Charge Breeding Experiences with an ECR and an EBIS for CARIBU

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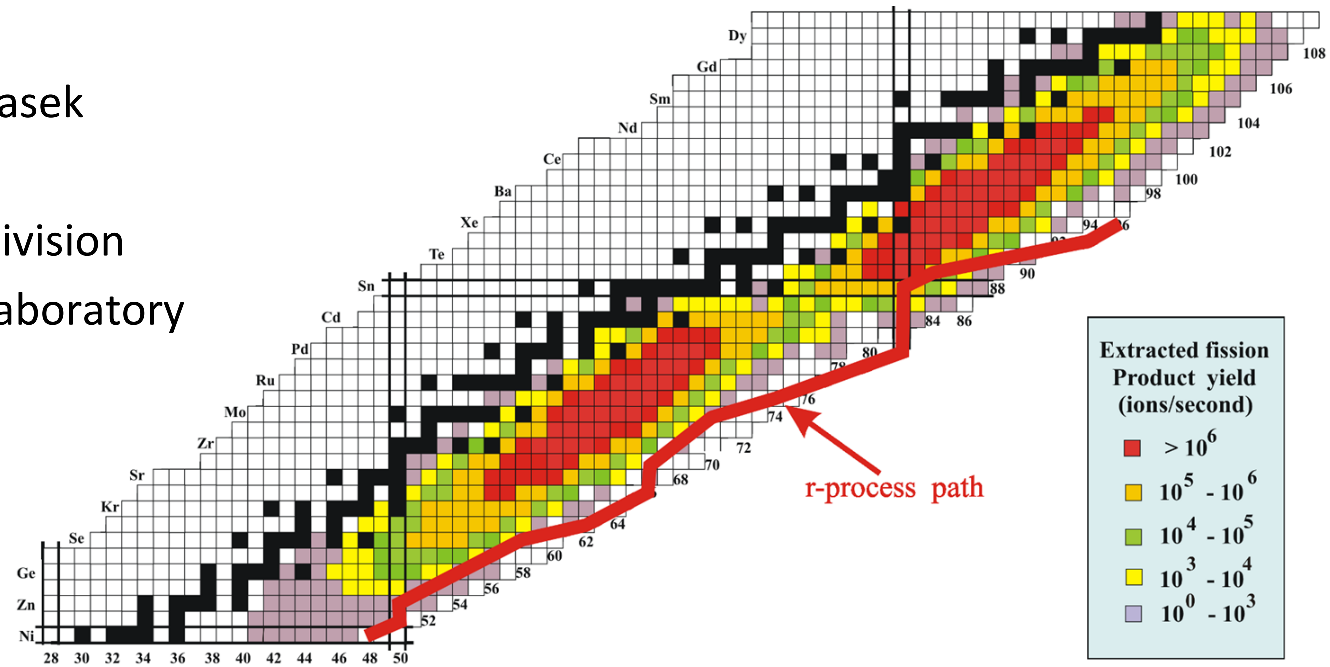
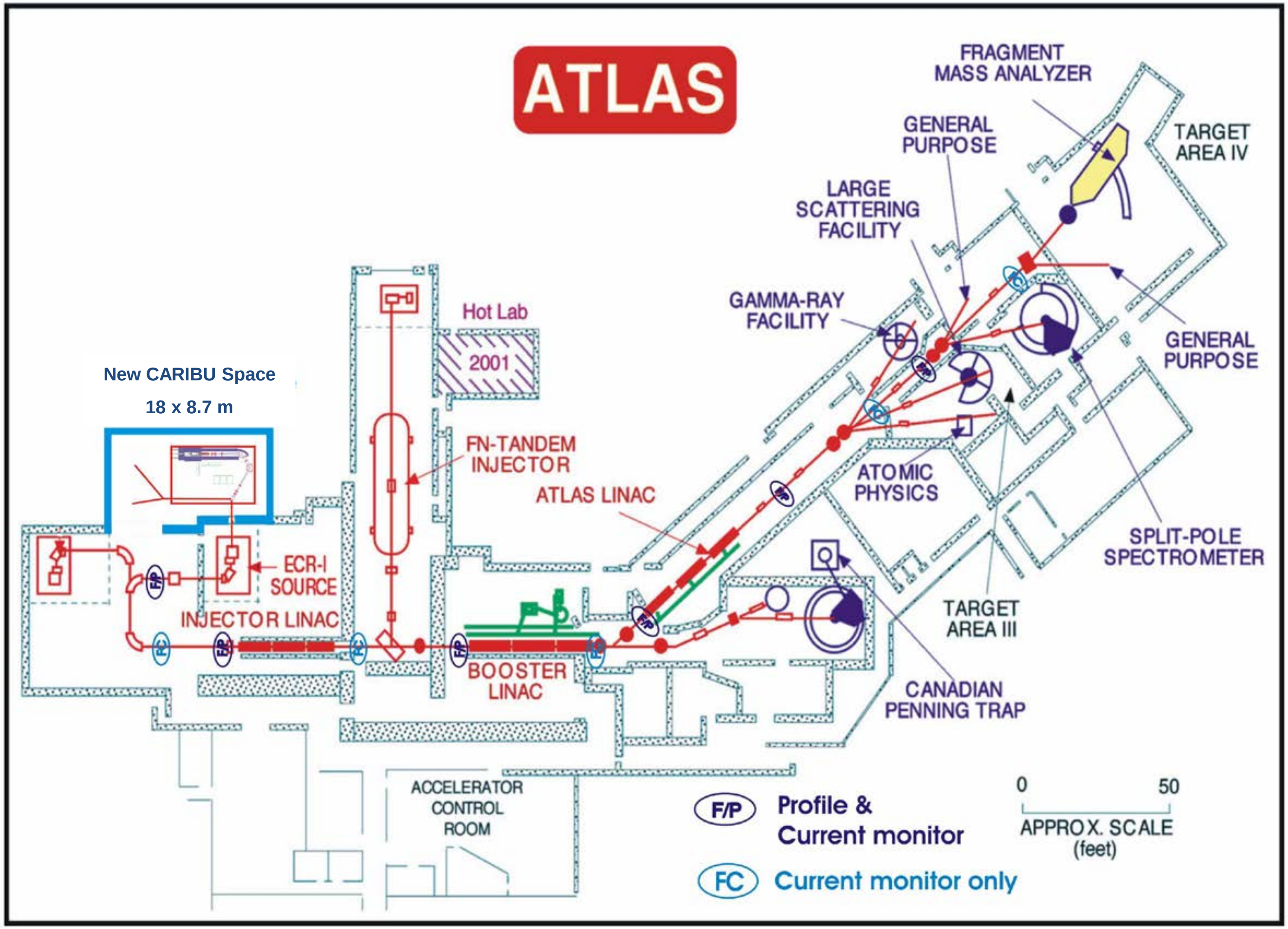


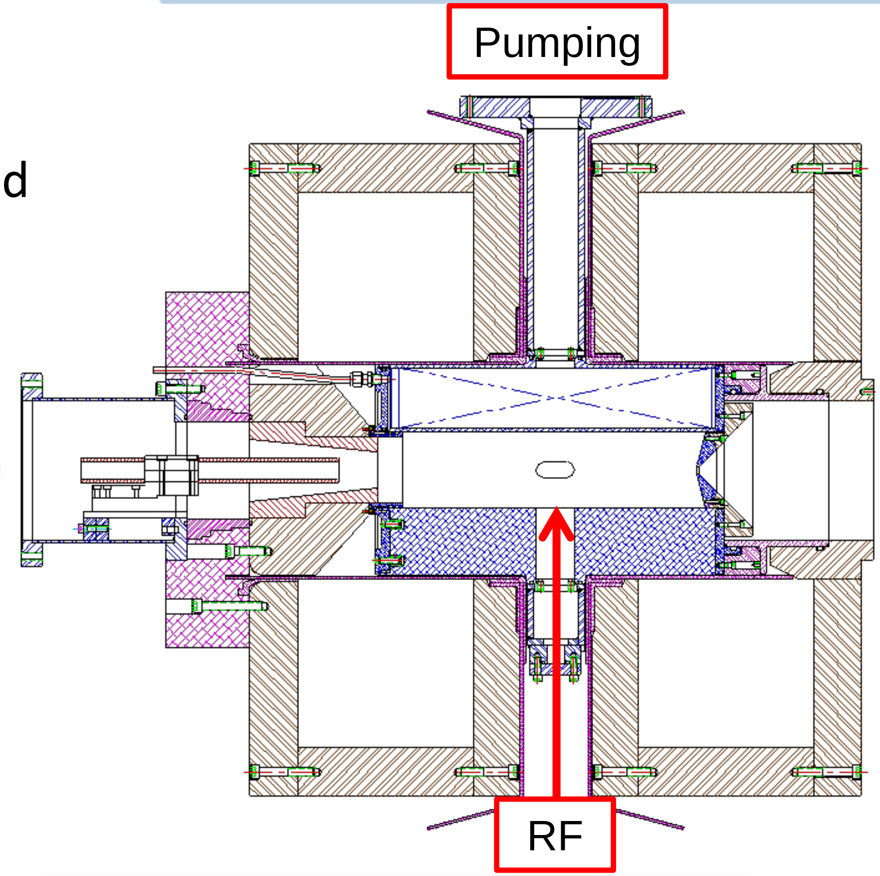
- Implementation of ECR charge breeding at Argonne
- Development and installation of EBIS charge breeder

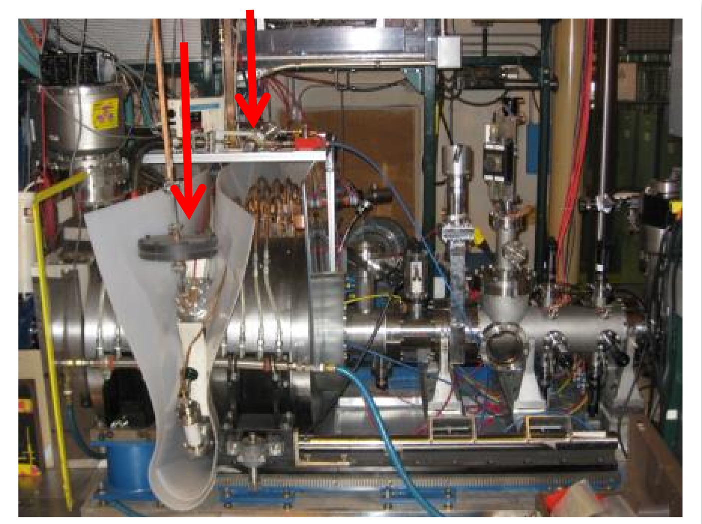
ATLAS – Argonne Tandem Linac Accelerator System



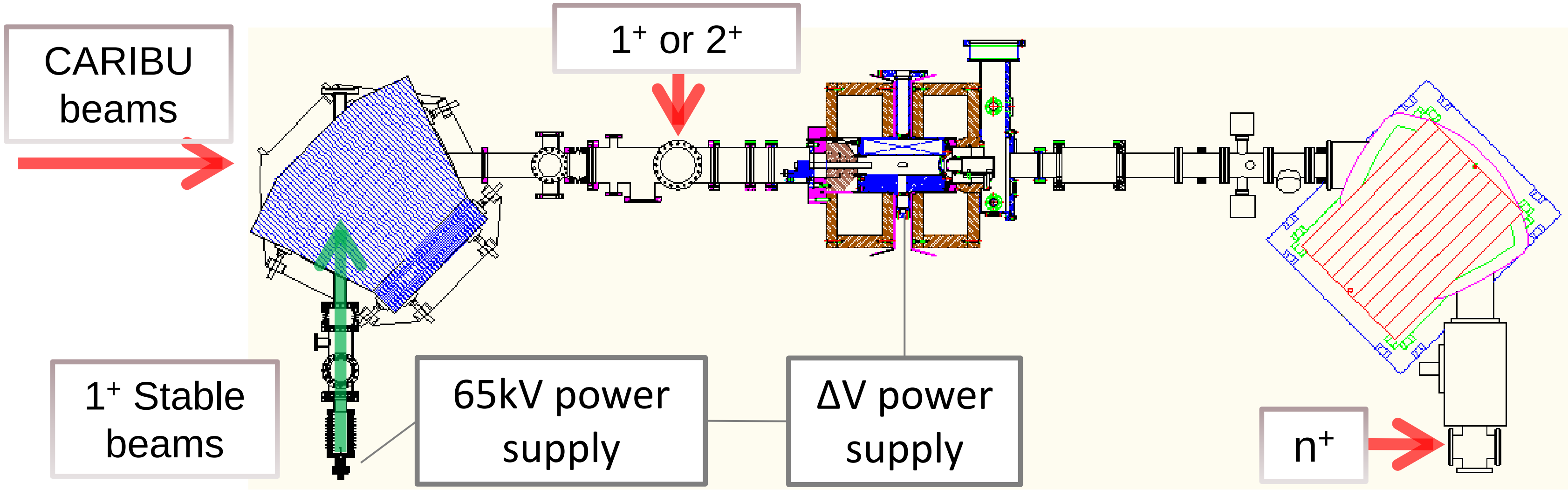
ECR charge breeder design

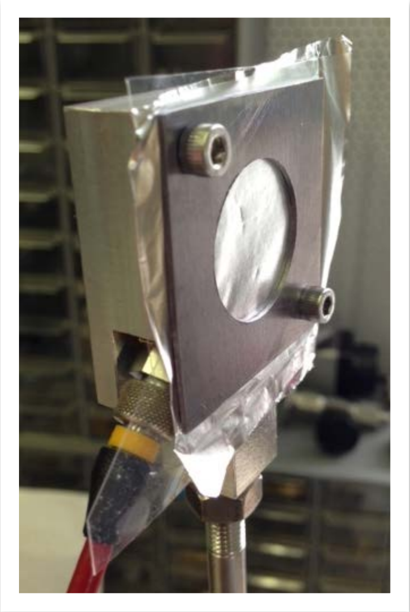
- For grounded tube penetration, reshaped the iron to maximize B_{inj} (1.3 T) and maintain symmetric magnetic field
- Linear motion stage with 3 cm of travel
- Open hexapole allows radial RF injection and provides direct pumping of plasma chamber
- Multiple frequency operation
  - Klystron: 10.44 GHz, 2 kW
  - TWTA: 11→13 GHz, 0.5 kW
- Turbo pumps at injection and extraction tanks of ion source
  - Base pressure of 2.0e-8 mbar
- 50 kV high voltage isolation
- All components constructed of 6061 aluminum

