EBIS/T charge breeders: news and future trends

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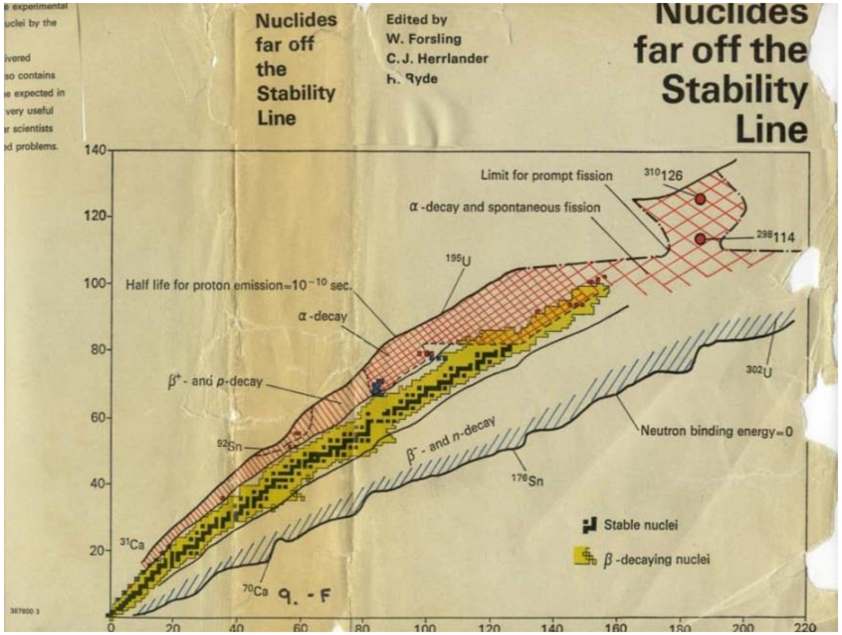
60 YEARS / ANS CERN

EBIS/T charge breeders:
news and future trends

First ideas/suggestions for post-acceleration of radioactive ion beams: “Nuclides far off the Stability Line” (1966) Sweden

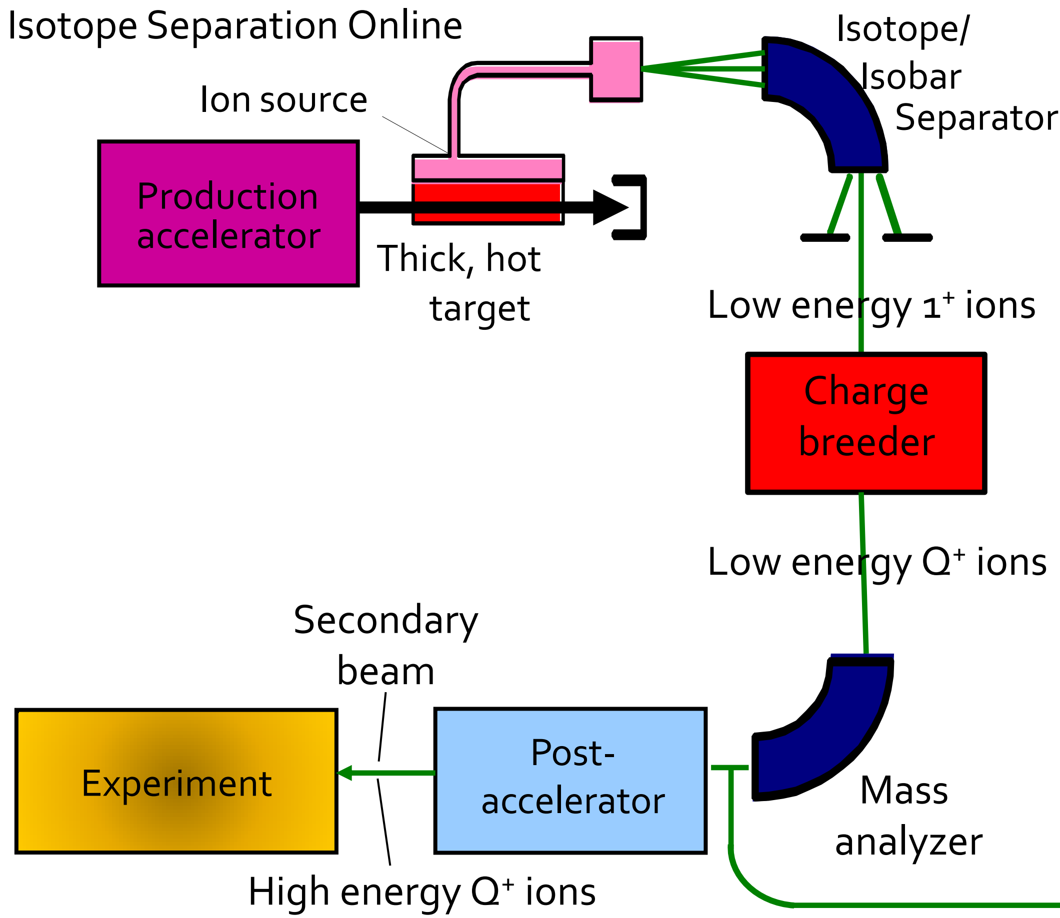
“…rich field of information that would be opened by a possible future use of unstable targets and projectiles in nuclear reaction studies.”



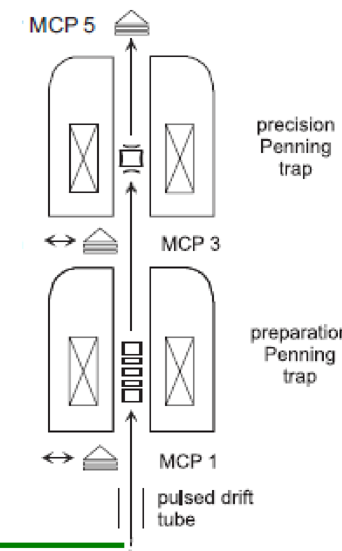
Courtesy of M. Huyse

Background

Two applications
different requirements



M. Mukherjee et al.
Eur. Phys. J. A 35, 1–29 (2008)



1. Post acceleration

Energy (few MeV/u) $\propto$ q in linac; q^2 in cyclotron

Short & compact accelerator

Typically $3 < A/q < 9$

2. Trap mass measurement

$m/\Delta m \propto (q \cdot B/m) \cdot T_{rf} \cdot \sqrt{N}$

Emphasize
- * Few ions
- * High charge state
- * Fast breeding

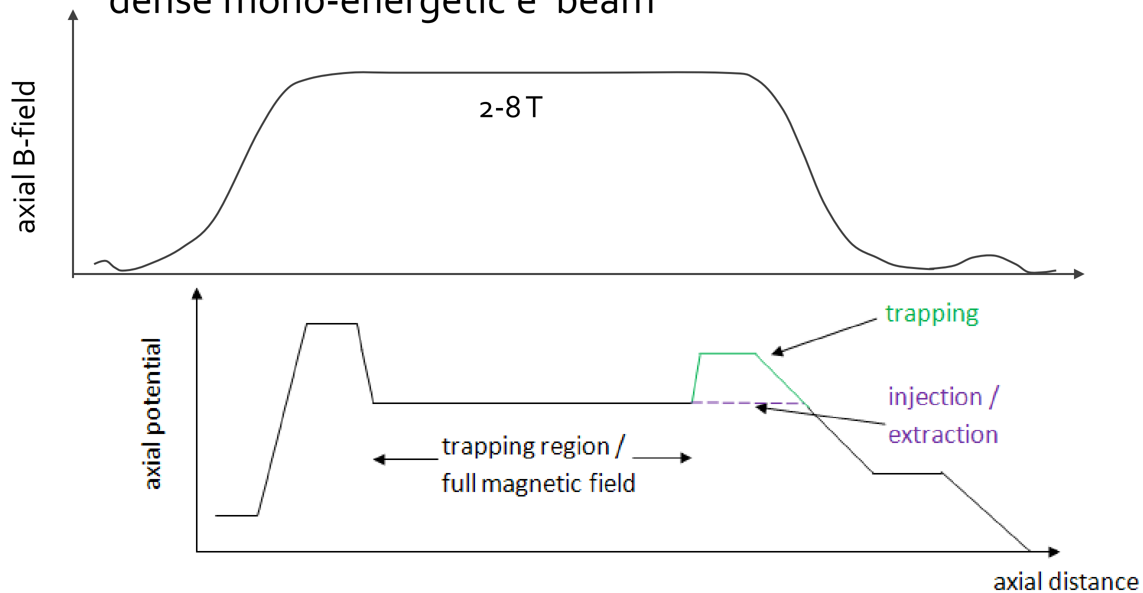
Electron Beam Ion Source / Trap

* Produces highly charged ions

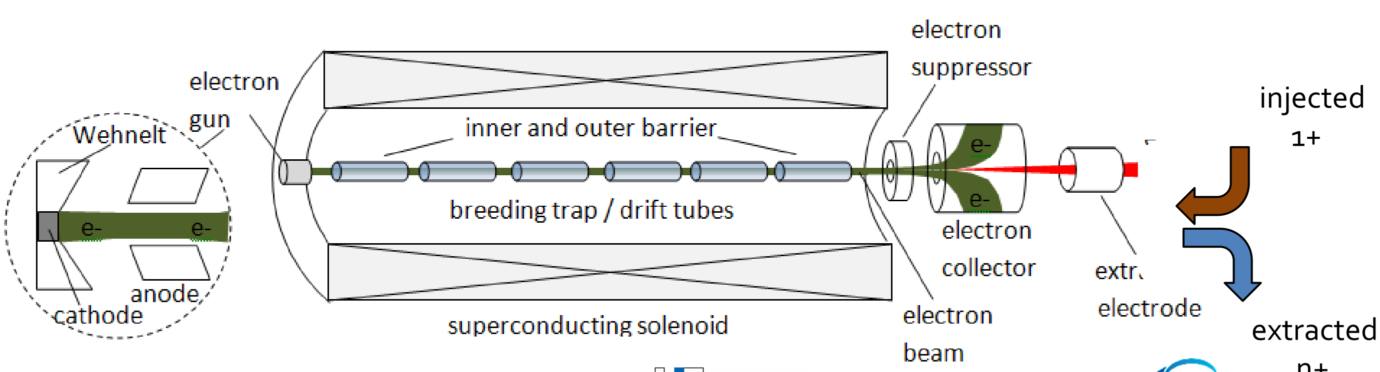
* e^- beam compressed by solenoid B-field

* Ions are trapped in a magneto-electrostatic trap

* Ionisation by e^- bombardment from a fast, dense mono-energetic e^- beam



* Essentially a pulsed device
* UHV device ($<10^{-9}$ mbar)
* Superconducting magnet



