Plasma diagnostics of Charge Breeder ECR ion sources

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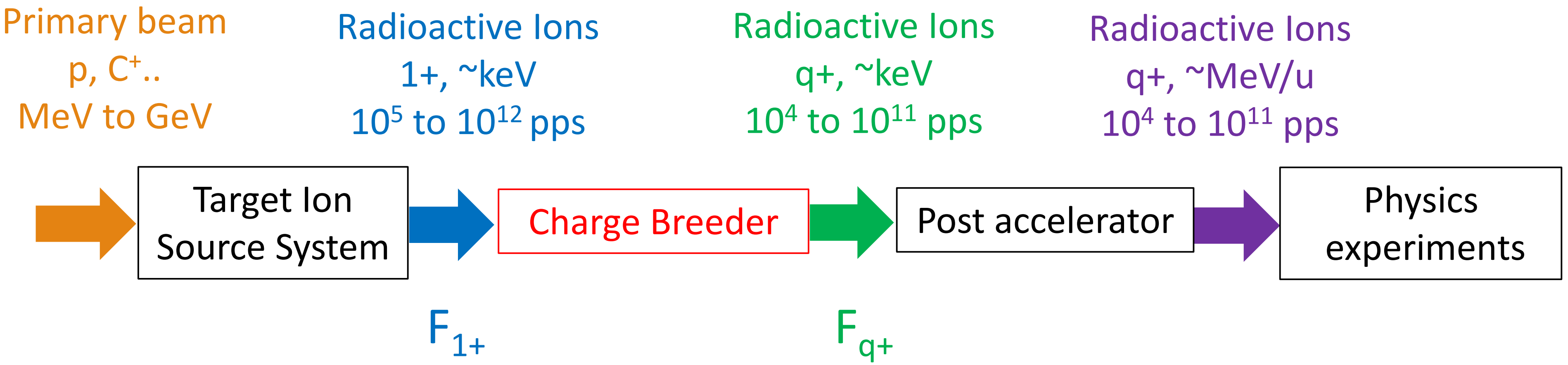
ISIS Neutron and Muon Source

Outline

- Introduction
- PHOENIX ECR charge breeder
- LPSC 1+N+ test bench
- ECR CB plasma studies
  - Fly through ions
  - Captured ions
- Conclusion

Introduction

Isotope Separation On Line (ISOL) scheme



ECR – Charge Breeders developed since the 1990s
Based on 2nd gen. min-B ECRIS, mainly characterized by:

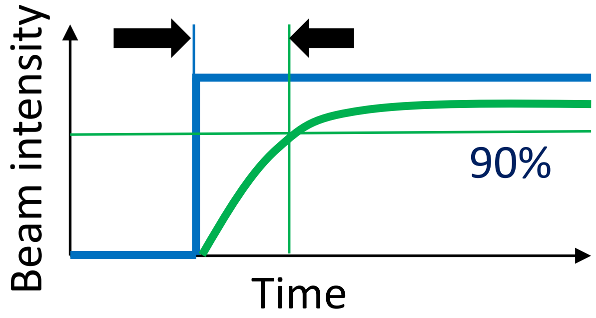
Efficiency on charge state q :

$$\eta_q = \frac{F_{q+}}{F_{1+}}$$

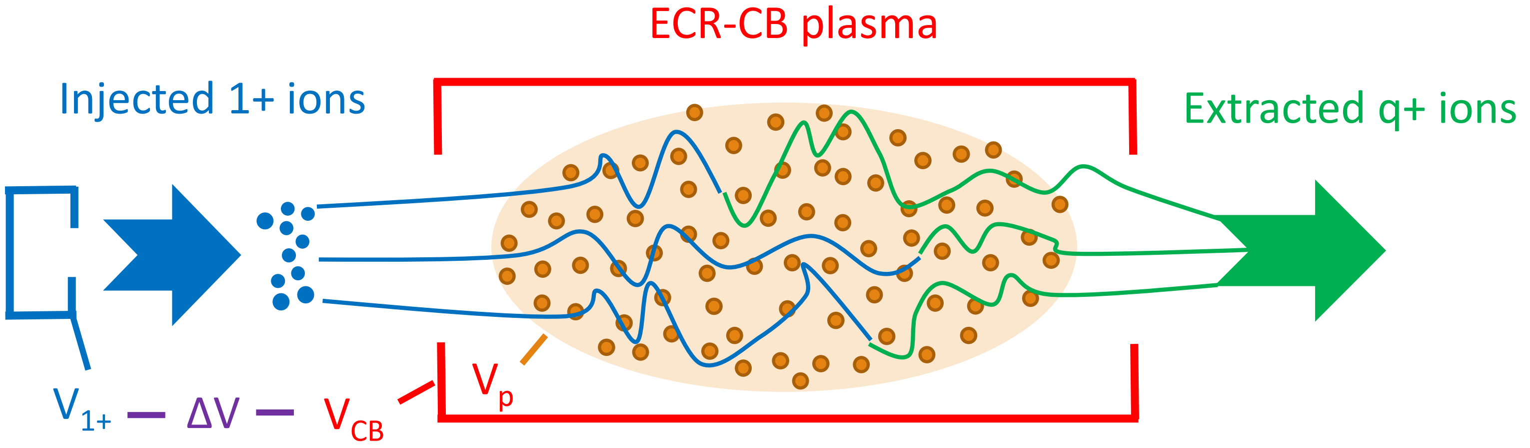
Total efficiency :

$$\eta_g = \sum_q \eta_q$$

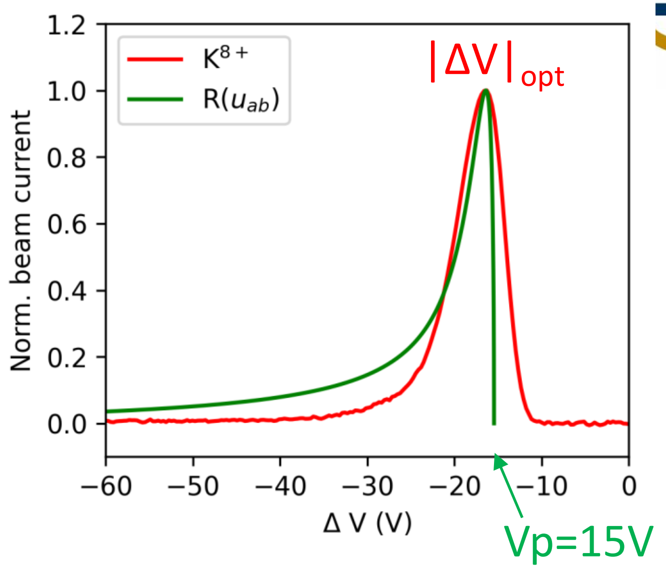
Charge breeding time :



Introduction



Capture curve – He plasma



$$S_{ab} = \frac{\langle \Delta v_{a,||} \rangle}{\Delta t} \qquad S_{ab} = -\frac{n_b}{4\pi\varepsilon_0^2}\left[\frac{q_a q_b e^2}{m_a \langle v_b \rangle}\right]^2 \left(1 + \frac{m_a}{m_b}\right) R(u_{ab}) ln\Lambda$$

$$R(u_{ab}) = \frac{2}{\pi^{1/2}} \frac{1}{u_{ab}^2} \int_0^{u_{ab}} x^2 e^{-x^2} dx \qquad u_{ab} = \frac{v_{a,||}}{\langle v_b \rangle}$$

$R(u_{ab})$ maximum when $u_{ab}=1$ so when $v_{a,||} = \langle v_b \rangle$

a injected species, ***b*** plasma species
n density, ***q*** charge, ***m*** mass, ***v*** velocity, ***ln Λ*** Coulomb logarithm

Considering a Maxwellian distribution for the plasma ions speed :

$$|\Delta V|_{opt} = \frac{4 m_{1+}}{\pi m_i} \frac{k T_i}{e} + V_p$$

Charge state distribution at the CB extraction depends on:

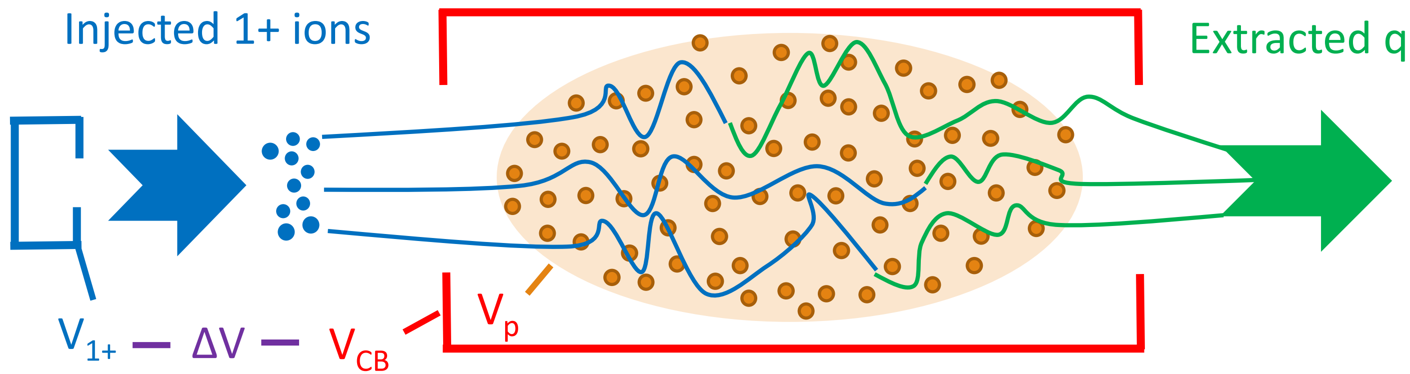
Ionisation rate : $n_e * \langle \sigma v \rangle^{inz}$

Charge exchange rate : $n_0 * \langle \sigma v \rangle^{cx}$

$$\langle \sigma v \rangle = \int_0^\infty \sigma(v) v f(v) dv$$

Confinement time : τ_q

Introduction



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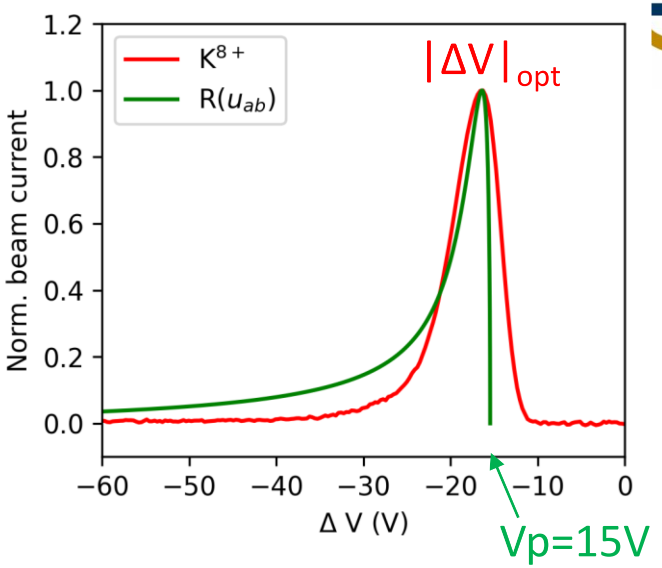

