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Fast High Capacity Annular Gas Puff Valve Design Concept

Edward L. Ruden, AFRL, Directed Energy Directorate

A fast opening gas valve design concept is presented that can theoretically inject a few grams of D_2 gas radially outward into a coaxial annular vacuum region with a radius of about 10 cm in less that 100 μs. The concept employs a single turn 20-30 T pulsed magnetic field coil that axially accelerates an Mg alloy ring, which seals a gas plenum, to high velocity, releasing the gas. Both coil and ring are profiled to minimize stress in the ring. Such a device could be used to supply the initial gas load for a proposed 5 MJ Dense Plasma Focus driven by AFRL's Shiva Star Capacitor bank. The intent here is keep the vacuum current feed insulator under high vacuum during the discharge to avoid surface breakdown. Alternatively, a high energy rep ratable plasma flow opening switch could be supplied with such a valve. This work is funded by the USAF.

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Annular valve design concept

A valve employing a cover which lifts off of an orifice of **radius** R with **acceleration** g exposing a plenum at **pressure** P containing a gas with **specific heats ratio** γ, **molecular mass** m, and **temperature** T will have an early time **particle transfer rate** as a function of **time** t of approximately,

$$\frac{dN}{dt} \approx \frac{1}{2}\left(2\pi R\right)\left(\frac{1}{2}gt^2\right)\left(\frac{P}{kT}\right)\left(\sqrt{\frac{\gamma kT}{m}}\right) \tag{1}$$

The terms in parenthesis are, from left to right, the **orifice circumference**, the **displacement of the cover**, the initial **number density in the plenum**, and the initial **speed of sound** in the plenum. The last two terms may easily be modified to take into account a depleting and adiabatically cooling plenum of given volume, but this will do for now.

Integrating, then, the ejected **mass** is

$$M \approx \frac{1}{6}\pi g R P \left(\frac{\gamma m}{kT}\right)^{\frac{1}{2}} t^3 \tag{2}$$

So,

$$gR \approx \frac{6M}{\pi P t^3}\left(\frac{kT}{\gamma m}\right)^{\frac{1}{2}} \tag{3}$$

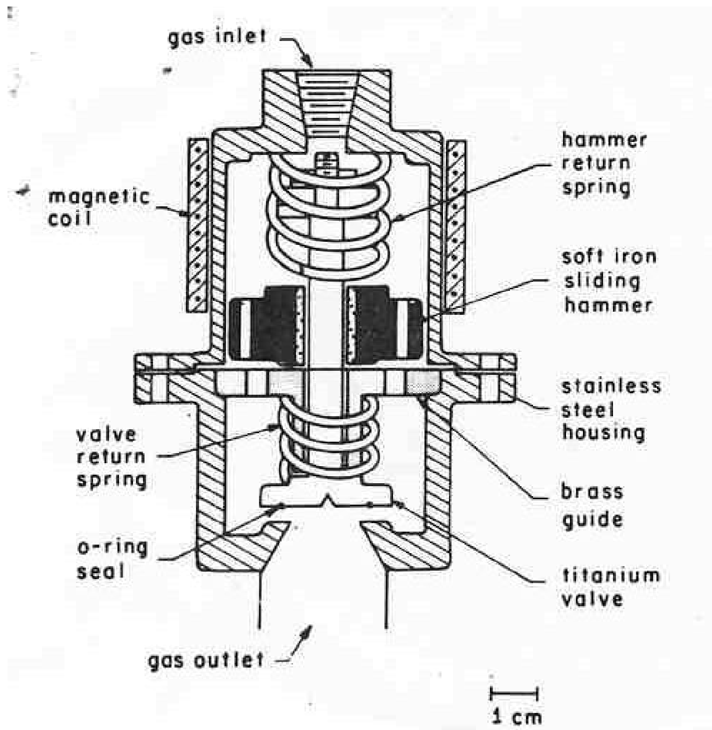
Given constraints on the terms on the right, gR is a **figure of merit** for a fast high capacity valve design.

