Kinetic of plasma particles and electron beam relaxation zone in a vacuum arc

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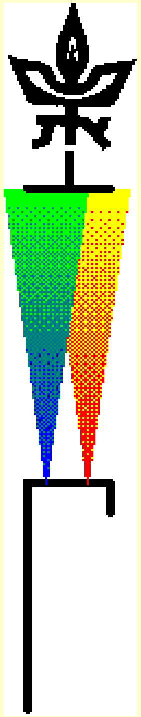
2005 Workshop on NCETIP

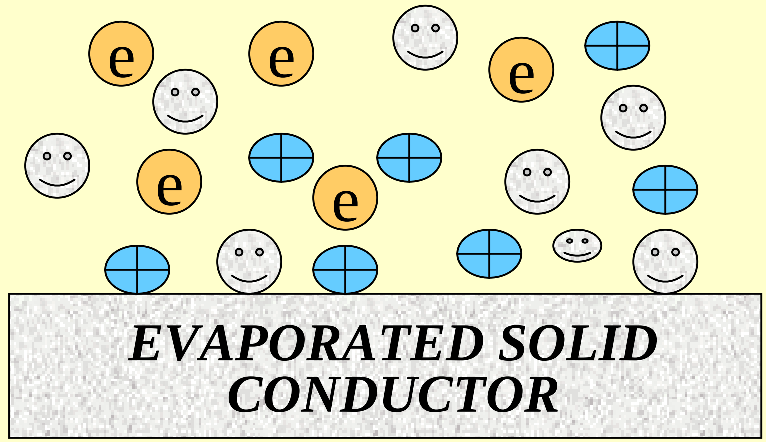
Main Issues

- **SUBJECT and the PROBLEM**
- **VAPORIZATION PHENOMENA. DIFFERENT PLASMA SYSTEMS**
  - ***Laser action on metals*.**
  - ***Ablative plasma accelerators***
  - ***MHD power conversion.***
  - ***Vacuum arc Cathode spot***
  - ***Unipolar arcs in Tokamaks.***
- **KINETIC OF A CONDENSED MATERIAL VAPORIZATION INTO VACUUM**
  - **Langmuir approach. Knudsen model**
  - **Non-equilibrium layer. Back flux to the surface**
- **KINETIC OF ARC CATHODE VAPORIZATION**
  - **Plasma in vacuum arc cathode spot. Electron transport**
  - **Cathode evaporation**
- **DIFFERENT CATHODE MATERIALS**
- **SUMMARY**

SUBJECT and PROBLEM



IONIZED VAPOR CONTACTS THE EVAPORATED SOLID CONDUCTOR



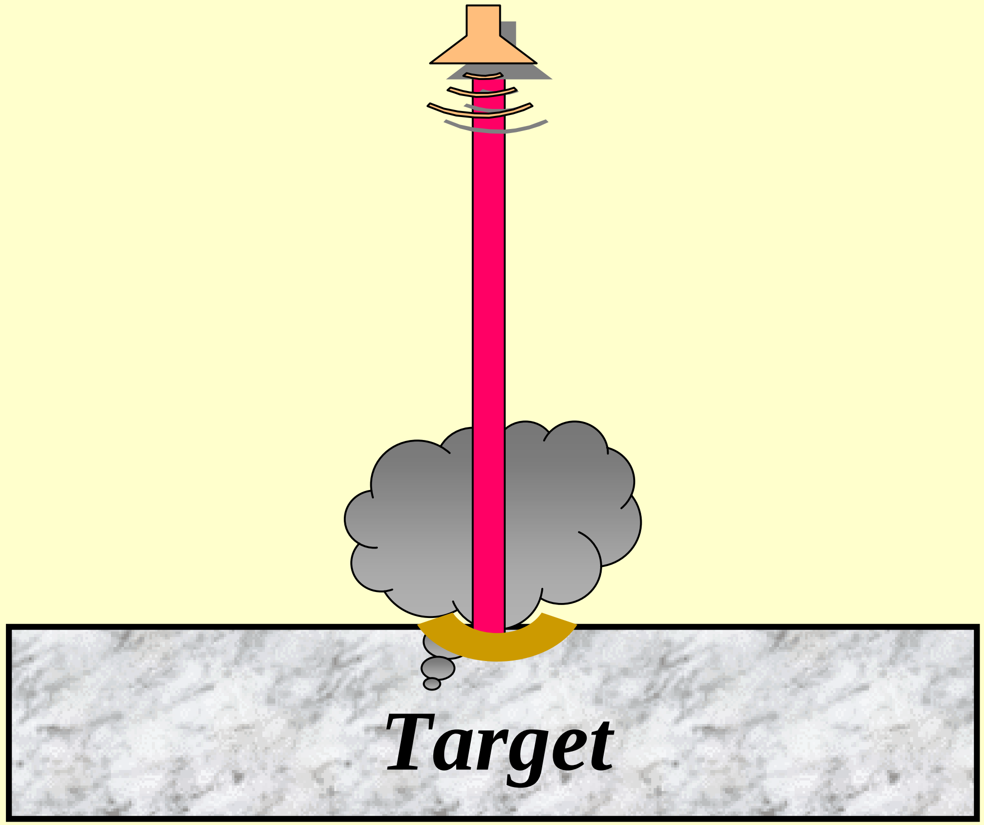
MECHANISM OF EVAPORATION INTO the IONIZED VAPOR ?

WHAT is the RELAXATION ZONE for THE PARTICLES?

HOW THE CURRENT CONTINUITY IS SUPPORT?

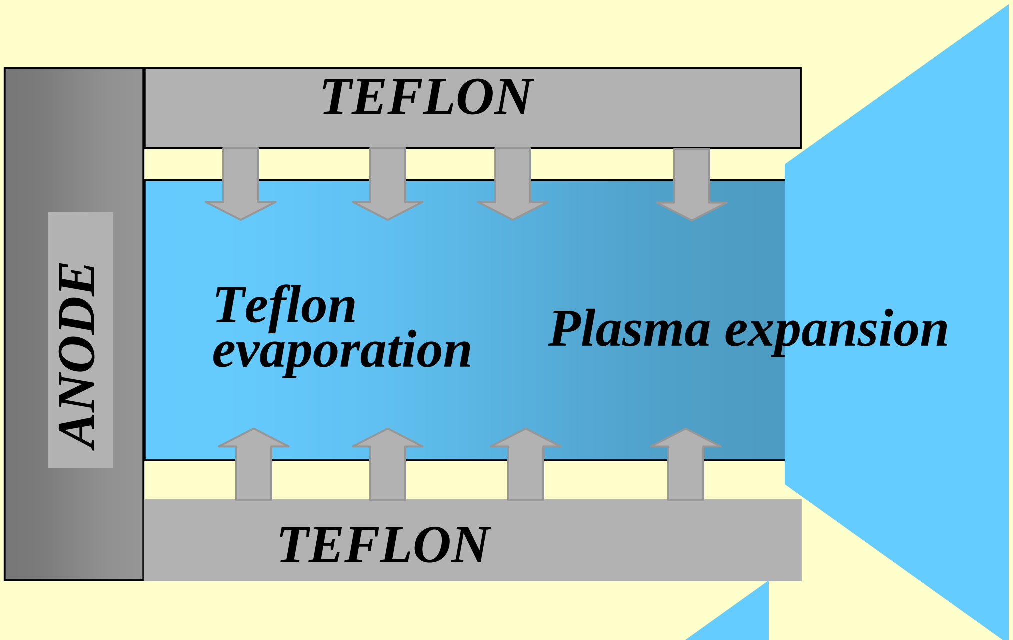
SYSTEMS WITH VAPORIZATION PHENOMENA

Target Evaporation by Laser or Electron Beam Action

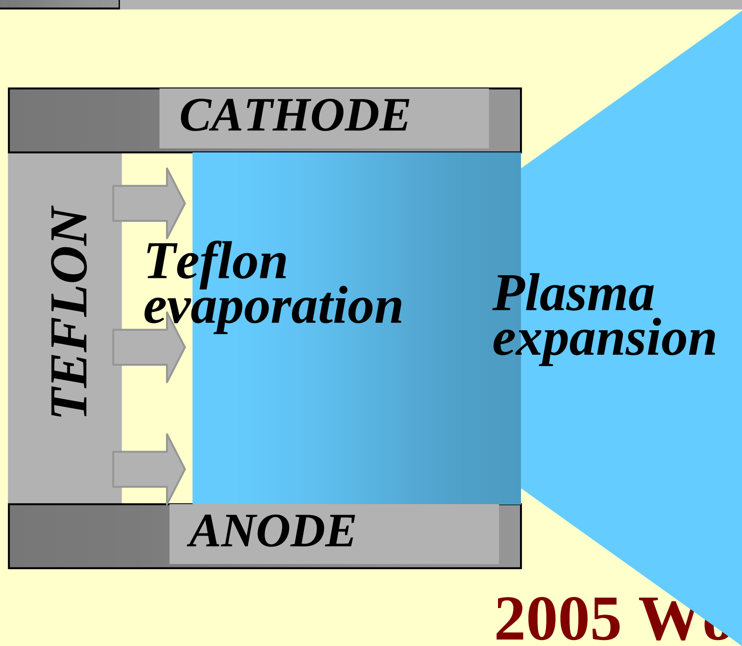


The heat flux is given and for it moderate value the vapor consists mostly of neutral atoms

Ablative Plasma Accelerators



Pulsed Plasma Thrusters *TYPE I*



Pulsed Plasma Thrusters *TYPE II*

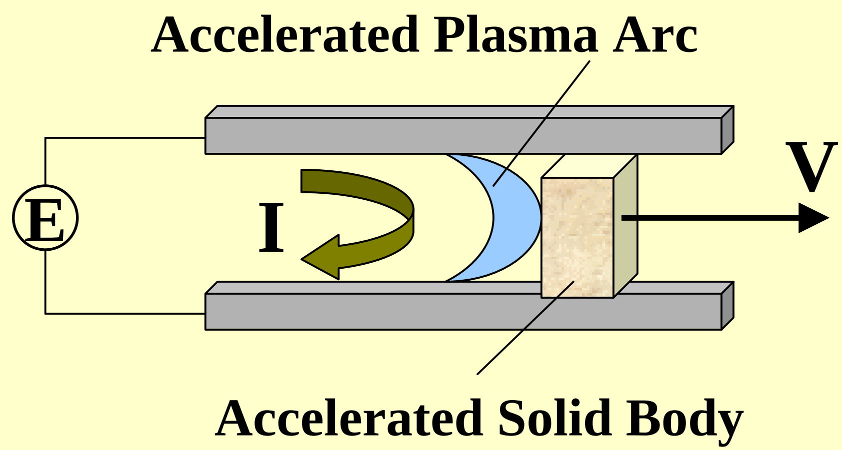
RAILGUN

- **Electromagnetic solid body acceleration**

The electromagnetic force generates in the current loop

$I \sim L_{in} dU/dt$, $I \sim B$

Arc plasma generates by the rail evaporation



MHD Power Conversion

IN MAGNETIC FIELD:

- **MHD-Generation of Electrical Power**

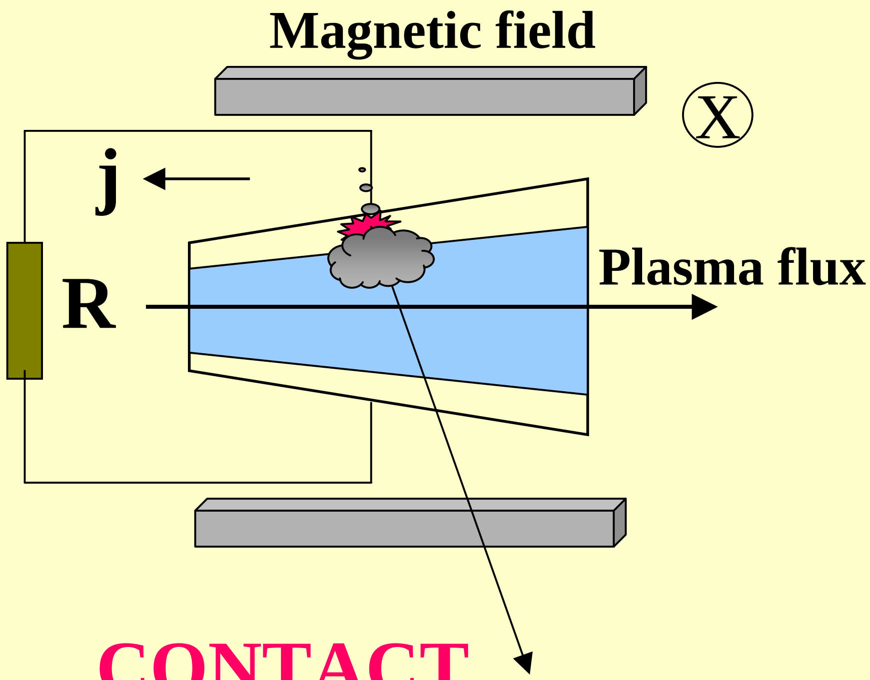
GIVEN: plasma flow V

OBTAIN: E-electrical field and the current

- **MHD-Plasma Accelerator**

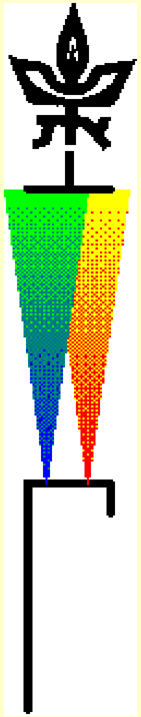
GIVEN: E-electrical field

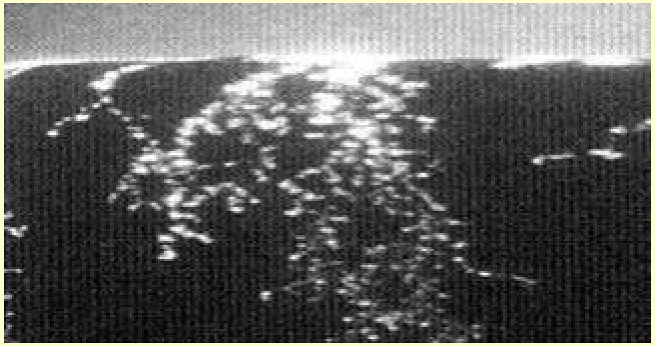
OBTAIN: plasma flow V

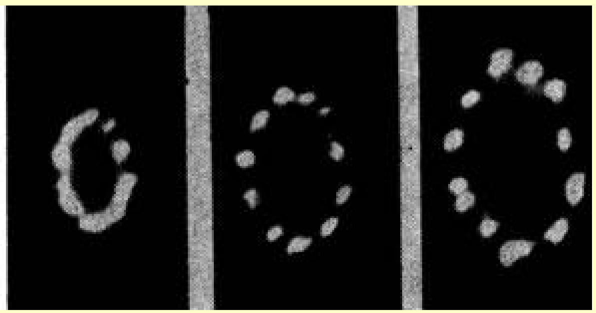


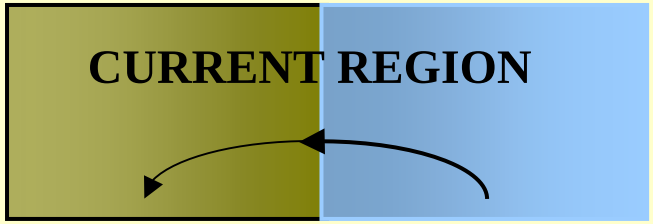
CONTACT EVAPORATION

Vacuum Arc.

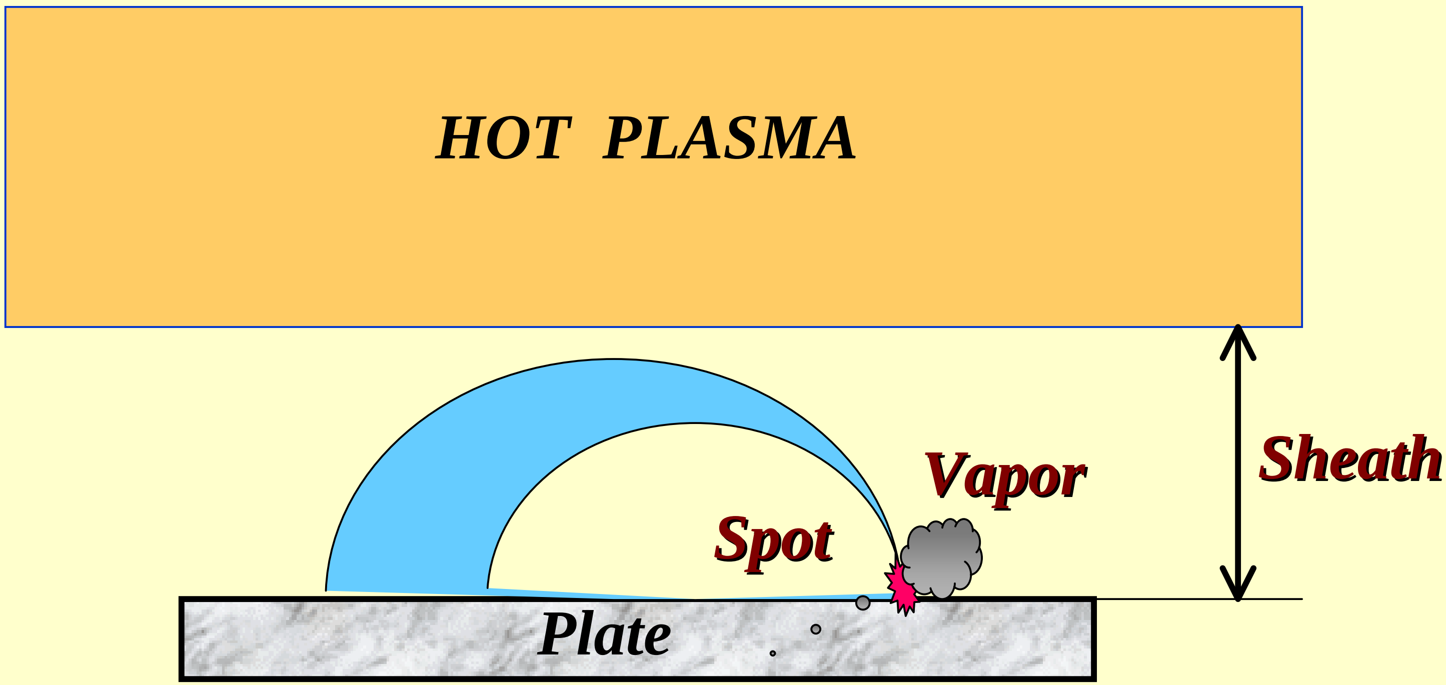








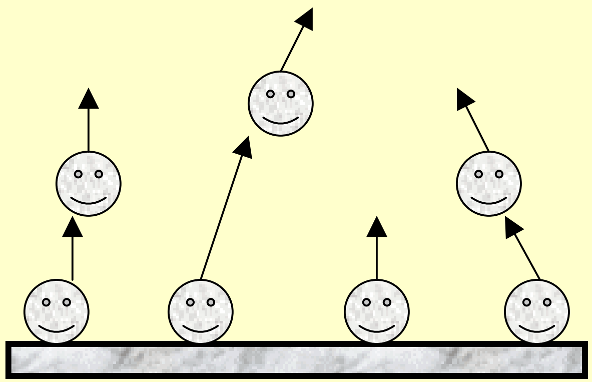
Unipolar arcs in Tokamaks.



