The 16th International Conference on Ion Sources

Off-line Commissioning of EBIS and Plans for Its Integration into ATLAS and CARIBU

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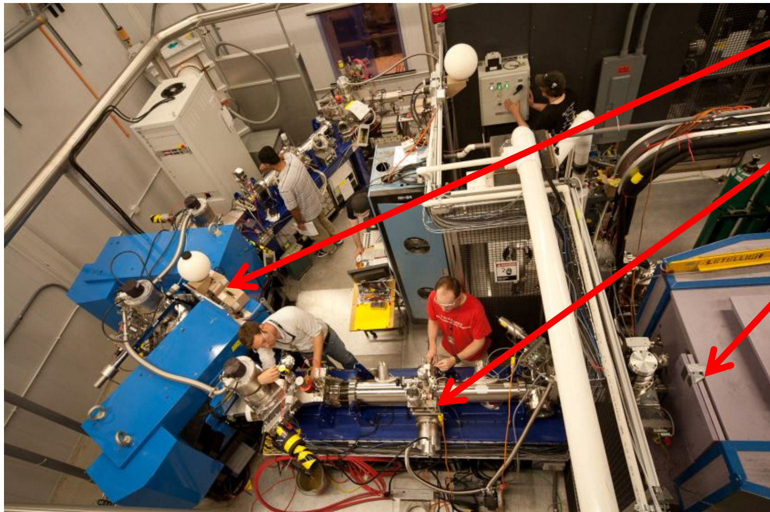
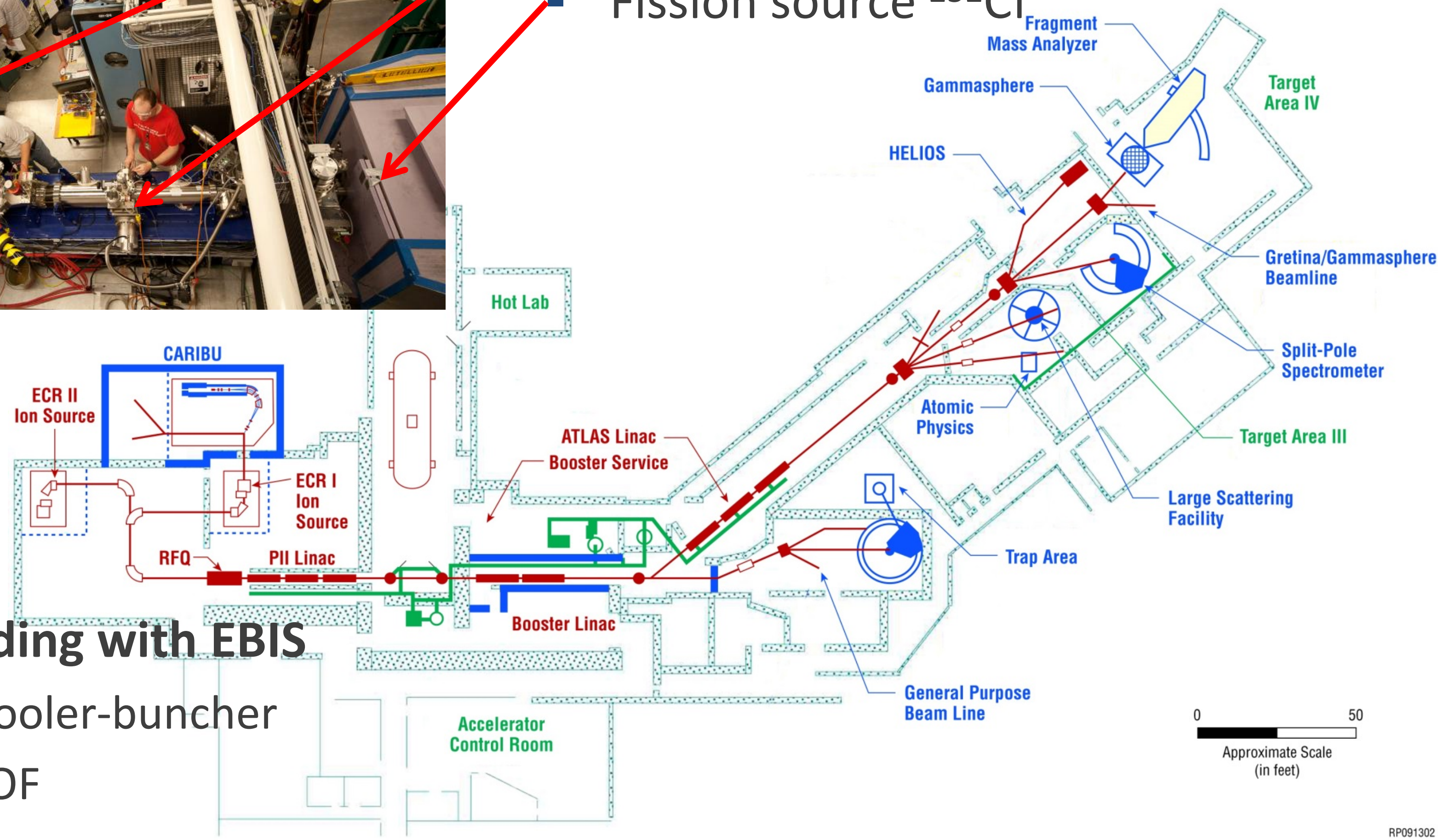
ATLAS and Californium Rare Isotope Breeder Upgrade (CARIBU)



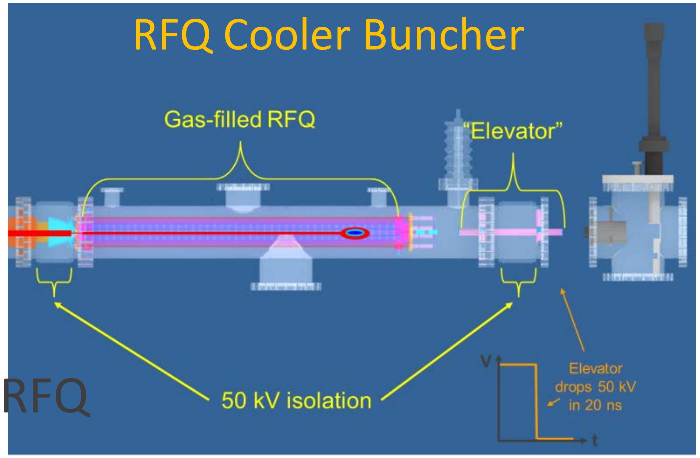
- Isobar separator
- Gas catcher with RFQ cooler
- Fission source ^{252}Cf

