Charge breeding

aka

Charge state boosting

aka

1+ \rightarrow n^+ \text{ transformation}

Fredrik Wenander

on Ion Sources, Senec Slovakia, 2012
1. Introduction and motivation

2. ISOL beam parameters and breeder criteria

3. Atomic physics processes for multiply charged ions

4. The different concepts
   - Stripping
   - ECRIS
   - EBIS

5. Preparatory devices and tricks

6. Facilities and the future
Introduction and motivation

Setting the stage
Radioactive nuclei: main interest for nuclear physics

To this date:
~6000 nuclei believed to ‘exist’
~3000 different nuclides experimentally observed
Less than 10% stable
RIB production techniques

IF (In-Flight fragment separator)

- Thin production target
- Driver beam (heavy ions - fusion, fission, fragmentation)
- Fragment separator
- Secondary beam

Down to us lifetimes
Large transverse emittance
Large energy spread
GeV beam energy

Isotope Separation Online (ISOL)

- Electrostatic DC acceleration
- Ion source
- Driver beam (light and heavy ions, p, n, e - spallation, fission, fragmentation)
- Thick, hot target
- Isotope/isobar separator
- Secondary beam

Pencil-like beams
Chemistry involved
Higher beam intensities than IF
Lifetimes >10 ms
$W_{total} < 100 \text{ keV}$
Interesting physics at $0.1 - 10 \text{ MeV/u}$

- Coulomb excitation
- Few-particle transfer
  - $(d,p), (^9\text{Be},^2\alpha), (^{10}\text{Be},^2\alpha), (p,\gamma), (p,p)_{\text{res}} \ldots$
- Fusion reactions at the Coulomb barrier

NB! $W_{\text{kin (total)}} = \text{MeV/u*A}$

Closing the energy gap

![Diagram showing energy levels and processes](image_url)

- Fragmentation (IF)
- Deceleration cooling (storage rings)
- Post-acceleration
- Isotope separation on-line (ISOL)
- Target-ion source

! Fill with *post-accelerated ISOL-beams*
Motivation for $Q^+$

$1^{st}$ motive for high $Q$

<table>
<thead>
<tr>
<th></th>
<th>$W_{\text{final}}$ (MeV/u)</th>
<th>Time structure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cyclotron</strong></td>
<td>$K^*(Q/A)^2$</td>
<td>cw (micro structure)</td>
</tr>
<tr>
<td></td>
<td>$K \sim (B/r)^2$, $[B]=T$, $[r]=m$ (cylotron B-field and radius)</td>
<td></td>
</tr>
<tr>
<td><strong>Linac</strong></td>
<td>$Q/A^*E(\text{ave})^*L$</td>
<td>SC - cw</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NC - usually pulsed</td>
</tr>
<tr>
<td></td>
<td>$E(\text{ave}) = \text{average acceleration field} \sim 3 \text{ MV/m for NC}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$[L]=m$ (linac length)</td>
<td></td>
</tr>
</tbody>
</table>

$\Rightarrow \text{Linac length} \sim A/Q$

Extra

Kilpatrick limit (valid for NC)

$f(\text{MHz}) = 1.64E(\text{peak})^2e^{-8.5/E(\text{peak})}$

$[E(\text{peak})]=\text{MV/m}$
**2nd motive for high Q**

If A/Q high => require low $f_{RF}$ to achieve adequate:

a. transverse focusing (focal strength $\sim 1/\sqrt{f_{RF}}$)

b. period length ($L_{period}$) of the first RF structure as the source extraction velocity is limited

Example: $A=220$, $Q=1$, $U_{extr}=100$ kV, $L_{period}=2$ cm

$$v_{extr} = \sqrt{\frac{2U_{extr} Q}{A}} = 3E5 \text{ m/s}$$

$$f_{RF} \sim \frac{v_{extr}}{L_{gap}} = 15 \text{ MHz}$$

**Motivation for Q$^+$**

open RFQ

ISAC 35 MHz RFQ for A/Q<30

Transverse tank dimensions scale with $1/f_{RF}$

**Bottom line:** low A/Q => + short linac + small transverse dimension

$\text{Linac cost } \sim \text{ length} \times \text{radius}^p \quad 1<p<2$
First ideas/suggestions for post-acceleration of radioactive ion beams: “Nuclides far off the Stability Line” (1966) Sweden
ISOL beam parameters and breeder criteria

What comes in and goes out

For ion source details see T. Stora’s lecture
Because of the pulsed structure of the proton beam (one 2.4 μs long proton pulse of about $3 \times 10^{13}$ protons every 1.2 s) the production of the radioactive ions can be measured as a function of time after the proton beam impact. Figure 8 shows a typical release curve for $^{8}\text{Li}$ ($T_{1/2} = 840$ ms) produced by target fragmentation of tantalum foils.

**ISOL beam parameters**

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion mass</td>
<td>4 to &gt;250</td>
</tr>
<tr>
<td>Intensity</td>
<td>few to &gt;1E11 ions/s</td>
</tr>
<tr>
<td>Charge</td>
<td>1+</td>
</tr>
<tr>
<td>Energy</td>
<td>several tens keV</td>
</tr>
<tr>
<td>Energy spread</td>
<td>few eV</td>
</tr>
<tr>
<td>Temporal structure</td>
<td>cw or quasi-cw</td>
</tr>
<tr>
<td></td>
<td>Driver beam – cw or pulsed</td>
</tr>
</tbody>
</table>

**Semi-continuous**

depending on release properties and ionization time

typical tens ms to minutes

(r=rise, f=fast, s=slow)

\[P(t, \lambda_r, \lambda_f, \lambda_s, \alpha) = \frac{(1-e^{-\lambda_r t})}{\text{Norm}} \left[ \alpha e^{-\lambda_f t} + (1-\alpha)e^{-\lambda_s t} \right]\]
ISOL beam parameters

