~~The~~ Some physics of beam transport in high power electron beam diodes*

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An overview of 10+ years of advancement in modeling high power diode operation

Topics reviewed:

- **Bi-polar flow and the importance of ions**
- **Effect of electron scattering/backscattering on the anode**
- **Effect of ionization in the A-K gap**
- **Magnetic self insulation**

Recent observations:

- **impedance lifetime**
- **role of electrode plasmas**
- **anomalous resistivity**

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This work has been conducted in collaboration with a large number of people

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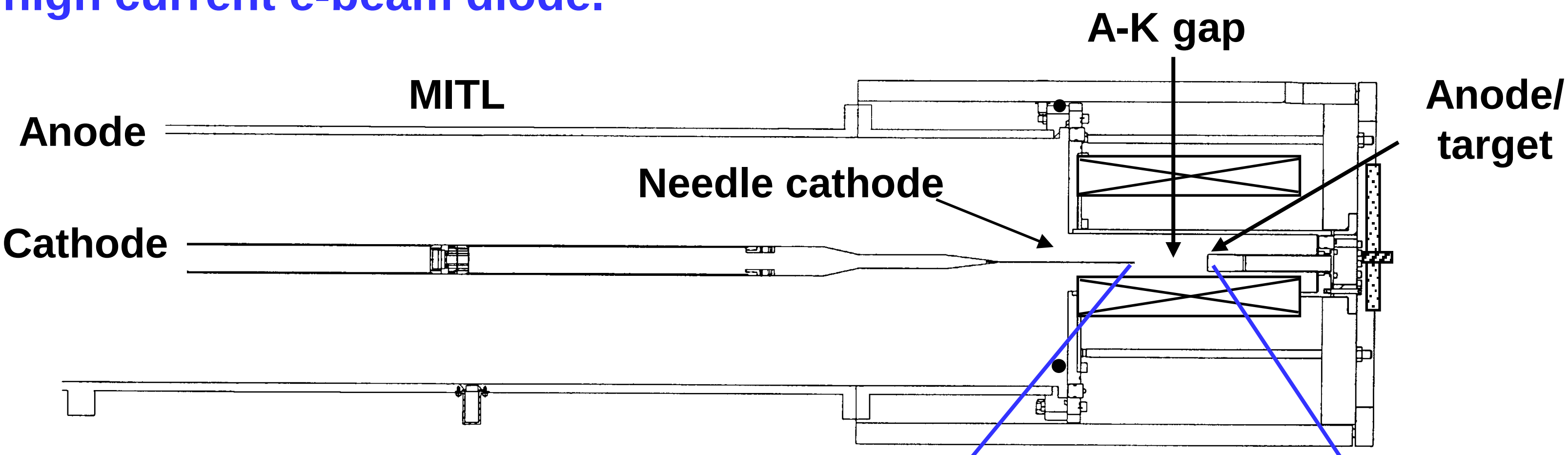
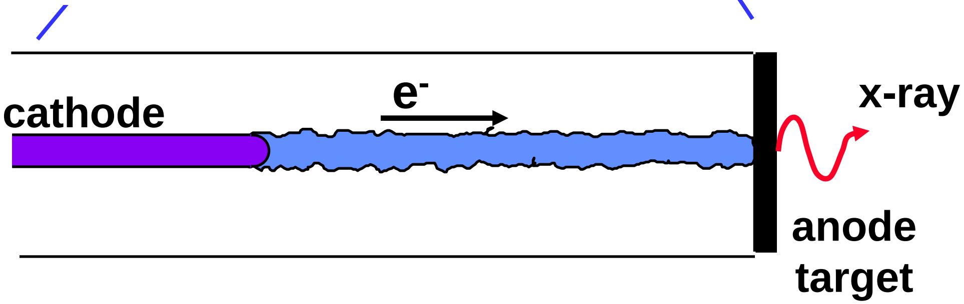
Sandia has been developing high power electron beam diodes for x-ray radiographic applications.

The electron beam is created in the accelerating gap of a high current e-beam diode.

