Intense Charged Particle Beam Physics and Applications

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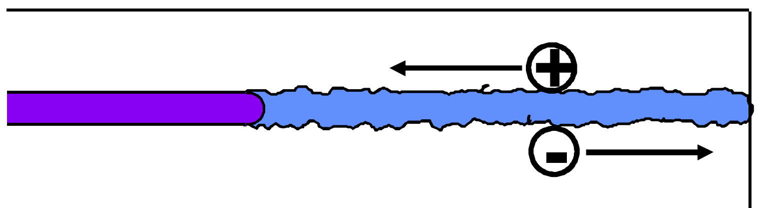
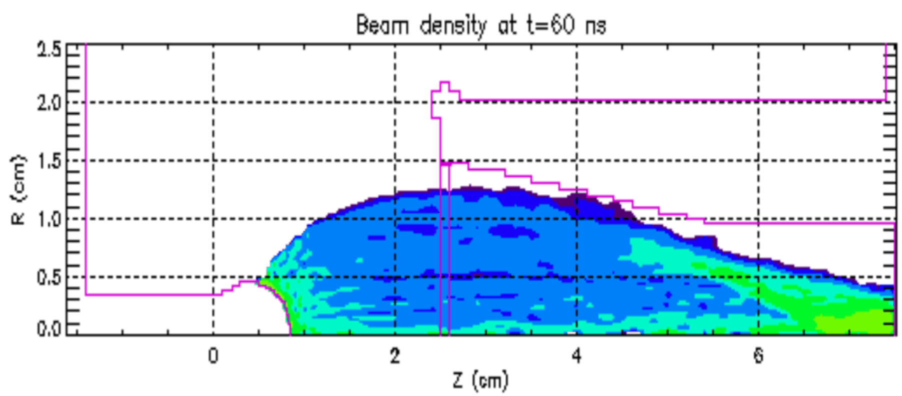
IEEE





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Outline

This lecture will present some theoretical constructs of intense charged particle beam generation and transport with occasional examples of present day use of such beams.

Introduction to Intense Beams:

Description and parameters
Force free equilibria for a cold e-beam in vacuum
Beam envelope equation

High Power Diodes:

Space charge limited emission
In the presence of background gas/plasma
With electron backscatter

Propagation:

e-beams in vacuum
e-beams in plasma - example, the paraxial diode
The ion hose instability

Magnetically insulated flow – equilibria

in vacuum
with ions

Introduction to Intense Beams

Intense charged particle beams have the unique characteristic that their density and velocity are large enough to induce strong electric and magnetic "self-fields" that are sufficient to greatly influence the beams' dynamics.

Advances in pulsed power technology over the last 30 years has led to the production of electron and ion beams with currents > 10 kA and kinetic energies ranging from 100 keV to > 10 MeV, with pulse durations in the 10-100 ns range.

The beams are generated in the accelerating gap of a high current diode and can either be accelerated after extraction from the diode to higher energies, transported in vacuum or in background gas/plasma, or they can be focused directly onto a target.

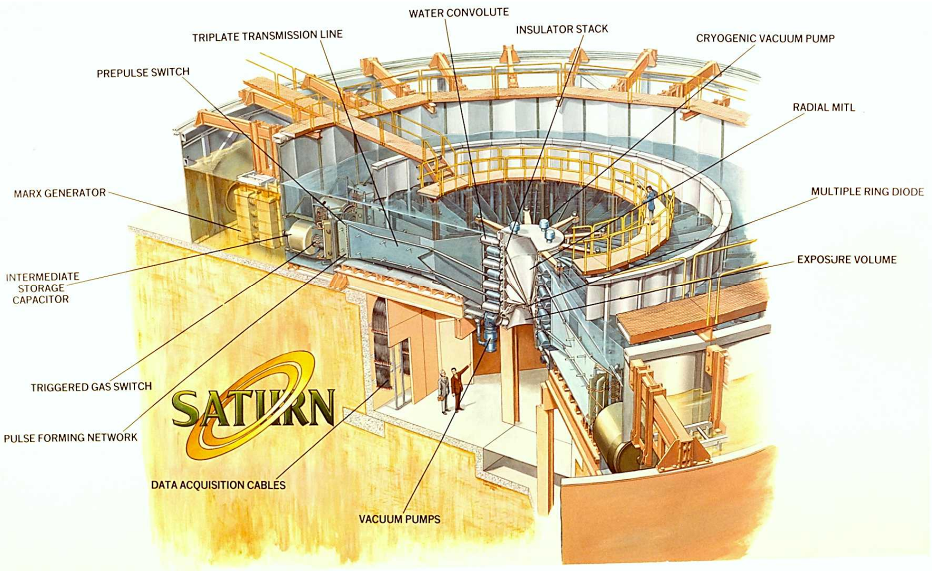
Applications include materials testing and modification, production of X-rays for lithography, radiography or nuclear weapon effects, high-power microwave generation, or nuclear fusion.

Key Overview References:

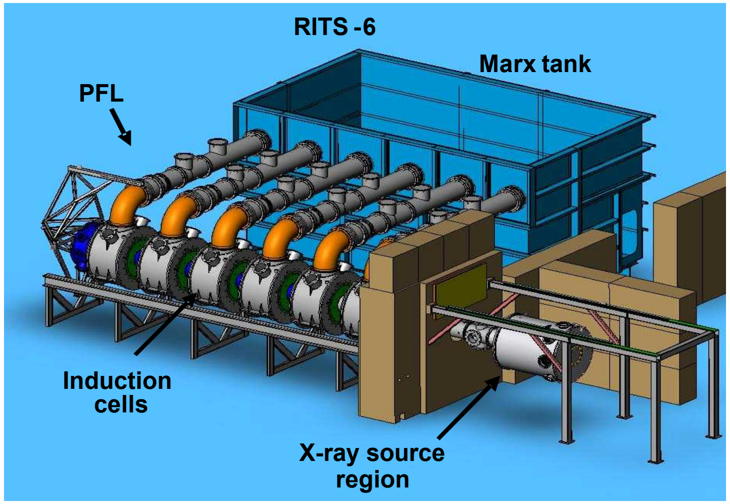
1. J.D. Lawson, *The Physics of Charged particle Beams*, Oxford Univ. Press, 1977
2. R.B. Miller, *Intense Charged Particle Beams,* Plenum Press, New York, 1982
3. S. Humphries, *Principles of Charged Particle Acceleration*, John Wiley and Sons., 1986
4. R.N. Sudan, Ch. 6.3 *Collective Beam-Plasma Interaction*, in Handbook of Plasma Physics Vol 2. Basic Plasma Physics II, edit. A.A. Galeev and R.N. Sudan, North-Holland Pub., 1984
5. R.C. Davidson, Ch 9.1 *Relativistic Electron Beam-Plasma Interaction with Intense Self-fields*, ibid

Introduction to Intense Beams

We will consider High power particle beams in the 10 GW– 10 TW range that are generated from pulsed power accelerators.



Saturn Accelerator,
Sandia National Laboratories
1.6 MeV, 10 MA, 40ns e-beam driver



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

The beams are generated in the accelerating gap of a high current diode and can either be propagated in vacuum or in background gas/plasma.