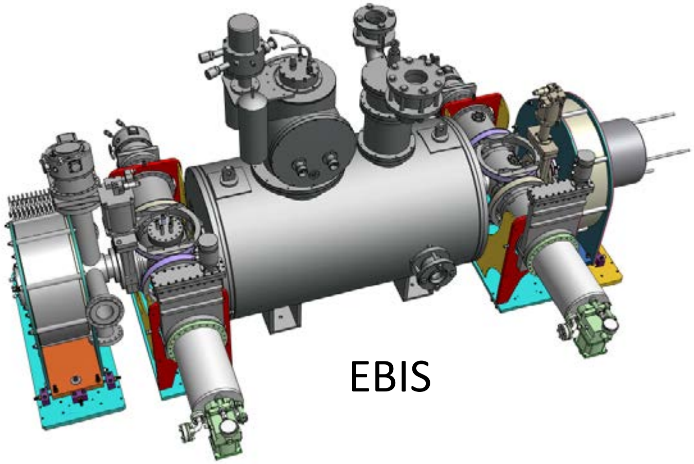


- **For breeding with EBIS**
  - RFQ cooler-buncher
  - MR-TOF

CARIBU and EBIS Charge Breeder

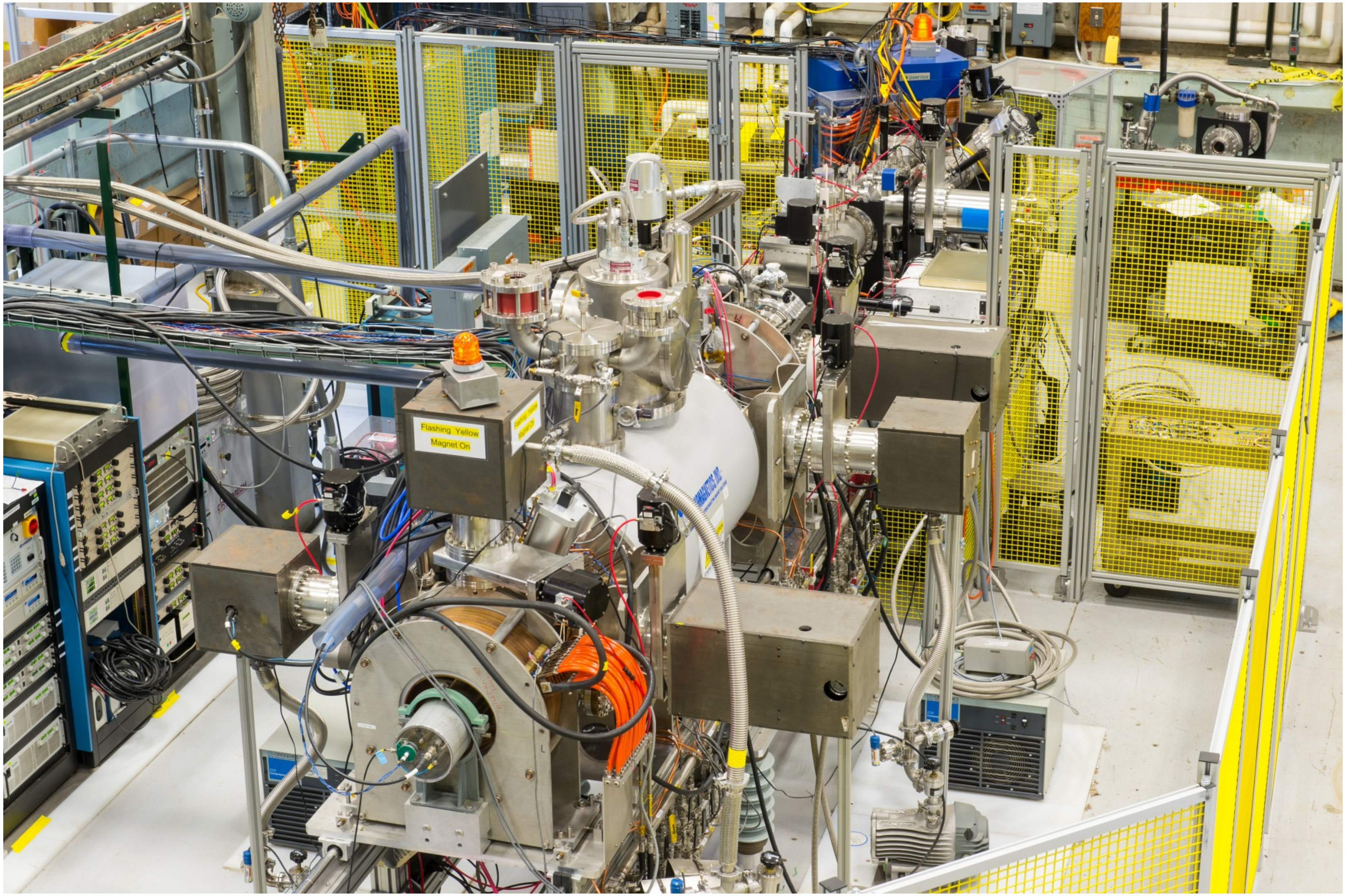
- Provides several important gains versus ECR charge breeding at CARIBU
  - Higher charge breeding efficiency for pulsed injection operation
  - Suppression of stable ions background
  - Faster breeding time
- An RFQ cooler buncher precedes the EBIS
  - Capable to operate up to 30 Hz repetition rate for highest intensity beams to avoid space charge effects in the RFQ
  - Nominally 30 msec breeding time, sufficient for breeding of any mass to accept for acceleration in ATLAS
  - Up to 55 μs 1+ beam pulse can be injected into the EBIS in pulsed mode



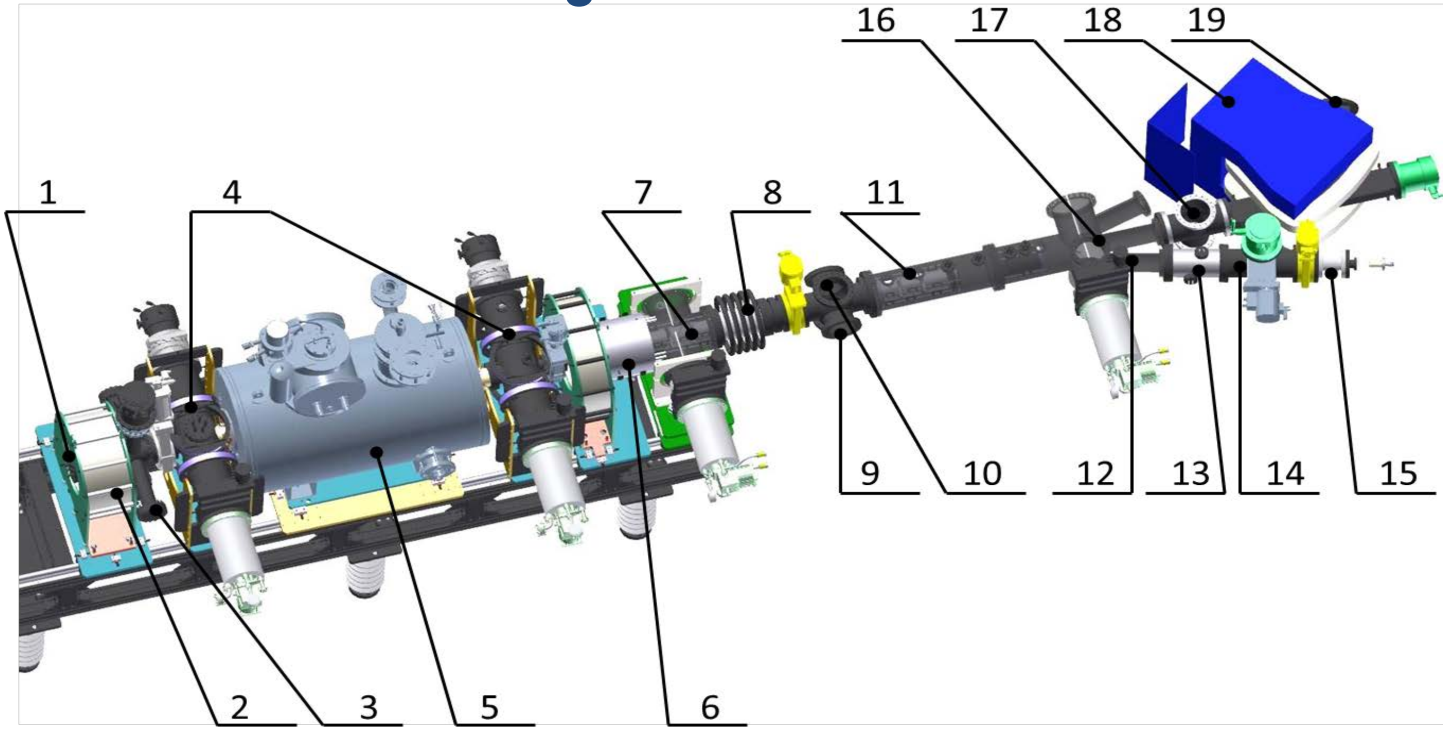


EBIS for CARIBU

- Off-line testing of the EBIS with singly-charged cesium source



Layout of EBIS Testing



- 3D model of CARIBU EBIS CB (1- e-gun, 2- room temperature solenoid, 3 – recently installed NEG pump, 4 - end crosses of the ion trap chambers, 5 - 6 Tesla superconducting solenoid, 6 - electron collector with room temperature coil, 7 - Einzel lens and steerers (EBIS potential), 8 - 75 kV accelerating tube, 9 – Faraday Cup for cesium beam (FC2), 10 – pepper pot MCP-based emittance probe, 11 - Einzel lens and steerers (ground potential), 12 - Faraday Cup for cesium beam (FC1), 13 - steerers, 14 – quadrupole lenses, 15 – Cs+ ion source and accelerating tube, 16 - electrostatic switchyard, 17 - Faraday cup for charge bred beam (FC3), 18 - 70° bending magnet, 19 – slits and Faraday Cup (FC5).

