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University of Maryland, Baltimore County

Topics of Plasma Experimentation: Basic Hardware

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Joint ICTP-IAEA College on Plasma Physics for Fusion Applications

Trieste, Italy

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SYSTEM DESIGN FOR FUSION RELEVANT EXPERIMENTATION

- What hypotheses are you interested in testing?
  - Many small scale experiments can be relevant to fusion plasmas, particularly in diagnostic development.
- What operating regimes are you aiming for?
  - n, T, τ is a useful guiding metric, even if not trying to be anywhere close to the Lawson criterion.
  - Density and temperature largely dictate the amount of power you need to have.
  - Confinement time / plasma time largely dictate the total energy that you need to have.
- Choice of working gas: typically hydrogen (or deuterium), but also helium, argon, etc.
- Magnetized or unmagnetized plasmas
  - Magnet design and availability, including its own power and switching system, is a subsystem in itself.
  - Magnets and its components typically the biggest single cost of hardware in an experiment.

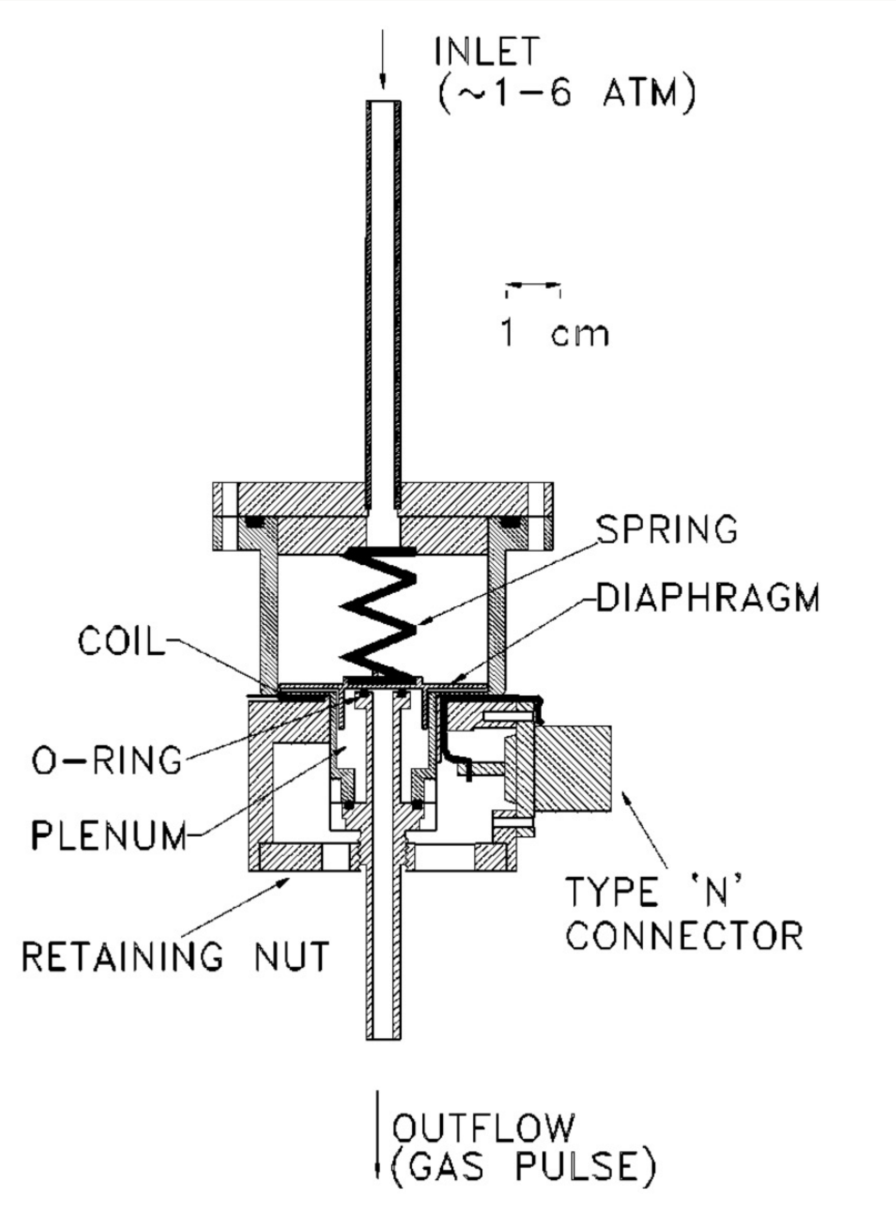
PLANNING FOR DENSITY

- Even cold plasmas are energetically expensive.
- Hydrogen (protium) is the typical gas for fusion related experiments.
  - Deuterium is closer in mass to D-T mixtures, but much more expensive than hydrogen, and radiation controls may be required.
  - The progression is (typically): develop and debug the experiment with hydrogen, then move to deuterium… only a few experimental groups have ever used D-T (but we need a lot more technical experience with tritium!)
- Choose the target number density. For example, hydrogen with $n = 10^{20}\ m^{-3}$.
  - Assume you start with a perfect vacuum chamber. Two options:
    - Flood the chamber slowly, or
    - Use a fast gas puff vale, synchronized with plasma initiation to minimize neutrals at the plasma edge in a fast pulse.
  - What should be the target neutral pressure before plasma starts?
    - You may use $p = n\,k\,T$ (since neutrals move as ideal gases).
    - In this example: $p = (10^{20}\ m^{-3})\times(1.38\times 10^{-23}\ kg\ m^2 s^{-2} K^{-1})\times(293\ K) = 0.4\ Pa = 3\ mTorr$.

GAS PUFF VALVES

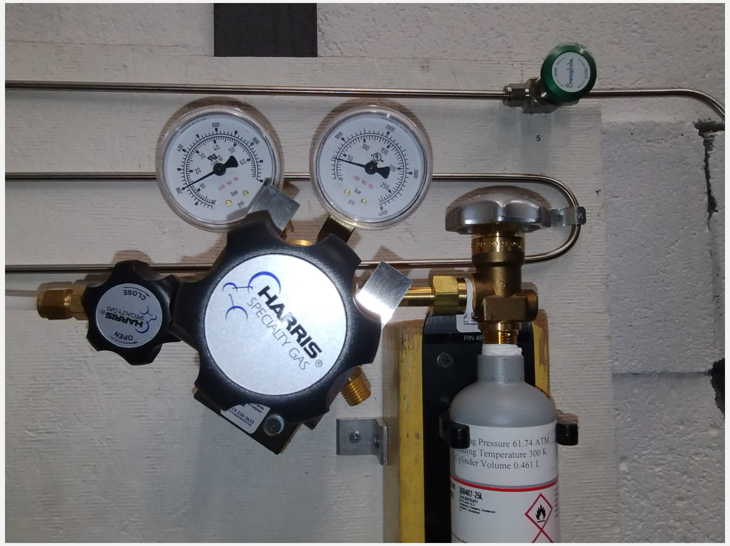
- Commercial gas puff valves usually have a small plenum, low throughput, or are too slow.
  - – Also require proprietary power supply.
- Custom gas puff valves can be designed and built to release higher density in shorter time than commercially available valves.

  ~100 μs or less
- Allows for most of the neutral inventory to be deposited in a sub-volume of the chamber, without flooding the entire chamber.



P. M. Bellan Rev. Sci. Instrum., Vol. 73, No. 8, August 2002

HOW MUCH NEUTRAL GAS DO YOU NEED?



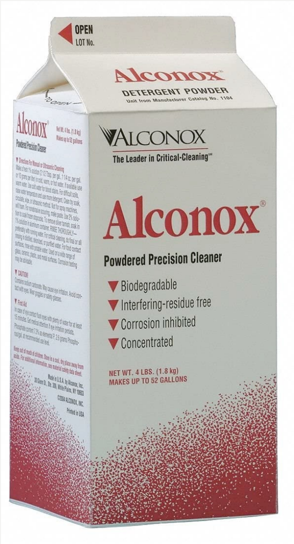
- Typical 300-size cylinders with high purity (research grade) gas have a volume of 49 L, and at pressurized at 18 MPa (2,600 psi).
  - If that volume expands to 1 atm (101.3 kPa or 14.7 psi), you get 8.7 m^3, but typical plasma experiments operate at pressures $\times 10^{-5}$ or less than atmospheric pressure, with volumes less than 1 m^3.
- One cylinder of ultra-high purity gas should last for years of plasma experimentation!
  - Even when there is an established flow (with a bleed valve and a vacuum pump constantly operating) that prevents the impurities from building up (from chemistry caused by the plasma discharge), tanks last a very long time.
- However, hydrogen and helium easily leak through connections and be absorbed by certain plastic tubing. These losses are minimized by choosing the appropriate connectors and tubing.

VACUUM TECHNOLOGY AND HARDWARE

- Impurities in plasmas are a constant concern in experiments of any size.
  - Radiate power, making plasmas more resistive and collisional.
  - Change the overall mass of the plasma.
  - Create chemicals/vapors that may react with instruments, coat windows, power feedthroughs, etc.
- Imperative to choose the right materials and the right procedures to deal with them.
  - The most common vacuum chamber material is Stainless Steel 304, but may outgas hydrogen if heated, thus appropriate for UHV, but during plasma discharges may outgas.
  - Aluminum (only certain types!) have lower outgassing rates than Stainless Steel, and may achieve XHV.
  - Stainless Steel 316L has low conductivity and low magnetic permeability, making it appropriate for pulsed magnetic fields.
- Why should we care about having UHV base pressure (say 10^{-8} Torr), if we'll flood the chamber with 10^{-3} Torr?
  - Impurities can be absorbed and adsorbed at the plasma-facing components: during a plasma discharge, the base pressure can increase orders of magnitude just from impurities.
  - Ion, electron impingement can dislodge impurities, but also EM radiation can heat up the surface rapidly.

VACUUM CLEANING TECHNIQUES

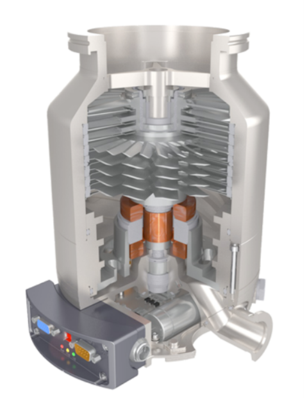
- Thorough cleaning of vacuum components is as important as vacuum compatible materials.
- Machined components usually have oils that spread to the inner surfaces of the vacuum chamber. Hydrocarbons and silicones are common lubricants for atmospheric pressures, but carry large amounts of impurities to the plasma.
- When ever possible, always wash parts with industrial detergent and an ultrasonic cleaner. After that, acetone, alcohol, deionized water may be used.



VACUUM PUMPS

- There are several types of vacuum pumps, but make sure these are dry / oil-free on the vacuum side.
- Vacuum pumps are grouped by their ultimate vacuum pressure (capable of achieving):
  - Roughing 100 kPa – 0.1 Pa (760 – 10^{-4} Torr)
  - HV 0.1 Pa – 10^{-5} Pa (10^{-8} – 10^{-4} Torr)
  - UHV 10^{-10} – 10^{-5} Pa (10^{-13} – 10^{-8} Torr)
  - XHV < 10^{-10} Pa (< 10^{-13} Torr)
- Pumps usually work in series with a roughing pump.

Roughing



Turbomolecular

Pump Station

Cryopump

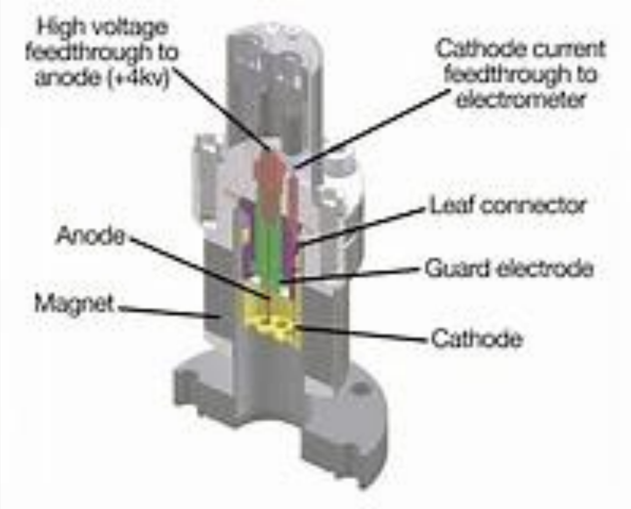
NEG

VACUUM CONDUCTANCE

- In molecular flow, the length, diameter, and number of turns in the vacuum lines makes a significant difference in the pumping speed.
- The mean free path in a gas is $\lambda = \frac{1}{\sqrt{2}\pi\, d_o^2\, n}$, where d_o is the molecular diameter and *n* is number density.
  - At UHV conditions, neutrals bounce on the walls of the chamber many times before getting to the pump… they don't push each other!
  - *E.g. for air at 20 °C,* $\lambda = \frac{0.005}{P\ (Torr)}$ *(cm)*
- Effective pumping speed, $S = \frac{Q}{P}$, where Q is throughput (in Pa-m^3/s or Torr-L/s), may be greatly diminished by low conductance, $C = \frac{Q}{P_2 - P_1}$
  - *E.g. a pump rated for 800 L/s may end up only pumping at ~ 20 L/s with a 6" pipe (15 cm), two elbows, and about 9 m length total.*

PRESSURE MEASUREMENTS

- Direct reading (Diaphragm, Bourdon Gauges, Capacitance).
- Indirect reading: Thermal conductivity (Pirani, thermocouple), Ionization gauge (Hot cathode, Cold cathode – or Penning trap).
- For a complete pumping system, it is advised to have gauges near atm pressure, at HV, and UHV.
- Magnetic fields are a concern for low pressure measurements:
  - Hot cathode may give the wrong reading, but ok in B-fields.
  - Cold cathode has a strong magnet inside, so it would not adequate near B-fields.



Cold cathode gauge


Hot cathode gauge

VACUUM QUALITY: RGAs

- Residual Gas Analyzer (RGA): There are many types of mass spectrometers/analyzers. Perhaps the most common type is the quadrupole one
- RGAs are not calibrated mass spectrometers (but with care may be turned into one), since they have 'cracking patterns'.
- They are too slow for plasma timescales, but are helpful in finding impurities present during plasmas.

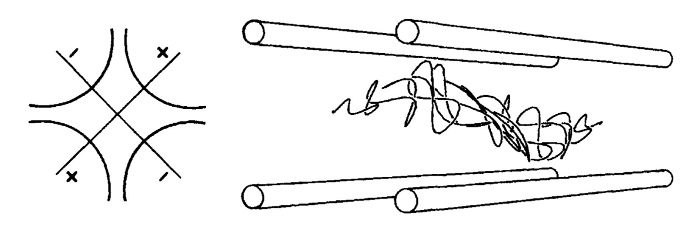
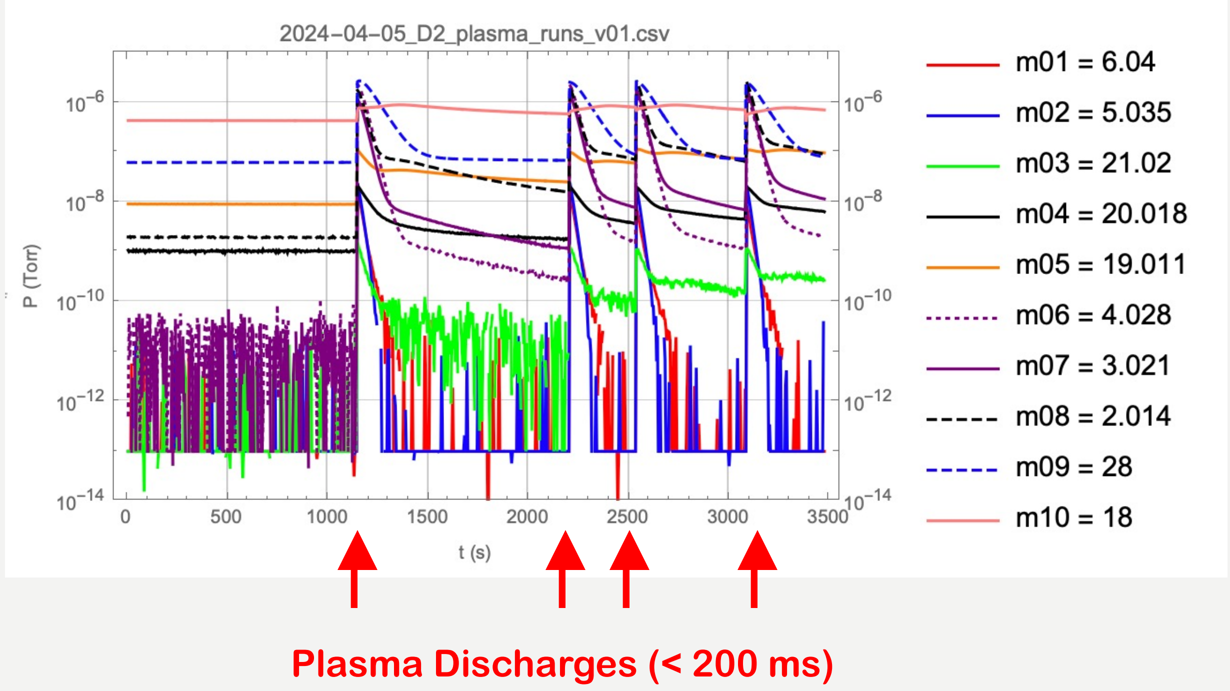
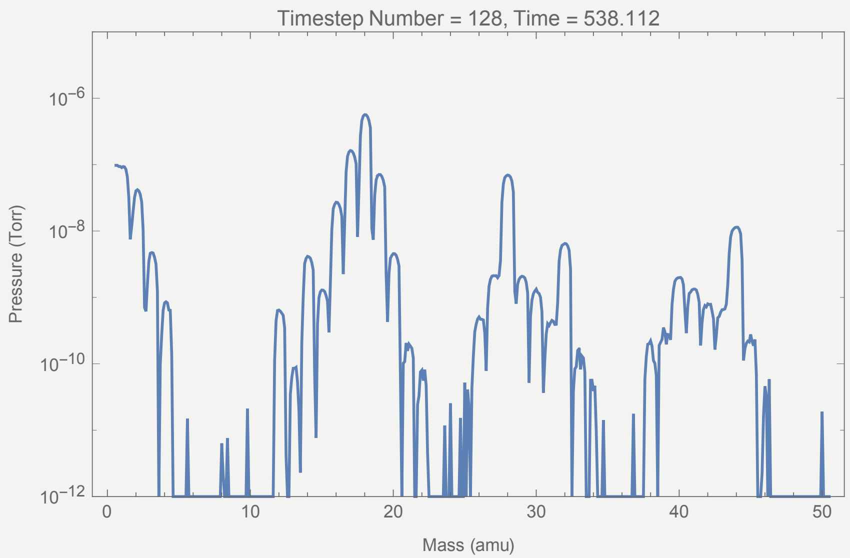


Fig. 8.10 Quadrupole mass filter. Left: Idealized hyperbolic electrode cross section. Right: Three-dimensional computer generated representation of a stable ion path. Courtesy of A. Appel, IBM T. J. Watson Research Center, Yorktown Heights, NY.

