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FAST ELECTRON CURRENT DENSITY PROFILE AND DIFFUSION STUDIES
DURING LHCD IN PBX-M

BY

S.E. JONES, S. VON GOELER, S. BERNABEI, ET AL.

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PPPL PRINCETON
PLASMA PHYSICS
LABORATORY

PRINCETON UNIVERSITY, PRINCETON, NEW JERSEY

Abstract

Successful current profile control experiments using lower hybrid current drive (LCHD) clearly require knowledge of (1) the location of the driven fast electrons and (2) the ability to maintain that location from spreading due to radial diffusion. These issues can be addressed by examining the data from the hard x-ray camera on PBX-M, a unique diagnostic producing two-dimensional, time resolved tangential images of fast electron bremsstrahlung. Using modeling, these line-of-sight images are inverted to extract a radial fast electron current density profile. We note that "hollow" profiles have been observed, indicative of off-axis current drive. These profiles can then be used to calculate an upper bound for an effective fast electron diffusion constant: assuming an extremely radially narrow lower hybrid absorption profile and a transport model based on Rax and Moreau¹, a model fast electron current density profile is calculated and compared to the experimentally derived profile. The model diffusion constant is adjusted until a good match is found. Applied to steady-state MHD quiescent modes on PBX-M, we obtain an upper limit for an effective diffusion constant of about $D^* = 1.1 \text{ m}^2/\text{sec}$.

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Fast Electron Current Density Profile and Diffusion Studies during LHCD in PBX-M

S.E. Jones¹, S. von Goeler², S. Bernabei², R. Kaita², J. Kesner¹, S. Luckhardt¹,
F. Paoletti¹, F. Rimini³, and the PBX-M group.

¹Plasma Fusion Center, Massachusetts Institute of Technology, Cambridge, MA 02139

²Plasma Physics Laboratory, Princeton University, Princeton, NJ 08543

³JET, Joint Undertaking, Abingdon, Oxfordshire OX14 3EA UK

1. Introduction

Many advanced tokamak designs utilize current profile control for attaining such benefits as second stability, enhanced confinement, and sawtooth stabilization. PBX-M is an experiment dedicated to investigate this potential by using Lower Hybrid Current Drive (LHCD)¹. Clearly any current profile control experiment using lower hybrid driven fast electrons requires knowledge of two key issues:

- (1) the radial location of the fast electrons;
- (2) the ability to maintain their spatial localization.

This paper reports on our efforts to address these two issues by using the novel 2-D hard x-ray imaging camera on PBX-M^{2,3}. These images are produced from bremsstrahlung x-rays emitted by LHCD-driven fast electrons as they collide with the thermal plasma. Although the images are line-of-sight and energy integrated, an inversion procedure has been developed³ to obtain a radial fast electron current density profile. Once these profiles are obtained, they can be fitted to theoretical predictions from a Fokker-Planck model for the fast electron distribution function, which includes a diffusion operator. From this procedure an effective fast electron diffusion constant can be computed.

The hard x-ray diagnostic on PBX-M was previously reported^{2,3}, but a brief description follows: The diagnostic is effectively an x-ray pinhole camera which views the plasma tangentially on the mid-plane. The detector itself is a two-dimensional medical x-ray image intensifier tube, and it is important to note the images are line-of-sight and energy integrated. The image is also time-integrated for as little as 4 msec, and 64 such images, or frames, from one discharge are stored. Thus, the time evolution of the image is obtained.

An example image from the camera is shown in Fig. 1 as a contour plot of detected x-ray intensity. This image was averaged over 32 frames at 4 msec/frame from the steady-state portion of discharge #298601. This 180 kA discharge at 14 kG was obtained using 310 kW of LHCD in conjunction with 500 kW of neutral beam injection. The loop voltage was 0.4 V, so the current drive was not 100%. Shortly after the auxiliary power was introduced, all sawteeth and MHD activity ceased.

