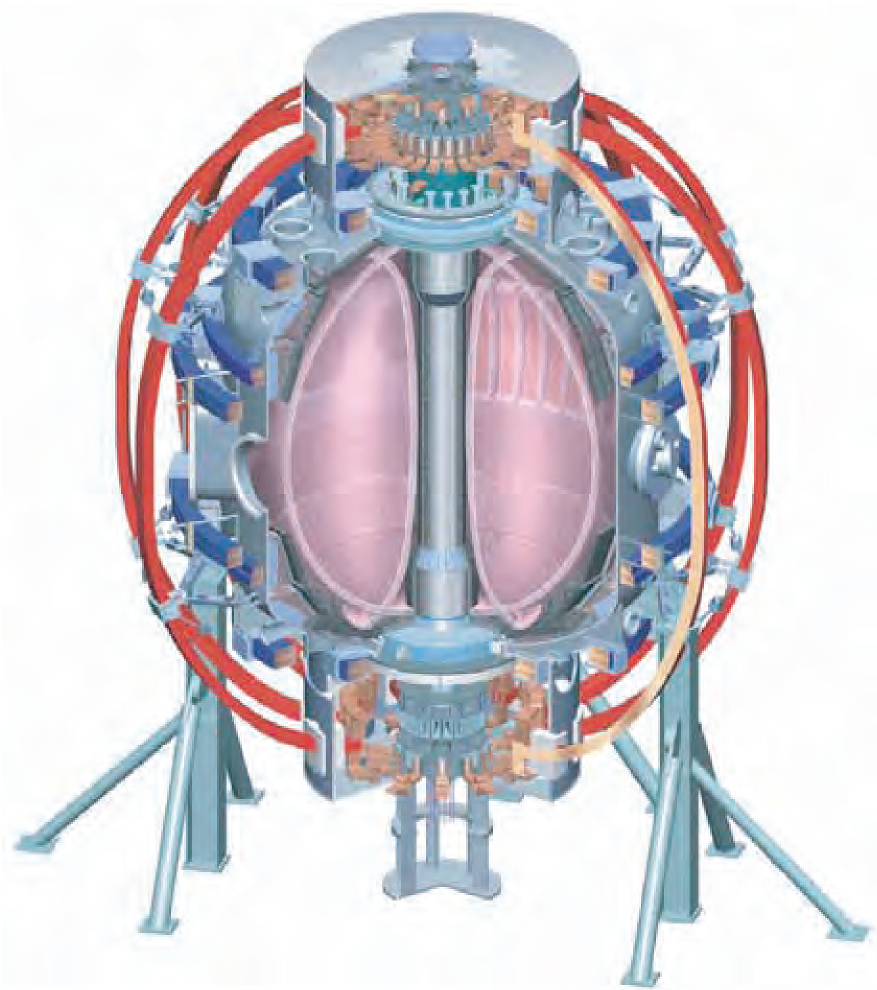
Progress towards measurement of ETG turbulence on NSTX



D. R. Smith, R. E. Feder,
E. Mazzucato, and H. K. Park

Princeton Plasma Physics Laboratory

L. Lin, C. W. Domier, M. Johnson,
and N. C. Luhmann, Jr.

*Department of Applied Science,
University of California at Davis*

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Abstract

Installation of the high-k scattering system on NSTX is complete and the first data has been acquired. The system measures density fluctuations on scales relevant to electron temperature gradient (ETG) turbulence. System components include a backward wave oscillator source providing approximately 150 mW at 280 GHz and a superheterodyne receiver with five simultaneous detection channels and noise temperatures of about 5000 K. The system is configured for tangential scattering with the probe beam and five scattered beams lying nearly on the toroidal midplane. The scattered beams sample radial density fluctuations with wavenumbers $k_r < 20\ cm^{-1}$. The 8 cm diameter probe beam provides good k-space resolution at $\Delta k_r < 0.7\ cm^{-1}$. Excellent spatial localization is achieved at small scattering angles due to the large toroidal curvature of the spherical torus geometry. Steerable launch and detection optics can position the scattering volume either near the magnetic axis at $\rho \sim 0.1$ or near the edge at $\rho \sim 0.8$. The system measures fluctuations with $k_r\rho_e < 0.6$ and $\delta n/n > 10^{-4}$ to investigate the existence of ETG turbulence. The connection between ETG turbulence and electron thermal transport remains a controversial issue.

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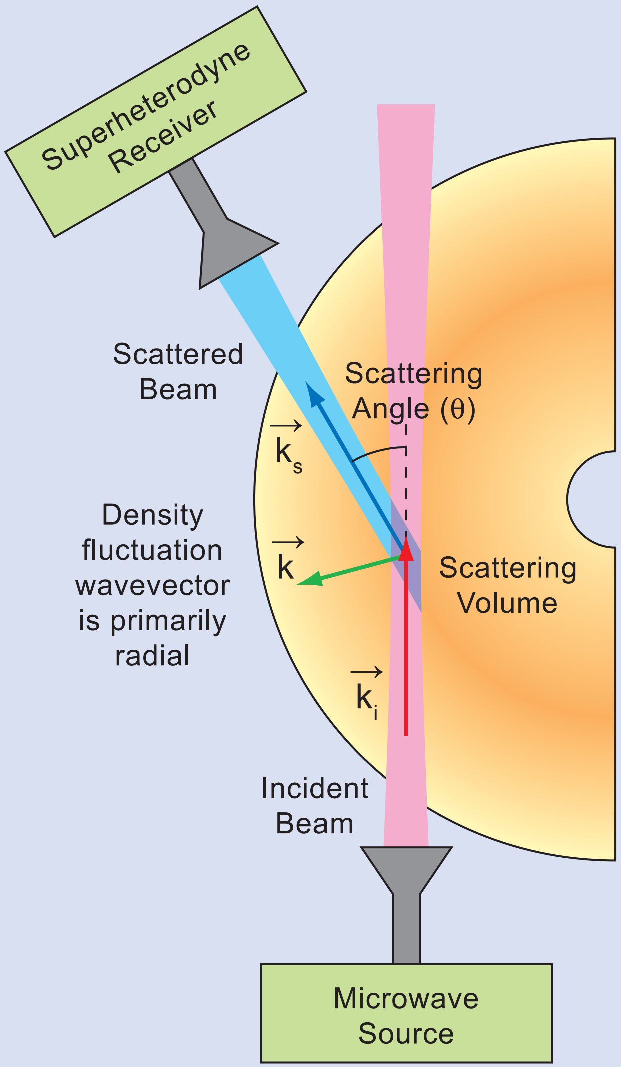
Scattering Basics

Tangential scattering on the toroidal midplane



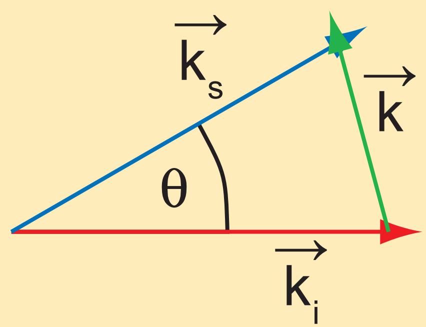
Photon-phonon interaction
(Brillouin scattering)

$$\vec{k}_s = \vec{k}_i + \vec{k} \qquad \omega_s = \omega_i + \omega$$

Scattered EM wave — Incident EM wave — Density fluctuation

High frequency probe beam

$$\omega_s \approx \omega_i >> \omega \qquad k_s \approx k_i$$



Bragg condition:
Scattering angle fixes wavenumber of measured fluctuations

$$k \approx 2\, k_i \sin(\theta/2)$$

Scattering of Electromagnetic Radiation

NSTX

Scattered Electric Field

$$\boldsymbol{E}_s(\boldsymbol{r},t) \simeq \frac{r_0}{r} \int n_e(\boldsymbol{r}',t')\ \hat{\boldsymbol{r}} \times \hat{\boldsymbol{r}} \times \boldsymbol{E}_i(\boldsymbol{r}',t')\ d^3r'$$

$$\boldsymbol{E}_s(\boldsymbol{r},t) \simeq \frac{r_0}{r}\ \hat{\boldsymbol{r}} \times \hat{\boldsymbol{r}} \times \boldsymbol{E}_i \int n_e(\boldsymbol{k},\omega)\ e^{i(\boldsymbol{k}_s\cdot\boldsymbol{r}-\omega_s t)}\ \frac{d\omega}{2\pi}$$

$$r_0 = \frac{e^2}{m_e c^2}$$

Classical electron radius

$$\vec{k}_s = \vec{k}_i + \vec{k}$$

$$\omega_s = \omega_i + \omega$$

$$\omega_s \simeq \omega_i \gg \omega$$

$$\vec{k}_s = \frac{\omega_s}{c}\hat{r}$$

Scattered Power

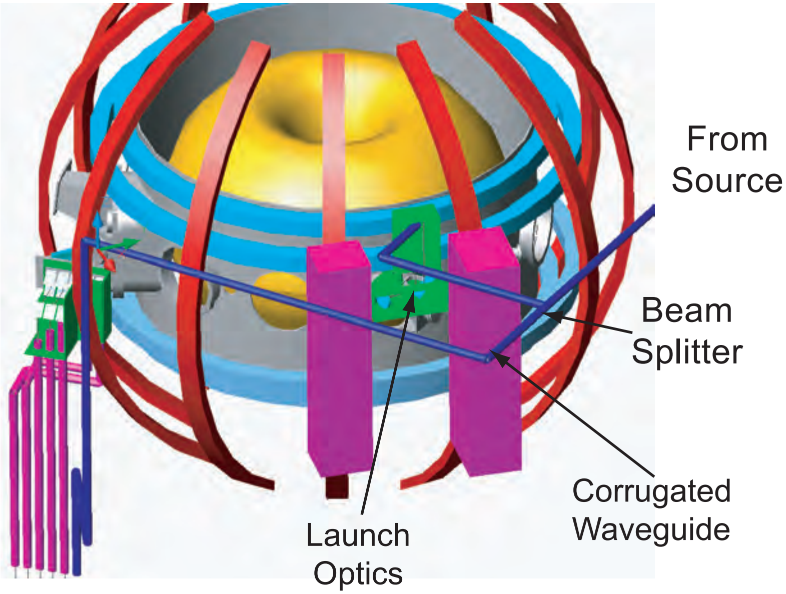
$$\frac{dP_s(\boldsymbol{r},t)}{d\Omega} \equiv r^2\ \frac{c}{4\pi}\ |\boldsymbol{E}_s(\boldsymbol{r},t)|^2$$