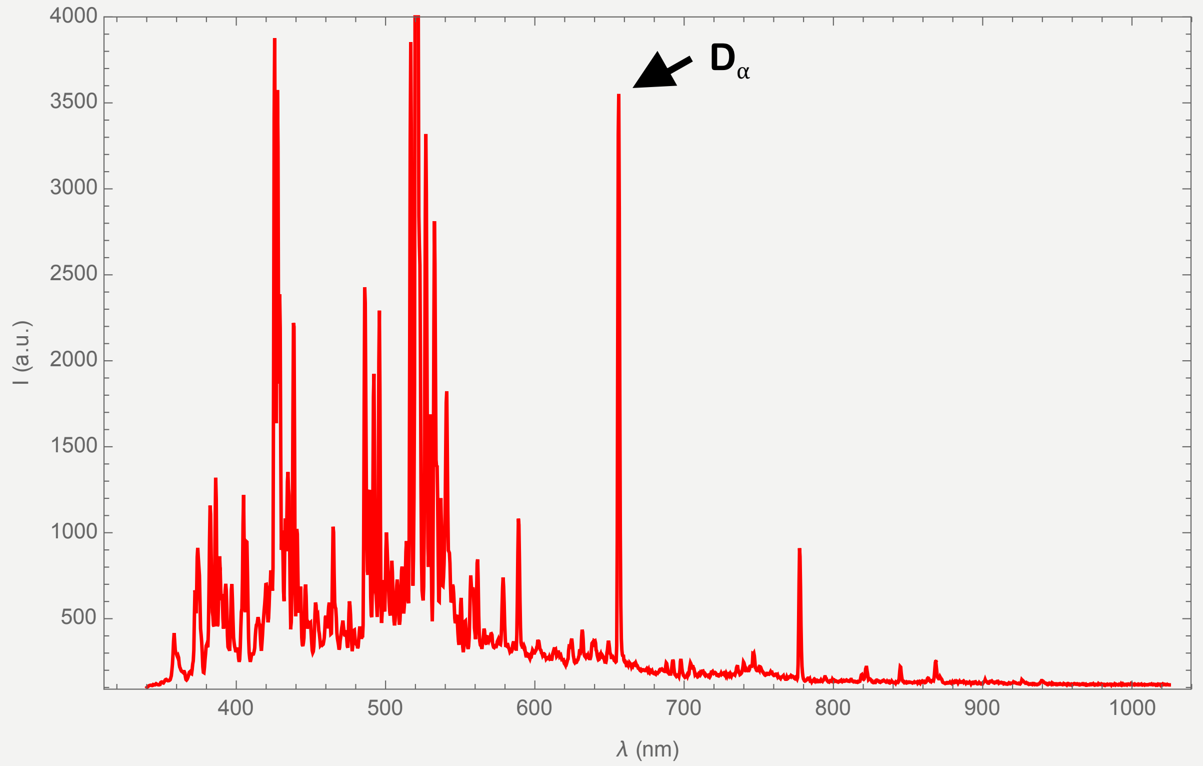
O'Hanlon, A User's Guide to Vacuum Technology, Wiley 2003.

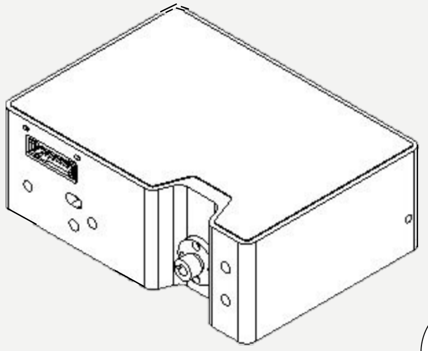




SURVEY ATOMIC SPECTROMETRY

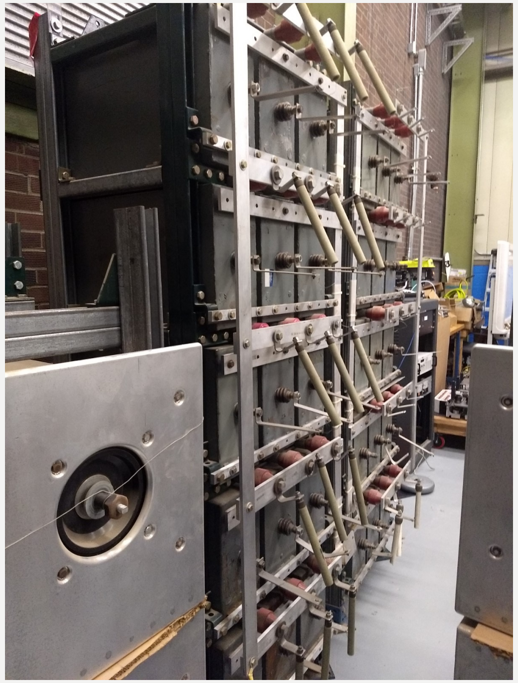
- Low resolution atomic emission spectrometry is helpful in identifying impurities during plasma discharges.
- These are particularly useful close to plasma-facing surfaces with low-temperature, collisional plasmas.
  - However, the low resolution makes it difficult to identify many elements, but the overall intensify and number of lines go down as impurities are removed.
  - Example on the right only identifies D_α but other suspected elements are N, O, Fe, Si, Al, W.



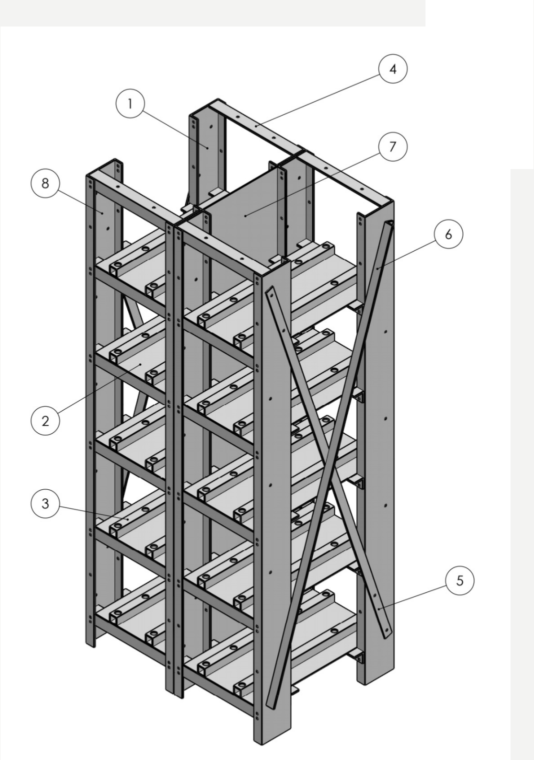


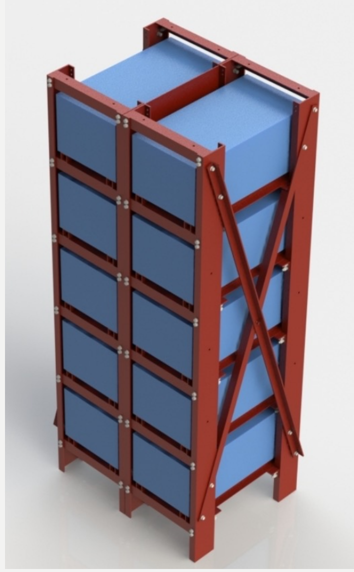
ENERGY STORAGE

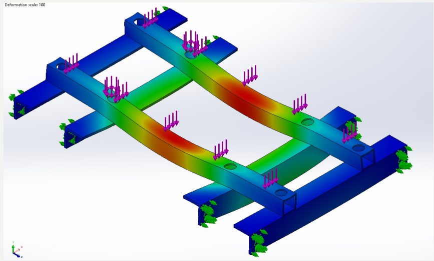
- Typical laboratories do not have enough wall-plug power to run plasma discharges (including all heating elements) and power for magnets (if any).
- Energy storage capacitors are usually adequate for discharges that can last from 10's of μs to 10's of ms.
- Energy storage capacitors can have a long life if they're **not overcharged, and you do not force reverse current on them during discharges**.
- Typical storage values: ~ 10 kJ/capacitor.



Unistrut (Metal) Racks





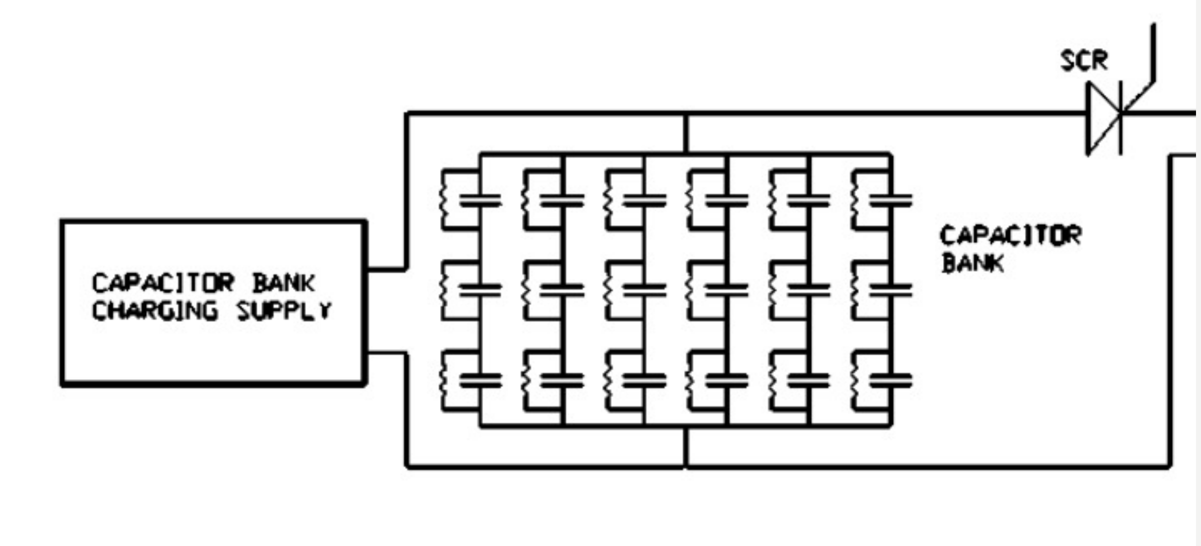


Fully Non-Conducting Racks

CAPACITOR BANK CALCULATIONS

- If a capacitor bank is required, and capacitors can be connected in parallel, the total stored energy is simply $\frac{1}{2}CV^2$, where $C = \sum_{i-1}^{N} C_i$ is the sum of all capacitances in the bank.
- If configuring capacitors in series, then $\frac{1}{C} = \sum_{i-1}^{N} \frac{1}{C_i}$, but must add resistors in parallel with each capacitor to limit the voltage at each capacitor.
- Or combinations of series / parallel.

- E.g. consider a bank with 24 identical $6\ \mu F$ capacitors in series rated for 60 kV, but say we limit the maximum charge voltage to 50 kV. The maximum energy stored is 360 kJ.



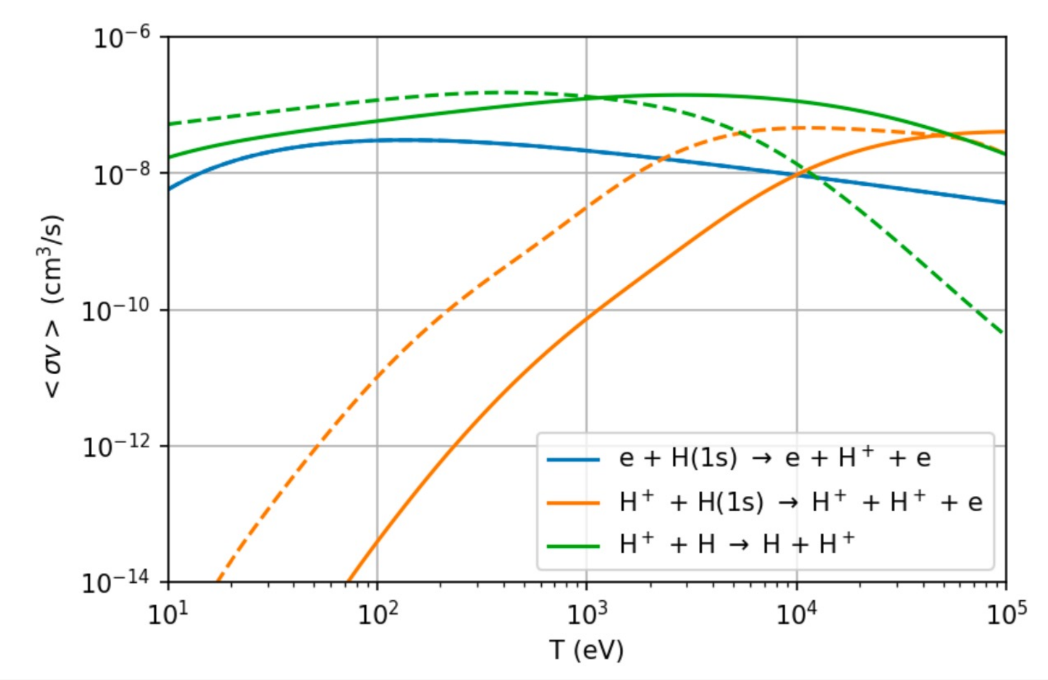
P. M. Bellan Rev. Sci. Instrum., Vol. 73, No. 8, August 2002

ESTIMATING ENERGY AND POWER

- How much energy and power do we need to sustain a plasma with density n and Δt?
  - Must overcome ionization potential and collisional recombination.
  - In cold plasmas, electrons recombine and decay as $N_e(t) \sim N_{e,max} e^{-\upsilon_{att} t}$ where υ_{att} is the collision attachment rate, that is dependent on the gas pressure.
  - For fusion plasmas attachment is not a problem, except at the plasma edges (but for atmospheric plasmas it is!).
- Rate of collision with neutrals that get recycled are a significant loss mechanism.

$$R_{ns}(\boldsymbol{v_s},\ \boldsymbol{v_n}) = n_s n_n v_r \sigma(v_r) f_s(\boldsymbol{v_s}) f_n(\boldsymbol{v_n}) \mathrm{d}^3\boldsymbol{v_s} \mathrm{d}^3\boldsymbol{v_n}$$

- When a collision occurs, a fast charged particle may collide with a neutral and impart energy to that neutral, exchanging charge and pushing the hot neutral (and its energy!) away from the confinement volume.
  - That neutral will come back cold and will need to get re-ionized and heated.



Rate coefficients for several collisions with neutrals: Solid: non-rotating plasmas. Dashed: rotating mirror plasmas

SWITCHES

- Conventional relay switches are typically too slow for plasma applications.
- Ignitrons, spark gaps / rail gaps, vacuum switches, solid state (SCR, IGBT), among others.
  - The required power level limits the options.
- E.g. Ignitrons: Mercury switches that can standoff high voltage and take high currents and are fast enough for plasma pulses.

25 kV Ignitrons

50 kV ignitrons

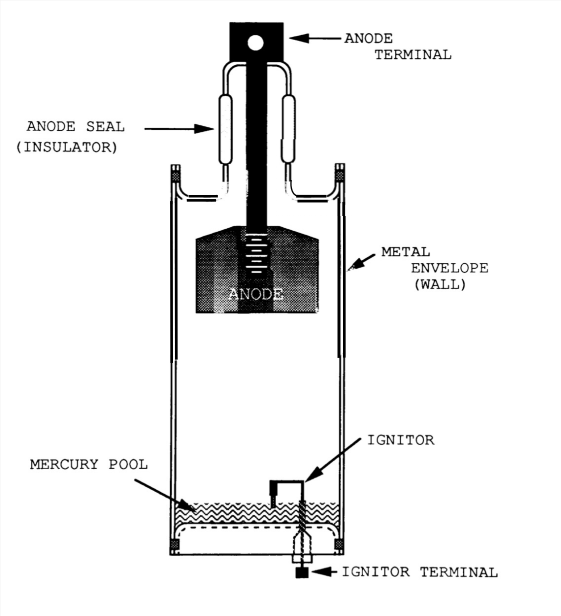
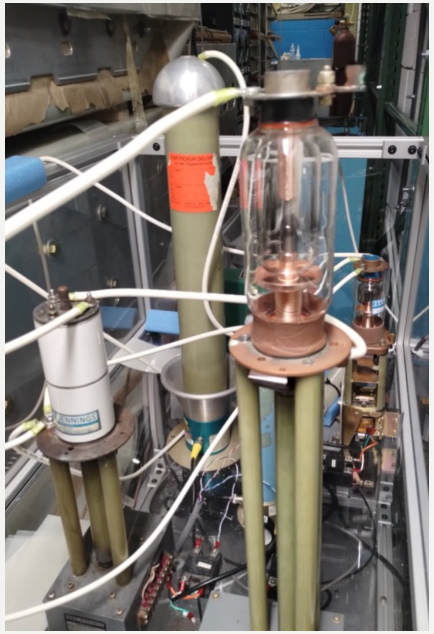


Figure 1. Basic ignitron.