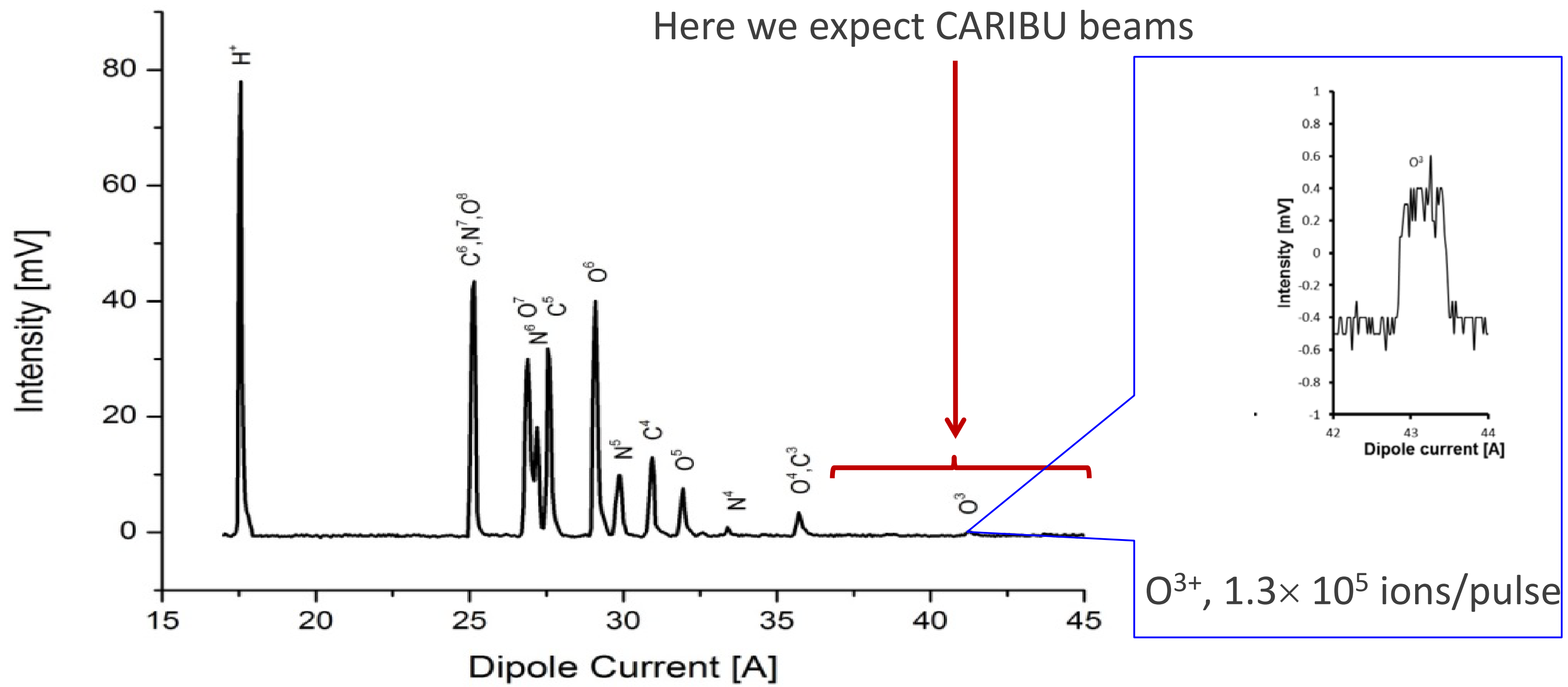
EBIS and Electron Beam Parameters

Parameter	Operational	Ultimate	Units
Magnetic field	5.0	6.0	T
Electron beam current, I_e	1.6	2.0	A
Cathode radius	2.1	2.1	mm
Magnetic field on cathode	0.15	0.15	T
EBIS platform bias voltage	20	50	kV
Trap length	0.5	0.7	m
*Electron beam radius in the trap	364	332	µm
*Electron beam density in the trap	385	577	A/cm^2
*Electron beam energy in the trap	6495	6265	eV
*Space charge potential well	299	374	V
*Electron beam velocity in the trap	$4.8 \cdot 10^7$	$4.7 \cdot 10^7$	m/s
**Normalized full acceptance	0.024	0.024	π×mm×mrad
*Trap capacity	23	30	nC
Repetition rate	up to 10	30	Hz
Duty cycle	up to 40	90	%

*Estimated using general EBIS theory
**Simulated with tracking codes.

EBIS Performance

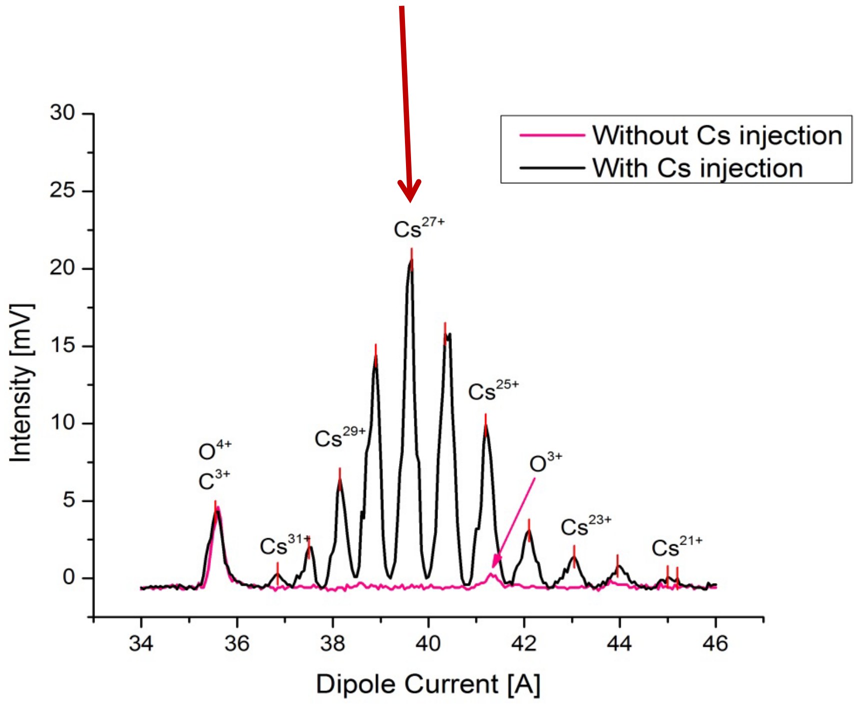
- After baking in February 2015, the vacuum is greatly improved, 1.3×10^{-10} Torr (e-gun side), 4.5×10^{-10} Torr (collector side)
- Residual gas ionization, confinement time is 30 msec



