THE GEORGE WASHINGTON UNIVERSITY

WASHINGTON, DC

Micro-propulsion and Nanotechnology Lab – The George Washington University – MPNL

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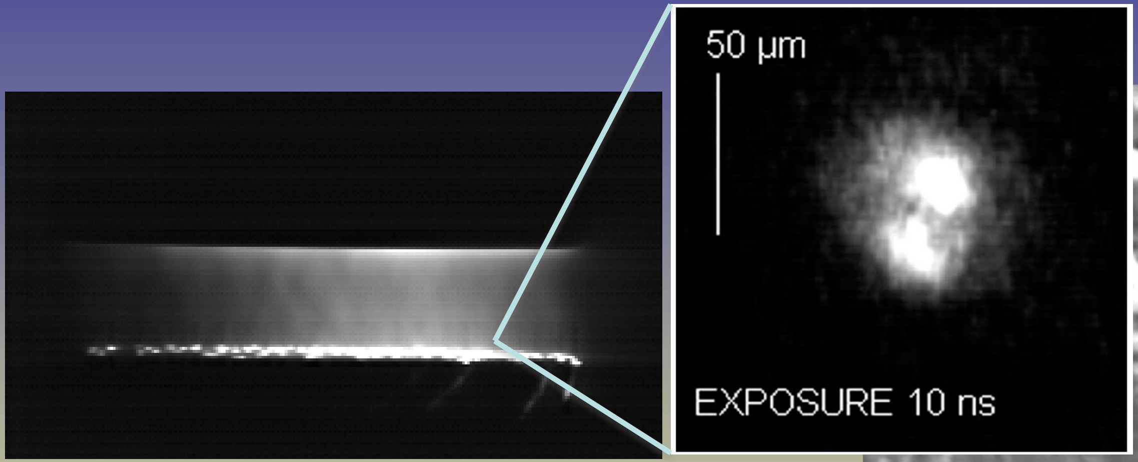
Acknow

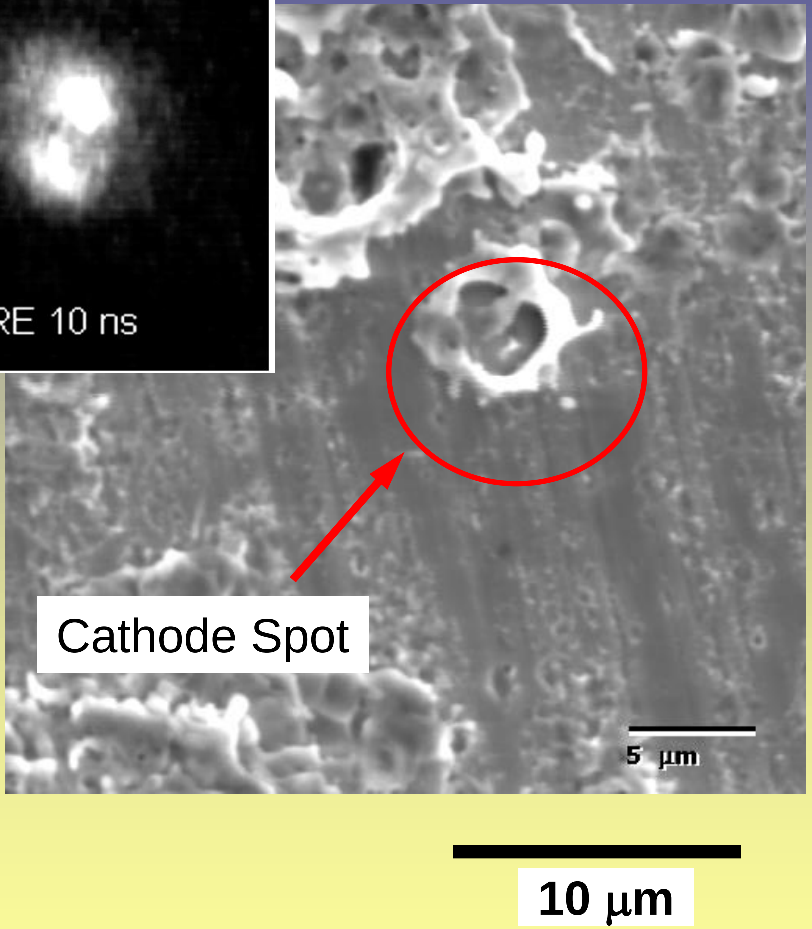
Smartphone summary:

vacuum arc plasmas are quite complicated

thus multiple approaches are required

Vacuum Arc





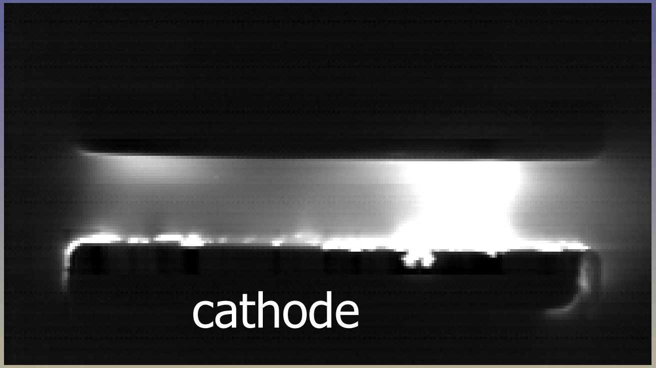
- Arc attaches to cathode at micron-sized spots called cathode spots
- At low current (up to 100 A for copper) one spot is formed at a time
- Current density at spot is 10^9 – 10^{12} A/m^2
- Spot lifetime ranges from nanoseconds to microseconds

Juttner, *J. Phys. D*, 2000
Beilis, *IEEE Trans. Plasma Sci.*, 2001

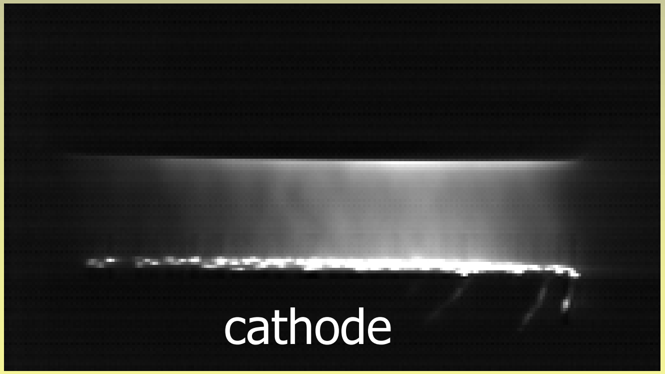
High Arc Current Vacuum Arc

- >1 kA
- Transition to the diffuse mode
  - Magnetic field effect
- Plasma model
  - Expansion of individual cathode jets
  - Formation of common channel from overlap
  - Single jet in the presence of high-current column (imposed voltage on single jet) and magnetic field

Columnar arc



Diffuse arc



The Free Boundary Model

$$m_i(\mathbf{v}_i \bullet \nabla)\mathbf{v}_i = -k(Z_i T_e + T_i)\frac{\nabla n}{n} + \frac{\mathbf{j}\times\mathbf{B}}{n}$$

$$\mathbf{j} = \sigma\left(\mathbf{E} + \frac{kT_e}{e}\frac{\nabla n}{n} - \frac{\mathbf{j}\times\mathbf{B}}{en} + \mathbf{v}_i \times \mathbf{B}\right)$$

$$\nabla \bullet (n\mathbf{v}_i) = 0$$

$$\nabla \bullet \mathbf{j} = 0$$

$$\mathbf{E} = -\nabla\varphi$$

$$\frac{3}{2}kN_e V\nabla T_e + 3\frac{j_e}{e}k\nabla T_e + kT_e div(j) = -P_e div(V) + \frac{j^2}{\sigma}$$

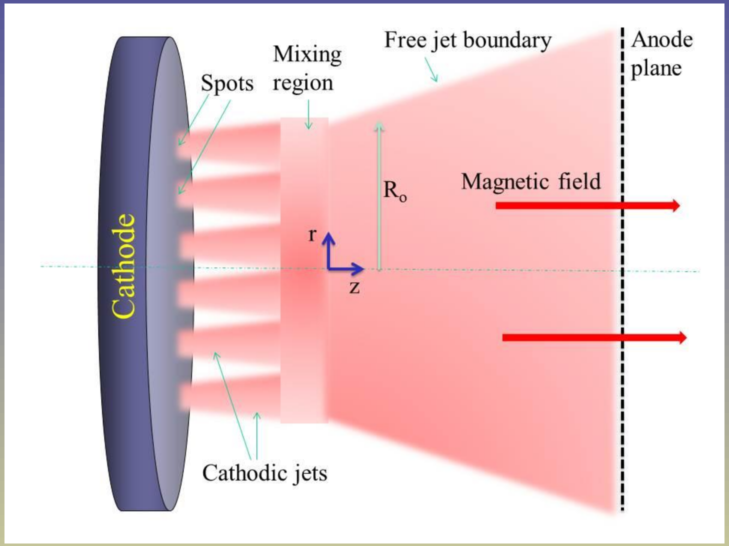
$$B_\theta(r) = \frac{\mu_0}{r}\int_0^r j_z r' dr'$$

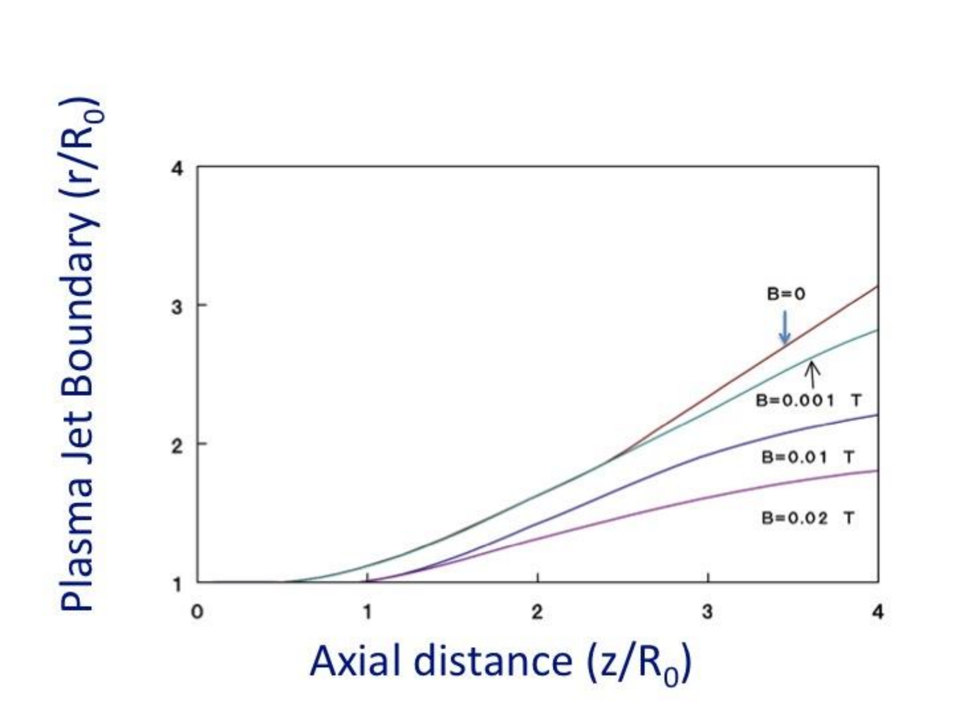
$$\frac{\partial\alpha}{\partial\tau} = \frac{1}{1+(\frac{V_n}{V_\tau})^2}\cdot\frac{\frac{\partial V_n}{\partial\tau}V_\tau - \frac{\partial V_\tau}{\partial\tau}V_n}{V_\tau^2}$$

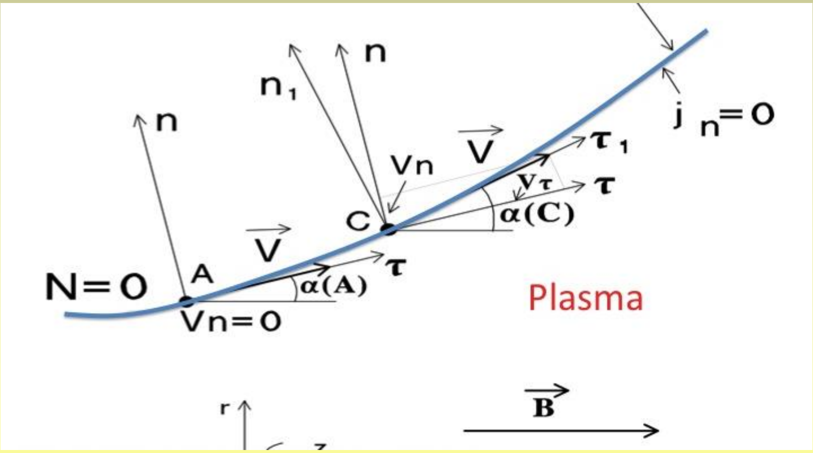
- Assumptions
  - Steady-state, fully ionized, collision dominated, quasi-neutral plasma
  - Anode acts as a passive current and particle collector
  - Cathode spots act as source of plasma at a specified jet angle and velocity
  - Cathode spots evenly distributed (no arc constriction) within a circular area
  - Magnetized electrons, unmagnetized ions
  - External magnetic field purely axial and uniform, self field purely azimuthal
- Numerical methods
  - Iterative scheme for solving for the potential
  - Implicit second-order accuracy method to calculate the velocity, current density, and density from the potential
- Two approaches:
  - self consistent solution
  - voltage is set by high-current column

Keidar et al, *J. Phys. D*, 1996

Free plasma jet boundary



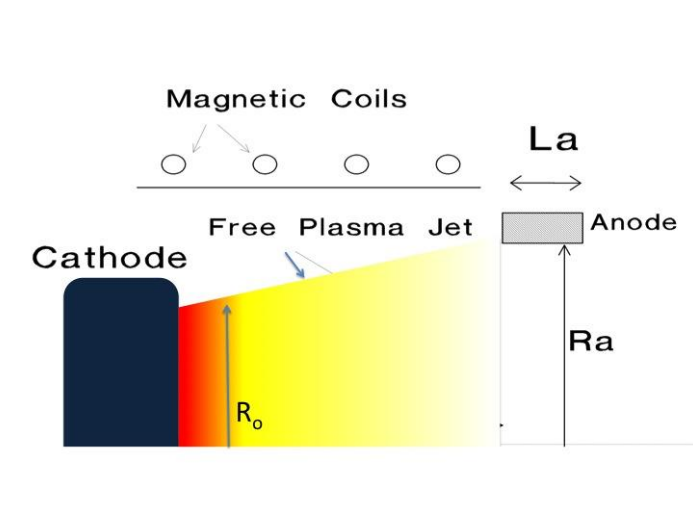


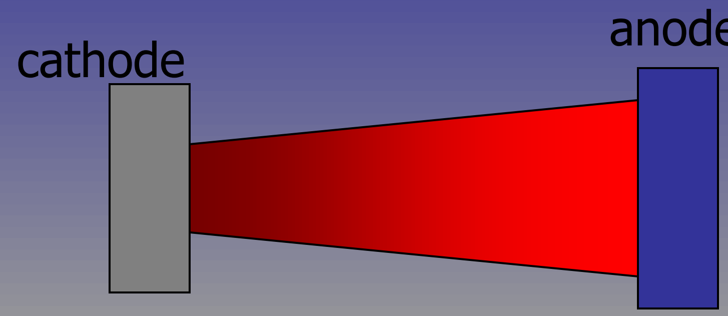


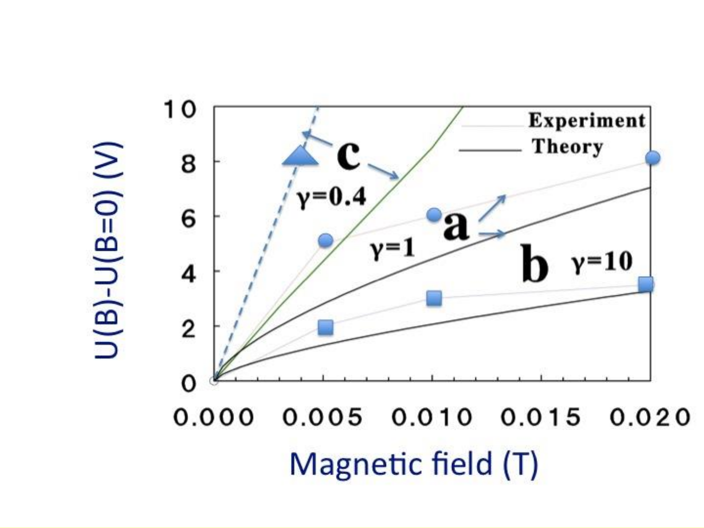
M. Keidar et al, *J. Phys. D*, 1996
M. Keidar and I. I. Beilis, Plasma Engineering, Elsevier, 2013

