Applying the CO_2 Laser Collective Thomson Scattering results from JT-60U to other machines.

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A collective Thomson scattering (CTS) system based on a pulsed CO_2 laser is being developed to demonstrate the feasibility of alpha-particle diagnostics. Tests on this system are being conducted on the JT-60U tokamak. The system consists of a pulsed laser (15J in 1us at 10.6um) and a wide band (~ 8GHz) heterodyne receiver with a quantum-well infrared photodetector (QWIP)[1]. Stray light is reduced by a notch filter containing hot CO_2 gas. The heterodyne receiver is absolutely calibrated using large area blackbody radiation source[2]. Results from the tests on JT-60U indicate a larger than expected noise background, especially for the lower velocity measurements determined by the smaller frequency shifts from the laser line. These results are used to estimate the signal-to-noise that would be expected for a CTS diagnostic installed on other devices; ITER, JET-EP and ASDEX. Calculations and possible system improvements are presented.

I. Introduction

A collective Thomson scattering diagnostic has been installed on the JT-60U tokamak to investigate the ion tail and to evaluate this diagnostic. The diagnostic is based on a high power pulsed CO_2 laser operating at 10.6 microns and a heterodyne receiver with a wideband QWIP detector. Collective scattering offers the opportunity to investigate ion behavior in various plasmas. For the scattering to be collective, the Salpeter parameter, α, must be greater than unity. The Salpeter parameter is given by:

$$\alpha = \frac{1}{k\lambda_D}$$

Where λ_D is the Debye length and k represents the scattered wave vector:

$$k = 2k_{input}\sin(\theta/2)$$

Here k_{input} is the input wave-vector of the laser and θ is the scattering angle. For the scattering to be collective at the CO_2 laser wavelength, the scattering angle must be very

small for tokamak conditions, typically 1 degree or less. The scattered power Ps into the solid angle dΩ and over frequency interval dω is given by:

$$P_s d\Omega d\omega = P_I r_o^2 n_e L d\Omega \frac{d\omega}{2\pi} S(k,\omega)$$

Where r_o is the classical electron radius, P_I is the input power, L is the scattering length and S(k,ω) is the spectral density function. S(k,ω)is effectively a cross section with contributions from each particle species in the plasma. For a successful measurement, the scattered power must exceed the background noise by some margin. For heterodyne detection, the post detection signal-to-noise ratio becomes:

$$\frac{S}{N} = \frac{P_S}{P_S + NEP}\sqrt{B\tau + 1}$$

With NEP the noise equivalent power, B the receiver bandwidth and τ the integration time set by the lasers pulse length. Ideally, the scattered power is chosen for Ps ~ NEP to optimize the signal-to-noise ratio. With B~1GHz and τ~1μsec, the signal-to-noise ratio would be around 16. The selection of the laser power and the scattering angle is then a function of the plasma parameters. Table 1 lists a comparison of these parameters for 6 different fusion devices.

II. Collective scattering on JT-60U

For JT-60U the expected scattered power spectrum is given in Fig.1. This is compared to the receiver's noise given in Fig. 2. Note that the receiver noise is rather constant and slightly below $1x10^{-18}$ W/Hz over the spectral region of interest. Operation of the diagnostic on JT-60U revealed a larger than expected noise. The source for the excess noise was investigated and determined to come from mode changes in the pulsed laser. The noise was only present with the pulsed laser, but did not track the temporal profile of the laser. The noise would enter several microseconds after the pulsed laser fired. To maintain collective scattering, the angle between the pulsed laser beam and the scattered beam was set at 0.5 degrees. Such a small angle permits some overlap of the wings. To reduce some of this noise, a telescope was added to the receiver beam to reduce its diameter near the pulsed lasers beam dump; this reduced the noise by almost one order of magnitude. The diagnostic has a notch filter (a 5-meter CO_2 absorption cell) that operates around 700K. The absorption width is adjusted by changing the cell pressure. By increasing the cell pressure, this noise could be reduced, but the notch filter would then also remove the scattered radiation near the laser line. The diagnostic uses an array of bandpass filters to select the scattered radiation over 5 frequency channels. The noise is confined to the lowest frequency band (0.4 to 0.7 GHz.) This band represents the signal expected from the bulk ions, and increasing the notch filters pressure to remove the noise would then also remove the ability to measure the scattered signal from the bulk ions. The noise was not observed in an earlier proof-of-principle test of the diagnostic on the ATF stellarator where the scattering angle was set at 0.86 degrees[3].

