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The effect of magnetic field and density variations on particle acceleration in a 3D RCS

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The outline

- **Observational evidences of p and e presence**
- **Current sheet topology with a guiding magnetic field**
- **The particle motion analysis in a 3D current sheet**
  - **Case 1 – Bz variable; case 2, Bz and Bx variable**
- **Electron and proton energy spectra from an RCS with a constant density**
- **E and p energy spectra from an model RCS with varying density and transversal magnetic field**

The evidences of accelerated particles in flares

- Electrons (well established – see talk by Fletcher):

  Bremsstrahlung hard X-ray emission;

  gyro-synchrotron MW-emission

  etc.

- Protons: ?-ray nuclear lines in some flares (Share et al, 2002-5).

  I m p l i c i t e v i d e n c e s: non-thermal UV-lines broadening and Ha impact polarisation (*Antonucci et al, 1984; Henoux*, *Chambe et al*, *1990*)

  Hard bremsstrahlung X-ray (>20KeV) can be partly produced by proton-energized electrons (*Simnett & Haines*, *1990*).

The mechanisms of particle acceleration

- **Acceleration by electric field inside the reconnecting current sheet**

(in upper corona)

-Semi-analytical solutions of motion equation for particles in non-neutral CS *(Spieser, 1965; Litvinenko, 1996; Litvinenko & Somov, 1993, 1995; Zhu and Parks, 1993; Tsuneta, 1995).*

-The numerical simulation of particles acceleration in 2D current sheet *(Vlahos, 1989; Martens & Young, 1990)* and 3D current sheet *Zharkova & Gordovskyy, 2004, 2005; Woods & Neukirch, 2005; Dalla and Browning, 2005).*

- **Acceleration by propagating plasma waves**

(in lower atmospheric levels)

- Thermal electron acceleration by MHD-waves (*Park and Petrosian*, 1995; Pryadko & Petrosian, 1997)

- Proton and electron acceleration by fast modes of MHD- waves (e.g. *Decker and Vlahos, 1986; Miller et al, 1996*)

- **Acceleration by MHD-shocks**

(see e.g. *Decker and Vlahos, 1986; Cargill et al., 1988; Anastasiadis and Vlahos,1991*)

Observed asymmetry of the footpoint brightness

- A spatial asymmetry between X-ray images of footpoints. The brighter X-ray source is often observed in the footpoint with weaker magnetic field *(Nitta et al., 1990; Sakao, 1994; Sakao et al, 1994).*

- A spatial asymmetry in MW images of the two separate footpoints was also observed in many flares. Unlike X-rays, the brighter MW footpoint corresponds to higher magnetic field *(Kundu et al., 1995, Masuda et al., 1996).*

- This effect was interpreted as a result of the different magnetic field convergence in different loop legs. The higher is the convergence the stronger is magnetic mirroring.

The temporal and spectral asymmetry in different footpoints

- In many flares, in addition to the brightness asymmetry, there is a spectral asymmetry in MW range: one footpoint has a power-law energy spectra while the other has the thermal one (e.g. *Takakura et al, 1995*).

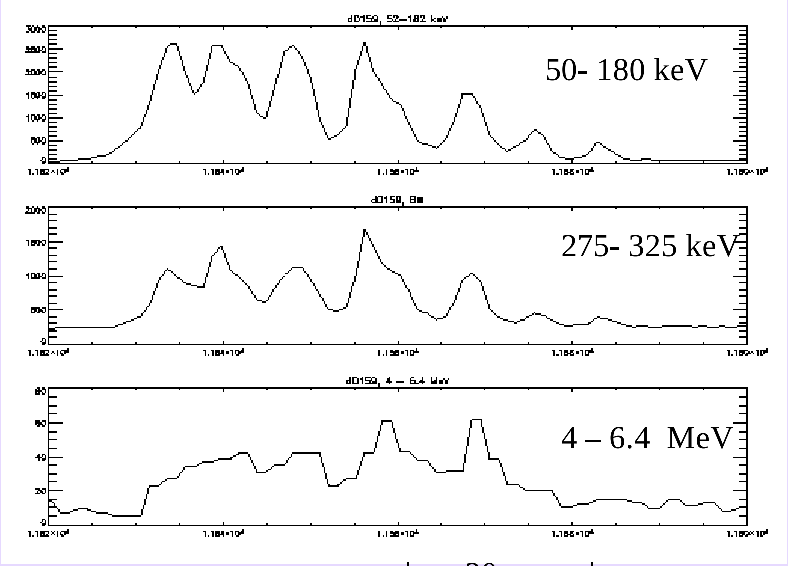
- In some flares there is a temporal delay in MW and gamma-ray emission appearing in different footpoints (so called ‘prolonged emission’ appearing either prior or after the main phase *(see e.g. Aschwanden, 1996; Aurass et al., 1999; Akimov et al., 1999, Share et al., 2003)*

- These two types of asymmetry can not be interpreted by a different magnetic convergence in the flaring loops.

Time delays in γ-ray line emission can be as small as <2 sec to as large as 10's of sec.

γ-ray line emission in 2002 July 23 flare may be delayed by ~10 sec from hard X-rays.

What does this say about acceleration-transport? Could be accounted for by trapping or is it intrinsic to the acceleration process?



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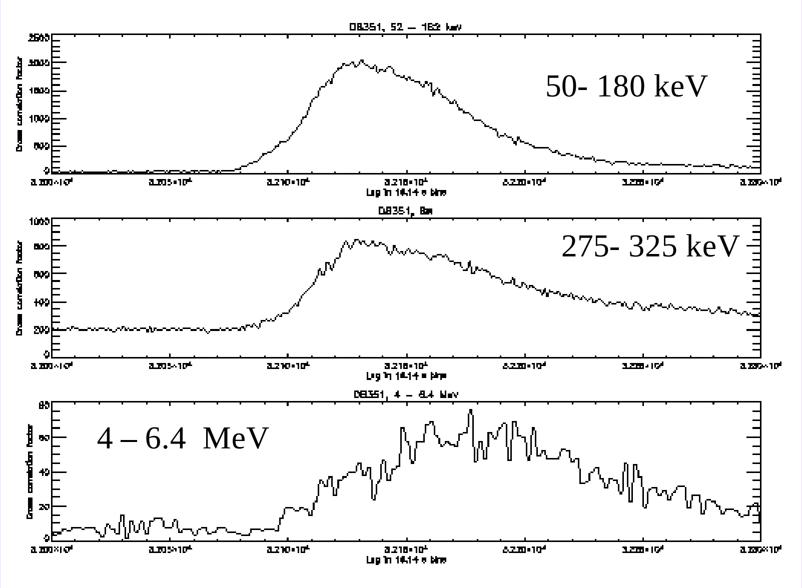
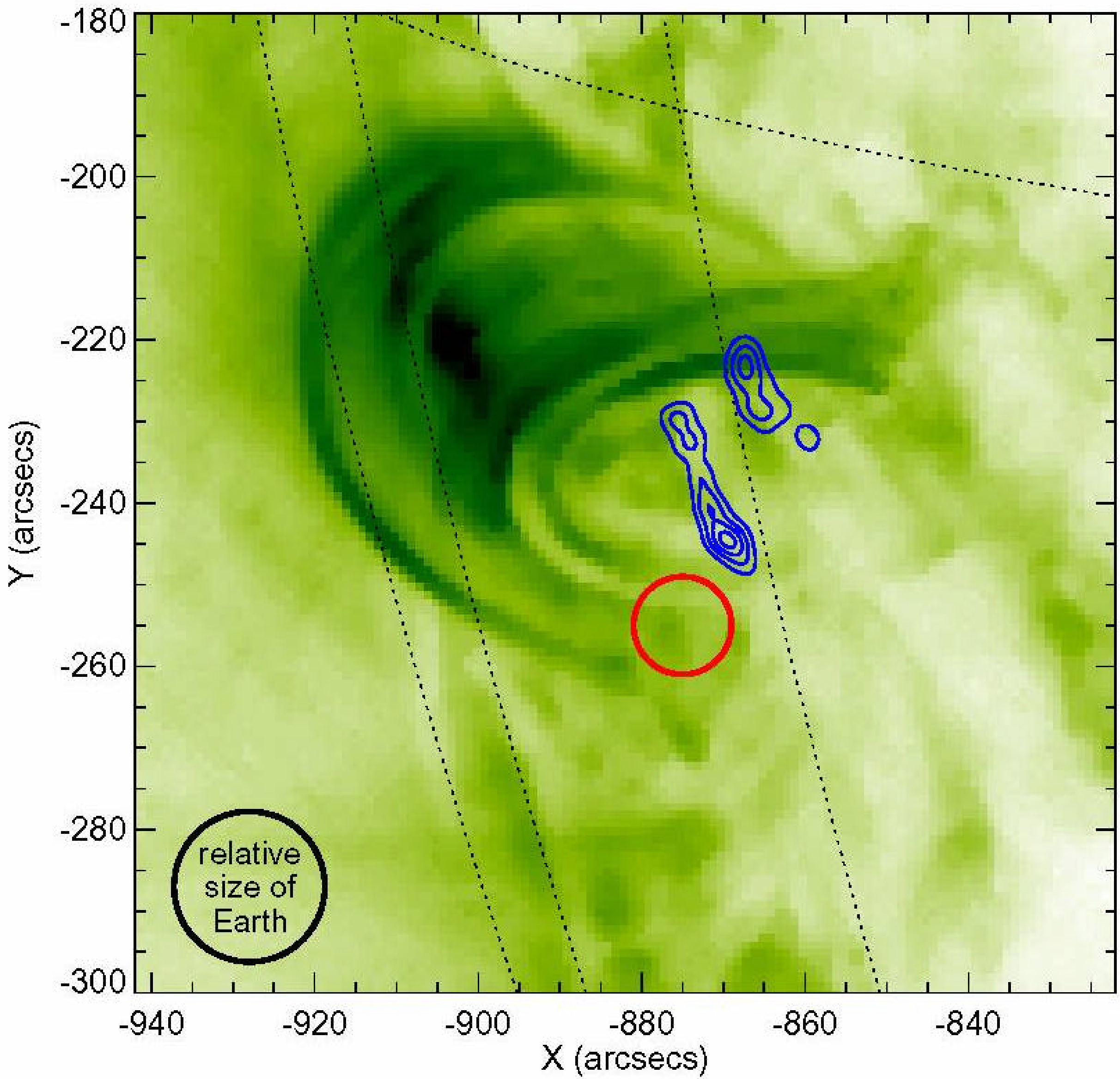


|------100 sec------|



-180
-200
-220
-240
-260
-280
-300
Y (arcsecs)
-940
-920
-900
-880
-860
-840
X (arcsecs)
relative size of Earth

