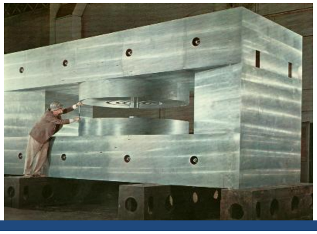
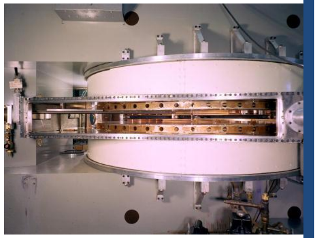
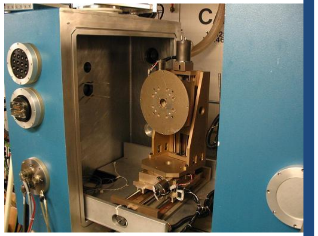
The 88-Inch Cyclotron



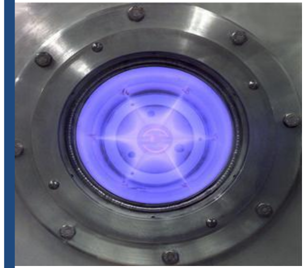


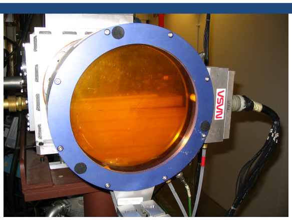



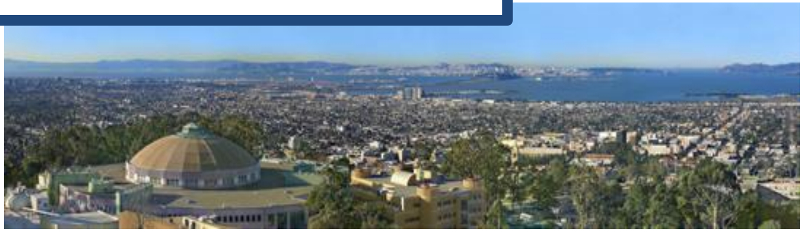
Larry Phair

Program Head, 88-Inch Cyclotron

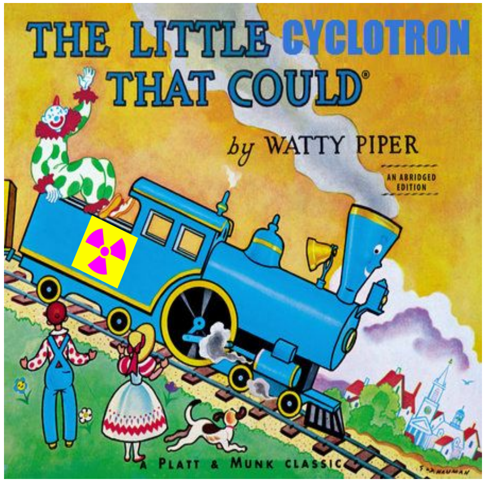
Lawrence Berkeley National Laboratory





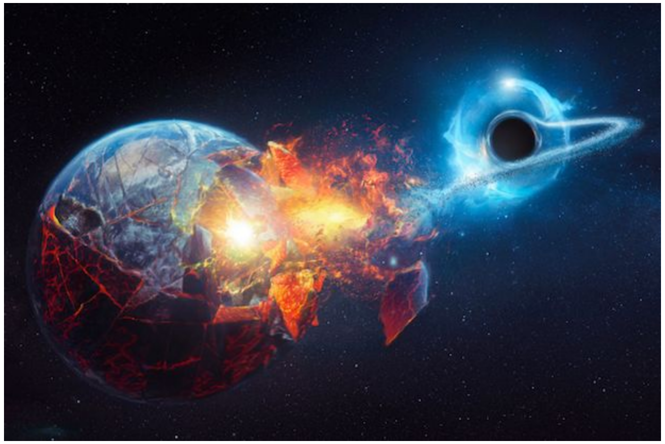
What is a "Cyclotron"?



As seen by Cyclotron Operations:
"Can-do" capability!

As seen by Lab Management:
Still going! Never say die!

As seen by Cyclotron Researchers:
Endless possibilities & flexibility!

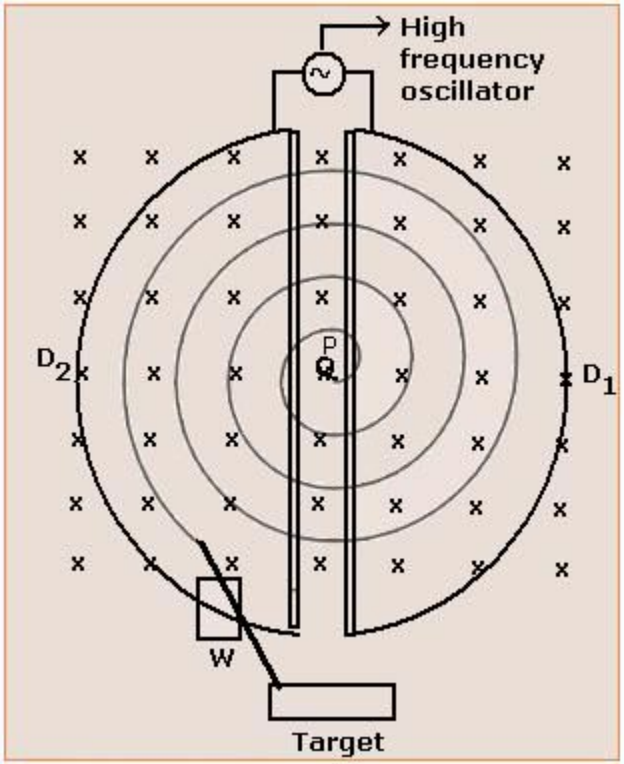


As seen by Conspiracy Crowd:
It makes black holes! It will destroy the Earth!

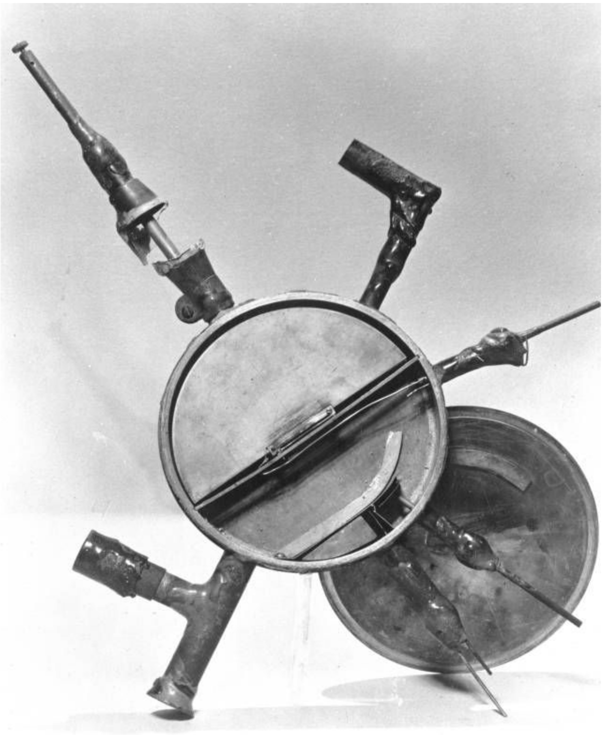
As seen by General Public:
Danger, Will Robinson!

As seen by Safety Personnel:
Old, hazardous, and scary!

Cyclotron Basics



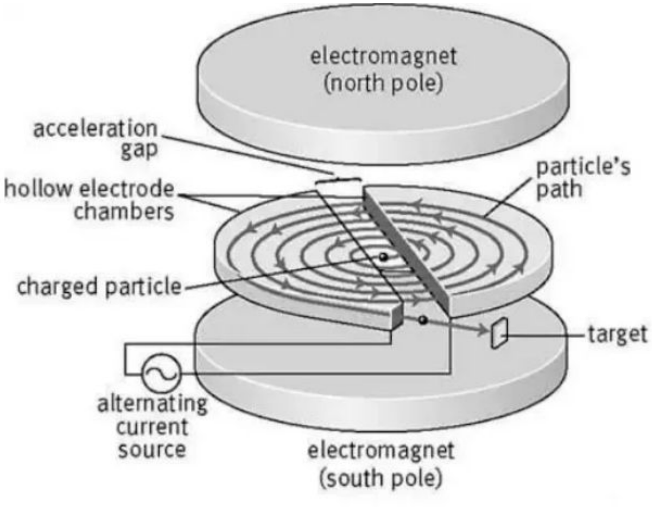
Cyclotron operation

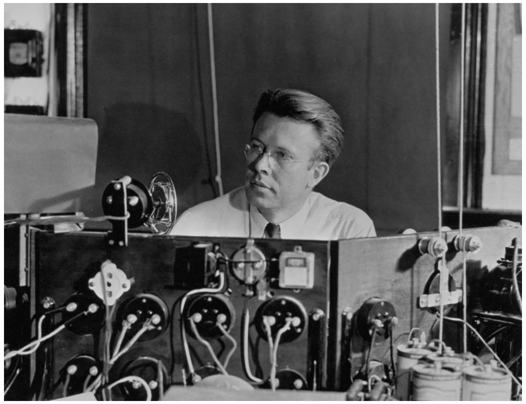


Lawrence's first (4-inch) cyclotron

Cyclotron Basics

Berkeley Lab's 184-Inch Cyclotron, the largest single-magnet cyclotron ever built.





Ernest O. Lawrence at the controls of the 37-Inch Cyclotron.

$$E/A = K\,(q/A)^2$$

E = energy

A = atomic mass number

K = "k-value" (maximum rigidity)

q = ion charge

$$m\,v = q\,B\,r$$

m = ion mass

v = ion velocity

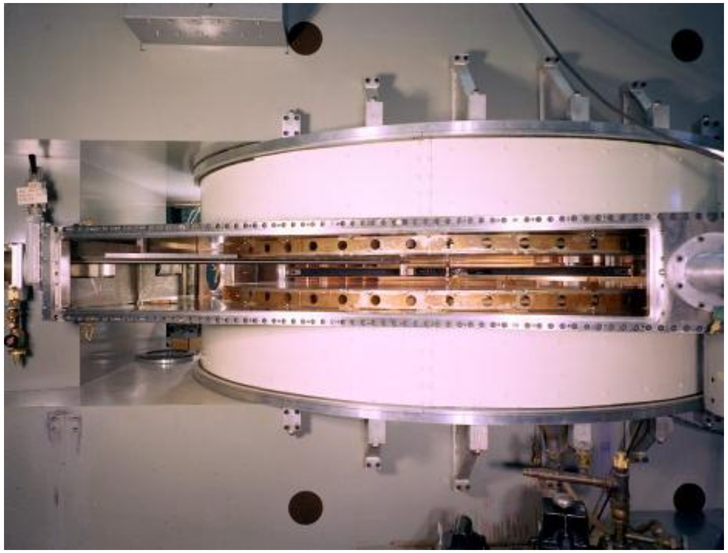
r = orbital radius

B = magnetic field

$$f = \frac{q\,B}{2\,\pi\,m}$$

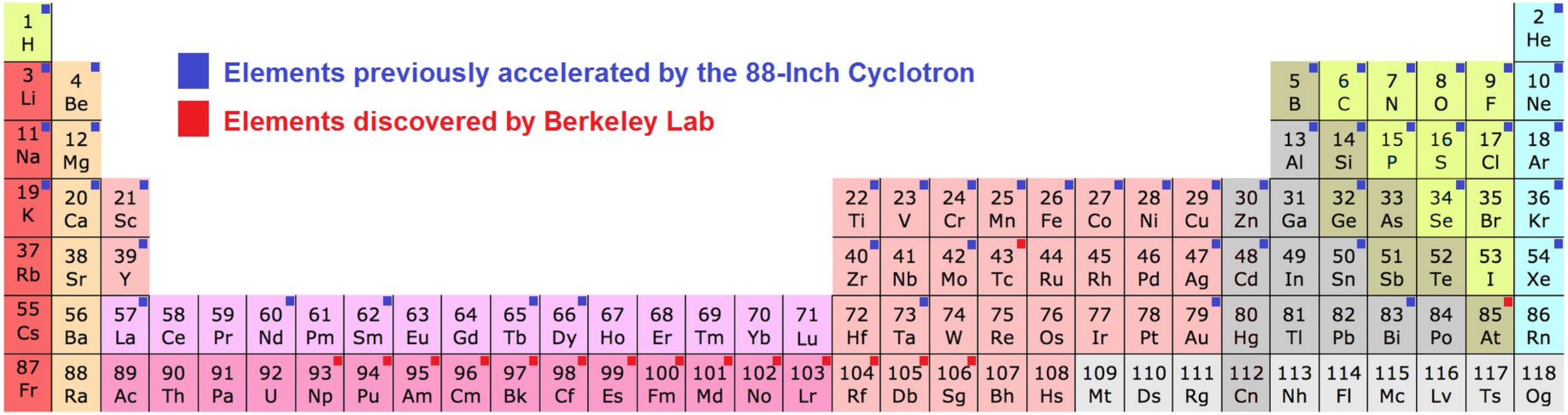
f = cyclotron resonance frequency

The 88-Inch Cyclotron



- 300 tons of metal
- First beam in Dec. 1961
- K = 140 (35 MeV/nucleon)
- Sector-focused: magnetic field increases with both angular position and radius
- Isochronous: frequency is constant between 5.6 and 16.5 MHz, with 1st and 3rd harmonics available
- We run 24/7, up to ~6,000 hours/year (currently at 3500 hours/year)
- Capable of accelerating H through U

