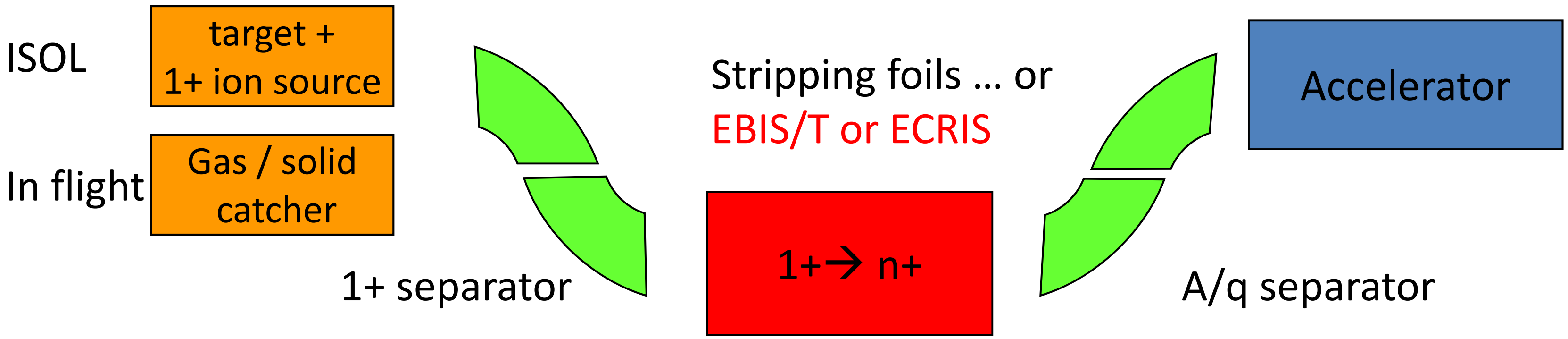
Charge breeding of Radioactive Ion Beams: status and perspectives

P. Delahaye, GANIL

A challenge of present and future facilities reaccelerating radioactive beams

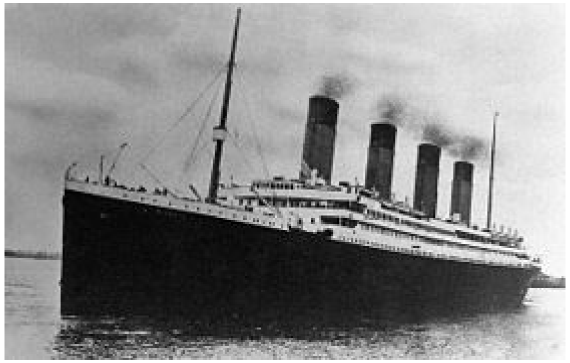


Charge breeding: matching the A/q acceptance of the post-accelerator

- higher charge states → **Higher energies**
  Compact postaccelerator

- Pure beams
- High efficiency and rapidity → Making the most of the rare and exotic beams: **I<<pA and $T_{1/2}$<1s**

A challenge of present and future facilities reaccelerating radioactive beams



Across the Atlantic

In Europe

Acquiring knowledge, know - how and understanding

27th of May 2012, Padova

Charge breeding:
World tour of major reaccelerating facilities

- Conclusions of EURISOL DS (FP6): ECRIS / EBIS comparison

- Latest news from ANL, TRIUMF
  - (ECRIS charge breeding)

- Latest news from ISOLDE and NSCL
  - EBIS/T charge breeding

VASA museum, Stockholm

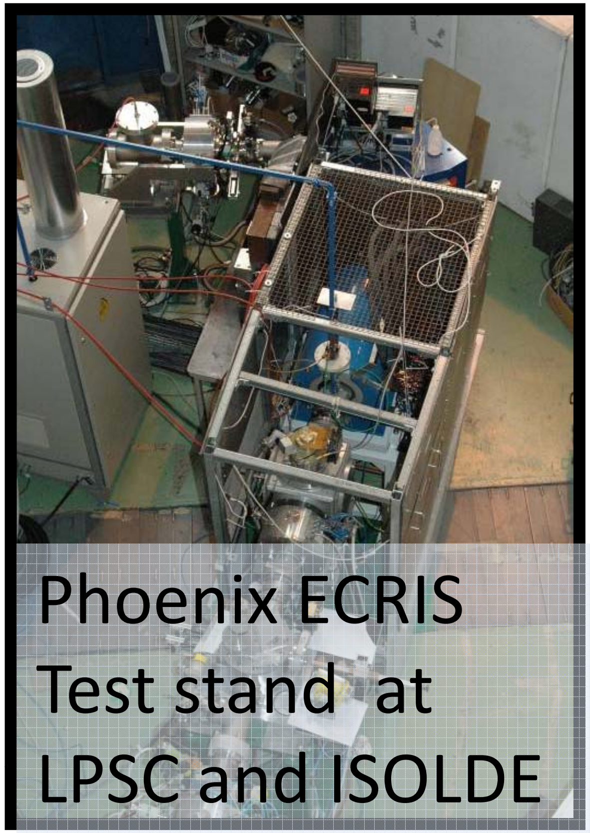
http://www.vasamuseet.se/en/

Comparison of charge breeding techniques

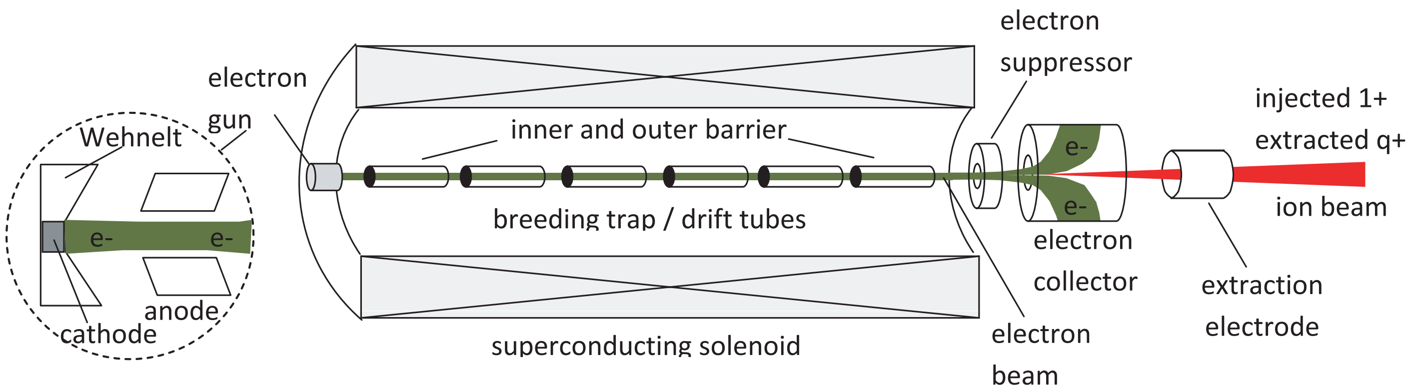
EURISOL Design Study

CERN

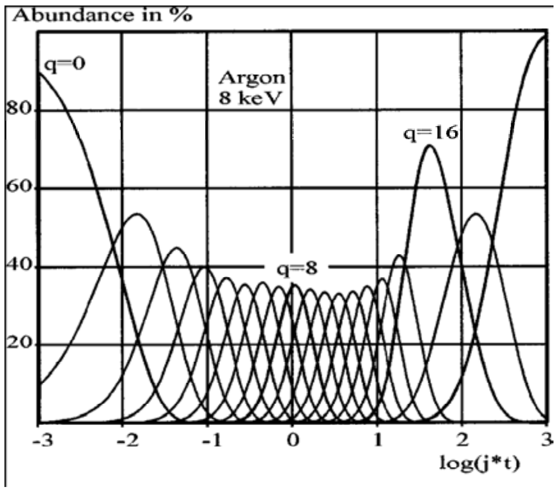
ISOLDE CERN



EBIS charge breeder principle



E. D. Donets, V. I. Ilyushchenko and V. A. Alpert, JINR-P7-4124, 1968
E. D. Donets, Rev. Sci. Instrum. 69(1998)614



R. Becker, Rev. Sci. Instrum. 71(2000)816

Average charge state

$\bar{q} \sim \log(j.\tau)$

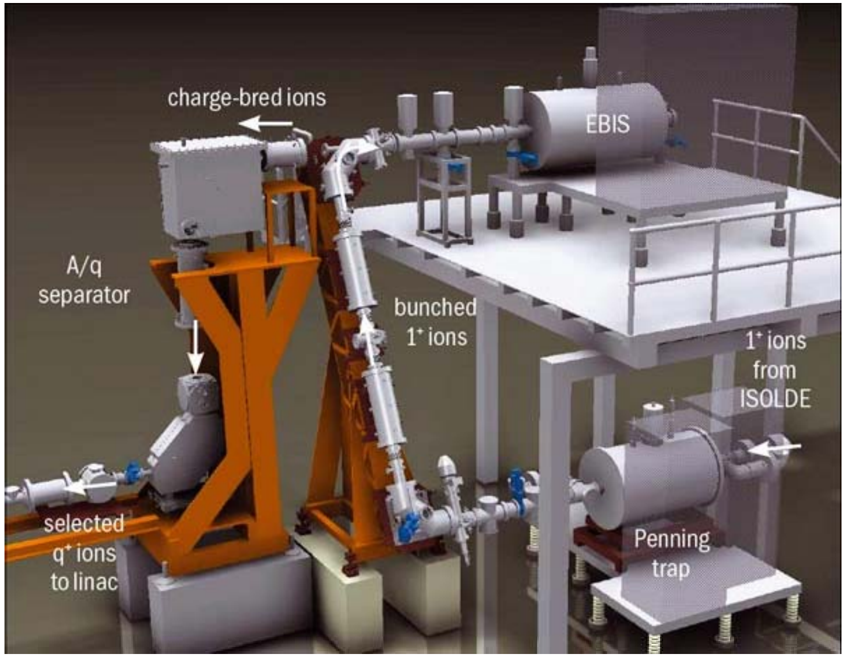
Trap capacity (elementary charges)

$Q=3.36\ 10^{11} L.I_e/E^{-1/2}$

Essentially a pulsed device

The REX-EBIS setup

The LaB_6 cathode



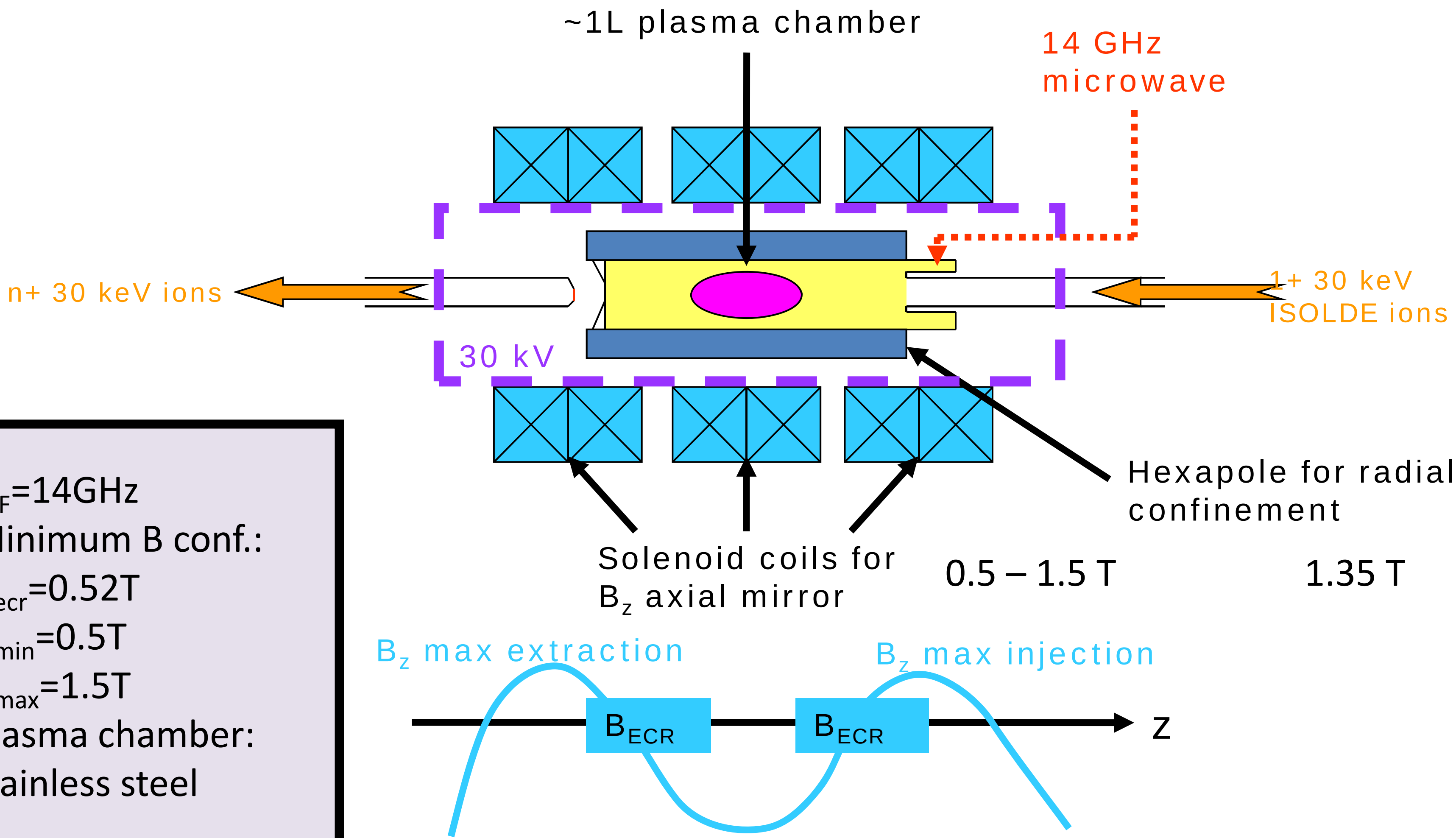
EBIS specifications

- LaB6 cathode
- $j_{cathode}$<20A/cm2
- $j_e = j_{trap} < 200 A/cm^2$
- Ie=460mA (normal operation 200mA)
- E=3.5-6keV
- 3 drift tubesL=200 to 800 mm
- Theoretical capacity $5 \cdot 10^{10}$ positive charges
- Ultra-high vacuum 10^{-10} - 10^{-11} mbar

The charge state is selected with a mass separator of Nier-Spectrometer type

Performances: F. Wenander et al.,
Rev. Sci. Instrum. 77, 03B104 (2006)
ICIS 05 Proceedings