III. Collective scattering in ASDEX and JET-EP

To avoid the noise problems found in JT-60U, it will be necessary to improve the mode lock on the pulse laser and further reduce any stray light coupling between the pulsed laser and the receiver. Most of this can be accomplished by increasing the scattering angle between the pulsed laser and the receiver. For JT-60U, the small angle of 0.5 degrees was necessary to maintain the collective nature of the scattering due to the modest density. For JET-EP (see Fig. 3) this angle can easily be increased to 0.75 degrees. This helps in two ways. First the laser beam and the receiver beam have much less of an overlap and second, the scattered spectrum is moved out in frequency in proportion to the angle. For ASDEX (shown in Fig. 4) this improves further with both a high density and a low electron temperature. With ASDEX it would be possible to explore the angular dependence of the scattered power. However, the scattered signals are still rather small for the ion tail portion of the scattering and improvements in the detector noise or increases in pulsed laser power would be necessary to operate near the condition Ps ~ NEP.

IV. ITER, FIRE and IGNITOR

For future devices the expected scattered spectrums improve with density as shown in Figs 5-7 for ITER, FIRE and IGNITOR. The noise found in JT-60U at the lower frequencies (<0.7 GHz) could be filtered with a notch filter without eliminating the ability to detect a portion of the bulk ion distribution. Again, it may be necessary to either increase the laser power or reduce the receiver's noise for an adequate signal-to-noise ratio, especially in ITER.

V. Conclusions

Tests of the collective Thomson scattering diagnostic on JT-60U indicate a larger than expected noise background due to mode changes in the pulsed laser. Future experiments will require a reduction in this noise, either by eliminating it or by adjusting the scattering conditions such as increasing the scattering angle. For all the tokamak devices considered, further improvements in the signal-to-noise ratios could be made with increases in the laser power or decreases in the receiver's noise.

Captions

Table 1: Comparison of plasma and diagnostic parameters used in calculating scattered poser for 6 fusion devices. For comparison purposes, the laser power was fixed at 10 MW for all calculations.

Fig1. Scattered power for JT-60U. Note that expected scattered signal decreases rapidly above 1 GHz.

Fig 2 The noise-equivalent-power, NEP, for the receiver system on JT-60U. The receiver is based on a wideband QWIP detector with receiver bandwidth limited by electronics. Note that the QWIP is a photoconductive detector with a minimum NEP=$2h\gamma=4x10^{-20}$ W/Hz. This allows up to a factor of 20 reduction in receiver noise with detector development. The spectrum was measured in three separate tests as noted by the three colors.

Fig. 3. The expected scattered power spectrum for JET-EP.

Fig. 4. The expected scattered power spectrum for ASDEX. Note that the ion tail feature is expected to yield about one order on magnitude more scattered signal than that for JT-60U shown in Fig 1.

Fig. 5. The expected scattered power spectrum for ITER

Fig. 6. The expected scattered power spectrum for FIRE

Fig. 7. The expected scattered power spectrum for IGNITOR With the high electron density, the ion tail feature is approaching the condition of Ps ~ NEP even at modest laser powers.

	JT-60U	ASDEX	JET-EP	ITER	FIRE	IGNITOR
Electron density 10^{20} m^{-3}	0.5	3	1	1	5.5	10
Electron temperature KeV	5	3	10	19	11	10.5
Bulk ion temperature KeV	15	3	20	19	11	10.5
Ion tail density 10^{20} m^{-3}	0.01	0.1	0.02	.02	0.1	0.2
Ion tail temperature KeV or alphas	400	100	Alpha	Alphas	Alphas	Alphas
Scattering angle Degrees	0.5	0.75	0.75	0.75	0.75	0.75