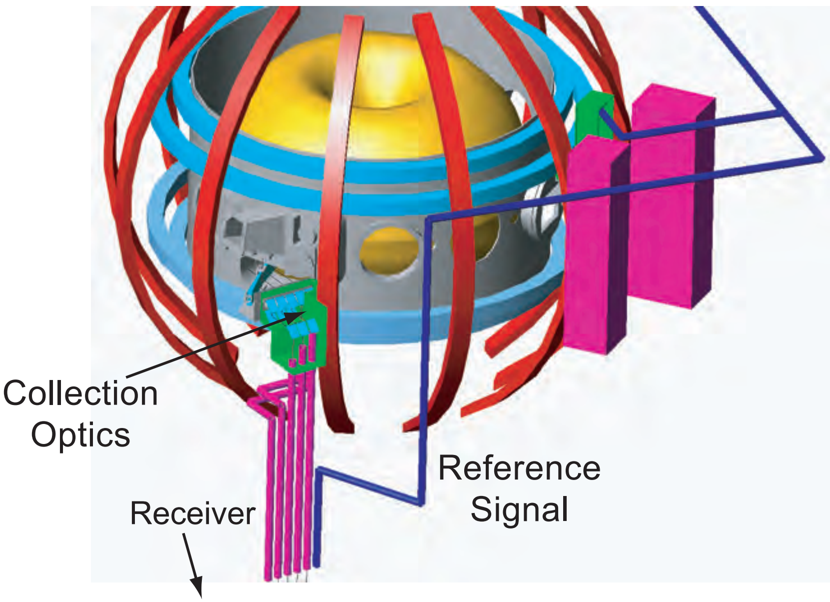
$$\left\langle \frac{dP_s(\boldsymbol{r},\omega_s)}{d\Omega\ d\omega_s/2\pi} \right\rangle_T = r_0^2\ \frac{P_i}{A}\ \left|\hat{\boldsymbol{r}} \times \hat{\boldsymbol{r}} \times \hat{\boldsymbol{E}}_i\right|^2\ \frac{|n_e(\boldsymbol{k},\omega)|^2}{T}$$

Scattered power can be Fourier decomposed to reveal the fluctuation spectral density

High-k Scattering System Overview

NSTX





Launch Configurations

Inboard launch to measure fluctuations near the **magnetic axis**

Outboard launch to measure fluctuations near the **edge**

Backward Wave Oscillator Millimeter Wave Source

Thomson-CSF Carcinotron model 4224

Provides about **150 mW** at **280 GHz**

λ_i = 1.07 mm and k_i = 58 cm^{-1}

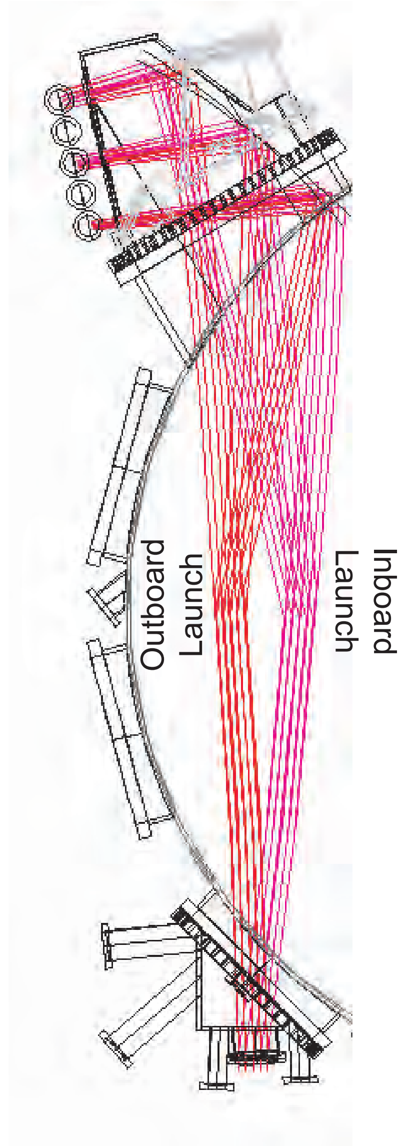
About 15 kHz line width

Superheterodyne Receiver

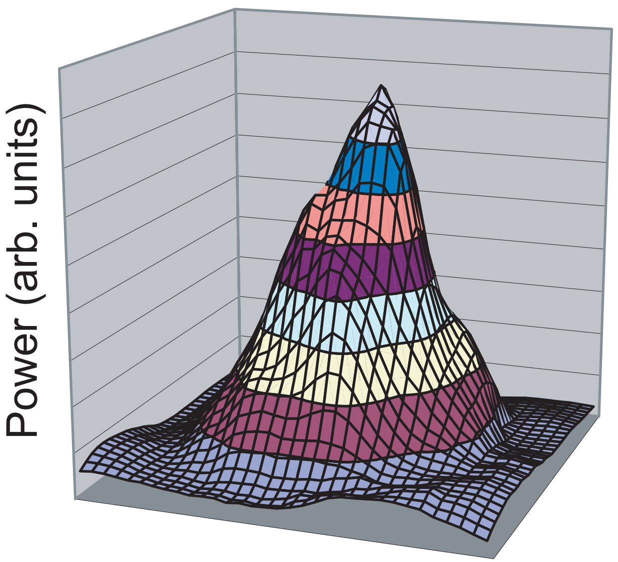
Five channels

About 5000 K nosie temperatures

Tracking circuit



Waveguide and Beam Characterization

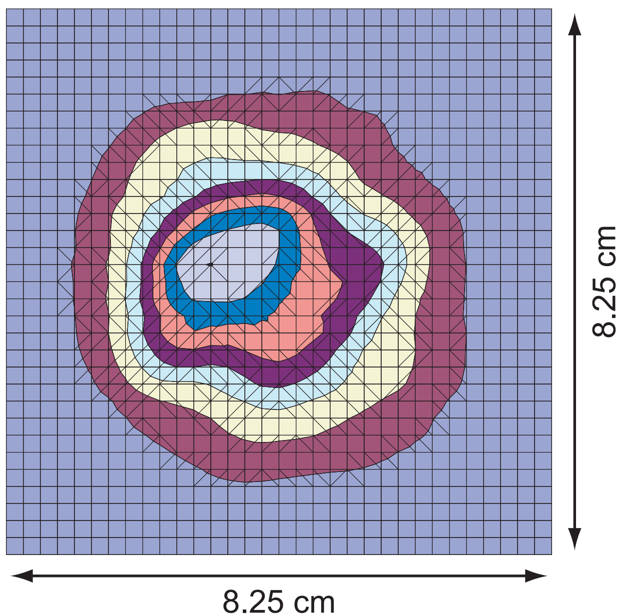


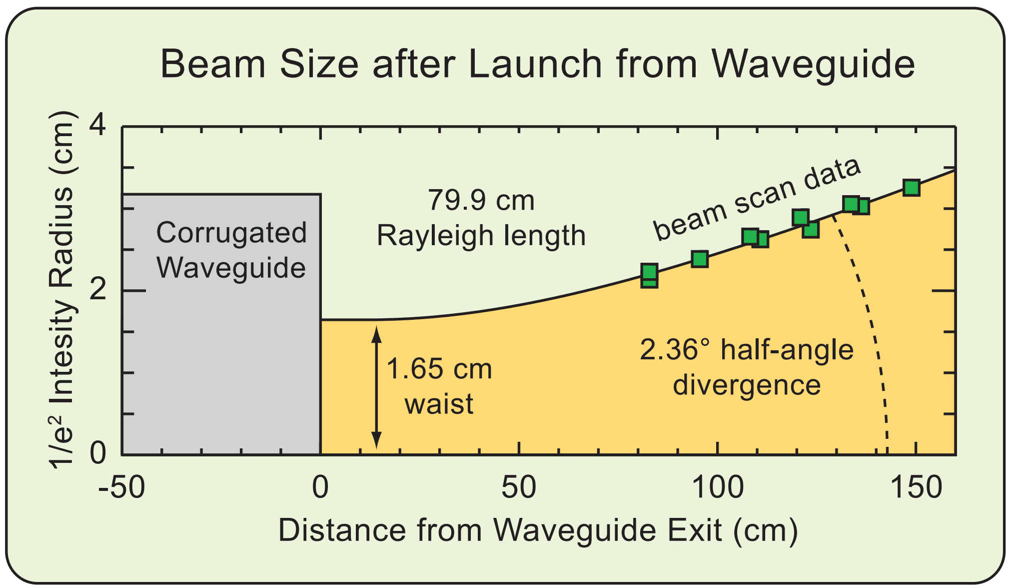
Beam Scans

2D scans of beam profile after waveguide launch were performed in lab using a pyroelectric detector.

Data at right take at 108.3 cm after waveguide exit.

An elliptical Gaussian profile was then fitted to the data.





