The effect of space-charge neutralization on charge breeding performance

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Background and Motivation

At the **TwinEBIS setup**, presently featuring a Brillouin electron gun [1], **mediocre results in terms of reachable charge state and number of ions extracted in the peak charge stage** [2] have been obtained using CW injection of CH_4 (for production of C ions), Ar and Xe. We asked ourselves if the **Brillouin beam**, which has strict requirements on alignment and matching to the solenoidal magnetic field, was causing excessive transverse heating to the ions, forcing them outside the electron beam and potentially even towards the drift tubes in the trapping region. The regular probing of the axial momentum spread would not reveal such a non-isotropic momentum distribution.

Breeding simulations using the *ebisim* code have been carried out without providing matching predictions for larger gas injection flows and longer breeding times.

We therefore performed **comparative measurements with the semi-immersed electron gun at REXEBIS**, which has a proven excellent performance for charge breeding of radioactive ions. The results were further **assessed with old published results of Xe-injection into KRION-2**.

1. Setups and Methods

Machine parameters

	TwinEBIS	REXEBIS [3]	KRION-2 [4]
Gun type	Brillouin, DC	Immersed with non-adiabatic element, DC	Immersed, pulsed
Electron energy (keV)	9	6.4	18
Electron current (mA)	536	242-250	120
Magnetic field (B)	2	2	2.25
Design current density (A/cm²)	~2000	230	150
Trap length (m)	0.8	0.8	1.2
Space charge capacity (C)	7.6E-9	4.2E-9	1.8E-9
Axial barrier voltage (V)	700	700	Unknown
Ion extraction	Pulsed	Pulsed	Pulsed
Drift tube radius (mm)	5	5	1.5
e-beam potential depth (V)	86	47	13
Beam axis potential depth (V)	754	358	72
Trap temperature (K)	293	293	4.2
P_{gun} / P_{coll}, without gas, (mbar)	<2E-10 / 2E-9	1E-11 / 3.2E-10	Unknown

Xe injection

* TwinEBIS: CW ^{129}Xe gas injection at trap center
* REXEBIS: CW ^{129}Xe gas injection at trap gun/center
  - Used P_{gun} as an indication of injected gas pressure; absolute values not comparable between machines

* KRION-2: Injection of ~1E8 Xe^{n+} (n low values) for 1 ms from neighbouring region

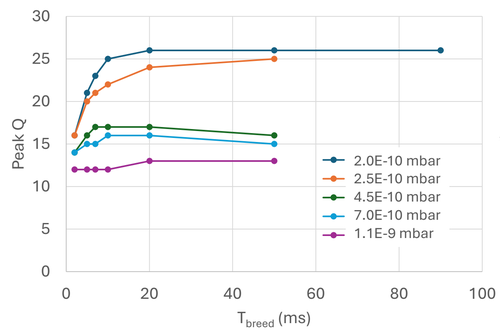
Measurement methods

* Charge state distributions
  - TwinEBIS and KRION-2 - Time-of-Flight
  - REXEBIS – A/Q separator with Faraday cup

* Total extracted charge
  - Faraday cup before TOF / separator

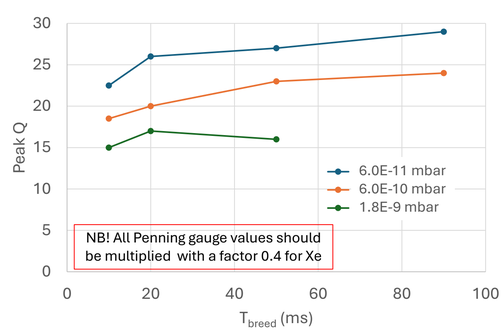
Absolute particle number from TwinEBIS TOF uncertain due to influence of A and Q on peak size

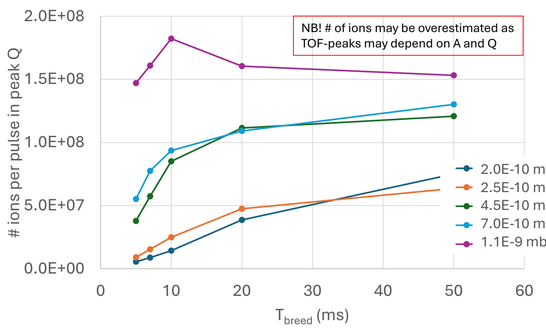
2. TwinEBIS Xe ions REXEBIS



Peak Q vs T_{breed}

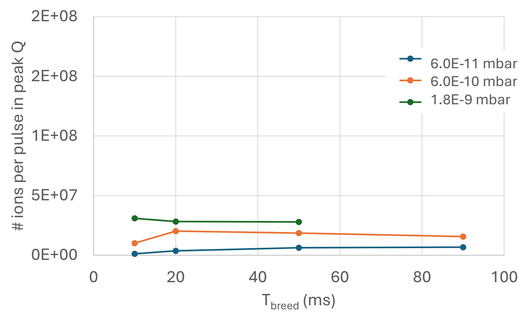
* Charge-state increase stalls for long T_{breed}
* High pressure penalizes peak Q
* Similar behaviour for Twin and REX

