ECOS-EURISOL Joint Town Meeting
Institut de Physique Nucléaire, Orsay
October 28-31, 2014

Charge Breeding of Radioactive Beams for EURISOL: status of the EMILIE project

P. Delahaye, GANIL
For the EMILIE collaboration

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

The **EMILIE** project

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

Charge breeding techniques for ISOL facilities

Started 1/1/2012 → End 2015

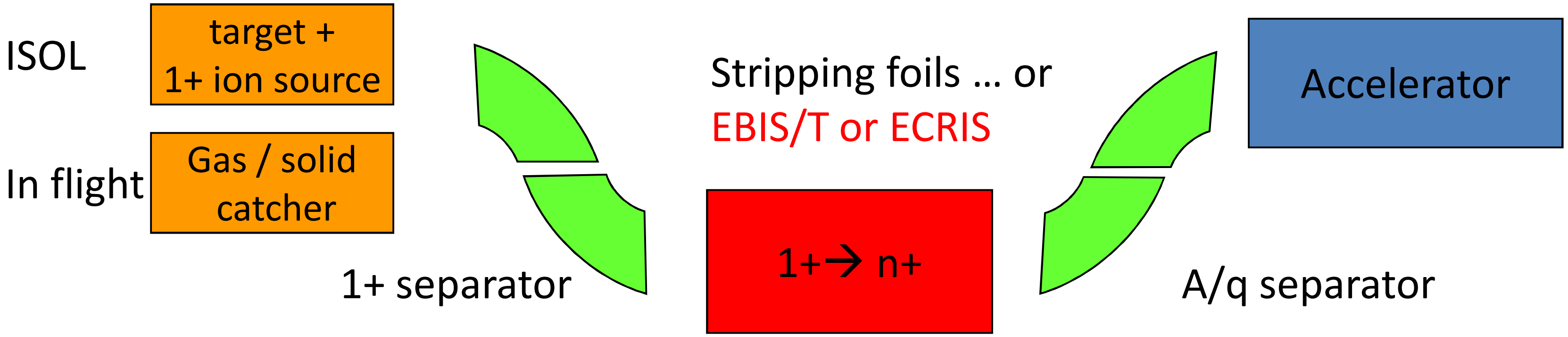
- Building an EBIS beam debuncher
- Testing and upgrading the Phoenix charge breeder

Consortium of 8 europeans laboratories

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

Charge breeding

A key-technology for facilities reaccelerating Radioactive Ion Beams



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

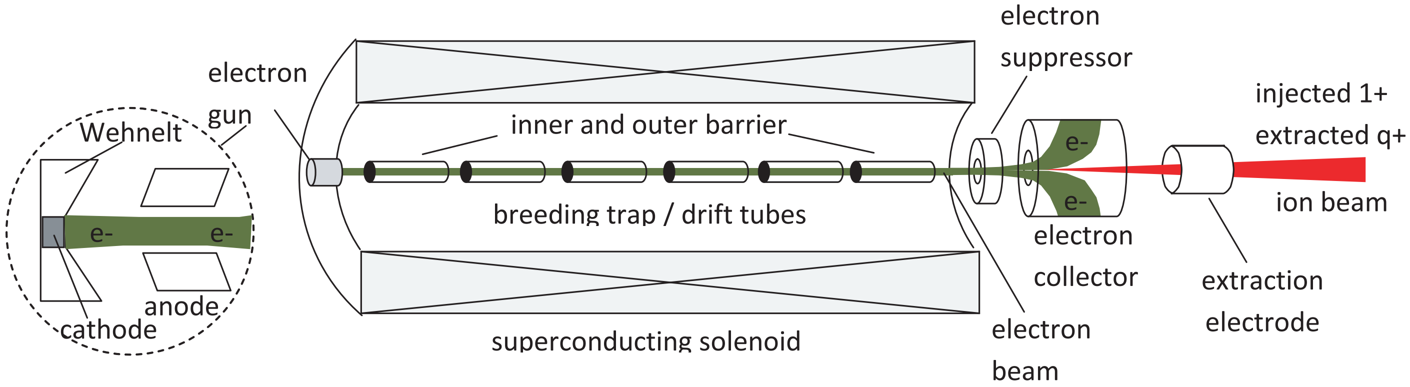
- higher charge states → **Higher energies**, Compact postaccelerator

- Pure beams
- High efficiency and rapidity

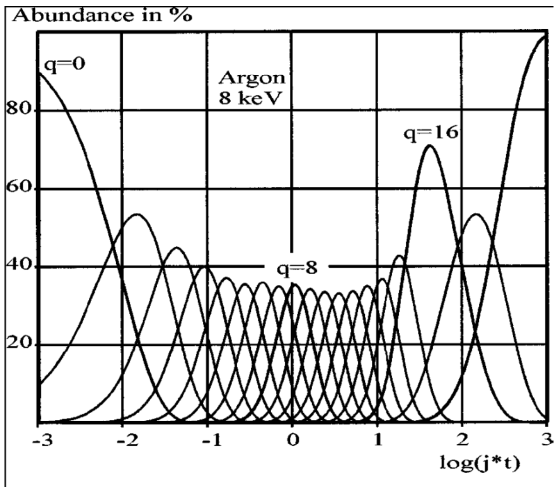
→ Making the most of the rare and exotic beams: **I<<pA and $T_{1/2}$<1s**

But also: **I~µA** EURISOL

EBIS/T 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

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

Trap capacity (elementary charges)

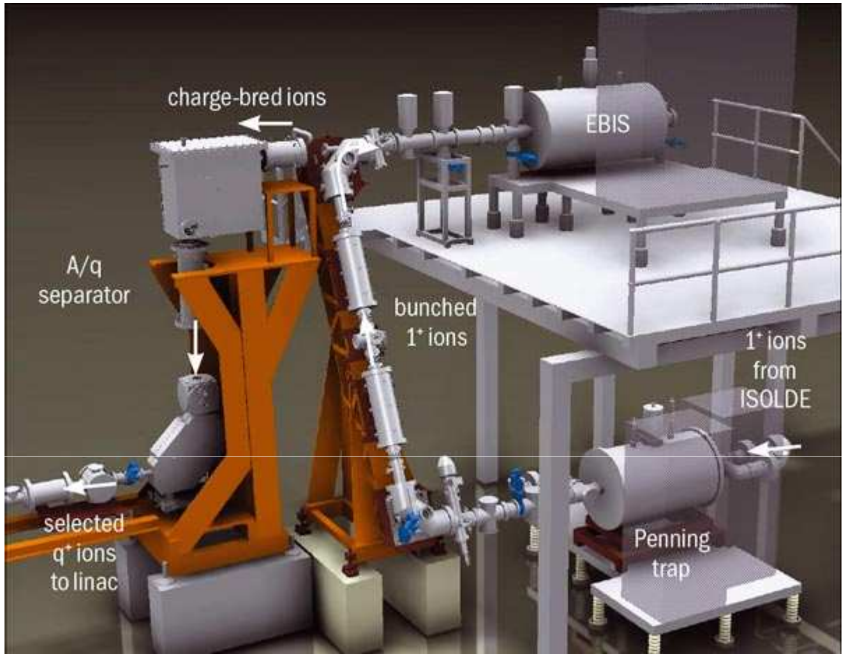
$Q=3.36\ 10^{11} L.I_e/E^{-1/2}$

Space charge limit ~10 ^{10} ion/s

Essentially a pulsed device

The REX-EBIS setup

The LaB_6 cathode



EBIS specifications

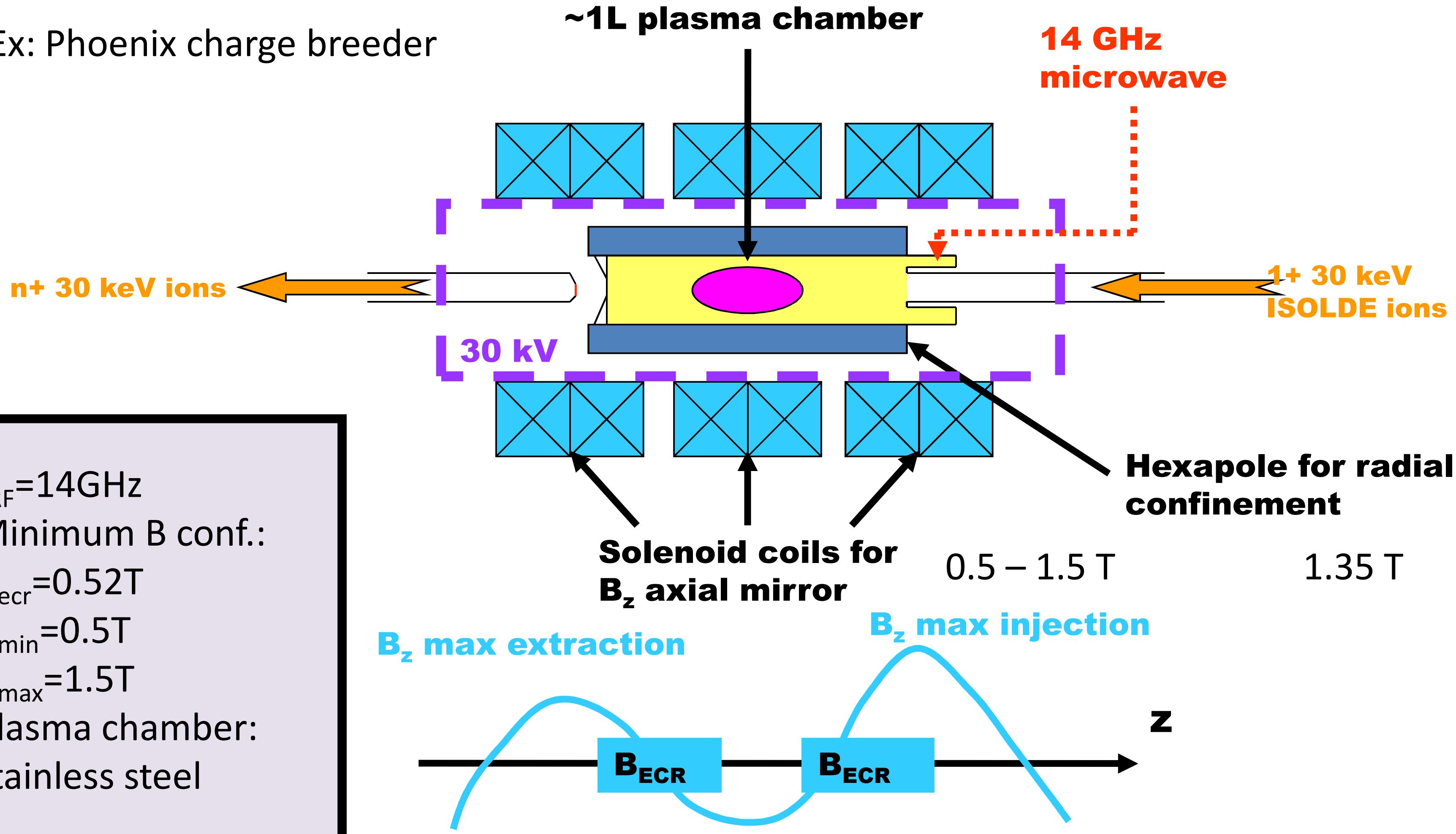
- LaB6 cathode
- $j_{cathode}$<20A/cm2
- $j_e=j_{trap}<200A/cm^2$
- Ie=460mA (normal operation 200mA)
- E=3.5-6keV
- 3 drift tubesL=200 to 800 mm
- Theoretical capacity $5\cdot10^{10}$ positive charges
- Ultra-high vacuum 10^{-10} - 10^{-11} mbar

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

ECRIS charge breeder principle

Ex: Phoenix charge breeder



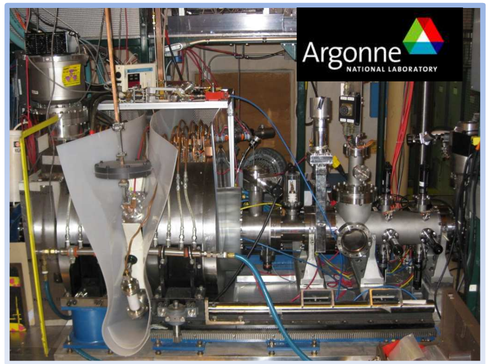
f_{RF}=14GHz
Minimum B conf.:
B_{ecr}=0.52T
B_{min}=0.5T
B_{max}=1.5T
Plasma chamber:
stainless steel

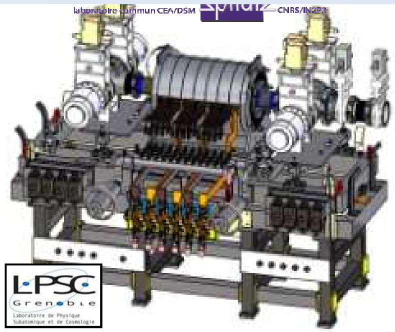
Performances: P. Delahaye et al., Rev. Sci. Instrum. 77, 03B105 (2006), P. Delahaye and M. Marie-Jeanne, NIM B 266 (2008) 4429

