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Conference Summary

Energetic particles in magnetic confinement systems

Report on the
6th IAEA Technical Committee Meeting
held at
Naka-machi, Naka-gun, Ibaraki, Japan
12–14 October 1999

1. Introduction and conference summary

H. Ninomiya (JAERI), K. Tobita (JAERI), U. Schneider (IAEA)

The 6th IAEA Technical Committee Meeting (TCM) on 'Energetic Particles in Magnetic Confinement Systems' was held in Naka, Japan, 12–14 October 1999 and hosted by Japan Atomic Energy Research Institute (JAERI). Previous meetings in this series, formerly entitled 'Alpha Particles in Fusion Research', were held in Kiev (1989), Aspenas (1991), Trieste (1993), Princeton (1995) and Abingdon (1997), covering alpha particles in magnetic confinement fusion as the main topic. The new title of this series of meetings indicates the growing interest now devoted to runaway electrons and other related phenomena in energetic particle physics.

The meeting was attended by over 60 participants from 10 countries and 3 international organizations (Euratom, France, Germany, Greece, IAEA, Italy, ITER (International Thermonuclear Experimental Reactor), Japan, Russia, Sweden, United Kingdom, Ukraine and the USA). Forty three papers were presented as invited talks (8), orals (17) and posters (18) accompanied by intensive discussions on the following topics: energetic alpha particles; runaway electrons; neutral beam (NB) heated and ion cyclotron resonance heated (ICRH) energetic particles and secondary effects; influence of Alfvén eigenmodes generated by energetic particles; further development of codes describing the behaviour of energetic particles in fusion plasmas; validation of theoretical models by experiments. The TCM emphasized experiments in a variety of magnetic confinement systems, such as conventional and spherical tokamaks, helical systems and a mirror device.

The Programme Committee consisted of the following: D. Campbell (NET, Garching), C.Z. Cheng (Plasma Princeton Physics Laboratory, USA), W. Heidbrink (University of California, USA), J. Jacquinot (JET Joint Undertaking), A. Jaun (Alfvén Laboratory, Royal Institute of Technology, Sweden), H. Kimura (JAERI, Japan), Ya. Kolesnichenko (Institute for Nuclear Research, Ukraine), S. Konovalov (Kurchatov Institute, Russian Federation), G. Martin (CEA-Cadarache, France), M. Rosenbluth (General Atomics, USA), U. Schneider (IAEA), K. Toi (National Institute for Fusion Science, Japan), J. Van Dam (University of Texas, USA), M. Yagi (Kyushu University, Japan), H. Zushi (Kyushu University, Japan), H. Ninomiya (chairman of the meeting, JAERI, Japan), and K. Tobita (local organizer for the meeting, JAERI, Japan).

This conference report contains summaries on energetic electrons by Martin (CEA-Cadarache), experiments on energetic ions by Heidbrink (University of California, Irvine) and theory by Kolesnichenko (INR-Kiev). The seven invited papers are published in this special issue of Nuclear Fusion. The proceedings of all the oral and poster presentations have appeared as a JAERI report (JAERI Conf. 2000–004).

2. Fast electrons

G. Martin (CEA-Cadarache)

Most of the papers presented on fast electrons (three orals and three posters) were related to runaway electrons produced during disruptions of fusion plasmas. Their status has changed from an innocuous phenomenon, mainly used to probe magnetic turbulence, to a serious threat to ITER (or any future large tokamak) first wall. Unfortunately, only a few scientists have focused their research on this phenomenon. Despite this, very interesting results were presented mainly from JT-60U (Yoshino, JAERI, and Tokuda, JAERI), Tore Supra (Martin, CEA-Cadarache) and ITER (Lukash, KIAE).

Two strong statements were made:

(a) Disruptions will occur in ITER; reliable avoidance schemes have still to be validated. Furthermore, present trends towards advanced operation scenarios are likely to further enhance ITER disruptivity.
(b) Runaway electrons will be produced during disruptions in tokamaks. Although precise scalings are not yet available for their production, all trends in magnetic field, stored energy, plasma current, machine size, etc. indicate that a large runaway component has to be expected.