Kinetic of a Condensed Material Vaporization into Vacuum

Evaporation in vacuum

Langmuir approach, *1913*

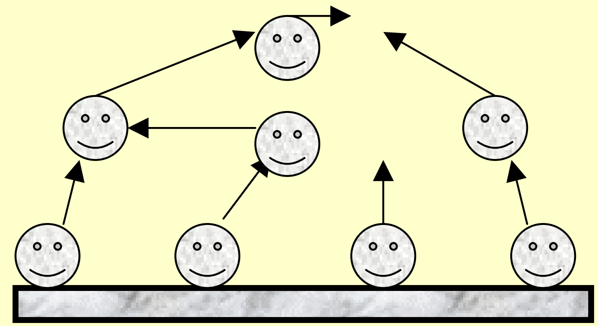


T_0 , P_0

$$\Gamma_0 = \frac{P_0}{\sqrt{2\pi m k T_0}}$$

Valid - low T_0
when $P_0 \leq 1$ torr

Knudsen approach, *1915*

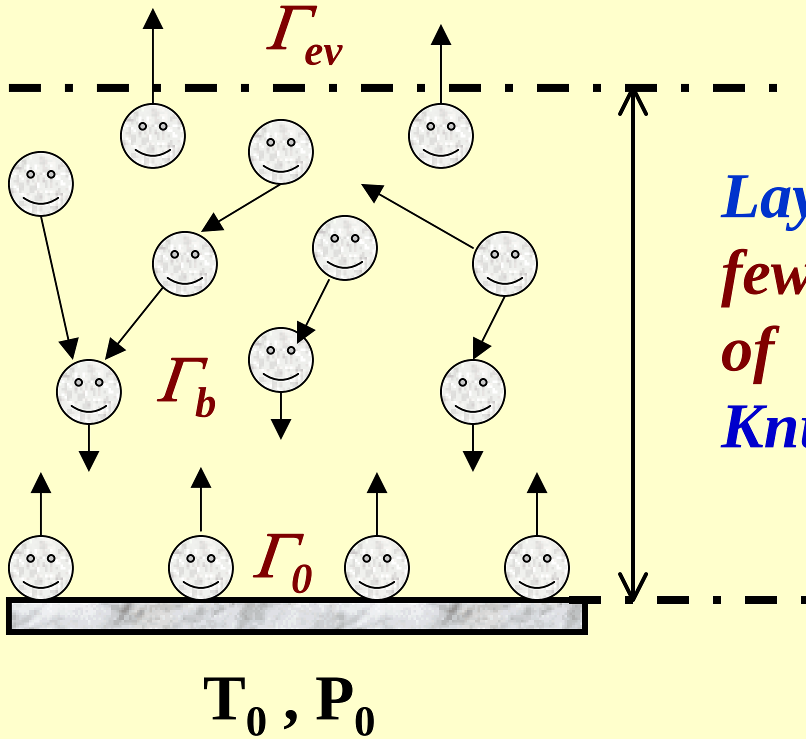


T_0

Rarefied collisions
Kinetic treatment

$P_0 > 1$ torr

Non-equilibrium layer. Back flux to the surface



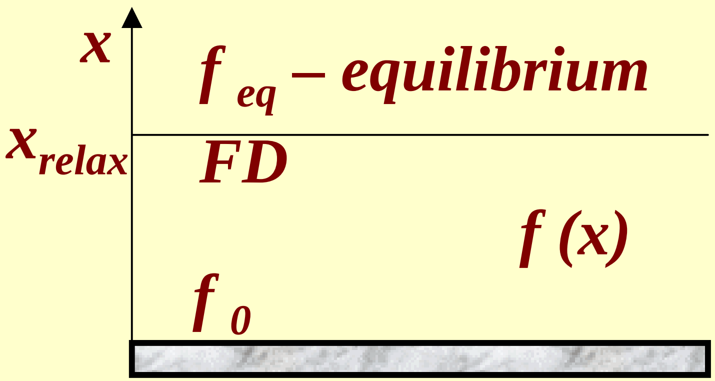
Layer – about few mean free path of the Particles - named Knudsen Layer

The back flux Γ_b to the surface is generated in the Knudsen Layer due to collisions

Evaporated flux: $\Gamma_{ev} = \Gamma_0 - \Gamma_b$

Γ_b !!! $\quad K_{er} = \Gamma_{ev} / \Gamma_0$

Back Flux. Theory



Kinetic equation in BGK (1954) approximation

$$\mathbf{v}\frac{\partial f}{\partial x} = \frac{f_{eq} - f}{\tau}$$

Boundary condition:

x=0 $$f_0 = n_0\left(\frac{m}{\pi 2kT_0}\right)^{3/2}\exp\left[-\frac{mv^2}{2kT_0}\right]$$ ***v_x>0***

x=∞ $$f_\infty = n_\infty\left(\frac{m}{\pi 2kT_\infty}\right)^{3/2}\exp\left[-\frac{m}{2kT_\infty}((v_x-u)^2+v_y{}^2+v_z{}^2)\right]$$

Conservation Low:

$$n(x) = \iiint f(x,\vec{v})d\vec{v}$$

$$n(x)u(x) = \iiint v_x f(x,\vec{v})d\vec{v}$$

$$\frac{3}{2}n(x)kT(x) = \frac{m}{2}\iiint (v_x-u)^2+v_y^2+v_z^2]f(x,\vec{v})d\vec{v}$$

Density: n(x)
Flux: n(x)u(x)
Energy: 3n(x)T(x)/2

Bimodal Theory

MODEL: Knudsen layer modeled as discontinuity layer,
Mott-Smih, 1951 and Anisimov, 1968
The Distribution Function (DF) is approximated as sum of DF before and after with unknown coordinate dependent coefficients:

$$f(x,v) = a(x)f_1(v) + [1-a(x)]f_2(v)$$

$$f_1(v) = f_0 \qquad v>0$$

$$f_2(v) = \beta f_\infty(v) \qquad v<0$$

For boundaries of the Knudsen layer:
$a(0)=1$ ***and*** $a(\infty)=0$

Using the Conservation Low n, T and v can be obtained on the external boundary of Knudsen layer!!!

The system is closed when V_∞ ***is given!!!***

Flow Regime in the Knudsen Layer

When $$v_\infty^2 = v_{sn}^2 = \frac{\gamma k T_\infty}{m}$$ ***The flow we named as <u>free flow regime</u>***

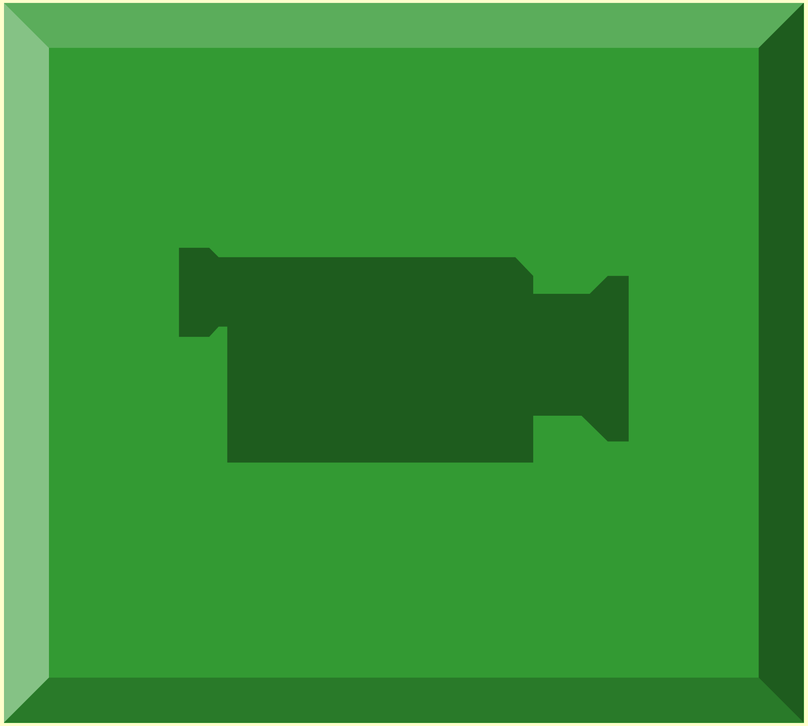
When $v_\infty < v_{sn}$

the flow will named as <u>non-free flow regime</u>

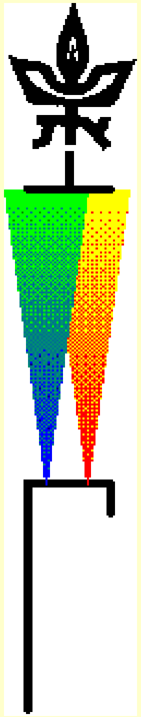
Cathode Spot

Observation:* *THE SPOT IS A SMALL MOVING LUMINOUS REGION

DEFINITION. The Spot -is an arc region **includes the** ***cathode bulk*** **and dense** ***plasma generation*** **area where the current continuity is supported**

