2370-5

School and Training Course on Dense Magnetized Plasma as a Source of Ionizing Radiations, their Diagnostics and Applications

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Energetic ions in Dense Magnetized Plasma and the Fundamental Premise of Thermonuclear Fusion

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Plan of the Talk

- Part-I: Significance of energetic ions and the fundamental premise of thermonuclear fusion
- Part II: State of understanding in DMP
  - Review of experimental data
  - Review of theoretical Models
- Part III: Recent developments
  - Identifying missing pieces of the puzzle
  - Progress in theoretical status

Part-I:

Significance of Energetic Ions and the Fundamental Premise of Thermonuclear Fusion

Why do we wish to study physics of Dense Magnetized Plasmas?

- Fusion reactions are mankind's best hope for energy in the long term:
  - $d+T \rightarrow \alpha+n+17.59$ MeV ("beam-target fusion reaction")
  - "beam of deuterons" "incident on" "tritium target at rest" "produces" "one alpha particle" "and" "one neutron" "and energy release of 17.59 MeV"
- Dictionary meaning of "beam":
  - a narrow unidirectional flow of electromagnetic radiation or particles: *a beam of light* ; *an electron beam*

Beam-target fusion reactions

- A unidirectional linear beam interacting with a stationary (solid??) target is not good enough for utilizing fusion energy.
- For every ion that produces a fusion reaction, millions of ions just lose their energy in collisions, heating the target.
- Eventually energy lost in collisions will be more than fusion energy produced and the target would become too hot to handle: a big problem!
- Brilliant Idea!!: Turn the problem into a solution!!
  - Birth of the idea of thermonuclear fusion

Thermonuclear fusion

- The energy lost in collisions can be made available to other ions for making their own *repeated attempts at producing fusion* if the energetic ions are assembled together in a *hot* plasma: hence *Thermo*nuclear Fusion.

- Different methods of producing and maintaining the hot plasma constitute the discipline of Fusion Physics.

Fundamental Premise of Thermonuclear Fusion

- The discipline of Fusion Physics makes a hidden assumption:
  - A hot confined plasma having a Maxwellian velocity distribution (3D isotropic Gaussian with zero average velocity) ***is the only way*** that a population of energetic ions can be maintained in a manner which saves their energy for *repeated attempts at fusion*.
  - Anything different is not worth considering
- Experimental data about Dense Magnetized Plasmas presents a contrary picture

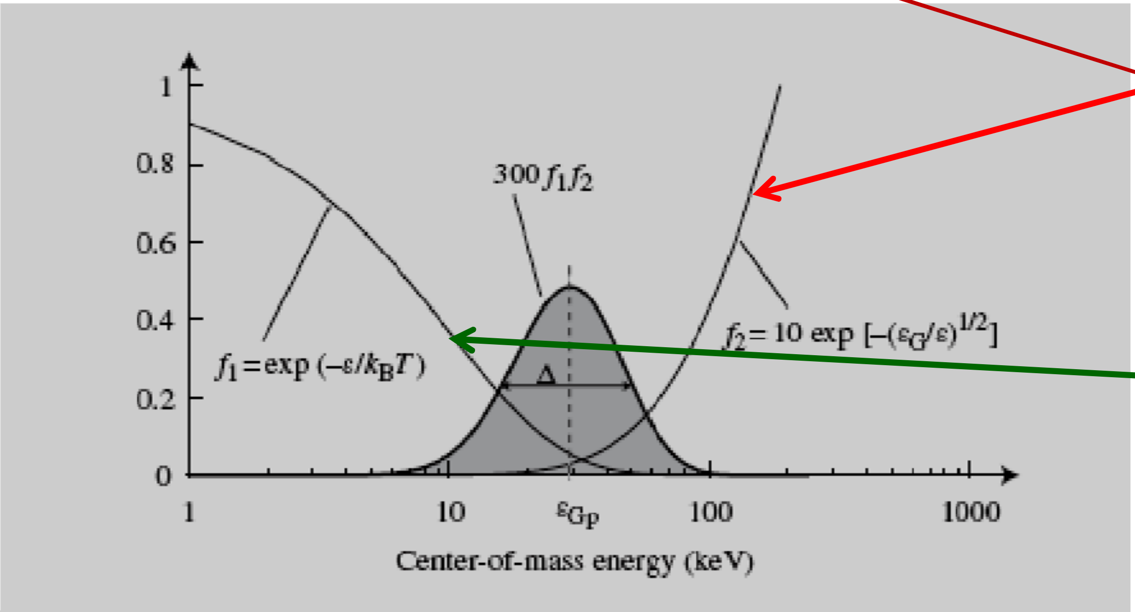
Maxwellian Velocity Distribution

- Statistical mechanics shows that collisions tend to relax an arbitrary velocity distribution with zero average velocity towards a Maxwellian velocity distribution (3D isotropic Gaussian with zero average velocity)
  - Requires “sufficient time” dependent on collision rate.
  - Collision rate depends on temperature and density
  - Is stable against inverse Landau damping.
  - Ions in the main body of distribution act as “moving target” for ions in the high energy “tail” of distribution.

Thermonuclear fusion

- Average reactivity for a thermonuclear plasma

$$\langle \sigma v \rangle = \iint d\vec{v}_1 d\vec{v}_2 \sigma_{1,2}\left(\left|\vec{v}_1 - \vec{v}_2\right|\right)\cdot\left|\vec{v}_1 - \vec{v}_2\right|\cdot f\left(\vec{v}_1\right)$$



Cross-section

Maxwellian velocity distribution

From http://fds.oup.com/www.oup.co.uk/pdf/0-19-856264-0.pdf

Energetic ions vs ion beams

- There is a tendency in literature to refer to fusion reactions from non-Maxwellian velocity distributions as “beam-target” (or “generalized beam-target”) fusion.
  - ***This is incorrect***:

- “beam” is a linear, unidirectional flow.
- Non-Maxwellian ion populations having a higher fraction of high energy ions as compared with a Maxwellian distribution with same average energy are more correctly called “energetic ions” rather than ion beams

Emitted ions vs confined ions

- Fast ions of fusion fuel *emerging* from the plasma can be analyzed using
  - Thomson parabola (Sadowski et al. Physics Lett A, 113, 1985 p. 25, Schneider, 1988, NSWC TR-88-394.)
  - Nuclear activation techniques (Gullickson and Sahlin, J. Appl. Phys. 49, 1978 p1099)
  - Nuclear track detectors (Kwiatkowski et. al. NUKLEONIKA 57 (2012) p67)
  - Faraday cups (Gerdin Styger & Venneri J. Appl. Phys. 52, 3269 (1981)
- Ions which *stay within the plasma* and generate fusion are analyzed using fusion products
  - Important for understanding some special features of Dense Magnetized Plasmas

