Status of the FRIB project at MSU and ECR Ion Source development

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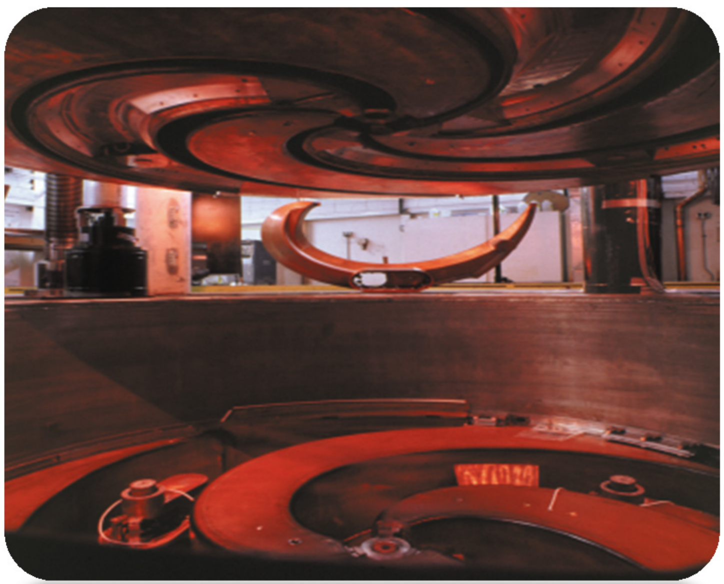
Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

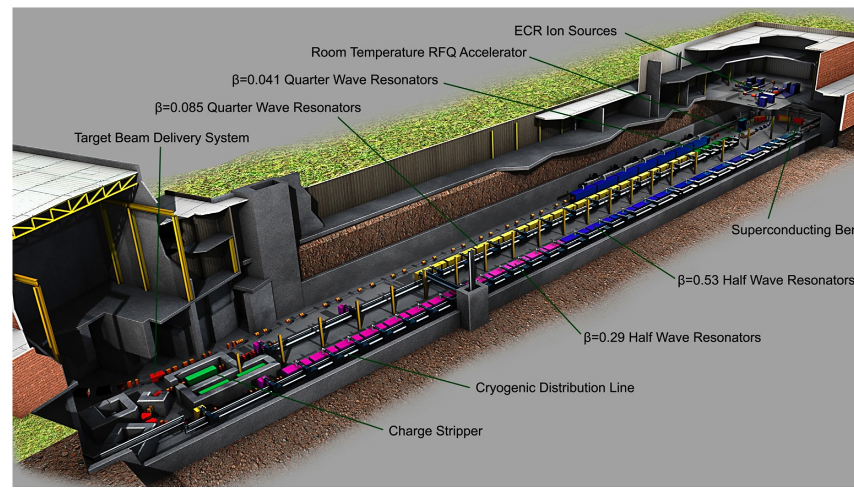
Outline

- FRIB Overview
- Preliminary design of FRIB SC-ECR
- Uranium beam development for FRIB done with VENUS
- Schedule
- Summary

NSCL/ FRIB

- NSCL/FRIB activities focused on production of Rare Isotope Beam for research on nuclear science, nuclear astrophysics, study of fundamental interactions





1kW beam 160 MeV/u

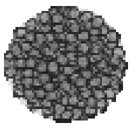
400kW beam 200 MeV/u

Upgrade to 400 MeV/u

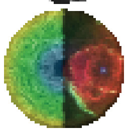
Toward FRIB

- 1999: ISOL Task Force Report – proposes **RIA concept**
- 2003: RIA ranks 3rd in DOE 20-year Science Facility Plan
- 2005: DOE cancels draft of RIA-RFP (request for proposal)
- DOE and NSF charge RISAC to assess science case for RI Facility
- 2006: DOE cancels RIA and pursues a lower cost option
- RISAC endorses construction of a Rare-Isotope Facility
- 2007: NSAC: FRIB is 2nd-highest priority for nuclear science
- 2008: DOE issues a FOA for FRIB.
- **2008 DOE selects MSU for the fabrication of FRIB driver linac**

The Science with Rare Isotope Beams



Properties of nucleonic matter



Nuclear processes in the universe

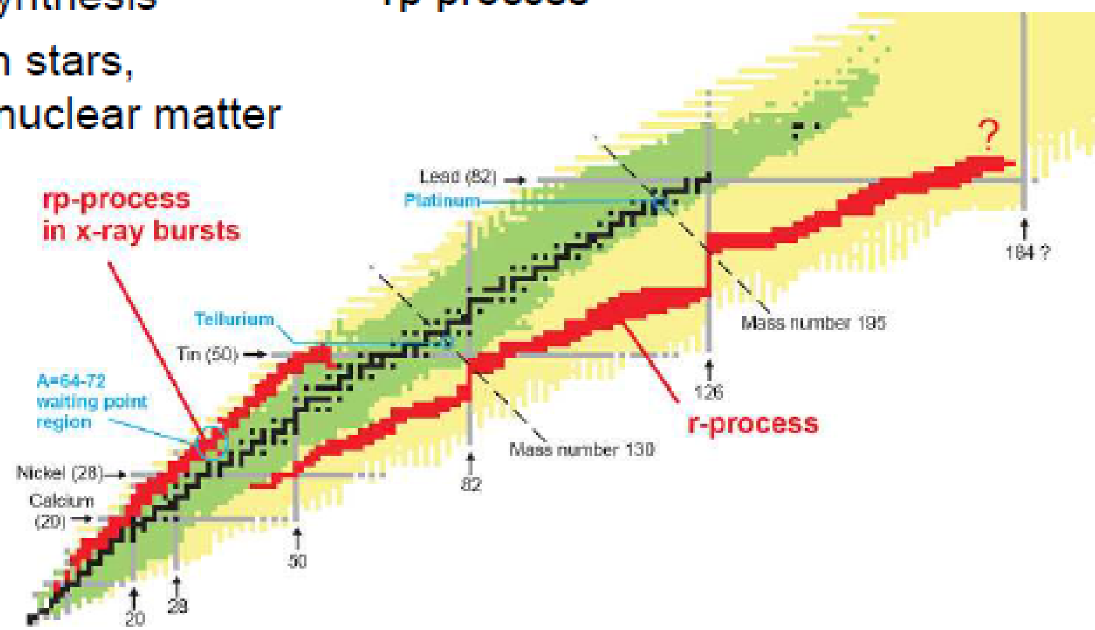
- Energy generation in stars, (explosive) nucleo-synthesis
- Properties of neutron stars, EOS of asymmetric nuclear matter

Origin of the elements in the cosmos ?

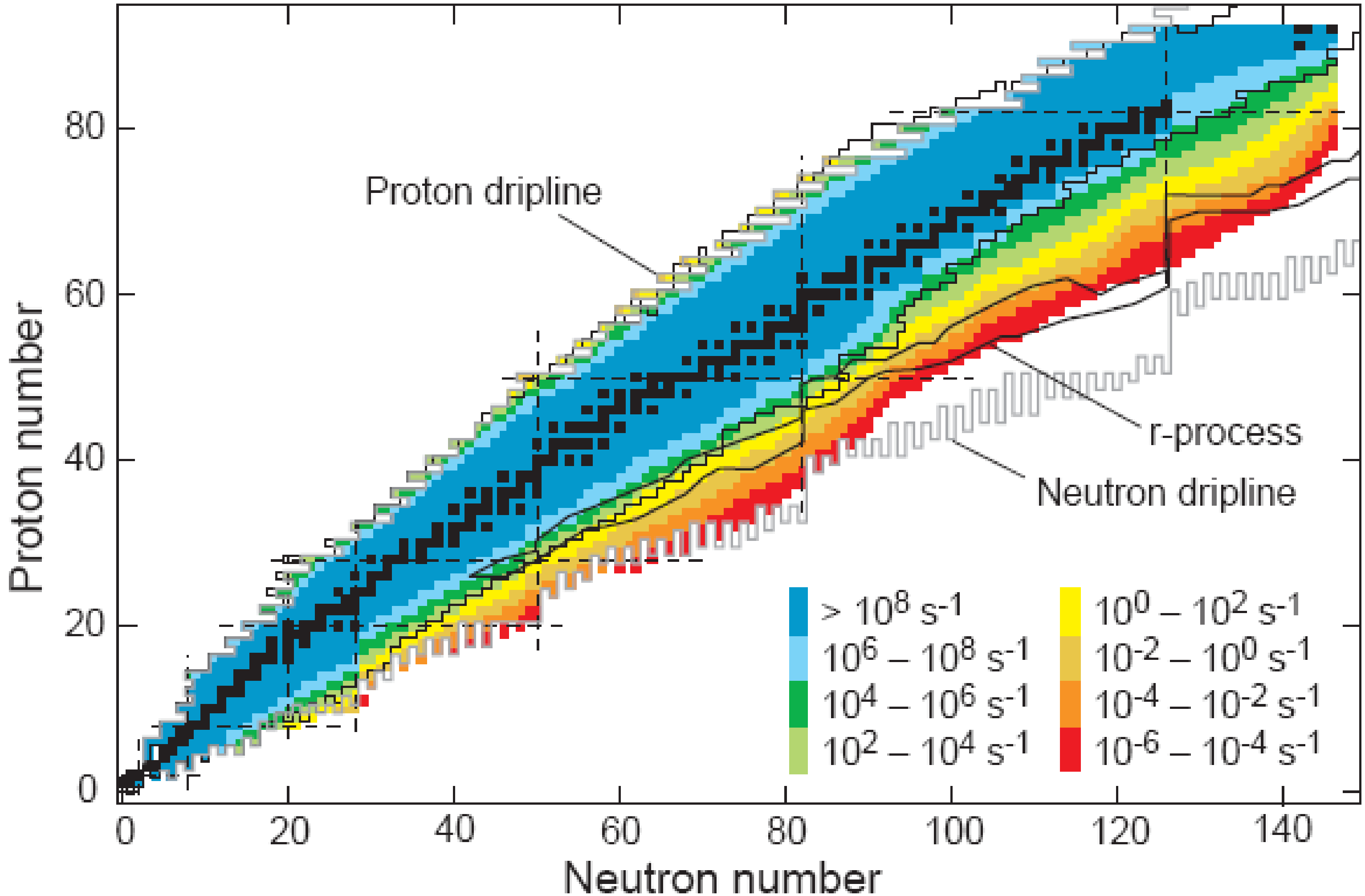
- Synthesis of neutron-rich nuclei heavier than iron: **r-process.** What is the production site ?
- Synthesis of proton-rich nuclei: **rp-process**

Needed: Data

- FRIB: Experimental data (m, $T_{1/2}$), plus improved nuclear theory
- Precision observations of abundance patterns produced by the r-process



