Electron Acceleration by DC Electric Fields in the Flaring Corona

6th *RHESSI* Workshop

– Group V: Theoretical Implications –

H. Önel, G.Mann

April 6, 2006

4th – 8th April 2006 – Meudon, France

Electron Acceleration by DC Electric Fields in the Flaring Corona

6th *RHESSI* Workshop

– Group I: Electron Acceleration and Propagation –

H. Önel, G.Mann

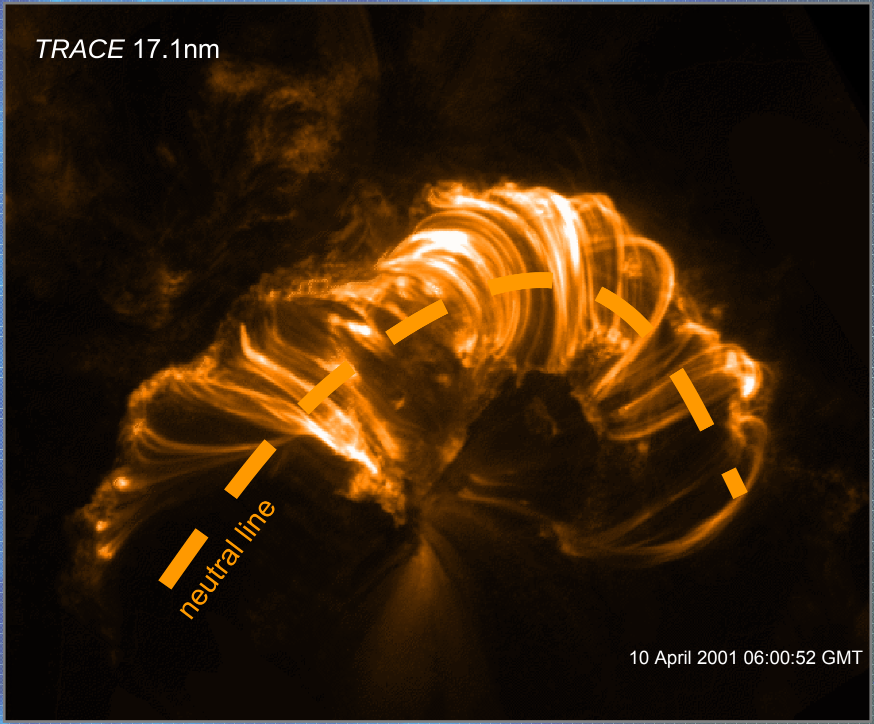
April 6, 2006

4th – 8th April 2006 – Meudon, France

H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

Introduction

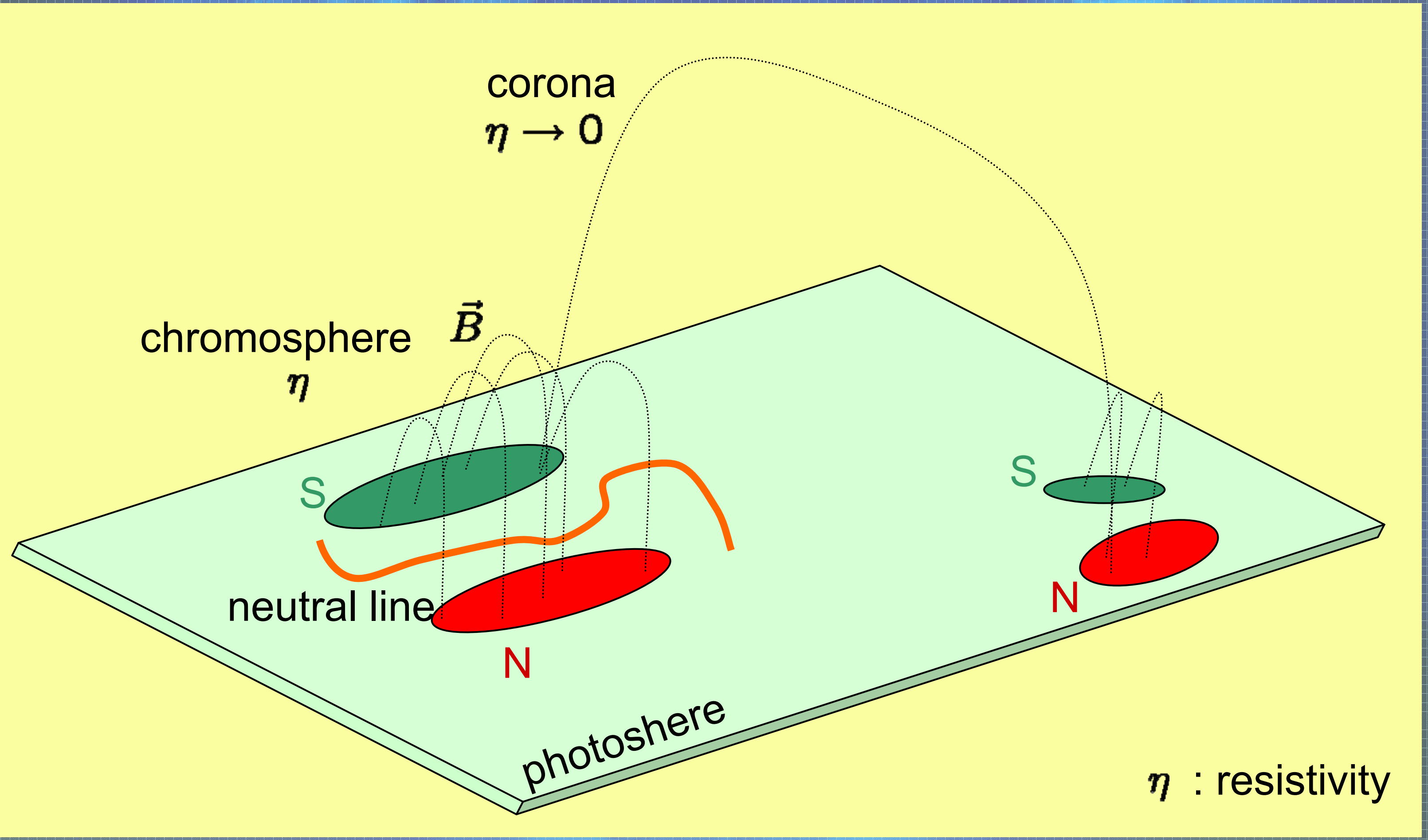
- **arc-like structures of magnetic fields can be observed at active regions**
- **different active regions (temporarily) become magnetically connected with each other**



Reference: TRACE (NASA)

H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

Current Model (I)



H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

AIP

Resistivities (I)

$$\eta = \frac{\mu\,\nu[N, v^{-3}]}{N q^2}$$

Resistivities are almost independent from the particle density.

$$\eta \approx \frac{\mu\,\nu[N, v^{-3}]}{N q^2}$$

$$\nu_j = \frac{4\pi C_j^2 \ln\left[\Lambda_j\right] N_j}{\mu_j^2 v_j^3}$$

$$\mu_j = \left(\frac{1}{m_e} + \frac{1}{m_j}\right)^{-1}$$

$$v_j = |v_j - v_e|$$

$$C_j = \frac{(-e)\cdot q_j}{4\pi\epsilon_0}$$

$$\Lambda_j = \sqrt{\frac{\lambda_D^2 + b_{0,j}^2}{2b_{0,j}^2}}$$

$$\lambda_D = \sqrt{\frac{\epsilon_0 k_B T}{N e^2}}$$

$$b_{0,j} = \frac{C_j}{\mu_j v_j^2}$$

Estimation

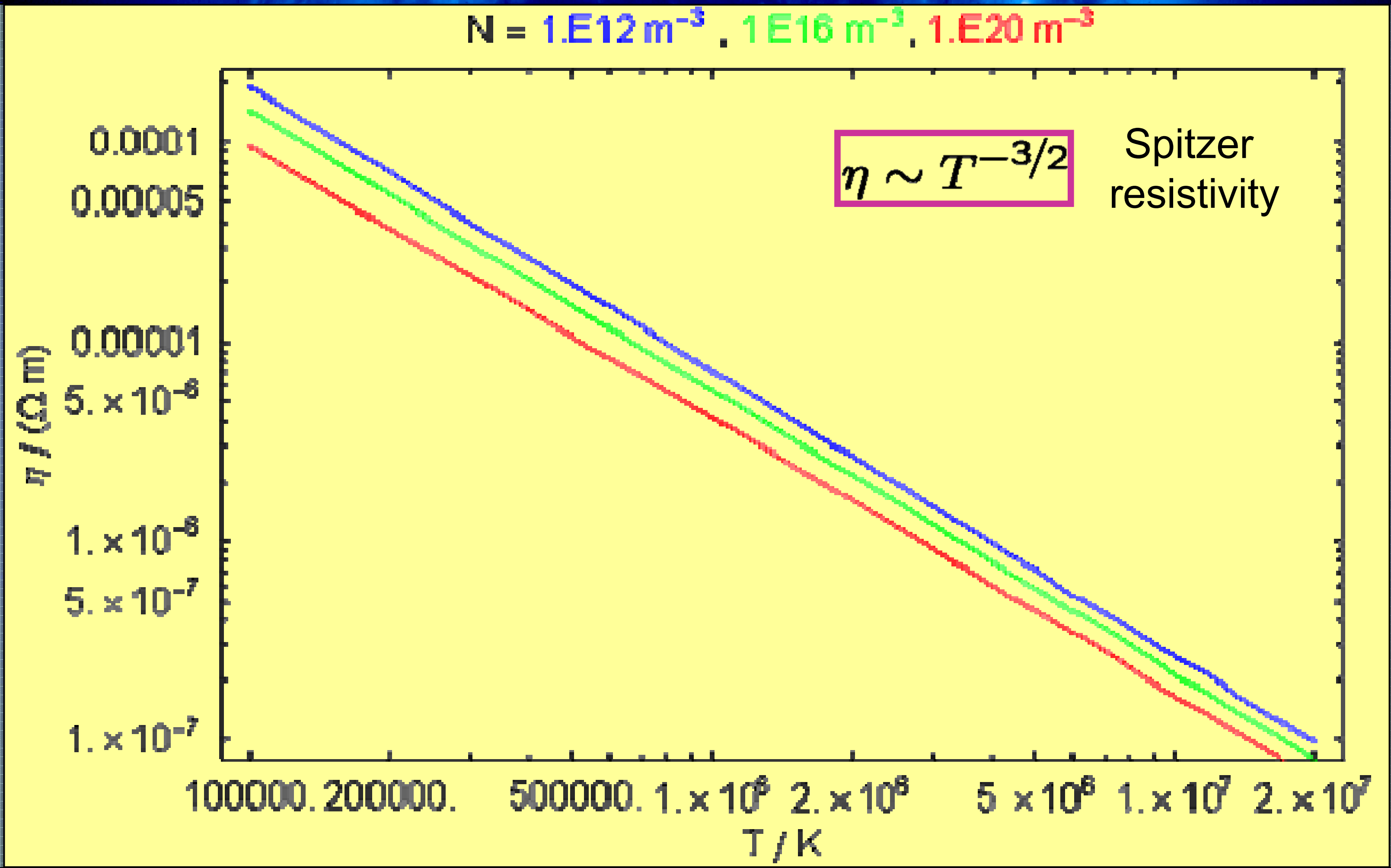
$$v^{-3} \to v_{th}^{-3} = \sqrt{\frac{\mu^3}{k_B^3}} \cdot T^{-3/2}$$

Spitzer resistivity $\eta \sim T^{-3/2}$

Reference: Priest, Solar Magnetohydrodynamics (Kluwer Academic Publishers, 2000 (p.78))