Faraday Rotation and Beam Polarization

Faraday rotation angle

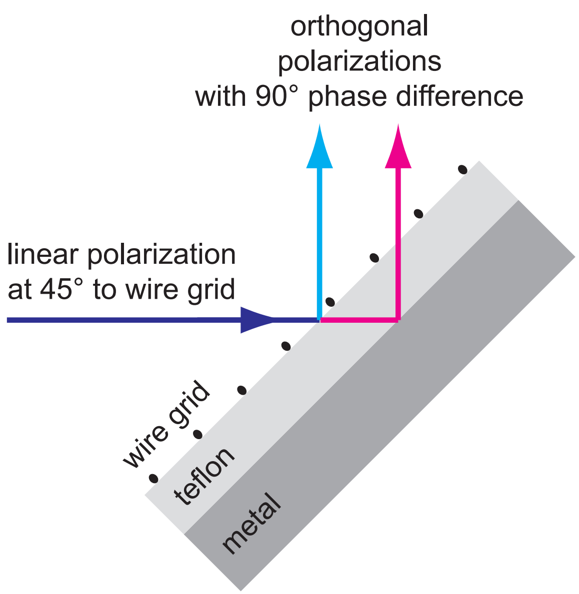
$$\alpha \approx \frac{e}{2\, m_e\, c} \frac{\omega_{pe}^2}{\omega^2} B\, L$$

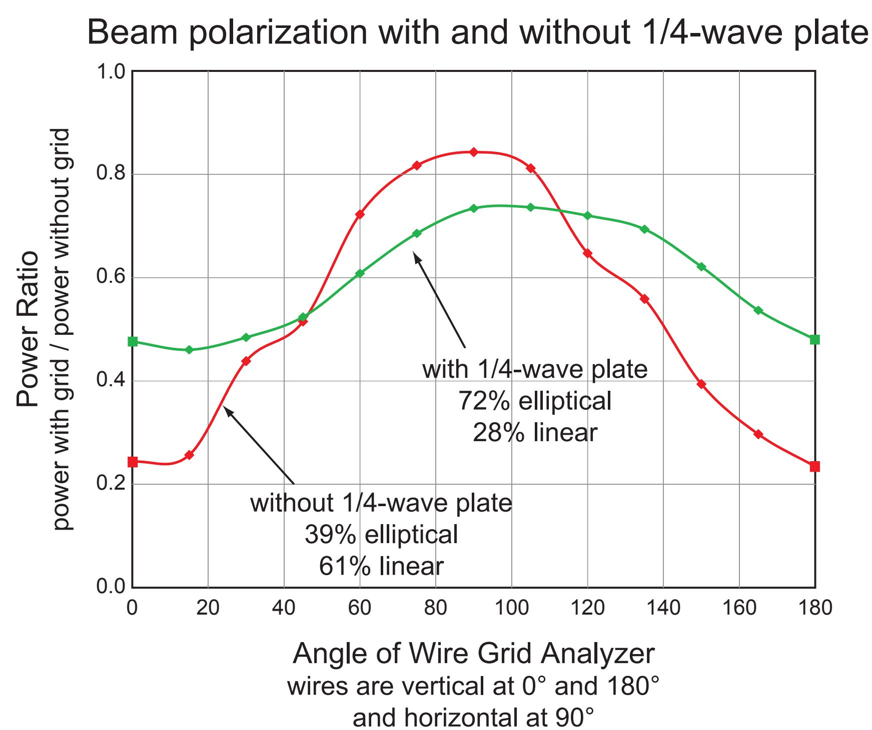
For 280 GHz beam in NSTX

$\alpha \approx 100°$

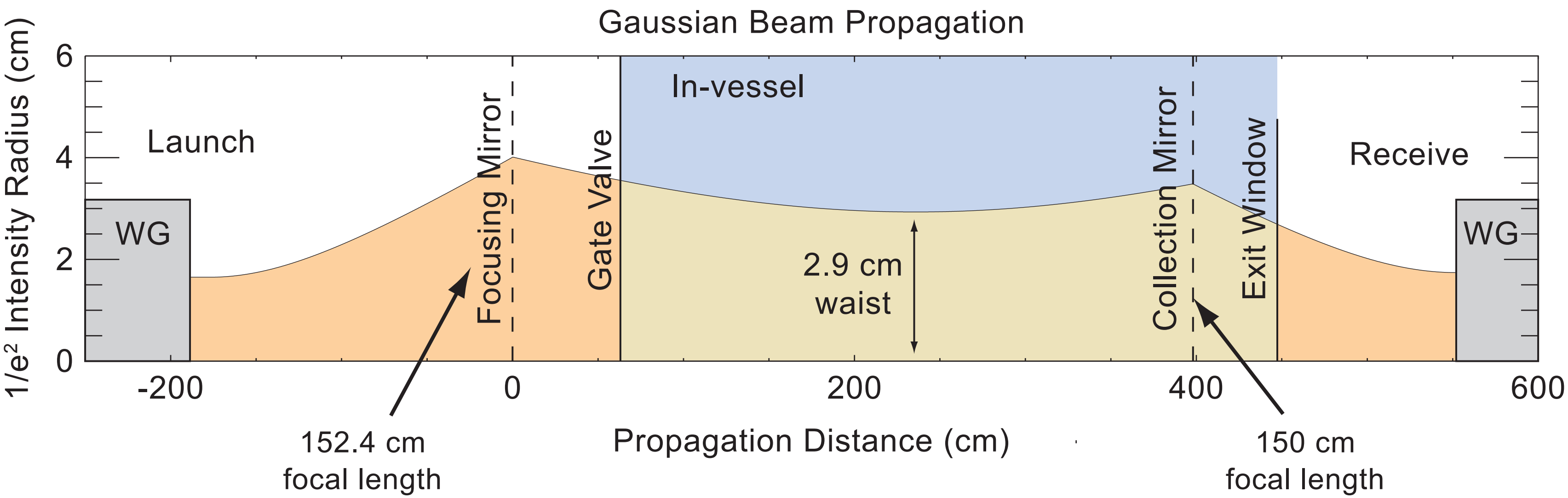
The Schottky diode mixers are **polarization dependent**, so the probe beam needs to be **elliptically polarized**.

A **quarter-wave plate** transforms a linearly polarized beam into an elliptically polarized beam.





Quasi-Optical Design



Entrance and Exit Windows

Windows cut from water-free quartz.

Window thicknesses cut to maximum transmission based upon etalon analysis.

With the 2.9 cm beam waist, the wavenumber resolution is

$\Delta k \approx 2/w \approx 0.7\ cm^{-1}$

Ray Tracing

With $\omega > \omega_{pe}, \Omega_e$
consider only
cold plasma electron modes

$$D \equiv D(\vec{r}, t, \vec{k}, \omega)$$

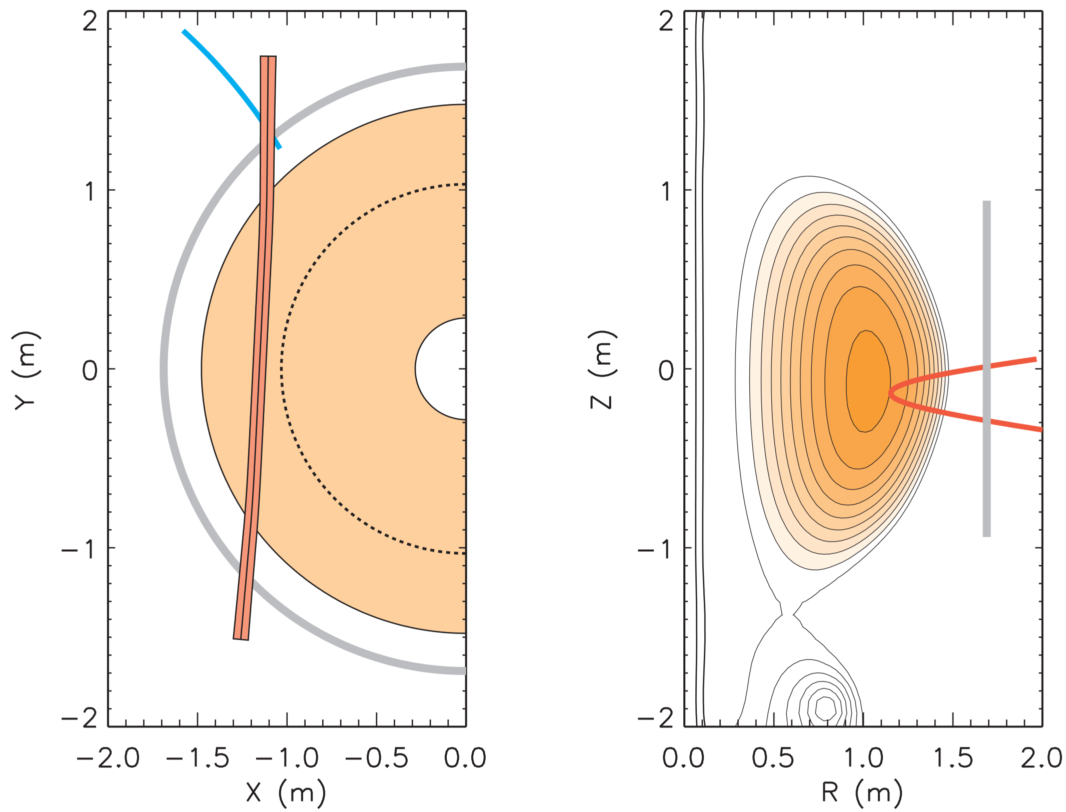
Dispersion Relation

$$D=0$$

Ray Tracing Equations

$$\frac{d\vec{r}}{dt} = -\frac{\vec{\nabla}_k D}{\partial D/\partial \omega}$$

$$\frac{d\vec{k}}{dt} = \frac{\vec{\nabla}_r D}{\partial D/\partial \omega}$$



RT equations numerically integrated using
2nd order Runge-Kutta algorithm

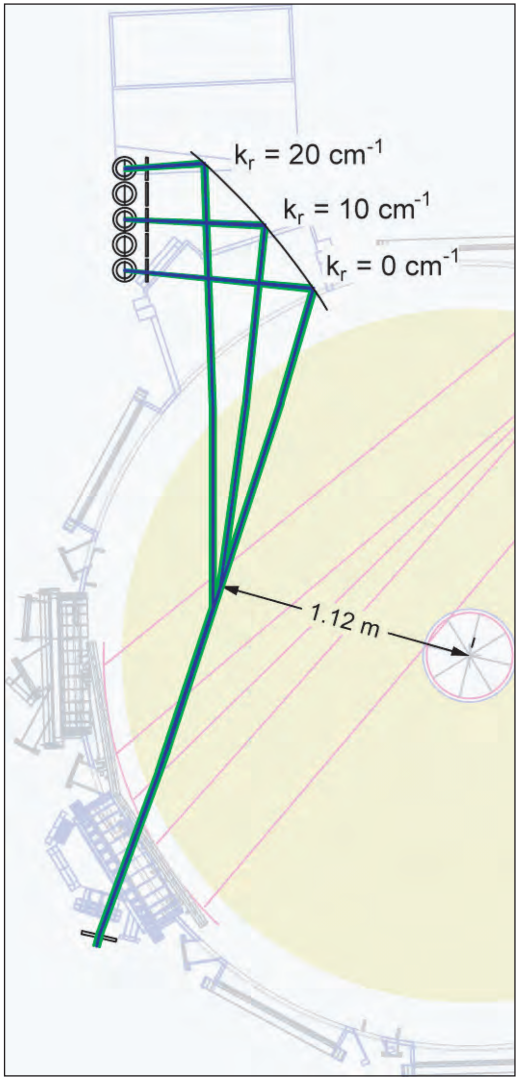
Density profile from Thomson scattering
and magnetic field from EFIT

