Musings on Intense Beam Generation, Propagation and Application

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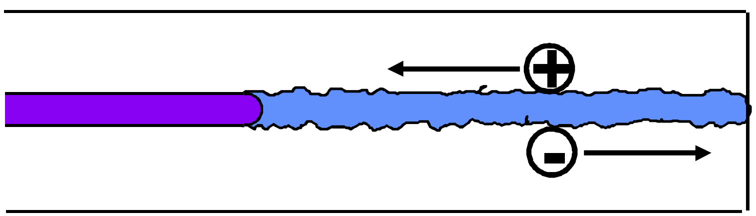

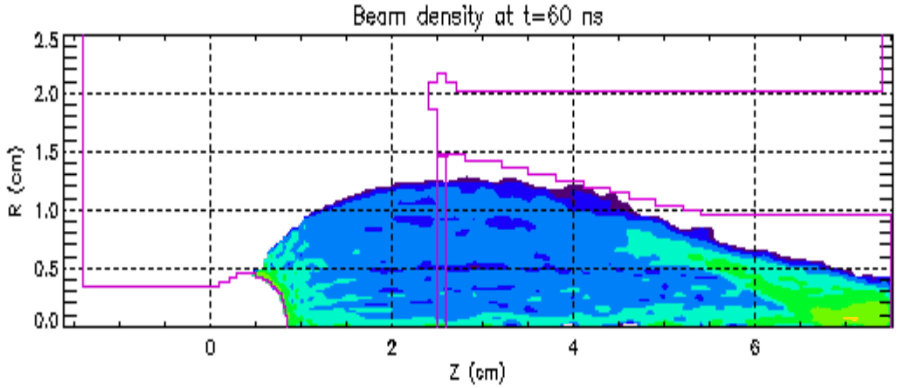

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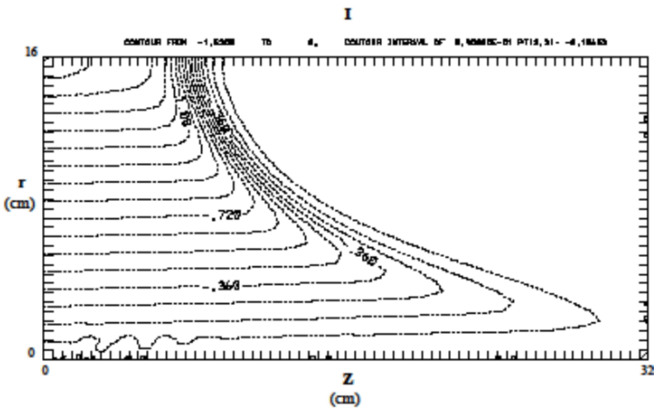
The Russian Invasion and Electron Hall MHD

A host of plasma and pulsed power physicists from Russia descended upon LPS in the late '80s and early '90s, L.I. Rudakov, G. Mesyats, D.D. Ryutov, V. P. Smirnov,…

A particularly fruitful theoretical interaction on Electron Hall MHD began in the Summer of 1990. L. I. Rudakov introduced us to the convective skin effect and KMC (Kingsep, Mokhov and Chukbar) shock wave field penetration. A collisionless fast field penetration mechanism driven by field advection with the electron fluid

$$u = \frac{1}{2}\lambda^2 \Omega_e \frac{1}{n}\frac{\partial n}{\partial x}$$

which could be much faster than the diffusive velocities $(\eta/t)^{1/2}$.

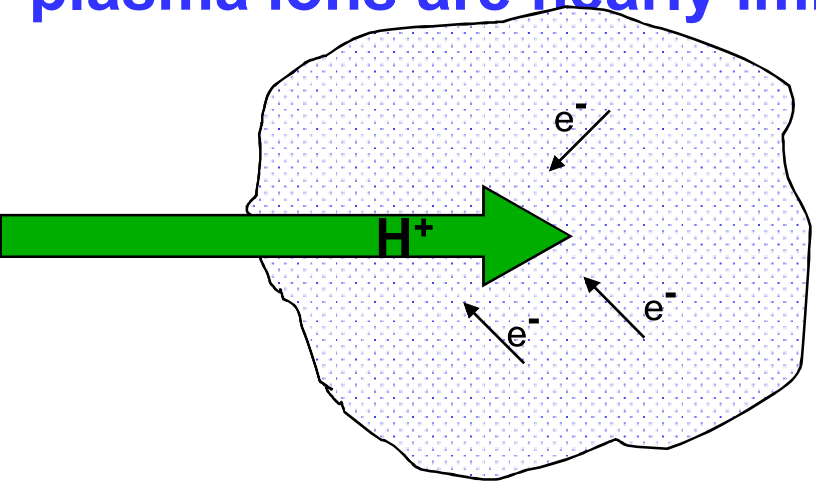


We also considered the role of electron inertia….which is important near boundaries and in developing high 'k' spatial structures (vorticies) on order the collisionless skin depth $\lambda = \frac{c}{\omega_{pe}}$ and again could result in field penetration at velocities significantly faster than diffusion

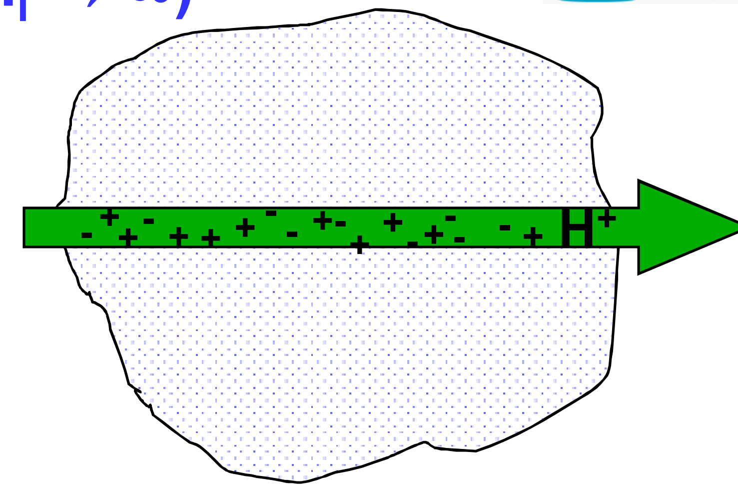
This initial work carried me into the realm of current neutralization of beams and rings in plasma. Everything I needed to know, Rudakov summarized in '88[1].

