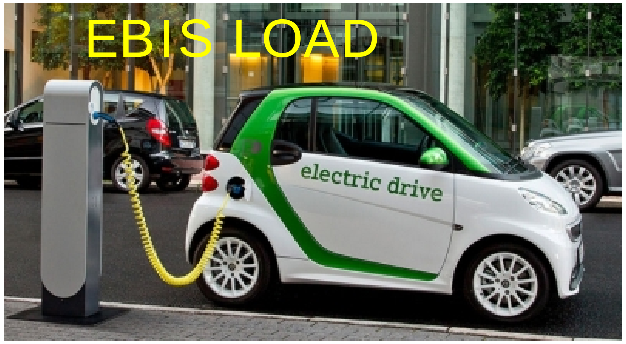
STATUS AND PROSPECTS OF ELECTRON CYCLOTRON RESONANCE CHARGE BREEDER

T. Thuillier , J. Angot, P. Sole, J. Jacob, A. Leduc, T. Lamy, B. Bhaskar, L. Bonny, LPSC

XXIII Workshop on ECR Ion Sources, Catania, Sept. 2-4th 2018

Outline

- Motivation
- Status of ECR CB operation
- Can ECR booster be improved?
- prospects for EURISOL RIB facility

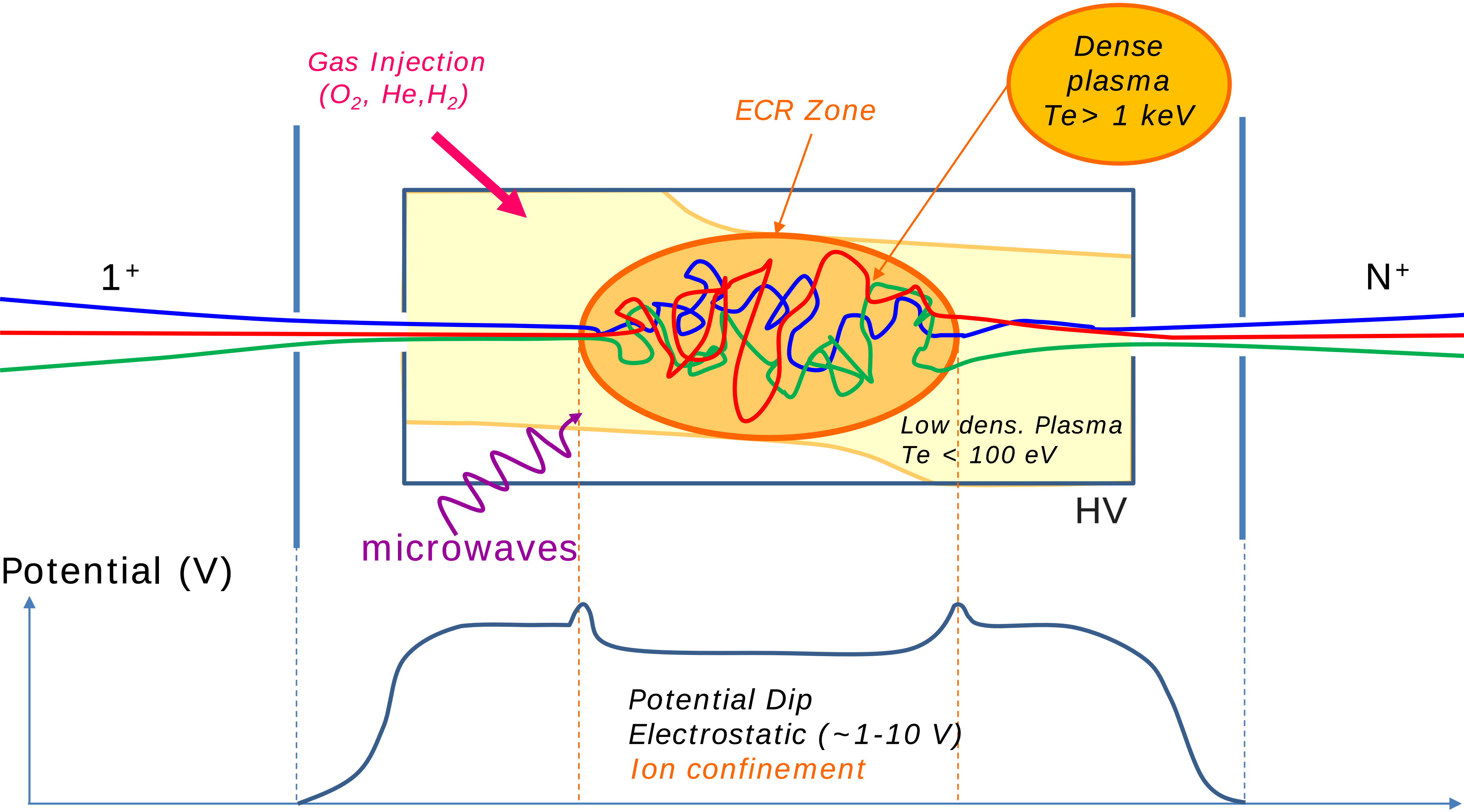


MOTIVATION

- Argonne stopped its ECR charge breeder and switched to an EBIS one
- TRIUMF is building an EBIS charge breeder to improve the RIB purity for experiments
  - Many RIB physicists have consequently concluded ECR boosters research is« dead » (« RIP » ECR CB!)
- Are ECR CB Really DEAD?
- Can they be upgraded?
- Is there a future to ECR charge breeders?
- Testing ideas with you

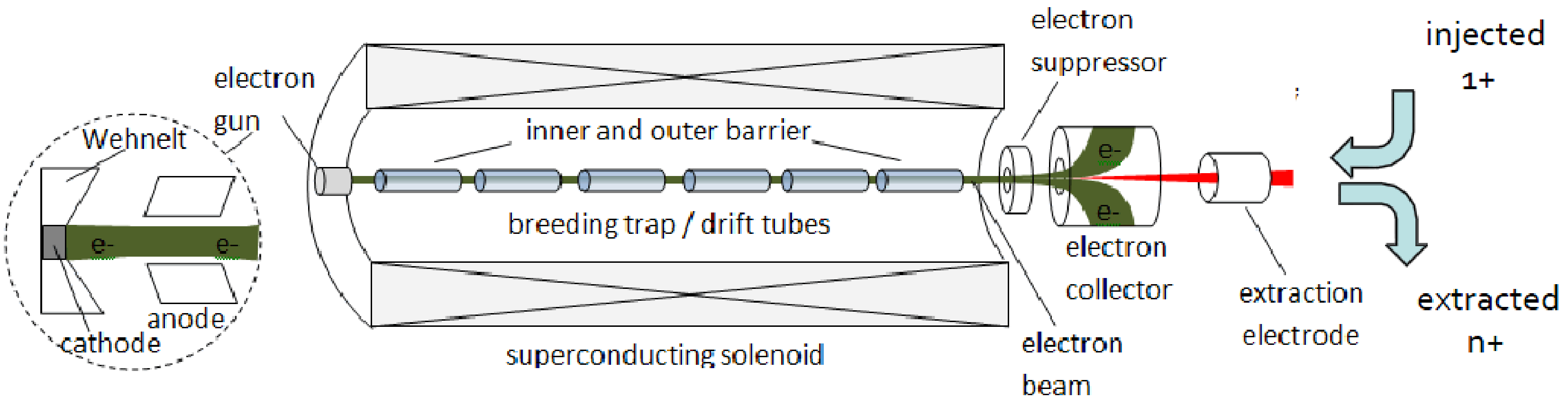
ECRIS CB Ion Capture

- Coulomb collision→ thermalisation →diffusion →ionization →capture



EBIS Technology

- Pulsed
- 1+ intensity limited to ~nA ($< 10^{10}\ pps$)
- 1+N+ Efficiency ~25-30% / Very High Charge state
- Hot electron density $\sim 10^{13} - 10^{14} cm^{-3}$
  - short total CB time~10 ms , even for highly charged ions
- Base vacuum $\sim 10^{-10}\ mbar$
- Electrons created and dumped outside the trap
  - Low contamination induced : $10^2 - 10^3/s$ per $\frac{M}{\Delta M} \sim 300$