D. L.. Loree Thesis 1991



50 kV Vacuum switches

MAGNETIC FIELD DESIGN

- Magnets and related structures design is iterative and usually starts with an idealized magnitude and shape (a sketch).
- Theory dictates strength and shape, but engineering state of the art and cost may require compromise.
  - Since stored energy is non-linear with field strength and volume, it is easy to go beyond strength of materials or cooling capacity for resistive magnets, or beyond critical currents and fields in superconductor magnets.
- A good first step is to calculate the magnetic field of the magnetostatic case, calculate the magnetic flux, then use that for dynamic case if the field is pulsed.
- May use stored energy as $\frac{1}{2}\mathrm{L}I^2$ and as $\frac{B^2}{2\,\mu_o}V$ to get a sense of the scale of the energy/power required to run the magnet (and the cost!).
  - Forces between magnets/structures always very important!
- If calculating non-circular loops, may need to use specialized software

VACUUM FIELD SOLVER

- Calculation of the vacuum magnetic field and inductance produced by filamentary circular loops.
- Start with the calculation of magnetic flux through a surface, and use Stoke's theorem,

$$\int_S B\,ds = \int_S (\nabla \times A)\,ds = \oint_C A\,dl.$$

- For a circular loop, the only non-zero component of the vector potential is A_φ, which is constant along $\boldsymbol{dl}$ for a given radius r.
- Thus the flux through a circular contour is $\psi = 2\pi r A_\varphi$.
- Using equation 5.37 from Jackson's Electrodynamics (in spherical coordinates)

$$A_\phi(r,\theta) = \frac{4Ia}{c\sqrt{a^2+r^2+2ar\sin\theta}}\left[\frac{(2-k^2)K(k)-2E(k)}{k^2}\right]$$

- The argument in the elliptical functions:

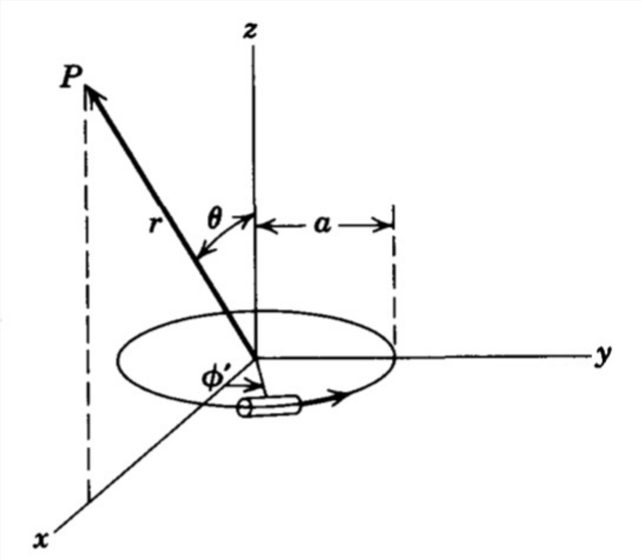
$$k^2 = \frac{4ar\sin\theta}{a^2+r^2+2ar\sin\theta}$$

- The components of B can then be calculated as

$$B_r = \frac{1}{r \sin\theta} \frac{\partial}{\partial\theta}(\sin\theta A_\phi)$$

$$B_\theta = -\frac{1}{r}\frac{\partial}{\partial r}(r A_\phi)$$

$$B_\phi = 0$$



- For computation of ψ the elliptical integrals can be approximated as*

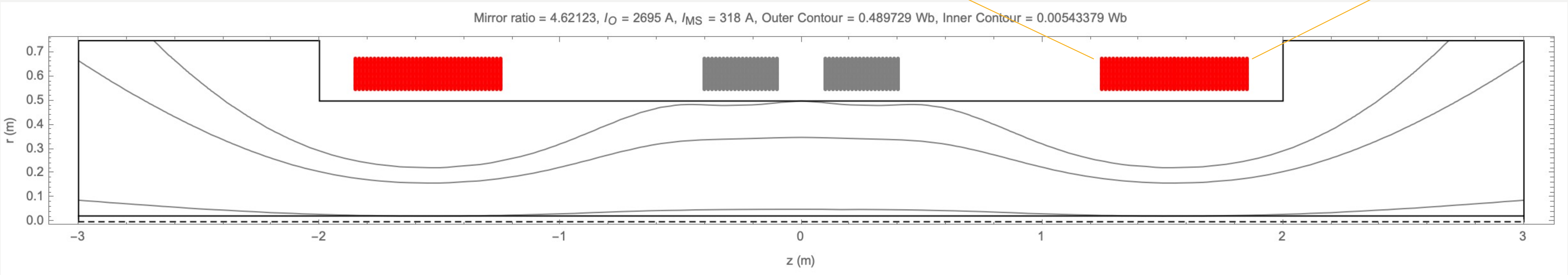
```
K[k_] := 1.3862944 + 0.1119723 (1 - k^2) + 0.0725296 (1 - k^2)^2 - (0.5 + 0.1213478 (1 - k^2) + 0.0288729 (1 - k^2)^2) Log[(1 - k^2)]
E[k_] := 1 + 0.4630151 (1 - k^2) + 0.1077812 (1 - k^2)^2 - (0.2452727 (1 - k^2) + 0.0412496 (1 - k^2)^2) Log[(1 - k^2)]
```

- To calculate inductance of a winding, calculate the total flux linking a given loop, $L_i = \frac{\Sigma\, \psi(r,z)}{I_i}$
- Another good reference for B-field components: J. Simson, J. Lane, C. Immer, and R. Youngquist, Simple Analytic Expressions for the Magnetic Field of a Current Loop, NASA/TM-2013-217919

*Approximate solution to elliptic integrals (M. Abramowitz and I. Stegun, Eds. Handbook of mathematical functions with formulas, graphs, and mathematical tables (U. S. Govt. Print. Off., Washington, D.C., 1972)

EXAMPLE OF VACUUM FIELD SOLUTION

- Coils with large number of windings can be represented with the same number of filamentary currents.
- The flux at any cross-section is the contribution from the flux produced by all coils.
- Each coil has 600 turns, each at a different place in the {r,z} plane.

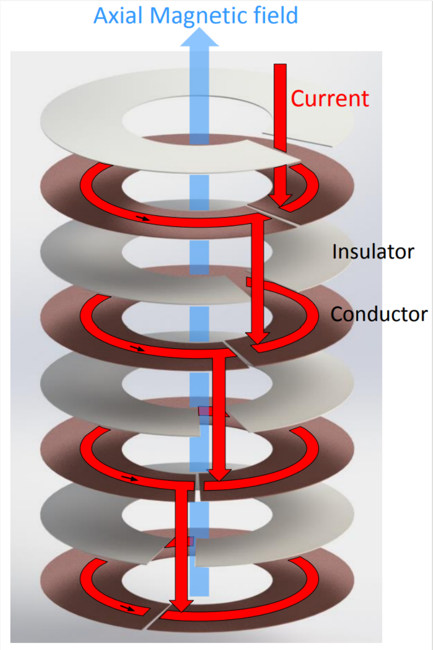


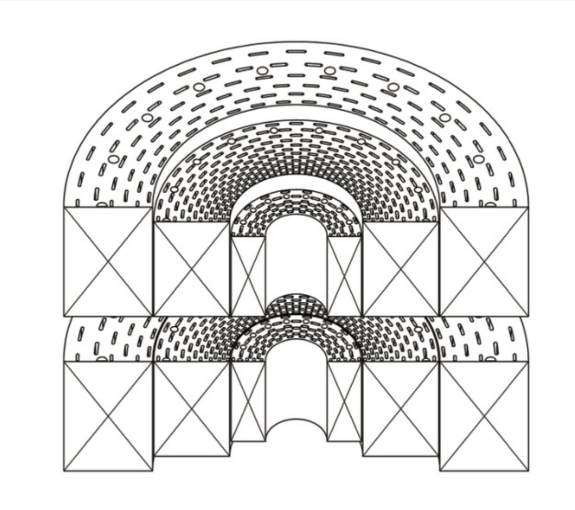
- For a single coil, with evenly spaced windings, a summation function may look like this:

$$\psi\text{multi}[\rho\_, z\_, Le\_, Ne\_, Ie\_, a1\_, a2\_, Nlayers\_] := \sum_{j=0}^{Nlayers-1} \sum_{k=0}^{Ne-1} \Psi\left[\rho, -z + \left(k \frac{Le}{Ne-1}\right), Ie, \left(a1 + j \frac{a2 - a1}{Nlayers - 1}\right)\right]$$

BITTER MAGNETS

- Resistive magnets, named after Francis Bitter, possible to achieve fields higher than superconductors in some cases.
- Conducting plates are collated with insulating plates, all with aligned cooling holes to run large amounts of water to remove Ohmic heating from large currents.

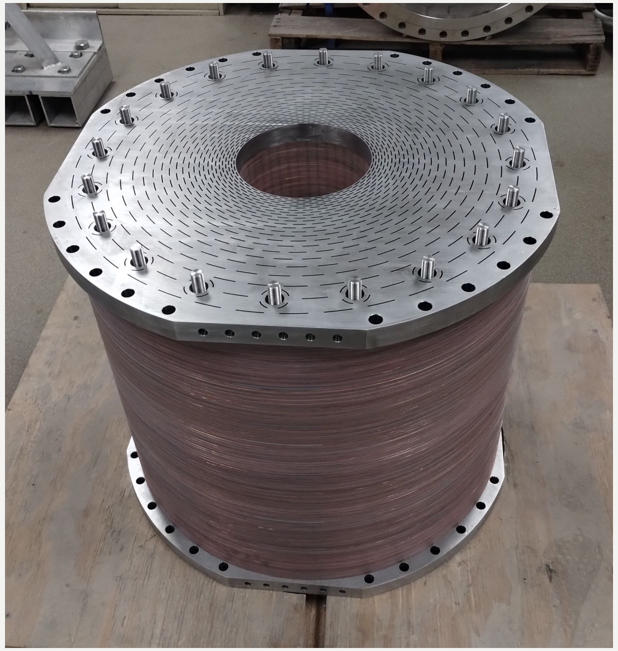




$$\mathbf{J}(r) = \frac{1}{\rho_{\text{avg}}}\mathbf{E} = \frac{V_o}{2\pi\rho_{\text{avg}} r}\hat{\theta}.$$

$$I = \int_{r_i}^{r_o}\int_{0}^{h} \frac{V_0}{2\pi\rho}\frac{1}{r}\hat{\theta}\cdot(\lambda dz dr\hat{\theta}) = \frac{V_0\lambda h}{2\pi\rho}\ln\frac{r_o}{r_i}.$$

$$R_o = \frac{V_o}{I} = \frac{2\pi\rho_{\text{avg}}}{\lambda h \log\left(\frac{r_o}{r_i}\right)}.$$

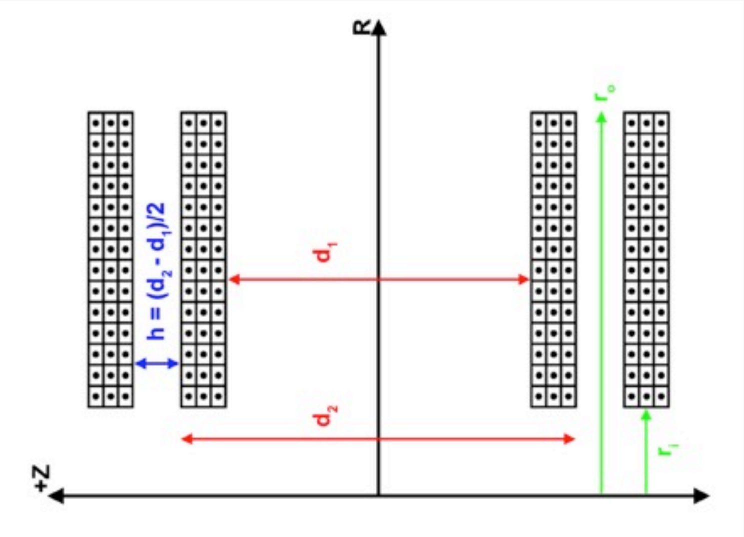


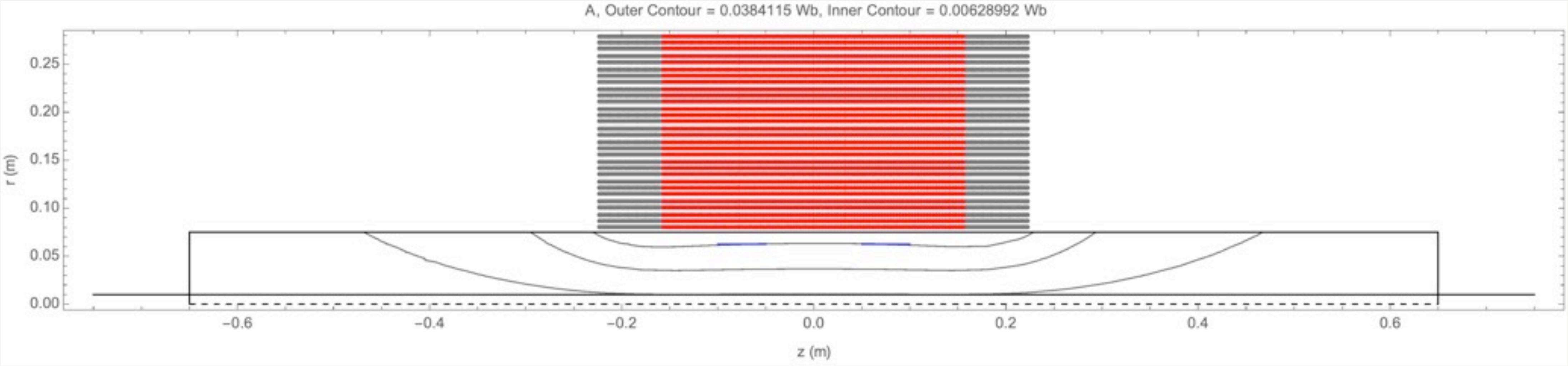
E. M. Bates, PhD Thesis, UMBC 2017

MAGNETIC FIELD CALCULATIONS (2)

- For Bitter magnets, the disks can be discretized in filaments such that the filamentary approximation of circular loops above can be used.

$$I_c = \frac{1}{\eta_r \eta_z} \frac{V_0 \lambda}{4\pi\rho r} (r_o - r_i)(d_2 - d_1).$$

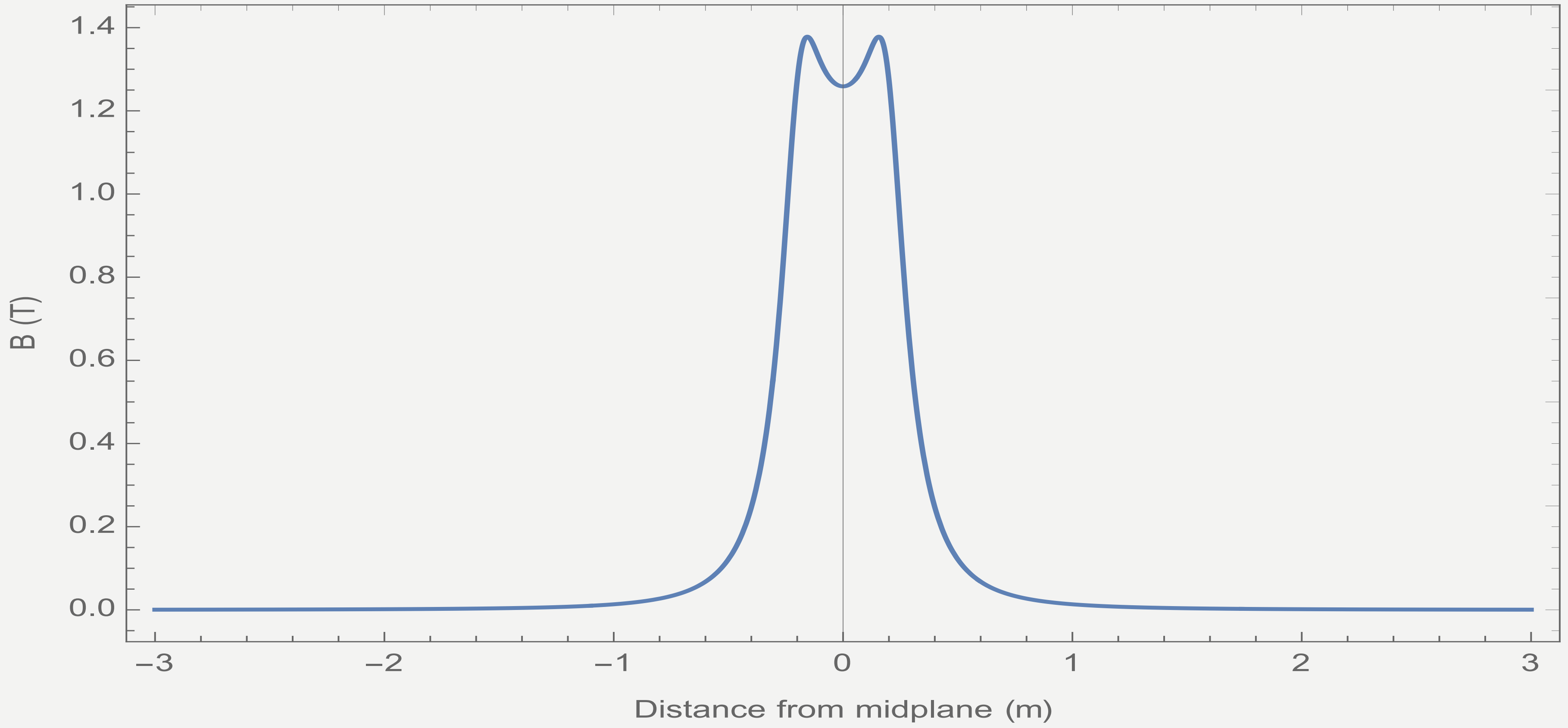




E. M. Bates, W. J. Birmingham, and C. A. Romero-Talamás, IEEE Transactions on Magnetics 53, 7200310 (2017)

MAGNETIC FIELD CALCULATIONS (3)

- Calculations of the magnetic field along the axis of a filamentary circular loop is the usual analytical solution: $B_z = \frac{\mu_o N I}{2L}\left(\frac{L-z}{\sqrt{a^2+(L-z)^2}} + \frac{L-z}{\sqrt{a^2+z^2}}\right)$ (where N and L refer to number of turns and length of the solenoid).



FINITE ELEMENT CALCULATIONS

- For more refined iterations, 3D dynamic fields, induced currents, realistic permeabilities, force and pressure calculations, commercial software is usually adequate.

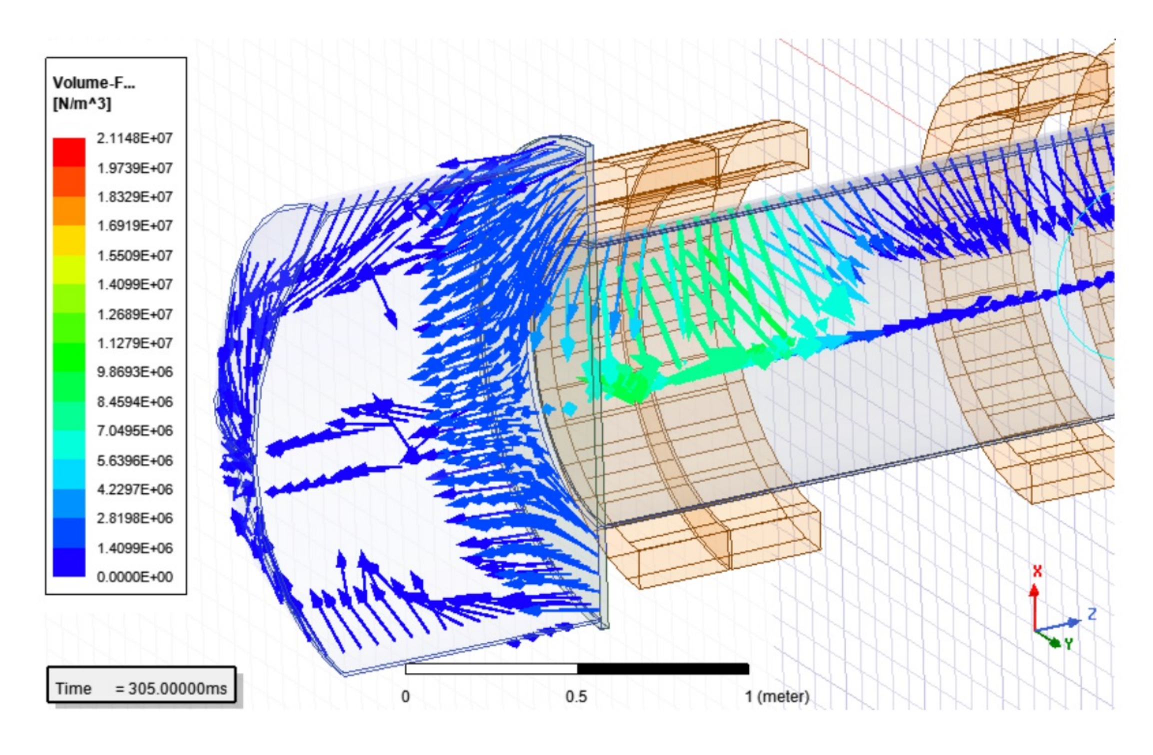
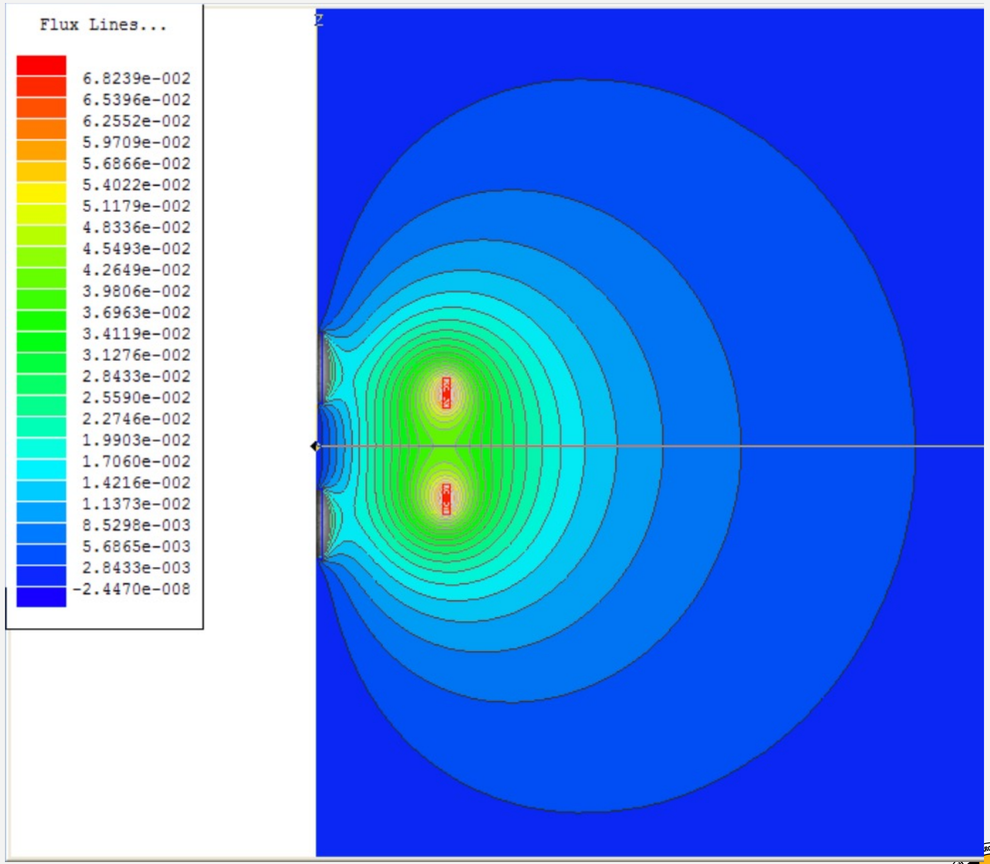


