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Accelerators for the Advanced Exotic Beam Facility

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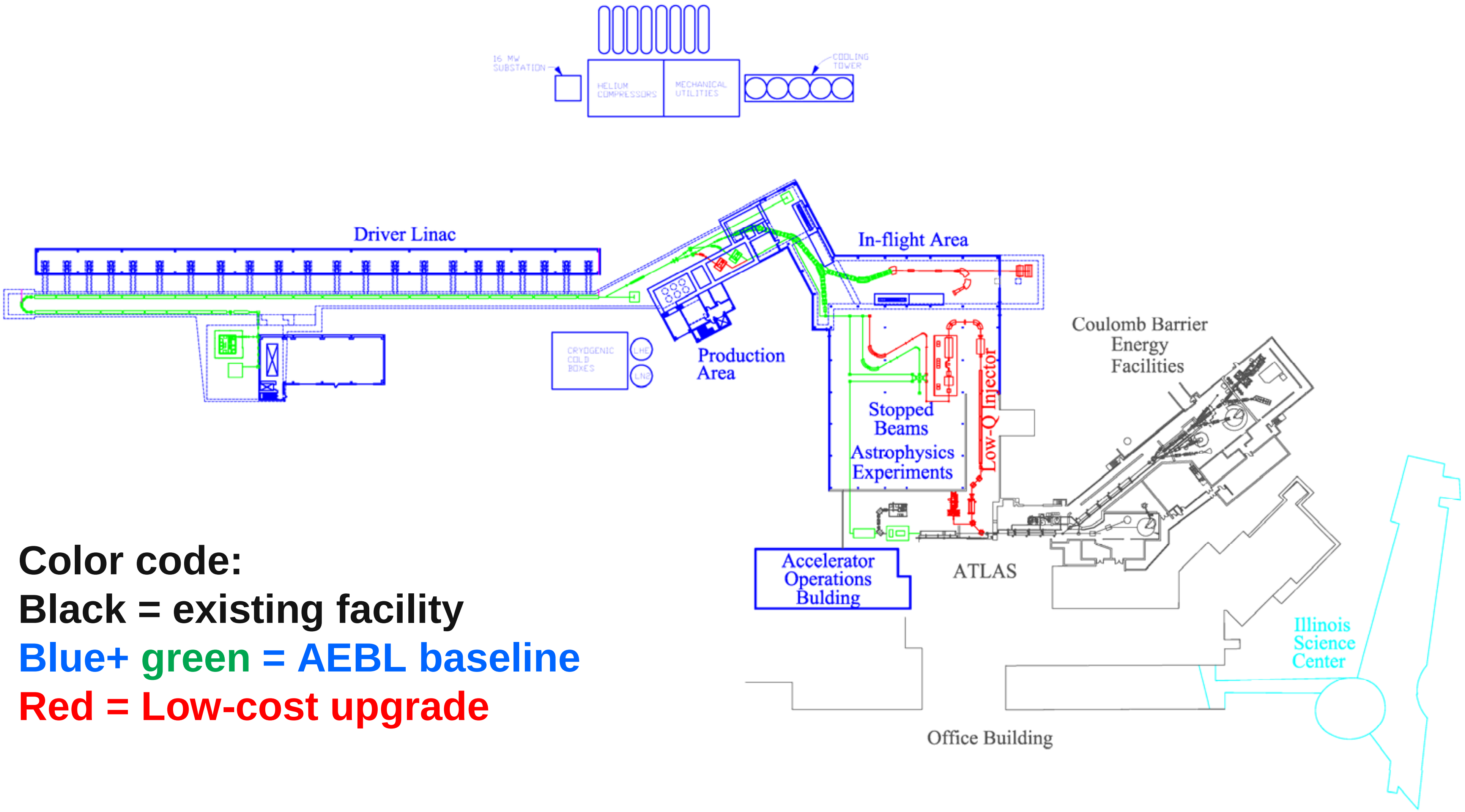
Content

- Facility for Radioactive Ion Beams (FRIB)
  - Short introduction to the current status
  - Major differences from RIA
- Heavy-ion Driver Accelerator
  - Impact of the R&D and prototyping on the design, expected performance and cost
  - Accelerator lattice and beam parameters
- Current R&D related to the FRIB
  - Super CARIBU (Post Accelerator)
  - Test of the liquid Li stripper
  - Beam diagnostics
- Conclusion

Layout of the FRIB at ANL – 200 MeV/u, 400 kW



Color code:
Black = existing facility
Blue+ green = AEBL baseline
Red = Low-cost upgrade

FRIB includes

- Heavy-ion driver linac capable of producing 400 kW beams
  - All ion species
  - Uranium 200 MeV/u
  - Protons 580 MeV
- Production area
  - Fragment separator and gas cell
  - Two ISOL targets (can be excluded from the baseline due to the cost)
- Post-accelerator
  - Charge breeder + RFQ
  - ATLAS
- Experimental systems
  - In-flight fragmentation area
  - All ATLAS instruments
  - Stopped beams facility
  - Astrophysics facility

FRIB vs RIA

	RIA	FRIB
TPC (actual dollars)	$1.1B	$550M
Driver linac	Superconducting CW linac	
Total voltage	1400 MV	833 MV
Uranium energy	400 MeV/u	200 MeV/u
Protons	1000 MeV	580 MeV
Beam power (kW)	400 kW	400 kW
Post-accelerator	Low-q injector + ATLAS	Charge breeder + ATLAS
In-flight experimental facility	yes	limited
Gas catcher	yes	yes
Number of ISOL targets	4	1 or 2
Intensity of ISOL RIBs	High	Same as RIA
Multi-user capability	Extensive	Limited

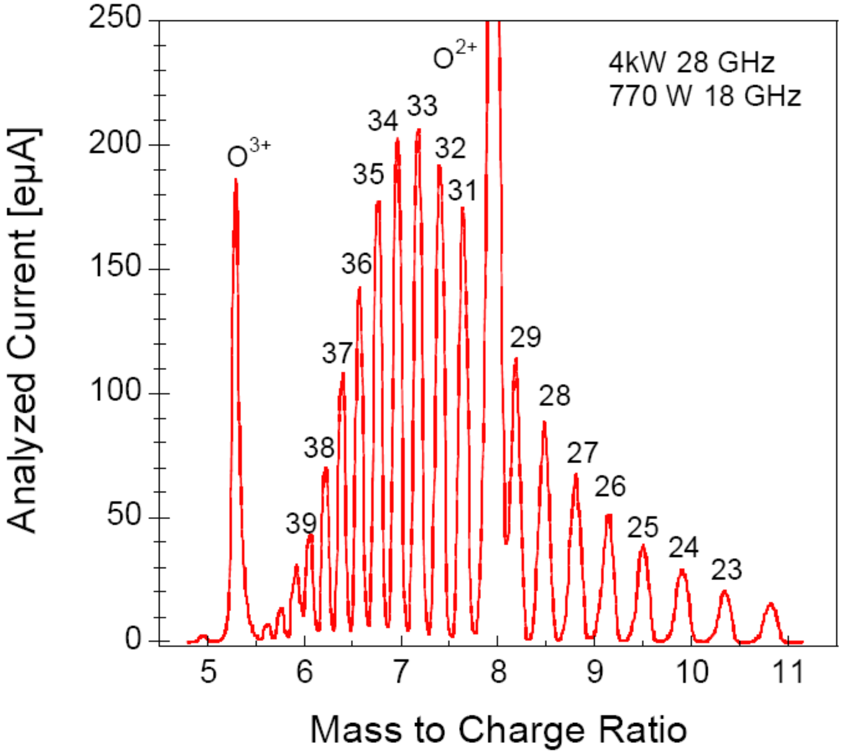
Heavy-ion Driver Linac and Production Complex, R&D

- Advanced ECR ion source (LBNL)
- Prototyping of the Front end for a High Intensity Heavy Ion linac
  - 2Q-LEBT
  - 57 MHz cw RFQ
- SRF technology
  - Higher gradients
  - Higher quality – lower cryogenic load
  - Lower microphonics
- High-power targets and strippers
  - 15 μm liquid lithium film required for the stripping has been demonstrated
  - Liquid lithium fragmentation target has been demonstrated
- Beam dynamics
  - Code development
  - Linac design, large scale simulations on supercomputers
  - Large acceptance fragment separators

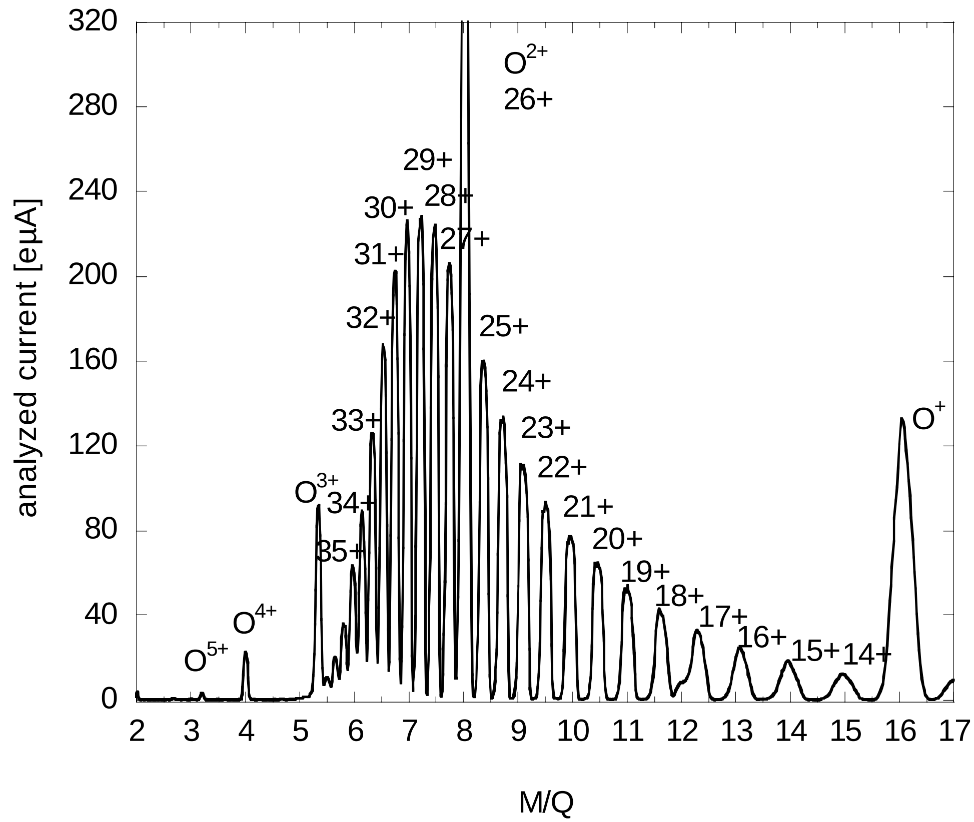
VENUS ECR ion source data, LBNL (Berkeley)

- Uranium 6 pμA is sufficient for 400 kW with the following two-charge-state LEBT

Uranium (6 pμA)

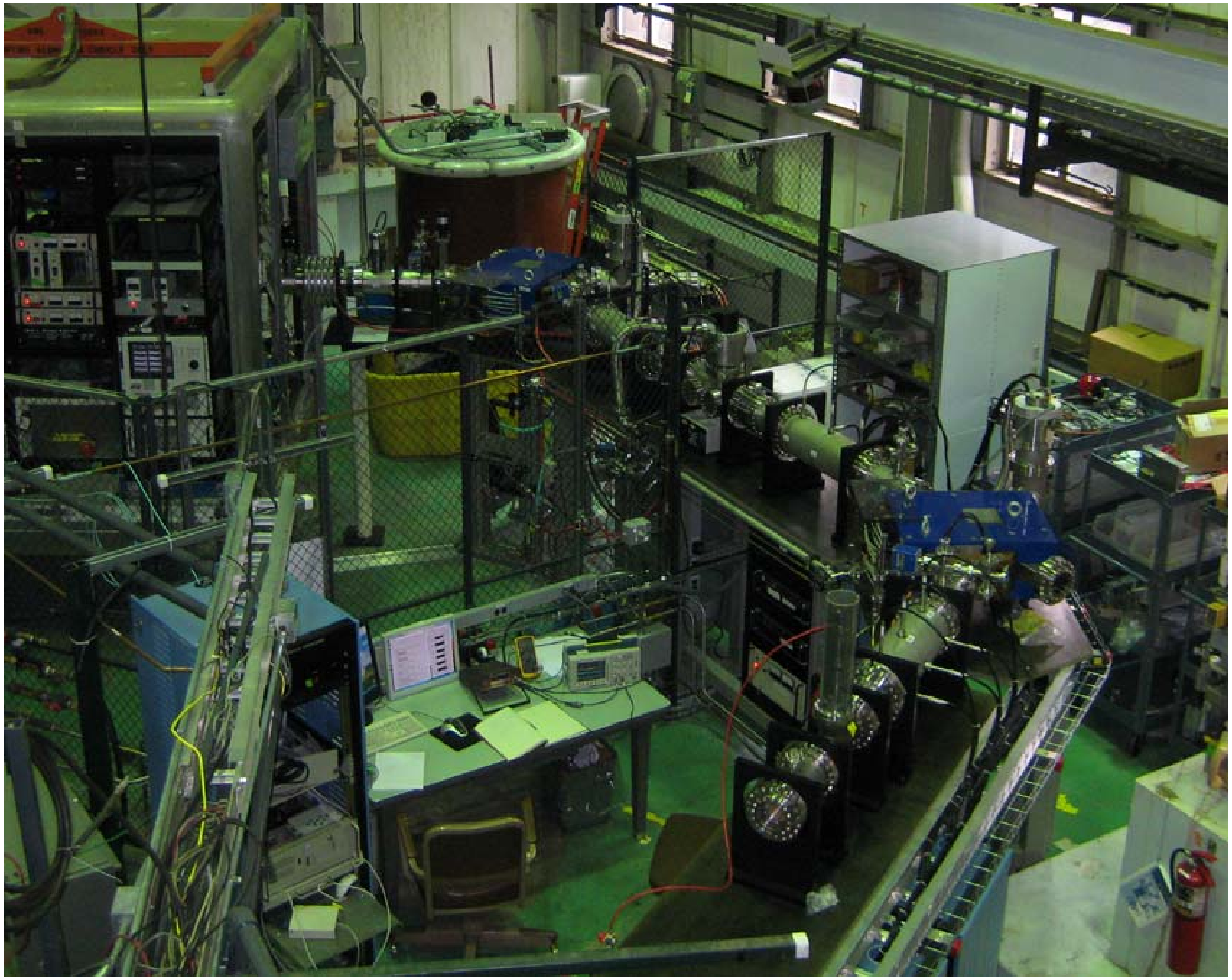


Bismuth (8 pμA)



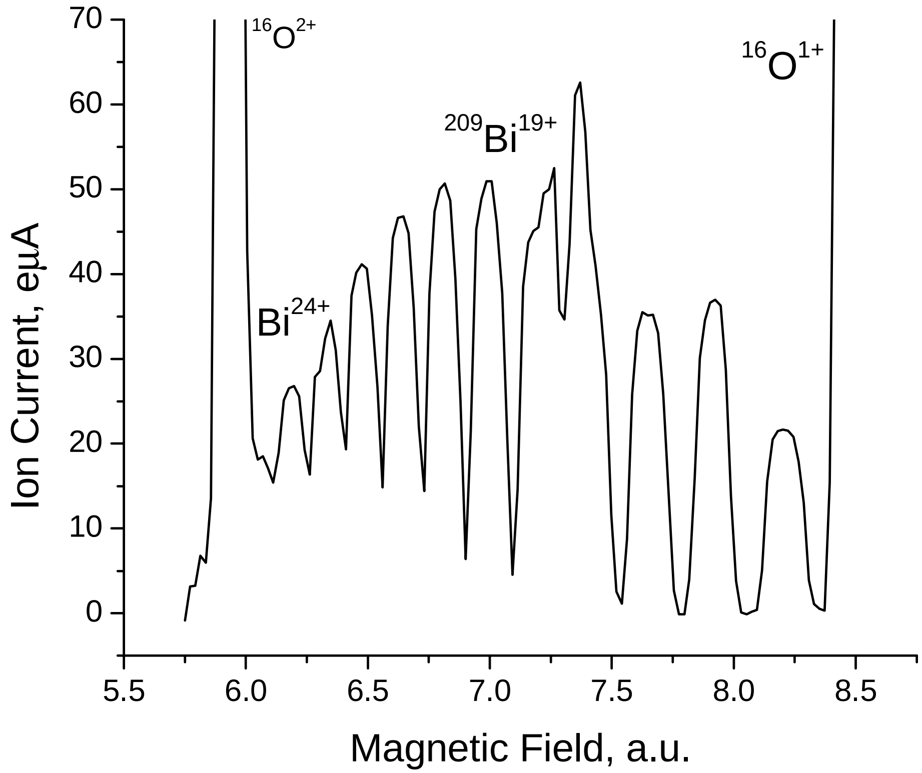
Multi-q ion beam studies at ANL

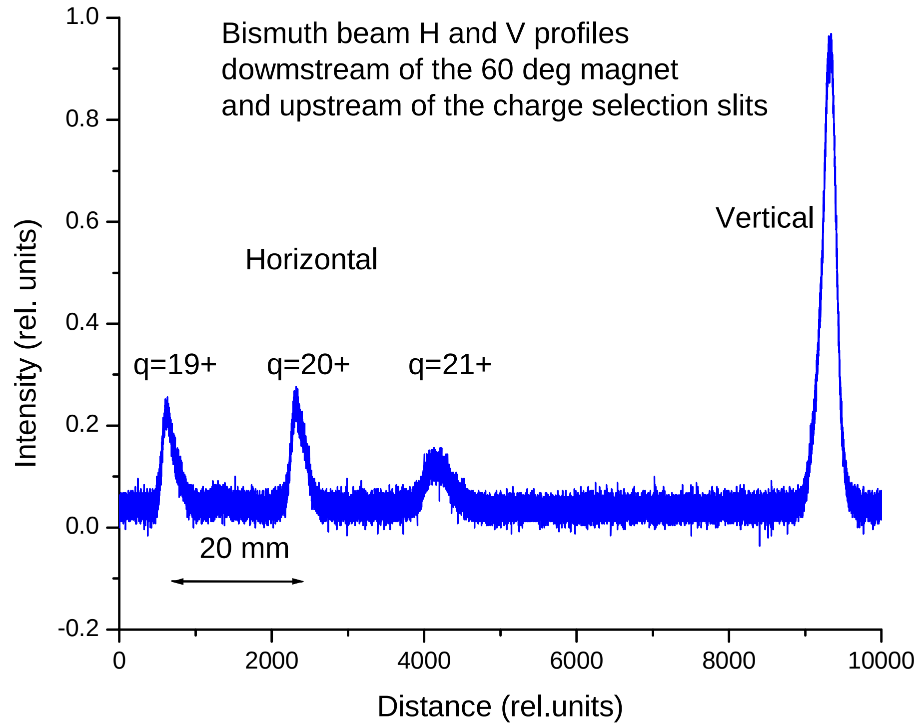
- Permanent Magnet ECR on 100 kV platform voltage
- Achromatic bending system to extract and combine multi-q beams
- Electrostatic focusing