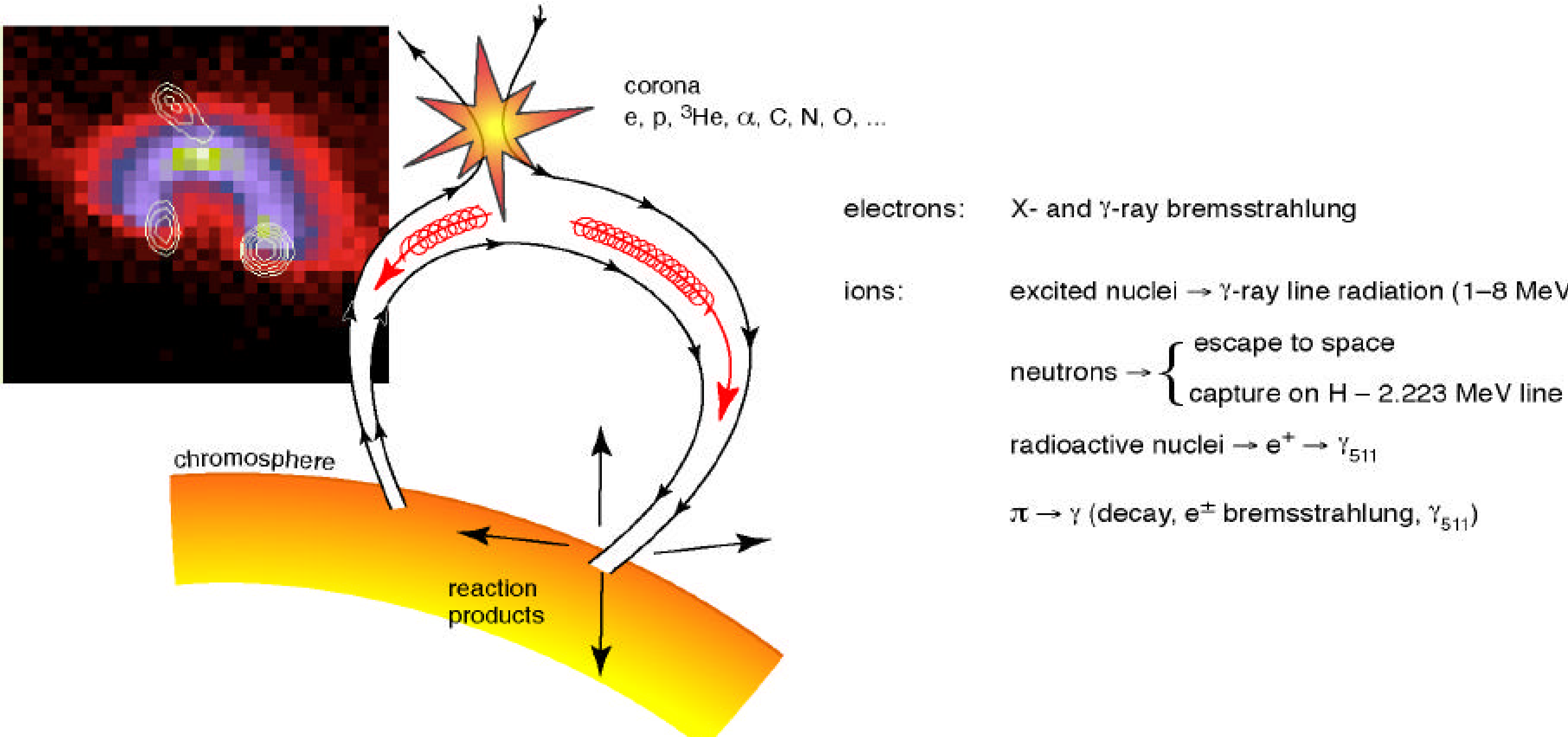
•Hence, the energy spectra and temporal asymmetry between footpoints can be caused by the **magnetic field topological effects** governing particle acceleration in the current sheet

ß

This is the motivation to investigate proton and electron motions inside a 3D current sheet

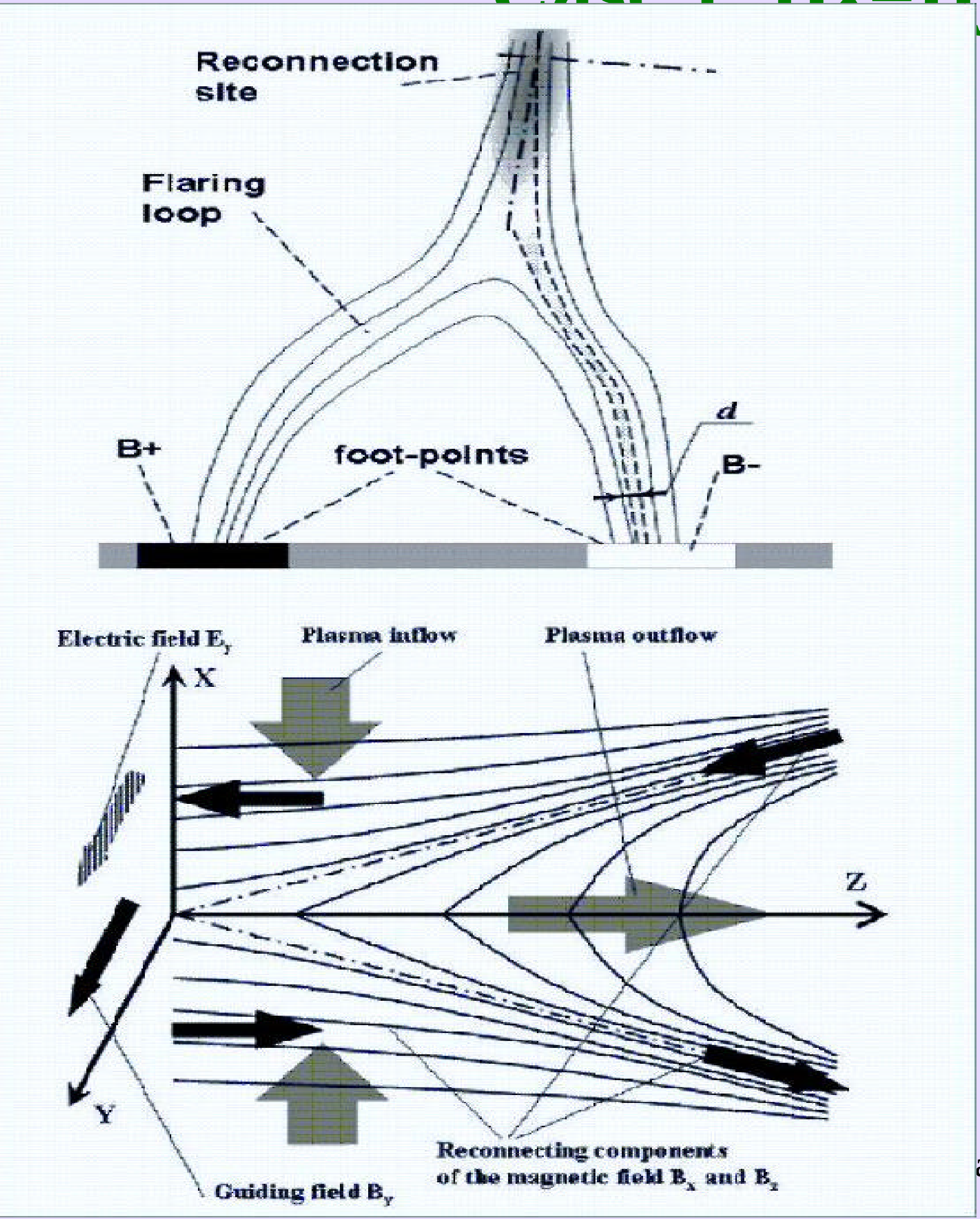
From Share and Murphy, 2004, RHESSI Workshop (Sonoma)

γ-RAY AND NEUTRON PRODUCTION IN SOLAR FLARES



Magnetic field topology –

Case 1. Bx=By =const



(Zharkova&Gordovskyy, MNRAS, 2005)