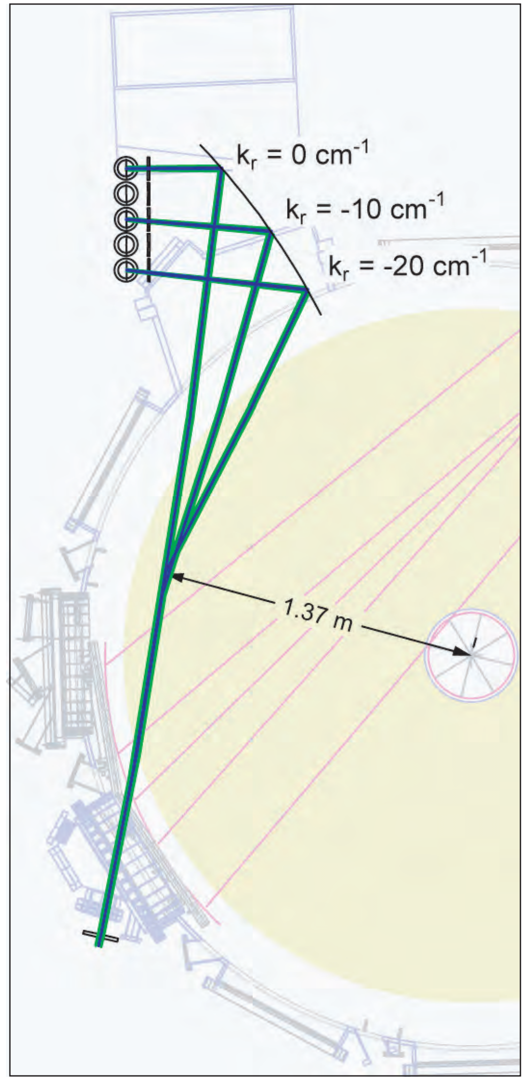
Launch Configurations

Inboard Launch

Tangency radius (flux normalized) $\rho \approx 0.05$

Measure fluctuations up to $k_r\rho_e \approx 0.6$





Outboard Launch

Tangency radius (flux normalized) $\rho \approx 0.7$

Measure fluctuations up to $k_r\rho_e \approx 0.3$

Anisotropic Fluctuations and Instrument Selectivity

NSTX

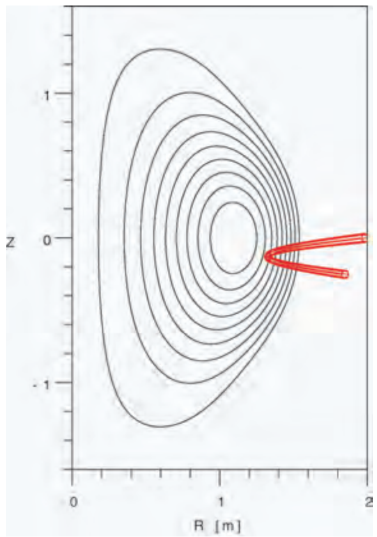
Plasma microturbulence is anisotropic and satisfies

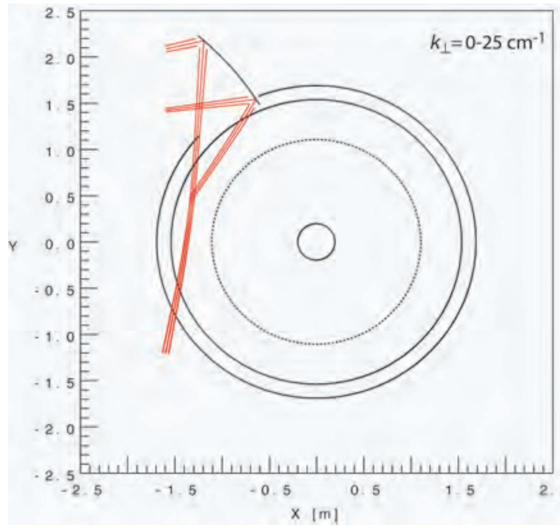
$$\mathbf{k} \cdot \mathbf{B} \approx 0 \quad \rightarrow \quad k_\perp >> k_\parallel$$

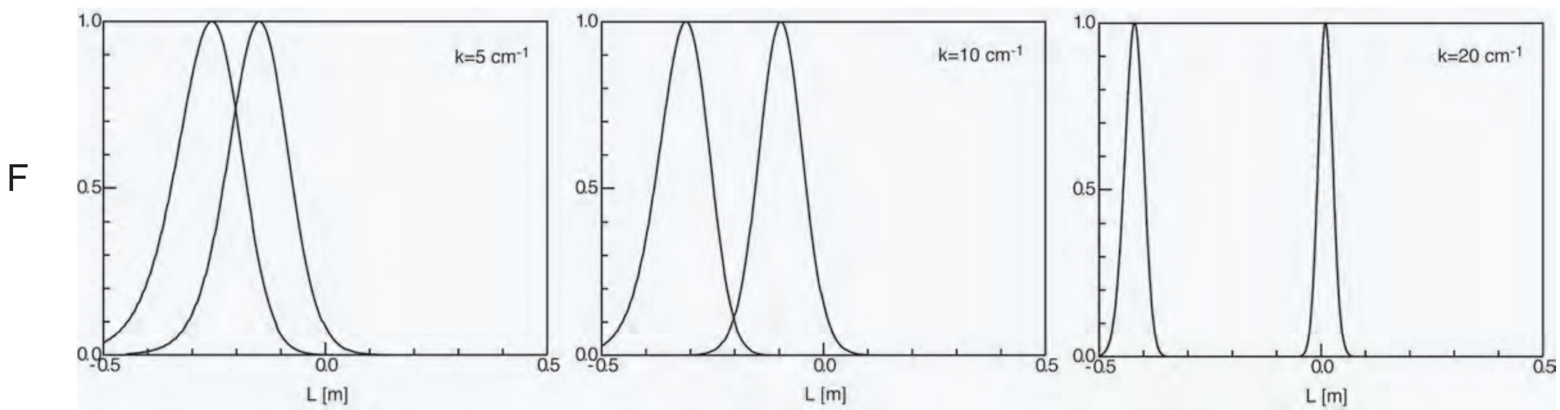
This condition imposes an additional factor on the spatial resolution known as the instrument selectivity fuction:

$$F(k, \theta_{kB}, \Delta k) = \exp\left[-\left(\frac{k \cos(\theta_{kB})}{\Delta k} \right)^2 \right]$$

where θ_{kB} is the angle between **k** and **B** and Δk is the wavenumber resolution.

