RFQs in BNL

M. Okamura
Collider-Accelerator Department
Brookhaven National Laboratory

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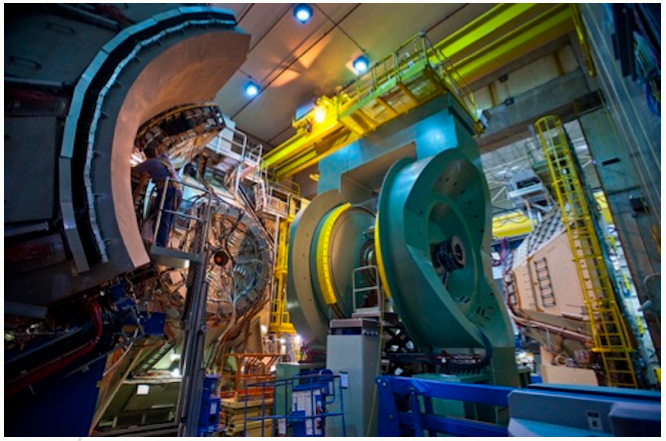
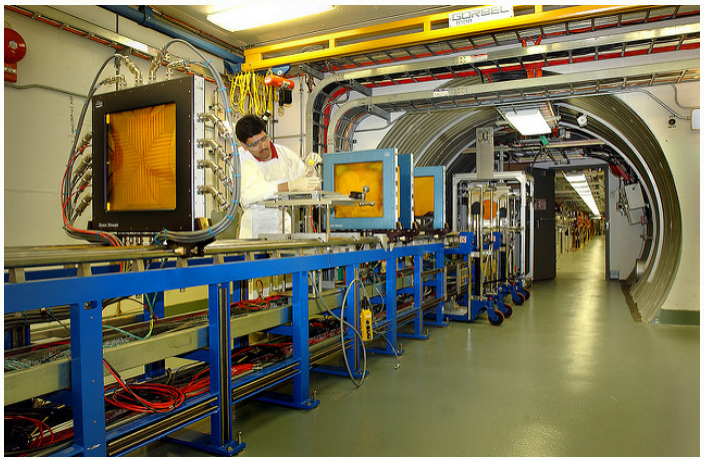
Three user facilities using RFQ at BNL



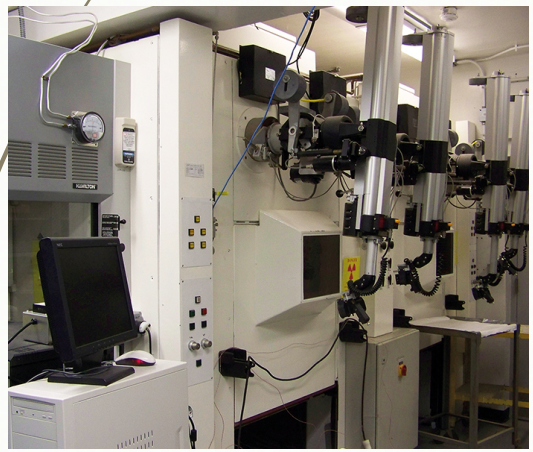
Relativistic Heavy Ion Collider

Polarized proton and gold beams



NASA Space Radiation Laboratory

Many kinds of heavy ion beams



Brookhaven Linac Isotope Producer

Negative proton beam

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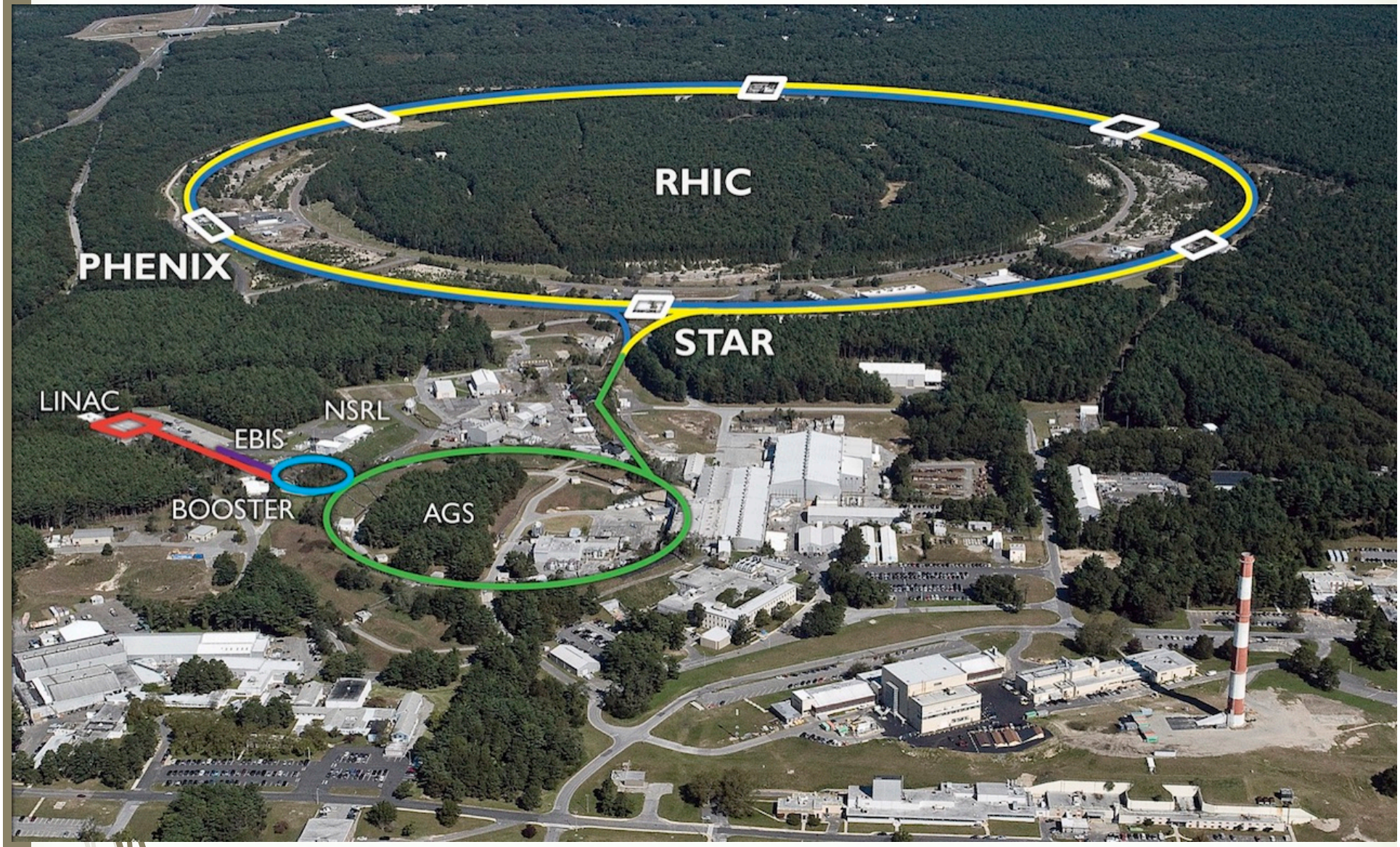

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RFQ's at BNL

- Polarized H^- RFQ

20 keV →750 keV 1985-1999

- High current H^- RFQ

35 keV →750 keV 1987-

- DPIS TEST RFQ

Replaceable vane 2005-

- EBIS RFQ

16.2 keV/u →300 keV/u 2009-

Polarized H- RFQ

20 keV →750 keV 1985-1999

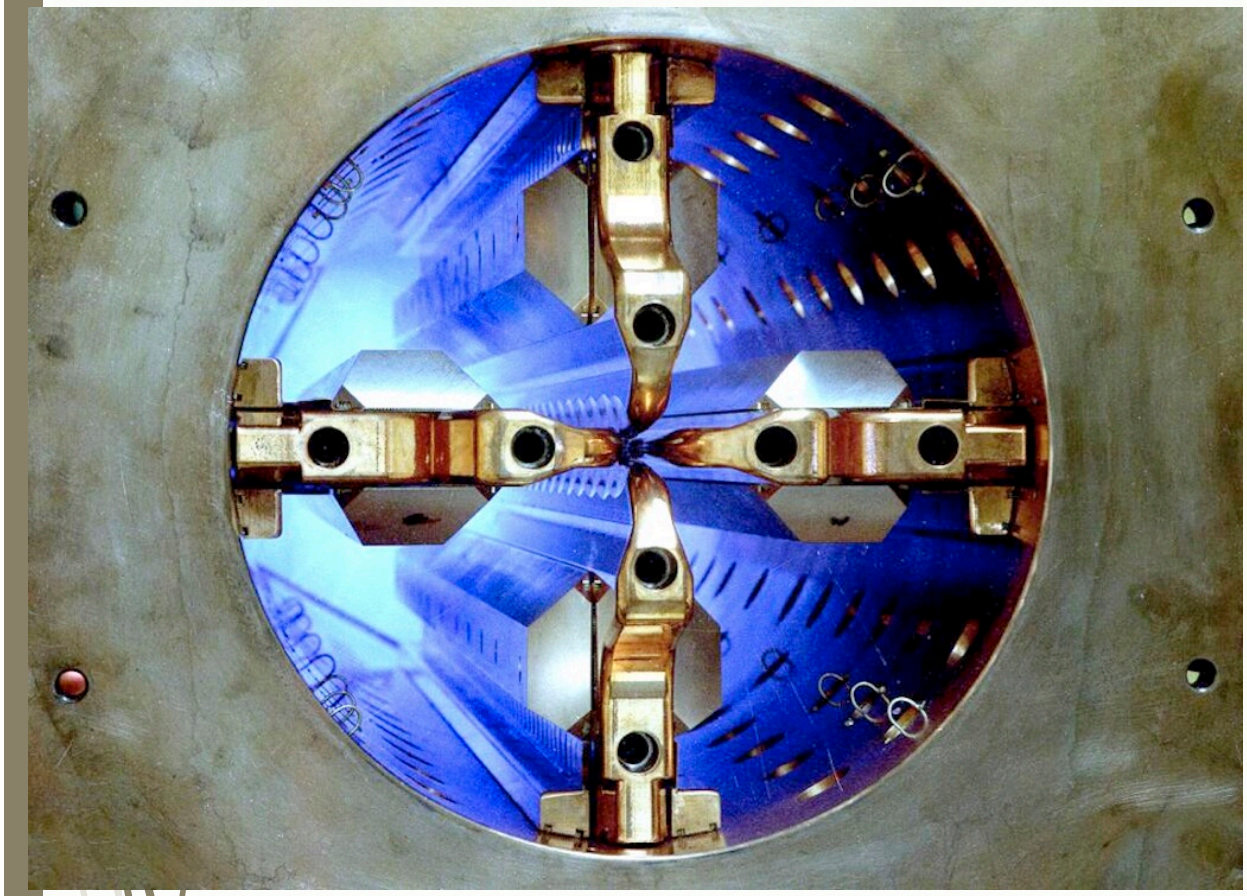


TABLE I
RFQ DESIGN PARAMETERS

Frequency	201.25 MHz
Ion Species	H^-
Cavity Length	148.27 cm
Cavity Diameter	32.4 cm
No. of Cells (in vane)	144
Vane Length	130.28 cm
Intervane Voltage	63 kV
Peak Surface Field	20.9 MV/m
Average Radius, r_o	0.4638 cm
Final Radius, a_f	0.299 cm
Final Modulation, m	1.969
Initial Synchronous Phase, ϕ_i	-90°
Final Synchronous Phase, ϕ_ϕ	-30°
Estimated Peak RF Power	60 kW (120 kW operating)
Nominal Current Limit	56 mA
Nominal Acceptance	2.7 π mm-mr (normalized)
Initial Energy	20 keV
Final Energy	760 keV

Proceedings of the 1984 Linear Accelerator Conference, Seeheim, Germany

DESIGN, FABRICATION, AND TESTING OF THE BNL RADIO FREQUENCY QUADRUPOLE ACCELERATOR*

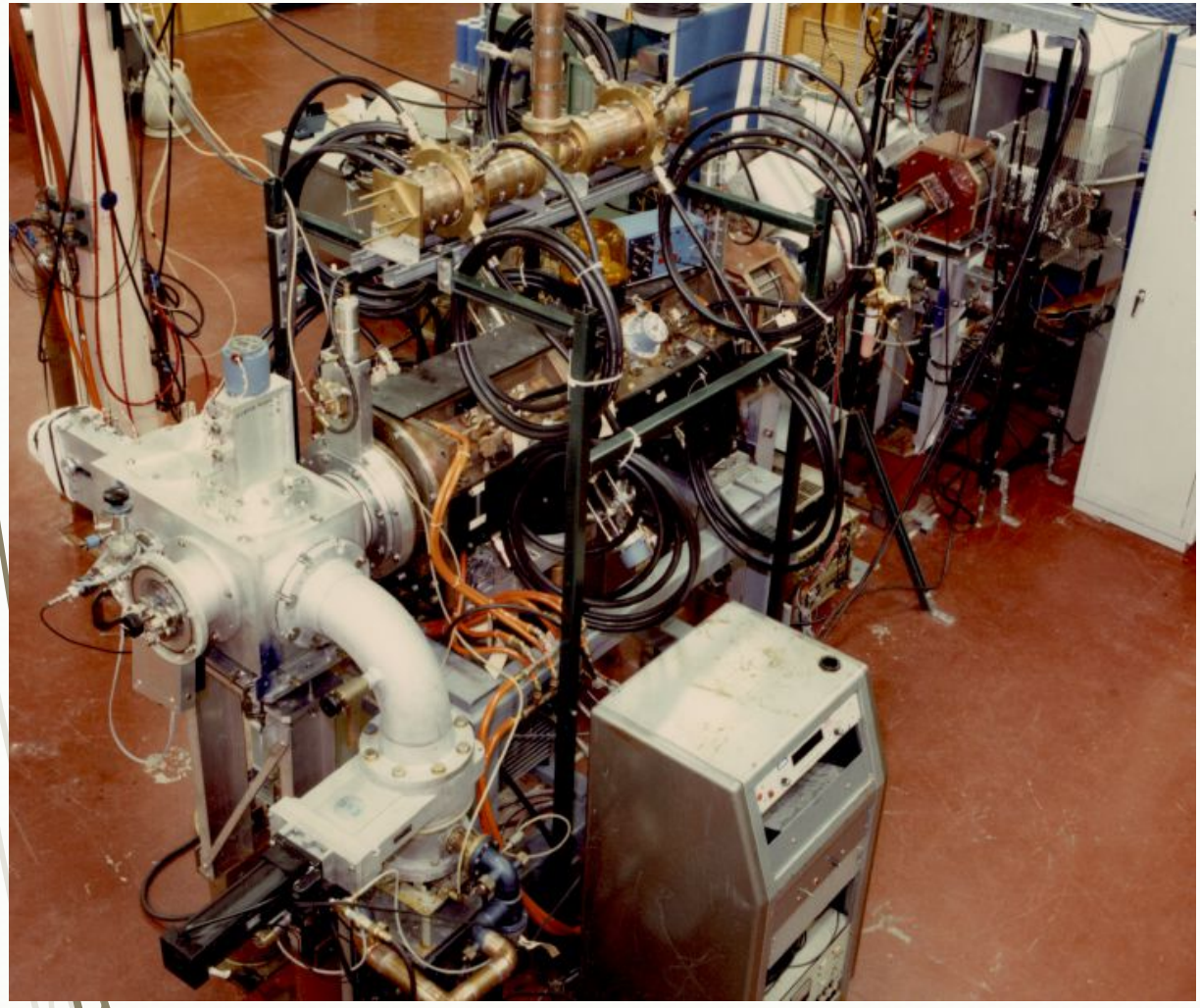
H. Brown, T. Clifford, S. Giordano, F. Khiari,#
R. McKenzie-Wilson, M. Puglisi,+ P. Warner

Brookhaven National Laboratory, Associated Universities, Inc.
Upton, New York 11973 U.S.A.

Dedicated to polarized proton beam. The injection energy was 20 keV.