Cs Breeding

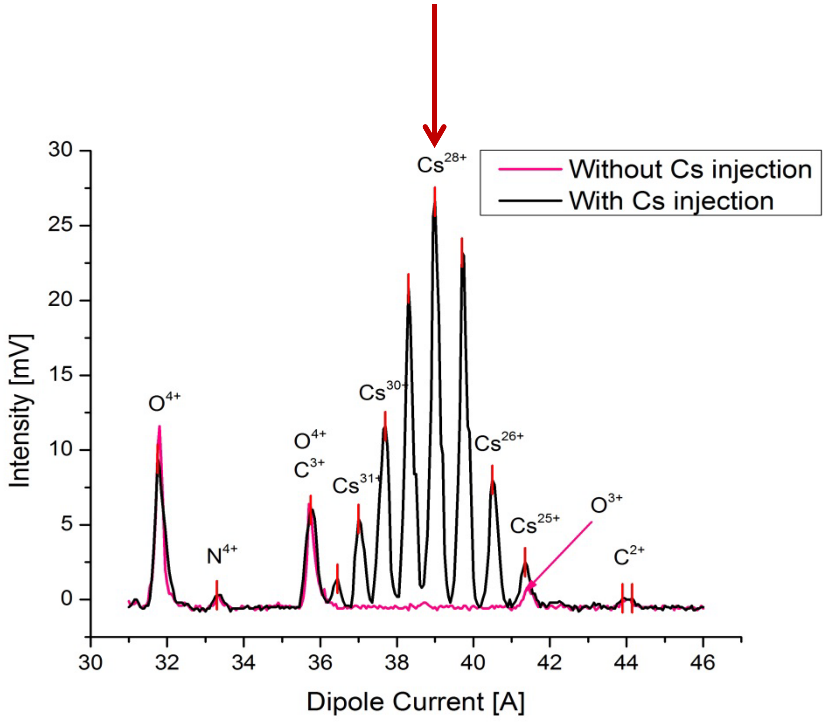
20 msec

Cs^{27+}, M/Q=4.925



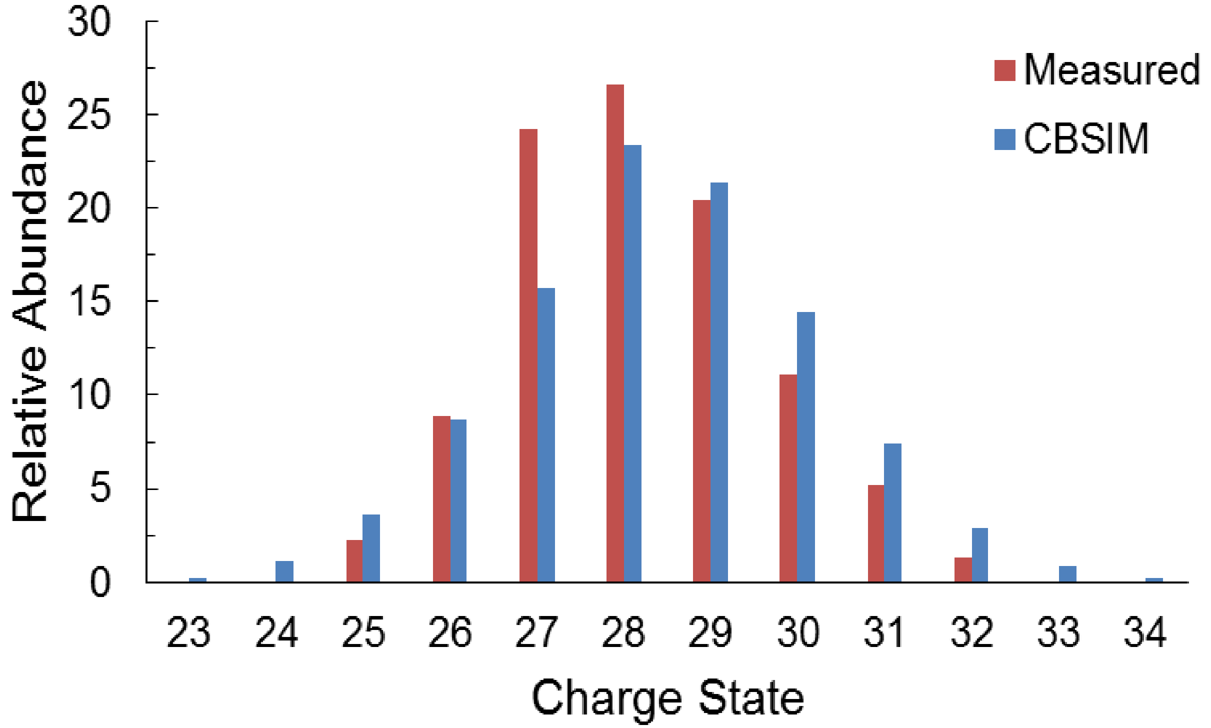
30 msec

Cs^{28+}, M/Q=4.75



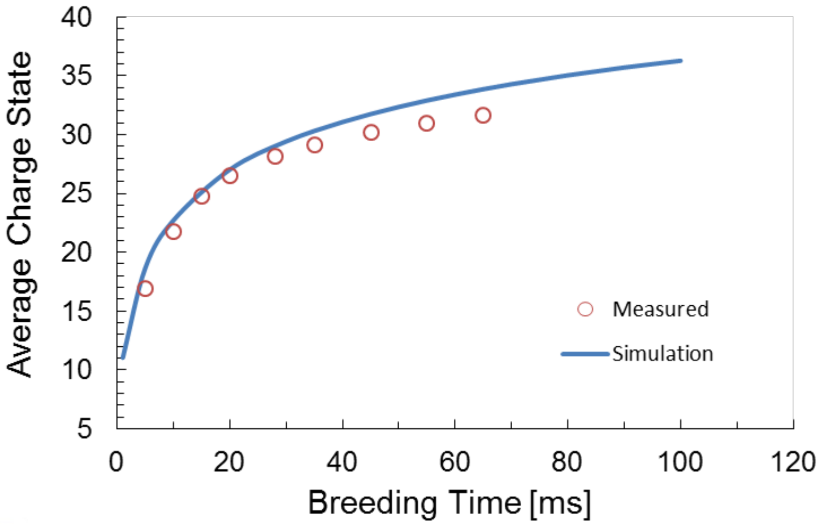
Efficiency

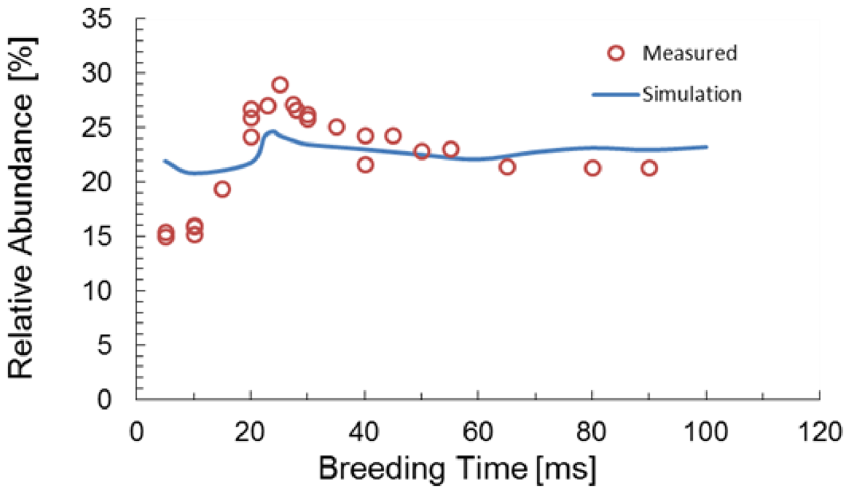
- Breeding efficiency into q=27 and 28 is ~20%
- Cs transmission through EBIS is typically ~75%, can be increased up to 80%
- With lower emittance of radioactive beams, the projected efficiency is 27%



Average Charge State and Relative Abundance, Comparison with CBSIM Code

- Average charge state
  - Good agreement up to 30 msec
  - Possible beam current reduction along the pulse
- Highest relative abundance
  - Charge state distribution is wider at breeding times < 20 ms
  - Ion beam is not fully overlapped for lower charge states at low breeding times



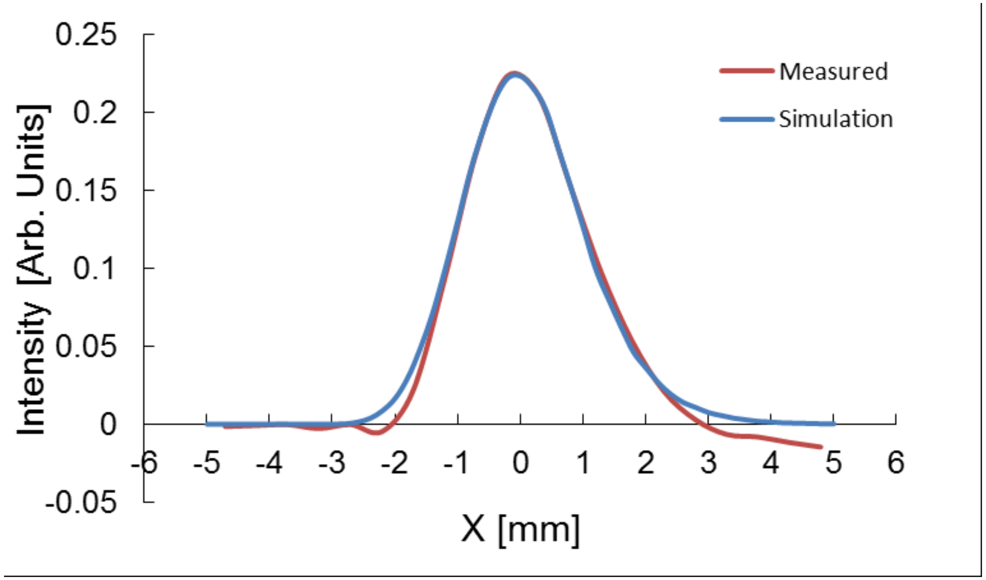


Extracted Beam Energy Spread

- Extracted cesium beam profile, Cs^{17+}, 10 ms breeding time
- Tracking code was used to fit the simulated and measured profile
- The RMS energy spread is q×51.2 eV, ~q× 220 eV for 99% of ions which is less than the depth of the potential well, 299 eV.

Transverse emittance
$\varepsilon_n = 5 \cdot 10^{-2}$ π mm mrad
(Gaussian)

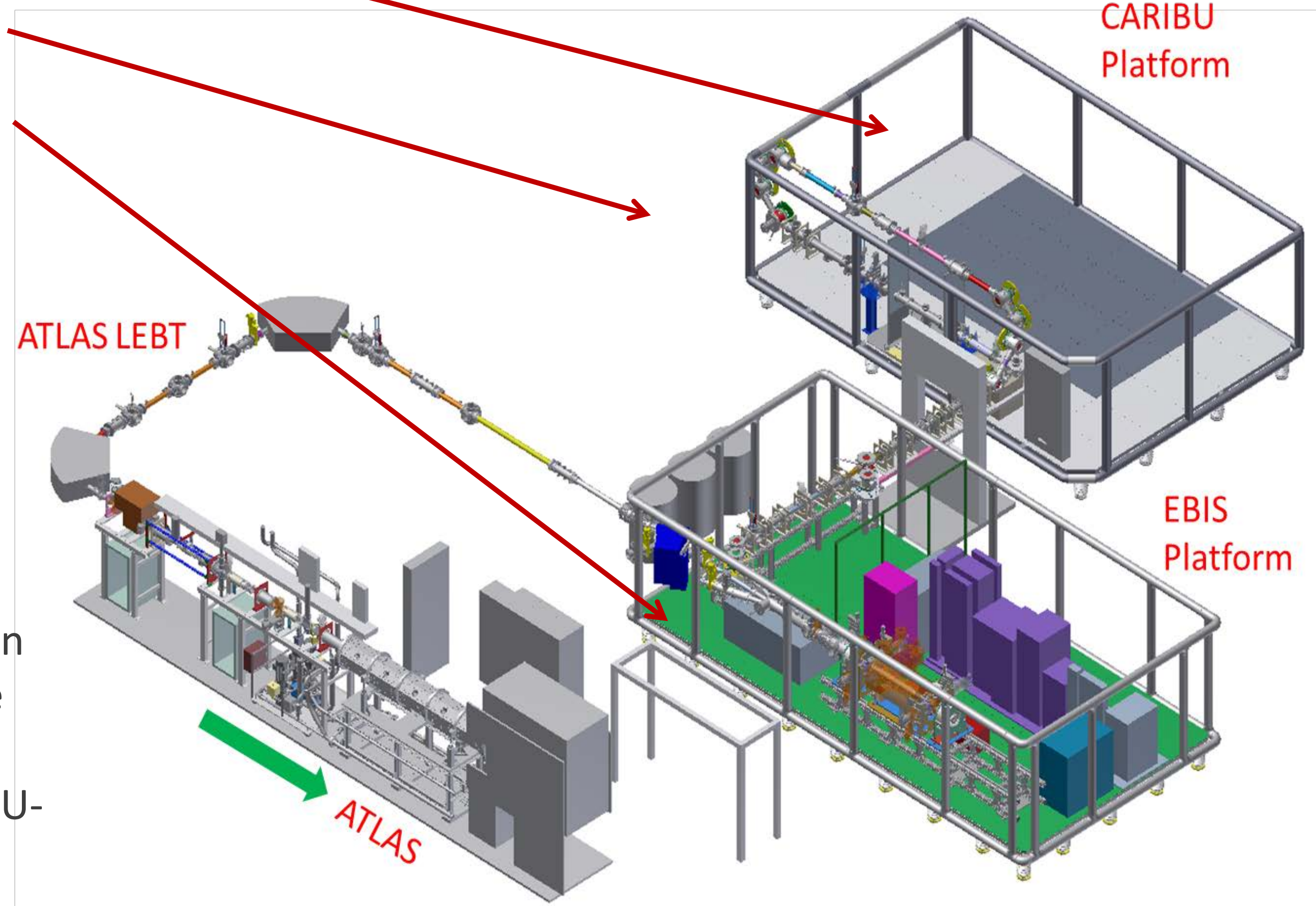
$$f(K;\frac{5}{2},k_B T_Q) = \frac{4}{3\sqrt{\pi}} \frac{K^{3/2}}{(k_B T_Q)^{5/2}} e^{-\frac{K}{kT_Q}}$$



