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PPPL- 4579

PPPL- 4579

Microtearing Instability In The ITER Pedestal

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December, 2010

Prepared for the U.S. Department of Energy under Contract DE-AC02-09CH11466.

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Abstract

Unstable microtearing modes are discovered by the GS2 gyrokinetic simulation code, in the pedestal region of a simulated ITER H-mode plasma with approximately 400 MW DT fusion power. Existing nonlinear theory indicates that these instabilities should produce stochastic magnetic fields and broaden the pedestal. The resulted electron thermal conductivity is estimated and the implications of these findings are discussed.

The main goal of the ITER project [1] is to achieve a DT fusion power amplification factor Q > 10, which relies on a high confinement H-mode plasma whose performance hinges on the electron temperature T_e at the top of the pedestal. Various estimates end up with T_e ~5keV there [2, 3]. This means steep temperature and density gradients in the pedestal which can drive various instabilities. The present studies of the pedestal emphasize the peeling-ballooning instability; it can explain experimental observations associated with the edge-localized mode (ELM) very well. The heat flux released by large ELMs is known to be a problem for large tokamaks. The plasma facing components in ITER are not compatible with unmitigated type-I ELMs, and RMP coils [4] are being planned to eliminate them. Such a scheme has been successfully demonstrated in the DIII-D tokamak. The steep temperature gradient can also drive other instabilities like electron temperature gradient modes (ETG), trapped-electron modes (TEM), ion temperature gradient modes (ITG) and microtearing modes [5]. In this paper, we focus our attention on the microtearing instability in the ITER pedestal because it can produce very high electron thermal transport at $T_e \sim 5$keV and lead to significant changes in the pedestal profile.

The ITG mode propagates in the ion diamagnetic drift direction, while ETG, TEM and microtearing modes propagate in the electron diamagnetic drift direction. The microtearing mode is distinctly different from the other modes in the symmetry properties of its eigenfunctions. The perturbed electric potential $\delta\phi$ and the parallel magnetic field $\delta B_{||}$ are anti-symmetric about the minimum magnetic field location along the magnetic field while ITG, ETG and TEM modes have symmetric eigenfunctions. However, in a tokamak plasma with a single-null divertor (SND), the magnetic field near the separatrix is not up-down symmetric, and the symmetry of the eigenfunctions will be reduced. The GS2 gyrokinetic simulation code [6, 7] has been used extensively to investigate microtearing instabilities in the NSTX tokamak [8, 9]. In beam-heated plasmas, there is usually a competition between ITG and microtearing modes as to which is the most unstable. Fig.1a shows the ITG eigenfunctions of $\delta\phi$ and $\delta B_{||}$ at r/a=0.75 – far from the separatrix. An ITG mode propagates in the ion direction ($\omega>0$) with a symmetric eigenfunction, while a microtearing mode propagates in the electron direction ($\omega<0$) with an anti-symmetric eigenfunction (Fig.1b). At r/a=0.85 – close to the separatix, only an ITG ($\omega>0$) mode can be found; the eigenfunction is shifted to $\theta=2\pi$, and it is not exactly symmetric about $\theta=2\pi$ as shown in Fig.1c. This is an important feature in the study of microinstabilities in the pedestal region of a tokamak.

A recently published simulated ITER H-mode plasma [10] 2006P07 was chosen for our investigation. It has approximately 400 MW DT fusion power at t=300s. The GS2 code finds the most unstable mode at specified values of $k\rho_s$. When one scans the value of $k\rho_s$, the most unstable mode can vary; this usually happens when there is a jump-discontinuity in the ω versus $k\rho_s$ plot as shown in Fig.2a. Microtearing instabilities are discovered this way near the top of the pedestal where r/a=0.973, $n_e=7.5\times10^{13}$ cm^{-3}, $T_e=5.3$ keV$=T_i$, with $k\rho_s$ in the region $2.4 < k\rho_s < 3.2$. Fig.2b depicts the anti-symmetric eigenfunctions at $k\rho_s=3.0$. At r/a=0.98, near the middle of the pedestal, microtearing modes are found with $k\rho_s$ in the region $4.8 < k\rho_s < 5.6$. Their eigenfunctions are only approximately anti-symmetric as shown in Fig 3 because this location is closer to the separatrix and the up-down asymmetry of the magnetic field affects the eigenfunctions. This effect becomes even more severe near the bottom of the pedestal.