1. L.I. Rudakov, "*Macroscopic instabilities of a high-current beam in a gas in a guiding magnetic field*", Sov. J. Plasma Phys., 14, 1988

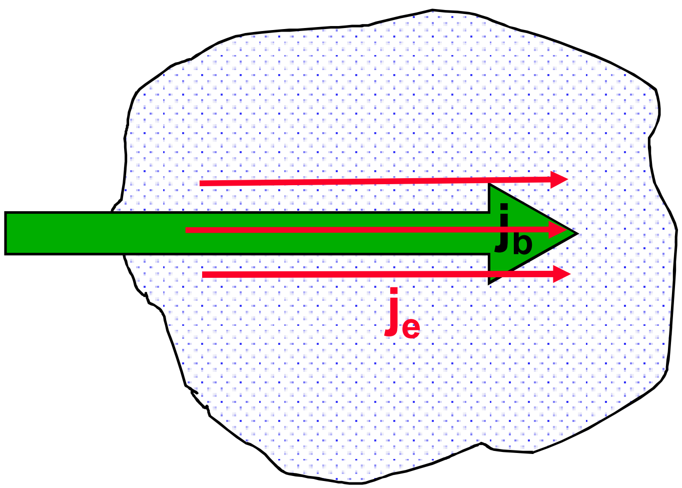
Beam neutralization in plasma when plasma ions are nearly immobile ($m_i \to \infty$)



Ion-beam attracts plasma electrons



Creates a plasma channel so beam + plasma is quasi-neutral: $n_i - n_e + n_b \cong 0$



Ohm's law $$j_e = \sigma\left(E + \frac{v_e}{c} \times B\right); \qquad \sigma = \text{conductivity}$$

$$\nabla \times B = \frac{4\pi}{c}\left(j_e + j_b\right); \qquad j_i \cong 0$$

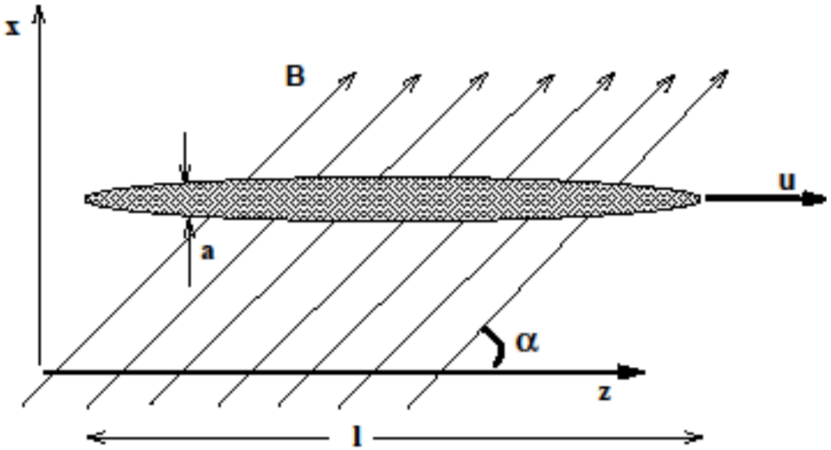
$$\nabla \times E = -\frac{1}{c}\frac{\partial B}{\partial t};$$

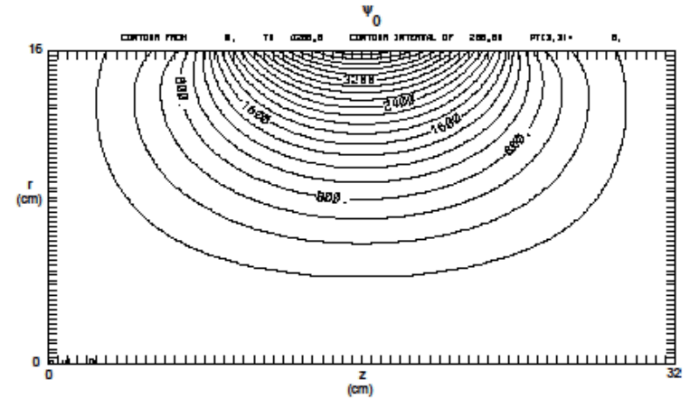
$$m_i \frac{dv}{dt} = q(E + v \times B)$$

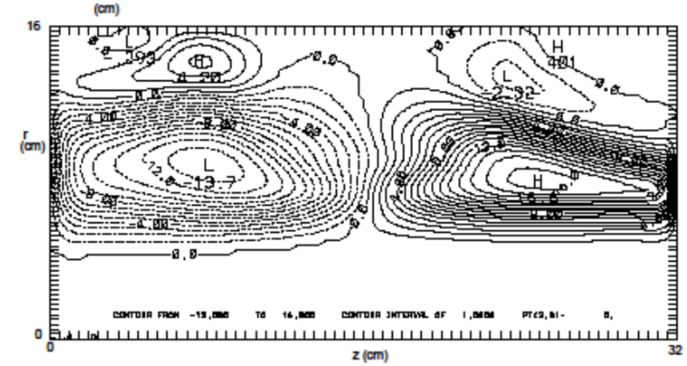
Plasma return current driven by inductive electric field and determined by generalized Ohm's law

Hybrid fluid/PIC codes were used to study beam and plasma dynamics

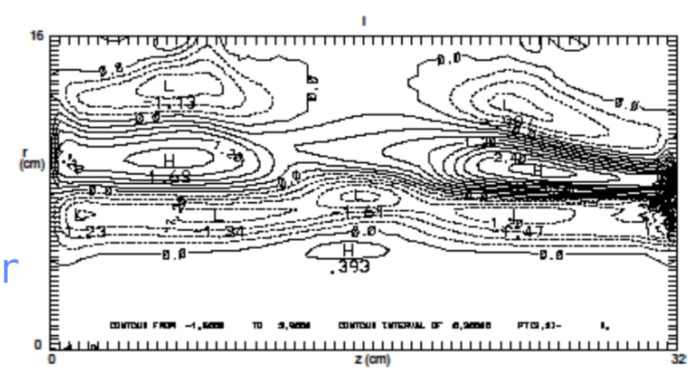
Beam injection into plasma filled magnetic lenses[1]







Field line advection, whistler wave generation and current diffusion…all fun stuff



$$\frac{\partial B}{\partial t} = -\nabla\times\frac{c}{4\pi e n_e}\left(\nabla\times B - \frac{4\pi}{c} j_b\right)\times B + \nabla\times\frac{c^2}{4\pi\sigma}\left(\nabla\times B - \frac{4\pi}{c} j_b\right)$$

Hall current advection   Resistive diffusior

1. B.V. Oliver and R.N. Sudan, Phys. Plasmas 3, 1996

…South to the Naval Research Labs: Ion Beams and Rod-Pinches

Arrival on “stirring day!”

Self-pinched beam equilibria in vacuum….which followed the laminar equilibria of Creedon[1] from magnetic insulation theory.