Off-line commissioning of EBIS is complete and it is ready to be relocated and integrated into CARIBU & ATLAS

EBIS Integration

- CARIBU mass-separator
- RFQ, MR-TOF
- EBIS platform

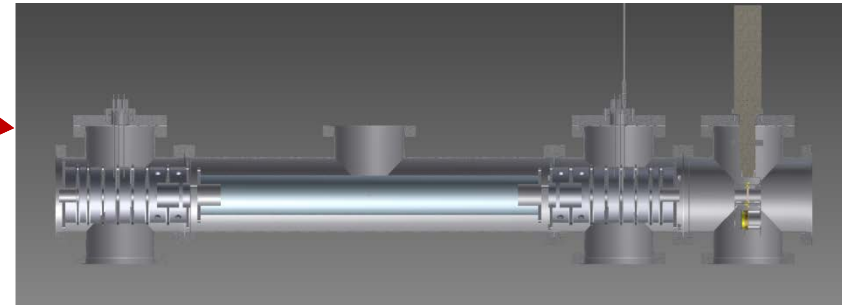


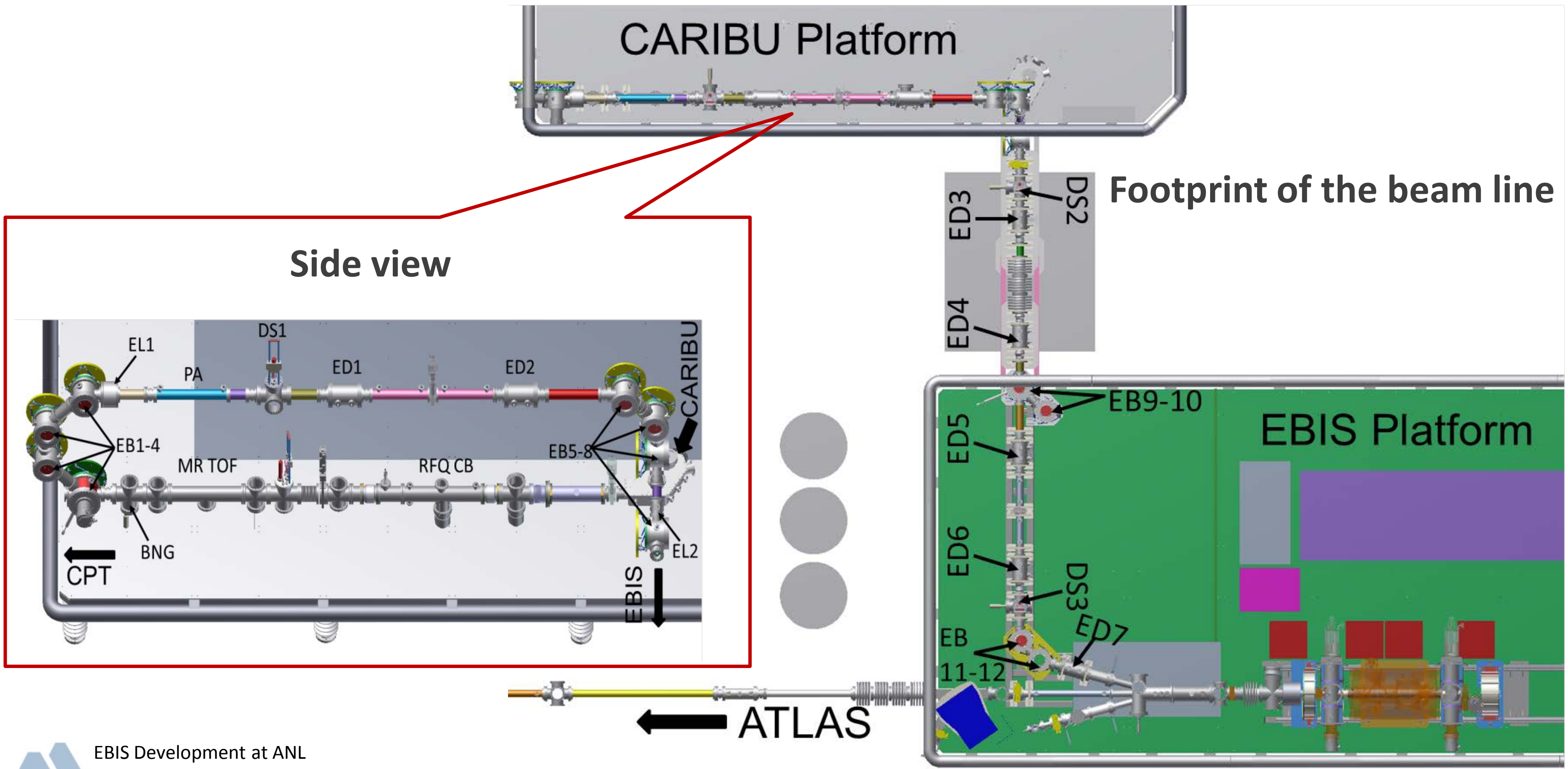
Beam line
Design Requirements
(CARIBU to EBIS)

- ~100% transmission
- Minimal emittance growth
- Matching to CARIBU-EBIS acceptance
- Space constraints

CARIBU to EBIS Beamline

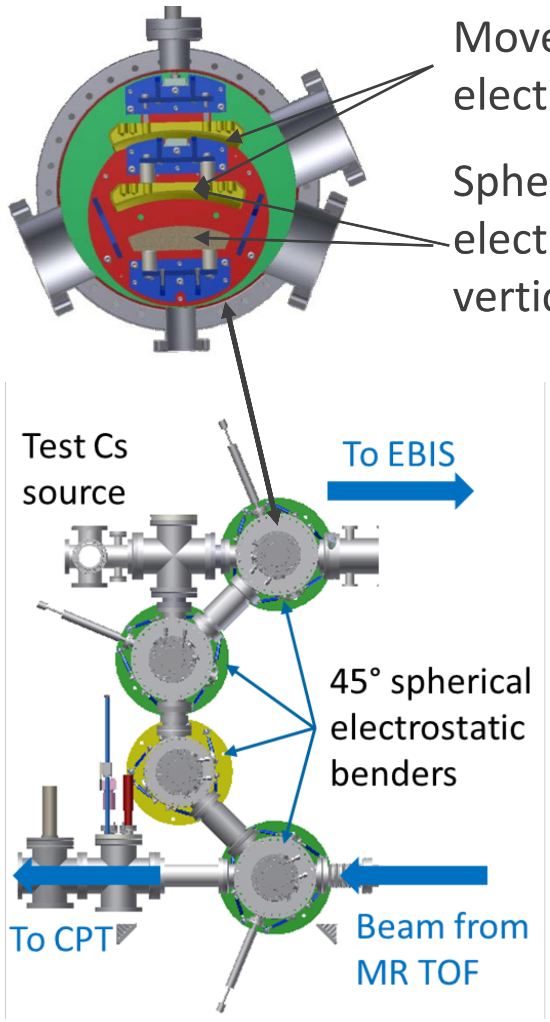
- 5 keV beam after the MR-TOF
- Pulsed acceleration in “elevator”
- Two 180° turns due to limited space