The electron temperature in the ITER pedestal is in the multiple keV range; the electron-ion collision rate ν_{ei} is very low, and the growth rate of the microtearing instability should increase with ν_{ei} as shown in Fig.4; the real frequency of the most unstable mode may drop below the growth rate at very high electron-ion collision frequency. When one raises the electron temperature gradient, the growth rate increases rapidly as expected, and the most unstable mode has $k\rho_s < 1$ with higher real frequency. This suggests the possibility to control the instability with a gas jet. Deuterium neutral gas can penetrate the first few centimeters of the pedestal, cool down the electron temperature, and raise ν_{ei} as well as the electron temperature gradient as shown in Fig.5, so the instability growth rate should go up at that location. One can mimic the effect of the gas jet by changing T_e to $T_e /2$, ν_{ei} to 2.83 ν_{ei} , $\partial_r T_e$ to 2 $\partial_r T_e$ at r/a=0.985 and microtearing modes appear at $k\rho_s <1$. Fig.6 depicts the eigenfunctions at $k\rho_s =0.32$, which is approximately anti-symmetric about $\theta=-4\pi$. From the fusion reactor performance point of view, it is highly desirable to have a steady state H-mode pedestal without ELMs, but it is not obvious that such a steady state solution can always be achieved. Intermittent duty cycle ELM behavior may occur. The steepened 'cold-front' may propagate into the plasma interior as observed in the NSTX experiment [11].

Existing nonlinear theory [12] indicates that microtearing instabilities should saturate at the level of $\delta B/B \sim \rho_e/L_T$ where δB is the perturbed magnetic field, ρ_e is the electron gyro-radius, and L_T is the electron temperature gradient scale length. Microtearing modes produce magnetic islands near the rational magnetic surfaces where q=m/n. When neighboring island chains overlap, stochastic magnetic fields are produced which can greatly enhance electron thermal transport in high temperature plasmas. Since ITER is a very large device, microtearing modes have very high mode numbers ($100 < n < 1000$); the rational magnetic surfaces are tightly packed, and island overlap happens very easily. One can use Eq.(6) in Ref.[9] to estimate the Chirikov stochasticity parameter. With $k\rho_s = 0.32$ at r/a=0.985, one can get $S>100>>1$; much higher values of S are obtained for $k\rho_s >1$. This means that the result for the electron thermal conductivity from Ref.[13] is applicable to the pedestal of ITER where the electron mean-free-path λ_{mfp} is much longer than the field line connection length qR, i.e., the electrons are in the collisionless regime, and the electron thermal conductivity in the stochastic magnetic field becomes

$$\chi_e = (\lambda_{mfp}/qR)\ (\rho_e/L_T)^2\ v_e^2/(\nu_{ei}\ q) \qquad (1).$$

It is apparent from Eq.(1) that $\chi_e \sim (T_e)^4$; it increases very rapidly with T_e. At $r/a=0.985$, T_e =3.2 keV, $n_e \sim 7\ x10^{13}\ cm^{-3}$, L_T=5.4cm, L_n=25cm, q=3.5, $qR/\lambda_{mfp} \sim 0.15$ and Eq.(1) yields $\chi_e \sim 2x10^7\ cm^2/s$. At r/a=0.973 , near the top of the pedestal, T_e~5.3keV, L_T=7.8cm, n_e~$7.5x10^{13}cm^{-3}$, $qR/\lambda_{mfp} \sim 0.05$ and $\chi_e \sim 1.4x10^8\ cm^2/s$. Such high values of χ_e should overwhelm the heat transport due to other microinstabilities. The value of χ_e obtained from transport analysis [10] of the ITER pedestal region, self-consistent with the heat flux and the temperature profile, is below $3x10^5\ cm^{-3}$, two orders of magnitude lower than the above values. This simply means that such a steep temperature profile will not hold - the pedestal will be broadened by the unstable microtearing modes.

Microtearing instabilities have been observed in the edge of conventional tokamaks in the past [14,15]. Therefore, it should not be a surprise to find them unstable in the edge of ITER. Although this finding involves no new physics, it has serious implications for ITER that may influence the future research direction in this area as we shall consider in the following.

Accurate prediction of the pedestal height and width is a high priority research topic for the ITER project. EPEDE1 [3] is the prevailing model; it is an extension of the peeling-ballooning theory coupled with empirical scaling of experimental results from existing tokamaks (or KBM constraints) that can predict the pedestal height and width simultaneously for ITER. One would feel more comfortable with these predictions should the ITER pedestal be governed by the same instability as in existing conventional tokamaks, which does not seem to be the case. The typical electron temperature is only a few hundred eV in the edge of most existing tokamaks, and the thermal electrons are in the collisional regime. The χ_e due to stochastic magnetic fields is only in the 10^4 cm^2/s range. Unlike the ITER case, microtearing modes in existing conventional tokamak experiments do not play a dominant role in edge electron thermal transport due to the low edge electron temperature.

It is important to notice that EPEDE1's prediction of the ITER pedestal profile is steeper than the profile we use in our analysis. DIII-D experiments [4] have already demonstrated that externally imposed stochastic magnetic fields could eliminate ELMs by keeping the pedestal stable against the peeling-ballooning instabilities. Once the magnetic field becomes stochastic, it makes no difference whether it is from over-lapping of large magnetic islands due to externally driven currents, or from overlapping of small islands due to microtearing instabilities [16]. Based on the above analysis, we can expect that microtearing modes will become unstable before the peeling-ballooning modes in the ITER pedestal. This spontaneous process will broaden the pedestal and avoid large ELMs, which is a desirable outcome. On the other hand, the pedestal may become so broad that the required H-mode may not be accessible, and the main goal of $Q>10$ may not be achievable. Therefore, it is important to understand the details of the nonlinear dynamics associated with the instability saturation, pedestal formation and relaxation processes. This is an important, complex and interesting problem for future research.