Fusion neutron spectra as diagnostic tools

- The fusion reaction *rate* depends on the *relative velocity.* Fusion neutron *energy* depends on the *center-of mass energy*. Hence the fusion neutron spectrum is sensitive to the *velocity distribution* of the reacting ion populations.
- Width of neutron spectrum in DD thermonuclear fusion reaction depends on the temperature

$$E_n\left(\mathrm{keV}\right) \approx 82.5\sqrt{kT_D\left(\mathrm{keV}\right)} \qquad \text{(FWHM)}$$

- Anisotropy in neutron spectra implies non-Maxwellian velocity distribution

Significance of ion velocity distribution

- Ion velocity distribution contains information about fundamental plasma processes
  - Collisions tend to make it Maxwellian
  - Electric fields tend to accelerate ions causing spatial non-uniformity and anisotropy
  - Magnetic fields tend to keep them confined
  - Streaming (escape) causes loss of higher velocity ions
  - Random EM fields cause acceleration
  - Repeated collisions with a shock wave cause acceleration

Significance of ion velocity distribution

- Understanding the velocity distribution of energetic ions, which remain confined within the plasma and participate in the fusion reaction, opens a window looking at the fusion process.
- Can provide important information necessary for design and control of a fusion energy producing device.

Energetic Ions, enable us to look at the validity of Fundamental Premise of Thermonuclear Fusion

END OF Part-I:

Significance of Energetic Ions and the Fundamental Premise of Thermonuclear Fusion

Part II:

State of understanding in DMP

- Review of experimental data
- Review of theoretical Models

Q: Can a Maxwellian velocity distribution of ions explain fusion in Dense Magnetized Plasmas?

Comparison of actual neutron yields with thermal estimates for various ZPs

- From Coverdale et.al. PHYSICS OF PLASMAS 14, 056309 (2007)

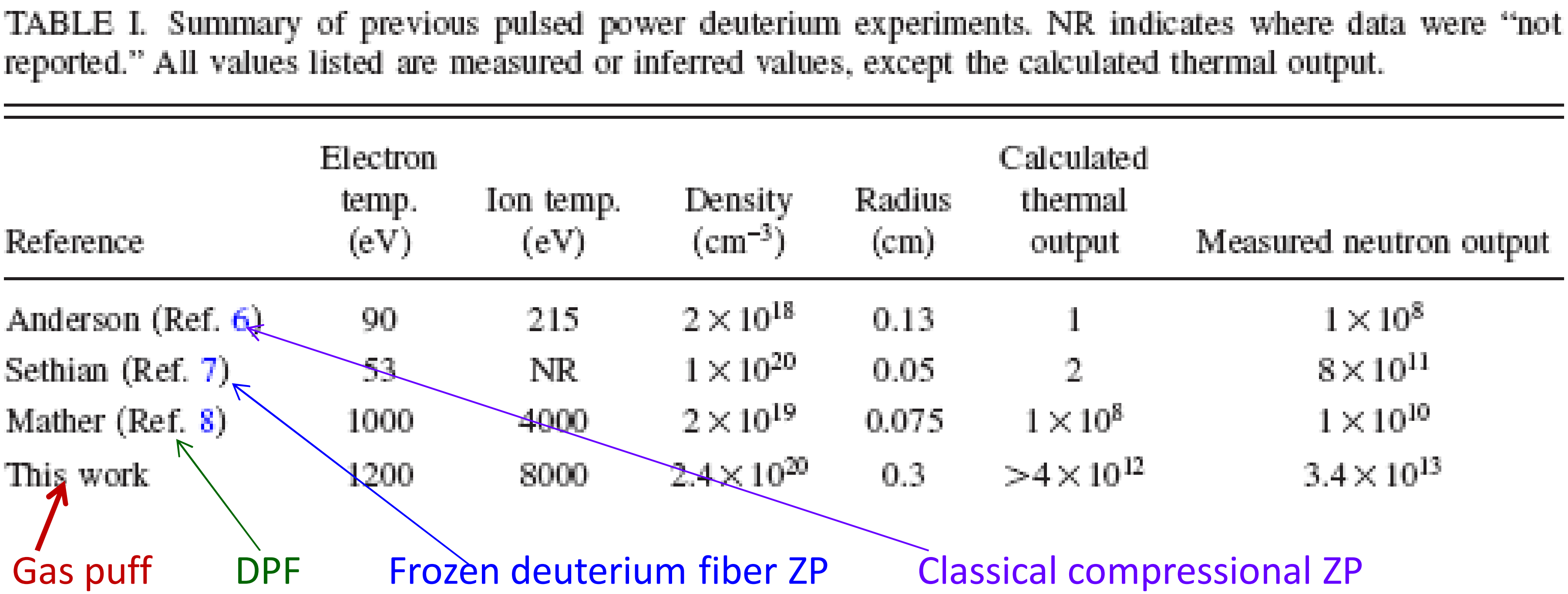


TABLE I. Summary of previous pulsed power deuterium experiments. NR indicates where data were "not reported." All values listed are measured or inferred values, except the calculated thermal output.