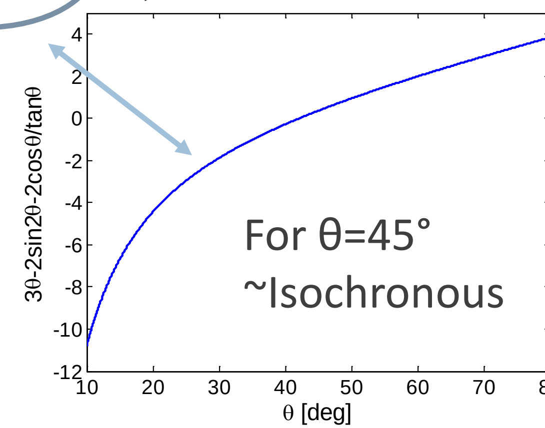
180° Turn with Four Electrostatic Deflectors

- 4x45° is good identity, in both planes, achromatic, zero aberrations



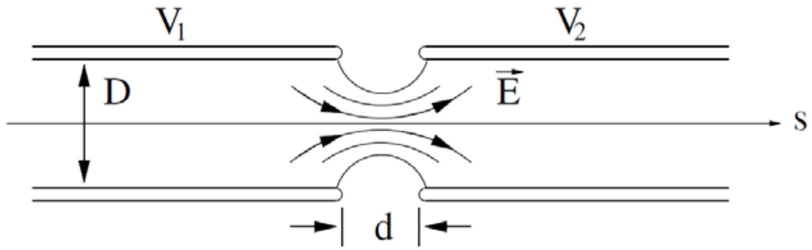
$$M^4 = \begin{pmatrix} \langle x|x\rangle & \langle x|x'\rangle & \langle x|\delta_K\rangle & 0 \\ \langle x'|x\rangle & \langle x'|x'\rangle & \langle x'|\delta_K\rangle & 0 \\ 0 & 0 & 1 & 0 \\ \langle T|x\rangle & \langle T|x'\rangle & \langle T|\delta_K\rangle & 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 2\langle T_{1/2}|\delta_k\rangle & 1 \end{pmatrix}$$

- ✓ Identity transformation
- ✓ Achromatic
- ✓ Second order geometric aberrations cancel

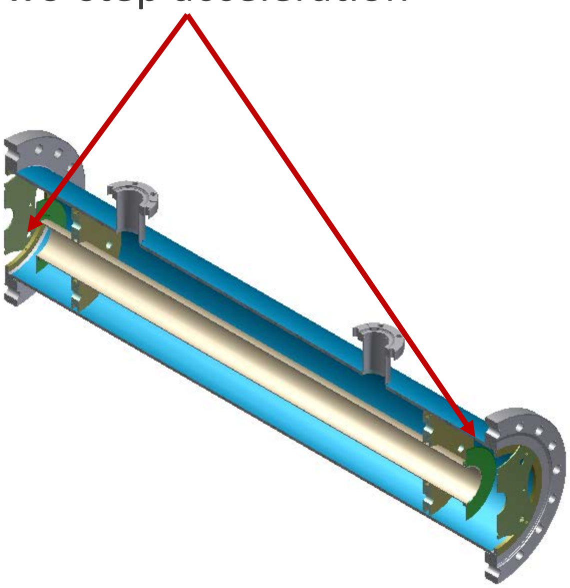


Pulsed Acceleration of Short Bunches

- Two step acceleration from 5 keV to 50 keV to avoid strong over focusing
- The beam energy should match to the deceleration voltage of the EBIS platform bias
- Solid state Belhke switches are used to pulse DC HV power supplies
- Limits the beam pulse length to ~2.5 μs



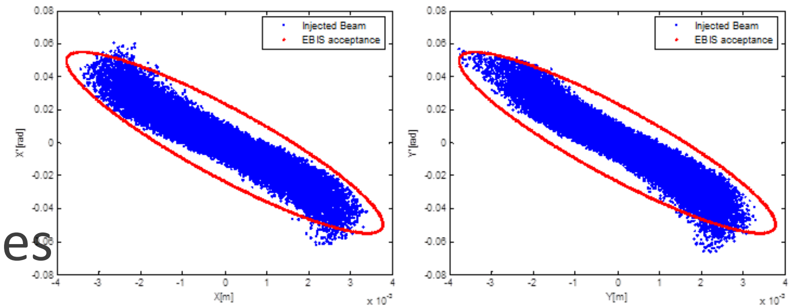
Two-step acceleration



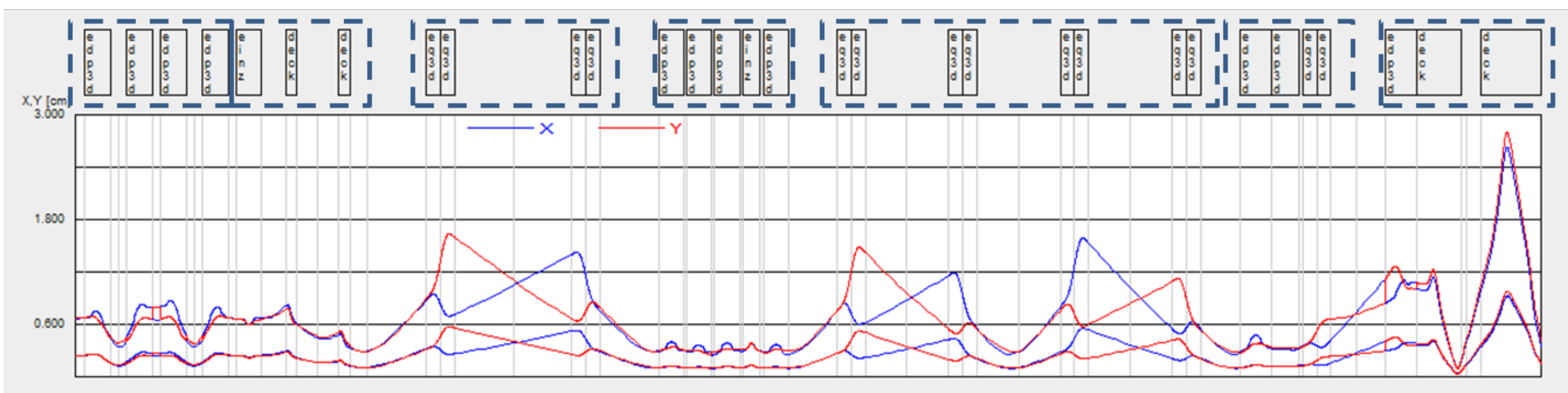
Beam Optics

- All-electrostatic 15-m long beam line
- Emittance growth is minimal
- Beam is well matched
- The simulations were done for 3 times larger emittance than after the RFQ cooler-buncher, 0.003 $\pi\times$mm$\times$mrad

Matching to the EBIS acceptance

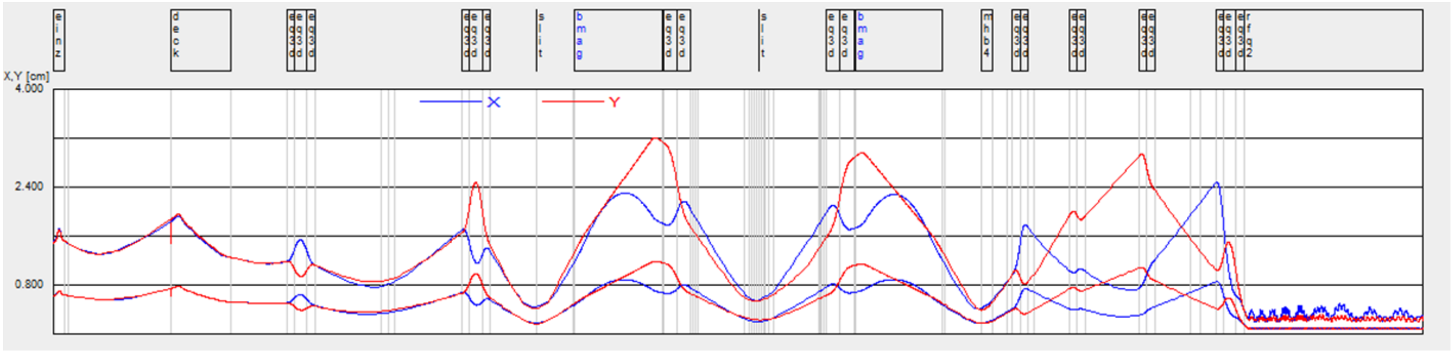


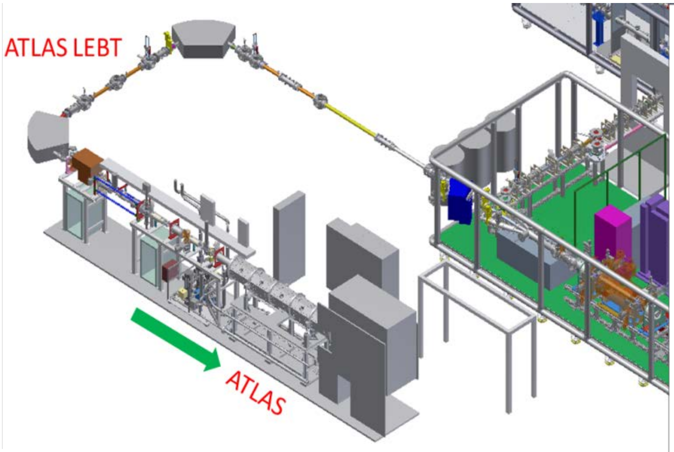
EB1-4 EL1+PA ED1-2 EB5-8 EL2 ED3-6 EB11-12 ED7 Injection\ Extraction



