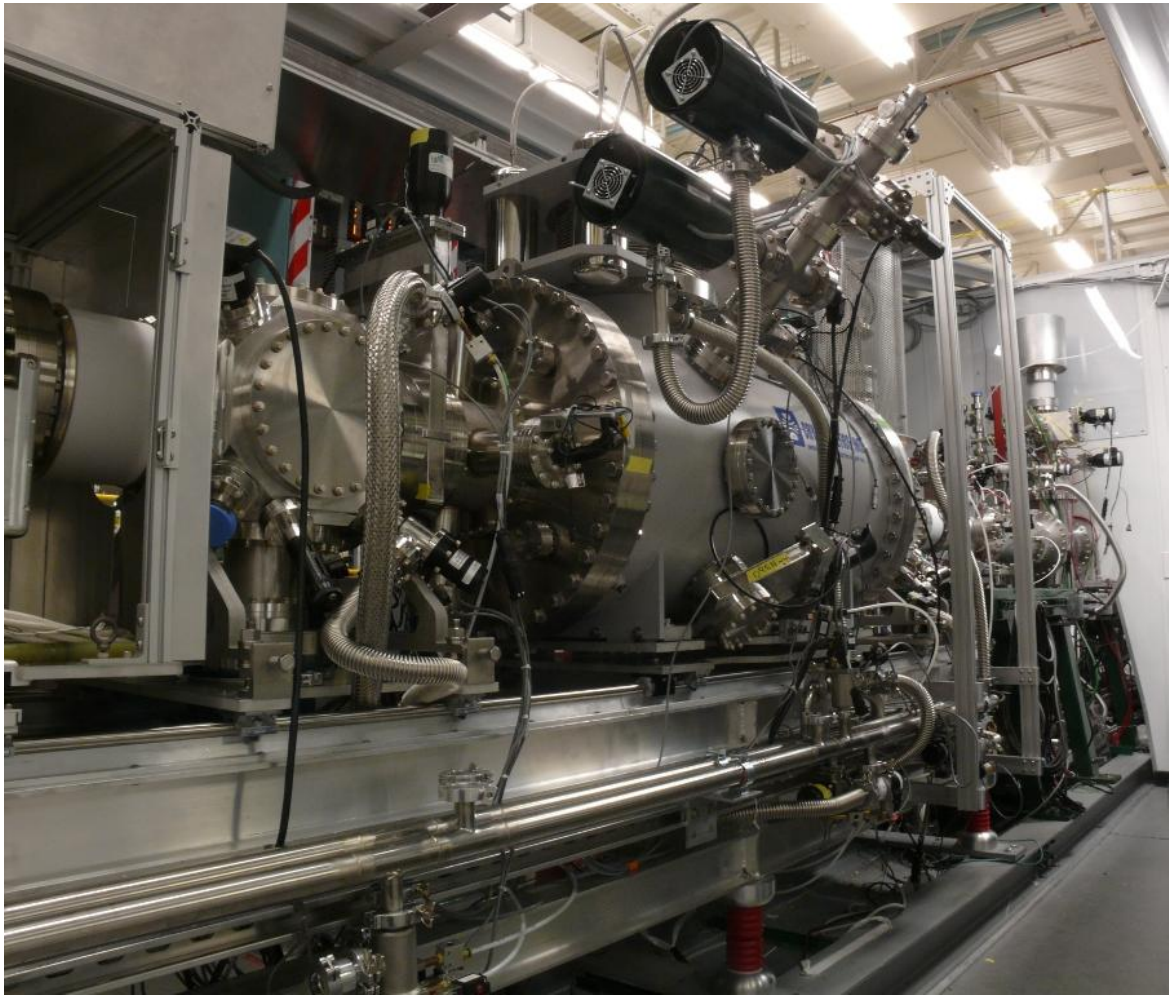
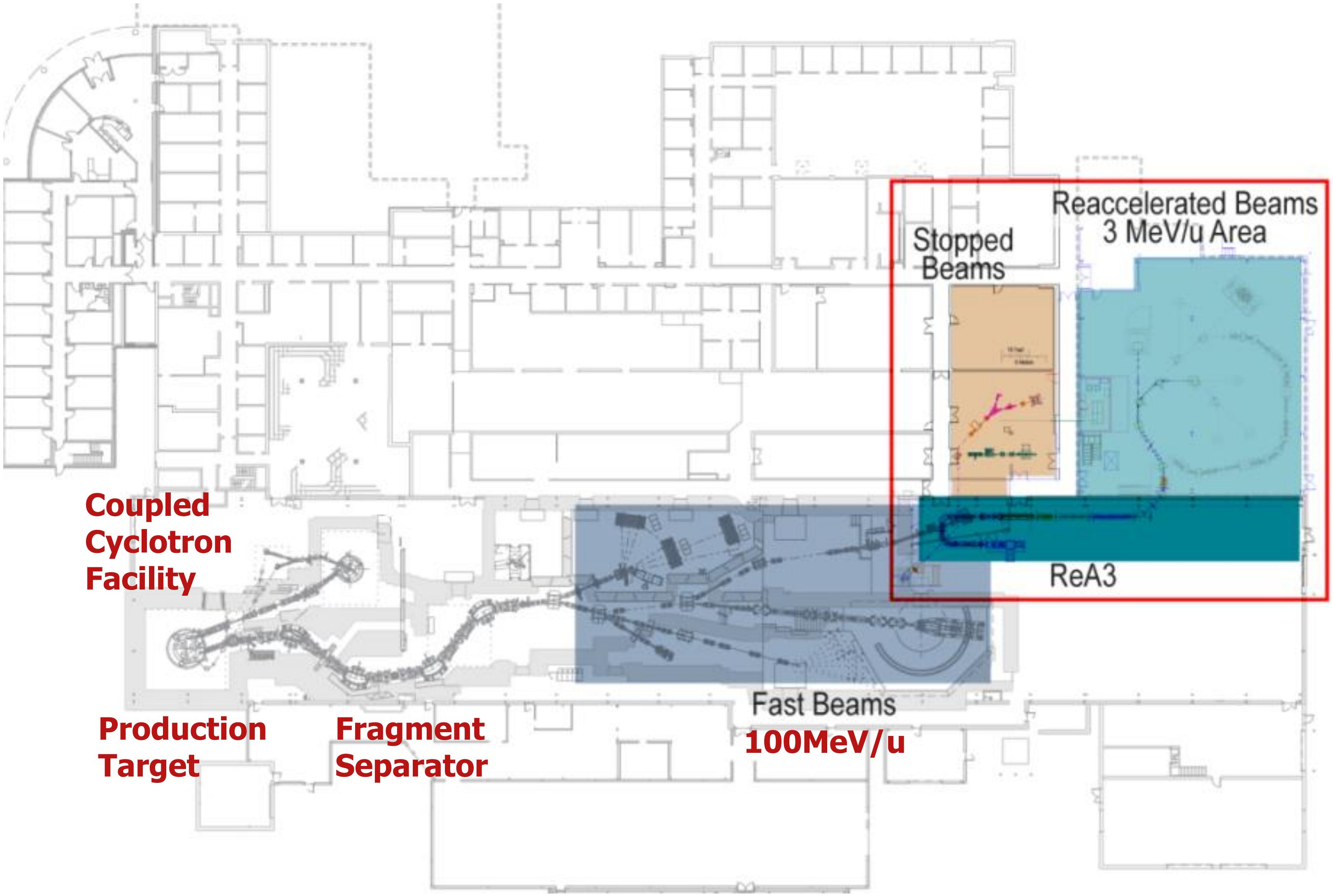
The Electron-Beam Ion Trap charge breeder in the NSCL re-accelerator

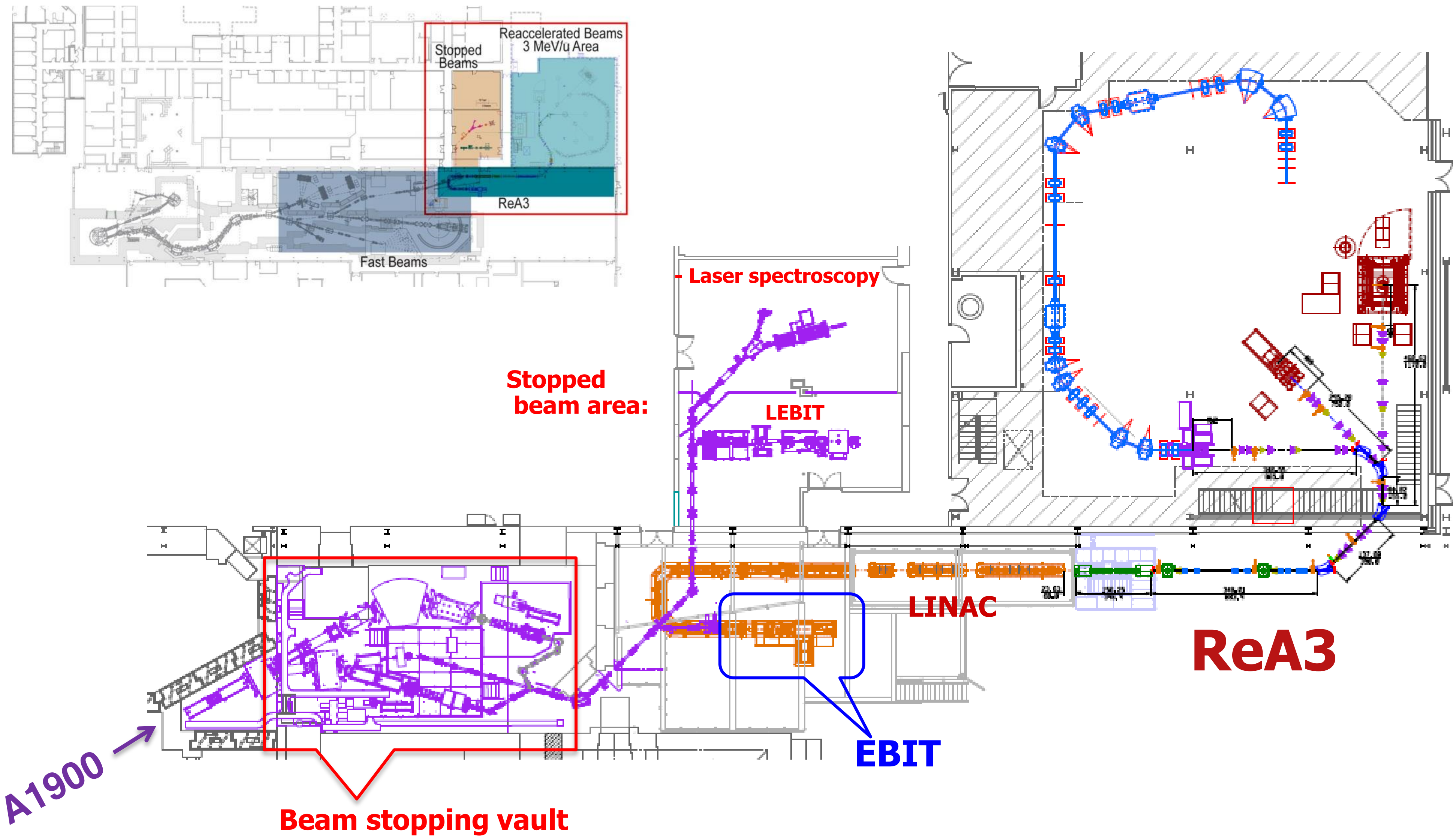


The NSCL EBIT within ReA
- Stopping / EBIT / LINAC
- EBIT
  commissioning
  first results, status

ReA: From fast to not-so-fast



From fast to not-so-fast

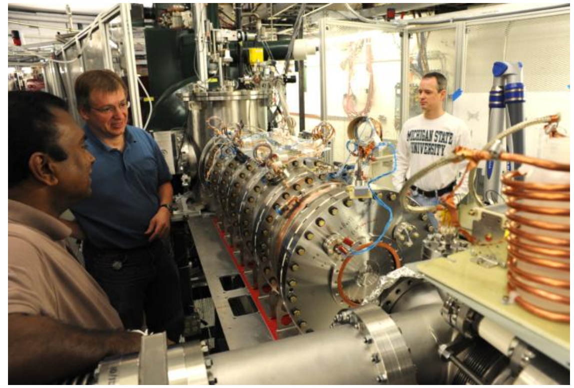


120 MeV/u → (Fully stripped) **STOP** → (1+) **60 keV** → (1+) **12 keV/u** (EBIT) → (n+) **3 MeV/u and more**

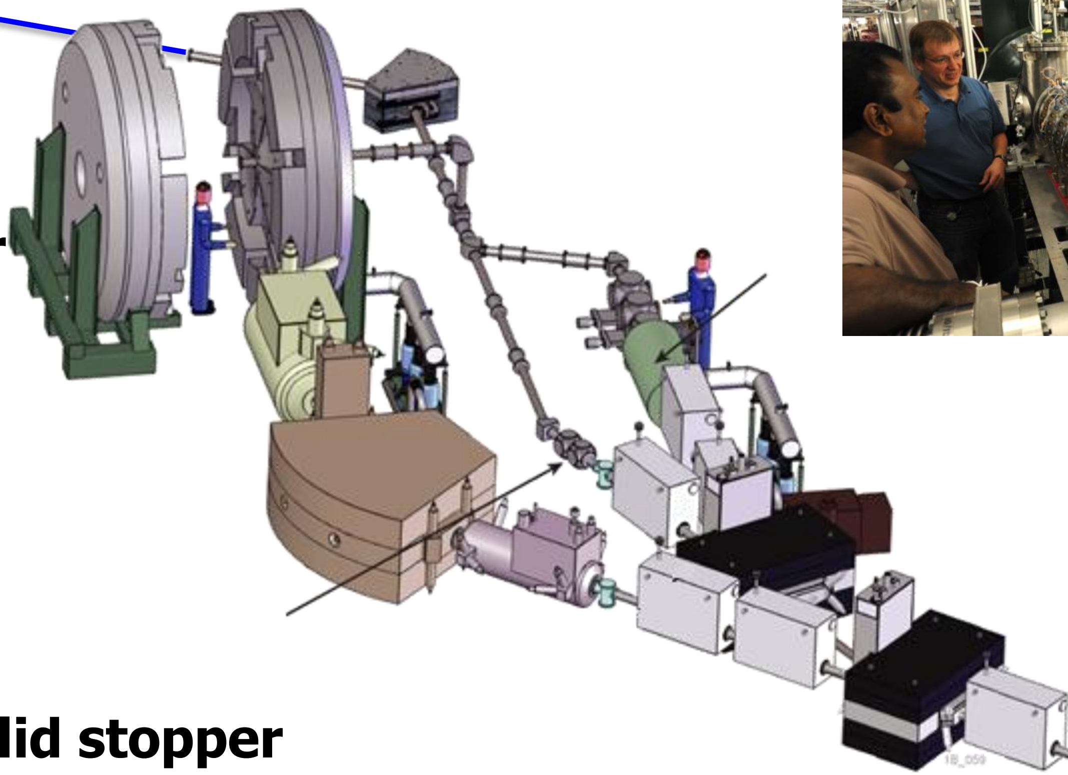
NSCL beam stopping

Stopper options:

- **Large linear gas stopper → ReA3**
  - Low-pressure with RF carpets
  - Collaboration with ANL (FRIB R&D)



- Future:
  Cyclotron stopper
  Funded by NSF
  Under construction

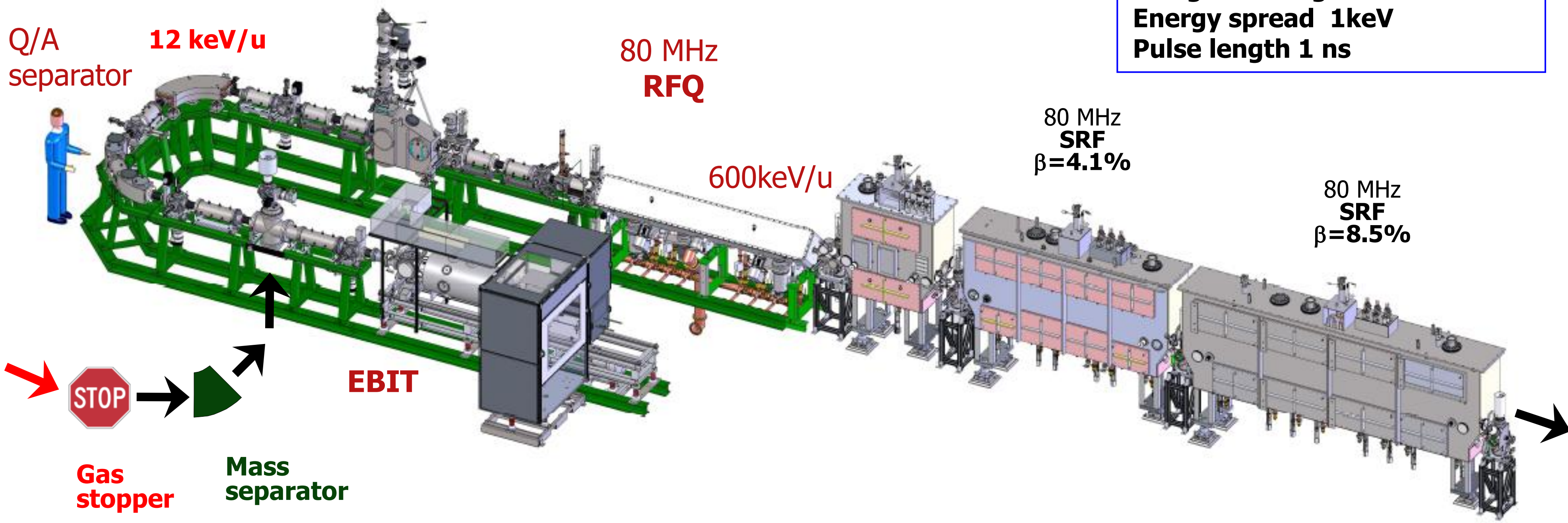


- **Solid stopper**

→ For special elements and very high beam rates
Example: ^{15}O, I >10^{10}/s

ReA3

Energy 0.3- 3 MeV/u for ^{238}U,
higher for lighter ions
Energy spread 1keV
Pulse length 1 ns



- **Gas stopping** of RIBs from fast fragmentation or in-flight fission
- High-intensity **EBIT** for charge breeding ($1^+ \rightarrow q^+$)
- Compact **linear accelerator**: MHB, RFQ + SRF modules
- expandable **space** for experiments