Table 1

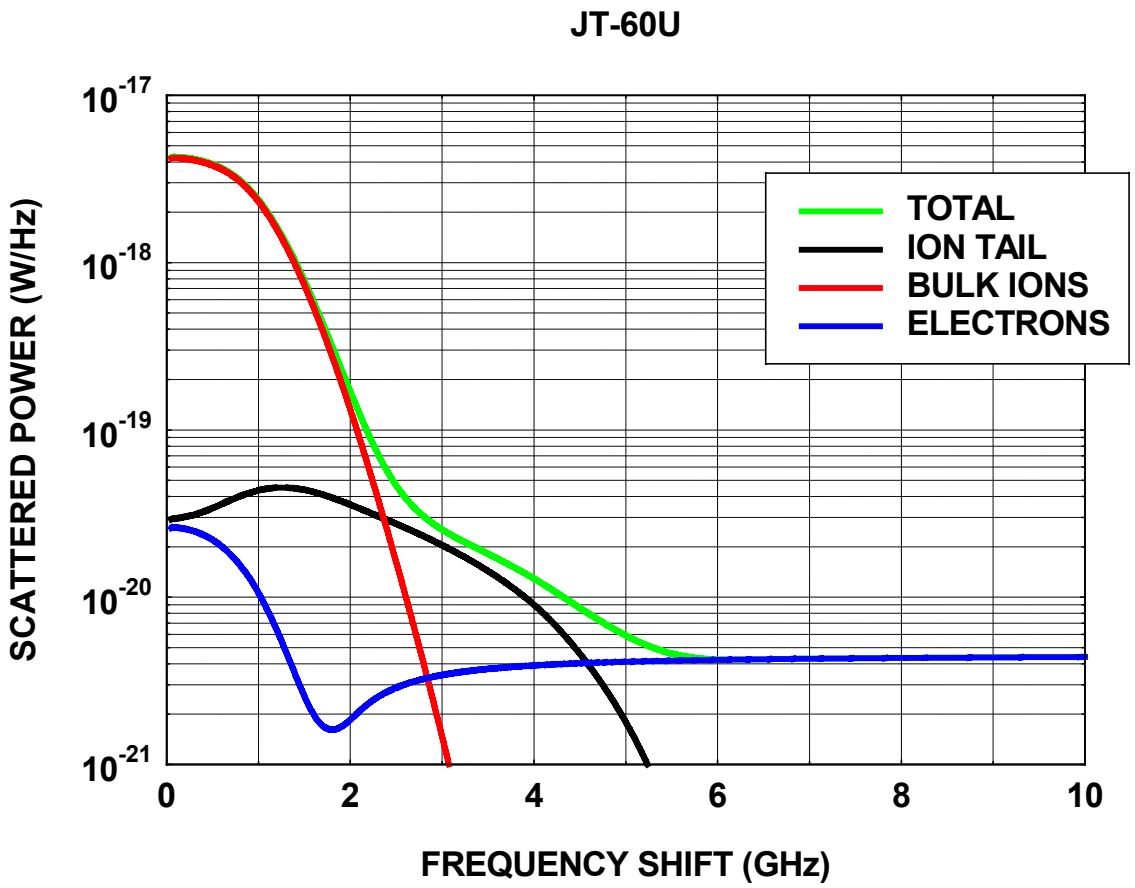
JT-60U
SCATTERED POWER (W/Hz)
10-17
10-18
10-19
10-20
10-21
0
2
4
6
8
10
FREQUENCY SHIFT (GHz)
TOTAL
ION TAIL
BULK IONS
ELECTRONS