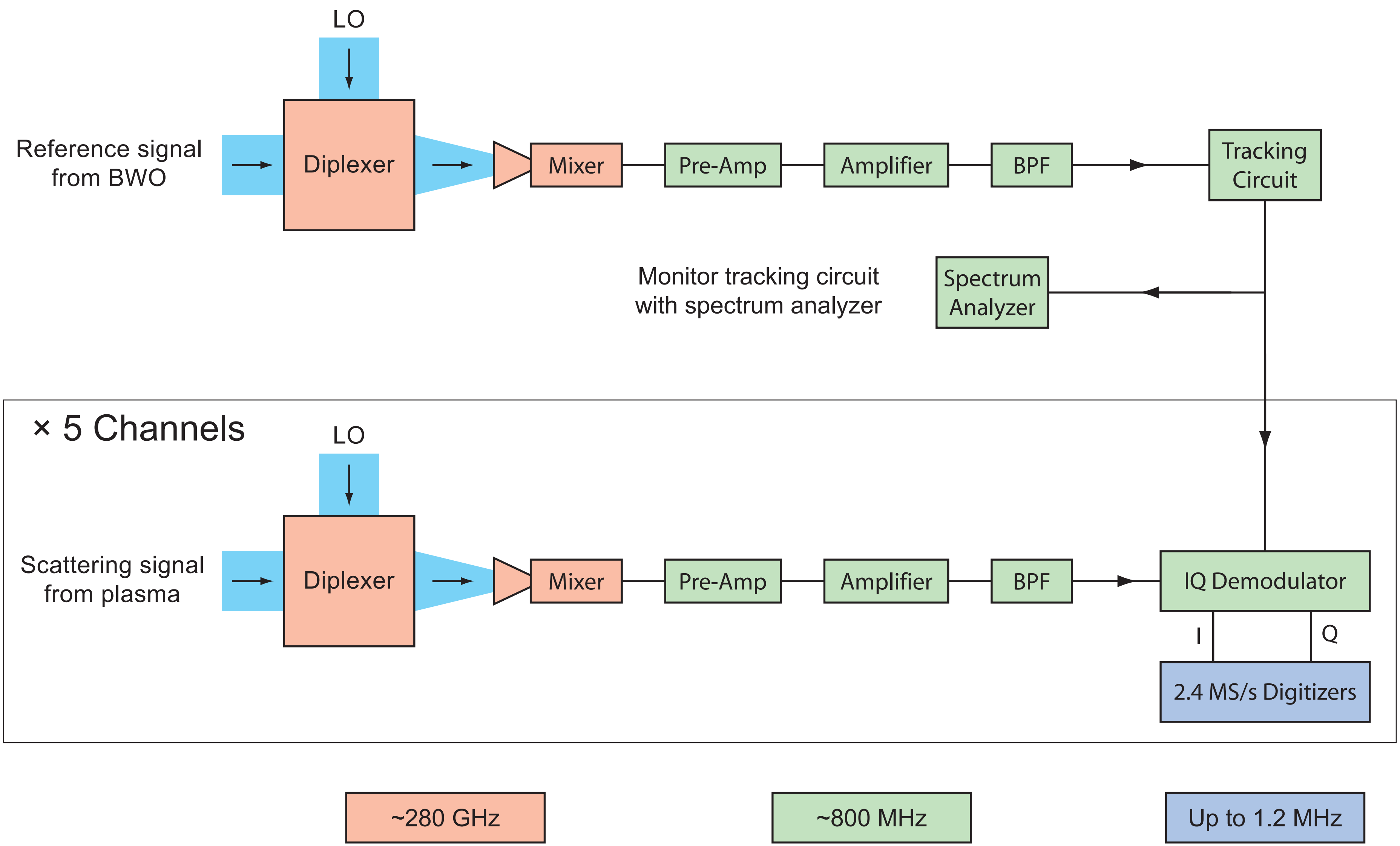






Distance along beam path

Superheterodyne Receiver



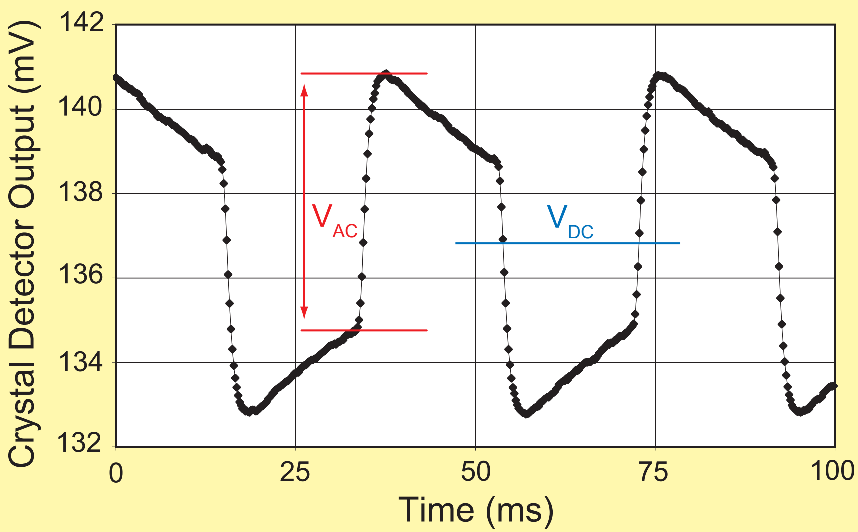
Receiver Noise Temperature

Noise Temperature

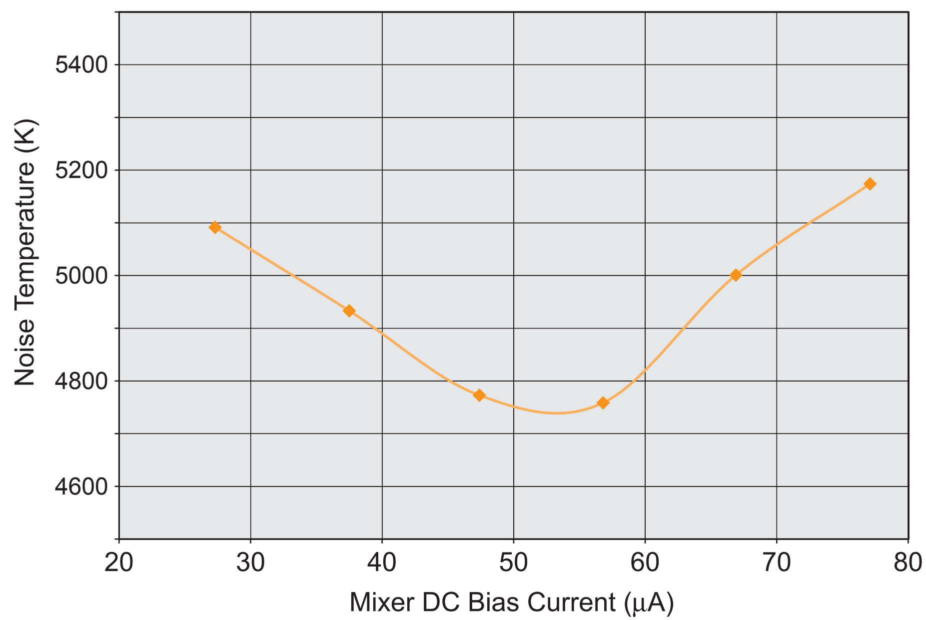
$$T_N \approx \frac{V_{DC}}{V_{AC}} \times (290\ \mathrm{K} - 77\ \mathrm{K})$$

Noise temperature measured by chopping the receiver's view between hot (290 K) and cold (77 K) blackbodies.

Hot/cold load measurements



Optimal Mixer DC Bias Current



Mixer 1:	Damaged
Mixer 2:	4492 K
Mixer 3:	6279 K
Mixer 4:	6130 K
Mixer 5:	4759 K

Inboard Window (Mixer 1)

Outboard Window (Mixer 5)

Minimum Detectable Fluctuation

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For a coherent density fluctuation, the scattered power can be approximated as

$$\frac{P_s}{P_i} \approx \frac{1}{4}\left(\frac{\omega_{pe}}{\omega_i}\right)^4 k_i^2\, L^2 \left(\frac{\tilde{n}_e}{\bar{n}_e}\right)^2 \left(\frac{2}{k_\perp a}\right)^2$$

scattering volume length (L) — probe beam radius (a)

The receiver noise power is

$$P_N = k_B\, T_N\, BW$$

For T_N = 5000 K and BW = 4 MHz

$$P_N \approx 2.8 \times 10^{-13}\ \text{W}$$

Assuming...

$$\frac{P_S}{P_N} = 2$$

$k_\perp = 20\ \text{cm}^{-1}$

$P_I = 100$ mW

$a = 4$ cm

$\omega_I = 2\pi \times 280$ GHz

$L = 10$ cm

$n_e = 2 \times 10^{13}\ \text{cm}^{-3}$

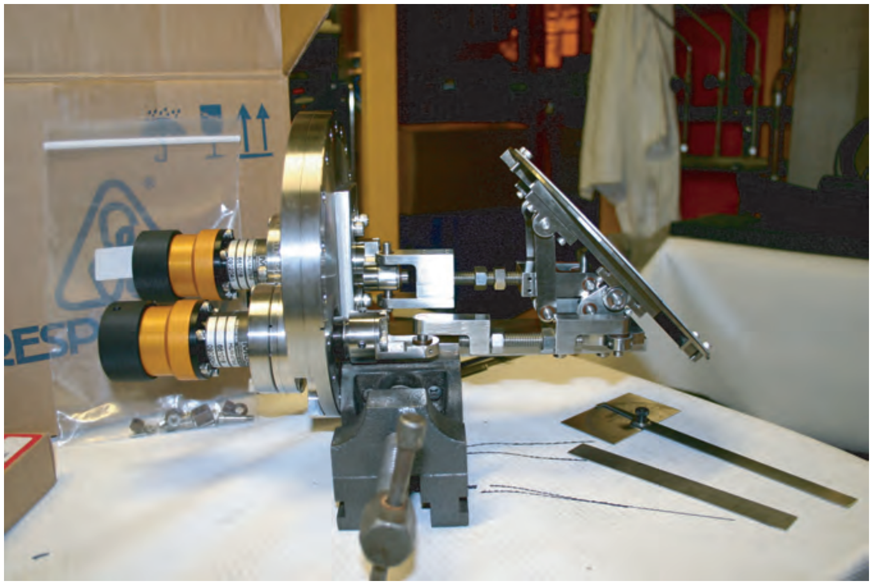
...the minimum detectable fluctuation is

