Automated Operation of EBIS Injector at BNL

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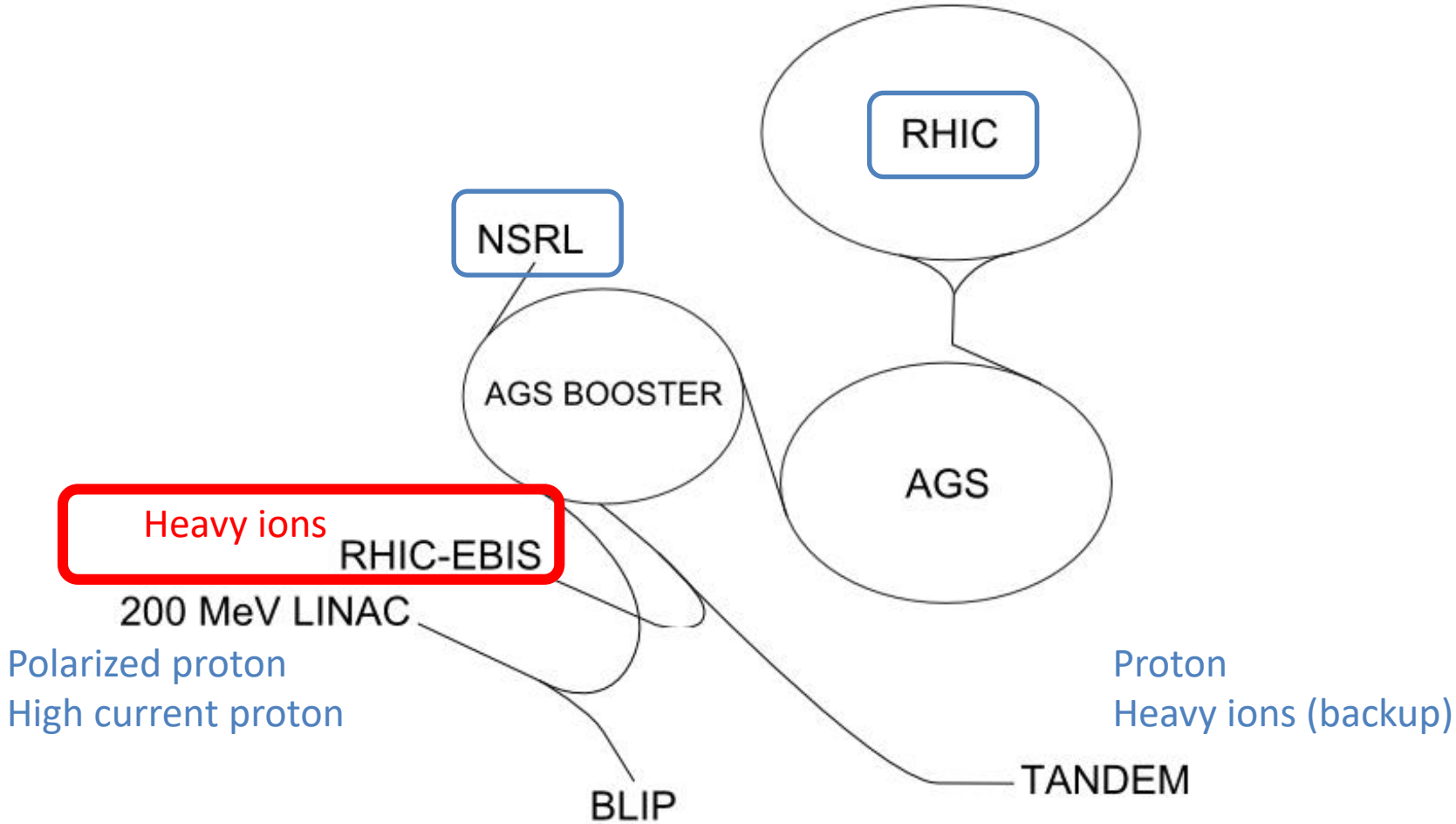
Outline

- RHIC and NASA Space Radiation Laboratory (NSRL)
- Motivation for automated species change:
  - Galactic Cosmic Ray (GCR) simulator at NSRL
- RHIC-EBIS Pre-injector (2 MeV/u heavy ions)
- Operation mode
  - Beam for RHIC
  - Beam for NSRL
- Operational performance
  - Reliable >100 switched/day without EBIS experts
- Summary

RHIC accelerator complex



- **RHIC-EBIS supplies all heavy ions for RHIC and NSRL "simultaneously" (sequentially)**

NASA Space Radiation Laboratory (NSRL)

- Mission: Ground based high energy ion source for space radiation research

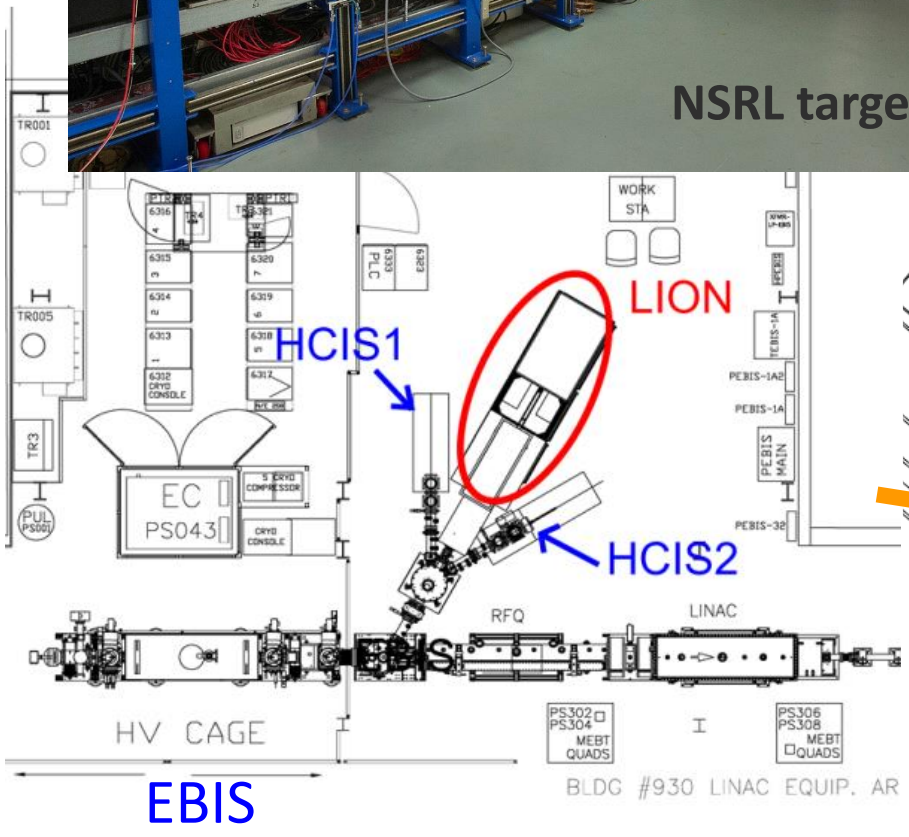
Galactic cosmic Ray (GCR)