$B_z = B_0 \tanh(- x/d)$

$B_x = B_0 (z/a)^a$

$B_y = +/- By_0 = 0.0001Tl$

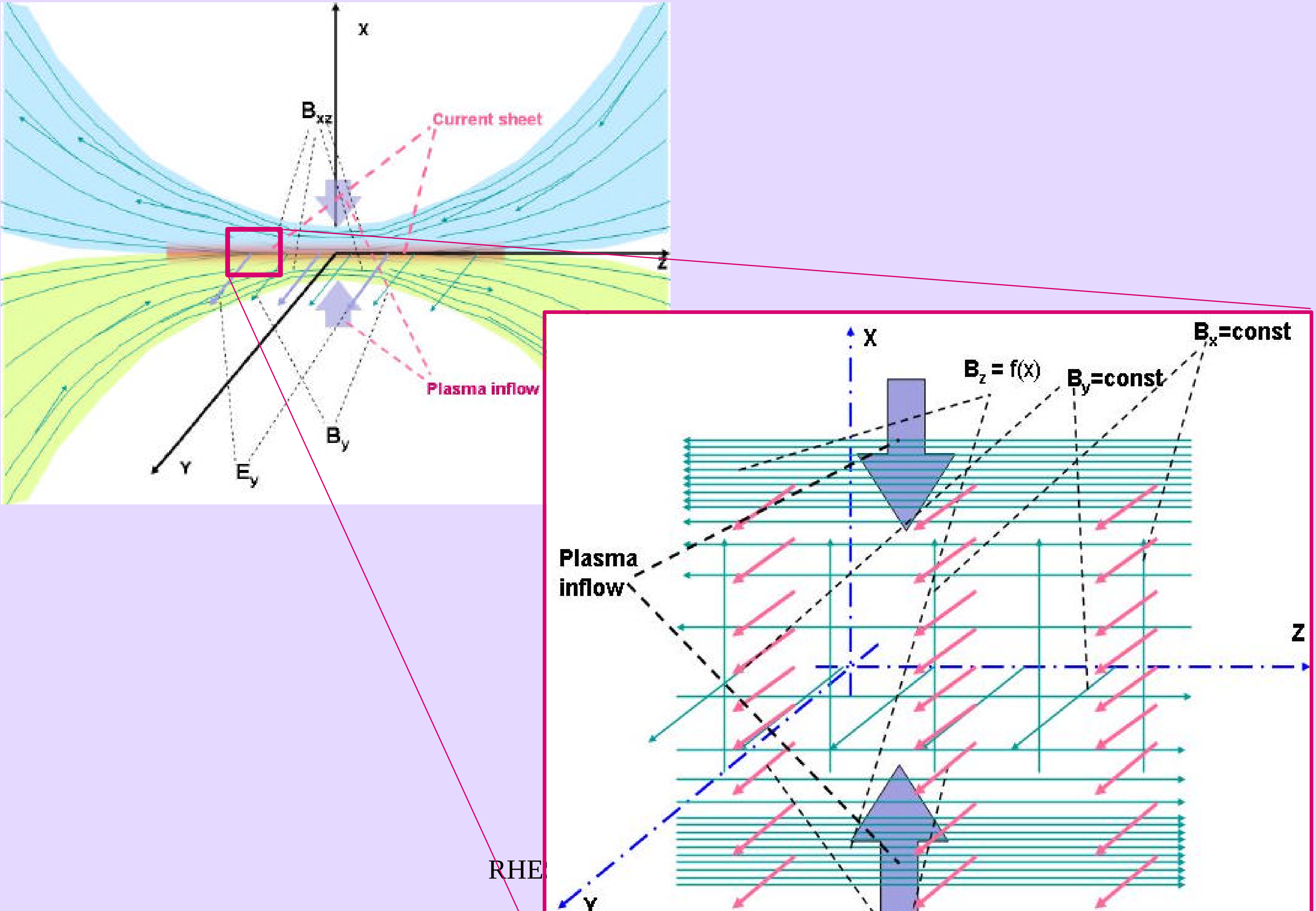
$B_0 = 0.01Tl$

$E_{y0} = B_0 V_{inflow} – 1/\sigma \mu \, dB_z/dx$

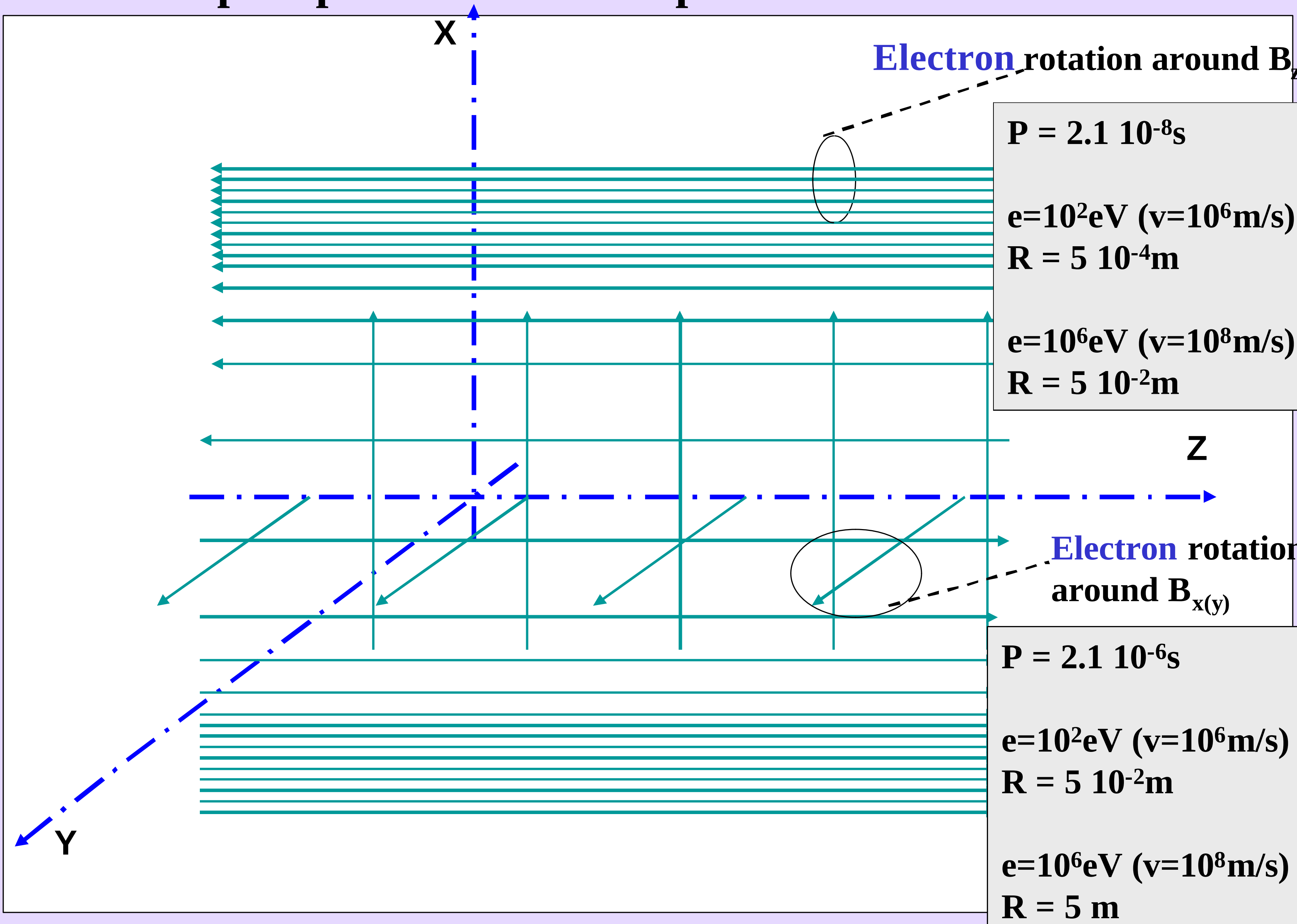
V_{inflow} » $0.01 V_{alfven}$ » $10^4 m/s$

$E_{y0} = 100V/m$

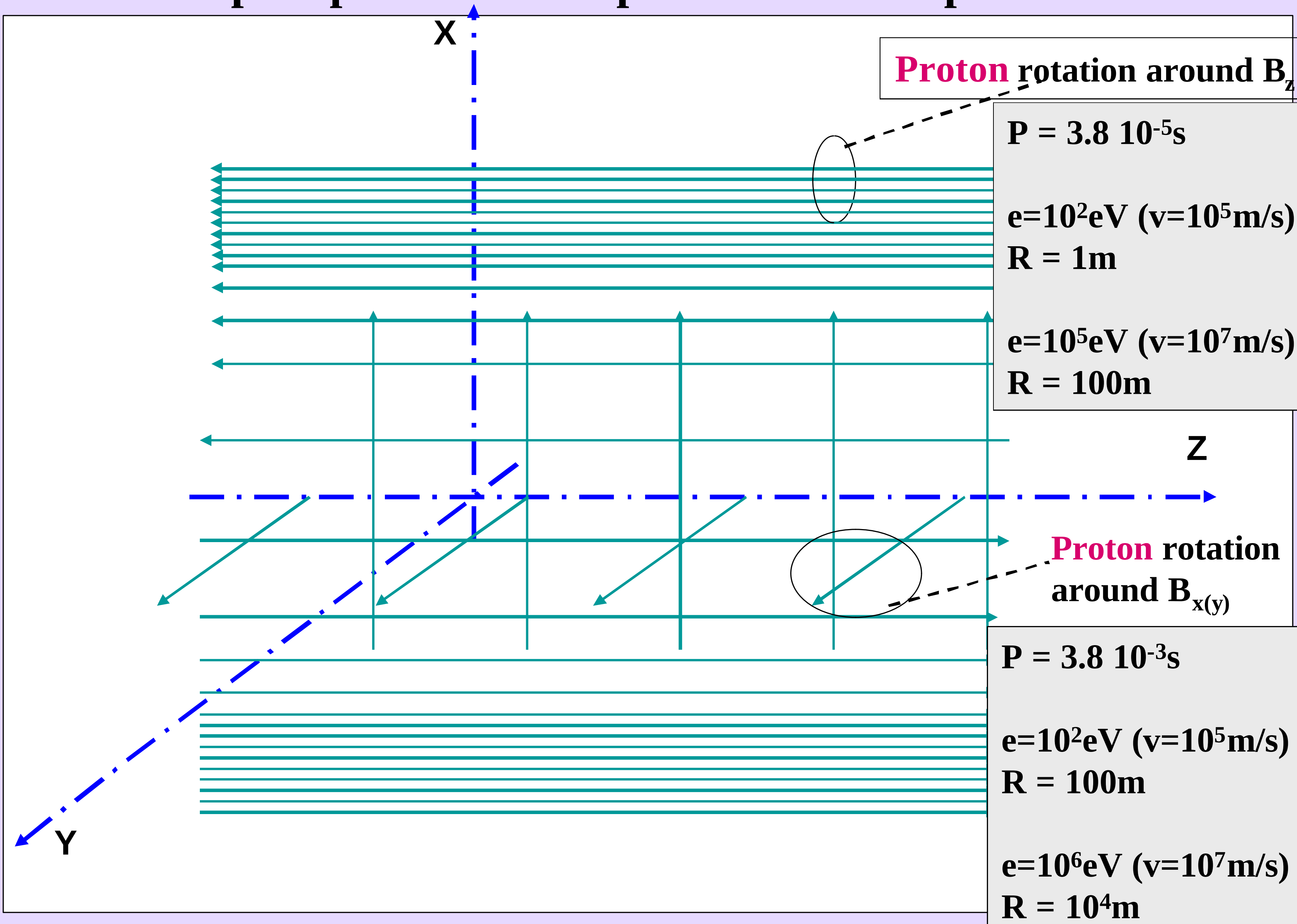
Accepted current sheet scheme – case 1 (B_x=B_y=const)



Accepted parameters of the particle motion: electrons



Accepted parameters of particle motion: protons



The motion equation of charged particles in the electric and magnetic fields:

$$\ddot{\mathbf{r}}(t) = q/m\ (\ \mathbf{E}(\mathbf{r}) + [\ \dot{\mathbf{r}}(t) \times \mathbf{B}(\mathbf{r})\ ]\ )$$

The method of calculations

- The particle-in-cell approach was used (10^5 particles)
- The second order of accuracy Runge-Kutta method (predictor-corrector scheme)
- A time step for each sort of particles is much smaller than the correspondent gyro-period

$$\delta t << m\,/q\ |\ \mathbf{B}\ |^{-1}$$

General analysis of the particle motion: trajectories Zharkova &Gorodvskyy, ApJ 2004

- Electric field is the force that governs **a straightforward movement of accelerated particles along the Y-axis**, so for a particle with the charge q the Y-component will have a velocity V_y

$$\mathbf{V_y} \text{ » } \mathbf{q/m\ E_y}\ t$$

- Obeying the X-component of magnetic field, by Lorenz force, ***particle is rotated through the angle of ~90^o*** before being ejected with:

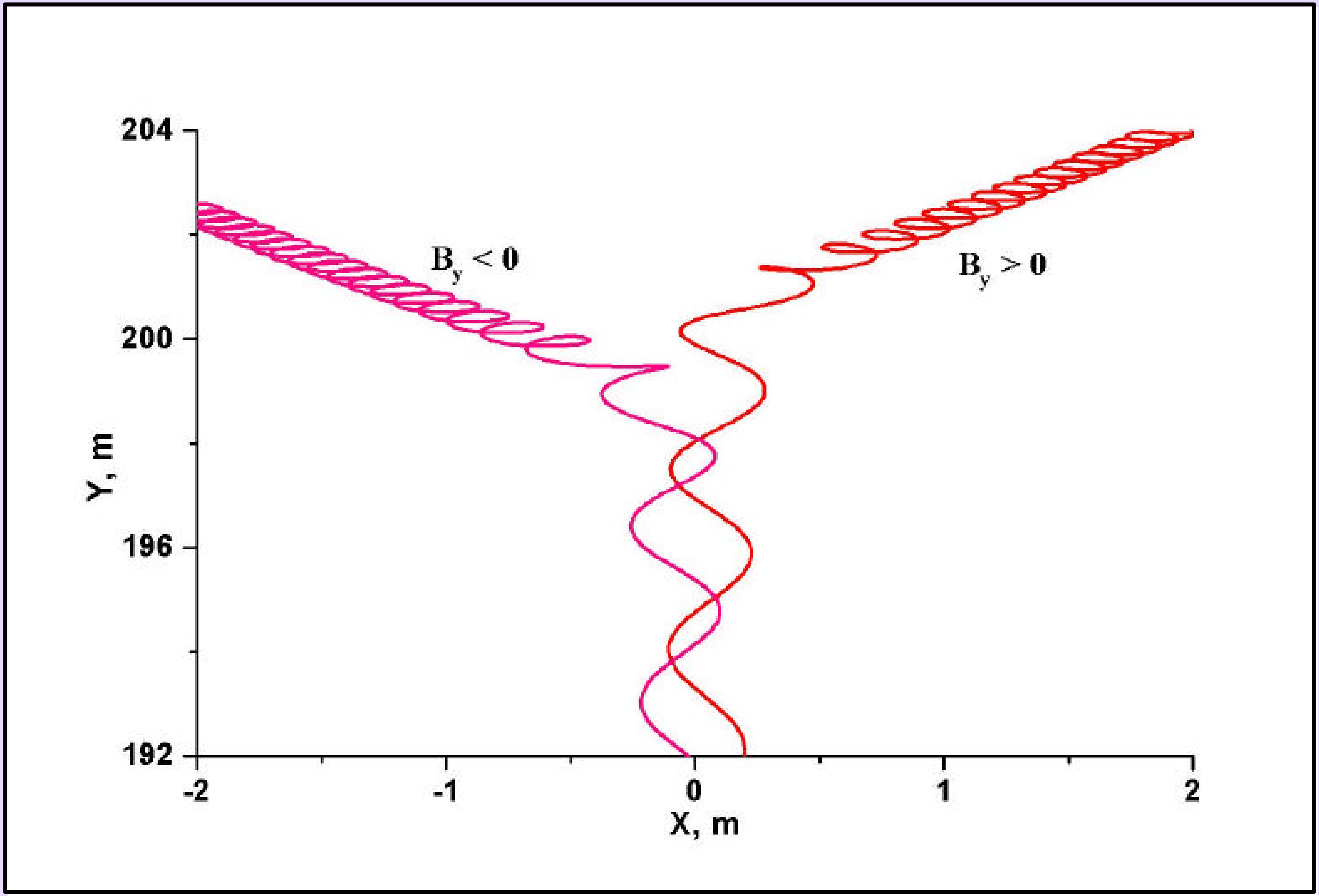
$$\mathbf{V_z} \text{ » } \mathbf{q/m\ V_y\ B_x}\ t = \mathbf{q^2/m^2\ E_y\ B_x}\ t^2$$

- The particle velocity V_x ***occurring owing to a gyration*** is defined by the Y-component of magnetic field and the Z-component of a particle velocity as follows:

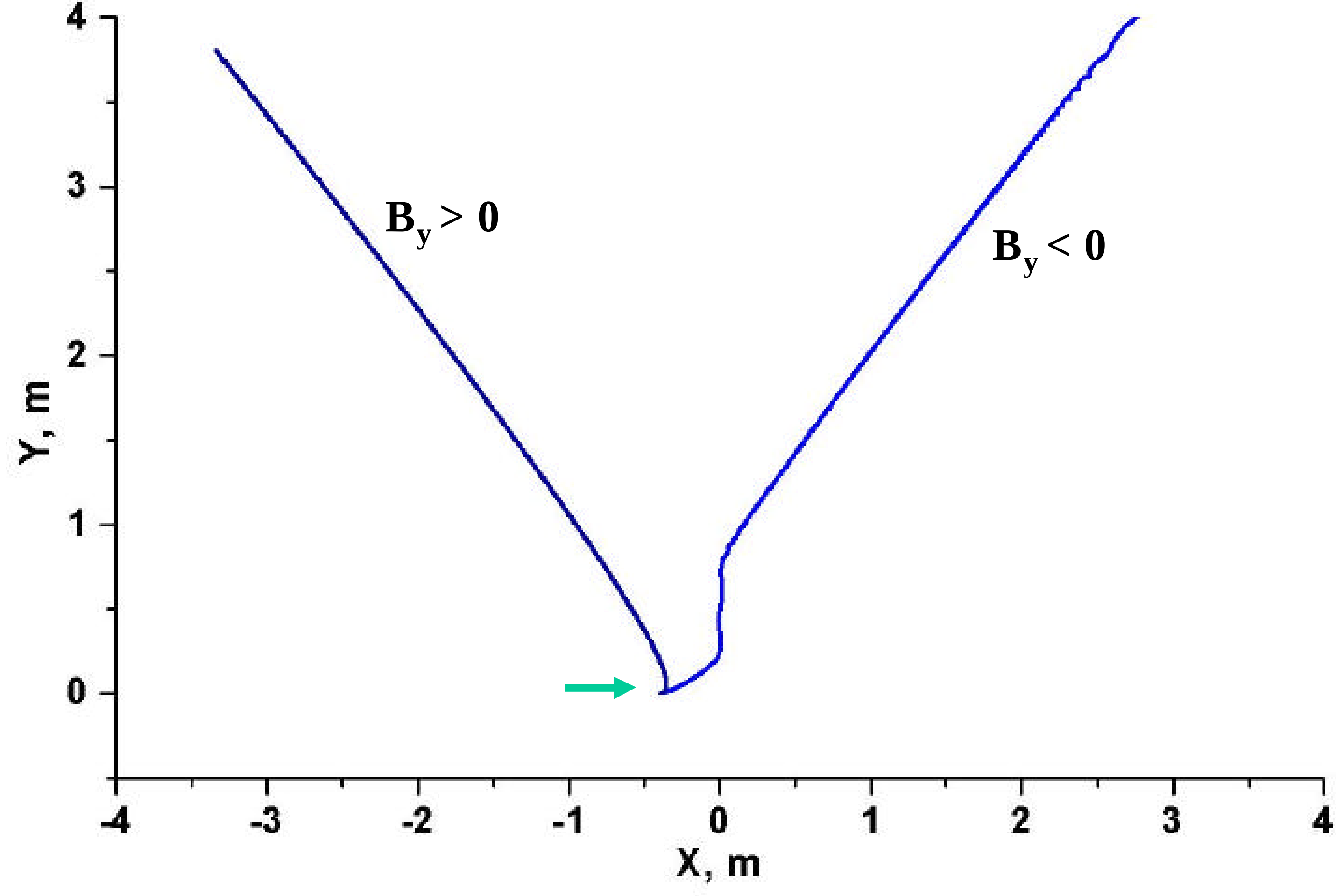
$$\mathbf{V_x} \text{ » } \mathbf{q/m\ V_z\ B_y}\ t \text{ » } \mathbf{q^3/m^3\ E_y\ B_x\ B_y}\, t^3$$

- Hence, **V_x is positive for electrons and negative for protons, if $B_y>0$, and vice versa if $B_y < 0$.**

Proton trajectory (ApJ 2004



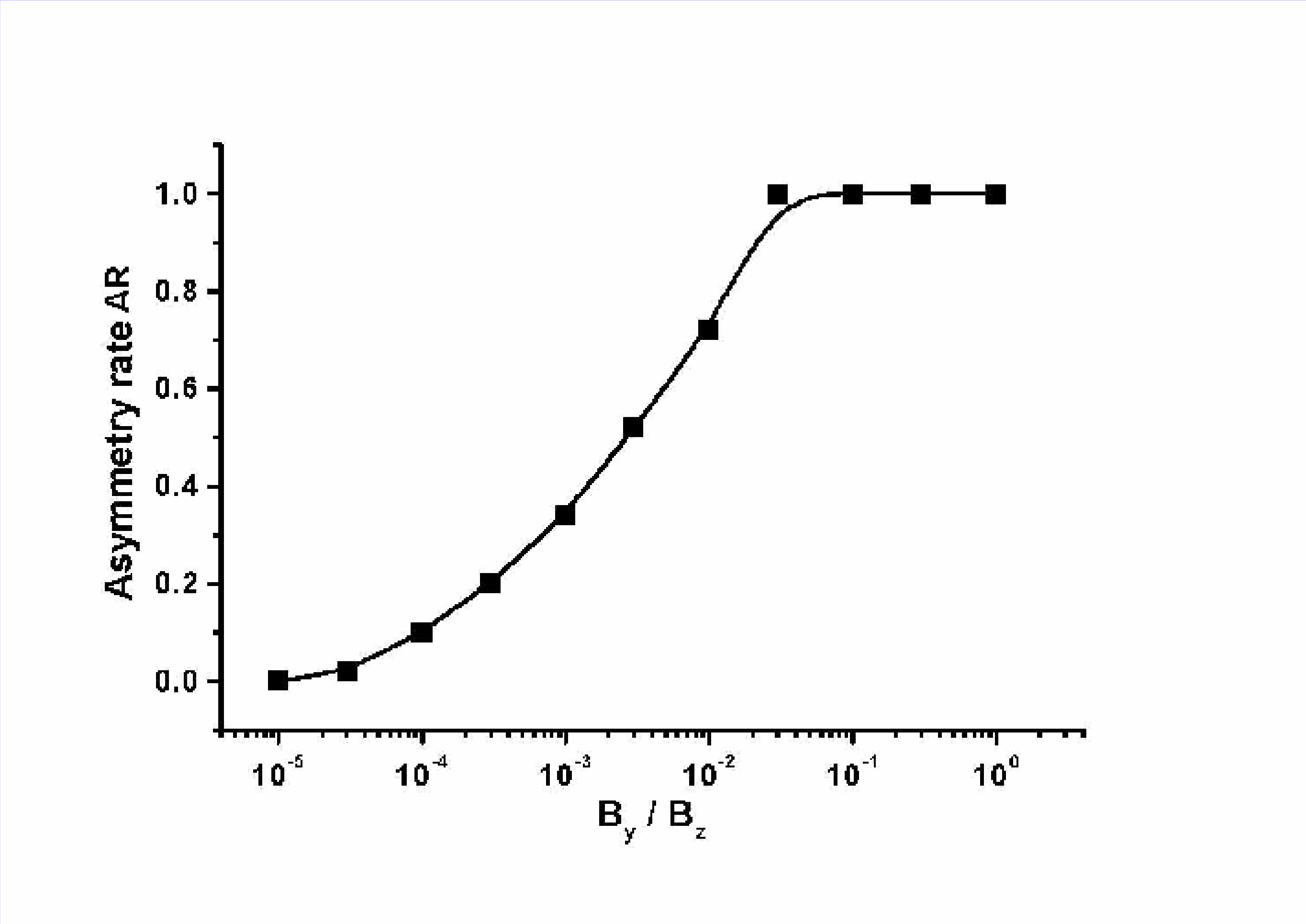
Electron trajectories (ApJ 2004



Asymmetry rate (ApJ 2004)

AR= $[N_{p+} - N_{p-}) - (N_{e+} - N_{e-})\ ]/$

$[N_{p+} - N_{p-}) + (N_{\ +} \ - N_{e-})]$



Analysis of the particle motion: acceleration time and path (Speiser, 1965; Martens and Young, 1990)

