STATUS AND PERSPECTIVE OF ELECTRON CYCLOTRON RESONANCE CHARGE BREEDERS

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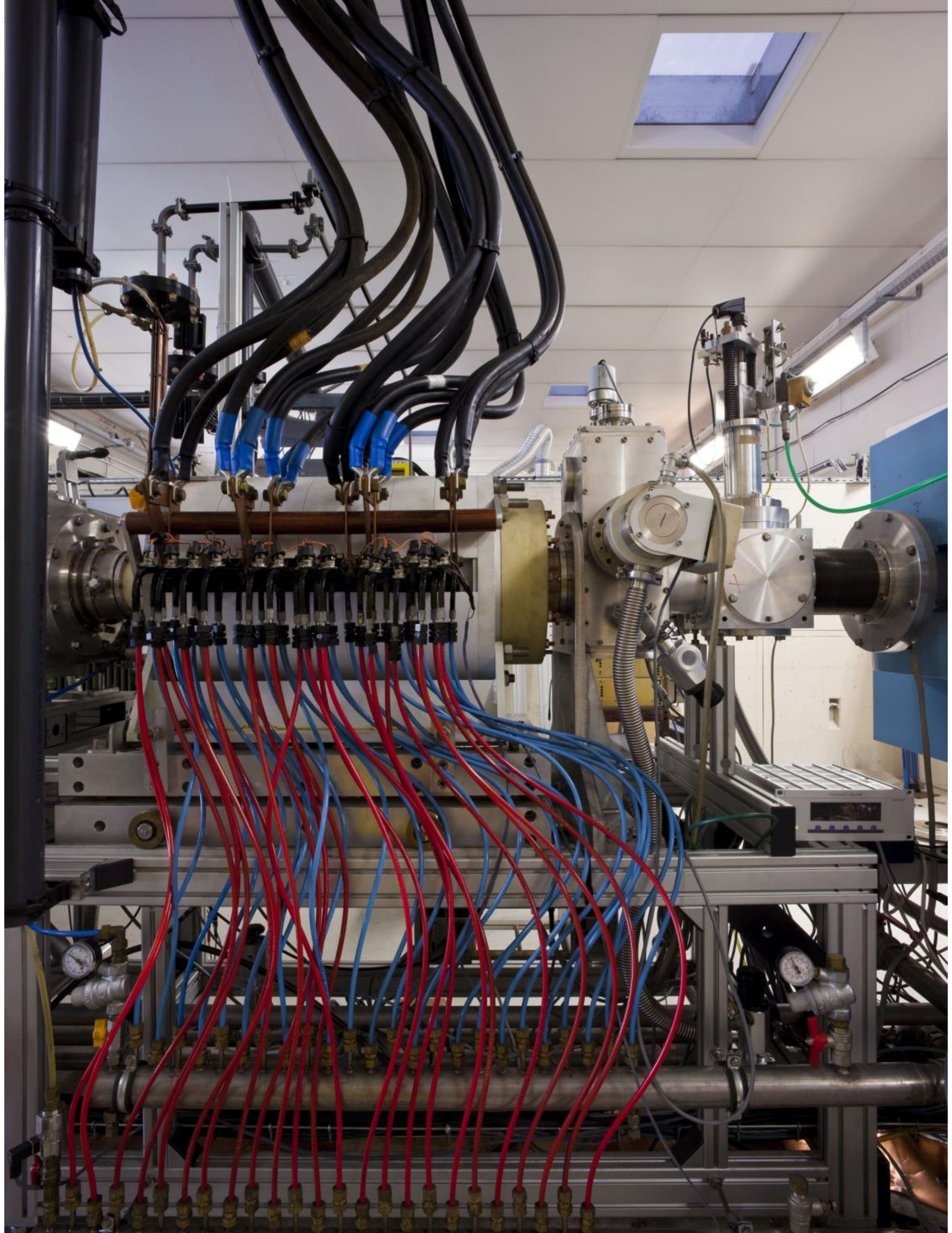


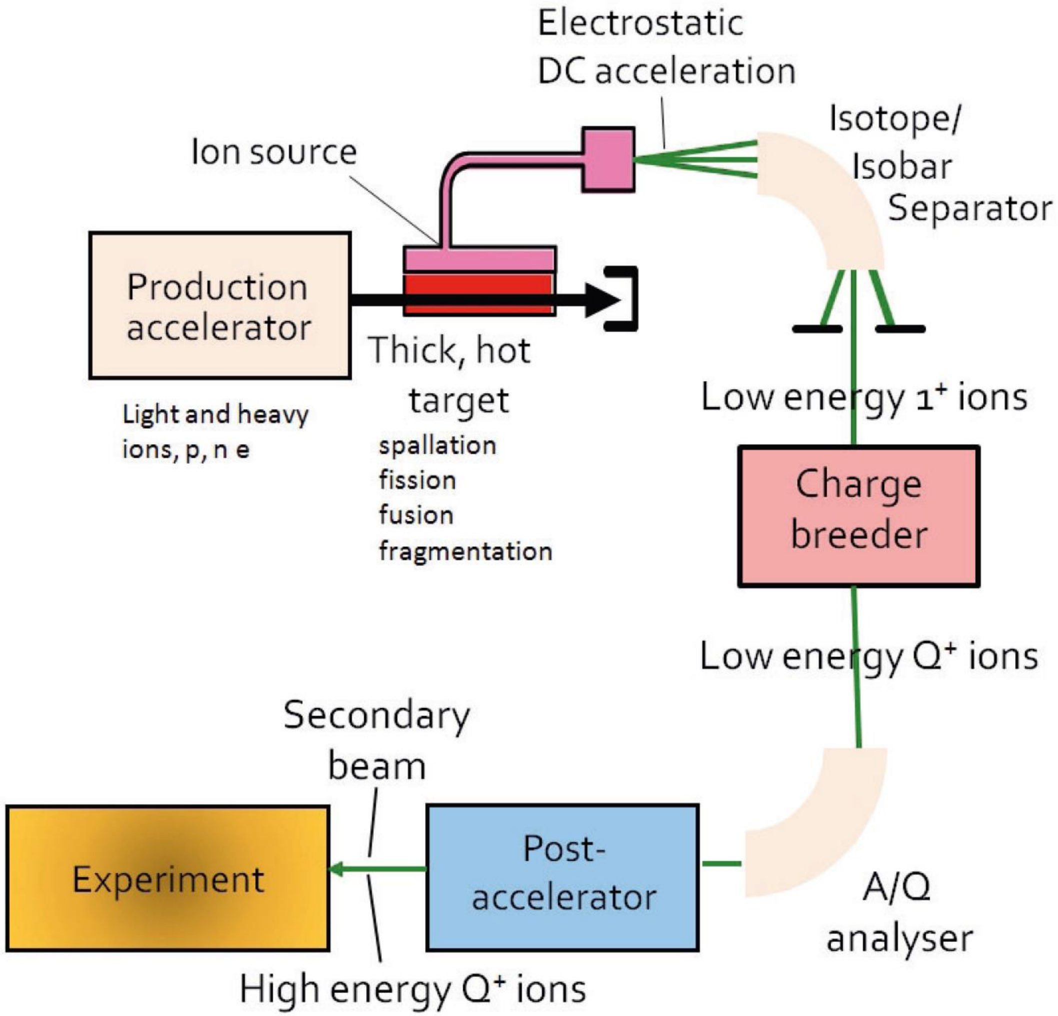
HIAT 2022 Darmstadt – June 27, 2022

Outline

- Introduction
- Beam Purity issue
- Developments
- Performances
- Future prospects
- Conclusion