H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

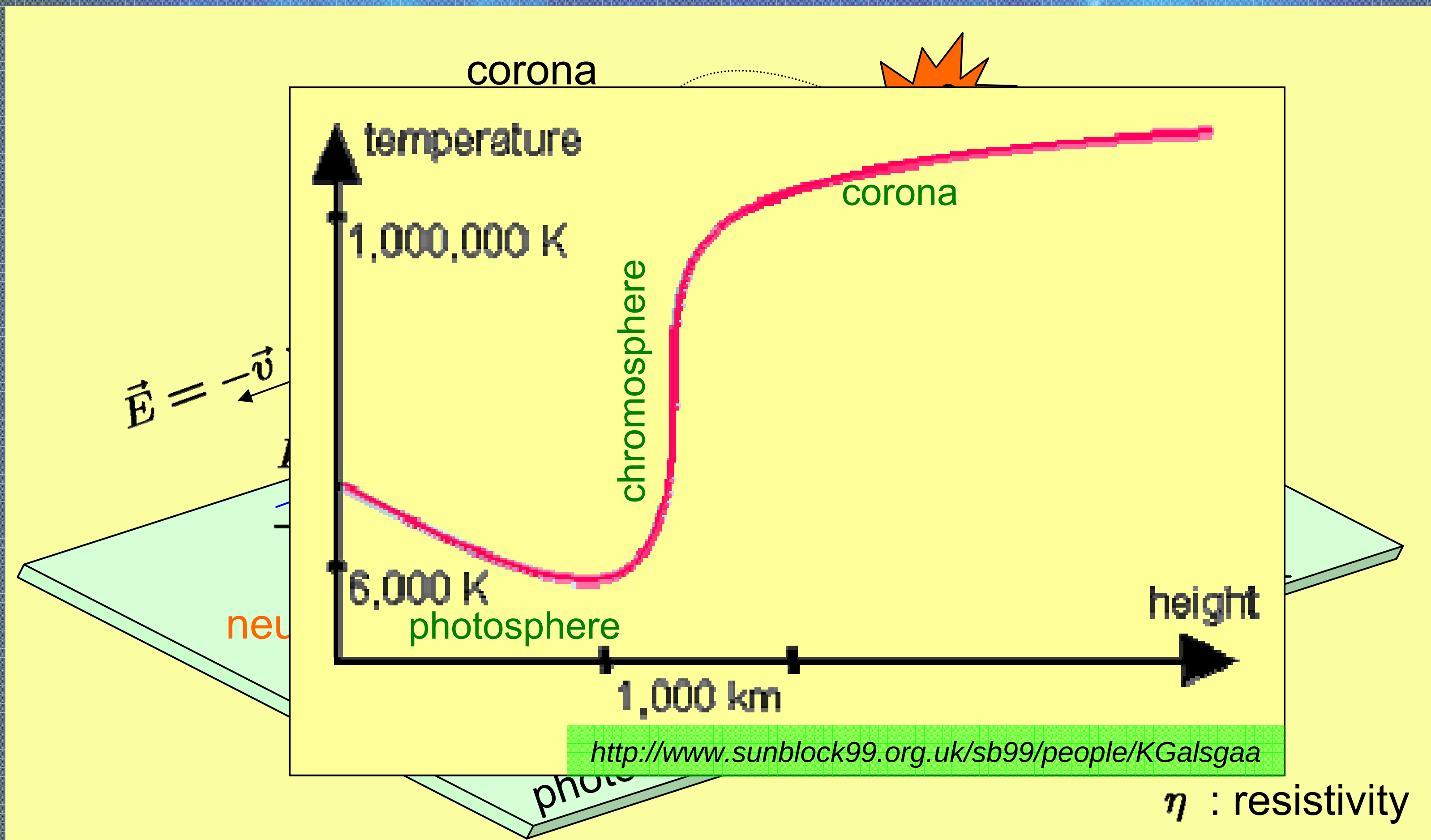
Resistivity (II)
– Temperature Dependence –



Reference: Priest, Solar Magnetohydrodynamics (Kluwer Academic Publishers, 2000 (p.78))

H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

Current Model (II)



References: Li et al. (2004JATP…66.1271L), Alfvén & Carlqvist (1967SoPh….1..220A)

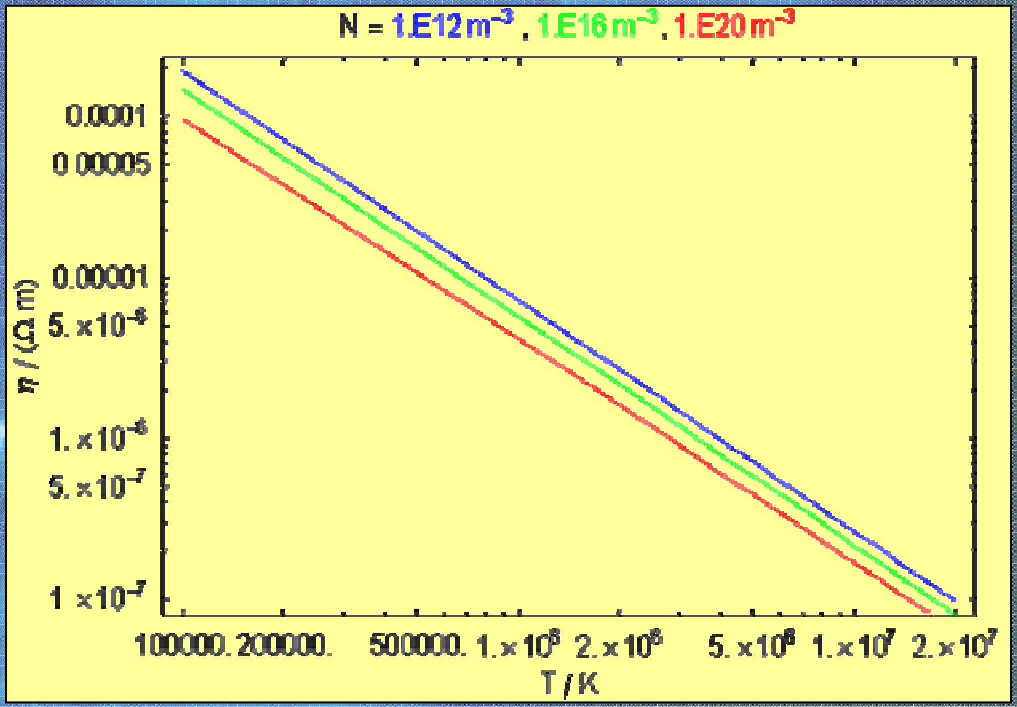
H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

Frozen Field Lines

Condition for frozen field lines:

- **Infinite conductivity**
  ➔ Vanishing resistivity

$$\eta \longrightarrow 0$$



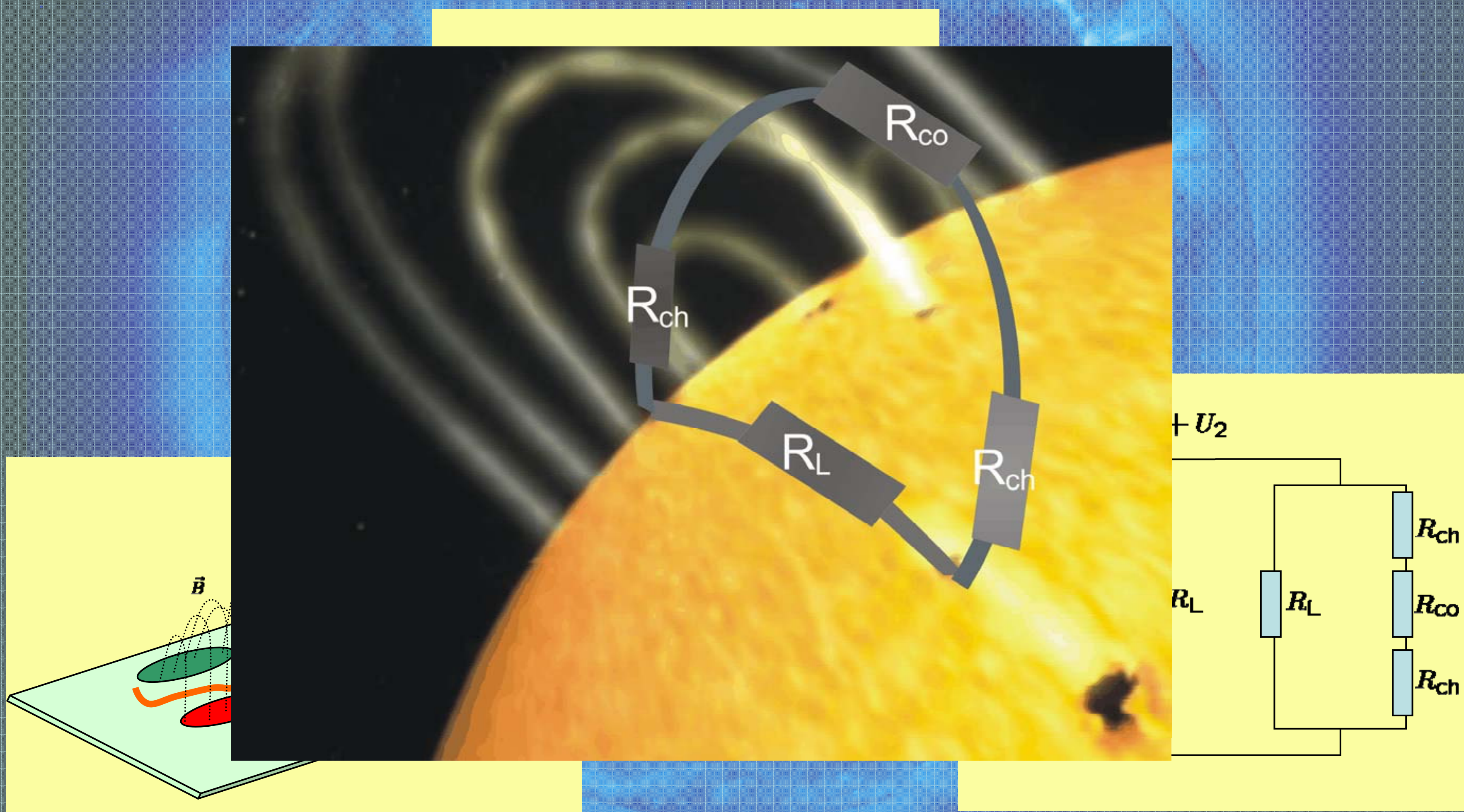
Thus:

- **Frozen Fields exist in the Corona, but not in the Photosphere**

Reference: Krall & Trivelpiece, Principles of Plasma Physics (McGraw-Hill Book Co., 1986)

