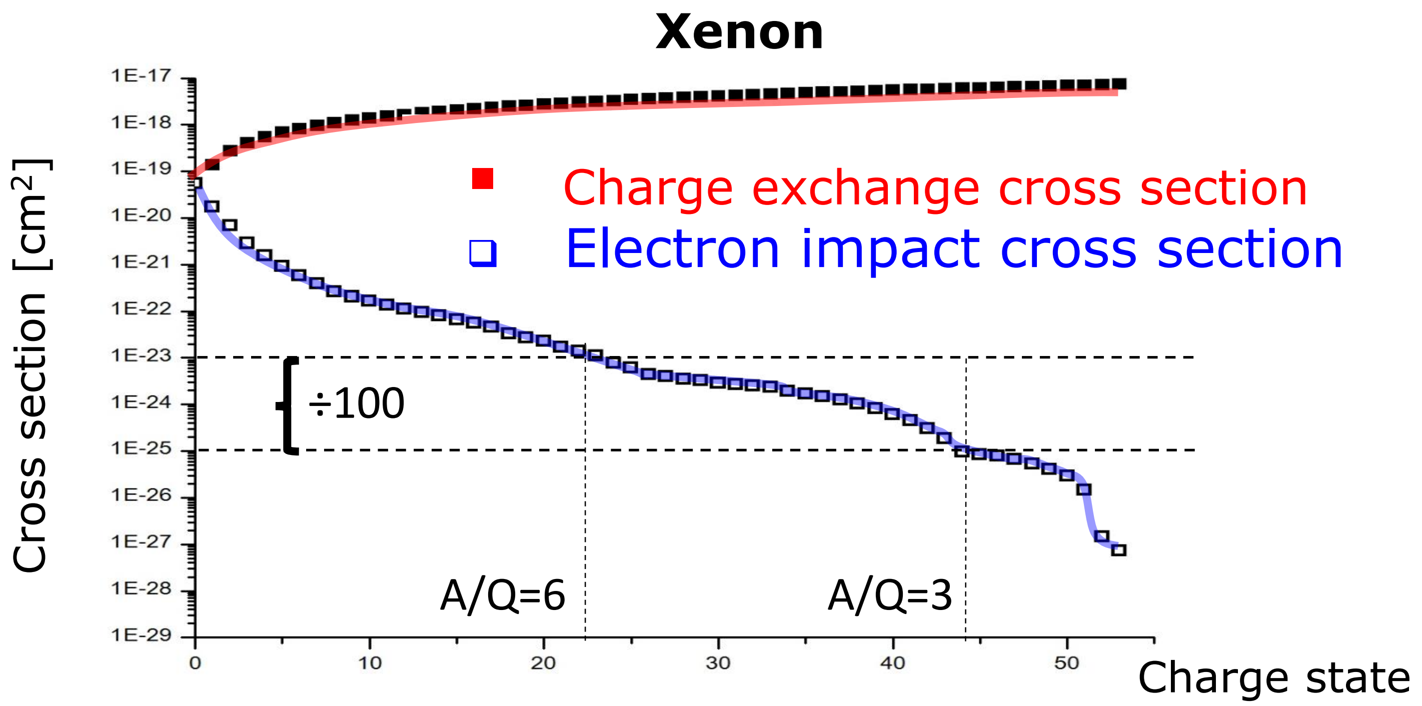
Thuillier, ECRIS 2018 workshop

ECR technics

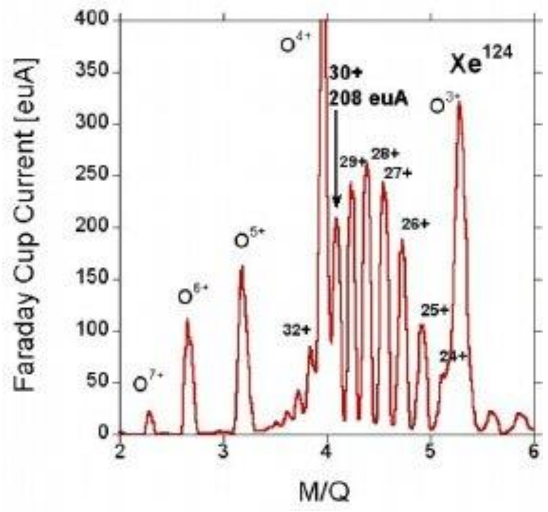
$$\frac{dn^q}{dt} = \underbrace{n_e n^{q-1}\langle\sigma v_e\rangle^{ion}_{q-1\to q}}_{\text{gain}} - \underbrace{n_e n^q\langle\sigma v_e\rangle^{ion}_{q\to q+1}}_{\text{loss}} + \underbrace{n_0 n^{q+1}\langle\sigma v_i\rangle^{cex}_{q+1\to q}}_{\text{gain}} - \underbrace{n_0 n^q\langle\sigma v_i\rangle^{cex}_{q\to q-1}}_{\text{loss}} - \underbrace{\frac{n^q}{\tau^q}}_{\text{confinement}} = 0$$