Essentially a CW device, but can be pulsed

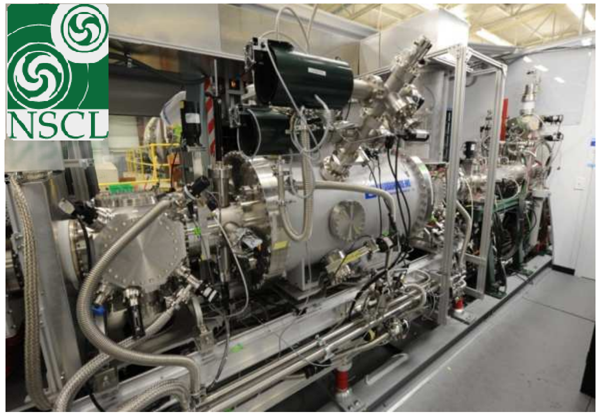
EBIS/T and ECRIS charge breeders

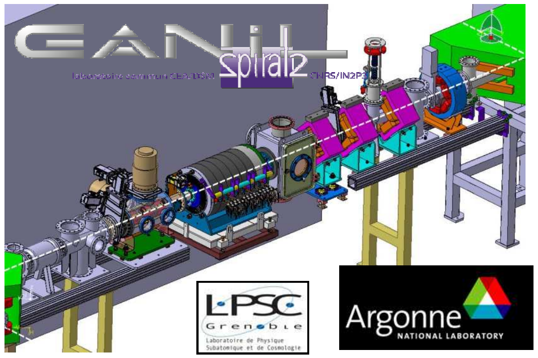
for radioactive ion beam facilities





LPSC - SPIRAL2 charge breeder



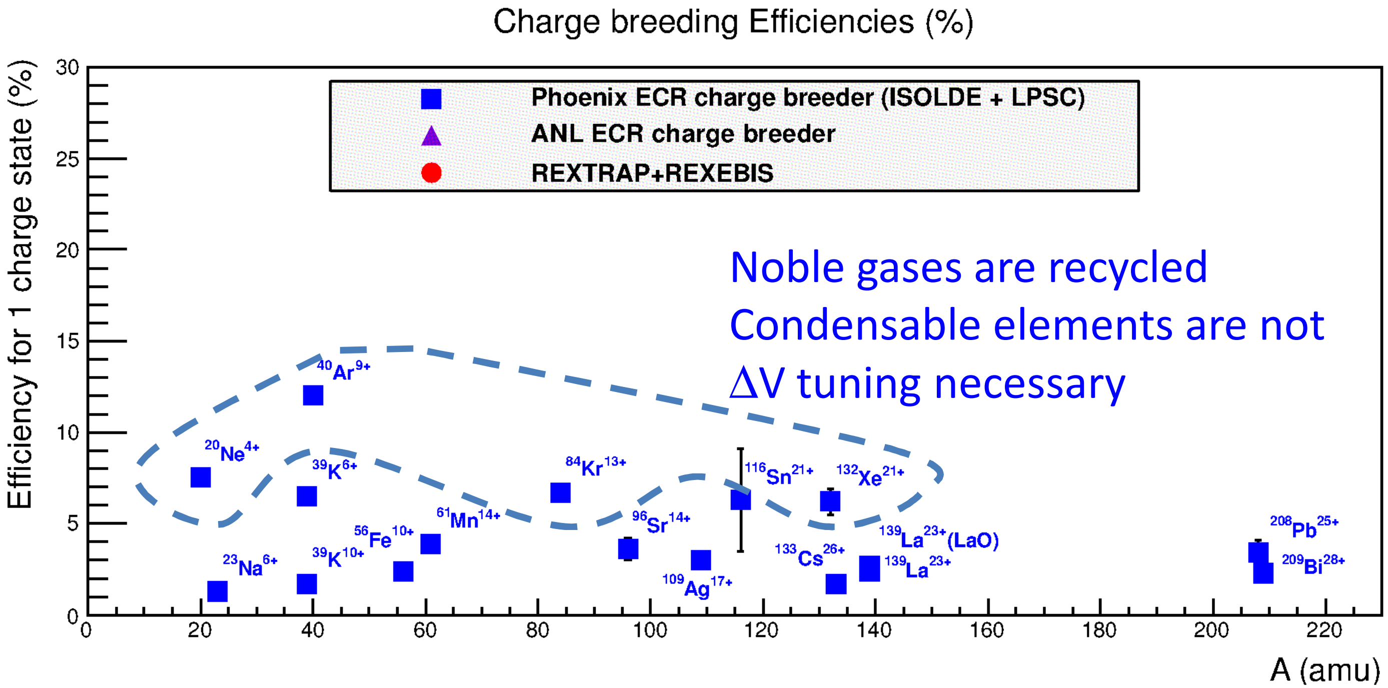


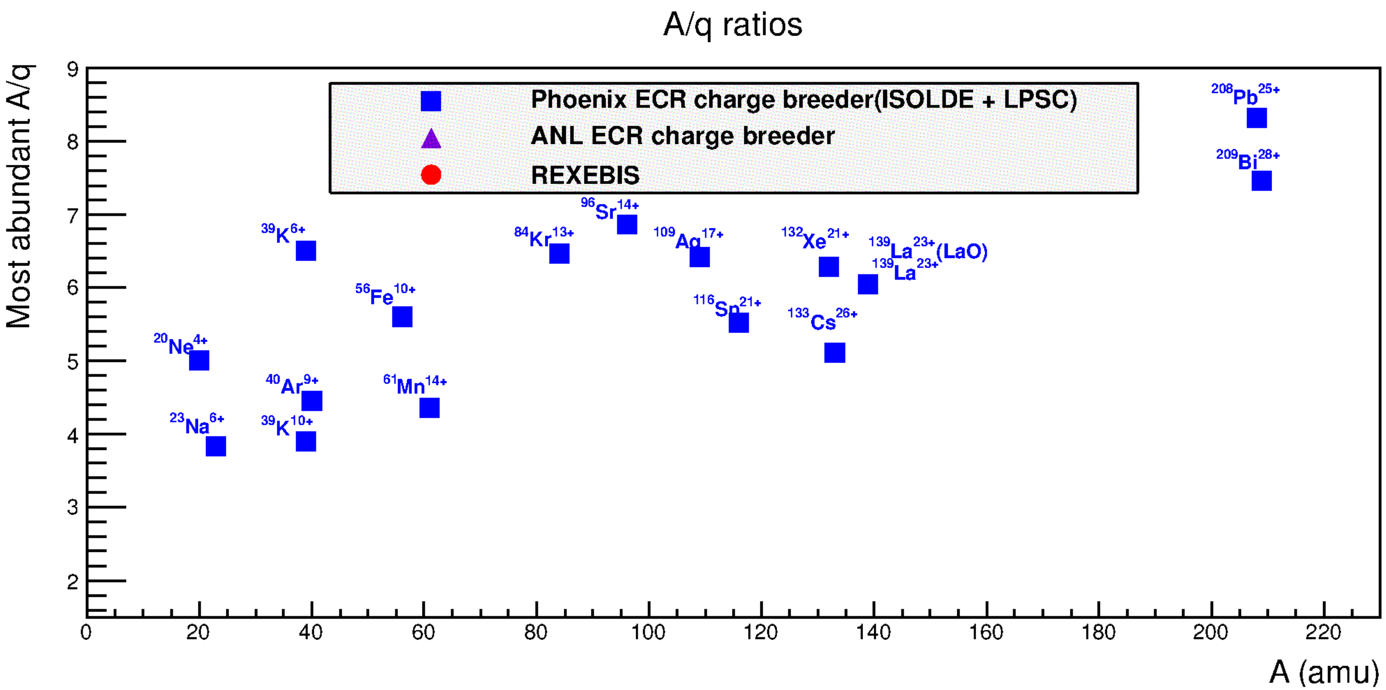
Charge state breeding performances

- EBIS
  - REXEBIS
- ECRIS
  - PHOENIX (ISOLDE + LPSC)
  - ANL Charge breeder

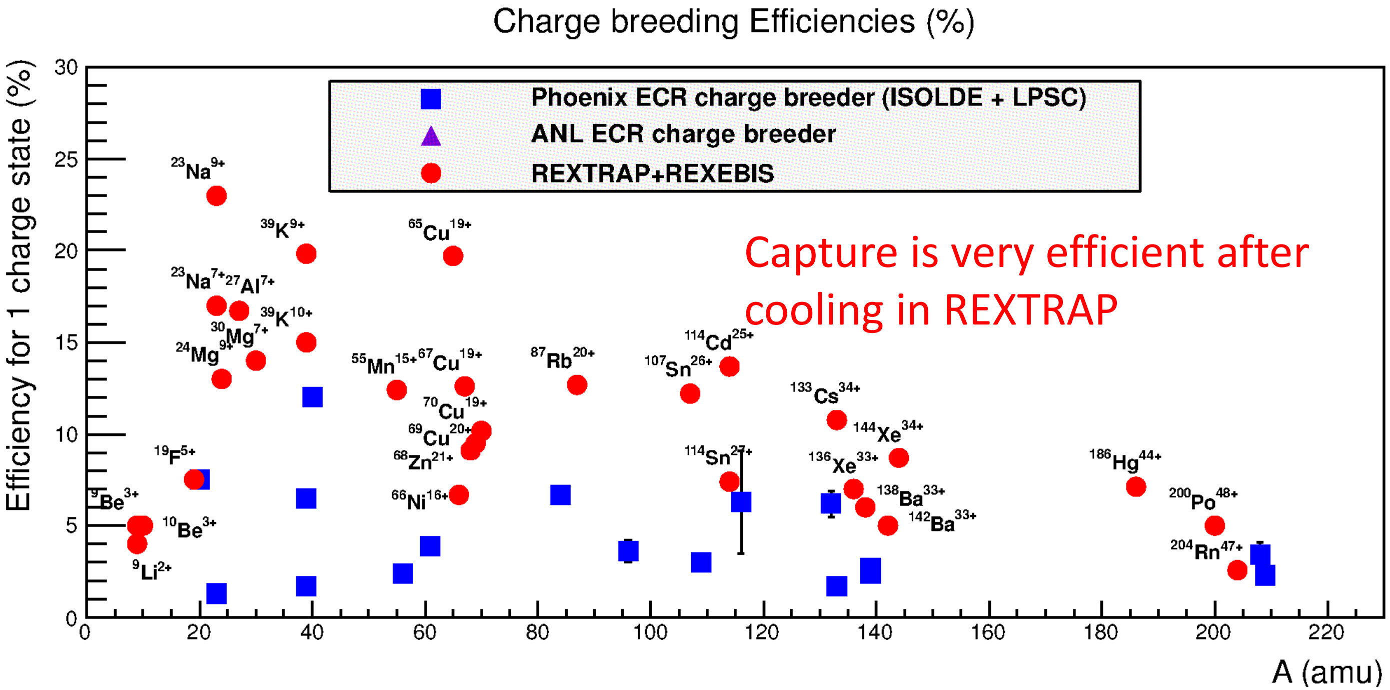
Efficiencies
Charge states (A/q ratios)
Charge state breeding time