H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

Replacing the Current Model by an Electrical Circuits



H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

Resisto

For Comparison: Large Flares

Energy release: 10^{25} J

Power: 10^{22} W

==============================

Timescale: ≈ 10 Minutes

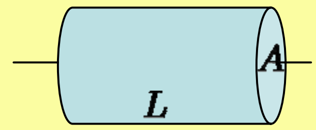
AIP

	R_i	R_L	R_{ch}	R_{co}
L	26 Mm	10 Mm	2.6 Mm	120 Mm
r	2.6 Mm	2.6 Mm	2 Mm	5.2 Mm
η	$4\ 10^{-3}\ \Omega$m	$4\ 10^{-3}$ ...		...m
T	6000 K	6000 ...		...K
N	$4\ 10^{19}\ m^{-3}$	$4\ 10^{19}$ ...		...$^{-3}$
R	$4.8\ 10^{-9}\ \Omega$	$1.8\ 10^{-9}\ \Omega$	$5.9\ 10^{-10}\ \Omega$	$1.1\ 10^{-13}\ \Omega$

macroscopic conductor

$$R = \frac{\eta L}{A}$$

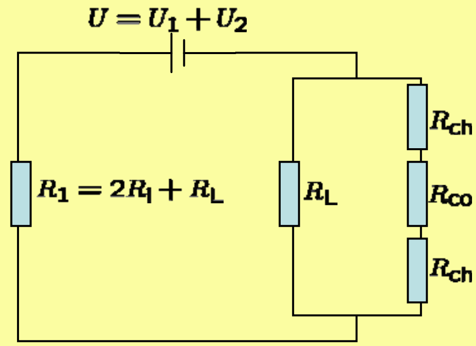
$$A = \pi r^2$$



DC-Acceleration

$$U_{co} \approx 326\,\text{kV}$$

$$E_{co} \approx -2.7\,\text{mV/m}$$



Induction

$$v = 0.5\,\text{kms}^{-1}$$

$$B = 0.05\,\text{T}\ (= 500\,\text{G})$$

$$U_1 = U_2 = vBL[R_i] = 0.65 \cdot 10^9\,\text{V}$$

Power

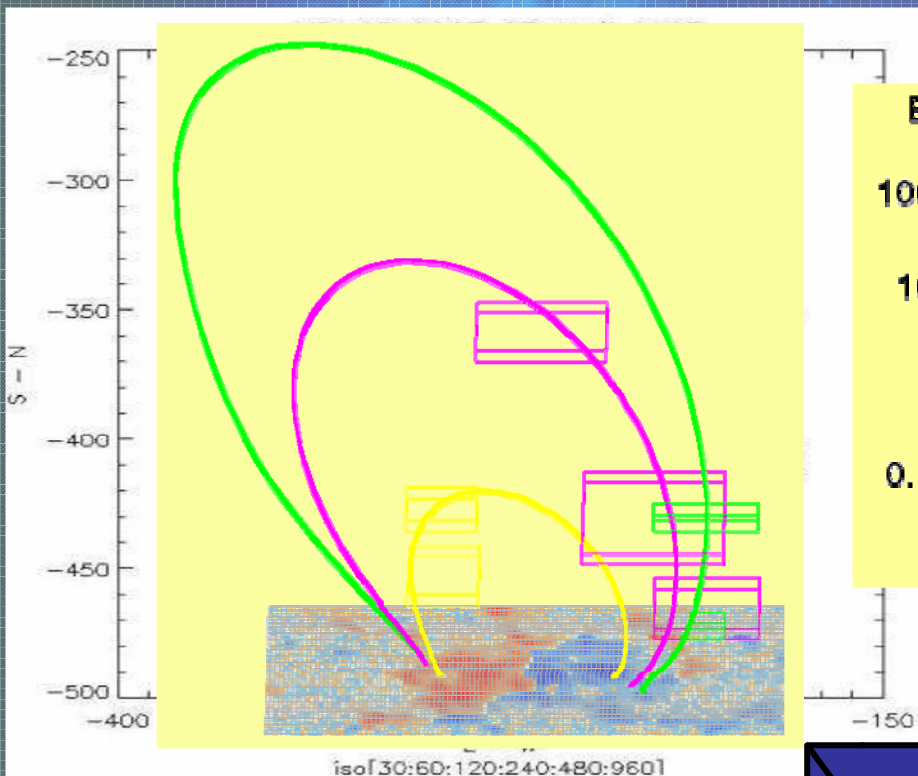
$$P_{co+ch} \approx 2.3 \cdot 10^{27}\,\text{W}$$

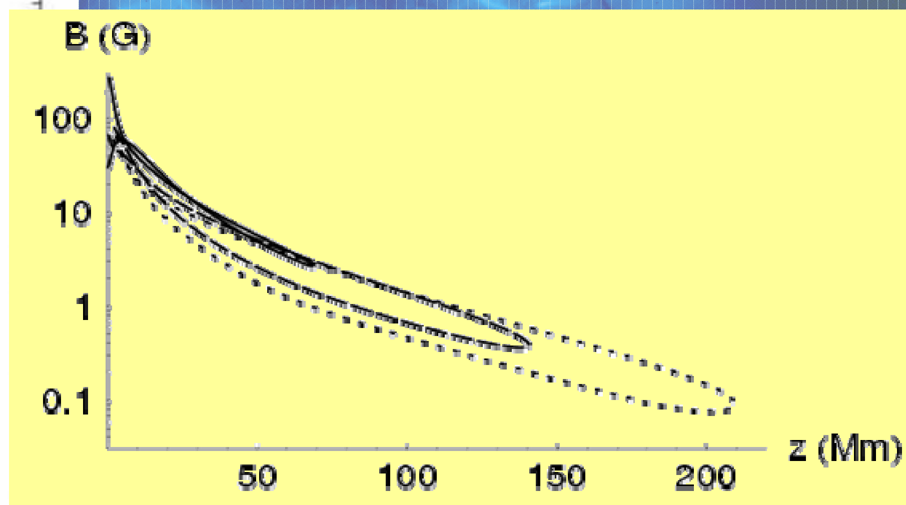
$$P_{co} \approx 4.8 \cdot 10^{20}\,\text{W}$$

References: Aurass et al. (2005A&A...435.1137A), Dr. Axel Hofmann (AIP)

H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

Resistors
– Estimation of Parameters –

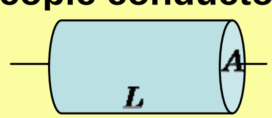




macroscopic conductor

$$R = \frac{\eta L}{A}$$

$$A = \pi r^2$$

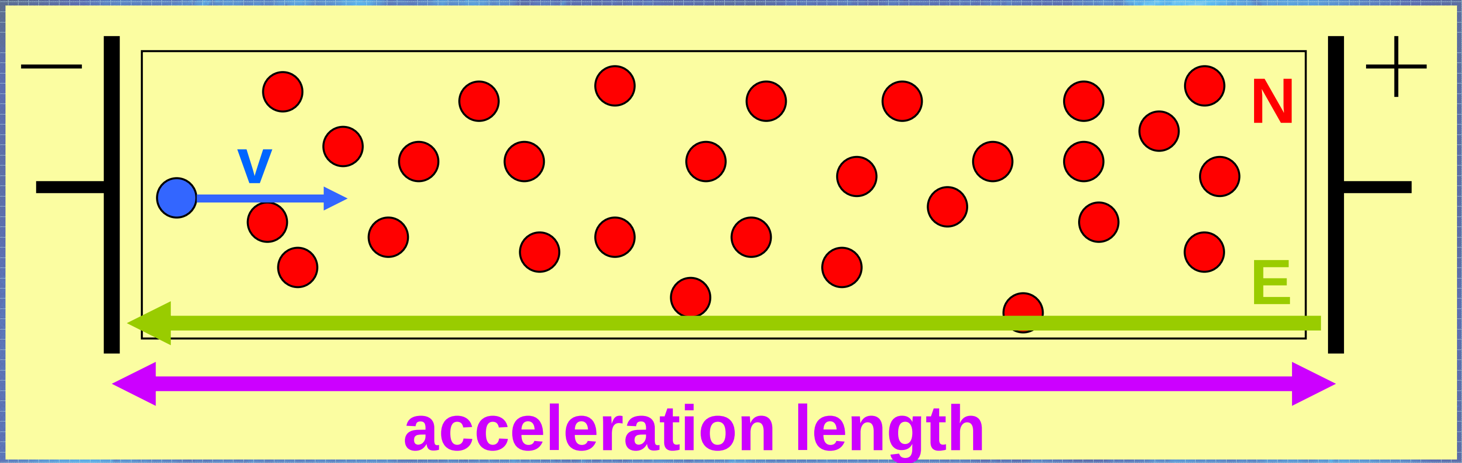


	R_i	R_L	R_{ch}	R_{co}
L	26 Mm	10 Mm	2.6 Mm	120 Mm
r	2.6 Mm	2.6 Mm	2 Mm	5.2 Mm

Reference: Aurass et al. (2005A&A…435.1137A)

H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

DC-Field Electron Acceleration – Condenser –



Setup for Calculations

- 1D calculation
- full relativistic
- initial particle distribution corresponds to a κ – distribution

Reference: G. D. Holman (1985IAUS..107..191H)

H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

Relativistic 1D-Acceleration of Electrons with DC Fields

Law of Motion

$$\frac{\mathrm{d}p}{\mathrm{d}t} = m_\mathrm{e} c \gamma^3 \frac{\mathrm{d}\beta}{\mathrm{d}t} = -eE - \mathrm{sign}[\beta]\,(D_\mathrm{e} + D_\mathrm{p})$$

Brief Summary

$\beta_\mathrm{end}[t] = \beta_\mathrm{end}[\beta_\mathrm{initial}, E, t]$

Dreicer Velocity & Dreicer Field

$$\exists!\beta_\mathrm{Dreicer} \in [0,1) \cap \mathbf{R} \quad : \quad \left.\frac{\mathrm{d}p}{\mathrm{d}t}\right|_{\beta_\mathrm{Dreicer}} = 0$$

$$\Longrightarrow E_\mathrm{Dreicer} := E|_{\beta_\mathrm{Dreicer}} \sim \frac{1}{\beta^2_\mathrm{Dreicer}}$$

$$\beta = v/c$$

$$\gamma = \left(1 - \beta^2\right)^{-1/2}$$

$$\mu_\mathrm{j} = \frac{m_\mathrm{e}\, m_\mathrm{j}}{m_\mathrm{e} + m_\mathrm{j}}$$

$$D_\mathrm{j} \sim \frac{Z_\mathrm{j}^2 N_\mathrm{j}}{\mu_\mathrm{j}^2} \cdot \frac{1}{\beta^2}$$

$$v_\mathrm{D} = c\,\beta_\mathrm{Dreicer}$$

Coulomb Collisions (Coulomb Friction)

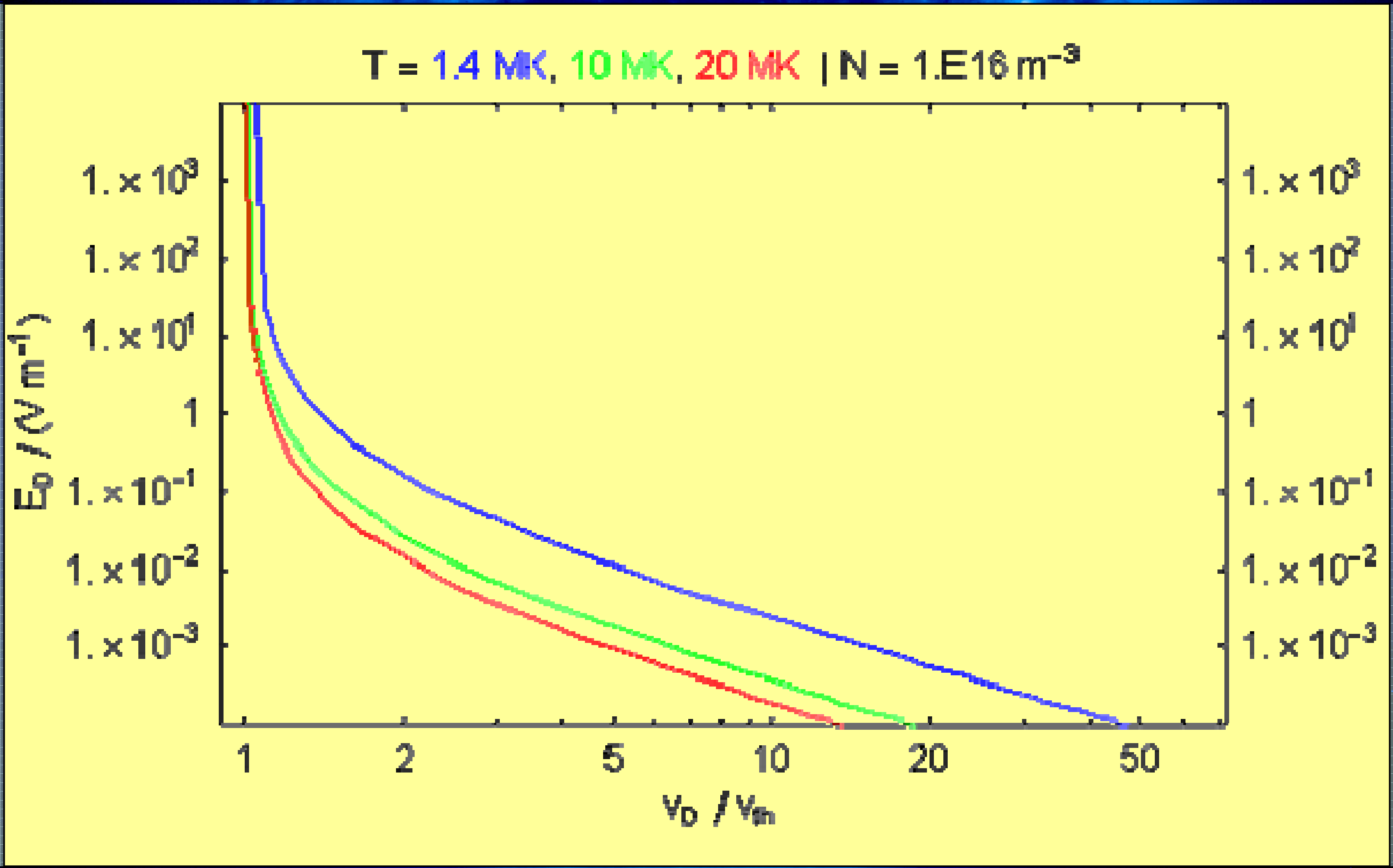
$$D_\mathrm{j} \sim \frac{Z_\mathrm{j}^2 N_\mathrm{j}}{\mu_\mathrm{j}^2} \cdot \beta^{-2}$$

$$\lim_{\beta \to \tilde{\beta} \gg \beta_\mathrm{Dreicer}} [D_\mathrm{j}] \sim 0$$