EXAMPLE - Using D_2

Ejected **mass** $M = 2.5 \times 10^{-4}$ kg (250 mg)
Time for D_2 to travel 0.1 m $t = 1 \times 10^{-4}$ s
Plenum **Pressure** $P = 10^7$ Pa (100 atm)

Requires $gR \approx 3 \times 10^4\ \mathrm{m}^2/\mathrm{s}^2$

(Narrative) For a proposed DPF experiment, for example, we require $M = 2.5 \times 10^{-4}$ kg (250 mg) be ejected before the leading edge travel a distance of 0.1 m. With a D_2 sound speed of 923 m/s, that gives us $t = 1 \times 10^{-4}$ s. Practical plumbing considerations limit our plenum pressure to about $P = 10^7$ Pa (100 atm). So, with $T = 300$ K, $\gamma = \frac{7}{5}$, $m = 6.8 \times 10^{-27}$ kg, and $k = 1.38 \times 10^{-23}$ J/K, we need $gR \approx 3 \times 10^4\ \mathrm{m}^2/\mathrm{s}^2$



Fisher, et.al., Rev. Sci. Instrum. **49**(6) 1978

(Nar.) Reusable fast gas puff valves have reached their highest level of refinement in devices designed for gas puff Z-pinches due to the demands of the application. Most gas puff valves designs are based on Amnon Fisher's 1977 design while at UC, Irvine [A. Fisher, F. Mako, and J. Shiloh, Rev. Sci. Instrum. **49**(6) 1978 pp. 872-873] and involve an iron ring that is electromagetically accelerated up a valve stem and hits a flange on the top, pulling on the stem and opening an orifice on the bottom, as shown.

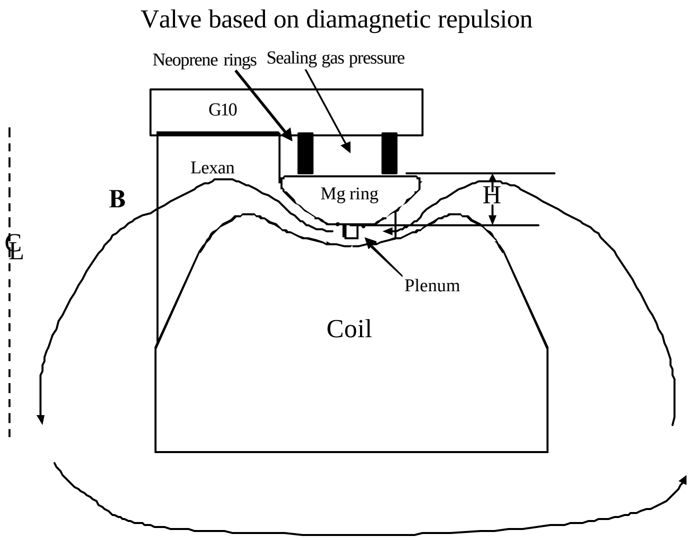
The principle performance limiting factor in this design is the tensile **yield strength** Y of the valve stem. Approximating the stem as a cylinder of **density** ρ, and **Height** H the maximum acceleration of the stem is

$$g = \frac{Y}{\rho H} \sim 10^6 \text{ m/s}^2 \tag{4}$$

So, for our example we require

$$R = 0.03 \text{ m}$$

(Nar.) H must be about 10 cm or so to allow flux penetraion of the conducting iron "hammer" to get up to speed, although lower conductivity ferrite materials could be employed. Ti 6Al4V alloy has $Y/\rho \approx 3 \times 10^5$ Pa-m^3/kg, give a limit of $g \approx 3 \times 10^6$ m/s^2. In practice, the nonuniform loading, and fatigue considerations and necessary attachments to the cylinder, in the actual design a more realistic acceleration is $g \approx 1 \times 10^6$ m/s^2. From our FOM, then, that $R = 3$ cm is required. This is larger than has been built. In practice, several smaller valves around the circumference would be used to meet the symmetry requirements.



$g \approx 2 \times 10^7$ and $R \approx 0.1$ m possible with 22 T coil.