EBIS/T parameters

Breeding time

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

-> Chose A/q by adjusting the breeding time

j_e between <50 and 5000 A/cm²

Current density

$$j_e = \frac{I_e}{\pi r_{ebeam}^2}$$

-> High j_e requires small electron beam radius or high current

Ion capacity

$$N^- = 1.05 \cdot 10^{13} \frac{k L_{trap} I_e}{\sqrt{U_e}}$$

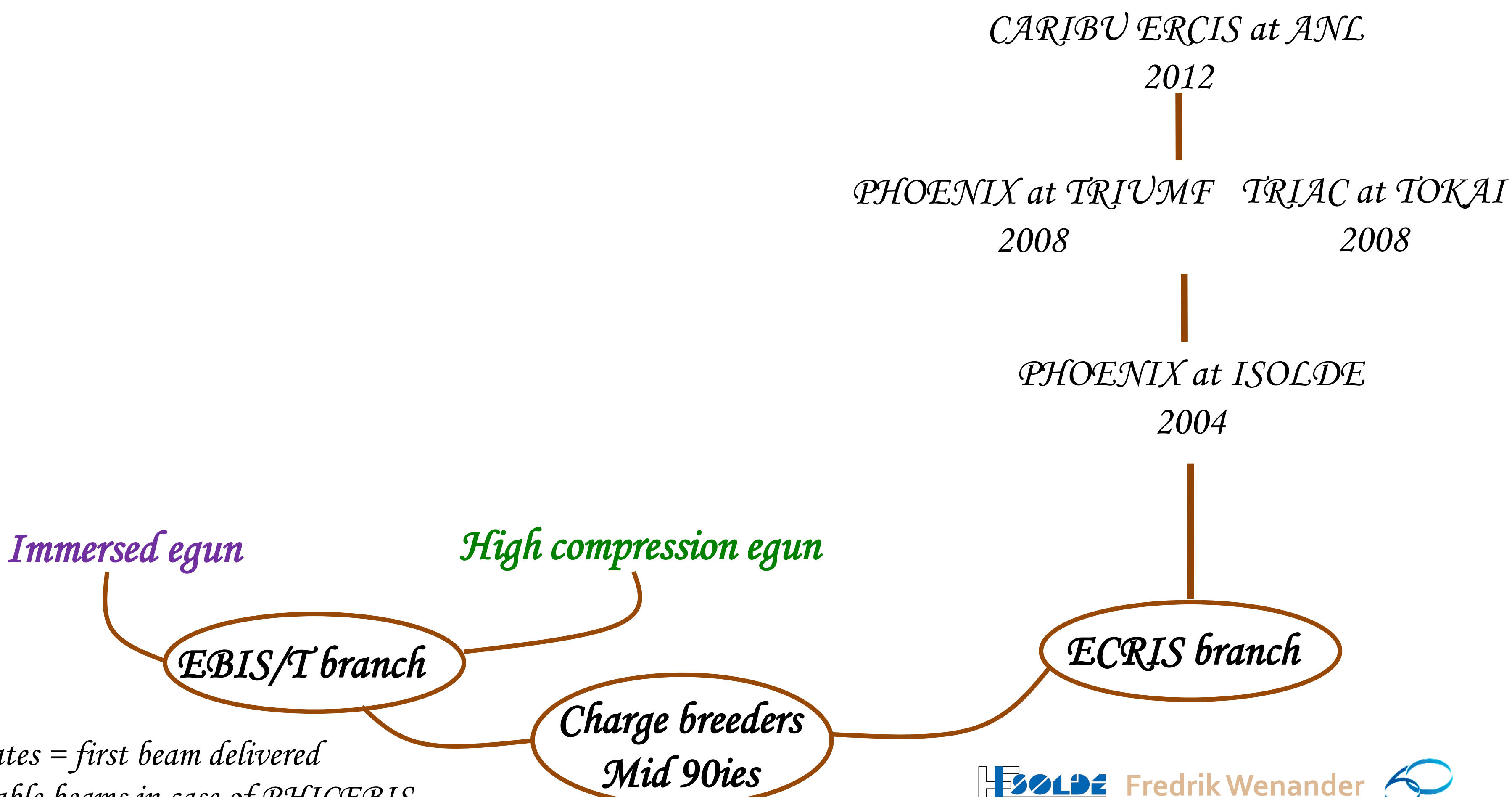
Example $^{132}Sn^{34+}$ using REXEBIS parameters:
I_e = 0.25 A, U_e = 5 keV, L = 0.8 m, k = 50% => ~$1.5 \cdot 10^{10}$ charges
=> $1.5 \cdot 10^{10}$ / 34 x 0.2 ~ **10^8 ions in one charge state per pulse**

~20% in desired charge state

Electron energy

E_e should be ~3 x highest requested ionization potential
for A/q=4 beams ~ 5 to 10 keV is sufficient
for Li-like uranium 150 keV is required

Genealogy



Dates = first beam delivered
Stable beams in case of RHICEBIS

Genealogy

CARIBU ERCIS at ANL
2012

PHOENIX at TRIUMF
2008

TRIAC at TOKAI
2008

PHOENIX at ISOLDE
2004

ECRIS branch

* E- and B-field compression
* >10000 A/cm^2 in trapping region but I_e <100 mA
* currents up to ~1 A, but then lower j_e

High compression egun

* B-field compression
* <600 A/cm^2 in trapping region
* currents up to 20 A

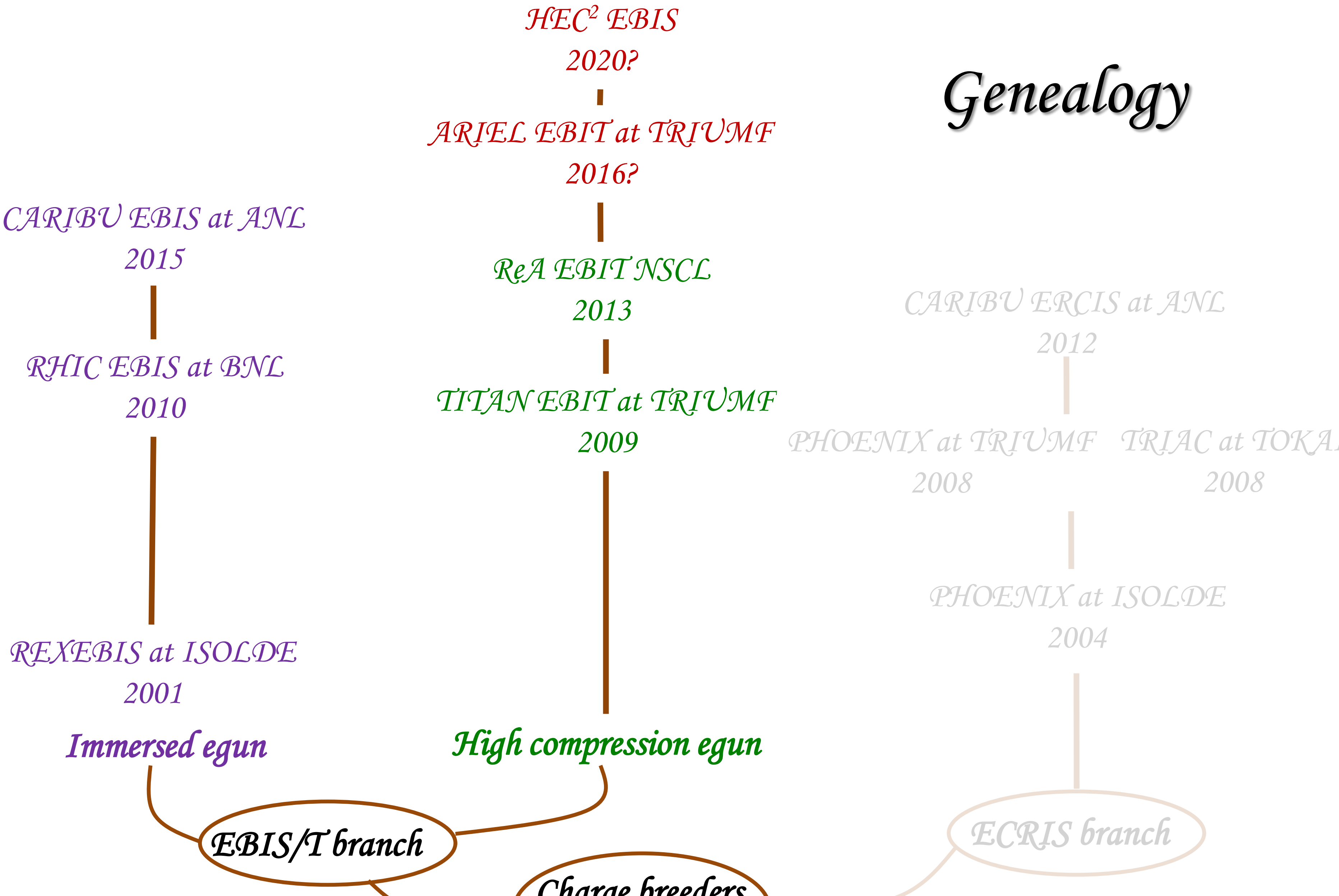
Immersed egun

EBIS/T branch

Charge breeders
Mid 90ies

Dates = first beam delivered
Stable beams in case of RHICEBIS

Genealogy

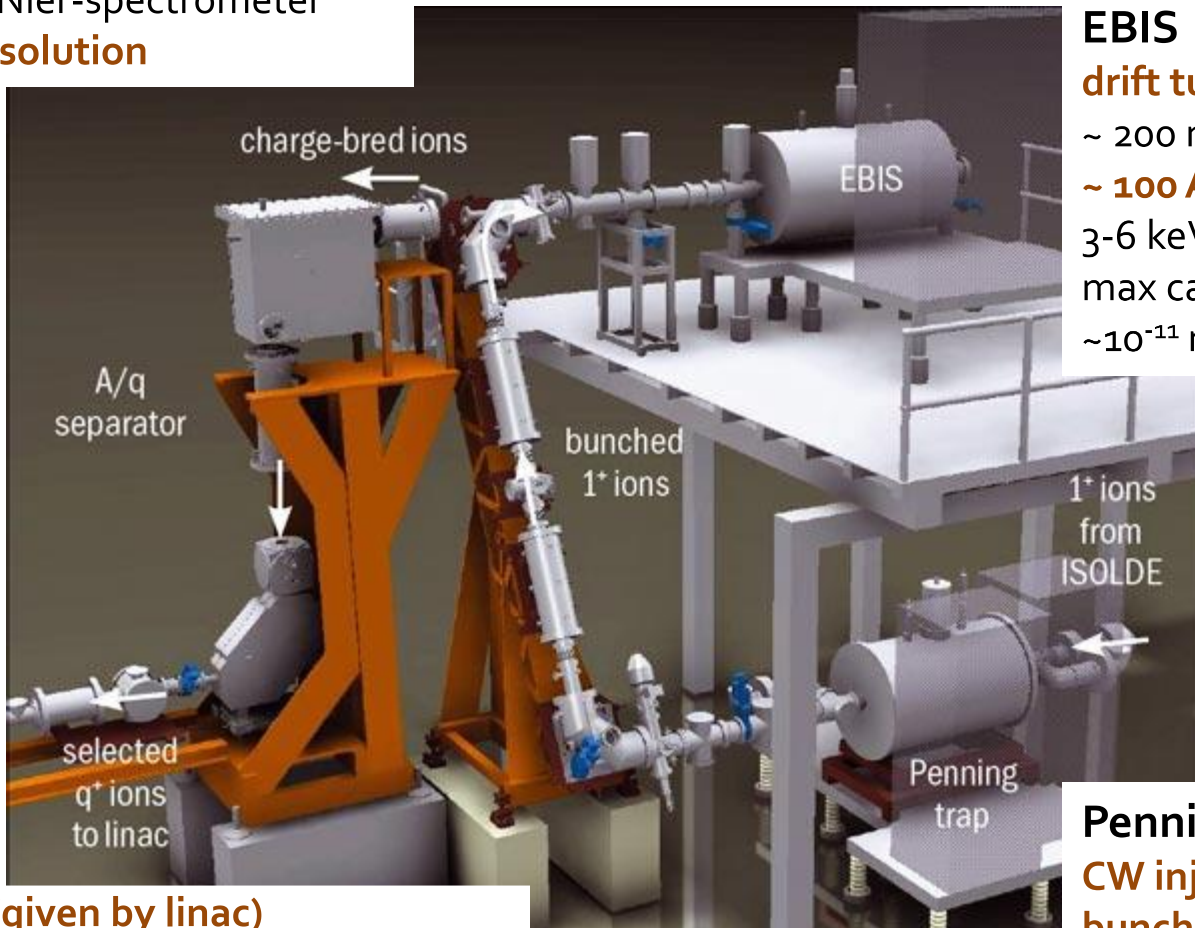


Dates = first beam delivered
Stable beams in case of RHICEBIS

REX-ISOLDE low-energy layout

Mass separator
achromatic Nier-spectrometer
~150 A/Q resolution

F. Wenander 2010 ***JINST*** 5 C10004



EBIS
drift tubes at 293 K
~ 200 mA electron beam
~ 100 A/cm² current density
3-6 keV electron beam energy
max capacity $3 \cdot 10^{10}$ charges
~10^{-11} mbar in trapping region