FRIB Rare Isotope Beams

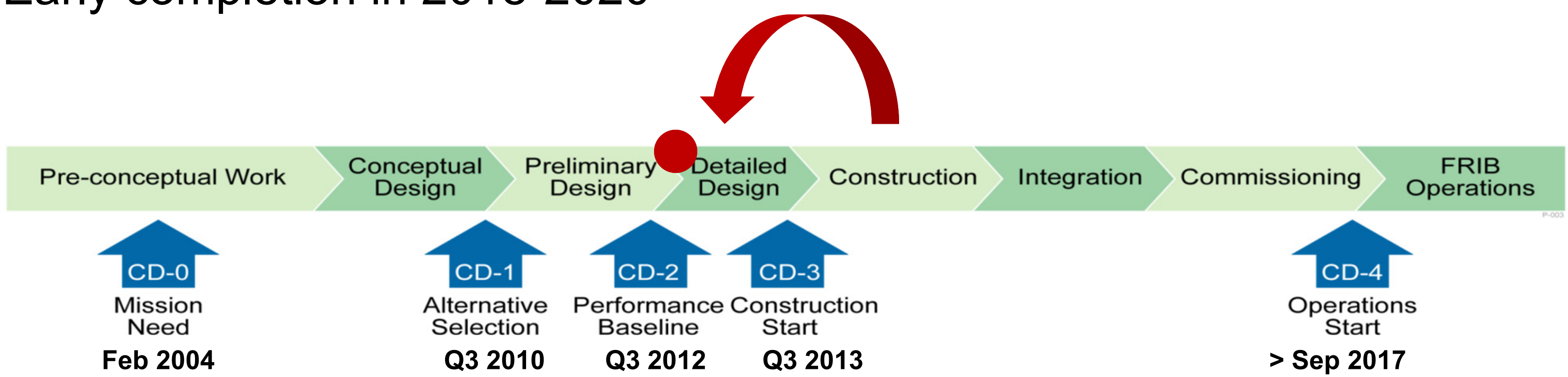


Gain factors of 10-10000 over operational and planned facilities

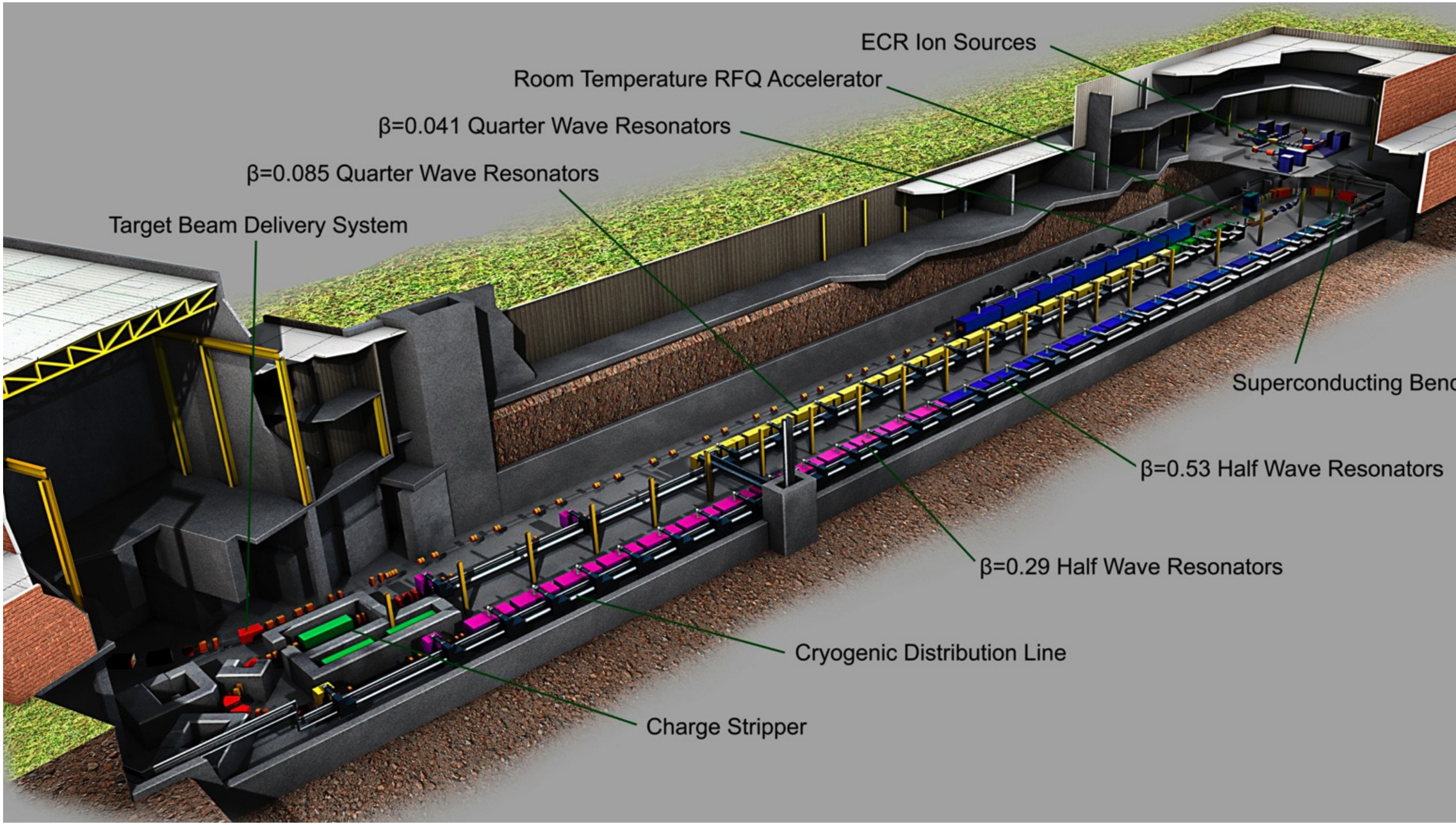
FRIB Project Overview

- Project Requirements :
  - 200 MeV/u, 400 kW SC heavy-ion driver linac
  - include fragmentation of fast heavy-ion beams combined with gas stopping and reacceleration
  - accommodate 100 users at a time, 400-500 per year

- Project setup through cooperative agreement between DOE and MSU
  - design, build, commission for total project cost of 550 M$
  - Contribution of 100M$ from MSU
  - Early completion in 2018-2020

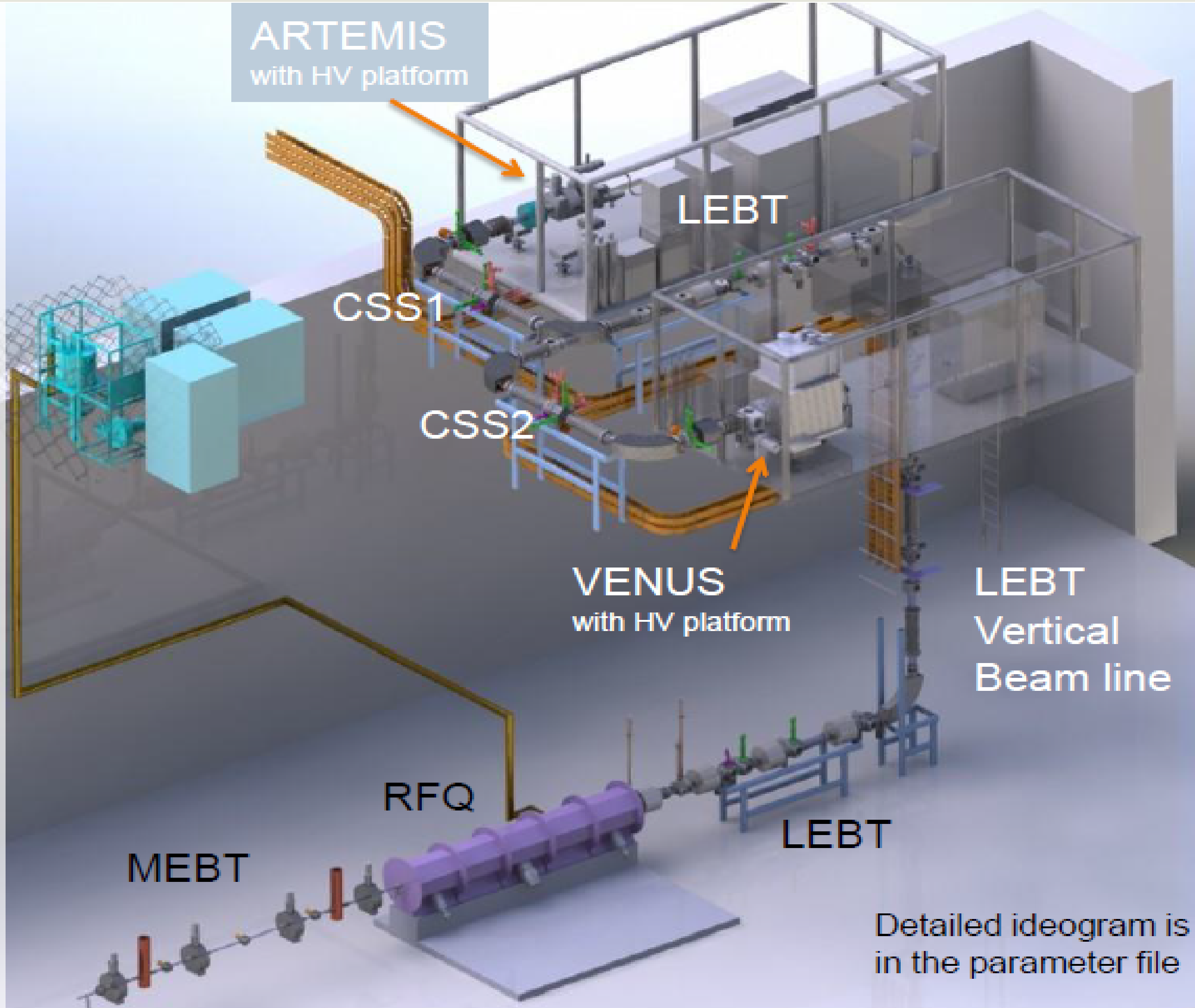


FRIB Driver Accelerator Layout



Front End Systems

- Two ECR sources on HV platforms
  - ARTEMIS - commissioning
  - VENUS – high performance
- Two charge selection systems
- LEBT
  - Chopper
  - Collimation system
  - Vertical transport line
  - Buncher and velocity equalizer
- RFQ
  - E=500 keV/u
- MEBT
  - Two bunchers, solenoids
- Instrumentation



