

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

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- 118 elements

Where things stand today

1 1A 1A	2 IIA 2A																	18 VIIIA 8A
1 H Hydrogen 1.008													13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012												5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.99	12 Mg Magnesium 24.305	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B		13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.06	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38		31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.799
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414		49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592		81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine [210]	86 Rn Radon 222.018
87 Fr Francium 223.021	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [265]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [281]	111 Rg Roentgenium [289]	112 Cn Copernicium [285]		113 Nh Nihonium [286]	114 Fl Flerovium [289]	115 Mc Moscovium [288]	116 Lv Livermorium [293]	117 Ts Tennessine [294]	118 Og Oganesson [294]
Lanthanide Series			57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967	
Actinide Series			89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium [257]	101 Md Mendelevium [261]	102 No Nobelium [262]	103 Lr Lawrencium [262]	
			Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Semimetal	Nonmetal	Halogen	Noble Gas	Lanthanide	Actinide						

- 118 elements
- 28 artificially-produced

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

Where things stand today

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1 H Hydrogen 1.008																		2 He Helium 4.003																																																																																																																																																																																																																																																											
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11 Na Sodium 22.990	12 Mg Magnesium 24.305	3 III 3B	4 IV 4B	5 V 5B	6 VI 6B	7 VII 7B	8 VIII		9 VIII	10 VIII	11 IB 1B	12 IIB 2B	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948																																																																																																																																																																																																																																																											
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.799																																																																																																																																																																																																																																																												
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294																																																																																																																																																																																																																																																												
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine [209.987]	86 Rn Radon 222.018																																																																																																																																																																																																																																																												
87 Fr Francium 223.025	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [277]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [281]	111 Rg Roentgenium [289]	112 Cn Copernicium [285]	113 Nh Nihonium [284]	114 Fl Flerovium [289]	115 Mc Moscovium [288]	116 Lv Livermorium [293]	117 Ts Tennessine [294]	118 Og Oganesson [294]																																																																																																																																																																																																																																																												
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89 Ac Actinium 227.028																		90 Th Thorium 232.038																		91 Pa Protactinium 231.036																		92 U Uranium 238.029																		93 Np Neptunium 237.048																		94 Pu Plutonium 244.064																		95 Am Americium 243.061																		96 Cm Curium 247.070																		97 Bk Berkelium 247.070																		98 Cf Californium 251.080																		99 Es Einsteinium [254]																		100 Fm Fermium 257.085																		101 Md Mendelevium 258.1																		102 No Nobelium 259.101																		103 Lr Lawrencium [262]																	
Alkali Metal																		Alkaline Earth																		Transition Metal																		Basic Metal																		Semimetal																		Nonmetal																		Halogen																		Noble Gas																		Lanthanide																		Actinide																																																																																																											

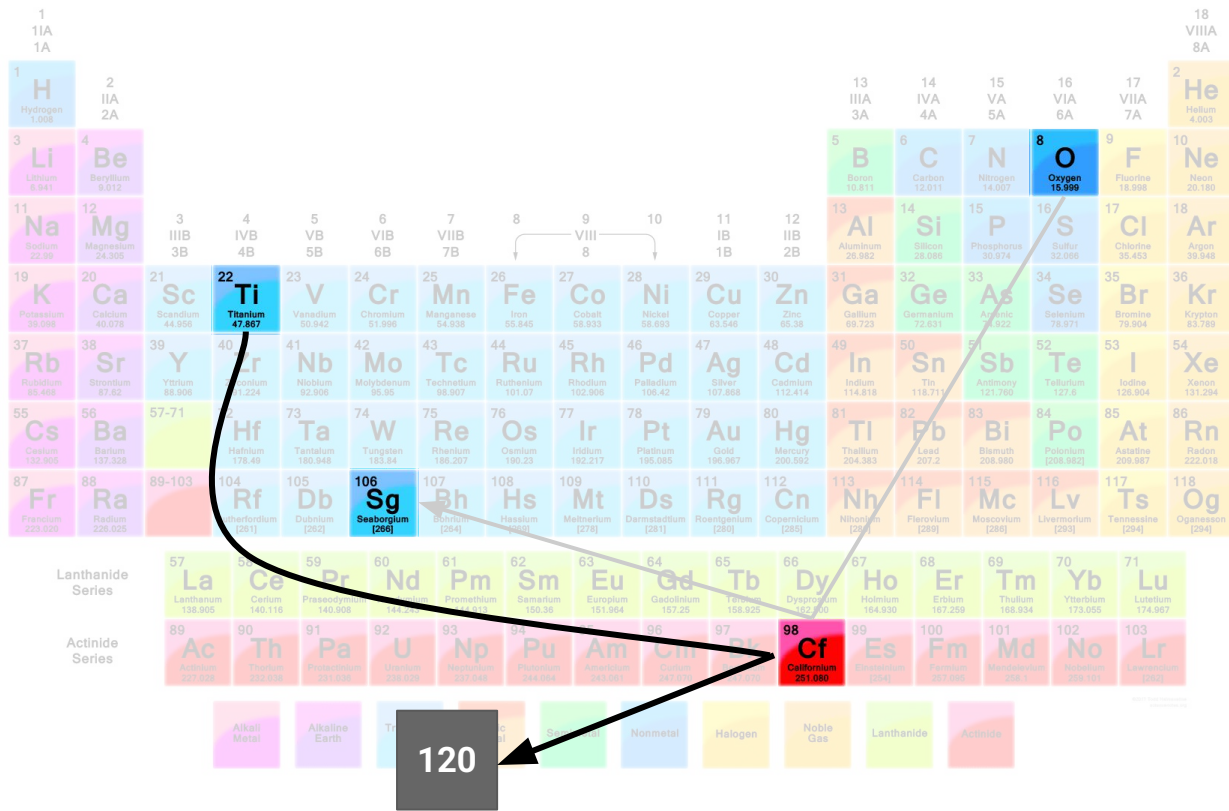
- 118 elements
- 28 artificially-produced
- 16 discovered at or by LBNL
 - LBNL's last: Sg in 1974

Where things stand today

I/A																VIII/A															
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186.207																190.23															
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Roentgenium																Copernicium															
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Praseodymium																Neodymium															
140.908																144.242															
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Europium																Gadolinium															
151.964																157.25															
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Terbium																Dysprosium															
158.925																162.50															
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Holmium																Erbium															
164.930																167.259															
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Tm																Yb															
Thulium																Ytterbium															
168.934																173.055															
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Lu																Hf															
Lutetium																Hafnium															
174.967																178.49															
89																90															
Ac																Th															
Actinium																Thorium															
[227.028]																232.038															
91																92															
Pa																U															
Protactinium																Uranium															
231.036																238.029															
93																94															
Np																Pu															
Neptunium																Plutonium															
237.048																244.064															
95																96															
Am																Cm															
Americium																Curium															
243.061																247.070															
97																98															
Bk																Cf															
Berkelium																Californium															
247.070																251.080															
99																100															
Es																Fm															
Einsteinium																Fermium															
[252]																[257]															
101																102															
Md																No															
Mendelevium																Nobelium															
258.1																259.101															
103																104															
Lr																															
Lawrencium																															
[260]																															
Alkali Metal																Alkaline Earth															
Transition Metal																Basic Metal															
Semimetal																Nonmetal															
Halogen																Noble Gas															
Lanthanide																Actinide															