The peeling mode is an external kink mode [17] driven by edge current; the ballooning mode is driven by plasma pressure. These are ideal MHD modes described by J' (current density gradient) and p' (pressure gradient). The stability boundary in this case is a line in the corresponding 2D plane [3]. Microtearing instability involves kinetic effects; the mode is primarily driven by the temperature gradient T'. but it also involves the density gradient n' , the local magnetic shear and the collision frequency ν_{ei} which affects the trapping and detrapping of electrons. Four variables have already been identified for the instability, and the stability boundary becomes a 3D surface in a 4D manifold – it is a more challenging problem. It seems that much more work would be needed for a reliable prediction of the ITER pedestal parameters.

Finally, it should be pointed out that the GS2 code was not written to study edge phenomena in tokamaks. For ITER's parameters, $\rho_D / L_T \sim 0.19cm / 6.4cm << 1$, $\rho_D / L_n \sim 0.19cm / 27cm << 1$, i.e, the basic assumptions of gyrokinetic theory are still valid. However, q changes rapidly and ω^*/k_y is not constant in the pedestal, and the complexity associated with the magnetic separatrix is not considered. The results presented here only represent a first cut at looking into the problem with the tool available to us. These results should be confirmed by more appropriate simulation codes, which may still be years away.

Acknowledgements: We are grateful for helpful discussions with Drs. R. J. Hawryluk, G. W. Hammett and R. B. White. This work is supported by USDoE Contract No. DE-AC02-09CH11466.

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Figure captions

Fig.1. Eigenfunctions for an NSTX SND plasma(#116313): (a) Symmetric eigenfunction for ITG mode at r/a=0.75, $k\rho_s$=0.3, (b) anti-symmetric eigenfunction for microtearing mode at r/a=0.75, $k\rho_s$=0.6. (b) Reduced symmetry of ITG eigenfunctions at r/a=0.85, $k\rho_s$=0.6. $\boldsymbol{\theta}=(l_s/qR)\mathbf{B}/B$ is the normalized distance along a field line, and θ=0 is the point on the outboard mid-plane where B is at its minimum value.

Fig.2. (a) The frequency of the most unstable mode at r/a=0.973 in ITER at various values of ky=$k\rho_s$. (b) Microtearing mode eigenfunction at $k\rho_s$ =3.0.

Fig.3: Approximately antisymmetric eigenfunctions at r/a=0.98, $k\rho_s$=4.8 in ITER.

Fig.4: (a) Variation of the mode frequency(blue) and the growth rate(red) of the most unstable microtearing mode with electron-ion collision frequency at r/a=0.973 in ITER. (b) Schematic drawing for the change in edge electron temperature profile due to a deuterium gas jet.

Fig.5: Approximately anti-symmetric eigenfunctions with $k\rho_s$ =0.32 at r/a=0.985 in ITER after the change of parameters (changing T_e to T_e /2, ν_{ei} to 2.83 ν_{ei} , and $\partial_r T_e$ to 2 $\partial_r T_e$) to mimic the gas jet effects.

