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High-Beta Experiments with Neutral-Beam Injection on PDX*

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Abstract

We report experimental investigations of high-beta plasmas produced in PDX with near perpendicular neutral-beam injection. Systematic power scans have been performed over a wide range of toroidal fields ($0.7\text{T} < B_T < 2.2\text{T}$) and plasma currents ($200\text{ kA} < I_p < 500\text{ kA}$). At high toroidal fields, the change in total stored energy due to beam injection increases linearly with input power and also increases with plasma current. At lower toroidal fields and low injection-power levels, the stored energy also increases with power and plasma current. However, at high power and low toroidal fields, a saturation in heating is observed. This result suggests the onset of a β_T limit for circular cross-sectional tokamaks with near-perpendicular injection. Scaling experiments indicate that this β_T limit increases with rising $(1/q)$. Values of $\beta_T \approx 3\%$ at $q_y = 1.8$ have been achieved.

At high values of $\beta_T q$, short bursts of MHD activity are observed synchronized with sharply increased fluxes of perpendicular charge-exchange neutrals and rapid decreases in the rate of beam-driven neutron production. When strong bursts occur, there is a significant depletion of the fast-ion population. Estimates of the fast-ion loss indicate that it could explain the observed decrease in heating, although an additional reduction in thermal-plasma confinement cannot be ruled out. Numerical studies using measured pressure profiles predict that the equilibria obtained become unstable to the ideal $n = 1$ internal mode, at about the same value of $\beta_T q$ where the new fluctuations are observed.

I. Introduction

Extensive studies have been made of plasma heating in the PDX tokamak with high power neutral beams. The PDX device operates in several divertor and limiter configurations [1,2] and is characterized by $B_T < 2.4$ T and $I_P < 500$ kA. The four neutral beams use 50 keV, 100A duopigatron sources [3] which deliver up to 5.5 MW of H^0 or 7.2 MW of D^0 beams through the vacuum vessel ports, for pulse lengths up to 300 msec. The beams inject at an angle of 14° from perpendicular at the center of the vacuum vessel. Unless specifically noted, the data presented here result from operation with carbon rail limited H^+ discharges with $R, a = 143, 42$ cm, and with D^0 injection along the direction of the plasma current.

The first objective of the PDX program was to evaluate the effectiveness of near perpendicular injection. As reported in references [4],[5], and [6] for limiter discharges ($R, a = 143, 44$ cm) with $\bar{n}_e$ in the range $2.2 - 3.4 \times 10^{13} \text{ cm}^{-3}$ at high field (2.2 T) and high current (500 kA), ion heating efficiencies $\eta_i = (n_e \Delta T_i) / P_{\text{abs}}$ of up to $4.5 \times 10^{13} \text{ cm}^{-3} \text{ keV/MW}$ were obtained with central ion temperatures reaching 6 keV. (P_{abs} here denotes the portion of the neutral beam power ionized in the plasma.) These values are comparable to results in similar discharges with tangential injection on PLT [7]. The parameter η_i was found to increase with plasma current (200 - 500 kA) and to be comparable in divertor and limiter discharges with the same current. $\beta_p + l_i/2$ was measured magnetically for power scans at 200, 300, and 480 kA. Subtracting $l_i/2$ calculated from the measured $T_e(R,t)$ by solving the magnetic diffusion equation, the results show a linear increase in stored energy with absorbed power, and a favorable scaling of heating with plasma current. Using measured $n_e(R,t)$, $T_e(R,t)$, and radiation profiles along with $T_i(0)$, transport analysis [6] of these discharges yields global thermal confinement times $\tau_E(a)$

of ~ 22 msec for the higher currents and ~ 12 msec for the 200 kA case. These values are significantly less than the corresponding ohmic values, but show no significant dependence on absorbed power.

Recent work has concentrated on studying high β_T plasmas at lower toroidal fields (0.7 - 1.5 T). These experiments are the primary subject of this report. Concurrent efforts have addressed the questions of power loading and impurity control [2] and pellet fueling [8], particularly as these relate to operation with high power neutral injection.

