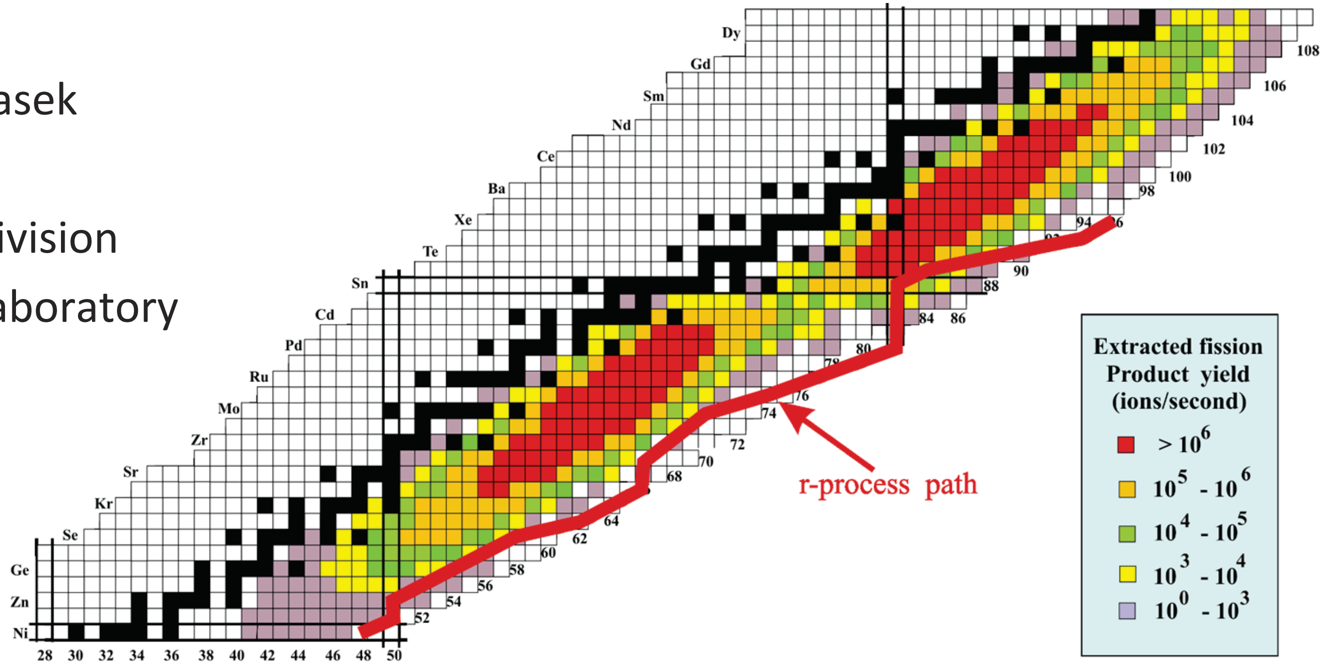
Charge Breeding Experiences with an ECR and an EBIS for CARIBU

Richard Vondrasek

ATLAS, Physics Division

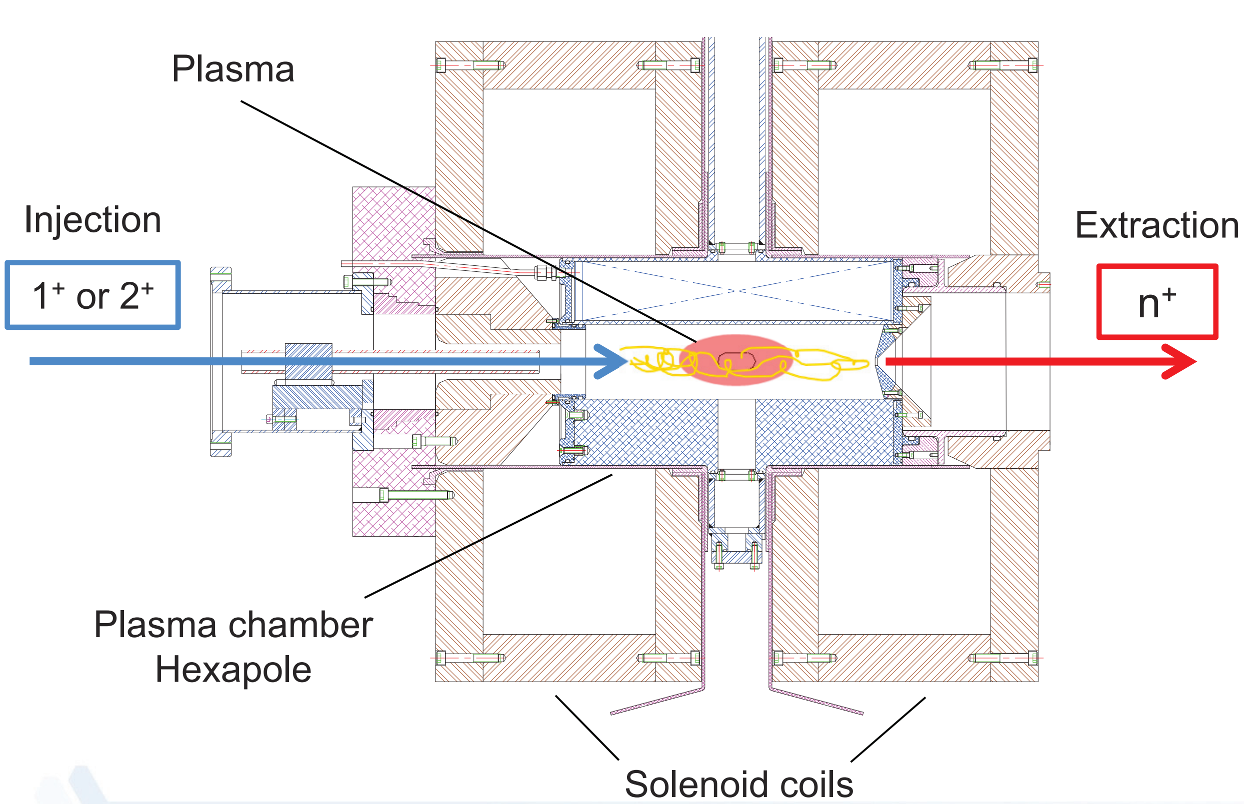
Argonne National Laboratory

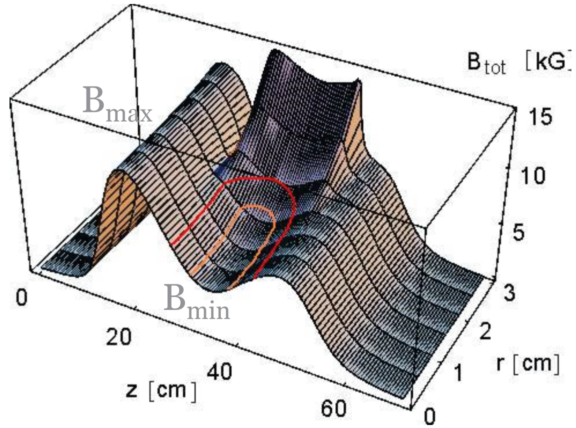


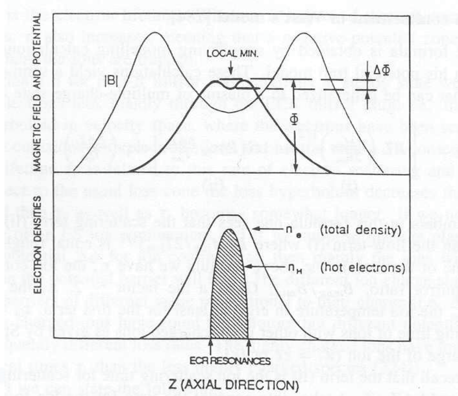
- ECR and EBIS charge breeders
- ECR charge breeding results and investigations
- Commissioning of EBIS charge breeder

ECR charge breeding concept

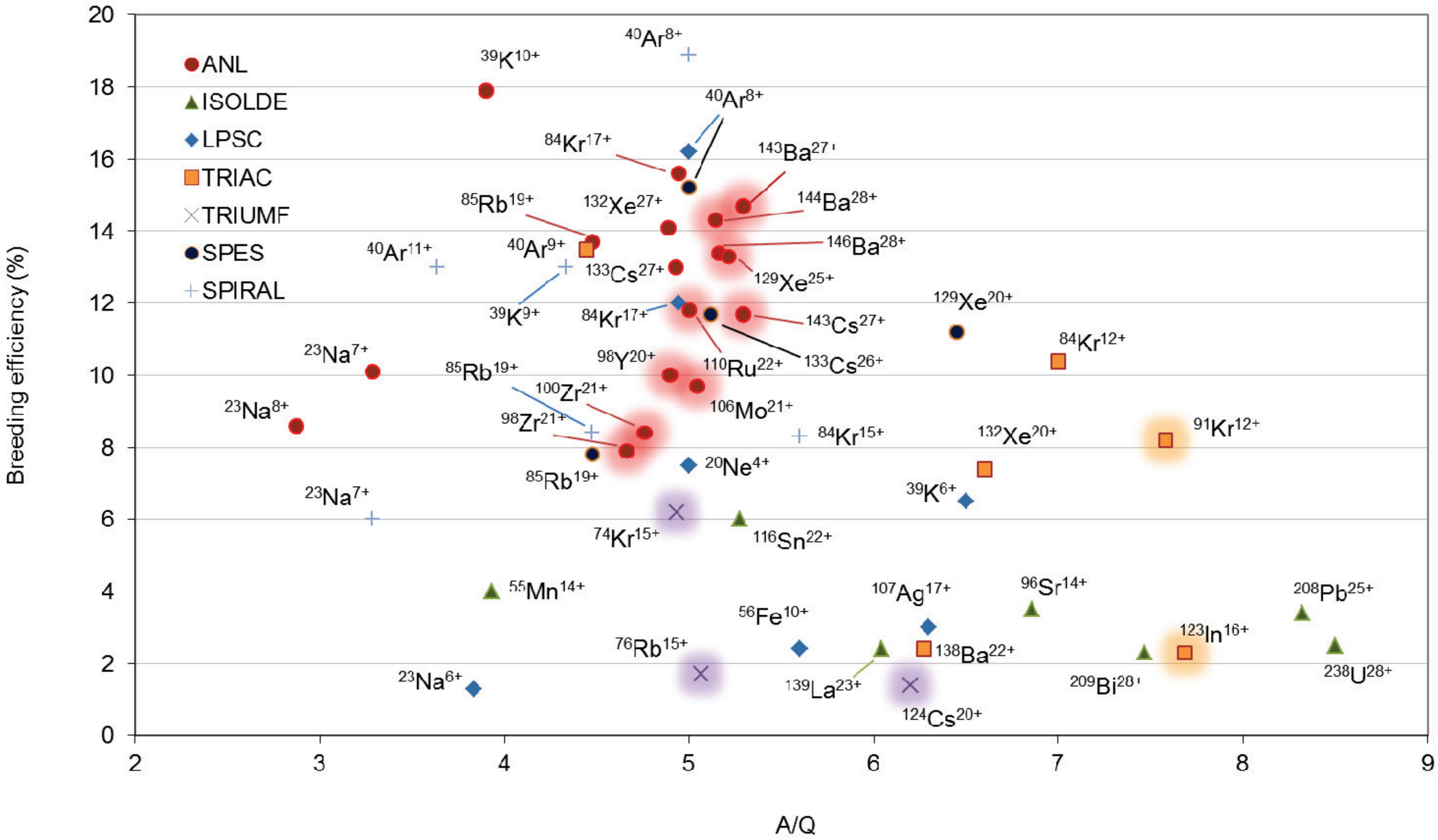
- Solenoid coils provide axial confinement
- Permanent magnet hexapole provides radial confinement
- Plasma excited by RF typically in the 10-14 GHz range and <1 kW
- Ion confinement via plasma potential generated by trapped electrons
- Highly charged ions produced via step-wise ionization with energetic electrons





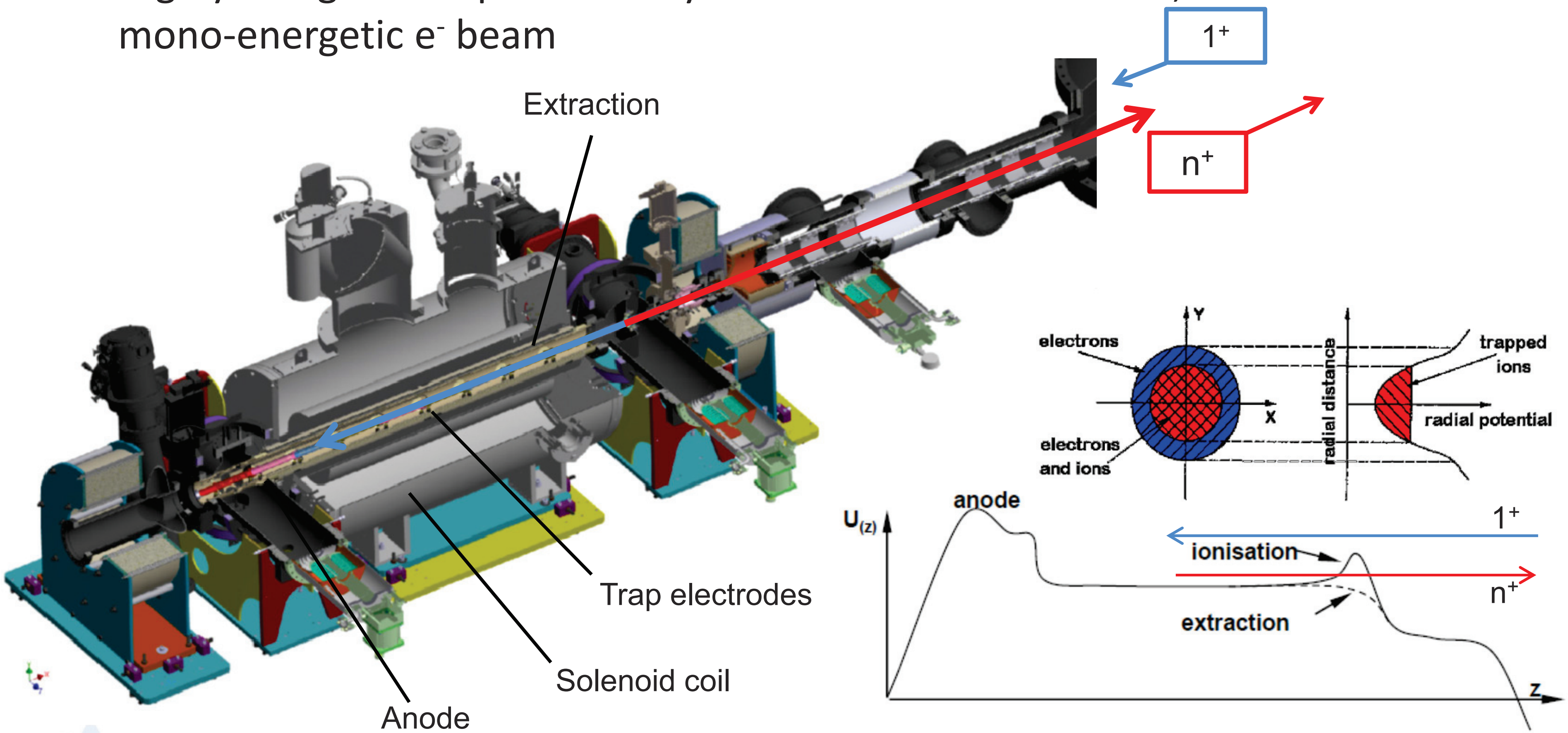


ECR charge breeder performance



EBIS charge breeding concept

- Trap electrodes provide axial ion confinement
- Electron beam provides radial ion confinement
- Strong solenoid coil for electron beam compression
- Highly charged ions produced by bombardment from a fast, dense mono-energetic e^- beam



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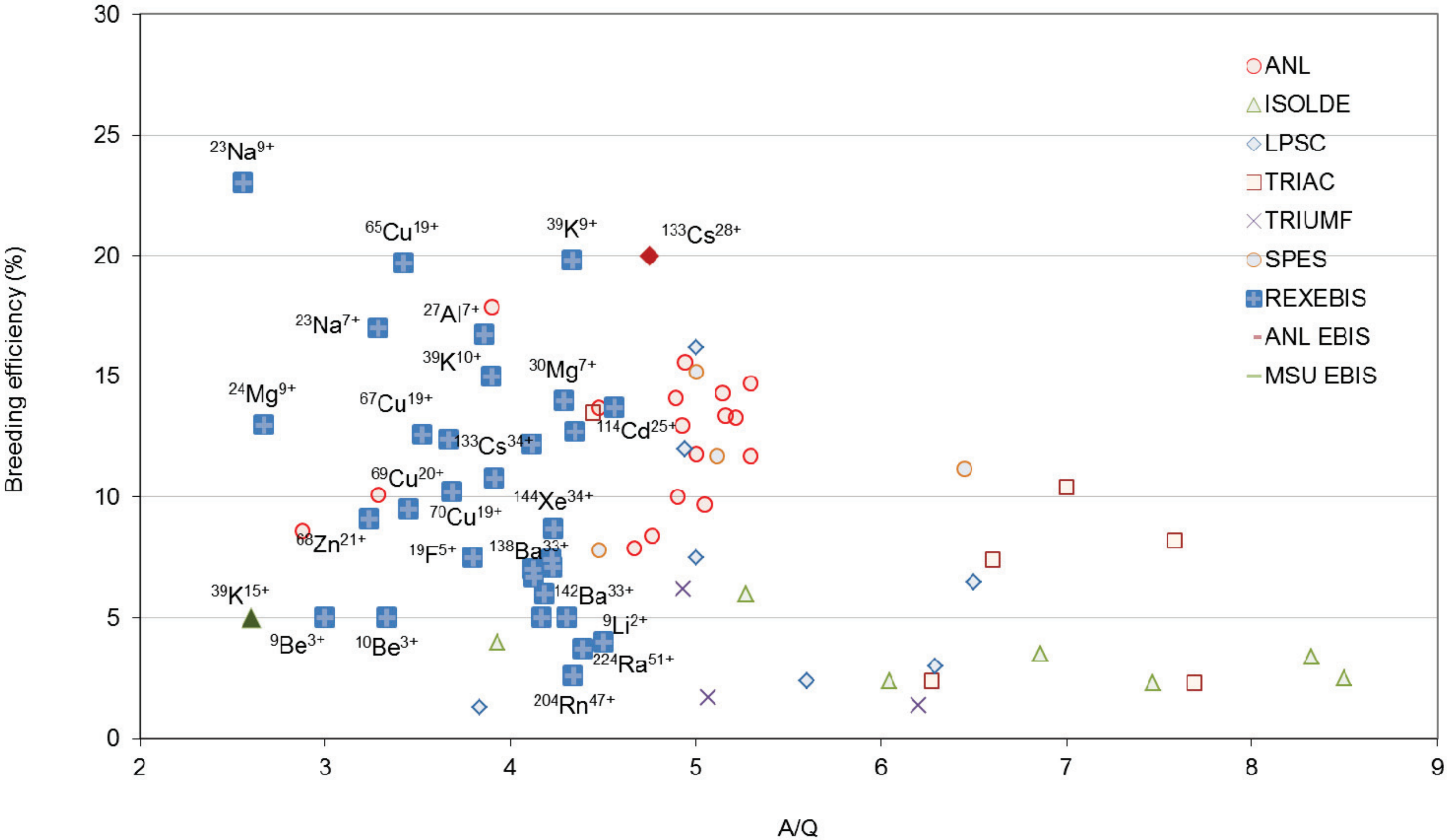
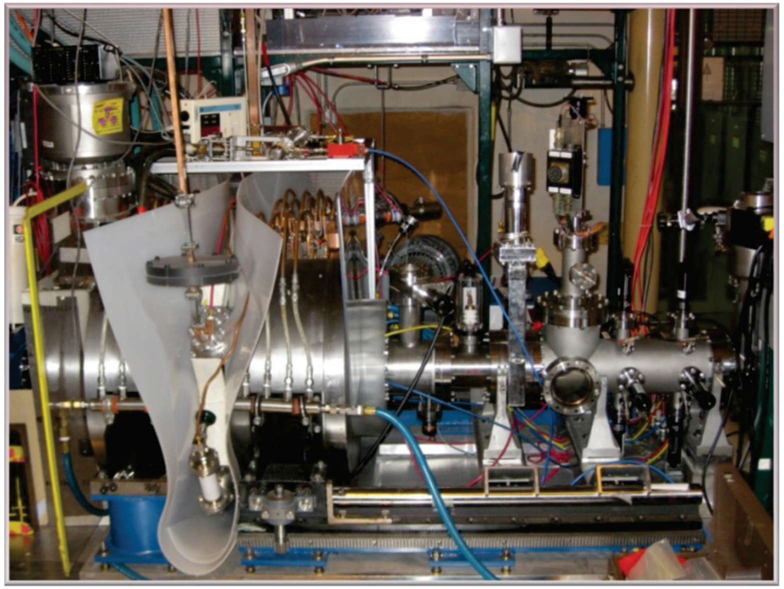
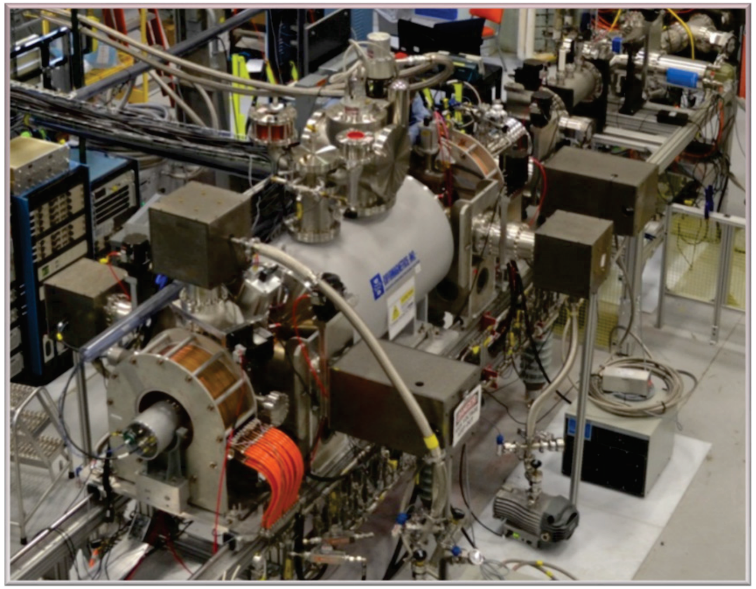