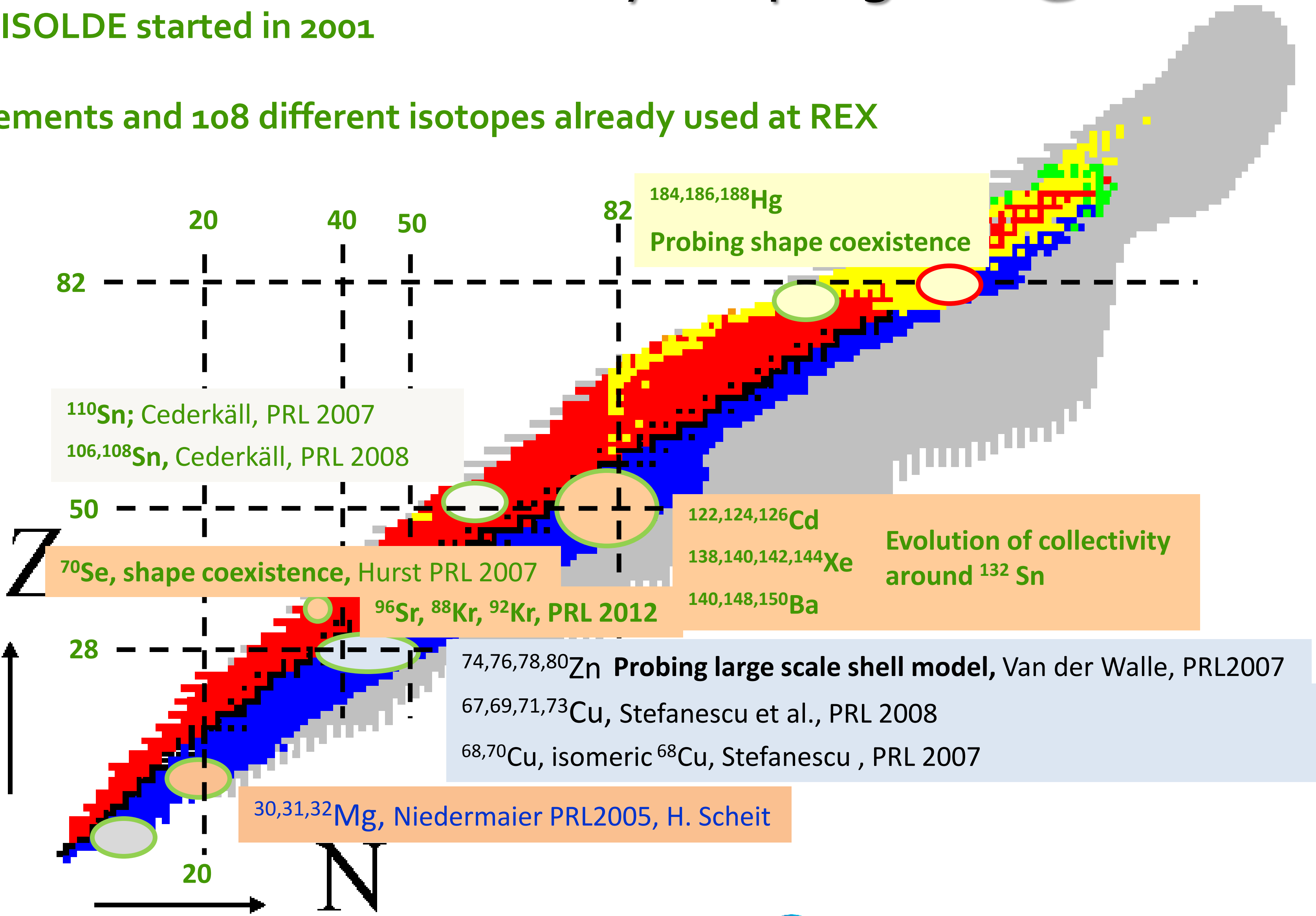
Penning trap
CW injection,
bunched extraction
3 T solenoid field
buffer gas filled ($5 \cdot 10^{-4}$ mbar)
cooling time ~20 ms

* **A/q < 4.5 (given by linac)**
* beam intensity a few to 10^9 particles/s
* pulsed machine
* repetition rate 50 to ~2 Hz

Physics program @ REX

REX-ISOLDE started in 2001

33 elements and 108 different isotopes already used at REX



Courtesy of M-J Borge

Ion injection, extraction and beam contamination

Ion injection

+ Small transverse emittance ε

but also

- Small transverse acceptance α

~0.02 mm mrad

$$\alpha_{geo} \propto r_{ebeam}\sqrt{\frac{I_e}{v_e}}$$

=> α larger for immersed e-gun than for high compression

Need for Penning trap or RFQ cooler !

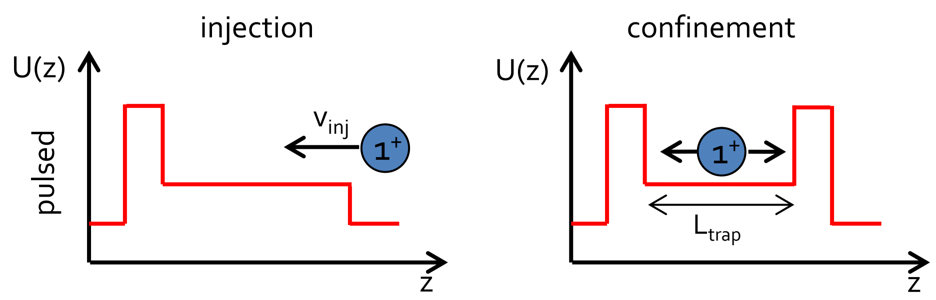
* Bunched or cw cooler?

* Bunched ion capacity $\sim \frac{N^{-}(EBIS)}{Q_{charge\ bred\ ion}}$

(in the order of 10^8 to 10^{10} ions)

Pulsed or CW injection

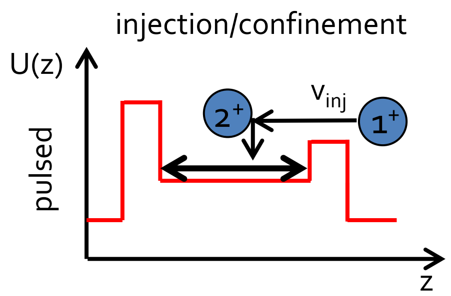
'Pulsed injection'



$$\text{efficiency} = \left(\frac{\alpha}{\epsilon}\right)^2$$

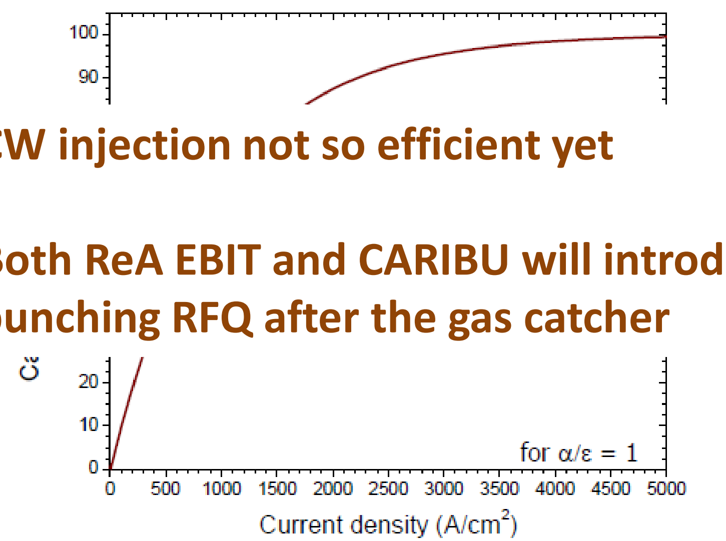
for $t_{injection\_pulse} < t_{round\text{-}time}$ and $\alpha/\varepsilon \leq 1$

'cw injection'



*** CW injection not so efficient yet**

*** Both ReA EBIT and CARIBU will introduce a bunching RFQ after the gas catcher**



S. Schwarz *et al.*, Rev. Sci. Instrum. **85**, 02B705, 2014 T. M. Baumann, Slide 8 / 23

Two requirements:

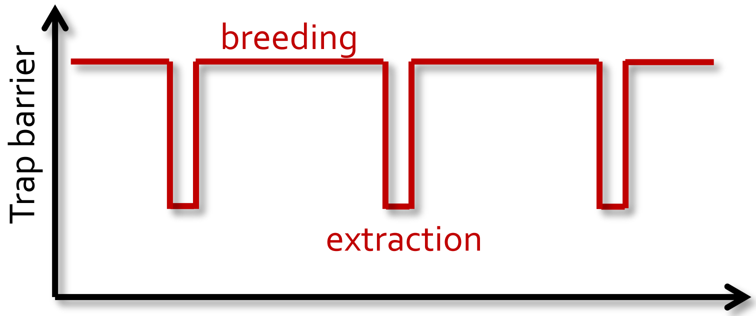
electron and ion beams overlapping

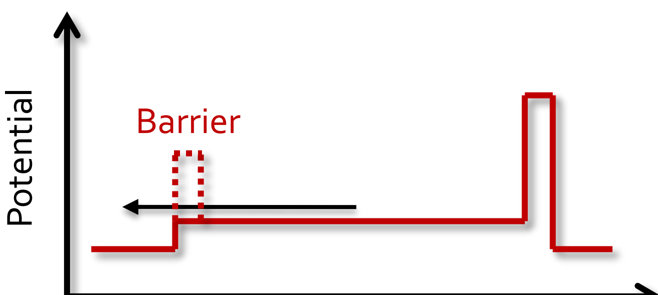
ionisation from 1+ to 2+

Ion extraction times

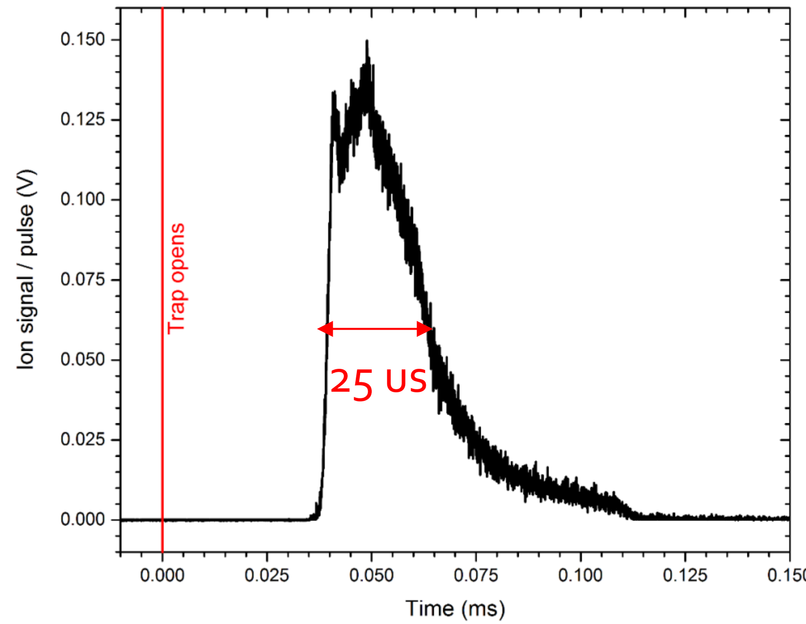
Inherently a pulsed machine

1. CW ion injection possible
2. pulsed extraction necessary





Measured ion pulse shape



At REX 24 h beam time =>

15 min delivered beam

+ excellent signal-to-noise ratio
+ suited for normal conducting (pulsed) linac
+ adjust EBIS HV between injection and extraction
- high instantaneous rates (DAQ dead-time, pile-up)

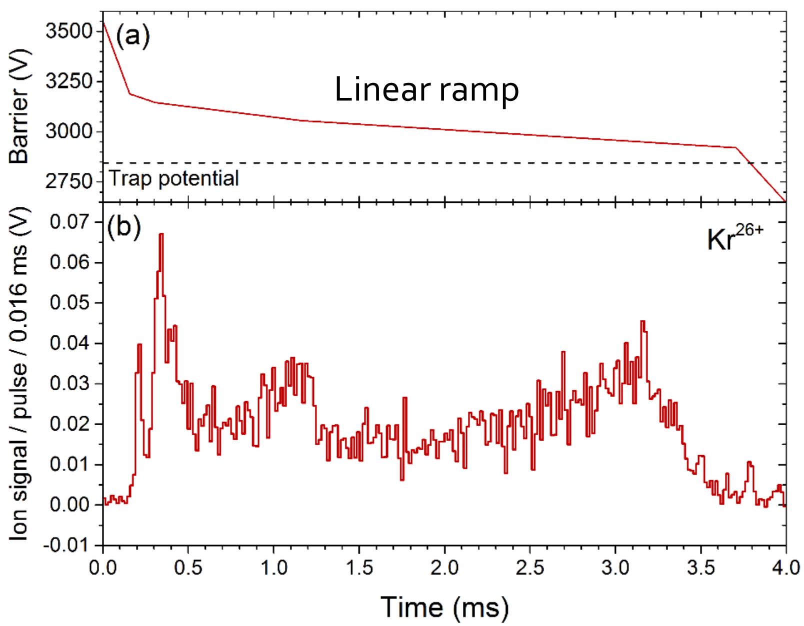
Courtesy of T. Baumann NSCL-MSU

Courtesy of T. Baumann NSCL-MSU

Slow ion extraction

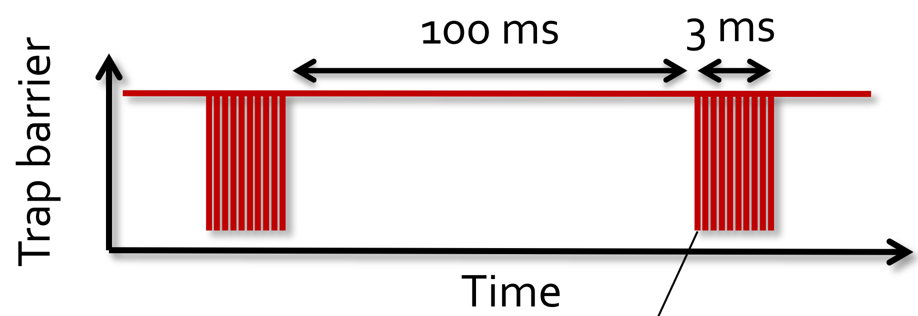
'Slow ramp scheme'