Introduction

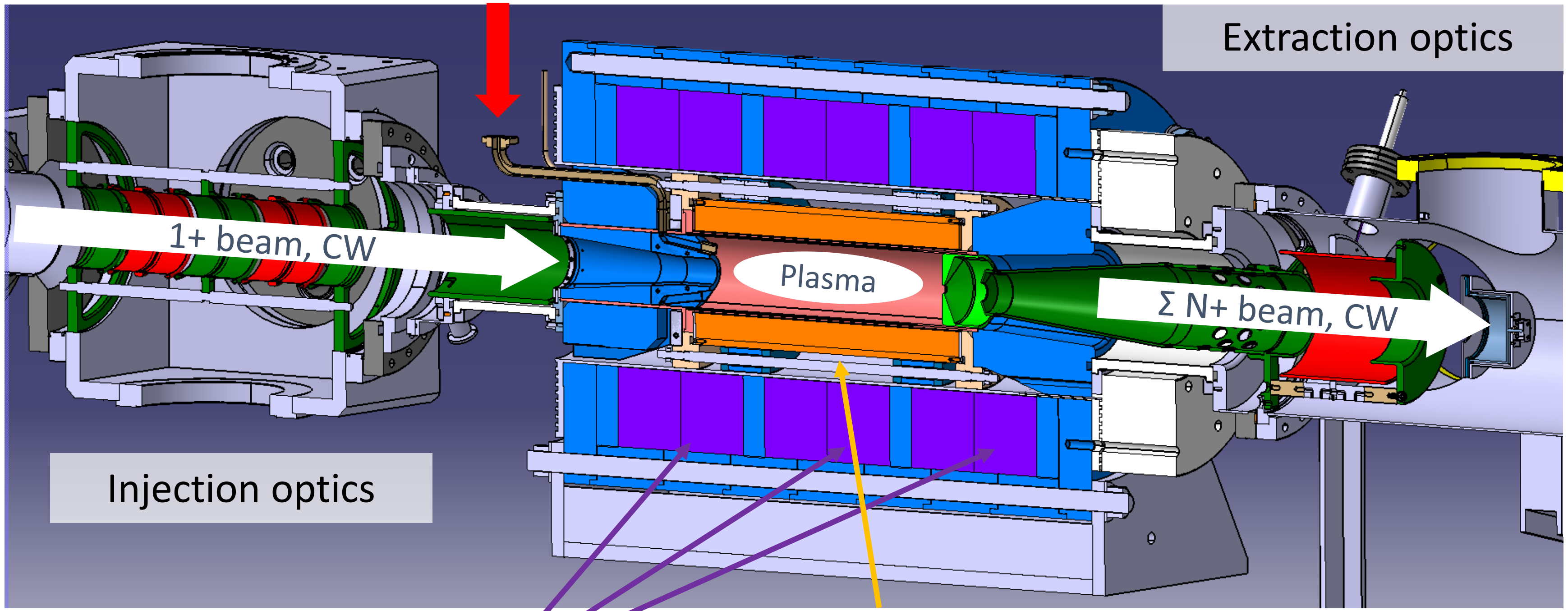
Principle of the Isotope Separation On Line method

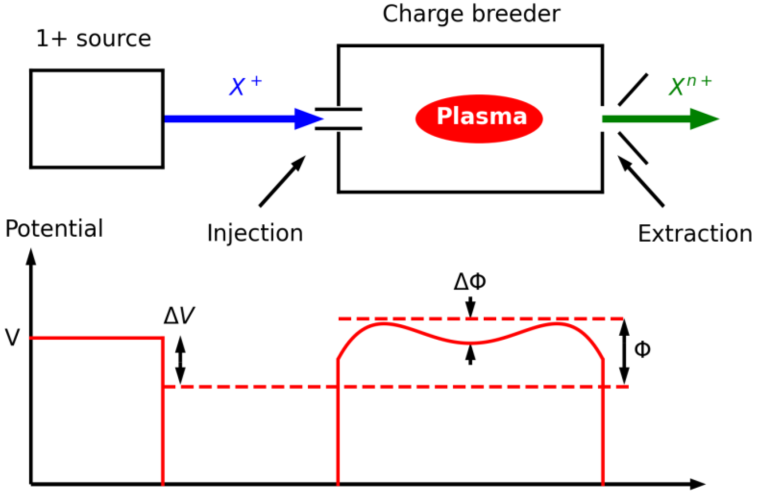


Introduction

14.5 GHz 500W

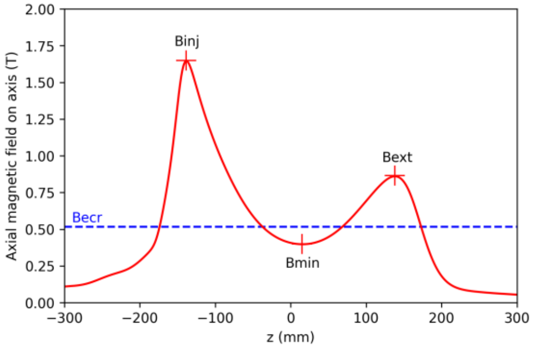
Injection, capture, multi ionisation, extraction

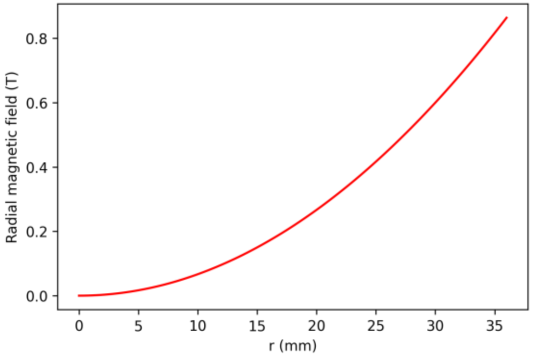




3 coils + yoke
Axial B field

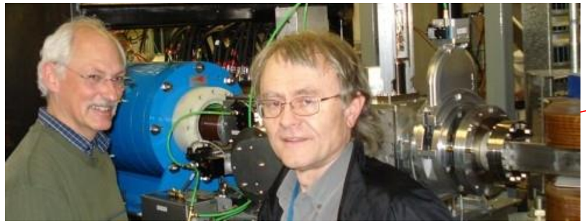
Hexapole
Radial B field



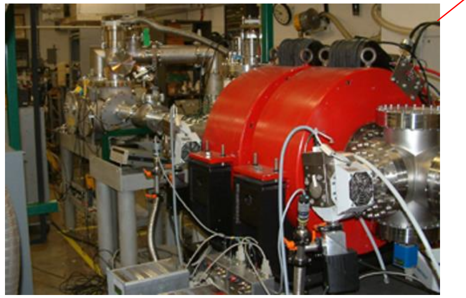


Capture process theory based on small angle deviations by ion-ion collisions with the buffer gas plasma ions leading to their thermalisation

