On-line Operation of the EBIT Charge Breeder of the ReA Post-Accelerator

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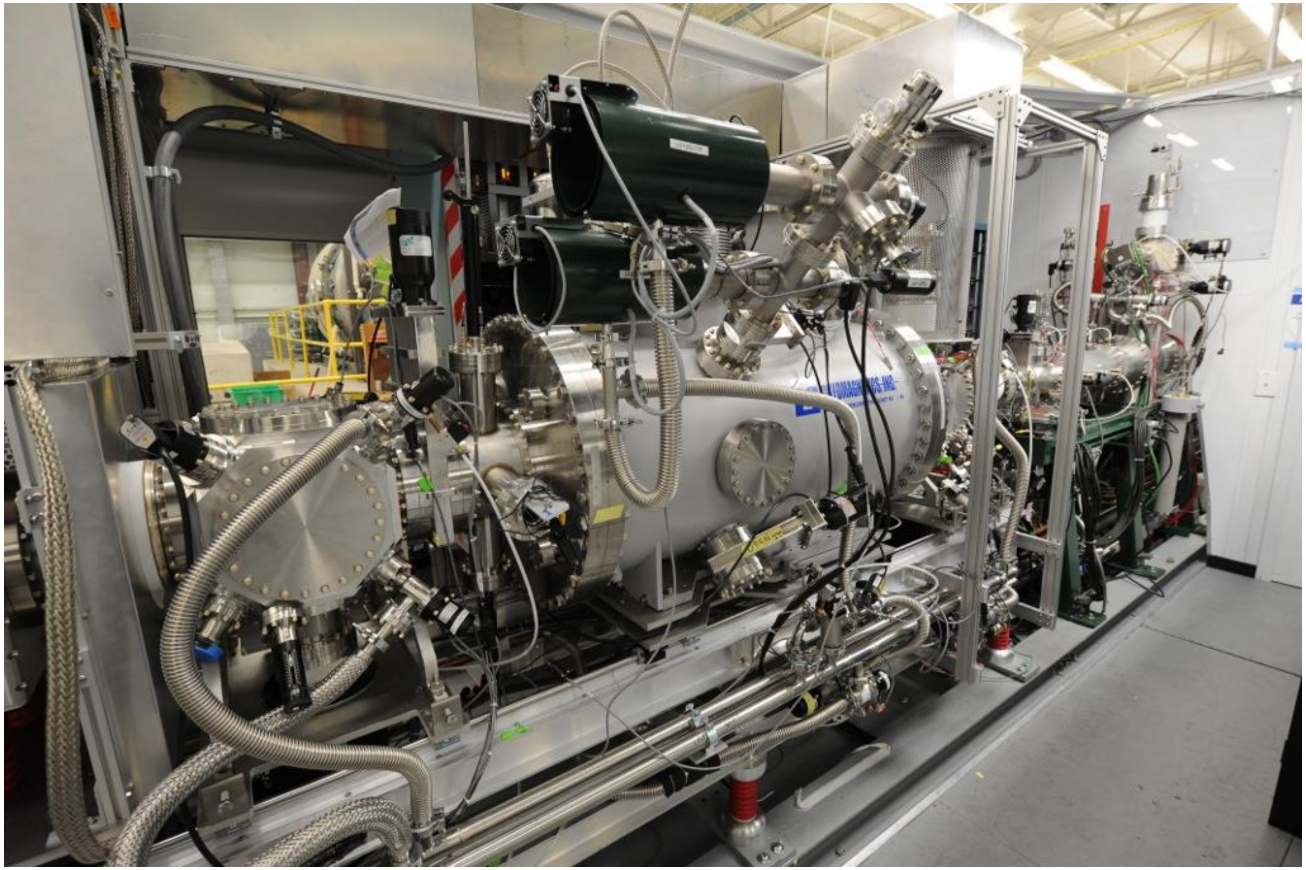

NSCL FRIB U.S. Department of Energy Office of Science
National Science Foundation
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MICHIGAN STATE UNIVERSITY

Outline

PART I

- Motivation for a post-accelerator: ReA
- Reacceleration concept
- ReA EBIT charge breeder

Started on-line operation in Sept 2015

PART II

- Results of on-line operation:
  - Charge-breeding efficiencies
  - Stretching of EBIT pulses (ejected ion time distributions)
  - Contamination study

Conclusion

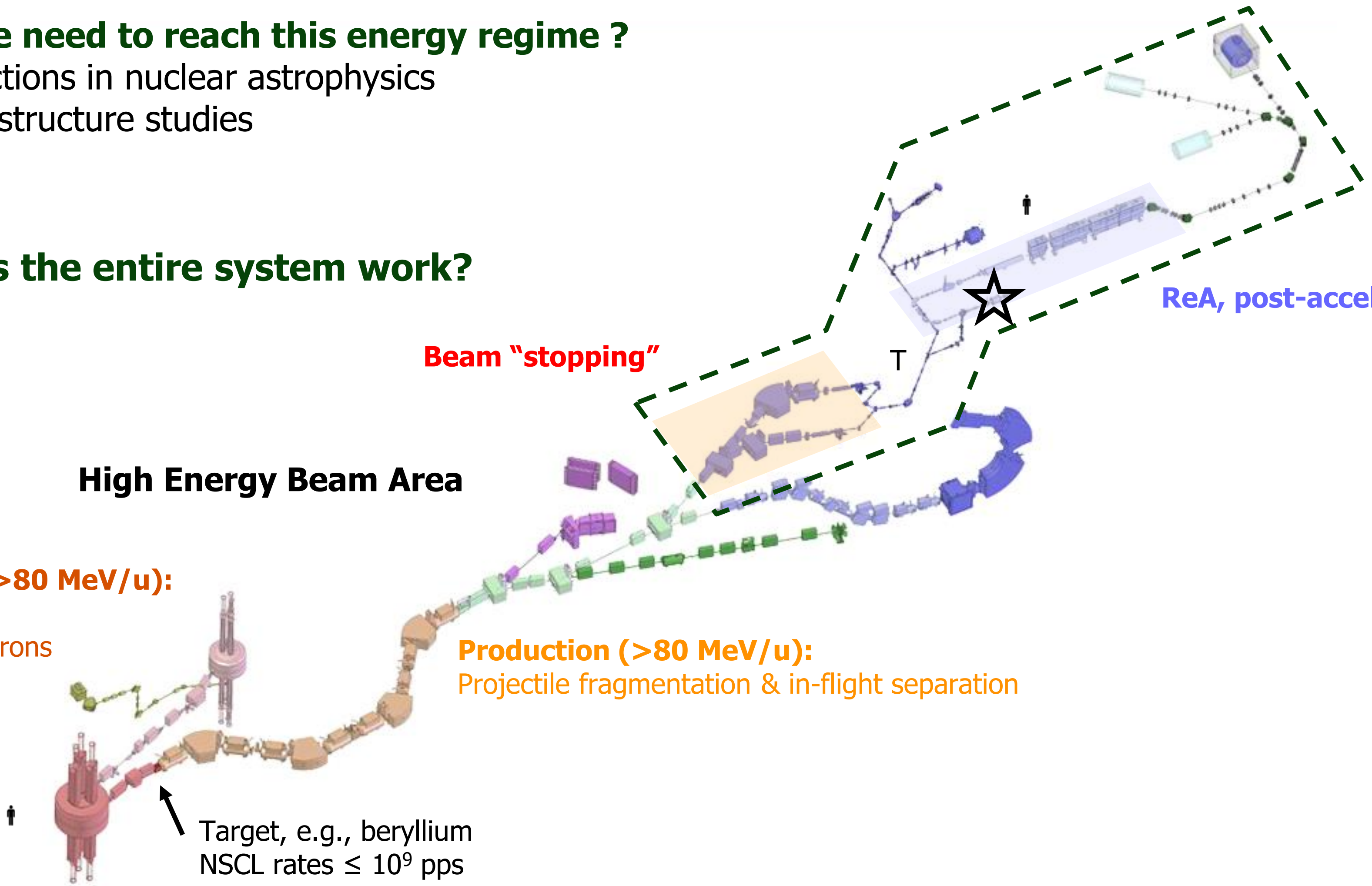
ReA: Reaccelerator of rare isotopes

National Superconducting Cyclotron Lab. @ MSU
- User facility producing rare-isotope beams by projectile fragmentation.

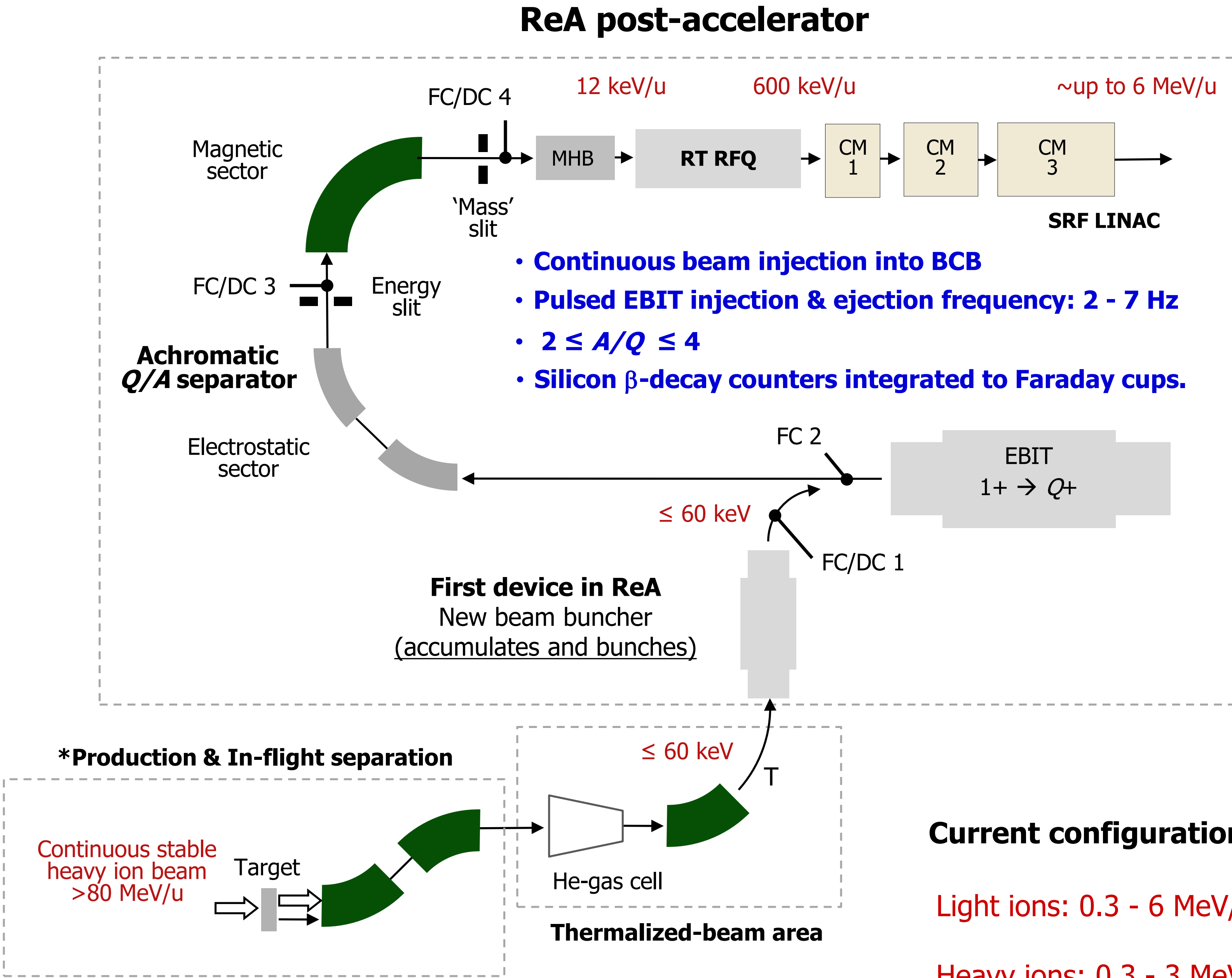
ReA @ NSCL
- Post-accelerator built for reacceleration of rare-isotope beams to several MeV/u.

Why do we need to reach this energy regime ?
- Key reactions in nuclear astrophysics
- Nuclear structure studies

How does the entire system work?



The ReAcceleration concept



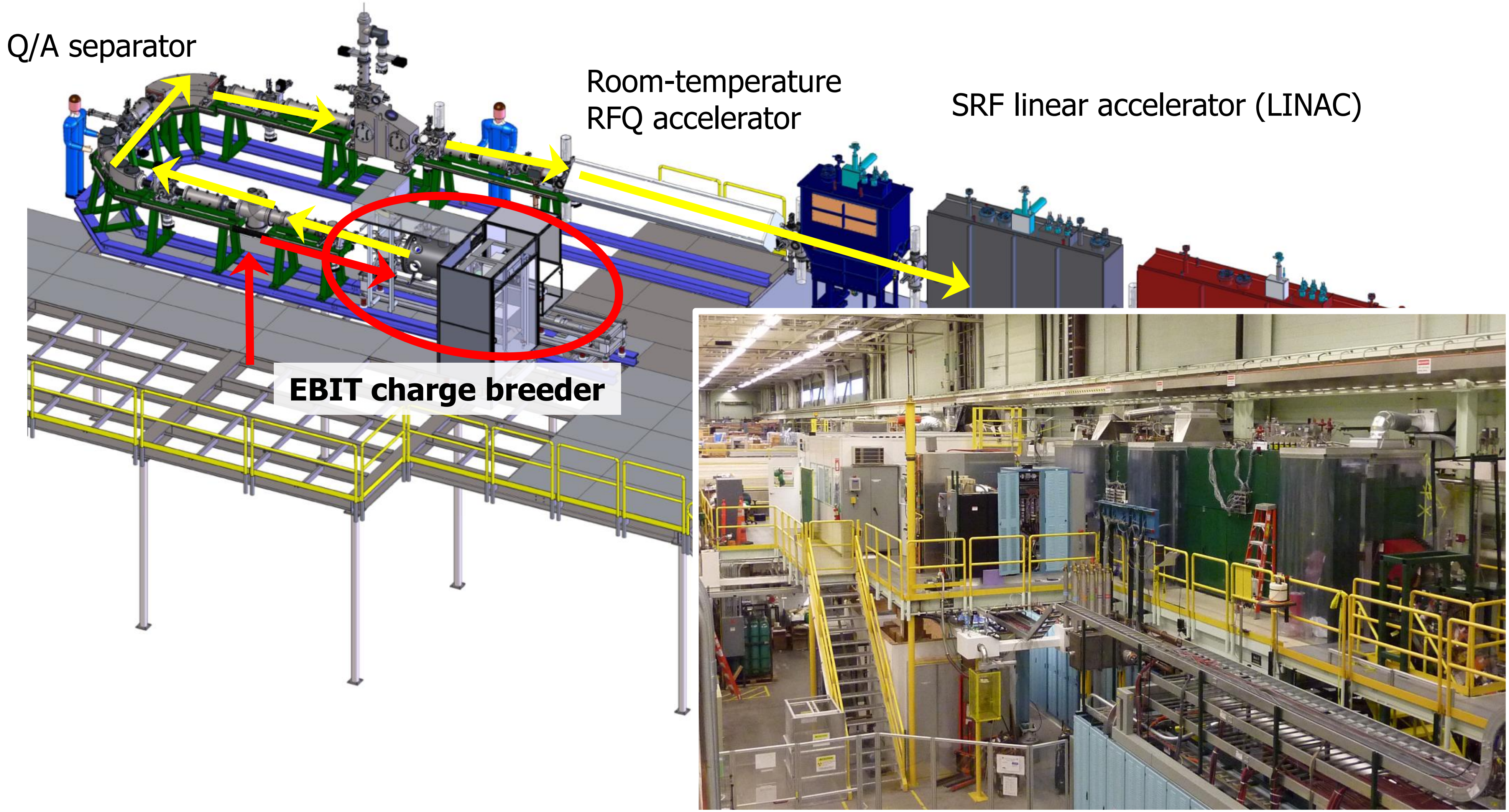
- **Continuous beam injection into BCB**
- **Pulsed EBIT injection & ejection frequency: 2 - 7 Hz**
- **$2 \leq A/Q \leq 4$**
- **Silicon β-decay counters integrated to Faraday cups.**

Current configuration, ReA3

Light ions: 0.3 - 6 MeV/u (^{48}Ca)

Heavy ions: 0.3 - 3 MeV/u (^{238}U)

EBIT charge breeder in the ReA facility



Why do we use an EBIT Charge Breeder?