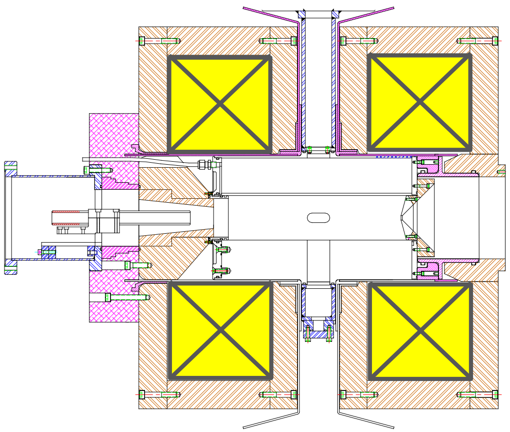
2-8 T

Source : F. Wenander CAS 2012

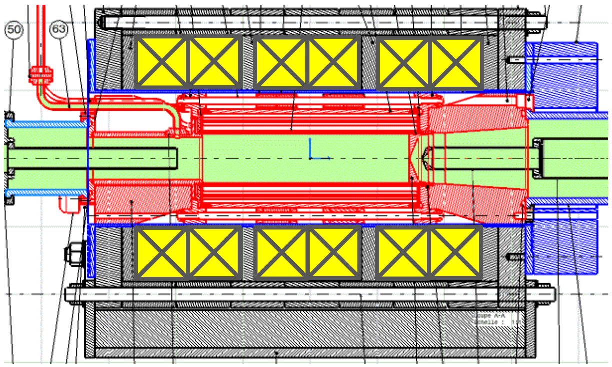
Today ECRIS CB technology

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

- Based on 20-30 years old 14 GHz ECRIS design
- CW or pulsed 1^+ beam
  up to ~1-10 pμA $(\sim 10^{13} - 10^{14}\ pps)$
- CB time~1-10 ms/charge
- 1+N+ Efficiency 1 charge state: ~5-20%
- Max charge state:
  - A/Q~3 up to A=50
  - A/Q~7 up to A=150
- Vacuum~10^{-7} - 10^{-8} mbar (non UHV)
  - Gas contamination
- The plasma intercepts the walls
  - condensable sputtering from stainless steel, copper, aluminum alloy...
  - ANL result: within $\frac{M}{\Delta M} \sim 300$, contamination $\sim 10^4\ pps$



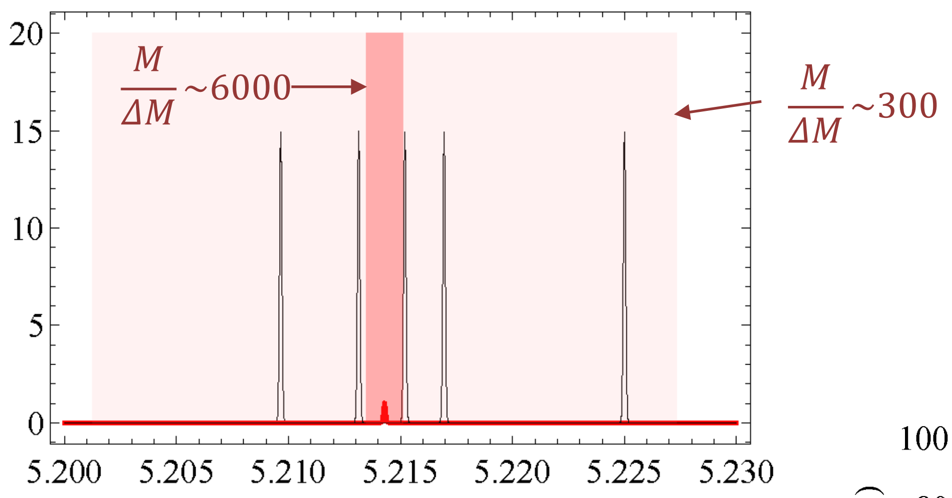
A-ECR (ANL)



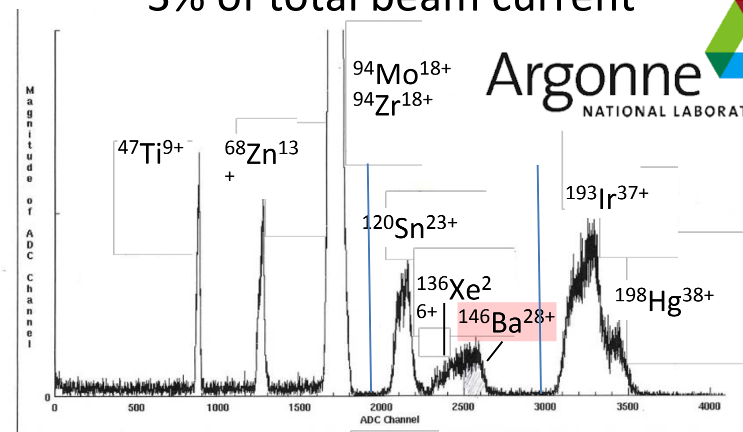
PHOENIX BOOSTER
(LPSC, GANIL, TRIUMF, SPES)

ANL Experience : ^{146}Ba run

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



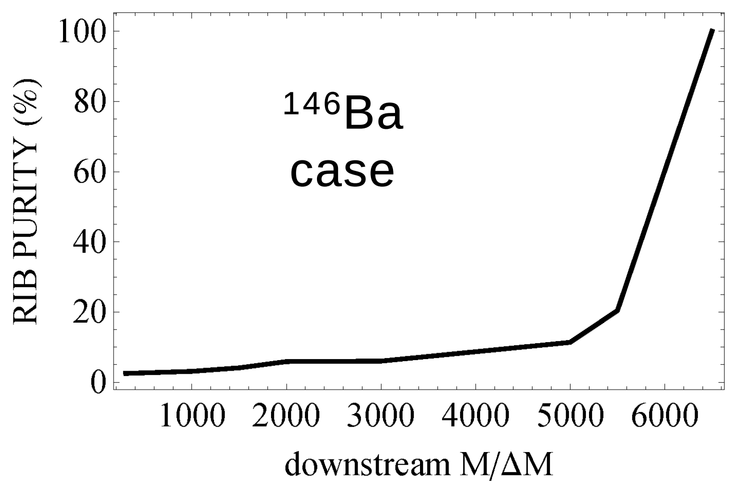
~3% of total beam current



Ionization chamber signals

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

- 60% RIB in $\frac{M}{\Delta M}\sim 300$ would need RIB intensity increased by 60