Multi-q beam in the 2Q-LEBT

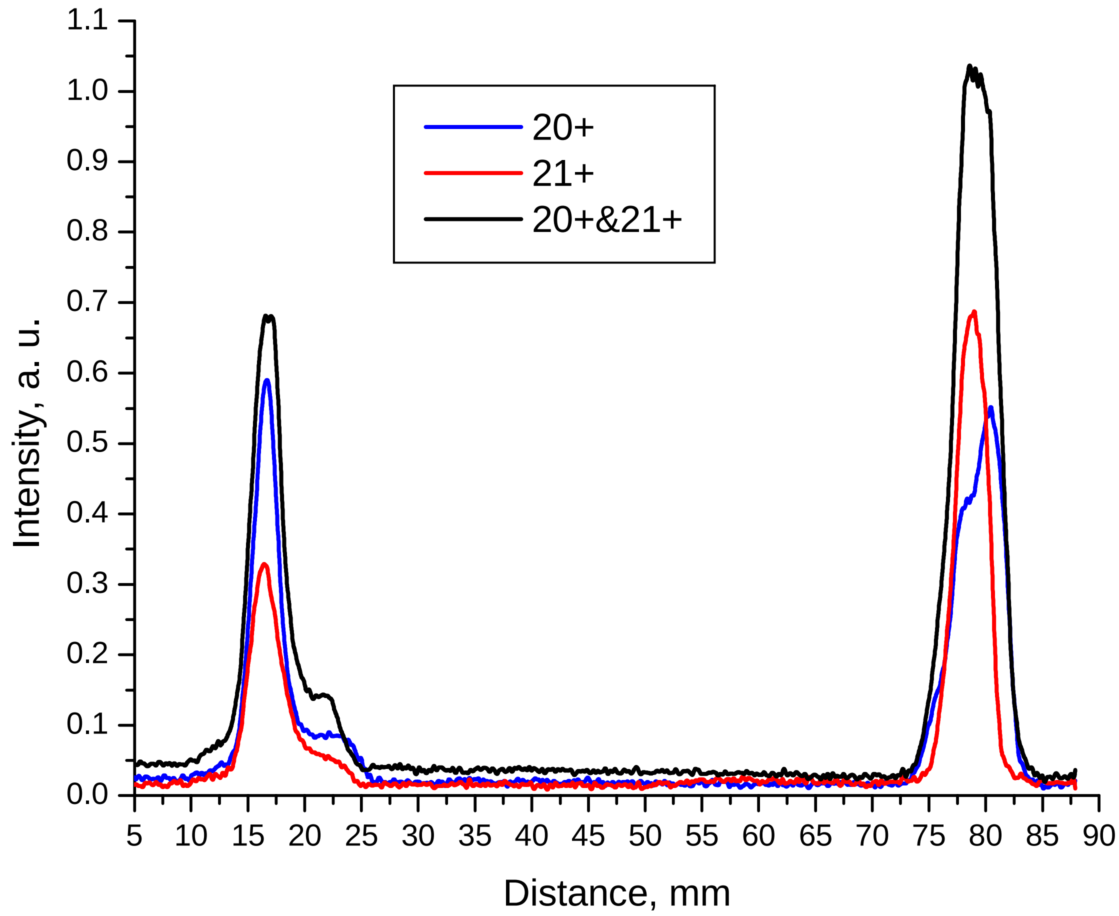
- We are extracting more than ~1 pμA of Bismuth in each charge state 20+ and 21+





100% transmission of two-charge state beam

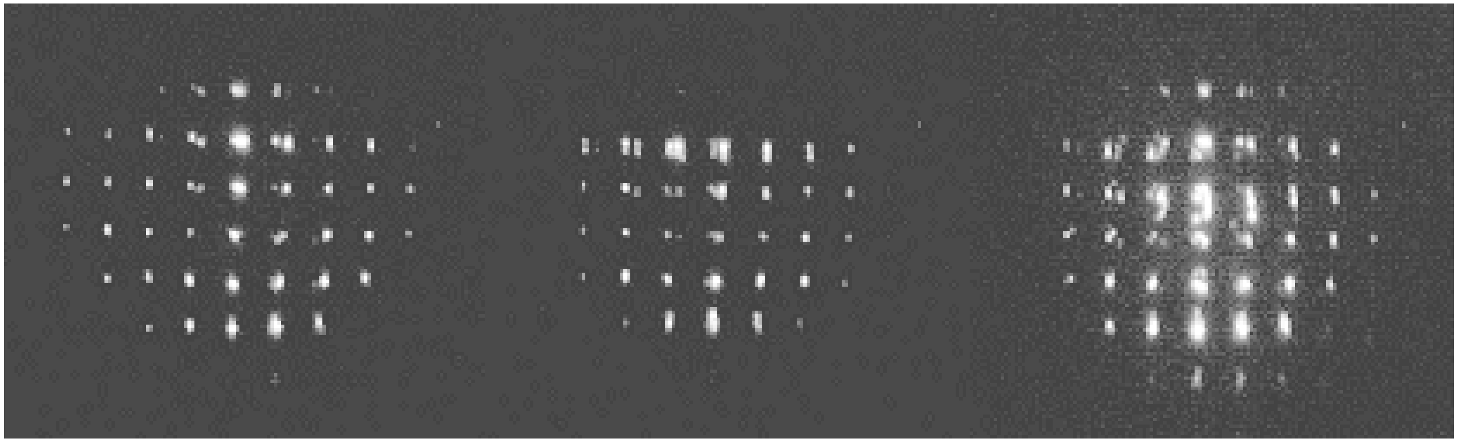
- Beam profiles (X-, Y-) taken by rotating wire (slightly non-linear reading) at the end of beamline



Combining of two charge states of Bismuth ions

- The first measurements

20+	21+	20+ and 21+



Rms emittances

X	19 π mm-mrad	17 π mm-mrad	22 π mm-mrad
Y	16 π mm-mrad	20 π mm-mrad	38 π mm-mrad

Beam current

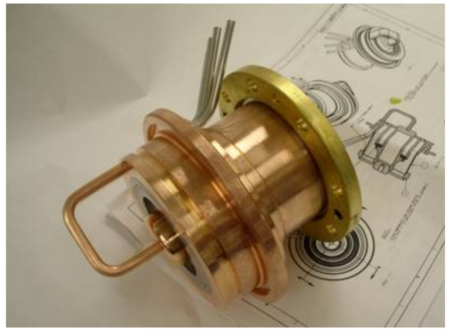
20 eμA	24 eμA	44 eμA

Beam current in 3 charge sates (19+,20+,21+)=63 eμA

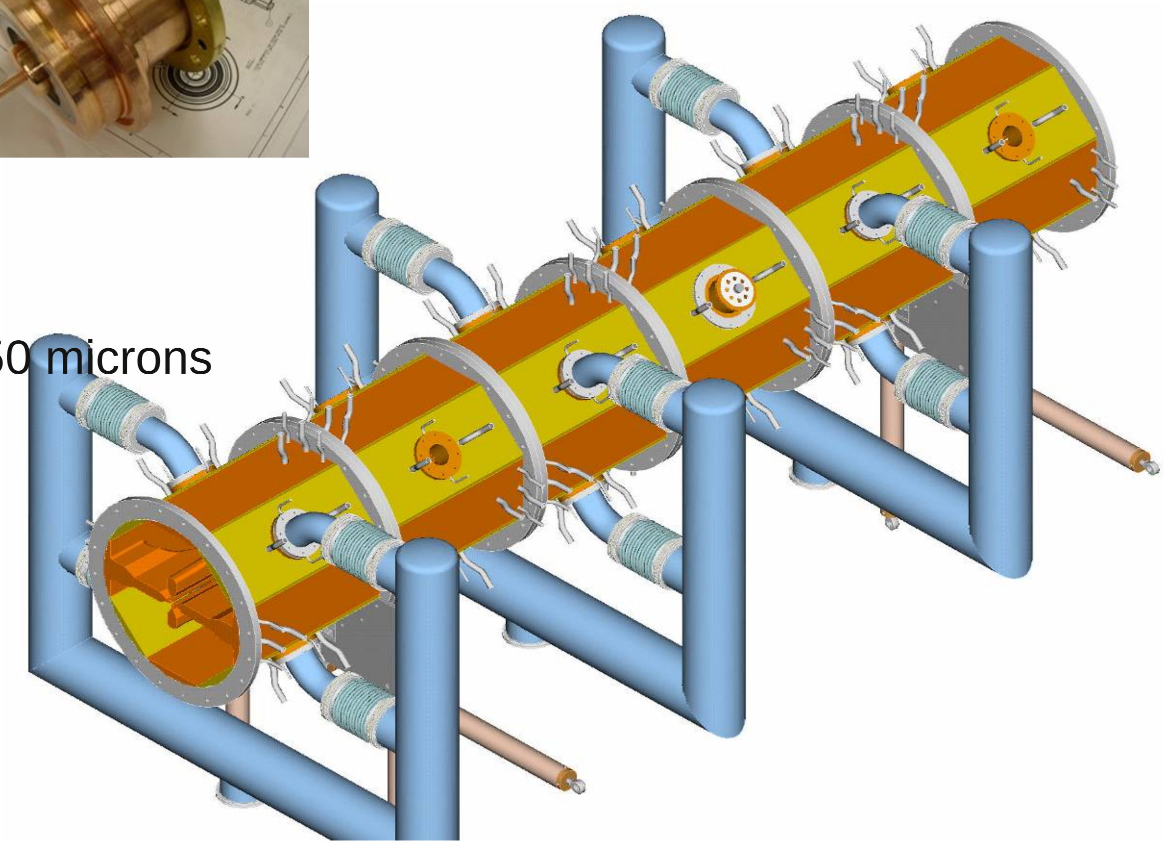
Prototyping of 2q 57 MHz CW RFQ, q/A=33/238 $\rightarrow$ 1
Required for the high intensity heavy-ion driver

Pre-brazed assembly

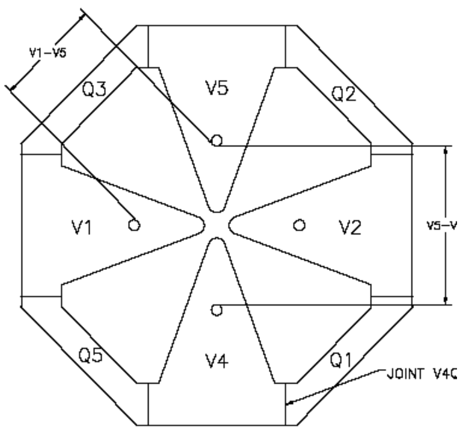
Coupling loop



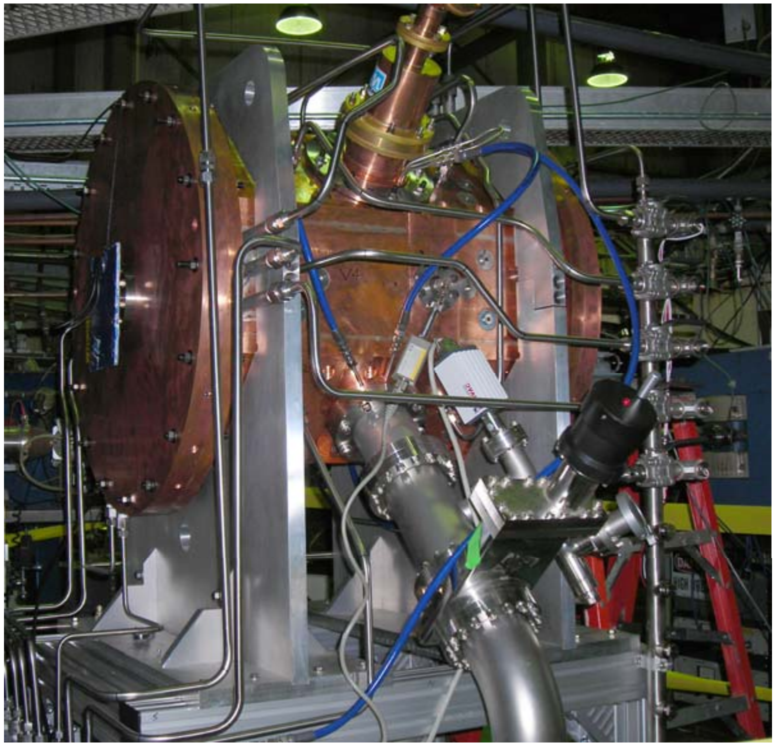
Fabrication technology:
High-T furnace brazing, OFE copper