Fig 1

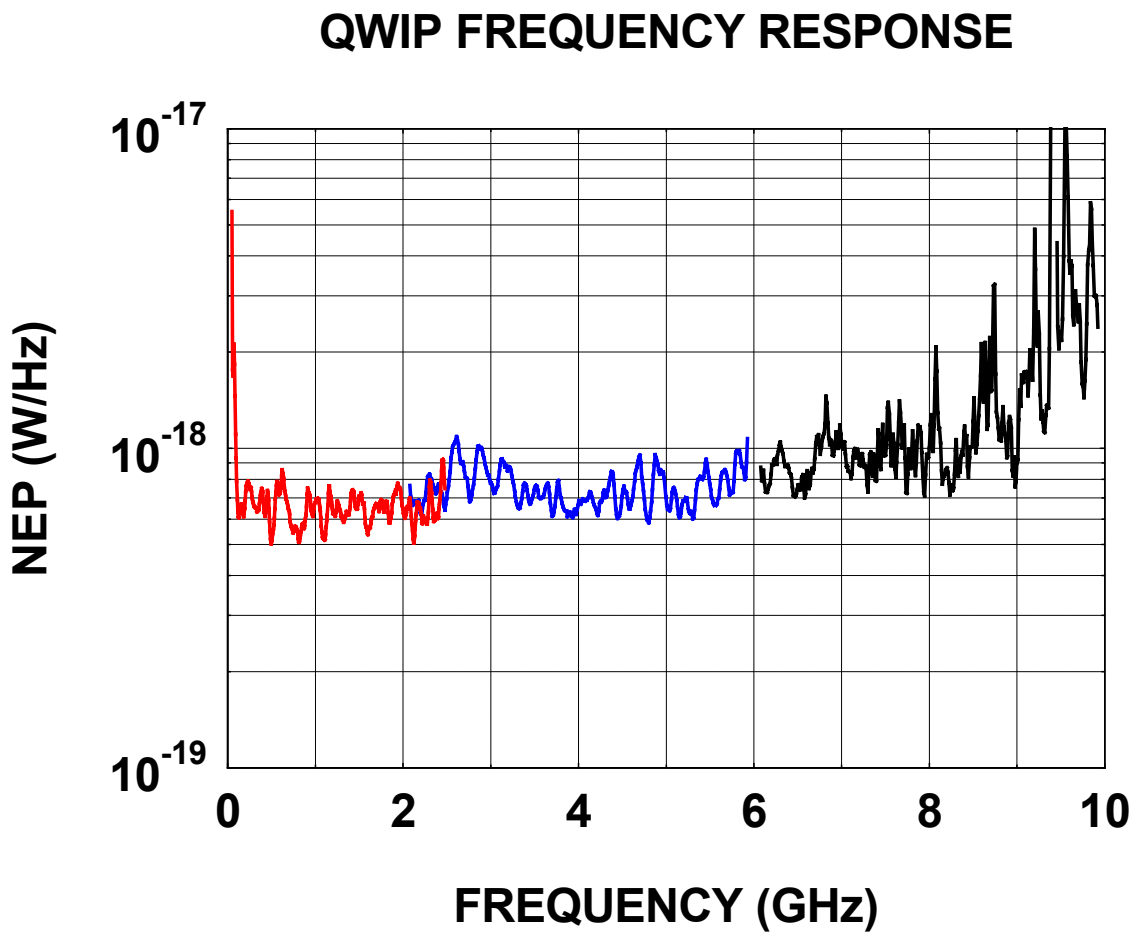
QWIP FREQUENCY RESPONSE
NEP (W/Hz)
10-17
10-18
10-19
0
2
4
6
8
10
FREQUENCY (GHz)

