



High-Energy Single-Event Effects Testing at Michigan State University

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NEPP 2021 High-Energy SEE Testing Users Meeting

April 13, 2021

MICHIGAN STATE
UNIVERSITY

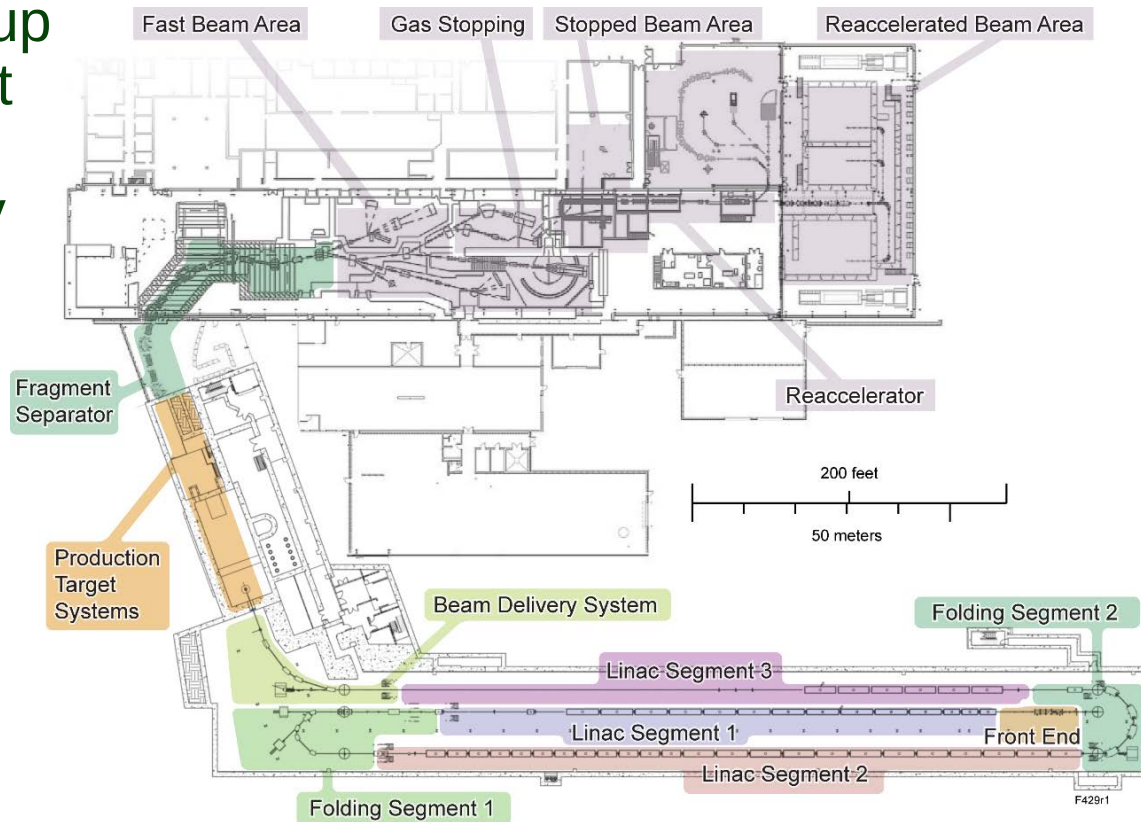


U.S. DEPARTMENT OF
ENERGY

Office of
Science

Facility for Rare Isotope Beams (FRIB) at Michigan State University

- FRIB is a U.S. Department of Energy Office of Science (DOE-SC) User Facility supporting the mission of the Office of Nuclear Physics.
- The FRIB accelerator is a 400 kW superconducting linear accelerator which can accelerate ions up to uranium to energies of at least 200 MeV/u. The accelerator is currently in a commissioning phase.
- The coupled cyclotrons, which provided beams for SEE testing in past, have been turned off. Both cyclotrons could remain in place.

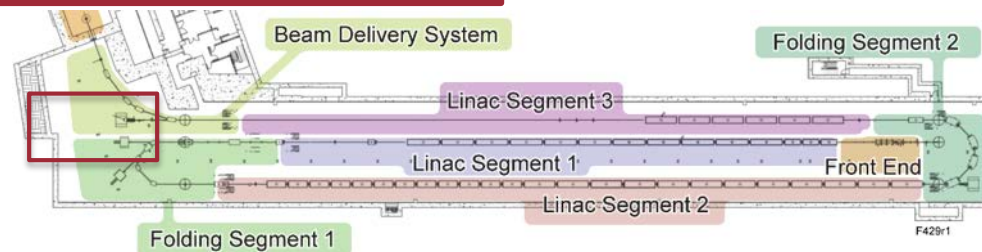
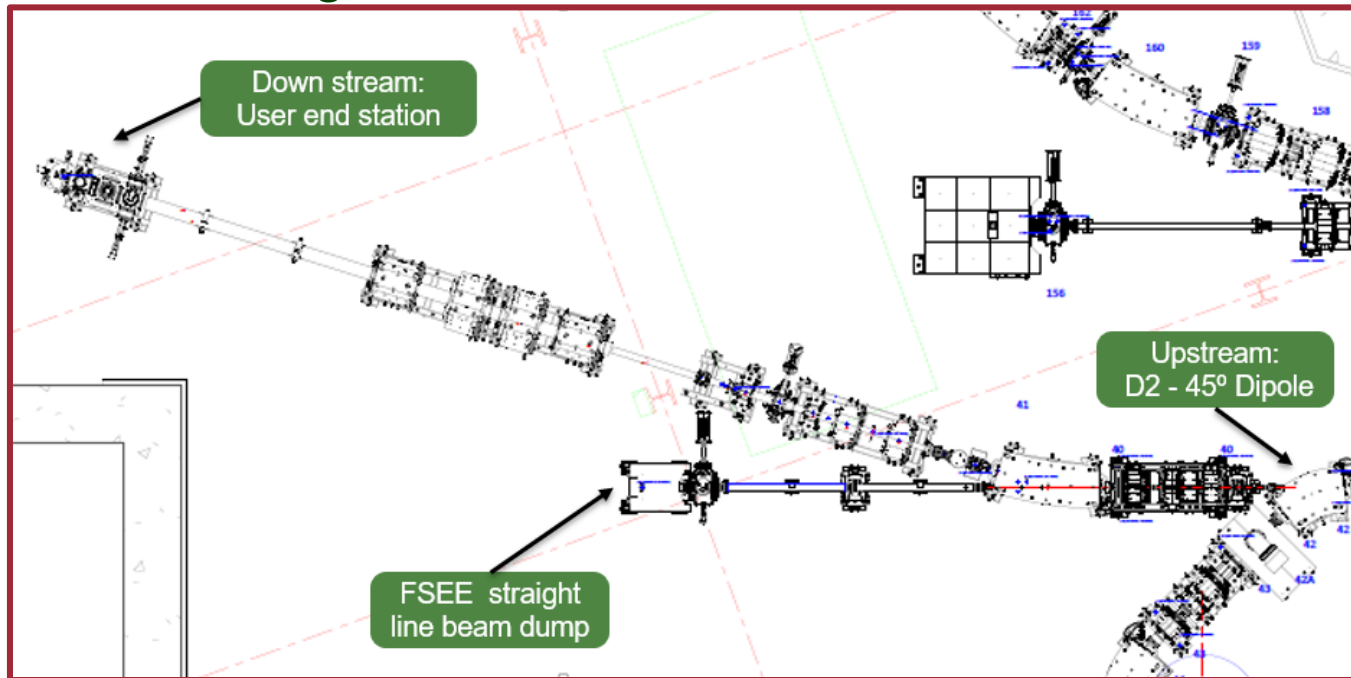