1. John Creedon. JAP 46, 2946 (1975)

$$\mathrm{v}\cdot\nabla\gamma\mathrm{v} = -\frac{\mathrm{e}}{\mathrm{m}}\left(\nabla\phi + \frac{\mathrm{v}}{\mathrm{c}}\times\mathrm{B}\right)$$ Momentum

$$\nabla^2\phi = 4\pi e(\mathrm{n} - Z\mathrm{n}_b)$$ Poisson

$$\nabla\times\mathrm{B} = \frac{4\pi}{\mathrm{c}}\left(\mathrm{j}_b - e\mathrm{n}\,\mathrm{v}\right)$$ Ampere

$$\gamma - \phi = 1;$$ Cons. of energy

$$\gamma = \sqrt{1/(1 - \mathrm{v}^2/\mathrm{c}^2)}$$

, $\lambda^2_b = mc^2/4\pi e^2 n_b$

$$\Rightarrow \frac{1}{r}\frac{d}{dr}\left(\frac{r\gamma'}{\sqrt{\gamma^2 - 1}}\right) = \sqrt{\gamma^2 - 1} - \beta_b\gamma$$

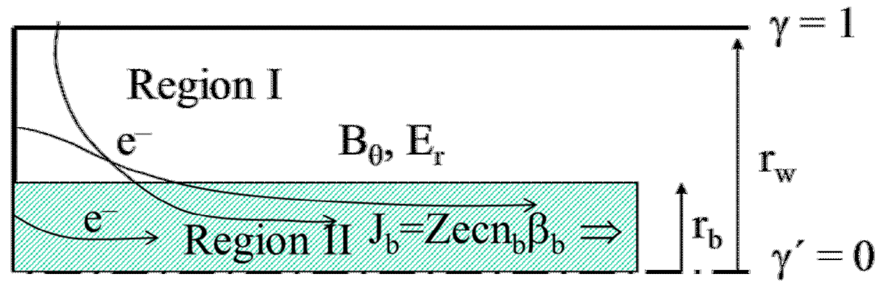
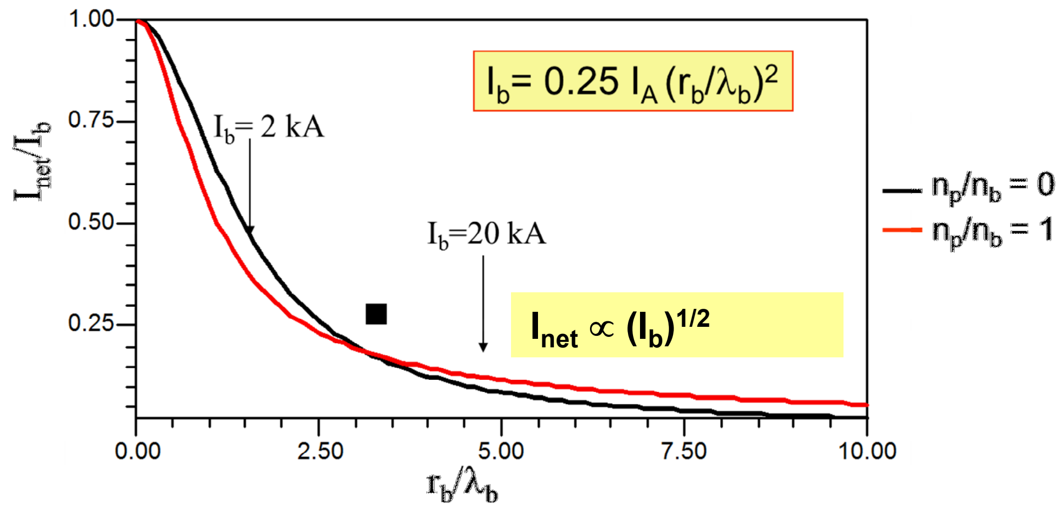


Illustration of e-neutralization in vacuum



…..And, Gerry Cooperstein’s favorite diode, the Rod-Pinch.

The Rod-Pinch diode: an example of self-magnetically insulated flow with ions

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Diode current well modeled by critical current formulation[1]:

$$I = \alpha I_{crit}, \qquad 2.0 < \alpha < 2.6$$

$$I_{crit} = 8.5 \frac{\sqrt{\gamma^2 - 1}}{\ln(r_c / r_a)} \ \text{kA}, \qquad \gamma = 1 + eV/mc^2$$

Operation and α is described by self-insulated flow theory with the inclusion of ions[2]

Region I

$$\nabla^2 \phi = n_e - n_i,$$
$$\nabla \times B = n_e v_e$$
$$\nabla \phi + v_e \times B = 0,$$

Region II

$$\nabla^2 \phi = -n_i.$$
$$n_i v_i = \frac{r_c}{r} j_c$$

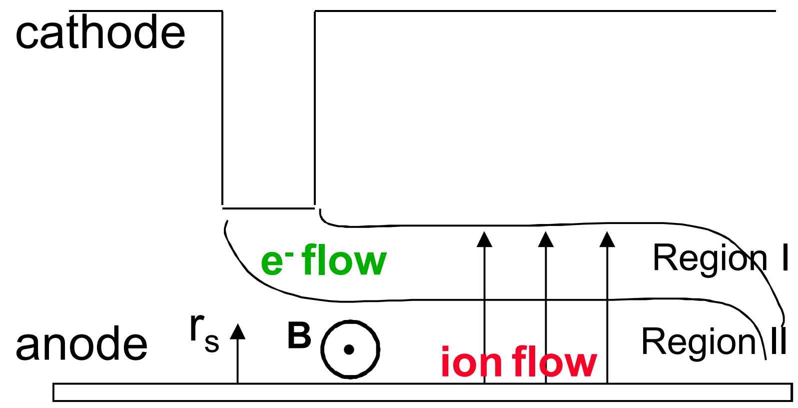
Ions are absolutely necessary for operation!