Elements

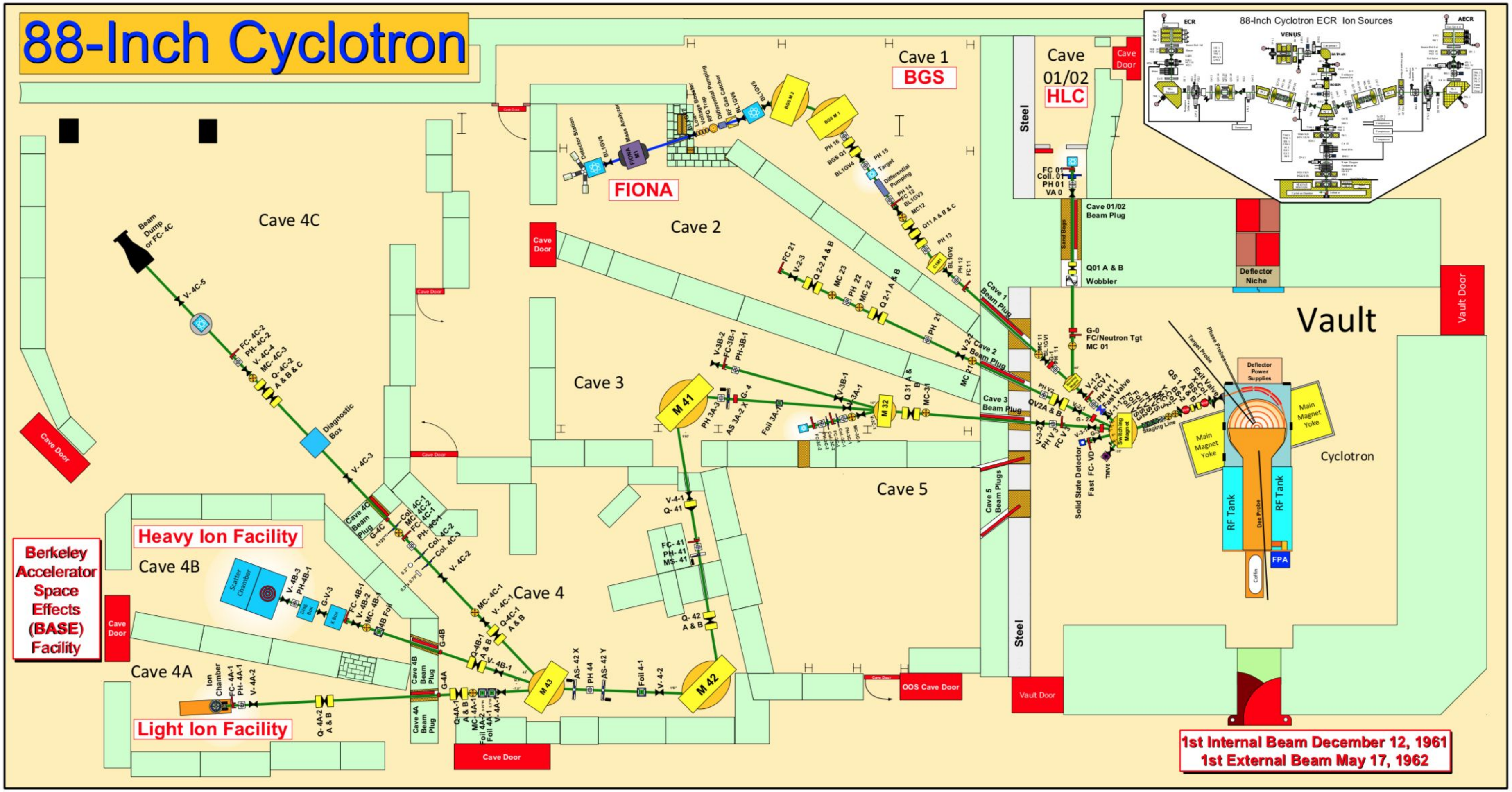


🟦 Elements previously accelerated by the 88-Inch Cyclotron

🟥 Elements discovered by Berkeley Lab

1 H 🟦																															2 He 🟦
3 Li 🟦	4 Be 🟦																									5 B 🟦	6 C 🟦	7 N 🟦	8 O 🟦	9 F 🟦	10 Ne 🟦
11 Na 🟦	12 Mg 🟦																									13 Al 🟦	14 Si 🟦	15 P 🟦	16 S 🟦	17 Cl 🟦	18 Ar 🟦
19 K 🟦	20 Ca 🟦	21 Sc 🟦															22 Ti 🟦	23 V 🟦	24 Cr 🟦	25 Mn 🟦	26 Fe 🟦	27 Co 🟦	28 Ni 🟦	29 Cu 🟦	30 Zn 🟦	31 Ga	32 Ge 🟦	33 As	34 Se 🟦	35 Br	36 Kr 🟦
37 Rb	38 Sr	39 Y 🟦															40 Zr 🟦	41 Nb	42 Mo 🟦	43 Tc 🟥	44 Ru	45 Rh	46 Pd	47 Ag 🟦	48 Cd 🟦	49 In	50 Sn 🟦	51 Sb	52 Te	53 I	54 Xe 🟦
55 Cs	56 Ba	57 La 🟦	58 Ce	59 Pr	60 Nd 🟦	61 Pm	62 Sm 🟦	63 Eu	64 Gd	65 Tb 🟦	66 Dy 🟦	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	72 Hf	73 Ta 🟦	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au 🟦	80 Hg	81 Tl	82 Pb	83 Bi 🟦	84 Po	85 At 🟥	86 Rn
87 Fr	88 Ra	89 Ac	90 Th	91 Pa	92 U	93 Np 🟥	94 Pu 🟥	95 Am 🟥	96 Cm 🟥	97 Bk 🟥	98 Cf 🟥	99 Es 🟥	100 Fm 🟥	101 Md 🟥	102 No 🟥	103 Lr 🟥	104 Rf 🟥	105 Db 🟥	106 Sg 🟥	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

88” Cyclotron, internal beams (protons)



Outline (path through the caves)

Roof: ECR ion sources

Caves 0, 5: neutron beams

Caves 1, 2: Super-heavy elements

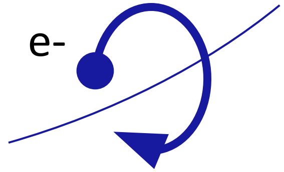
Caves 4A, 4B: Radiation effects testing

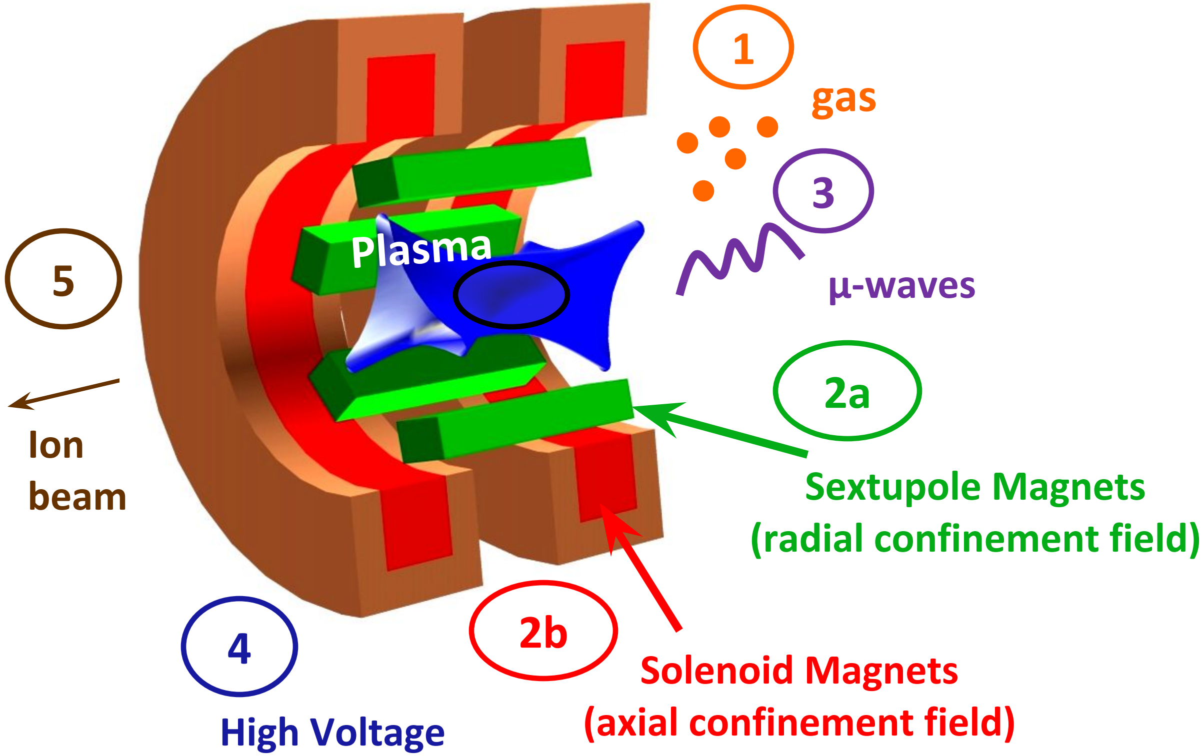
ECR Ion Source Physics

ECR: Electron Cyclotron Resonance

$$\frac{e\cdot B_{ECR}}{m_e} = \omega_{\mu-wave}$$

$$\omega_{\mu-wave} = 28GHz \rightarrow B_{ECR} = 1T$$





1 gas

3 µ-waves

2a

Sextupole Magnets
(radial confinement field)

5

Ion beam

4

High Voltage

2b

Solenoid Magnets
(axial confinement field)

Key Ingredients

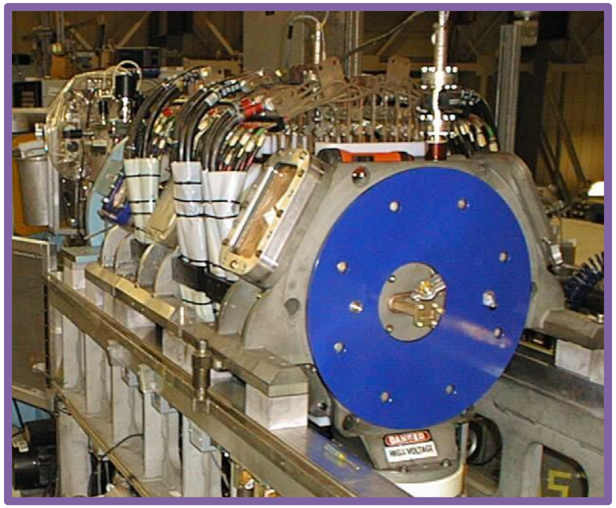
1 gas
\+
2a radial field
\+
2b axial field
\+
3 µ-waves
\+
4 High Voltage
=
5 Ion beam

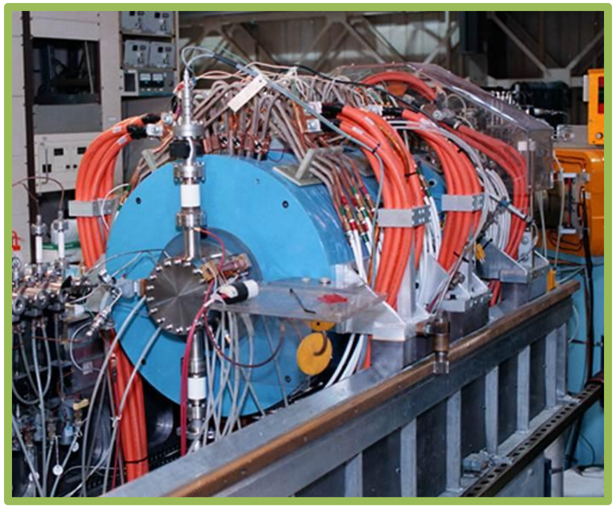
New ion source proposed at the 88

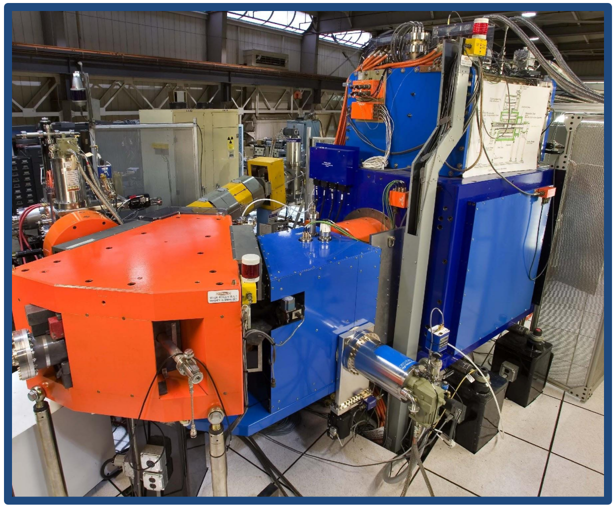
ECR (Gen 1)
1980s
Max B-Field: 0.4 T
Frequencies: 6.4 GHz
Max Power: 0.6 kW