SEE Efforts at the FRIB Laboratory

- **FRIB Linac Segment (LS) 1 SEE Beamline (<45 MeV/u)**
 - Addition a SEE beamline to the FRIB DOE-SC user facility, supporting the mission of DTRA and the SEE community without adverse impact on the DOE-SC mission for FRIB
 - Contract discussions underway – can technically be operational in 2021
- **FRIB Linac Segment 3 SEE Beamline (>100 MeV/u)**
 - Possibility to provide High-Energy SEE testing
 - Could move LS1 SEE Beamline to LS3, or duplicate LS1 beamline
- **K500 Cyclotron (<70 MeV/u)**
 - K500 was completely refurbished for CCF project (2001)
 - Starting to plan SEE beamline – can be operational in 2022/23, depending on scope and contract instrument
- **K1200 Cyclotron (>100 MeV/u)**
 - Needs to be refurbished after technical evaluation
 - Cost effectiveness evaluation needed – 2023

FRIB Linac Segment 1 SEE Beamline

- Beam line extension in the underground accelerator tunnel after the first linac segment

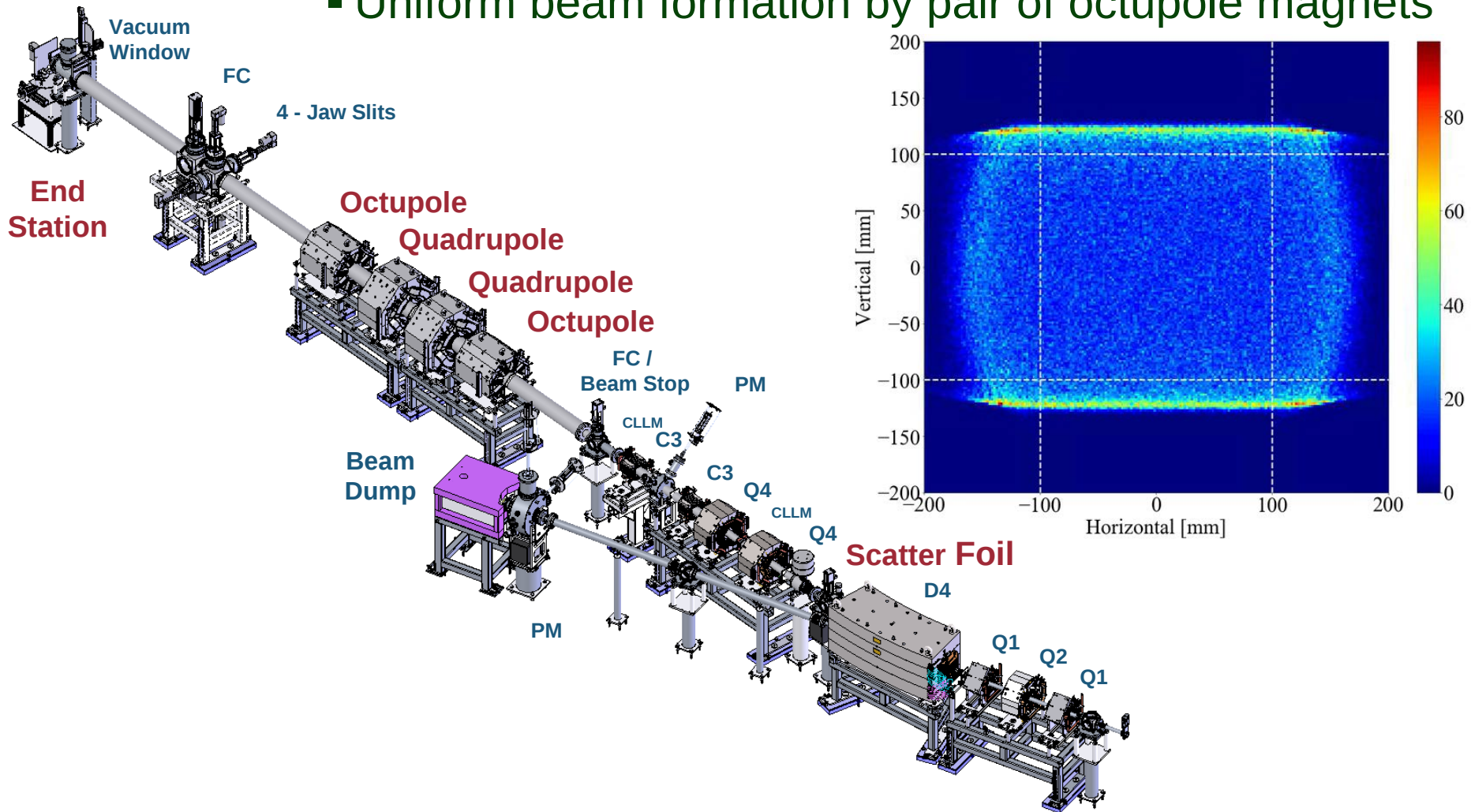


FRIB LS1 SEE Design Meets AOA Requirements

Key Performance Parameter (KPP)	Variable Description	Threshold Values	Objective Values
Simulation of mission environment (e.g., GCR, solar events)	Range of entrance Linear Energy Transfer (LET) in Si [MeV cm ² /mg] at normal incidence	0.7 – 82	0.1 - 120
Provide a range of flux inclusive of target value	Ions/(cm ² -s)	< 100, 106	10, 106
Simulation of mission environment (e.g., GCR, solar events)	Kinetic energy [MeV/u]	5 - 44	Same as Threshold
Variable beam diameter (100% spot size)	cm	0.5 – 2.5	0.5 – 50
Beam uniformity (dosimetry over spot size)	N/A	+/- 10%	+/- 5%
Beam structure	Average flux variance	+/- 15%	+/- 5%
Beam structure	Instantaneous flux variance (no less than 10% duty factor)	+/- 15%	+/- 5%
Homogeneity in ion species composition		>95%	Same as Threshold
Homogeneity in ion energy		>90%	Same as Threshold