Focusing and Arc Voltage

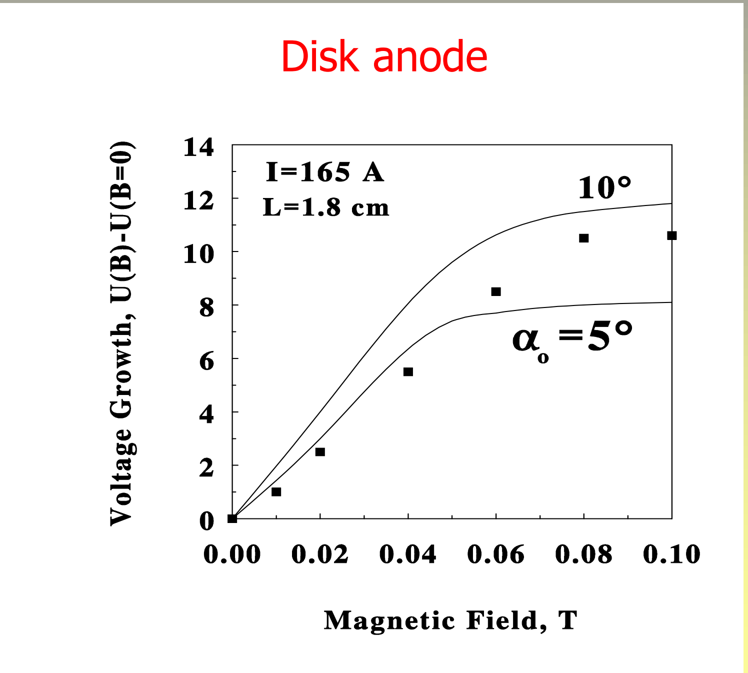
Ring anode







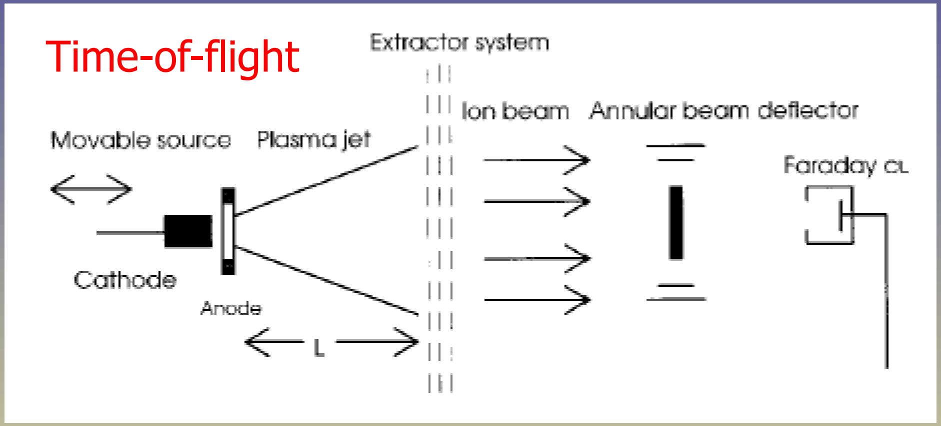
Keidar *et al*, *J. Phys. D*, 1996; *J. Appl. Phys.*, 1998; *IEEE TPS*, 1997



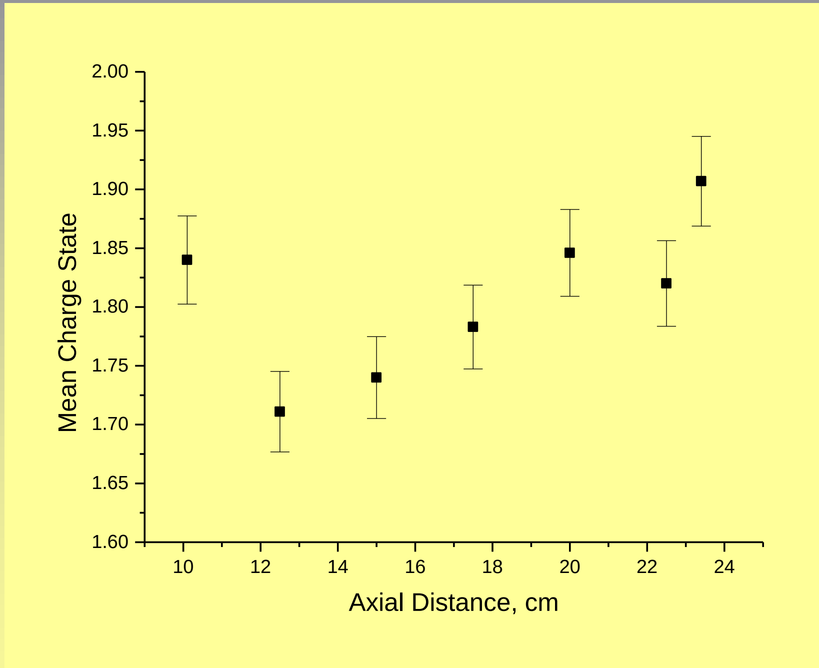
Experiment: Heberlein and Porto, IEEE Trans. Plasma Sci., 11, 152 (1983)

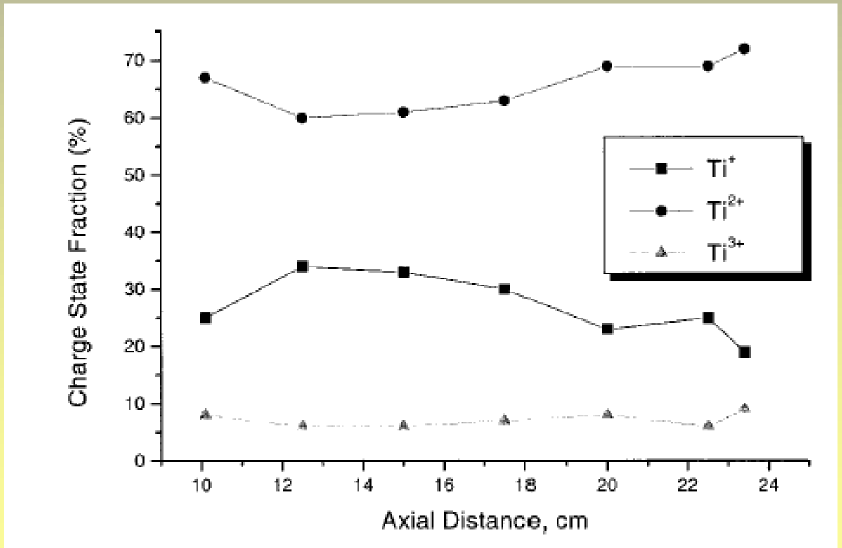
Multiply charged ion transport

Mean ion charge state generally >1



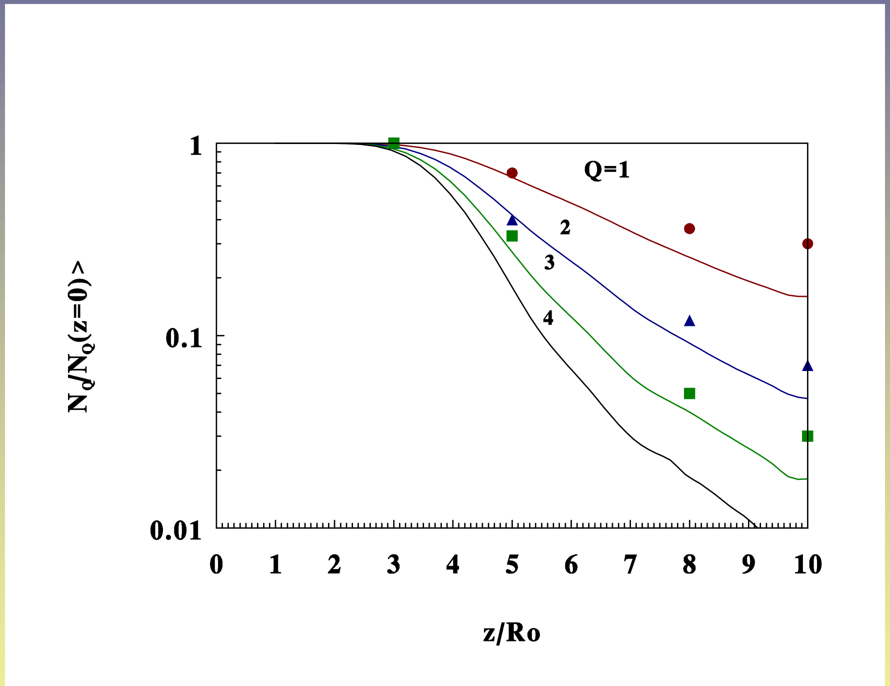
Mean Charge along the jet

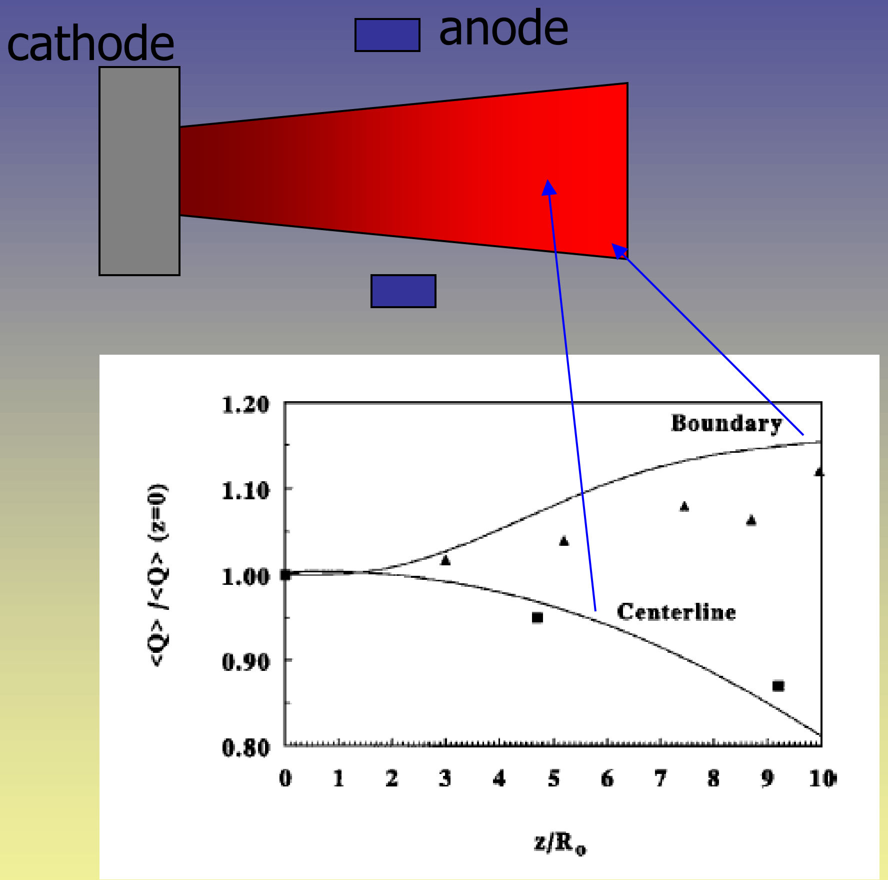




Keidar & Brown, *Rev. Sci. Instr*. 2000

Comparison with Experiment

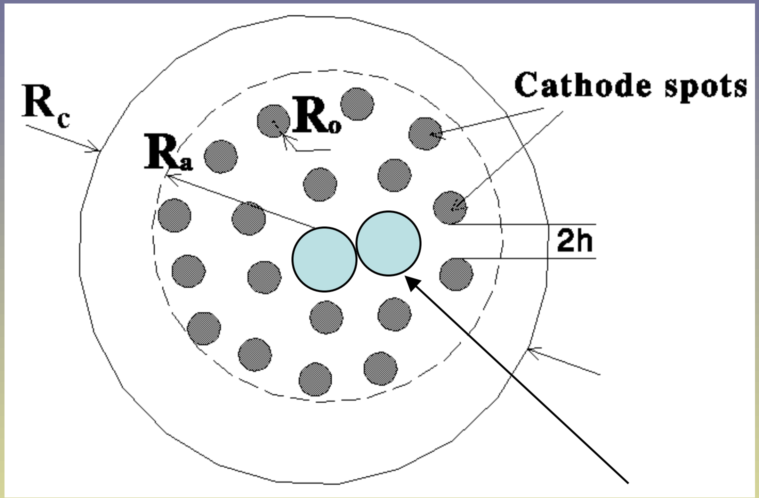




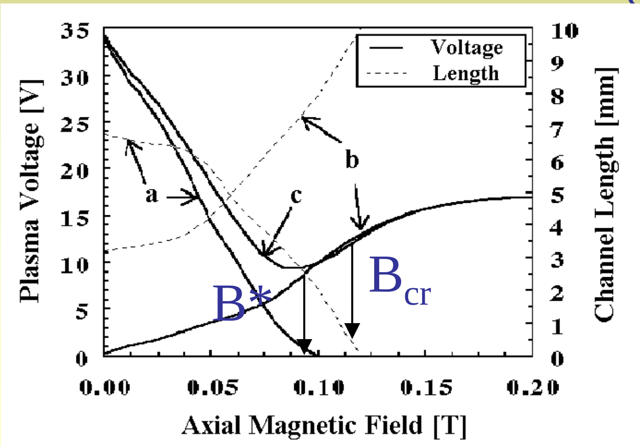
Experiment: V.M. Khoroshikh, Sov. Phys. Tech. Phys., 33(6) 723 (1988)

