

Lisbon, Portugal



Charge breeding of exotic isotopes for EURISOL: the EMILIE project



P. Delahaye, GANIL



18th of October, Lisbon



Roadmap to EURISOL



Acquiring knowledge, know-how and understanding on key-technologies

Opening a new route towards discoveries



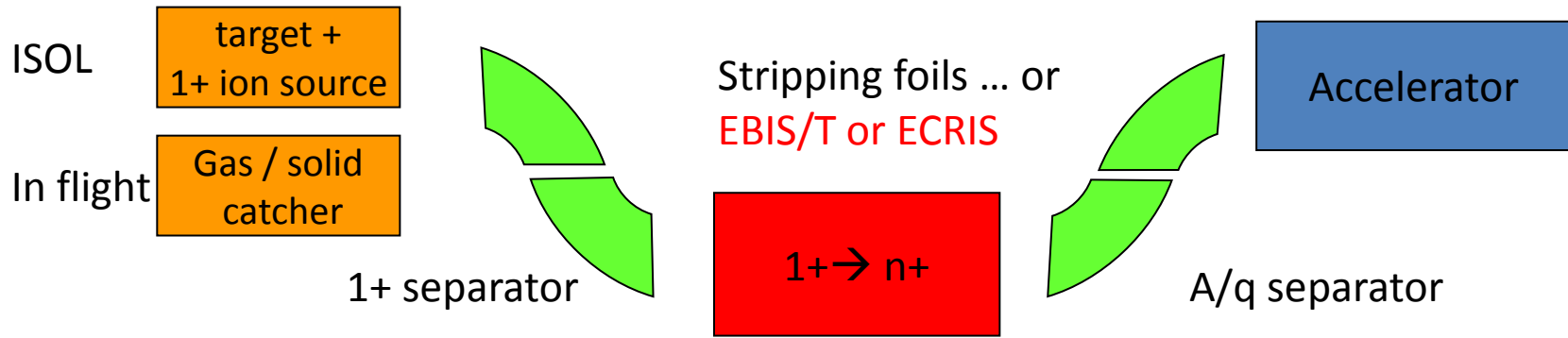
Consortium of 8 european labs



EMILIE: Enhanced Multi-Ionization of short-Lived Isotopes for EURISOL



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: $I \ll \mu\text{A}$ and $T_{1/2} < 1\text{s}$

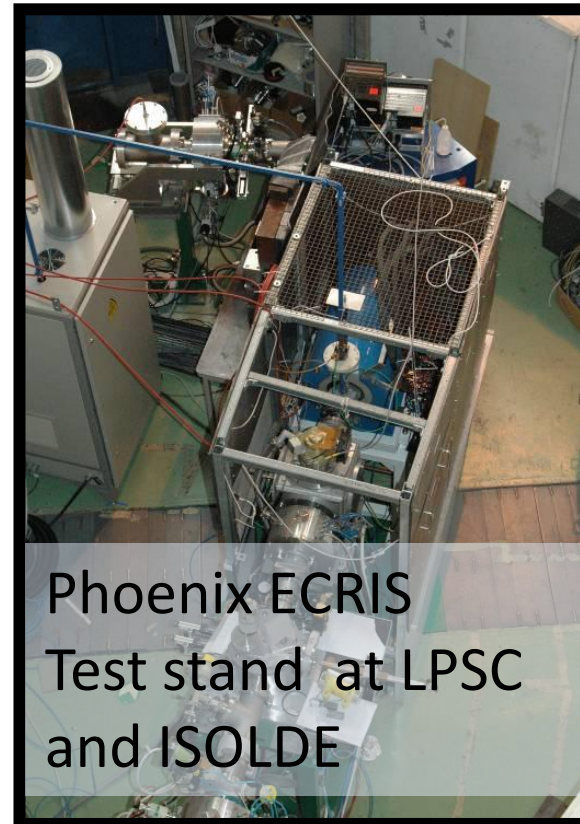
But also: $I \sim \mu\text{A}$



FP6: Comparison of charge breeding techniques



REX-EBIS
Operational at
REX-ISOLDE



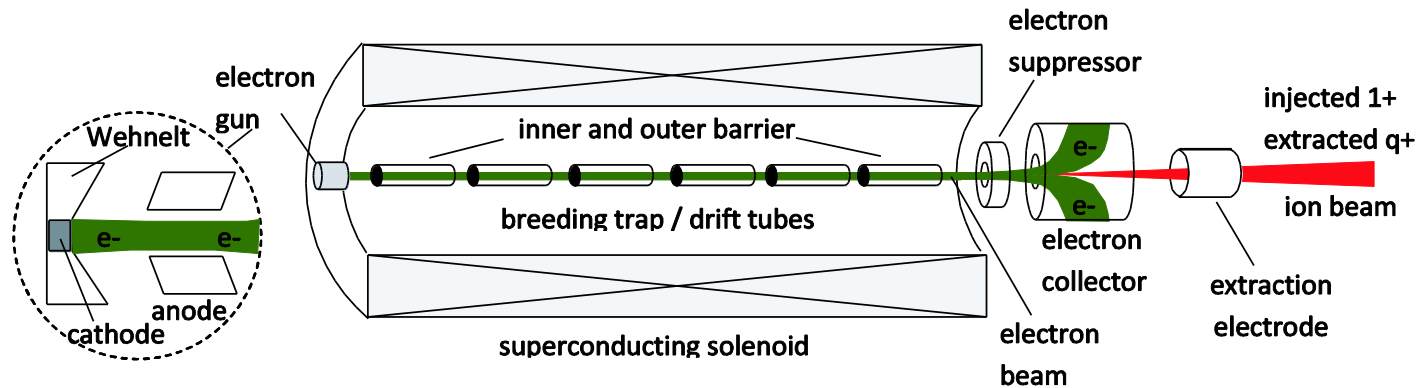
Phoenix ECRIS
Test stand at LPSC
and ISOLDE

Present status EBIS

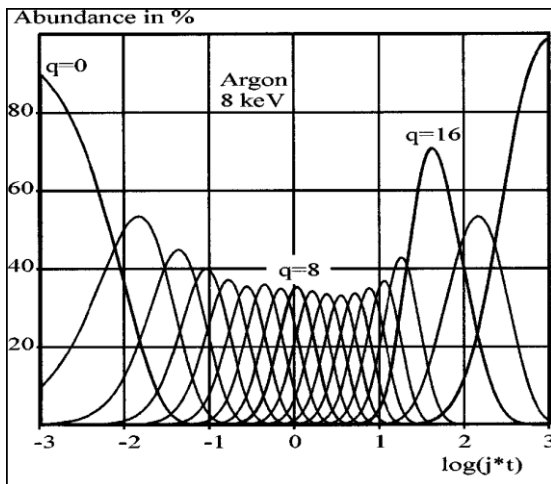


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EBIS charge breeder principle



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



Average charge state

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

Trap capacity (elementary charges)