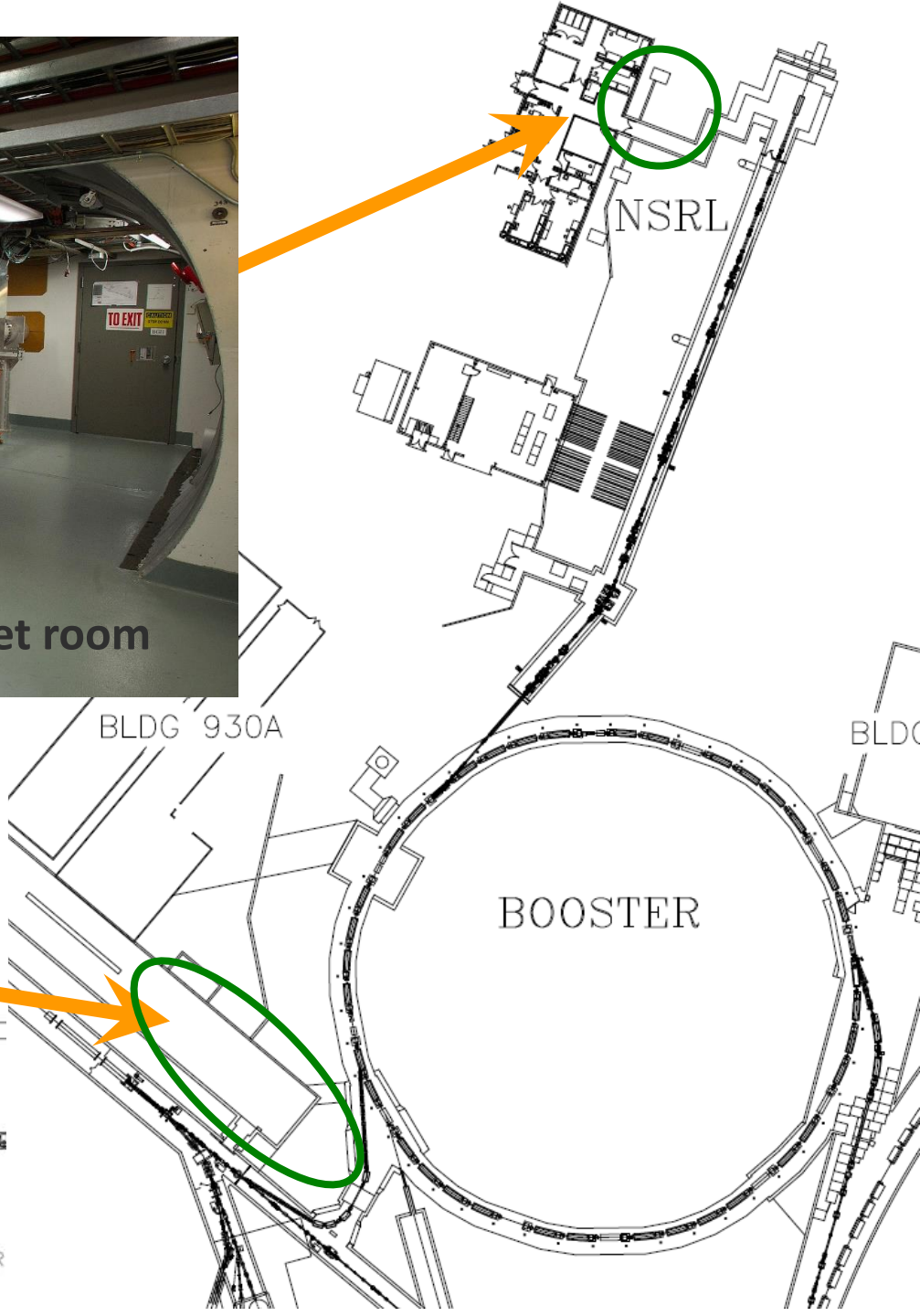
- High-energy **protons and various heavy ion species** coming from outside of solar system.
- A few MeV/u to well above 1 TeV/u, with the peak of the distributions tend to be around 1 GeV/u
- Evaluation of risk is essential for interplanetary missions beyond Earth

How to simulate?

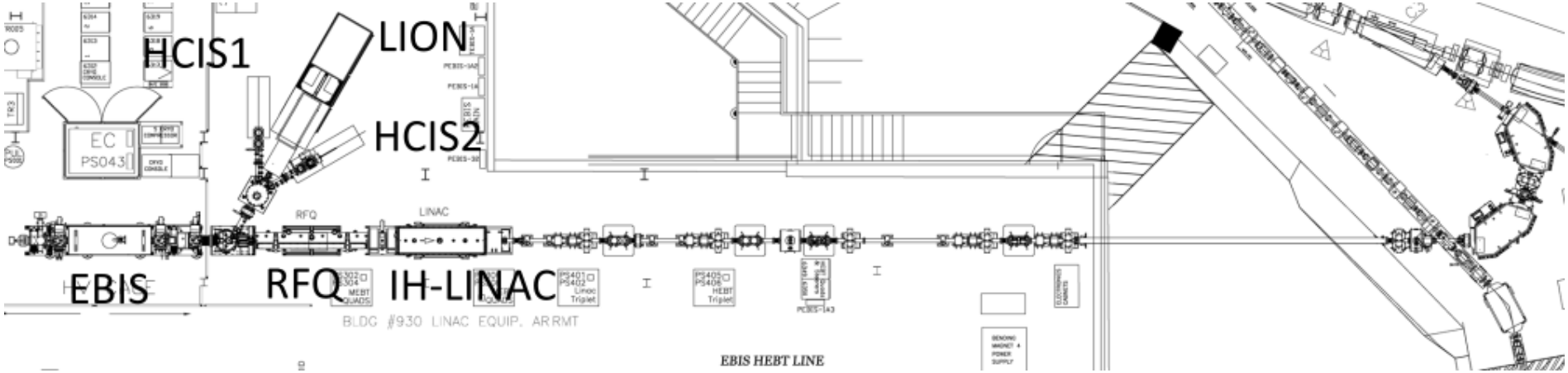
- Up to 1.5 GeV/u of heavy ions and 2.5 GeV of proton from AGS-Booster
- **Mixed radiation by sequences of exposures**