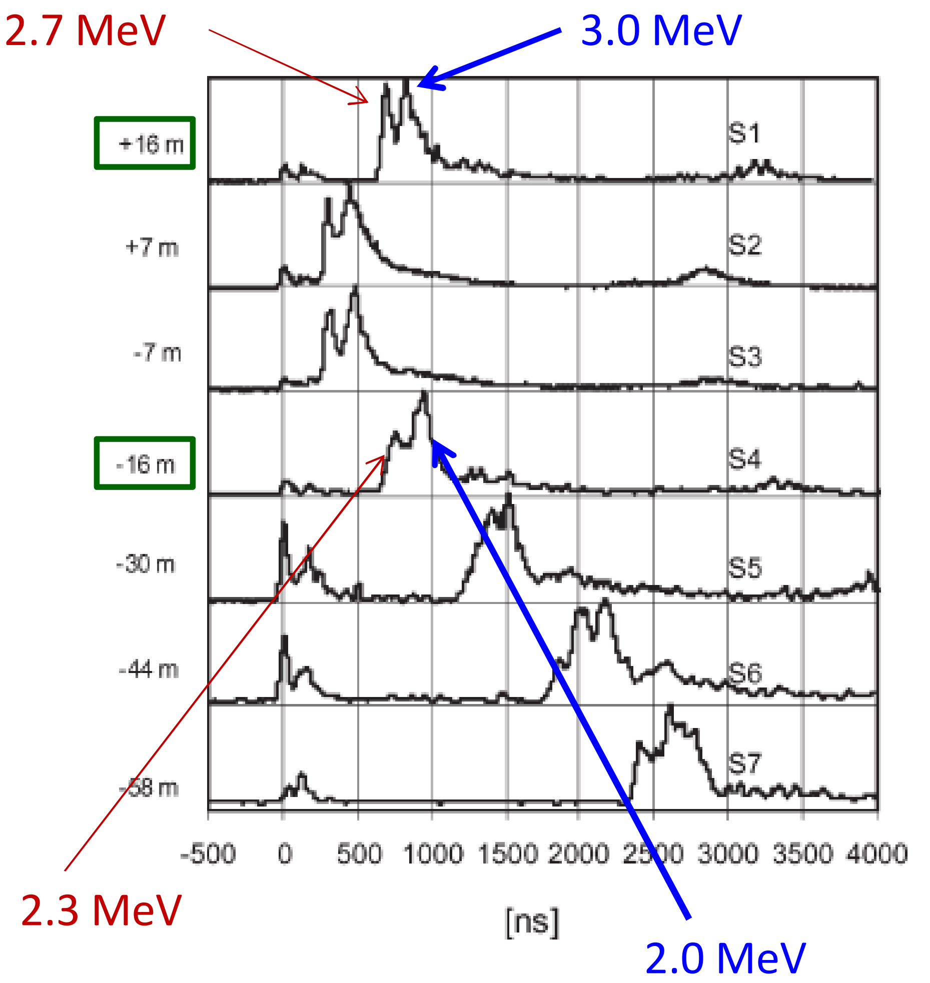
Reference	Electron temp. (eV)	Ion temp. (eV)	Density (cm^{-3})	Radius (cm)	Calculated thermal output	Measured neutron output
Anderson (Ref. 6)	90	215	2×10^{18}	0.13	1	1×10^{8}
Sethian (Ref. 7)	53	NR	1×10^{20}	0.05	2	8×10^{11}
Mather (Ref. 8)	1000	4000	2×10^{19}	0.075	1×10^{8}	1×10^{10}
This work	1200	8000	2.4×10^{20}	0.3	$>4\times10^{12}$	3.4×10^{13}

Gas puff　DPF　Frozen deuterium fiber ZP　Classical compressional ZP

Comparison of actual neutron yields with thermal estimates in DPF

- Heidelberg group carried out spatially and temporally resolved laser light scattering experiments on the Stuttgart, Frascati and Heidelberg PF devices and measured plasma density & ion temperature.
  - Sensitivity of quoted results to errors was discussed in detail. (G. Böckle, et. al: Plasma Physics and Controlled Fusion,. 34, pp. (1992) p801-841)
- Calculated thermonuclear yield was less than 4% of observed yield

Anisotropy in neutron emission from PF


2.7 MeV

3.0 MeV

2.3 MeV

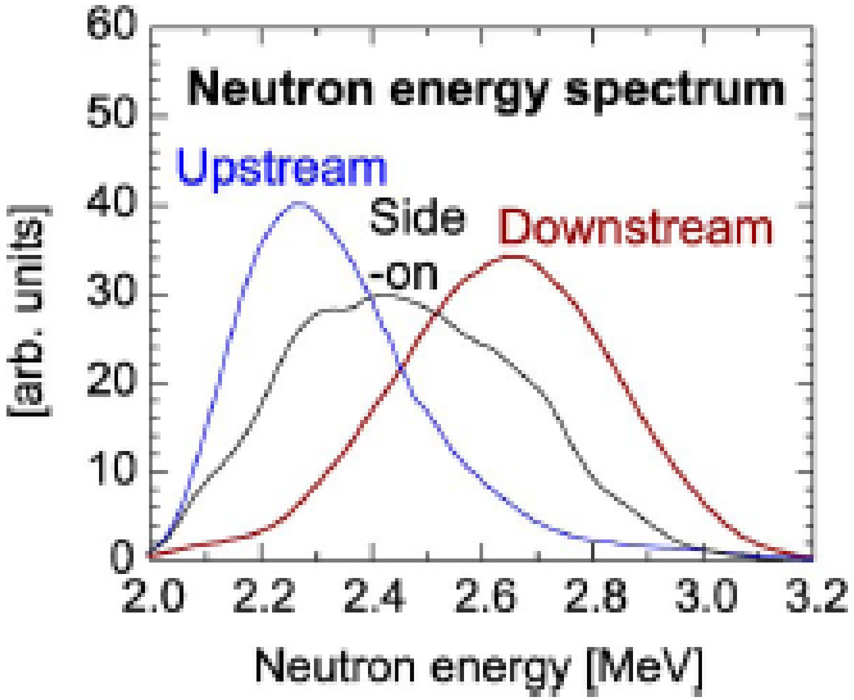
2.0 MeV

Fig. 4. Shot 4618. Record of the hard X-rays and neutrons from the detectors placed downstream at distances of 7.0 (S1) and 16.3 m (S2), and from those placed upstream at distances of 7.0 (S3), 17.0 (S4), 30.3 (S5), 44.3 (S6), and 58.3 m (S7).

- Neutron energy is more along the current (0°) than opposite to the current (180°).
- Center of mass of reacting deuterons moves along the current
- “Accelerated linear ion beam”??

From Kubes et. al.
IEEE TPS, 34, 2006, p.2349

Anisotropy in neutron emission from Gas Puff Z-Pinch



- In a different DMP, evidence for a "linear ion beam"!!

From Kubes et al IEEETPS 37 (2009) p 425

Neutron spectra at Frascati 1 MJ DPF

MM Milanese and J O Pouzo,
Nuclear Fusion 18 (1978) p533

Flight path 128 m at 90° to axis

- “Ion temperatures” between 6 keV and 37 keV
- *Side peaks cannot be explained in terms of a linear beam*
- A 100 keV deuteron loop in the plane determined by the gun axis and the observational direction gives a spectrum with lateral peaks.