References: Dreicer (1959PhRv..115..238D & 1960PhRv..117..329D)

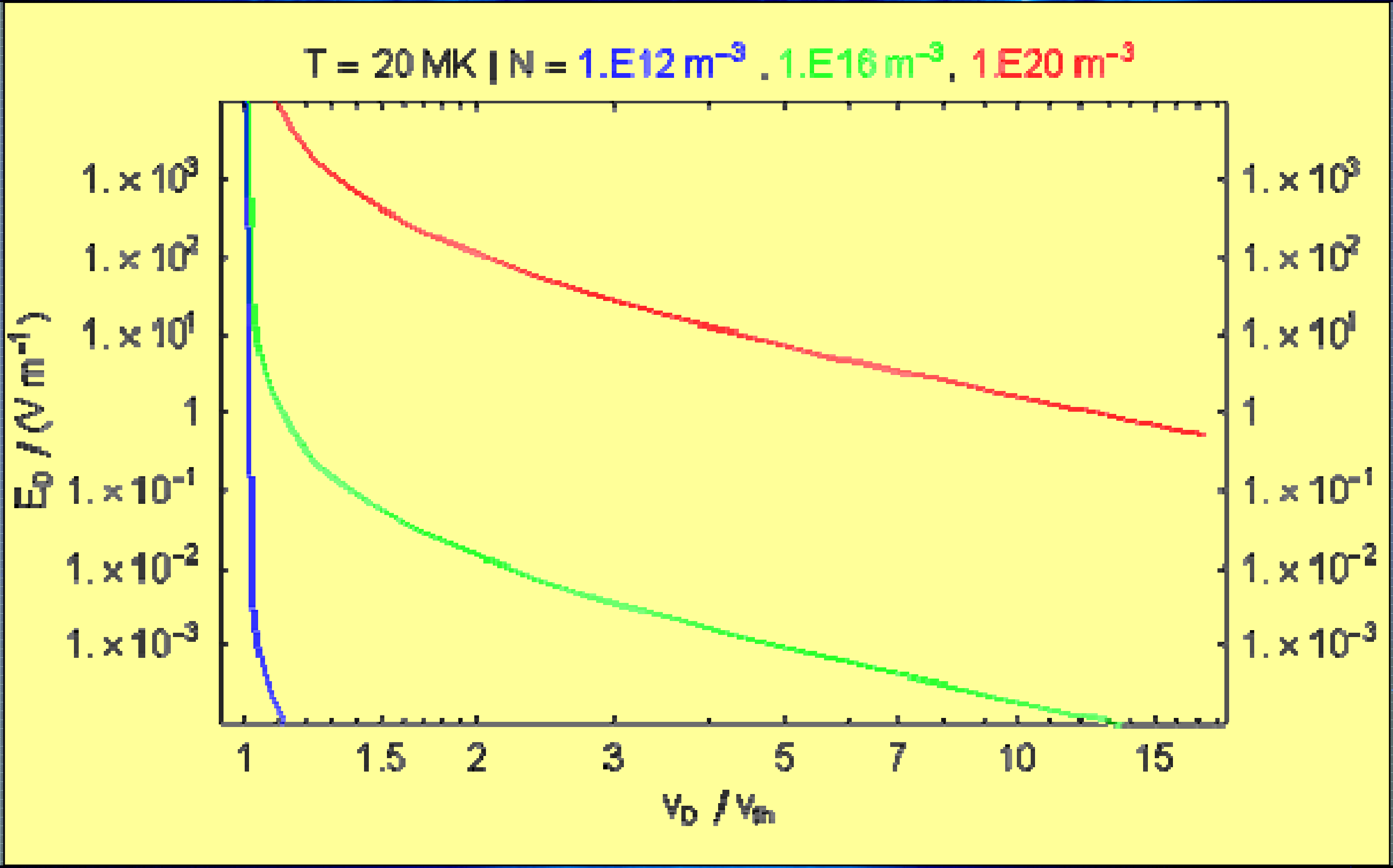
H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

Dreicer Field
– Temperature Dependence –



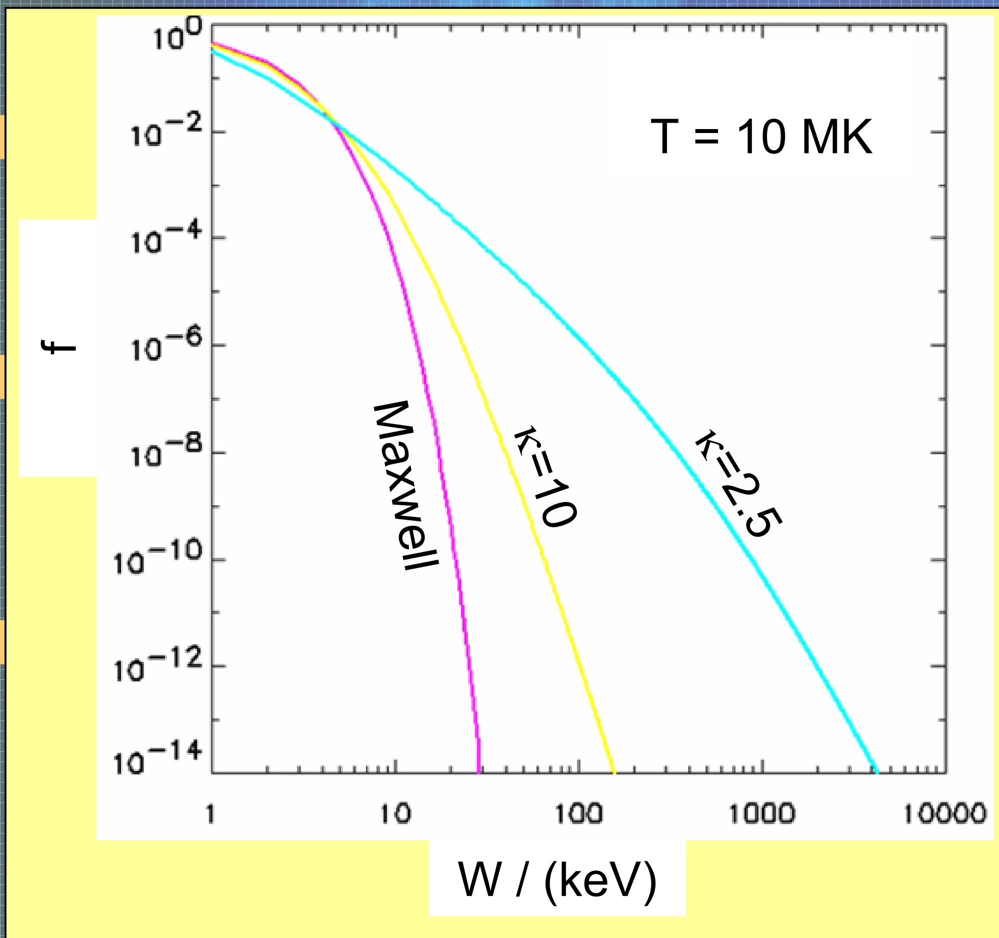
H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

Dreicer Field
– Density Dependence –



H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

Kappa Distribution



Brief Summary:

At energies much higher than the thermal energy the distribution does not decrease exponentially (as Maxwell Distribution) but corresponding to a power law.

$$= \frac{1}{\sqrt{2\pi\kappa\varepsilon_\kappa c^2}} \frac{\Gamma[\kappa+1]}{\Gamma[\kappa+1/2]} \quad \text{if } \varepsilon_\kappa \ll 1$$

ture

$$\Longrightarrow \varepsilon_\kappa = \frac{(\kappa-1/2)}{\kappa}\varepsilon_{\text{therm}}$$

$$\varepsilon = \frac{W_{\text{kin}}}{m_e c^2} = \gamma - 1$$

Reference: Vocks & Mann (2003ApJ…593.1134V) Courtesy: Prof.Gottfried Mann (AIP)

H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

Distribution Function and the Flux for the Accelerated Electrons

Distribution Function

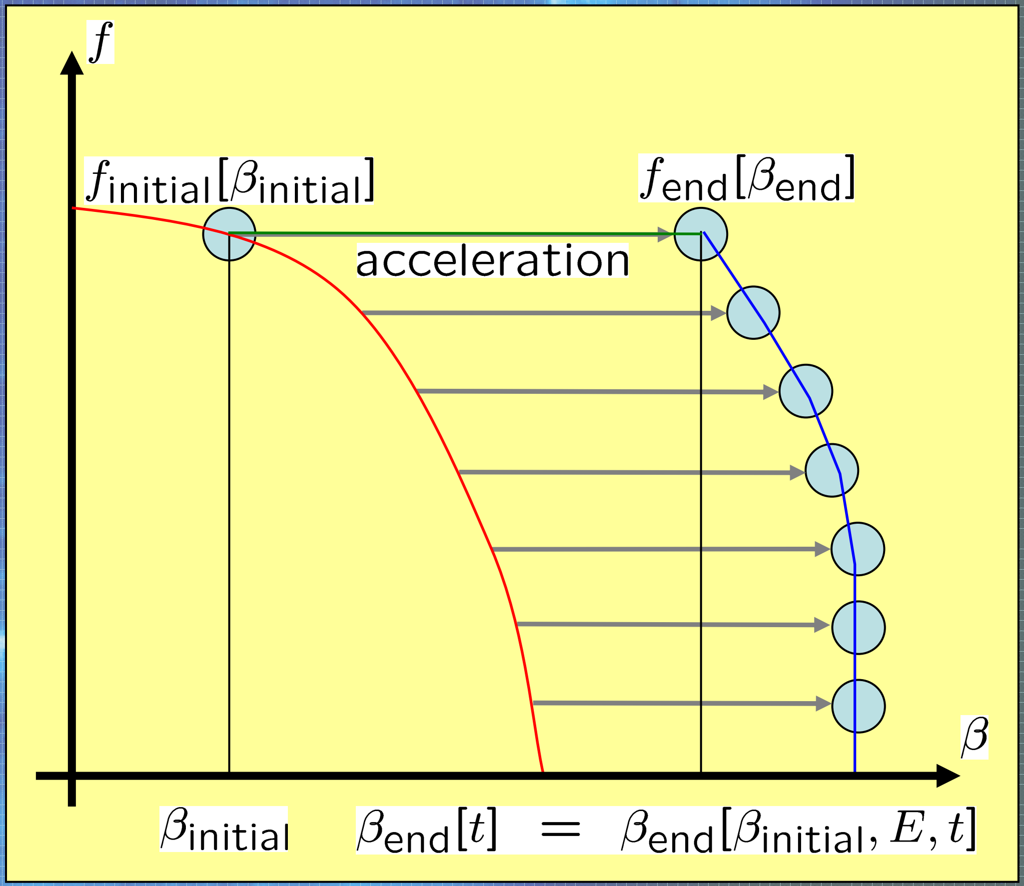
- single particle acceleration
- shifted distribution function
- extended condenser

Total Flux

$$\Phi = N_0 c^2 \int_0^\infty \mathrm{d}\varepsilon \cdot \left(\frac{\mathrm{d}\beta}{\mathrm{d}\varepsilon} \cdot \beta f[\varepsilon] \right)$$

Differential Flux

$$j = \frac{\mathrm{d}\Phi}{\mathrm{d}W_{\mathrm{kin}}} = \frac{\mathrm{d}\Phi}{\mathrm{d}\varepsilon} \cdot \frac{\mathrm{d}\varepsilon}{\mathrm{d}W_{\mathrm{kin}}}$$



H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

AIP

Flux

Brief Summary:
At energies much higher than the thermal energy the differential flux does not decrease exponentially but corresponding to a power law.