- Assuming that the particle is accelerated during about a period of its gyration around perpendicular component of magnetic field the acceleration time can be estimated as follows:

$$t = 2\pi\, m/q\, B_x^{-1} \quad (s)$$

- Then the acceleration path (here y_{ej}-y_{inj}) can be estimated as

$$p = 2\pi^2\, m/q\, E_y\, B_x^{-2} \quad (m)$$

Analysis of particle motion: energies

(Speiser, 1965, MY90)

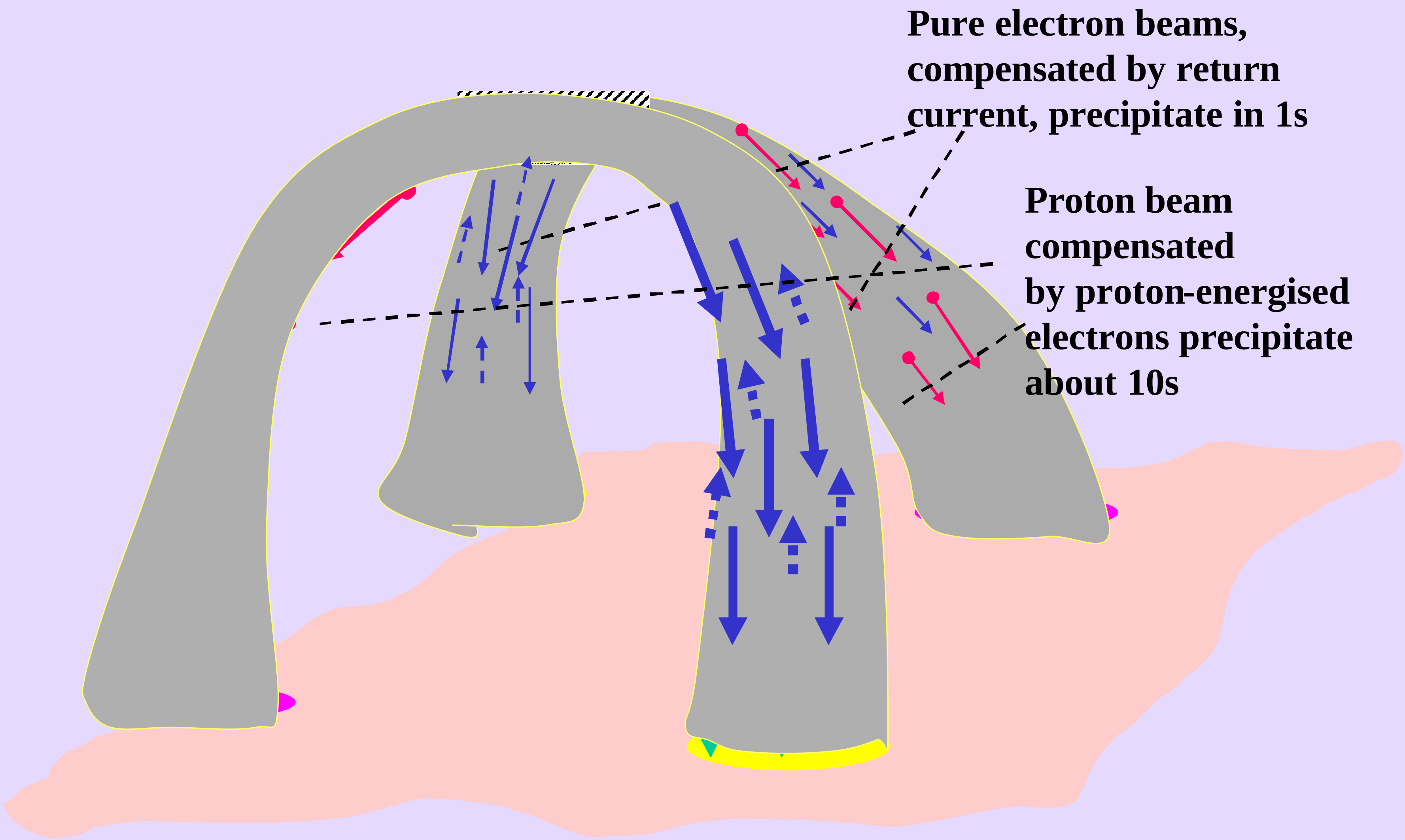
- Assuming that acceleration time and path to follow the formula above, the energy of accelerated particle can be estimated as:

$$e = \pi^2/2\ m/q\ E_y^{\,2}\ B_x^{\,-2}$$

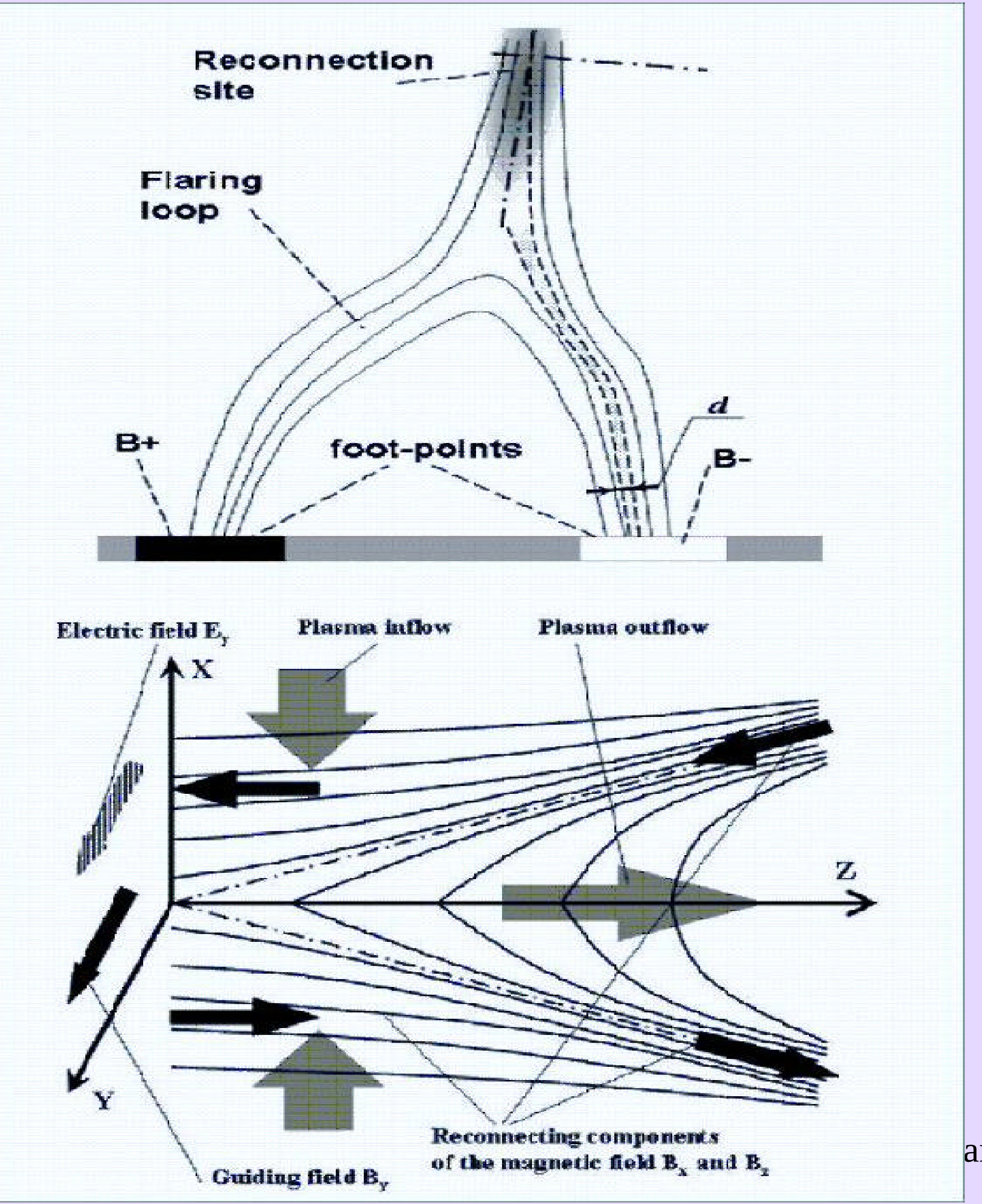
- Estimations of acceleration time and energy at ejection for protons and electrons are summarised in the table:

	t , s	**e, eV**
p^+	$6.3\ 10^{-4}$	$5\ 10^4$
e^-	$3.5\ 10^{-7}$	$\sim 10^2$

The suggested scheme of proton/electron acceleration and precipitation



Magnetic field topology - Case 2, By =const



(Zharkova&Gordovskyy, MNRAS, 2005)

$B_z = B_0 \tanh(-x/d)$

$B_x = B_0 (z/a)^a$

$B_y = +/- By_0 = 0.0001Tl$

$B_0 = 0.01Tl$

$E_{y0} = B_0 V_{inflow} - 1/\sigma\mu \, dB_z/dx$

$V_{inflow} \approx 0.01 \, V_{alfven} \approx 10^4 m/s$

$E_{y0} = 100V/m$

Table 2: Comparison of the acceleration times, energies and velocities found from the estimations and simulations

	Accel. time		Energy		V_x
	estimated	simulation	formula (10)	simulation	
	RCS thickness d = 10 m				
protons	6.3×10^{-4}	10^{-4} - 10^{-3}	5×10^5	1×10^5	4.5×10^6
electrons	3.5×10^{-7}	10^{-5} - 10^{-4}	$\sim 10^2$	3×10^4	7×10^7
	RCS thickness d = 100 m				
protons	6.3×10^{-4}	10^{-4} - 10^{-3}	5×10^5	2×10^5	6.2×10^6
electrons	3.5×10^{-7}	10^{-5} - 10^{-4}	$\sim 10^2$	5×10^4	9×10^7

Zharkova and Gordovskyy, ApJ 2004

Electron/proton motion in an RCS

Zh& G, MNRAS, 2005

$B = 10^{-4}$ T

	Gyroradius (m)	Gyroperiod (s)
e = 100 eV	0.33/14	$3.6 \times 10^{-5}/6.5 \times 10^{-2}$
e = 10 keV	$3.3/1.4 \times 10^{2}$	$3.6 \times 10\text{-}5/6.5 \times 10^{-2}$