Polarized H^- RFQ

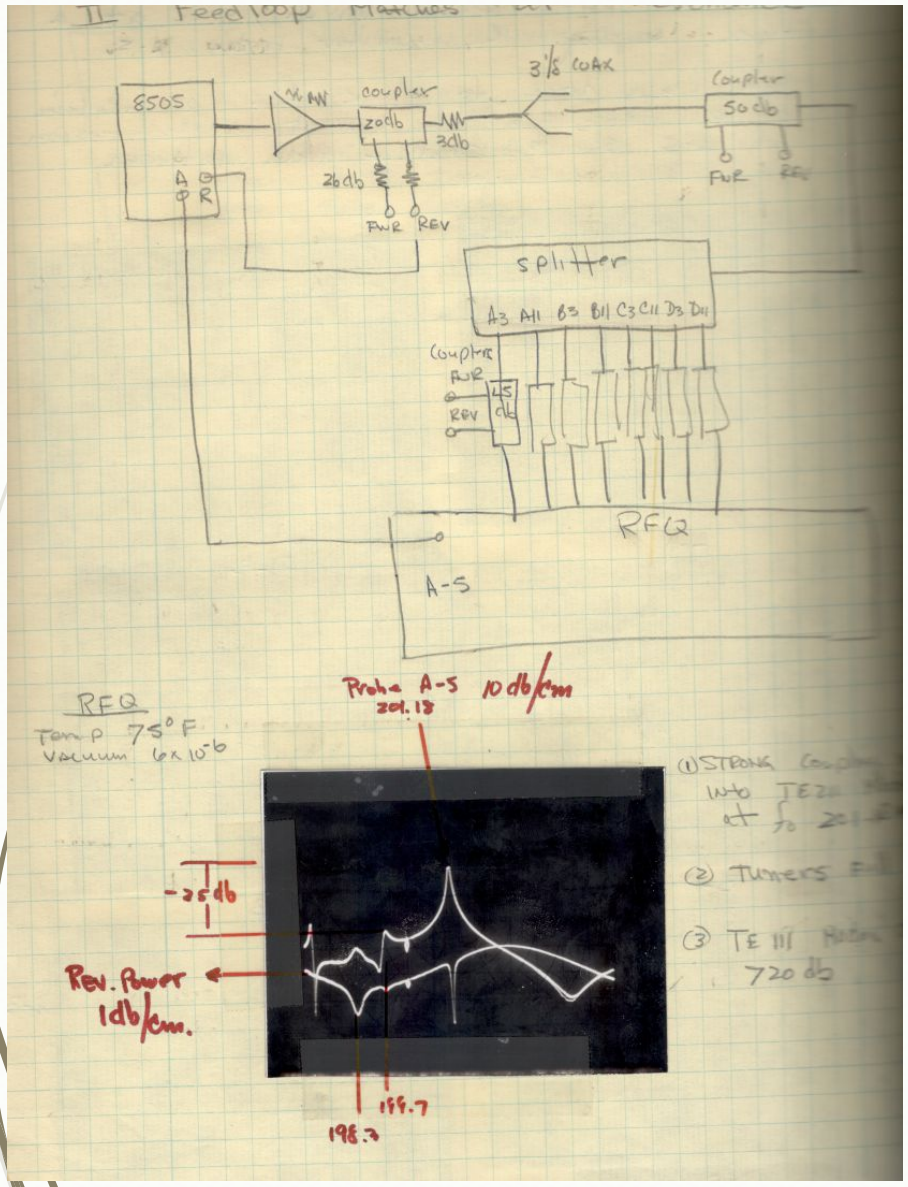
20 keV →750 keV 1985-1999

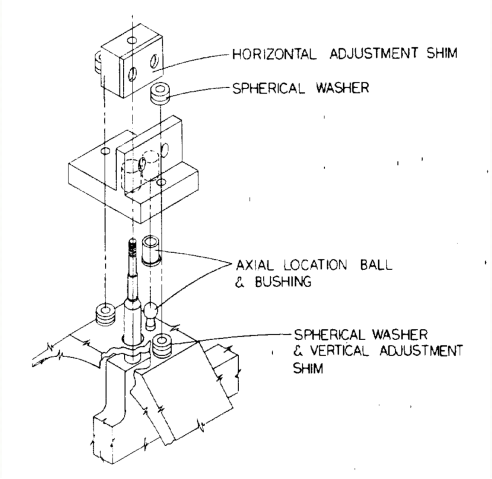


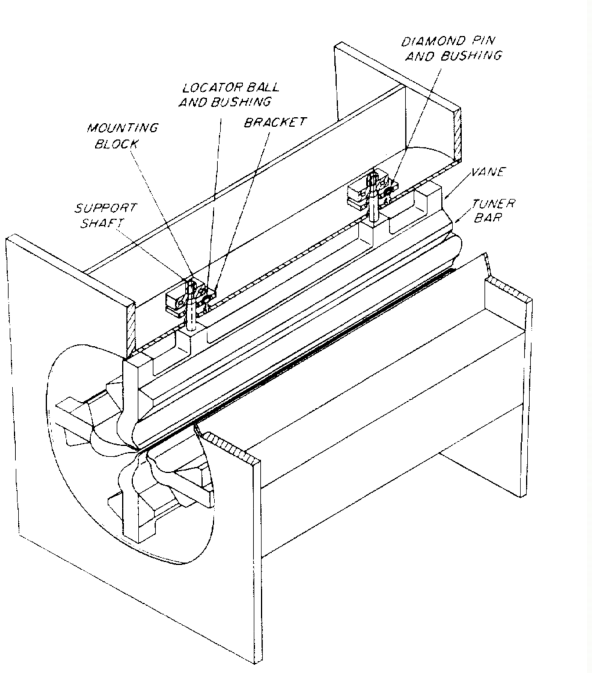
- Four vane structure
- Designed and built at BNL.
- RF power fed from 8 loops.
- Many tuner ports.
- Capacitive tuners at end plates.
- The first beam at Sep. 21, 1985 with 20 uA 80% Tr.
- 700 uS at 5 Hz

Polarized H⁻ RFQ

20 keV →750 keV 1985-1999







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Polarized H^- RFQ

20 keV →750 keV 1985-1999

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High current H^- RFQ

35 keV →750 keV 1987-

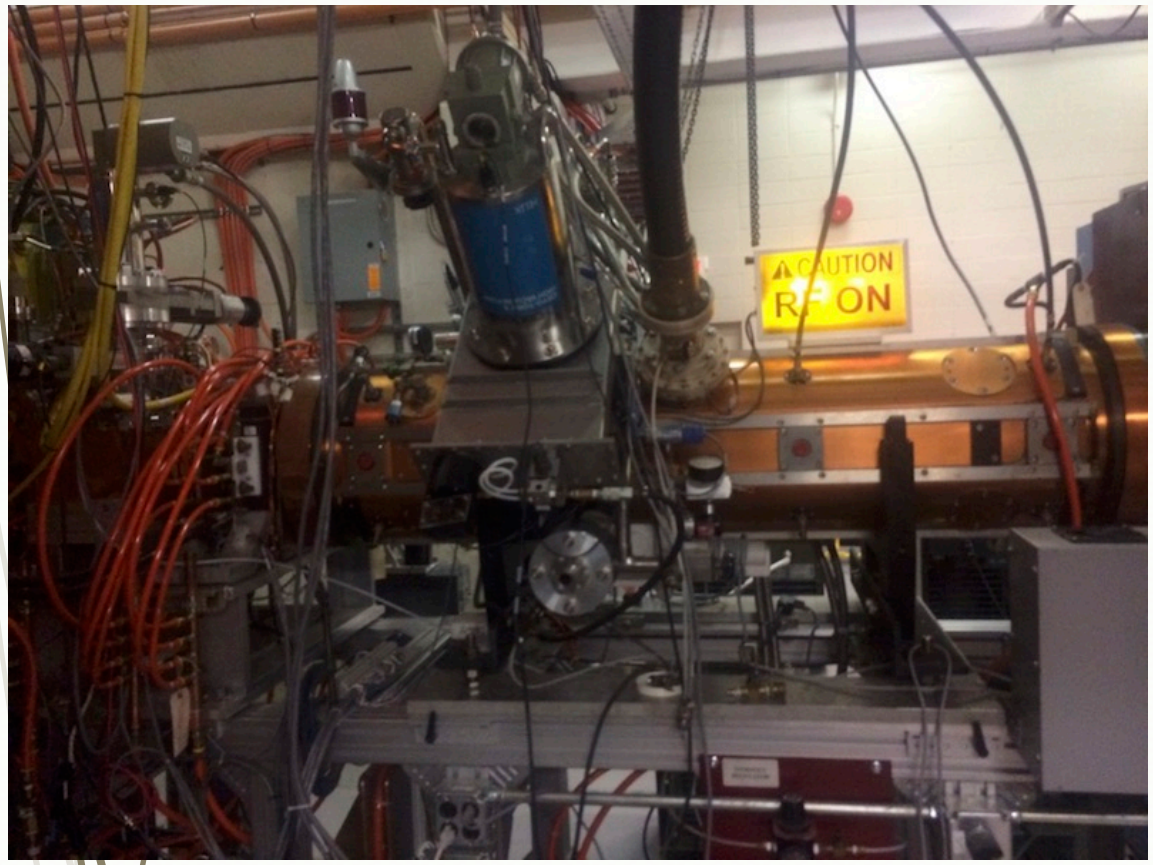

Table 1: Summary of RFQ Parameters

Ion	$H^{\pm}$	
Frequency	201.25	MHz
Energy	35 - 753	keV
Current limit	> 100	mA
Normalized emittance	0.1π	cm-mrad
Vane Length	161.89	cm
Mean radius (r_o)	0.418	cm
Surface field	20.3	MV/m
Peak cavity power	100.5	kW
Max duty factor	0.007	
Stored energy	0.5	Joules

Designed and fabricated by LBL
The third RFQ by LBL
Operated at 6.67 Hz
Constantly supplying more than 50 mA to BLIP
Installed on Dec. 1988
Almost no trouble

Our record output : 100 mA

BNL and Fermi Lab worked with LBL on a RFQ design
200 Mhz RFQ built for BNL – Fermi canceled their option

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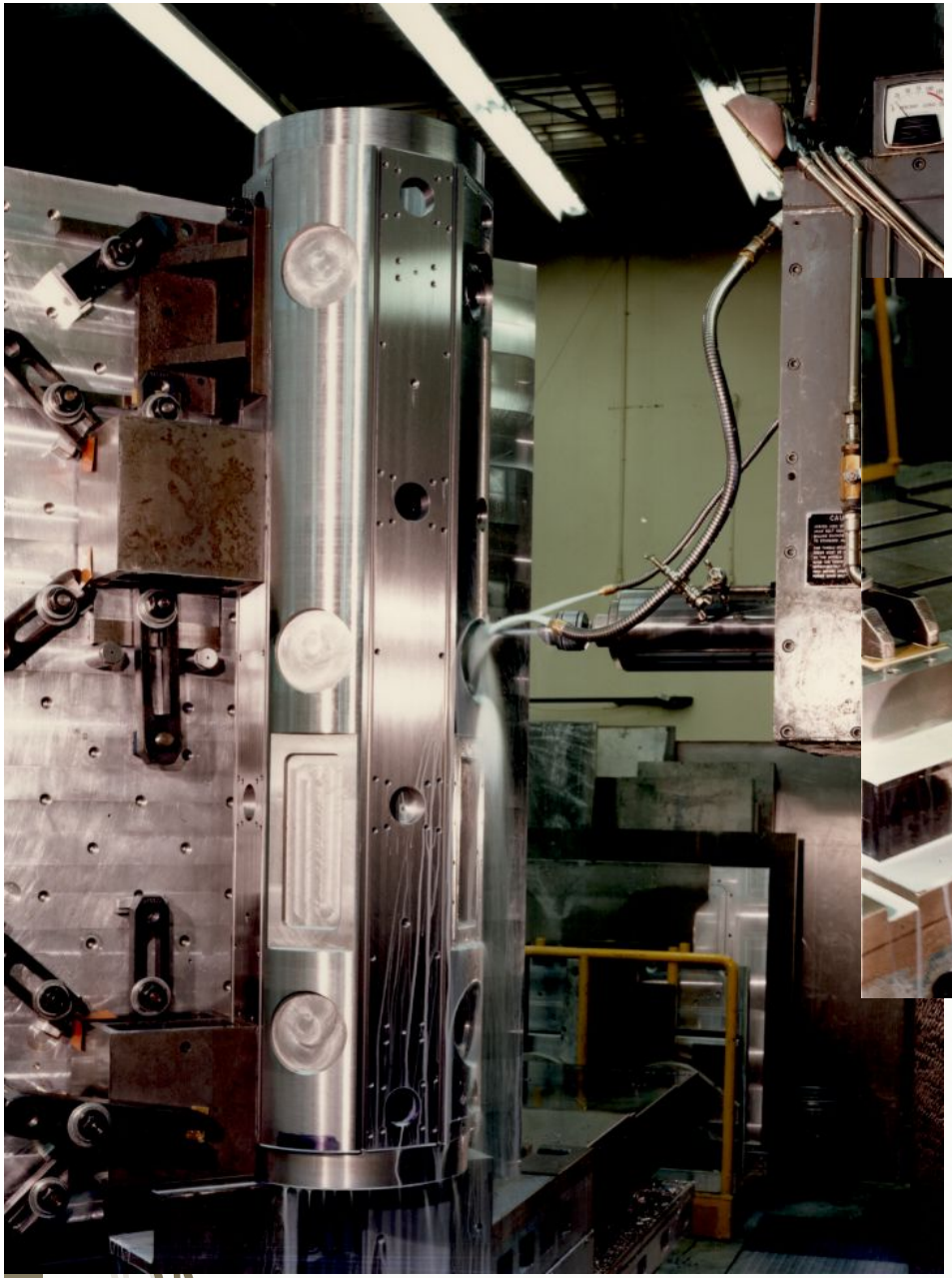
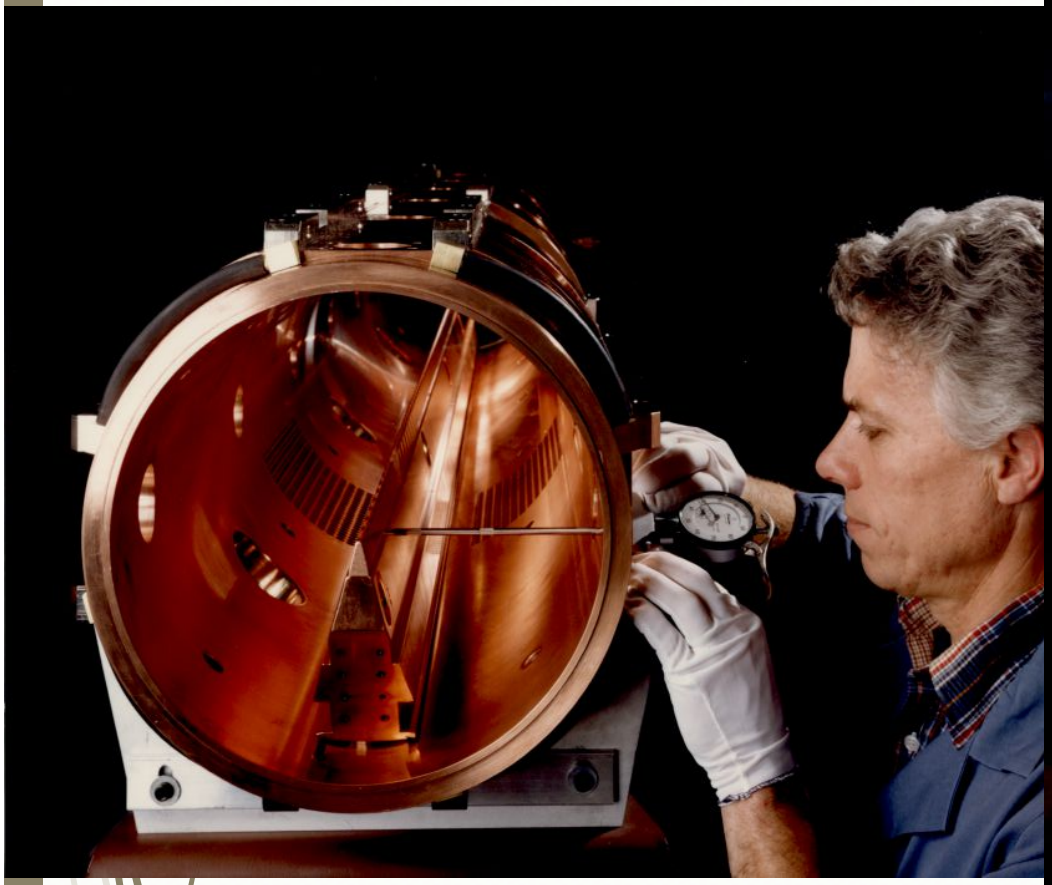
High current H^- RFQ

