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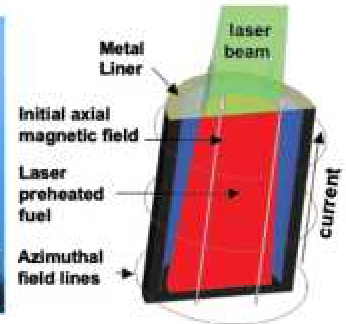

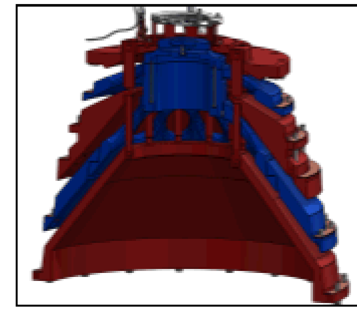

Reducing Convolute Loss in the Z Machine

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Sandia National Laboratories
August 18, 2014

Presentation Material Compiled from Slides from M. Gomez, C. Jennings, P. Miller, D. Coleman., M. Cuneo - Sandia National Laboratories

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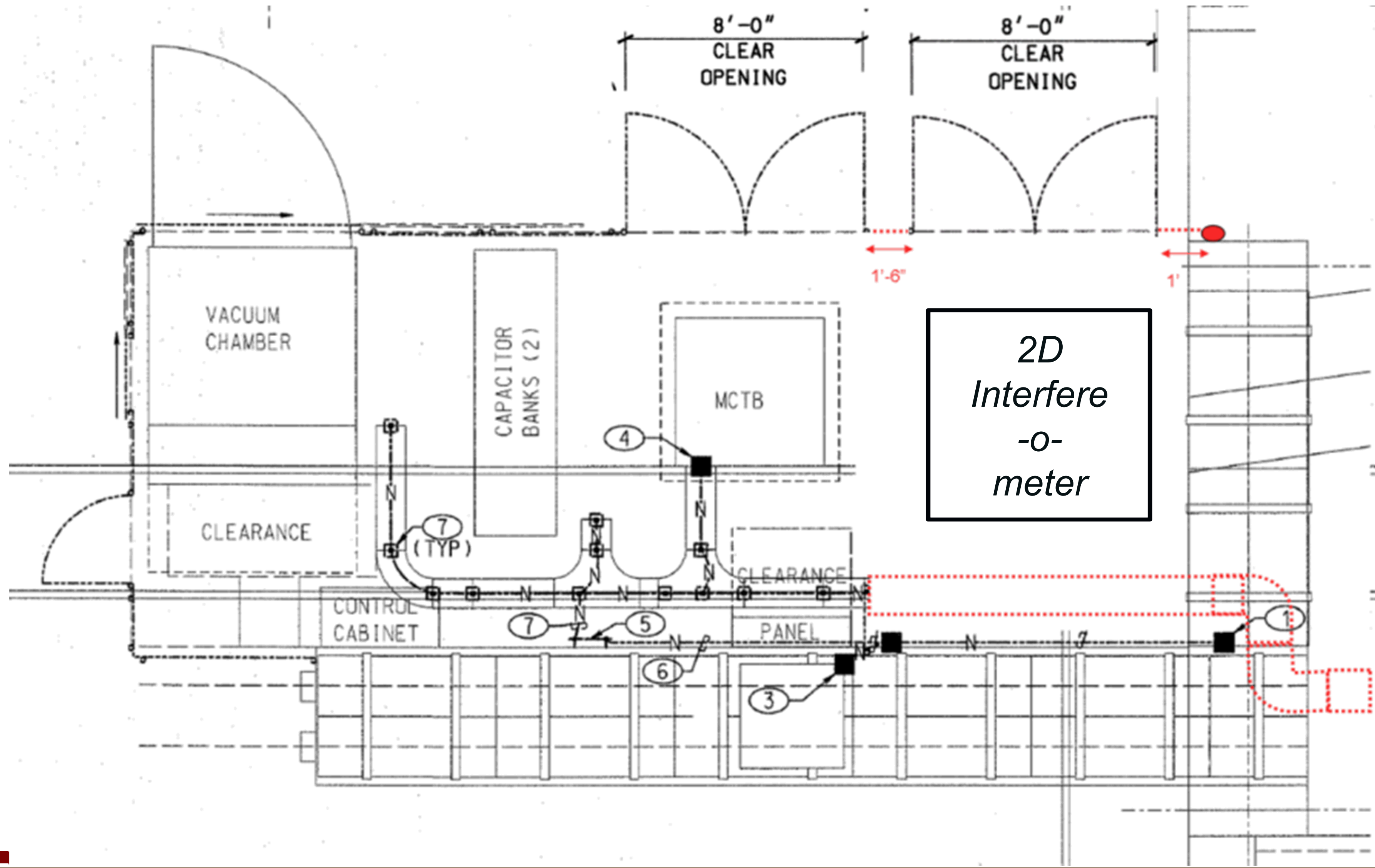
Who am I? Why am I standing here talking?

- In 2009, with the MagLIF concept on the horizon, SNL group 1680 needed a facility to develop and deploy new capabilities to the Z Machine
  - Support for MagLIF coil design as well as experimental testing
  - Facility floor plan was developed for testbed for coil testing
- In 2010, we were approached to accept the fledgling restart effort for a gas-puff capability on Z
  - AASC-developed nozzle + driver design and incorporate into Z
- Maturing these capabilities for Z required extensive engineering efforts, test campaigns, design reviews
- After installing and commissioning of each capability on Z, a need for continued shot support was apparent

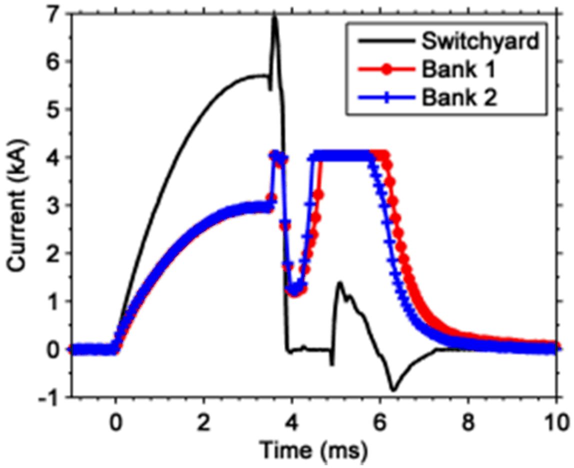
Systems Integration Test Facility, 2009

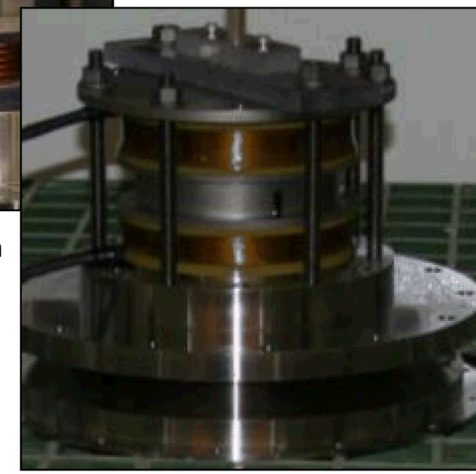


SITF (2014) is a developmental testbed for experimenters and load hardware production facility supporting the Z Machine

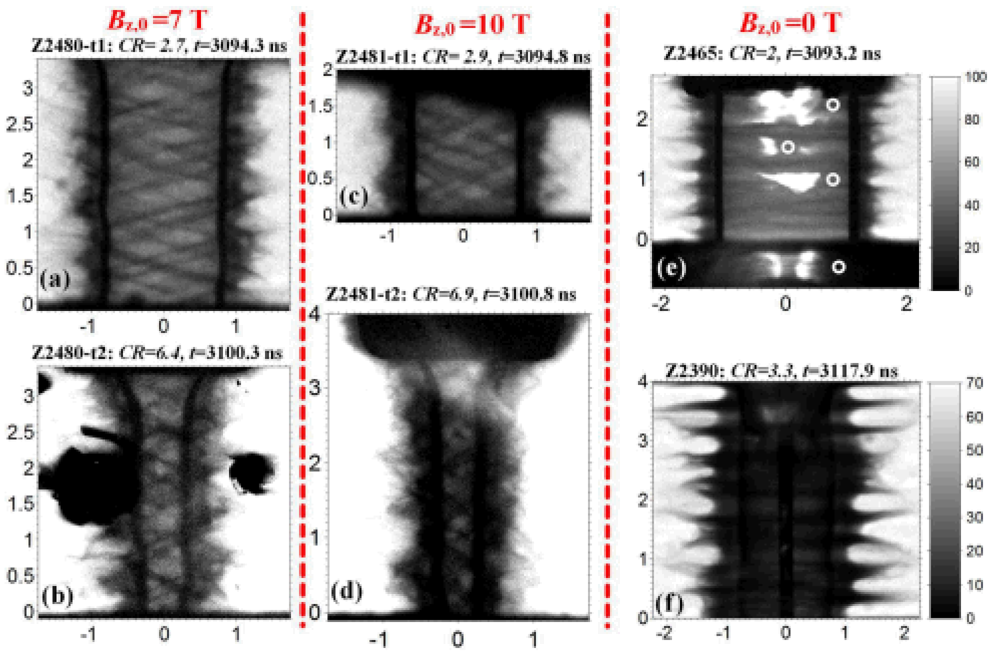
- 900kJ, 8mF capacitor banks
- Gas-puff driver, interferometer
- Cleanroom-like assembly station
  - Nozzle assembly
- Vacuum chamber
  - ~1e-7 torr
  - Can hold up to 4' MITL transitions
- Approved for clean storage of Z hardware

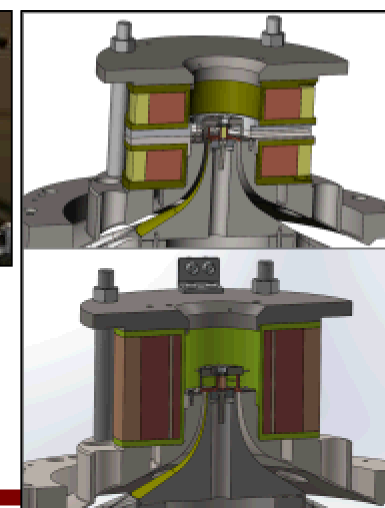
Applied Magnetic Field Capability





D. Rovang, et al., RSI manuscript in preparation





Awe, et al., Phys. Rev. Lett. 111, 235005

ABZ hardware on Z is not reusable

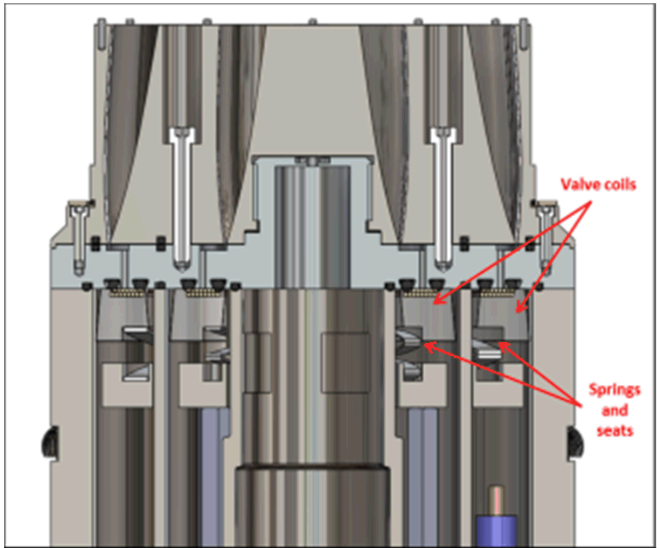
After

Before

Gas-puff Capability for Z Machine

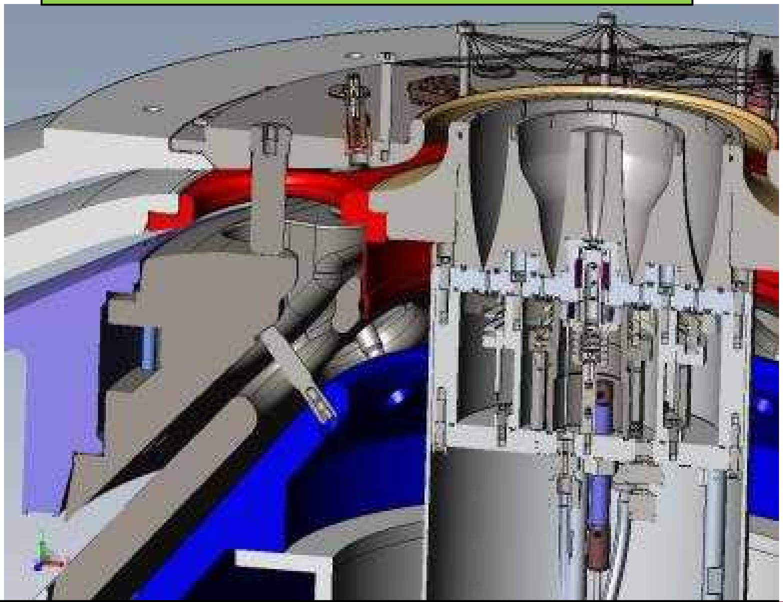
- Two- and three-plenum nozzles at 8cm (Ar) and 12cm (Kr) experiments for x-ray sources
- Deuterium gas-puffs on the horizon