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Confinement time : τ_q

Introduction

In 2010, European ISOL context :

- Short term : upgrade of CERN-HIE ISOLDE, development of GANIL - SPIRAL2 and LNL - SPES
- Longer term : EURISOL project aimed to enhance the RI intensities by 10 to 100

  - European “Enhanced Multi-Ionization of short-Lived Isotopes at EURISOL” (EMILIE) project to increase the EBIS and ECR charge breeder performances

CERN - GANIL - JYFL - LNL - LPSC – Warsaw University laboratories

ECR-CB : Efficiency 3 – 10 %, Total efficiency 50 – 60% ➔ possible improvement of capture – performances

  - Better knowledge of the plasma characteristics (electron – ion densities, energy distributions, plasma potential..)
  - Experimental campaigns with the LPSC ECR-CB and “1+N+” test bench
  - Collaboration has been ongoing : GANIL - JYFL - LNL - LPSC , support by CNRS IN2P3 institute

PHOENIX ECR Charge Breeder

Developed since ~2000

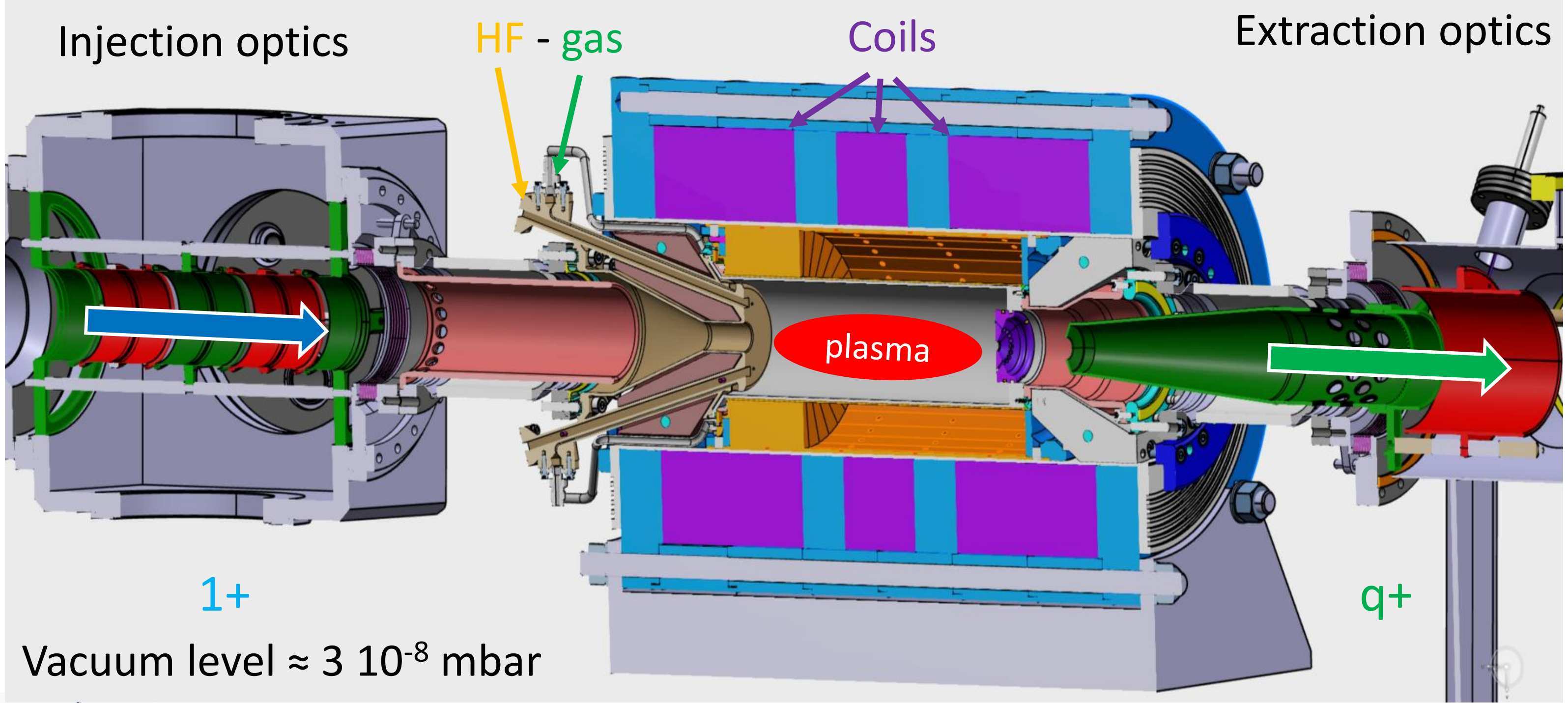
Min-B ECRIS modified for 1+ ions injection

- 14.5GHz, 200 – 800W
- 3 coils
- 1 sextupole

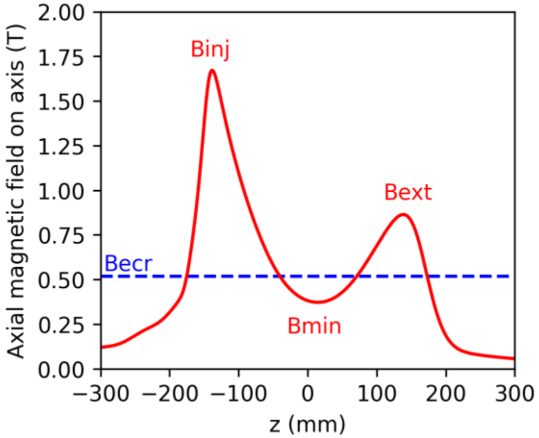
3 versions installed at GANIL, LNL and TRIUMF + 1 LPSC for R&D

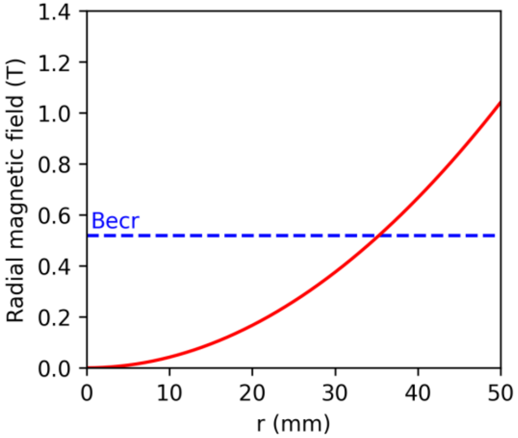
Efficiency optimisation through CB tuning :