II. High Beta Operating Parameter Range

A data base from over 1000 PDX discharges has been assembled during the neutral beam heating experiments. An important criterion for selection of the data is the MHD character of the discharge: plasmas with continuous $m = 2$ activity or disruptions prior to the analysis time have been discarded. For all discharges in the data base, equilibrium magnetic data are available, while for discharges with $B_T < 1.5$ T diamagnetic data are also included. For the majority of cases Thomson scattering profiles of $T_e(R)$, $n_e(R)$, central ion temperatures, and radiated power profiles have also been measured. A wide range of additional magnetic, kinetic, and fluctuation measurements necessary for confident interpretation of the data is also available. Figure 1 shows the ranges in B_T and I_p for the subset of ~ 600 discharges used in the scaling discussion which follows. The principal boundaries of the operating region illustrated in Fig. 1 are $I_p > 200$ kA and $q_{cyl} > 1.7$ ($q_\psi > 1.9$). Neutral beam injection below 200 kA, while possible, results in the loss of $> 10\%$ of the heating power through classical bad-orbit losses. Operation at $q_\psi \sim 1.7$ has been achieved at $a = 40$ cm, but to reach even our typical operating values $q_\psi \sim 2.0$ requires careful tuning of the discharge.

Each circled cluster of points in Fig. 1 represents a fully documented, controlled power scan. Power scans were performed typically at constant field and current, varying the beam power by changing the number of beams injecting. The density could not be maintained precisely constant. Ohmic values were typically $\bar{n}_e \sim 2.5 \times 10^{13} \text{ cm}^{-3}$ while the density with 1 - 4 beams could be maintained close to a chosen level of typically $4 \times 10^{13} \text{ cm}^{-3}$. At the highest beam powers, plasma currents, and toroidal fields, however, $\bar{n}_e$ exceeded the selected value, reaching $6 - 8 \times 10^{13} \text{ cm}^{-3}$ in the most extreme cases. While this variation affects the partition of the stored energy between ions, electrons, and beam particles, and thus affects the thermal confinement analysis, experience at $B_T \sim 2 \text{ T}$ [4] and limited scaling experiments at low field show no consistent variation of total stored energy with density in this range.

Z_{eff} measured from visible bremsstrahlung emission, ultra-violet spectroscopy, and plasma resistivity, is in the range of 1.5 ± 0.5 for all of the recent discharges with $B_T < 1.5 \text{ T}$. Radiation from the central region of the plasma ($r < a/2$) was measured by bolometry to constitute a negligible drain (<10%) on the electron power balance.

III. Comparison of Measurement Techniques for Beta

Figure 2 shows a scatter plot of the diamagnetic measurements of β_p and β_T for each discharge in Fig. 1 with $B_T < 1.5 \text{ T}$.¹ Toroidal betas of 3% have been achieved at $\beta_p \approx 1$. Also shown in this figure is a rough boundary between points which clearly exhibit a strong new form of MHD fluctuation, and

¹We use $\beta = 2\mu_0 \langle p \rangle / B^2$ where $p = P_{\text{el}} + P_{\text{ion}} + P_{\text{beam}}^{\text{I}}$ for the diamagnetic values and $p = P_{\text{el}} + P_{\text{ion}} + 1/2 (P_{\text{beam}}^{\text{I}} + P_{\text{beam}}^{\text{II}})$ for the equilibrium values; $B = B_T$ evaluated at the geometrical center and $B = \mu_0 I_p / 2\pi a$ for toroidal and poloidal cases respectively. $\langle \rangle$ indicates volume average.

points which do not. These new fluctuations have come to be known as "fishbones" and will be described in detail later in this paper.

The data in Fig. 2 are based on a determination of the diamagnetic flux using measurements of the voltage and current in the toroidal field coil system [9]. A second method [10] uses values of B_V and I_p to obtain $\beta_p + \ell_i/2$. A simple model of the form $\ell_i/2 = f[q(a)]$ is used to arrive at equilibrium beta values. The $\ell_i/2$ model has been developed on the basis of magnetic diffusion calculations which use measurements of $T_e(R,t)$, as for the high field cases.

Two other techniques make use of large-scale numerical codes. One code, adapted from the PEST equilibrium package [11], simulates MHD equilibrium in PDX. It uses the pressure profile shape derived from Thomson scattering $n_e(R)$ and $T_e(R)$ data, poloidal flux and poloidal field coil current measurements, and the location of the $q = 1$ surface determined from X-ray measurements to determine beta. Finally, a transport analysis code [12] uses measured values of $n_e(R)$, $T_e(R)$, and $T_i(r=0)$, and assumes classical beam ion thermalization to calculate beta values. A sample of the single-shot Thomson scattering profiles used in these codes is shown in Fig. 3.