Typical Beam Parameters

Energy E_b= 0.1-20 MeV,

Current I_b= 0.01-10 MA,

Pulse length τ_b= 10-100ns,

Beam radius r_b= 0.1-10 cm,

Velocity v_b/c = 0.1-1

Current density j_b= 1-1000 kA/cm^2,

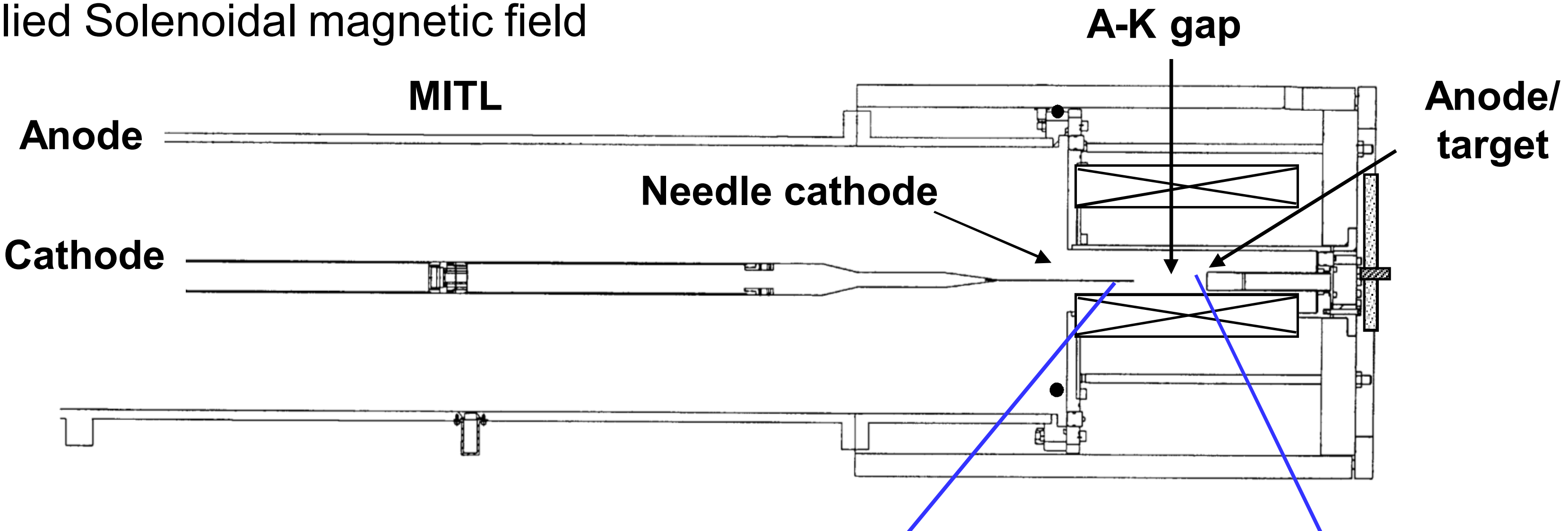
Beam density n_b= 1-10 cm^{-3},

Total charge Q_b= 5-500 mC

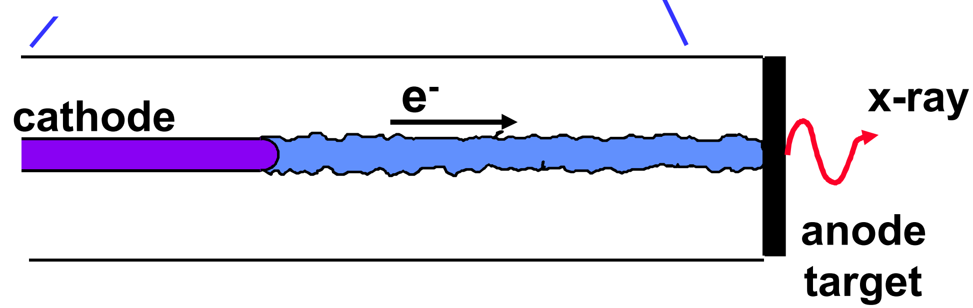
Relativistic factor $\gamma = \frac{1}{\sqrt{1-v^2/c^2}}$ **= 1-40**

Example: Pulsed-power driven e-beam diode for x-ray radiography applications

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 Self-field Forces

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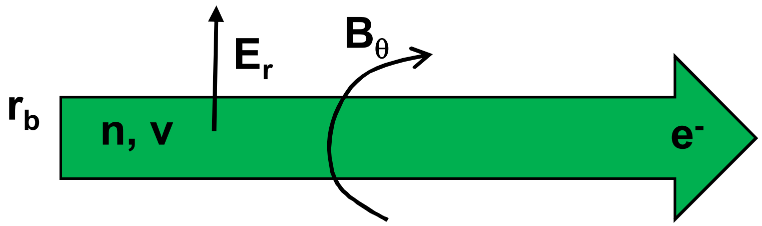
Consider the 1-D radial forces on a cold (zero emittance) uniform density electron beam drifting in vacuum.



The self-fields at the beam edge $E_r = 2\pi e n r_b$

$B_\theta = 2\pi e n r_b (v/c)$

Gaussian units are used

$c = 3\times10^{10}$ cm/s

The radial Lorentz force acting on the beam

$$F_r = e(E_r + v \times B_\theta)$$

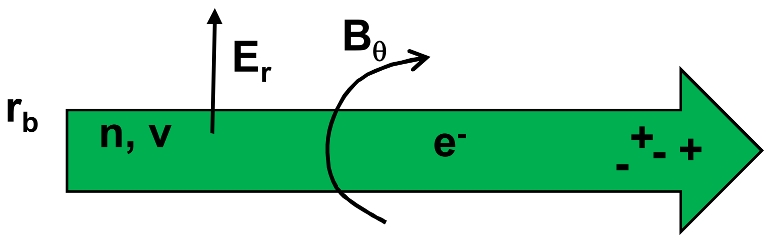
$$= 2\pi e^2 n r_b (1 - (v/c)^2) \equiv 2\pi e^2 n r_b / \gamma^2$$

The beam will only be in force balance (F=0) when v=c ($\gamma \rightarrow \infty$). Hence all beams will expand under their self-electric field unless their space-charge (en) is partially neutralized.

The Beam Envelope Equation

For relativisitic beams propagating in vacuum with finite emittance ε and axial velocity v_z, the force balance equation for the beam radial edge r_b (envelope) is

$$\frac{d^2 r_b}{dz^2} = \frac{2\nu}{\beta^2 r_b}\left[1 - f_e - (1 - f_b)\,\beta^2\right] + \frac{\varepsilon^2}{r_b^3}$$



Where the conditions $v_z >> v_r, v_\theta$ such that $d/dt \cong v_z\, d/dz$, and

$\beta = v_z/c$, $\gamma = 1/\sqrt{1-\beta^2}$

ε= beam emittance,

$$\nu \equiv \frac{eI_b}{\gamma\beta mc^3} \equiv \frac{I_b}{I_A}$$

$I_A = \gamma\beta\ 17\ (kA)$, is the Alfven current

$$\varepsilon = 4\sqrt{<r^2><r'^2>-<rr'>^2}$$

$$f_e = \frac{n_p}{n_b}$$ is the charge neutralization fraction

$$f_b = \frac{I_p}{I_b}$$ is the current neutralization fraction

Intense Beam Generation

Diodes

Space-charge limited diodes[1].

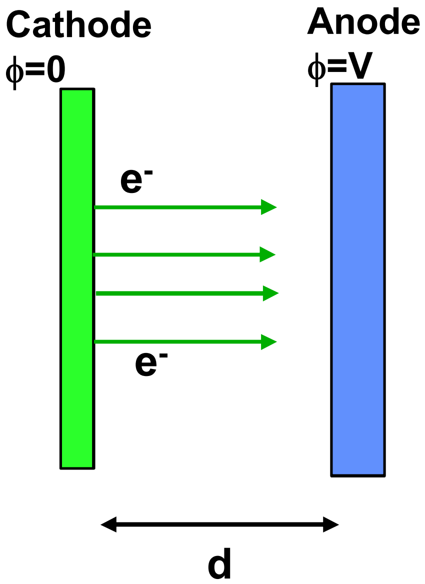
SCL diode: e.g. 1-D, non-relativistic large area

$$\frac{d^2\varphi}{dz^2} = en_e$$

$$j = en_e v = const.$$

$$\frac{1}{2}mv^2 = e\varphi$$

$$\rightarrow \quad \boldsymbol{j \propto \frac{1}{d^2}\sqrt{\frac{2e}{m}}\, V^{3/2}}$$



If there is some space charge neutralization, than

$en_e \rightarrow en_e$(1-f) $\quad$ f=n_i/n_e

$$\rightarrow \quad \boldsymbol{j \propto \frac{1}{(1-f)d^2}\sqrt{\frac{2e}{m}}\, V^{3/2}}$$

1. I. Langmiur and K. Blodgett, Phys. Rev. **22**, 347 (1923); C.B. Wheeler, J. Phys. A **10**, 631 (1977)

Bi-polar (electron + ion) space charge limited and self-magnetic field limited diodes.

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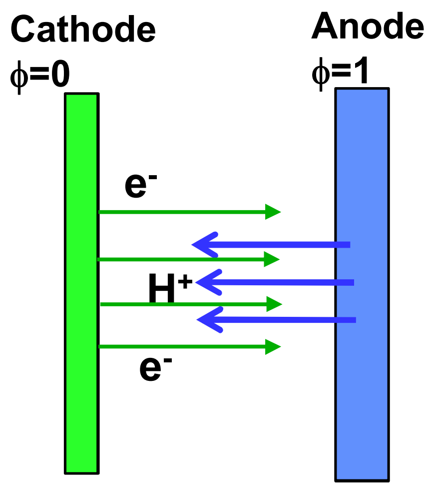
SCL diodes[1]: e.g. 1-D, non-relativistic large area

$$I = \alpha I_{cl}, \qquad 0.5 < \alpha < 5 \quad (\alpha = 1.86 \text{ for planar bi-polar diode})$$

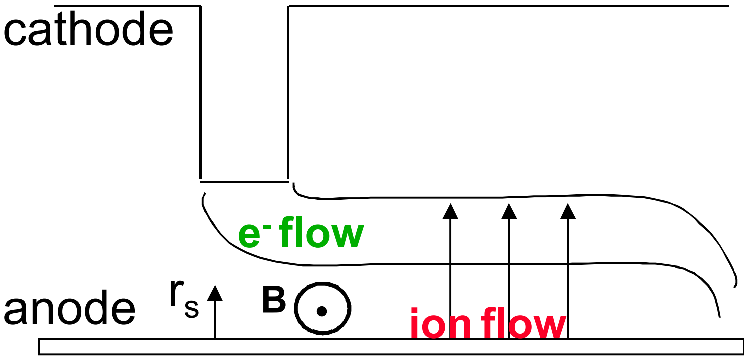
$$I_{cl} = \frac{1}{9\pi}\sqrt{\frac{2e}{m}}\frac{V^{3/2}}{d^2} \ \text{A},$$



Self-limited diodes: e.g. rod-pinch[2]

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

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



The factor α, is dependent on geometry, voltage, and ion distribution

1. I. Langmiur and K. Blodgett, Phys. Rev. **22**, 347 (1923); C.B. Wheeler, J. Phys. A **10**, 631 (1977)
2. G. Cooperstein et al. Phys. Plasmas, **8**, 4618 (2001)

The effect of electron backscatter at the anode[1]