AECR (Gen 2)
1990s
Max B-Field: 1.7 T
Frequencies: 10, 14 GHz
Max Power: 2.6 kW

VENUS (Gen 3)
2000s
Max B-Field: 4.0 T
(superconducting)
Frequencies: 18, 28 GHz
Max Power: 12 kW



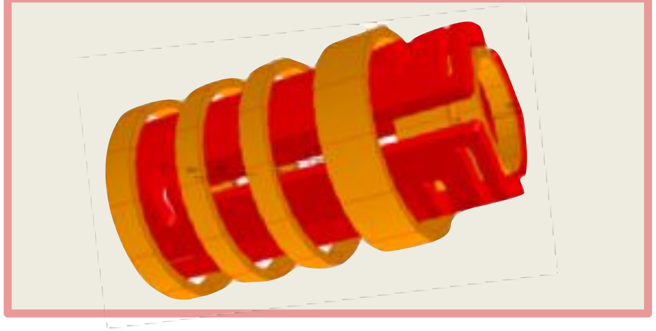




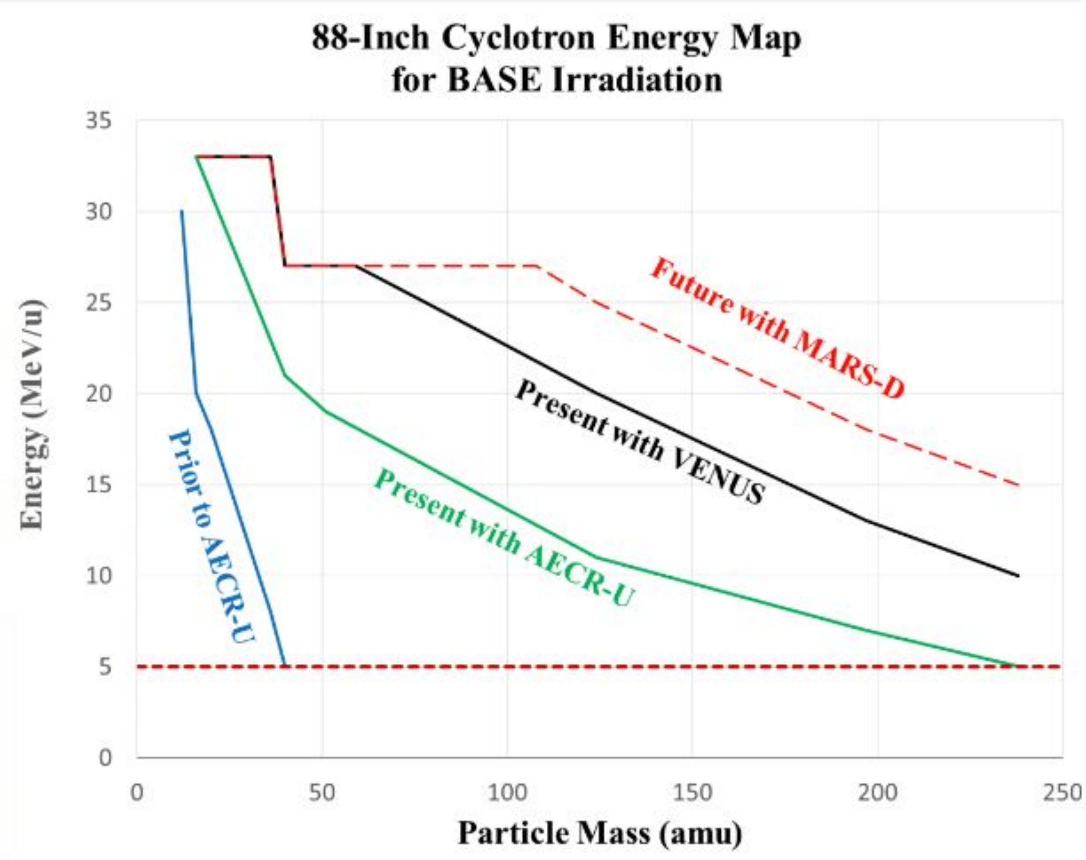
Under development:

Proposal submitted this year.

MARS (Gen 4)
Max B-Field: 5.7 T
Frequency: 45 GHz
Max Power: 20 kW



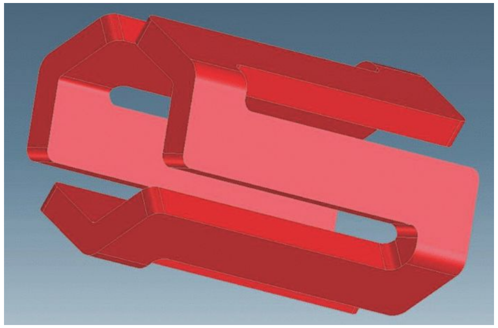
MARS Ion Source



$$\overset{\uparrow}{E}/A = K\,(\overset{\uparrow}{q}/A)^2$$

- Higher charge-state ions going into the cyclotron means higher energy beams at the output
- MARS allows for higher beam intensities than previous ion sources by a factor of 5 (for ions with the same charge state)
- An additional ion source adds redundancy, which reduces failure time

MARS will have NbTi closed-loop sextupole windings



3D view of MARS windings

World-leading ECR ion source group

VENUS records

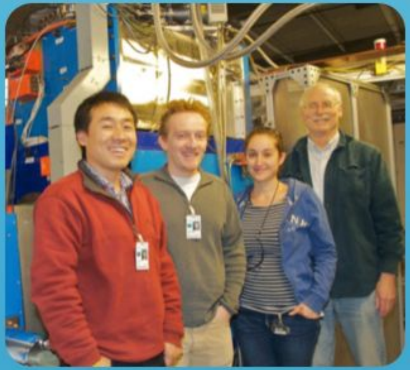
Ion	Chg	Intensity (eμA)
^{4}He	2+	11,000
^{16}O	6+	3,000
^{40}Ar	11+	860
^{209}Bi	31+	300
^{209}Bi	50+	5.3
^{238}U	33+	440
^{238}U	50+	13
^{40}Ca	11+	400

Why these records are important...

FRIB needs very high intensity high-charge-state beams.

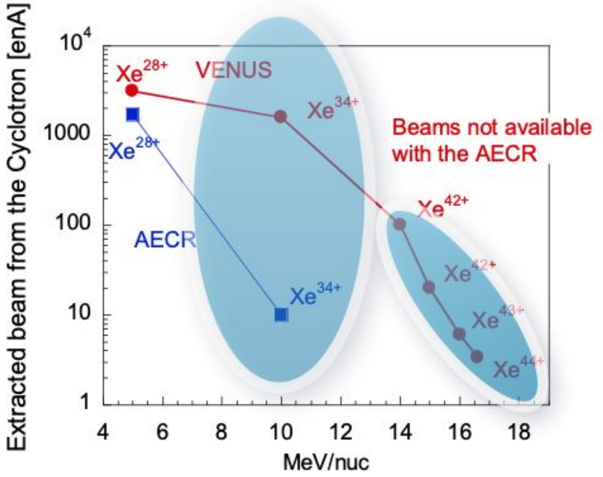
- Low emittance beams for high intensity transmission (super heavy studies)

  - BASE community can use the tails for higher LET in the cocktail
    - Xe in the 16 AMeV cocktail
    - Bi in the 10 AMeV cocktail

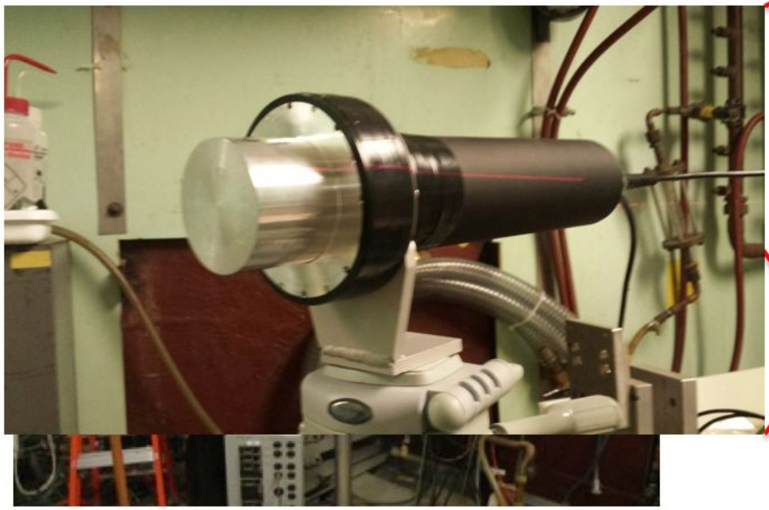


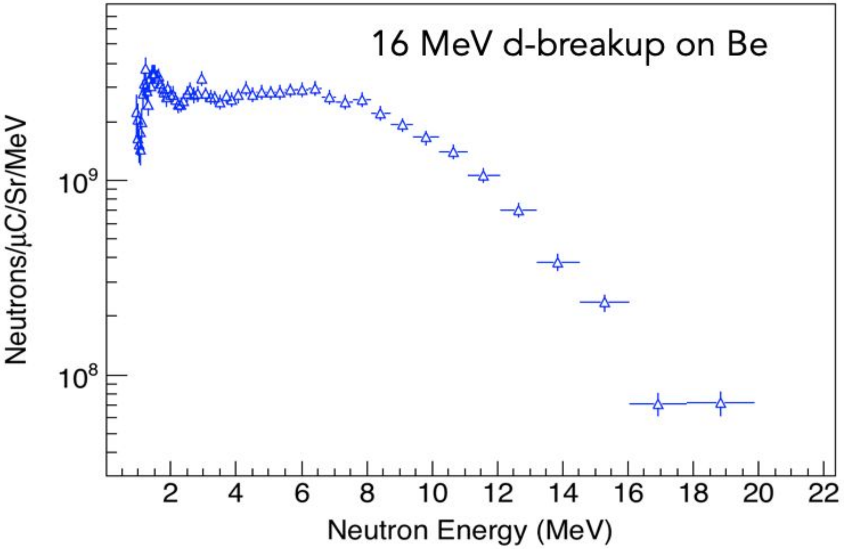
Collaboration with MSU

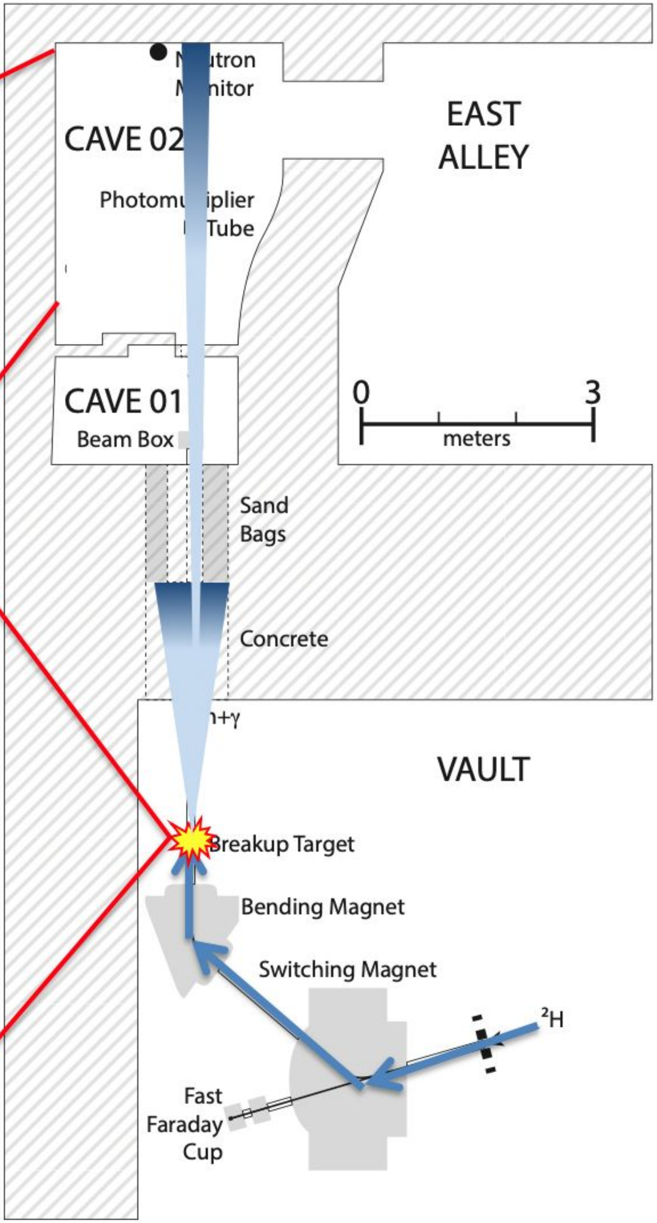
$^{238}U^{33+}$: 430 µA



D-Breakup Neutron Source



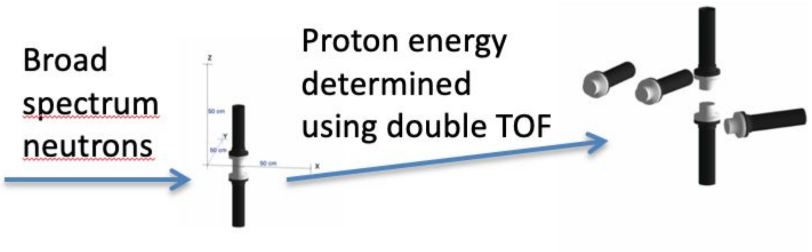




K.P. Harrig , B.L. Goldblum, et al., Nucl. Instrum. Meth. (2017).

