Electromagnetic Systems for Production of Stable Isotopes

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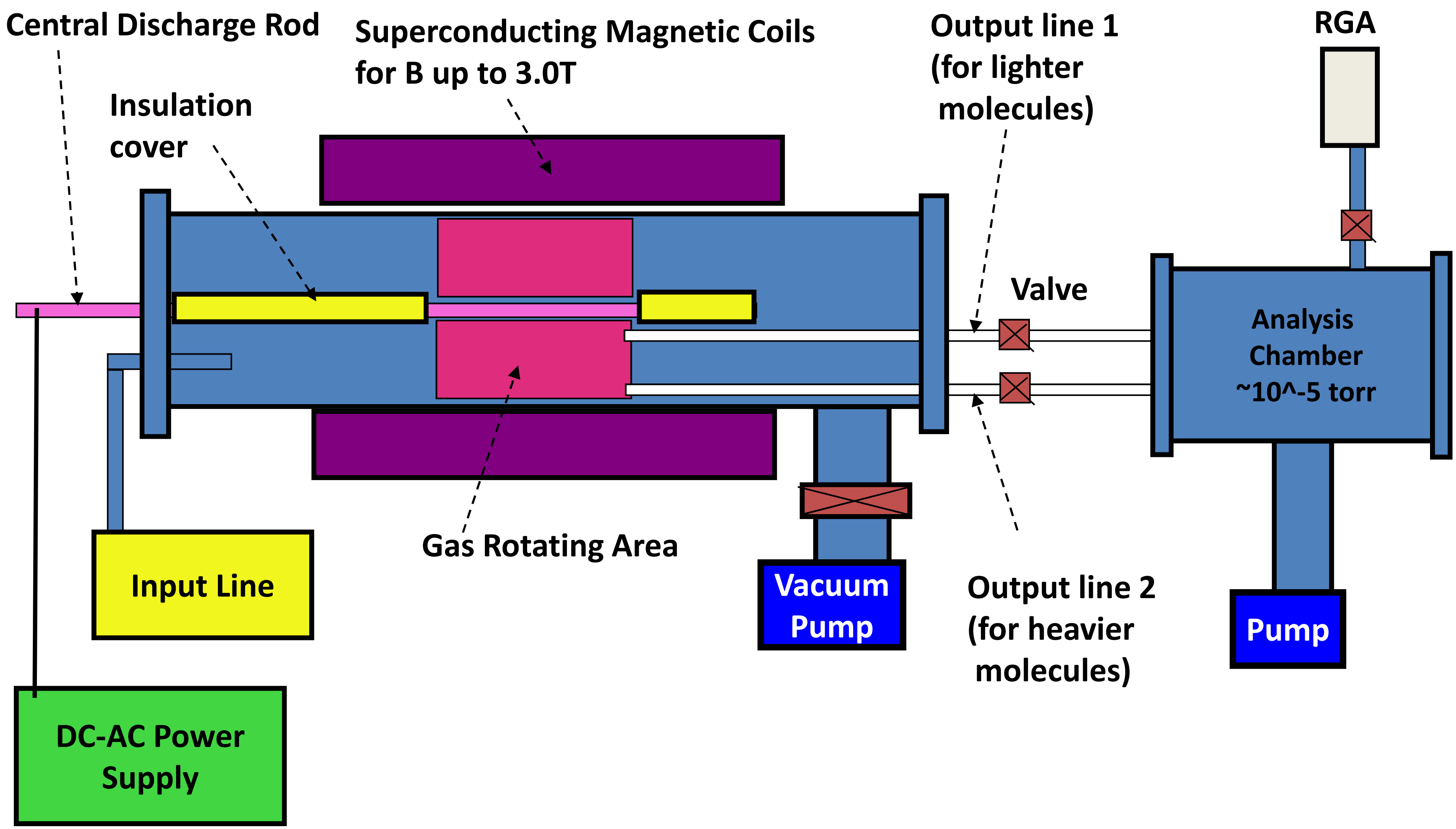
Special Features

- Electromagnetic spin (ES) - an ultra-high-speed centrifuge with no mechanical moving parts.
- Rotation speed and size are not limited by material tensile strength. Up to 40,000 RPS (revolutions per second) observed. 700 m/s to over 15,000 m/s peripheral speed.
- JxB forces rotate gas or solid-vapor via ion-neutral coupling. Direct separation of solid materials.
- High density operation - 10 Torr or 5×10^{17} /cm^3
- Low temperature – neutrals dominate and hold temperature down to rotation and vibration values.

Characteristics

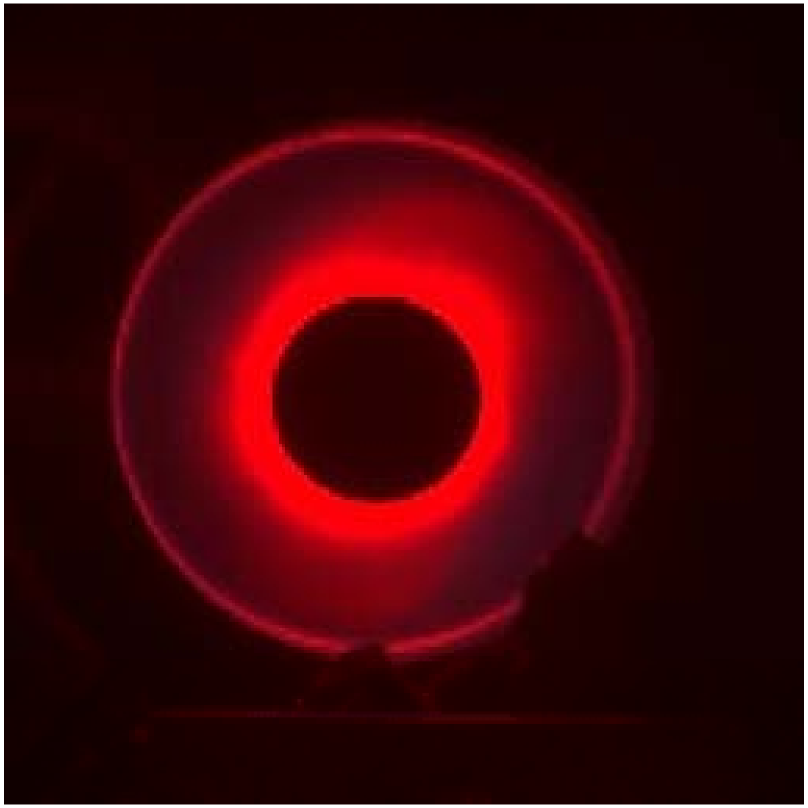
- ES system leverages high neutral-ion collision rates to lock neutral particles to ion rotation rates, using small ion populations (1 ion for 10^5 neutrals).
- Highest plasma rotation rates: 40,000 RPS.
- Highest neutral densities: 10^{18} /cc .
- Combine RF and DC power for production and separation.