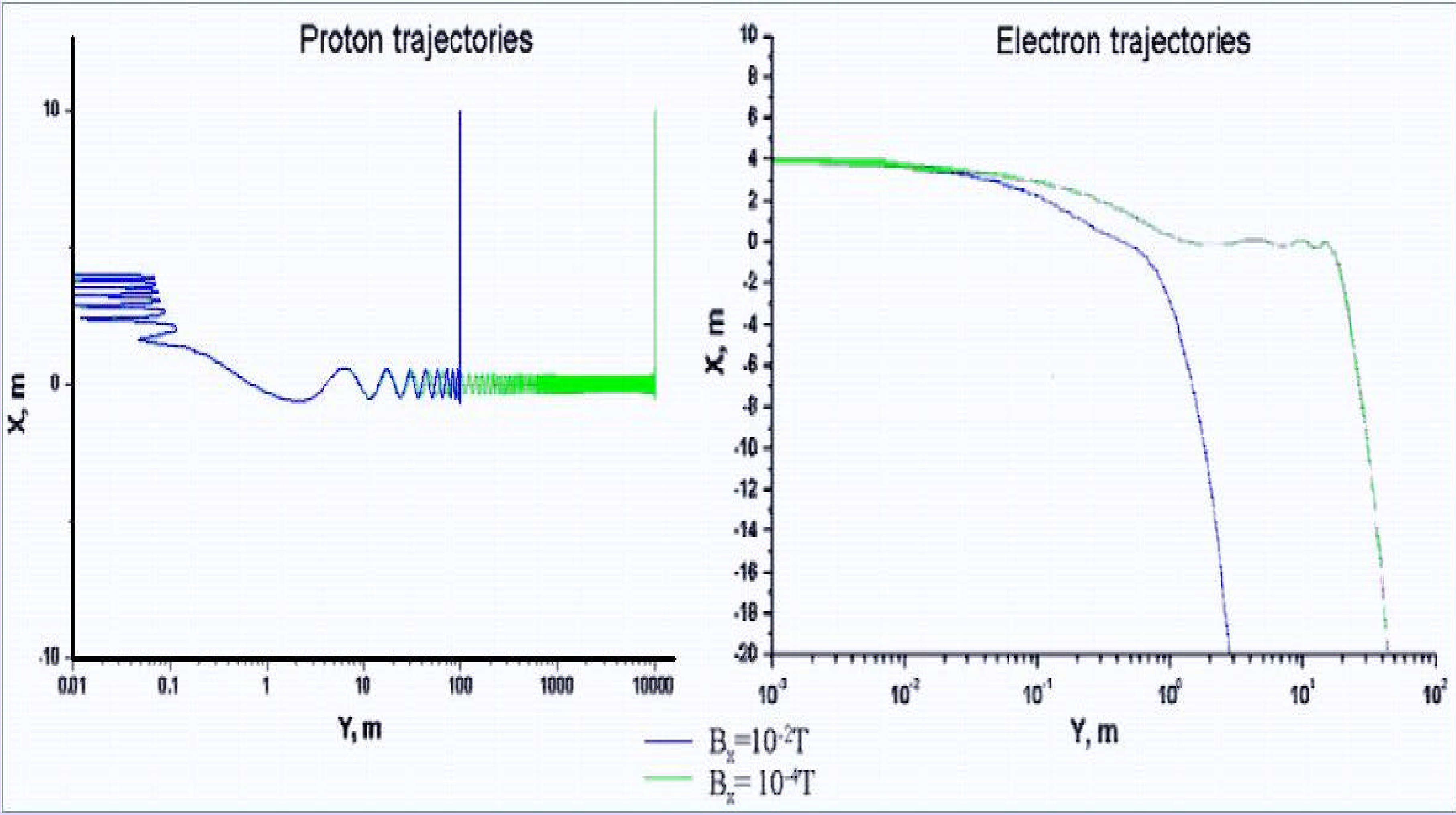
$B = 10^{-2}$ T

	Gyroradius (m)	Gyroperiod (s)
e = 100 eV	$3.3 \times 10^{-3}/0.14$	$3.6 \times 10^{-7}/6.5 \times 10^{-4}$
e = 10 eV	$3.3 \times 10^{-2}/1.4$	$3.6 \times 10^{-7}/6.5 \times 10\text{-}4$

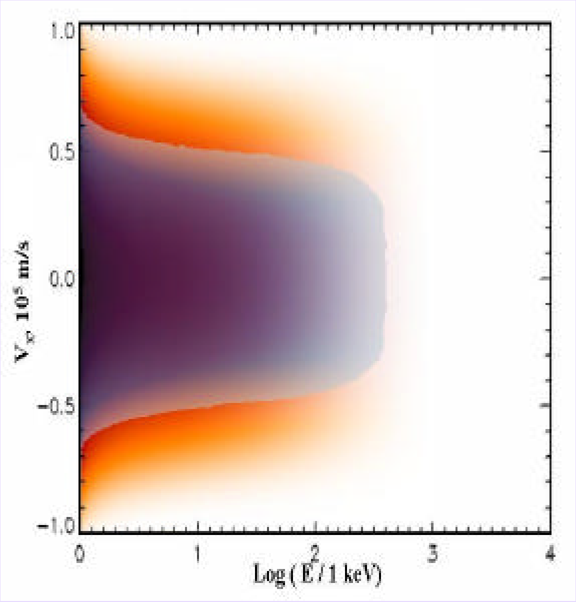
Particle trajectories – case 2 ($E \sim B_x^{-2} \sim z^{-2}$)

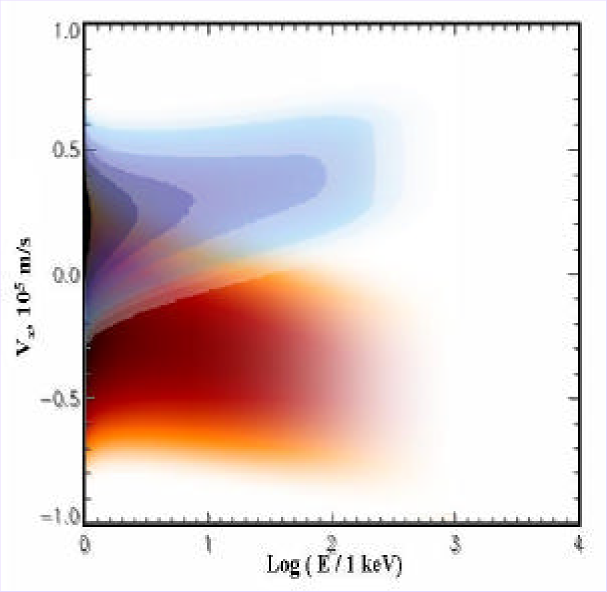
blue – RCS edge, green – close to X-point

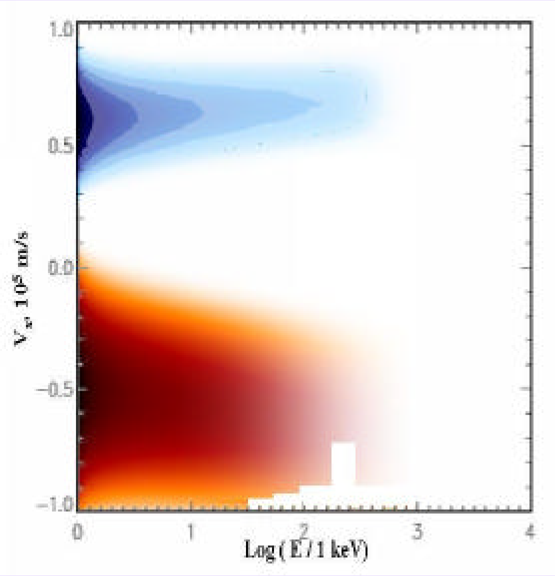
Zh& G, MNRAS, 2005



Particle velocity spectra at ejection protons (blue) and electrons (brown) Zh& G, MNRAS, 2005







Neutralised beams, AR$<10^{-4}$

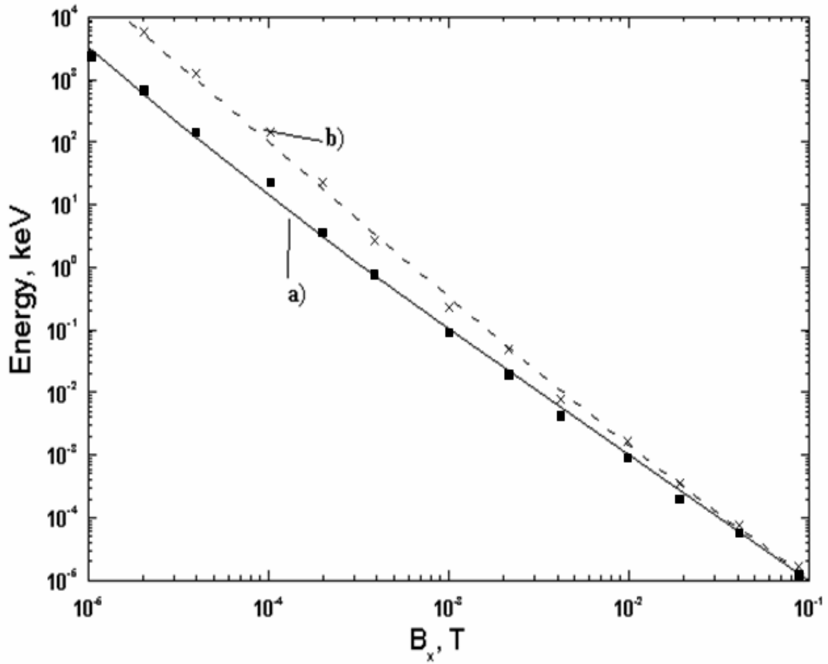
Partially separated beams

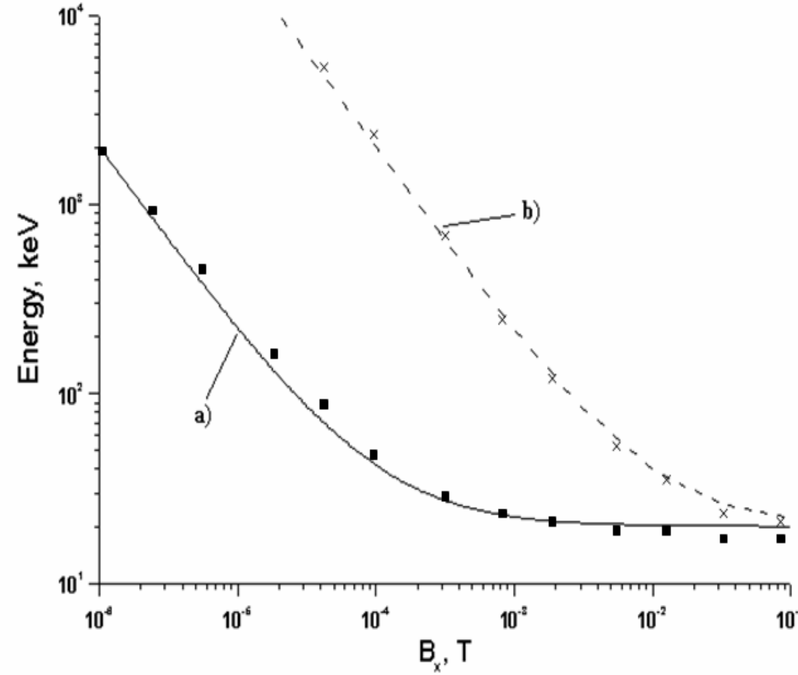
Fully separated beams, **AR$>10^{-2}$**

Energy spectra: p (left) and e (right)

$B_y=10^{-4}$T (solid) *vs* $B_y=10^{-2}$T (dashed)