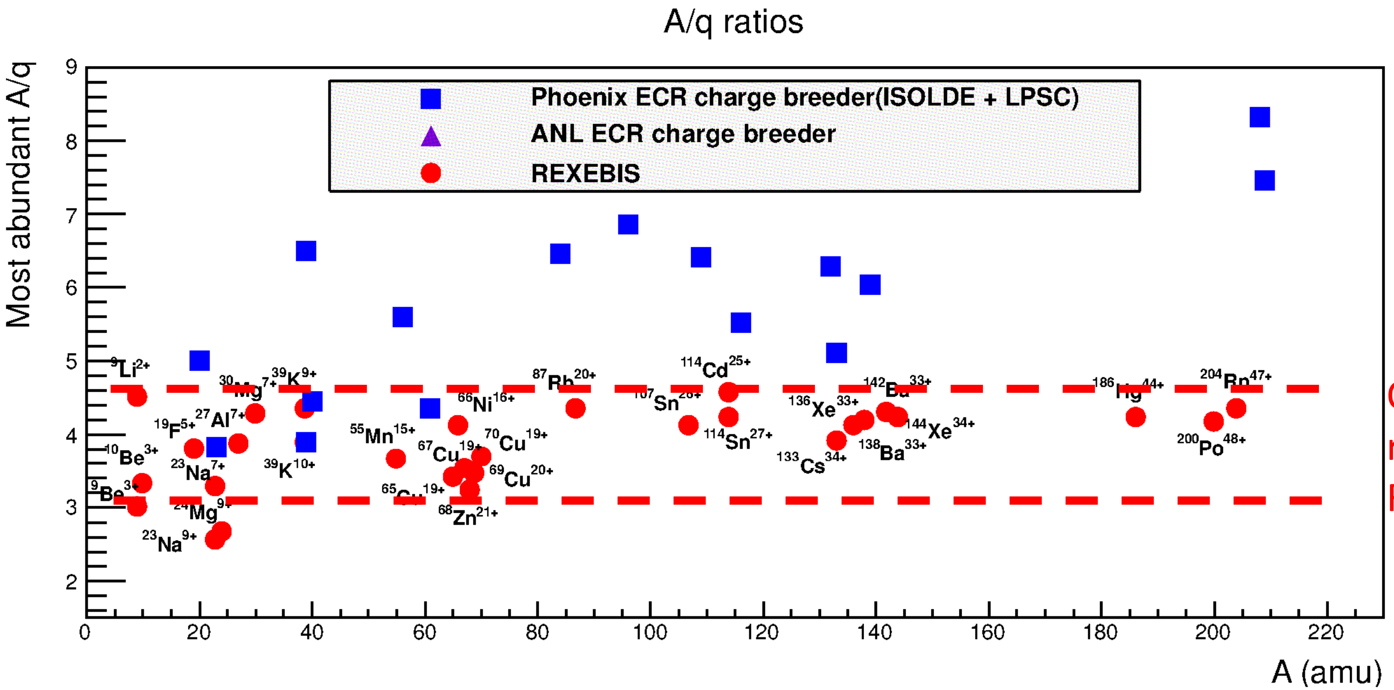
Phoenix ECRIS





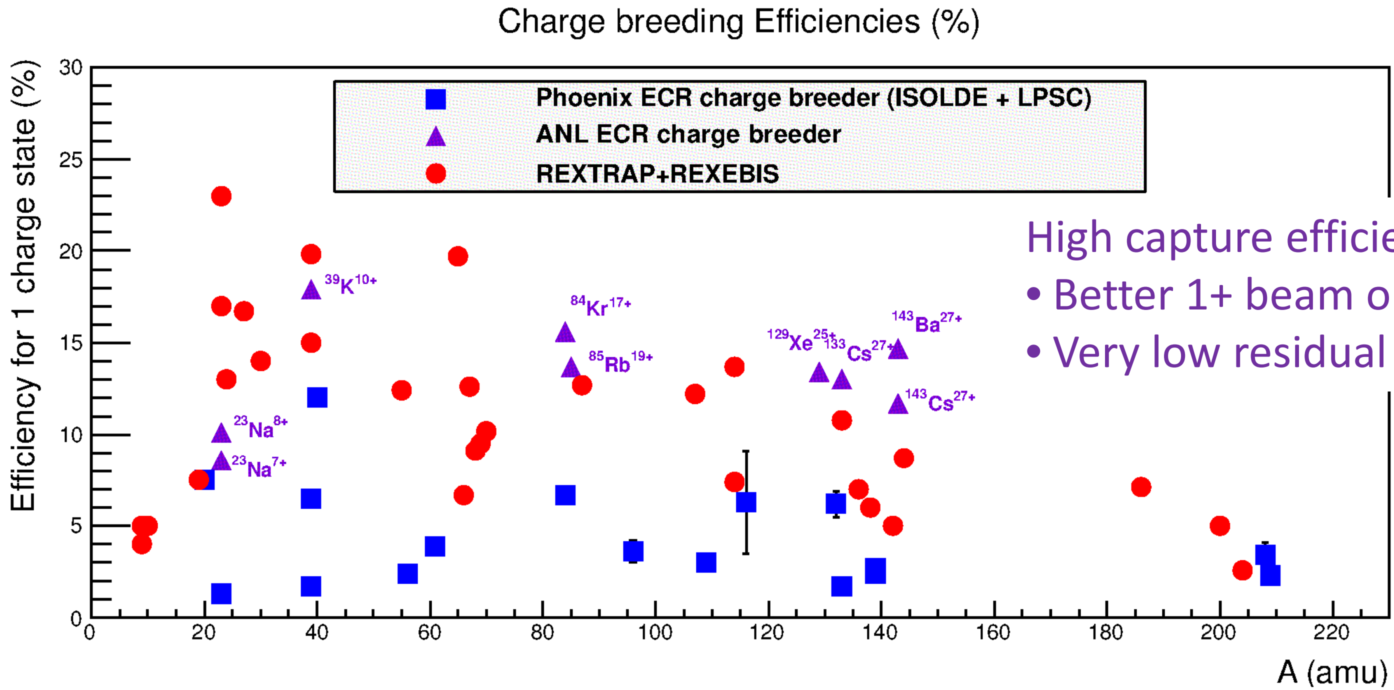
REXTRAP - REXEBIS



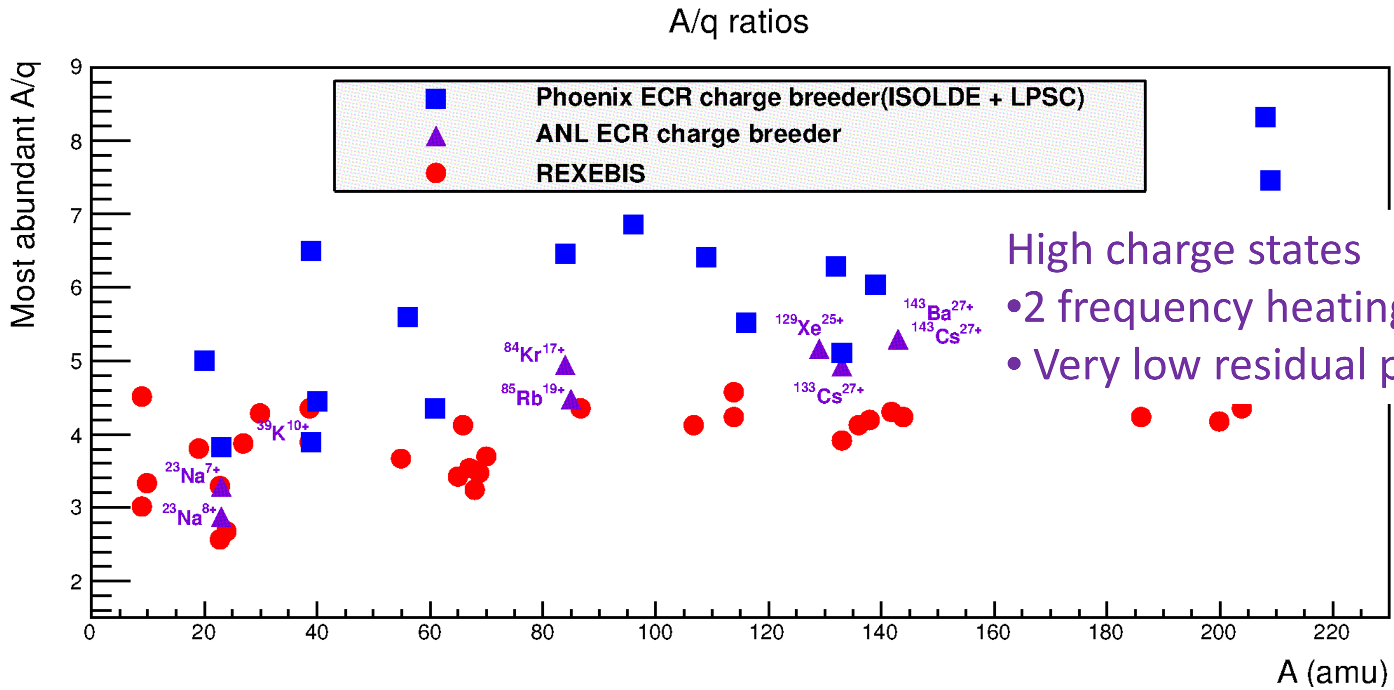


Operating range REX-ISOLDE

ANL ECRIS



High capture efficiency
- Better 1+ beam optics
- Very low residual pressure

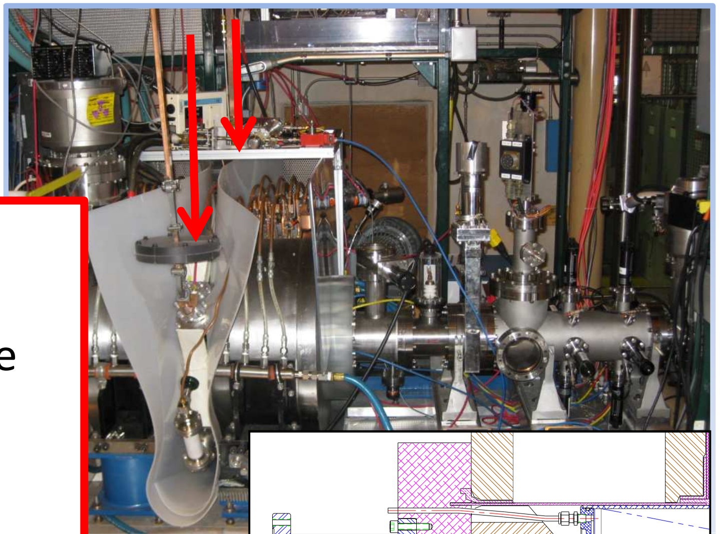


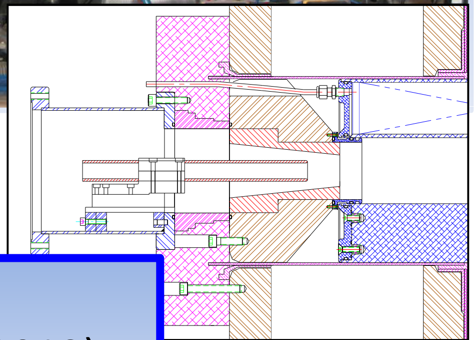
High charge states
- 2 frequency heating
- Very low residual pressure

ANL ECRIS charge breeder

See talk R. C. Pardo

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

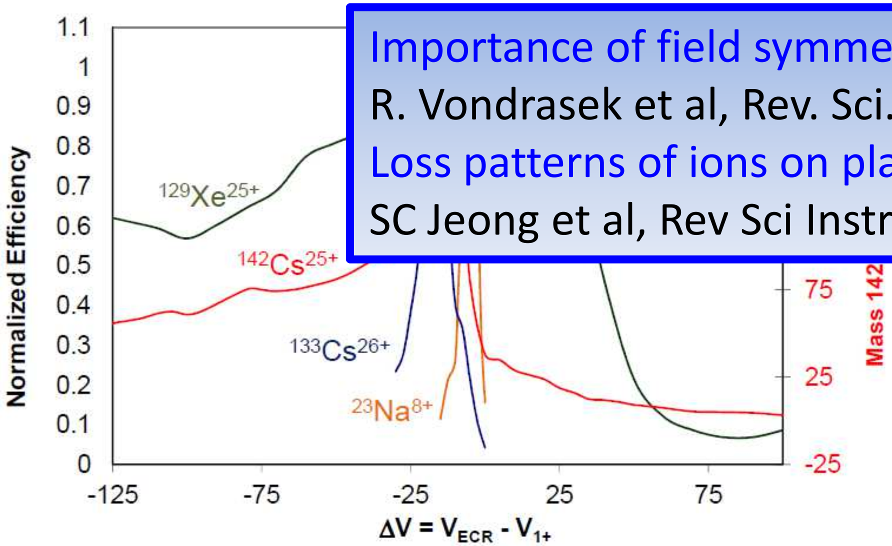




nded tube
with 2.5 cm of travel
- 50 kV high voltage

What is so different?

- Field symmetries
- Tunable grounded tube
- Excellent vaccuum
- 2 Frequency heating
- Cold 1+ beams
- …?



Importance of field symmetry

R. Vondrasek et al, Rev. Sci. Instrum. 83, 113303 (2012)

Loss patterns of ions on plasma chamber and electrodes

SC Jeong et al, Rev Sci Instrum. 83, 02A910 (2012)

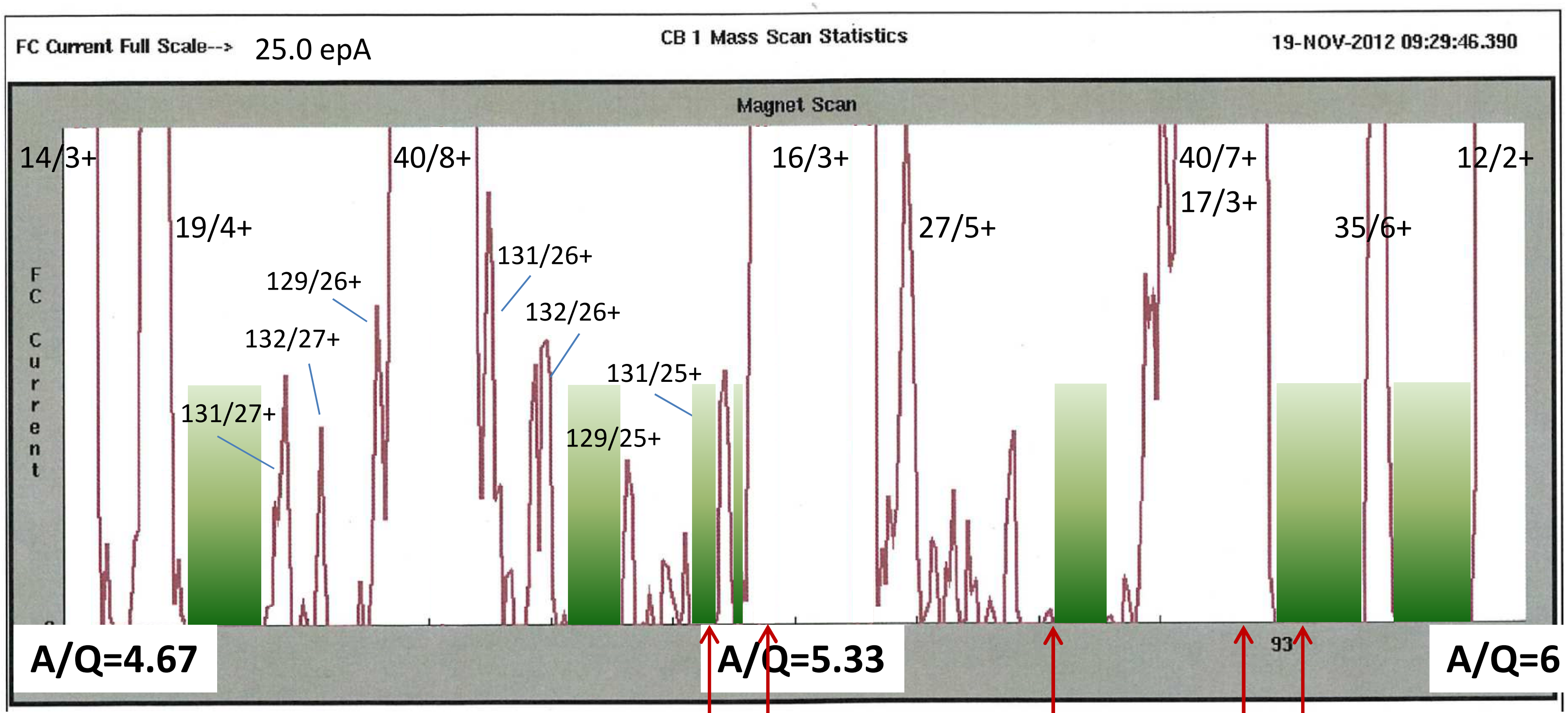
		ing condition
		1.16 T
B_{min}	0.31	0.27
B_{ext}	0.85	0.83
$B_{(radial)}$		0.86 T
Last closed surface		0.61 T