Orders of Magnitudes

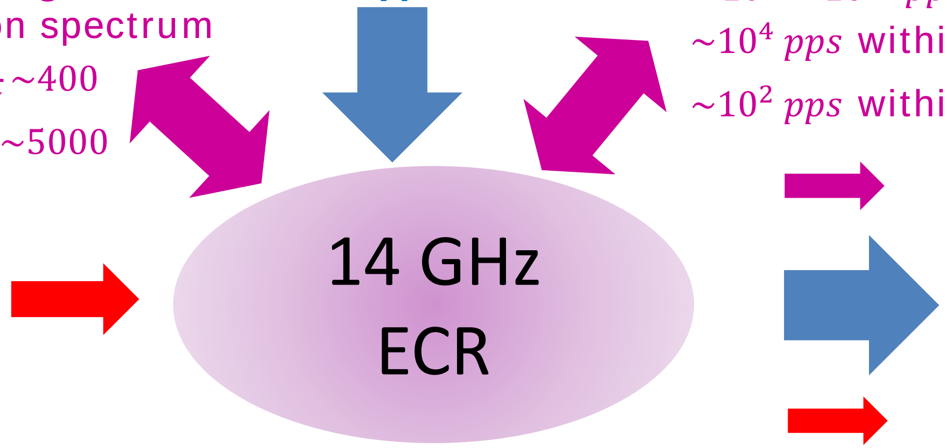
LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

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

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 $\frac{M}{\Delta M} \sim 5000$

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 $10^{13}\ pps$



contaminants

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

N+ signal

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

	Signal (pps)	10^2	10^3	10^4	10^5	10^6
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%

CARIBU (ANL) , TRIAC (TRIUMF)

Is it Game Over for ECR CB?

- Performances are based on 20 years old ion source designs
  - Not UHV, plastic O-rings, many materials facing plasma
  - Magnetic field and volume not optimized

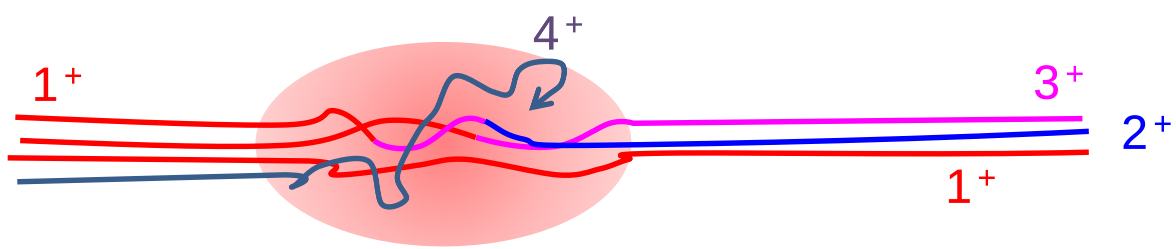
- Ion Source know-how dramatically improved since 20 years

NO!

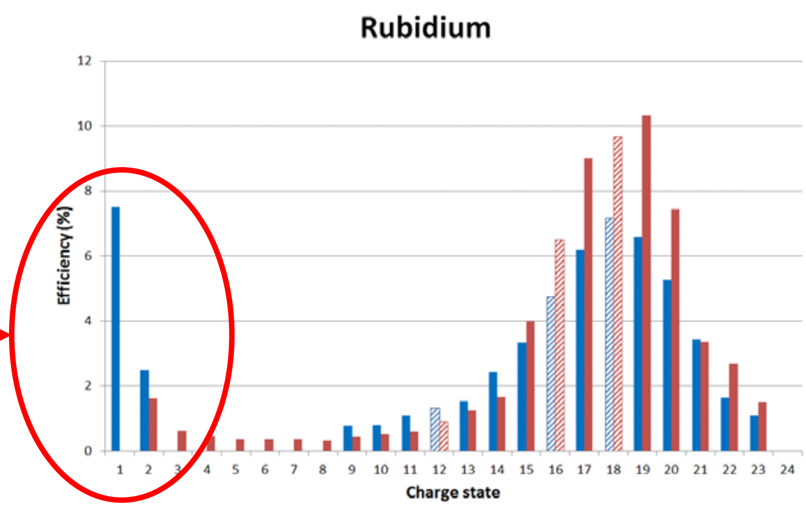
LET'S REVIEW WHAT CAN BE DONE

Improve the ion capture

- Optimize the capture with a longer (or denser) plasma
  - Today, a part of the 1+ beam is not captured, even some 2+ and 3+ are ionized on flight and not captured (10-20% lost)



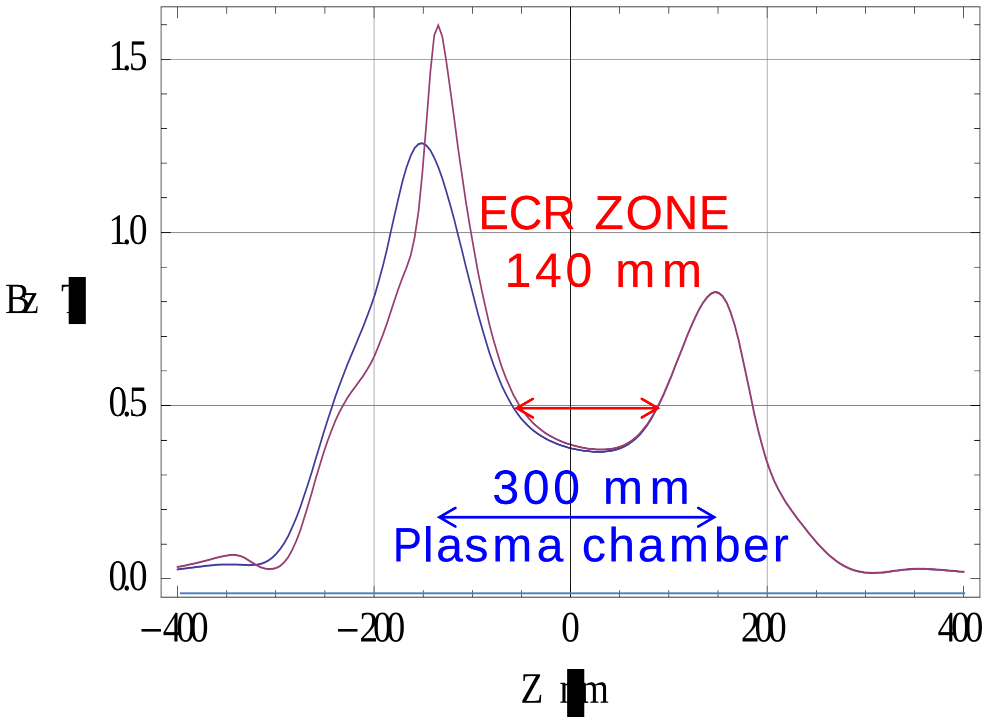
10-20% Non-captured ions

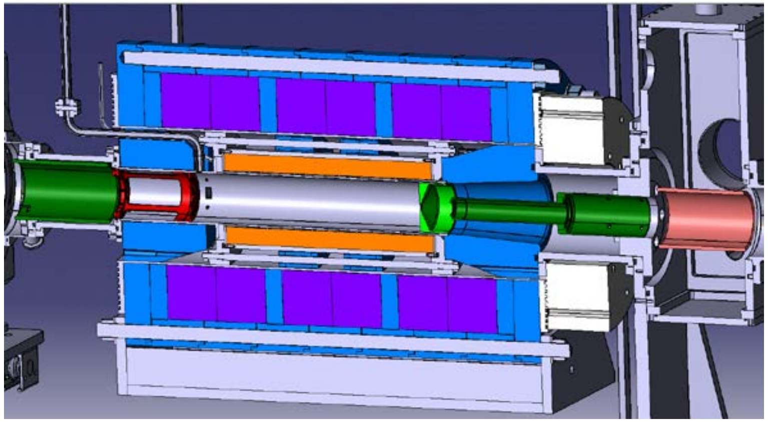


Improve the ion capture

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

- Indirect experimental confirmation with PHOENIX ECR CB
  - The axial magnetic field profile maximizing the 1+N+ efficiency is the one maximizing the ECR zone length