Total Flux

$$\Phi = N_0 c^2 \int_0^\infty \mathrm{d}\varepsilon \cdot \left(\frac{\mathrm{d}\left[\beta^2/2\right]}{\mathrm{d}\varepsilon} f[\varepsilon] \right)$$

Differential Flux

$$j = \frac{\mathrm{d}\Phi}{\mathrm{d}W_{\mathrm{kin}}} = \frac{\mathrm{d}\Phi}{\mathrm{d}\varepsilon} \cdot \frac{\mathrm{d}\varepsilon}{\mathrm{d}W_{\mathrm{kin}}}$$

Example: Non-Accelerated κ–Distribution Flux

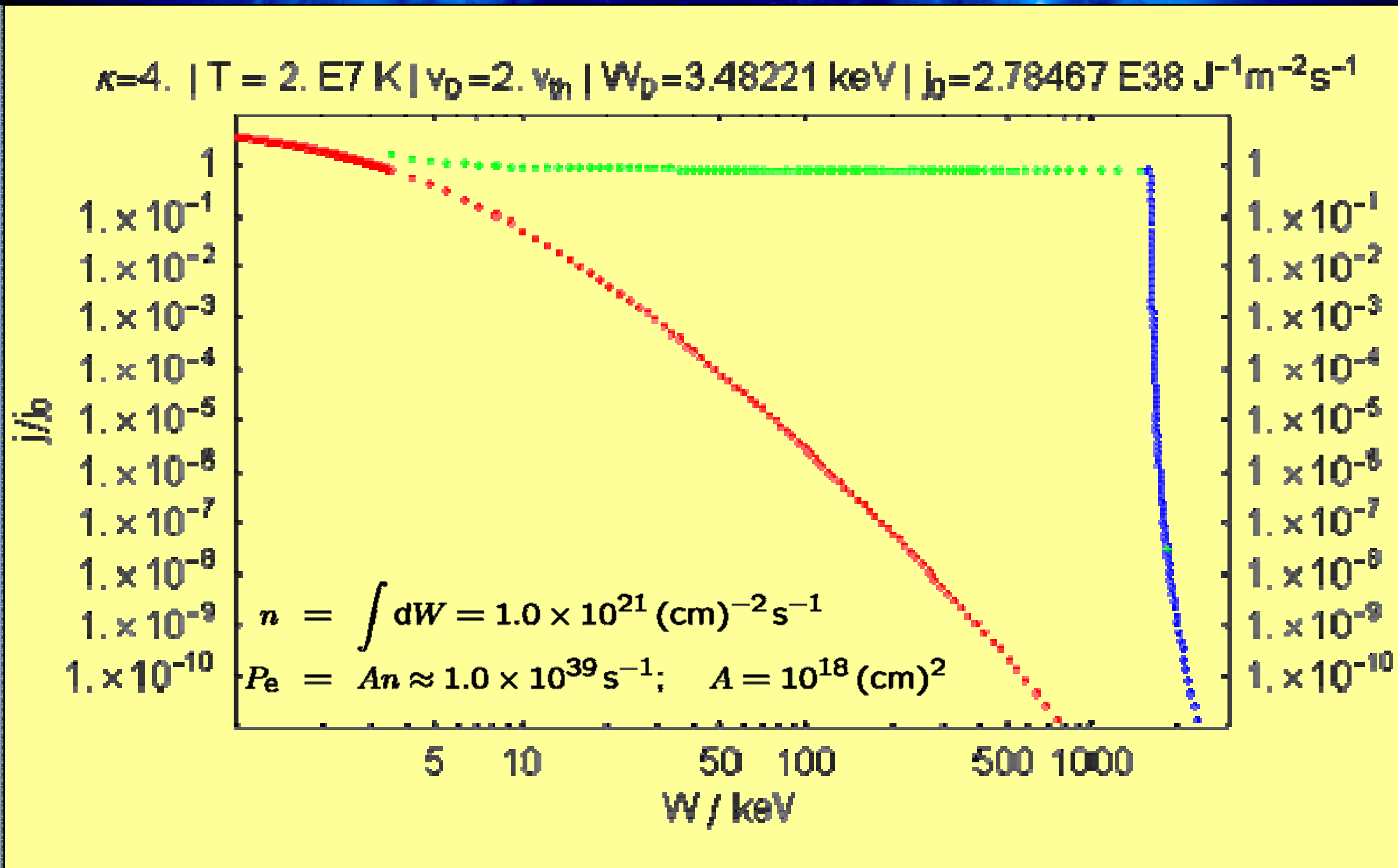
$$j = \frac{j_0}{\sqrt{2\pi\kappa\varepsilon_\kappa}} \cdot \frac{\Gamma[\kappa+1]}{\Gamma[\kappa+1/2]} \cdot \frac{1}{(1+\varepsilon)^3} \cdot \left(1 + \frac{\varepsilon}{\kappa\varepsilon_\kappa}\right)^{-\kappa-1}$$

$$j_0 = \frac{N_0}{m_e c}$$

H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

Calculation (I)

Electric Field: – 13.53 mV m^{-1} j_0= 4.46 E18 (keV)$^{-1}$ (cm)$^{-2}$ s^{-1}



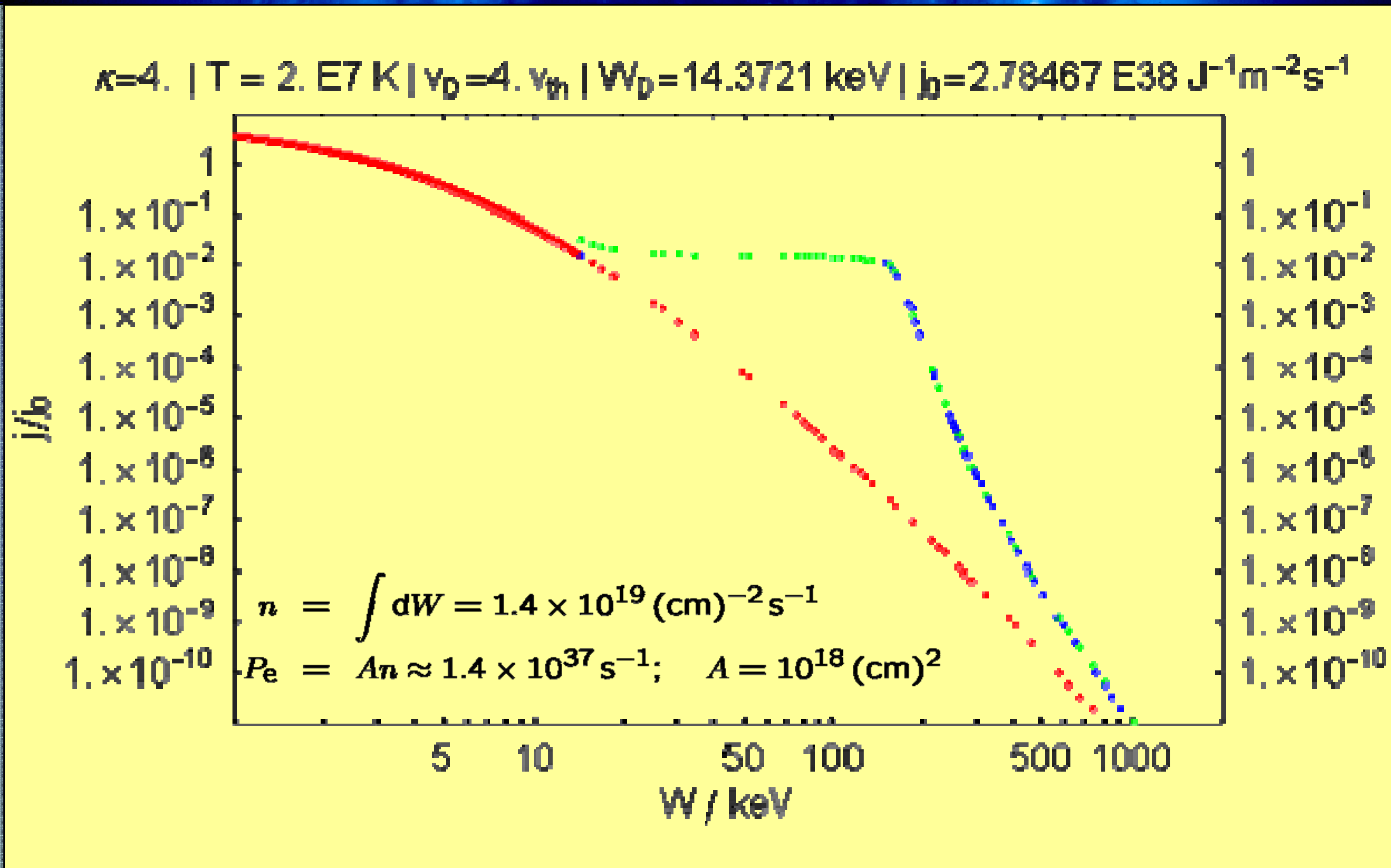
Acceleration length: 120 Mm **Electron density: 10^{16} m^{-3}**

H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

Calculation (II)