8cm nozzle on Z



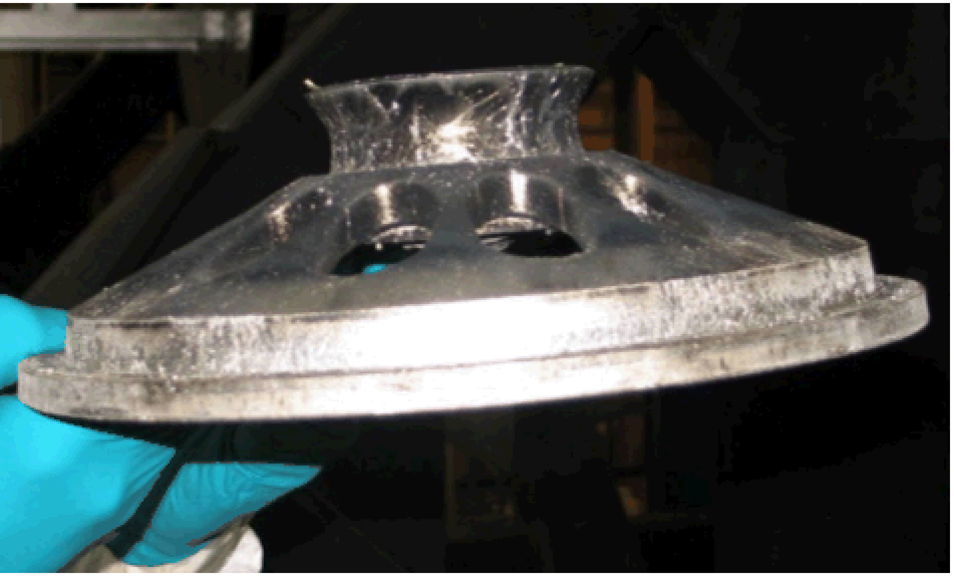
8cm nozzle cross-section (no CJ)

12cm nozzle on Z

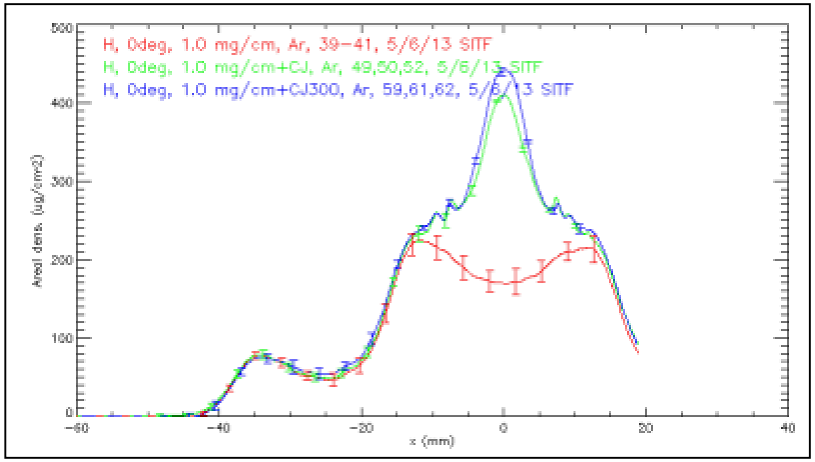


12cm nozzle, with 31cm convolute HW, (with CJ)

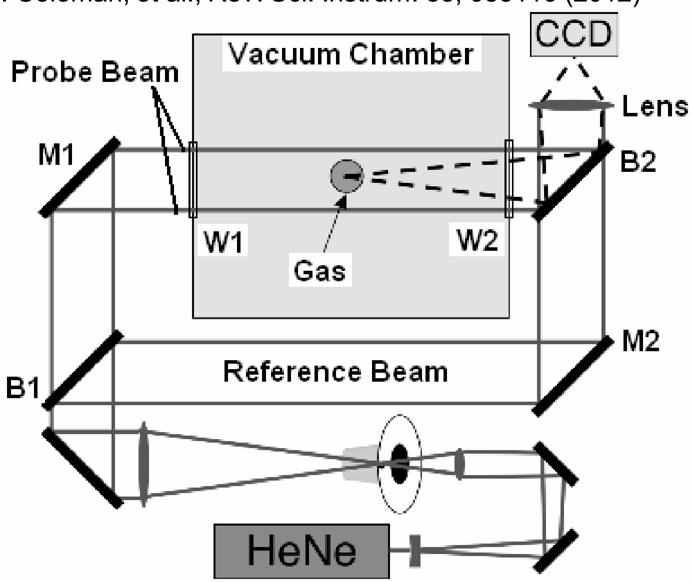
Gas-puff Hardware on Z is not reusable



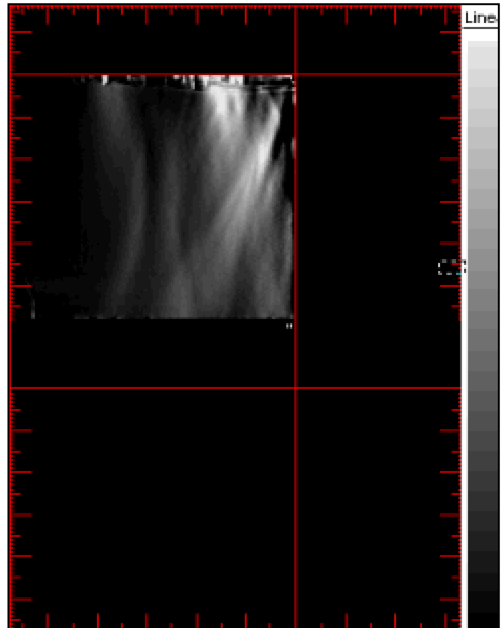
SITF Interferometer characterizes each gas-puff nozzle before delivery to Z



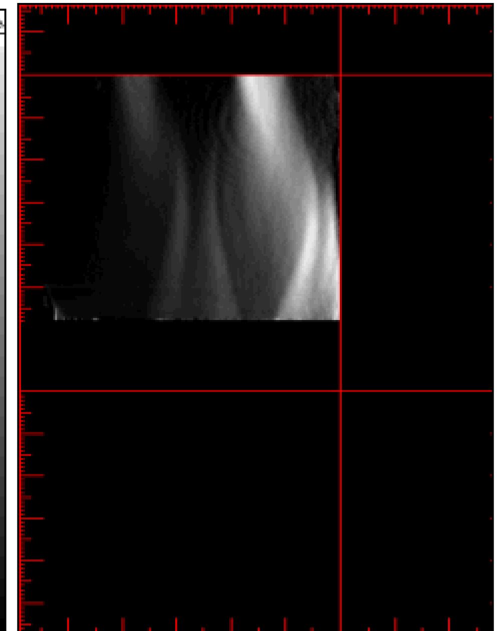
P.L. Coleman, et al., Rev. Sci. Instrum. 83, 083116 (2012)



Interferometer propagates 9cm beam through gas puff flow to measure puff density profilometry



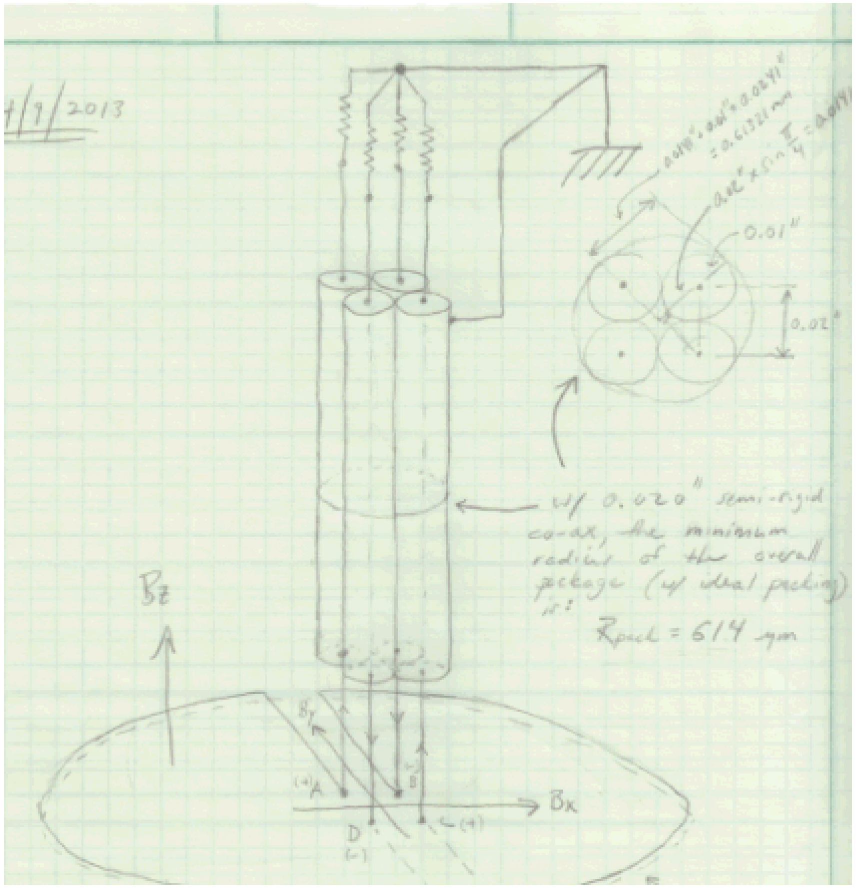
Abel-inverted density profile WITH wire grid (1:1.6 ratio)