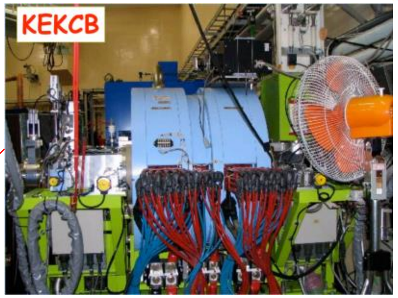
Introduction



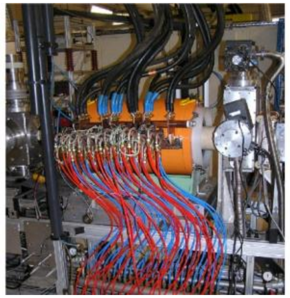
TRIUMF
PHOENIX 14GHz



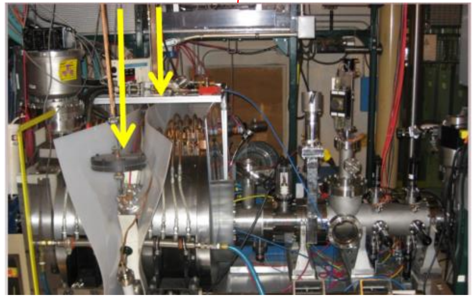
TEXAS A&M
14GHz



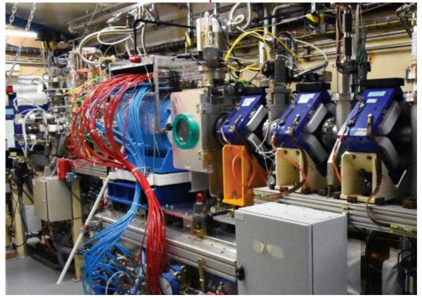
KEK
KEK CB 18GHz



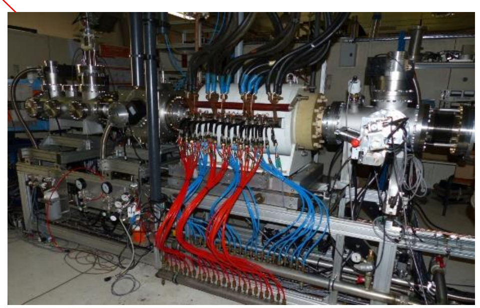
LNL
PHOENIX 14GHz



ANL
AECR 10 – 14GHz

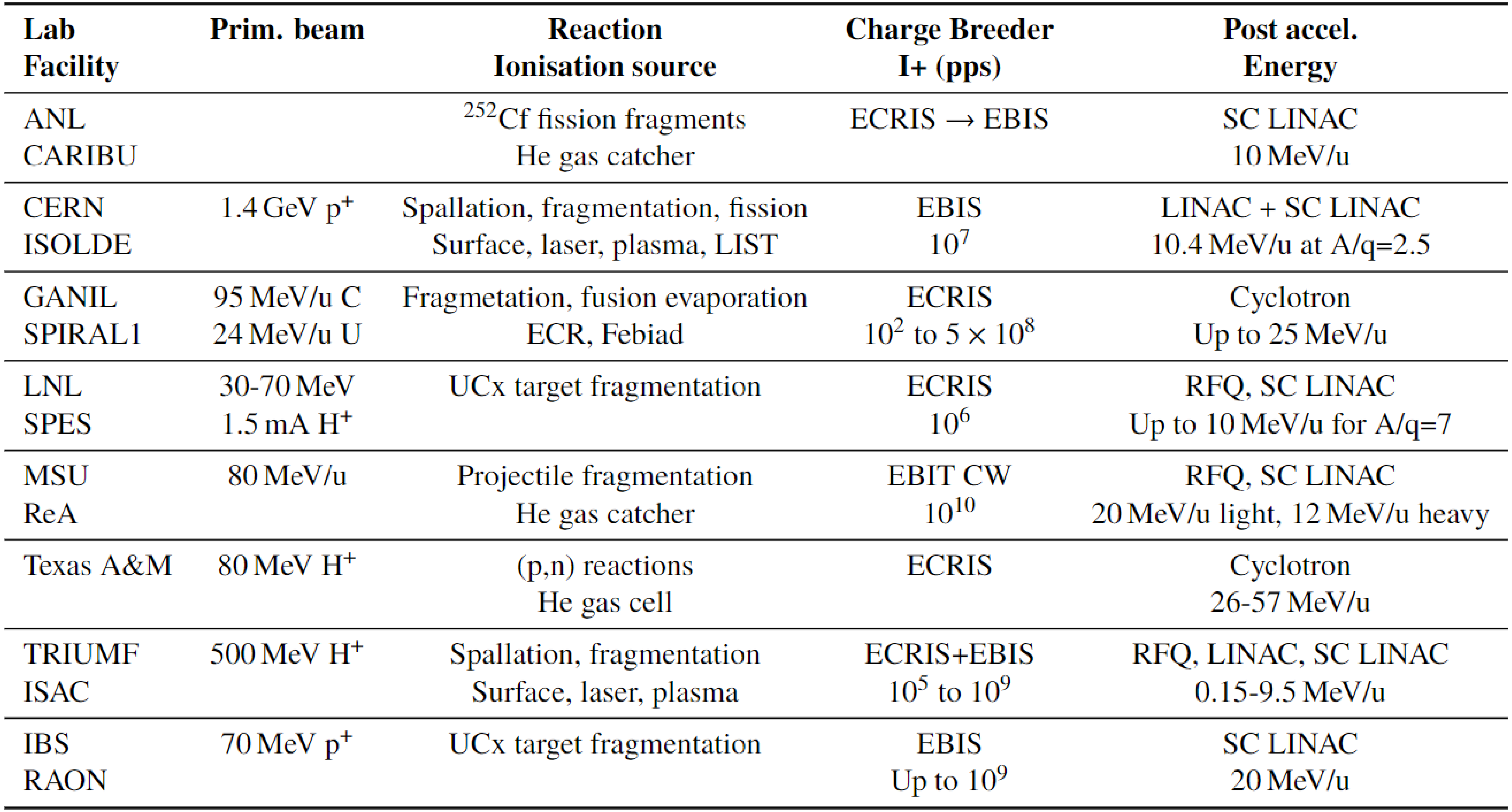


GANIL
PHOENIX 14GHz



LPSC
PHOENIX 14GHz

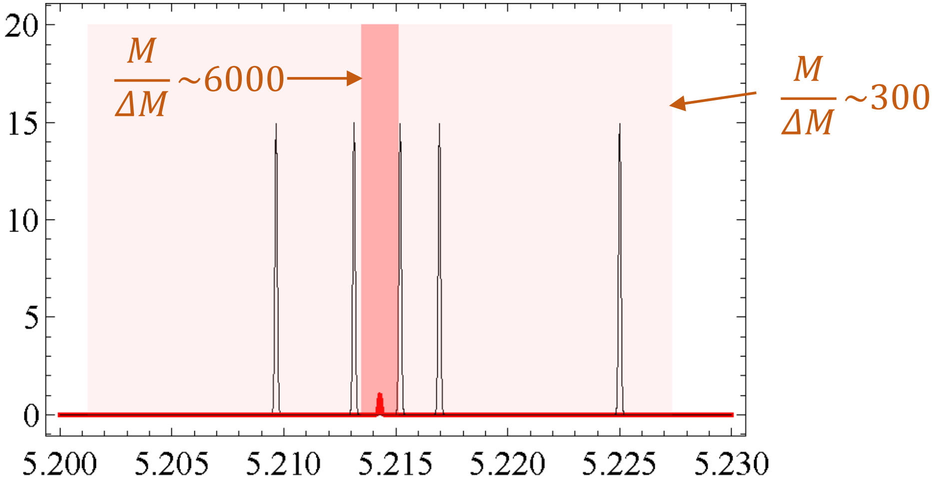
Introduction



Lab **Facility**	**Prim. beam**	**Reaction** **Ionisation source**	**Charge Breeder** **I+ (pps)**	**Post accel.** **Energy**
ANL CARIBU		^{252}Cf fission fragments He gas catcher	ECRIS → EBIS	SC LINAC 10 MeV/u
CERN ISOLDE	1.4 GeV p^+	Spallation, fragmentation, fission Surface, laser, plasma, LIST	EBIS 10^7	LINAC + SC LINAC 10.4 MeV/u at A/q=2.5
GANIL SPIRAL1	95 MeV/u C 24 MeV/u U	Fragmetation, fusion evaporation ECR, Febiad	ECRIS 10^2 to 5×10^8	Cyclotron Up to 25 MeV/u
LNL SPES	30-70 MeV 1.5 mA H^+	UCx target fragmentation	ECRIS 10^6	RFQ, SC LINAC Up to 10 MeV/u for A/q=7