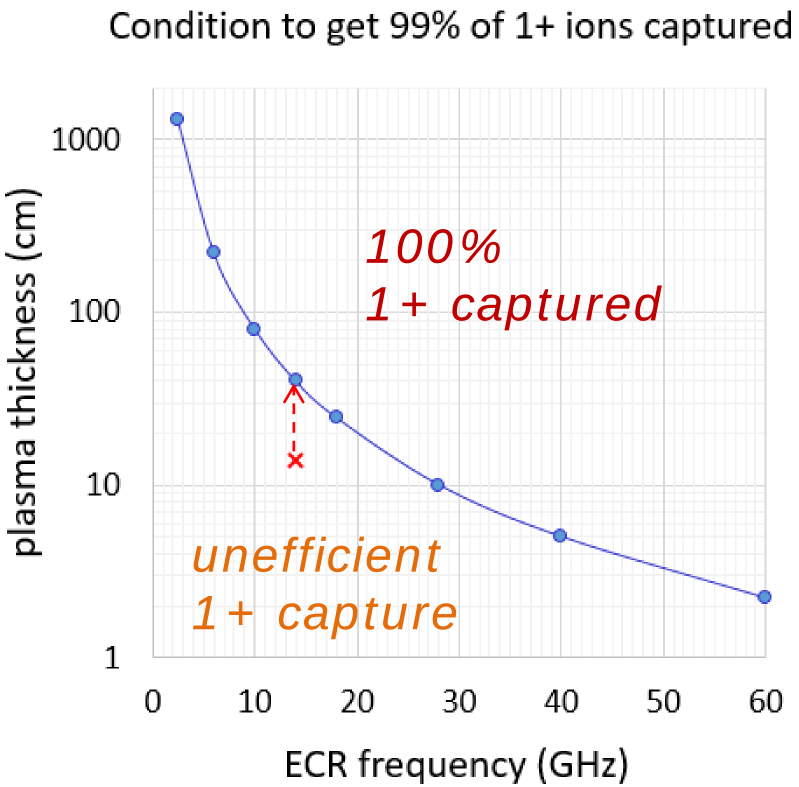


VENUS ECR zone length is ~180 mm @18+28 GHz For a 500 mm long plasma chamber

Improve the ion capture

- Lenghtening the ECR plasma of the booster at 14 GHz:
  - from 14 to 40 cm would grant a 99% 1+ capture
- At higher frequency (eg: 18 GHz):
  - 25 cm plasma is necessary to capture all the 1+

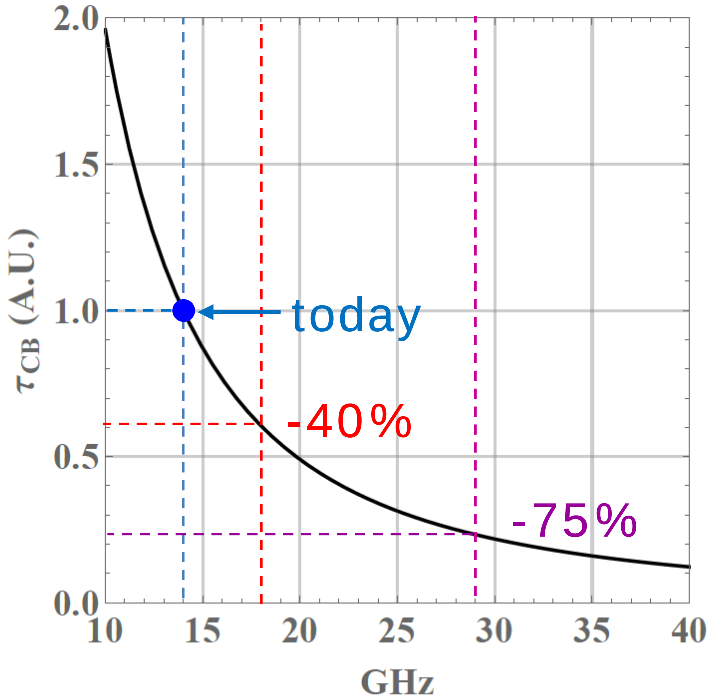
→1+N+ Efficiency would increase up to +20%



Reduce the CB time?

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

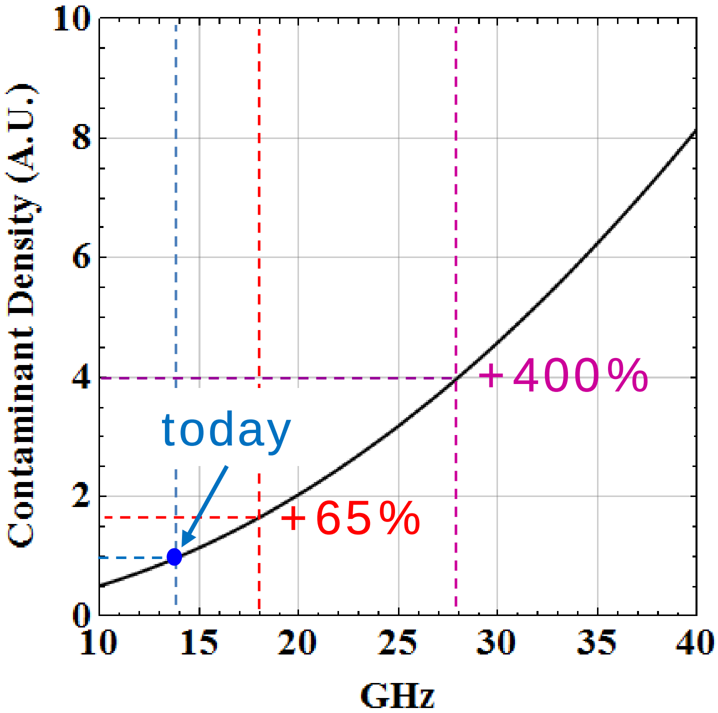
- ECR frequency scaling law : no limit so far up to 28 GHz operation
- Plasma density : $n_p \leq \frac{4\pi^2 m_e \epsilon_0}{e^2} f_{ECR}^2$
- Charge Breeding Time: $\tau_{CB} \propto \frac{1}{n_p} \propto f_{ECR}^{-2}$
  - Today, standard ECR CB are operated at f_{ECR} =14 GHz
  - An 18 GHz ECR CB would reduce τ_{CB} by -40%
  - A 28 GHz ECR CB would reduce τ_{CB} by -75%
    - With respect to 14GHz operation

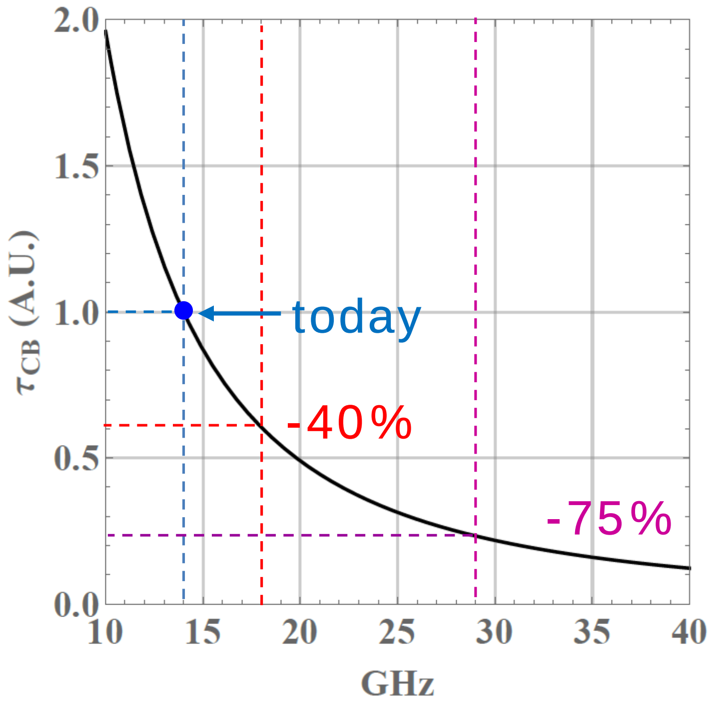


GREAT PROSPECT, **BUT** ...