NSRL target room
TO EXIT


LION
HCIS1
HCIS2
EC
PS043
RFQ
LINAC
HV CAGE
EBIS
BLDG #930 LINAC EQUIP. AR


NSRL
BLDG 930A
BOOSTER

The 2 MeV/u RHIC-EBIS pre-injector

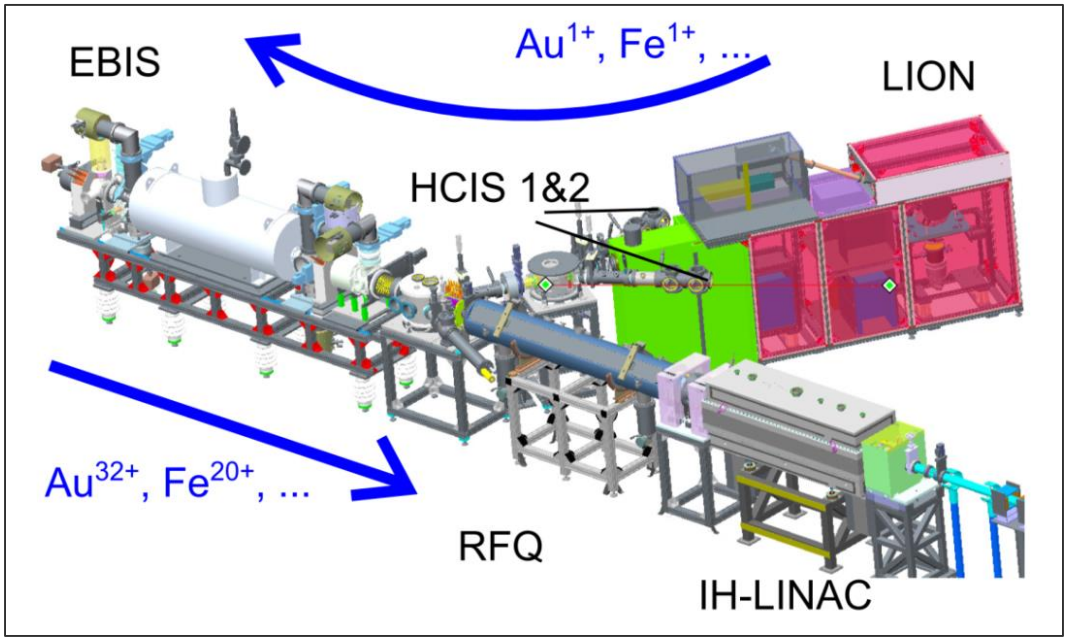


- Primary (1+) ions from external ion source
  - Laser ion source (**LIS**) and hollow cathode ion sources (**HCIS**)
- Electron Beam Ion Source (**EBIS**) as charge multiplier
- **RFQ** from 17 keV/u to 300 keV/u
- **Rebuncher**
- **IH-Linac** from 300 keV/u to 2 MeV/u
- 2 **debunchers**
- 2 of 72.5 degrees **bending magnet** (1 T)

Q/m >1/6 (Au^{32+})
RF cavities at 100.625 MHz

Switching between species < 1 sec after EBIS
(Due to ramping of bending magnet)

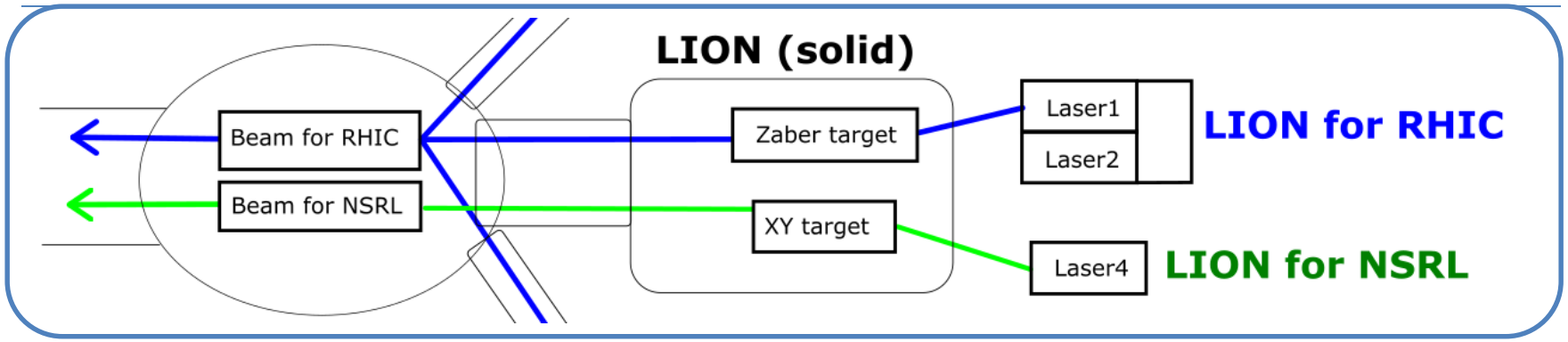
External ion injection + EBIS



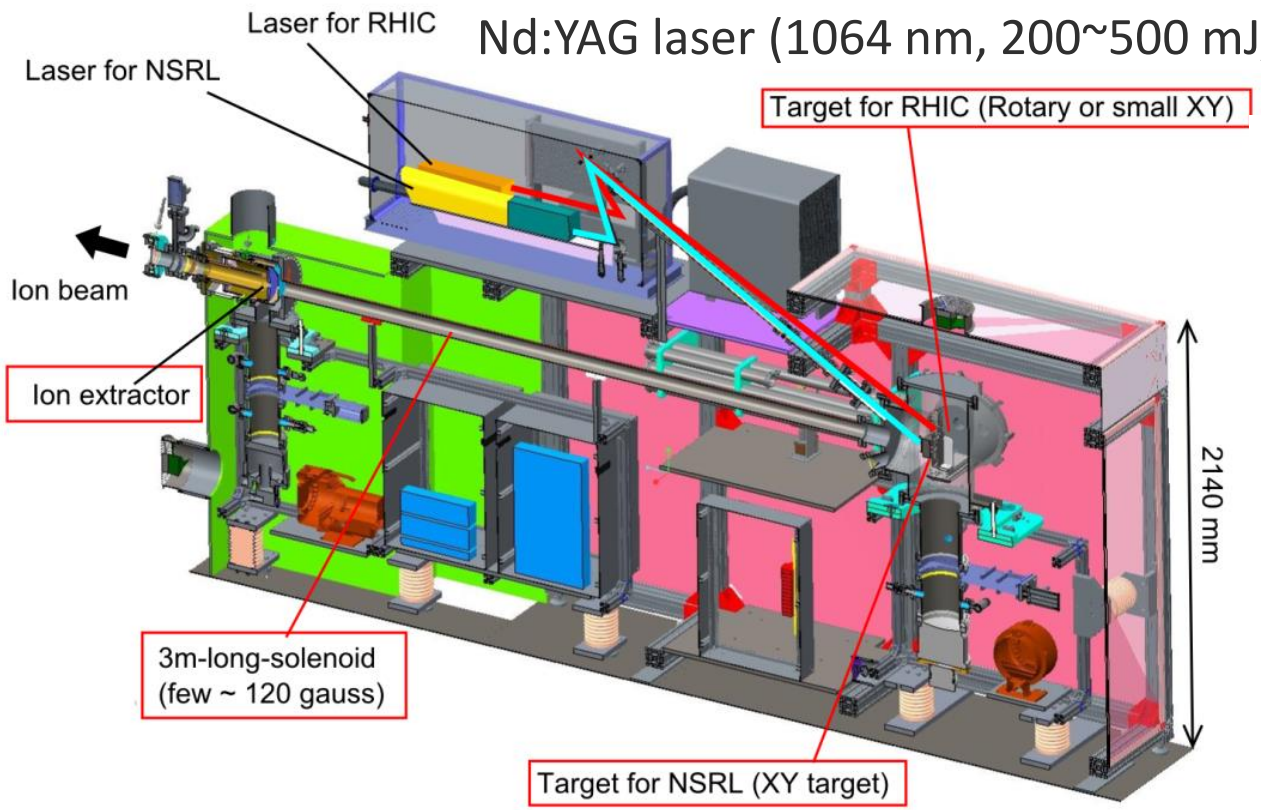
- **EBIS can switch species within 200 ms**
- EBIS runs as charge multiplier
- Primary (+1) ion beams are from external sources
  - LION (Solid target) and HCIS (gas)
- No memory effect of previous ion