Experimental ES Gaseous System

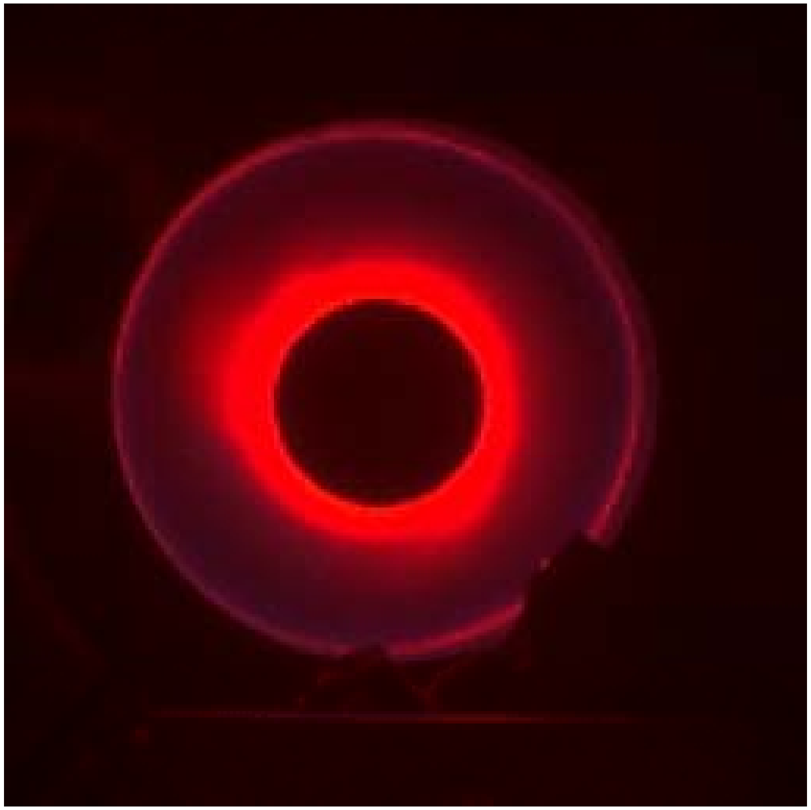


Prototype ES Device at NID

Plasma Rotation Videos

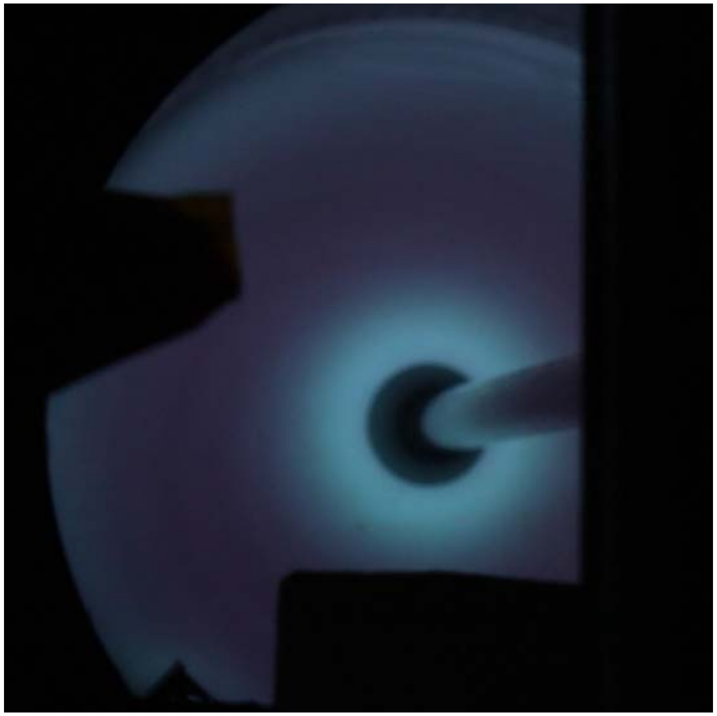


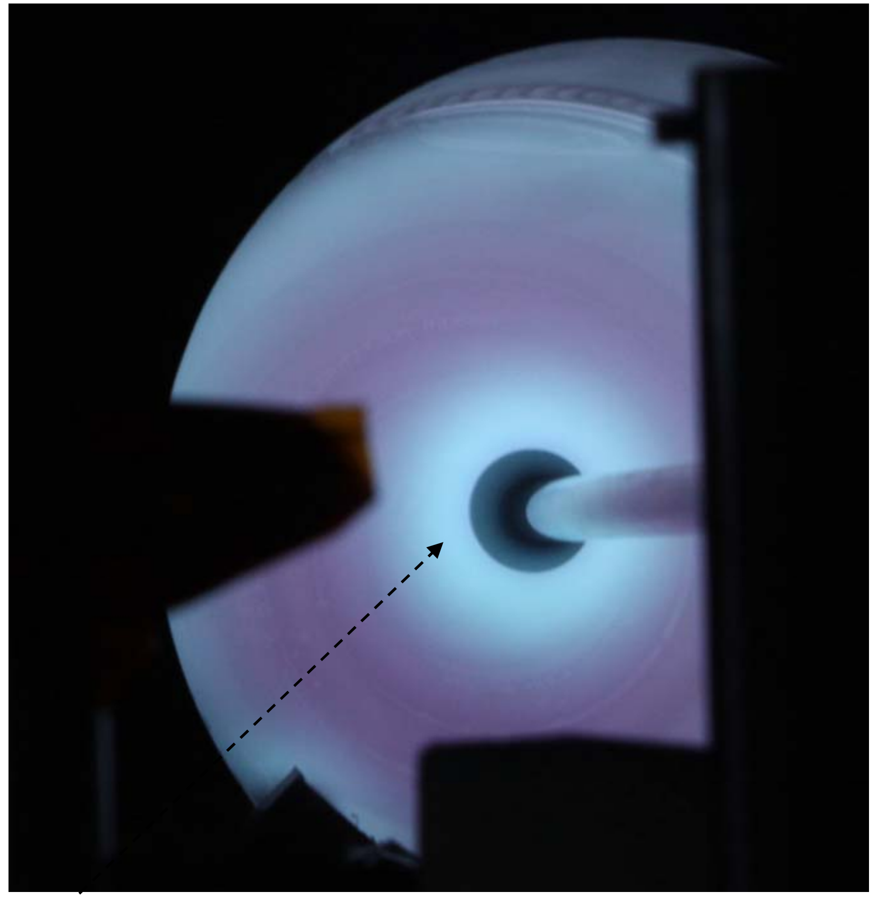
Low Current 20A



High Current 37A

RF discharge through Double Quartz window With Ge (coated) sputtering target 9/8/10



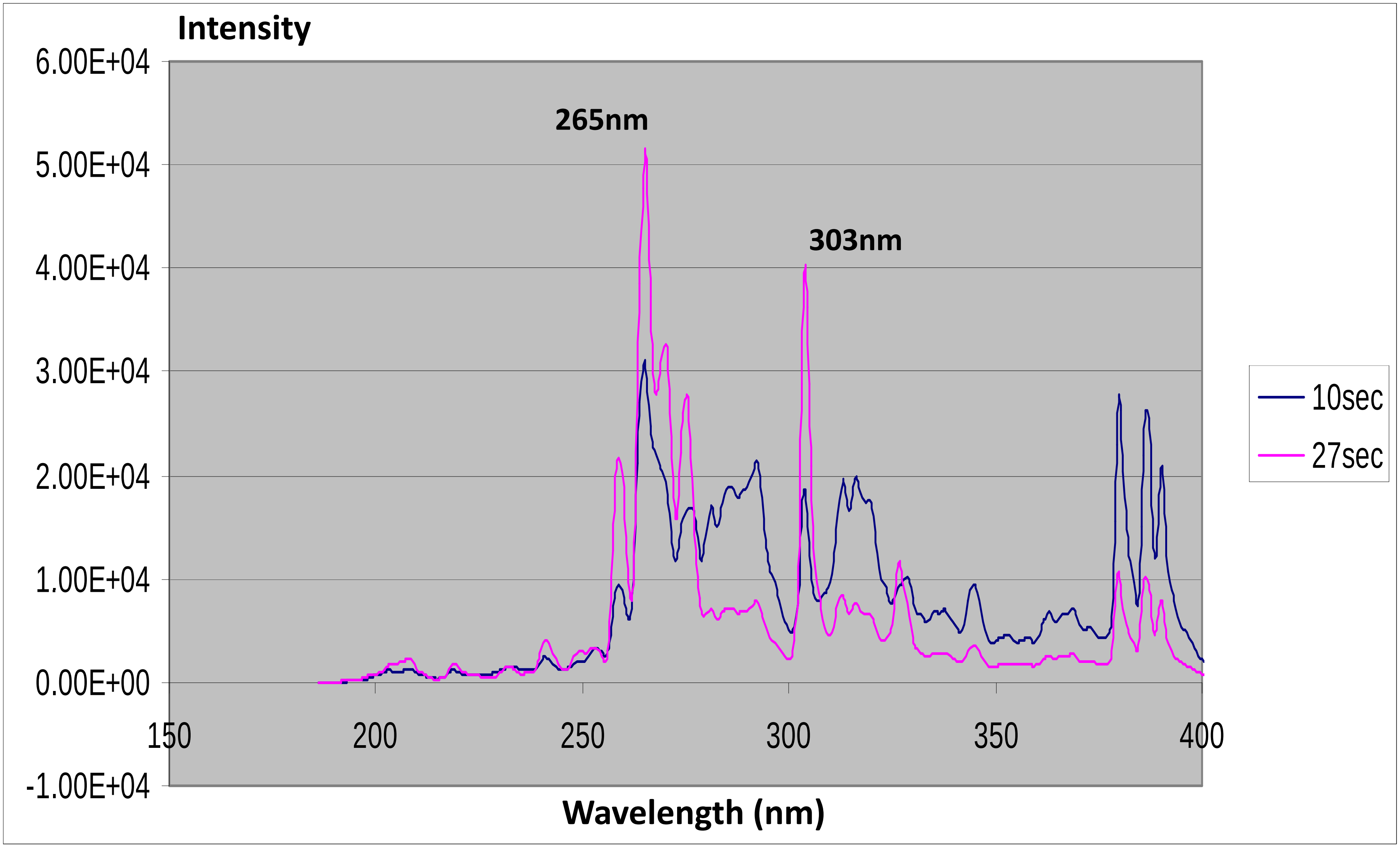


RF 600W (10W Ref.)
-250V bias -78mA current
Ar pressure; 400mtorr

RF 600W (10W Ref.)
-250V bias -100mA current
Ar pressure; 700mtorr

Strong Ge spectral lines observed; 180 g/day

Strong Germanium lines at 265nm, 303nm 9/9/10



Theory

Plasma and neutral gas as single conducting fluid:

$$\frac{\partial n}{\partial t} + \nabla \cdot n\vec{v} = 0$$

$$mn\left[\frac{\partial \vec{v}}{\partial t} + (v \cdot \nabla)\vec{v}\right] = -\nabla p + \vec{j} \times \vec{B} + \eta \nabla^2 \vec{v}$$

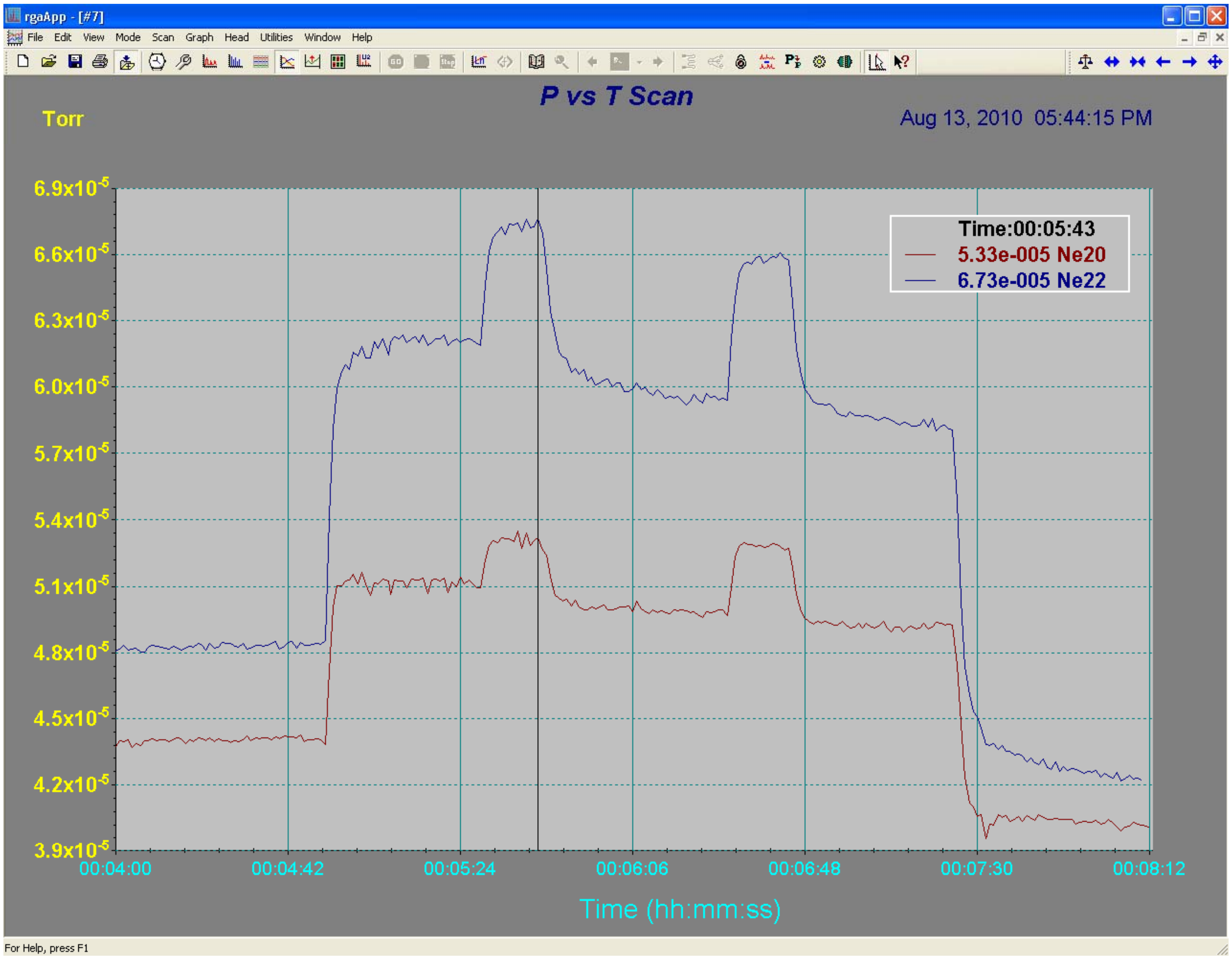
Under steady state in cylindrical coordinates:

Radial Direction $-\nabla p + \frac{nmv_\Theta^2}{r} = 0$ gives

$$n = n_o EXP\left[\frac{\omega^2 r^2 m}{kT}\right]$$

$$\text{where } \omega = \text{rotation velocity}$$

RGA Data on Ne-20/Ne-22 Separation at edge of medium



* Ne22 pressure is multiplied by a factor of 10 for visual comparison

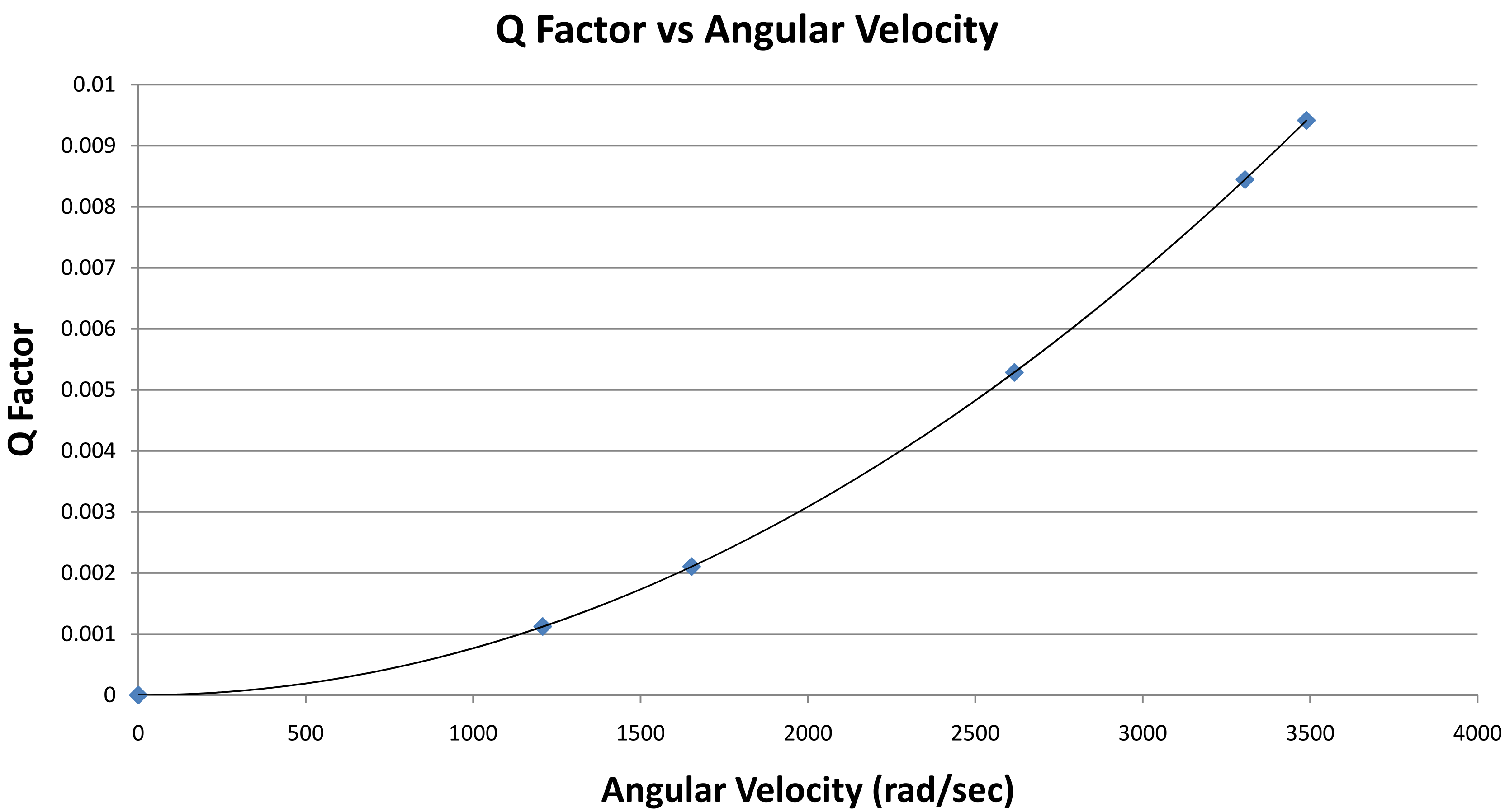
Radial Enrichment Factor q(r)

Definition of q(r) or Q factor:

$$q(r)+1$$
$$=[N_2(r)/N_2(r=0)]/[N_1(r)/N_1(r=0)]$$
$$=\exp[\omega^2 r^2 \Delta M/2kT] \quad *$$

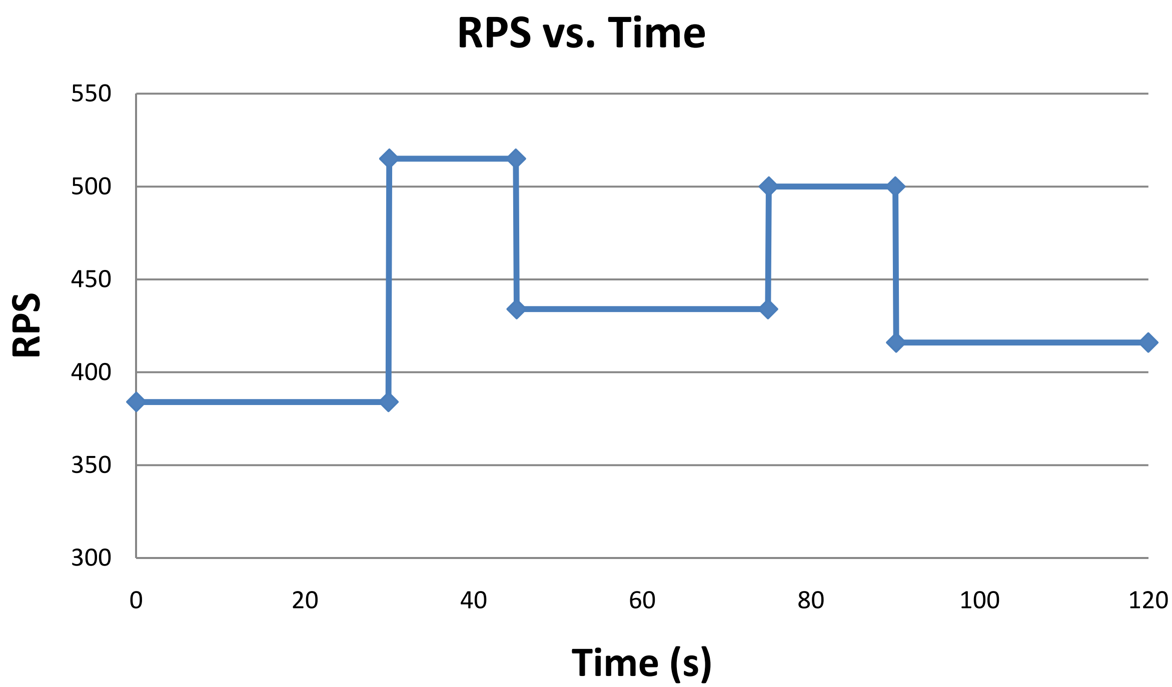
* M.Geva et al., Vacuum arc plasma centrifuge for element and isotope separation, IEEE Trans, Plasma Sci., vol. PS-15, pp. 583-588, Oct, 1987

Q Factor vs. Angular Velocity



Rotation Rates of Alternating Low & High Currents

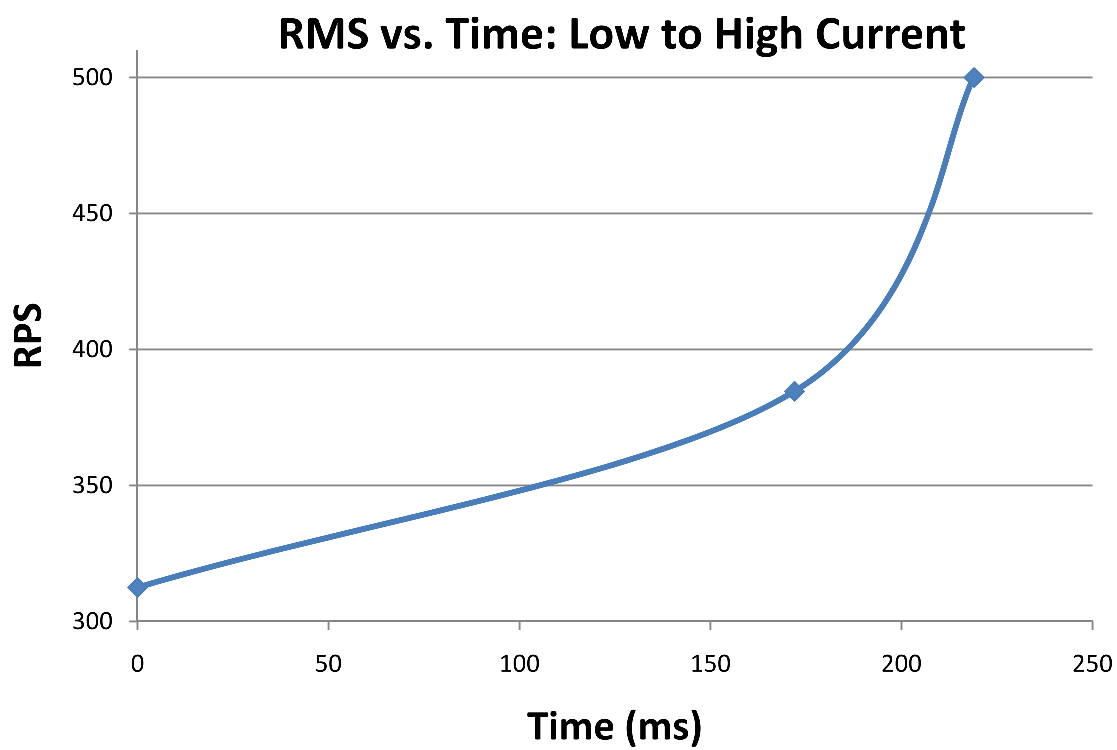
Exp. #6: I=15A-45A; B=1.3T; P=3Torr 8/13/10