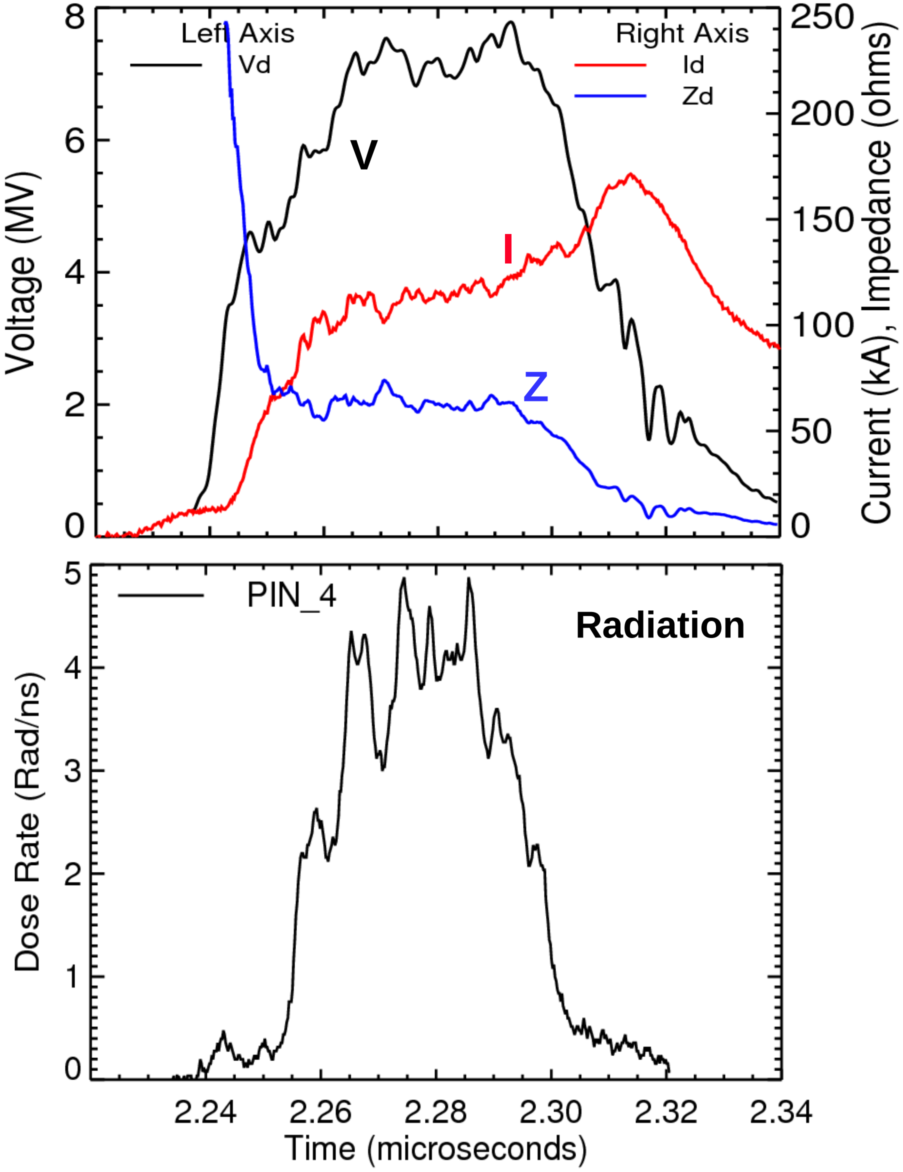


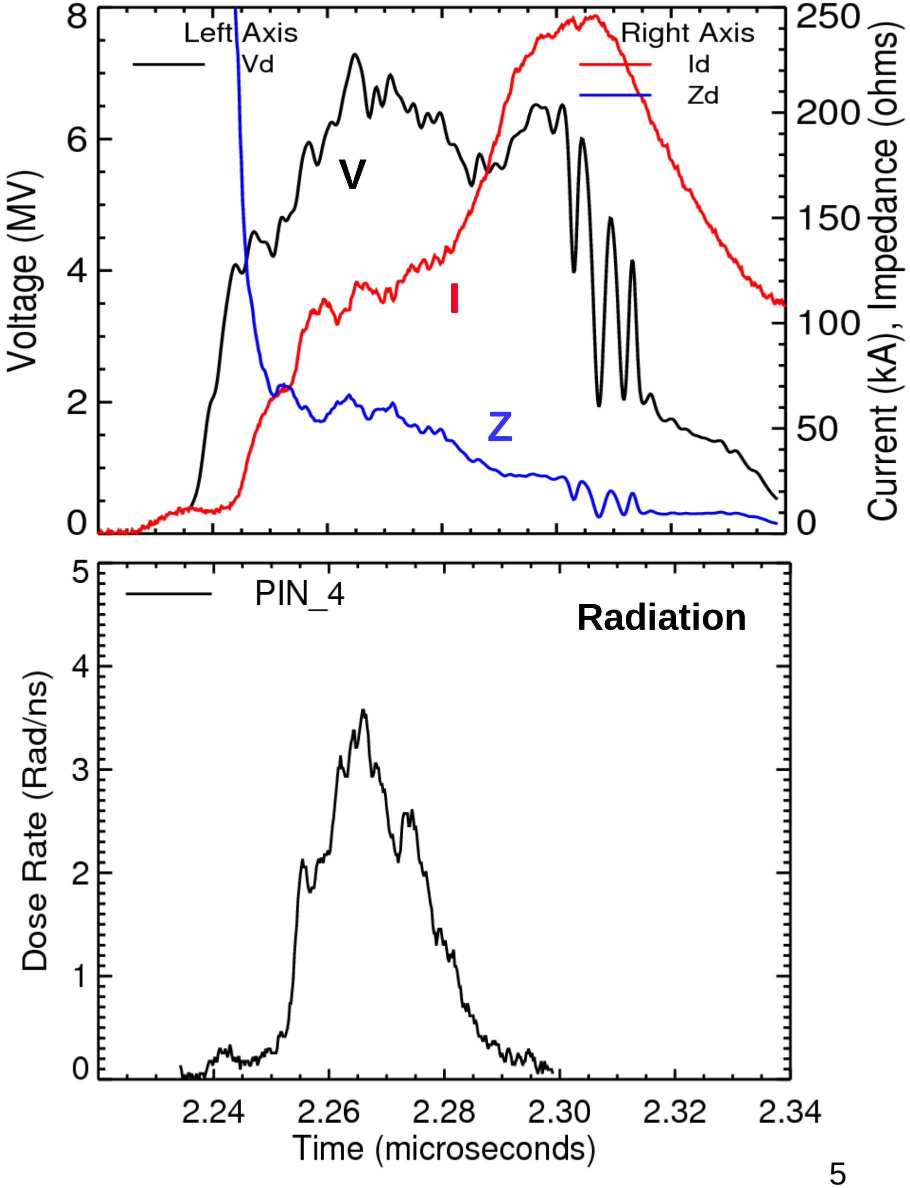
Bremmstrahlung x-rays are created when the e-beam is stopped in a high atomic number converter.



Energy = 2-10 MeV, Current = 20-150 kA, Pulse length = 50-100ns
Power =0.1-1.0 TW

A primary issue in optimizing radiation output is control of the diode impedance[1].


NPRP shot 777


NPRP shot 748

1. M.D. Johnston, B.V. Oliver et al, Proc. 51st APS-DPP conf. (2009)

Ions/plasmas are ubiquitous to these diodes and need to be controlled for stable operation.

The energy densities are large

$E/\pi r_b^2 \sim 10^2 - 10^3\ (\mathrm{kJ/cm^2})$

as are the current densities!

$J \sim 10^2 - 10^3\ (\mathrm{kA/cm^2})$

And the pulses are longer than the plasma formation time!

$$\frac{\Delta T}{\Delta t} = \frac{dE}{dx}\,\frac{J/e}{\rho C_v} \approx 10\ J\ (^{o}C/ns) \text{ for Ta.}$$

$$2.5\ J\ (^{o}C/ns) \text{ for C.}$$

$t_p < 2$ ns for desorption of carbon*

desorption → ionization → plasma

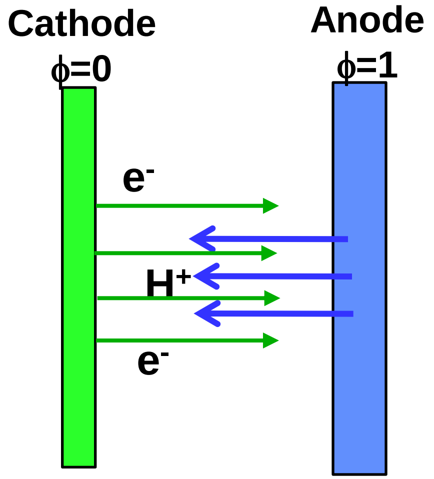
*assumes thermal desorption of hydrocarbons after heating ~ 400^0 C
see Sanford et al. JAP, **66**, 10. 1989; Lipinski et al. Phys. Fluids B, **2**, 2764 1990;
Welch et al. Laser and Particle Beams, **16**, 285 (1998)