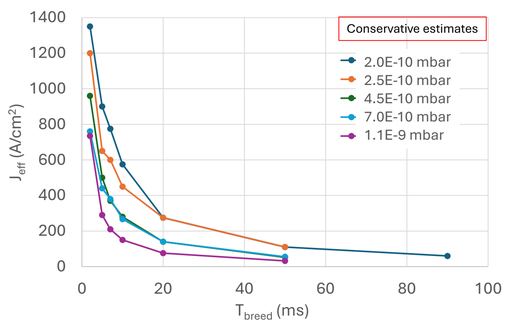




ions vs T_{breed}

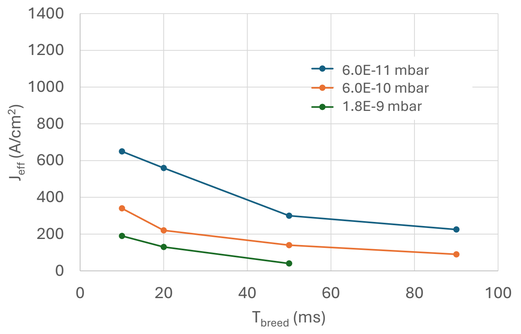
* Extracted # ions doesn't scale with pressure (if high)

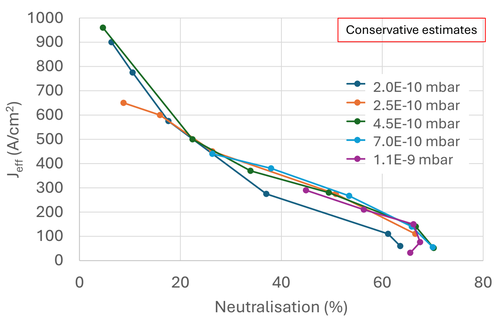




J_{eff} vs T_{breed}

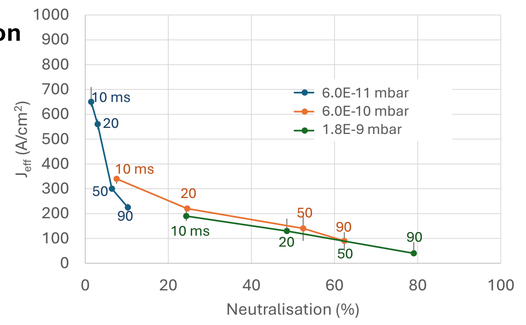
* Effective current density J_{eff} estimated from basic *ebisim* simulations
* J_{eff} drops with T_{breed}
* Lower J_{eff} for higher pressures





J_{eff} vs neutralisation

* J_{eff} is governed by neutralisation and not actually by T_{breed}
* Similar behaviour for Twin and REX

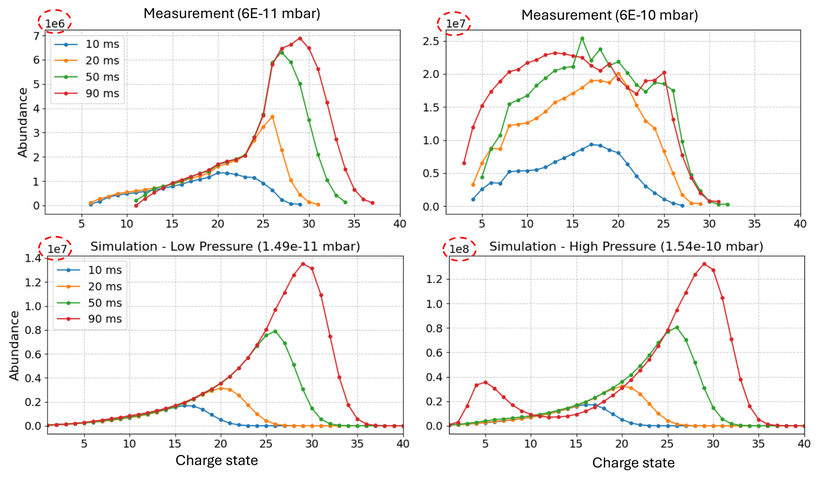


3. ebisim simulations

Conditions

* Simulated Xe gas into REXEBIS
  I_e=0.25 A, E_e=6400 eV
* Used advanced version of *ebisim* [5]
  (incl. RR, CX, ion heating, thermalisation, neutralization and ion escape)

* Simulation pressures chosen to reproduce total number of extracted ions at T_{breed}=20 ms for cases 6E-11 and 6E-10 mbar



Findings

* At low pressure, the simulations mimic the CSD shapes well, although with lower peak Q for shorter breeding times.