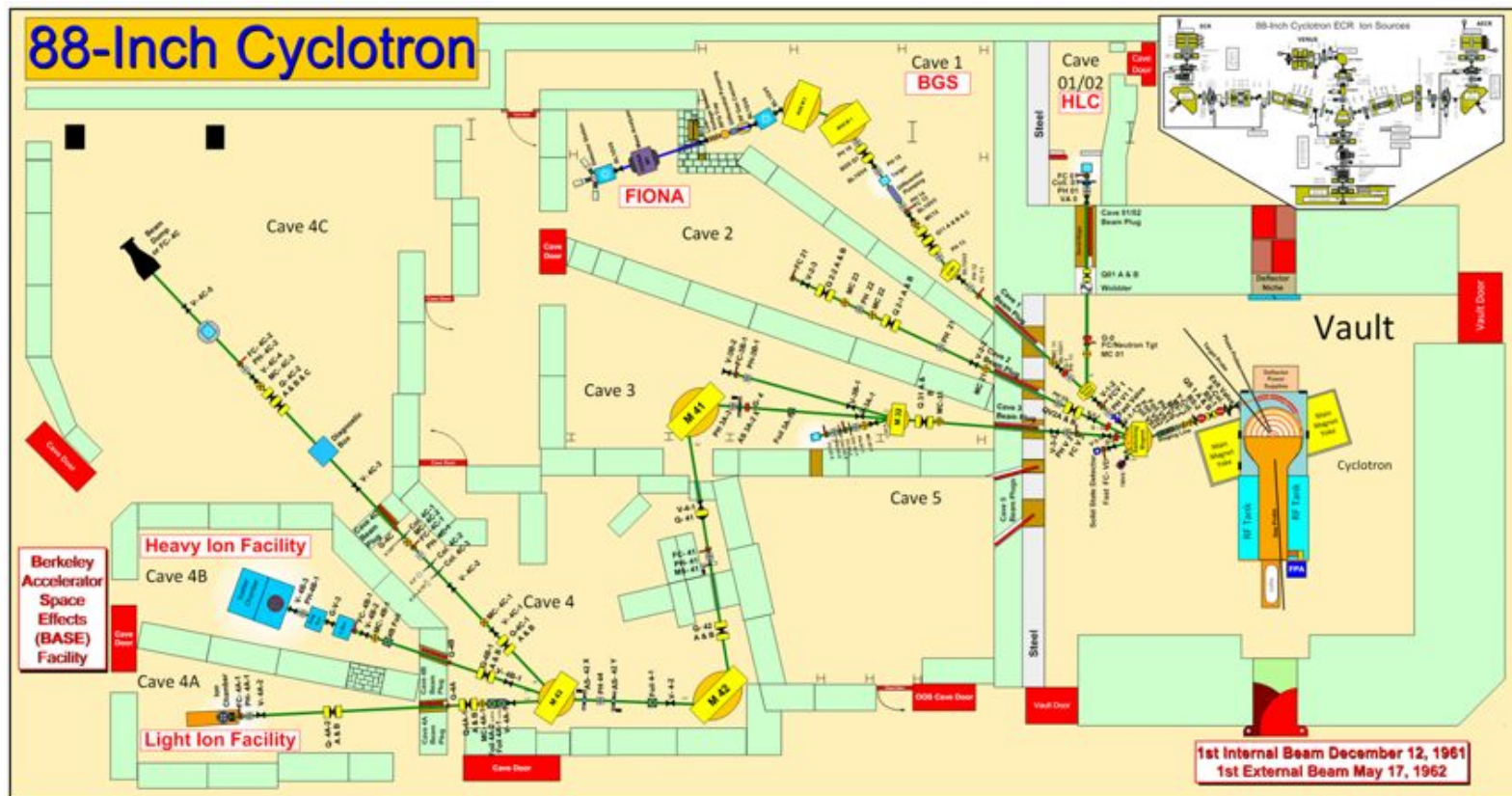
- 118 elements
- 28 artificially-produced
- 16 discovered at or by LBNL
 - LBNL's last: Sg in 1974
- 5 heaviest using ^{48}Ca beams
 - can't go further with ^{48}Ca (no heavier targets!)

Where things stand today

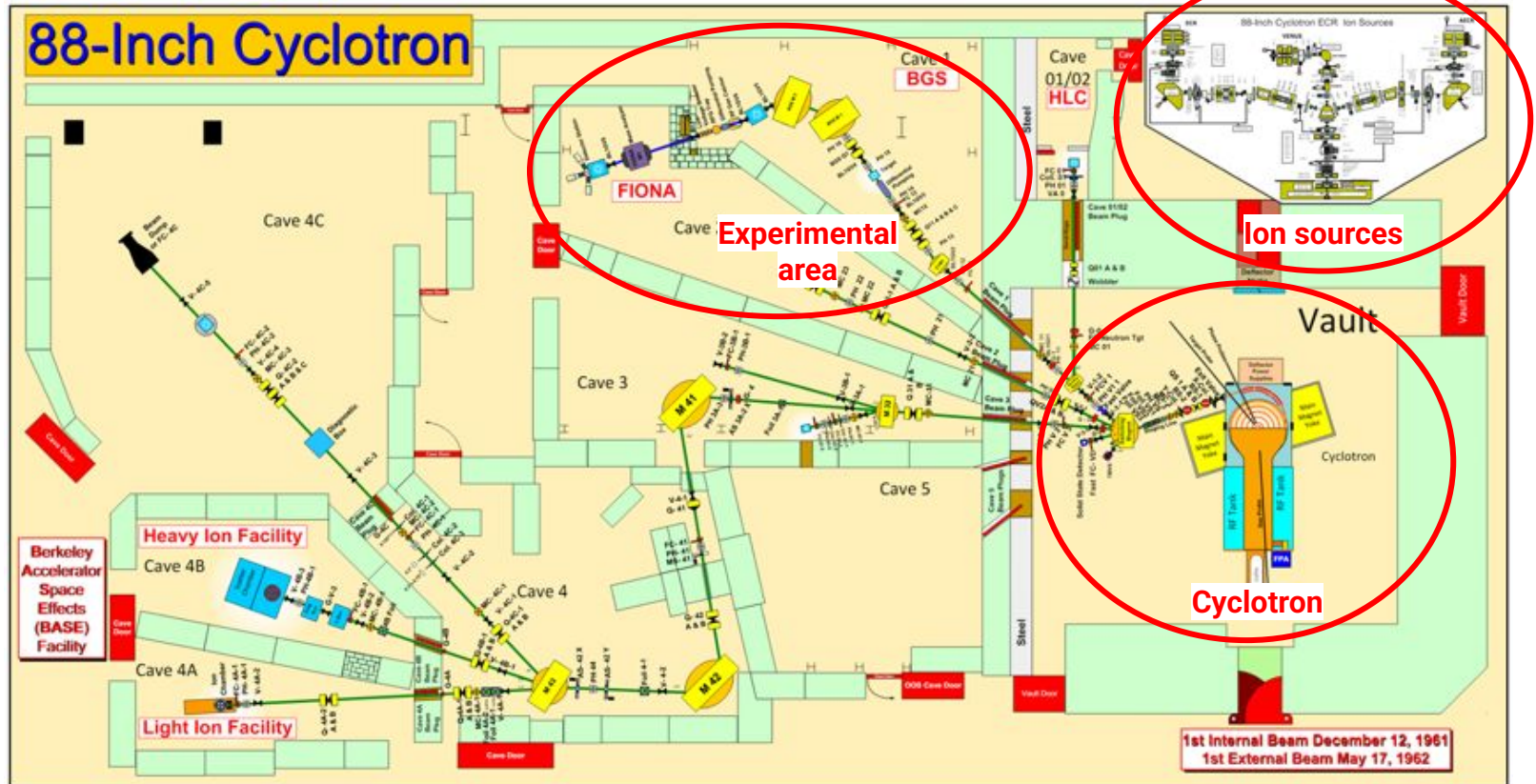


- 118 elements
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 - LBNL's last: Sg in 1974
- 5 heaviest using ^{48}Ca beams
 - can't go further with ^{48}Ca (no heavier targets!)
- LBNL to return to Cf targets
 - Use ^{50}Ti to make element 120!

LBL's 88-Inch Cyclotron facility

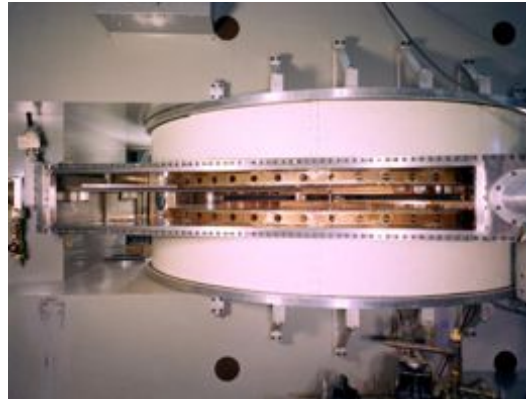


LBL's 88-Inch Cyclotron facility

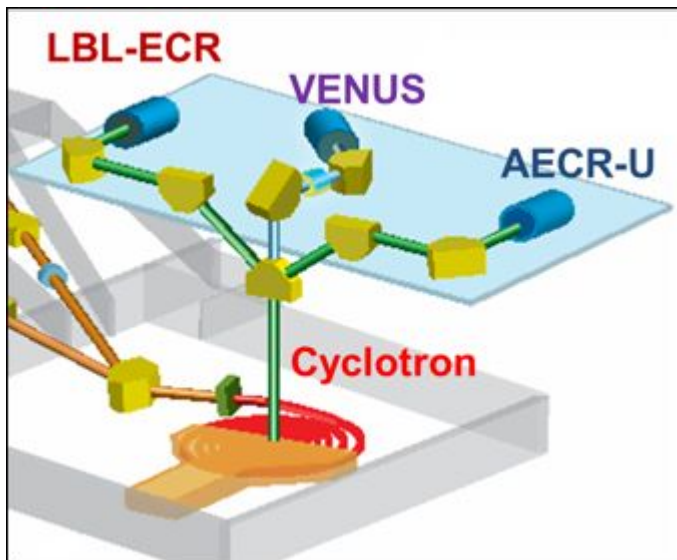


88-Inch Cyclotron

- 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

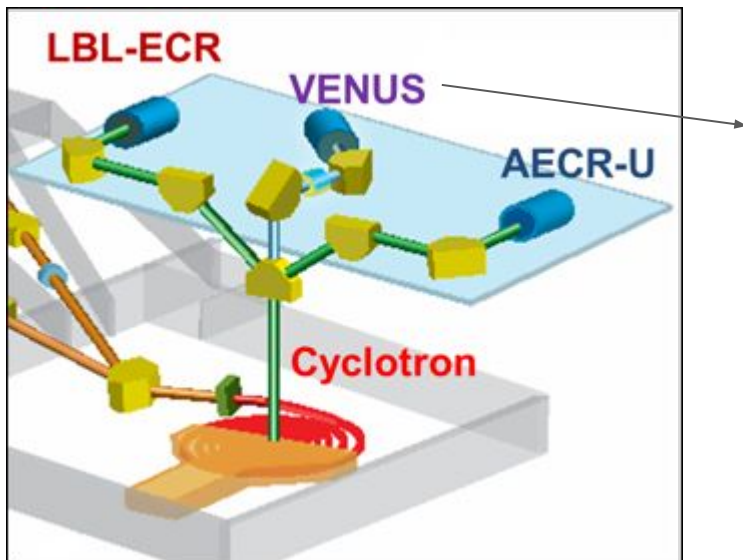
✓ = Elements previously accelerated by the 88-inch Cyclotron