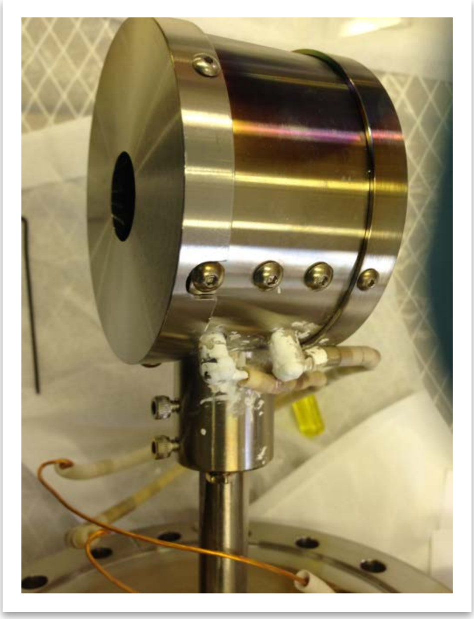


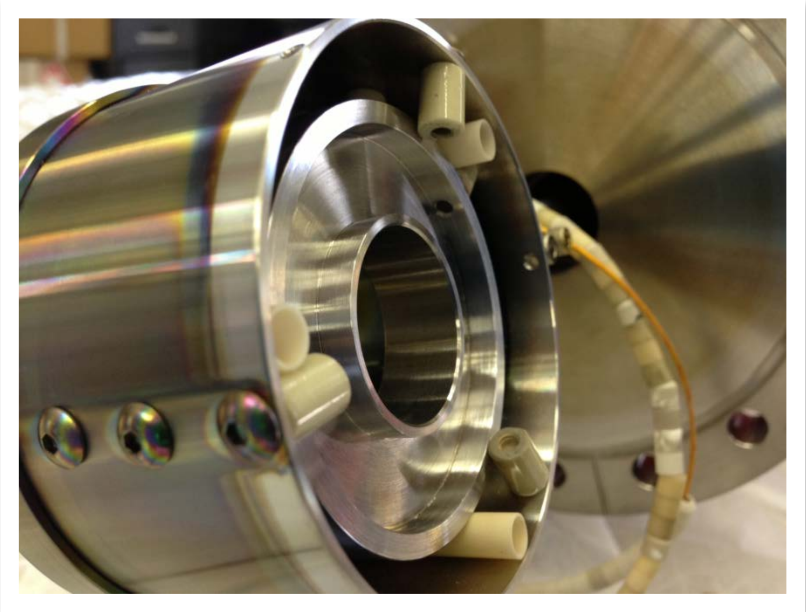


ECR charge breeder diagnostics

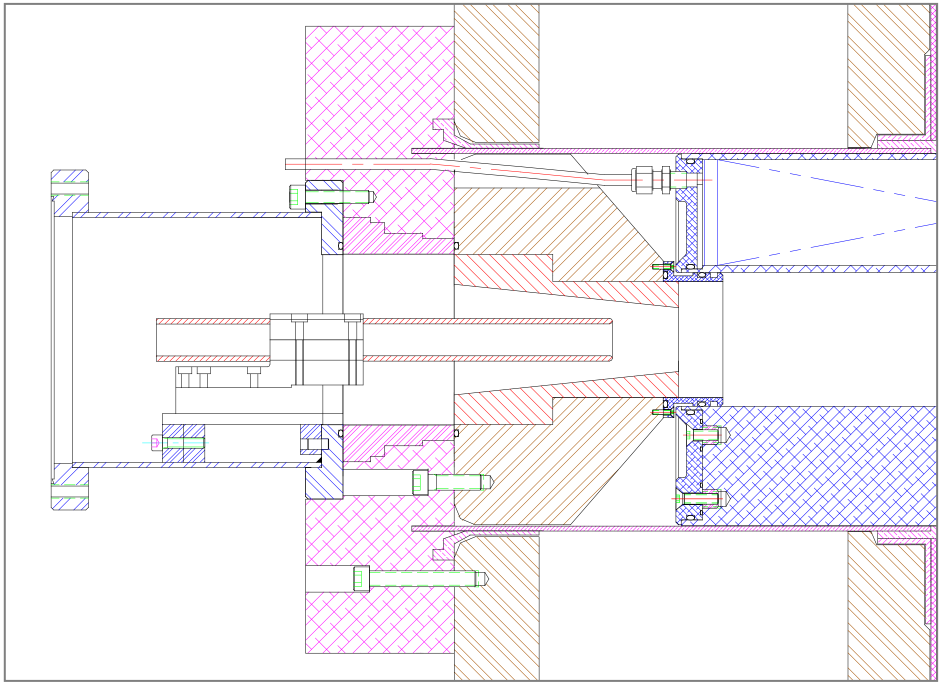


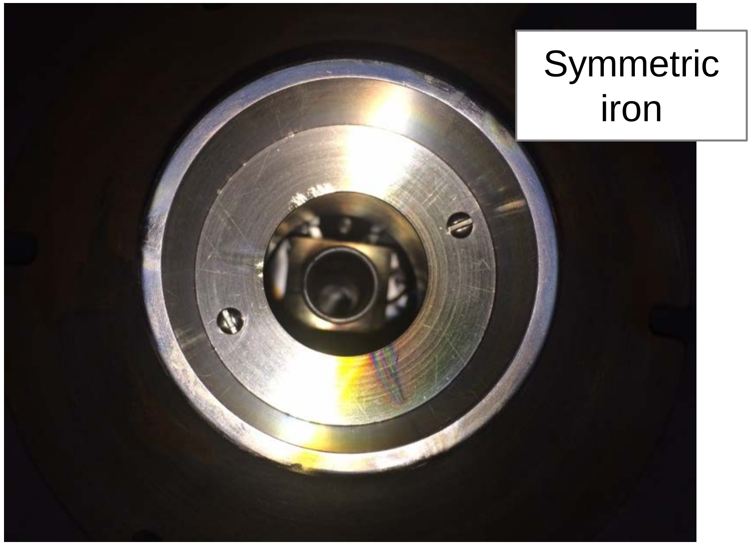


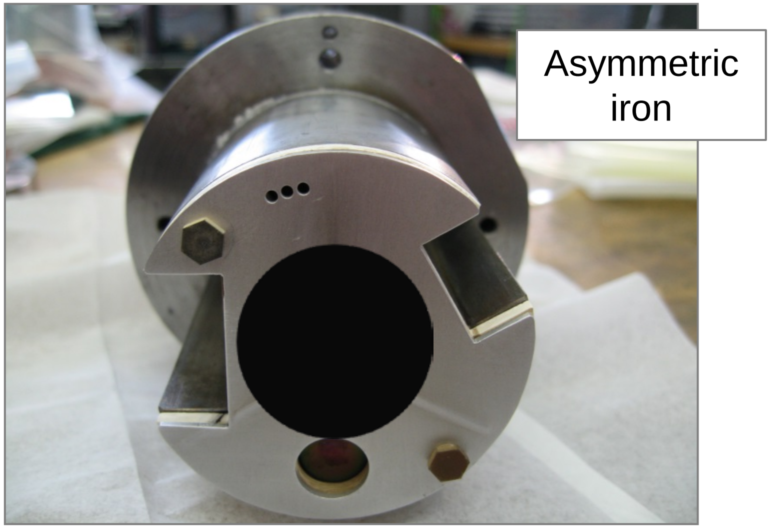




Injected ion penetration

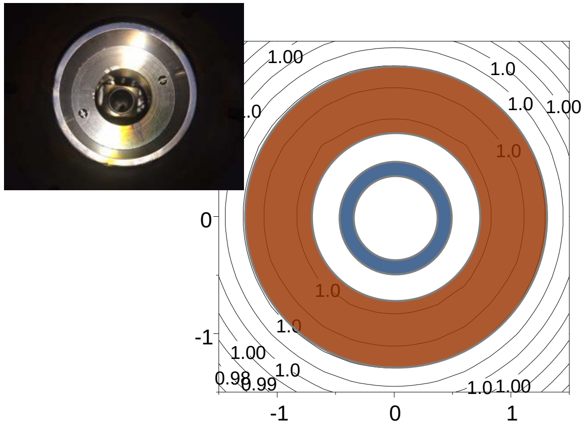
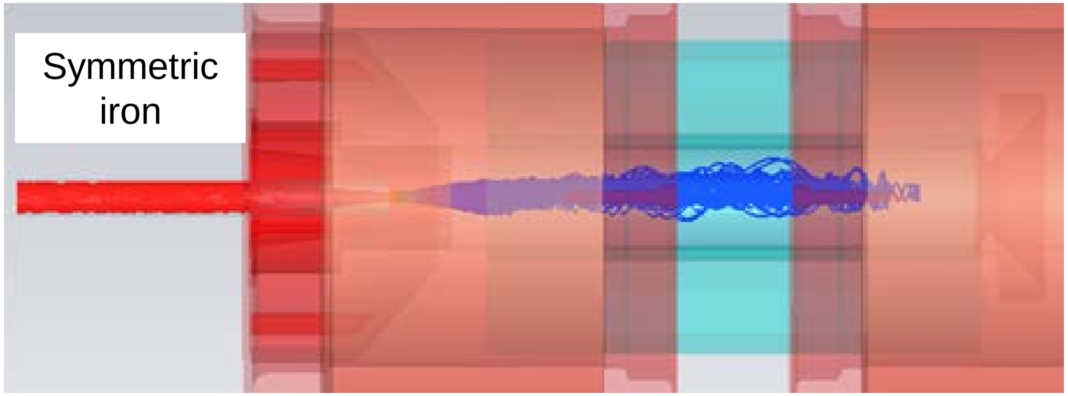


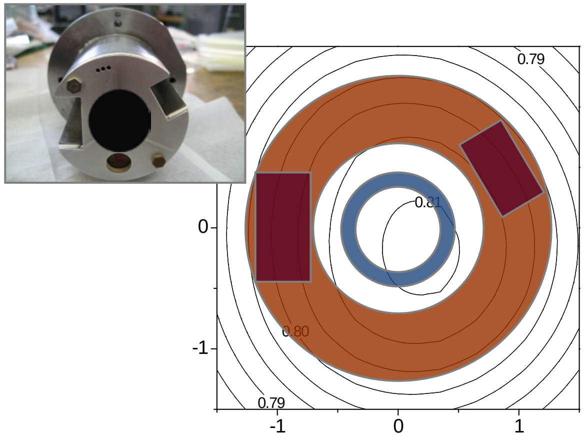
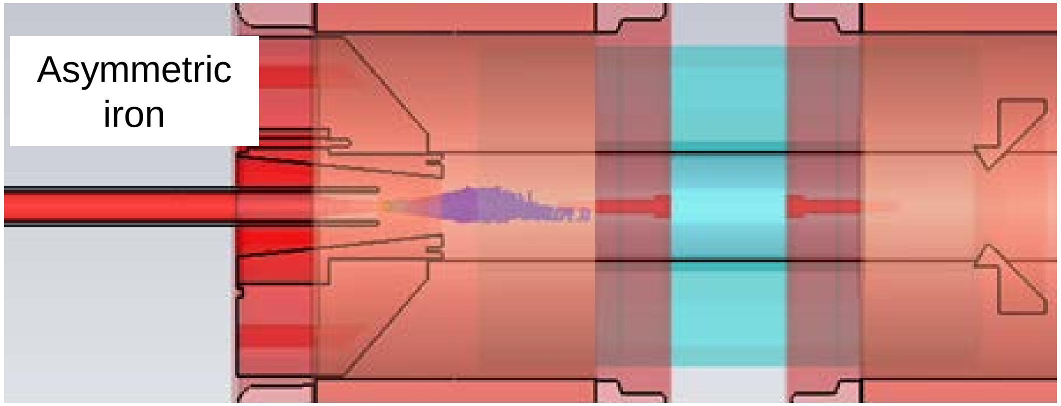




- Looked at two cases
  - Symmetric iron with no cut outs for waveguides and RF is launched radially
  - Asymmetric iron which has cut outs for axial RF launch

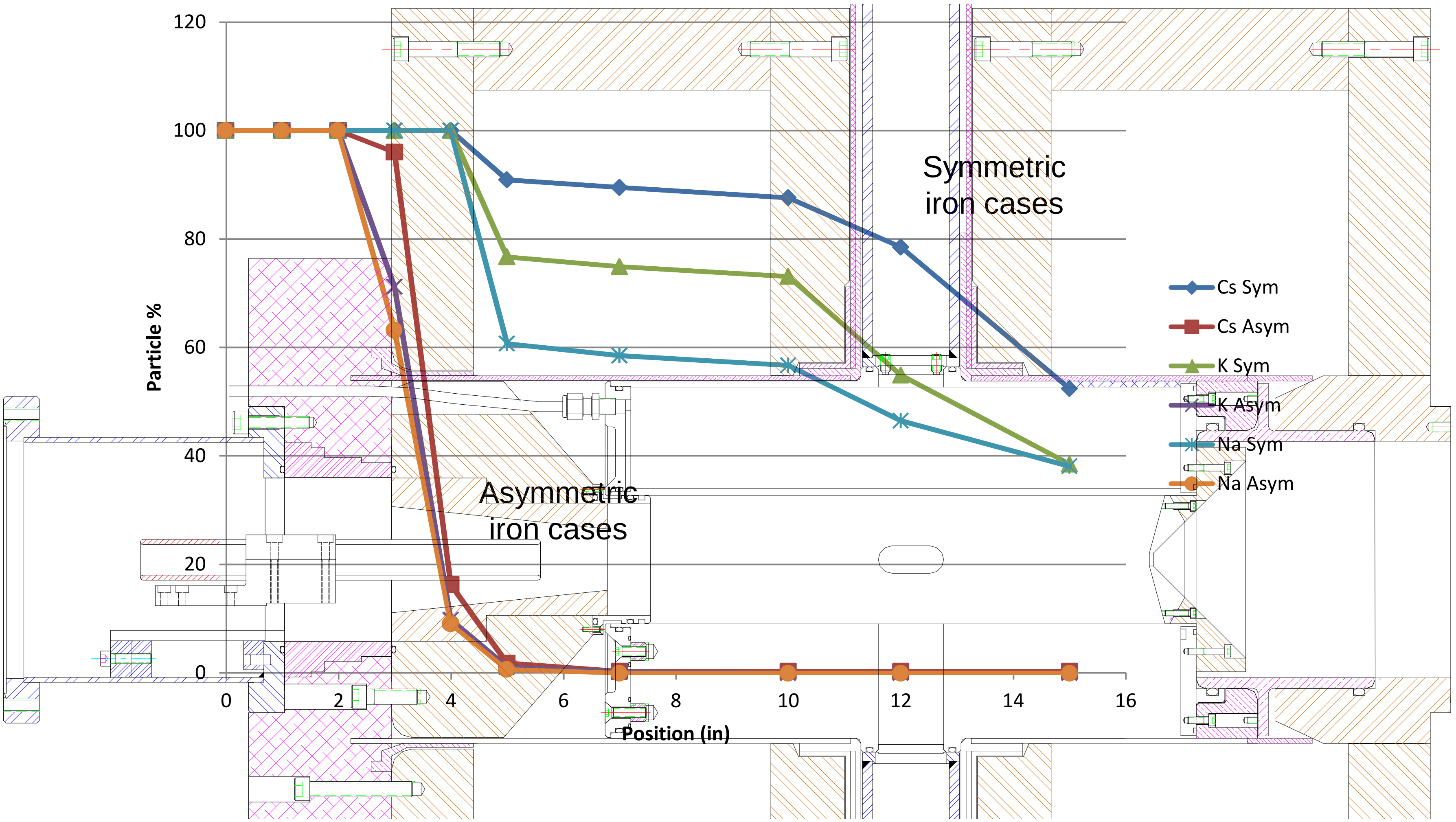
Injected ion penetration

- $^{133}Cs^{+}$ 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

Injected ion penetration

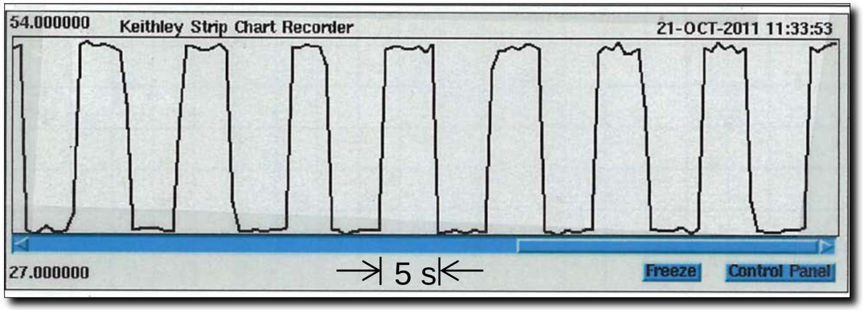


- $^{133}Cs^{+}$, $^{39}K^{+}$, $^{23}Na^{+}$ ions
- V_{1+}: 30 kV, ΔV: -10 V

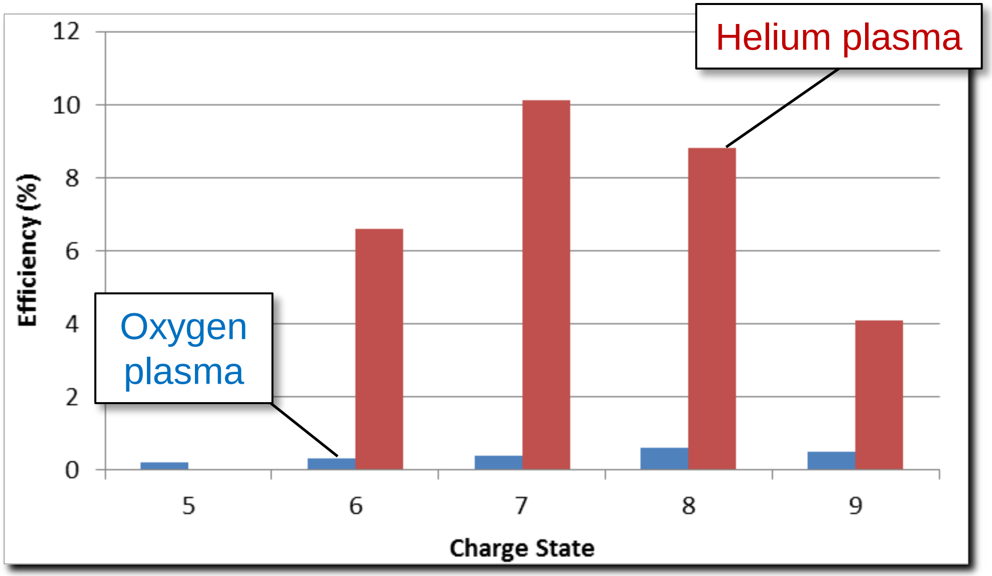
Low-A performance

- Potassium and sodium produced from surface ionization source
- Base pressure: 3.7 x 10^{-8} mbar
- Helium plasma: ~9.0 x 10^{-8} mbar
  - Adding oxygen reduced breeding efficiency
  - Using He-3 vs. He-4 made no difference in efficiency