Keidar, *J. Appl. Phys*. 1998; *Rev. Sci. Instr*. 2000

Condition for critical AMF



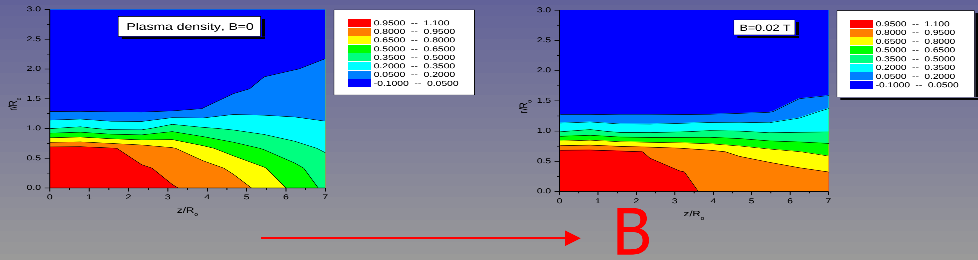
$R_o + \Delta r_{jet}$



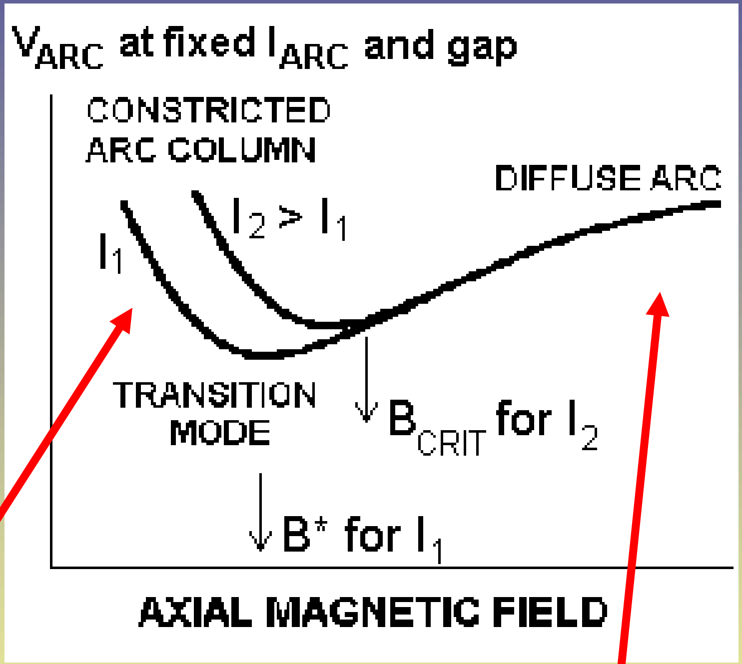
- Δr_{jet} $(L, B_{cr}) = h$ (I_{arc}, R_a)
- L is the gap length
- $\Delta r_{jet}(L, B)$ is the increase of the plasma jet radius due to the radial expansion
- $2h(I_{arc}, R_a)$ is the distance between two individual adjacent channels

Columnar & Diffuse Arc in a Magnetic Field

Plasma density

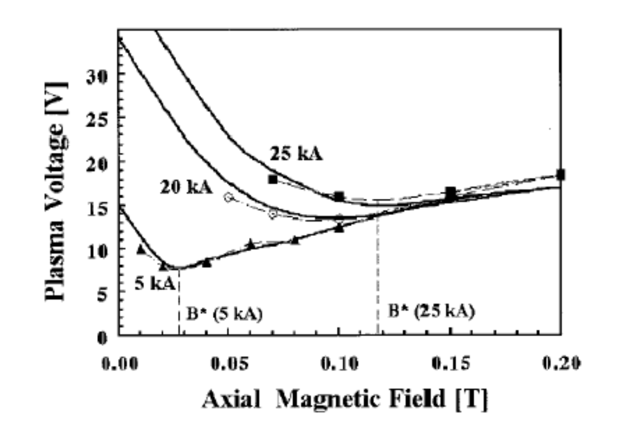


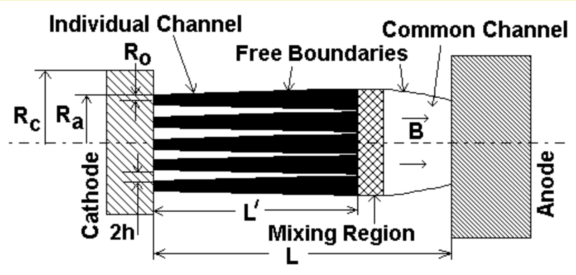
V-shape voltage characteristic

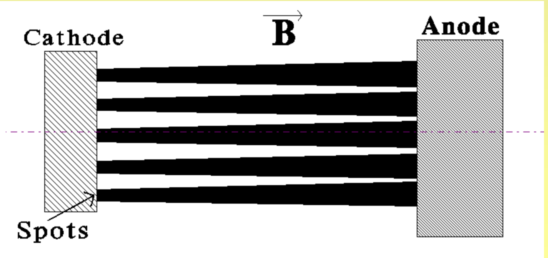


Gundlach, *ISDEIV*, 1972

Model prediction

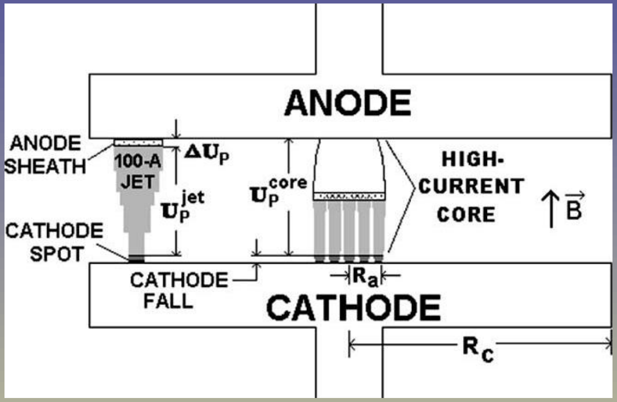


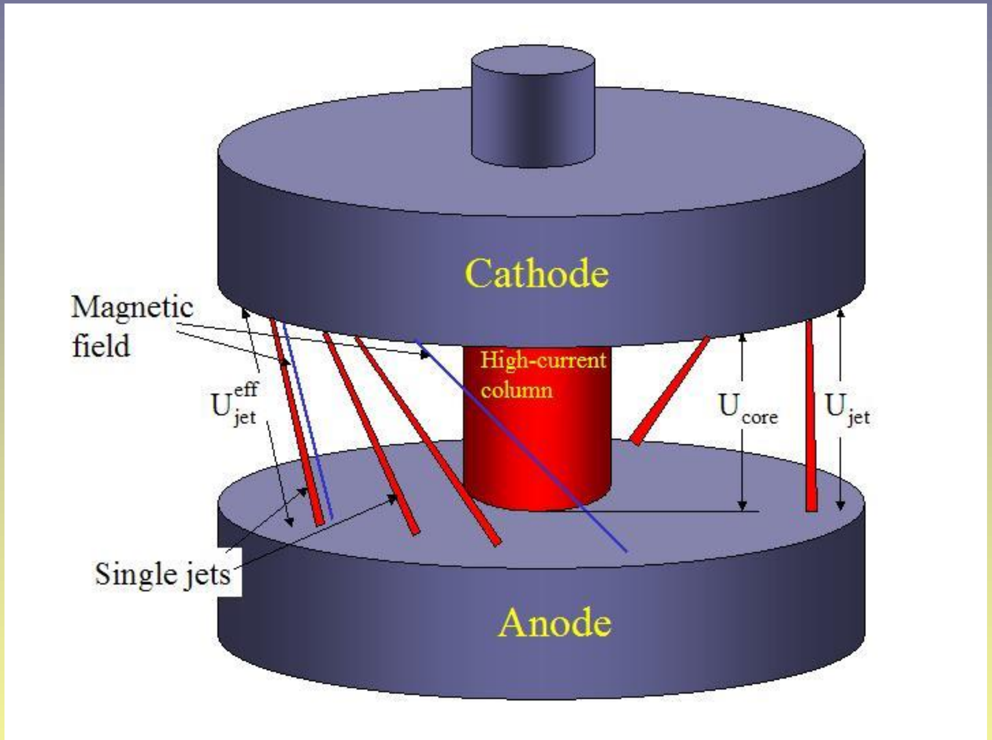




Keidar & Schulman, *IEEE Trans. Plasma Sci*, 2000, 2001

High-current vacuum arc





- Two-dimensional free expansion of the plasma jets
- Voltage is calculated for the individual jets and high-current column
- *Diffuse column arc:* Expansion of single cathodic jet burning in parallel to high current column

Anode sheath potential drop

Anode sheath potential drop

$\Delta\varphi = T_e \ln[j_{th}(r,z)/j(r,z)]$

- $j_{th}(r,z)$ electron thermal current depends on density
- $j(r,z)$ current density

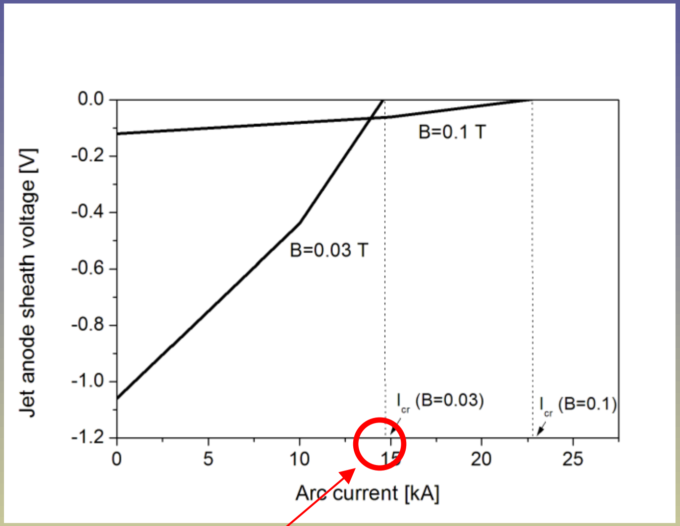
Single jet existence criteria

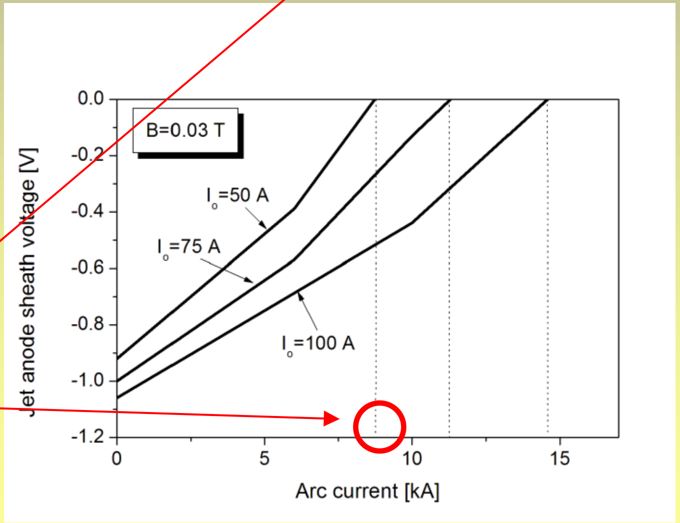
$\Delta\varphi = 0,\ I = I_{cr}$

- $I > I_{cr}$ the isolated jet extinguishes
- $I < I_{cr}$ the isolated jet is stable, which is characteristic of diffusing arcs

Critical arc current

Anode sheath potential drop

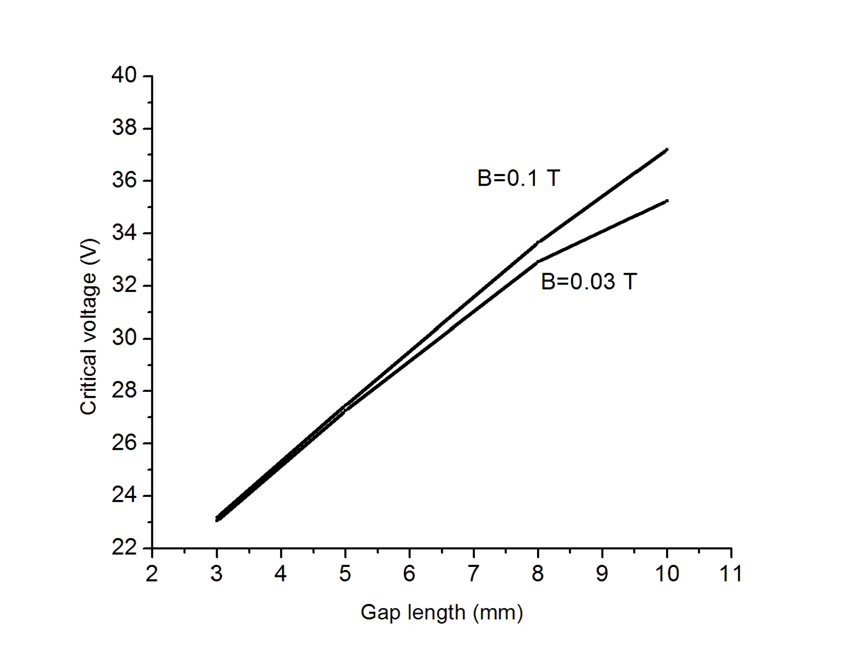




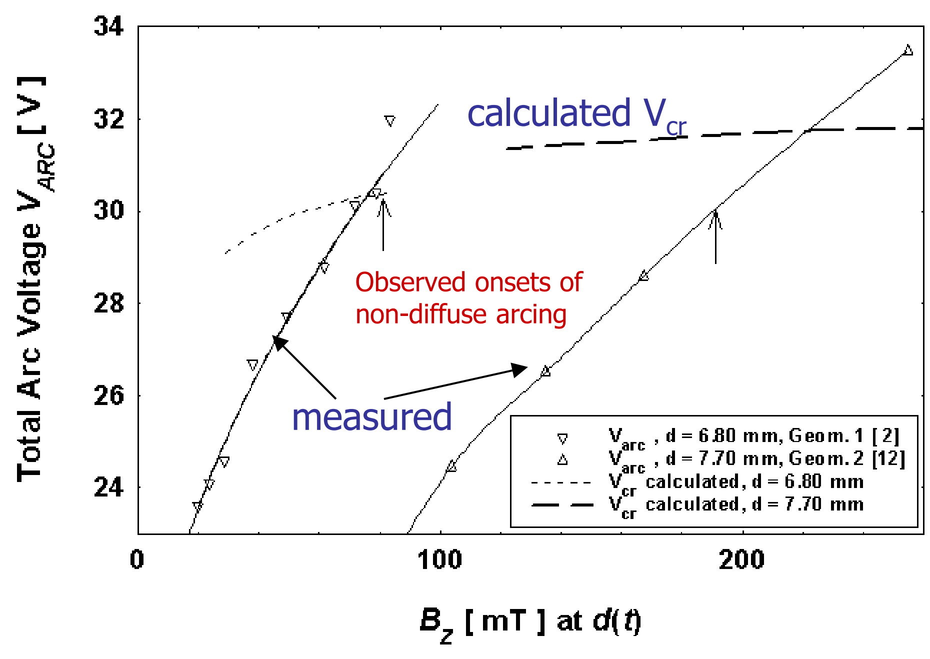
Keidar et al, *IEEE Trans. Plasma Sci*, 2004