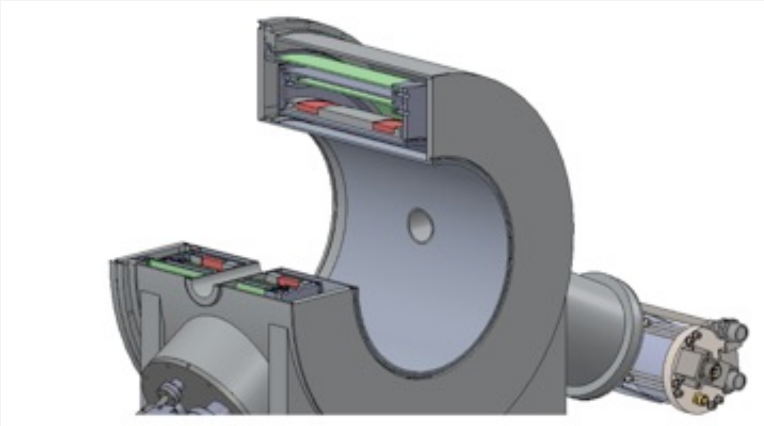
Figure 5: FEA Results Solving Lorentz Forces on Vacuum Chamber Structures During Resistive Magnet Ramp



N. Eschbach, PhD Thesis (in preparation), UMBC 2024.

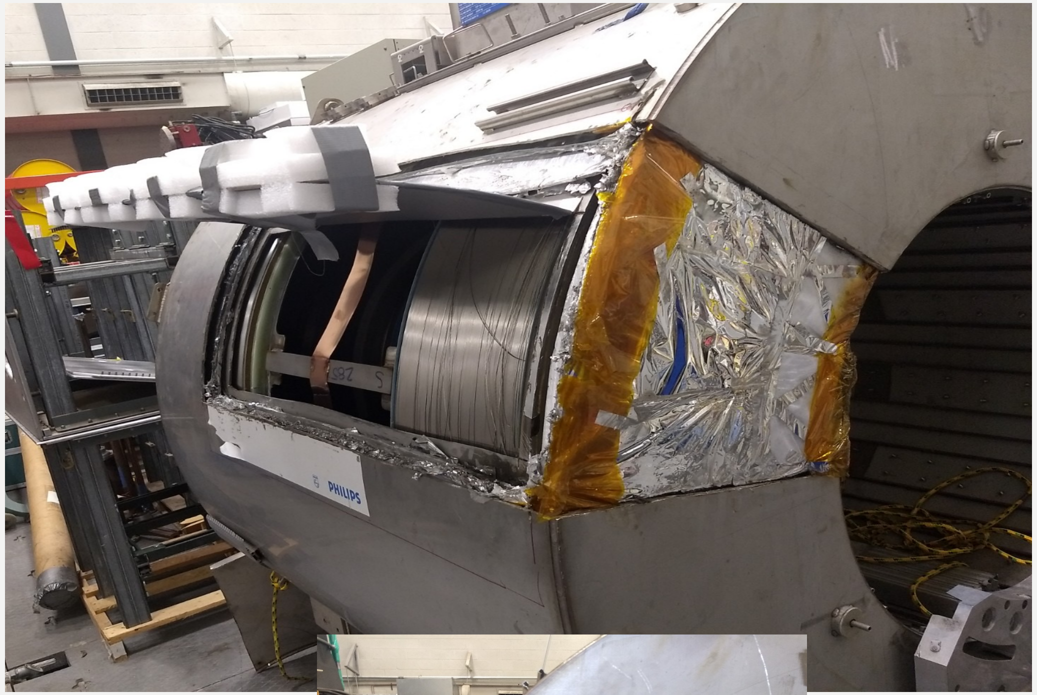
SUPERCONDUCTING MAGNETS

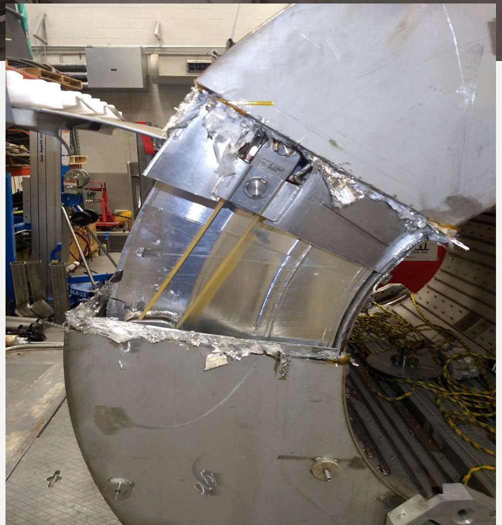
- Superconductors have zero resistivity, but need constant cooling with specialized cryogenic compressors.
- Most of the superconductors in use are low temperature superconductors (LTS).
  - Require liquid helium temperatures, 4 K.
  - Various types have different current and field limitations.
- New high temperature superconducting (HTS) tapes have much higher critical current and fields, and can withstand the $\mathbf{J}\times\mathbf{B}$ forces.
  - "High temperature" is 20 K, but that opens up the range of coolants available.
- Need careful (and expensive) maintenance, and require low ramp up rate.

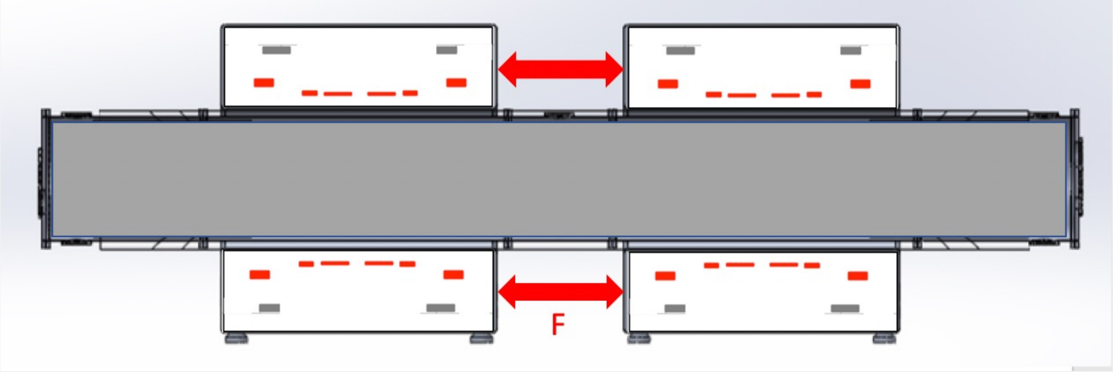


Parameter	Value
Warm Bore Radius	15 cm
Windings Inner Radius	18 cm
Wire Diameter	0.64 mm
Wire Turns	64
Wire Layers	16
Windings Dimensions	9 mm x 41 mm
Windings Separation, center	15 cm
Nominal Current	93.5 A
Jcoil	251 A/mm^2
Peak Field	1.536 T
Energy per Coil	6 kJ
Axial Force, quench	-8.9 kN
Radial Force, quench	27.4 kN

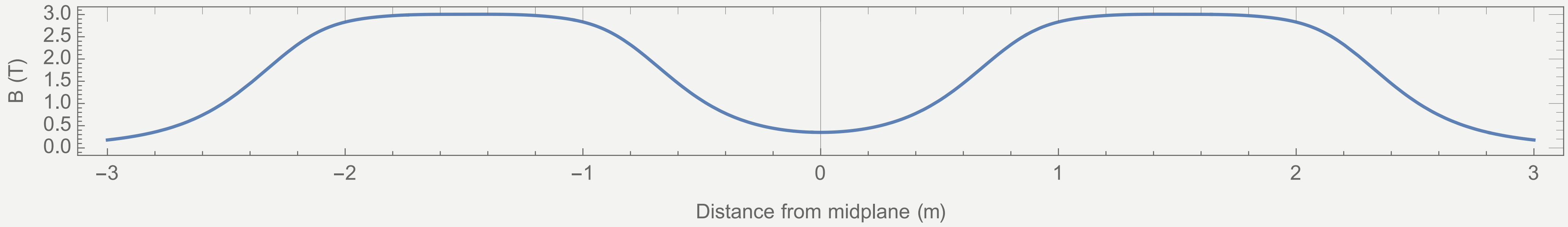
REPURPOSING MRI MAGNETS

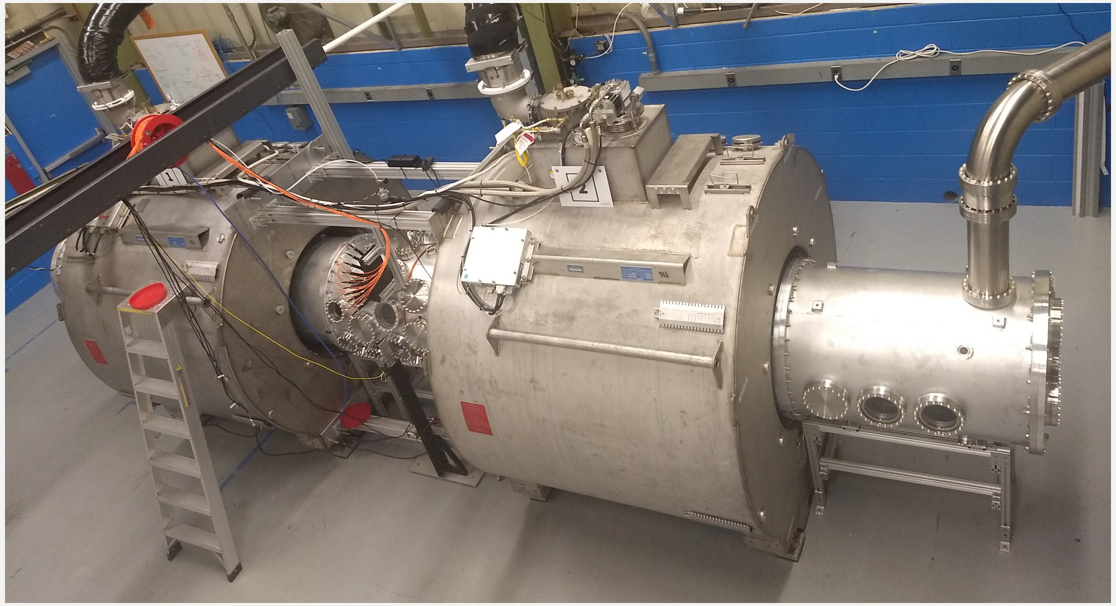


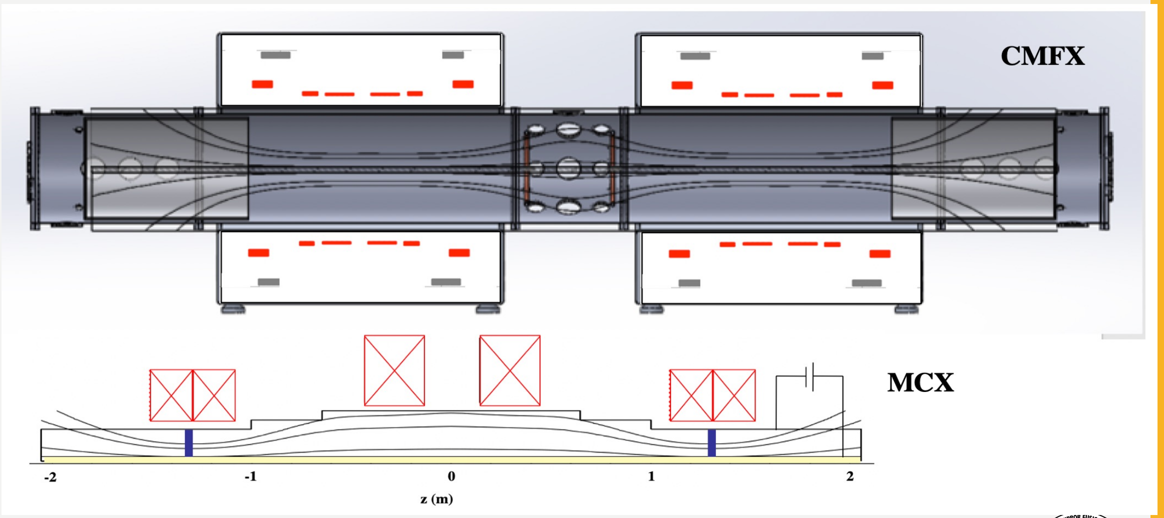




THE CENTRIFUGAL MIRROR FUSION EXPERIMENT, CMFX

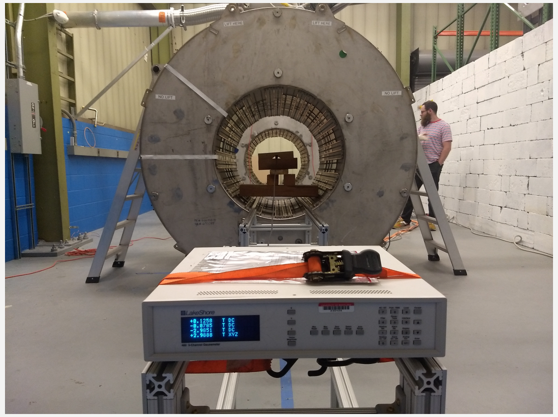


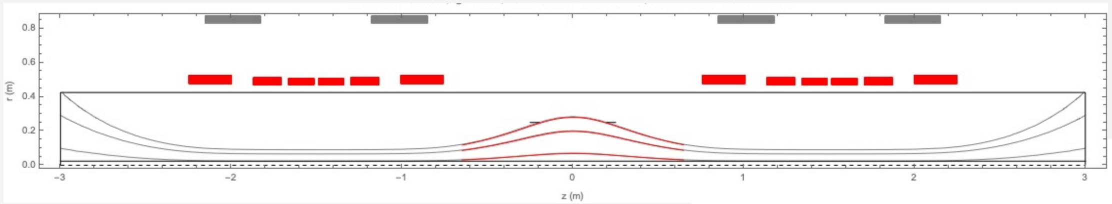


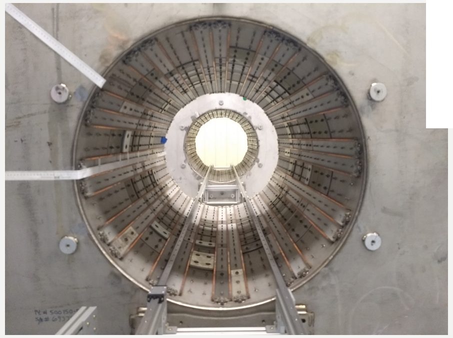


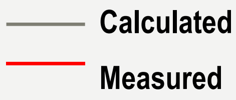
MAGNET INSTALLATION AND TESTING

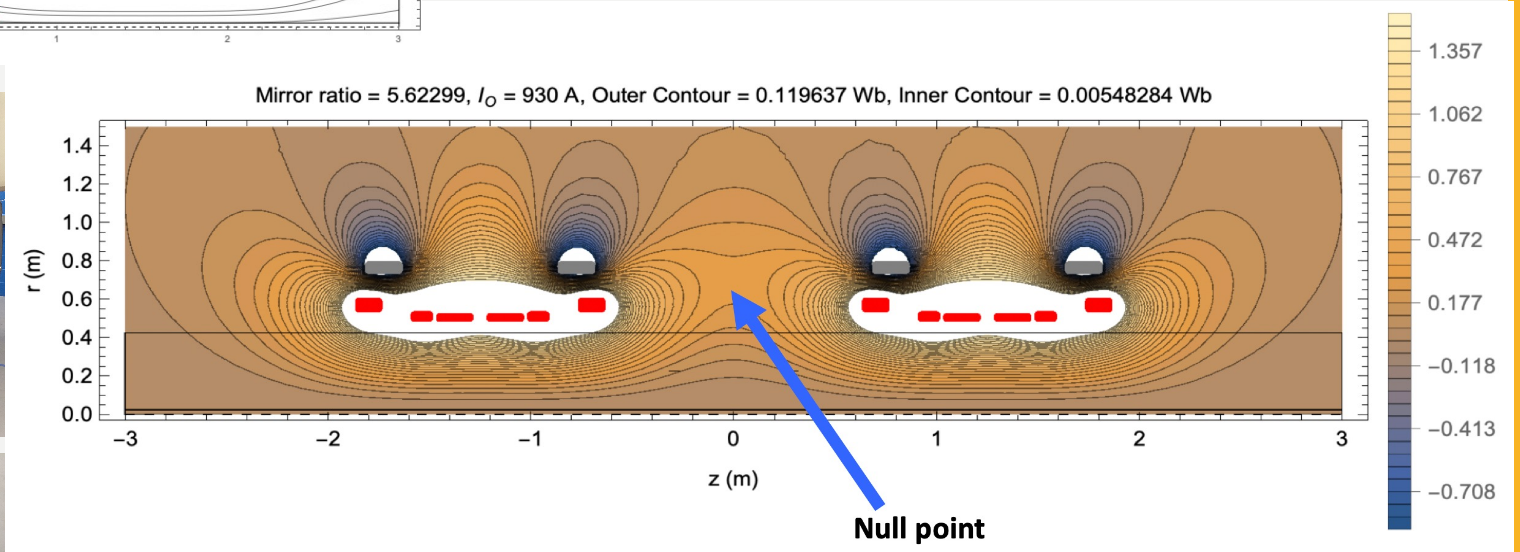
- Magnets installed, aligned, and tested at full field separately and together.
- Field mapping numerically from warm magnet
- Meas. of full field and field mapping shows good agreement with calculation.







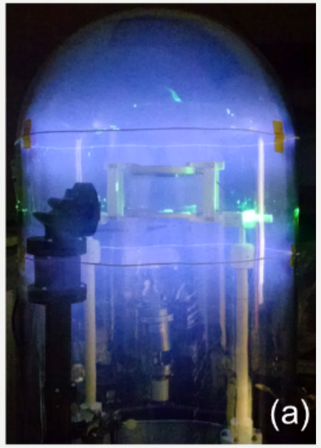




Magnetometer measurements will be used to verify magnetic flux calculations, and the null point at z=0 and r ~0.66 m.