MSU ReA	80 MeV/u	Projectile fragmentation He gas catcher	EBIT CW 10^{10}	RFQ, SC LINAC 20 MeV/u light, 12 MeV/u heavy
Texas A&M	80 MeV H^+	(p,n) reactions He gas cell	ECRIS	Cyclotron 26-57 MeV/u
TRIUMF ISAC	500 MeV H^+	Spallation, fragmentation Surface, laser, plasma	ECRIS+EBIS 10^5 to 10^9	RFQ, LINAC, SC LINAC 0.15-9.5 MeV/u
IBS RAON	70 MeV p^+	UCx target fragmentation	EBIS Up to 10^9	SC LINAC 20 MeV/u

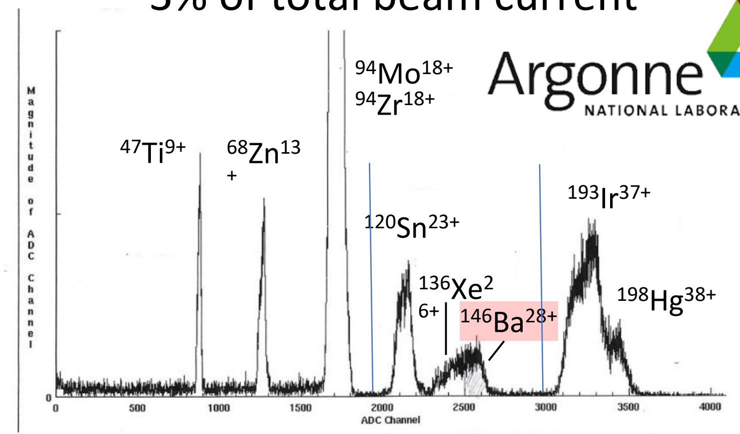
Beam purity issue

2.7% of RIB content in the beam with $\frac{M}{\Delta M} \sim 300$

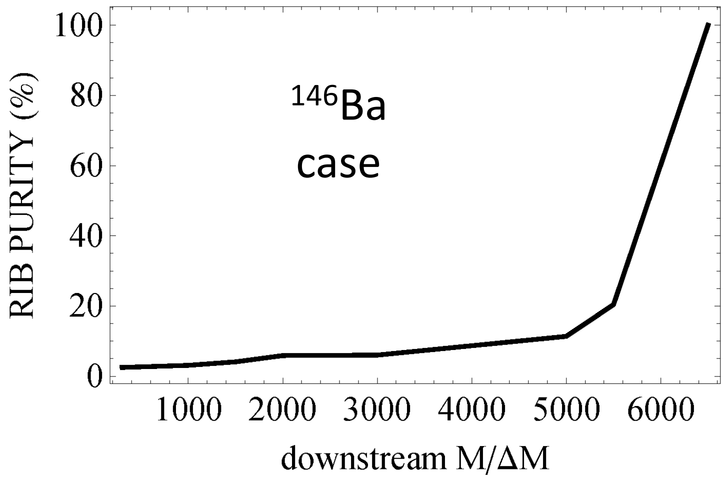


60% RIB would need $\frac{M}{\Delta M} \sim 6000$

~3% of total beam current

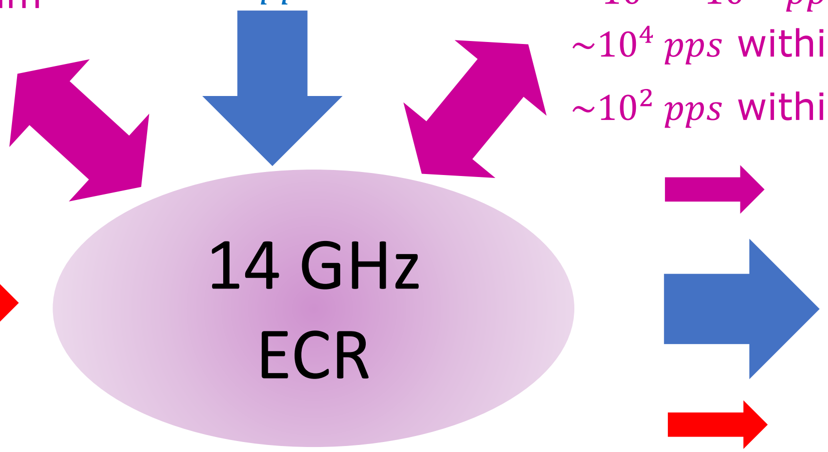


Ionization chamber signals



Thuillier, ECRIS 2018 workshop

Beam purity issue



Wall sputtering
$\sim 10^9 - 10^{10}\ pps$ whole ion spectrum
$\sim 10^4\ pps$ within $\frac{M}{\Delta M} \sim 400$
$\sim 10^2\ pps$ within $\frac{M}{\Delta M} \sim 5000$

Buffer gas
$\sim 10^{16}\ pps$

Gases contaminants
$\sim 10^9 - 10^{13}\ pps\ whole\ spectrum$
$\sim 10^4\ pps$ within $\frac{M}{\Delta M} \sim 400$
$\sim 10^2\ pps$ within $\frac{M}{\Delta M} \sim 4000$