Beam purity issue

Courtesy R. Vondrasek

ANL mass spectrum

A/Q=4.67



141/27+
~1 kHz
background
rate in SBD

143/27+
330 kHz
background
rate in SBD

144/26+
10 kHz
background
rate in SBD

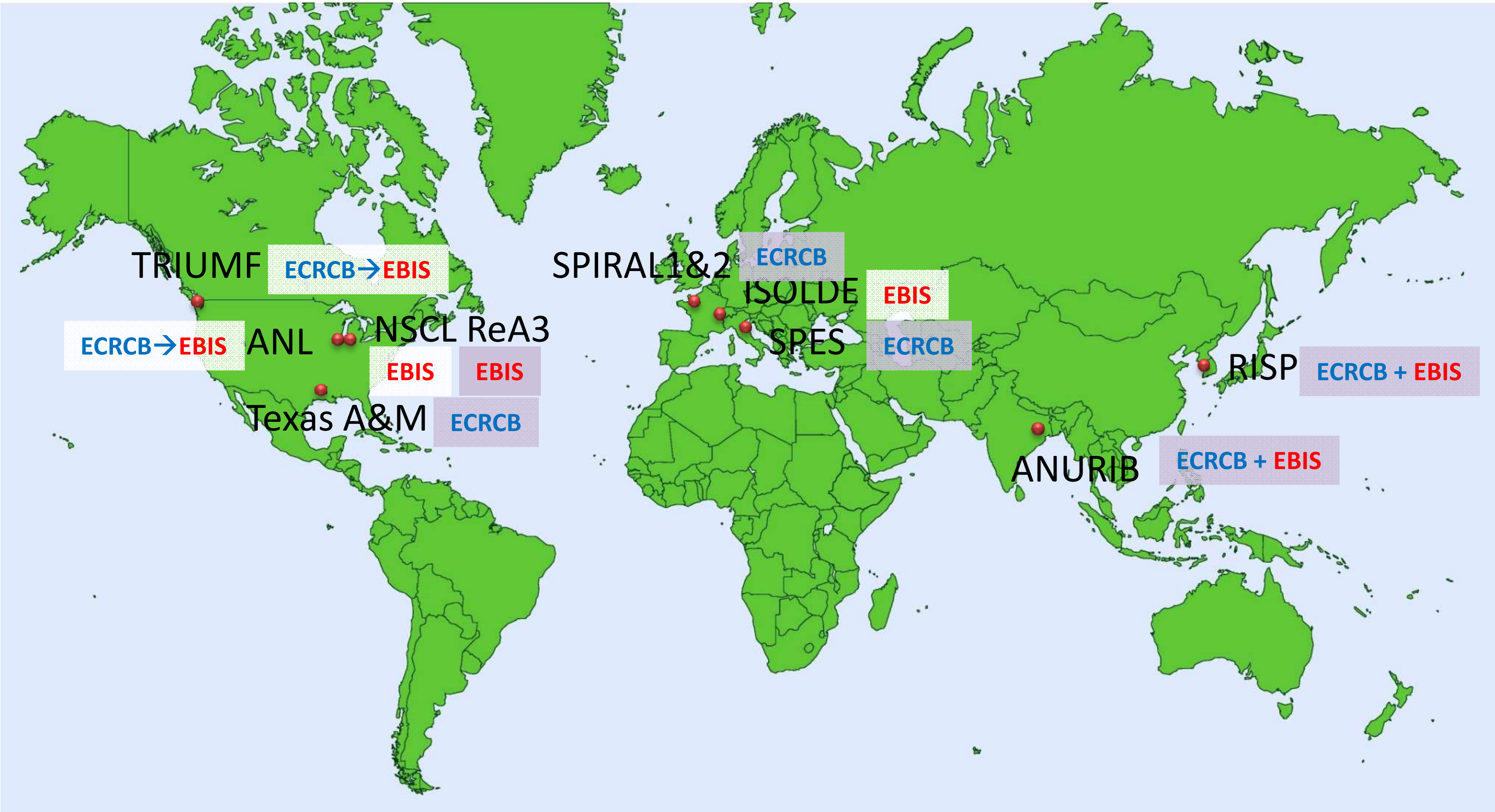
143/25+
66 kHz
background
rate in SBD

144/25+
900 Hz
background
rate in SBD

Background current <0 epA

SBD=Surface barrier detector

World status: 2014

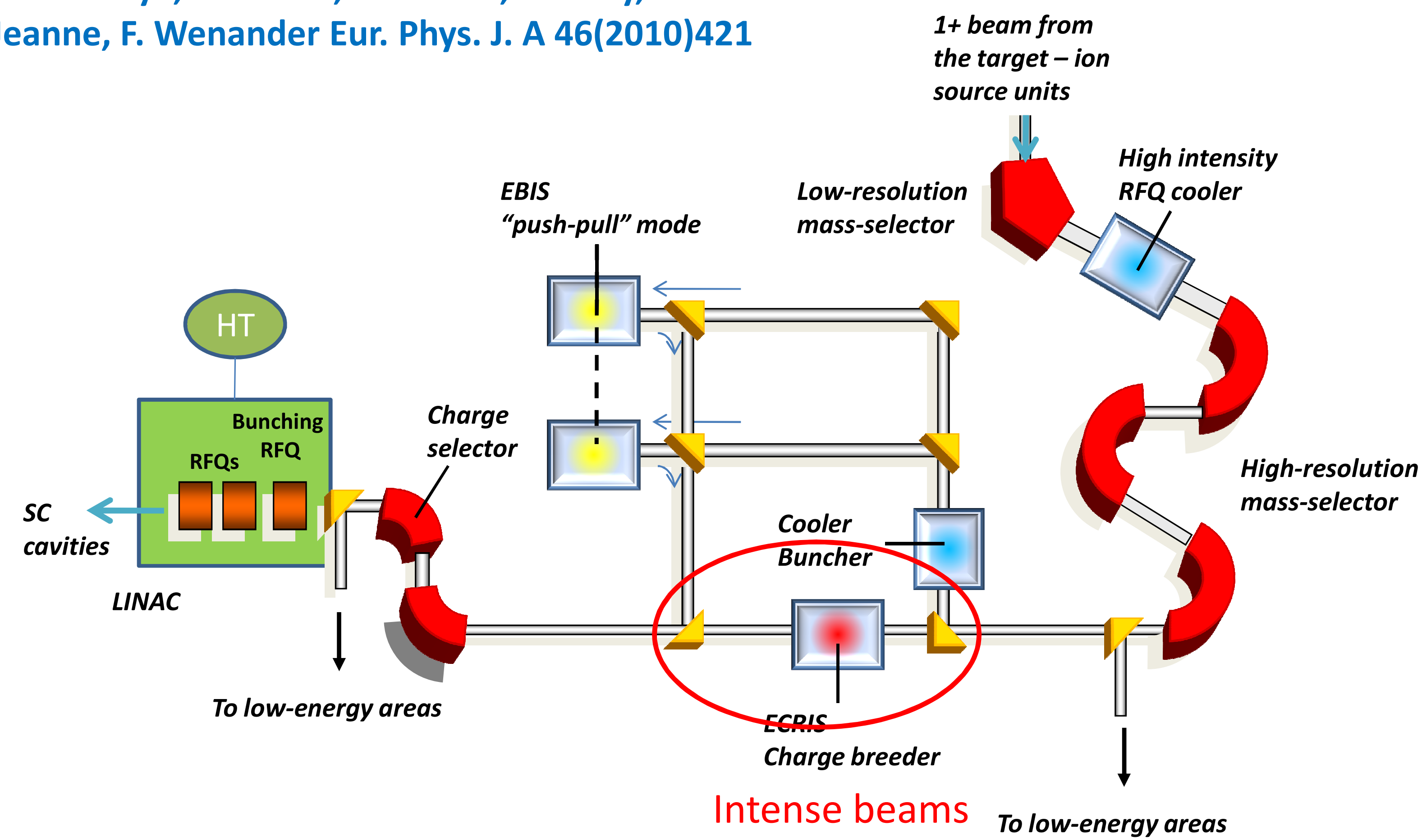


ECRCB In commissionning or planned

EBIS running

Following the suggestion made for EURISOL

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

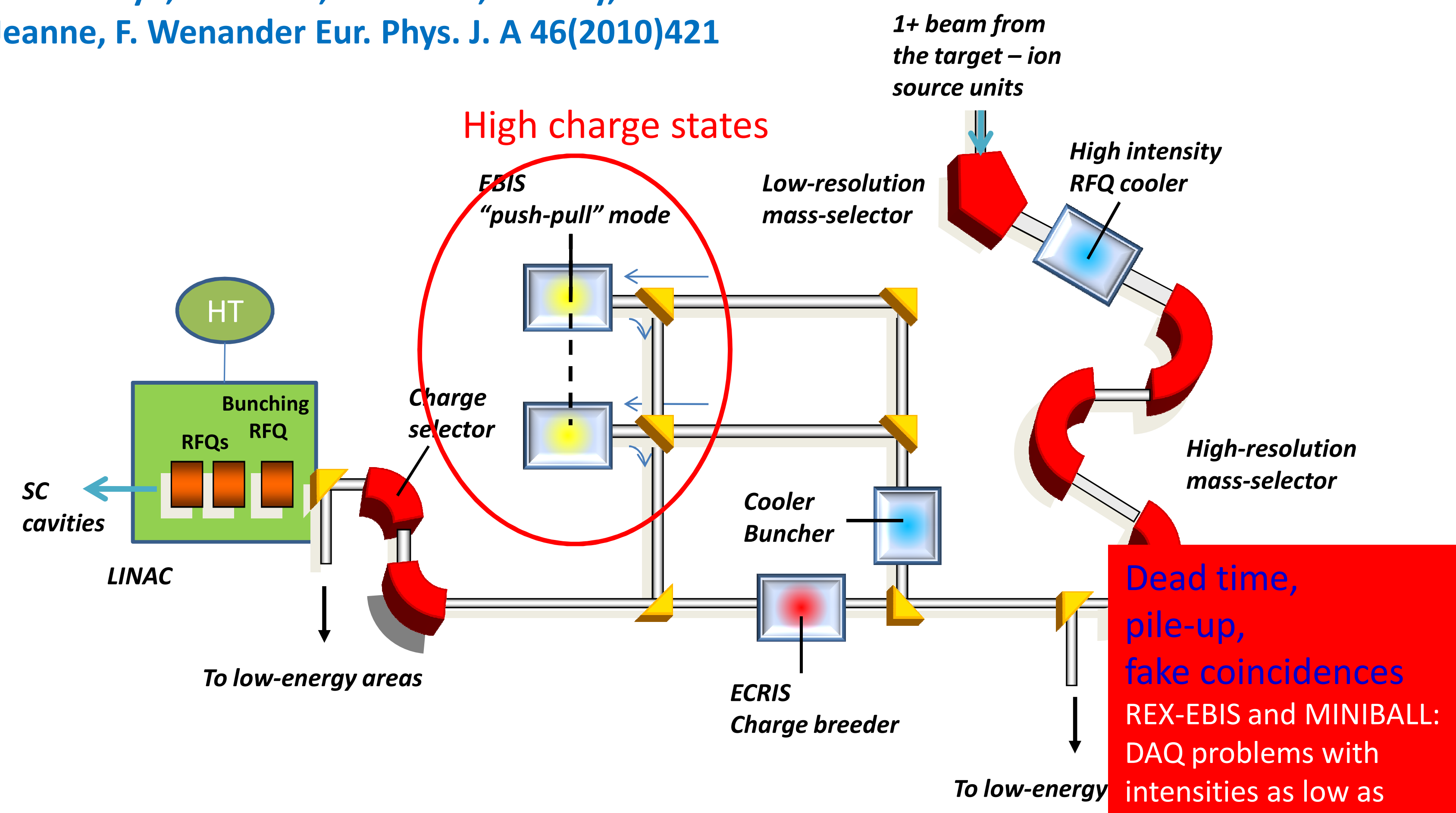


ECRIS challenges

Beam purity and capture efficiency optimizations

Following the suggestion made for EURISOL

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



Dead time,
pile-up,
fake coincidences

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

EBIS challenges

For mid-term ISOL facilities time structure is the main issue

(before space charge limitations)

EMILIE objectives

- **EBIS debuncher**
  - Simulation, Construction and test of a novel concept of EBIS beam debuncher