* Trap barrier is lowered slowly
* Barrier power supply controlled by an Arbitrary Function Generator
* Can calculate optimum $U_{barrier}(t)$ from particle energy distribution

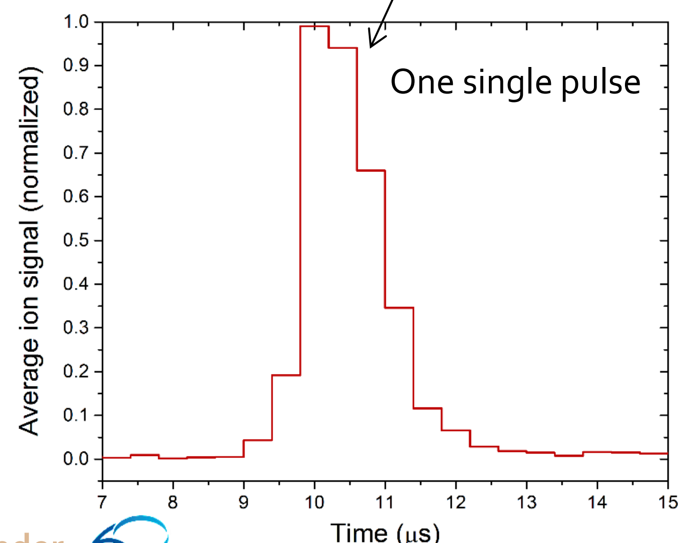


See also
F. Ullman et al., "SHAPING OF ION PULSES FROM AN ELECTRON BEAM ION SOURCE…", Proceedings of IPAC2011, San Sebastián, Spain

'Pulse train scheme'

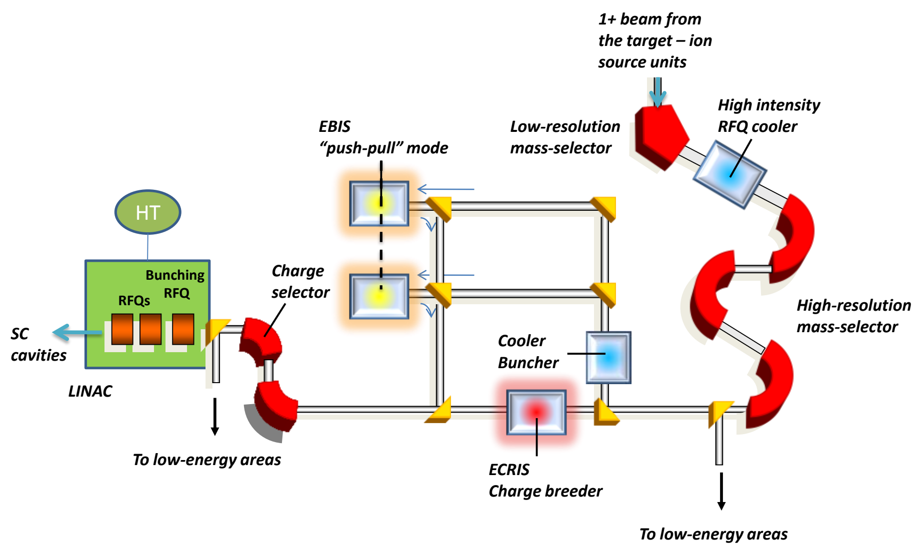


* Barrier potential controlled by fast HV switch (< 500 ns)
* Trap opened for 2 µs
* 10 kHz opening rate



CW ion extraction

Alt 1. Two EBIS in push-pull mode
(one charge breeds while the other extracts)

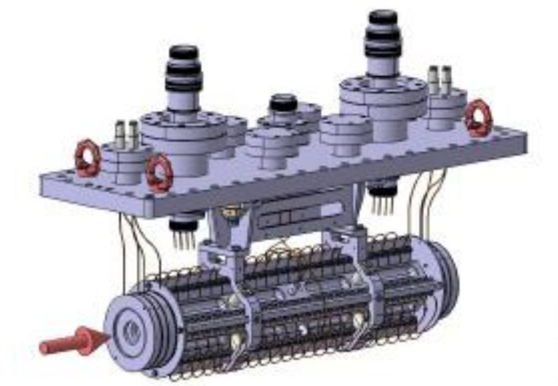


Detail of the EURISOL Layout

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

Alt 2.EBIS beam debuncher

Linear RFQ under UHV

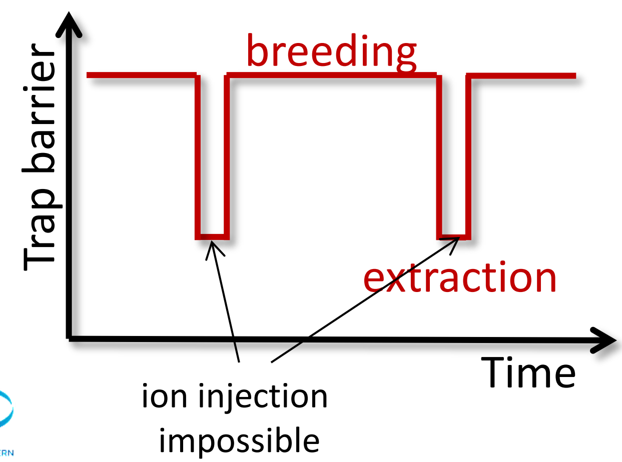


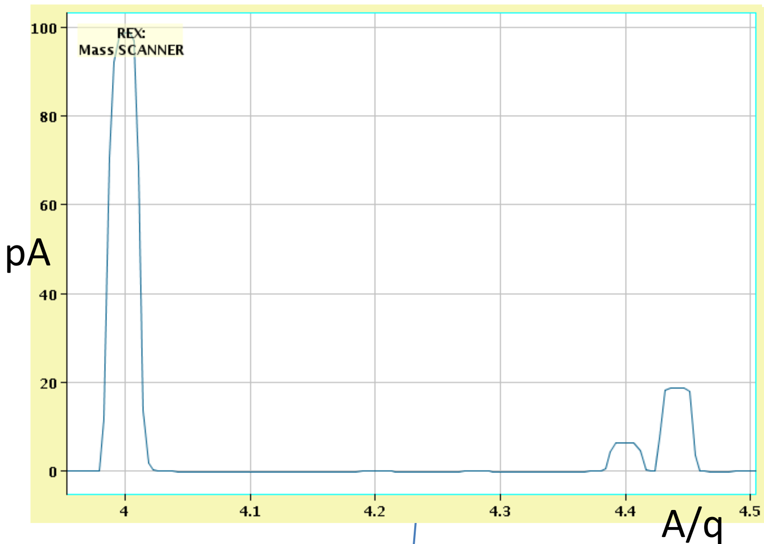
Courtesy of P. Delahaye

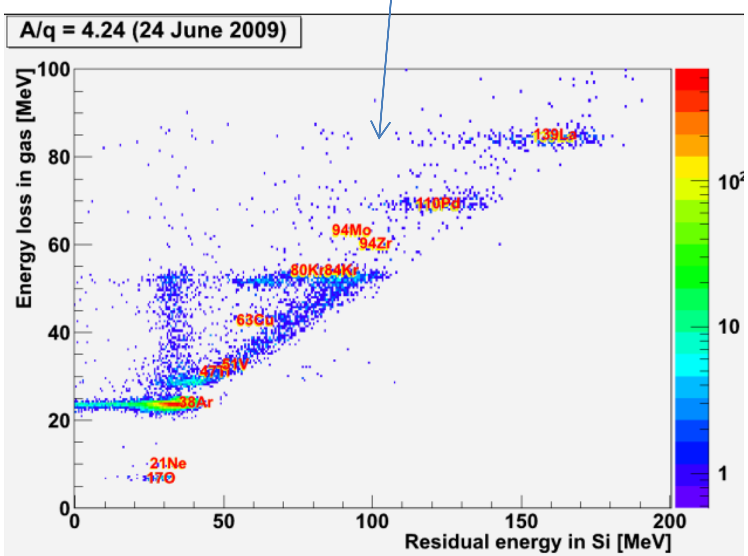
NB! Long $t_{extraction}$ only useful with:

*** buncher in front of breeder (can't accept ions during extraction)**

*** cw linac (limited RF pulse length for room temperature linac)**

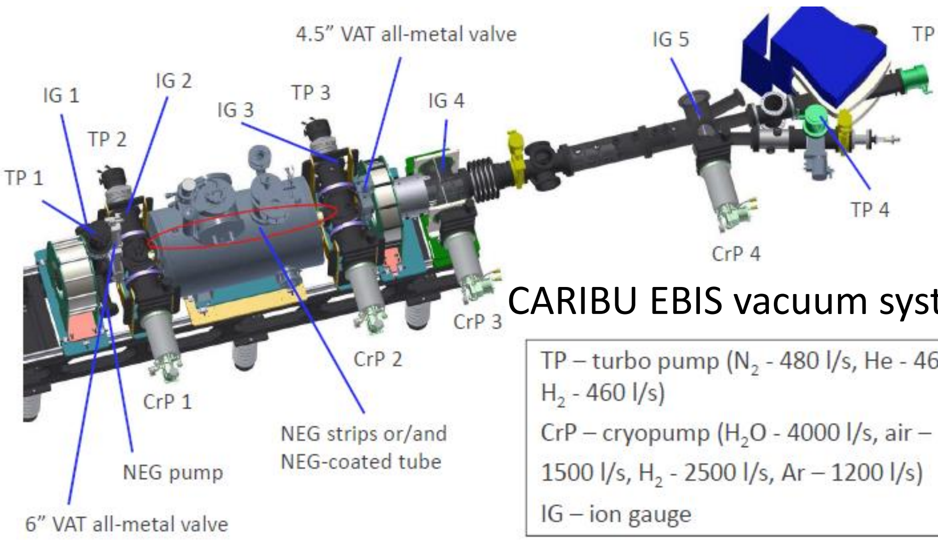






Beam contamination

* Stable A/q contamination from ISOL-target and breeder



CARIBU EBIS vacuum system

TP – turbo pump (N_2 - 480 l/s, He - 460 l/s, H_2 - 460 l/s)
CrP – cryopump (H_2O - 4000 l/s, air – 1500 l/s, H_2 - 2500 l/s, Ar – 1200 l/s)
IG – ion gauge

Courtesy of S. Kondrashev

Highly advanced vacuum system

Beam contamination

Trapping region at:

* room temperature
(REXEBIS, CARIBU, RHICEBIS)

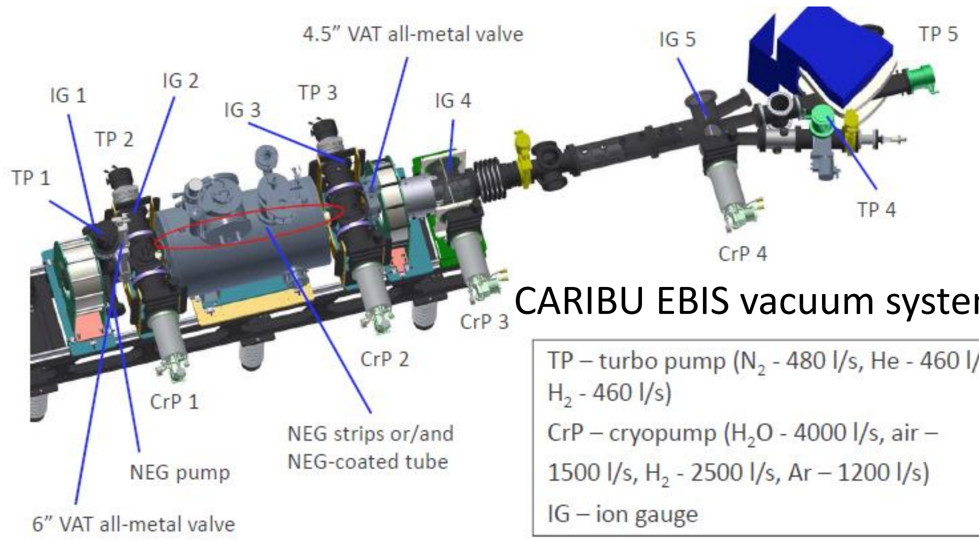
* cryogenic temperature
(TITAN, ReA EBIT)