<table>
<thead>
<tr>
<th>Transverse emittance</th>
<th>10-50 mm mrad</th>
<th>90% at 60 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-life</td>
<td>&gt;10 ms</td>
<td>Limited by ISOL-system</td>
</tr>
<tr>
<td>Selection</td>
<td>Not necessarily isobarically clean</td>
<td>Use e.g. resonant ionizing laser ion source</td>
</tr>
</tbody>
</table>

The farther one recedes from the valley of beta stability, the shorter the half-life of the nuclide to be investigated typically becomes. Half-lives very close to the neutron and proton drip lines range from milliseconds to a few tens of milliseconds. This means that very fast techniques for beam handling, cooling and trapping are required.
# Checklist for breeder design

<table>
<thead>
<tr>
<th></th>
<th>Achievable A/Q (3&lt;A/Q&lt;9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>High breeding efficiency</td>
</tr>
<tr>
<td></td>
<td>rare radionuclides</td>
</tr>
<tr>
<td></td>
<td>limit machine contamination</td>
</tr>
<tr>
<td></td>
<td>chain of machines</td>
</tr>
<tr>
<td>2</td>
<td>Short breeding / confinement time</td>
</tr>
<tr>
<td></td>
<td>handle short-lived ions</td>
</tr>
<tr>
<td>3</td>
<td>Clean extracted beams</td>
</tr>
<tr>
<td>4</td>
<td>High ion throughput capacity</td>
</tr>
<tr>
<td>5</td>
<td>Good beam-quality (large α, small (\varepsilon_{\text{trans}}), small (\Delta E_{\text{extr}}))</td>
</tr>
<tr>
<td></td>
<td>good trapping efficiency</td>
</tr>
<tr>
<td></td>
<td>high linac/seperator transmission (\eta)</td>
</tr>
<tr>
<td></td>
<td>good mass separation</td>
</tr>
<tr>
<td>6</td>
<td>Pulsed or cw machine / beam extraction time structure</td>
</tr>
<tr>
<td></td>
<td>dependent on accelerator</td>
</tr>
<tr>
<td>7</td>
<td>Easy handling and reliable</td>
</tr>
<tr>
<td></td>
<td>to be used in an accelerator chain on a production basis</td>
</tr>
</tbody>
</table>

\[
\eta_{\text{breed}} = \frac{I(Q)}{Q \cdot I(1^+)}
\]
Atomic physics processes for multiply charged ions

Short revision

See also lectures by
M. Kowalska and G. Zschornack
Electron impact ionization is more efficient than proton and photon impact $\hbar \nu$.

Multistep (successive) ionization: the process takes time.

$$e + A^{i+} \rightarrow A^{(i+1)+} + 2e$$

Ionization time has to be shorter than lingering time in the source.
Average time to reach the charge state $q$ with multistep ionization for electrons with defined kinetic energy:

$$
\bar{\tau}_q = \sum_{i=1}^{q-1} \tau_{i\rightarrow i+1} = \frac{e}{j_e} \sum_{i=1}^{q-1} \frac{1}{\sigma_{i\rightarrow i+1}}
$$

Lotz’s semi-empirical electron impact ionization cross-section formula for the case of high ionization energies $E_{\text{kin}} > P_i$ is:

$$
\sigma_{q\rightarrow q+1} = 4.5 \cdot 10^{-14} \cdot \sum_{nl} \ln\left(\frac{E_{\text{kin}}}{P_i}\right) \cdot \left(\frac{E_{\text{kin}}}{P_i}\right) \left[ \text{cm}^2 \right]
$$

Energies in eV and nl sum over n shell and subshell l

$E_{\text{kin}}$ - energy of the incident electron

$P_i$ = $E_{nl}$ - binding energy

**Cross-section**

* Energy threshold = ionization energy
* Max at ~2.7 times the ionization potential
* Decreases with charge state for very high electron energies

**Ionization time**

$\sigma$ – single ionization cross-section cm$^2$

$j_e$ – electron current density A/cm$^2$

valid for electrons with fixed energy
Charge state distribution

Ionization a statistical process
⇒ charge state distribution

Typically 15-25% in most abundant state

Electron energy

10 to 40 eV for singly charge ions
several 100 eV for multi-charged states
keV to tens of keV for highly charged ions

Charge state distribution as function of $n_e \times T_{\text{confinement}}$
Competing processes

\[
\frac{dN_i}{dt} = n_e v_e \left[ \sigma_{i\rightarrow i-1}^{EI} N_{i-1} - \left( \sigma_{i\rightarrow i+1}^{EI} + \sigma_{i\rightarrow i-1}^{RR} + \sigma_{i\rightarrow i-1}^{DR} \right) N_i \right] + \left( \sigma_{i+1\rightarrow i}^{RR} + \sigma_{i+1\rightarrow i}^{DR} \right) N_{i+1} \] 

- \ n_0 v_{ion} \left[ \sigma_{i\rightarrow i+1}^{CX} N_i - \sigma_{i+1\rightarrow i}^{CX} N_{i+1} \right] - N_i R_i^{ESC}

N_i \text{ – number of ions with charge } i 

n_e, v_e \text{ – electron density and velocity} 

n_0 \text{ – neutral particle density} 

v_{ion} = \sqrt{2kT_{ion}/M_{ion}} \text{ – averaged ion velocity} 

EI \text{ – electronic ionization} 

RR \text{ – radiative recombination} 

DR \text{ – dielectronic recombination} 

CX \text{ – dielectric exchange} 

R_i^{ESC} \text{ – escape rate} 

See also AIP Conf. Proc. 572, 119 (2001)
**Charge exchange vs ionization**
Vacuum pressure at which gain by ionization equals loss by charge exchange for lead ions

From R. Becker

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**Electron ion heating**
Radial well voltages $eU_{\text{trap}} = kT_{\text{ion}}$ to trap multiply charged ions heated by electrons of 1 keV (dashed line) and 10 keV (full lines)

$$\Delta U_{\text{radial}} [V] = \frac{6.2}{Z \cdot A} e \sum_{i=1}^{q} \frac{i^2}{\sigma_{i \rightarrow i+1}}$$