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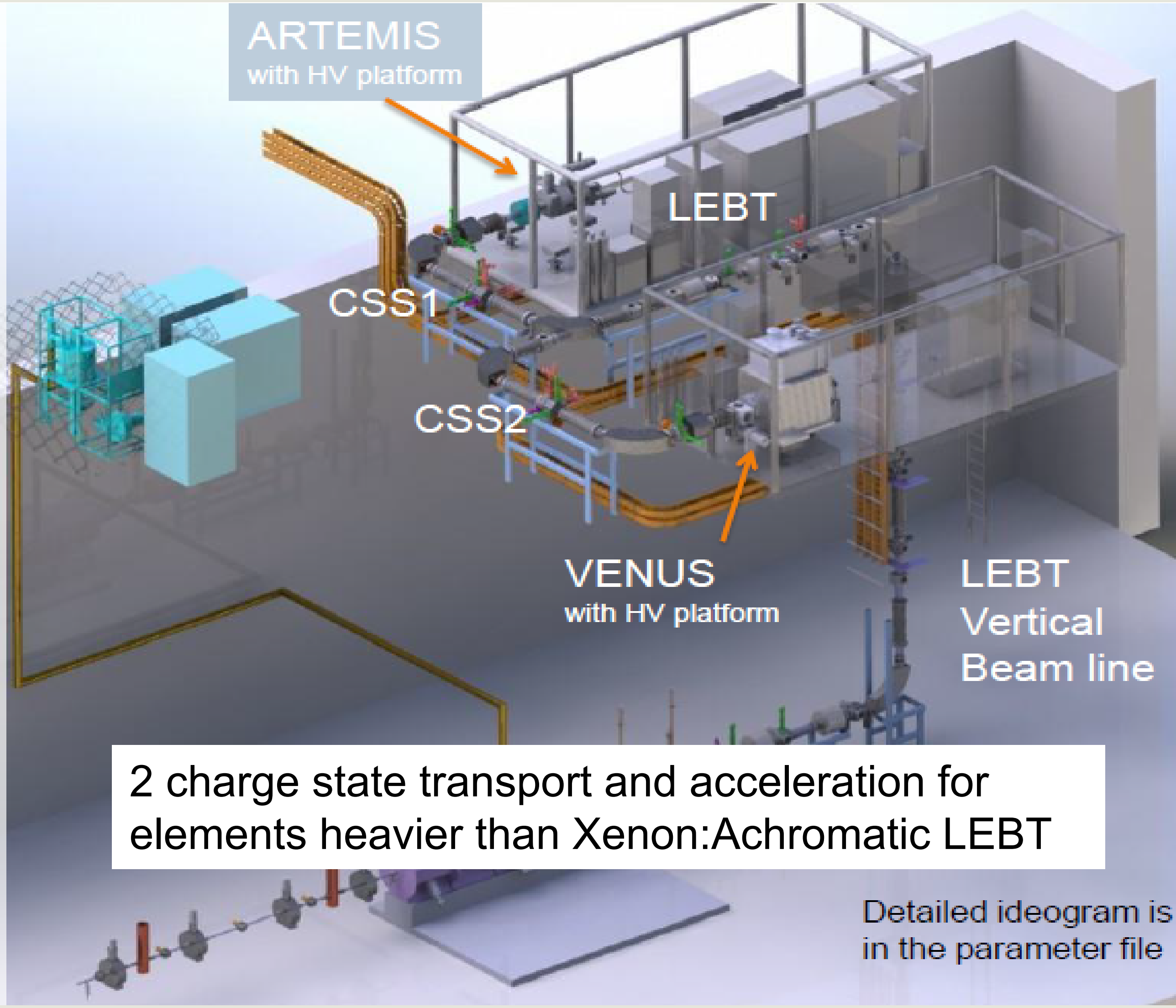
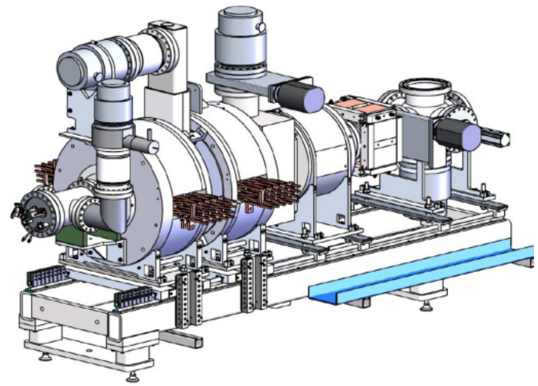
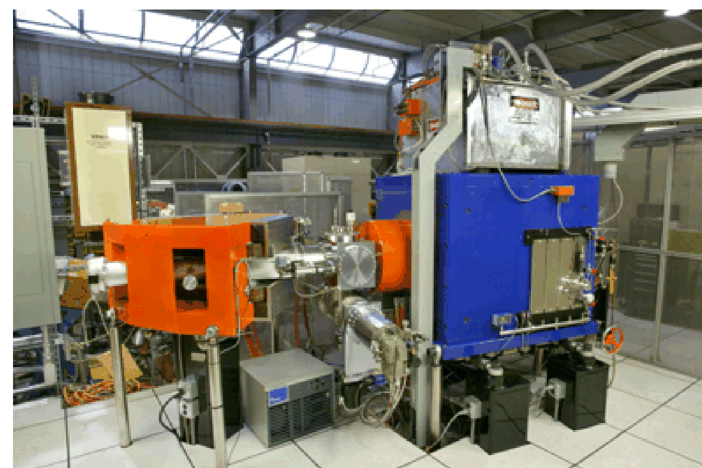


ECR Ion sources for FRIB

- Commissioning ECR ion source based on ARTEMIS-B
  - Operates at 14.5 GHz. AECR based design
  - Source used for R&D (offline)
  - Meets FRIB CD-4 operational requirement for light ions (Argon, Krypton)
  - ARTEMIS-B ion source has been modified from vertical to horizontal
  - Should be operational within a year



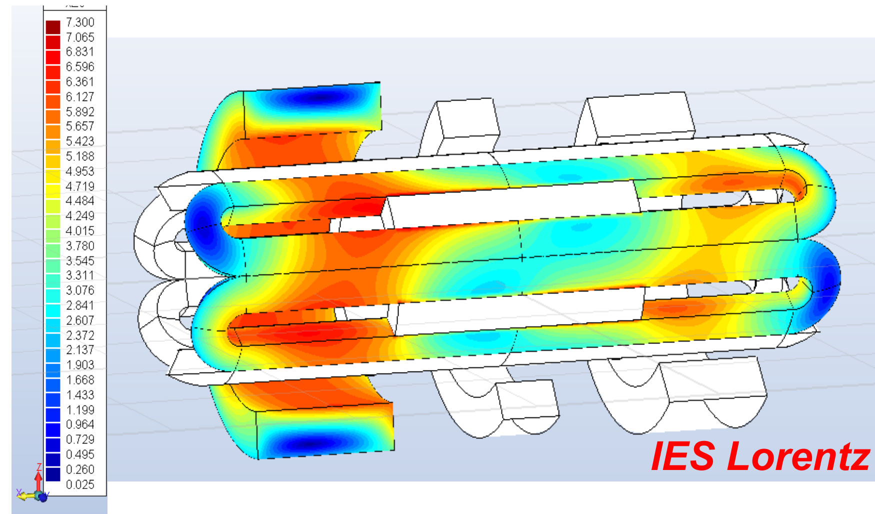
- High performance SC-ECR based on VENUS
  - Demonstrated Uranium intensity requirement.
  - Demonstrated operation at 28 GH
  - Can energize solenoids independently from sextupole coil
  - No retraining needed after warm-up



FRIB SC-ECR Coils Parameters

- FRIB SC-ECR magnet based on VENUS magnet
  - Magnetic Parameters (Calculated)

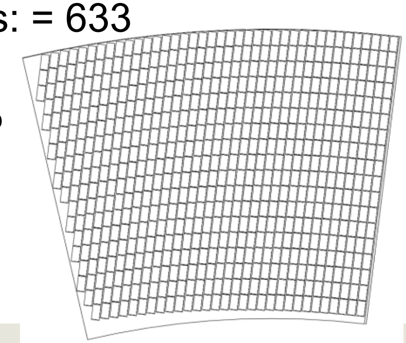
	Hexapole	Injection Solenoid	Middle Solenoid	Extraction Solenoid
Bmax (T)	7.3	6.14	4.22	5.47
I (A)	430	226	-223	223
B(Axis) (T)	2.2 (PC Wall)	3.95	0.36	2.98



- Mechanical Parameters (Based on VENUS)

	Hexapole	Injection Solenoid	Middle Solenoid	Extraction Solenoid
Total Turns	637	6272	2208	4480
ID(mm)	200	340	340	340
OD(mm)	270	458	441	458
NbTi Wire Dimensions (mm)	1.8 x0.9	1.57x 0.88	1.57x 0.88	1.57x 0.88

- Layout of Sextupole cross section
  - Total Number of Turns: = 633 (VENUS: 637)
  - Packing factor: 81.1%



Build another VENUS ? What could go wrong?

- MSU SC-ECR Ion source SuSI was based on the design of VENUS. Magnet was designed to operate at least at 18 GHz but the focus was on 28 Ghz.

- SuSI Field limited by coil performances
  - Hexapole alone can reach current for 28 GHz operation (600A) after training
  - All solenoids can reach current needed for operation at 28 GHz. No training
  - Combined coils limited to 22-24 Ghz operation. Ramping coil together necessary.
- SuSI magnet is slightly different from VENUS
  - NbTi wire properties were changed
  - Banding of Hexapole coils did not extend to the sextupole ends
  - No vacuum impregnation of the space created after the metal bladders were inflated

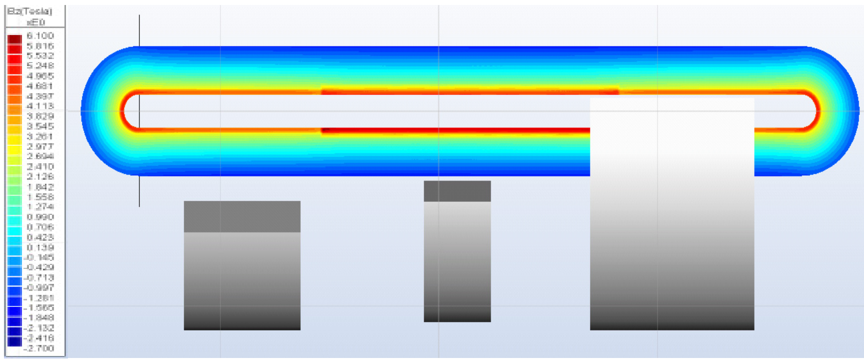
Selection of NbTi Conductor

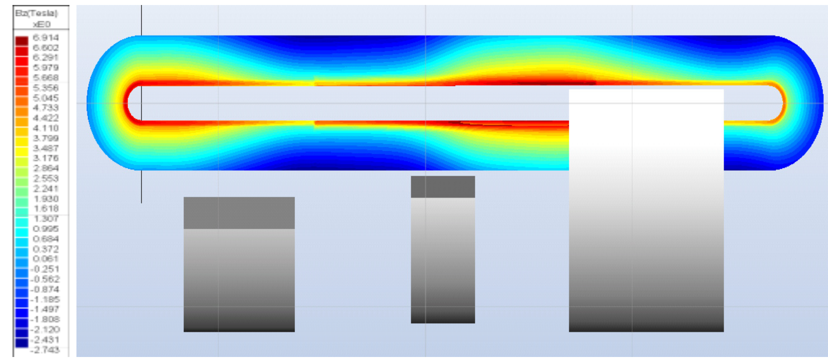
- FRIB SC-ECR tries to follow same NbTi conductor used with VENUS but custom made conductor are difficult to procure. Needed to prioritize conductor properties
  - NbTi Copper to Superconductor ratio considered essential to stabilize the coils during micro movements of the coils
    - Keep a reasonable current density at 75% of critical current at 7T
  - High RRR copper improve thermal properties
  - Small NbTi filaments improve stability

FRIB SC-ECR NbTi Coonductor	**Solenoid**	**Sextupole (Original VENUS)**
Ic (A)	600 @ 5T	680@ 7T
Cu:Sc Ratio	4:1	3:1
RRR	100 or higher	140 or higher/ 200
NbTi filaments size	<100 um	<50um/ <30um

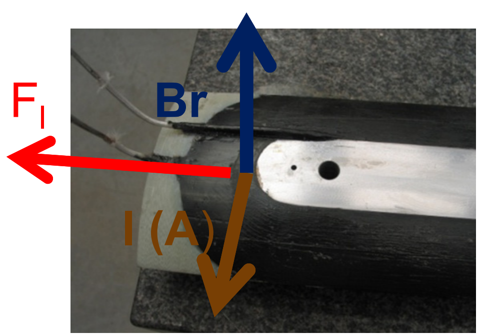
Clamping of the sextupole coils [1]

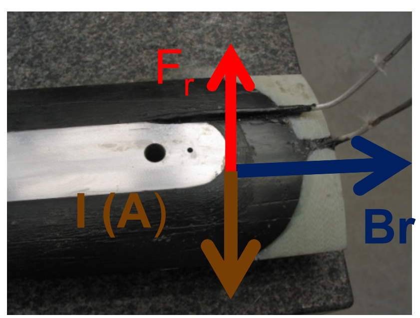
- Modifications of the field (radial) in sextupole when running solenoids





- Strong Azimuthal force in the straight section of sextupole
- Ends section experience both, longitudinal force cause by radial field and radial force cause by the longitudinal component of B field





