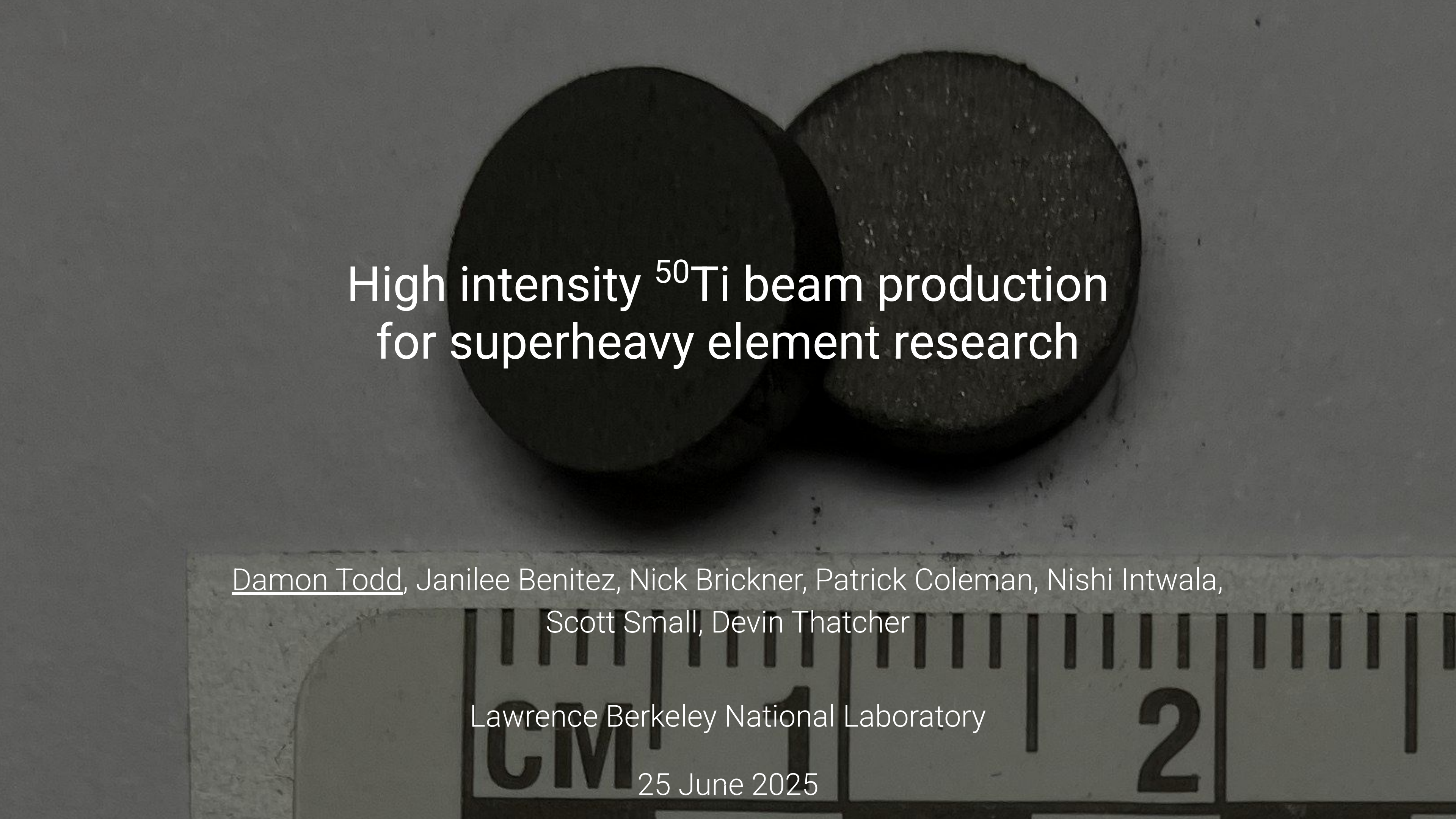


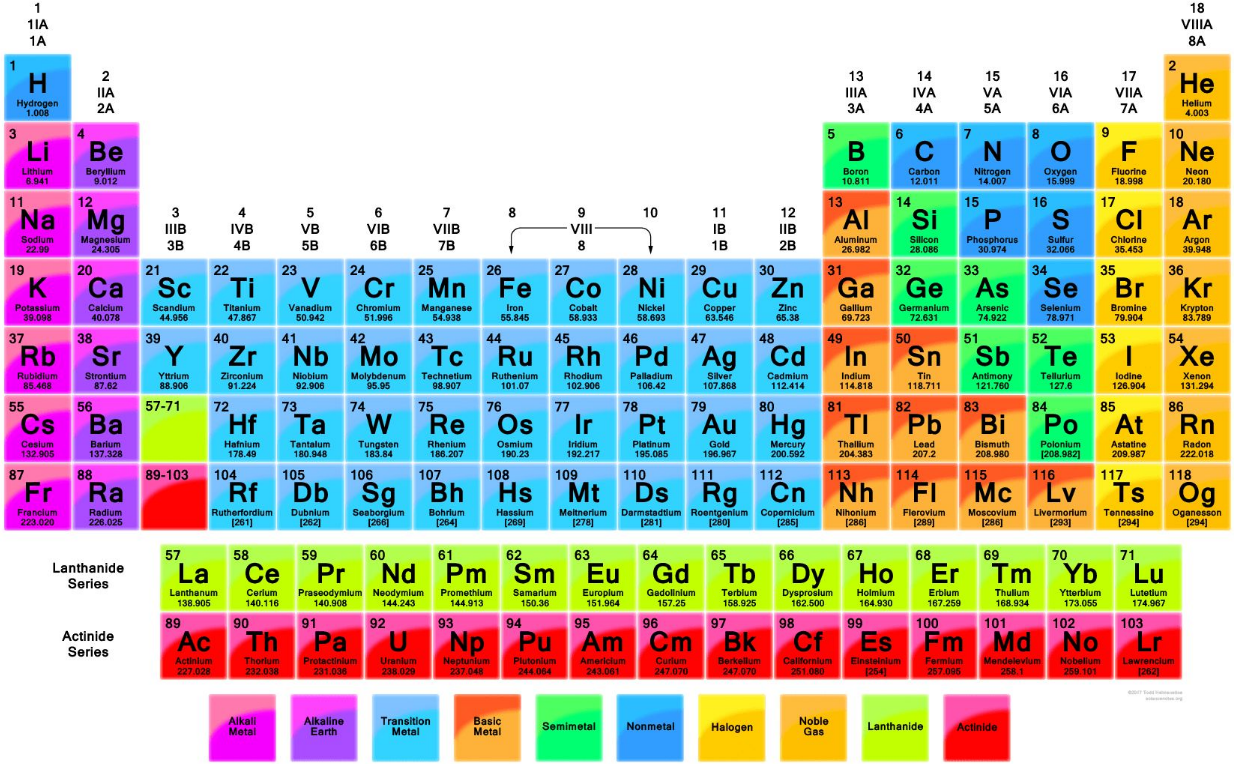
High intensity ^{50}Ti beam production for superheavy element research

Damon Todd, Janilee Benitez, Nick Brickner, Patrick Coleman, Nishi Intwala,
Scott Small, Devin Thatcher