Fig 2

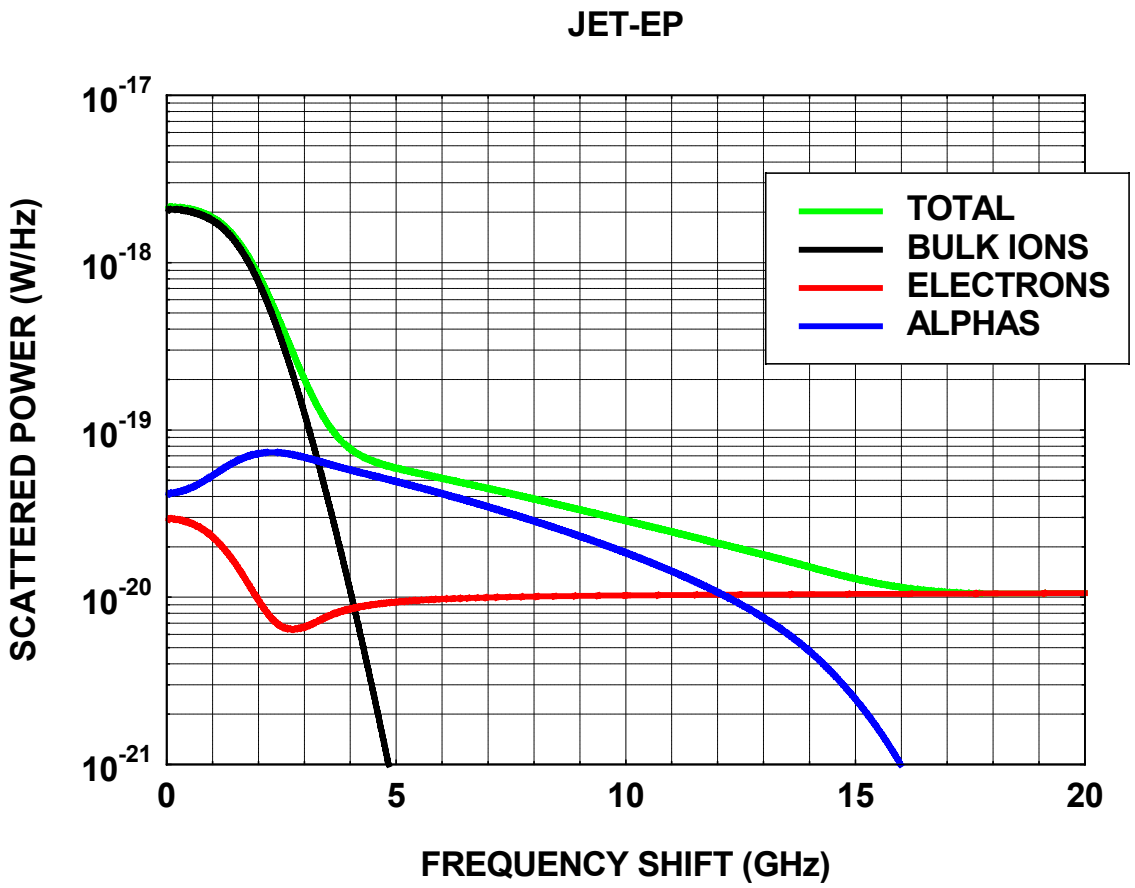
JET-EP
SCATTERED POWER (W/Hz)
10-17
10-18
10-19
10-20
10-21
0
5
10
15
20
FREQUENCY SHIFT (GHz)
TOTAL
BULK IONS
ELECTRONS
ALPHAS

Fig 3

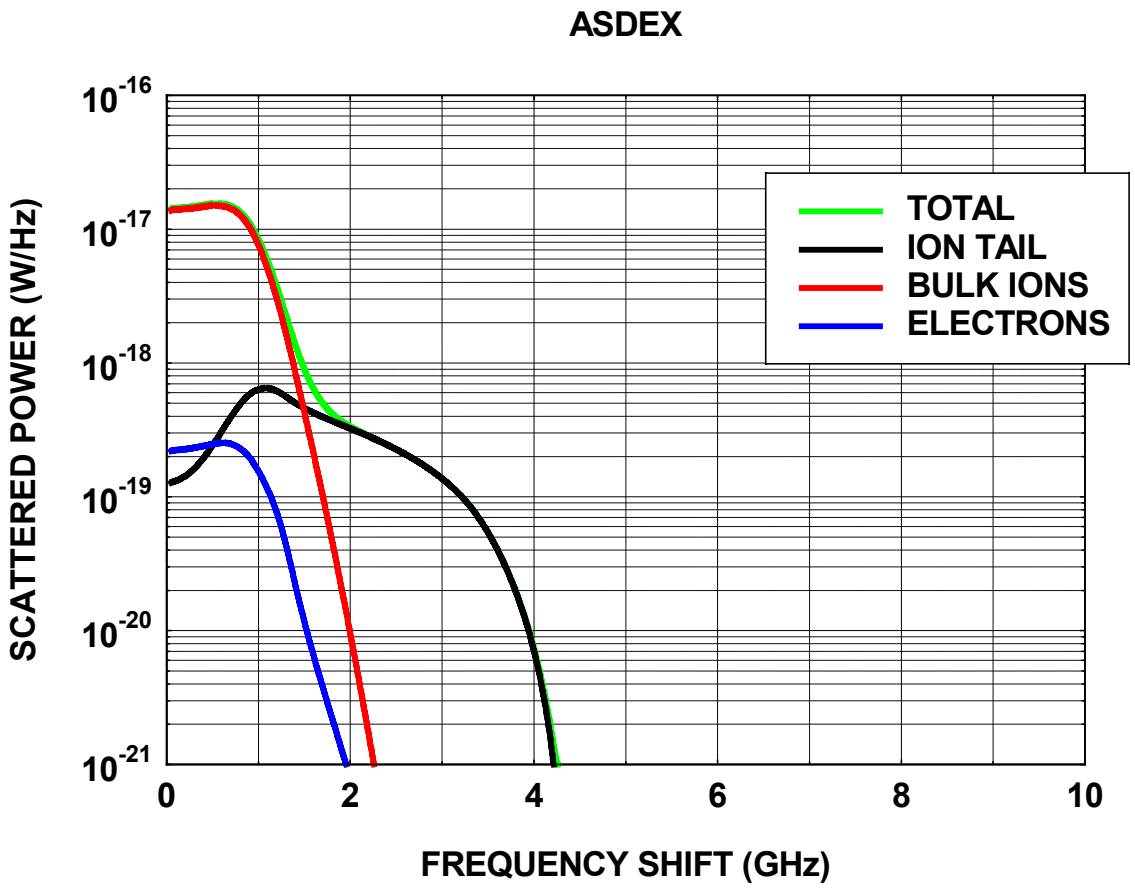
ASDEX
SCATTERED POWER (W/Hz)
10-16
10-17
10-18
10-19
10-20
10-21
0
2
4
6
8
10
FREQUENCY SHIFT (GHz)
TOTAL
ION TAIL
BULK IONS
ELECTRONS