Several questions need to be resolved:

(i) How many electrons will be accelerated? As a first assumption, a large fraction of the plasma current with a mean energy of around 15 MeV will result in around 30 MJ of energy in the electron beam. Experiments increasingly indicate that avalanche multiplication is the main phenomenon (Martin, CEA-Cadarache).
(ii) How strong is the confinement of these electrons? Strong effects of magnetic perturbations have been reported at various time and space scales, both experimentally and numerically (Tokuda, JAERI). As observed in JT-60U, a limitation technique for runaway production could be developed (Yoshino, JAERI), but further studies are required before any practical application to ITER.
(iii) What can be expected of electron impact on the first wall? Damage of first wall components has been observed in Tore Supra and JET even at beam energies less than 1 MJ due to strong peaking of the losses. Full calculations for ITER are difficult as all the components of disruption physics have to be included in the models such as vertical displacement events (VDEs), halo and eddy currents, impurity influx, etc. (Lukash, KIAE).

3. Fast ion experiments

W.W. Heidbrink
(University of California, Irvine)

The presentations on this topic could be classified in three categories: evolution of the velocity distribution function, confinement and fast ion driven instabilities.

3.1. Velocity evolution

The classical Coulomb scattering rate usually provides an accurate description of the deceleration process of energetic ions. New results presented at this meeting are consistent with classical expectations. Energy transfer from alpha particles to electrons has been observed in the JET tokamak as expected (Sharapov, JET). JET measurements of the energy spectra of alpha particles and deuterons in the MeV range show the expected features associated with large energy transfer events, as well as features caused by small angle Coulomb scattering collisions. Evidence of knock-on tails has also been observed in the 14 MeV neutron spectra (Källne, Uppsala University). New results on the acceleration of energetic ions by waves in the ion cyclotron range of frequencies were reported. Bulk ion heating is observed in JET in two regimes without extensive tail heating: deuterium minority in a tritium majority plasma and ^{3}He minority in a bulk deuterium–tritium plasma (Sharapov, JET). In the DIII-D tokamak, fourth harmonic heating of the deuterium beam ions exhibits the expected dependence on beam ion gyroradius (Heidbrink, University of California, Irvine). Anomalies in the ion cyclotron resonance heating efficiency are caused by losses of energetic tail ions, as observed in the W7-AS stellarator (Werner, IPP-Garching).

3.2. Confinement

New studies were presented on energetic ion confinement in equilibrium magnetic and electric fields of tokamaks and stellarators. In the JFT-2M tokamak, reduction of the toroidal field ripple by ferritic inserts reduced the flux of beam ions to the vessel wall (Kimura, JAERI). Tokamak plasmas with reversed shear and positive shear were compared in JT-60U, showing reduced ICRF heating efficiency in the reversed shear plasma due to increased ripple transport of the accelerated tail ions (Tobita, JAERI). Static helical perturbations to the equilibrium field have only little effect on fusion product confinement, as reported from DIII-D

(Carolipio, University of California, Irvine). Beam ion losses on the W7-AS stellarator agree qualitatively with the expected dependences on pitch angle and pitch angle scattering rate (Werner, IPP-Garching). In the CHS torsatron, three different diagnostic techniques were used to explore fast ion confinement. Prompt losses and collisional pitch angle scattering losses of several classes of orbit were measured with an edge scintillator (Darrow, PPPL; Kondo, NIFS). Neutron measurements during short 'blips' of perpendicular neutral beams indicate very rapid transport of the injected beam ions (Isobe, NIFS). The spectrum of escaping neutrals is sensitive to the angle of observation; the radial electric field probably causes the variations (Osakabe, NIFS).

Other studies explored transport associated with waves and instabilities. The large tearing modes observed in DIII-D induce orbit stochasticity in the phase space (describing the beam ion orbits) resulting in rapid transport (Carolipio, University of California, Irvine). Fast ion tail formation during ICRH is sensitive to wave phasing as seen in JET; calculations show that the wave induced drift is directed radially inward for efficient heating but outward for the unfavourable phase (Sharapov, JET). Neutral particle measurements in JET indicate radial transport of MeV ions during a class of MHD events (Gondhalekar, JET). In CHS, the temporal behaviour of fast ions, expelled in fishbone-like bursts, is sensitive to the pitch angle of observation (Kondo, NIFS).

3.3. Fast ion driven instabilities

The perpendicular fast ion tail produced during fourth harmonic ICRF heating in DIII-D transiently stabilizes the sawtooth instability (Heidbrink, University of California, Irvine) as does parallel injection of a 350 keV neutral beam in JT-60U (Tobita, JAERI). Many new observations of bursting fast ion driven instabilities with frequencies that change on a millisecond timescale were reported; phenomenologically, these modes resemble the fishbone instabilities first observed in the PDX tokamak but with different frequencies, mode numbers and fast ion populations. Chirping modes have been observed in the START spherical tokamak (McClements, UKAEA), in JT-60U during 350 keV NBI (Kramer, JAERI; Shinohara, JAERI), CHS and LHD (Toi, NIFS). Sometimes modes chirp up in frequency, sometimes down.