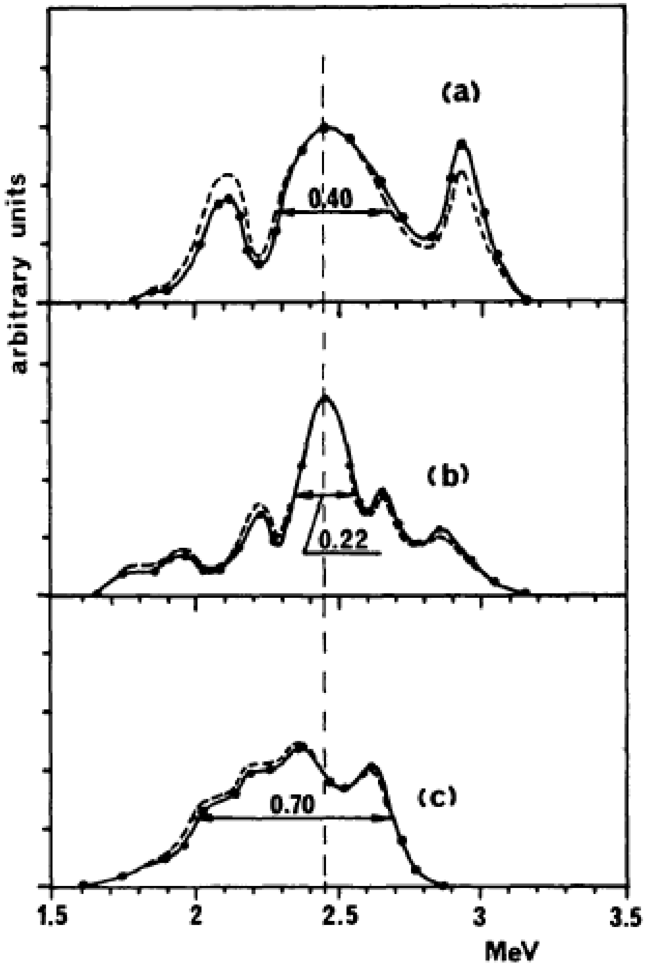


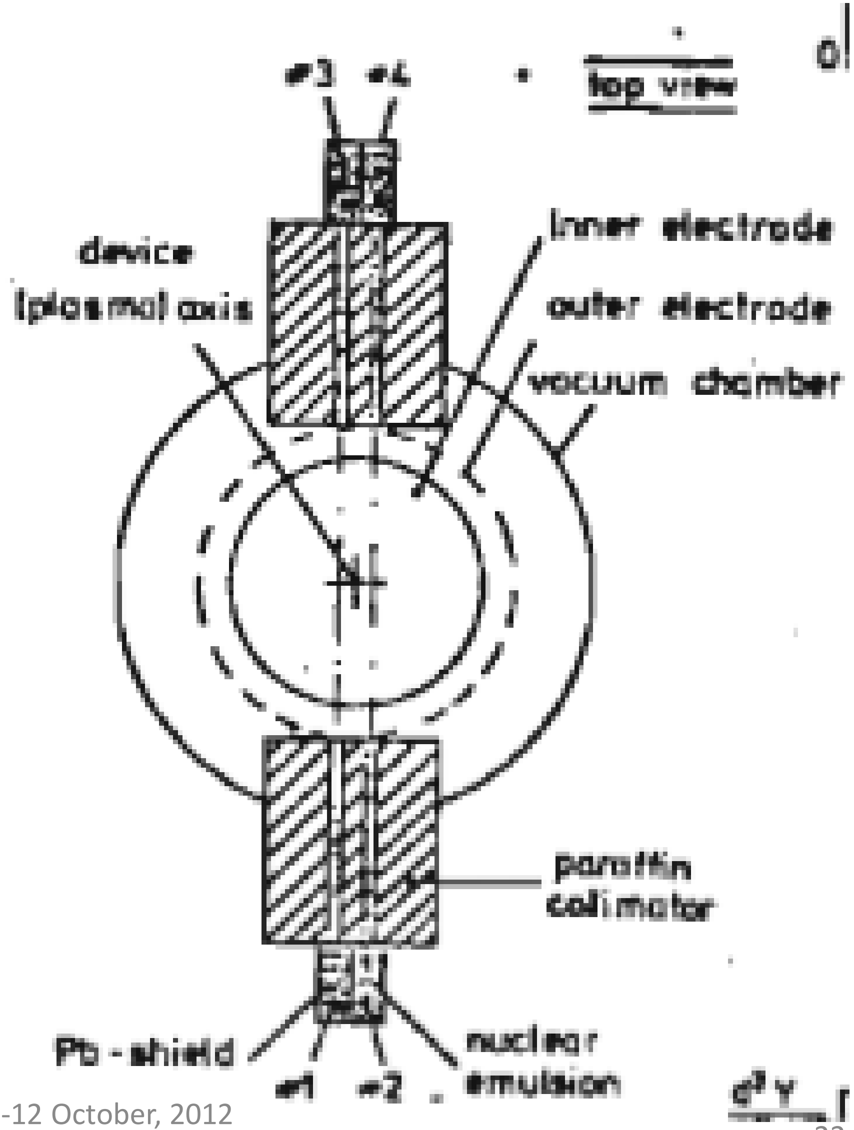
FIG.3. Typical energy spectra of neutrons measured near 2.5 MeV. The dotted curves represent the spectra after correction for scintillator response.