$$J_i = \frac{4}{9} \frac{(\gamma_a - \gamma_s)^{3/2}}{(r_s - r_a)^2}.$$

Child Langmuir like

$$I \cong 17\, r_s \sqrt{J_i}\, [\gamma_a - 1]^{1/4} \ \text{kA}.$$

rod-pinch diode



Normal Rod pinch diode

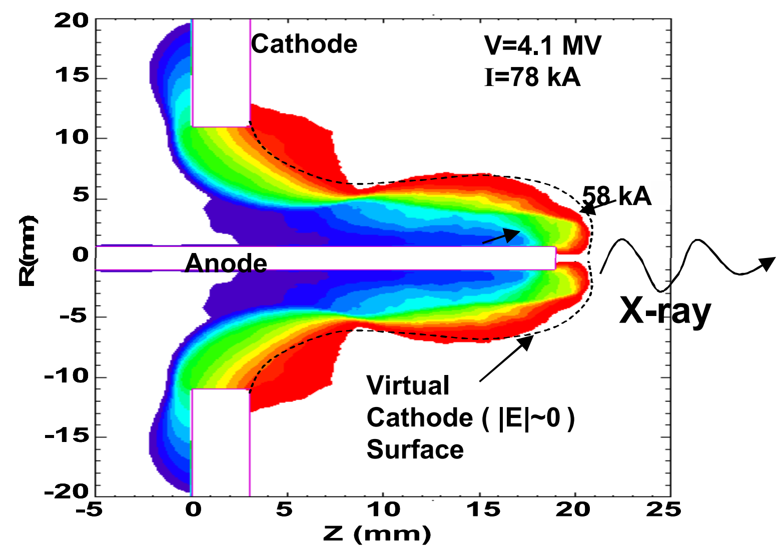
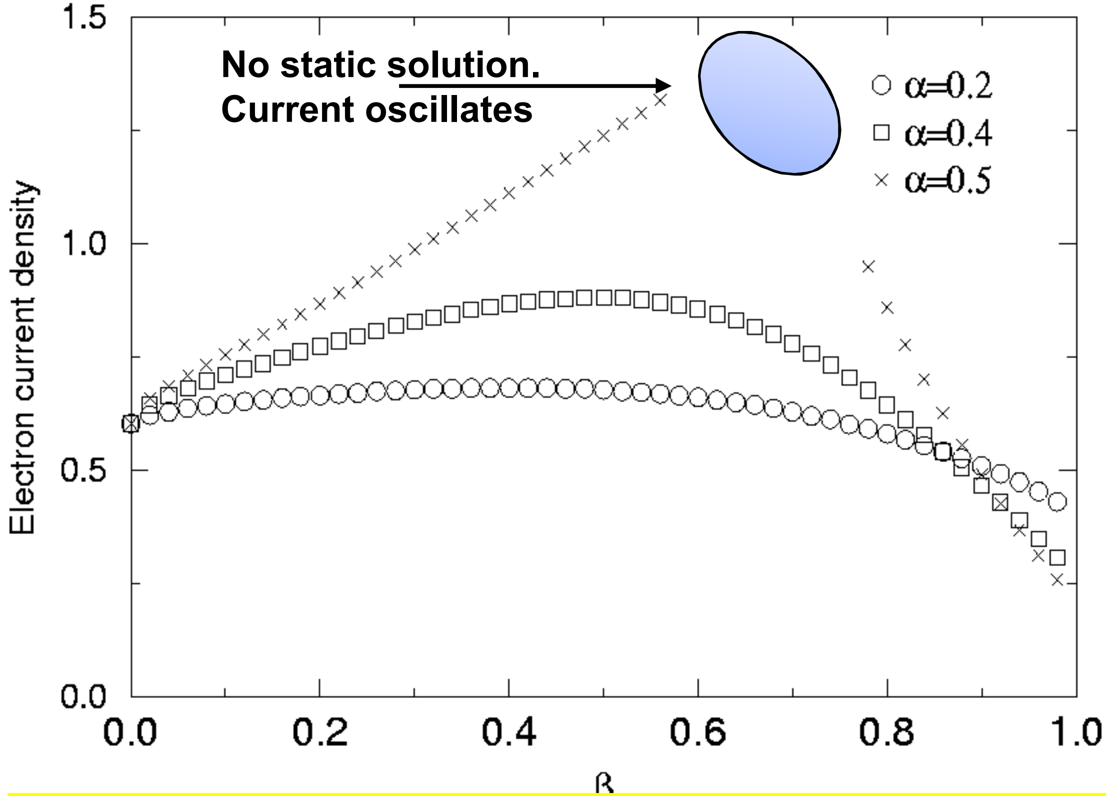
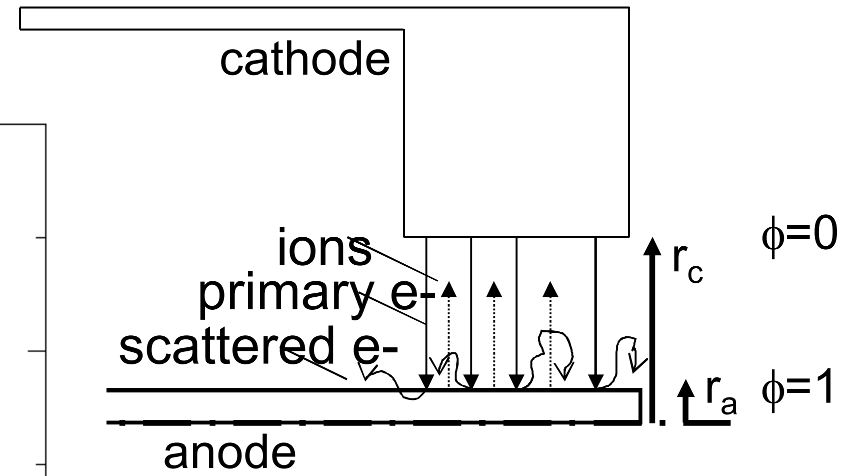


Fig. courtesy of S. Swanekamp, NRL

1. G. Cooperstein et al. Phys. Plasmas, **8**, 4618 (2001)
2. B.V. Oliver et al. Phys. Plasmas, **11**, (2004);

Electron backscatter can be significant in cylindrical diodes, results in decreased but stable impedance!





$$j_{cl} = \frac{1}{9\pi}\sqrt{\frac{2eV}{m}}\frac{V}{d^2}$$

$$j_{scat} = \alpha\, j_{incident}$$

$$E_{scat} = \beta E_{incident}$$

As the fraction of reflected beam current goes up, so does the total current. However , there is a maximum and the current is stable.

1. N.R. Pereira, JAP **54,** 6307 (1986)
D. Mosher, G. Cooperstein et al, Proc. 11th Intl. Beams Conf. (1996)
V. Engelko, V. Kusnetsov et al. JAP **88**, 3879 (2000)
B.V. Oliver, T.C. Genoni et al., JAP 90, 4951 (2001)