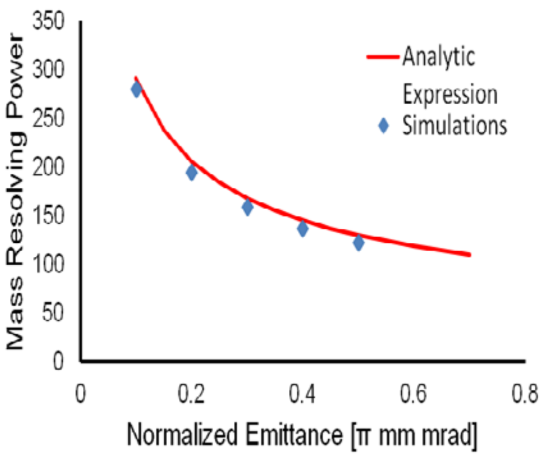
From EBIS to ATLAS RFQ, Q/A≥1/7

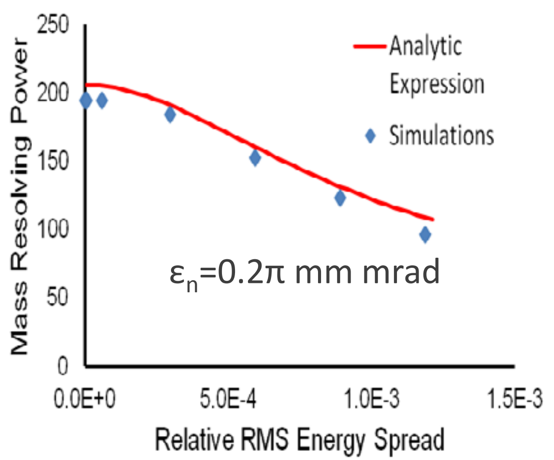
- Emittance growth due to chromaticity is canceled
- Mass resolving power is nearly 200, depends from the emittance and energy spread
- Additional contamination suppression in ATLAS RFQ





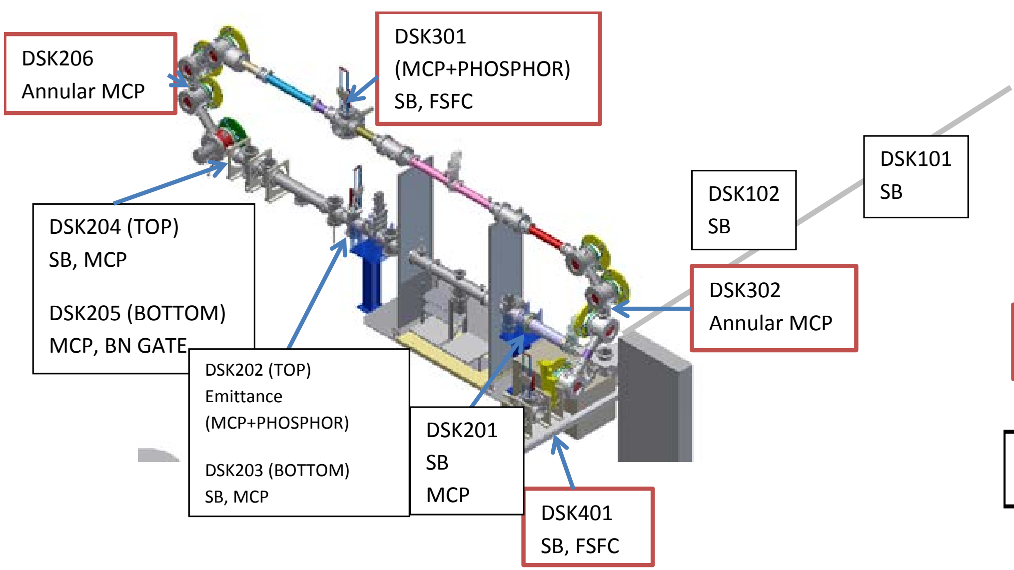
EBIS Development at ANL

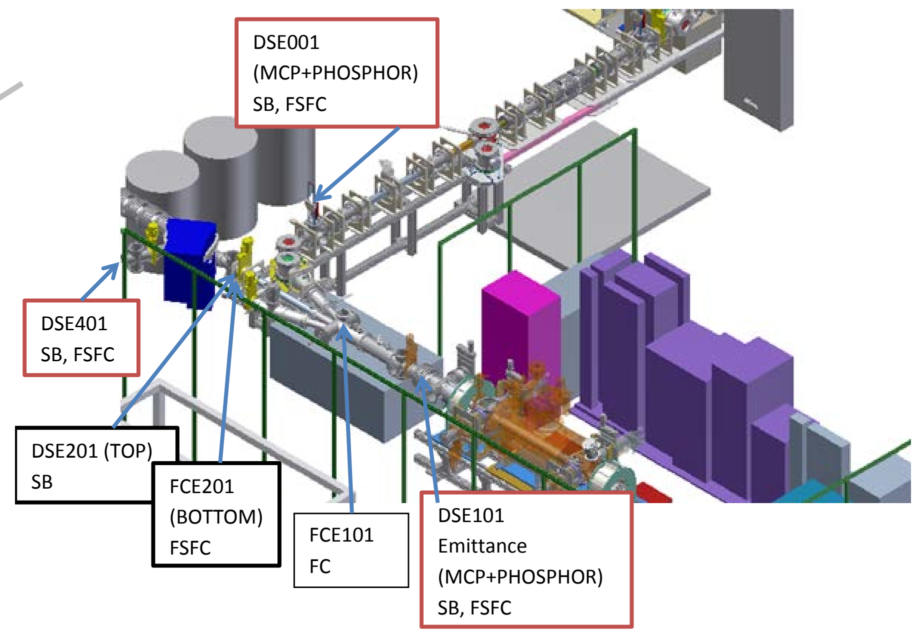




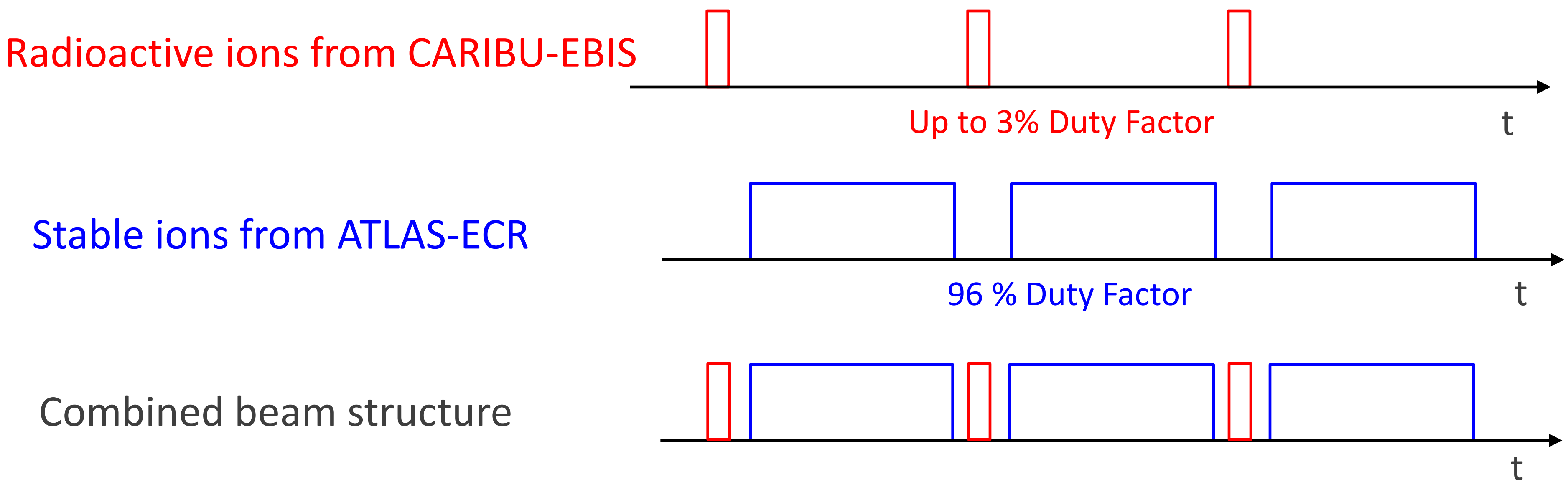
Beam Diagnostics

- MCP based FCs, shielded, isolated from the ground
- MCP based emittance/image probes
- Silicon detectors for unstable ions
- 1+ cesium source upstream of the RFQ C-B for the beamline tuning