Consider:

1. pumping speed
2. memory effects
3. electron beam loss effects

NB! Need high-resolution ionisation chambers for particle identification

* Stable A/q contamination from ISOL-target and breeder



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IG – ion gauge

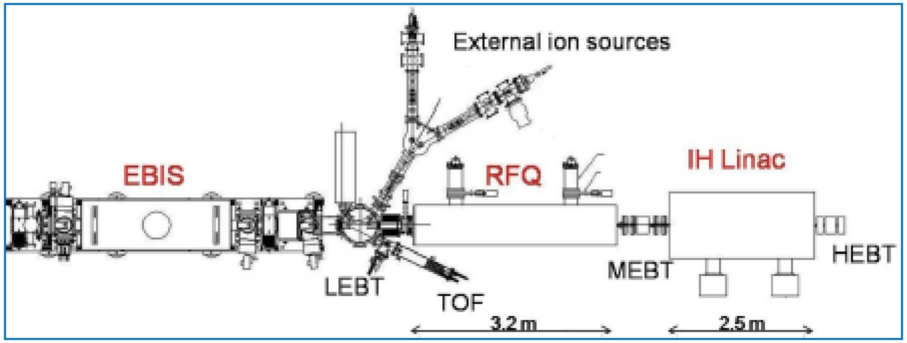
Courtesy of S. Kondrashev

REXEBIS cleanest beam so far, but also a modest electron beam

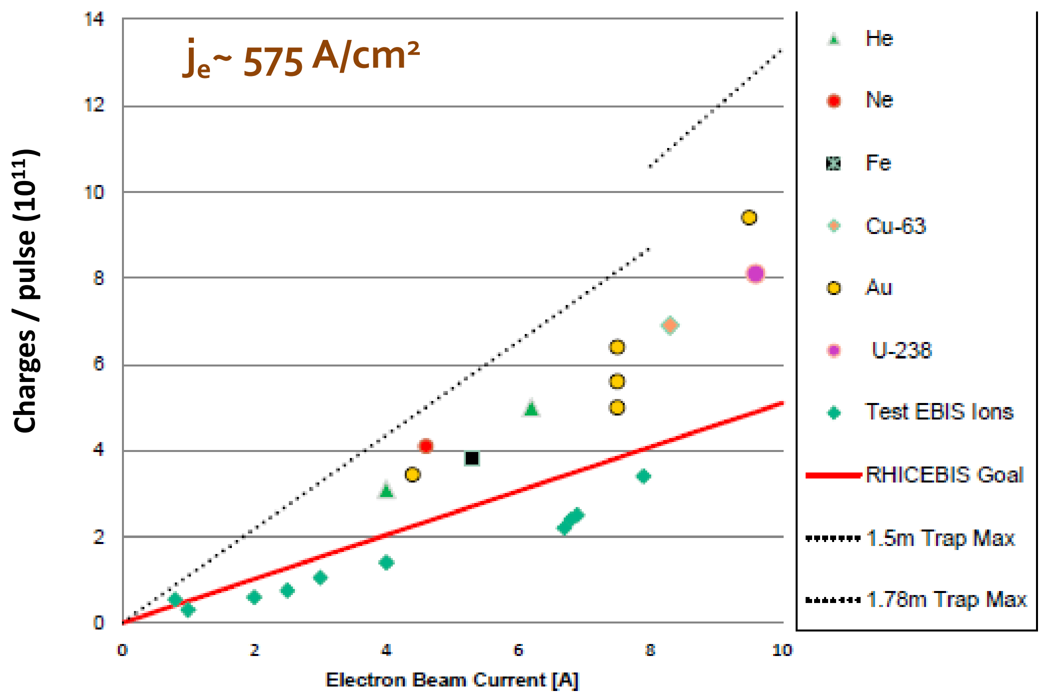
New EBIS/T breeders

RHICEBIS at BNL

Stable ion injector using external injection



Ions	He - U
Q / m	≥1/6
Current	> 1.5 emA (10 μS)
Pulse length	10-40 μs
Rep rate	5 Hz
Output energy	2 MeV / u
Time to switch species	1 second



Key elements:

- 10 A IrCe electron gun
- >100 kW collector

Courtesy of BNL Advanced ion source group

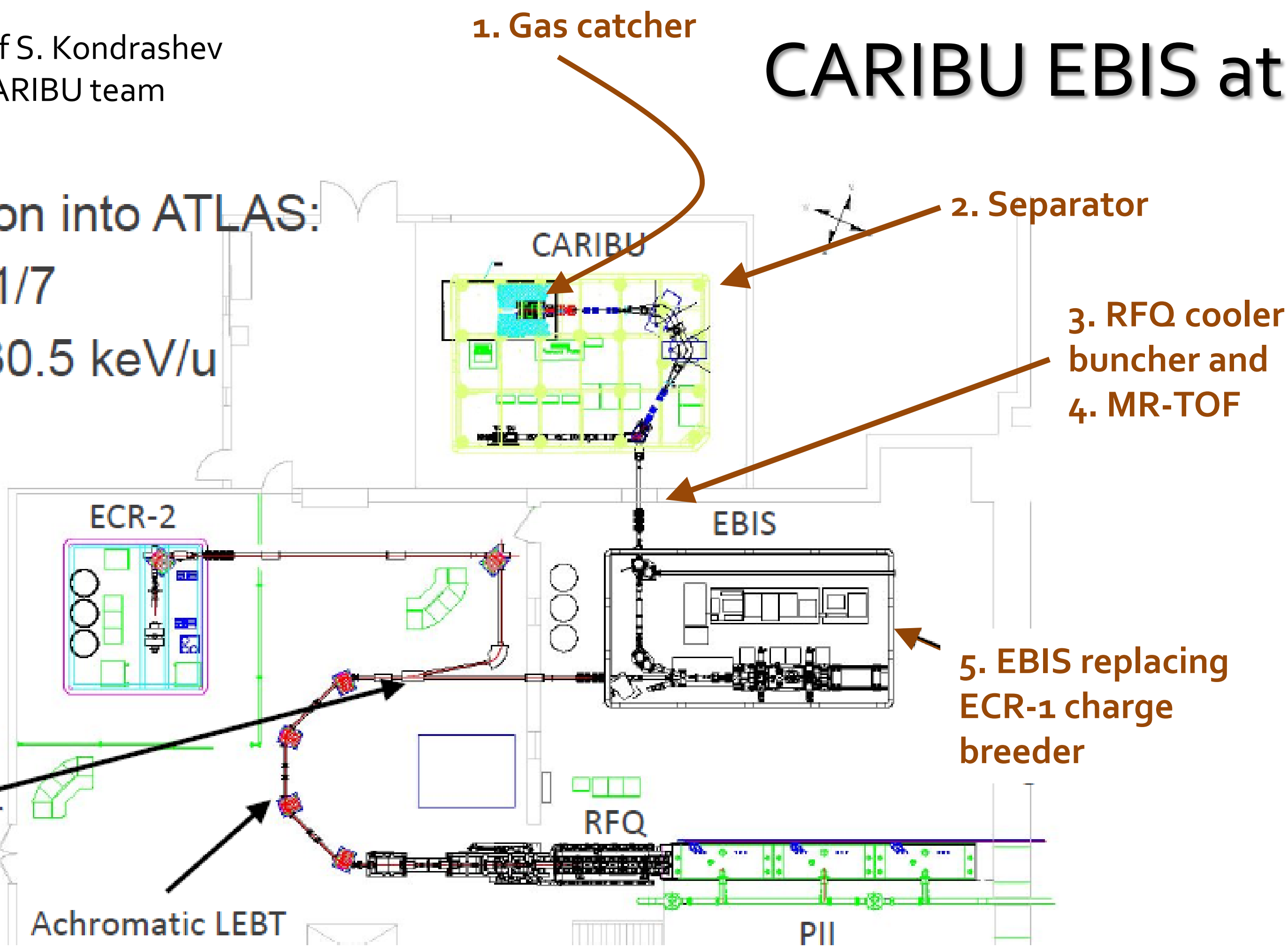
CARIBU EBIS at ANL

Courtesy of S. Kondrashev
and CARIBU team

Injection into ATLAS:

$q/A \geq 1/7$

$W_n = 30.5$ keV/u



✓ CARIBU beams are mass separated, injected into the RFQ cooler-buncher, additionally mass separated in the MR-TOF and transported into the EBIS

Overall transmission and setup complexity?

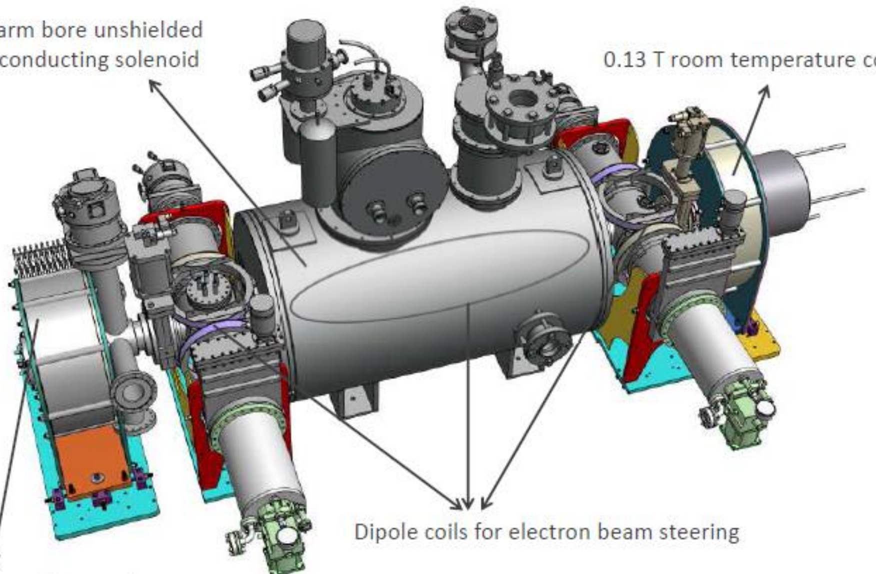
Courtesy of S. Kondrasev
and CARIBU team

CARIBU EBIS results

* **Scaled down version of RHICEBIS**
  - immersed egun
  - 2 A, 750 A/cm^2, 5 keV
  - $2 \cdot 10^{11}$ charges
  - A/q < 7
  - 30 Hz repetition rate
  - Goal 15% in Cs^{19+}