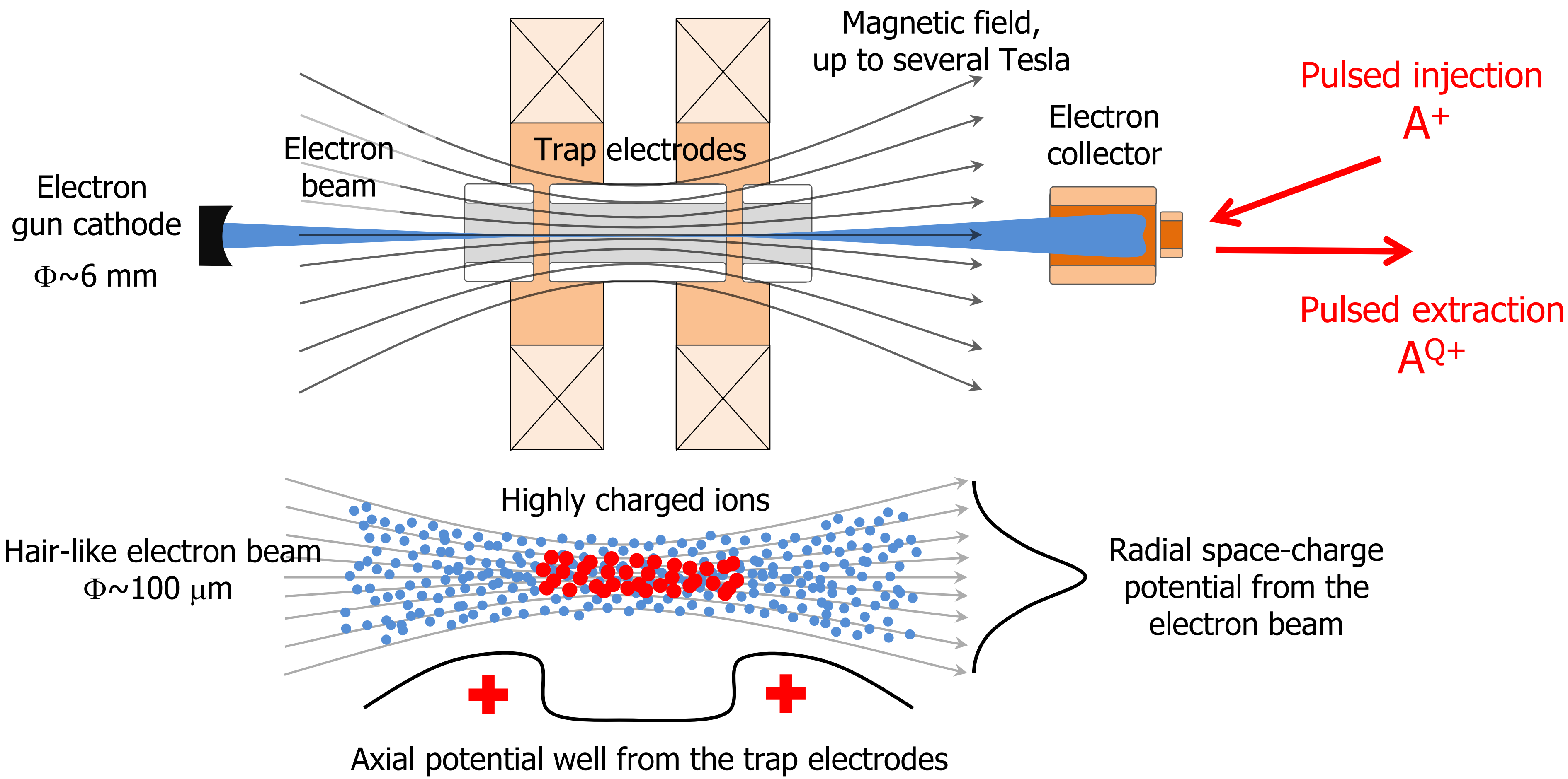
- High efficiency (narrow charge state distributions; less ions lost in many charge states)
- Fast & variable breeding times (~10 ms up to 1 s; for charge-state optimization)
- High beam purity (low contamination level)
- Variable ejected ion distribution in time (extracted pulse widths) (~20 μs up to ~100 ms)

Improve S/N ratio !

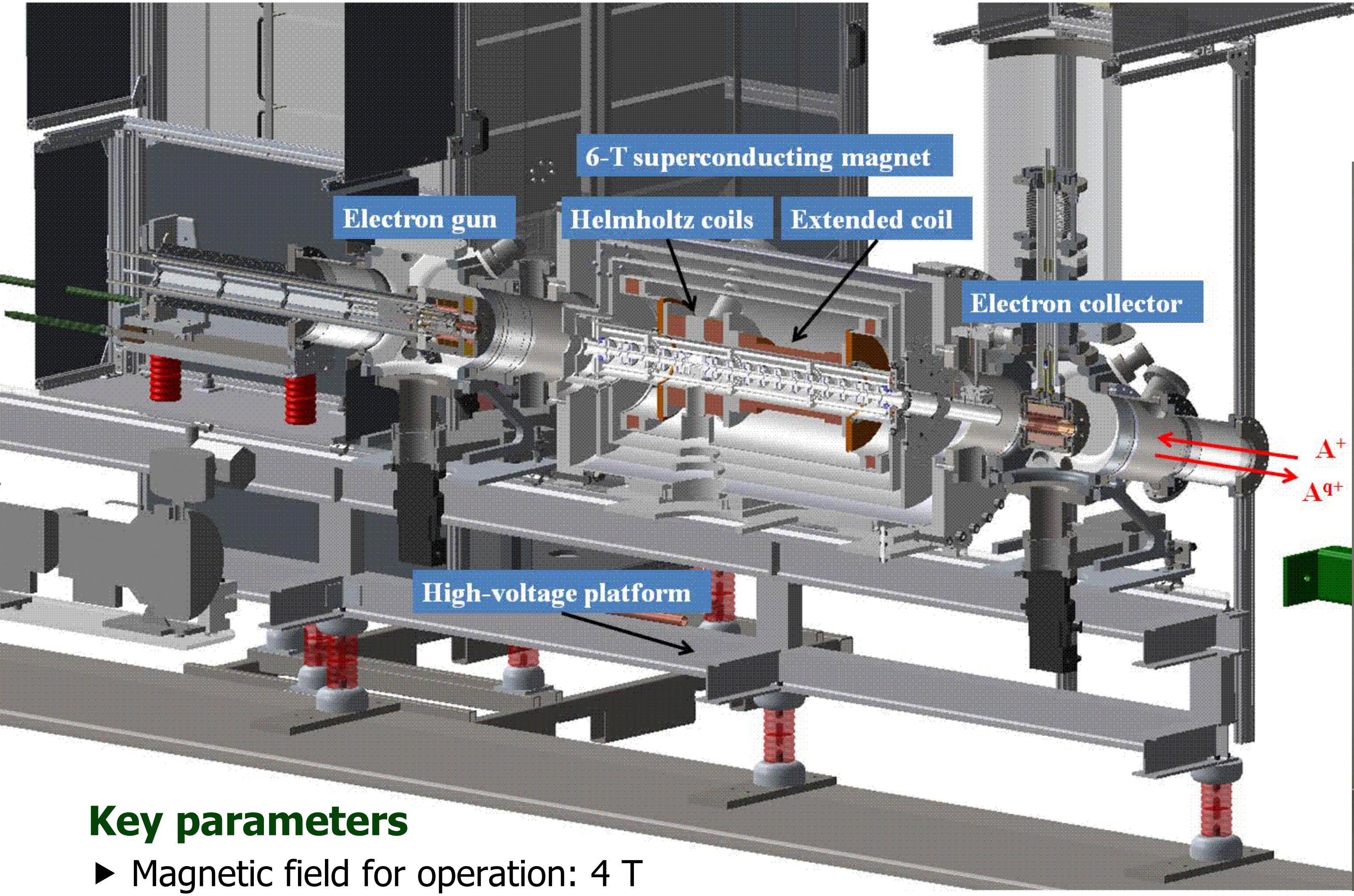
Working principle of an EBIT

What is an Electron-Beam Ion Trap (or Source) ?

- Produce & trap highly charged ions with a high-current density electron beam
- 3 main components: e-gun, trap + "strong" magnet, e-collector
- Magnetic field: Electron-beam compression & Ionization by electron impact
- Axial ion confinement provided by a potential well (trap electrodes)
- Radial ion confinement by the electron-beam space-charge potential



The ReA EBIT



Trap structure

* 1.2 m long

* 23 Ti electrodes

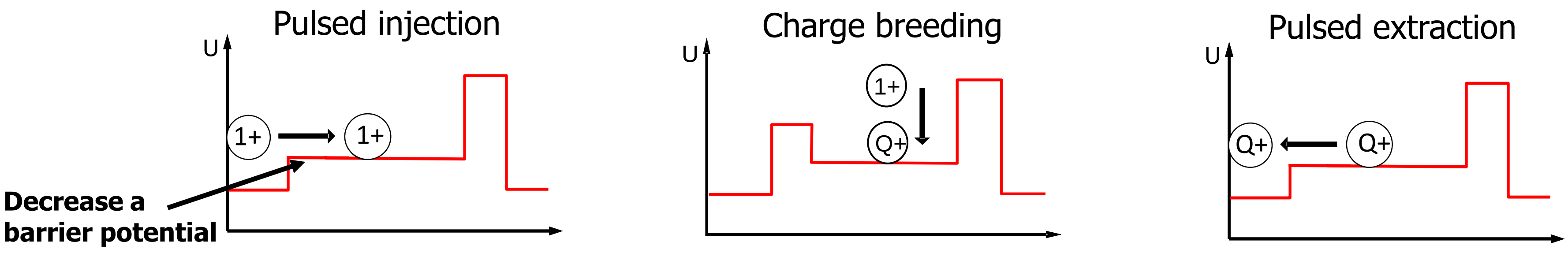
Key parameters

- Magnetic field for operation: 4 T
- Electron-beam current < 1.4 A
- Current density: ~170 A/cm^2 for 300 mA (stable 24/7 operation)
- E-beam energy < 30 keV (e.g., Ne-like U^{82+})
- Length of the trapping region: 0.64 m
- Cold trap structure at 4 K

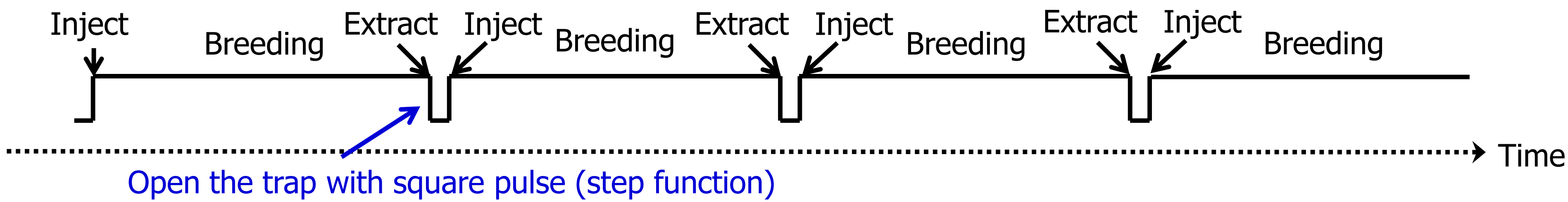
How do we inject & extract ions ?

Ions axially trapped in a potential well created with 2 barriers

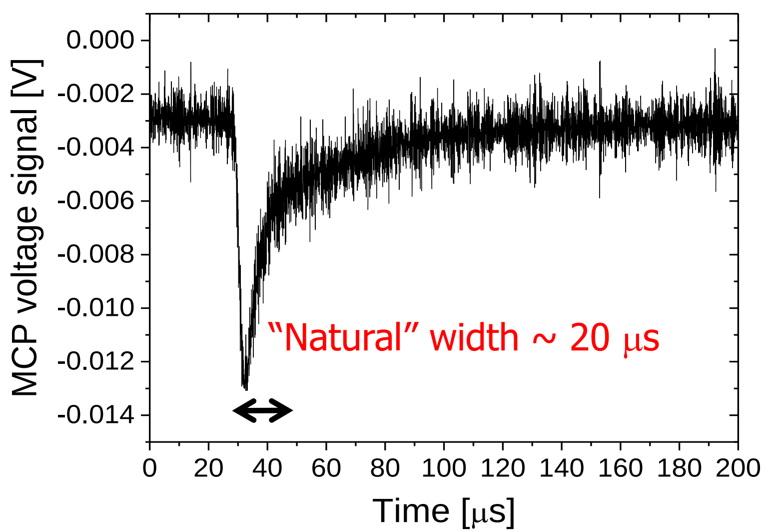
Pulsed injection scheme



Time sequence of the barrier potential



Extracted K^{10+} after the Q/A separator



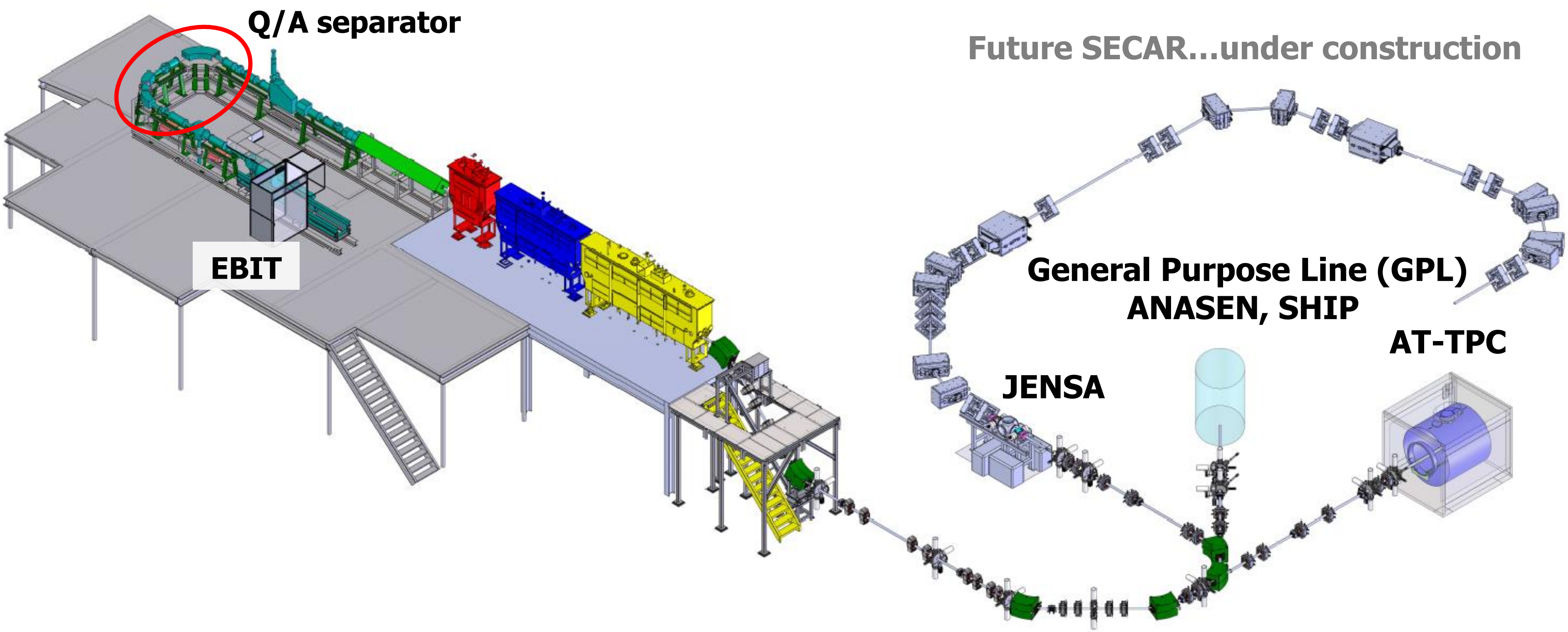
Natural width of an extracted ion pulse

- Typical pulse width (~20 μs) defined by the time taken by the trapped ions to freely exit the trap.
- In many cases, instantaneous rate of each pulse is too high for nuclear-physics experiments.
- New extraction schemes being developed to spread in time pulses by tens ms → Results at the end…

ReA operation –Results

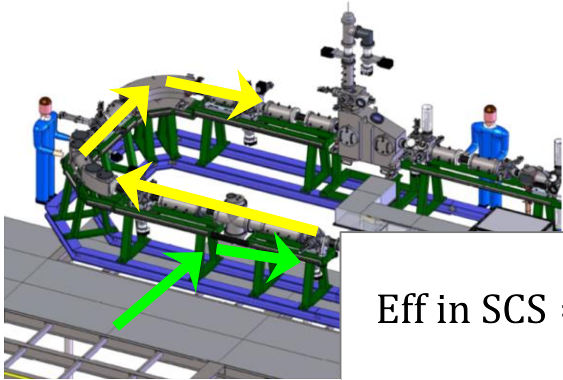
ReA officially started (on-line) operation in September 2015

- Delivered pilot beams of stable-isotope → BCB: ^{39}K, ^{85}Rb
- Delivered 7 rare-isotope beams: ^{46}Ar, ^{46}K, ^{34}Ar, ^{47}K, ^{37}K, ^{75}Ga, ^{77}Br.
- Efficiency measurements conducted with stable and rare isotopes after the Q/A separator.
- Pulse stretching tests performed with reaccelerated beams delivered to experiments (<u>during operation</u>).



Charge-breeding efficiency of stable-isotope beams

Measure ion-beam currents



Ratio of # extracted ions to # injected ions.

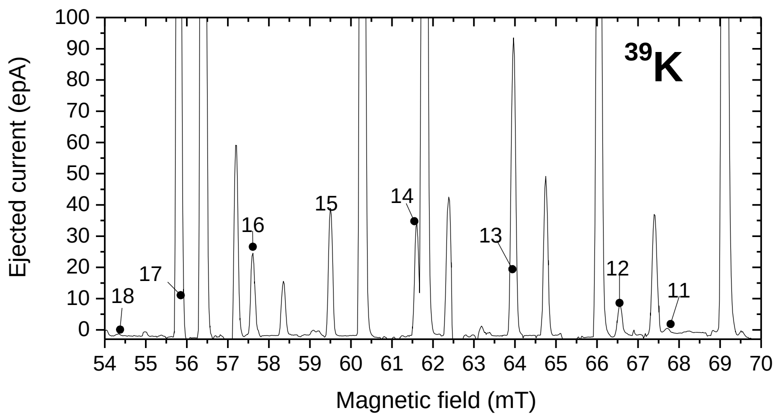
$$\text{Eff in SCS} = \frac{(I_i^{out}/Q_i)}{I^{in}}$$

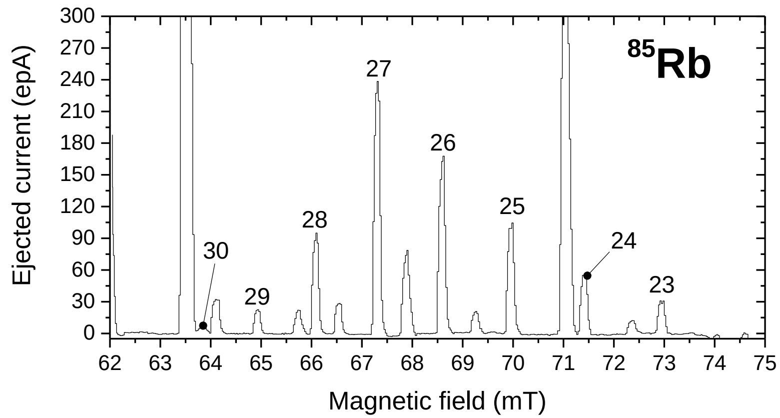
Eff in ACS = Sum over all SCS eff.