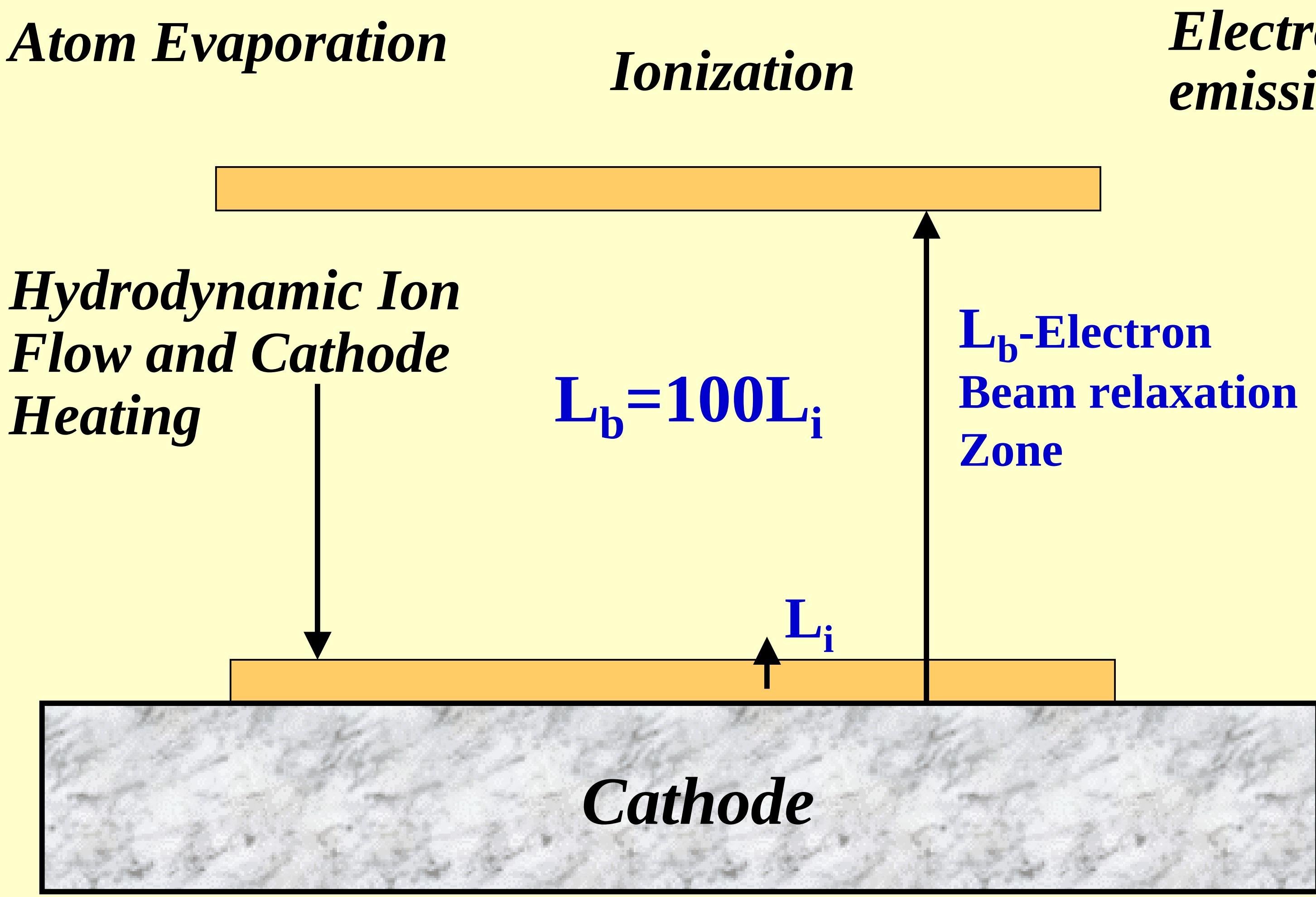


Plasma in a Copper Cathode Spot



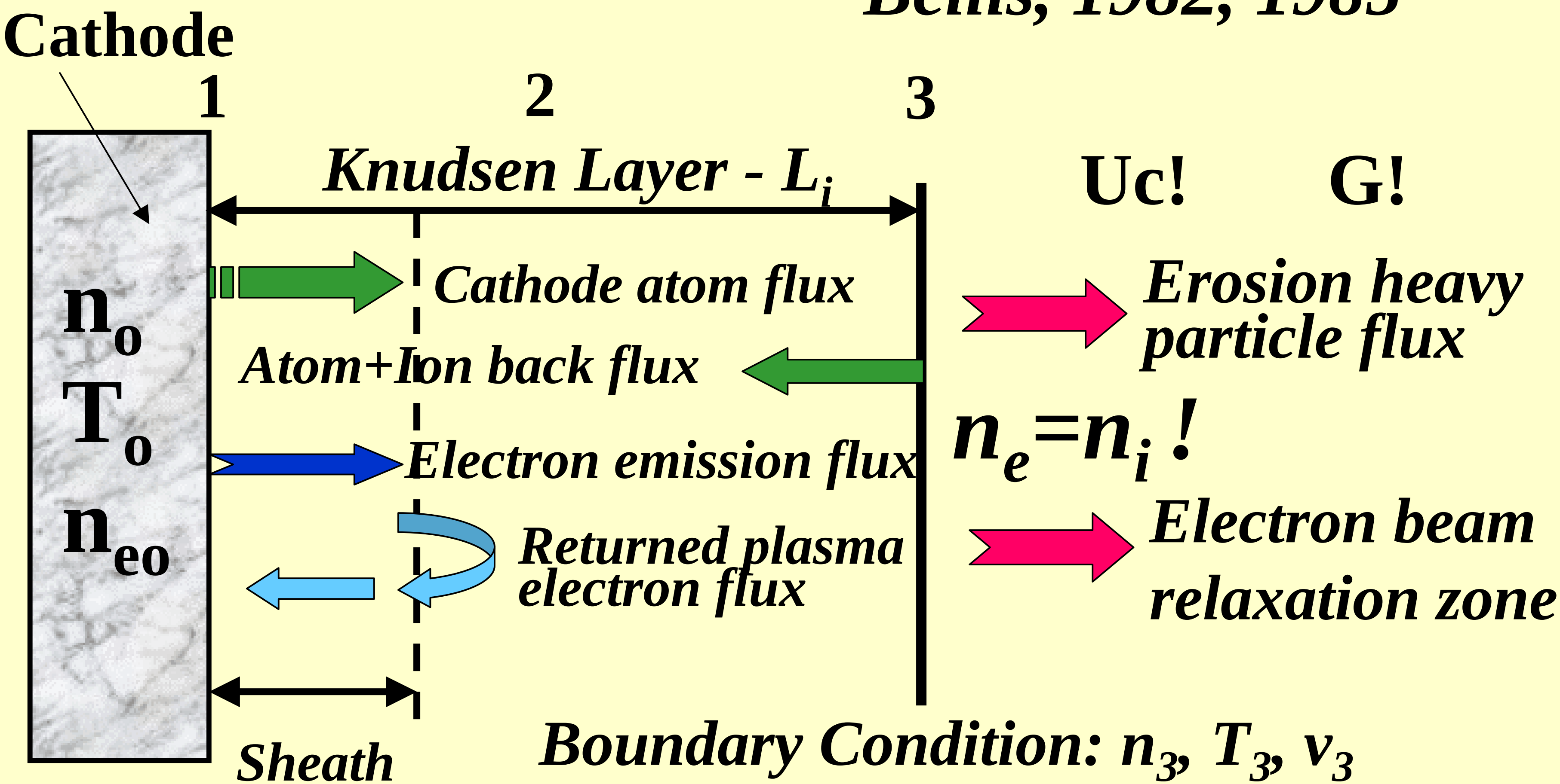
- Spot Size — 10-100 μm
- Cathode potential drop — 15 V
- Spot current — 10-200 A
- Cathode erosion rate — 30-100 μg/C
- Plasma jet velocity — 10^6 cm/s
- Heavy particle density — ~10^{20} cm^{-3}
- Electron temperature — ~1 eV
- Ionization fraction — ~0.1
- Electron beam mean free path (mfp) — L_b~1μm
- Ion and plasma electron mfp — L_i~0.01
- Cathode sheath thickness — ~0.01

Current Continuity .



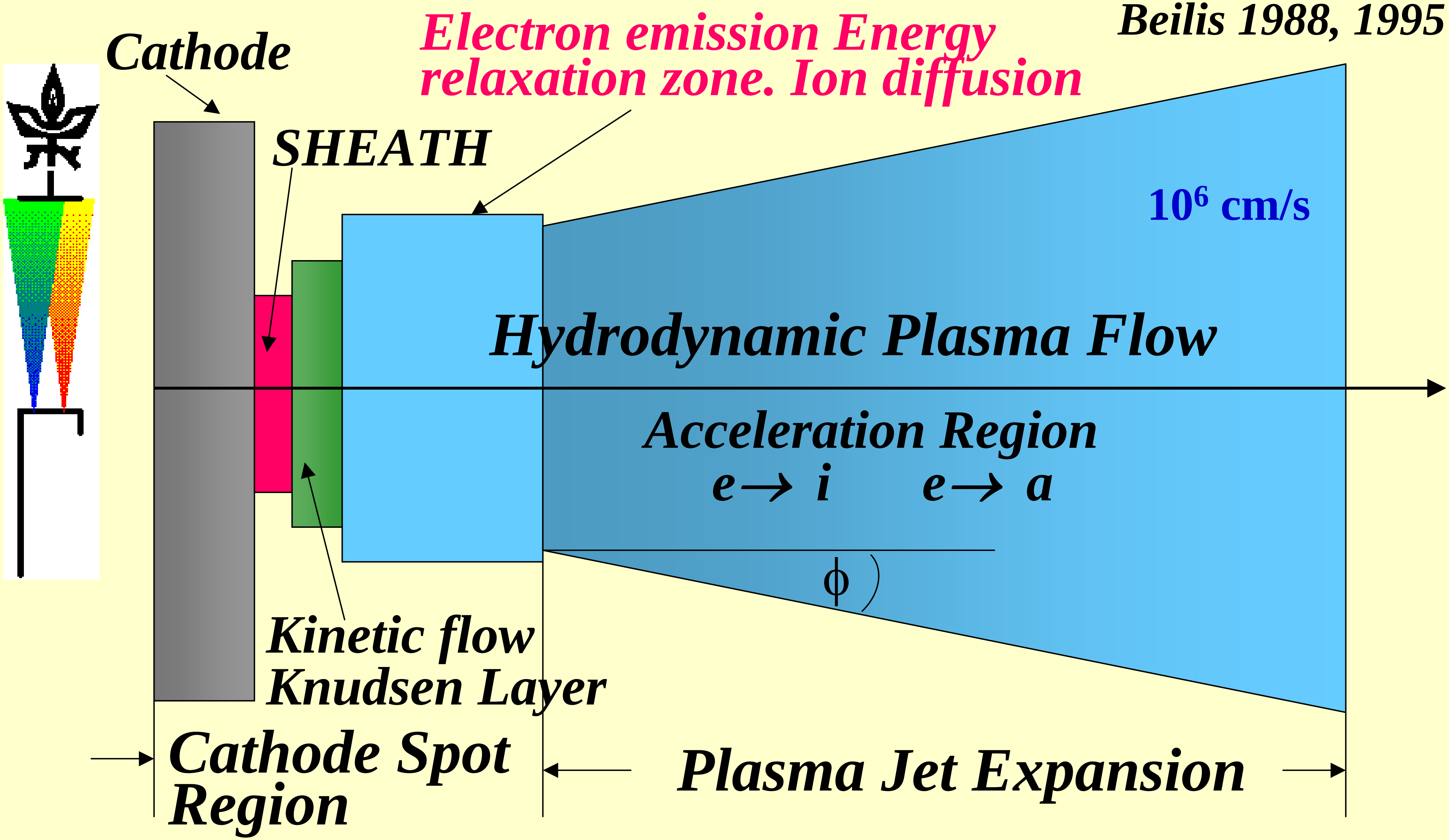
Atom, electron evaporation. Cathode Erosion Mechanism