The First Alternative

Stripper foil

ECR plasma

EBIS beam
Classic concept – stripping

* Doesn’t really classify as charge breeder
  + Simple method, passive elements.
  + Sub-us half-life isotopes easily reachable
  + Very high beam capacity >100 eμA
  + No additional beam contamination

* Foil materials: Be, C, Al, Al₂O₃, mylar

* Bohr criterion: electrons whose orbital velocity is larger than projectile velocity are retained

Baron’s formula for equilibrium charge state distribution (CSD)

\[
\bar{Q} = Z_{\text{proj}} \cdot C_1 \left(1 - C_2 e^{-83.28 \beta / Z_{\text{proj}}^{0.447}}\right)
\]

\(C_1=1\) for \(Z_{\text{proj}}<54\)
\(C_1=1-\exp(-12.905+0.2124 Z_{\text{proj}}-0.00122 Z_{\text{proj}}^2)\) for \(Z_{\text{proj}}\geq 54\)
\(C_2=1\) for energies \(W>1.3\) MeV/u
\(C_2=0.9+0.0769W\) for \(W<1.3\) MeV/u

NB! ~only dependent on velocity

\(v_{\text{proj}}=\beta c\) and \(Z_{\text{proj}}\)
Gaussian CSD distribution
* assuming no significant atomic shell effects
* $Q$ is not too close to $Z$

$$
\sigma = 0.5 \sqrt{Q \cdot \left(1 - \left(\frac{Q}{Z_{\text{proj}}}\right)^{1.67}\right)} \quad \sigma = \sqrt{Q \cdot (0.07535 + 0.19(\frac{Q}{Z_{\text{proj}}}) - 0.2657(\frac{Q}{Z_{\text{proj}}}^2))}
$$

for $Z_{\text{proj}} < 54$

for $Z_{\text{proj}} \geq 54$

Light elements (low $Z_{\text{proj}}$)
=> narrow distribution
=> high fraction in a single charge state

Heavy elements (high $Z_{\text{proj}}$)
=> wide distribution
=> less fraction in a single charge state

See also: G. Schiwietz, P.L. Grande, Improved charge-state formulas NIMB 175-177 (2001) 125-131
Refined formulae for foil and gas stripping
Foil equilibrium thickness

Equilibrium thickness =>
CSD do not change when the target thickness is further increased

Equilibrium thickness $\approx 2*x_{66}$

$\chi_{66} = 2.43W_{\text{proj}}^{1.47}$


* Typical carbon foil thicknesses: 5-1000 ug/cm$^2$ -> 25 nm to 5 um

* Pre-acceleration to >500 keV/u

* Foil thicknesses < 5 ug/cm$^2$ (< 25 nm) practically difficult to mount
  => use gas strippers for low velocity beams
Assume $U_{acc} = U_{total\ energy} = 200\ keV$

What's the energy per nucleon and particle velocity? Use this to calculate $q_{mean}$

In solid stripper the collision frequency is larger than the frequency of Auger and radiative decays, leading to higher $Q$ than in the same integrated thickness for gas stripper.

* Used for very low velocity: 5-25 keV/u
* Very thin integrated thickness: fraction of ug/cm$^2$
* Usually noble gases
* Small charge increase from 1+ to 2+, 3+ or 4+

Gas stripping

Extra

- Used for very low velocity: 5-25 keV/u
- Very thin integrated thickness: fraction of ug/cm$^2$
- Usually noble gases
- Small charge increase from 1+ to 2+, 3+ or 4+

Extra

In solid stripper the collision frequency is larger than the frequency of Auger and radiative decays, leading to higher $Q$ than in the same integrated thickness for gas stripper.

Helium stripping efficiency of heavy ions as a function of beam energy.

P.N. Ostroumov et al., PAC 2001
Facility based on stripping technique

Ideally strip as soon the increased velocity enables a higher charge state
+ make maximum use of the accelerating voltage
- but at each stripping stage the transmission is reduced due to the CSD

Example
Bunching efficiency 65%
Gas stripping to 2+ at 8 keV/u ~55%
Stripping foil to 23+ at 500 keV/u 20%
In total (single charge acc of $^{132}$Sn) 7%

A bunch rotating rf cavity is mandatory in order to generate a time focus at the stripper to minimise the longitudinal emittance growth due to energy straggling.

Figure 1: Helium stripping efficiency of heavy ions as a function of beam energy.
Multi-charge state acceleration

* Accelerate multiple q after the stripper
* $\Delta q/q$ of $\sim 20\%$ can be accepted

😊 Higher intensities

* Synchronous phase of multi-q beam
* The same final energy for all charge states

 siè (trans. and long.) $\sim 3$ larger compared with single charge state acceleration

Extra

MCA and overall stripping efficiency (RIA proposal)
### Stripping technique drawbacks

<table>
<thead>
<tr>
<th>Drawback</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>☹ Needs pre-acceleration</td>
<td>In gas stripping 8 to 20 keV/u</td>
</tr>
<tr>
<td>☹ Emittance increase</td>
<td>In foil stripping ~500 keV/u</td>
</tr>
<tr>
<td>☹ Emittance increase</td>
<td>Energy straggling</td>
</tr>
<tr>
<td>☹ Emittance increase</td>
<td>Angular straggling</td>
</tr>
<tr>
<td>☹ No macro-bunching capability</td>
<td>=&gt; CW accelerator needed</td>
</tr>
<tr>
<td>☹ Foil lifetime</td>
<td>1. Radiation damage</td>
</tr>
<tr>
<td>☹ Foil lifetime</td>
<td>2. Sublimation at high power levels (&gt;150 W/cm²)</td>
</tr>
<tr>
<td>☹ Foil lifetime</td>
<td>=&gt; Not limiting for radioactive beam intensities</td>
</tr>
<tr>
<td>☹ Limited efficiency for high-Z elements</td>
<td></td>
</tr>
</tbody>
</table>