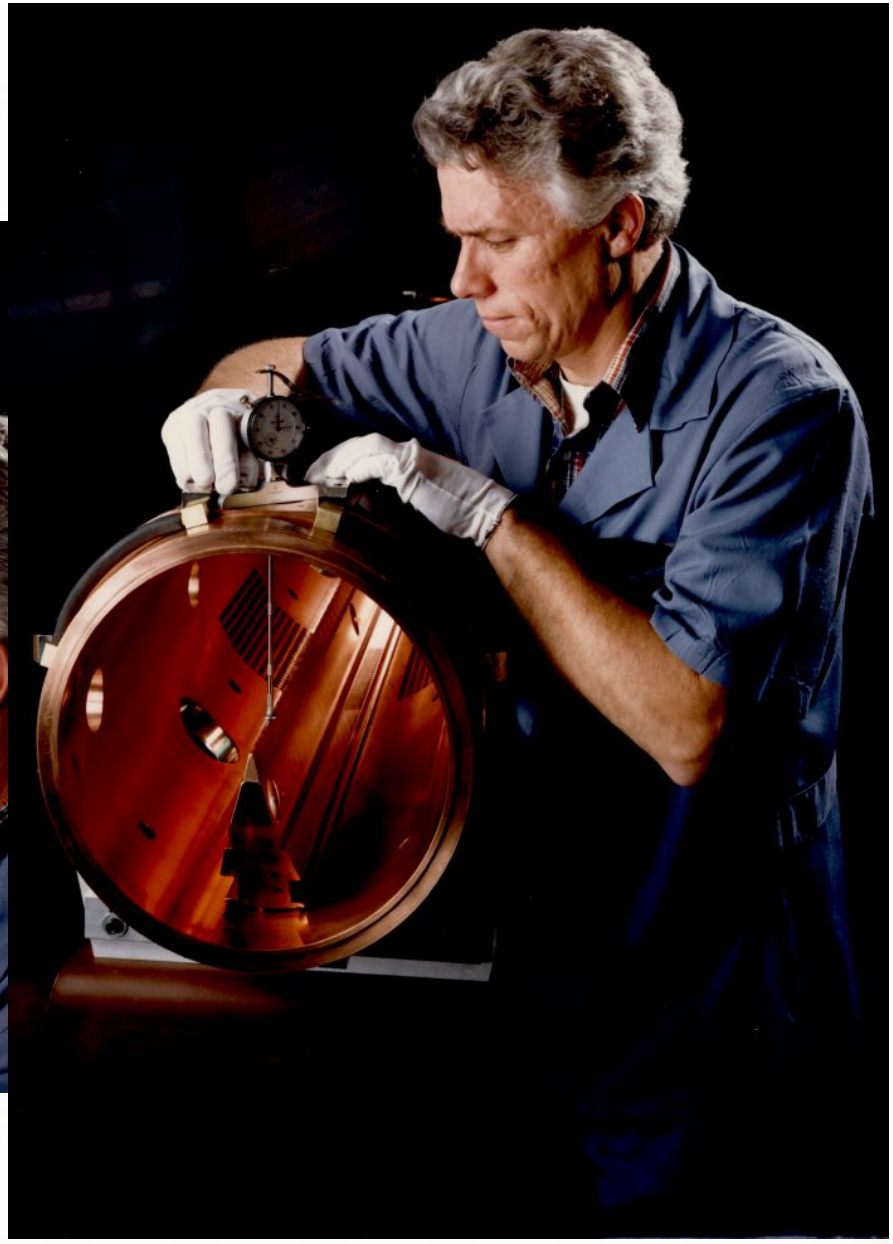
35 keV →750 keV 1987-



High current H^- RFQ

35 keV →750 keV 1987-





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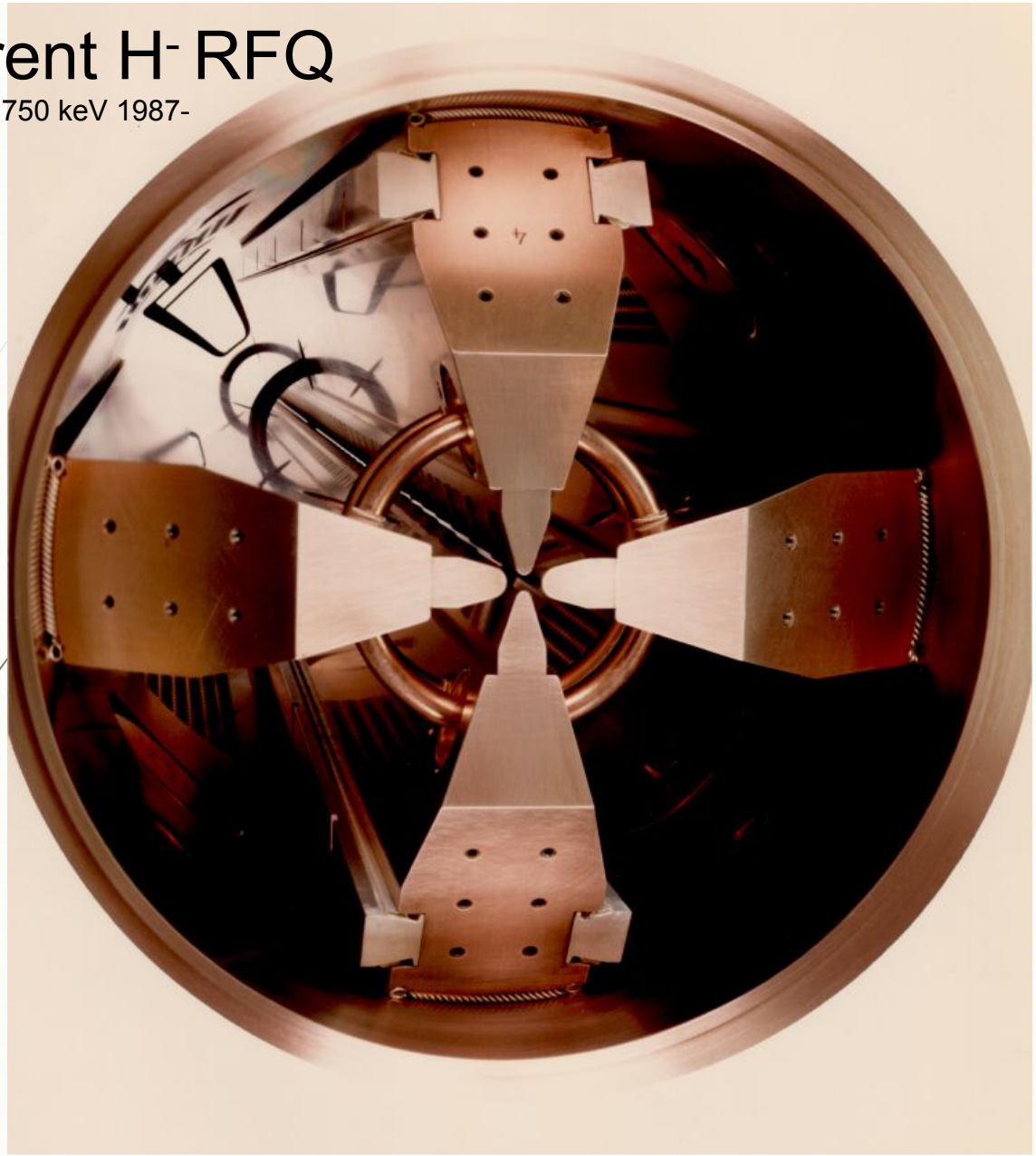
High current H^- RFQ

35 keV →750 keV 1987-



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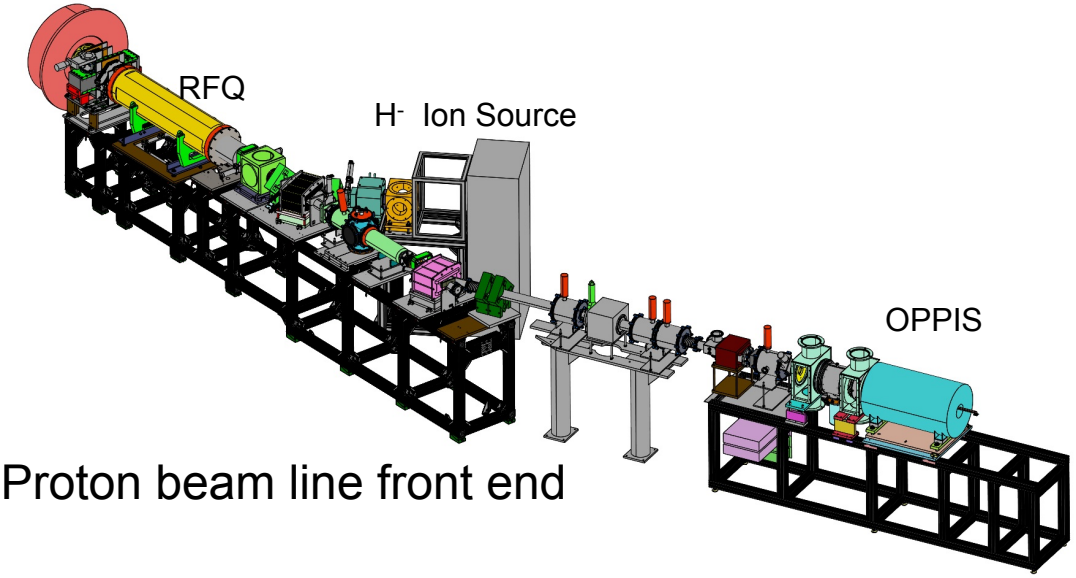
RFQ (750 keV) and Alvarez (200 MeV)

For RHIC: 200 MeV, 500 μA beam current, 400 μs pulse length, polarization as high as possible, and emittance as low as possible.

For BLIP: 66 - 200 MeV, 600 μs pulse length, current as high as possible (~50 mA), uniform beam distribution at the target, and losses as low as possible.



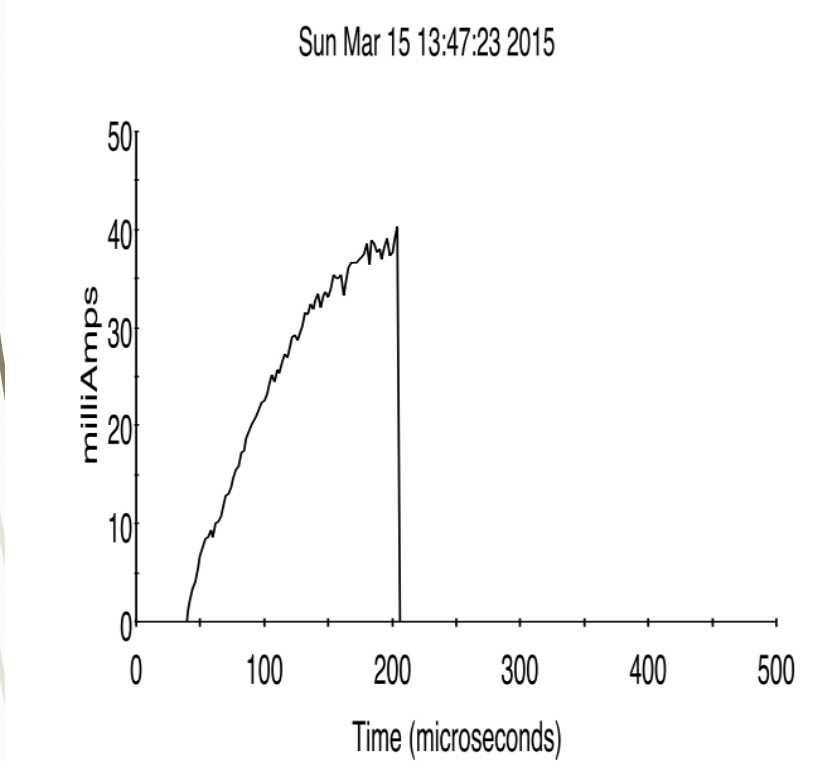
Proton beam line front end

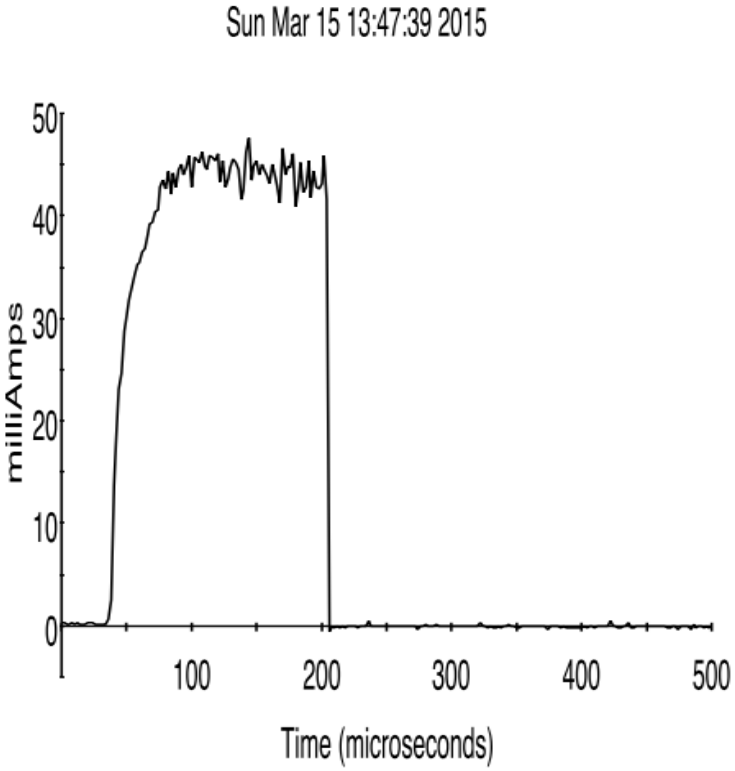
6.67 Hz operation: two pulses per every 4 seconds are polarized beam for RHIC. The rest of pulses are for isotope production (BLIP).

High current H^- RFQ

35 keV →750 keV 1987-

At LEBT, Xe gas neutralization is used.





Xenon gas in the LEBT at 4.2×10−6 Torr.

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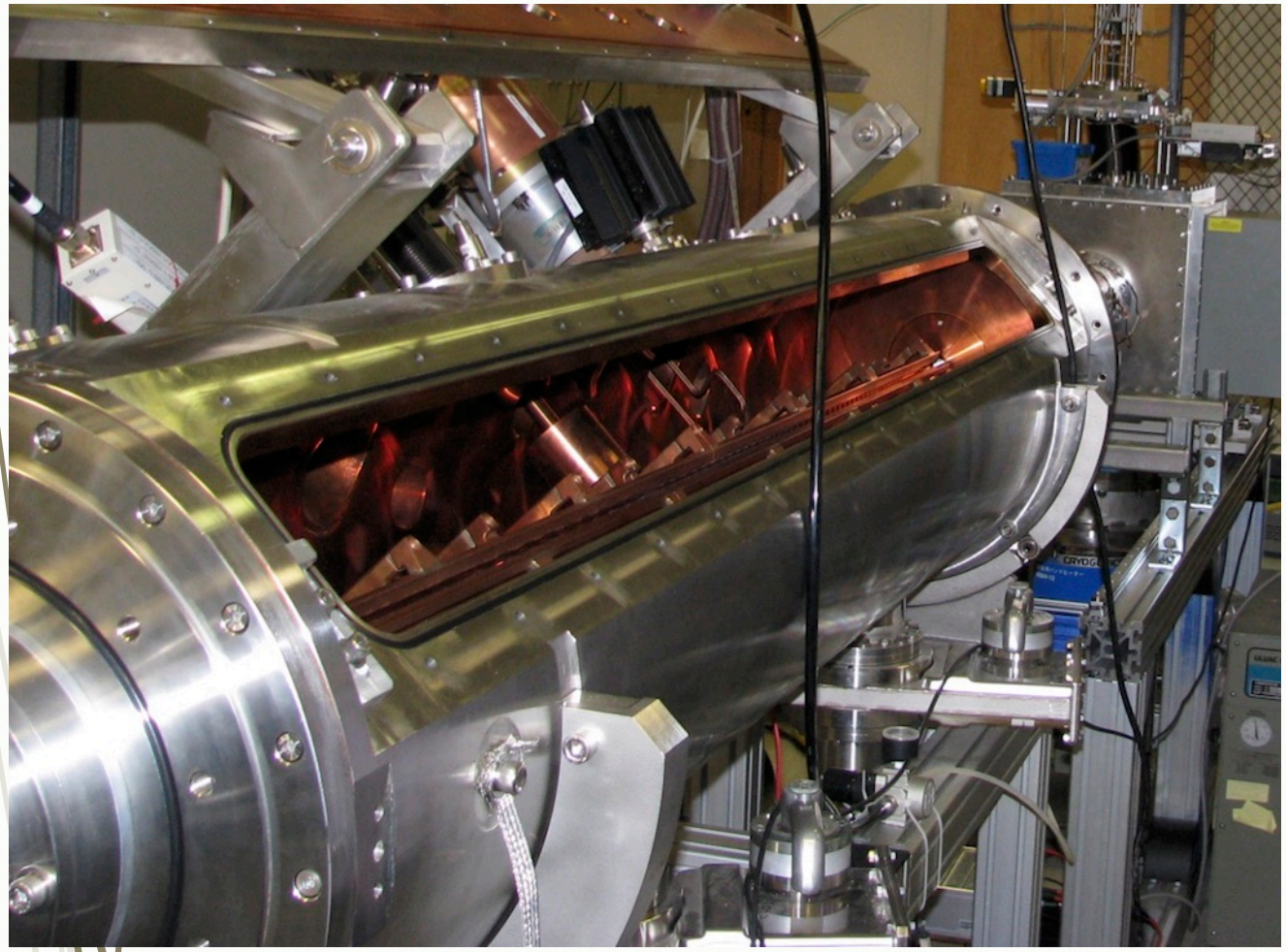
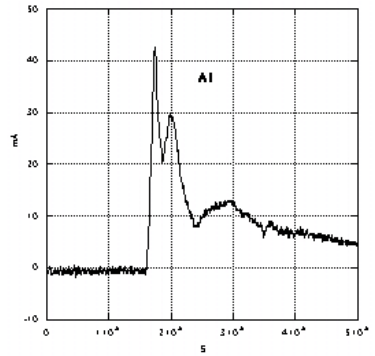
DPIS TEST RFQ