To reach higher charge state :

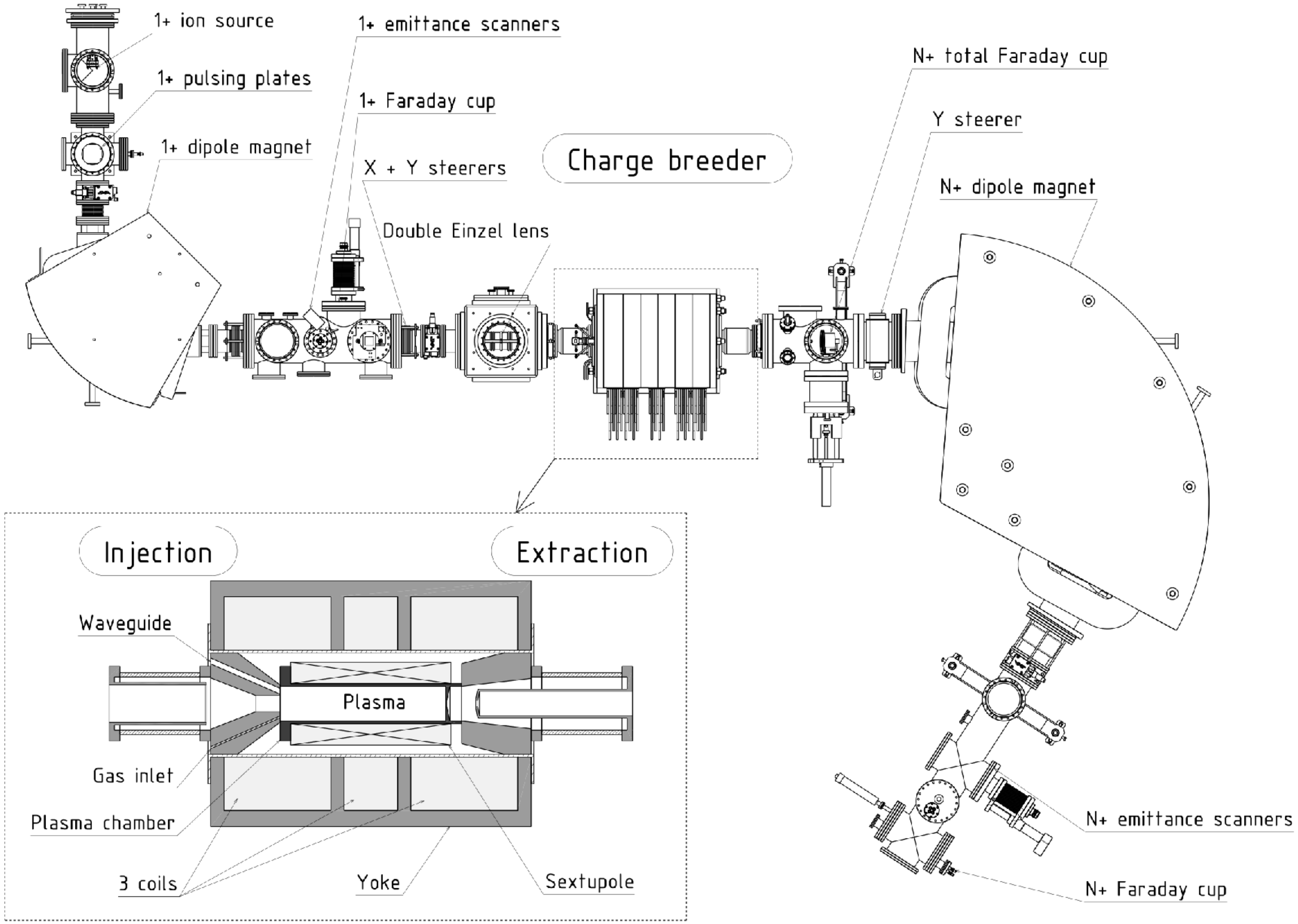
- Increase the plasma energy content to enhance ionization (higher frequency)
- Reduce residual pressure to prevent charge exchange
- Confinement time
  - A minimum confinement time is necessary to reach a given charge state
  - In the same time the confinement time has to be short for ion extraction