Figure 1

Fig.1a

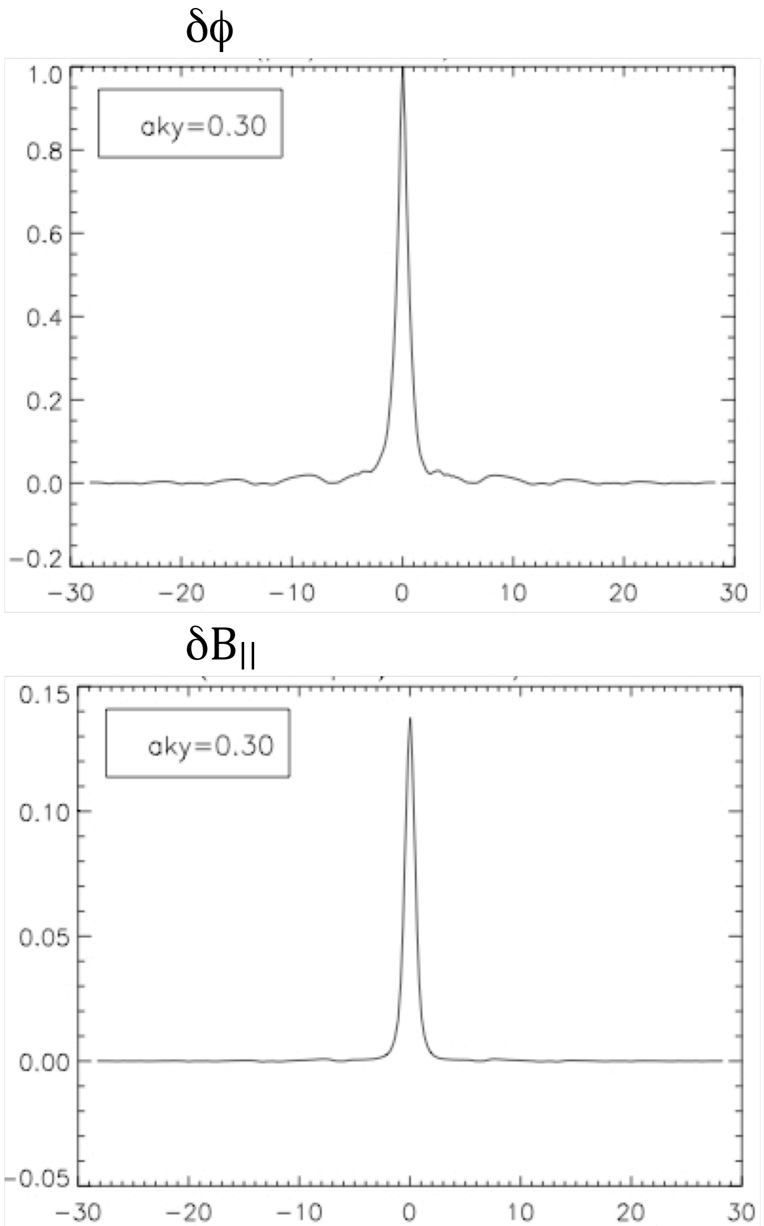
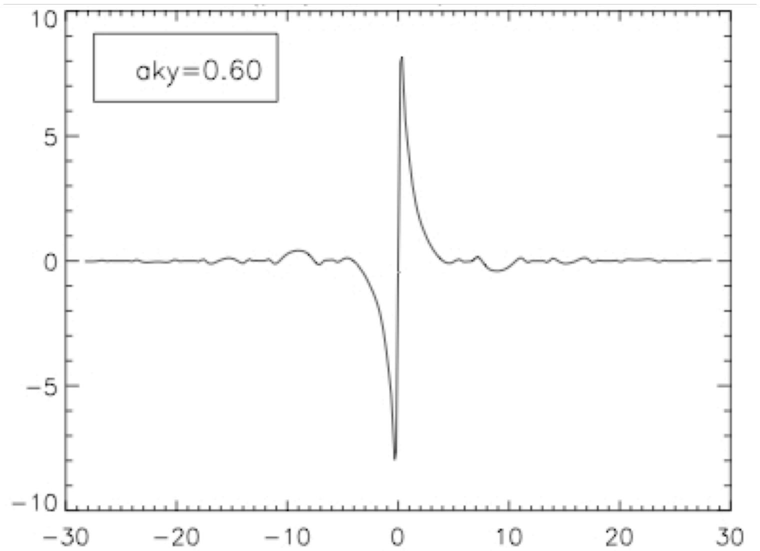