The 14GHz Phoenix booster

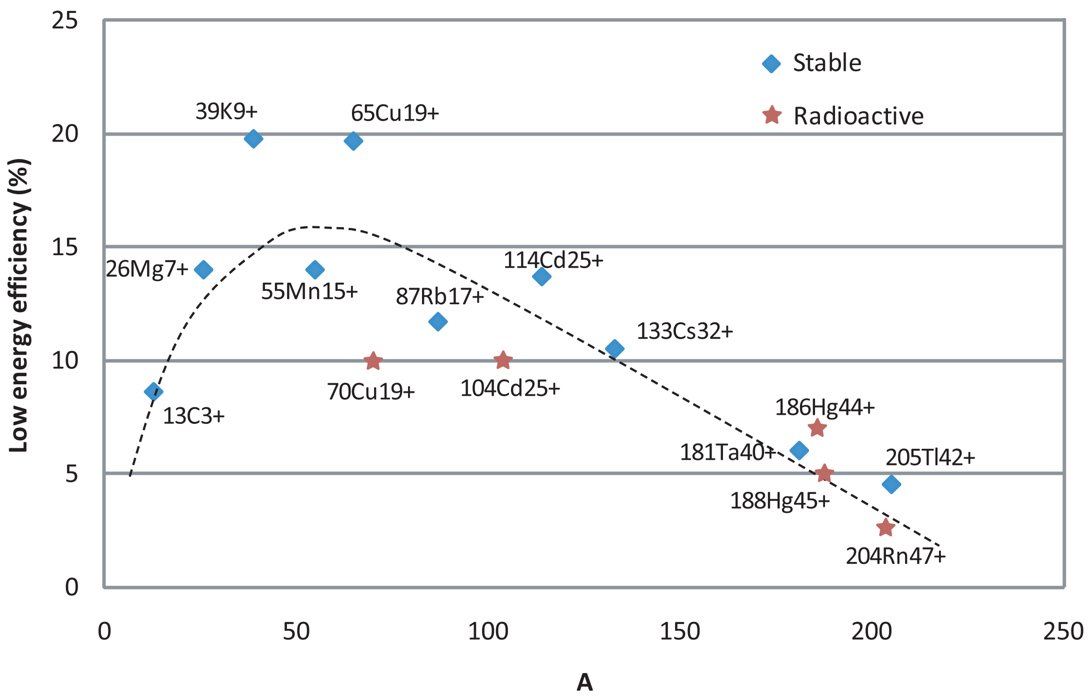


f_{RF}=14GHz
Minimum B conf.:
B_{ecr}=0.52T
B_{min}=0.5T
B_{max}=1.5T
Plasma chamber: stainless steel

Performances: P. Delahaye et al., Rev. Sci. Instrum. 77, 03B105 (2006), P. Delahaye and M. Marie-Jeanne, NIM B 266 (2008) 4429

Charge breeding performances REX-EBIS

Sample of data 2008 - 2009



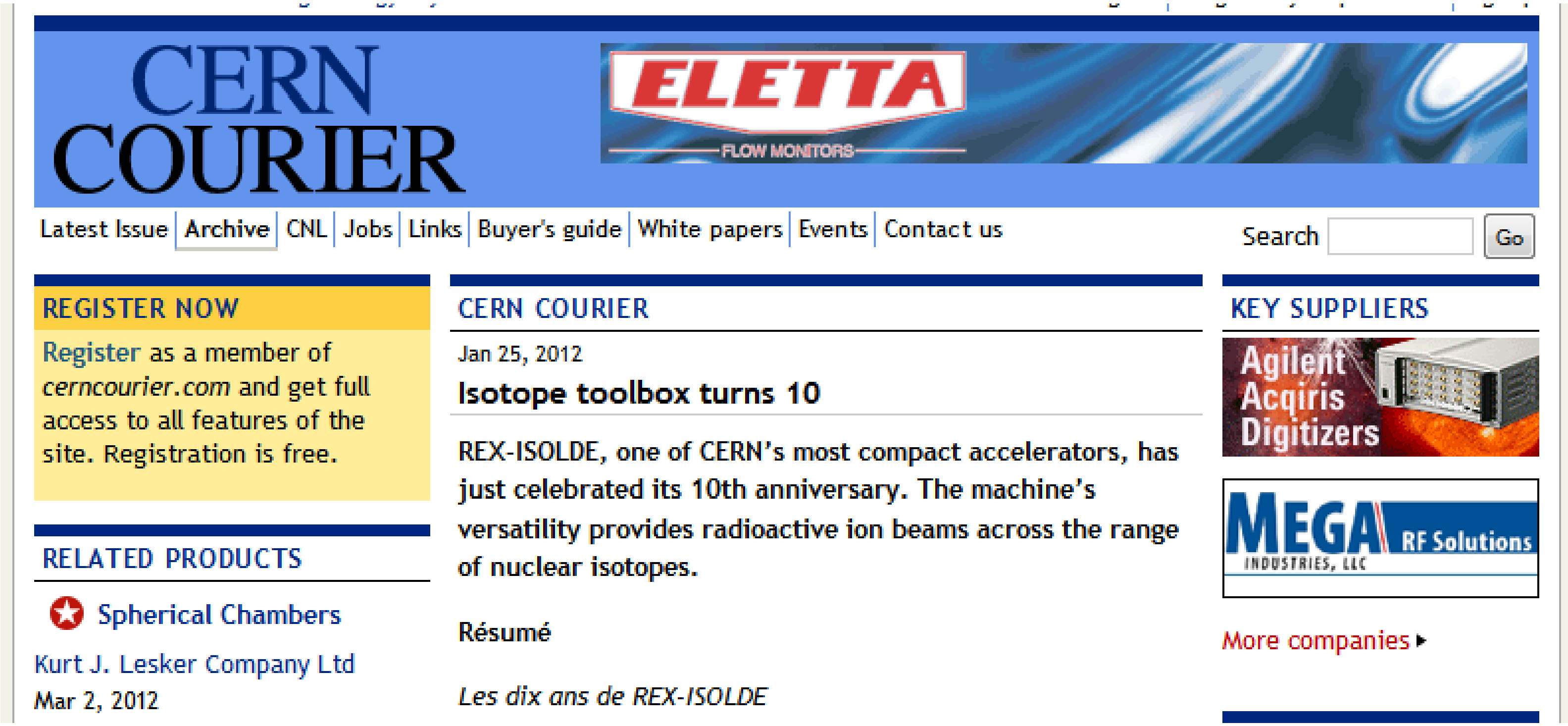
Includes cooling, trapping and charge breeding efficiencies

A/q ratios: from 3.5 to 4.5

Charge breeding times:
From 10 ms to 200ms for mass ~200

Background < pA
Very low residual gas pressure

10 years of REX-ISOLDE physics



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CERN COURIER

Jan 25, 2012

Isotope toolbox turns 10

REX-ISOLDE, one of CERN's most compact accelerators, has just celebrated its 10th anniversary. The machine's versatility provides radioactive ion beams across the range of nuclear isotopes.

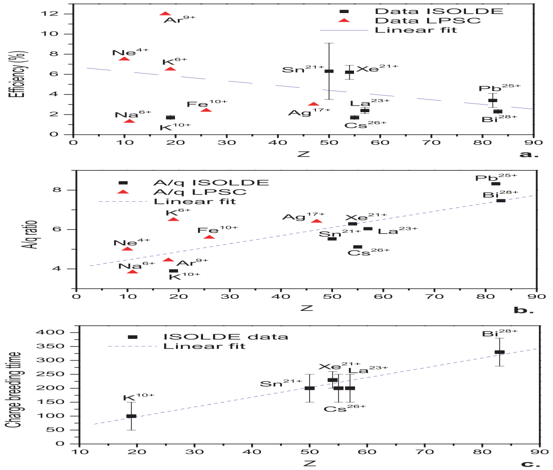
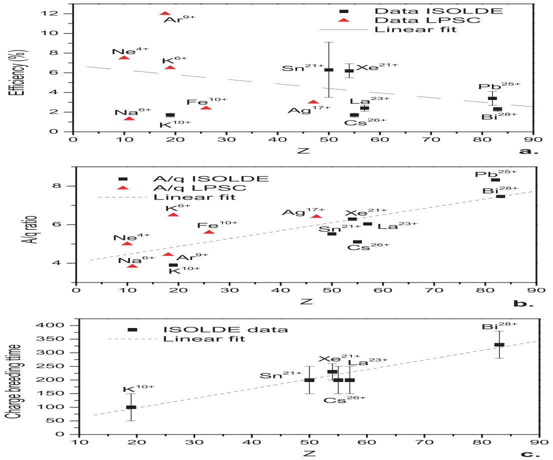
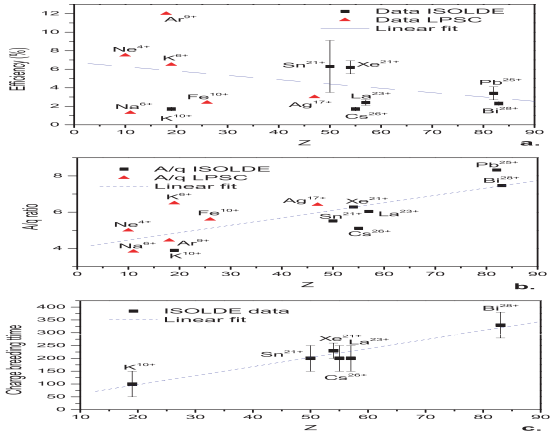
Résumé

Les dix ans de REX-ISOLDE

- Close to 100 isotopes and 30 elements accelerated
- 2011: 20 isotopes of 10 different elements

Charge breeding performances Phoenix ECRIS

- Present performances

Efficiency	Charge state	Confinement time
		
6%	A/q=132/21~6.3	<200ms No losses

Beam emittance: ε_{phys}~10π.mm.mrad at 19.5*q keV

$\varepsilon_{norm}=\beta\gamma * \varepsilon_{phys}$~2.5 10^{-2} π.mm.mrad

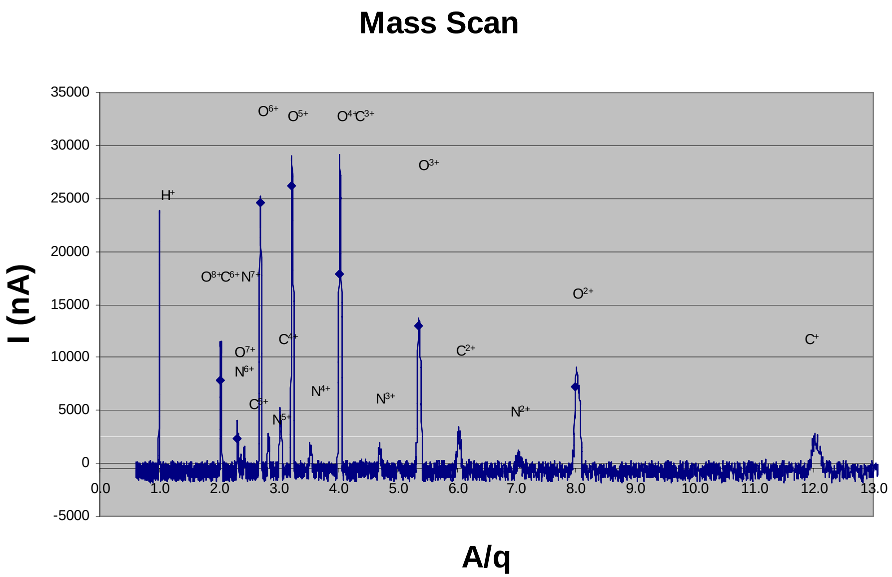
Stable beam background ~<nA <<µA

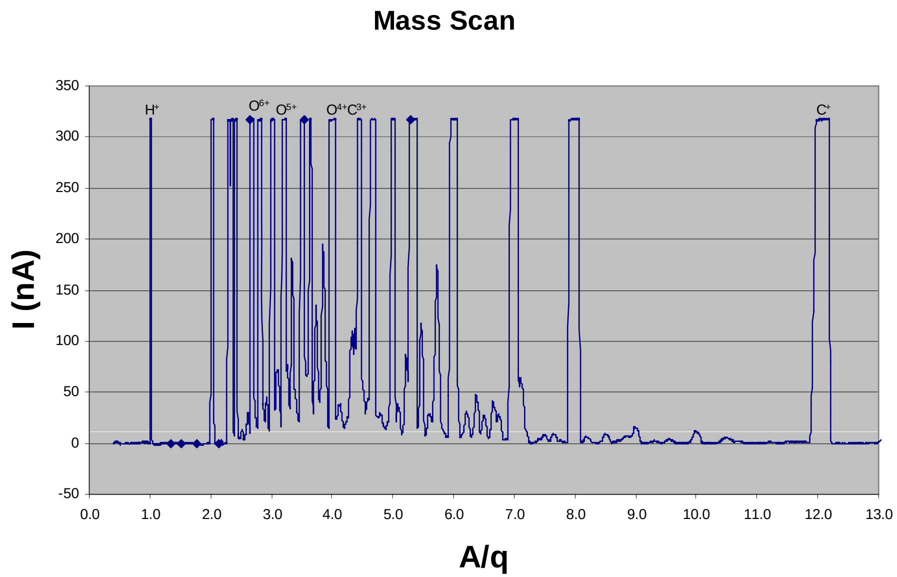
P. Delahaye and M. Marie-Jeanne, NIMB 266 (2008) 4429

Residual gas spectrum

Entrance of the ECR P=5.10^{-7}mbar

Exit P=2.10^{-7}mbar



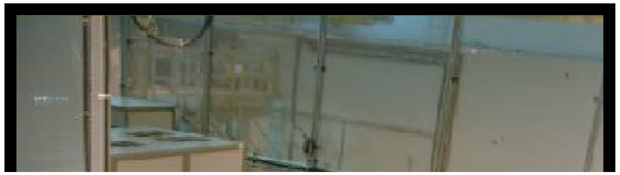


C,N,O stable components of the plasma

Background >5nA 2<A/q<7

Conclusions of FP6

EURISOL Design Study

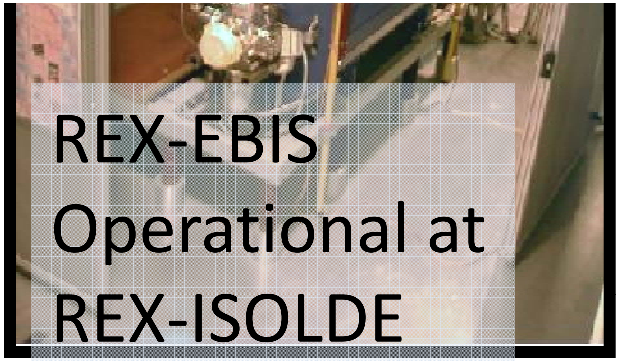


^{136}Sn ~ 10^5 ions/s

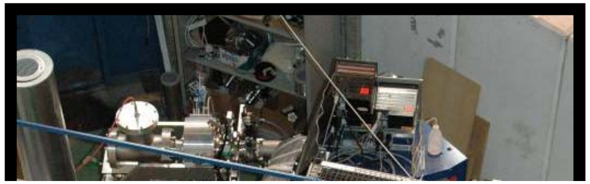
EBIS best suited

-Higher charge states

-Higher purity



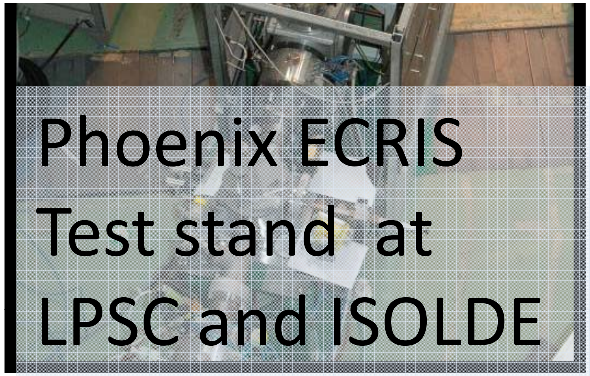
CERN



^{132}Sn > 10^{13} ions/s

ECRIS best suited:

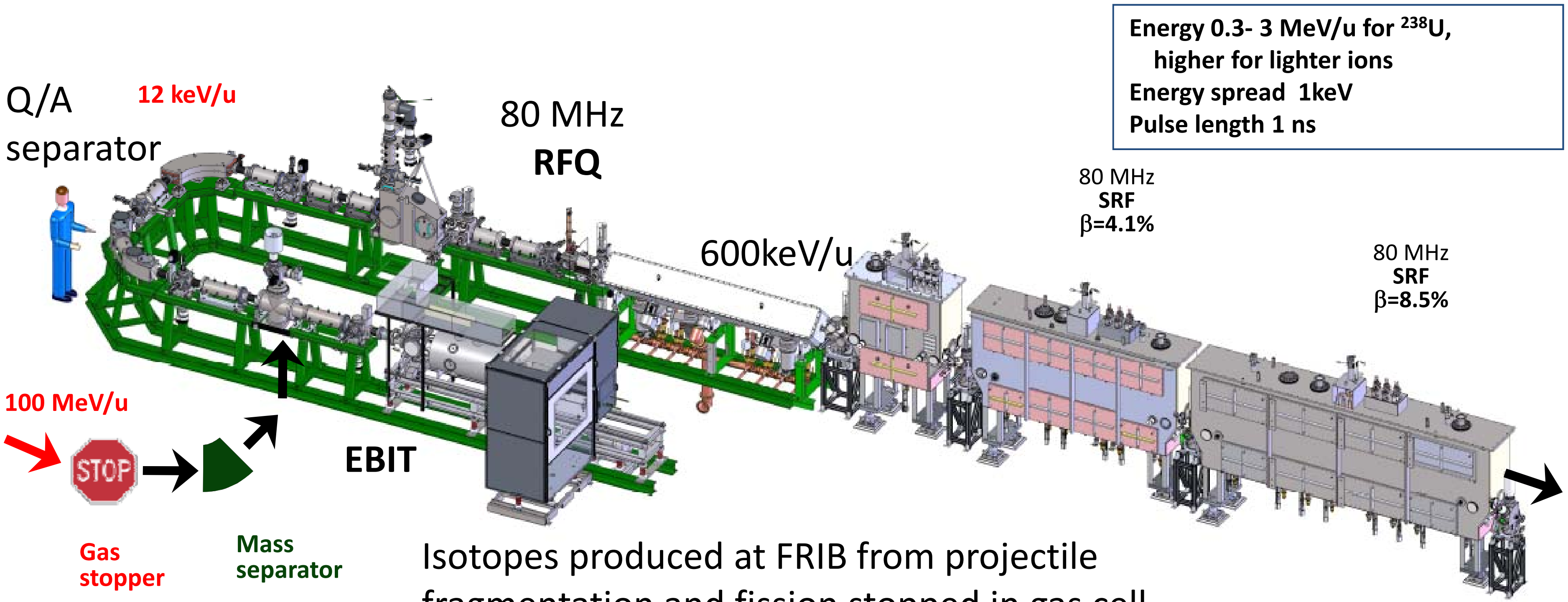
- Not space charge limited
- CW device



Efficiency 1-20% depending on Z

Since then…

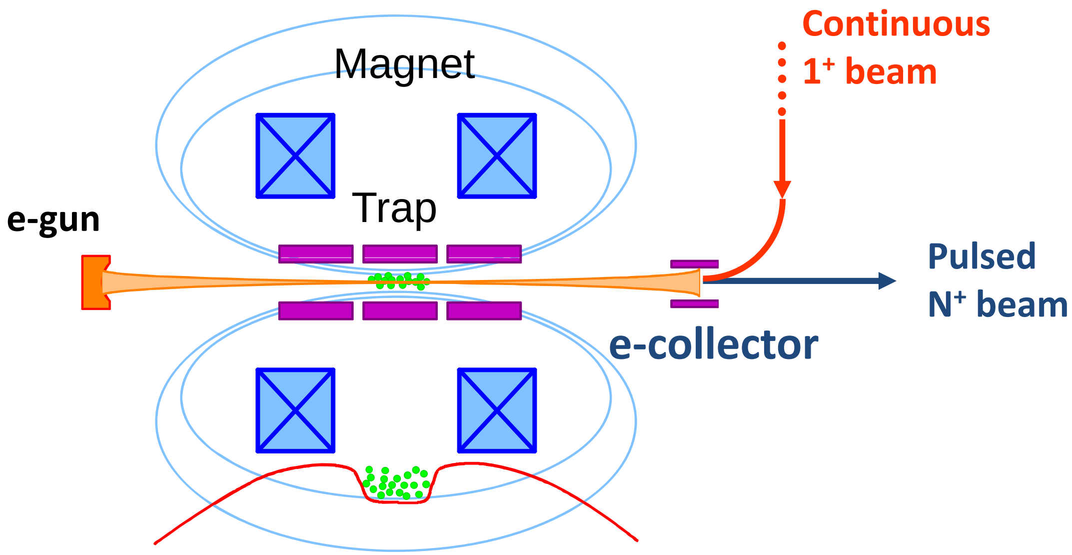
- ReA facility: in comissionning



Isotopes produced at FRIB from projectile fragmentation and fission stopped in gas cell

EBIT design: continuous accumulation

Over the barrier injection

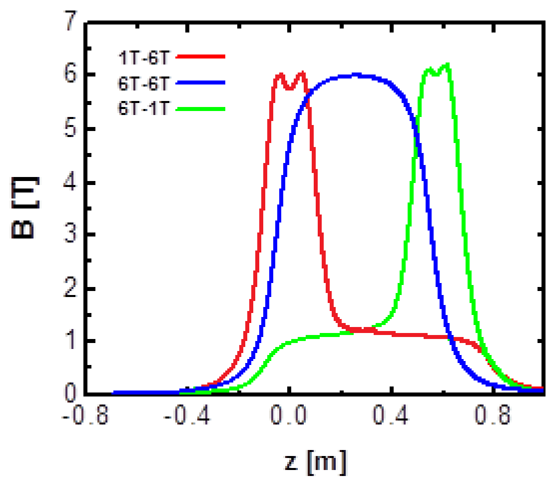


Expected performance

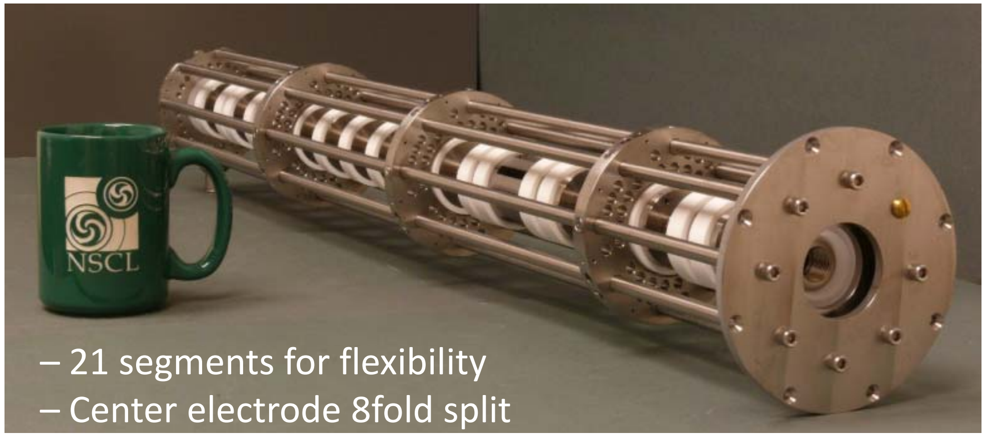
- Breeding times << 50 ms
- Efficiency > 50%
- Beam rates > 10^9/s
- Variable duty cycle
- Clean beams

EBIT: Key design parameters:

- magnetic field: up to 6 T
- **I_e= 0.5…5 A, E_e < 30keV**
- **current density: up to ~10^4 A/cm^2**



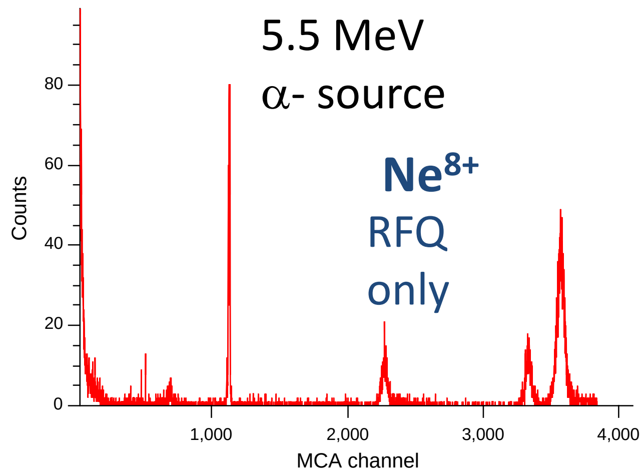
Trap: ~ 0.8m long



Recent achievements

July 2011:
Accelerated Ne^{8+}

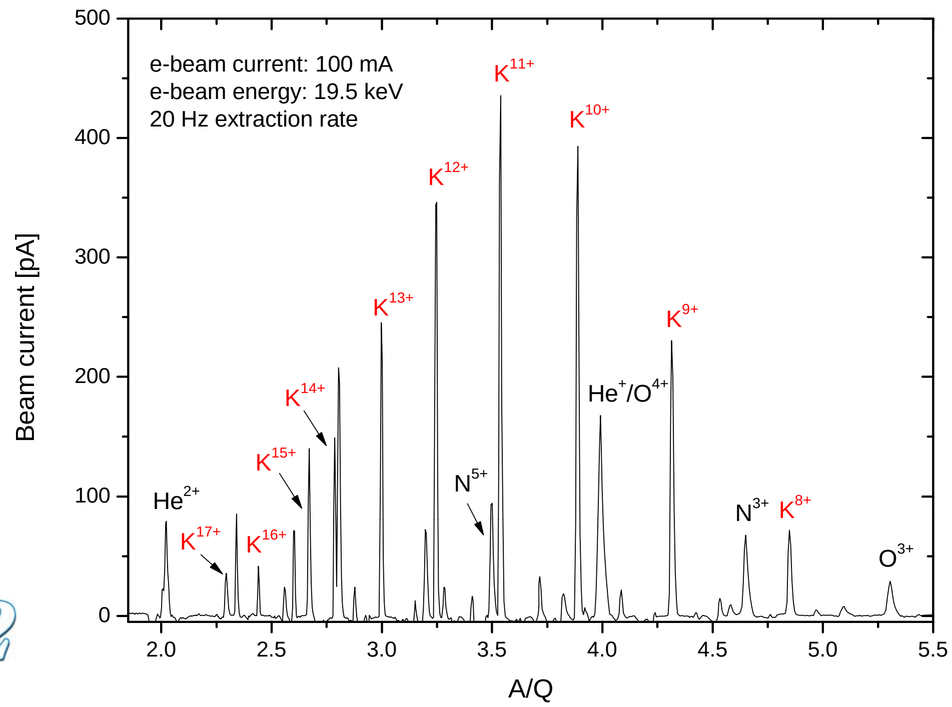
- From gas injector
- Pulsed extraction, up to 10Hz
- 2T field
- 15 keV, 36mA electrons
- 30kV extraction



RFQ +
1 SRF cavity
at different acceleration gradients

/ Energy

Mass-over-charge spectrum of charge-bred ^{39}K ions from TIS



May 2012:

First acceleration of charge-bred, externally produced ions with RFQ + SRF:

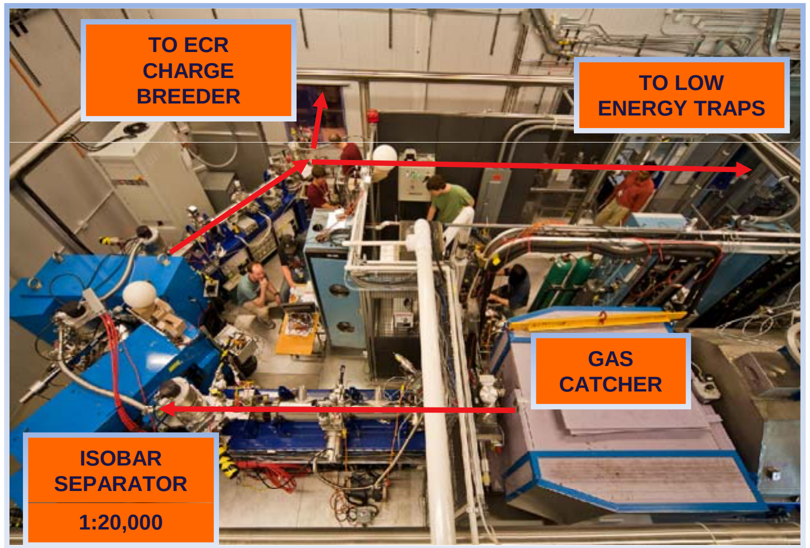
K^{16+} → ~ 1MeV/u

Results from CARIBU

- ANL: the world champion of ECRIS charge breeding

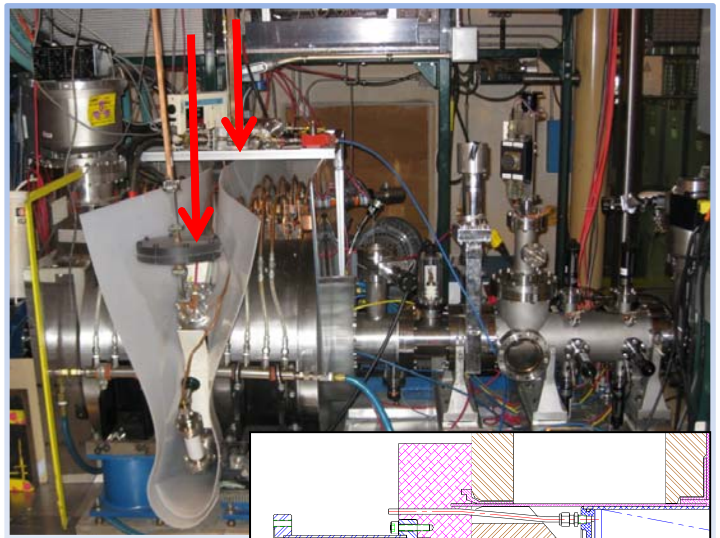
- A 55 mCi ^{252}Cf fission source provides radioactive species for charge breeding
  - $T_{1/2}$=2.6 a   3.1% fission branch
  - Maximum approved source strength of 1.0 Ci, delivery expected in summer 2012
- ^{252}Cf fission yield is complimentary to uranium fission
- Stopped beams or post-acceleration energy up to 10 MeV/u

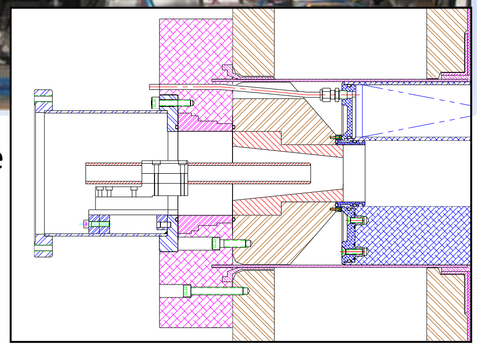
Isotope	Half-life (s)	Low-Energy Beam Yield (s^{-1})	Accelerated Beam Yield (s^{-1})
^{104}Zr	1.2	6.0×10^5	2.1×10^4
^{143}Ba	14.3	1.2×10^7	4.3×10^5
^{145}Ba	4.0	5.5×10^6	2.0×10^5
^{130}Sn	222.	9.8×10^5	3.6×10^4
^{132}Sn	40.	3.7×10^5	1.4×10^4
^{110}Mo	2.8	6.2×10^4	2.3×10^3
^{111}Mo	0.5	3.3×10^3	1.2×10^2