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

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

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

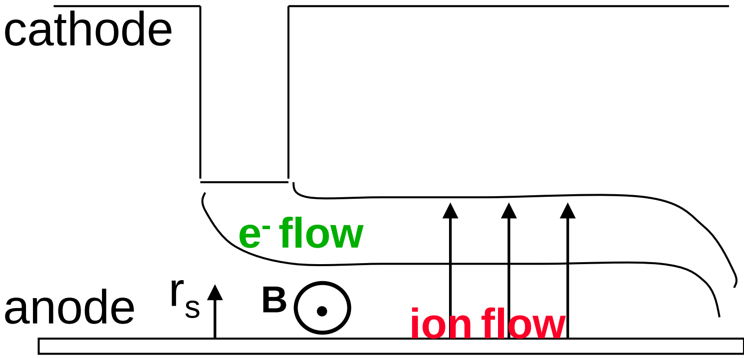
$$I_{cl} = \frac{1}{9\pi}\sqrt{\frac{2e}{m}}\,\frac{V^{3/2}}{d^2}\ \text{A},$$



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

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

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



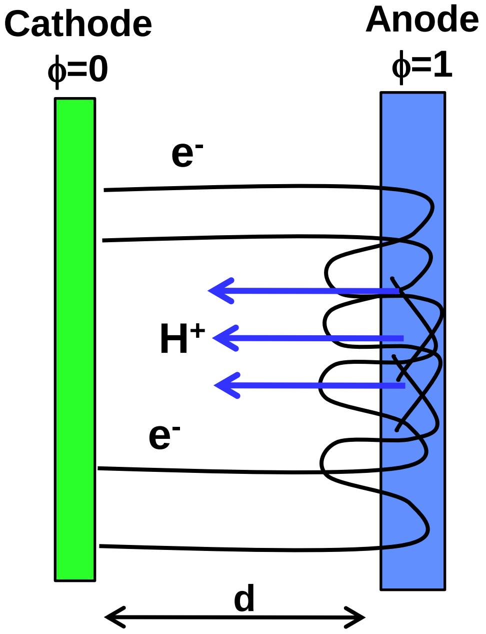
The factor α, is dependent on geometry, voltage, and ion distribution

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]

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

This enhance the ion space charge emission and changes the impedance



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

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

$$+\,2\sum_{k=1}^{\phi>1-\beta^k} \alpha^k \sqrt{\left(\phi-1+\beta^k\right) + \frac{eV}{2mc^2}\left(\phi-1-\beta^k\right)^2}$$

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

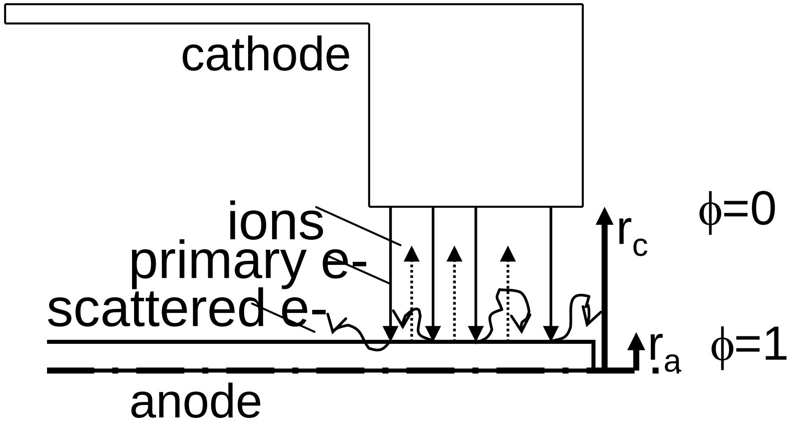
$$j_{scat} = \alpha\, j_{incident}$$

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

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, but does not cause impedance collapse[1]!