Lawrence Berkeley National Laboratory

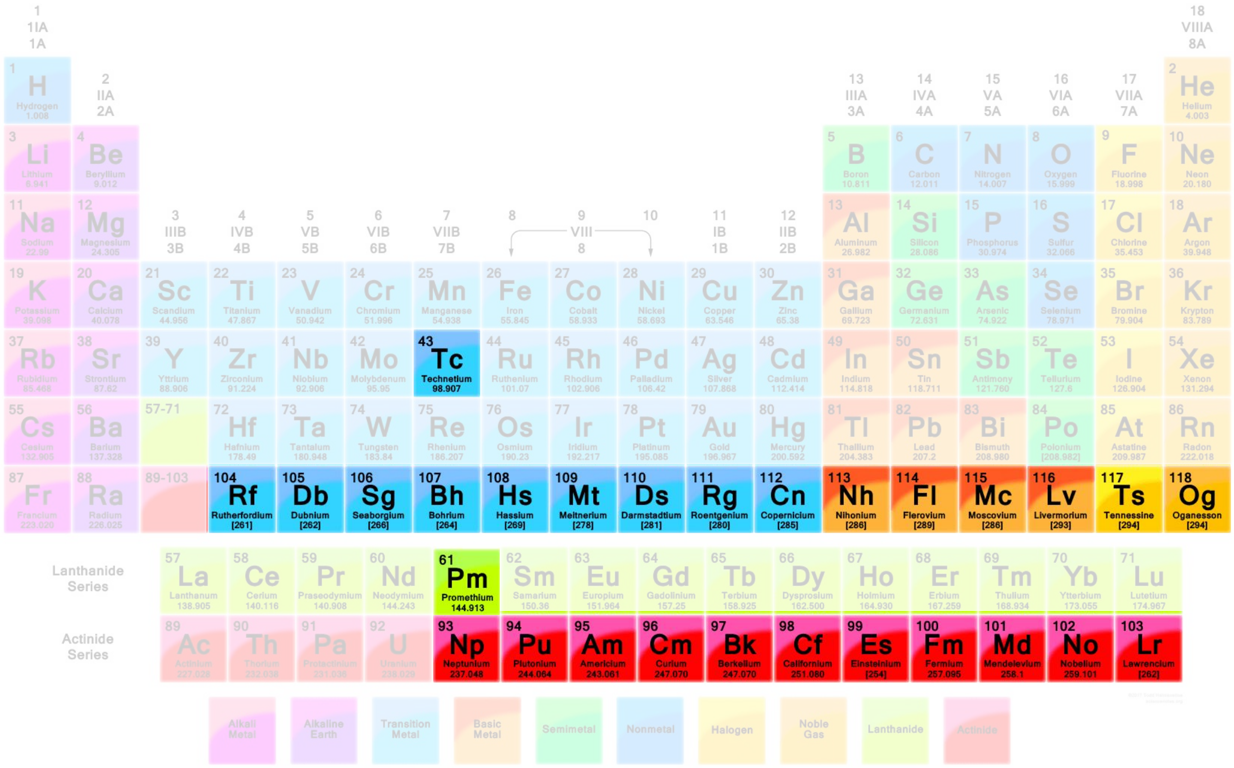
25 June 2025

Where things stand today



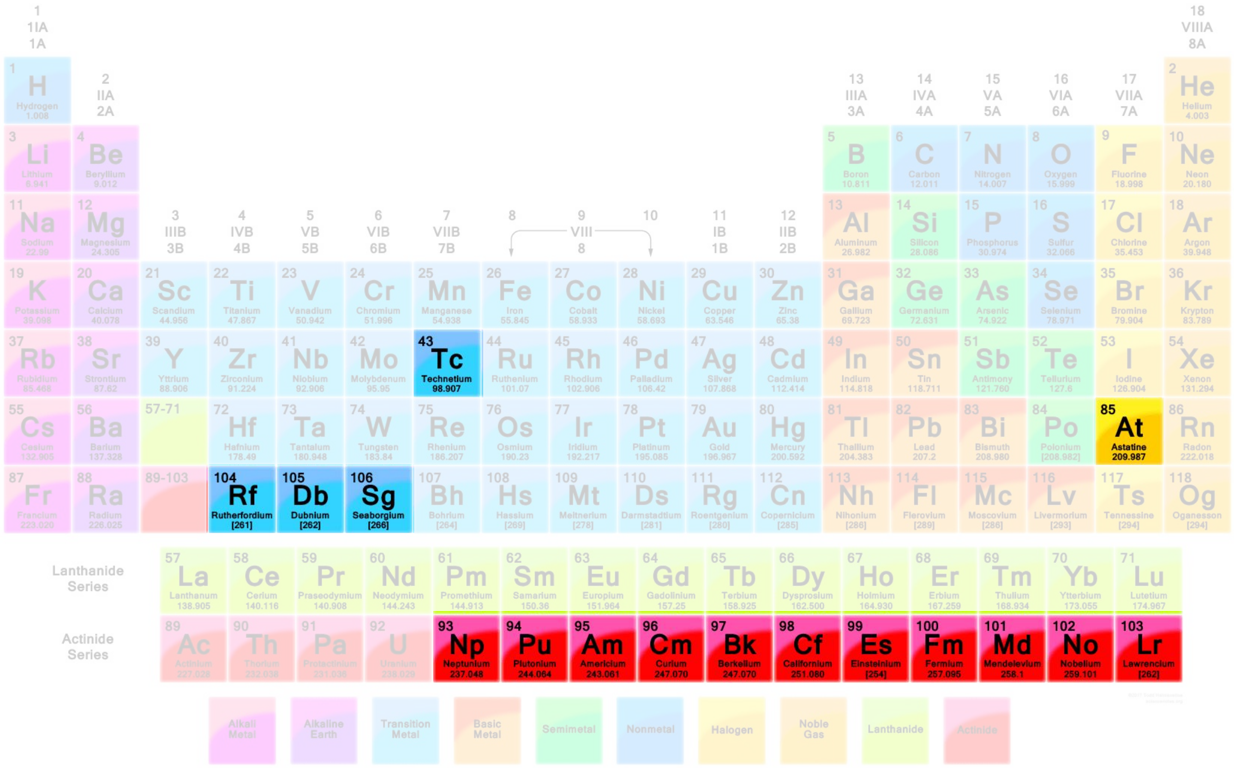
- 118 elements

Where things stand today



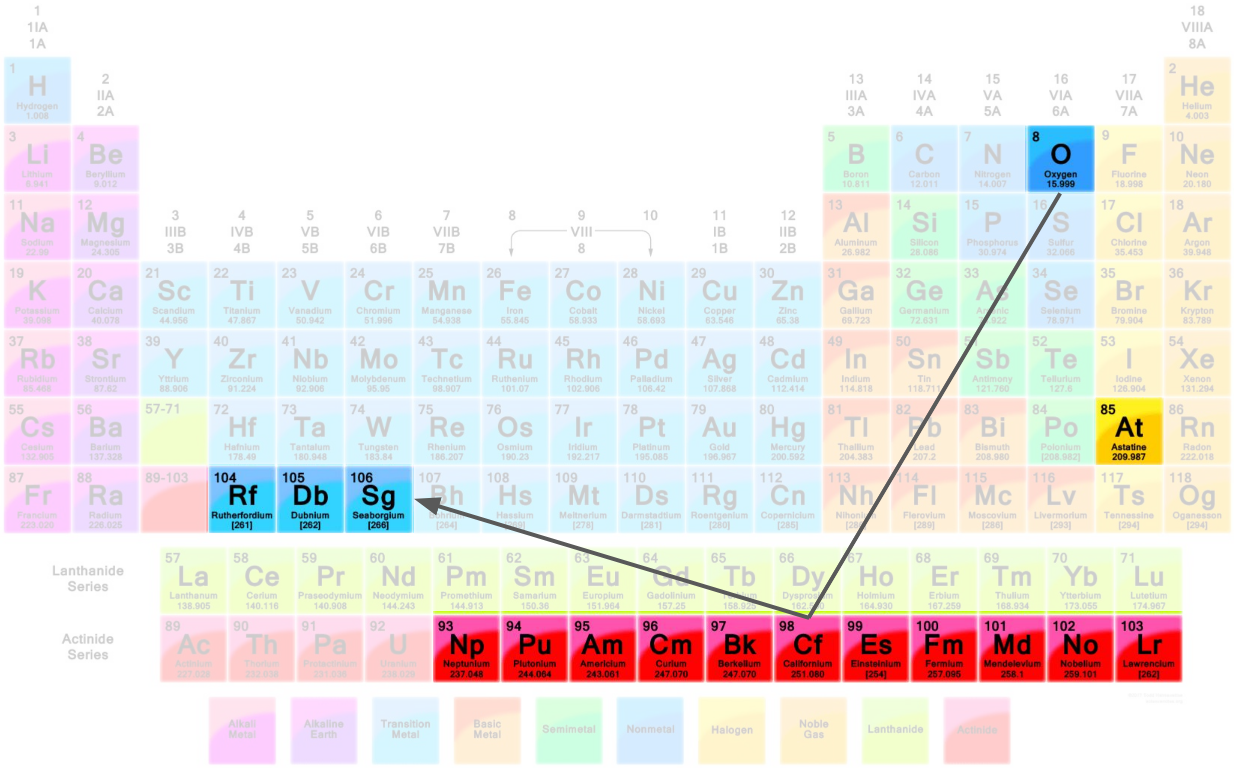
- 118 elements
- 28 artificially-produced

Where things stand today



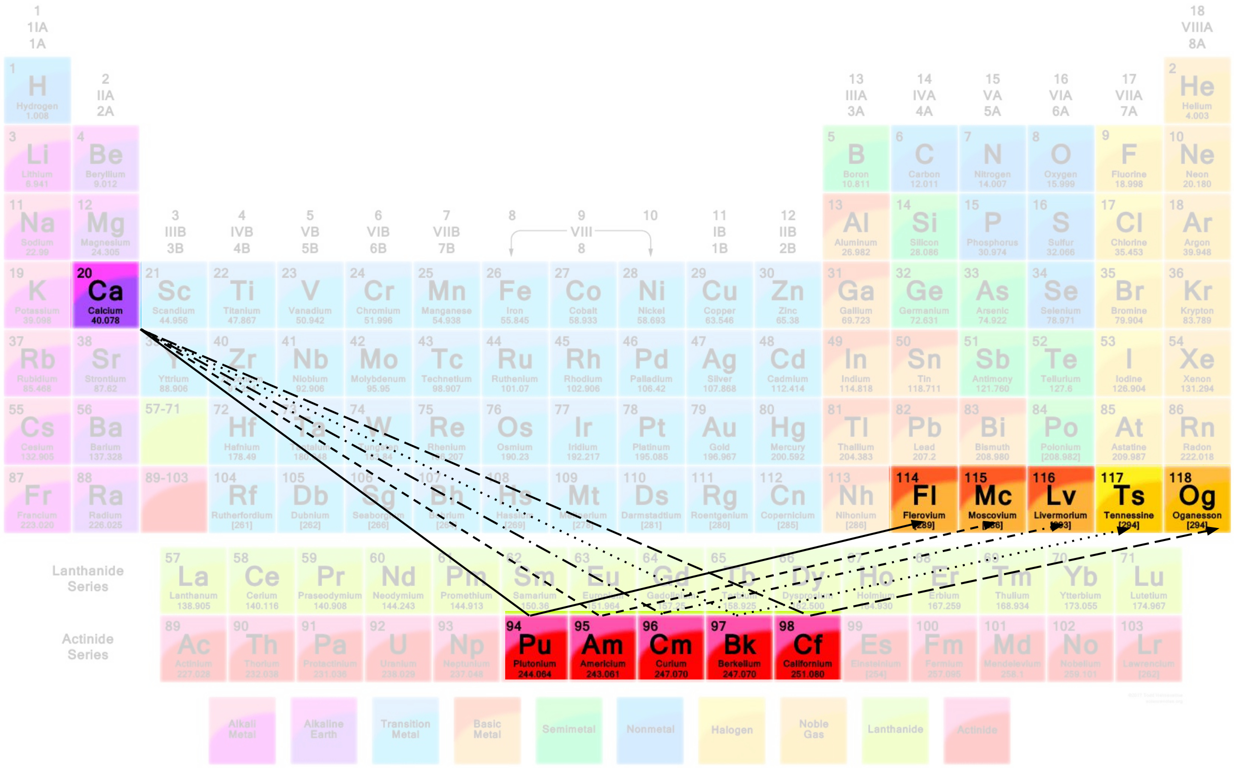
- 118 elements
- 28 artificially-produced
- 16 discovered at or by LBNL

Where things stand today



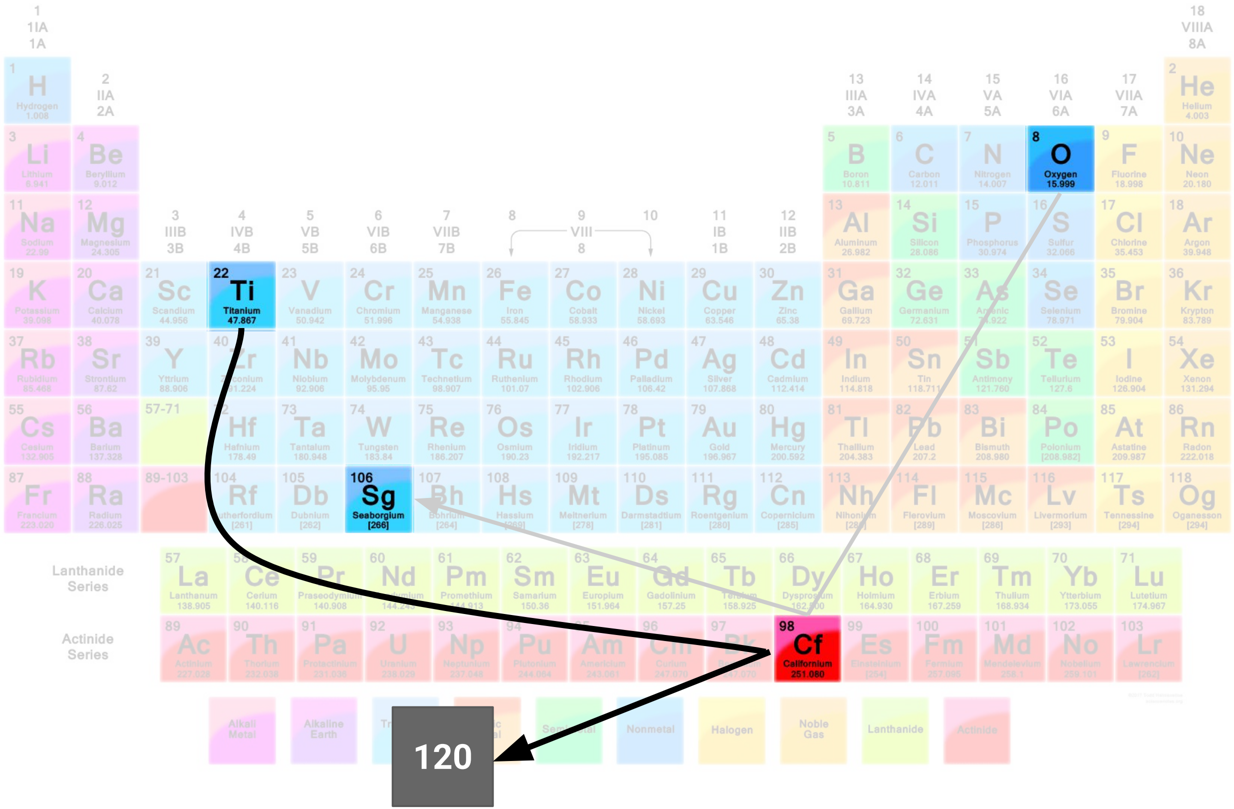
- 118 elements
- 28 artificially-produced
- 16 discovered at or by LBNL
  - LBNL's last: Sg in 1974