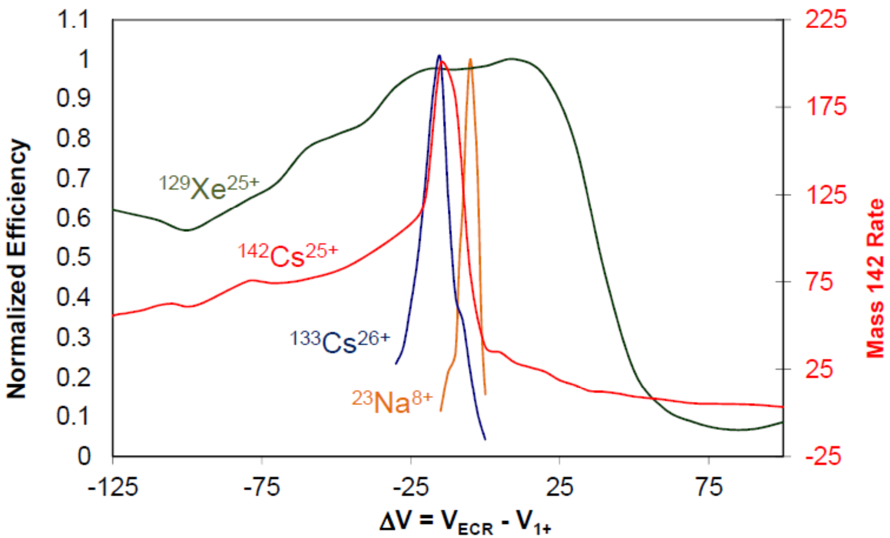
ANL ECRIS charge breeder

- Multiple frequency operation
  - Klystron: 10.44 GHz, 2 kW
  - TWTA: 11→13 GHz, 0.5 kW
- Open hexapole structure
  - RF is injected radially
  - Uniform iron in the injection region for symmetrical fields
  - Improved pumping to the plasma chamber region
    - Base pressure: $2x10^{-8}$ mbar
    - Operation: $7x10^{-8}$ mbar
    - Extraction pressure: $4x10^{-8}$ mbar



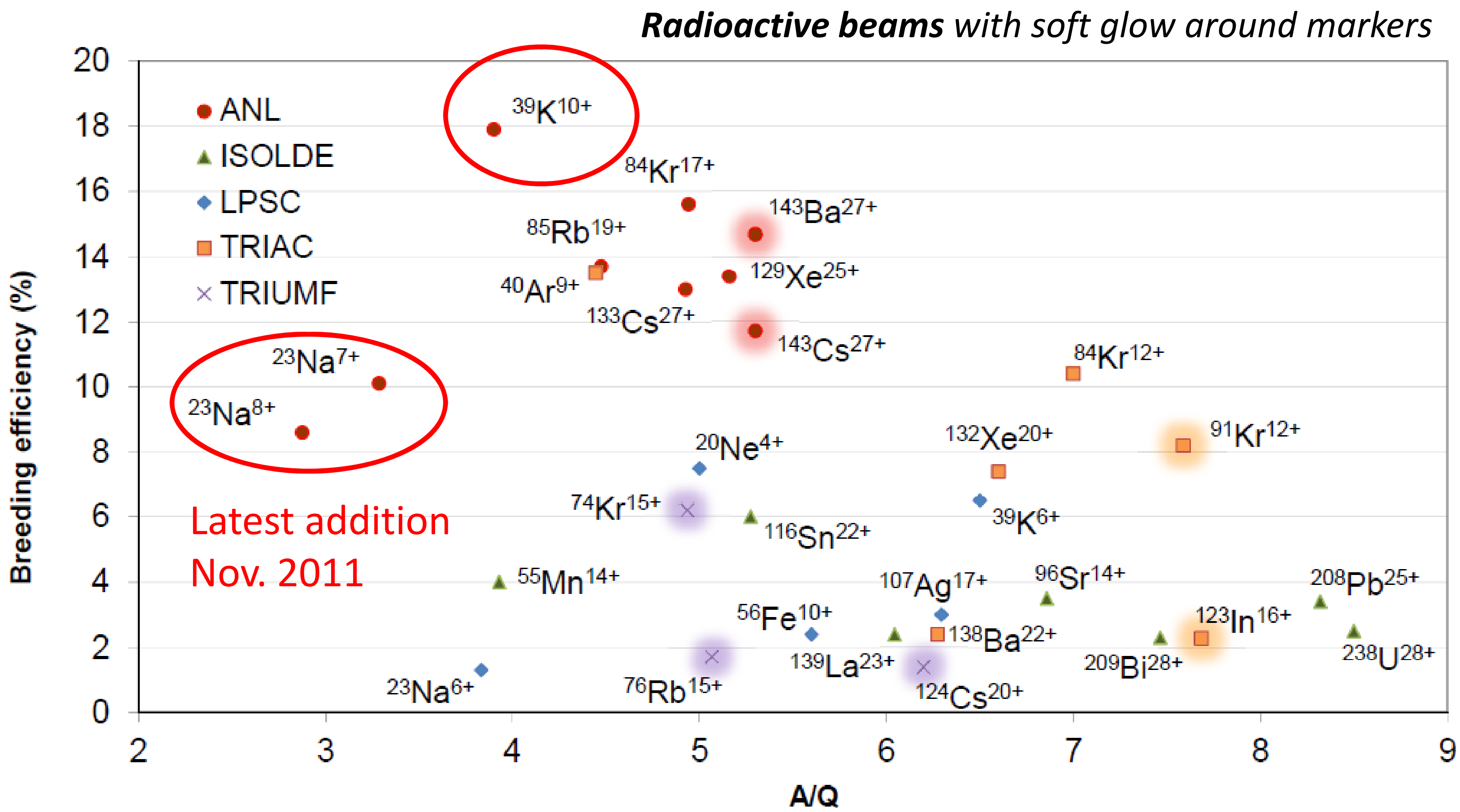


- Movable grounded tube with 2.5 cm of travel
- 50 kV high voltage isolation



	Design value	Running condition
B_{inj}	1.31 T	1.16 T
B_{min}	0.31	0.27
B_{ext}	0.85	0.83
$B_{(radial)}$		0.86 T
Last closed surface		0.61 T

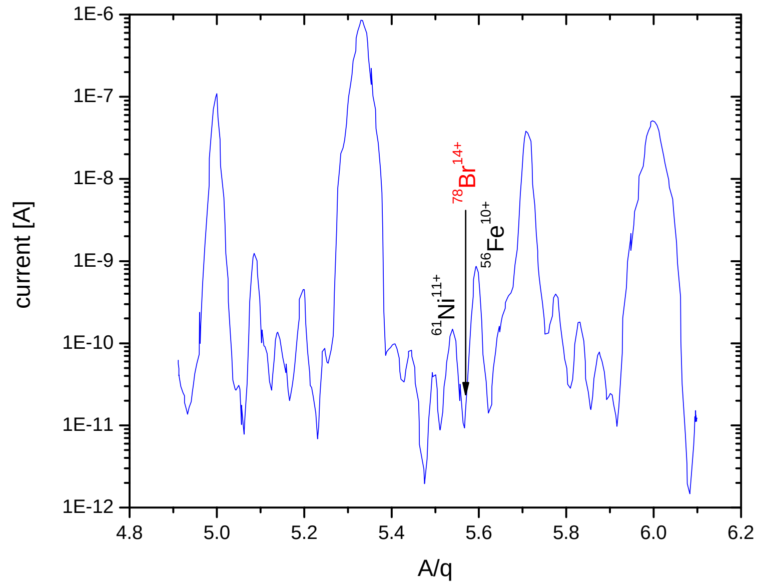
Impressive results



Latest news from TRIUMF

A number of charge bred radioactive isotopes

isotope	q	A/q	efficiency [%]	I (in) [1/s]	background [pA]
46K	9	5.11	0.5	4.0E4	340
64Ga	13	4.92	0.7	8.4E4	150
64Ga	14	4.57	0.75	8.4E4	210
74Br	14	5.28	3.1	3.2E7	10000
74Br	15	4.93	2.1	3.2E7	25
78Br	14	5.57	4.5	2.8E7 AlBr	20
74Kr	15	4.93	6.2	2.1E6	25
76Rb	15	5.07	1.68	3.8E6	15
80Rb	13	6.15	1.17	5.7E7	35
80Rb	14	5.71	1.1	5.7E7	70000
122Cs	19	6.42	1.1	3.1E5	6
124Cs	20	6.2	1.37	2.75E7	50



$^{78}Br^{14+}$ (1E6 ion/s) A/q = 5.57 amu/e

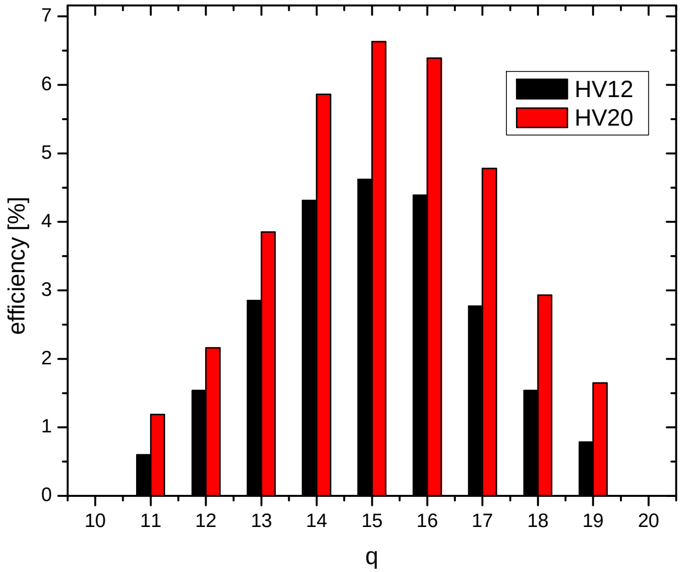
- injected as AlBr from ZrC target
- accelerated to 5MeV/u
- measured at TIGRESS detector
- background ≈ 20 pA

Fighting against large background from stainless steel and residual gases

From Stainless steel to Aluminum

- Significant efficiency increase with an Al plasma chamber
- Injection/Extraction electrodes in Al
- Iron plugs coated with ultra-pure Al (as for TRIAC charge breeder)

Pen Duick III



^{80}Rb charge state distribution from Al plasma chamber with different injection/ extraction voltage

	steel	Al
$^{48}K^{9+}$		0.67%
$^{46}K^{9+}$	0.5 %	
$^{80}Rb^{15+}$		4.5% (6.5%
$^{76}Rb^{15+}$	1.68%	
$^{124}Cs^{20+}$	1.37%	2.0%

Background significantly reduced
More news in the next few weeks

Charge breeding for future ISOL facilities in Europe: the EMILIE project

« Enhanced Multi-Ionization of short Lived Isotopes for EURISOL »

Consortium of 8 europeans laboratories aiming at SPES, HIE-ISOLDE, SPIRAL 2 and … EURISOL!

Coordinator

Dep. Coordinator

J. Angot, G. Ban, L. Celona, J. Choinski, , P. Delahaye (GANIL IN2P3, coord.), A. Galata (INFN, deputy coord.), P. Gmaj, A. Jakubowski, P. Jardin, T. Kalvas, H. Koivisto, V. Kolhinen, T. Lamy, D. Lunney, L. Maunoury, A. M. Porcellato, G. F. Prete, O. Steckiewicz, P. Sortais, T. Thuillier, O. Tarvainen, E. Traykov, F. Varenne, and F. Wenander

- Testing a CW EBIS concept: EBIS debuncher
- Gaining understanding in ECR charge breeding

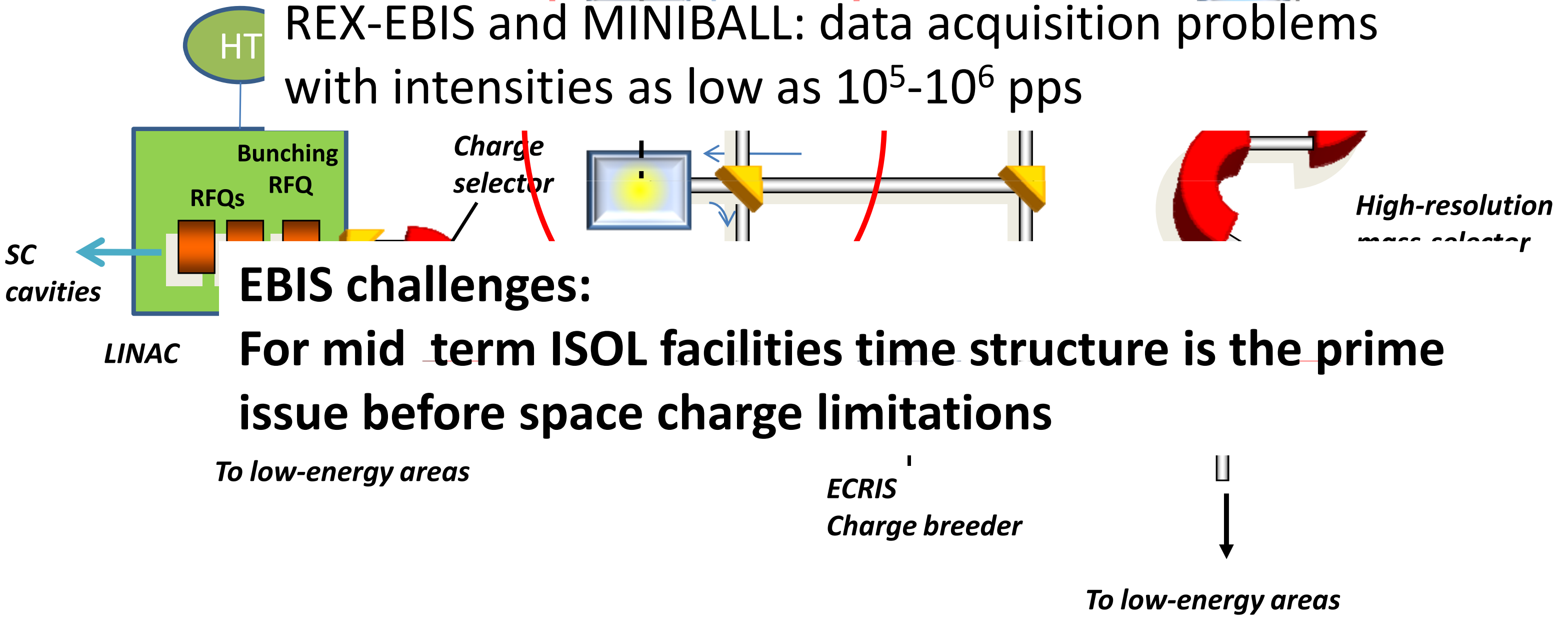
EBIS debuncher: motivations

Suggestion for EURISOL:
P. Delahaye, O. Kester, C. Barton, T. Lamy, M. Marie-Jeanne, F. We

CW EBIS charge breeder

Less dead time, piling-up and fake coincidence problems

REX-EBIS and MINIBALL: data acquisition problems with intensities as low as 10^5-10^6 pps



EBIS challenges:

For mid term ISOL facilities time structure is the prime issue before space charge limitations

CW beams!