Qualitatively, the "hollowness", or off-axis distribution of the energetic electrons, is reflected by the slight concavity and widening of contour lines just to the right of the central peak. This significant result demonstrates that steady-state off-axis current drive is possible. The rest of this paper focuses on this experimental image for extracting a radial fast electron current density profile and for computing an effective fast electron diffusion constant.

2. Fast Electron Current Density Profile for shot #298601

Since the x-ray images are line-of-sight and energy integrated, an inversion process is required to obtain the radial fast electron current density profile. This procedure has been previously reported², so the following description will be short. Rather than doing a difficult direct Abel-like inversion, we obtain the profile by modeling: using four variables to describe the fast electron velocity distribution function and

Figure 1. Contour plot of hard x-ray image during steady state portion of shot #298601. This image was averaged over 32 frames.

Figure 2. Simulated contour plot of the x-ray image for shot #298601, based on the radial fast electron current density profile in Fig. 3 and velocity space distribution in Fig. 4.

three variables to describe the superthermal electron (se) current density radial profile, the local hard x-ray emissivity is obtained. Specifically, we assume a separable fast electron distribution of the form

$$F_{se} = f_{se}(P_{||}, P_{\perp}) g(\Psi).$$

where

$$f_{se}(P_{||}, P_{\perp}) = \begin{cases} \exp(-P_{||}^2/2T_{||}^{\text{forward}} - P_{\perp}^2/2T_{\perp}) & P_{||} > 0 \\ \exp(-P_{||}^2/2T_{||}^{\text{backward}} - P_{\perp}^2/2T_{\perp}) & P_{||} < 0 \\ 0 & P_{||}^2/2 > E^* \end{cases}$$

and

$$g(\Psi) = \begin{cases} \exp(-(\Psi - \Psi_{se})/\Delta\Psi_{seo})^2 & \Psi > \Psi_{se} \\ \exp(-(\Psi - \Psi_{se})/\Delta\Psi_{sei})^2 & \Psi < \Psi_{se} \end{cases}$$

Line-of-sight integrations are then performed, including the effects of various absorbers and the detector efficiency, yielding a simulated image which can be compared to the experimental image. The simulated image is recomputed using different parameters until a good comparison is found.

This procedure was applied to the discharge #298601 (Fig 1). A best-case simulated image is seen in Fig. 2, using the radial profile shown in Fig. 3 and velocity distribution function shown in Fig. 4. The location of the off-axis peak Ψ_{se} and the inboard (Ψ_{seo}) and outboard (Ψ_{sei}) scale lengths are sensitive to fitting to about a factor of 10%. This result clearly shows an off-axis location for the fast electrons, and since this shot was steady state this location was maintained.

3. Theoretical Model

A quantitative measure of the ability to maintain an off-axis fast electron current density profile is to calculate an effective diffusion constant and compare the diffusion time scale with the classical slowing-down time scale. Our approach is to assume a plausible physics model where the diffusion constant is a free parameter and the lower hybrid power absorption profile is extremely narrow. A diffusion constant is guessed initially and the model fast electron current density profile is calculated and compared to the

Figure 3. Model fast electron current density used for simulated Fig. 2.

Figure 4. Model fast electron momentum space distribution used for simulating Fig. 2

experimental profile. The process is iterated using different diffusion constants until a good match is found. Since the lower hybrid power absorption profile might not be in reality as narrow as we assumed, this effective diffusion constant is an upper bound.

