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Reflectometry for Density Fluctuation and Profile Measurements in TST-2

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Introduction

- Microwave reflectometry is sensitive to denstity fluctuations.
- A Ka-band reflectometer was designed and applied to TST-2 in order to measure the internal density fluctuation induced by RF and the density profile.
- The optics of the reflectometer was optimized by Kirchhoff integration.

Plasma diagnostics by reflectometry

Microwave is reflected by the cutoff surface inside a plasma.

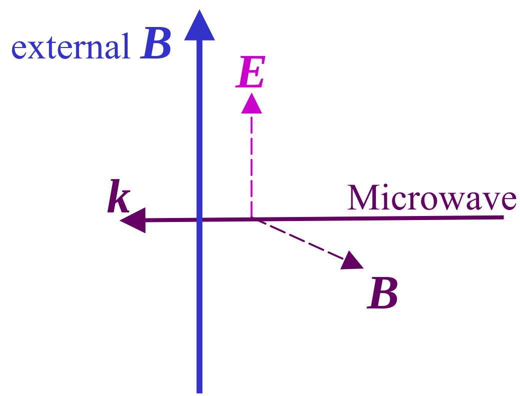
Dispersion relation
of O-mode

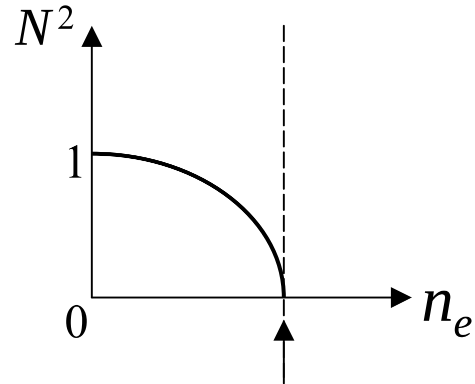
$$N^2 = 1 - \frac{\omega_p^{\ 2}}{\omega^2} = 1 - \frac{n_e}{n_c}$$

Electron plasma frequency

$$\omega_p^{\ 2} = e^2 n_e / (\varepsilon_0 m_e)$$

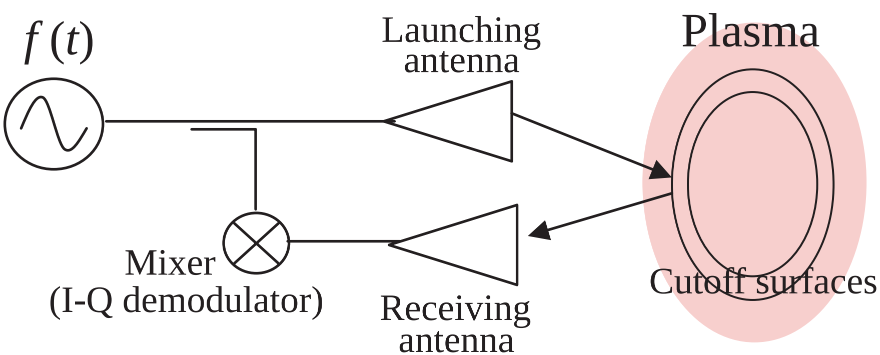
O-mode





$n_c = \varepsilon_0 m_e \omega^2 / e^2$
cutoff density

Homodyne reflectometer



Phase fluctuation corresponds to the fluctuation of cutoff.

$$\delta\phi = 4\pi\delta r/\lambda$$

$$\delta n_e = (\mathrm{d}n_e/\mathrm{d}r)\delta r$$

$$= \lambda(\mathrm{d}n_e/\mathrm{d}r)\delta\phi/4\pi$$

$$\lambda = 1.7\lambda_0$$

Previous works of the RF measurements

ICRF induced density oscillation in GAMMA-10 tandem mirror (right Fig.).

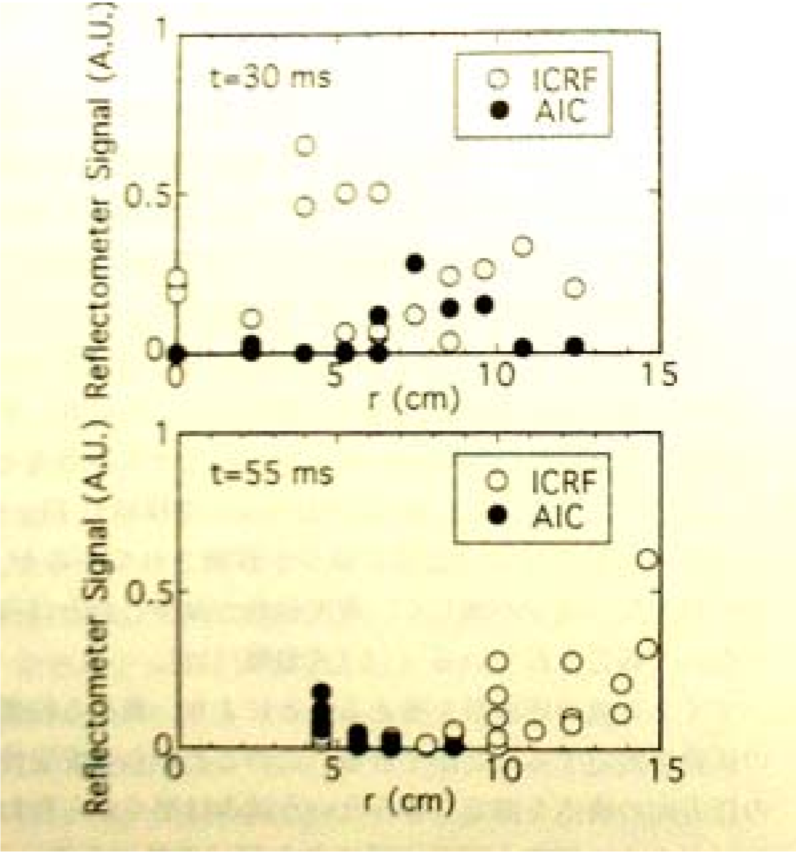
A. Mase *et al.*: Rev.Sci.Instrum. **66**, 821(1995).