Electric Field: – 1.60 mV m^{-1} j_0= 4.46 E18 $(keV)^{-1}$ $(cm)^{-2}$ s^{-1}

AIP

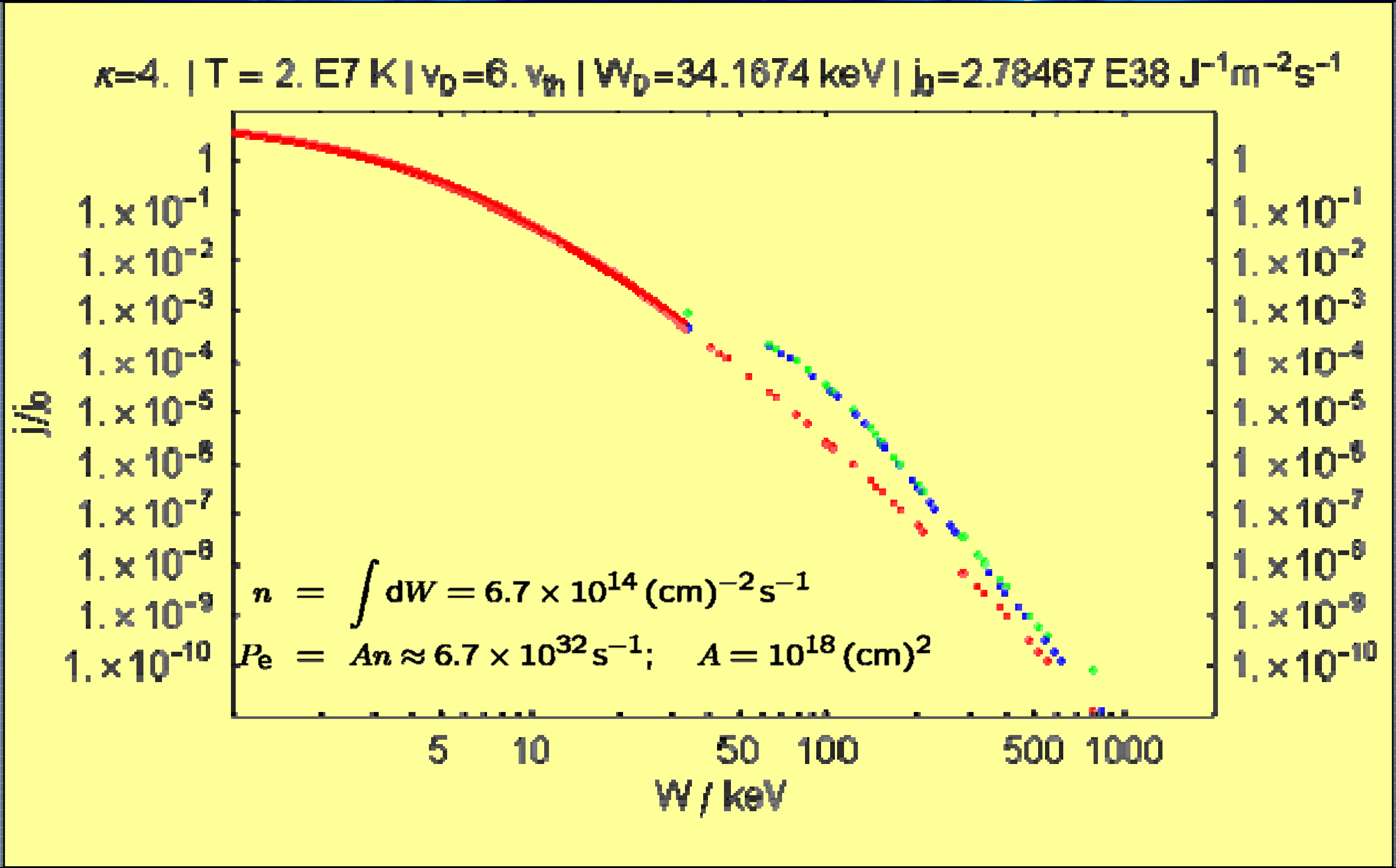


Acceleration length: 120 Mm **Electron density: 10^{16} m^{-3}**

H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

Calculation (III)

Electric Field: – 0.59 mV m^{-1} j_0= 4.46 E18 (keV)$^{-1}$ (cm)$^{-2}$ s^{-1}

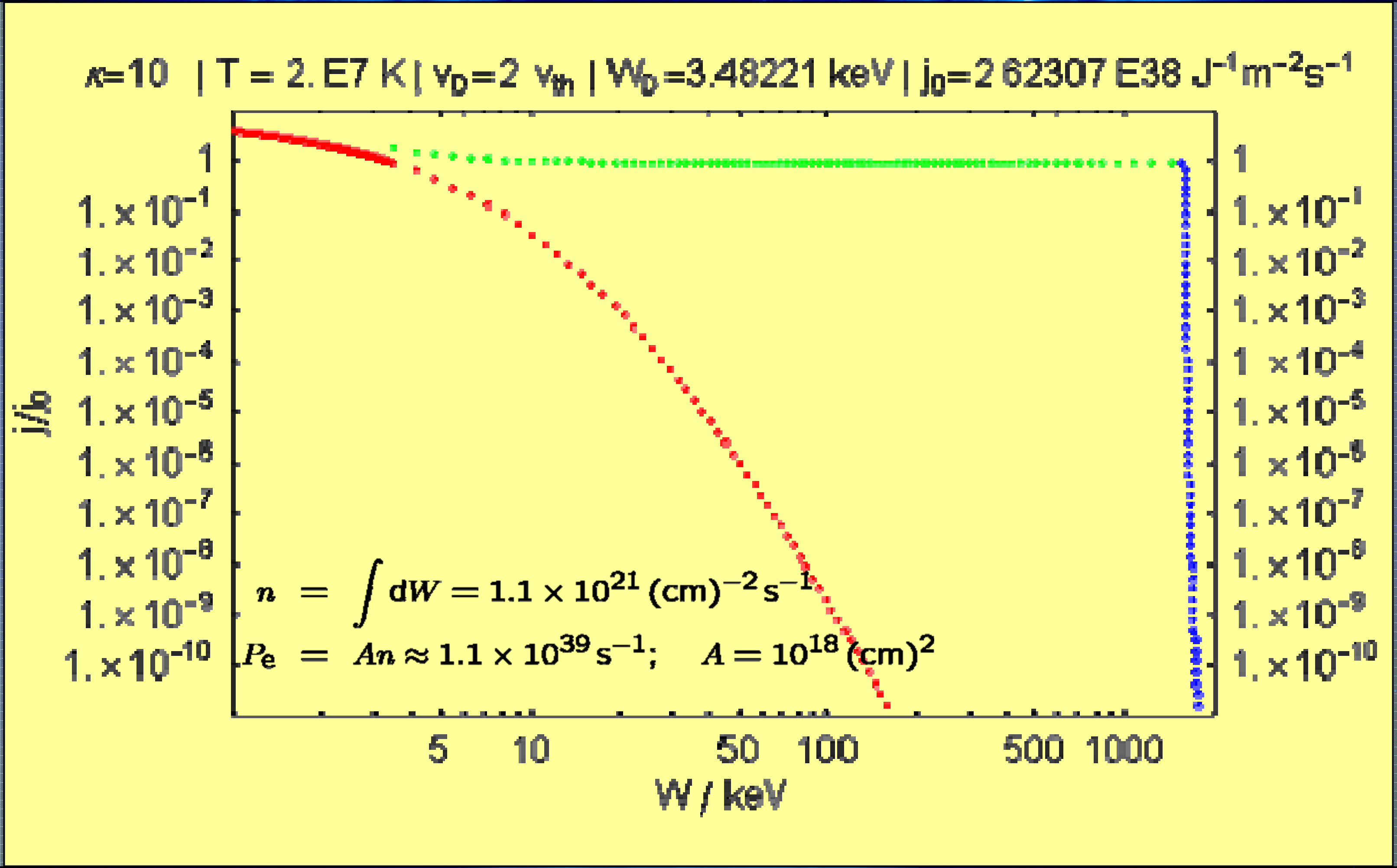


Acceleration length: 120 Mm   **Electron density: 10^{16} m^{-3}**

H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

Calculation (IV)

Electric Field: – 13.53 mV m^{-1} j_0= 4.20 E18 $(keV)^{-1}$ $(cm)^{-2}$ s^{-1}

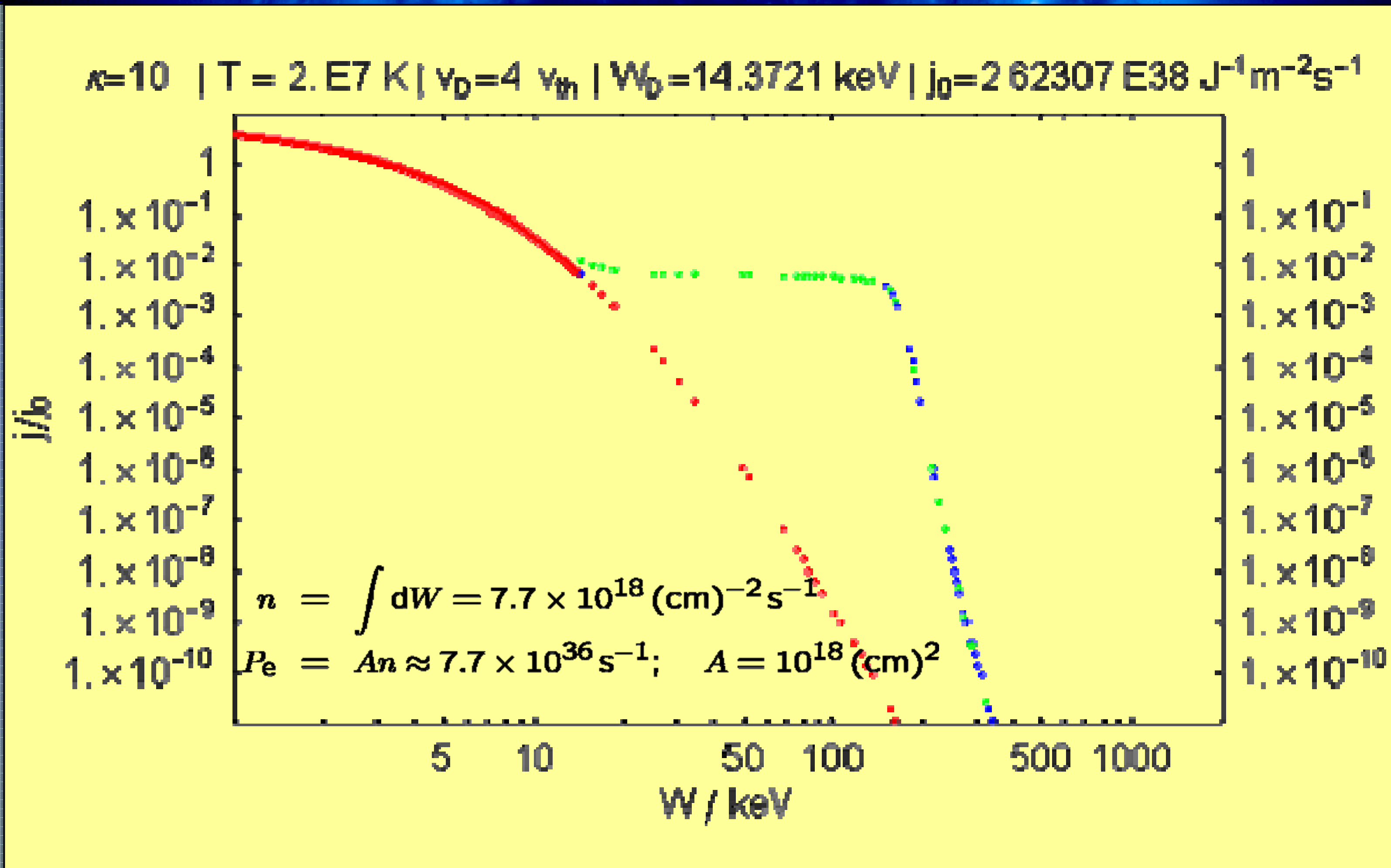


Acceleration length: 120 Mm **Electron density: 10^{16} m^{-3}**

H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

Calculation (V)