Period	RPS
0-30	384
30-45	515
45-75	434
75-90	500
90-120	416

Transitional Rotation Rate from 19.8A to 49.2A

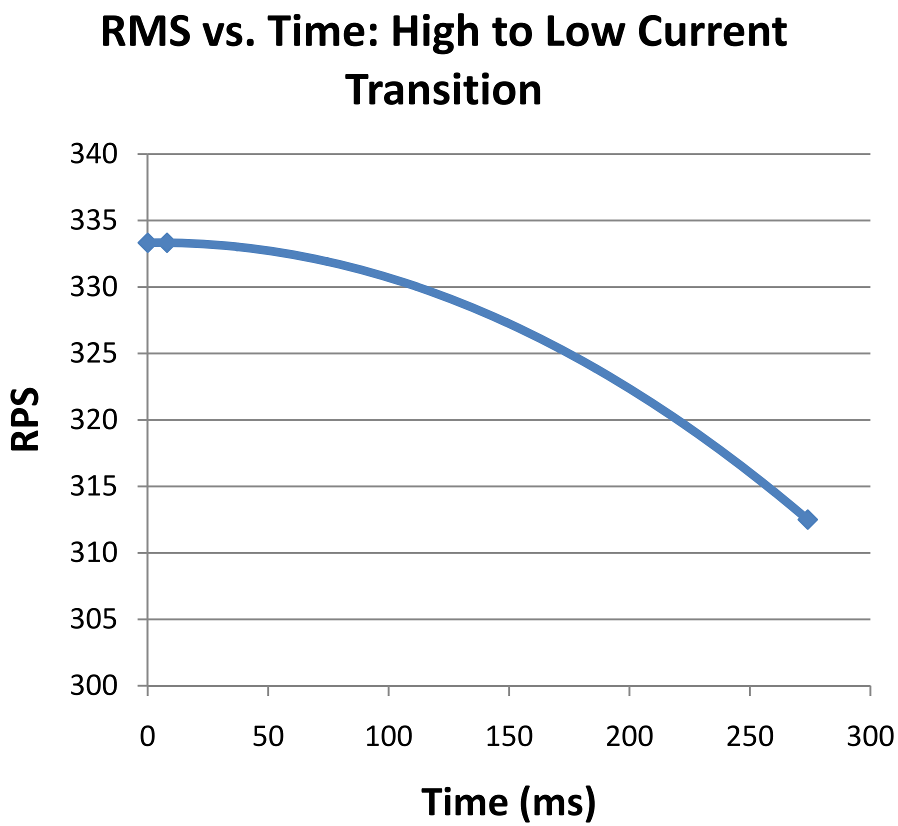
Exp. #12: I=19.8A-49.2A; B=1.3T;P=3.75 Torr



T(ms)	RPS
0	312.5
172	384.6154
219	500

Transitional Rotation Rate from 23A to 13A

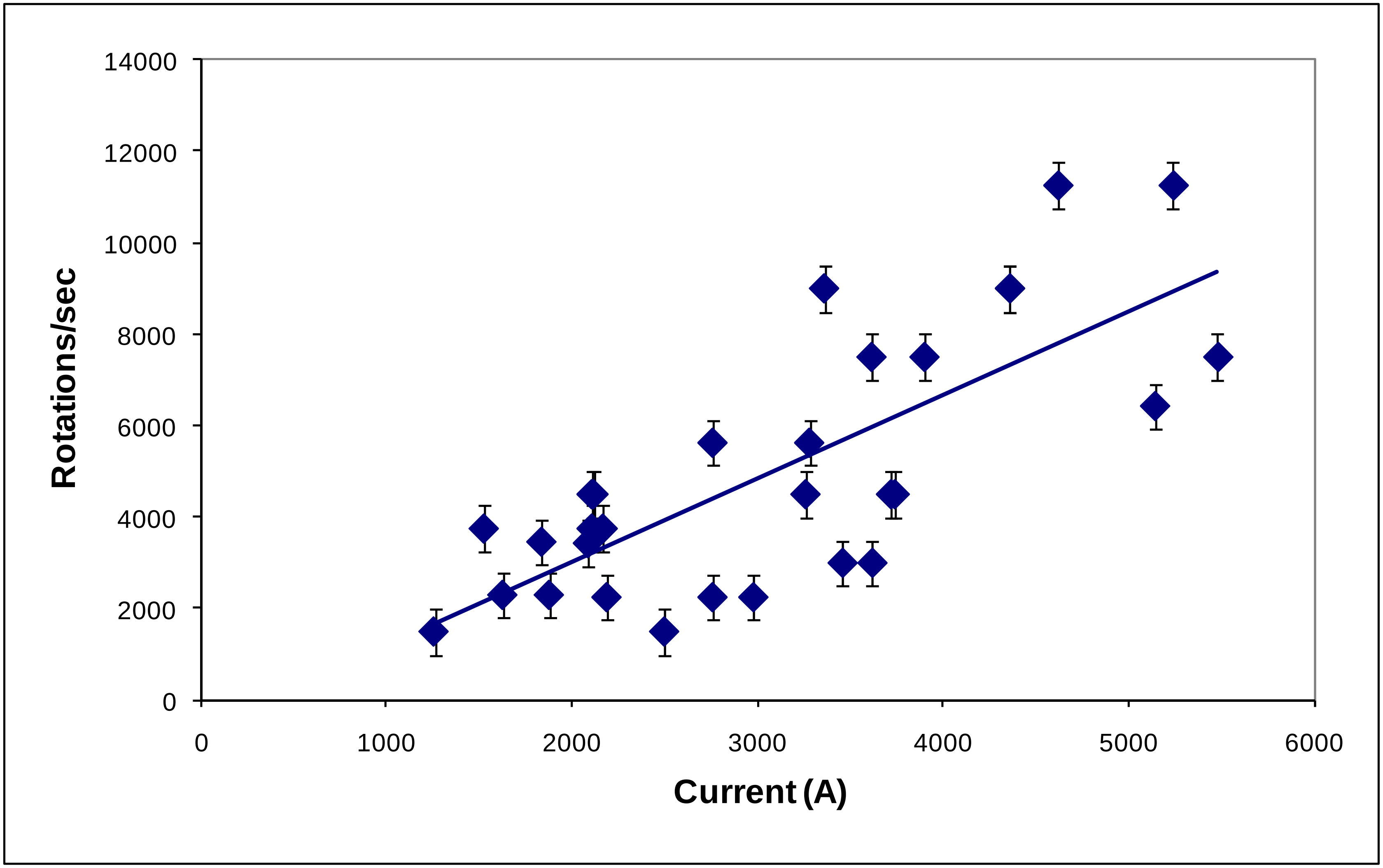
Exp. #4: I=23A-13A; B=1.3T; P=3.75 Torr



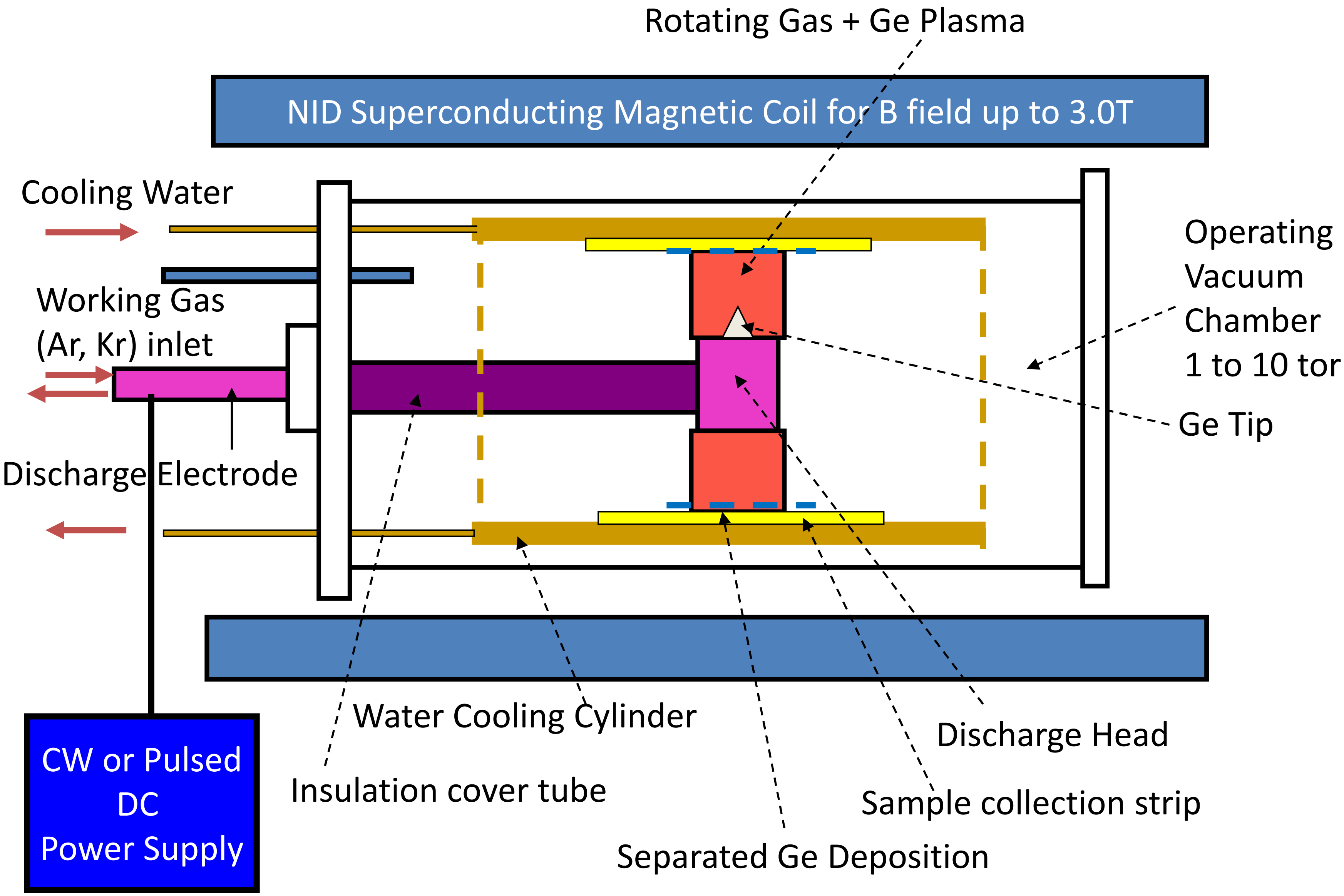
T(ms)	RPS
0	333.3333
8	333.3333
274	312.5