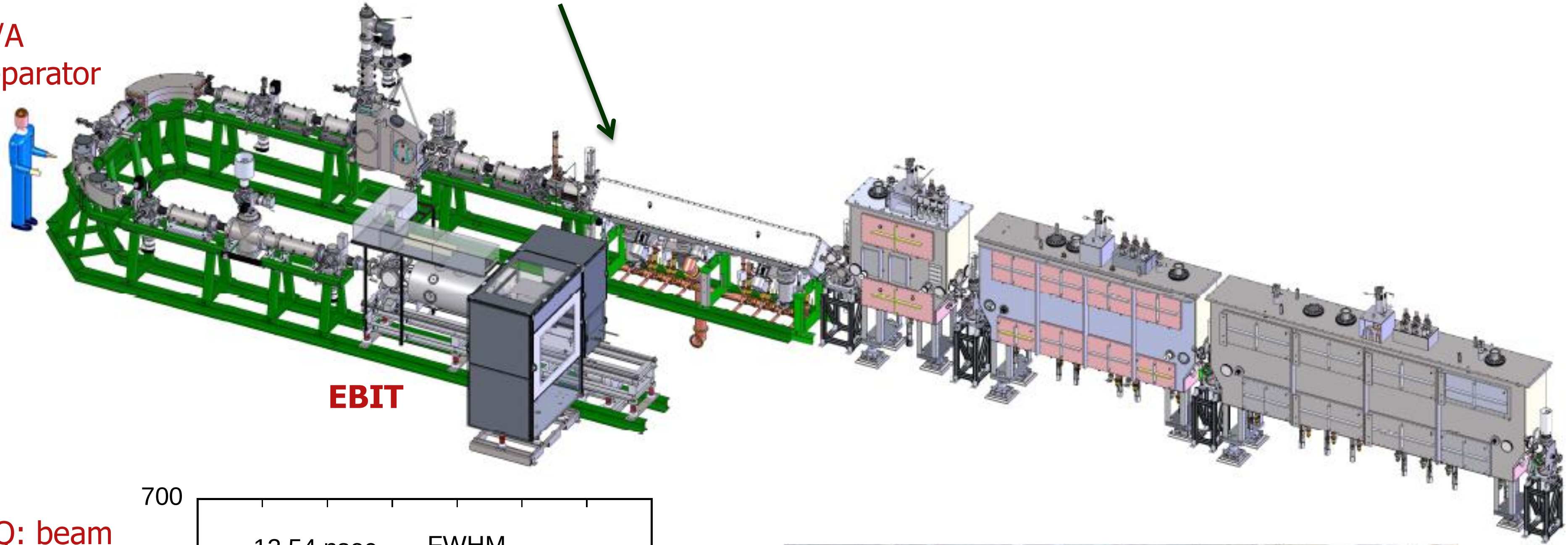
- ReA3: funded, ReA6, ReA12 proposed

→ **Compact, cost-efficient, highly efficient, expandable**

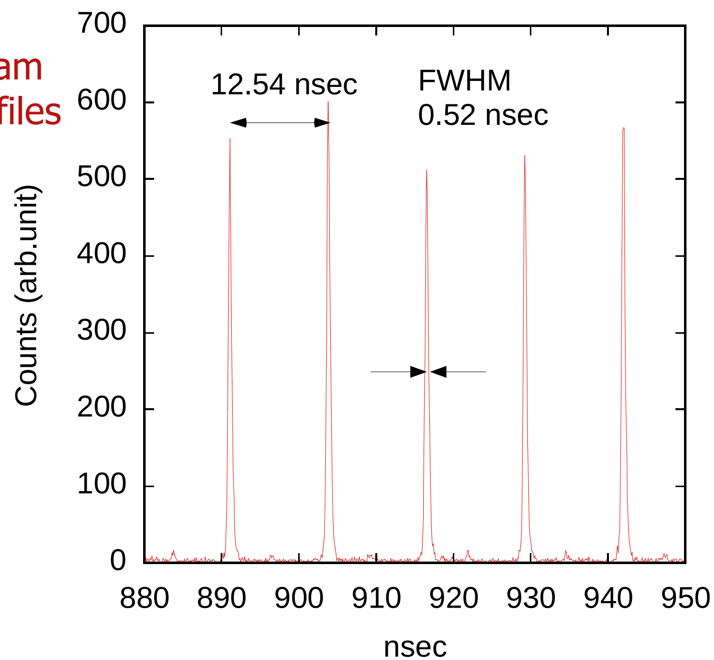
ReA commissioning, RFQ

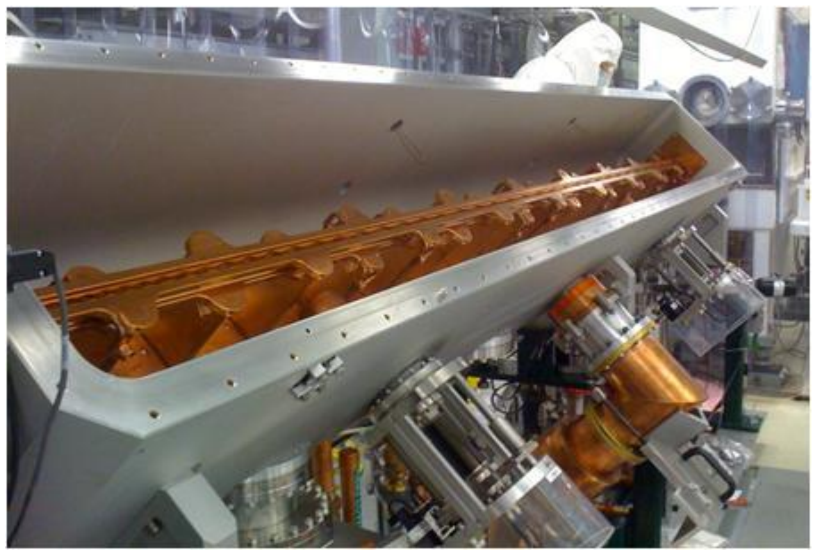
LB+ RFQ section
9/10-3/11

Q/A
separator



RFQ: beam
time profiles





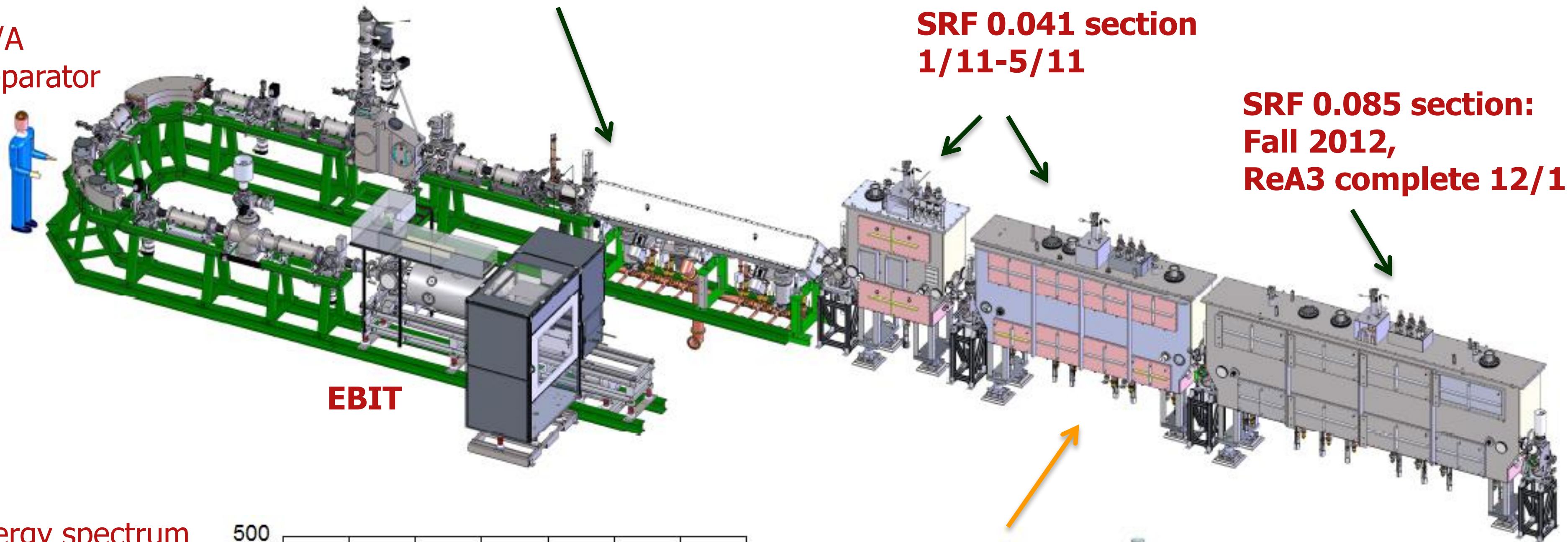
ReA commissioning, SRF modules

Q/A separator

LB+ RFQ section
9/10-3/11

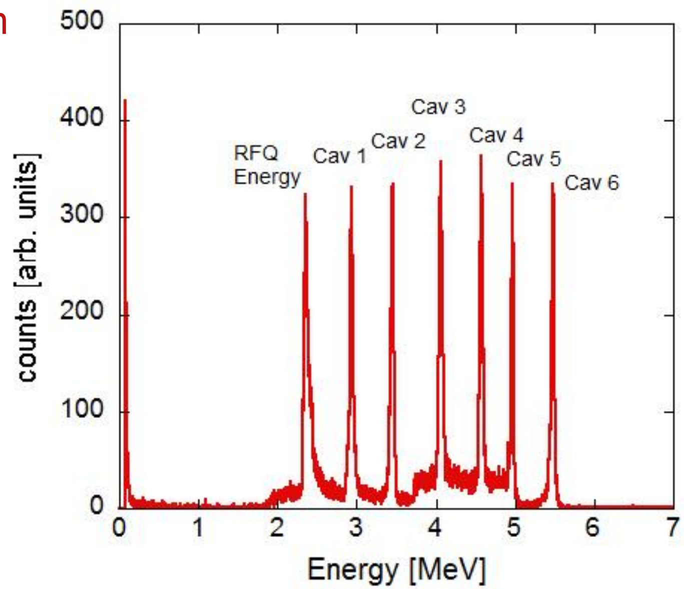
SRF 0.041 section
1/11-5/11

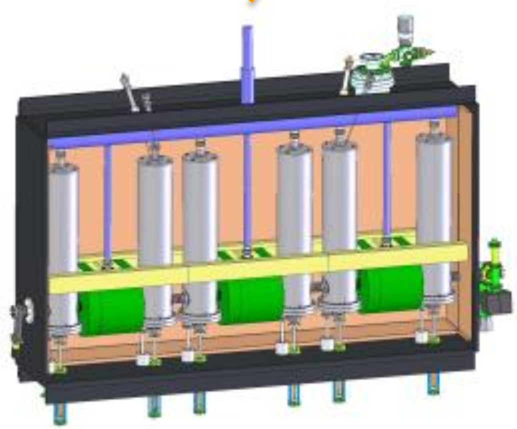
SRF 0.085 section:
Fall 2012,
ReA3 complete 12/12



EBIT

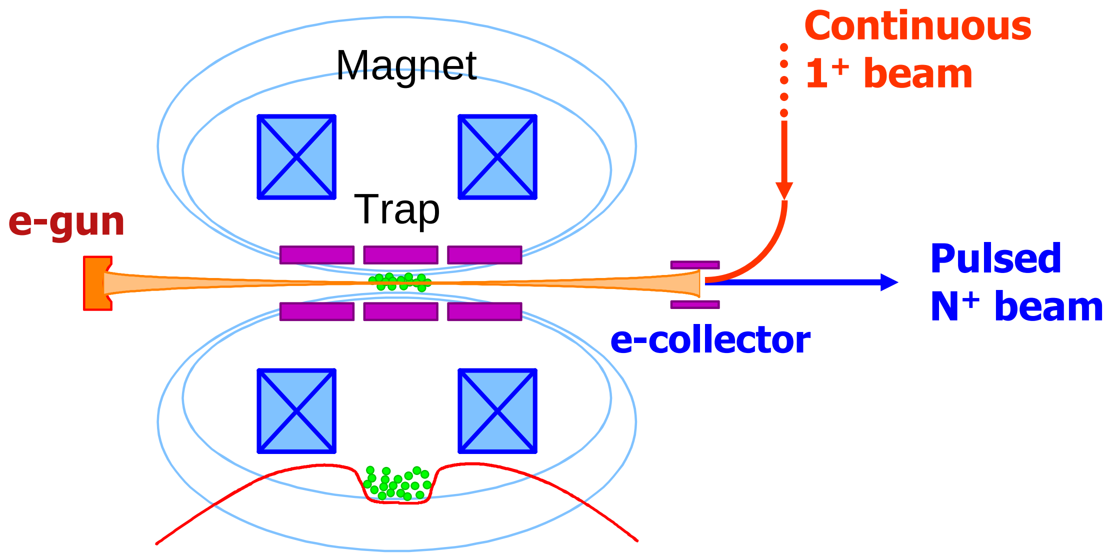
Energy spectrum after CM2





Cryo-module #2

ReA3 – EBIS/T charge breeder



Expected performance

- Breeding times << 50 ms
- Efficiency > 50%
- Beam rates > 10^9/s
- Variable duty cycle
- Clean beams

EBIT: Key design parameters:

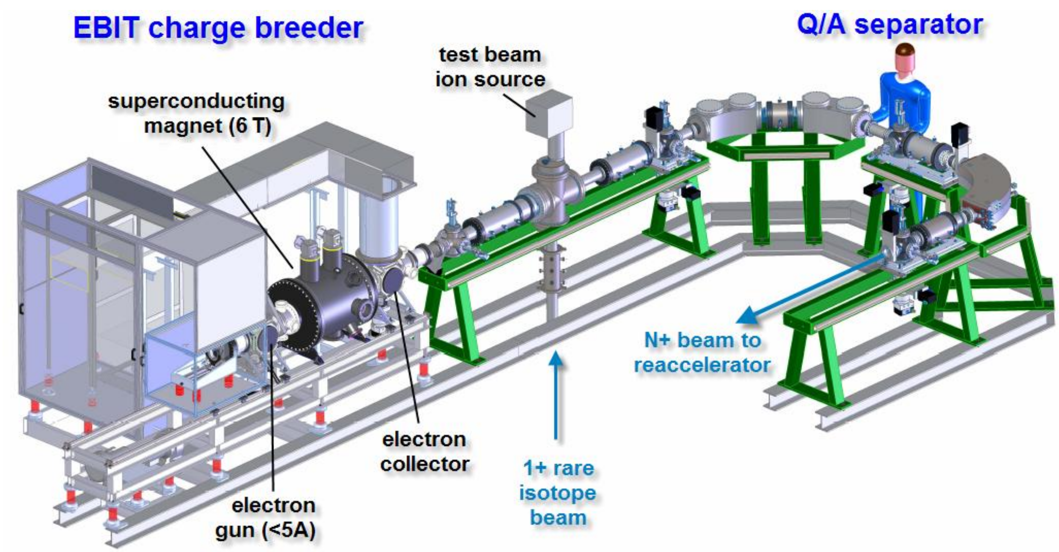
- magnetic field: up to 6 T
- **I_e= 0.5…5 A, E_e < 30keV**
- **current density: up to ~10^4 A/cm^2**

In Collaboration with

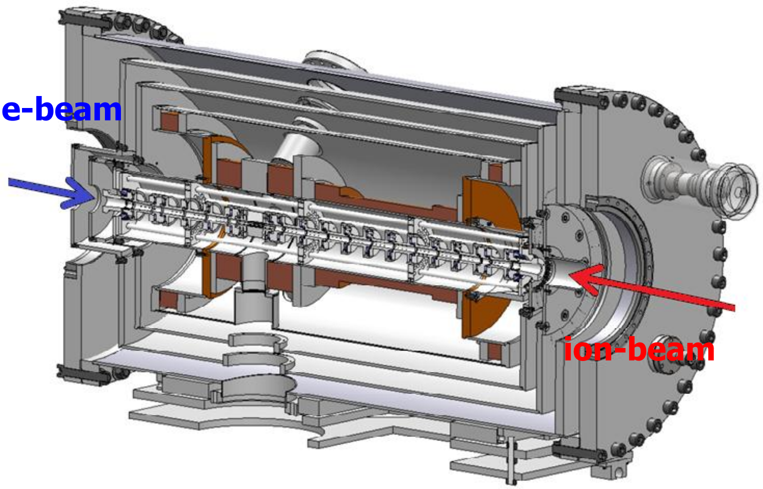
Max-Planck-Institut für Kernphysik — J. R. Crespo López-Urrutia

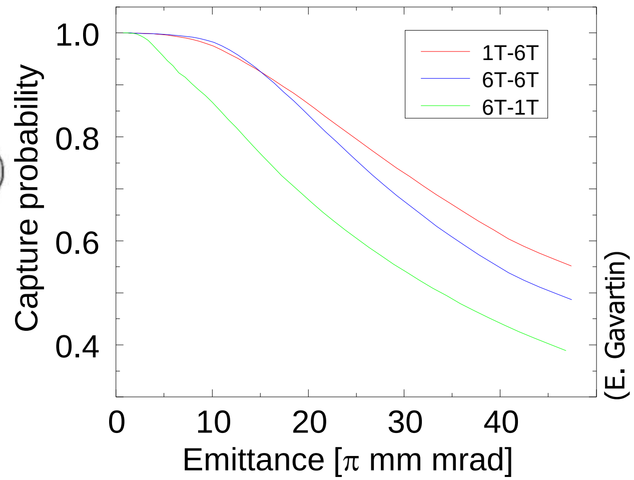
GSI — O. Kester

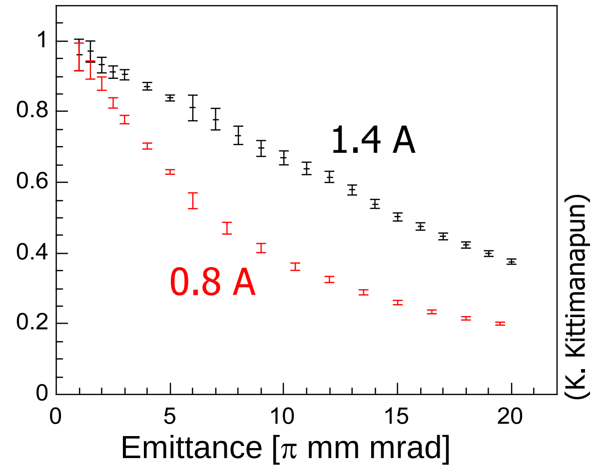
TITAN ISAC-TRIUMF — J. Dilling



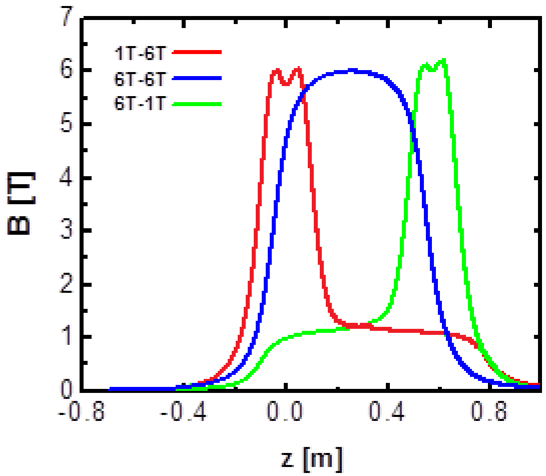
EBIS/T design – hybrid trap



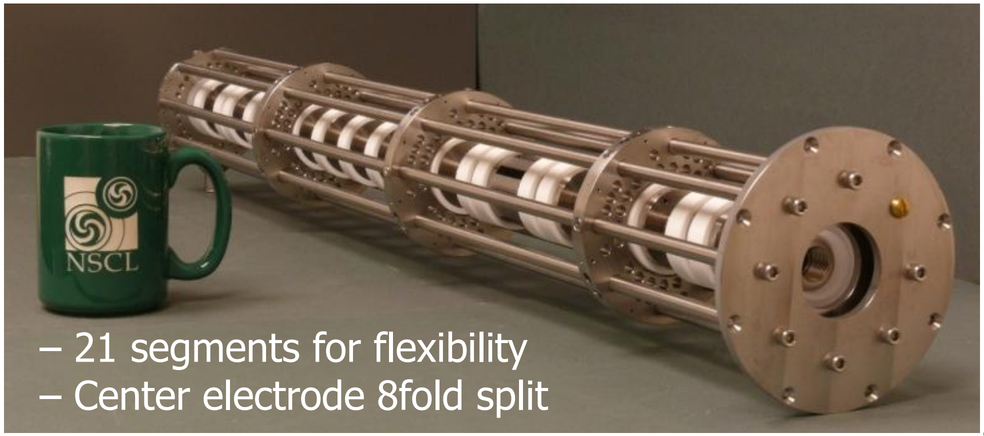




Moderate compression + large e-beam current
+ longer trap needed = good acceptance
→ **Two traps for high acceptance and fast breeding**