1 ✓ H Hydrogen																	2 ✓ He Helium				
3 ✓ Li Lithium	4 ✓ Be Beryllium															5 ✓ B Boron	6 ✓ C Carbon	7 ✓ N Nitrogen	8 ✓ O Oxygen	9 ✓ F Fluorine	10 ✓ Ne Neon
11 ✓ Na Sodium	12 ✓ Mg Magnesium															13 ✓ Al Aluminum	14 ✓ Si Silicon	15 ✓ P Phosphorus	16 ✓ S Sulfur	17 ✓ Cl Chlorine	18 ✓ Ar Argon
19 ✓ K Potassium	20 ✓ Ca Calcium	21 ✓ Sc Scandium	22 ✓ Ti Titanium	23 ✓ V Vanadium	24 ✓ Cr Chromium	25 ✓ Mn Manganese	26 ✓ Fe Iron	27 ✓ Co Cobalt	28 ✓ Ni Nickel	29 ✓ Cu Copper	30 ✓ Zn Zinc	31 ✓ Ga Gallium	32 ✓ Ge Germanium	33 ✓ As Arsenic	34 ✓ Se Selenium	35 ✓ Br Bromine	36 ✓ Kr Krypton				
37 ✓ Rb Rubidium	38 ✓ Sr Strontium	39 ✓ Y Yttrium	40 ✓ Zr Zirconium	41 ✓ Nb Niobium	42 ✓ Mo Molybdenum	43 ✓ Tc Technetium	44 ✓ Ru Ruthenium	45 ✓ Rh Rhodium	46 ✓ Pd Palladium	47 ✓ Ag Silver	48 ✓ Cd Cadmium	49 ✓ In Indium	50 ✓ Sn Tin	51 ✓ Sb Antimony	52 ✓ Te Tellurium	53 ✓ I Iodine	54 ✓ Xe Xenon				
55 ✓ Cs Cesium	56 ✓ Ba Barium	*	71 ✓ Lu Lutetium	72 ✓ Hf Hafnium	73 ✓ Ta Tantalum	74 ✓ W Tungsten	75 ✓ Re Rhenium	76 ✓ Os Osmium	77 ✓ Ir Iridium	78 ✓ Pt Platinum	79 ✓ Au Gold	80 ✓ Hg Mercury	81 ✓ Tl Thallium	82 ✓ Pb Lead	83 ✓ Bi Bismuth	84 ✓ Po Polonium	85 ✓ At Astatine	86 ✓ Rn Radon			
87 ✓ Fr Francium	88 ✓ Ra Radium	*	103 ✓ Lr Lawrencium	104 ✓ Rf Rutherfordium	105 ✓ Db Dubnium	106 ✓ Sg Seaborgium	107 ✓ Bh Bohrium	108 ✓ Hs Hassium	109 ✓ Mt Meitnerium	110 ✓ Ds Darmstadtium	111 ✓ Rg Roentgenium	112 ✓ Cn Copernicium	113 ✓ Nh Nihonium	114 ✓ Fl Flerovium	115 ✓ Mc Moscovium	116 ✓ Lv Livermorium	117 ✓ Ts Tennessine	118 ✓ Og Oganesson			

*	57 ✓ La Lanthanum	58 ✓ Ce Cerium	59 ✓ Pr Praseodymium	60 ✓ Nd Neodymium	61 ✓ Pm Promethium	62 ✓ Sm Samarium	63 ✓ Eu Europium	64 ✓ Gd Gadolinium	65 ✓ Tb Terbium	66 ✓ Dy Dysprosium	67 ✓ Ho Holmium	68 ✓ Er Erbium	69 ✓ Tm Thulium	70 ✓ Yb Ytterbium
*	89 ✓ Ac Actinium	90 ✓ Th Thorium	91 ✓ Pa Protactinium	92 ✓ U Uranium	93 ✓ Np Neptunium	94 ✓ Pu Plutonium	95 ✓ Am Americium	96 ✓ Cm Curium	97 ✓ Bk Berkelium	98 ✓ Cf Californium	99 ✓ Es Einsteinium	100 ✓ Fm Fermium	101 ✓ Md Mendelevium	102 ✓ No Nobelium
*														

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

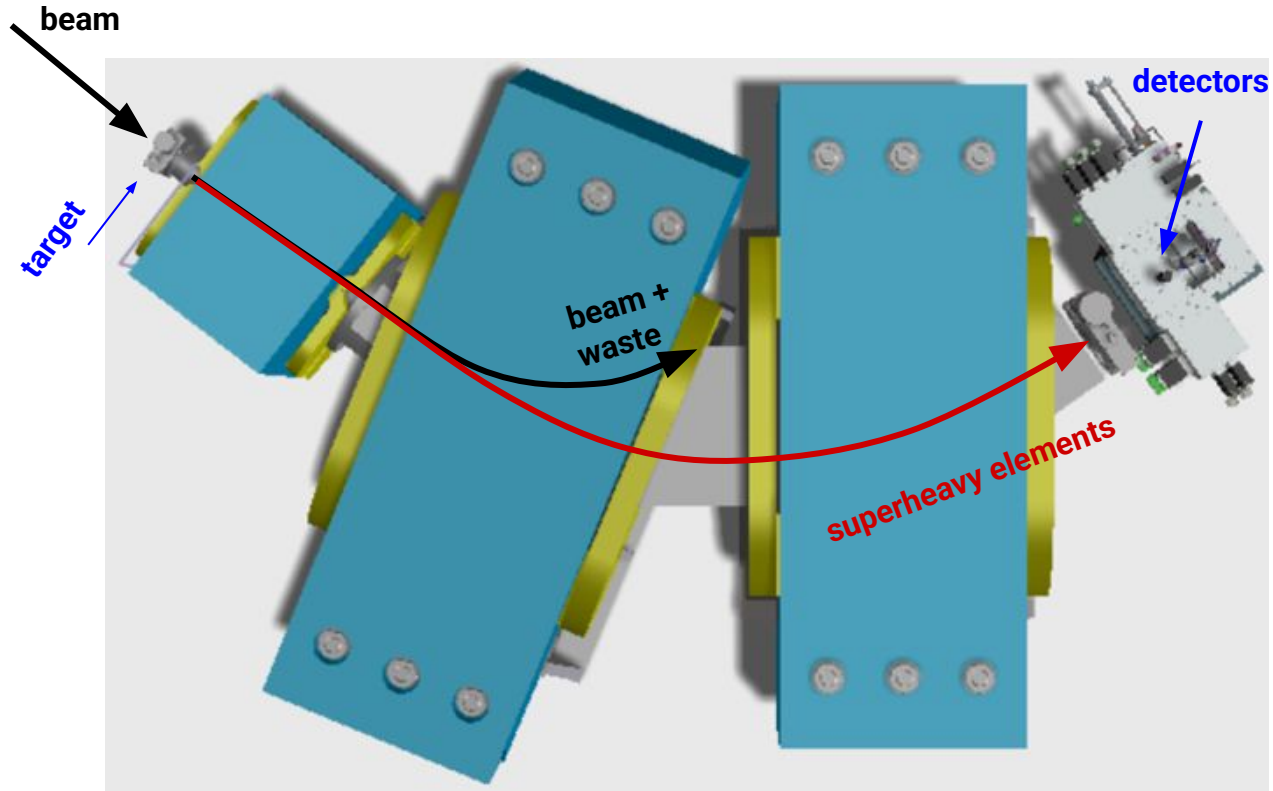
Example beams

high currents
> 4.7 mA O^{6+}
> 20 mA He^+

high charge states
 $^{197}Au^{61+}$ out of cyclotron
> 2.3 GeV!