Rotation Rate vs. Pulse Current

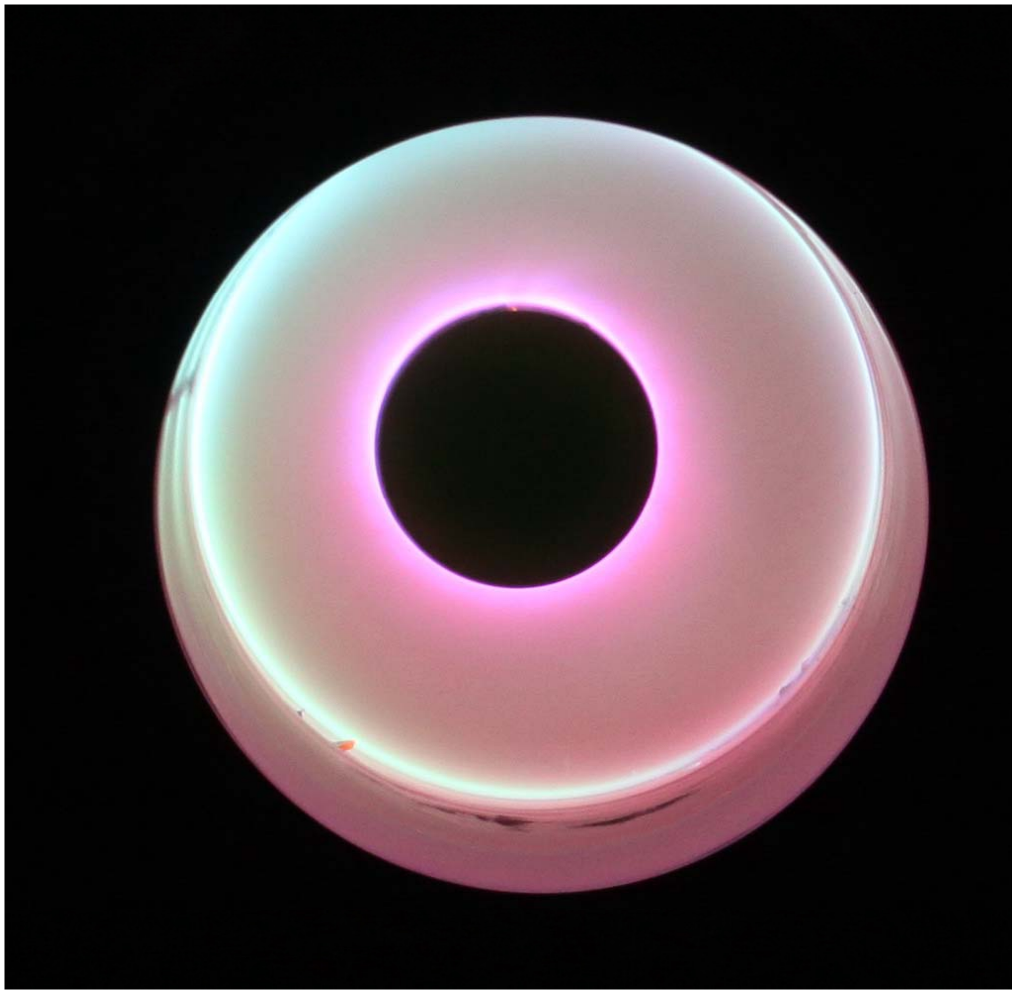
Pressure = 1Torr, B-field = 0.5T

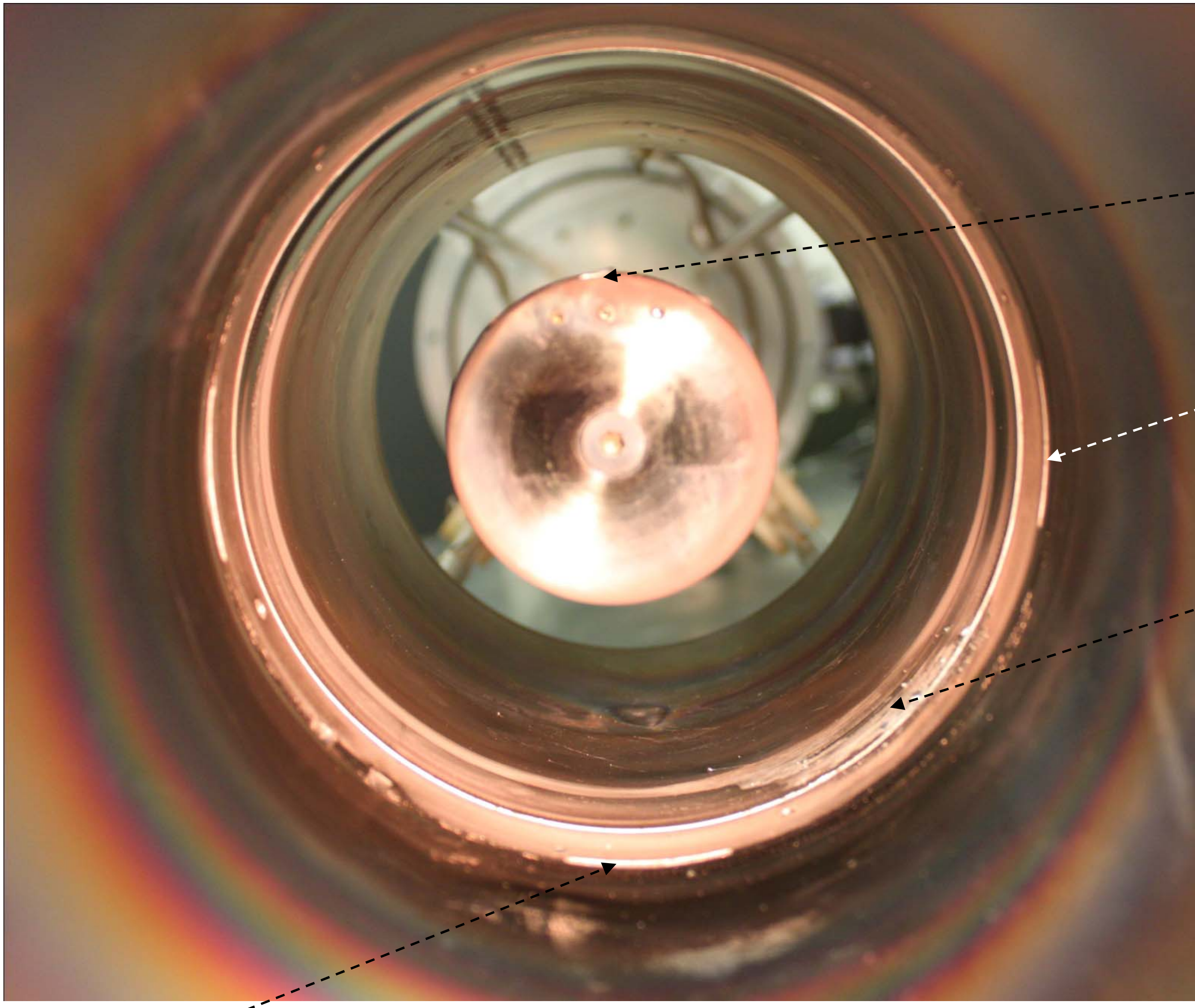


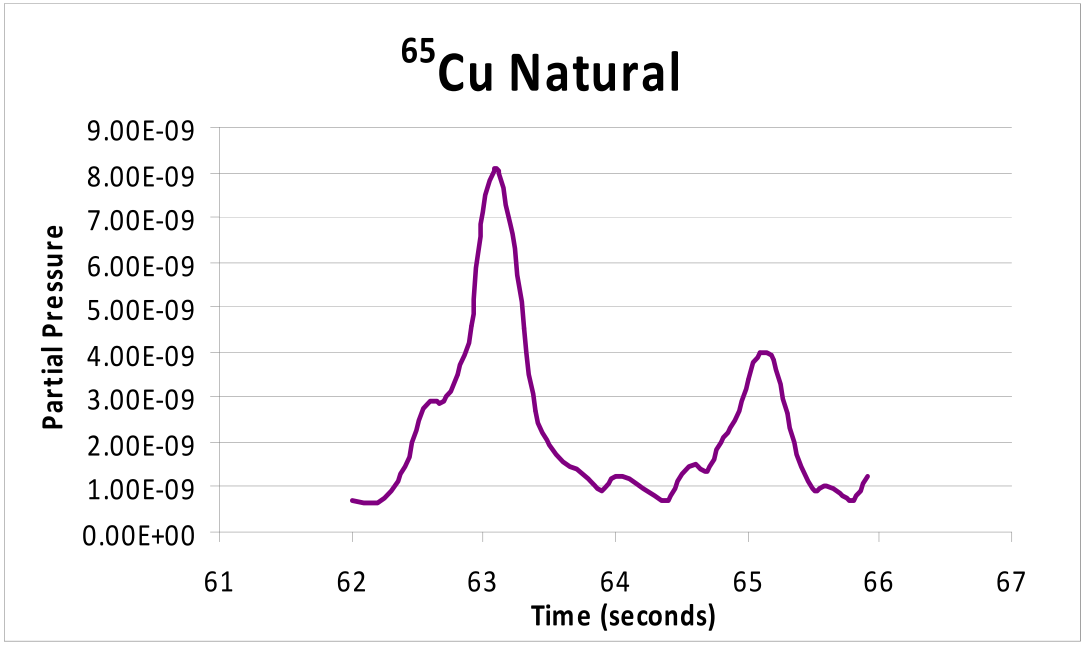
Solid (Ge) Separating Device by Plasma Bombardment



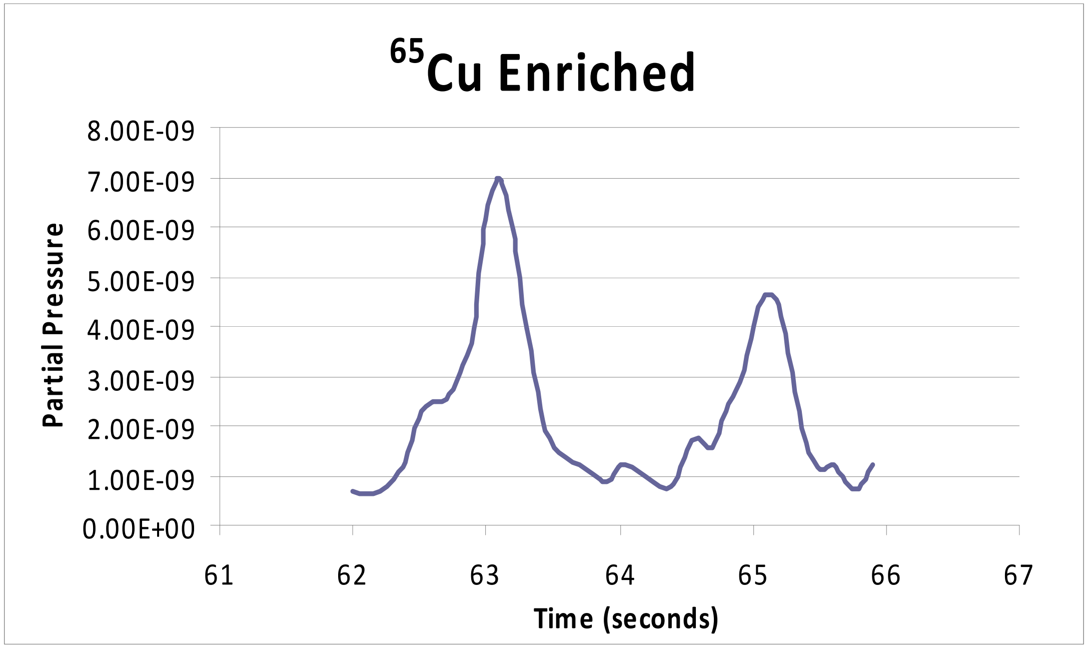
^{63}Cu Enrichment




Germanium
Sputtering
Source.
4 slots on the
Collecting area
Germanium
Deposition.
Cu63 3% enrichment from the slot near the edge of the copper coating area