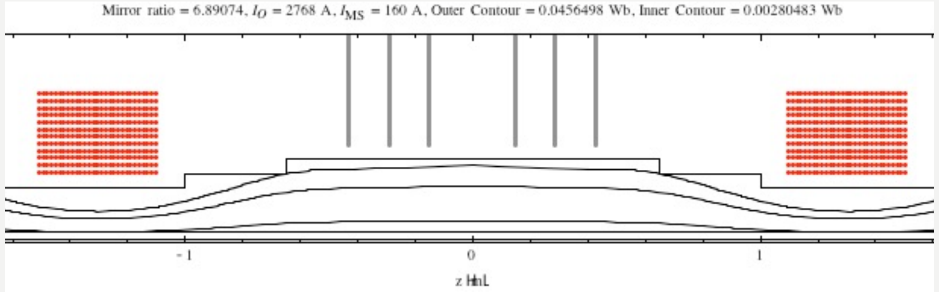
HOW TO START THE PLASMA?

- Several ways to go from neutral inventory to ionized plasma:
  - High Voltage breakdown,
  - RF: capacitively coupled / inductively coupled,
  - Laser / microwaves.
- Regardless of the initiation mechanism, there is always a transient period (and this may be part of the theory your testing!).
  - Seen as a circuit, the plasma becomes a load that have variable resistance, and may have significant capacitance and or inductance.



Unmagnetized resistive plasma

UMBC



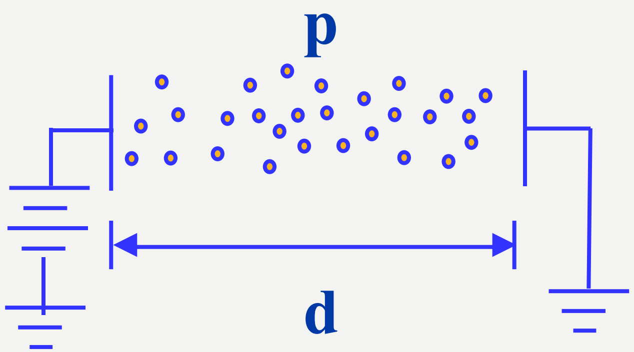
Magnetized plasma with variable capacitance
Centrifugal Mirrors

UMBC, UMD

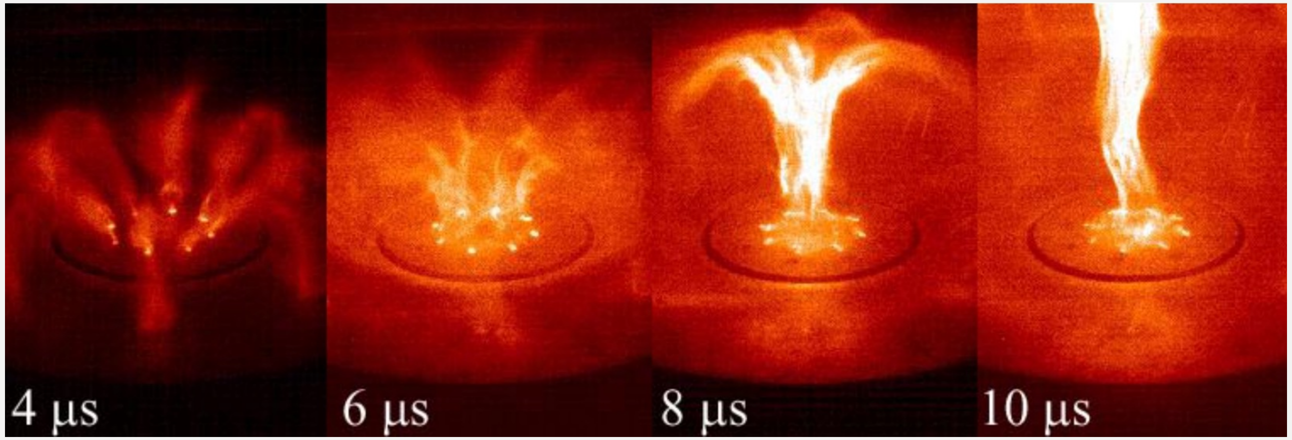
Magnetized plasma with variable inductance

P. M. Bellan, Caltech

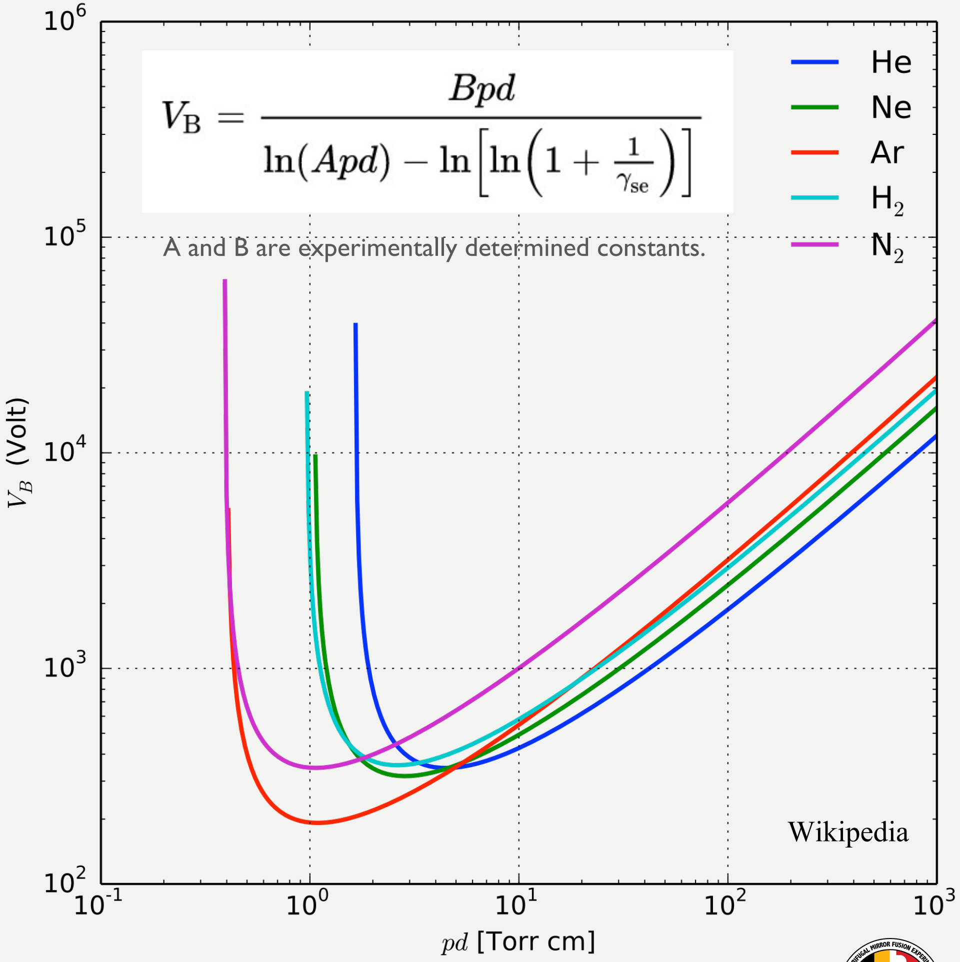
PASCHEN BREAKDOWN



- For high voltage breakdown, Paschen breakdown is a good guideline.
- Semi-empirical relation adjuted to each gas.
- If you stay to the left of the Paschen curve, can use this as electrical insulation criterion!
- If magnetic fields are present, the length along field lines is used.



S. You, G. S. Yun, and P. M. Bellan, Phys. Rev. Lett. **95**, 045002 (2005)

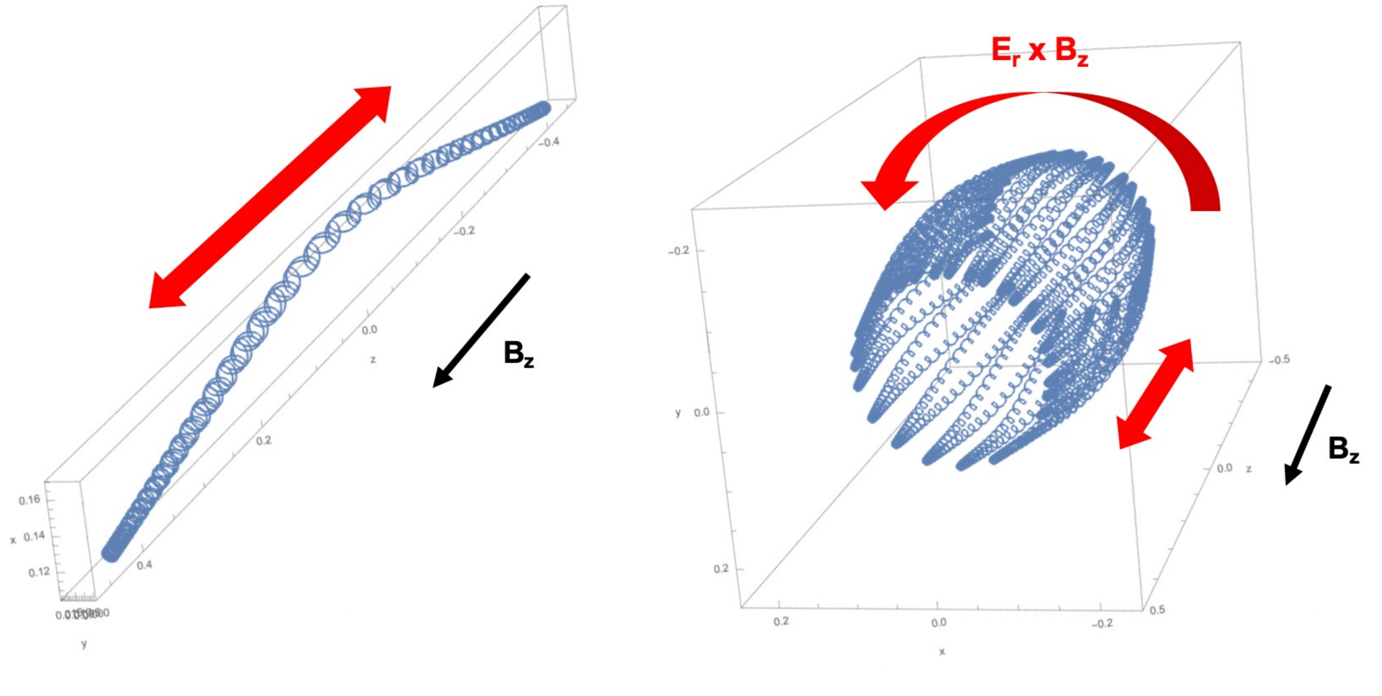


E x B DRIFTS AND CENTRIFUGAL CONFINEMENT

- We start from the principle of E x B drifts: If we apply a radial electric field, E_r, to a magnetic mirror with magnetic field nominally in the axial direction, B_z, then we get an azimuthal velocity in particles,

$$v_\phi = \frac{E \times B}{B^2}$$

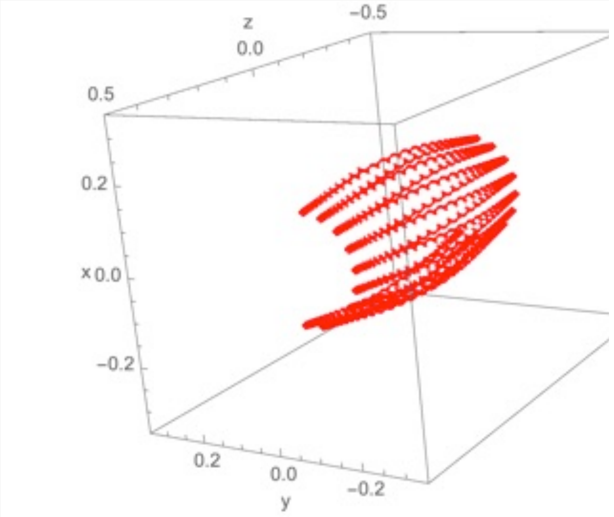
- For the same starting particle energy, the bounce length for a particle with ExB drift is less than without.
  - The loss cone is smaller!



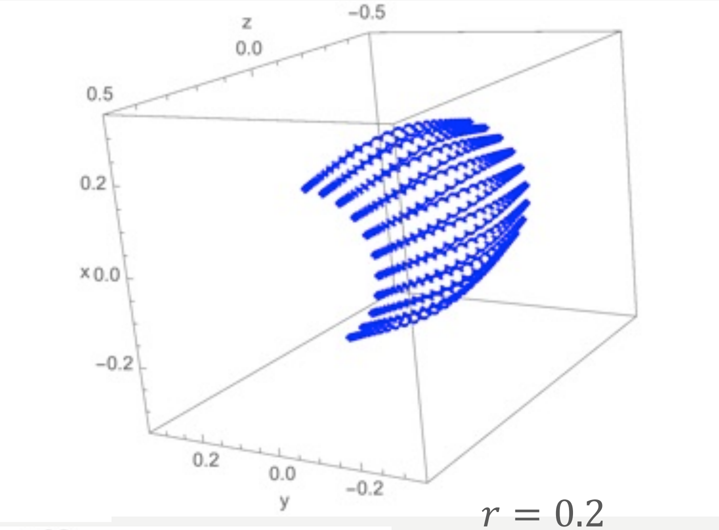
Mirror without rotation **Mirror with E_r and rotation**

SINGLE PARTICLE SOLUTIONS HINT AT SHEARED FLOW

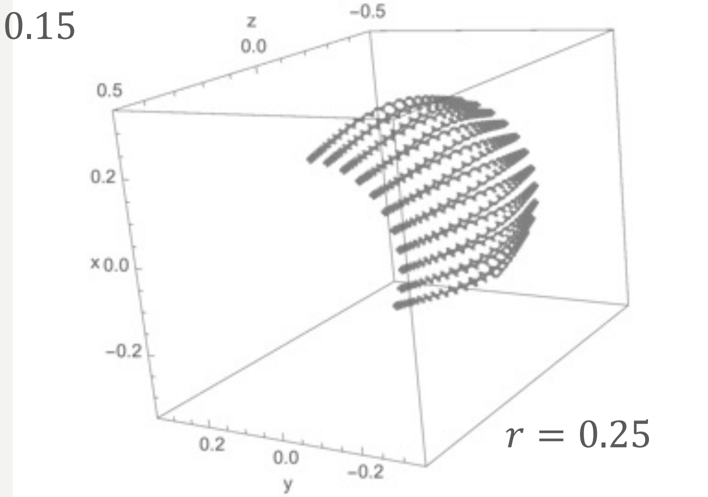
All particles start with the same initial $v_{||}$ and $v_{\perp}$ and the z location



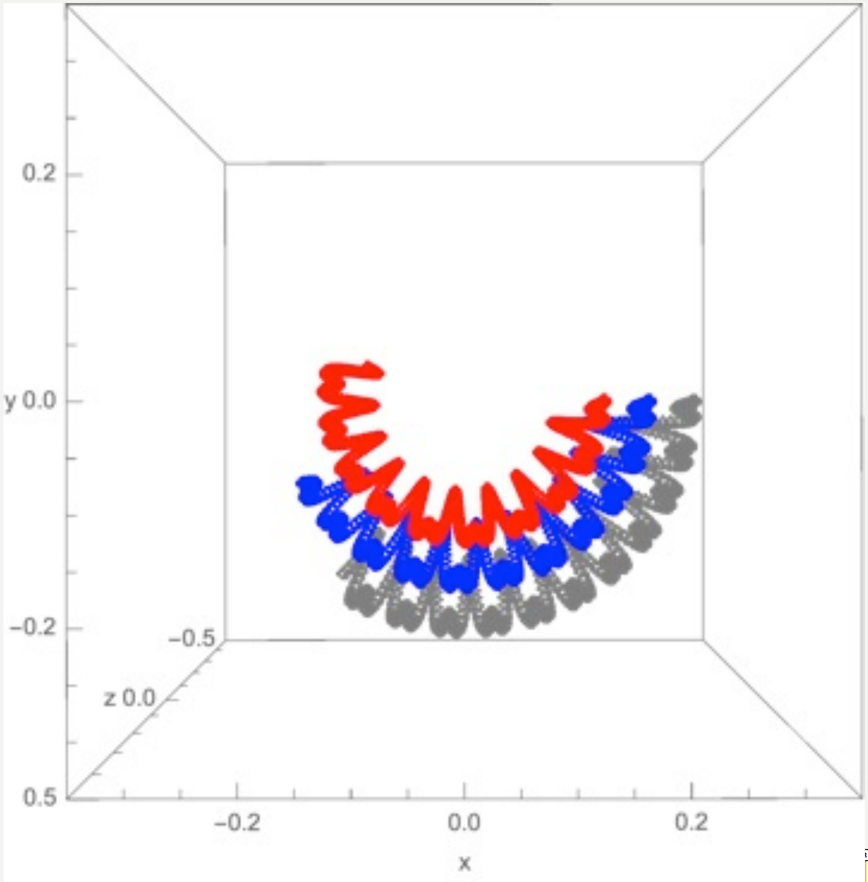
$r = 0.15$



$r = 0.2$



$r = 0.25$



MHD MODEL OF CENTRIFUGAL MIRRORS

- The equilibrium equation that we start with is

$$nM\left(\frac{\partial \mathbf{u}}{\partial t}+\mathbf{u}\cdot\nabla\mathbf{u}\right)=-\nabla p+\mathbf{j}\times\mathbf{B}-nM\left(\nu_{in}\mathbf{u}-\mu_{\perp}\nabla^2\mathbf{u}\right)$$

where n is number density, M is particle mass, p is pressure, ν_{in} is the ion-neutral collision frequency,

- Let's first assume that the configuration is in steady state, then $\frac{\partial}{\partial t}\to 0$
- In cylindrical coordinates, let's look at the radial direction components:

$$nM\left(\mathbf{u}\cdot\nabla\mathbf{u}\right)_{\psi}+\nabla p_{\psi}=\left(\mathbf{j}\times\mathbf{B}\right)_{\psi}-nM\nu_{in}u_{\psi}$$

- For now, let's assume that radial flows are small compared to azimuthal flows, $u_{\psi} << u_{\varphi}$, so we can neglect the rightmost term. With this assumption, we now can express the velocity as:

$$\mathbf{u} = R\Omega\hat{\phi}$$

$$\mathbf{u}\cdot\nabla\mathbf{u} = R\Omega^2\nabla R=-\nabla\left(\frac{R^2\Omega^2}{2}\right)$$

- Replacing these velocity expressions into the radial components, we see that poloidal currents balance the radial pressure profile, as well as centrifugal force,

$$j_\phi B = \frac{nMR^2}{2}\nabla_\psi(\Omega^2) + \nabla_\psi p$$

- The radial current balances the angular momentum lost to neutral collisions and viscous dissipation,

$$(\mathbf{j}\times\mathbf{B})_\phi = j_\psi B = nM\left(\nu_{in} - \frac{\rho_i^2\nu_{ii}}{a^2}\right)u_\phi$$

- If we perform a volume integral on the above expression,

$$B\int_{Vol} j_\psi \, d^3x = I_p B = \frac{NMu_\phi}{\tau_\perp}$$

with $\tau_\perp$ being the momentum confinement time: $\nu_{in} - \rho_i^2\nu_{ii}/a^2 = \tau_\perp^{-1}$