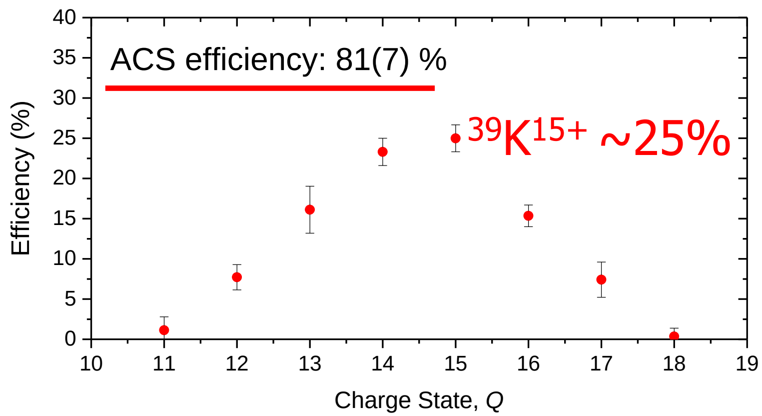
Element\ Isotope (Max. CS)	Electron current [mA]	Inj. current [epA]	Inj. freq. [Hz]	Brd.+ej. time [ms]	Max. SCS eff.[%]	ACS eff.[%] (MS)
^{39}K (15+)	302(10)	13(1)	6.98	110+23	25(2)	81(7)
^{85}Rb (27+)	333(10)	37(2)	7.12	110+20	24(1)	75(4)
^{133}Cs (38+)	573(10)	15(1)	7.00	110+23	11(1)	89(6)

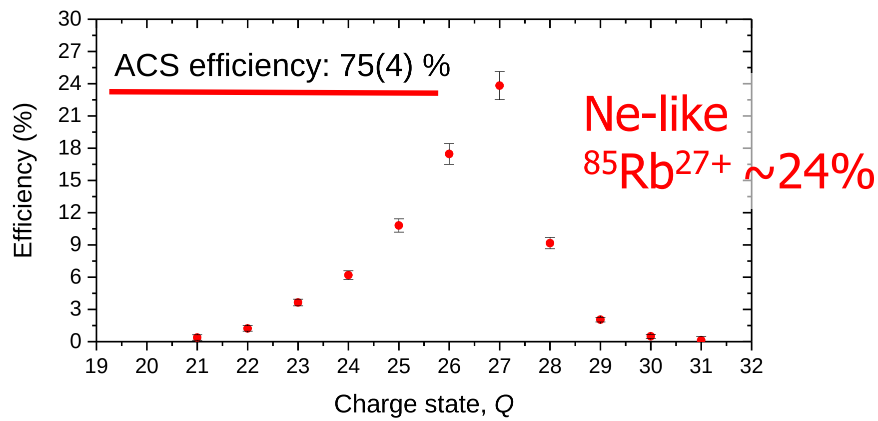
Caution: Does NOT include BCB efficiencies

Charge-state distributions: ^{39}K & ^{85}Rb



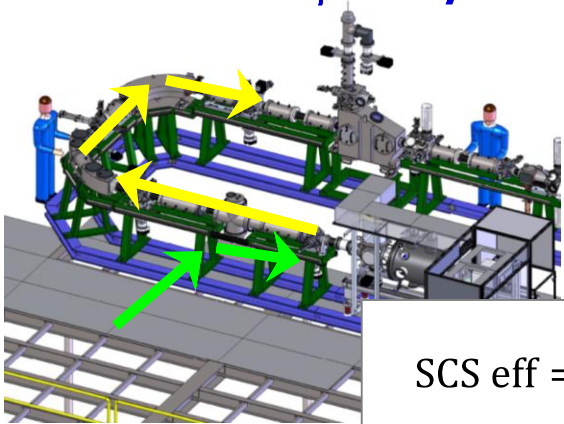






Charge-breeding efficiency of rare-isotope beams

Measure β-decay rates



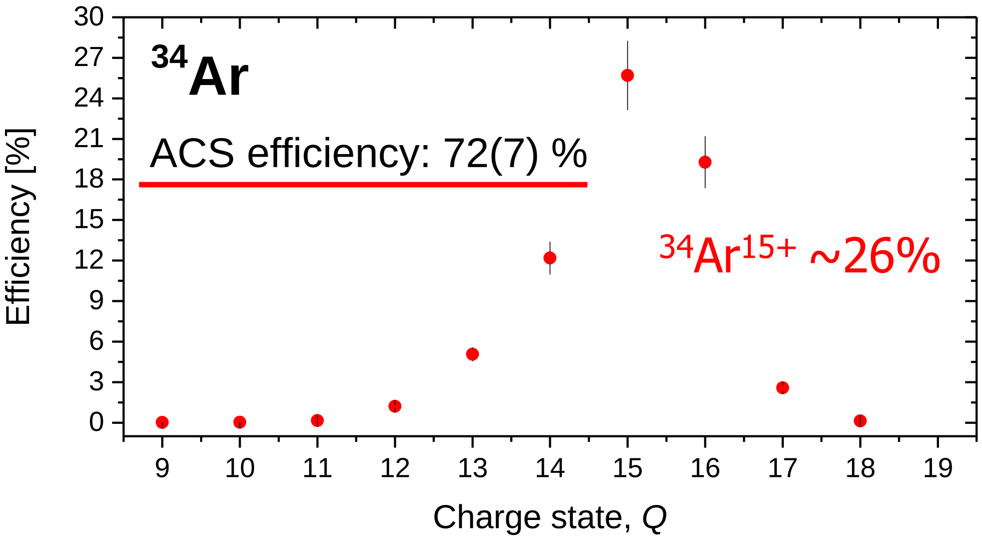
$$\text{SCS eff} = \frac{R_i^{out}}{R^{in}}$$

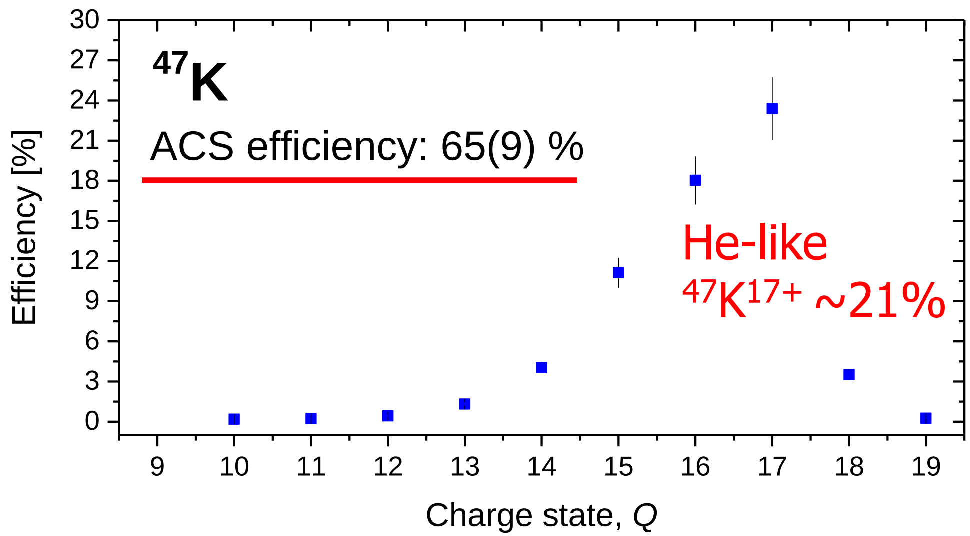
Ratio of extracted rate to injected rate

Element\ Isotope	Electron current [mA]	Brd.+Ej. time [ms]	SCS eff.[%]	ACS eff.[%] (ES)	ACS eff. [%] (MS)
$^{46}Ar^{17+}$	364(10)	369+122	15(1)	72(5)	-
$^{46}K^{18+}$	367(10)	369+122	6(1)	98(8)	61(9)
$^{37}K^{17+}$	569(10)	369+122	8(3)	79(7)	-
$^{34}Ar^{15+}$	347(10)	125+65	26(2)	-	72(7)
$^{47}K^{17+}$	332(10)	350+100	21(2)	65(9)	65(9)

Caution: Does NOT include BCB efficiencies & corrected for decay losses

Charge-state distributions: ^{34}Ar & ^{47}K

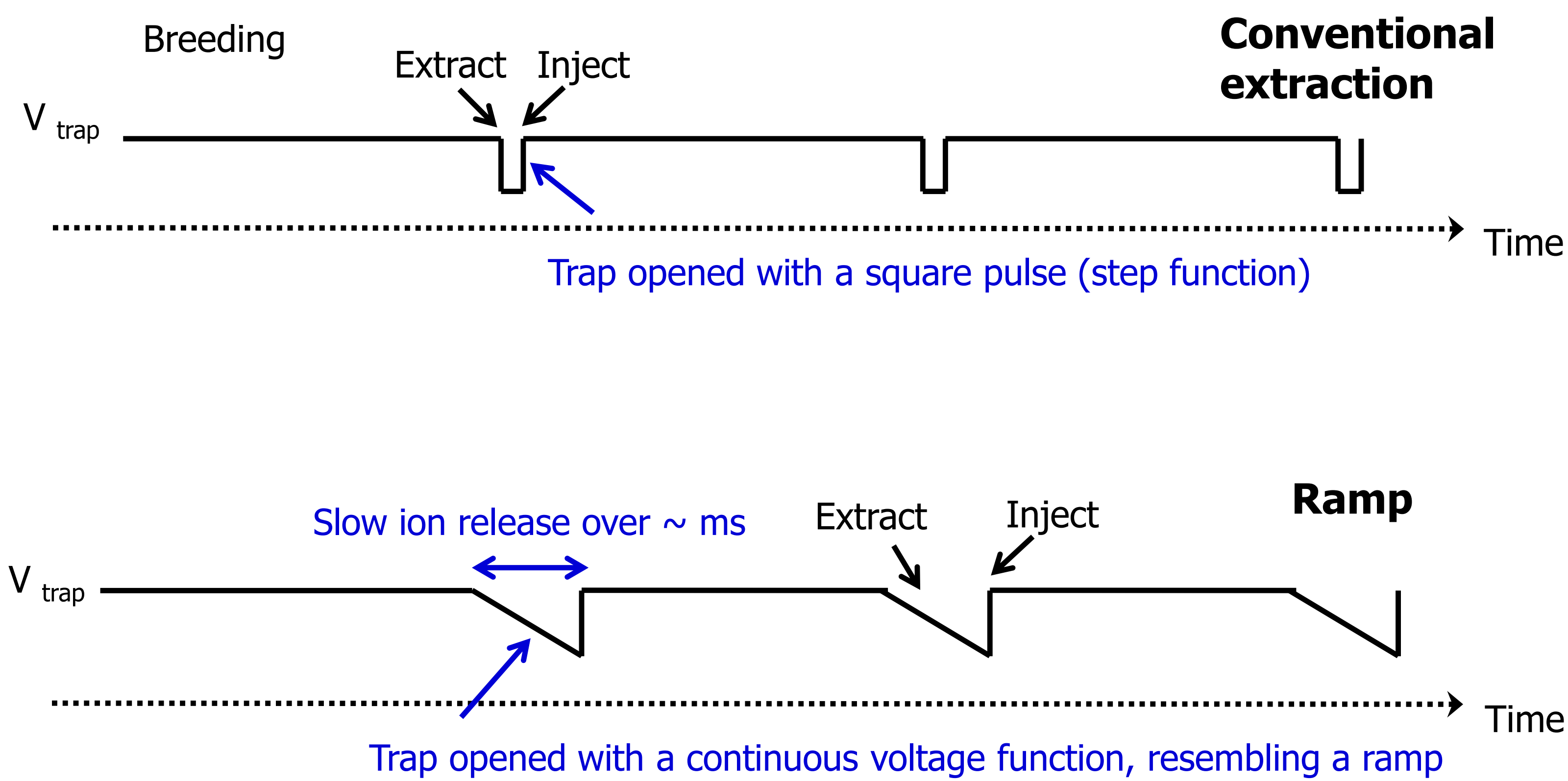




Stretching of EBIT pulse widths

Spreading in time the distribution of the ejected ions from the EBIT is important to reduce the instantaneous rate delivered to experiments.

- Instantaneous rate → # of ions per pulse width
- Each ion must arrive at the user's detector outside the dead time of the DAQ system



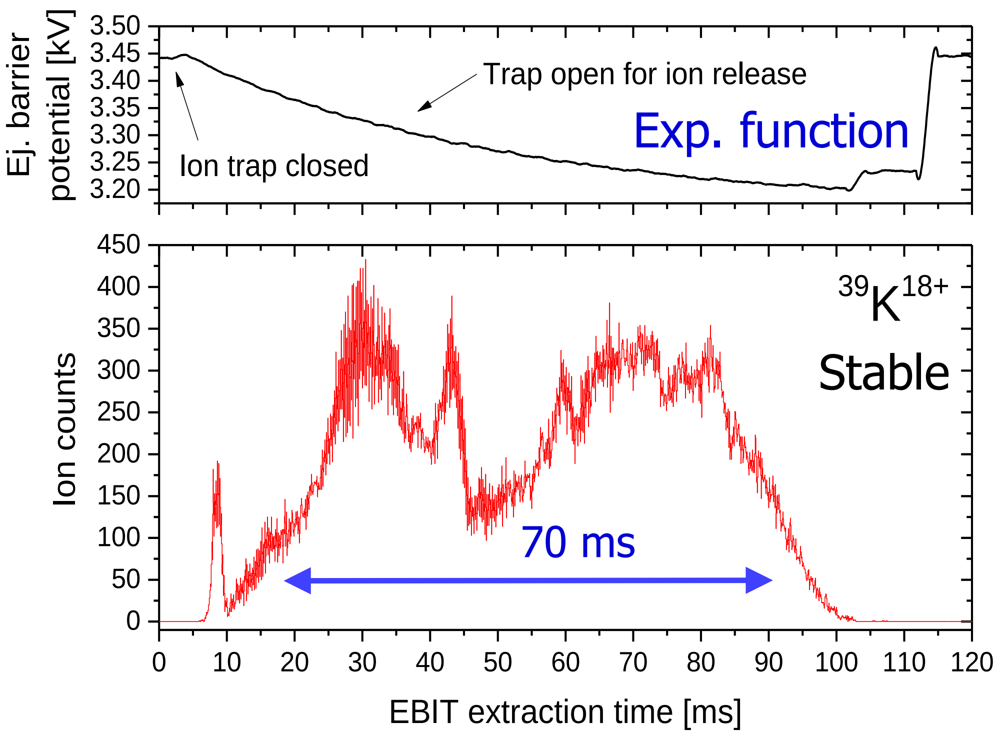
Pulse stretching –The Ramp

Trap physics → Highly charged ions confined to the bottom of the axial trapping potential

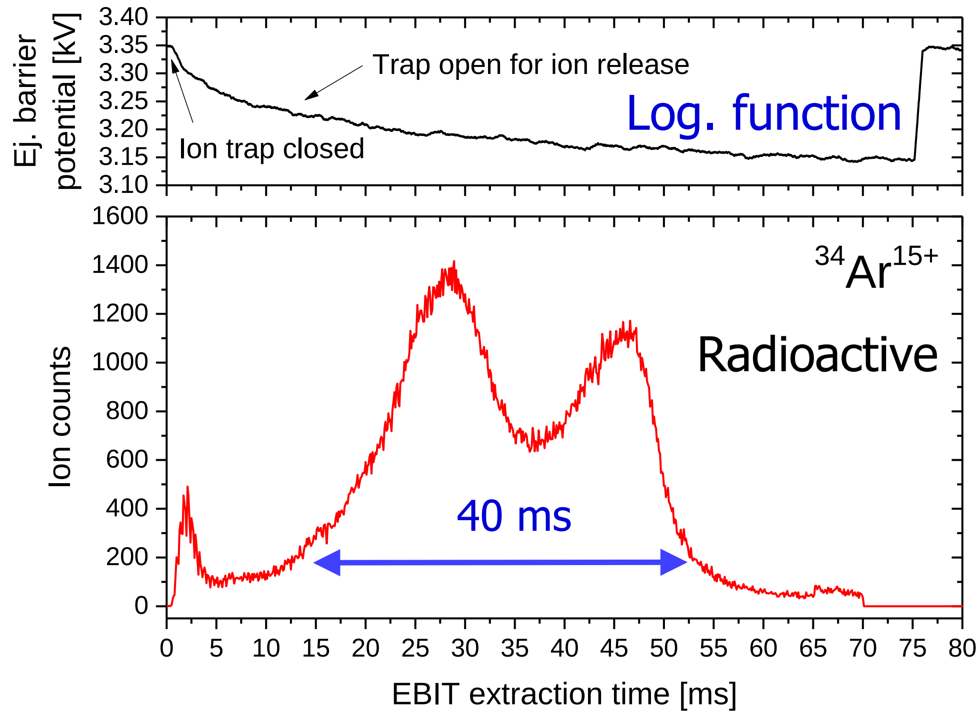
- To optimize time spread: fast barrier potential drop to reach ion position, and then slow decrease
- Best functions: Exponential or logarithmic ejection ramps
- Ion distributions (pulse widths) stretched from ~20 μs up to ~70 ms
- Two-peak structure may be caused by two potential regions in trap (?).