Switching time depends on eternal ion sources

Laser Ion Source (LION)

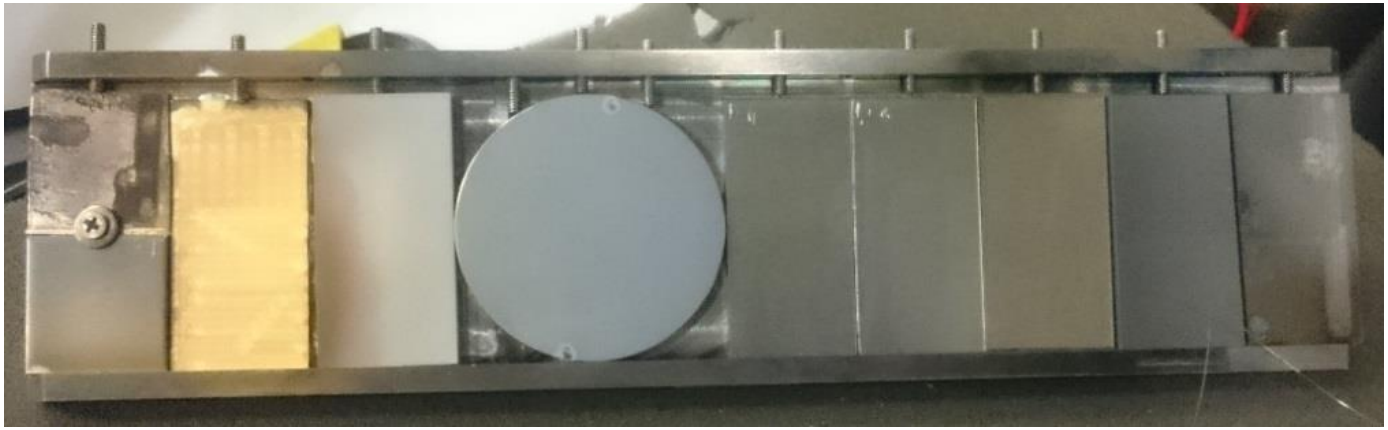


Nd:YAG laser (1064 nm, 200~500 mJ/6ns)



- Laser ablation
- Pressure < 10^{-4} Pa
- No coupling between beam for RHIC and NSRL
- 1+ ions
- Norm. rms emittance 0.06 π mm mrad (Good)
- 100 μA ~ 1 mA
- ~200 μs

LION target for NSRL



- XY target (multiple targets on a 2D linear stage)
- **Number of targets depends on target holder**
  - Typically 10 at a time
- Pure or compound (O from alumina (Al_2O_3)
- **Switching time depends on stage motion**
  - At most 25 sec (10 mm/s now)
  - Laser spot can be shifted if faster switch is required in the future

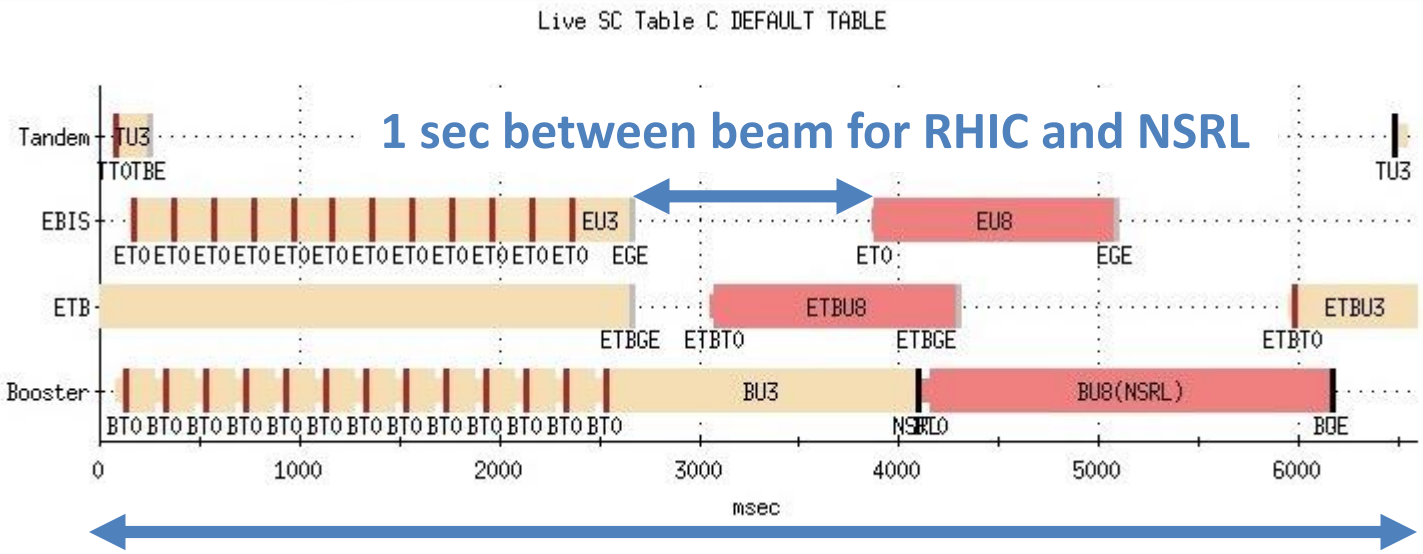
Hollow Cathode Ion Source

Primary ions provided by Hollow Cathode Ion Sources

- Discharge **gas ions**
- Metallic ion beam from cathode
- Plasma induced by cathode sputtering in a glow discharge

- Normalized RMS emittance 0.03 πmmmrad (Good)
- **Low peak current (5~50 μA) and long pulse (10~40 ms).**
  - **"Slow injection" scheme of EBIS**
- **Need to replace gas or cathode to change species (~30 min)**

Operation mode



"Supercycle" = 6.6 sec

- This is the highest load for RHIC EBIS
  - 12 pulses at 5 Hz for RHIC + 1 pulse for NSRL within supercycle
  - (12-6-2 merge in AGS)
- Minimum number of pulses is
  - 1 pulse as standby + 0 pulse for NSRL
- **RHIC-EBIS always switch species between RHIC and NSRL within 1 second in a supercycle**
- Stable and reliable with large variation of duty and amplitude