Where things stand today



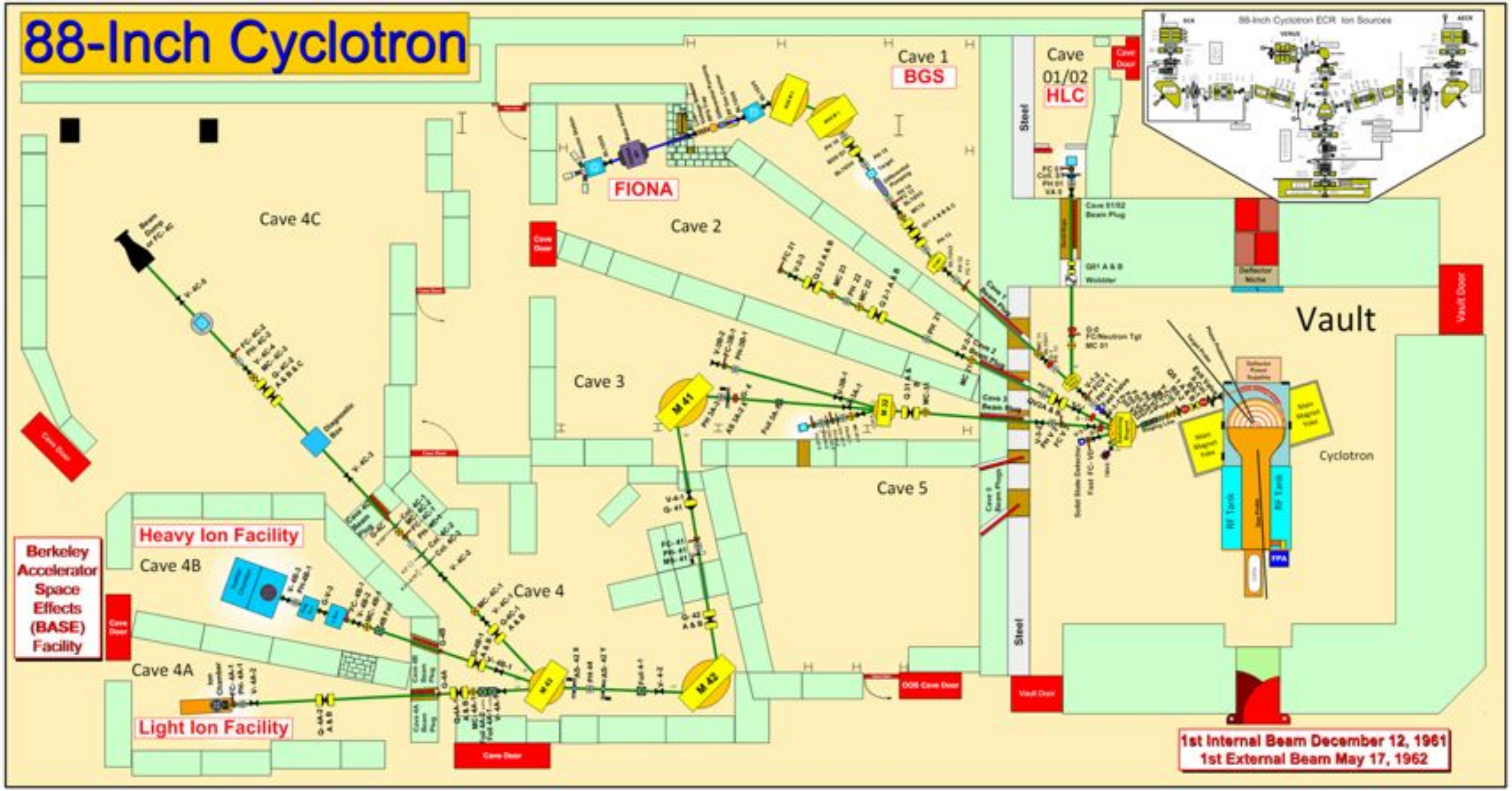
- 118 elements
- 28 artificially-produced
- 16 discovered at or by LBNL
  - LBNL's last: Sg in 1974
- 5 heaviest using ^{48}Ca beams
  - can't go further with ^{48}Ca (no heavier targets!)

Where things stand today

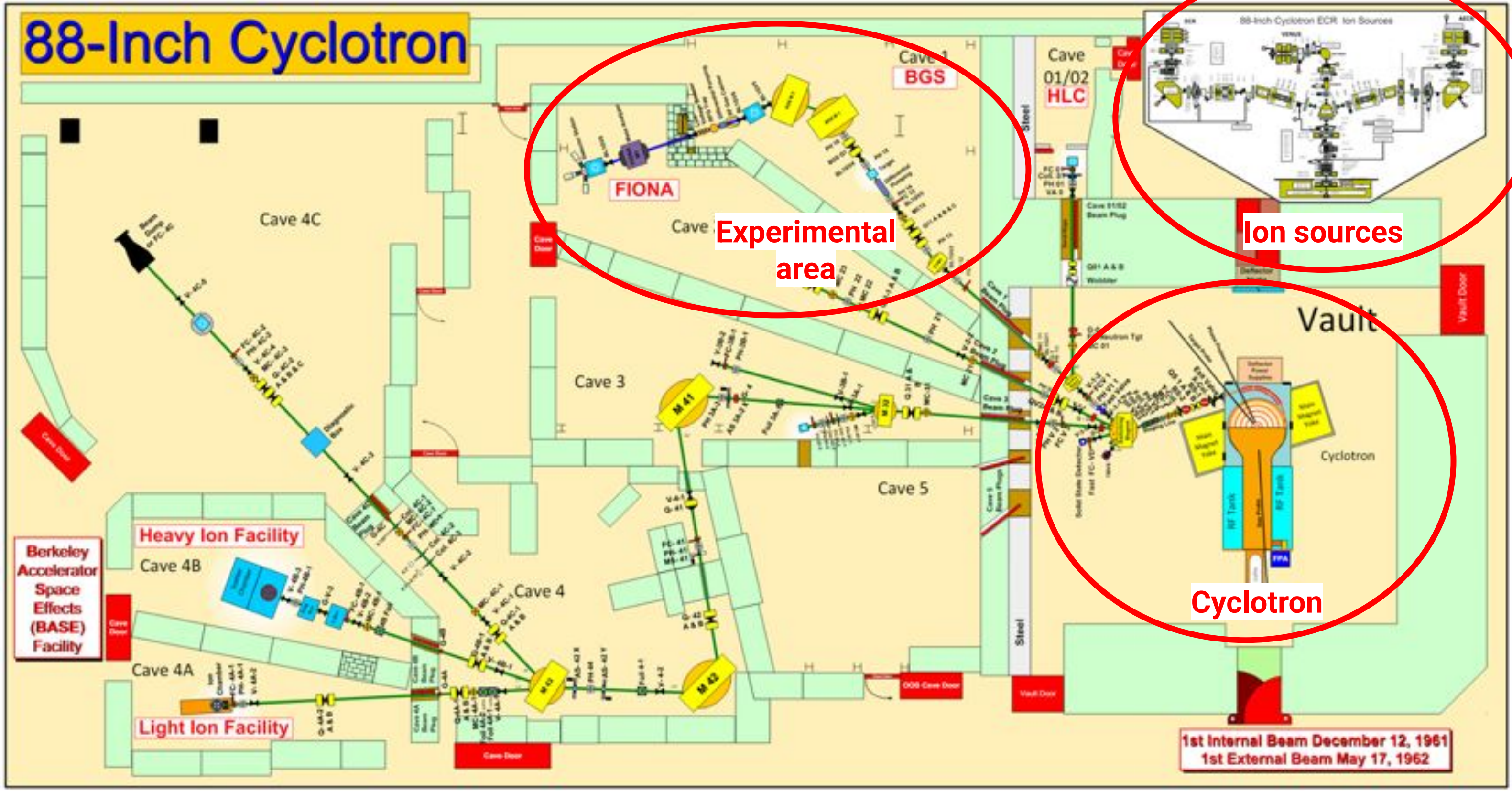


- 118 elements
- 28 artificially-produced
- 16 discovered at or by LBNL
  - LBNL's last: Sg in 1974
- 5 heaviest using ^{48}Ca beams
  - can't go further with ^{48}Ca (no heavier targets!)
- LBNL to return to Cf targets
  - Use ^{50}Ti to make element 120!

LBNL's 88-Inch Cyclotron facility

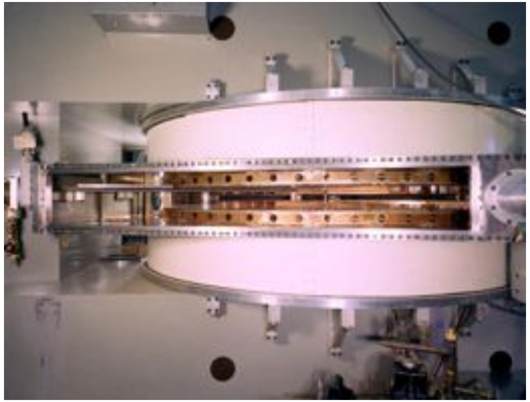


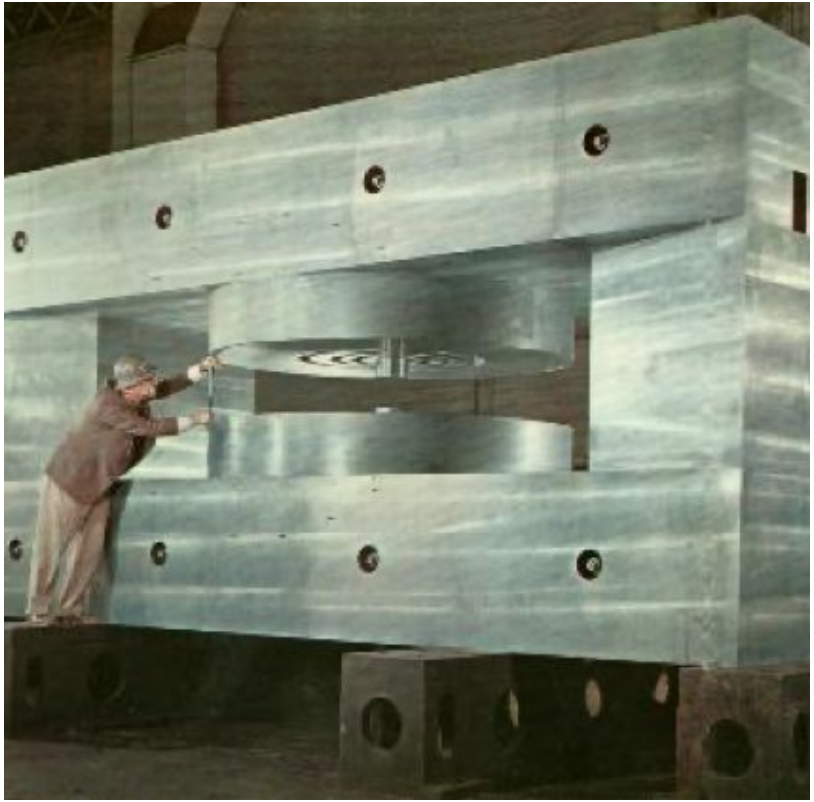
LBNL's 88-Inch Cyclotron facility



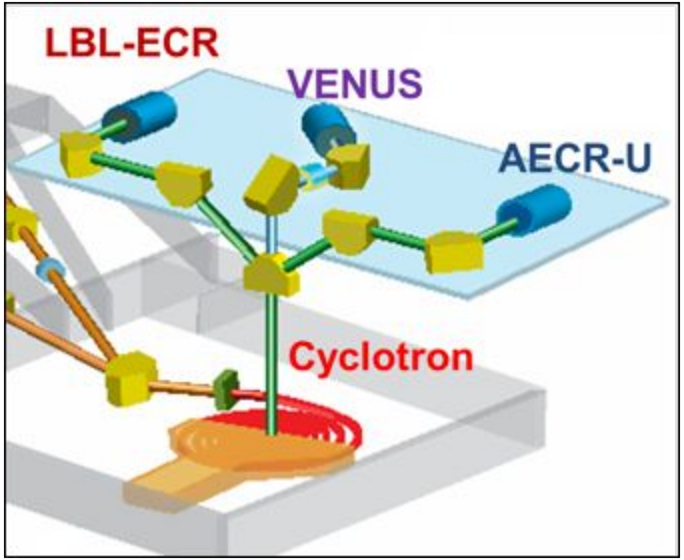
88-Inch Cyclotron

- Sector-focused, K140 cyclotron
- 88 inch (2.24 m) diameter pole
- RF: 5.6 to 16.5 MHz, up to 70 kV
- Designed as a flexible light ion accelerator