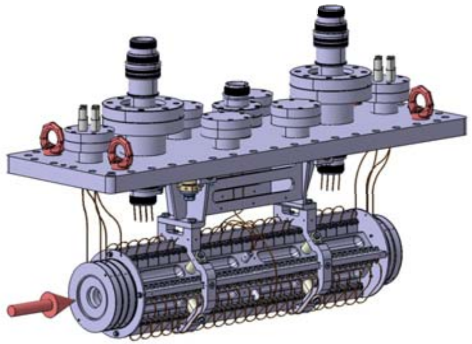
Detail of the EURISOL Layout

Modified from P. Butler's presentation, NuPECC meeting June 2007

A Paul trap as debuncher

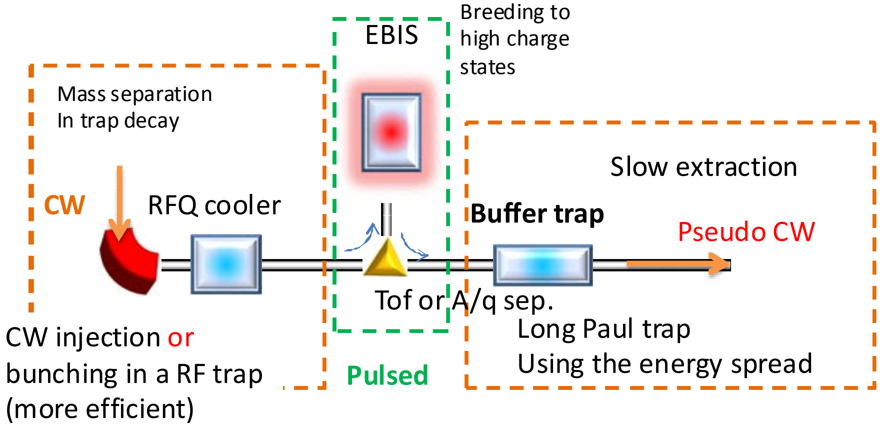
See Emil Traykov's poster

- Linear RFQ under UHV

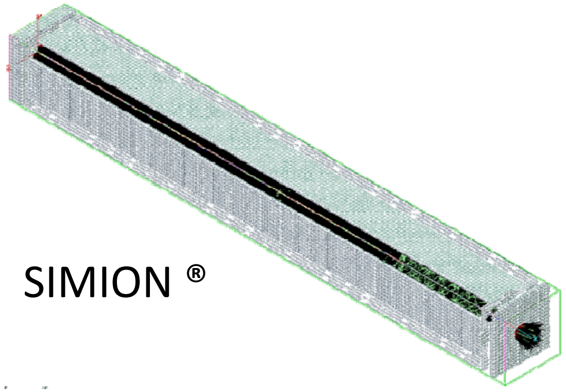


  - Design completed by LPC Caen!

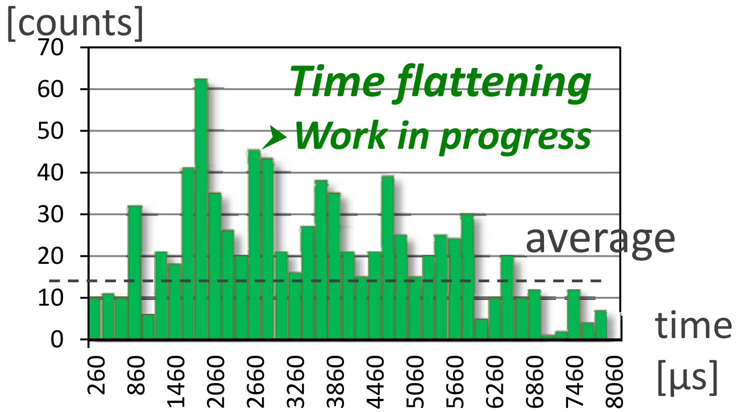
CW EBIS concept



- Simulations ongoing



Flatening the time structure



Tests in GANIL in 2013 with ECRIS chopped beams

Gaining understanding on ECRIS charge breeding

- Optimization of the Phoenix charge breeder for SPES, SPIRAL and SPIRAL 2

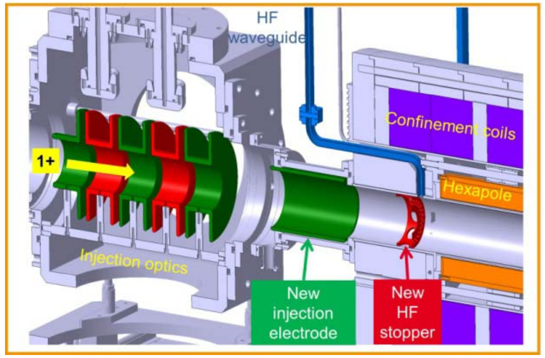
LPSC inventor of the ECR charge breeding method

First operational ECR charge breeder design: LPSC PHOENIX BOOSTER
Two copies Tested at ISOLDE and TRIUMF (presently operational)
A few upgrades performed

Symmetrization of the magnetic field at the 1+ beam injection

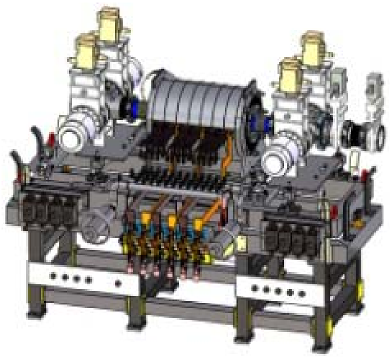
High voltage improvement

Grounded tube suppression, HF coupling improvement



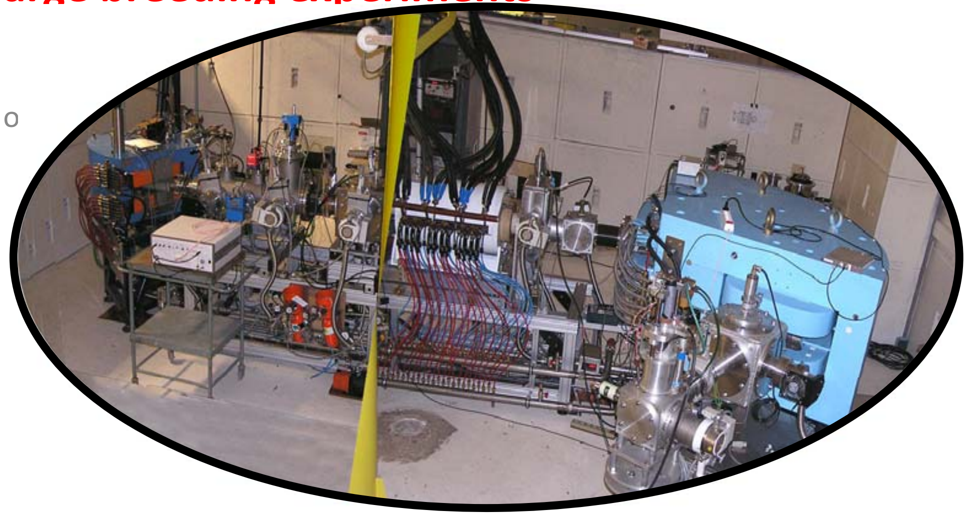
Unique test stand fully dedicated for ECR charge breeding experiments

Available for EMILIE experimental program, and for LPSC R&D



LPSC - SPIRAL2 charge breeder

7th o



Extensive simulation program at INFN

NUMERICAL SIMULATION ON:

***MW coupling to the Phoenix Booster*:**

- **Influence of the Grounded Tube**

- **Taking into consideration the Magnetic profile**

CONCEPTUAL DESIGN OF A NEW PLASMA CHAMBER

***1+ Beam Capture*:**

- **Influence OF the ECR plasma**

- **Low Mass Ions Injection**

- **Influence ON the ECR plasma**

INTEGRATE AN EXISTING ECR PLASMA SIMULATION TOOL DEVELOPED @ LNS

Modeling of electron and ion dynamics with Monte-Carlo calculations: ELECTRONS

A MATLAB code solves the equation of motion of a single particle:

$$\frac{d\vec{v}}{dt} = \begin{cases} \frac{q}{M}\left[\vec{v}\times\vec{B}+\vec{E}_s\right] & (i) \\ \frac{q}{m}\left(1-\frac{v^2}{c^2}\right)^{3/2}\left[\vec{v}\times\vec{B}_S+\vec{v}\times\vec{B}_{em}+\vec{E}_{em}-\frac{1}{c^2}\left(\vec{E}_{em}\cdot\vec{v}\right)\vec{v}\right] & (e) \end{cases}$$

$$\begin{aligned}
\dot{x} &= v_x \\
\dot{y} &= v_y \\
\dot{z} &= v_z \\
\dot{v}_x &= F(v)[(v_yB_z - v_zB_y) + (v_yB_{em_z} - v_zB_{em_y}) + E_{em_x} - \\
&- \frac{1}{c^2}\left(E_{em_x}v_x + E_{em_y}v_y\right)v_x] \\
\dot{v}_x &= F(v)[(v_zB_x - v_xB_z) + (v_zB_{em_x} - v_xB_{em_z}) + E_{em_y} - \\
&- \frac{1}{c^2}\left(E_{em_x}v_x + E_{em_y}v_y\right)v_y] \\
\dot{v}_z &= F(v)[-B_xv_y + v_xB_y - B_{em_x}v_y + v_xB_{em_y} - \\
&- \frac{1}{c^2}\left(E_{em_x}v_x + E_{em_y}v_y\right)v_z]
\end{aligned}$$

Magnetostatic field for the plasma confinement

Magnetic and electric fields associated with the pumping wave

MATLAB solves the six first order ODEs by means of the "*ode45*" Runge-Kutta routine.

- 3000 electrons/week, 8 CPU

- $\delta t = 10^{-12}$ s ~ 10 points of integration per Larmor radius

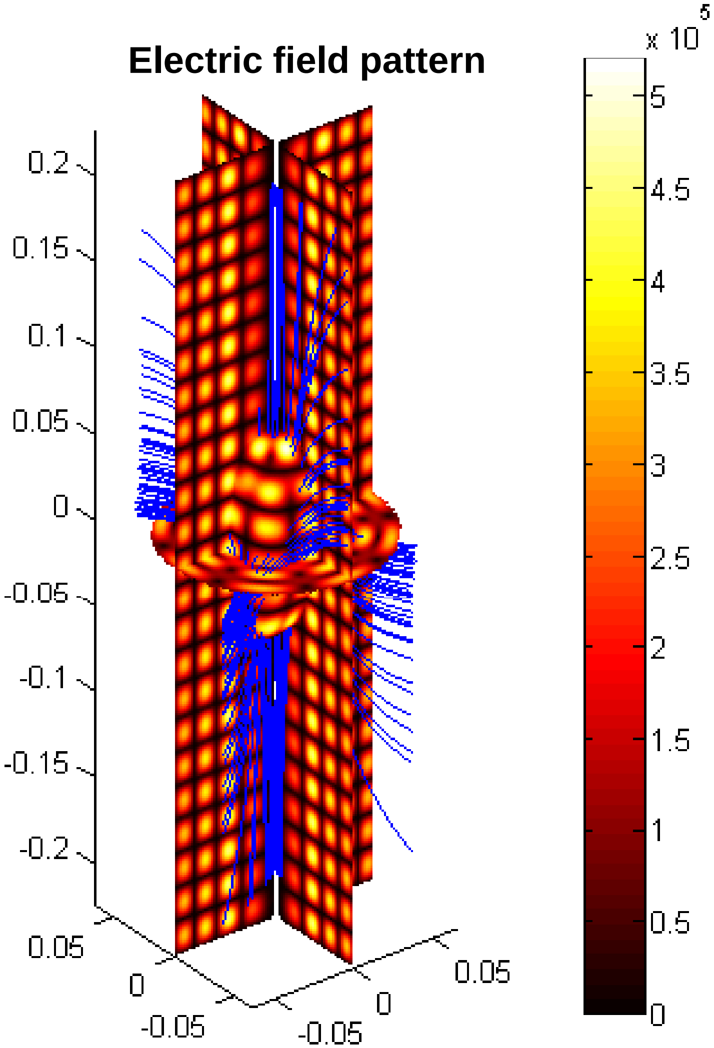
- **Collisions are taken into account**

- Fully 3D calculations with B-min structure

The pattern of the electromagnetic field influences also the plasma density distribution so:

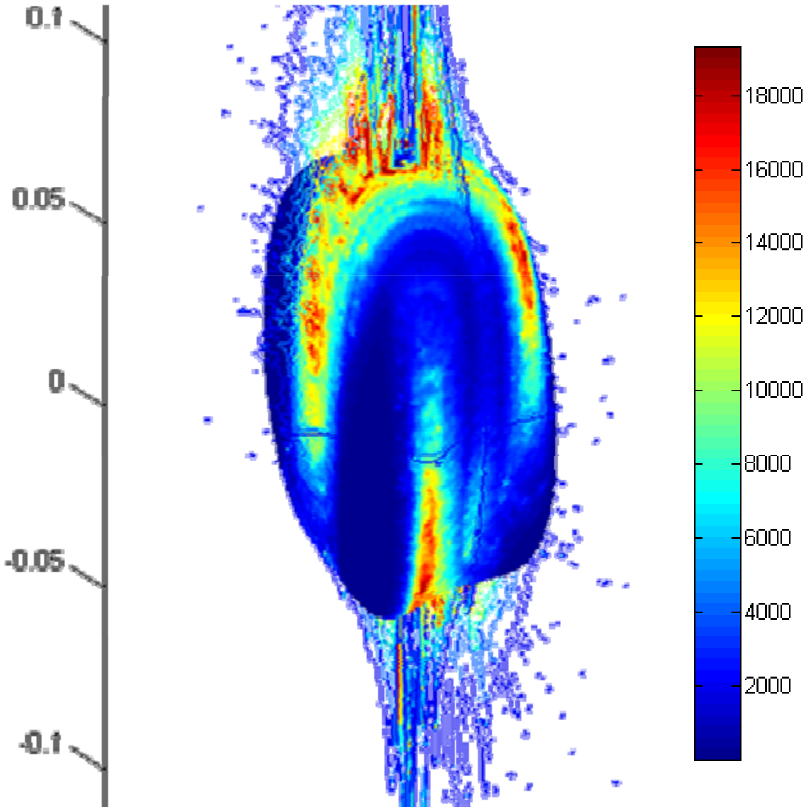
WHICH IS THE INFLUENCE ON THE CAPTURE OF THE 1+ BEAM?