Space resolved Neutron spectra from Frascati

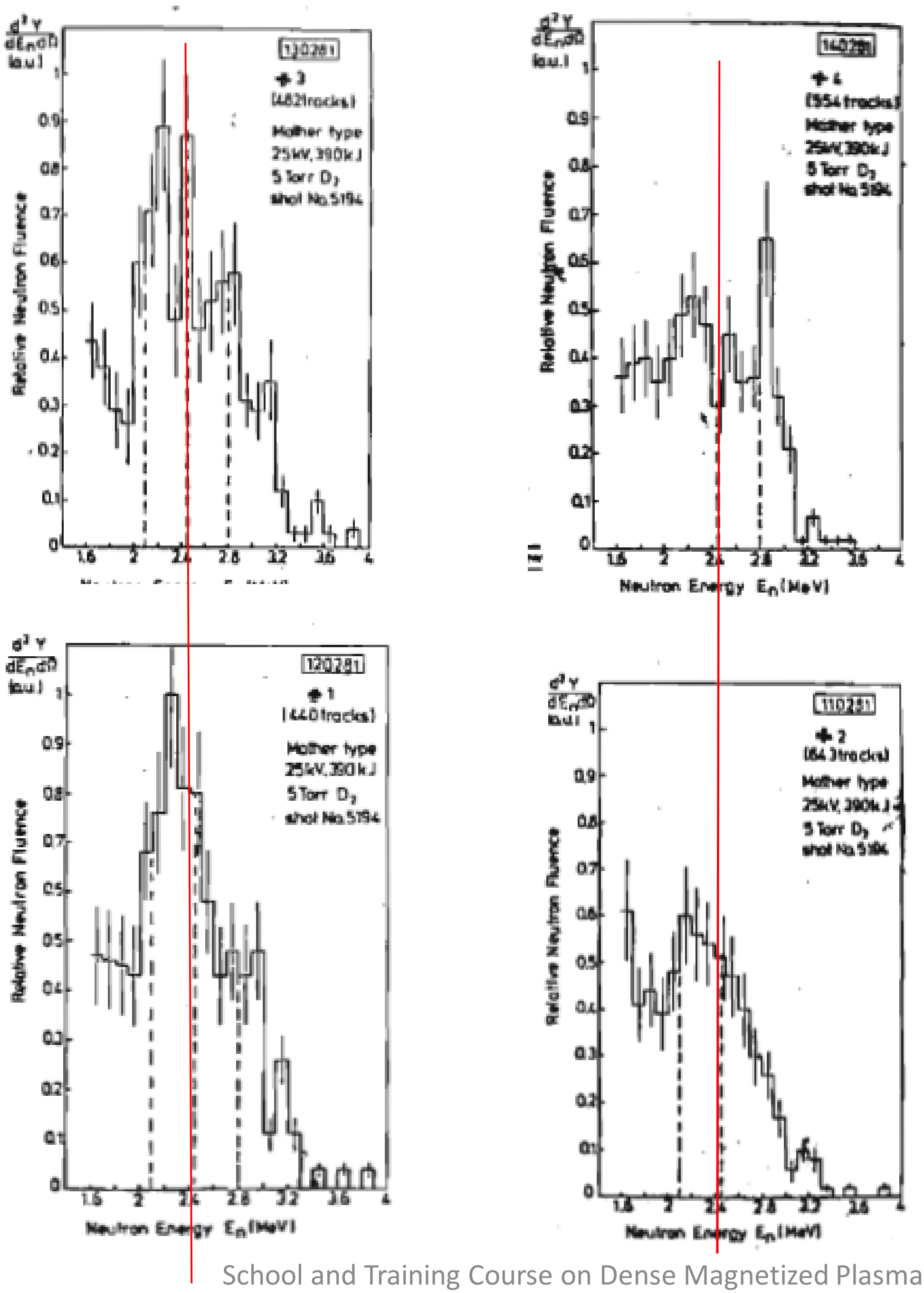
- Rotational feature of neutron emission

Data reproduced from Frascati Report 81.43, 1981.

Presented at 10th European Conf. on Plasma Physics and Controlled Thermonuclear Fusion, Moscow, 14-19 September, 1981.

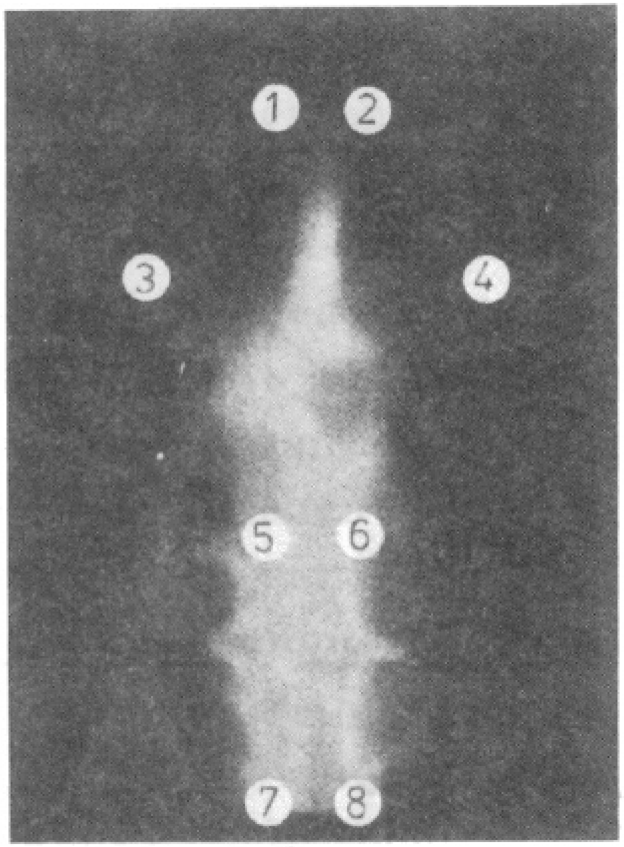


Top view



“Irregular patterns of lines have main features centered around 2.2, 2.45 and 2.8 MeV obeying a scheme of deuteron motion circling around the experiment axis”
- J.P.Rager, Frascati Report 81.43C, 1981

Evidence from Stuttgart: Rotation



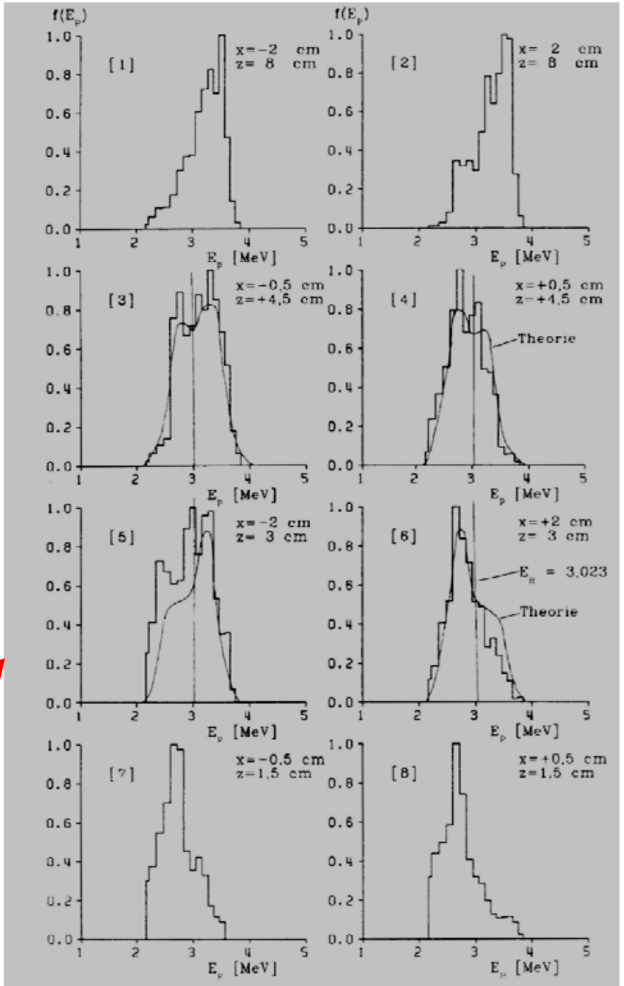


Abb. 5.20d : Protonenspektren aus Nr 6566. Die Orte der Meßpunkte sind in Abb. 5.20b,c angegeben