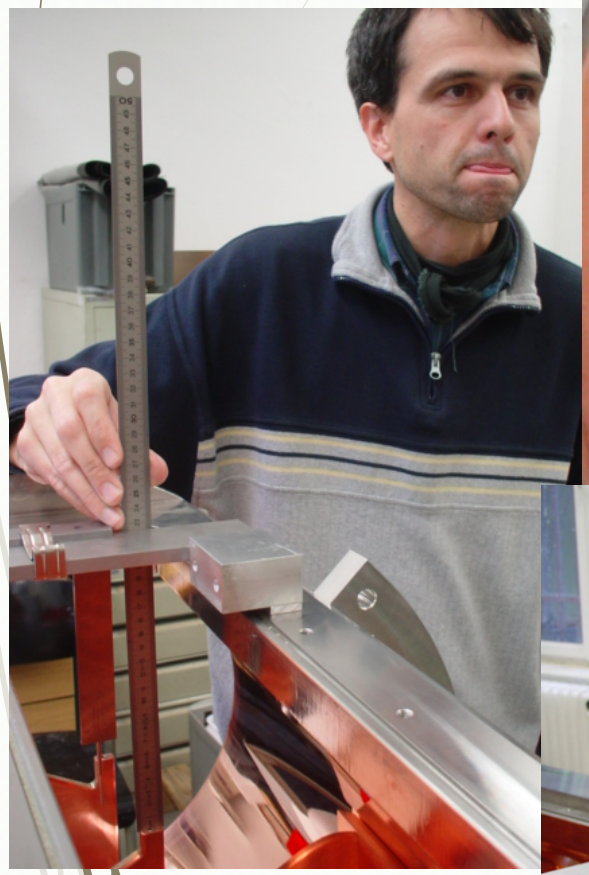
First beam: Dec. 14, 2005
60 mA $Al^{9+, 10+ \text{ and } 11+}$ beam

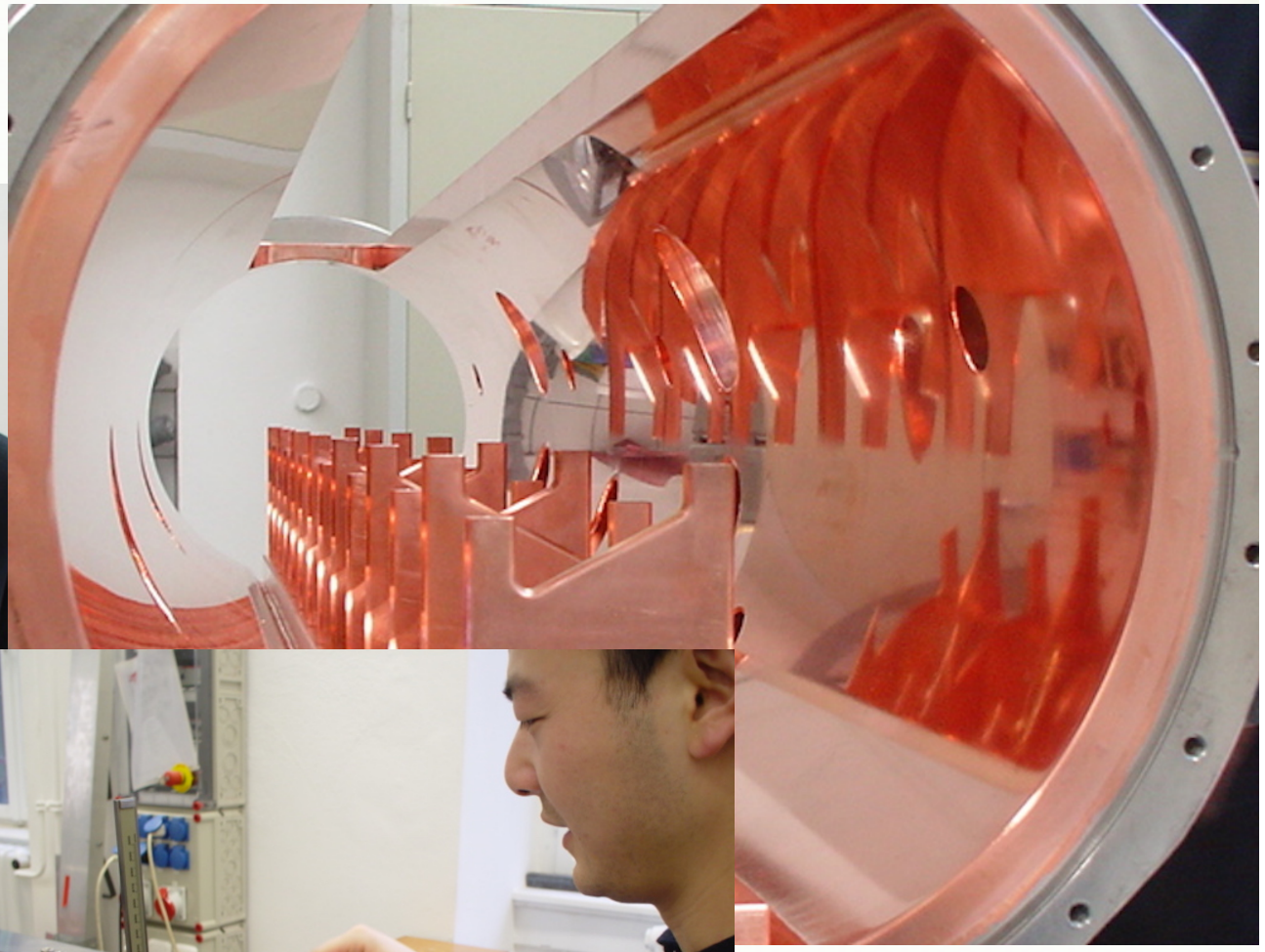
Built by Frankfurt Univ.

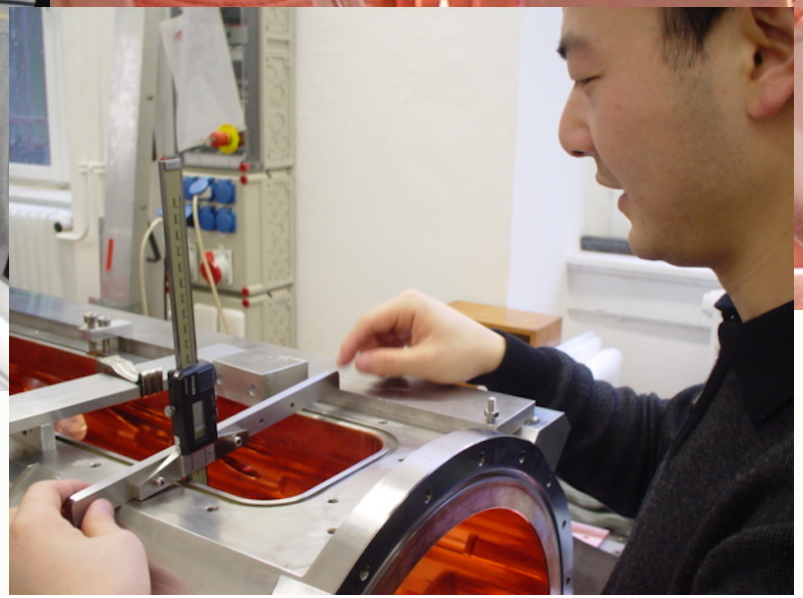
100 MHz, 0.5 % duty
Total length 2.0 m

DPIS TEST RFQ

@Frankfurt University







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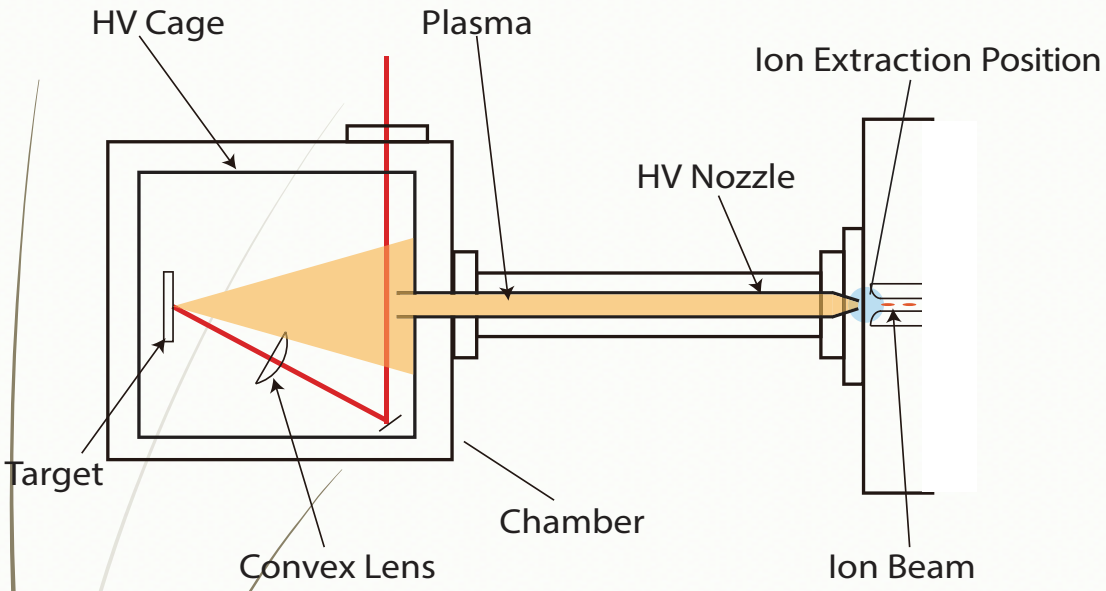
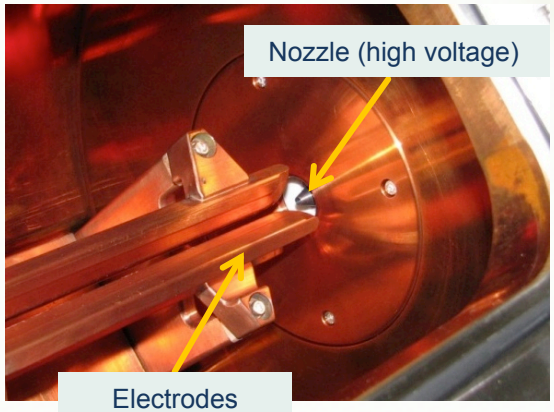
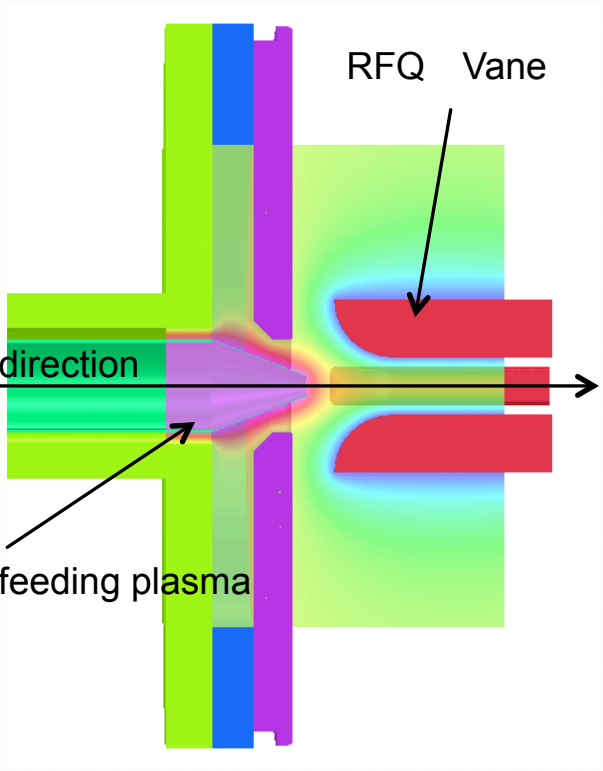
Direct Plasma Injection Scheme





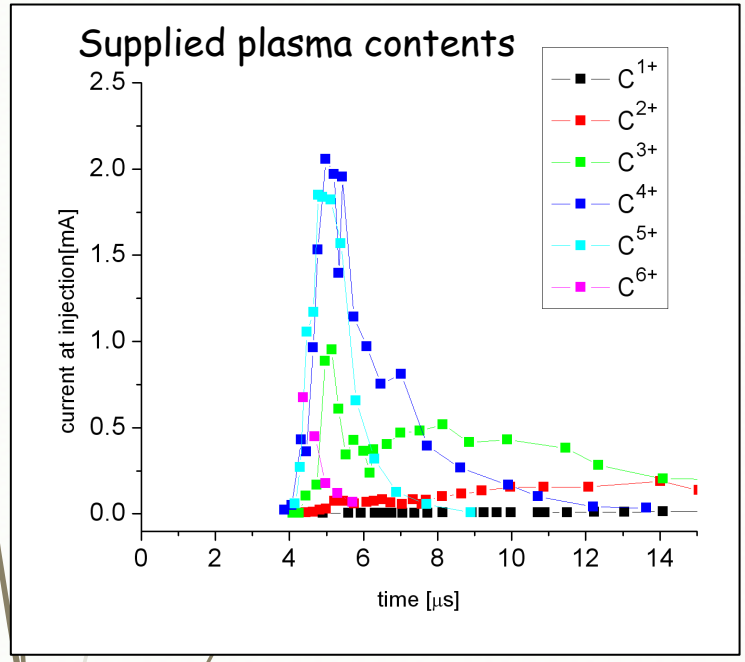


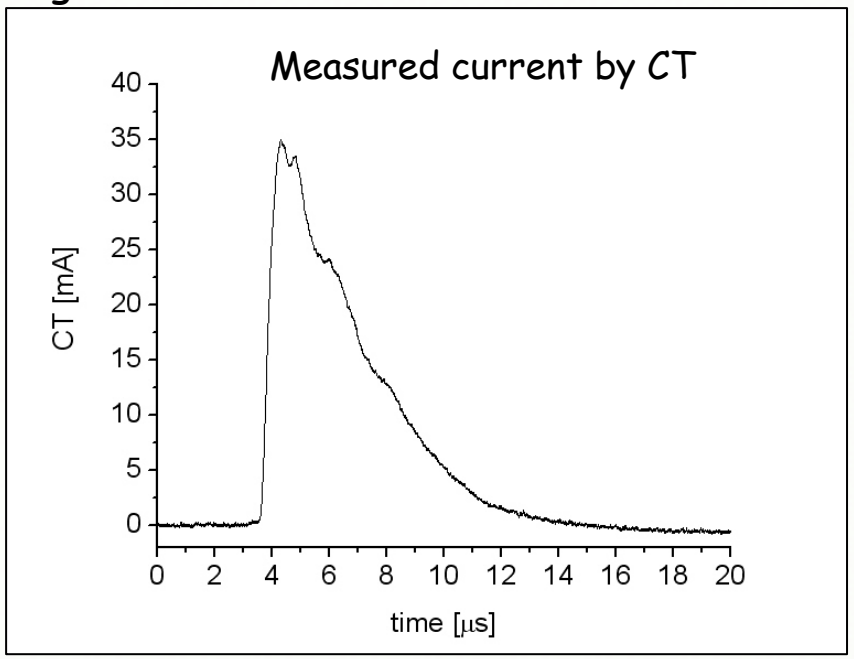
- Ions are delivered in neutral plasma state
- Beam extraction is done in accelerator
- No need to build low energy beam transport (LEBT)

High density plasma directly converted to bunched beam.