$$\frac{\delta n_e}{n_e} \approx 1.6 \times 10^{-5}$$

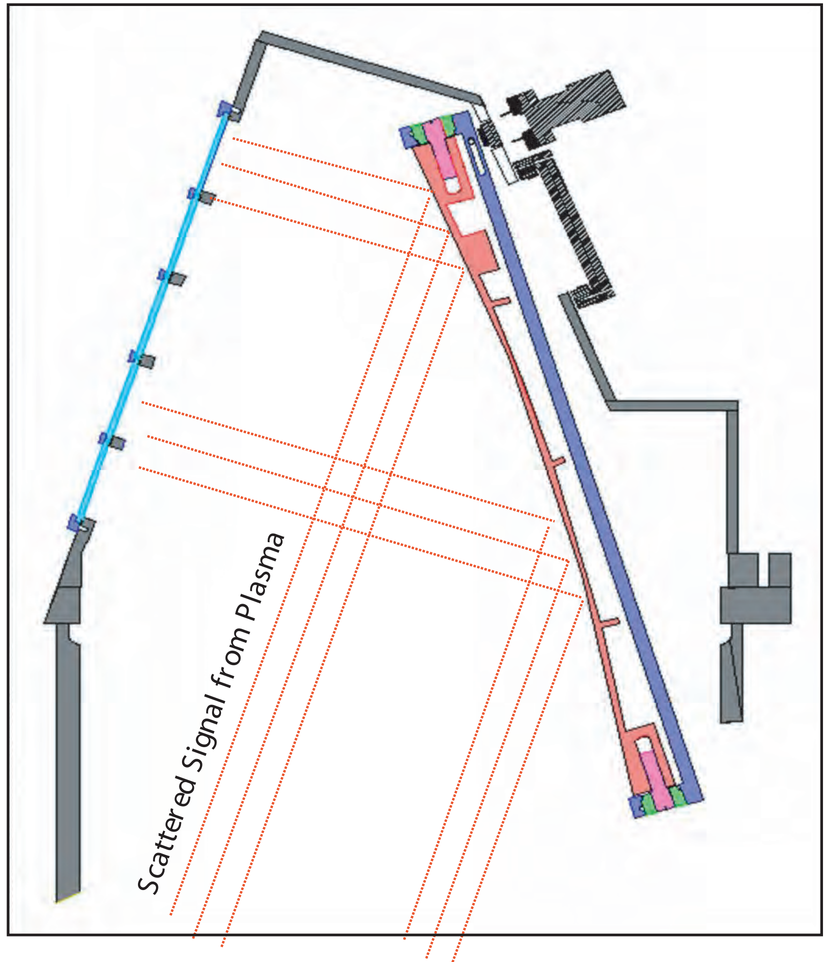
In-Vessel Hardware

NSTX

Probe beam steering mirror



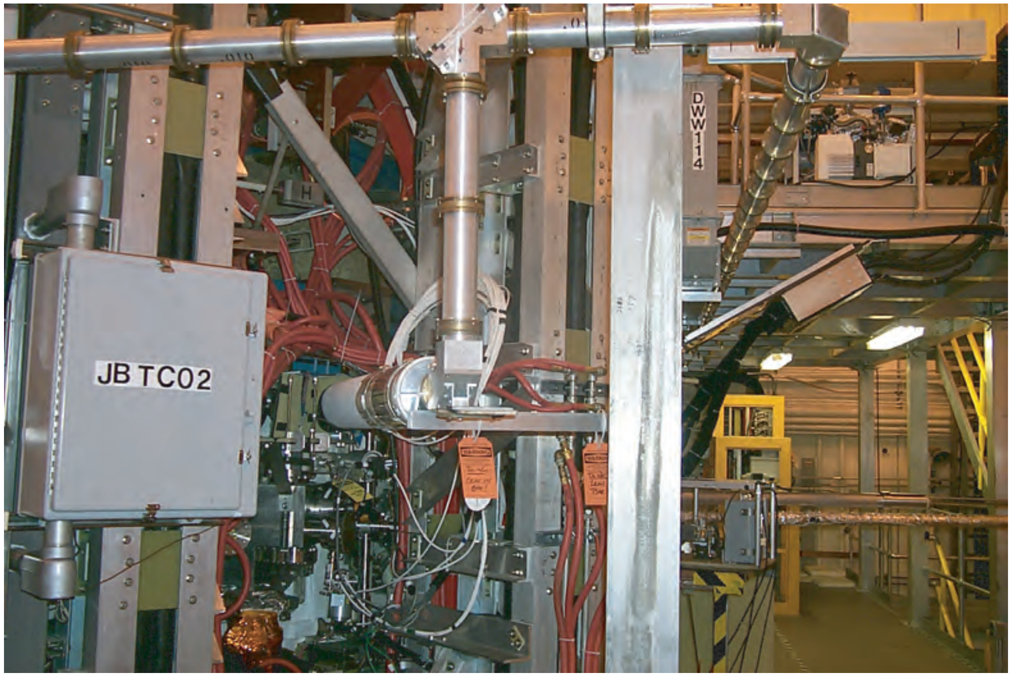
Collection mirror



Launch and Receiving Ports

Receiving Port

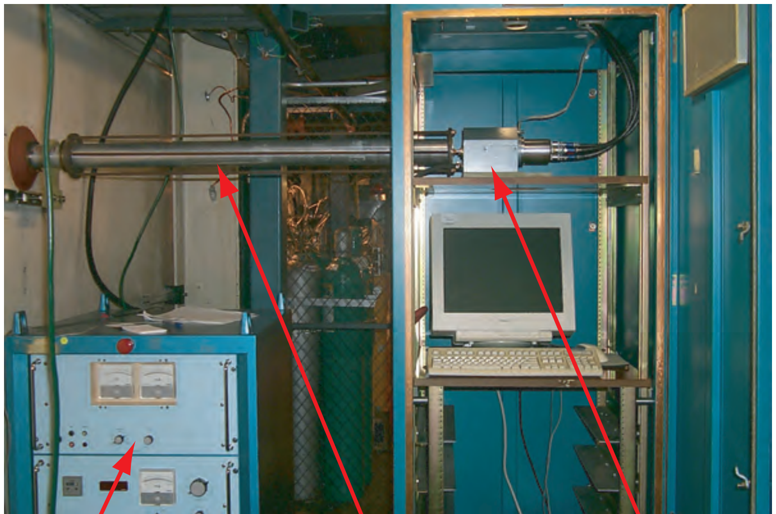
Launch Port



BWO Source and Receiver

NSTX

BWO Source



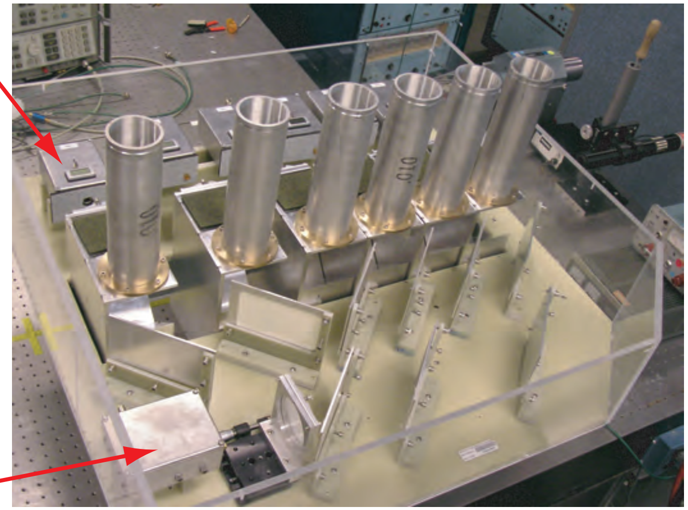
Power Supply

Waveguide Taper