* For high pressure, the agreement is poor as the measured CSDs have strange shapes and low number of ions in peak Q. Neither are reflected in the simulations, where peak Q is unaffected by gas pressure and extracted # charges in peak scales linearly with Xe gas pressure.

* Charge exchange is not the cause.

* *ebisim* assumes a Maxwell-Boltzmann energy distribution at each integration step, which is not correct due to long self-collision times. This fact, in combination with a rapid space-charge neutralization, may cause a poor overlap between electron beam and ion cloud.

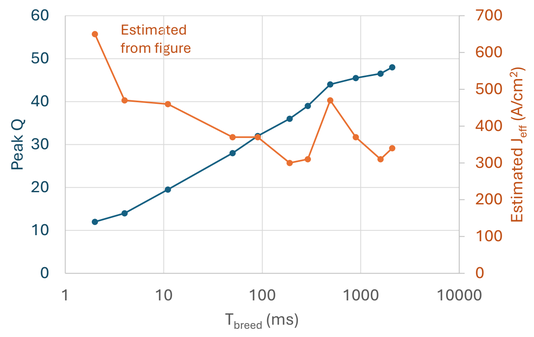
* Note the large difference in CSD width between KRION-2 and REXEBIS high pressure case.

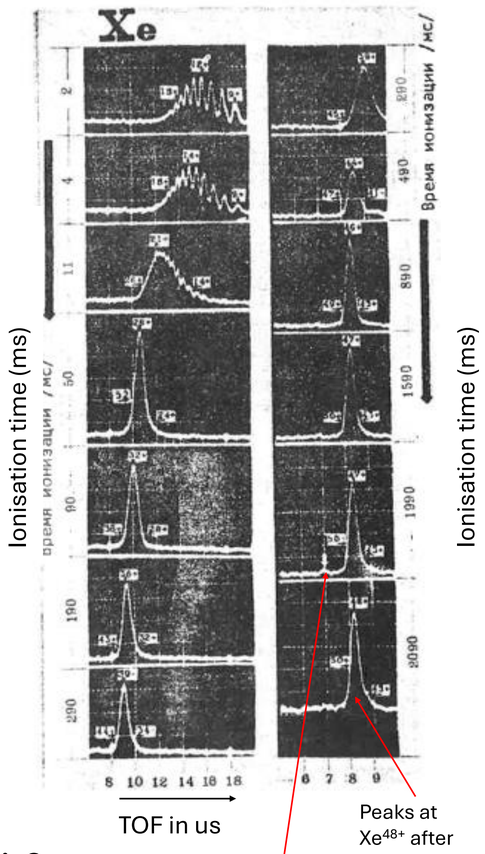
4. KRION-2 Xe production

Results

For T_{breed}=2.09 s:
* 5E6 Xe^{47+}, 1E7 Xe^{48+}, 5E6 Xe^{49+}
* ~1E9 charges extracted per pulse (very narrow CSD)

* No dramatic drop in Jeff with T_{breed}
* Q keeps on increasing with T_{breed}
* Estimated neutralization ~10% (low compared to CERN's Xe cases)





Estimated residual gas pressure <1E-12 Torr. Low because the light ions boiled off?

Why better performance than REX/Twin?

1. Pulsed injection; flooding with low-charged Xe for 1 ms
2. Fewer total number of ions => degree of neutralization is lower
3. Probably made use of evaporative cooling over the axial barrier
4. Relatively low J_e => time for cooling interactions at high Q
5. Cryogenic system freezing out lost Xe ions/atoms?

5. Conclusions

1. Achievable charge state Q and number of extracted ions in peak Q stalls at TwinEBIS, typically:
   Q=26 and 6E7 ions per pulse for low gas pressure
   Q=15 and 1.5E8 ions per pulse for high gas pressure

2. Lowering the axial barrier for evaporative cooling only reduces the overall ion number but does not shift CSD

3. Since REXEBIS, whose semi-immersed beam behaves predictably for charge breeding of few ions, but displays a similar poor behaviour for high pressure gas injection, we rule out anomalous ion heating effects in the TwinEBIS Brillouin beam

=> Need to apply pulsed gas injection to attain high charge and narrow CSD

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