(Nar.) There is an alternative to this approach that would also be more appropriate given the symmetry of system. A single valve with greater values of g and R could be built using diamagnetic repulsion of a conducting ring to open an annular orifice which would inject the gas axisymmetrically through the inner conductor, as illustrated in Fig. 2. The general concept is based on a diamagnetic valve also designed by Amnon Fisher et.al. [J. Keisel, R. Prohaska, and A. Fisher, Rev. Sci. Instrum. **62**(10) pp. 2372-2374]. In this concept, flux penetration is not necessary (or desired) and a magnetic pressure *greater* than Mg's yield strength (22 T) could be applied quickly (<100 μs) by a single turn field coil, provided the coil and ring are taylored to distribute the magnetic pressure optimally over the bottom of a conducting ring. Mg with $Y/\rho \approx 1 \times 10^5$ Pa-m^3/kg would be more suitable for this geometry because of Ti's low conductivity. The long stem is no longer needed and the equivalent H for use in Eq. 4 (the height of the ring) could be as small as 5 mm. furthermore, one has more control over the magnetic pressure profile, so the factor of three engineering overdesign would be unnecessary. From Eq. 5, then $g \approx 2 \times 10^7$. The equivalent value of R is now the radius of the annulus, which could easily be about 0.1 m. The figure of merit would then be

$$gR \approx 2 \times 10^6 \text{ m}^2/\text{s}^2 \tag{5}$$

This is two orders of magnitude more than needed so, in practice, a less expensive 5 or 10 T coil and an Al ring should suffice.

Consider a ring of **height** H and **width** W with a parabolic lower shape $y = 4Hx^2/W^2$ in the high aspect ration (rectalinear) limit. We can taylor the coil **lower profile** $y = Y(x)$ for minimal stress in the high conductivity limit of a broad-flat high ring we may assume $\mathbf{B} \approx B(x)\hat{\mathbf{y}}$ and that **flux** ϕ in the ring-coil gap is conserved. This gives,

$$\frac{1}{2\mu_0}\left(\frac{\phi}{Ax^2 - Y}\right)^2 = \rho g\left(H - Ax^2\right) \qquad A = \frac{4H}{W^2} \tag{6}$$

The LHS () is B in gap and the RHS () is the "depth" of the ring from its flat top. Solving for Y,

$$Y = \frac{4H}{W^2}x^2 - \sqrt{\frac{CW^2}{H\left(W^2 - 4x^2\right)}} \qquad \text{where} \qquad C = \frac{\phi^2}{2\mu_0 \rho g} \tag{7}$$

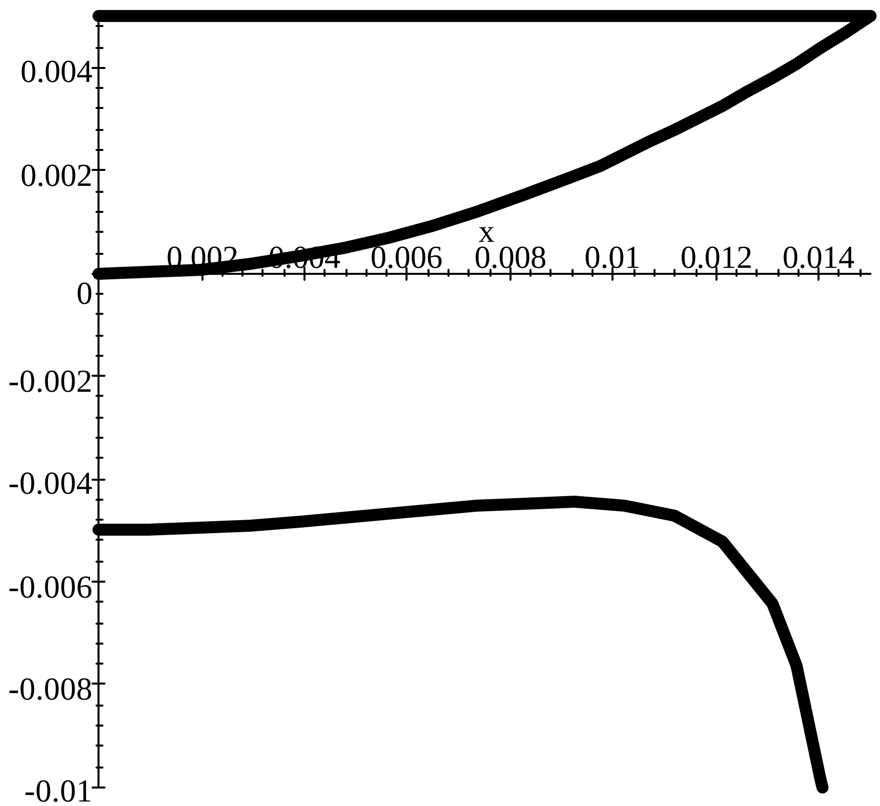
(Nar.) Theoretically, if the magnetic pressure is carefully taylored to the bottom of the ring so that it increases in proportion to the vertical distance from a flat top, then there would only be isotropic pressure within the ring (no deviatoric stress). The Mg would have the pressure profile of a liquid supported in a magnetic "bucket" (constant gradient).