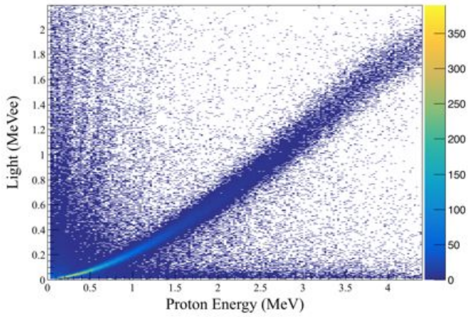
Light Yield Measurements – UCB/LBNL Approach

New dTOF method developed at the 88-Inch extends the indirect technique using a high flux tunable broad spectrum d-breakup neutron source



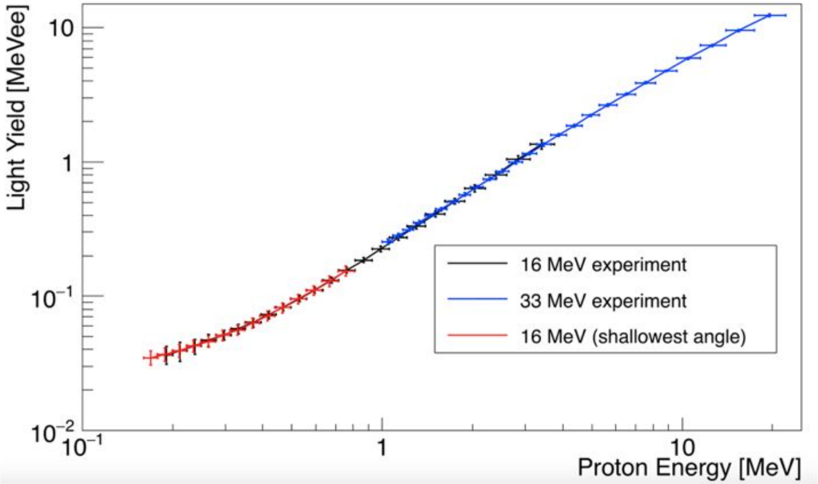
Broad spectrum neutrons

Proton energy determined using double TOF



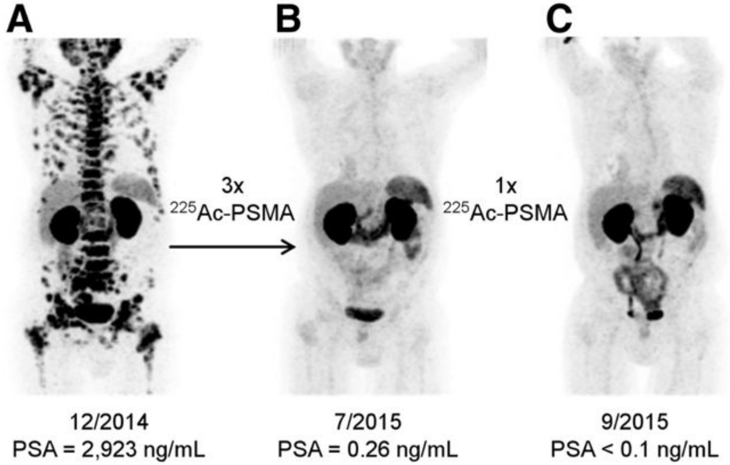
Each detector pair results in a continuous light yield measurement over a broad energy range

- ***Higher flux = Shorter measurement times***
  - DD generator (commercial): <10^5 n/s/sr
  - DT generator (commercial): <10^7 n/s/sr
  - DD generator (dedicated facility): <10^8 n/s/sr
  - ***88-Inch Cyclotron: >10^9 n/s/sr at 0 °***
- ***Higher flux = More accurate measurements***—Smaller detectors and larger flight times (i.e. more accurate scattering angle) while maintaining reasonable event rates



Consistent LY measurements from 200 keV to 20 MeV with full UQ

Production of ^{225}Ac ($t_{½}$= 9.9 d) via thick target D-breakup

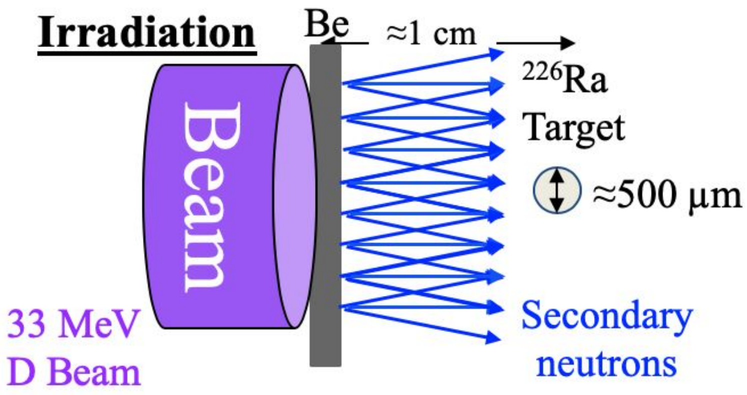


12/2014
PSA = 2,923 ng/mL

7/2015
PSA = 0.26 ng/mL

9/2015
PSA < 0.1 ng/mL

Irradiation



Preliminary Results

- Pre-separation ^{225}Ac activity: 53.9 kBq (1.46 uCi)
- Post-separation ^{225}Ac activity: 49.3 kBq (1.33 uCi)
- Separation efficiency: 91.4 %
- Production rate: **2.1 mCi/mAh/g with r < 0.5 mm**
- Subsequent milking would produce more

2-month count period on HPGe show:

- No fission fragments identified in separated ^{225}Ac.
- No measurable activity of ^{227}Ac ($t_{½}$=21.8 y)) contaminant (^{227}Ac MDA: ≈218 Bq (5.9 nCi) or **<0.4% radio-impurity)**

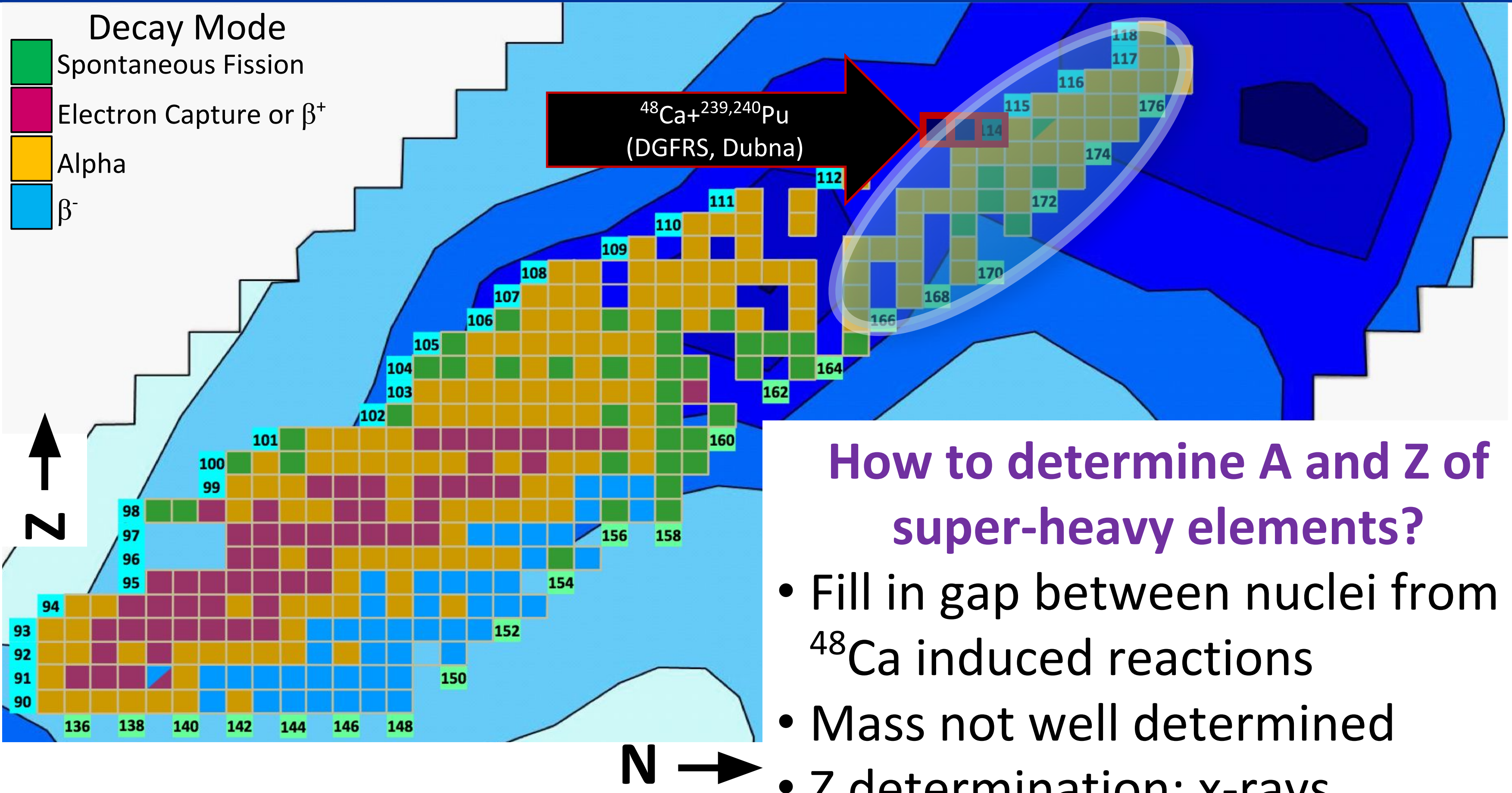
Next Steps:

- Pre-clean ^{226}Ra sample to remove ^{228}Th
- Use different deuteron energies to optimize yield
- Optimize chemical separation procedure.

We need to know $^{d^2\sigma}/_{dE_n d\theta_n}$ for thick target D-breakup

Caves 1 and 2: Home of the Super-Heavy Element (SHE) Program

Chart of the Nuclides



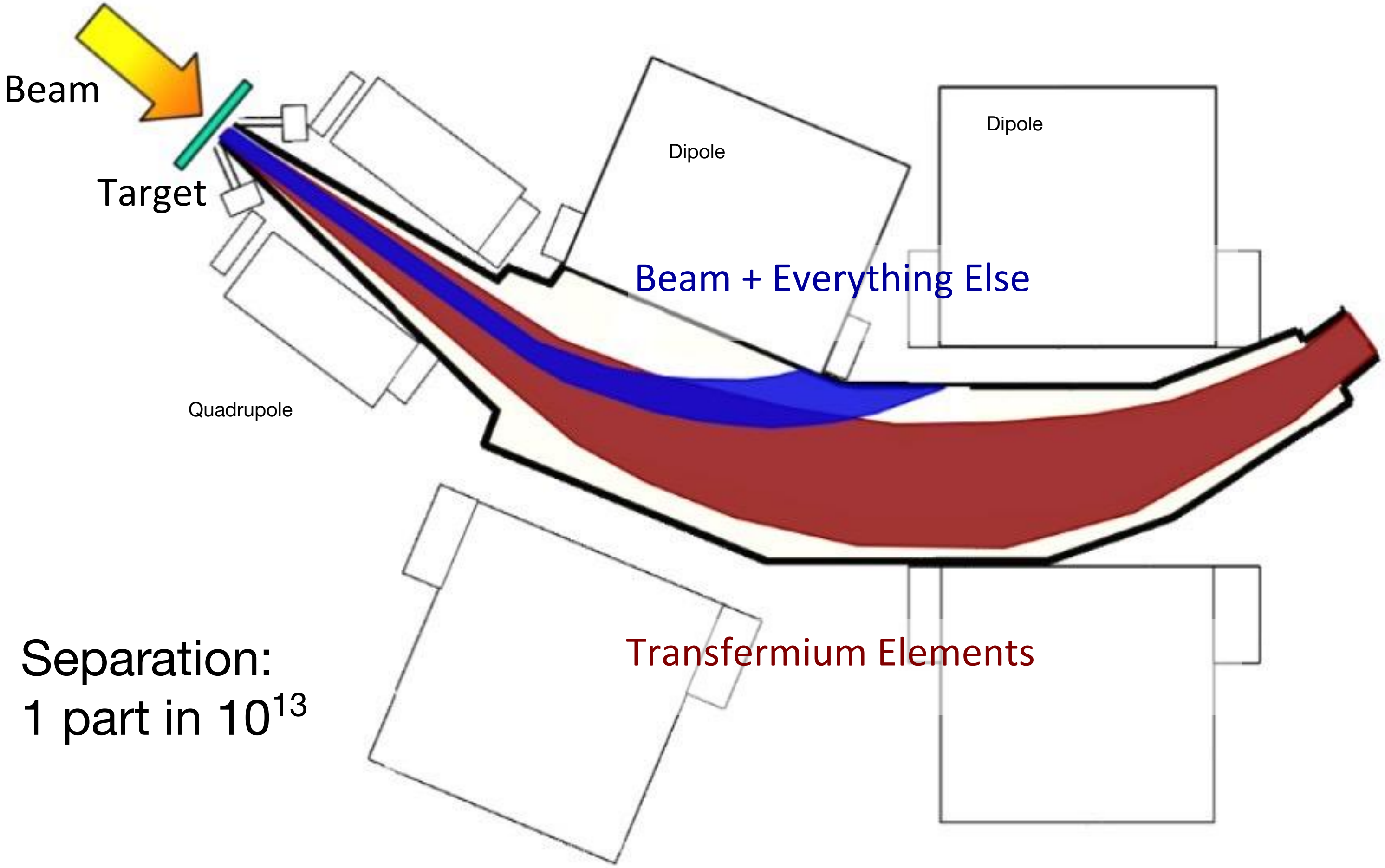
$^{48}Ca + ^{239,240}Pu$
(DGFRS, Dubna)