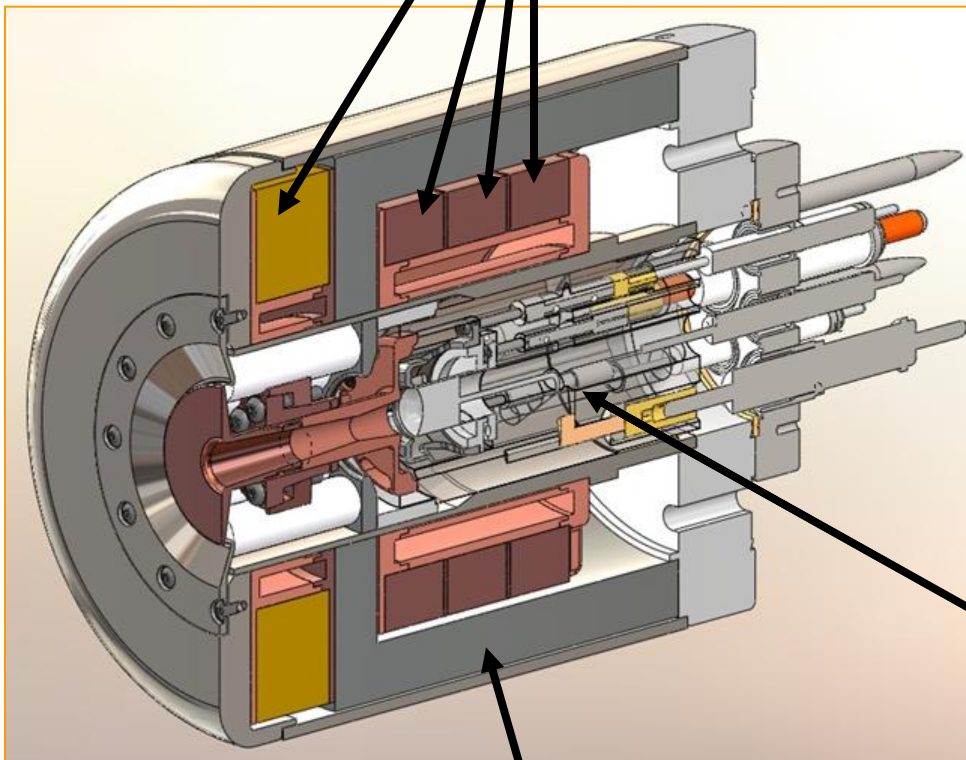
Trap: ~ 0.8m long



The electron gun

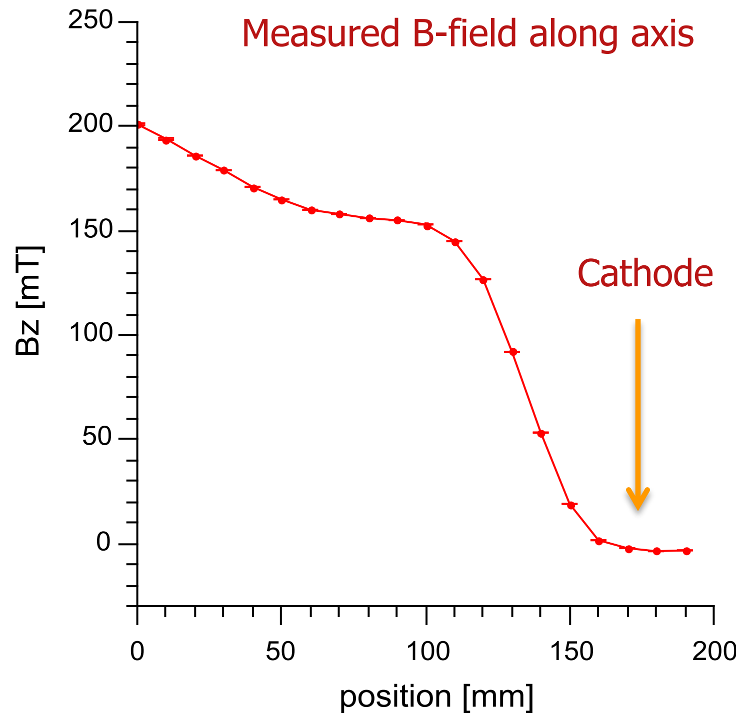
Flexibility by modular design - shape electric & magnetic fields as needed

Bucking coils
- 3 inside iron shield → ~ 60 G per A
- 1 at front → ~ 120 G per A



Core
= cathode, focus + anode assembly comes out through front

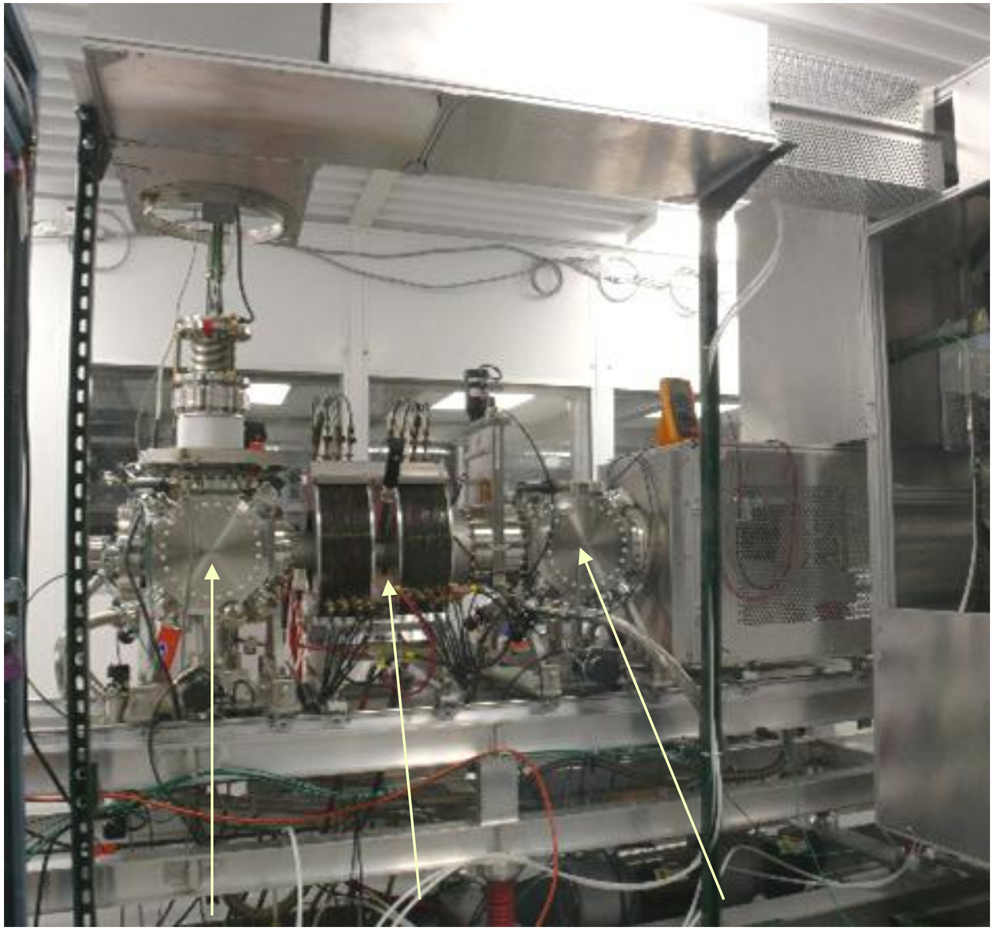
Soft-iron shield



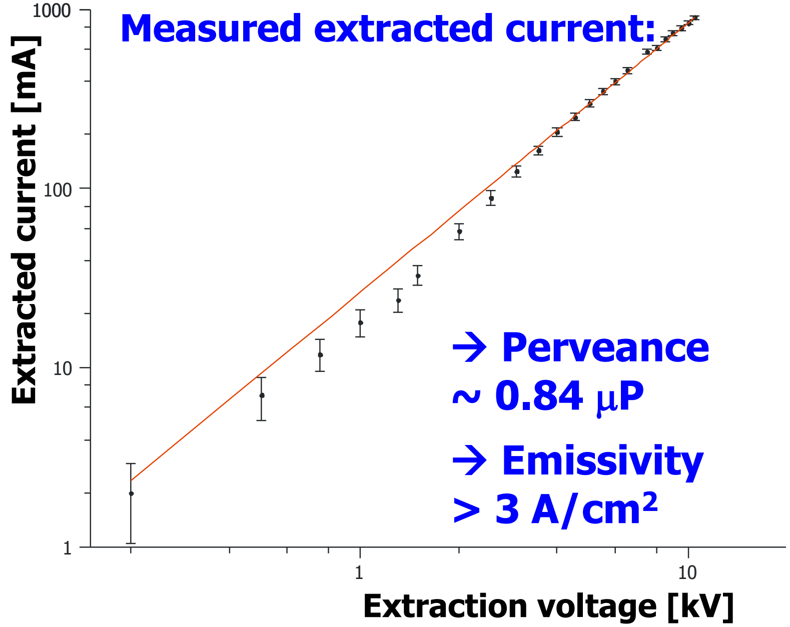
Two cathode options:
1.4 A(1.1μP) / 2.4 A (1.8μP)

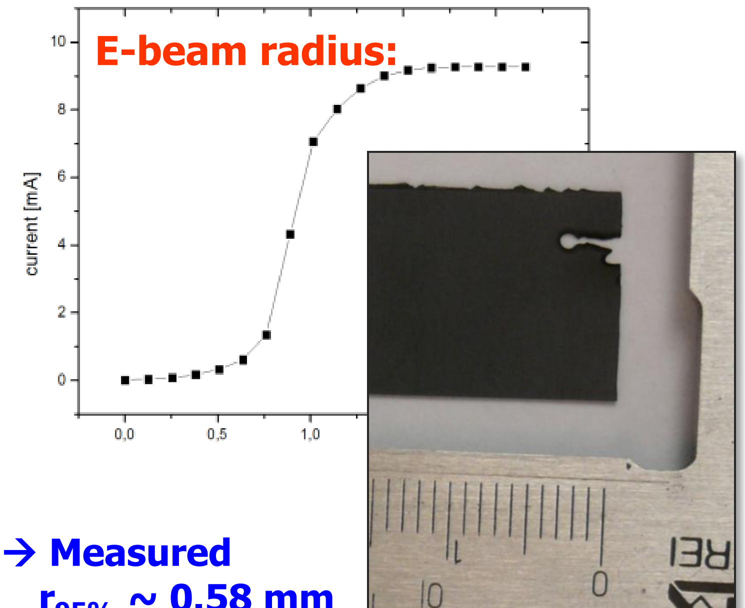
Commissioning of e-gun and collector

… with a 0.4 T RT coil



collector test coil e-gun

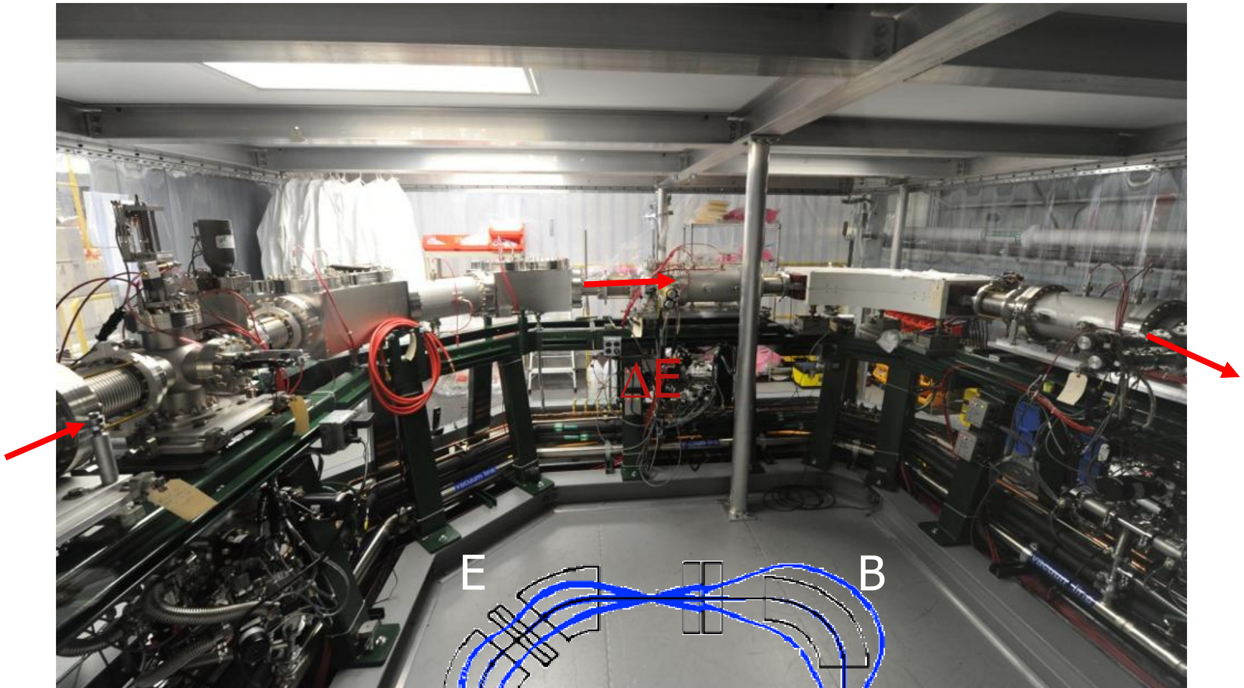


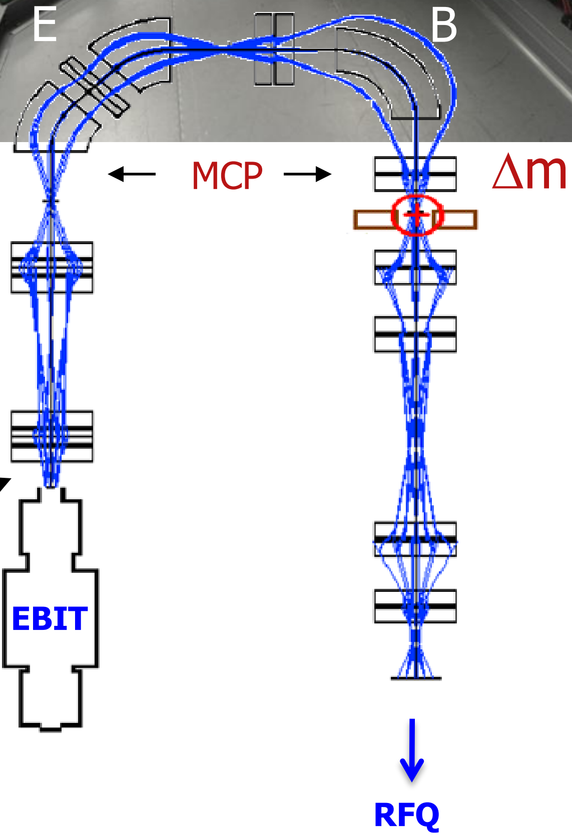


To be repeated with the 6T SC magnet

→ Measured $r_{95\%}$ ~ 0.58 mm agrees well with $r_{Herrmann}$

Commissioning of the Q/A separator



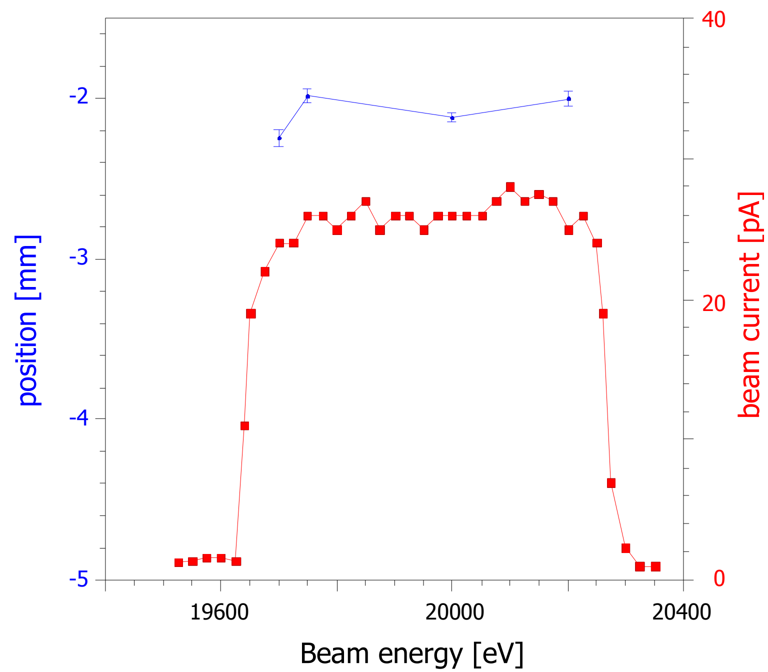


For commissioning just a temp ion source (alkali/He-discharge)

Design parameters:

- 12 keV/u, A/Q = 2 to 5
- ε_n = 0.6 π mm mrad
- R > 100, verified
- mass dispersion 10mm/%, verified
- Achromatic: dE > ±0.2%

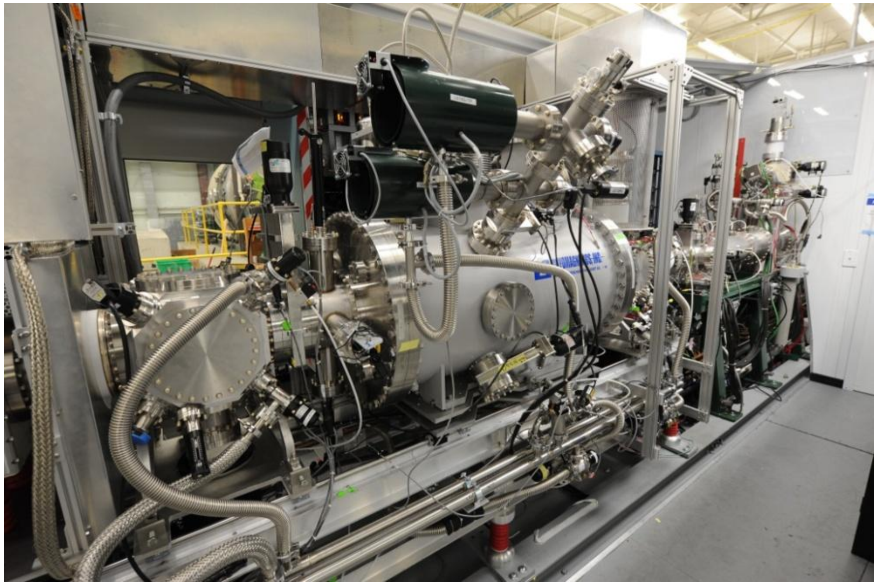
Energy acceptance:

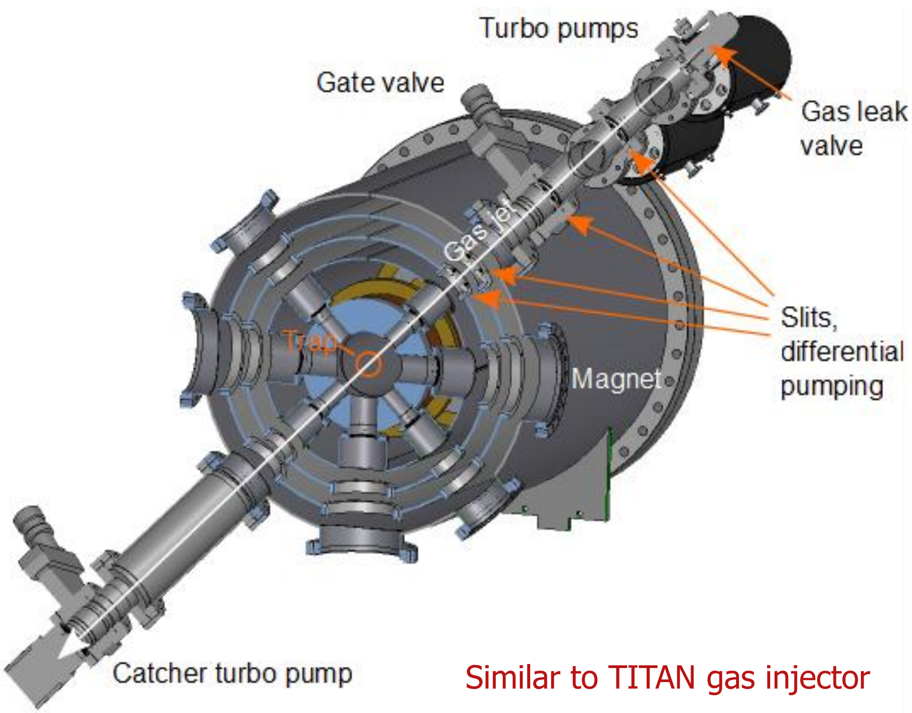


→ accepted E-spread ~±1.5 %

Beam optics:
M. Portillo

Charge-breeding of Ne ions from the gas injector

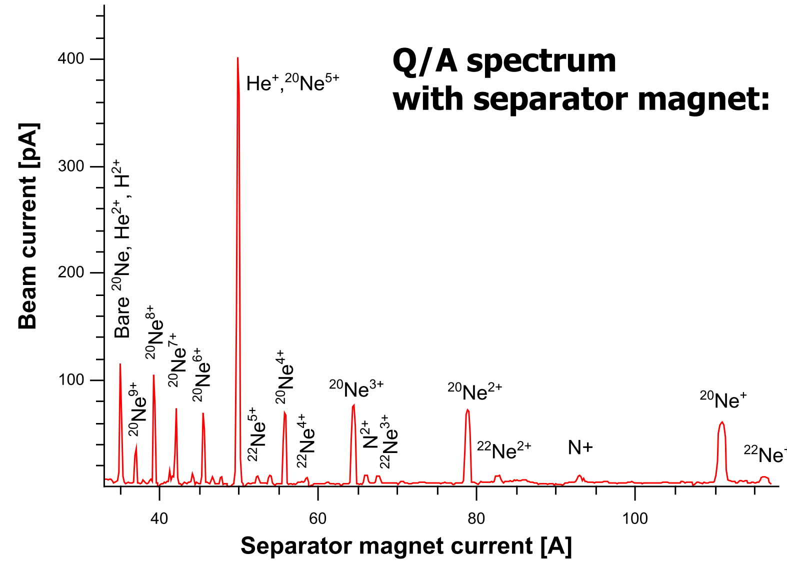




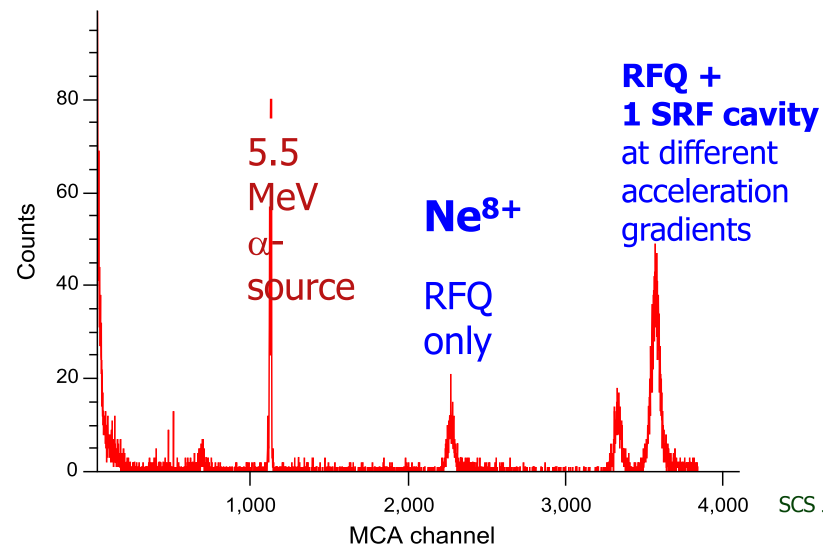
Similar to TITAN gas injector

June/July 2011: First breeding & Q/A scan of Neon

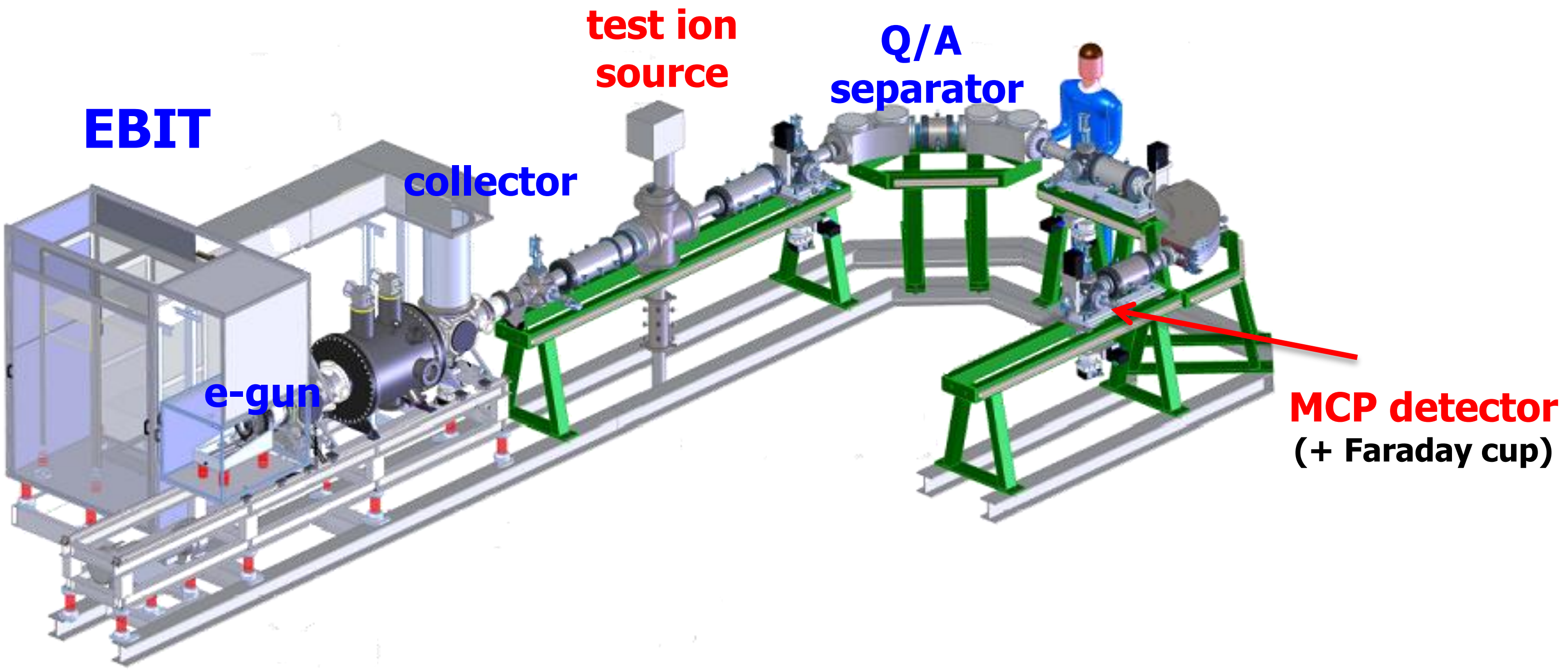
- 'Leaky mode' + pulsed extraction
- 2T field, 15 keV, 36mA electrons, 30kV extraction



Accelerated Ne^{8+}: Energy spectrum



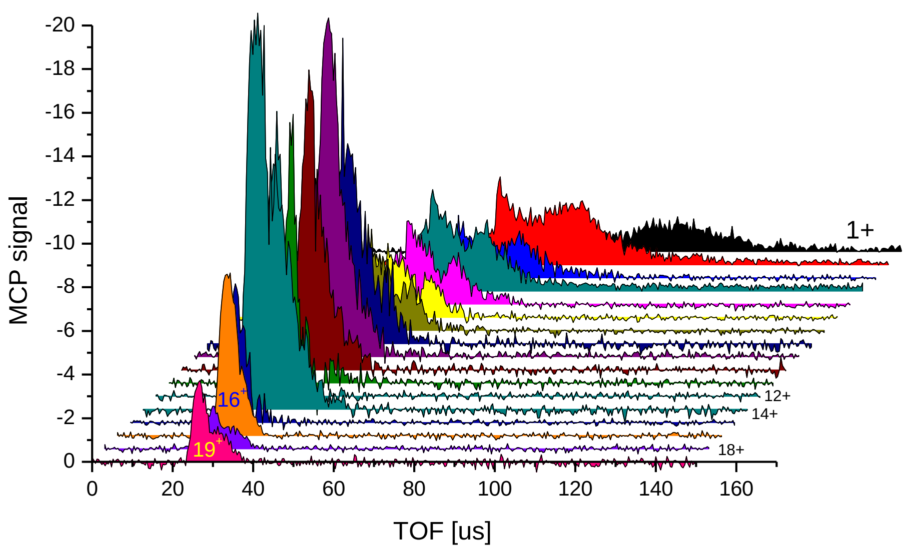
Charge-breeding of alkali ions from the test ion source



Since Fall 2011:

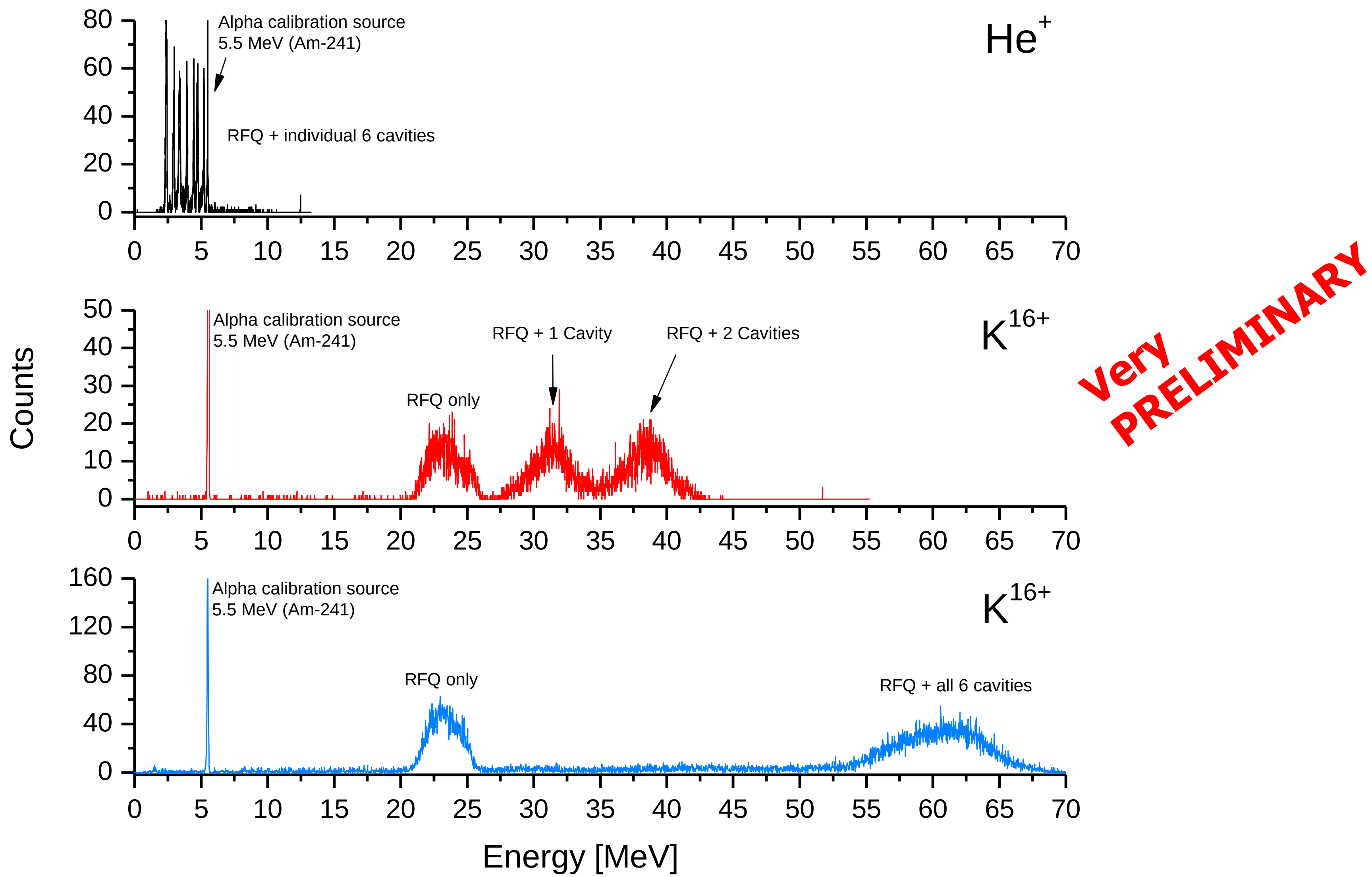
Capture and charge-breeding of External ions

TOF spectra for Q/A-separated K charge states:



Electron current: 88 mA
Electron energy: 16.5 keV
Ion energy: 15 kV*q
Injected ion current: 18 pA

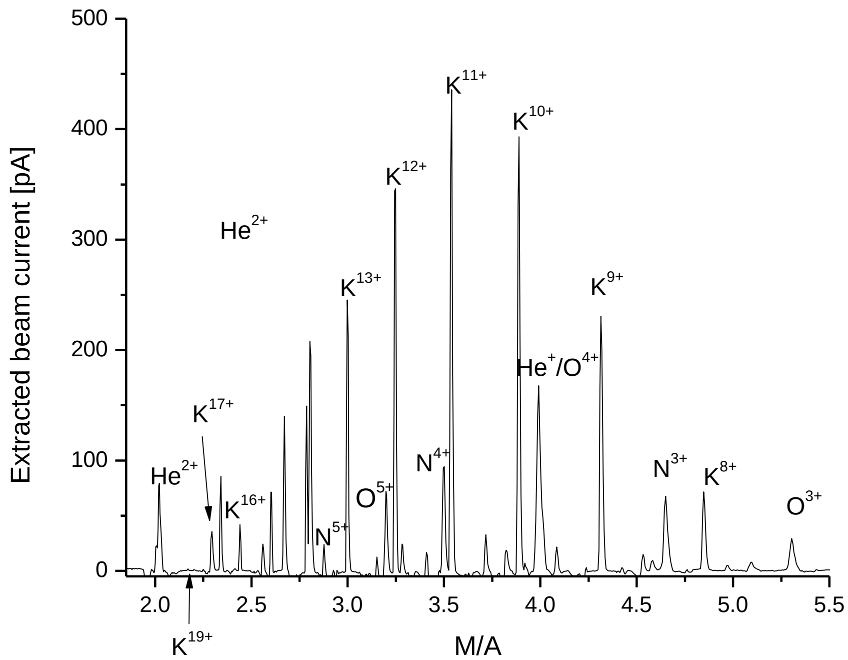
Accelerated alkali ions from the test ion source

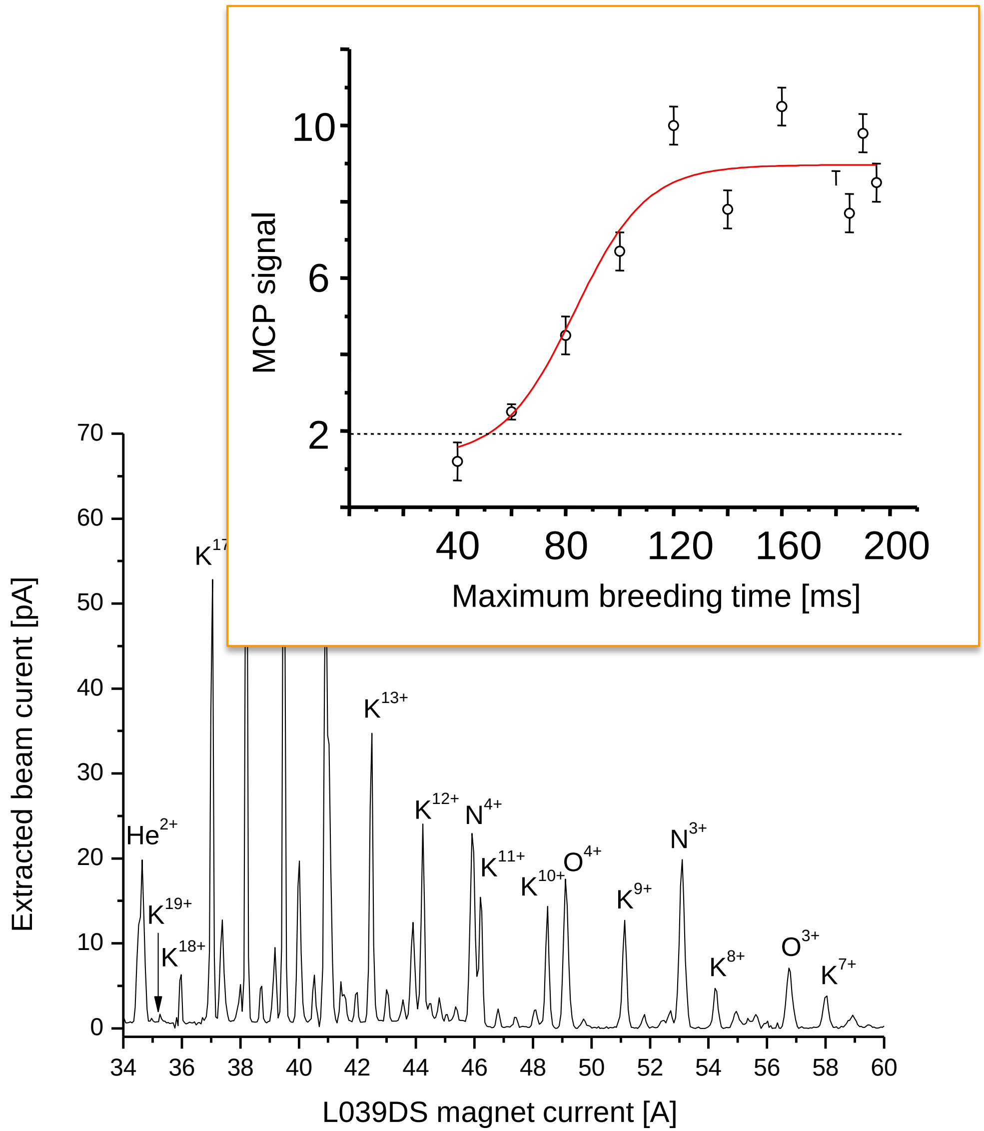


Breeding time

Q/A spectra with K from test ion source:

K^+ beam current: ~10 nA
I-beam energy: ~29keV * q
100 mA electron beam



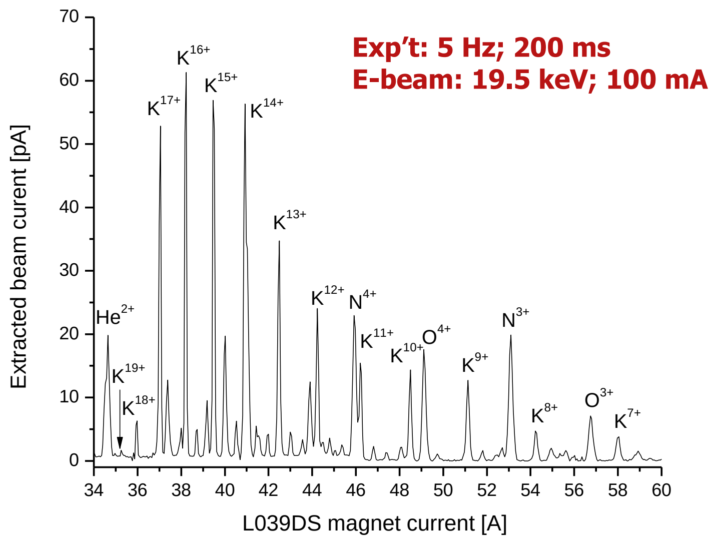


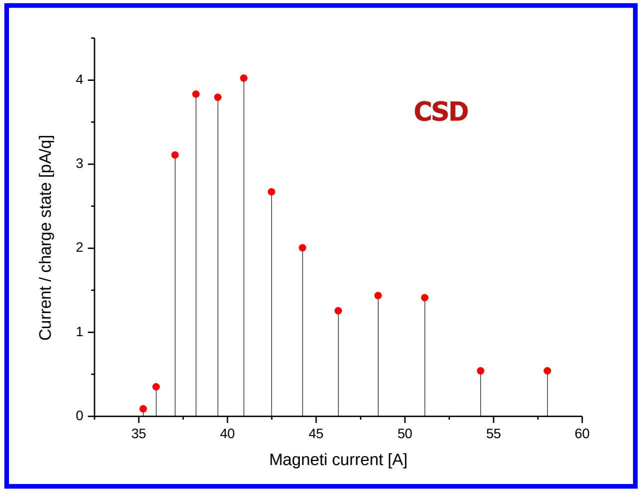
20 Hz extraction rate
→ up to 50ms breeding time

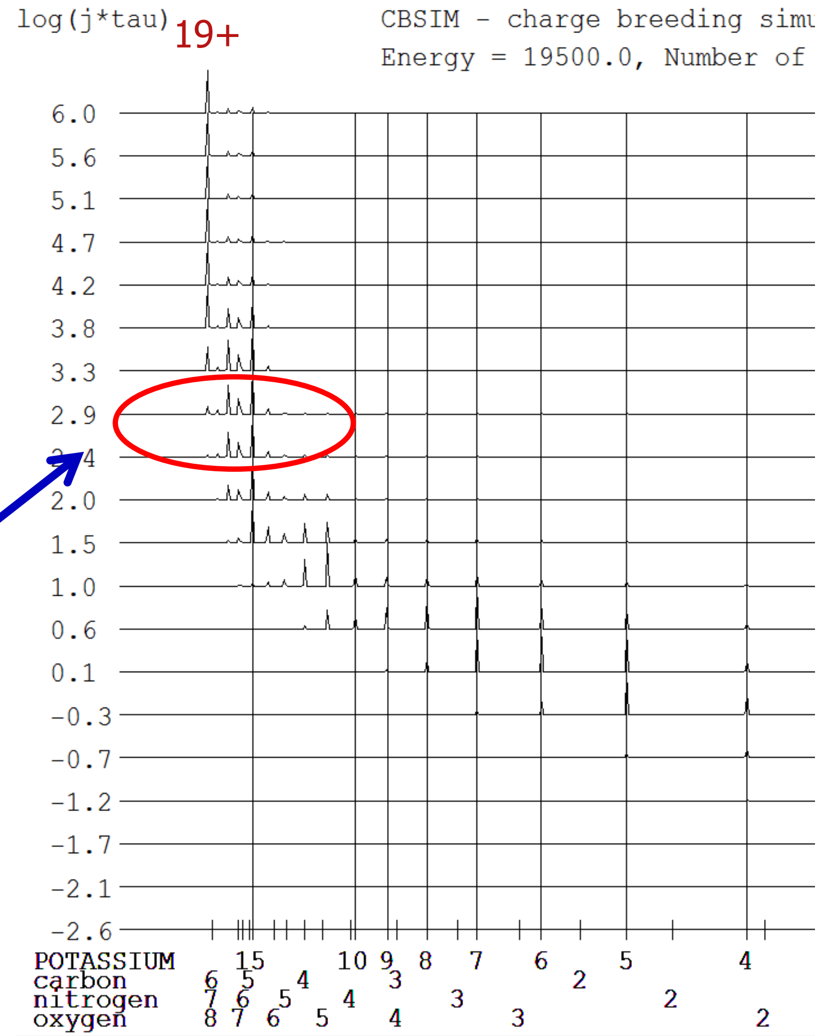
5 Hz extraction rate
→ up to 200ms breeding time

Charge state distributions, CBSIM, j

Exp't: 5 Hz; 200 ms
E-beam: 19.5 keV; 100 mA



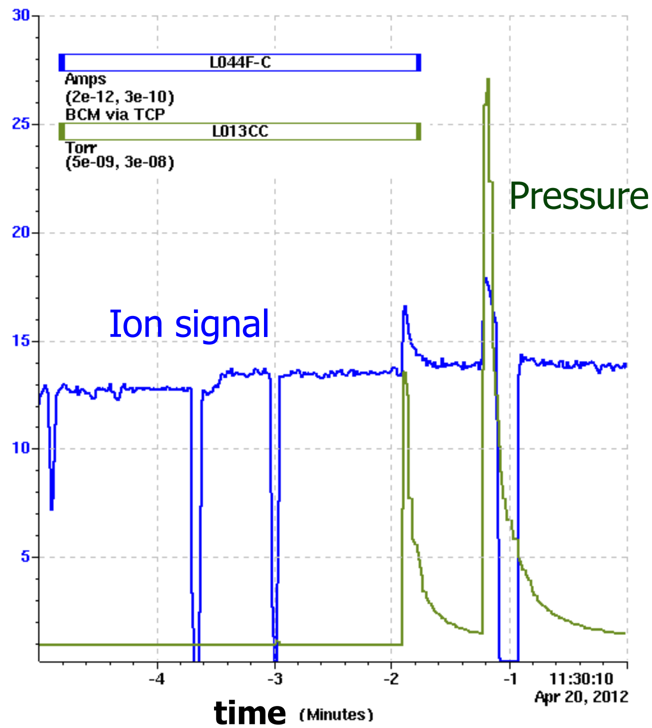




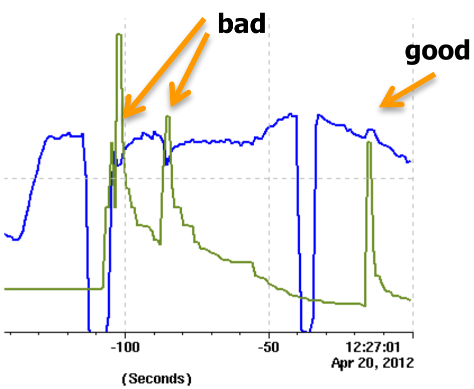
CBSIM code (Becker/Kester):
Log(j*t) ~ 2.4
Using residual gas …
Exp't 态 **j~1000 A/cm2** (3 T, average)
t~250 ms

Ion cooling with He

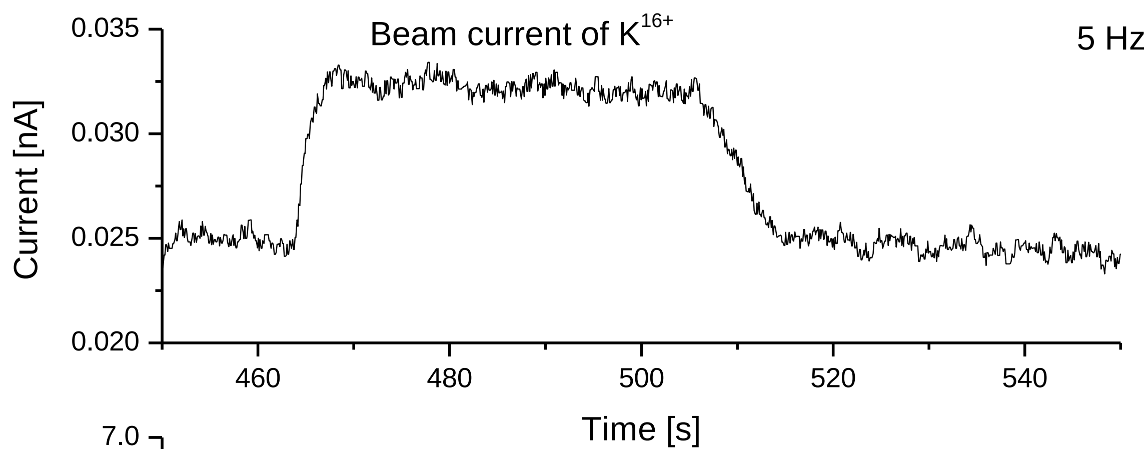
He pressure bursts …
and effect on K^{16+} production:

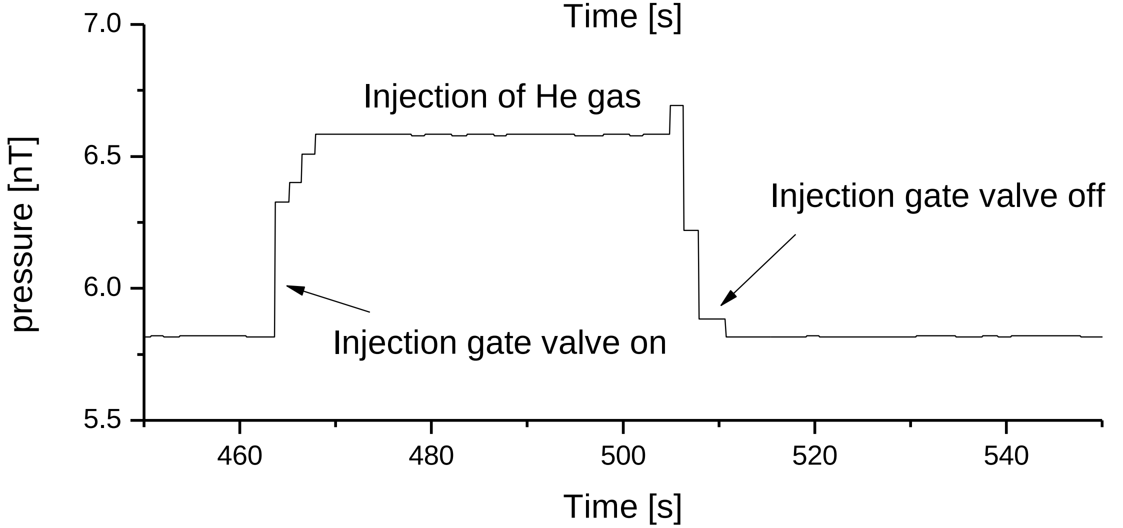


Another example:



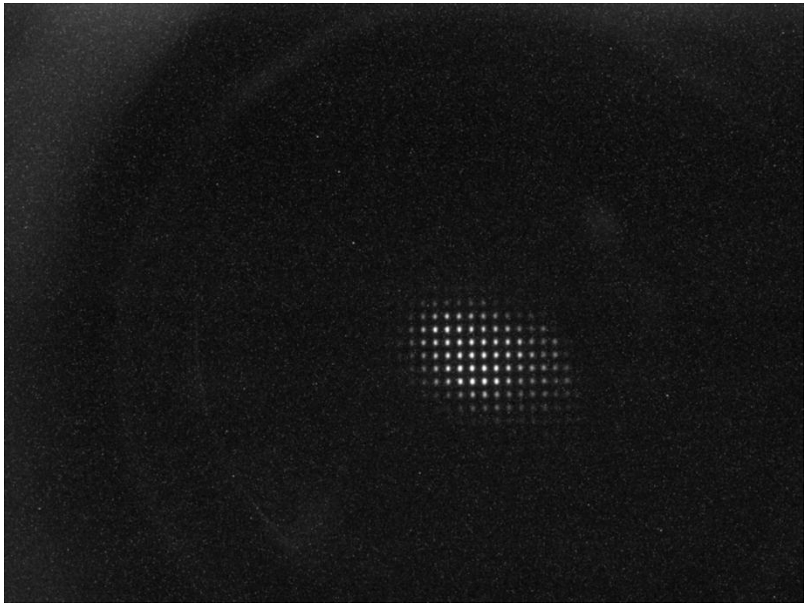
Remember the gas injector … add He deliberately!





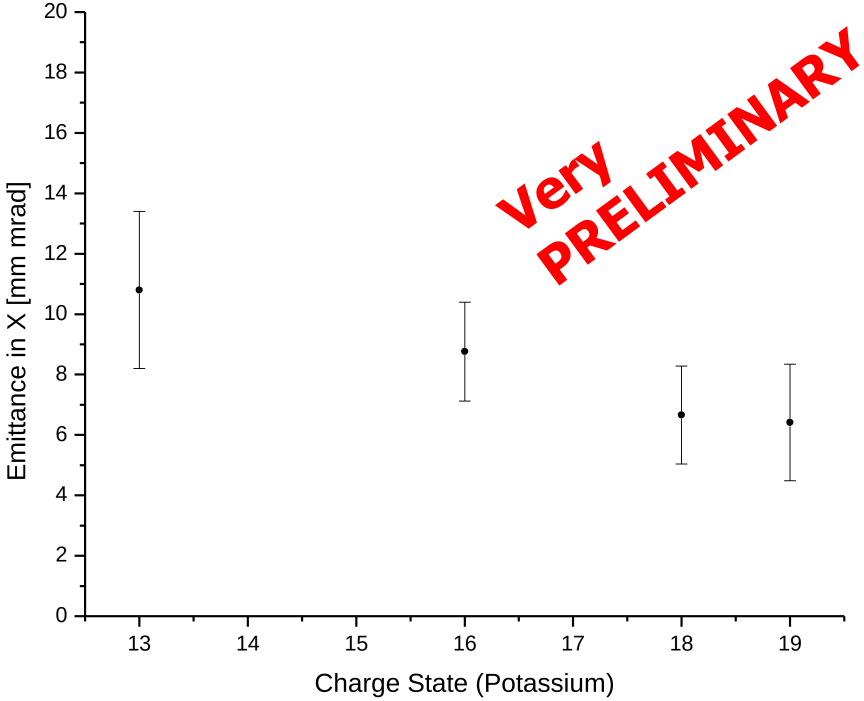
Emittance measurements

K^{18+} beam on the Pepperpot meter



Ion beam energy: 29.223 kV * q
Electron beam current: 100 mA

Emittance *vs* charge state



Outlook

EBIT: First accelerated charge-bred ions with EBIT-RFQ-SRF
To do: Increase I !

ReA3:

2011: Accelerated highly-charged beams

2012: Complete ReA3

2013: Limited user program with ReA3

Thanks to …

MICHIGAN STATE UNIVERSITY
NSCL
Max-Planck-Institut für Kernphysik
GSI

G. Bollen, *K. Kittimanapun*, ***A. Lapierre,*** D. Leitner … and MANY MANY MORE
J. R. Crespo López-Urrutia
O. Kester

Thanks for listening!