Stretched ion (time) distributions accelerated to experiments

Si detector in SHIP (GPL)

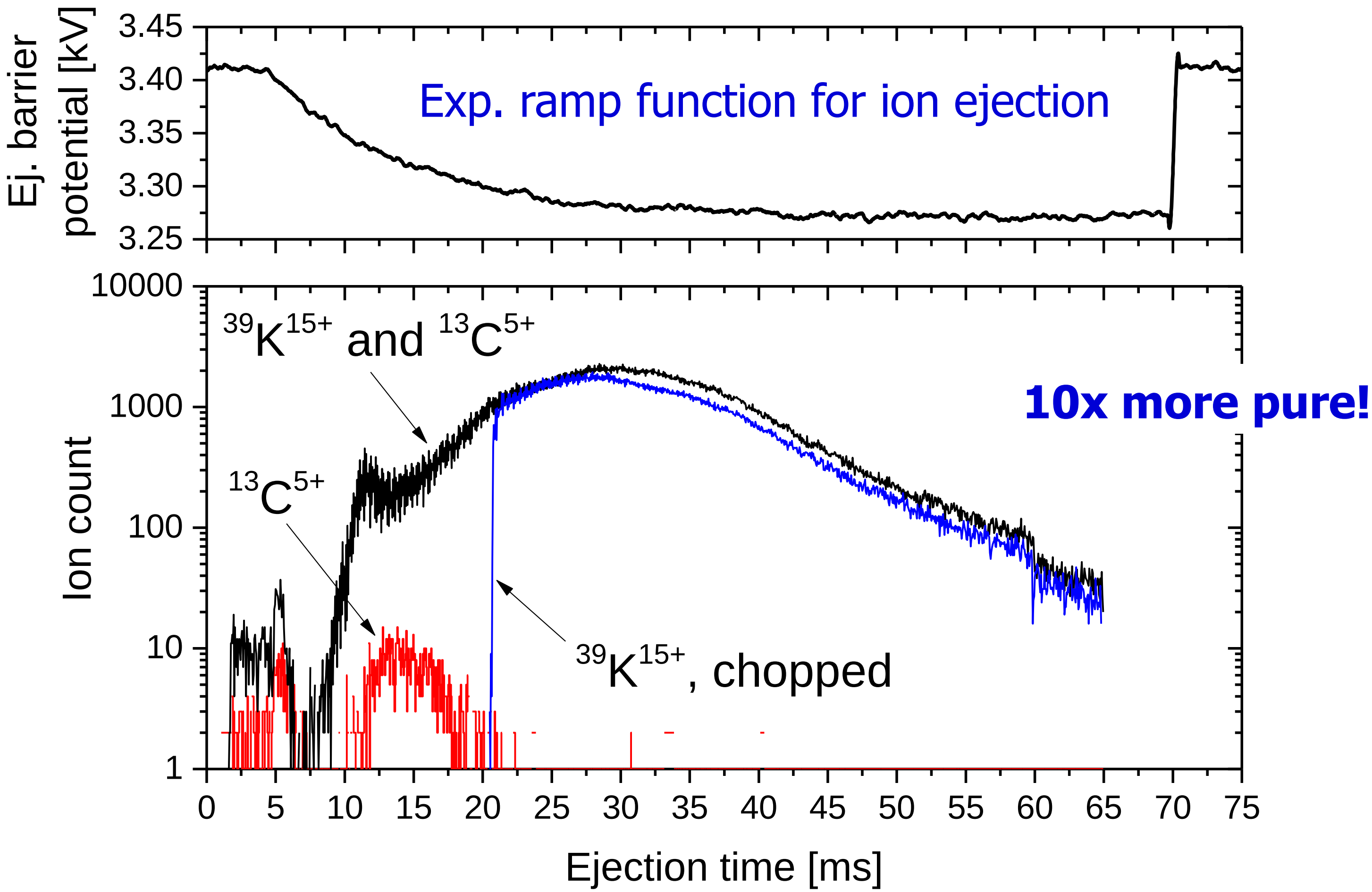


Si detector in JENSA



Stretched pulses *vs.* Contamination

Beam transported to GPL and detected with Si detector



In stretched extraction, ions of low charge state are ejected first compared to high-Q ions

- Ions of low charge states are less bound to the trapping potential.
- “Feature” can be used for beam purification.
- Red: ^{13}C-only ion distribution by blocking ^{39}K from BCB → EBIT contamination, only.
- Blue: Ion distribution cleaned by delaying the RFQ on-time period to prevent ^{13}C acceleration.

Conclusion

- ReA EBIT started (on-line) in September 2015
- Charge breeding efficiencies in single charge states, up to 25 %
- Efficiency over all charge states ~76 %
- Ion distributions stretched up to 70 ms
- Future work:
  - Investigate ion losses
  - Stable operation with 1 A (higher current densities and beam acceptance)
  - More uniform ion distributions

Thank you.

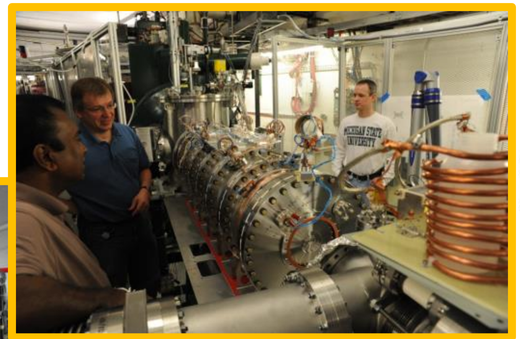
Back-up slides

The beam “stopping” area

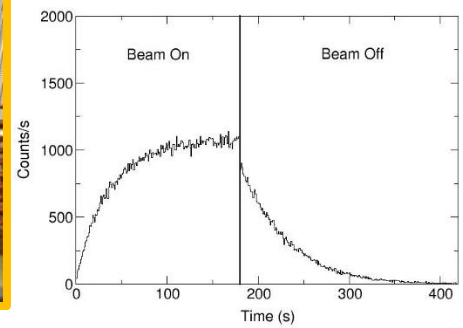
The purpose of beam thermalization

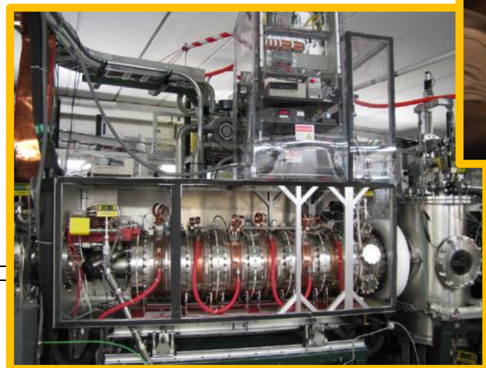
- Decelerate the rare isotopes.
- Reduce emittance to 2 mm mrad (95%, 30 keV) for eff. beam transport to ReA and low-energy facilities.
- Equipped with alkali ion source for pilot beam production.

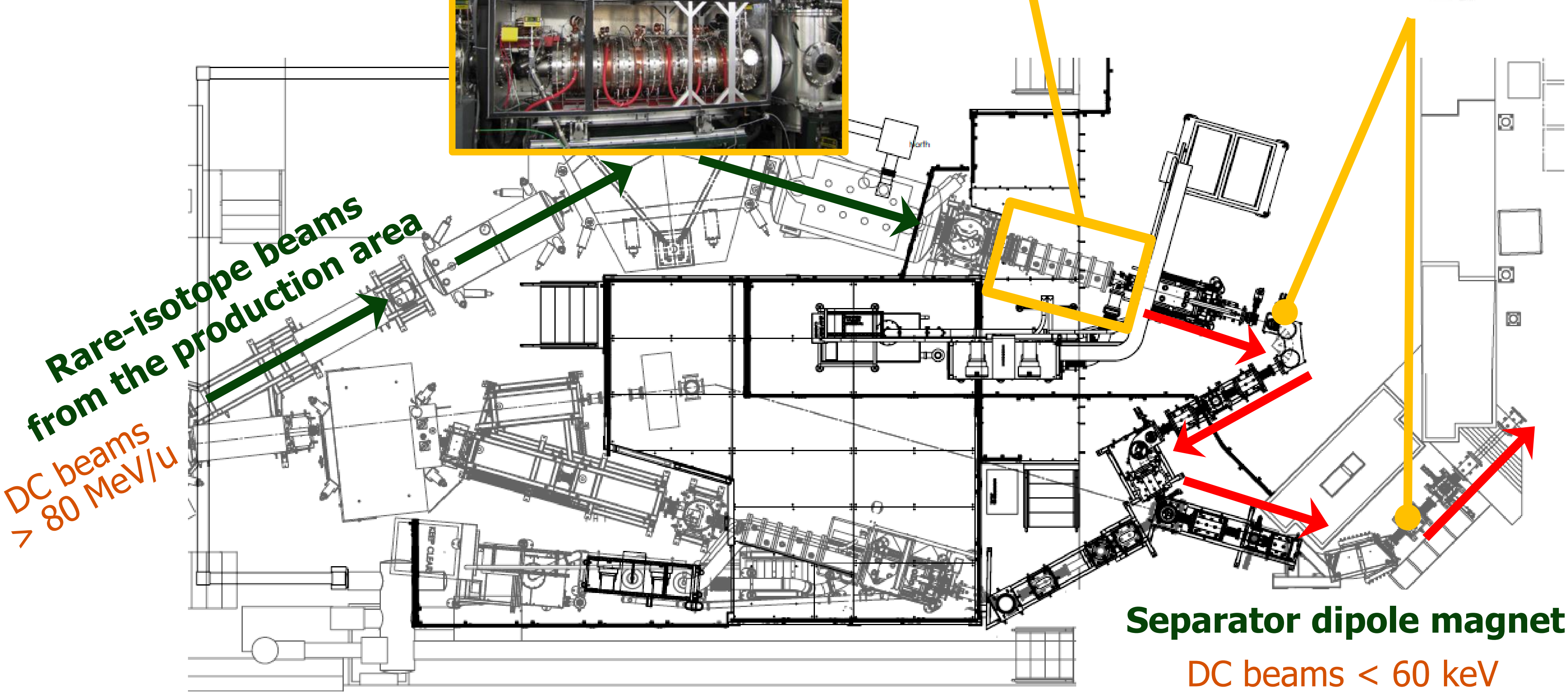
He gas cell (Argonne lab) [Gas + Degrader]



Si det. measure β activity for particle ID & beam transport optimization





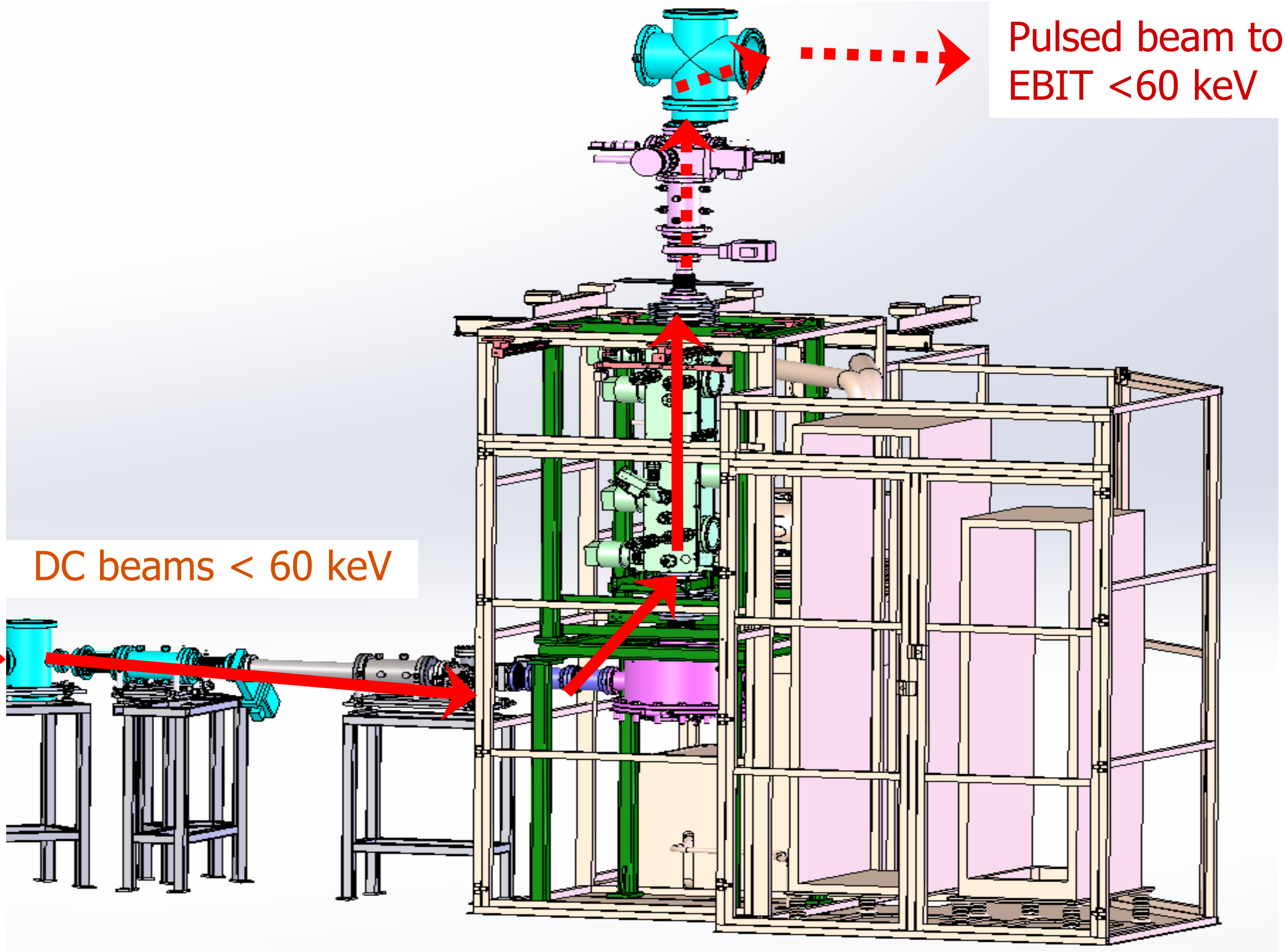


Beam cooler buncher for pulsed injection

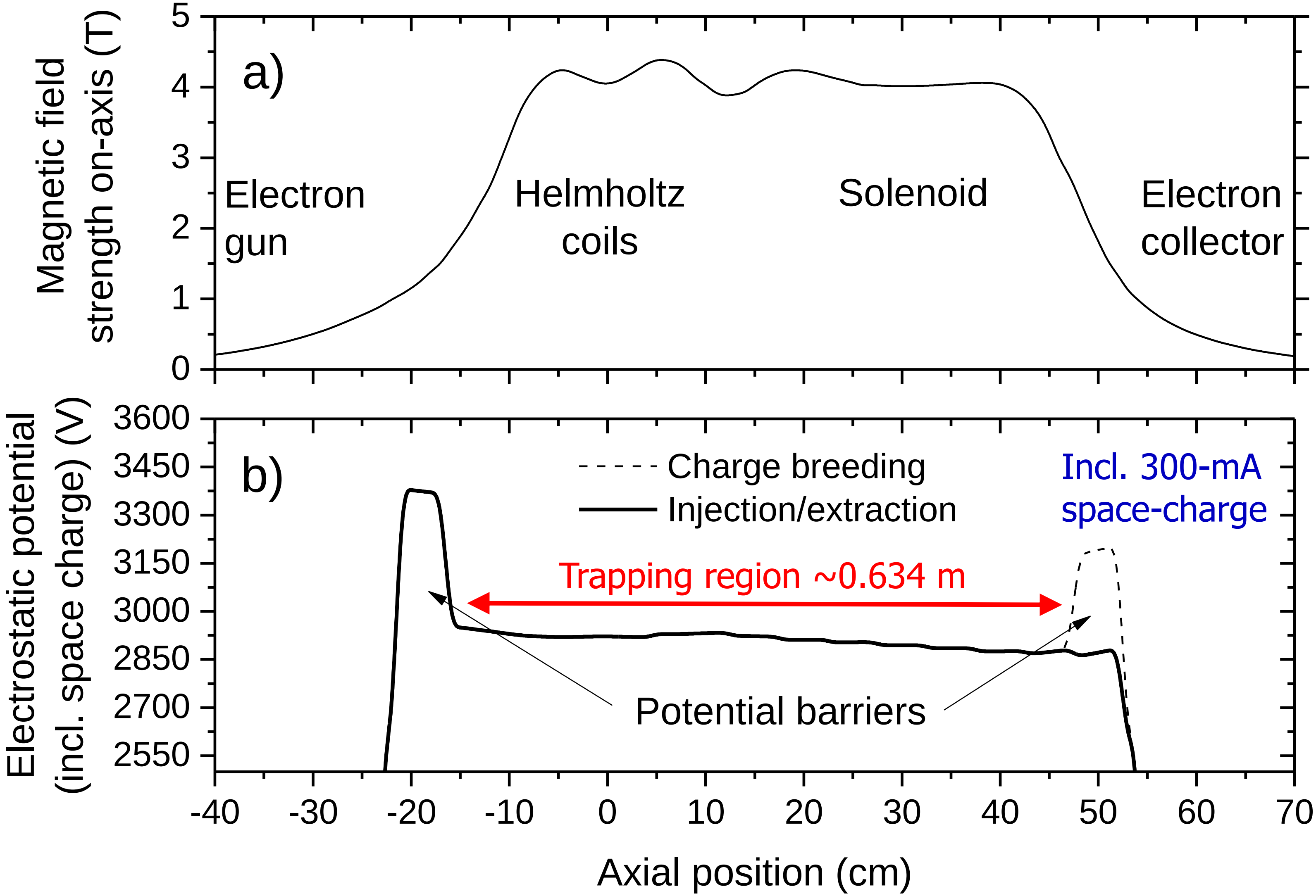
He-gas-filled radio-frequency quadrupole (RFQ) ion trap (Paul trap)

- NEW device added to help improve EBIT injection efficiency for low-current electron beams
- Started operation in September 2015
- Efficiencies between 50% - 100% (depend on injection optics)
- Equipped with alkali ion source for production of pilot beams

*After mass separation
with separator magnet



The ReA EBIT magnetic & electrostatic fields



Some imperfections…

- Magnetic field is not homogenous within ± 3%
- Combined with the e-beam space-charge potential, central electrostatic potential experienced by ions in the trap is non-uniform **(does not seem to impede charge breeding…)**.

Typical operational parameters

Injection energy < 40 keV

Ejection energy = 12 keV/u x A/Q (def. by RFQ velocity accept.)

