ASDEX HEAT PULSE PROPAGATION AS A FORCED BOUNDARY PROBLEM

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Traditionally, two types of methods are used to determine the eletron heat conductivity, χ: initial value and Fourier. Initial value analyses compare the observed temporal evolution during the rise phase of the heat pulse with Kadomtsev's model for sawtooth reconnection. The crucial disadvantage is that one must make assumptions about the plasma inside the mixing radius, namely one assumes that χ is known and unchanged inside the $q = 1$ surface and therefore the natural thermal equilibrium is the temperature before the crash. Fourier methods average over the sawtooth period and thus the results are heavily weighted in favor of the slow decay phase of the heat pulse. During this latter phase the initially sharp spatial gradients of the pulse have relaxed and Ohmic heating and electron ion energy transfer as well as boundary conditions become important.

To analyze the ASDEX heat pulse, we solve the heat equation numerically as a forced boundary value problem. The measured time evolution of the first electron cyclotron emission channel outside the mixing radius is used as input for the the time dependent boundary condition. The electron heat conductivity is then given a functionally parametrized form such as $c/n(r)$, where the parameter is determined by a best fit to the channels located outside the input channel.

This approach has several important advantages over the standard method of fitting the arrival time of the peak of the pulse to a theoretically initialized perturbation. The region inside the mixing surface, where the conductivity may be anomalously large, is excluded from consideration. No assumptions on the position of the $q = 1$ surface or the radial redistribution of energy are necessary. The conversion of magnetic energy into heat is automatically taken into account. Finally, the ECE measurements give a time history of the heat pulse at a few spatial locations and the method makes effective use of this information.

We use a standard Crank-Nicholson scheme with $T(r = r_o, t)$ evolving in time. Convective, dissipative and reheat terms may be included. The time interval may be the rise phase, the entire sawtooth period, or the entire sequence of sawteeth to simulate the effect of pulse pile up.

To model the boundary layer outside the separatrix we assume that the temperature decays exponentially with a decay length λ. We integrate the heat equation over the last half grid point and define $\alpha\chi(1) = \lambda\chi_{bl}$ where χ_{bl} is the effective conductivity outside the separatrix. Thus the last half mesh volume evolves as

$$\frac{\Delta r}{2}\frac{\partial T}{\partial t} = \chi[-\alpha T - \frac{\partial T}{\partial r}]$$

where the minus denotes the inside derivative. Since the boundary layer is believed to be a highly nonlinear function we treat α as a free parameter. Results which depend sensitively on α are of little value.

The method is tested on a standard Ohmic discharge with the following parameters, $q(a) = 3.3, T(0) = 1075ev, n = 2.4 * 10 * *13, Z_{eff} = 1.3$. The input channel is at 18.1cm and the fit channel at 25.6 cm. Ten sawteeth are averaged over the sawtooth period.The period is 13ms,the crash time is 1ms,the amplitude is 90ev,and the peak of the pulse arives at r=18.1cm in 1.65ms and at 25.6cm in 2.65ms. Figure 1 compares the smoothed experimental data with numerical calculations for $\chi = c * n(.47)/n(r)$ during the first 5ms of the pulse. The top curve is $c = 8.8m^2/sec$, the middle curve is $7.7m/sec$ and the bottom curve is 6.5. The best fit to least squares integral is 7.35, to the relative least squares, (time averaged temperature at 25.6cm normallized to 1.0) is 6.8 and the best fit to time integral of $T_{measured} - T_{num}$ is 7.7. The boundary heat flux parameter α is 2.0. Thus the choice of norms varies the result by 5%. The power balance χ is between 1.2 and $2.0m^2/sec$. In practice, the pulse has four characteristic parameters,the amplitude of the peak, slope of the temperature rise ,the time of arrival of the peak and the slope of the decay. We are able to fit the first two parameters with a chi of approximately $7m^2/sec$. When the radial dependence is varied from constant to inversely proportional to density the value of chi at the input channel varies only a few percent during the rise and early decay phase. The discrepency between the observed and computed time of arrival of the peak is larger. Since in fitting the peak we are essentially specifying the second derivative of $T(t)$, the poorer fit is to be expected. It may also be partially related to the presence of convection.

The temporal decay depends on both the assumed radial profile of χ and on the heat transfer parameter α. As α decreases, the rate of increase of χ with radius must increase. Figures 3a,b,c give the computed values of the temperature at $r = 25.6$ for $\alpha = 0.1, 2.0$ and 40.0 respectively. In each case, the top curve is $\chi = 7.3m^2/sec$, the middle curve is $7.3n(.475)/n(r)$ and the bottom curve has a inverse square dependence on density. Clearly the boundary condition determines the radial variation of χ.

We now analyze the same case with the initial value approach and determine χ by fitting the differential time of arrival of the peak at 18.1 and 25.6. We assume a parabolic current profile and initialize the code with the perturbation given by conservation of energy and flux. The experimental temperature and density profiles are used. For a differential time of arrival of 1ms we find $\chi = 4.1m^2/sec$. The temporal evolution at

18.1 and 25.6 cm are displayed in Fig 3a,b. The amplitude of the temperature pertubation just outside the mixing radius is in good agreement with theory. The actual crash time of one msec is comparable with the time of arrival. The difference in arrival times occurs because the initial value approach assumes that the crash is instananeous. The forced boundary value approach automatically took this into account. For neutral beam cases, the crash time is .1ms and the agreement will be better.