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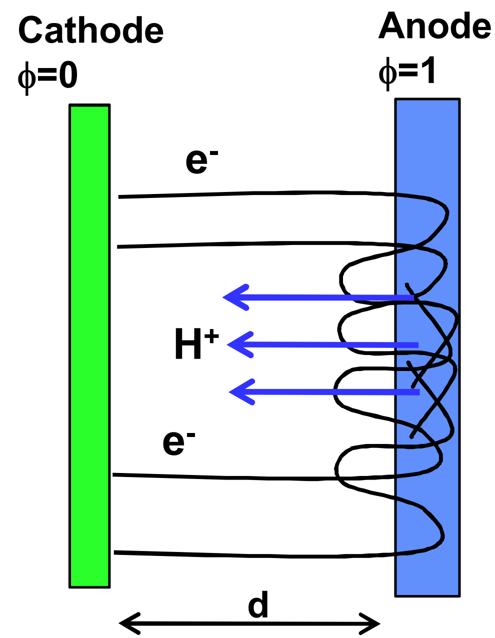
Bi-polar Child-Langmuir currents are modified by the presence of the extra electron space charge scattered into the A-K gap

This enhances the ion space charge emission and changes the impedance



$$\left(\frac{d\phi}{dx}\right)^2 = \frac{16}{9}\frac{j_e}{j_{cl}}\, g(\phi)$$

$$g(\phi) = \sqrt{\phi + \frac{eV}{2mc^2}\phi^2} - \left(\frac{M}{m}\right)^{1/2}\frac{j_i}{j_e}\left(1-\sqrt{1-\phi}\right) +$$

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

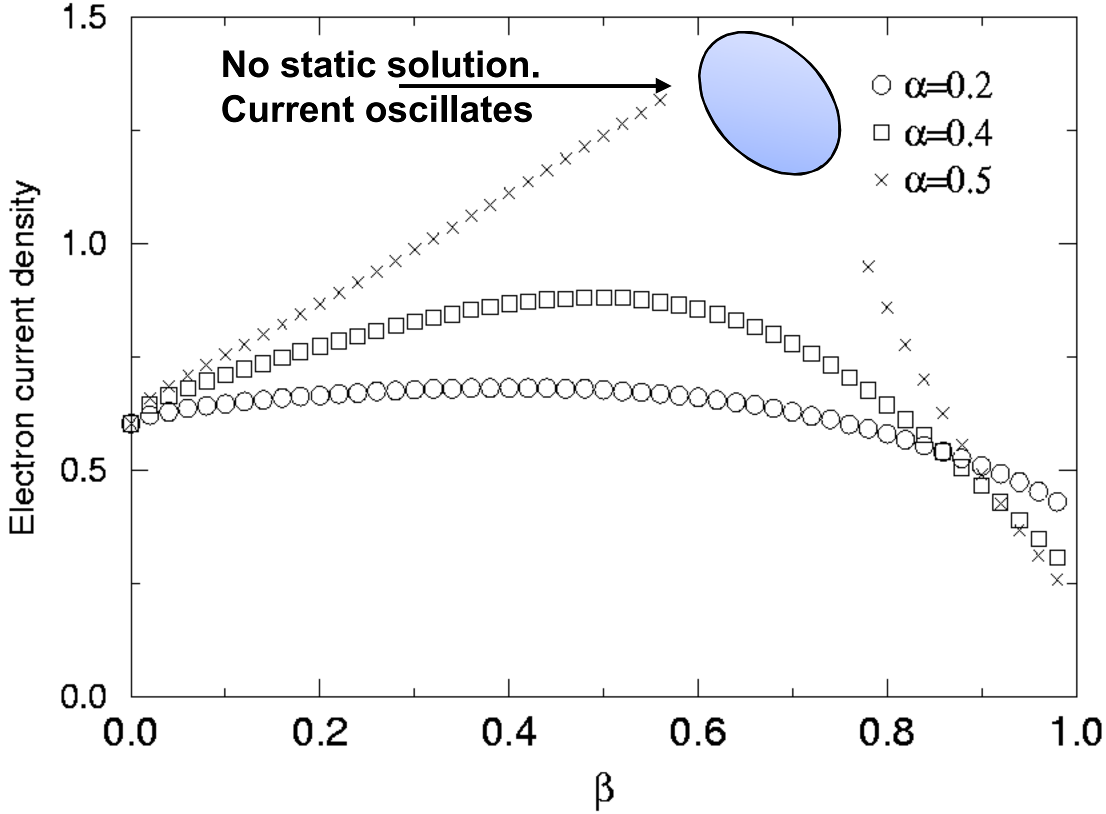
$$j_{scat} = \alpha\, j_{incident}$$

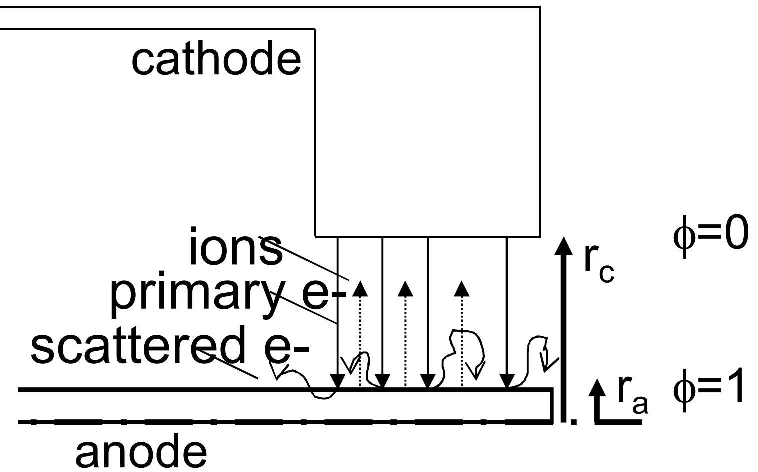
$$E_{scat} = \beta E_{incident}$$

Extra terms due to scattering

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)

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





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

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

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

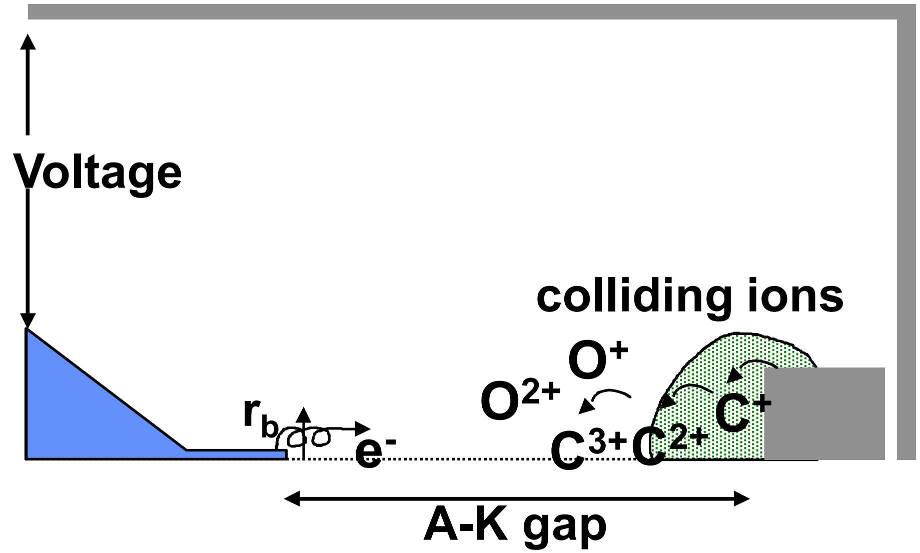
As the fraction of reflected beam current goes up, so does the total current. However , there is a maximum and the current is stable.

1. B.V. Oliver, T.C. Genoni et. al J. Appl. Physics **90** , 4951 (2001)

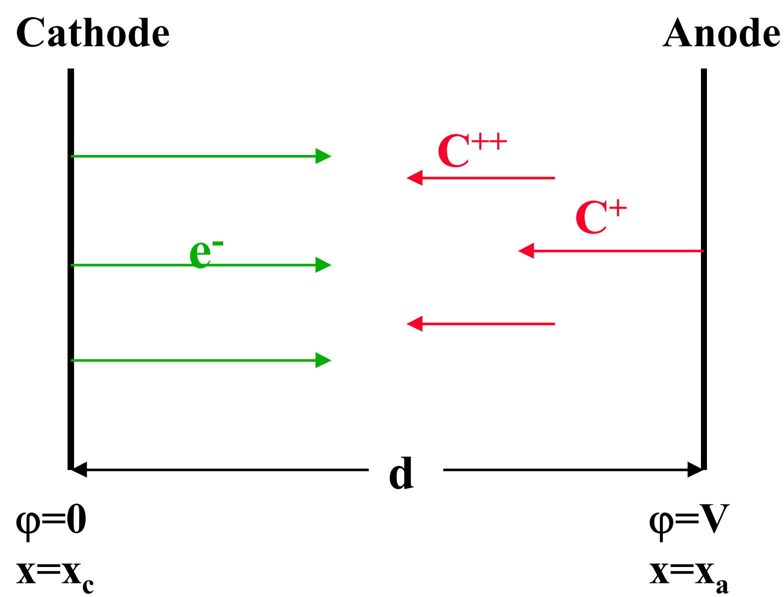
Charge stripping of ions can increase electron emission and thus current[1]

Non-protonic ions (e.g. C,O) from the anode collide and charge-strip while traversing the A-K gap.