Efficiencies in single charge states ~ 10 – 25 %

Breeding time < 369 ms

Ejection time < 125 ms

E-beam current ~ 300 - 600 mA

E-beam density ~ 174 - 329 A/cm^2

E-beam energy ~ 15.5 keV

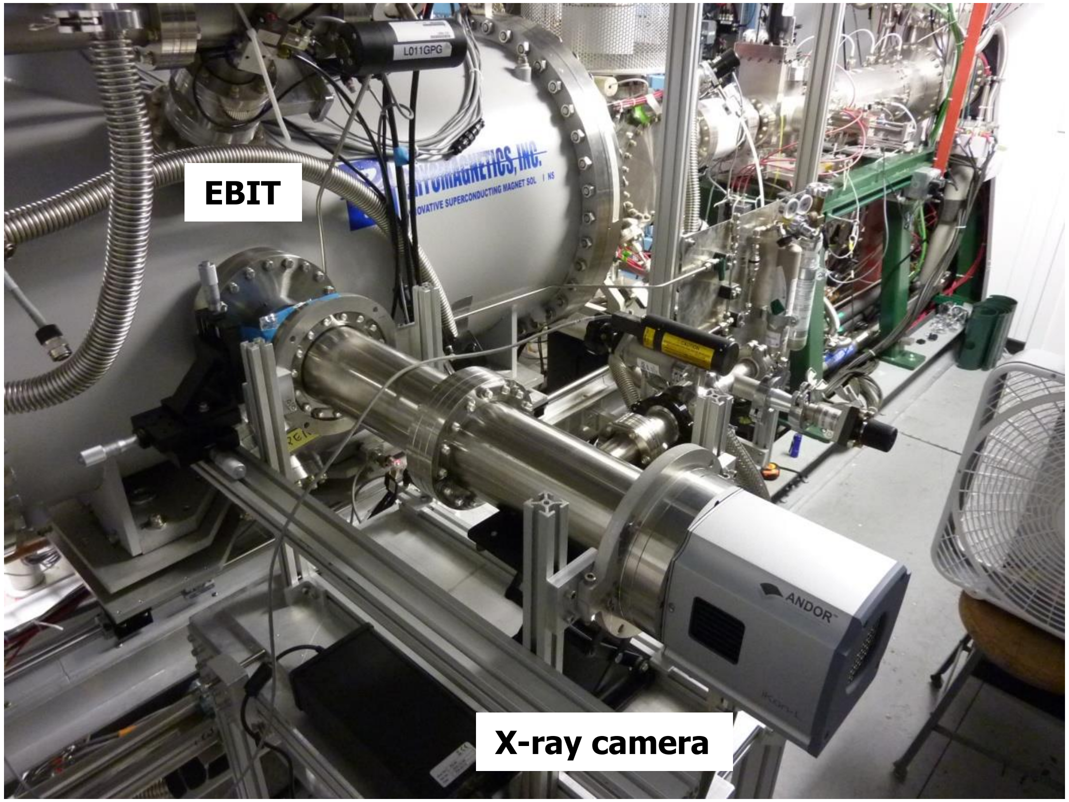
Field configuration: 4T - 4T

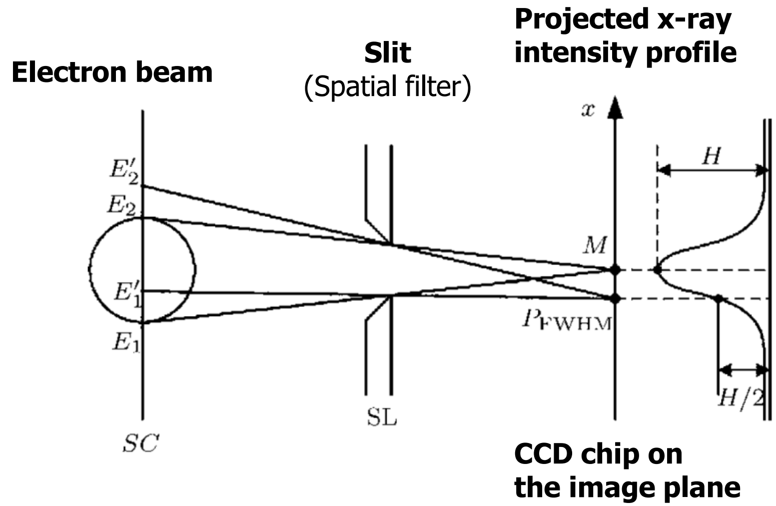
Trapping region: 0.64 m

- Electron current can reach up to ~1.4 A. Due to beam instabilities, the current is kept low during operation.

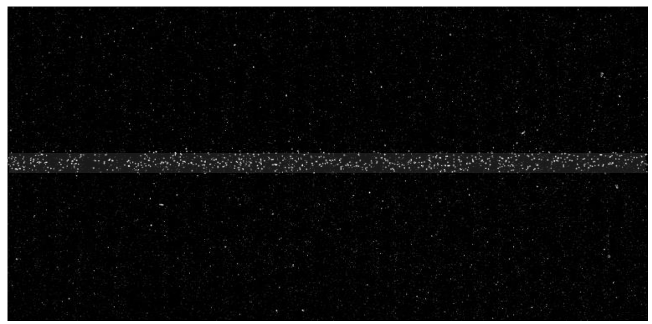
Measured radius of the electron beam by x-ray imaging

X-ray pinhole camera installed on a radial port of the EBIT





X-ray image of the electron beam



r_e (80%) ~ 212(19) μm for 800 mA in 4 T

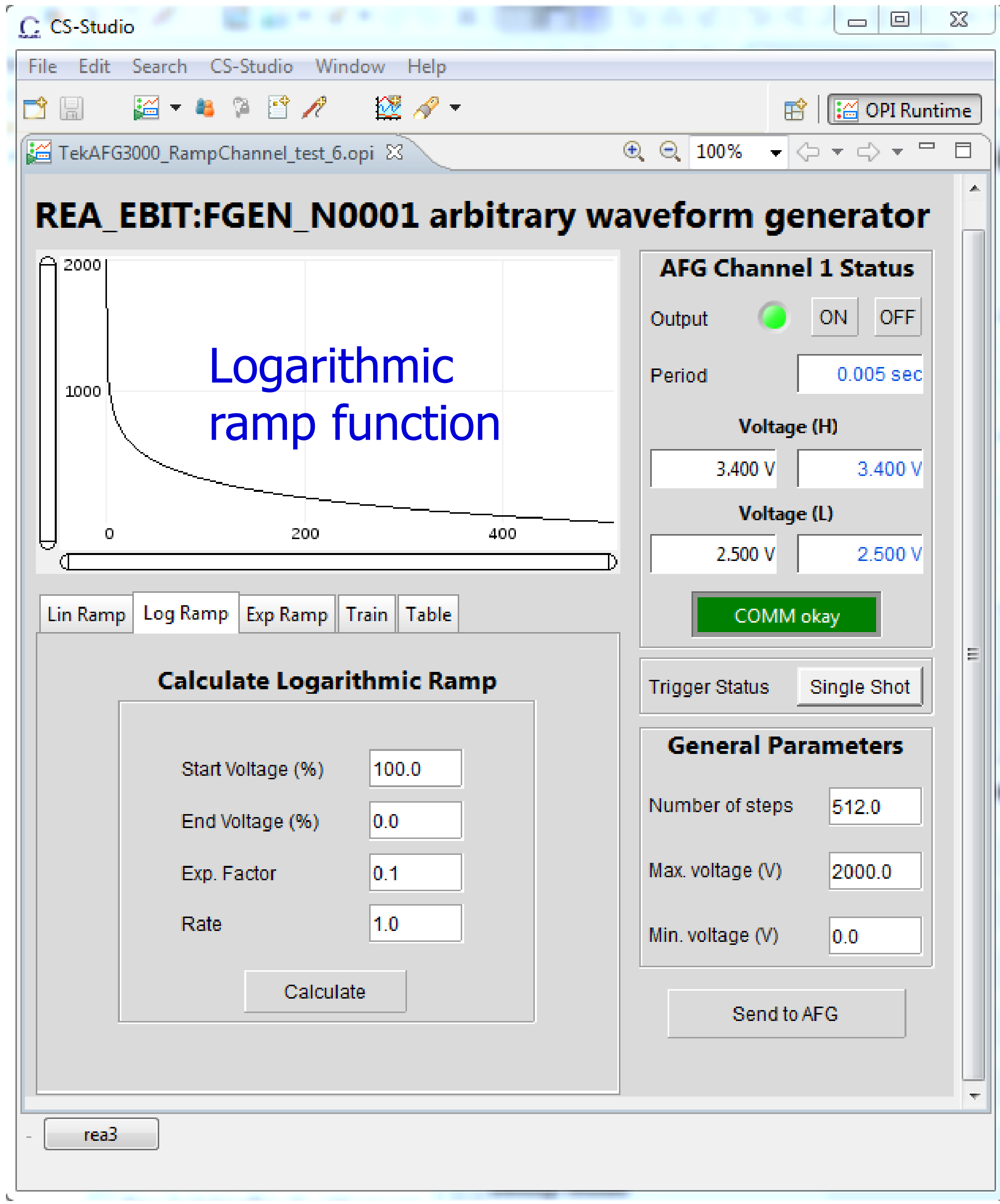
j_e ~ 454(83) A/cm^2 for 800 mA in 4 T

T. Baumann, A. Lapierre, S. Schwarz, K. Kittimanapun, D. Leitner, G. Bollen, RSI 85, 073302 (2014)

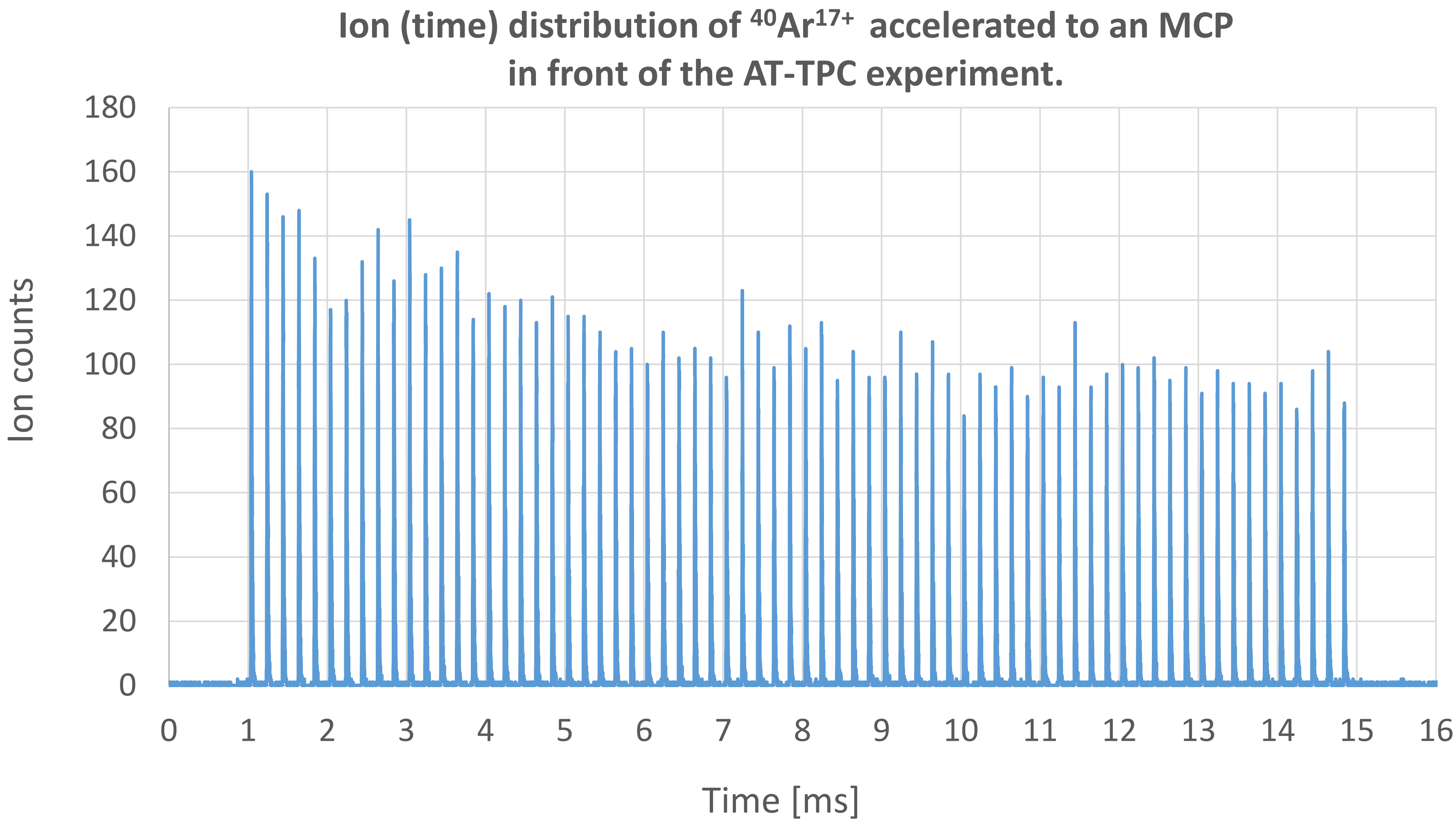
Pulse stretching – The Ramp

- Output of the (voltage) amplifier can be controlled by an Arbitrary Function Generator (AFG)
- Using specialized Controls apps, extraction ramp functions can *easily* be uploaded to an AFG: multi-segments Lin, Exp, Log, etc.

Snap shot of a Controls app….



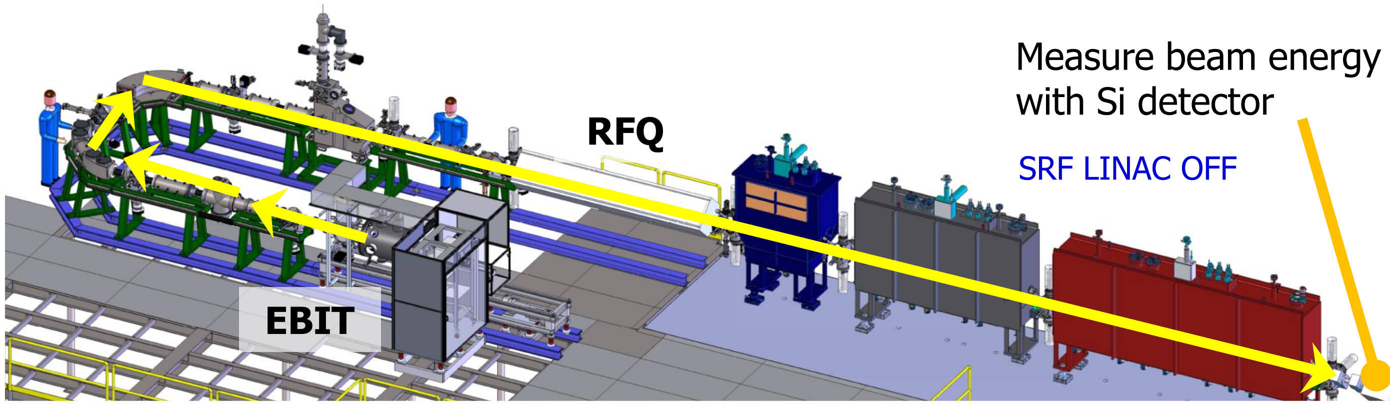
Pulse stretching – Latest result of the Train

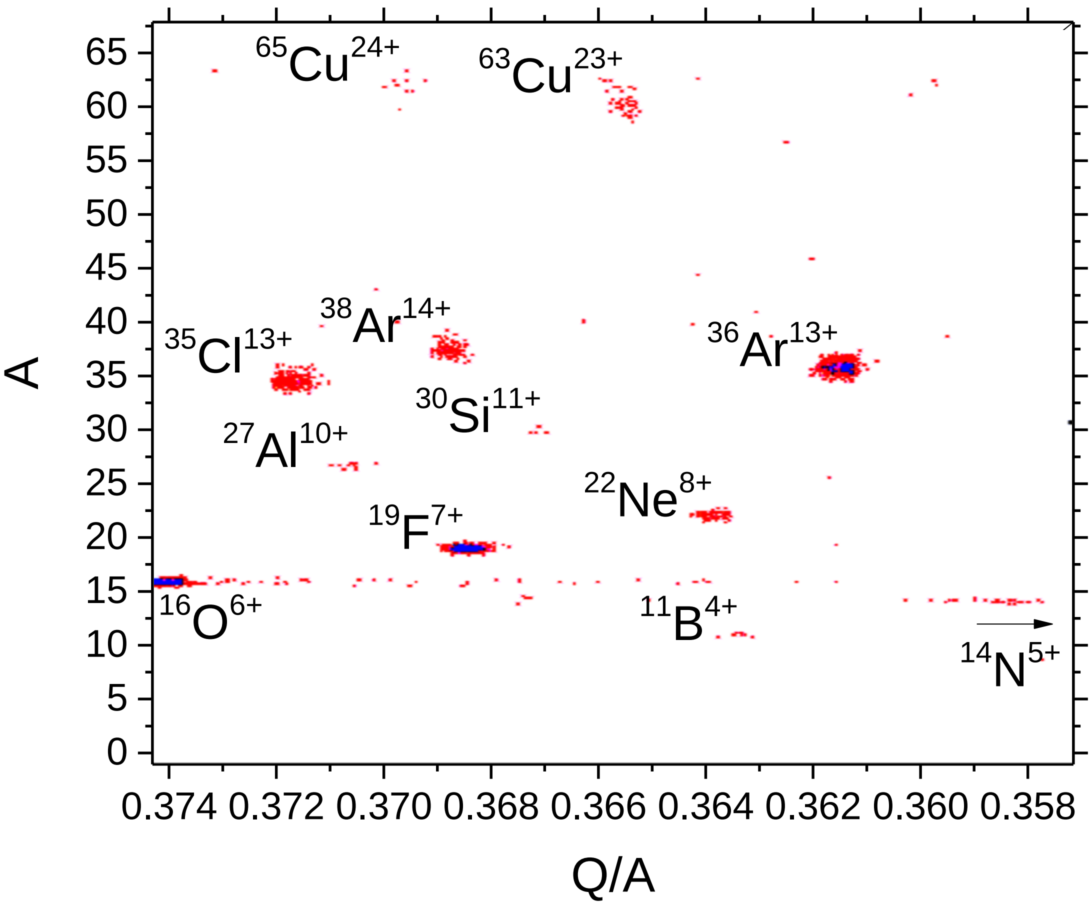


- *Amplifier applied voltage to the extraction potential barrier
- ~1 - 2 μs trap opening time, spaced by 100 μs
- **Up to 70 pulses within 15 ms (each micropulse containing a few ions)**
- Try to develop…faster HV switch to inject pulses into RF cycles of RFQ (~60 ns, 100 kHz)

Contamination maps

Identifying contaminants is essential to eliminate them & provide rare-isotope beams of high purity





Program to map Q/A regions

Q/A separator measures the Q/A: $B \propto \sqrt{A/Q}$

Fixed RFQ accel. energy: $E_{RFQ} = 600$ [keV/u] $\times A$

By scanning the field of Q/A sep. and measuring beam energy with Si det., the A and Q/A can be disentangled.

Typical EBIT contaminants:

Na, Cl → NaCl (fingerprint?)