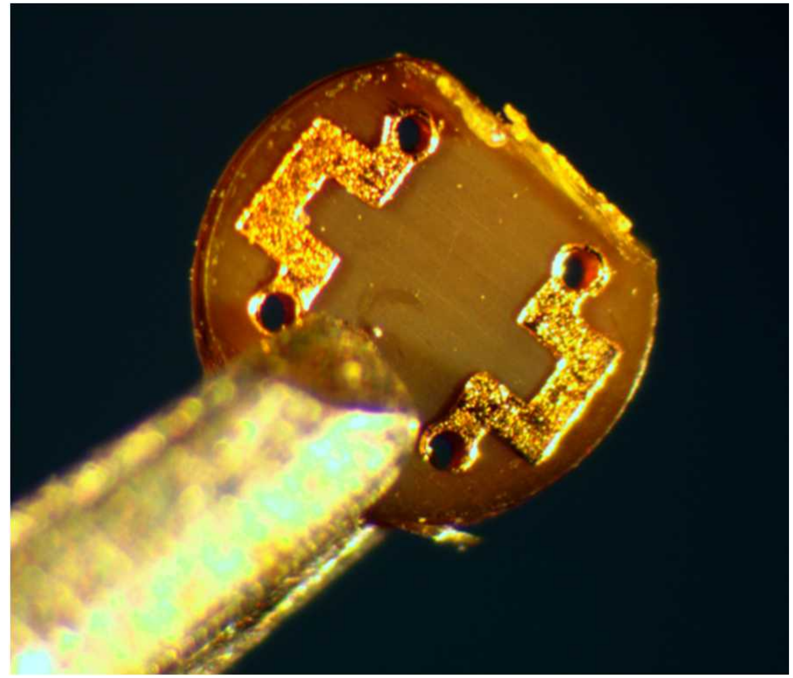


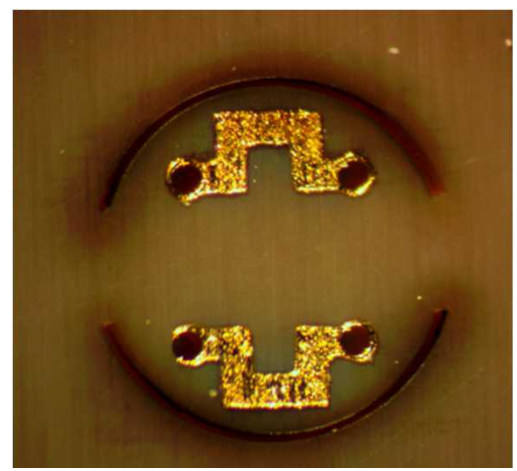
Abel-inverted density profile WITHOUT wire grid (1:1.6 ratio)

2D interferometer in clean room

On-axis B-dot development for flux compression LDRD





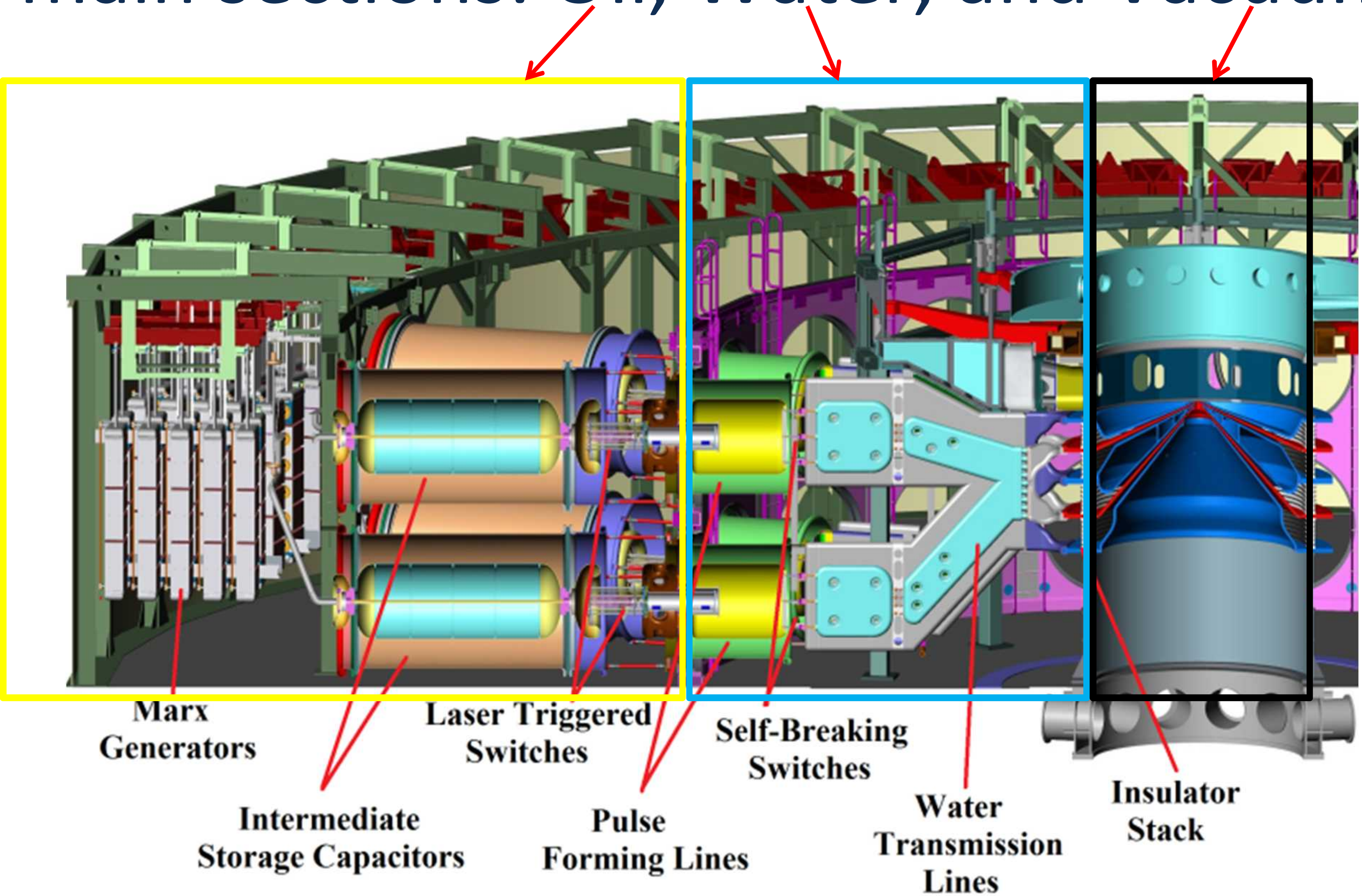


R. McBride Innovention

FY14-16 grand challenge LDRD has brought renewed interest to convolute loss

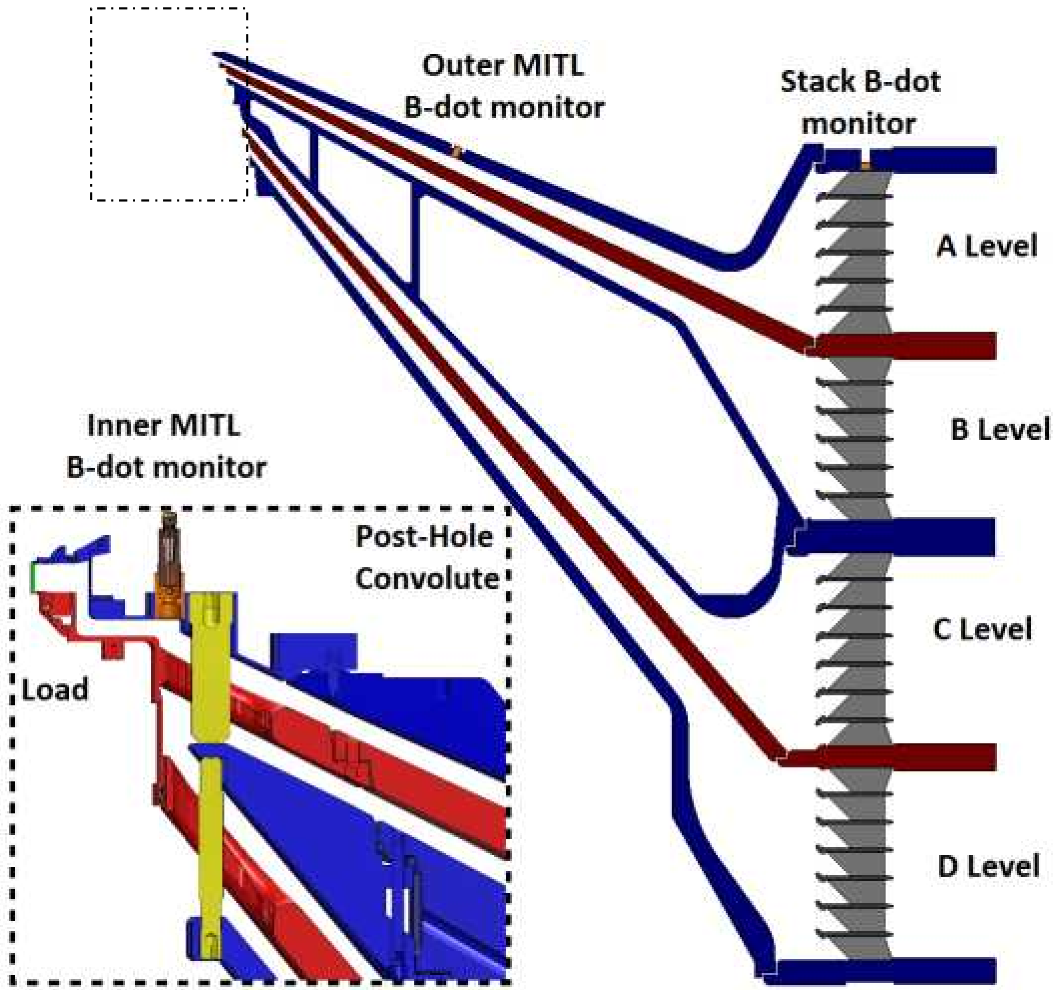
- The M. Cuneo-championed FY13 LDRD proposal netted prestigious grand challenge project extending from FY14 through 16
- LDRD Integrated Product Team (IPT) Task 3: “Current Loss Reduction”
- Multidisciplinary effort to understand and mitigate loss in Z convolute
  - Materials science – surface contamination on Z hardware during lifecycle
  - Renewed M&S and experimental efforts for convolute loss
    - Improved electrode cathode plasma model; micro-scale resolution; macro-scale sim
    - Use of surface coatings on anode power flow surface to explore gap closure from anode ion species
    - Pursue anode coating effect on Self Magnetic-Pinch diode setup Stinger
    - **Perform subscale experiments on intermediate facilities**

The Z accelerator consists of three main sections: Oil, Water, and Vacuum



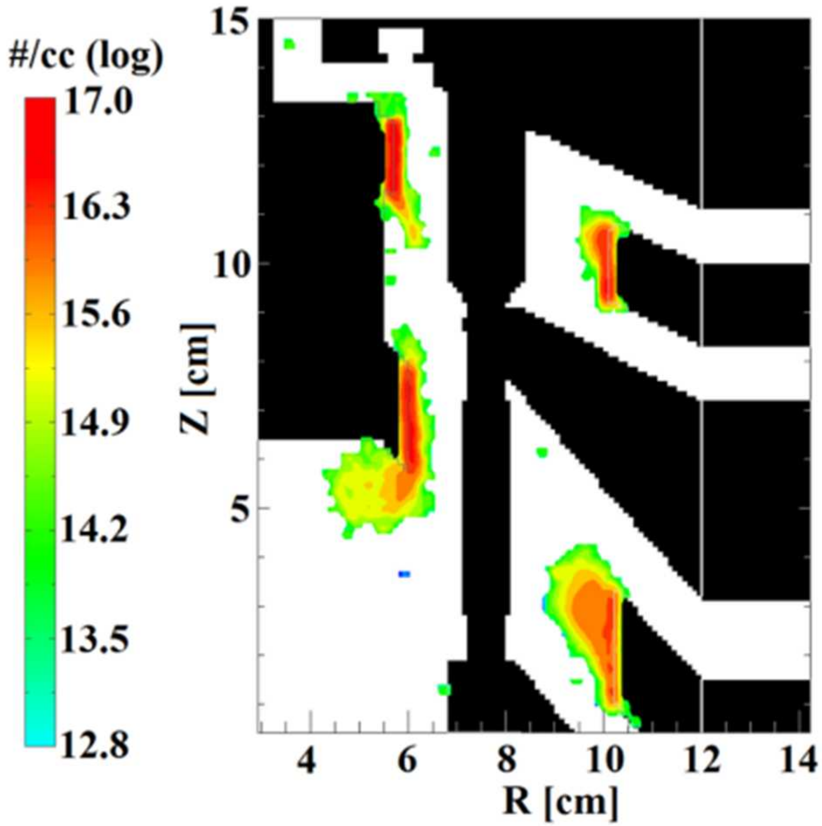
The Z machine utilizes 4 parallel MITLs and a double post-hole convolute to transfer the current from the vacuum insulator stack to the load.