Electric field pattern



D. Mascali et al., Proceedings of ECRIS 2010

Plasma density distribution in proximity of ECR surface



NOTE that the plasma is almost completely confined inside the resonance surface

Summary experimental work

- At LPSC
  - Hot 1+ ECR source
  - New hexapole for Phoenix
  - New plasma chamber from studies from INFN
- At JYFL and HIL
  - Tests of metallic ion beam production with double RF heating in ECRIS
- At GANIL
  - Optimization of the SPIRAL charge breeder towards light masses

2.45 and 5.7 GHz hot ion sources developments

Most of the experimental time on the tests stand is spent on the 1+ beam tuning

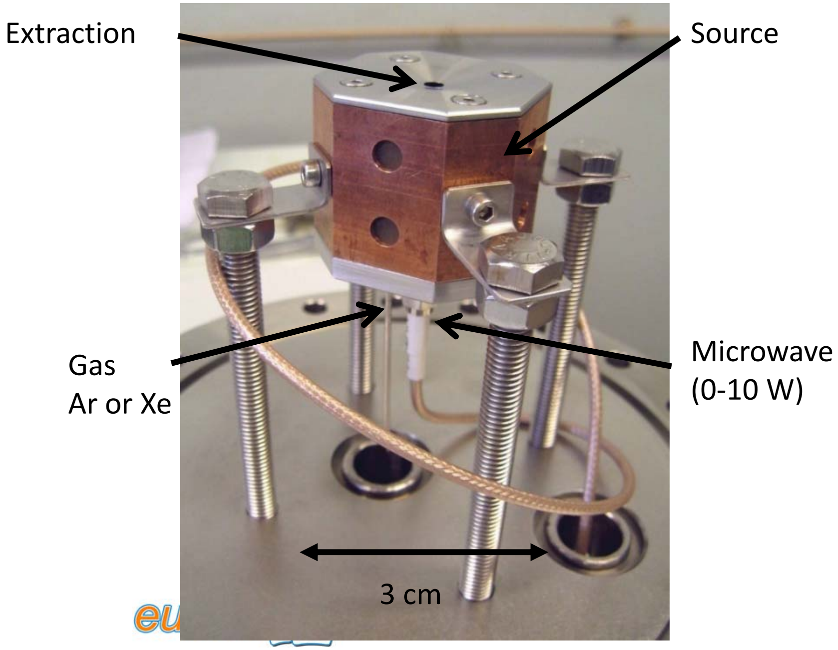
Purpose: to decrease this time in order to focus on the 1+/n+ process optimization itself

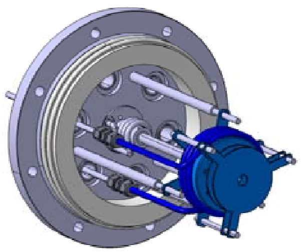
To establish confident efficiency measurements

Intensity (~ 200 to 1000 nA) and stability have to be highly controlled

A few low charges have to be produced to study the capture process

Source developments based on the COMIC source (2 prototypes foreseen 600 and 1200 °C)



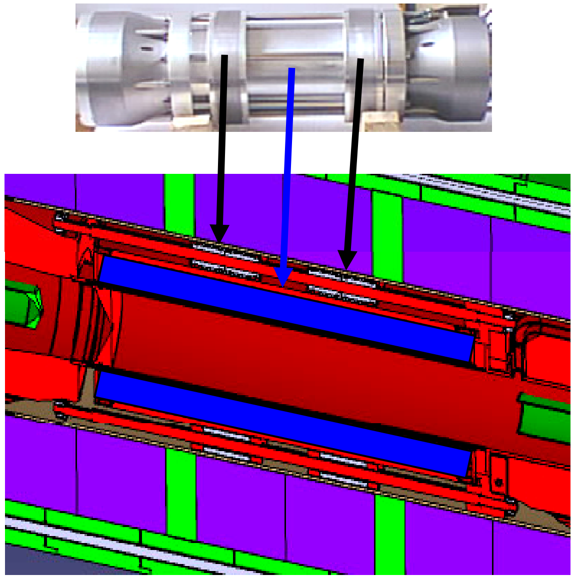


Thermal analysis under study (ANSYS)

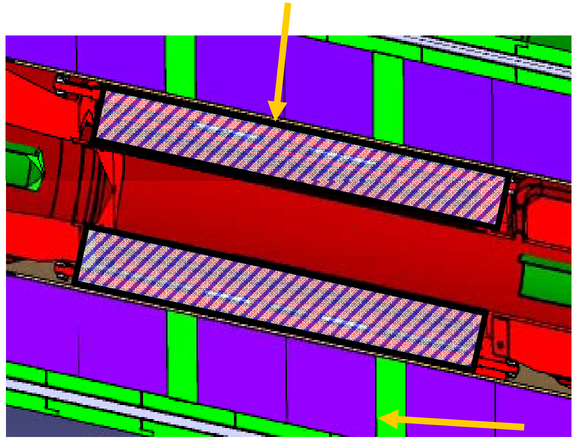
PHOENIX Booster magnetic field optimization

Hexapole change for optimum 18 GHz operation

Present hexapole
with two iron rings



Future higher diameter hexapole
without iron rings



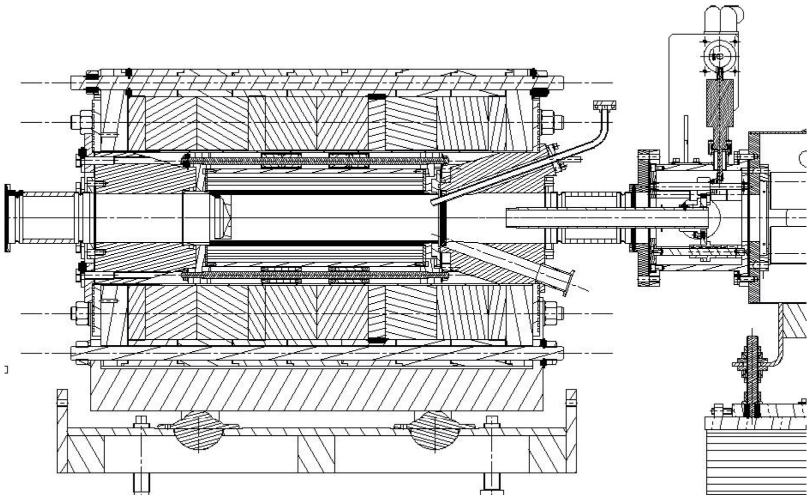
Higher magnetic field gradient and shorter Booster to be studied

To take advantage of the PHOENIx-V2 source improvements for the SPIRAL2 Phase 1 project

Higher charge states

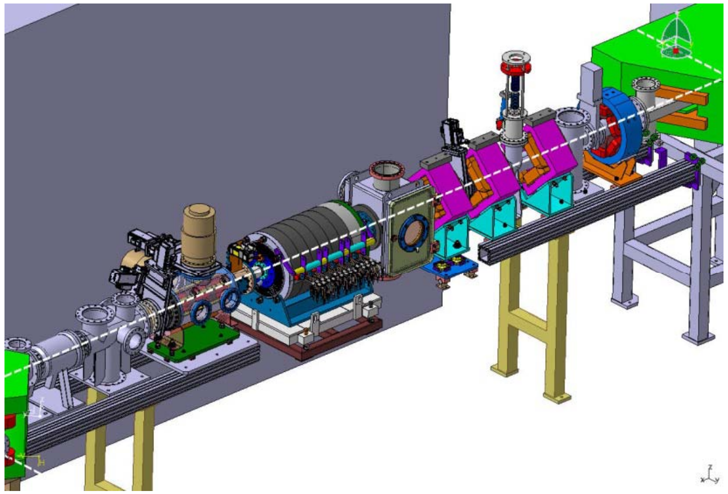
Better plasma (i.e. ion beam) stability

Phoenix charge breeder upgrade and installation at SPIRAL

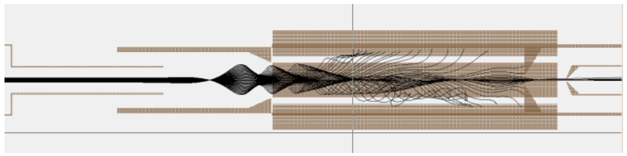


Remote controlled injection tube
Modified HF injection
UHV design

ENSAR : pure beams



Optimization towards light masses



SIMION ® calculations ongoing

euroRIB'12 Latest tests at ANL: up to 9.6% Na^{8+} and 17.7% for K^{10+}

Thanks a lot for your attention

and thanks a lot to my friends and colleagues:

Alessio Galatà

Luigi Celona

Rick Vondrasek

Thierry Lamy

Laurent Maunoury

Fredrik Wenander

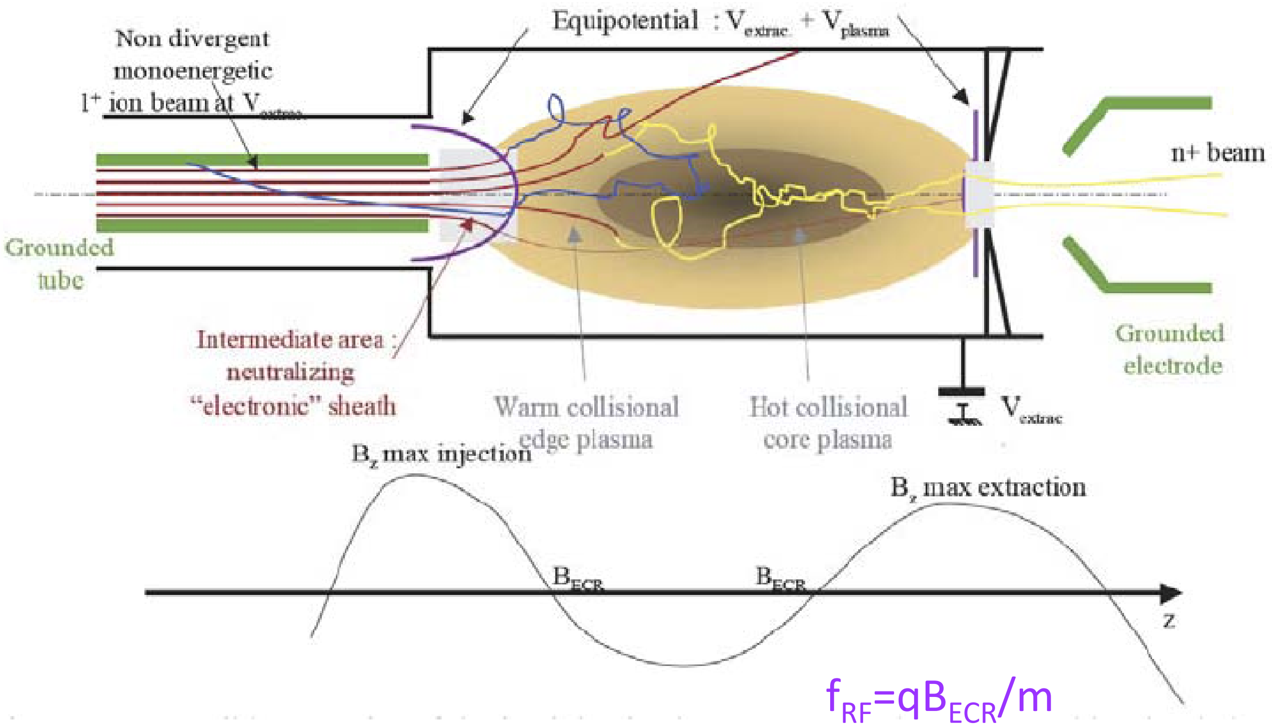
Emil Traykov

Friedhelm Ames

Stefan Schwarz

Additionnal material

Charge breeding in an ECR



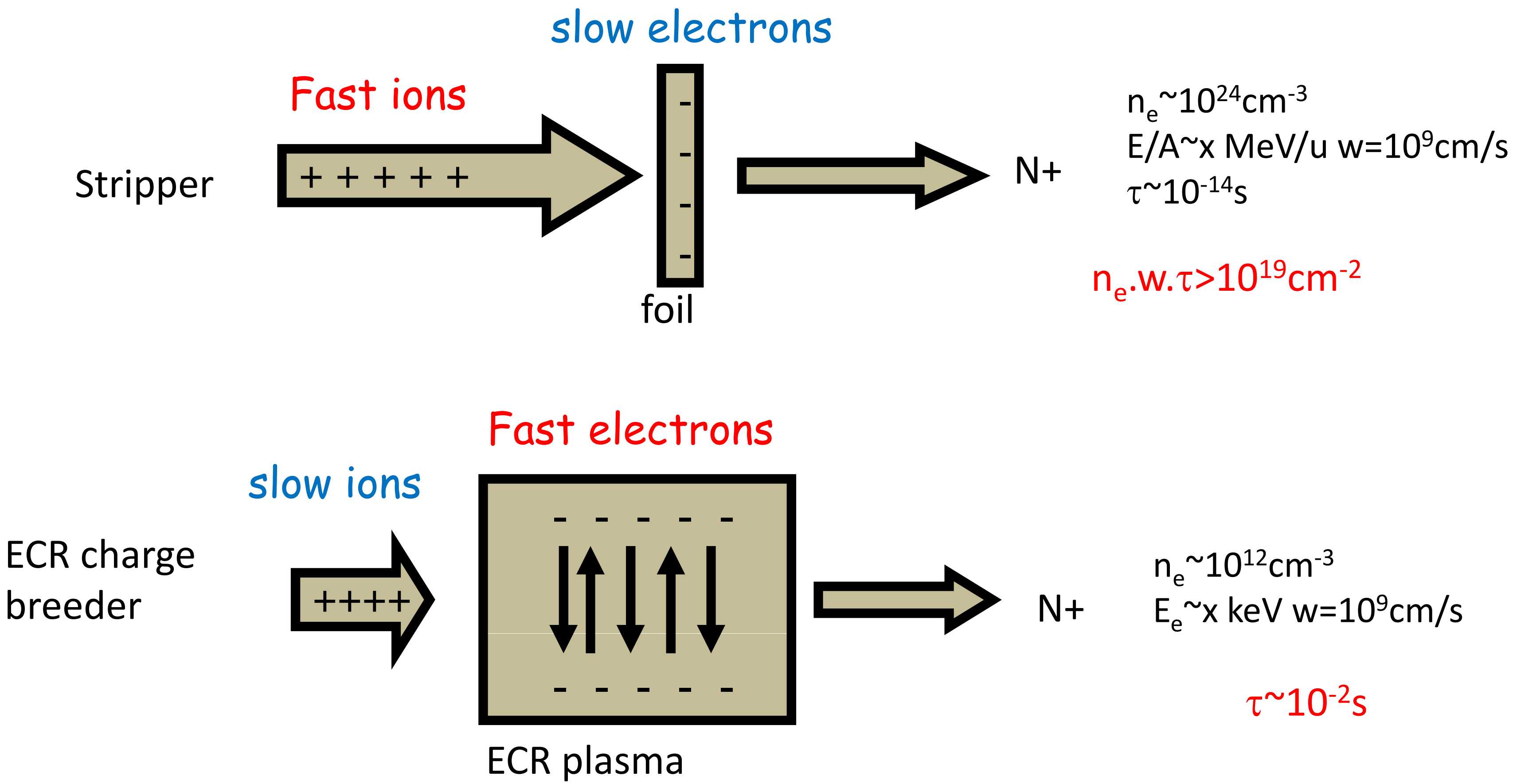
$f_{RF}=qB_{ECR}/m$

R. Geller, *Electron Cyclotron Resonance Ion Source and ECR plasmas*, IOP, Bristol, UK, 1996.

Essentially a CW device, but can be pulsed

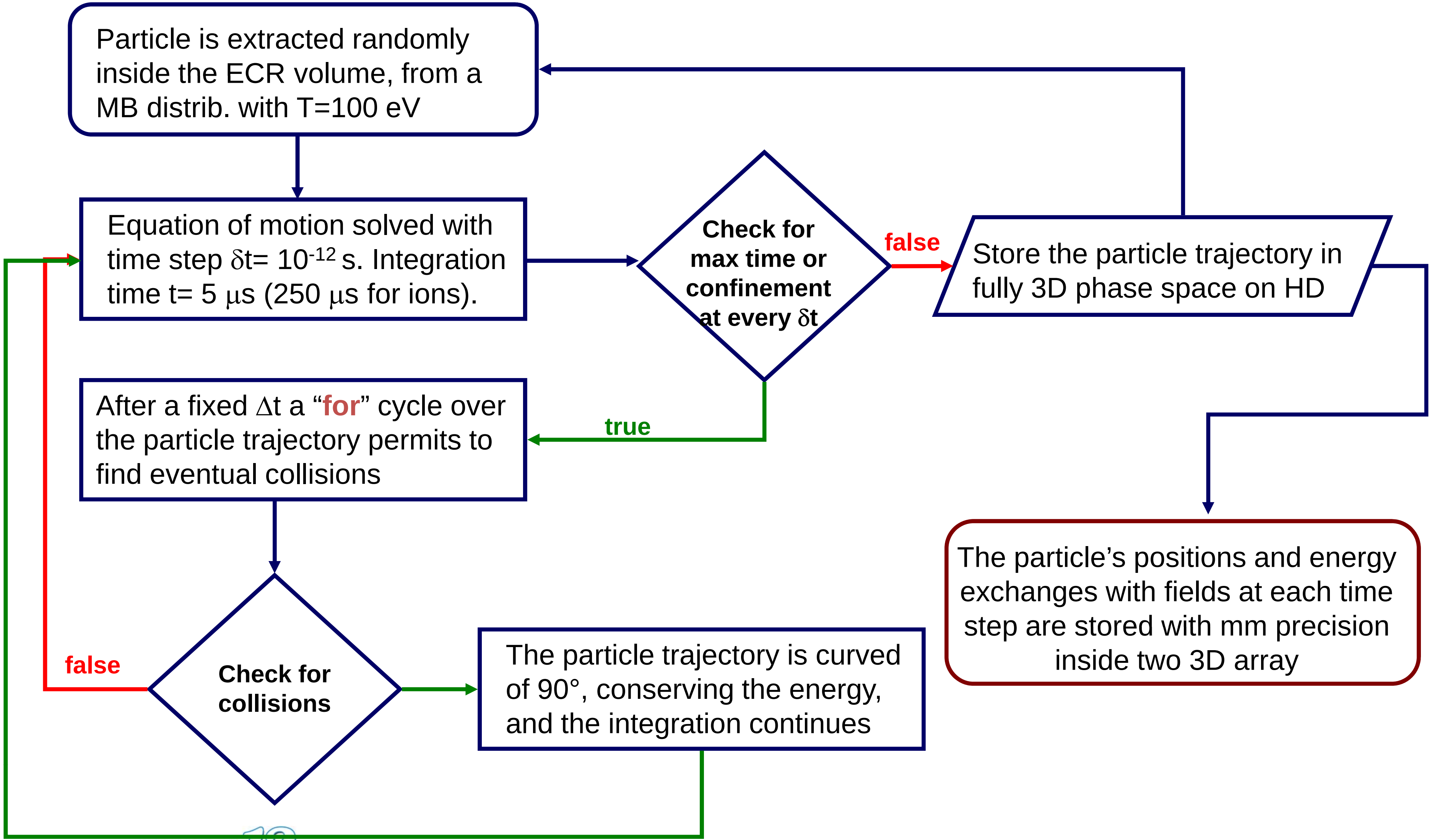
Analogy

- $<q> \sim \log(n_e . w . \tau)$

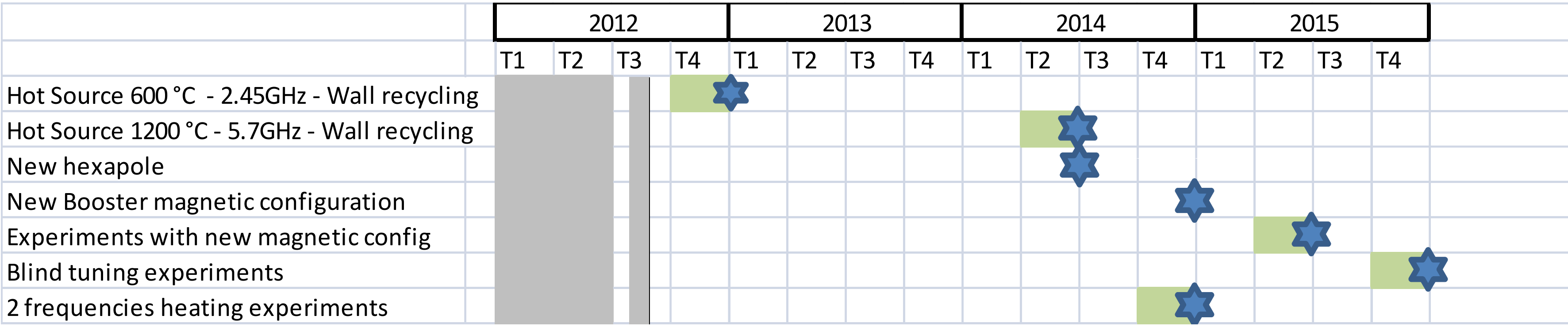


R. Geller, Annu. Rev. Part. Sci. 40,15(1990)

Modeling of electron and ion dynamics with Monte-Carlo calculations



LPSC EMILIE Planning



EBIS debuncher

Example: Post-accelerated beams for SPIRAL 2

Baseline scenario: Phoenix ECR charge breeder from LPSC

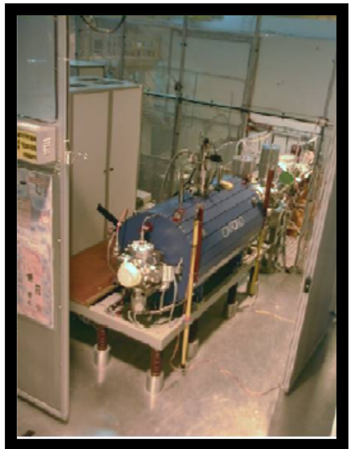
Limitation in energy, especially for the second fission bump

^{132}Sn

Charge state	Energy (AMeV)	Intensity (pps)
18+	5.0	$1.8^{E}7$
25+	9.6	$1.8^{E}6$

Not favourable for transfer experiments!!

Solution: EBIS + buffer trap = CW EBIS



REX-EBIS

$^{132}Sn^{33+}$ is feasible!

($^{138-144}Xe^{34+}$ already done)

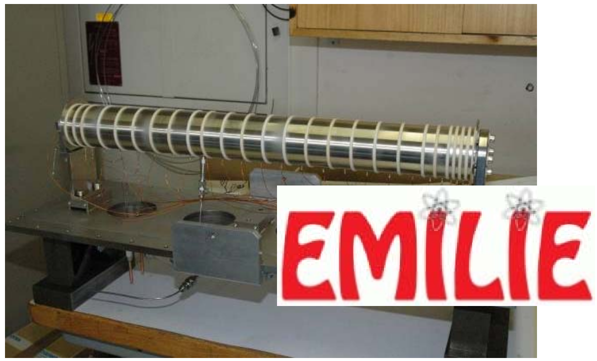
No intensity decrease

Up to 15 AMeV

Pulsed device (10-500μs pulses)

+

ISCOOL like RF trap



The **EMILIE** project

« Enhanced Multi-Ionization of short Lived Isotopes for EURISOL »

Charge breeding techniques for ISOL facilities

Improving performances of charge breeders based on:

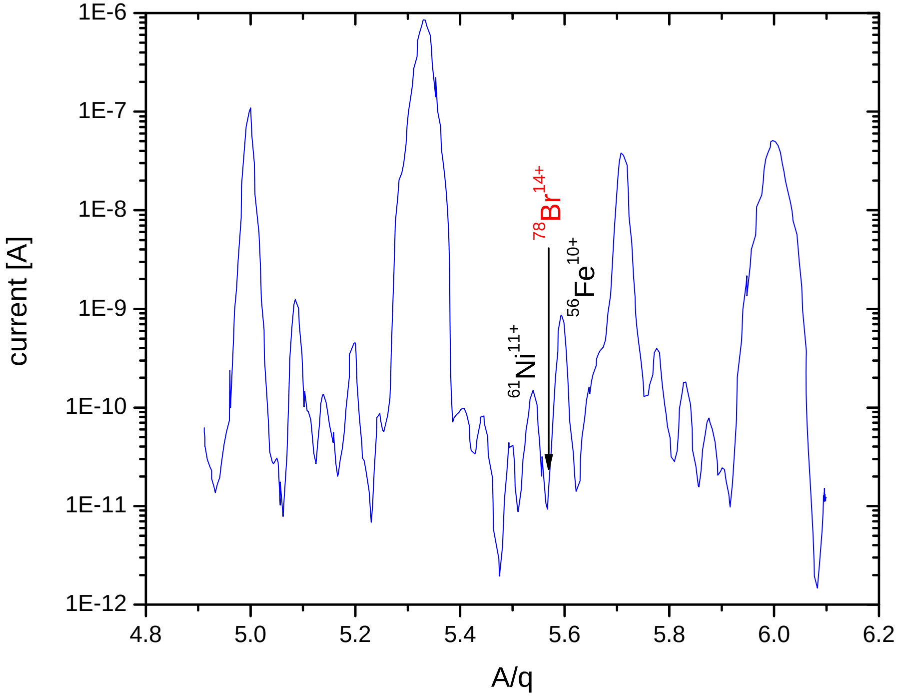
- **EBIS**
  - Testing a concept of debuncher using a Paul trap to produce CW beams
- **ECRIS**
  - Improving charge breeding efficiencies for metallic ions

Partner	Funds
IN2P3 (coord)	250k€
INFN	80 k€
HIL	159 k€
JYFL	24 k€

Consortium of 9 europeans laboratories including CERN as associate partner

J. Angot, G. Ban, L. Celona, J. Choinski, , P. Delahaye (GANIL IN2P3, coord.), A. Galata (INFN, deputy coord.), P. Gmaj, A. Jakubowski, P. Jardin, T. Kalvas, H. Koivisto, V. Kolhinen, T. Lamy, D. Lunney, L. Maunoury, A. M. Porcellato, G. F. Prete, O. Steckiewicz, P. Sortais, T. Thuillier, O. Tarvainen, E. Traykov, F. Varenne, and F. Wenander

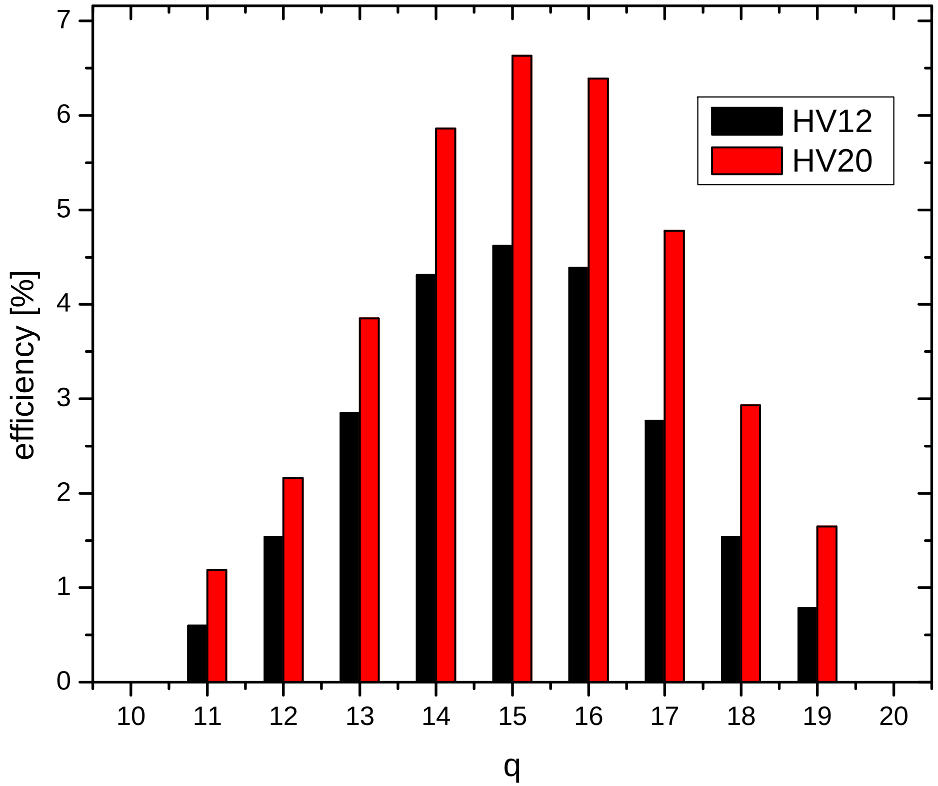
background stainless steel plasma chamber



$^{78}Br^{14+}$ (1E6 ion/s) A/q = 5.57 amu/e
injected as AlBr from ZrC target
accelerated to 5MeV/u
measured at TIGRESS detector
background ≈ 20 pA

A/q	Isotopes (+/- 0.005amu/e)
5	$^{40}Ar^{8+}$, $^{20}Ne^{4+}$,…
5.11	$^{133}Cs^{26+}$
5.14	$^{36}Ar^{7+}$
5.2	$^{52}Cr^{10+}$, $^{78}Kr^{15+}$, $^{130}Xe^{25+}$
5.24	$^{84}Kr^{16+}$, $^{131}Xe^{25+}$
5.33	$^{16}O^{3+}$
5.41	$^{54}Cr^{10+}$, $^{54}Fe^{10+}$, $^{130}Xe^{24+}$
5.44	$^{136}Xe^{25+}$
5.5	$^{22}Ne^{4+}$, $^{132}Xe^{24+}$
5.54	$^{61}Ni^{11+}$, $^{133}Cs^{24+}$
5.6	$^{28}Si^{5+}$, $^{56}Fe^{10+}$
5.66	$^{17}O^{3+}$, $^{136}Xe^{24+}$
5.71	$^{40}Ar^{7+}$
5.78	$^{52}Cr^{9+}$, $^{133}Cs^{23+}$
5.83	$^{134}Xe^{23+}$
5.88	$^{129}Xe^{22+}$
5.90	$^{53}Cr^{9+}$, $^{124}Xe^{21+}$
6	$^{12}C^{2+}$, $^{18}O^{3+}$, $^{54}Cr^{9+}$, $^{54}Fe^{9+}$, $^{60}Ni^{10+}$,…

aluminum plasma chamber efficiency



^{80}Rb charge state distribution from Al plasma chamber with different injection/ extraction voltage

charge breeding efficiency
of radioactive ions from stainless steel
and aluminum plasma chamber