Shell effects from Sobiczewski et al: Phys. Rev. C 63 (2001) 034306

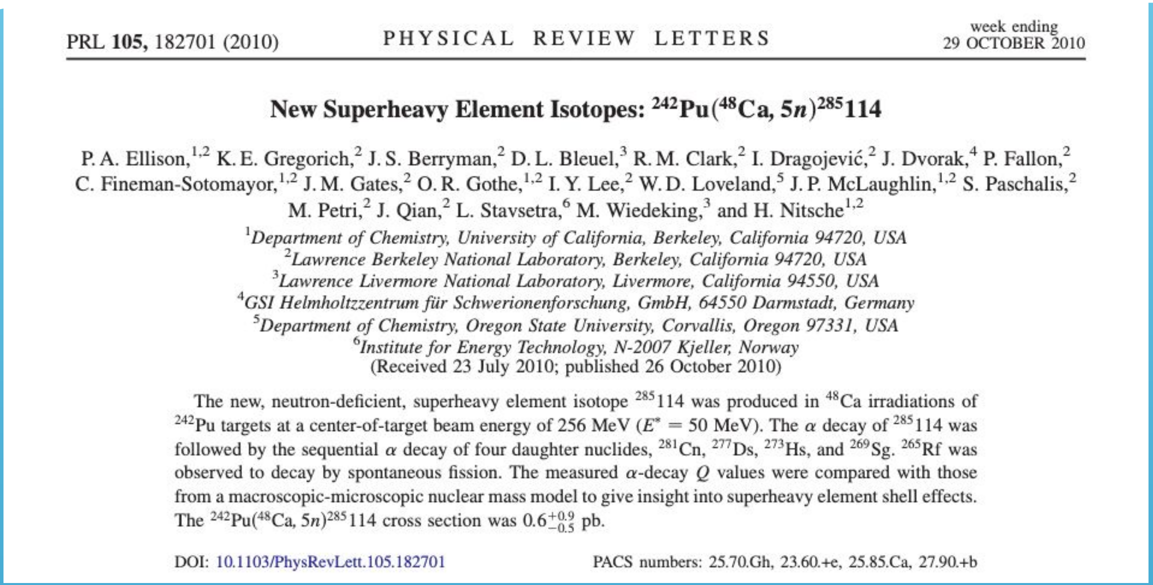
How to determine A and Z of super-heavy elements?

- Fill in gap between nuclei from ^{48}Ca induced reactions
- Mass not well determined
- Z determination: x-rays
- A determination: mass measurement

Berkeley Gas-filled Separator (BGS)



Separation:
1 part in 10^{13}



PRL **105,** 182701 (2010) PHYSICAL REVIEW LETTERS week ending 29 OCTOBER 2010

New Superheavy Element Isotopes: ^{242}Pu(^{48}Ca, 5n)^{285}114

P. A. Ellison,[1,2] K. E. Gregorich,[2] J. S. Berryman,[2] D. L. Bleuel,[3] R. M. Clark,[2] I. Dragojević,[2] J. Dvorak,[4] P. Fallon,[2]
C. Fineman-Sotomayor,[1,2] J. M. Gates,[2] O. R. Gothe,[1,2] I. Y. Lee,[2] W. D. Loveland,[5] J. P. McLaughlin,[1,2] S. Paschalis,[2]
M. Petri,[2] J. Qian,[2] L. Stavsetra,[6] M. Wiedeking,[3] and H. Nitsche[1,2]

[1]*Department of Chemistry, University of California, Berkeley, California 94720, USA*
[2]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[3]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[4]*GSI Helmholtzzentrum für Schwerionenforschung, GmbH, 64550 Darmstadt, Germany*
[5]*Department of Chemistry, Oregon State University, Corvallis, Oregon 97331, USA*
[6]*Institute for Energy Technology, N-2007 Kjeller, Norway*
(Received 23 July 2010; published 26 October 2010)

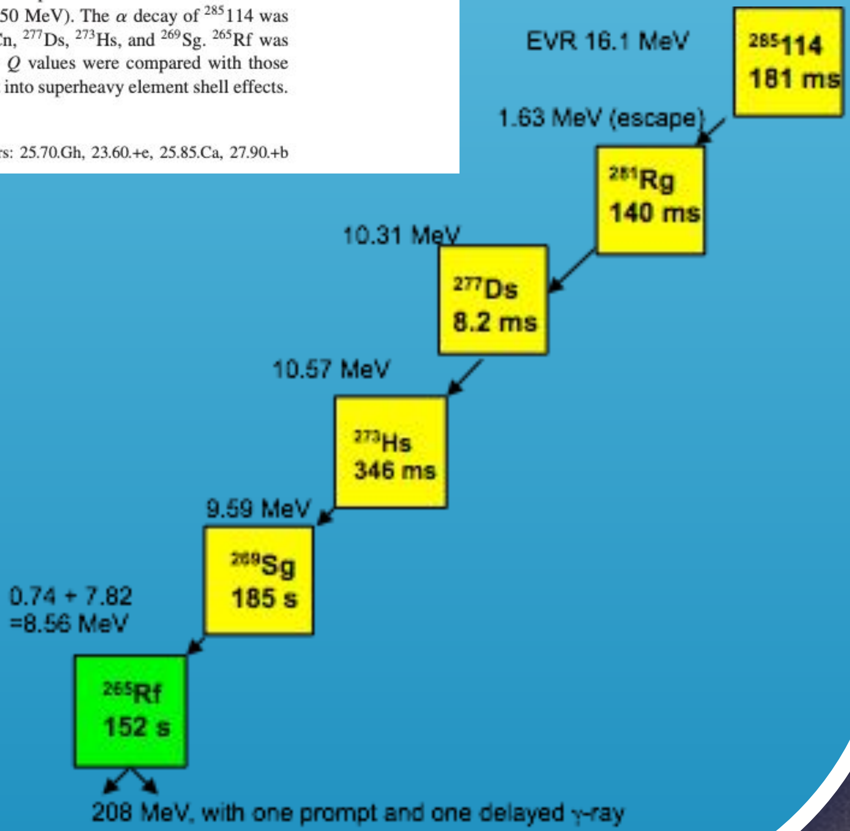
The new, neutron-deficient, superheavy element isotope ^{285}114 was produced in ^{48}Ca irradiations of ^{242}Pu targets at a center-of-target beam energy of 256 MeV ($E^* = 50$ MeV). The α decay of ^{285}114 was followed by the sequential α decay of four daughter nuclides, ^{281}Cn, ^{277}Ds, ^{273}Hs, and ^{269}Sg. ^{265}Rf was observed to decay by spontaneous fission. The measured α-decay Q values were compared with those from a macroscopic-microscopic nuclear mass model to give insight into superheavy element shell effects. The ^{242}Pu(^{48}Ca, 5n)^{285}114 cross section was $0.6^{+0.9}_{-0.5}$ pb.

DOI: 10.1103/PhysRevLett.105.182701 PACS numbers: 25.70.Gh, 23.60.+e, 25.85.Ca, 27.90.+b

Berkeley Gas-filled Separator (BGS)

Provides highly efficient and selective separation of SHE residues (separated from the beam)

Example: 7-week 24/7 experimental campaign with high intensity ^{48}Ca yielded six new isotopes of Flerovium



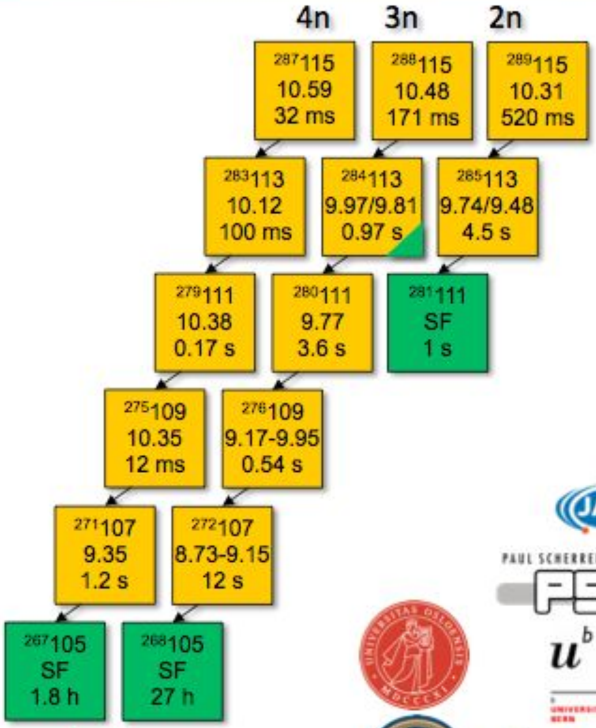
Two Experiments on Decay Spectroscopy of E115

- $^{48}Ca+^{243}Am$ reaction investigated with TASISpec (GSI) and C3 (LBL)
- 46 events of element 115 were observed at LBL and 30 events of 115 observed with TASISpec
- Multiple α-photon coincidences were observed between the two experiments

Rudolph: PRL **111** (2013) 112502

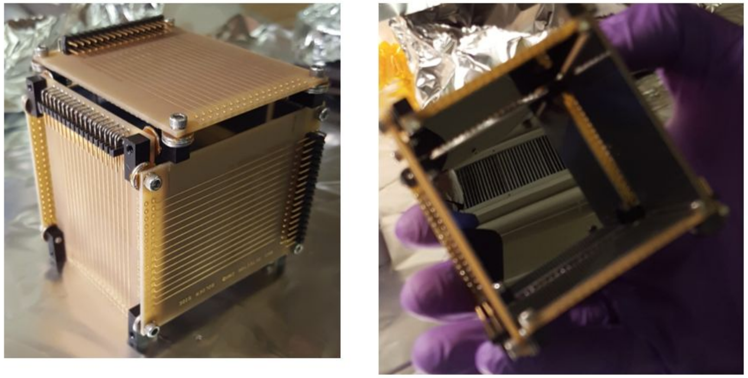
Rudolph*:* Acta Phys. Pol. B **45** (2014) 263

Gates: PRC **92** (2015) 021301R



First Scientific Campaign: Mass Number ID of E115

- Produced E115 using the ^{48}Ca + ^{243}Am reaction at the LBNL 88” cyclotron
- First scientific result from FIONA using 30 days of beam time with an average intensity of 1 puA ^{48}Ca beam