Reduce the CB time?

- A « catch 22 » situation as contaminant density follows: $n_e \propto f_{ECR}^2$





CB time reduction is opposed to background reduction

CB reduction time would work with

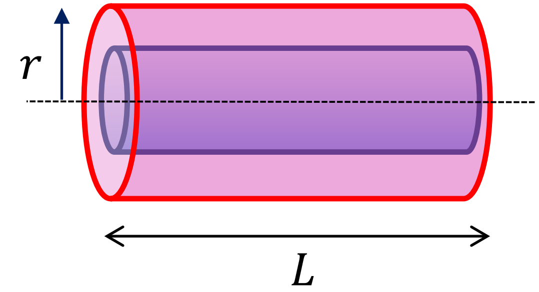
a very high mass separator downstream $(\frac{M}{\Delta M} \sim 6000)$

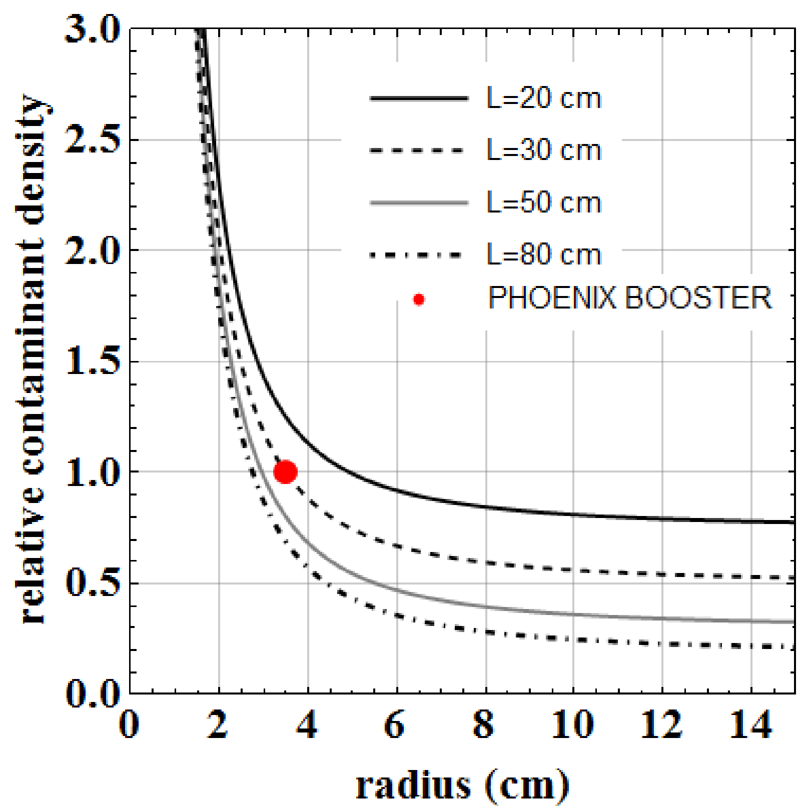
Background reduction is a key parameter

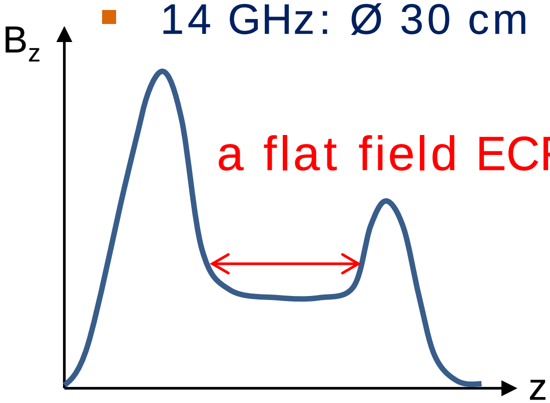
Reduce wall contamination

LPSC Grenoble – Laboratoire de Physique Subatomique et de Cosmologie

- Geometrical background reduction :
  - Contaminant flux from wall is $\propto S = 2\pi r L + 2\pi r^2$
  - Plasma volume is $\propto V = \pi r^2 L$
  - Contaminant density $C \propto \frac{S}{V} = \frac{2}{r} + \frac{2}{L}$
  - Increasing plasma chamber radius *r* and length *L* reduces the contaminant density
  - 14 GHz: Ø 16 cm , L 50 cm → -60%
  - 14 GHz: Ø 30 cm , L 80 cm → -80%



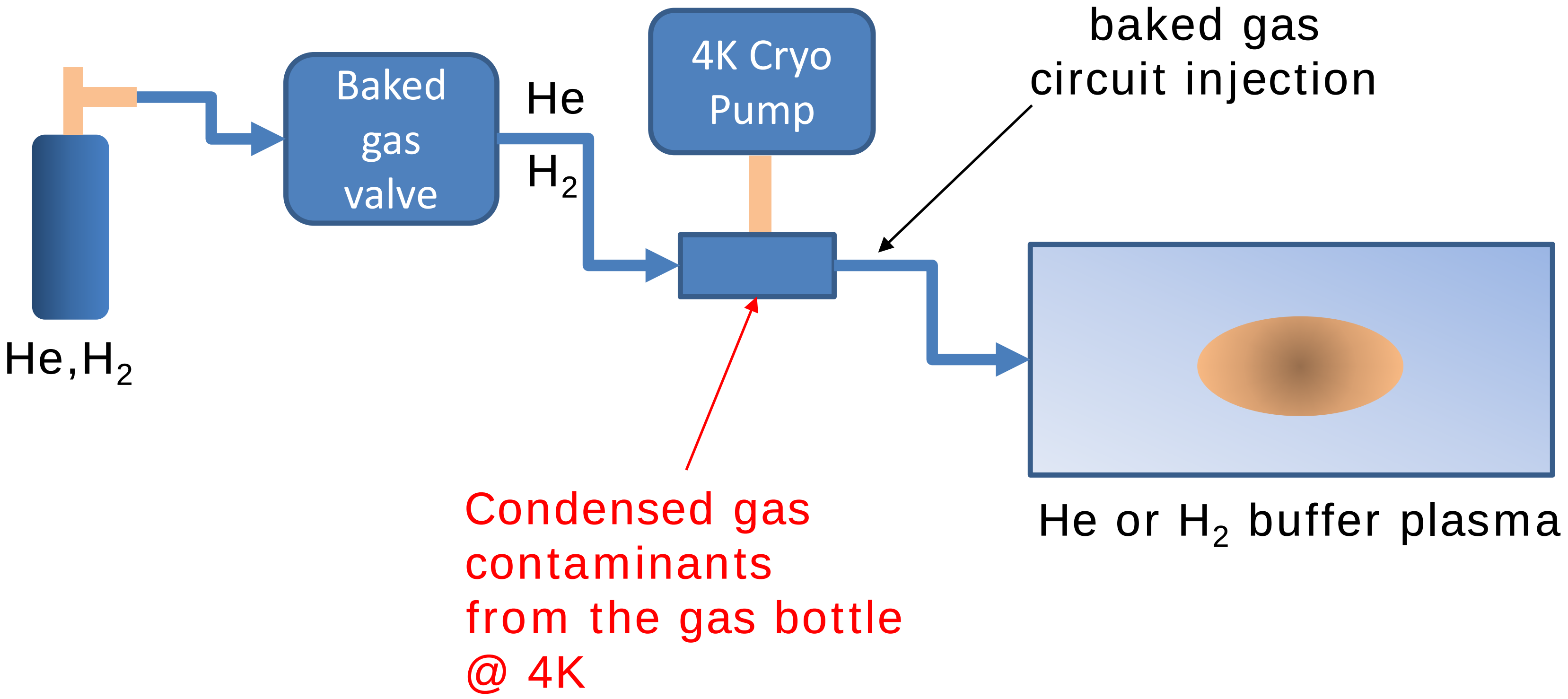




a flat field ECR would make the job!