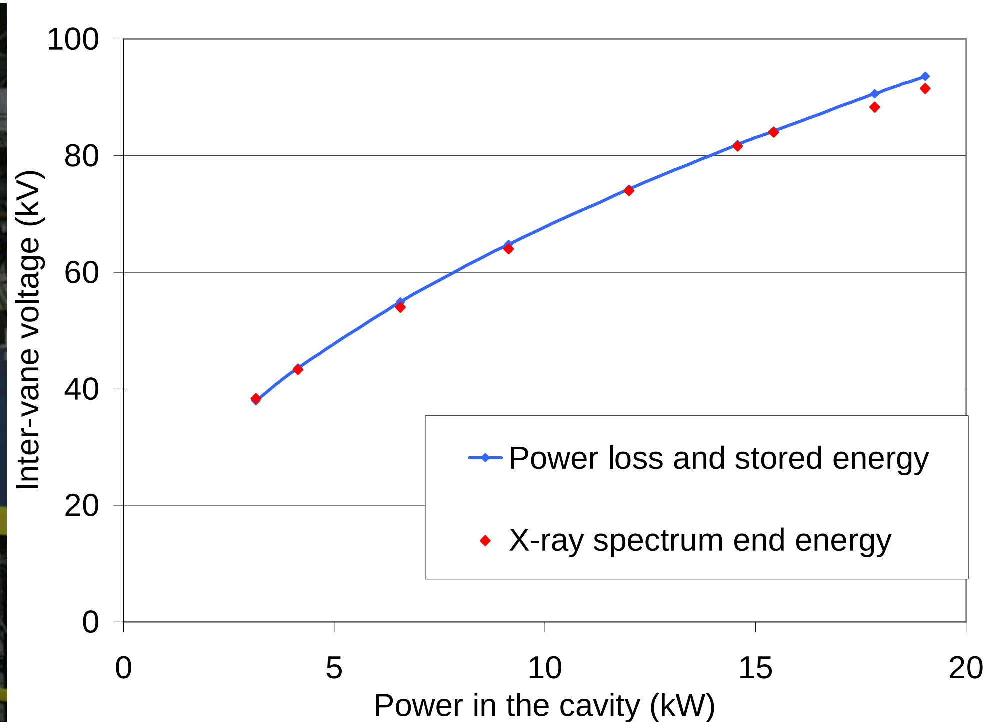


Vane tip alignment is better than 50 microns



The 57.5 MHz RFQ was successfully tested

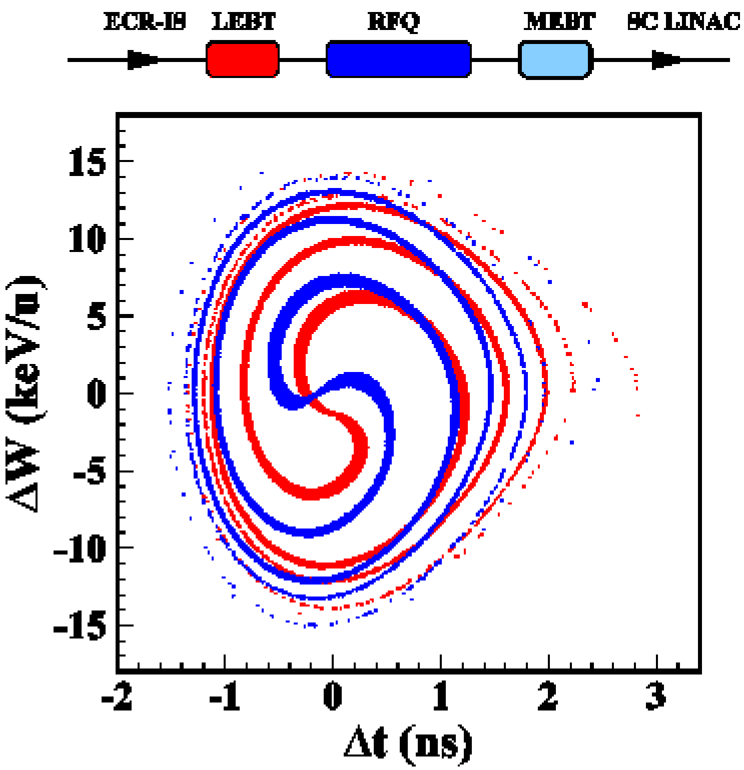


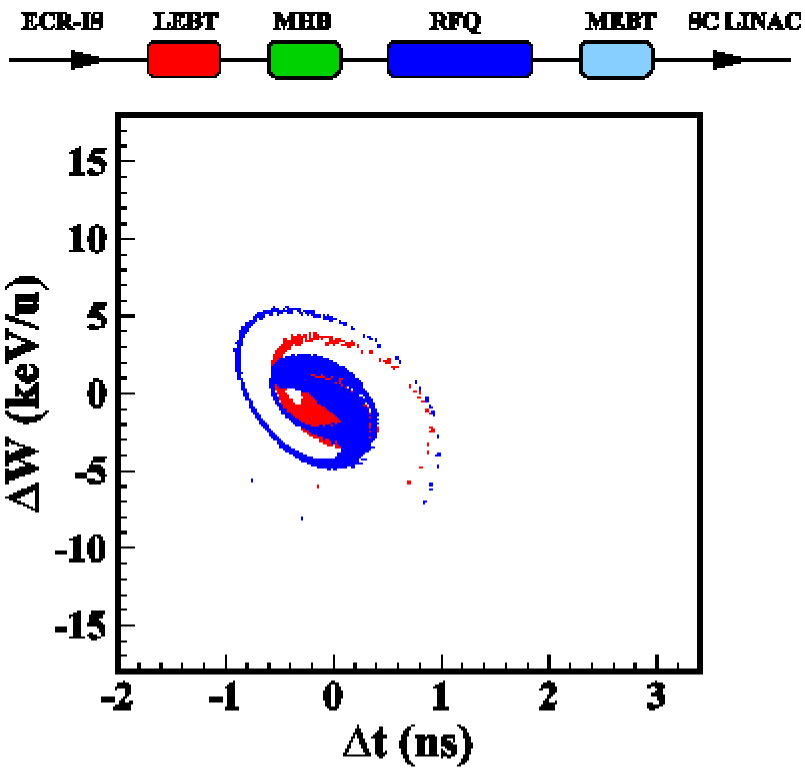


- Stable operation in wide dynamic range of rf power
  - Limiting voltage is higher than 91 kV
- Q-factor: Simulation = 9300, Measured = 8860 95% of theoretical value
- 4-meter length RFQ will provide 300 keV/u beams of ions
- Cooling: 2 chillers with total 40 G/min water flow

RFQ options

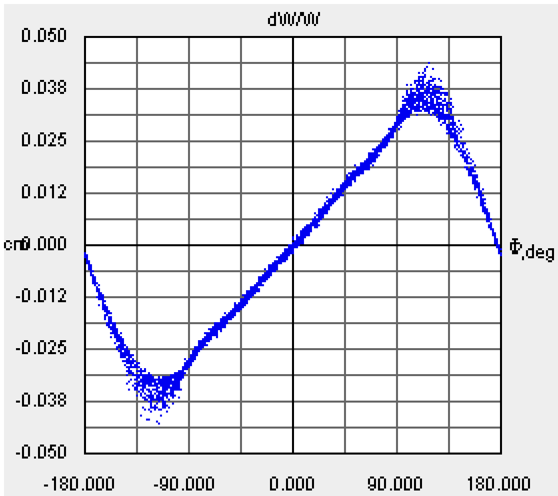
- Conventional RFQ with build-in adiabatic bunching
- RFQ + Multi-Harmonic Buncher

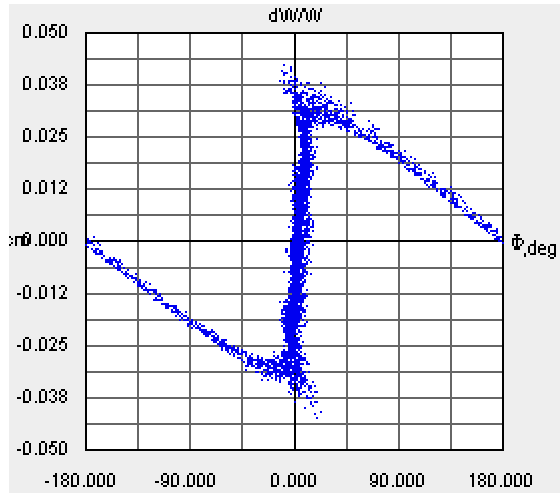


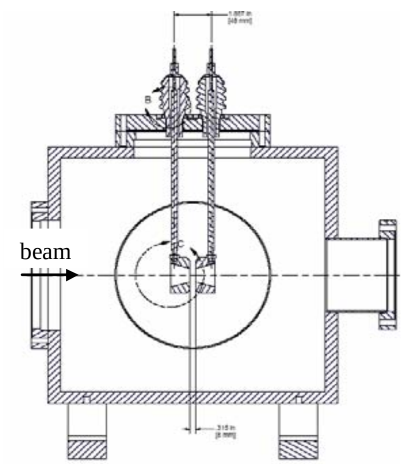


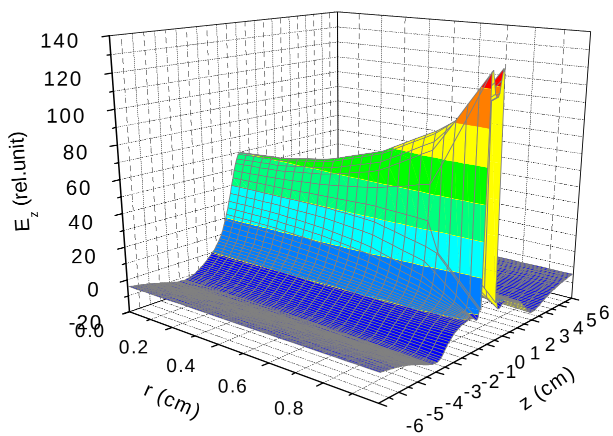
MHB

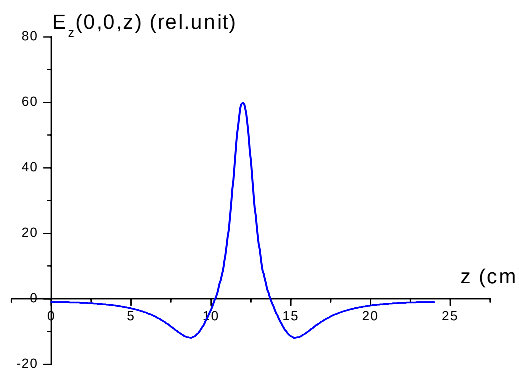
- Main function is to form a low longitudinal emittance at sub-harmonic frequency





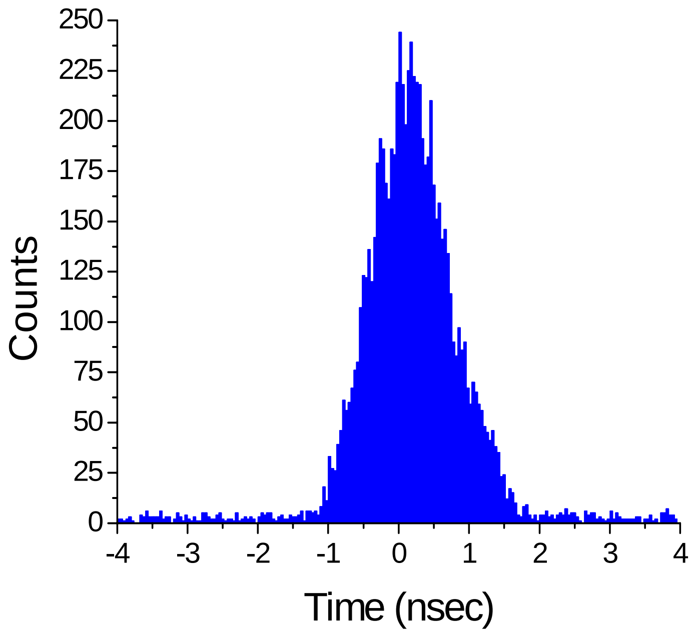


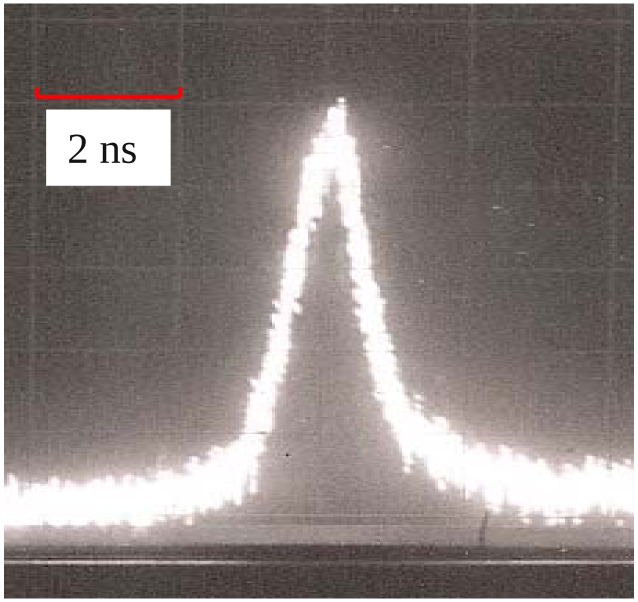




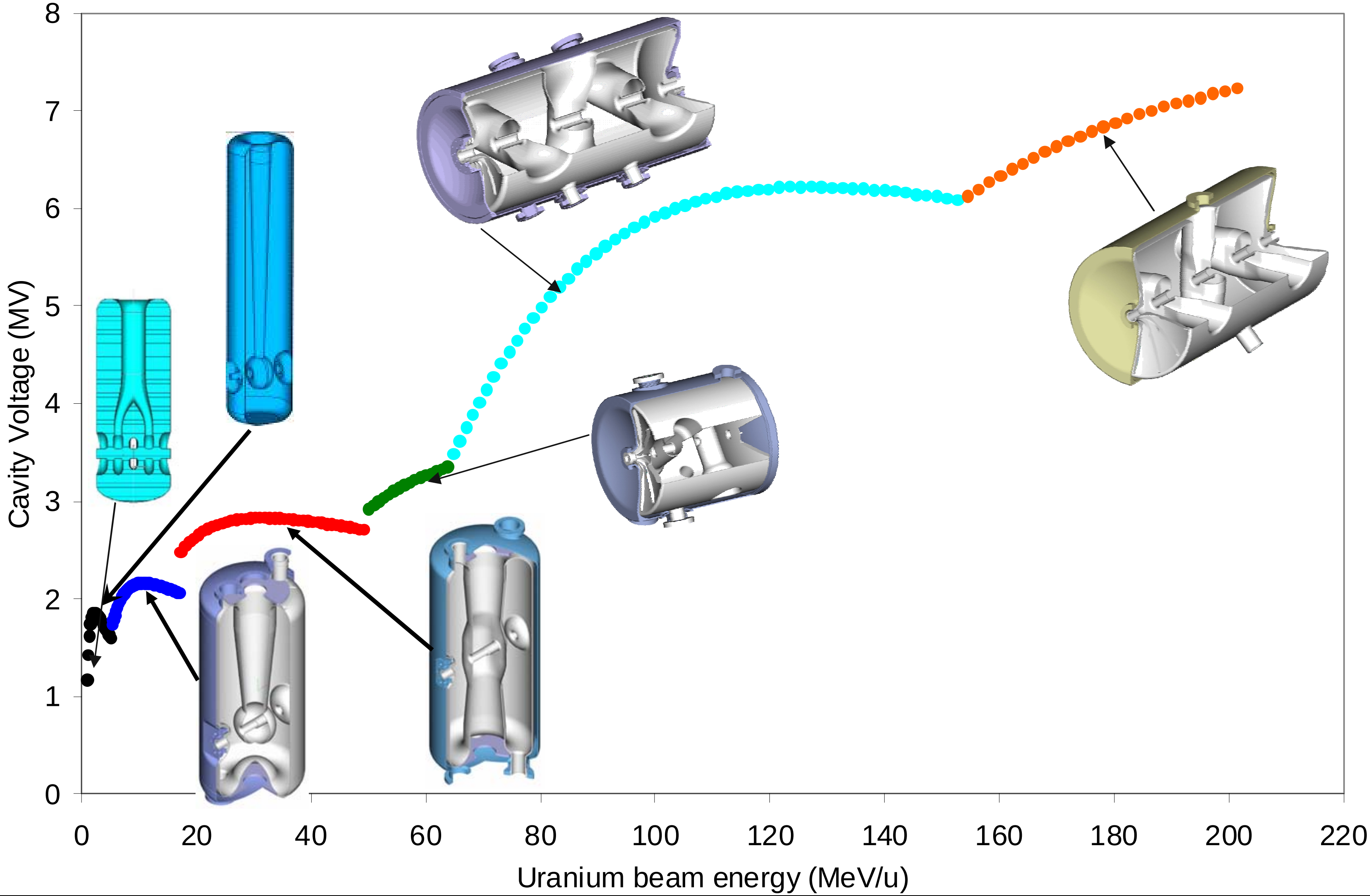
ATLAS MHB, 12.125 MHz

- Simulated and measured bunch intensity distribution
- Forms very low Longitudinal emittance
- Capture efficiency is 80%





Voltage gain per cavity in the SC section



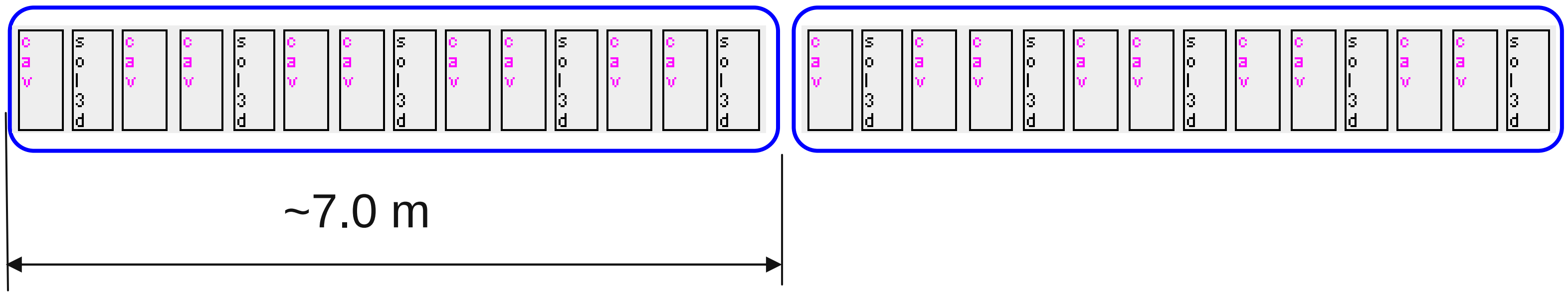
FRIB Driver Linac - SC Resonator Configuration

- Input of uranium 33+ and 34+ at beta = .0254

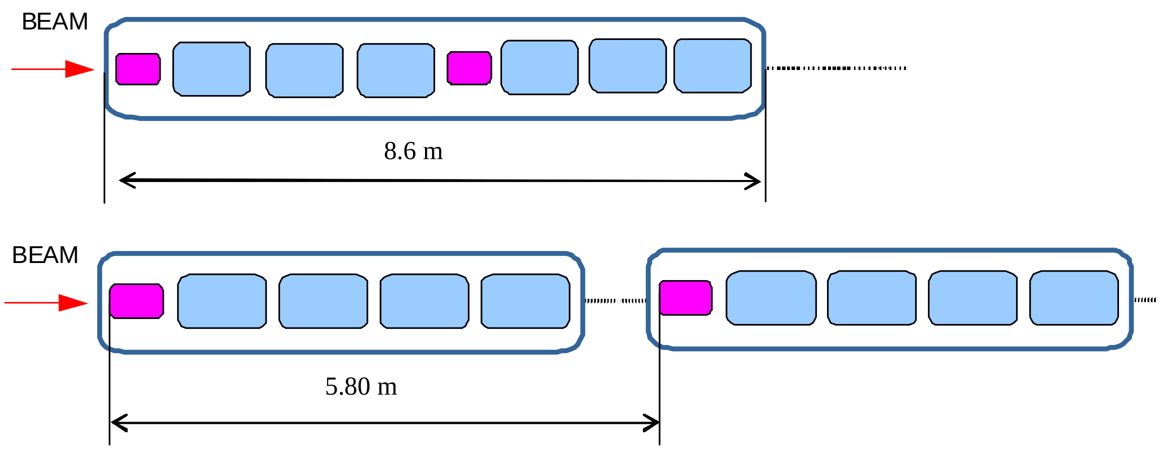
Beta	Type	Freq	Length	Esurf	Eacc	# Cav
		MHz	cm	MV/m	MV/m	
0.031	FORK	57.5	25	22.4	5.60	3
0.061	QWR	57.5	20	27.5	9.29	21
0.151	QWR	115.0	25	27.5	8.68	48
	STRIPPER			Subtotal		72
0.263	HWR	172.5	30	27.5	9.45	40
0.393	2SPOKE	345.0	38.1	27.5	9.17	16
0.500	3SPOKE	345.0	65.2	27.5	9.55	54
0.620	3SPOKE	345.0	80.9	27.5	9.26	24
				Subtotal		134
		Total Cavity Count =				206