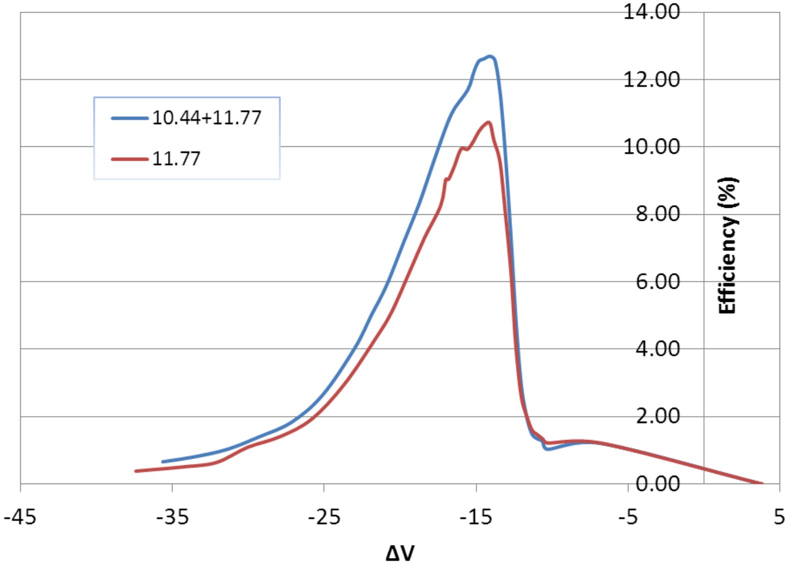
Ion	Charge State	Efficiency (%)	A/Q
^{23}Na	6+	6.6	3.83
	7+	10.1	3.29
	8+	8.6	2.87
	9+	3.4	2.56
^{39}K	7+	3.0	5.57
	8+	4.9	4.87
	9+	15.6	4.33
	10+	17.9	3.90



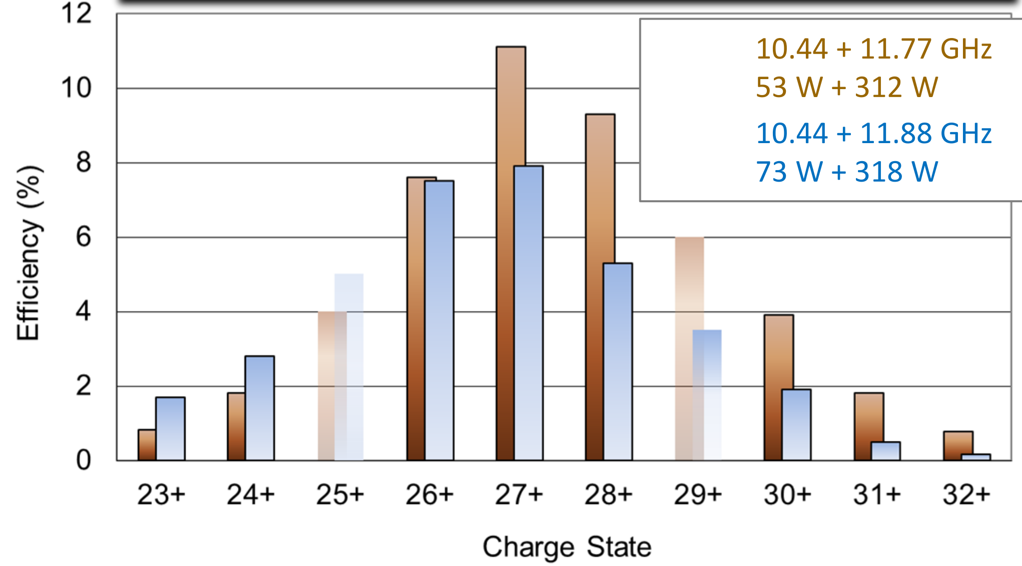
Response of $^{39}K^{10+}$ beam current to pulsing an incoming K^{+} beam with an intensity of 17 enA. Beam is pulsed with electrostatic steerer immediately after the surface ionization source.