cathode

ions

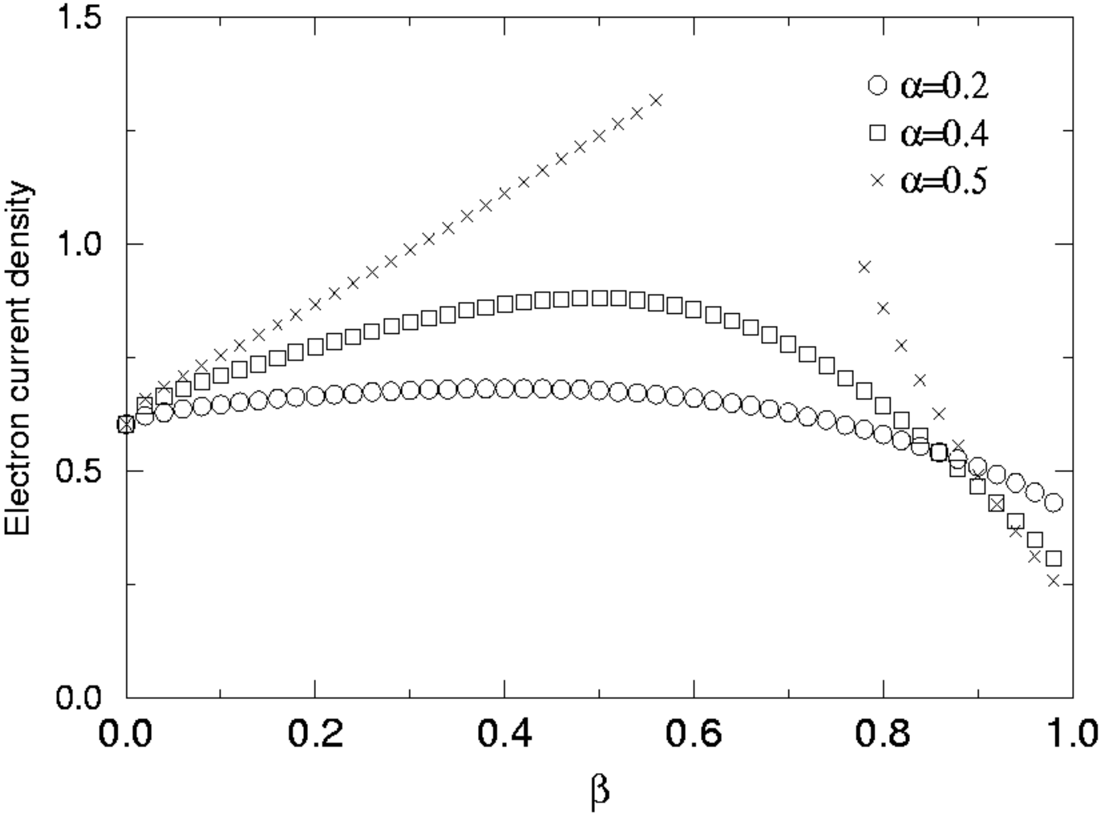
primary e-

scattered e-

anode

r_c $\phi=0$

r_a $\phi=1$



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

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

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

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

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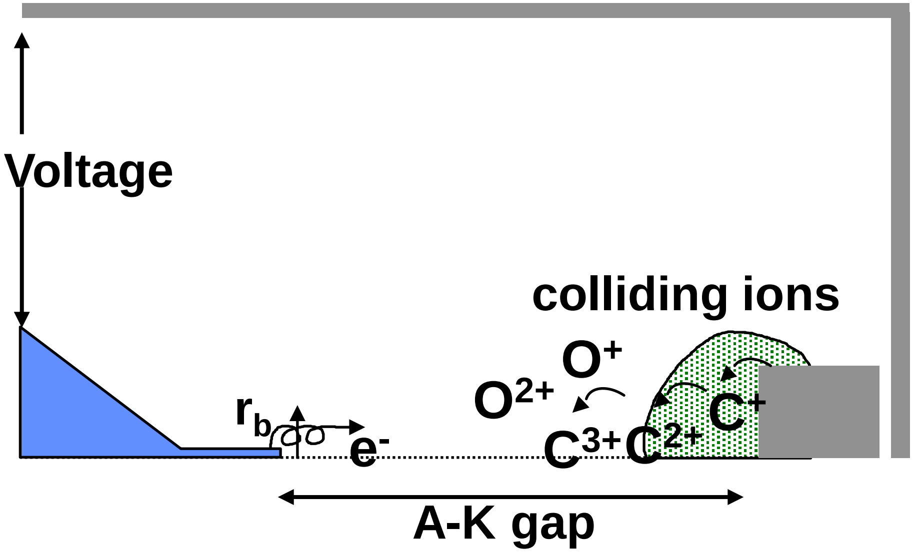
1. B.V. Oliver, T.C. Genoni et. al J. Appl. Physics **90** , 4951 (2001)

Charge stripping of ions can decrease diode impedance[1]

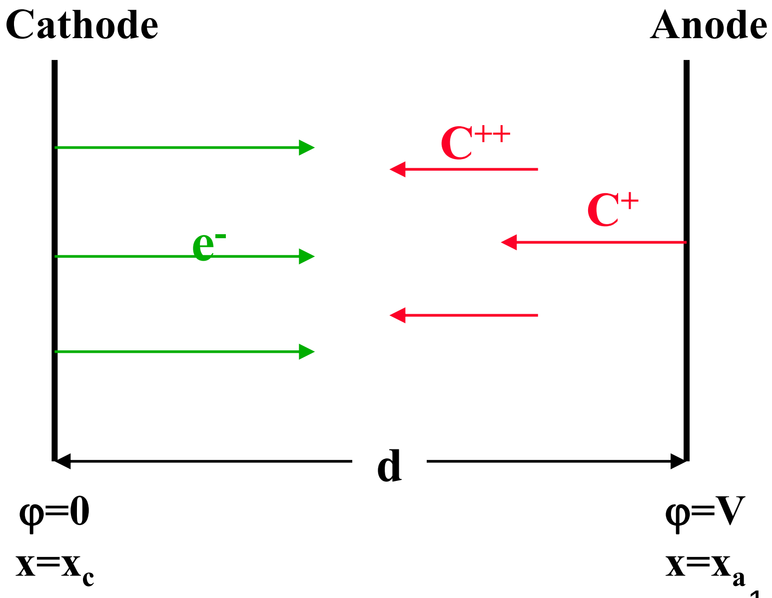
Non-protonic ions (e.g. C,O) from the anode collide and charge-strip while traversing the A-K gap.

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



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

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



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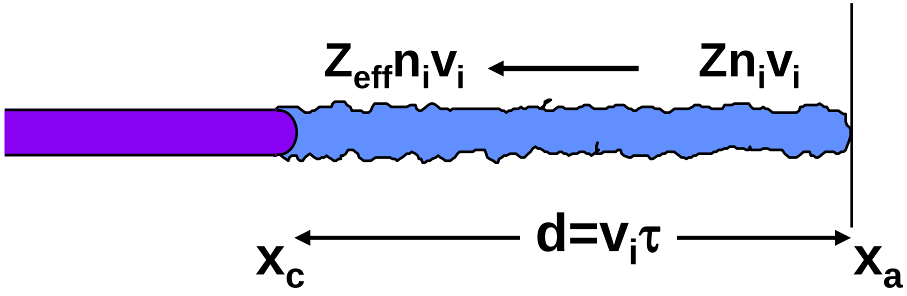
[1] B.V. Oliver, D.R. Welch, et. al, Bull. Am. Phys. Soc. **48**, 95, (2003)

The ion current density increases during transit across the gap

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}:

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

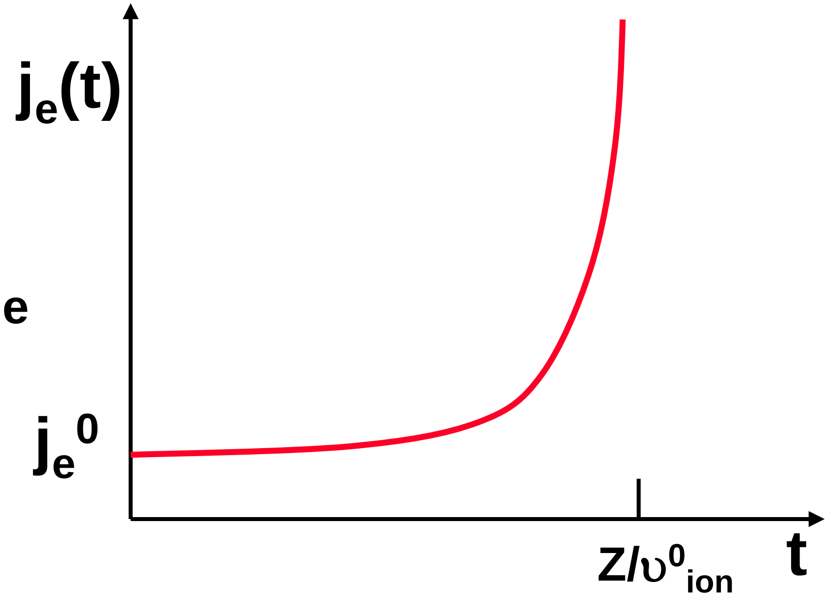
Non-linear response occurs because Z_{eff} is proportional to j_i through ν_{ion}

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}.