The electron current I_e increases when the excess ion charge reaches the cathode. Feedback causes impedance collapse.



$$j_i = j_e \sqrt{\frac{Zm}{M}(1+eV/2mc^2)}$$



But $j_i(x_c,t) \neq j_i(x_a,t)$ because of charge stripping during ion transit across the gap!

1. B.V. Oliver, D.R. Welch, et. al, Bull. Am. Phys. Soc. **48**, 95, (2003)

The ion current density increases during transit across the gap

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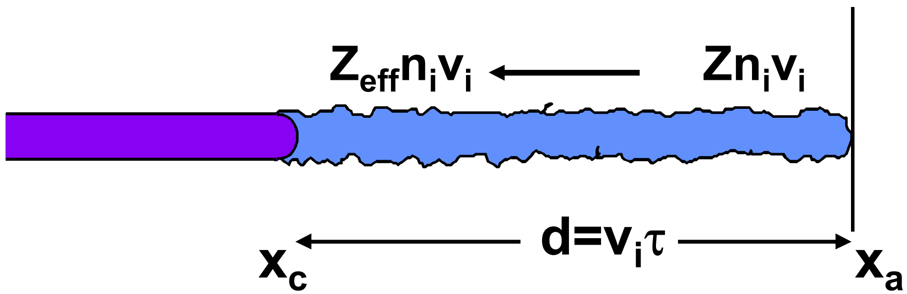
Ion current density increases in proportion to the ionization fraction.



$$Z_{eff} = Z + \nu_{ion}\tau, \qquad \tau = \frac{d}{v_i}$$

$$j_i(x_c, t) = \frac{Z_{eff}}{Z}\, j_i(x_a, t - \tau)$$

The ionization frequency ν_{ion} is proportional to the ion current density at the anode and the ionization cross-section σ_{ion}:

$$\nu_{ion} = n_i < v_i \sigma_{ion} > \;\approx\; \frac{j_i(x_a, t-\tau)}{Ze}\sigma_{ion}$$

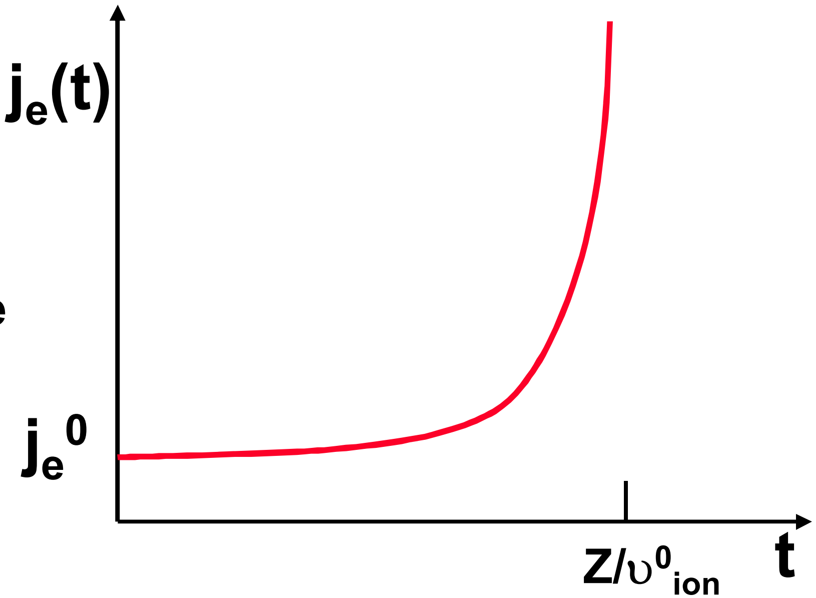
Non-linear response occurs because Z_{eff} is proportional to j_i through ν_{ion}

Non-linear (explosive) electron current time-dependence results[1]

The time dependent solutions for the electron current density are nonlinear because of the relation of J_i to J_e and Z_{eff}.

$$\left(\frac{Z_{eff}}{Z}-1\right) = \frac{\nu_{ion}\tau}{Z} = \frac{j_i(x_a,t-\tau)\tau}{Z^2 e}\sigma_{ion} \equiv \sqrt{\frac{Zm}{M}(1+eV/mc^2)}\;\frac{j_e(x_a,t-\tau)\tau}{Z^2 e}\sigma_{ion}$$