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

Space charge limit $\sim 10^{10}$ pps

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

Essentially a pulsed device



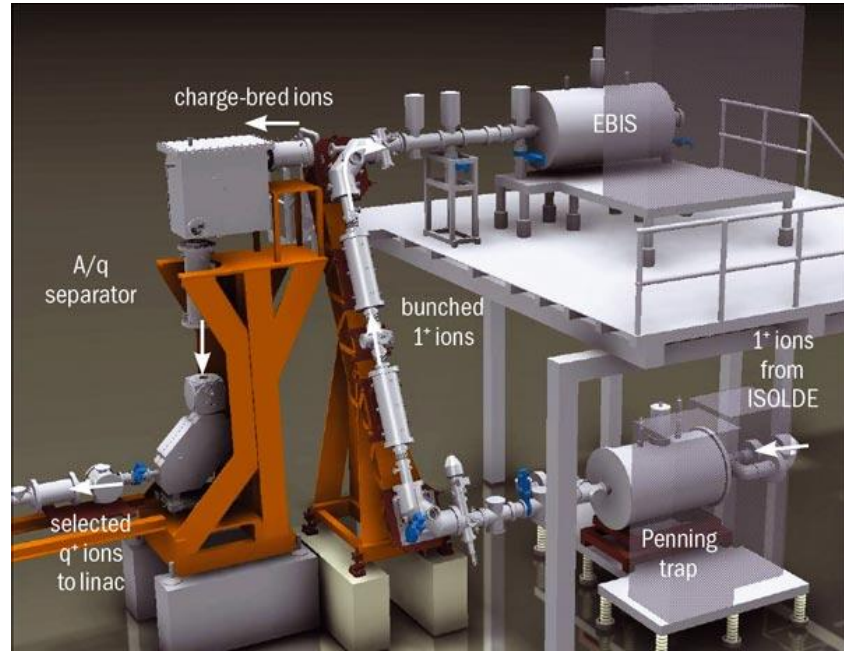
The REX-EBIS setup



The LaB₆ cathode

EBIS specifications

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

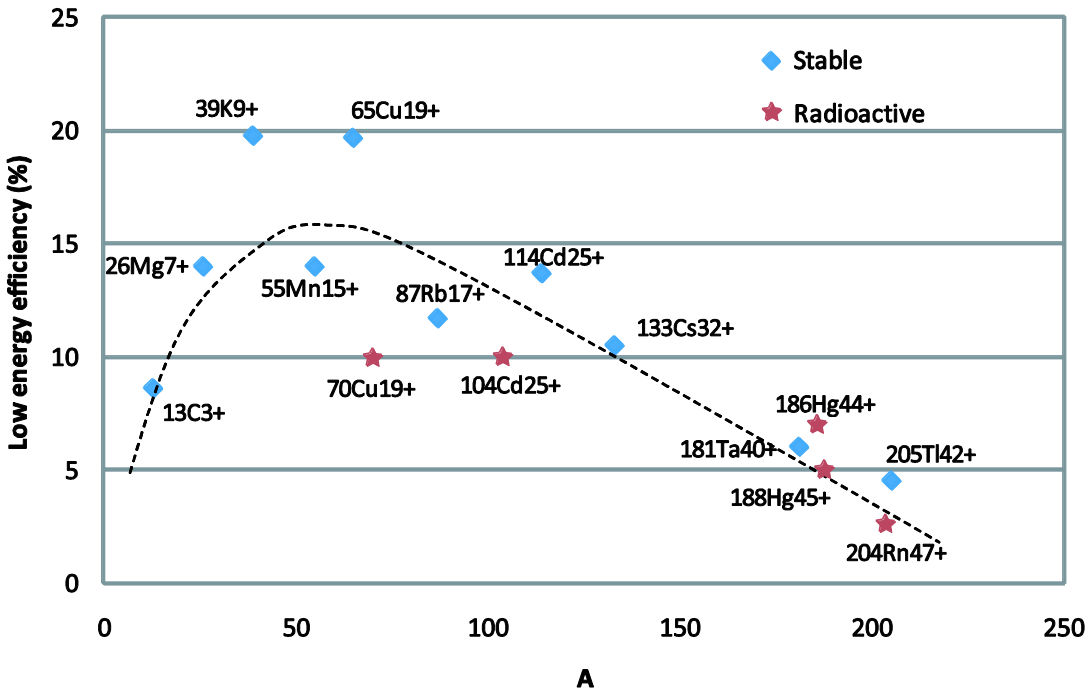


The charge state is selected with a mass separator of Nier-Spectrometer type

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

Charge breeding performances REX-EBIS

Sample of data 2008 - 2009

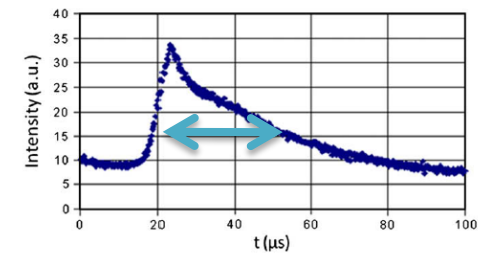


A/q ratios: from 3.5 to 4.5

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

Background < pA
 Very low residual gas pressure

Includes cooling, trapping and charge breeding efficiencies

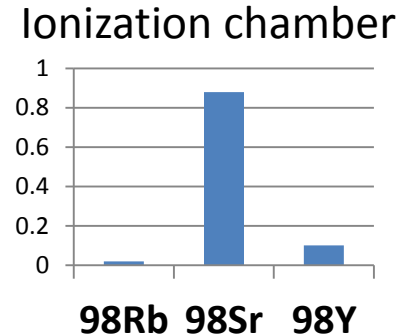
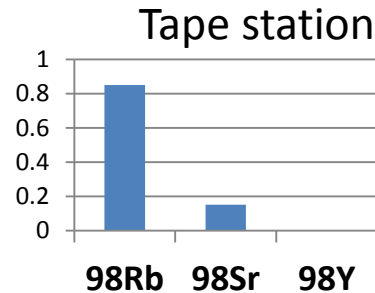
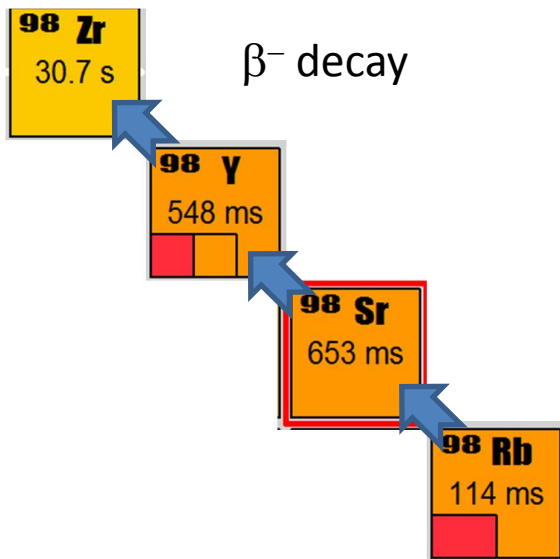


FWHM $\sim 30 \mu s$

In EBIS / trap decay and beam purity issues

Ex: IS451 E. Clément sp.

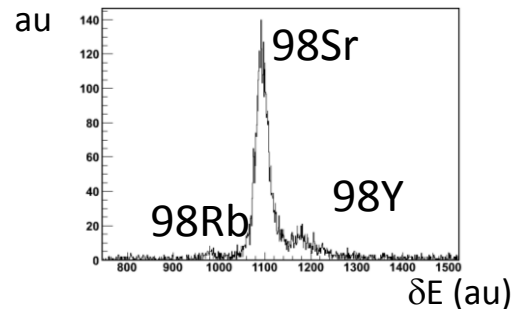
Coulomb excitation of ^{98}Sr at MINIBALL