Modes with frequencies between 100 and 150 kHz have been observed in reversed shear plasmas on TFTR (Nazikian, PPPL). Although these modes have some characteristics similar to the toroidicity induced Alfvén eigenmode (TAE), there are also differences that are reminiscent of the 'BAE' instability seen on DIII-D. Modes with a gradual frequency evolution (100 ms timescale) that differs from the evolution expected for global TAEs have been found in TFTR (Gorelenkov, PPPL) and JT-60U (Kramer, JAERI); these modes may be the theoretically predicted energetic particle modes (EPMs).

TAEs are frequently observed in both tokamaks and stellarators; observations were reported from seven devices (Sharapov, JET; Toi, NIFS; Gorelenkov, PPPL; Kramer, JAERI; Heidbrink, University of California, Irvine; McClements, UKAEA; Werner, IPP-Garching). Ellipticity induced Alfvén eigenmodes (EAEs) and indentation induced Alfvén eigenmodes (NAEs) are also observed in most tokamaks. Global Alfvén eigenmodes are found in stellarators and low shear tokamaks. The presence and absence of alpha driven TAEs in TFTR (Nazikian, PPPL), and the appearance and disappearance of different modes, are consistent with the expected dependence on q (Sharapov, JET; Kramer, JAERI). The radial eigenfunction predicted by ideal MHD theory is inconsistent with data from DIII-D (Carolipio, University of California, Irvine), although initial measurements on JT-60U showed the expected ballooning structure (Shinohara, JAERI).

In the ion cyclotron range of frequencies, an Alfvén ion cyclotron mode in the GAMMA10 tandem mirror is driven unstable by the pressure anisotropy of ICRH tail ions, resulting in the scattering of perpendicular ions into the loss cone (Ichimura, Tsukuba University).

3.4. Status of the field

Many aspects of fast ion behaviour are well understood, including Coulomb deceleration, the basic confinement properties of tokamaks and the existence of Alfvén gap modes in toroidal devices. The confinement properties of fast ions in stellarators need further clarification. Another 'hot' topic is the role of kinetic and non-linear Alfvén instabilities. Promising topics for future advances include explanations for rapid frequency chirping, unambiguous identification of EPMs and a quantitative understanding of the radial structure of Alfvén modes.

4. Theory of energetic ions in fusion plasmas

Ya.I. Kolesnichenko (Institute for Nuclear Research, Ukraine)

The present theoretical investigations cover many important physics issues associated with energetic ions in conventional tokamaks and stellarators, and some of them are also relevant to spherical tokamaks. Both fast ion driven instabilities and fast ion transport induced by such instabilities were presented. In addition, the redistribution of fast ions caused by plasma MHD activities such as sawtooth oscillations is studied. A number of investigations contribute to the development of the neoclassical theory of fast ions. Attention was also paid to the interpretation of experimental data and modelling of fast ion behaviour in experimental devices.

4.1. Alfvén instabilities

In his talk, Gorelenkov (PPPL, Princeton) described the kinetic non-perturbative code HINST and its results applied to TFTR and JT-60U experiments. The experimentally observed frequency chirping could be explained by the change of the safety factor (in TFTR) and the evolution of the fast ion distribution function (in JT-60U). Results of TAE studies in NSTX based on a perturbative approach (NOVA-K code) were also presented by Gorelenkov. He predicted that TAEs exist for many toroidal mode numbers n and that several TAEs can occur for each n. The calculated growth rate of the unstable modes is rather large.

An analytical description of the EPM instability associated with fast ions produced during ICRH was presented for TFTR (Zonca, ENEA-Frascati). He considered high frequency EPMs ($\omega \approx \omega_A/2$), assuming the pitch angle distribution of energetic ions to be strongly anisotropic.

Cheng (PPPL, Princeton) has drawn attention to an important role of core plasma kinetic effects in MHD phenomena. He developed a non-linear kinetic–fluid model including kinetic effects of all particle species in high-β plasmas. As an example, the finite Larmor radius of the bulk ions combined with trapped electron dynamics leads to the generation of a longitudinal electric field, which essentially increases β_{crit} of the kinetic ballooning instability.

Fukuyama (Kyoto University) described a three dimensional full wave code, TASK/WM, applied for studying AEs in tokamaks with reversed shear configuration. He found that Alfvén eigenfrequencies are very sensitive to the magnitude of q_{min}, when q_{min} is slightly below an integer.