Magnetized e-beams for x-ray radiography applications

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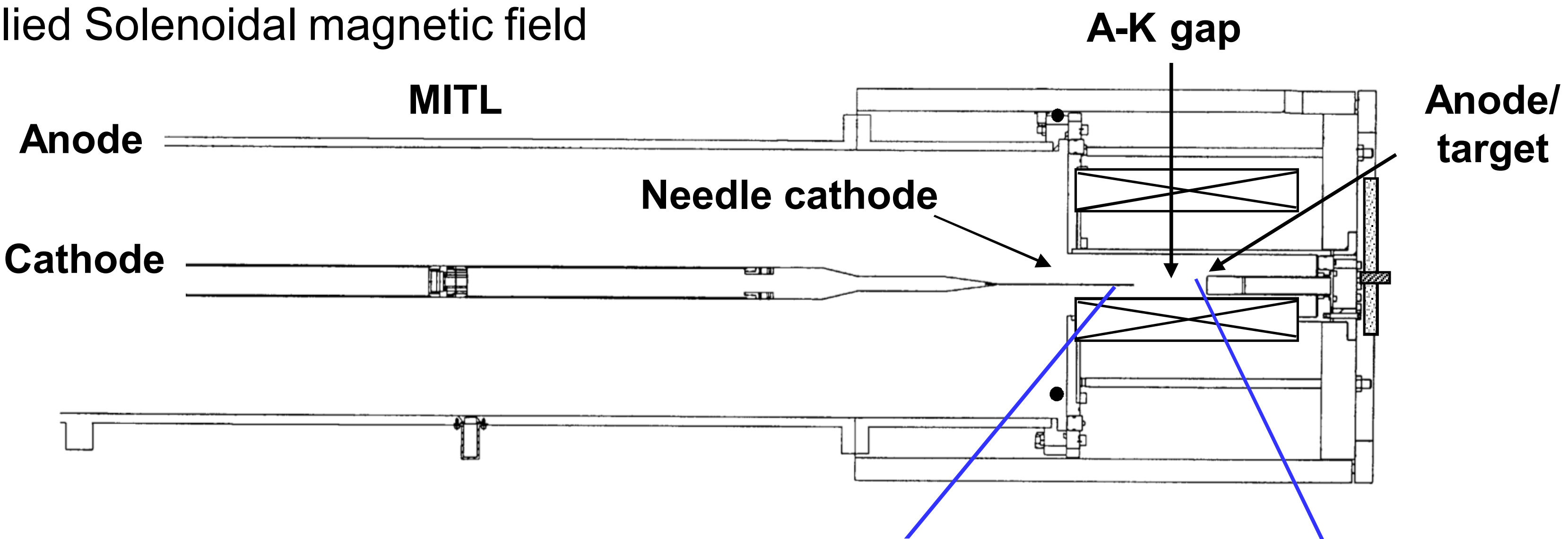
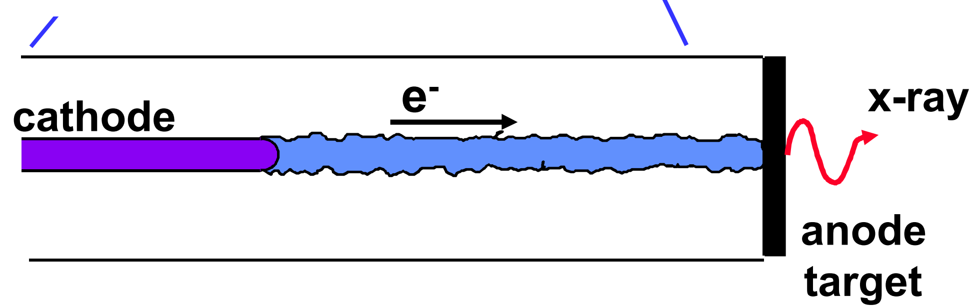
The Immersed B_z diode[1]: the electron beam is created in the accelerating gap of a high current diode and guided in vacuum to an anode/target via an applied Solenoidal magnetic field



Bremmstrahlung x-rays are created when the e-beam is stopped in a high atomic number converter.



Energy E_b= 2-10 MeV, Current I_b= 20-150 kA, Pulse length τ_b= 50-100ns

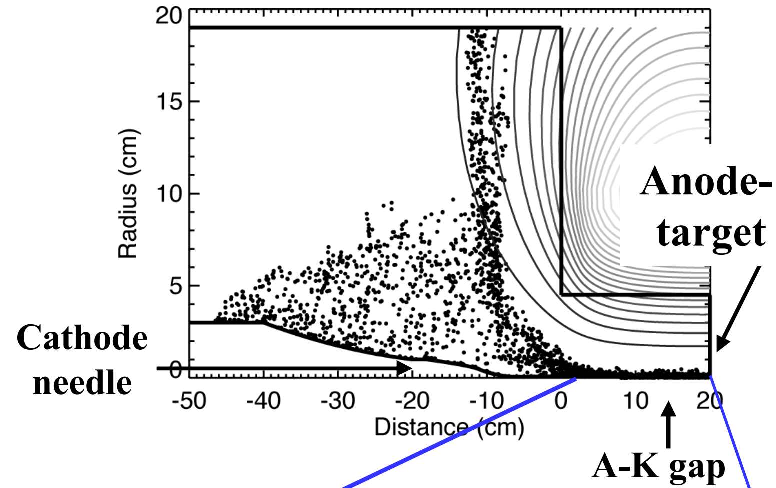
1. M.G. Mazarakis et al. Appl. Phys. Lett **70**, 832 (1997)

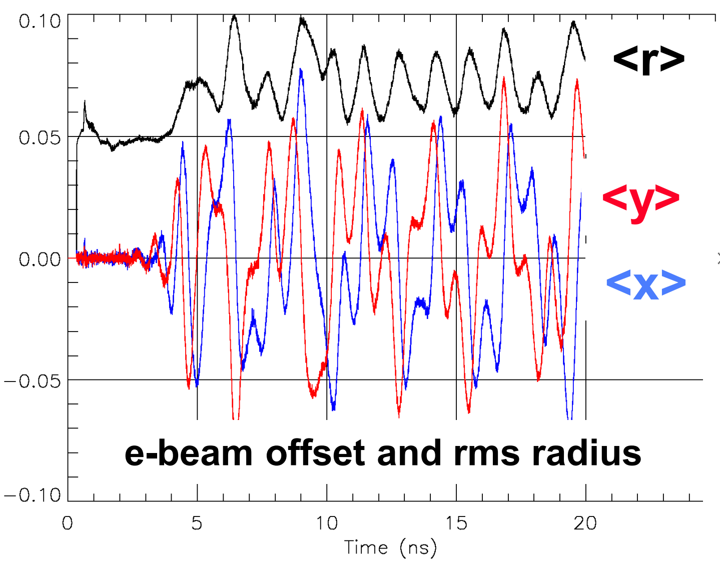
Beam target interactions led to development of 3-D simulations (LSP) and nonlinear modeling of ion-hose instability.

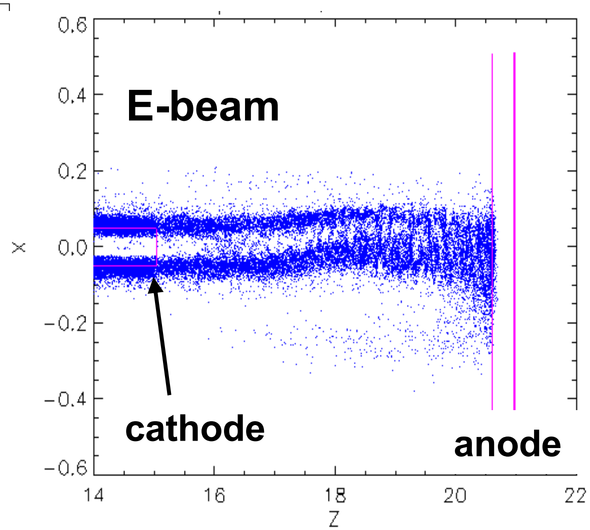
Immersed-B[1]: Diode used for creating high intensity bremsstrahlung radiation.