- Multiple magnetically insulated transmission lines (MITLs) are used to reduce inductance
- The double post-hole convolute is used to recombine the currents
- Current is monitored at stack, outer MITL, and inner MITL locations
- A difference is observed between current at outer and inner MITL locations

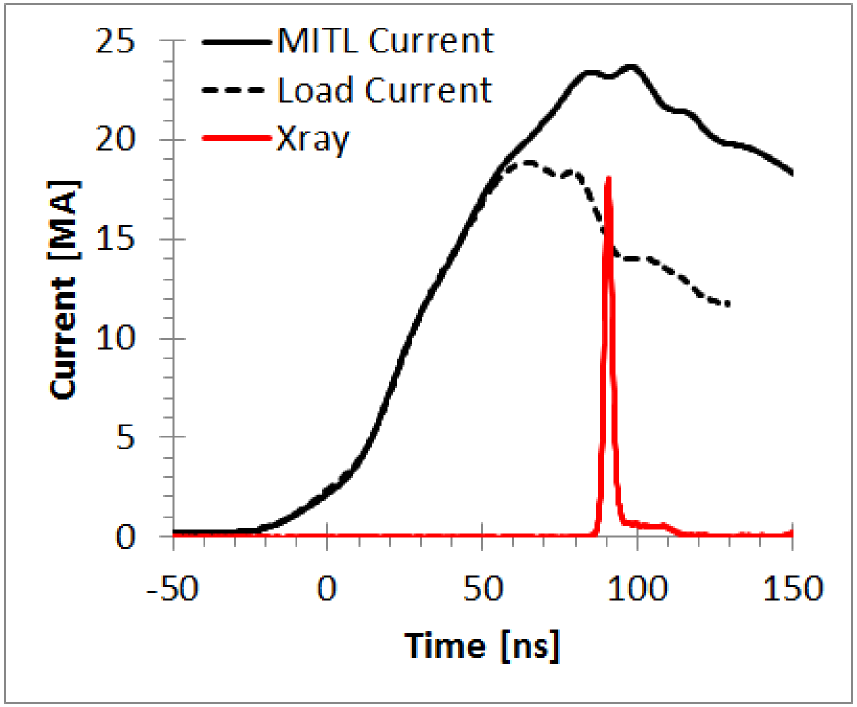


Large current losses on the Z machine are attributed to plasma formation in the convolute

LSP Convolute simulation by D. V. Rose

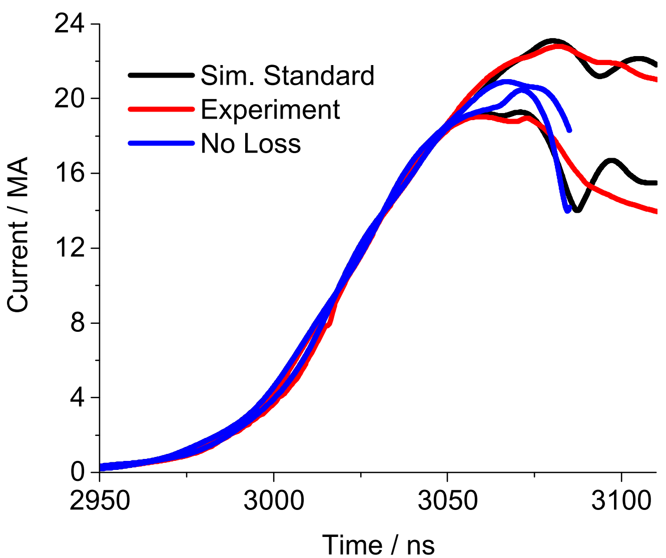


Experimental data from large diameter wire array shot on Z

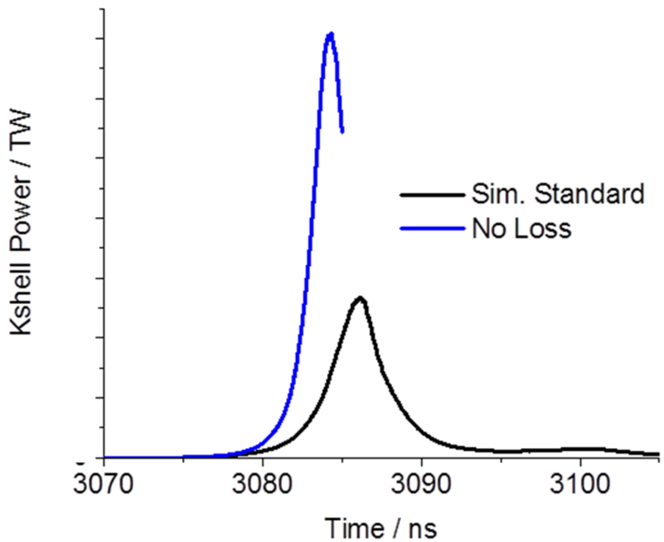


D. V. Rose, et al., Pulsed Power Conference Proceedings (2009).

Convolute loss represents appreciable loss in radiation efficiency for certain load types



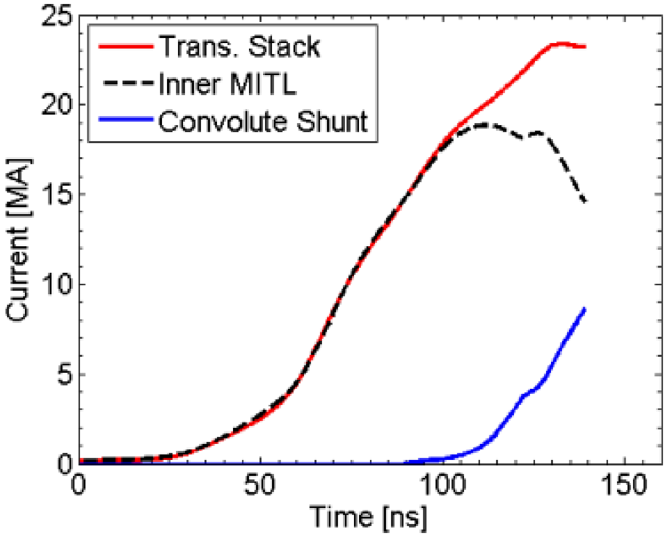
Colored pairs represent convolute and load currents

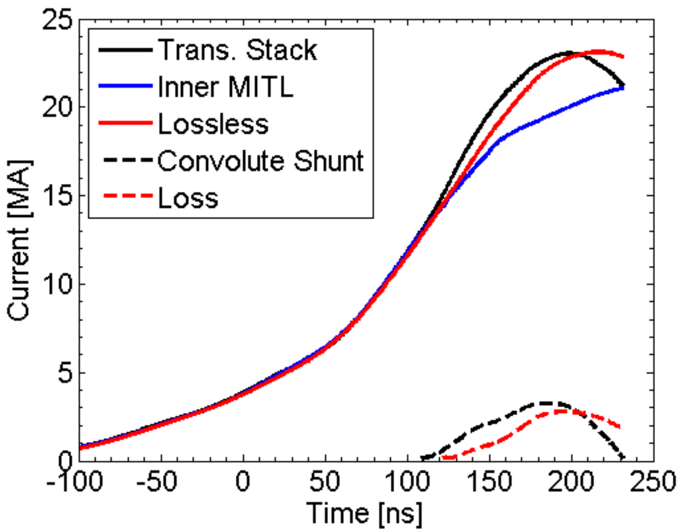


- C. Jennings simulation of nested stainless steel wire array (large dL/dt) shows appreciable efficiency improvement when loss "turned off"
- Caveat that full gains may not be reasonable, given resultant convolute voltage

Simulations by C. Jennings, 07.2014

The difference between a lossless propagation of the stack current[1,2] and the load current can be significant

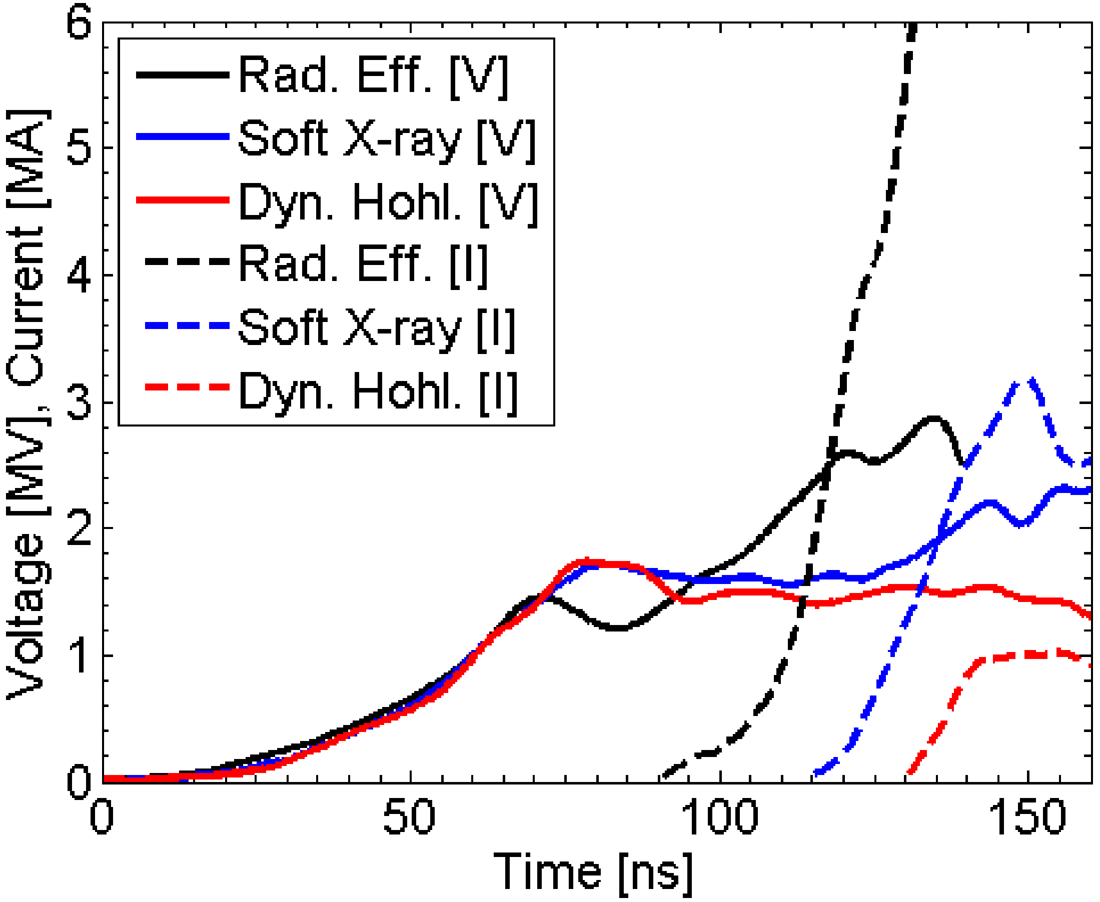




- Decreased load current negatively impacts nearly all Z experiments
  - Achievable pressure in dynamic materials experiments
  - Radiated power in wire array experiments
  - Fuel compression in MagLIF experiments
- Losses also negatively impact pulse shapes
  - Unwanted shocks in DM samples

[1]C. A. Jennings, et al., IEEE Trans. Plasma Sci. **38**, No.4, pp. 529-539 (2010).
[2]R. D. McBride, et al., Phys. Rev. ST Accel. Beams **13**, 120401 (2010).

The current shunted through the convolute is highly dependent on the load and machine configuration



- Peak convolute shunt current increases with increasing convolute voltage
- Turn-on time of convolute shunt current decreases with increasing convolute voltage

The initial inductance and the rate of change in inductance are important

$$V = L * \frac{dI}{dt} + I * \frac{dL}{dt}$$

- Initial inductance is dependent on initial load dimensions
- $L[nH] = 2h[cm]Ln\left(\frac{R_o}{R_i}\right)$
- Rate of change of inductance depends on implosion trajectory

Task 3 is employing a staged strategy to visit theoretical understanding with experimental validation / calibration for convolute loss

Theory and Simulation Activities

Develop next-generation cathode- and anode-plasma theory / models

- Perform advanced simulations
- Compare to experiments
- Optimize simulations

Light Laboratory Experiments

Analysis of diode materials and surface science applications

- SEM, AES, XPS, TOF SIMS, ICP MS, etc.