- Support gas selection + gas dosing
- Coils
- HF power
- ΔV

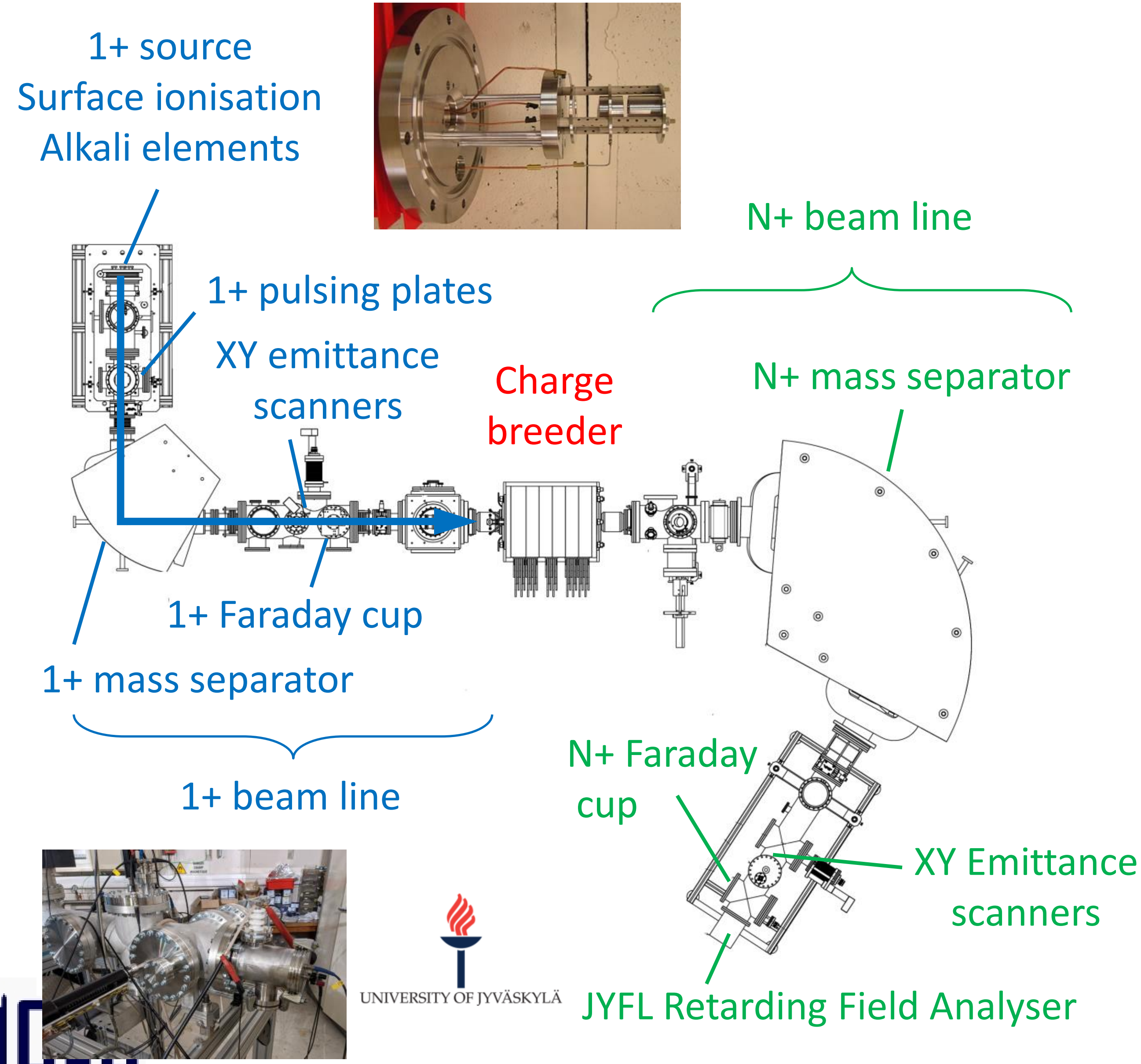


Vacuum level ≈ 3 10^{-8} mbar

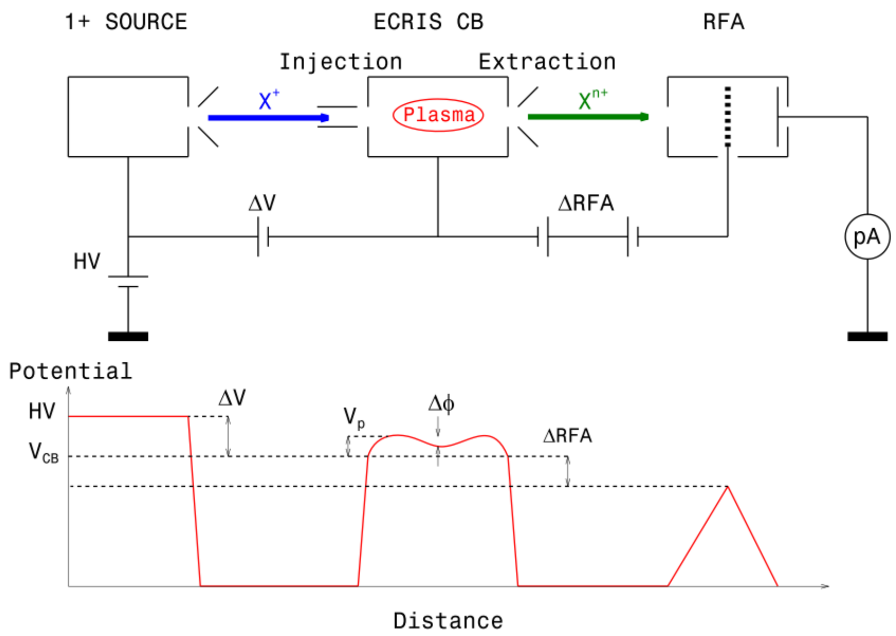




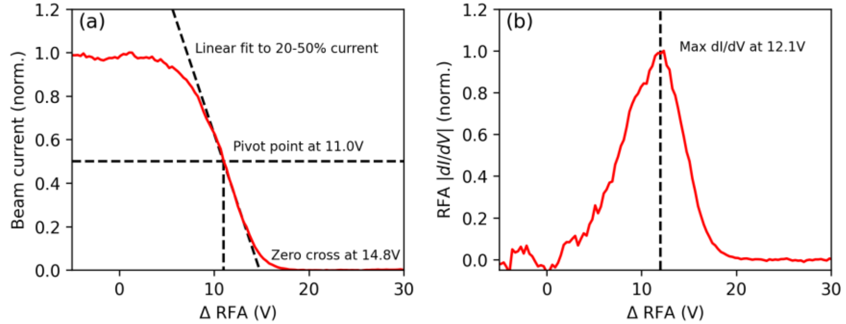
LPSC 1+N+ test bench



1+N+ electrical configuration



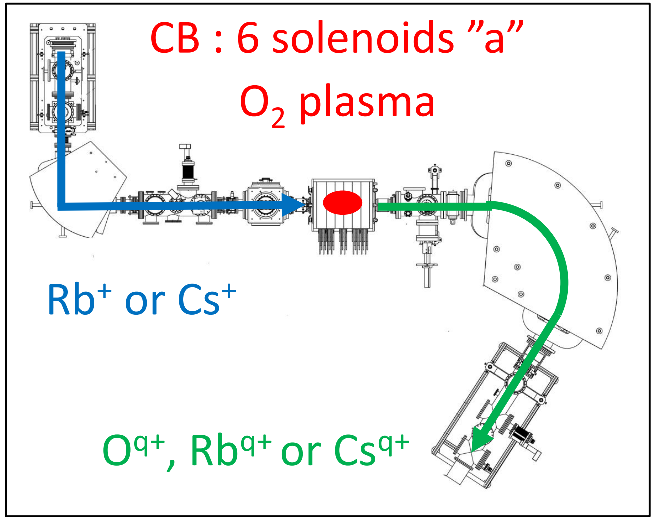
RFA : plasma potential estimate

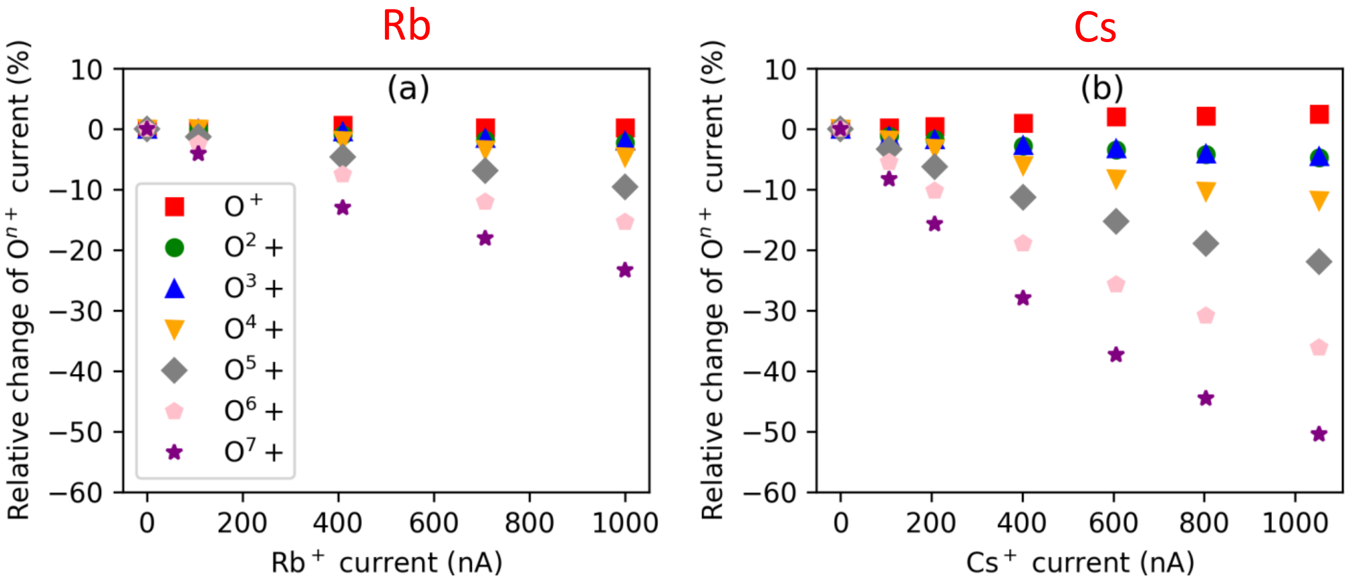


CB ECR plasma studies : plasma perturbation by 1+ ions injection

Purpose : study the effect of 1+ beam injection on plasma ions

- ➢ Injection of different masses and increase of 1+ beam intensity

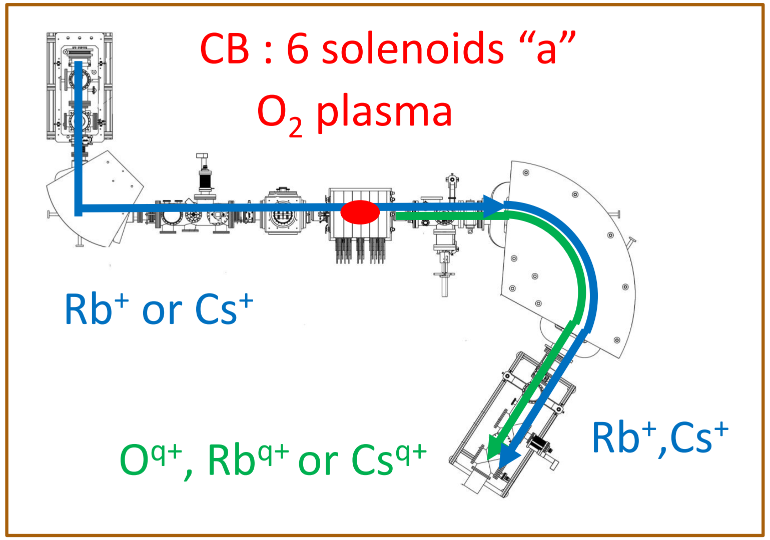


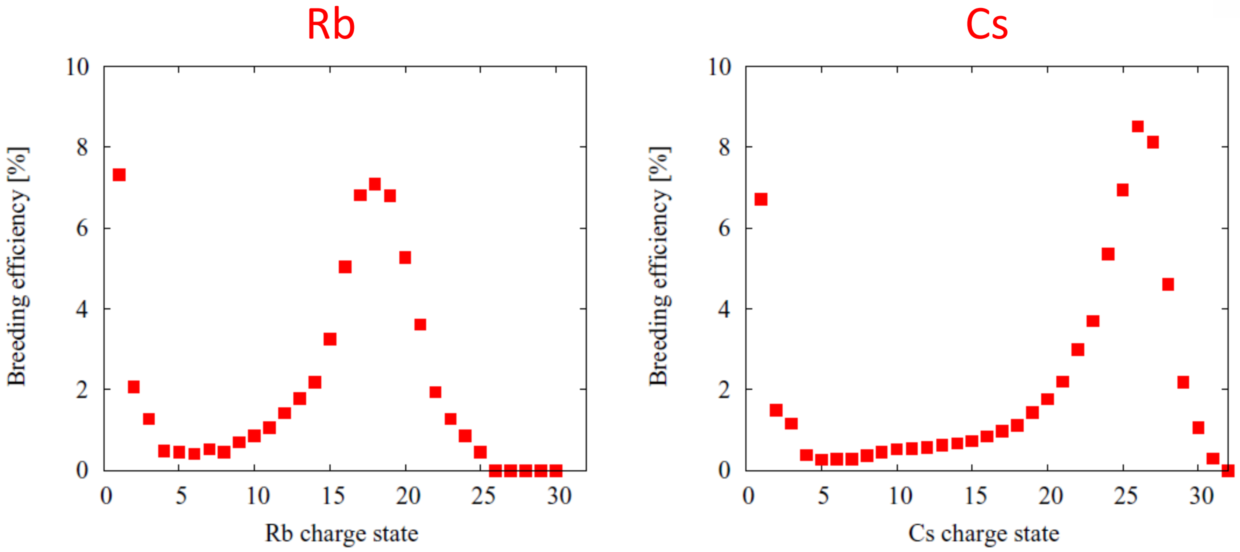


- O^{q+} beam intensity drop dependant on 1+ mass and beam intensity
- No increase of low charge states
- Time scale of O^{q+} decrease identical to CB time of Rb or Cs