FW induced density oscillation in DIII-D.

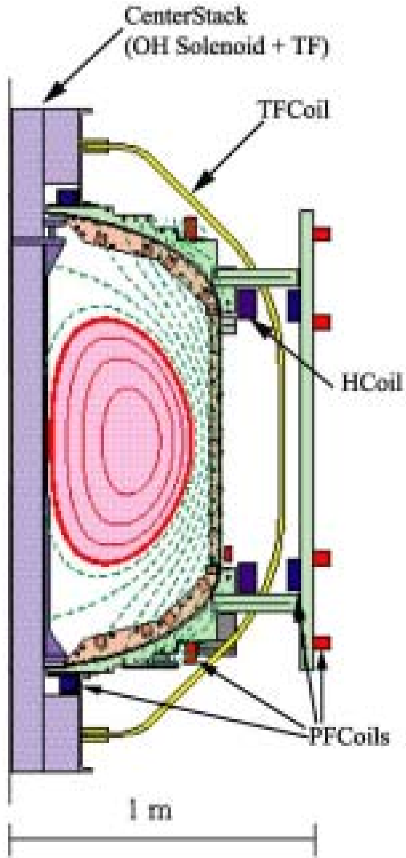
J. H. Lee *et al.*: Rev.Sci.Instrum. **66** (1995) 1225.

HHFW indude density oscillation in NSTX (edge region).

J. B. Wilgen *et al.*: Rev.Sci.Instrum. **66** (1995) 10E933.



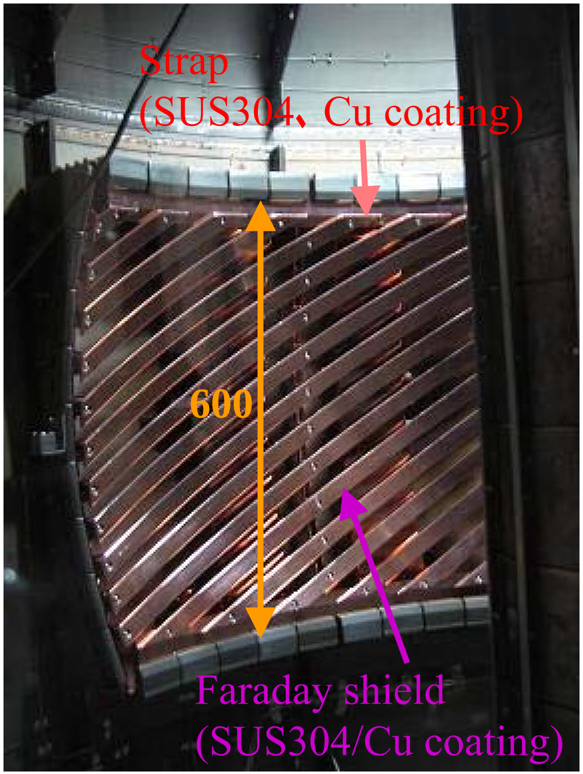
TST-2 Spherical Tokamak

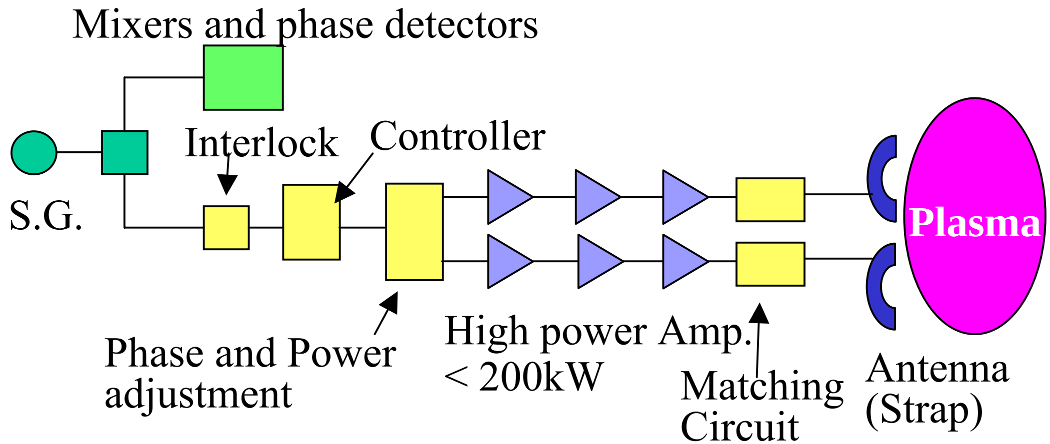


Parameters

- $R_0 \sim 0.38\,\mathrm{m}$
- $a \sim 0.25\,\mathrm{m}$
- $A = R_0/a > 1.5$
- $n_{e0} \sim 2 \times 10^{19}\,\mathrm{m}^{-3}$
- $B_t = 0.14\,\mathrm{T}$ (at $R = R_0$)
  $\sim 0.1\,\mathrm{T}$ (at $R \sim 0.6\mathrm{m}$)
- $I_p < 70\,\mathrm{kA}$
- $t_{\mathrm{discharge}} = 15\,\mathrm{ms}$

High harmonic fast wave heating





- Two-Strap antenna.
- 21 MHz, ~260 kW.

