Transformation of the plasma column during neutron production in plasma focus discharge

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Active study of plasma column during HXR and neutron production in CTU Prague 2012 -2013

Transformation of the pinch structure during acceleration of the deutron beams on PF-1000 in IPPLM Warsaw

Influence of the applied magnetic field on the pinch dynamic and neutron emission on PF-1000 in IPPLM Warsaw and on PFZ-200 in CTU Prague

Study of implosion of deuterium with heavier gases and generation of the MeV electron and ion beams on GIT-12

Study of the fusion neutrons on the laser system PALS and tokamak COMPASS in Prague
Plasma source 1: PF-1000 IPPLM Warsaw, Poland
Laboratory of International Centre for Magnetized Plasma
23 kV, 2 MA, 350 kJ, D-D reaction, D\textsubscript{2} gas
neutron yield 10\textsuperscript{10}-10\textsuperscript{12},

Source of deuteron beams
Ed ~20 – 300 keV
Nd ~10\textsuperscript{17} per pulse
Energy a few kJ in pulse

Neutron diagnostics

scintillator BC-408 + photomultiplier Hamamatsu

registration outside the chamber
HXRs – product of fast electrons, neutrons – product of fast deuterons
velocity of neutrons with energy 2.45 MeV ..... 2.16 cm/ns
Signals of HXRs and neutrons

detectors in 7 m distance
50 – 70 ns

1. neutron pulse
   smaller anisotropy

2. neutron pulse
   higher anisotropy

energy distribution
Scenario of neutron production in PF

Dominant beam-target mechanism downstream

beam of fast deuterons:
1-10 keV → heat the plasma, $T_i$ above 1 keV due to Coulomb interaction
10-300 keV → neutrons with probability $10^{-6}$

Scenario of neutron production in PF

Dominant beam-target mechanism downstream

fusion neutrons
2-3 MeV

2 MeV

3 MeV

2.45 MeV

anode face
Interferometry – PF-1000

16 pictures in one shot (Dr. M. Paduch, E. Zielinska)
evolution of the plasma column during HXR and neutron emission

system of 52 mirrors and prisms
0, 10, 30, 40, 60, 70, 90, 100, 120, 130, 150, 160, 180, 190, 210, 220 ns
Different structures in the pinched column

cathode disc

dense plasma column

shot 9209_+91 ns
3 cm
anode face

shot 9181_-21 ns

shot 9181_+99 ns

plasmoids
constriction
lobules – part of toroidal tubes prolapsed through the surface
helical tubes - coalescence of axial and toroidal I living 120 ns

⇒ Existence of toroidal currents and poloidal magnetic fields
Correlation of interferometry and neutron diagnostics

1st HXR and neutron pulse

Instant and region of HXRs; 5-20 ns time delay of maximum neutrons after HXRs

Region of neutron production
- Mean density $3 \times 10^{24} \text{m}^{-3}$
- Dimension $\sim 2 \text{ cm}$

2 steps:
- Transport of the plasma from boundary to the axis
- Formation of the plasmoid and its transport downstream
2nd HXR and neutron pulse

Shot 8406, NY: $9 \times 10^{10}$

1. evolution of $m=0$ instability
2. formation of the plasmoid in the constriction
3. radial jets of the plasma from the constriction and formation of plasmoids in the neighbouring column
3. explosion of the rests of the constriction and plasmoids
Existence of closed toroidal currents and their poloidal magnetic field?

The toroidal currents with poloidal magnetic field are self-generated during evolution of the pinch (magnetic dynamo)?

Conditions for generation:

transport of the plasma through magnetic field inhomogeneities in densities, velocities and magnetic fields, ⇒ turbulences ⇒ toroids, plasmoids

Experimental evidence by magnetic probes at PF-1000:
Conclusions following from results obtained from B probes

1. Bz exists in front and in imploding current sheath

2. Bz onset correlates with formation of toroidal and plasmoidal structures and Bz decrease correlates with decay of constrictions and plasmoids

3. Values of Bz in the toroids and plasmoidal structures reach 6-8 T; 10-30% of Bφ.

4. Neutron production correlates with changes of Bz

5. In z-pinch column exist the closed currents

6. Bz is component of poloidal magnetic field

7. Neutron production correlates with transformation of magnetic lines

Results were published:

It is possible to describe an evolution of magnetic field in PF?
Conclusion from interferometry and neutron diagnostics on PF-1000
Possible scenario of magnetic field evolution in the plasma column

Dense magnetized plasma is example of magnetic confinement in which poloidal magnetic field is self-generated and plays important role in its dynamic.

Acceleration of fast electrons and ions correlates with transformation and decay of internal magnetic fields.

The energy of produced fast particles increases with velocity of transformations of internal structures and with velocity of decay of magnetic fields.

Possible scenario of magnetic field evolution

- Dense plasma layer
- Current sheath
- Toroid
- Toroidal disk
- Plasma jet
- Layer of azimuthal current
- Implosion of current sheath
- Formation of toroids
- Formation of toroidal disk
- Formation of plasmoids
- Opposite currents
- Stagnation after 1. neutrons
- Evolution of instabilities
- Disintegration of constriction and plasmoid
- Constriction
- Opposite currents

1NP
2NP
1. Existence of toroidal current during plasma implosion

\[ B_\phi \text{ and } B_z \Rightarrow \text{helical current; } I_\phi \approx 20-30\% I_z, \text{ sign of } B_z \]

\[ \text{Azimuthal current } I_\phi \approx 1\% I_z, \text{ sign of } B_z \]
2. Tearing of toroidal current into a few toroids