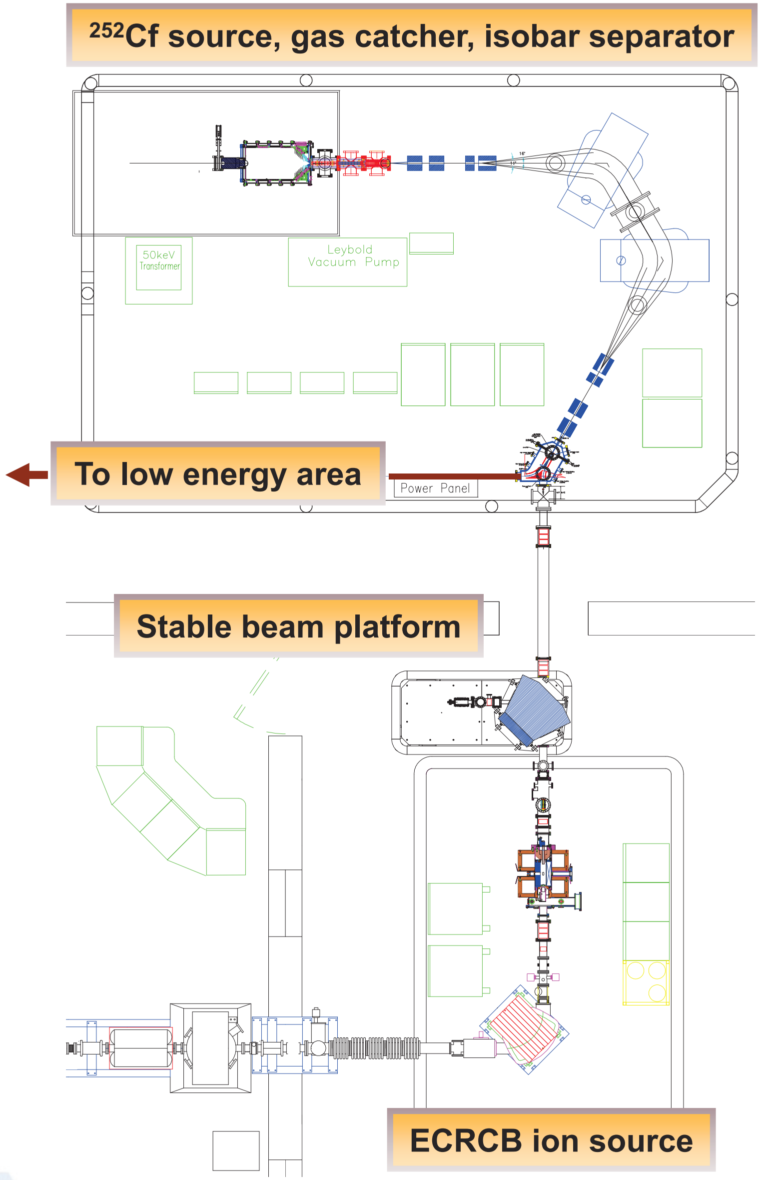
ECR and EBIS charge breeding comparison



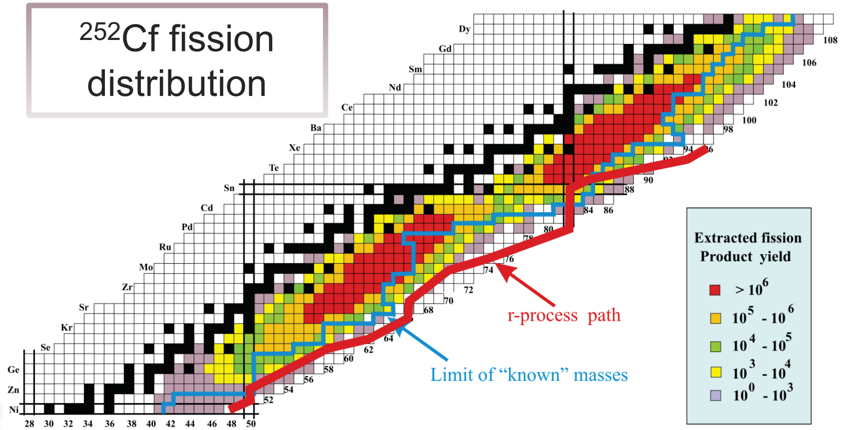


ECR		EBIS
≤19%	Efficiency	≤25%
3.0 – 5.5	A/Q	2.5 – 5.0
10-20 ms/q	Breeding time	10 - 100 ms (total)
pμA (~10^{13} pps)	Maximum injected beam	pnA (~10^{10} pps)
> pA	Contamination	< pA
CW or pulsed	Mode of operation	Pulsed

CARIBU - Californium Rare Ion Breeder Upgrade



- ^{252}Cf fission source provides radioactive species
  - $T_{1/2}$=2.6 a   3.1% fission branch
  - 1.7 Ci source installed May 2014
- Helium gas catcher + µRFQ's
  - Energy spread of 1 eV
  - Emittance of 3·π·mm·mrad
- Stopped beams and reaccelerated beams up to 15 MeV/u
- Highest yields are in the mid-mass species



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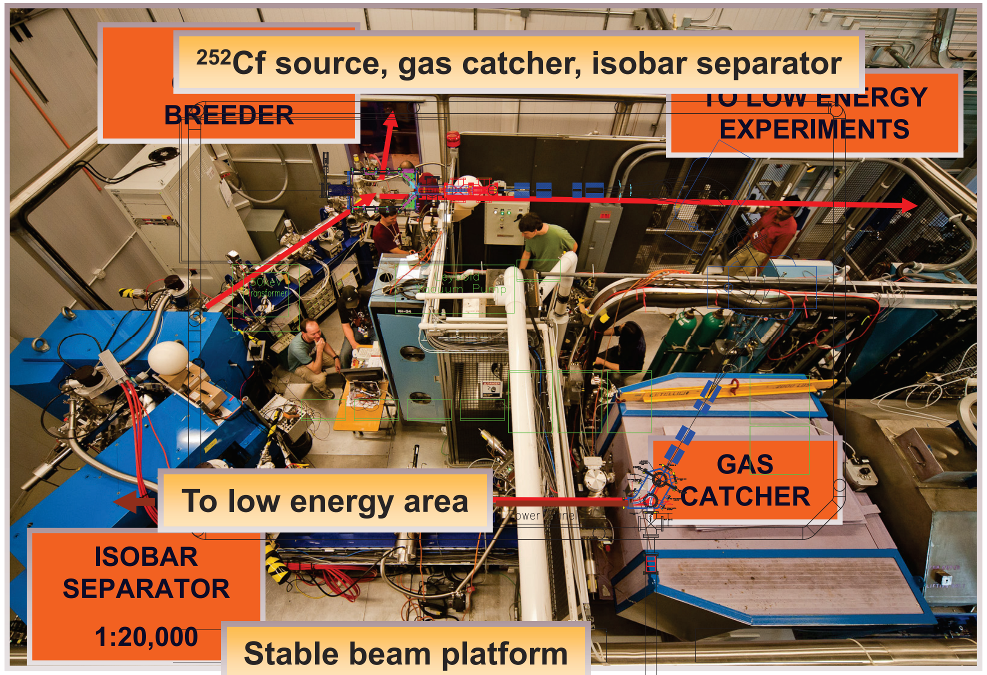

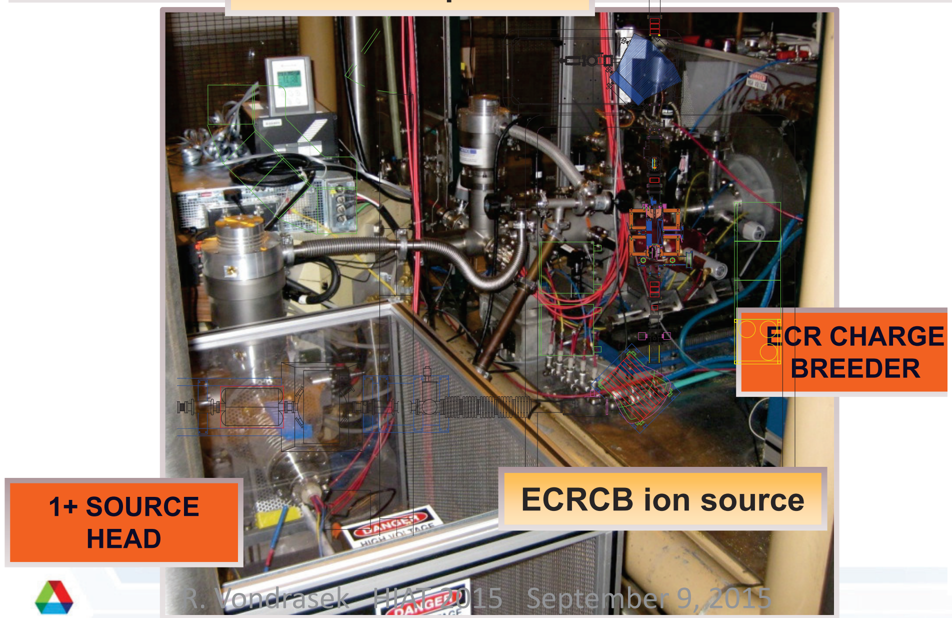

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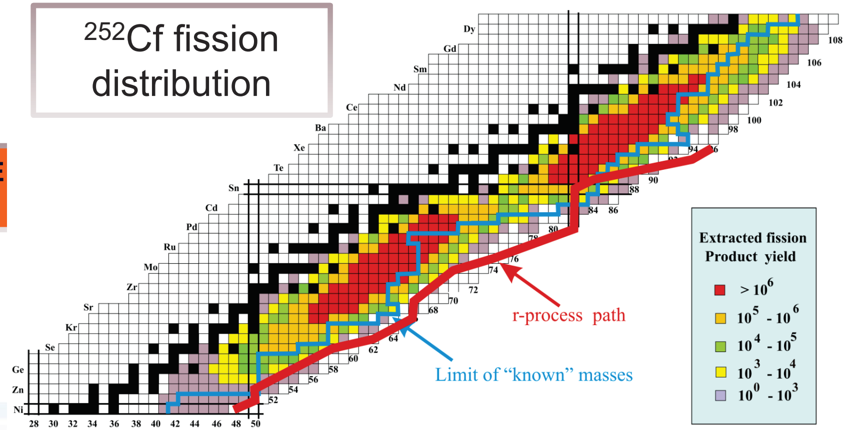
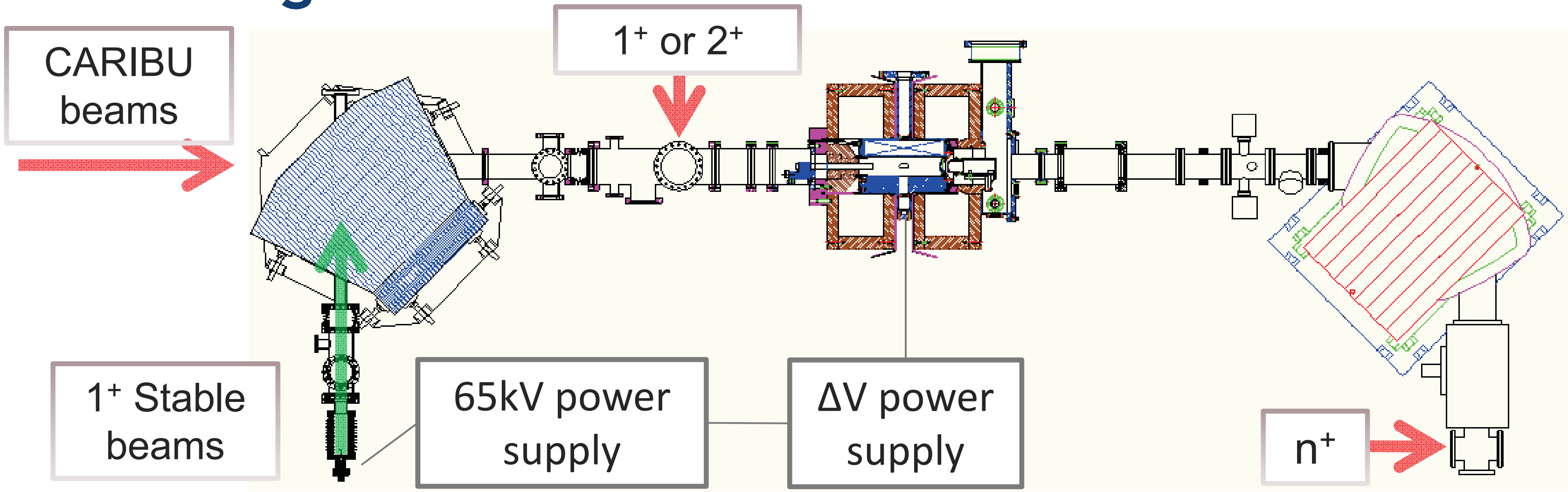
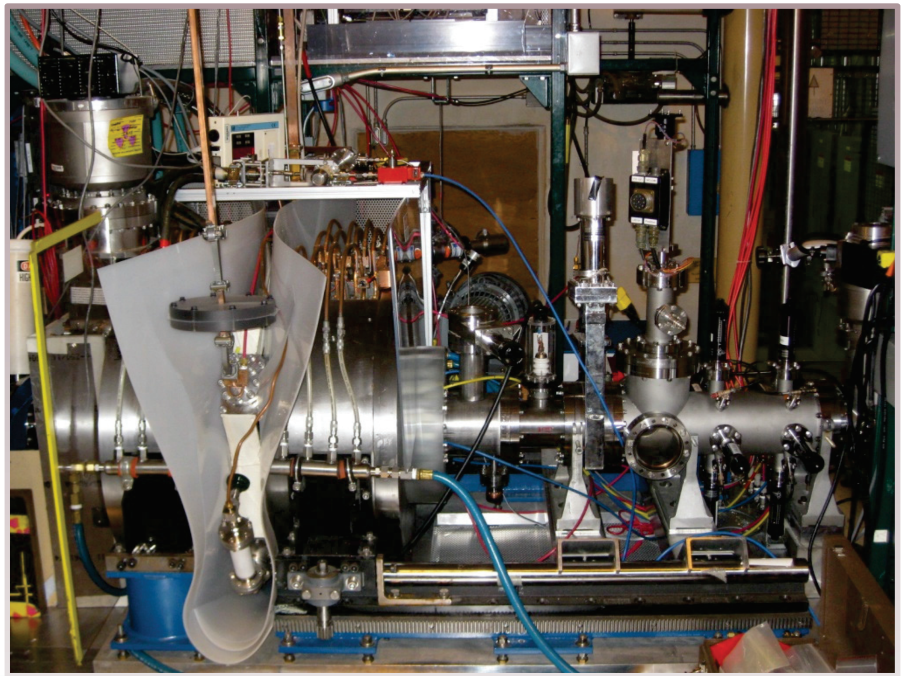
^{252}Cf fission distribution



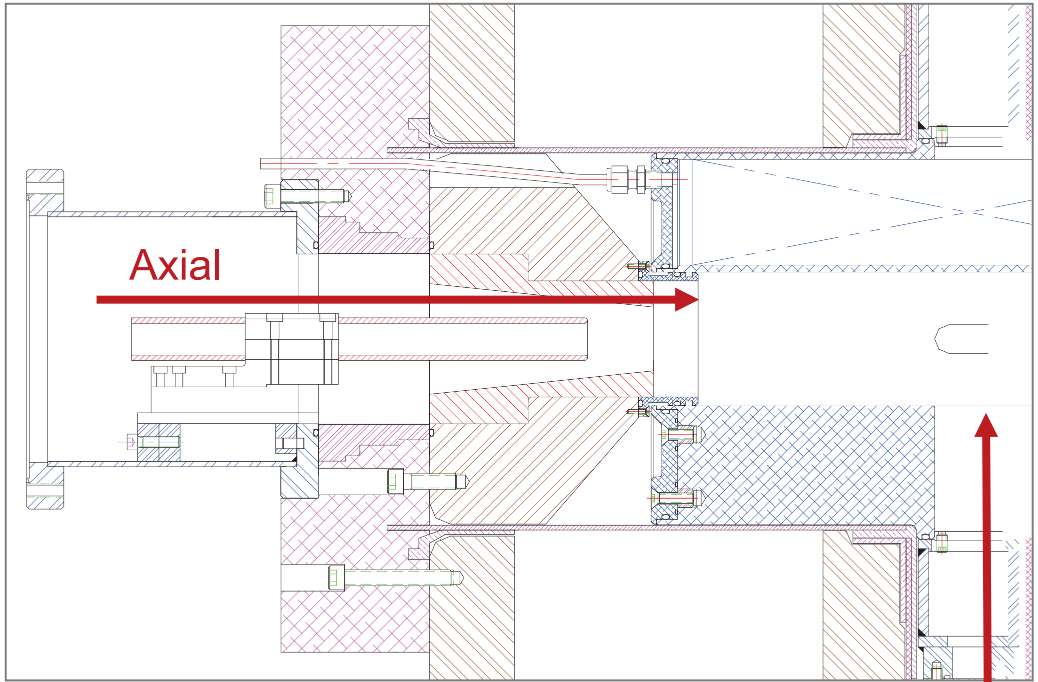
ECR charge breeder

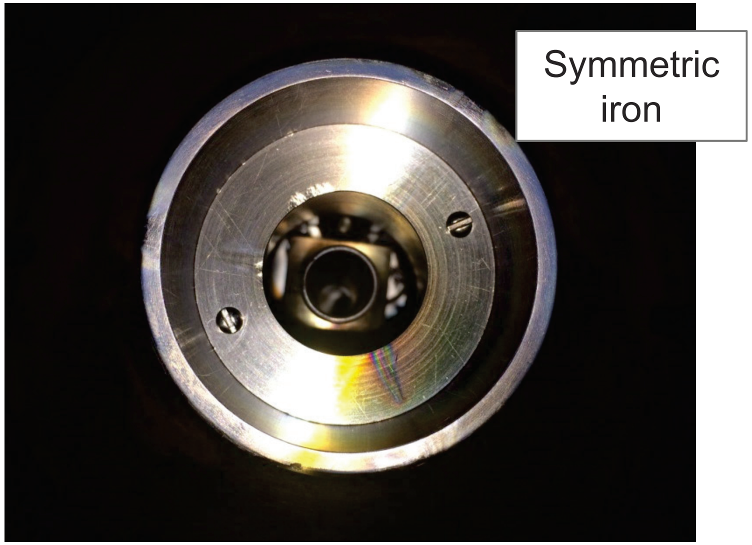


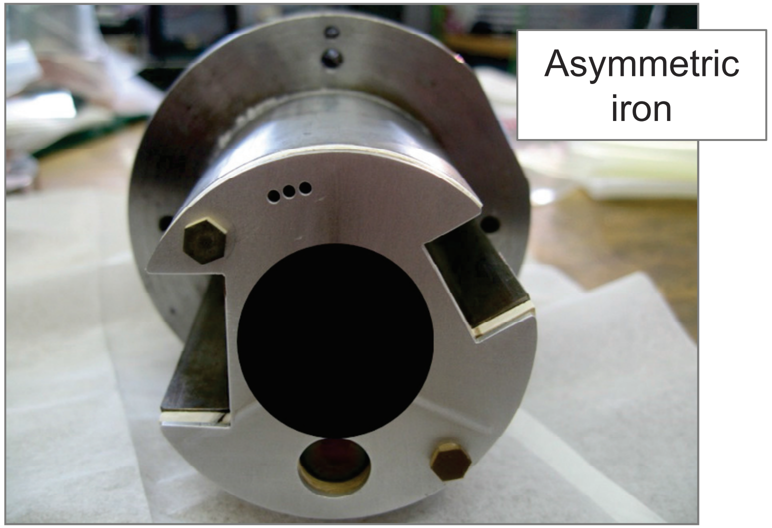
- Open hexapole structure
  - Improved pumping to plasma chamber region: 2×10^{-8} mbar
  - Radial RF injection
- Multiple frequency operation
  - Klystron: 10.44 GHz, 2 kW
  - TWTA: 11→13 GHz, 0.5 kW
- Stable beam source used for guide beams and breeding studies



Injected ion penetration

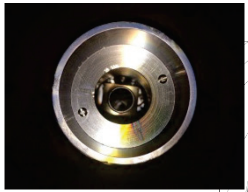


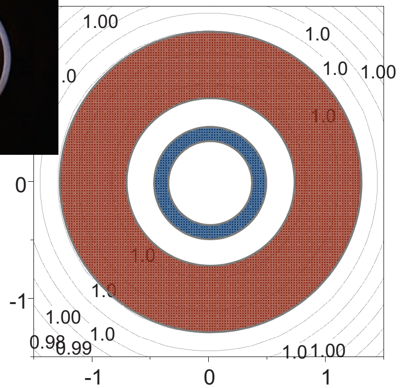


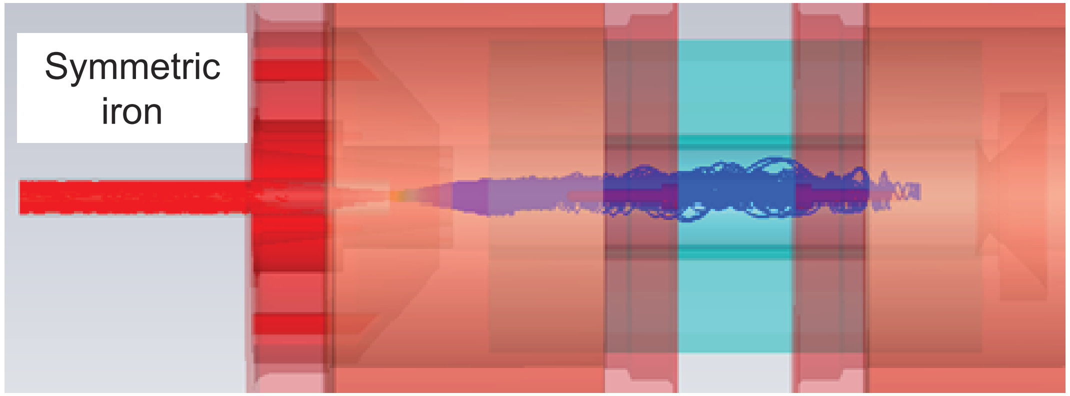


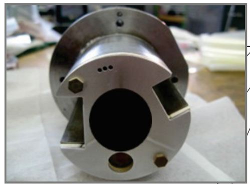
- Symmetric iron
  - RF is launched radially
  - No cut outs for waveguides
- Asymmetric iron
  - RF is launched axially
  - Cut outs for waveguides

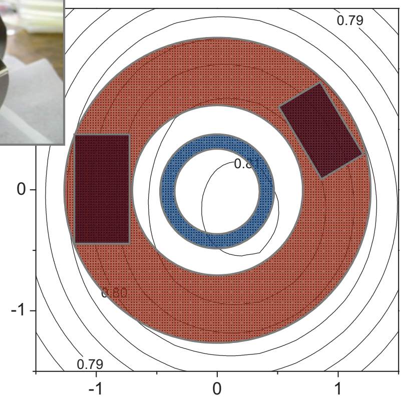
Injected ion penetration

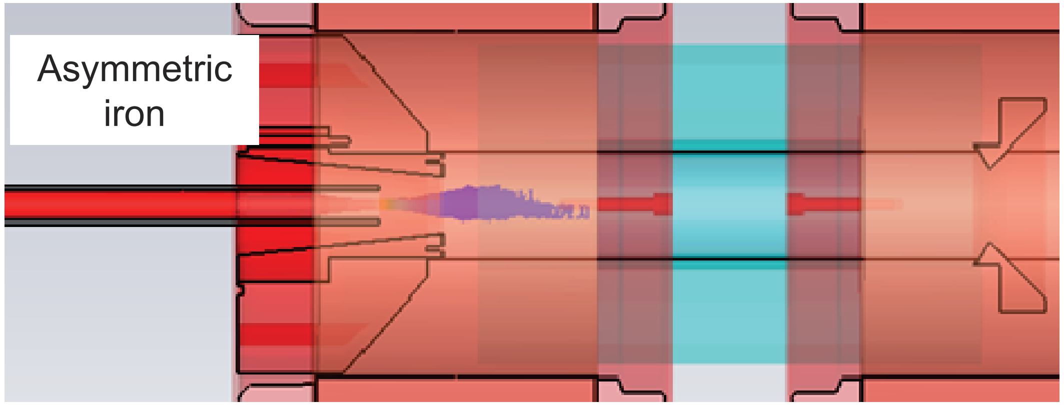






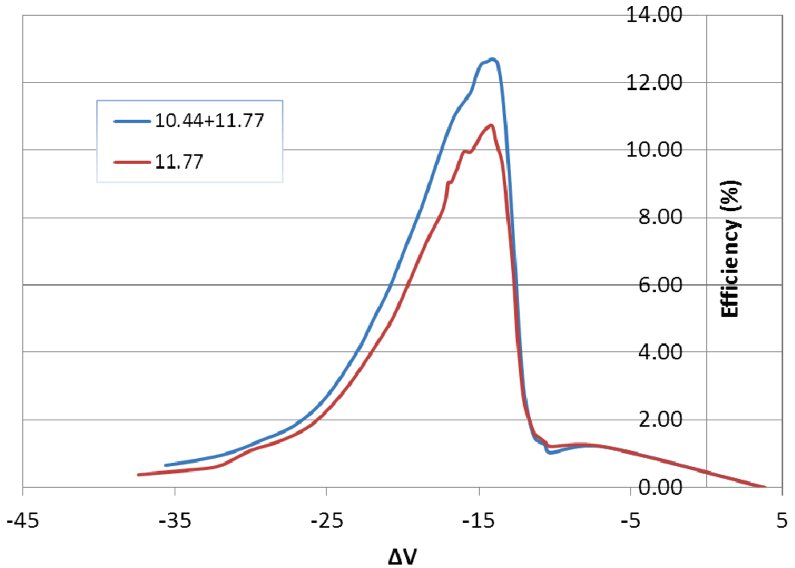




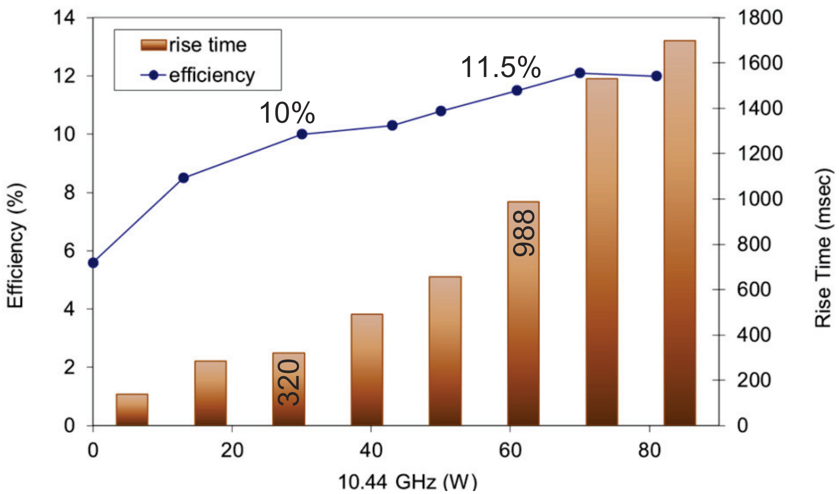


- $^{133}Cs^{+}$ ions, V_{1+}: 30 kV, ΔV: -10 V
- 3D field calculations - Computer Simulation Technology Electromagnetic Studio
- Simulations utilized running conditions for coils, hexapole, and potentials
- No plasma or collision effects included in simulation