3n

^{288}115
10.48
171 ms

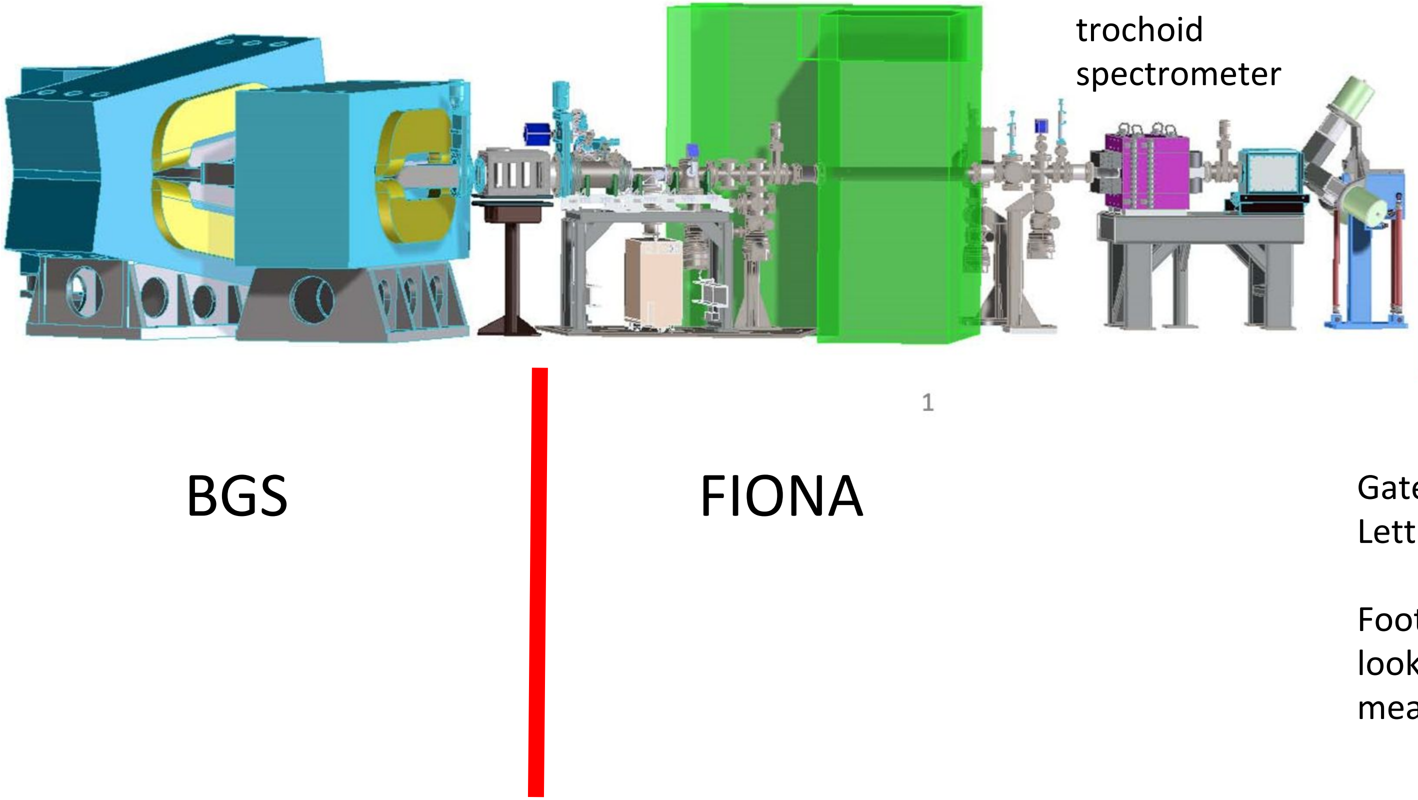
^{284}113
9.97/9.81
0.97 s

^{280}111
9.77
3.6 s

^{276}109
9.17-9.95
0.54 s

^{272}107
8.73-9.15
12 s

^{268}105
SF
27 h



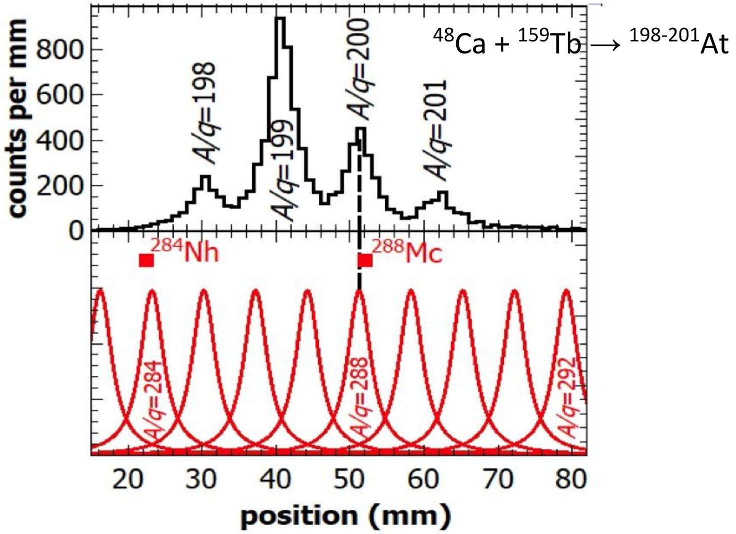
Gates *et al.*: Phys. Rev. Lett. 121, 222501 (2018)

Foot race: Japanese group looking to do a mass measurement.

First Direct SHE Mass Number Measurement

$$^{48}_{20}\mathrm{Ca} + ^{243}_{95}\mathrm{Am} \longrightarrow ^{288}_{115}\mathrm{Mc}$$

Calibration with $^{198\text{-}201}$At ions



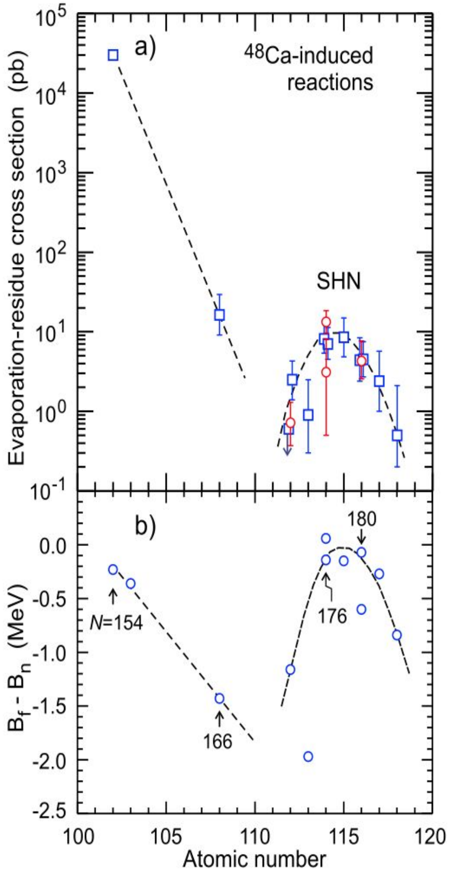
Gates *et al.*: Phys. Rev. Lett. 121, 222501 (2018)

Confirm with Decay Measurements

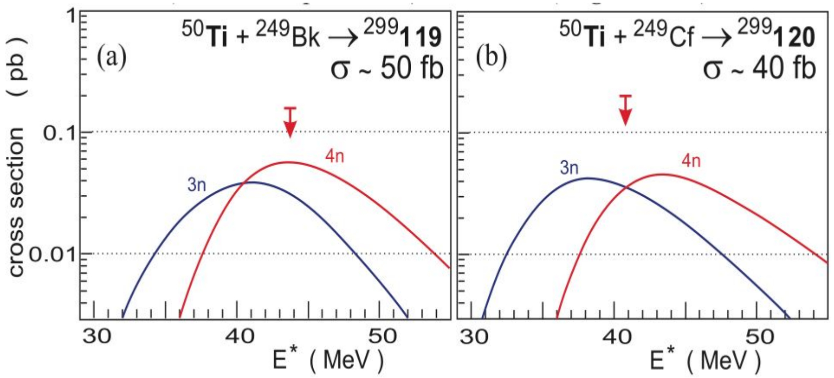
Decay Properties		Event Chain 1	Event Chain 2
10.2-10.6 MeV 159 ms	**^{288}Mc**		**^{288}Mc** 10.29(6) MeV
9.98 MeV 0.94 s	**^{284}Nh**	**^{284}Nh** 9.93(6) MeV	**^{284}Nh** unobserved
9.78 MeV 4.14 s	**^{280}Rg**	**^{280}Rg** unobserved	**^{280}Rg** 9.70(6) MeV 9.998 s
9.10-10.0 MeV 0.63 s	**^{276}Mt**	**^{276}Mt** unobserved	**^{276}Mt** 9.30(6) MeV 4.384 s
9.08 MeV 11.0 s	**^{272}Bh**	**^{272}Bh** 9.19(6) MeV 34.376 s *x*=22.4 mm	**^{272}Bh** 9.02(6) MeV 2.324 s *x*=51.9 mm

First alpha decay
in the gas
catcher

Predicted Cross Sections



Oganessian and Utyonkov (2015)



Zagrabaev, Karpov, and Greiner (2013)

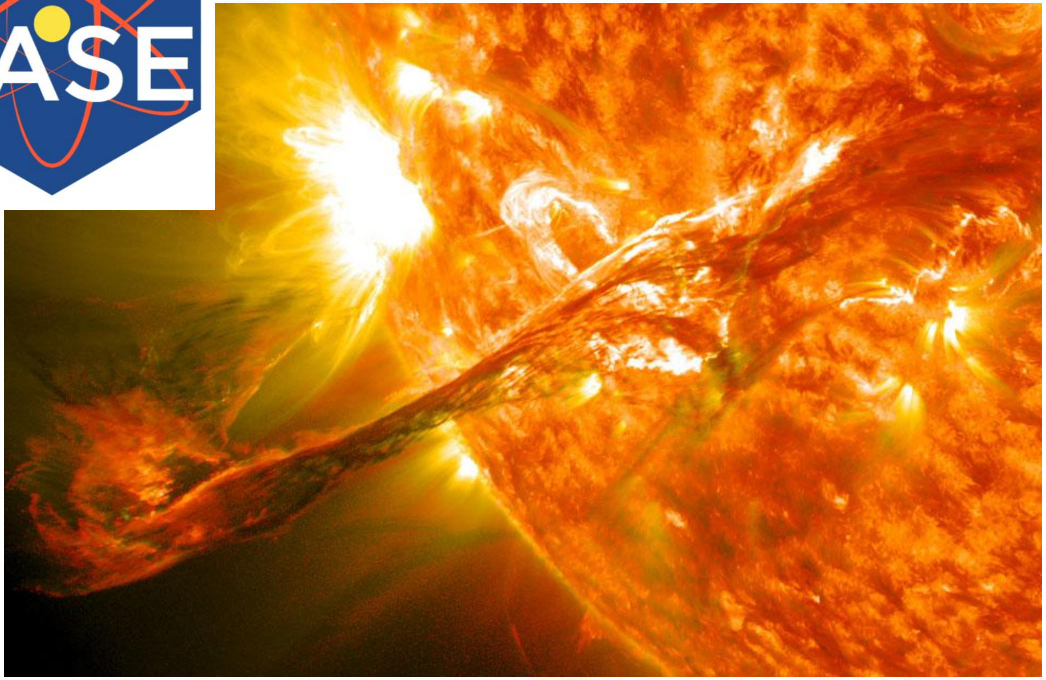
Run out of actinides for ^{48}Ca-induced reactions for E119, E120 production (need mg's of Es and Fm)

Experimental systematic and reaction theories generally suggest:

- ^{50}Ti induced reactions are better than ^{51}V, ^{54}Cr
- Cross sections will be a few tens of femto-barns

Element 120?

BASE Facility Mission

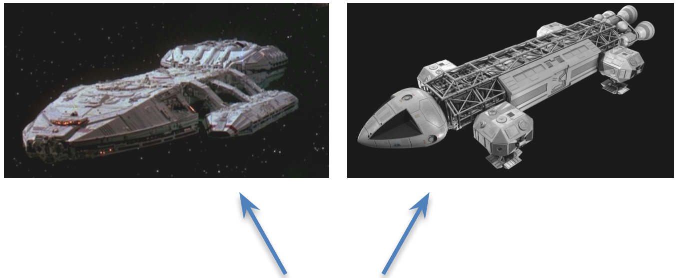


Solar filament, accompanied by a coronal mass ejection (CME), captured by the Solar Dynamics Observatory (SDO) in September of 2012. Parts for SDO were tested at the BASE Facility.

<u>Berkeley Accelerator Space Effects Mission</u>:

Support national security and other US space programs in the area of radiation effects testing.

- <u>Nearly all American spacecraft</u> have had one or more parts tested at the 88-Inch Cyclotron BASE Facility.



Examples of typical spacecraft.

88-Inch Contributions to Space Exploration

Apollo 17 (experiment with lunar soil sample)
Solar Terrestrial Relations Observatory (STEREO)
Solar Dynamics Observatory (SDO)
Parker Solar Probe
Genesis (Solar Wind Sample Return)
Messenger (Mercury)
Pioneer Venus
Van Allen Probes
IMAGE/Explorer 78
Landsat
Global Positioning System (GPS)
Lunar Reconnaissance Orbiter (LRO)
Mars Pathfinder
Mars Polar Lander
Mars Climate Orbiter
Mars Exploration Rover (MER) / Spirit & Opportunity Rovers
Mars Science Laboratory (MSL) / Curiosity Rover
Mars Atmosphere & Volatile Evolution (MAVEN)
Mars Odyssey
Phoenix (Mars)
ExoMars
InSight (Mars) Lander
Dawn (Asteroid Belt)
Galileo (Jupiter)
Juno (Jupiter)
Europa Clipper (Jupiter)
Cassini-Huygens (Saturn)
Voyager (Jupiter, Saturn, Uranus, Neptune)
New Horizons (Pluto)
Stardust (Comet Sample Return)
Deep Space 1 (Comet & Asteroid Flyby)
Atlas Launch Vehicles
Delta Launch Vehicles
Space Shuttle
Orion Multi-Purpose Crew Vehicle
International Space Station (ISS)
James Webb Space Telescope
Spitzer Infrared Telescope Facility
Swift Gamma-Ray Burst Mission
...and many more!