Critical voltage

Critical voltage as a function of gap length



Comparison with experiment



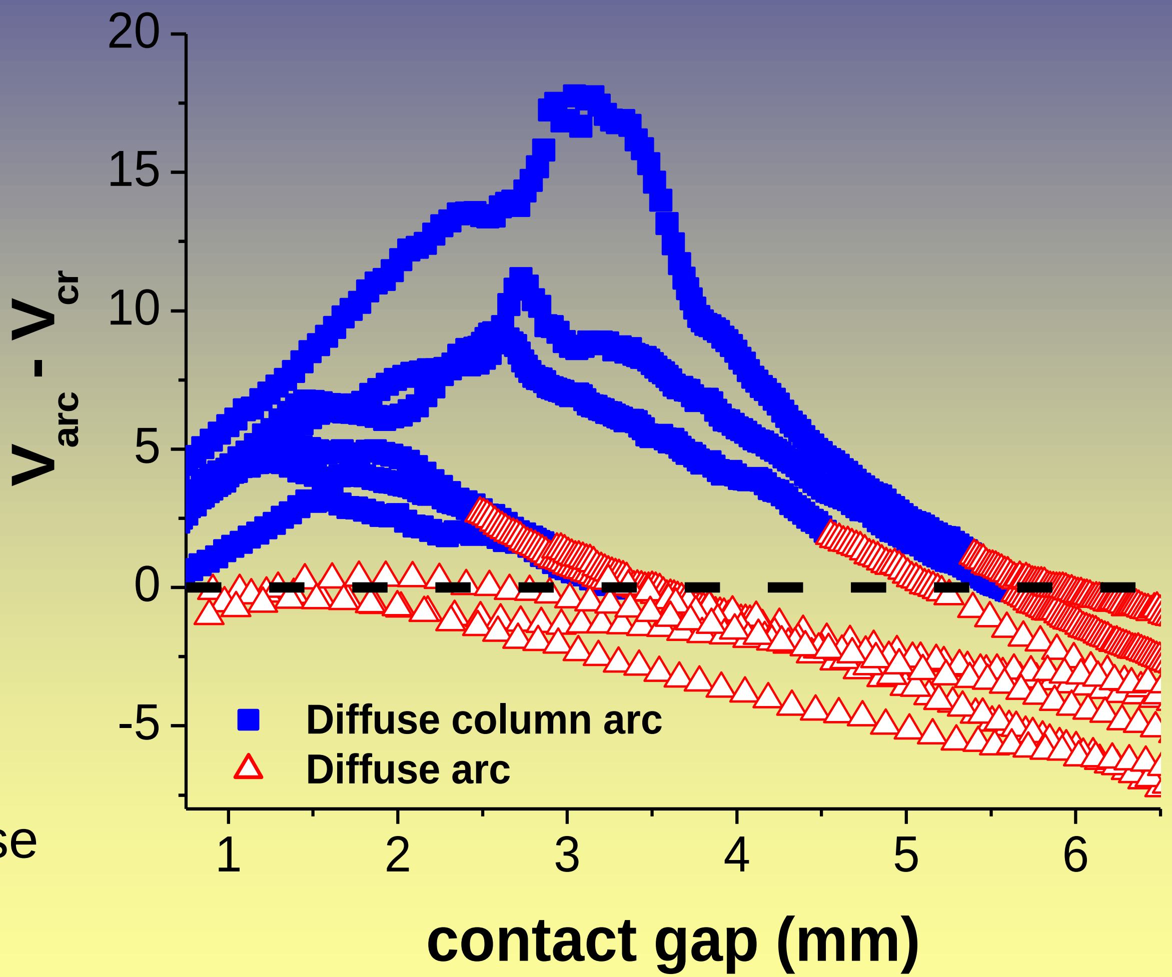
$V_{arc} < V_{cr}$ – is diffuse arc condition

Experiment

M. B. Schulman and H. Schellekens, 2000

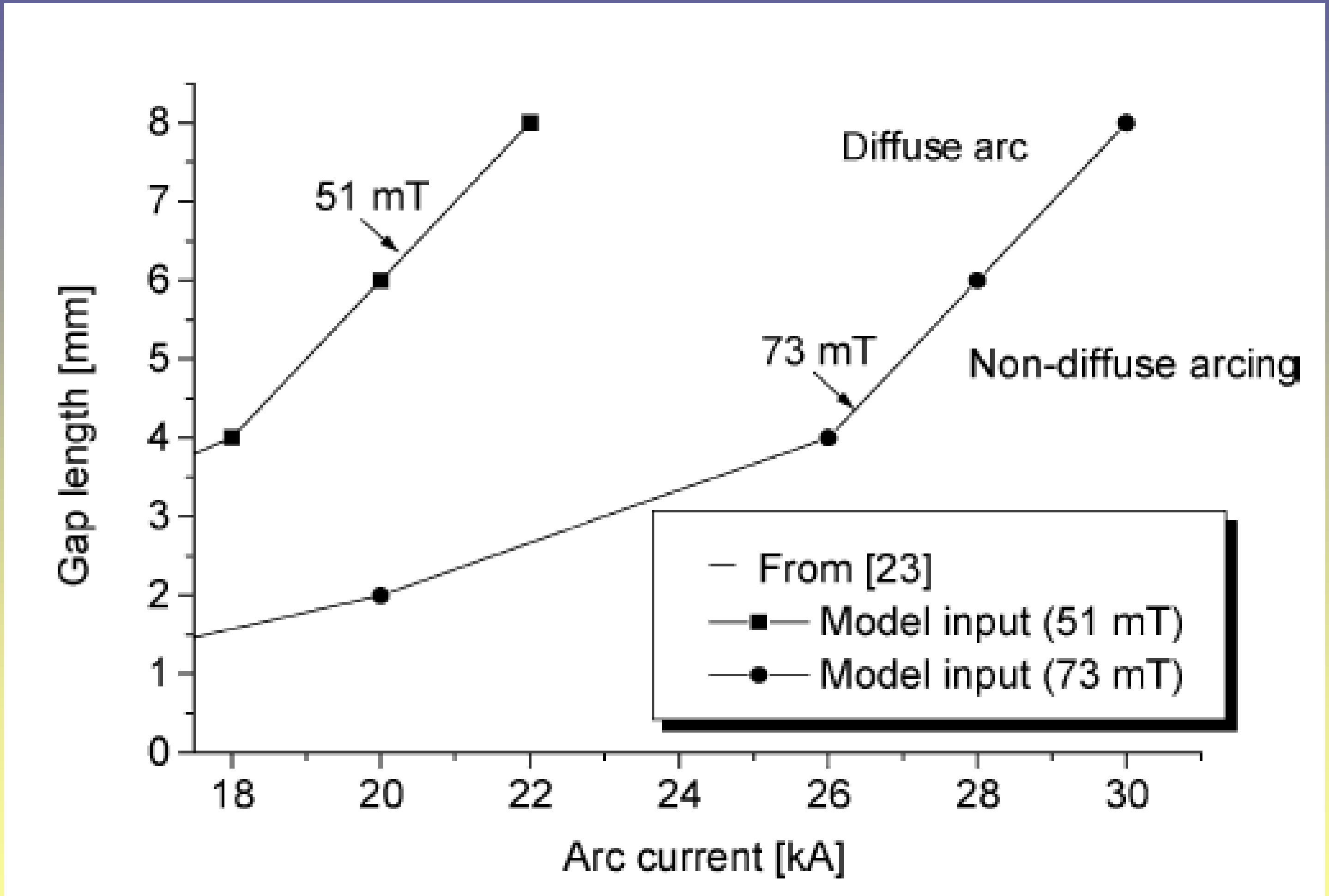
Keidar et al, *IEEE Trans. Plasma Sci*, 2004

Comparison with experiment



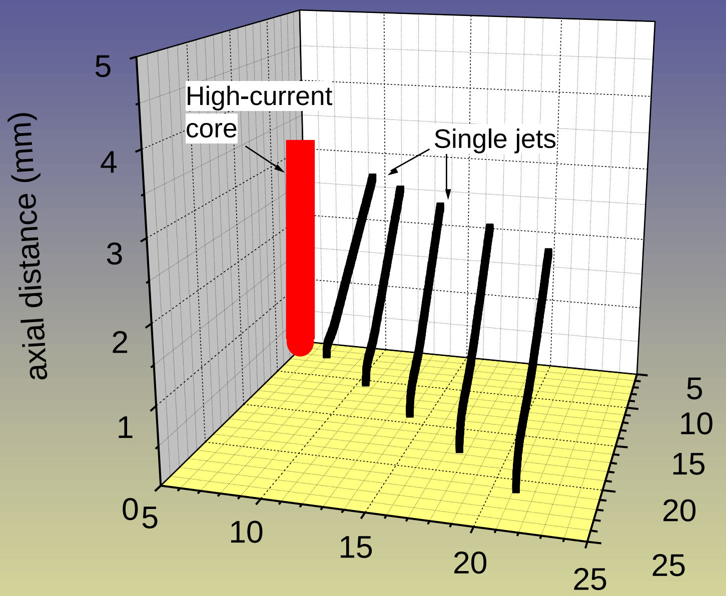
$V_{arc} < V_{cr}$ – is diffuse arc condition

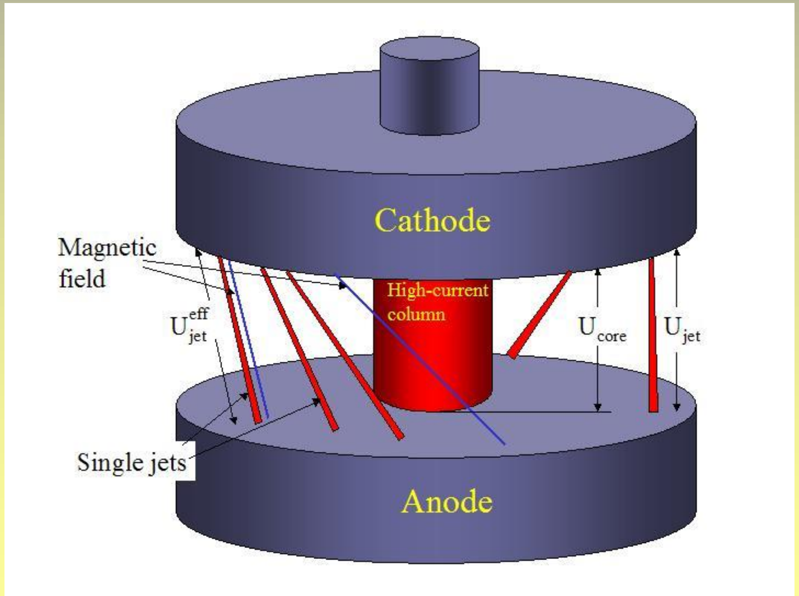
Diagram of Modes



Arc Voltage Criterion

- Single jets appear even when $V_{arc} > V_{cr}$
- Single jet appearance is common phenomenon during evolution into a high-current diffuse arc
- More general criterion is required based on effective voltage



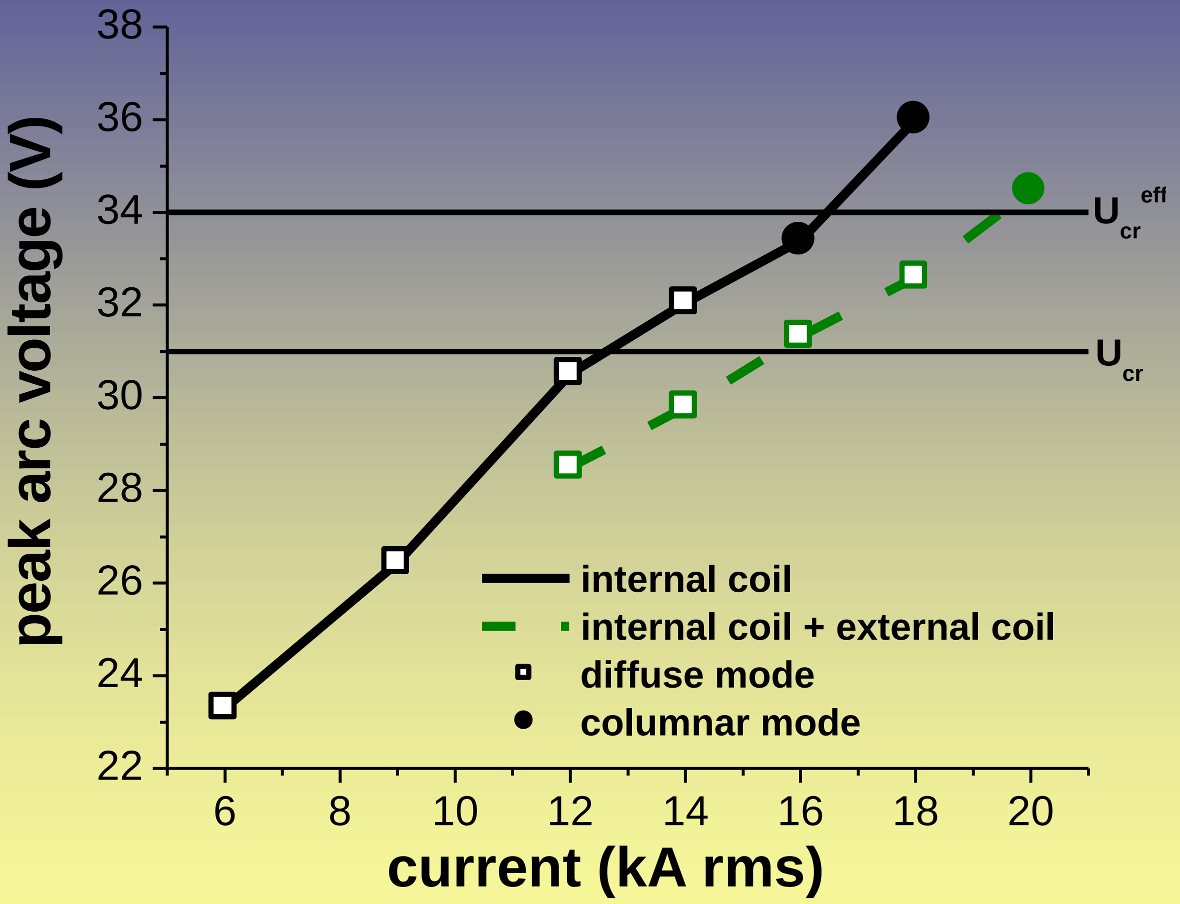


$$U_{jet}^{eff} = \int_{0}^{l_{eff}} E(\lambda)\, d\lambda$$

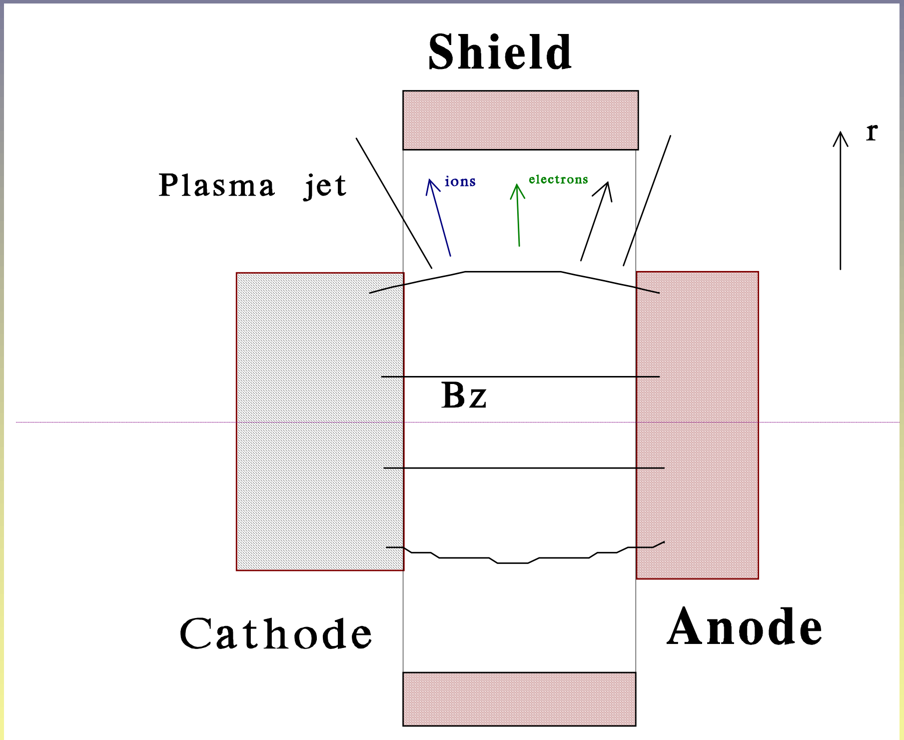
$$U_{cr}^{eff} \geq U_{arc} \geq U_{jet}^{eff}$$

