Electronics Testing at NSRL

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29 October 2021

Outline

- **Introduction to NSRL**
- Units and Scale
- Accelerator Fundamentals & Testing Implications
- Radiation Interactions
    - Ion/Energy choices
- NSRL Beamline & Hardware
- Useful Resources

Introduction

Introduction
Who What When Where Why

NSRL Staff

- 4 Scientific/Operations, 1 administrator, 1 engineer

Accelerator Staff

- Main control operators
- Ion source members (EBIS and proton LINAC)
- C-A Support
  - Power supplies, RF/acceleration cavity, magnets, cryo, access controls, health phys., software devs

BNL Staff

- Shipping/receiving/rigging
- Admins (financial, DoE, legal)
- Medical

In total, 18 full-time equiv. employees directly supporting, ~55 people involved

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Introduction

Who What **When** Where Why

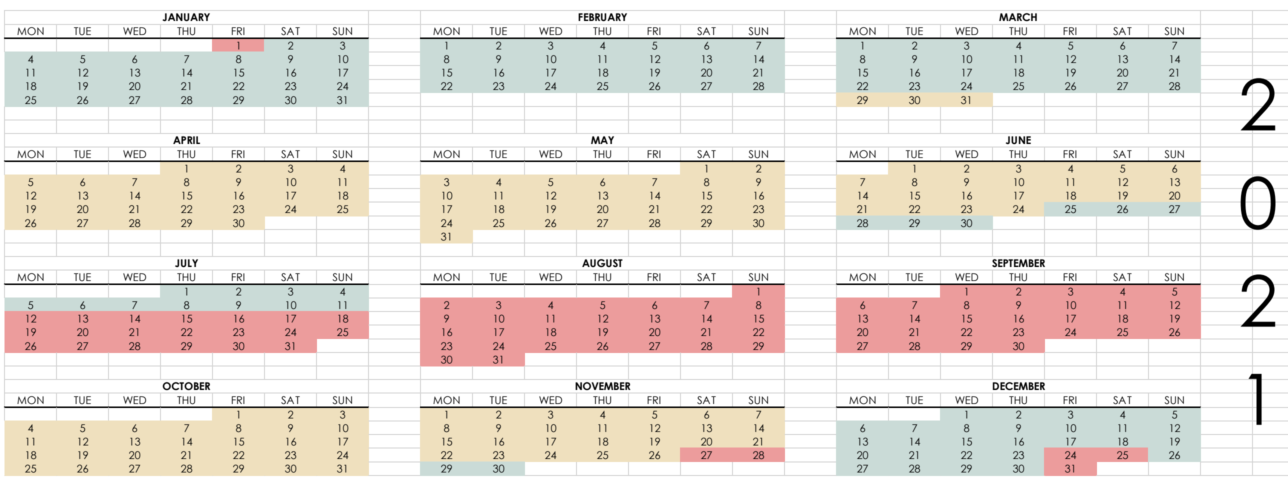
NSRL operates about 9 months of the year

- Summer is a forced shutdown (maintenance period)

- NASA HRP campaigns prioritized
  - End of March to late June
  - End of September to Thanksgiving weekend

Currently operating 16 hours per day, ~6 days per week (some exceptions)

Typical Yearly Schedule
- Red: No users
- Yellow: NASA
- Green: Electronics



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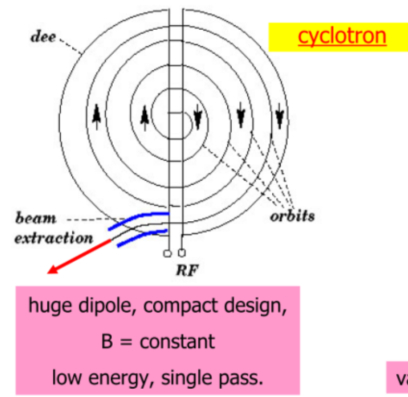
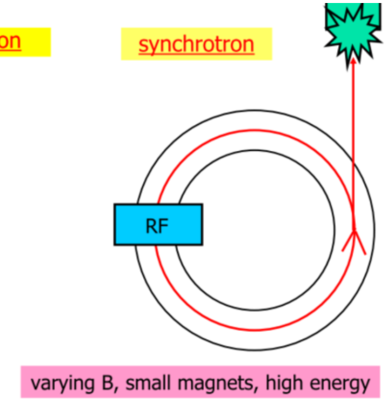
Introduction

Who **What** When Where Why



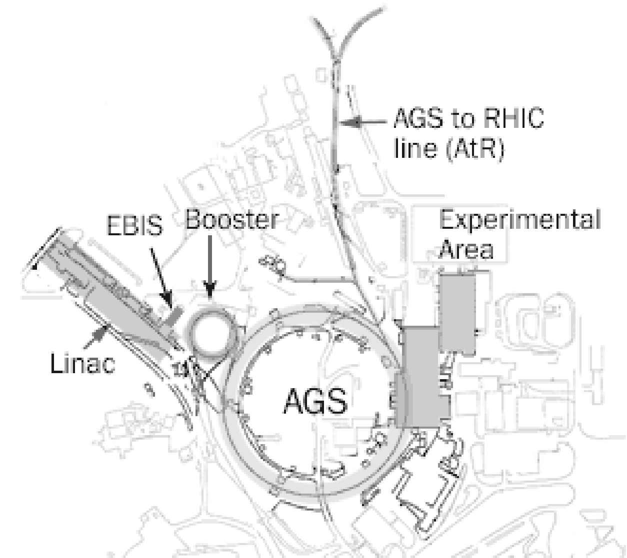


Synchrotron Accelerator (NOT A CYCLOTRON!)

- Ions pass through the same general orbit as energy increases
- Timing crucial in ion injection, magnet ramp, ion extraction

RHIC Complex

- Electron Beam Ion Source (EBIS), proton Linac
- Booster (1st stage, low energy), AGS (2nd stage, high energy), Collider (3rd stage, storage ring/collisions)



Booster Applications Facility (now NSRL)

- 100 meter beamline spur from Booster
- Dipoles (steering), quadrupoles (shaping), octupoles (area)
- Target room equipped for electronics testing
  - Laser alignment
  - Easily adjustable tungsten collimator
  - BNC & Cat-5e ethernet passthrough to user areas

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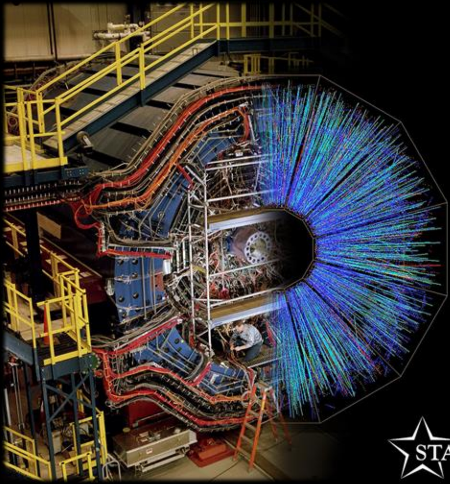

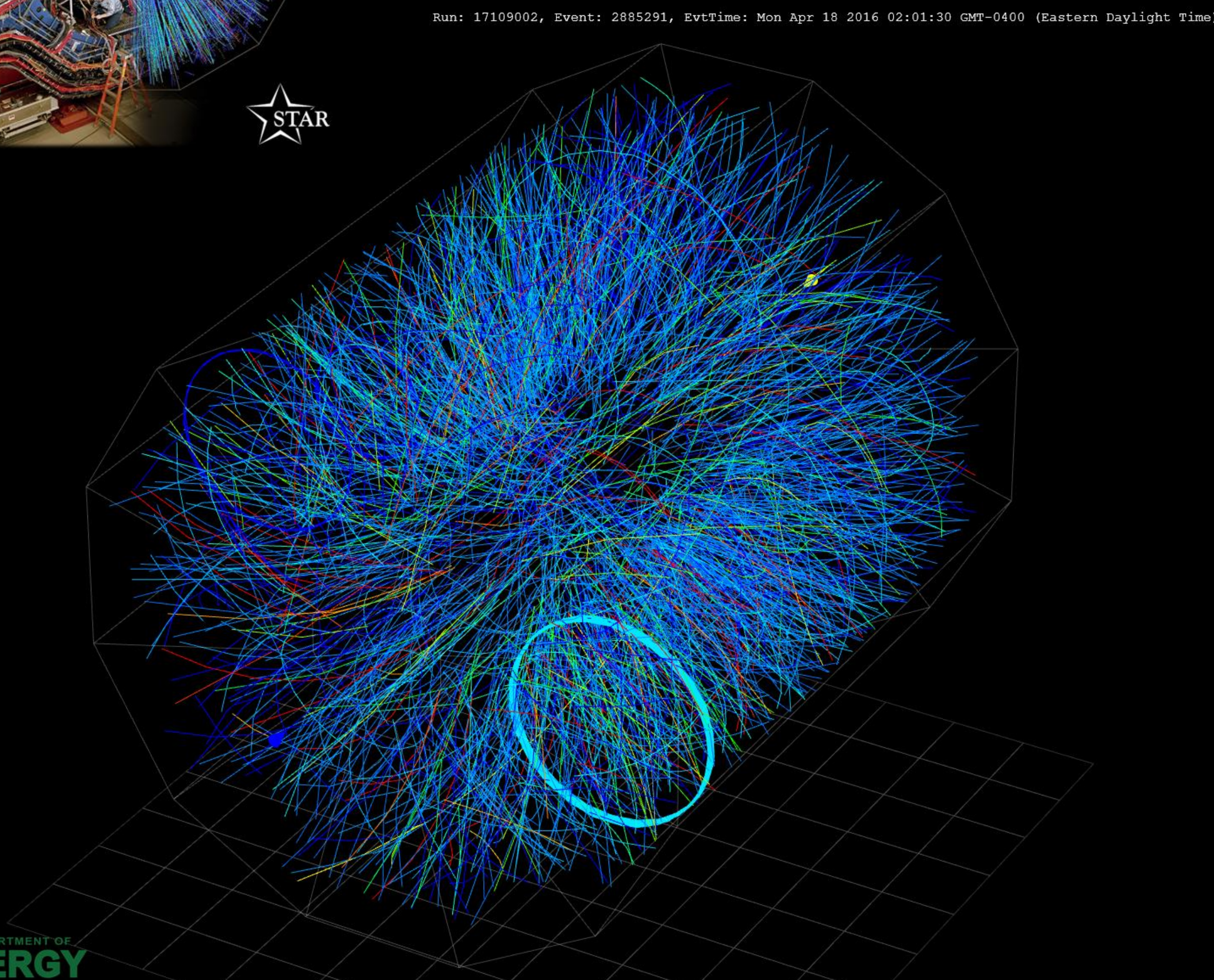

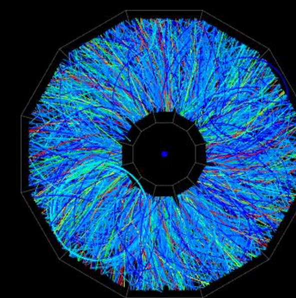

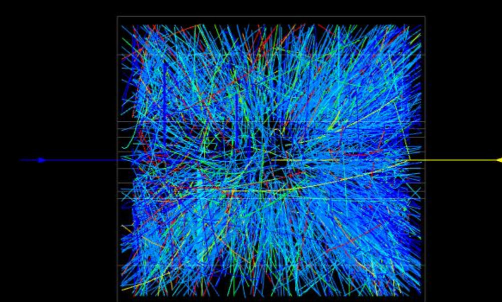

https://online.star.bnl.gov/aggregator/livedisplay/

Events: pre-recorded (raw)