Energy straggling:

\[
\theta_{T1/2}^2 = \theta_{I1/2}^2 + \theta_{S1/2}^2
\]

Angular straggling:

\[
\varepsilon_T = \pi \cdot x_{T1/2} \cdot \theta_{T1/2}
\]

- \(x_{T1/2}\) = incident beam spot size
- \(\theta_{T1/2}\) = divergence exiting beam
- \(l\) = Incident, \(T\) = traverse, \(S\) = Scattering

\[
I_{1/2} = \text{incident beam spot size}
\]

\[
T_{1/2} = \text{divergence exiting beam}
\]
The Second Alternative

Stripper foil

ECR plasma

EBIS beam

Fast ions

Slow electrons

Slow ions

Fast electrons

Slow ions

Q+

Q+
ECRIS as charge breeder

General principle
- inject very slow ions through a plasma of hot e⁻
ECRIS physics

‘Magnetic bottle’ confinement of plasma
* Longitudinally by Helmholtz coils
* Radially by powerful permanent multipole
  => min-B field – increases in all directions

\[ \omega_e = \frac{e \cdot B}{m} = \omega_{rf} \]

\[
\begin{align*}
q \cdot v \cdot B &= m \cdot \omega^2 \cdot r \\
\omega &= \frac{v}{r} \\
r &= \frac{m \cdot v}{q \cdot B}
\end{align*}
\]

\( B = 1 \text{T} \)
\( f = 28 \text{ GHz} \)
\( r_{\text{Larmor}} = 0.01 \ldots 1 \text{ mm} \)

Photo of plasma

\[ \text{Electron confinement time: } \tau_e = \frac{T_e^{3/2}}{n_e} \cdot \text{const} \]

\( \text{e}^- \) temperature distributions
Cold <200 eV: lowest confinement time
Warm < 100 keV: ionization process
  (main source of bremsstrahlung)
Hot > 100 keV: highly confined
What RF is needed?

- To produce Ar\(^{16+}\)\( ne = 5\times 10^{16}\) s/m\(^3\)
- Typical confinement time 0.1 s
  => need \( n_e \approx 1\times 10^{12}\) cm\(^{-3}\)

Extra
- Compare with stripper foils
  \( n_e \approx 1\times 10^{24}\) cm\(^{-3}\) inside the foil
  \( v_{ion} = 1\times 10^{9}\) cm/s, \( d_{carbon_foil} = 0.5\) um
  => \( n_e \times \tau = 5\times 10^{10}\) s/cm\(^3\)

\( f_{RF} \) needs to be higher than the plasma frequency \( f_p \) (cut-off frequency)

\( n_e < 1.2\times 10\ f_{RF}^2\) cm\(^{-3}\)
\( f_{RF} = \) in gigahertz

\( \omega_p = \sqrt{\frac{e^2 n_e}{\varepsilon_0 m_e}} \)
We know \( n_e \sim 1 \times 10^{12} \ \text{cm}^{-3} \) for charge breeding ECRIS

Assume:

* plasma volume \( r=2 \ \text{cm}, l=10 \ \text{cm} \)
* confinement time 0.1 s
* 10% radioactive ions
* 20% in the desired charge state 10+

\[ \Rightarrow 2.5 \times 10^{12} \ \text{radioactive ions/s extracted (0.4 puA)} \]

Beam injected into a PHOENIX CB
from >2\mu A of In+ down to <100pA

The large capacity – a major strength of the ECRIS CB concept!
Stopping ions in ECRIS plasma

1\textsuperscript{st} electrostatic slow-down
2\textsuperscript{nd} subsequent long-range ion-ion Coulomb collisions lead to 90° deflection*
3\textsuperscript{rd} ionized
=> Ions trapped

* Cumulative deflection due to small-angle scattering is larger than those due to single large-angle scattering (Spitzer/Chandrasekhar theory)

Mean free path for 90° deviation smaller than plasma size?

\[ \lambda_{90°} \approx \frac{W_a}{4\pi n_e z_a z_b e^2 \ln \Lambda} \]

\( W_a = 10 \text{ eV} \quad z_a = 1, \quad z_b = 10, \quad \ln \Lambda = 10 \)

=> \( \lambda_{90°} \approx 5 \text{ cm} \)
Injection velocity into ECR plasma

What is the optimal velocity for stopping inside a plasma?

\[ \frac{\Delta v_a}{\Delta t} \sim \frac{n_b}{2\pi\varepsilon_0} \left[ \frac{Z_a Z_b e^2}{m_a \bar{v}_b} \right]^2 R(u_{ab}) \ln \Lambda \]

**Assumption**
1. low intensity of injected particles
2. only interaction via long distance cumulative plasma collisions
3. plasma particles Maxwellian velocity distribution
4. distance between 90° deviations < plasma size

**Example**
* ECR oxygen plasma T⁺ = 2 eV
* Rb⁺⁺ ISOL ions
  \[ \Rightarrow E_{inj}(\text{Rb}^{++}) \sim 2\text{eV} \times \frac{m_{\text{Rb}}}{m_\text{O}} \sim 10 \text{eV} \]

If we’d like to inject \(^{11}\text{Li}^+\), optimum energy would be <2 eV => difficult

**Optimal slowing down when:**
\[ v_{\text{injected particle}} = <v> \text{ plasma particles} \]

**Compatible with previous slide!**
Longitudinal acceptance

\[ \Delta U = U1 - U2 \]

Potential distribution for ion injection

- \( U_1 \) = plasma potential
- \( U_2 \) = plasma chamber potential
- \( \Delta U \) curve for efficiency yield (%) on the most abundant \( n \) charge state.