$E_p \sim 2000$ V/m (estimated from calculation).

Substituting $v = E_p \times B_t$ to $\dfrac{\partial n_e}{\partial t} + (v \cdot \nabla) n_e = 0$,

$\omega_{rf} \delta n_e \sim \dfrac{E_p}{B_t} \dfrac{\partial n_e}{\partial r}$, so the flucs. estimated are

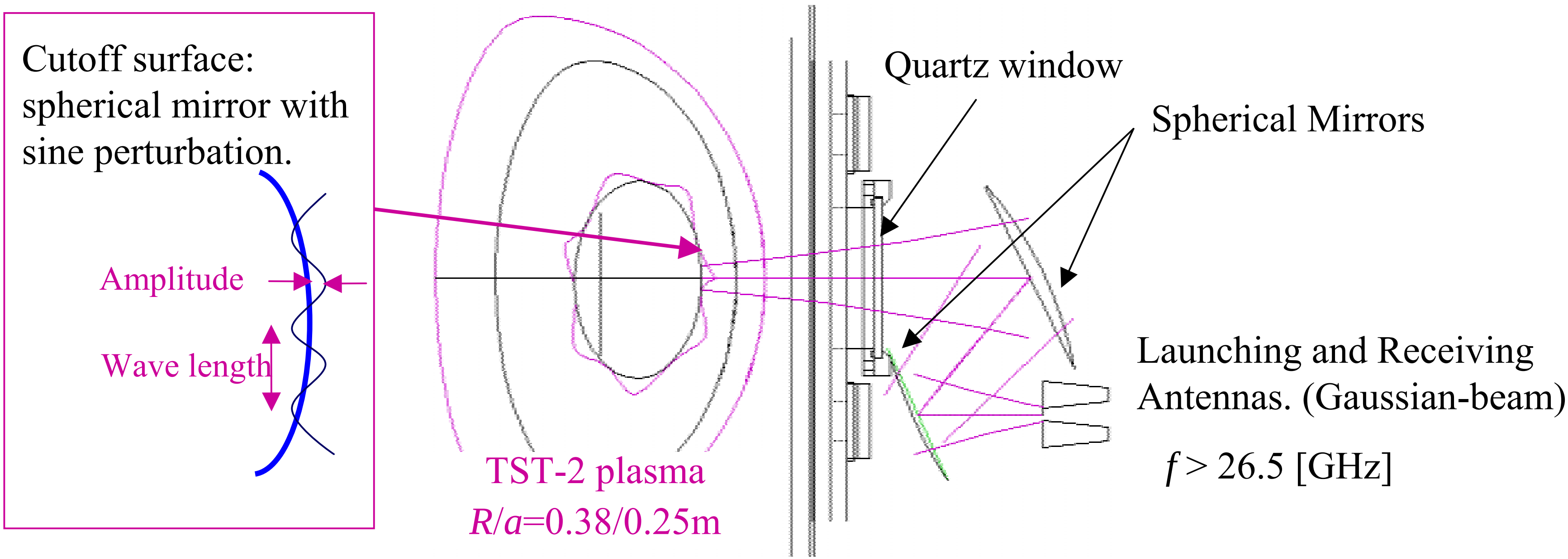
$$\frac{\delta n_e}{n_e} \sim \frac{E_p}{\omega_{rf} B_t a} = \frac{2000}{10^8 \times 0.1 \times 0.25} = 0.1\%,$$

$$\delta \phi \sim \frac{2}{1.7} \frac{\lambda_{rf}}{\lambda_0} \frac{E_p}{c B_t} = \frac{2 \times 10^3 \times 2000}{1.7 \times 3 \times 10^8 \times 0.1} = 0.08 \text{ rad.}$$

Designing a reflectometer

The microwave optics of the reflectometer was designed by using Kirchhoff integration.

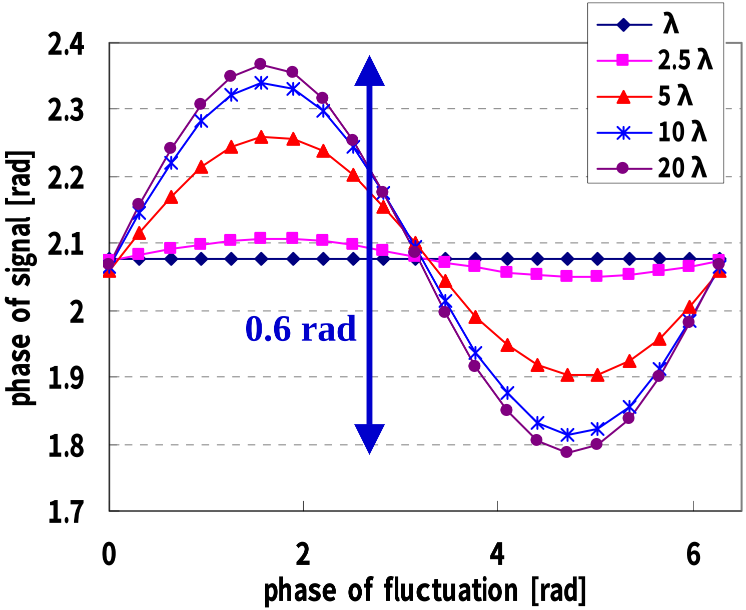
$$E_P = \frac{1}{4\pi}\int_S \left(E_S \frac{\partial}{\partial n}\frac{e^{-ikr}}{r} - \frac{e^{-ikr}}{r}\frac{\partial E_S}{\partial n}\right) dS$$



The simulation includes all optical elements (antennas, mirrors and cutoff surface) in 3-D configuration.