Radiation Effects Testing: The Early Days

Starfish Prime explosion as seen from Honolulu in 1962.

1859: A solar coronal mass ejection hits the Earth, damaging (even burning down) telegraph stations and electrically shocking operators in the U.S. and Europe. Northern and southern auroras visible ***simultaneously*** from high elevations near the equator. It is known today as the "Carrington Event".

1958: America's first satellite, Explorer I, discovers the Van Allen belts.

1959: Operation Argus nuclear test over the south Atlantic Ocean creates the ***first artificial radiation belt*** around the Earth.

1961: The **88-Inch Cyclotron** comes online and produces its first internal ion beam.

1962:

- An American nuclear weapons test known as "Starfish Prime" was conducted in space over the Pacific Ocean. The explosion damaged electrical grid components, knocked out streetlights, set off burglar alarms, and shutdown telephone communications in Hawaii. Radiation belts created by the blast eventually cripple multiple satellites in low Earth orbit, including Telstar 1 (the first commercial telecom satellite) and Ariel 1 (the UK's first satellite).

- Soviet "Test 184" over Kazakhstan ***caused fires*** and ***destroyed a civilian power plant*** in the city of Karaganda. It also shuts down and damages telephone lines, radio, and RADAR equipment over a span of hundreds of miles.

- Wallmark and Marcus postulate that single particles could upset electronic devices as they got smaller.[1]

---

[1] *"Minimum size and maximum packing density of non-redundant semiconductor devices", Proc. IRE, vol. 50, pp. 286-298, Mar. 1962.*

Early Radiation Effects

Early radiation effects testing focused on a handful of areas:

- Total Ionizing Dose Effects: Caused by cumulative (displacement) damage to the semiconductor lattice from ionizing radiation over time.
- Transient Effects: Caused by the rapid, high-intensity pulse of radiation, typically occurring during a nuclear explosion.
- Electromagnetic Pulse (EMP) Effects: Caused by a short burst of electromagnetic radiation that transfers energy via electric field, magnetic field, electromagnetic radiation, and electrical conduction.

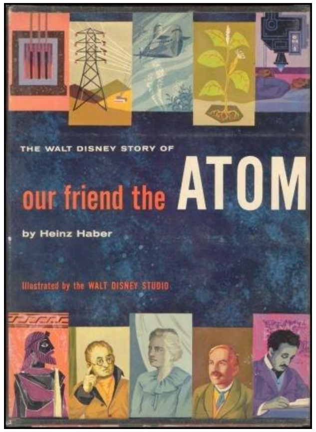
These early effects laid the groundwork for the discovery of *single event effects*, and continue to have an impact to this day.

Radium chocolate - 1930's Germany.

The first and only test (codename "Grable") of the M65 atomic cannon at the Nevada Test Site in 1953.

"Radium Girls" - circa 1922. United States Radium Corporation.

Disney's "Our Friend the Atom" book from 1956. There was also a Disney cartoon episode by the same name the following year.



Collision Course

1972: A Hughes satellite suffers a temporary (96-second) failure. Hughes researchers (Binder, Smith, and Holman) suspect a cosmic ray induced single event upset. After much difficulty in getting it accepted, they succeed in publishing a paper. ***Nobody in the radiation effects community really believes them.***

1978: Intel Corporation discovers that alpha particles from naturally occurring isotopes in computer chip packaging is causing errors and malfunctions. ***Finally, engineers start paying attention.***

1979: The ***very first*** *"single event effects" test in the world* is performed at Berkeley Lab's 88-Inch Cyclotron by the Aerospace Corporation. The test was only permitted after "much pleading", since the Cyclotron researchers were uninterested in such a "mundane engineering experiment".[2] ***Single Event Effects and the 88-Inch Cyclotron collide!***

1984: The first U.S.-based Electron Cyclotron Resonance (ECR) ion source begins operation at the 88-Inch Cyclotron. ***Cocktail beams*** were developed for single event effects testing.

1989: A solar flare and coronal mass ejection flare strike the Earth in March. Several military and civilian satellites are damaged. Space Shuttle Discovery experiences hydrogen fuel cell anomalies. Power grid goes down in Quebec. Some people concerned that a nuclear first-strike is in progress. Five months later in August, ***another*** solar storm shuts down Toronto's stock market for 3 hours.

1990s: In unrelated news, Radiation effects testing at the 88 increases to 15-20% of the total beam time.

---

[2] *"The Single Event Revolution," Peterson, Koga, Shoga, Pickel, & Price, IEEE Transactions on Nuclear Science, Vol. 60, No. 3, June 2013.*

Single Event Effects

Single-Event Effect (SEE): Any measurable or observable change in state or performance of a microelectronic device, component, subsystem, or system (digital or analog) resulting from a single energetic-particle strike.

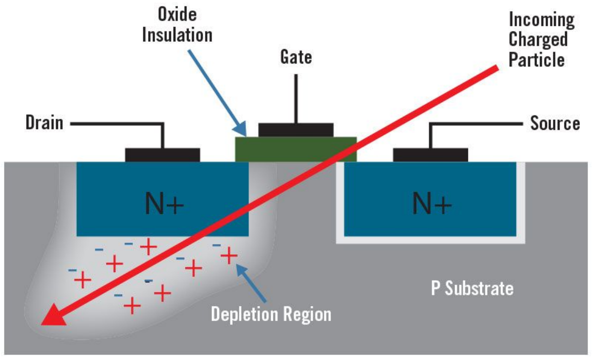
Examples of Single Event Effects:

Single-Event Upset (SEU): A soft error caused by a single ionizing particle striking a sensitive node.

Single-Event Latchup (SEL): An abnormal high-current state with loss of device functionality; requires cycling power to restore operation.

Single-Event Burnout (SEB): High-current state in a device that results in catastrophic failure.

Single-Event Functional Interrupt (SEFI): A soft error affecting a device's internal control signals that causes it to reset, lock-up, or otherwise malfunction.



Courtesy of COTS Journal

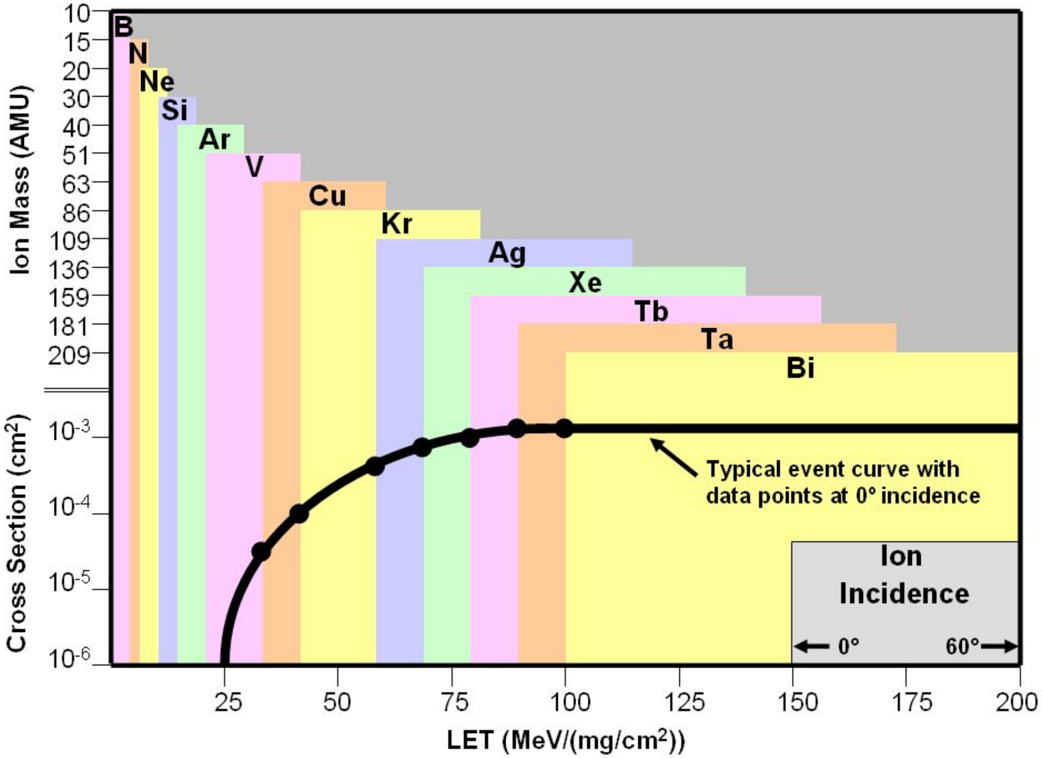
Causes of SEE's:

-Cosmic rays	-Van Allen belts
-Solar	-Nuclear weapons
-Natural isotopes	-Fission

Sampling of Upsets, Unclassified (1970s & 80s)

Spacecraft	Failure
Intelsat IV	TTL Flip-FLop
Voyager	CMOS Memory
Pioneer VENUS	TL RAM, PMOS Shift Register
TIROS-N	Potential CMOS RAM SEL
DMSP	NMOS Memory
SDS	64-bit TTL Schottky RAM
GPS	NMOS Memory
SMM	Fast Bipolar Memory
Landsat D	Memory & possible CMOS SEL
Galileo	Possible CMOS PROM SEL
LES 8 & LES 9	TTL Flip-Flop

SEE & Cocktails



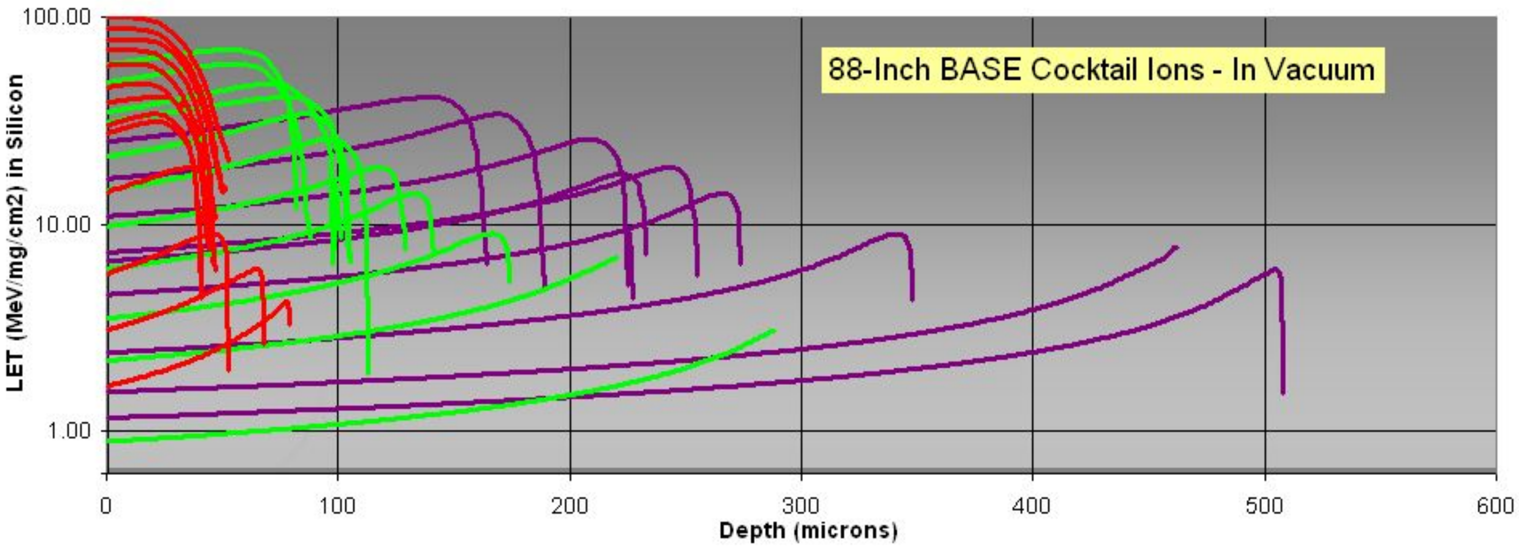
<u>What is a 'Cocktail'?</u>

- Multiple ion species are injected into the Cyclotron simultaneously, which are then selected and separated by simply changing the frequency.

- Normally, it would take hours to retune the Cyclotron to a new ion. With our ion sources, we can change ions in less than <u>3 minutes</u>.

A nuclear cocktail with mushroom cloud.

BASE Cocktails



Legend:

4.5 AMeV

10 AMeV

16 AMeV

New:

20 AMeV (incl. Xe)

25 AMeV up to Kr?

- Cocktails allow users to efficiently deposit the right amount of energy at the desired depth.
- High LET ions are the most difficult to tune out of the machine, but thanks to ion source and Cyclotron improvements, we can achieve very high fluxes for even our heaviest ions.
- MARS will allow for higher energy cocktails.