Beam for RHIC

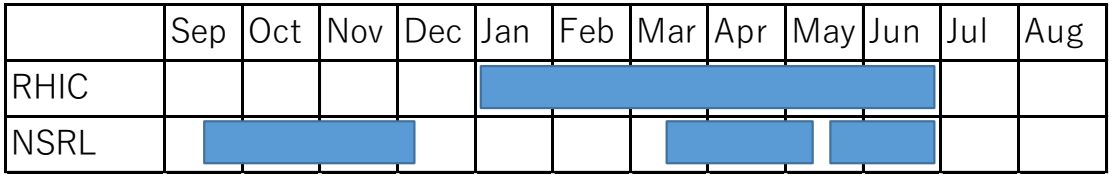
- 12 pulses for >30 min for RHIC fill including setup at every 0.5-20 hours
- 12 pulses for injector setup during store
- 1 pulse/supercycle in other time (standby)

MCR use a sequencer

Automatically decrease the number of cycles and EBIS cathode heater current after RHIC fill

MCR use a automated sequencer to increase the number of pulses and increase cathode heater power

Beam operation for NSRL



- **Heavy ion beams and proton beam** from AGS-Booster
  - Proton is from 200 MeV Linac or Tandem
- **One pulse per supercycle** (~4 sec during RHC shutdown, interleaved in RHIC (6 sec) when RHIC is running)

- **NSRL or MCR switches species automatically without assistance of EBIS experts**
  - 10 species from LION
  - 2 from 2 HCISs
  - proton
- **In GCR simulator mode, species changes is controlled by a dosimetry system at NSRL**
  - Dose on sample is precisely controlled
  - Beam cut off time is ~ms order

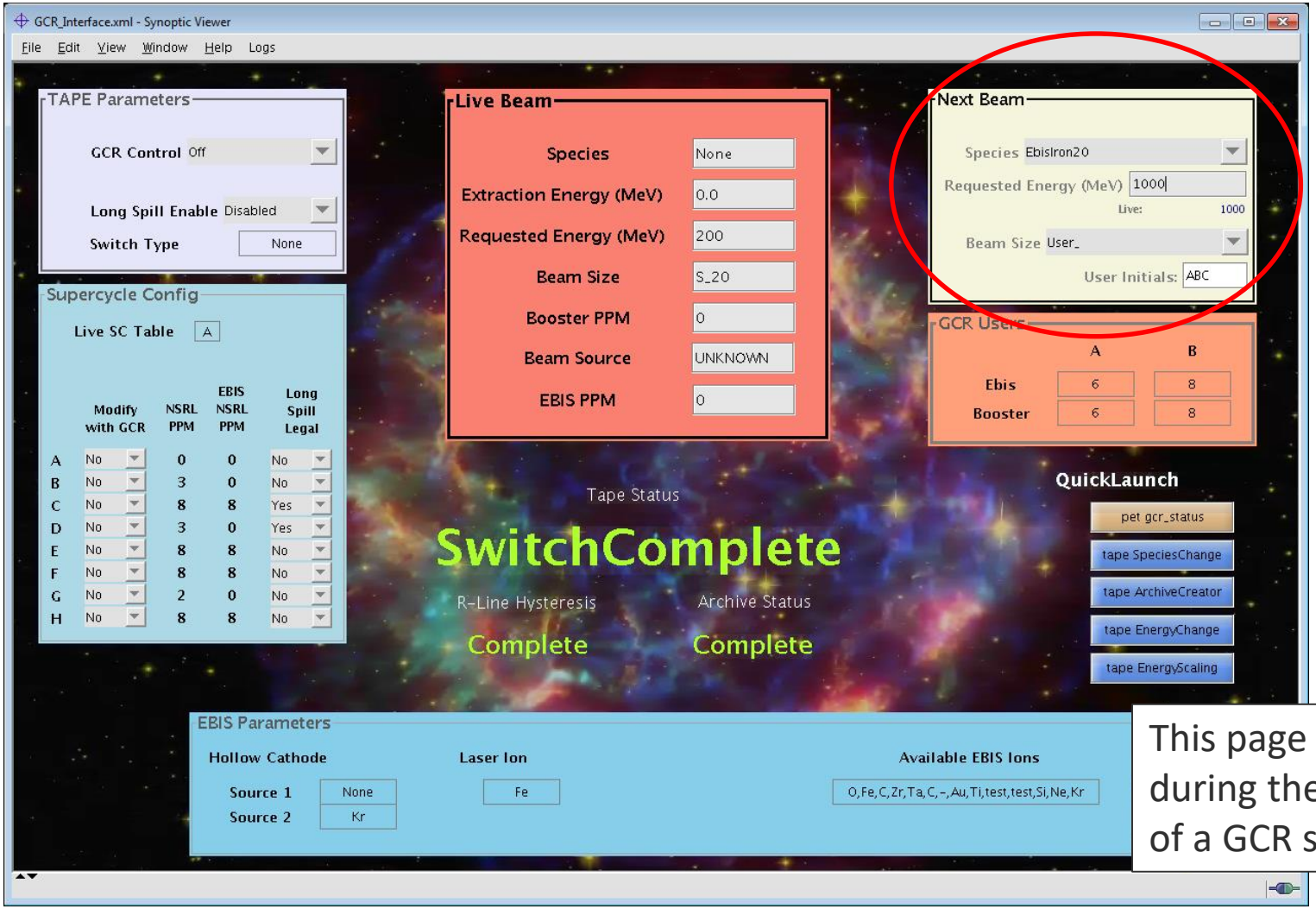
How to automate NSRL species change?

- **Optimized parameters are "archived" for each species**
- Archived setting of "next" species is restored on "next" (or background) ppm user
  - "Ppm user" contains machine parameters for different beam
- Stop EBIS electron beam to avoid failure (e.g. timing glitch)
- **Switch ppm user to activate parameter change**
- Switch species of external source, start electron beam

- Above procedures are automated by the sequencer
- **Reliable and reproducible. Once archives are created, EBIS is unattended for routine operation**