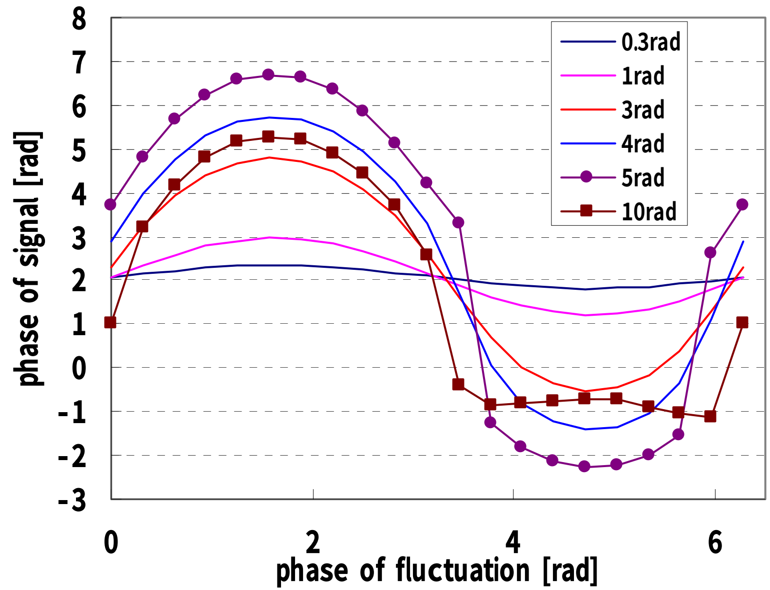
Performance of the reflectometer

Dependence on the fluctuation wavelength (Fluctuation amplitude = 0.3 rad of phase shift of the reflectometer).



The fluctuation could be measured when the wave length was over 5λ.

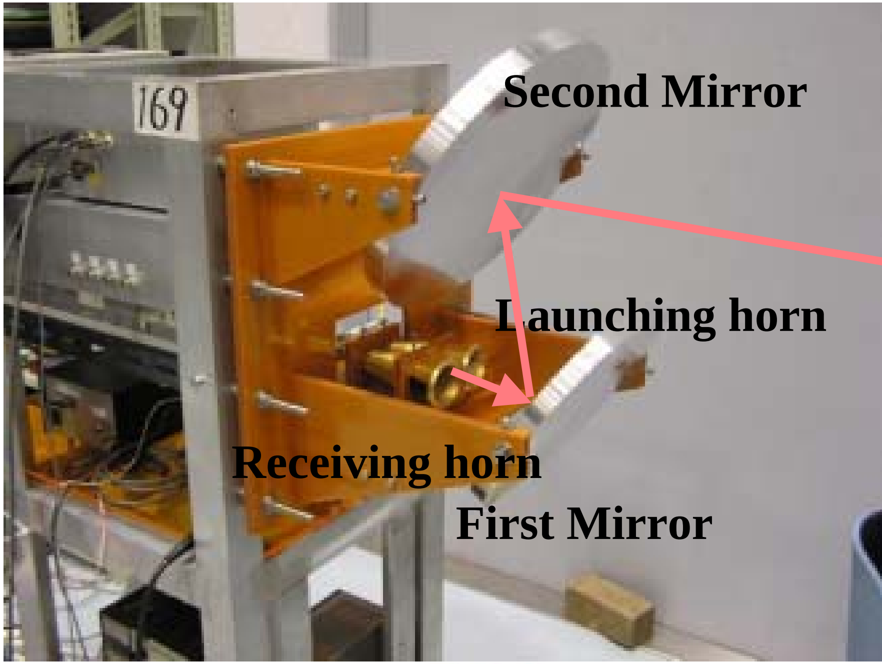
Dependence on the fluctuation amplitude (Wave length of fluctuation = 10λ).

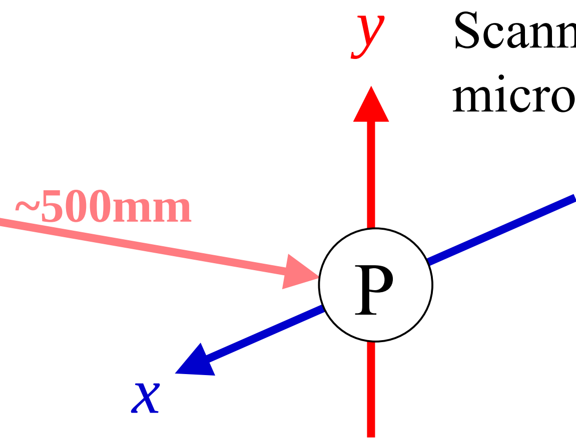


The phase of signal began to corrupt when the amplitude of the fluctuation was over 5 rad.

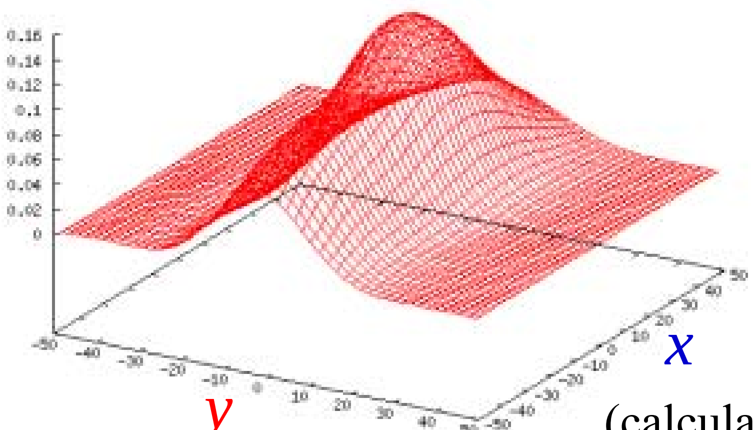
Linear response is preserved for long wavelength and small amplitude perturbations.