1+ signal
up to $10^{13}\ pps$

14 GHz
ECR

contaminants

Itotal~1 mA
($\sim 10^{15} - 10^{16}$ pps)

N+ signal

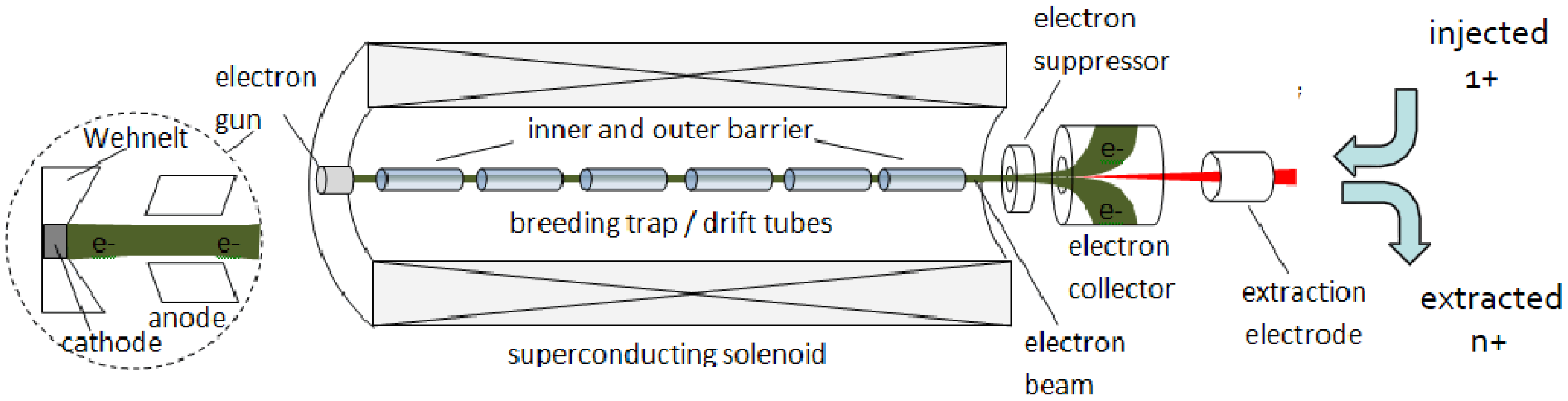
- **Signal** to **noise** ratio is a key parameter for ECRIS CB at low RIB intensity:

	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%

ANL

Thuillier, ECRIS 2018 workshop

Beam purity issue : Electron Beam Ion Sources



2-8 T

- Operate in pulse mode to reach high efficiency

- The charged particules have low interactions with the walls, base vacuum ≈ 10^{-11} mbar ➔ high beam purity
- A cooler-buncher is necessary to prepare the beam for injection
- Total efficiency of the cooler-buncher + EBIS : 5 to 20%
- CB time of cooler-buncher + EBIS : 10 to 100 ms

Main limitation

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

ECR Charge Breeder developments

Developments to improve ECR CB purity :

Use of NEG material

Plasma chamber coating with pure Al

Vacuum improvement

Cleaning technics

Extensive developments by the laboratories to improve ECR CB performances :

1+ beam injection

Injection electrode geometry / position

Magnetic field at injection symmetrized to prevent steering

Plasma conditions

Increase the injection magnetic field (better confinement)

Microwave double frequency heating

And frequency tuning

KEK, RSI 79,02A906(2008)

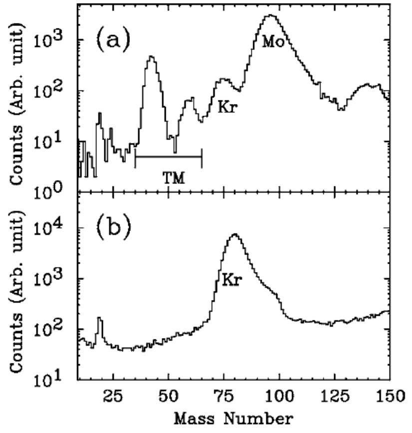


FIG. 3. Impurities originating from the KEKCB. The A/q=7.68 ratio is defined by the slit and the analyzing magnet. (a) The mass spectrum obtained before cleaning of the plasma chamber and electrodes. (b) The mass spectrum obtained after cleaning. TM stands for transition metals. Mo and Kr indicates molybdenum and krypton ions.

TRIUMF, ICIS 2021 poster

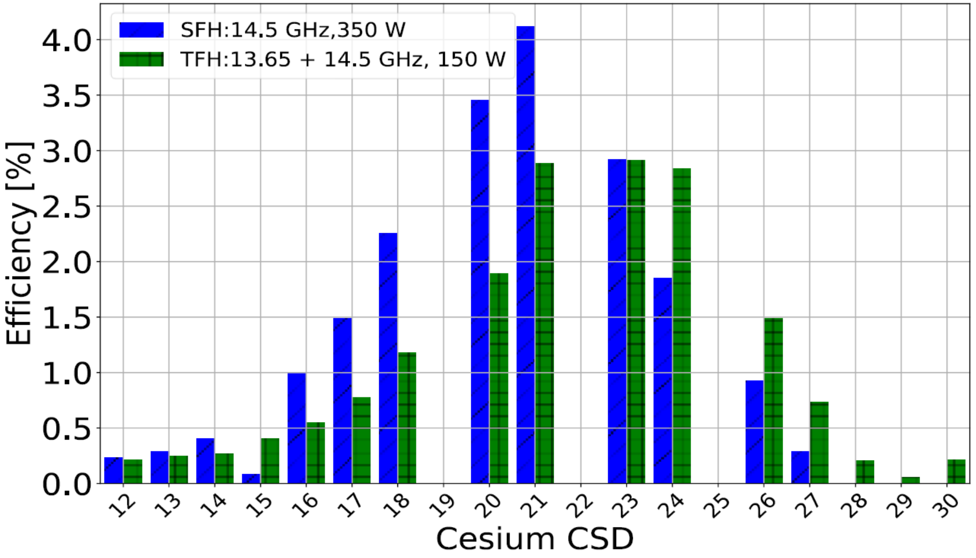
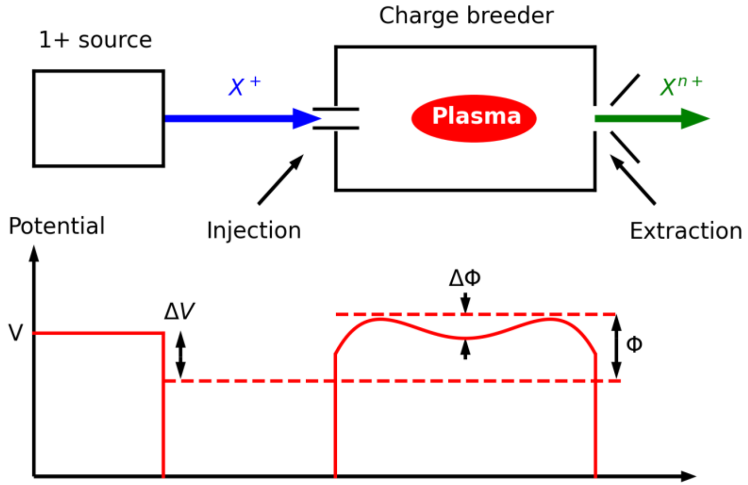