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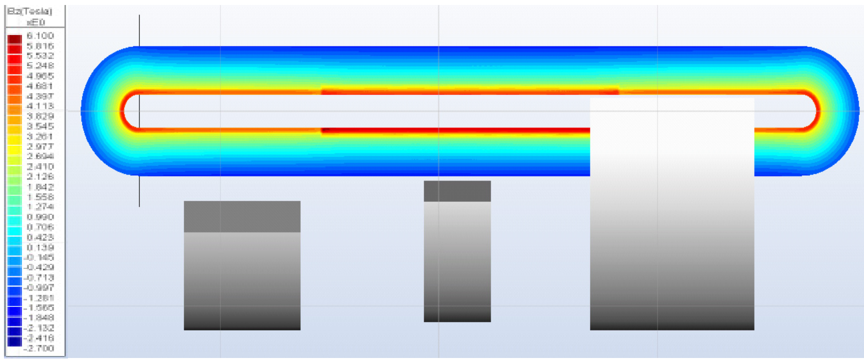
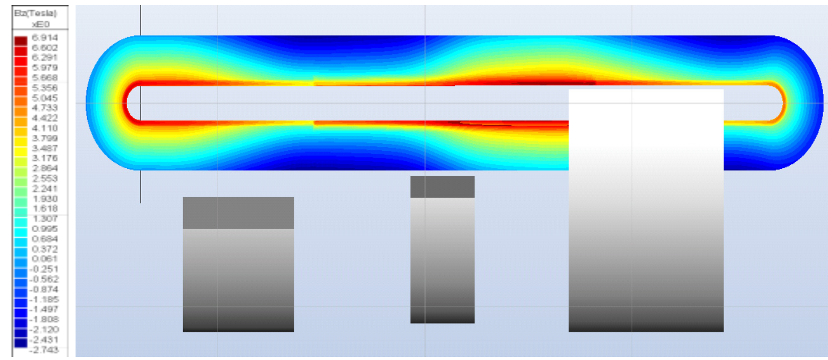
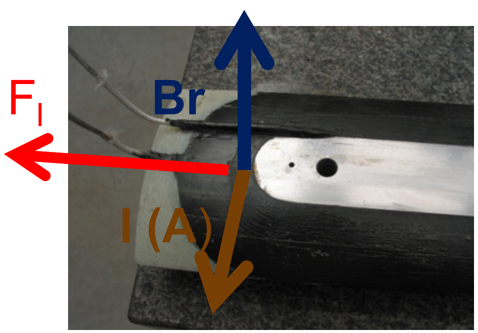
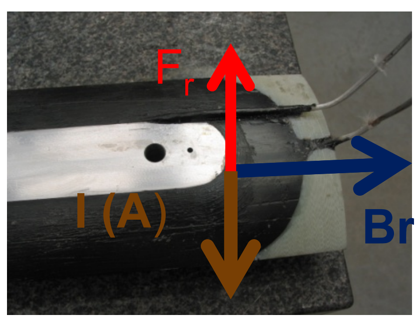
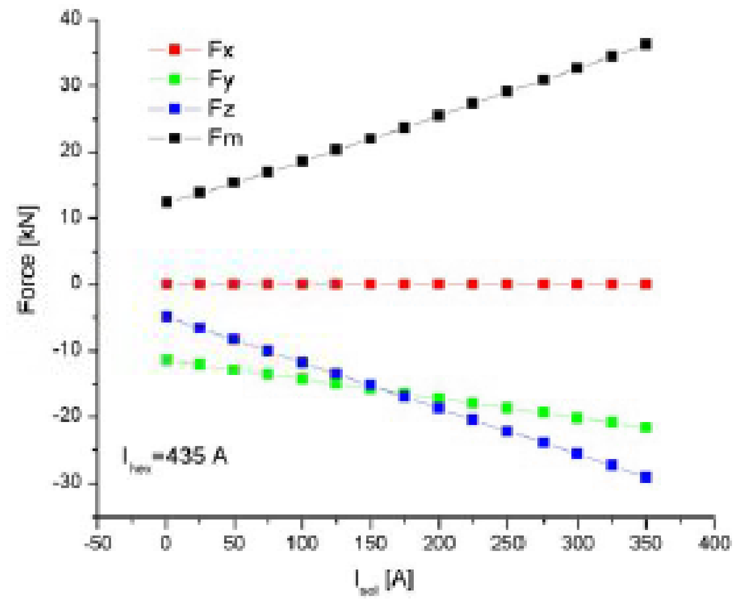




- Strong Azimuthal force in the straigh
- Ends section experience both, longitu
  and radial force cause by the longituc

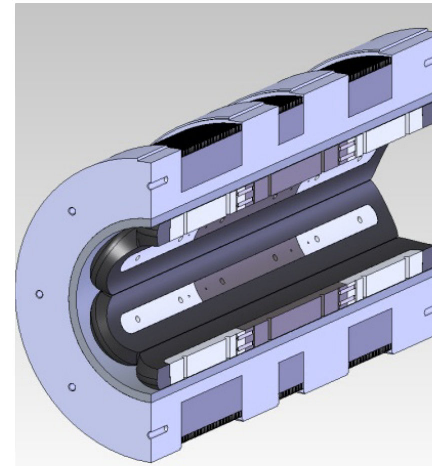




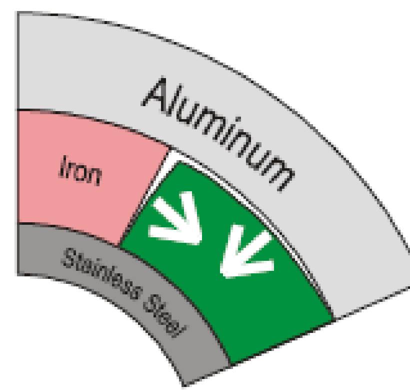


Clamping of sextupole coils [2]

- To Restrict motion of sextupole in radial direction:
  - Use Aluminum material for bobbin surrounding sextupole coil
  - Measure thermal contraction of NbTi+ epoxy assembly
  - Evaluate force require to know stiffness of coil (measured by LBNL Supercon group)

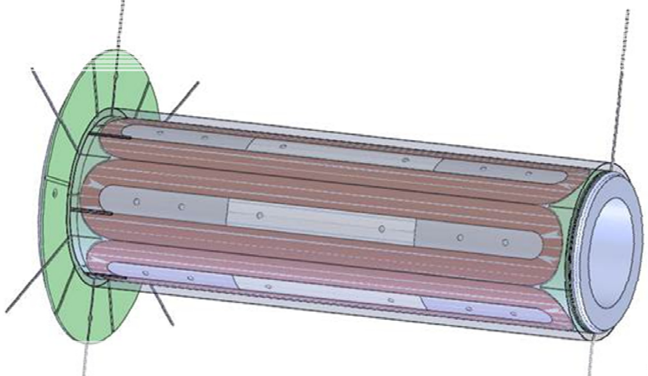


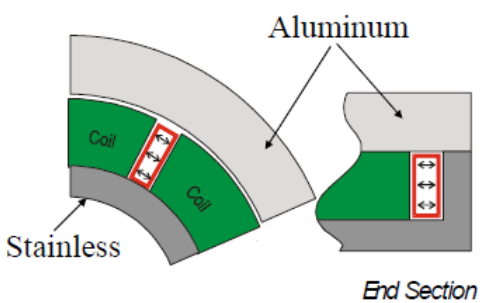
- To restrict motion of sextupole in azimuthal direction
  - Insertion and inflation of “bladders” between each sextupole coil to apply hoop stress
- To restrict motion of sextupole in Longitudinal direction
  - Insertion and inflation of end bladders



Bladders Technique

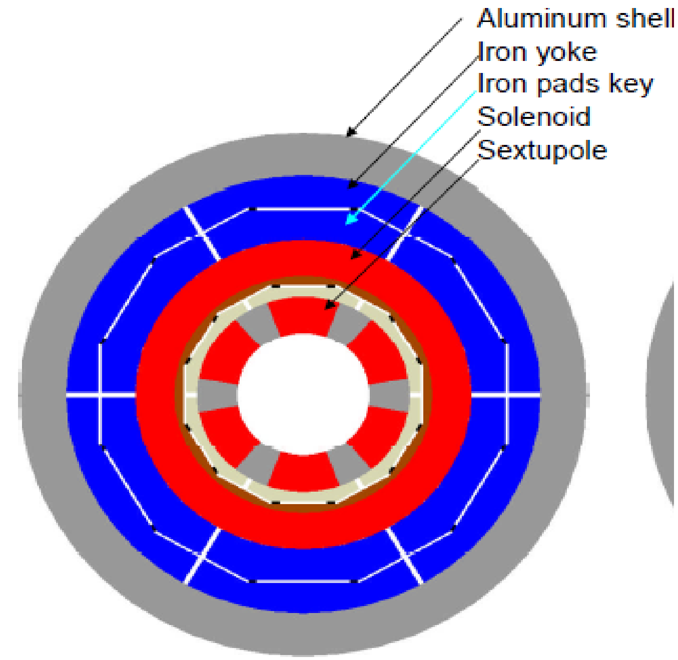
- Metal filled bladders (Indalloy 117) used with Original VENUS





- Option selected for FRIB

- Water filled + keys +pads Included in Nb3Sn magnet, GenIV



- Would require substantial Engineering work

Status of FRIB SC-ECR Cold mass design

- Detailed Drawings of cold mass complete (based on VENUS parameters)
  - New banding structure around the sextupole
  - Sextupole Aluminum and Iron insert sized based on thermal contraction
  - NbTi Leads transition to cryostat

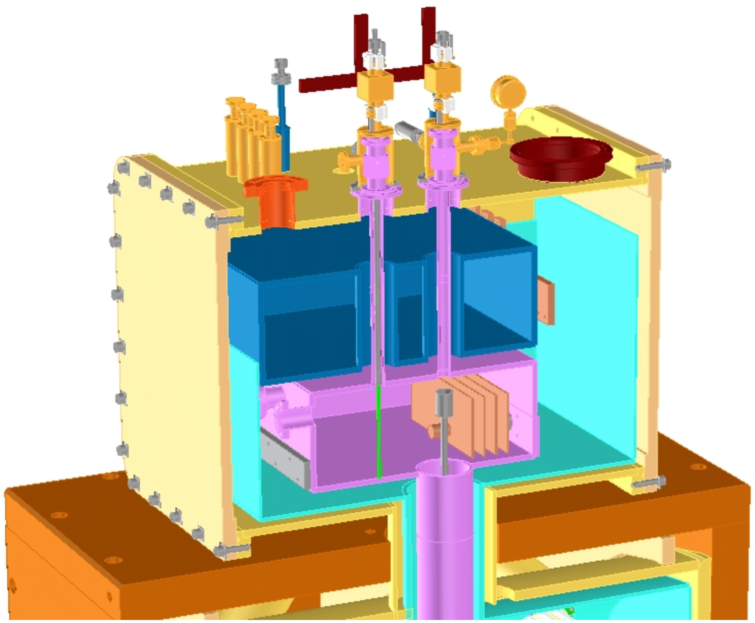
- Next is to Complete analysis of stress on coils

1. Stress Analysis after Inflation of the bladders → 2. Stress Analysis after cool down → 3. Evolution of forces after energizing the coils