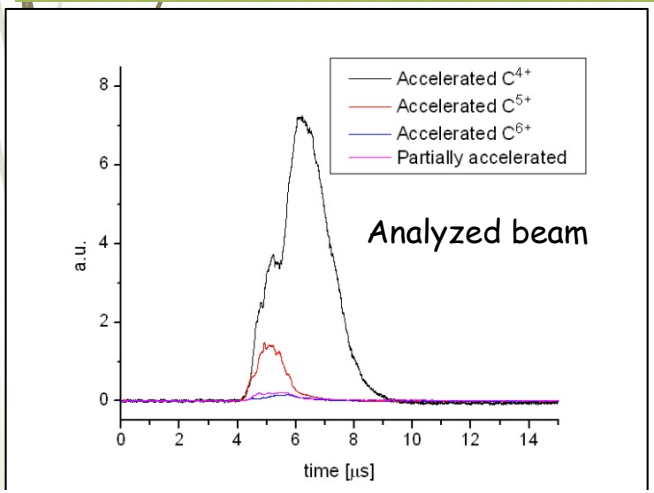
Carbon 4+ acceleration

Terminal voltage 60kV





900 Gauss 100 cm was applied to extend ion pulse width in four times.



C^{4+} occupies 87% of accelerated beam
Peak current : 35.8 mA
Pulse width : 2.1 μs
Number of particles : 1.2×10^{11}

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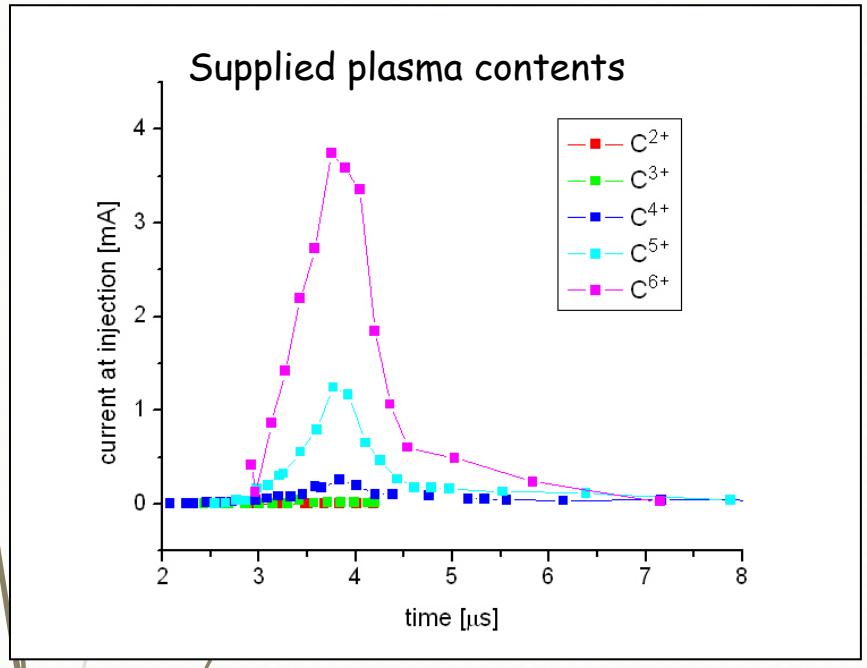
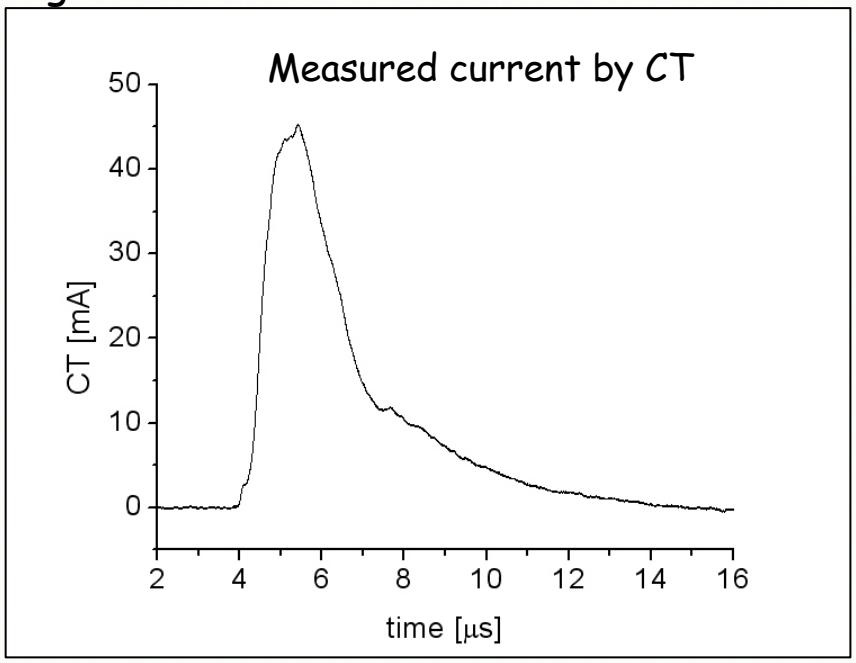
Carbon 6+ acceleration

Terminal voltage 40kV





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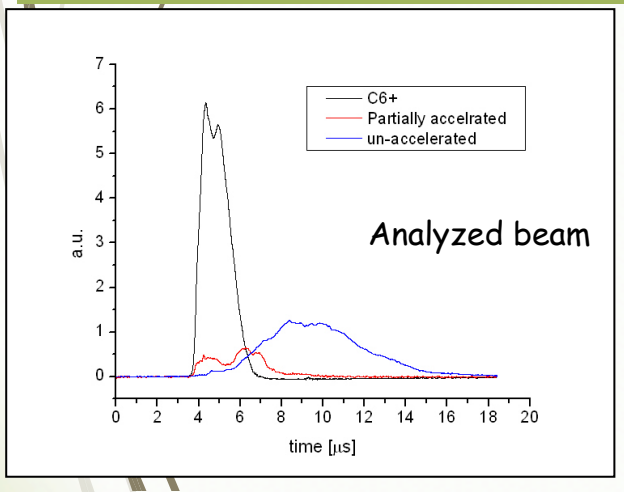

Peak current : 32.8 mA
Pulse width : 1.6 μs
Number of particles : 5.2×10^{10}

Applied Physics Letters **105**, 193506 (2014); doi: 10.1063/1.4902021

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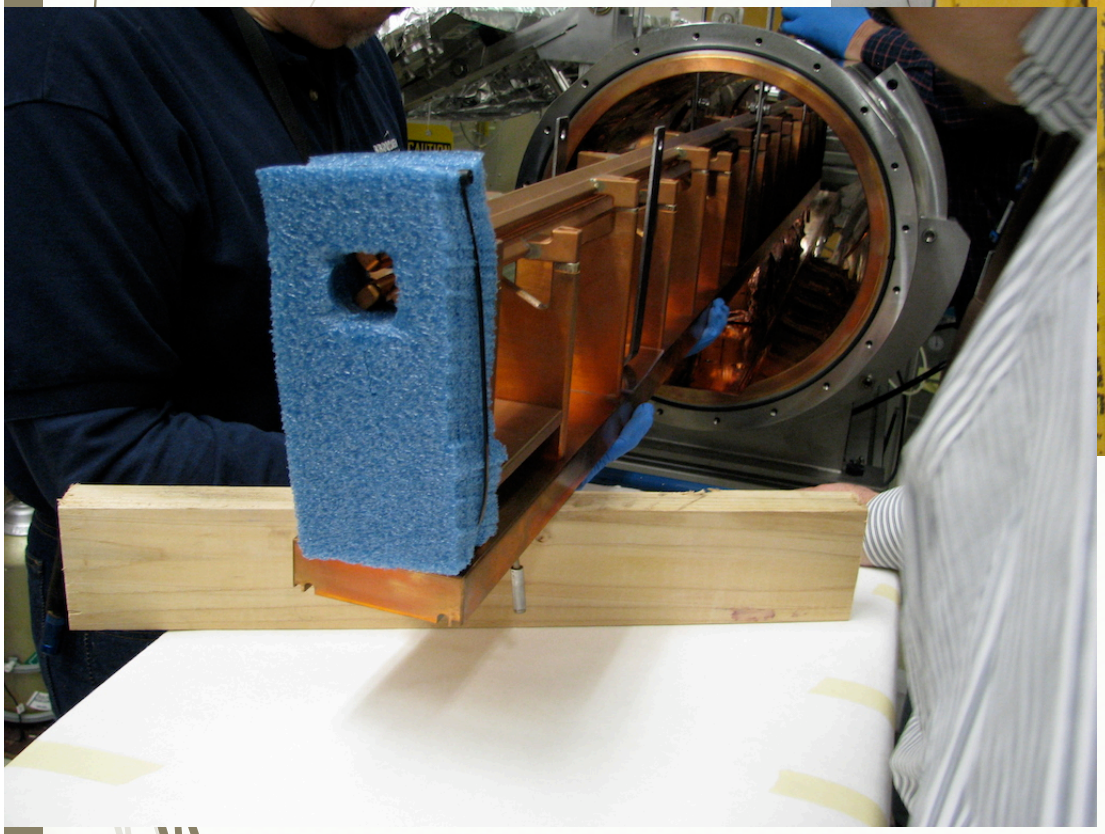
DPIS TEST RFQ



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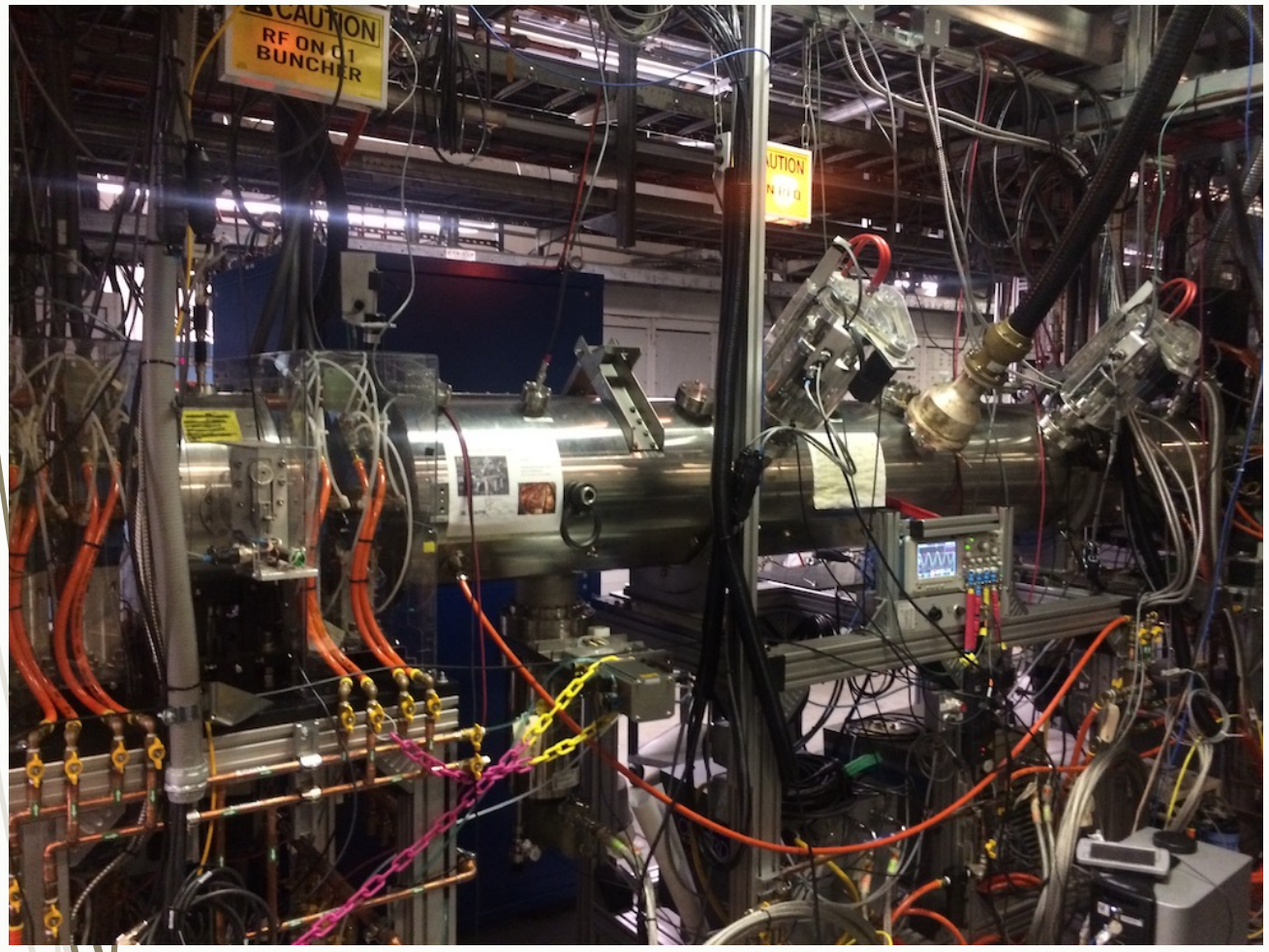
EBIS RFQ

16.2 keV/u →300 keV/u 2009-



The first beam at bench:
Jan. 18, 2009
Commissioning on line:
Mar. 2010
Constructed by
Frankfurt University

Frequency	100.625 MHz
Input energy	17 keV/u
Output energy	0.3 MeV/u
Mass to charge ratio	6.25
Beam current	10 mA
Outp trans. emitt rms norm. 90%	< 0.38 π mm mrad
Output long. emittance 90%	< 220 deg keV/u
Transmission	98%
Electrode voltage	70 kV
RFQ length	3.1 m
Cell number	189
Aperture min - max	2.96-5.25 mm

4-Rod-RFQ	100.625 MHz
Tank diameter	350 mm
Tank length	3100mm
Beam axis height	147 mm
Stem number	20
Stem distance / thickness	158 mm / 10mm
Aperture	5.2-2.96 mm
Modulation factor	1-1.99

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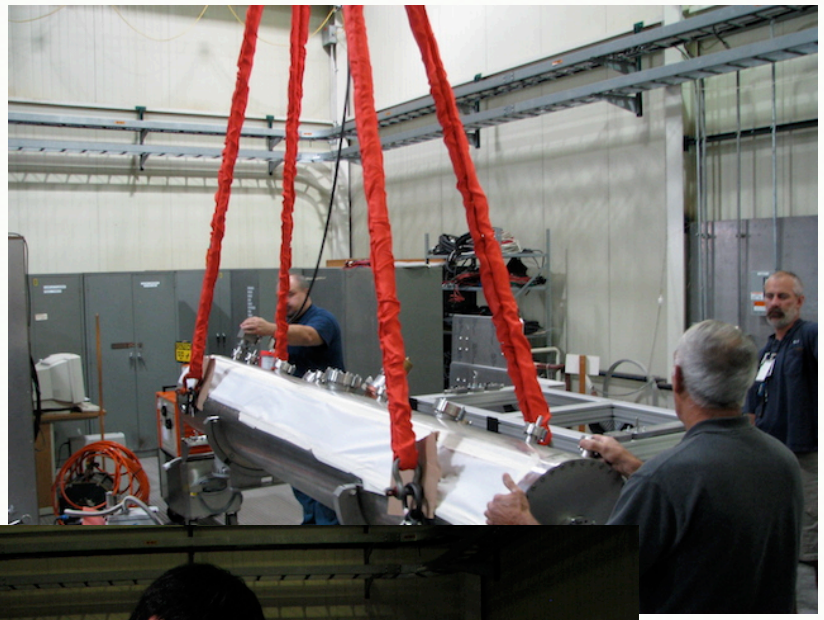
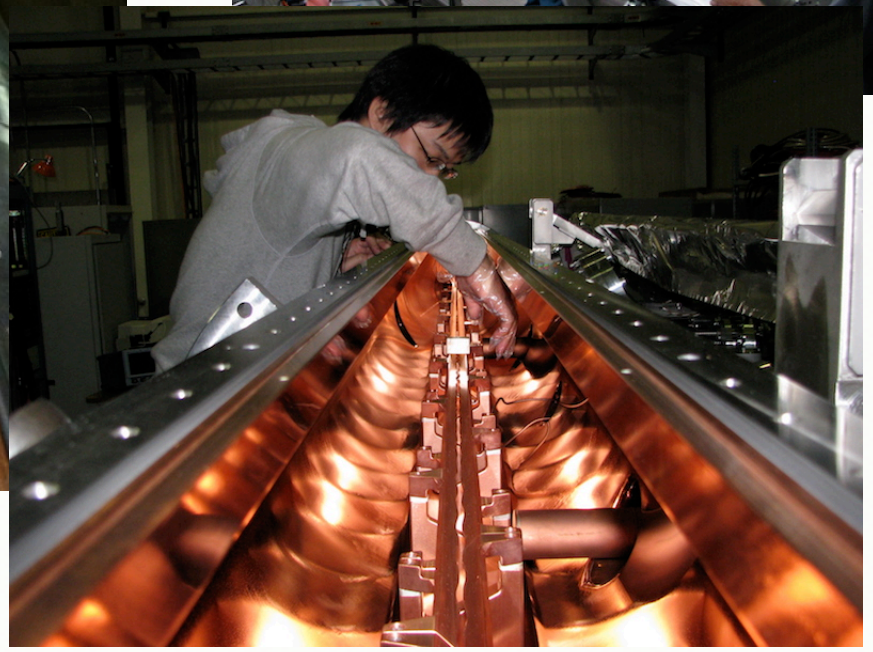
EBIS RFQ