Fig 4

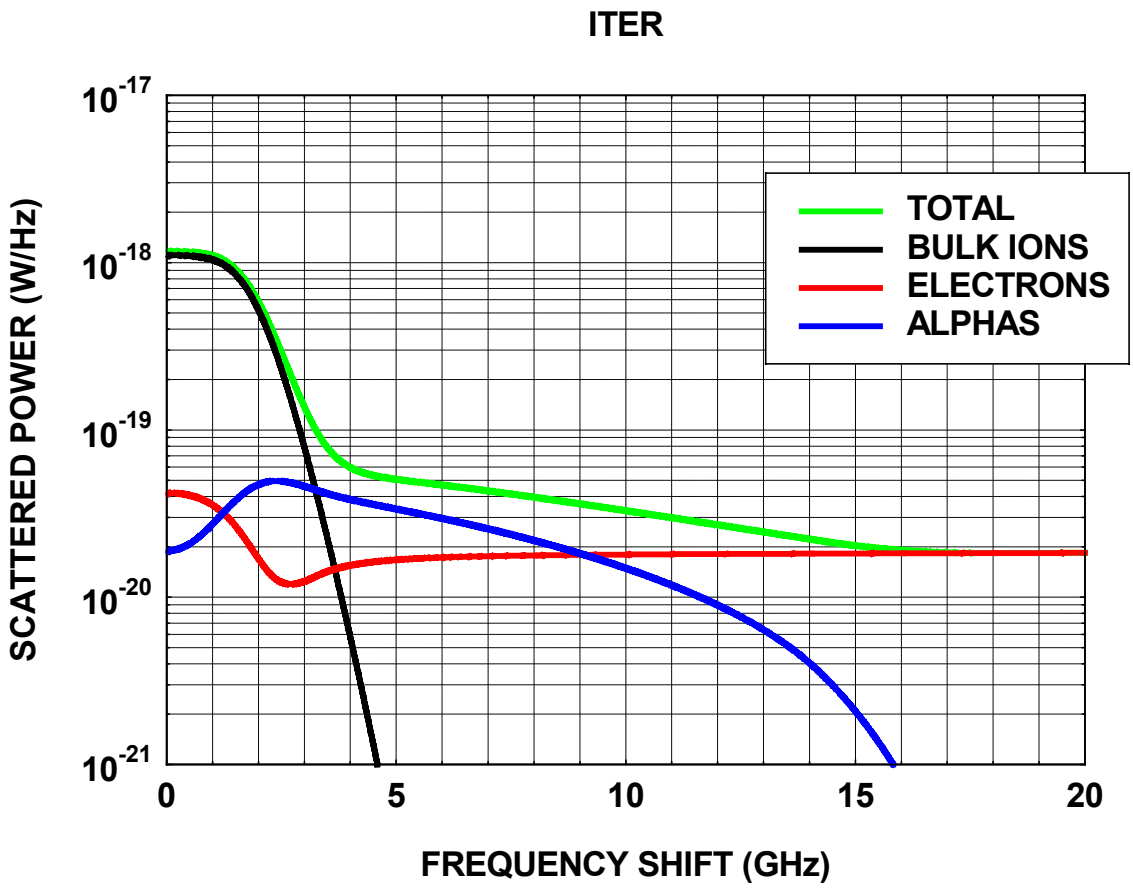
ITER
SCATTERED POWER (W/Hz)
10-17
10-18
10-19
10-20
10-21
0
5
10
15
20
FREQUENCY SHIFT (GHz)
TOTAL
BULK IONS
ELECTRONS
ALPHAS