Experiment: Berkeley Gas-Filled Separator (BGS)



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

Needs from Cyclotron

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

Needs from ion source

- $\sim 100\text{ }\mu\text{A}$ $^{50}\text{Ti}^{12+}$ @ 22 kV extraction voltage
- low material consumption ($< 5\text{ mg/hour}$)
- 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)

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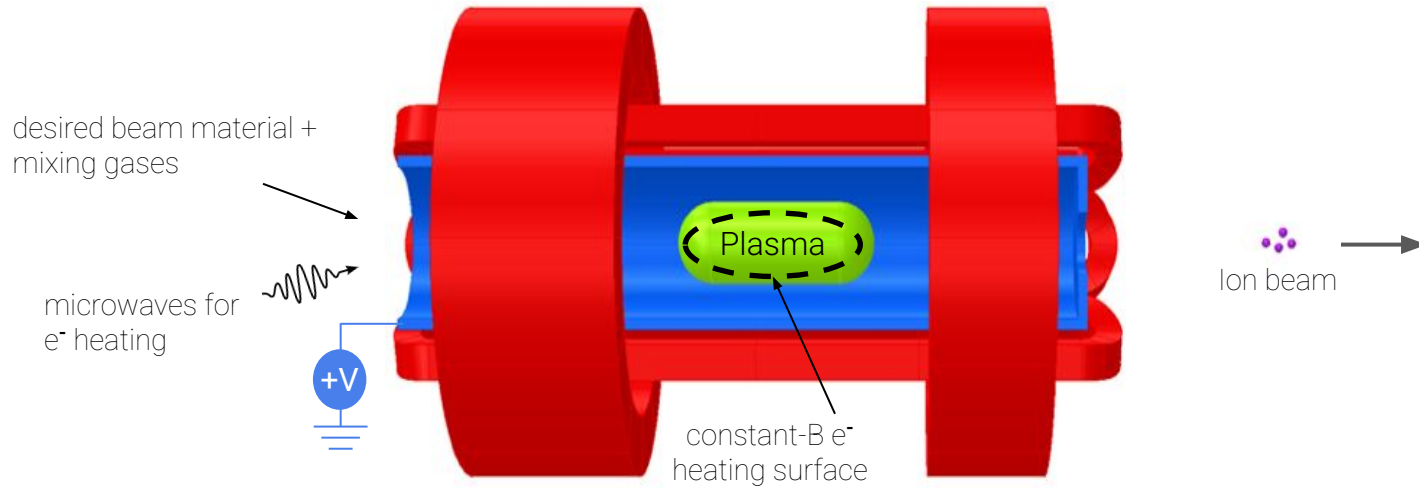
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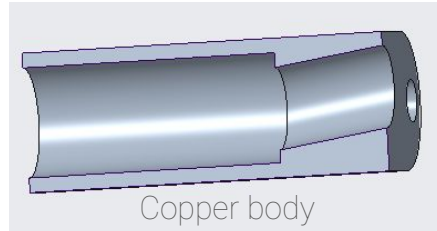
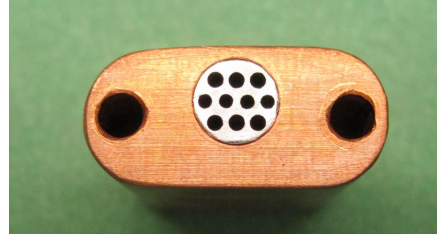
- Cyclotron has demonstrated weeks-long, 1-2 pA $^{48}\text{Ca}^{11+}$ beams at similar energies (see D.S. Todd, *et al.*, Proc. Cyclotrons 2013, MO2PB02, pp. 19-21)
- Difficult questions:
 - Can source produce these beams with these requirements
 - Can ^{50}Ti be used for superheavy production

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: $\sim 600^\circ\text{C}$
- Maximum operating temperature: $\sim 700^\circ\text{C}$

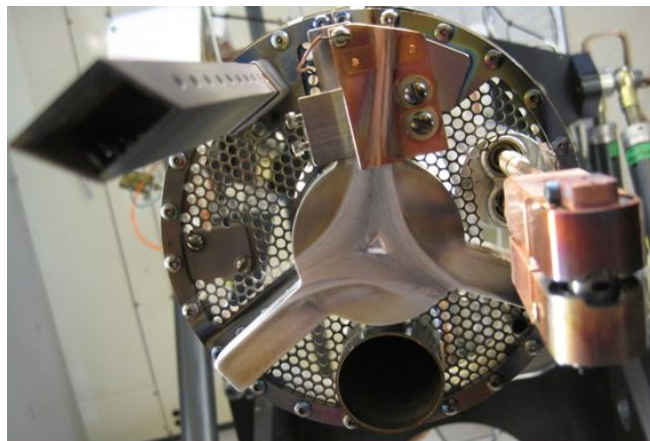
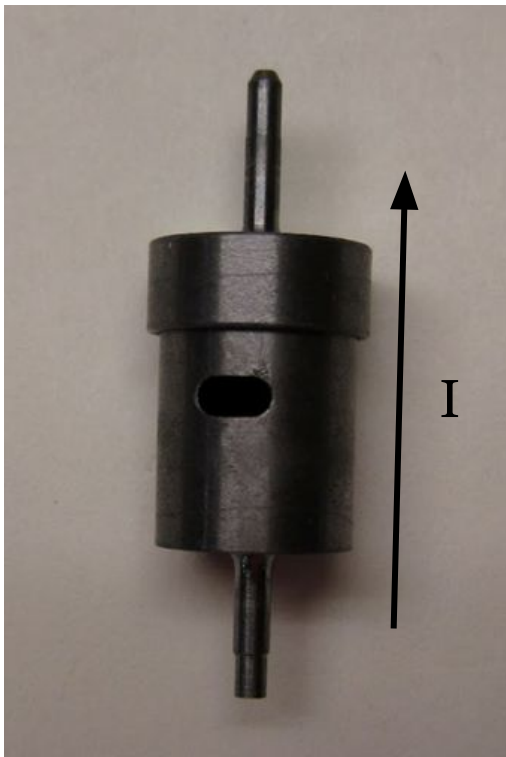
VENUS' high-temperature resistive ovens



Resistive ovens:

- Custom-made (Ta, W, and Re)
- Thickness ~ 0.25 mm
- Volume ~ 0.3 cm³
- $T > 2000$ °C
- Consumption ≤ 5 mg/hour

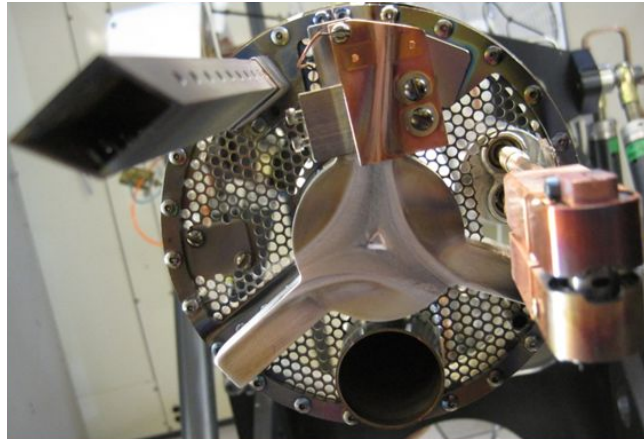
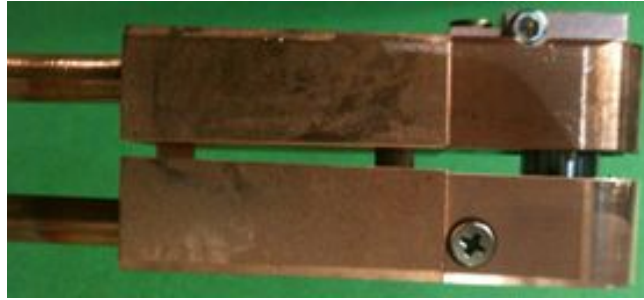
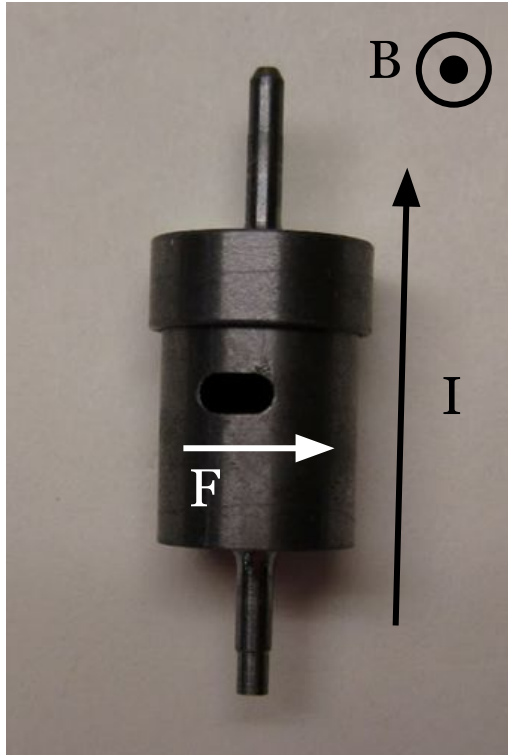
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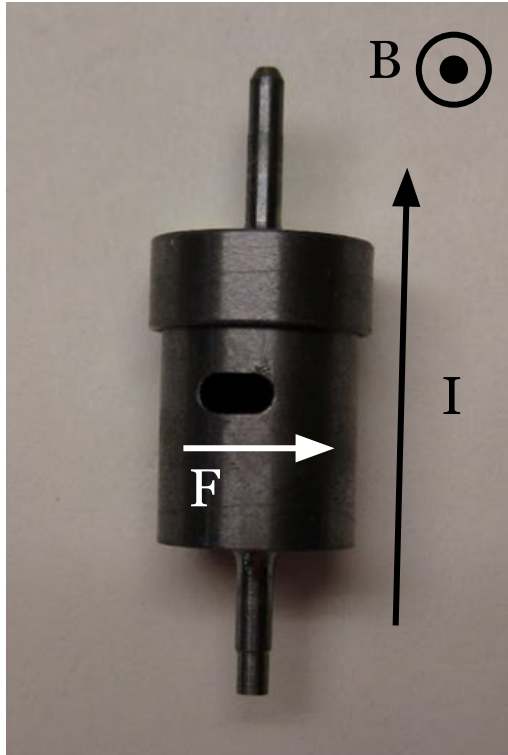
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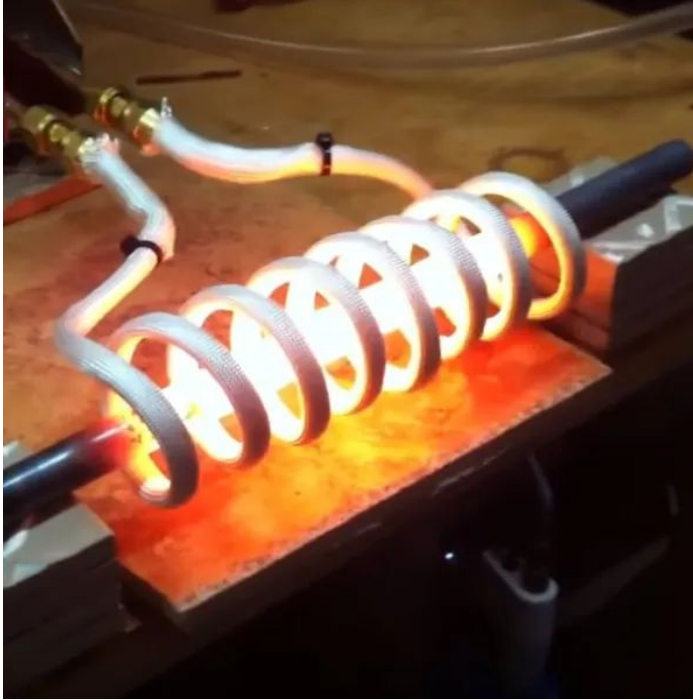