Two of the possible cross-comparisons of these techniques are shown in Fig. 4. The agreement is close at low beam power in both cases. For beam heated discharges, the diamagnetic beta is, in general, slightly greater than the equilibrium value, as expected on the basis of classical beam ion thermalization. There is a class of cases at high beam power and low toroidal field where the kinetic code consistently calculates a higher value of beta than determined from the other analyses. A possible explanation for this is that there is a significant loss of fast perpendicular beam ions in these cases, which is not taken into account in the transport analysis calculations shown here.

IV. High Beta Scaling

From the scaling of neutral beam heating with plasma current and toroidal field observed in PDX [4], ISX-B [13], and DITE [14], the region of parameter space where the highest β_T is expected in PDX is at low B_T , high beam power, and the lowest q_ψ obtainable. In approaching this region, however, either by increasing power at fixed low B_T and low q , or by lowering B_T at fixed low q and high power, the full expected increase in β_T was not obtained. Attention then focused on studying the apparent limitation in β_T , both through scaling studies described in this section, and through MHD fluctuation measurements reported in section V. Unless otherwise indicated, the scaling results derived in this section and supporting data presented result from the diamagnetic determination of β .

Figure 5 shows β_p from three power scans conducted at $B_T = 1.5, 1.2$, and 0.7 T, with I_p in the range of $220 < I_p < 270$ kA. It is clear that despite the similar currents in these scans, the functional dependence of β_p on P_{tot} (the total ohmic plus ionized beam power) depends significantly on B_T , in contrast to results reported from ISX-B [13]. At high powers, the low field data show clear saturation, while the high field points continue to rise linearly. Evidently it would be inappropriate to use a simple power law scaling of the form $\beta_p \propto P_{tot}^x I_p^y B_T^z$ to fit this data.

Figure 6 shows β_T versus total power for the controlled current and power scan at $B_T = 1.2$ T. Saturation curves of the form $\beta_T = C_1[1 - \exp(-P_{tot}/C_2)]$ have been fitted through the data as guides for the eye. Ohmic heated plasmas, which have been omitted from all the scaling studies reported here, generally fall above the fitted curves (i.e., have better gross confinement) and, in general, show quite different scaling from that obtained for beam-heated discharges. In all cases employed in these scaling studies, even with beam injection, $P_{oh}/P_{tot} < 20\%$.

A striking feature of the curves shown in Fig. 6, and common to all of our scaling studies to date, is that at fixed B_T only the amplitude of the curves varies with I_p , while the shape remains fixed. Insofar as these curves each show a similar degree of saturation with increasing P_{tot} , this indicates that the limiting β_T for each case will depend favorably on $1/q$, consistent with results from [13] and [14]. Averaging the somewhat different q -scalings observed in the wide current scans at 1.5 T and 1.2 T, and in the more limited range of currents at 0.7 T and 1.0 T (see Fig. 1), we find that plotting $\beta_T q_{cyl}^x$ against P_{tot} with $x = 1.15$ succeeds in generating a unique curve for each value of B_T (Fig. 7a-d). The degree of curvature in $\beta_T q_{cyl}^{1.15}$ vs P_{tot} is evidently a monotonically decreasing function of B_T . This explains why our previous results at $B_T = 2.2T$ showed no sign of saturation, even at low currents and $\beta_p = 2.0$ ($\epsilon\beta_p = 0.6$).

The curves shown in figures 7a-d are highly suggestive of a limit to $\beta_T q_{cyl}^{1.15}$ in the vicinity of 0.055, which is approached with varying degrees of severity as a function of toroidal field. (We cannot, of course, eliminate the possibility of a much higher limit, or no limit at all, for the 1.5T data, which show no discernible curvature. In addition, no aspect ratio scaling of the limit can be deduced from this data set, since a and R are held constant.) In order to collapse the four curves of Fig. 7 with the rest of our data base (including 0.8T and 0.9T, and $a = 40$ cm data) into a single universal curve, we are free only to scale the horizontal axis with a function of B_T . The best fit for the diamagnetic measurements, using a horizontal axis of the form $P_{tot}/B_T^{1.4}$, is shown in Fig. 8. Evidently the shapes of the curves at different values of B_T fit together into a single tight curve with the chosen scaling of P_{tot} . The limiting value of $\beta_T q_{cyl}^{1.15}$ is closely approached by data in the range of $0.7 T < B_T < 1.0 T$. There is only a modest