Cryomodules: rectangular, ATLAS type

- Separated cavity and cryostat vacuum
- QWR, HWR



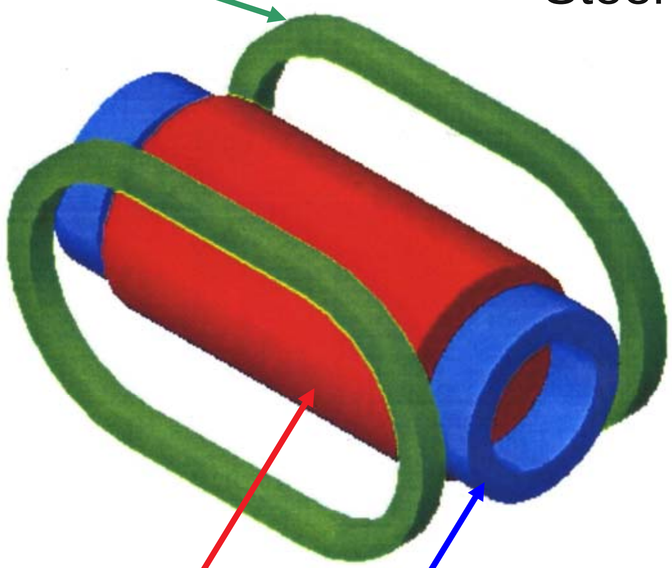
- Spoke resonators



SC Solenoids

- 9 Tesla solenoids, 30 mm and 40 mm bore

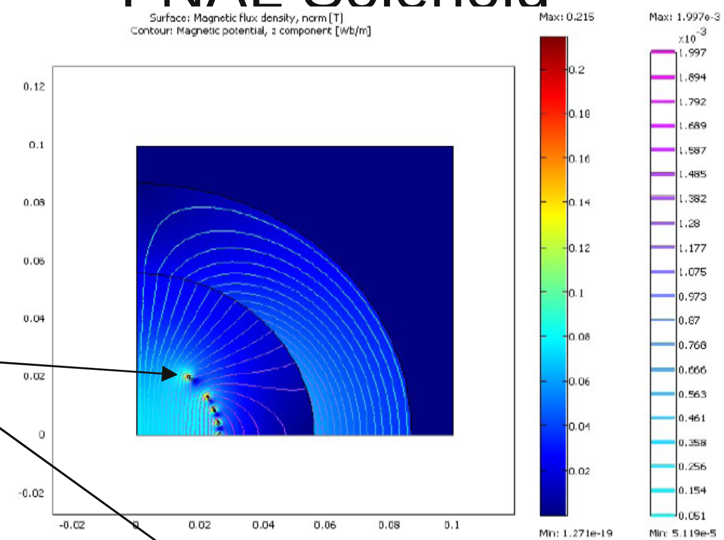
Steering coil



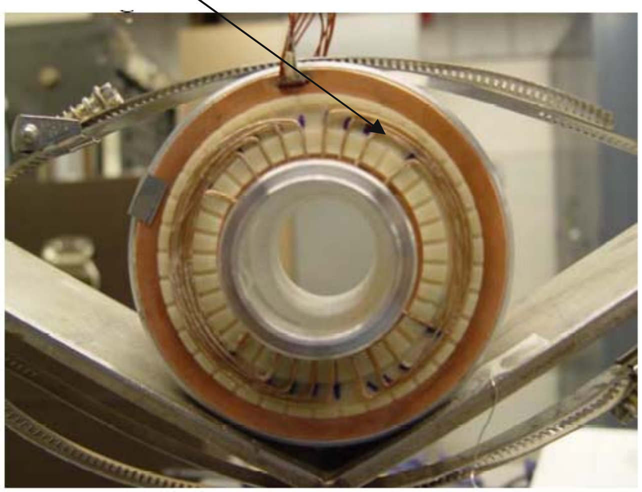
Solenoid

Bucking coil

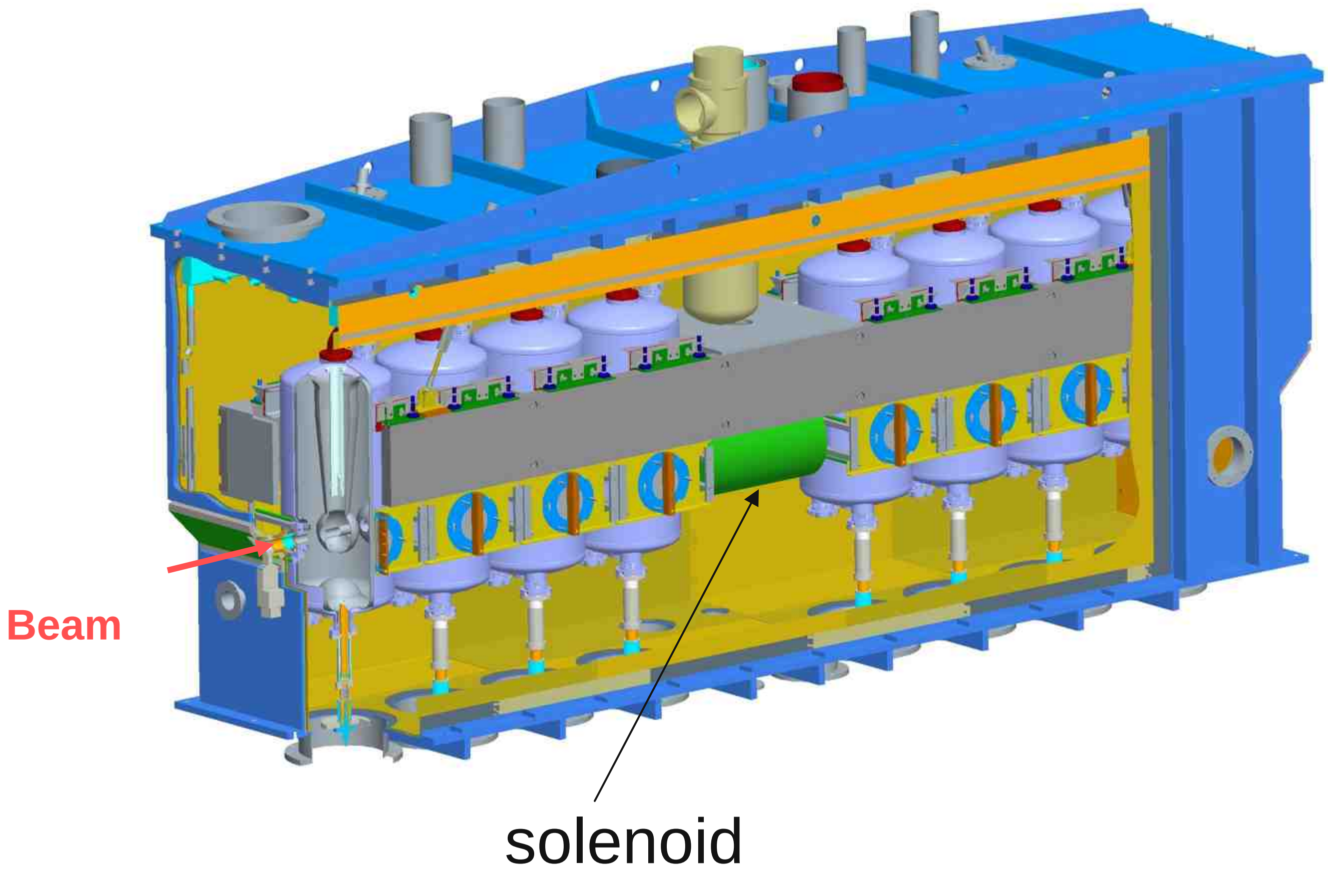
FNAL Solenoid



Steering coils



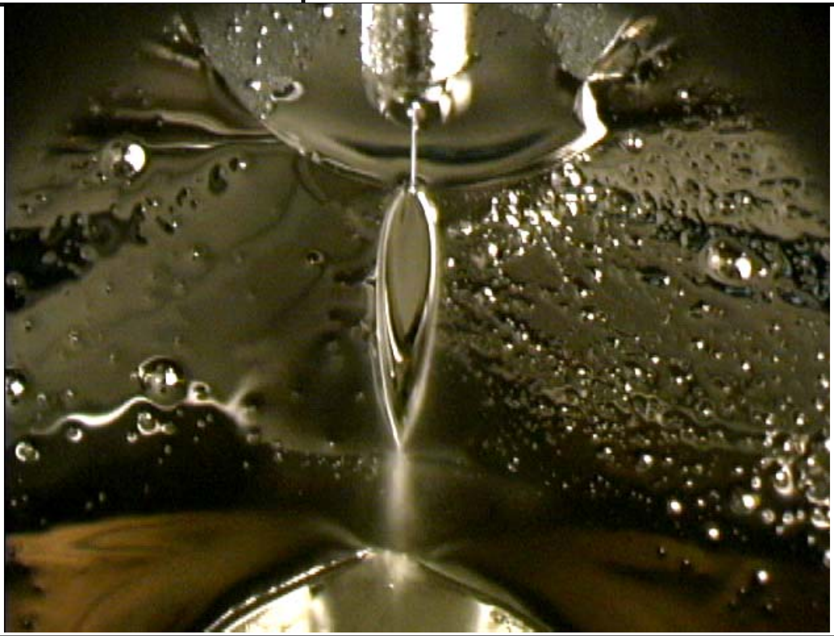
ATLAS upgrade & FRIB Prototype Cryomodule Assembly



Liquid Lithium stripper

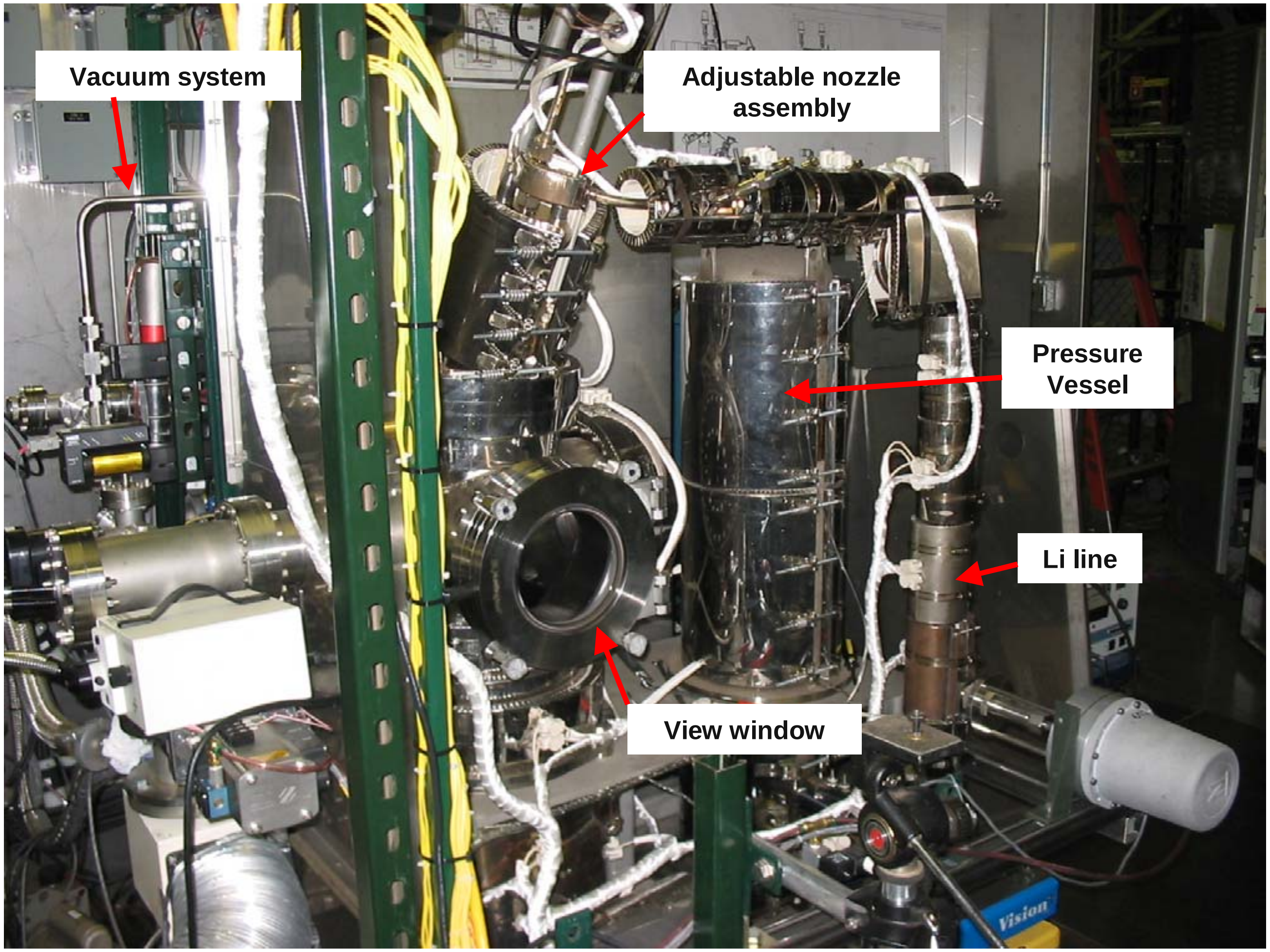
1	**Uranium energy on the stripper**	**17 MeV/u**
2	**Stripper material** **Density**	**Lithium film** **0.511 g/cm^3**
3	**Thickness**	**1.12 mg/cm^2 or 22 μm**
4	**U average energy loss from SRIM code**	**0.51 MeV/u**
5	**Central charge state**	**79**

A jet of 15 μm liquid lithium film was demonstrated



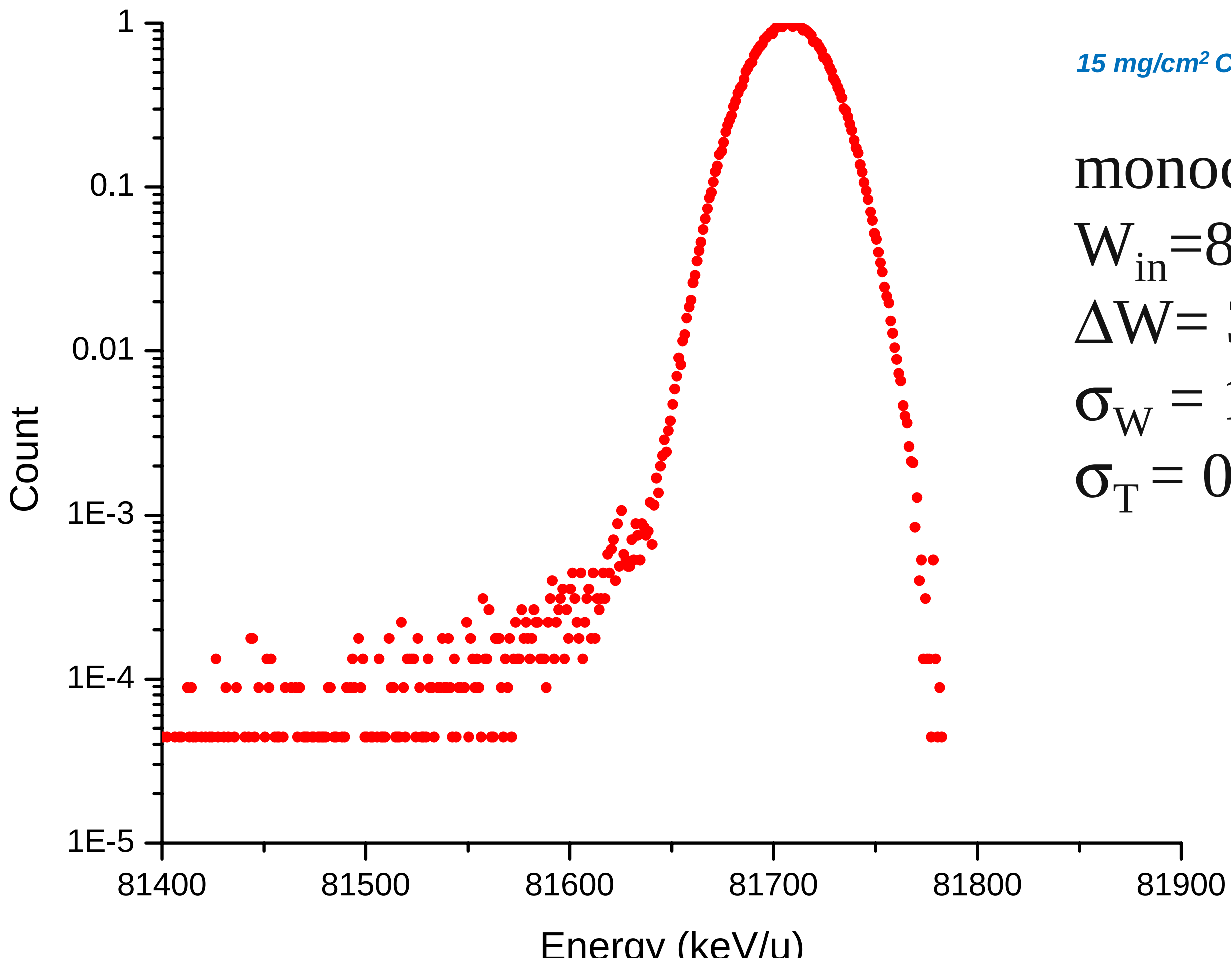
Liquid Lithium Thin Film

– Liquid Li thin film system



SRIM results, 10^6 particles

SRIM = Stopping Range of Ions in Matter
by J.F. Ziegler, J.P. Biersack and U. Littmark