Measured and calculated beam profile

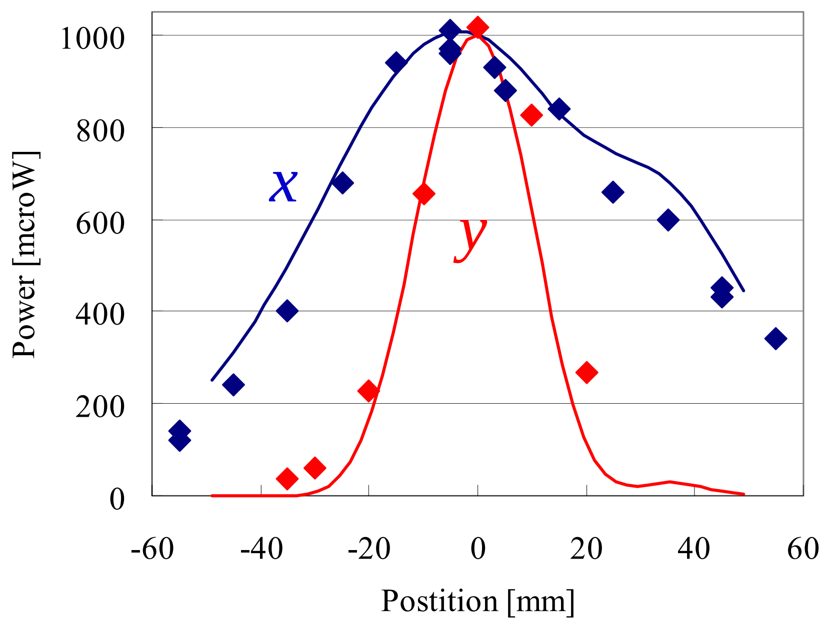




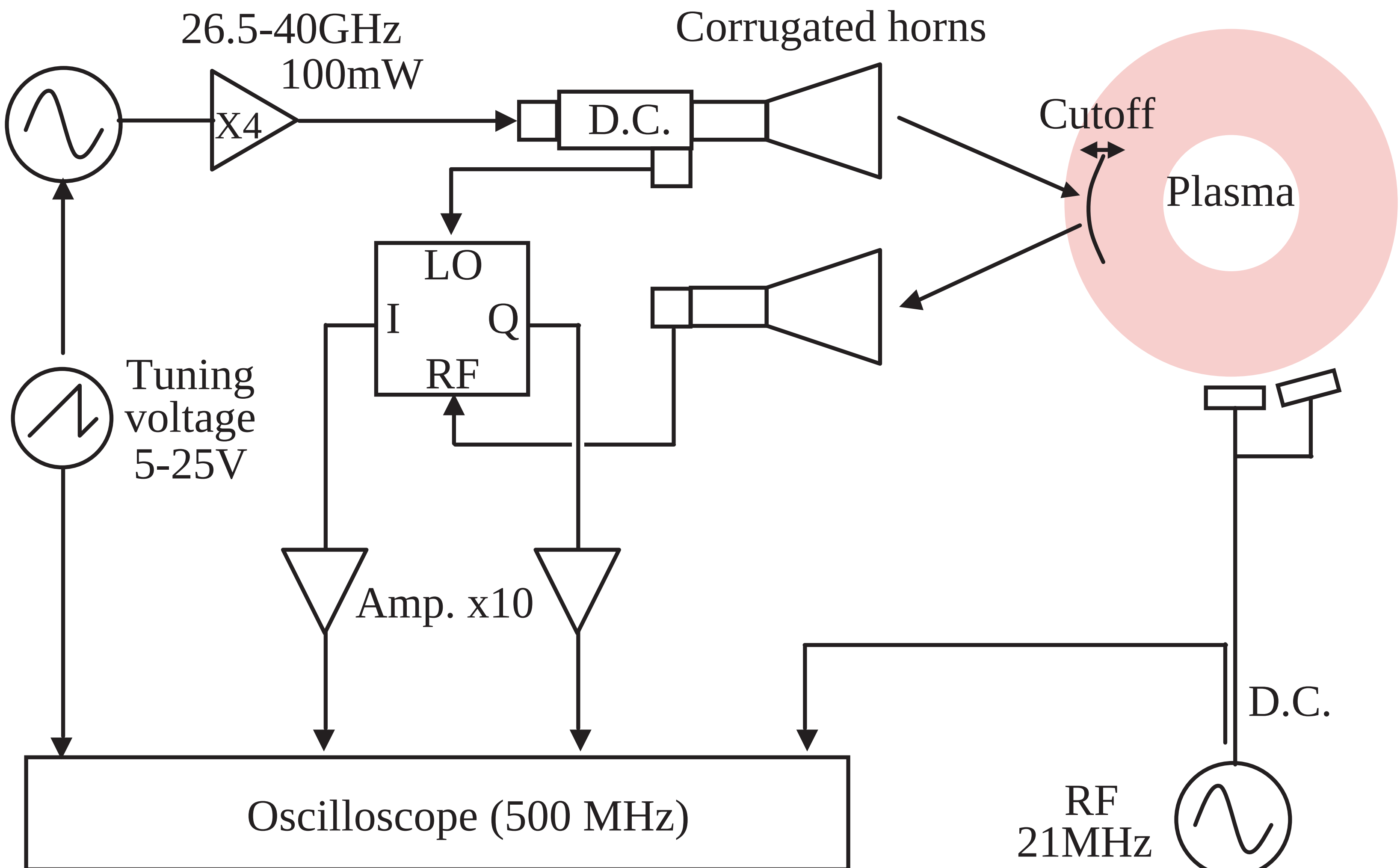
Scanned the microwave power.