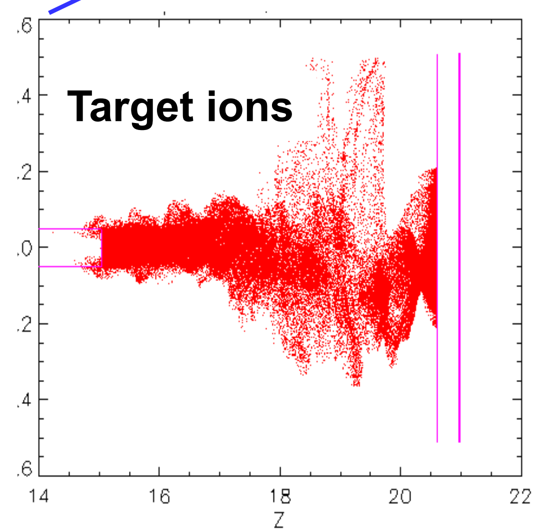
Beam spot on target determined by ion-hose saturation amplitude

$$< r_{sat} > \approx \frac{c}{\Omega_e}\sqrt{2\gamma\frac{I_b}{I_A}}$$









3-D PIC simulations of immersed-B diode electron and ion dynamics

1. M.G. Mazarakis et al. Appl. Phys. Lett **70**, 832 (1997)
D.R. Welch et al. Laser and Particle Beams **16**, 285, (1998)

Paraxial diode: a classic beam propagation problem in overdense plasma $n_b/n_e \ll 1$. Gas-cell acts as a ¼ betatron focusing lens[1].

Gas breakdown sufficient for complete charge neutralization but incomplete current neutralization.

$$\frac{d^2 r_b}{dz^2} \cong -\frac{1}{r_b}\frac{2I_{net}}{I_A} + \frac{\varepsilon^2}{r_b^3}, \qquad I_{net} = I_b + I_{plasma}$$

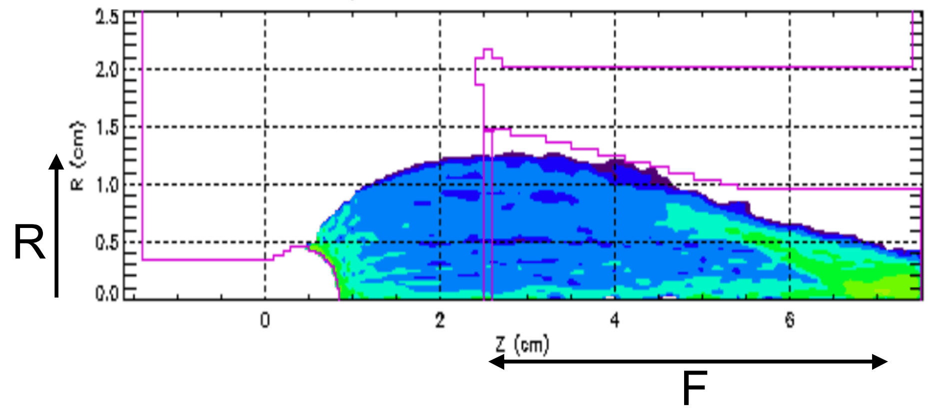
For $\varepsilon^2 \ll 2R^2 I_{net}/I_A$

$$F \cong \frac{R}{2}\sqrt{\frac{\pi I_A}{I_{net}}}, \quad \propto \sqrt{\frac{\gamma}{I_{net}}}$$

$$I_A = \gamma\beta\, 17\ \text{(kA)},$$

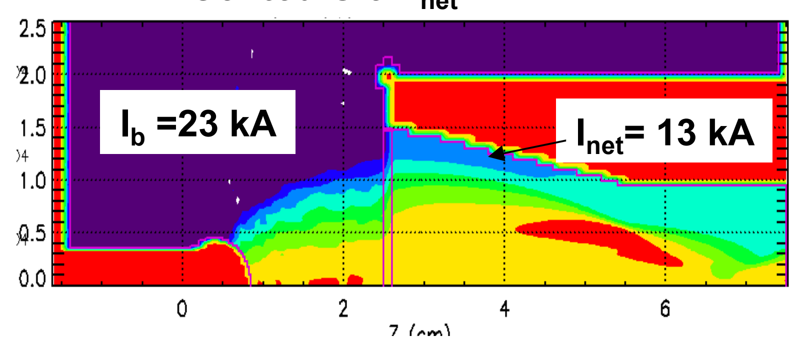
$$\varepsilon = 4\sqrt{\langle r^2\rangle\langle r'^2\rangle - \langle rr'\rangle^2}$$

Beam density contours from Lsp simulations



Net current (beam + plasma) $I_{net} = crB_\theta/2$

Contours of I_{net}



Focal sweeping due to time dependent net current is the primary contributor to larger than desired time integrated spots.

1. B.V. Oliver, D. Short, G. Cooper and J. McLean, IEEE Trans. on Plasma Science **33**, 704 (2005).

Plasma cells have advantages provided if one controls kinetic effects and anomalous resistivity.

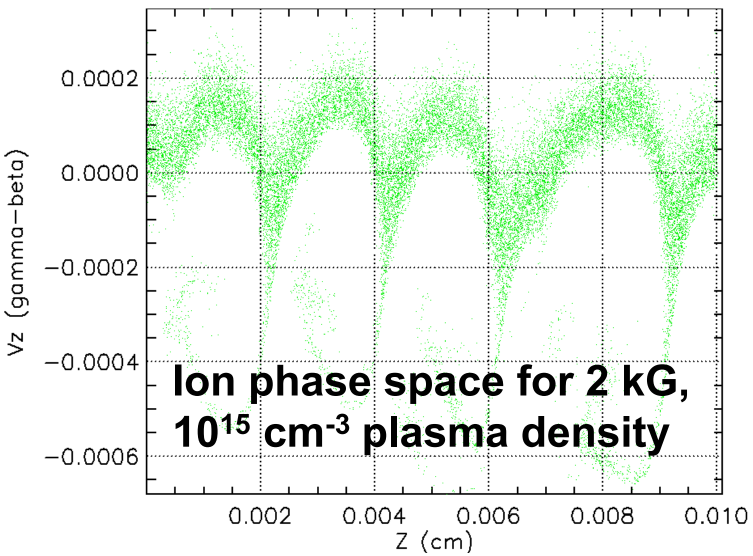
Theory/simulation[1] of cross – field plasma currents show susceptibility to unstable Bernstein modes (Resistance as high as 60x classical)