Large Area Uniform Beam Spots

- Uniform beam formation by pair of octupole magnets

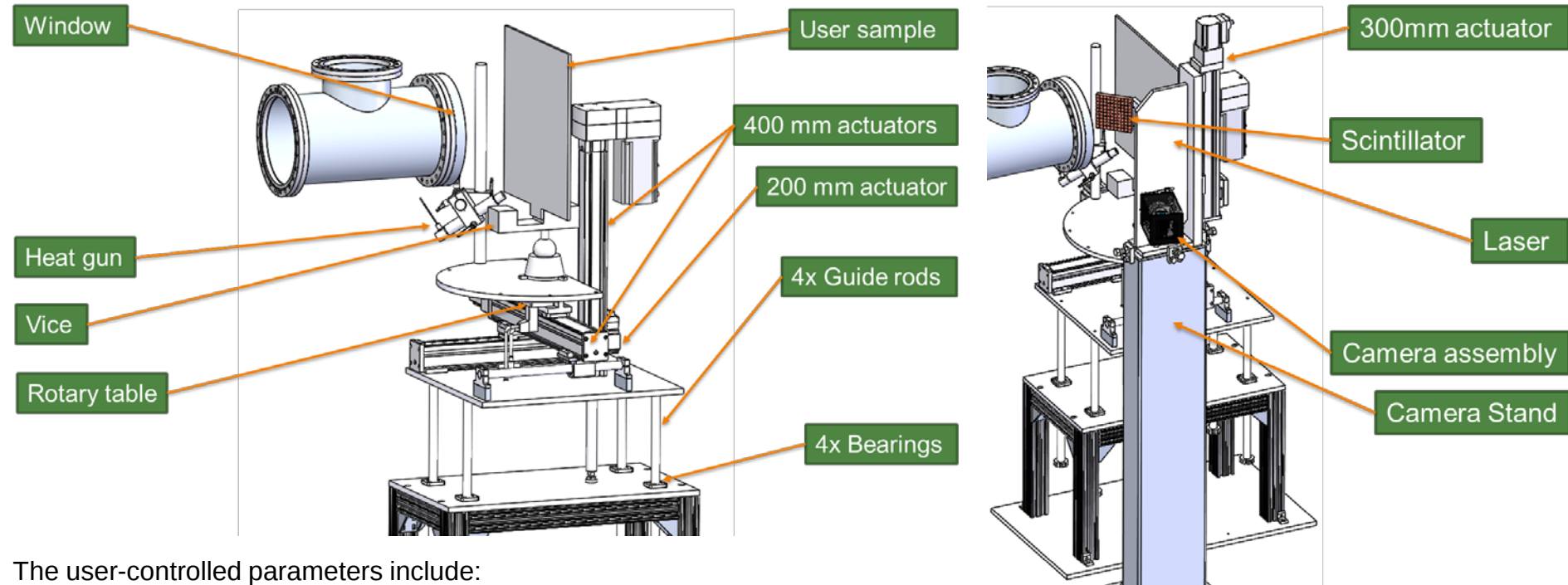


User End Station Features

- Generates and deposits reproducible and predictable amounts of charge to electronic device-sensitive volumes and structures
- Varies the incident ion species, kinetic energy, Linear Energy Transfer (LET), ion flux, and angle of incidence on the device under test (DUT)
- Provides accurate dosimetry; instantaneous, run to run, and cumulative on the DUT
- Supports in-air studies at room temperature
- User test and support equipment can be staged within the irradiation vault close to the DUT
- Ability to stage users, user equipment, and route user-provided cabling outside the irradiation vault
- Users can control and monitor beam parameters and dosimetry through a simple user interface.
- The SEE user test station provides
 - Compatibility with Texas A&M University Cyclotron Institute board mounting,
 - Remote control for transverse and longitudinal positioning, yaw angle
 - Optical DUT alignment
 - Option to host user-provided cryogenic dewar

User End Station Design

- Satisfies sample positioning and alignment requirements
- Currently in procurement and fabrication for FRIB linac SEE



The user-controlled parameters include:

- Stage rotational orientation (remotely controlled actuator)
- Stage x/y/z position (remote controlled actuator)
- Scintillating view screen and camera acquisition (remotely controlled actuator and image acquisition)
- Heat gun (remotely controlled)
- Thermal imaging system (remotely controlled image acquisition)

Dosimetry and Controls

- **Dosimetry will be provided by several independent measurements**

- Integrated to controls and reporting system

- **Beam power or particle rate**

- Continuously measured with secondary emission monitor
- Cross-calibrated with beamline Faraday cup

- **Transverse particle distribution**

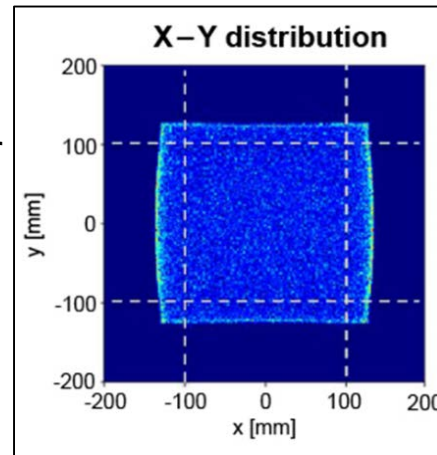
- Measured with in-air scintillating screen and digital camera
- Verified pre- and post- exposure