Introduction

Who What When Where Why

Cyclotron facilities measure their ion range in micrometers;

NSRL synchrotron measures ion range in centimeters to meters

Ion Species [1]	Max Energy [2] (MeV/n)	LET in Si at Max Energy [6] (MeV/(mg/cm^2))	Peak LET in Si (MeV/(mg/cm^2))	Range in Si (mm)
H^1	2500	0.00171	0.51	5470
He^4	1500	0.006919	1.5	2960
C^{12}	1500	0.06227	5.2	972
O^{16}	1500	0.1107	7.3	351
Ne^{20}	1000	0.178	9	583
Si^{28}	1000	0.351	14	248
Ar^{40}	1000	0.600	18.7	207
Ti^{48}	1000	0.854	24.2	175
Fe^{56}	1000	1.189	29.3	146
Kr^{84}	383*	3.3	41	26.9
Nb^{93}	520	3.6	47.4	37.5
Ag^{107}	575	4.65	59.4	17.9
Xe^{129}	350*	7.67	69.3	16.1
Tb^{159}	446	9.32	78.2	21.4
Ta^{181}	342*	13.5	87.7	12.8
Au^{197}	242*	19.2	94.4	6.9
Bi^{209}	359	17.6	100.0	12.2
High Charge State Beams *(Lower Max Beam Intensity)*				
Kr^{84}	721	2.54	41	70.5
Xe^{129}	589	6.1	69.3	35.8
Ta^{181}	475	11.7	87.7	21.1
Au^{197}	400	15	94.4	14.9

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	Ion	Mass (amu)	A MeV	Total Energy (MeV)	Range in Si (µm)	Range to Bragg Peak (µm)
15 A MeV	^{4}He	4.003	15	60	1449	1446
	^{14}N	14.003	15	210	422	418
	^{20}Ne	19.992	15	300	311	302
	^{40}Ar	39.962	15	599	231	217
	^{63}Cu	62.930	15	944	174	151
	^{84}Kr	83.912	15	1259	170	149
	^{109}Ag	108.905	15	1634	149	113
	^{129}Xe	128.905	15	1934	146	107
	^{141}Pr	140.908	15	2114	154	99
	^{165}Ho	164.930	15	2474	151	102
	^{181}Ta	180.948	15	2714	159	111
	^{197}Au	196.967	15	2954	159	108
25 A MeV	^{4}He	4.003	24.8	99	3523	3519
	^{14}N	14.003	24.8	347	1009	1002
	^{22}Ne	21.991	24.8	545	799	791
	^{40}Ar	39.962	24.8	991	493	484
	^{63}Cu	62.930	24.8	1561	357	334
	^{84}Kr	83.912	24.8	2081	332	311
	^{107}Ag	106.905	24.8	2651	287	260
	^{129}Xe	128.905	24.8	3197	286	255
40 A MeV	^{14}N	14.003	40	560	2334	2327
	^{20}Ne	19.992	40	800	1655	1647
	^{40}Ar	39.962	40	1598	1079	1070
	^{78}Kr	77.920	40	3117	622	602

TAMU Cyclotron Institute, K500 Cyclotron Heavy Ion Beam List
https://cyclotron.tamu.edu/ref/images/heavy_ion_beams.pdf

For higher confidence in LET based testing, use the highest energy and highest mass ion

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- Introduction to NSRL
- **Units and Scale**
- Accelerator Fundamentals & Testing Implications
- "Radiation" Interactions
  - Ion/Energy choices
- NSRL Beamline & Hardware
- Useful Resources

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Units & Scale

Units & Scale
Mass & Energy

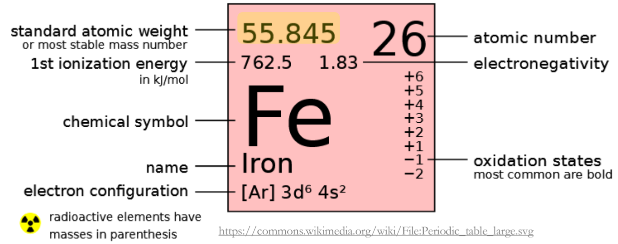
Unified Atomic Mass Unit (a.k.a. Dalton) – amu, u, Da, (per nucleon, /*n*)

$$1\,m_u = \frac{M\left({}^{12}C\right)}{12N_A} = 1.66054\ \cdot 10^{-27}kg$$

$M\left({}^{12}C\right)$ Accounts for mass of 6 protons, 6 neutrons, electrons, and binding energy

$$m_u = 1.66053 \cdot 10^{-27} = 1.000000\,u$$
$$m_p = 1.67262 \cdot 10^{-27} = 1.007276\,u$$
$$m_n = 1.67492 \cdot 10^{-27} = 1.008664\,u$$
$$m_e = 9.10938 \cdot 10^{-31} = 0.000548\,u$$

Beam ion masses are isotope specific (Xe-129, Ag-107)



https://en.wikipedia.org/wiki/Isotopes_of_silver

Main isotopes of silver ($_{47}$Ag)

Isotope			Decay	
	abun-dance	half-life ($t_{1/2}$)	mode	pro-duct
^{105}Ag	syn	41.2 d	ε	^{105}Pd
			γ	–
^{106m}Ag	syn	8.28 d	ε	^{106}Pd
			γ	–
^{107}Ag	51.839%	stable		
^{108m}Ag	syn	418 y	ε	^{108}Pd
			IT	^{108}Ag
			γ	–
^{109}Ag	48.161%	stable		
^{110m}Ag	syn	249.95 d	β$^-$	^{110}Cd
			γ	–
^{111}Ag	syn	7.45 d	β$^-$	^{111}Cd
			γ	–

Standard atomic weight $A_{\mathrm{r,\,standard}}$(Ag) 107.8682(2)[1]

^{107}Ag[n 9]	47	60	106.905097(5)

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Units & Scale
Mass & Energy

$$Kinetic\ energy = \frac{mv^2}{2} \rightarrow \left[\frac{kg \cdot m^2}{s^2}\right] = Joules$$

With Einstein's mass-energy equivalence, total energy of a particle:

$$E^2 = (pc)^2 + (m_0c^2)^2, \qquad KE = mc^2 - m_0c^2$$

Ex: Proton rest mass

$$p = 0 \rightarrow E = m_pc^2$$

$$proton\ mass, m_p = 1.6726 \cdot 10^{-27} kg, \qquad c = 299792458\ \frac{m}{s}$$

$$E = m_pc^2 = 1.503257 \cdot 10^{-10} J \rightarrow 938.3 \cdot 10^6\ eV \rightarrow 938\ MeV$$

$$proton\ mass, m_p = 938\ \frac{MeV}{c^2}$$

https://en.wikipedia.org/wiki/Electronvolt

Measurement	Unit	SI value of unit
Energy	eV	$1.602\,176\,634 \times 10^{-19}$ J
Mass	eV/c^2	$1.782\,662 \times 10^{-36}$ kg
Momentum	eV/c	$5.344\,286 \times 10^{-28}$ kg·m/s

amu	1.660540×10^{-27} kg	1.000000 u	931.5 MeV/c^2
Neutron	1.674929×10^{-27} kg	1.008664 u	939.57 MeV/c^2
Proton	1.672623×10^{-27} kg	1.007276 u	938.28 MeV/c^2
Electron	9.109390×10^{-31} kg	0.000548 u	0.511 MeV/c^2

Units & Scale
Mass & Energy

Ex: $150\,\frac{MeV}{u}\ {}^{209}\mathrm{Bi}$

$$m_{^{209}Bi} = 208.9803\,u = 194664\,\frac{MeV}{c^2}$$

$$150\,\frac{MeV}{u}\cdot 208.9803\,u = 31347\,MeV\ \ \text{total kinetic energy}$$

According to WolframAlpha…

Comparison as kinetic energy

≈ (0.031 ≈ 1/32) × approximate kinetic energy of a flying mosquito ($\approx 1.6\times10^{-7}$ J)

$$31347\,MeV = 5.022\cdot 10^{-9}\,J$$

$$E^2 = (pc)^2 + (m_0c^2)^2 \;\rightarrow\; (pc)^2 = KE^2 + 2KE\cdot m_0c^2 + \cancel{m_0{}^2c^4 - m_0{}^2c^4}$$

$$pc = \sqrt{KE^2 + 2KE\cdot m_0c^2} \;\rightarrow\; p = 114834\,\frac{MeV}{c}$$

$$With\ \ p = \gamma m_0 v \;\rightarrow\; v = \sqrt{\frac{(p/m_0)^2}{\left(1 - \frac{(p/m_0)^2}{c^2}\right)}} = 0.5081\,c$$

94650 miles per second

$$\boxed{\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}}$$

$$Compare\ to\ KE = \frac{1}{2}mv^2 \rightarrow v = \sqrt{\frac{2\cdot KE}{m}} = 0.5675\,c$$

105720 miles per second

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Units & Scale
LET

LET – Linear Energy Transfer $\frac{MeV}{mg/cm^2}$ *(energy per length, per density)*

- The instantaneous rate of energy that the ion transfers to the surrounding material
- Depends on *Ion*: **charge, energy**

  and *Material*: **electron density** n, **electron excitation** energy I
- Described by the Bethe–Bloch Formula (https://en.wikipedia.org/wiki/Bethe_formula)

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$

where c is the speed of light and ε_0 the vacuum permittivity, $\beta = \frac{v}{c}$, e and m_e the electron charge and rest mass respectively.