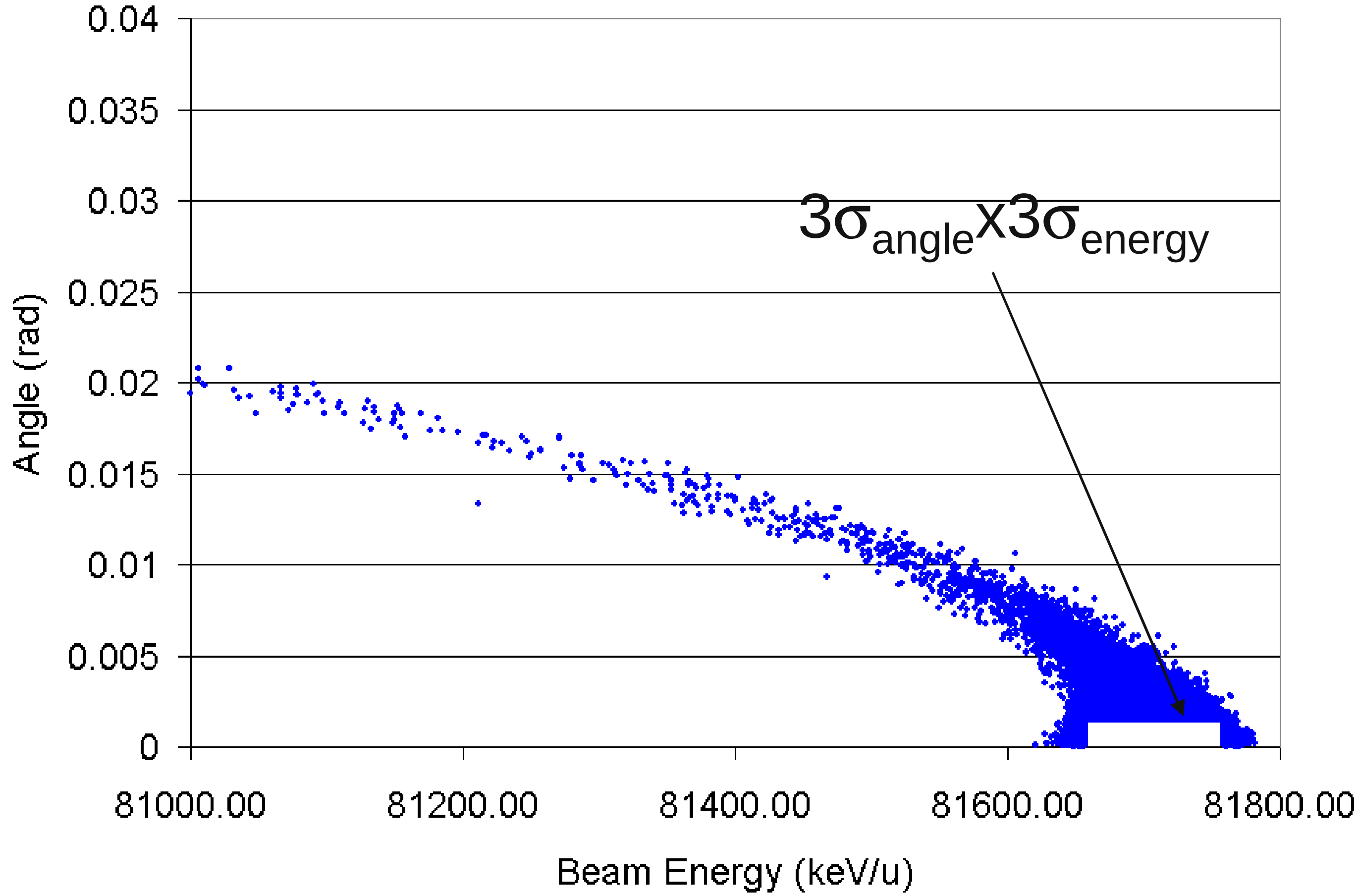


15 mg/cm² Carbon foil

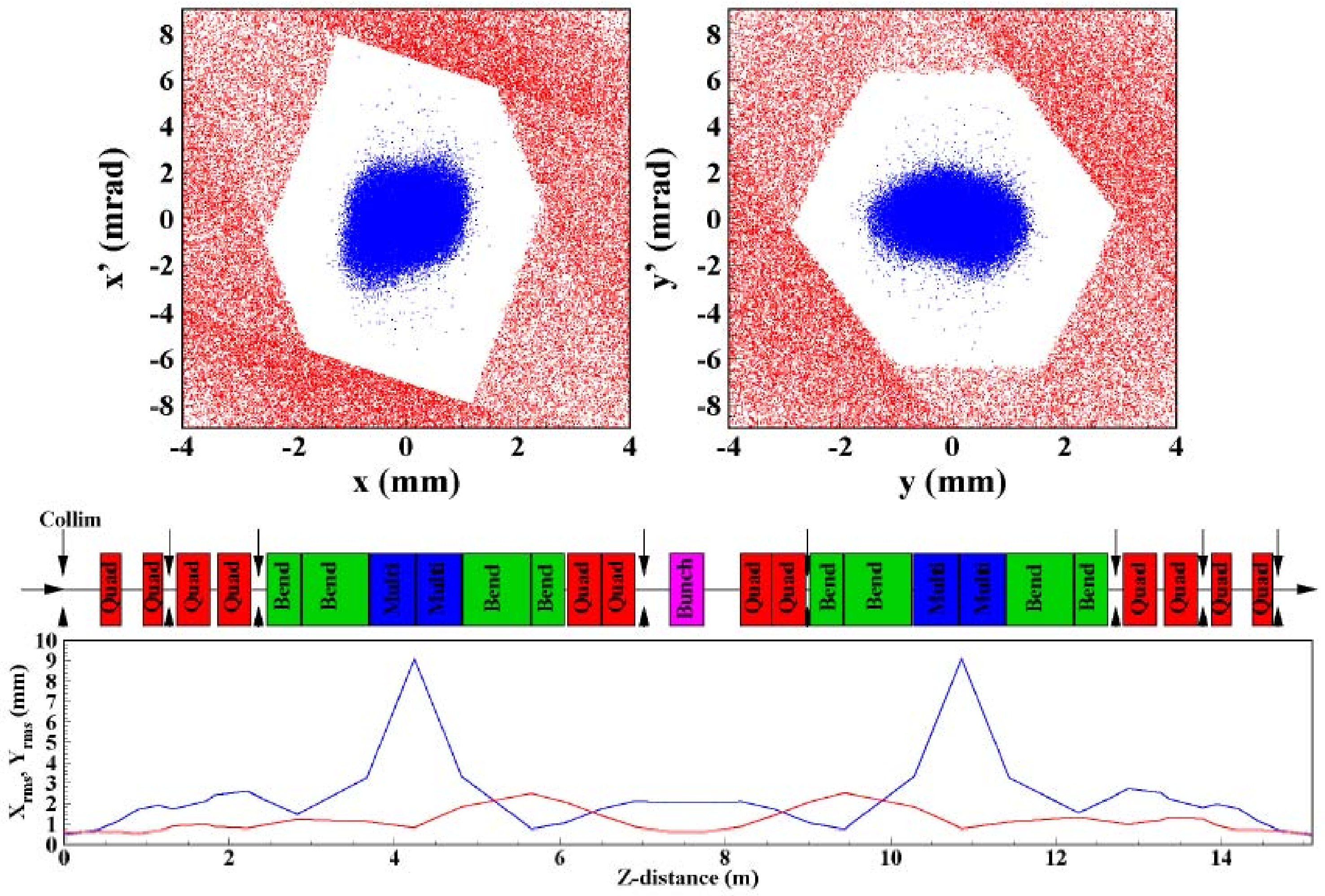
monochromatic input beam
W_{in}=85 MeV/u
ΔW= 3.29 MeV/u
σ_W = 17.5 keV/u
σ_T = 0.5 mrad

SRIM results, 10^6 particles, angle= $\sqrt{x'^2 + y'^2}$

- Fluctuation of the film thickness can result to large longitudinal emittance growth

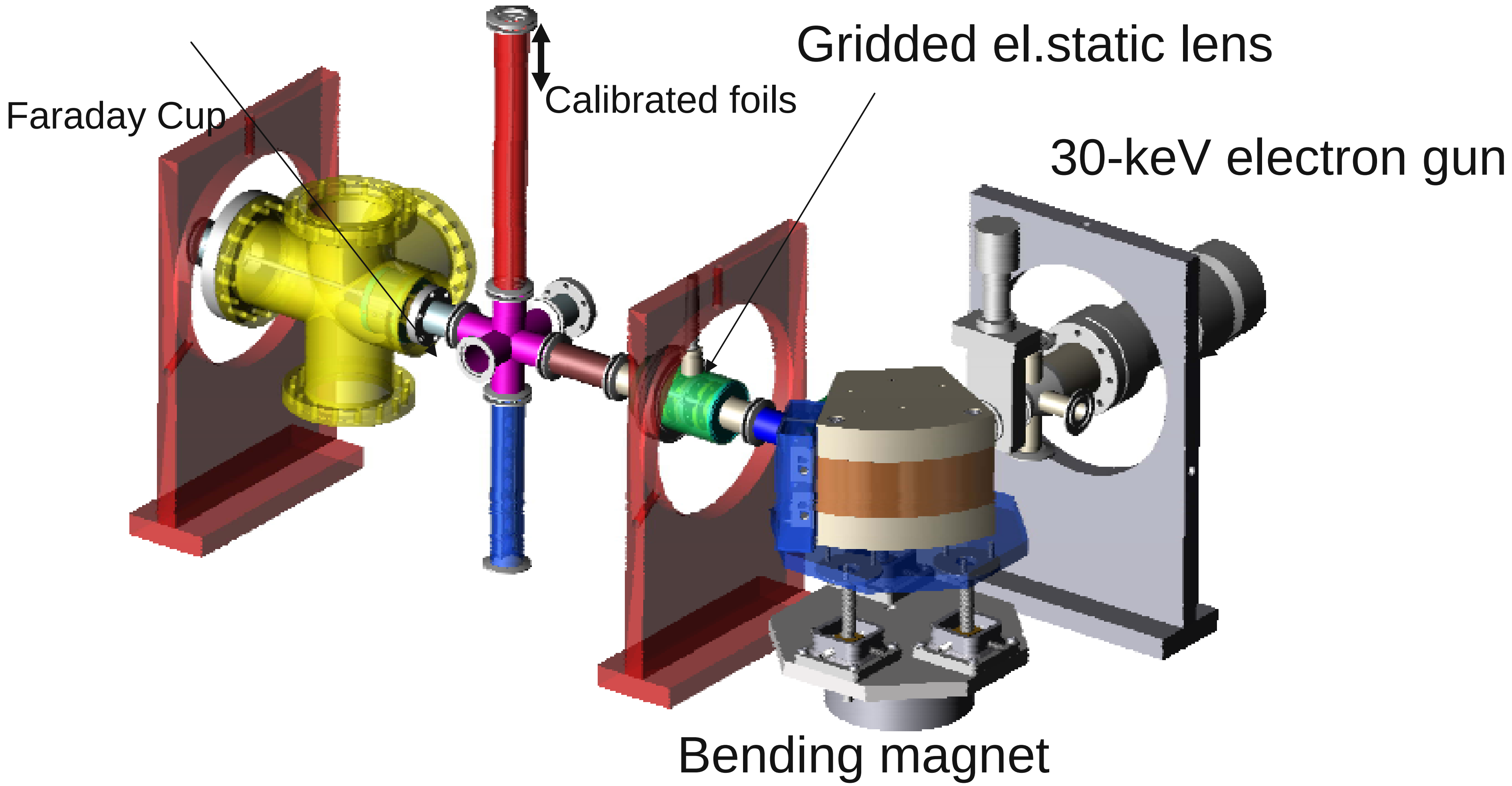


Post-stripper chicane and beam collimation



Set-up for measurement of thin film thickness

- Measurement of electron beam current attenuation behind a thin foil



Machine errors

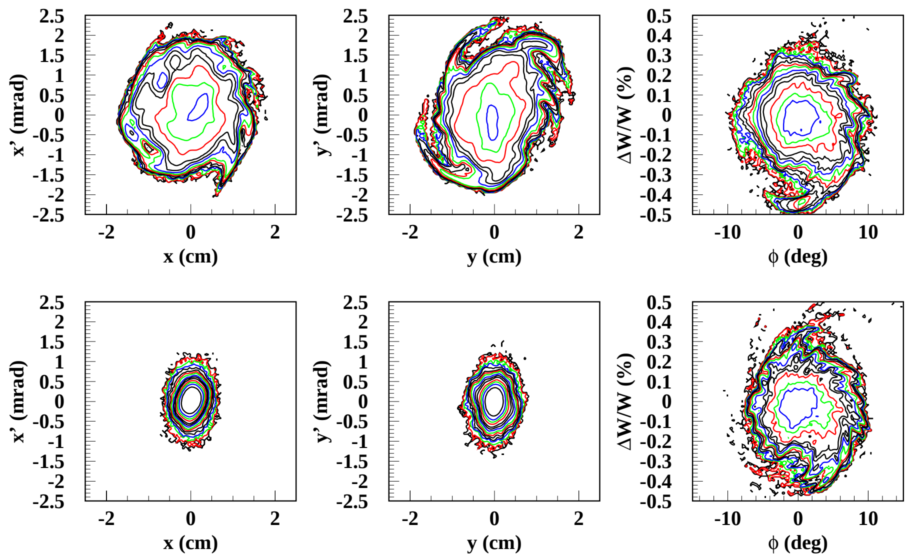
- Large-statistic beam dynamics simulations including all known errors
  - Static errors are corrected for each simulation seed
  - Dynamic errors are not correctable
- Most studies have been performed for Uranium beam
  - 2 charge states from the ECR
  - 5 charge states after the stripper

Table 2: Typical values of misalignment and RF errors.

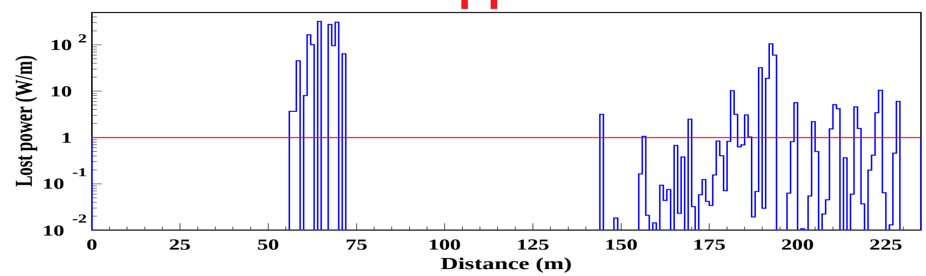
Error	**Value**	**Distr.**
Sol. end displacement		Uniform
Short (20-25 cm)	0.15mm (max)	
Long 1(32-50 cm)	0.2 mm (max)	
Quad. end displacement	0.15mm (max)	Uniform
Quad. rotation (z-axis)	5 mrad (max)	Uniform
Cav. end displacement	0.5 mm (max)	Uniform
Cav. field jitter error	0.5 % (rms)	Gaussian
Cav. phase jitter error	0.5^{o}(rms)	Gaussian

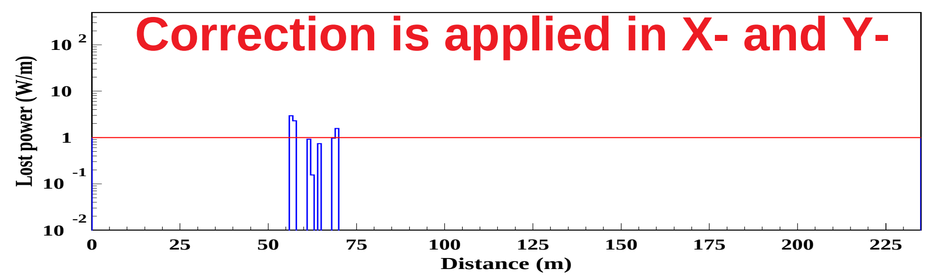
Beam parameters in the driver linac (all errors are included)

- Large statistics simulations:
  - Generate 200 different linacs with random static errors
  - Apply correction to static errors in each linac
  - Simulate 0.5M particles with dynamic errors through each linac
  - Detect lost particles