- **Optimization of the performances of ECR charge breeders of Phoenix type**
  - MW coupling simulations and new plasma chamber
  - Hot sources and wall recycling
  - Reproducibility of results and magnetic field optimization
  - Multiple frequency heating

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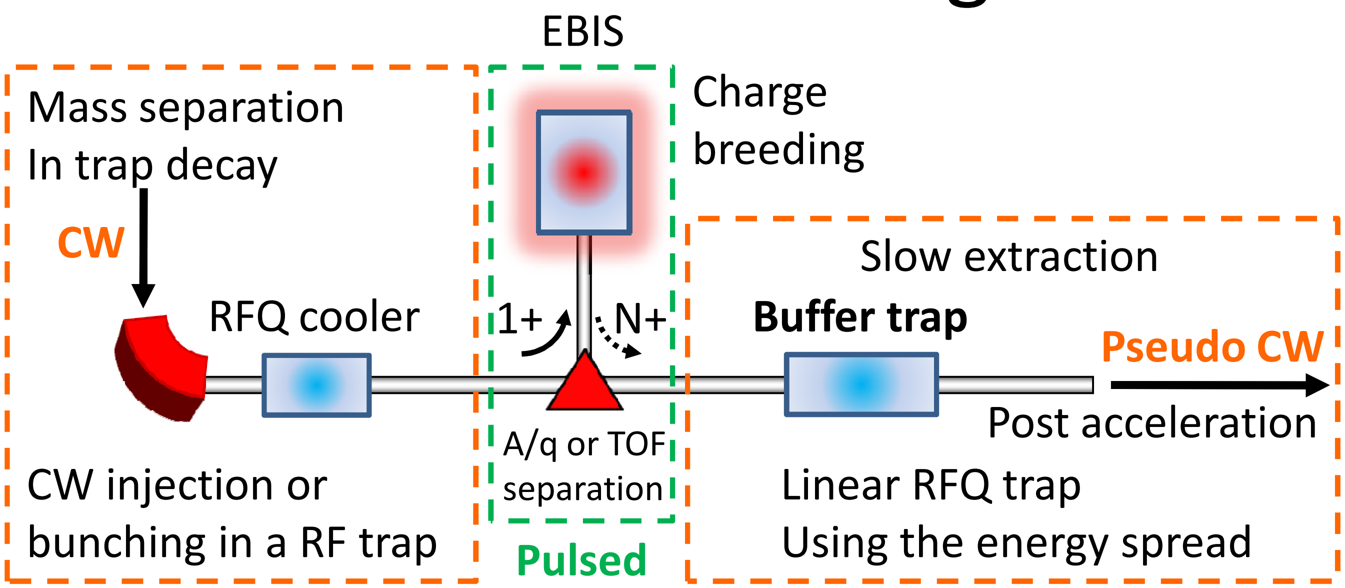
CW EBIS charge breeder



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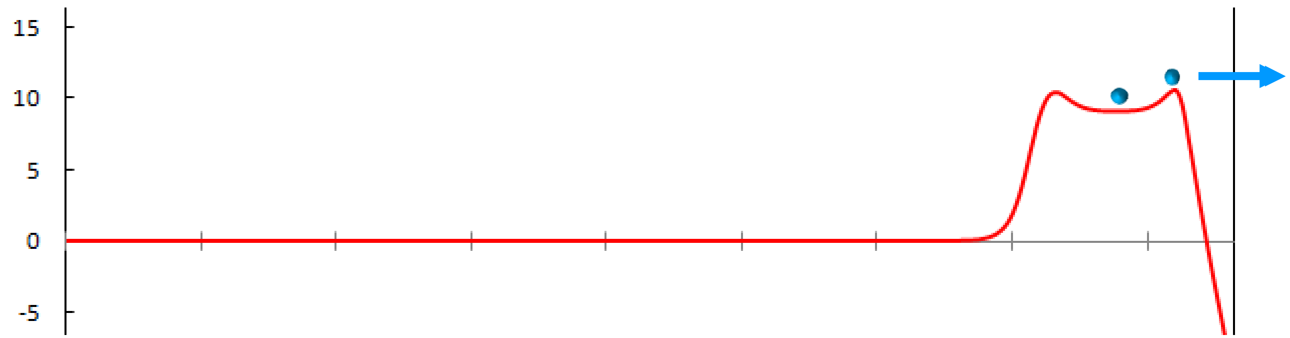
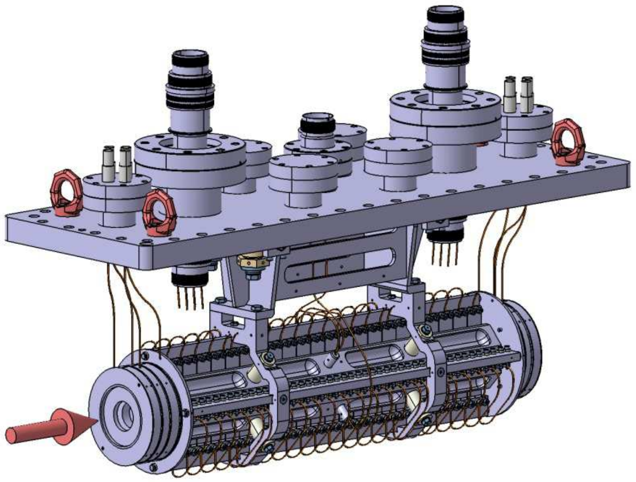
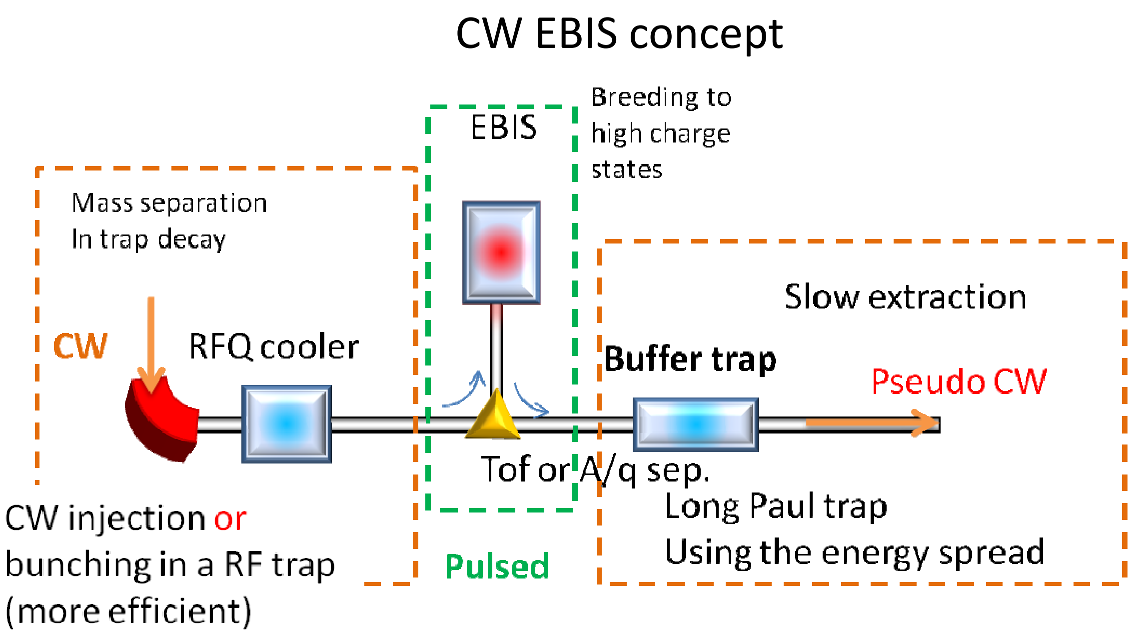


EBIS beam debuncher

- **Linear RFQ under UHV**



CW EBIS concept

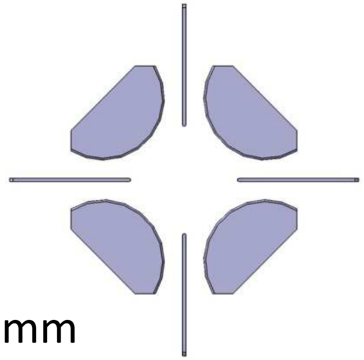


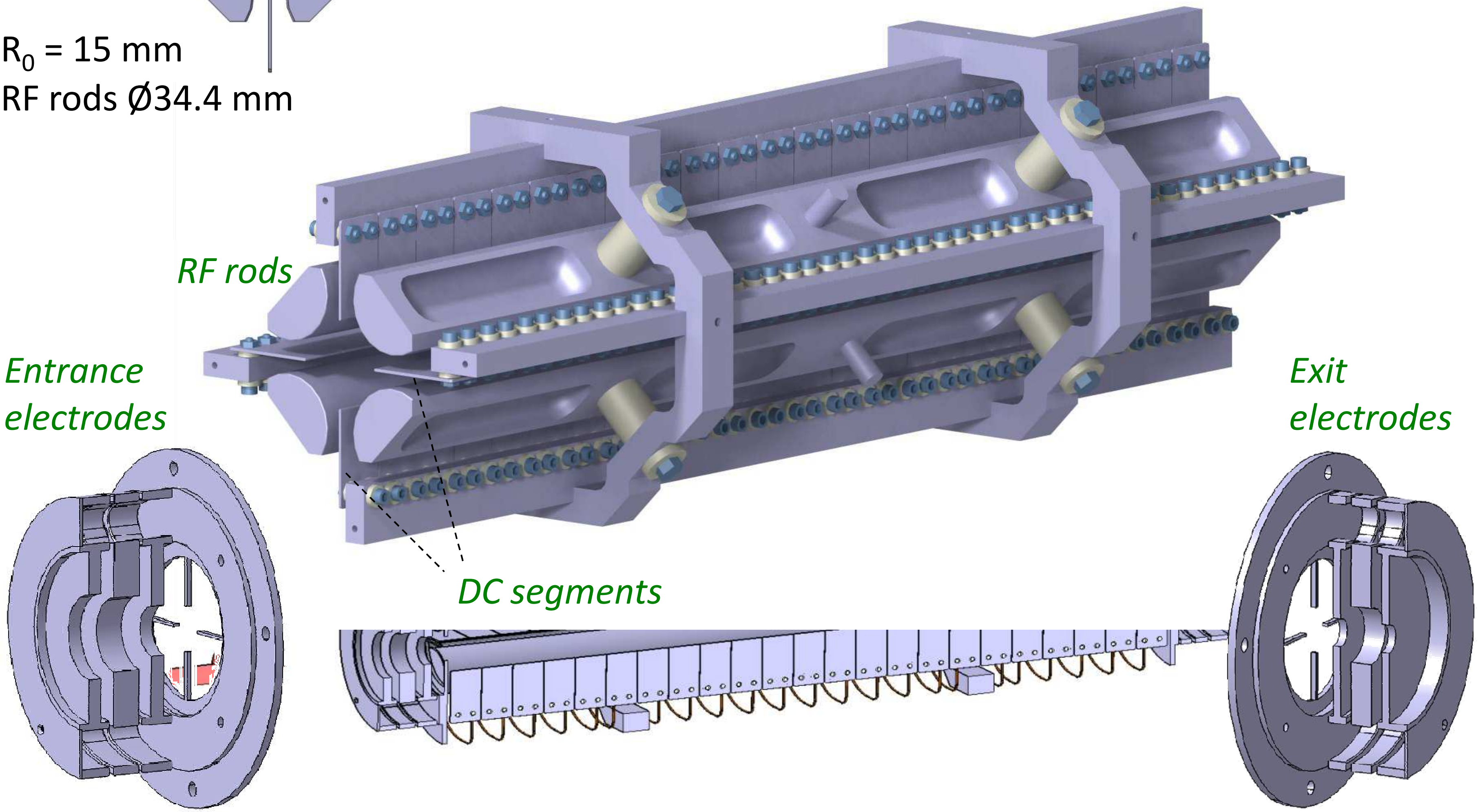
- RF for radial confinement of A/q~4 (400V, 2MHz, r_0=1.5cm)
- DC potentials on the segments for longitunal space phase manipulation (a few 100V)
- UHV for avoiding recombinations P<5 10^{-11} mbar
- Length of the trap for accepting all ions L~1m
  - pulse <with δt =50µs δE=10·q eV
  - Ion capacity >> RFQ cooler buncher - up to 10^9/bunch