Noble gases
- wall recycling

Condensable/metallic elements
- only one trapping chance

Mean sojourn time given by Frenckel’s law

\[ \tau_d = \tau_0 e^{E_d / k_B T} \]

\( \tau_0 \sim 1 \times 10^{-13} \) s, \( E_d \) – binding energy

Wide range: Ar \( 1 \times 10^{-11} \) s, Ni 100 years

\[ \Delta V \text{ tuning} \]

Extra

- \( W_{\text{inj}} \)
  - too high
  - too low

Noble gas
- 1+ beam extraction voltage

Metallic ions

Ionization efficiency vs injection voltage

Plasma chamber high voltage
The attainable charge state is mainly depending on the:
- electron density $n_e$
- confinement time $\tau_{\text{ion}}$
- electron energy distribution EEDF

In reality adjust:
1. RF power $Q_{\text{opt}} = P_{RF}^{1/3}$
2. buffer gas pressure or mixture -> ion-ion cooling
   charge exchange probability
3. $B_{\text{ext}}$ since $Q_{\text{opt}} \propto \ln B_{\text{ext}}$

$F_z = -\frac{1}{2} \frac{m v_r^2}{B} \frac{\partial B_z}{\partial z} = -\mu \frac{\partial B_z}{\partial z}$

Conserved
- total energy
- magnetic moment $\mu$

$\Rightarrow$ Magnetic bottle

$\text{longer } \tau_e \Rightarrow \text{longer } \tau_{\text{ion}}$
* Extracted energy spread few eV

* Total $I_{\text{extracted}} \sim 100 \mu\text{A}$:
  + radioactive ions
  - buffer gas ions (He, Ne or O)
  - ions from the plasma chamber
    sputtering of chamber material
    desorption of implanted ions – memory effect

Loss lines for a hexapole structure
ECRIT mode

Normal operation mode:
cw injection
cw extraction

Make use of afterglow:
1. Switch off RF
2. Heating of electrons stops
3. Electron confinement stops
4. Plasma instability / Coulomb expulsion of trapped ions

Result:
a. ion trapping (some 100 ms)
b. pulsed beam extraction (some ms)

Pulsed linac operation possible
Practical design aspects

* Similar magnetic-field relations for charge breeding ECRIS CB as for high-Q ECRIS:

\[ \frac{B_{\text{inj}}}{B_{\text{ecr}}} \approx 4, \frac{B_{\text{ext}}}{B_{\text{ecr}}} \approx 2, \frac{B_{\text{min}}}{B_{\text{ecr}}} \approx 0.8, \frac{B_{\text{rad}}}{B_{\text{ecr}}} > 2, \frac{B_{\text{ext}}}{B_{\text{rad}}} < 0.9 \]

\( B_{\text{inj}} (B_{\text{ext}}) \) is the B-field max at injection side (extraction side)

\( B_{\text{rad}} \) the radial B-field of the sextupole at the plasma chamber wall

\( B_{\text{min}} \) the minimum B-field between the magnetic mirrors

* Grounded injection tube just inside \( B_{\text{inj}} \)

* Radial RF injection preferred to axial

---

Radial RF wave-guide

Better pumping of the chamber

Only put plasma chamber on HT, keep source body at ground

Symmetrical B-field at injection region

Movable grounded injection tube

RF injected radially

Axial RF wave-guide

Asymmetric B-field deflects injected particles
**ECRIS CB facility**

- ECRIS charge breeder specifications: \( A/Q < 7 \) for \( A < 150 \)
- \( cw \) injection and extraction
- Superconducting linac
- Combined electrostatic and magnetic selection
The Third Alternative

Stripper foil
- Fast ions
- Slow electrons
- Q+

ECR plasma
- Slow ions
- Fast electrons
- Q+

EBIS beam
- Fast electrons
- Slow ions
- Q+
• Produces highly charged ions
• $e^{-}$ beam compressed by solenoid B-field
• Ions are trapped in a magneto-electrostatic trap
• Ionisation by $e^{-}$ bombardment from a fast, dense mono-energetic $e^{-}$ beam

Electron Beam Ion Source / Trap

EBIT - in principle an EBIS but:
1. higher electron current density
2. shorter (few cm)
3. smaller $r_{ebeam}$

Some consequences for CB!
Breeding time

The average time necessary to reach the charge state \( q \):

\[
\bar{\tau}_q = \sum_{i=1}^{q-1} \bar{\tau}_{i \rightarrow i+1} = \frac{1}{j_e} \sum_{i=1}^{q-1} \frac{e}{\sigma_{i \rightarrow i+1}}
\]

- \( \bar{\tau}_q \) – time necessary to reach charge state \( q \)
- \( \sigma \) – single ionization cross-section cm\(^2\)
- \( j_e \) – electron current density A/cm\(^2\)
- valid for mono-energetic electrons

- \( j_e \) usually machine fix
- \( j_e \) between 50 and 5000 A/cm\(^2\)

\( \Rightarrow \) Chose \( A/Q \) by adjusting the breeding time

\[ t = 78 \text{ ms} \quad j_e \sim 100 \text{ A/cm}^2 \]

\[ t = 158 \text{ ms} \quad j_e \sim 100 \text{ A/cm}^2 \]

NB! \( I_e = j_e \times r_{beam}^2 \times \pi \)  
1\(^{st}\) reason for high \( I_e \)
Ion injection EBIS

Desired: overlap between injected ion beam and electron beam
If injection outside electron beam => effective \( j_e \) low => increased \( T_{\text{breed}} \)

\[
\alpha_{\text{max}} = \pi \frac{r_{\text{ebeam}}}{\sqrt{2U_{\text{ext}}}} \cdot \left( Br_{\text{ebeam}} \sqrt{\frac{q}{m}} + \sqrt{\frac{qB^2 r_{\text{ebeam}}^2}{4m}} + \frac{\rho_i}{2\pi \varepsilon_0} \right)
\]

Geometrical transverse acceptance

NB1. ion neutralization reduces the acceptance

NB2. + EBIS/T small \( \varepsilon \) -\>
  - EBIS/T small \( \alpha \)