Electric Field: – 1.60 mV m^{-1} j_0= 4.20 E18 $(keV)^{-1}$ $(cm)^{-2}$ s^{-1}

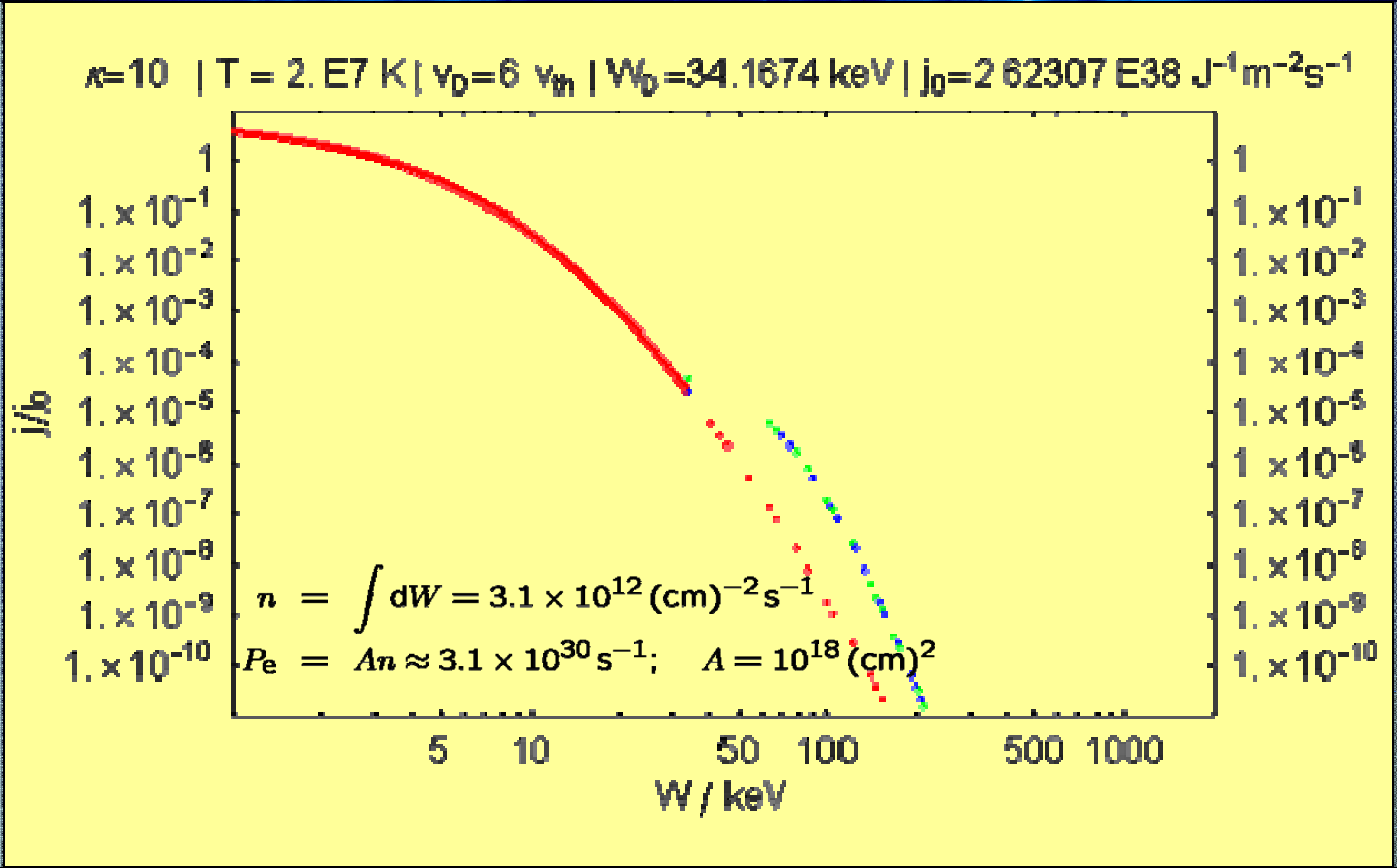


Acceleration length: 120 Mm **Electron density: 10^{16} m^{-3}**

H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

Calculation (VI)

Electric Field: – 0.59 mV m^{-1} j_0= 4.20 E18 (keV)$^{-1}$ (cm)$^{-2}$ s^{-1}

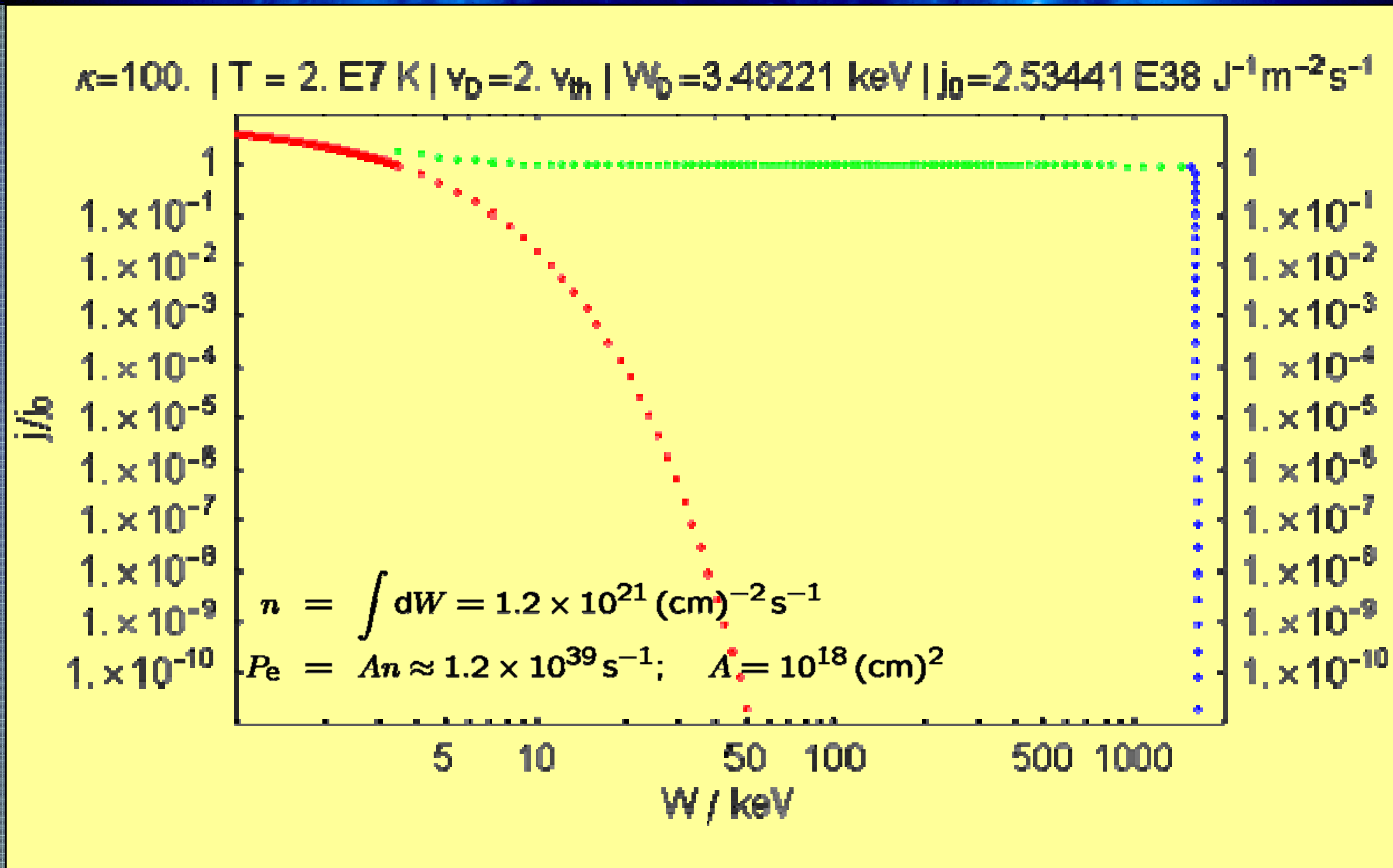


Acceleration length: 120 Mm **Electron density: 10^{16} m^{-3}**

H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

Calculation (VII)

Electric Field: – 13.53 mV m^{-1} j_0= 4.06 E18 $(keV)^{-1}$ $(cm)^{-2}$ s^{-1}

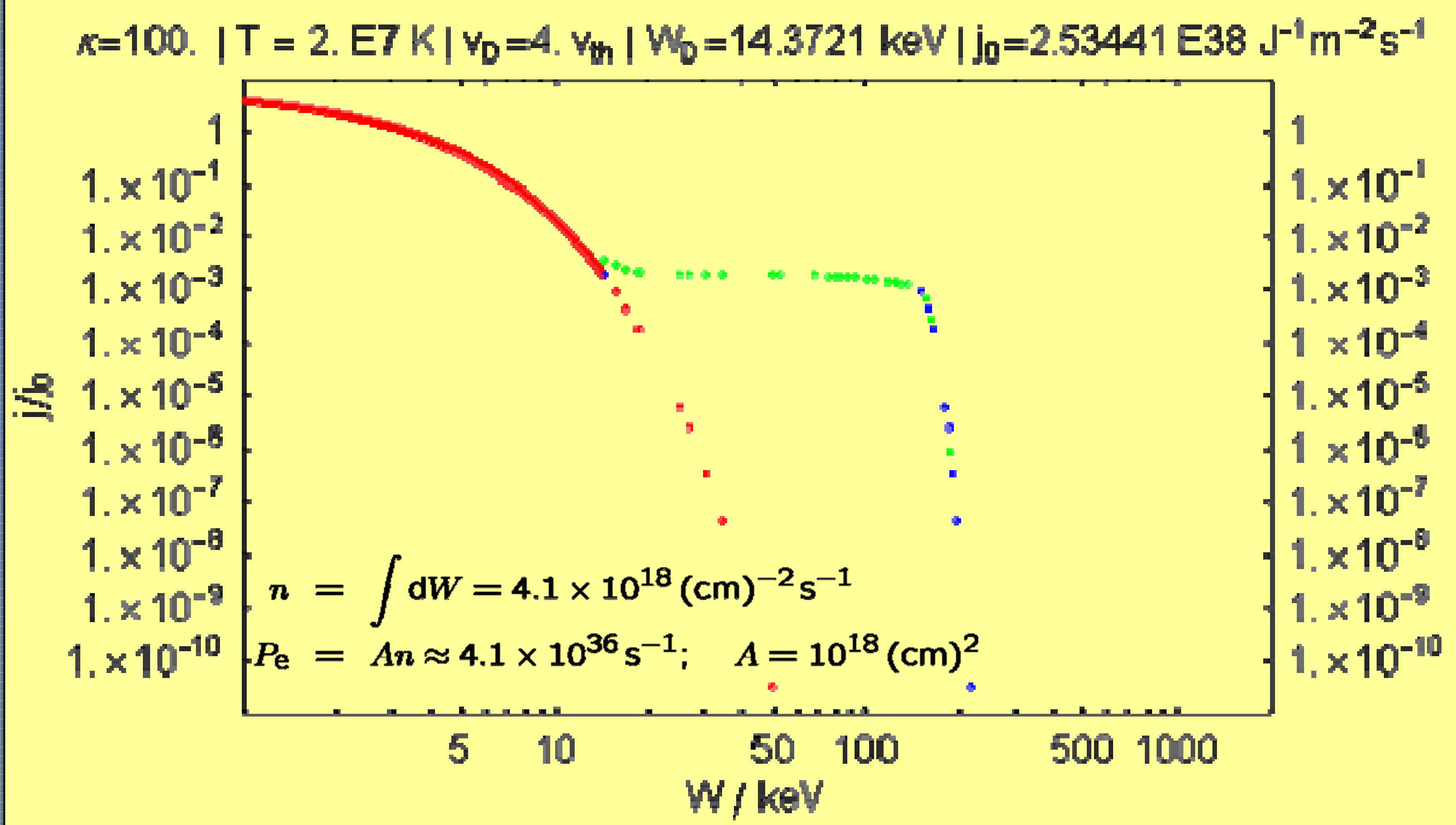


Acceleration length: 120 Mm **Electron density: 10^{16} m^{-3}**

H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

Calculation (VIII)