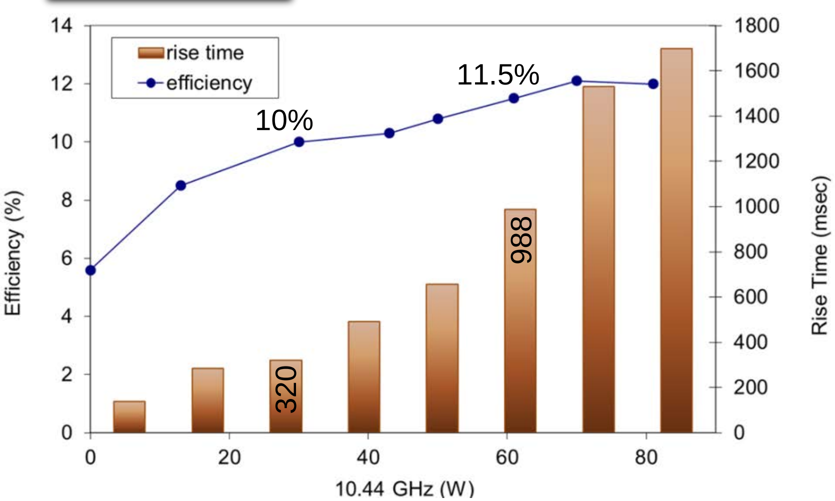
Charge breeding results



TWT frequency shift with Cesium

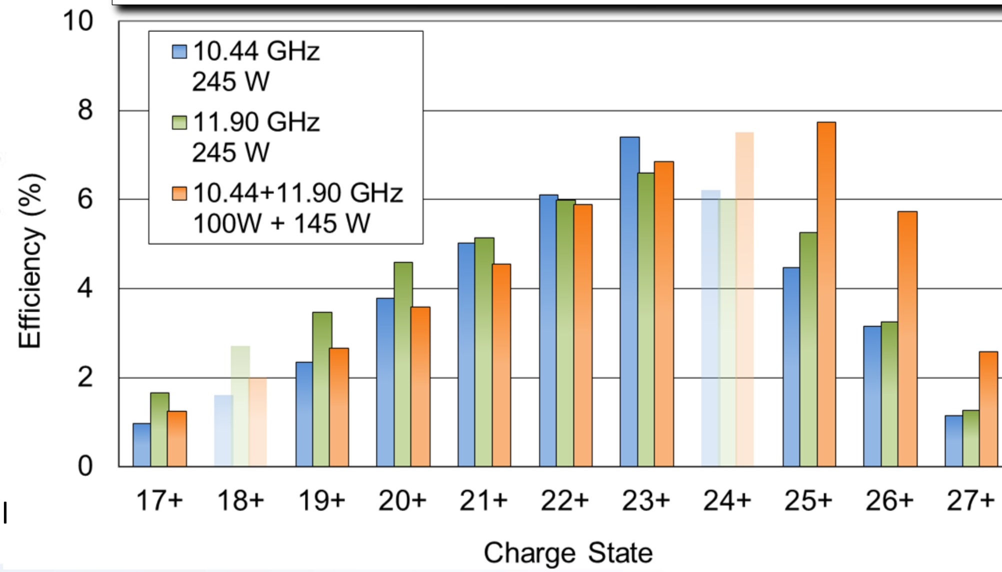


$^{85}Rb^{20+}$



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

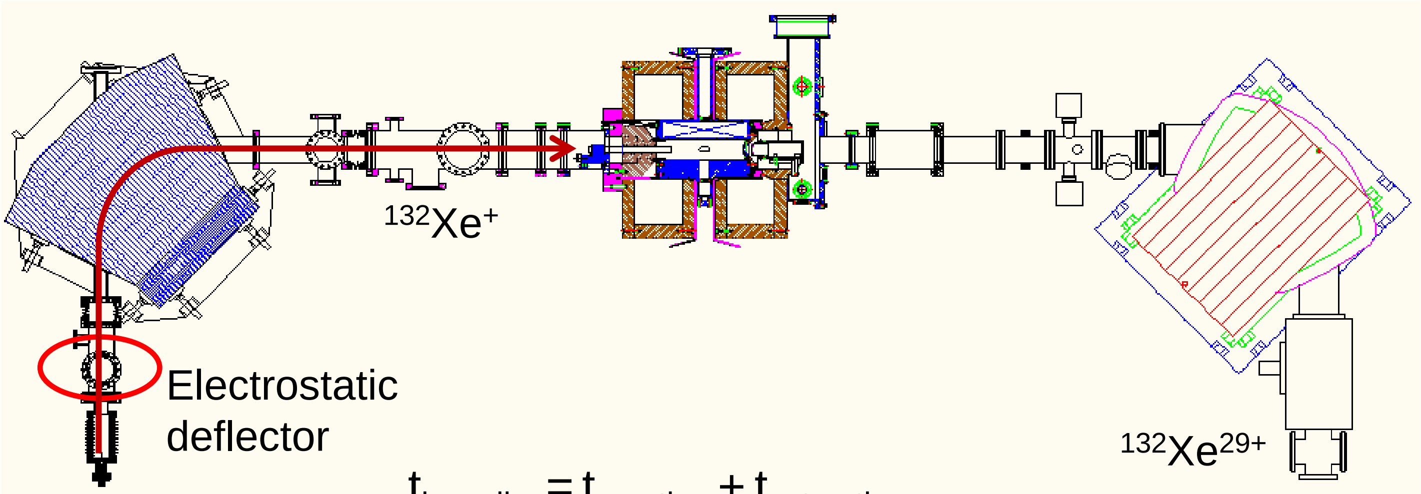
Two-frequency heating with Xenon



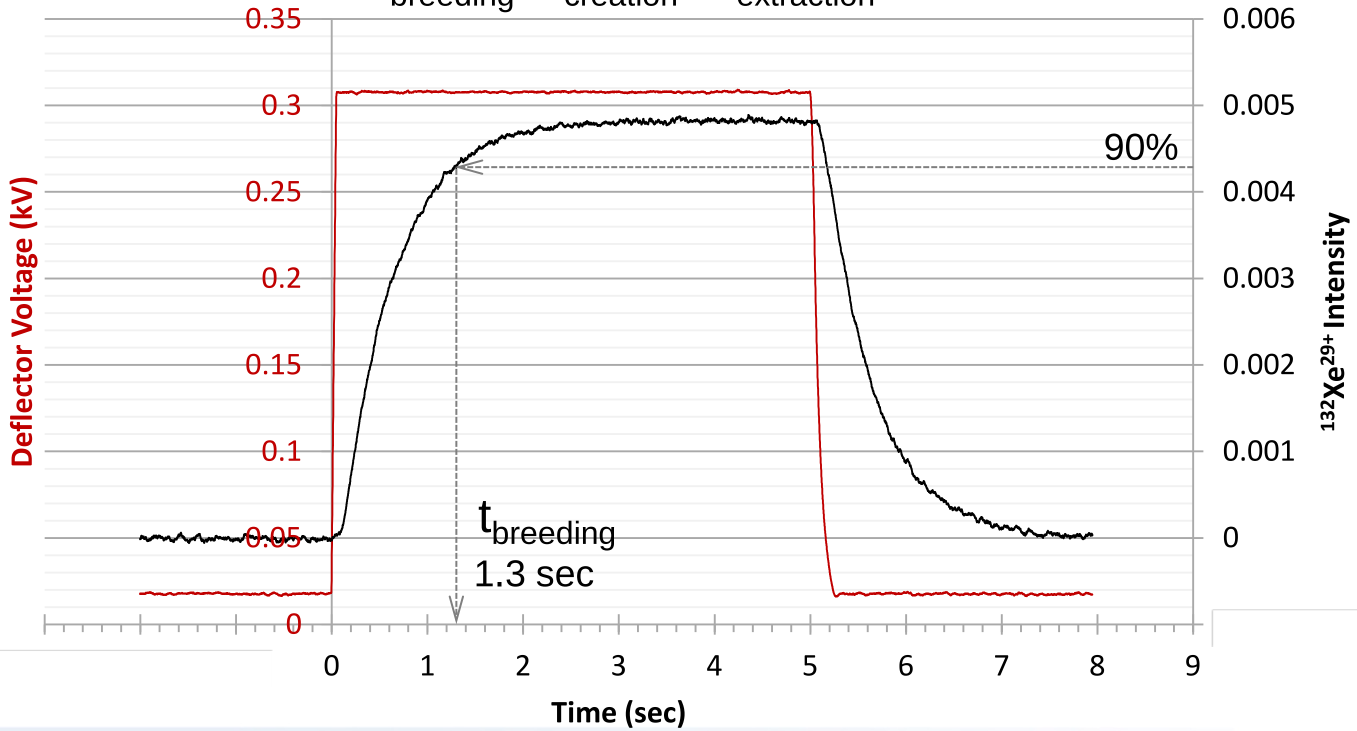
Charge breeding performance

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

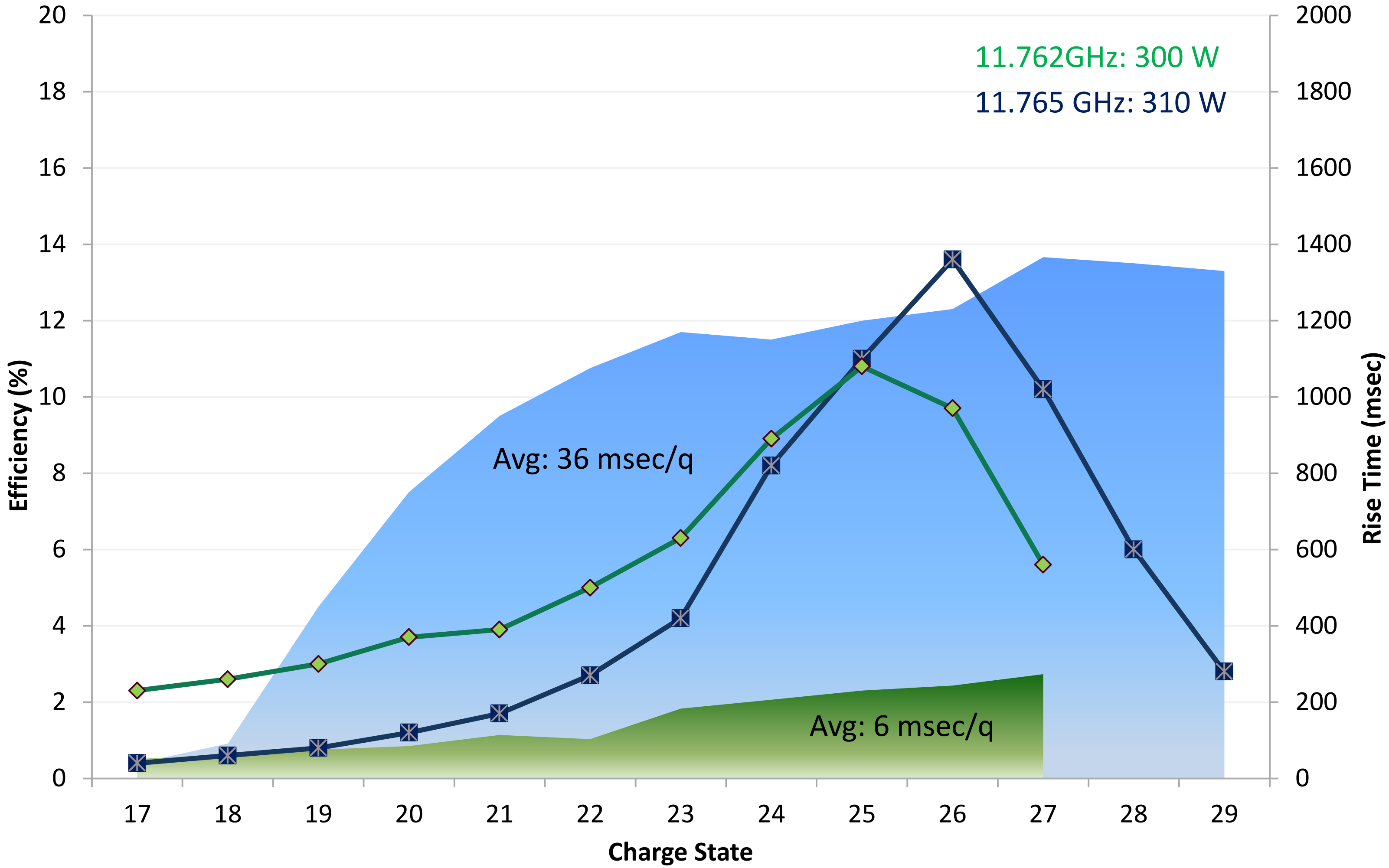


$t_{breeding} = t_{creation} + t_{extraction}$



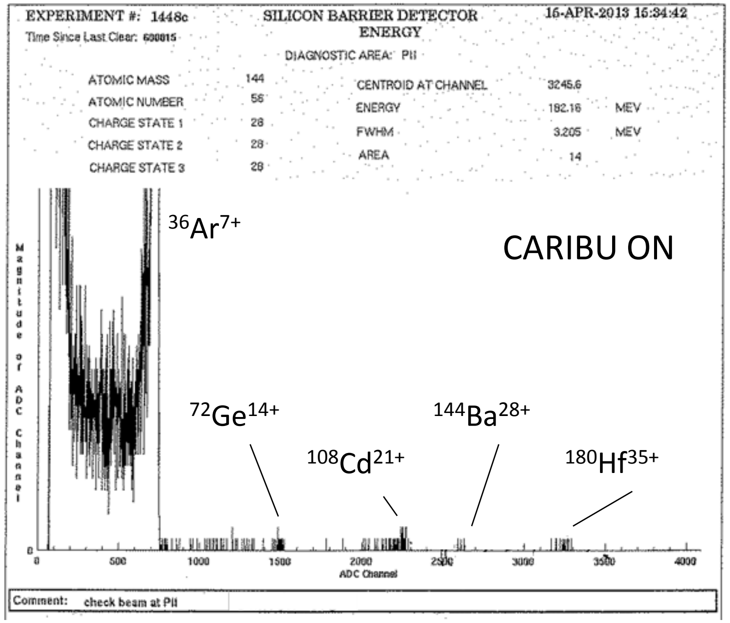
Breeding efficiency and rise time - RF frequency

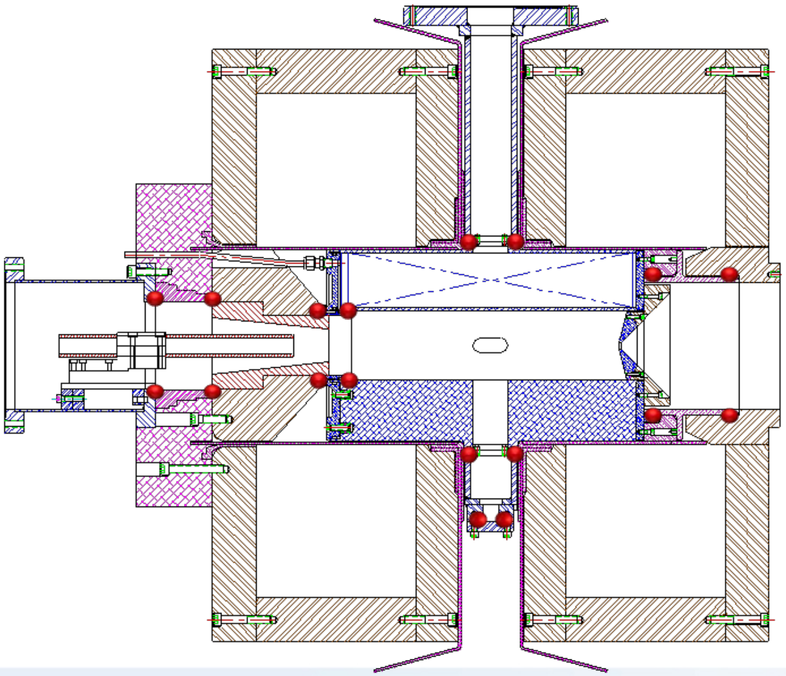
- Xe-132 from RF discharge source
- Oxygen plasma, single-frequency heating – TWTA only

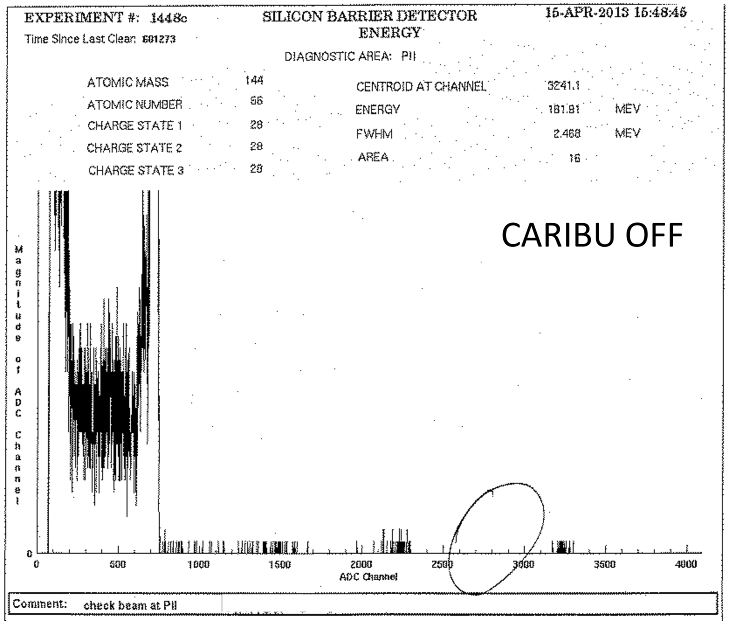


ECR contamination from air

- During $^{144}Ba^{28+}$ run we encountered a background beam of $^{36}Ar^{7+}$ with small amounts of $^{72}Ge^{14+}$, $^{108}Cd^{21+}$, $^{180}Hf^{35+}$
- Source of Ar-36
  - O-ring permeation
  - 17 Viton o-rings with cumulative leak rate of 3.0e-5 torr-l/s







ECR contamination from surfaces

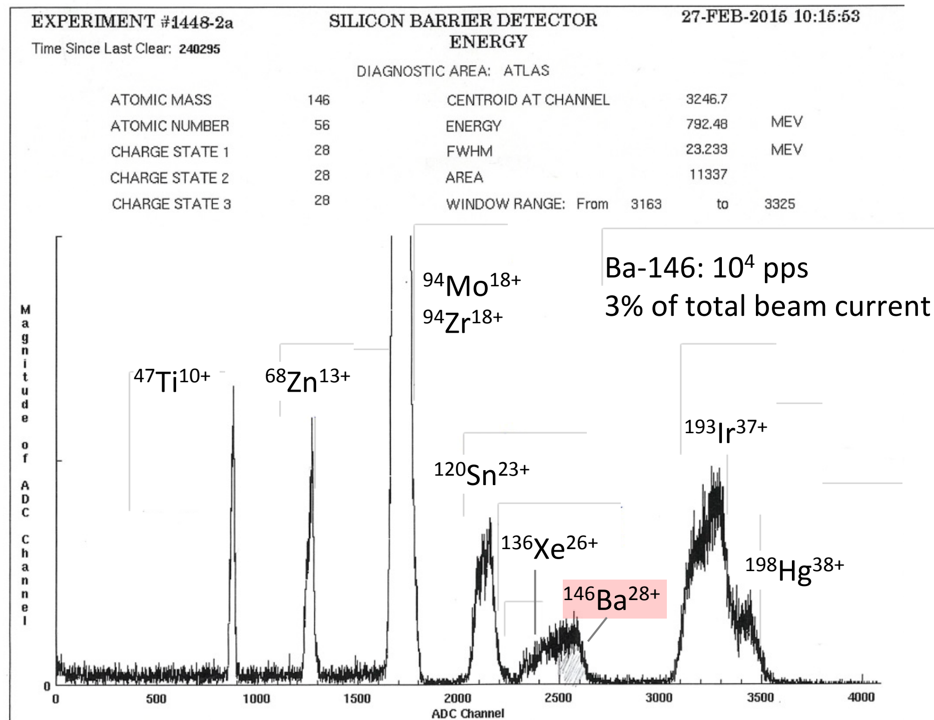
δBρ	Extraction Voltage, kV	Platform Voltage, kV	Atomic # or Symb.	Atomic Mass (p+n)	Charge State	$M_0/\delta M$ Threshold:	300.0
0.010	36.000	130.000	ba	146	28	Include Radioactive Ions y/n (default - y):	n
						(Optional)	

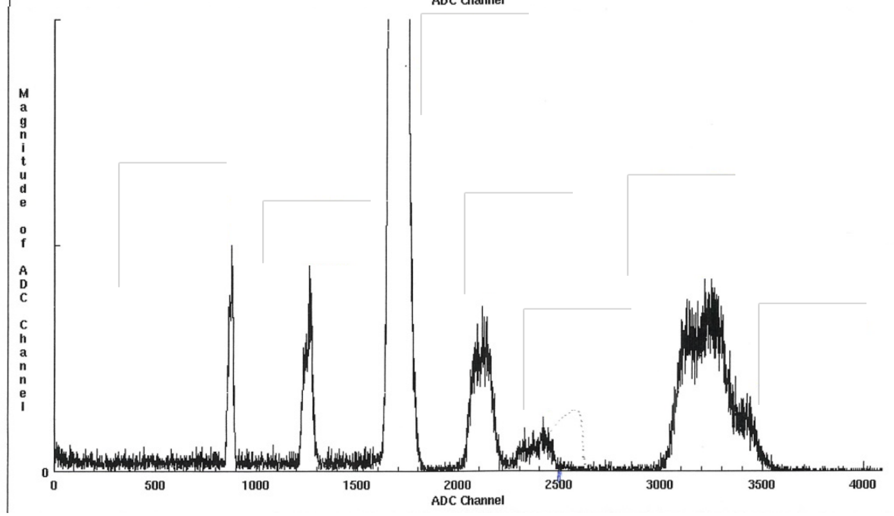
Calculate

Ion Atomic Number:	56
Central Ion Mass:	145.93028
Magnet Radius, m:	0.400
Total flight time, nsec.:	9582.83

Beam Rigidity, kG-m:	0.6248284
Mag. Field, kG:	1.5620710
Upper Bρ, kG-m:	0.63108
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

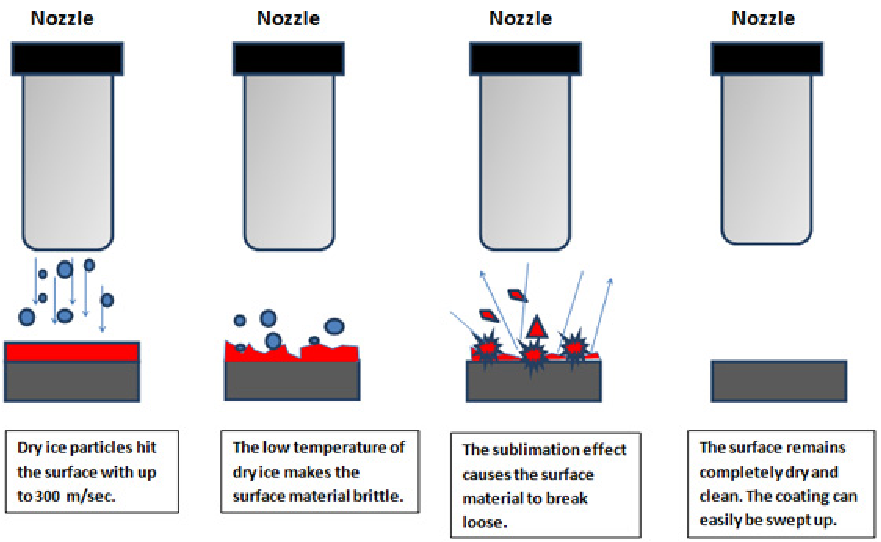


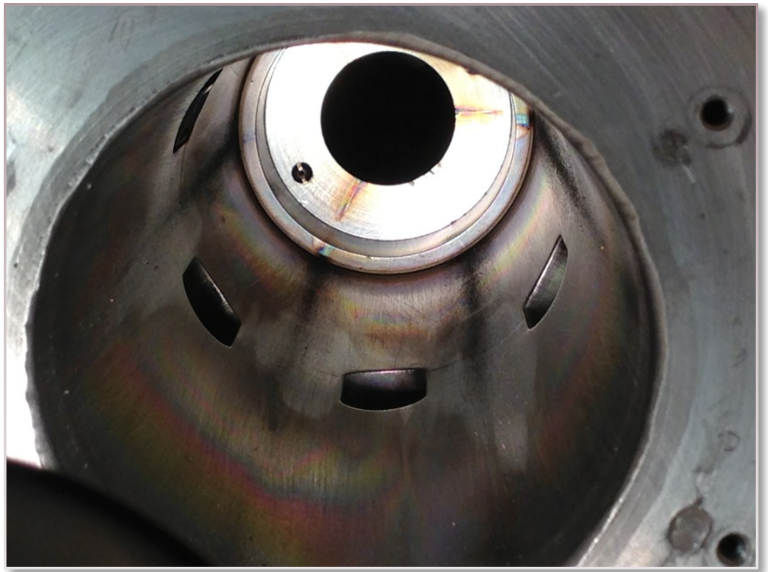


Background reduction

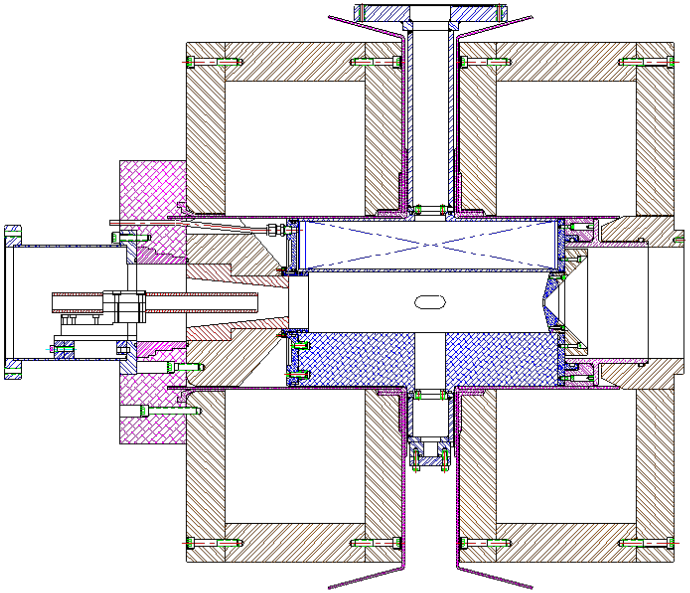
- Solid species – surface and bulk contamination
  - Plasma chamber liners
  - Sand blasting
  - High-pressure rinsing
  - CO_2 “snow” cleaning
  - High-purity aluminum coating