Si → Aluminized mylar tape adhesive

F → Scroll-pumps: Bearing lubricant & tip seal (Teflon)

S → Dichronite UHV bearing lubricant (WS_2)

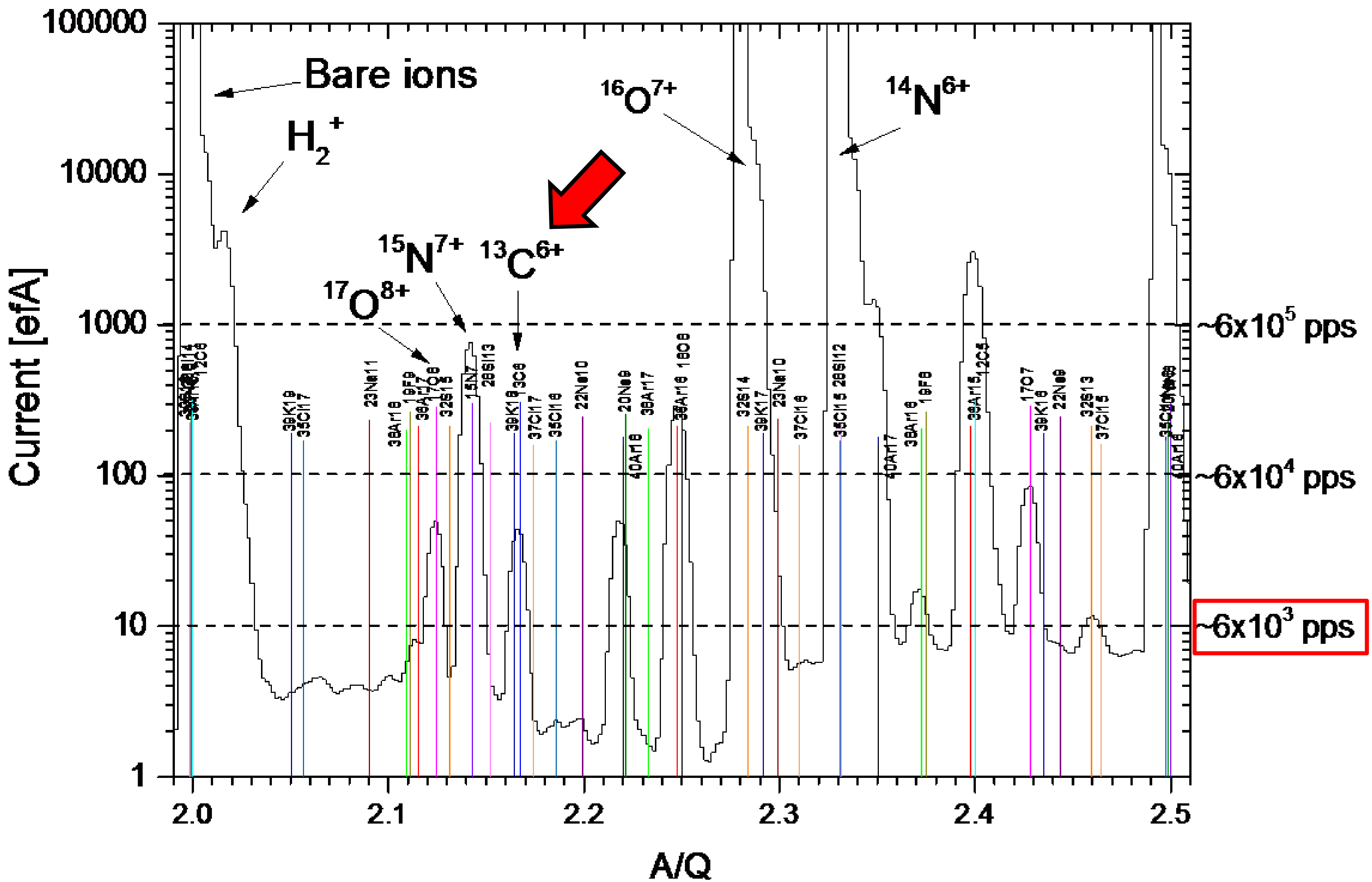
Ba, W → Dispenser cathode (not detected !!!)

Cu → Collector, anode…

All stable isotopes of C, N, O, Ar → Residual "air"

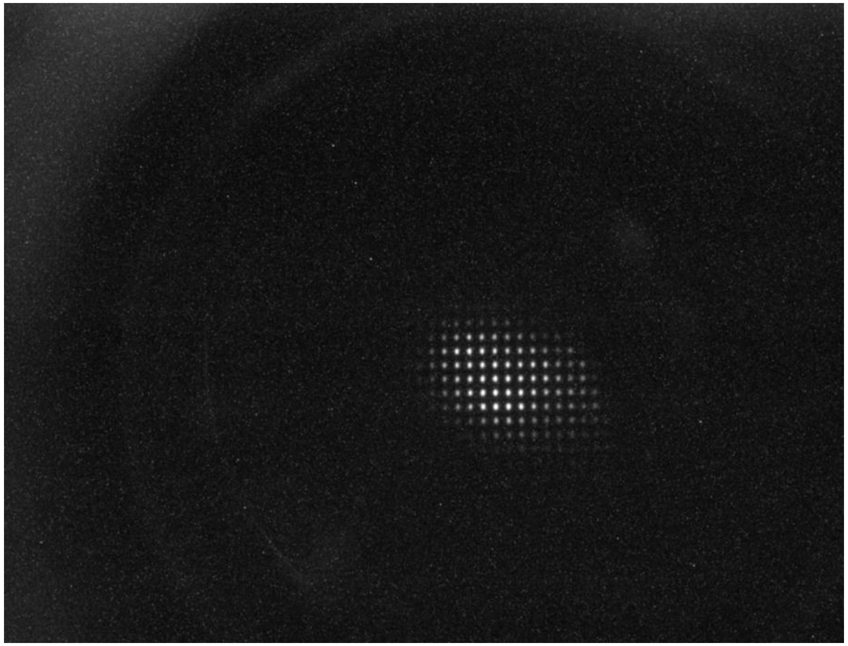
Contamination measurements

- Trying quantifying contaminants by measuring beam current with high sensitivity with Faraday cup
- Using a commercial low-noise ammeter with long averaging → ~ 10 efA; 6000 pps for *Q*=10

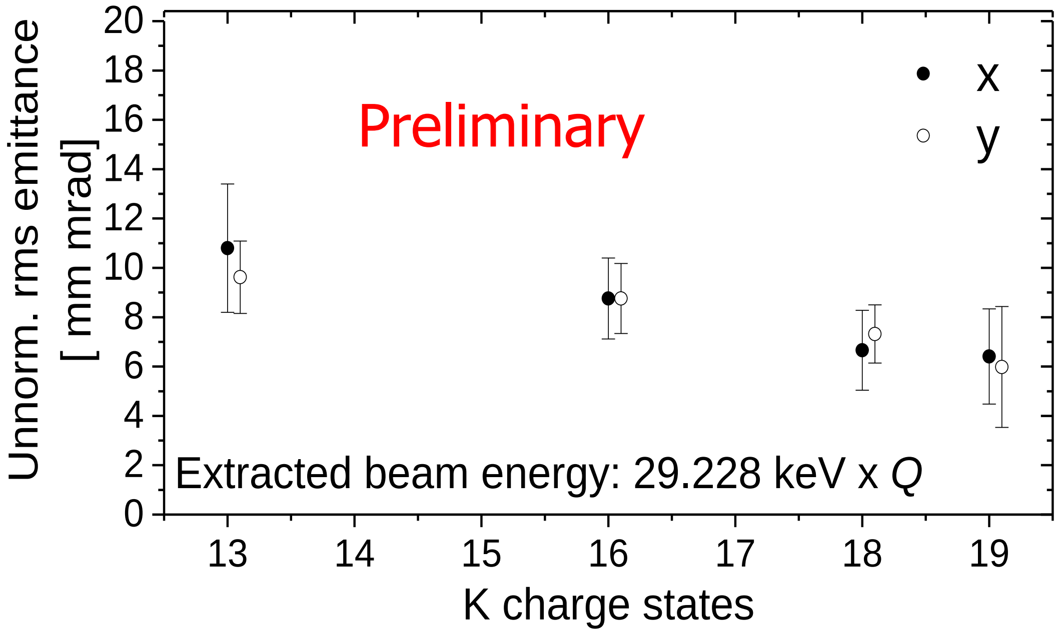


Transverse emittance measurements with Pepperpot-meter

K^{18+} beam on MCP viewer



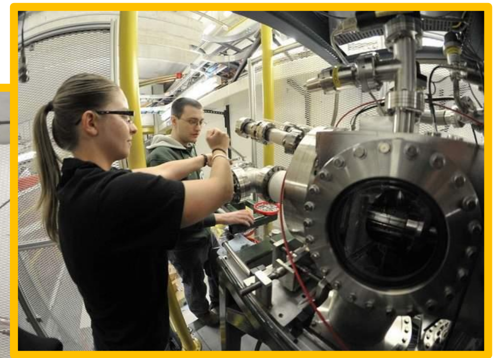
Emittance *vs* charge state

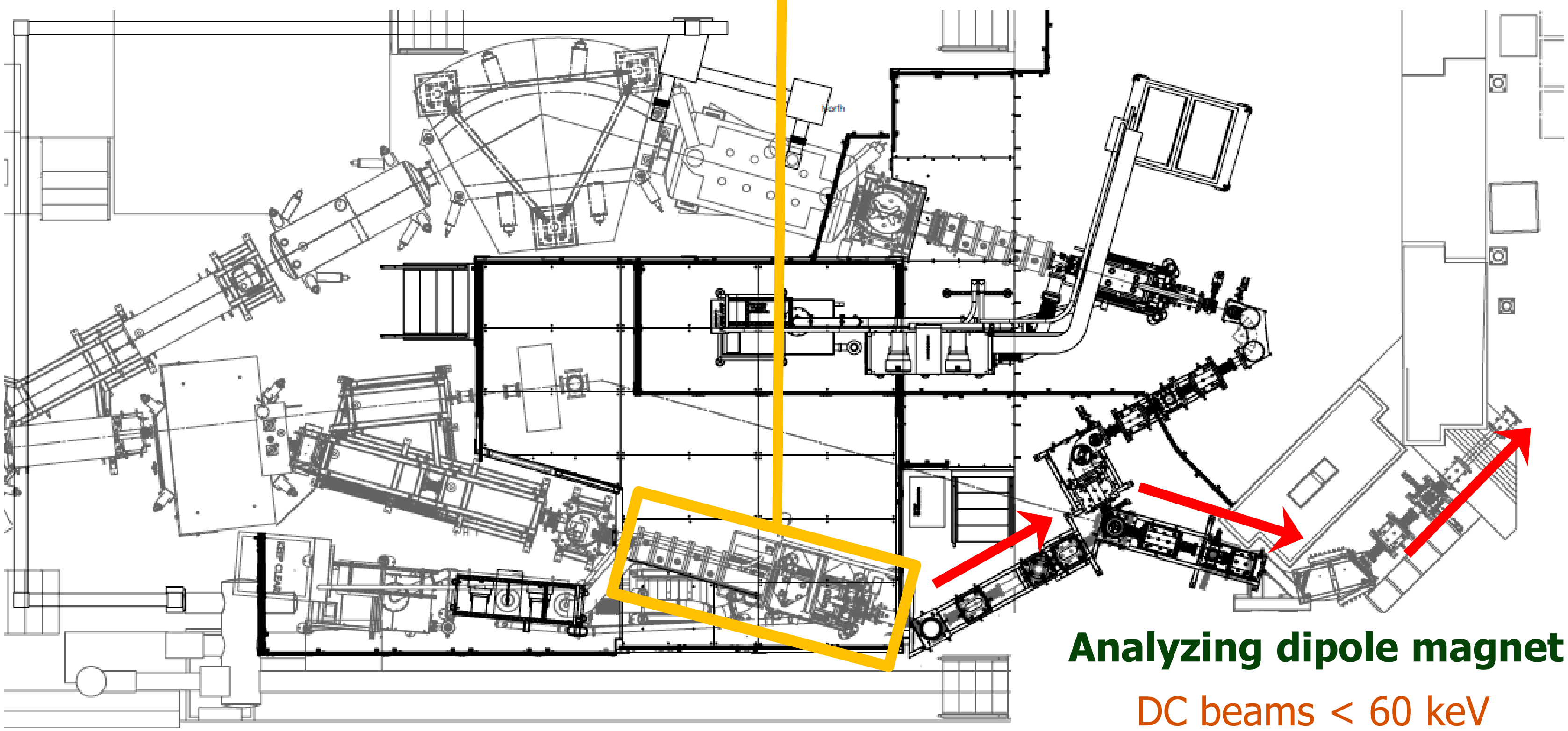


The beam “stopping” area

Second beam line:

- Equipped with offline (surface) ion source (e.g., K, Rb…)
- For commissioning purposes

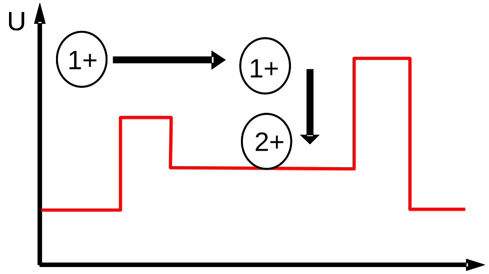




ReA EBIT: Double-magnet configuration

Over-the-potential barrier injection

"Quasi-continuous"



Solenoid: Long low-field region

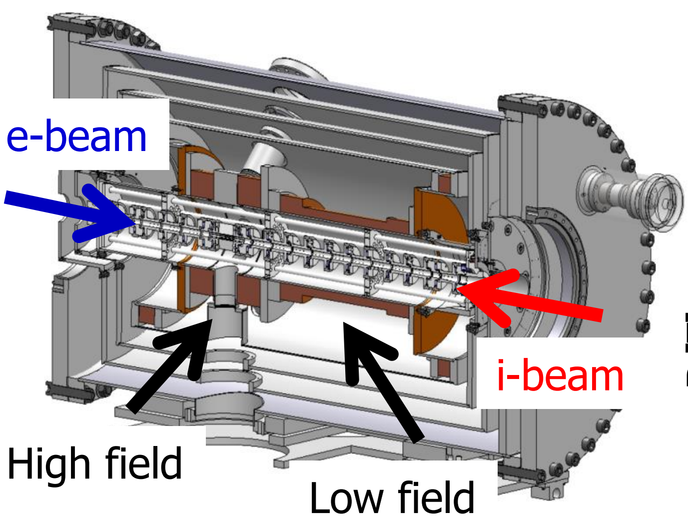
To maximize ionization of 1+ ions within a roundtrip:

Keep e-beam diameter for high electron-ion beam overlap upon injection → High capture probability

Helmholtz coils: Short high-field region

Reduce e-beam diameter for high current density → High charge states and fast charge breeding

Location of the two field regions

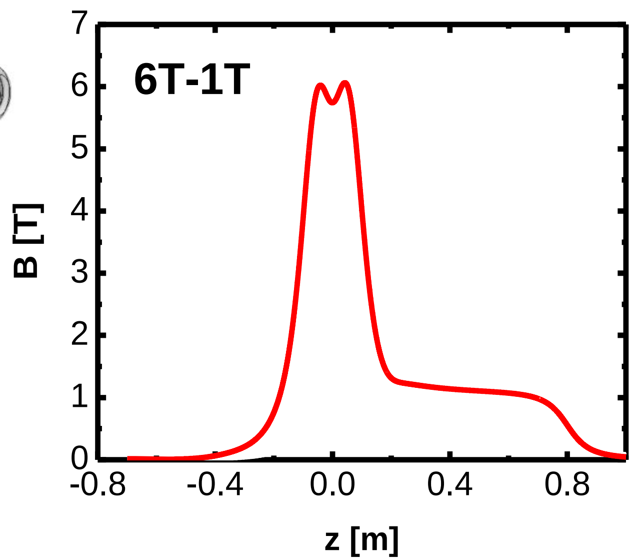


Monte-Carlo simulations of capture eff.:

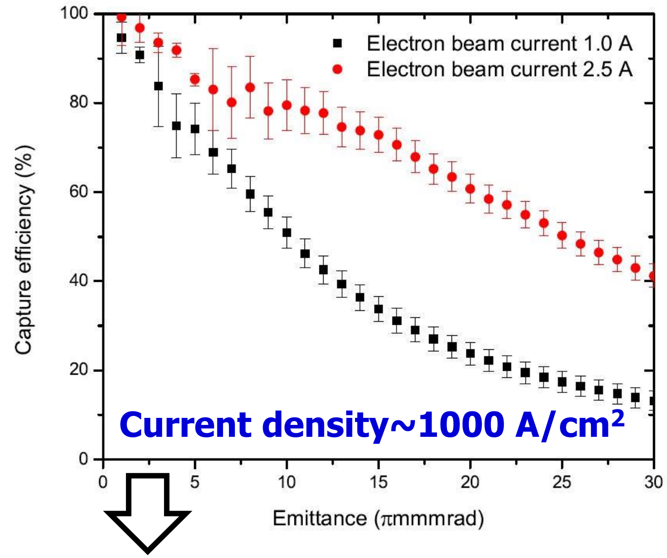
E. Gavartin – M.Sc. Thesis, MSU,

K. Kittimanapun – PhD, MSU.

Preferred B-field distribution



Capture efficiency from Monte-Carlo simulations



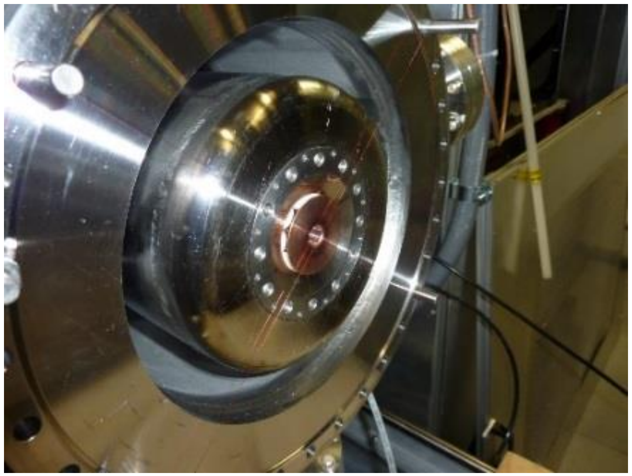
@1A: >80% for <3 π mm mrad

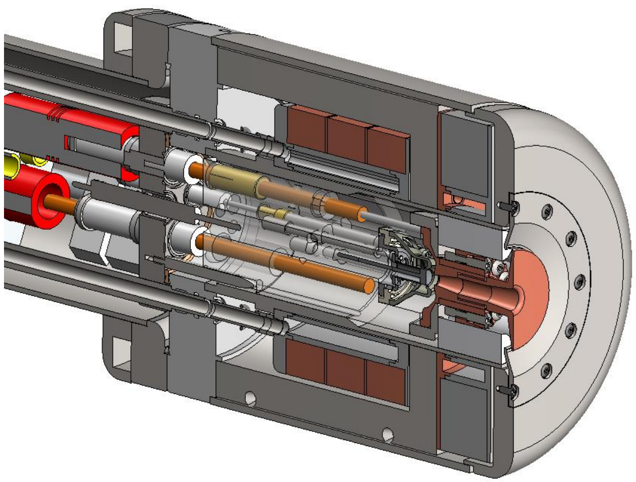
High-current electron gun to maximize the capture efficiency of injection ions

- Thermionic electron gun
- Ba-dispenser cathodes
- 6-mm in diameter
- Modular cathode assembly