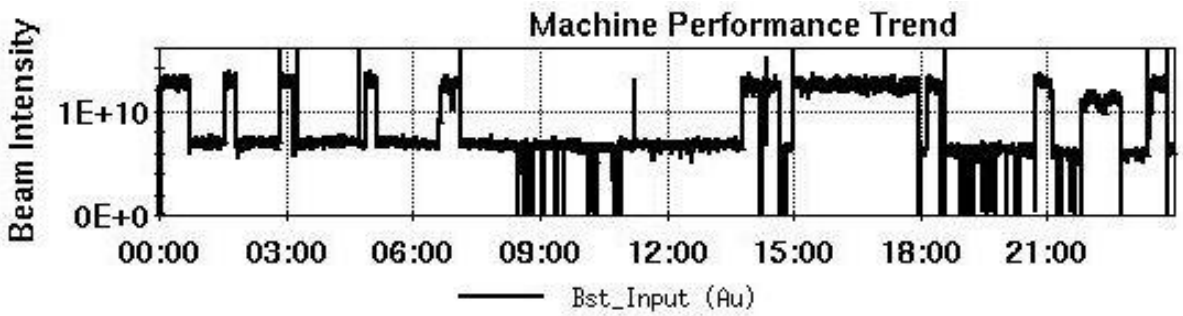
NSRL interface for fast species switch

Just need to set here

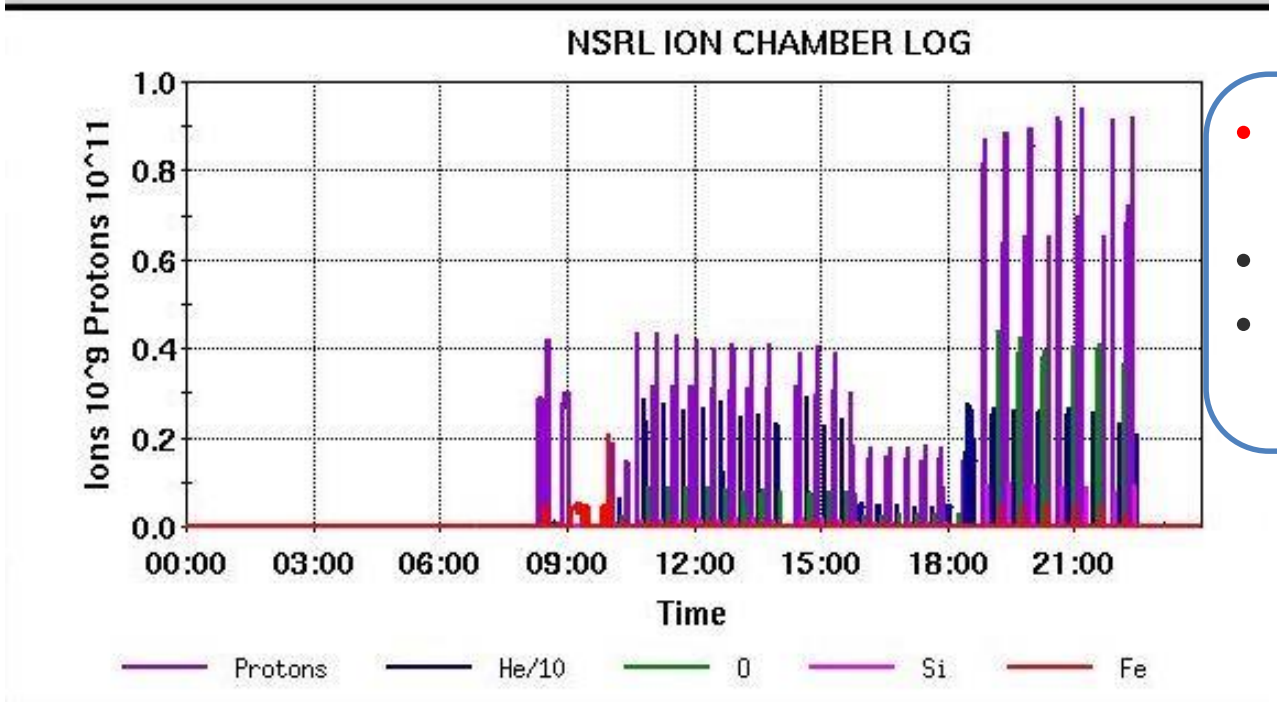


This page is not used during the execution of a GCR sequence.

A day of GCR simulator + RHIC injection

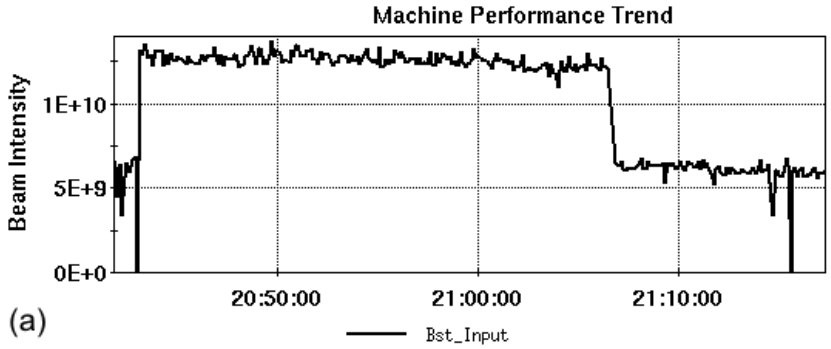


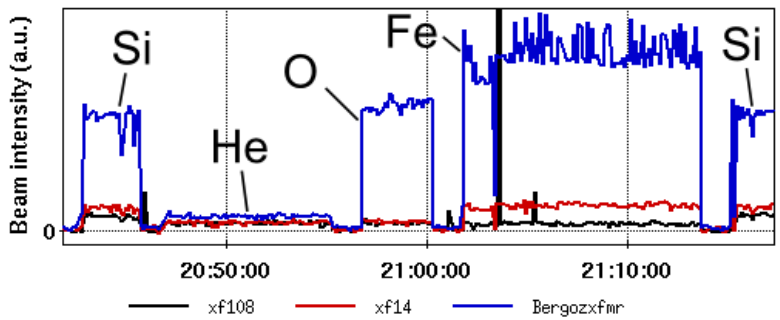
- Beam for RHIC and injector at Booster input

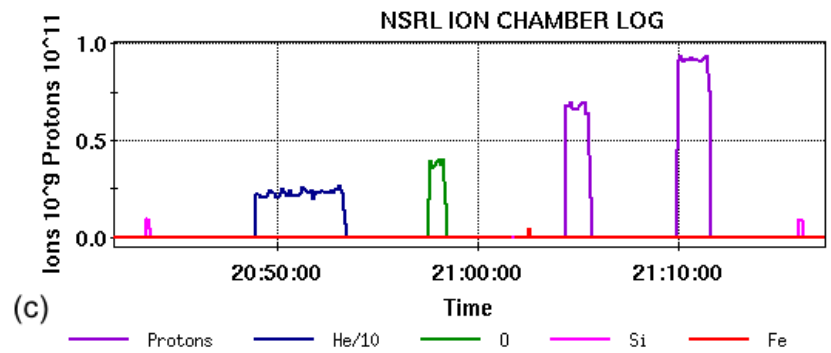


- **> 130 species changes** for NSRL
- He, O, Si, Fe from EBIS
- Proton from 200 MeV linac