Fig.1b

$\delta\phi$



$\delta B_{||}$

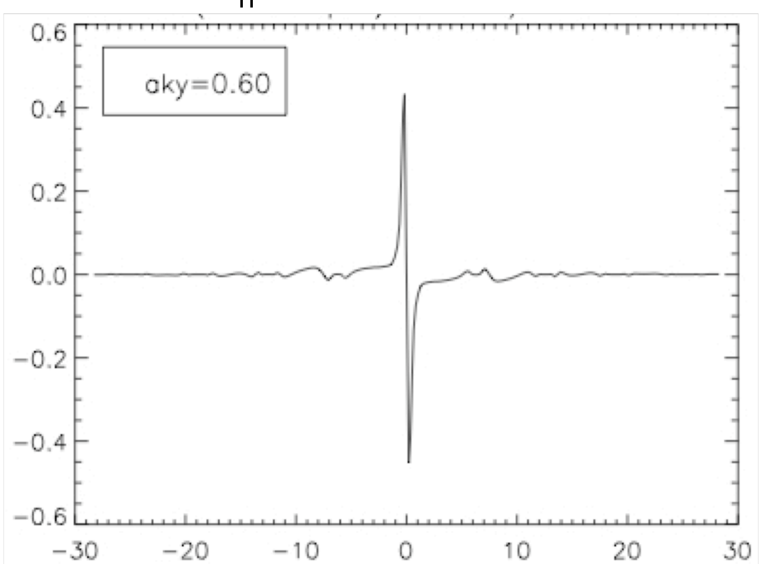
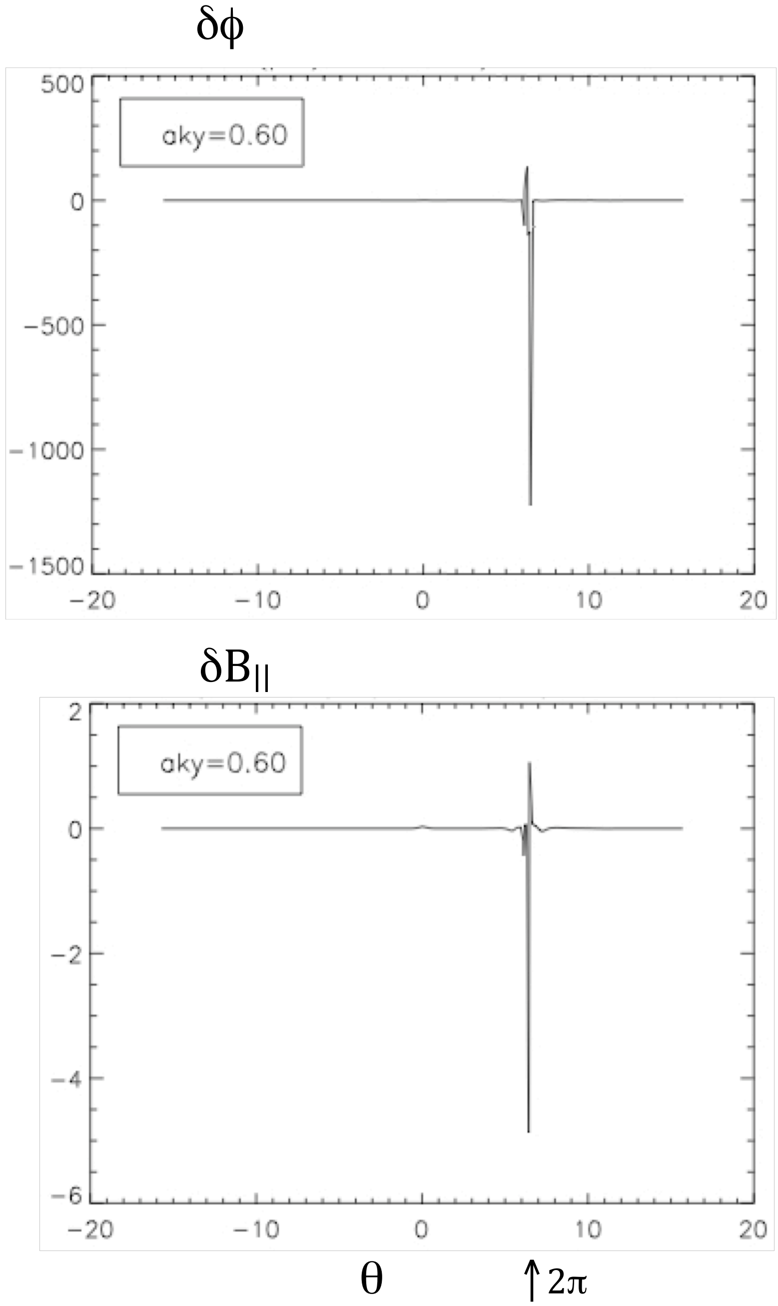


Fig.1c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500
0
−500
−1000
−1500
−20
−10
0
10
20
δB||
aky=0.60
2
0
−2
−4
−6
−20
−10
0
10
20
θ
↑2π