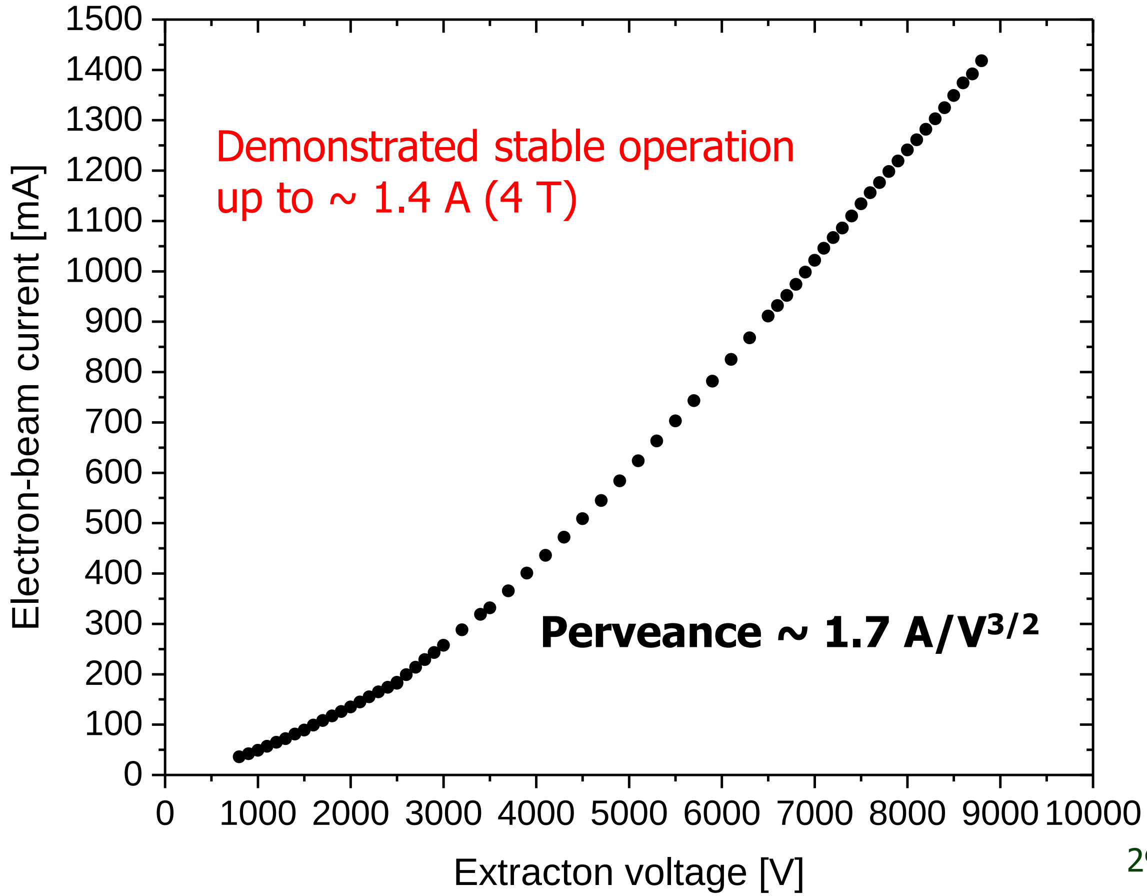
Modular ass'y includes:

- *Anode*
- *Focus elec.*
- *Cathode*

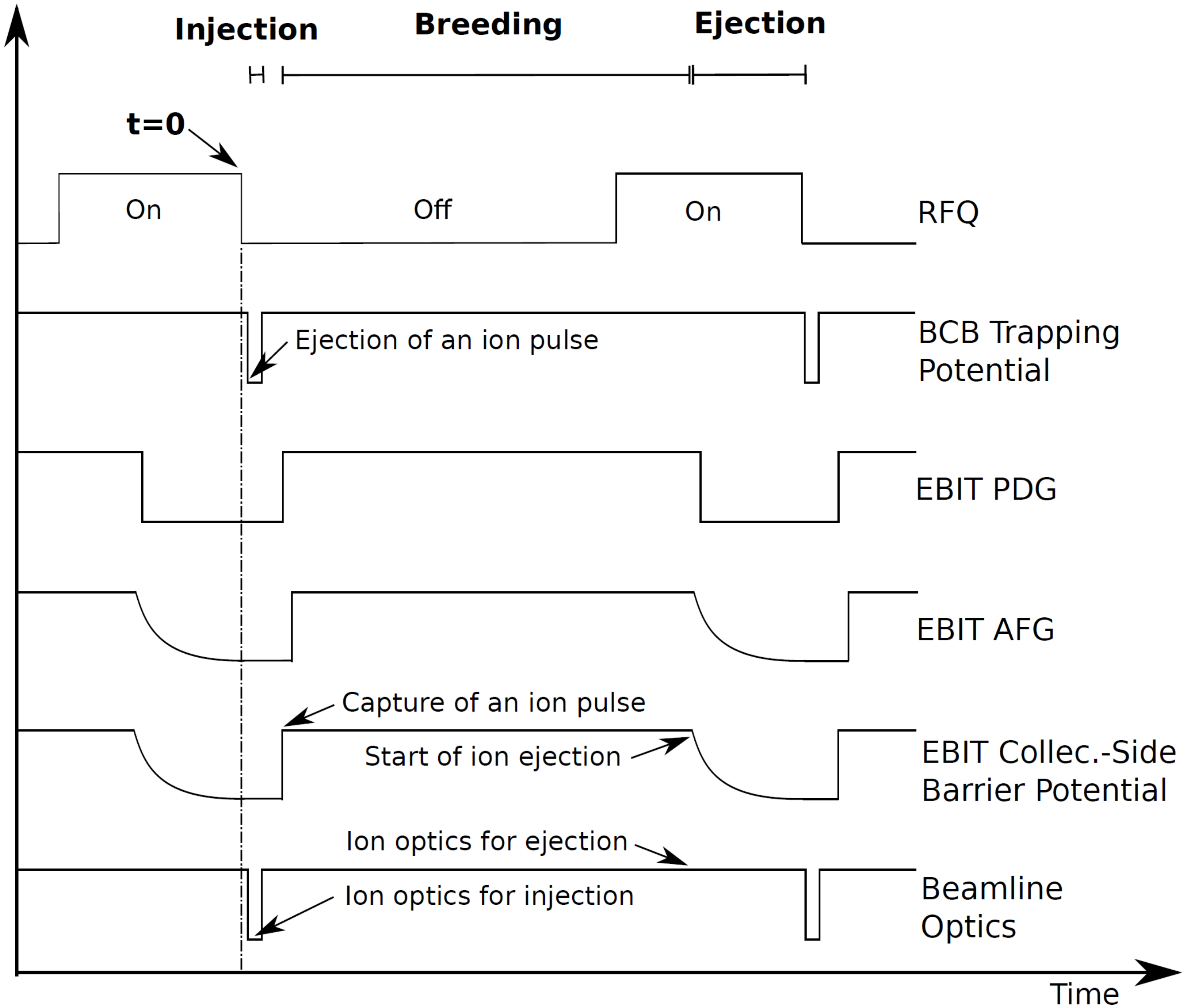




E-beam current vs. extraction voltage

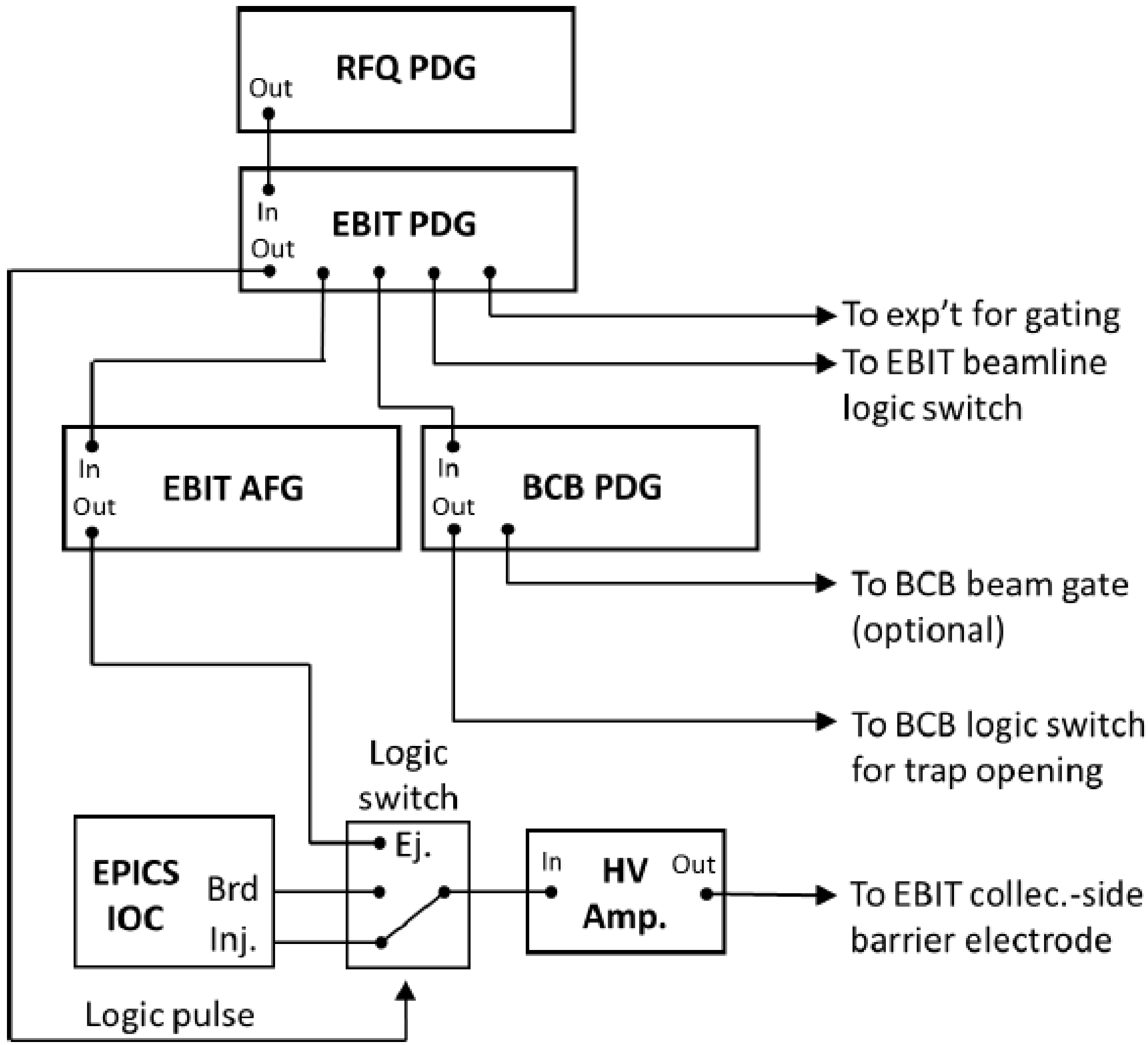


Time sequence



Pulse stretching –Ramp

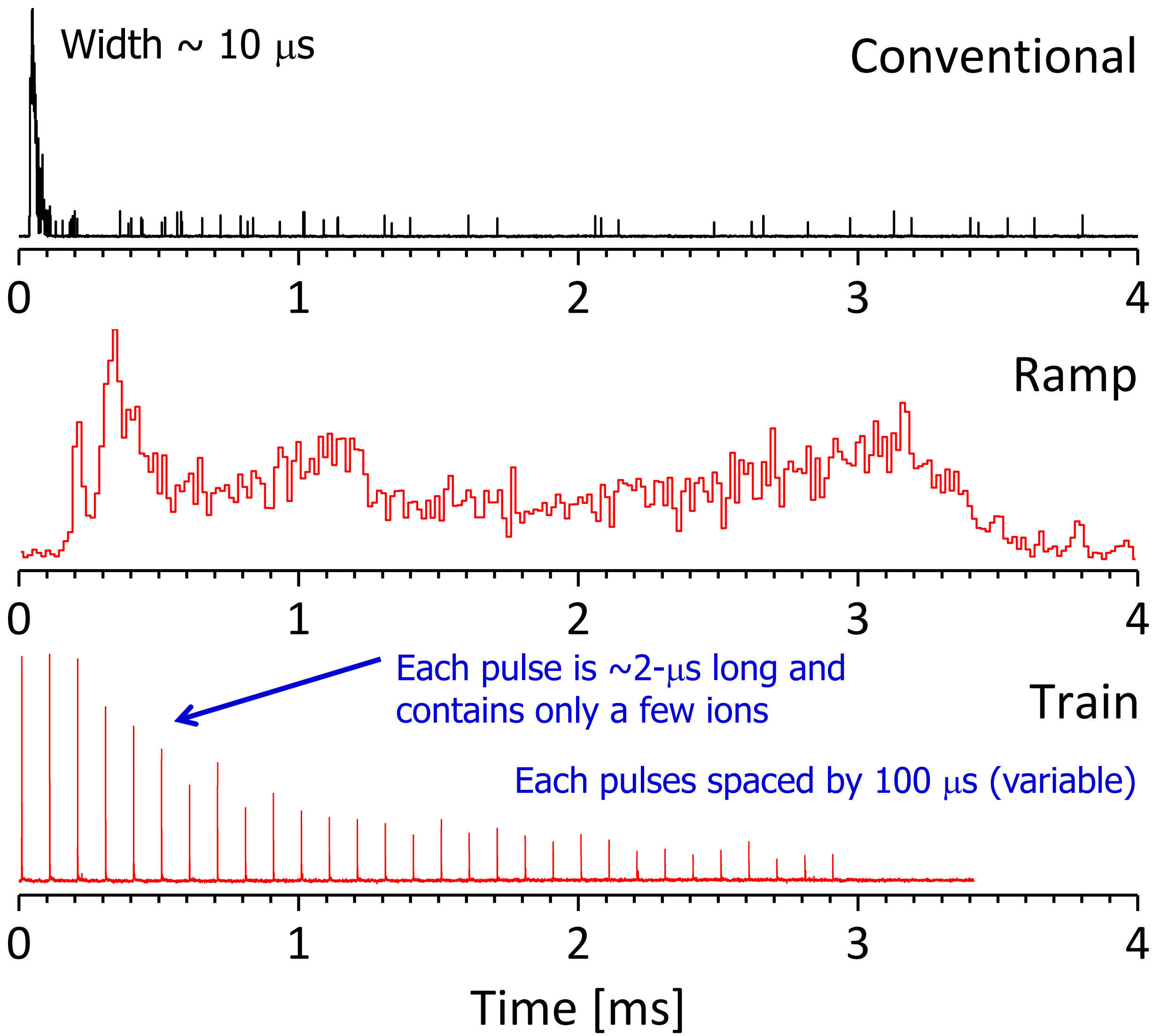
- Voltage amplifier applies voltage to the extraction potential barrier.
- Output voltage of the amplifier controlled by an Arbitrary Function Generator (AFG)



Time stretching of EBIT extracted pulses

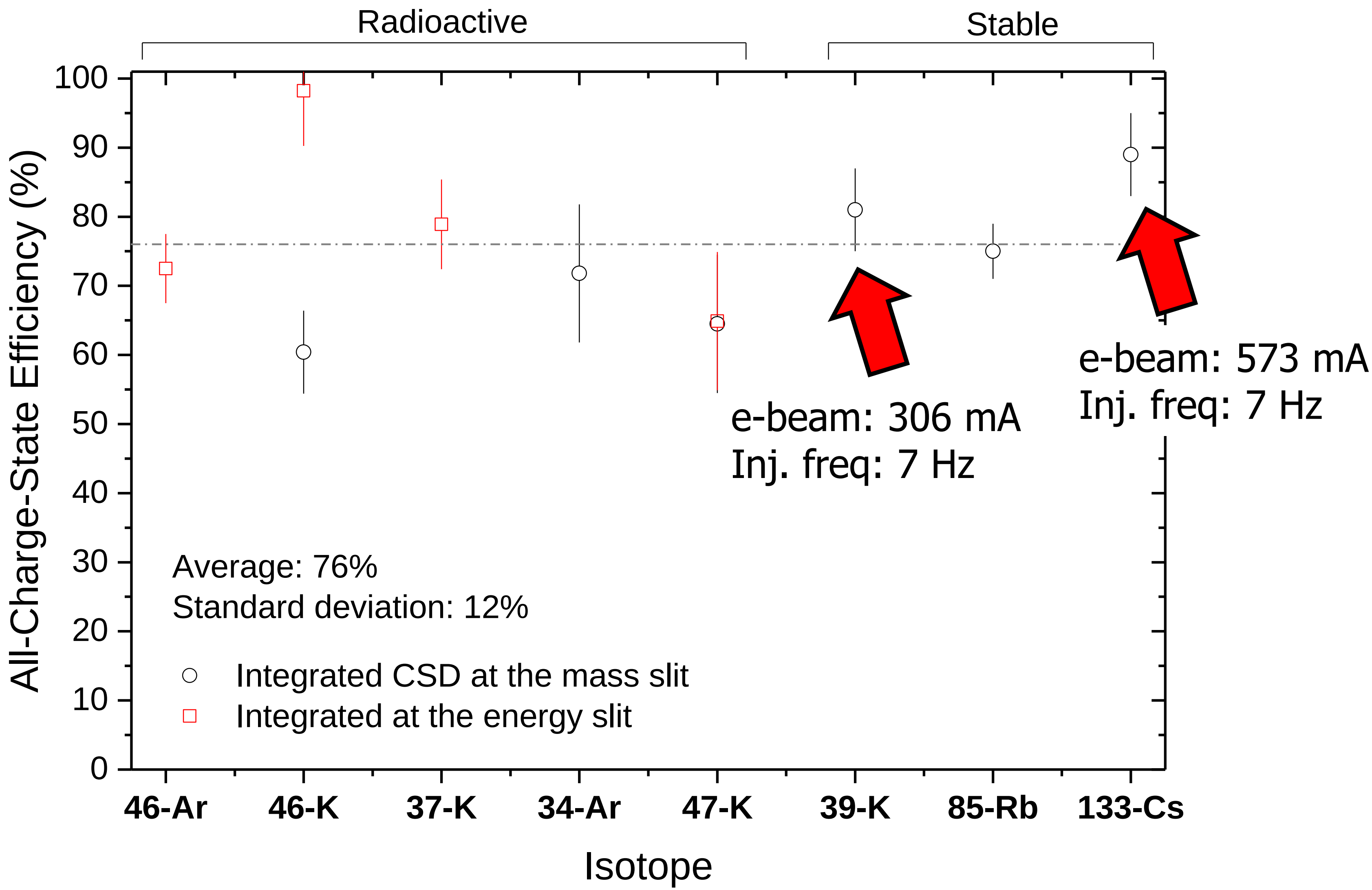
Measured with a microchannel plate after the Q/A separator