BASE Facility Layout & Capabilities

Heavy Ions, Low Energy Protons, Microbeams

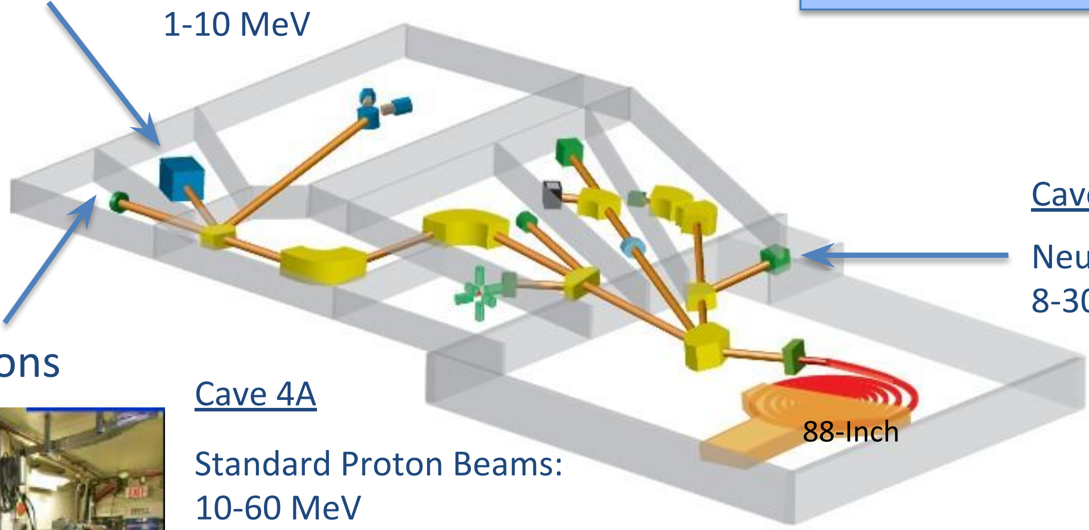
Cave 4B

Standard Cocktail Beams:
4.5, 10, 16, and 20 AMeV

Up to 1E6 ions/cm^2/sec

Low Energy Protons:
1-10 MeV

"One-stop" facility for radiation effects testing:
- Heavy Ions
- Light Ions
- Protons
- Low Energy Protons
- Neutrons
- Microbeams



Cave 0

Neutrons:
8-30 MeV

Light Ions, Protons

Cave 4A

Standard Proton Beams:
10-60 MeV

Up to 1E9 protons/cm^2/sec

Light Ion Cocktails:
30 and 32.5 AMeV

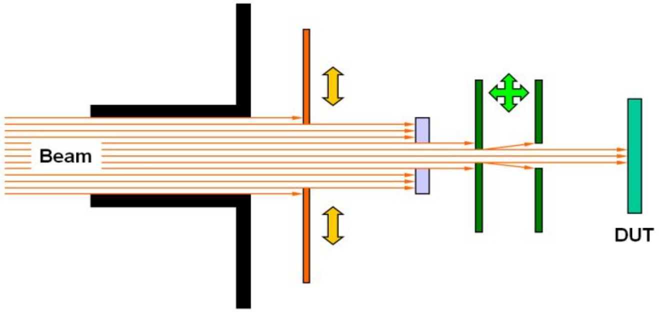
BASE Microbeams

- As semiconductor parts become more miniaturized, new modes of failure appear. A new capability is needed: **Microbeams**

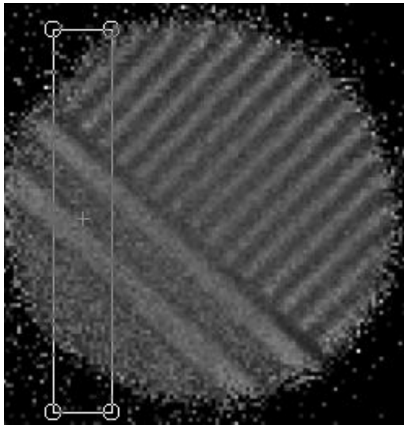
- Chip testers already test *whole* components, but increasingly need to isolate and probe *small sections* of their parts to pinpoint problems.

- 88-Inch is unique in being able to provide the highly parallel beams needed in vacuum

- Two recent microbeam efforts at the Cyclotron:
  - Micro-RDC: Diffuse, high-intensity parallel beam, collimated with precision slits. 10 micron resolution
  - Sandia: Optical reconstruction of low intensity beam. 5 micron resolution

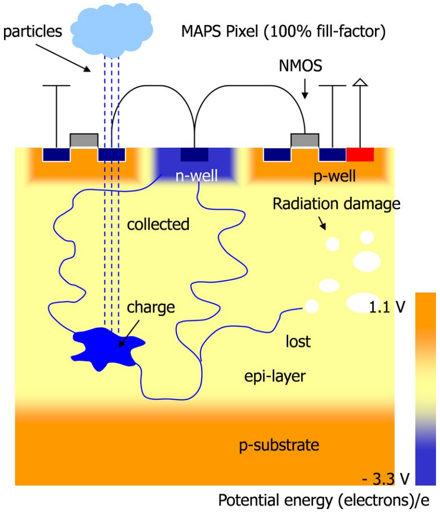


Micro-RDC – 10 um resolution



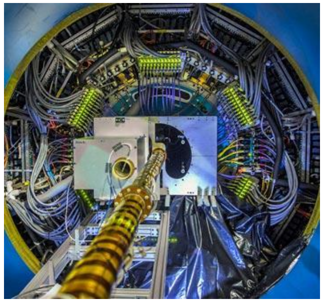
Sandia – 5 um resolution

Monolithic Active Pixel Sensor (MAPS)

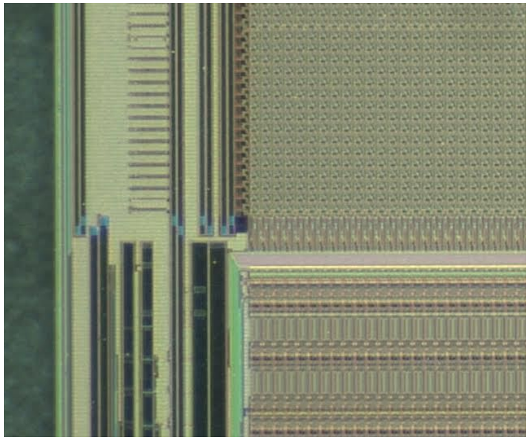


MAPS Diagram

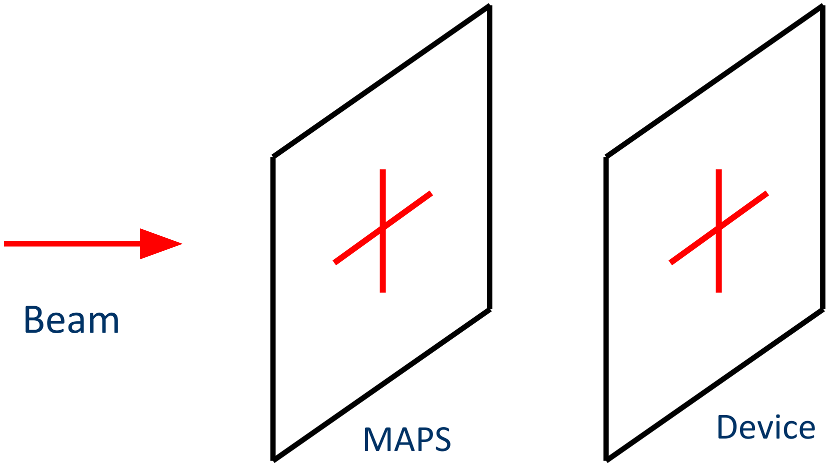
- Beam positioning with CMOS sensors
- Developed for the STAR Heavy Flavor Tracker (HFT) at RHIC by Berkeley Lab researchers
- Repurposed for the BASE Facility
- Approximately 22-micron pixel size
- 50 microns thick
- Better than 10-micron resolution
- Excellent solution for BASE microbeams



Heavy Flavor Tracker at RHIC



MAPS Sensor



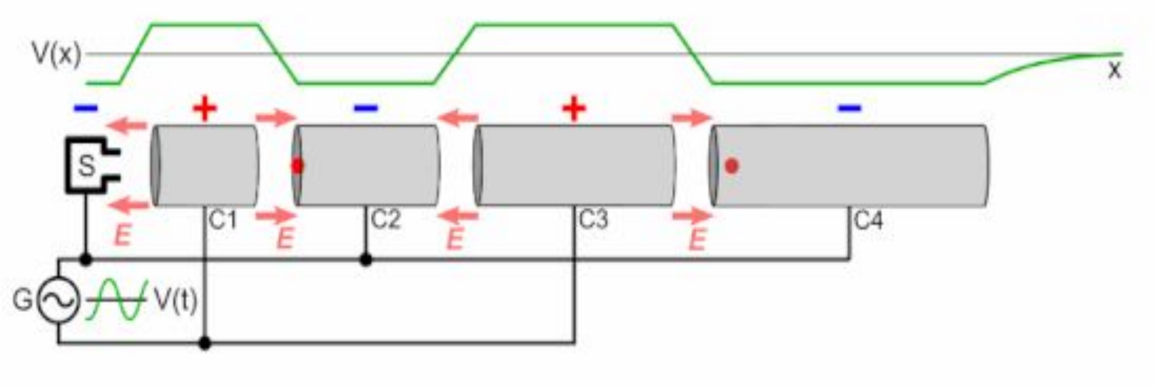
Beam

MAPS

Device Under Test

Booster LINAC

- Higher energies needed to get through silicon overlayers
- Collaboration between 88-Inch Cyclotron and SLAC
- Air Force, NASA have expressed strong interest
- Connect at the output of the cyclotron
- Immediate goal of 25 AMeV cocktail; 100-250 AMeV possible
- Potential to eliminate (expensive) chip de-lidding and test as you fly!



LINAC
Beam Direction →

High-energy
Beam Output

Cyclotron Concerns

Funding:

- Air Force and NASA agreements
- National Academies study of SEE infrastructure
- Getting more support from the operations side of DOE

Hardware:

- Spare parts and upgrades
- Cooling tower is failing
- Vacuum, vacuum, vacuum
- We will eventually need to fix cooling water pipes inside the Cyclotron itself; currently using “band-aid” approach

Loctite (threadlocker) and Seal-Up (radiator sealant) used for plugging holes in 88-Inch cooling systems

Personnel:

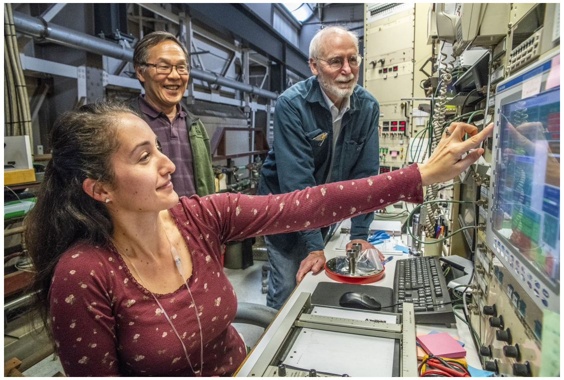
- Impact on reliability
- Technical staff, rad workers
- Bureaucracy and red tape

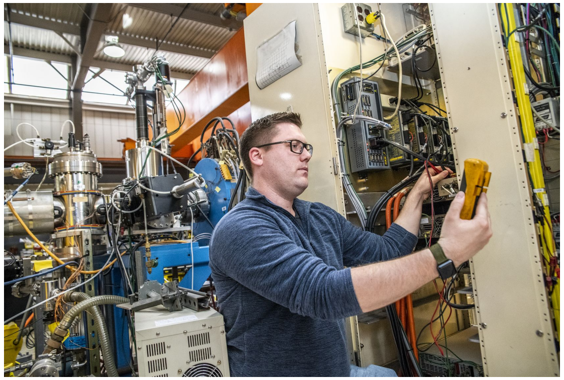
Building the 88-Inch Cyclotron. Internal cooling water lines are shown.

People

- Humans are expensive (80% of our $8 million/year operating costs). BUT…
- ...at the end of the day, the *most valuable resource* we have at the 88-Inch Cyclotron is PEOPLE.
- Thanks to the ingenuity of our staff and researchers, we keep reinventing our facility to do things the original designers *never could have imagined*. As such, we will always have a need for individuals with **expert skills**, **sound reasoning ability**, and **brilliant creativity***** who are willing to both work with AND challenge the current paradigm.

****Do not try this at home. These are not actors. They are real 88-Inch Cyclotron people.*





Summary

- ECR ion source development = fountain of youth for the 88” Cyclotron. (MARS ion source is next)
- Turn-key neutron beams added in the last 5 years.
- SHE program is looking to increase its beam time usage, more experiments where mass identification is useful (FIONA), and possibly for an element 120 search (2000 hours/year)
- For the radiation effects side of the 88-Inch program, several parallel efforts are in progress to help with the challenges of testing satellite technology:
  - MARS ion source (higher beam energy & intensity, improved facility reliability)
  - Booster LINAC (path to *significantly* higher beam energy)
  - Microbeam & MAPS Detector (precision testing)
- The 88-Inch Cyclotron is a *versatile, flexible, and adaptable* accelerator for both basic research and physics/engineering applications. Combined with the right *people*, there are untold possibilities.