Intermediate Facility Experiments

Characterize or evaluate strategies and methods

- Diode materials or surface processing on Stinger
- Spectroscopic plasma characterization at COBRA

Demonstrate proof of concept from intermediate- to full-scale.

Test and validate strategies and methods

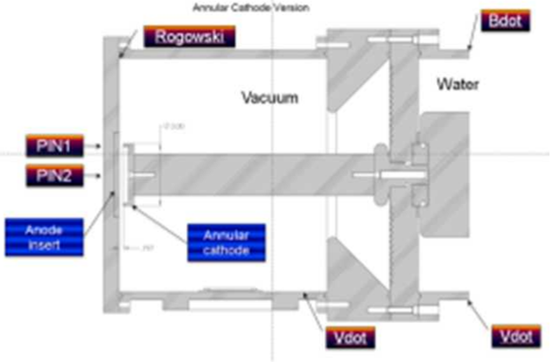
- Diode materials and surface processing
- Diode geometry and configuration

Demonstrate proof of concept at full-scale

- Increased dI/dt

Can we reduce current loss by using novel coatings?

- Standard model: Contaminants leave electrodes when electron bombardment causes temperature rise to 400C. These contaminants form plasma responsible for current loss
- Approach: Delay temperature rise by using surface coatings with low electron stopping power and high heat capacity.
  - NRL demonstrated the effect using e-beam pinches, which require anode plasma.
  - Carbon is best, high-Z is worst.
  - Need coating thickness ~0.1% of electron range.
- Test this model on Stinger and on Z.
  - “Bookend” tests: compare best and worst coatings.
  - Compare diamond-like carbon to tantalum.
  - Stinger front end modified for this work.
  - Six sets of “Shelf shot” Z hardware currently in-hand.



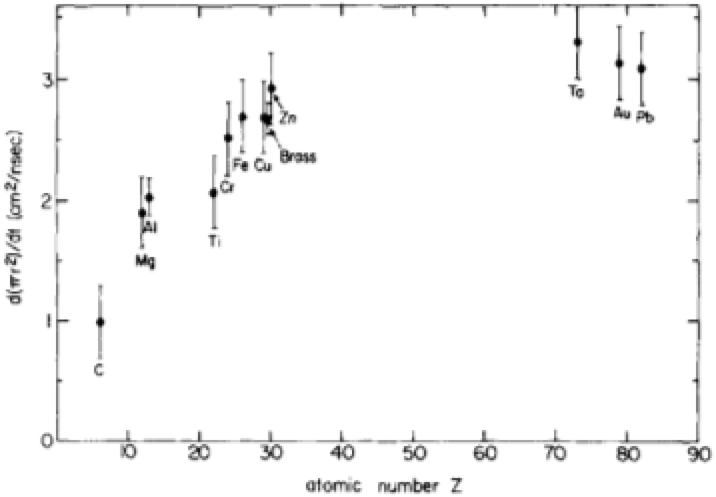
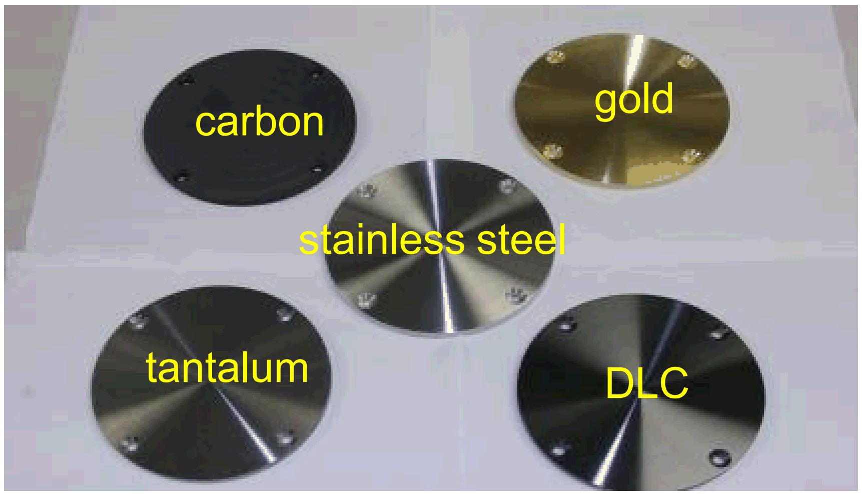


FIG. 6. The areal collapse velocity as a function of the atomic number of the anode material (Gamble I, $D_0 = 6.0$ mm).

1. G. Cooperstein and J. J. Condon, “Impedance characteristics of diodes operating in the selfpinch mode”, JAP, vol 46, p1535, 1975

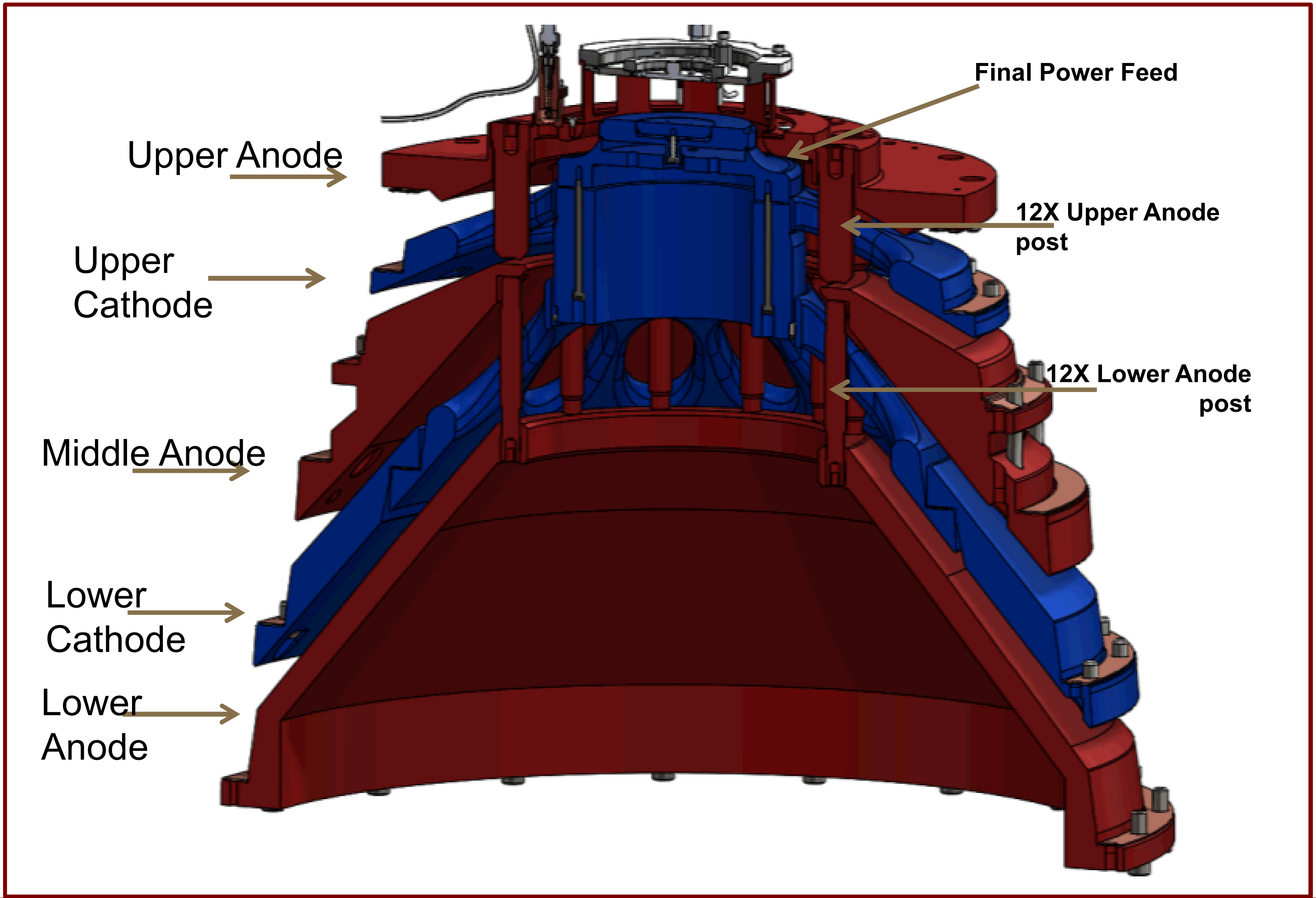
Pursuing coated anode inserts for SMP diode driven by Stinger

- NRL work indicated coating thicknesses need to be only ~0.1% of a range to behave as if they were very thick.
  - Thick DLC coatings are a challenge. But are they needed?



	NRL's 0.001*Range					
	Coating thickness (um)					
Energy (MeV)	C	Al	Fe	Cu	Ta	Au
.3	0.5	0.4	0.2	0.1	0.1	0.1
0.4	0.7	0.6	0.2	0.2	0.1	0.1
0.5	1.0	0.8	0.3	0.3	0.2	0.2
0.7	1.6	1.3	0.5	0.5	0.3	0.3
2	5.6	4.5	1.7	1.5	1.0	0.8
3	8.7	6.9	2.6	2.3	1.4	1.2
4	11.7	9.2	3.4	3.1	2.2	1.6

Surface coatings to be included over all anode power flow surfaces in one foot diameter