$$j_e(x_a,t) = j_e^0\,\frac{1}{1-\alpha t}$$



Solutions result in explosive behavior on time scale $1/\alpha$ ~Z/ν^0_{ion}

$$\alpha = \frac{j_e^0}{Z^2 e}\sqrt{\frac{Zm}{M}(1+eV/2mc^2)}\quad\sigma_{ion}$$

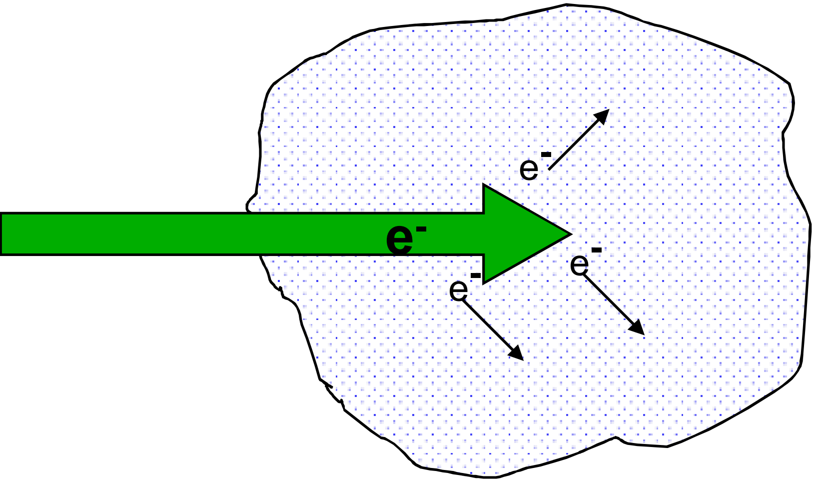
~ 10 ns

1. B.V. Oliver, D.R. Welch, et. Al, proceedings of the 45th APS-DPP, 2003

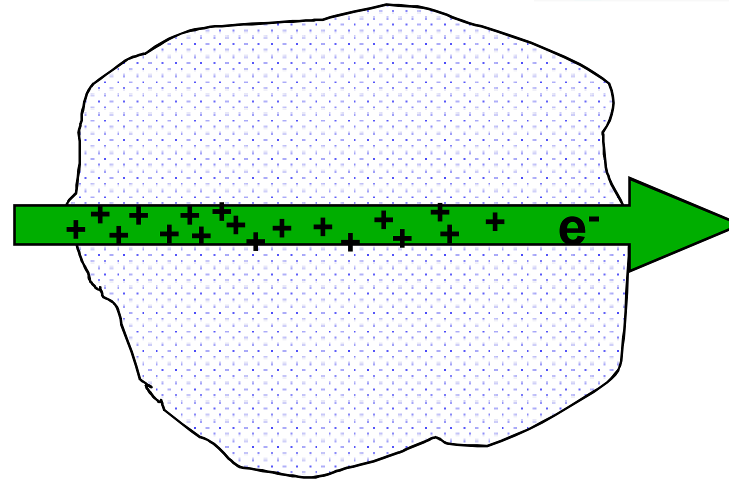
Beam Propagation

In vacuum and gas/plasma

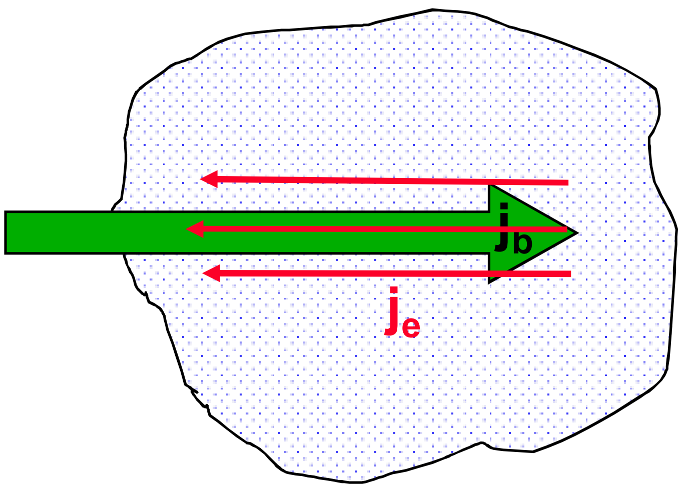
Electron beam neutralization in plasma



e-beam expels plasma electrons



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



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

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

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

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

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

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

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

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

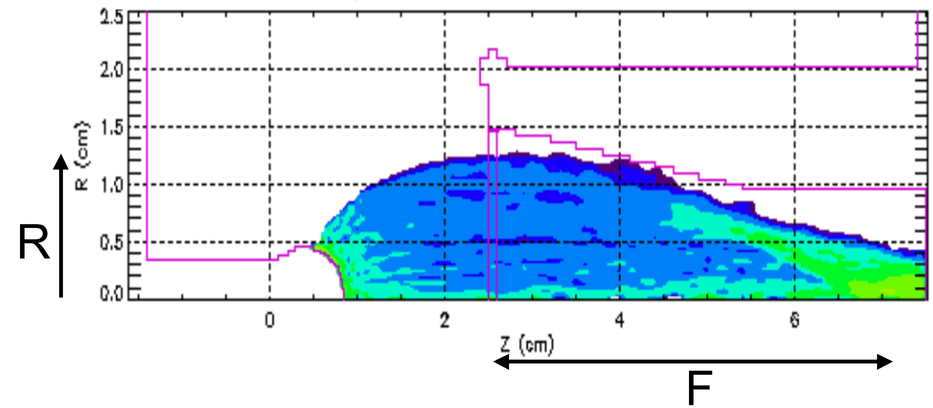
For $\varepsilon^2 << 2R^2 I_{net}/I_A$

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

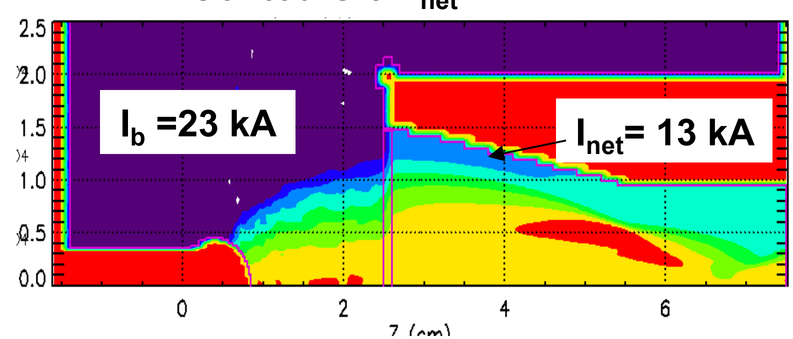
$$I_A = \gamma\beta\ 17\ (\text{kA}),$$

$$\varepsilon = 4\sqrt{<r^2><r'^2> - <rr'>^2}$$

Beam density contours from Lsp simulations



Contours of I_{net}



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

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

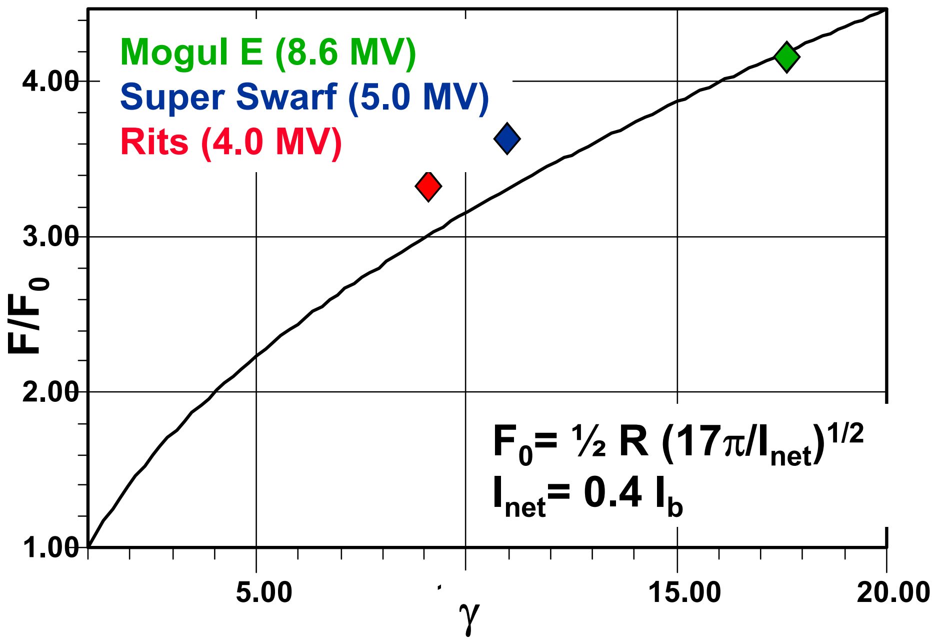
Hall current advection — Resistive diffusion

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

Data suggests average net current in cell ~ 0.3-0.4 I_b

Envelope oscillation wavelength $\lambda \approx 2\pi a(I_A/I_{net})^{1/2}$
Equilibrium radius $a \approx \varepsilon(I_A/2I_{net})^{1/2}$

Focal length vs. γ,



Beam radius vs. drift length

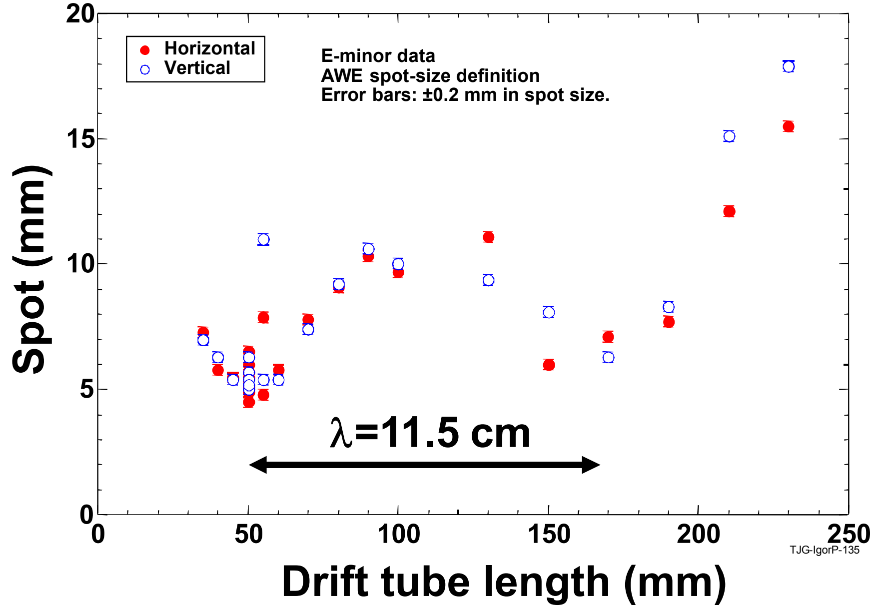


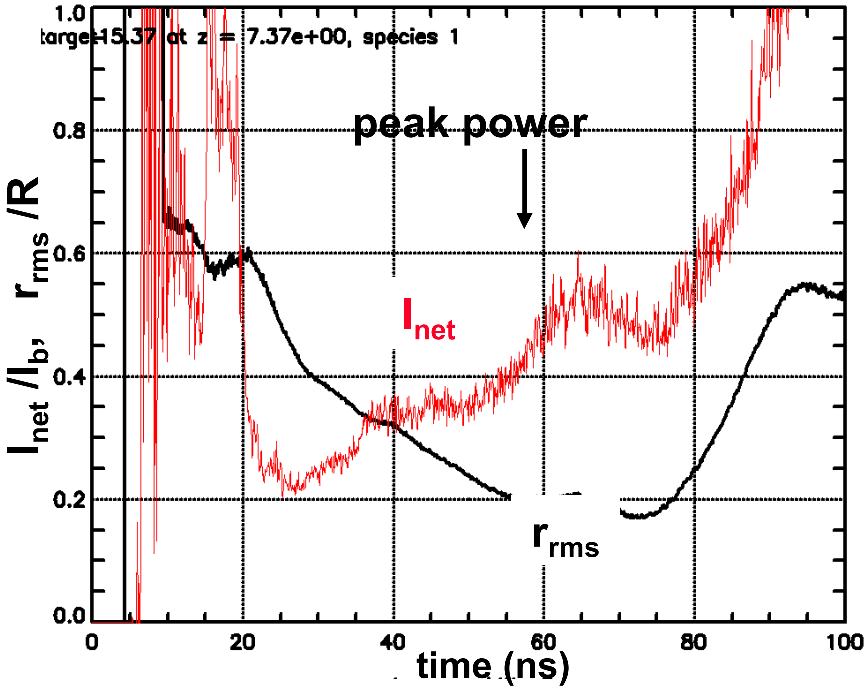
Fig. courtesy of A. Birrell[1]

Data from AWE[1,2] (5.3 MV, I_b=33 kA)
λ = 11.5 cm implies a time average net current $I_{net}/I_b \sim 0.4$
a = 0.5 cm implies emittance $\varepsilon \sim 0.18$ cm-radian

1. A. Birrell et al. IEEE Trans Plasma Sci. 28, 1660 (2000)
2. B.V. Oliver and D. Welch Proc. Intl Conf. Intense Beams, Russia, 2004

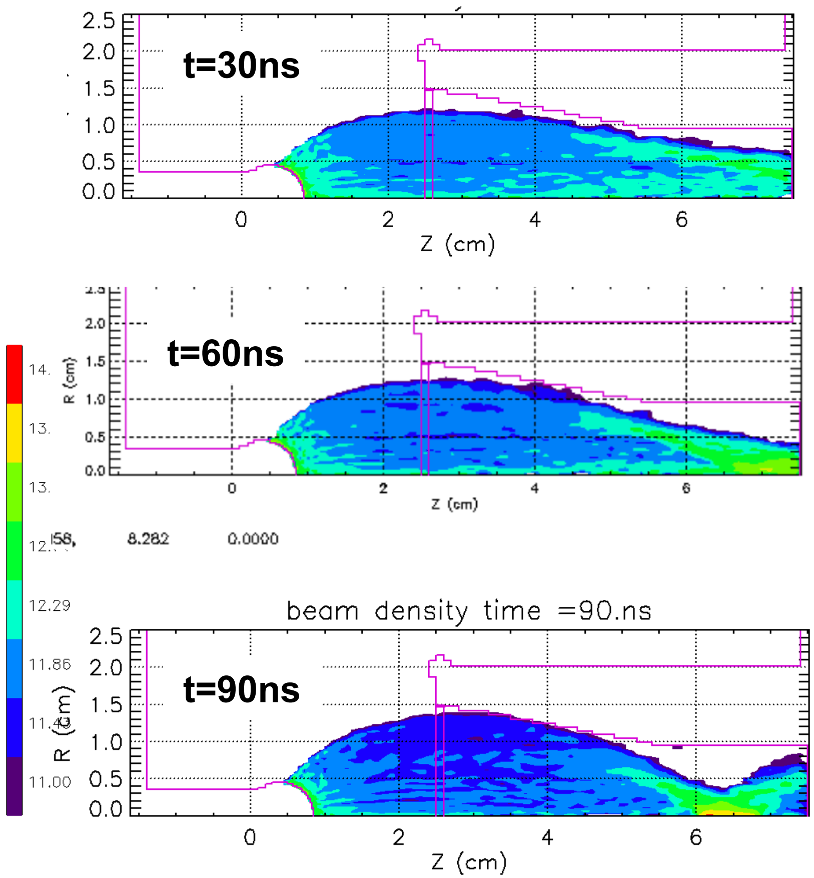
Time dependence of I_{net} causes a sweeping focus!