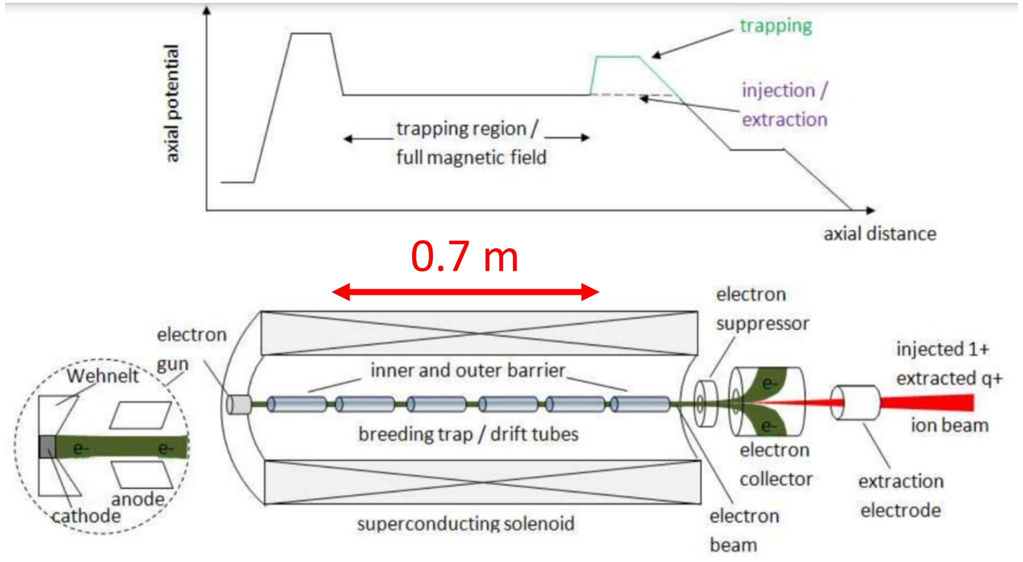
VENUS 28GHz ECRIS spectrum



LPSC 1+N+ test bench at LPSC



Electron Beam Ion Sources CB



Wenander, JINST 5 C10004

Superconducting solenoid
B: 2-8T
Electrodes for longitudinal trapping
e- beam: 0.2 - 3A , 5 - 30 keV
e- beam radius : < 0.6mm
Pulse mode

Lapierre, Snowmass2021 Ion Source Working Group

Characteristics

- A cooler buncher is necessary to prepare the beam (accumulation, bunching, cooling)
- Total efficiency of the cooler-buncher + EBIS : 5 to 20% (EBIS alone up to 35%)
- CB time of cooler-buncher + EBIS : 10 to 100 ms
- A/q : 2 - 3 for light ions, 5 -7 for heavy ions, tunable with breeding time
- The charged particules have low interactions with the walls, base vacuum ≈ 10^{-11} mbar ➔ high beam purity