Zh& G, MNRAS, 2005





$e_p \sim C\, E_y^2 / B_x^2\, (1 + By/B_0)^{1/2}$

$E^p_{low} \sim E_y^2/B_0^2\ \ (1 + B_y/B_0)^{1/2}$

$e_e \sim C_1\, E_y\, (\, 1 + B_y^2/B_x^2\,)^{1/2}$

$E^e_{low} \sim A\, E_y\ \ \ (1 + B_y/B_0)^2)^{1/2}$

Particle energy spectra from an RCS with density variations **Zh& G, MNRAS, 2005**

$$dN/d\,e = \frac{dN(z)/dz}{d\,e[Bx\,(z),\,By\,,\,Ey\,]/dz}$$

For a constant density:

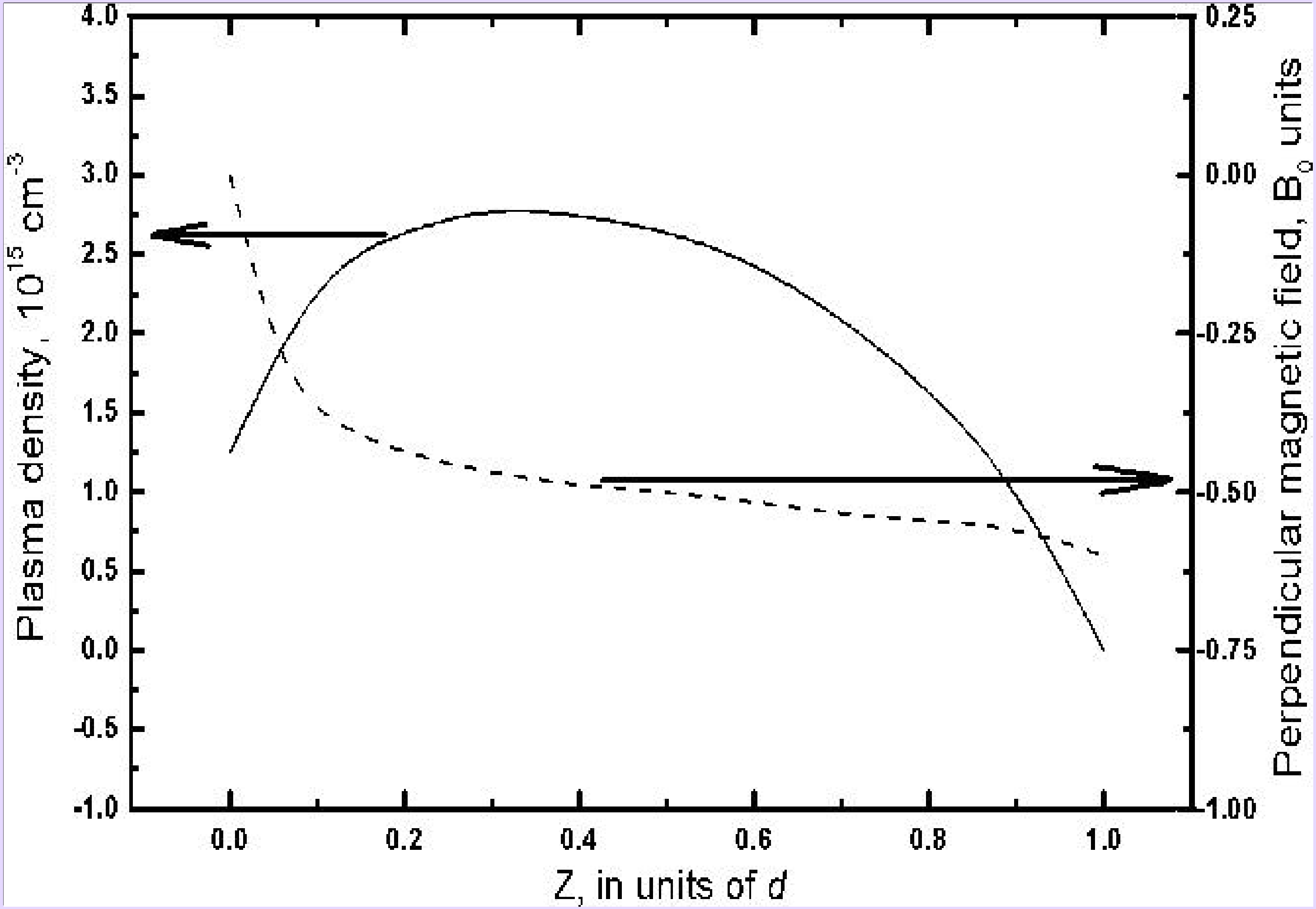
$$\mathbf{dN/d\,e \sim A\,e^{-1.5}}$$ ***protons***

$$\mathbf{dN/d\,e \sim B\,e^{-2.0}}$$ ***electrons***

Let us consider the RCS density

$$N=N_0\,(z/a)^L\,\exp(-Lz/a)$$

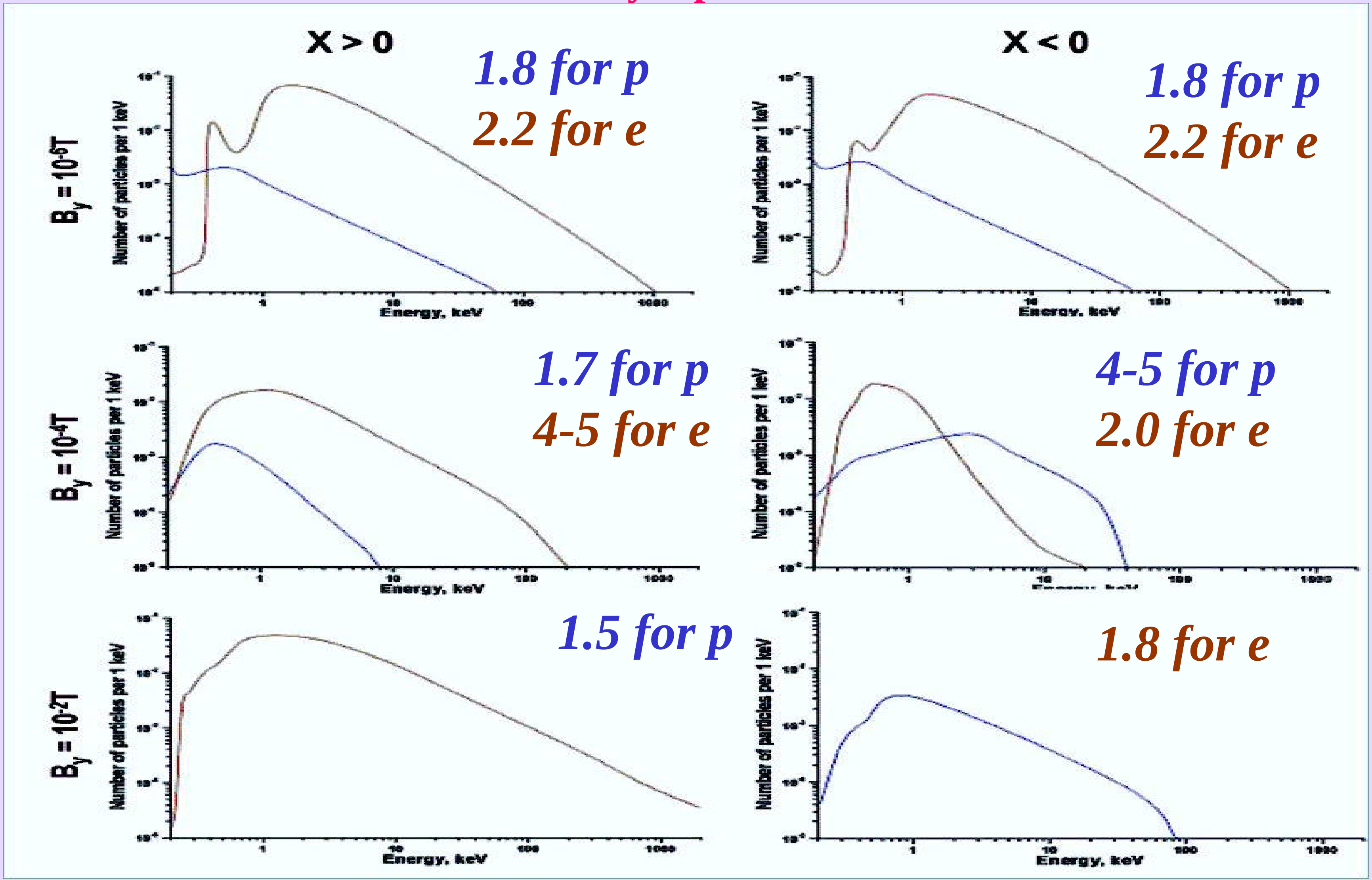
Model RCS
magnetic field B_x and density
(MHD simulations by Oreshina and Somov, 2000):



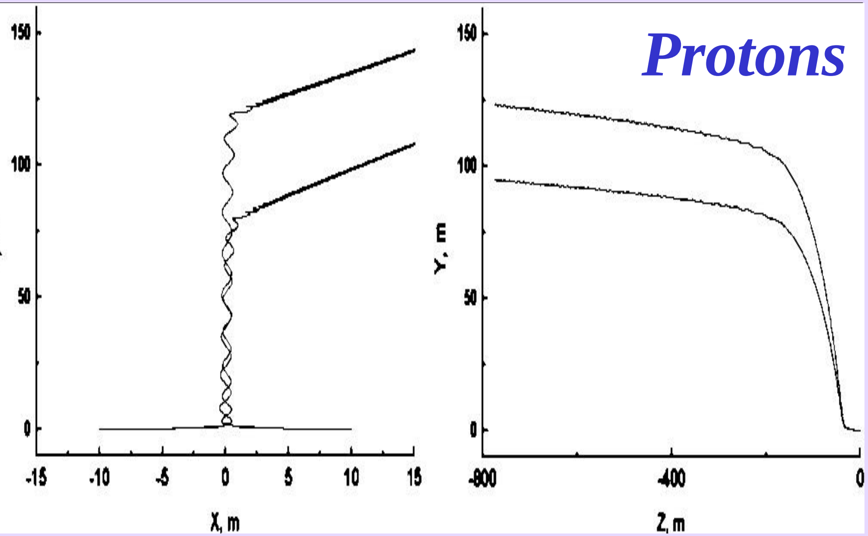
Energy spectra $B_x = B_0(z/a)$ (L=1):

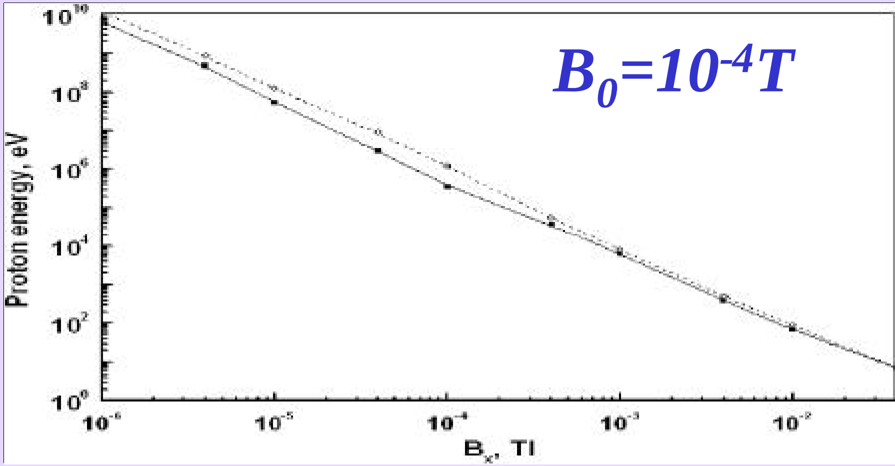
e (blue) and p (black)