Figure 2

Fig.2a

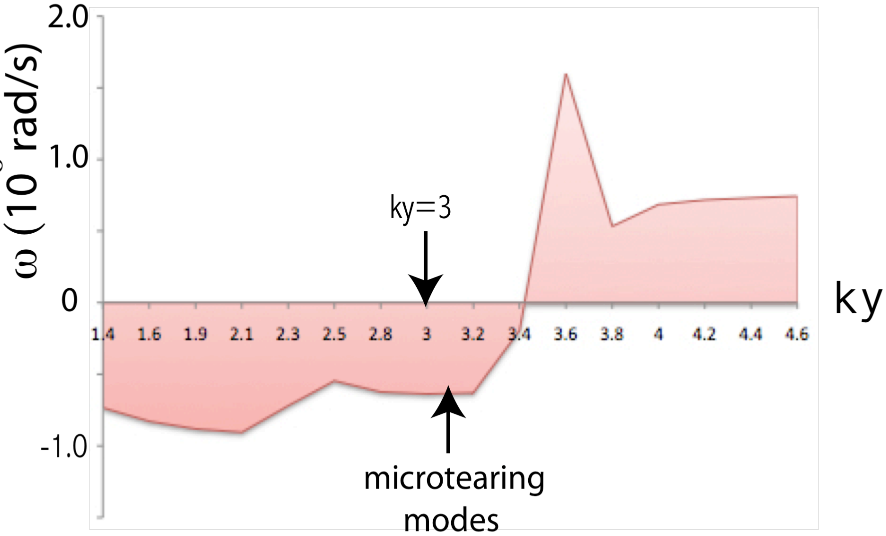
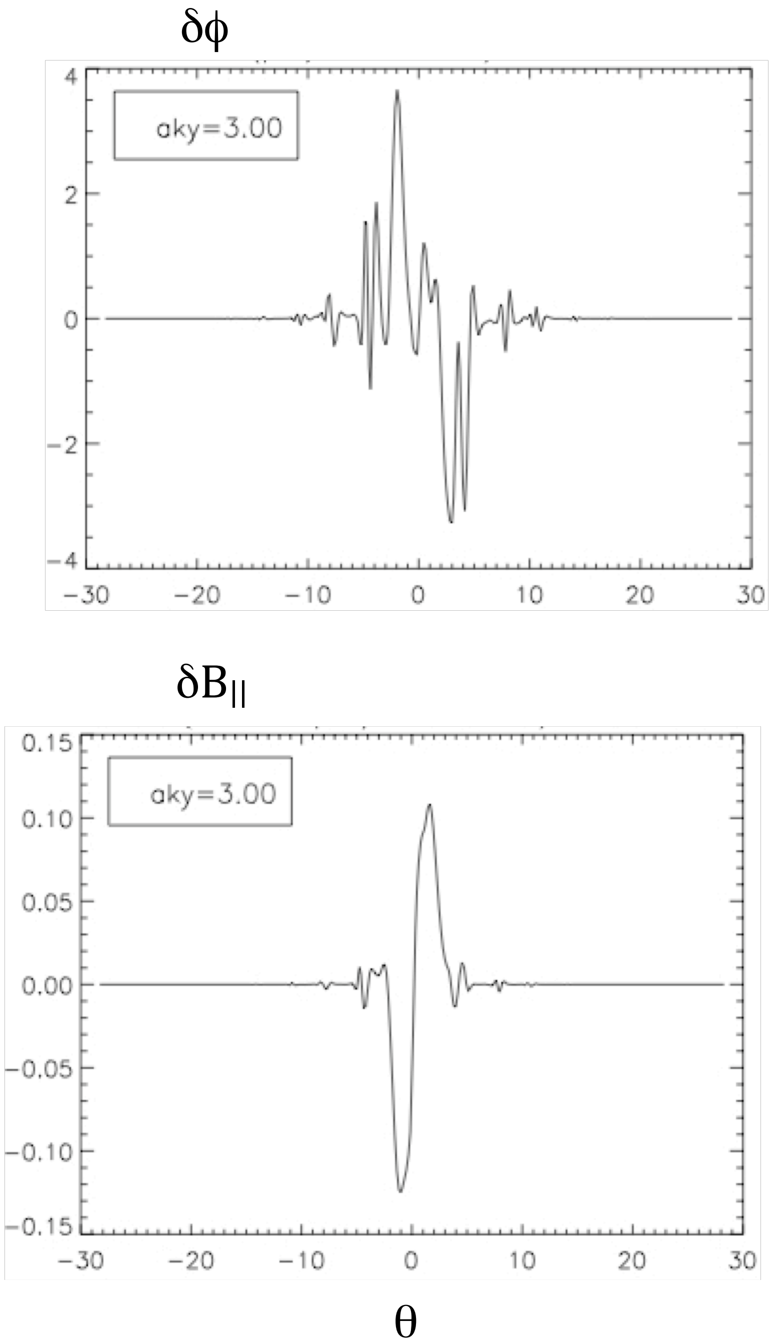