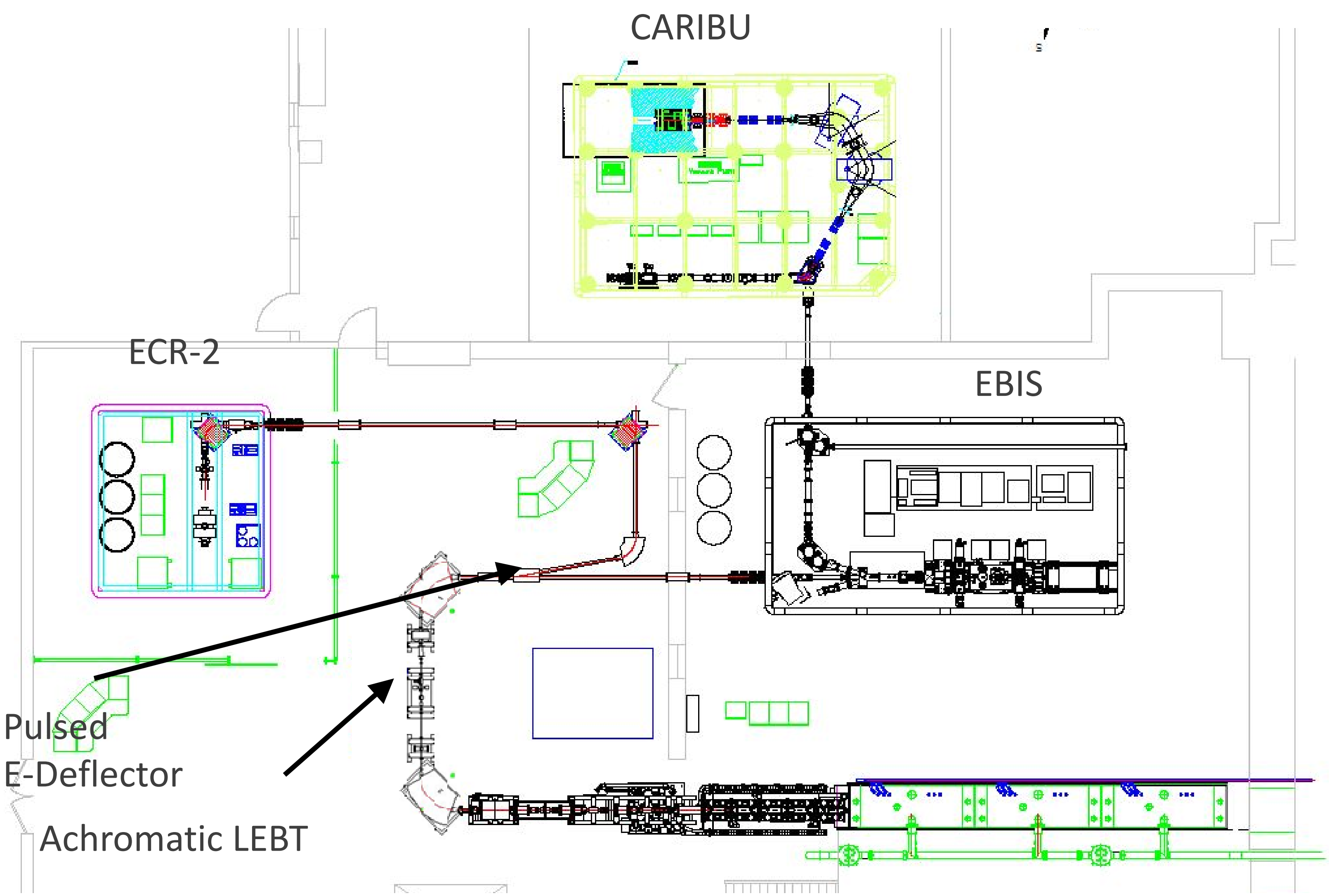


Time Structure of CARIBU-EBIS and ATLAS-ECR Beams



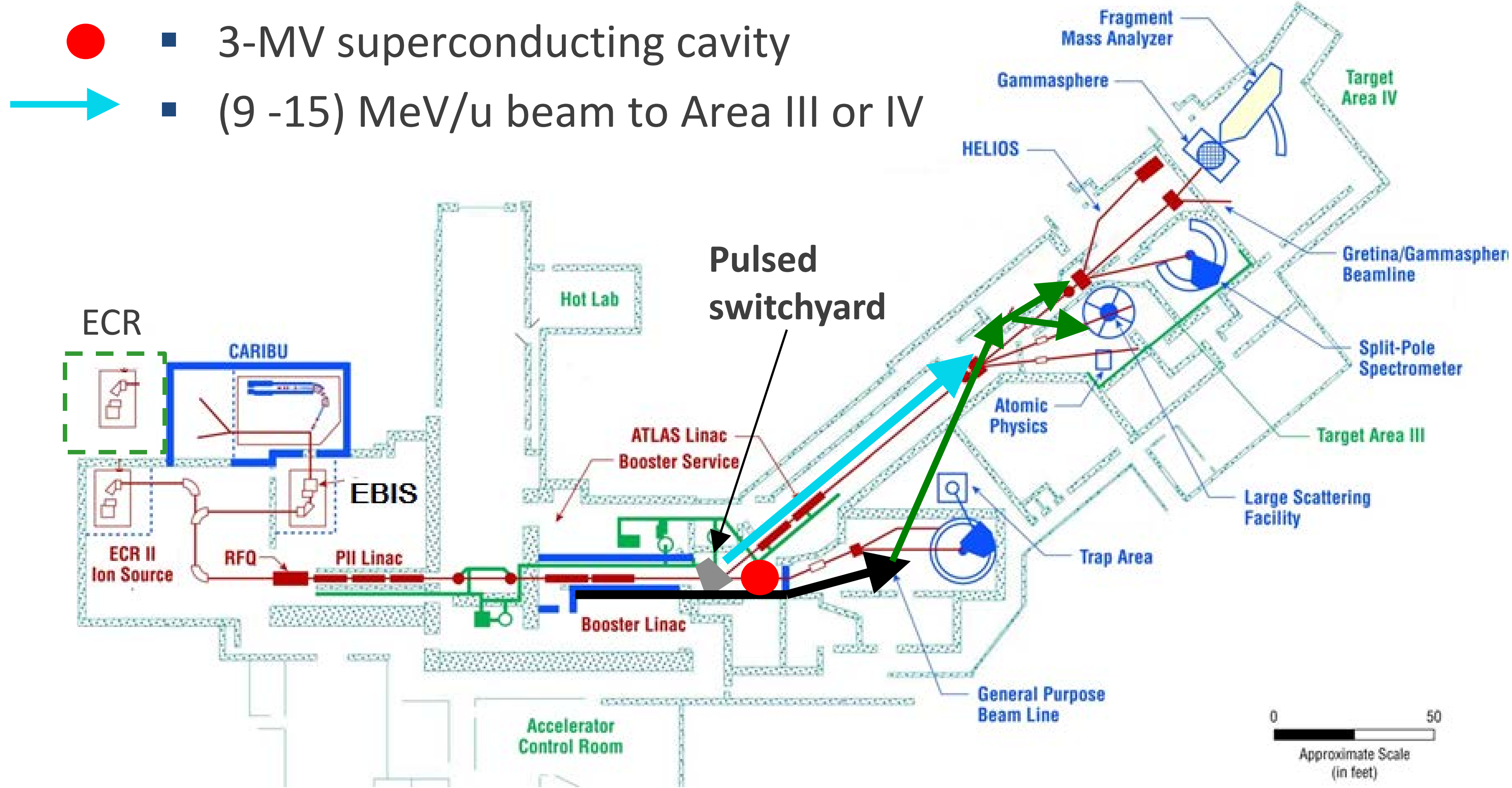
- ✓ EBIS beam is ~ 10 μs to 1 ms pulse up to 30 Hz repetition rate → < 3 % DF
- ✓ DC beam from ECR could be injected into ATLAS in the remaining 97% DF
- ✓ CARIBU Beam masses range from 80 to 170 with Z ranging from 30 to 70
- ✓ The highest charge-to-mass ratio they could be ionized to is 1/4.
- ✓ ATLAS accelerates any beam with a charge-to-mass ratio > 1/7
- ✓ The useful charge-to-mass ratio range for the multi-user capability is 1/7 to 1/4
- ✓ Higher q/A ≈ 1/3 can be achieved if EBIS is operated at 10 Hz,

ATLAS Front End with Multi-User Upgrade



ATLAS as a Multi-User Facility

- Area II, ~ 6 MeV/u ion beam
- 6 MeV/u beam transported to Area III or IV
- 3-MV superconducting cavity
- (9 -15) MeV/u beam to Area III or IV



Summary

- EBIS charge breeder is an excellent match to the CARIBU beams
- Electron beam in the EBIS so far: 2 A for low power mode, 1.6 A for 40% duty cycle, 1.0 A for 90% duty cycle
- Fast and efficient breeding of cesium ions was demonstrated
  - EBIS is ready to breed CARIBU beams with 10 Hz rep. rate
- Absolute breeding efficiency into single charge state is 20% at 75% beam transmission through EBIS
  - Higher breeding efficiency, >25% is expected for CARIBU beams with very small emittance
- Physics and engineering design of the ATLAS integration is complete
- EBIS relocation is in progress
  - All beam line hardware is being fabricated and assembled
  - The HV platform for the EBIS is being constructed
- EBIS is the key component for the future ATLAS multi-user facility