Break

F. Wenander's emittance formula → acceptance

Capture probability = f(trap length, electron energy, B-field, emittance) using F. Wenander's formula + Lotz' X-section

cathode radius	rc	mm	3.18
e-energy	Ee	keV	20
mean energy in trap	Eion	eV	100
Ionization x-section	$\sigma_{1 -> 2}$	A^2	0.03340
mean velocity in trap	$<v_t>$	m/s	22232.5

Color code:
- affected by acceptance
- affected by time in trap / j
- affected by both
- >99%

Capture probability [%]

↓ current / trap length →

I [A] = 0.1

dz [m] = 0.16: ↓ ε / B →	1	2	4	6
3	2.2	4.3	6.2	7.6
10	0.9	1.3	1.9	2.3
30	0.3	0.4	0.6	0.8
50	0.2	0.3	0.4	0.5

dz [m] = 0.4: ↓ ε / B →	1	2	4	6
3	5.4	10.5	14.4	17.1
10	2.2	3.1	4.3	5.1
30	0.7	1.1	1.4	1.7
50	0.5	0.6	0.9	1.0

dz [m] = 1.2: ↓ ε / B →	1	2	4	6 T
3	15.4	28.2	35.2	38.0
10	6.3	8.5	10.5	11.4
30	2.1	2.8	3.5	3.8
50	1.3	1.7	2.1	2.3

I [A] = 1.5

dz [m] = 0.16: ↓ ε / B →	1	2	4	6
3	24.7	46.3	72.7	86.2
10	24.7	46.3	57.4	55.5
30	13.8	17.5	19.1	18.5
50	8.3	10.5	11.5	11.1

dz [m] = 0.4: ↓ ε / B →	1	2	4	6
3	50.9	78.8	96.1	99.3
10	50.9	78.8	75.9	63.9
30	28.3	29.8	25.3	21.3
50	17.0	17.9	15.2	12.8

dz [m] = 1.2: ↓ ε / B →	1	2	4	6 T
3	88.1	99.1	100.0	100.0
10	88.1	99.1	79.0	64.4
30	49.0	37.4	26.3	21.5
50	29.4	22.5	15.8	12.9

I [A] = 2.4

dz [m] = 0.16: ↓ ε / B →	1	2	4	6
3	33.6	61.0	86.8	95.5
10	33.6	61.0	86.8	78.0
30	24.9	29.9	29.1	26.0
50	14.9	17.9	17.5	15.6

dz [m] = 0.4: ↓ ε / B →	1	2	4	6
3	64.1	90.5	99.4	100.0
10	64.1	90.5	99.4	81.6
30	47.4	44.3	33.4	27.2
50	28.4	26.6	20.0	16.3

dz [m] = 1.2: ↓ ε / B →	1	2	4	6 T
3	95.4	99.9	100.0	100.0
10	95.4	99.9	100.0	81.6
30	70.5	48.9	33.6	27.2
50	42.3	29.3	20.2	16.3

I [A] = 5

dz [m] = 0.16: ↓ ε / B →	1	2	4	6
3	47.4	81.5	98.0	99.8
10	47.4	81.5	98.0	99.8
30	47.4	61.8	49.1	39.9
50	34.9	37.1	29.4	24.0

dz [m] = 0.4: ↓ ε / B →	1	2	4	6
3	80.0	98.5	100.0	100.0
10	80.0	98.5	100.0	100.0
30	80.0	74.8	50.1	40.0
50	58.8	44.9	30.0	24.0

dz [m] = 1.2: ↓ ε / B →	1	2	4	6 T
3	99.2	100.0	100.0	100.0
10	99.2	100.0	100.0	100.0
30	99.2	75.9	50.1	40.0
50	73.0	45.5	30.0	24.0

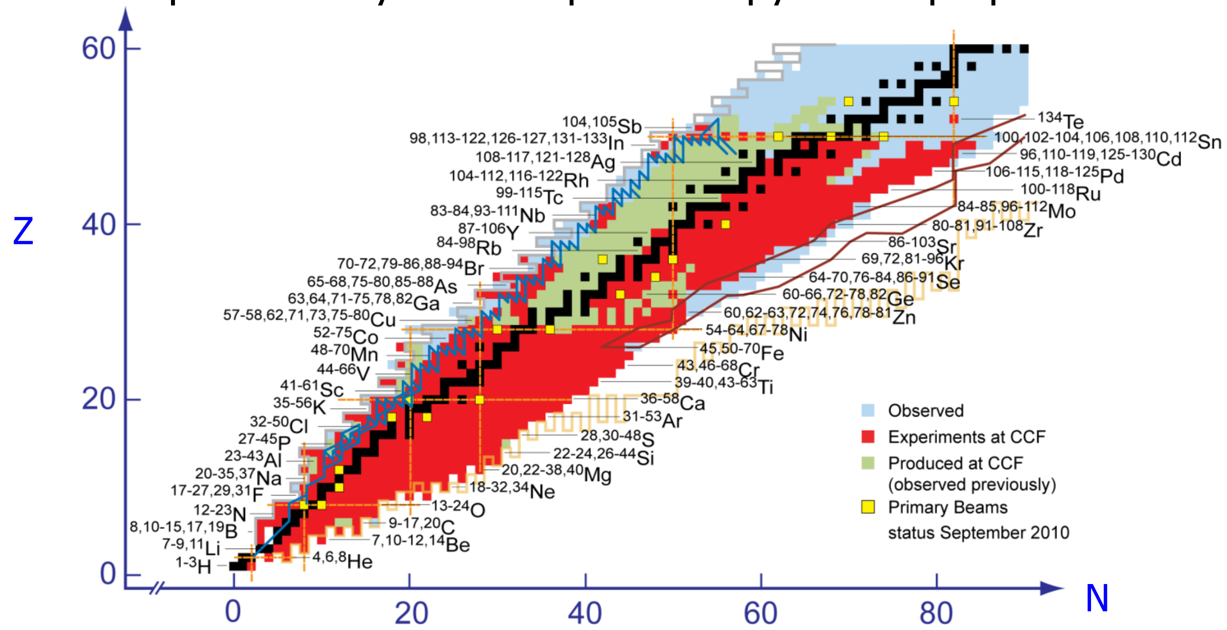
π mm mrad

Wenander et al. - REXEBIS - the Electron Beam Ion Source for the REX-ISOLDE Project, *Design and Simulations* CERN 1999

Reaccelerated beams at the NSCL

NSCL: User facility, RIB production by projectile fragmentation and fission

- NSCL has successful program with stopped beams – LEBIT facility for Penning trap mass spectrometry – laser spectroscopy under preparation



> 1000 RIBs made
> 830 RIBs used in experiments

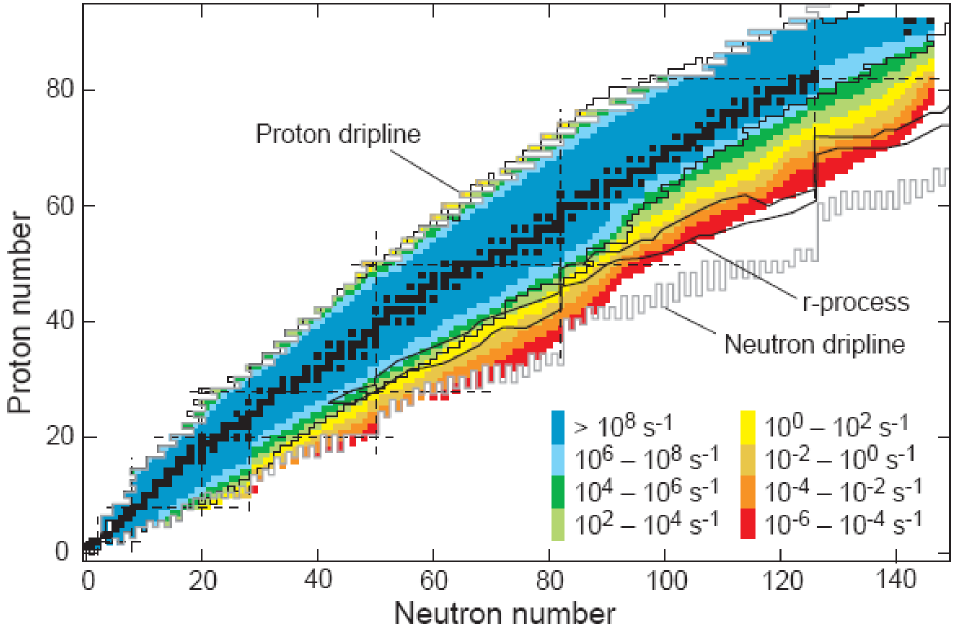
ReA3 → new science opportunities with rare isotopes from projectile fragmentation

- Nuclear astrophysics: key reactions at near-stellar energies
- Nuclear structure via Coulomb excitation or transfer reactions

Reaccelerated beams at the NSCL and FRIB

NSCL: User facility, RIB production by projectile fragmentation and fission

- NSCL has successful program with stopped beams – LEBIT facility for Penning trap mass spectrometry – laser spectroscopy under preparation



FRIB
- more than 1000 new isotopes at useful rates
- High fraction of the reaccelerated beams projected to be available at 10^6 to 10^8/sec
- Special cases, e.g., ^{15}O will have 2x10^{10}/s

ReA3 → new science opportunities with rare isotopes from projectile fragmentation

- Nuclear astrophysics: key reactions at near-stellar energies
- Nuclear structure via Coulomb excitation or transfer reactions

FRIB expansion: includes fast, stopped, and reaccelerated beams

- ReA3 provides beams for astrophysics - one of the science pillars of FRIB.
- Develop programs and techniques in reaccelerated beams before FRIB operation

B-related relations

Breeding time: Herrmann radius: $r_H \propto 1/\sqrt{B}$, → Charge density $j \propto B$
Appearance time for certain charge state i: $t_i = e / j\ \Sigma\ 1/\sigma_i$

→ Charge-breeding time ɑ 1/B

Trap capacity: For fully compensated e-beam R

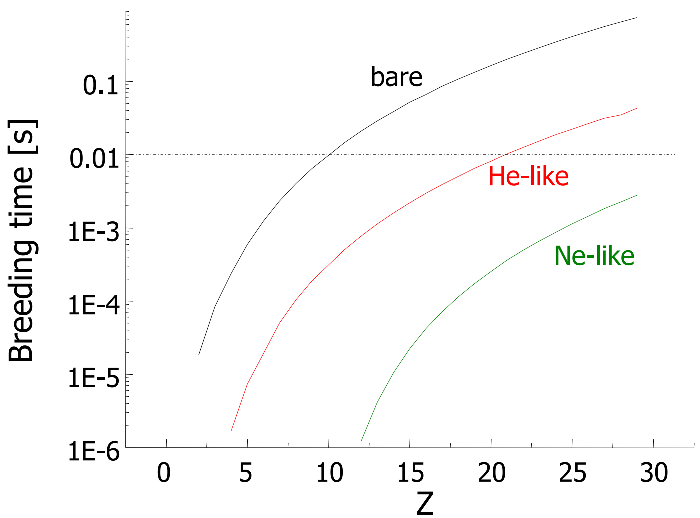
→ Trap capacity ɑ B

$$r_b[\mu\mathrm{m}] = \frac{150}{B[T]}\sqrt{\frac{I_e[A]}{\sqrt{E_e[\mathrm{keV}]}}}$$

$$r_h = r_b\sqrt{\frac{1}{2}+\frac{1}{2}\sqrt{1+4\left(\frac{8kT_c r_c^2 m}{e^2 r_b^4 B^2}+\frac{B_c^2 r_c^4}{B^2 r_b^4}\right)}}.$$

$$R_i \approx \frac{N_i}{t_i^{\mathrm{app}}} = \frac{I_e^2 l B}{2\sqrt{2}e^2\pi r_c v_e\sqrt{\frac{mkT_c}{e^2}}\hat{q}_i\sum_{j=0}^{\hat{q}_i}\frac{1}{\sigma_j^{ET}}}$$

$$\approx 1.84\times10^{42}\frac{I_e^2 l B}{r_c v_e\sqrt{kT_c}\hat{q}_i\sum_{j=0}^{\hat{q}_i}\frac{1}{\sigma_j^{ET}}}\left[\frac{\mathrm{ions}}{s}\right]$$



$E_{ele} = 2 * E_{bdg}$

$j = 10^4$ A/cm^2

$I_e = 0.5$ A, $B = 6$ T
$B_c = 20$ G, $r_c = 3.2$mm

→ $j \sim 4\cdot10^3$ A/cm^2

Charge state and breeding times

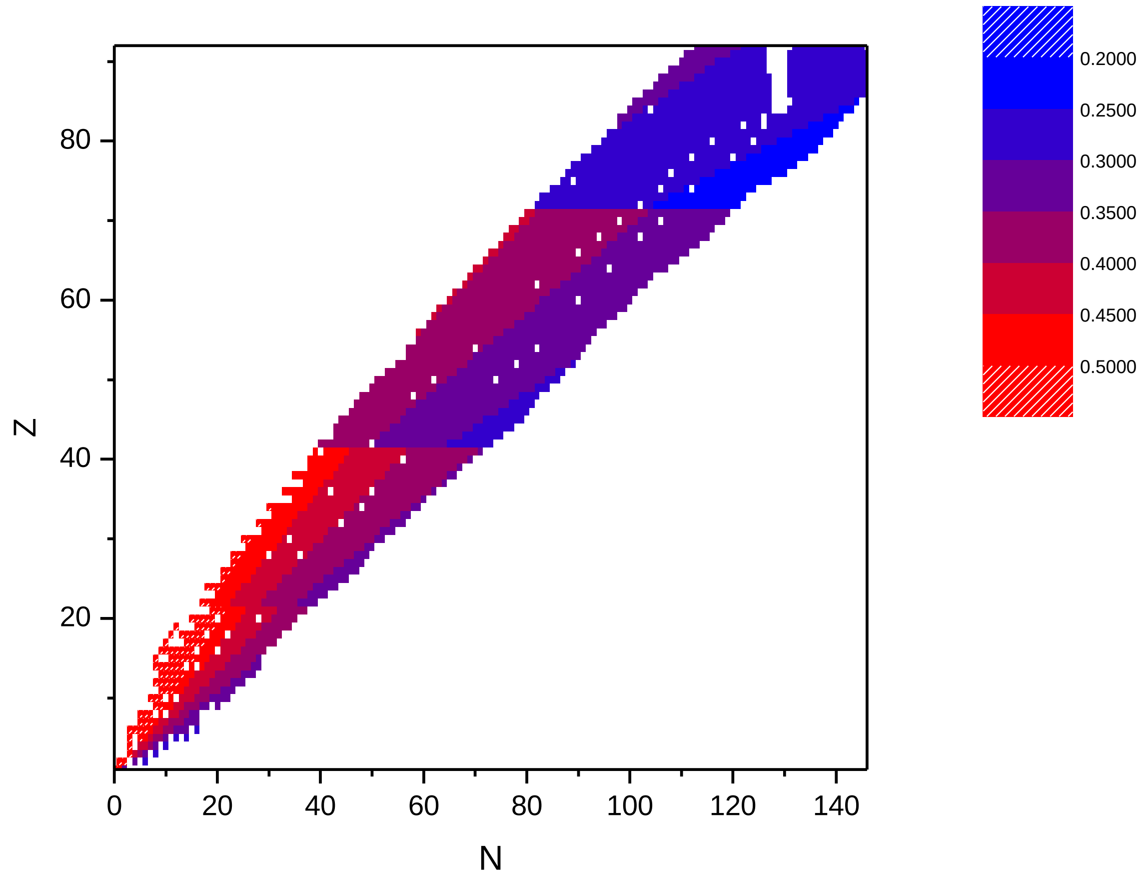
large trapping region ~ (40 cm)
high current, above 1 A
high current density (>10^4A/cm2)
strong magnetic field: 6T

Z	charge state	breeding time [ms]	q/A
1-44 (H-Ti)	fully stripped or He like	2 - 40 ms	0.5-0.4
41-75 (Nb-Re)	Ne-like	20 - 35 ms	0.33-0.35
71-92 (Lu-U)	Ni-like	25 - 40 ms	0.25-0.27

Q/A landscape

Assumption
- Z=1-22 (H-Ti) fully stripped
- Z=18-44 (Ar-Ru) He-like
- Z=41-75 (Nb-Re) Ne-like
- Z=71-92 (Lu-U) Ni-like

Simplified graph
- Z=1-20 fully stripped
- Z=21-42 He-like
- Z=43-72 Ne-like
- Z=73-92 Ni-like



EBIS/T or ECR

Breeder requirements

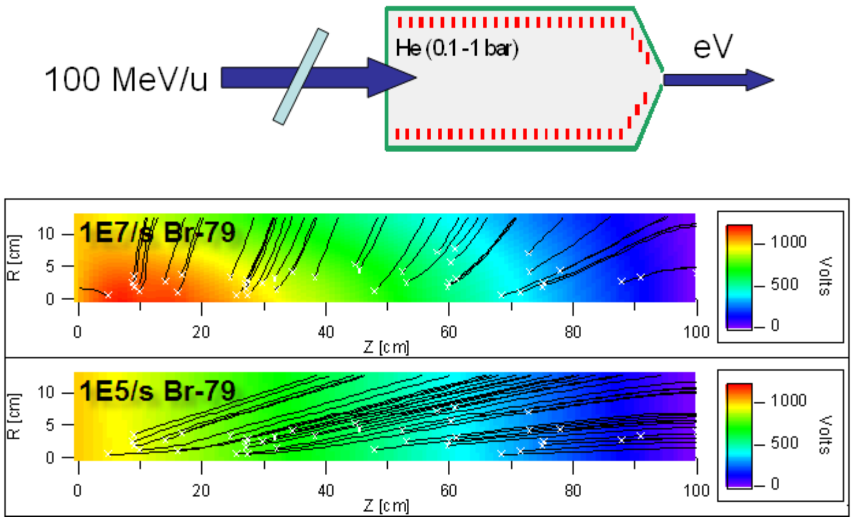
- High efficiency, breed into 1 charge state
- Breeding times ~ 10 ms
- Beam intensity ~ 10^9 ions/s
- Continuous injection
- High acceptance, low emittance
- Fast and slow extraction

Expected performance of ECR and EBIS/T:

	ECR	EBIT/EBIS	1+ scheme	ε(EBIT)/ε(1+)
ε (A<40)	<20% (1 CS)	> 60% (1 CS)	40% (1-2 CS)	1.5 – 3
ε (A=100)	<20% (1 CS)	> 50% (1 CS)	16% (3 CS)	3 – 10
ε (A=200)	<20% (1 CS)	> 40% (1 CS)	12% (4 CS)	3 – 12
Breeding times	50 ms	10 ms	%	↑
Beam limit	>> 10^9/s	> 10^9/s	>> 10^9/s	Single charge state
Risk	present performance: 20% of values	present performance : 25 - 50% of values	no	

Gas Stopper Systems

Linear Stopper

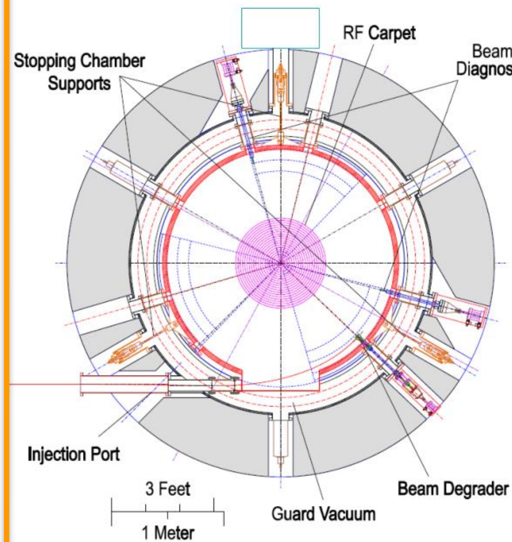


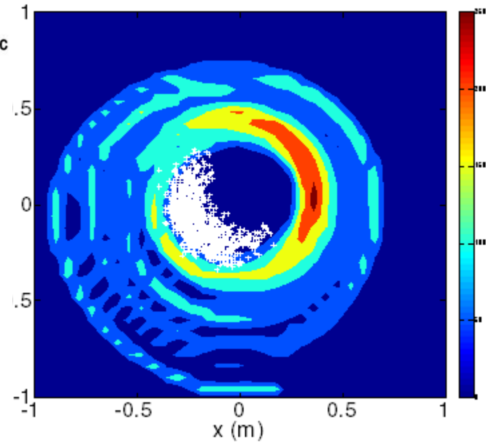
- L > 1.2 m, p<300 mbar
- Good efficiency for heavy ions and rates < 10^7/s

MSU: <u>cryogenic</u> gas stopper with RF carpet transport

ANL: linear gas catcher based on CARIBU concept (**FRIB R&D**)

Cyclotron Gas Stopper





- Superconducting magnet system
- B_{max} = 2.3 T, r_{inj} = 0.95 m, k = -0.28, $B\rho_{inj}$ = 1.6 Tm
- Vacuum chamber in guard vacuum cryogenically cooled
- Vertical orientation matches momentum compression
- High efficiency for light ions and rates >10^8/s