Fig. 7: Efficiency of Cs with Single and Two-frequency Heating

ECR Charge Breeder developments : 1+ beam capture experiments

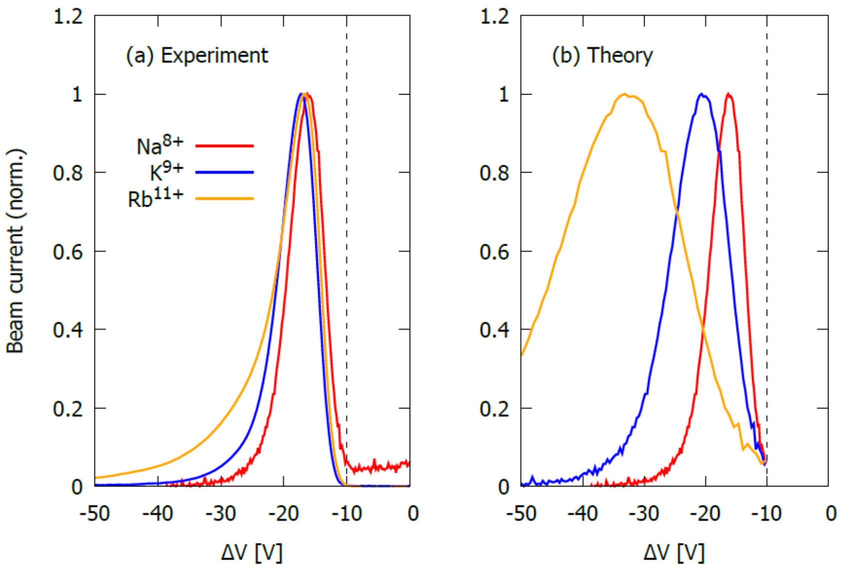


$$|\Delta V|_{opt} = \frac{4m_{1+}}{\pi m_i}\frac{kT_i}{e} + \varnothing$$

Measurements : $\varnothing \approx 10V$ and kT_i= 5 to 28 eV
Not in good agreement with the theory
Experiments to test the mass dependency of the stopping term

Experiments vs theory

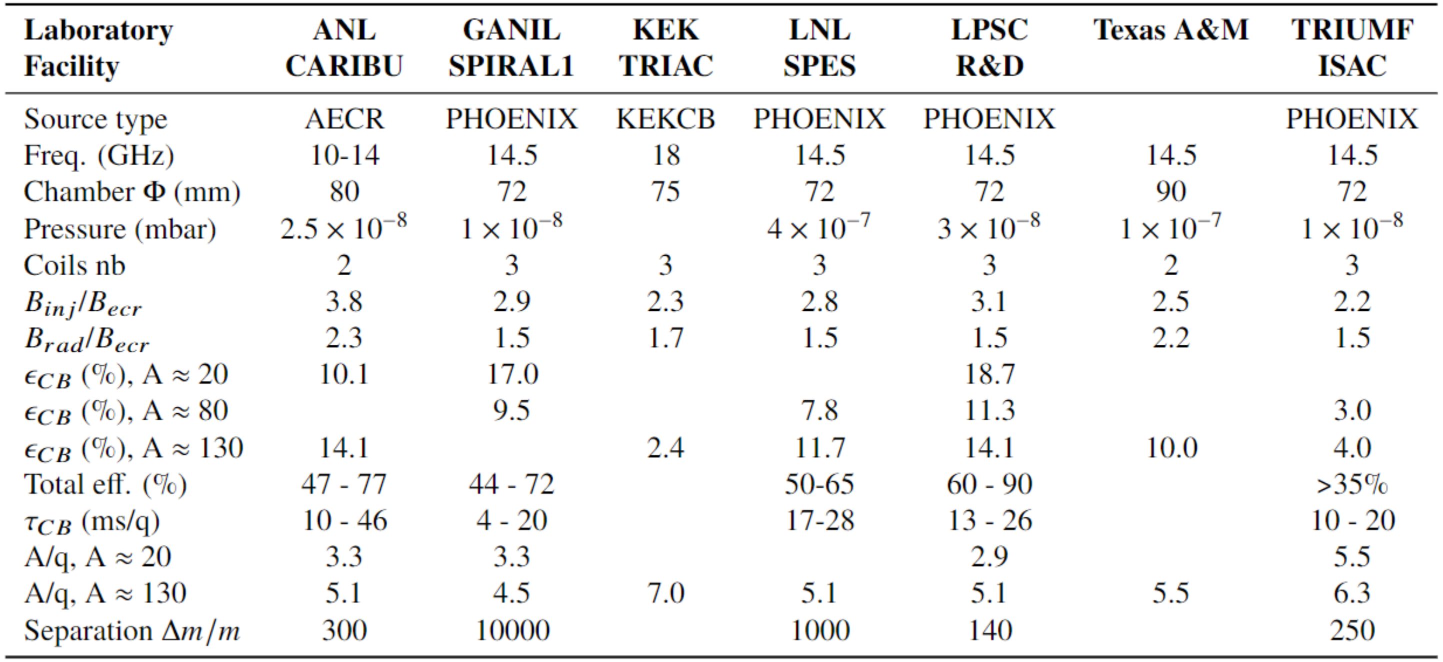
Support gas : He



- Main slowing down due to the plasma potential
- Ionisation to 2+ by the plasma electrons
- Influence of the potential dip in the capture

O. Tarvainen *et al.*, submitted in PSST

ECR Charge Breeder performances



Laboratory **Facility**	**ANL** **CARIBU**	**GANIL** **SPIRAL1**	**KEK** **TRIAC**	**LNL** **SPES**	**LPSC** **R&D**	**Texas A&M**	**TRIUMF** **ISAC**
Source type	AECR	PHOENIX	KEKCB	PHOENIX	PHOENIX		PHOENIX
Freq. (GHz)	10-14	14.5	18	14.5	14.5	14.5	14.5
Chamber Φ (mm)	80	72	75	72	72	90	72
Pressure (mbar)	2.5×10^{-8}	1×10^{-8}		4×10^{-7}	3×10^{-8}	1×10^{-7}	1×10^{-8}
Coils nb	2	3	3	3	3	2	3
B_{inj}/B_{ecr}	3.8	2.9	2.3	2.8	3.1	2.5	2.2
B_{rad}/B_{ecr}	2.3	1.5	1.7	1.5	1.5	2.2	1.5
ϵ_{CB} (%), A ≈ 20	10.1	17.0			18.7		
ϵ_{CB} (%), A ≈ 80		9.5		7.8	11.3		3.0
ϵ_{CB} (%), A ≈ 130	14.1		2.4	11.7	14.1	10.0	4.0
Total eff. (%)	47 - 77	44 - 72		50-65	60 - 90		>35%
τ_{CB} (ms/q)	10 - 46	4 - 20		17-28	13 - 26		10 - 20
A/q, A ≈ 20	3.3	3.3			2.9		5.5
A/q, A ≈ 130	5.1	4.5	7.0	5.1	5.1	5.5	6.3
Separation $\Delta m/m$	300	10000		1000	140		250