* REXEBIS value \( \sim 10 \pi \text{ mm mrad} \)
  for 90% @ 60 keV

2nd reason for large \( l_e \)
**CW ion injection EBIS**

**Condition for trapping**

1. Transverse ionization acceptance
2. Ionization acceptance

No dissipative forces but

$U_{\text{barrier}}$ doubles when $1^+ \rightarrow 2^+$

$\Rightarrow$ axially confined

$t_{1\rightarrow2} \rightarrow e/(\sigma_{1\rightarrow2} \cdot j_e)$

$\text{Prob}(1^+ \rightarrow 2^+) = 1 - \exp(-t_{\text{inside_ebeam}}/t_{1\rightarrow2})$

Example $^{14}\text{N}$

$\sigma_{1\rightarrow2} = 1 \times 10^{-17} \text{cm}^2$

$j_e = 200 \text{ A/cm}^2$

$\text{Prob} = 0.5$

$\mathbf{t_{1\rightarrow2} = 55 \text{ us}}$

Thus:

Inject with low energy for long round-trip time

But too low energy $\Rightarrow$ magnetic reflection

High acceptance for a CW injected beam is obtained, if $L_{\text{trap}}$ long and $r_{\text{ebeam}}$ large and $j_e$ large

(last two in contradiction as $l_e = j_e \cdot r_{\text{ebeam}}^2 \cdot \pi$)
Reality even more complicated...

1. Entangled parameters
2. Benefits from reduced emittance

→ preparatory RFQ buffer gas cooler or Penning trap

Longitudinal acceptance:

\[ W_{\text{inj}} < e \cdot U_{\text{well}} \quad \text{(some 100 eV)} \]

\[ \Delta T < 2 \cdot L_{\text{trap}} / v_{\text{inj}} \sim 50 \text{ us} \]

\[(L_{\text{trap}}=1 \text{ m}, W_{\text{inj}}=100 \text{ eV}, A=14)\]

Radial potential

U_{\text{well}} = \frac{I_e}{4\pi\varepsilon_0} \sqrt{\frac{m_e}{2eU_e}}

I_e – electron beam (A)
U_e – electron beam voltage (V)
How to choose electron beam energy $U_e$ for charge breeders?

1. Related to the available current through the perveance: $I_e = PU_e^{3/2}$ (practical limit $P \sim 5$ uPerv)
   Example $I_e = 1$ A  $\Rightarrow$  $U_e > 3500$ eV

2. $U_e$ has to be larger than the ionization potential $I_p$ for required charge state $Q$.
   Worst case - reach elements close to neutron dripline, since excess of neutrons.

<table>
<thead>
<tr>
<th>Z</th>
<th>A (neutron rich)</th>
<th>Q (A/Q~4)</th>
<th>$I_{ionization}$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>60</td>
<td>15</td>
<td>900</td>
</tr>
<tr>
<td>40</td>
<td>110</td>
<td>27</td>
<td>1500</td>
</tr>
<tr>
<td>60</td>
<td>161</td>
<td>40</td>
<td>2800</td>
</tr>
<tr>
<td>80</td>
<td>210</td>
<td>52</td>
<td>3100</td>
</tr>
</tbody>
</table>

Cross section max at $2.7 \times I_{ionization}$

$\Rightarrow$ No need for $U_e > 9000$ eV
Space charge capacity – determined mainly by the electron beam

\[ N^- = k \frac{L_{\text{trap}} r_{\text{beam}}^2 \pi}{e} \rho_e \quad \rho_e = \frac{j_e}{v_e} = \frac{I_e}{\pi \cdot r_{\text{beam}}^2} \sqrt{\frac{m_e}{2eU_e}} \]

\[ N^- = 1.05 \cdot 10^{13} \frac{kL_{\text{trap}} I_e}{\sqrt{U_e}} \]

\( N^- \) = number of elementary charges

\( I_e \) and \( U_e \) = electron beam current and energy

\( k \) = attainable space charge compensation degree

\( L_{\text{trap}} \) = trap length

Example \(^{132}\text{Sn}^{34+}\) using REXEBIS parameters:

\( I_e = 0.5 \text{ A}, \quad U_e = 5 \text{ keV}, \quad L = 0.8 \text{ m}, \quad k = 50\% \Rightarrow \sim 3 \cdot 10^{10} \) charges

\( \Rightarrow 3E10/34*0.2 = 2E8 \text{ ions/pulse} \)

\( \sim 20\% \) in desired charge state

\( \text{NB! Ion throughput (ions/s)} = \frac{\text{ions/pulse}}{T_{\text{breed}}} \)
Beam extraction scenarios

For REXEBIS duty factor
\[ \frac{T_{\text{extr}}}{T_{\text{breed}}} \sim 100 \text{ us} / 100 \text{ ms} \]

=> Good signal-to-noise-ratio

if heating by e- and ion-ion cooling neglected

\[ v_{\text{ion\_extr}} \sim v_{\text{ion\_inj}} \left( W_{\text{inj}} \sim 100 \text{ eV} \right) \]

\[ \Delta T_{\text{extr}} \sim \frac{L_{\text{trap}}}{v_{\text{ion\_extr}}} \sim 25 \text{ us for } ^{14}\text{N} \]

Reduce instantaneous rate to experiment, 1 ms

Speed up extraction for multi-turn injection into synchrotron <10 us
EBIT CB facility

3 MeV/u re-accelerator of thermalized projectile fragmentation and fission beams

Design goals
– Continuous injection and accumulation of ions
– Variable extraction duty cycle
  (ms pulse to quasi-continuous)
– Electron current density >1E4 A/cm²
– Beam rates >1E9 ions/s
– Highest efficiency
  (> 50% in a single charge state)

With 1E4 A/cm² ->
1. charge breed ions with Z<35 into Ne-like or higher within 10 ms
2. ionize from 1+ to 2+ within <1 us

MSU-EBIT for ReA3

Cryogenic trapping region
Preparatory devices and tricks
Remember: often deal with $<10^4$ pps $\Rightarrow 1.7$ fA

Beam impurities:
- a. isobaric contamination from ISOL-target

Beam contamination
Can’t see the trees for the forest

1 GeV proton beam on a lanthanum (La) target.

- $^{132}$Cs
- $^{132}$Sn

Production rate (a.u.)