Switching performance for NSRL





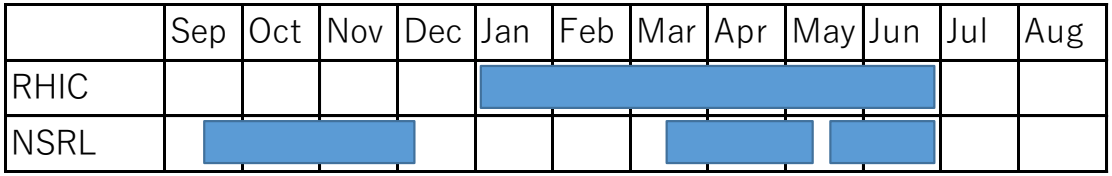


- Au for RHIC at Booster input

- RHIC-EBIS beam for NSRL
  - Blue: Out of EBIS
  - Red: out of IH-Linac
  - Black: after bending magnet
- **Switching time at RHIC-EBIS is ~40 sec**
- **No asistance from EBIS experts**

- Beam at NSRL target room
- GCR mode: Dosimetry system cut off beam to control dose on sample, and initiate species change

RHIC-EBIS for NSRL in Run-17 and Run-18



		LION											HCIS				
	EBIS Days for NSRL	Li	C	O	Si	Ti	Fe	Zr	Nb	Ta	Au	Th	He	Ne	Ar	Kr	Xe
Run 17	104	5	14	20	38	12	51	1	1	5	7	2	35	0	1	4	11
Run 18 (as of 6/6)	98	0	22	28	49	21	56	0	0	31	5	5	35	8	0	11	16

- This table contains not only for user operation but set up time
- EBIS routinely provide multiple heavy ion species for NSRL simultaneously with RHIC

Species from RHIC-EBIS pre-injector

	Charge state	Q/M	Confinement time (ms)
He	2	0.500	17
Li	3	0.429	27
B	4	0.364	106
C	5	0.417	51
C	6	0.500	111
O	7	0.438	81
Si	11	0.393	118
Si	13	0.464	418
Ar	11	0.275	36
Ca	14	0.350	106
Ti	18	0.375	242
Fe	20	0.357	242
Fe	24	0.429	822
Kr	18	0.214	45
Xe	27	0.205	81
Ta	38	0.210	217
Au	32	0.162	85
Th	39	0.168	130

- Charge state is adjusted to match Q/M >1/6 for RFQ injection
- This is the list of ions delivered for NSRL
- In addition, Au, Cu, Pb, U were used for RHIC.

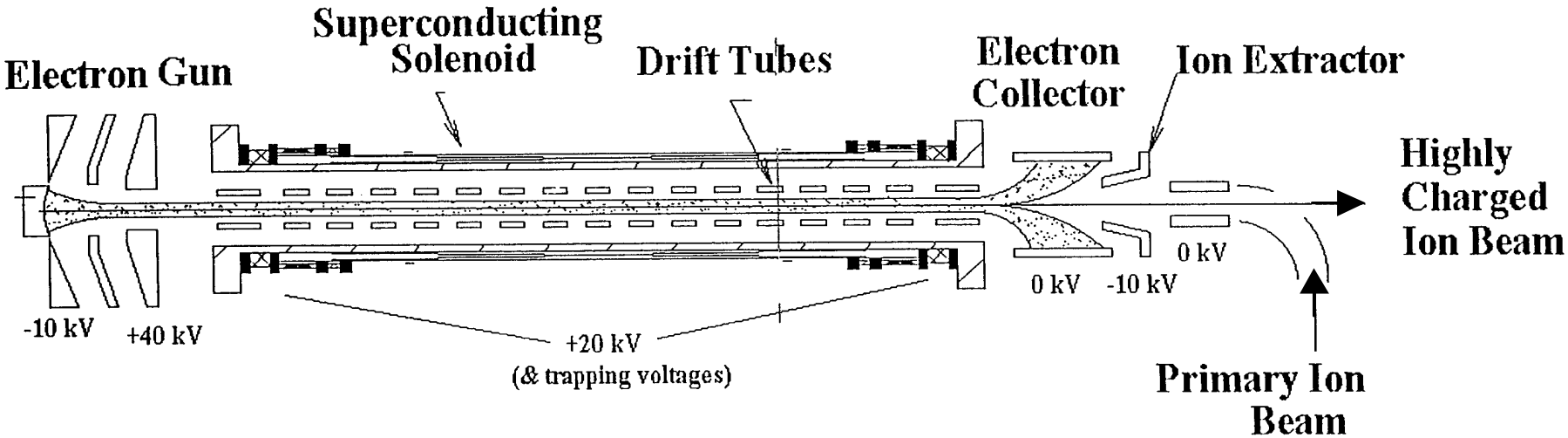
Species	Charge state	Bst_input n per pulse
He	2	9.0E+09
C	5	4.4E+09
Si	11	2.7E+09
Fe	20	8.1E+08
Au	32	1.1E+09

Summary

- RHIC-EBIS pre-injector is providing heavy ion beam for RHIC and NSRL
- Switching time between RHIC beam and NSRL beam is ~1 sec
- Automated fast species change and GCR simulator mode for NSRL has been developed and now routinely used
- The number of species change can be > 100
- Available heavy ion species to switch is typically 12 (10 from LION and 2 from 2 HCISs)
- NSRL switches species at any time without EBIS experts
- Switching time for NSRL at RHIC-EBIS pre-injector is ~40 sec
- Reliability is very high and RHIC-EBIS is unattended for normal operation