1. Tearing of the azimuthal current into toroidal loops $I_t$
2. Stable toroidal current stabilized with discharged current $\Rightarrow$ helical form $\Rightarrow$ existence of poloidal component $I_p$ $\Rightarrow$
3. Opposite $-I_p$ to $I_z$ in axis
4. Existence of point $B_\phi = 0$
5. Toroidal current depresses implosion
6. Higher pressure near anode inject the plasma in the center of toroid
3. Transformation of toroid into toroidal disk

1. Jet of plasma into helical B
2. Increase of plasma density in toroidal centre
3. Increase of the poloidal current $I_p$ due to $\alpha$ effect
4. Existence of both closed currents $I_t$ and $I_p$
4. Transformation of toroidal disk into plasmoid

Start of 1. neutron pulse

1. Spontaneous transformation of poloidal and toroidal I and B.
2. Formation of the plasmoidal structure due to reconnection of magnetic lines.
3. Pumping of energy into plasmoid through turbulent structures
4. Formation of intense closed currents
5. Production of 1. neutron pulse
5. Decay of plasmoid and continuation of 1. neutron pulse

1. Decay of plasmoid and closed internal currents
2. Plasma column expands
3. Penetration of the discharge current into column
4. Stabilization of the column with azimuthal current
5. Orientation of Ip?
6. Start of instabilities
Formation of toroids and toroidal disks

1. Tearing of the layer $I_\phi$ into toroidal loops $I_t$
2. Stable toroidal current is stabilized with discharged current $\Rightarrow$ helical form $\Rightarrow$ increase of $I_p$
3. Opposite component of poloidal component of the current in axis
4. Existence of point $B_\phi = 0$
5. Toroidal current depresses implosion
6. Higher pressure in neck injects the plasma in the center of toroid

analog with plasma implosion
8. Formation of constrictions and plasmoids
Start of next neuron pulse

Jet of plasma into toroidal B
Increase of plasma density in toroidal centre
Existence of turbulence
Self-generation of the Ip due to $\alpha$ effect
Pinch in the axis region
Pumping of energy into plasmoid
9. Decay of constrictions and plasmoids
Production of next neuron pulses

1. Decay of closed currents and magnetic field
2. Production of neutrons due to reconnections and decay of magnetic lines
Possible scenario of pinch evolution

During pinch evolution the closed toroidal and poloidal currents and their B are generated in forms of toroidal and helical structures.

These structures are compressed with discharge pinching current.

The toroidal structures depress the implosion and plasma from neighborhood more compressed regions is injected into the center of toroids.

Plasma streams interact with Bp inside the toroids, are confined inside them and form toroidal disks. During this process the turbulent structures are produced and support dynamo effect.

The kinetic energy of plasma streams transforms into the magnetic energy in the toroidal disk and in the final phase in the plasmoid.

The neutrons are produced during formation and dis-integration of plasmoids and constrictions. The reconnection and decay of closed internal currents and their magnetic fields contribute to the deuteron acceleration.
Influence of the tungsten evaporated in anode on the pinch dynamic and on the neutron emission

Diagnostics:
- Multiframe interferometry, 16 figures, Δt=10, 20 ns
- Scintillation detectors 7m: 0°, 90°, 180°
- MCP filtered by polyster 10 μm,
- 4 PIN in positions 0-3, 1.5-4.5, 3-6,6-9 cm
- Filtered with beryl

[Diagram showing anode, cathode rods, and MCP view]

View of four X-ray PIN
Conclusions
from experiments with tungsten anode

a. 1% tungsten admixtures after 1. neutron pulse
b. neutron yield decreased to 40%
c. decrease of the mean energy of fast deuterons to 80% to 90 keV
d. reduction of the DD cross-section about 40%
e. lower velocity of transformations of the constrictions and the plasmoids enabled the more detail description of the plasma column evolution
f. Recombination radiation of tungsten makes possible its localization
Influence of applied magnetic field on pinch dynamic and neutron emission on PF-1000 in IPPLM Warsaw

PF-1000 (2 MA) 20-50 mT

Compression ratio 10x => Bz≈ 2-5 T
the same order as the Bz which is generated spontaneously
Without application of permanent magnets
Conclusions
which follows from application of magnetic field
on the pinch dynamic and neutron emission
on PF-1000 in IPPLM Warsaw

The magnetic field of permanent magnets of 40-70 mT was compressed 100 times
to the value of 4-7 T.

This value is comparable with the magnetic field registered by magnetic probes.

This magnetic field decreases the total neutron yield to 20-50%.

The smooth, symmetry and stability of the plasma focus was increased.

The life-time of internal structures - plasmoids, constrictions and toroids or helicals
was increased and velocity of transformations was depressed.

The magnetic field dissipates from the dense column after evolution of instabilities
after 150-200 ns.

The anisotropy of fast deuterons producing observed neutrons is higher, the side-
on component is depressed.
Conclusions
which follows from application of magnetic field and tungsten anode
on the pinch dynamic and neutron emission
on PF-1000 in IPPLM Warsaw

HXR and neutrons are produced in correlation with formation and decay of plasmoids and constrictions.

The plasmoid formation is possible to interpret by confinement of the plasma streams containing the current $I_z$ associated with $B_\phi$ with the $B_p$ field in toroidal or helical structures.

At this interaction, $B_\phi$ increases in the centre, as $B_t$. Both components relax to state of minimal energy, spheromak-like structure, plasmoid.

At the decay of the plasmoid, $B_t$ in the central region decays, the plasmoid expands due to released $B_p$.

During neutron production the reconnection of the magnetic lines occurs at the increase and decay of internal closed magnetic lines.

Energy necessary for acceleration of electron and ion beams is delivered (i) by kinetic energy of plasma beams injected to the plasmoid, which is partially transformed into magnetic energy of plasmoids and (ii) by decay of magnetic energy released at the expansion of the plasmoid and constriction.
Thank you for your attention
Publications 2012-2013