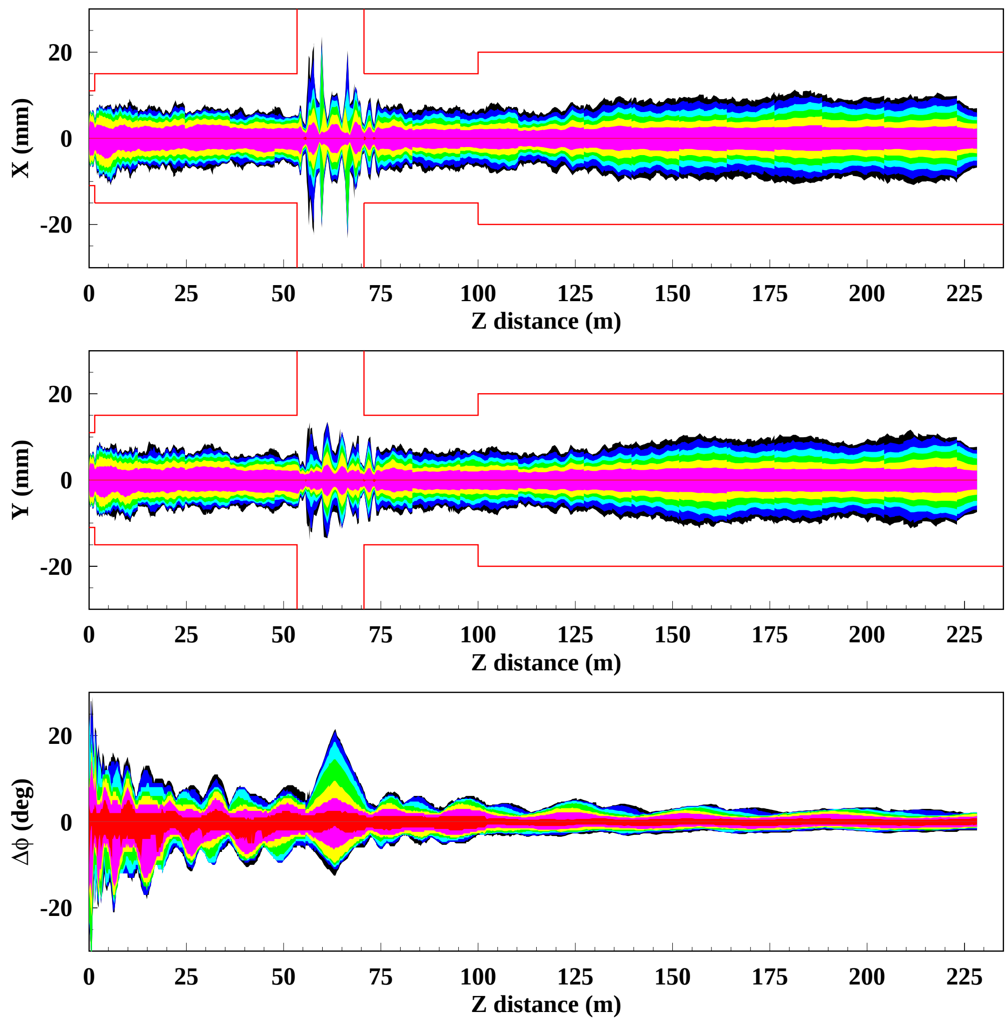


No correction is applied in X- and Y-





X-, Y- and φ-profiles along the Linac, large statistics simulations, 200 seeds each with 200k particles



Larger errors

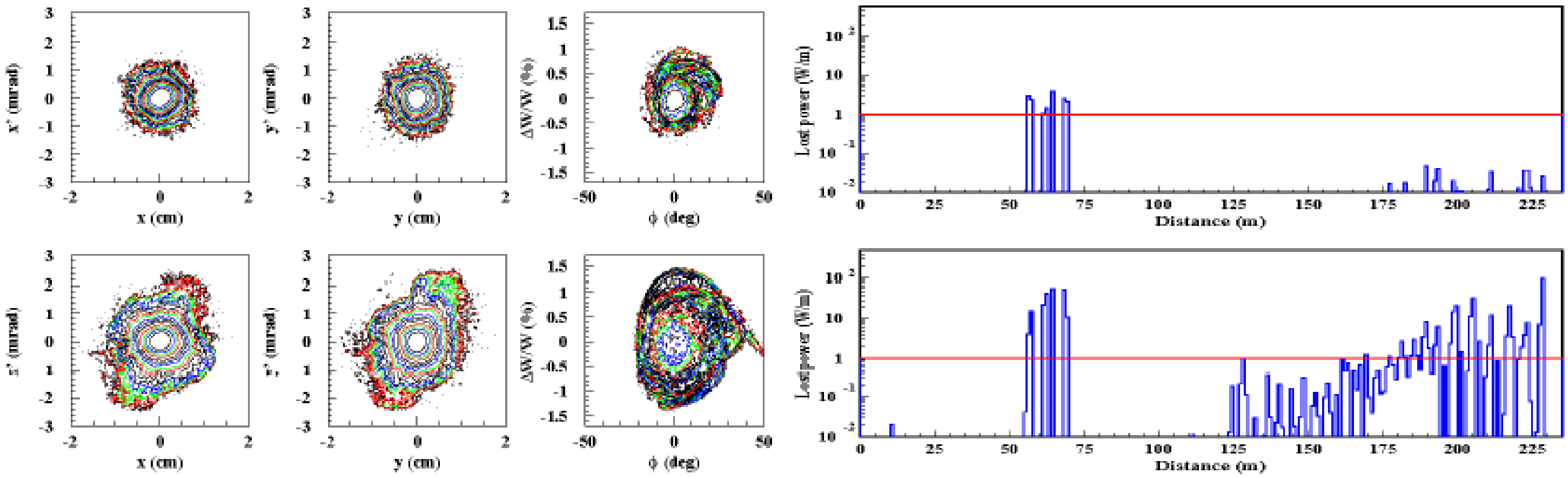


Figure 9: Left: Phase space plots for (1^o,1%) RF errors (top) and (2^o,2%) (bottom). Right: Beam loss in Watts/m along the linac for (1^o,1%) RF errors (top) and (2^o,2%) (bottom).

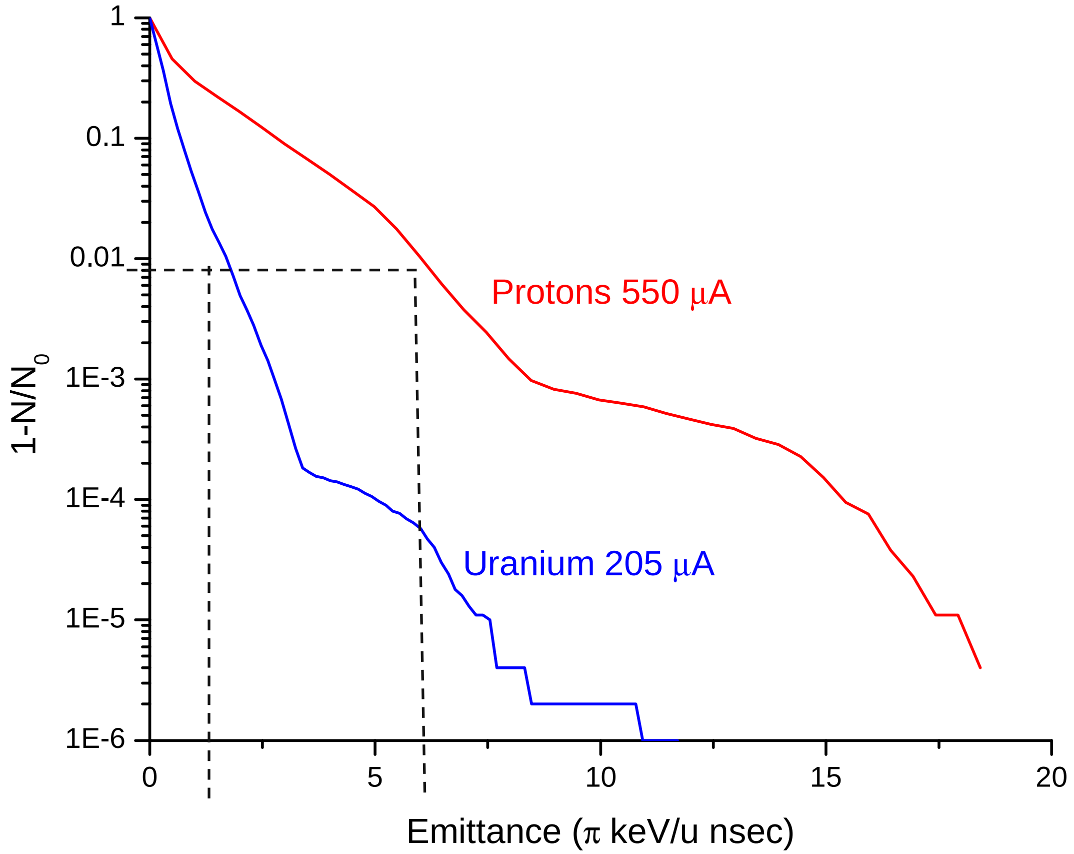
Proton beam dynamics in the RIA driver linac

- To reduce the cost we like to avoid additional injector for light ions
- Main issues:
  - The driver linac is optimized for the heaviest ions. Must be re-tunable for protons and other light ions.
  - 200 MeV/u Uranium and 580 MeV protons
  - Space charge effects of low-energy (14 keV/u) pre-bunched proton beams upstream of the RFQ:

$$K = \frac{q}{A} \frac{I\lambda}{20\sqrt{5}\pi\varepsilon_0 m_e c^3 \gamma^3 \beta^2}$$

$$K \sim \frac{q}{A} I \qquad \frac{K_P}{K_U} = \frac{1}{\frac{33}{238}} \cdot \frac{0.8}{0.25} = 23$$

Beam quality in the longitudinal phase space after the RFQ



Fraction of particles outside of a given longitudinal emittance as a function of the emittance.

- Simulation of proton beam does not show any losses along the linac

RF power requirement

- CW operation
- Beam loading is high: from 0.6 kW to 5.2 kW
- Microphonics require some additional rf power
- For high reliability of the facility operation, all cavities should be supplied by fast tuners (piezo- or magnetostrictive).
- Power specifications to the amplifiers is:

f, MHz	57.5	115	172.5	345
Power, kW	3	3	5	10
$\Delta f/2$, Hz	~30	~30	~25	from 27 to 48

Summary of the R&D

- 400 kW is possible for all beams including uranium at 200 MeV/u with
  - Advanced ECR source capable of producing required beam intensity
  - Acceleration of multiple-charge-state beams
- SRF R&D in recent years resulted in
  - Significant reduction of the number of SC cavities and RF amplifiers; We need just 206 SRF cavities (+1 rebuncher) to obtain 833 MV for the driver linac in the velocity range from 0.025c to 0.6c
  - Significant reduction of the cryogenic load due to demonstrated low residual resistance (or high quality) of SC cavities. Operation at 2.1K is more efficient
  - Shorter accelerator tunnel and smaller support building;
  - Significant cost reduction of the low-q post-accelerator by applying high gradient SC cavities in the velocity range 0.014c to 0.046c
  - RIA-type SC spoke cavities are being developed and used for the FNAL proton driver in pulsed regime

Summary of the R&D (cont'd)

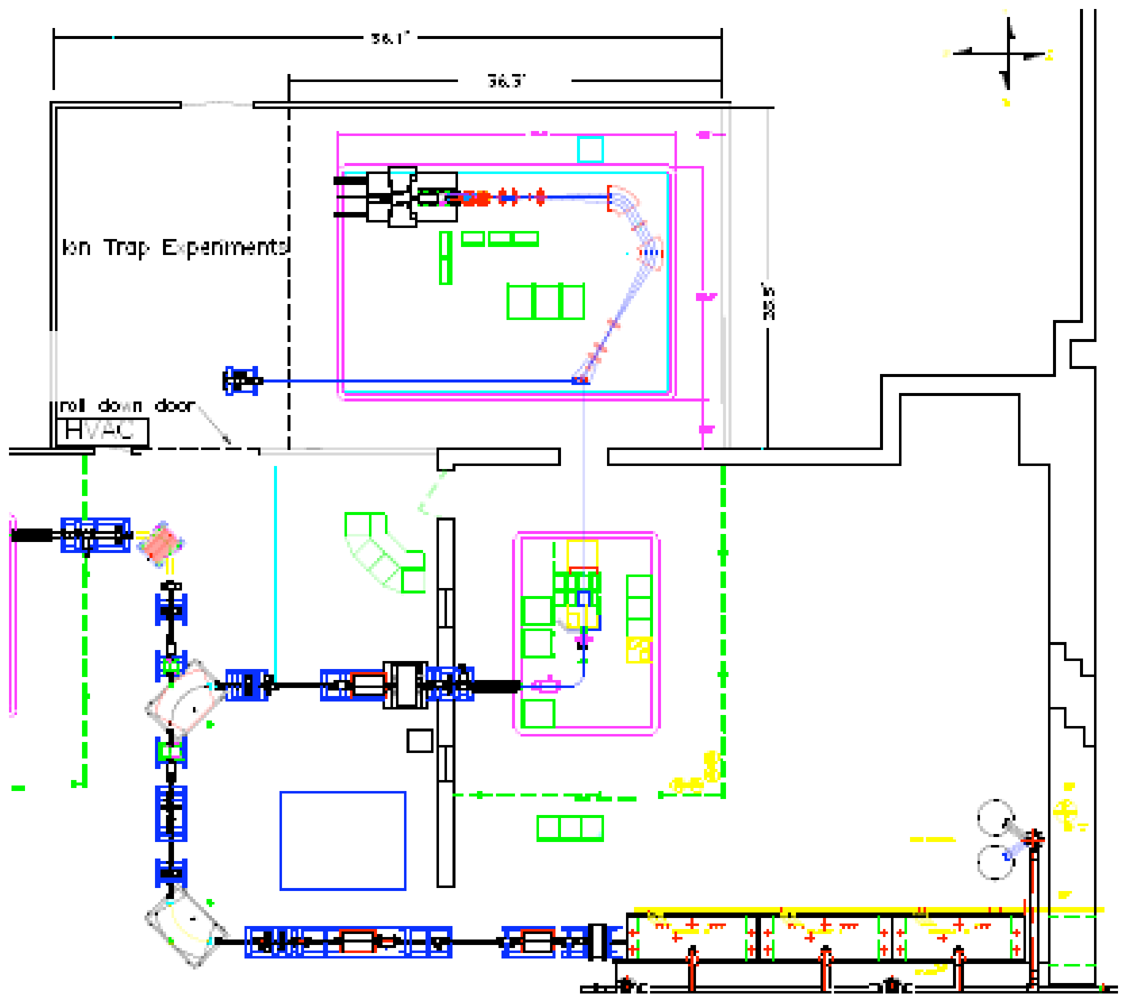
- Large-scale beam dynamics simulations at BlueGene/L supercomputer at ANL
  - No beam losses except in the designated area
  - Excellent quality of multiple-charge state beams
  - The driver linac delivers a CW sequence of bunches into the target
    - *~1 nsec bunch width with repetition rate of 57.5 MHz.*
    - *Energy spread* $\leq$ *0.5%*
    - *Can be focused on the production target less than 1 mm in diameter if necessary.*
- One stripper at 17 MeV/u results in optimal linac lattice
  - Substantially simplifies Linac design and operation
  - High power dissipation on the stripper is removed by liquid lithium film

Recent and current R&D

- Complete Assembly and test of the ATLAS Cryomodule
  - 12.5 MV/m accelerating fields are demonstrated (FRIB spec = 8.7 MV/m)
- Design of the Super-CARIBU post-accelerator
- Minimize cavity count in the high-energy section of the AEBL driver linac
- Electrodynamics, structural and thermal optimization of SRF cavities
  - Four types of interdigital four-gap cavities for SuperCARIBU and AEBL
  - Two types of triple-spoke cavities for the AEBL
- Liquid lithium film tests with ~0.5 kW low energy bunched proton beam; Thickness measurements of the liquid lithium film using 30 kV electron beam
- Development of a bunch length detector with resolution of several picoseconds

CARIBU

- ^{252}Cf fission source
- Gas cell
- Isobar separator, ~20000
- Charge breeder
- ATLAS



Yields for Representative Species

Calculated beam intensities for a 1 Ci ^{252}Cf fission source using expected efficiencies.