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

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



Solutions result in explosive behavior on time scale $1/\gamma \sim Z/\nu^0_{ion}$

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

~ 10 ns

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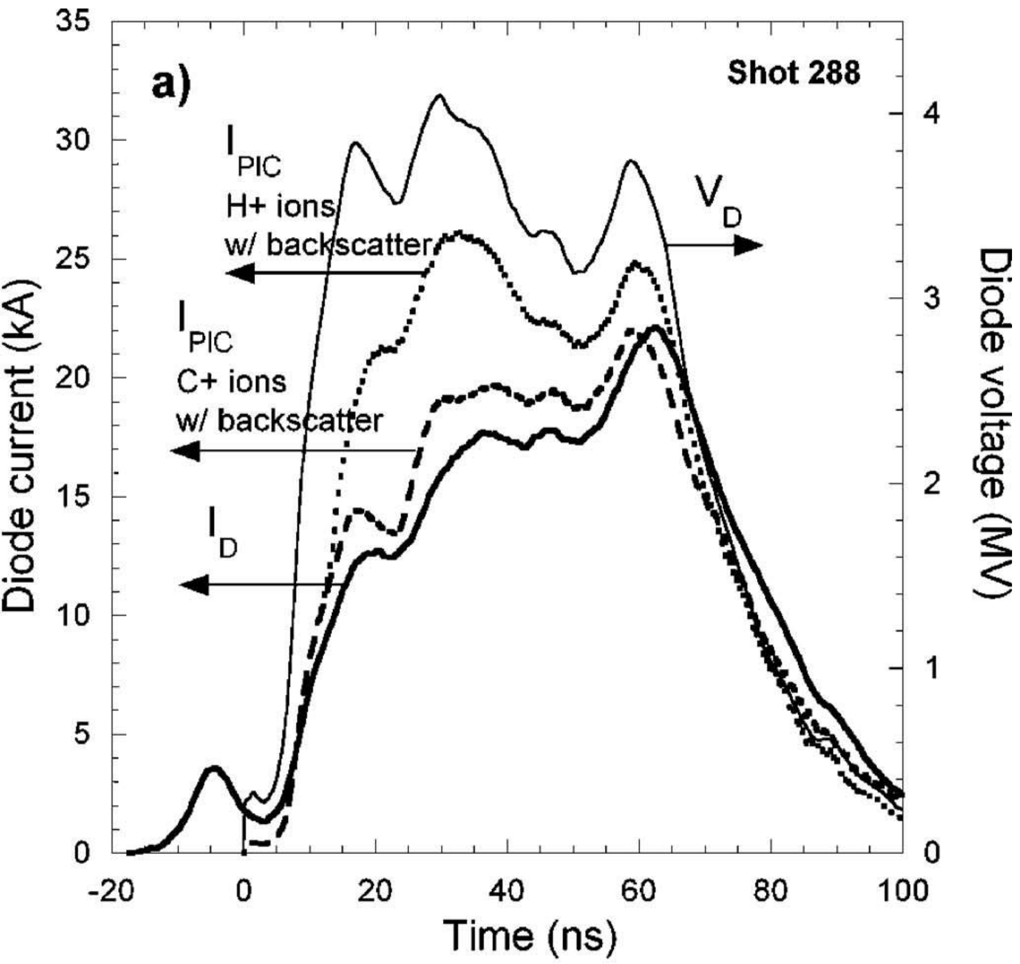
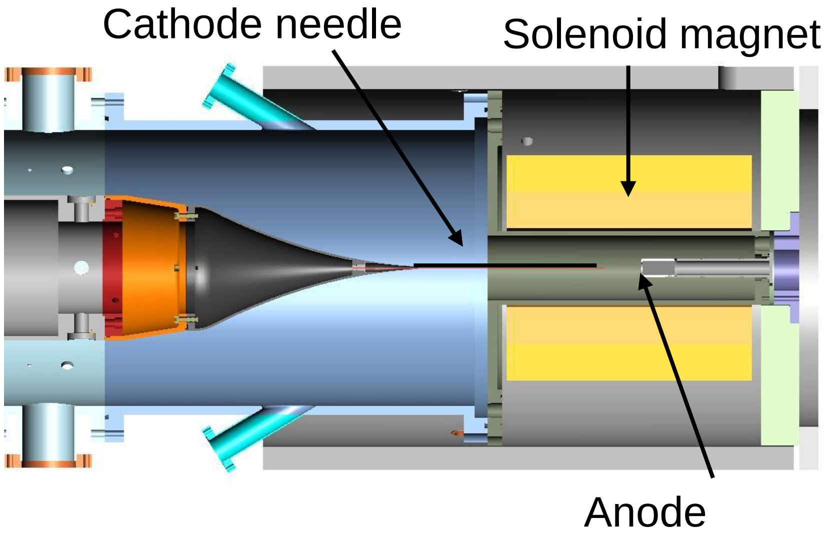
1. B.V. Oliver, D.R. Welch, et. Al, proceedings of the 45th APS-DPP, 2003