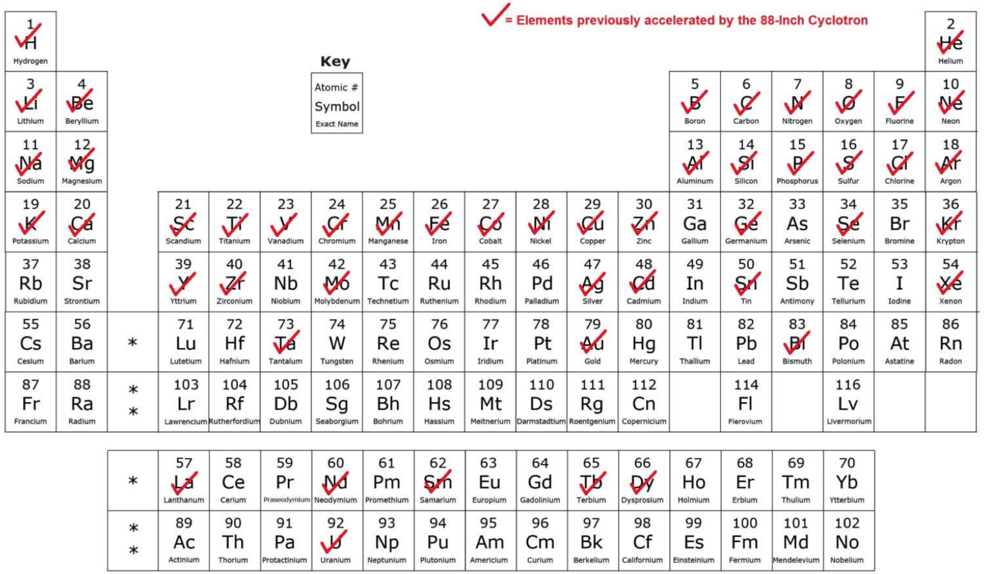




Our electron cyclotron resonance (ECR) ion sources

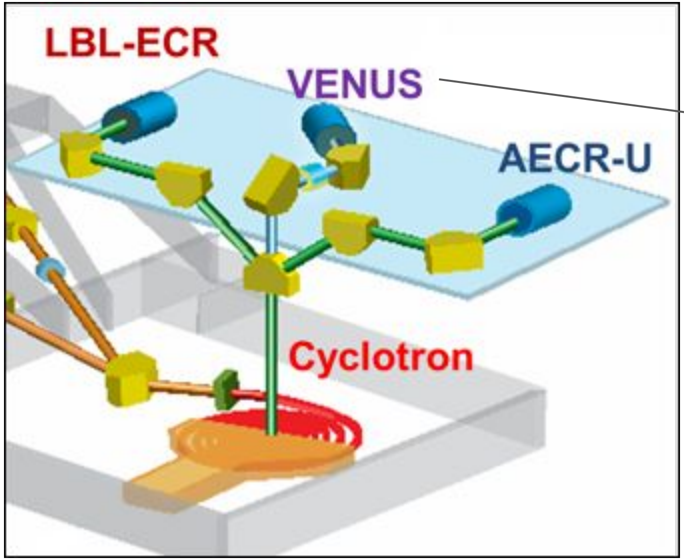


Periodic Table of the Elements



over half the periodic table accelerated by 88” cyclotron

Our electron cyclotron resonance (ECR) ion sources



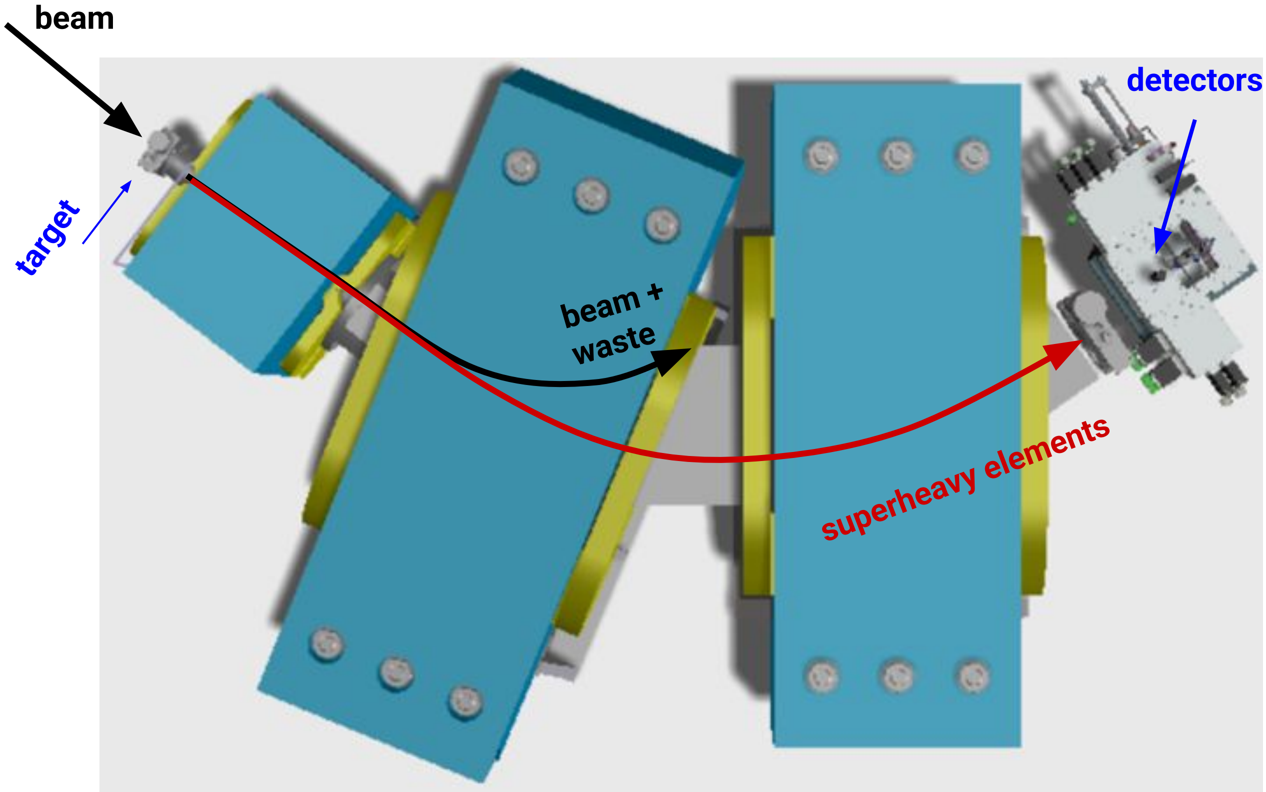
VENUS ion source

- World's first fully-superconducting ECR ion source designed for 28 GHz operation
- Prototype source for FRIB
- Microwave heating: 28 GHz (10 kW) and 18 GHz (4 kW)
- Maximum fields: 4T

<u>Example beams</u>

high currents	high charge states
> 4.7 mA O^{6+}	$^{197}Au^{61+}$ out of cyclotron
> 20 mA He^{+}	> 2.3 GeV!

Experiment: Berkeley Gas-Filled Separator (BGS)



Needs in preparation for element 120 search via $^{50}Ti \rightarrow {}^{249}Cf$ reaction

Needs from Cyclotron

- 5-6 MeV/u ^{50}Ti beams
- High current (> 1pμA)
- continuous, 10+ day runs

Needs from ion source

- ~100 μA $^{50}Ti^{12+}$ @ 22 kV extraction voltage
- low material consumption (<5 mg/hour)
- continuous, 10+ day runs
- fast material change (hours)

Needs from experiment

- Proof that ^{50}Ti can be used for superheavy element production (make something ^{48}Ca made)

Needs in preparation for element 120 search via $^{50}Ti \rightarrow {}^{249}Cf$ reaction

Needs from Cyclotron

- 5-6 MeV/u ^{50}Ti beams
- High current (> 1pμA)
- continuous, 10+ day runs

Needs from ion source

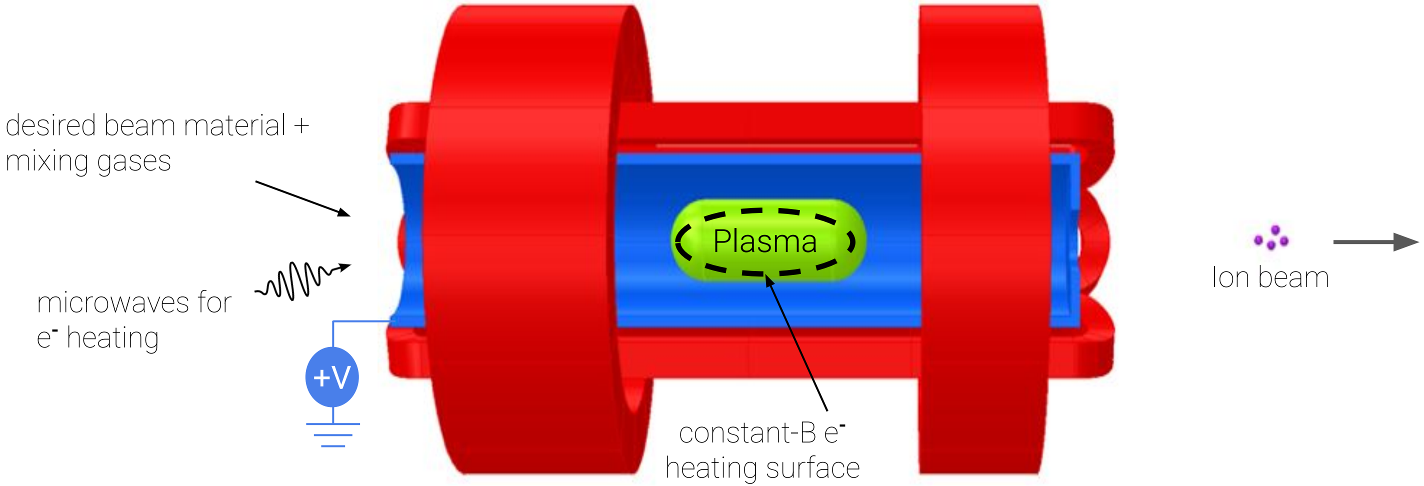
- ~100 μA $^{50}Ti^{12+}$ @ 22 kV extraction voltage
- low material consumption (<5 mg/hour)
- continuous, 10+ day runs
- fast material change (hours)

Needs from experiment

- Proof that ^{50}Ti can be used for superheavy element production (make something ^{48}Ca made)

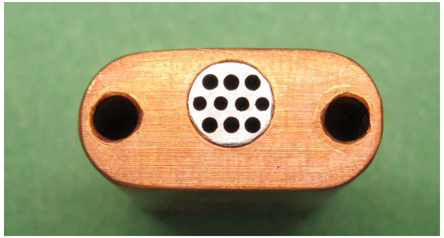
- Cyclotron has demonstrated weeks-long, 1-2 pμA $^{48}Ca^{11+}$ beams at similar energies (see D.S. Todd, *et al.*, Proc. Cyclotrons 2013, MO2PB02, pp. 19-21)
- Difficult questions:
  - Can source produce these beams with these requirements
  - Can ^{50}Ti be used for superheavy production

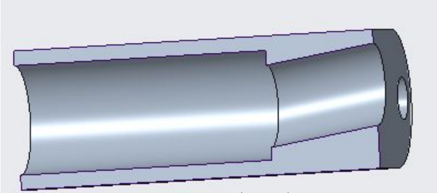
One slide on ECR ion sources



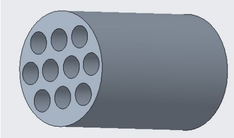
- Electron cyclotron resonance (ECR) ion sources can produce DC ion beams from ANY material injected into the plasma without destroying plasma
- High charge states found near axis
- Titanium not captured goes to walls and acts as “getter” → plasma instability

Example: low-temperature oven used for ^{48}Ca beams from VENUS





Copper body



Stainless steel insert:
- 8.5 mm long
- 5.6 mm diameter

VENUS low-temperature oven performance

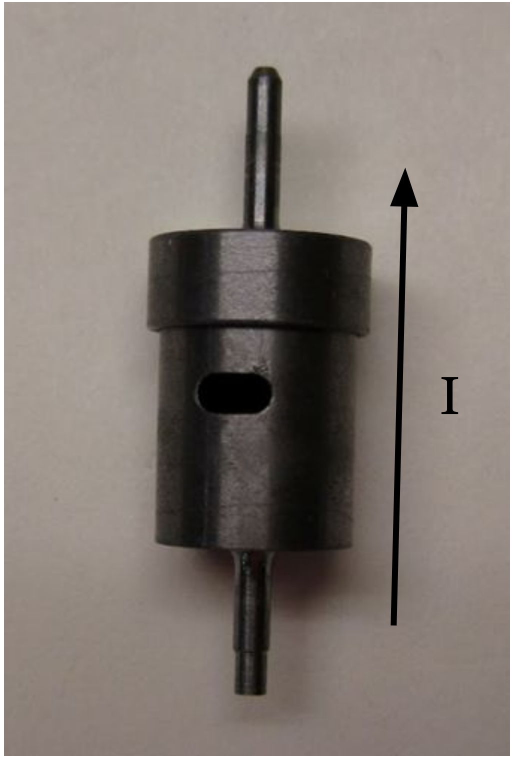
- ^{48}Ca Consumption: ~0.5 mg/hr
- Conductively heated
- Operating temperature for calcium: ~600°C
- Maximum operating temperature: ~700°C