- Let's now take a look at the components along the magnetic field, by dotting with the steady state momentum equation with $\boldsymbol{B}$,

$$\mathbf{B}\cdot nM\left(\mathbf{u}\cdot\nabla\mathbf{u}\right) = -\mathbf{B}\cdot\nabla p + \overset{0}{\mathbf{B}\cdot(\mathbf{j}\times\mathbf{B})} - nM\mathbf{B}\cdot\left(\nu_{in}\mathbf{u} - \mu_\perp\nabla^2\mathbf{u}\right)$$

- Assuming now that axial flows are much smaller than azimuthal flows, $u_b/u_\phi << 1$, the dotted equation reduces to

$$nM\mathbf{B}\cdot(\mathbf{u}\cdot\nabla\mathbf{u}) = -\mathbf{B}\cdot\nabla p$$

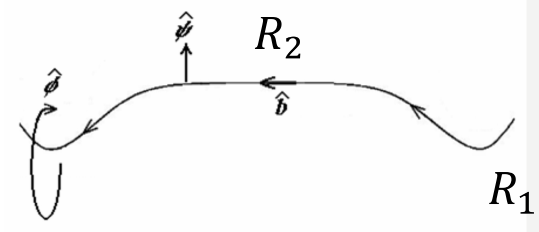
- Again replacing the velocity with term with $\mathbf{u} = R\Omega\hat{\phi}$ and $\mathbf{u}\cdot\nabla\mathbf{u} = R\Omega^2\nabla R = -\nabla\left(\frac{R^2\Omega^2}{2}\right)$

and assuming that any given flux surfaces is isothermal (and recall $p = nT$, with T in eV).

$$\frac{\mathbf{B}\cdot\nabla n}{n} = \frac{M}{2T}\mathbf{B}\cdot\nabla(R^2\Omega^2) = \mathbf{B}\cdot\nabla\left(\frac{R^2\Omega^2}{2c_s^2}\right)$$

with $c_s = \sqrt{T/M}$ as the sound speed. We can now integrate and evaluate in R_1 and R_2,

$$\frac{p_2}{p_1} = \exp\left[\frac{1}{2}\frac{(R_2^2 - R_1^2)\,\Omega^2}{c_s^2}\right]$$



- Define the sonic Mach number as $M_s = \frac{v_\phi}{c_s} = \frac{R\Omega}{c_s}$ we can rewrite the above expression:

$$\frac{p_2}{p_1} = \exp\left[\frac{M_s^2}{2}\left(1 - \frac{R_1^2}{R_2^2}\right)\right]$$

- It is not practical to obtain R_1 or R_2, but we know B_{max} and B_{min}
- The shape of magnetic field is given by the flux profile along the magnetic field, then for B_{min} and B_{max} we have for any given flux surface, the flux is the same along at both places

$$B_{min}\pi {R_2}^2 = B_{max}\pi {R_1}^2$$

- Let's define the mirror ratio as $R_M = \frac{B_{max}}{B_{min}}$, so we can write

$$\frac{B_{min}}{B_{max}} = \frac{{R_1}^2}{{R_2}^2} = \frac{1}{R_M}$$

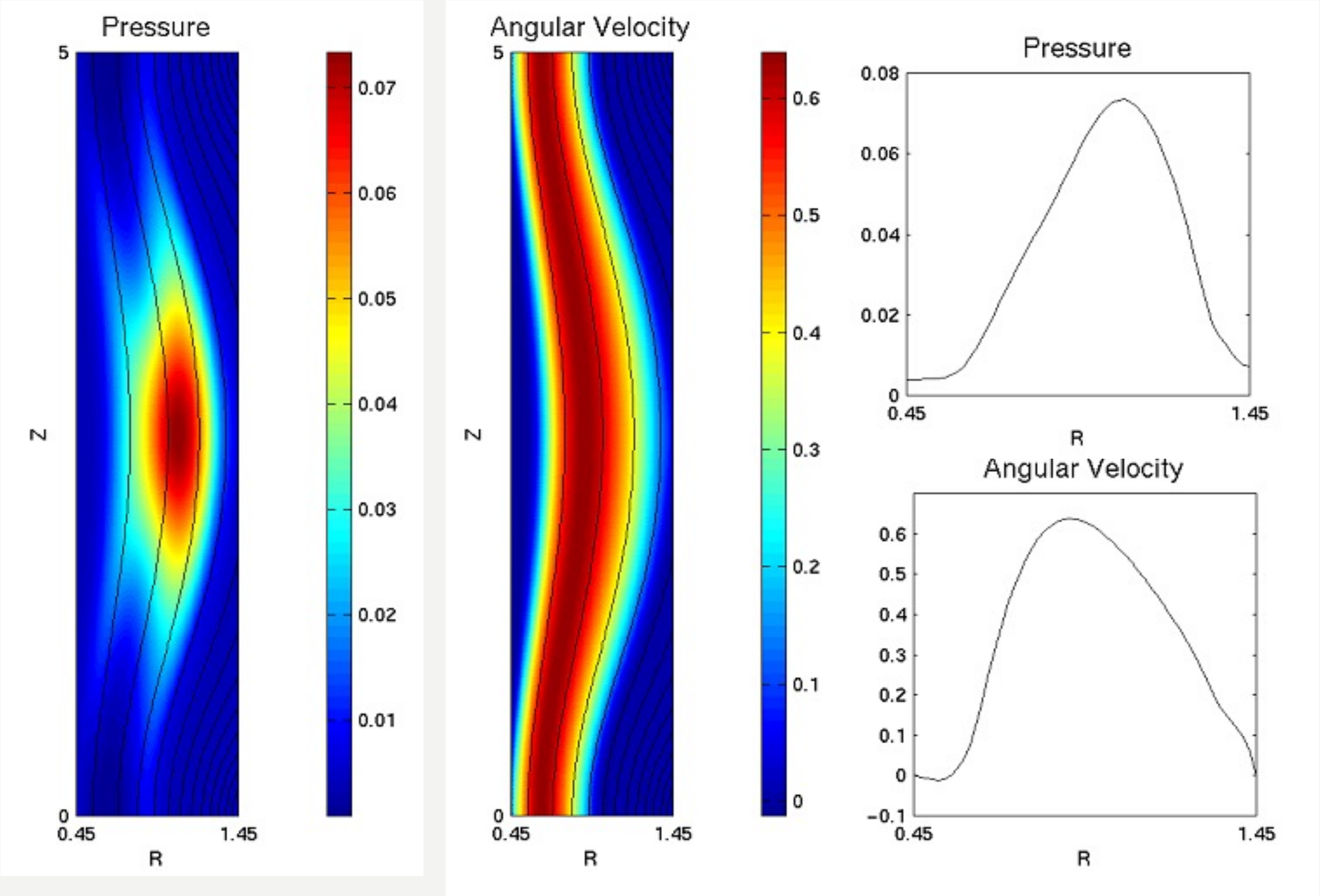
- The integrated expression can be re-written as

$$\frac{p_{\mathrm{Mid}}}{p_{\mathrm{End}}} = \exp\left[\frac{{M_s}^2}{2}\left(1 - \frac{1}{R_M}\right)\right]$$

- Showing that a high mirror ratio, and fast plasma rotation, effectively closes the mirror loss cone.

MHD SIMULATIONS SHOW HALLMARKS OF CENTRIFUGAL CONFINEMENT

- The pressure is concentrated in midplane.
  - Peaked axially, as well as radially.
- At any given flux surface, the rotation velocity is the same.
  - Across flux surfaces, the rotation velocity is sheared.

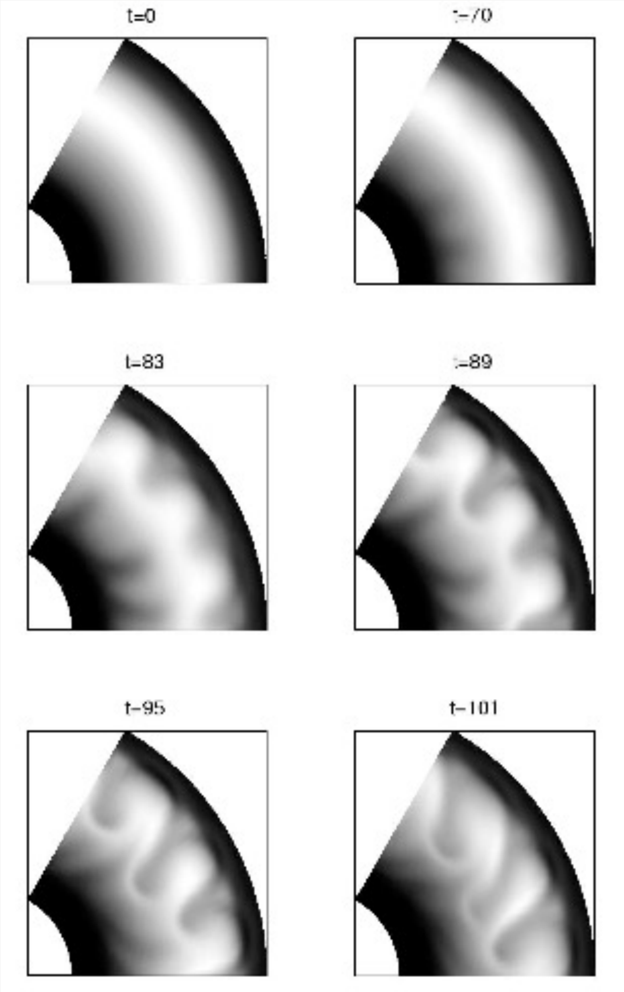


Yi-Min Huang and A. B. Hassam, PRL **87**, 235002 (2001)

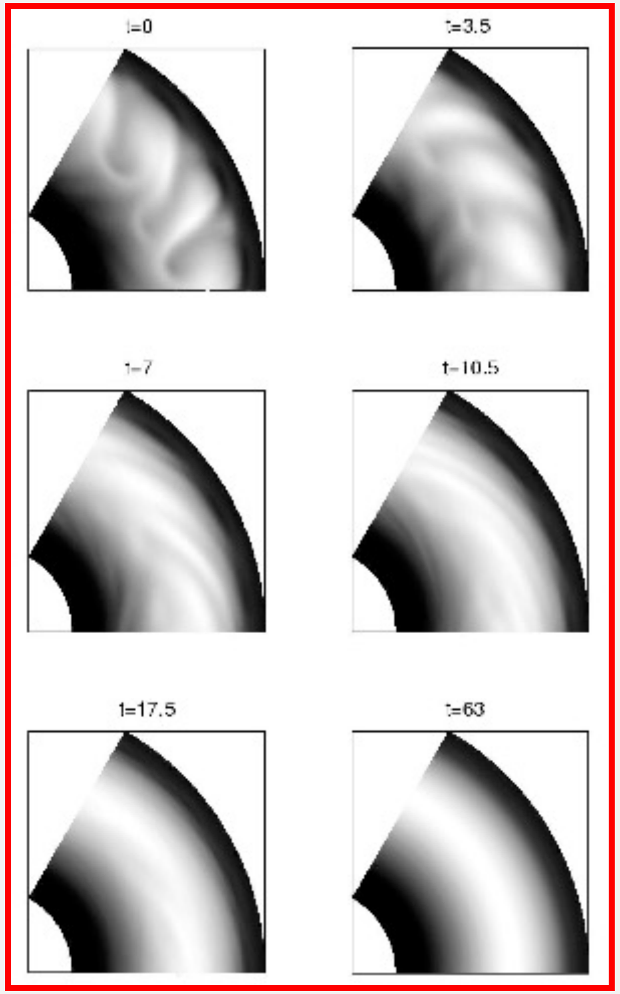
INTERCHANGE STABILIZATION

- If the rotation is supersonic, possible to stabilize against interchange modes.

Mirror without rotation



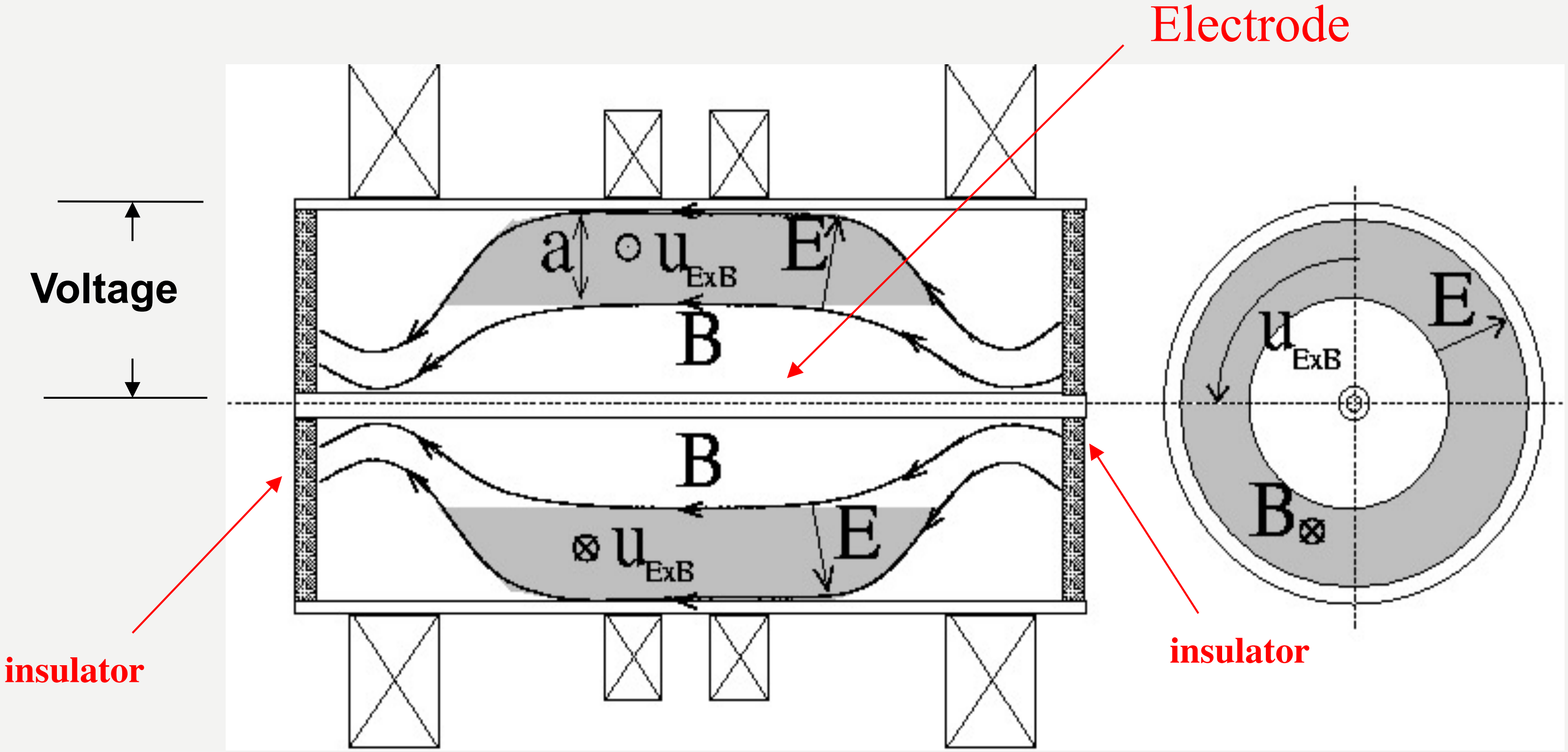
Mirror with rotation



Yi-Min Huang, “Magnetohydrodynamic equilibrium and stability of centrifugally confined plasmas” Ph.D. Thesis, University of Maryland, p.p. 25-28 (2004).

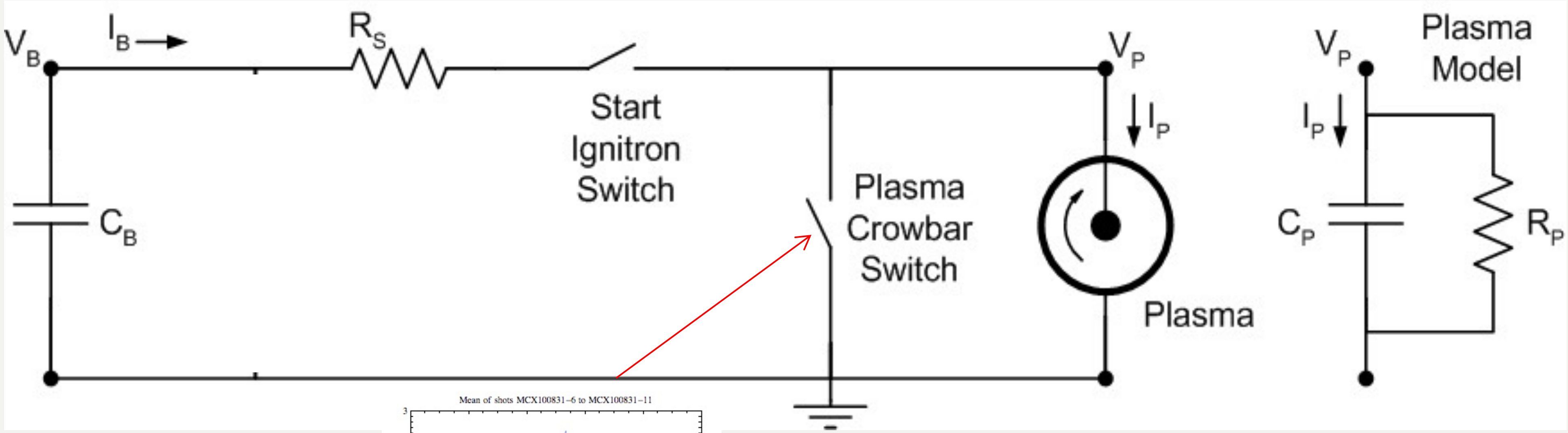
HOW TO IMPOSE THE ROTATION?

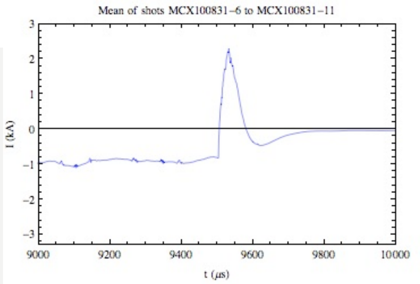
- A practical mirror requires a biased center conductor to impose a radial electric field, and insulators to prevent flux surfaces from being shorted.



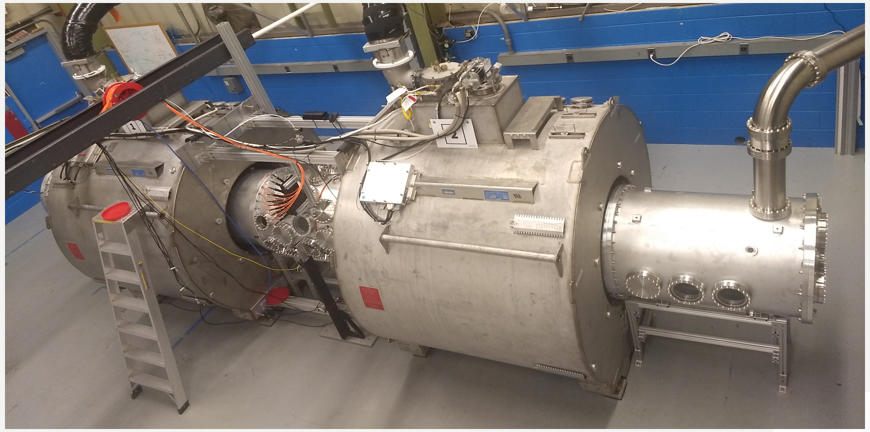
HOW TO POWER THE DISCHARGE?