* **State-of-the art design**

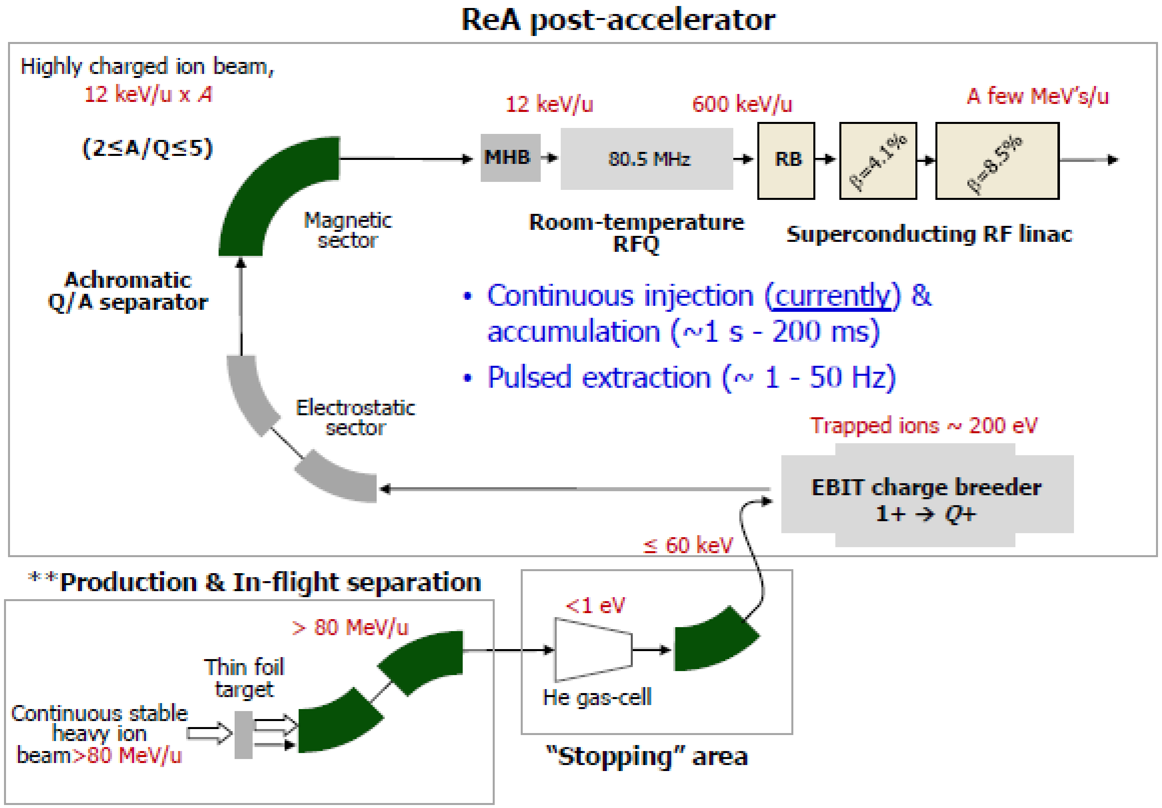
Complete assembly of ion trap was done inside class 100 clean room



* **Results**
  - Off-line commission finished
  - 1.7 A reached (low duty cycle)
  - >10% in one Cs charge state

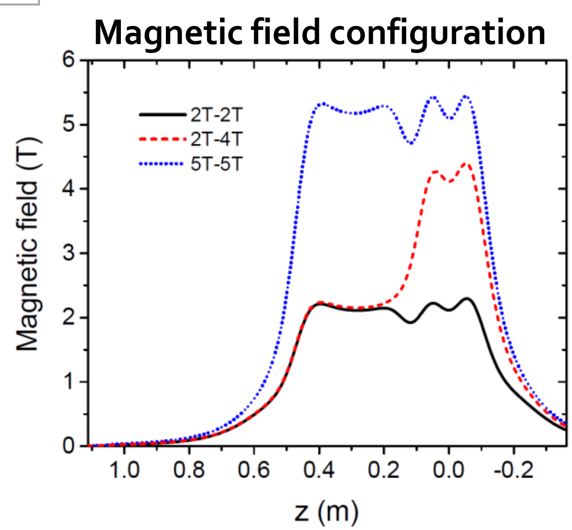
* **Move setup on-line 2015**

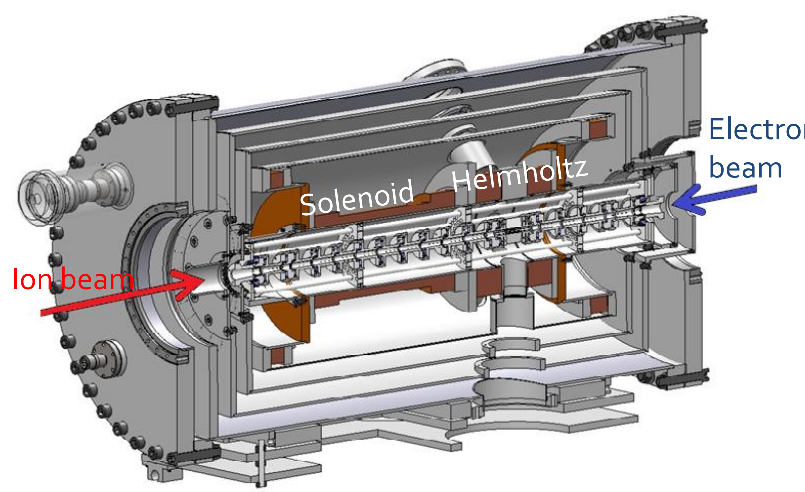
ReA EBIT at MSU



Design parameters

- high compression gun
- 4 K trap
- I_e up to 2.4 A
- E_e < 30 keV
- j_e ~ 5000 A/cm² for 2.4 A
- ion capacity ~10^9 part

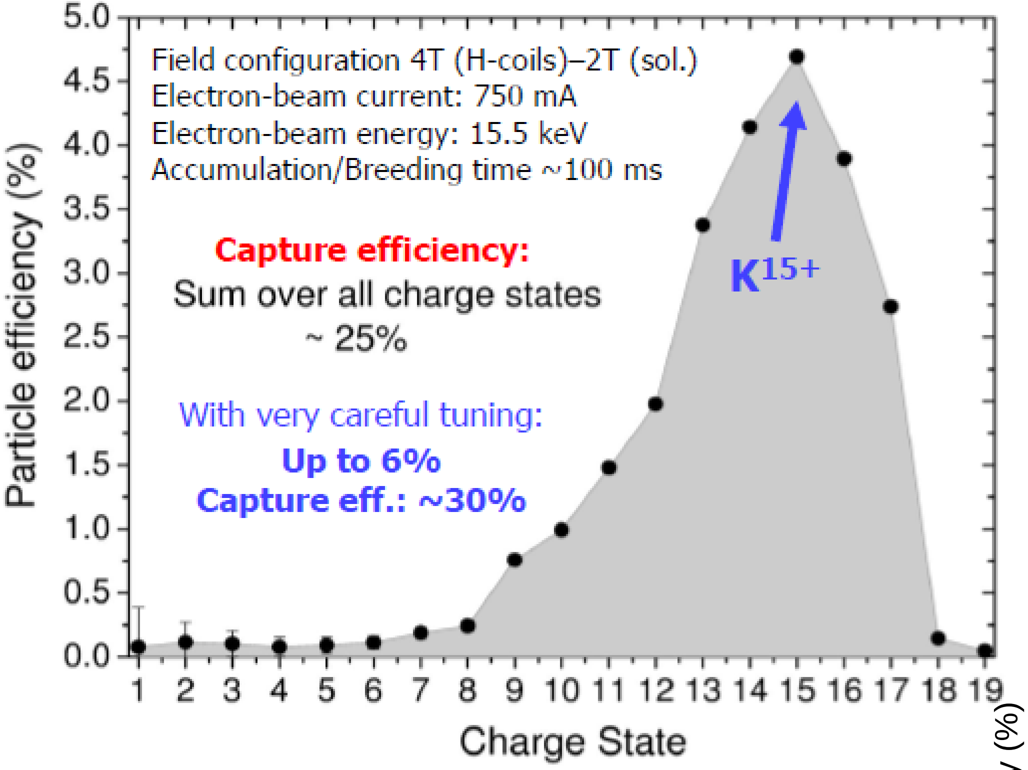




Courtesy of T. Baumann and ReA EBIT team

ReA EBIT results

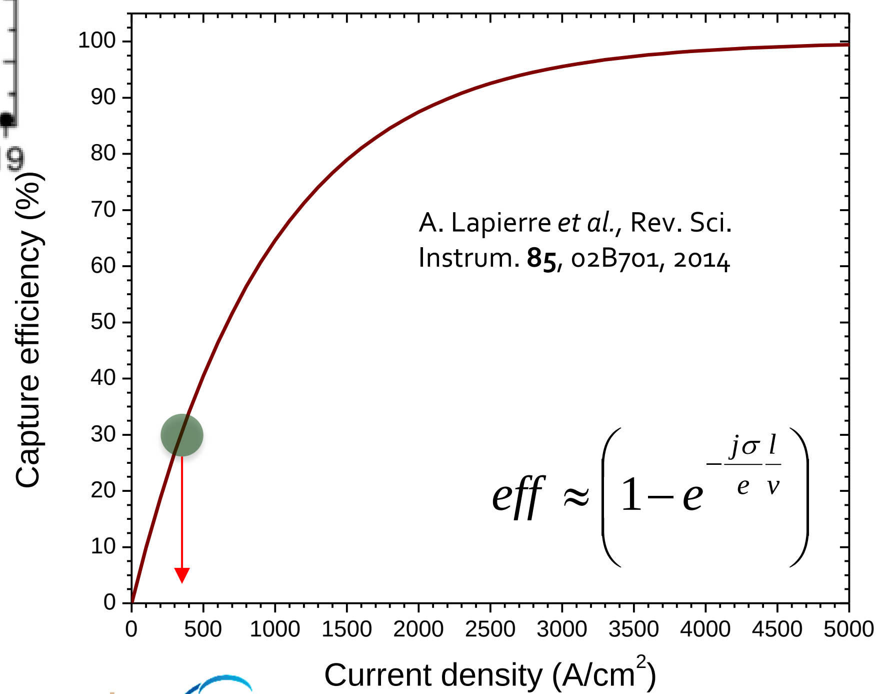
Single charge state efficiency for $^{39}K^{1+}$ injection



Achieved so far:

I_e = 0.8 A

j_e = 450 A/cm² (X-ray measurement)