^{65}Cu Natural
Partial Pressure
9.00E-09
8.00E-09
7.00E-09
6.00E-09
5.00E-09
4.00E-09
3.00E-09
2.00E-09
1.00E-09
0.00E+00
61
62
63
64
65
66
67
Time (seconds)



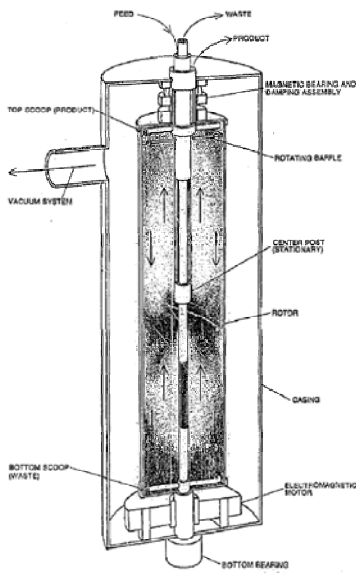
^{65}Cu Enriched
Partial Pressure
8.00E-09
7.00E-09
6.00E-09
5.00E-09
4.00E-09
3.00E-09
2.00E-09
1.00E-09
0.00E+00
61
62
63
64
65
66
67
Time (seconds)

Increased Rotation Speed Greatly Improves Performance

(Estimated Enrichment of ^{22}Ne from 9% to 50%)

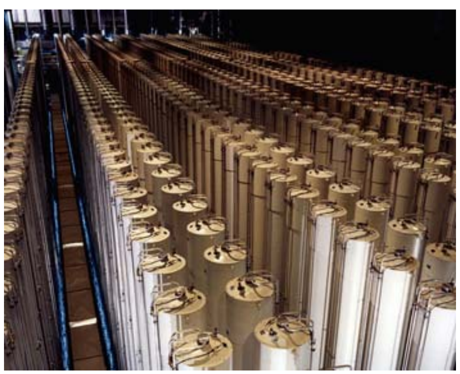
Traditional

V_{rot} ~ 600 m/s



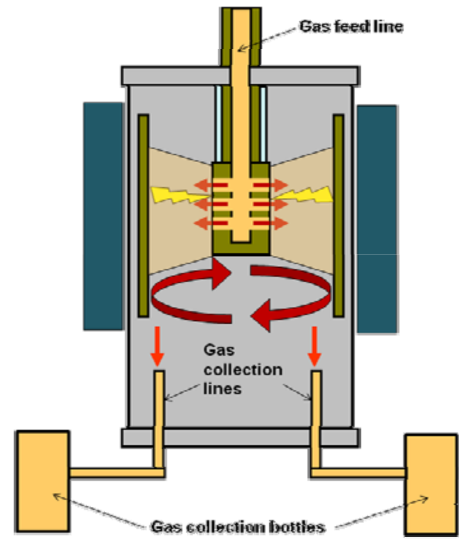
2m

>4000 centrifuge, 12 stage cascade



Plasma

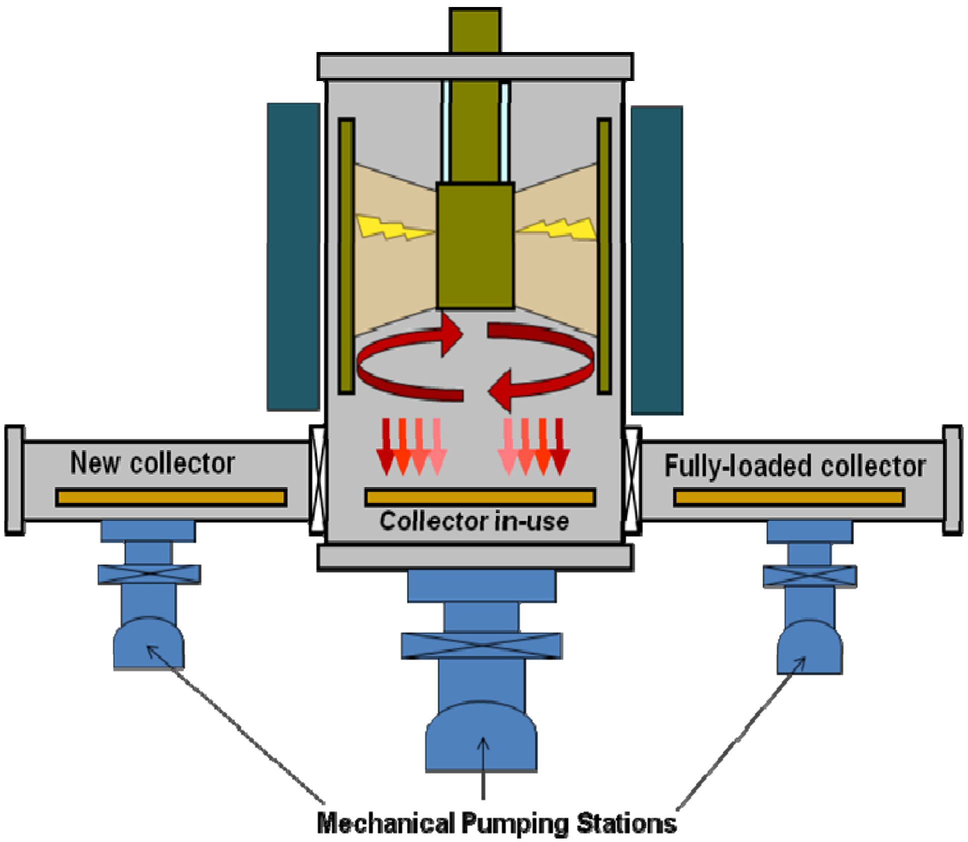
V_{rot} ~ 3700 m/s



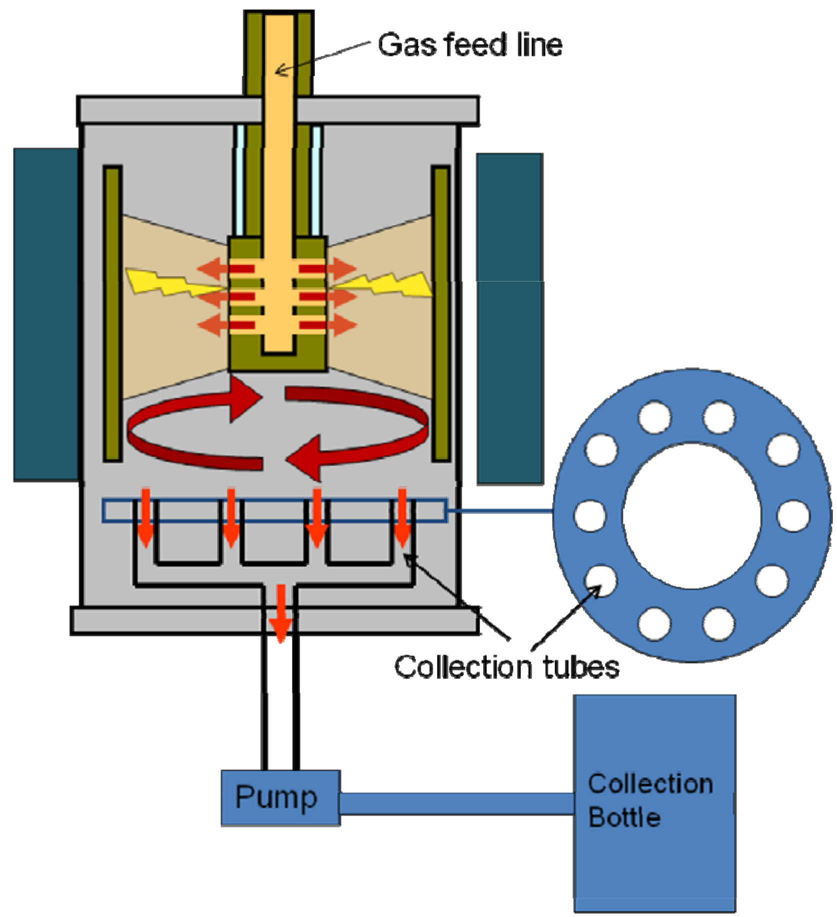
2m

1 centrifuge only, no cascade

Mass-Production Vertical ES Systems



Solid Separation System



Gas Separation System

Simplification for Large-volume Production with High Efficiency

- Single DC power supply- low voltage and current
- Cooling at boundary layer helps collection at lower T
- Heat power is used to vaporize solid source, e.g. Ge
- Digital control with feedback
- Fast camera monitoring
- Laser diagnostics of neutral density
- One device operation – gases and solids.
- No limit to size or rotation speed as no mechanical part is involved.

Rate of Rotation

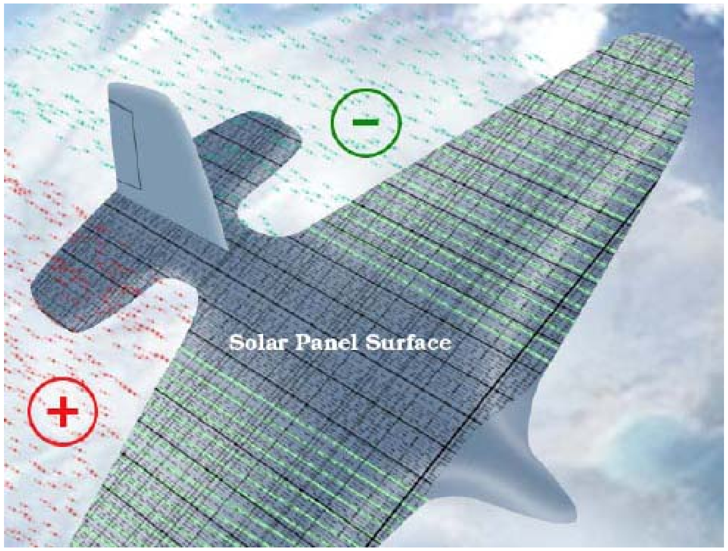
- The higher the rate of rotation, the better the separation
- The rate of rotation is determined by the magnetic field and the current
- The force is balanced by the viscous drag at the inner and outer walls
- In the highly collisional plasma, both ions and neutral rotate together. Nonlinear KH instabilities also play a role in this solid-body rotation.