Fig. 2b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2
0
−2
−4
−30
−20
−10
0
10
20
30
δB||
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0.15
0.10
0.05
0.00
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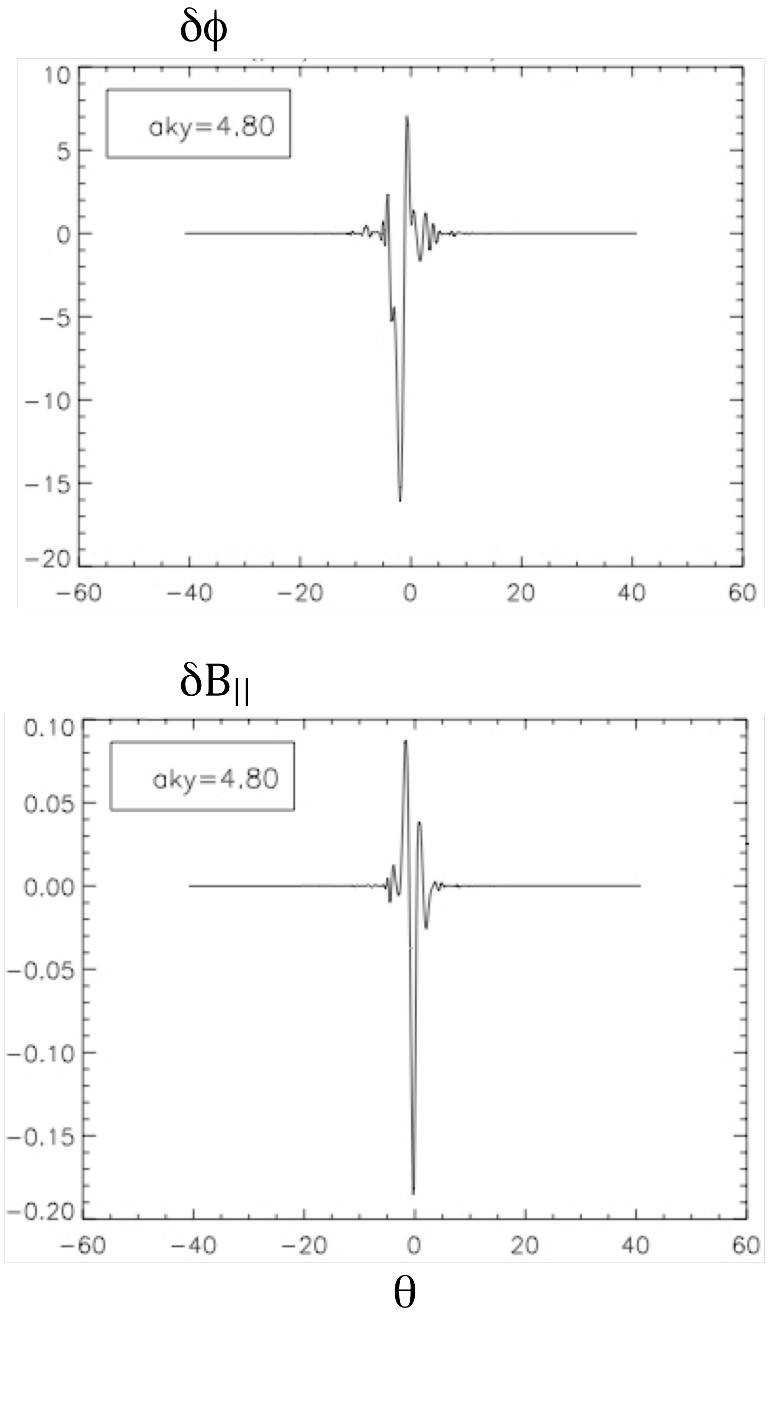
−0.10
−0.15
−30
−20
−10
0
10
20
30
θ

Figure 3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−5
−10
−15
−20
−60
−40
−20
0
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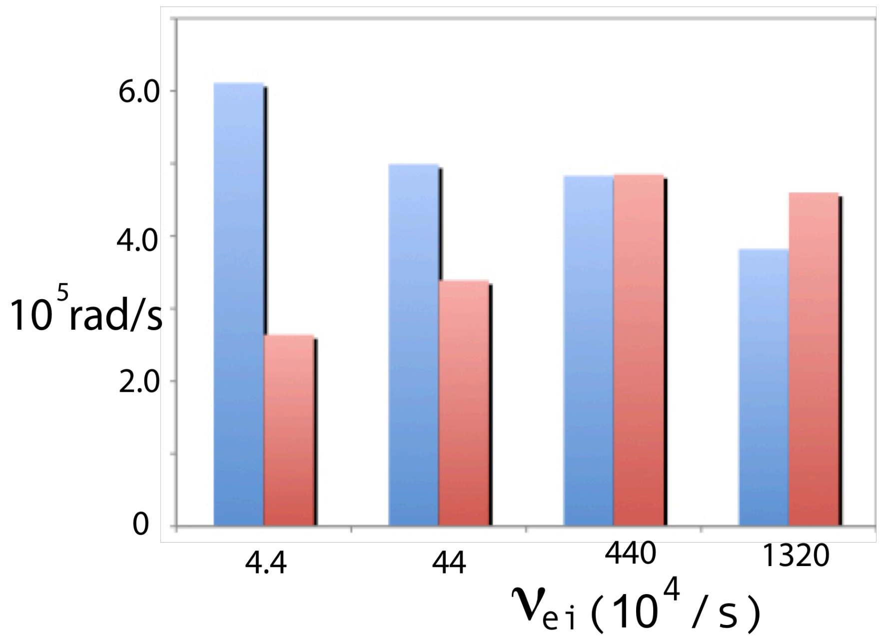
40
60
δB||
aky=4.80
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.20
−60
−40
−20
0
20
40
60
θ

Figure 4

(a)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4.0
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0
4.4
44
440
1320
νei (10^4 / s)

(b)