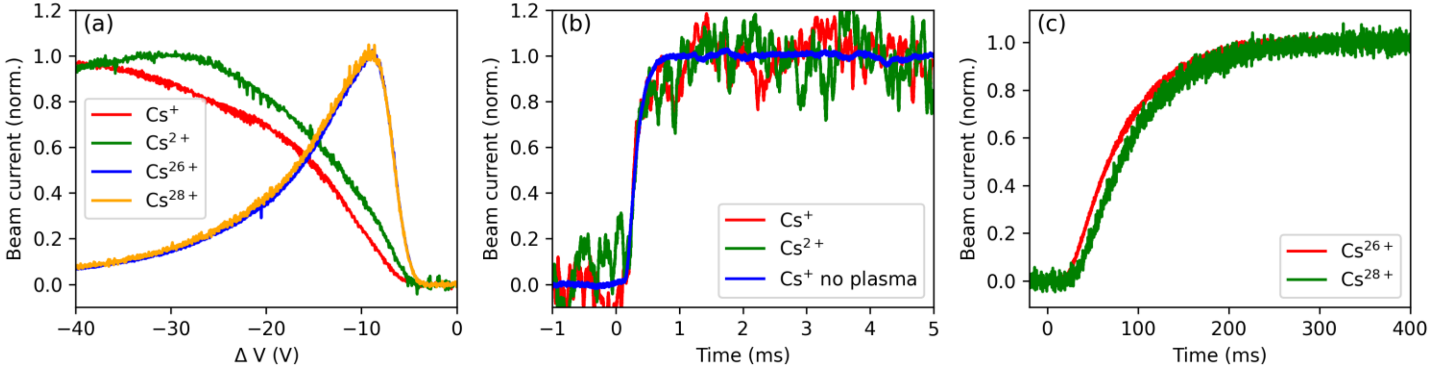
- ➢ Gas mixing effect : Coulomb collisions leading to the thermalization of injected ions and heating of plasma ions
- ➢ Mitigate the perturbation caused by the 1+ beam injection for later experiments : low 1+ beam intensity
- ➢ CB efficiency optimized when $m_{inj}/ m_{plasma} > 5$

CB ECR plasma studies : fly through ions





High values of 1 – 3+ when comparing with min-B ECRIS

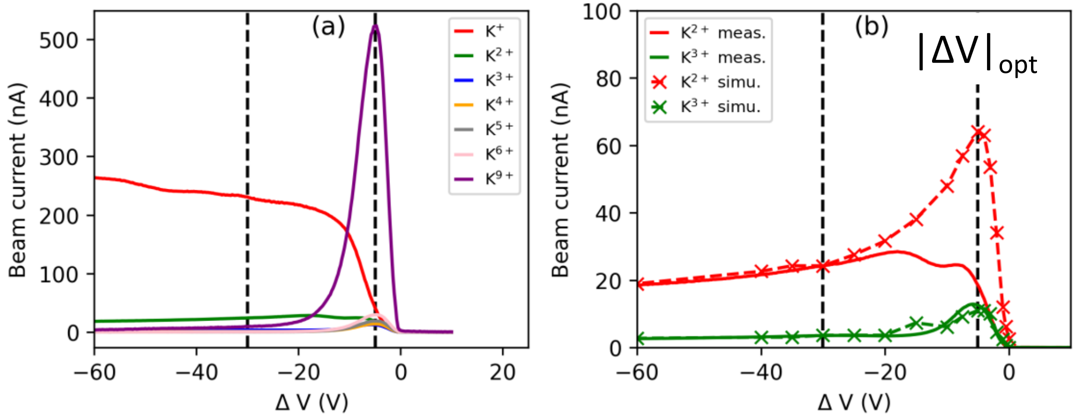


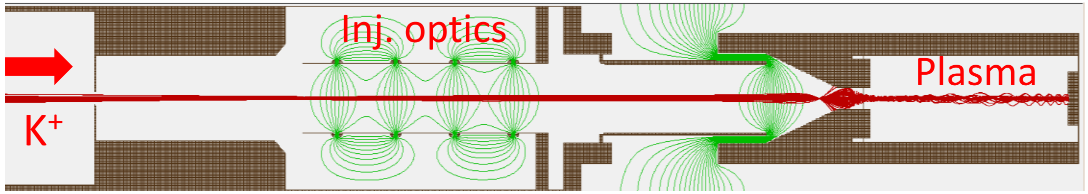
- Capture curve : different low – high charge state
- CB Time : different low – high charge state
- ➢ Some injected ions fly through the plasma
- ➢ In flight ionisation to 2+ - 3+

CB ECR plasma studies : fly through ions

CB configuration : large diameter (recent measurements)

K^+ charge breeding, He plasma



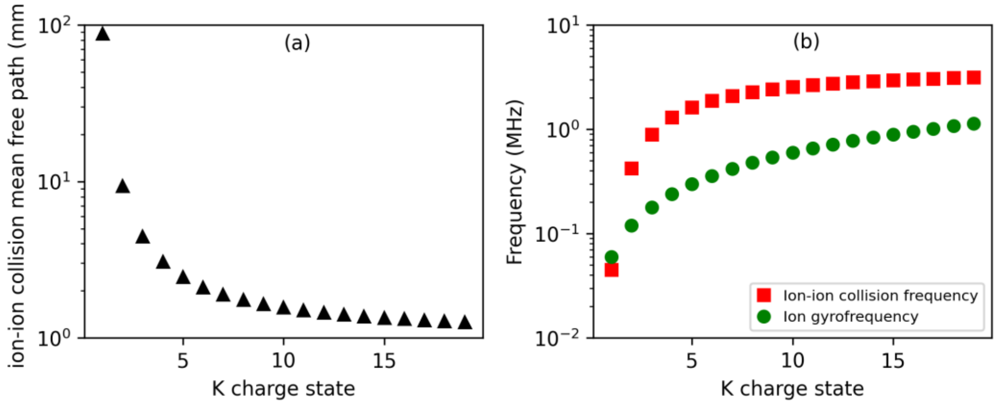


- 2 ΔV domains
- IF ionisation fraction to 2+ ➔ ne and λi estimate, at ΔV = -30V
- Simion model to simulate
  - the 1+ beam injection
  - in flight ionisation in ECR zone, with a Monte Carlo method
- $|\Delta V|_{opt}$ corresponds to maximum IF ionisation to 2+

$$n_e = \frac{v_i p}{\langle \sigma v_e \rangle dl} \qquad \lambda_i = \frac{v_i}{n_e \langle \sigma v_e \rangle}$$

- $\langle \boldsymbol{\sigma v_e} \rangle$: from literature
- ***p***: ionisation probability
- ***dl***: unit length
- **λ**: mean free path

$n_e \approx 8\ 10^{10} cm^{-3}$, $\lambda_i \approx 2500mm$



At $|\Delta V|_{opt}$ = -5.0V:

- Estimation of ion-ion collision mean free path

$$\lambda_c = -\frac{L}{\frac{L}{\lambda_i} + \ln(\frac{I_{1+ext}}{I_{total}})}$$

- I_{1+ext}: 1+ fly through intensity fraction
- I_{total}: total extracted particle current

- $\lambda_c \approx$ 88.4mm
- ion-ion collision freq. vs ion gyrofrequency

CB ECR plasma studies: plasma potential estimate

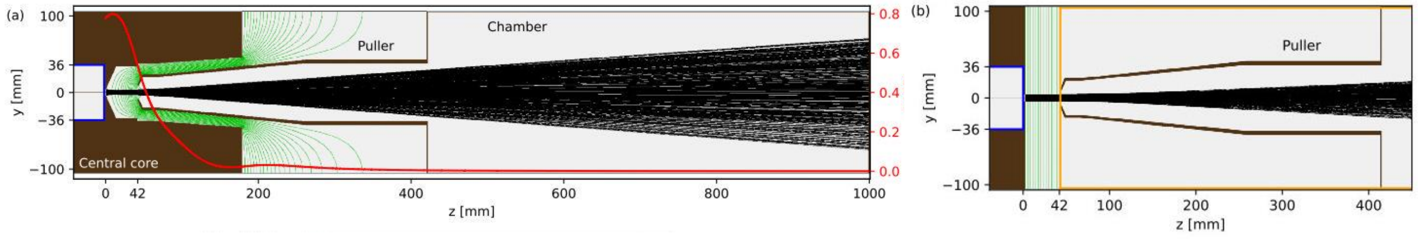
Purpose : estimate the CB plasma potential for capture studies

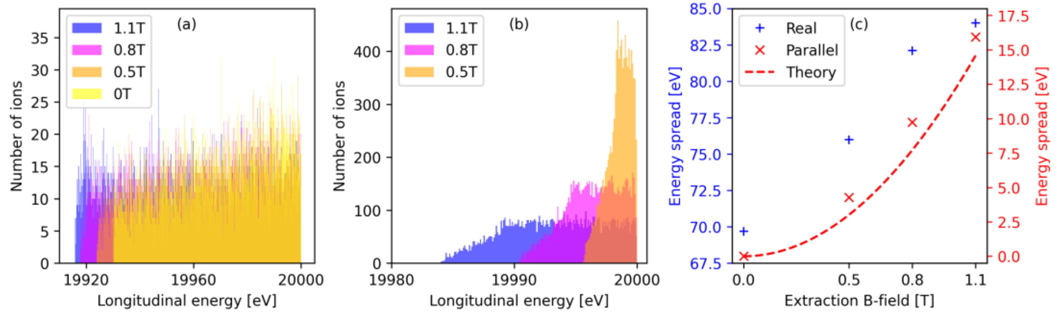
1. Study the parameters acting on the longitudinal energy spread of extracted ions (SIMION + IBSimu simulations)
   Bfield, Electrostatic potential, Ion mass, charge state, initial longitudinal energy, energy spread

Real extraction model

Parallel V potential

B_{ext} effect , $^{16}O^{+}$

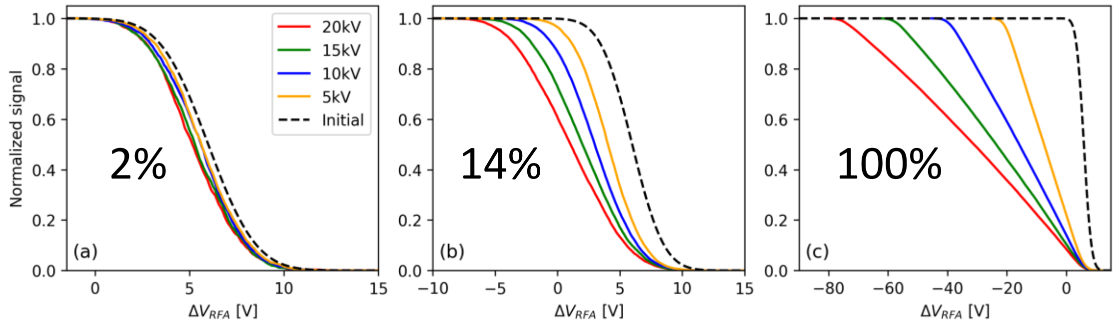




➢ Electrostatic potential (extraction electrodes and plasma meniscus) predominant