Main limitation

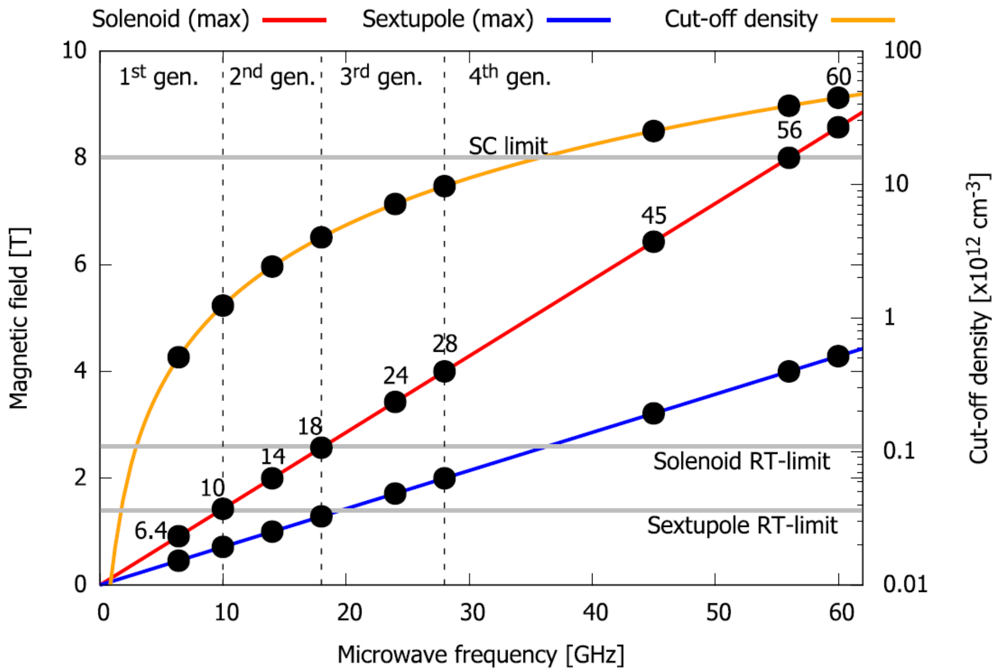
- Limited 1+ beam flux (<10^{11} pps) due to the max. number of charges stored into the cooler buncher or into the EBIS

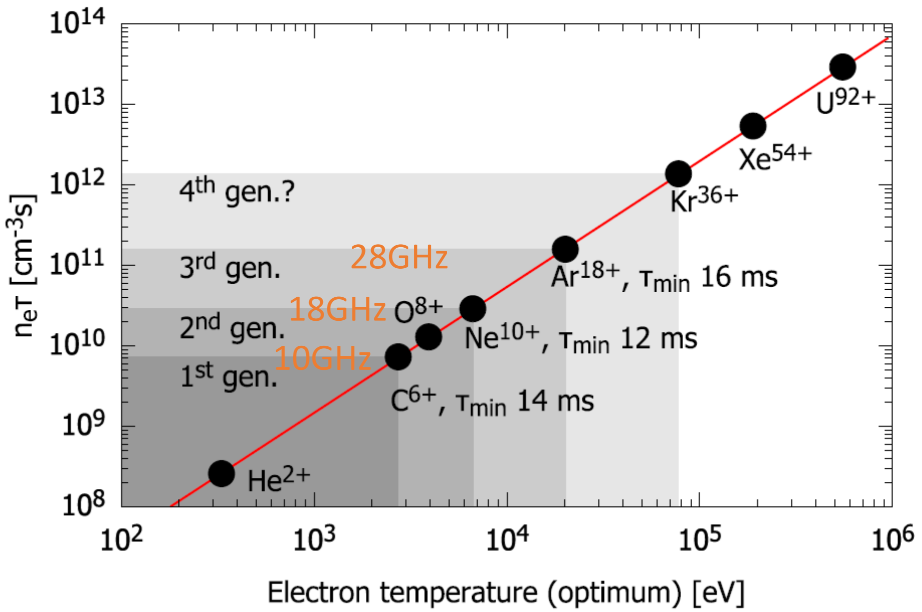
R&D on ECRIS CB

Technology	EBIS CB	ECRIS CB
Max 1+ RIB intensity (pps)	$<10^{11}$	$>10^{13}$
CB time (ms)	10 - 100	100 - 300
Operation mode	Pulsed	CW or pulsed
Robustness	Medium	High
1+N+ conversion efficiency (%)	5 -20 %	10 – 20%
RIB total contamination rate extracted (pps)	$\sim 10^5$	$\sim 10^9$ - 10^{10}
Upstream requirement	Ion cooling	None
Maximum A/q : A ~ 60 Maximum A/q : A ~ 150	2 - 3 6 - 7	2 - 3 5 - 6

- ECR CB offers high 1+ beam acceptance > 10^{13} pps with a constant contamination yield but higher than EBIS CB
- High RIB fluxes are expected in future ISOL facilities like FRIB (10^{12}pps in some cases, under commissioning) or EURISOL (10^{12} pps)
- TRIUMF facility recently equipped with both technologies

ECRIS





O. Tarvainen Rev. Sci. Instrum. **90**, 113321 (2019)