Reduce gas contamination

- Follow ANL steps to get rid of gas contamination
- Use He or H_2 as buffer gas



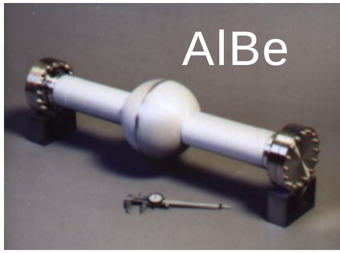
Reduce gas contamination

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

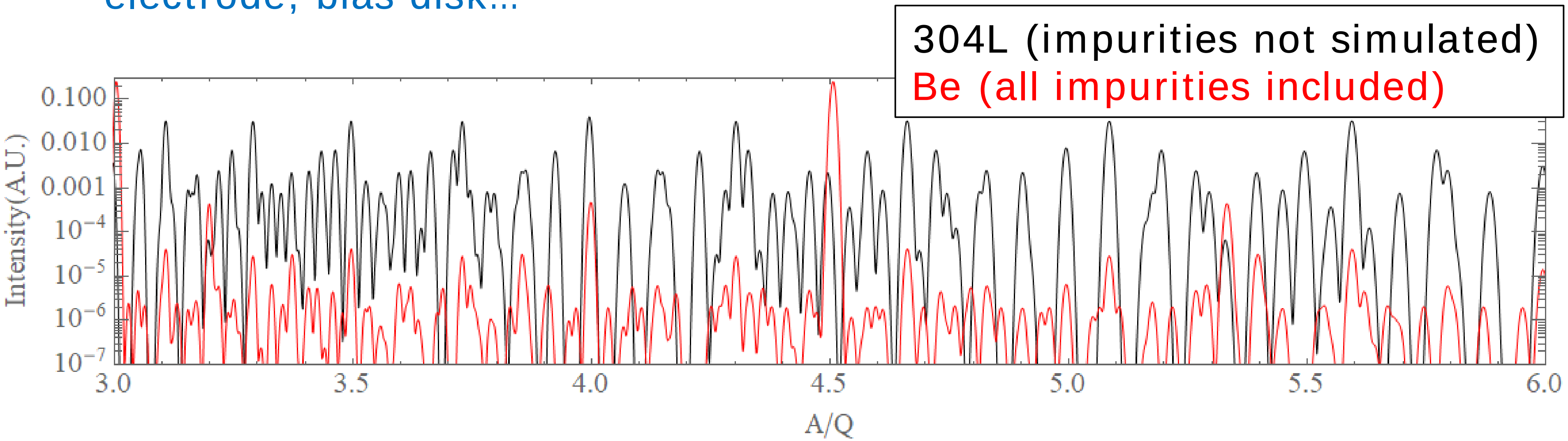
- Make a fully UHV Bakeable ECRIS Booster
  - Get rid of all the plastic O-rings
- Make a fully UHV Bakeable LEBT
  - With differential pumping close to the ECR CB
  - Get a $10^{-9} - 10^{-10}\ mbar$ base pressure
  - Have gas contaminant reduced by a factor 100

Minimize the contaminant species

- Go further with the R&D performed by ANL, TRIUMF, SPES, GANIL
  - Extend the M/Q spectrum areas with low background
- Banish complicated alloys to make the plasma chamber AND the Surrounding vacuum chambers
  - Select a pure material without isotopes , as light as possible:
    - ^{4}Be (melts 1287° C); ^{27}Al (melts 660° C) AlBe (melts 644° C); ^{55}Mn ; ^{59}Co ; ^{93}Nb ; ^{181}Ta ; ^{197}Au
    - The lighter the mass, the better



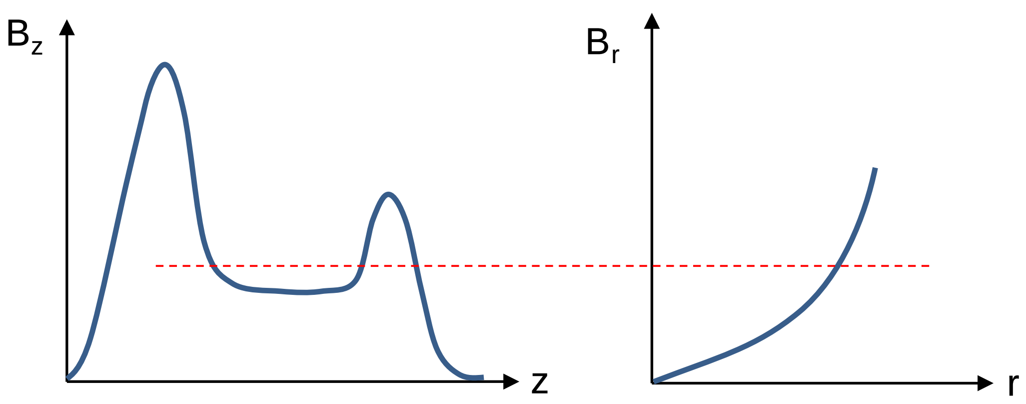
- And have everything made with this material: waveguide, plasma electrode, bias disk…

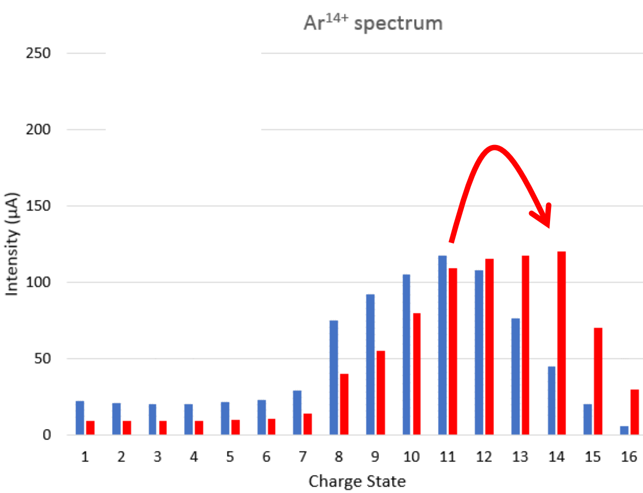


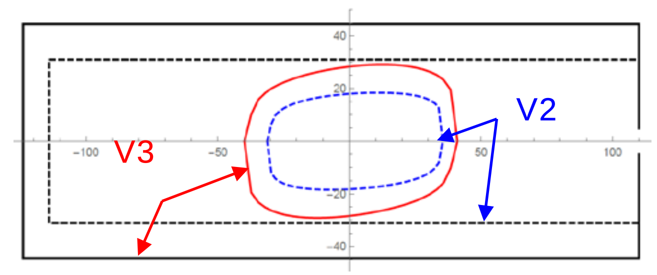
Increase the N+ ion charge state

- Optimize the magnetic confinement using up to date know-how

- Larger plasma chamber radius
  - Shown with PHOENIX V2→V3 upgrade (SPIRAL2)
- With an optimized ECR CB:
  - Xe^{42+} (A/Q~3 ; A=132)
  - U^{42+} (A/Q~6 ; A=238)







Summary

- What can be improved in ECR charge breeders?
  - Capture efficiency =>+20% 1^+N^+ efficiency
  - Higher Charge states (U^{42+}, Xe^{42+}) with better magnetic confinement
  - Gas contaminant can be reduced by a factor 100 at least
  - Condensable contaminant density can be geometrically reduced by -80%
  - Condensable peak distribution can be favorably concentrated on a few peaks => 1/100 to 1/1000 reduction possible
  - charge breeding time can be reduced by -75% at 28 GHz ECR frequency provided the RIB facility gets a very high resolution spectrometer ($\frac{M}{\Delta M} \sim 6000$)
- Is it worth continuing R&D? YES!