160ms trapping

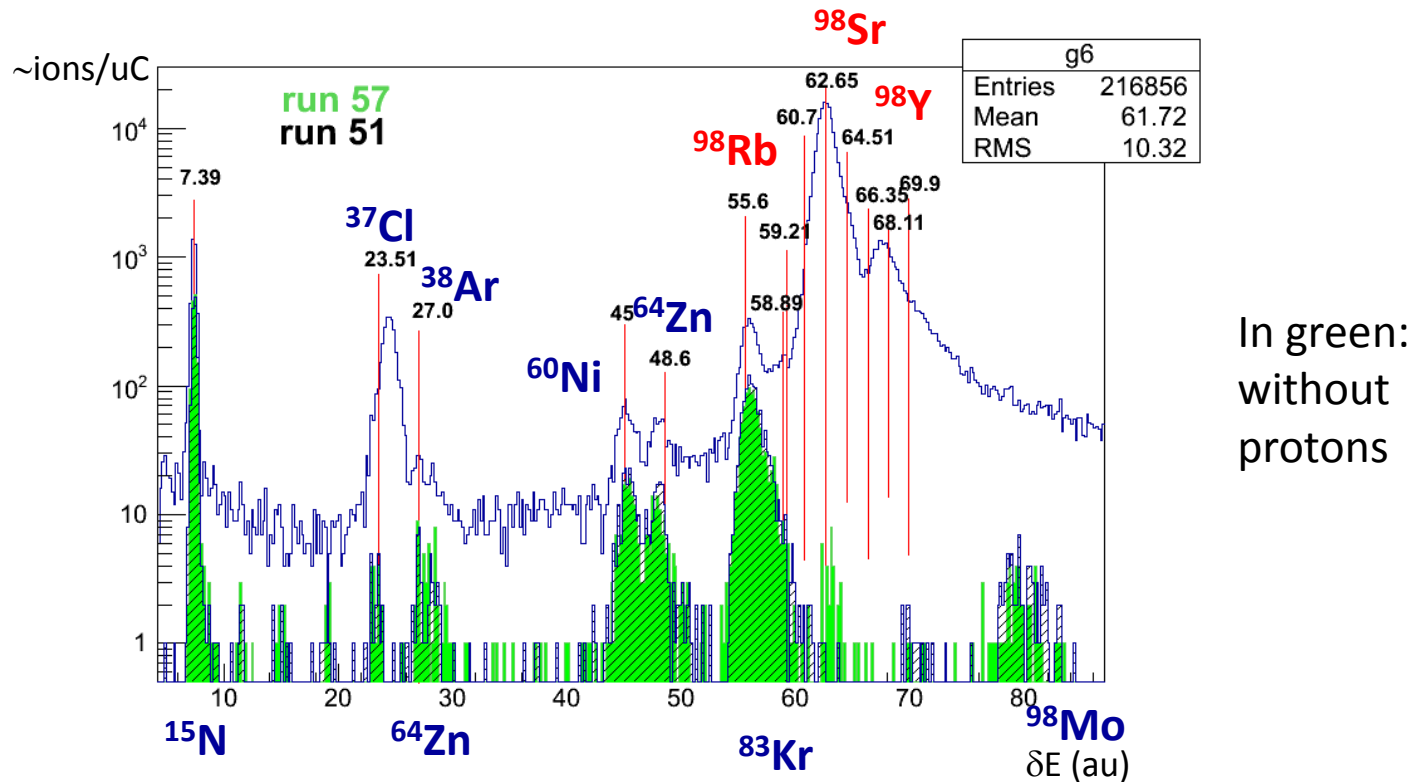
160ms charge breeding

4.5% low energy efficiency
charge breeding + trapping + decay



Ionization chamber signal

In EBIS / trap decay and beam purity issues



Stable beam contaminants from EBIS ~a few 100/s

News from other facilities

EBIS/T charge breeding

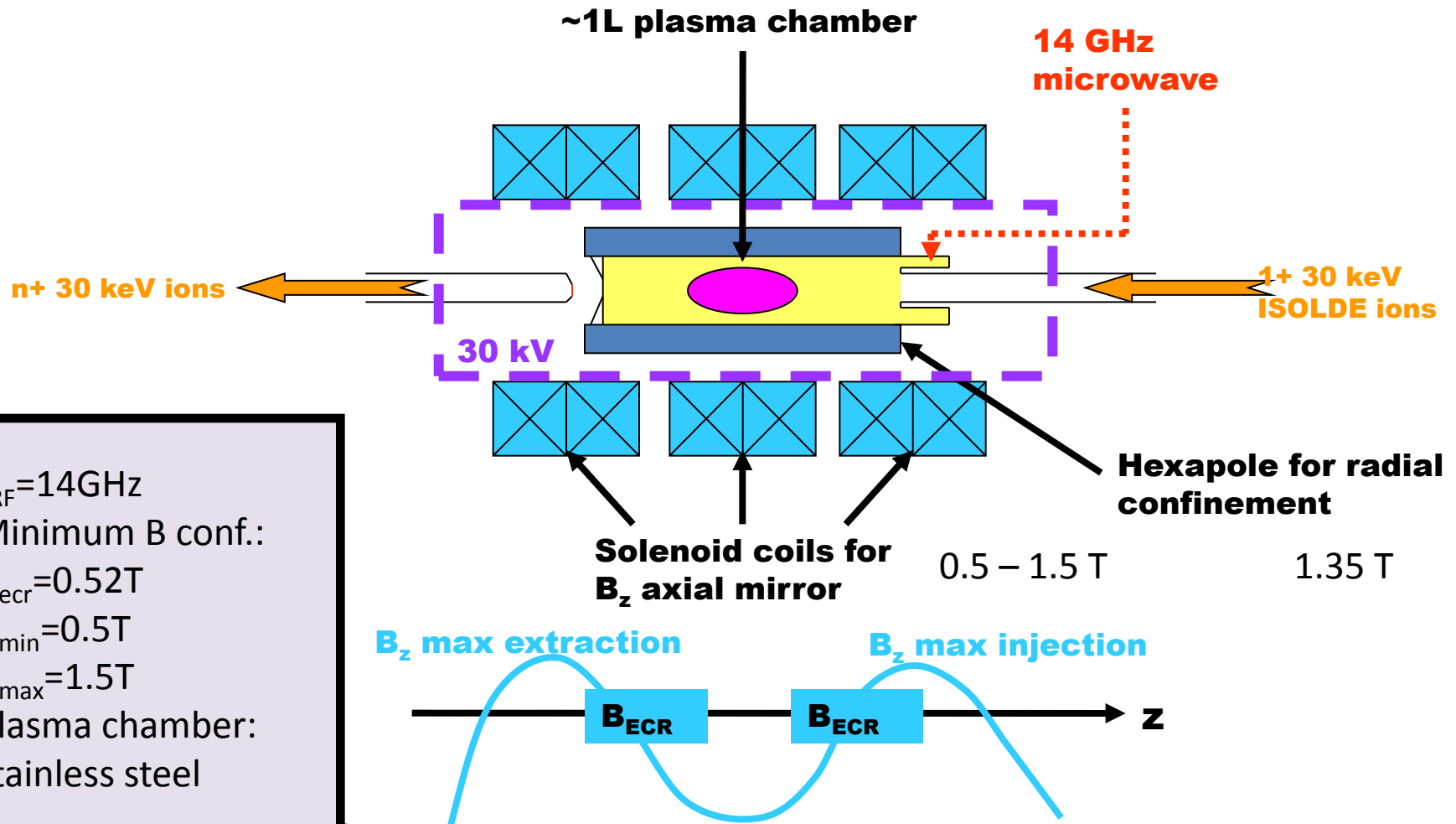
- NSCL EBIT: design value 5A, two traps to allow for a continuous injection
 - In commissioning
 - faster breeding times expected
- ANL EBIS in design phase
- EBIS/T connected to Penning trap systems
 - Ex: Titan EBIT at TRIUMF

Present status ECRIS



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The 14GHz Phoenix booster



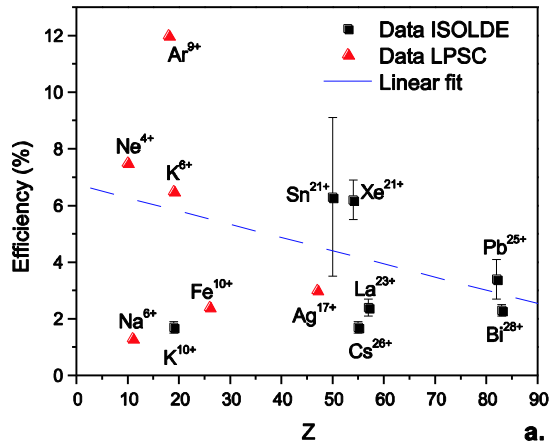
$f_{RF}=14\text{GHz}$
 Minimum B conf.:
 $B_{ecr}=0.52\text{T}$
 $B_{min}=0.5\text{T}$
 $B_{max}=1.5\text{T}$
 Plasma chamber:
 stainless steel



Charge breeding performances Phoenix ECRIS

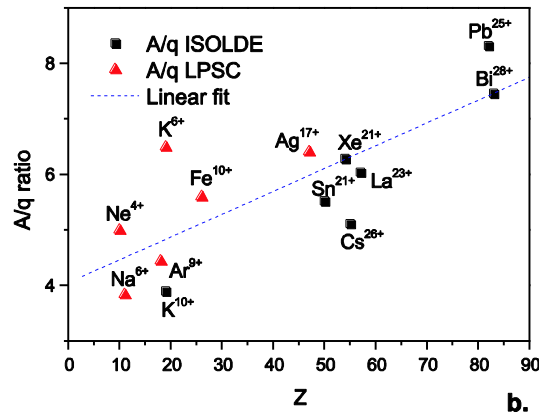
- Performances obtained so far

Efficiency



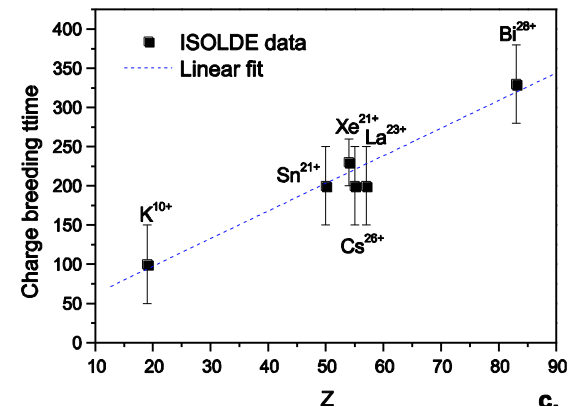
6%

Charge state



$A/q=132/21 \sim 6.3$

Confinement time



<200ms
No losses

Beam emittance: $\epsilon_{\text{phys}} \sim 10\pi \cdot \text{mm} \cdot \text{mrad}$ at $19.5 \cdot q$ keV