Advantages

- Much higher rotation rates can be achieved compared to conventional gas centrifuge (no rotating rotor involved, therefore not subject to material strength limitation)
- Energy consumption is much lower than ECRH microwave source since only weak ionization is needed
- One economic solution for both gaseous and solid isotope separation

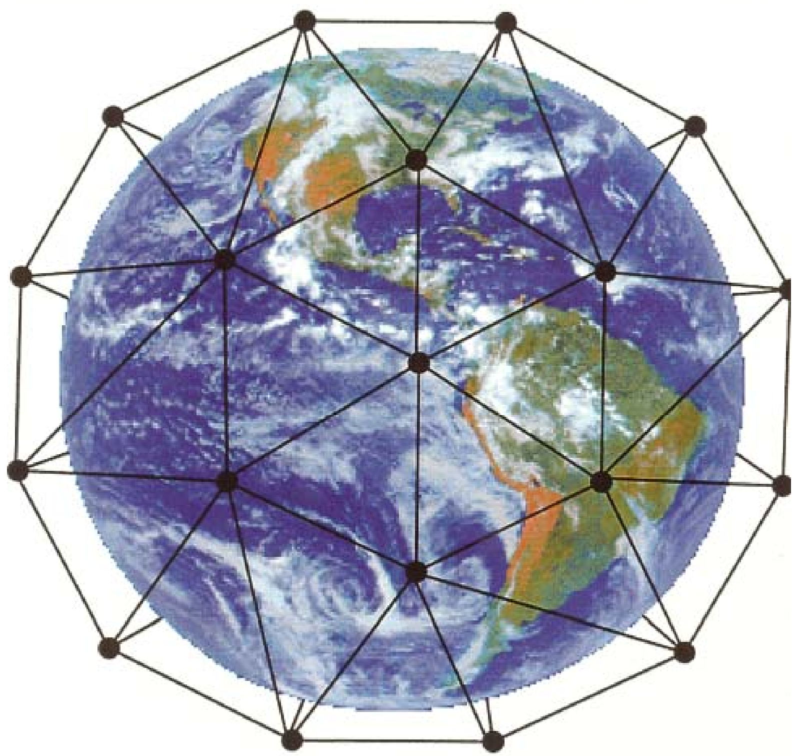
An Innovation Incubator

Astroplatforms
- cell towers in the sky



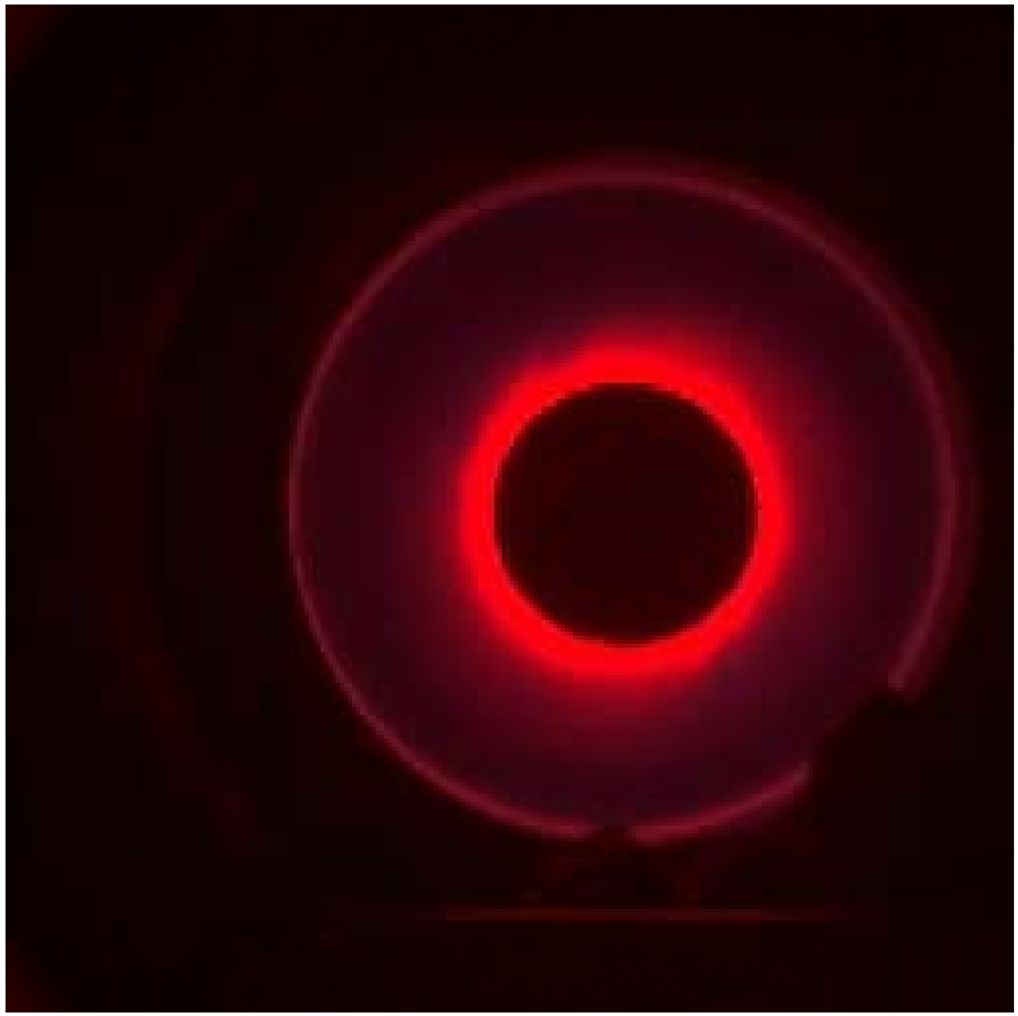
Early prototype tested at NASA facility

Astroplatforms
- cell towers in the sky



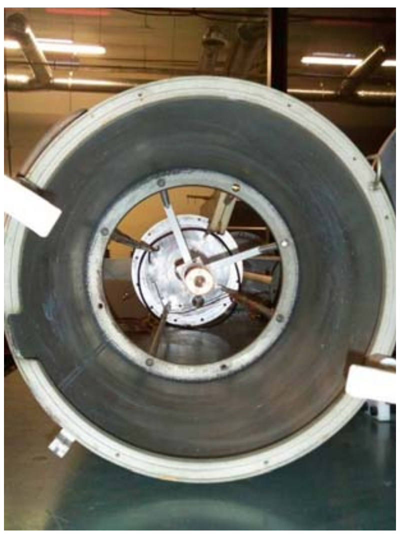
- Stationery stratospheric platforms ("Astroplatforms") which will be stationed 60,000 to 100,000 feet in a geostationary position above the earth
- These astroplatforms will be used to provide telecommunications connectivity to companies offering broadband wireless services around the world at much higher frequencies 30GHz and up.
- Higher bandwidths and more information space.

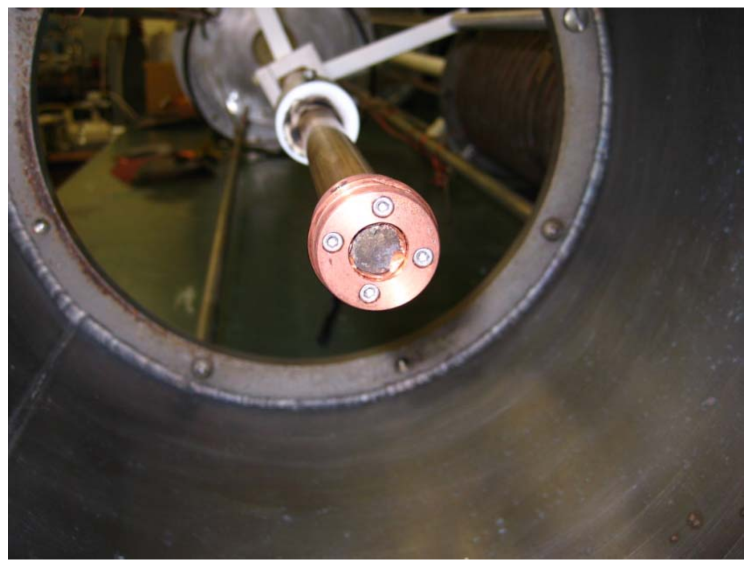
Transition in Plasma Rotation Speed



Gold/Copper Separation

- Coaxial configuration
- Target / raw material – cylindrical core, attached to the water-cooled central electrode.





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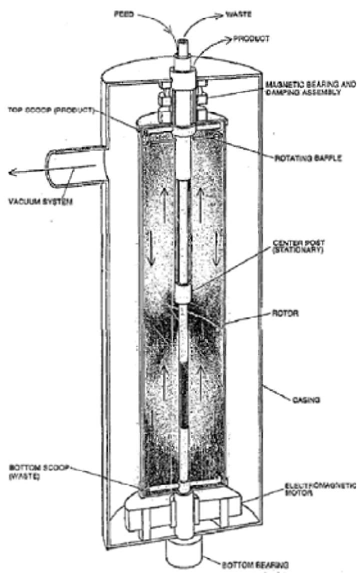

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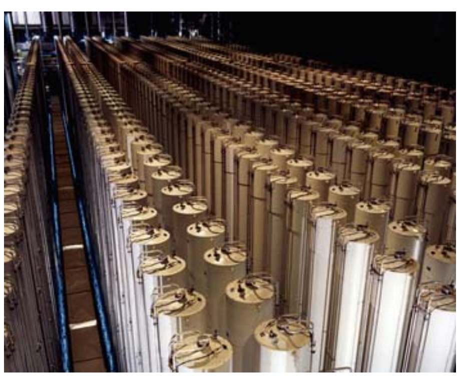