Debuncher prototype design

Completed in 2012 at LPC

Y. Merrer
P. Desrues

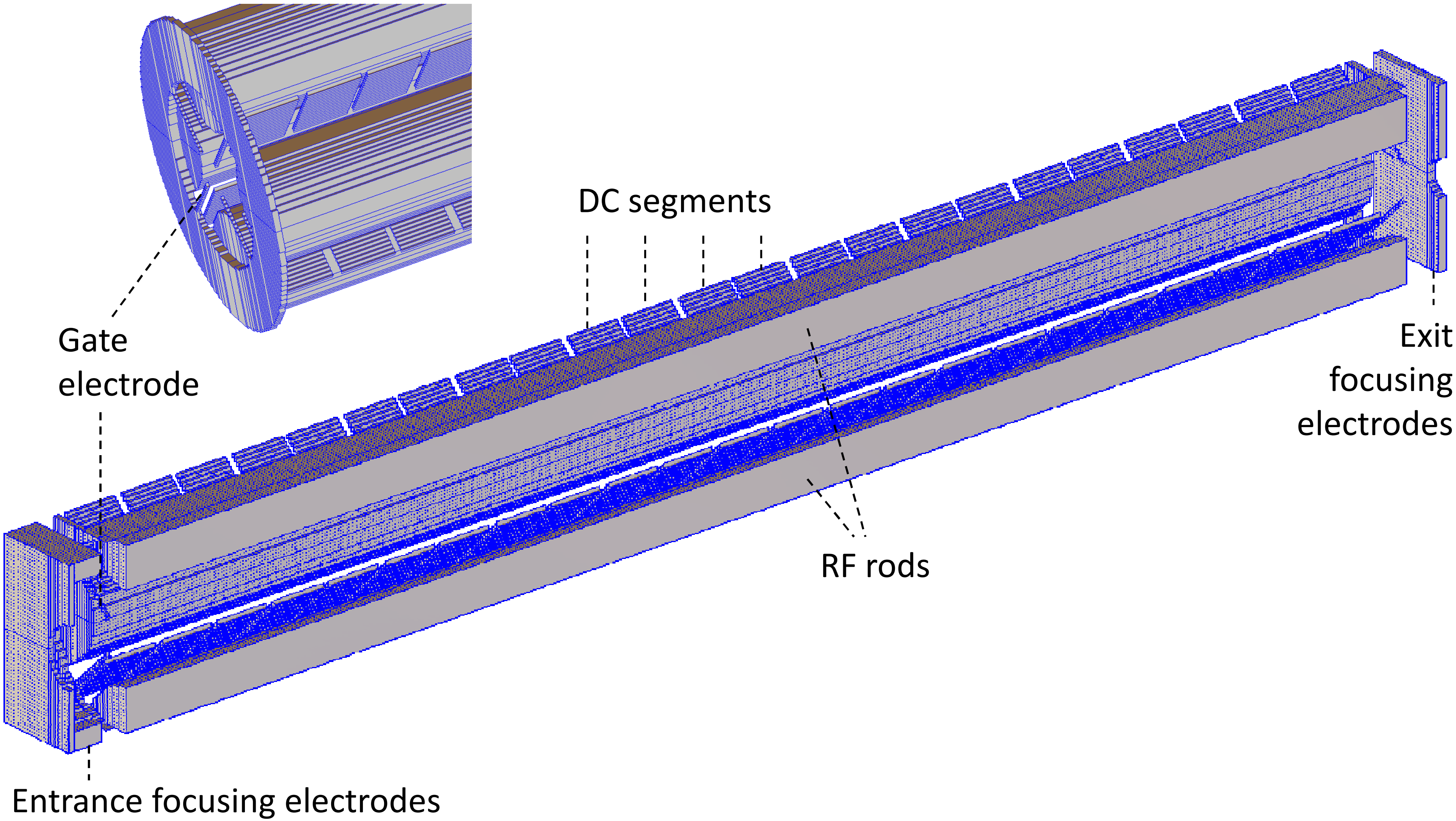




Simulations with SIMION

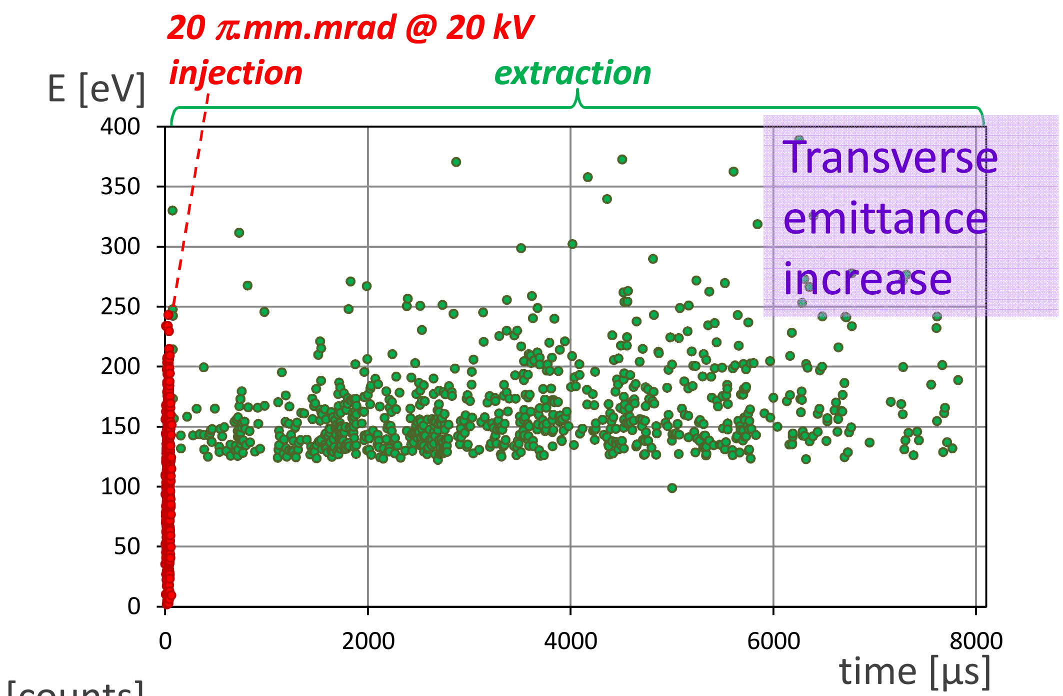
Started in 2012 at GANIL, ongoing

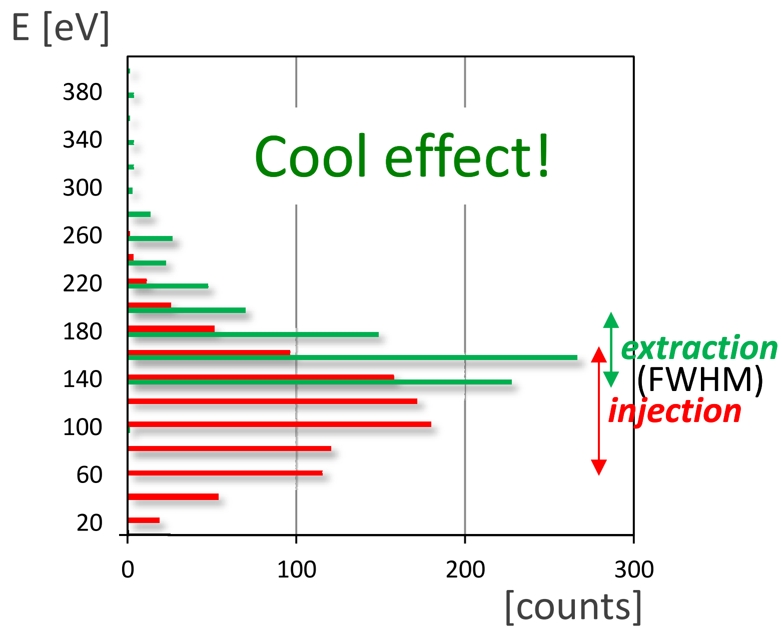
E. Traykov

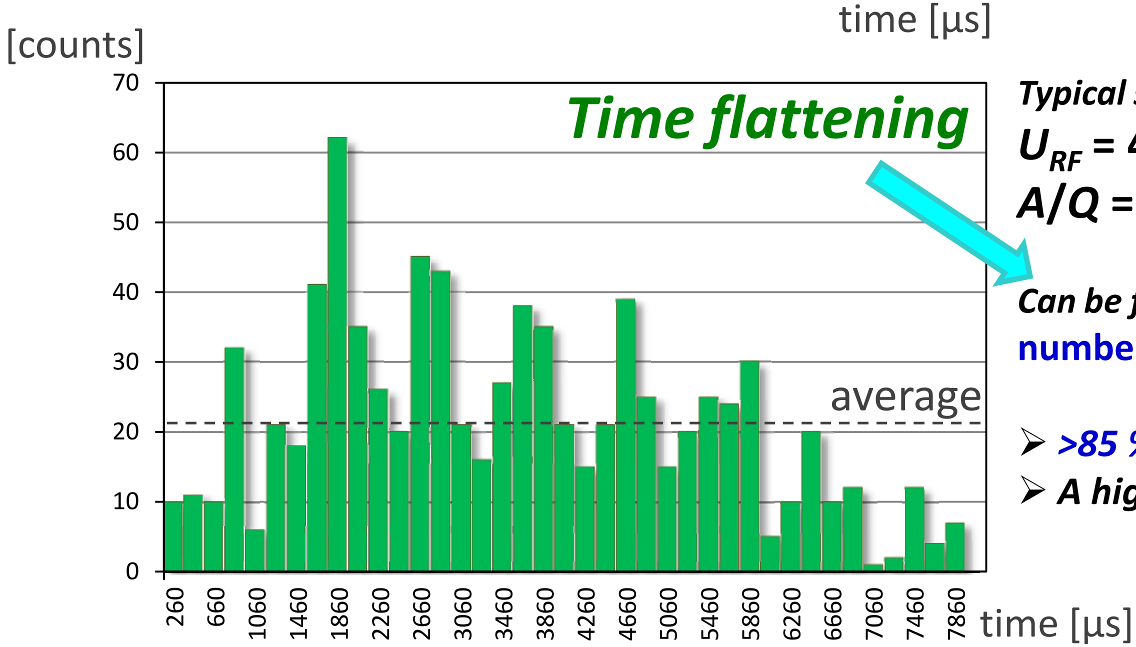


Simulations with SIMION – results 2012

E. Traykov







Typical settings:

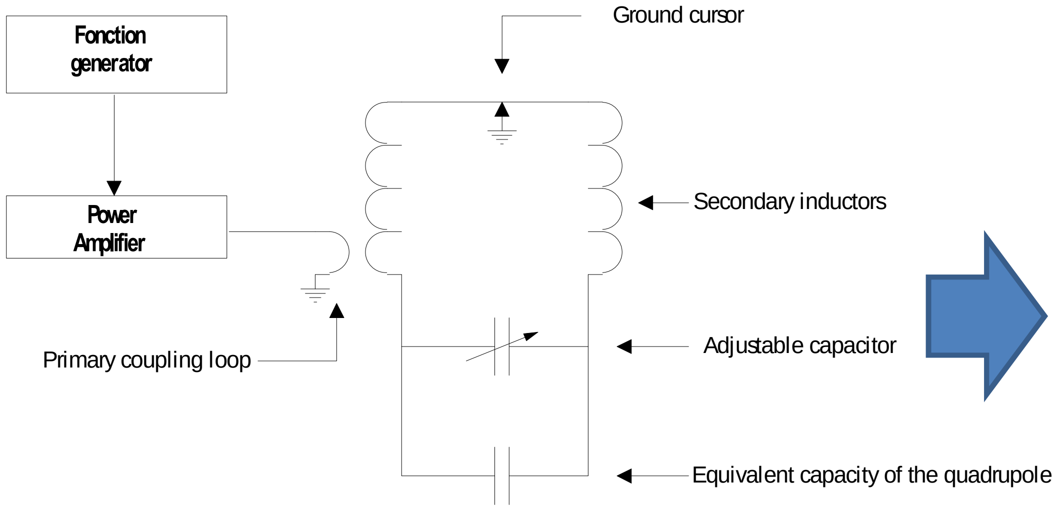
U_{RF} **= 400 V,** f_{RF} **= 4 MHz,** T_{cycle} **= 8000 µs,**
A/Q **= 3.5,** ΔE **= 10.Q eV ,** ΔTOF **= 50 µs.**

Can be flattened further by
number/size of drawers, DC rise time, overlapping

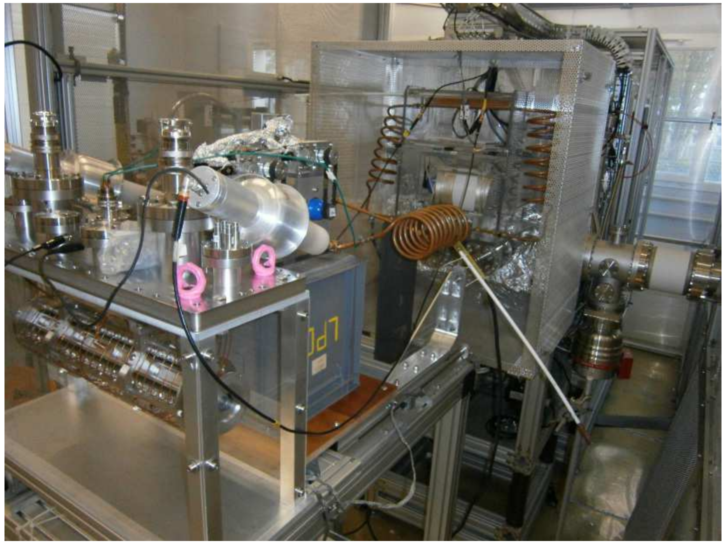
- ***>85 % transmission for a 45 cm long debuncher***
- ***A higher energy spread would require***
  - ***→ longer debuncher***
  - ***→ stronger confinement***