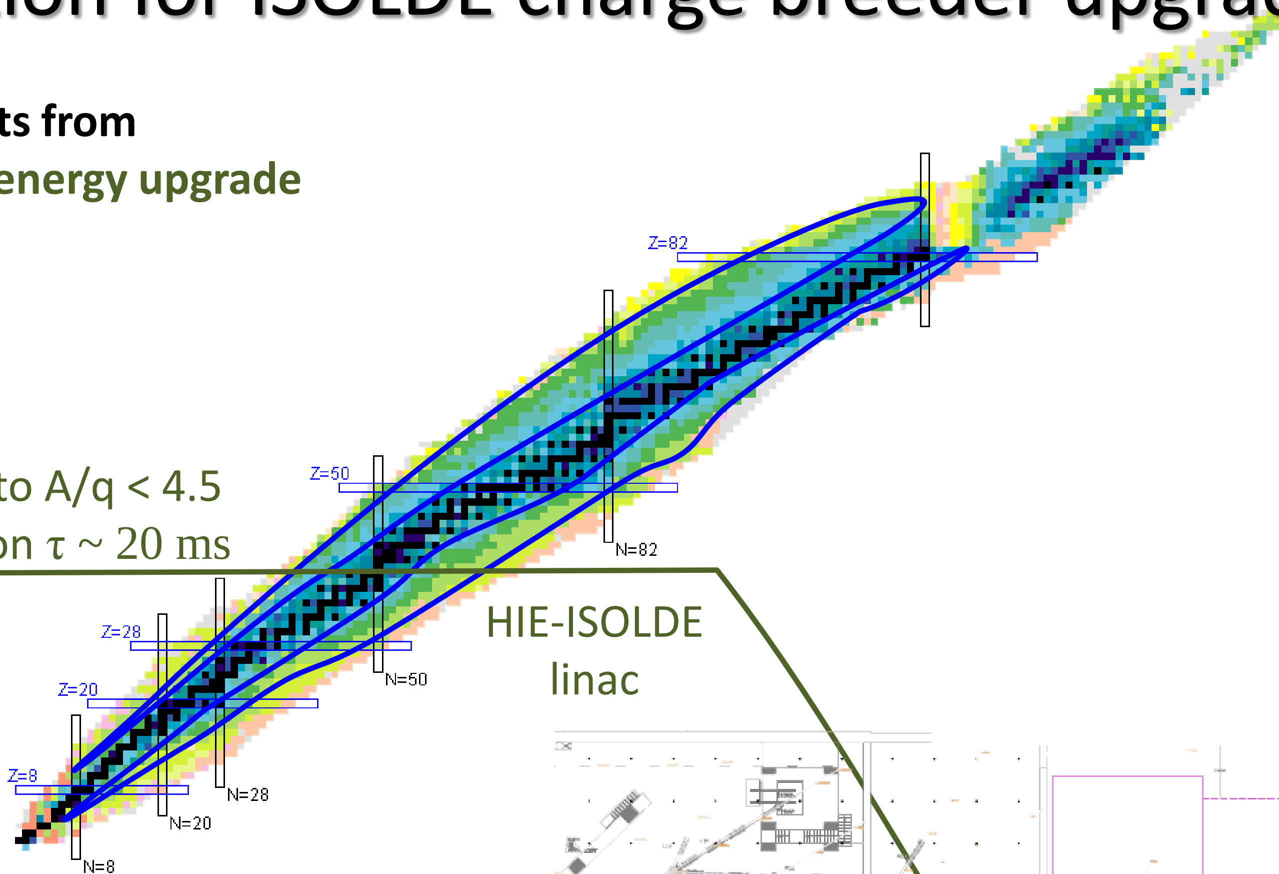


Courtesy of T. Baumann and ReA EBIT team

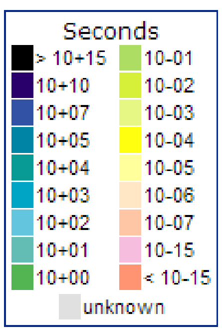
The future

Motivation for ISOLDE charge breeder upgrade

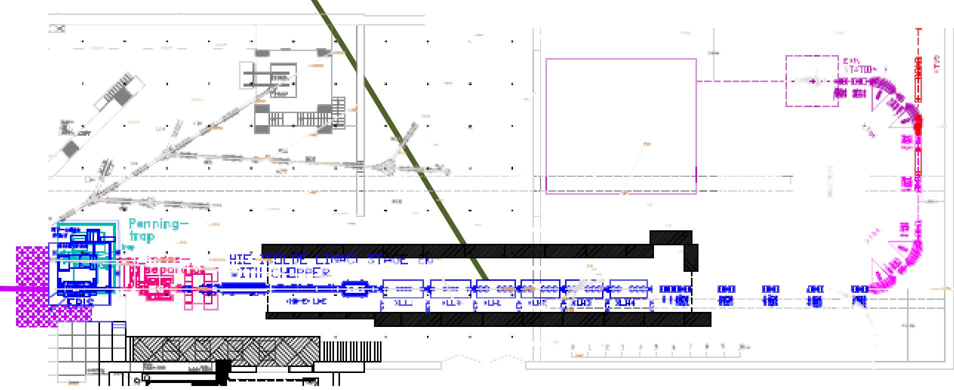
User requests from
HIE-ISOLDE energy upgrade



Faster breeding to A/q < 4.5
for reacceleration τ ~ 20 ms



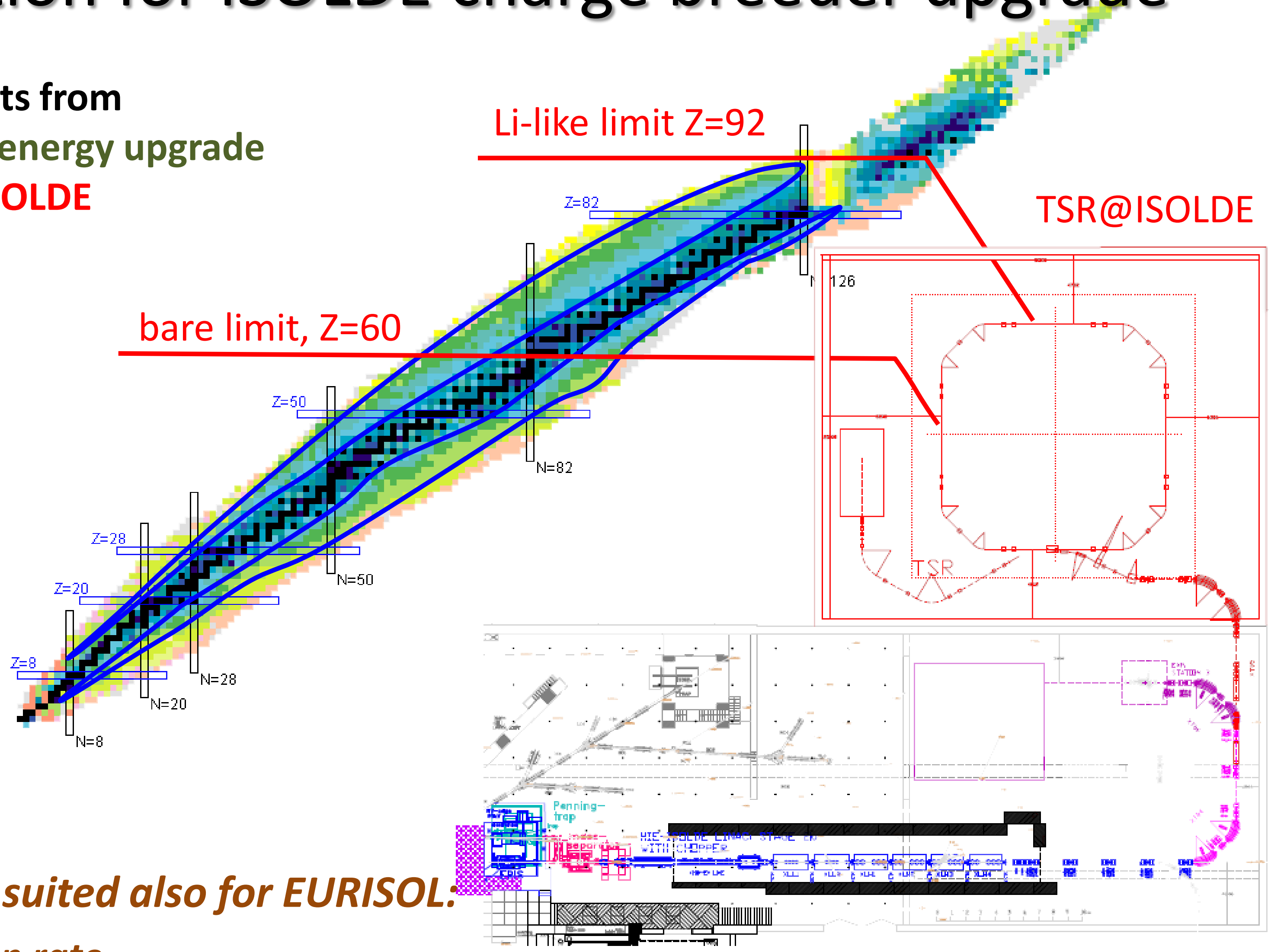
HIE-ISOLDE
linac

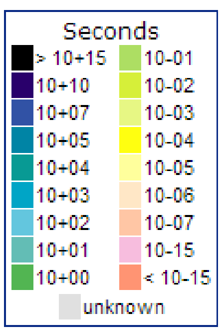


Upgrade of the charge breeder
REXEBIS to HEC^2 EBIS

Motivation for ISOLDE charge breeder upgrade

User requests from
HIE-ISOLDE energy upgrade
and TSR@ISOLDE



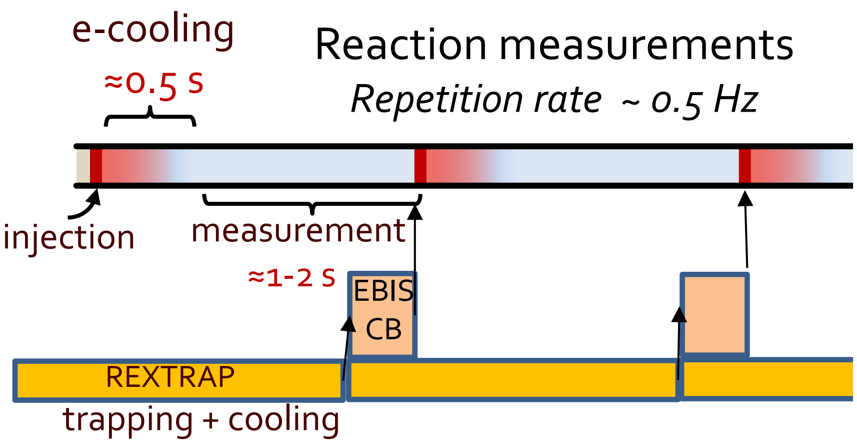


Such a breeder is suited also for EURISOL:

high repetition rate
large throughput

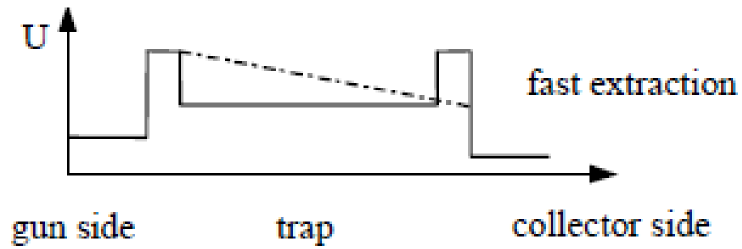
Penning trap + EBIS = TSR prerequisite

Collect ions in REXTRAP



Fast ion extraction from REXEBIS

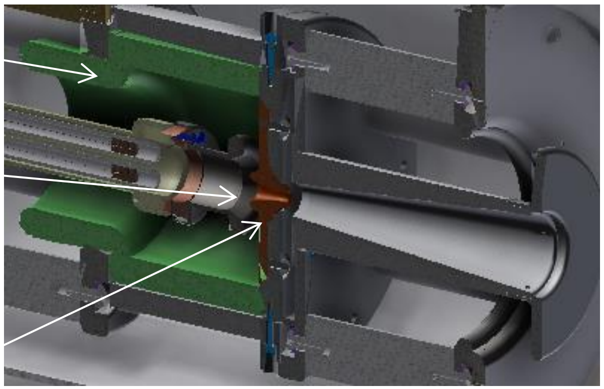
Speed up ion extraction for multi-turn injection into synchrotron <30 us



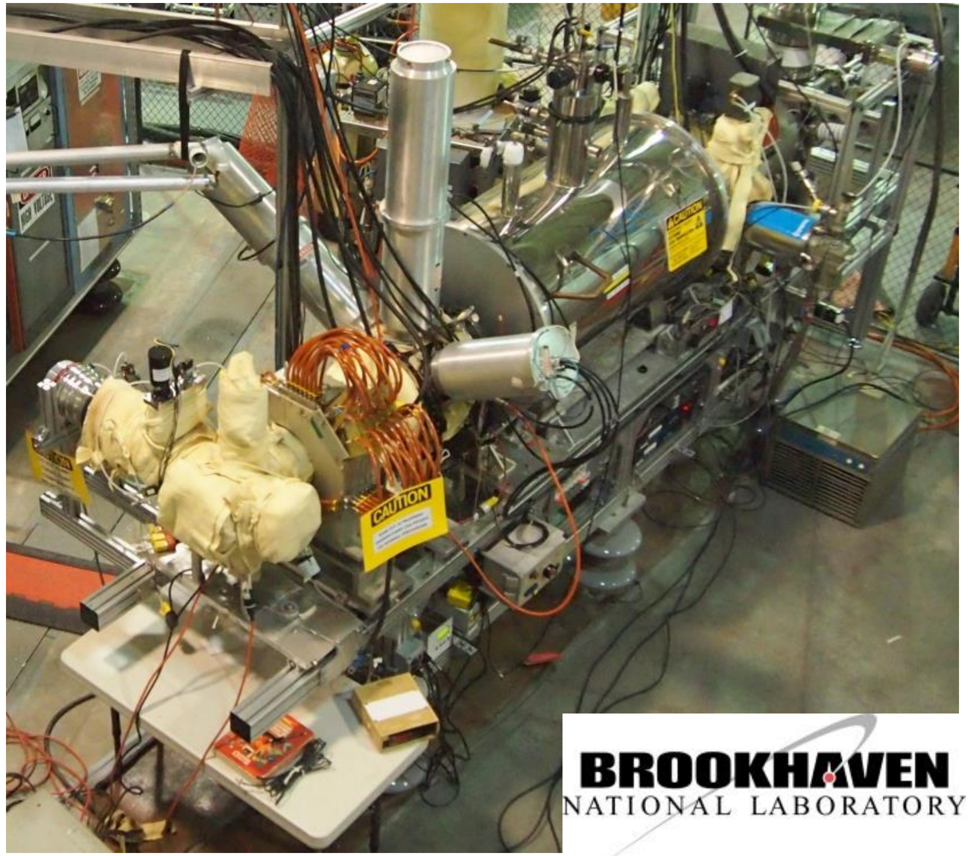
REXEBIS will work for many of the TSR experiments but one benefits from higher:

* *ion charge q*
* *current density j_e*
* *electron beam energy E_e*

High Energy Current Compression gun - HEC^2



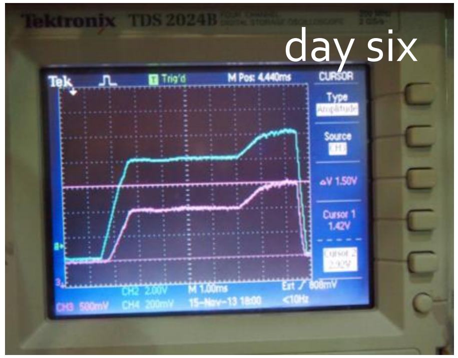
High compression Brillouin-type gun with passively shielded cathode