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- Volume ~ 0.3 cm³
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- Consumption $\lesssim 5$ mg/hour

Inside VENUS, reliable temperatures reached are typically $\lesssim 1500$ °C, 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

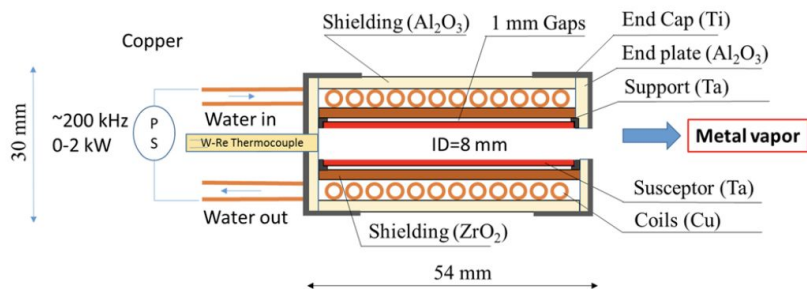


FIG. 4. Schematic view of the mini-inductive heating oven-2020. The inner diameter (ID), outer diameter (OD), and length of the oven body are 8 mm, 30 mm, and 54 mm, respectively.

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

Facility for Rare Isotope Beams, East Lansing, MI

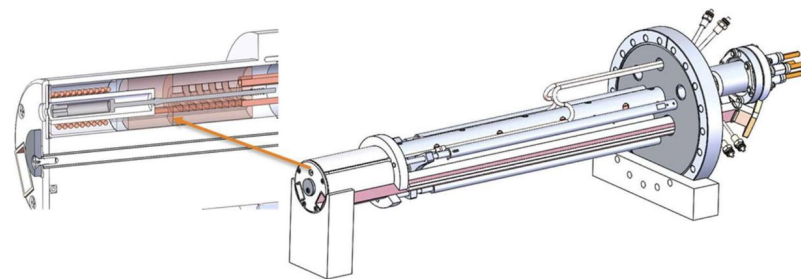
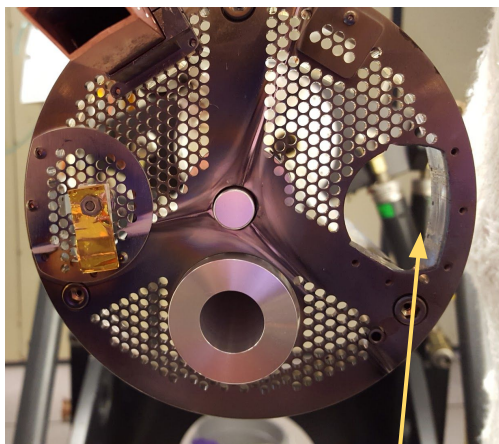


Figure 10. FRIB inductive oven design completed.

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

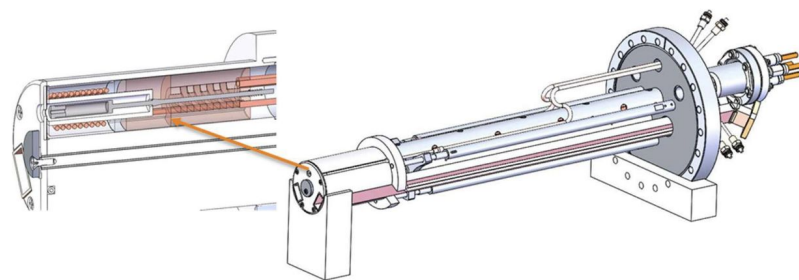
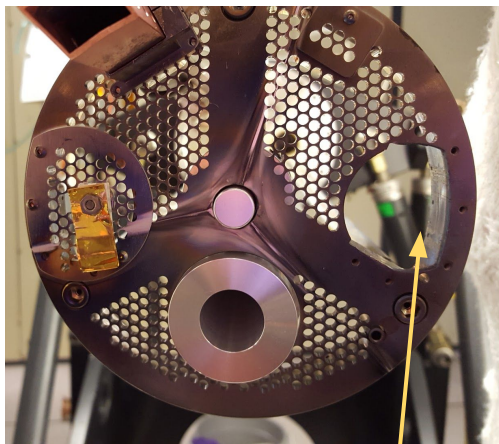


Figure 10. FRIB inductive oven design completed.

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Inductive oven development for ECR ion sources

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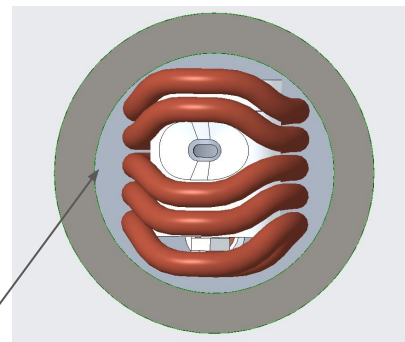
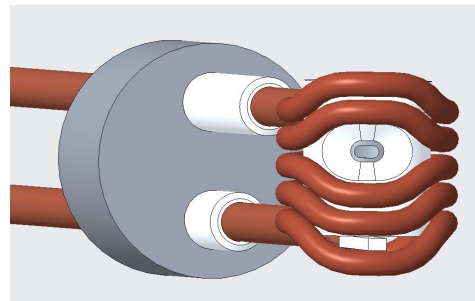
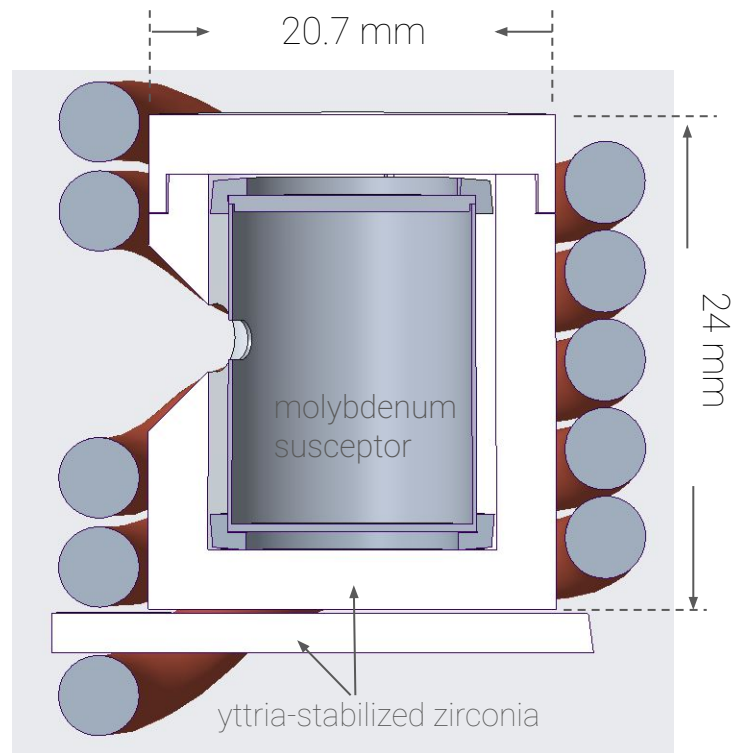


oven port

Goals for VENUS inductive oven:

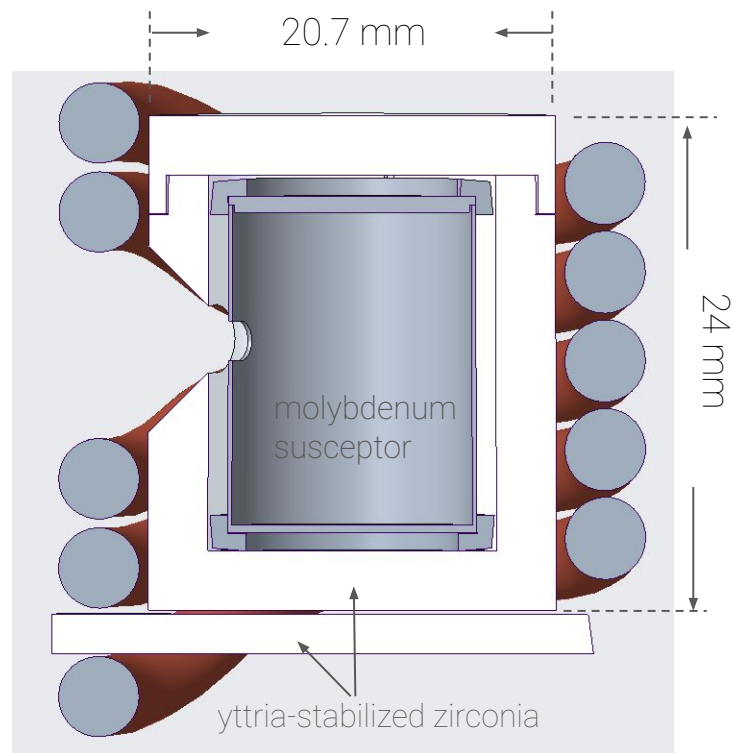
- Hold enough material for weeks-long runs
- Aim output at plasma center
- Entire assembly fit through 38.1-mm-diameter port for fast changes

LBL's vertical inductive oven design



must pass through 38.1-mm-diameter port

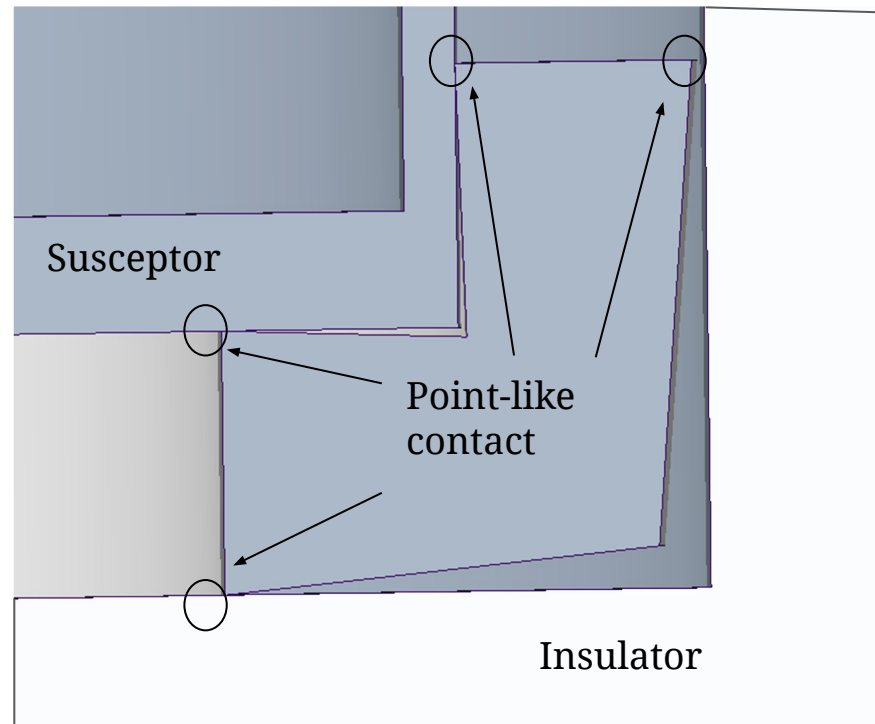
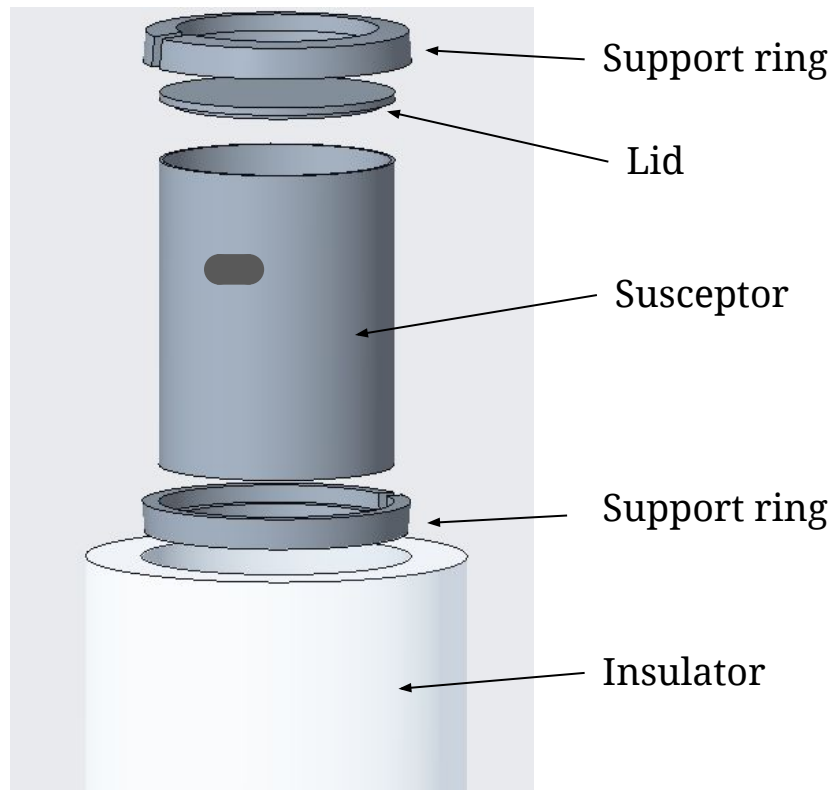
LBL's vertical inductive oven design