Upgraded Charge Breeder for EURISOL

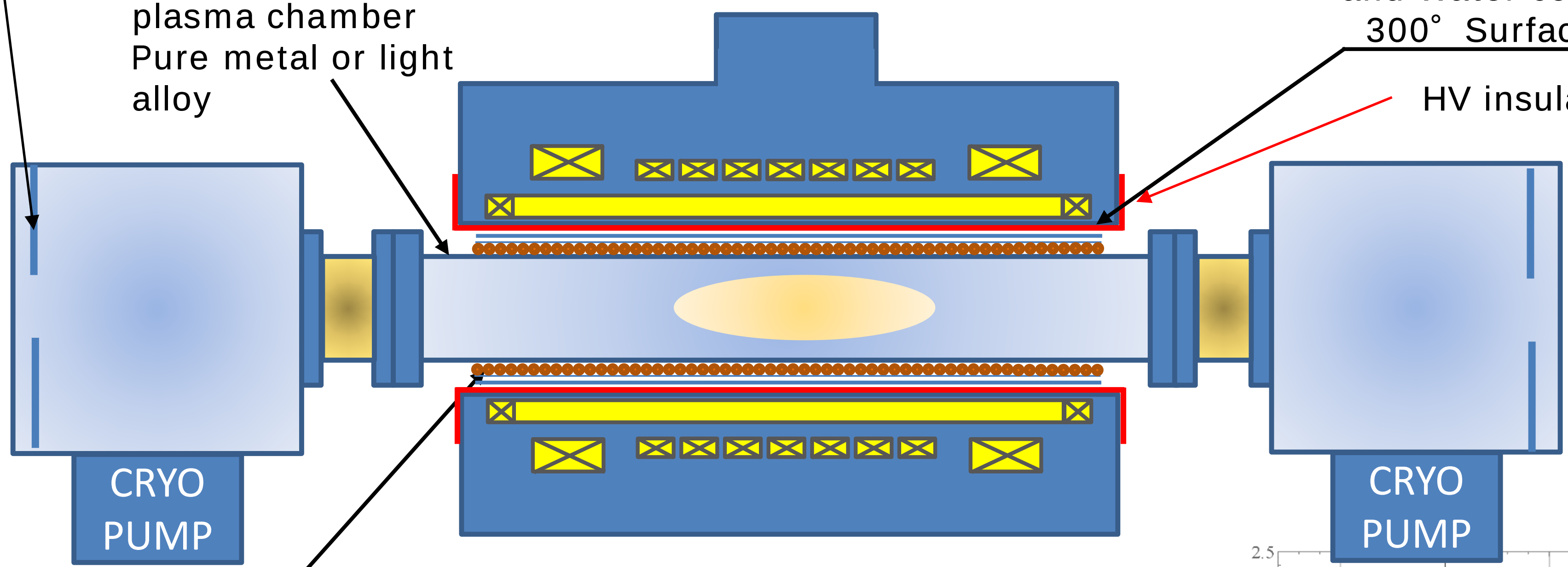
Flat Field ECR CB @ 14-18 GHz, NbTi@4 K

differential pumping

plasma chamber
Pure metal or light alloy

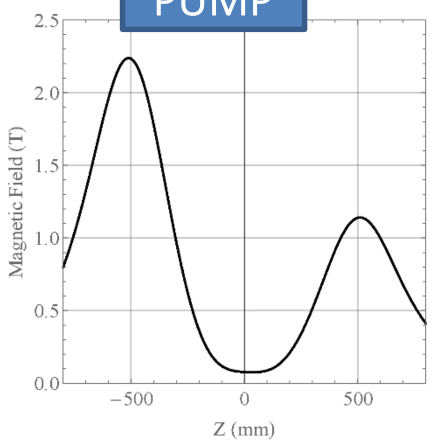
Thermal screen
and Water cooled
300° Surface

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



ECRIS18 WORKSHOP CO_2 FOOTPRINT

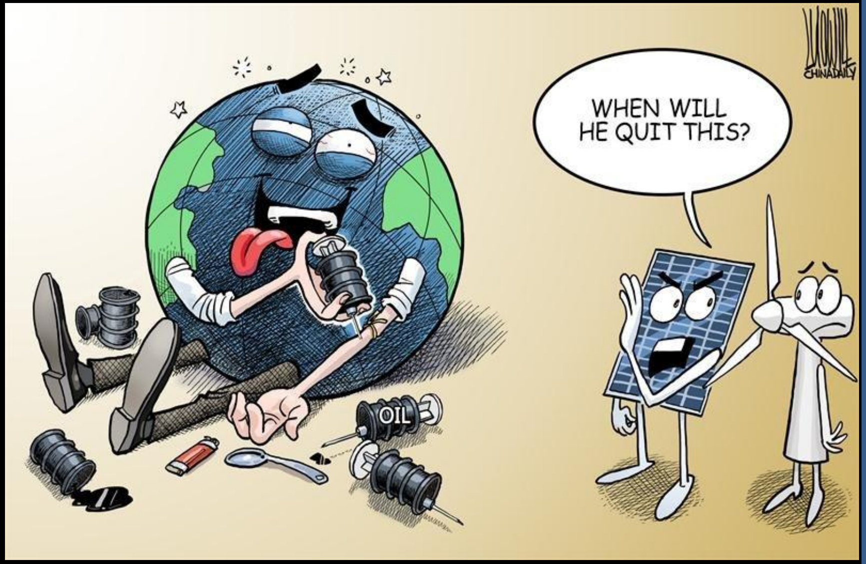
city	round trip	#	kg CO2
Argonne	1130,208	1	1130
Beijing	934,276	3	2803
Berkeley	1637,24	3	4912
Bhat	1114,836	1	1115
Busan	1307,596	2	2615
Caen	383,324	4	1533
College station	1626,016	1	1626
Debrecen	366	2	732
Dubna	600,728	3	1802
East Lansing	1098,732	2	2197
Darmstadt	404,552	2	809
Geneve	672,952	2	1346
Groningen	445,788	1	446
Jyvaskyla	664,168	3	1993
Kyoto	1527,196	1	1527
Lanzhou	1221,708	7	8552
Grenoble	319,152	3	957
Legnaro	268,888	2	538
Nizhnyi	817,4	4	3270
Saclay	383,324	2	767
Lund	462,38	1	462
Nishina	1302,716	1	1303
Xi'an	1164,368	1	1164
		52	43599
	per capita		838