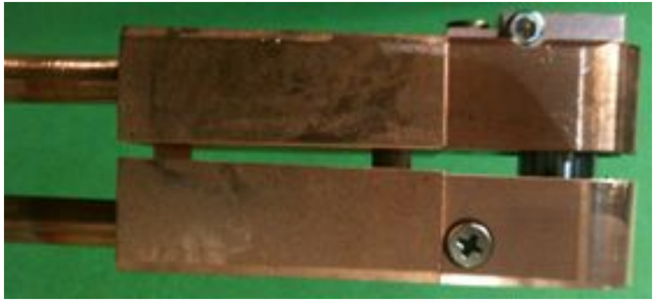
VENUS' high-temperature resistive ovens

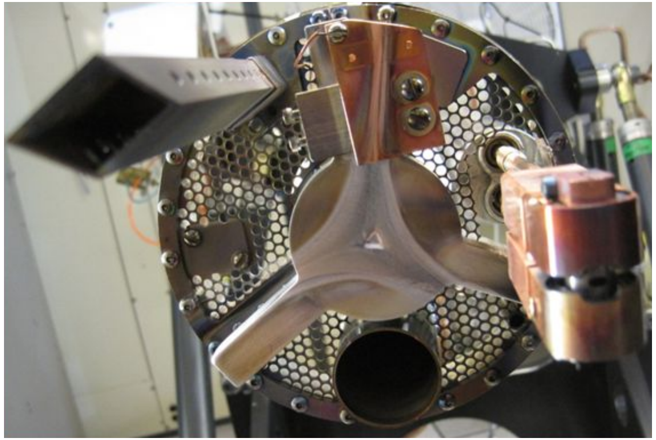
Resistive ovens:

- Custom-made (Ta, W, and Re)
- Thickness ~0.25 mm
- Volume ~0.3 cm^3
- T > 2000 ℃
- Consumption ≲ 5 mg/hour

VENUS’ high-temperature resistive ovens



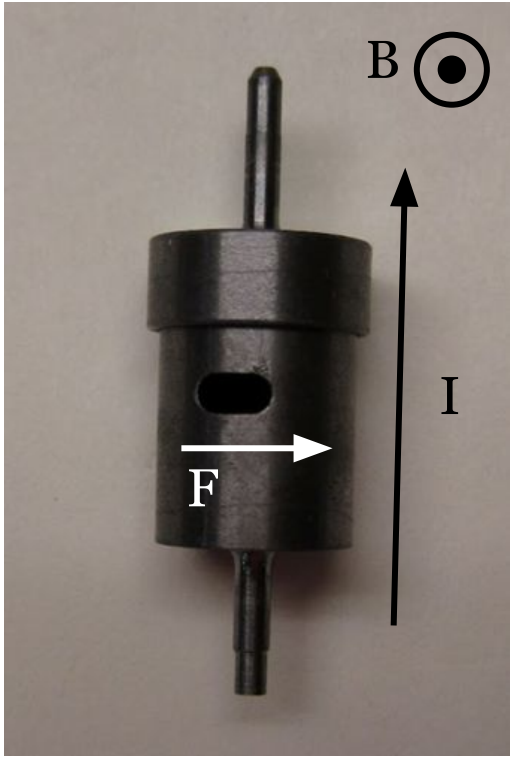


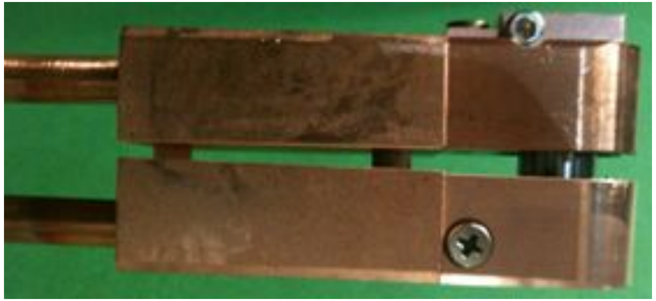


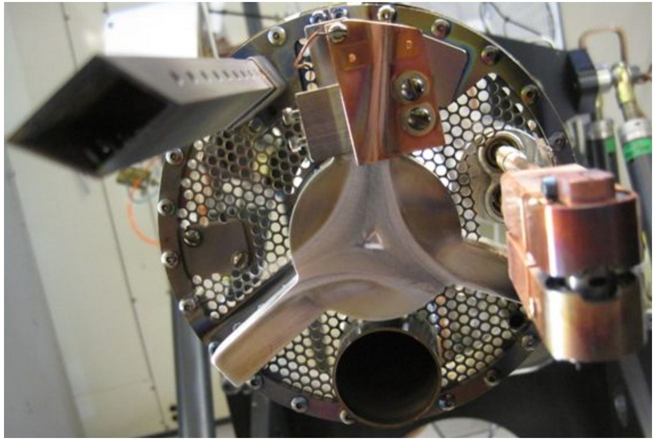
Resistive ovens:

- Custom-made (Ta, W, and Re)
- Thickness ~0.25 mm
- Volume ~0.3 cm^3
- T > 2000 ℃
- Consumption ≲ 5 mg/hour

VENUS’ high-temperature resistive ovens



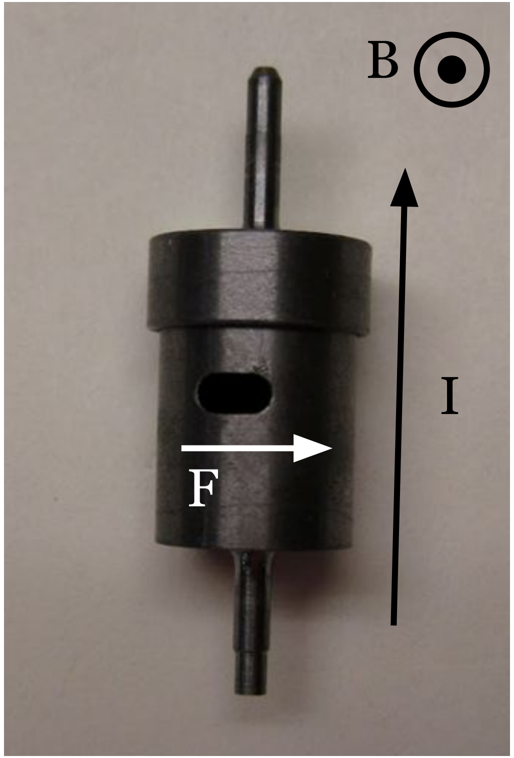




Resistive ovens:

- Custom-made (Ta, W, and Re)
- Thickness ~0.25 mm
- Volume ~0.3 cm^3
- T > 2000 ℃
- Consumption ≲ 5 mg/hour

VENUS' high-temperature resistive ovens

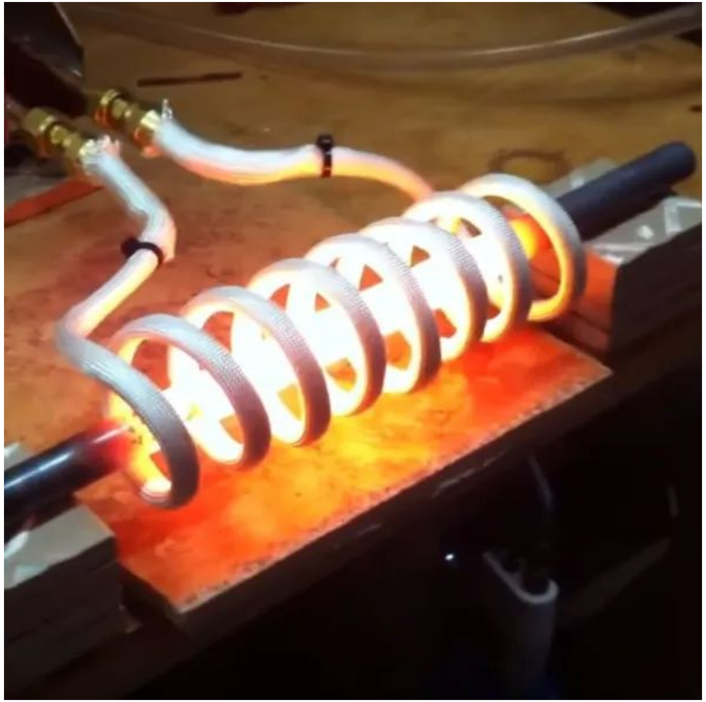


Resistive ovens:

- Custom-made (Ta, W, and Re)
- Thickness ~0.25 mm
- Volume ~0.3 cm^3
- T > 2000 ℃
- Consumption ≲ 5 mg/hour

Inside VENUS, reliable temperatures reached are typically ≲ 1500 ℃, dictated largely by hot metal chemistry

Inductive heating



Concept for ECR ion source ovens:

- Drive oscillating (175-200 kHz) current through water-cooled coil
- Metallic susceptor holding material of interest at coil center is inductively heated to outgassing temperatures

Inductive oven development for ECR ion sources

Institute of Modern Physics, Lanzhou, China

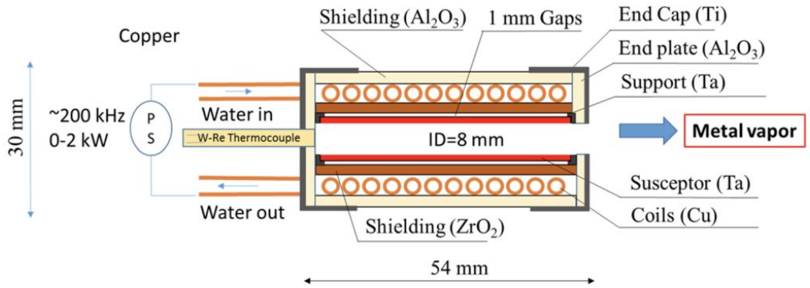


FIG. 4. Schematic view of the mini-inductive heating oven-2020. The inner diameter (ID), outer diameter (OD), and length of the oven body are 8 mm, 30 mm, and 54 mm, respectively.

Wang Lu, *et al.*, Rev. Sci. Instrum. **92** 033302 (2021)

Facility for Rare Isotope Beams, East Lansing, MI

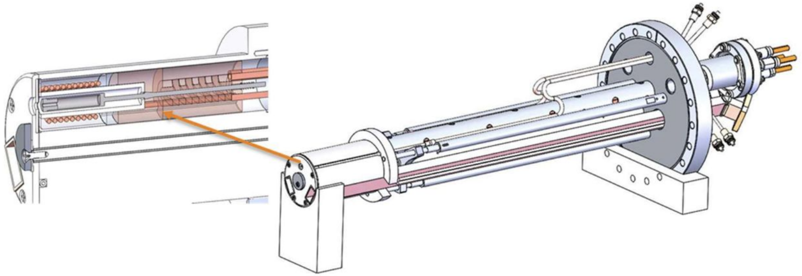
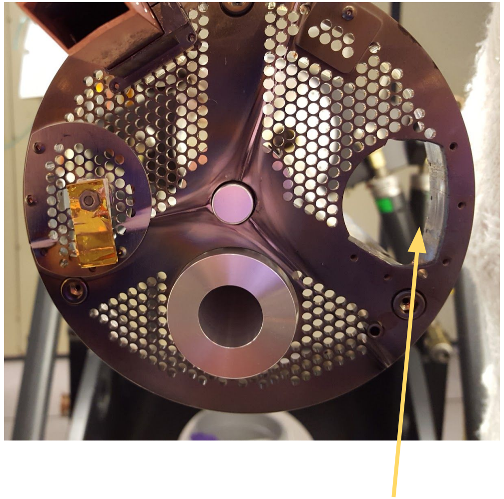


Figure 10. FRIB inductive oven design completed.