Observations from Immersed-B_z[1] diodes





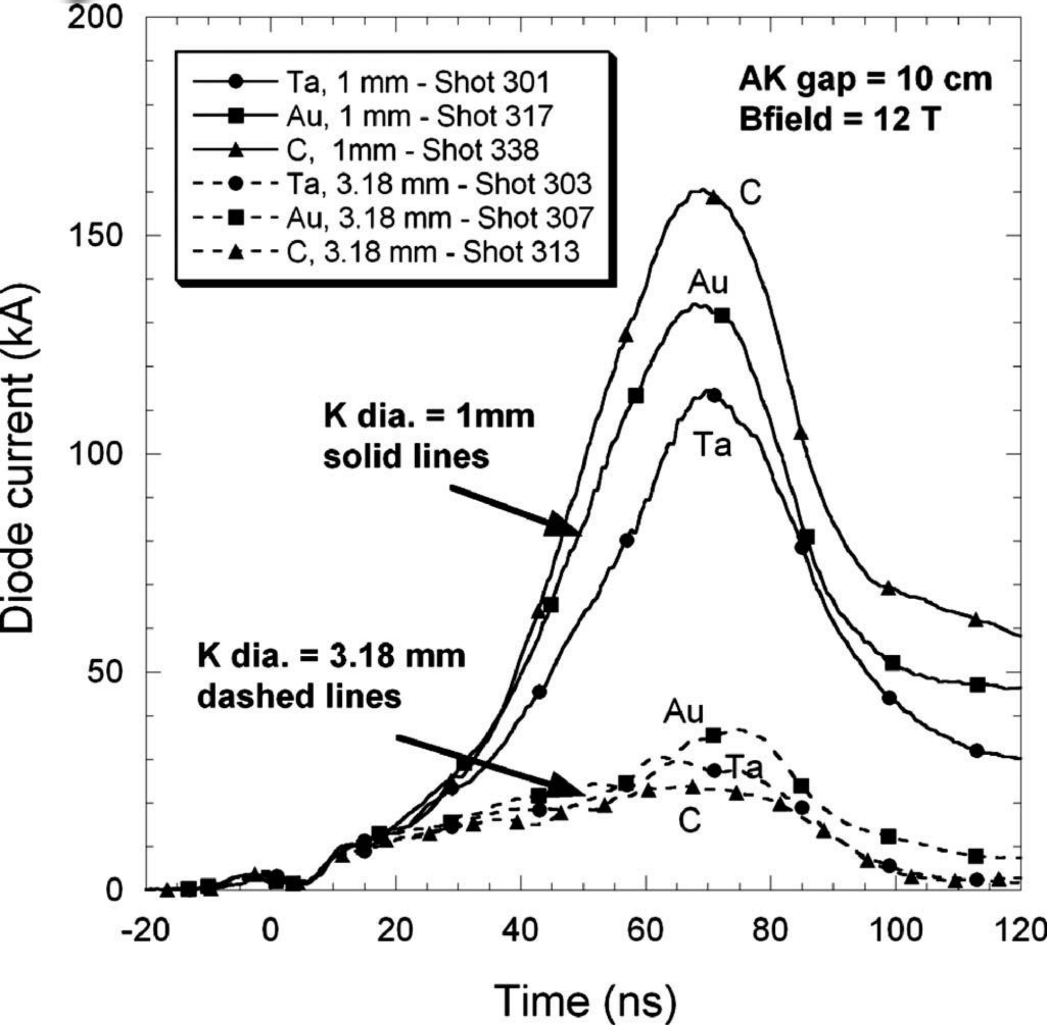
Immersed-B_z diode is a high impedance bi-polar diode with large A-K gap.[1]

Stable impedance measured for current densities j_e at anode < 200 kA/cm^2.

Bi-polar flow characterized by C^+ ions and includes electron backscattering at anode[2].

1. M.G. Mazarakis, J.W. Poukey, D.C. Rovang, et al., Appl. Phys. Lett. **70**, 832 (1977)
2. D.C. Rovang, N. Bruner, et. al, Phys. Plasmas **14**, 113107, (2007)

Rapid impedance collapse characteristic of charge stripping[1].



Higher current densities > 250 kA/cm^2 result in rapid impedance collapse.

Impedance collapse is much faster than plasma closure times.

Cryogenic frozen Xe anodes (very low hydro-carbon fraction) also showed rapid impedance collapse.

Expect ion charge build up in A-K gap due to stripping of bulk anode material (Ta, Au, Xe etc.)

1. D.C. Rovang, N. Bruner, et. al, Phys. Plasmas **15**, 093105, (2008)

Self-magnetically insulated diodes are limited by the Critical current

Example: the Rod-pinch[1] .

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

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

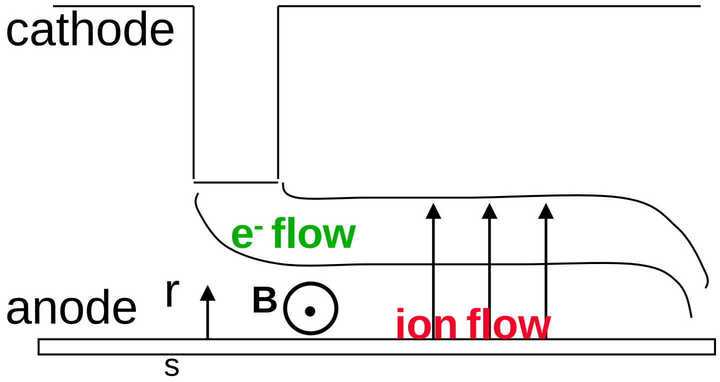
Ions are critical for operation. Operation is described by self-insulated flow theory with the inclusion of ions[2].

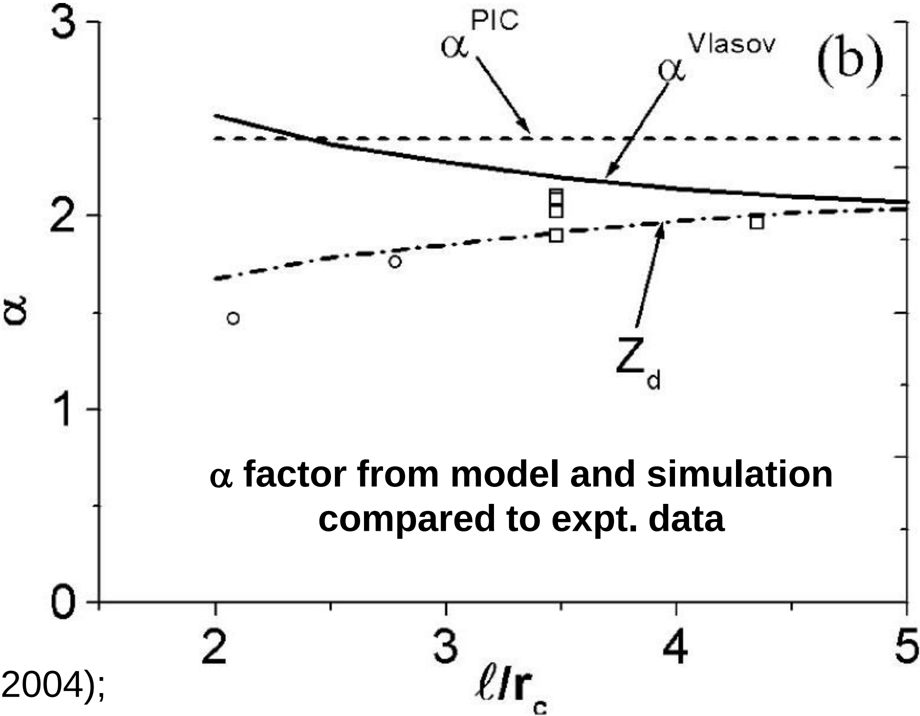
$$I \cong 17\, r_s \sqrt{J_i}\, [\gamma_a - 1]^{1/4} \quad \mathrm{kA.}$$