$\epsilon_{\text{norm}} = \beta\gamma * \epsilon_{\text{phys}} \sim 2.5 \cdot 10^{-2} \pi \cdot \text{mm} \cdot \text{mrad}$

Stable beam background $\sim <nA \ll \mu A$

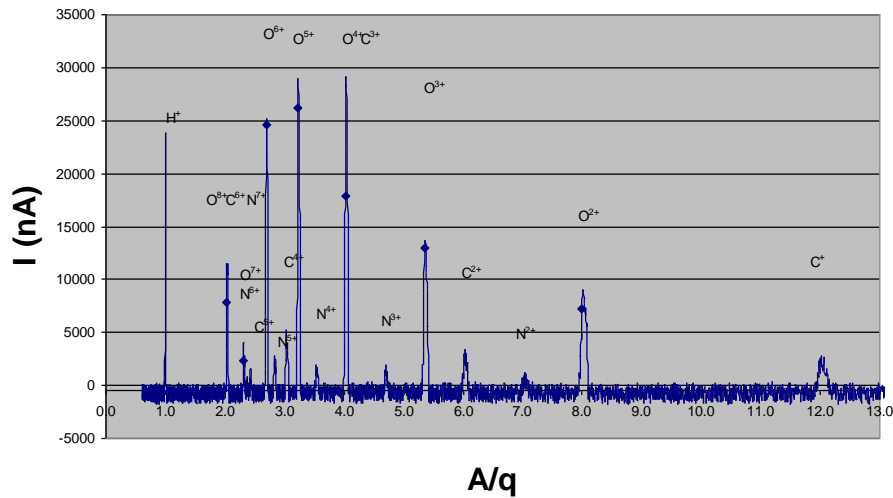


Residual gas spectrum

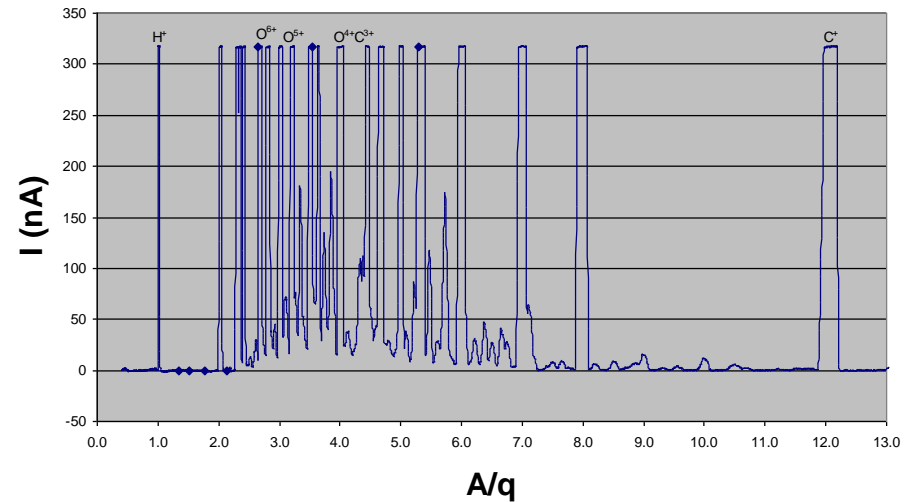
Entrance of the ECR $P=5.10^{-7}$ mbar

Exit $P=2.10^{-7}$ mbar

Mass Scan



Mass Scan



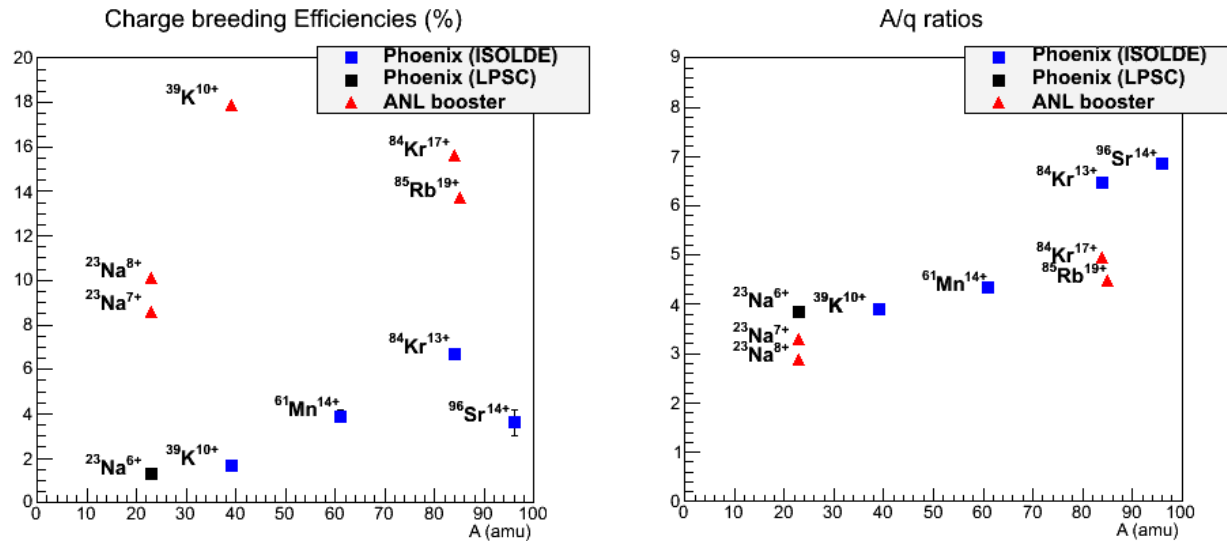
C,N,O + metallic elements from stainless steel
... Many stable components of the plasma

Background >5 nA $2 < A/q < 7$

News from other facilities

ECRIS charge breeding

- World record efficiencies from the ANL charge breeder



- Beam purity issues observed at TRIUMF with the Phoenix charge breeder
 - Beam purity will be an issue with a superconducting LINAC
 - Using Al coating and Al pieces \rightarrow decreasing the stable contamination to the pA level

Charge breeding for EURISOL

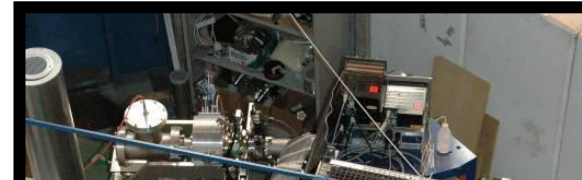


P. Delahaye, 18th of October 2012, Lisbon

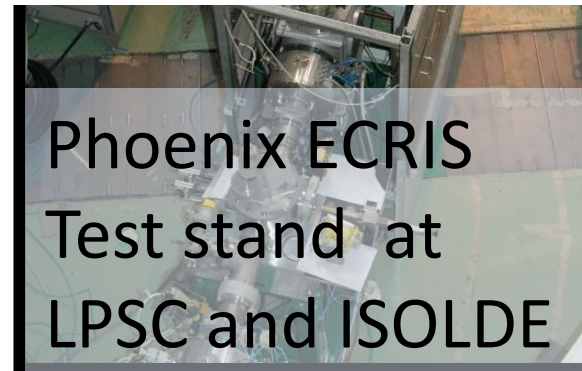
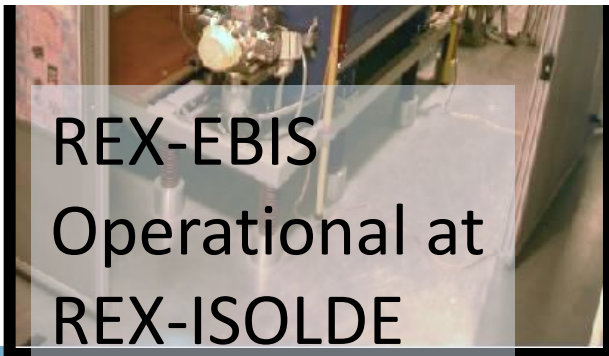
Conclusions of FP6