Haitao Ren, *et al.*, J. Phys.: Conf. Ser. **2244** 012008 (2022)

Inductive oven development for ECR ion sources

VENUS plasma chamber end



oven port

Facility for Rare Isotope Beams, East Lansing, MI

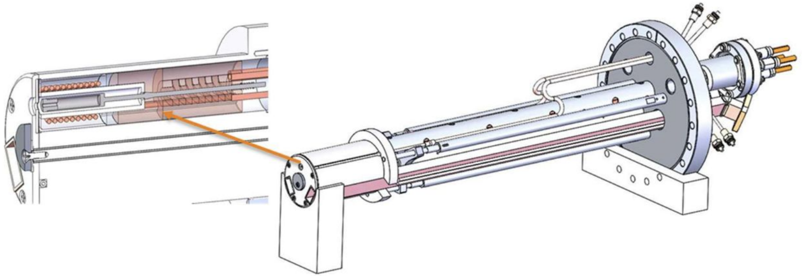
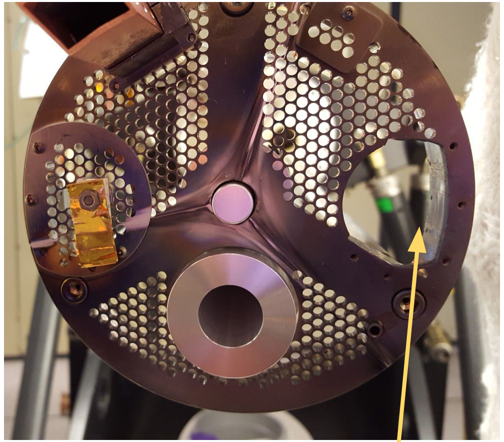


Figure 10. FRIB inductive oven design completed.

Haitao Ren, *et al.*, J. Phys.: Conf. Ser. **2244** 012008 (2022)

Inductive oven development for ECR ion sources

VENUS plasma chamber end

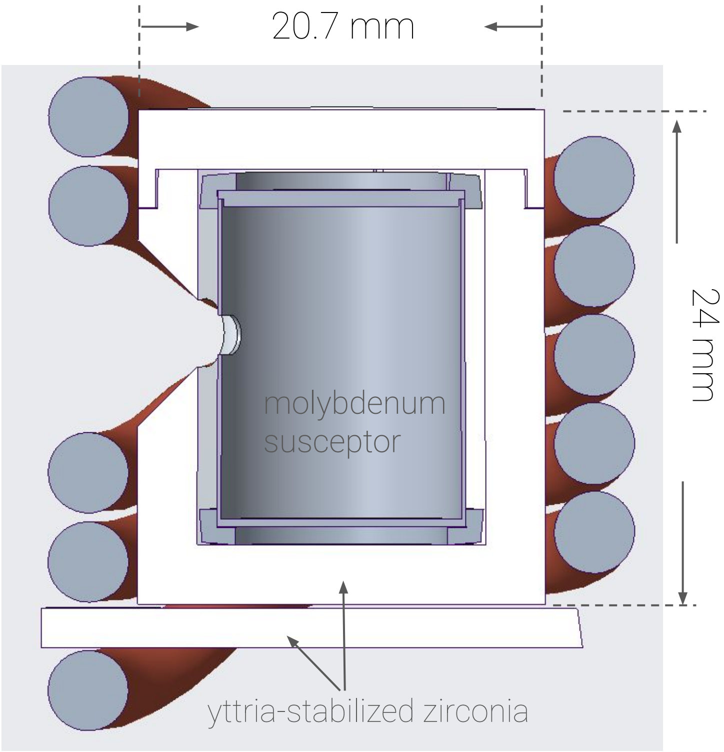


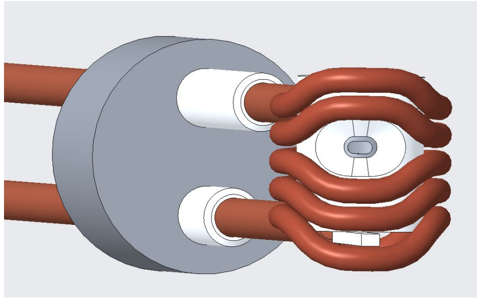
oven port

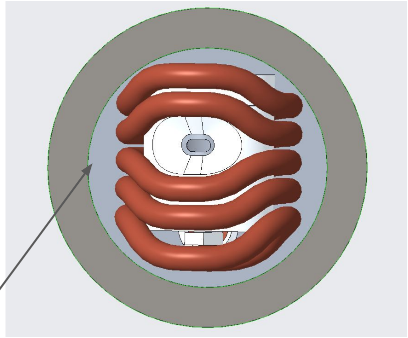
Goals for VENUS inductive oven:

- Hold enough material for weeks-long runs
- Aim output at plasma center
- Entire assembly fit through 38.1-mm-diameter port for fast changes