Fig 5

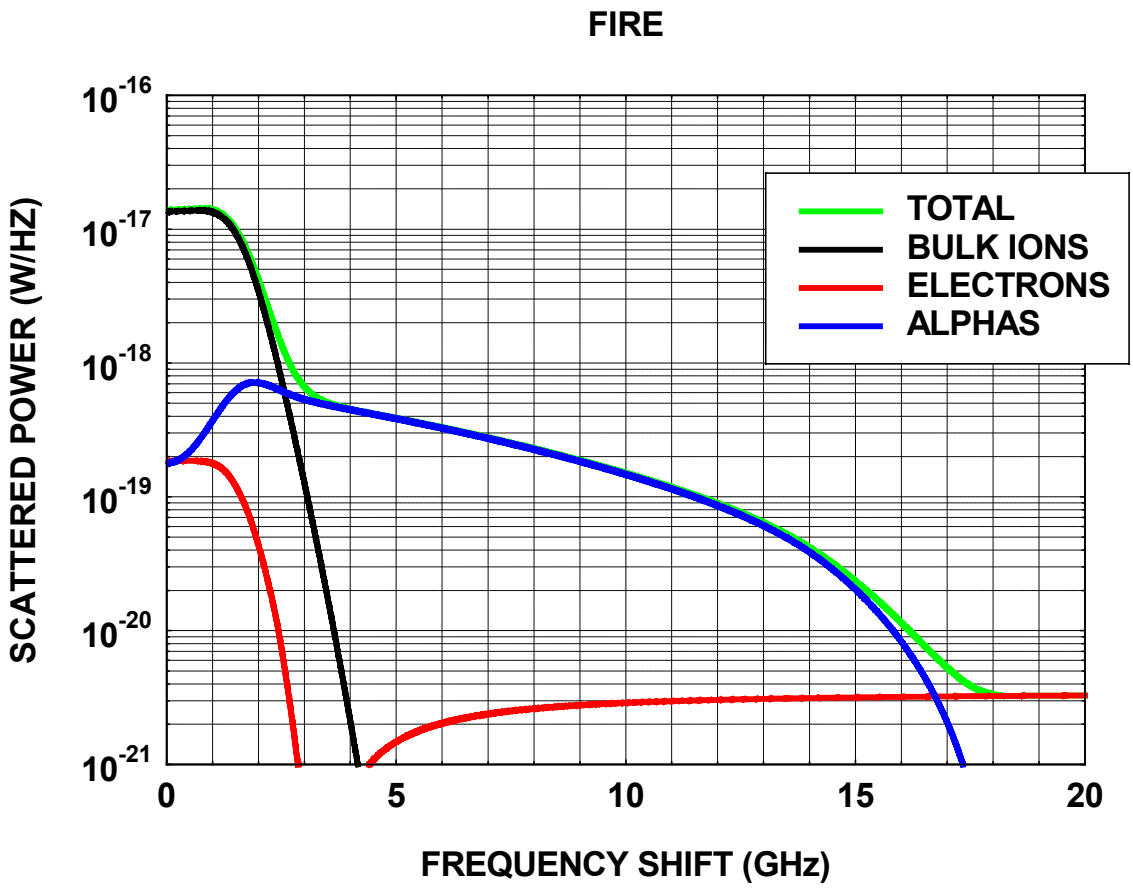
FIRE
SCATTERED POWER (W/HZ)
10-16
10-17
10-18
10-19
10-20
10-21
0
5
10
15
20
FREQUENCY SHIFT (GHz)
TOTAL
BULK IONS
ELECTRONS
ALPHAS