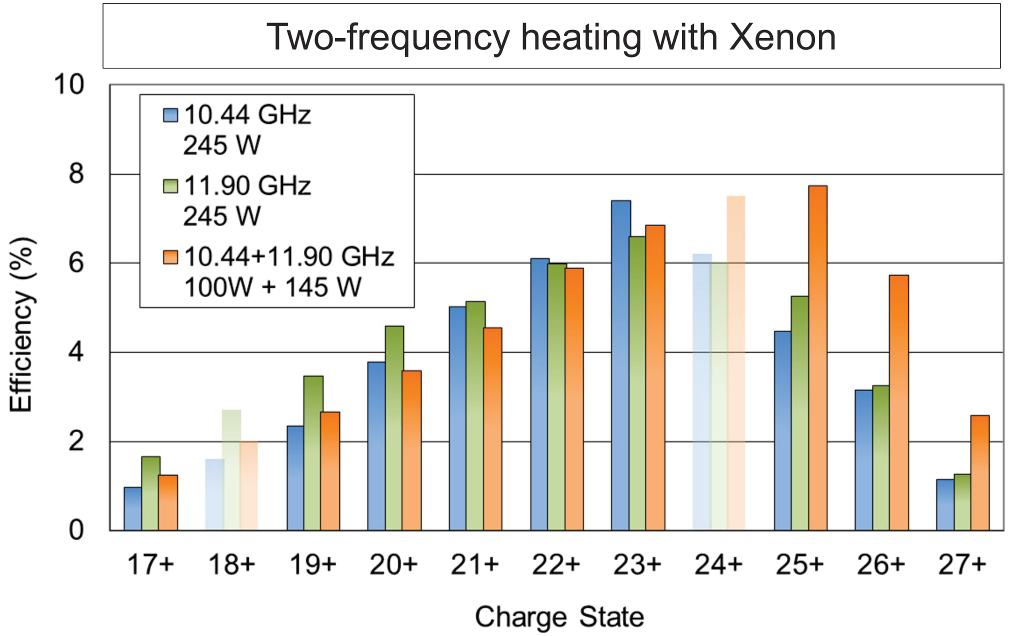
Multiple frequency heating

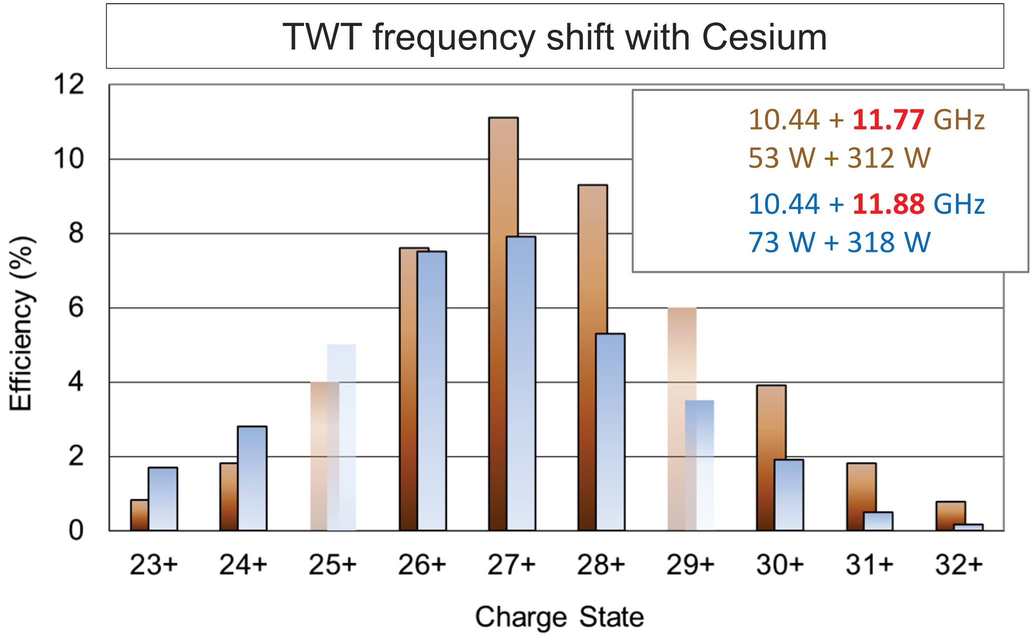


$^{85}Rb^{20+}$



Kept 11.77 GHz constant at 331 W, varied 10.44 GHz power level

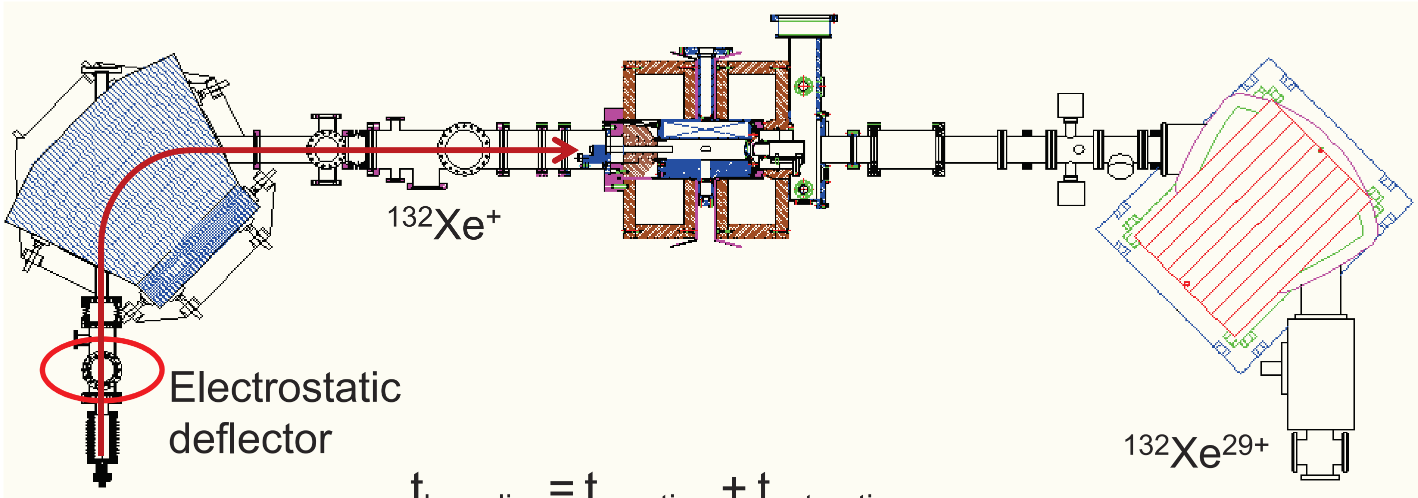




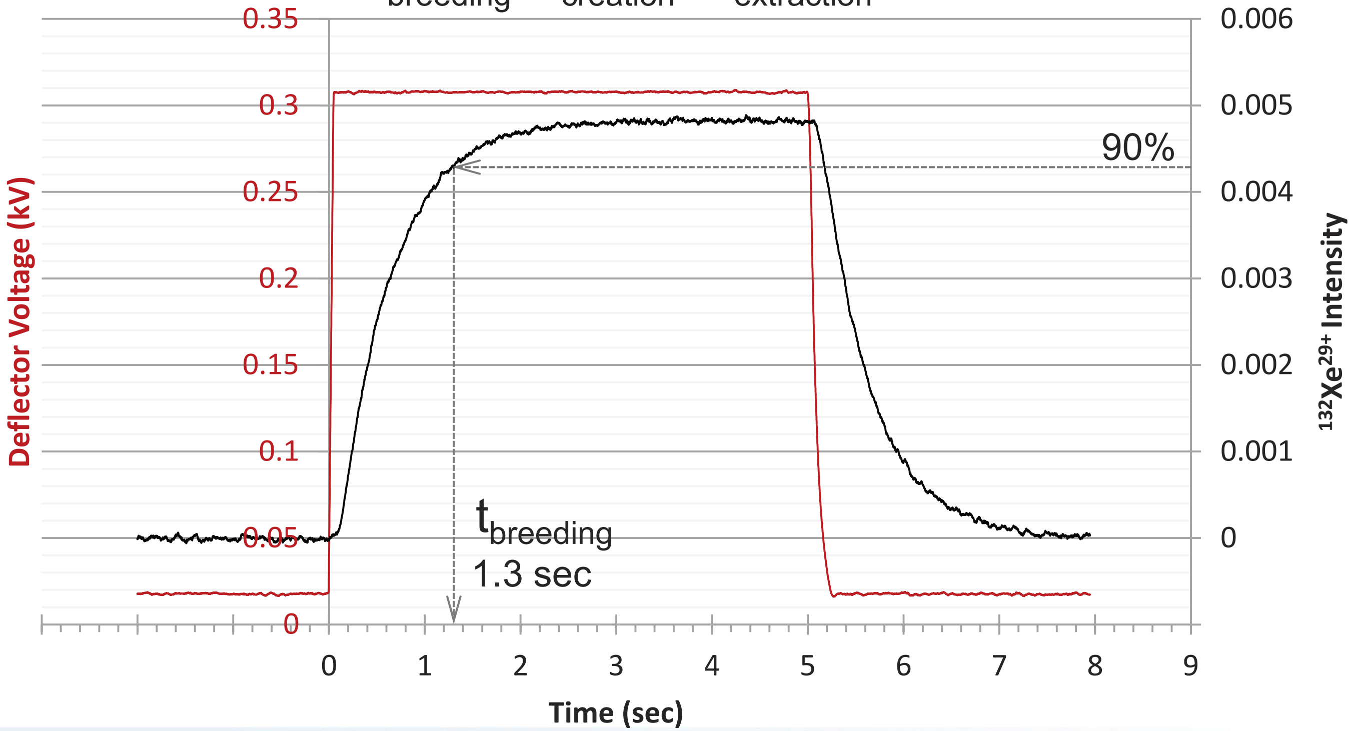
Charge breeding performance

Ion	Charge State	Efficiency (%)	A/Q
^{23}Na	7+	10.1	3.29
^{39}K	10+	17.9	3.90
^{84}Kr	17+	15.6	4.94
^{85}Rb	19+	13.7	4.47
^{110}Ru (1+) $t_{1/2}$ = 11.6 s	22+	11.8	5.00
^{135}Te (1+) $t_{1/2}$ = 19.0 s	26+	5.0	5.19
^{129}Xe	25+	13.4	5.16
^{132}Xe	27+	14.1	4.89
^{133}Cs	26+	14.7	5.11
^{133}Cs	27+	13.5	4.93
^{141}Cs (1+) $t_{1/2}$ = 24.8 s	27+	12.3	5.22
^{142}Cs (1+) $t_{1/2}$ = 1.69 s	27+	7.3	5.26
^{143}Cs (1+) $t_{1/2}$ = 1.79 s	27+	11.7	5.30
^{143}Ba (2+) $t_{1/2}$ = 14.3 s	27+	14.7	5.30
^{144}Ba (2+) $t_{1/2}$ = 11.5 s	28+	14.3	5.14
^{146}Ba (2+) $t_{1/2}$ = 2.22 s	28+	13.3	5.21

Charge breeding time

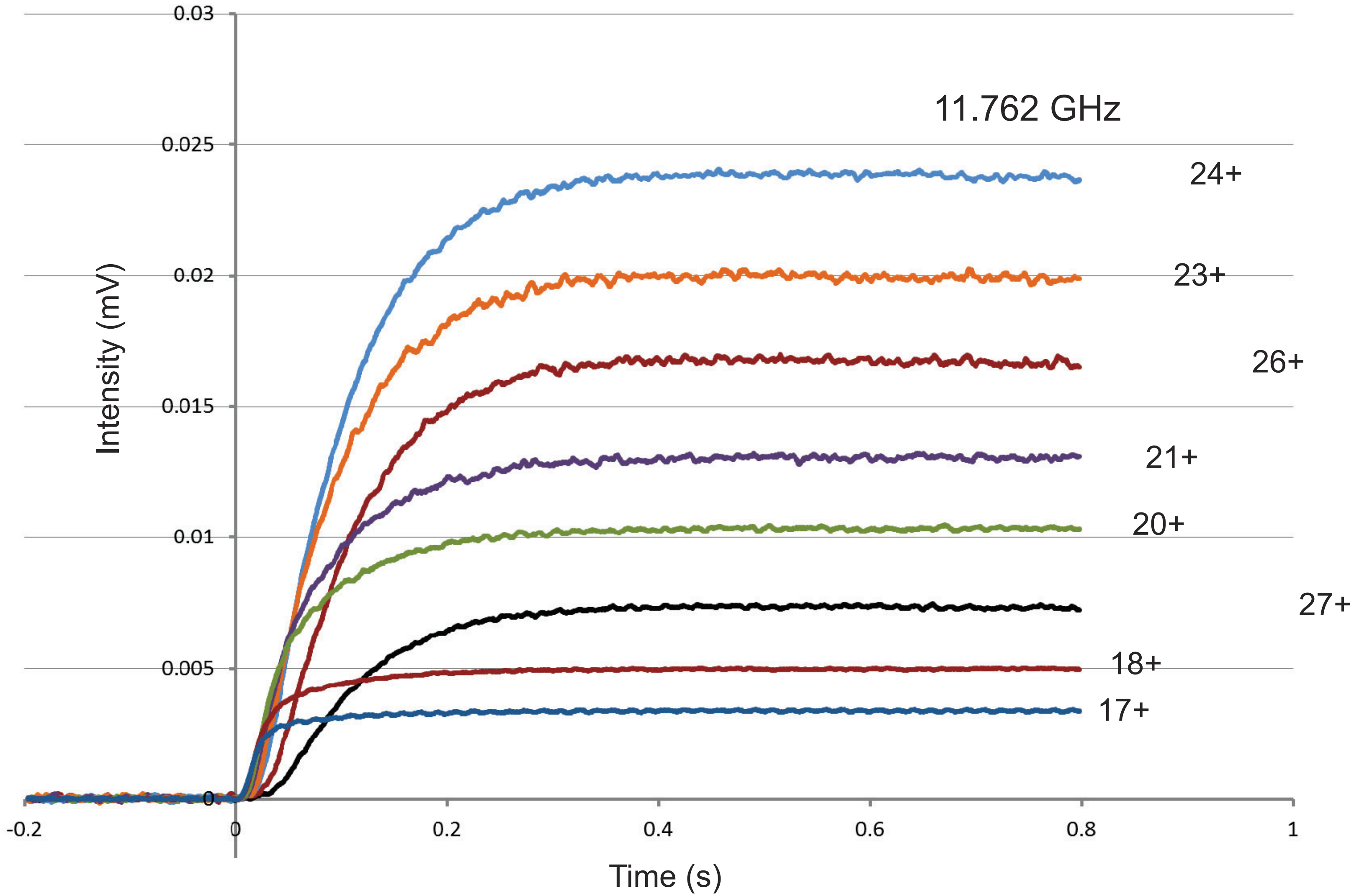


$t_{breeding} = t_{creation} + t_{extraction}$



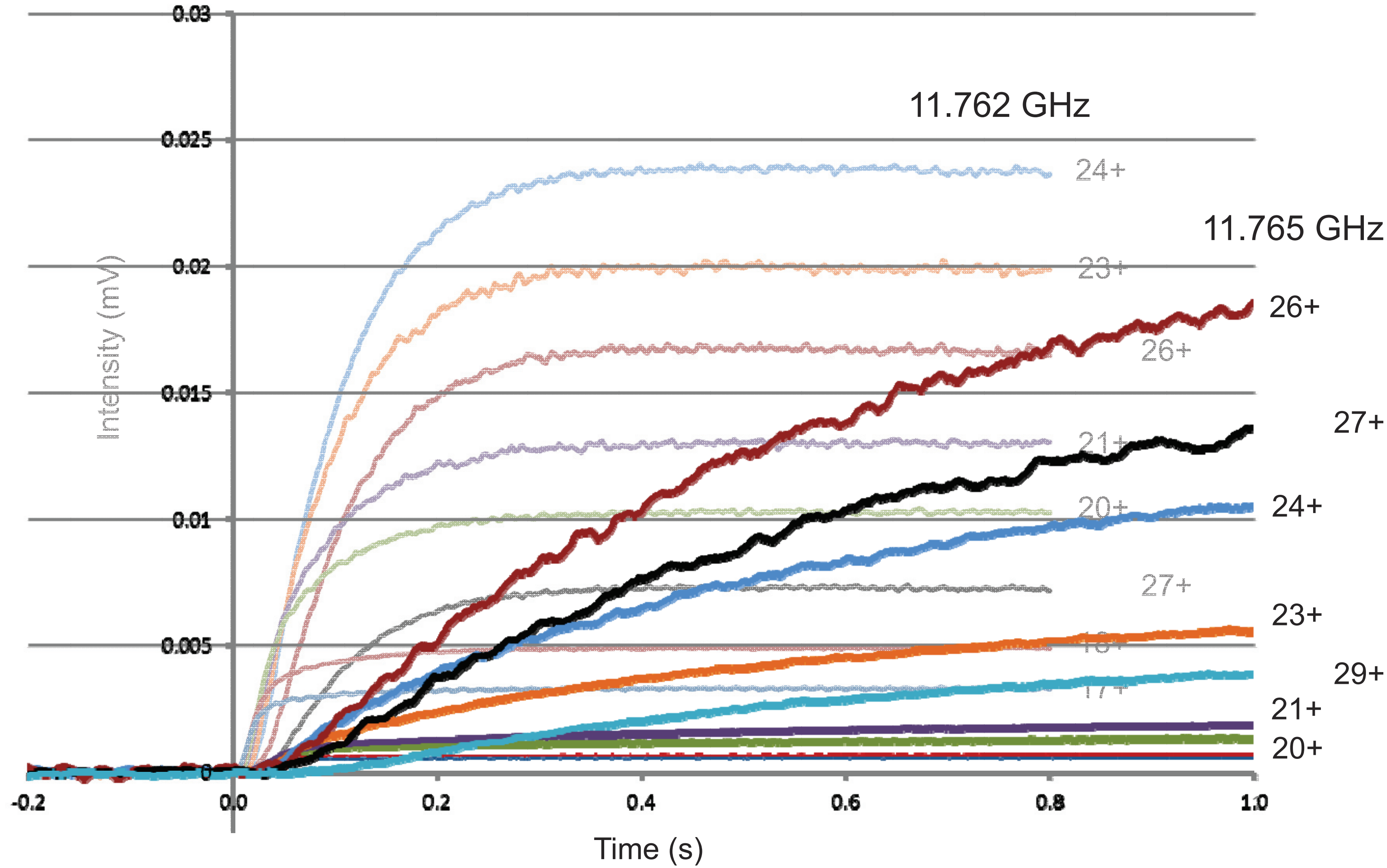
Charge breeding time - ^{132}Xe

- Oxygen plasma, single-frequency heating – TWTA 11.762 GHz



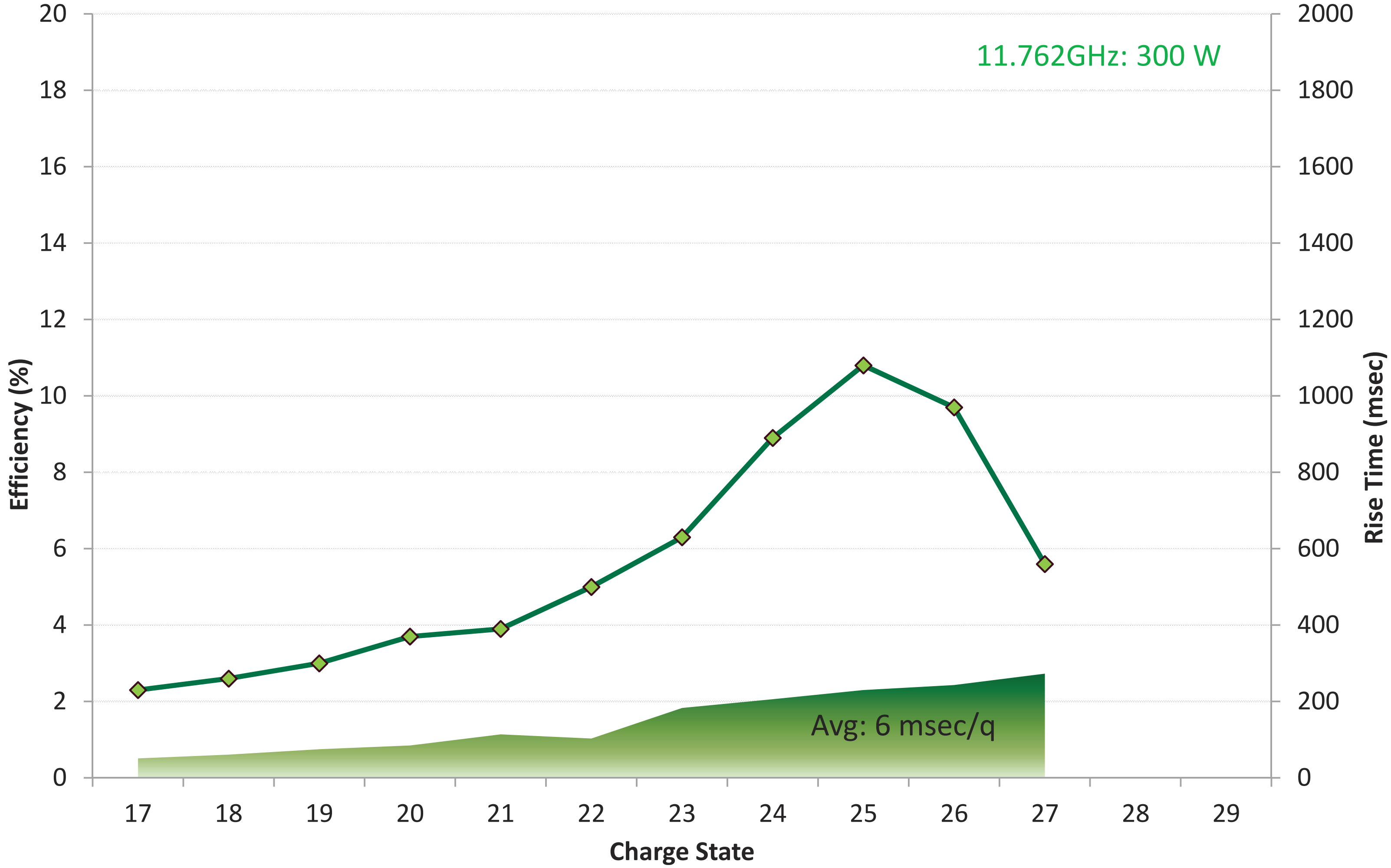
Charge breeding time - ^{132}Xe

- Oxygen plasma, single-frequency heating – TWTA 11.765 GHz (Δf = 3 MHz)



Breeding efficiency and rise time - RF frequency

- Xe-132 from RF discharge source
- Oxygen plasma, single-frequency heating – TWTA only