16.2 keV/u →300 keV/u 2009-





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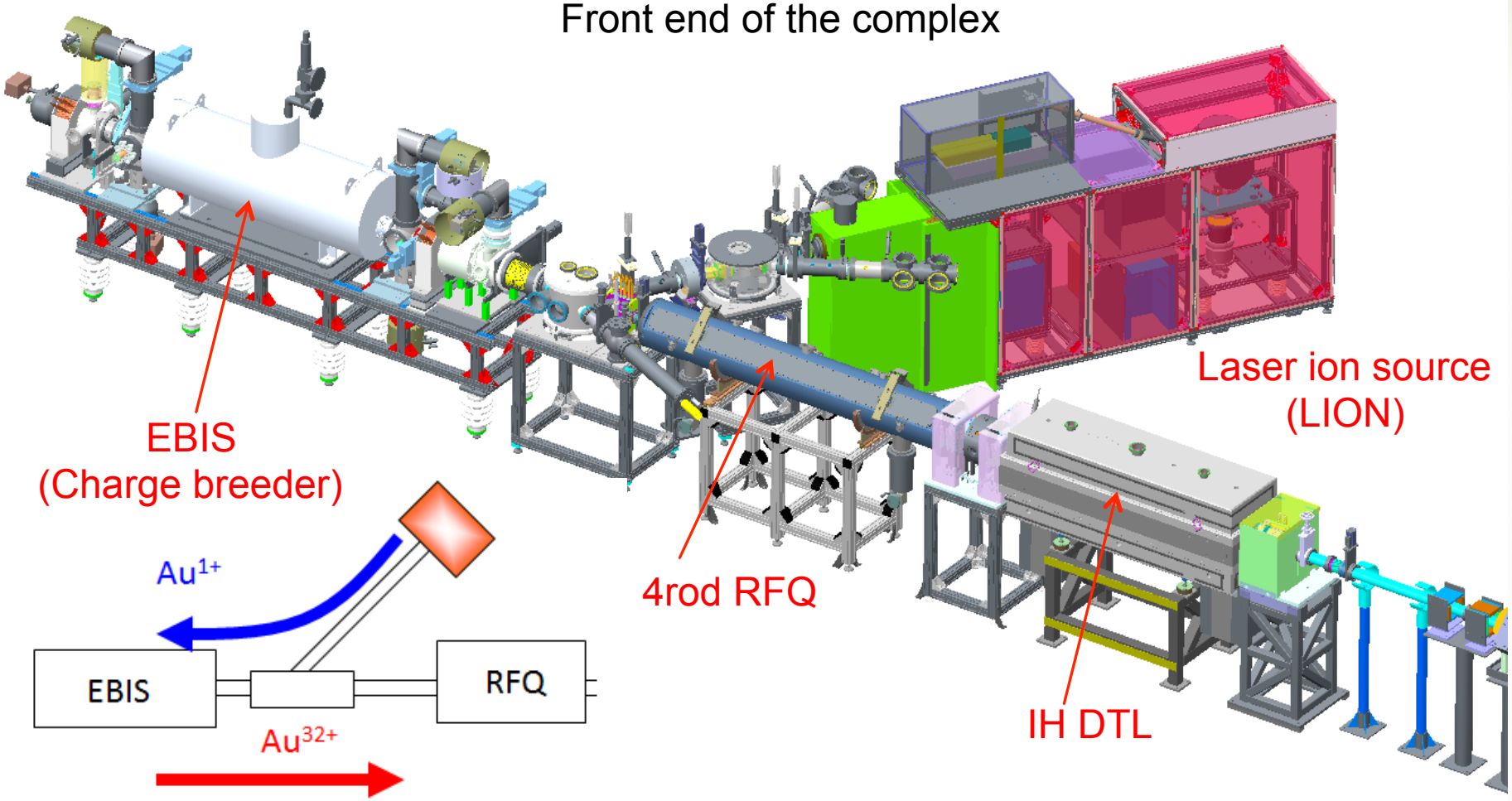
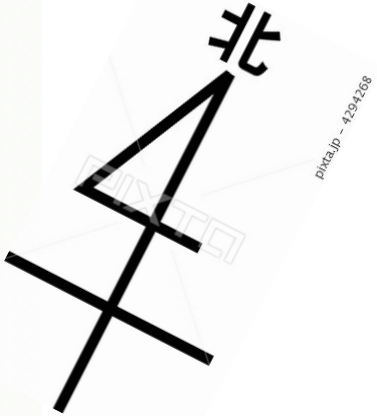
Front end of the complex

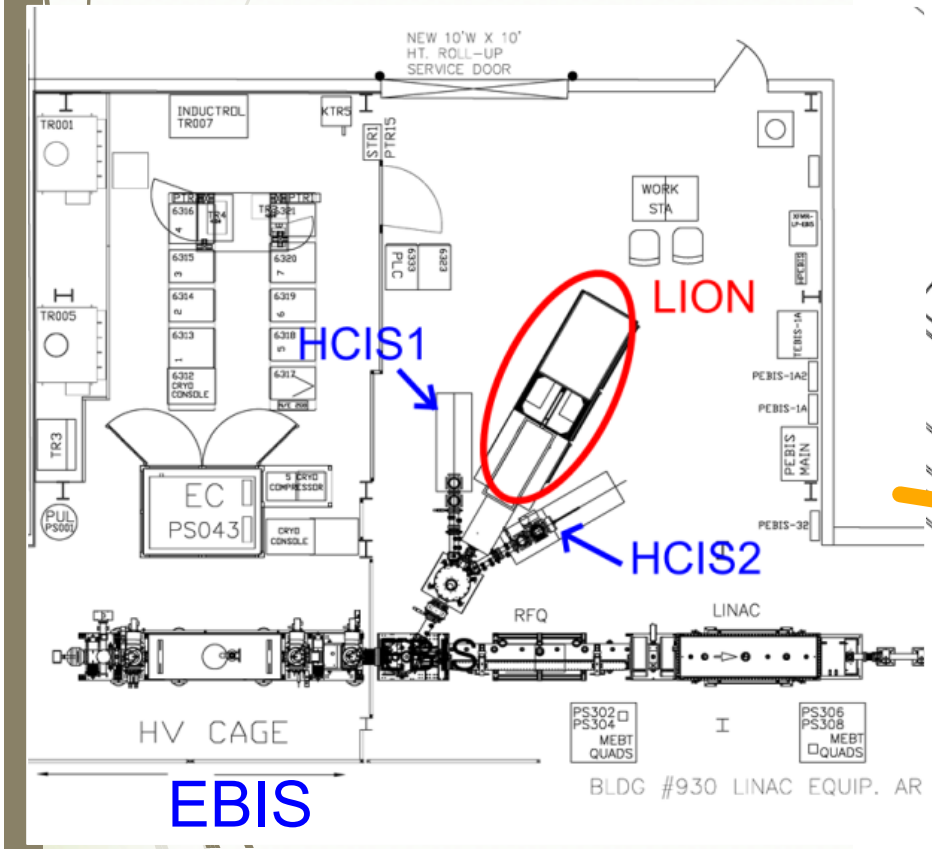


Typical timing sequence:
The entire accelerator complex is triggered at a signal of every 6 seconds.
Within a period of 6 seconds:
RHIC accepts 12 laser pulses at 200 ms interval. (standby mode needs 1 pulse.)
NSRL needs 1 laser pulse.

风水离子源

We care for the earth field too.





LION for RHIC

	Days
Run14 Au	34
Run15 Au	43
Run15 Al	15
Run16 Au	200
Run17 Au	68
Run18 ^{96}Zr	97
Run18 Au	41

or

	weeks
Run14 Au	4.9
Run15 Au	6.1
Run15 Al	2.1
Run16 Au	28.6
Run17 Au	9.7
Run18 ^{96}Zr	13.9
Run18 Au	5.9

RHIC-EBIS for NSRL

	EBIS NSRL days	LION NSRL day
Run16	93	81
Run17	104	89
Run18	119	112

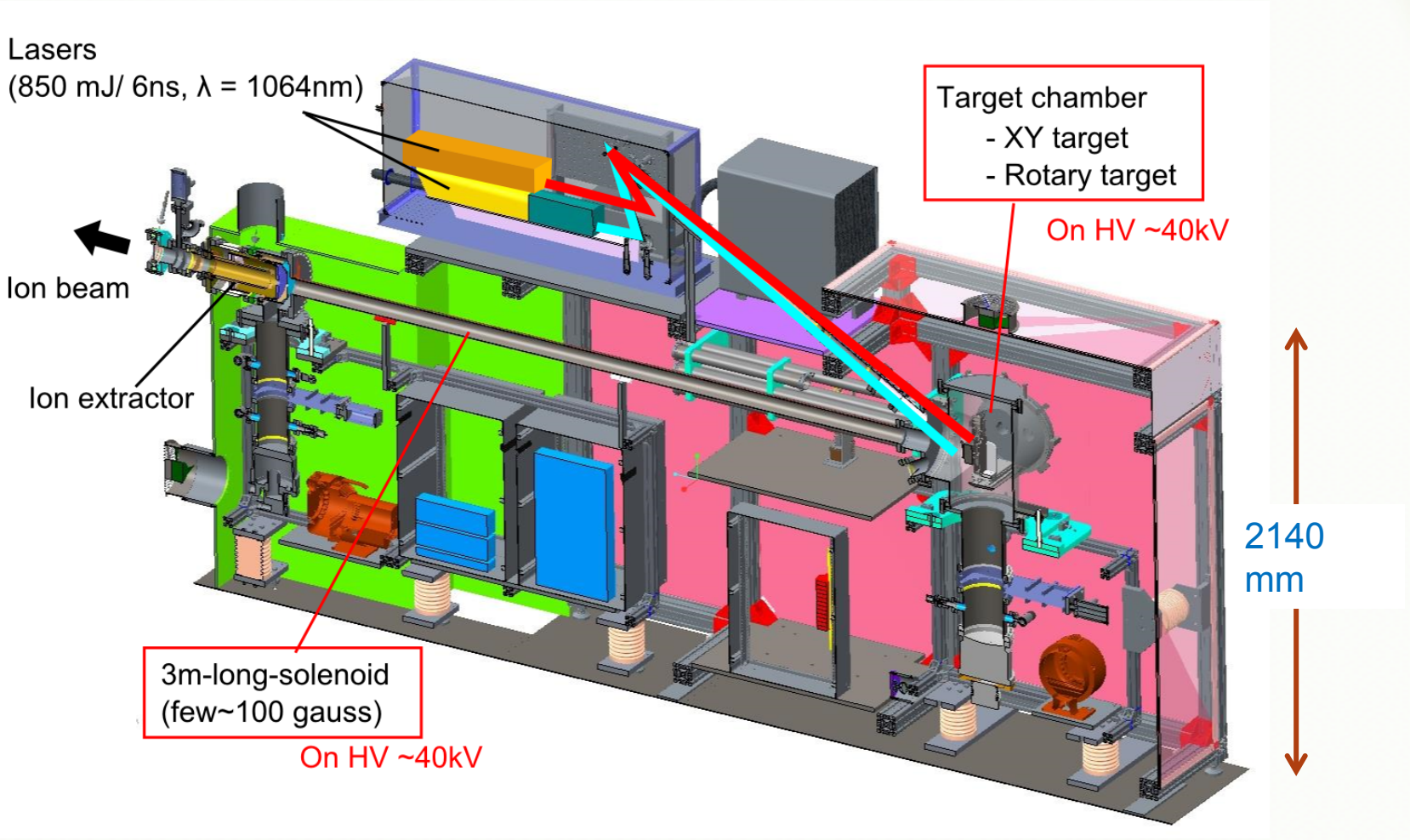
LION

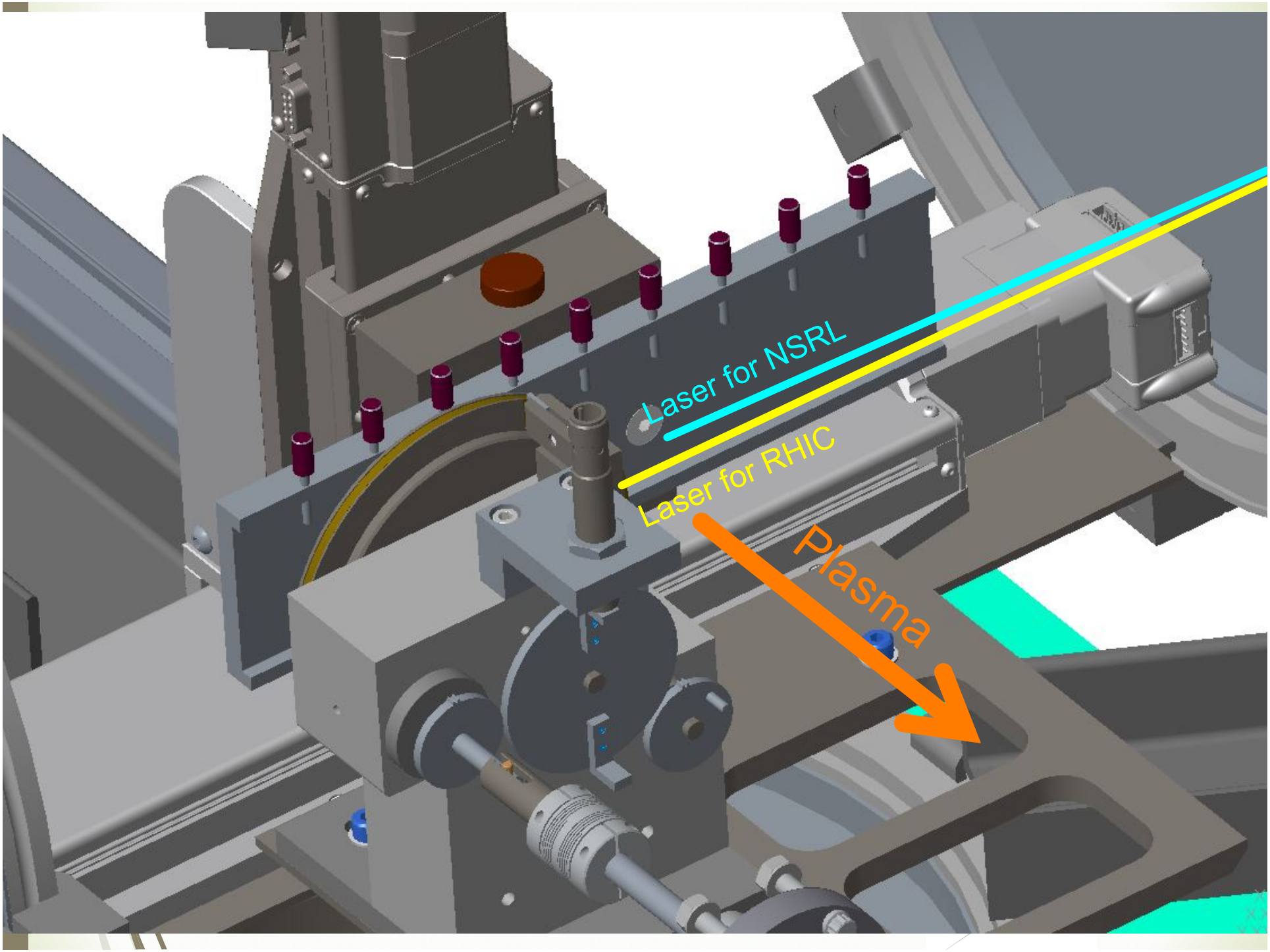
	Li	B	C	O	Si	Ca	Ti	Fe	Zr	Nb	Ta	W	Au	Th
Run16		2	7	13	17	6	8	36			8		3	
Run17	5		14	20	38		12	51	1	4	2	1	7	2
Run18			29	36	58		28	74			41		16	5