2. RFA simulations for plasma potential value estimate (ideal RFA)

➢ Heavy collimation allows studying the plasma properties
ie plasma potential and ion temperature

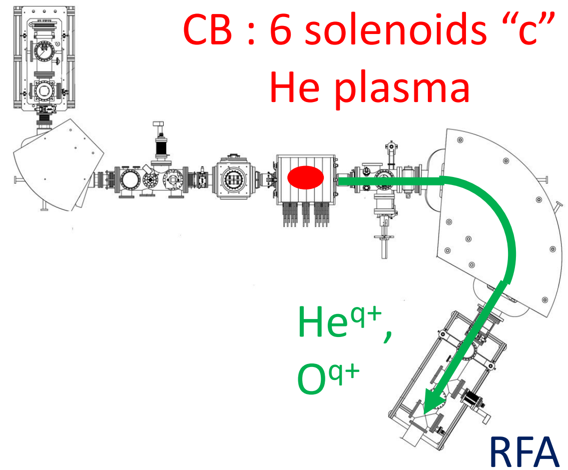


CB ECR plasma studies: plasma potential

Purpose : estimate the CB plasma potential for capture studies

3. Experiments phase :

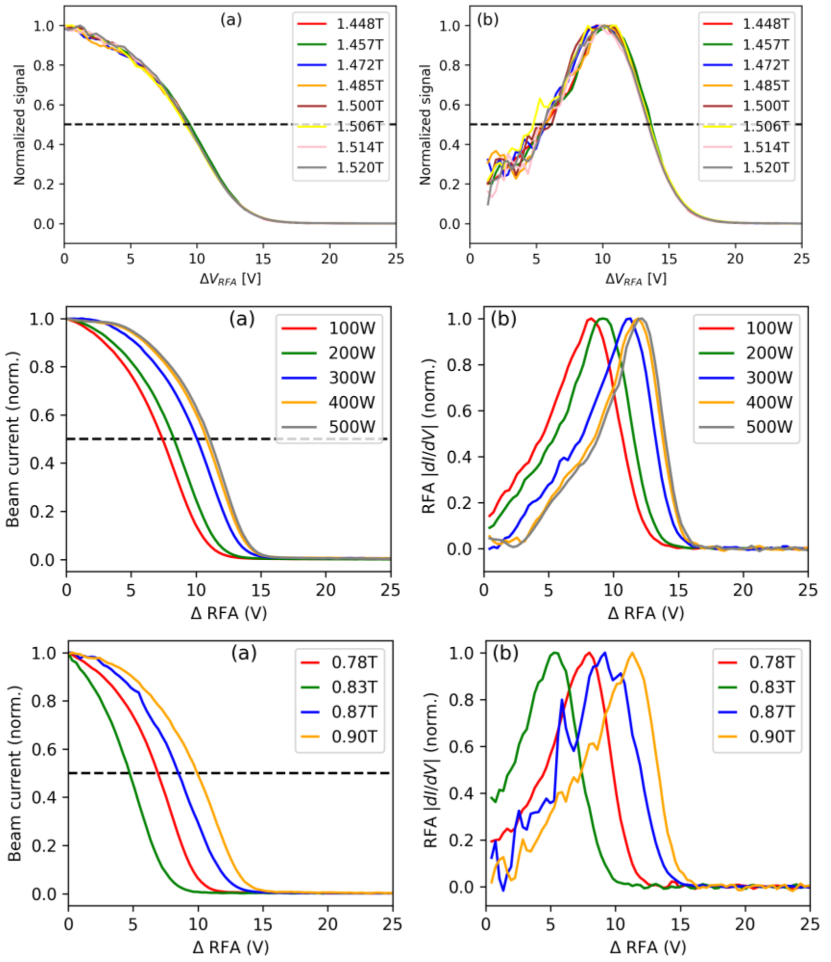
- Improvement of the JYFL RFA resolution with smaller mesh grid
- parametric studies on HF power, Binj, Bmin, Bext, Gas dosing



B_{inj}

HF power

B_{ext}



Plasma potential affected by :

- Microwave power
- B_{ext}

➢ Both parameters influence the dynamics of cold electron population

- Qualification of the RFA for plasma potential estimation

CB ECR plasma studies : the optimum 1+ beam capture

Purpose : study discrepancies between experiments plasma parameters findings and capture theory

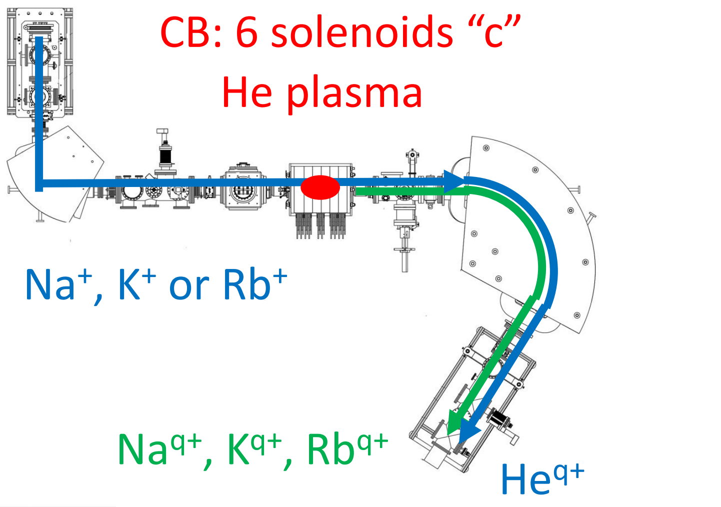
$$|\Delta V|_{opt} = \frac{4m_{1+}}{\pi m_i}\frac{kT_i}{e} + V_p$$

From experimental results :

- $m_{1+}/m_i > 5$ for good ECR CB efficiency
- Ion temperature in ECRIS plasma 5 - 28eV (optical spectroscopy measurements)
- ➢ $|\Delta V|_{opt} > 50V$ for Na^+ injected into a He plasma, even considering $V_p = 0V$
- ➢ 5 – 15 V values are typically measured

Proposition of new model :
$|\Delta V|_{opt} = V_p$

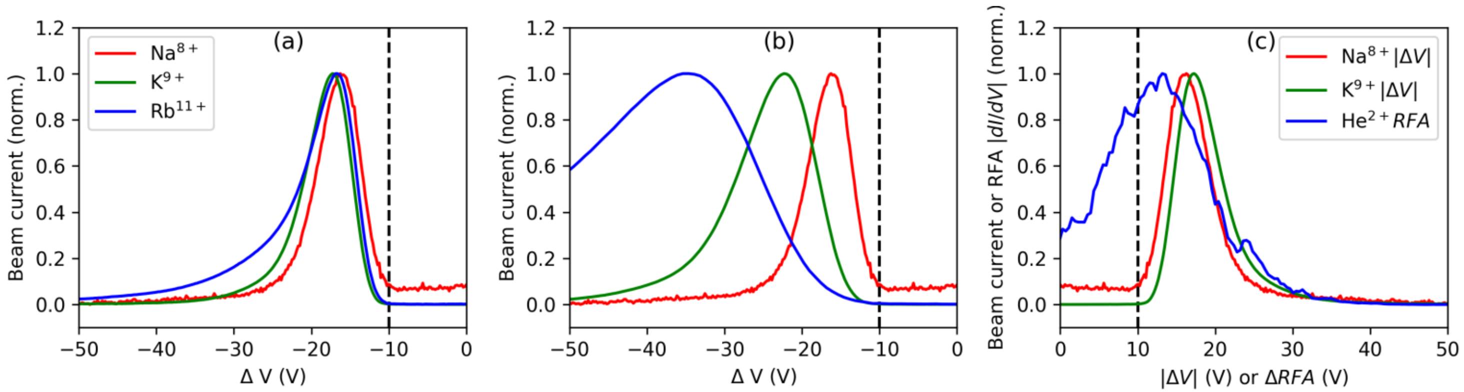
1st term mass dependency study



Measurement
He support gas

Curves reconstruction

RFA vs ΔV

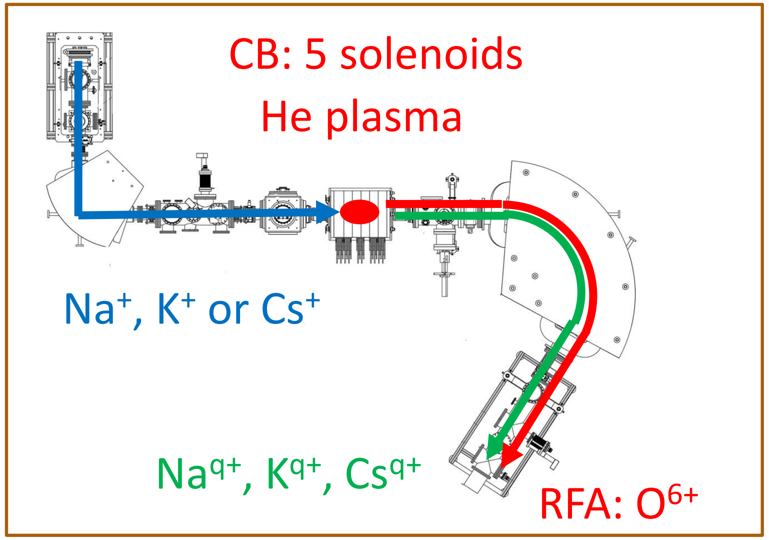


- ➢ Similar behavior for H_2 as support gas
- ➢ Weak dependency of $|\Delta V|_{opt}$ on mass ratio
- ➢ Plasma potential from RFA ➔ minimum ΔV providing HCS efficiency