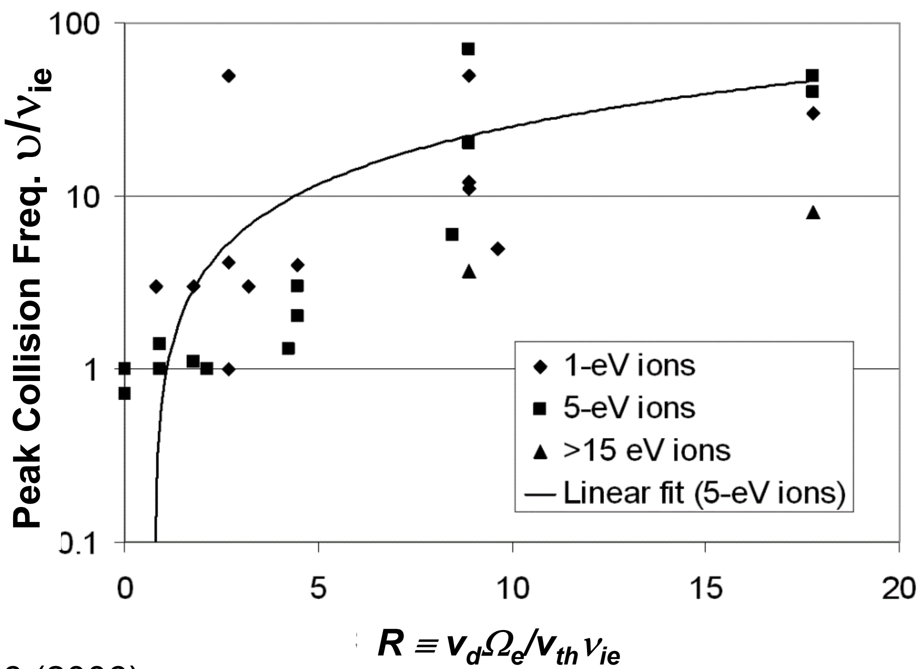
$$1 = \frac{\omega_{pe}^2}{\lambda_e} \sum_{n=1}^{\infty} \frac{2n^2 e^{-\lambda_e} I_n(\lambda_e)}{(\omega - k v_d)^2 - (n\Omega_e)^2} + \frac{\omega_{pi}^2}{\lambda_i} \sum_{n=1}^{\infty} \frac{2n^2 e^{-\lambda_i} I_n(\lambda_i)}{\omega^2 - (n\Omega_i)^2},$$

Resistivity nearly classical for:

< 0.5 kA at 10^{15} cm^{-3} plasma density

< 10 kA net current at 10^{16} cm^{-3} density





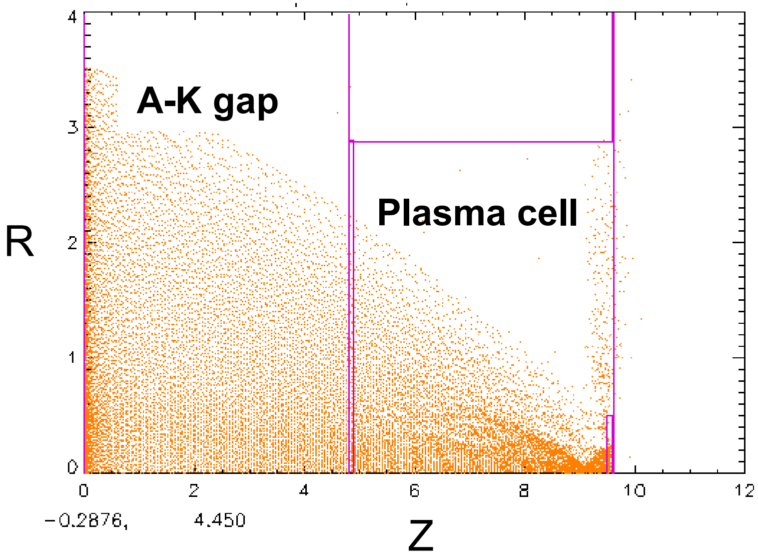
1. Welch, Genoni, Oliver et al., Phys. Plasmas 13, 103106 (2006)

Coming full circle: ….plasma cells are nice but electron advection from the boundaries still causes issues.

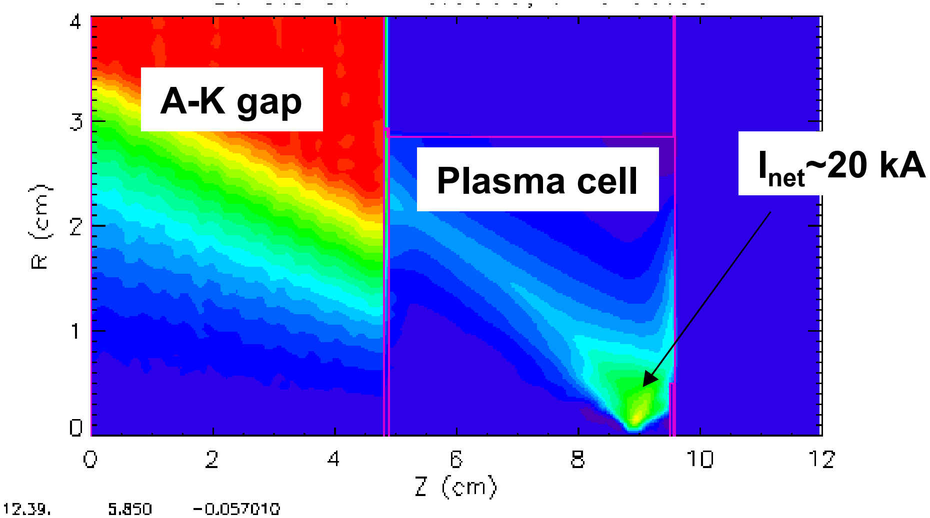
" Bryan, the future of plasma physics is that you'll do the same problem on a bigger computer"!, Rod Mason, 1994

Net current grows near target region. This is due to electron inertial effects at wall[1] and advection with the plasma return current electrons[2]

electron configuration space



Contours of I_{net}



Simulations of 20 torr H_2, 1.3% ionized (10^{16} cm^{-3})

[1] B. V. Oliver, L. I. Rudakov, R. J. Mason, and P. L. Auer, Phys. Fluids B **4**, 294 (1992).
[2] A.S. Kingsep, L.I. Rudakov and Chuckbar, Sov. Phys. Dokl **27**, 140 (1982)