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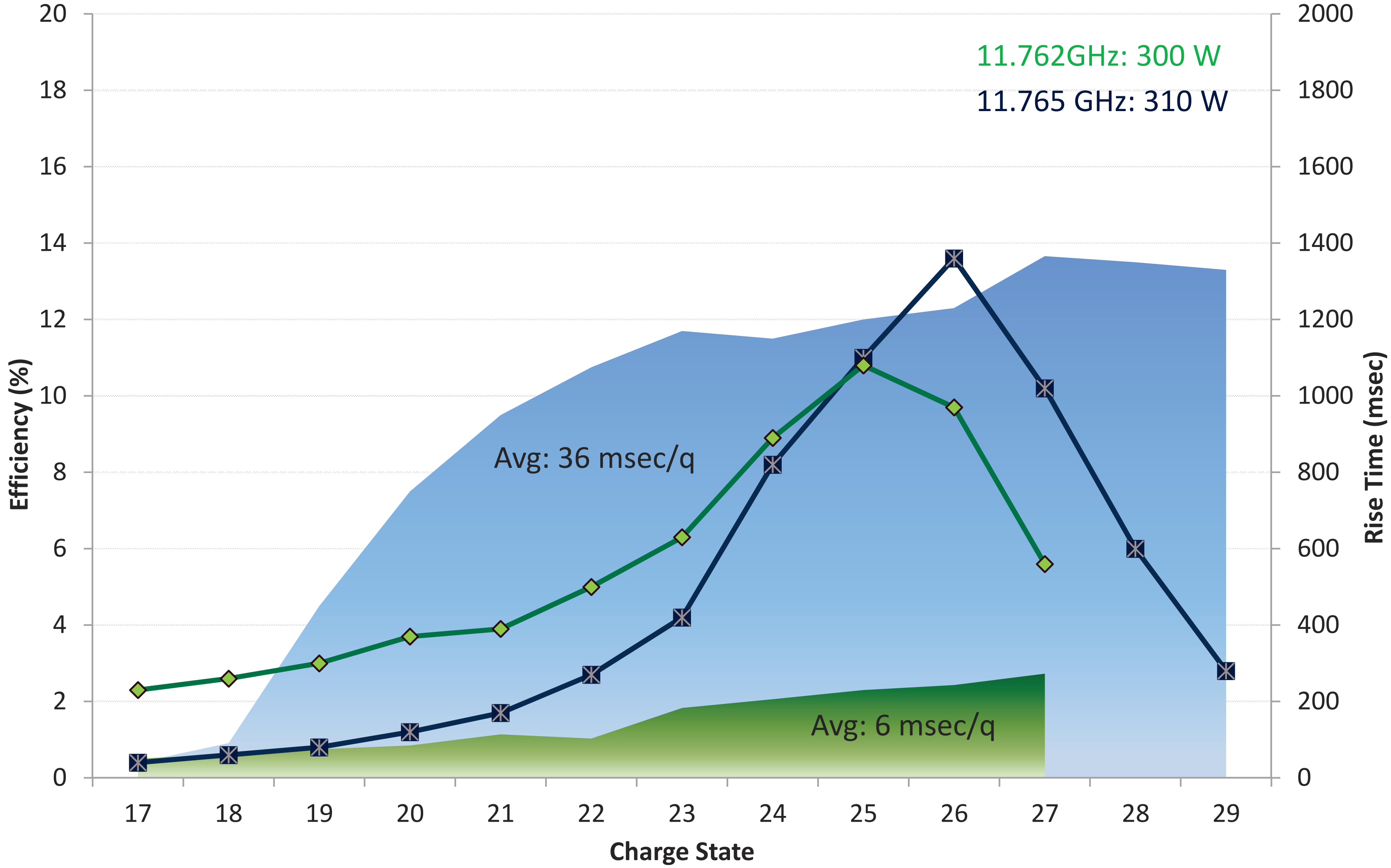
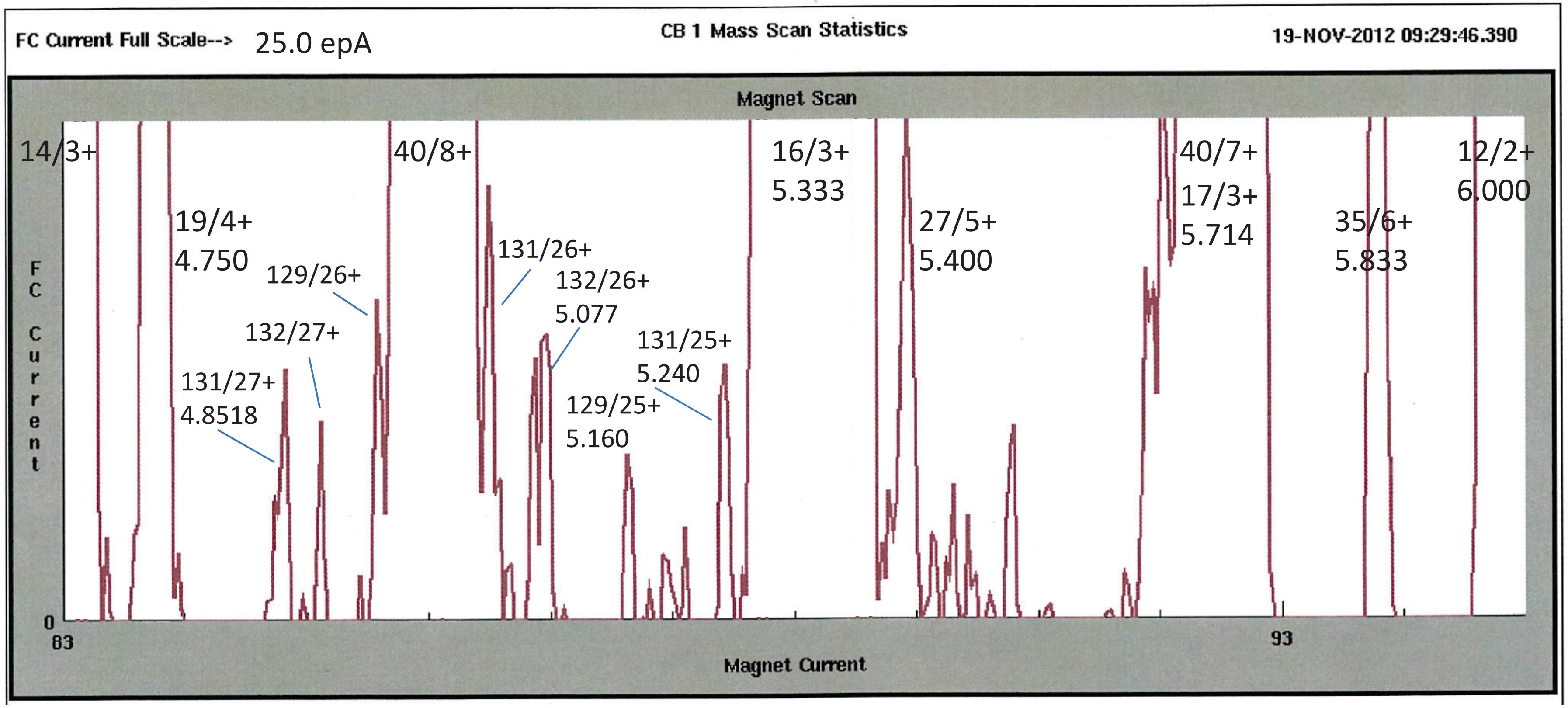


ECR background beams – A/q region of interest



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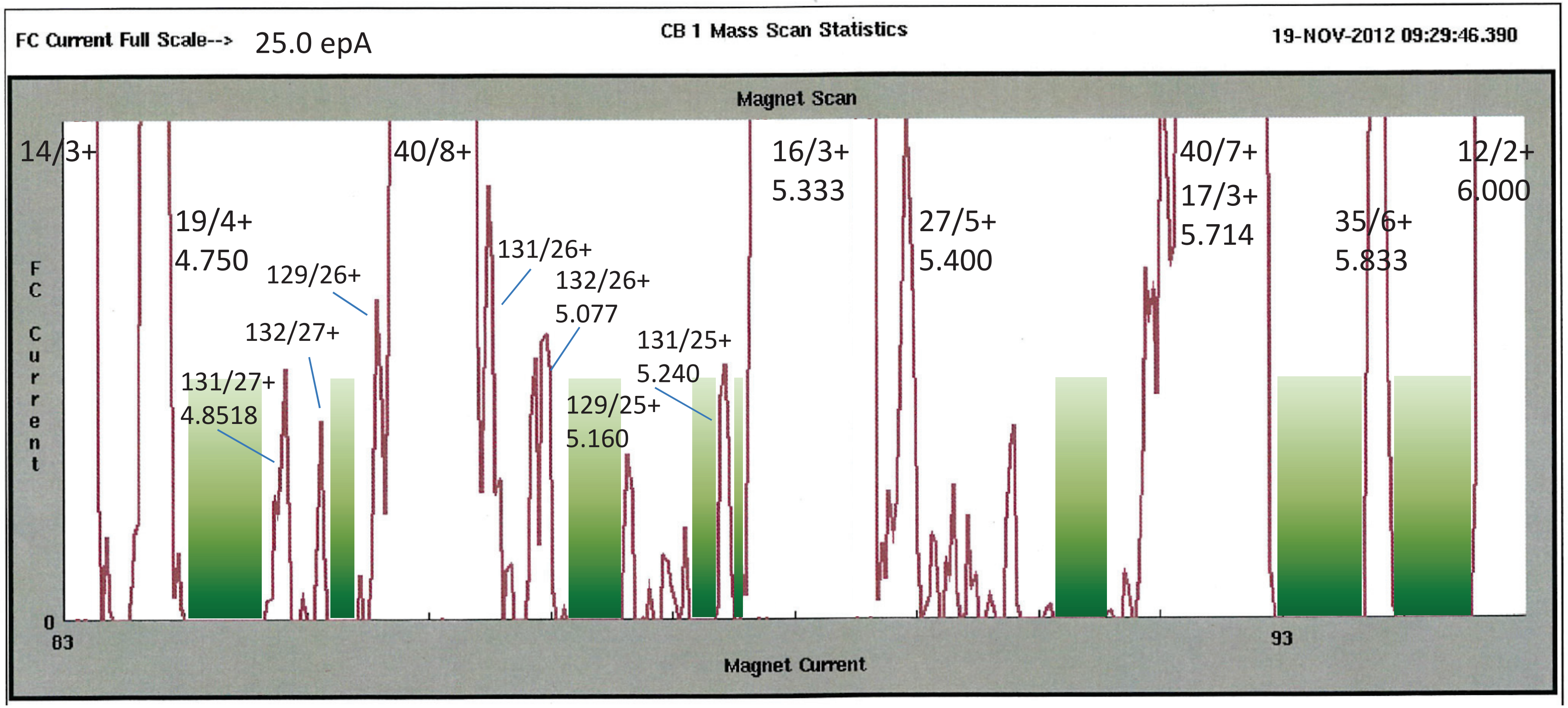
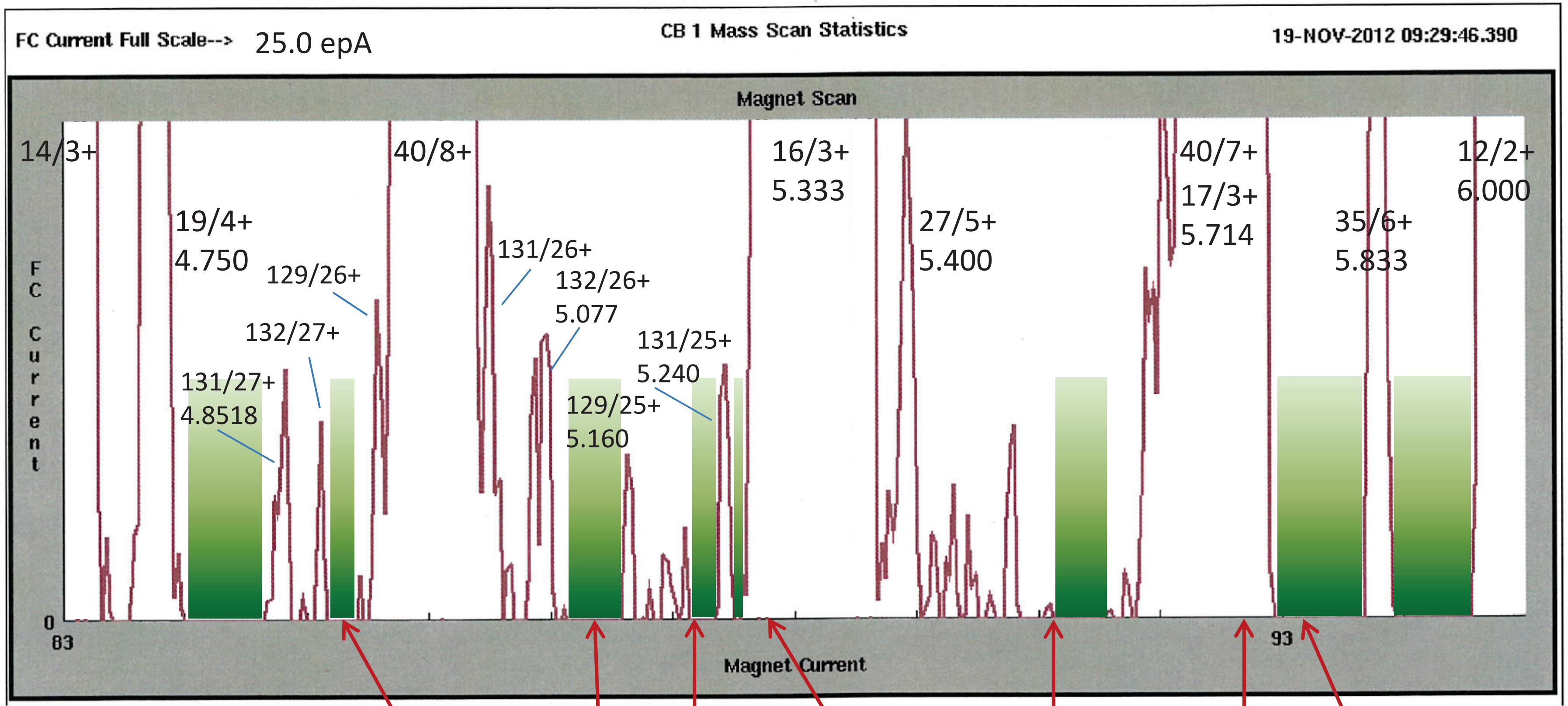


No measureable background current with picoammeter

SBD – silicon barrier detector

ECR background beams - A/q region of interest



No measureable background current with picoammeter

SBD – silicon barrier detector

98/20+
970 Hz background rate in SBD
4.900

144/28+
2500 Hz background rate in SBD
5.143

146/28+
500 Hz background rate in SBD
5.214

143/27+
330,000 Hz background rate in SBD
5.296

144/26+
10,000 Hz background rate in SBD
5.538

143/25+
66,000 Hz background rate in SBD
5.720

144/25+
900 Hz background rate in SBD
5.760

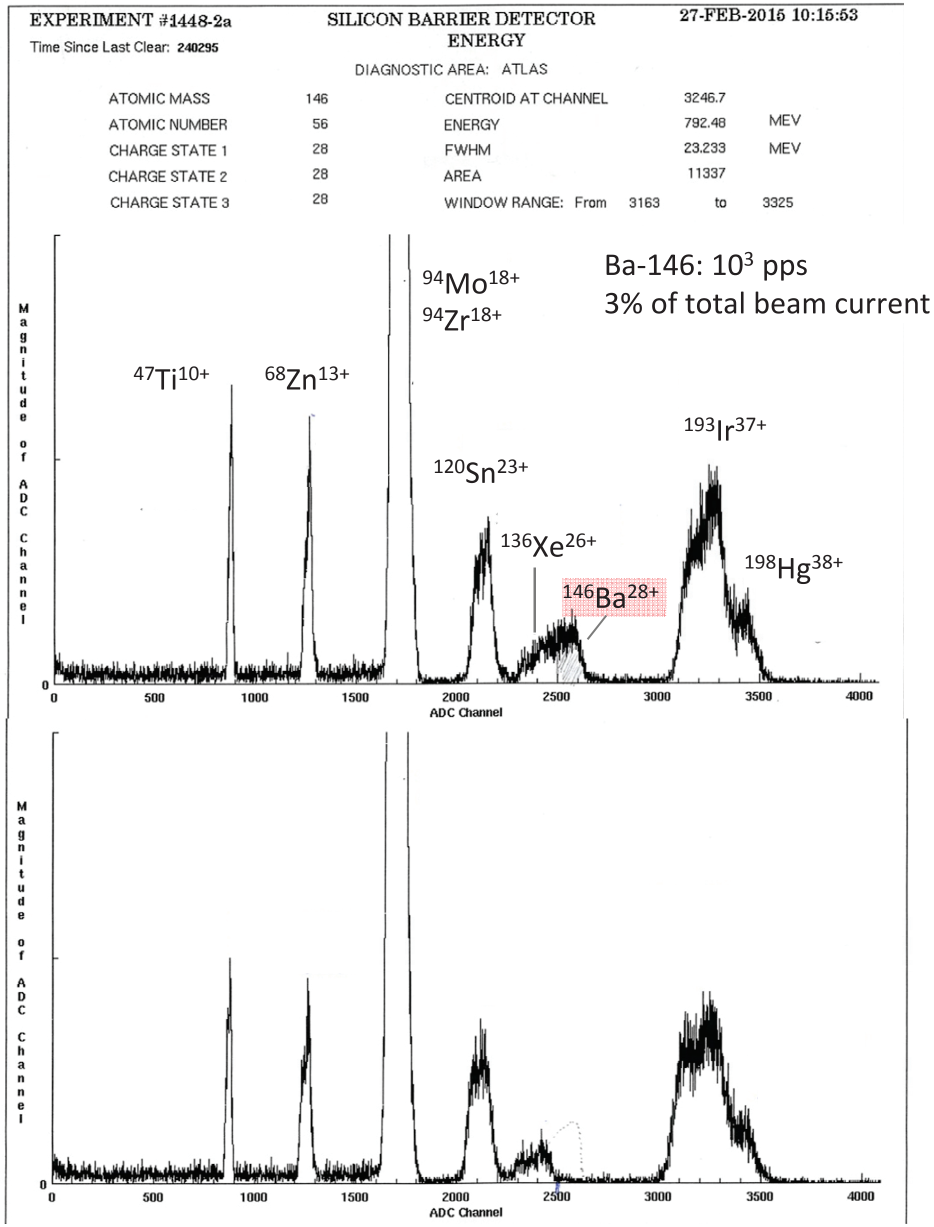
ECR contamination for $^{146}Ba^{28+}$

δ Bρ	Extraction Voltage, kV	Platform Voltage, kV	Atomic # or Symb.	Atomic Mass (p+n)	Charge State	M₀/δM Threshold:	300.0
0.010	36.000	130.000	ba	146	28	Include Radioactive Ions y/n (default - y): (Optional)	n

Calculate

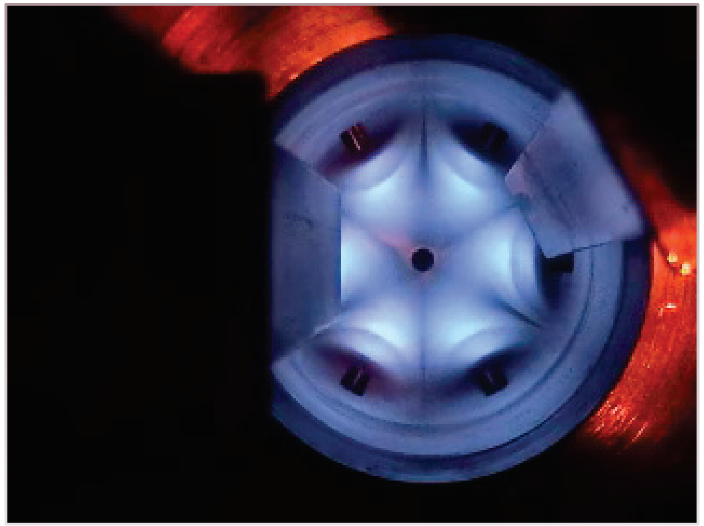
Ion Atomic Number:	56	Beam Rigidity, kG-m:	0.6248284
Central Ion Mass:	145.93028	Mag. Field, kG:	1.5620710
Magnet Radius, m:	0.400	Upper Bρ, kG-m:	0.63108
Total flight time, nsec.:	9582.83	Lower Bρ, kG-m:	0.61858

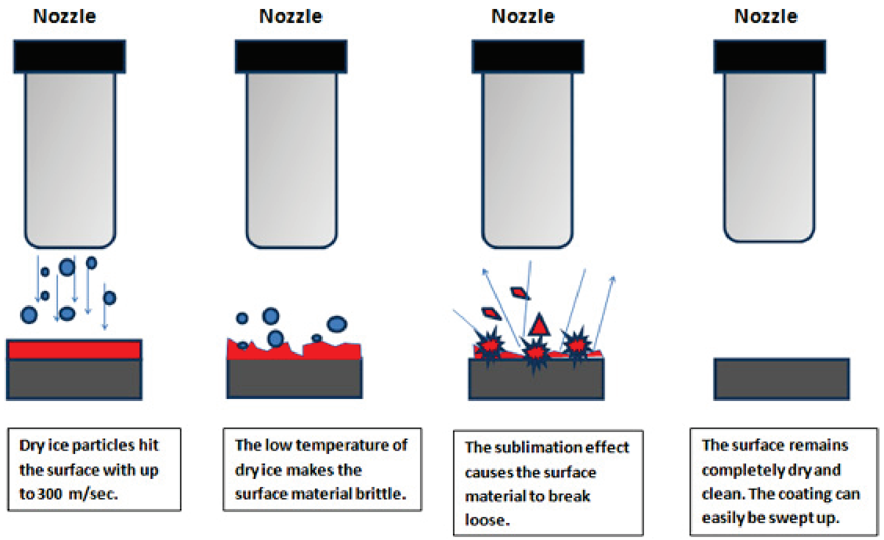
ID	Mass	Q	Abund.	Br, kG-m	B, kG	δB	M0/DM	dTime, ns
Zn	68	13	18.80	0.6256	1.5640	0.0020	395.06	12.1
Ba	130	25	0.11	0.6239	1.5597	-0.0023	-335.28	-14.3
Ba	136	26	7.85	0.6257	1.5644	0.0023	340.59	14.1
		**********	Lower Probability Contaminants			**********		
Mg	26	5	11.01	0.6239	1.5598	-0.0023	-341.15	-14.1
Ti	47	9	7.30	0.6251	1.5628	0.0008	1028.61	4.7
Ge	73	14	7.80	0.6246	1.5616	-0.0004	-1750.60	-2.7
Se	78	15	23.50	0.6238	1.5595	-0.0026	-301.11	-15.9
Kr	78	15	0.35	0.6238	1.5595	-0.0026	-304.74	-15.7
Zr	94	18	17.33	0.6251	1.5629	0.0008	998.12	4.8
Mo	94	18	9.25	0.6251	1.5628	0.0008	1011.36	4.7
Ru	99	19	12.70	0.6245	1.5611	-0.0009	-837.89	-5.7
Ru	104	20	18.70	0.6238	1.5596	-0.0025	-315.39	-15.2
Pd	104	20	11.14	0.6238	1.5596	-0.0025	-314.07	-15.3
In	115	22	95.70	0.6255	1.5637	0.0017	469.20	10.2
Sn	115	22	0.40	0.6255	1.5637	0.0017	470.23	10.2
Sn	120	23	32.40	0.6249	1.5623	0.0002	3879.92	1.2
Te	120	23	0.10	0.6249	1.5623	0.0002	3660.72	1.3
Te	125	24	7.14	0.6244	1.5610	-0.0011	-700.09	-6.8
Te	130	25	33.80	0.6239	1.5597	-0.0023	-335.24	-14.3
Xe	130	25	4.10	0.6239	1.5597	-0.0023	-332.91	-14.4
Xe	136	26	8.90	0.6258	1.5644	0.0023	338.33	14.2
Xe	141	27	0.00	0.6253	1.5632	0.0012	676.01	7.1
Cs	141	27	0.00	0.6253	1.5632	0.0011	698.15	6.9
La	141	27	0.00	0.6253	1.5631	0.0011	731.10	6.6
Ce	136	26	0.19	0.6258	1.5644	0.0023	338.42	14.1
Pr	141	27	100.00	0.6252	1.5631	0.0010	743.91	6.4
Nd	146	28	17.19	0.6248	1.5620	-0.0001	-8499.14	-0.6
Sm	146	28	0.00	0.6248	1.5620	-0.0001	-8492.22	-0.6
Eu	151	29	47.80	0.6244	1.5609	-0.0011	-680.11	-7.0
Gd	156	30	20.47	0.6240	1.5599	-0.0022	-362.13	-13.2
Dy	156	30	0.06	0.6240	1.5599	-0.0021	-363.96	-13.2
Dy	162	31	25.50	0.6255	1.5638	0.0017	447.40	10.7
Er	162	31	0.14	0.6255	1.5638	0.0018	444.95	10.8
Er	167	32	22.95	0.6251	1.5628	0.0007	1078.91	4.4
Yb	172	33	21.90	0.6247	1.5618	-0.0002	-3252.18	-1.5
Hf	177	34	18.60	0.6244	1.5609	-0.0011	-687.25	-7.0
W	182	35	26.30	0.6240	1.5601	-0.0020	-392.58	-12.2
W	183	35	14.30	0.6257	1.5644	0.0023	339.46	14.1
Os	188	36	13.30	0.6254	1.5634	0.0014	566.53	8.5
Ir	193	37	62.70	0.6250	1.5626	0.0005	1524.43	3.1
Pt	198	38	7.20	0.6247	1.5618	-0.0003	-2465.02	-1.9
Hg	198	38	10.10	0.6247	1.5617	-0.0003	-2430.98	-2.0
Tl	203	39	29.52	0.6244	1.5610	-0.0011	-706.52	-6.8
Pb	208	40	52.40	0.6241	1.5602	-0.0019	-421.00	-11.4
Bi	209	40	100.00	0.6256	1.5640	0.0019	409.92	11.7
U	234	45	0.01	0.6242	1.5604	-0.0016	-478.77	-10.0
U	235	45	0.72	0.6255	1.5638	0.0017	457.07	10.5