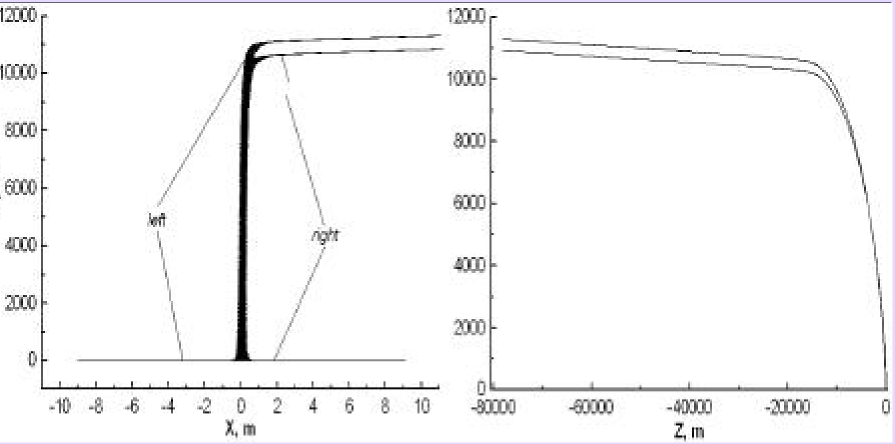
upper panel – neutral, middle – semi-neutral, lower – fully separated beams

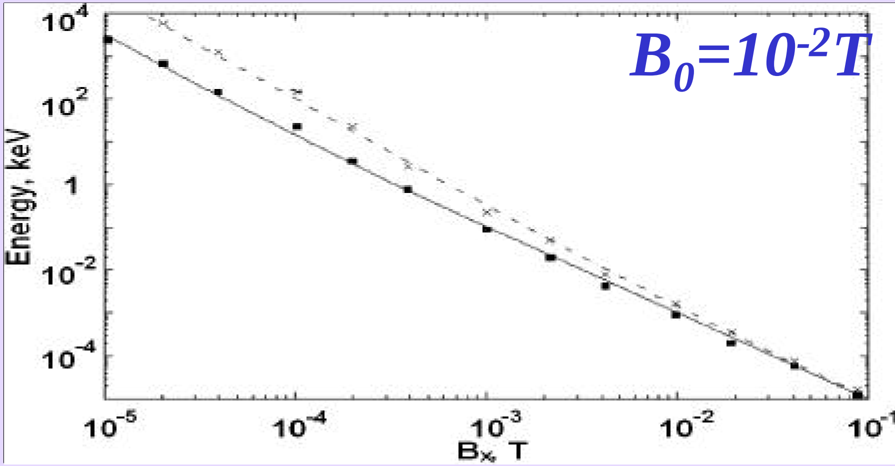


Case 3: Role of the transversal component $B_x=B_0\,(z/a)^{\alpha}$ **for L=1**: - Zh&G, Space SciRev, 2006

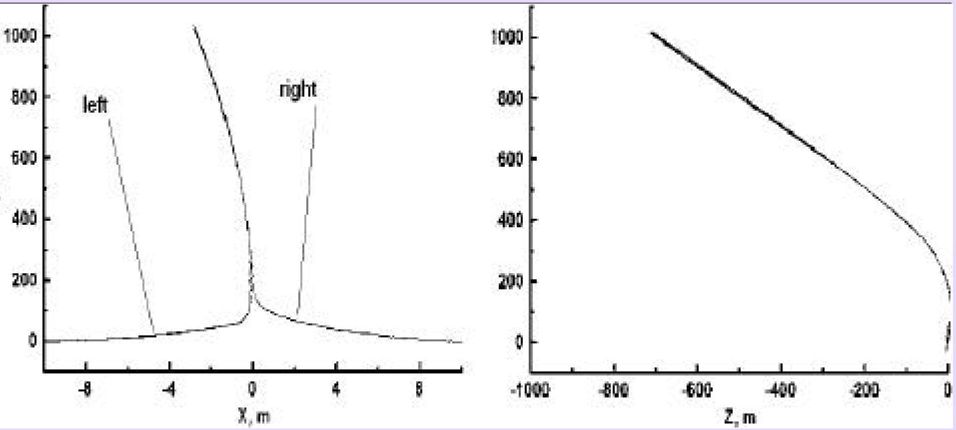


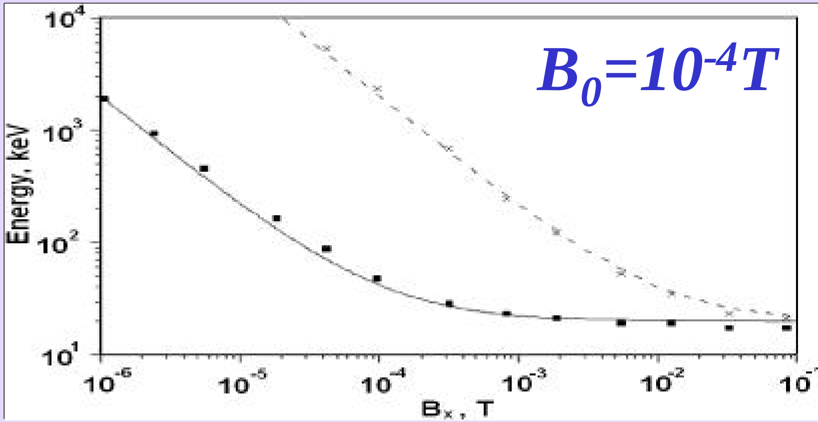


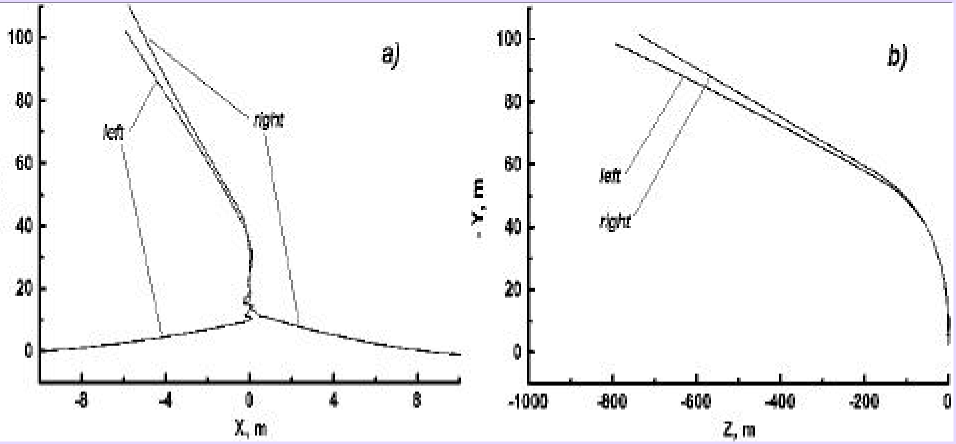




Role of the transversal component (L=1): $B_x=B_0\,(z/a)^{\alpha}$ - electrons







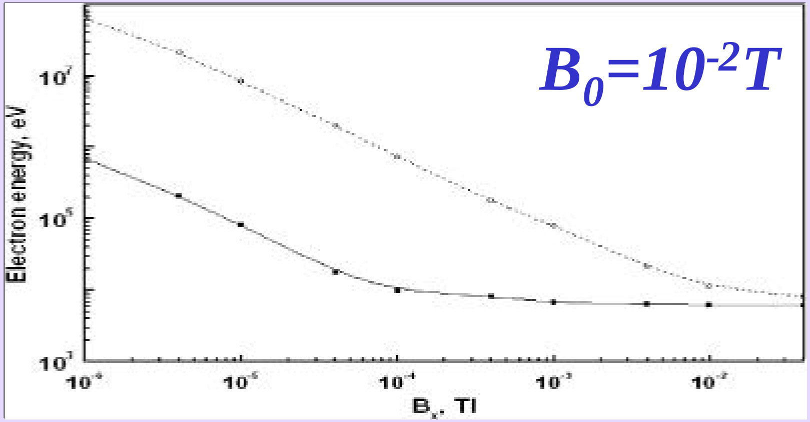


Table II. The spectral indices γ of proton beams calculated for different exponential indices α and λ of the B_x and density variations with z.

	λ				
α	0	1/2	1	2	3
0.5	2	2.5	3	4	5
1	1.5	1.75	2	2.5	3
2	1.25	1.38	1.5	1.75	2
3	1.17	1.25	1.33	1.5	1.67

Table III. The spectral indices γ of electron beams calculated for different exponential indices α and λ of the B_x and density variations with z.

	λ				
α	0	1/2	1	2	3
0.5	3	4	5	7	9
1	2	2.5	3	4	5
2	1.5	1.75	2	2.5	3
3	1.33	1.5	1.67	2	2.33

$$\gamma = \frac{1}{2}\left(1 + \frac{1+\lambda}{\alpha}\right) = \gamma_1 + \frac{\lambda}{2\alpha}. \tag{27}$$

The electron spectral indices γ calculated for various α and λ are presented in Table III.

The resulting spectral index for electrons is directly proportional to λ (the density index) and reversely proportional to α (the B_x index) for a weak guiding field and to the doubled α for the strong field. In general, the spectral indices γ for electron and proton beams are strongly increased with the increase of the index λ of density variations in a vicinity of the X-nullpoint. The increase of the index α leads to a decrease of the resulting spectral index γ if $\alpha \succeq 1$ and an increase of γ if $0 < \alpha < 1$.

Zh& G, SpSciRev, 2006

Electron spectral indices G dependence on α and L

Electrons

$G = 1 + L/(2\alpha)$ – strong guiding field ($ß > 10^{-2}$)

$G = ½(1 + L/\alpha)$ – weak guiding field ($ß < 10^{-2}$)

Protons

$G = 1 + L/(2\alpha)$ – any guiding field

Conclusions

- **Electrons and protons accelerated in a non-neutral RCS with weak longitudinal and transversal components of magnetic field are ejected separately into different halves from Bx=0 depending on the By sign.**
- **Particles can be accelerated to very high energies (MeVs for electrons, GeV for protons).**
- **Particles leave a model RCS with power law energy spectra with the indices**
  - G= 1+ L /(2 α) **(protons and electrons in strong guiding field)**
  - G= ½(1+ L /α) **(electrons in moderate and weak GF).**
  - **Indices can vary from 1.2 to 9 for some combinations of** L and α

- **The indices and lower energy cutoffs are dependent on the electric and magnetic field components and can be increased by 2-4 for another models.**
- **This opens new perspectives for magnetic field diagnostics in solar flares and geomagnetic tail from hard X-ray and** G-ray **spectral indices**