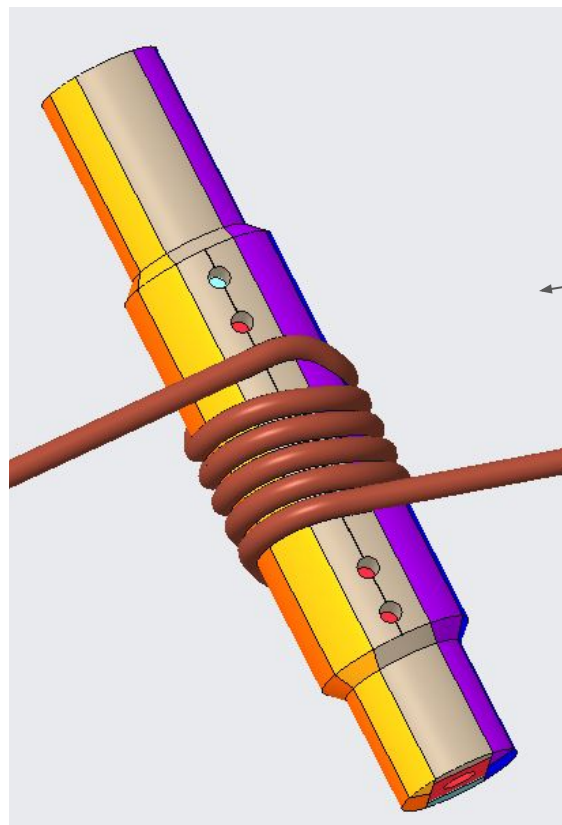
Support post provides alignment



Oven exploded view

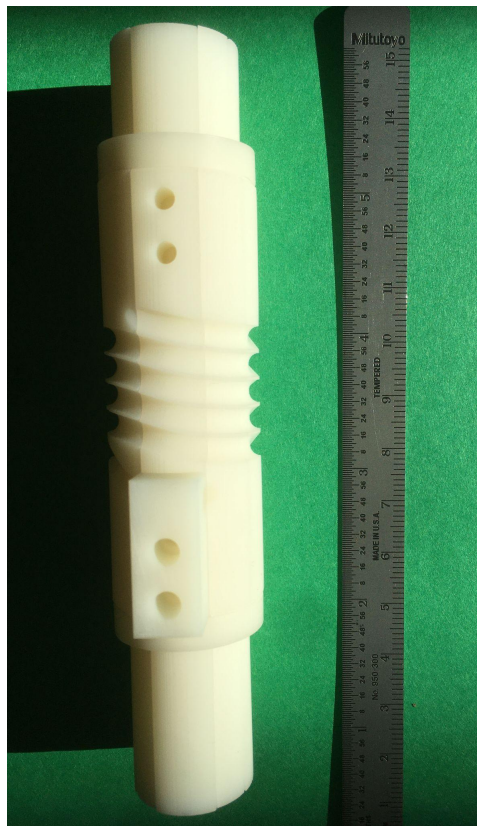


Coil winding using 3D printed winding fixture

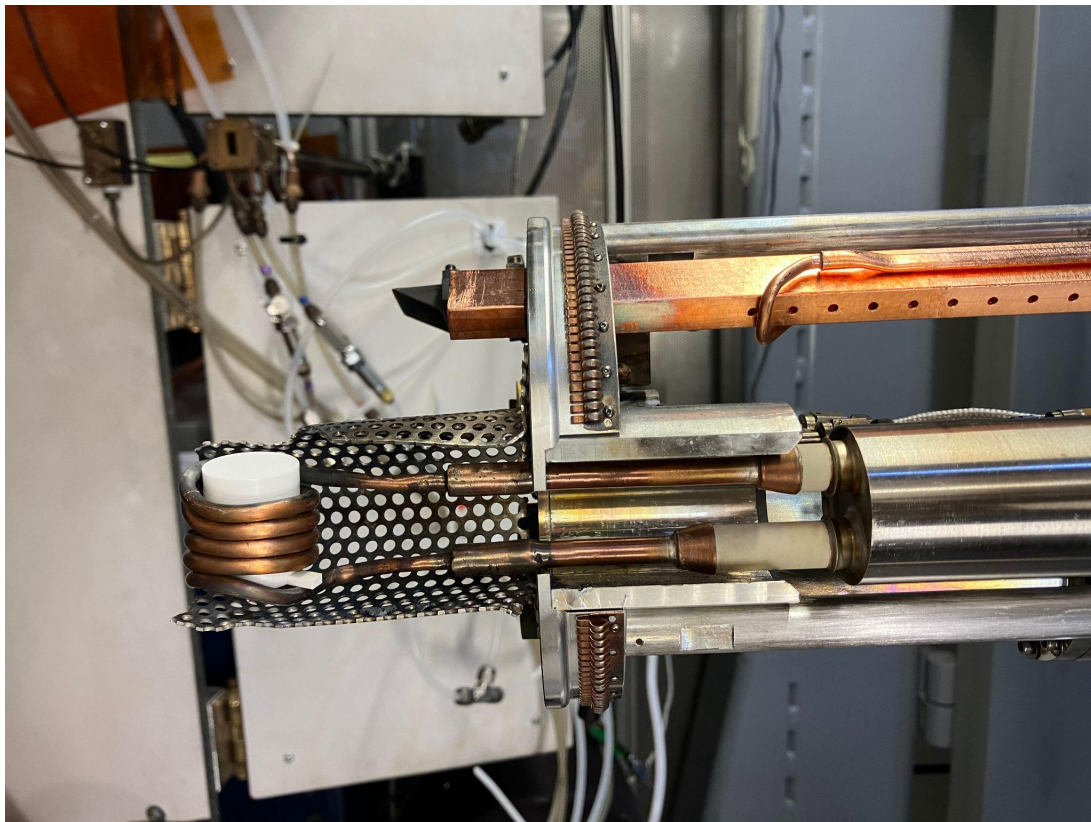


Design

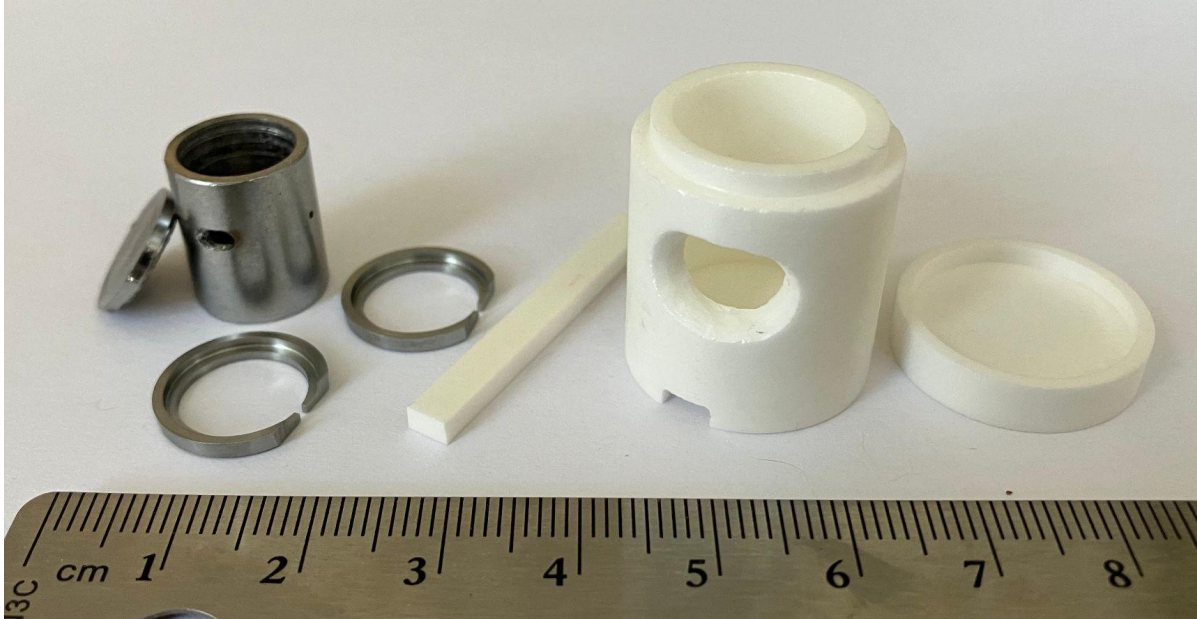
Constructed
fixture



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



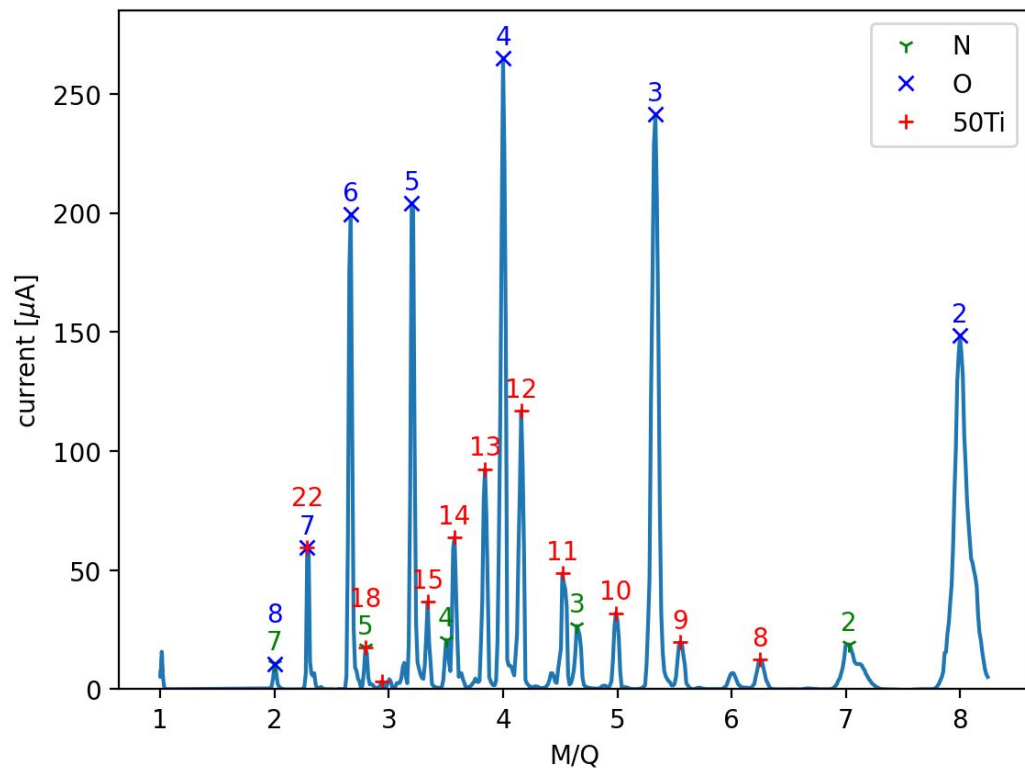
Susceptor:

- 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 $>100 \mu\text{A } ^{50}\text{Ti}^{12+}$
- Can load ~1.2 g of disks, or 11-20 days

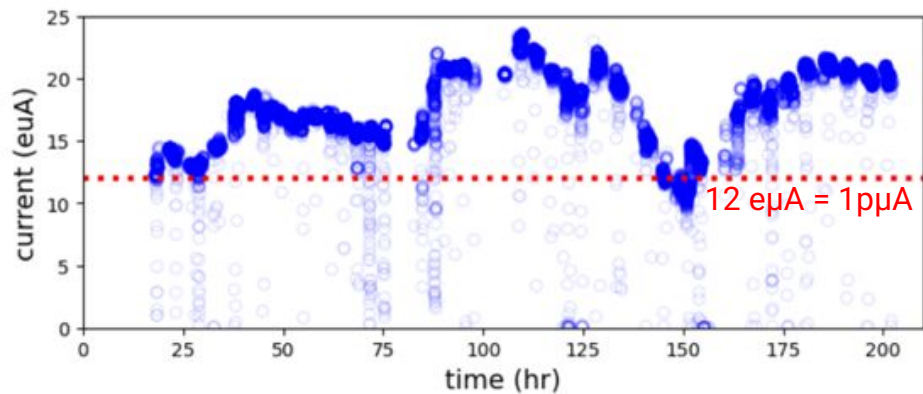
Source operation:

- 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!)