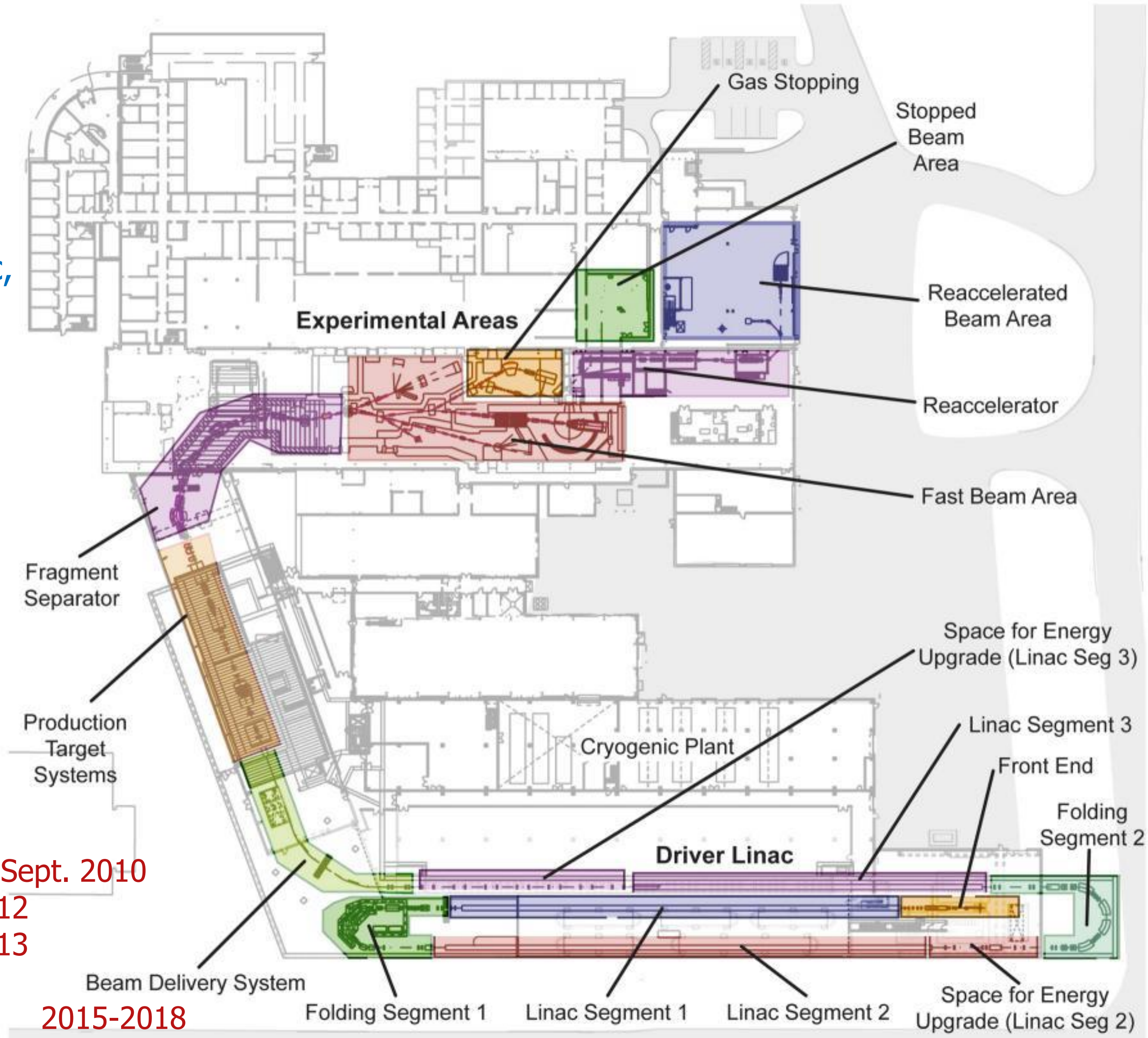
MSU in collaboration with RIKEN and GSI

Towards FRIB

Driver linac:
E/A ≥ 200 MeV for all ions,
P_{beam} ≥ 400 kW

upgrade options:
E/A = 400 MeV U driver linac,
ISOL, multi-user capability …

Use of existing NSCL
– Enables pre-term science
– Fast start of FRIB science



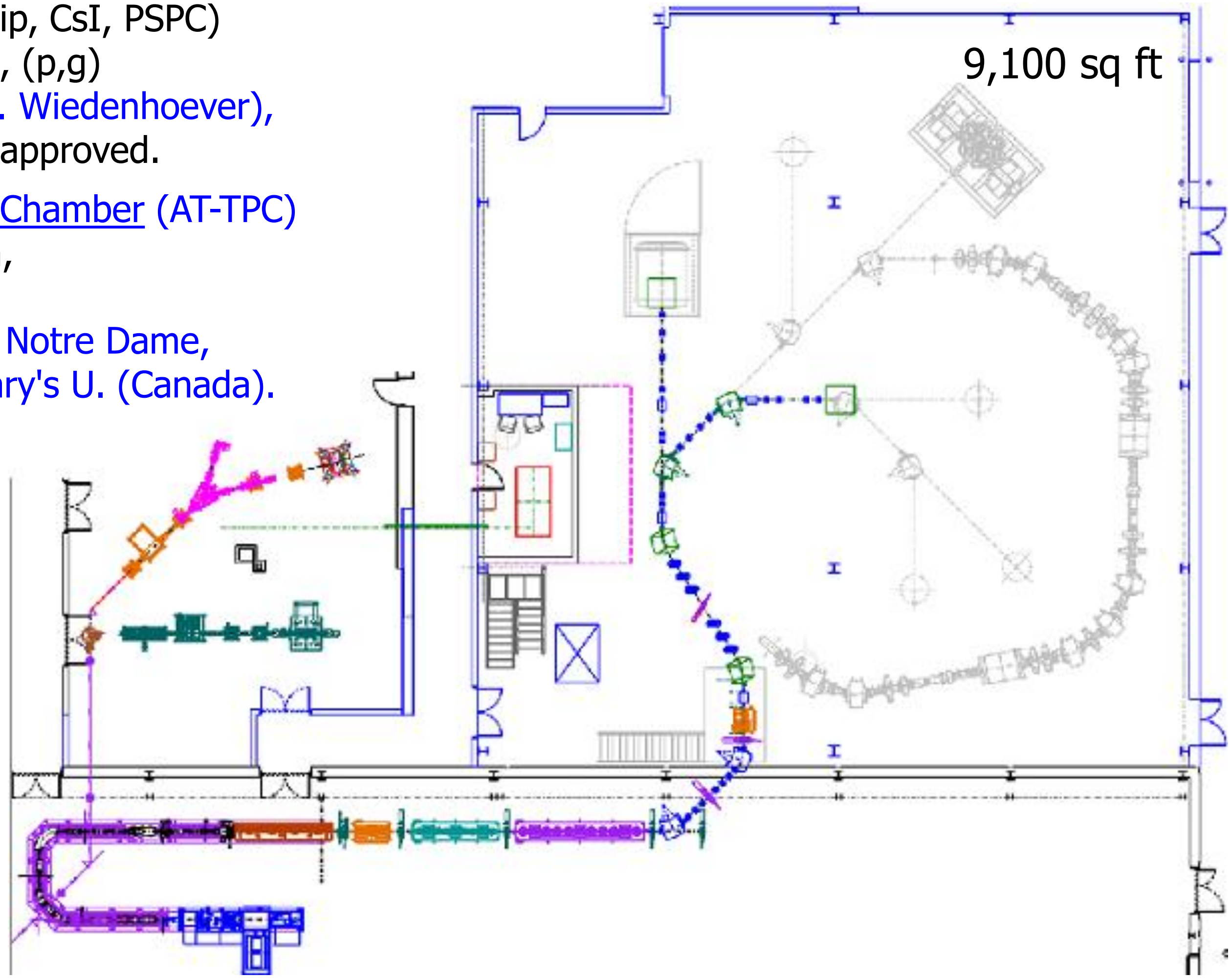
Project phases
Conceptual design – completed Sept. 2010
Preliminary design 2010-2012
Final design 2012-2013
Construction begins 2012
Integration/commissioning 2015-2018
Project completion 2018-2020

3 MeV/u experimental hall

Room for flexible experimental stations + some larger permanent installations of equipment

In work:

- Array for Nuclear Astrophysics Studies with Exotic Nuclei (ANASEN)
  Si-barrel detector array (Si-strip, CsI, PSPC)
  for nuclear astrophysics, (a,p), (p,g)
  LSU (J. Blackmon) and FSU (I. Wiedenhoever),
  funding by NSF/MRI program approved.
- Active Target Time Projection Chamber (AT-TPC)
  4p solid angle, high resolution,
  low reaction rates
  MSU (A. Bickley, W Mittig), U. Notre Dame,
  WMU, LLNL, LBNL, and St. Mary's U. (Canada).
  Proposal submitted to DOE.



Existing at MSU

- Miniball detector array
  + other detectors

Future

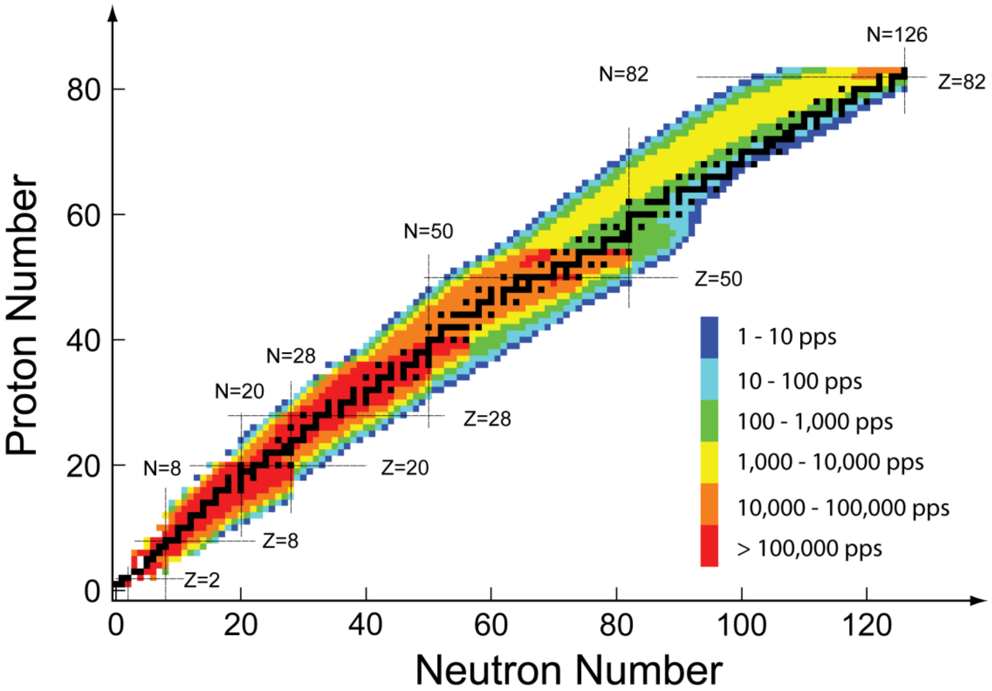
- Window-less gas target, (a,p), (p,g) (JINA)
- SECAR recoil separator (submitted to DOE)

Beam rate estimate and beam properties

Beam rate estimates – assumptions:

- Predicted beam rates (LISE)
- Rate dependent stopping and extraction efficiency

  1% for 10^8/s, 5% for 10^7/s, 20% for 10^6/s
- Breeding efficiency: 60%
- Transport efficiency: 70%
- Delay time (stopping + breeding) for decay losses: 100 ms



Expected beam properties

- Beam energies:

  ^{238}U: 0.3-3 MeV/u

  ^{48}Ca: 0.3-6.2 MeV/u
- Beams with <u>variable duty cycle</u>: from microsecond macro-pulses to quasi-continuous beams

Beam rate estimates have <u>large</u> uncertainties (one order of magnitude)

On-line tool for rate estimates and energy range:

http://www.nscl.msu.edu/exp/sr/yields

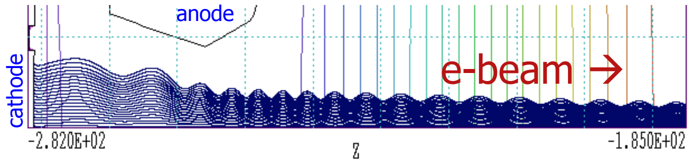
e-gun - simulations

Want: High current density

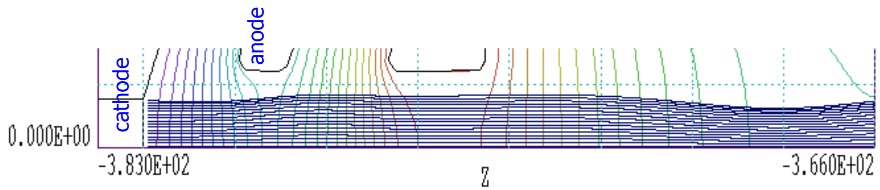
Use: Magnetic compression

Fight: Space charge

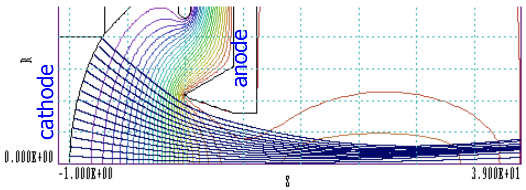
Titan - EBIT – 0.44A



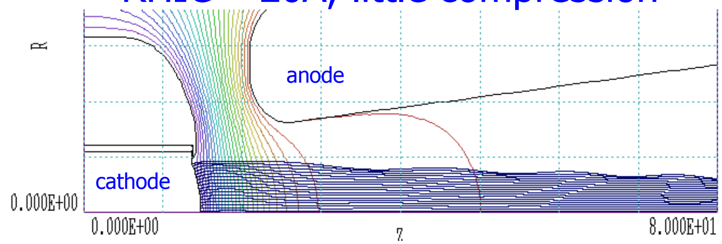
REXEBIS – 412 mA



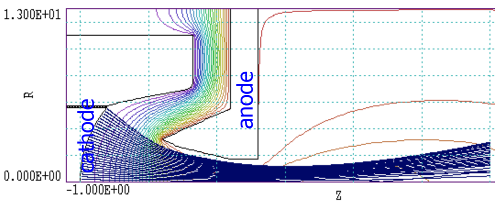
Frost – scaled to 2 A



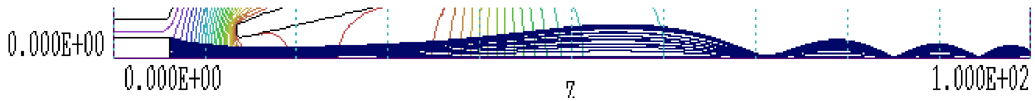
RHIC – 20A, little compression



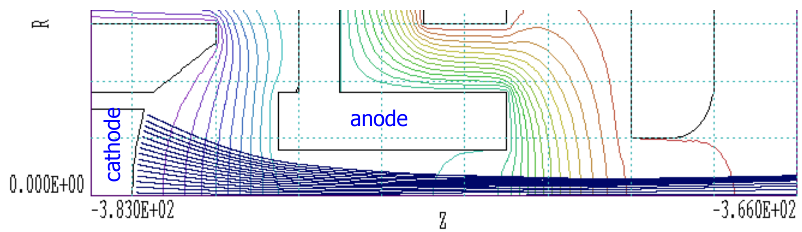
Frost3 – scaled to 1.55 A



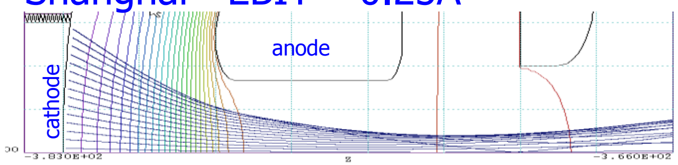
R. Becker – 0.4A



Tokyo- EBIT – 0.28A



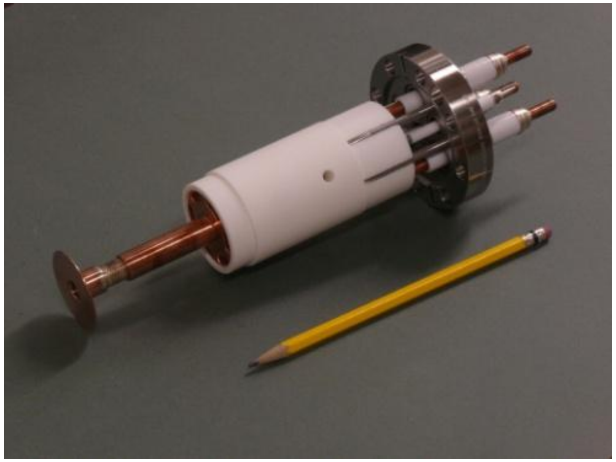
Shanghai - EBIT – 0.25A

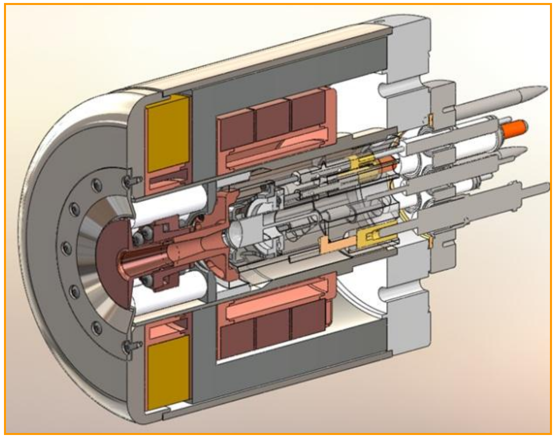


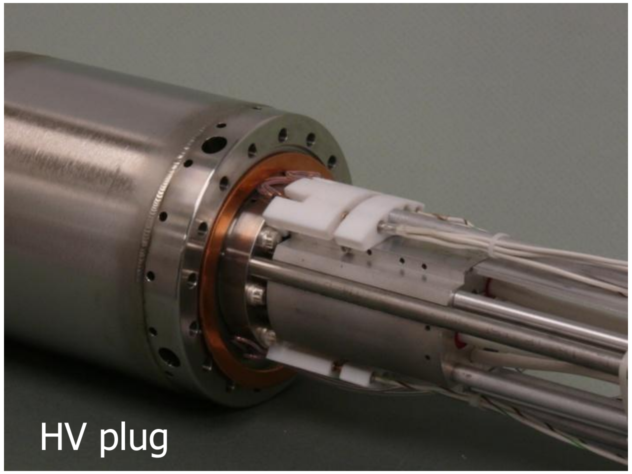
(M. Kostin + SCS)