Fig 6

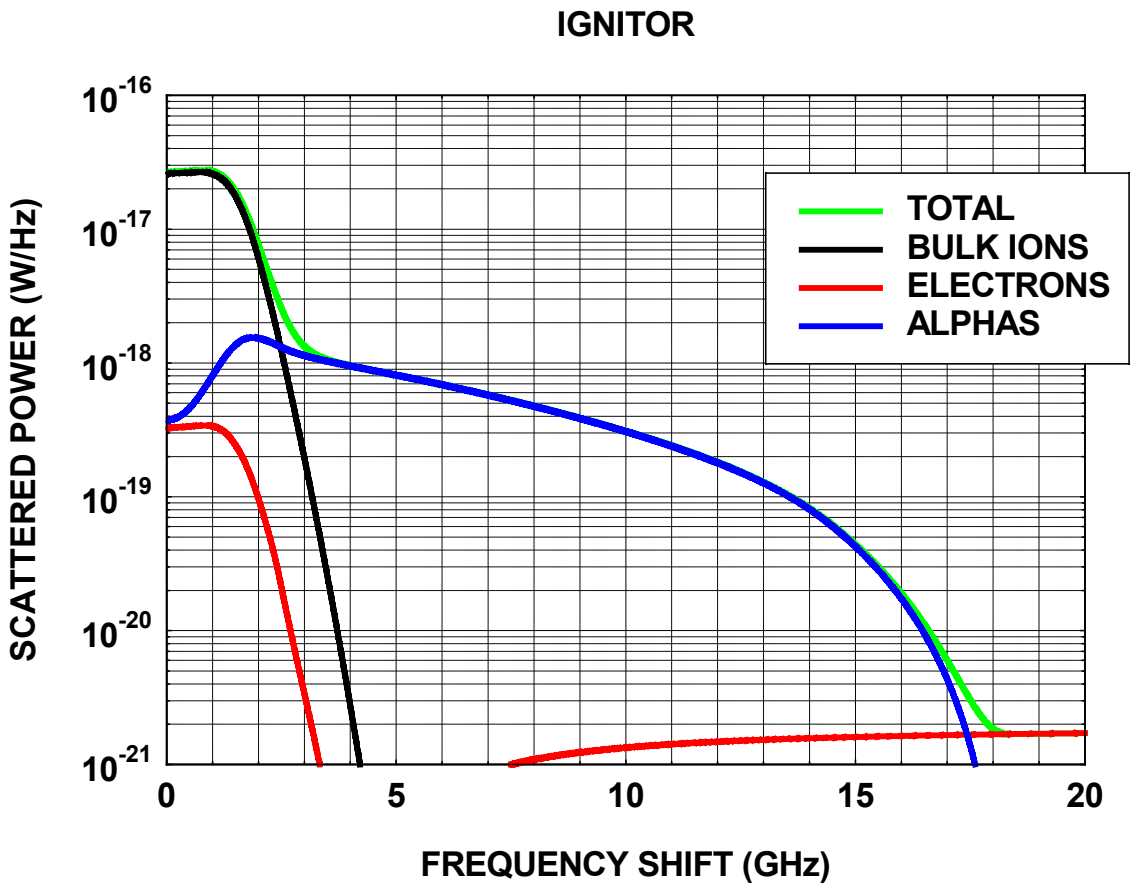
IGNITOR
SCATTERED POWER (W/Hz)
10-16
10-17
10-18
10-19
10-20
10-21
0
5
10
15
20
FREQUENCY SHIFT (GHz)
TOTAL
BULK IONS
ELECTRONS
ALPHAS

Fig 7

References

[1] H. C. Liu, G. E. Jenkins, E. R. Brown, K. A. McIntosh, K. B. Nichols, and J. M. Manfra, "Optical heterodyne detection and microwave rectification up to 26 GHz using quantum well infrared photodetectors", *IEEE Elect. Dev. Lett*. Vol.16, No. 6, (1995).
[2] C. A. Bennett, R. K. Richards, and D. P. Hutchinson, "Absolute Broadband Calibration Procedure for Infrared Heterodyne Receivers", *Appl. Opt*., Vol 27, No. 16, (1988).
[3] R. K. Richards, D. P. Hutchinson, C. A. Bennett, H. T. Hunter, and C. H. Ma, "Measurement of CO2 Laser Small Angle Thomson Scattering on a Magnetically Confined Plasma," *Appl. Phys. Lett*., Vol 63 No1, (1993).