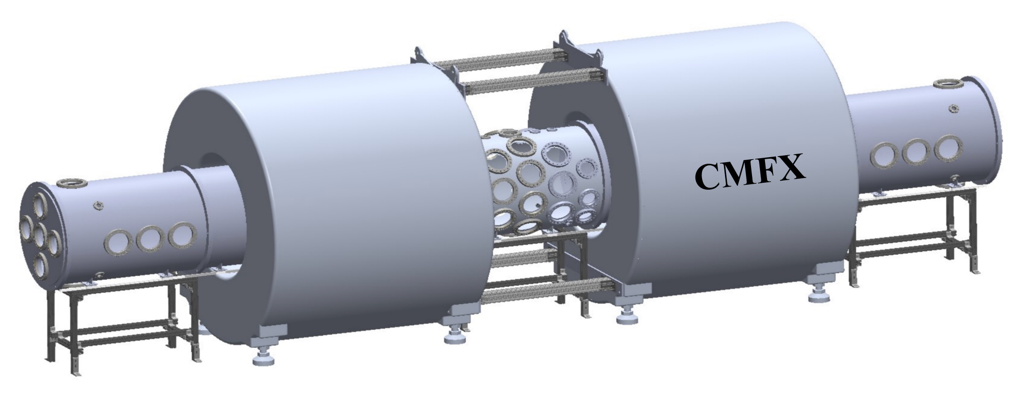
- A simple discharge circuit can be used with a capacitor bank (or a DC power supply) to drive the plasma
- Plasma is modeled as a resistor in parallel with a capacitor.

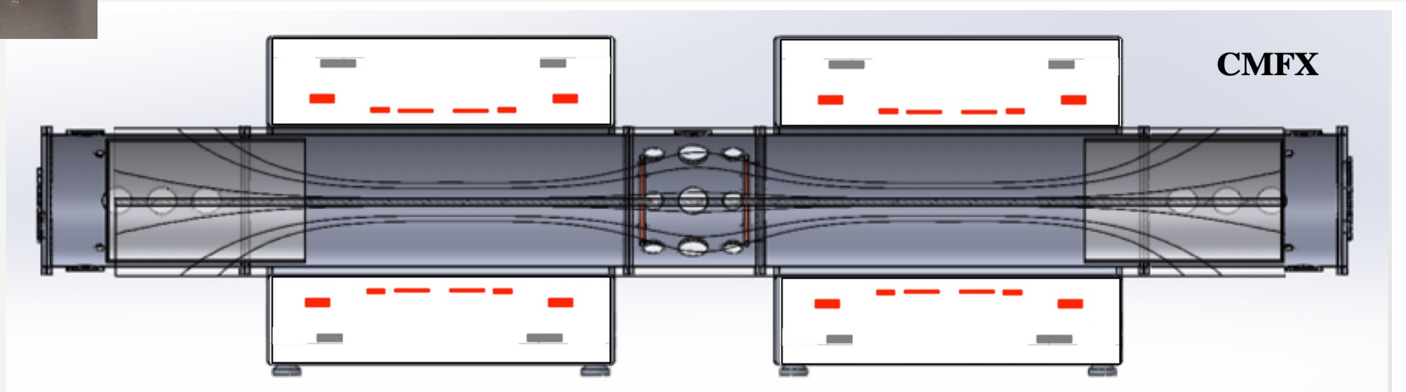




THE CENTRIFUGAL MIRROR FUSION EXPERIMENT, CMFX 2020 - PRESENT

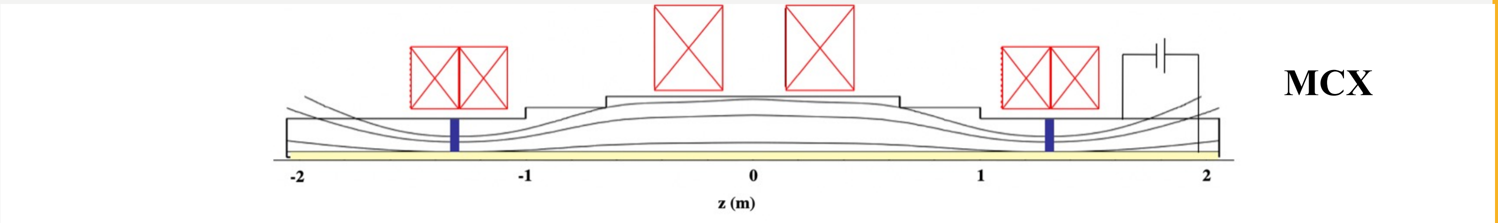






CMFX Improvements:

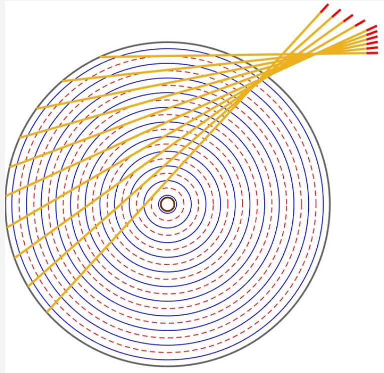
- Stronger mirror and midplane fields. Superconductors.
- Higher applied voltages.
- Reduced plasma/surface interactions.
- Density control

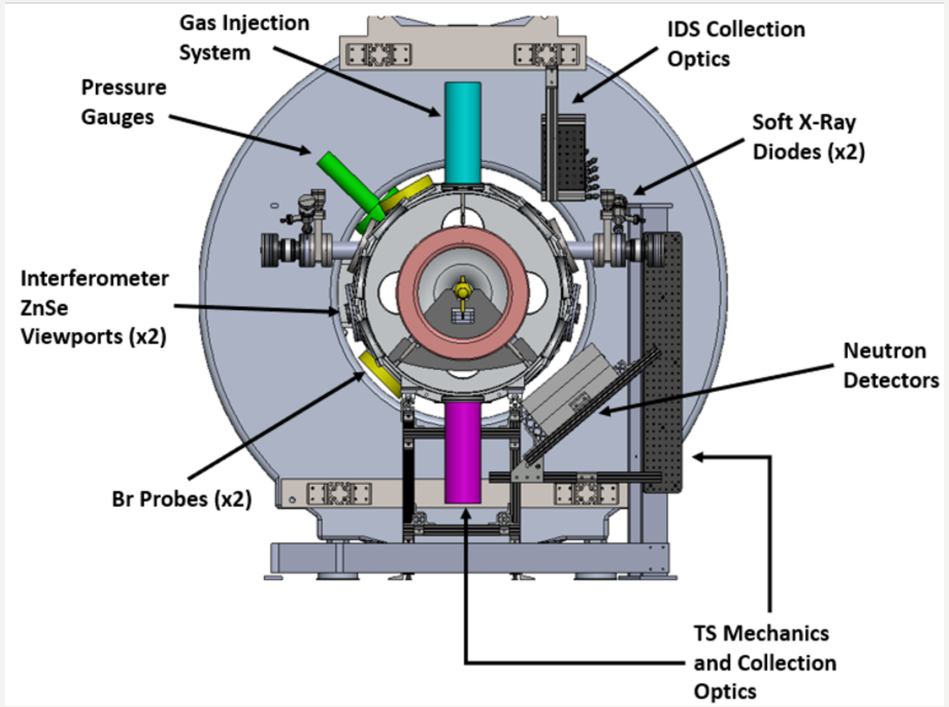


CMFX DIAGNOSTICS

- Plasma voltage and current
  - Crowbar
- Ion Doppler Spectrometry
- Diamagnetic Loops
- B_r Probes
- RGA and Fast Ion Gauges
- Neutron Detectors
- Density Interferometer

Under design/construction:
- Soft X-ray Diodes
- Thomson Scattering





Center (Midline) Ports: Z = 0 cm

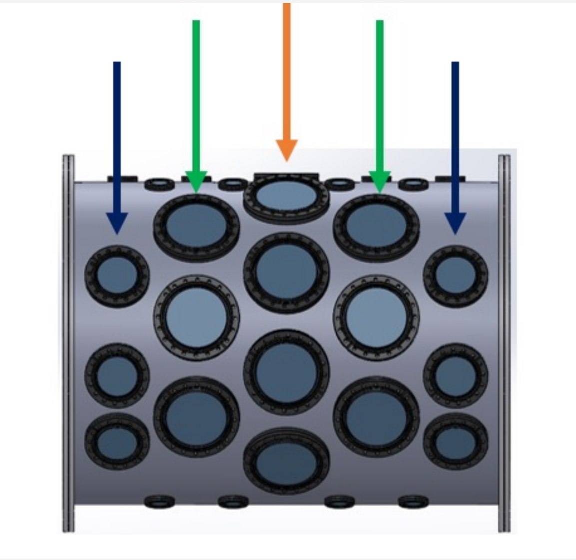
- Measurements available for y = 3-31 cm radially

Middle Ports: Z = +- 21 cm

- Measurements available for y = 3-31 cm radially

Edge Ports: Z = +- 40 cm

- Measurements available for y = 3-26 cm radially

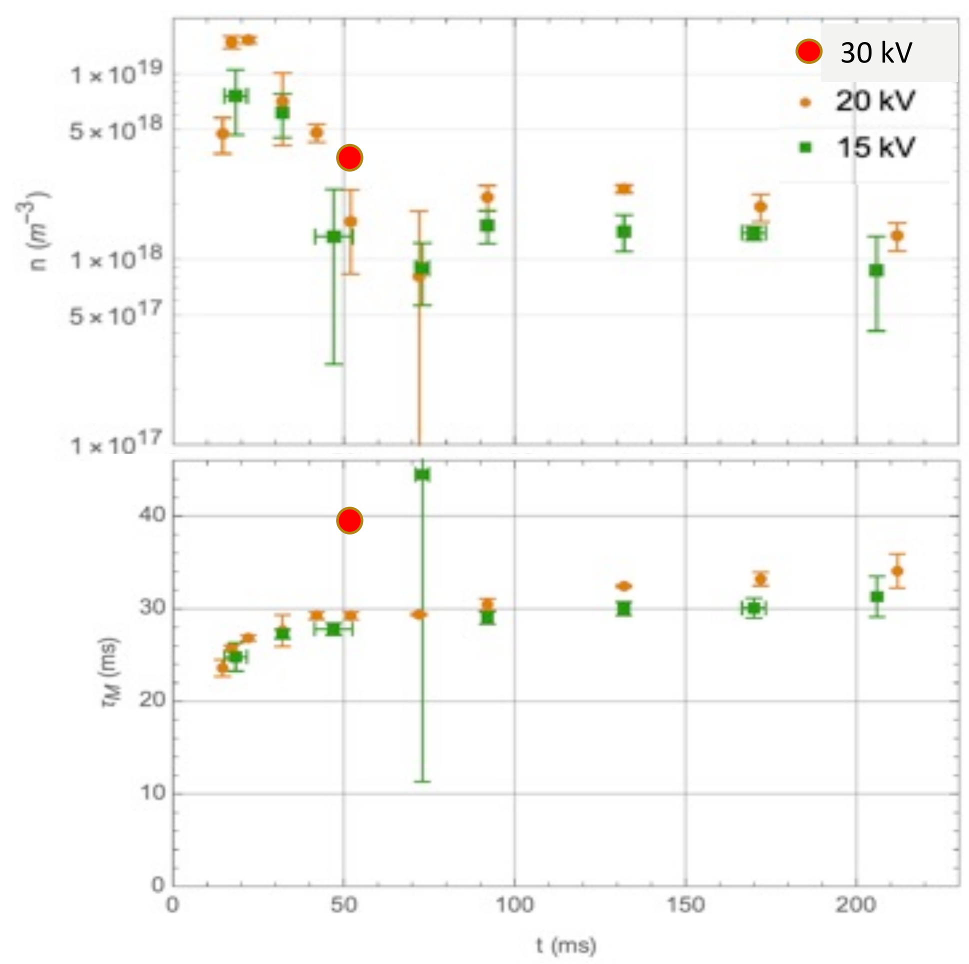


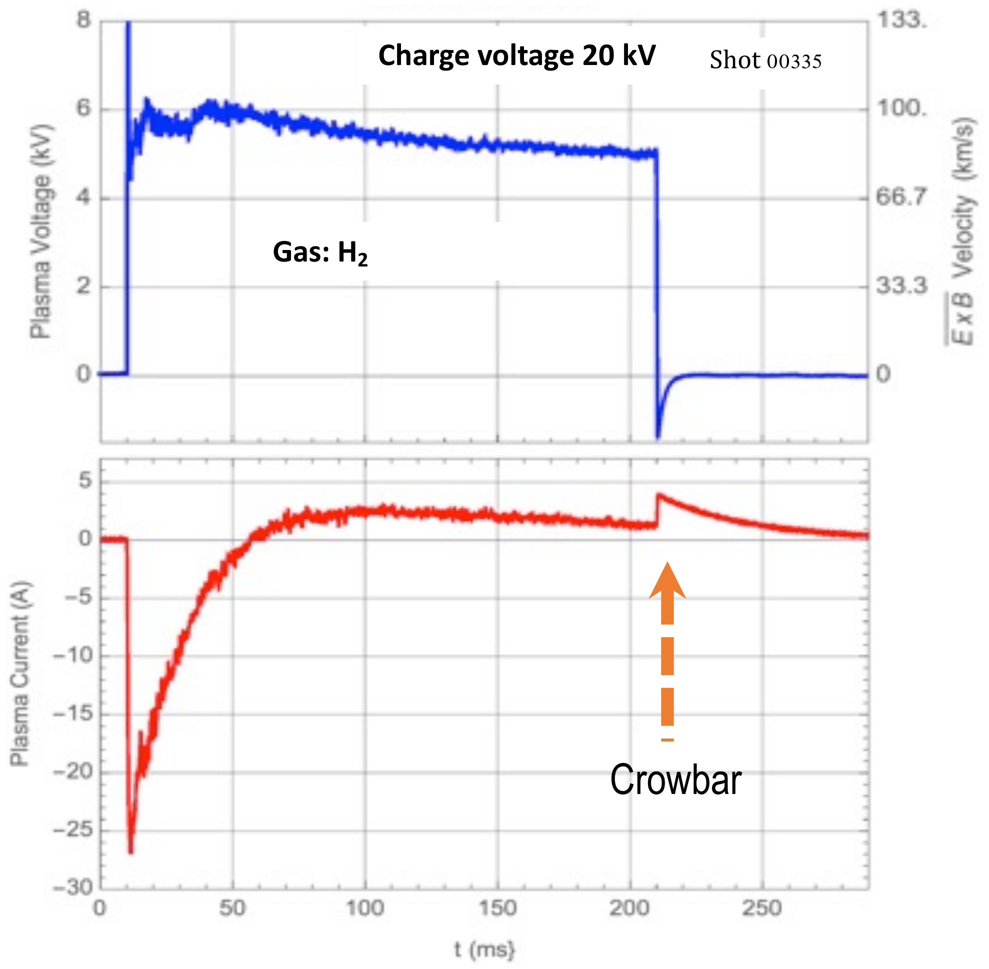
DENSITY AND τ_M FROM CROWBAR

- The centrifugal mirror behaves like a capacitor.
- The crowbar switch directs any stored energy to ground.
- The rate of decay, $\boldsymbol{\tau}$, is the $\boldsymbol{R_p C_p}$time of the capacitor, measured as one e-fold time from the current.
  - We know $\boldsymbol{R_p = V_p/I_p}$, so $\boldsymbol{C_p = \tau/R_p}$.
    - *Alternatively, we can integrate the power after crowbar and obtain* $\boldsymbol{C_p}$ *from* $\boldsymbol{\frac{1}{2} C_p {V_p}^2}$.
  - We also know the total charge stored in the plasma capacitor $\boldsymbol{Q = V_p\, C_p}$
  - So the number density is **n =** $\boldsymbol{Q}$**/Vol.**
- Assuming all the rotation damping is from collisions and charge exchange with neutrals, then $\boldsymbol{\tau_M = R_p C_p}$. [1]

[1] Ellis, RF; Hassam, AB; Messer, S; et al. Phys. Plasmas **8**, 2057 (2001)

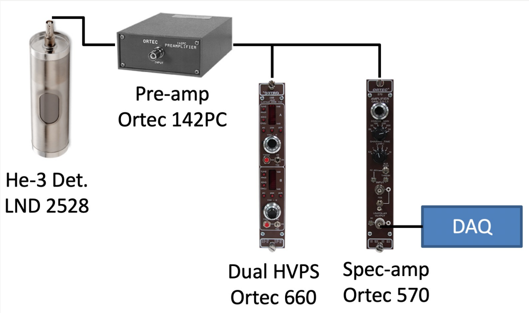
LONG PULSE AND HIGH τ_M

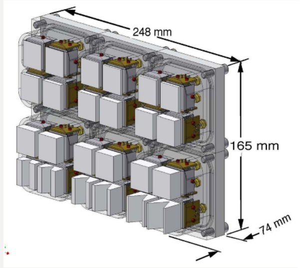


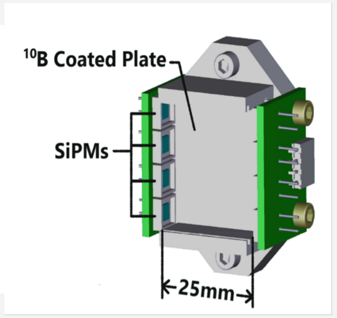


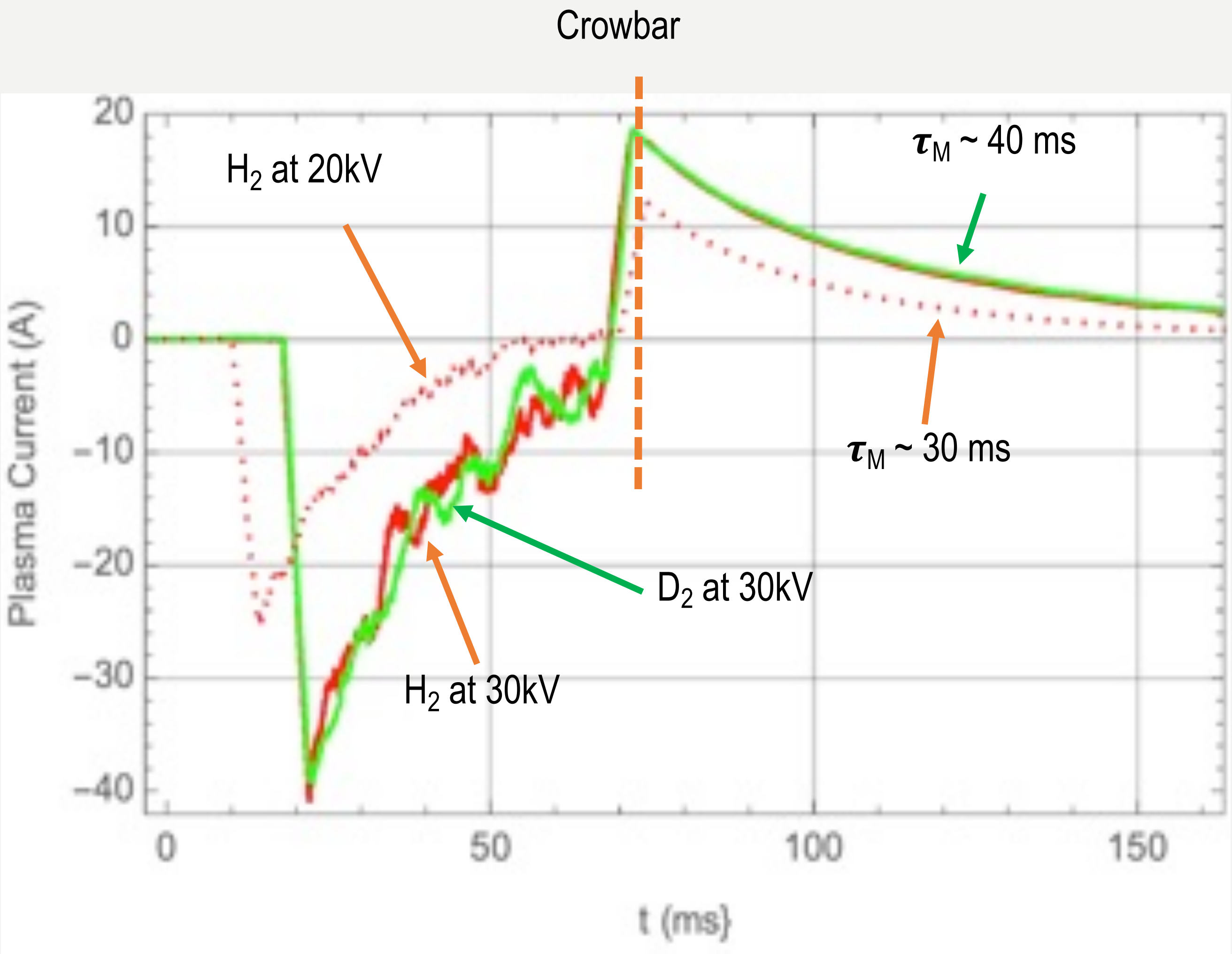
FIRST EXPERIMENTS WITH D_2 PLASMAS

- First experiments with D_2 indicate that discharge characteristics are similar to those with H_2.
- We are now testing the neutron detectors.