LBNL's vertical inductive oven design

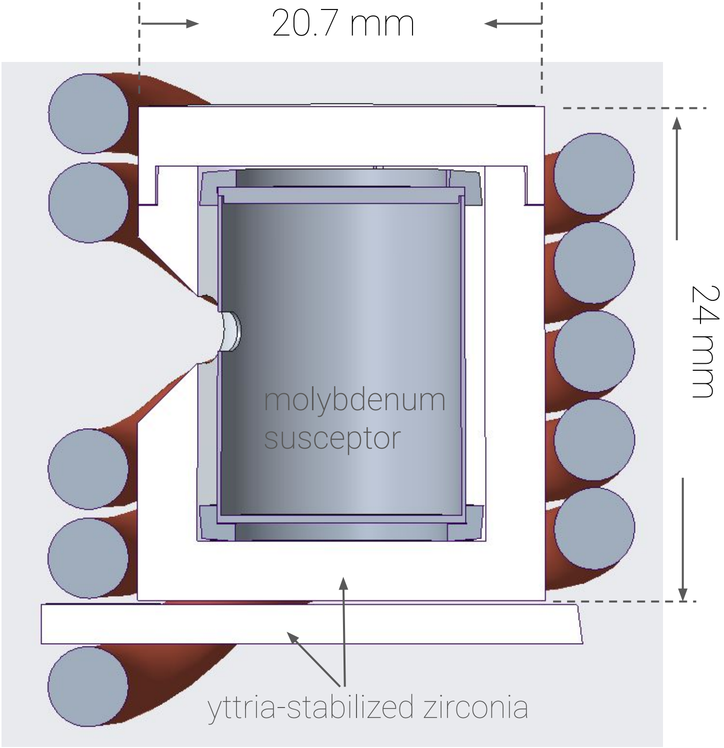




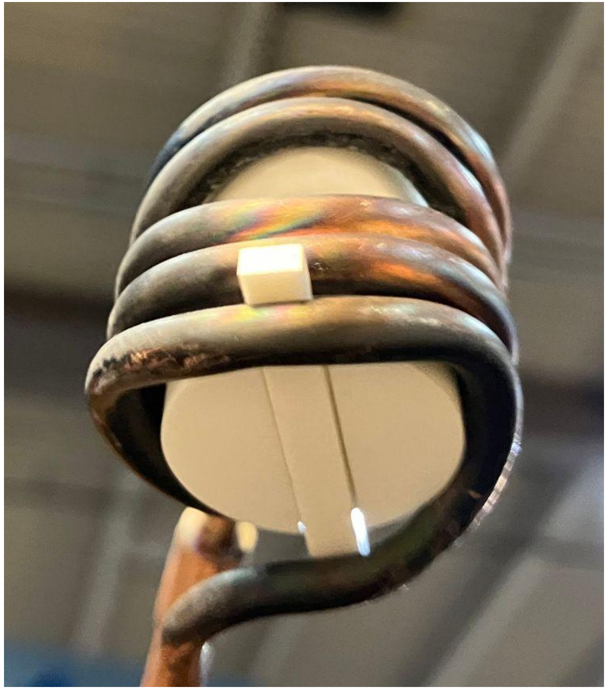


must pass through 38.1-mm-diameter port

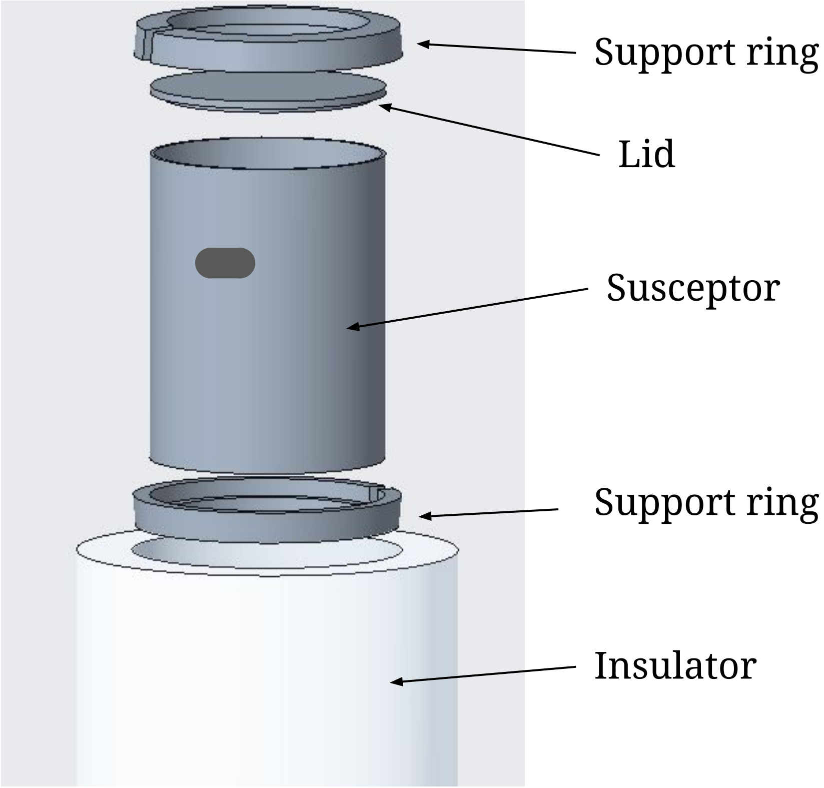
LBNL's vertical inductive oven design

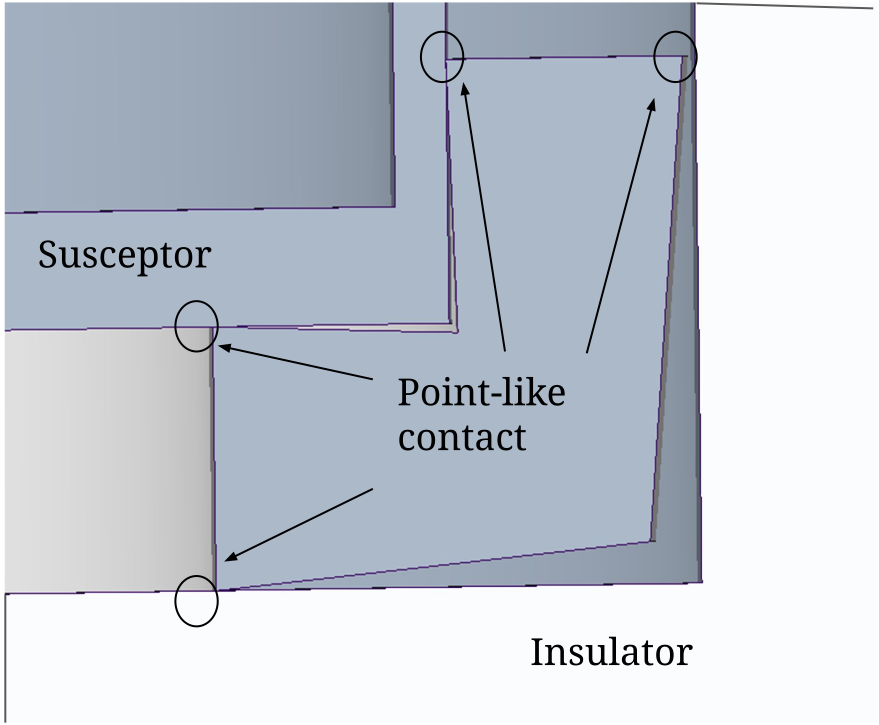


Support post provides alignment

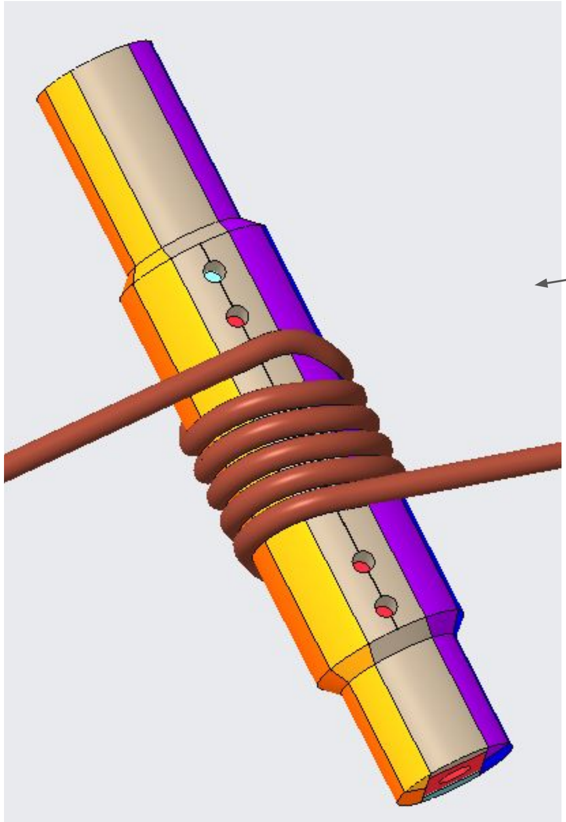


Oven exploded view



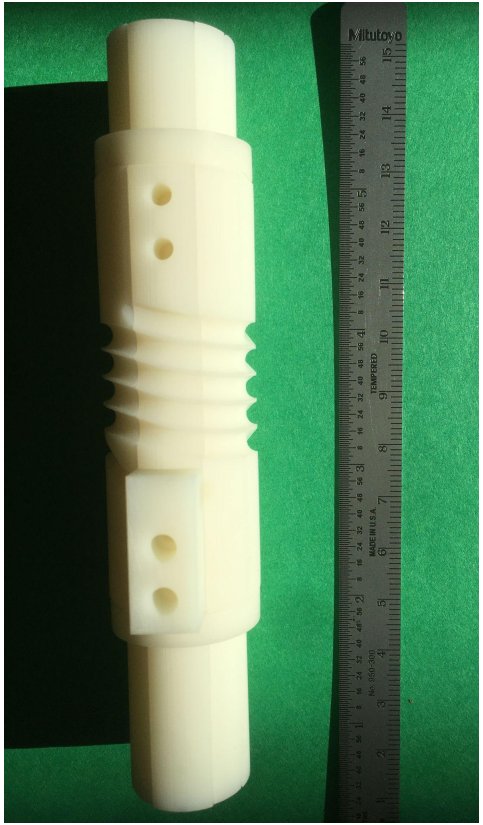


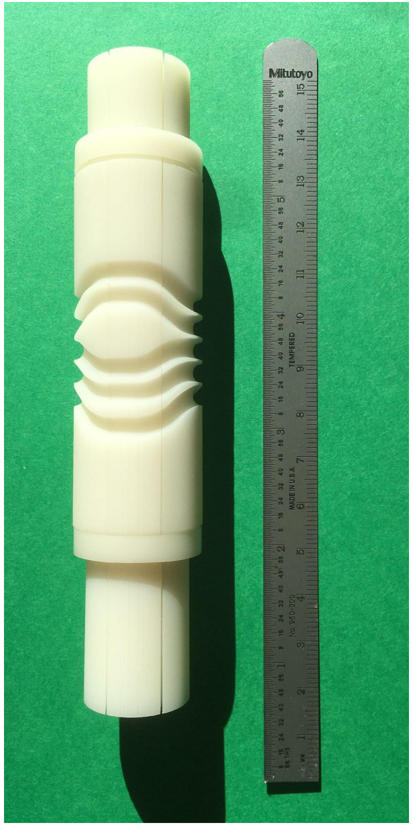
Coil winding using 3D printed winding fixture



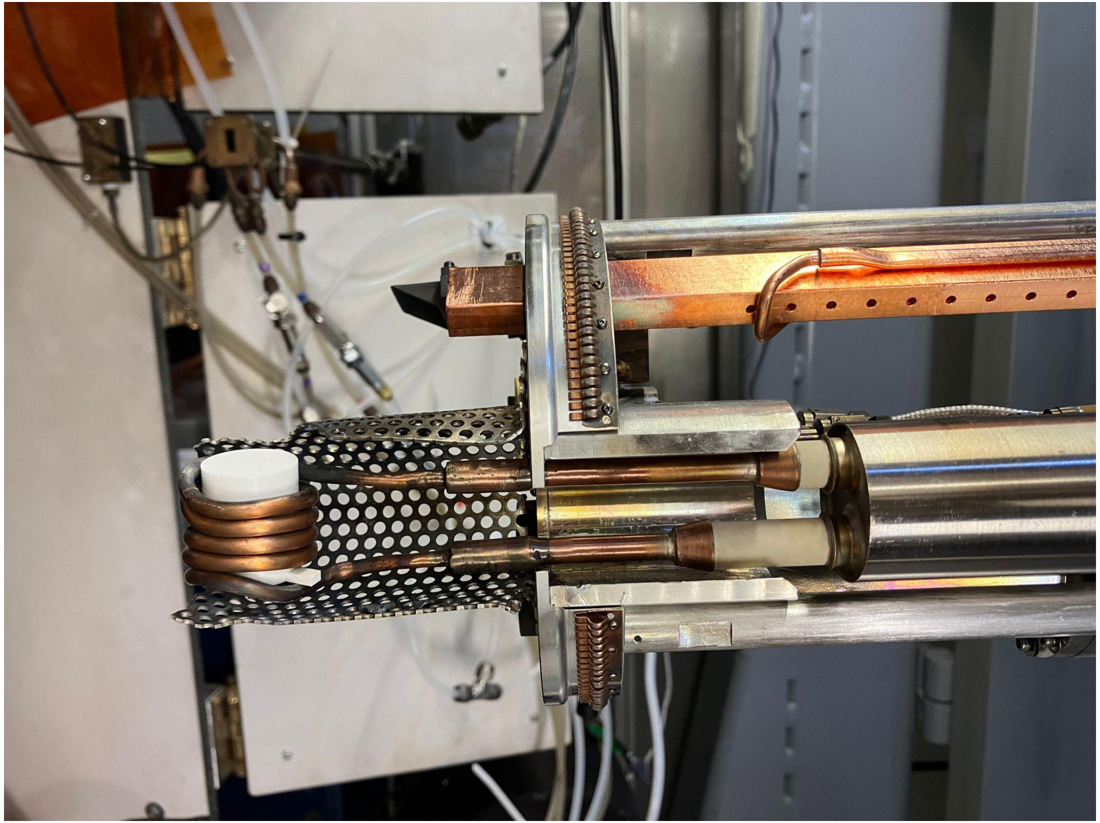
Design

Constructed fixture

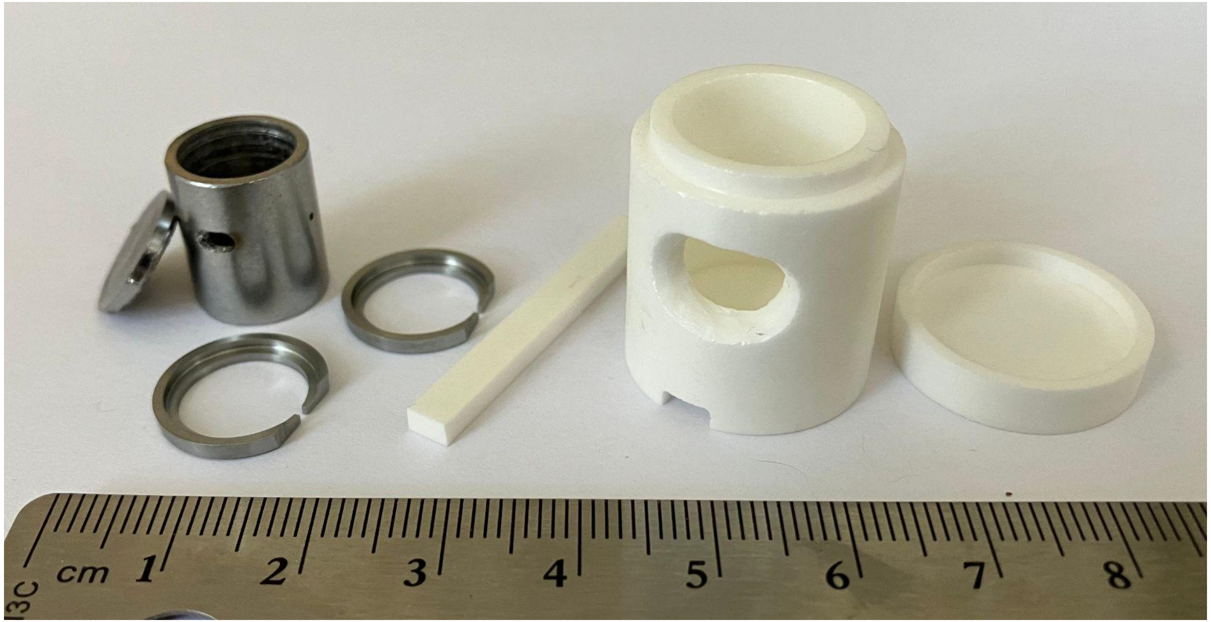




Installed with safety catch (no longer used)



Inductive oven inner parts



Susceptor:

- Ran for ~100 days before showing signs of damage

Insulators:

- Large aperture used to prevent clogging

Inductive oven inner parts

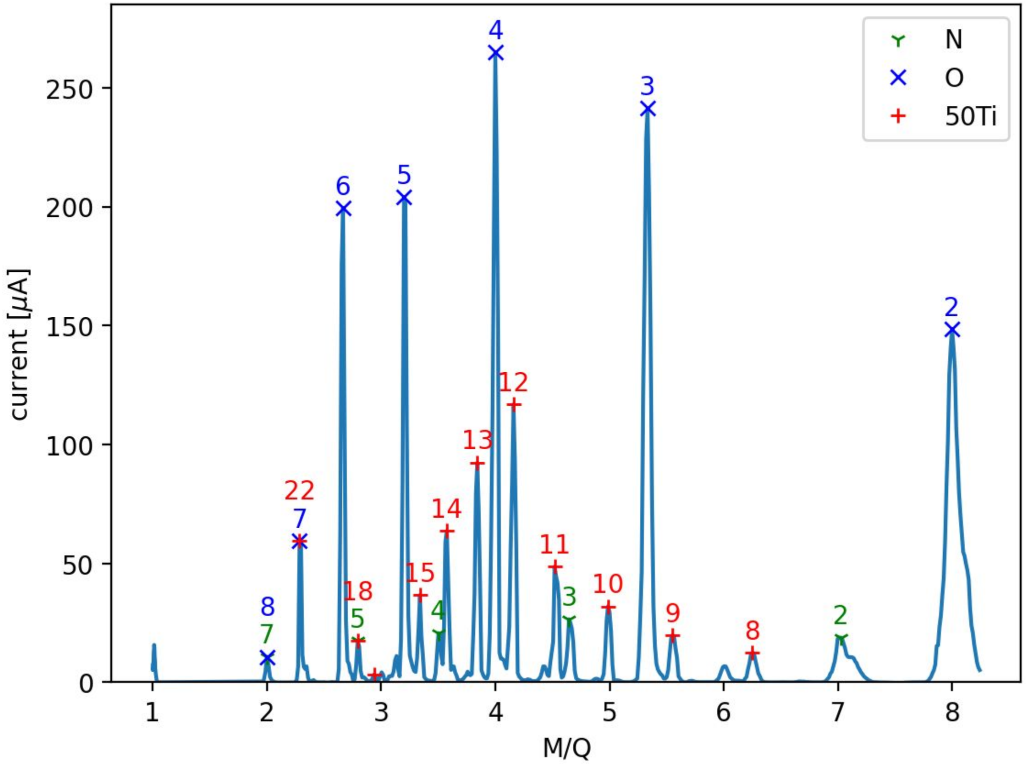
Susceptor:

- Ran for ~100 days before showing signs of damage

Insulators:

- Large aperture used to prevent clogging
- Only can be used once (~$800)

Typical source/oven operation



Oven operation:

- 800-1000 W of ~175 kHz inductive heating to produce >100 μA $^{50}Ti^{12+}$
- Can load ~1.2 g of disks, or 11-20 days

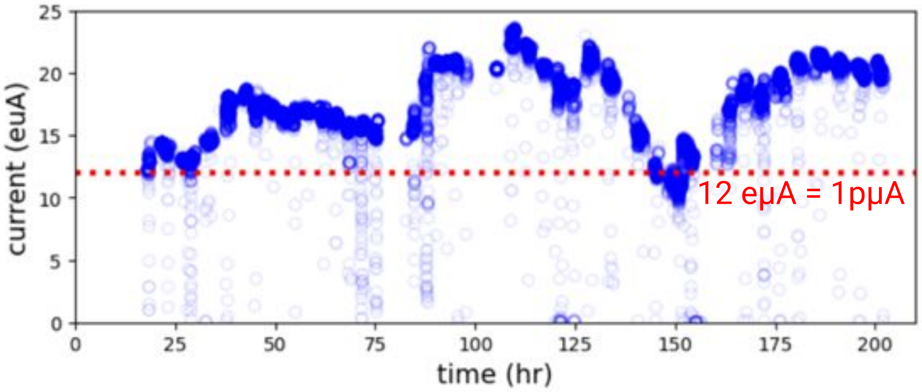
Source operation:

- Only using ~700 W of 18 GHz microwaves at 18 GHz operation magnetic fields
- Expect higher performance with 28 GHz and more power (need development time!)