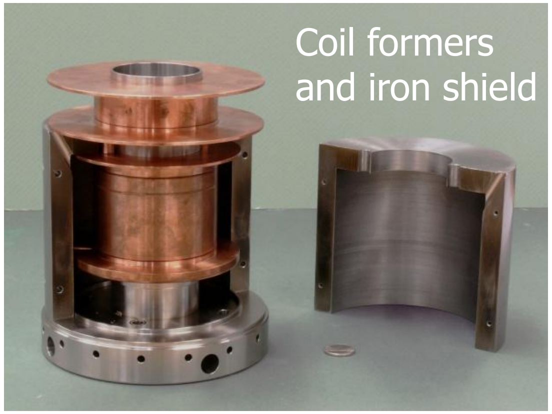
The e-gun - construction

Core
= cathode, focus + anode



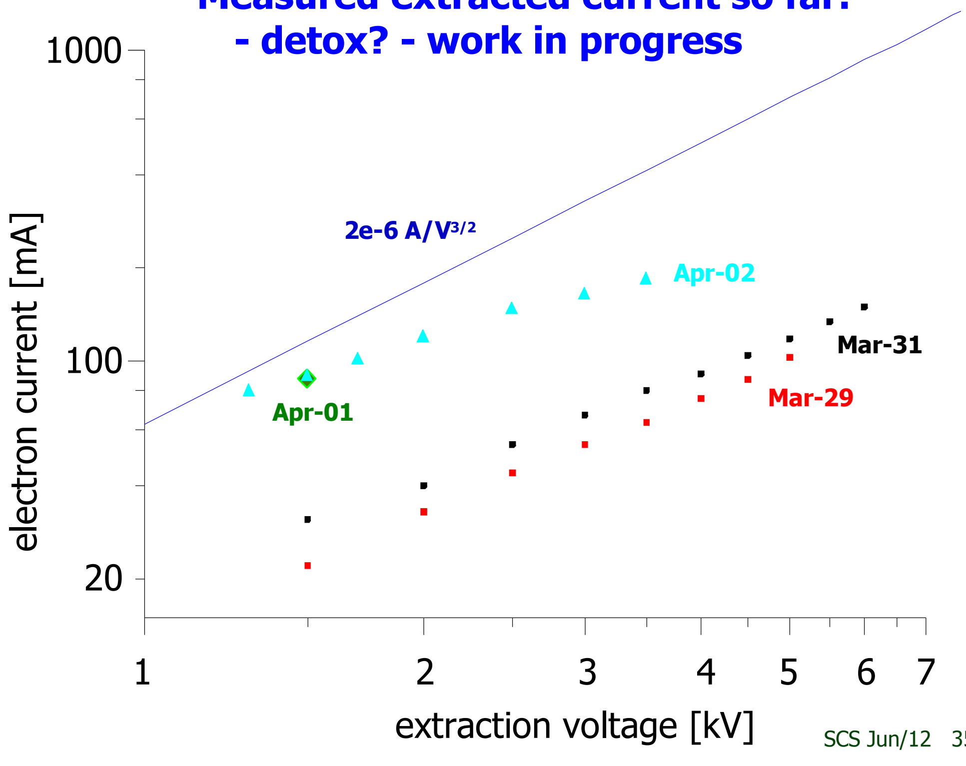




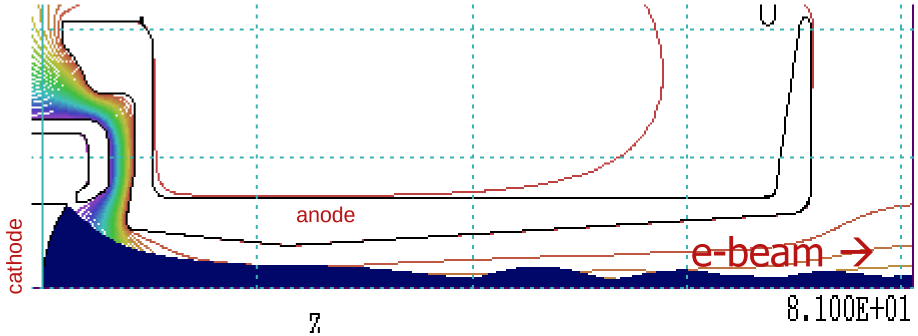


Starting tests with 'Papa'

Measured extracted current so far:
- detox? - work in progress



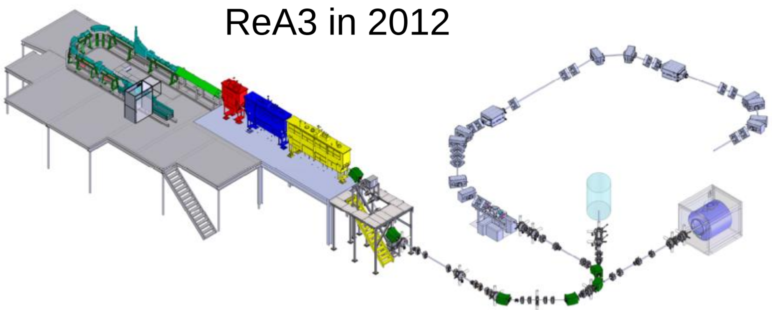
'Papa'-cathode: 2.4A at 11.5 kV

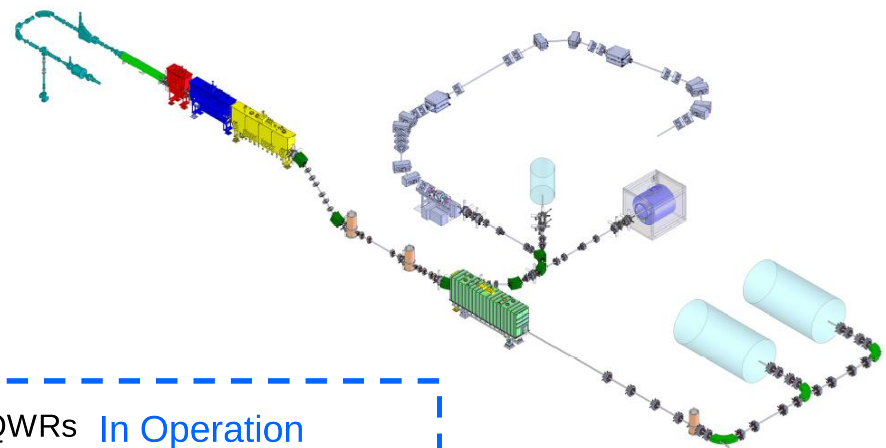


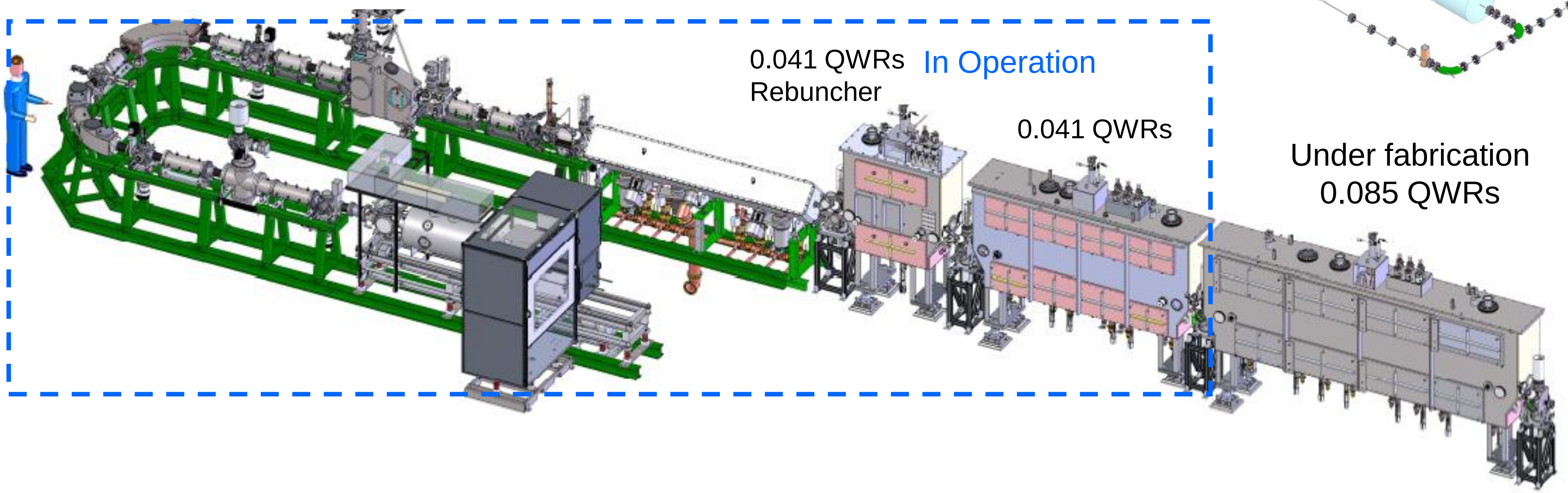
ReA - SRF

MSU ReA3, ReA6

- MSU-funded project
- First SRF linac at MSU
- Test bench for FRIB QWRs

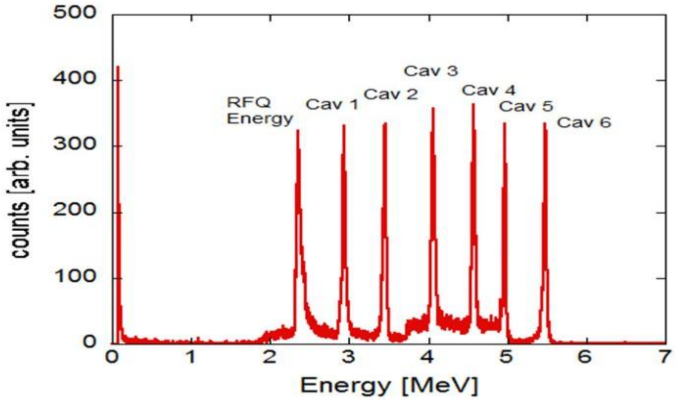




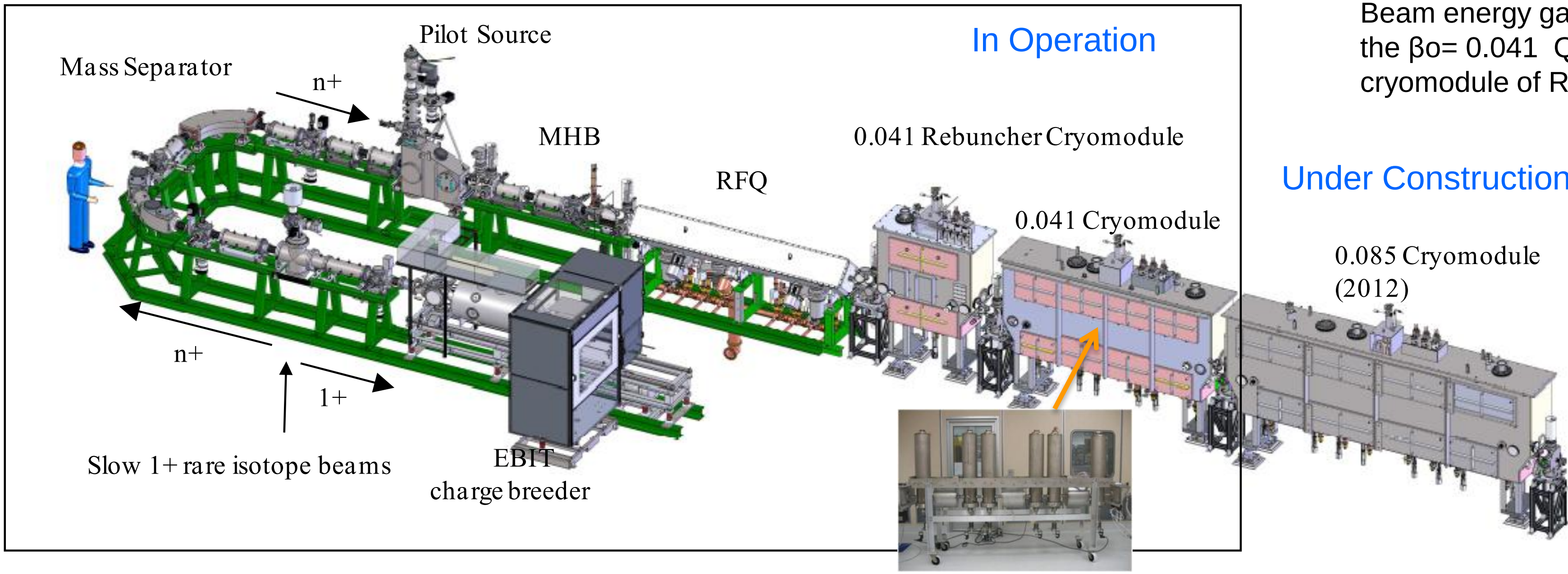


ReA3 Reaccelerator Linac

- First SRF linac at MSU, in operation for 1 year
- Excellent test bench for FRIB QWRs
- Similar QWRs as in FRIB
- Operation T = 4.5 K



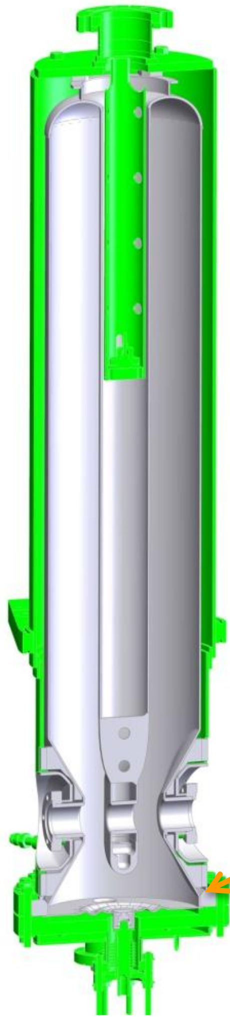
Beam energy gain in the βo= 0.041 QWR cryomodule of ReA3

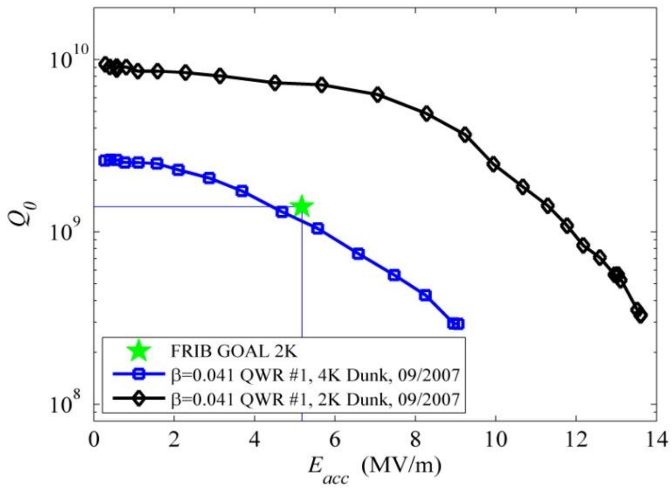


A. Facco, June 2012 ASAC Review - 07

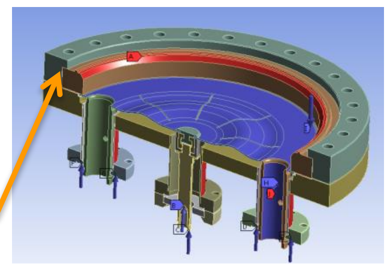
0.41 QWR – 1 Year of Operation in ReA3

- In ReA3
  - Operation at 4.5K, Ep=16 MV/m, Bp=35 mT successfully achieved
  - 7 cavities operating on line
  - Reliable and reproducible phase and amplitude lock
  - FRIB fields reached, but plate overheating
- Naked test at 2 K
  - E_p=80 MV/m, B_p=140 mT
- Test with He vessel
  - Q drop at high field
- In FRIB
  - Operation foreseen at 2 (2.1) K, with E_p=30 MV/m, B_p=53 mT
  - Bottom ring in high RRR Nb for reliable cooling at 2K





Record performance in naked tests of prototype (2007)

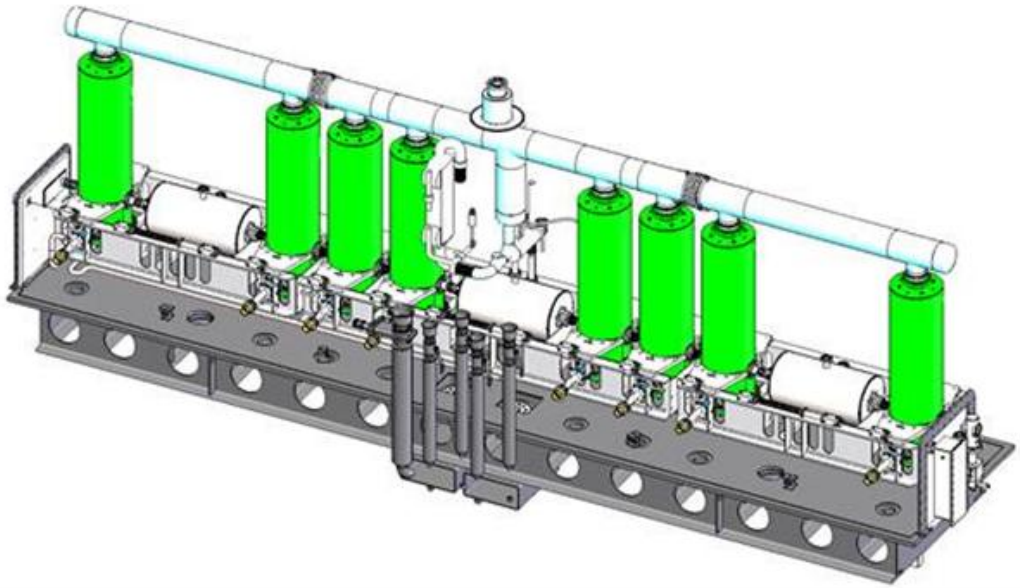


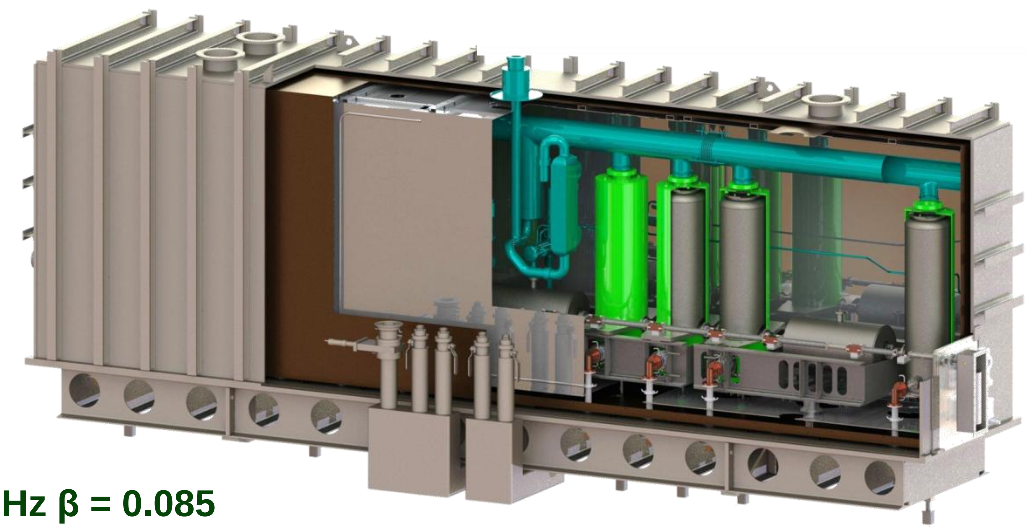
NbTi ring inReA3
high RRR Nb ring in FRIB

A. Facco, June 2012 ASAC Review - 07

FRIB QWR Cryomodule Designs

ReA6, β=0.085 cryomodule…
FRIB prototype
To be tested in ReA6





80.5 MHz β = 0.085 QWR
Configuration:
Length = 5.99 m
Height = 3 m
Width = 1.28 m
Weight = 9,375 kg

80.5 MHz β = 0.085
8 QWR Resonators x 3 Solenoids

M. Johnson + J. Ozelis, ASAC Review
June 2012 ASAC Review