- **Beam energy spread**

- Measured with in-air silicon detector

- **Ion species purity**

- Verified with in-air silicon detector



```
Run number           : 11
Run file name        : CI-TAMU Feb 2020.#07
Run start date and time : 20/12/16 13:35:32
Run end date and time  : 20/12/16 13:35:42
Duration of the run    : 00:00:10 (+ 0 days)
Number of events      : 8
```

```
Selected beam        : 15.0 MeV/u Ar @ K500
Al degrader thickness (mil) : 0.000
Number of layers (layer file name) : 3 (30 mm air Si)
Beam energy (MeV/amu) : 13.3
Beam energy (MeV)     : 531
Target material       : silicon
Nominal LET (MeVcm2/mg) : 8.2
Nominal range (um)    : 193.8
Effective LET (MeVcm2/mg) : 8.2
Effective range (um)  : 193.8
DUT location         : In-air
Position set name     : K500-standard(air)
```

```
Effective fluence (ions/cm2) : 9.491E+003
Dose (rad)                   : 1.249E+000
Live time (s)                : 4
Dead time (s)                : 0
Average flux (ions/(cm2s))   : 2.373E+003
Average flux error (%)       : 1.6
Overall uniformity (%)       : 98
Overall central shift (%)    : 2
Calibration factor           : 0.997215
```

```
DUT X coordinate      : -0.000 in
DUT Y coordinate      : -0.000 in
DUT Z coordinate      : -30.001 cm
DUT tilt angle        : -0.000 deg
Roll angle            : 1.500 deg
Unused coordinate     : 1.500 in
Selected Al degrader number : -0.000 steps
Degradation rotation angle : 0.000 deg
```

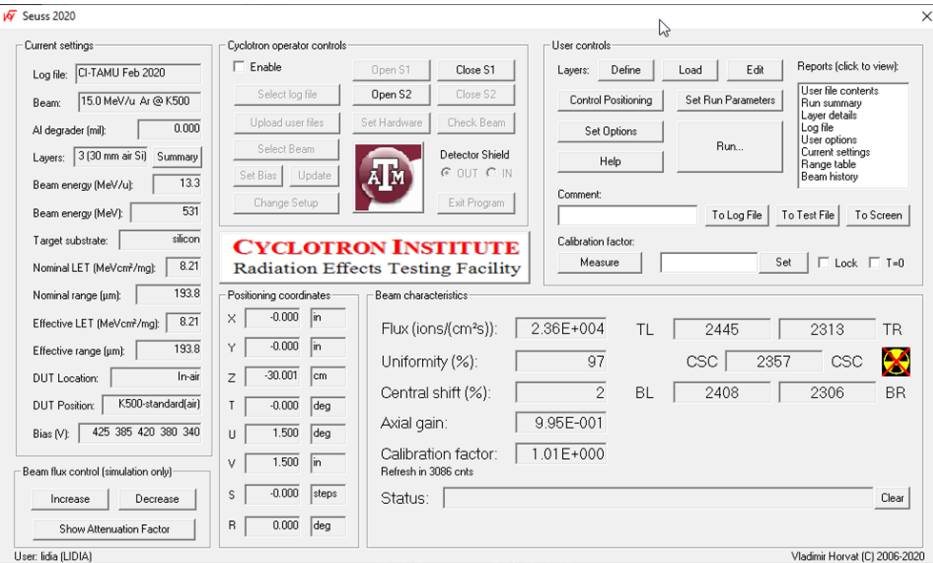
```
Detector bias (V)     : 425 385 420 380 340
```

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Layer summary:
silicon      ROT      0 um
air gas      FIX     30000 um
aramica      FIX      25.4 um
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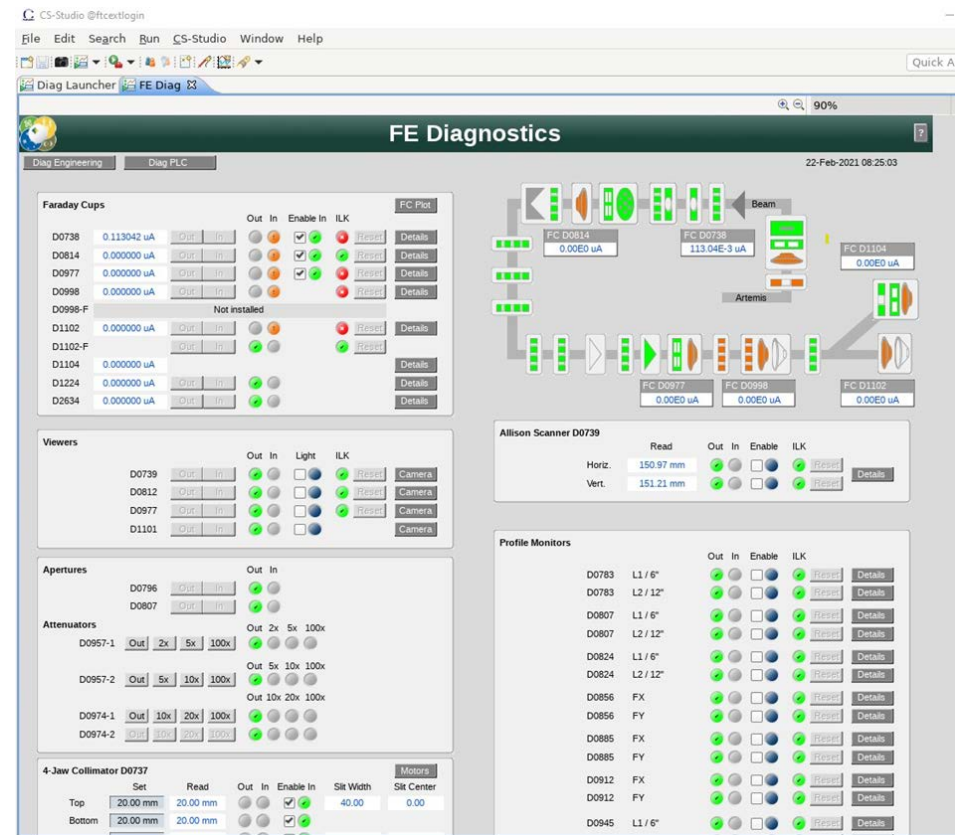
Post-run
report
(example)