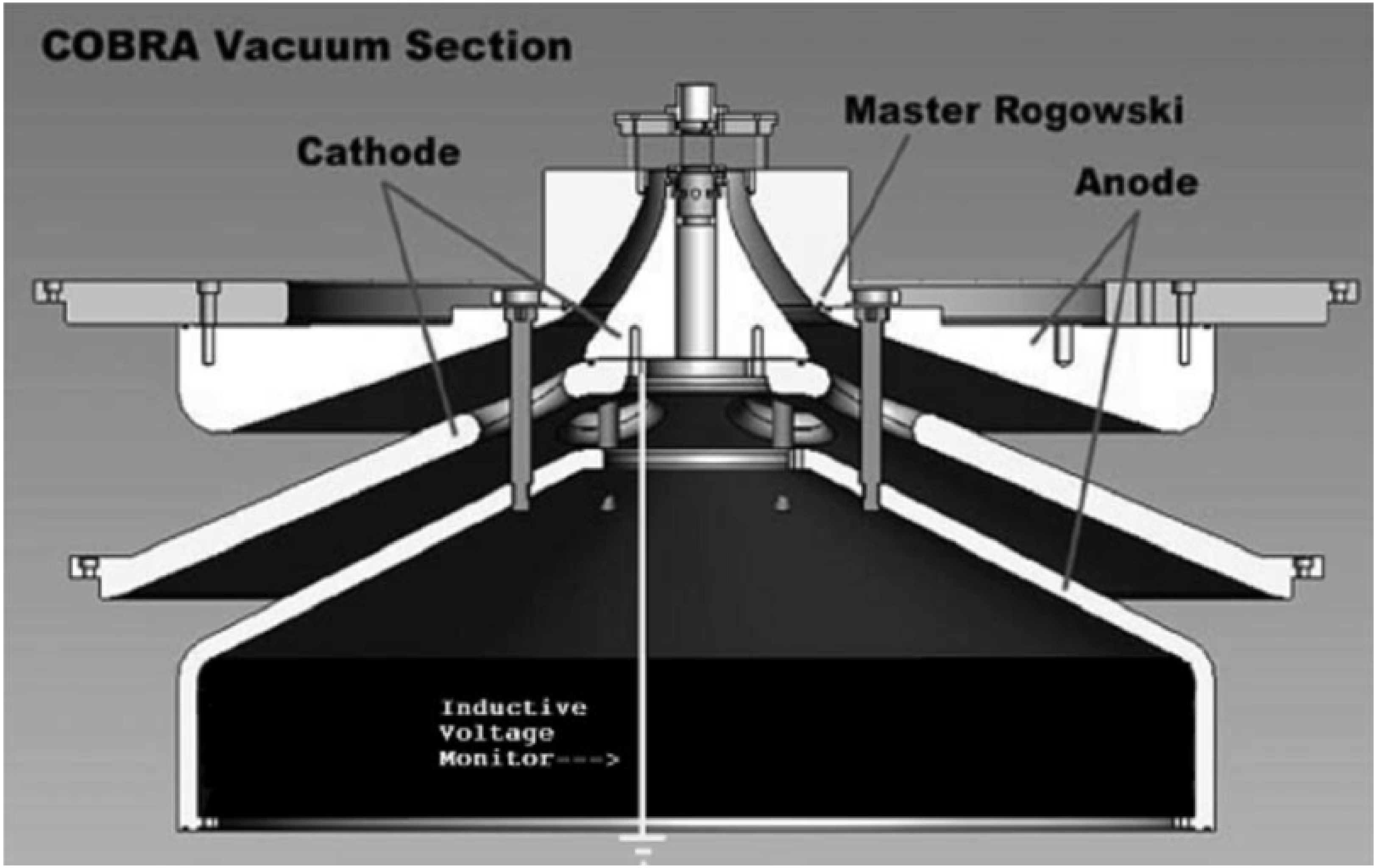


Use of intermediate test facilities enables quicker execution of experiments

- Stinger SMP diode for evaluating influence of coatings

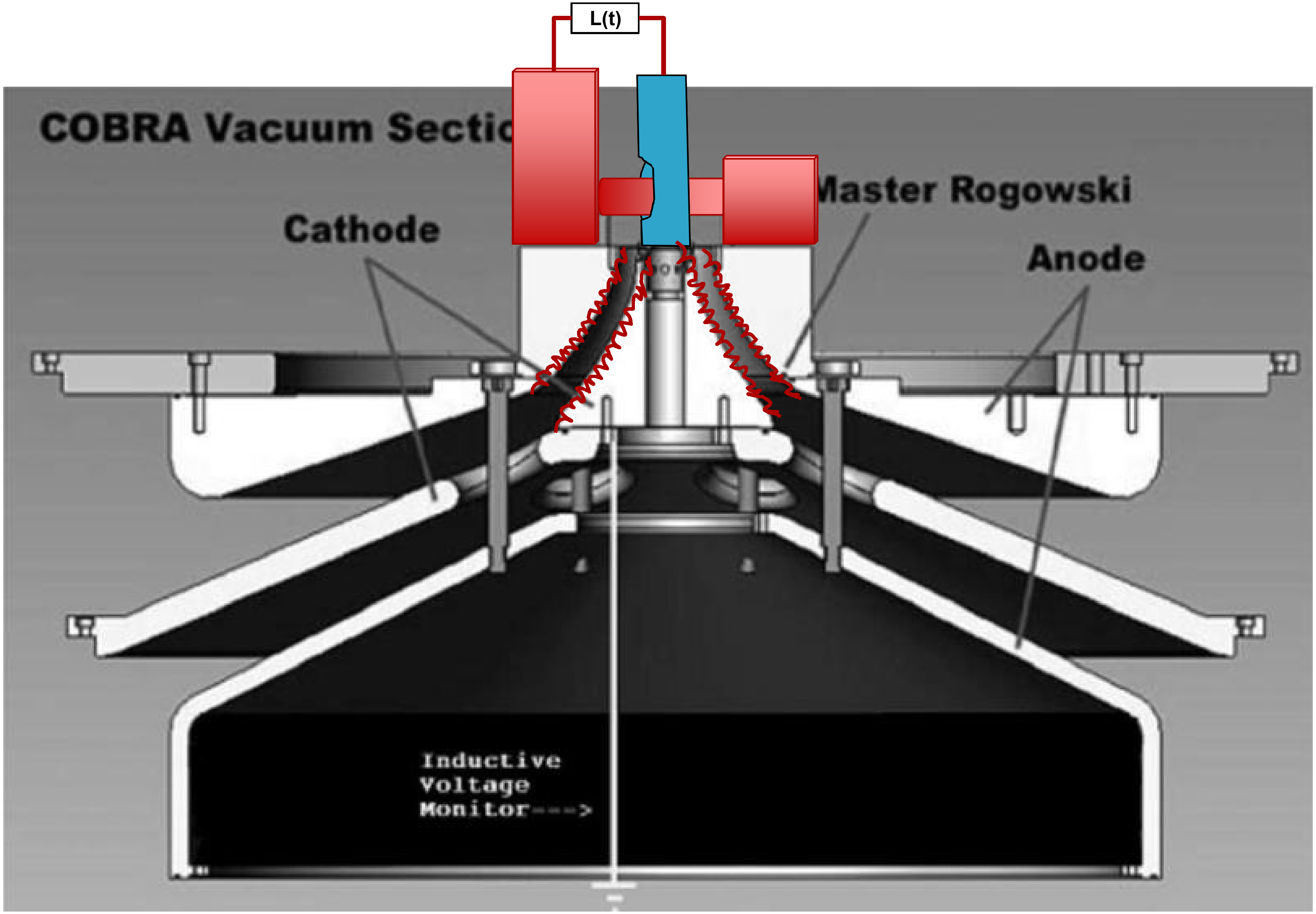
- Convolute loss experiments in subscale configuration
  - M. Gomez has a lot of subscale and Z experience
  - If an experimental configuration can be designed that enters loss regime relevant to Z Machine, requesting shots on COBRA is very attractive
  - Quickly collect data (multiple shots per day, multiple campaigns per year, reusable hardware)

COBRA vacuum section



1. J. B.Greenly, et al., Review of Scientific Instruments **79**, 073501 (2008)

Creation of smaller convolute post-hole into diagnostic region, powerflow material treatments



Research Goals

- Utilize a high shot-rate subscale facility with designed shot campaigns to study convolute physics, loss mechanisms
- Employ and/or develop new diagnostics, LOS, into convolute to understand current loss, gap plasmas:
  - Faraday cups on anode, cathode faces for ion plasmas
  - B-dots, rogowskis to capture time evolution of current loss.
  - Passive spectroscopic diagnostics, interferometry
  - Develop novel diagnostic implementations with LOS to Z
- Design convolute topologies to study ability to influence evolution of current loss
  - Surface coatings?
  - Changes to physical convolute topology

A three-year plan to explore convolute loss

(assuming 15 shots / week is reasonable, one week per 3-4 months)

- Year 1:
  - Design and procure convolute posthole geometry that is similar to Z
    - Scale design to ballpark Z loss regime for fields and ohmic heating
    - Test campaign to confirm production of loss regime (30-45shots)
  - Design loads with varying L_0, dL/dt to increase convolute voltage (15 shots)
- Year 2: Incorporate new diagnostics to see where loss is
  - New convolute topologies, hopefully informed by modeling, to manipulate loss (15 shots)
  - Faraday cups, lines of sight for passive spectroscopy or diagnostics (30 shots)
  - PIC simulation-informed hardware design (15 shots)
  - Develop phenomenological convolute loss model based on accumulated data
- Year 3:
  - Continue diagnostic development and calibration of PIC modeling (30 shots)
  - Demonstrate manipulation of current loss with hardware changes (30 shots)

Questions and random thoughts

- Gas-puff across diode terminals for corona-like load with appreciable dL/dt
- Surface coatings in final power feed region?
- Roughen power flow surfaces to ensure copious gap plasmas present
- Novel diagnostics?
- Novel lines of sight?
- Can we approximate Z loss regime in this device (current density, fields, geometry)?
- Can we approximate double post-hole configuration with asymmetric loading?
- Pulse-modes available for COBRA? Inductance budget?

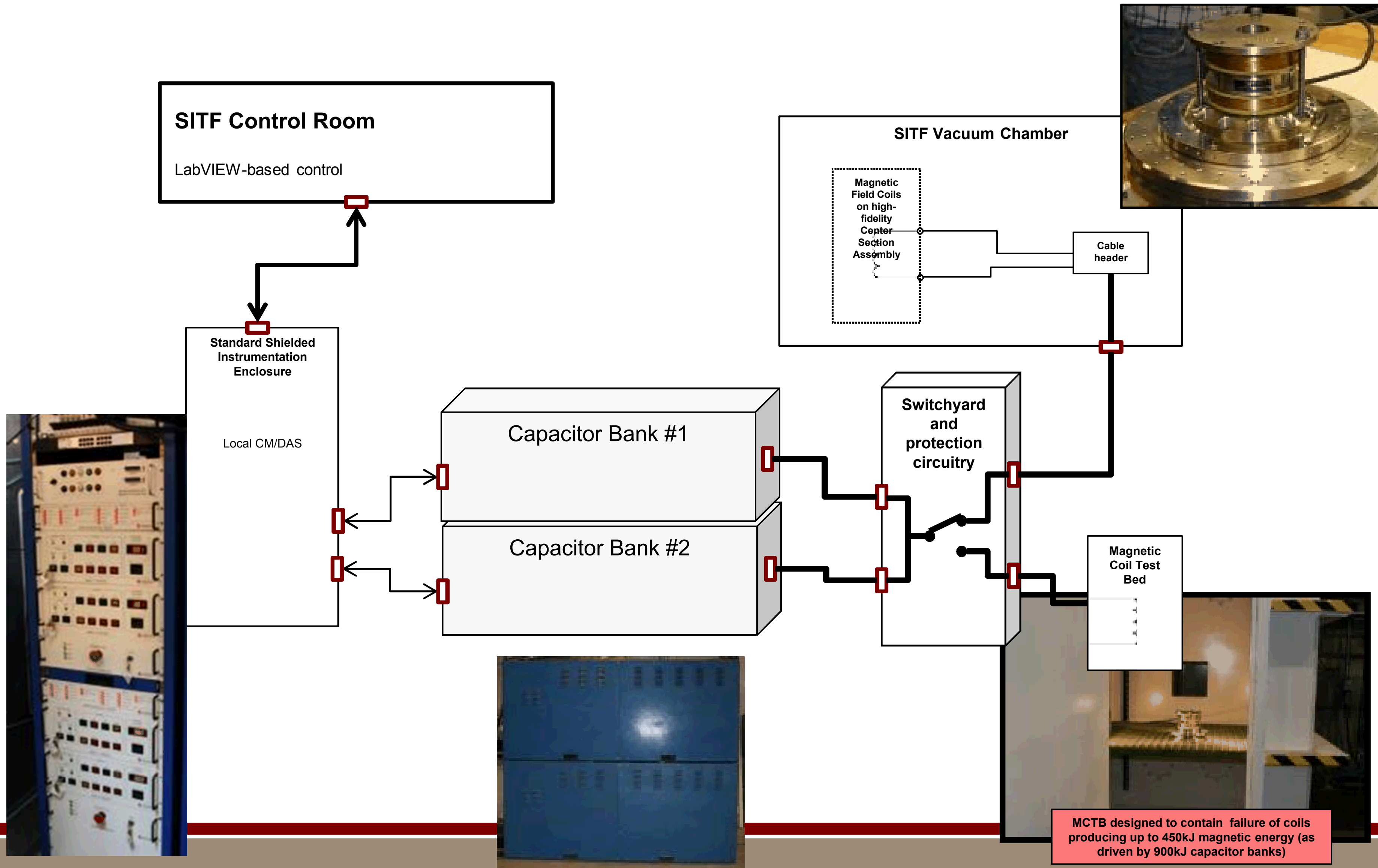
My personal agenda for the next few days

- Learn about the COBRA accelerator, its diagnostics, its day-to-day operations
  - How many shots per day?
  - Available diagnostics, detection spectra, resolution, etc.
  - Hardware cycle and design options
  - SNL-Cornell interface
- Speak to J. Greenly about micro B-Dot manufacturing capabilities
- Brainstorm ideas for diagnosing plasmas in convolute regions.
- See P. De Grouchy PLIF system for gas puff density measurements

Learn. Make contacts, collect references, become conversant in HEDP and its diagnostics.