CB ECR plasma studies : the optimum 1+ beam capture

2nd term : plasma potential dependency

$$|\Delta V|_{opt} = \frac{4m_{1+}}{\pi m_i}\frac{kT_i}{e} + V_p$$



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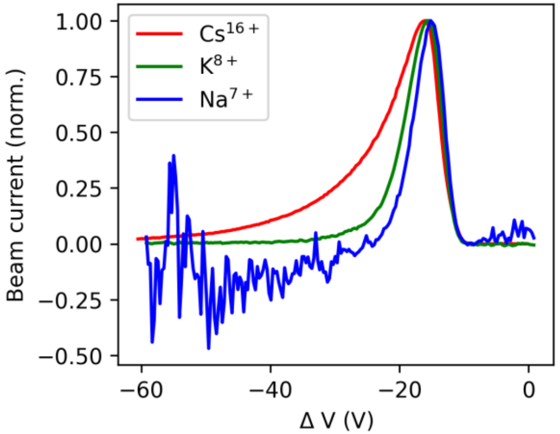
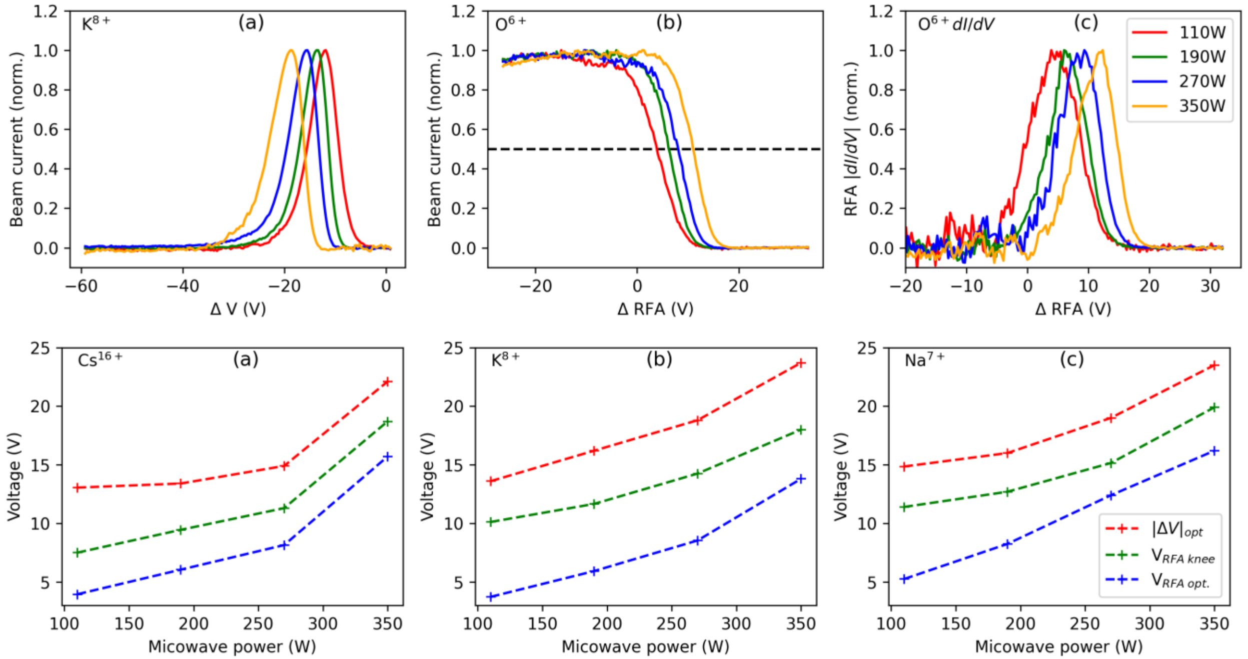


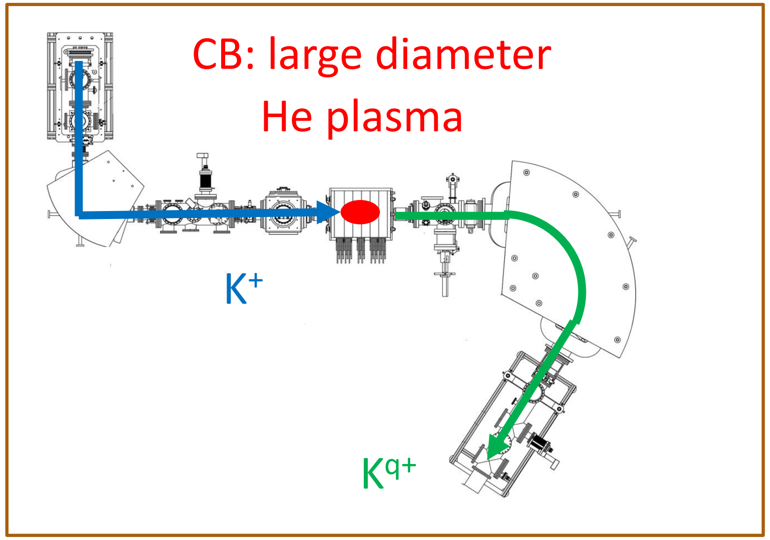
Capture curves

RFA measurements

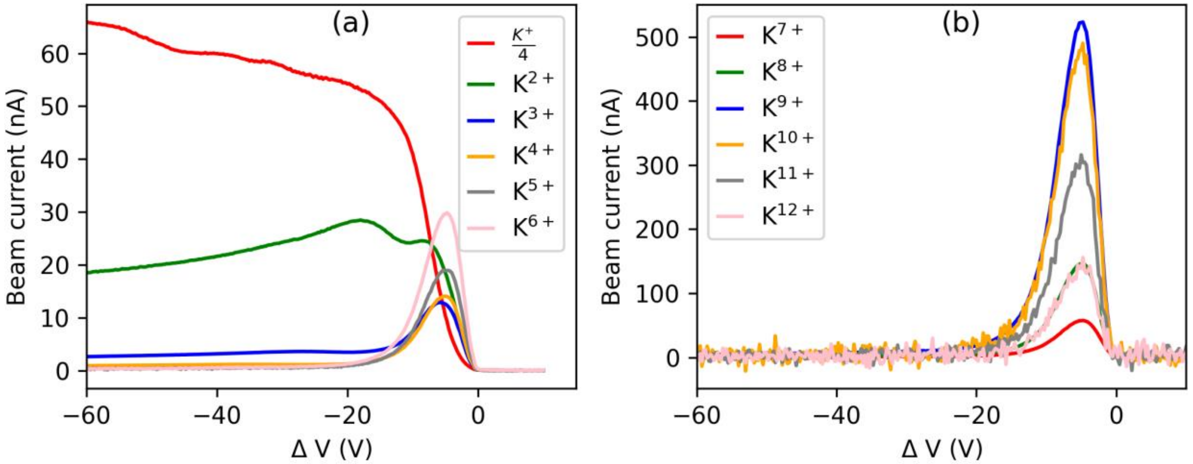


- $|\Delta V|_{opt}$ correlated to the plasma potential
- Vp always lower than $|\Delta V|_{opt}$
- $|\Delta V|_{opt}$ also poorly dependant on masses
  - ➢ Corroborate the new model
  - ➢ Offset: mirror field, injected beam emittance. Plasma potential not symmetric (inj/ext)?
  - ➢ $|\Delta V|_{opt}$ independent of plasma ion temperature (T_i estimation not possible)

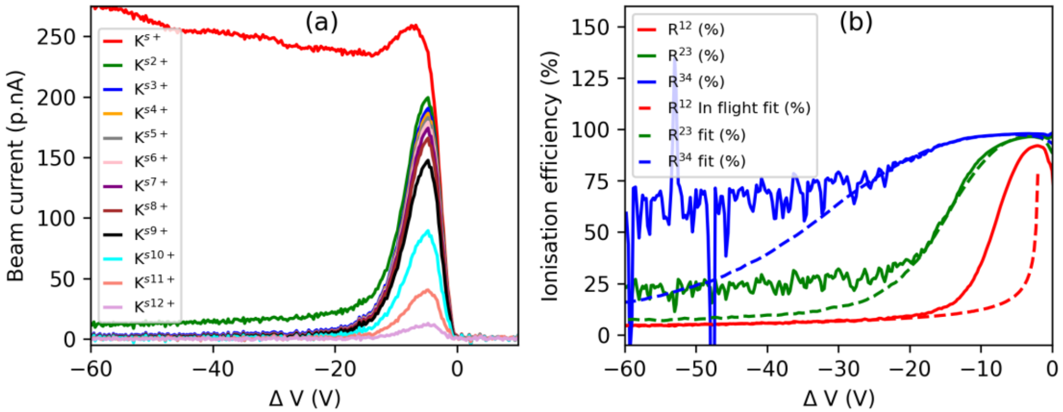
CB ECR plasma studies : the capture curve profile



Careful measurement of K^{+} - K^{12+}



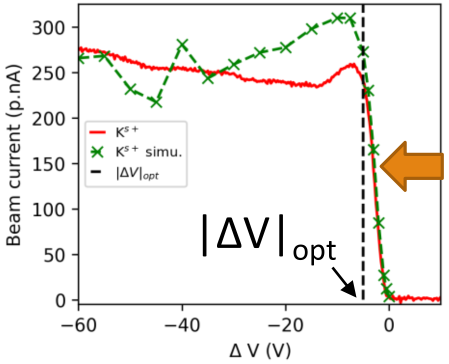
- "Delay" of K^{+}
- "Shift" of $|\Delta V|_{opt}$



- K^{S+} signals
  - ➢ K^{s2+} close to HCS capture curve ➔ 1+ to 2+ ionisation important
  - ➢ High efficiency then charge exchange at high charge state
- R^{q_q+1} ratios : $R^{12} = K^{s2+}/K^{s1+}$
  - ➢ Fit with in flight ionisation (red dashed)

CB ECR plasma studies : the capture curve profile

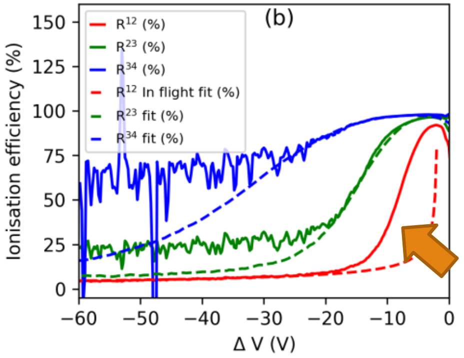
Total extracted intensity fit with simulation



K^{S1+} fit with simulation signal

- gives: V_p= 1.55V, Espread ≈ 1.0V
- Rising shape of the curve well reproduced by injection simulation
- Optimum injection corresponds closely to where a maximum of ions can pass the injection mirror and plasma potential

Ionisation efficiency R^{q_q+1}

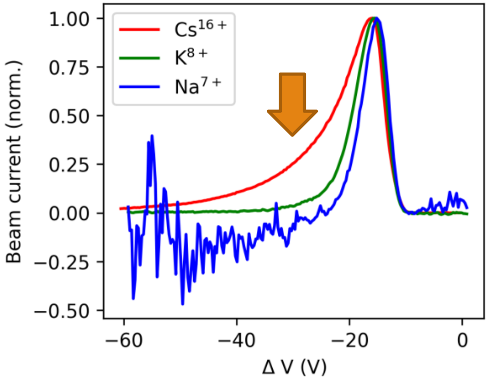


Conversely, ion speed must be as low as possible for ionisation to 2+

- Decay shape of the capture curve mainly driven by ionisation to 2+ (R^{12})
- Reinforced by the shape of the decay as a function of ion mass : multi ionisation efficiency proportional to ion speed (at given ΔV the speed differs as a function of mass)

➢ $|\Delta V|_{opt}$ is at compromise value between the number of injected ions and their speed

Capture curve of different masses



➔ Extensive simulation studies by Dr A. Galatà, see poster "Numerical Analysis of the Influence of Plasma Parameters on the 1+ Beam Capture in the ECR-based Charge Breeder"