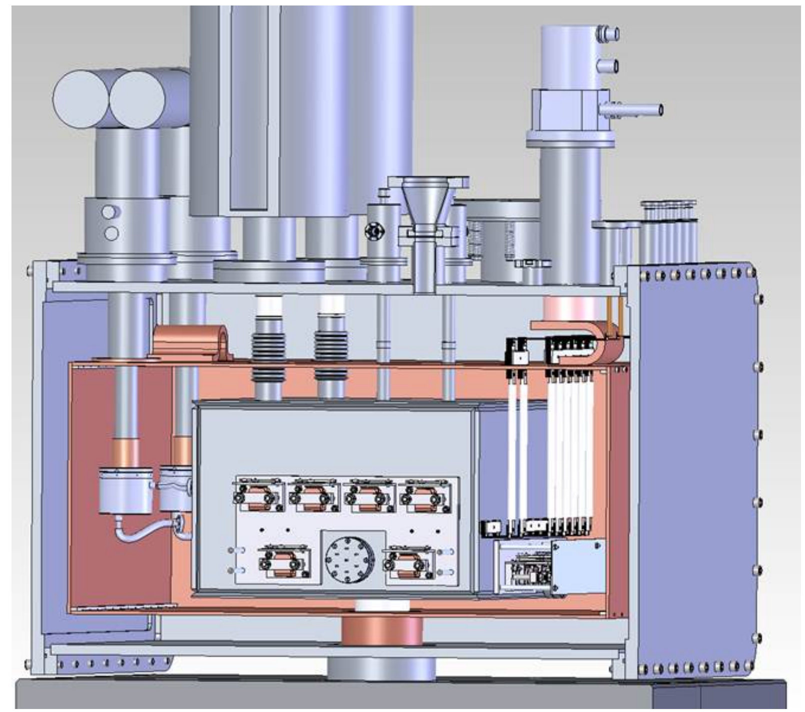
- Plan for fabrication and assembly
  - Coil winding through outside vendor
  - Assembly including bladders inflation and insertion into solenoid bobbin to be done at MSU

Preliminary design of FRIB SC-ECR Cryostat

- Modifications have been made to original VENUS cryostat to
  - Operation compatible on high voltage platform
  - Increase the dynamic Heat Load (10W)



Original VENUS Cryostat



FRIB SC-ECR Cryostat

Modifications to VENUS Cryostat

- Modifications to original VENUS cryostat includes:
  - Addition of 3rd port on vacuum vessel for better accessibility
  - Removal of nitrogen reservoir
  - Modification of 50 k shield for insertion of GM-JT cryocooler .
  - Insertion of Al330 single stage cryocooler to cool the shield
  - Optimization of thermal intercepts position on the warm and cold shield to minimize the heat leak through current leads
  - Replaced GM type cryocooler with pulse tube cryocoolers
  - Modifications of Helium reservoir to connect GM-JT cryocoolers insert tube and bellows
  - Shortened the cold leads
  - Heat load calculated for the shield and cold mass
  - MLI included in the design

- Design of FRIB SC-ECR cryostat well advanced

Uranium Beam development for FRIB

- Intensity Requirement from the ion source

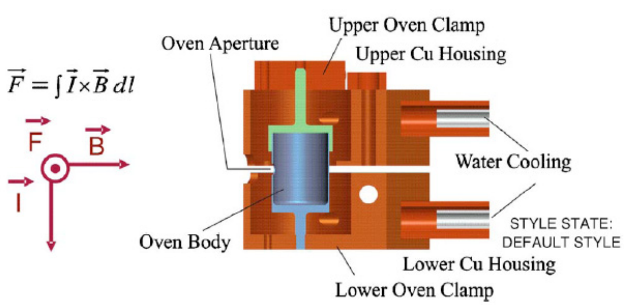
$$P = IV, \quad \overline{E} = \frac{QeV}{A} \Rightarrow I = \frac{PQe}{\overline{E}A} \qquad I_p = \frac{I}{Q} = 8.4\,p\mu\text{A}$$

	Target	Linac Seg.3	Linac Seg.2	Stripper	Linac Seg.1	Front End	ECR
	400 kW 200MeV/u			Q= U76+ to U80+			Q= U33+ to U34+
I (pμA)	8.4	8.4	8.4	8.4	10.5	10.5	**13.1**
Losses (%)	0	0	0	**30**	0	**20**	**0**
$\overline{Q} =$	78	78	78	78	33	33	33

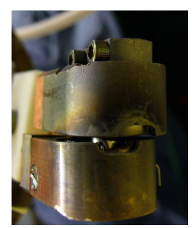
~432eμA

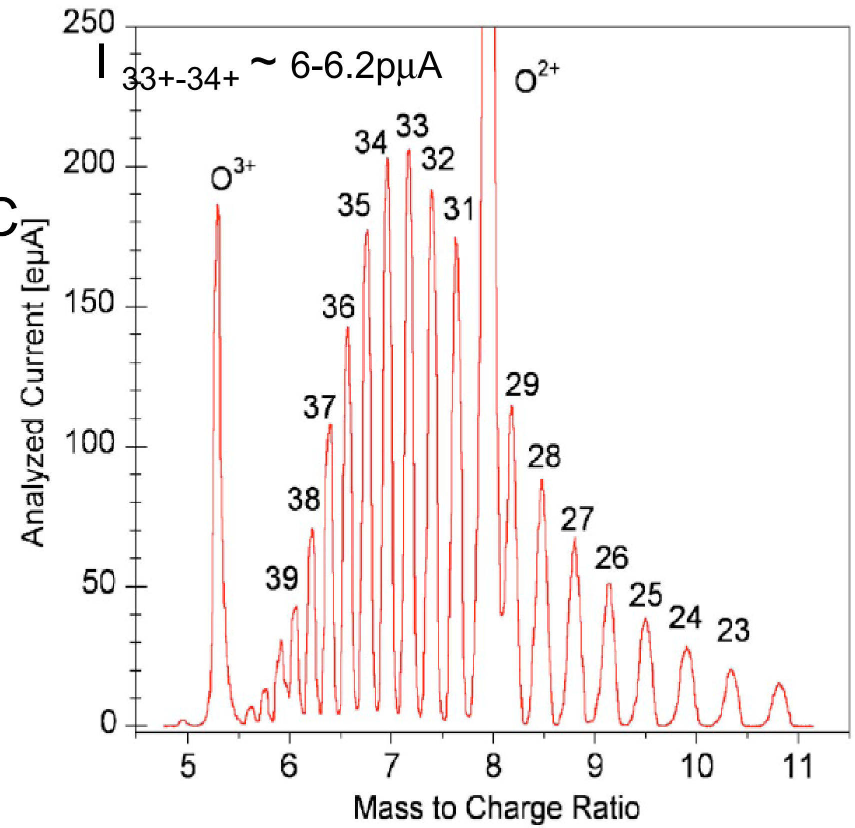
Uranium development with VENUS in 2007

- Previous Uranium development with VENUS for U33+ and U34+ in 2007
  - •URe2 Compound (Temperature between 1800C to 2000C)
  - •Tantalum crucible
- Intensity limited by:
  - •Phase transition of URe_2 above 2000C
  - •Damage to oven under Lorentz forces



D.Leitner et *al* Rev. Sci. Instrum. 79, 02C710 (2008)





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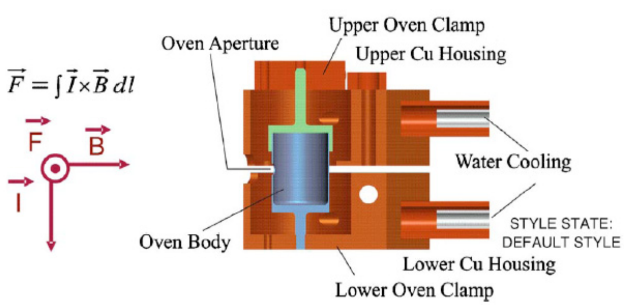

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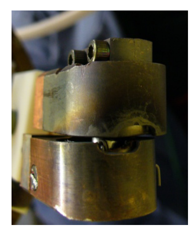
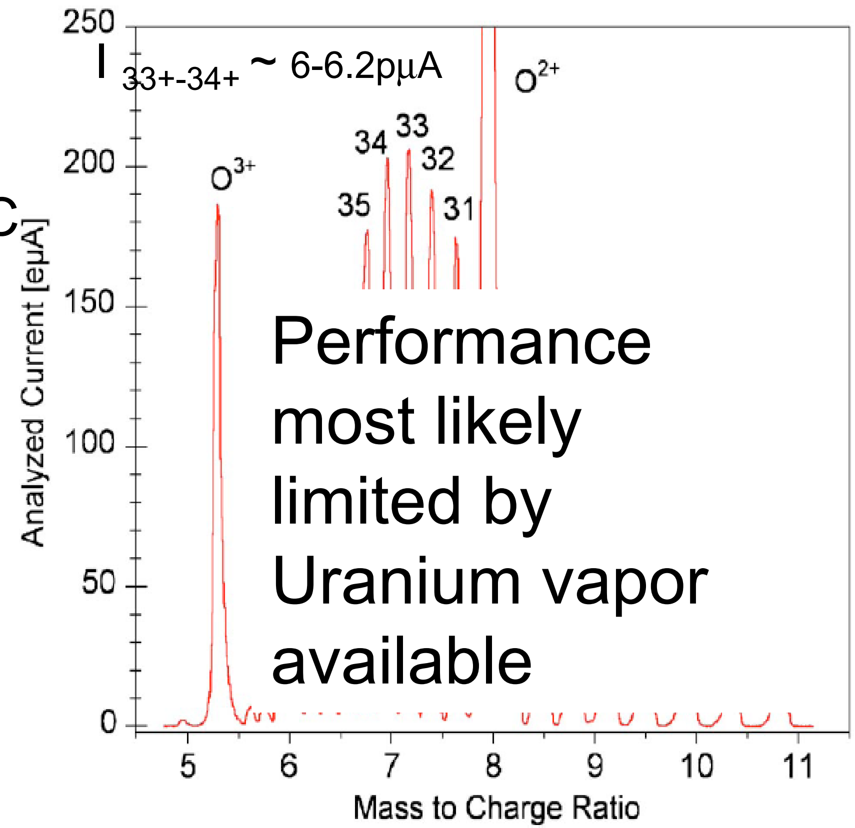
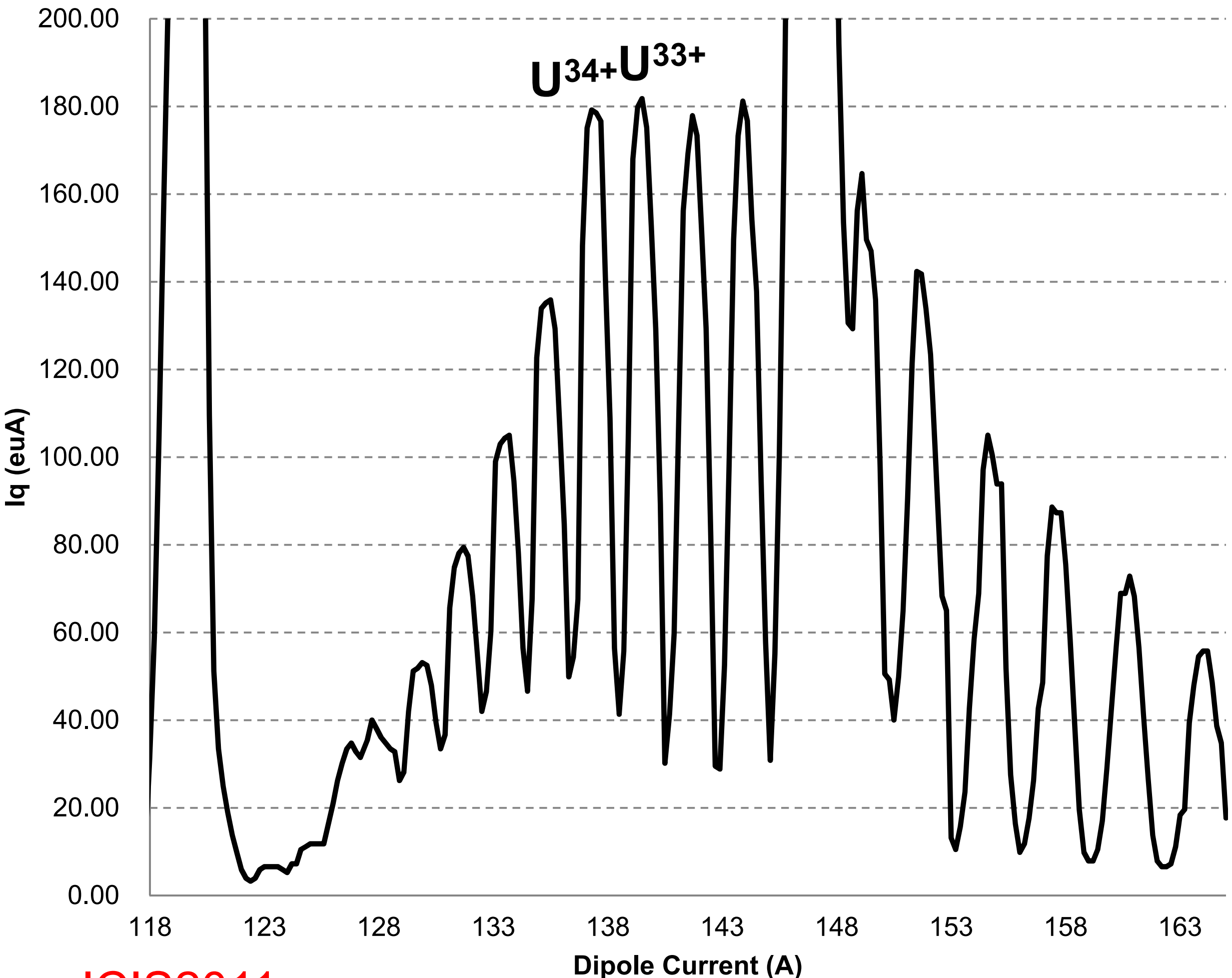