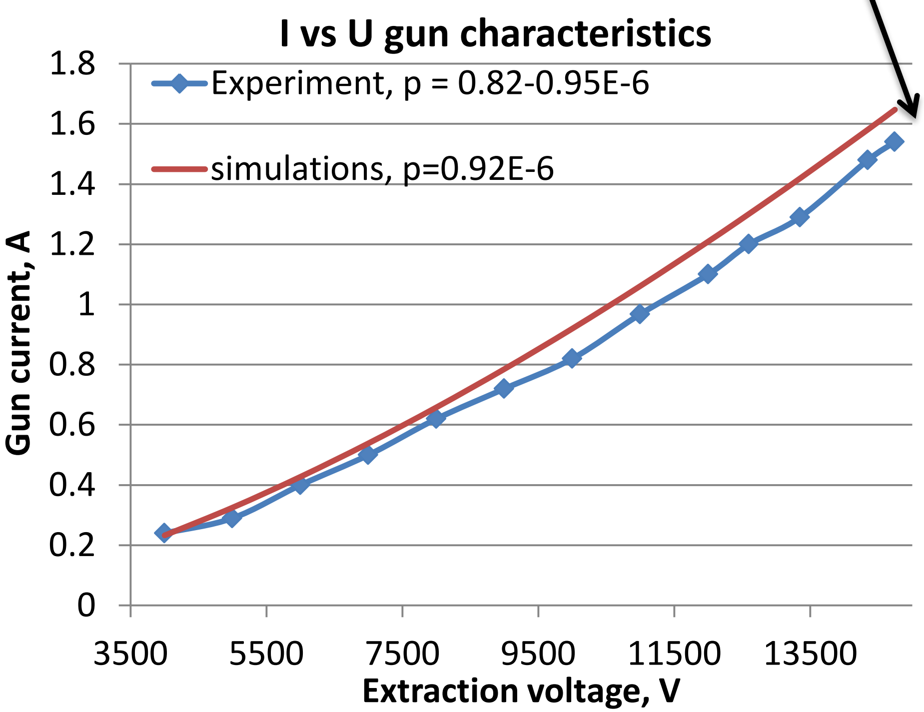
- Prototype gun design by BNL, built by CERN
- First version of HEC^2 gun installed at TestEBIS setup at BNL
- Full-scale test device

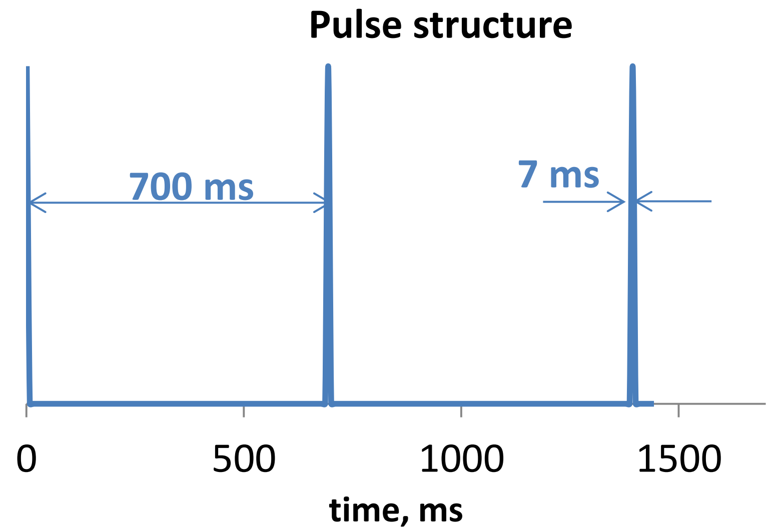
HEC² gun tests at BNL

Current



First beam time:
08.11.2013-15.11.2013





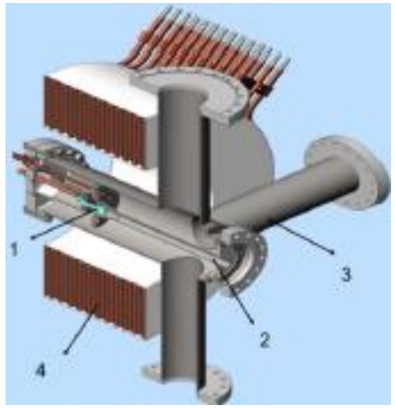
- Record current for a high-compression beam: 20 ms long beam pulses of 1.7 A
- Limited by loss current
- Improved gun design in fabrication

Technological challenges

Electron gun

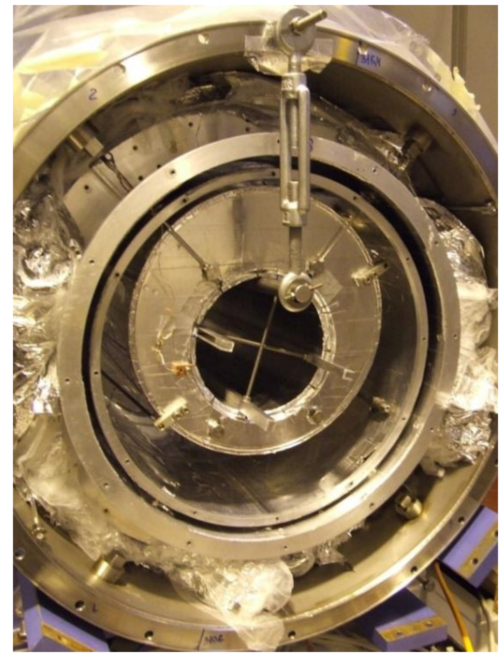
* Cathode lifetime
* Current density
* Two major gun design players

Courtesy of S. Kondrashev



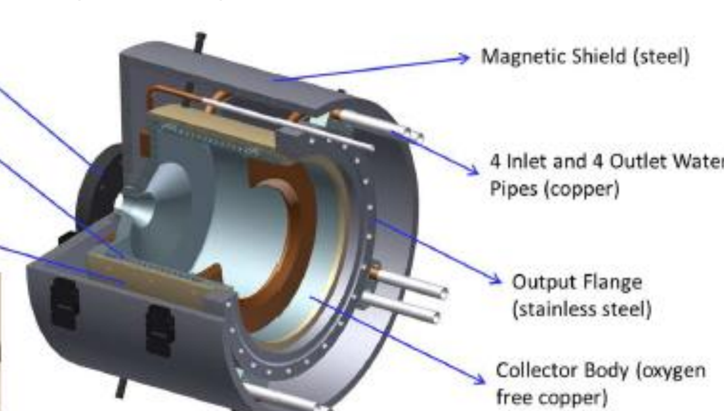
Superconducting magnets

* LHe consumption (REX)
* Winding coils broken (NSCL-MSU)
* He gas from cryostat to vacuum



Electron collector

* Up to 100 kW dumped electron power
* Cooling and fatigue issues



Courtesy of S. Kondrashev

Different schools

* cryocooler
* manual LHe filling

Future

North America now the frontrunner…

…proposal to the EURISOL study within ENSAR2

Innovative Charge Breeding Techniques (ICBT)

CERN, GANIL and HIL

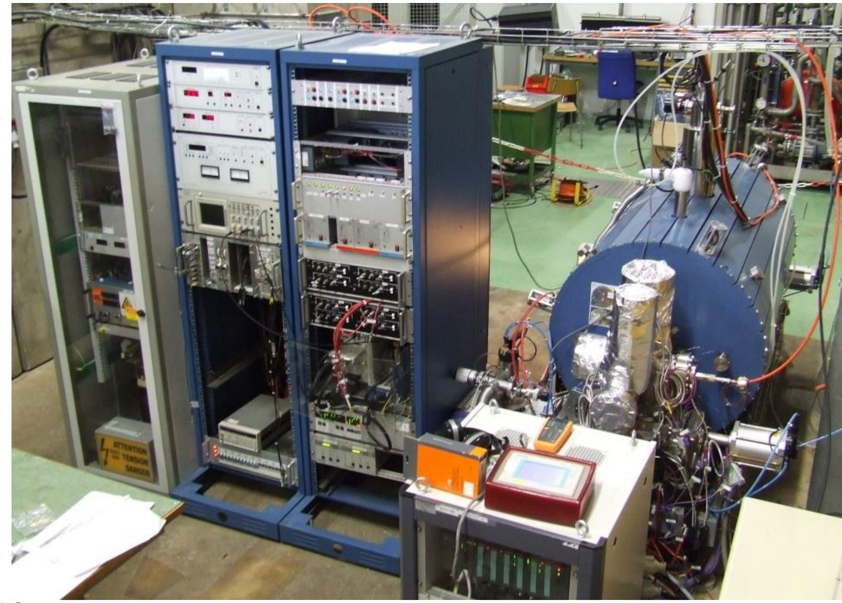
Strive to:

**** perform very fast charge breeding, production of fully stripped ions and CW beams using Electron Beam Ion Breeders***

**** and to improve the efficiency of ECR ion source breeders***

TwinEBIS test-bench

Streamlined replica of REXEBIS



Phase 1

Test bench for cathodes and poisoning effect

IrCe cathode from V. Osynniakov

LaB_6 cathode from KIMBALL PHYSICS

Electron beam modifications

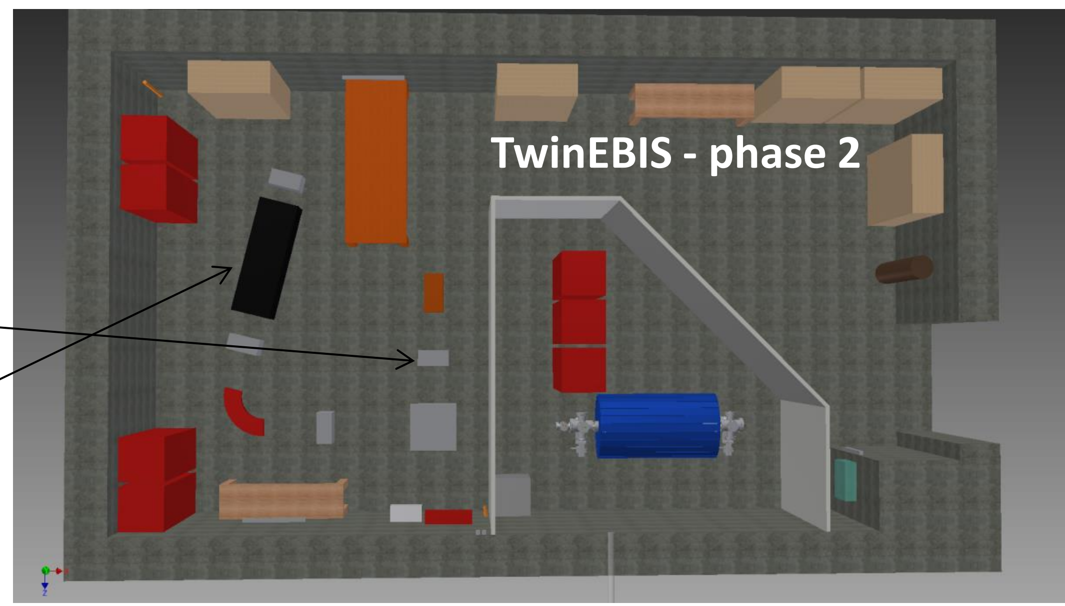
understand loss current limitation at REXEBIS

Ion extraction modulation

Phase 2 (pending resources)

External ion injection

Provide highly charged ions for CW trap tests



Charge breeders for RIBs worldwide

ISAC, TRIUMF
* ECRIS
* Operation

RISP
* ECRIS and EBIS
* Commissioning / Design

TITAN, TRIUMF
* EBIT
* Operational

ARIEL, TRIUMF
* EBIT
* Planning

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

ReA, MSU
* EBIT
* Operational

TRIAC, JAERI
* ECRIS
* Stopped

CARIBU, ANL
* ECRIS/EBIS
* Operation/Commissioning

SPIRAL/SPIRAL2
* ECRIS
* Design

SPES, LNL
* ECRIS
* Design

VECC
* ECRIS
* Commissioning

Conclusions

* Several EBIS/T charge breeders going on-line

* Decisions to take:

  room temperature or cryogenic trapping region
  CW or pulsed injection (pulsed in the lead)
  immersed or highly compressed electron beam

* Don't underestimate the complexity of the systems

* New challenges:

  high intensity?
  'CW' beam extraction
  high charge states