$$F(t) \cong \frac{R}{2}\sqrt{\frac{\pi I_A}{I_{net}(t)}}$$



Beam rms radius and I_{net} vs time. At peak power, I_{net}= 9 kA, r_{rms}= 0.2 cm

Contours of beam density

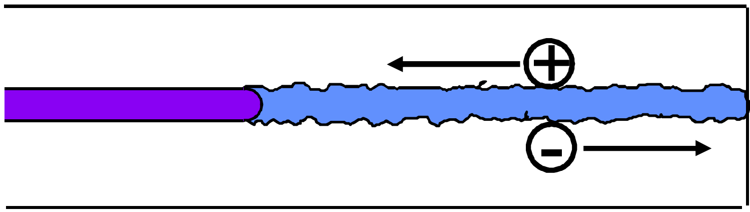


Focal sweeping is a primary contributor to larger than desired time integrated spots.

The ion-hose instability

IFR ion hose instability[1]:

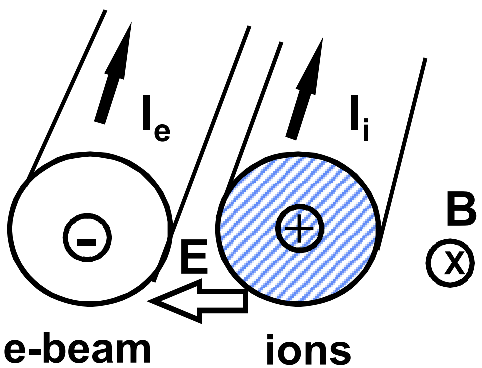
Backstreaming ion channel causes space-charge attraction of e-beam. With finite ion mass → ions move →convective instability.



Growth rate ~ ion inertial time
$\Gamma \approx \omega_{pi} = (4\pi e^2 n_b/M)^{1/2}$ ~ 5 x 10^9 s^{-1}

Convective length
$\lambda \approx (c/\omega_p) = (\gamma mc^2/4\pi e^2 n_i)^{1/2}$

In the presence of a solenoidal field, beam rotates and growth rate is modified in limit $(\Omega_e/\omega_p) >> 1$ [2]



$\lambda_{ce} \approx \lambda\,(\Omega_e/\omega_p)$ ~ 1 cm immersed-B_z diode
10 cm linear induction accelerators

Time and length scales imply non-linear evolution and saturation.

1 H. L. Buchanan et al, Phys. Fluids **30**,1456 (1987); EP. Lee Phys. Fluids **21**, 1327 (1978)
2 D.V. Rose, T.C. Genoni, D.R. Welch, Phys. Plasmas, **11**, 4990 (2004)

Nonlinear modeling of ion-hose saturation amplitude in good agreement with 3-D LSP simulations.

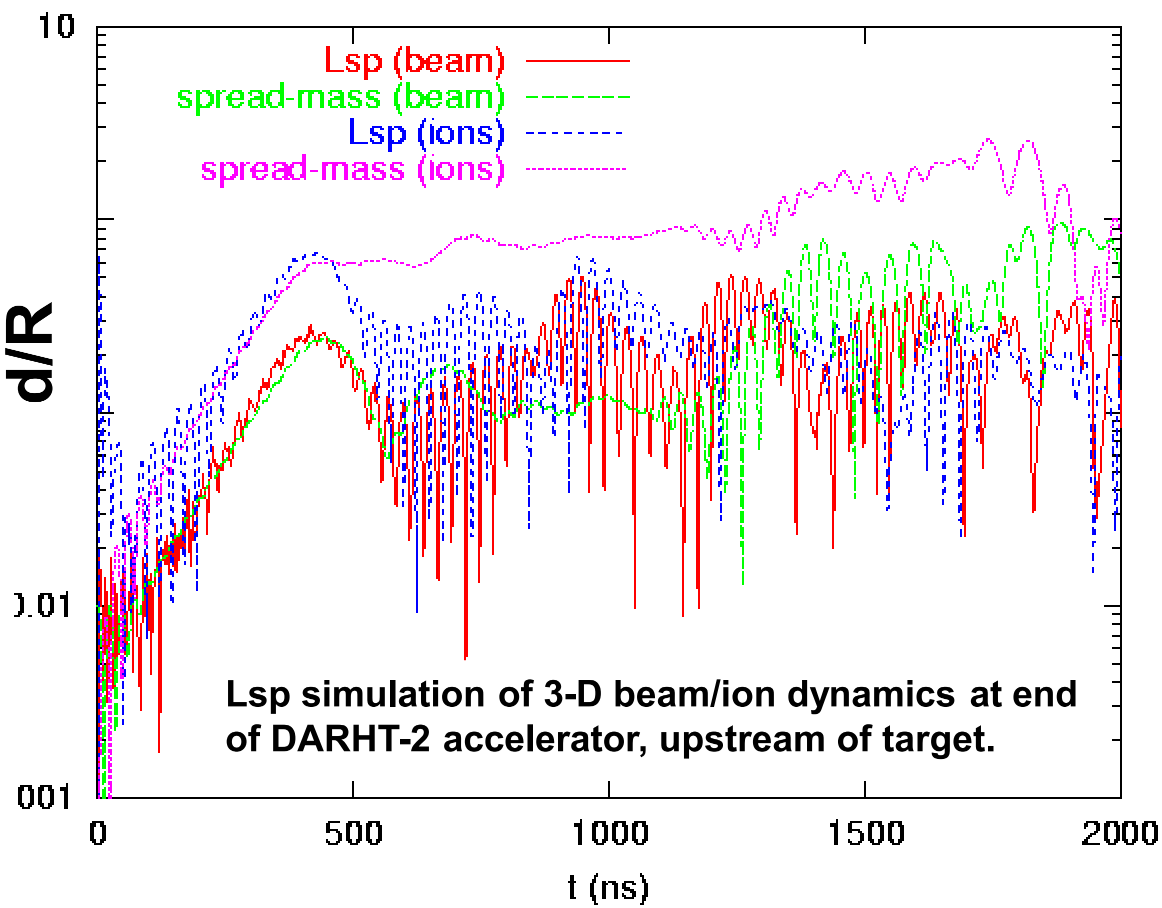
Linear and non-linear theory of ion-hose instability captures primary 3-d dynamics of the beam ion interaction.

Nonlinear evolution occurs within 3-4 growth times.

Spread-mass[1] modeling of ion-hose saturation provides information for scaling to different beam and plasma conditions.

Saturation amplitude scales with linear growth rate $1/\lambda_{ce} \propto 1/B$.

Beam and ion centroid displacement vs. time (normalized by beam radius R)



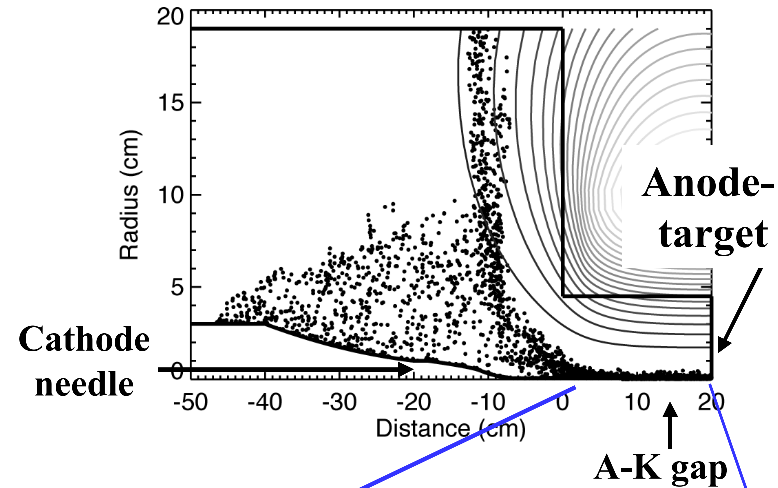
1. E.P. Lee Phys. Fluids 21, 1327 (1978)
2. D.V. Rose, T.C. Genoni, D.R. Welch, Phys. Plasmas, **11**, 4990 (2004):