- Different CB configurations
- Different facility configurations

- Efficiency : 5 to 20%
- Total efficiency : 35 to 90%
- CB time : 10 – 28 ms/q

ECR CB offer high 1+ beam acceptance > 10^{13} pps with a constant contamination yield

High RIB fluxes are expected in future ISOL facilies like FRIB (>10^{10}pps in some cases, under commissionning) or EURISOL (10^{12} pps)

At FRIB a High Capacity EBIS is under development, should accept 10^{11} pps for low mass A≈20 (H.J. Son, NACB 2021)

ECR Charge Breeder prospects

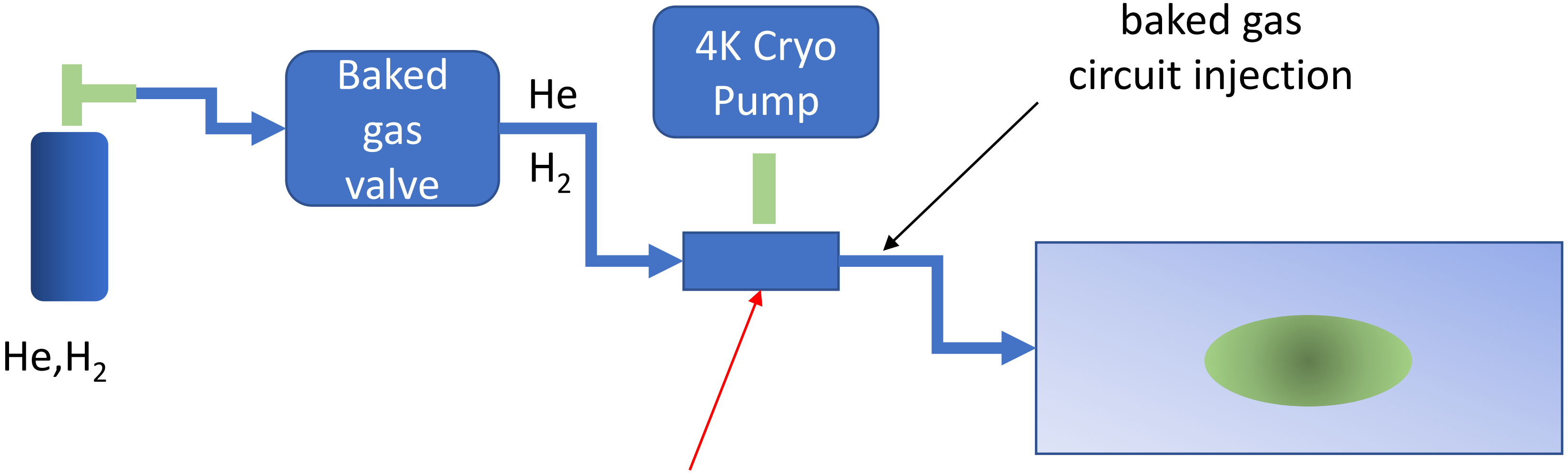
Possible improvement of ECR Charge Breeding technics :

- Increase microwave frequency :
  increase electron density ➔ better capture, shorter CB time, higher charge state
- Large plasma chamber radius ➔decrease the density of contaminants, higher charge state
- Increase magnetic field at injection ➔ better trapping of the ions

ECR Charge Breeder prospects : beam purity

All the sources of contamination must be addressed:

- Use of pure material in front of the plasma
- Follow ANL steps to get rid of gas contamination (He or H_2 as support gas)



baked gas
circuit injection

Condensed gas
contaminants
from the gas bottle
@ 4K

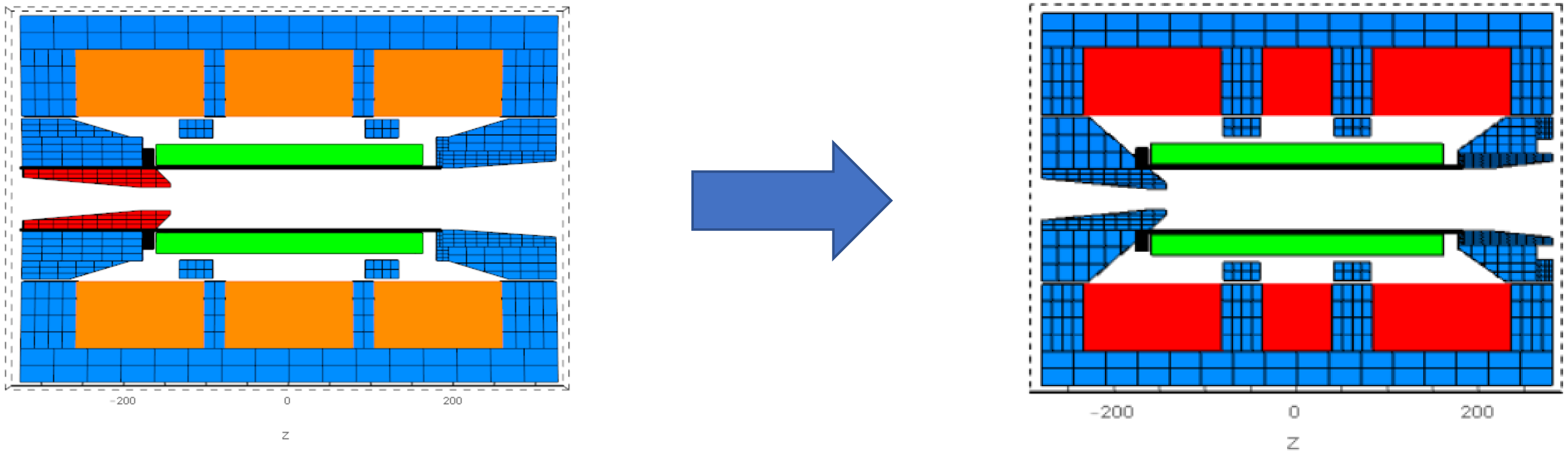
He or H_2 buffer plasma

ECR Charge Breeder prospects

R&D program at LPSC on PHOENIX type CB

5 coils configuration : ease the tuning and stabilize the plasma

- Improve the axial magnetic field profile
- Decrease the cross talk between the coils



Beam purity improvement (LNL LPSC GANIL collaboration)