Here, the electron density of the material can be calculated by

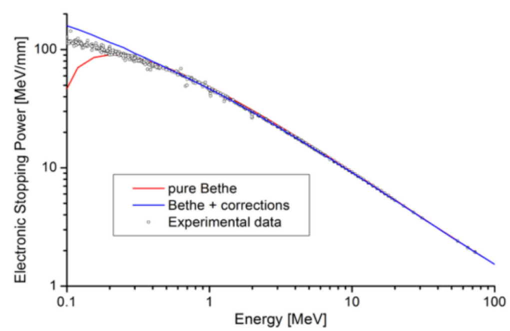
$$n = \frac{N_A \cdot Z \cdot \rho}{A \cdot M_u},$$

where ρ is the density of the material, Z its atomic number, A its relative atomic mass, N_A the Avogadro number and M_u the Molar mass constant.

In the figure to the right, the small circles are experimental results obtained from measurements of various authors, while the red curve is Bethe's formula.[4] Evidently, Bethe's theory agrees very well with experiment at high energy. The agreement is even better when corrections are applied (see below).

For low energies, i.e., for small velocities of the particle $\beta << 1$, the Bethe formula reduces to

$$-\frac{dE}{dx} = \frac{4\pi n z^2}{m_e v^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e v^2}{I}\right)\right]. \qquad (2)$$

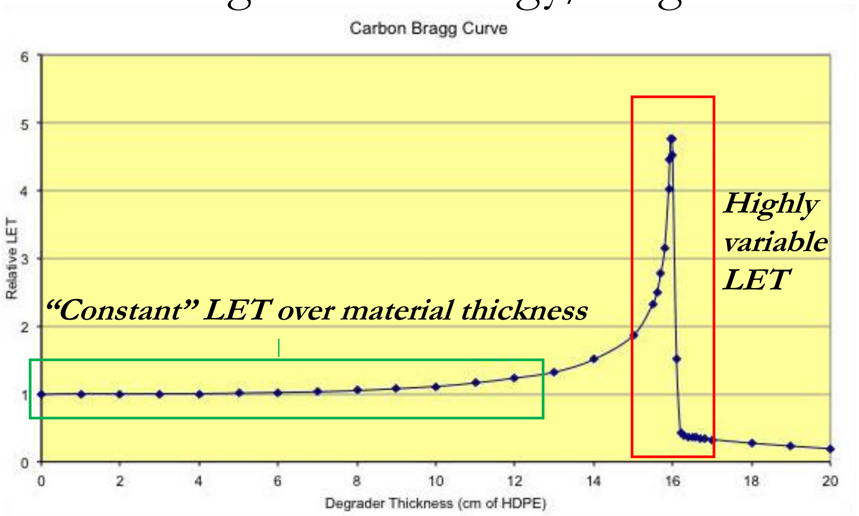


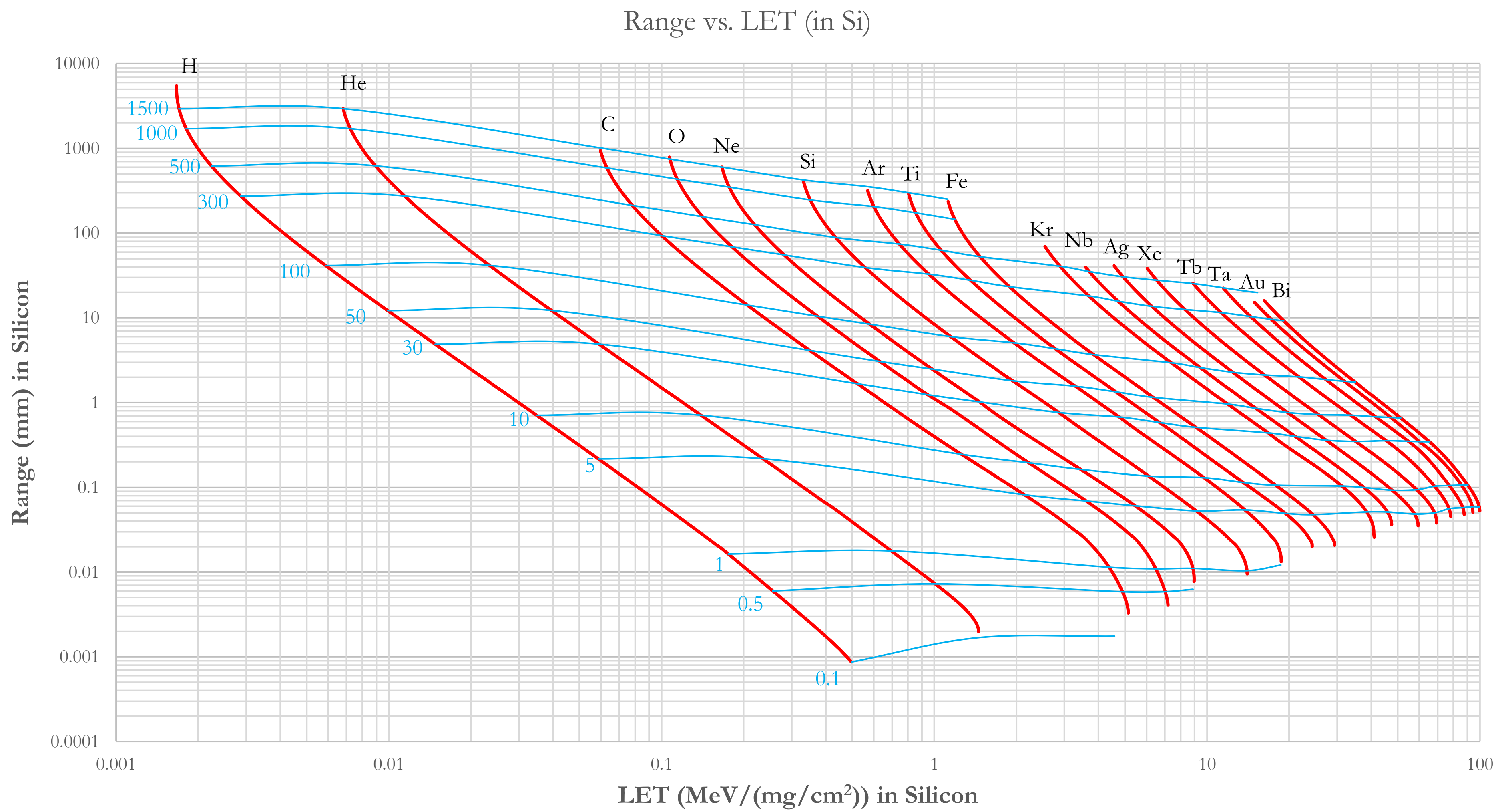
Excerpt from Wikipedia

Units & Scale
LET

LET – Linear Energy Transfer $\frac{MeV}{mg/cm^2}$

- LET is really $\left\langle\frac{dE}{dx}\right\rangle$, the energy lost in an infinitesimally small thickness of material
- Ion energy is decreasing as it passes through material and consequently the LET increases as the energy approaches the Bragg peak
- Relatively constant plateau of LET for high energy/range
- Steep LET rate of change at low energy/range




Range vs. LET (in Si)
Range (mm) in Silicon
LET (MeV/(mg/cm²)) in Silicon
10000
1000
100
10
1
0.1
0.01
0.001
0.0001
0.001
0.01
0.1
1
10
100
H
He
C
O
Ne
Si
Ar
Ti
Fe
Kr
Nb
Ag
Xe
Tb
Ta
Au
Bi
1500
1000
500
300
100
50
30
10
5
1
0.5
0.1

Units & Scale Summary

- Total energy is represented in eV
- Ion energy is better represented in eV per nucleon
  - Cosmic ray spectrum peaks between 300 MeV/n to 1000 MeV/n

- LET is a representation of how energy is deposited in material
- Testing at high LET (45+) can introduce large variance in ion-to-ion energy deposition *(more on that later)*

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Accelerator Fundamentals & Testing Implications

Accelerator Fundamentals & Implications
Synchrotrons – The Life of a Beam

From the starting point as a chunk of material, the entire system is under vacuum

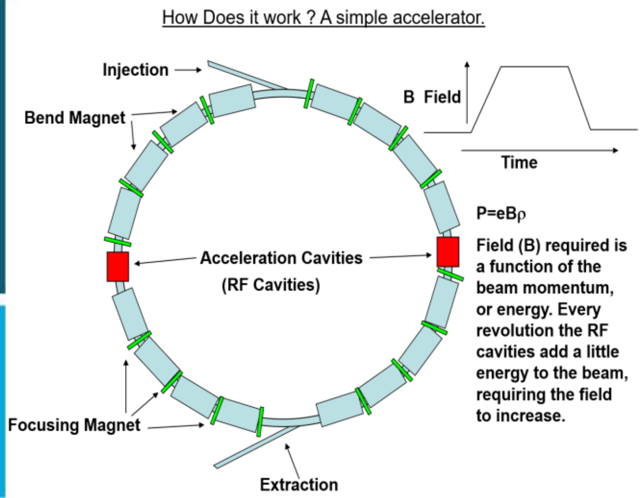
Material is ablated by laser, drifts by EM forces into EBIS, more electrons removed