43 TONS of CO_2

20 TONS Kerozene

0.3 TWh

13000 years Of 1 slave Work



https://www.icao.int/environmental-protection/CarbonOffset/Pages/default.aspx

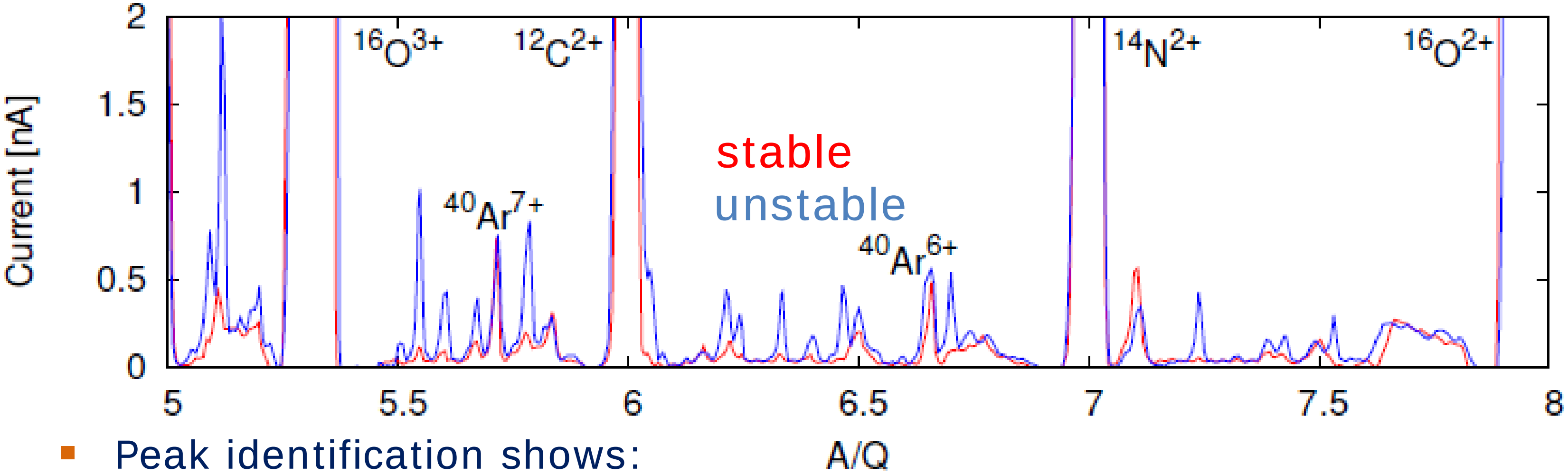
https://eco-calculateur.dta.aviation-civile.gouv.fr/

THANK YOU FOR YOUR ATTENTION

Plasma stability and background level

- Plasma kinetic instabilities transiently generate a huge plasma potential
  - V_p~1 kV
  - Strong sputtering from the wall

Joint study with JYFL & IAP RAS

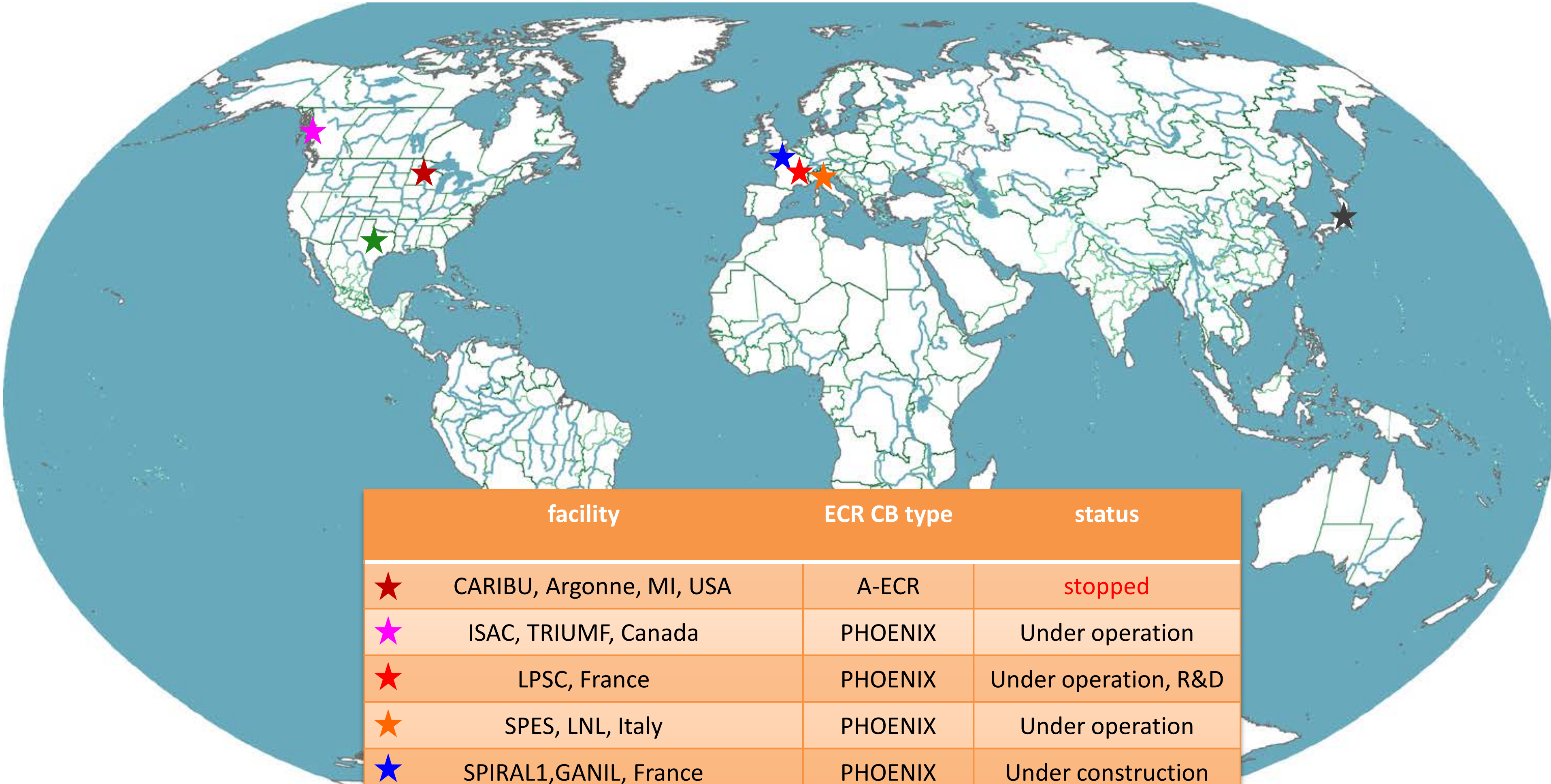


- Peak identification shows:
  - stainless steel plasma chamber composition: Fe, Cr, Mo, Ni, Al, Zn, Cu, Mn
  - Electrodes composition (Al alloy 2017): Al, Cu, Mn, Zn
  - Release of previous condensed 1+ beam (Cs,Rb,K)

Prospect: Make sure next ECR CBs operate with a steady plasma

ECR Charge Breeders in the World

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie



	facility	ECR CB type	status
★	CARIBU, Argonne, MI, USA	A-ECR	stopped
★	ISAC, TRIUMF, Canada	PHOENIX	Under operation
★	LPSC, France	PHOENIX	Under operation, R&D
★	SPES, LNL, Italy	PHOENIX	Under operation
★	SPIRAL1,GANIL, France	PHOENIX	Under construction
★	Texas A&M, College station, TX, USA	A-ECR	Under operation
★	TRIAC, KEK- JAERI, Japan	KEK-CB	Facility closed