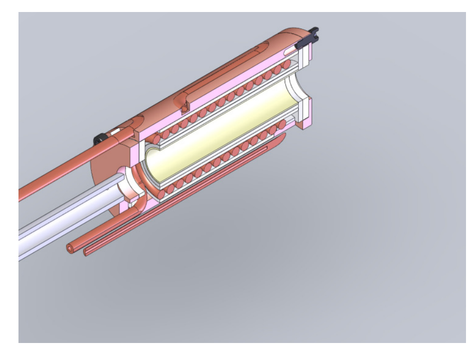
Uranium Development at MSU with SuSI



ICIS2011

Source Conditions:
- SuSI field: 20 GHz high-B
- power: 3.4 kW @18GHz
- Source potential: 25 kV
- Support gas: $^{16}O_2$

RF Oven Conditions:
- Oven: 860W
- Loaded Material: 1700 mg UO_2



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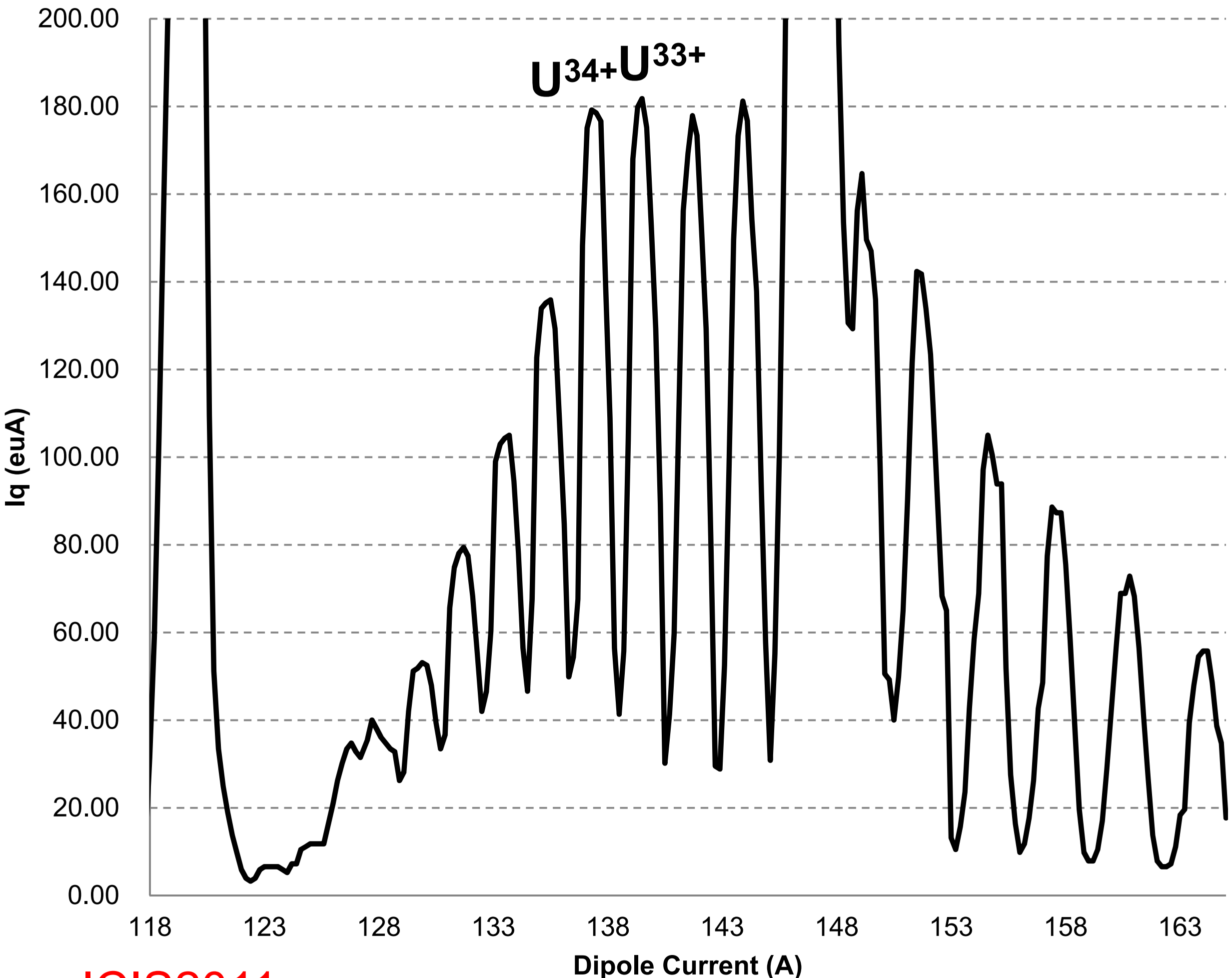

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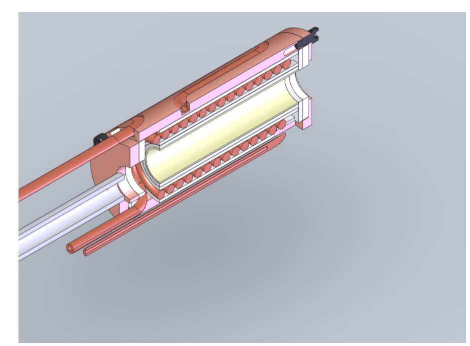

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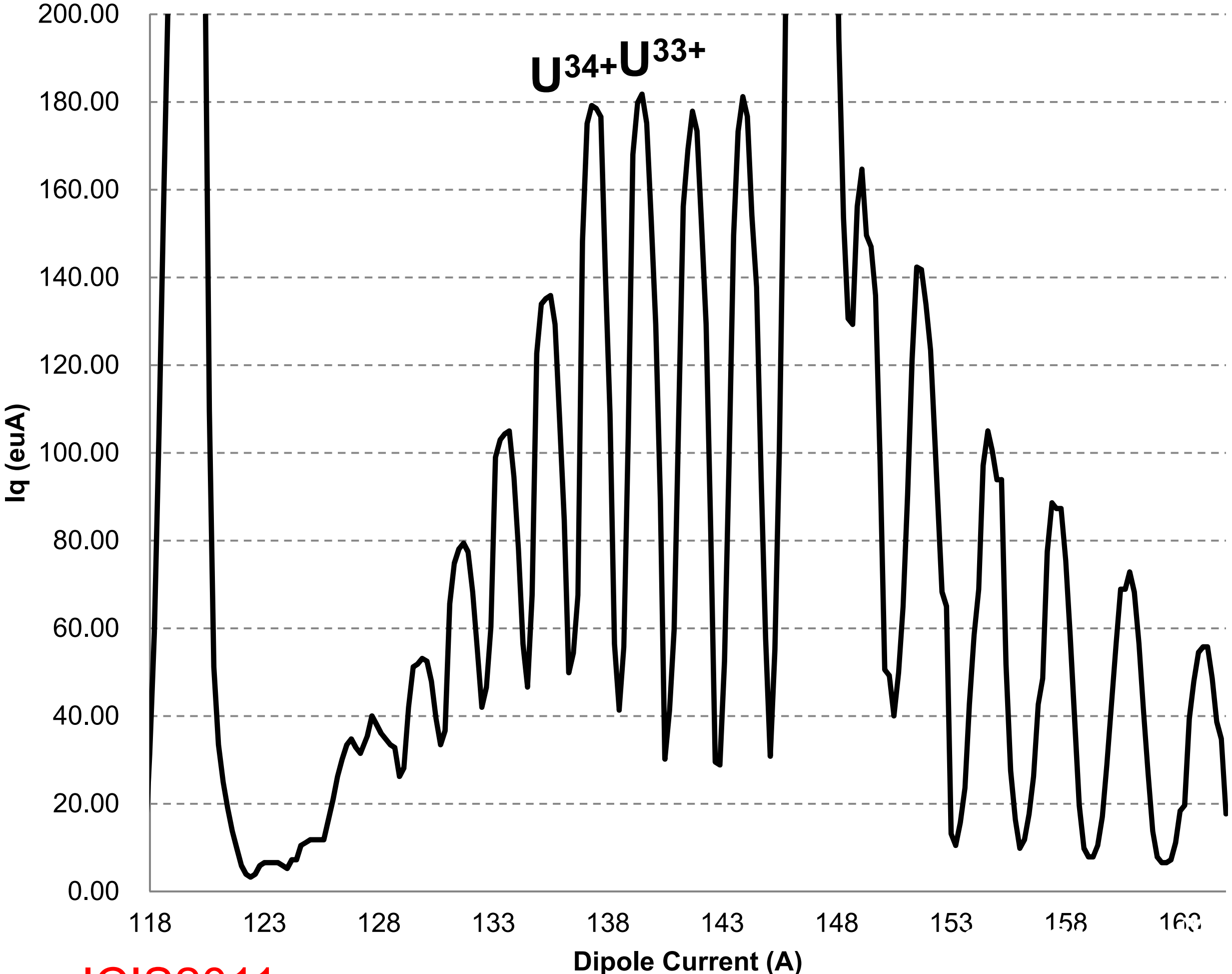

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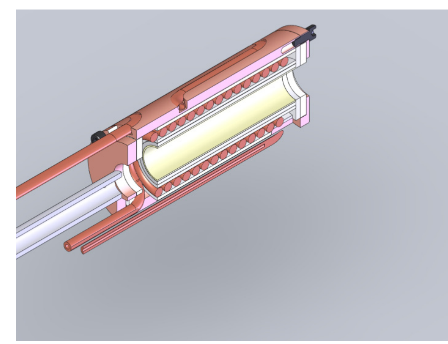