$^{50}Ti^{12+}$ delivery to superheavy element experiment

- 80-140 eμA $^{50}Ti^{12+}$ from source
- Continuous runs up to 10 days (end of run)
- 1-2 pμA on target
- Consumption: 2.5 - 4.5 mg/hour
- Oven changes: 2-3 hours for beam back on target

Example data: beam delivered to BGS for 10-day run



Success: Two element 116 atoms from 22 days of running ($^{50}Ti \rightarrow {}^{244}Pu$)

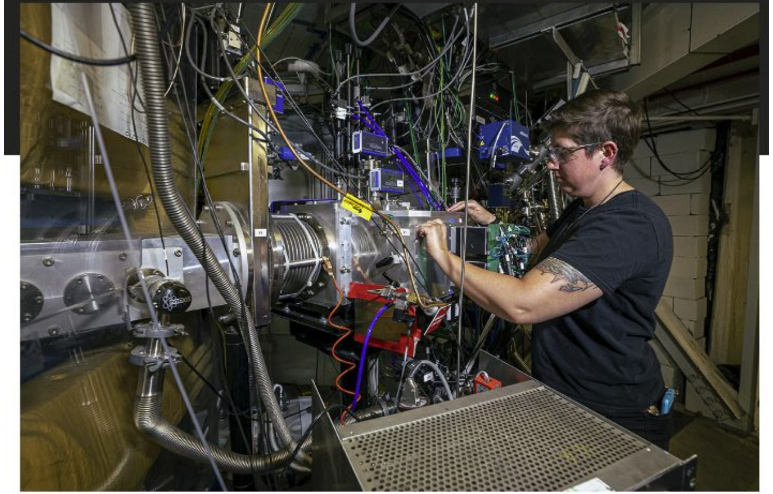
Science

NEWS | PHYSICS

U.S. back in race to forge unknown, superheavy elements

Two atoms of element 116 demonstrate path to hunt for element 120 and extend the periodic table

23 JUL. 2024 • 5:00 P.M. ET • BY ROBERT F. SERVICE



Jacklyn Gates leads superheavy element research at Lawrence Berkeley National Laboratory. MARILYN SARGENT/ LAWRENCE BERKELEY NATIONAL LABORATORY

nature

Explore content | About the journal | Publish with us | Subscribe

nature > news > article

NEWS | 23 July 2024 | Correction 30 July 2024

Heaviest element yet within reach after major breakthrough

Success with a new route to producing superheavy elements paves the way to making the elusive element 120.

By Katherine Bourzac

SCI AM

Introducing SciAm Games—Play Now!

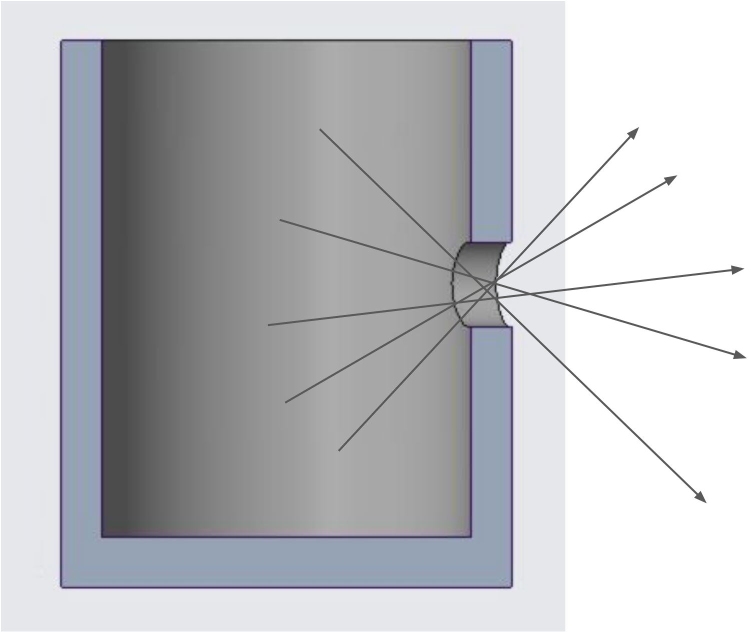
JULY 24, 2024 | 4 MIN READ

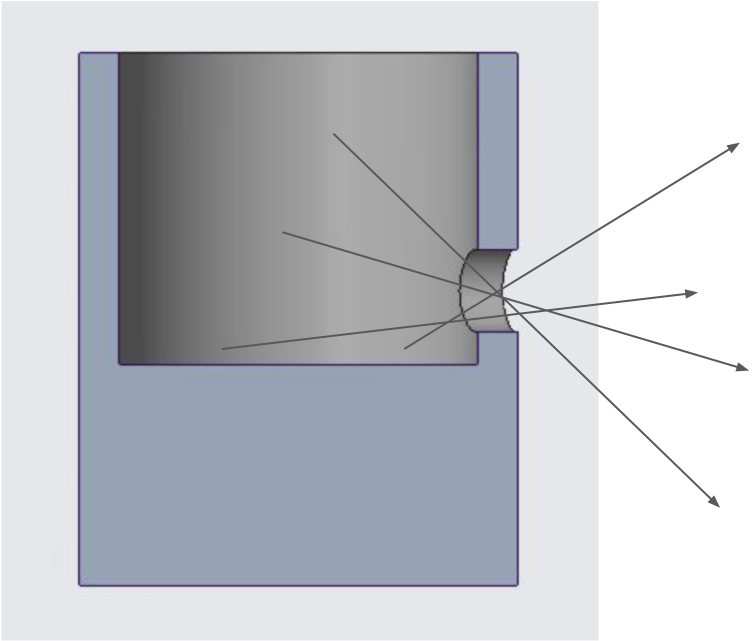
New Superheavy Element Synthesis Points to Long-Sought 'Island of Stability'

A novel way of making superheavy elements could soon add a new row to the periodic table, allowing scientists to explore uncharted atomic realms

BY MAX SPRINGER

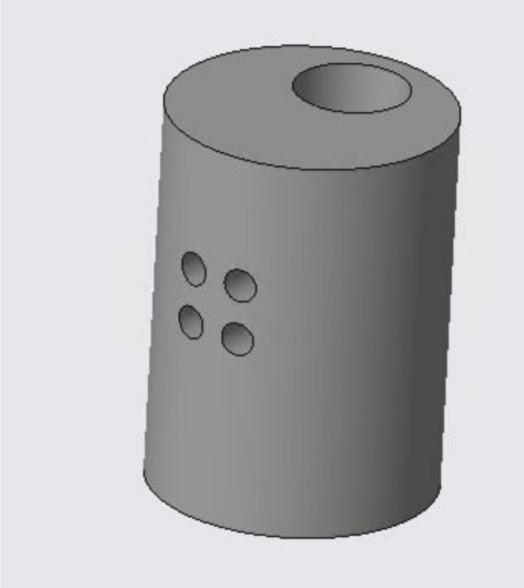
Decrease exit angle by raising bottom

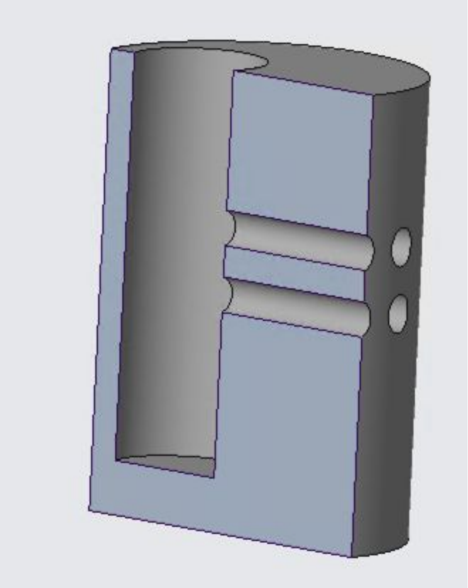




- Decreased capacity
- Unclear whether consumption has been reduced—need more data

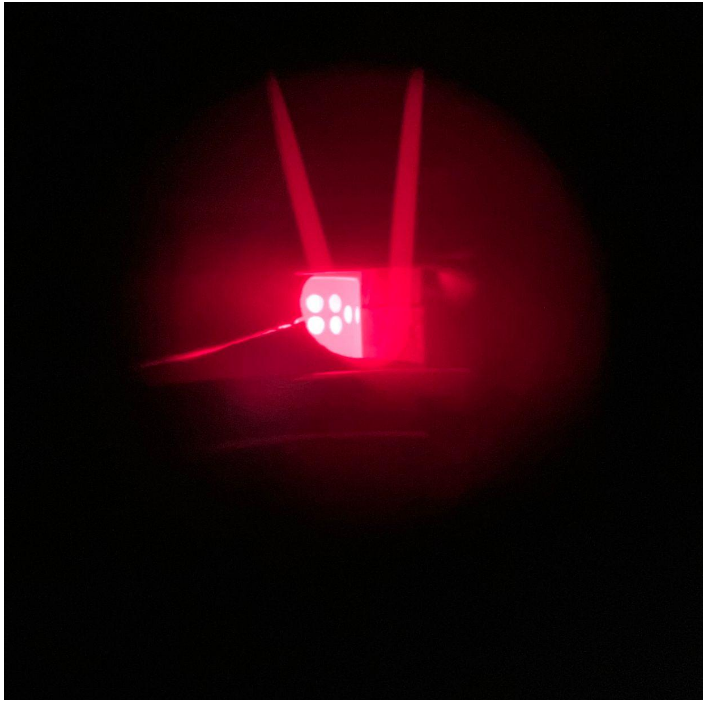
Further improvements: aiming





Proof of principle design:

Further improvements: aiming



Proof of principle design:

- In test stand, found channels are hotter than body (shouldn't clog)

Further improvements: aiming

Proof of principle design:

- In test stand, found channels are hotter than body (shouldn't clog)
- Tested in VENUS for ~3 day runs with natural titanium — no clogging
- Produced >100 uA $^{48}Ti^{11+}$
- Alignment optimization needed to optimize consumption
- Lid sticks — will address

Conclusions

- Developed new inductive oven for titanium beams
- Produced element 116 using 1-2 pμA $^{50}Ti^{12+}$ beams
- Maintained consumption rates of 2.5-4.5 mg/hour
- We will optimize channeled oven to get closer to low-temperature oven's ~0.5 mg/hour consumption rates

Collaborators and acknowledgements

88” Operations
Larry Phair, Janilee Benitez, Brien Ninemire, Nick Brickner, Patrick Coleman, Nishi Intwala, Mike Johnson, Devin Thatcher

Engineering Team
Jaime Cruz Duran, John Wirdzek

Electrical Team
Michel Kireeff Covo, Rick Bloemhard, Collin Anderson, Nathaniel Bohm, Brendan Ford, Eric Line

Mechanical Team
John Garcia, Brian Bell, Roman Nieto, Nathan Siedman, Sean Zhong

This work was supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract number DE-AC02-05CH11231 (LBNL)

Thank you for your attention!