(calculation)

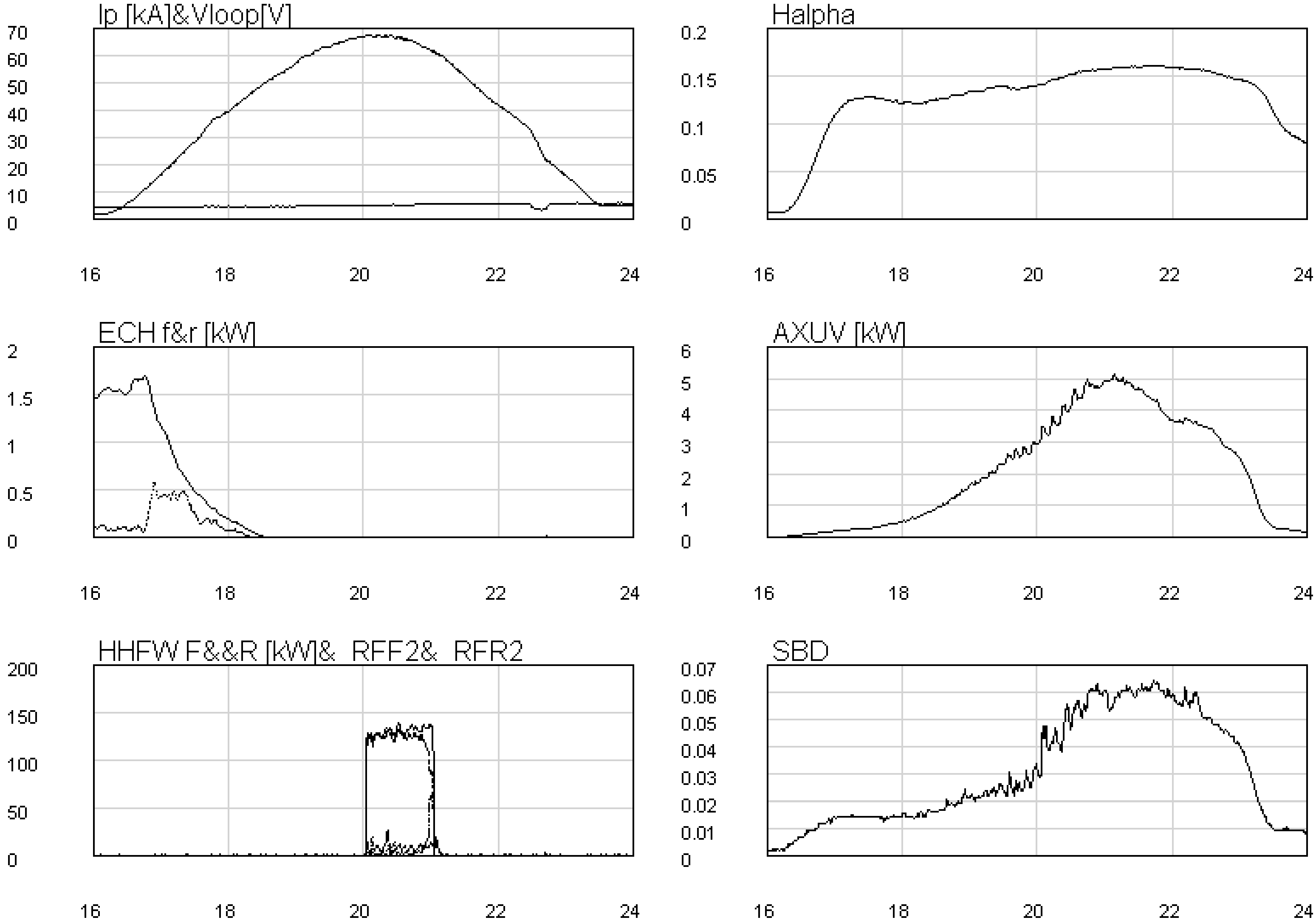


Schematic of the reflectometer



Typical discharge of TST-2

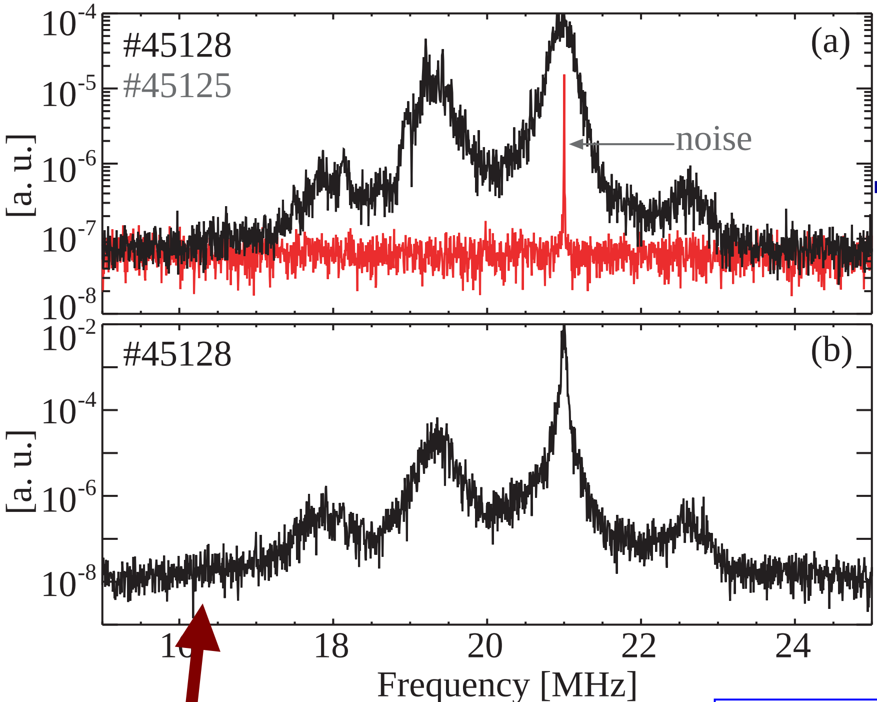
#45128



Detection of RF by Gunn

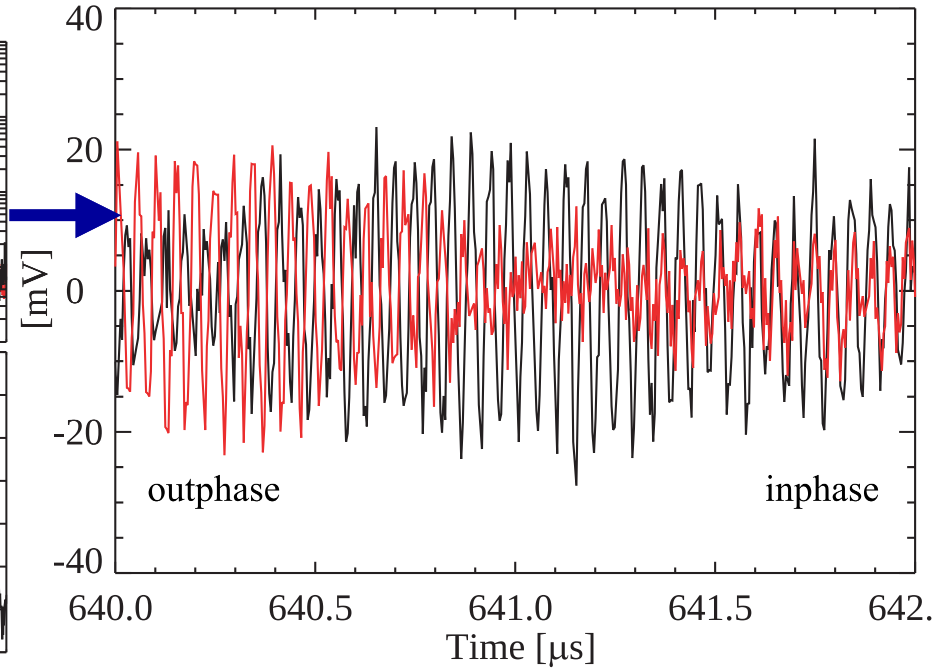
(25.85GHz)