To maintain the high conductivity approximation, we want both H and the minimum gap $\sqrt{C/H}$ to be a few skin depths. Equating these distances eliminates C, so

$$C = H^3 \tag{8}$$

and,

$$Y = \frac{4Hx^2}{W^2} - HW\sqrt{\frac{1}{W^2 - 4x^2}} \tag{9}$$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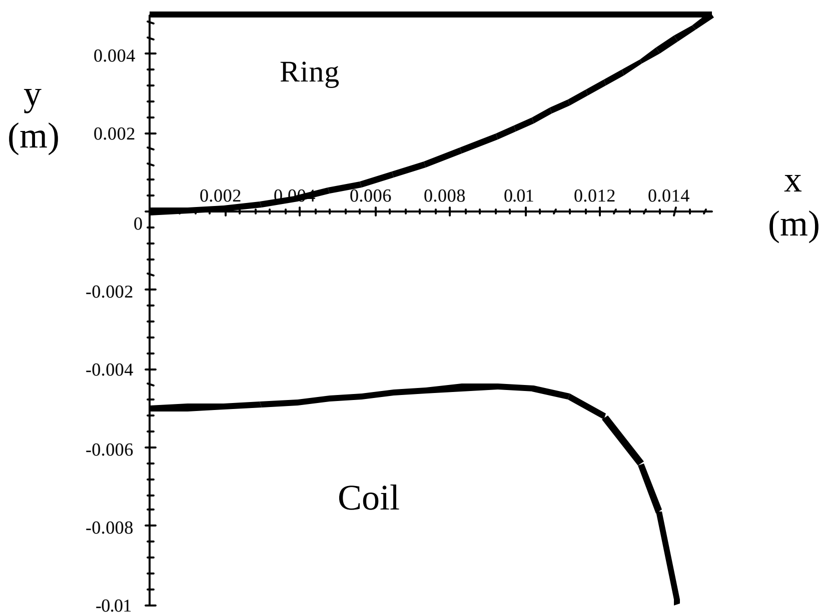

Figure 1:

For 10 kHz current drive, skin depth in Mg is 1 mm. Profile for H=5 mm, W=30 mm is plotted.

(Nar.) Recall, our goal is to inject the gas in less than 100 μs, so a current frequency of about $f = 10^4$ s^{-1} would be optimal. Skin depth is

$$\delta = \sqrt{\frac{\rho}{\pi f \mu_0}} \tag{10}$$

The resisitivity of Mg is $\rho = 4.456 \times 10^{-8}$ - $-$m and $\mu_0 = 4\pi \times 10^{-7}$ H/m. This gives $\delta = 1 \times 10^{-3}$ m (1 mm). $H = 5 \times 10^{-3}$ m should do. $W = 30 \times 10^{-3}$ m is a good test case. From Eq. 9 then we have plotted the ring profile and coil shape Y