Back-up

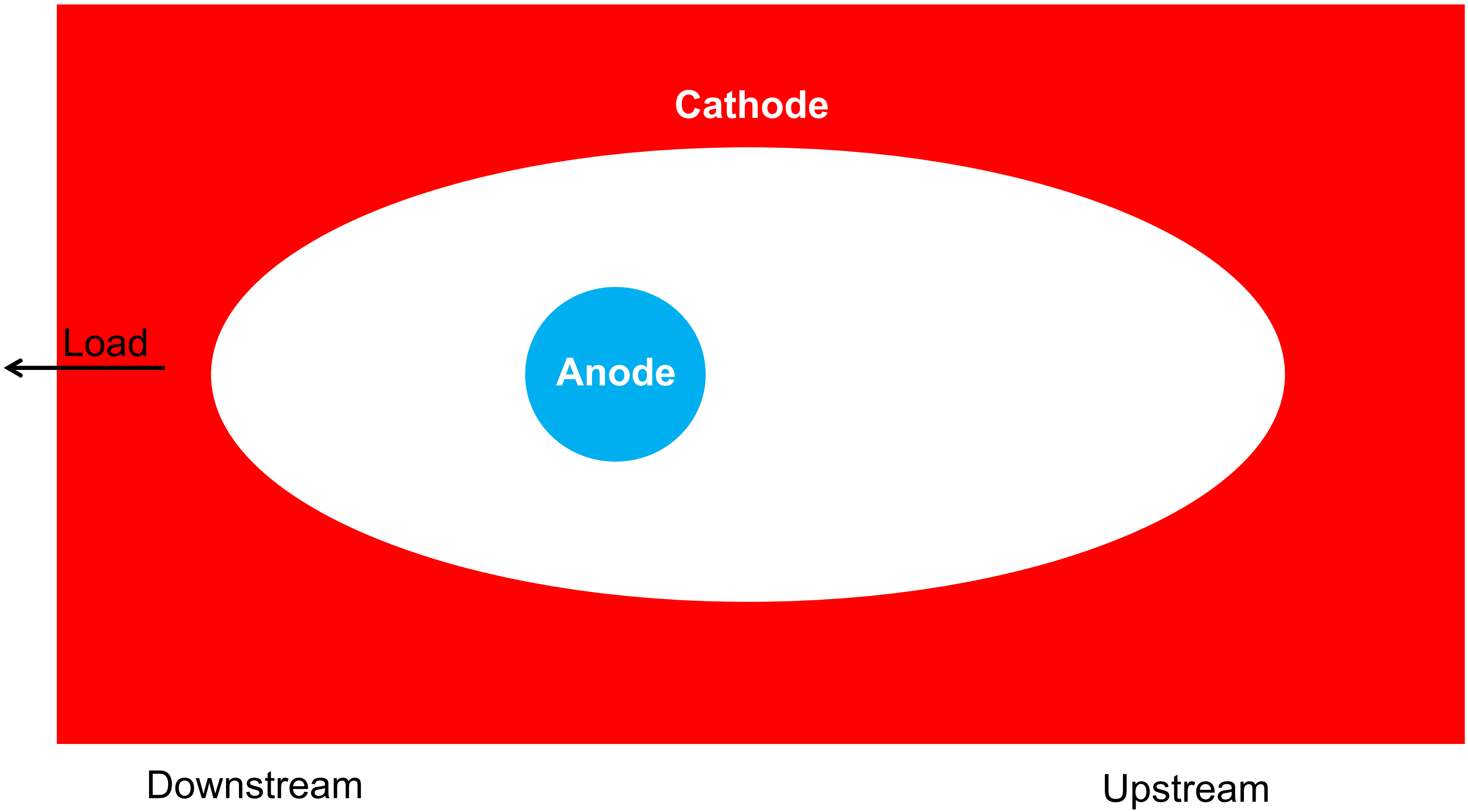
SITF Maintains Applied B on SITF (ABS)
Driver for Applied B coil design verification



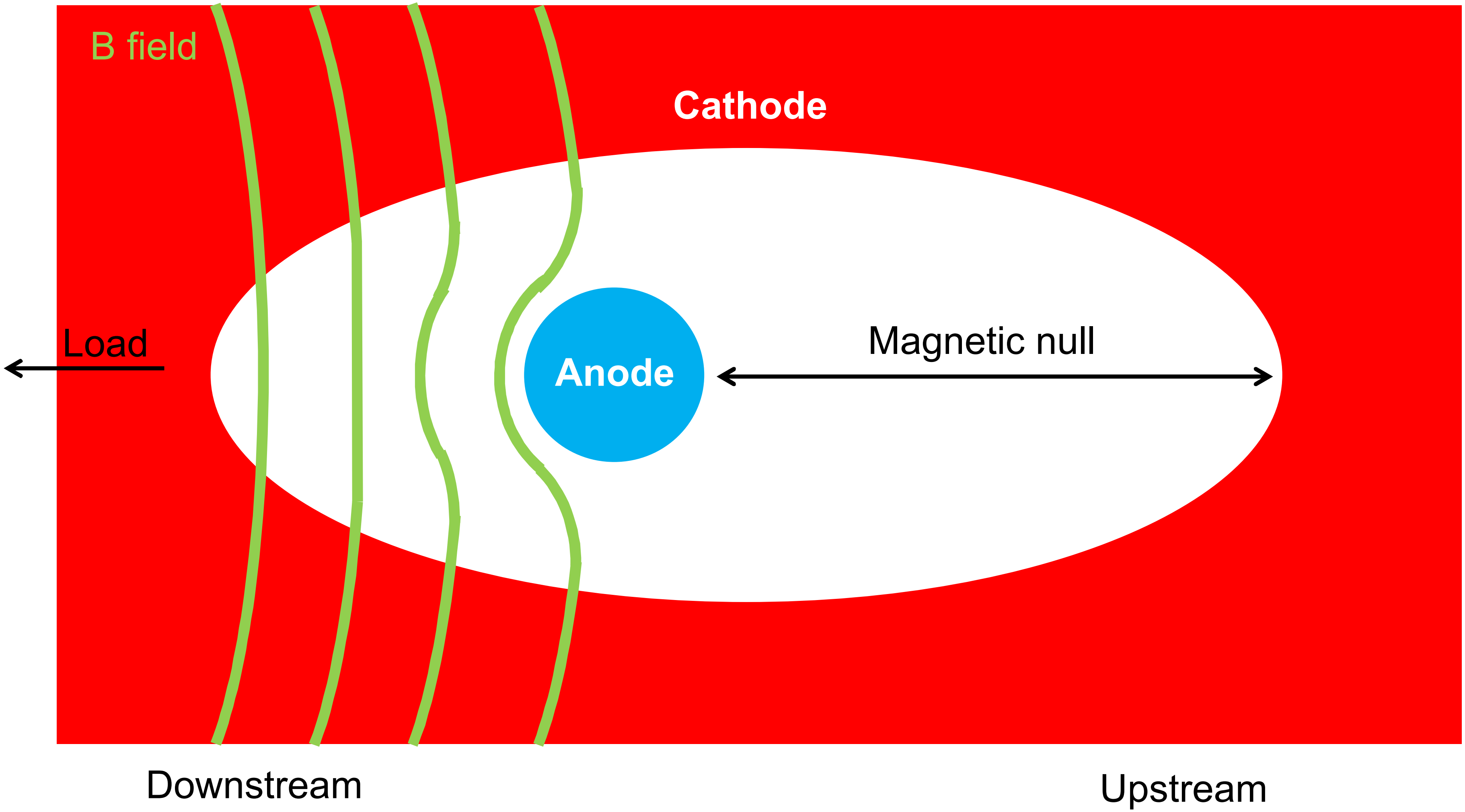
Speculation about the convolute loss mechanism

- Once voltage exceeds a threshold (~0.5 MV), plasma begins to form on cathode surface
  - Pulse shaped cylindrical liner is below 0.5 MV for 100s of ns without obvious impact on current delivery
- Plasma drifts along magnetic field lines and is accelerated by voltage
  - Higher voltage will cause losses to start sooner
- Plasma collects down stream of convolute
  - Plasma density observed spectroscopically, increases with time
- Plasma fills in regions closest to cathode first and progresses towards anode
  - Density observed to increase near cathode first
  - Shorter magnetic field lines for positions closer to the cathode

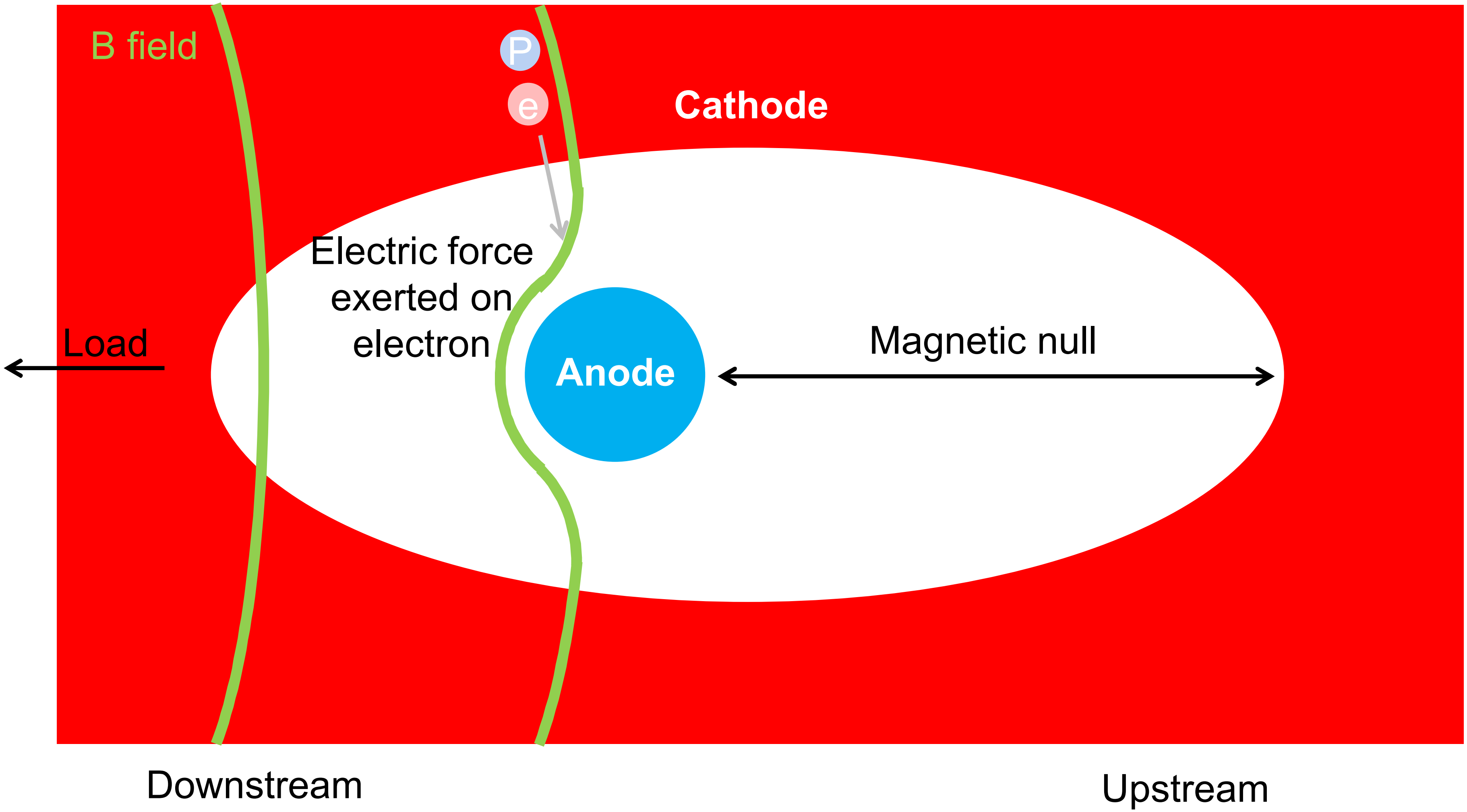
Speculation about the convolute loss mechanism continued