Space-resolved reaction proton spectra

U. Jaeger, Ph.D. Thesis, IPF-86-1, 1986
Jaeger & Herold, Nucl Fusion, 27 1987, p 407

Other pinches

- Limeil DPF: Neutron spectrum FWHM at 90° to axis is 400 keV ($T_D \sim$23 keV) while at 0° to axis is 150 keV (Bernard et. al. Phys. Fluids, 18, (1975), p160).
- NRL Frozen deuterium fiber pinch: ion temperature ~ 40 keV (FWHM 520 keV) from neutron ToF spectrum at 90°. (Sethian et. al. PRL, 59 (1987), p.892).
- Wire array imploding on a deuterated polyethylene fiber: neutron spectrum FWHM at 90° is 450 keV vs 350 keV at 0° (Klir et. al. PHYSICS OF PLASMAS 15, 032701 2008)
- GIT-12 Gas puff pinch: 1 MeV FWHM at 90°$\Rightarrow$150 keV deuteron "temperature". (Klir et. al. PHYSICS OF PLASMAS 19, (2012) 032706).

Fast ions in backward direction

- Some neutrons with energy higher than 2.45 MeV detected in backward direction
  - 3 MeV, M. J. Bernstein and G. G. Comisar, Phys. Fluids 15, (1972) p.700
  - 2.95 ±0.15 MeV, H. Schmidt et. al. Physica Scripta. 66, (2002) p168,
  - D. Klir et. al. Plasma Phys. Control. Fusion 54 (2012) p015001
- Fast deuterons (>500 keV) are detected in backward direction in PF by carbon activation, having 328 keV threshold
  - (Roshan et al. Physics Of Plasmas 16, 074506 ,2009)

Particle and Energy content Analysis

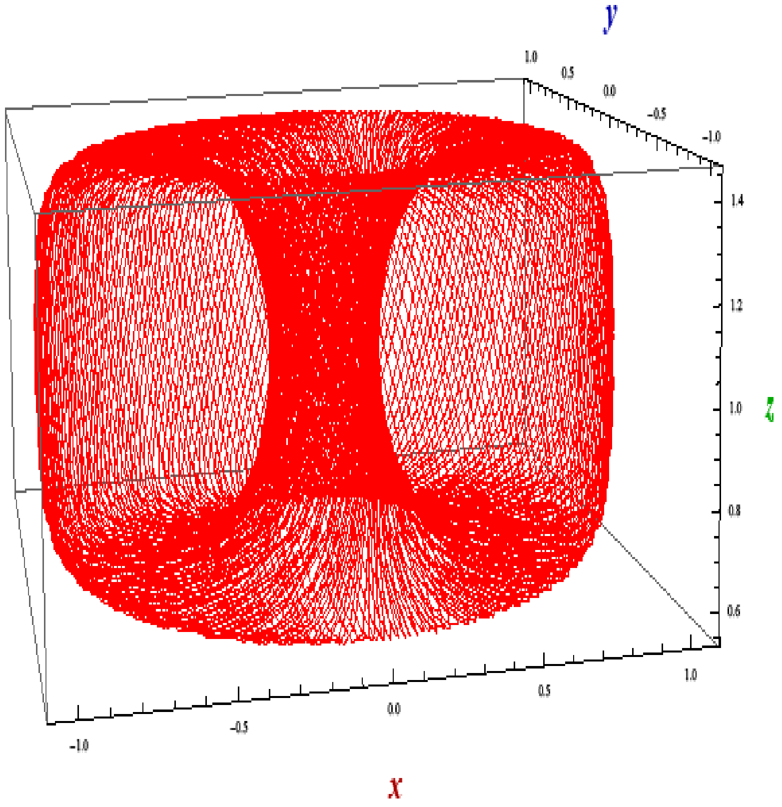
- Experimental data on large DPF devices (Frascati 1 MJ, POSEIDON and PF-1000) suggests that particle and energy content of the pinch is not sufficient to produce observed neutron yield unless the energetic ions are assumed to remain in the plasma for many transit times.
  - “Folded” trajectories of size comparable to plasma size

Statutory Warning: Limited Data!!

- All published data on directionality of energetic ions in DPF is based on analysis of very small number of shots.
- Unless repeated under varying experimental conditions and in different installations, there is a chance that the data may be attributed to artifacts due to improper experimental and data analysis techniques.

What is the directionality of energetic ions

- Energetic ions move along +z direction and also in –z direction
- They move in loops in r-z plane
- They have an azimuthal motion
- A toroidal trajectory agrees with this description



Summary of Experimental Data

- Spectra of neutrons and fusion protons are not consistent with an isotropic ion velocity distribution in a variety of Dense Magnetized Plasmas.
- FWHM of neutron spectra are many times greater than the 10 keV Lawson condition.
- Ions move in trajectories which enable them to retain their energy for many attempts at fusion
- Neutron yields are orders of magnitude higher than Maxwellian estimates using measured plasma parameters.

THEN WHY ARE DENSE MAGNETIZED PLASMAS NOT FAVORED CANDIDATES FOR FUSION POWER?

- The answer lies in the state of theoretical understanding!!
- There is NO THEORY which predicts fusion yield of Dense Magnetized Plasmas:
  - *No design basis for a fusion reactor concept.*

Fundamental Premise of Thermonuclear fusion – the Truth

- A mixture of energetic ions moving in toroidal trajectories and a hot plasma is a viable alternative to a hot plasma for generating fusion reactions efficiently

- Only Maxwellian plasmas are presently considered as fusion reactor candidates because there is no theory which predicts the high fusion reactivity of Dense Magnetized Plasmas.

Theoretical models for energetic ions

- What is the question?
  - What causes high average energy of ions?
  - What causes the *spread* in energies of ions?
  - What governs the trajectories of ions?
  - What keeps the ions confined within the plasma?
- Classification of models:
  - Kinematic models: numerical calculation of ion trajectories *under assumed conditions*.
  - Dynamical models*:* discuss *origin of conditions* under which ions get accelerated.
  - Data analysis models*: find out conditions* which are consistent with observed data

- Kinematic models: numerical calculation of ion trajectories *under assumed conditions*.