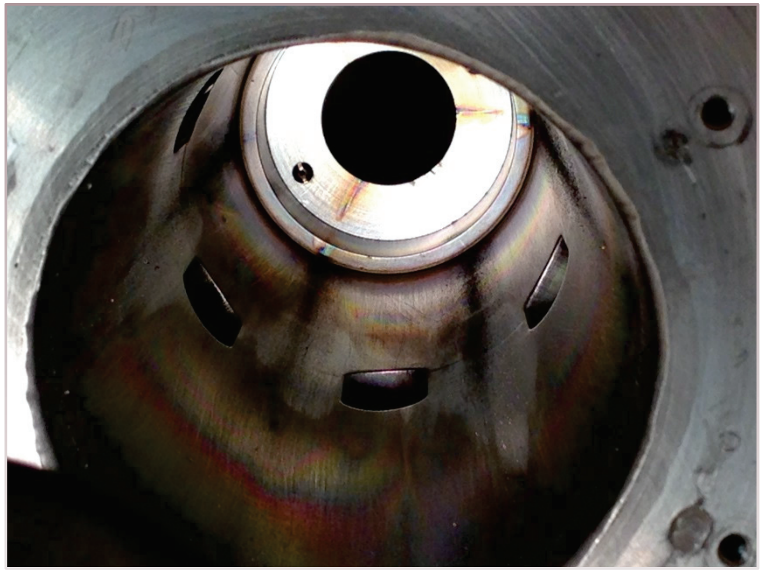


Background reduction

- Solid species – surface and bulk contamination
  - Plasma chamber liners
  - Sand blasting
  - High-pressure rinsing
  - CO_2 "snow" cleaning
  - High-purity aluminum coating







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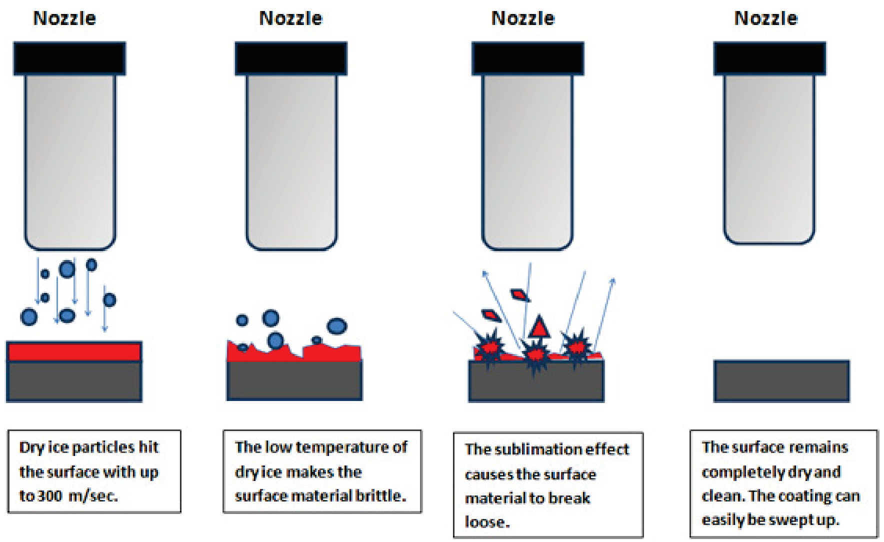
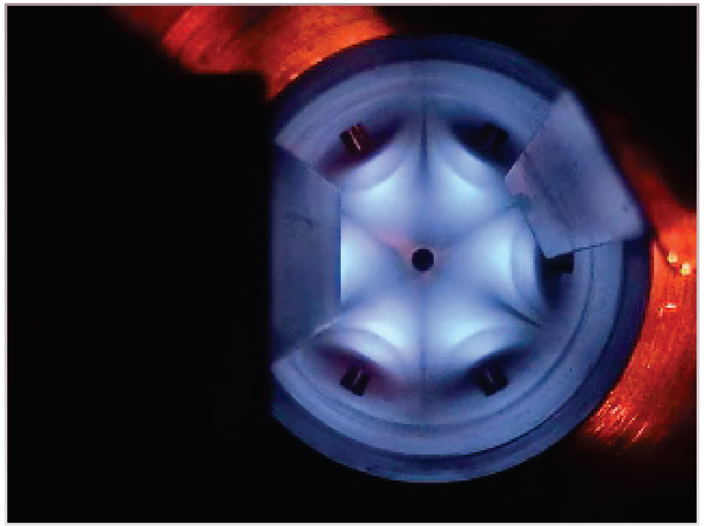
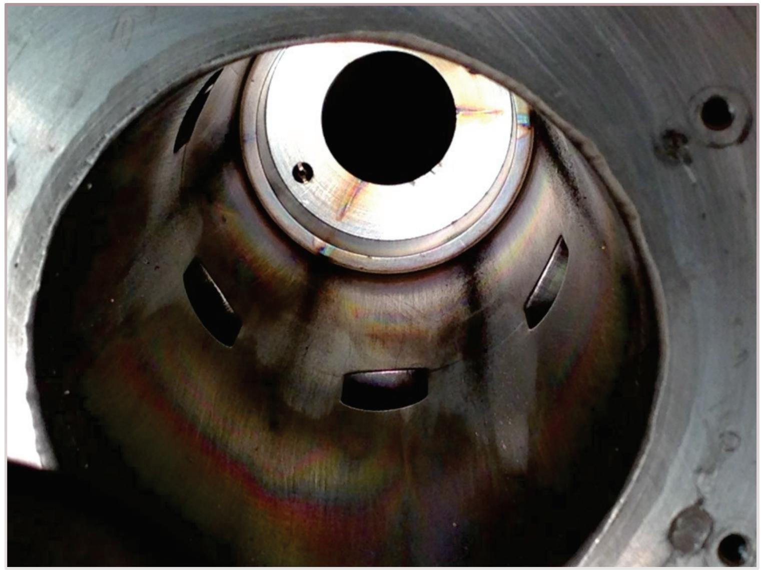
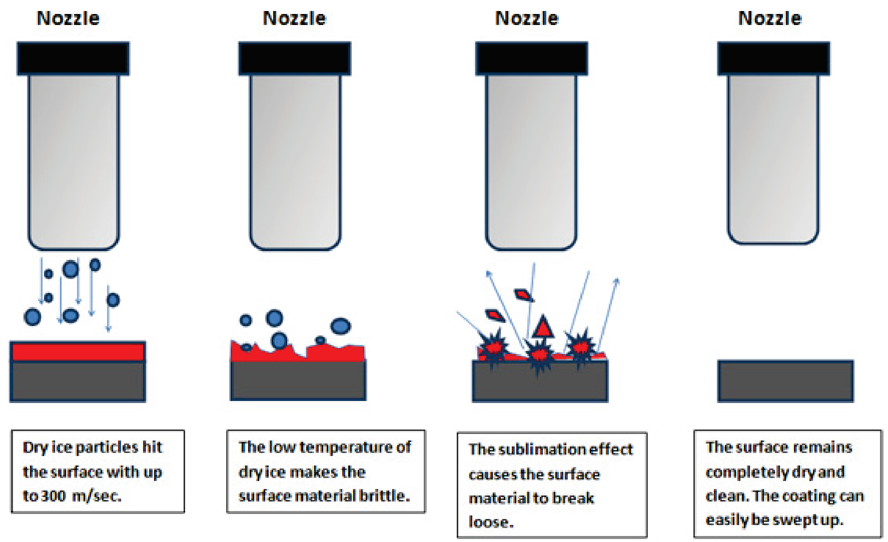


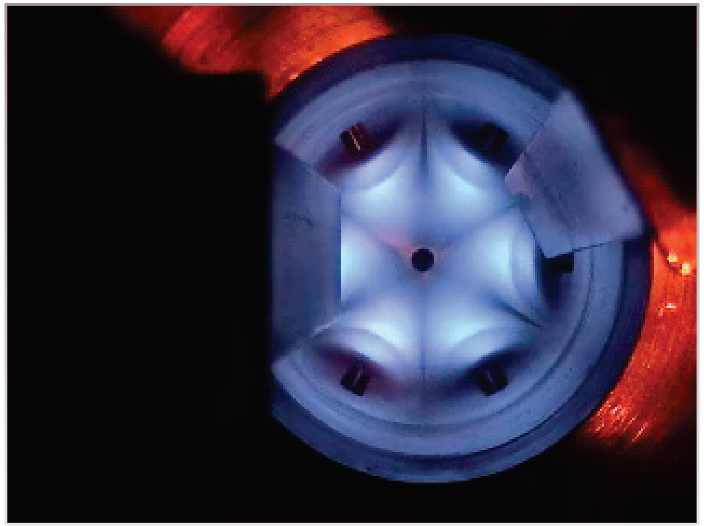


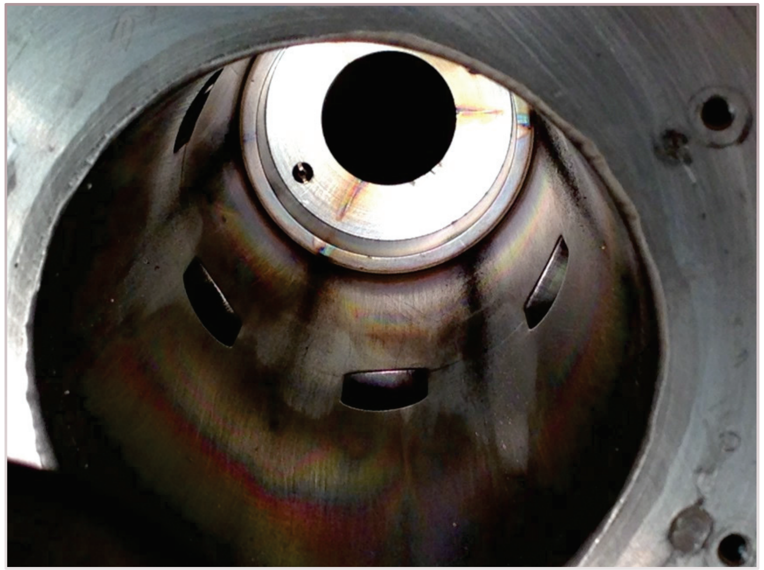


Background reduction

- Solid species – surface and bulk contamination
  - ~~Plasma chamber liners~~
  - ~~Sand blasting~~
  - High-pressure rinsing
  - CO_2 “snow” cleaning
  - High-purity aluminum coating







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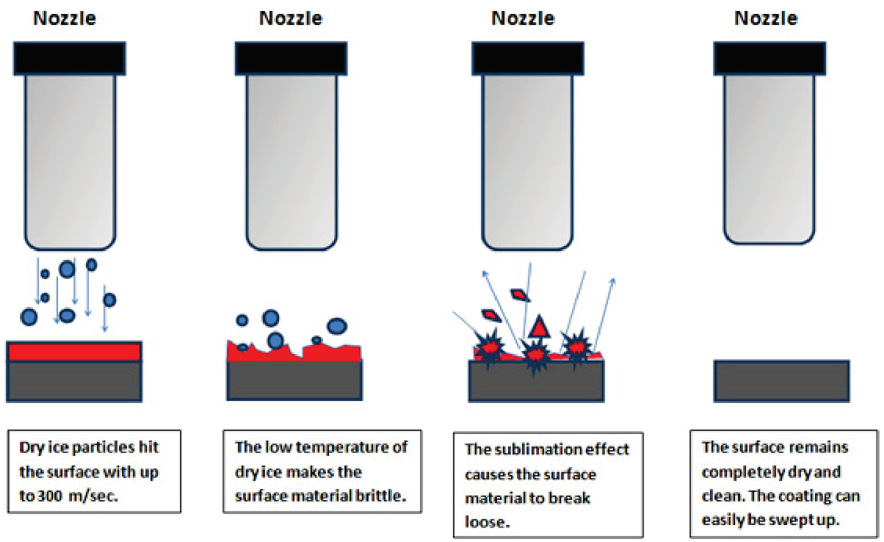
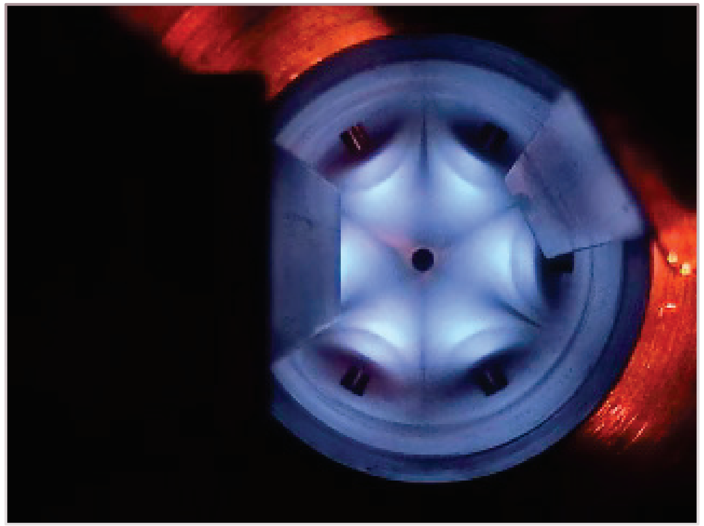
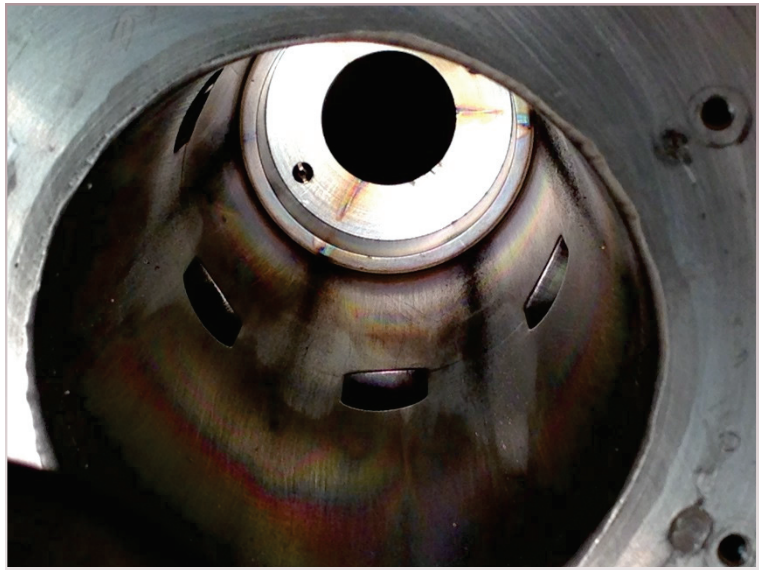
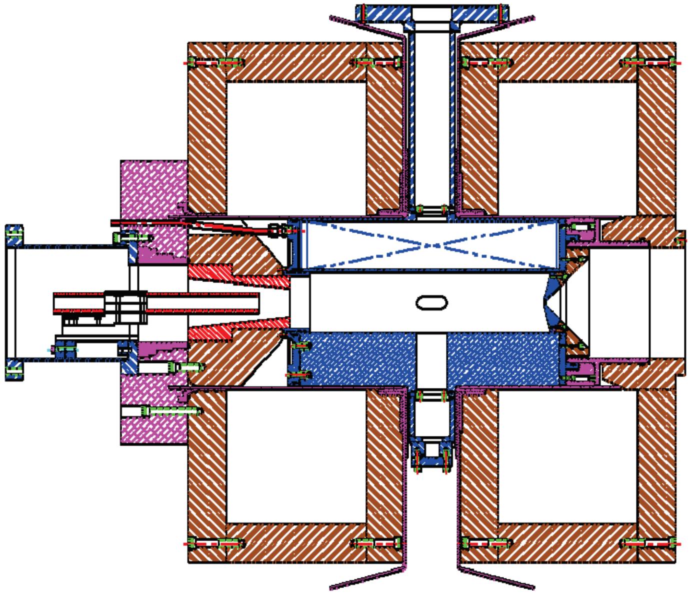


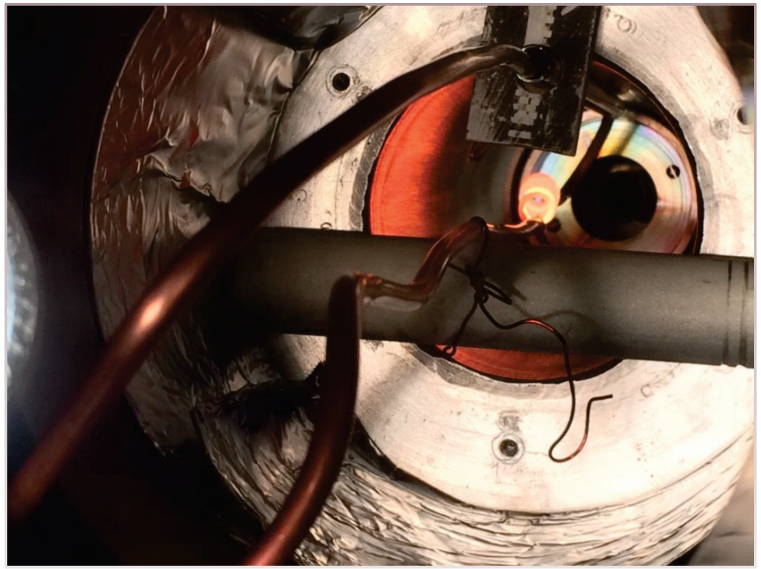


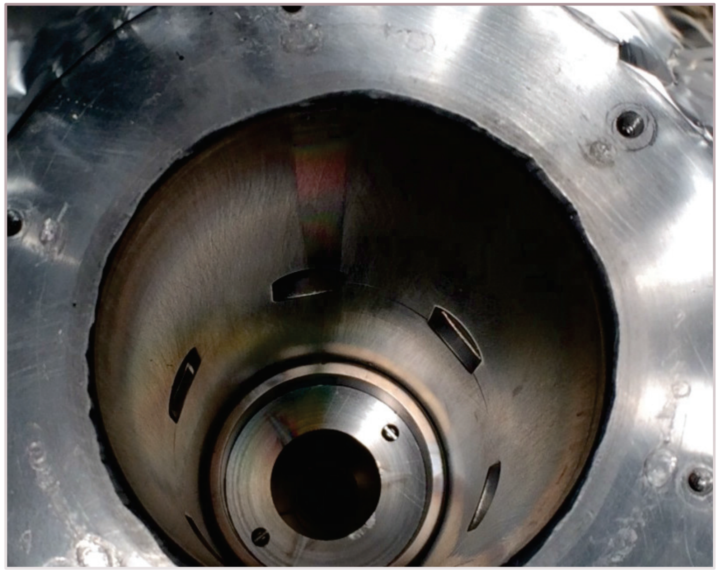


Background reduction – Aluminum coating

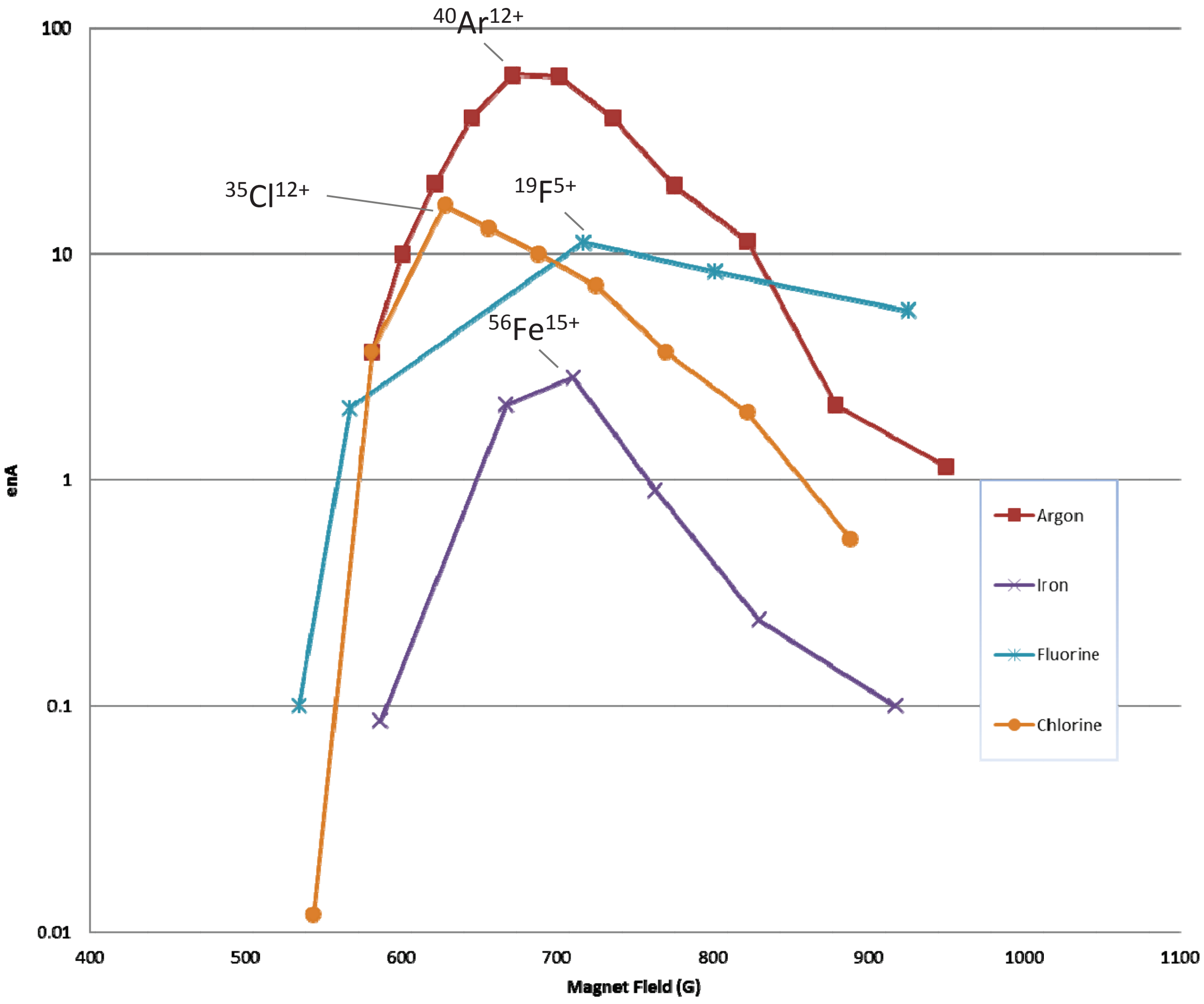


- Cleaned chamber with CO_2
- Used W coil with high-purity (99.999%) aluminum wire
- Source pressure: 5.0e-7 Torr
- Wall covered with 1 micron layer
- Vented to oxygen
- Not all surfaces were adequately coated