q_{cyl} range in the strongly saturated data ($1.6 < q_{cyl} < 2.1$). Thus the q scaling of saturation rests in large part on the similar degree of curvature of the 1.2 T data at various q 's (Fig. 6). It is also supported by the agreement of the non-linearity of the higher- q 1.2 T data with that of the lower q , $B = 0.7 - 1.0$ T data, which show strong saturation at higher $P_{tot}/B_T^{1.4}$. However, to determine accurately the precise power of the q scaling of the β_T limit is not possible on the basis of this data set.

Insofar as the variation of $\beta_{Tq_{cyl}}^{1.15}$ at low $P_{tot}/B_T^{1.4}$ approximates simple proportionality, one can derive the low power scaling of "diamagnetic" global confinement,

$$\tau_g^* \equiv \frac{3\pi^2}{2\mu_0} \beta_T B_T^2 R a^2 / P_{tot}$$

to be $\tau_g^* \propto I_p^{1.15} / B_T^{0.55}$. A study of the scaling of equilibrium values of β_T similar to that which has been described here for the diamagnetic values, but also including the 2.2 T data, gives close to the same saturation limit, and results in a low power confinement scaling $\tau_g^* \propto I_p / B_T^{0.2}$. The favorable scaling with current is, of course, not unexpected. The weak inverse B_T scaling at low power is, perhaps, surprising, not unprecedented [14]. It is, also a consistent feature of our data set (see, for instance, the one-beam points in Fig. 5). This scaling result would be further tested by systematic B_T scans at fixed I_p and fixed (very low) power, which we have not performed.

V. High Beta MHD Fluctuations and Loss of Fast Ions

As shown by the boundary in Fig. 2, which approximates a line of constant $\beta_{T\text{cyl}}$, nearly all the high beta discharges are characterized by "fishbone" activity. The name "fishbone" derives from the appearance of repetitive short bursts of oscillation on the Mirnov traces, which form an overall pattern reminiscent of the bone structure of a fish. At its highest levels this MHD fluctuation is so pronounced that it is observed on nearly all diagnostics with sufficient time response.

The soft X-ray emissivity and the $\tilde{B}_\theta$ measurement of the Mirnov coils are used to characterize the evolution of MHD activity as beam power increases. At low beam power and low toroidal field ($\beta_{Tq} < 0.025$) the $m = 1$ sawtooth precursor oscillation observed near the $q = 1$ surface on the soft X-ray system couples out to higher m mode magnetic oscillations at the plasma boundary, which are detected on the Mirnov coils. At higher injected powers ($\beta_{Tq} \sim 0.045$) envelopes of $m = 1$ activity are seen on the soft X-ray signals not only at the sawtooth fall, but also at frequent intervals during the rise of the sawtooth, without an accompanying drop in the central chord X-ray emissivity. These $m = 1$ bursts also couple out to the Mirnov coils as higher m modes. At low B_T and the highest beam powers, the fishbones do cause drops in the central X-ray emissivity and the sawtooth structure disappears, so that the fishbones dominate both the X-ray and Mirnov signals as shown in Fig. 9.

The mode spectrum of the magnetic oscillations seen on the Mirnov coils contains a mixture of components with $m > 2$. The period between bursts ranges from 2 to 10 msec and scales roughly as B_T . The frequency of the oscillations internal to the fishbones ranges from 8 to 20 kHz and scales about as E_{inj}/I_p which is similar to the scaling of the precession frequency of the injected fast ions. At highest beam powers, an additional high frequency (50-150 kHz) precursor oscillation is observed.