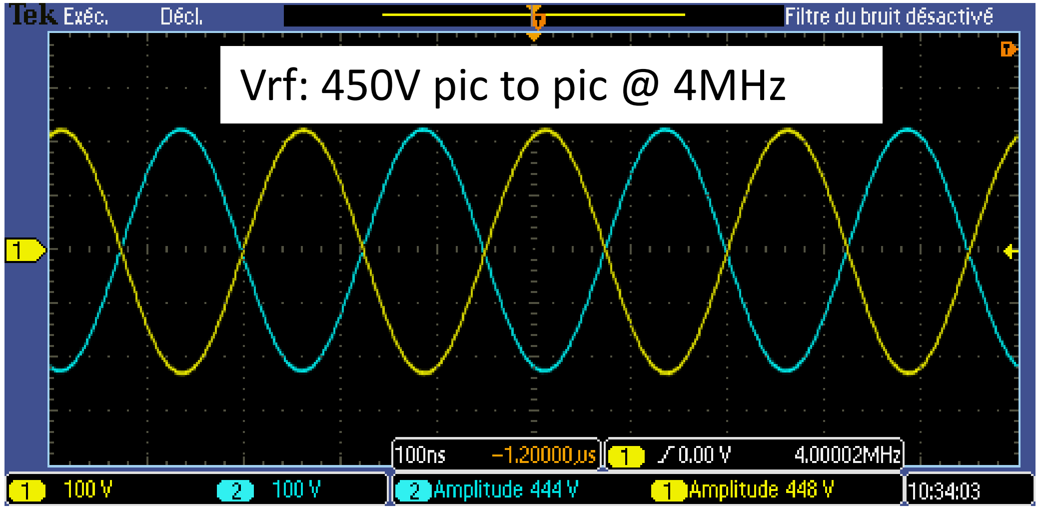
Production of RF voltages on the quadrupole

JF Cam



Principle of the production system RF





- **Frequency range: 2MHz to 6 MHz**
- **Voltage range: (pic to pic) : 0 to 1.2kV**

@ low power (< 10 Watts)

Debunching voltage ramp generator

JF Cam

Goal: Produce 8 voltages ramps (few volts/ms to 100 v/ms)

Sequencer: gate and delay generator → 2x4 channels AWG LECROY ArbStudio → 8 channels voltage Amplifier 500V G=50 & BW=15KHz → Wired splitter 8 -> 23 channels

x2

optical fiber link

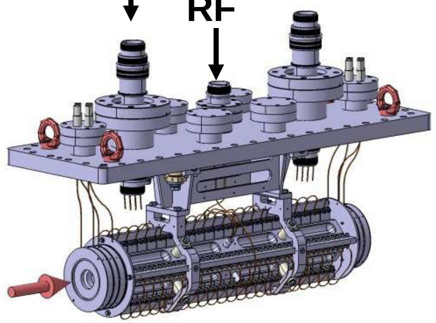
Computer to set AWG generators

Ramping voltage exemple

11

12

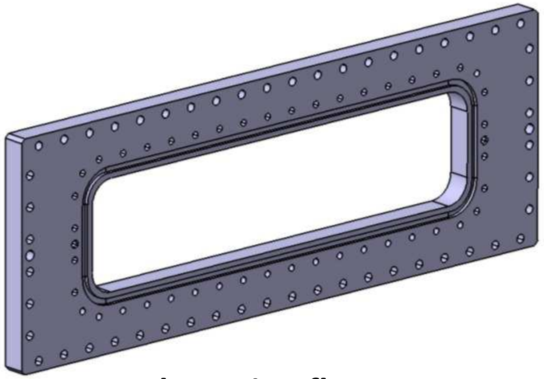
RF



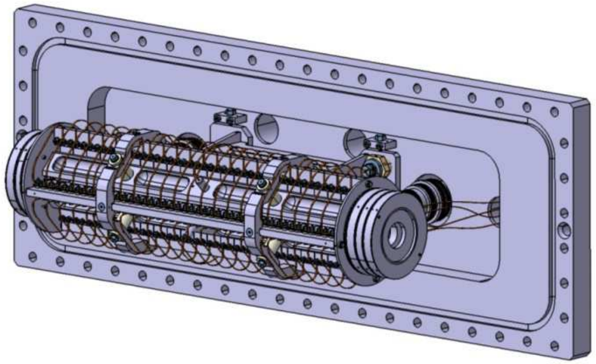
Emilie quadrupole

Tests bench mechanical adaptation

SPIRAL2 high intensity RFQ cooler demonstrator (SHIRaC) at LPC CAEN



Adaptation flange



Emilie debuncher on the adaptation flange

Emilie debuncher on the test bench

EMILIE: Summary and future plans

- **EMILIE debuncher status**
  - EBIS debuncher is built!
    - Design done
    - Main simulations finished
    - Machining and assembly done
    - Electronics purchased and tests in final phase
- **Next step**
  - EBIS debuncher prototype commissioning
    - Tests with singly charged ions at LPC Caen in the beginning of 2015
- **Future plans**
  - Tests with multiply charged ions at GANIL in 2015 – 2016
  - Possible tests with TWIN EBIS

Within ENSAR 2!
See Fredrik's presentation

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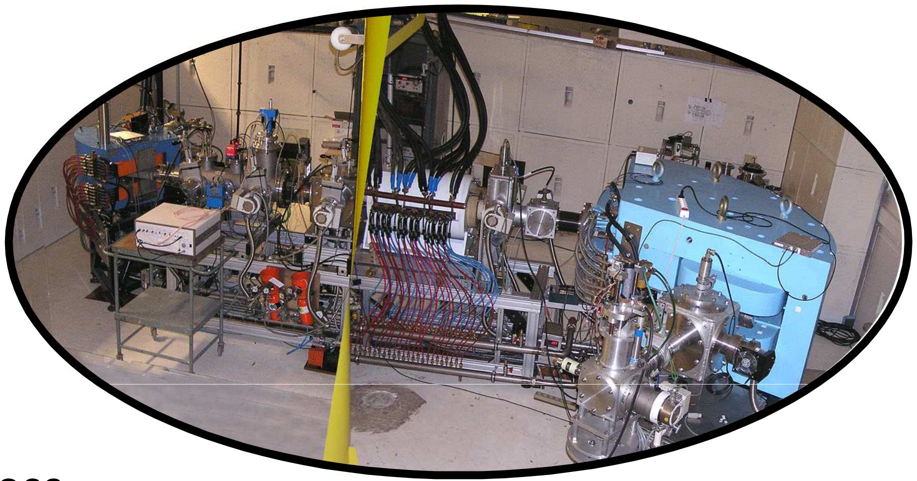
  - Multiple frequency heating

ECRIS optimizations

- Optimizing charge states and capture efficiencies with
  - double frequency heating
  - Gas mixing
  - Using molecular beams (CO)
  - Light ions

H. Koivisto et al, RSI 85 (2014)
L. Maunoury et al, RSI 85 02A504 (2014)
P. Delahaye et al, NIM A 693(2012)104



Phoenix ECRIS at the LPSC test stand

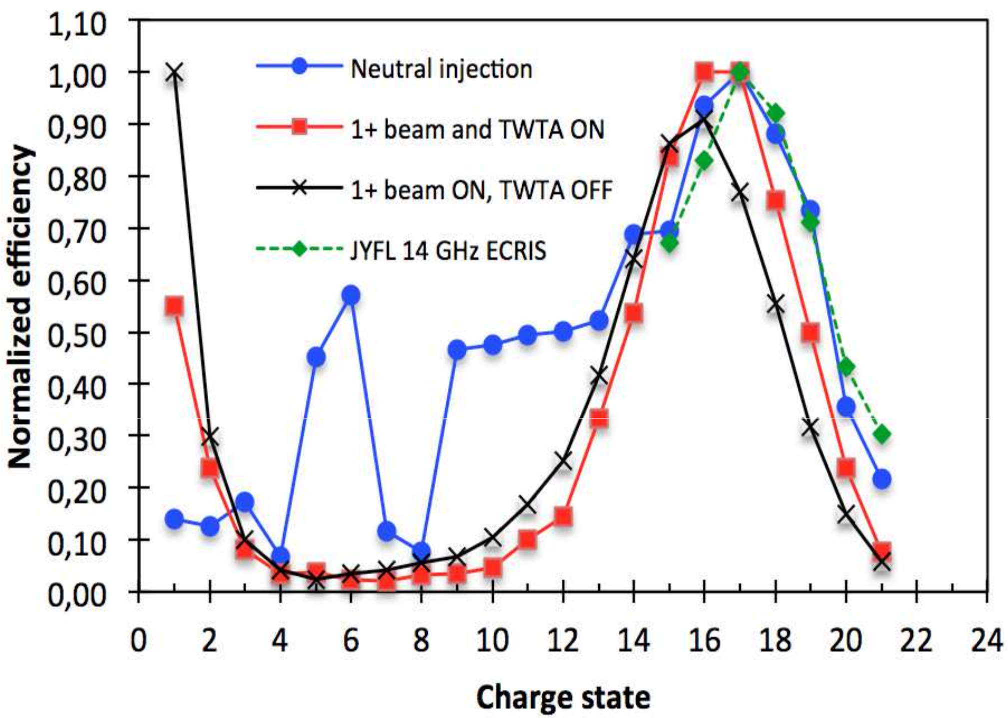
- Studies of the 1+ beam capture process
  - 1+ beam slowing down simulations
  - 1+ beam capture experimental investigations
    - Low charge states as a diagnostic for the capture
    - Influence on the plasma composition

Work in progress
See ECRIS 2014 T. Lamy et al, to appear in JACoW

- Off-line tests of SPES and SPIRAL charge breeders

Tests at LPSC until September 2015

Double frequency heating



Comparison of performances for a 14GHz source and a 14 GHz charge breeder

Phoenix at LPSC vs JYFL ECRIS

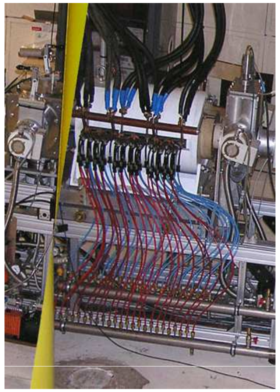
Same conclusions, despite lower magnetic field confinement and no bias disc in Phoenix

Double frequency heating → higher charge states, higher efficiencies

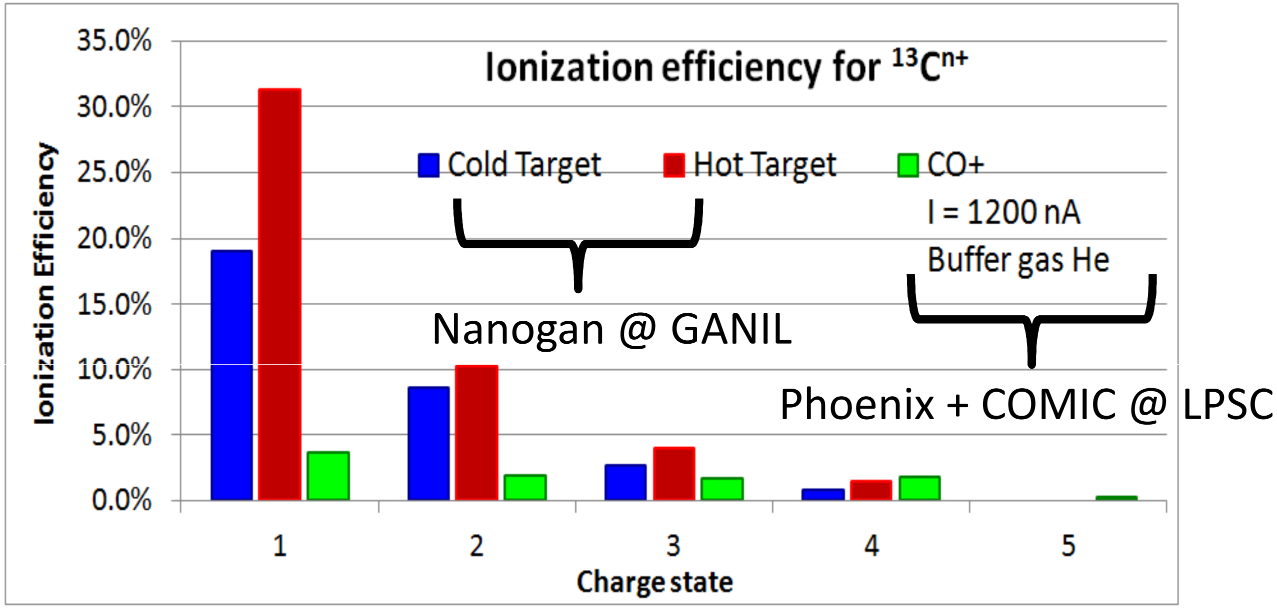
Presented at ICIS 2013 H. Koivisto et al, RSI 85 (2014)

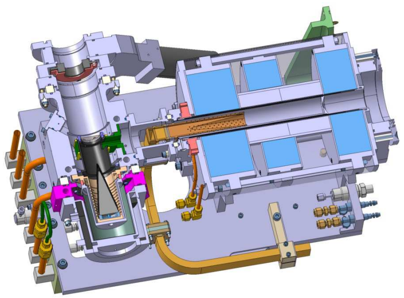
PREMAS task 3 +

Ionization of C beams at LPSC and GANIL



Phoenix @LPSC





Nanogan @ GANIL

For Carbon beams direct multi-ionization in Nanogan is prefered compared to charge breeding in Phoenix

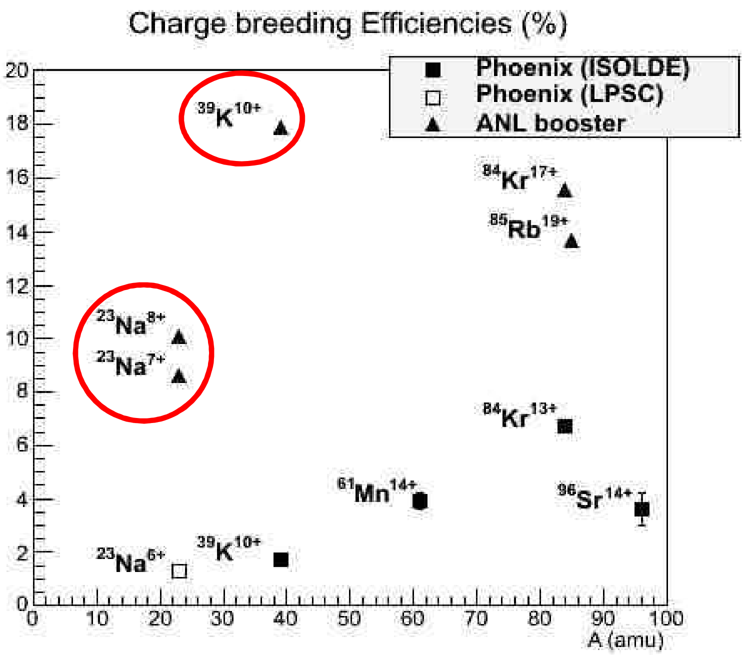
BUT: Phoenix possibly better for higher charge states and beam purity

Presented at ICIS 2013 L. Maunoury et al, RSI 85 02A504 (2014)

Light ion charge breeding at ANL

Nov. 2011

- Efficiencies for Na and K improved by a great amount
  - Playing with jaws to optimize efficiency



May 2014

Emittance measurements

- Pepper pot not sensitive enough
- Dead spot in the 1+ FC complicated the analysis

➢No conclusions about the emittance

➢ Efficiency >6% for $^{39}K^{+} \rightarrow$ $^{39}K^{9+}$ with a non cut beam is feasible

possible effect of the emittance of the 1+ beam?