Our model is derived from the response function technique described by Rax and Moreau⁴ which solves the following time dependent Fokker-Plank equation:

$$\left[\frac{\partial}{\partial t} - \frac{1}{p^2} \frac{\partial}{\partial p} + E \frac{\partial}{\partial p_{||}} - \frac{Z+1}{2p^3} \frac{\partial}{\partial \mu} (1 - \mu^2) \frac{\partial}{\partial \mu} - \frac{D(p)}{r} \frac{\partial}{\partial r} r \frac{\partial}{\partial r} \right] K(p, p', \mu, \mu', r, r', t, t') = d(p-p')d(r-r')d(\mu-\mu')d(t-t') / p^2 r \quad [1]$$

P is the normalized momentum variable, μ is the pitch angle variable, t is the normalized time variable, E is the normalized electric field, $p_{||}$ is the normalized parallel momentum, r is the normalized radial variable, Z is the effective charge, and D is the normalized effective diffusion constant. Since the Rax and Moreau solution use $E=0$, approximations are introduced to include a weak electric field, an important aspect of PBX-M. The full distribution function for the superthermal electrons (se) is written in terms of the response function as

$$F_{se}(p, \mu, r, t) = \int p'^2 r' dp' dr' d\mu' dt' W_a(p', \mu', r', t') [dp' d/dp' + d\mu' d/d\mu'] K(p, p', \mu, \mu', r, r', t, t') \quad [2]$$

where W_a is a kernel describing the lower hybrid power absorption, and the fast electron current density can be written as

$$J(r) = q \int 2\pi^3 p^3 \mu F_{se}(p, \mu, r) dp d\mu \quad [3]$$

Our solution, including the weak electric field approximation, takes the form

$$K = \theta(t-t') \delta \left[\frac{p-p'}{\mu E} - \frac{1}{2(\mu E)^{3/2}} \ln \left(\frac{(1+p\sqrt{\mu E})(1-p'\sqrt{\mu E})}{(1+p'\sqrt{\mu E})(1-p\sqrt{\mu E})} \right) - t + t' \right] \sum (2l+1) \\ \times \exp(-k^2 H(p, p')) \left(\frac{\frac{p}{\sqrt{1-p^2 \mu E}}}{\frac{p'}{\sqrt{1-p'^2 \mu E}}} \right)^{l(l+1)(Z+1)/2} \frac{J_0(kr') J_0(kr)}{J_1(k)^2} P_l(\mu') P_l(\mu) \quad [4]$$

where J_0 and J_1 are Bessel functions, P_l are Legendre polynomials, k are the zeros of J_0 , the summation is over l and k , and

$$H(p, p') = \int_p^{p'} \frac{u^2 D(u)}{1-u^2} du. \quad [5]$$

4. Results and Conclusion

This model was applied to shot #298601, and radial fast electron current density is shown in Fig. 3 assuming

$$W_a(p, \mu, r) = W_0 \frac{p'}{p} \delta(r-r') \delta(\mu-1) \quad p < p' \\ = 0 \quad p > p'$$

where $p' = 0.5$ and $r' = 0.57$. A best-fit profile from eq. 3 was obtained with $D_{\text{eff}} = 1.1 \text{ m}^2/\text{sec}$, as shown in Fig. 4. Variations in the diffusion constant by a factor of two leads to clear departures from the experimental profile in Fig. 3. The sensitivity of this result was tested by varying the loop voltage, the lower hybrid absorption profile in velocity space, Z_{eff} , and adding up to 7 radially discrete sources to roughly model the effect of a broader radial absorption profile. In all cases, the best fit profile for the effective diffusion constant varied by less than about a factor of two. Note the diffusive time scale is 90 msec - much longer than the collisional slowing down time of about 7 msec.

Figure 5. Theoretical results for the fast electron current density profile for 3 different values of an effective diffusion constant with a loop voltage of 0.4 v. Notice that $D^* = 1.1$ gives the best-fit to the experimental profile seen in Fig. 3, and that factors of two larger or smaller lead to significant departures.

In conclusion, the hard x-ray camera has observed steady state off-axis current drive, and a radial fast electron current density profile has been obtained. A theoretical model simulating this shot produces an upper limit for an effective diffusion constant of about 1-2 m^2/sec . and sensitivity studies indicate that this result is good to within a factor of two.

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