Chemical Element	% Present
Magnesium (Mg)	0.80 - 1.20
Silicon (Si)	0.40 - 0.80
Titanium (Ti)	0.0 - 0.15
Chromium (Cr)	0.04 - 0.35
Manganese (Mn)	0.0 - 0.15
Iron (Fe)	0.0 - 0.70
Copper (Cu)	0.15 - 0.40
Zinc (Zn)	0.0 - 0.25
Aluminium (Al)	Balance

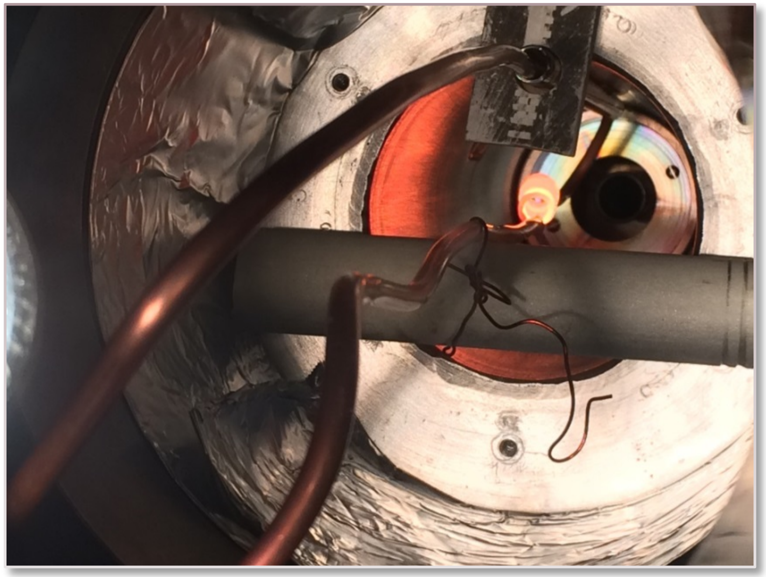


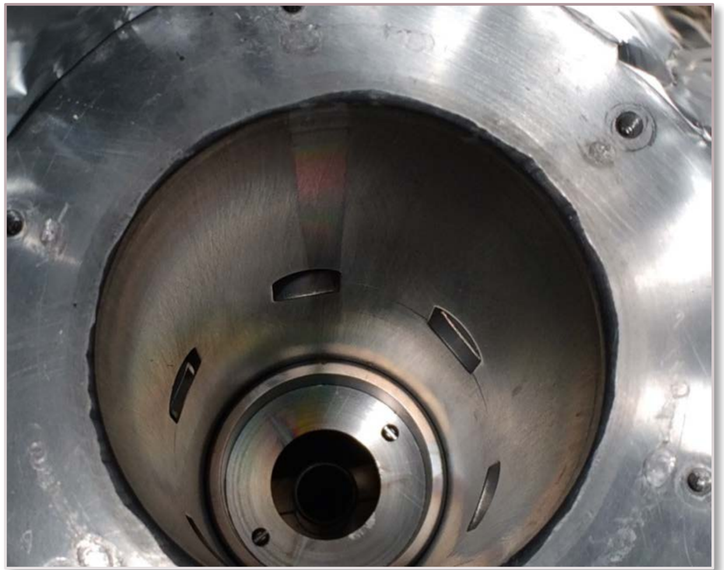


Background reduction - Aluminum coating

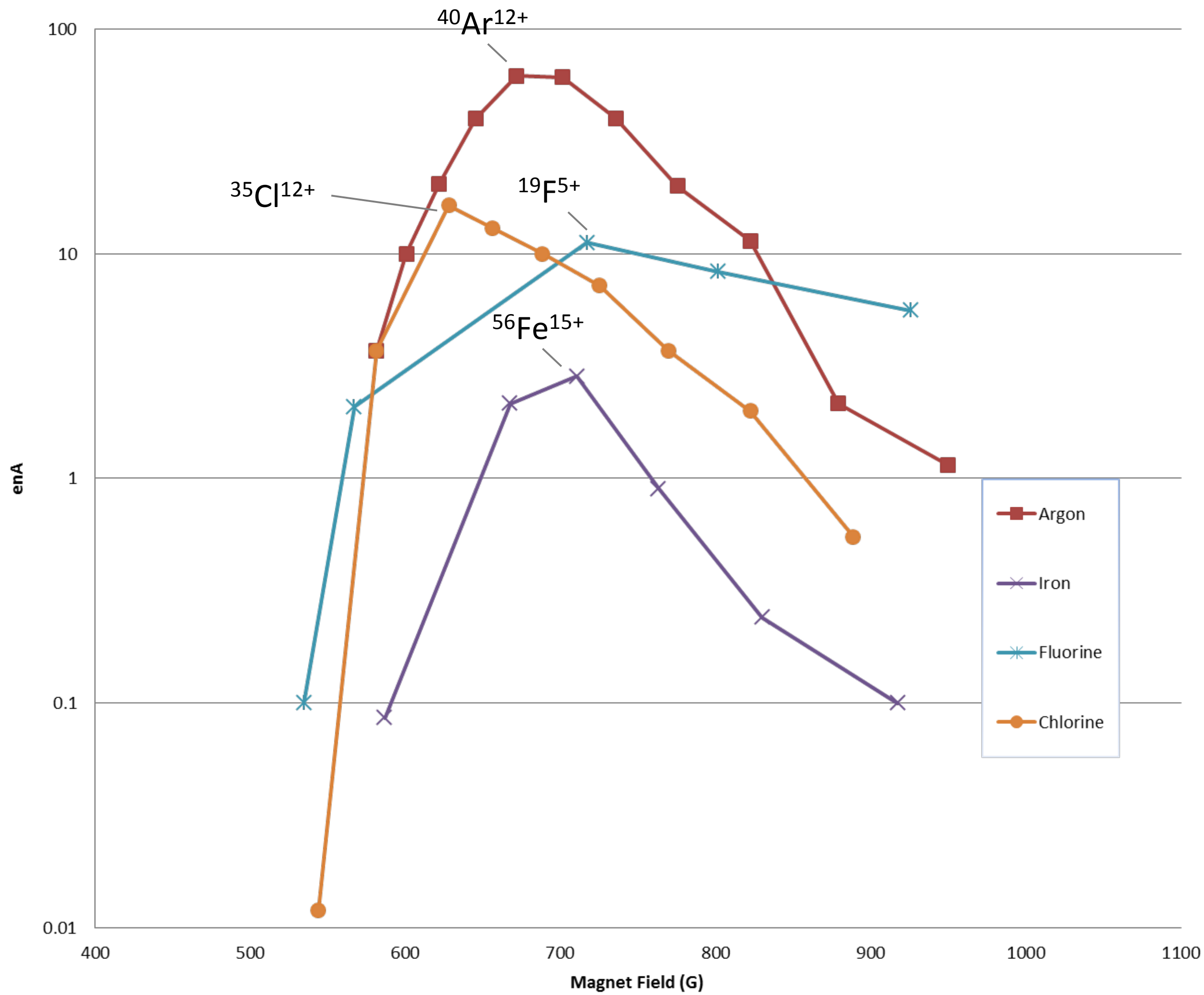


- Cleaned chamber with CO_2
- Used W coil with high-purity (99.999%) aluminum wire
- Source pressure: 5.0e-7 Torr
- Wall covered with 1 micron layer
- Vented to oxygen
- Not all surfaces were adequately coated