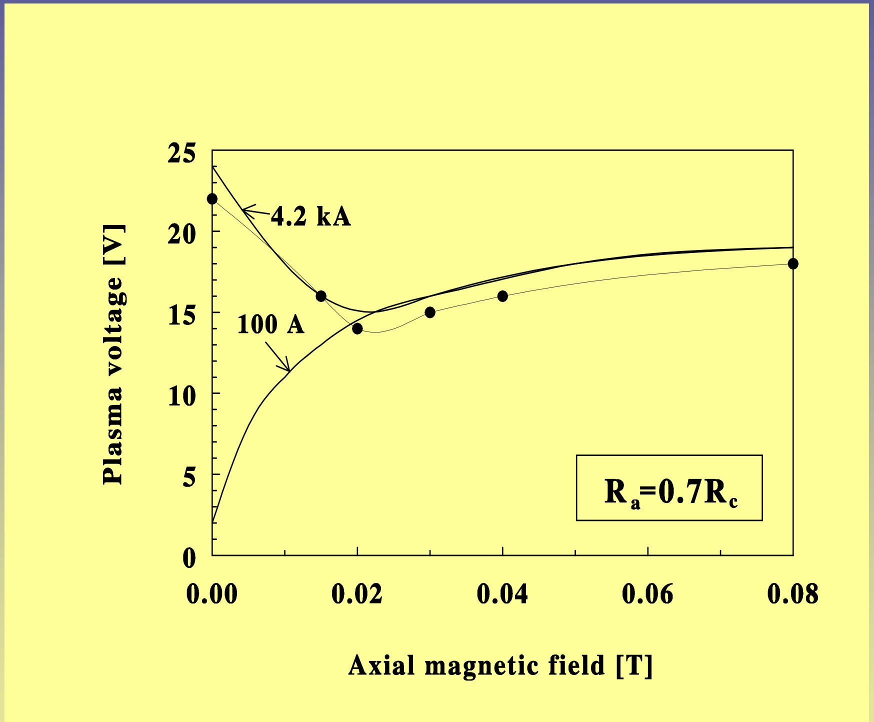
Comparison with experiment

Generalized condition agrees better with observations



Radial plasma flow





Kimblin & Voshall,Proc. IEE, 119, 1754 (1972)

The model

Similar to the model of the interelectrde gap

- hydrodynamic
- multicomponent plasma
- ambipolar flow

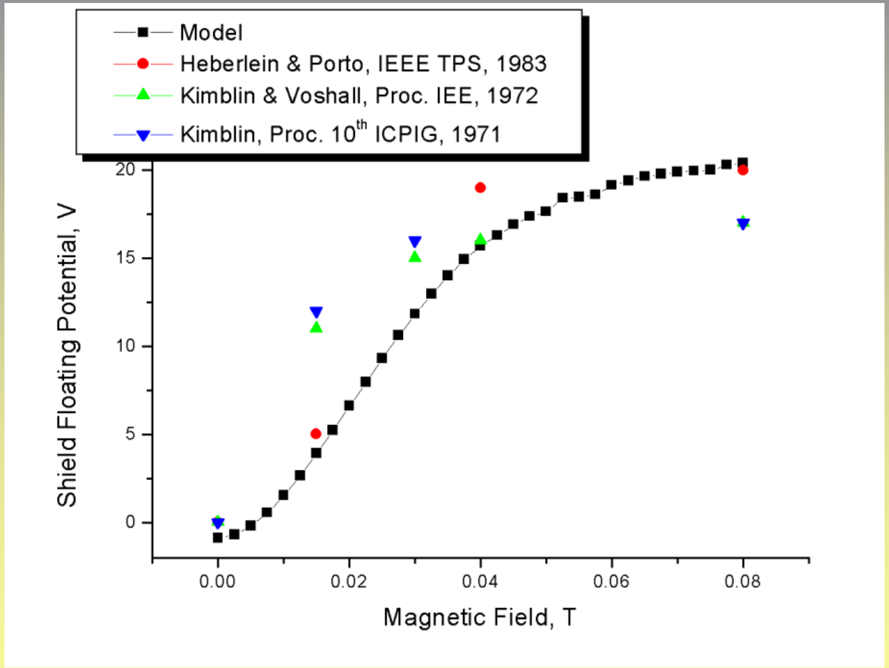
Potential distribution:

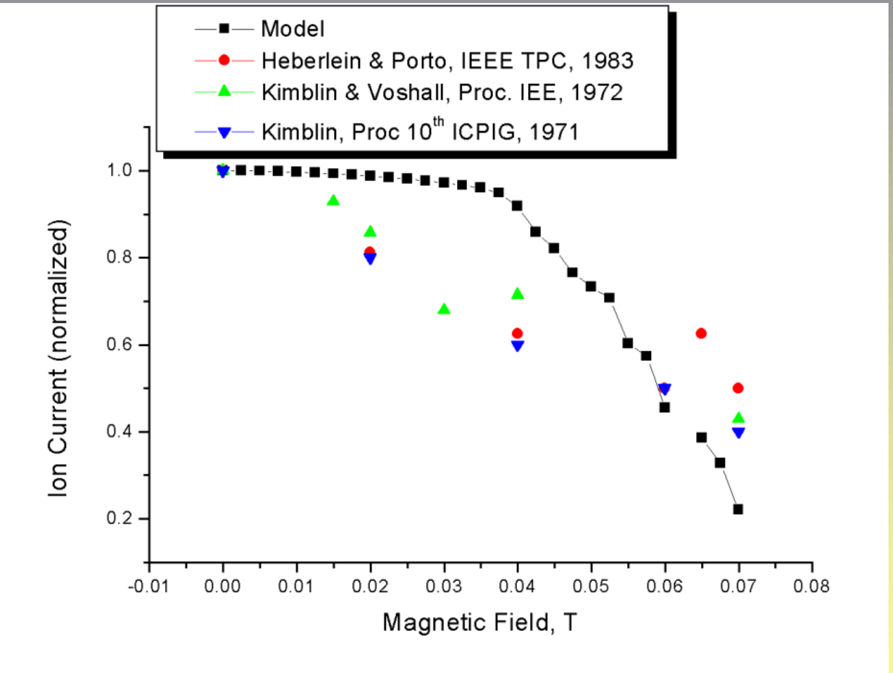
$$dU/dr = kT_e/e \cdot \nabla \ln(\sum Z_j n_j) + B\beta_e(\sum Z_j n_j V_j / \sum Z_j n_j)$$

Density gradient

Magnetic Field

Radial Flow

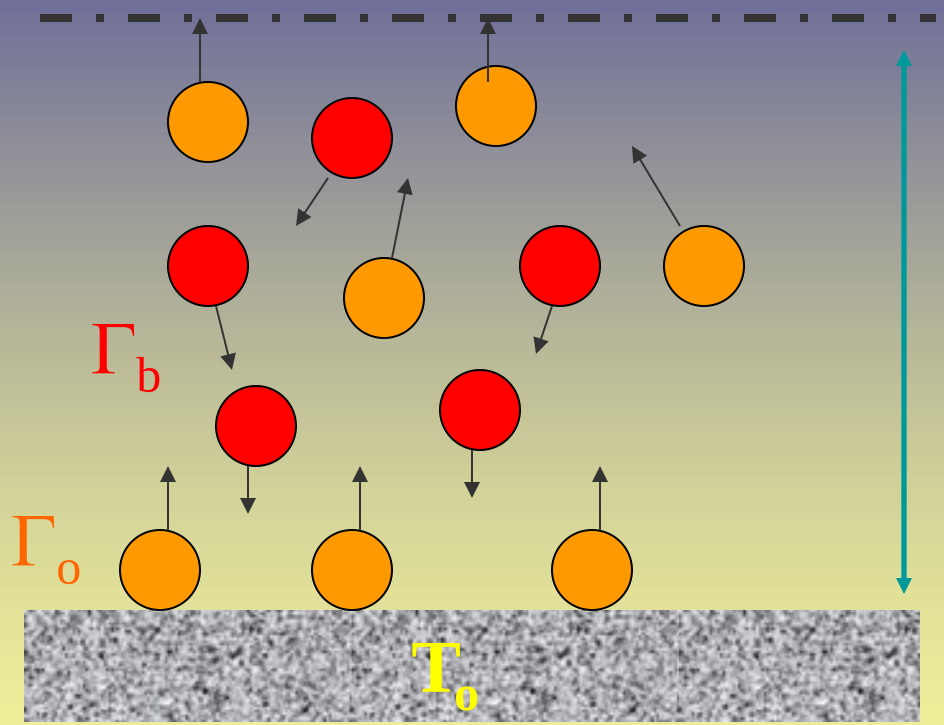




20 eV peak good agreement

Rustenberg et al. IEEE Trans. Plasma Sci., 1995

Material ablation: non-equilibrium layer



Existing models (Langmuir) can describe only low pressure <1 torr cases

Knudsen layer
~few mean free paths

The back flux Γ_b is generated due to collisions

Evaporation flux: $\Gamma_{ev} = \Gamma_o - \Gamma_b$

Keidar *et al*, *J. Appl. Phys*., 2001

Non-equilibrium layer

x

f_1

Equilibrium plasma

f(x)

f_o

Boundary conditions

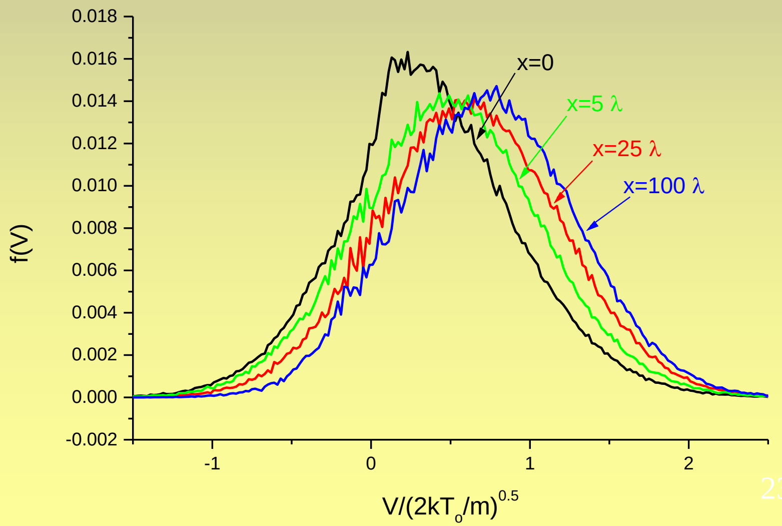
$$f_1(v) = n_0\left(\frac{m}{2\pi k T_w}\right)^{3/2} \exp\left(-\frac{m((V_x - U)^2 + V_y{}^2 + V_z{}^2}{2kT_w}\right)$$

$$f_o(v) = n_0\left(\frac{m}{2\pi k T_w}\right)^{3/2} \exp\left(-\frac{mV^2}{2kT_w}\right)$$

$\int V_x f(V)\, dV$ = const **(mass)**

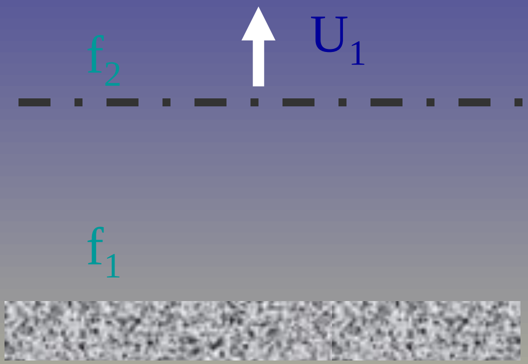
$\int V_x^2 f(V) dV$ = const **(momentum)**

$\int V_x V^2\, f(V) dV$ = const **(energy)**



Keidar *et al*, *J. Appl. Phys.*, 2001

Kinetic model of the Knudsen Layer



Analytical and particle (DSMC) approaches:

$f(x,\mathbf{V}) = \xi(x)f_1(\mathbf{V}) + (1 - \xi(x))f_2(\mathbf{V})$

where $\xi(x=0)=1$ and $\xi(L)=0$ with $x=0$

[Mott-Smith, 1951]

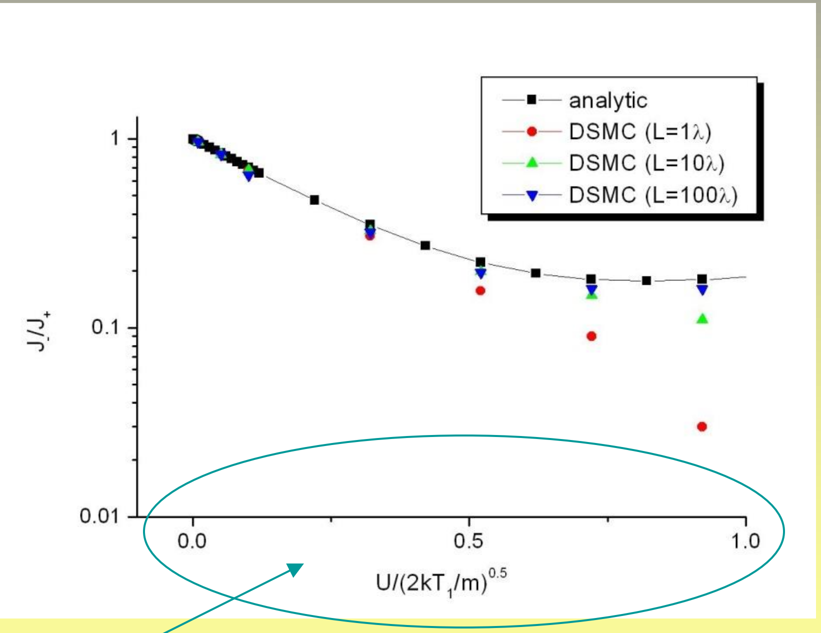
$f_1(\mathbf{V}) = n_o\beta^{3/2}\exp(-V^2)$ $\quad V_x>0$

$f_1(\mathbf{V}) = \delta f_2(\mathbf{V})$ $\quad V_x<0$

$f_2(\mathbf{V}) = n_1\beta^{3/2}\exp(-(v-U)^2)$

[Anisimov, 1968]

Sound speed is assumed !