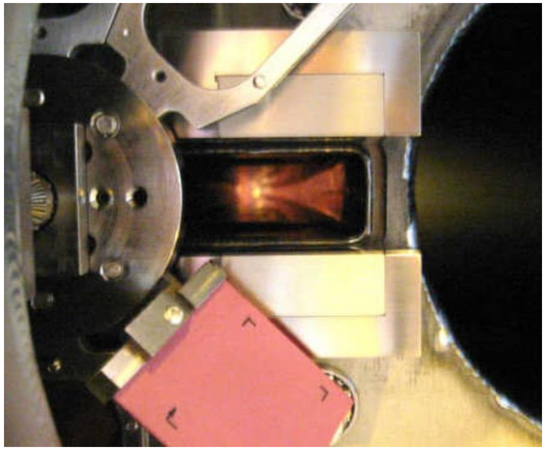
Ions are steered, injected, and accelerated as a group called a "bunch"

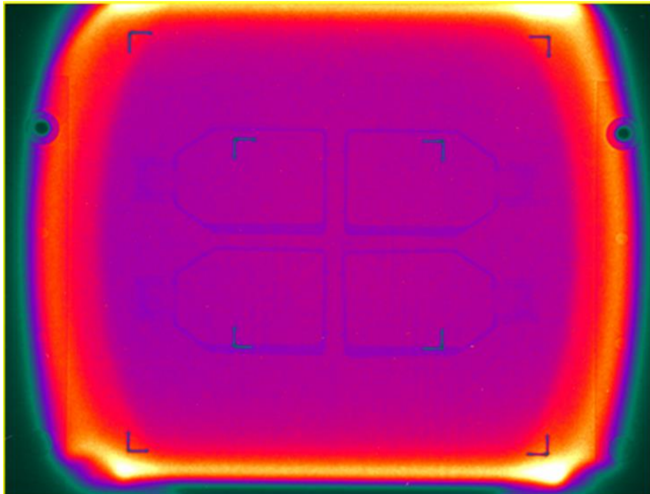
A bunch will travel many millions of rotations during acceleration

After reaching the desired energy, beam is extracted over many rotations

Extracted beam moves through R-line (NRSL) where it is shaped into desired format



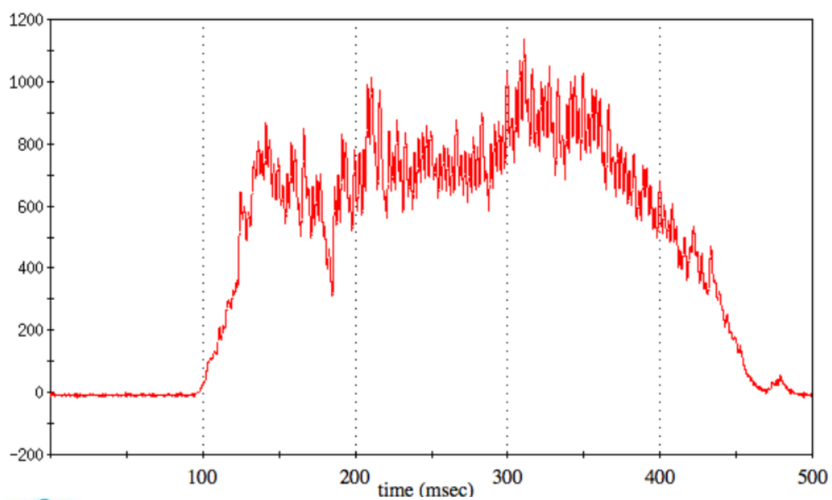


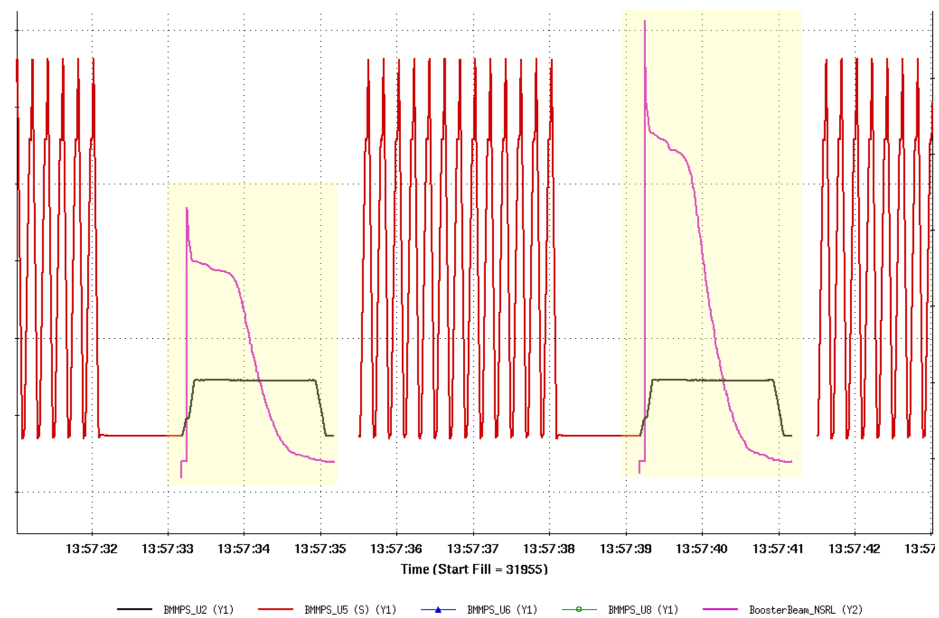


Accelerator Fundamentals & Implications
Synchrotrons – "Spills"

Booster services NSRL and RHIC sequentially/simultaneously

- Accelerator optics can only handle one charge/mass ratio at a time
- Ion source, power supplies, and system controls switch between "users"
- Time divided between systems (for 6 second cycle, approx. 3 & 3 split)
- When RHIC is not operating, cycle is shortened to half
- Extraction of beam is generally around 350 ms, varies by beam (100-600 ms)





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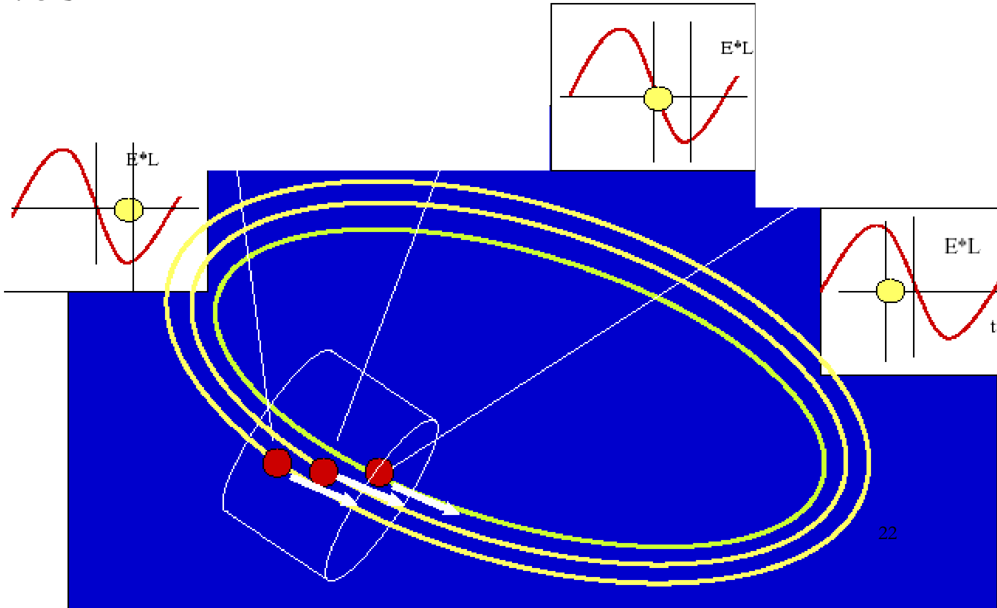
Accelerator Fundamentals & Implications
Beam Energy

Due to the nature of bunched ions, RF cavities, and oscillations in synchrotrons, beam ions will not be mono-energetic

Approximately $0.5\% \frac{\Delta p}{p}$ (momentum-based) variation

Using example with $150 \frac{MeV}{u}$ ^{209}Bi on slide 14, ion energy per spill can range between 149.3 < E < 150.65

Energy spread can be several MeV for ions with higher energy and/or lower mass



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Accelerator Fundamentals & Implications Summary

- Booster operates with non-continuous beam
- Spills are approx. 300 ms in time, with 6 second (start-to-start) cycle
- Ions within a spill have small spread of energy