End

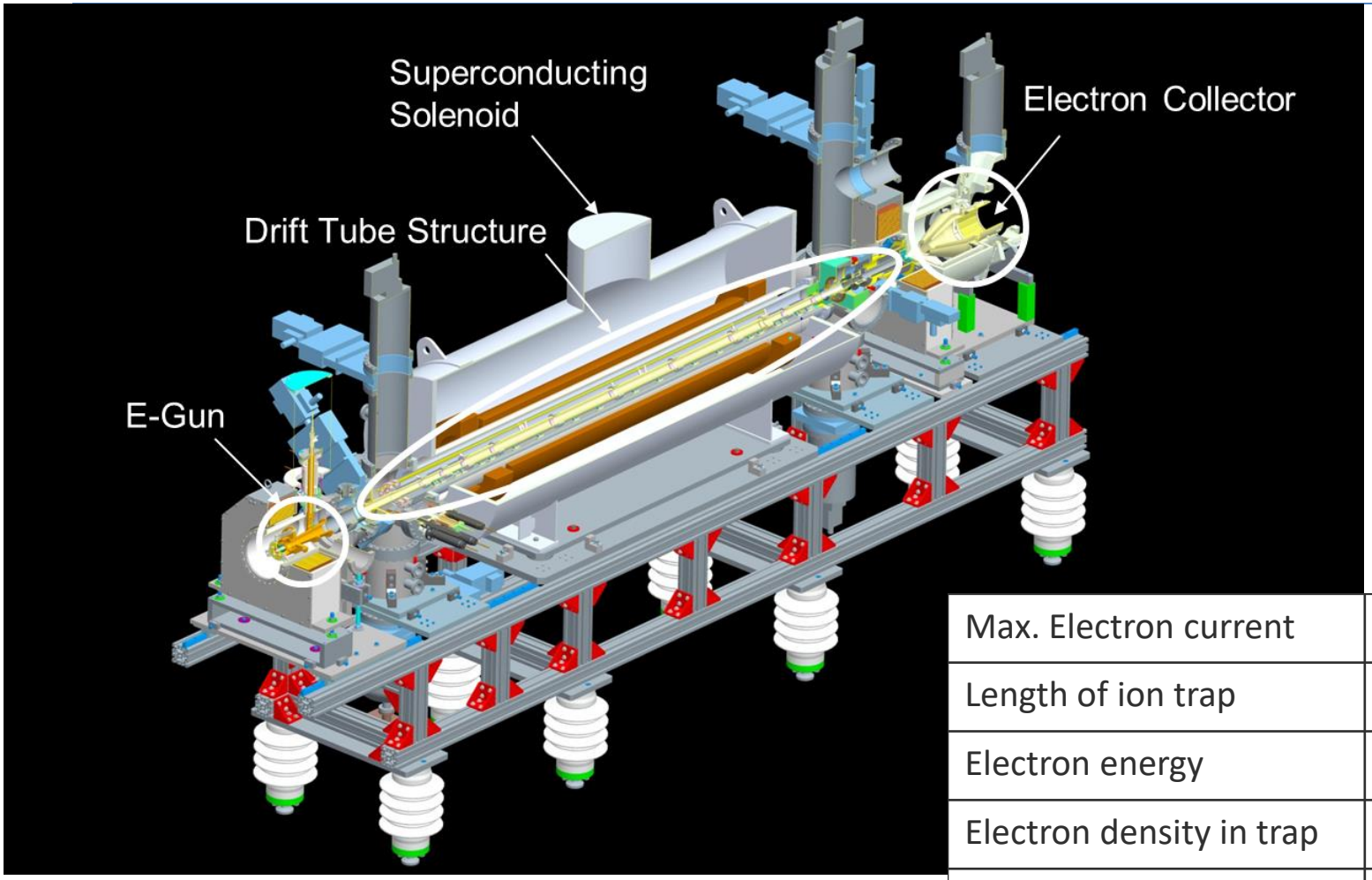
Electron Beam Ion Source



Radial trapping of ions by the space charge of the electron beam.
Axial trapping by applied electrostatic potentials on electrode at ends of trap.
The total charge of ions extracted per pulse is ~ (0.5 – 0.8) x (# electrons in the trap)

- **Ion output per pulse is proportional to the trap length and electron current.**
- **Ion charge state increases with increasing confinement time.**
- **Charge per pulse ~ independent of species or charge state!**
- **Switching time < 200 ms**
- **No memory effect from previous species with external ion injection**

Electron Beam Ion Source



Max. Electron current	7~10 A
Length of ion trap	188 cm
Electron energy	20-24 keV
Electron density in trap	300—500 A/cm^2
Length of ion trap	188 cm
Max. solenoid fied	5 T

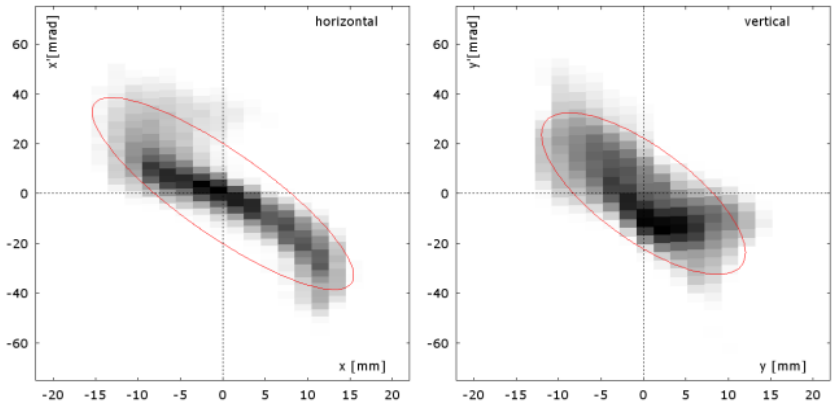
Very reliable, excellent pulse-to-pulse stability, and long life time.

Laser Ion Source is the key for fast species change

Charge state 1+

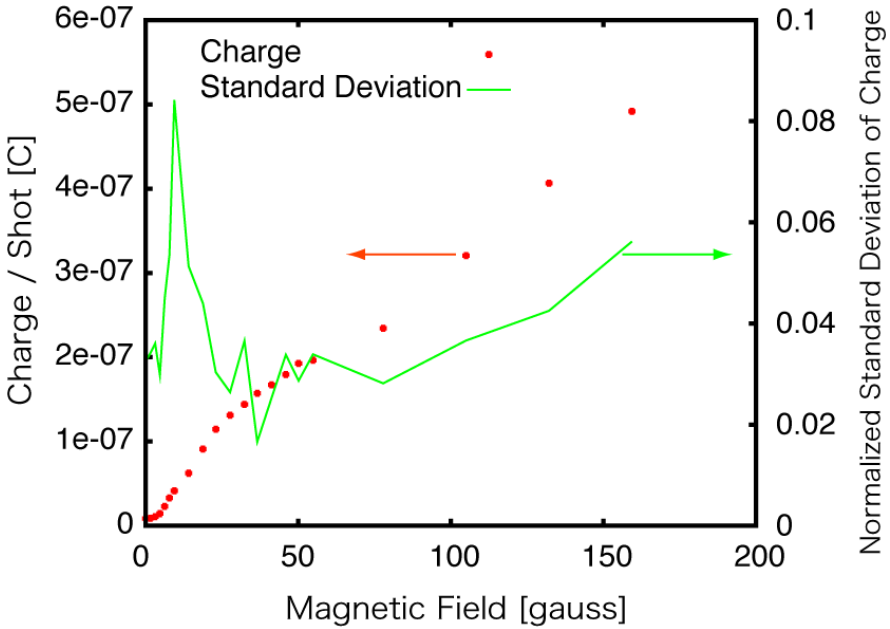
- **Any solid target** by laser ablation in vacuum
- 10^8 ~ 10^9 [W/cm^2] for 1+ ions
- Beam out of LION
  - 100 μA ~ 1 mA, ~200 μs (“fast injection” scheme of EBIS)

Low emittance



	Au beam Norm. RMS
X	0.067 π mm mrad
Y	0.058 π mm mrad

Plasma transport by solenoid



Beam operation for RHIC

- RHIC runs from around January to the end of June
- RHIC-EBIS provides beam **for >30 min to refill RHIC at every 0.5-20 hours**
- **For RHIC injection, 12 pulses at 5 Hz within a supercycle (overall repetitive sequence of the accelerator facility) of 6 s**
- 12 pulses are also used for injector setup during store
- Other time, EBIS runs at **1 pulse/supercycle as standby mode** to keep the system up. Cathode heater current is reduced to save life time

- Duty changes a lot from 1 to 12 cycles per supercycle (6 s)
- More chances of electron beam fault
- **MCR use the automated sequencer to change from standby to operational mode without EBIS experts' help**