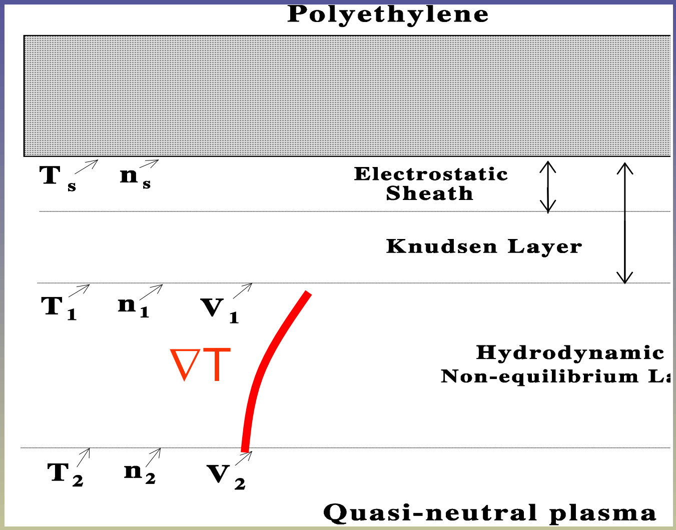


Depends on velocity

Keidar *et al*, *J. Appl. Phys.*, 2001

Thermal conductivity

Kinetic model of Knudsen layer: effect of thermal conductivity



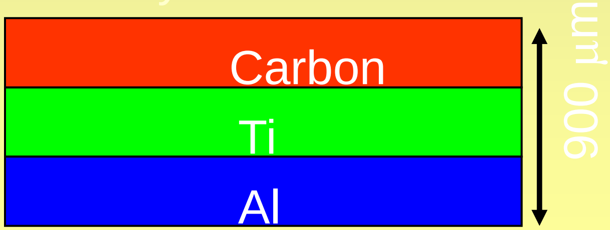
VDF in plasma

$$f_u(\vec{V}) = n_1 \cdot f_M(\vec{V}) \cdot \left\{ 1 - \frac{V_T \cdot V_1}{\nu} \cdot \left[\frac{(V_x - u)}{V_1} \cdot \left(\frac{(V_x-u)^2 + V_y^2 + V_z^2}{V_1^2} - \frac{5}{2} \right) \cdot \frac{d}{dx}(\ln T) + \right.\right.$$

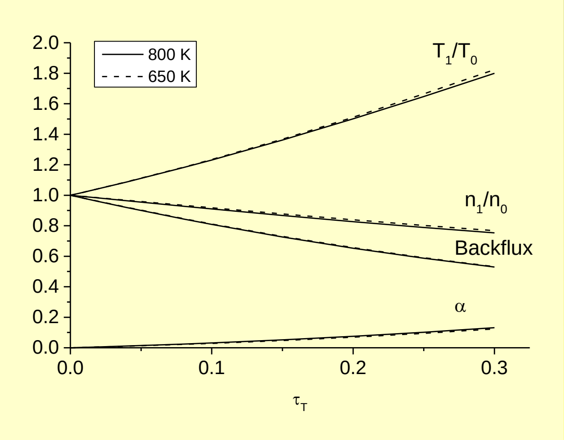
$$\left.\left. + 2 \cdot \left(\frac{2 \cdot (V_x-u)^2 - V_y^2 - V_z^2}{3 \cdot V_1^2} \right) \cdot \frac{du}{dx} \right] \right\}$$

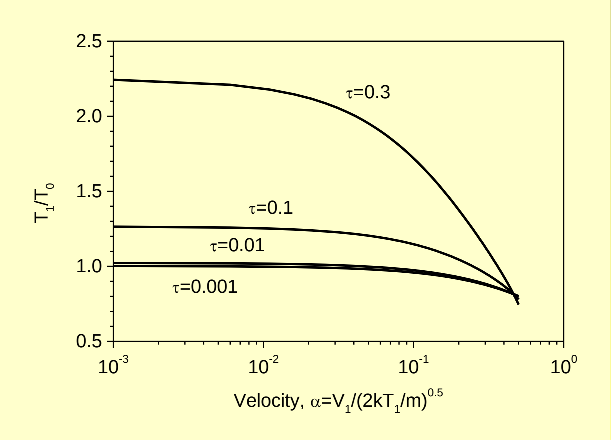
Effect of thermal conductivity

Layer structure



Pekker, Keidar *et al.* J. Appl. Phys. 2008





Keidar *et al*, *J. Appl. Phys.*, 2001, 2004

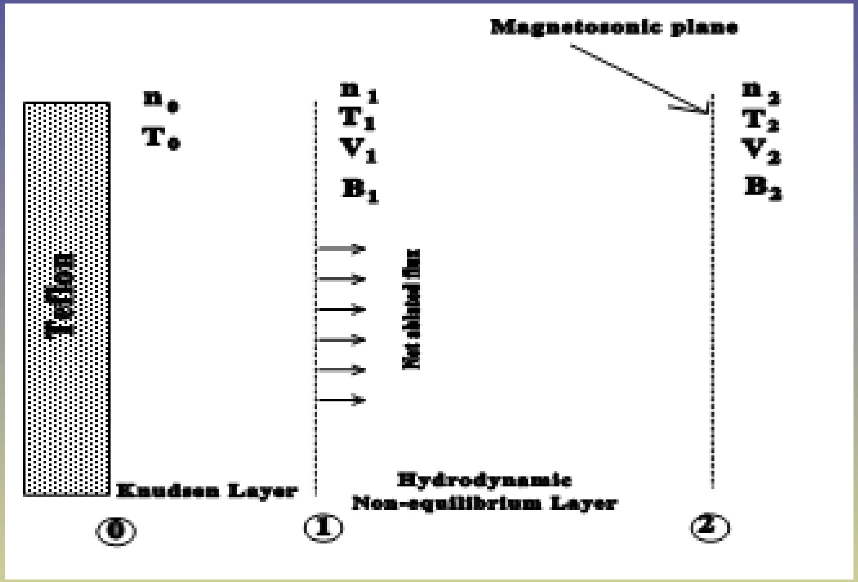
Hydrodynamic Layer

$$\nabla \cdot (nV) = \beta_{ioniz}$$

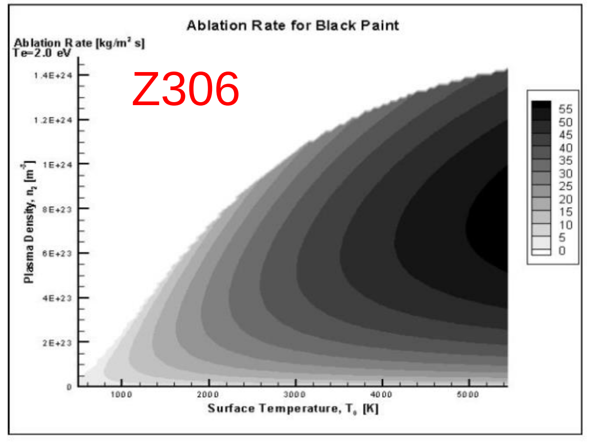
$$M(V \cdot \nabla V) = -\nabla P + j \times B$$

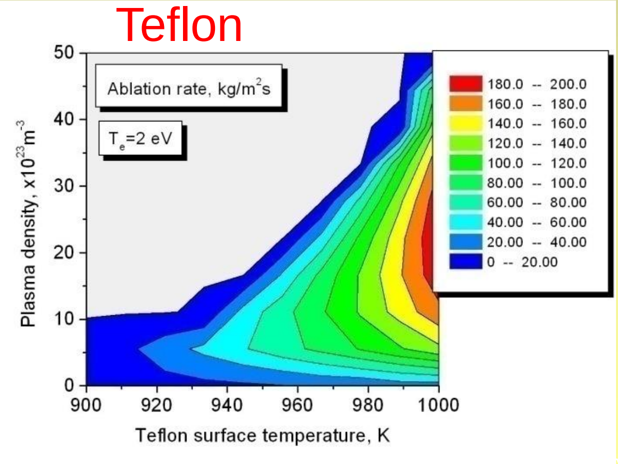
1D limit

$$\frac{MU_1^2}{2kT_1} = \frac{\frac{n_1}{2} - \frac{T_2 n_2}{2T_1} + \frac{1}{4} \cdot \frac{\mu (jd)^2}{kT_1}}{\frac{3}{2} \cdot \frac{n_1^2}{n_2} - n_1}$$



U_1 depends on the specifics of acceleration (n_2, j)

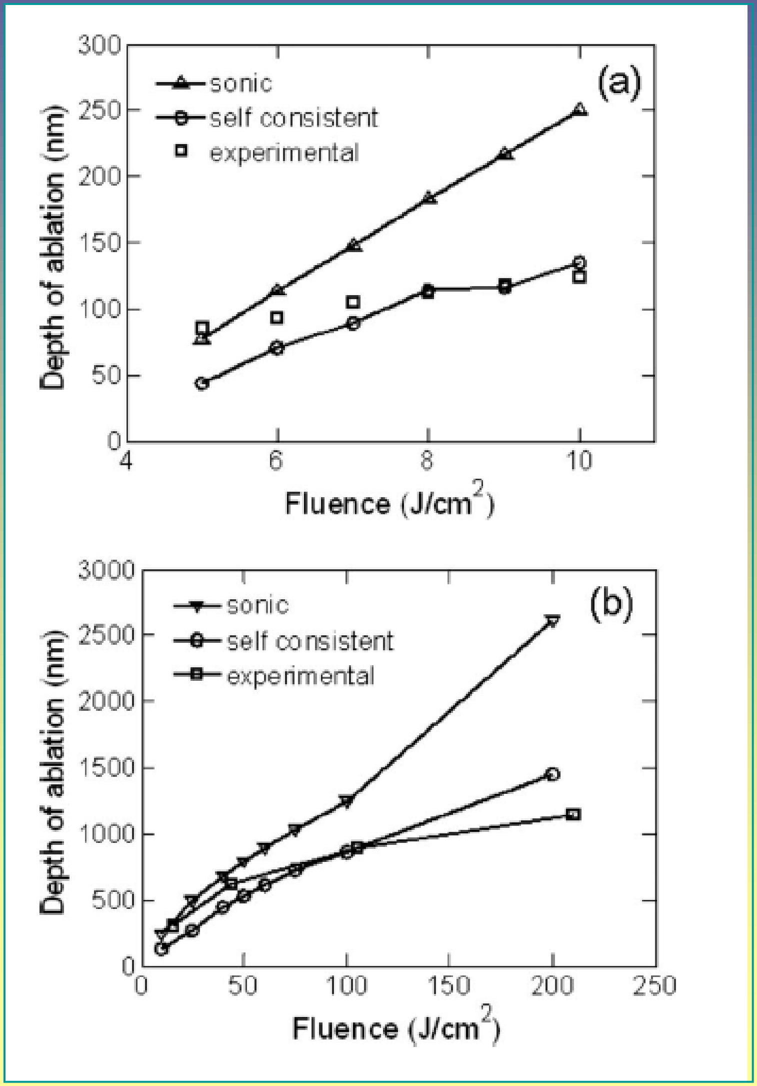




Keidar *et al.* J. Phys.D, 2001, J. Appl. Phys. 2001, 2004

Why and where this interactions are important ?

Model validation-directed energy



- Al alloy

  Pulse duration 15 ns, λ = 308 nm, Fluence 1-10 J/cm2

  Dou et.al., IEEE J. Quantum Electron. **6**, 689 2000

- Cu

  Pulse duration 6 ns, λ = 532 nm, Fluence 10-200 J/cm2

  Semerok et.al., Laser Part. Beams **20**, 67 2002

Predicting charring

Ablation rate

$$\Gamma = m n_1 \sqrt{\frac{1}{m} \cdot \frac{(k n_2 T_2 - k n_1 T_1)}{(n_1 - \frac{n_1^2}{n_2})}}$$

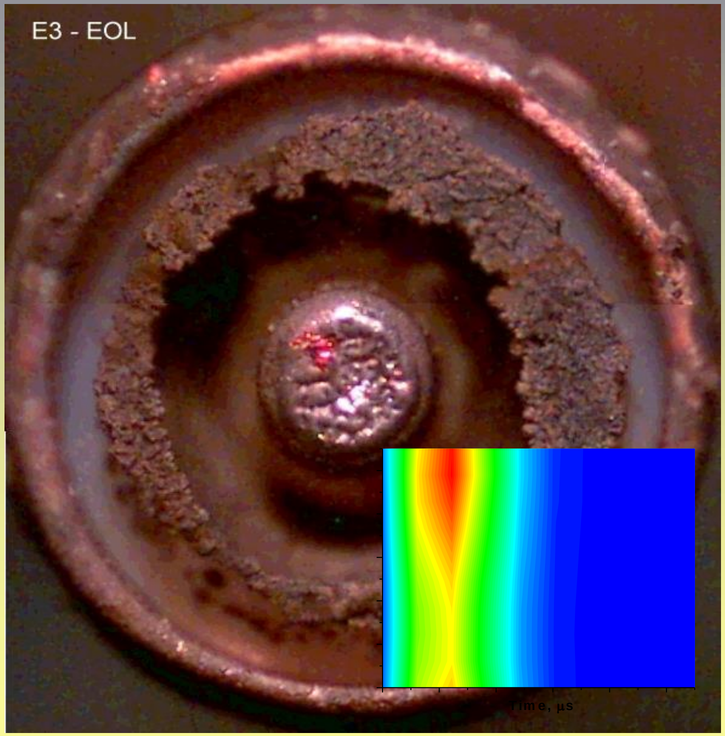
Condition: $kT_2 n_2 < kT_1 n_1$ and $n_1 > n_2$

