Energy Transformations in Z-Pinches

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Introduction

In magnetic pinches there are **two principal problems**: limitation of **instabilities** and a way of generation of **high energy particles** and **radiation**.

The first problem is solved by fast increase of the current, by high cylindrical symmetry of the load and plasma, by high density of the plasma or by present of the high magnetic field which magnetized charged particles.

Generation of high energy particles and radiation is usually explored by transformations of mechanic into thermal energy with **passive role of magnetic field** with partial success only.

In this presentation some remarks are discussed to the **active** role of magnetic field at energy transformations.

Transformation of kinetic energy into radiation

Main part of energy at the pinch phase is released as the black-body radiation at equilibrium conditions.

The energetic transformations are usually presented as a chain:

magnetic energy → kinetic energy → heating of the pinched plasma → radiation

Bennett equation:

$$I^2 \approx 3.2\times10^{10} NT$$

[A, cm^{-1}, eV]

radiated power:

$$P = (1-\alpha) A \sigma T^4.$$

On this scenario is based fusion concept of indirect drive at z-pinch devices at USA and Russia.

Generation of high energy particles and radiation

Only a few percentage of particles take part at a non-thermal processes.

Ions – three possible mechanisms for acceleration:

direct acceleration due to generation of a high inductive voltage during current breakdown after formation of the neck (qualitative picture Trubnikov 1986 on the base of diameter decrease)

mechanism related to compressional heating in the neck releasing by ejection of hot plasma from its ends (described by Vikhrev 1986 on the base of Bennett equilibrium).

the stochastic acceleration of the tails of the ion distribution function due to microturbulence in a plasma with relatively low density

Electron beams

Formation of electron beams is strongly suppressed by the presence of the transversal magnetic field in the pinch.

Electrons can be accelerated by runaway process if they have high enough initial energy. But only a small fraction of the electrons can be involved in a runaway process.

High energy X-ray are generated by high energy electron beams.

High energy particles can be strongly affected by the presence of axial magnetic field - on one side limitation of necking and on the other side broadening the zone of particle acceleration.

Z-pinch at high plasma density of thick fibers

For study of fast non-thermal phenomena the experiments at the high plasma density have been performed – they depressed development of **instabilities** and their **temporal evolution** is of the slower scale.

Experiments with C, Al, Cu fibers of diameter 100-300 μm.

Devices – CTU Prague (30 kA), PF 1000 (1.5 MA) at IPPLM in Warsaw, S-300 (3 MA) at Kurchatov Institute in Moscow.

Axial magnetic field generation - experiments

Observation of **helical structures** → existence of axial magnetic field → spontaneous self-generation of **axial magnetic field** during implosion or explosion of the plasma (IPP AS Prague, FEE CVUT in Prague, S-300 Moscow, PF-1000 Warsaw). Helical form is unstable, expansion is dominating.

Observation of relative **long living pinch phase** (PF-1000 Warsaw, S-300 Moscow) → **magnetic confinement** → energy in compressed axial magnetic field.

Observation of t**ime delay** between formation of the pinch phase and release of the high energy photons a few 10th ns (PF-1000) → conservation of energy → **magnetic confinement** with compressed axial magnetic field before and after photon pulse.

Expansion behavior of the helical form

A dynamic behavior of the helical formations can be roughly estimate from a ratio of imploding pressure of azimuthal magnetic field B_φ and expanding pressure of axial magnetic field B_z. We will suppose a simple model for current distribution in helical formations as a thin cylindrical layer with diameter of $2r$ and helical curve of current lines with the deviate angle between z axis and helical curve of α. Then the azimuthal and the axial currents:

$$I_\varphi = I \sin \alpha \qquad (1)$$

$$I_z = I \cos \alpha . \qquad (2)$$

Both current components are imagined in Fig.

For azimuthal and axial magnetic field value the simple formulas can be used:

$$B_\varphi = \frac{\mu I \cos\alpha}{2\pi r}, B_z = \frac{\mu I \sin\alpha}{2r}$$

The ratio of the imploding and expanding pressure can be written as

$$\frac{B_\varphi^2}{B_z^2} = \frac{\cos^2\alpha}{\pi^2 \sin^2\alpha} \approx 0.3$$

These estimations implicate a dominating role of expansion in the helical form. The existence of relative stable helical formations then should be conditioned by an addition compression of the upper corona layers. Upper layer of the corona with cylindrical symmetry the ring-shape necks plays probably the role of addition compression. In the case, when this rings are the loops of the induced azimuthal current of opposite orientation (- I_φ in Fig.) to the internal helical form, the total axial magnetic field inside the loop is zero. An expansion pressure of the magnetic field is vanishing during the time of diffusion and penetration of opposite magnetic fields of both currents I_φ and - I_φ . This process enables the pinching of the rings and emission of the high energy photons.

Generation of the opposite current loops is not clear. Probably they could be formed by radial plasma streams flowing from the corona, which are partially caught and reversed to the rings by the outer magnetic field, in which orientation of B_z component is opposite to the internal component of the helical formation due to the closed magnetic lines. We can estimate the induced voltage U:

$$U = \frac{\Delta B}{\Delta t}\pi r^2 \approx \frac{100}{10^{-8}}\pi\left(5\times10^{-3}\right)^2 \approx 8[kV].$$

Scenario of generation of high energy particles and photons

Non-thermal radiation is emitted from high energy ions (PF-1000 Warsaw, S-300 Moscow) → temporal correlation between acceleration of electrons and ions → the some high electric field / generation of high Z-ions due to overcharging.

→ **mechanism of high energy particles and photons generation can be based on the fast transformations of magnetic field and induction of electric field**

In some **time integrated** filtered pinhole camera images we can see **helical structure as a source of high energy photons** (PF-1000 Warsaw, S-300 Moscow) → transformation of magnetic field inside the helical structure.

If it is accepted as accelerating mechanism the magnetic field transformation, than it must be the internal transformation inside of helical form.

Summary

During implosion and explosion of the plasma the spontaneous axial magnetic field is generated in the corona of thick fibers.

Kinetic energy transforms into energy of compressed axial magnetic field with helical configuration.

Mechanism of generation of high energy particles and photons can be based on the fast transformation and release of magnetic field which induce high electric field.

Generation of axial magnetic field in Z-pinch devices is in analogy with magnetic dynamo in stars and planets.

Hypothesis: Fast transformation of magnetic fields producing high energy particles and photons may aspects of polarity variation in stars and planets.

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