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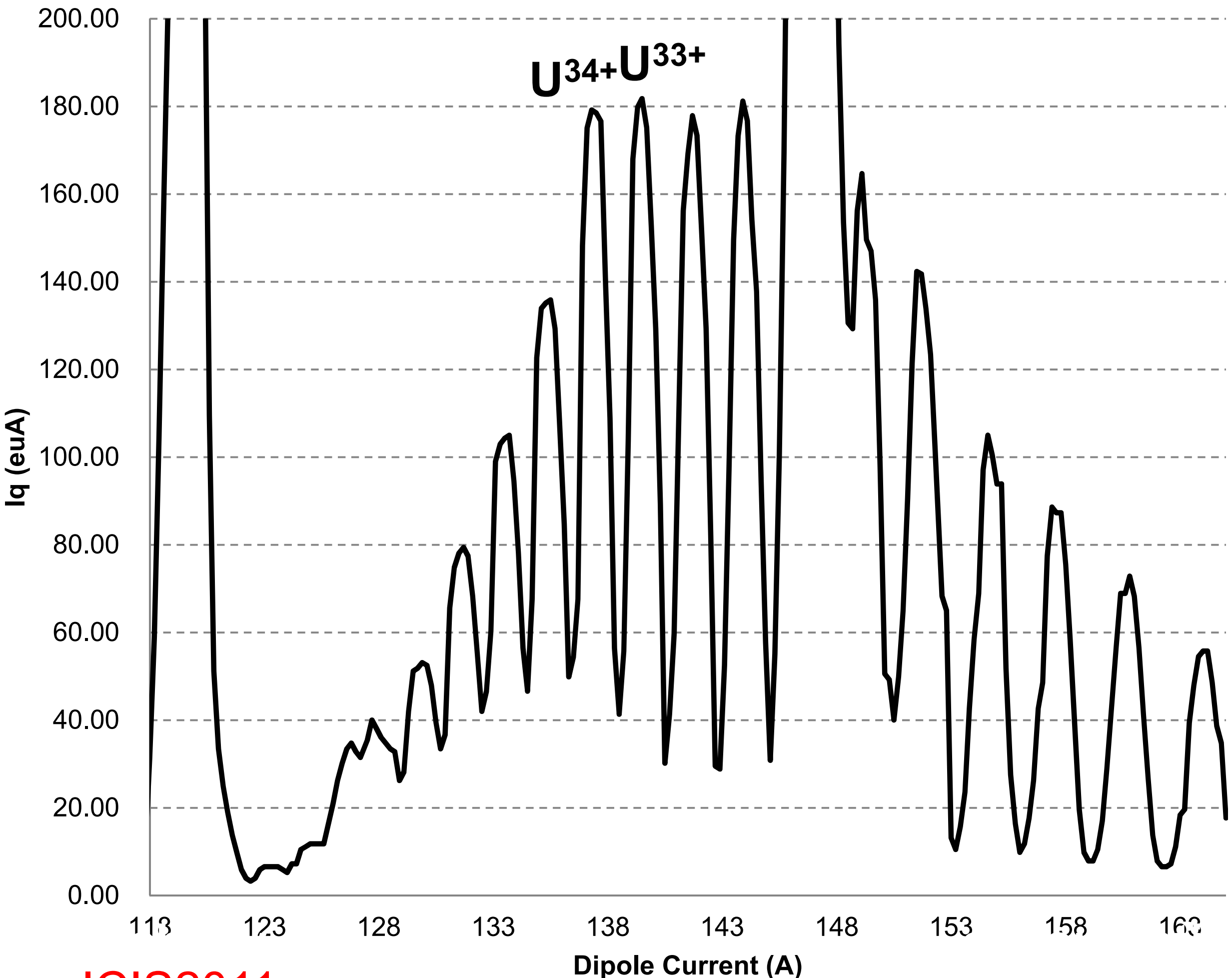

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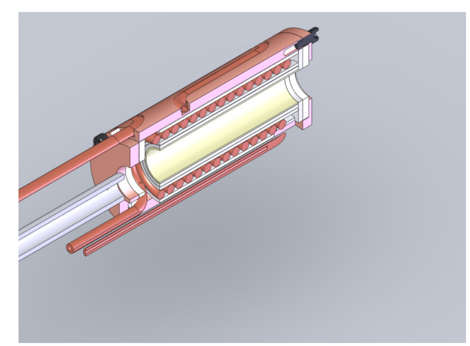
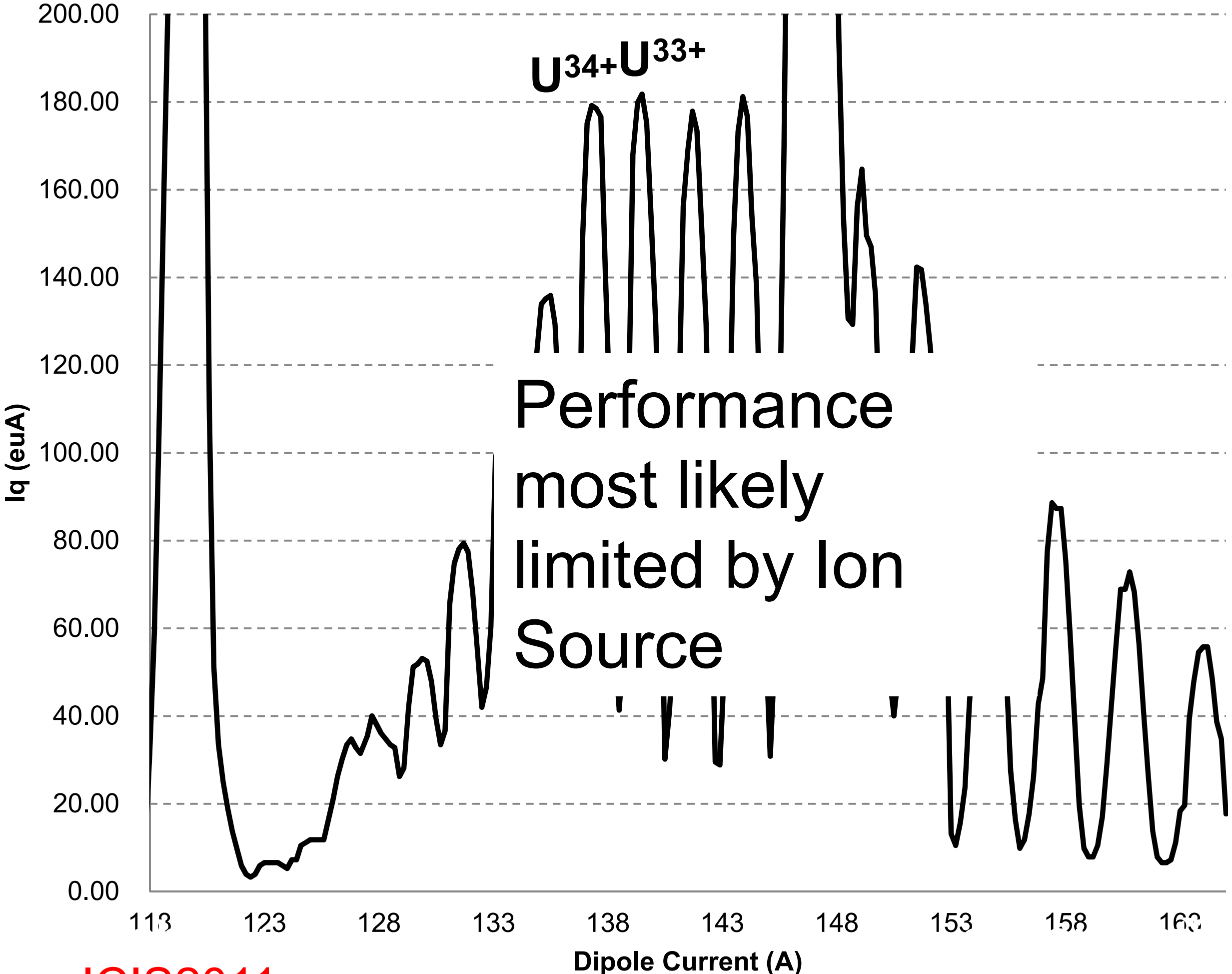


Uranium Development at MSU with SuSI



Performance most likely limited by Ion Source

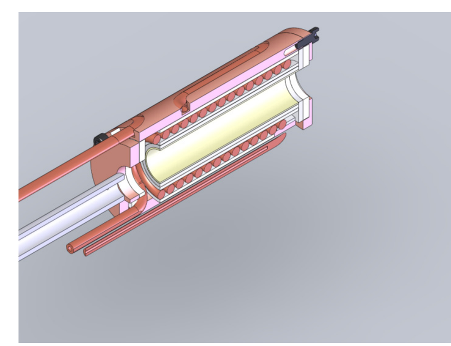
ICIS2011

Source Conditions:

- SuSI field: 20 GHz high-B
- power: 3.4 kW @18GHz
- Source potential: 25 kV
- Support gas: $^{16}O_2$

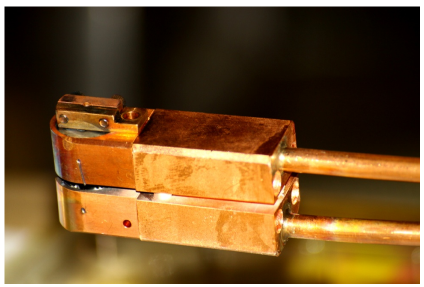
RF Oven Conditions:

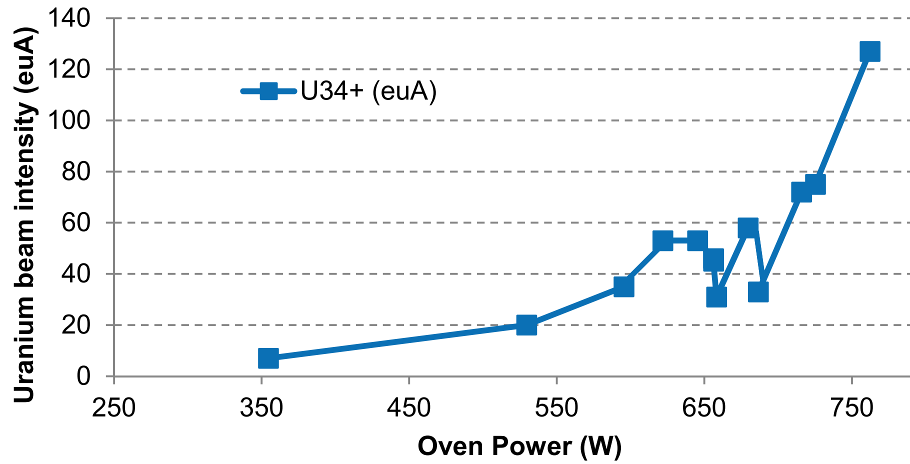
- Oven: 860W
- Loaded Material: 1700 mg UO_2



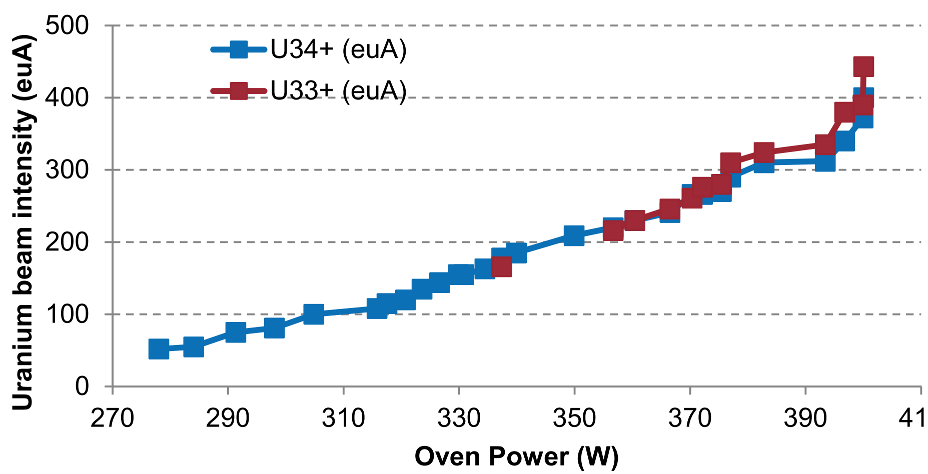
U production with Rhenium and Tungsten oven

- Results of U beam development with W crucible limited
  - Very unstable beam
  - Large power coupled to the oven
  - Melted copper support