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

- 80-140 e μA $^{50}\text{Ti}^{12+}$ from source
- Continuous runs up to 10 days (end of run)
- 1-2 p μA 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 ($^{50}\text{Ti} \rightarrow ^{244}\text{Pu}$)

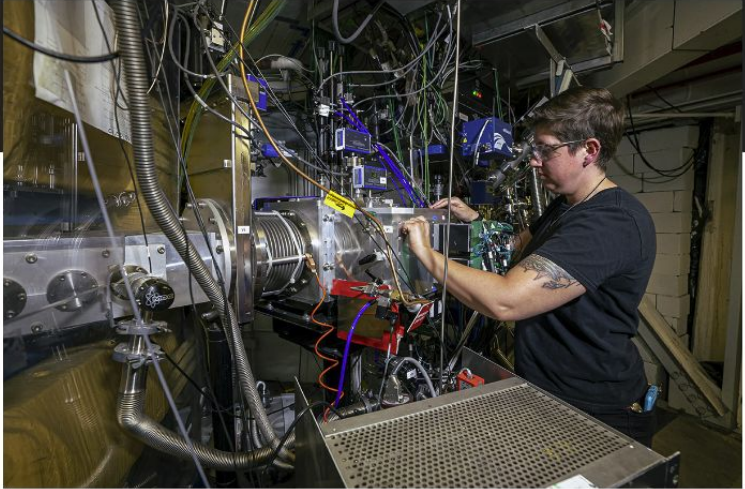
Science

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

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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](#)

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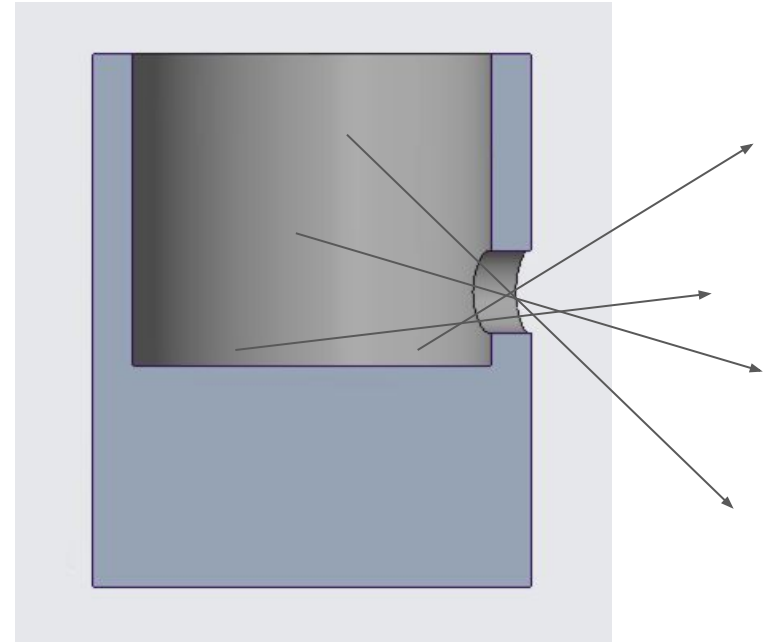
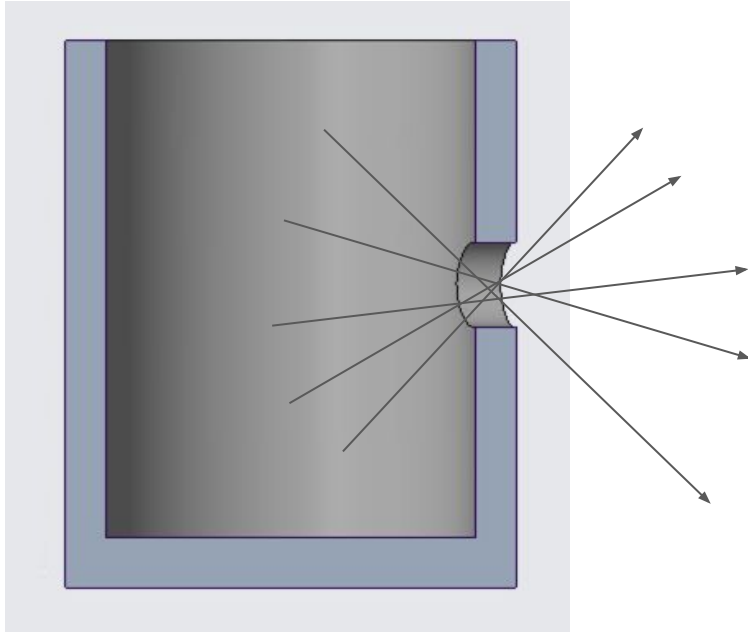
JULY 24, 2024 | 4 MIN READ

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

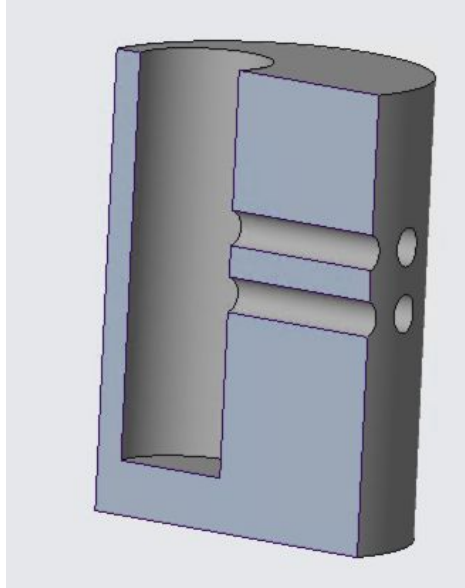
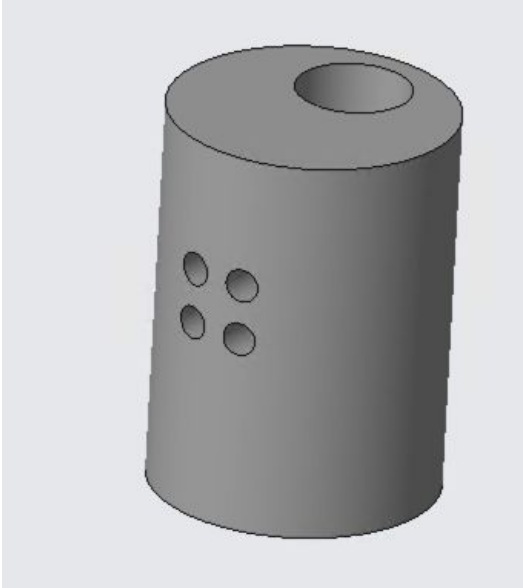
BY MAX SPRINGER

Decrease exit angle by raising bottom



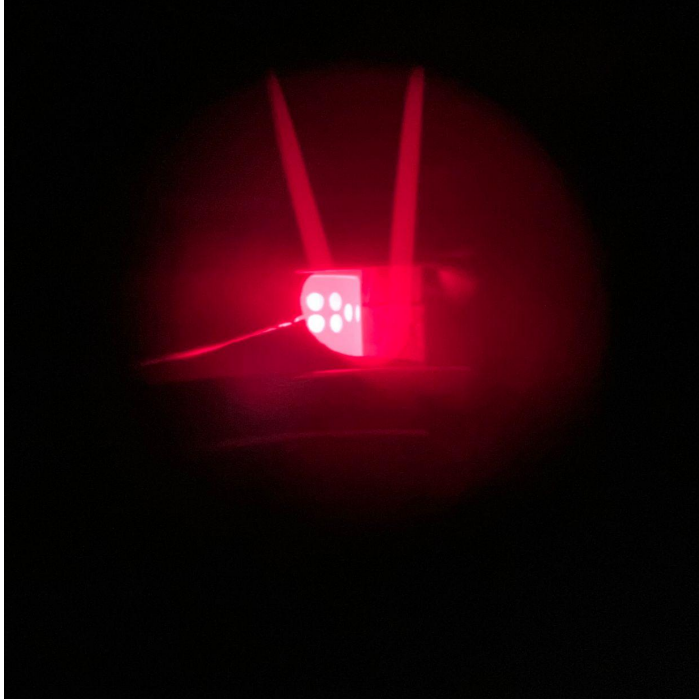
- Decreased capacity
- Unclear whether consumption has been reduced—need more data

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 $>100 \text{ uA } ^{48}\text{Ti}^{11+}$
- 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 $^{50}\text{Ti}^{12+}$ 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

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Brien Ninemire, Nick Brickner,
Patrick Coleman, Nishi Intwala,
Mike Johnson, Devin Thatcher

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Jaime Cruz Duran, John Wirdzek

Electrical Team

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Collin Anderson, Nathaniel Bohm,
Brendan Ford, Eric Line

Mechanical Team

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

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Thank you for your attention!