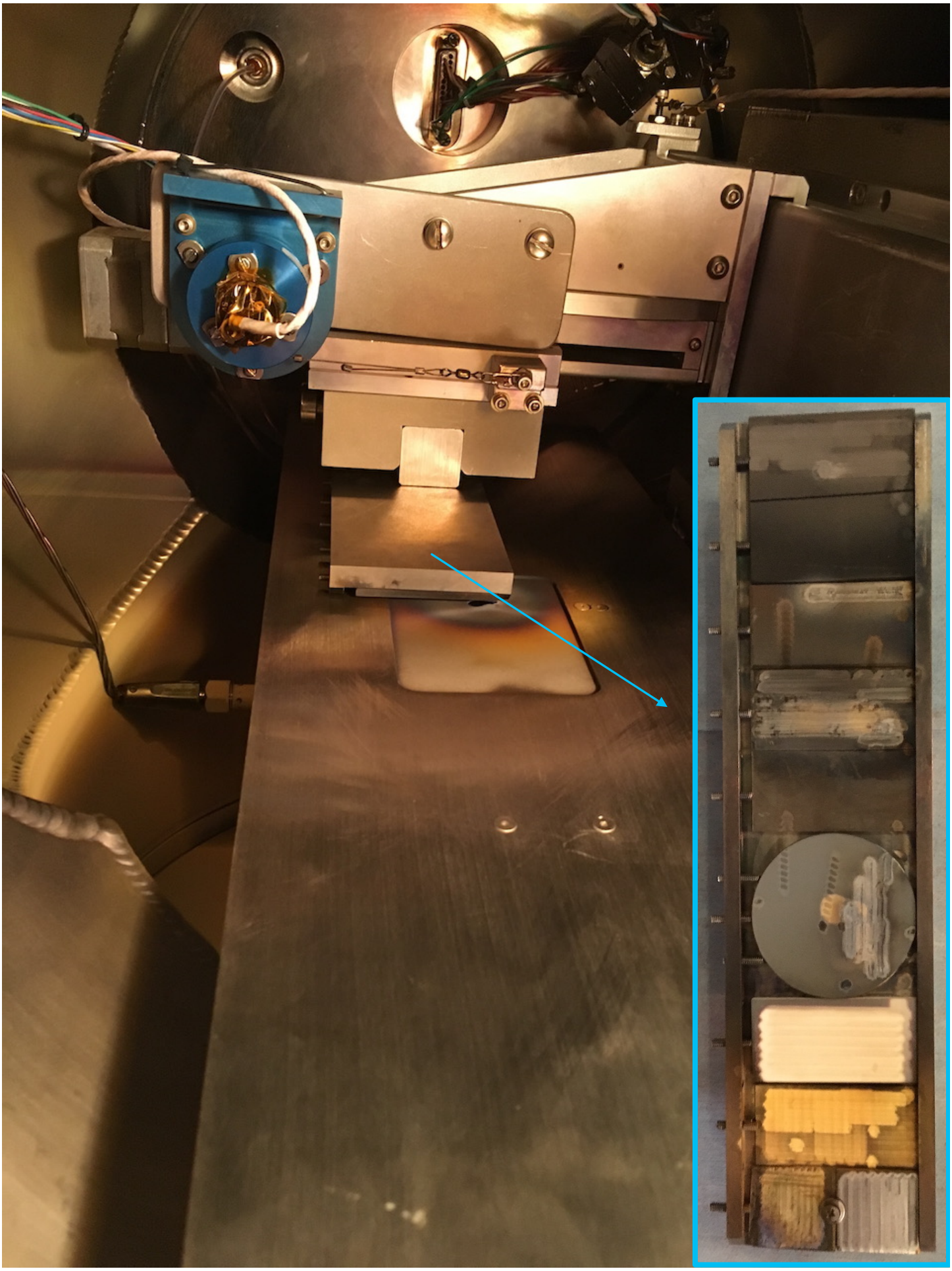
HCIS

	He	O	Ne	Kr	Ar	Xe
Run16	14	2	1	5		1
Run17	35			4	1	11
Run18	42		8	11	1	22

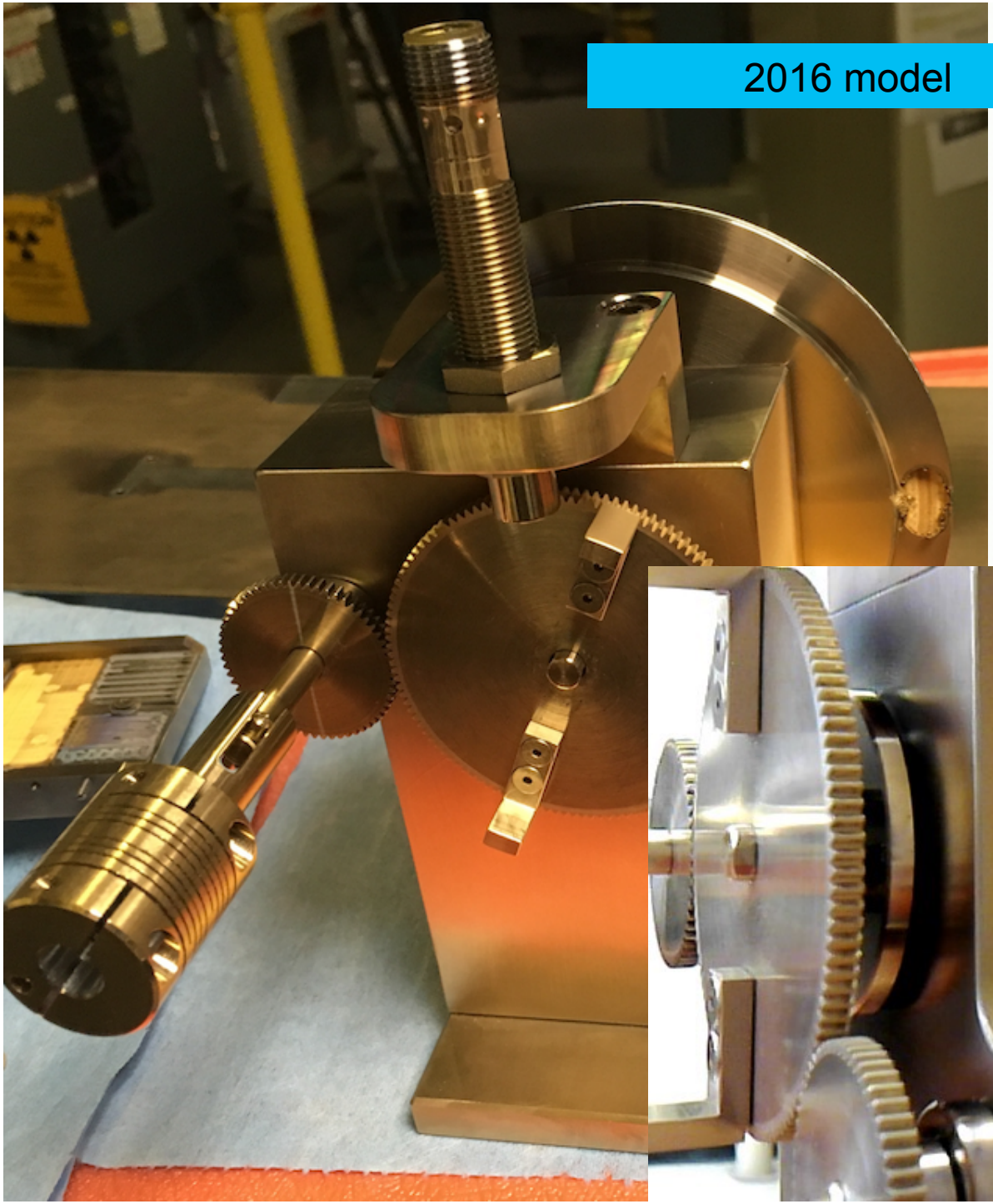
- Since Run16, oxygen was provided from LION
- Since Run17, rapid species change from ion source to NSRL was tested, and fully automated GCR simulator mode was developed
- Since Run18, GCR simulator mode has been routinely used (>150 switched per day is possible)

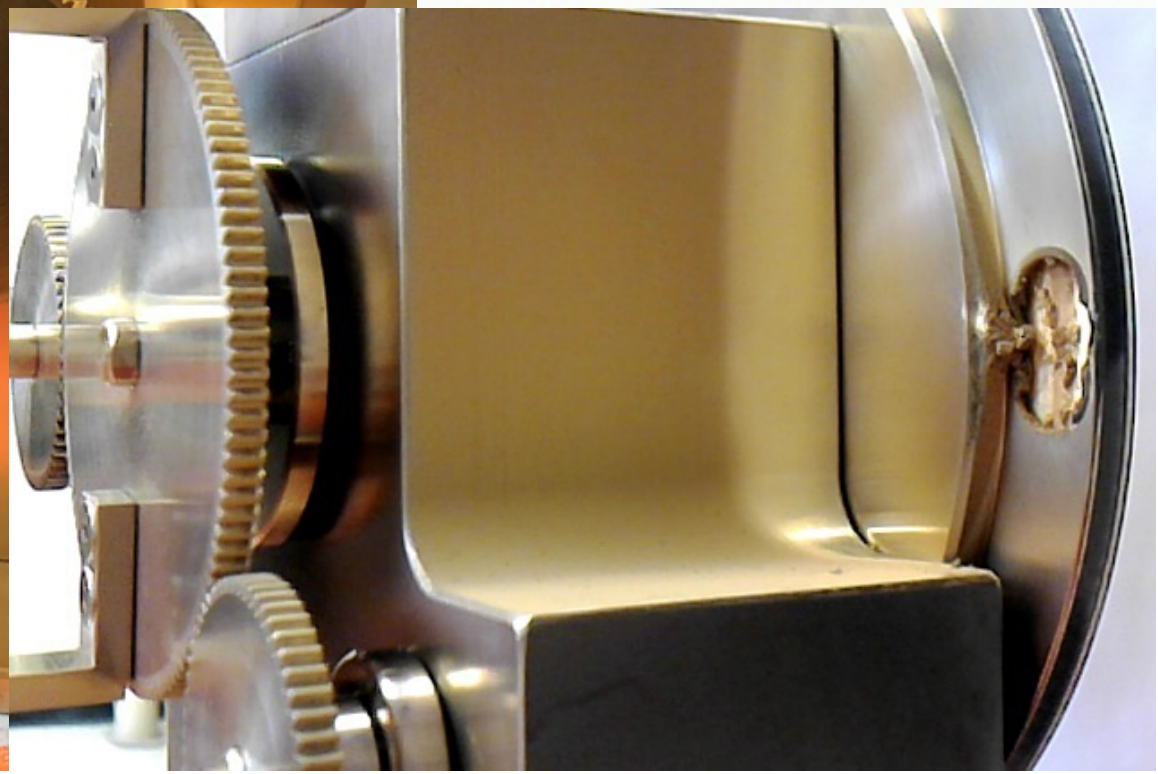

Lasers
(850 mJ/ 6ns, λ = 1064nm)
Target chamber
- XY target
- Rotary target
On HV ~40kV
Ion beam
Ion extractor
2140
mm
3m-long-solenoid
(few~100 gauss)
On HV ~40kV


Laser for NSRL
Laser for RHIC
Plasma



2016 model





EBIS RFQ

16.2 keV/u →300 keV/u 2009-

Vane alignment was redone in 2013 Summer shut down period.

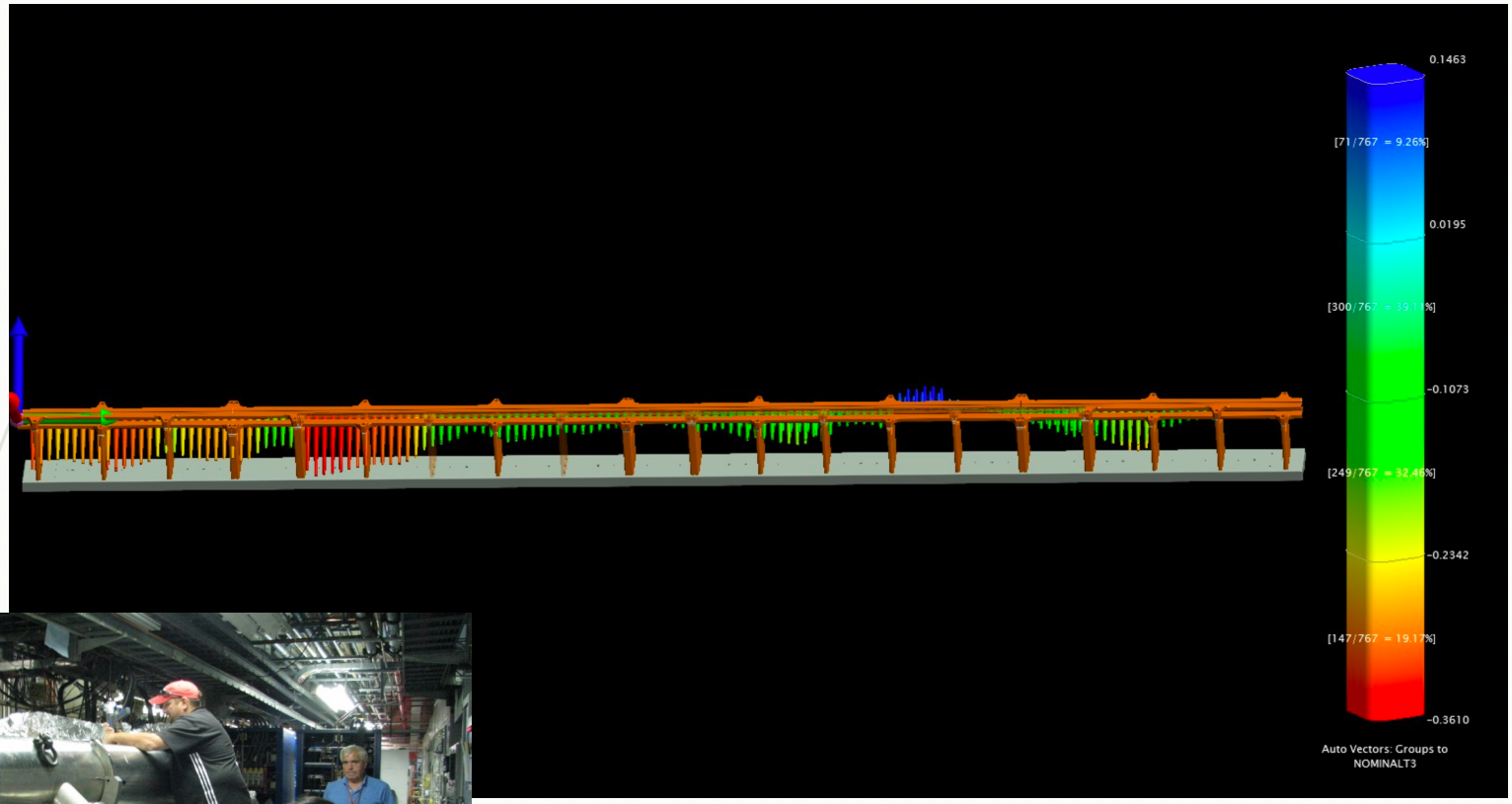
RF feed loop was retuned in 2017.

The RFQ was designed to accelerate various species, from He^{2+} to Au^{32+}. Depend on the operation schedule, the RF amplitude changes drastically. About 140 kW peak power for Au^{32+} (A/q = 1/6.2), 20 kW for $C6^{+}$.

EBIS RFQ

16.2 keV/u →300 keV/u 2009-

Vane realignment, July 2013



The resonating structure can be taken out easily and we can directly measure vane positions. Faro gage or laser tracker were used.