CB ECR plasma studies : short pulse experiments

Purpose : study the charge breeding time and dynamics of HCS ions production

- The plasma characteristic times studied from the balance equation system:

$$\frac{dn^q}{dt} = +\langle\sigma v\rangle^{inz}_{q-1\to q} n_e n^{q-1} - \langle\sigma v\rangle^{inz}_{q\to q+1} n_e n^q + \langle\sigma v\rangle^{cx}_{q+1\to q} n_0 n^{q+1} - \langle\sigma v\rangle^{cx}_{q\to q-1} n_0 n^q - \frac{n^q}{\tau^q}$$

Ionisation time $\tau^q_{inz} = \left[n_e\langle\sigma v\rangle^{inz}_{q\to q+1}\right]^{-1}$

Charge exchange time $\tau^q_{cx} = \left[n_0\langle\sigma v\rangle^{cx}_{q\to q-1}\right]^{-1}$

Confinement time τ^q

Equation translates to $\frac{d}{dt}I^q = a_q I^{q-1} - b_q I^q + c_q I^{q+1}$ for extracted beam intensities

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Development of the "CT method" based on :

Experiments :

- 1+ beam short pulse injection into the CB and measurement of extracted transients over consecutive charge states

Classical method of short pulse injection into ECR plasma, init R. Pardo

Numerical analysis :

- Fit of the transients providing a_q b_q c_q parameters
- Optimisation procedure on (ne,$\langle E_e\rangle$) to resolve reduced equations and determine $\tau^q_{inz}, \tau^q_{cx}, \tau^q$, n_e , $\langle E_e\rangle$

Method advantages:

- Precise tuning of injected beam intensity and energy
- Reduced number of assumption: ions confinement and CX models, n_0
- Accounts for ionisation rate uncertainties
- Local solutions in terms of (ne,$\langle E_e\rangle$)

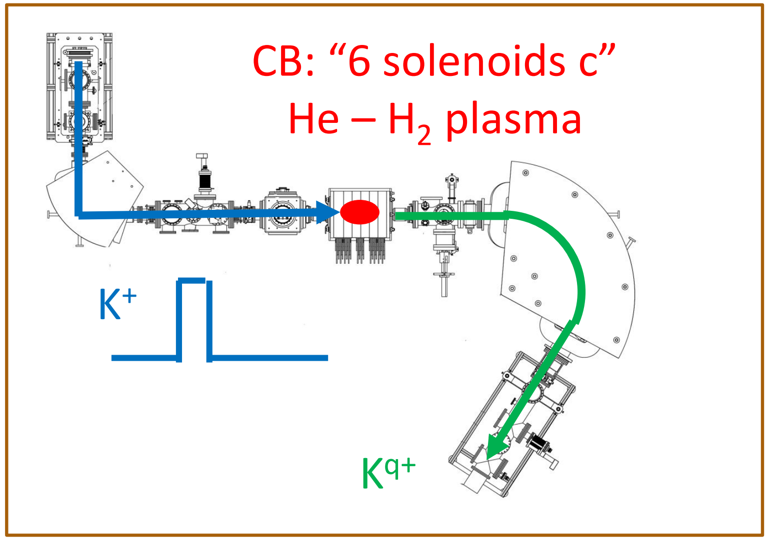
Method caveats :

- at least 5 consecutive transients
- high uncertainties on ionisation rates

CB ECR plasma studies : short pulse experiments

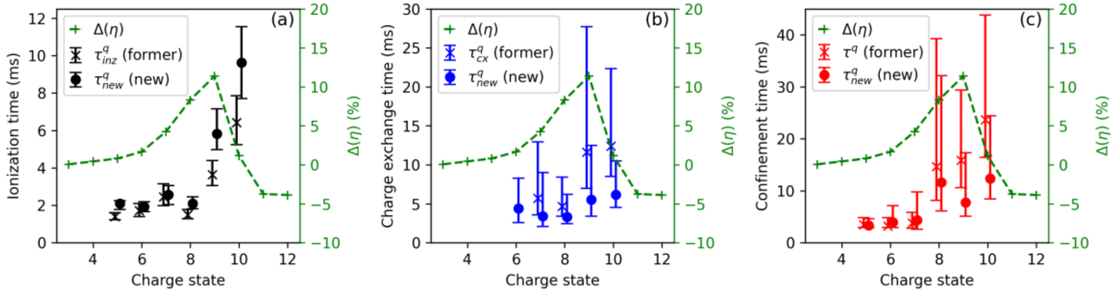
Purpose : study the charge breeding time and dynamics of HCS ions production

Example: method used to compare CB configurations leading to K^{9+} efficiency increase from 8.9% to 20.4%

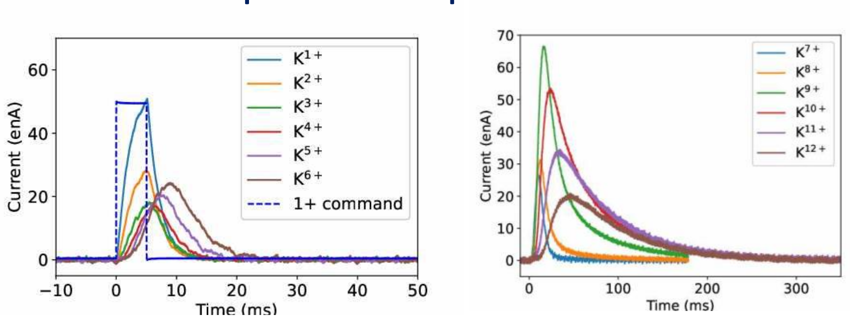


Parameter	Configuration	
	Former	New
B_{inj} (T)	1.58	1.57
B_{min} (T)	0.45	0.44
B_{ext} (T)	0.83	0.84
μW power (W)	504	530
Support gas species	He	H_2
P_{inj} ($\times 10^{-8}$ mbar)	9.0	13.6
K^+ intensity (nA)	710	500
Injection pulse width (ms)	5	5

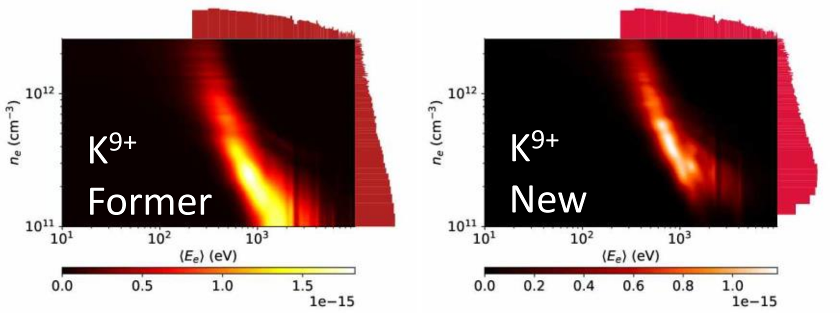
Characteristic times and efficiency change



q+ time responses



(ne,$\langle E_e \rangle$) solutions sets



K9+ efficiency enhanced by:

- Increase of τ^q_{inz} and decrease of τ^q_{cx} for high q
  ➔ CSD shift to lower q
- Decrease of τ^q ➔ faster extraction
- ➢ Pile up of K^{9+} (closed shell)
- ➢ CSD driven by the characteristic times of all q

Other experiments carried out with CT method:

- 2 species injection in same plasma conditions to reduce uncertainties
- Parametric studies on the CB tuning (gas, HF power, B_{min} ..)

Conclusion

The different studies allowed a better understanding of the Charge Breeding process

- reduced effect of Coulomb collisions, ionisation to 2+ appear to be a key parameter
- Slowing down by plasma potential, which was found to be dependent on HF power and B_{ext}

and estimating ECR plasma parameters using classical diagnostics and 1+ beam as a probe

  - Fly through : ne , λi , λc
  - Capture : plasma potential, plasma potential symmetry
  - Pulse: characteristic times, CSD build up

Future experiments : add optical spectroscopy on the CB to monitor the plasma populations

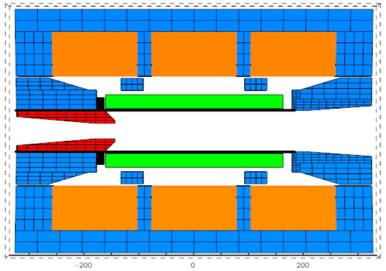
Improve ECR-CB technics ? :

  - increase plasma length and plasma density should enhance the capture and efficiencies
  - Contaminants reduction : ➔ see following Dr T. Thuillier presentation "Design of a hollow hexapole applicable to ECR charge breeder to mitigate the plasma contamination by sputtering"

Thank you for your attention

Additional slides

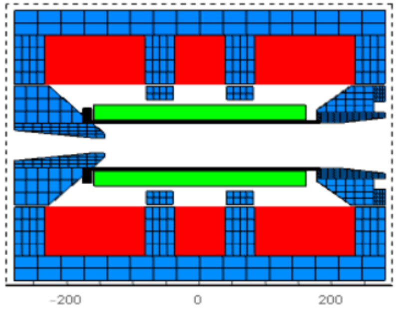
PHOENIX ECR Charge Breeder



<u>6 solenoids</u>

- "a" August 2010 — HF coupling, Stabilize the plasma
  - Injection electrode, HF blocker
- "b" March 2014 — Injection optics
  - Injection Bfield symmetry
- "c" June 2016 — Enhance confinement
  - Injection plug, rings position

- Efficiencies 10 - 20 %
- CB Time 5 - 30 ms/q
- Stable plasma
- HF power reduced
- Good Reproducibility