Kinematic models of ion acceleration

- Bernstein's model (Phys. Fluids 13, 1970, 2858)
  - Model formula for current density in moving plasma sheath
  - Numerical calculation of ion trajectories from resulting fields (cyclotron acceleration) with different initial conditions
  - Average path length of ions much larger than plasma dimensions, can explain axial energy /flux anisotropy
  - Cannot explain azimuthal motion of ions, requires many assumptions concerning plasma motion.
- Subsequent improvements along similar lines:
  - Gary & Hohl, Phys. Fluid, 16, 1973, 997
  - Includes free streaming acceleration of ions on axis because of abrupt decrease of current

Kinematic models of ion acceleration

- Deutsch & Kies’ model: (PP & Cont Fus. 30, 1988, 263)
  - Repeated reflection of ions from the magnetic piston leads to runaway acceleration of ions (Fermi acceleration)
  - Does not need abrupt decrease of current or instability or anomalous resistance for causing ion acceleration.
    - **Neutron emission in SPEED-II and first pulse in POSEIDON are NOT correlated with m=0 instability**
  - Cannot explain azimuthal motion of energetic ions

- Dynamical models*:* discuss *origin of conditions* under which ions get accelerated.

Dynamical models:

- Non-MHD model of m=0 instability (Imshennik et.al. 1984, IAEA-CN-44/D-III-6-1, p. 579)
  - – Numerical model, self-consistently evolves plasma parameters in the region close to the m=0 neck

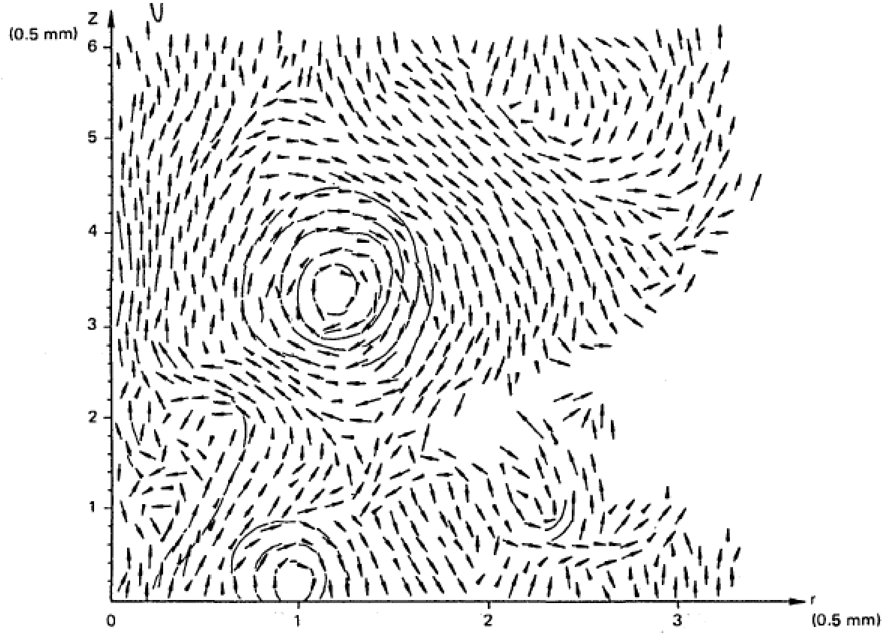


FIG.5. Velocity field in (r, z) plane for $t_2 = 20$.

-Reproduces the vortex like flow in (r,z) plane required to explain the neutron ToF spectrum of Milanese and Pouzo (1978) and backward ion acceleration.

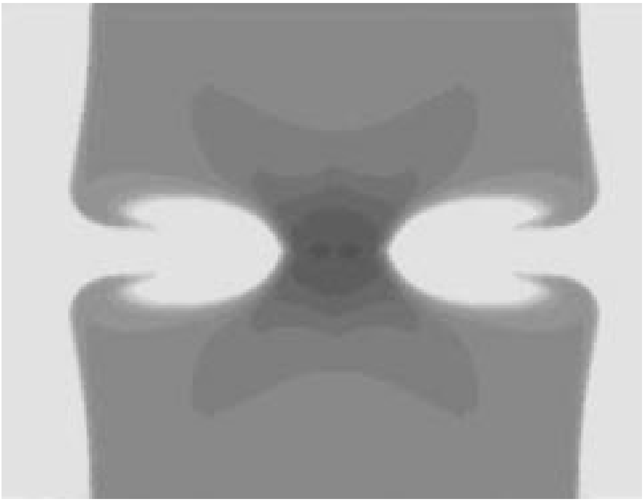
- Azimuthal velocity is *assumed* to be zero

Dynamic models

- Trapped magnetic flux model: (Nakafuji et al. 1996, IEEE conference on plasma science, 4D09: Only abstract is published)
  - Magnetic Rayleigh Taylor instability traps magnetic flux in a toroidal cavity as the sheath implodes. Compression of the magnetic flux creates poloidal electric field
  - No azimuthal velocity is possible in this model
- Garanin and Mamyshev's Model: (Plasma Physics Reports, 2008,34pp. 639–649)
  - 2-D MHD calculations with only B_θ component
  - Self-consistent electric field is used to calculate ion acceleration
  - No azimuthal velocity is possible

Dynamic Models

- Generation of fast ions in the plasma surrounding the pinch column: (Vikhrev et.al. NUCLEAR FUSION, Vo1.33, No.2, 1993; Vikhrev and Korolev, Plas Phys. Rep, 2007 33, p. 356)
  - Numerical simulation of m=0 instability up to the stage of cavity formation
  - Highly non-uniform electric and magnetic fields lead to *radial* ion acceleration at the entrance of cavity to MeV levels
  - No azimuthal ion acceleration



Dynamical models:

- Kondoh and Hirano’s Model:(Phys. Fluids 21, 1617 (1978))
  - Self-consistent solution of snowplow model, circuit equation, electromagnetic fields and ion trajectories
  - Shows reversal of axial electric field within the plasma
  - Shows a strong free-streaming acceleration of ions along the axis.
  - Azimuthal flow is neglected

- Data analysis models*: find out conditions* which are consistent with observed data