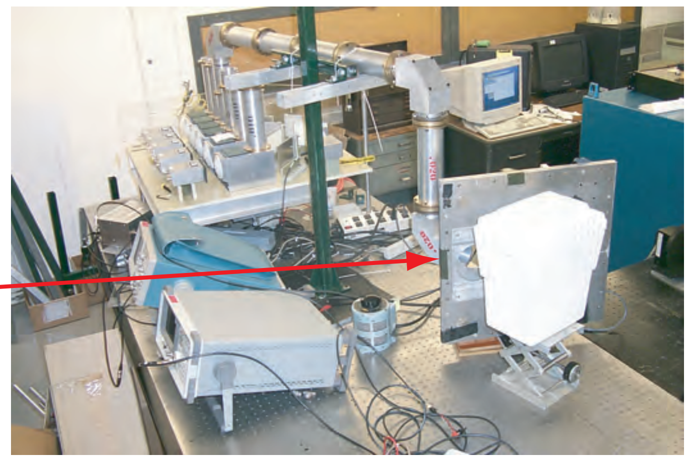
BWO

Receiver

Mixers/ Pre-Amps



LO

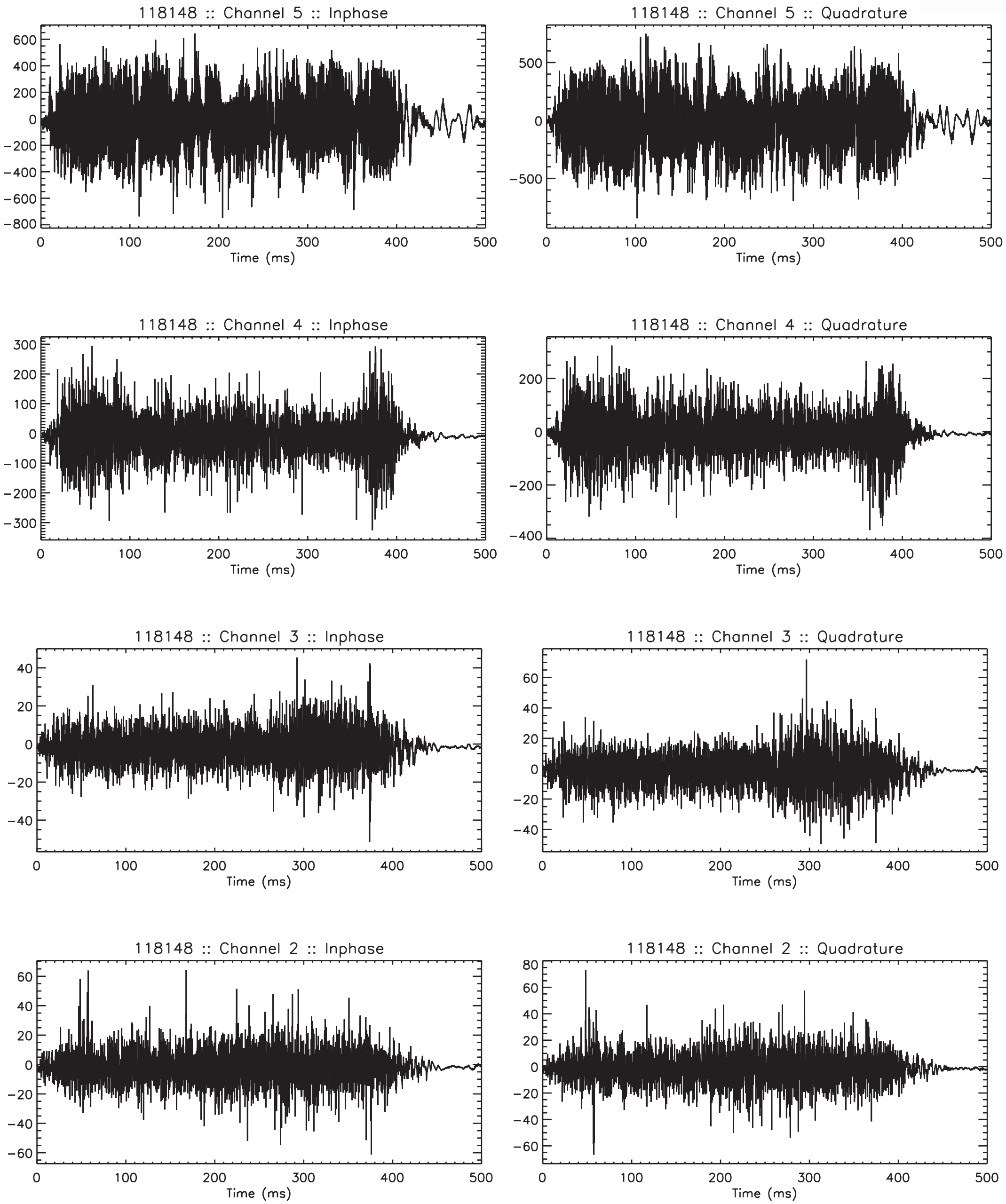


Hot/Cold Load Testing

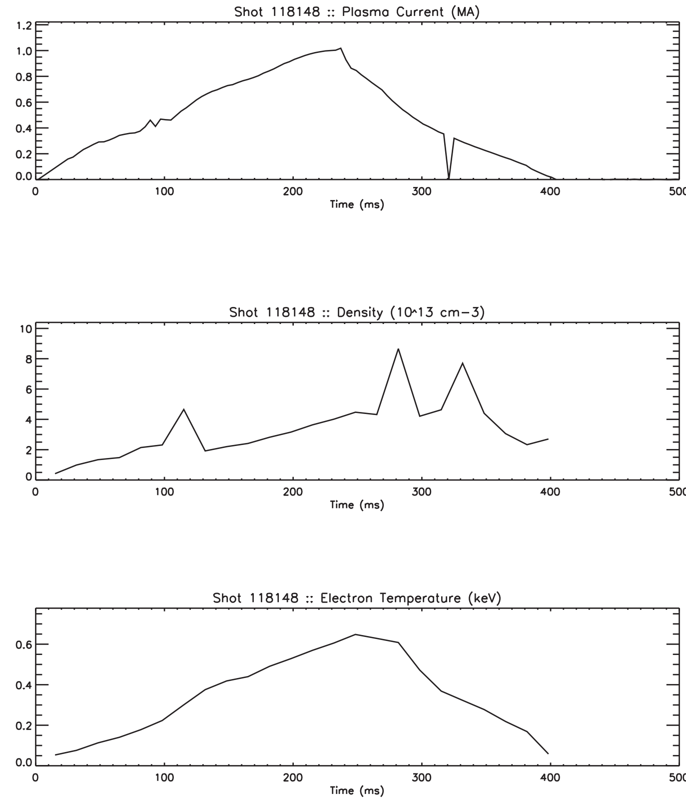
Preliminary Data

Low-k Channel

High-k Channel



Ohmic Discharge



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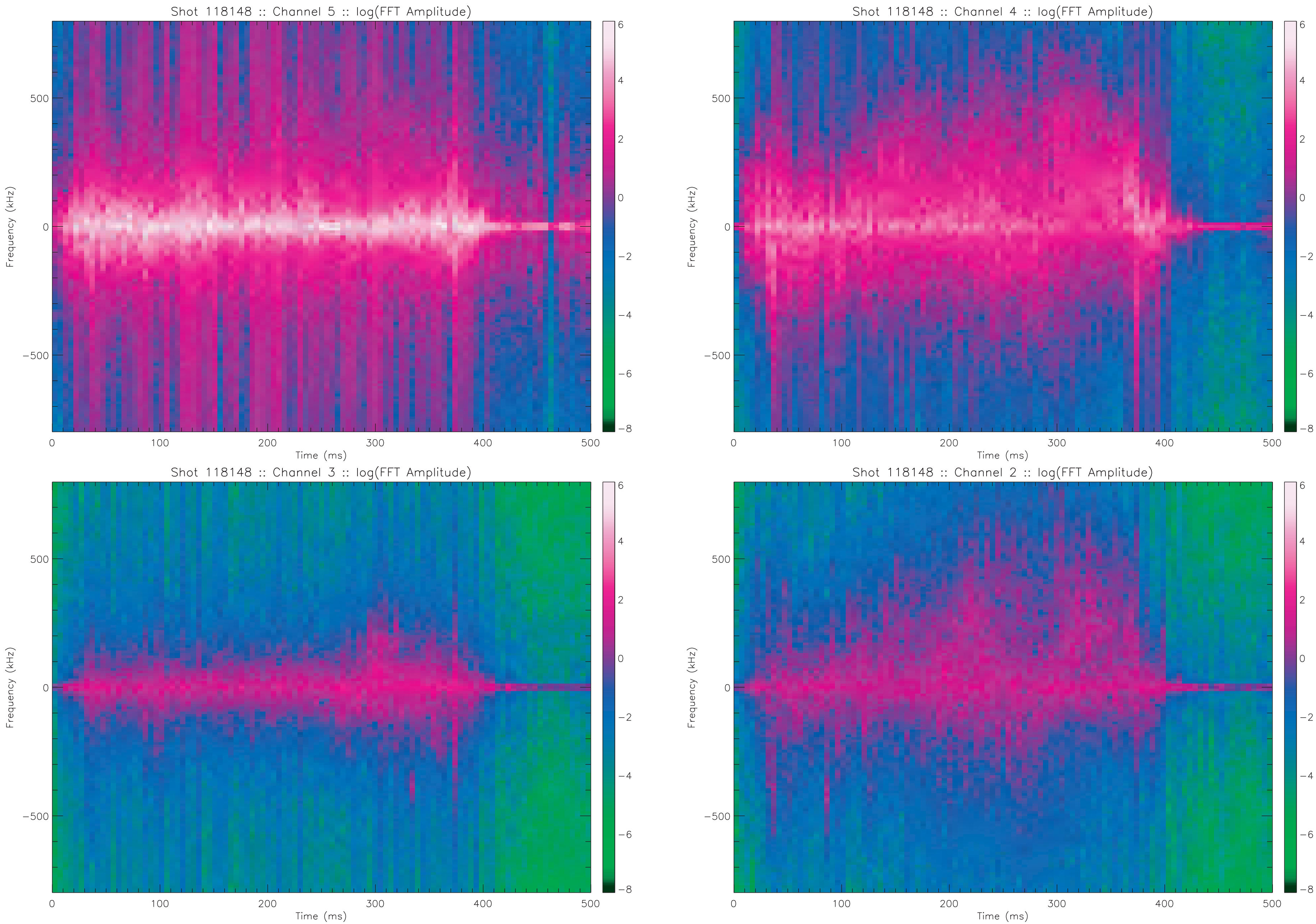

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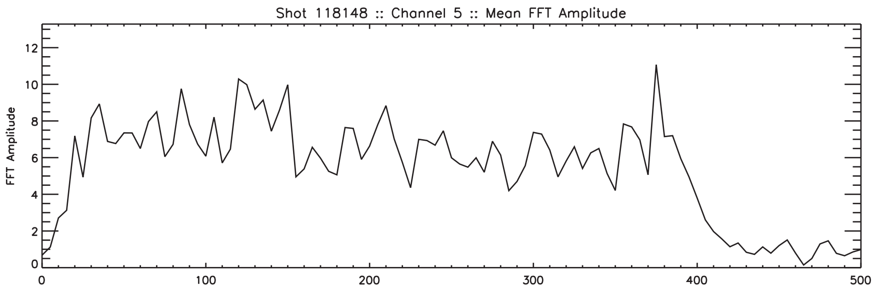