- Experiments will be done with liners
- Support gas decontamination

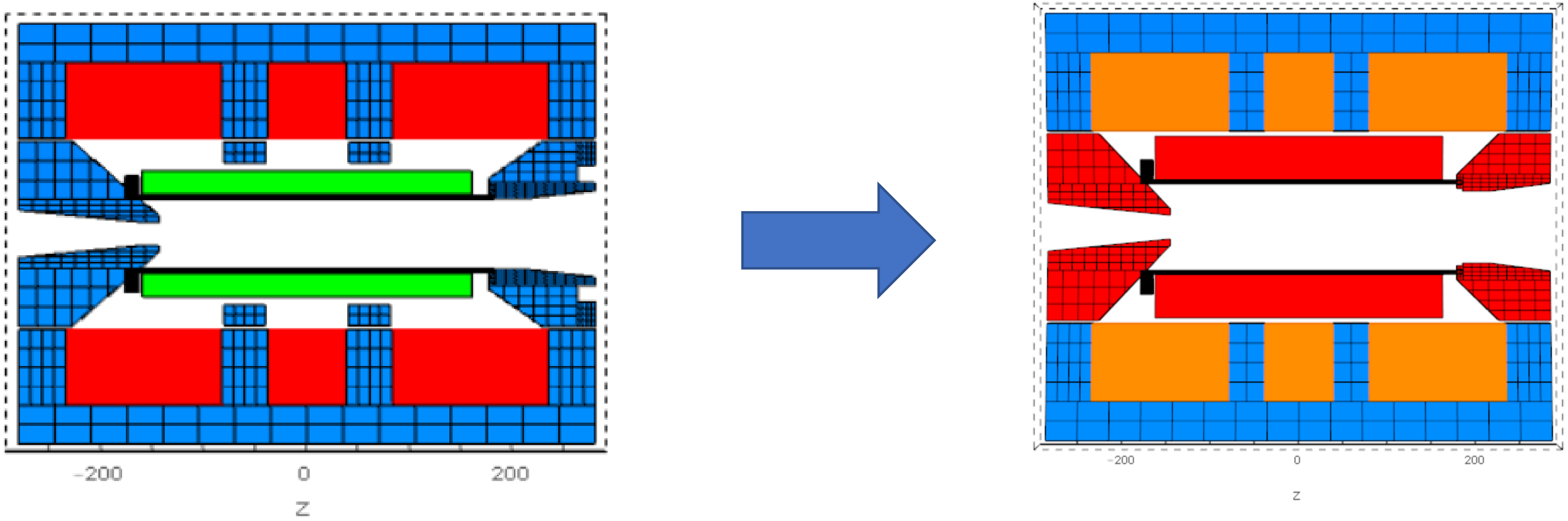
Assembly in September 2022

ECR Charge Breeder prospects

R&D program at LPSC on PHOENIX type CB

Large diameter configuration:

- increase high charge state production
- Decrease the density of contaminants



- Plasma chamber diameter : 72 ➔ 100 mm
- Larger hexapole
- sealing exclusively with metal gaskets
- 18GHz operation, two frequency heating

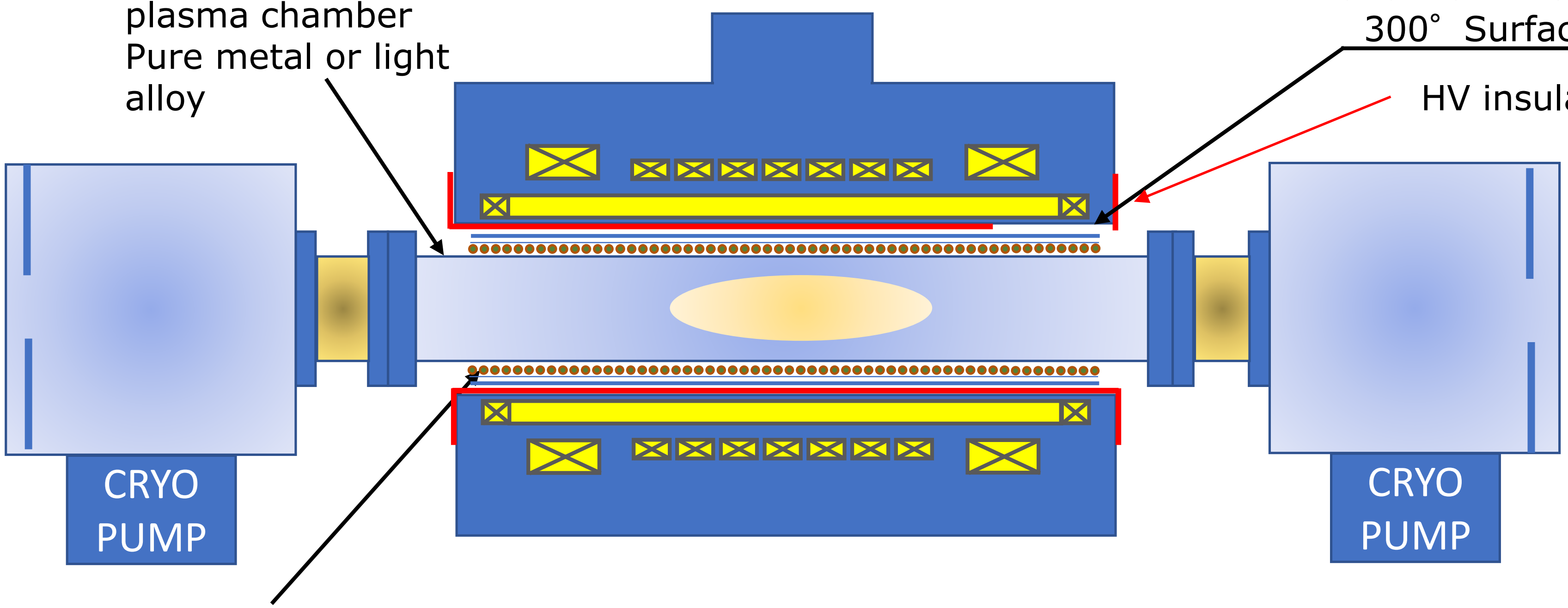
Assembly in 2023

ECR Charge Breeder prospects

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



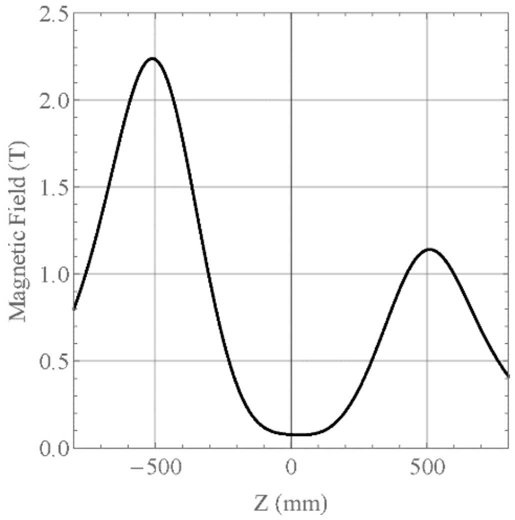
plasma chamber
Pure metal or light
alloy

Thermal screen
and Water cooled
300° Surface

HV insulator

Heater wire to bake
The plasma chamber
Online up to 400° C

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



Thuillier, ECRIS 2018 workshop

Conclusion

- ECR Charge Breeders are efficient instruments that accept a very high 1+ beam flux which could be of high interest for future ISOL facilities with high production yield
- The beam purity issue can be addressed with high downstream separation and additional R&D must be carried out to reduce the contaminants
- ECR Charge Breeding technics can be improved and solutions are identified to enhance the performances through a new generation of source

Thank you for your attention