Beilis, 1982, 1985



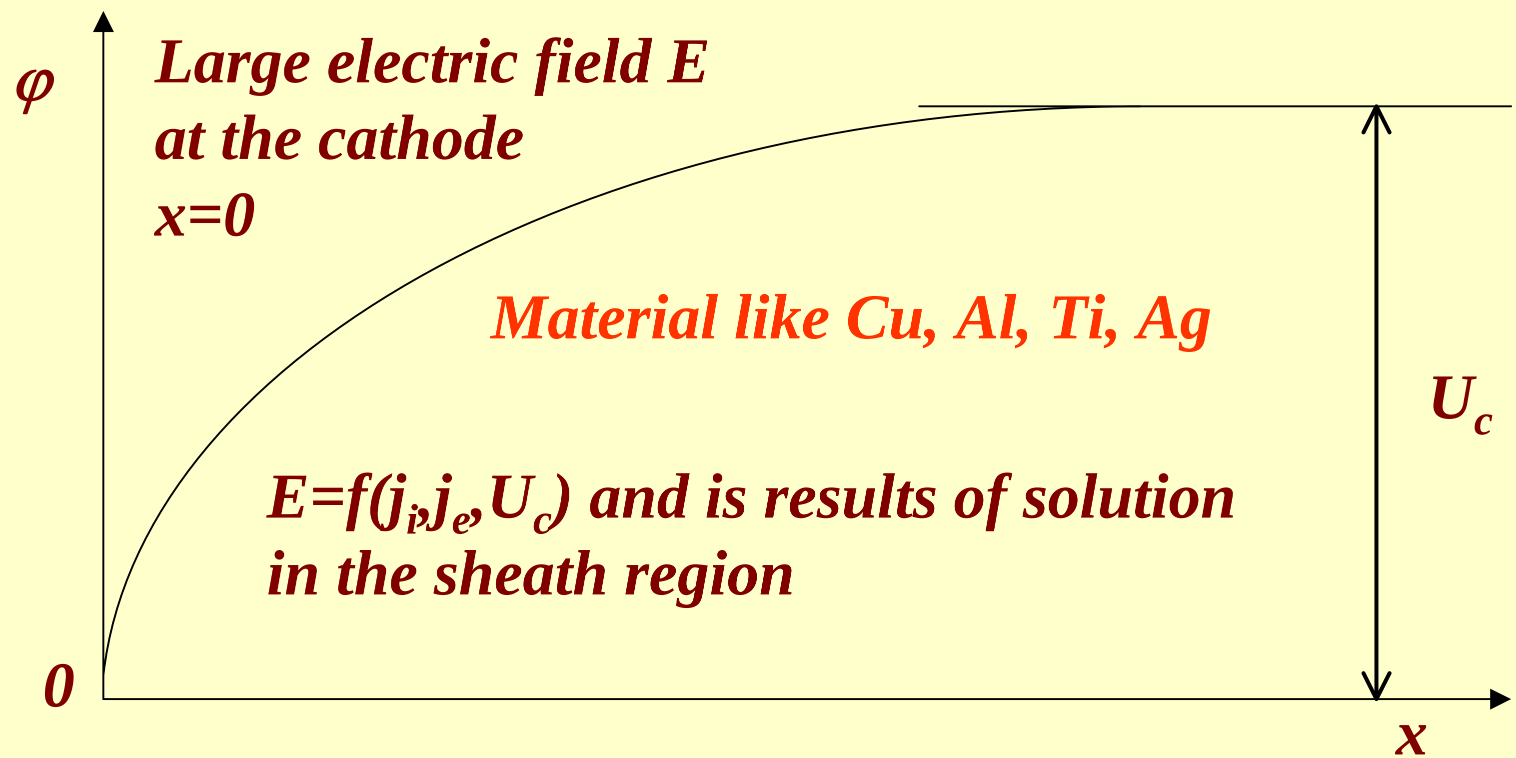
Cathode Spot & Cathode Plasma Jet

Beilis 1988, 1995



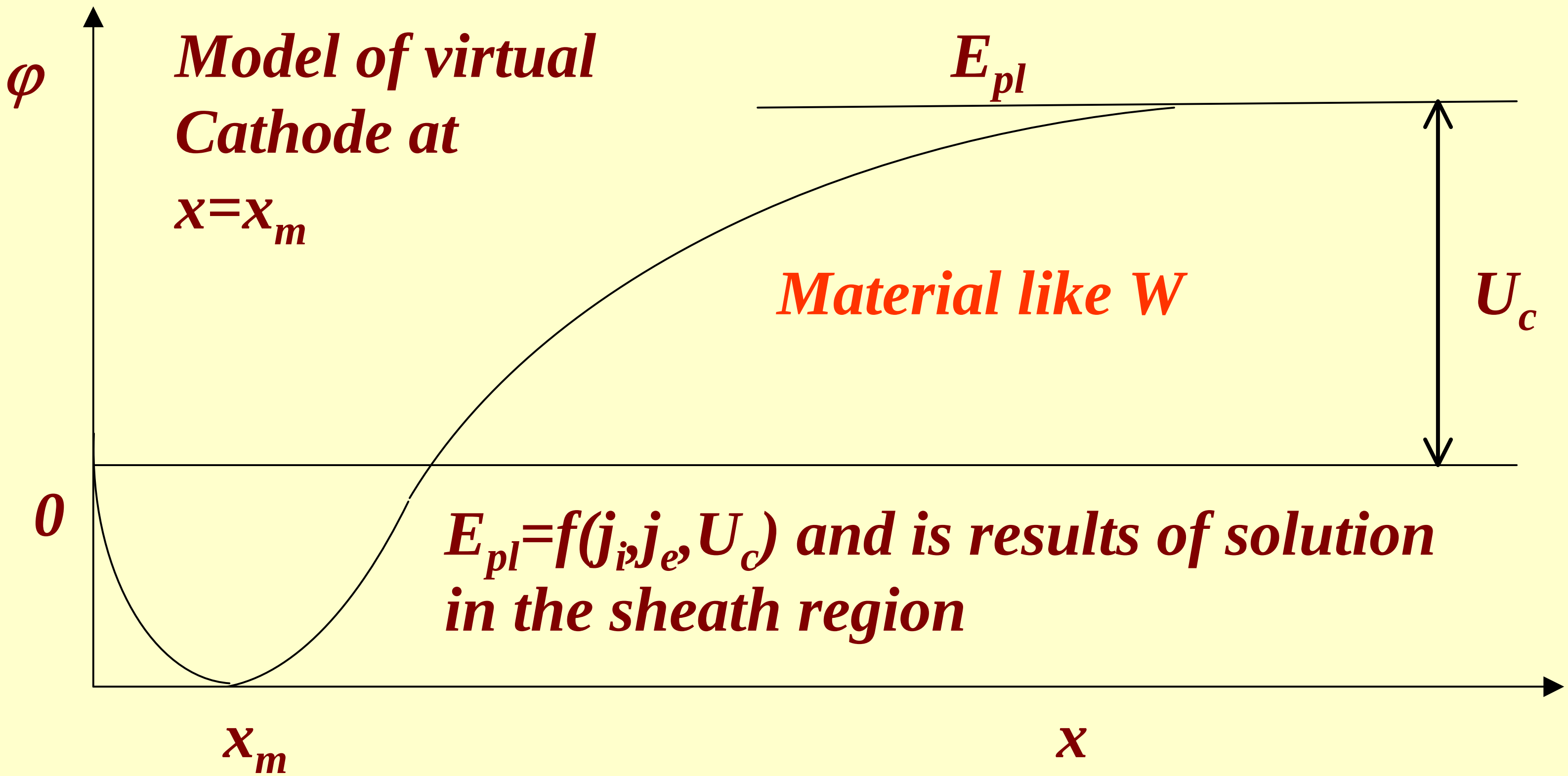
Enhanced Cathode Electron Emission

McKeown 1929, Ecker 1973, Beilis 1974



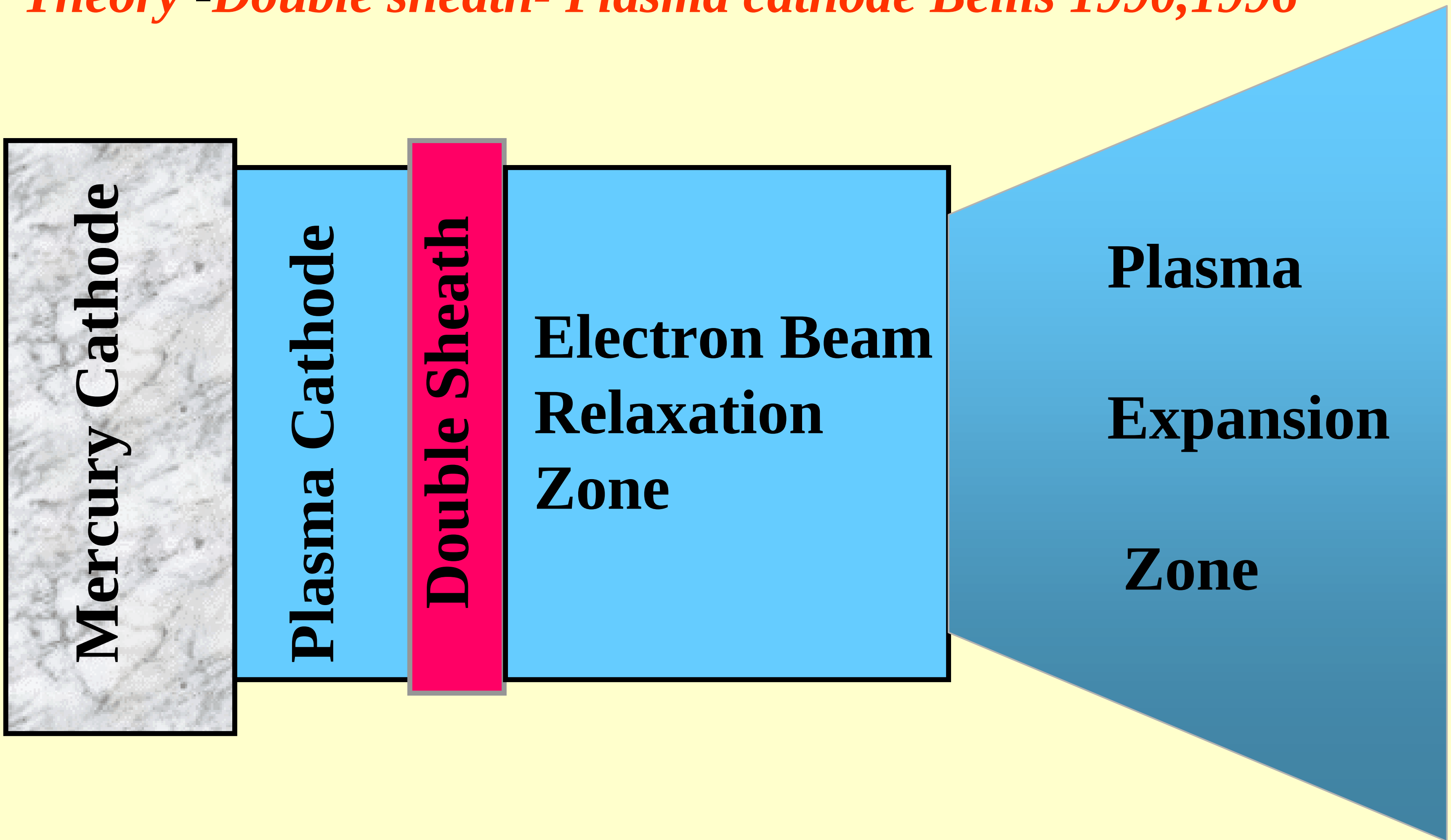
Reduced Cathode Electron Emission

Beilis 1988, 2004