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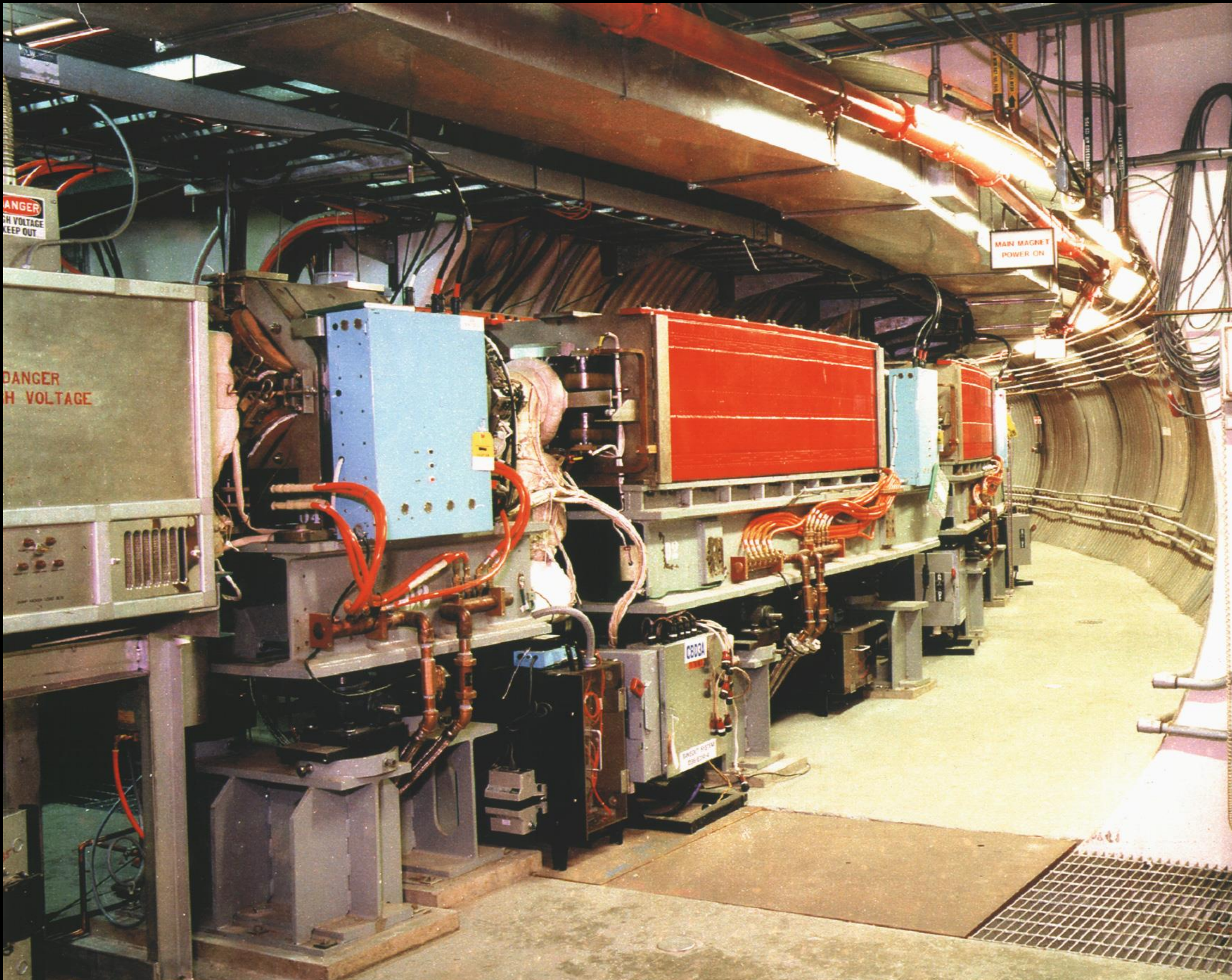
MAIN MAGNET
POWER ON
DANGER
H VOLTAGE
KEEP OUT

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Radiation Interactions

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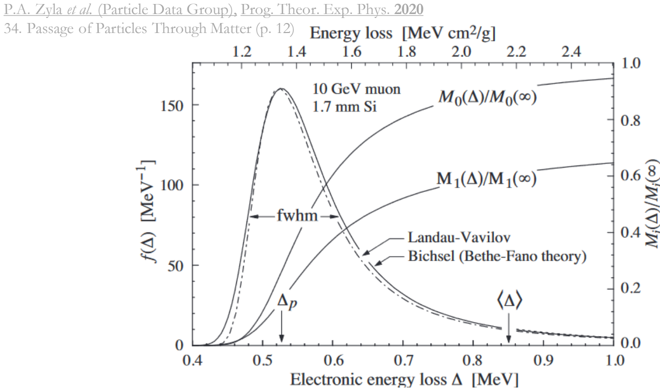
Radiation Interactions Energy Loss

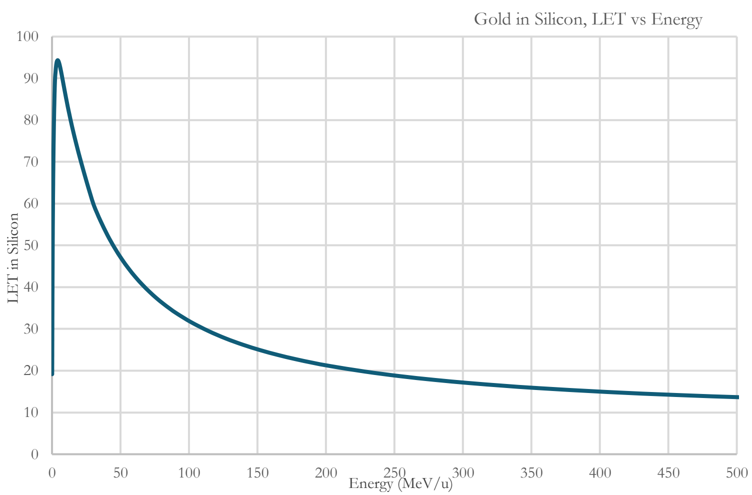


Charged particle energy loss is a statistical process via electromagnetic "collisions" between the ion and the surrounding atomic electric fields

- From Bethe formula, electron dense materials have higher stopping power
- Charged particles continuously lose energy as they traverse a non-vacuum medium
- Towards the end of the ion's path, the dE/dx reaches a maximum, the Bragg peak

Bragg Peak

- Energy loss towards high end of available energies is relatively flat
- Materials in the path of ions will lower the energy and effective range, while increasing LET
- As ions slow towards peak, LET begins to rapidly increase and will not be constant through a volume of material



Radiation Interactions Scattering & Straggling

As charged particles interact with the surrounding electric fields, the trajectory will see multiple small angle scattering effects

Straggling refers to the fluctuation in range (longitudinal straggling) or XY plane position (transverse straggling) brought on by scattering

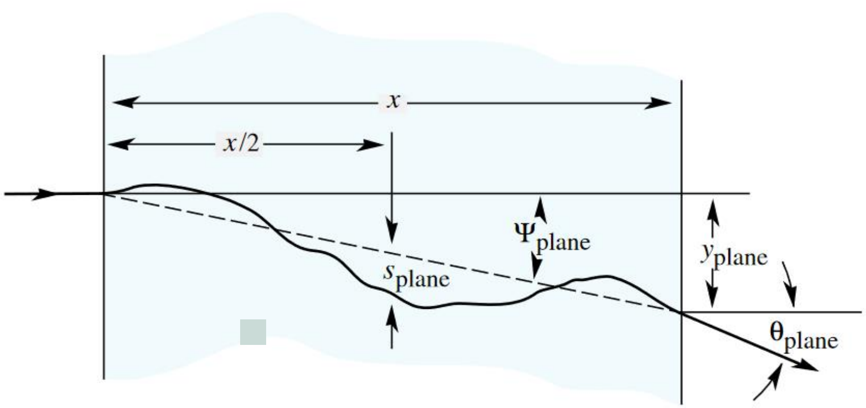
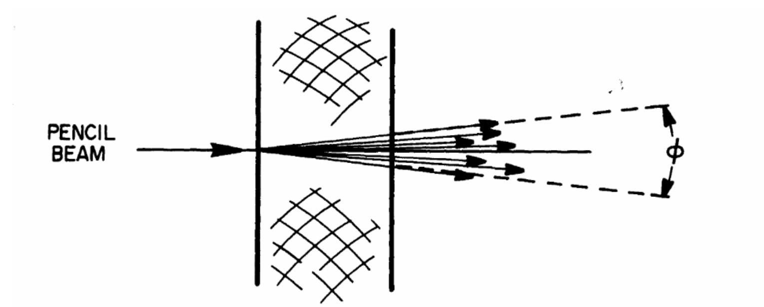


Figure 33.10: Quantities used to describe multiple Coulomb scattering. The particle is incident in the plane of the figure.

P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020) and 2021 update
34. Passage of Particles Through Matter (p. 15)

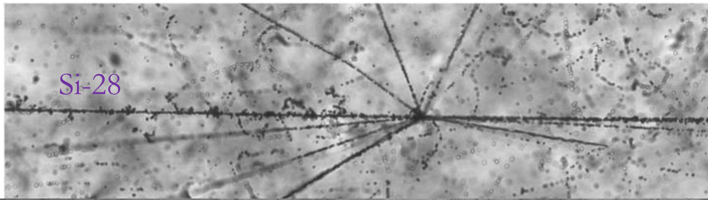


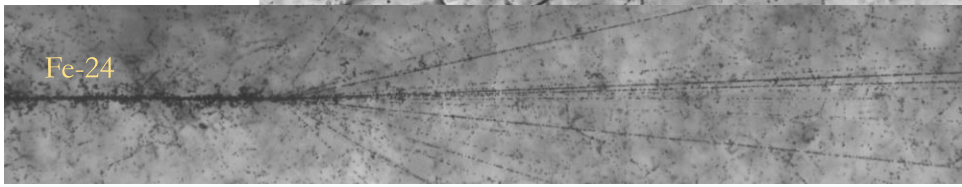
URE 7.7. Multiple Coulomb scattering causes spread in a pencil beam of charged icles as they penetrate matter.