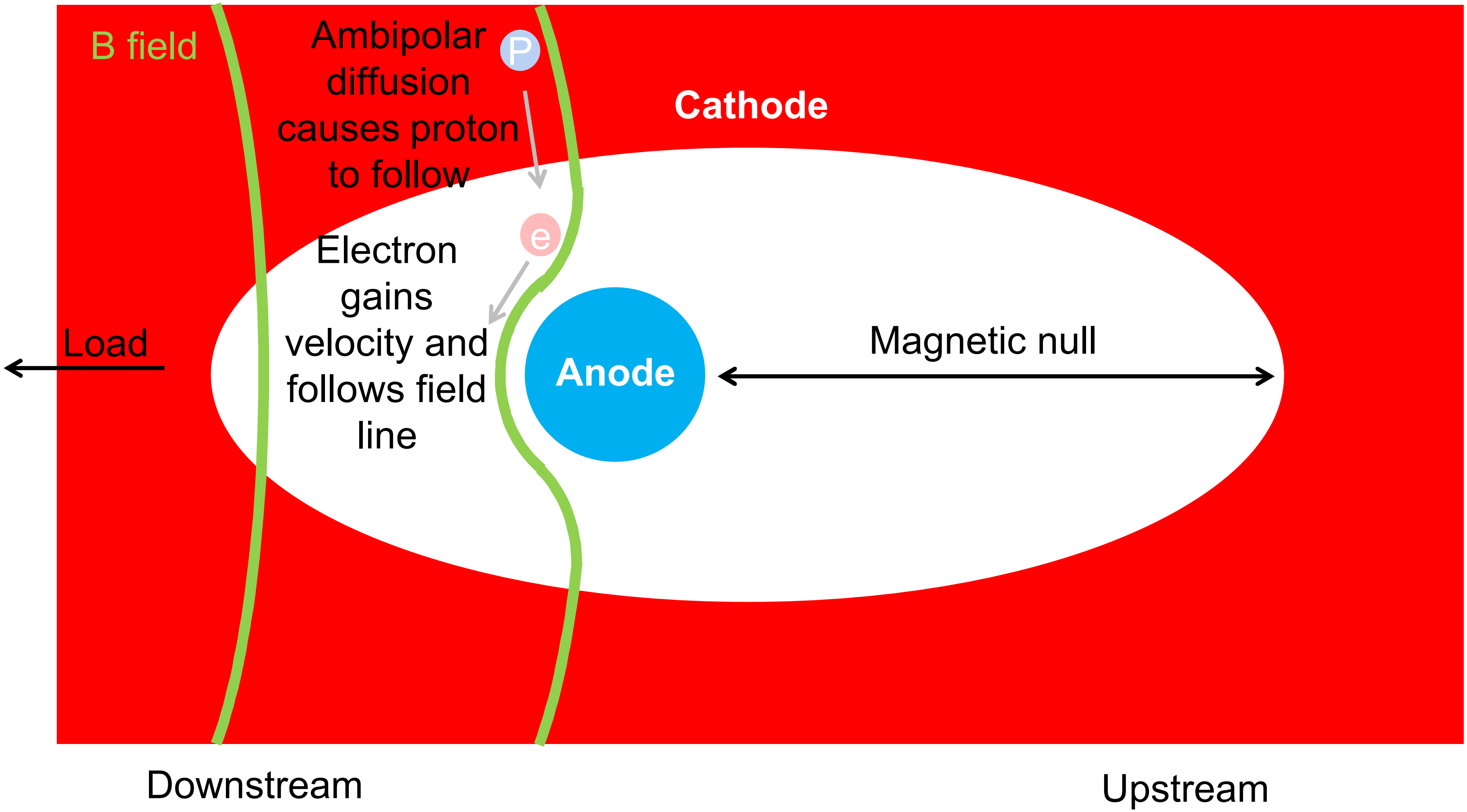
Speculation about the convolute loss mechanism continued



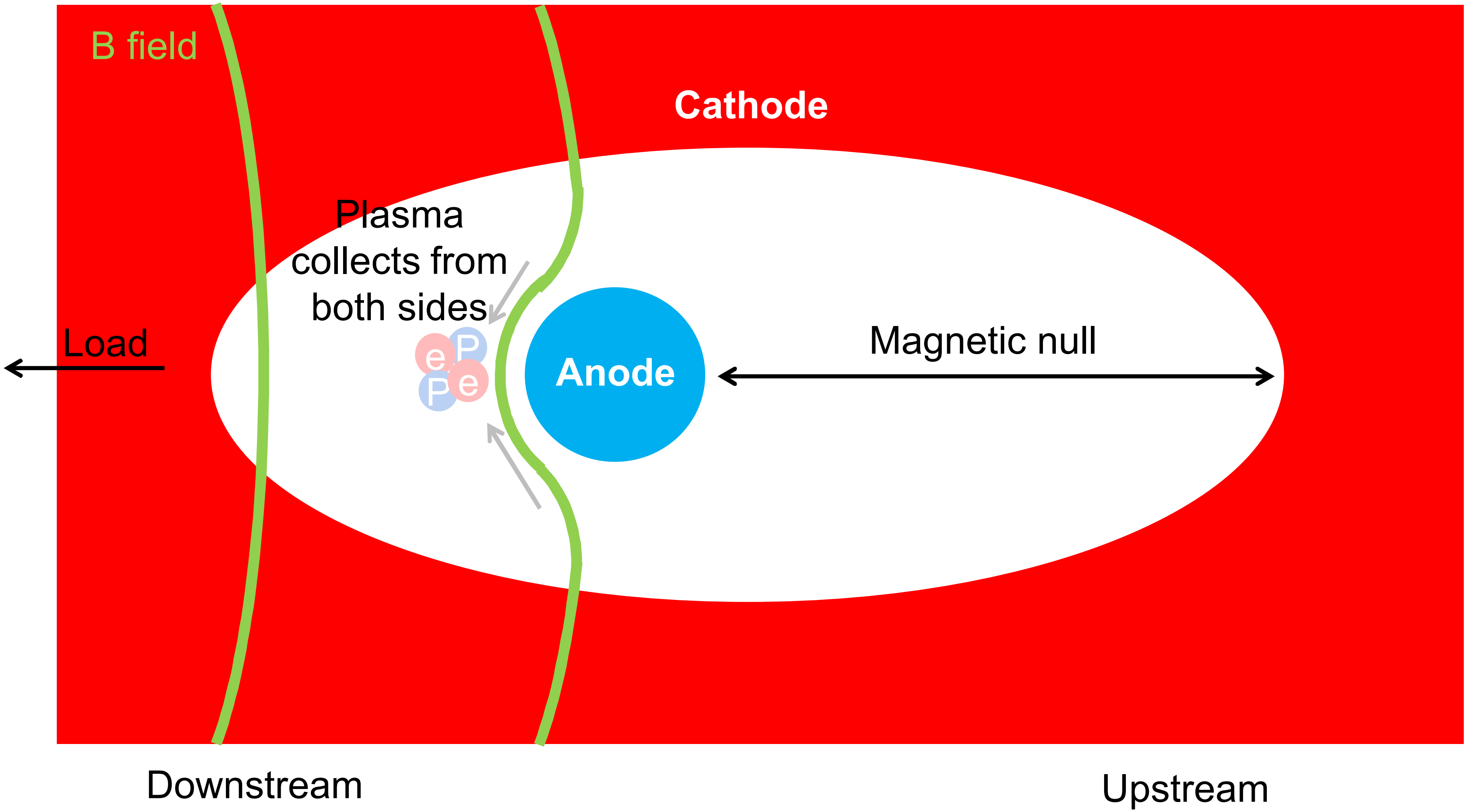
Speculation about the convolute loss mechanism continued



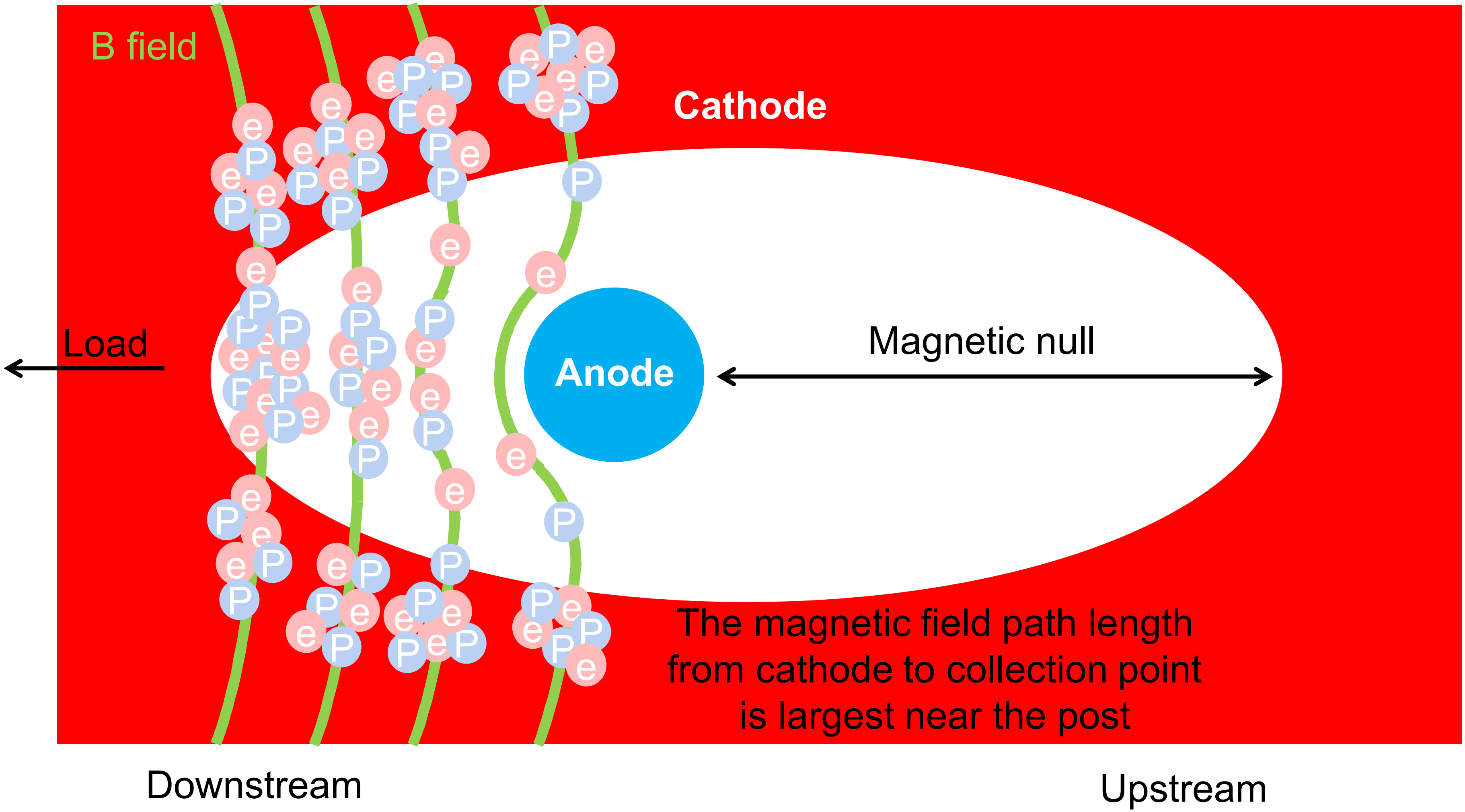
Speculation about the convolute loss mechanism continued



Speculation about the convolute loss mechanism continued



Speculation about the convolute loss mechanism continued



Additional speculation about convolute behavior

- The angle of the post relative to the transmission line is important
- Plasma collection downstream of the post is aided by the post not being normal to the transmission line surface