R. Vondrasek, P. Delahaye, S. Kutsaev and L. Maunoury, Rev. Sci. Instr. 83(2012)113303
P. Delahaye, L. Maunoury, R. Vondrasek, Nucl. Instr. Meth. A, 693(2012)104.

Studies of the 1+ beam capture process

Charge breeding efficiency is determined by

Capture efficiency of the 1+ beam

Ionization efficiency from 1+ to n+

Extraction efficiency of the n+ ions

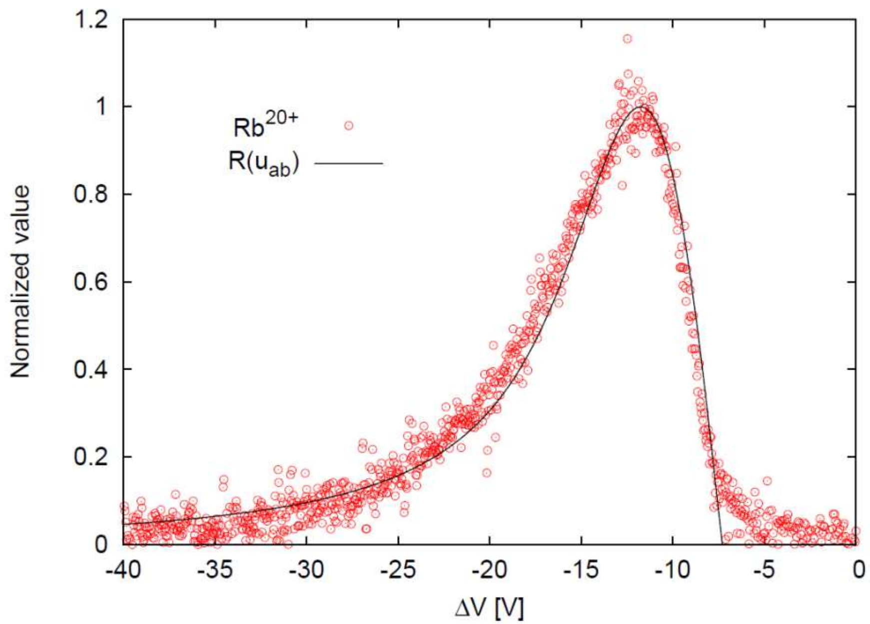
Slowing down coefficient of the incident 1+ ions in **ion-ion collisions**

O. Tarvainen et al, in preparation

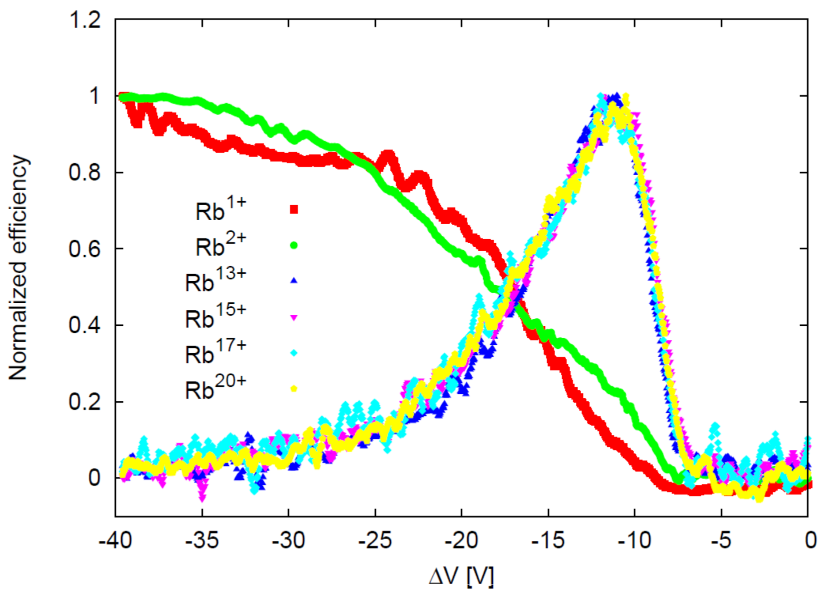
$$S_{ab} = \frac{\langle \Delta v_a \rangle}{\Delta t} = -\frac{n_b}{4\pi\epsilon_0^2}\left[\frac{q_a q_b e^2}{m_a \langle v_b \rangle}\right]^2 \left(1+\frac{m_a}{m_b}\right) R(u_{ab}) \ln \Lambda$$

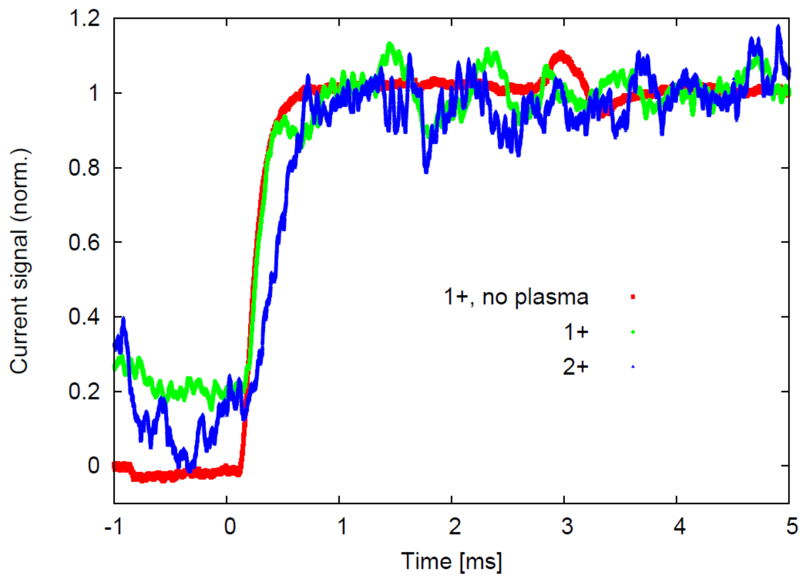
$R(u_{ab})$ is at maximum when the incident ion velocity equals the average speed of the plasma ions

Experiments with the Phoenix charge breeder at LPSC: breeding efficiency of high charge state ions as a function of incident velocity matches well with the prediction



Studies of the 1+ beam capture process





Low charge states extracted from the breeder behave differently

Incident **1+ ions can propagate through the breeder plasma**. This is **confirmed by comparing their 'breeding time' with the ion flight-time** without plasma.

2+ is produced via in-flight ionization

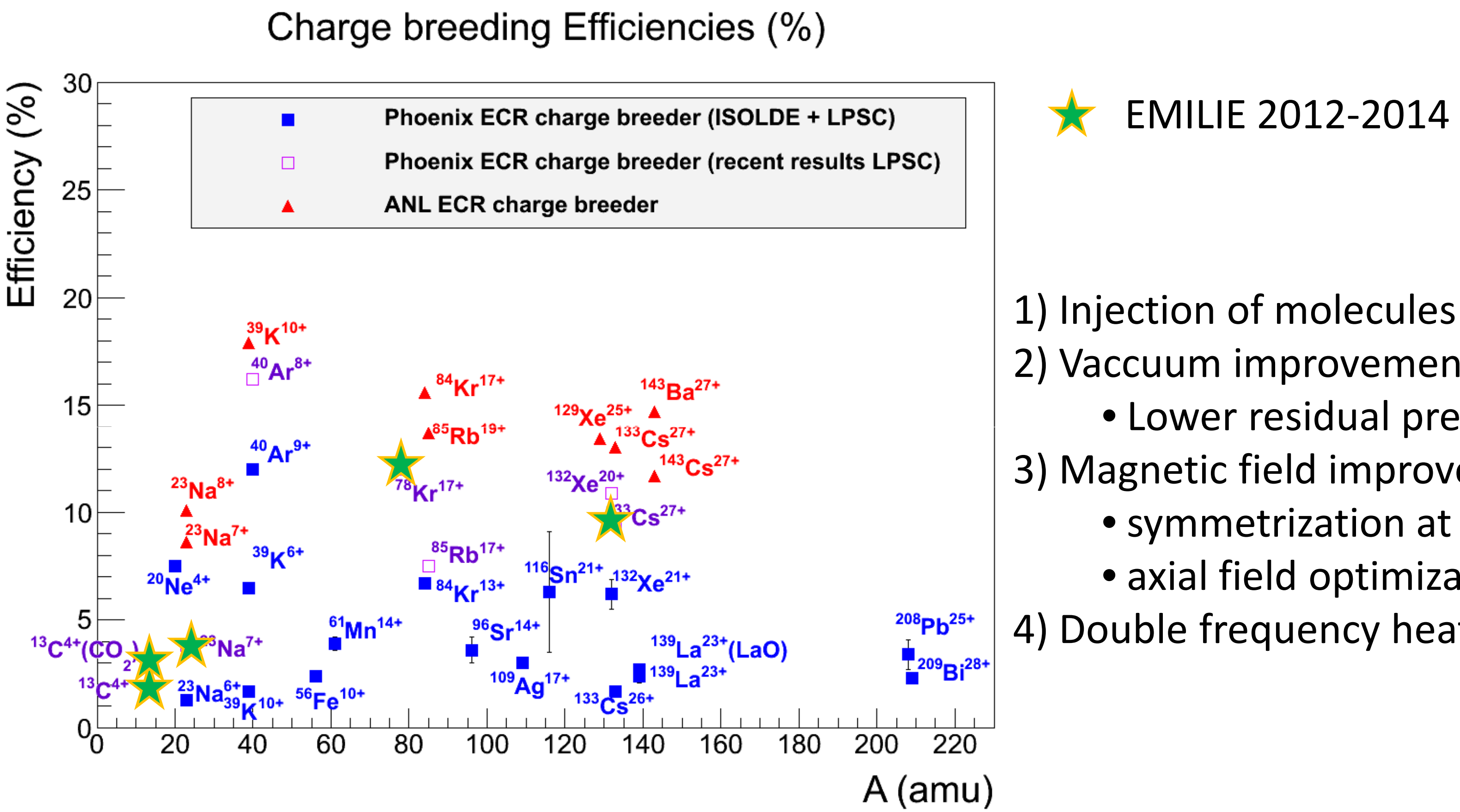
Measurement of the 1+ and 2+ 'breeding efficiencies' yields an **estimate for ion mean free path, ion-ion collision frequency and plasma density**

The incident 1+ beam is a perfect diagnostics tool for ECRIS plasmas!

Experiments with Na, Rb, Cs have been carried out, showing similar results.

O. Tarvainen et al, in preparation

Improvement of charge breeding efficiencies



1) Injection of molecules
2) Vaccuum improvement
   - Lower residual pressure
3) Magnetic field improvements:
   - symmetrization at injection
   - axial field optimization
4) Double frequency heating

P. Delahaye, NIM B 317(2013) ,
J. Angot et al, THYO02, ECRIS 2012
H. Koivisto et al, RSI 85 (2014)
L. Maunoury et al, RSI 85 02A504 (2014)
T. Lamy et al, ECRIS 2014

EMILIE: Summary and future plans

- **Phoenix charge breeder optimization**
  - Tests at LPSC for SPIRAL 1& 2 and SPES
  - Simulation work ongoing at INFN
    - MW coupling
    - reproducing the 1+ beam capture ΔV curve
  - Tests with the CARIBU CB for light ions at SPIRAL
  - Tests to come with upgraded Phoenix charge breeders
    - **with the SPES charge breeder**
      - Presently in construction at LPSC
      - Test until April 2015
      - Tests at SPES in 2015-17
    - **With the SPIRAL charge breeder**
      - Already built
      - commissioning at LPSC from April to September 2015
      - Tests at SPIRAL in 2016

- **ECR 1+ hot sources**
  - being assembled at LPSC
  - 650°C at 5.4GHz should be tested within EMILIE, 1200°C for a later stage

Thanks a lot for your attention!

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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