Spikes of greatly increased charge-exchange neutral efflux are observed to be phase and frequency correlated with the Mirnov signal, as seen in Fig. 9. At moderate instability levels, the spikes are observed in the energy range from $E_{inj}/2$ to E_{inj} . At high fishbone levels the spikes extend from thermal energies up to $1.5 \times E_{inj}$, well above the extent of the usual high energy tail. In the absence of fishbones, measured charge-exchange slowing down spectra, as functions of both angle and energy, show good detailed agreement with Monte-Carlo calculations. At high fishbone levels, however, there is a marked depletion in the fast ion distribution between $E_{inj}/2$ and just below E_{inj} . In the angular scan range available, from counter near-perpendicular to counter parallel, the charge-exchange spikes and depletion are seen to occur primarily at the near-perpendicular angles.

Also shown in Fig. 9 is the rapid drop observed in the neutron emissivity. The peak-to-peak modulation can be as high as 40% of the average emissivity (i.e., $\Delta I_n / \bar{I}_n = 0.4$). One can estimate a loss rate for high energy particles on the basis of this modulation and the fishbone repetition time τ_{FB}

$$\nu_{loss} = (\Delta I_n / \bar{I}_n) \tau_{FB}^{-1}$$

ν_{loss} is found to increase rapidly with increasing β_{Tq} (Fig. 10). Rough calculations [15] indicate that the neutron production in these $D^0 \rightarrow H^+$ plasmas has comparable contributions from beam-beam and beam-target reactions. Thus the relevant numbers to compare in order to estimate the importance of the fishbone beam-ion losses are perhaps $(2/3)\nu_{loss}$, and the inverse of the time required for a typical ion to slow down from E_{inj} to $E_{inj}/2$ which is $1/0.01 \text{ sec} = 100 \text{ Hz}$, for typical PDX parameters. At $\beta_{Tq}^{1.15} = 0.045$, where we begin to see saturation in heating efficiency, $\nu_{loss} = 60 \text{ Hz}$,

and fishbone losses can be expected to begin to compete significantly with classical slowing down. More detailed calculations in the transport analysis code using a fishbone loss model calibrated to the neutron modulation and charge-exchange measurements indicate that, within the considerable uncertainties of the model, fishbone losses of fast ions can serve to explain the observed saturation of heating, although an additional loss of thermal confinement cannot be ruled out. In the 1.0 T power scan, which shows a moderate degree of saturation in heating at the three and four beam levels, $\tau_E(a)$ in the ohmic plasma was 35 msec, and in the two beam case was 17.5 msec. At four beams, if the effects of fishbones on the fast ions are ignored, then $\tau_E(a)$ is calculated to be 13.5 msec. However, if the fishbone model is included, the calculated net heating power is reduced by 25% for this case, and $\tau_E(a)$ again is calculated to be 17.5 msec, as at the lower power. See reference [16] for a more detailed discussion of the fishbone observations and the fishbone loss model.

Stability limits on beta in PDX have been studied with the PEST code [17], using the numerically computed equilibria described in section III. In Fig. 11 typical values of the critical beta for stability of ideal pressure driven internal modes are plotted as a function of $q_{sh}(a)$ for toroidal mode numbers $n = 1, 3$, and infinity.² The PEST code results are overlaid on the data from the 1.2 T current and power scan. The critical β_T values decrease monotonically with q . Onset of the pressure driven $n = 1$ internal mode (discussed in more detail in [18]) coincides with the appearance of fishbone activity. However the marginal points are sensitive to the exact form of the pressure and q profiles. These results suggest that pressure driven (possibly

²We define $q_{sh}(a) = q_{cyl}(a) \{1 + a^2/R^2[1 + 1/2 (\beta_p + \ell_i/2)^2]\}$, the lowest order correction to the cylindrical aperture safety factor.

non-ideal) internal modes may be responsible for fishbones, and may contribute to limits on beta in PDX. The highest β_T cases obtained in PDX approximately reach the calculated threshold for infinite-n ballooning modes.

VI. Summary of Other Injection Experiments

High beta power scans with deuterium targets show better low power confinement (improved by a factor of order 1.5, as previously observed in divertor ohmic deuterium discharges [1]), but similar limiting $\beta_T q$ values and MHD characteristics when compared to the hydrogen target data described above. Divertor discharges ($D^0 + H^+$) with near-circular cross section follow the scaling of Fig. 8.