Data analysis models

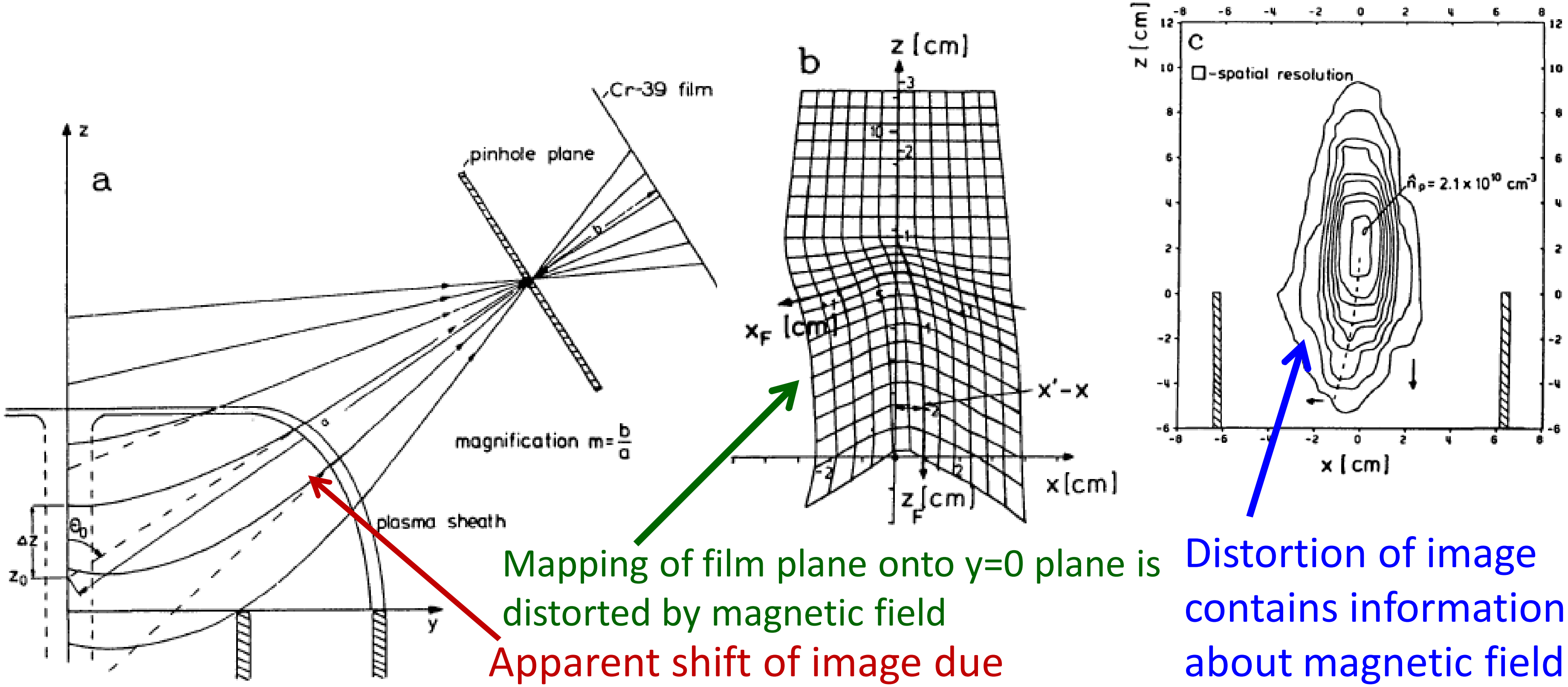
- Gyrating particle model (GPM): (Jaeger and Herold, 1987 Nucl. Fusion 27, p407)
  - "the trajectories of fast ions in the time varying structure of the focus pinch and in the surrounding gas are determined by a ray tracing code. The dynamics of the pinch and the profiles of n (r, z, t) and T (r, z, t) are taken from measurements for both phases in a schematic form."
  - "measurable quantities such as time resolved, time integrated and … spectrally resolved distributions of reaction protons and neutrons are obtained."
  - Comparison of **calculated measurable quantities** with **measured quantities** , *especially fusion proton spectra and images,* facilitates statements concerning properties of accelerated deuterons.

Basic idea of GPM

- Assume a “thermal” distribution of fast ions with certain quasi-temperature T_i^*
- Trace their trajectories in a time-dependent plasma-magnetic field configuration fitted to optical diagnostics measurements.
- Use ray tracing capability for “mathematical point-to-point backward imaging of the film plane grid into parallel planes through the focus pinch”

Basic idea of GPM

- *Evaluation of experimental reaction proton images and spectra is integral part of the model*



Mapping of film plane onto y=0 plane is distorted by magnetic field

Apparent shift of image due to magnetic deflection

Distortion of image contains information about magnetic field

Basic idea of GPM

- "What is the number and the total energy of fast deuterons necessary to produce experimentally observed fusion reaction yields according to GPM calculations?"
- Determine
  - -Spectra of thermal and fast deuterons (as a best fit to experimental data)
  - - Spectra of reaction protons (evaluation of CR-39 films)

- Magnetic field distribution at the time of neutron emission

Main insights from GPM

- Two groups of fast deuterons:

  (1) T_i^*~20-120keV (2)) T_i^*~200-400keV

- Separate estimation for quiet and turbulent phase: unique correlation between quasi-temp and yield only for quiet phase.
- Existence of axial magnetic field in pinch from distortion and shift of fusion proton image. The azimuthal current is always in -θ direction.
- Estimation of axial pinch current from angular distribution of reaction protons

Main insights from GPM

- Asymmetry of space-resolved fusion proton spectra from laterally mirror-symmetric points
  - Direct evidence of rotational center-of-mass motion of reacting deuterons.
- Existence of sub-millimeter size sources of deuterons with energy between 3 and 6 MeV in discharges with above-average fusion and x-ray yields, although, the contribution of these sources to the total yield is not significant

What GPM does and doesn’t do

- GPM is an important scientific work. It gives insights into “what is”, not “why it is so”.
- It shows which facts must be explained by a “cause and effect” theory. It does not provide any clue to the basis for such theory.

Summary of Theoretical Models

- Theoretical models do not comprehensively describe the directionality of ions motion.
  - Some aspects of ion motion (e.g. backward directed energetic ions, azimuthal motion) are not explained.
- How (and why) device properties affect ion motion is not understood

Impact on research environment

- With so little theoretical understanding of how (and why) plasma properties are influenced by device construction, Dense Magnetized Plasmas have receded from the attention of the scientific community interested in fusion.
  - No funding!!
- Proper attention needs to be given to develop predictive theoretical models

Thank You