The density fluctuation induced by RF was detected.
The noise has a sharp spectrum.



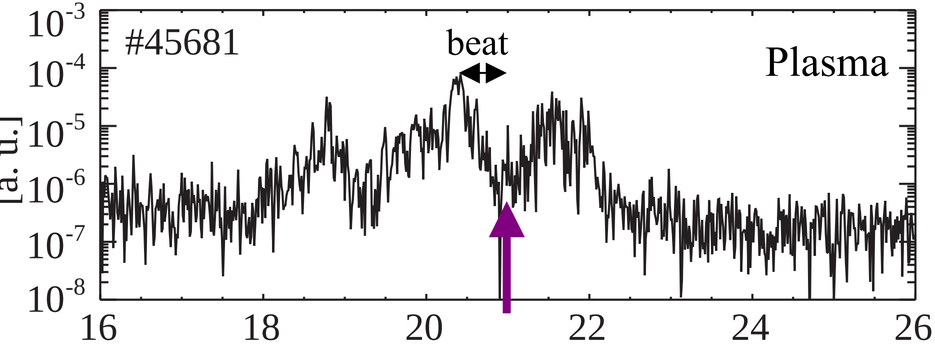
RF pickup probe has a same spectrum shape.

Magnification of the I-Q outputs (high passed). They repeat inphase and outphase, so that it is not pickup noise.