Ion current is determined by Child-Langmuir with spatial gap = insulation gap. Determines α!

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

rod-pinch diode





α factor from model and simulation compared to expt. data

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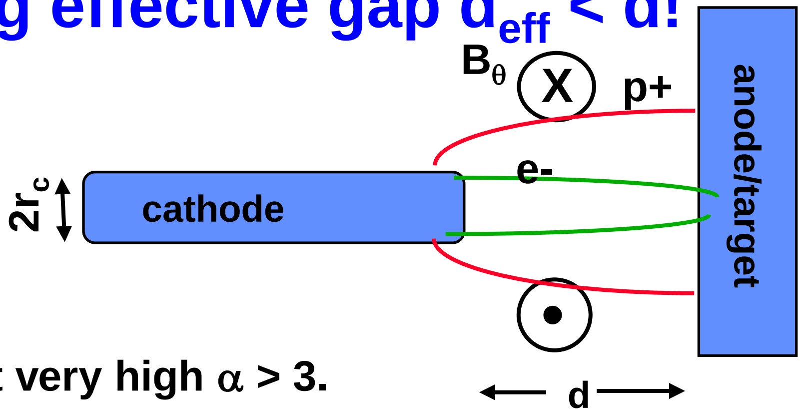
1. G. Cooperstein et al. Phys. Plasmas, **8**, 4618 (2001)
2. B.V. Oliver, P.F. Ottinger et al. Phys. Plasmas, **11**, 3976 (2004);

The Self-Magnetic pinch diode acts similar to rod-pinch, assuming effective gap d_{eff} < d!



Relativistic Bi-polar diode. High current I_b~150 kA

$$I_{smp} \cong 8.5\alpha \frac{r_c}{d}\sqrt{\gamma^2-1} = \frac{\alpha}{2}\frac{r_c}{d} I_A,$$

Experimental diode current measurements suggest very high $\alpha > 3$.

But focal spot information is contradictory, unless the effective gap A-K is smaller than the physical gap[1].

$$F \cong \frac{r_c}{2}\sqrt{\frac{\pi I_A}{I_b}},$$

$$spot \cong 2.4\frac{1}{\sqrt{\pi}}\frac{\varepsilon}{r_c}F$$

$$\xrightarrow{d_{eff} \cong F,}$$

$$\boxed{\begin{aligned} I_{smp} &\approx \frac{\alpha^2}{\pi} I_A \\ F &\approx \frac{r_c}{2}\frac{\pi}{\alpha} \end{aligned}}$$

Simulations confirm that 'd_{eff}' ≅ d/1.5 and thus α ~ 2.0.

Diode is not influenced by ion stripping because the A-K gap ion transit time is too small for growth, $d/v_i << Z/\upsilon_{ion}$.

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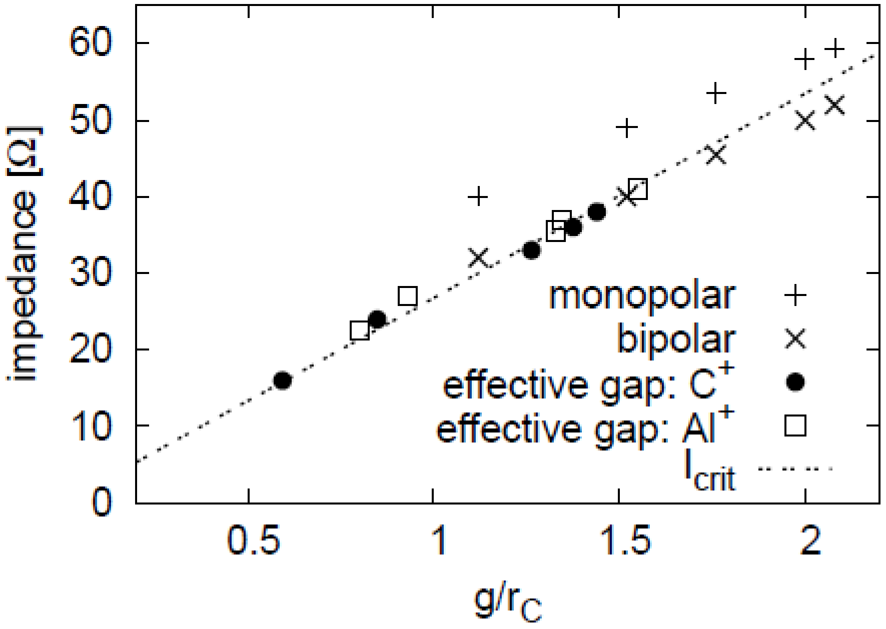
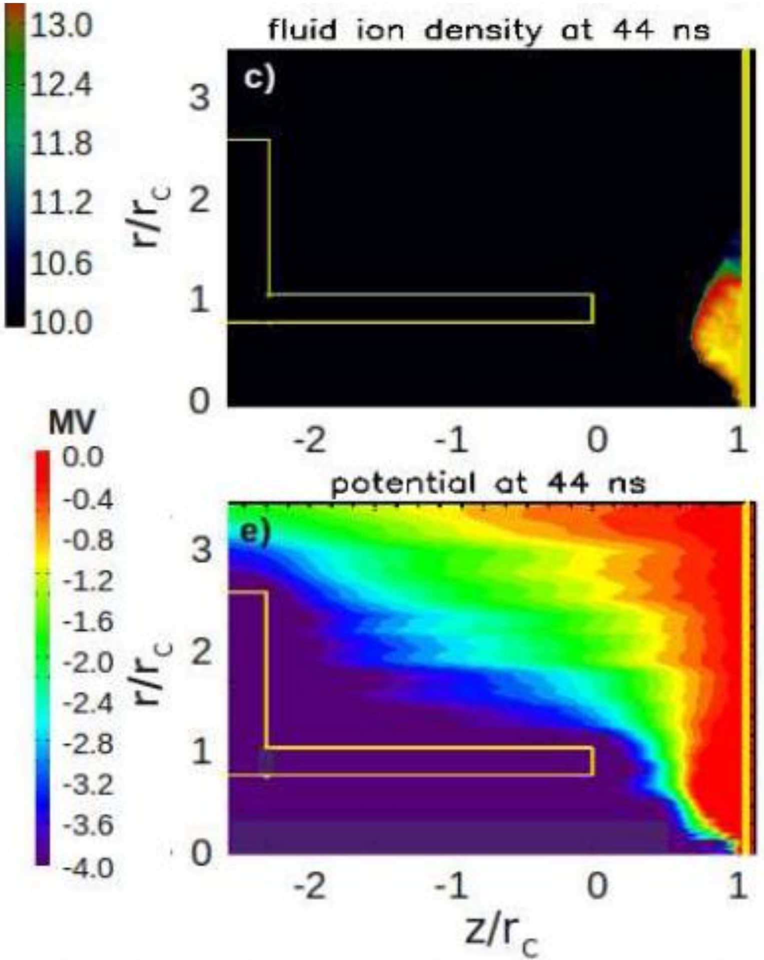
1. B.V. Oliver, K. Hahn et al. Acta. Phys. Pol A, **115**, 1044 (2009);