Isotope mass [amu]

J. Lettry, V. Fedoseev (CERN)
For most cases a resolution of about $m/\Delta m = 20,000$ is adequate at mass $A=100$ to obtain a separation between isobars of mass excess difference of 5 MeV.

Near $\beta$-stability $Q_{\beta} < 1$ MeV, for $A=100 \Rightarrow$ resolving power $>1E5$

Far from $\beta$-stability $Q_{\beta}$ is 3-10 MeV, resolution of 1000-30000 sufficient.

Problem: isobaric separation difficult

* Requires RFQ cooler for pre-cooling of transverse $\varepsilon$

* Tails of high intensity masses may go through selection system

Resolution required to separate:

| Neighbouring mass: | $R=250$ |
| Molecular ions (e.g. CO from $N_2$): | $R=500-1000$ |
| Isobars (e.g. $^{96}$Sr from $^{96}$Rb): | $R=5000-50000$ |
| Isomers: | $R=1E5 - 1E6$ |

Solution

1. Isobaric mass resolution inside Penning trap
2. Molecular beams
Preparatory beam cooling

Introduce a *Penning trap* in ISOL-line to:

- accumulate
- phase space cool
- bunch the beam

With buffer gas and RF coupling between $v_+$ and $v_-$ all three motions cooled $\Rightarrow$ amplitudes reduced
**REX-ISOLDE**

- **9-GAP RESONATOR** @ 202.56 MHz
- **7-GAP RESONATORS** @ 101.28 MHz
- IHS
- RFC
- **MASS SEPARATOR**
- **REXTRAP** 60 keV
- **REXEBIS**

**Penning trap**

**Charge breeder**

**Non-cooled**

**Cooled**

* Bunching: few us
* Transverse emittance: $25 \rightarrow \sim 10 \pi \text{ mm.mrad at } 30 \text{ keV}$
* $\Delta E \cdot \Delta t \sim 10 \text{ eVps}$

**EBIS injection ok!**
Resolving isobars in Penning trap

* Low $m/\Delta m \sim 300$ in REXTRAP in normal mode
* Can be setup with $m/\Delta m > 10000$

Procedure

- cool down the ion cloud (normal operation)
- shift out the ion cloud (desired and contaminants) with a mass independent dipolar excitation $v_{RF} = \nu_0$ to $r > 5$ mm
- selectively re-centre the desired species with $v_{RF} = \nu_c$
- at extraction only the centered ions survive

$$\omega \pm = \frac{\omega_c}{2} \left( 1 \pm \sqrt{1 - \frac{2 \omega_z^2}{\omega_c^2}} \right)$$

$\omega_+ + \omega_- = \omega_c = \frac{e}{m} B$

Shrink all
Shift out
Re-center selectively

NB! Re-centering is mass dependent

1. Use chemical properties to separate isobars e.g. $^{96}\text{Rb}$ from $^{96}\text{Sr}$

2. Create a molecular sideband ($^{96}\text{Sr}^{19}\text{F}^{+}$) with gas leak at ISOL-target

3. Molecular ions are extracted and selected in the separator (A=115 selection)

4. Keep molecules inside trap, break them in EBIS

5. Charge breed as usual and obtain clean $^{96}\text{Sr}$
Beam contamination
Can’t see the trees for the forest

Beam impurities:
- a. isobaric contamination from ISOL-target
- b. residual gases in CB

Remember: often deal with <1E4 pps => 1.7 fA

$$I_{\text{residual}} \propto \sigma_{0->1+} P_{\text{res gas}}$$

What’s problem?

Yield = C . \( \sigma \) . \( \varepsilon \) . \( \Sigma_{i_{\text{beam}}} \)

10\% impurity small correction
75\% impurity determine Z e-by-e
99\% impurity difficult

EBIS extracted spectrum

Radioactive

\( ^{22}\text{Ne}^{7+} \)

A/q = 3

\( ^{28}\text{Mg}^{7+} \)

A/q = 3.1111

Blue – with \(^{28}\text{Mg}\)
magenta - background

J. Lettry, V. Fedoseev (CERN)
Separator after breeder

1. **Separator magnet** selects $A/Q$

   $$B_p = \frac{A\Delta v}{Q}$$

   ambiguous $A/Q$ if $\Delta v$ large

   $$\frac{\Delta x}{x} \approx \frac{\Delta A}{A} + \frac{\Delta v}{v}$$

Combine 1 & 2 $\Rightarrow E_{\text{def}} r_{\text{def}} = (B_p)^2 \frac{(A/Q)}{A}$

* Only a single $A/Q$ transmitted
* Can suppress ions with wrong energy

Even so, some $A/Q$ contaminants difficult to resolve

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Mass</th>
<th>Charge</th>
<th>R (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^7\text{Be}$</td>
<td>$^{14}\text{N}$</td>
<td>$^{15}\text{N}$</td>
<td>450</td>
</tr>
<tr>
<td>$^{18}\text{F}$</td>
<td>$^{12}\text{C}$</td>
<td>$^{13}\text{C}$</td>
<td>19200</td>
</tr>
</tbody>
</table>

$$\frac{\Delta(A/Q)}{(A/Q)}$$ typically a few hundred

for a breeder separator
Facilities and the future
**CB for low-energy experiments**

* Not only for post-acceleration!