If backflux is higher than the primary flux –deposition

Deposition rate

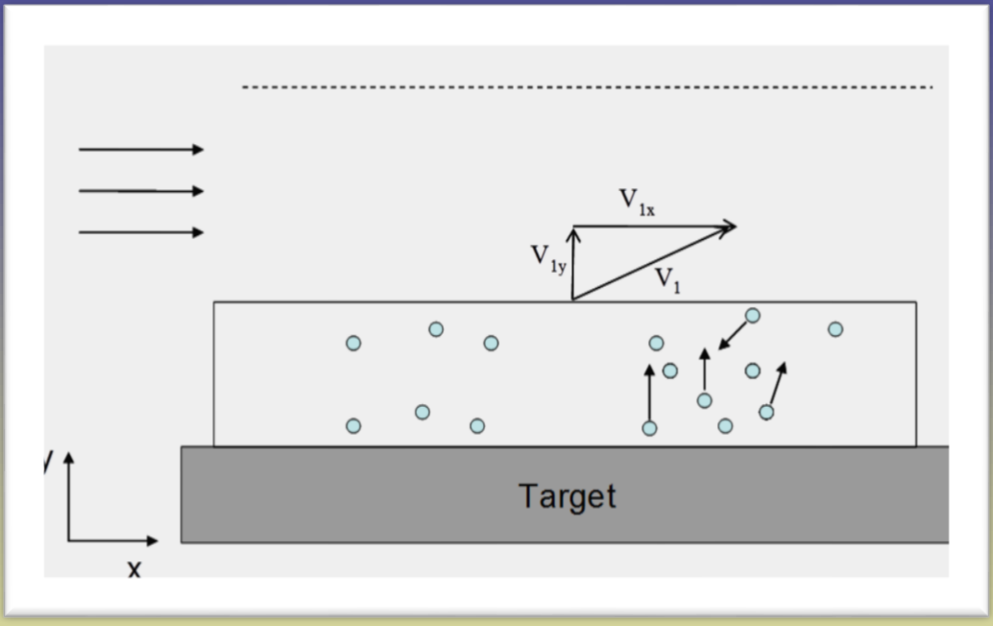
$\Gamma = - m(kT_2/m)^{0.5} n_{C2}$

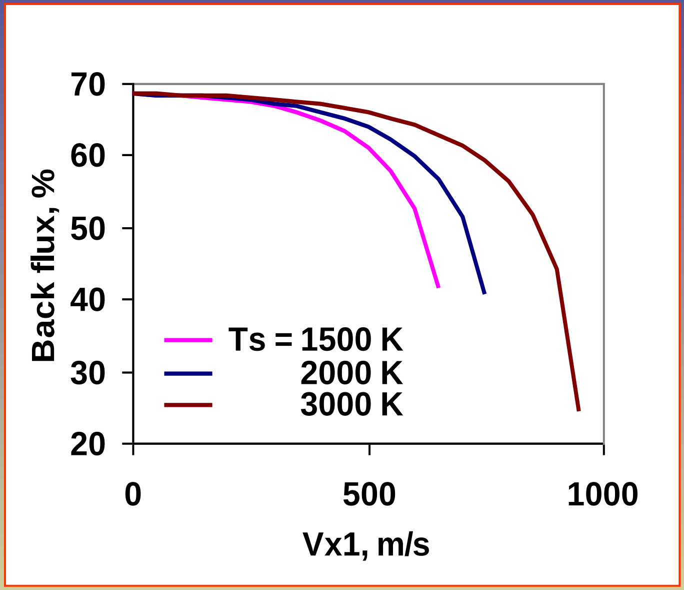
Backflux in Teflon micro-thruster

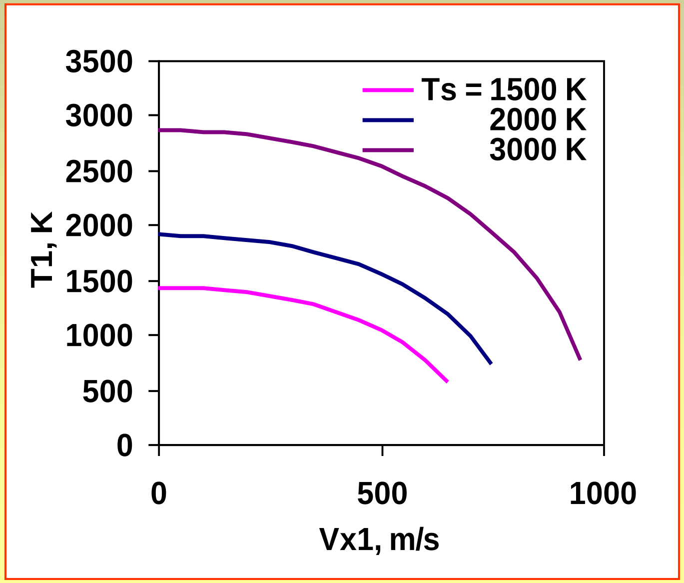


Keidar *et al*. J. Prop. Power 2004, p. 978

Effect of cross flow (moving target)



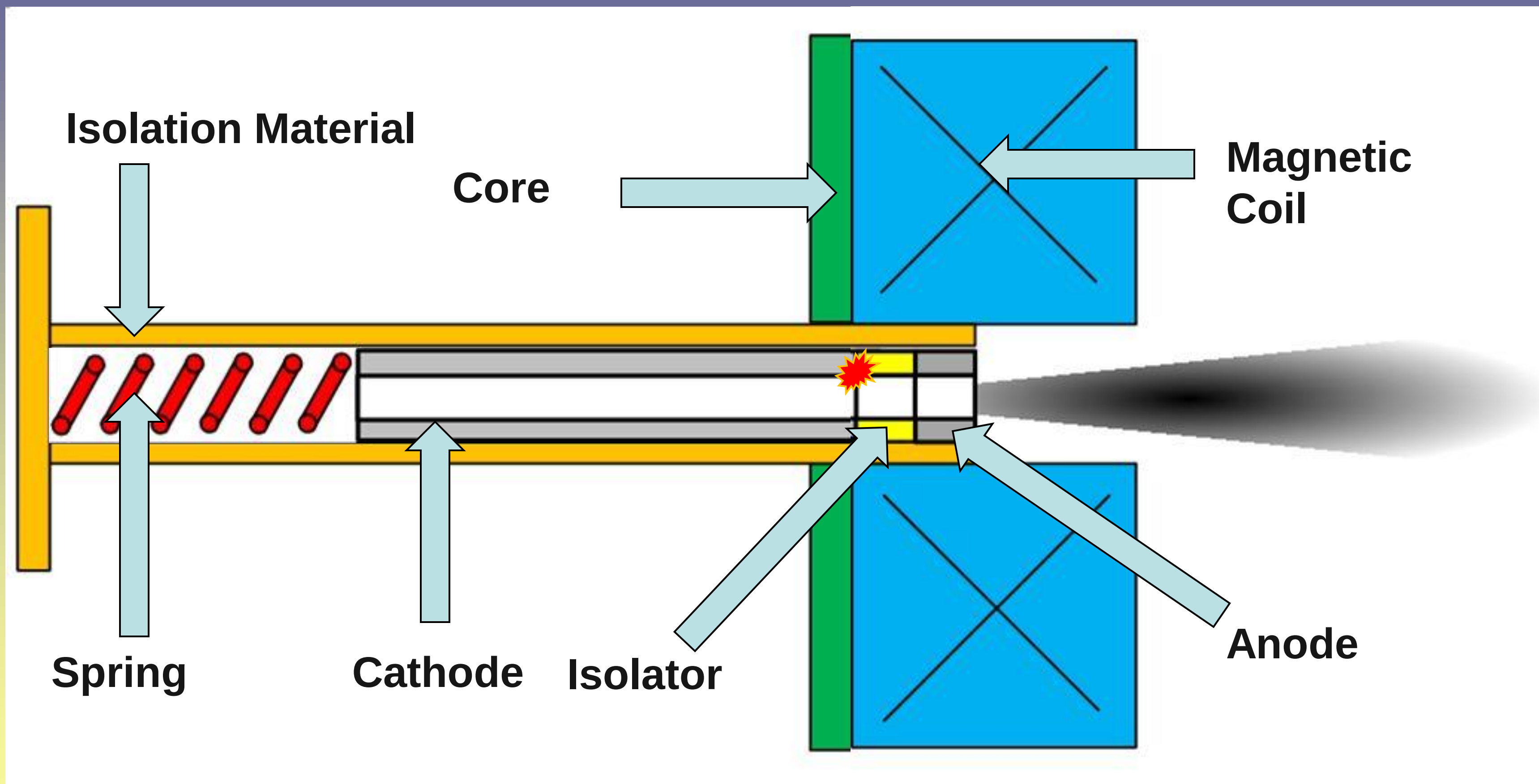




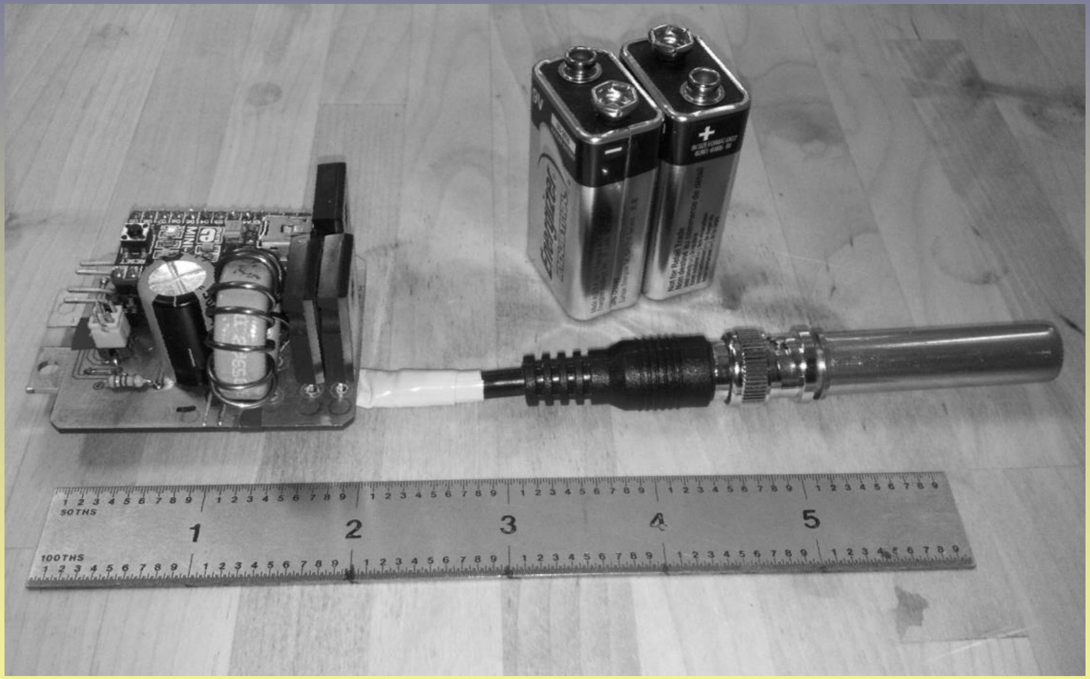
- Back flux decreases with the increase of cross flow velocity
- vapor temperature at KL outer edge decreases with the increase of cross flow velocity
- Ablation rate increases

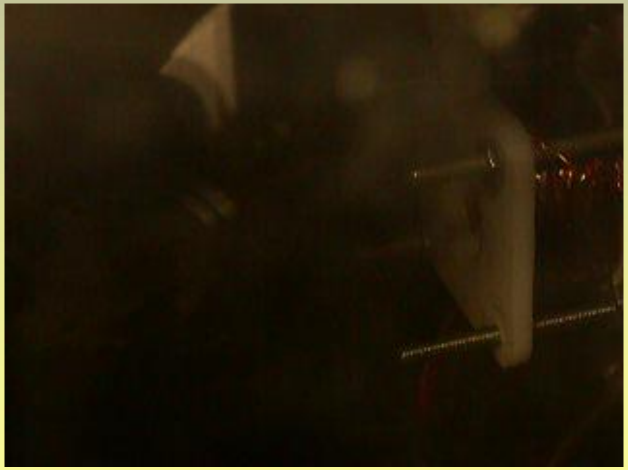
Micro-Cathode Thruster with Extended Lifetime

Schematic of μCT Feed Mechanism

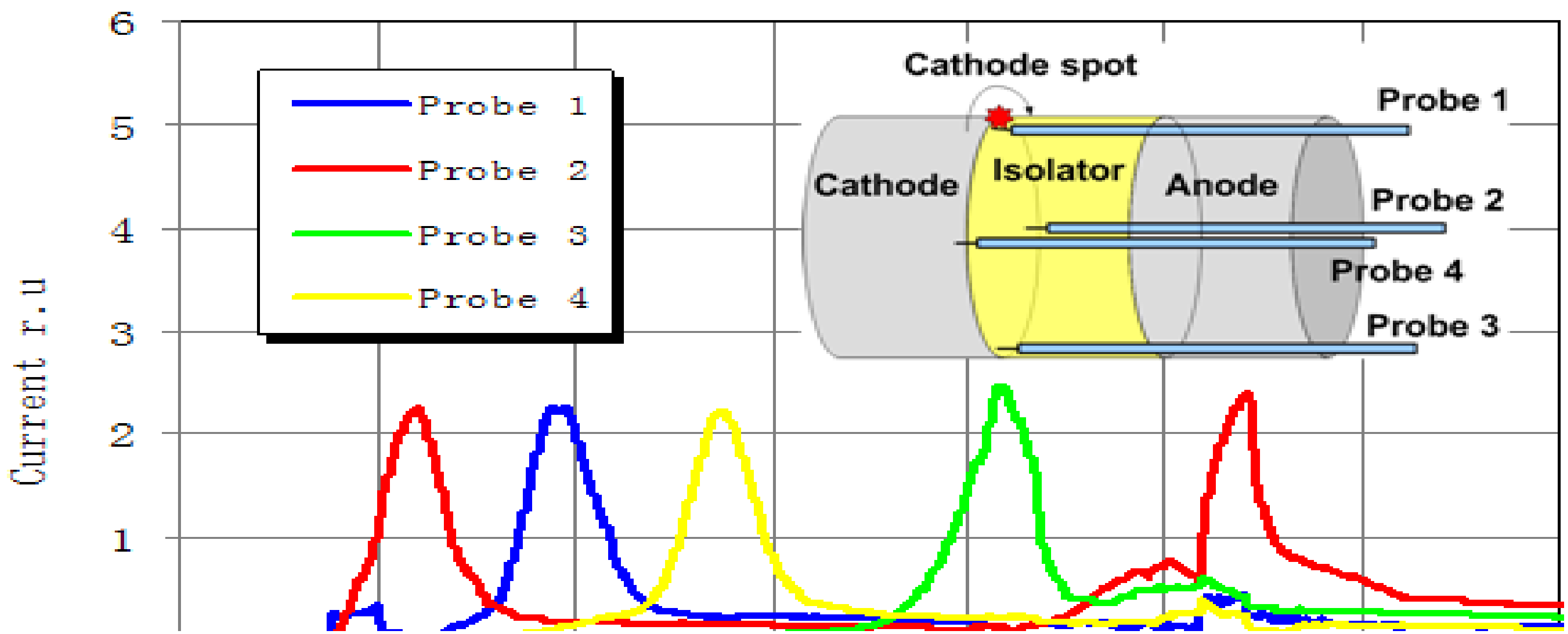


Micro-cathode arc thruster (μCAT)