U. Illinois, NPRE 441 Lecture Notes, Spring 2020, Ling Jian Meng
Original source unknown

P. Zarubin et al, Joint Institute for Nuclear Research
http://becquerel.jinr.ru/movies/movies.html

Radiation Interactions Fragmentation

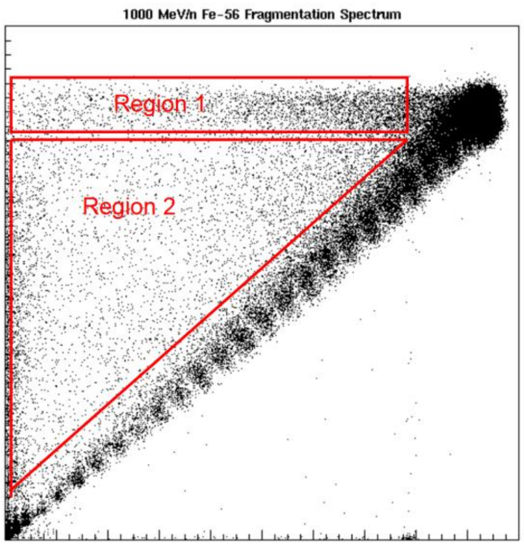


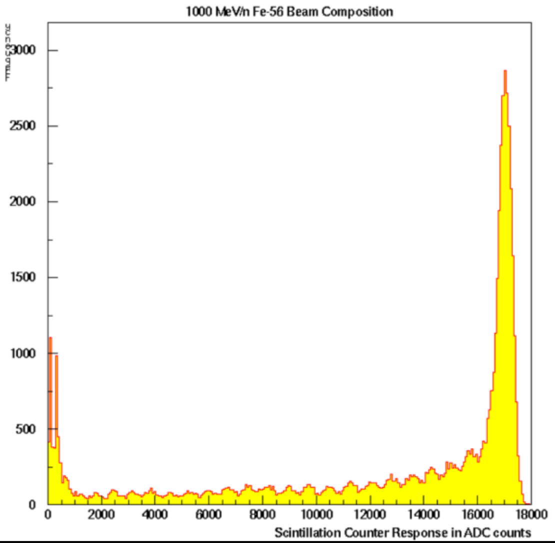


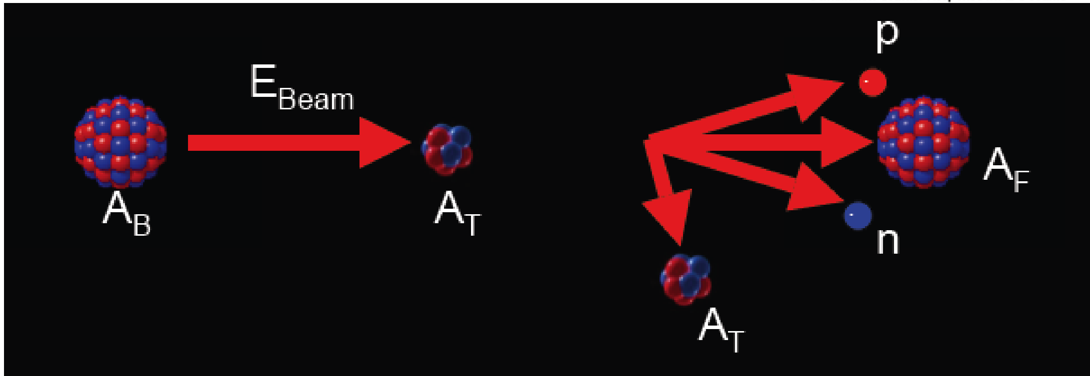
Heavy ions, being a collection of bound neutrons and protons, can "break apart" at high kinetic energies

The most likely fragments would be the primary beam with one fewer proton or neutron

The fragment, if equal in velocity to primary ion, will always have lower LET & longer range







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Mike Sivertz, NSRL
https://www.bnl.gov/nsrl/userguide/beam-fragmentation.php

Radiation Interactions
Why is this important?

We have seen that beam *ions undergo a series of countless interactions* that can *change their energy, position, trajectory, and even their composition*

No two beam ions will be exactly the same. Take into consideration how many *significant figures* you use and the potential *errors bars* that are built in to claims about LETs and survivability

"Yes, we should test with Au @ 25.00 MeV/u"

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Ion & Energy Considerations

What are you testing for? Does only LET matter?

Testing at the highest kinetic energy and highest Z ensures high range and lower variance in LET across the test volume

To hit specific LET points, highest energy isn't always valuable, but try to keep above 150 $\frac{MeV}{u}$

For high LETs, we use highest Z ion (Bismuth currently) at energy 147 $\frac{MeV}{u}$ and add degrader to lower energy; allowing quick step throughs of degrader thicknesses towards higher LETs

Use SRIM/TRIM to determine what entrance energy of Bi will produce your desired LET
Then we will determine necessary polyethylene degrader thickness from initial energy

Our new initiative, called "SEE-Library", will mean we have pre-made and calibrated beams of certain energies which are degraded to appropriate energy for most device "stack-ups"

https://www.bnl.gov/nsrl/userguide/beam-ion-species-and-energies.php

Ion & Energy Considerations

Sample list of LET-based ion/energy choices

LET in Silicon MeV/(mg/cm^2)	Ion & Energy MeV/n	Range in Si mm
0.1	C @ 300	93.92
0.5	Si @ 370	55.43
1	Si @ 121	8.42
2	Fe @ 270	19.73
3	Fe @ 142	6.74
4	Nb @ 417	26.65
5	Nb @ 270	13.28
6	Nb @ 199	8.06

LET in Silicon MeV/(mg/cm^2)	Ion & Energy MeV/n	Range in Si mm
7	Ag @ 246	9.97
8	Ag @ 197	6.95
9	Ag @ 163	5.09
10	Tb @ 381	16.81
12.5	Tb @ 247	8.51
15	Ta @ 278	9.26
20	Bi @ 273	8.06
25	Bi @ 180	4.22

LET in Silicon MeV/(mg/cm^2)	Ion & Energy MeV/n	Range in Si mm
30	Bi @ 130	2.59
35	Bi @ 100	1.75
40	Bi @ 79	1.24
45	Bi @ 64	0.92
50	Bi @ 53	0.70
55	Bi @ 44	0.55
60	Bi @ 36	0.44

Current list of available ions and max energy

Ion Species [1]	Max Energy [2] (MeV/n)	LET in Si at Max Energy [6] (MeV/(mg/cm^2))	Peak LET in Si (MeV/(mg/cm^2))	Range in Si (mm)	Max Flux [3] (ions/spill)
H^{1}	2500	0.00171	0.51	5470	2.2×10^{11}
He^{4}	1500	0.006919	1.5	2960	0.3×10^{10}
C^{12}	1500	0.06227	5.2	972	1.2×10^{10}
O^{16}	1500	0.1107	7.3	351	0.4×10^{10}
Ne^{20}	1000	0.178	9	583	1.2×10^{10}
Si^{28}	1000	0.351	14	248	0.3×10^{10}
Ar^{40}	1000	0.600	18.7	207	0.02×10^{10}
Ti^{48}	1000	0.854	24.2	175	0.08×10^{10}
Fe^{56}	1000	1.189	29.3	146	0.2×10^{10}
Kr^{84}	383*	3.3	41	26.9	2.0×10^{7}
Nb^{93}	520	3.6	47.4	37.5	1×10^{7}
Ag^{107}	575	4.65	59.4	17.9	6×10^{6}
Xe^{129}	350*	7.67	69.3	16.1	5.0×10^{7}
Tb^{159}	446	9.32	78.2	21.4	4.0×10^{7}
Ta^{181}	342*	13.5	87.7	12.8	4.5×10^{7}
Au^{197}	242*	19.2	94.4	6.9	1.0×10^{8}
Bi^{209}	359	17.6	100.0	12.2	7.0×10^{7}
High Charge State Beams *(Lower Max Beam Intensity)*					
Kr^{84}	721	2.54	41	70.5	
Xe^{129}	589	6.1	69.3	35.8	
Ta^{181}	475	11.7	87.7	21.1	
Au^{197}	400	15	94.4	14.9	

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https://www.bnl.gov/nsrl/userguide/beam-ion-species-and-energies.php

Outline

- Introduction to NSRL
- Units and Scale
- Accelerator Fundamentals & Testing Implications
- "Radiation" Interactions
    - Ion/Energy choices
- **NSRL Beamline & Hardware**
- Useful Resources

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NSRL Beamline & Hardware

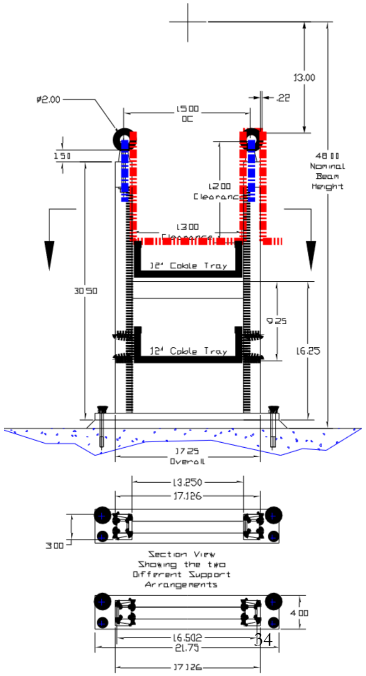
Electronics testing generally done at 38 inches from vacuum window.
  We prepare beam energies for that position (air-corrected).

Standard beam sizes are 20 x 20 cm^2 and 10 x 10 cm^2 uniform area
However, some low energy (E < 120 MeV/u) beams can lose uniformity beyond 18x18 cm^2
Large 60 x 60 cm^2 beams only possible far from vacuum

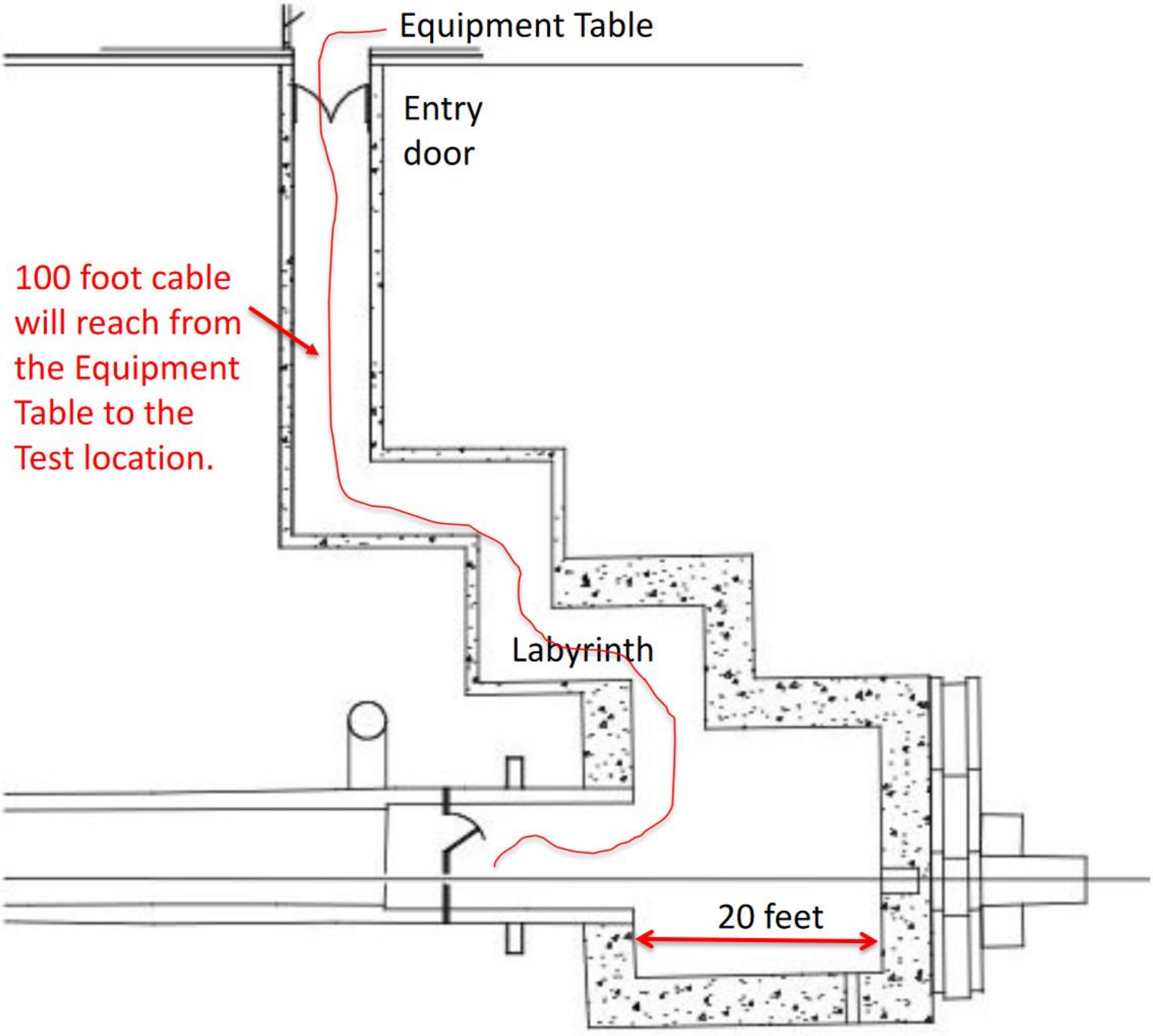
Target stands and other equipment use ¼”- 20 threading