High precision mass measurements

\[
\frac{\Delta m}{m} \sim \frac{m}{qT_{rf} B \sqrt{N}}
\]

m – ion mass  
q – ion charge  
\(T_{rf}\) – rf excitation time  
B – magnetic field  
N – number of measurements

Ideally only one ion per measurement cycle
Charge breeders for RIBs worldwide

- **ISAC, TRIUMF**
  - *ECRIS* (Operation)

- **REX-ISOLDE, CERN**
  - *EBIS/ECRIS* (Operation/Stopped)

- **KoRIA**
  - *ECRIS and EBIS* (Design)

- **TITAN, TRIUMF**
  - *EBIT* (Operational)

- **ARIEL, TRIUMF**
  - *EBIS?* (Planning)

- **EURISOL, Europe**
  - *EBIS/ECRIS* (Design)

- **TRIAC, JAERI**
  - *ECRIS* (Stopped)

- **ReA, MSU**
  - *EBIT* (Commissioning)

- **CARIBU, ANL**
  - *ECRIS/EBIS* (Operation/Commissioning)

- **SPIRAL/SPIRAL2**
  - *ECRIS* (Design)

- **SPES, LNL**
  - *ECRIS* (Design)

- **VECC**
  - *ECRIS* (Commissioning)
Radioactive ISOL beam yields

What to expect?

Next generation facilities

* Increased intensities

* Shorter half-life along drip lines

J. Äystö & P. Butler

* Challenges with EURISOL

Take data from Wenander JINST
Two main paths

1. Very exotic low-intensity (<1E7 ions/s) beams for ‘standard’ experiments

2. High intensity beams (>1E9 ions/s) to generate even more neutron rich beams – beam purity not of utmost importance

Further information
‘Final Report of the EURISOL design study’
Nov 2009

What to expect?

The real challenges:

1. Inject ions into storage rings ⇒ fully stripped charge for Z>60

2. Breeding of beta beams (e.g. $^6$He and $^{18}$Ne)
⇒ 1 s trapping of high intensity
<table>
<thead>
<tr>
<th>Extra</th>
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<tbody>
<tr>
<td></td>
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<table>
<thead>
<tr>
<th>Weight function according personal preference</th>
</tr>
</thead>
<tbody>
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<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Simple &amp; Complicated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Simplicity</th>
<th>Stripper</th>
<th>EBIS</th>
<th>ECRIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>3, passive element</td>
<td>1, complicated (SC, UHV, e-gun)</td>
<td>2, medium (RF, beam tuning)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Beam properties in</th>
<th>Stripper</th>
<th>EBIS</th>
<th>ECRIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>3, no special requirements</td>
<td>1, bunched, small acceptance</td>
<td>2, CW, medium acceptance</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Beam properties out</th>
<th>Stripper</th>
<th>EBIS</th>
<th>ECRIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, emittance blow-up</td>
<td>3, us or ms bunch, small emittance</td>
<td>2, CW or ms bunch</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Low intensities</th>
<th>Stripper</th>
<th>EBIS</th>
<th>ECRIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>3, no contamination</td>
<td>2, some &lt;0.1 pA</td>
<td>1, high rest-gas level</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rapidity</th>
<th>Stripper</th>
<th>EBIS</th>
<th>ECRIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>3, instant, us isotopes</td>
<td>2, 10 to few 100 ms</td>
<td>1, some 10 ms to a few 100 ms</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CSD</th>
<th>Stripper</th>
<th>EBIS</th>
<th>ECRIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>3, narrow, varying charge state</td>
<td>3, narrow, high charge state</td>
<td>2, broad CSD, moderate charge</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CSD tuning</th>
<th>Stripper</th>
<th>EBIS</th>
<th>ECRIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, not tunable</td>
<td>3, change $T_{breed}$</td>
<td>2, many parameters</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Machine contamination</th>
<th>Stripper</th>
<th>EBIS</th>
<th>ECRIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>2, foil exchange</td>
<td>1, multiple parts</td>
<td>2, change plasma liner</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Storage time</th>
<th>Stripper</th>
<th>EBIS</th>
<th>ECRIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, non existing</td>
<td>3, up to several s</td>
<td>2, ~100 ms</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Beam capacity</th>
<th>Stripper</th>
<th>EBIS</th>
<th>ECRIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>3, very high, 100 uA</td>
<td>1, limited to nA</td>
<td>2, several uA</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy spread</th>
<th>Stripper</th>
<th>EBIS</th>
<th>ECRIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, $\Delta W/W \approx 1%$</td>
<td>2, a few 10 eV*q</td>
<td>3, some eV*q</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Stripper</th>
<th>EBIS</th>
<th>ECRIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>2, 5-15%</td>
<td>2, 5-20%</td>
<td>2, 5-20%</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass range</th>
<th>Stripper</th>
<th>EBIS</th>
<th>ECRIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, heavy masses difficult</td>
<td>3, full mass range</td>
<td>1, light masses difficult</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Life-time</th>
<th>Stripper</th>
<th>EBIS</th>
<th>ECRIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>2, foil breakage, 50 mC/cm²</td>
<td>1, electron cathode</td>
<td>3, klystron lifetime</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Price</th>
<th>Stripper</th>
<th>EBIS</th>
<th>ECRIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 high, (incl. pre-acc)</td>
<td>2, ~1 Meuro</td>
<td>3, ~0.5 Meuro</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weight function according personal preference</th>
<th>Stripper</th>
<th>EBIS</th>
<th>ECRIS</th>
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<tbody>
<tr>
<td>Extra</td>
<td>}</td>
<td>}</td>
<td>}</td>
</tr>
</tbody>
</table>
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- Charge breeding results and future prospects with electron cyclotron resonance ion source and electron beam ion source, R. Vondrasek, Rev. Sci. Instrum. 83, 02A913 (2012)
- Charge breeding of radioactive ions with EBIS and EBIT, F. Wenander, J. Instrum. 5, C10004 (2010)

Miscellaneous relevant conference proceedings
- International Workshop on ECR ion sources
- International Symposium on EBIS/T
- Radioactive Nuclear Beams (discontinued)
- International Conference on Electromagnetic Isotope Separators and Techniques Related to their Applications (EMIS2012)

http://www.eurisol.org/  Task 9