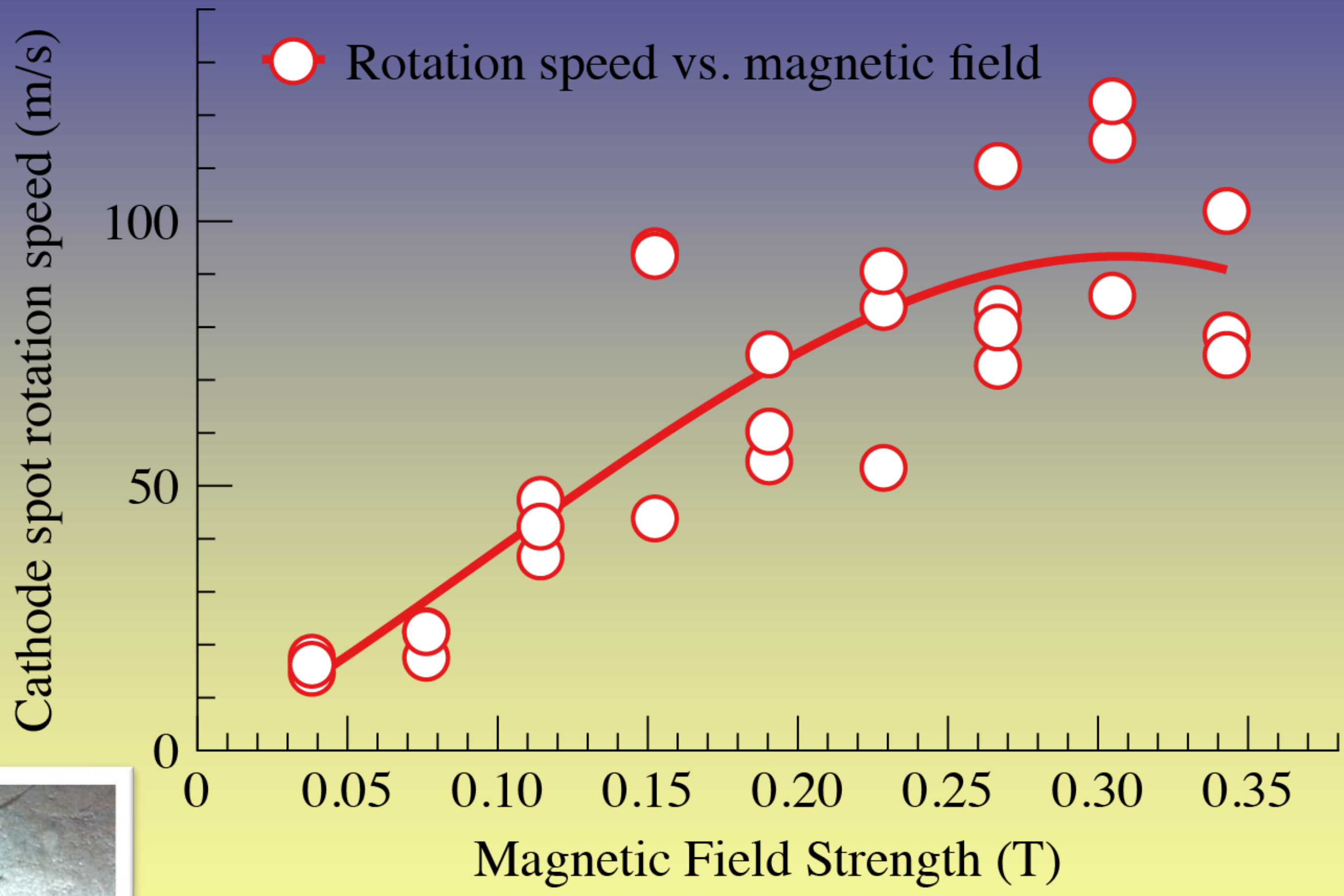


Cathode Spot Rotation

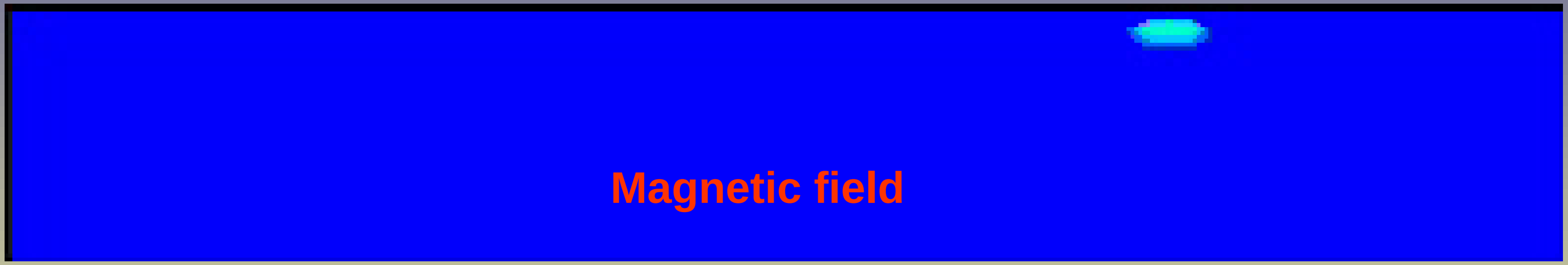


The Experiment Result shown that the Rotation Speed is *75m/s*
The Rotation As the Direction of –*J*×*B*

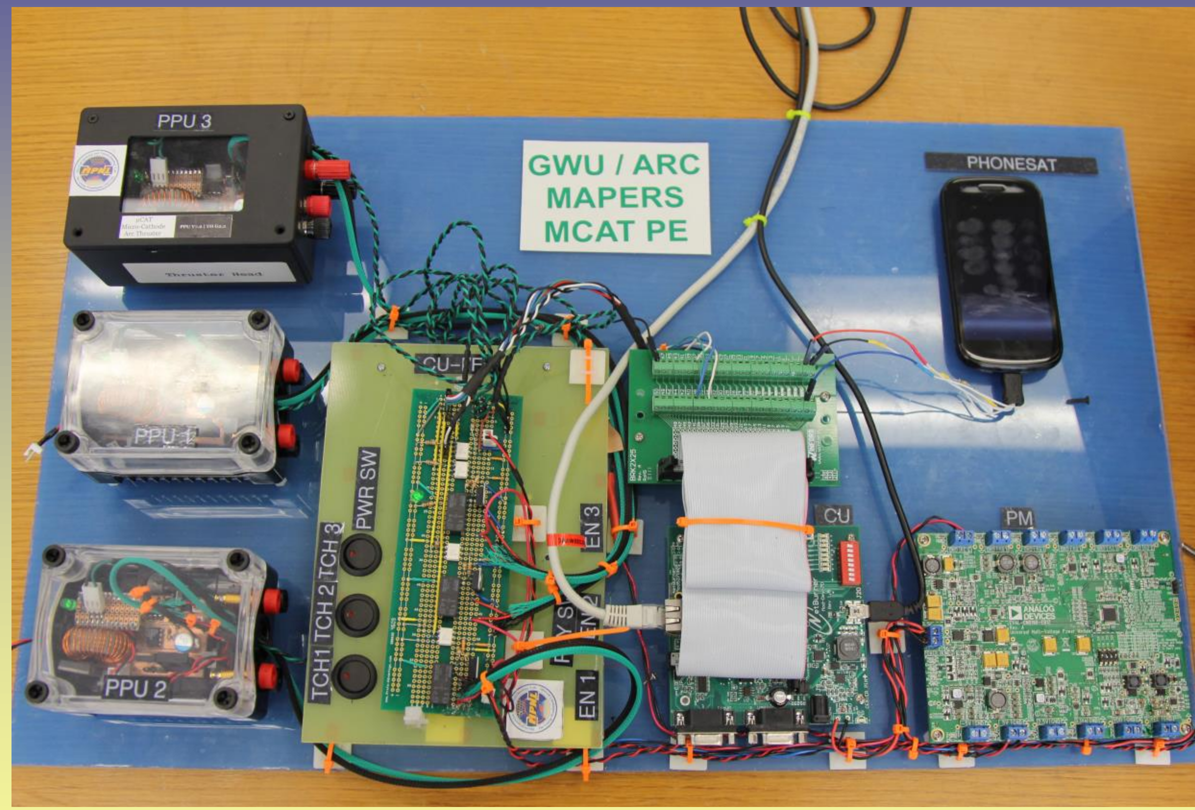
Cathode Spot Rotation



PIC simulations



NASA Ames PhoneSat Experiment

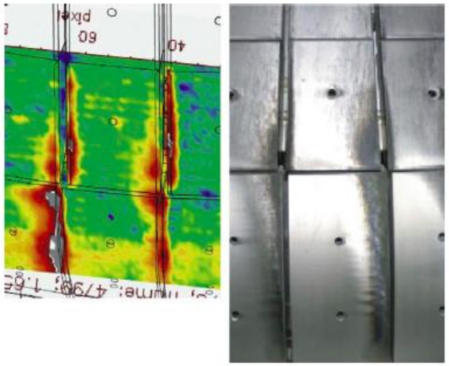


- NASA Ames PhoneSat selected micro-CAT

  Android app compatible with PhoneSat Bus will be capable of commanding uCATs

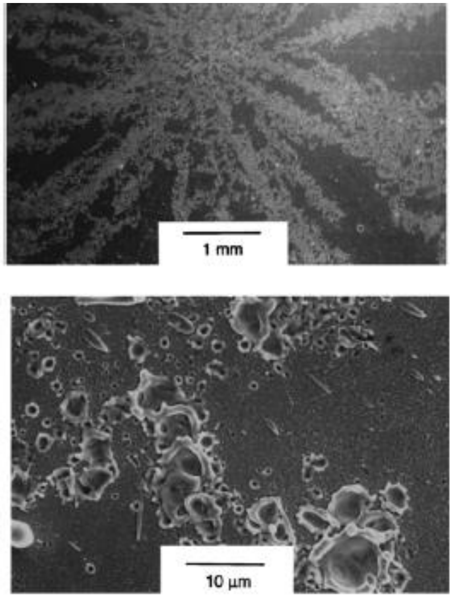
NASA ARC, August 2013

Unipolar Arcs

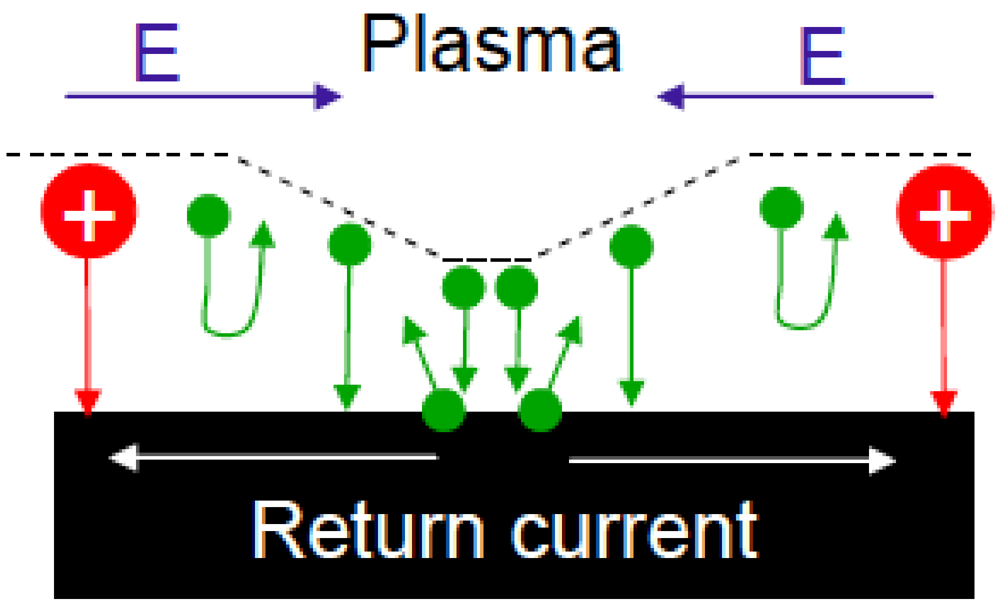


View of the IR-camera and photo of an arc pattern of a comparable region in the inner divertor on ASDEX-Upgrade

A. Herrmann et al., J. Nucl. Materials, 2009



Wang, Brown, Rev. Sci. Instr. 1999

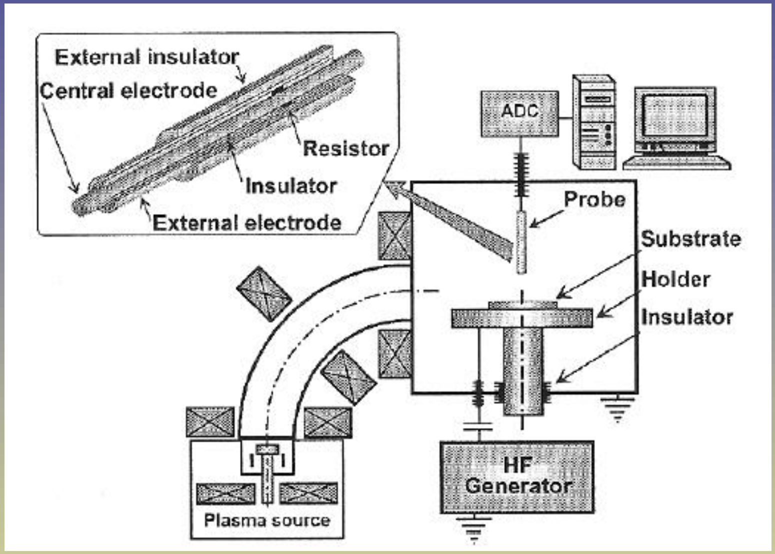


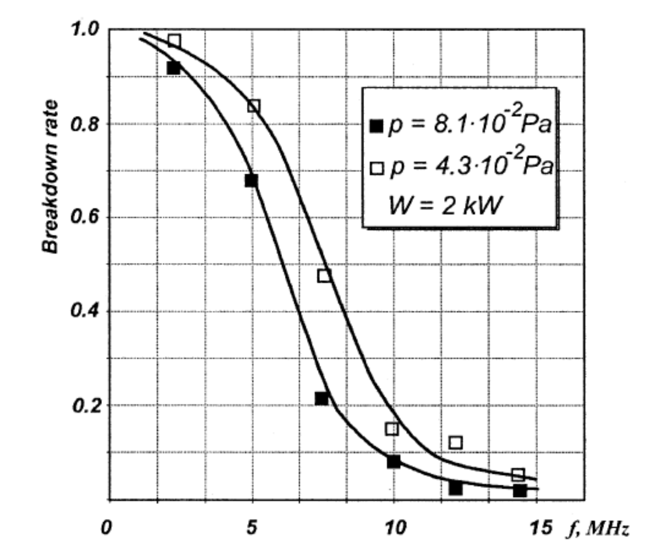
Conductive wall with electron emitting (δ) spot

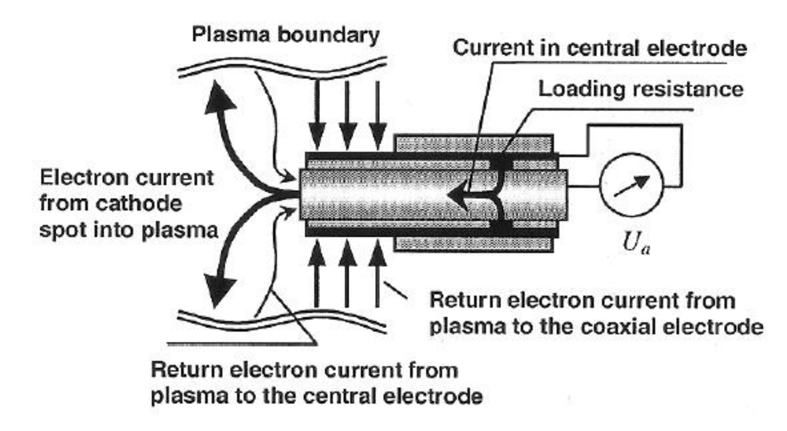
Global floating condition:

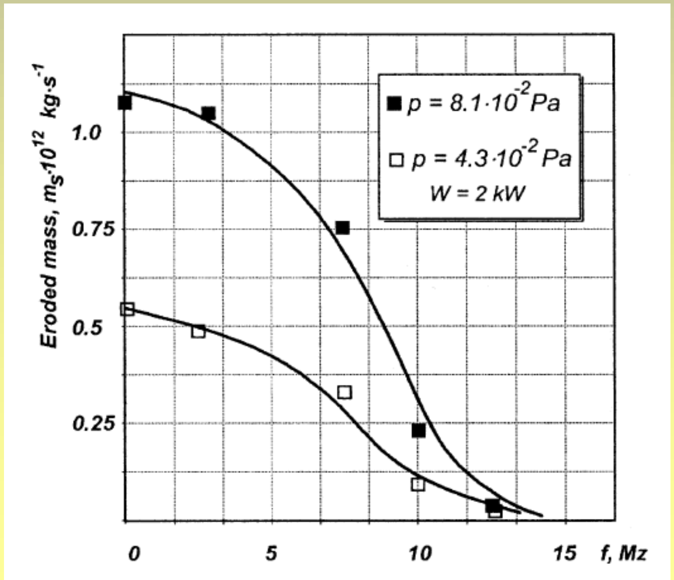
$$\int_S [J_e(1-\delta)-J_i]\cdot dS = 0,$$

Unipolar Arc Suppression









IEEE TPS, 2003

Summary

- Free boundary plasma jet expansion model developed in 90s still useful
- Predicts high-current vacuum arc behavior
- Kinetic erosion model
- Some new devices based on vacuum arcs
- Unipolar arcs suppression

Thank you !