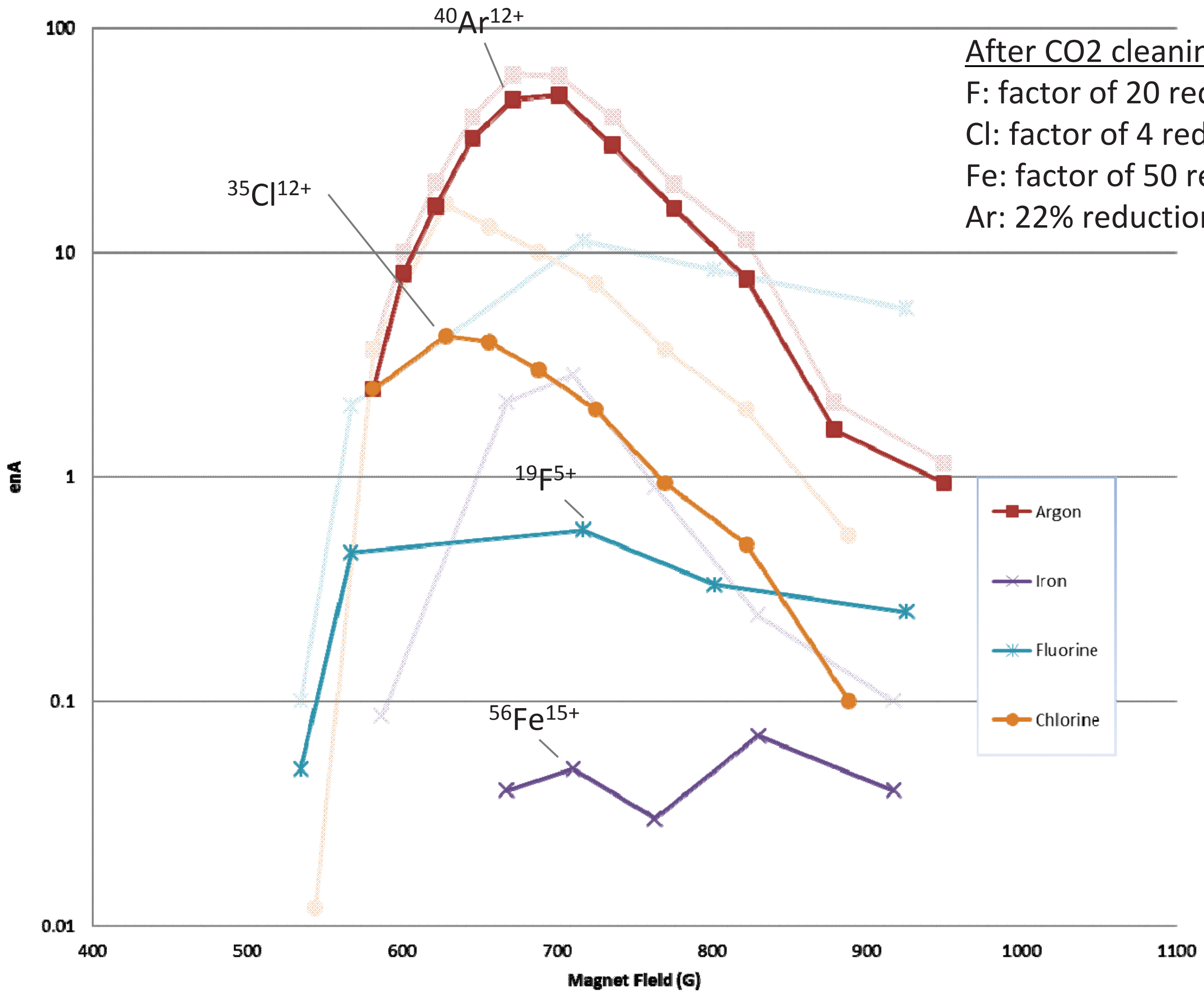




Background reduction – CO_2 cleaning

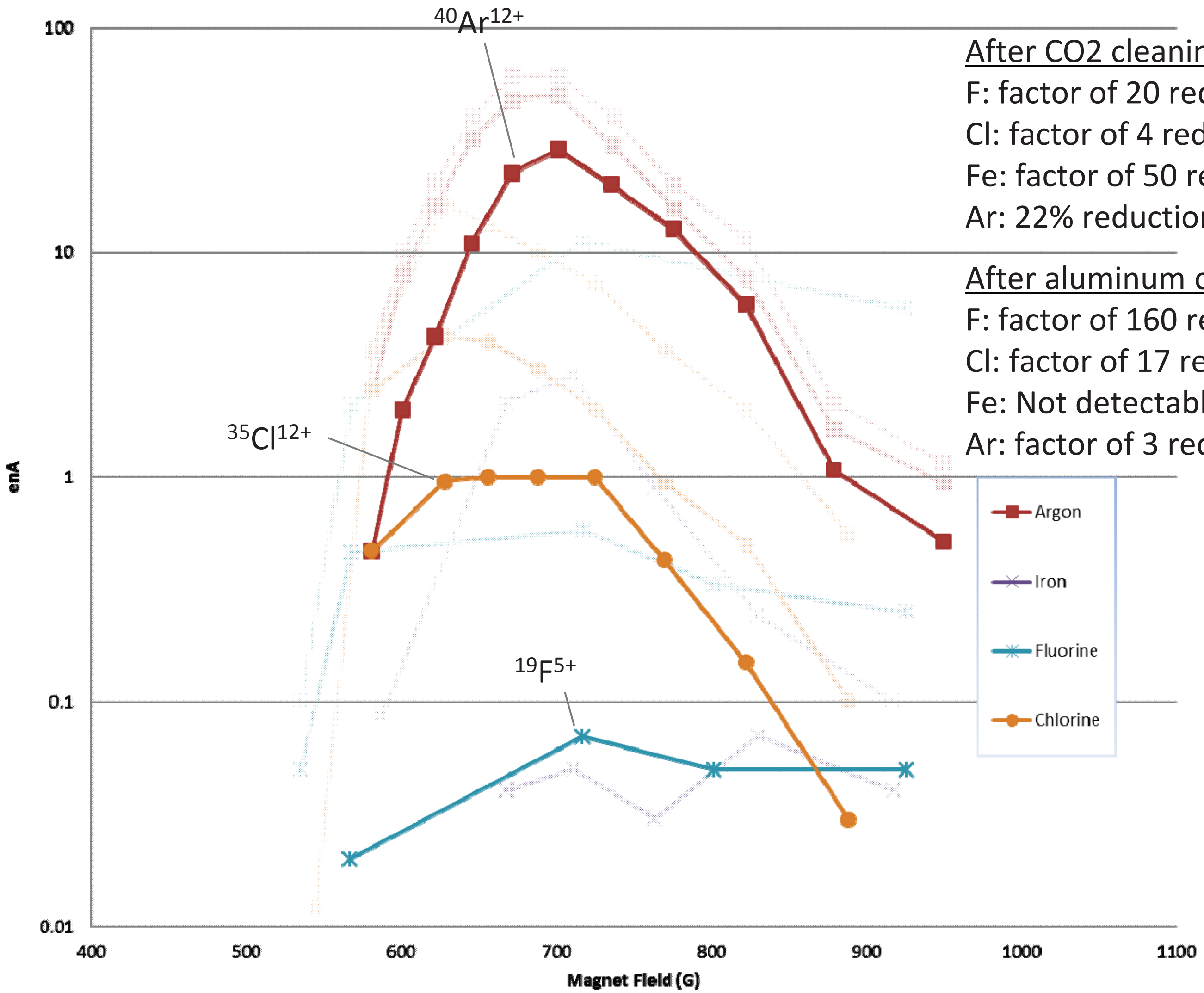


Background reduction - CO_2 cleaning



<u>After CO2 cleaning</u>
F: factor of 20 reduction
Cl: factor of 4 reduction
Fe: factor of 50 reduction
Ar: 22% reduction

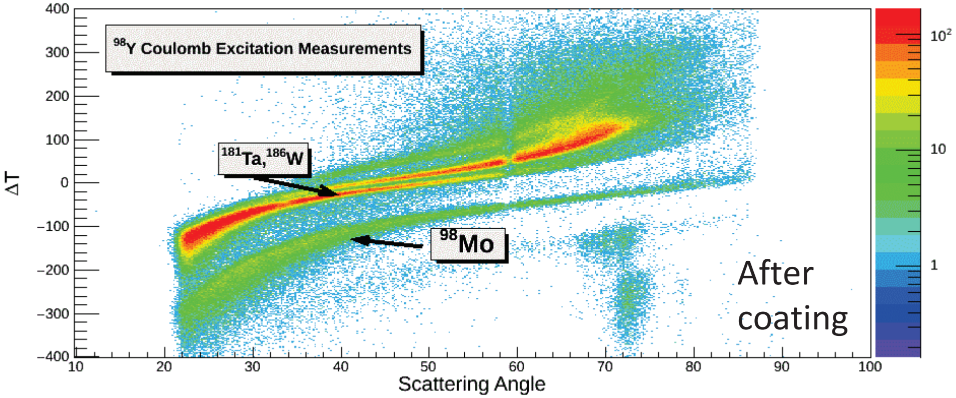
Background reduction – Aluminum coating

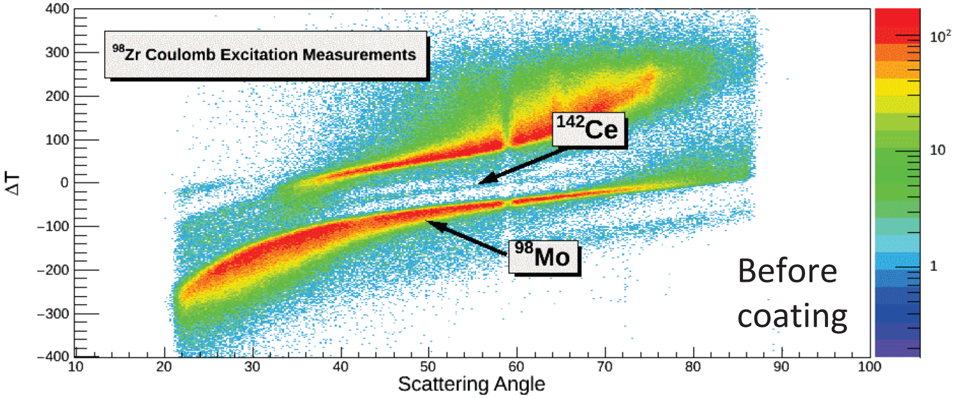


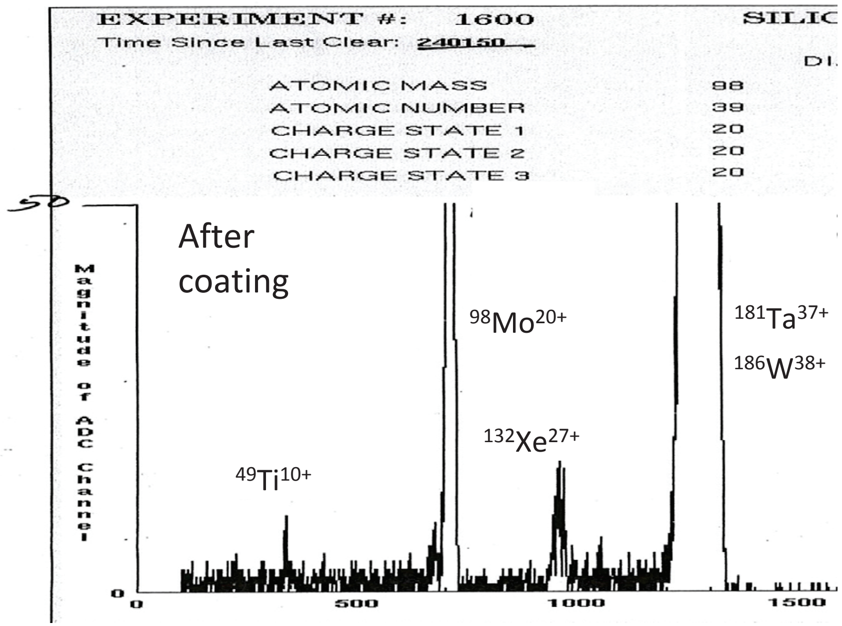
<u>After CO2 cleaning</u>
F: factor of 20 reduction
Cl: factor of 4 reduction
Fe: factor of 50 reduction
Ar: 22% reduction

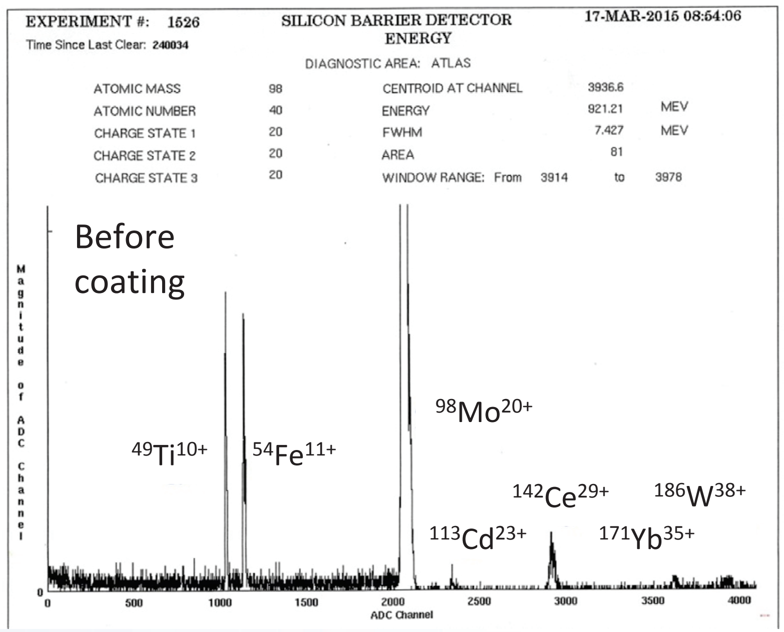
<u>After aluminum coating</u>
F: factor of 160 reduction
Cl: factor of 17 reduction
Fe: Not detectable
Ar: factor of 3 reduction

Reduction on target



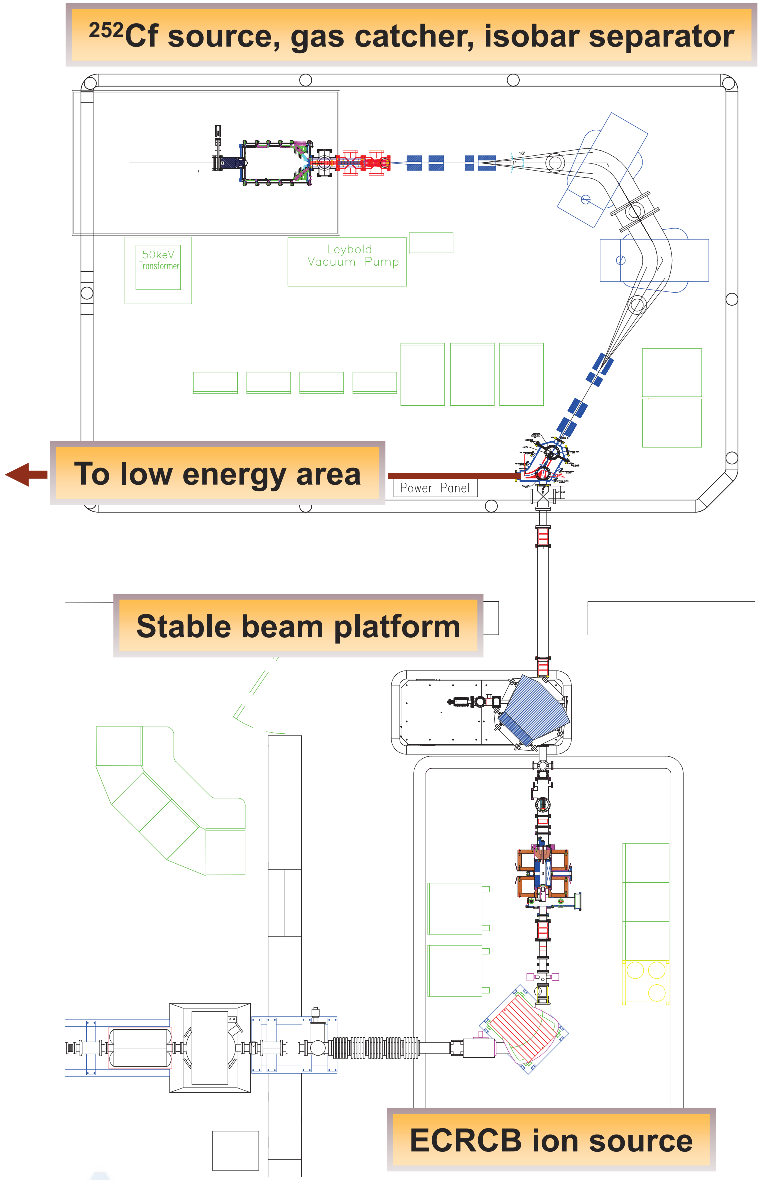


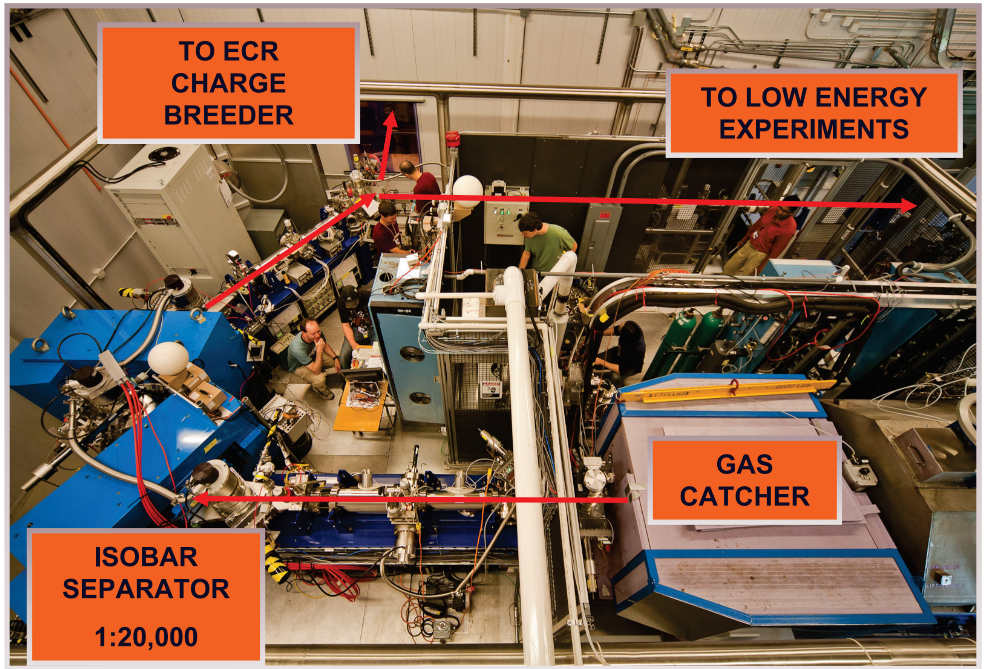


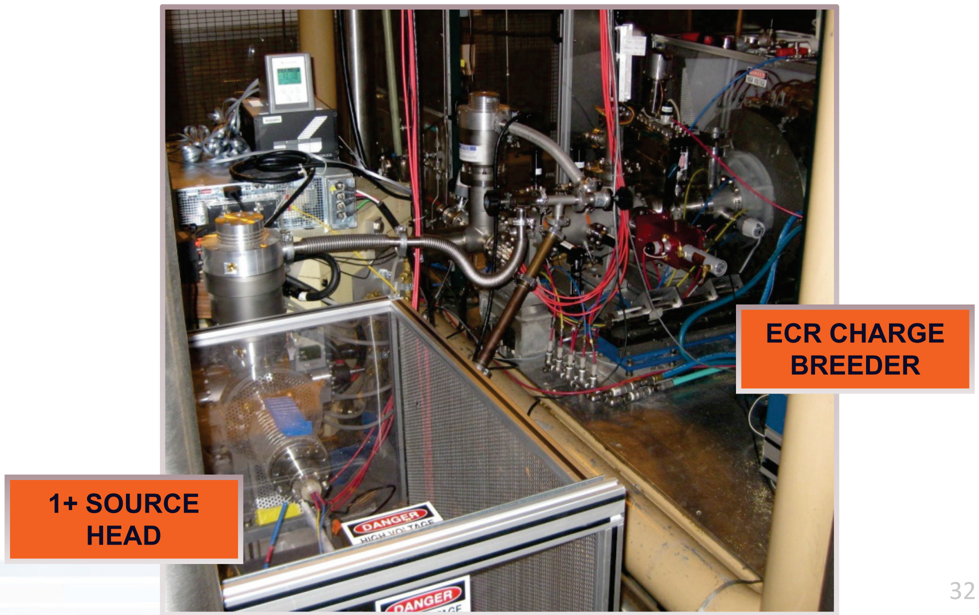


- Some contaminants were eliminated
- Mo-98 was reduced by x5 (on target)
- New contaminants Ta-181 & W-186
- Work remains to be done