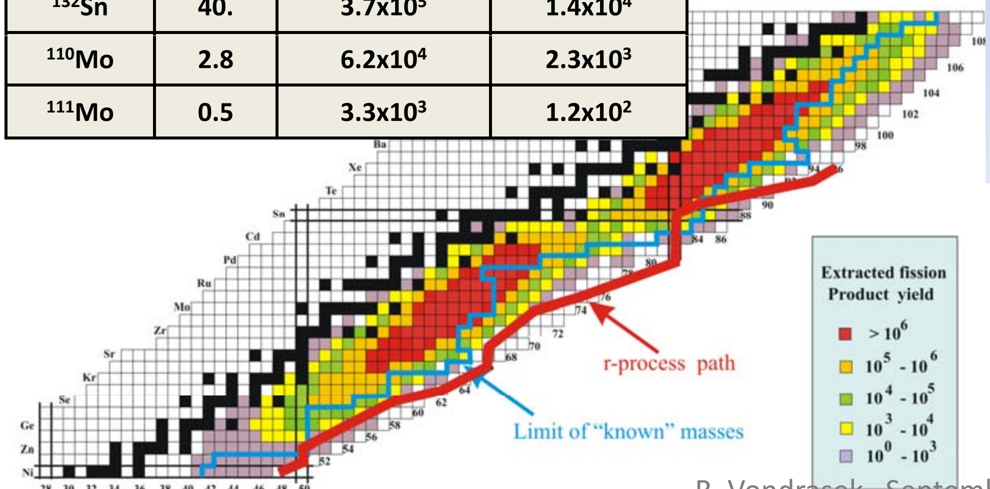
increase of efficiency

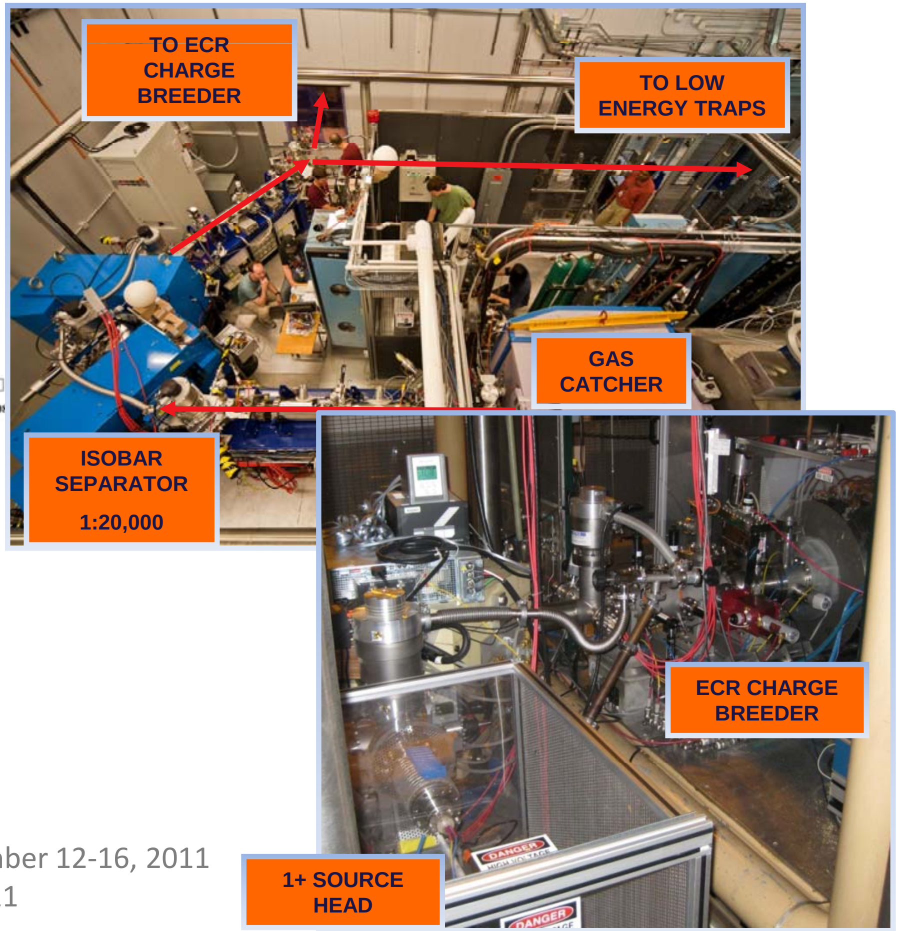
	steel	Al
$^{48}K^{9+}$		0.67%
$^{46}K^{9+}$	0.5 %	
$^{80}Rb^{15+}$		4.5% (6.5%
$^{76}Rb^{15+}$	1.68%	
$^{124}Cs^{20+}$	1.37%	2.0%

CARIBU – Californium Rare Ion Breeder Upgrade

- A 55 mCi ^{252}Cf fission source provides radioactive species for charge breeding
  - $T_{1/2}$=2.6 a 3.1% fission branch
  - Maximum approved source strength of 1.0 Ci, delivery expected in summer 2012
- ^{252}Cf fission yield is complimentary to uranium fission
- Stopped beams or post-acceleration energy up to 10 MeV/u

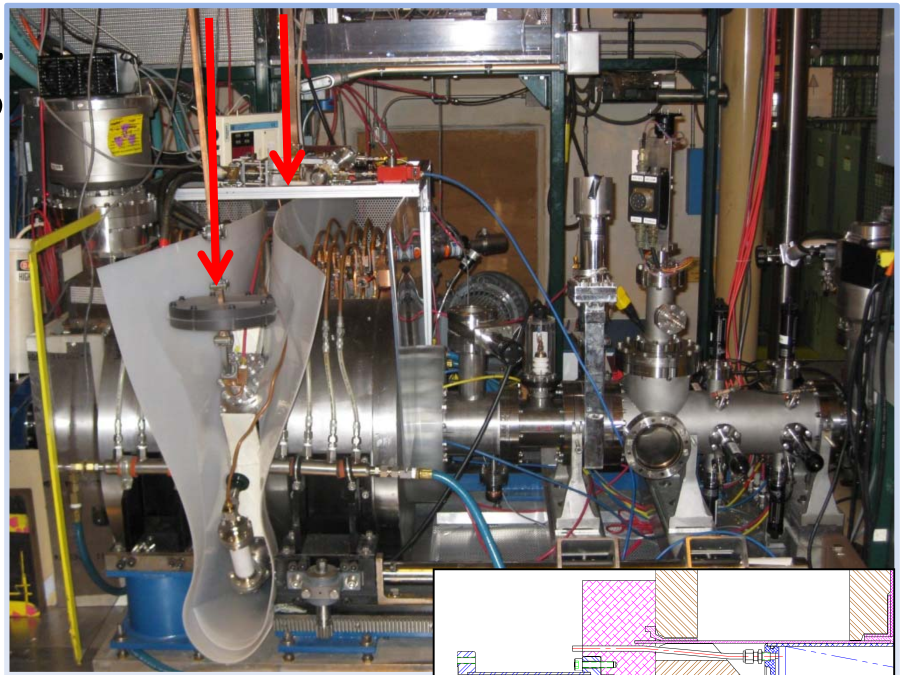
Isotope	Half-life (s)	Low-Energy Beam Yield (s^{-1})	Accelerated Beam Yield (s^{-1})
^{104}Zr	1.2	$6.0x10^5$	$2.1x10^4$
^{143}Ba	14.3	$1.2x10^7$	$4.3x10^5$
^{145}Ba	4.0	$5.5x10^6$	$2.0x10^5$
^{130}Sn	222.	$9.8x10^5$	$3.6x10^4$
^{132}Sn	40.	$3.7x10^5$	$1.4x10^4$
^{110}Mo	2.8	$6.2x10^4$	$2.3x10^3$
^{111}Mo	0.5	$3.3x10^3$	$1.2x10^2$

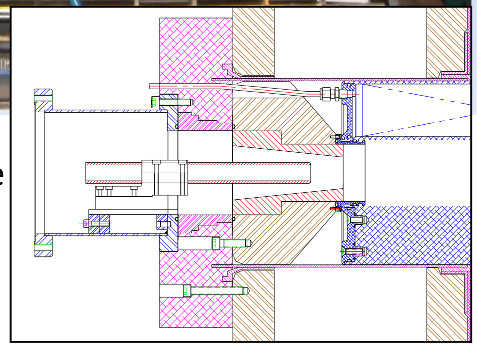




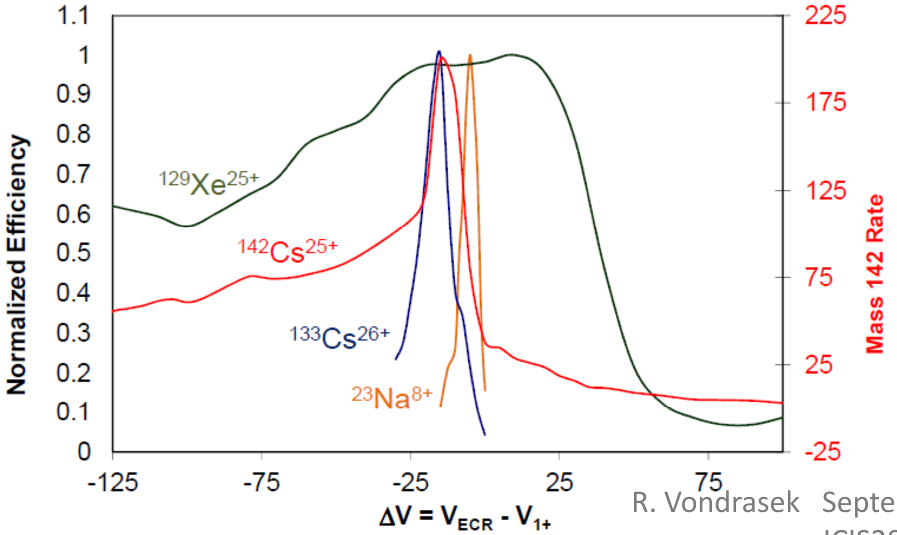
ECR charg

- Multiple frequency operation
  - Klystron: 10.44 GHz, 2 kW
  - TWTA: 11→13 GHz, 0.5 kW
- Open hexapole structure
  - RF is injected radially
  - Uniform iron in the injection region for symmetrical fields
  - Improved pumping to the plasma chamber region
    - Base pressure: 2×10^{-8} mbar
    - Operation: 7×10^{-8} mbar
    - Extraction pressure: 4×10^{-8} mbar

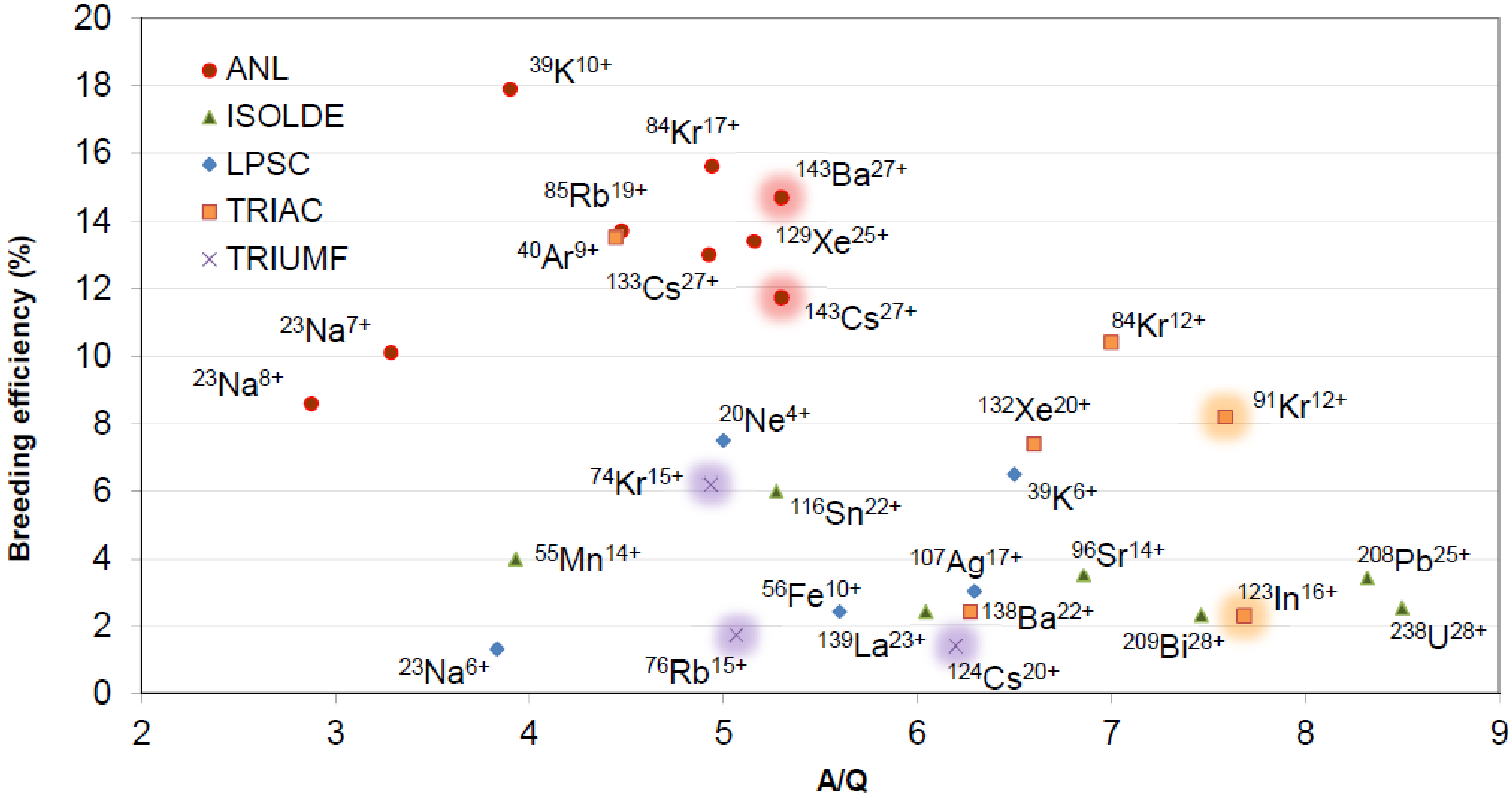




- Movable grounded tube with 2.5 cm of travel
- 50 kV high voltage isolation



	Design value	Running condition
B_{inj}	1.31 T	1.16 T
B_{min}	0.31	0.27
B_{ext}	0.85	0.83
$B_{(radial)}$		0.86 T
Last closed surface		0.61 T



Breeding efficiency (%)
A/Q
ANL
ISOLDE
LPSC
TRIAC
TRIUMF
0
2
4
6
8
10
12
14
16
18
20
2
3
4
5
6
7
8
9
$^{39}K^{10+}$
$^{84}Kr^{17+}$
$^{143}Ba^{27+}$
$^{85}Rb^{19+}$
$^{129}Xe^{25+}$
$^{40}Ar^{9+}$
$^{133}Cs^{27+}$
$^{143}Cs^{27+}$
$^{23}Na^{7+}$
$^{84}Kr^{12+}$
$^{23}Na^{8+}$
$^{132}Xe^{20+}$
$^{91}Kr^{12+}$
$^{20}Ne^{4+}$
$^{74}Kr^{15+}$
$^{39}K^{6+}$
$^{116}Sn^{22+}$
$^{55}Mn^{14+}$
$^{107}Ag^{17+}$
$^{96}Sr^{14+}$
$^{208}Pb^{25+}$
$^{56}Fe^{10+}$
$^{123}In^{16+}$
$^{138}Ba^{22+}$
$^{139}La^{23+}$
$^{209}Bi^{28+}$
$^{238}U^{28+}$
$^{23}Na^{6+}$
$^{76}Rb^{15+}$
$^{124}Cs^{20+}$

Charge breeding results – ANL CARIBU

Ion Species	n+ Charge State	Efficiency (%)	A/Q
^{23}Na	7+	10.1	3.29
^{39}K	10+	17.9	3.90
^{84}Kr	17+	15.6	4.94
^{85}Rb	19+	13.7	4.47
^{129}Xe	25+	13.4	5.16
^{133}Cs	27+	13.0	4.93
^{143}Cs (1+) $t_{1/2}$ = 1.79 s	27+	11.7	5.30
^{143}Ba (2+) $t_{1/2}$ = 14.33 s	27+	14.7	5.30