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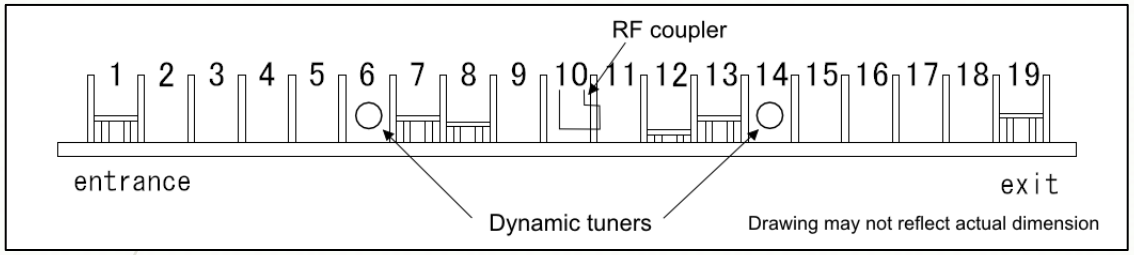
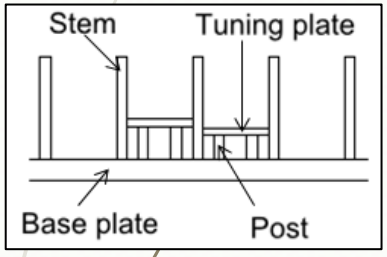
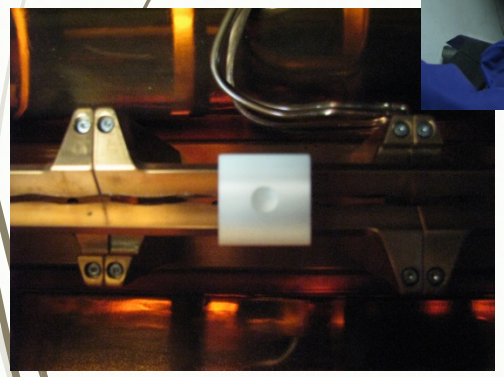
EBIS RFQ

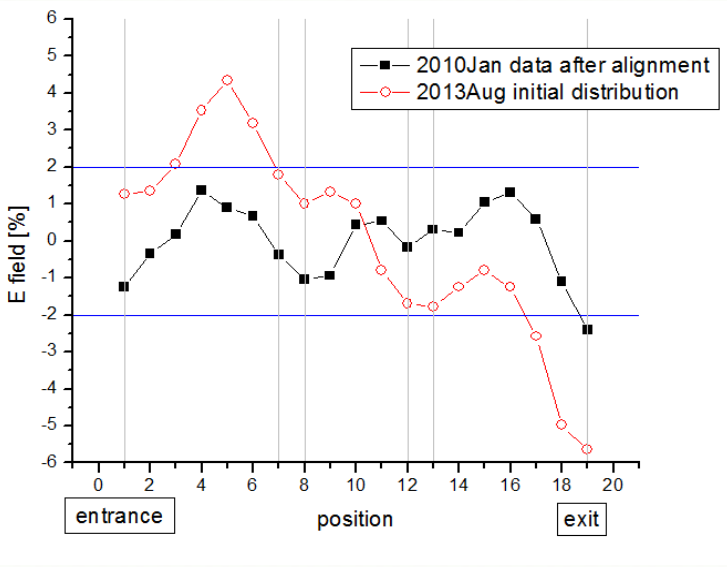
16.2 keV/u →300 keV/u 2009-

RF field distribution adjustment, Aug. 2013









After a long time operation of lower power condition, it takes a few days to recover discharge limit for high power operation.

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EBIS RFQ

16.2 keV/u →300 keV/u 2009-

Jan 9, 2017, RF loop coupling adjustment

Tuner position was fixed at 45.75 mm(Upstream) and 47.69 mm(Downstream)				
	Before adjustment (in vacuum)	After adjustment, lid open (in air)	After adjustment, lid close (in air)	After adjustment, (in vacuum)
f0 (MHz)	100.6256	100.596	100.598	100.626
Loss (dB)	-24.547	-53.63	-55.00	-56.2
Q	2024	2096	2124	2129
Z (Ω)	50.7	49.91	50.07	50.07

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EBIS RFQ

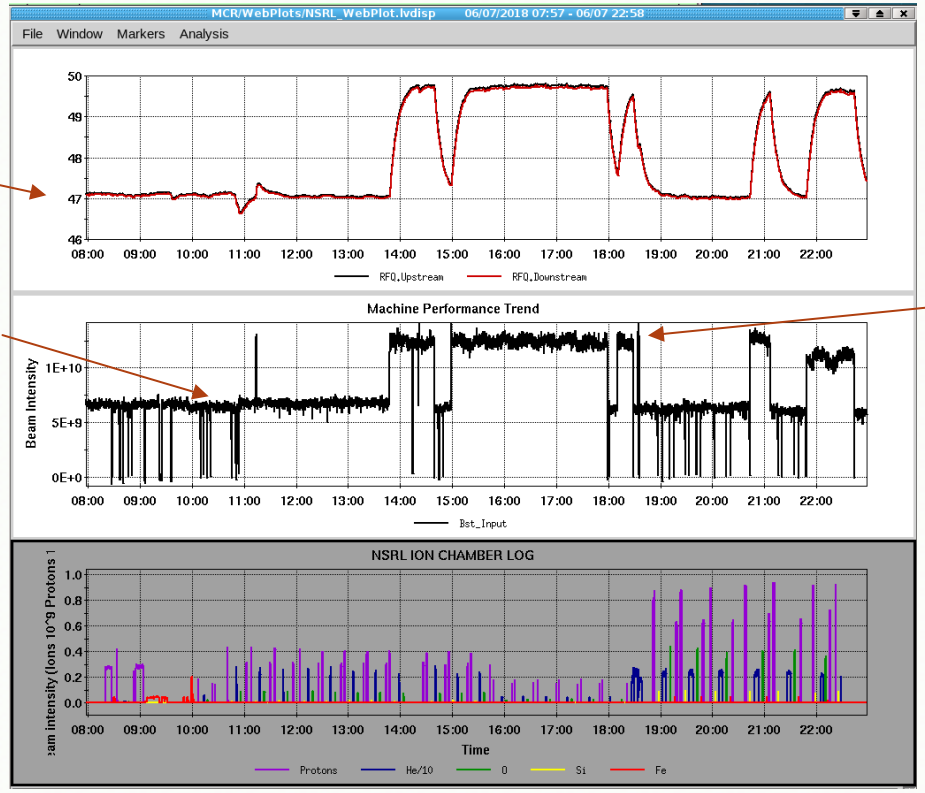
16.2 keV/u →300 keV/u 2009-

6/7/2018 12 pulses ^{96}Zr + NSRL (Fe, H (not from EBIS), He, O, Si)

RFQ tuner position [mm]
Larger = more inserted

^{96}Zr beam for
RHIC at Booster
entrance (at xf108)

6 pulses



12 pulses of 5 Hz beam
per 6.6 sec

Beam at NSRL target room
P (high current source), He (HCIS), Fe (Laser), O (Laser)

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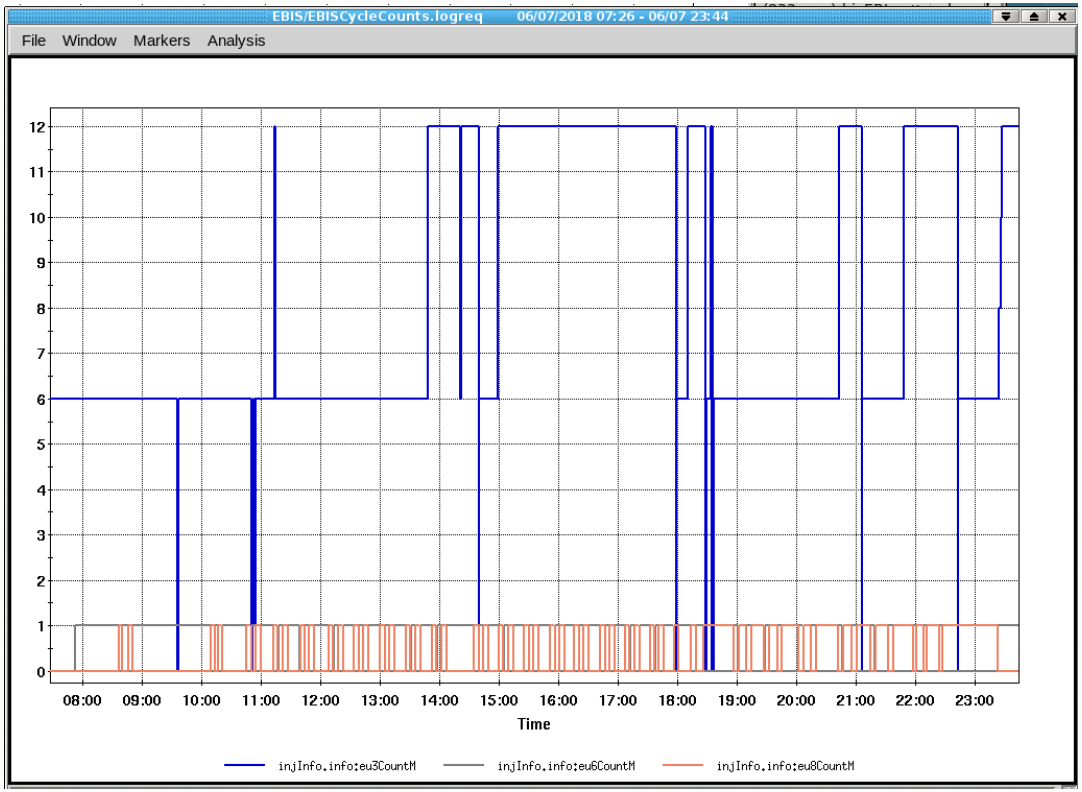
EBIS RFQ

16.2 keV/u →300 keV/u 2009-

4/9/2019 12 pulses Au + NSRL (Si, Ti, Fe)



12 pulses

User 6 and 8 for NSRL

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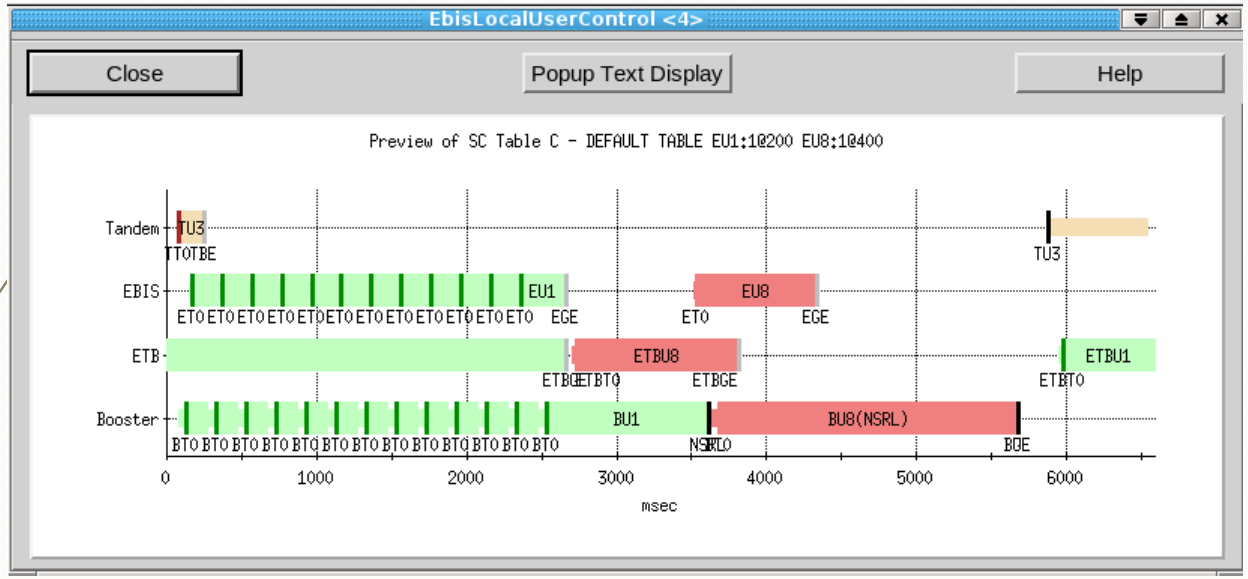
EBIS RFQ

16.2 keV/u →300 keV/u 2009-

4/9/2019 12 pulses Au + NSRL (Si, Ti, Fe)



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EBIS RFQ

16.2 keV/u →300 keV/u 2009-

4/9/2019 12 pulses Au + NSRL (Si, Ti, Fe)

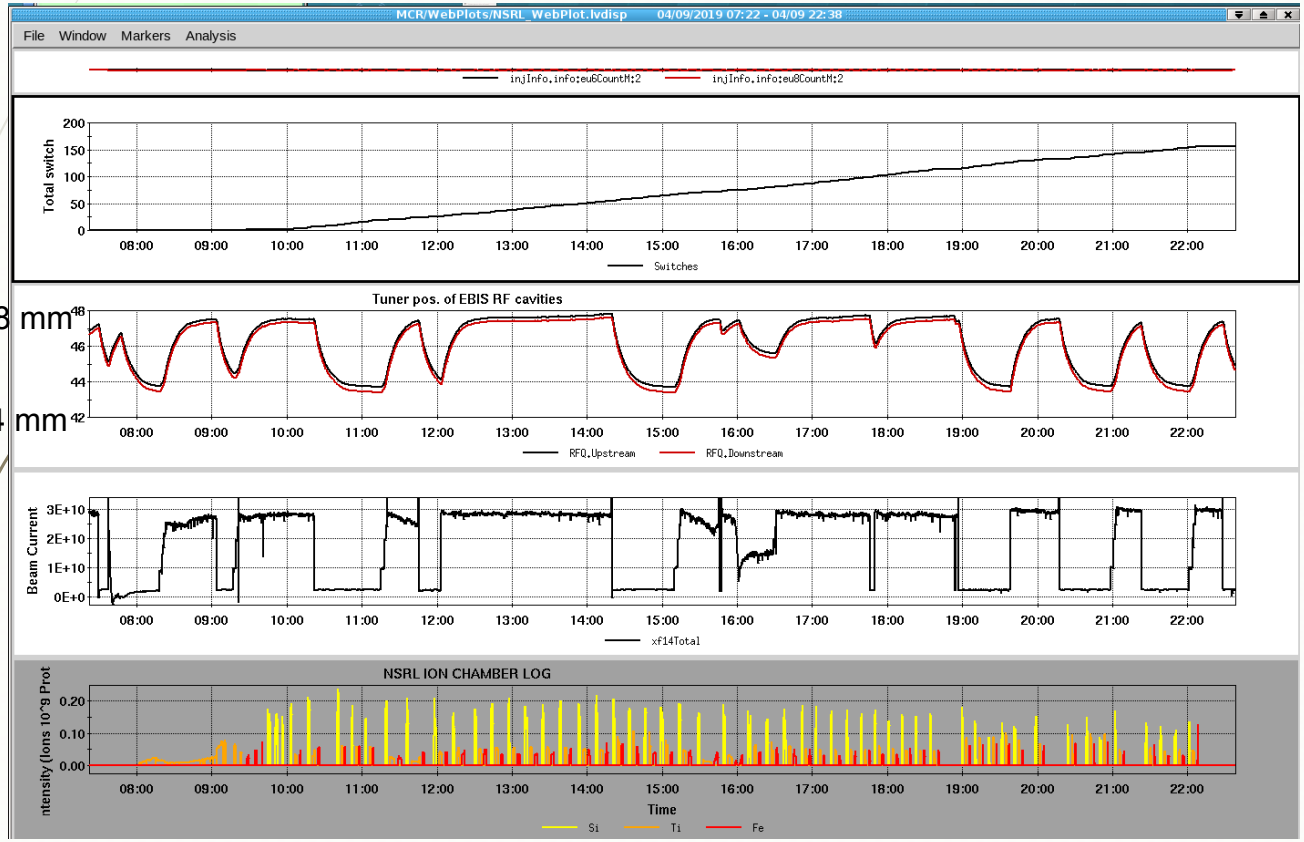
Total species switched

RFQ tuner position

48 mm

44 mm

Au beam for RHIC



Beam at NSRL target (Si,Ti,Fe)

Total 156 species change at EBIS From 10am-10pm

130kW for Au^{32+}
22 kW for Si^{11+}
26 kW for Ti^{18+}
23 kW for Fe^{20+}

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Summary

- We have experiences of four vane, four rod, proton, heavy ion RFQ accelerators.
- The first RFQ for polarized negative proton beam was shut down. Many troubles had been reported.
- The second negative proton RFQ provided by LBL has been working good for more than 30 years.
- Our machines operate with only low duty factor. So far, we have not met serious failures for decades.