CARIBU – Californium Rare Ion Breeder Upgrade







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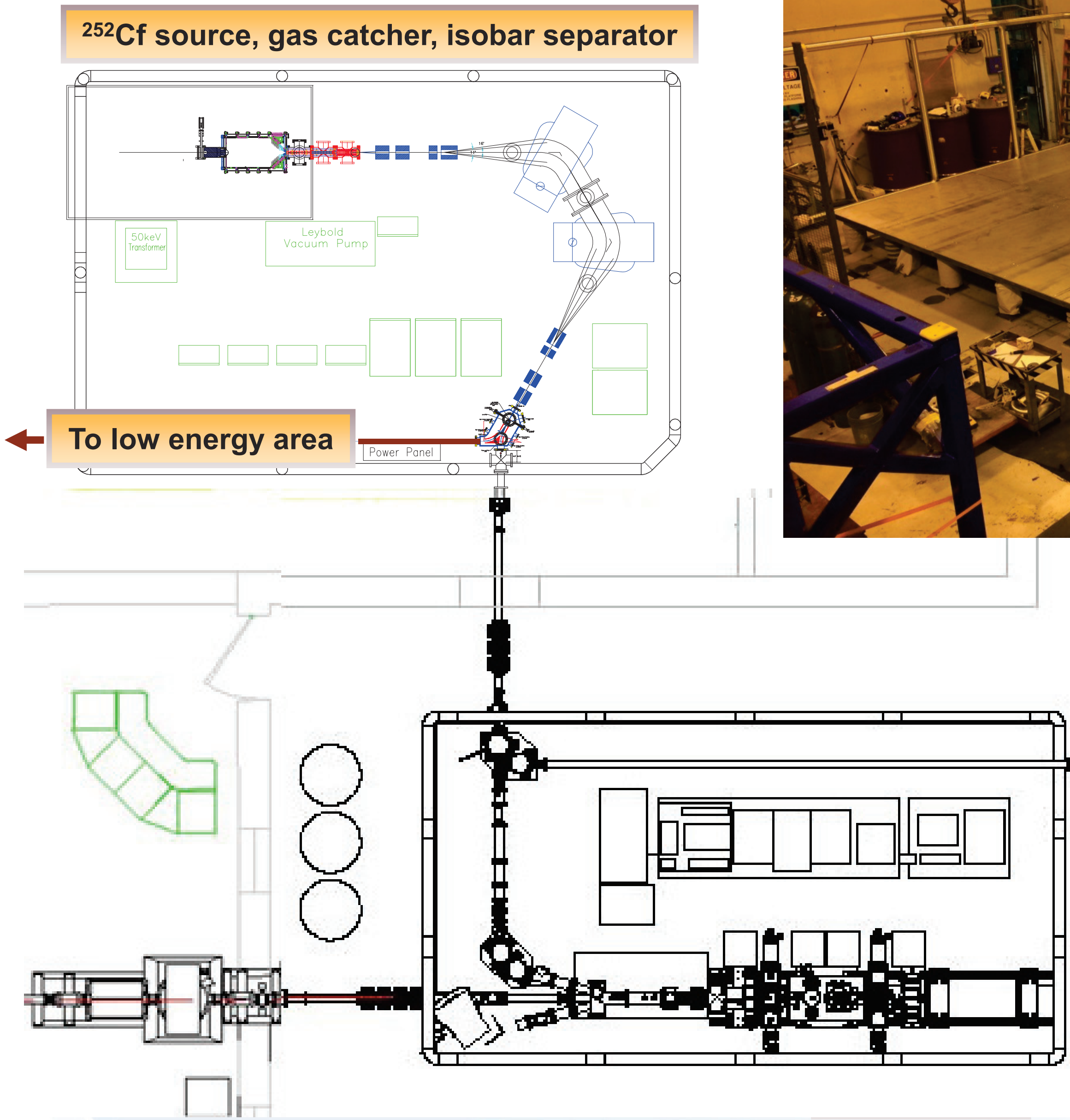
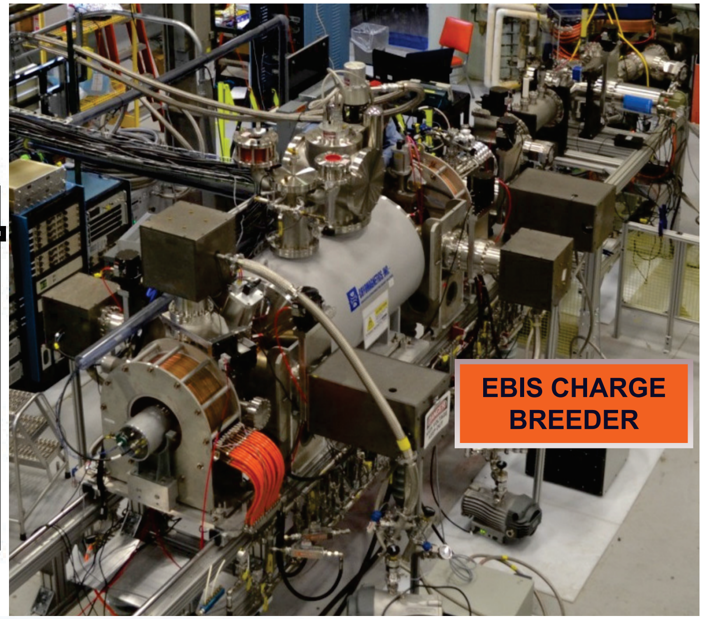
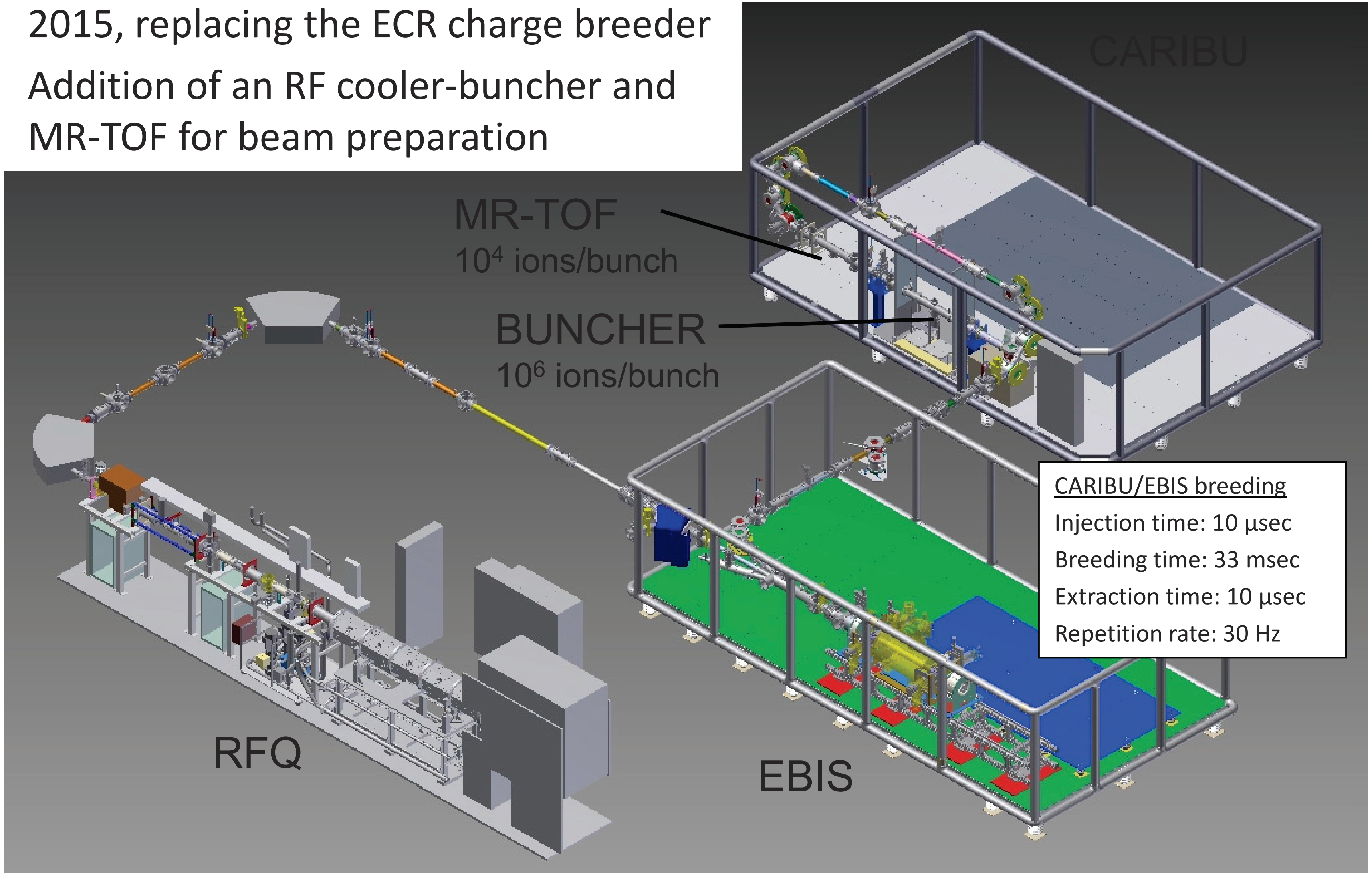




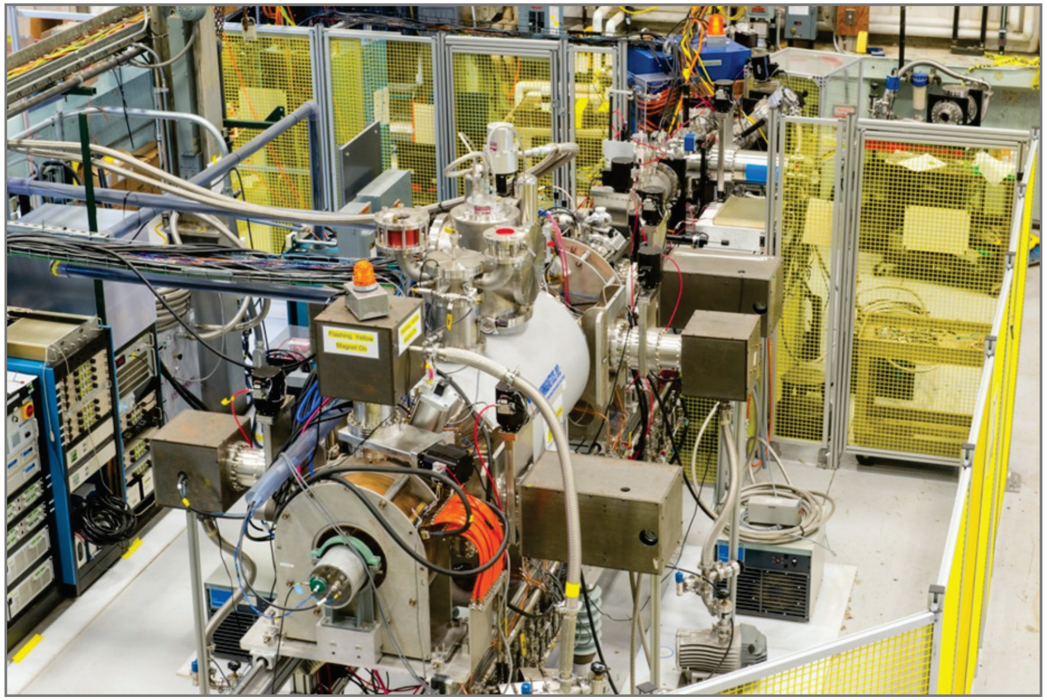
CARIBU - EBIS charge breeder

- EBIS system will be moved on-line in 2015, replacing the ECR charge breeder
- Addition of an RF cooler-buncher and MR-TOF for beam preparation



EBIS charge breeder

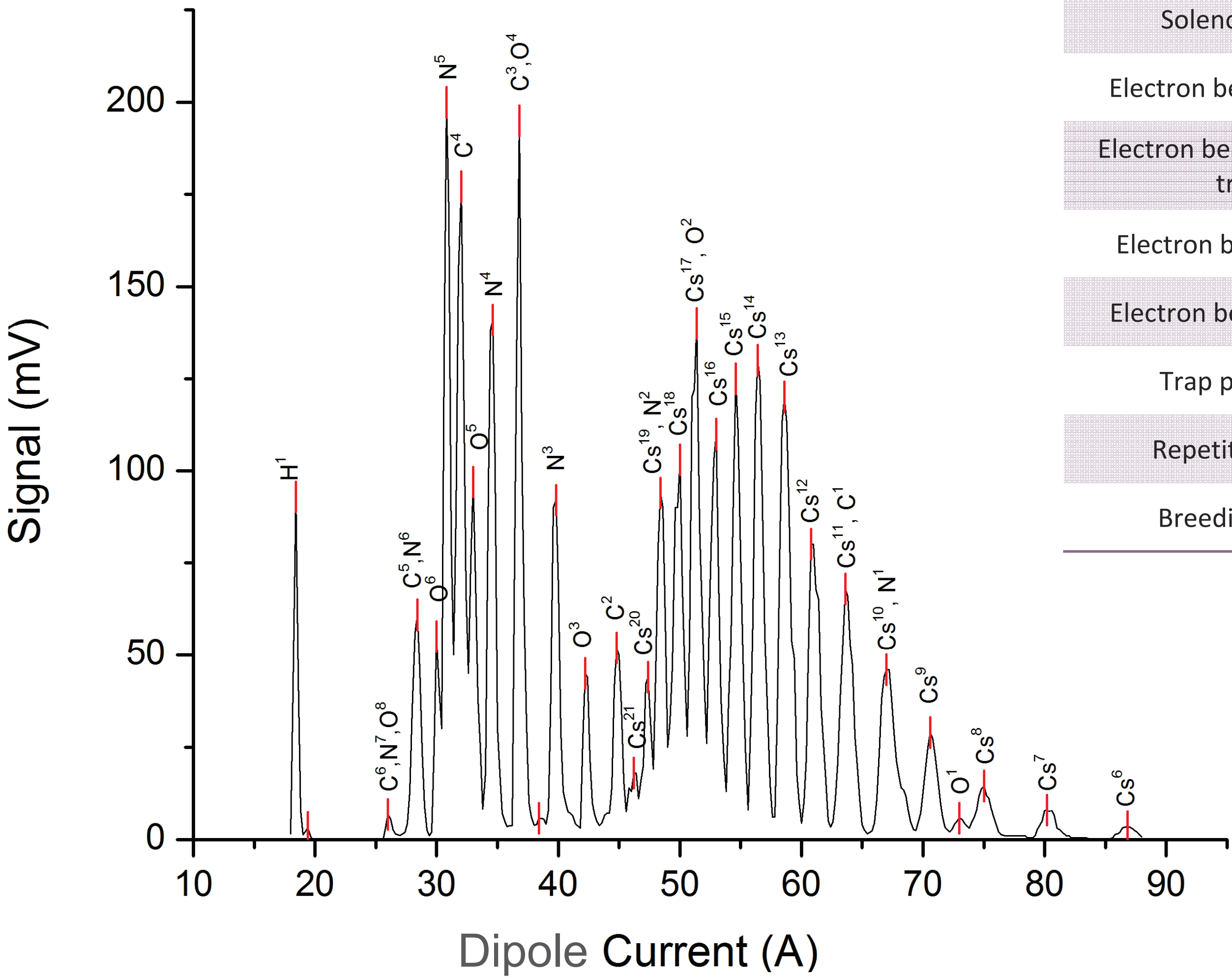
- Based upon RHIC Test EBIS design
- EBIS was commissioned off-line
- EBIS will be moved on-line in late 2015 expected to have entire system ready in early 2016



EBIS design parameters

Solenoid field	6 T
IrCe cathode diameter	4 mm
Electron beam current	2.0 A
Electron beam energy	5 keV
Electron beam radius	330 µm
Electron beam density	577 A/cm^2
Normalized full acceptance	0.024 π·mm·mrad
Trap capacity	30 nC
Injection time	10 µs
Repetition rate	30 Hz
Duty cycle	90 %

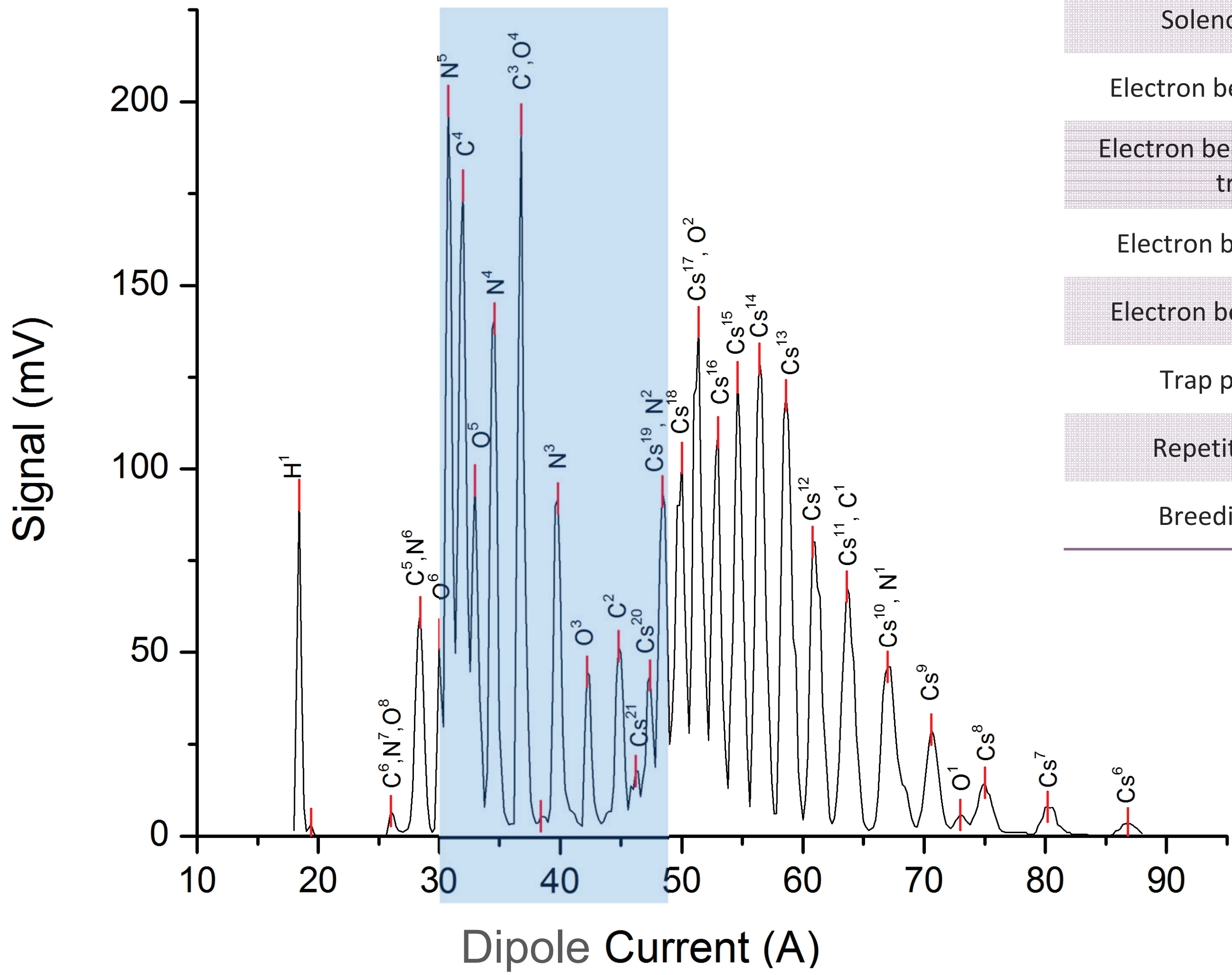
Charge bred cesium



EBIS operational parameters	
Solenoid field	4 T
Electron beam current	1.0 A
Electron beam energy in trap	9.4 keV
Electron beam radius	860 µm
Electron beam density	170 A/cm^{2}
Trap pressure	~3.0x10^{-10} Torr
Repetition rate	5 Hz
Breeding time	10 ms

- First results in May 2014
- 10% breeding efficiency into Cs^{14+}

Charge bred cesium



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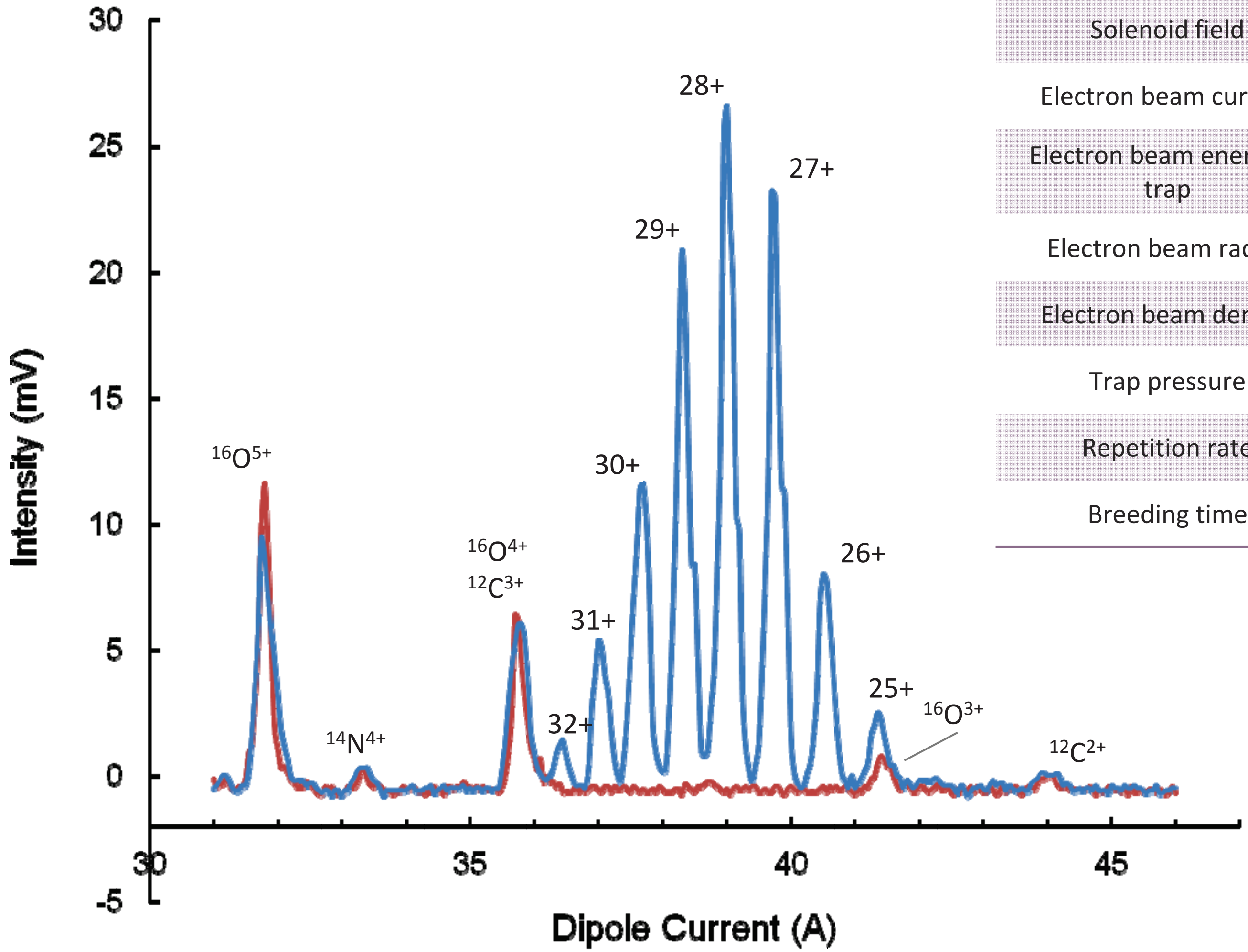
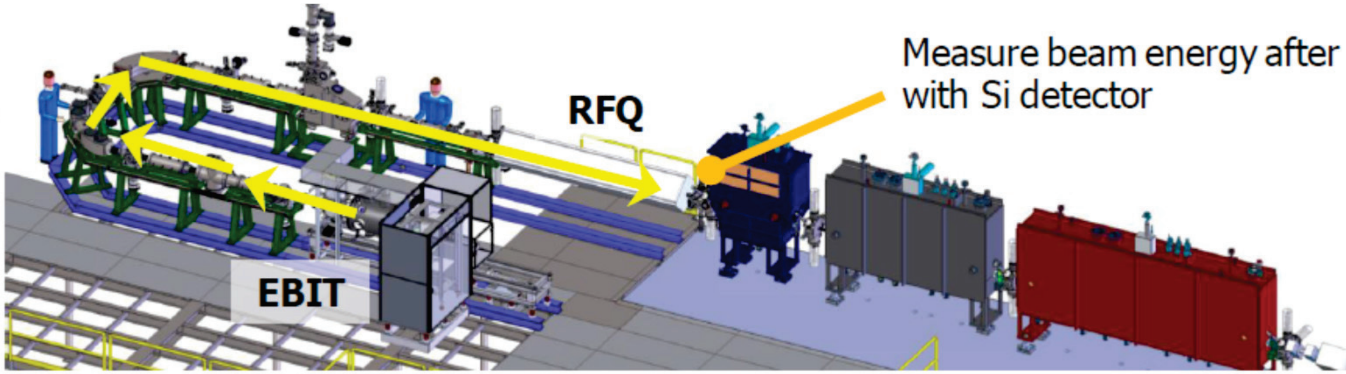