Peak intensities normalized to 1



T. Baumann, A. Lapierre, S. Schwarz, *et al.* AIP Conf. Proceedings (EBIST2014 International Symposium)

All-Charge-State efficiency

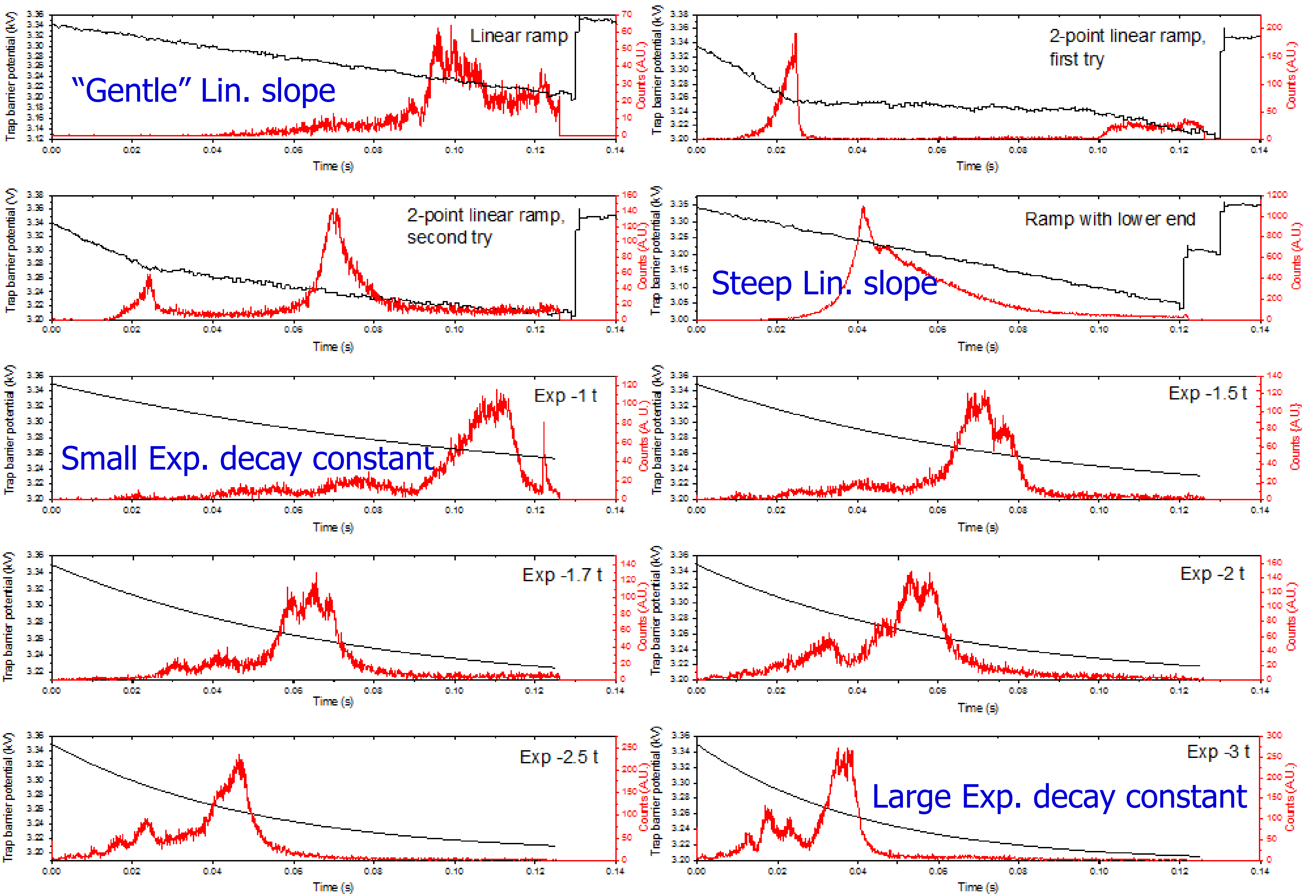


No clear discernable difference in efficiency for different parameters

- Electron-beam current
- Injected beam intensity (stable *vs.* rare)
- Reasons for ion losses being investigated…

Pulse stretching – First tests of the Ramp

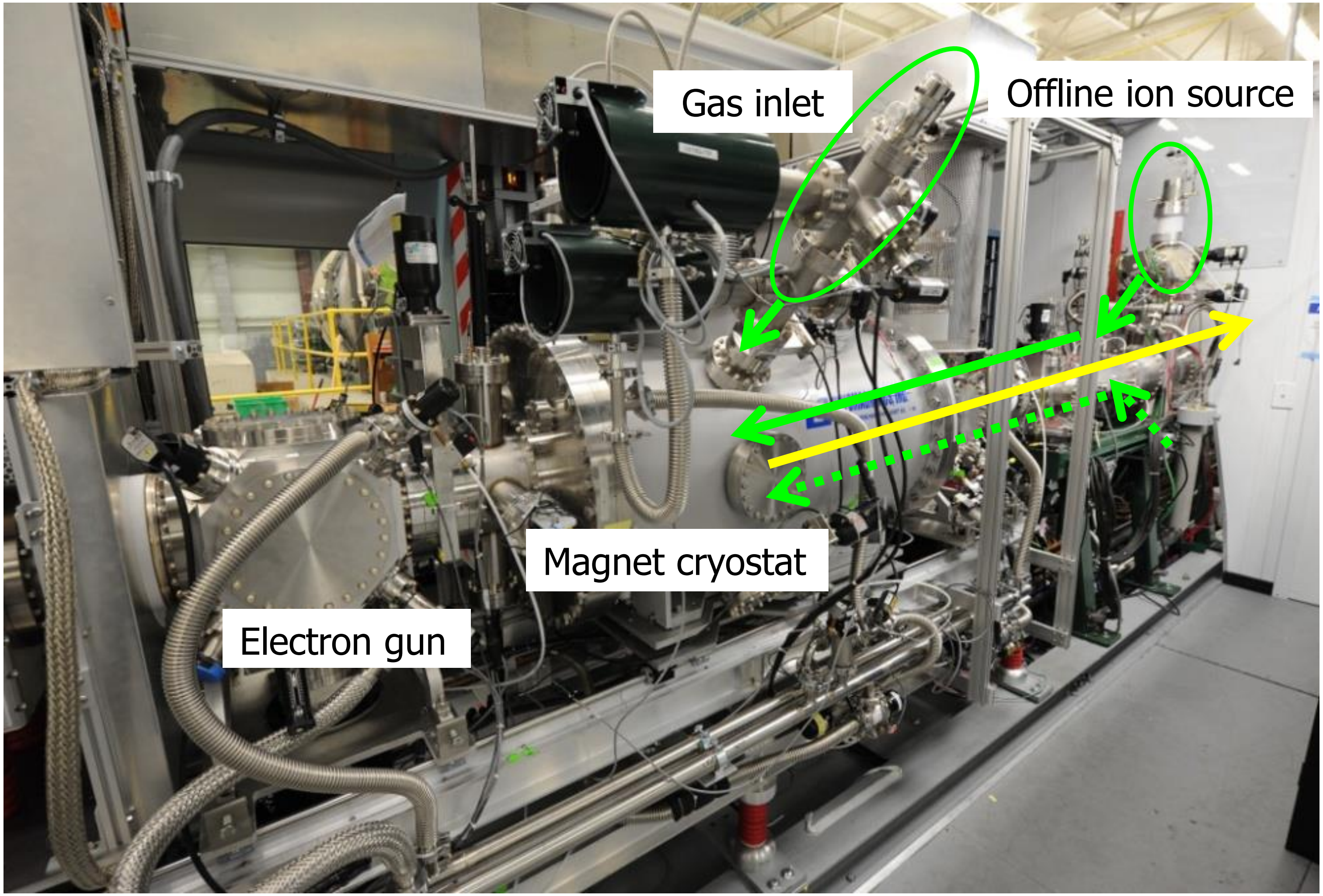
Lots of tests with $^{40}Ar^{16+}$ (residual gas) accelerated to AT-TPC ion chamber…



Injection sources

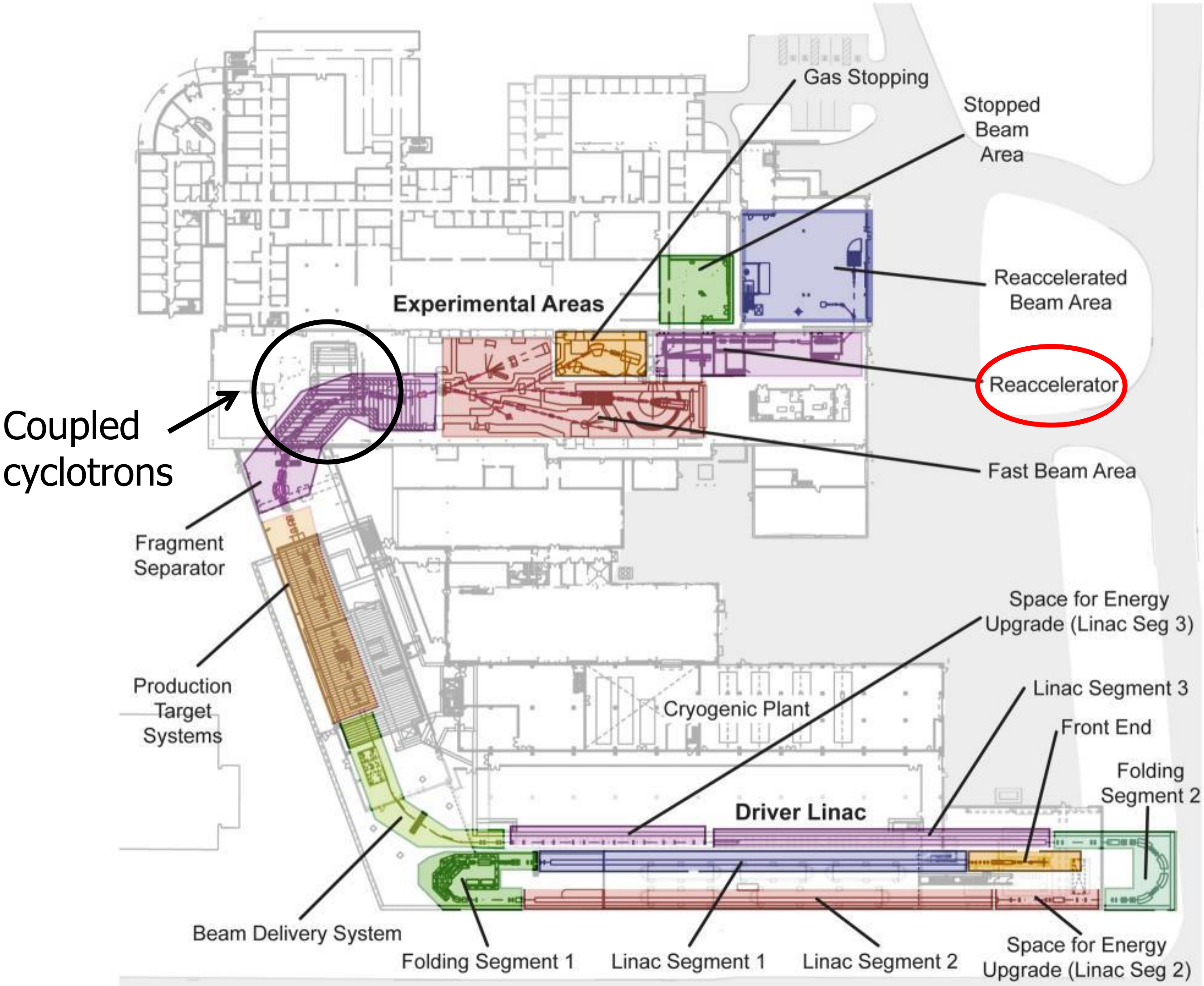
Different sources of injection to produce stable-isotope and rare-isotope beams

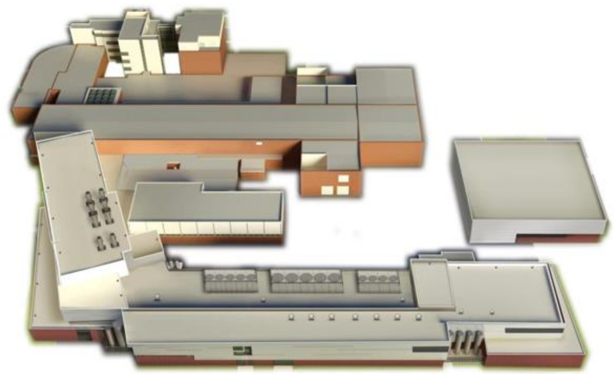
- Gas injection inlet (removed due to gas freezing on shields)
- Inject singly charged stable-isotope ions from **4** off-line sources (plasma and alkali ion sources)
- Inject rare-isotope beams from the beam stopping area
- Message: injection of multiple beams (elements) from different sources.



Facility for Rare Isotope Beams (FRIB)

In 2008, NSCL & MSU selected to establish the US facility (FRIB) for science with rare-isotope beams → Early completion ~2020

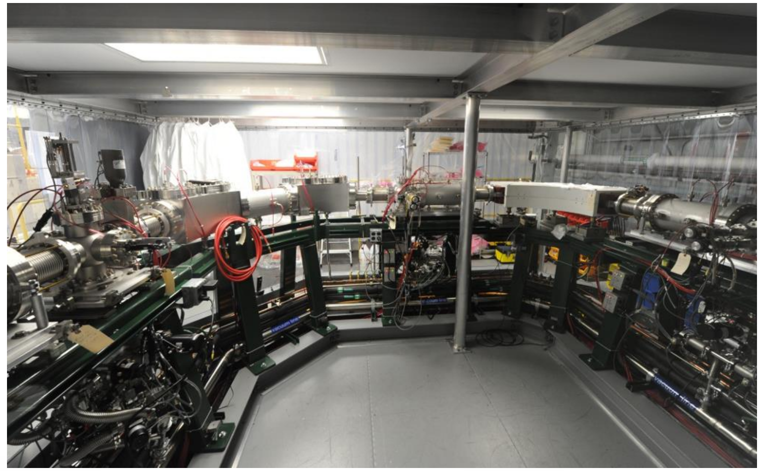




- The two NSCL coupled cyclotrons will be later replaced with a 400-kW superconducting heavy-ion "driver" linac.
- FRIB will increase the current production rates of rare isotopes by up to 2-3 orders of magnitude < 10^{12} pps

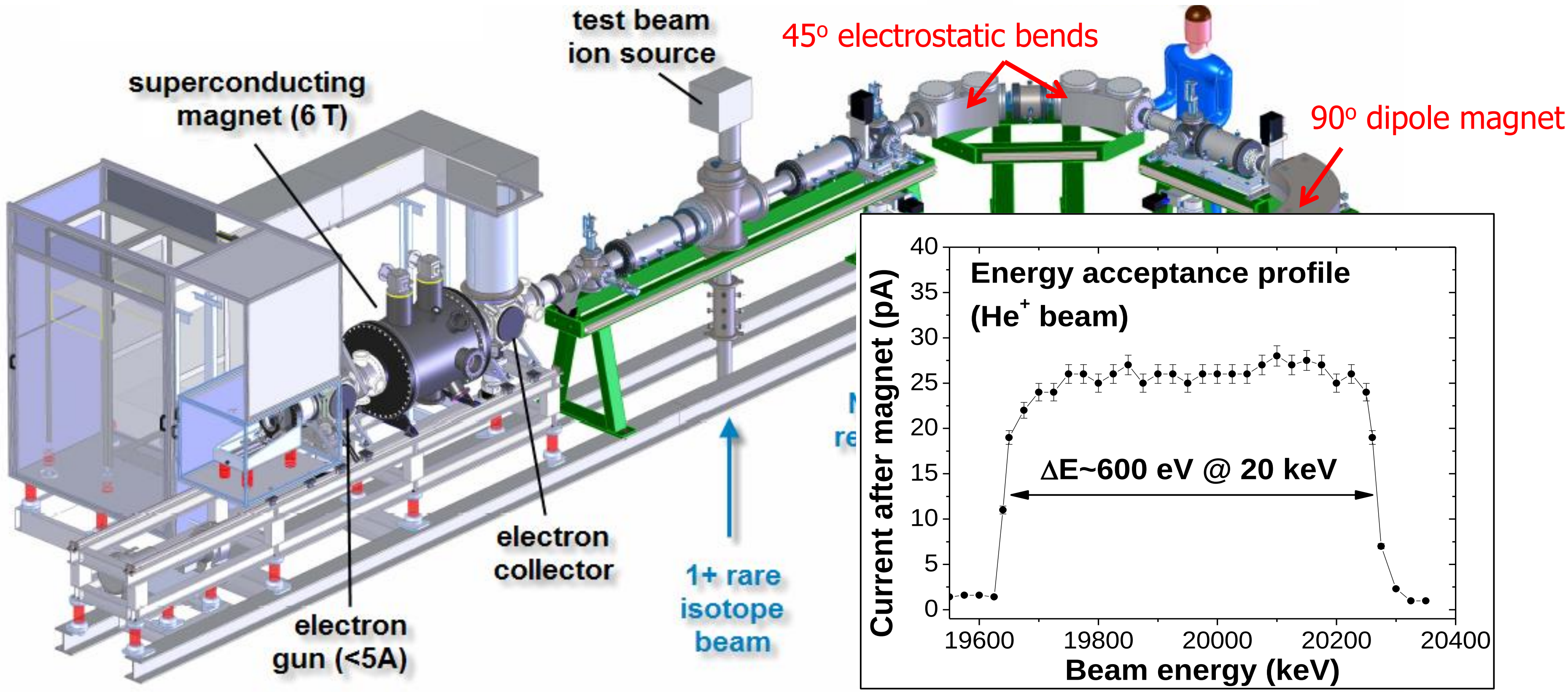
Charge-over-mass (Q/A) separator

Double-focusing (achromatic) spectrometer
(Nier-Johnson geometry)



Design parameters

- Measured resolving power (beam size: 90% of particles): **(A/Q)/Δ(A/Q)~400**
- Achromatic within **ΔE/E~3%**
- Measured EBIT energy spread: **~30 eV per Q** (300 eV for Ne^{10+})



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