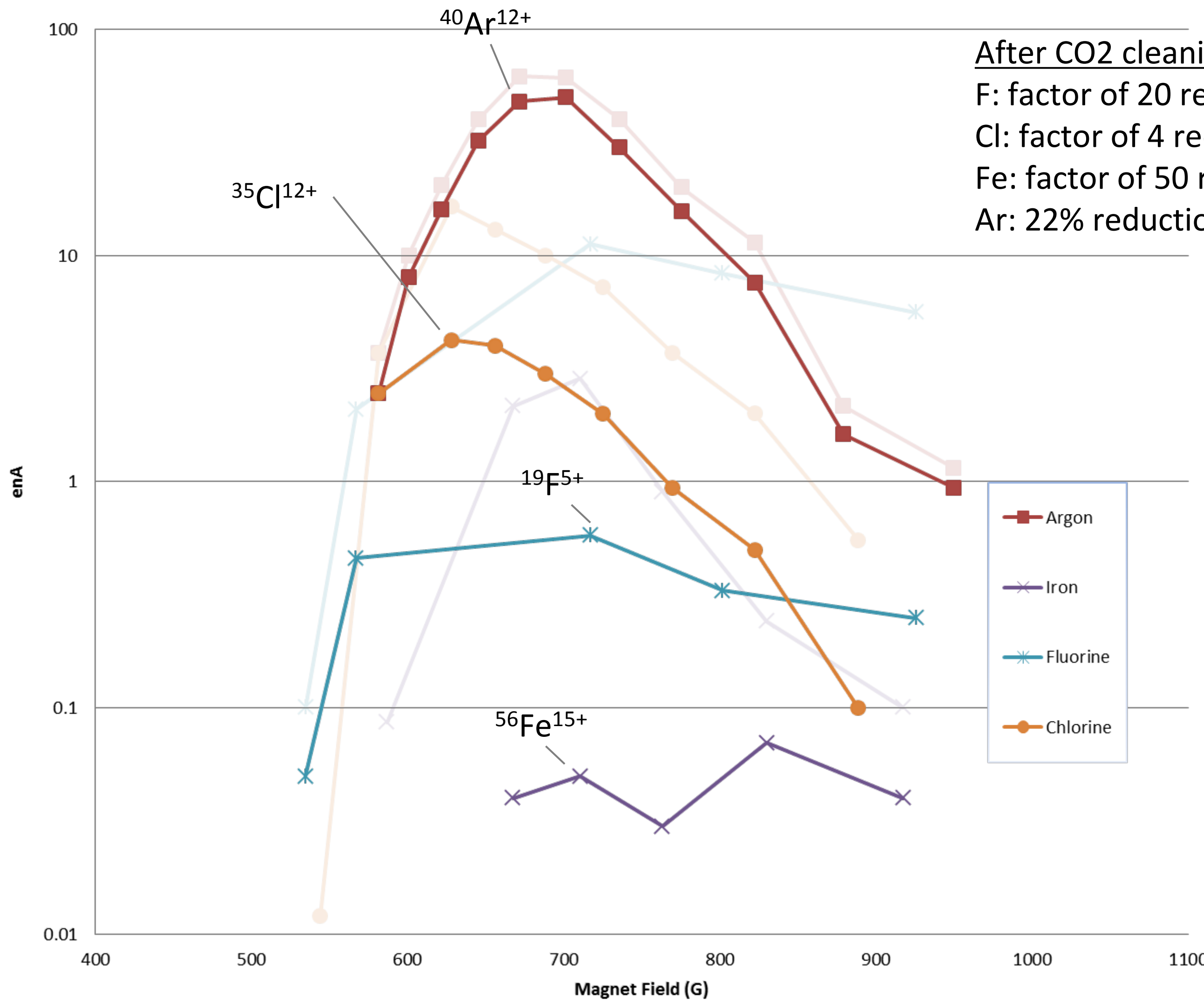




Background reduction - CO_2 cleaning

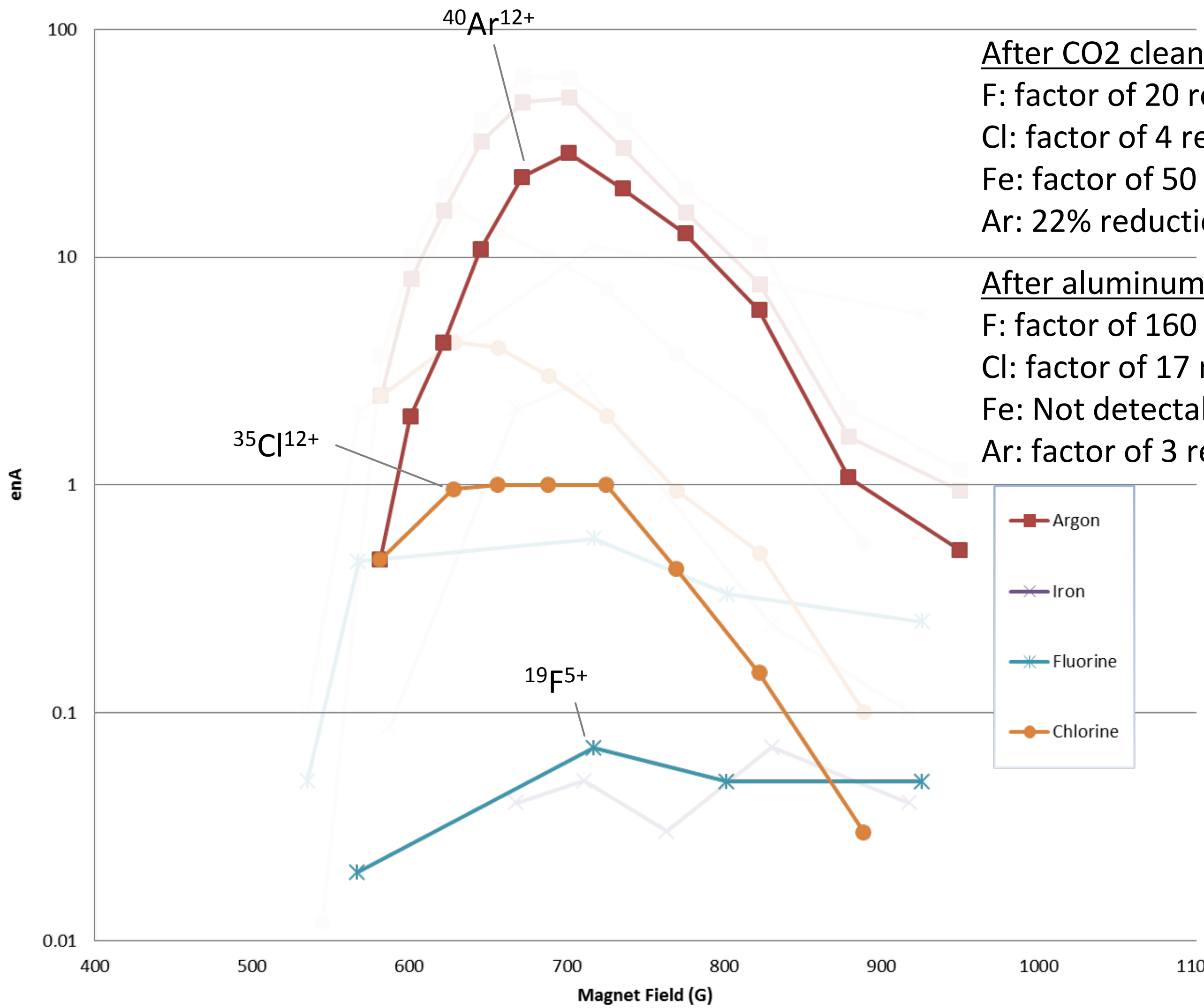


Background reduction - CO_2 cleaning



<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



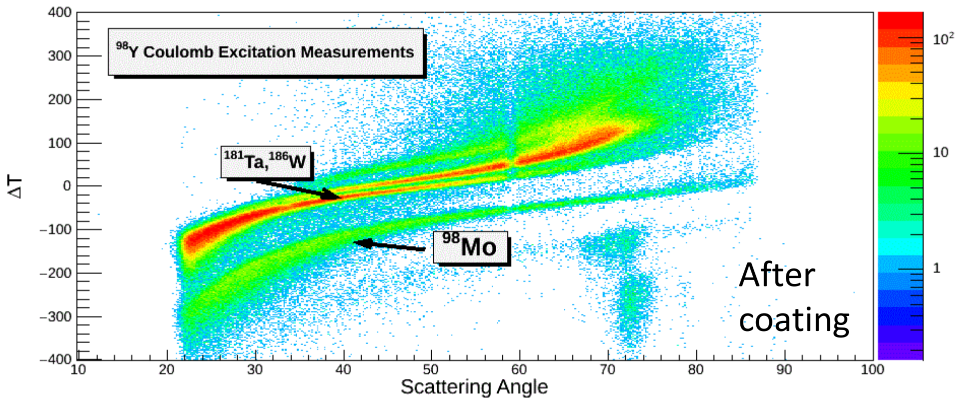
<u>After CO2 cleaning</u>

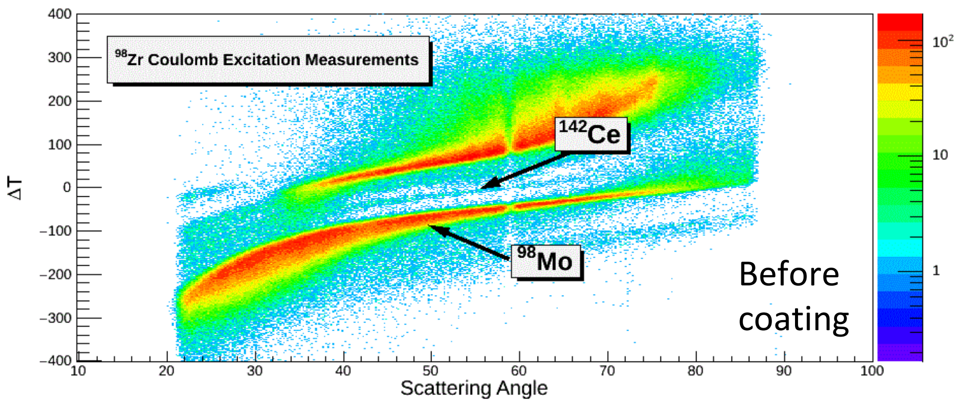
F: factor of 20 reduction
Cl: factor of 4 reduction
Fe: factor of 50 reduction
Ar: 22% reduction

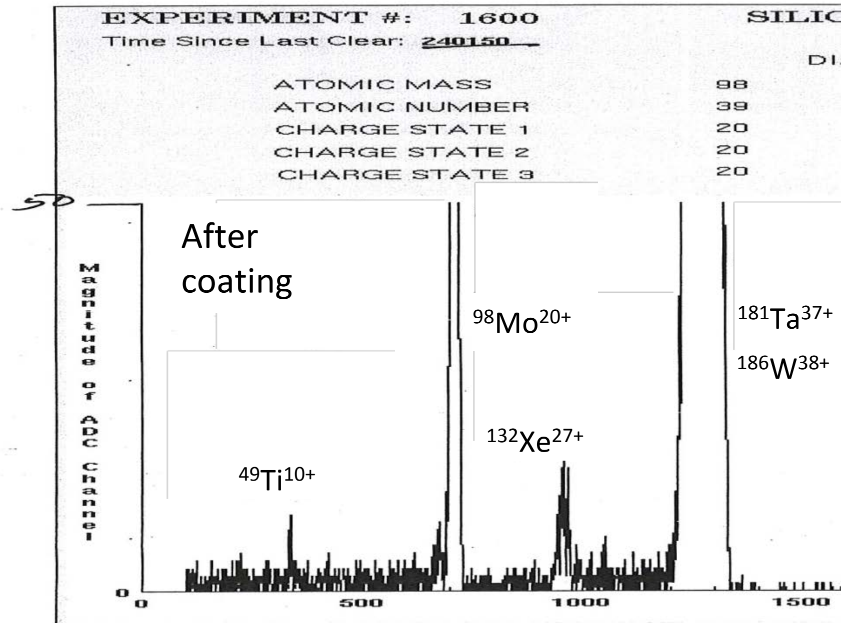
<u>After aluminum coating</u>

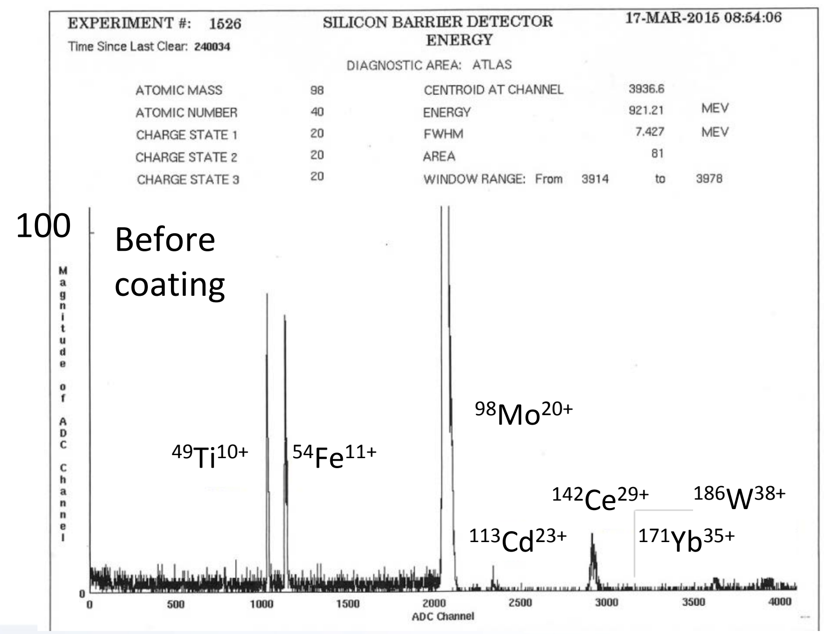
F: factor of 160 reduction
Cl: factor of 17 reduction
Fe: Not detectable
Ar: factor of 3 reduction

Reduction on target



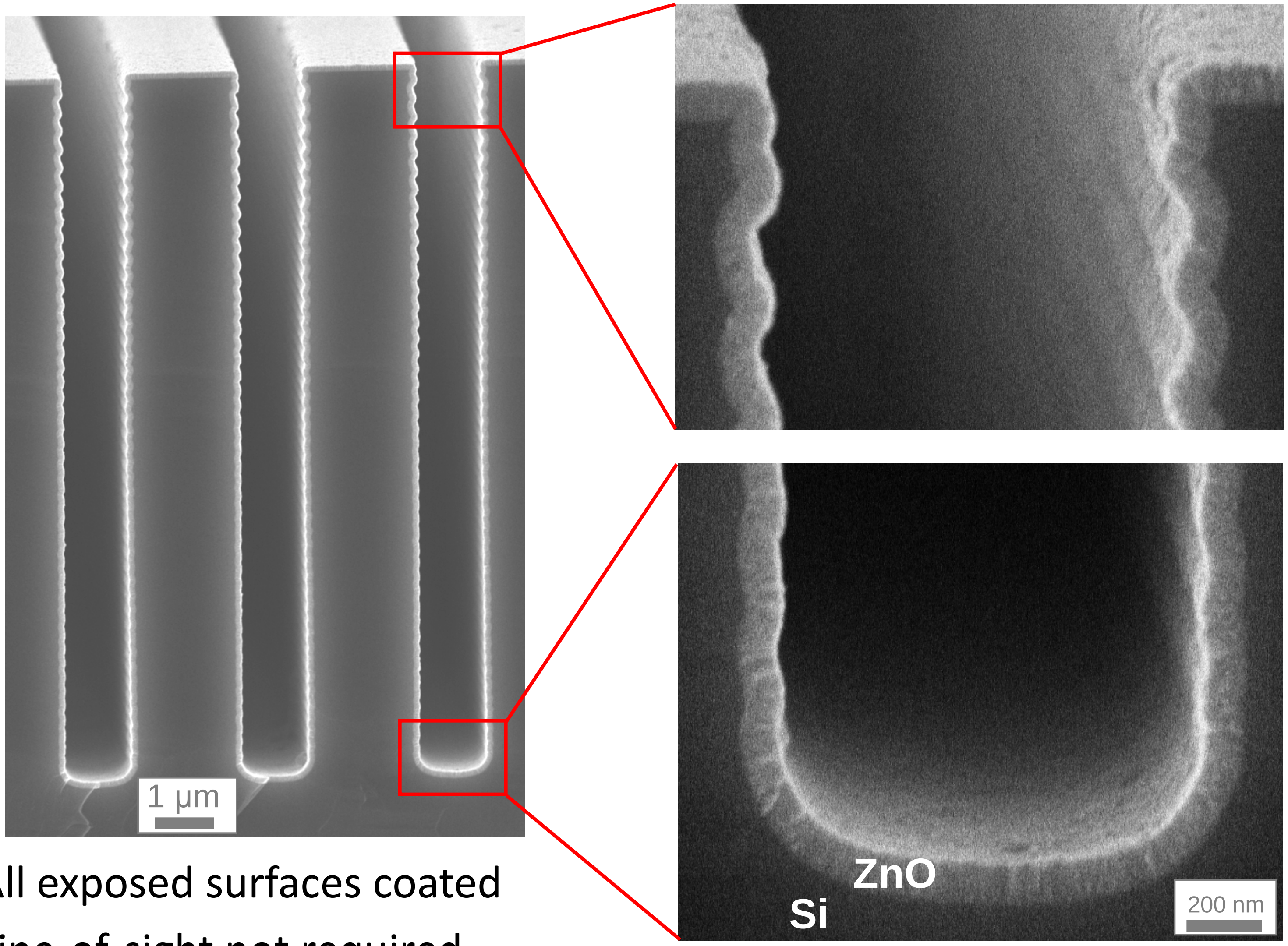






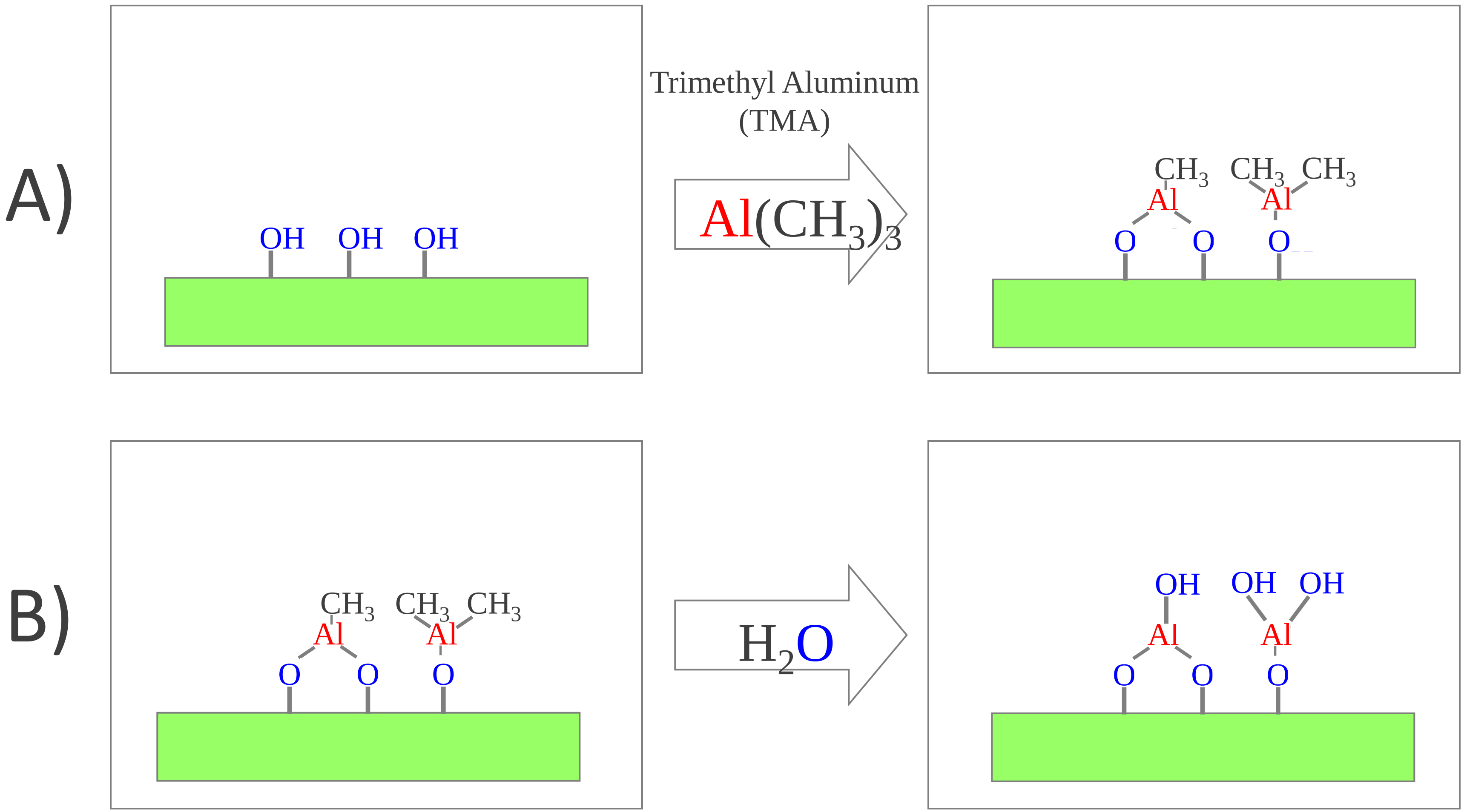
- Some contaminants were eliminated
- Mo-98 was reduced by x5 (on target)
- New contaminants Ta-181 & W-186
- Investigating new techniques