$^{136}\text{Sn} \sim 10^5$ ions/s
EBIS best suited
-Higher charge states
-Higher purity



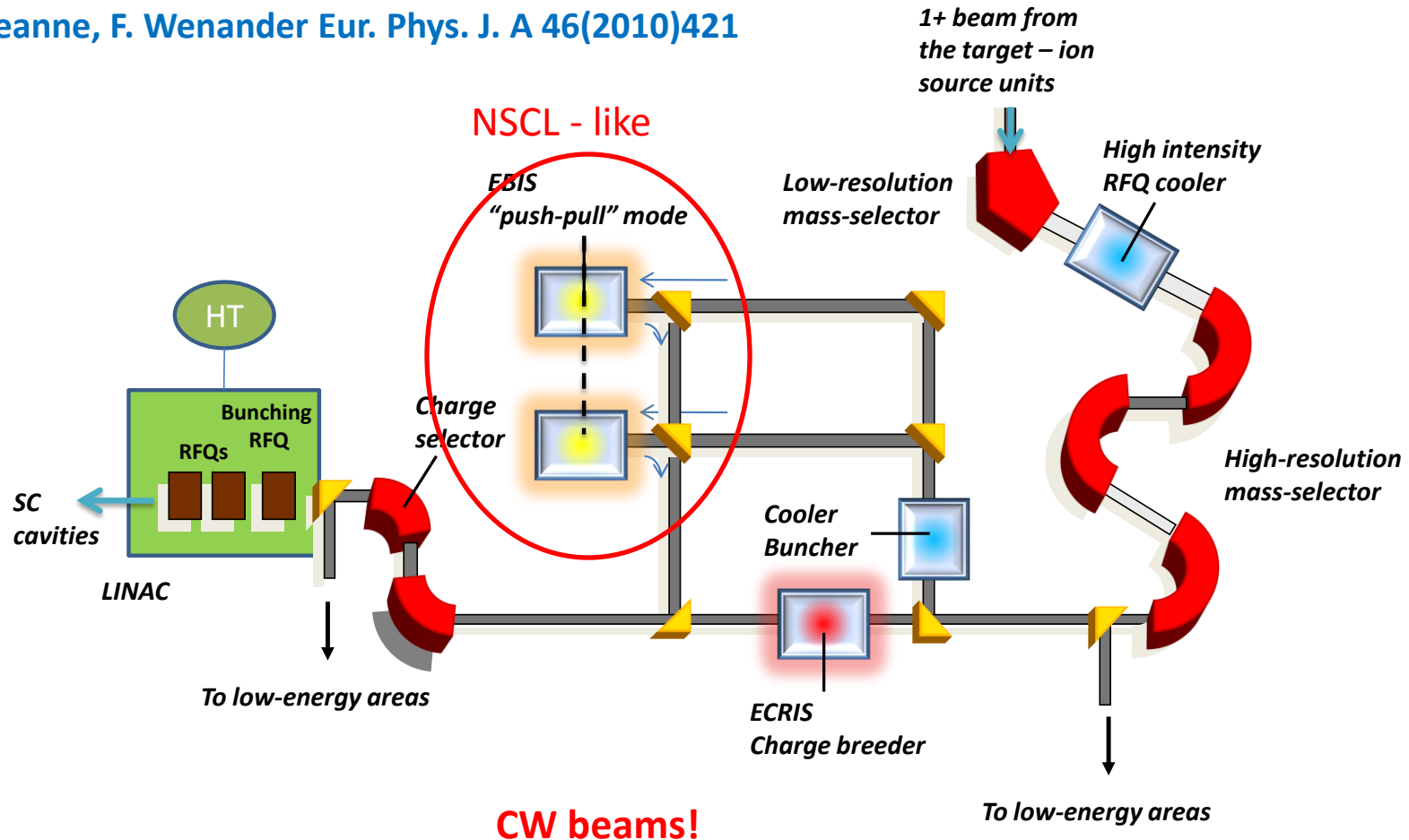
$^{132}\text{Sn} > 10^{13}$ ions/s
ECRIS best suited:
• Not space charge limited
• CW device



Efficiency 1-20% depending on Z

What was proposed for EURISOL

P. Delahaye, O. Kester, C. Barton, T. Lamy, M. Marie-Jeanne, F. Wenander Eur. Phys. J. A 46(2010)421



Detail of the EURISOL Layout

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

EMILIE project



P. Delahaye, 18th of October 2012, Lisbon



EMILIE in a nutshell



- Improving on EBIS/T and ECRIS charge breeding methods!
 - EBIS quite convenient for upcoming facilities if it was providing **continuous beams!**
 - Design and test of an EBIS debuncher
 - Efficiency, high charge states and **beam purity** improvement beneficial for ECRIS charge breeding at present and future facilities
 - Improvement of the Phoenix charge breeder
 - Restoring magnetic field symmetries, better injection optics for more efficient capture
 - Running two frequencies for higher charge states
 - Obtaining low residual gas pressure
 - **Simulating the 1+ beam capture in a plasma**

EBIS debuncher: motivations

Suggestion for EURISOL:

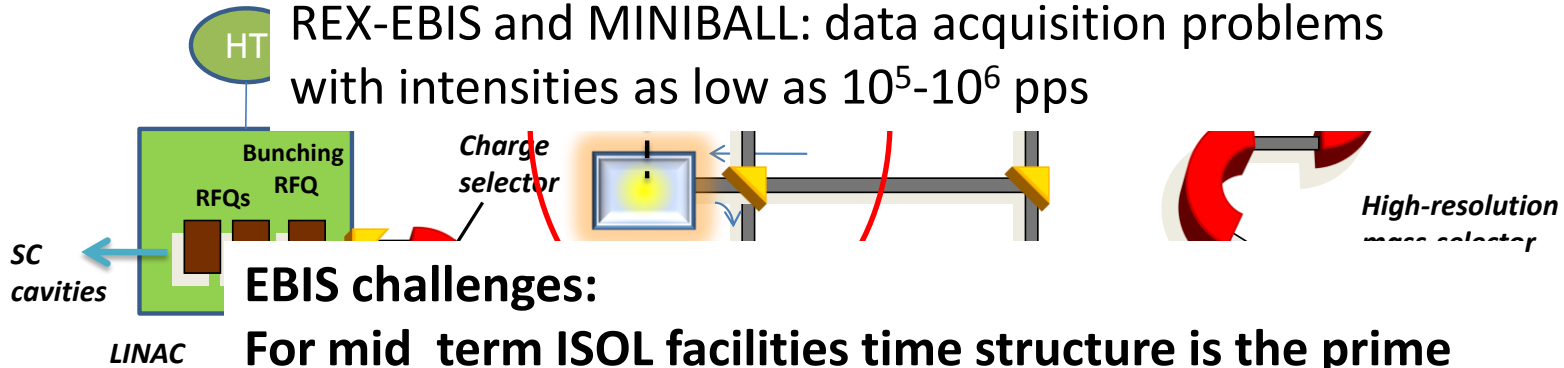
P. Delahaye, O. Kester, C. Barton, T. Lamy, M. Marie-Jeanne, F. We

1+ beam from the target – ion source units

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

To low-energy areas

ECRIS
Charge breeder

To low-energy areas

CW beams!