The most disturbing discrepency is the surprisingly large magnitude of the heat pulse away from the mixing radius. The theoretical prediction is based on a dipole character of the initialization. By assuming thermal equilibrium after the crash is the temperature before the crash, there is a net lack of thermal energy inside the $q = 1$ surface. This absence of heat mixes with the excess outside the inversion radius and causes a rapid decay. If the conductivity inside the $q = 1$ surface were greatly enhanced after the crash, the natural profile would be the flat final profile. Thus the heat pulse would propagate like a monopole localized between the inversion and mixing radii.

The experimental observations in ASDEX and TFTR seem to suggest that the temperature at the $q = 1$ surface is held constant throughout the sawtooth period. This is an intermediate case between a dipole and a monopole.

In conclusion, the forced boundary value method allows quantitative analysis of the time evolution of the measured signals. The major source of error are the spatial resolution of the ECE spectrometer and the lack of knowledge of the correct boundary condition. By averaging over several shots it should be possible to determine both the physical boundary condition and the radial profile of χ. For the sample ohmic case analyzed here we find that the heat pulse conductivity is a factor of four to five higher than the power balance conductivity and that the initial valve approach significantly underestimates the heat pulse χ.

Fig.1 Temperature (eV)

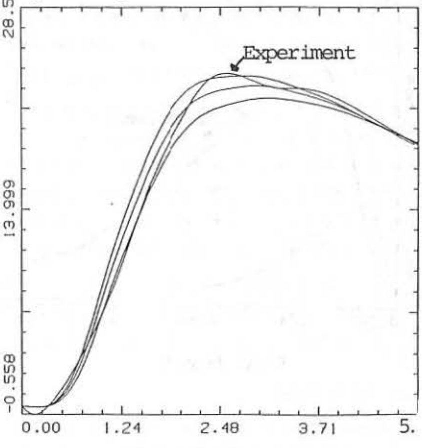


Fig.2a Temperature (eV)

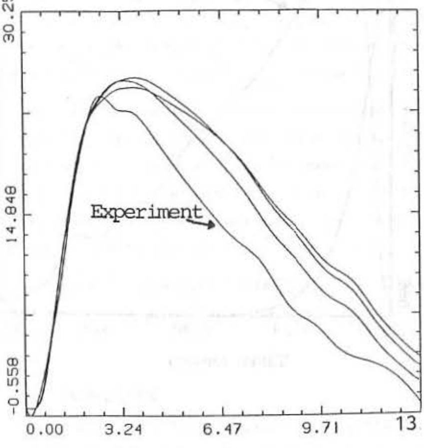
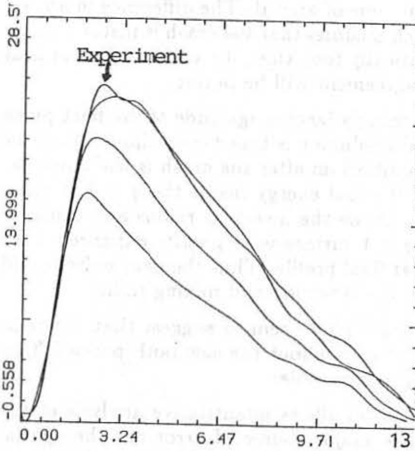
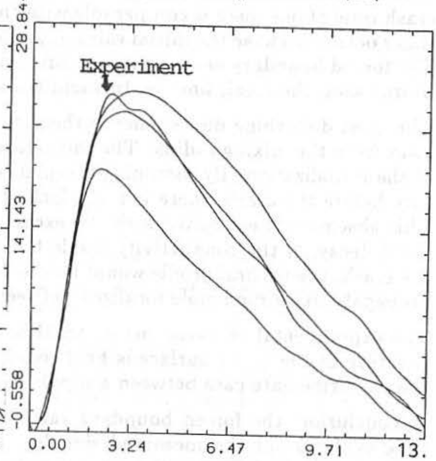


Fig.2b Temperature (eV)



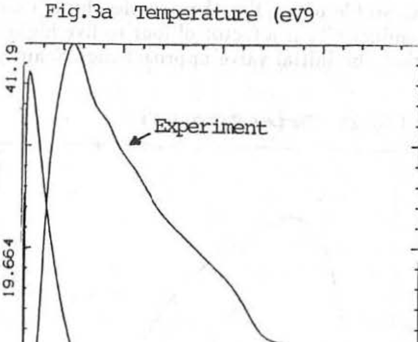
Time (msec)

Fig.2c Temperature (eV)



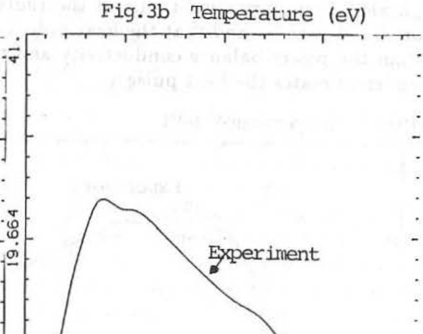
Time (msec)

Fig.3a Temperature (eV9



Time (msec)

Fig.3b Temperature (eV)



Time (msec)