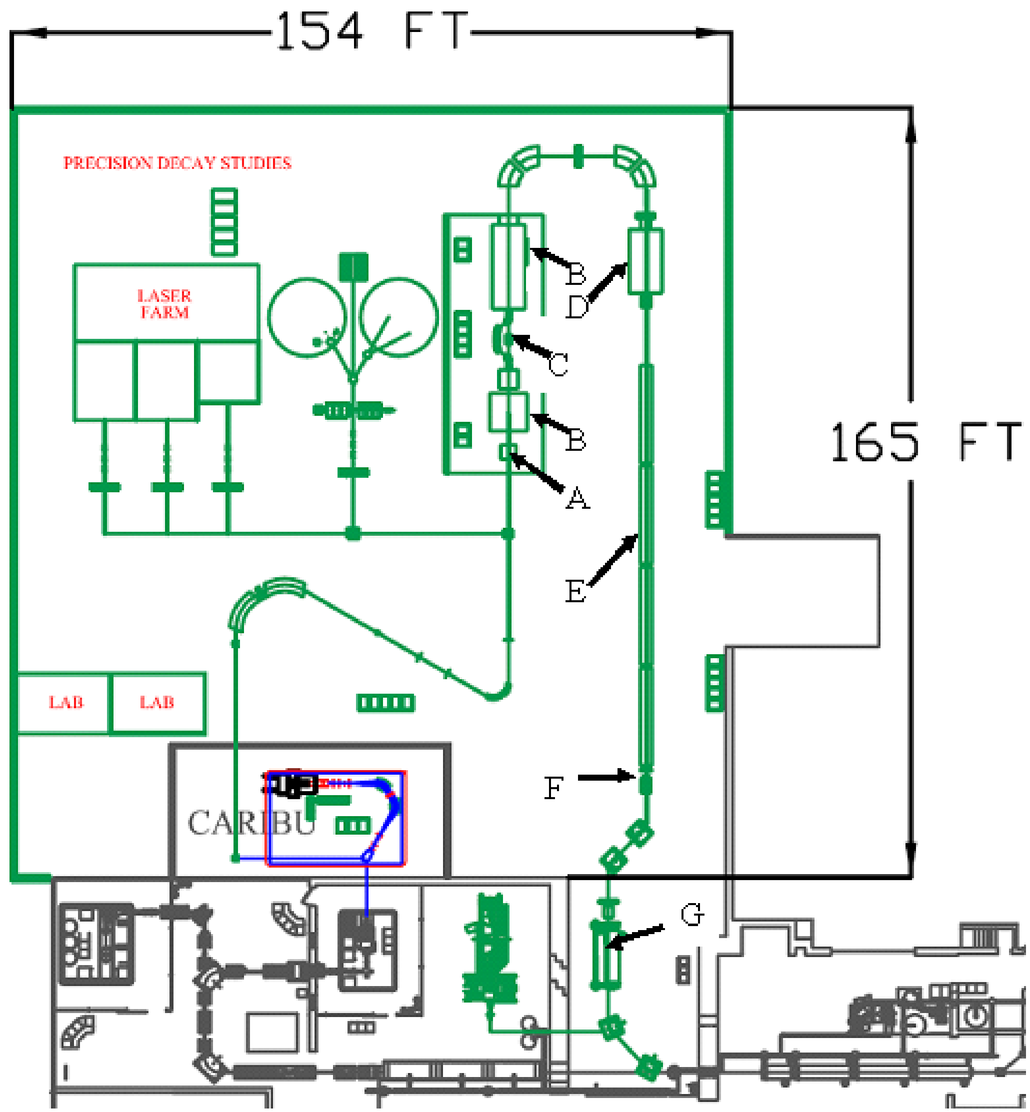
Isotope	Half-life (s)	Low-Energy Beam Yield (s^{-1})	Accelerated Beam Yield (s^{-1})
^{104}Zr	1.2	6.0×10^{5}	2.1×10^{4}
^{143}Ba	14.3	1.2×10^{7}	4.3×10^{5}
^{145}Ba	4.0	5.5×10^{6}	2.0×10^{5}
^{130}Sn	222.	9.8×10^{5}	3.6×10^{4}
^{132}Sn	40.	3.7×10^{5}	1.4×10^{4}
^{138}Xe	846.	9.8×10^{6}	7.2×10^{5}
^{110}Mo	2.8	6.2×10^{4}	2.3×10^{3}
^{111}Mo	0.5	3.3×10^{3}	1.2×10^{2}

SuperCARIBU

- Was designed as a part of the future FRIB
- SuperCARIBU is a significant upgrade of CARIBU capabilities by:
  - Using low-Q acceleration and stripping to gain factors of 5 to 8 in efficiency
  - Providing increased experimental space for stopped beam and astrophysics beam experiments,
  - Increasing the source fission rates, for example by using Cf-254 as the source material.

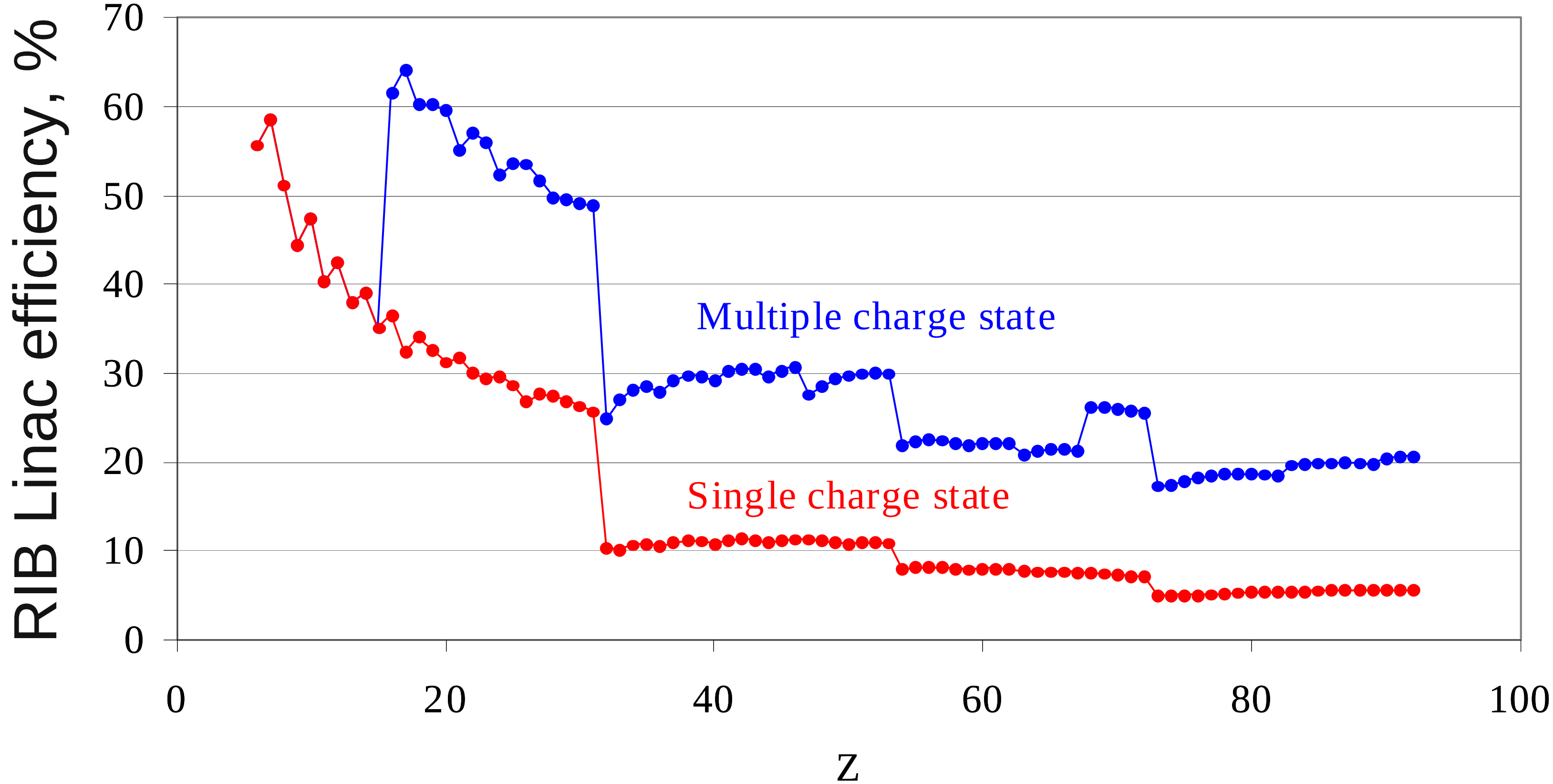
The floor plan proposed for SuperCARIBU.

- (A) high voltage platform
- (B) low-Q (1/238) RFQs
- (C) gas stripper
- (D) Hybrid RFQ (q/A=1/66)
- (E) low-Q SC linac (q/A=1/66)
- (F) carbon stripper foil
- (G) final SC linac section prior to ATLAS.
- Final energy is 1.0 MeV/u to 1.7 MeV/u
- General properties of the low-q injector
  - 92% transmission (acceleration efficiency) for masses ≤66
  - ~45% transmission for masses 228 ≥ A > 66



Overall efficiency of the RIB linac (W ≥10 MeV/u)

- Gas stripper, 7 keV/u and 22 keV/u
- Carbon stripper, 1 MeV/u to 1.7 MeV/u



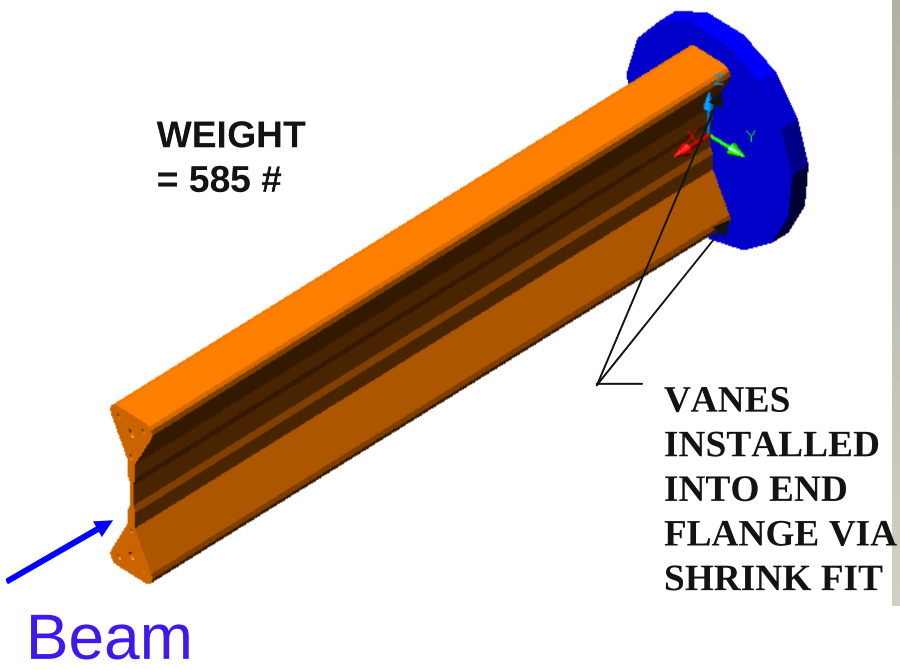
Basic parameters of the low-q RFQ

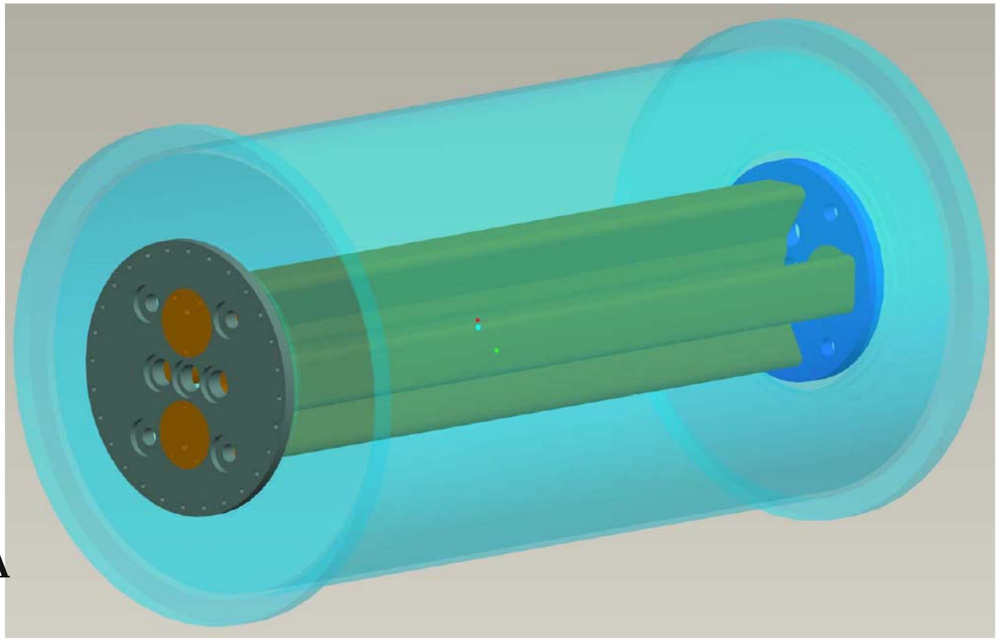
- Basic parameters of the low-q RFQ

Parameter	Value	
Duty cycle	100% (CW)	
Operating frequency	12.125 MHz	
Vane length	226 cm	
Average radius	0.7 cm	
Input beta	0.0009267	0.4 keV/u
Charge-to-mass ratio	≥1/238	
Design inter-vane voltage	82 kV	

A 12-MHz split-coaxial CW RFQ for the S-Caribu Project, U^{1+}

- The same tank as for $^{136}Xe^{1+}$ RFQ
- Design of vanes is significantly modified