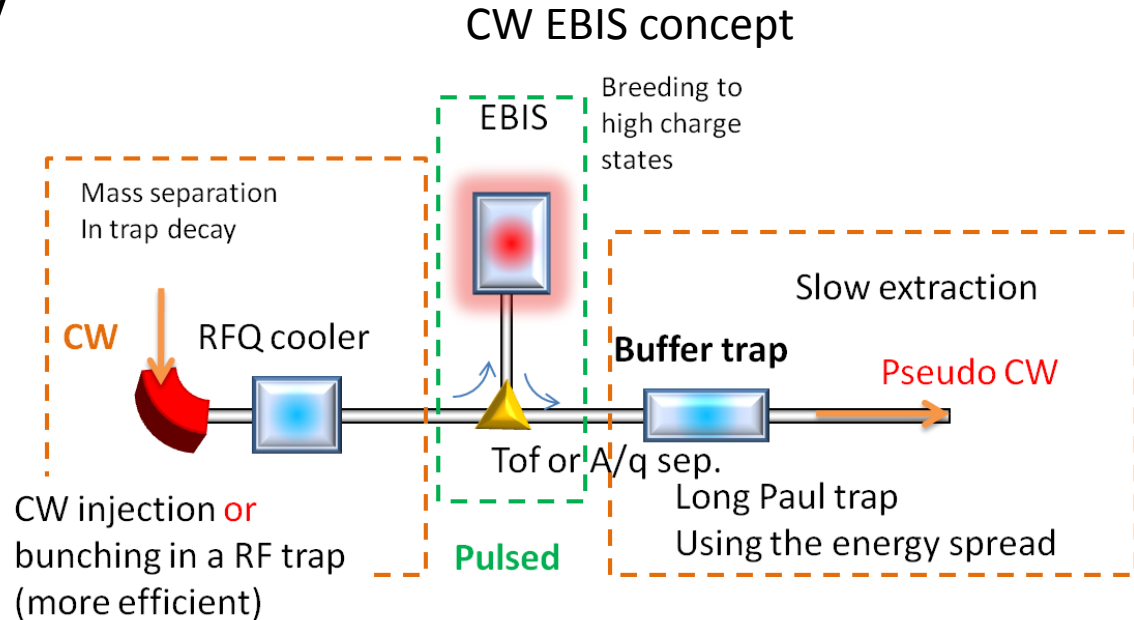
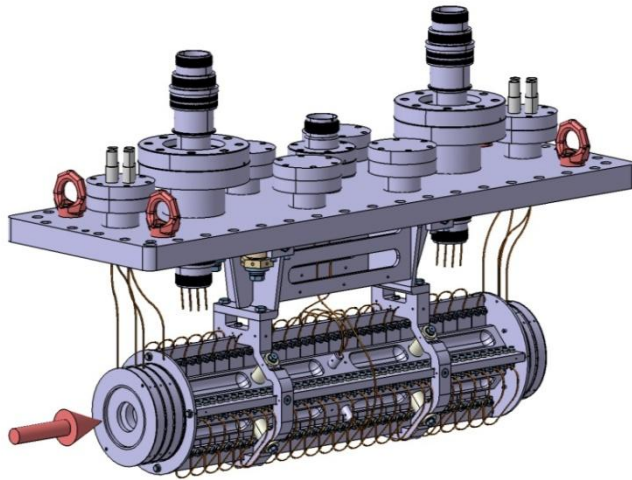
Detail of the EURISOL Layout

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



A Paul trap as debuncher

- Linear RFQ under UHV



- RF for radial confinement (400V, 2MHz)
- DC potentials on the segments for longitudinal space phase manipulation (a few 100V)
- UHV for avoiding charge exchange

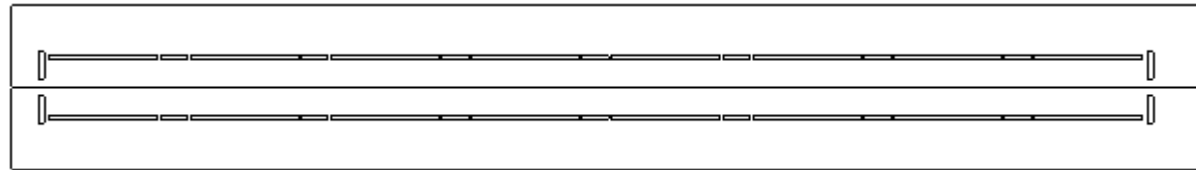
Buffer trap configuration

Segmented trap in UHV

Entrance
electrode

No buffer gas, UHV design
DC for axial + RF for radial trapping

Exit
electrode



Injection
from EBIS

Pulsed N⁺ beams
Width = 30-40 μ s

Example for ¹³²Sn
T = 180 ms
 $\Delta E = 10 * q$ eV?
Q = +33

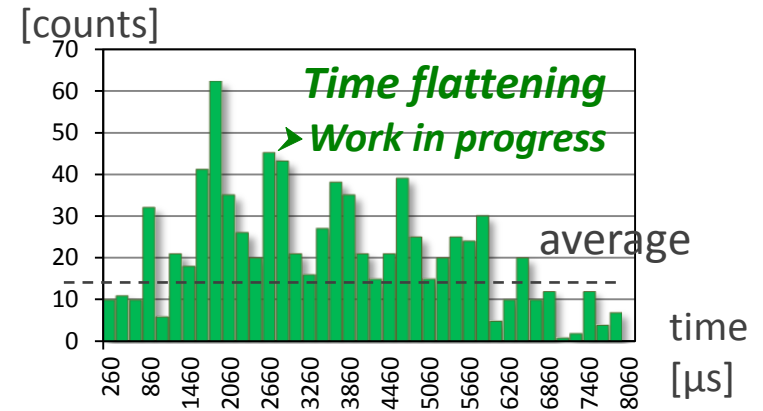
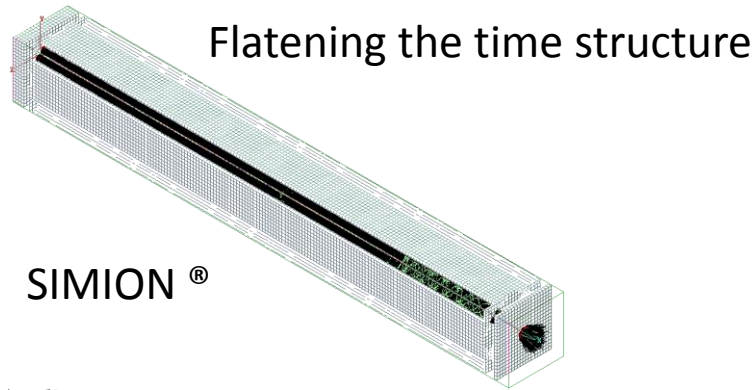
CW
beam

- CW beams using
 - 1) Injection in a long trapping area (flight time = injection pulse duration)
 - 2) Segmentation for forming bunches by raising barrier potentials
 - 3) E-spread for slow extraction of the bunches from the buffer trap one after the other

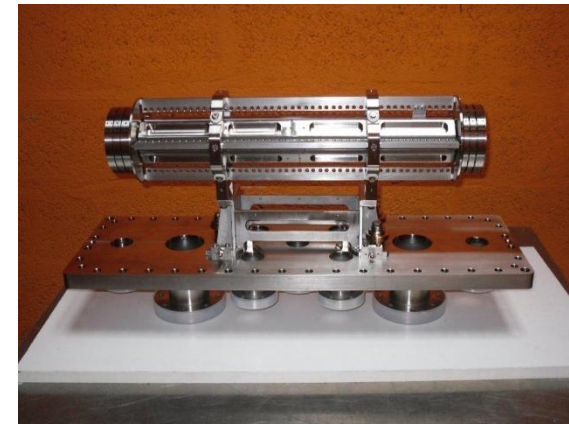
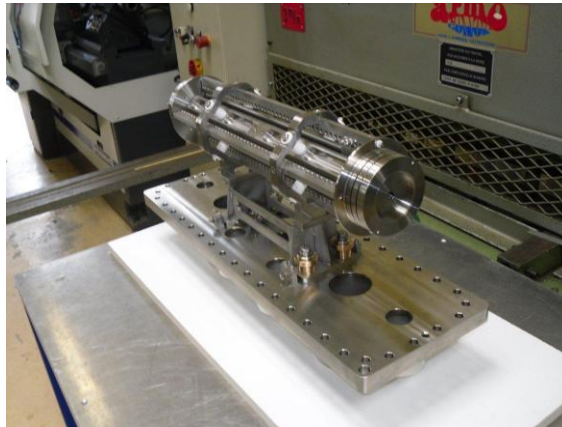
Segmentation allows for a lot of flexibility
One of the many DC programs to be investigated for a
“perfect CW”

Latest progresses

- Simulations - E. Traykov, GANIL



- Trap structure built by LPC Caen



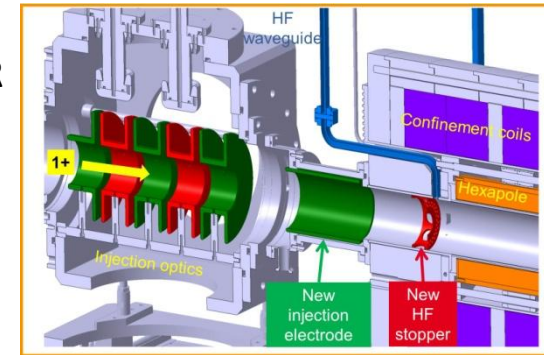
Gaining understanding on ECRIS charge breeding