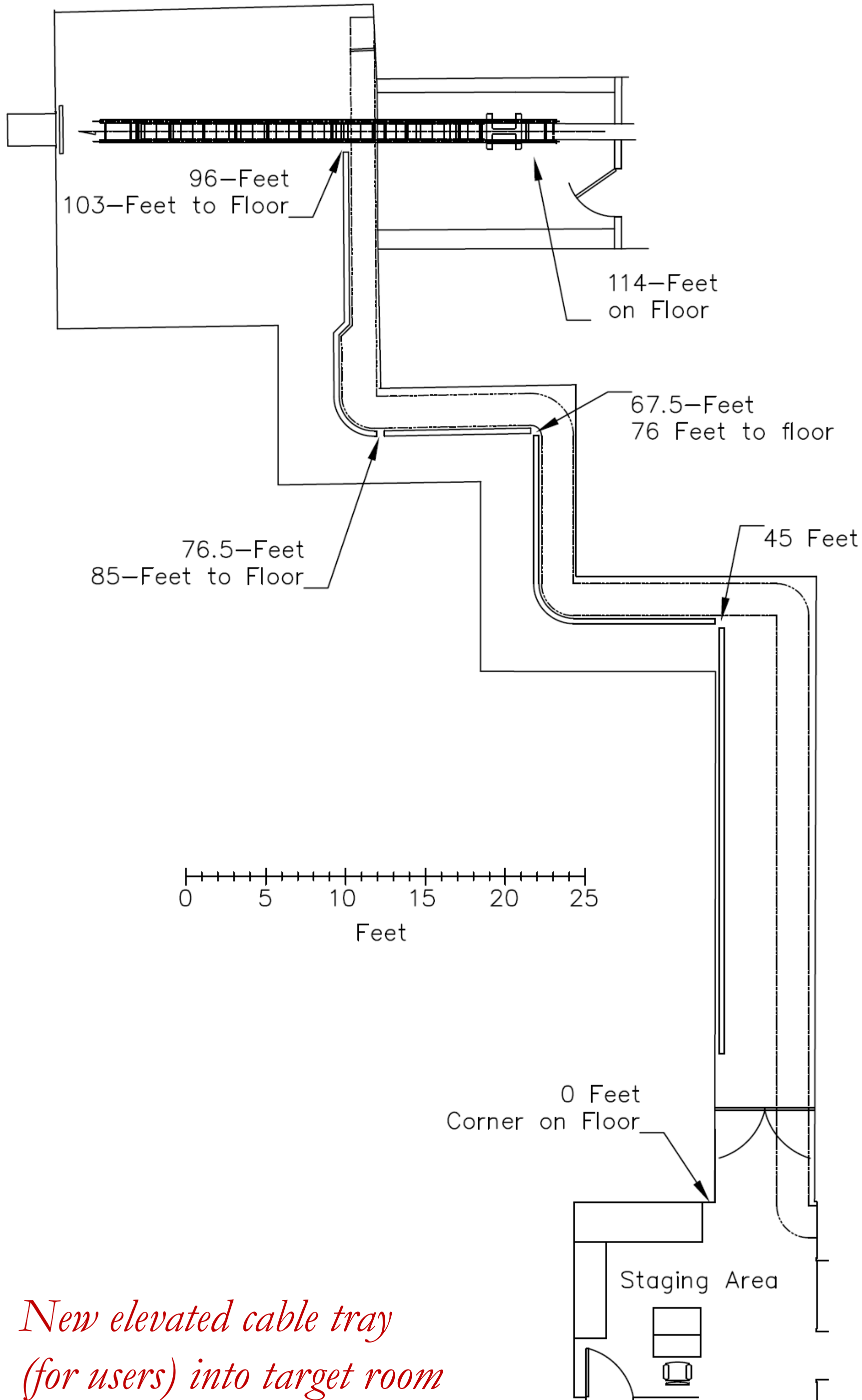
Beam center is 13 inches above rails
  Approx. 11.25 to 8.25 inches above target stand plate

Degrader is polyethylene with 12.7 mm max thickness (remote ctrl)
  with additional manually inserted blocks of 12.8 & 25.6 mm



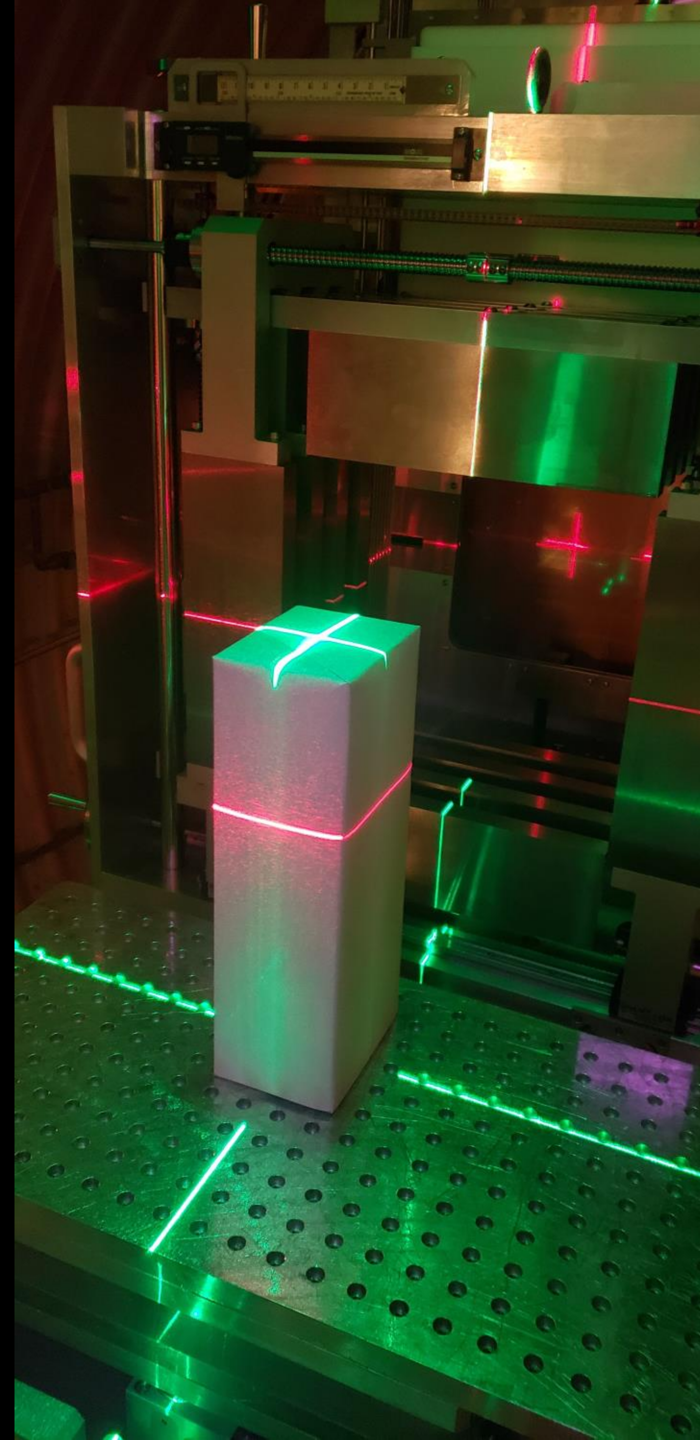
OFF
ON
1
2
3
1
2
3


Equipment Table
Entry
door
100 foot cable
will reach from
the Equipment
Table to the
Test location.
Labyrinth
20 feet