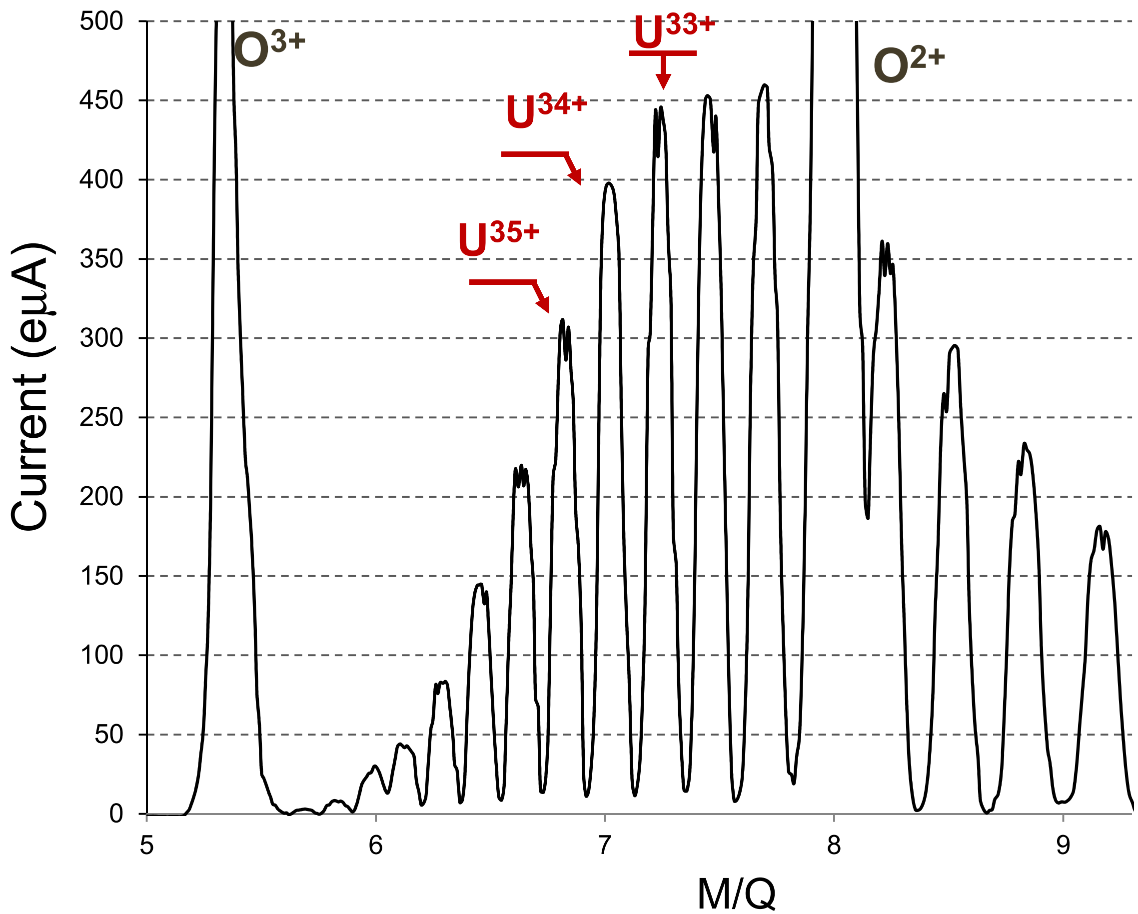


- Development with Rhenium
  - Higher resistivity material (less power)
  - Beam very stable



Uranium beam development with VENUS

- ^{238}U Intensity



- FRIB Requirement

Q ECR	I ECR (eμA)	I ECR (pμA)
33	432	13.1
34	445	13.1

- Beam Measurements with VENUS

Q ECR	I ECR (eμA)	I ECR (pμA)
33	443	13.42
34	400	11.76

Comments on Uranium development with VENUS

- Up to 8.3 kW Coupled to the VENUS ECR ion source
  - 18 GHz from Klystron: 1.8kW (Maximum available) 180eμA - 200eμA
  - 28 GHz from gyrotron: 6.5 kW injected out of 10kW

- Beam extraction and transport can be improved by increasing Ion Source Voltage
  - The ion source voltage used was limited to 22kV due to HV discharges in the extraction region.
  - Total extracted current exceeded 9ema for a beam transmission to the Faraday Cup of only 55%.

- High Intensity was maintained for about 10 hours
  - Consumption rate about 9mg/h

- Even at the maximum obtained ECR ion source still very responsive to power and oven
  - Magnetic field was not optimized. This could be further explored

Beam Emittance of U33+ and U34+ measured with VENUS

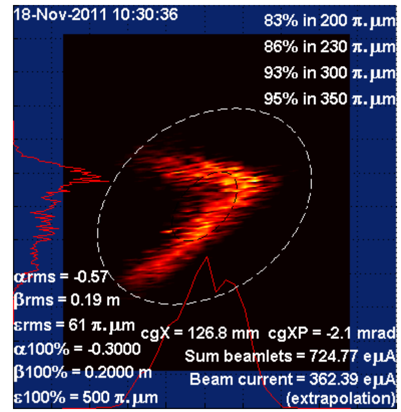
- Emittances
  - 28 GHz (6 kW) + 18 GHz (1.8kW)
  - Current extracted: 7.5mA

- I_{U33+}=365eμA

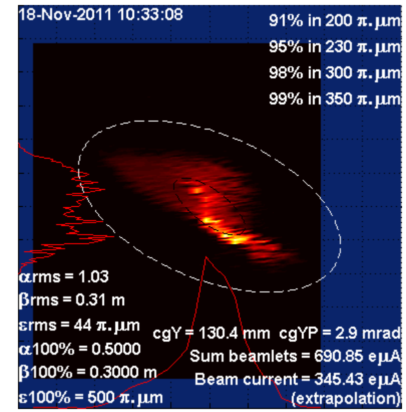
	εn (1RMS)	εn (6RMS)	% in 0.6 pi.mm.mrad	% in 0.9 pi.mm.mrad
Horizontal	0.156	0.94	86	95
Vertical	0.112	0.67	95	99

- I_{U34+}=311eμA

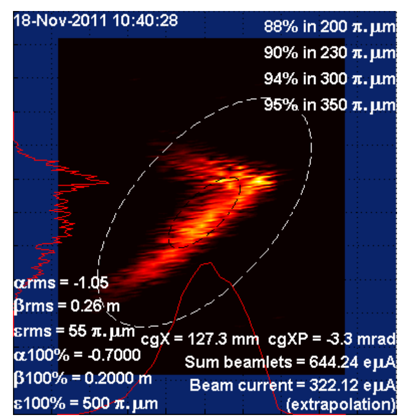
	εn (1RMS)	εn (6RMS)	% in 0.6 pi.mm.mrad	% in 0.9 pi.mm.mrad
Horizontal	0.141	0.843	90	95
Vertical	0.112	0.67	95	99



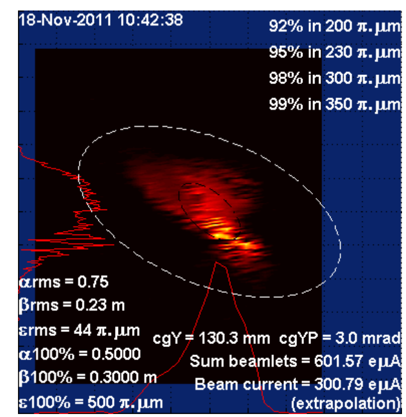
Horizontal



Vertical

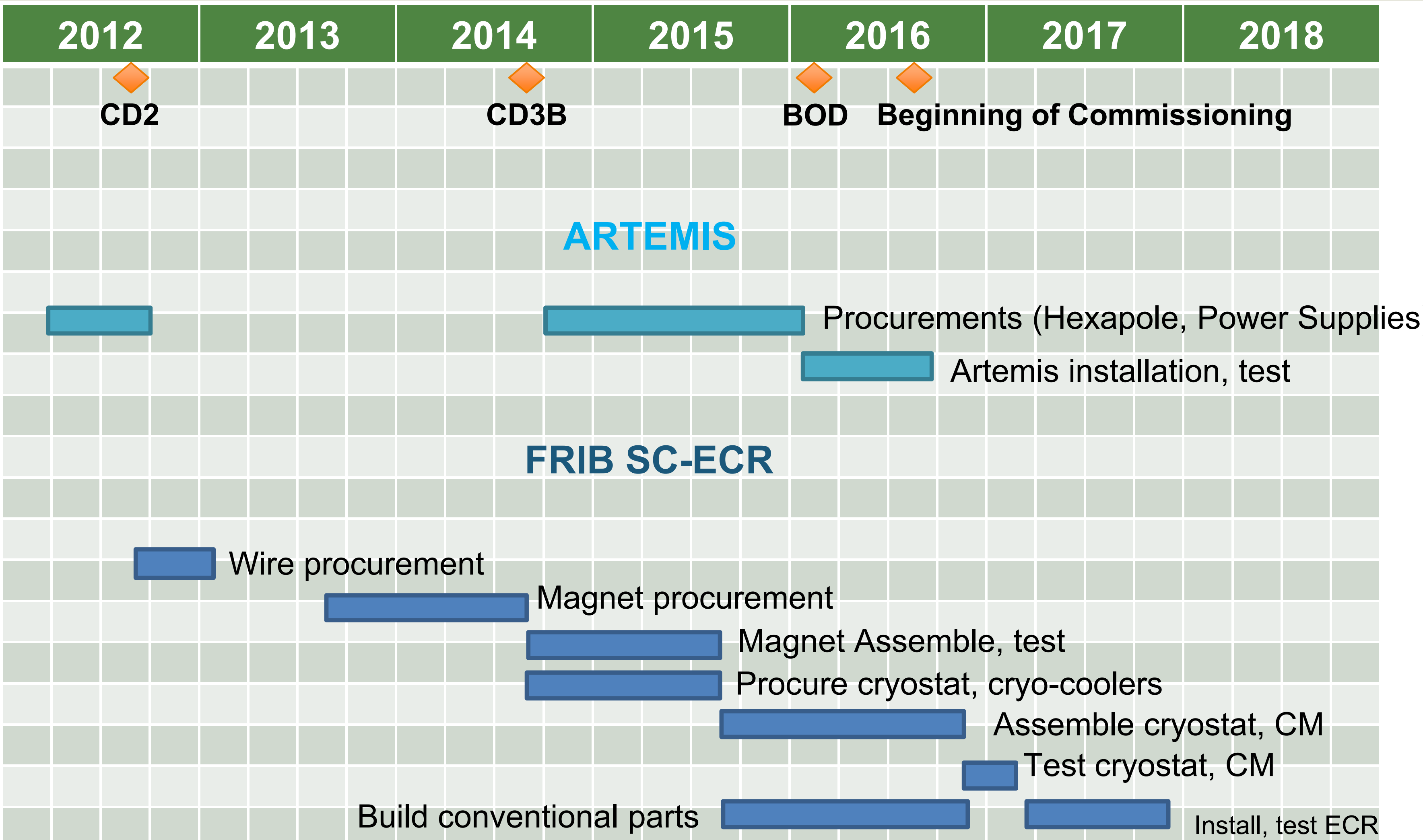


Horizontal



Vertical

Ion Source Schedule



Summary

- FRIB project through preliminary design
- Ready for construction of Linac tunnel
- Early completion of facility in 2018
- 2 ECR ion source for FRIB
  - ARTEMIS-B ion source is modified in FY12 to meet FRIB beam commissioning requirements
  - FRIB SC-ECR based on VENUS
- FRIB SC-ECR preliminary design well advanced
  - Procurement of NbTi conductor 2012
  - Analysis of forces on cold mass underway
  - Preliminary modifications to cryostat completed
  - Magnet procurement 2013
  - Cold mass test 2014
  - First Beam 2017