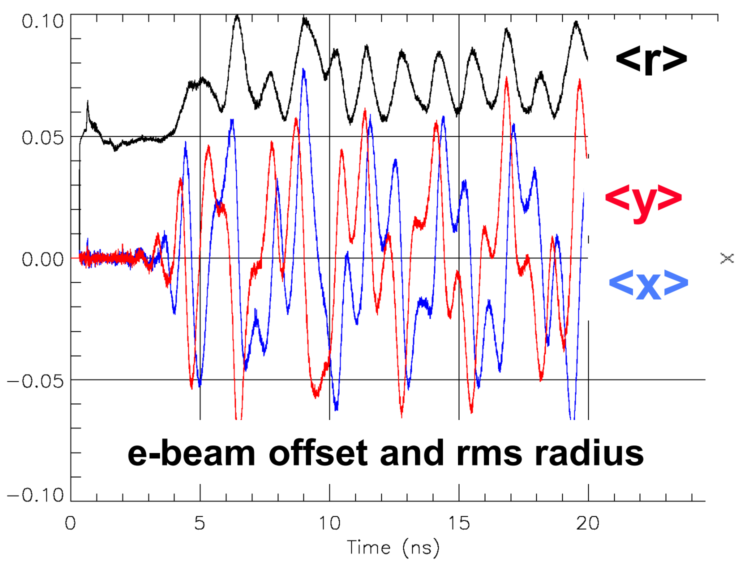
The ion-hose instability in the applied-B_z diode

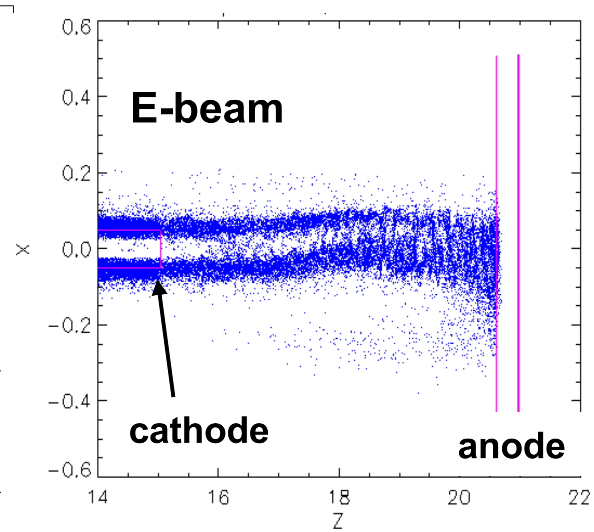
Immersed-B[1]: Diode used for x-ray radiographic applications. Creates high intensity bremmstrahlung radiation.

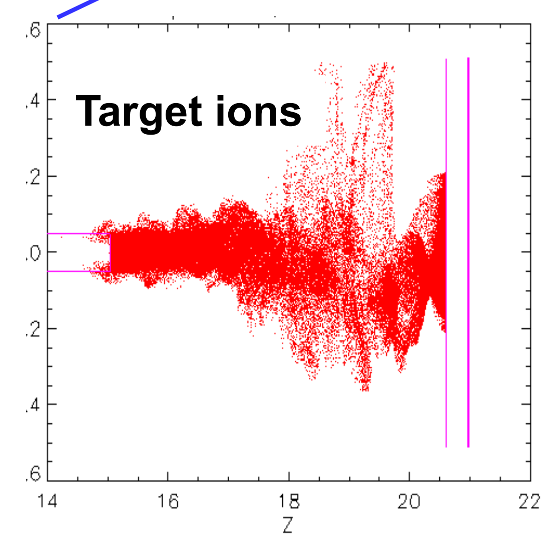
Beam spot on target determined by ion-hose saturation amplitude

$$\langle r_{sat} \rangle \approx \frac{c}{\Omega_e}\sqrt{2\gamma \frac{I_b}{I_A}}$$









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)

Magnetic Insulation

The Magnetically Insulated Transmission Line

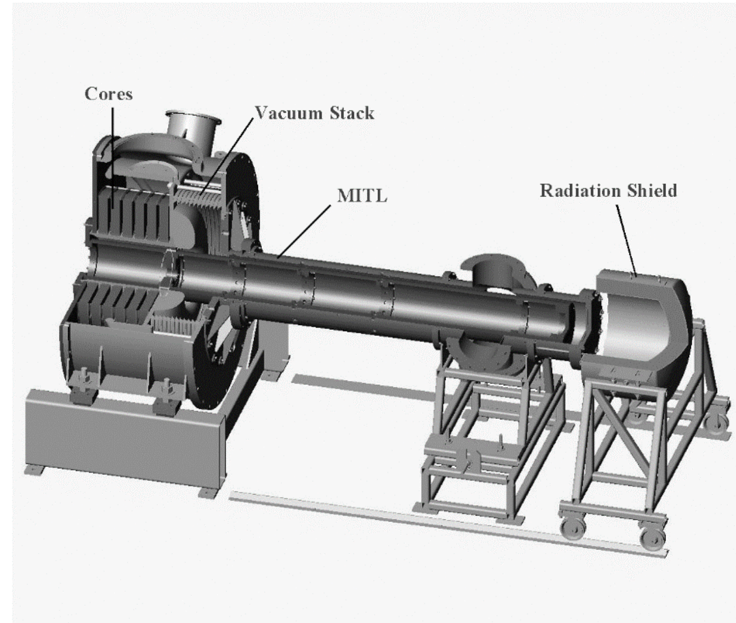
The MITL is a coaxial transmission line (solid metal conductor) that is an integral part of Inductive Voltage Adder (IVA) accelerators:

- -they act to connect in series each induction cell
- -they allow power transmission downstream

For high voltage systems, the electric field inside the coaxial transmission line exceeds the threshold for electron emission off the cathode surface (~ 200-250 keV/cm). And for high current systems, emitted electrons are magnetically insulated from crossing the A-K gap of the transmission line and flow downstream. Hence the name Magnetically Insulated Transmission Line.

The presence of the emitted electron space-charge and current, inside the line, changes the impedance of the transmission line from its vacuum value. Thus, the MITL's I,V characteristics (operating impedance) are considerably more complicated then a normal vacuum TL. In fact, the MITL impedance is non-linear:

$$Z_{MITL} = \frac{V}{I_{MITL}} = \frac{V}{I(V)}$$



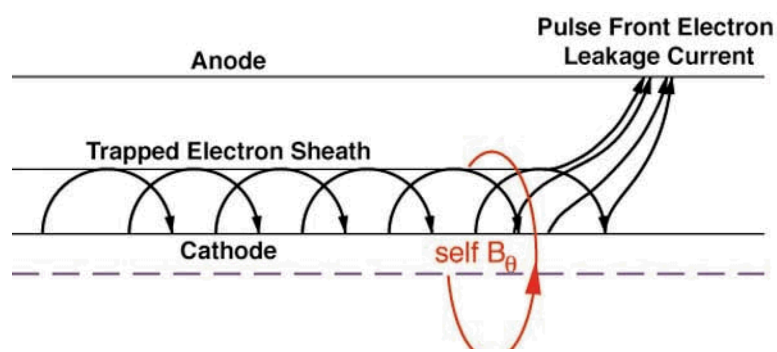


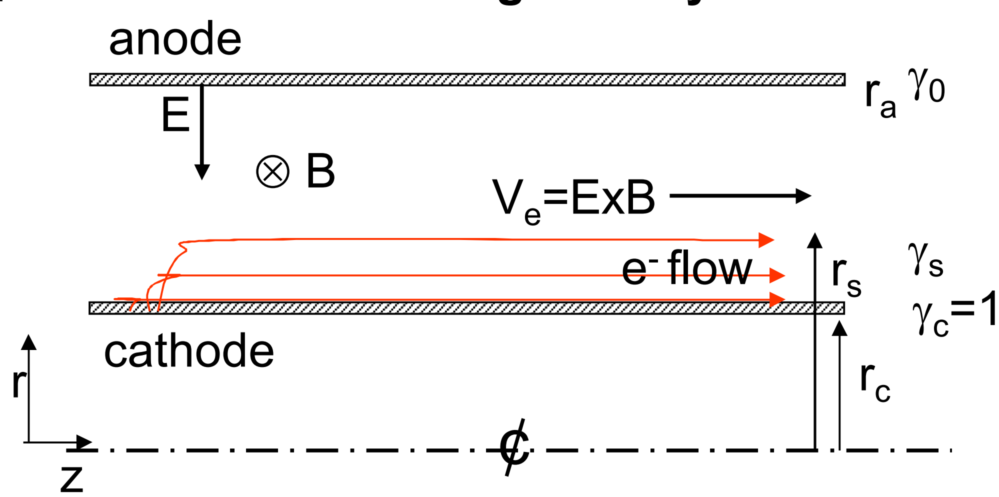
Illustration of axis-symmetric insulated flow in the MITL

1-D, equilibrium flow models

A lot of good theory was established in the mid 1970s on magnetic insulation which has been used extensively to determine the MITL impedance characteristics[1-3].

The relativistic electron flow is treated self-consistently assuming all electrons born at the same potential and the flow is governed by ExB drift. Vacuum solutions are matched at the edge of the electron sheath.