Simulations show effective gap $d_{eff} < d$ and show sensitivity to plasma gap closure

Simulations[1] demonstrate that expanding anode plasmas change the effective gap such that 'd_{eff}' $\cong d/1.5$ and thus $\alpha \sim 2.0$. But stable impedance can be achieved if the ion distribution is controlled





In the Self-pinch diode, ion distribution is critical to stable impedance and focal properties

1. N. Bruner, D. Welch, et al. , to be submitted to Phys. Plasmas (2010)

Anomalously high resistivity is possible in the beam/plasma environment of the diode

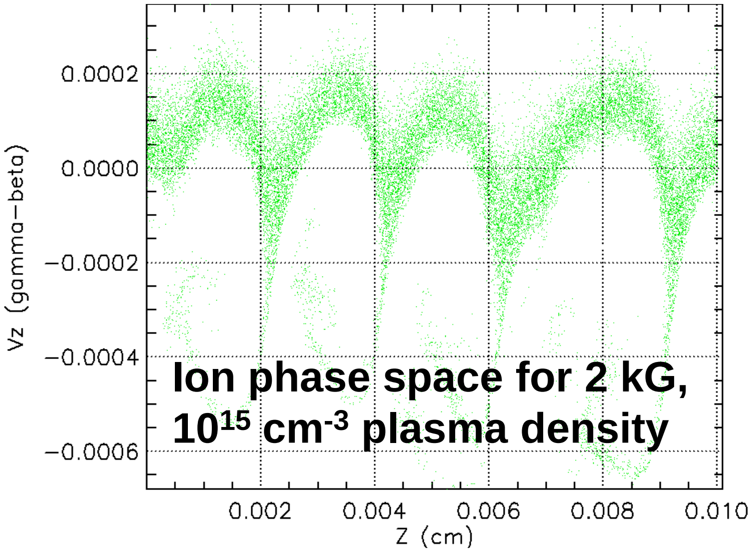
Theory/simulation[1] of cross – field plasma currents show susceptibility to unstable Bernstein modes (Resistance as high as 60x classical)

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

Simulations suggest resistivity greater than classical for currents:

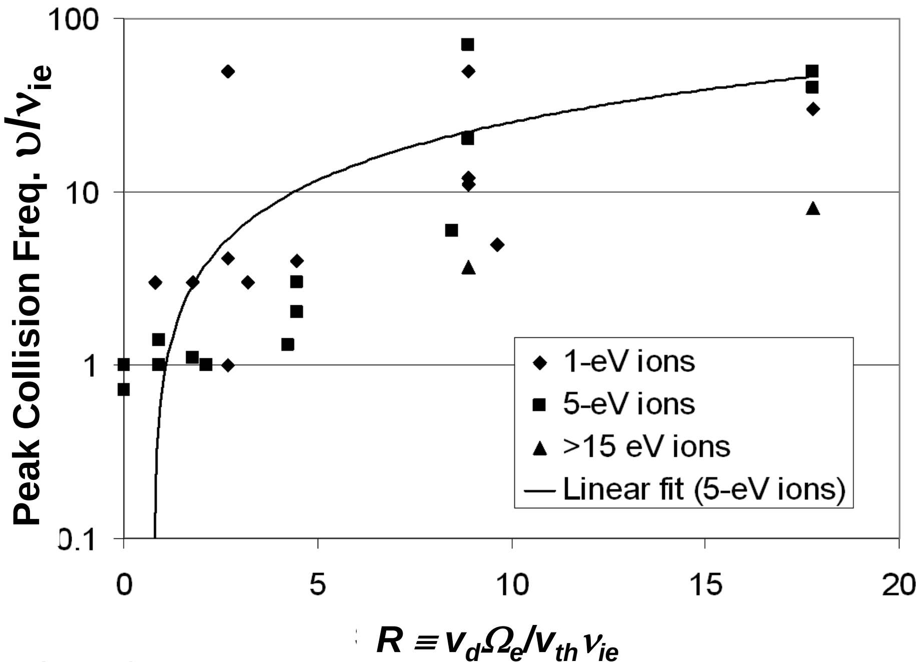
> 0.5 kA at 10^{15} cm^{-3} plasma density

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



Ion phase space for 2 kG, 10^{15} cm^{-3} plasma density

Ratio of effective collision freq. to spitzer freq.



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

Summary

Ions and Ion dynamics are critical to high power diode operation at current densities > 100 kA/cm^2

They are both necessary, but also dangerous.

Very rapid impedance collapse can occur if they are not controlled.

But effective control of:
1) ion species
2) ion distribution
3) diode geometry

can lead to very high power diodes with good impedance lifetime and behavior
Anomalous resistivity can also aid in maintaining impedance lifetime.

Thank you