Now....a partial lobotomy and oversite of pulsed power facilities

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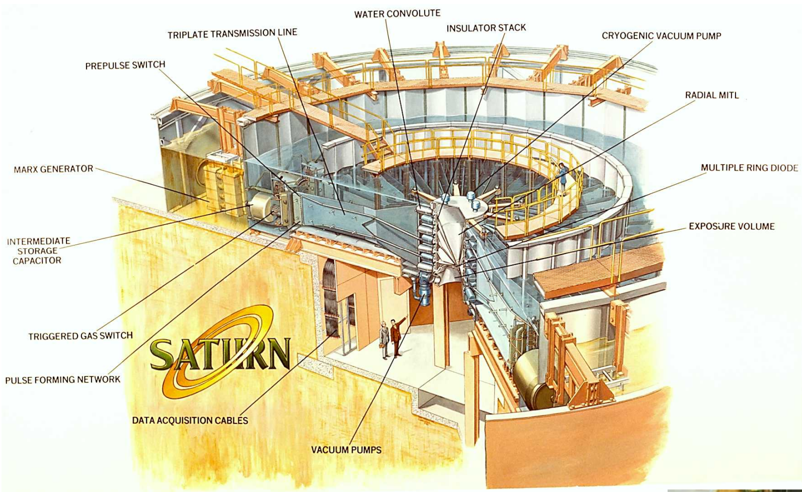
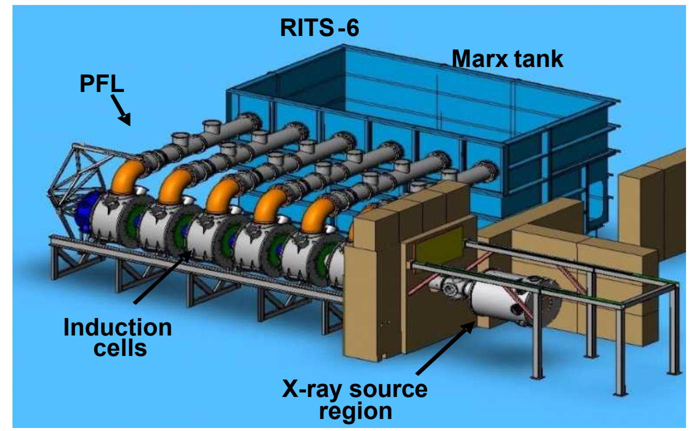
Nothing good can come from a theorist having oversight of pulsed power facilities in the 1-20 TW range.



Saturn Accelerator,
1.6 MeV, 10 MA, 40ns beam driver

RITS-6 Accelerator,
10 MeV, 180 kA, 70ns e-beam driver

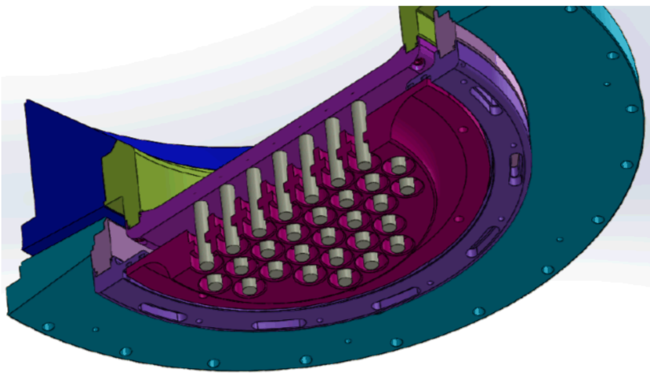


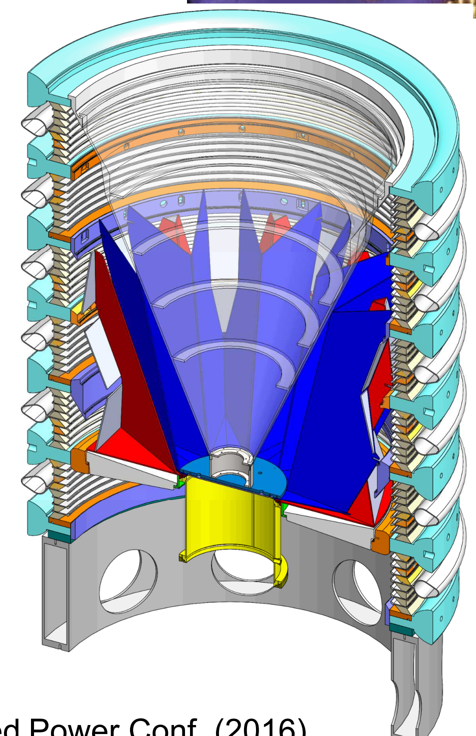
How to control vacuum on expts. at SuperSwarf, AWE

….but how it makes you appreciate pen, paper and the computer…and drive you to re-consider old ideas.

New diodes and power-flow on Saturn

Massively parallel rod-pinch array[1]



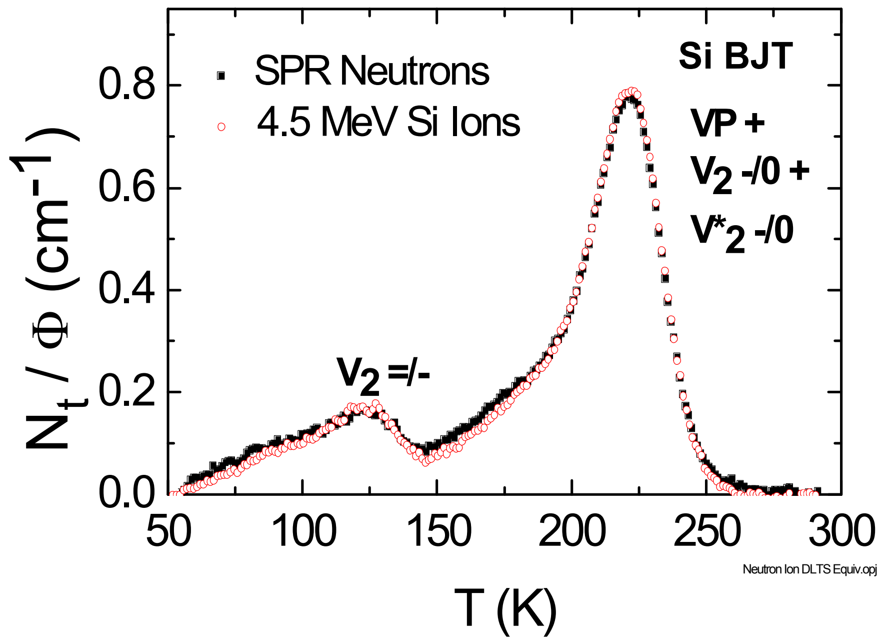


Clam Shell MITL[2]

Combine the power from Saturn's 36 modules into a single radial disk feed without magnetic-null losses, invert the voltage polarity, and drive large-area ion diode.

1. B.V. Oliver et. al., Proc. Euro-Asian Pulsed Power Conf. (2016).
2. P. Vandevender et. al., Phys. Rev. Accel. Beams, 18, 030403 (2015).

New applications: Ion beams to replicate neutron damage in electronics



Ion beam irradiation of transistors can emulate the effects of neutron damage

Deep Level Transient Spectroscopy[1] can interrogate the damage to transistors.

- **We can study materials like III-V GaAs under "neutron" irradiation**
- **Neutron damage exhibits deep broad DLTS features, suggestive of field-dependent emission (clustering effects more pronounced in III-V materials)**

1. D. V. Lang, JAP, 45, 3023 (1974)

Thanks for listening.

T (k)