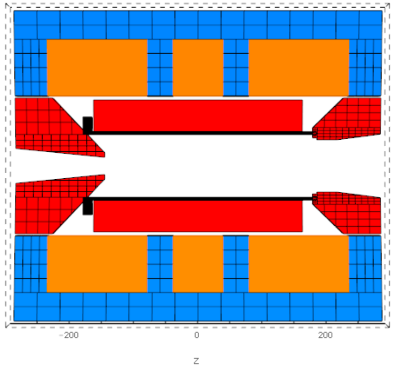
<u>5 solenoids</u>

January 2023 — Ease tuning, improve injection and extraction optics

- Yoke and coils rearrangement
- New plasma chamber
- New plugs

- 1+ beam capture experiments
- Beam purity experiments

➢ Plasma chamber failure



<u>Large diameter</u>

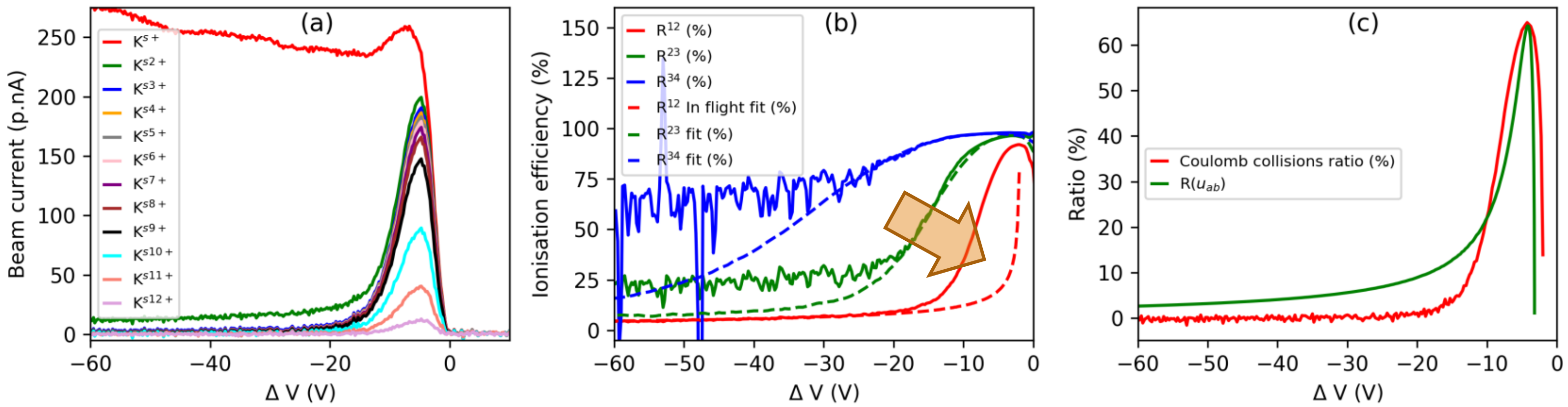
July 2024 — Increase high charge state
Enhance beam purity

CB central core modification:

- Sextupole
- Chamber
- Plugs

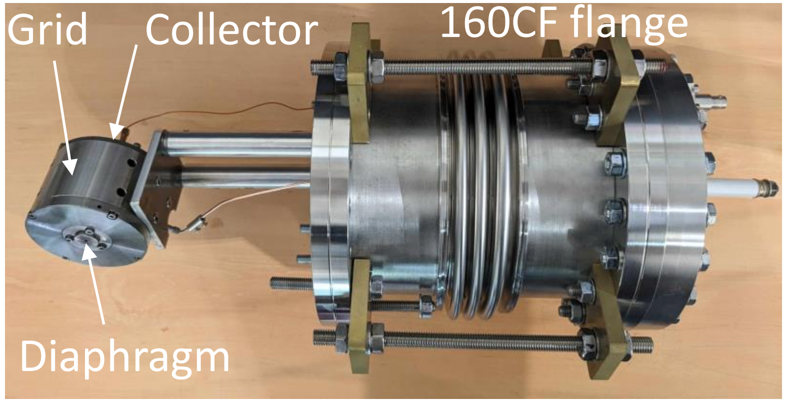
UHV design

16% efficiency K^{9+} Hydrogen plasma
11.4% efficiency K^{9+} Helium plasma


(a)
Beam current (p.nA)
ΔV (V)
(b)
Ionisation efficiency (%)
R12 (%)
R23 (%)
R34 (%)
R12 In flight fit (%)
R23 fit (%)
R34 fit (%)
ΔV (V)
(c)
Ratio (%)
Coulomb collisions ratio (%)
R(u_ab)
ΔV (V)

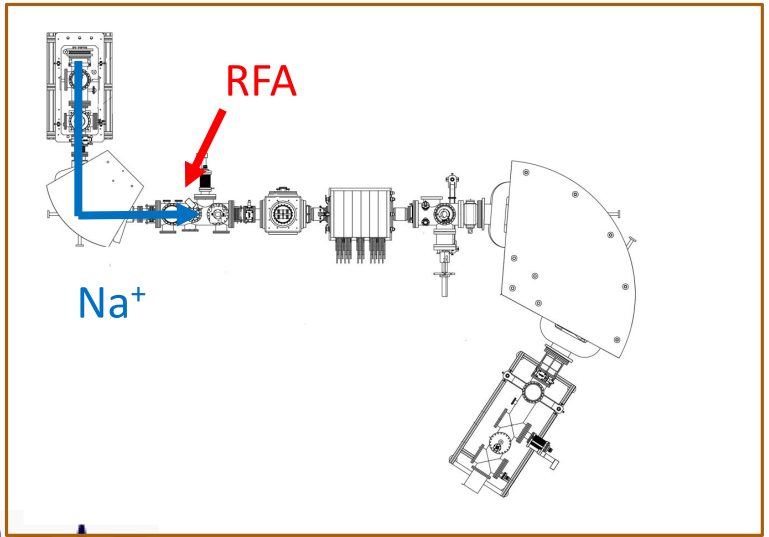
CB ECR plasma studies : the plasma potential symmetry

Purpose : compare the plasma potential value at both sides of the ECR-CB

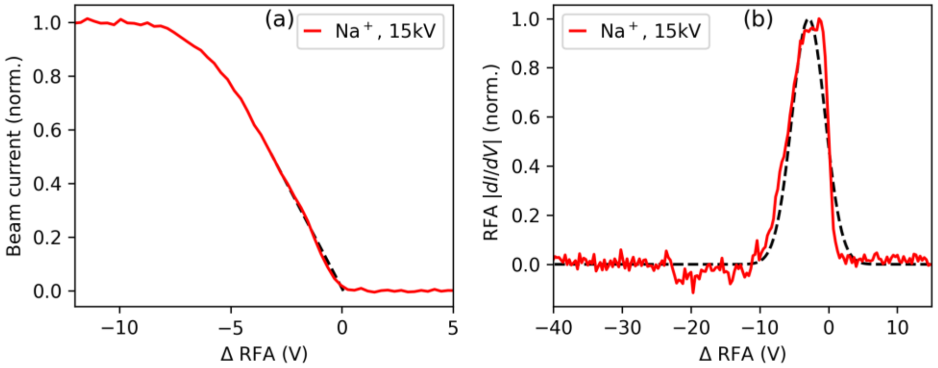


Development of a new RFA

- Compact Ø80mm L60mm
- planar, single very thin grid (~40µm mesh size)
- Grid potential > 25kV
- Mounted on bellow for precise alignment
- 2 copies



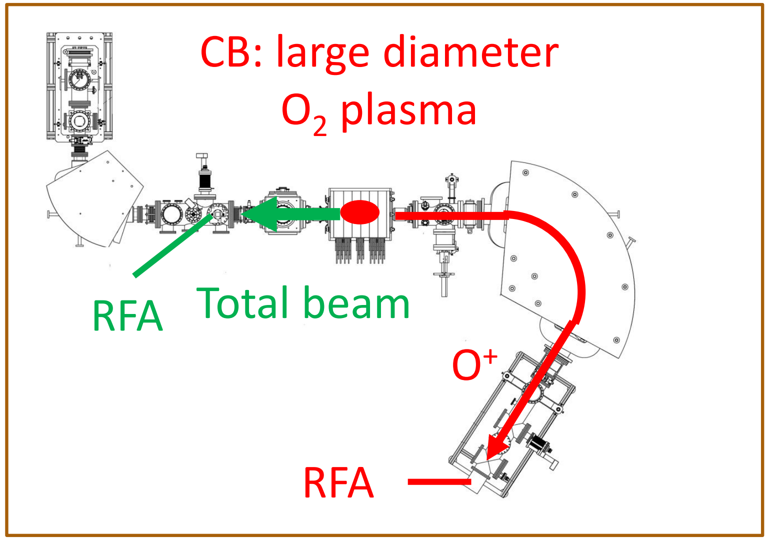
Resolution measurement in the 1+ beam line



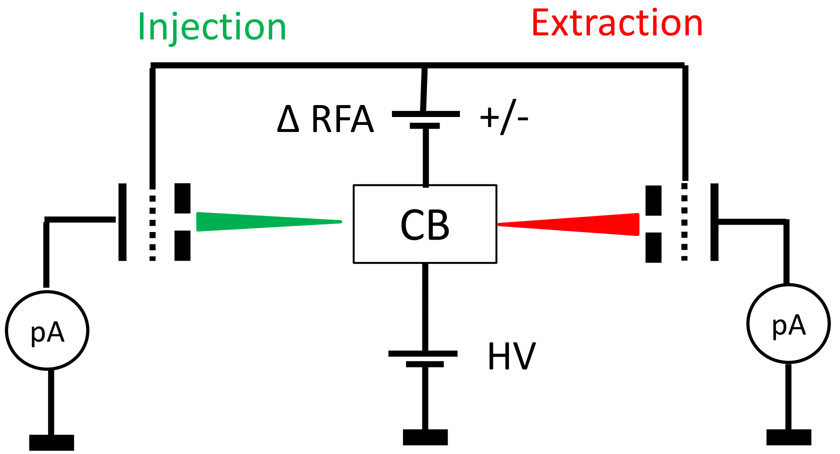
- Na^+ beam
- At 15kV, σ = 2.4V
- $\frac{\Delta E}{E} = 0.16\ 10^{-3}$

CB ECR plasma studies : the plasma potential symmetry

Purpose : compare the plasma potential value at both sides of the ECR-CB

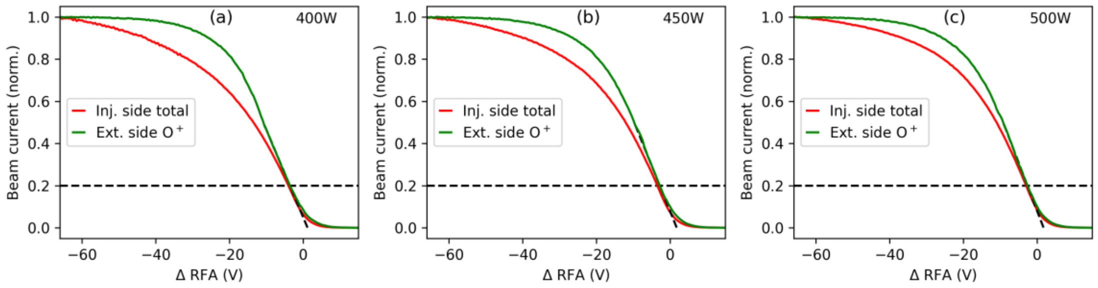


Electrical configuration



- Careful alignment of RFAs
- 2 RFA grids connected to the same supply “ΔRFA”, referenced to CB
- Same cable model, same length

Variation of CB HF power, record of RFA curves



Power (W)	400	450	500
Plasma Pot. Inj (V)	1.2	1.8	1.8

- Low plasma potential value around 1.5V
- Small effect of HF power on plasma potential here
- ➢ Behaviour due to new large diameter configuration with Aluminum parts

- Extraction PP found at higher value +0.5V
- But measurement very sensitive to alignment