Non-linear evolution of AEs based on 4-D and 5-D Fokker–Planck simulations was addressed in the investigations presented by Todo (NIFS). In particular, no steady saturation of alpha driven TAE instabilities in TFTR has been found using the 5-D code, which takes into account pitch angle scattering of fast ions.

Another important topic is stability of AEs in optimized tokamak scenarios as shown by Jaun (Alfvén Institute, Stockholm). Landau damping of mode converted kinetic Alfvén waves may be the dominant stabilizing mechanism of Alfvén instabilities.

Investigations of the nature of suprathermal ion cyclotron emission (ICE) from tokamak plasmas were presented by Lisak (Chalmers University of Technology, Göteburg). He considered the non-linear stage of the edge localized instability of compressional Alfvén waves excited by alpha particles. The developed theory enables calculation of the power irradiated from a plasma due to instabilities. The calculations are in agreement with ICE power measurements in the JET preliminary tritium experiment.

4.2. MHD events

Kolesnichenko (INR-Kiev) presented both an overview and new results on the transport of fast ions during sawtooth oscillations. In particular, two new mechanisms of particle redistribution by $n = 1$ perturbations were predicted:

(a) Stochastic motion induced by a monochromatic $m = n = 1$ mode with the amplitude threshold being the lowest for 'potato' trajectories;
(b) The particle motion along the so-called 'small action resonance domain' combined with sharp switching on/off of the perturbation.

The physics of fishbone instability, including its non-linear phase, was addressed in the talk of Breizman (University of Texas, Austin). It was found that weak MHD non-linearity of the $q = 1$ layer destabilizes fishbone perturbations. Breizman also showed a time dependent formalism representing a part of the efforts aimed at developing a hybrid kinetic–MHD code for the simulation of fishbone pulses.

Predictions can be made of the absolute stability of trapped particle induced fishbone modes in spherical tokamaks with sufficiently high plasma pressure, as reported by Kolesnichenko (INR-Kiev). The stabilization is a consequence of the reversal of the direction of the particle toroidal precession in high-β plasmas.

Lazaros (National Technical University of Athens) has considered a diffusive mechanism of the interaction of fast ions with MHD modes which may lead to the stabilization of sawtooth instabilities by circulating particles.

4.3. Neoclassical theory and numerical simulation

Murakami (NIFS) addressed work on the neoclassical transport of energetic ions in LHD. The study is based on a newly developed global neoclassical transport code (GNET), which solves the 5-D drift kinetic equation. The results of the calculations are in agreement with the experimental observations. It was shown that the orbit width could be essentially reduced, resulting in improved confinement in the inward shifted configuration.

Neoclassical transport coefficients for alphas, valid for a wide range of tokamak parameters, were obtained by using a variational method as reported by Taguchi (Nihon University).

The confinement of injected ions in NSTX was modelled using the EIGOL code as shown by Darrow (PPPL, Princeton). The calculated loss fraction strongly decreases with the plasma current which is essential in high-β discharges even at high currents (30% for $I = 1$ MA and $\beta = 40\%$). The loss could be reduced by lowering the inner beam line voltage in NSTX.

Simulations have also been undertaken by Darrow (PPPL, Princeton) for the NBI losses in CHS. It was found that the simple collisionless model used does not agree with the experimental observations.

Yavorskij (INR-Kiev) described the results of numerical simulation of charged fusion reaction products (CFRP) for TFTR and JET based on his earlier developed model. In particular, the inward shift of the SOL flux surface affects the CFRP loss in TFTR.

Yagi (Kyushu University) studied in more detail the thermonuclear burn in an ITER-like tokamak in the presence of internal transport barrier (ITB). Two mechanisms of ITB collapse were considered, namely a ∇p driven mechanism and triggering by sawteeth.

5. Concluding remarks
U. Schneider (IAEA)

The meeting hosted by JAERI was well organized by the local committee, and the meeting participants thanked the local hosts for the outstanding quality of the arrangements in Naka and Mito. The participants enjoyed the welcome reception at the Akogi-ga-ura Club on the first day of the meeting as well as the machine tour to the JT-60U tokamak. The next TCM in this series will be held in 2001 in Göteborg, Sweden, and will be arranged by M. Lisak, Chalmers University of Technology. The Programme Committee received strong interest from US members in hosting the 8th Technical Committee Meeting on Energetic Particles in Magnetic Confinement Systems in 2003.

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