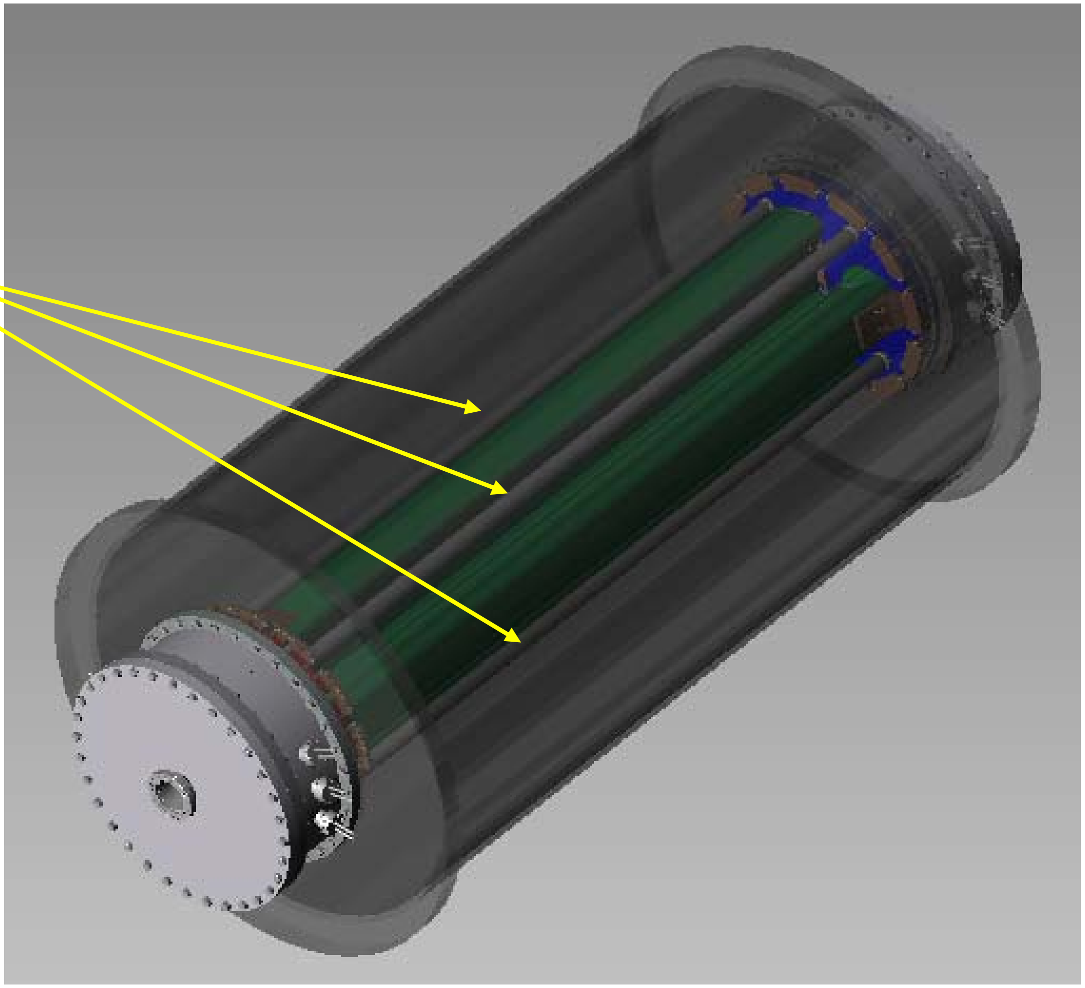




A 12-MHz CW RFQ for the S-Caribu Project, U^{1+}

- Cavity assembly

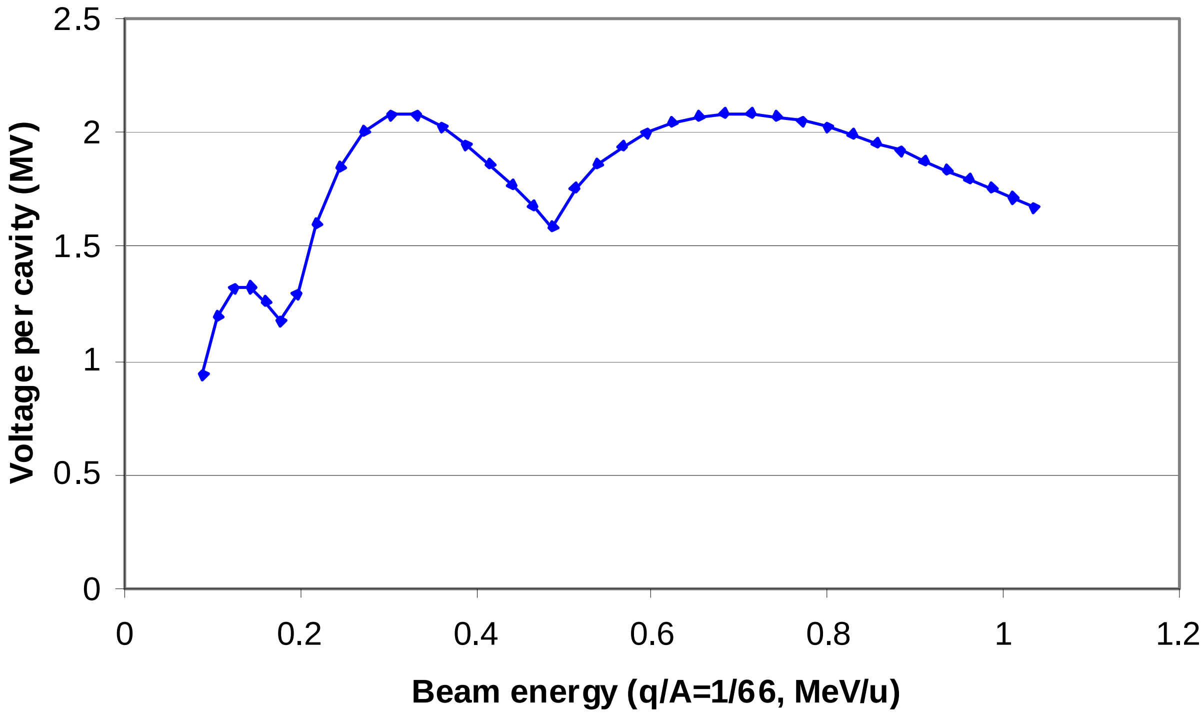
4 tie rods are used for the assembly



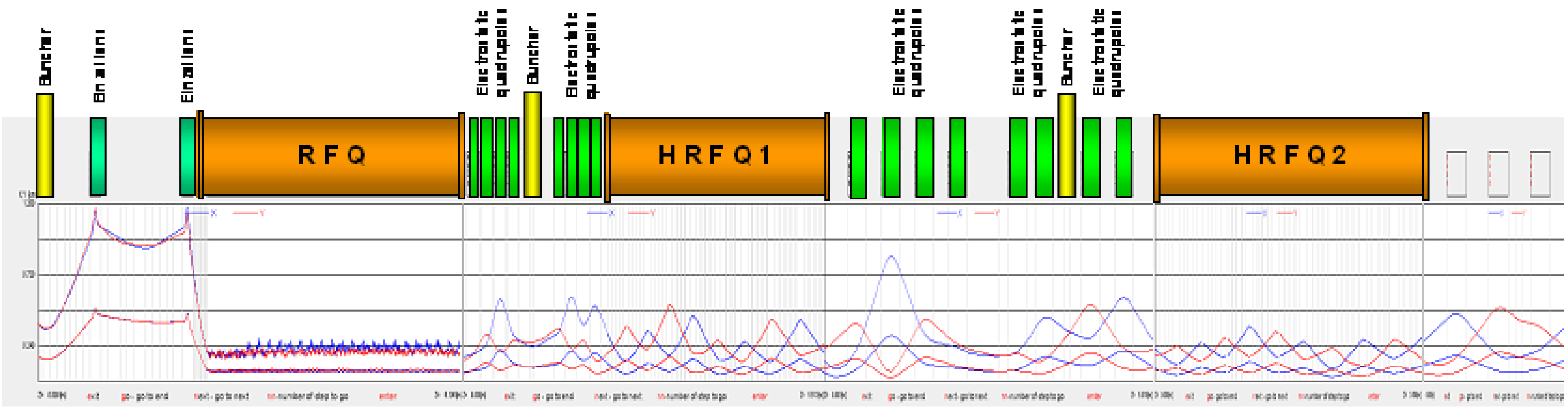
SC Linac for 1/6≥q/A≥1/66 from 75 keV/u to 1.0 MeV/u

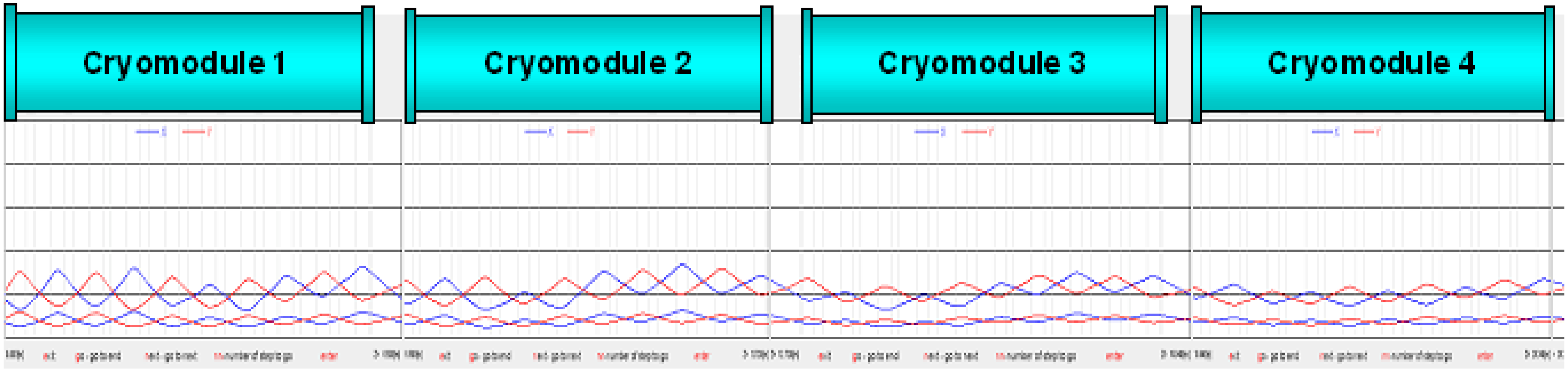
Parameter	Type-I	Type-II	Type-III
Frequency (MHz)	48.5	48.5	72.75
β_G	0.017	0.026	0.038
Aperture diameter (cm)	2.0	2.0	2.0
Number of cavities	6	12	20

Voltage gain per cavity, Win=75 keV/u

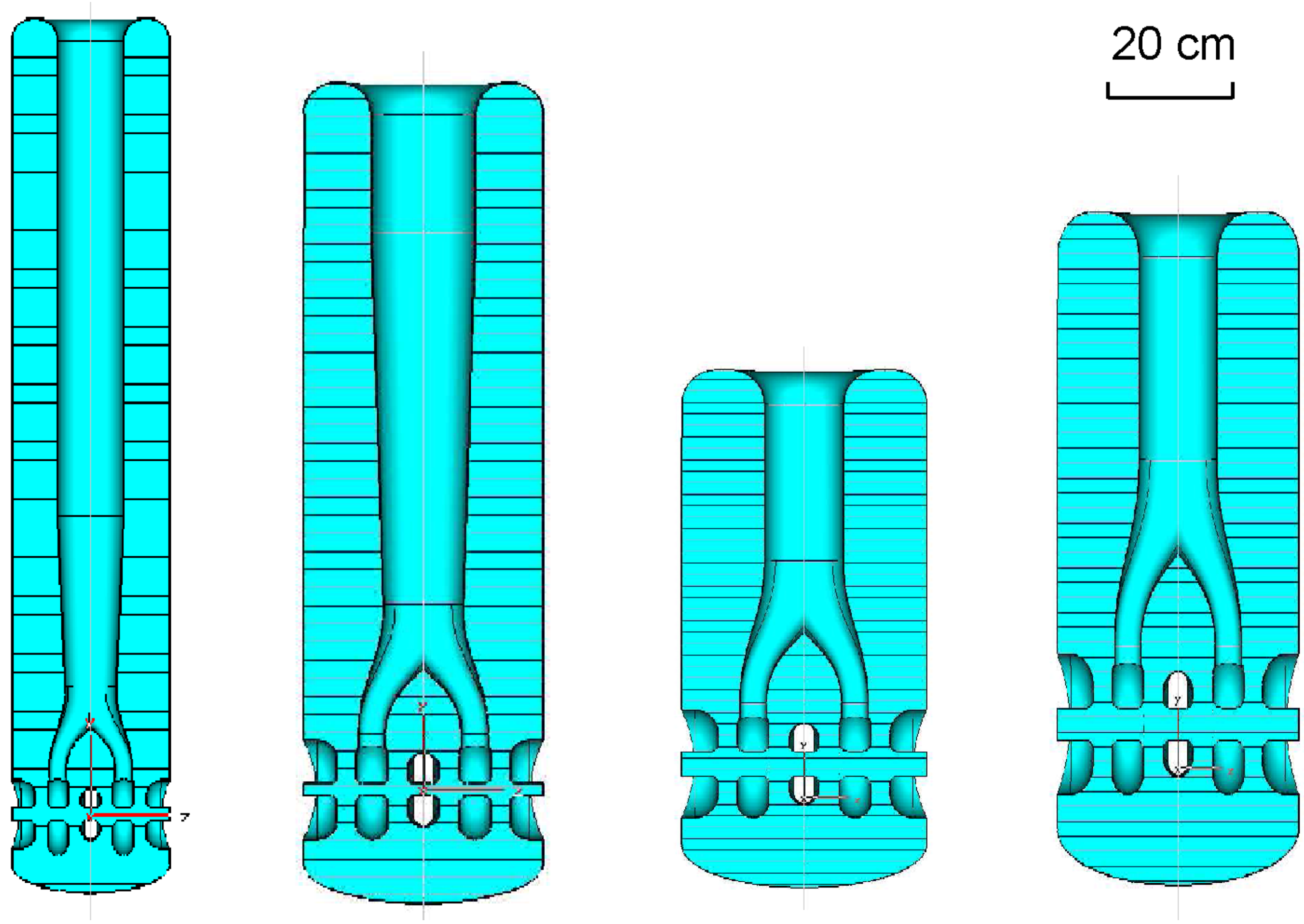


End-to-end simulations, q/A=1/66, from 0.4 keV/u to 1.0 MeV/u



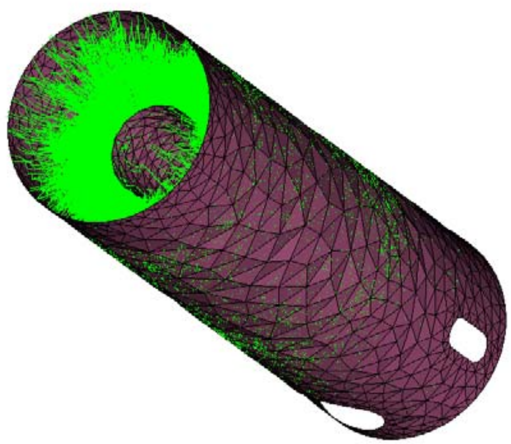


4-gap cavities for the S-CARIBU

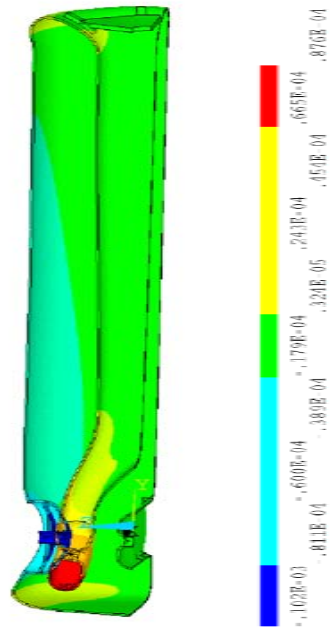


4-gap cavity

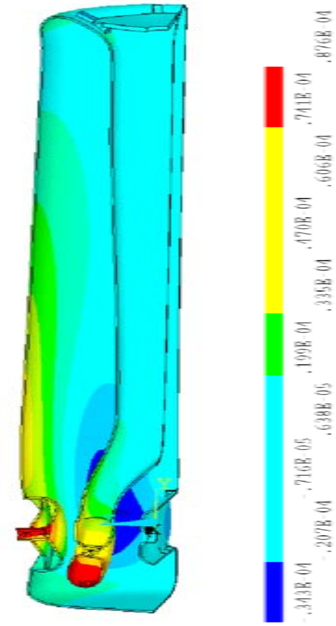
- Multipacting studies – ANALYST (STAAR)
- Helium pressure – MWS, ProE, ANSYS
- Mechanical tuner – MWS, ProE, ANSYS



Pressure



Pressure+Tuner



Paper accepted for publication in PRSTAB

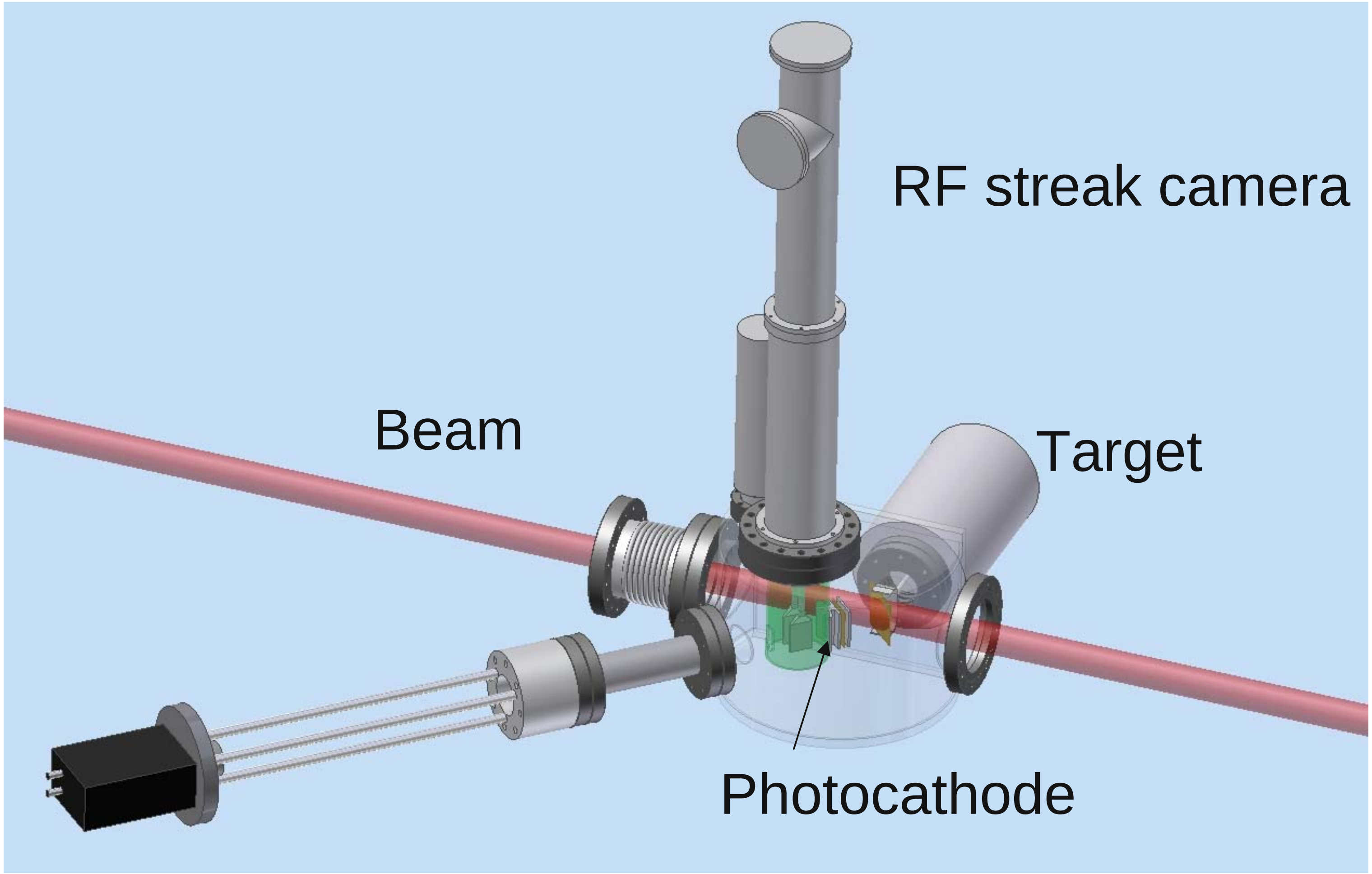
4-gap SC cavities can provide 10 MV/m

- Minimize ratio E_{peak}/E_{acc} and B_{peak}/B_{acc}
- Minimized df/dp
- Improve structural stability

Parameter	Units	ATLAS	Type-I	Type-II	Type-III	Type-IV
Mesh-points		385K	626K	2M	2M	2M
E_{PEAK}	MV/m	5.04	3.76	3.41	3.48	3.61
B_{PEAK}	Gauss	117	42	43	55	48
Length, L_c	cm	24.6	17	26	26	26.4
W	mJ	221	72	150	118	149
G	Ω	13.8	11.5	18.1	25.1	20.9
R/Q_0	Ω	900	1309	1486	1254	1298
β_G		0.025	0.017	0.026	0.038	0.031
Height	cm	110.5	139.5	131.3	80.8	107.3
Diameter	cm	30.48	23.54	37.0	37.0	37.0

Frequency	MHz	48.5	48.5	48.5	72.75	57.5

X-ray based bunch length detector with several psec time resolution



Conclusion

- A 400 kW 200 MeV/u reaccelerated rare isotope facility can be built for about half the cost of RIA.
- Vigorous R&D and prototyping of the FRIB technical systems resulted in
  - Significant reduction of the estimated cost
  - Extended scientific reach by improved production and collection of rare isotopes
- FRIB technologies are robust; the project can proceed with minimal risk
- Superconducting technology is only option for CW ion accelerators
  - NC accelerator is required in the front end
- Low-Q injector provides predictable, reliable high yields of rare isotopes including short-lived isotopes and will be the upgrade path fro the FRIB
- We observe significant impact of the RIA technology on accelerator projects worldwide
  - FNAL is interested in pulsed 8-GeV SC linac for H-minus beam based on ILC technology (“Project X”)
  - GANIL
  - TRIUMF
  - SARAF, Soreq