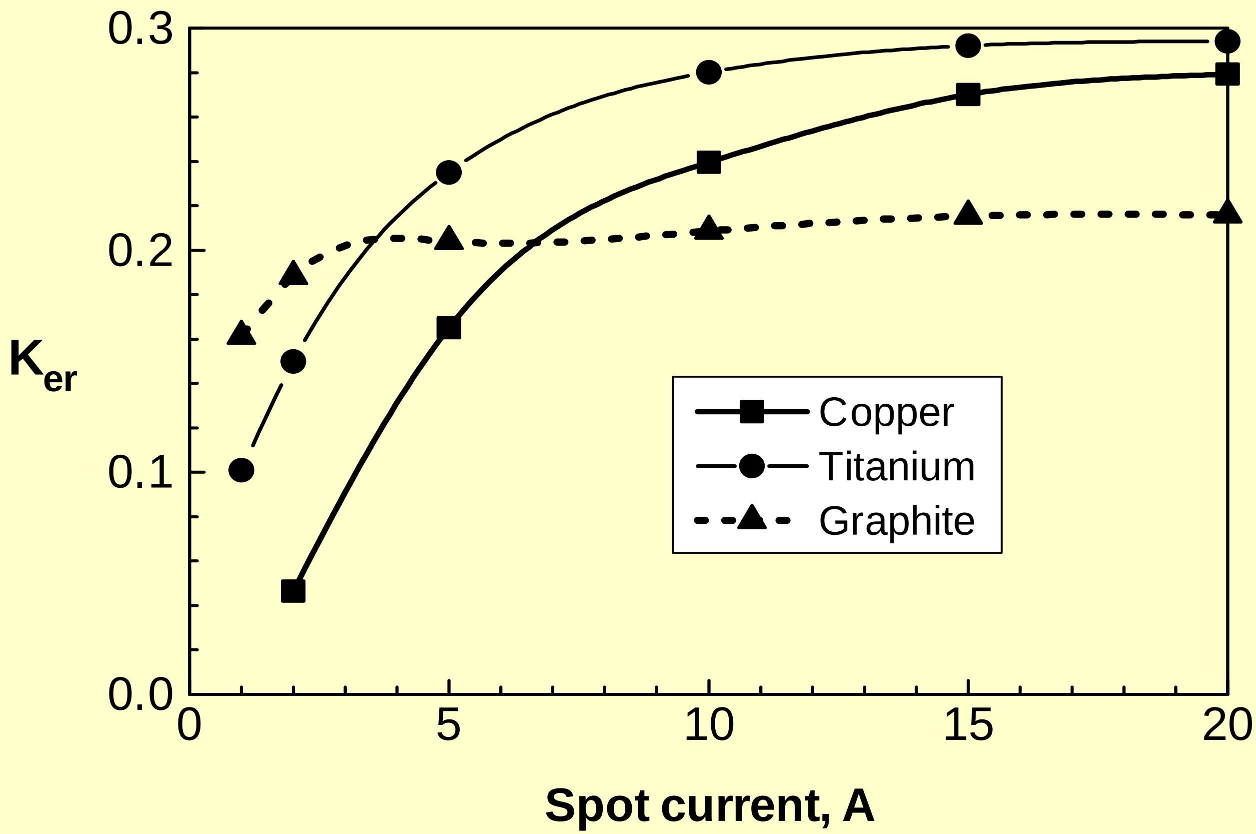
Low Cathode Emission. Volatile Cathode Hg

Theory -Double sheath- Plasma cathode Beilis 1990,1996



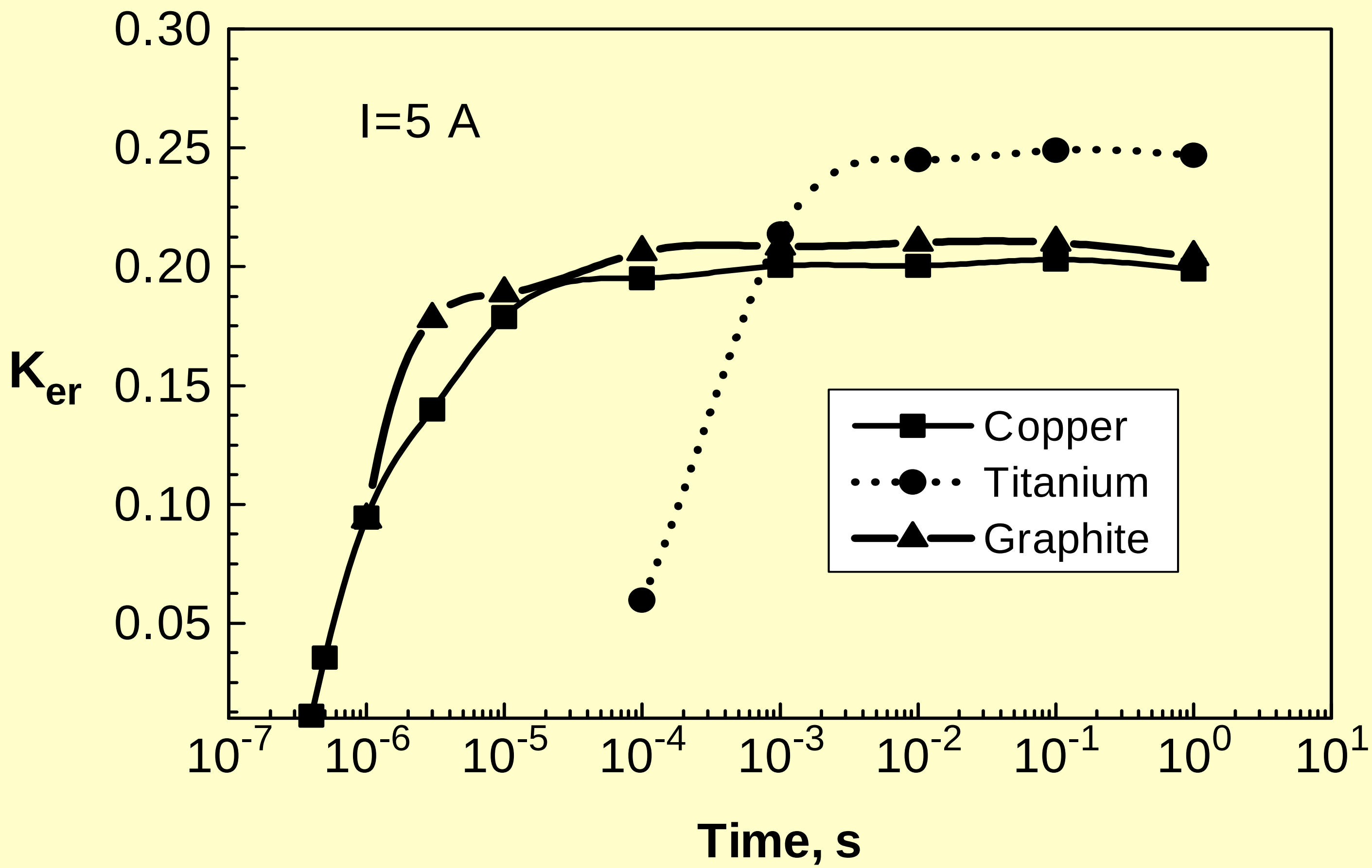
Evaporated flux fraction as function on spot current

$K_{er} = \Gamma_{ev} / \Gamma_0$



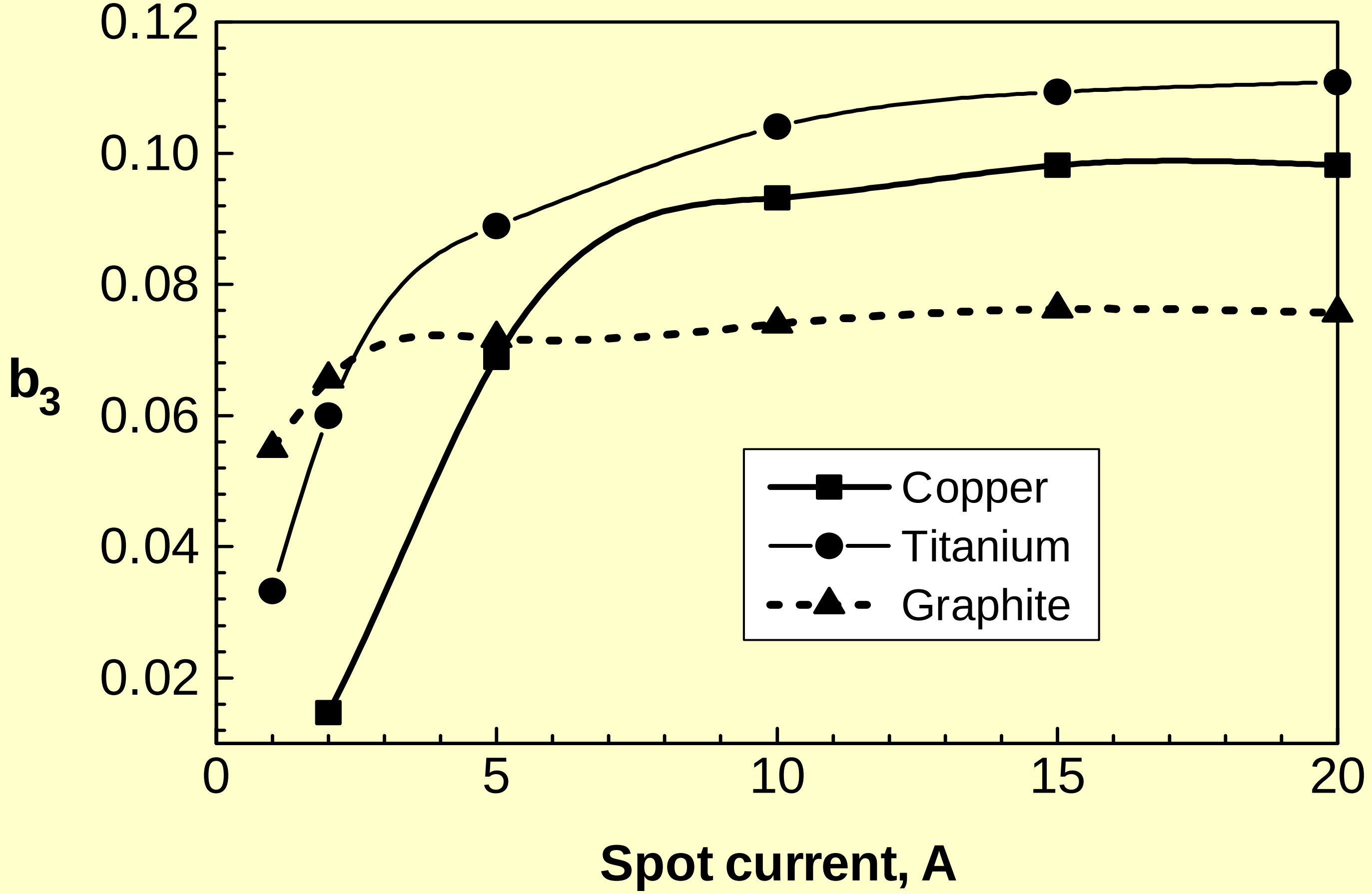
Evaporated flux fraction as function on time