- 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*

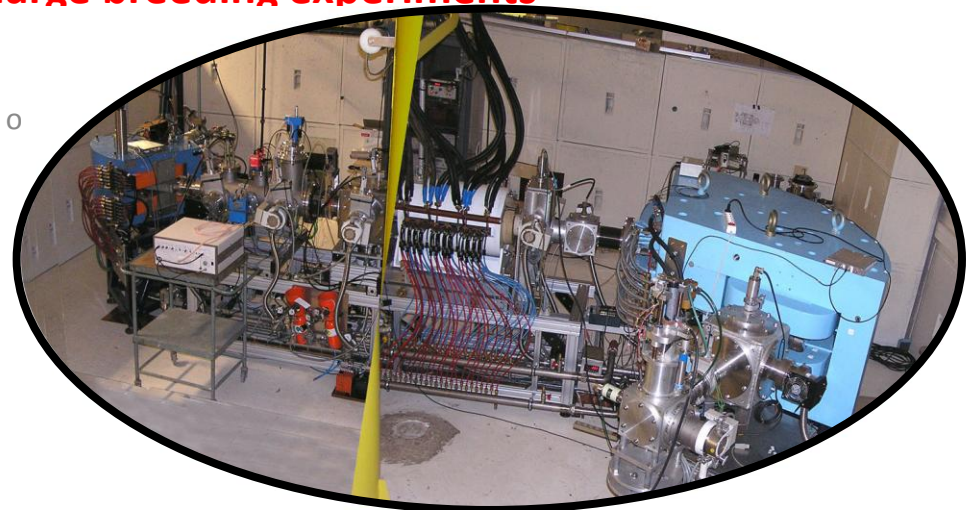


Unique test stand fully dedicated for ECR charge breeding experiments

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



LPSC - SPIRAL2 charge breeder



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**

Eurisol Topical and Town Meetings, Lisbon, 15th-19th October 2012



1+ Beam Capture:

- Influence OF the ECR plasma
- Low Mass Ions Injection
- Influence ON the ECR plasma

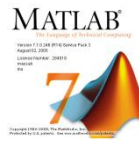


**INTEGRATE AN
EXISTING ECR PLASMA
SIMULATION TOOL
DEVELOPED @ LNS**



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

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



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

$$\begin{aligned} \dot{x} &= v_x \\ \dot{y} &= v_y \\ \dot{z} &= v_z \\ \dot{v}_x &= F(v) [(v_y B_z - v_z B_y) + (v_y B_{em_z} - v_z B_{em_y}) + E_{em_x} - \frac{1}{c^2} (E_{em_x} v_x + E_{em_y} v_y) v_x] \\ \dot{v}_y &= F(v) [(v_z B_x - v_x B_z) + (v_z B_{em_x} - v_x B_{em_z}) + E_{em_y} - \frac{1}{c^2} (E_{em_x} v_x + E_{em_y} v_y) v_y] \\ \dot{v}_z &= F(v) [-B_x v_y + v_x B_y - B_{em_x} v_y + v_x B_{em_y} - \frac{1}{c^2} (E_{em_x} v_x + E_{em_y} v_y) v_z] \end{aligned}$$

Magnetostatic field for the plasma confinement

Magnetic and electric fields associated with the pumping wave

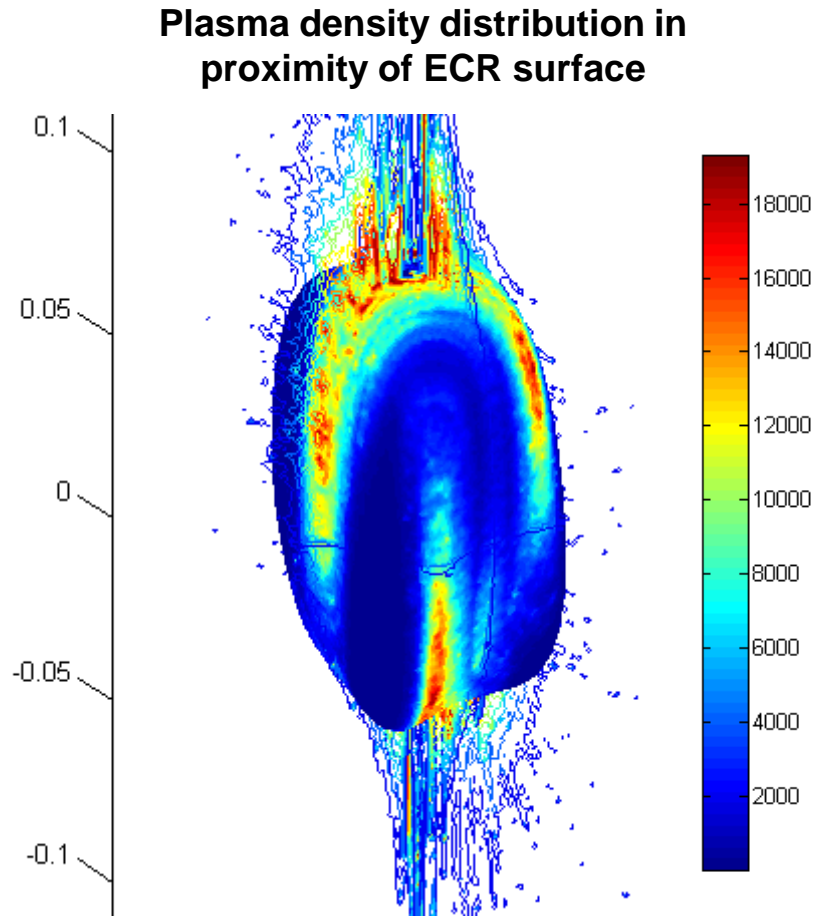
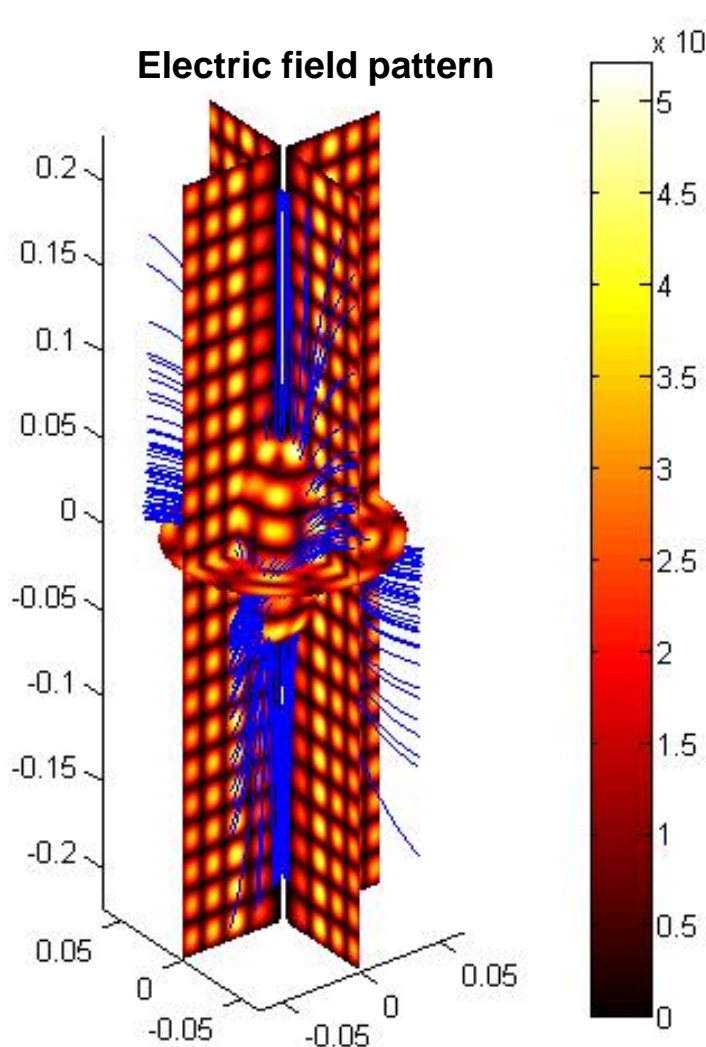
MATLAB solves the six first order ODEs by means of the “*ode45*” Runge-Kutta routine.