Conformal coatings by Atomic Layer Deposition



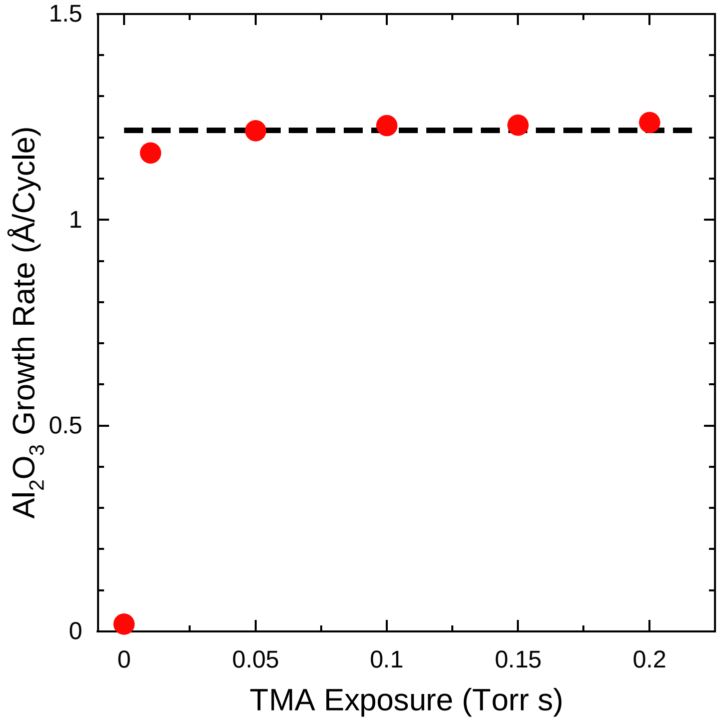
- All exposed surfaces coated
- Line-of-sight not required

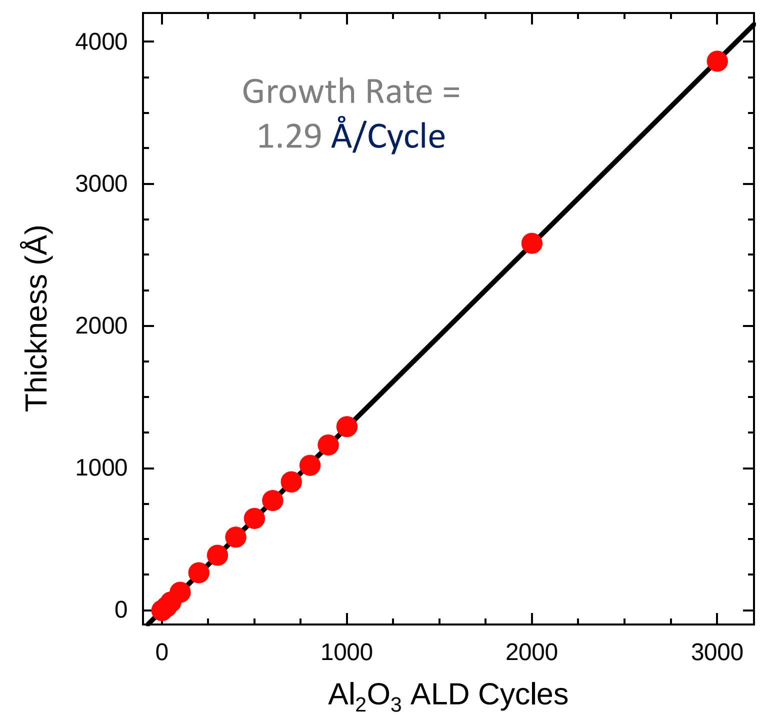
Atomic Layer Deposition of Al_2O_3



- 1 ALD Cycle of TMA/H_2O Deposits 1 Al_2O_3 "Monolayer"
- Process can be done in situ
- Care has to be taken with exposed surfaces

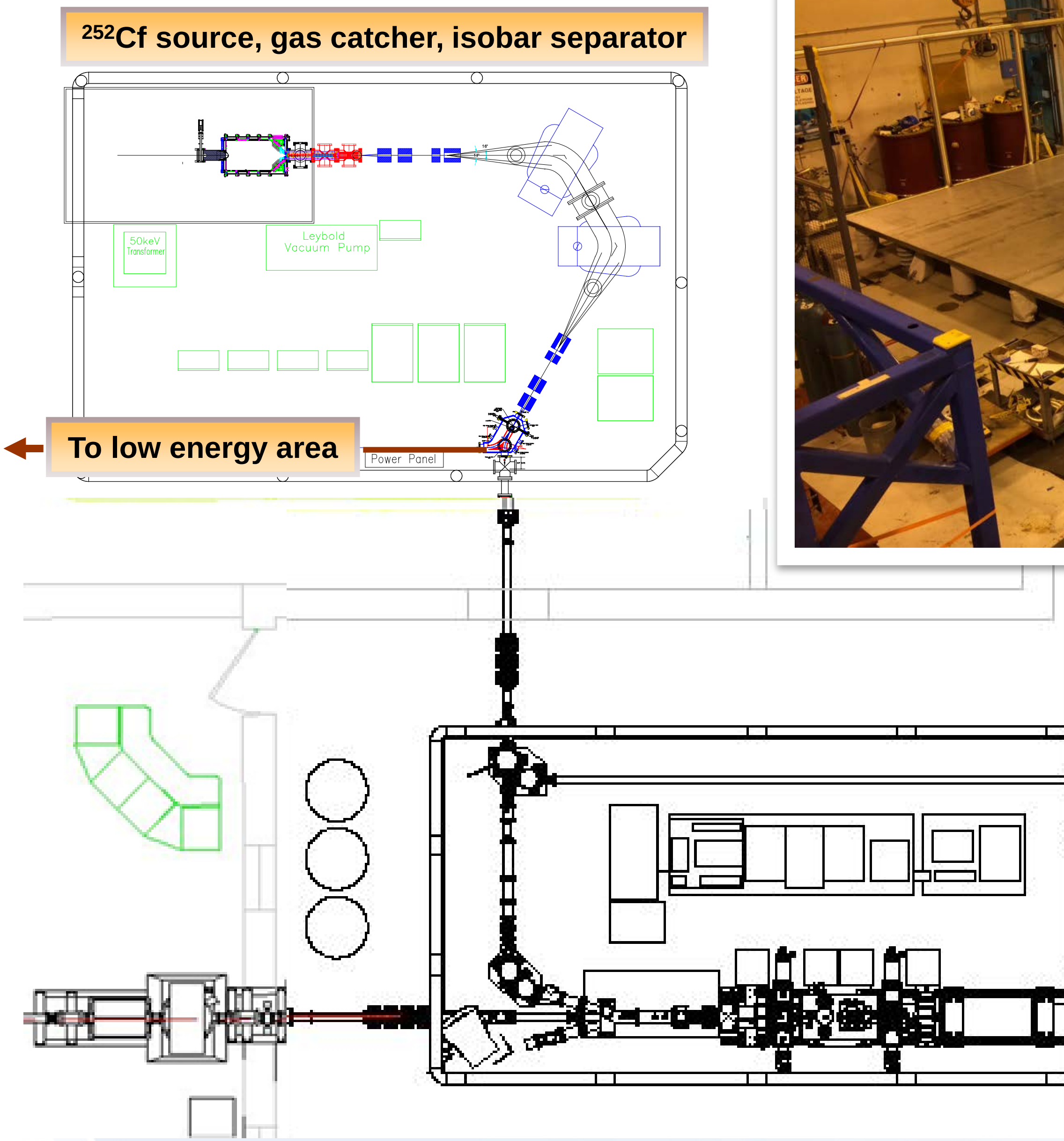
Characteristics of ALD Process



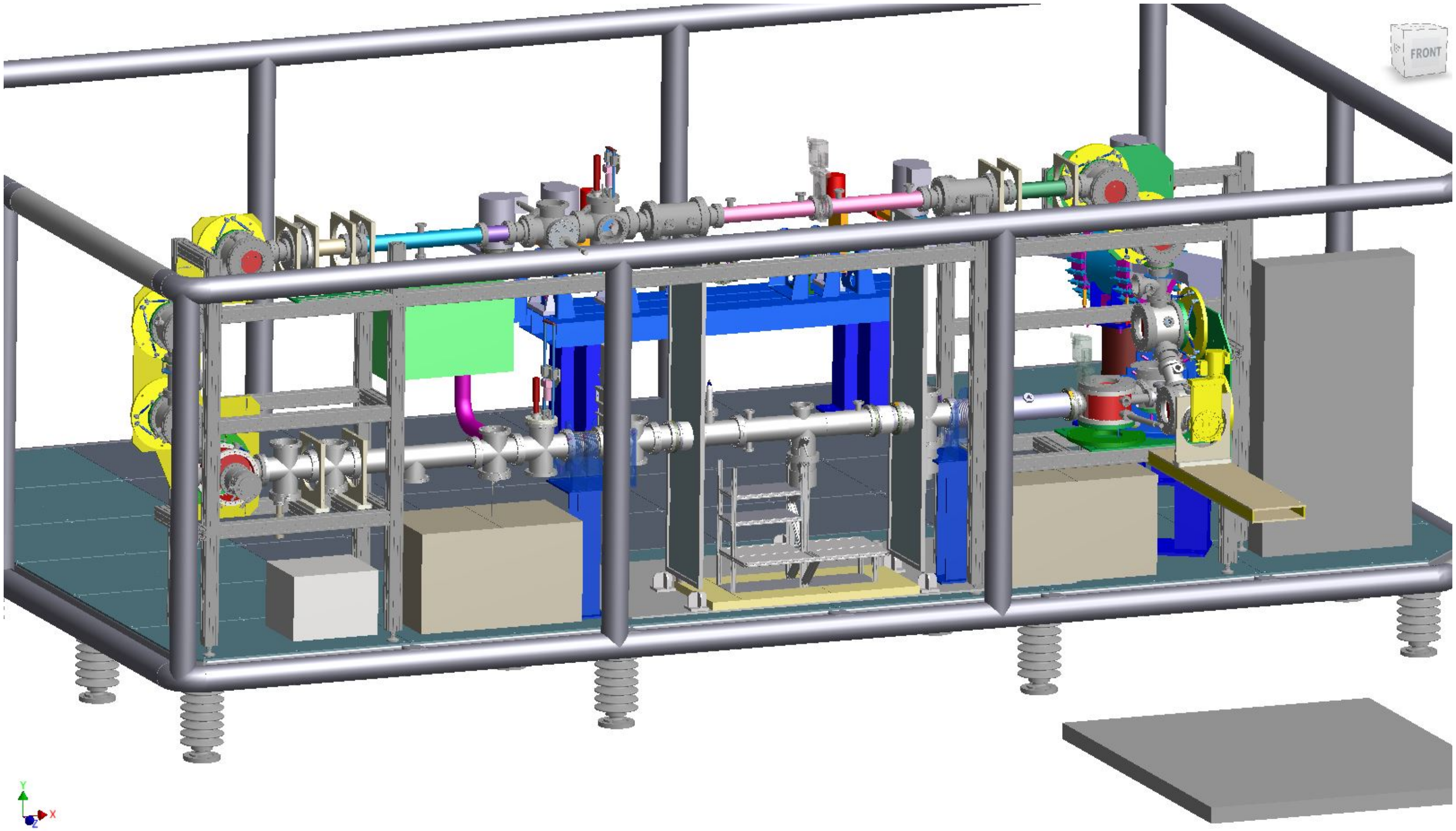


- Self-terminating surface reactions
- Film thickness is linear with ALD cycles
- To achieve 1 micron thickness will require 7751 cycles at 1 minute/cycle
- Possible path to coating all surfaces responsible for source contamination with a surface which is beneficial to source performance

CARIBU - Californium Rare Ion Breeder Upgrade



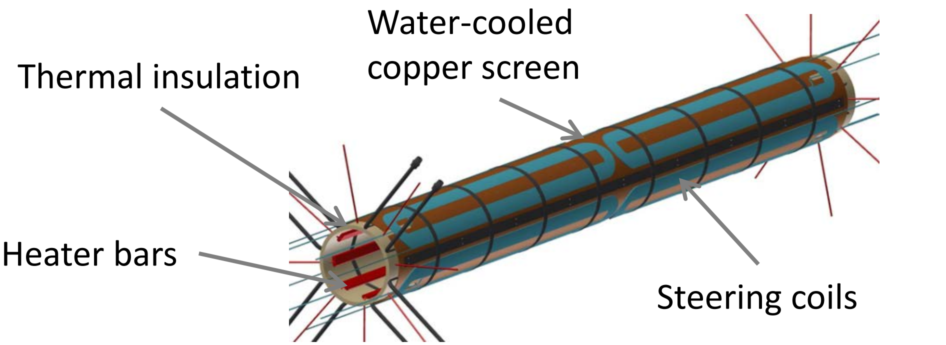
CARIBU system with RF cooler/buncher & MR-TOF

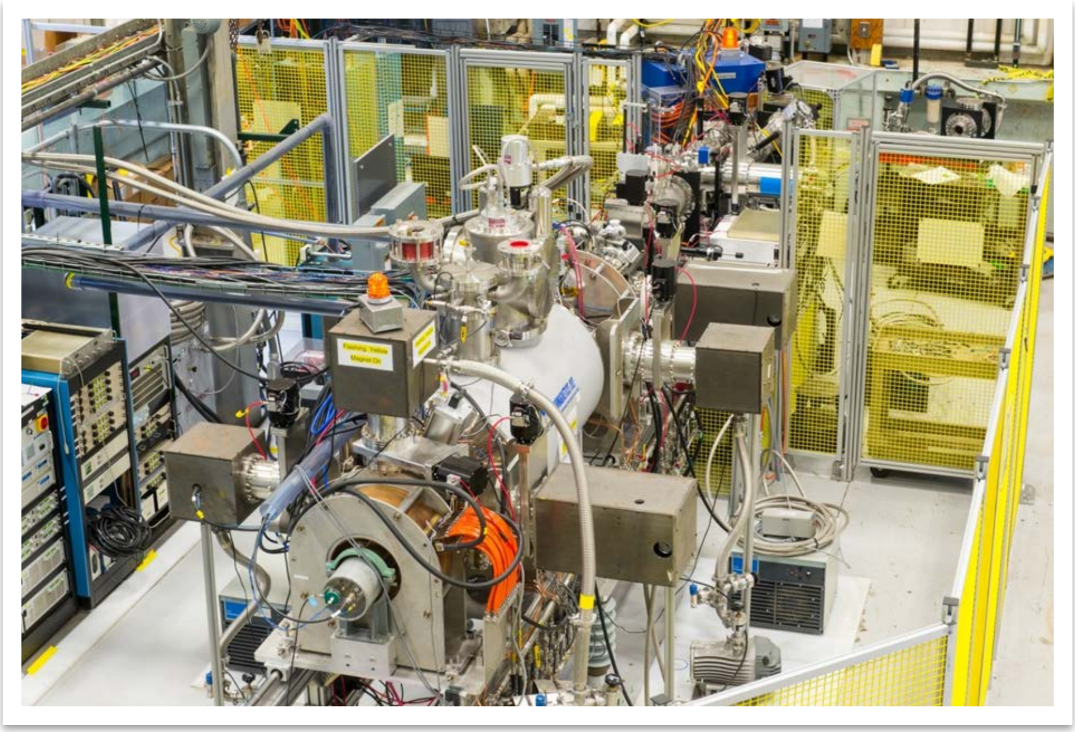


- Had to fit onto existing high voltage platform
- All electrostatic transport line

EBIS charge breeder

- Based upon RHIC Test EBIS design
- EBIS was commissioned off-line
- EBIS has been moved on-line and we expect to have the EBIS system operational in May2016