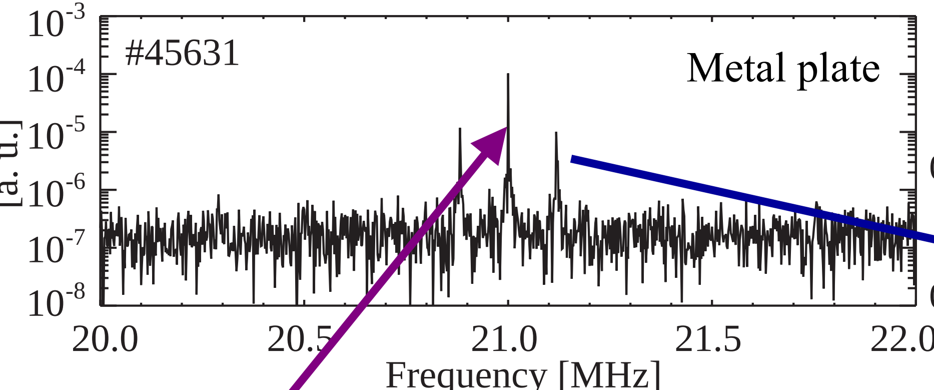


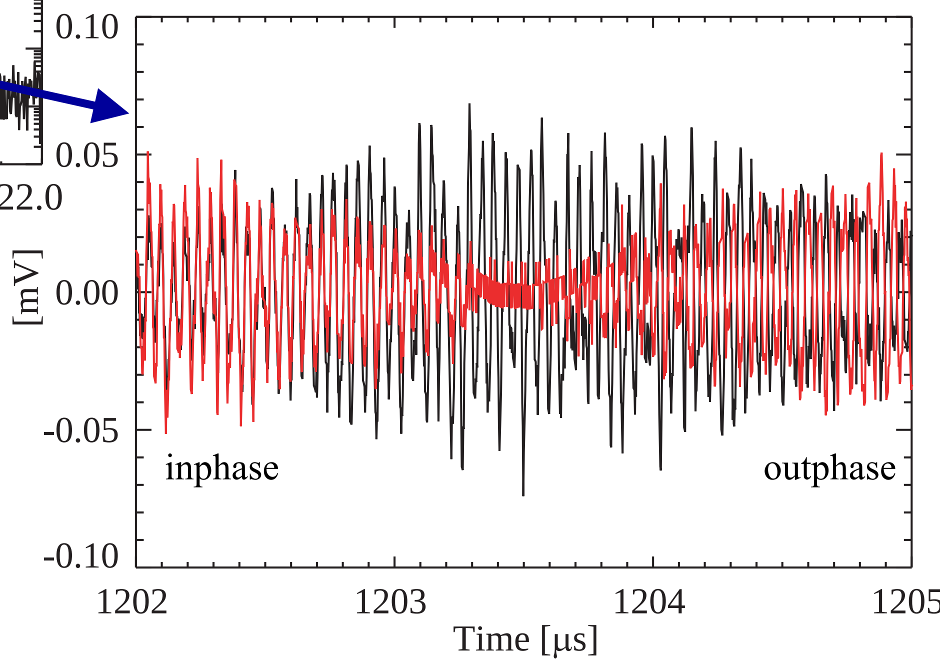
The poloidal electric field induced by RF was estimated to be ~ 1.3 kV/m.

Detection of RF by VCO



When the frequency is swept, the RF signal is modulated by the beat frequency and becomes f_{rf}+- f_{beat}. Pickup noise remains in f_{rf}.

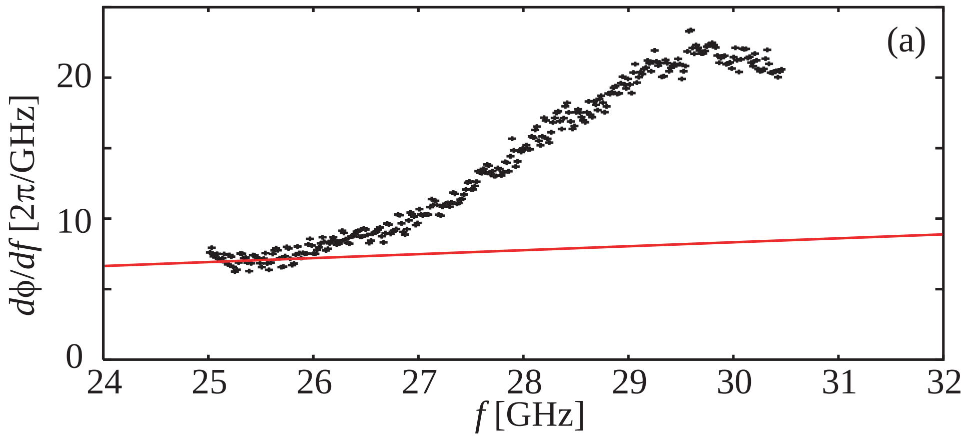




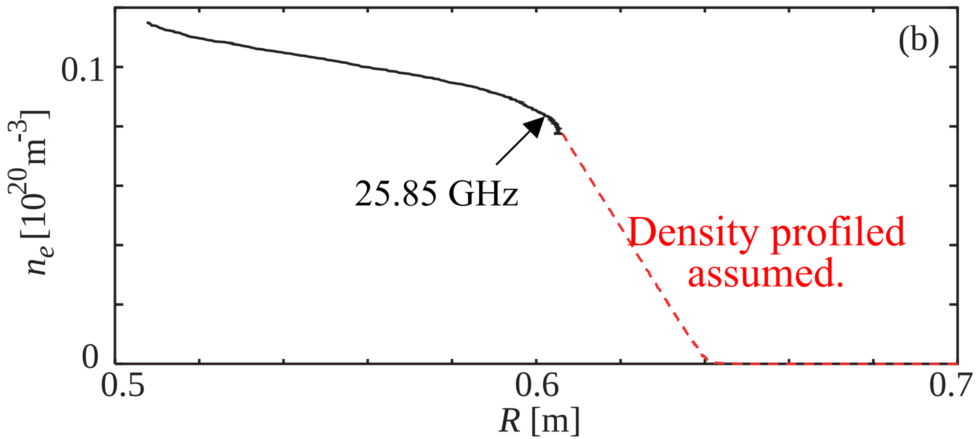
The f_{rf} component of the I-Q output is a pickup noise.

The f_{rf}+- f_{beat} components of the I-Q outputs are FM noise.

Profile measurements



Frequency derivative of the phase, which represents the group delay.



Density profile reconstructed by the reflectometer.
The density fluctuation at 25.85GHz is obtained by the density profile to be about 0.03% to 0.2%.

Simultaneous measurements of the fluctuation and the profile is in preparation.

Summary

- A reflectometer in Ka-band was designed and applied to TST-2.
- The arrangement of the reflectometer was determined by the calculation using Kirchhoff integration.
- Internal density fluctuations induced by HHFW heating were detected.
- The poloidal electric field excited by HHFW was calculated to be about 1.3 kV/m.