$K_{er} = \Gamma_{ev} / \Gamma_0$

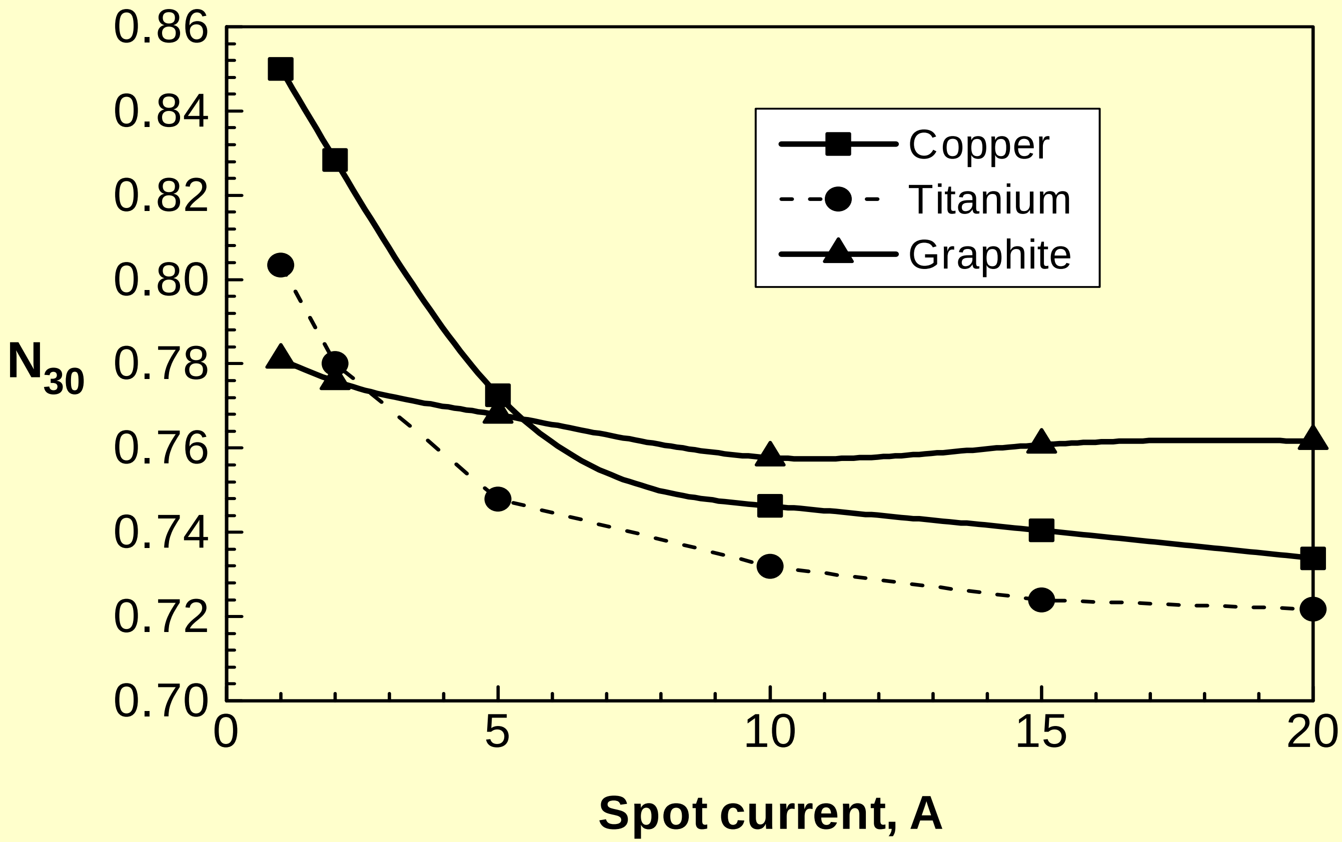


Normalized plasma velocity at external boundary of the Knudsen layer function on current

$b_3^2 = mv_3^2 / 2kT_3$



Normalized heavy particle density at external boundary of the Knudsen layer as function on I

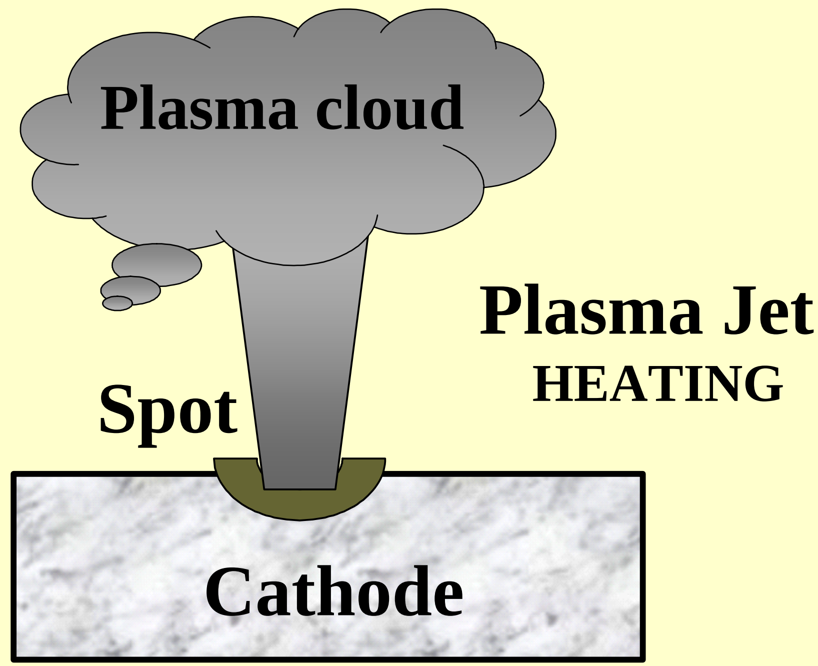


Density is close to equilibrium !

Non-free Cathode plasma expansion

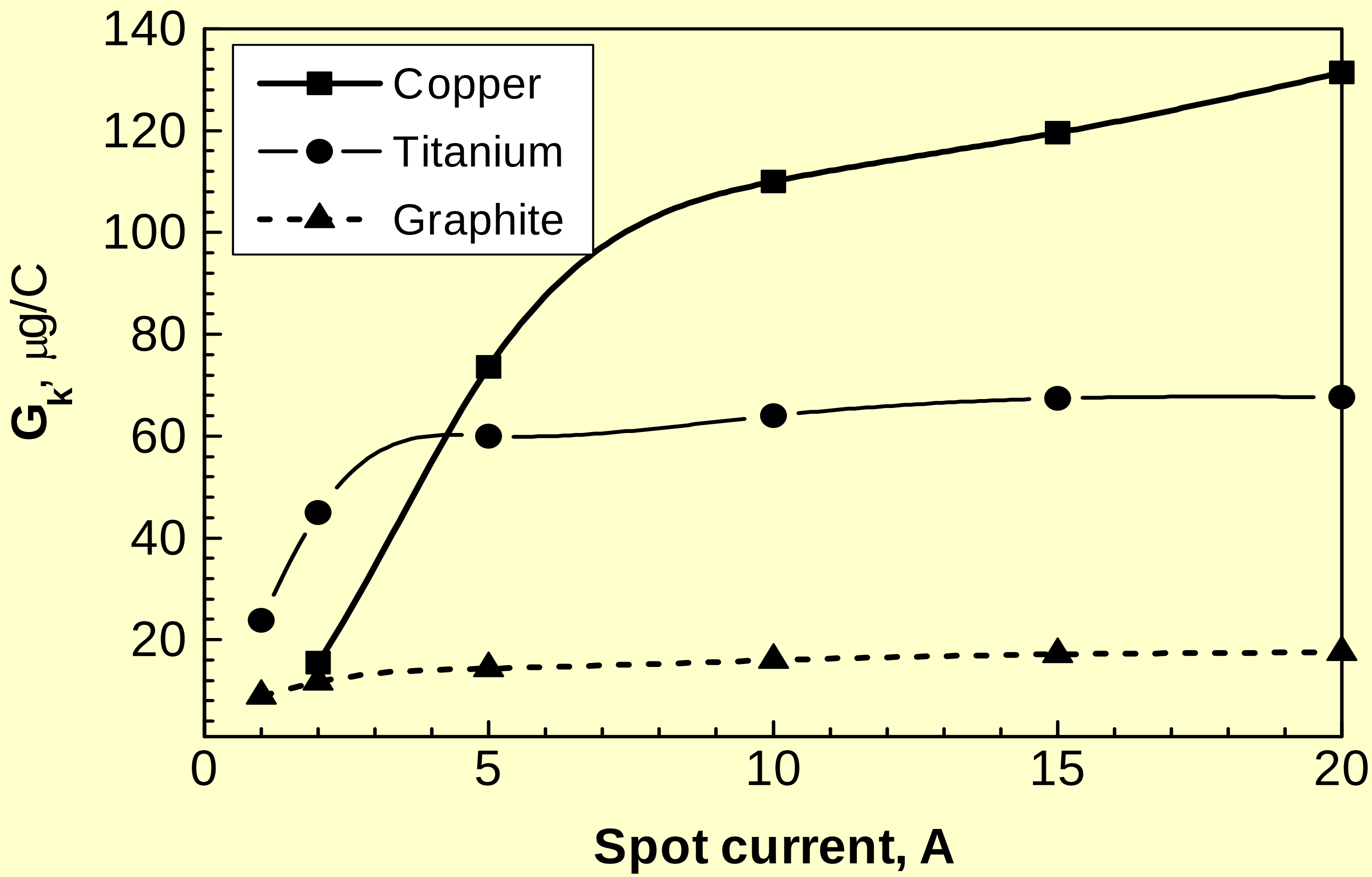
$v_{\infty} < v_{sn}$

Non-free flow is
due to plasma cloud
in the arc gap and
due to heat dissipation
inside of the plasma jet