Electric Field: – 1.60 mV m^{-1} j_0= 4.06 E18 (keV)$^{-1}$ (cm)$^{-2}$ s^{-1}

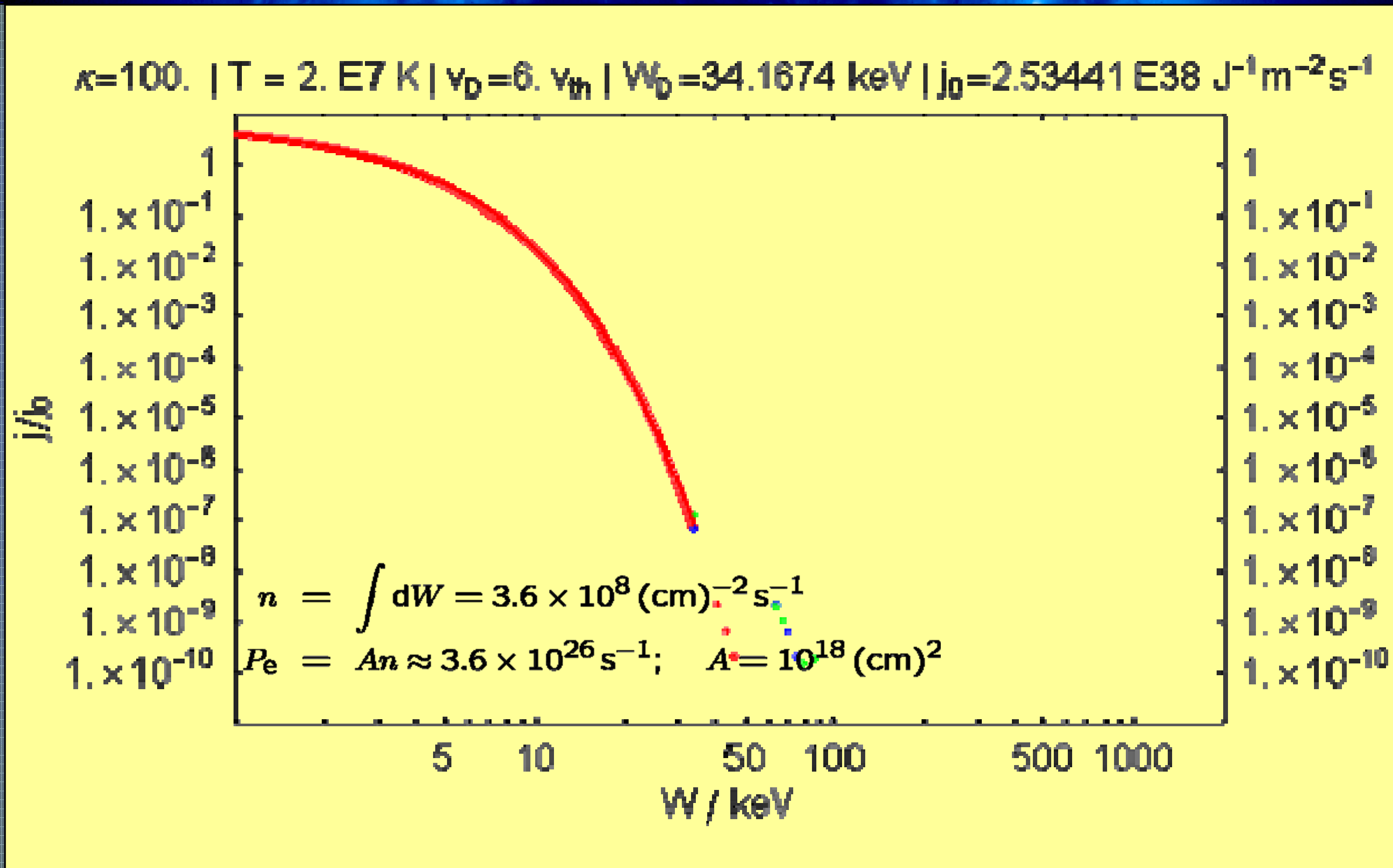


Acceleration length: 120 Mm **Electron density: 10^{16} m^{-3}**

H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

Calculation (IX)

Electric Field: – 0.59 mV m^{-1} j_0= 4.06 E18 (keV)$^{-1}$ (cm)$^{-2}$ s^{-1}

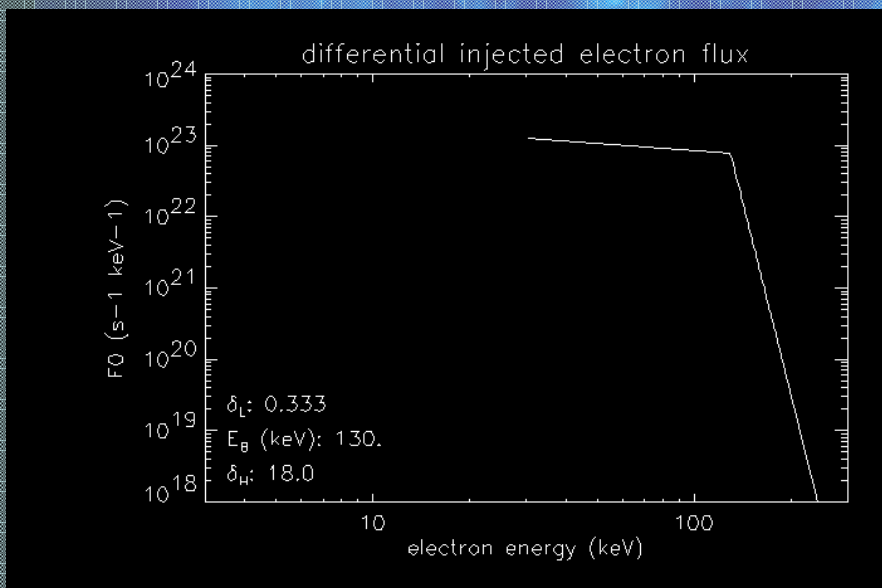


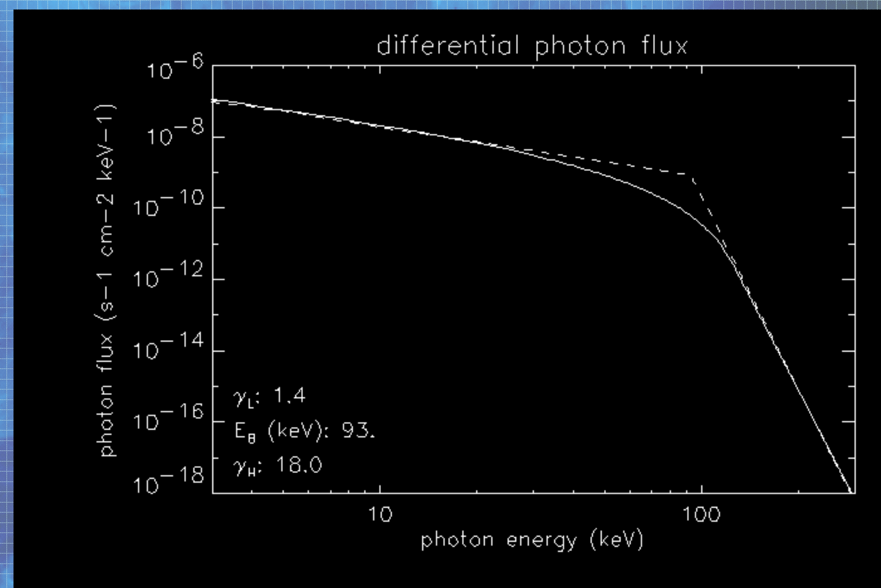
Acceleration length: 120 Mm **Electron density: 10^{16} m^{-3}**

H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

X-Ray Flux for Calculation (II)

κ=4. | T = 2. E7 K



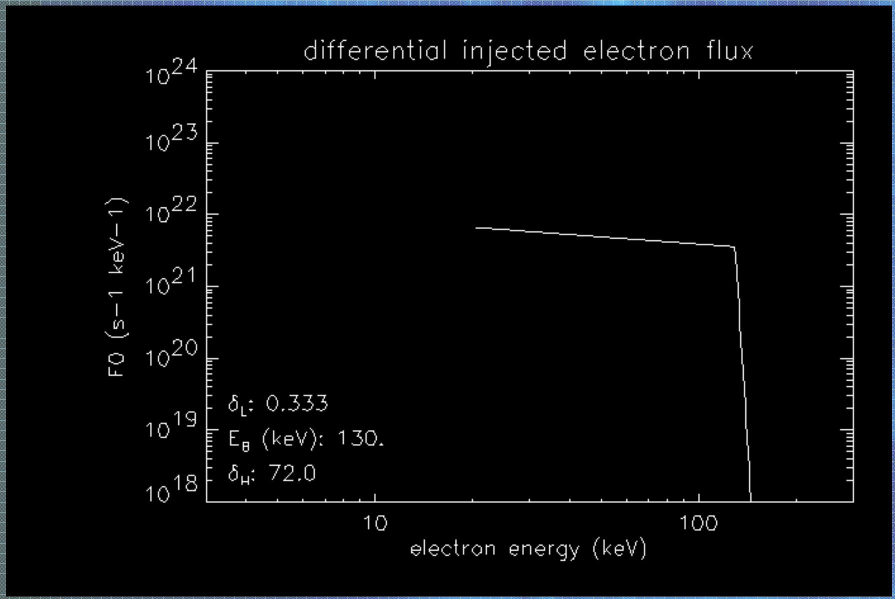


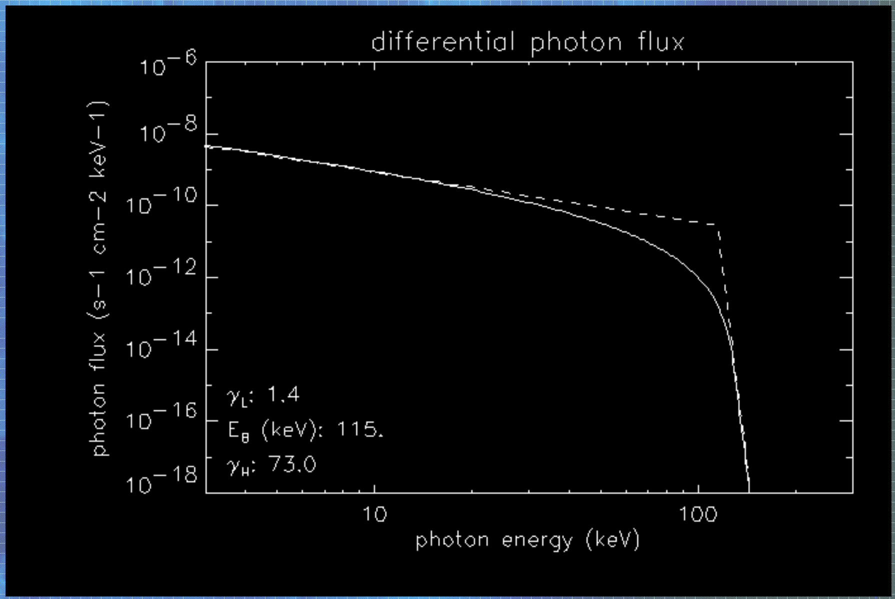
Courtesy: Dr. Alexander Warmuth (AIP)

H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

X-Ray Flux for Calculation (VIII)

κ=100. | T = 2. E7 K

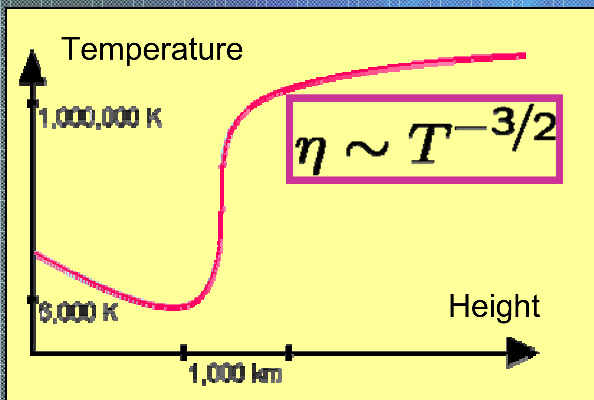




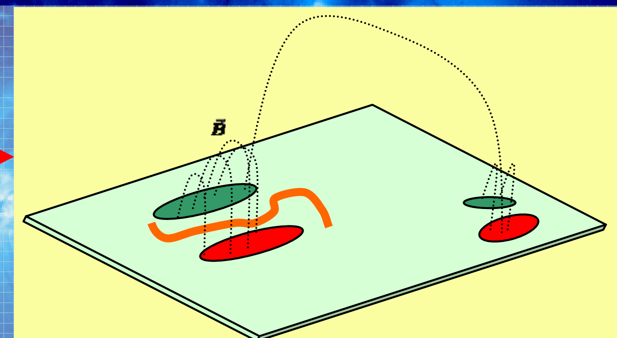
Courtesy: Dr. Alexander Warmuth (AIP)

H. Önel, Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany, honel@aip.de

Summary
Electron Acceleration by DC Fields



short circuited

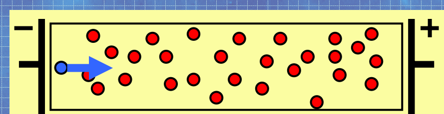


electric field induction by Photospheric footpoint motion

$U = U_1 + U_2$

Circuit Estimations

$P_{co+ch} \sim 10^{27}$ W
$P_{co} \sim 10^{20}$ W
$U_{co} \sim 300$ kV
$E_{co} \sim -3$ mV m^{-1}



acceleration by DC field