User Interface is Based on Industry Standard

TAMU SEE User Interface Application

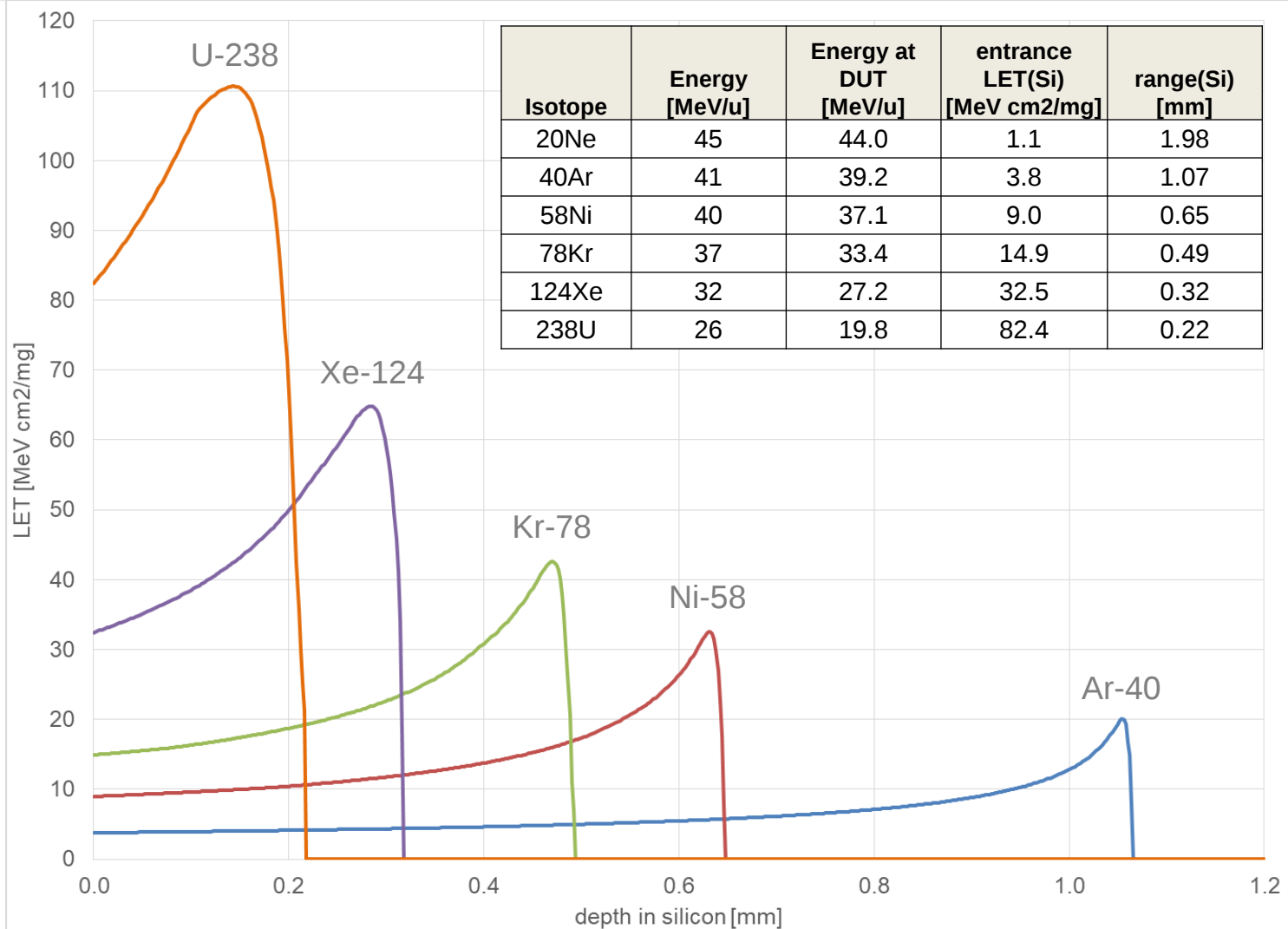


FRIB EPICS-based User Interface (example)



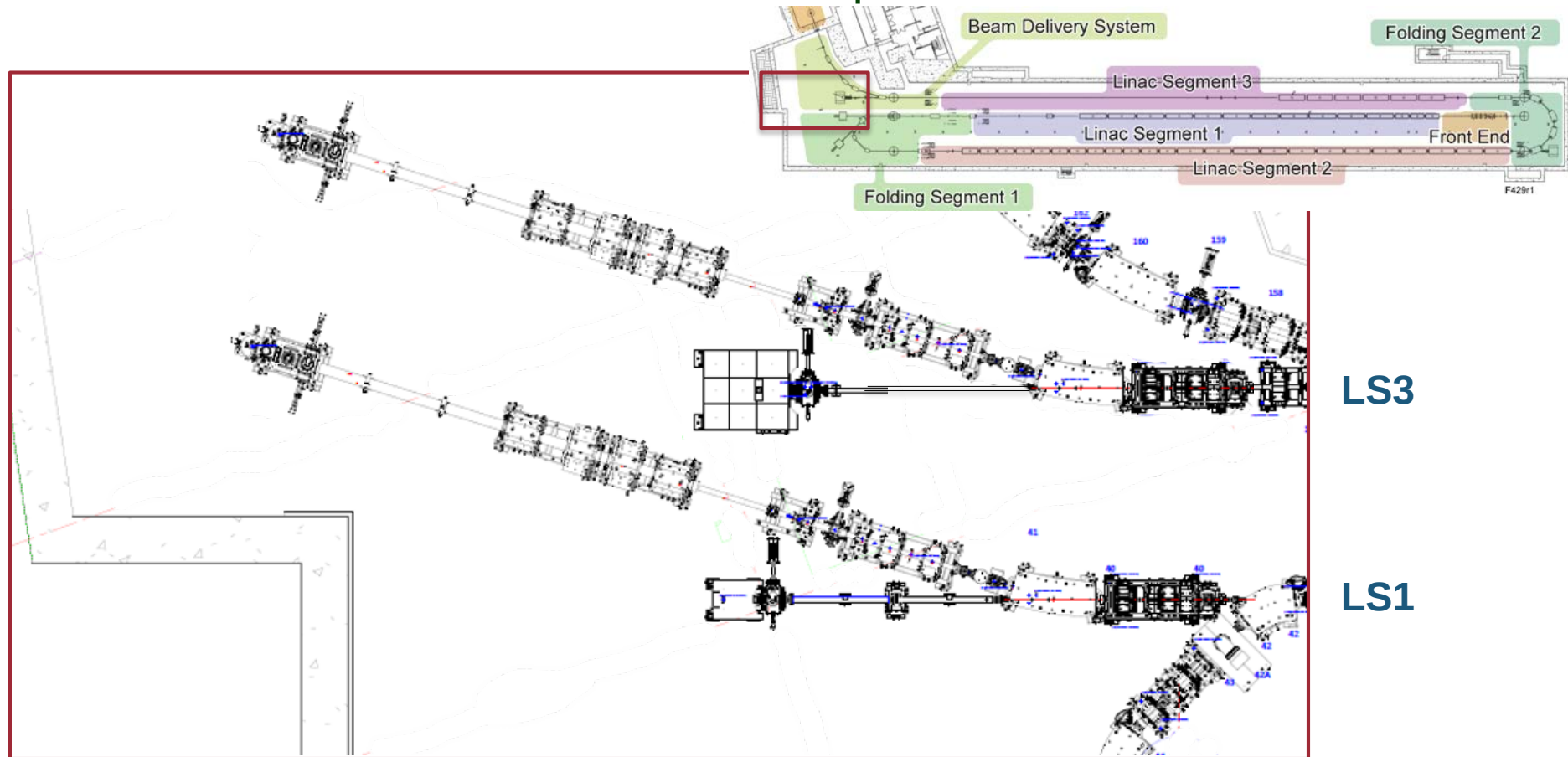
- Data will be acquired and archived during the execution of every test experiment.
- A post-run report will be generated following each test.
- Report data will be archived and may be regenerated upon request.