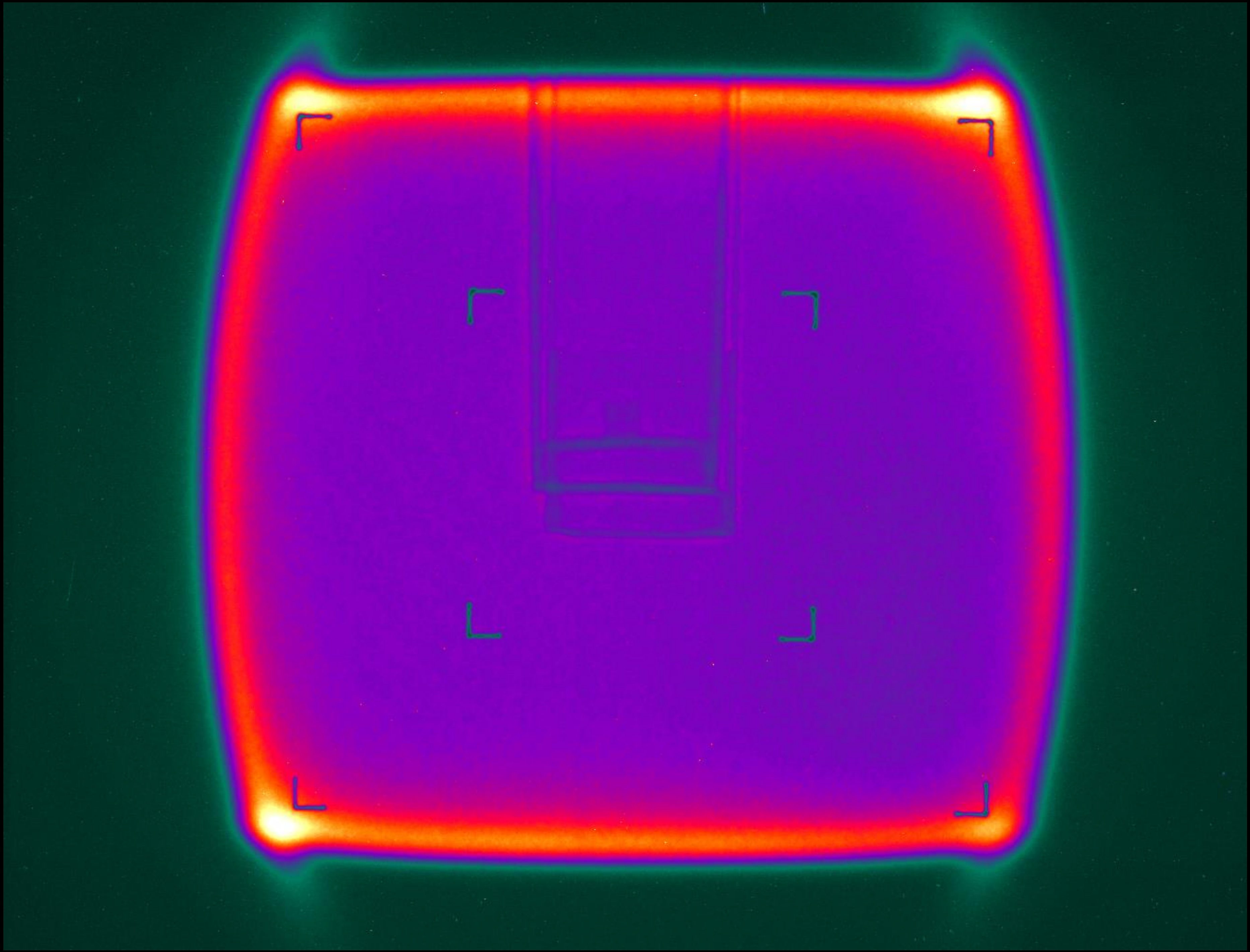


New elevated cable tray (for users) into target room


CAUTION
THIS DEVICE MAY
OPERATE REMOTELY


CAUTION



Down Stream



NSRL Beamline & Hardware Collected Data

Data is gathered and logged for every spill/cycle containing # of ions/cm^2 with a corresponding time stamp

After a period of time where users would apply a calibration manually, the data is now pre-calibrated

Example of spill-by-spill data sent to user:

- Note time stamps occur with 6 or 7 second increments (6.6 second cycle time)
- Spills with no beam can show values above or below 0 due to detector sending signal which is roughly ±1 – 5 an then calibrated

Redacted

Sat	10:42:15	2020	-0.6
Sat	10:42:21	2020	-0.6
Sat	10:42:28	2020	-2.6
Sat	10:42:34	2020	0.4
Sat	10:42:41	2020	0.4
Sat	10:42:48	2020	1.4
Sat	10:42:54	2020	0.4
Sat	10:43:01	2020	-2.6
Sat	10:43:07	2020	0.4
Sat	10:43:14	2020	3.4
Sat	10:43:21	2020	-2.6
Sat	10:43:27	2020	1.4
Sat	10:43:34	2020	-2.6
Sat	10:43:40	2020	-0.6
Sat	10:43:47	2020	0.4
Sat	10:43:54	2020	3.4
Sat	10:44:00	2020	823.4
Sat	10:44:07	2020	731.4
Sat	10:44:13	2020	744.4
Sat	10:44:20	2020	793.4
Sat	10:44:27	2020	762.4
Sat	10:44:33	2020	769.4
Sat	10:44:40	2020	759.4
Sat	10:44:46	2020	822.4
Sat	10:44:53	2020	741.4
Sat	10:45:00	2020	759.4
Sat	10:45:06	2020	685.4
Sat	10:45:13	2020	779.4
Sat	10:45:19	2020	813.4
Sat	10:45:26	2020	797.4
Sat	10:45:33	2020	759.4
Sat	10:45:39	2020	812.4
Sat	10:45:46	2020	799.4
Sat	10:45:52	2020	834.4
Sat	10:45:59	2020	727.4
Sat	10:46:06	2020	757.4
Sat	10:46:12	2020	914.4
Sat	10:46:19	2020	1025.4
Sat	10:46:25	2020	1016.4
Sat	10:46:32	2020	1413.4
Sat	10:46:39	2020	1501.4
Sat	10:46:45	2020	1937.4
Sat	10:46:52	2020	2065.4
Sat	10:46:58	2020	1952.4

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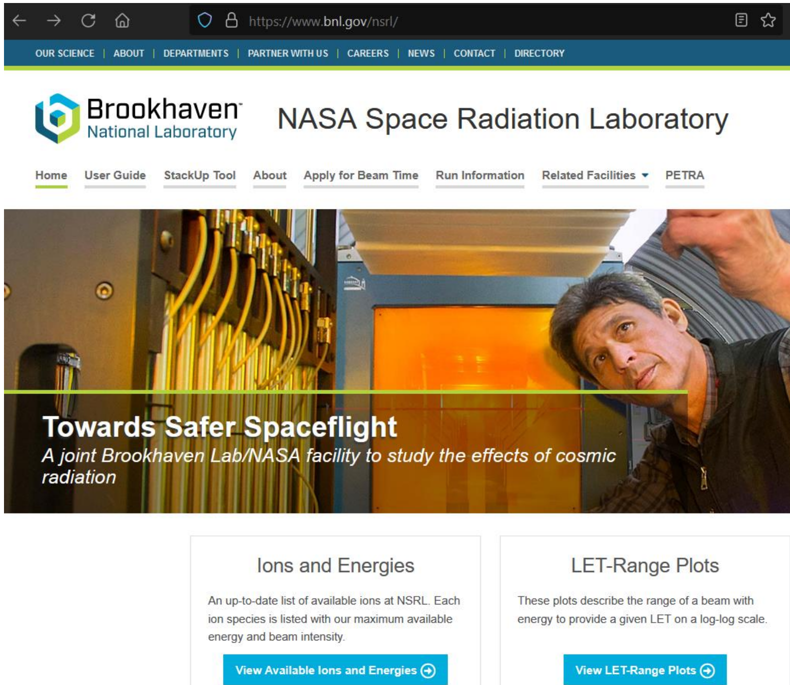
Useful Resources
NSRL Website

- Routinely updated list of ions & energy ranges available
  - Including suggestions for ion/energy choice for desired LETs in silicon
- Images of mounting equipment – vise grips, brackets, plates, etc.
- Collimator information
- SRIM StackUp Download
- User Guide



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Useful Resources
“SRIM StackUp” Calculator

Latest version available at:
bnl.gov/nsrl/stackup

Target:	Silicon
Ion:	Bi

E/ΔE/Δx Calculator

Energy [MeV/u]	dE/dx [MeV/(mg/cm^2)]	Range [mm]	Z Straggling [mm]	XY Straggling [mm]		
139	28.9202	2.8595	0.1069	0.0082	2.16E+03	ions/cm^2/rad

Range [mm]	Energy [MeV/u]	dE/dx [MeV/(mg/cm^2)]	Z Straggling [mm]	XY Straggling [mm]		
15	411.9636	16.5473	0.5991	0.0342	3.77E+03	ions/cm^2/rad

dE/dx [MeV/(mg/cm^2)]	Range [mm]	Energy [MeV/u]	Z Straggling [mm]	XY Straggling [mm]		
33	2.0307	110.5820	0.0747	0.0062	1.89E+03	ions/cm^2/rad
	0.0071	0.2028	0.0004	0.0005	99.9545 max dE/dx	11.811 min dE/dx

Multiple Layers Calculator

Beam Energy [MeV/u]: 100

	Material	Thickness [mm]	Exit Energy [MeV/u]	Residual Range [mm]	Entrance LET	Exit LET
Layer 1:	Polyethylene	1	77.96	2.21	46.59	53.91
Layer 2:	Aluminum	0.254	64.25	0.82	39.15	43.63
Layer 3:	Sn63Pb	0.1	51.87	0.32	29.32	32.56
Layer 4:	Copper	0.01	50.08	0.22	41.14	41.89
Layer 5:	Epoxy	0.05	47.27	0.60	63.00	64.96
Layer 6:	Silicon	0.2	34.65	0.41	52.82	61.43
Layer 7:	Silicon	0	34.65	0.41	61.43	61.43
Layer 8:	Gold	0	34.65	0.10	35.84	35.84
Layer 9:	Gold	0	34.65	0.10	35.84	35.84
Layer 10:	Gold	0	34.65	0.10	35.84	35.84

Useful Resources
"SRIM StackUp" Calculator

Database compiled from automated SRIM queries for all ion/material combinations. Materials in this list are driven by user community needs.

Interpolation performed for values between SRIM produced datapoints

- Input ion & target material (via drop-down box)
- E/ΔE/Δx Calculator section
  - Enter an energy to show LET and range
  - Enter desired LET to show corresponding energy and range
  - Enter required range to show minimum energy and max LET
- Multiple Layer Calculator section
  - Enter incident ion energy in appropriate field
  - For each layer, choose the material from drop-down box and enter thickness in mm
  - Read the LET-in and LET-out cell for the layer of interest

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Target:	Silicon
Ion:	Bi

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Concluding Remarks

NSRL operates differently to other SEE testing facilities

Consider these conditions and adjust test practices accordingly

Additional resources:

P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01
§34. Passage of Particles Through Matter
https://pdg.lbl.gov/2021/reviews/rpp2020-rev-passage-particles-matter.pdf

NSRL Website – User Guide
https://www.bnl.gov/nsrl/userguide/

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