- 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?



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

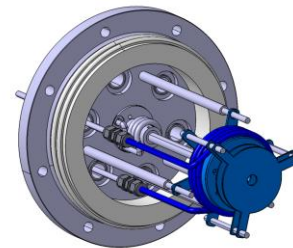
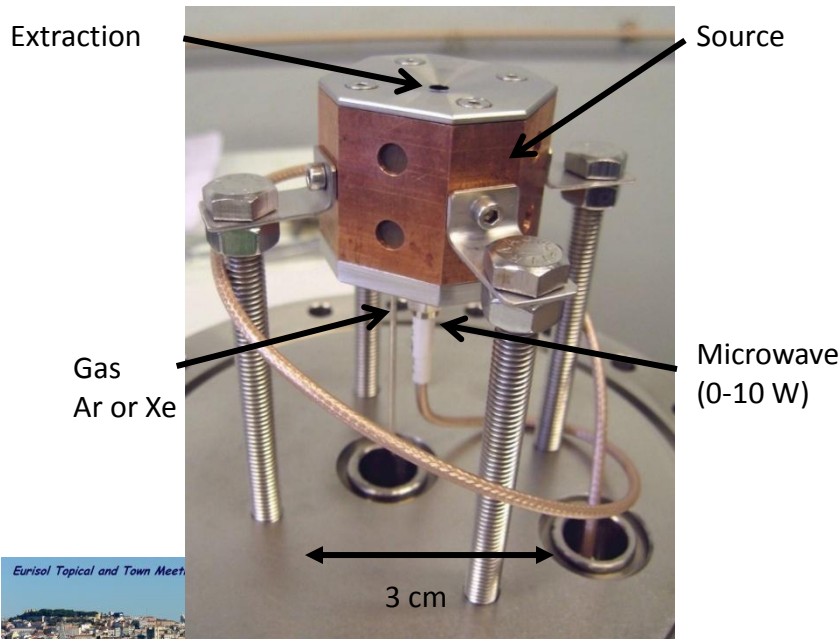
Purpose: to decrease this time in order to focus on the 1+/n+ process optimization itself

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)



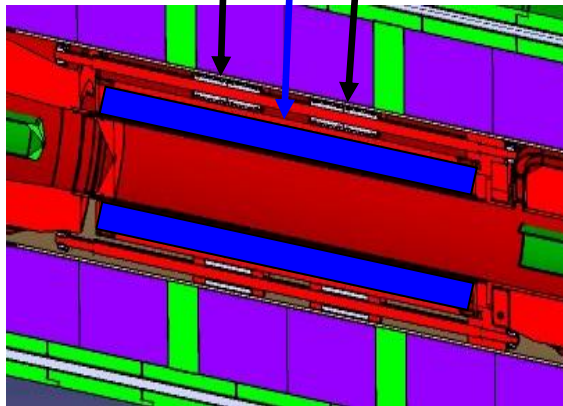
Thermal analysis under study (ANSYS)



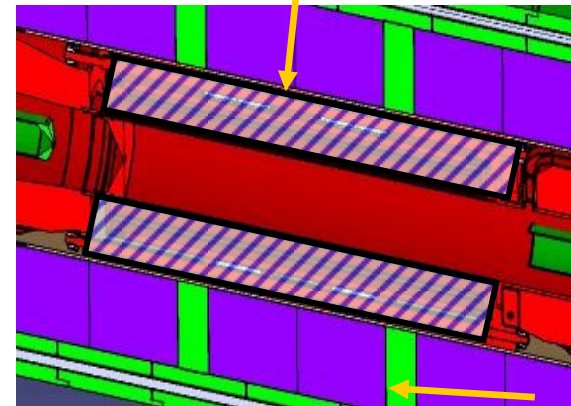
PHOENIX Booster magnetic field optimization

Hexapole change for optimum 18 GHz operation

Present hexapole
with two iron rings



Future higher diameter hexapole
without iron rings



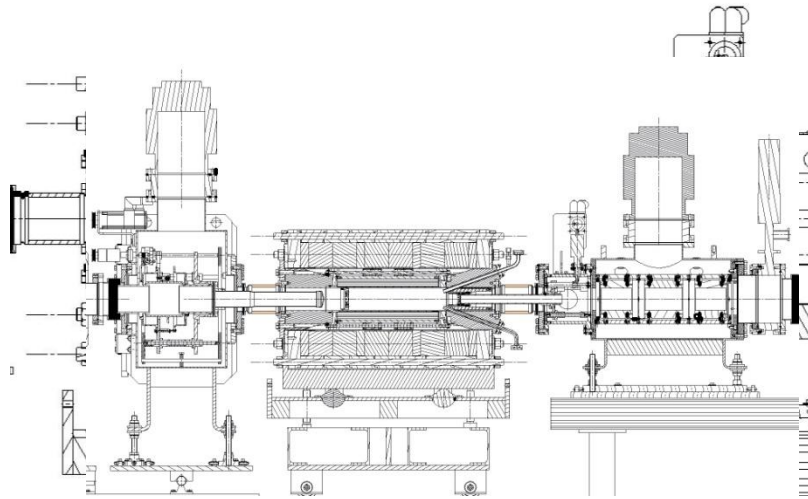
Higher magnetic field gradient and shorter Booster to be studied

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

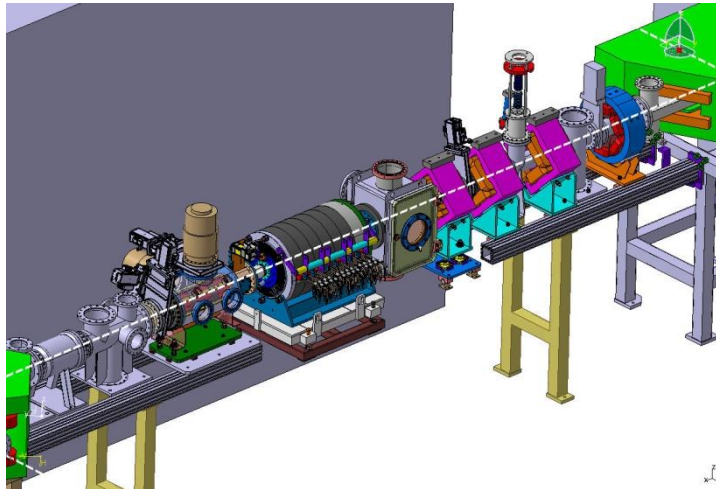
Higher charge states

Better plasma (i.e. ion beam) stability

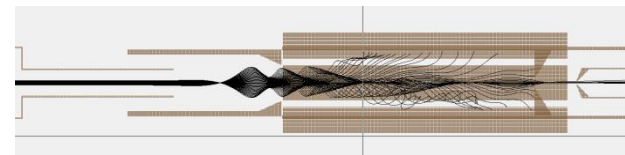
Phoenix charge breeder upgrade and installation at SPIRAL



Remote controlled injection tube
 Modified HF injection
 UHV design



Optimization towards
 light masses



SIMION[®] calculations ongoing

Latest tests at ANL: up to 9.6% Na⁸⁺ and 17.7% for K¹⁰⁺



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

Charge breeding techniques for ISOL facilities

- Started 1/1/2012
- Web site: <http://www.emilie-eurisol.eu/>
- Consortium agreement being finalised
- Logo found
- Activities summarized in the following!

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

Consortium of 9 europeans laboratories



CSNSM



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

Timeline

	2012	2013	2014	2015
EBIS debuncher (GANIL +LPC Caen +JYFL)				
Simulations				
Design and construction				
Tests at LPC Caen				
Tests at LIRAT with HCI				
Reporting				
ECR charge breeding				
Simulations INFN				
MW coupling studies				
1+ beam capture study				
New plasma chamber Phoenix				
Reporting				
Experimental work				
LPSC				
Hot ions sources (2.45 and 5.7GHz) and beam purity				
New magnetic field configuration Phoenix				
Experiments with new Phoenix (2RF heating,blind tuning)				
SPIRAL				
Phoenix charge breeder upgrade design				
Off-line assembly				
On line assembly				
On line tests (2 frequency heating, blind tuning...)				
JYFL				
2 Frequency heating tests with JYFL source				

Thanks a lot for your attention!
and thanks a lot to my friends and colleagues:



Additional material



27th of May 2012, Padova