FRIB LS1 Selected Ion Energies and LET

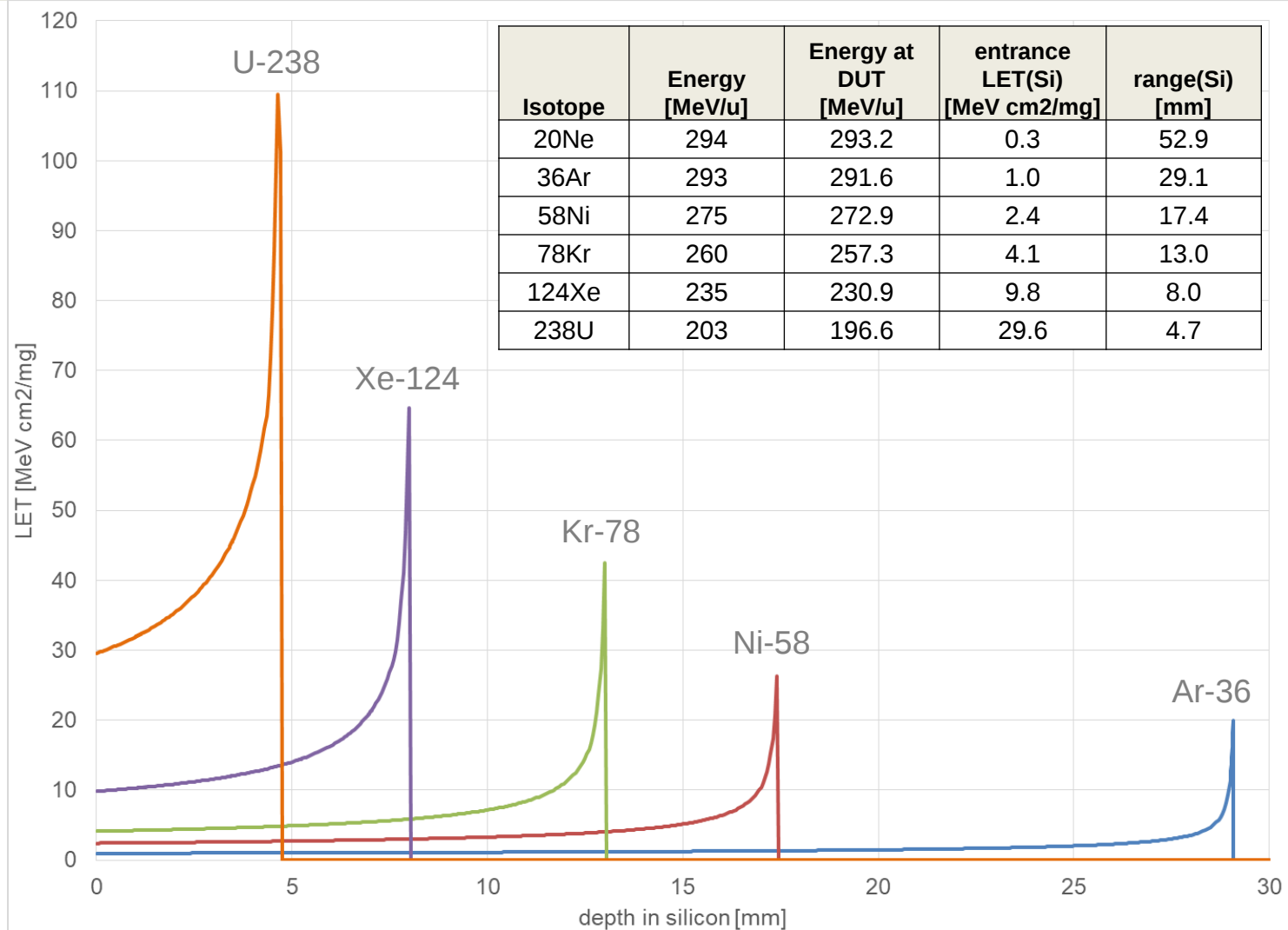


FRIB Linac Segment 3 SEE Beam Line

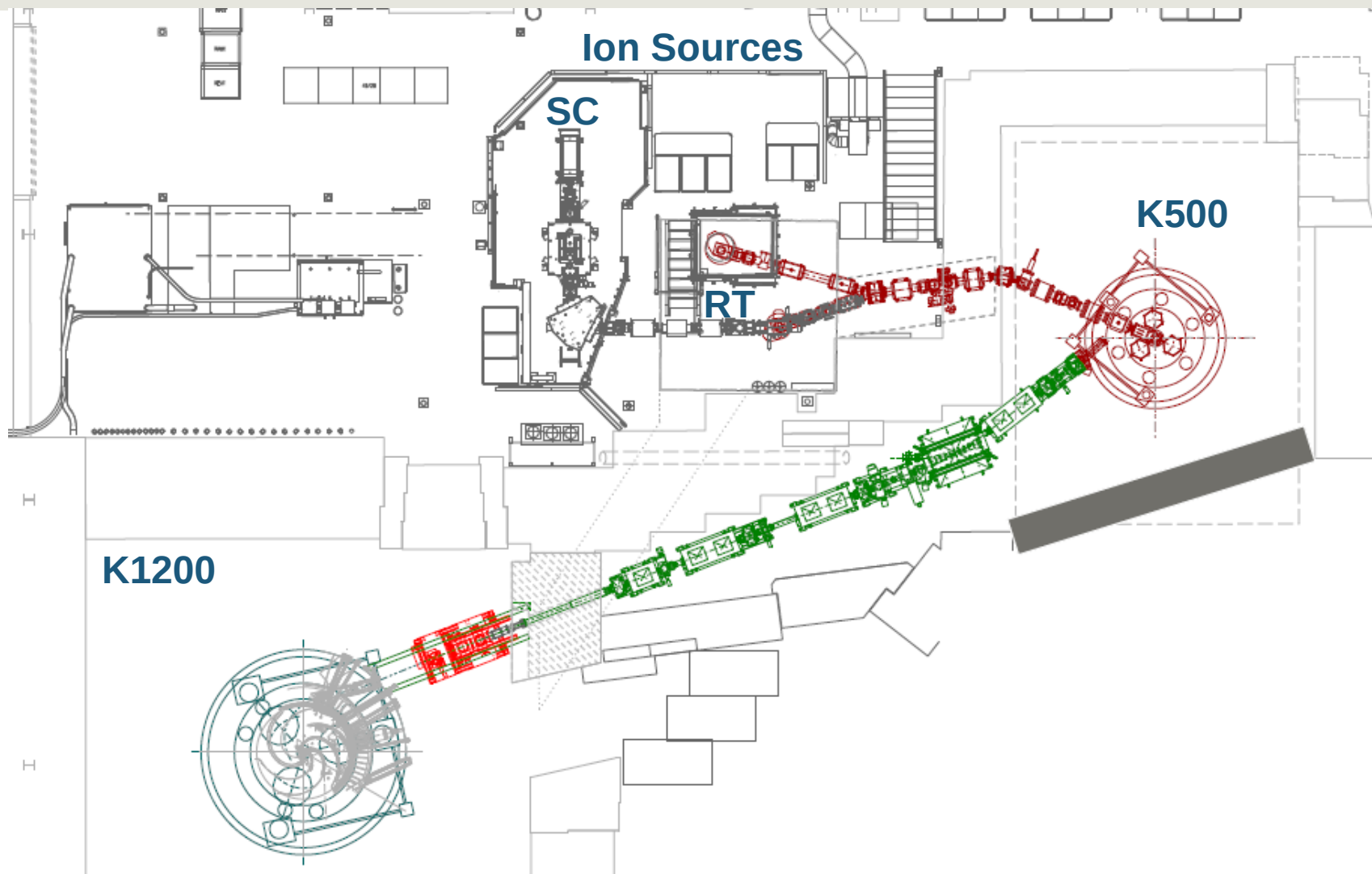
- Linac Segment 3 provides the full energy of the FRIB accelerator
- LS1 SEE Beamline could either be duplicated or moved



FRIB LS3 Selected Ion Energies and LET



K500 Cyclotron for SEE Testing



K500 with ARTEMIS Ion Source

- Operations of the K500 cyclotron with a 14 GHz room-temperature ECR ion source would provide heavy ion beams similar to what is available at the Texas A&M University Radiation Effects Facility:
 - He to Au with energies up to 15 MeV/u
 - He to Xe with energies up to 25 MeV/u
 - N to Kr with energies up to 40 MeV/u
- Maximum beam energies and LET for selected ion beams:

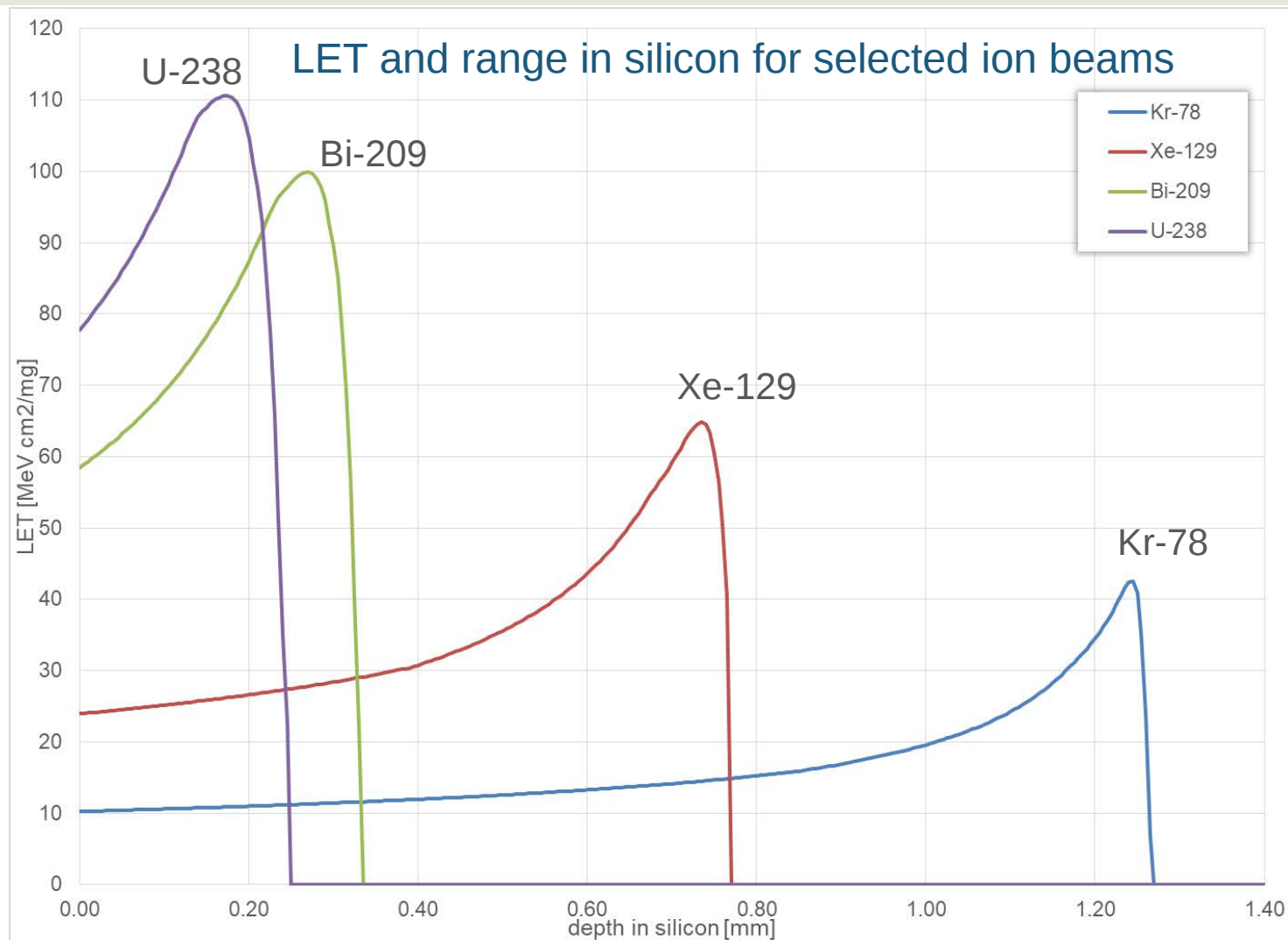
Isotope	Energy [MeV/u]	@50mm air [MeV/u]	entrance LET(Si) [MeVcm ² /mg]	range(Si) [mm]
40Ar	68.0	66.8	2.5	2.64
78Kr	57.4	54.9	11.0	1.06
129Xe	34.7	30.5	30.1	0.39
209Bi	23.2	17.1	77.5	0.18
238U	20.3	13.7	97.1	0.15