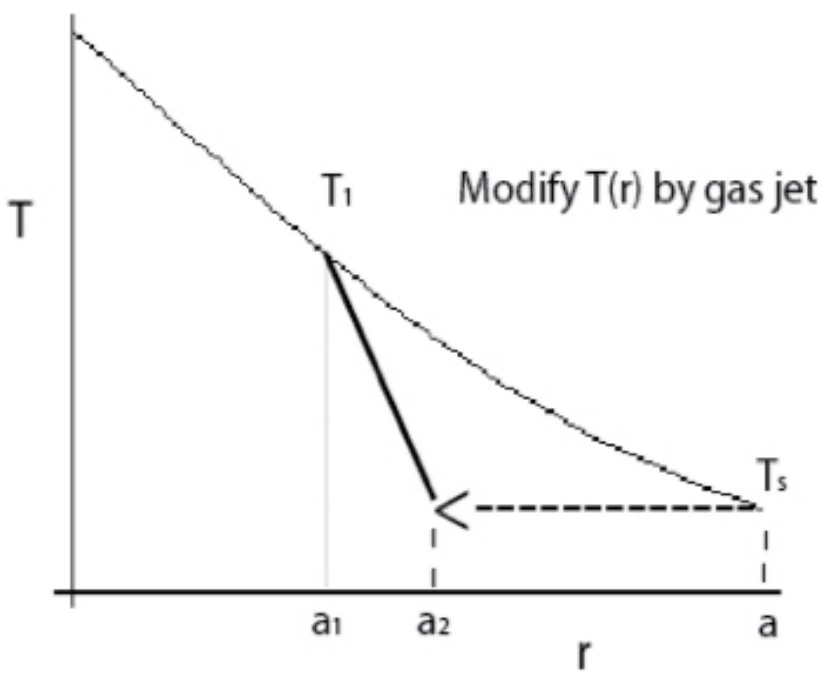
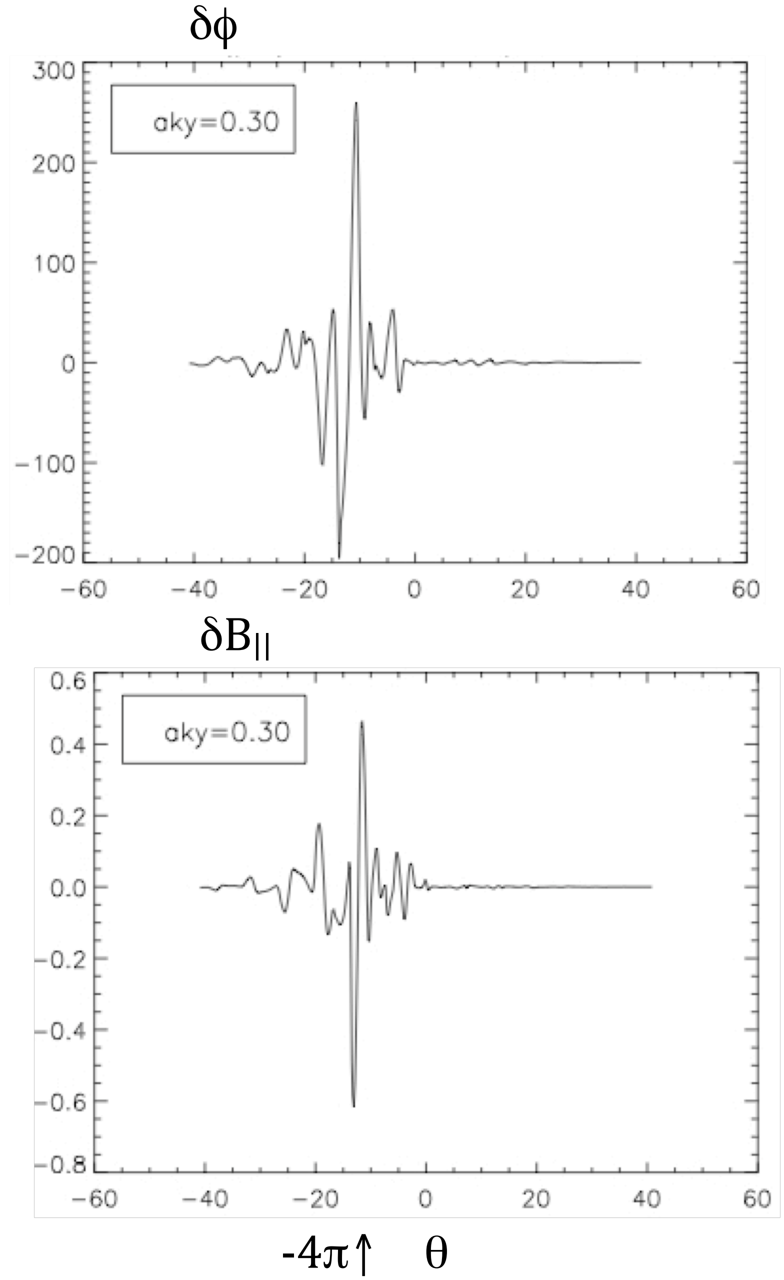

T
T1
Modify T(r) by gas jet
Ts
a1
a2
a
r

Figure 5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200
100
0
−100
−200
−60
−40
−20
0
20
40
60
δB||
aky=0.30
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−60
−40
−20
0
20
40
60
-4π↑
θ

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