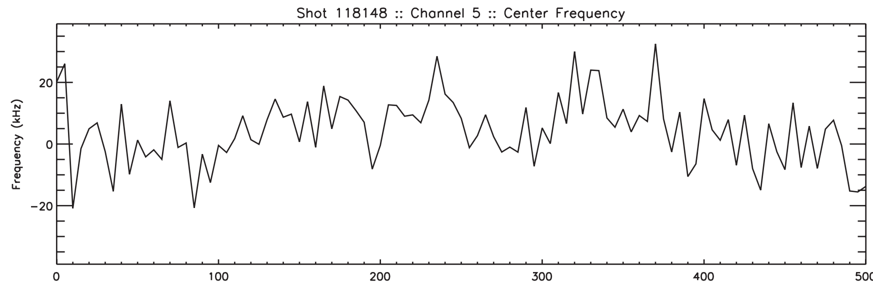

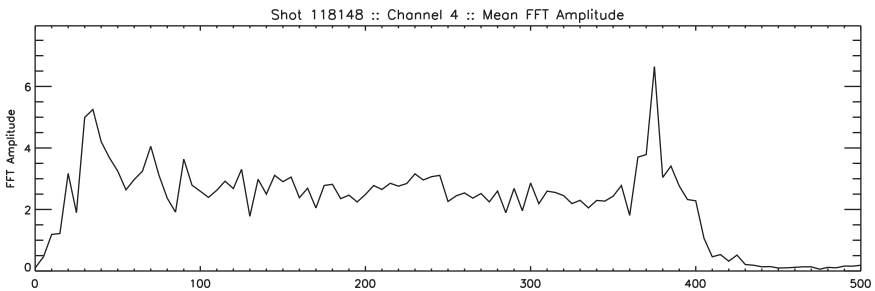

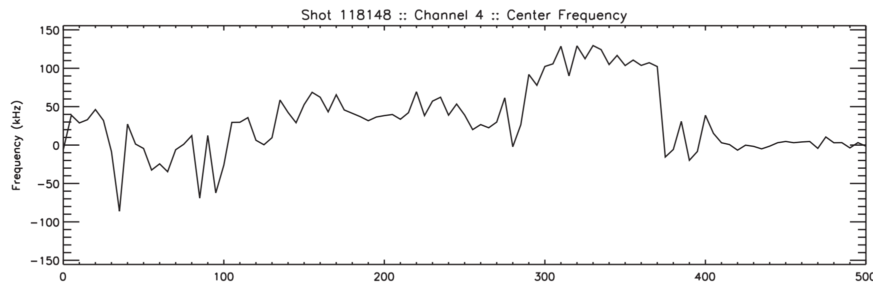

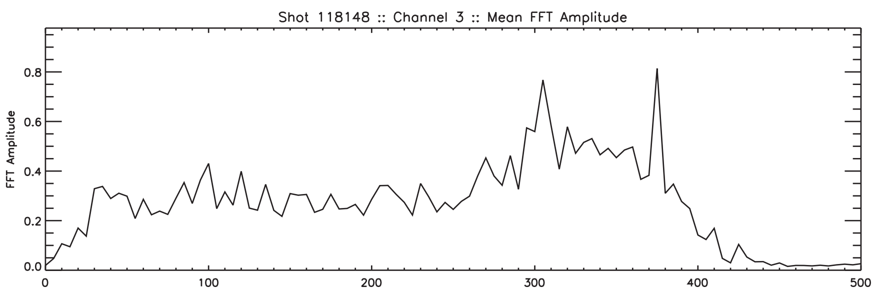

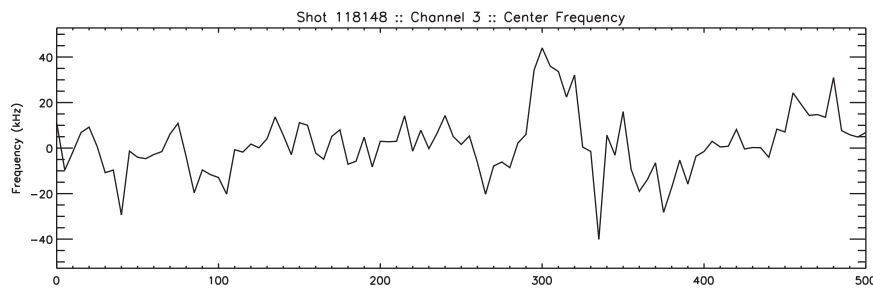

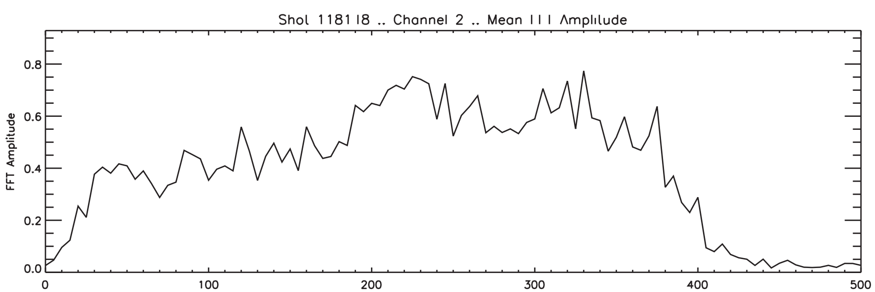

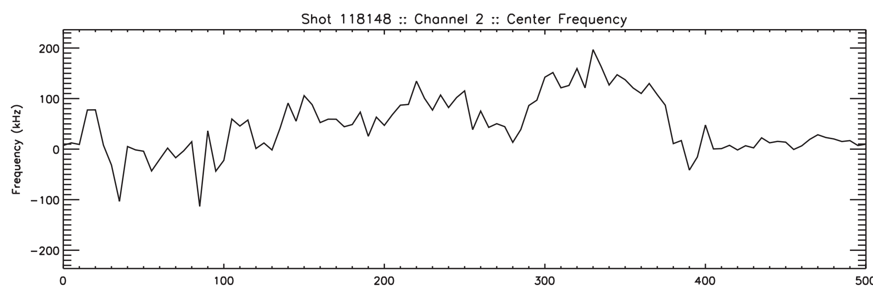

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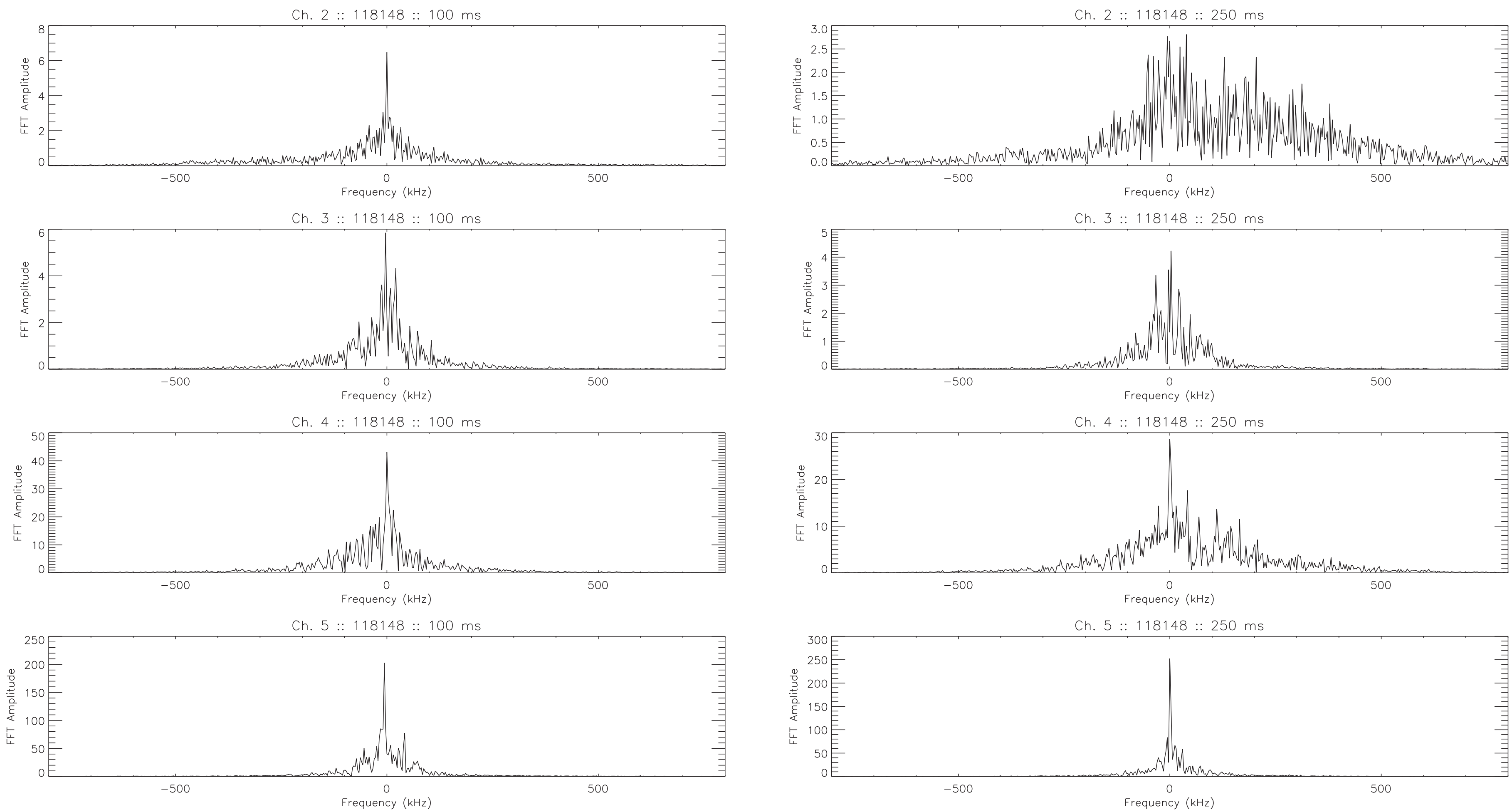
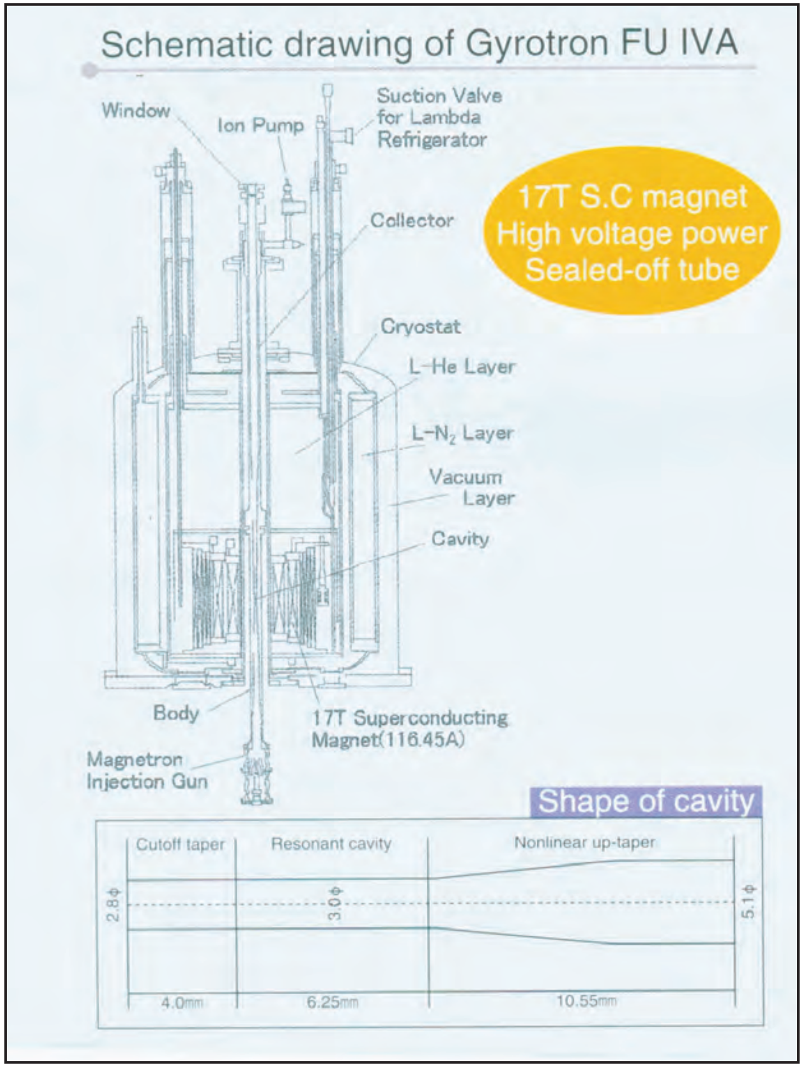
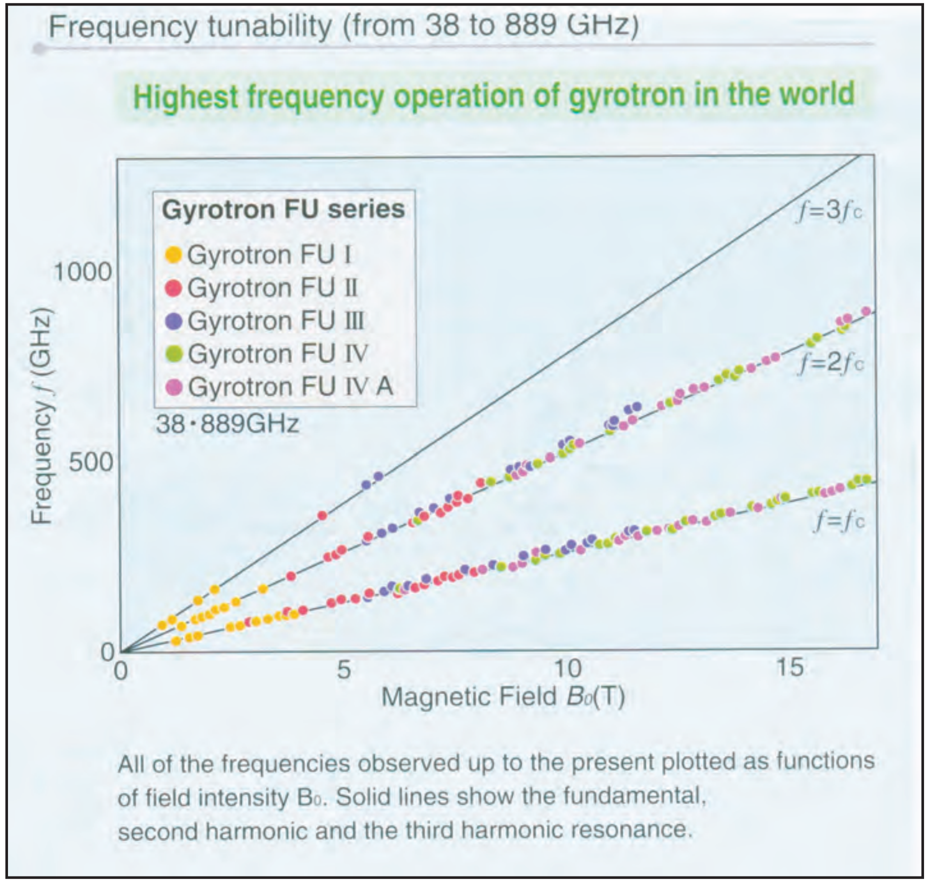


Gyrotron Upgrade





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