K500 with VENUS Ion Source

- Operations of the K500 cyclotron with a 28 GHz superconducting ECR ion source would provide heavy ion beams with higher energies, as such an ion source can provide ions with a higher charge over mass ratio.
- Maximum beam energies and LET for selected ion beams:

Isotope	Energy [MeV/u]	@50mm air [MeV/u]	entrance LET(Si) [MeVcm ² /mg]	range(Si) [mm]
40Ar	72.0	70.9	2.4	2.93
78Kr	63.6	61.2	10.2	1.27
129Xe	52.1	48.8	23.9	0.77
209Bi	33.4	28.5	58.4	0.33
238U	27.7	22.1	77.7	0.25

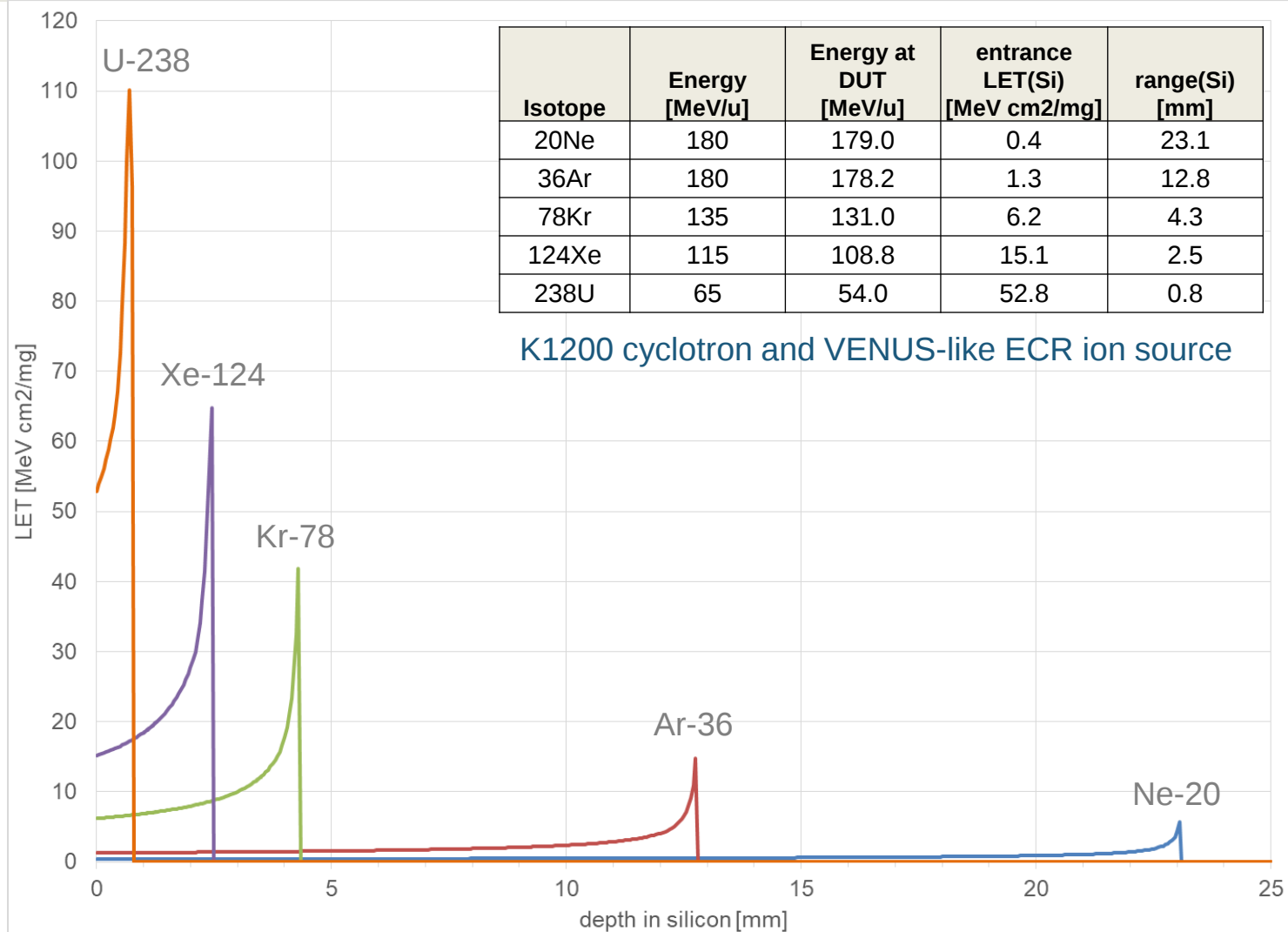
K500 with VENUS Ion Source



K1200 Cyclotron – Technical Evaluation Needed

- K1200 was not refurbished for the Coupled Cyclotron Facility project
 - K500 was taken apart, refurbished, and rotated
- Known technical issues and required actions
 - Reestablish axial injection (build beam line, fix central region vacuum leak)
 - Replace cryogen transfer line
 - Replace trim coil power supplies
 - Replace beam chamber
 - Replace RF system
 - Epoxy in superconducting coil is beyond its presumed neutron dose lifetime
- To use K1200 cyclotron for High-Energy SEE Testing:
 - Consider refurbishment similar to K500
 - Rotate by 120 degree
 - Add building addition for 2-3 user areas

K1200 Selected Ion Energies and LET



Summary

- FRIB Linac Segment (LS) 1 SEE Beamline (<45 MeV/u)
 - Contract discussions are underway – can technically be operational in 2021
- FRIB Linac Segment 3 SEE Beamline (>100 MeV/u)
 - Possibility to provide High-Energy SEE testing
 - Could move LS1 SEE Beamline to LS3, or duplication of beamline
 - Can be done quickly (few months) if needed
- K500 Cyclotron (<70 MeV/u)
 - Starting to plan – can be operational 2022/23, depending on scope
- K1200 Cyclotron (>100 MeV/u)
 - Possibility to provide High-Energy SEE testing
 - Technical and cost effectiveness evaluation needed – 2023