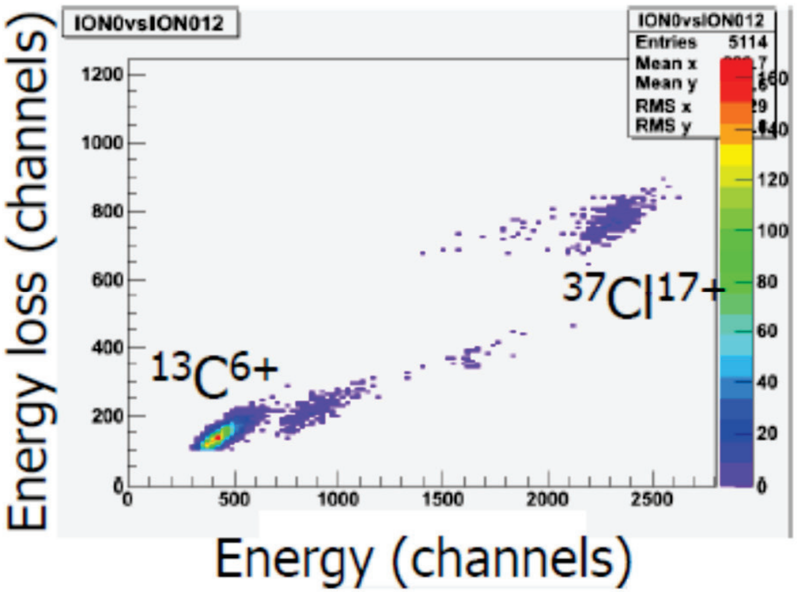
EBIS operational parameters

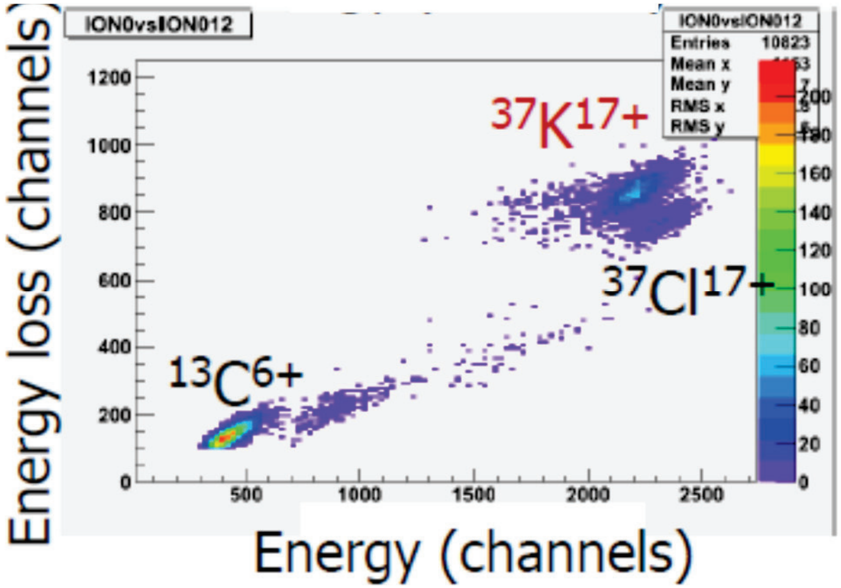
Solenoid field	5 T
Electron beam current	1.6 A
Electron beam energy in trap	6.5 keV
Electron beam radius	370 µm
Electron beam density	385 A/cm^2
Trap pressure	~8.0x10^{-10} Torr
Repetition rate	10 Hz
Breeding time	28 ms

- Latest results – several small leaks fixed, system baked out
- 20% breeding efficiency into $^{133}Cs^{28+}$

Overall background – ReA EBIT

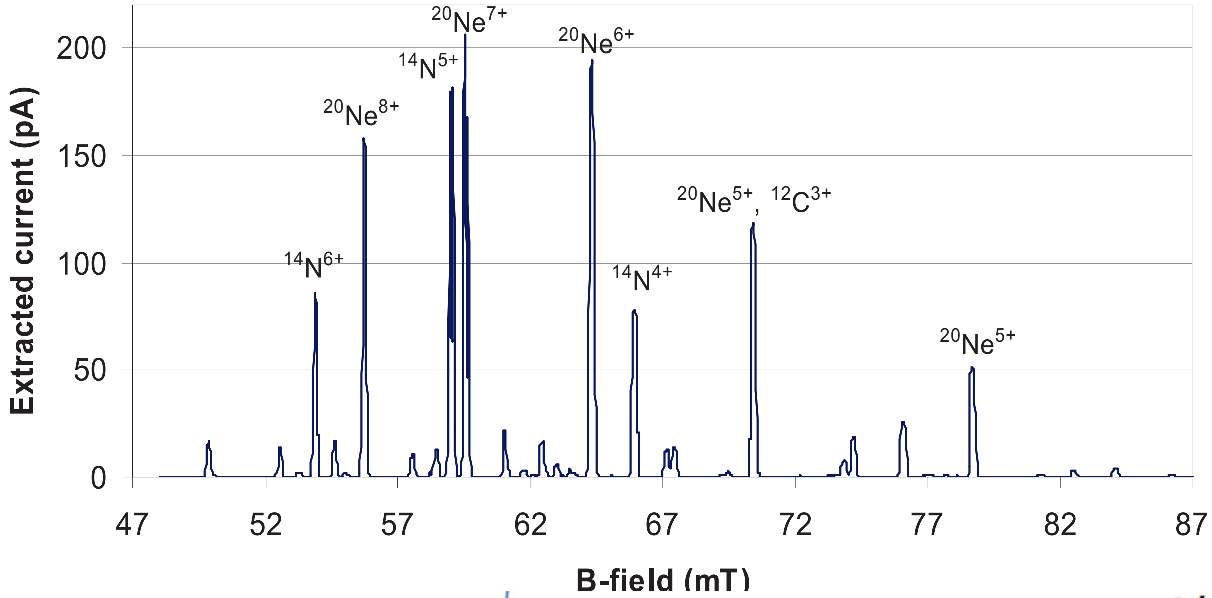




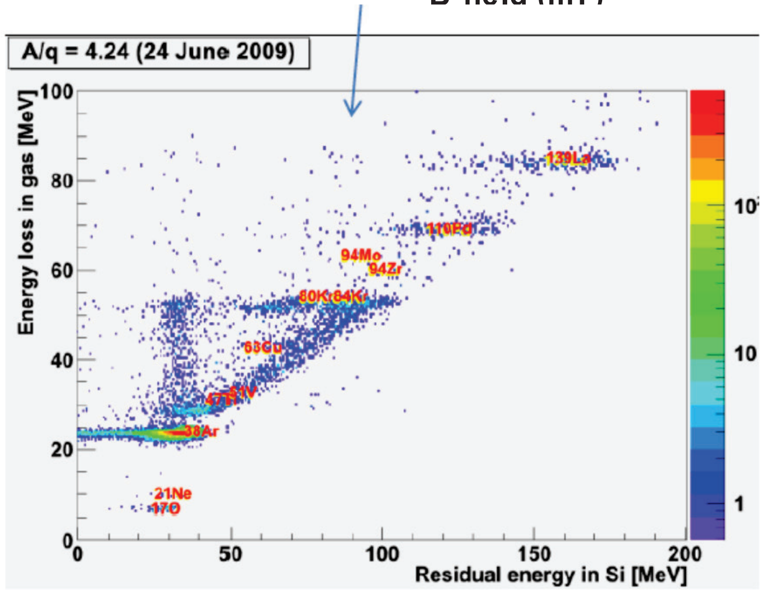


Courtesy of A. Lapierre. T. Baumann, NSCL, MSU

Overall background - REX-EBIS



- Residual gas spectrum
- Neon – trap gas
- 15 ms breeding
- 160 mA e^- beam
- More difficult to find A/q regions free of contaminants for low Z such as Li, Be, B



A/q=4.24

Isotope	A/q	Z	Origin
17O	4.250	8	residual gas
21Ne	4.2	10	buffer gas
38Ar	4.222	18	residual gas
47Ti	4.272	22	drift tubes
51V	4.25	23	NEG strips
63Cu	4.2	29	anode and collector
80Kr, 84Kr	4.21, 4.2	36	residual gas
94Zr	4.272	40	NEG strips
139La	4.212	57	cathode

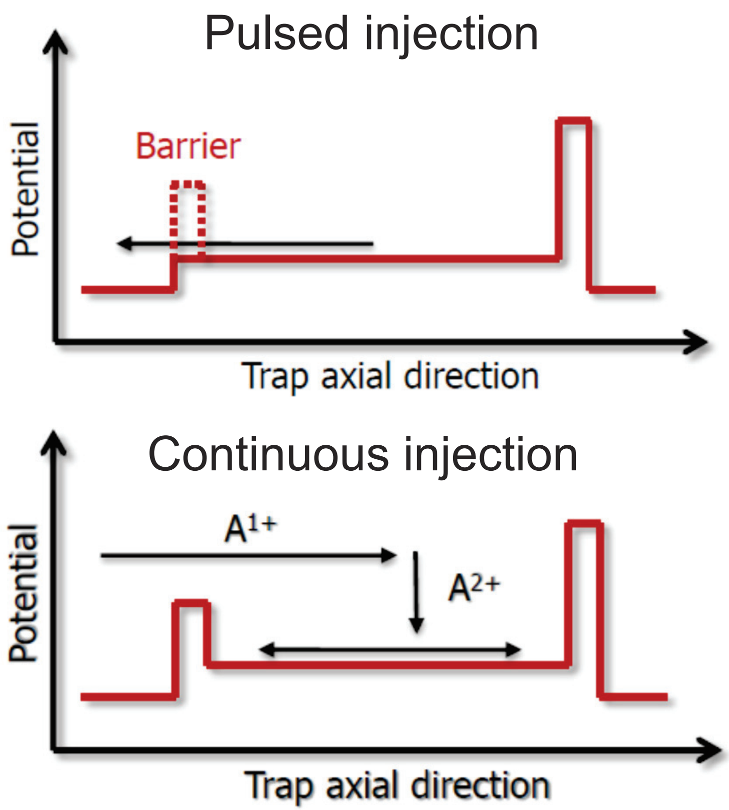
Other elements that can be present at other A/q are:

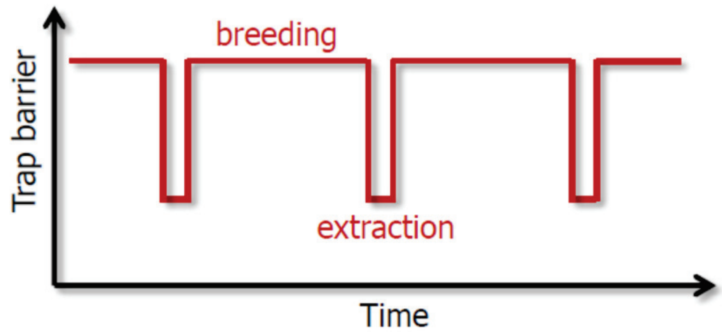
He, C, N	residual gases
B	cathode
Fe	NEG strips, stainless steel
Ni	stainless steel
Cr	stainless steel
Mo	stainless steel

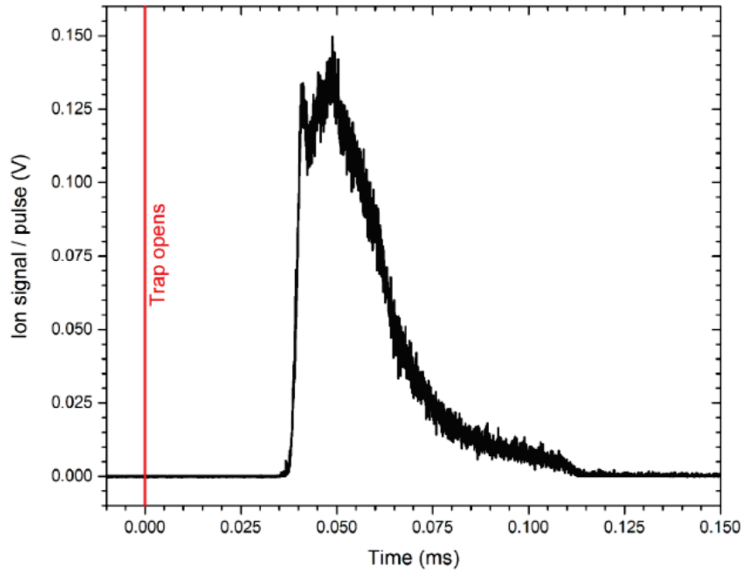
Courtesy of F. Wenander, REX-EBIS, CERN

Ion injection and extraction

- EBIS is an inherently pulsed device
  - Typical extraction pulse is 10-20 μs
  - High instantaneous rates can lead to detector dead time and pile up
  - REX-ISOLDE "15 minutes of delivered beam in every 24 hours of beam time"

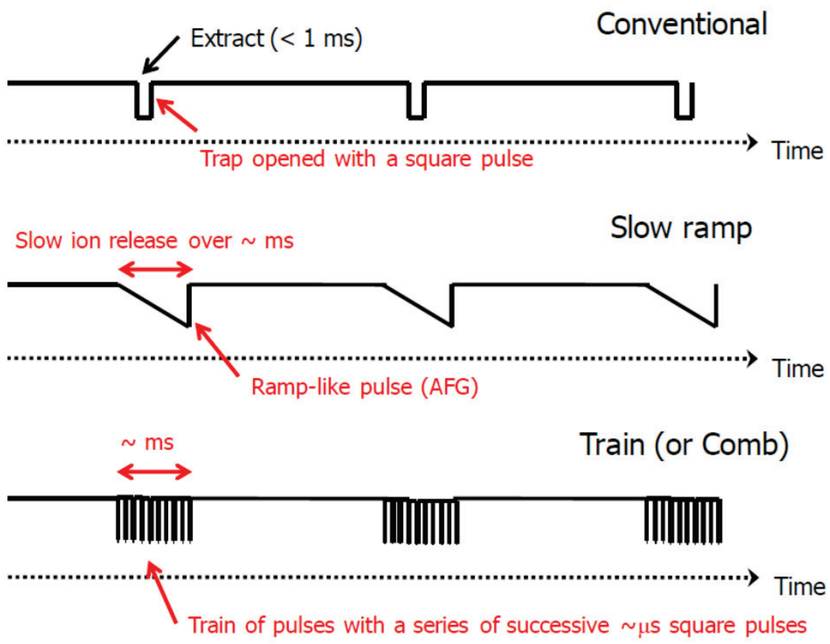


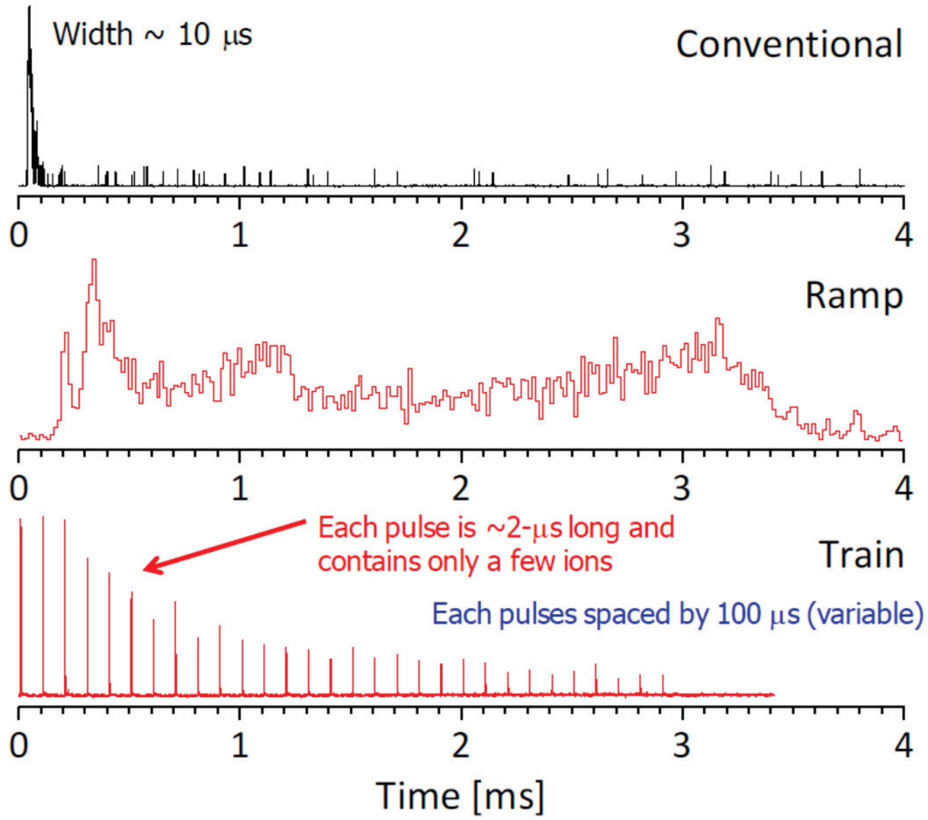




Courtesy of T. Baumann, NSCL, MSU

Ion extraction schemes – ReA EBIT

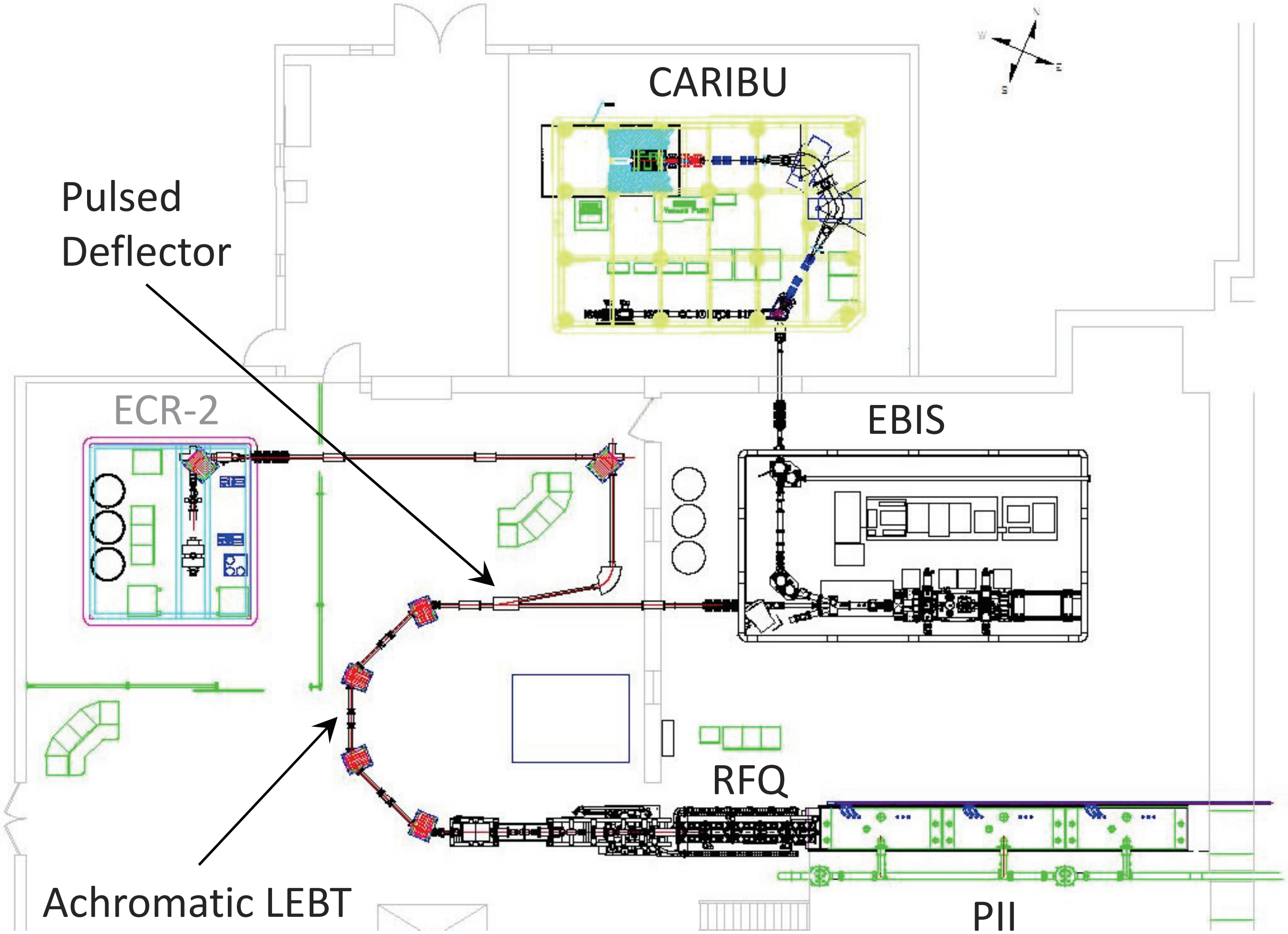




- Several schemes to reduce instantaneous rate on target
  - Linear or exponential Ramp scheme for slow continuous release of trap ions
  - Train or Comb scheme releases ions in multiple discrete pulses
- Cooler/buncher was recently installed to allow injection of bunched ion beams

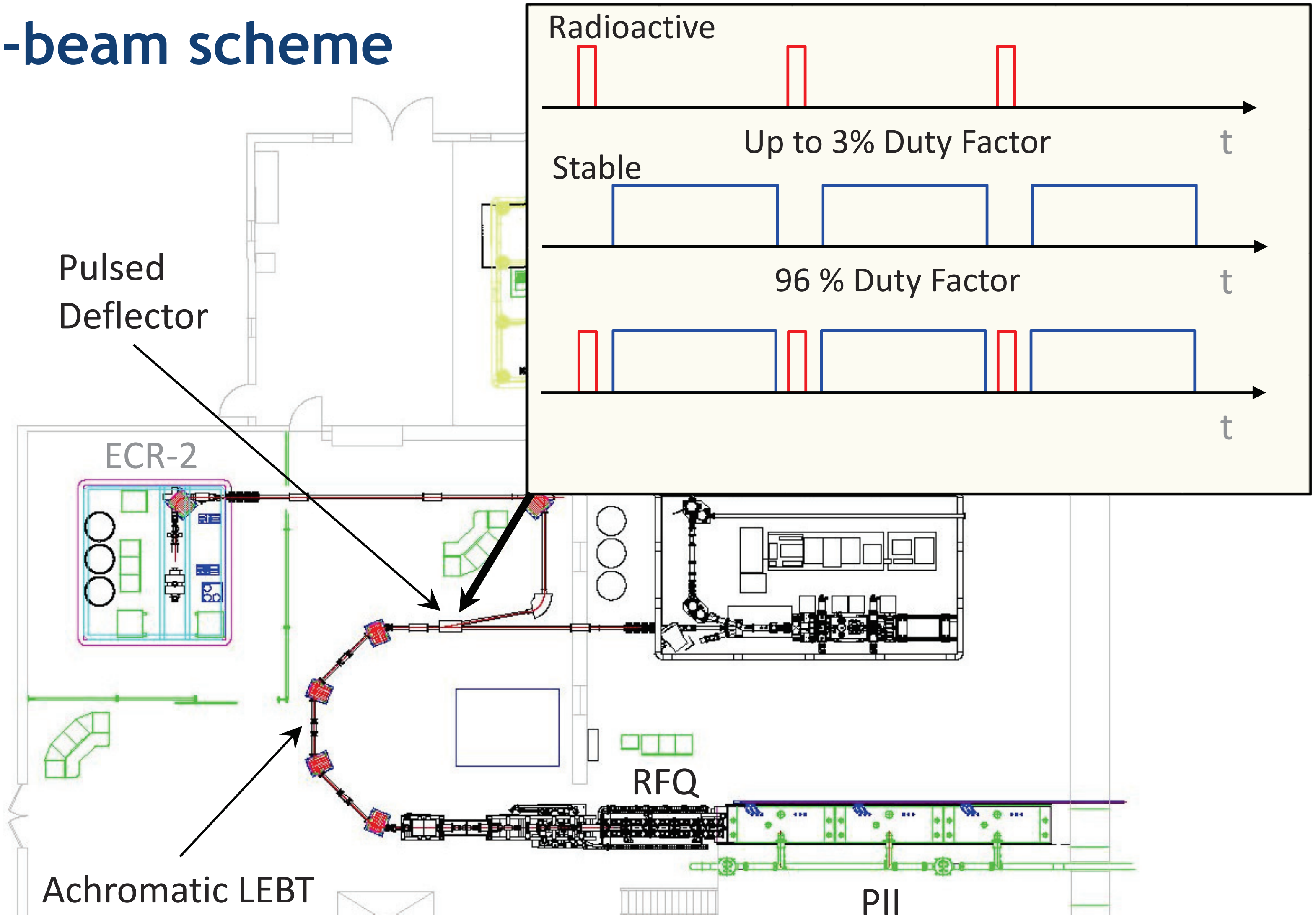
T. Baumann, AIP Conf Proceedings (EBIST2014)

Multi-beam scheme



- The simultaneous acceleration of two beam species
  - One stable from the ECR and one radioactive from CARIBU-EBIS
  - A/q required to be within 1% of each other

Multi-beam scheme



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  - A/q required to be within 1% of each other

Summary

- The ECR charge breeding program at ANL was successful
  - Advanced the state of the art for ECR charge breeding
  - Delivered 81 days of radioactive beams in final year
  - But level of background hindered the overall performance

- Installation of the EBIS charge breeder is progressing
  - Demonstrated 20% breeding efficiency in off-line tests
  - New high voltage platform is nearly complete
  - System should be operational in early 2016

Acknowledgements

This is the work of many people…

R. Pardo, G. Savard, R. Scott – ANL CARIBU and ECR

P.N. Ostroumov , C. Dickerson, S.A. Kondrashev, A. Barcikowski, S. Sharamentov,
J. Alessi, E. Beebe, A. Pikin
– EBIS development

B. Mustapha, A. Perry (IIT), M. Fraser (CERN) – Beam optics and hardware design