Plasma

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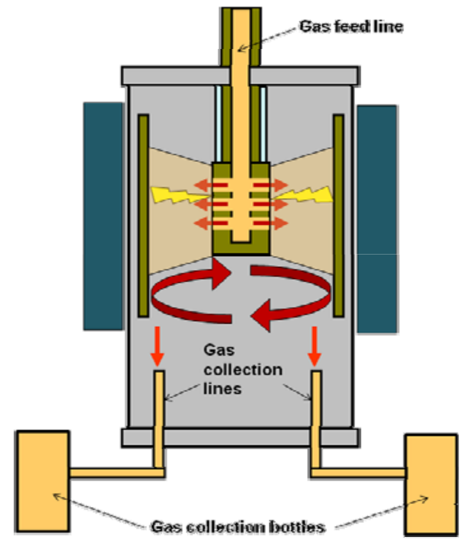
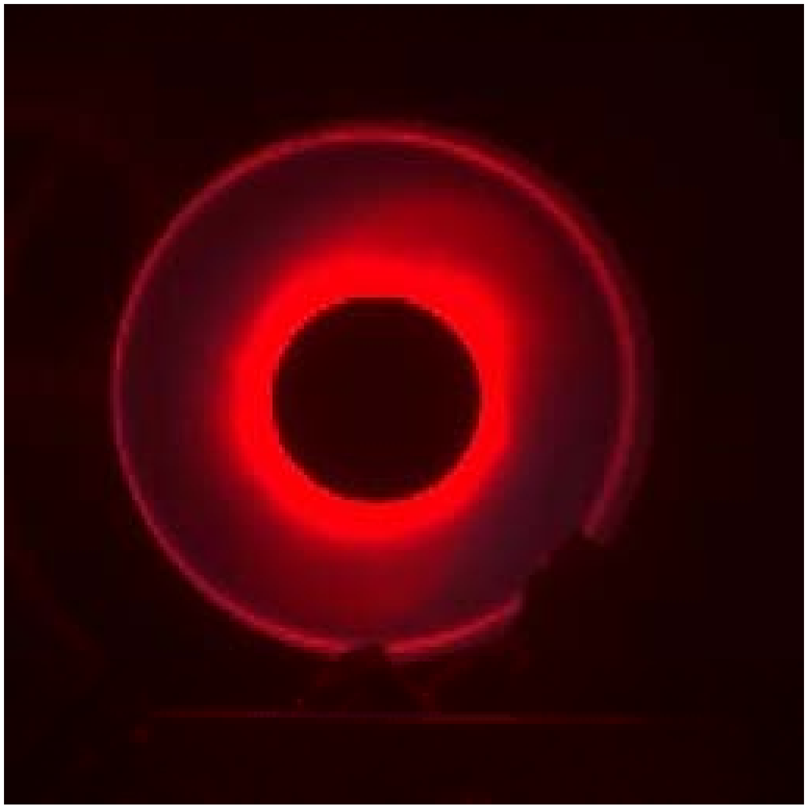


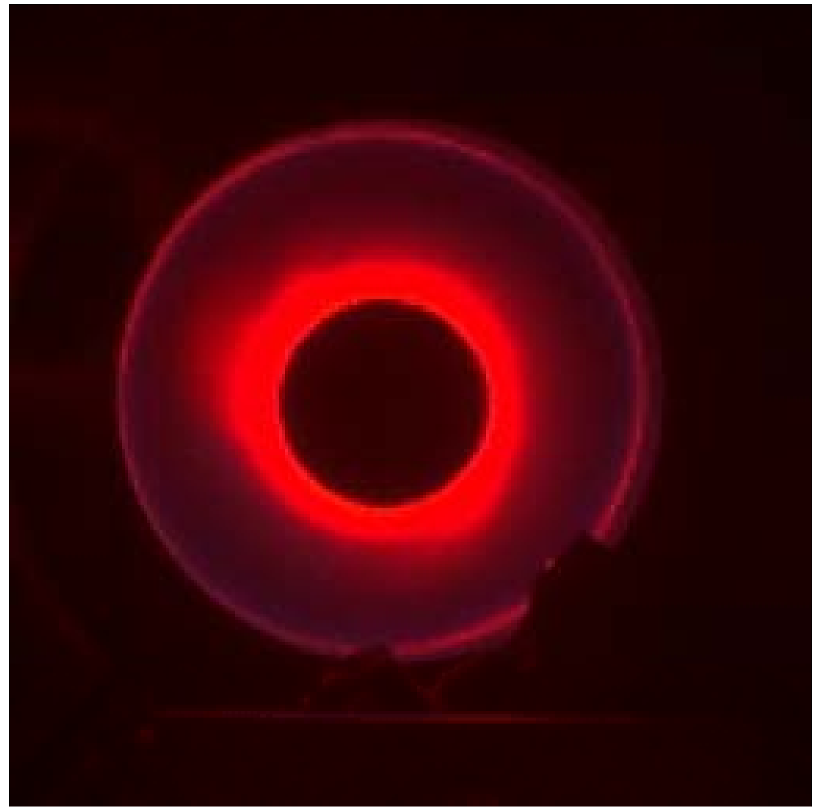
2m

1 centrifuge only, no cascade

Plasma Rotation Videos



Low Current



High Current

In two isotopes $(\eta_1, m_1; \eta_2, m_2)$ of a given element, the enrichment factor q can be defined as:

$$q(r) = \frac{\frac{N_{2(r)}}{N_2(r=0)}}{\frac{N_1(r)}{N_1(r=0)}} - 1$$

$$= EXP\left[\frac{\omega^2 r^2 \Delta M}{2kT}\right] - 1$$

Exponential dependence was confirmed experimentally.

Taking V_Θ component

$$(\eta\nabla^2\vec{v}) = j_r B$$

Balance of q viscous drag with j x B drive

$$\eta\left[\frac{\partial V_\Theta}{\partial r^2} + \frac{1}{r}\frac{\partial V_\Theta}{\partial r} - \frac{V_\Theta}{r^2}\right] = \frac{IB}{2\pi r L}$$

Viscosity for typical gas

$$\eta = 3.3 \times 10^{-4} \frac{kg}{m \cdot s}$$

Experimentally observed rotation rate:

$$f_{Experimental} \approx 340 - 500 Hz$$
$$f_{THEORY} \sim 437 Hz$$

Experimental observation:

Viscous drag is dominant at outer boundary

$$\eta \frac{\partial^2 V_\Theta}{\partial r} \approx \frac{IB}{2\pi r L}$$

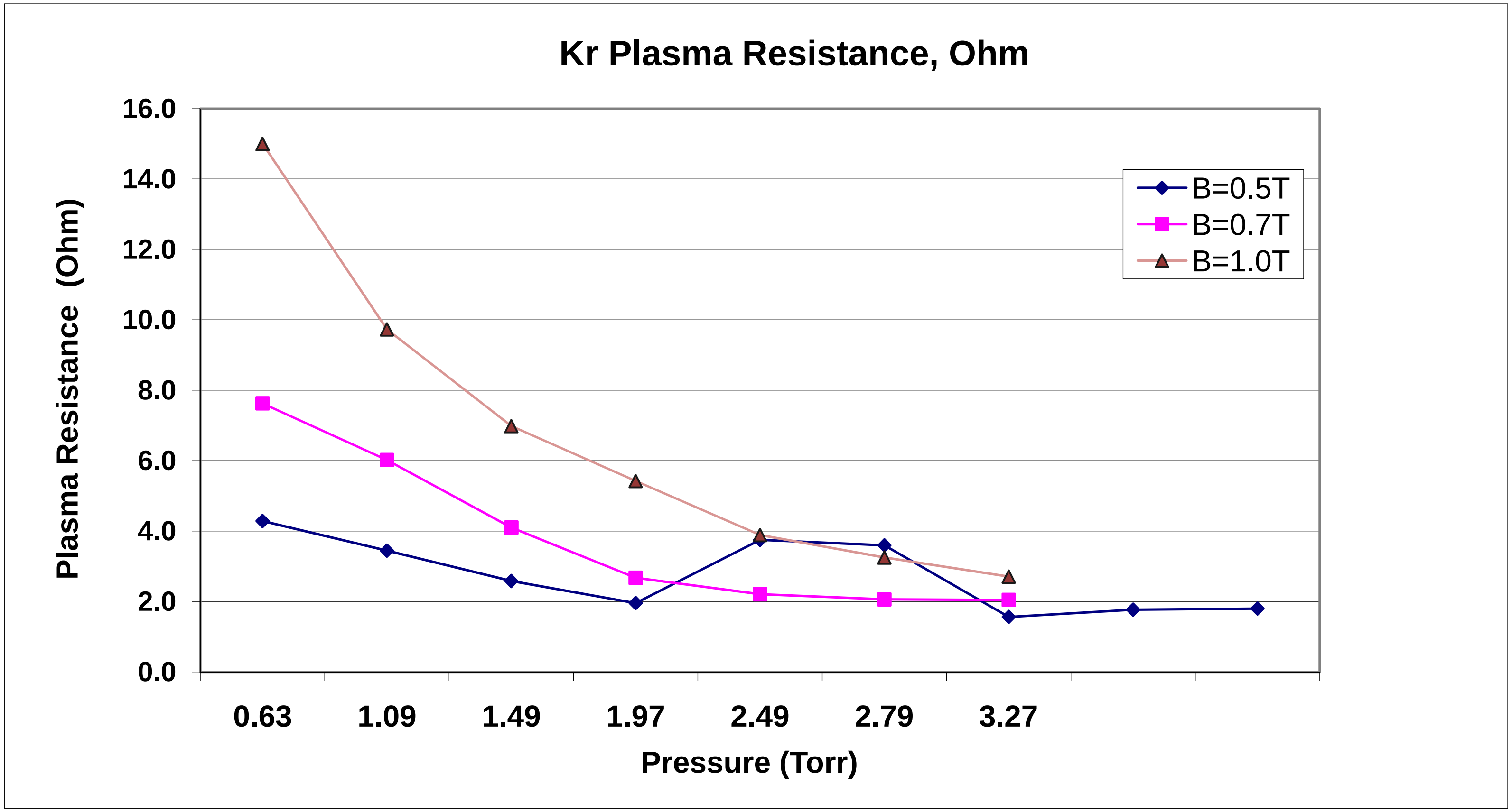
Dimensional Analysis

$$\eta \frac{V_\Theta}{(0.1 r_o)^2} \approx \frac{IB}{2\pi r L} \Rightarrow V_\Theta = \frac{IB(0.1 r_o)^2}{2\pi r_o L \eta}$$

$$V_\Theta = \omega r_o = \frac{IB[10^{-2} r_o^2]}{2\pi r_o L \eta} = \frac{10^{-2} IB}{2\pi L \eta} r_o$$

$$\omega = \frac{10^{-2} IB}{2\pi L \eta} = \frac{10^{-2} 40A(1.3T)}{2\pi (0.1m)(3.3\times 10{-}4)} /s = 2.8 \times 10^3 /s$$

$$f = 437 Hz$$



Kr plasma resistance data from June 9 & 10, 2009 suggest that the plasmaresistance decreases with increasing gas pressures and decreasing B field. Experimental conditions were 2.2-2.6kV pulse + 1.4kV CW with varying B fields and pressures. The plasma resistance was calculated from CW duration.

^{63}Cu Enrichment Test Results by RGA