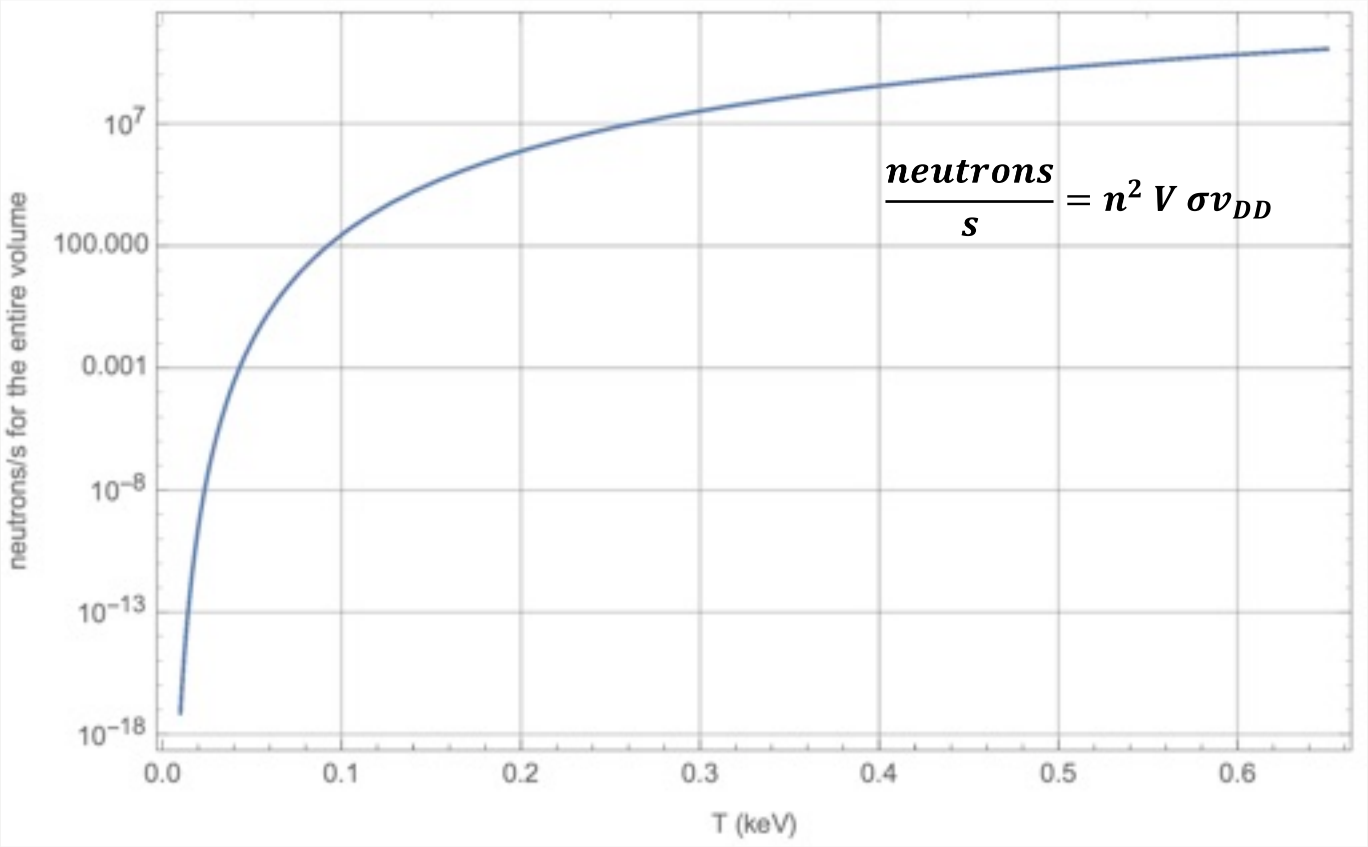


NEUTRONS AS A DIAGNOSTIC

- Using the well known reaction cross section vs temperature, for DD reactions, and if density is known, possible to get a 'ball park' estimate for T_i
- The assumed plasma volume is ~ 10^6 cm^3 and the assumed density is ~ 1×10^{19} cm^3.
- Neutronics for a (most likely) hollow cylinder volume is work in progress.
  - However, if neutrons come from a point source, a total yield of 10^7 neutrons gives about 10^4 neutrons at the ^{3}He detector location.

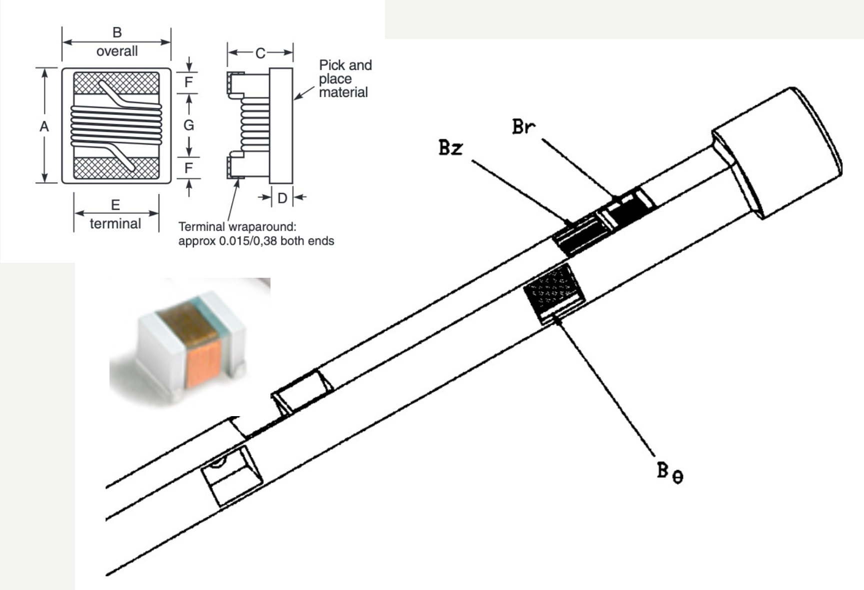
Formulae from NRL Plasma Formulary 2019 (T in keV, up to 25 keV):

```
σvDD[T_] := 2.33*10^-14 T^-2/3 Exp[-18.76*T^-1/3]; (* cm^3/s *)
```



$$\frac{neutrons}{s} = n^2\, V\, \sigma v_{DD}$$

B-DOT PROBES



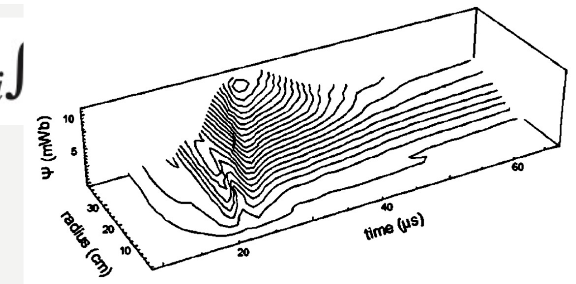
- Start with Faraday's induction principle: $\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$
- Integrate over the area of the coil, use Stoke's theorem to obtain $V = -d\Phi/dt$
- If the coil has N turns with area A, then $V = -NA(dB/dt)$
- To calibrate each winding, use a Helmholtz coil to obtain:

$$NA = \frac{a \int_{t_0}^{t} V_{\text{coil}}(t')dt'}{\left(\frac{4}{5}\right)^{3/2} \mu_0 n [I(t')]_{t_0}^{t}}$$

  where a, I(t), and n, are the Helmholtz coil radius, current, and number of turns, respectively.
- To calibrate an orthogonal cluster: $\mathbf{B} = \mathbf{C} \cdot \mathbf{B}_m$ where $\mathbf{B}_{m_i} = -1/NA_i \int$

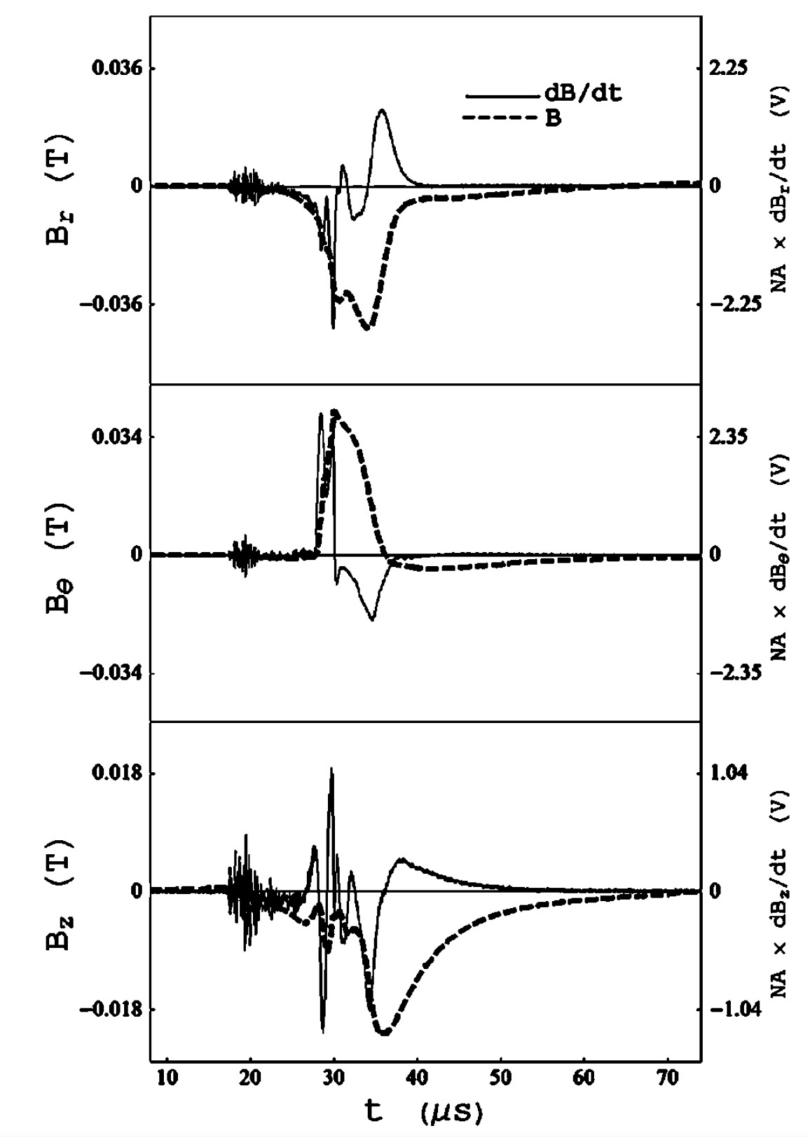
  and $C_{ij} = \frac{NA_j^{\text{perp}}}{NA_i}$ where

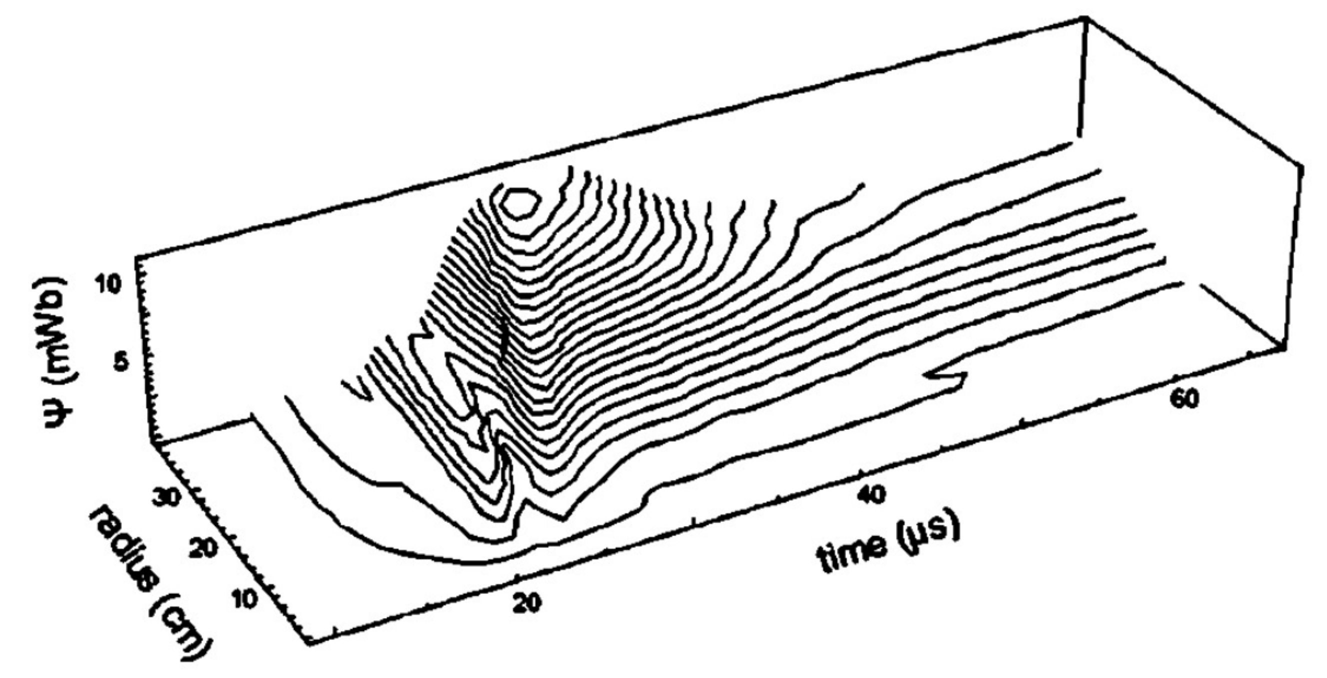
$$\mathbf{C} = \begin{pmatrix} 1 & -C_{R\theta} & -C_{RZ} \\ -C_{\theta R} & 1 & -C_{\theta Z} \\ -C_{ZR} & -C_{Z\theta} & 1 \end{pmatrix}$$



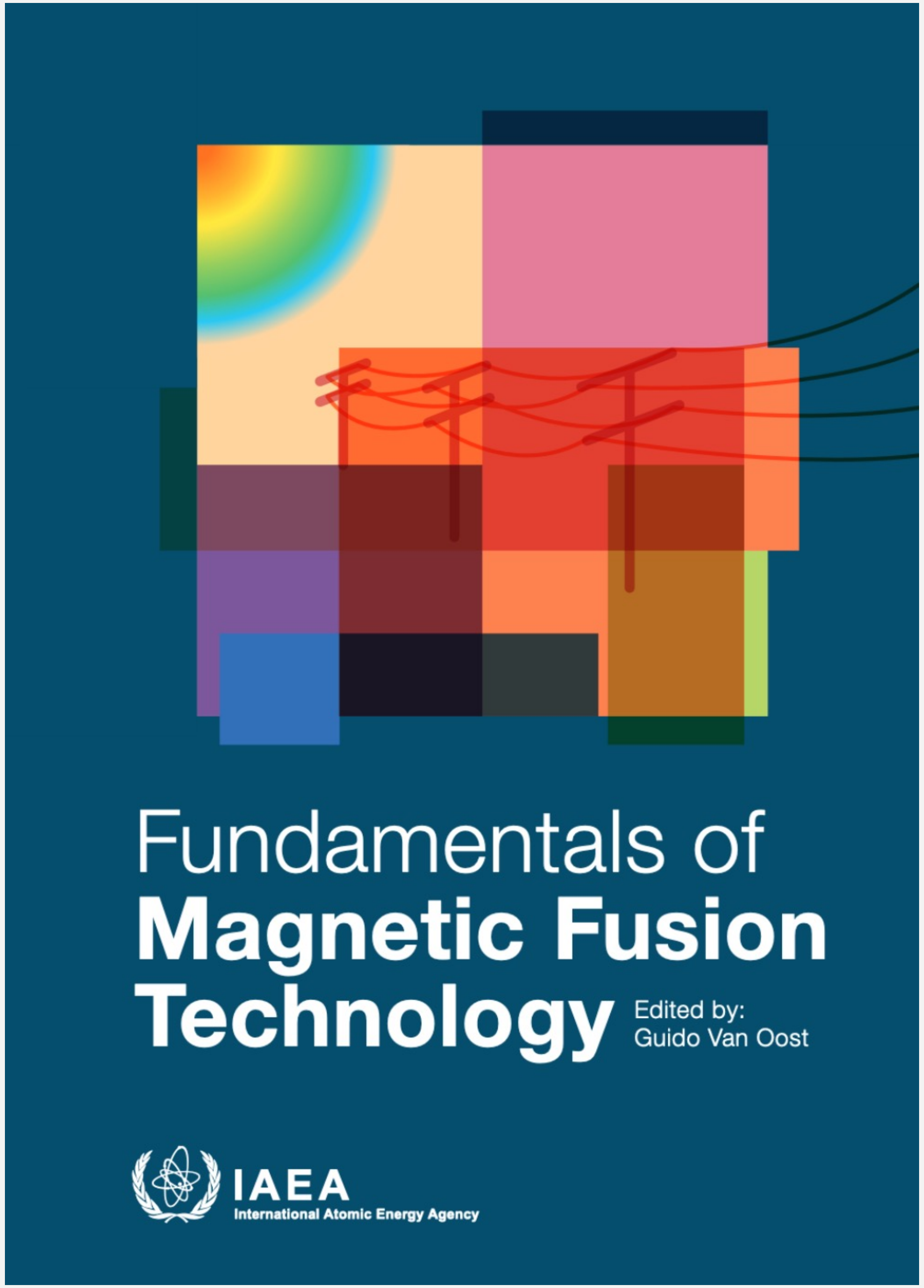
C. A. Romero-Talamás, P. M. Bellan, S. C. Hsu, Rev. Sci. Instrum., **75** (2004)

B-DOT PROBES (2)





C. A. Romero-Talamás, P. M. Bellan, S. C. Hsu, Rev. Sci. Instrum., **75** (2004)


Fundamentals of
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