MITL geometry



$$\nabla \phi \times B = v_e \qquad \text{momentum}$$

$$\nabla^2 \phi = n_e \qquad \text{Poisson}$$

$$\nabla \times B = -n_e v_e \qquad \text{Ampere}$$

$$\gamma - \phi = 1;$$

$$\gamma = \sqrt{1/(1 - v^2)} \qquad \text{Cons. of energy}$$

1. John M. Creedon, J. Appl. Phys, **46**, 2946 (1975)
2. M. Reiser, Phys. Fluids, **20**, 477 (1977)
3. A. Ron et al., IEEE Trans. Plasma Sci ps-1,85 (1973)

1-D, laminar flow model of Creedon

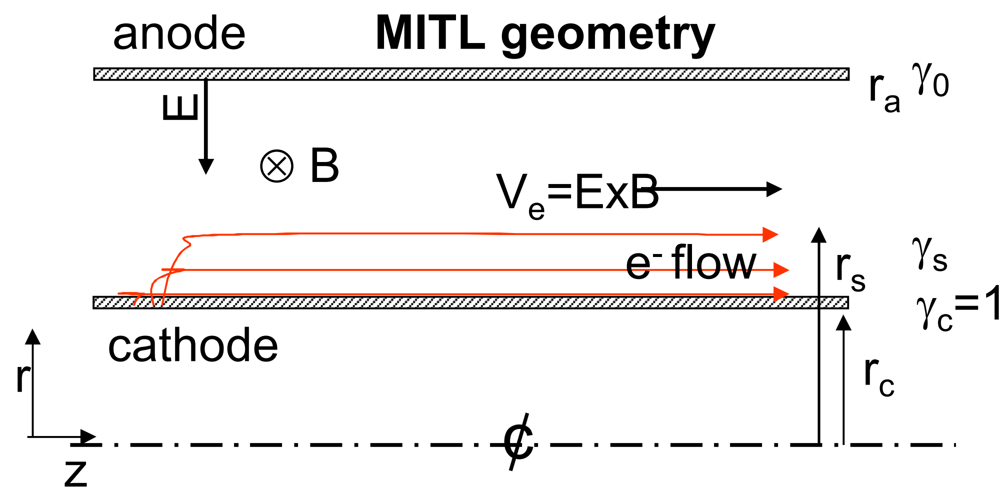
One obtains an infinite number of equilibria relating the MITL current to the voltage for various sheath thickness (energies), e.g. from Creedon[1]:

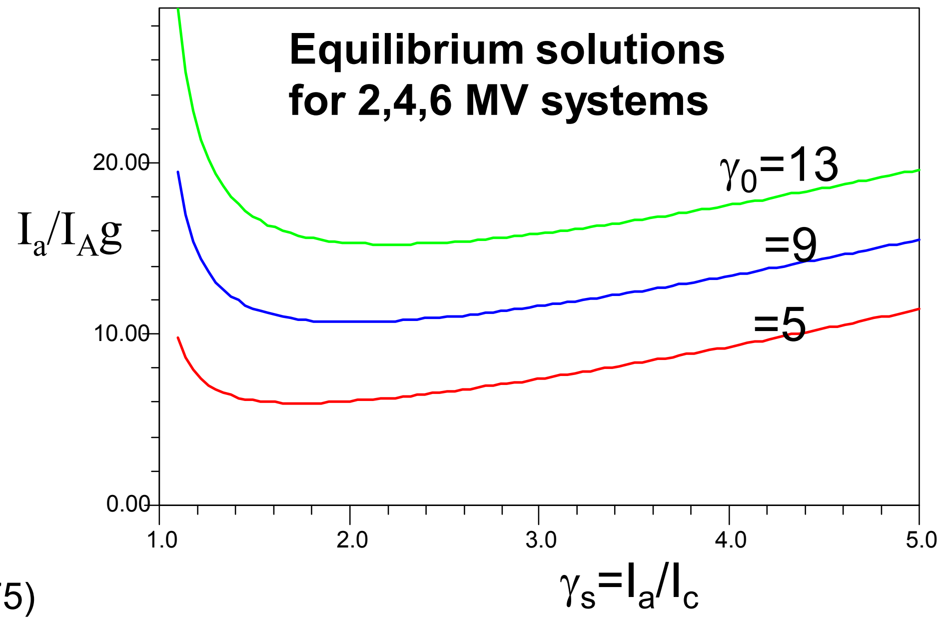
$$I_a = I_A g\, \gamma_s [\operatorname{acosh}(\gamma_s) + \frac{\gamma_0 - \gamma_s}{\sqrt{\gamma_s^2 - 1}}]$$

$$\gamma_s = \frac{I_a}{I_c}$$

I_A=8500 (kA), $g = 1/\ln(r_a/r_c)$,
γ_s=gamma @ electron sheath edge,
$\gamma_0 = 1+(eV/mc^2)$ = applied voltage

A more generalized model is described by Ottinger[2] et al.





1. John M. Creedon, J. Appl. Phys, **46**, 2946 (1975)
2. Ottinger et al. IEEE Trans. Plasma Sci. vol. 36, pp. 2708- 2008-2721, 2008

Insulation in the presence of ion emission

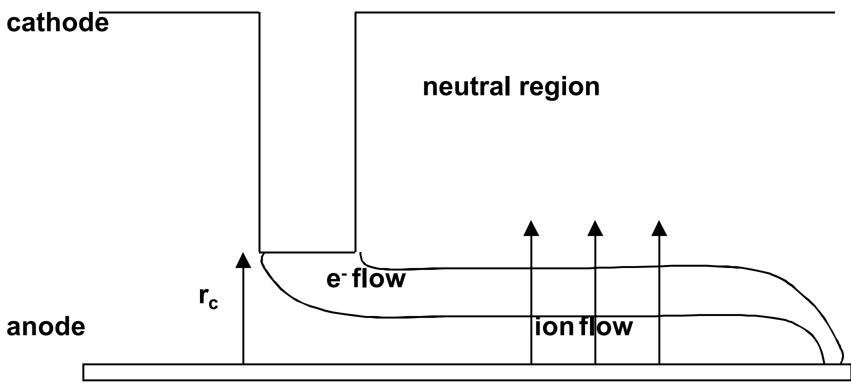
•Follows closely Creedon et al.[1] on 1-D radial relativistic equilibrium electron flow

•Includes a background ion space-charge

•Ion current is radial and included via a boundary current. Ion charge and current density are solved self-consistently.

•Considers the region downstream of the cathode blade. It is characterized by being charge and current neutral at radii > r_c

Schematic of insulated flow in the rod-pinch diode



$$\nabla \phi \times B = v_e \quad \text{momentum}$$

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$$\gamma - \phi = 1;$$

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Coupled ion response

$$\nabla \bullet J_i = 0. \Rightarrow r_c J_i = r\, n_i v_i = \text{const.}$$

$$\frac{1}{2} v_i^2 = \left(\frac{Zm}{M}\right)(\gamma_a - \gamma)$$

$$n_i = \frac{r_c J_i}{r\sqrt{2Zm(\gamma_a - \gamma)/M}}$$

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

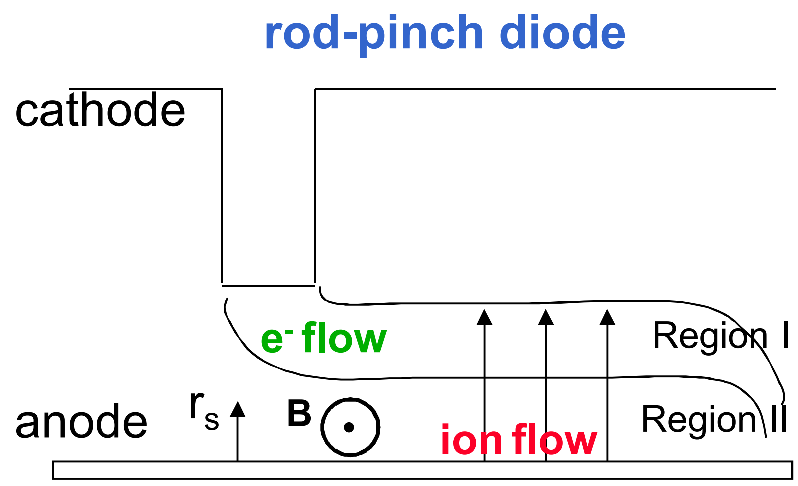
Sandia National Laboratories

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

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

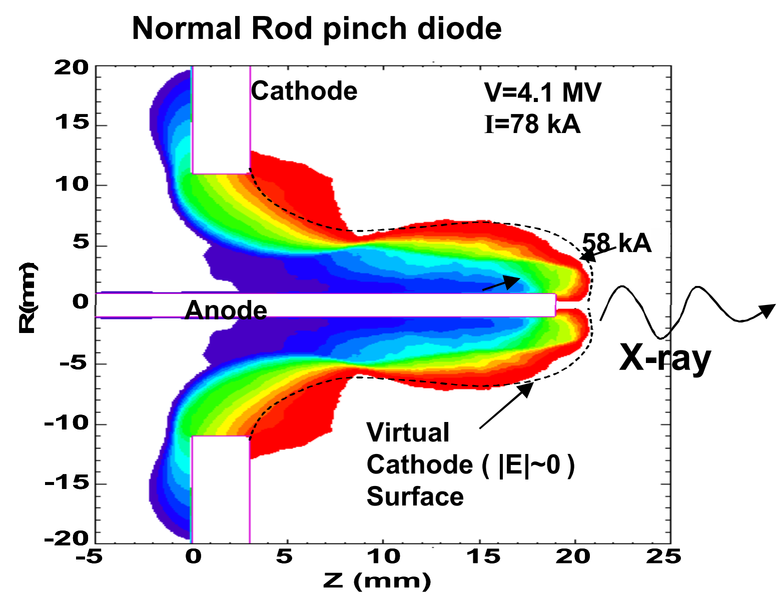


Fig. courtesy of S. Swanekamp, NRL

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