Most recently a short counter injection experiment was conducted by reversing the direction of the plasma current. High betas, identical to those obtained at comparable injected powers with co-injection, were obtained in spite of classical orbit losses calculated to be >50% and central radiation levels comparable to the total local input power to the electrons. Transport analysis for these discharges results in $\tau_E(a) \approx 35$ msec, as compared to 15 - 20 msec for the comparable co-injection case. No fishbone activity was observed, and the sawtooth drop extended over ~ 2 msec, as compared to ~ 100 μ sec for comparable cases of co-injection. These results suggest intriguing questions about the effects of radial electric fields on thermal plasma confinement, and about the interaction of beam ions with MHD activity. A differing q profile, specifically with higher $q(0)$, may play a role in the improved MHD stability of the counter-injection plasma.

VII. Conclusions

The major features of beta scaling in circular cross-sectional tokamaks with near perpendicular co-injection have been delineated. At relatively low injection powers or high toroidal fields, giving low values of $\beta_T q$, the gross energy confinement deteriorates relative to ohmic values, especially at low plasma currents, but total stored energy increases linearly with beam power. In this regime gross confinement with beam injection scales approximately linearly with I_p and may have a weak inverse dependence on B_T . At high beam powers and low toroidal fields, saturation in heating efficiency is observed, dependent both upon plasma current and toroidal field. The parameter $\beta_T q$ characterizes well the approach to saturation, indicating that both β_T and β_p play a role in the pressure limit, as indicated by ideal MHD theory. β_T values of $\sim 3\%$ have been achieved at $q_p = 1.8$.

At high values of $\beta_T q$ a new instability is observed, which causes substantial loss of injected beam ions. The estimated reduction in heating efficiency due to these losses can, within reasonable uncertainties, serve to explain the observed saturation.

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FIGURE CAPTIONS

- Fig. 1 Range of I_p and B_T covered by PDX β scaling experiments. Circled points represent fully documented, controlled power scans. $R = 143$ cm, $40 < a < 44$ cm. The $q_{cyl} = 1.7$ line is drawn for $a = 42$ cm.
- Fig. 2 Scatter plot of diamagnetic measurements of β_p and β_T , for $B_T < 1.5$ T. The hatched region roughly separates discharges which show distinct "fishbone" MHD activity from those which do not.
- Fig. 3 56-point Thomson scattering profiles taken across the horizontal midplane. Discharge parameters (4 beams): $B_T = 1.5$ T, $q_y = 2.05$, $U_e = 49$ kV, $\tau_E = 22$ msec. The asymmetry seen in the density profile is a regular feature of beam-heated discharges in PDX, but is not discussed in this paper.
- Fig. 4 Main graph: Comparison of β_T calculated from kinetic data with β_T from diamagnetic measurements. Inset: Comparison of β_T derived from plasma equilibrium and diamagnetism.
- Fig. 5 β_p vs total power at three values of B_T , for approximately fixed plasma current (220-270 kA). Total power, P_{tot} , denotes the sum of the beam power ionized within the plasma and the ohmic heating input power; beam charge exchange and bad-orbit losses have not been subtracted.
- Fig. 6 β_T vs P_{tot} at $B_T = 1.2$ T for different currents. Curves have been fitted to the data to guide the eye.

Fig. 7 $\beta_T q^{1.15}$ vs P_{tot} . The exponent of q is chosen to give the best overall fit for all B_T .

Fig. 8 $\beta_T q^{1.15}$ versus $P_{tot}/B^{1.4}$. Universal curve for all beam-heated PDX diamagnetic data at R, $a \approx 143$, 40 - 42 cm.

Fig. 9 Typical signatures of strong fishbone MHD activity on soft X rays (central chord), Mirnov coil, charge-exchange flux, and neutron emission on slow and fast time scales. Each individual burst of oscillation is called a "fishbone."

Fig. 10 Energetic particle loss rate determined from neutron flux modulation v_{loss} vs the scaling parameter $\beta_T q^{1.15}$.

Fig. 11 Overlay of experimental β_T from 1.2 T current and power scan with typical values of critical β_T computed from PEST for stability of various pressure driven modes, plotted against q_{sh} . Labels $n = 1W, 3W, \infty$ signify fixed boundary modes with indicated toroidal mode numbers. The hatched area marks onset of fishbone activity in the 1.2 T scan.

FIG. 1

FIG. 2

FIG. 3

82X0850

FIG. 4

FIG. 5

FIG. 6

FIG. 7

FIG. 8

FIG. 9

FIG. 10

82X0849

FIG. 11