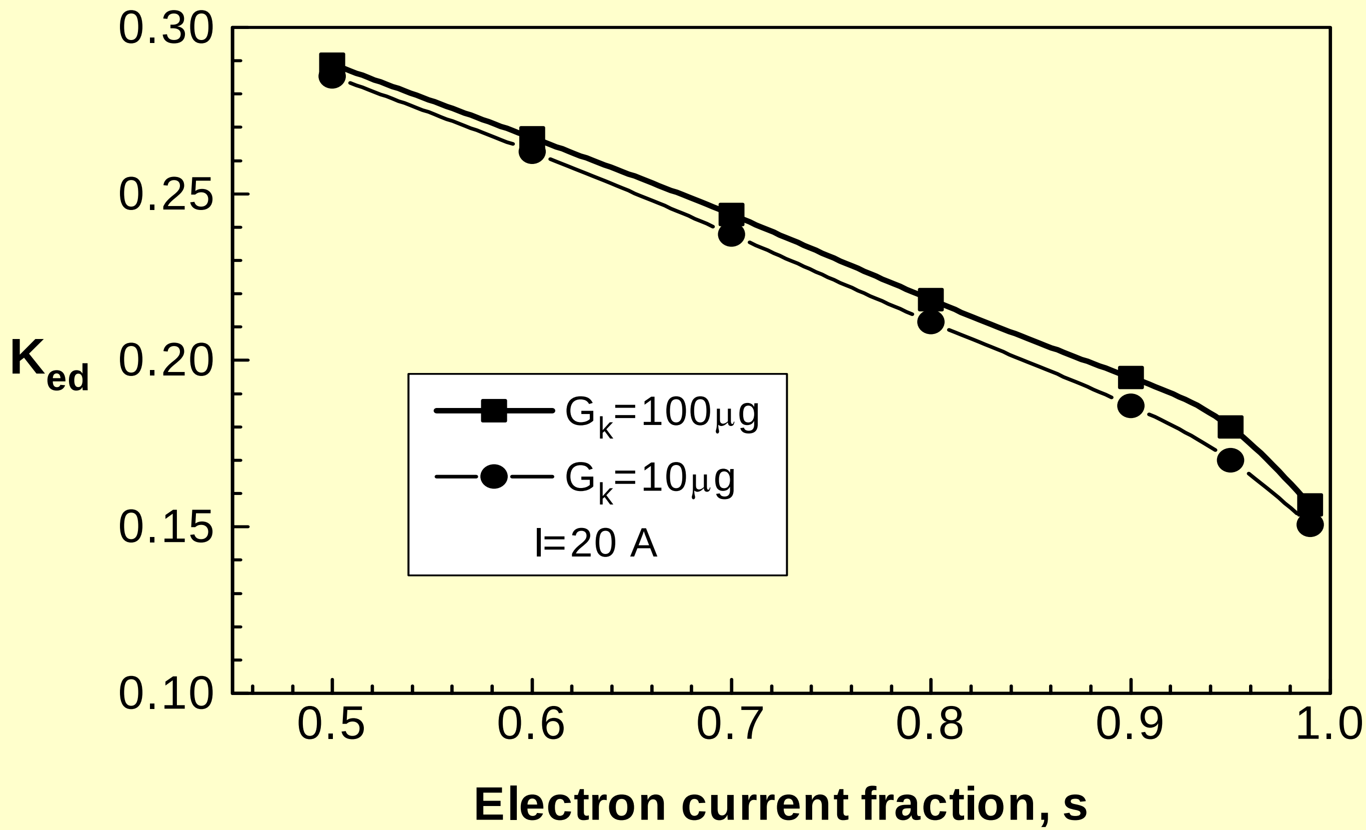
Cathode Erosion Rate

Observed: Cu~ 30-100; Ti~50; C~10 μg/C



Normalized Electric field at the sheath-plasma interface for virtual W-Cathode

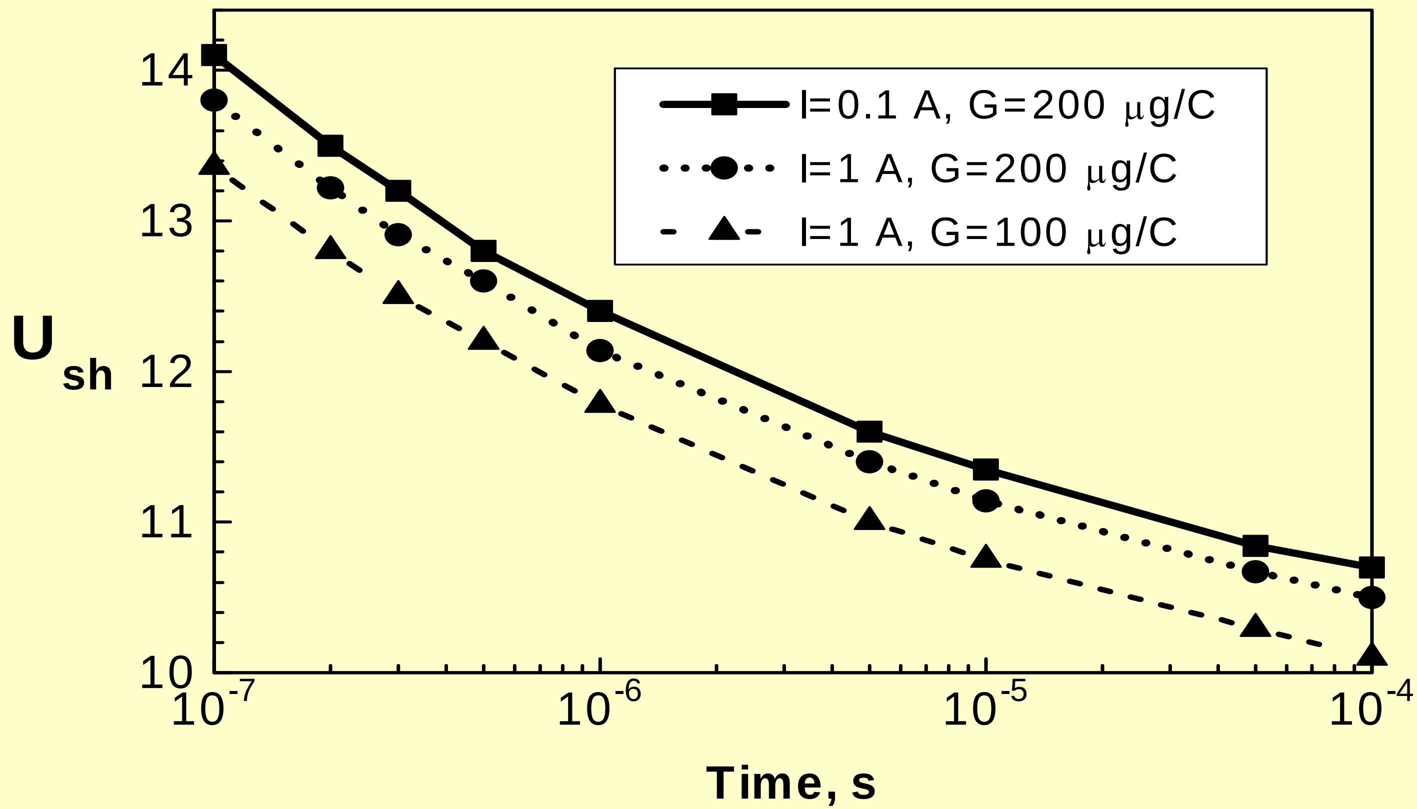
$$K_{ed} = E_{pl} L_D / kT_e$$



Sheath Potential Drop for Mercury Cathode

A spot mode with low cathode drop 9-10V was observed, Kesaev 1968

Double Sheath Model



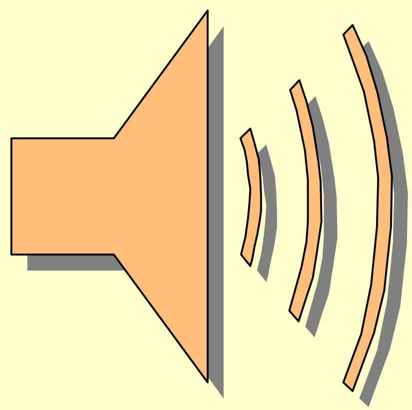
RESUME

- ***The structure of Knudsen layer in high current discharges is different from that by laser metal evaporation (independent energy source). The vacuum arc cathode mass flow is non-free and the normalized velocity $b_3<<1$.***
- **The relaxation zone of high energetic electron emission beam is much larger than the plasma particles mean free paths. The beam energy dissipation in this zone is the cause of cathode vapor non-free expansion.**
- **Cathode erosion rate agrees with measurements and is about 5-20% of the cathode mass loss determined by Langmuir formula (evaporation in vacuum) for *Cu, Ti, C***

RESUME

- ***Current continuity and the cathode sheath structure depend on the relation between rates of electron and atom evaporations.***
- **Electric field at the cathode surface changes from large value enhancing <u>the electron emission</u> (Cu) to zero in virtual cathode for W-cathode. A double sheath and plasma cathode occurs for close the current in plasma region of mercury cathode.**
- ***Electric field at the left side of virtual cathode is zero in the model while at the sheath-plasma interface a non-zero electric field occurs. Such structure supports an ion current fraction which necessary for self-consistent W-cathode spot operation.***

THANK YOU!!!



Sheath Structure. Volatile Cathode (Hg)