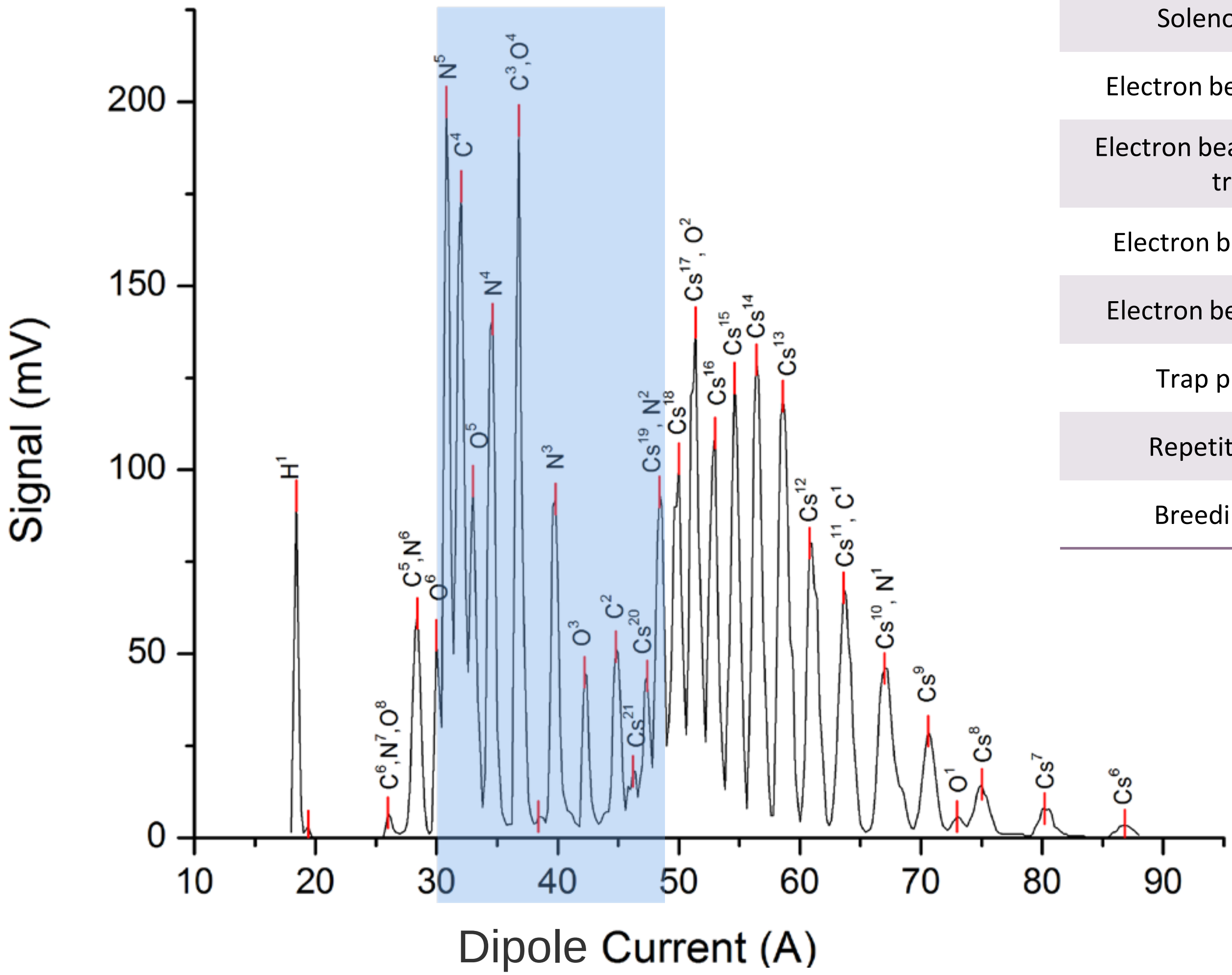




EBIS design parameters

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 %

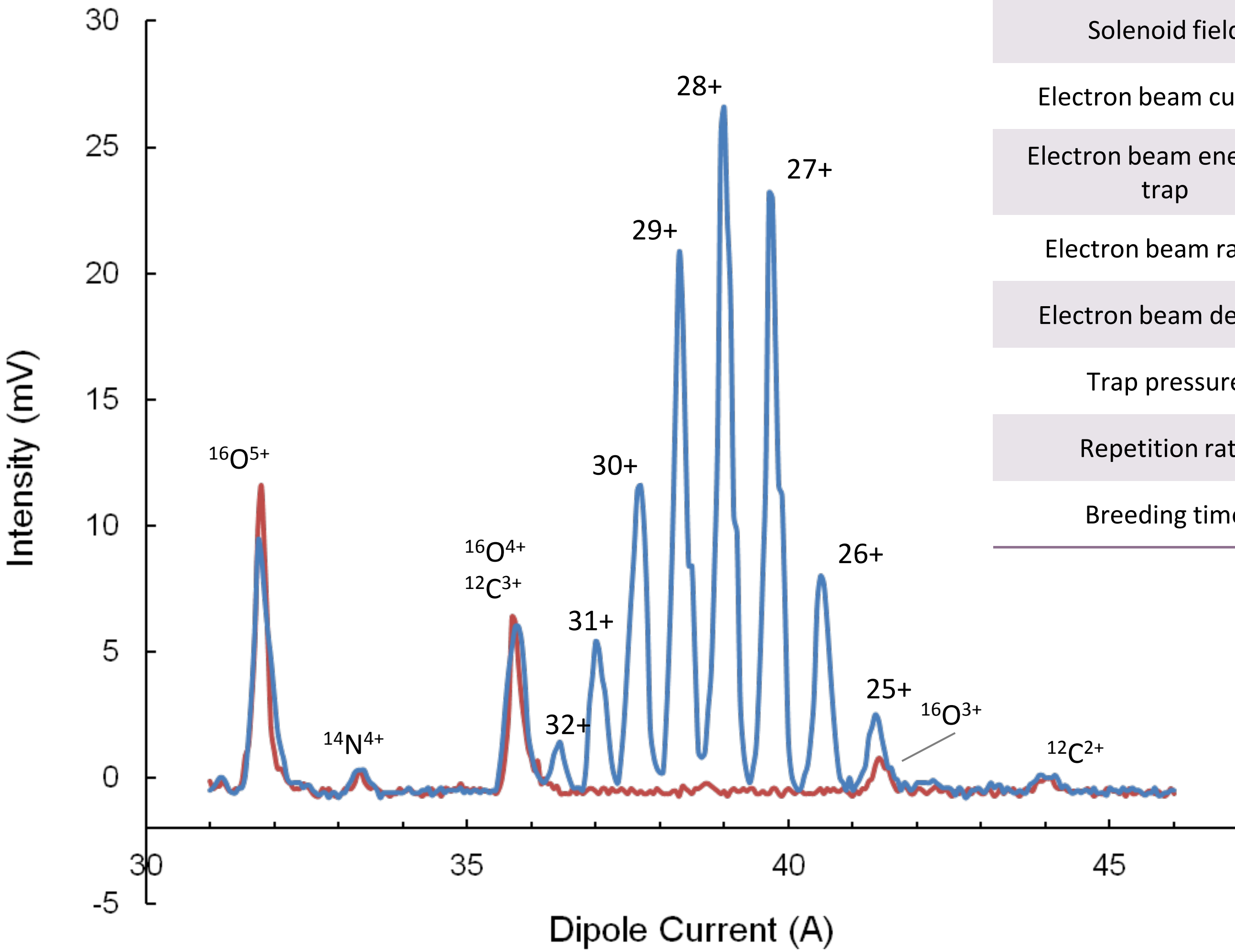
Charge bred cesium



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

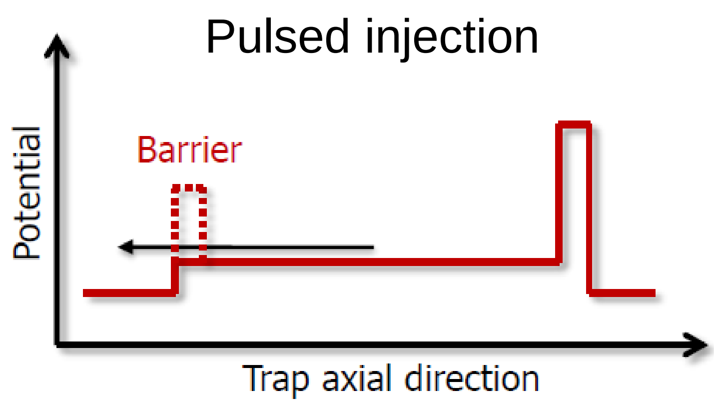


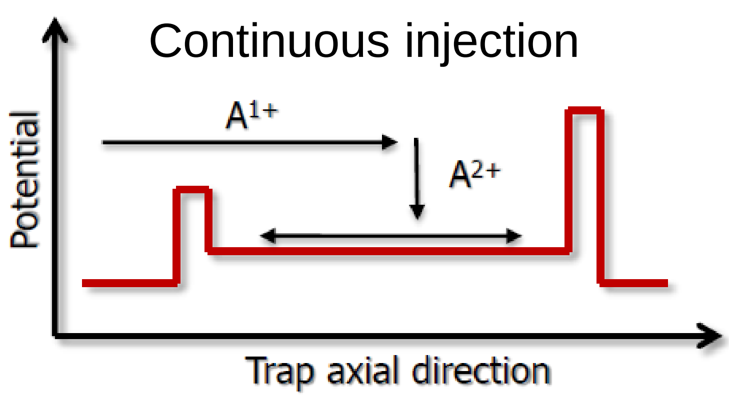
EBIS operational parameters	
Solenoid field	5 T
Electron beam current	1.6 A
Electron beam energy in trap	6.5 keV
Electron beam radius	370 µm
Electron beam density	385 A/cm^2
Trap pressure	~8.0x10^{-10} Torr
Repetition rate	10 Hz
Breeding time	28 ms

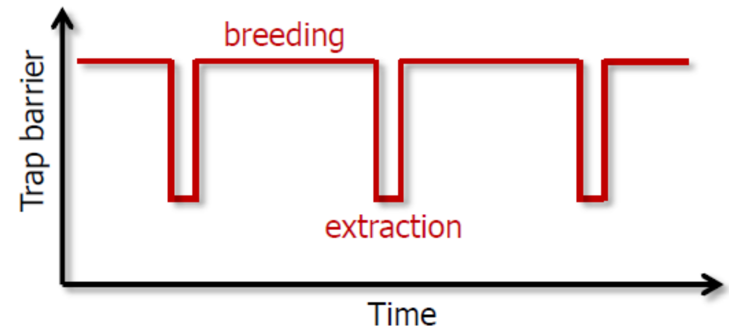
- Latest results – several small leaks fixed, system baked out
- 28% breeding efficiency into $^{133}Cs^{28+}$

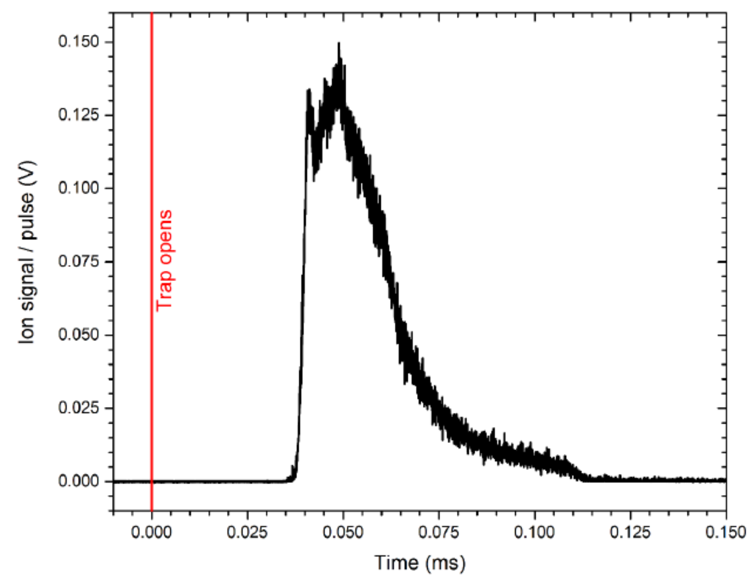
Ion injection and extraction

- EBIS is an inherently pulsed device
  - Typical extraction pulse is 10-20 µs
  - REX-ISOLDE “15 minutes of delivered beam in every 24 hours of beam time”
  - Plenty of time between bunches to do other things



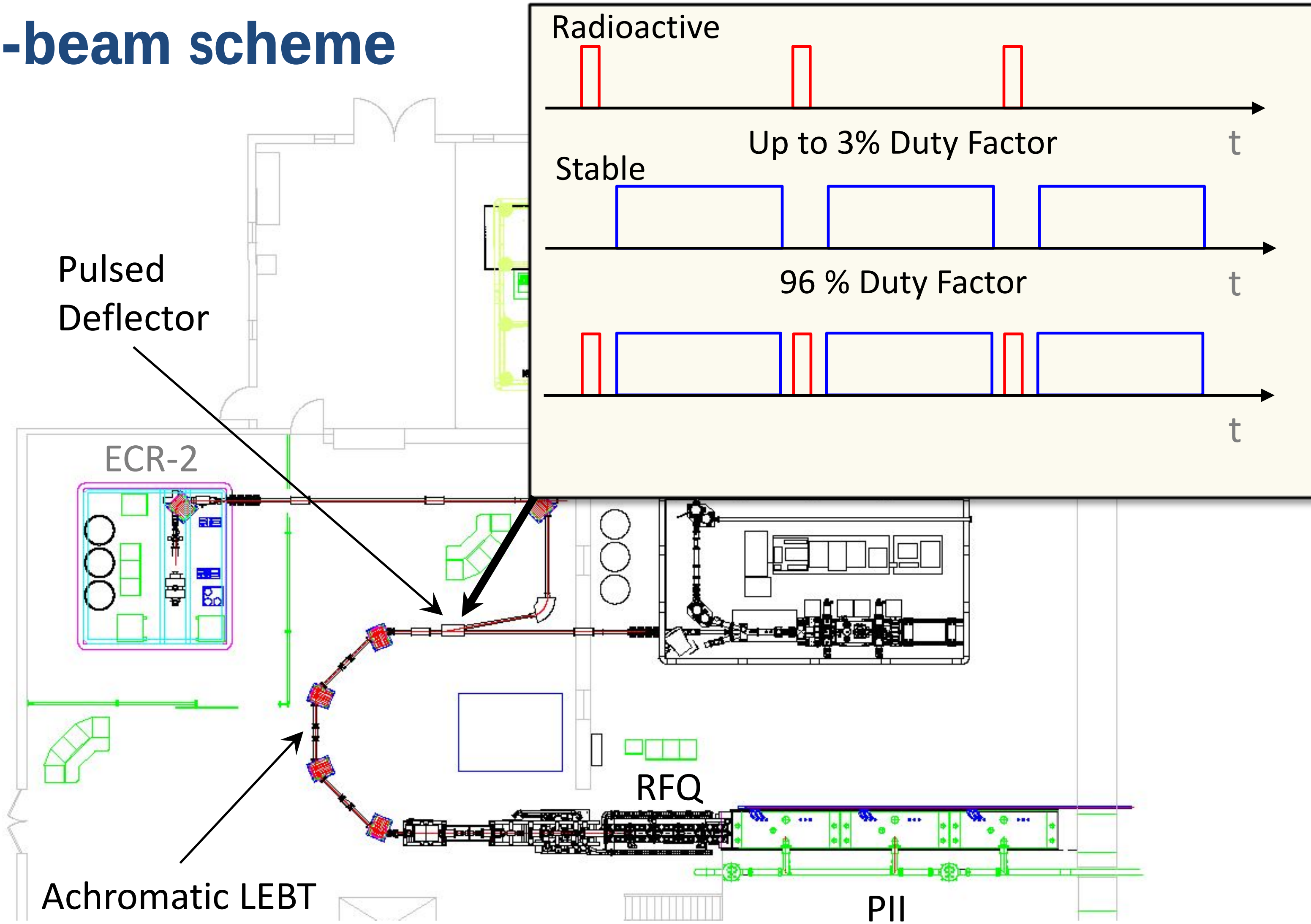






Courtesy of T. Baumann, NSCL, MSU

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

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
  - Even with background, many successful experiments

- Installation of the EBIS charge breeder is progressing
  - Demonstrated 28% breeding efficiency in off-line tests
  - New high voltage platform is complete
  - EBIS system should be operational in May 2016