Design and Installation of a Collective Scattering System on HELIX

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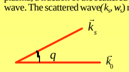
Motivation

The physics underlying the coupling of RF power into helicon plasmas remains a topic of ongoing research. One explanation proposed for the high RF absorption efficiency is the coupling of the RF power to strongly damped slow mode (Trivelpiece-Gould) waves at the plasma edge. The slow wave dispersion characteristics ($\lambda < 1$ mm, $f \sim 10$ MHz) do not allow direct measurements with physically realizable probes. Collective scattering is the only method capable of directly measuring these fluctuations. A compact collective scattering system is being installed on the Hot hELIcon eXperiment (HELIX) at WVU. The source is a 3.3 mW frequency tripled Gunn oscillator (f= 300 GHz) with an expected scattered power of ~ .01nW. The scattered power is collected with a homodyne detection system capable of resolving fluctuations up to 40 MHz. Scattering volume waists are 0.50– 0.70 cm at the plasma edge (r = 3.5 cm). The initial edge scattering geometry corresponds to a fluctuation wave number of65 cm^{-1}. Incident beam rotation will allow detection of wave numbers in the range of 45 to 85 cm^{-1}. By manually scanning the collection optics, fluctuations across the full radial plasma profile can be investigated.

Collective microwave scattering

When a plane polarized electromagnetic wave (k_0, w_0) scatters off an electron density fluctuation (k, w) in a plasma, a fraction of the scattered radiation appears at an angle q relative to the direction of the incident wave. The scattered wave (k_s, w_s) must conserve momentum and energy, thus



$$\Delta\vec{k} = \vec{k}_s - \vec{k}_0$$
$$\Delta w = w_s - w_0$$

For most laboratory plasmas, $w << w_0$ and the wavenumber equation becomes

$$|\Delta\vec{k}| \cong 2|\vec{k}_0|\sin(q/2)$$

with the added constraint of angular separation between the incident beam and the scattered radiation [*Slusher and Surko* , 1980].

Why 1 mm microwaves?

The Doppler shift of the scattered radiation due to the phase velocity of the electron density fluctuation is

$$\Delta w \cong v_p |\Delta\vec{k}|$$

and scattering from ions can be neglected due to their much larger mass [*Holzhauer et al*, 1990]. To observe collective particle fluctuations, the wavelength of the illuminating electromagnetic wave must satisfy

$$|\Delta\vec{k}|\, l_{De} < 1$$

where l_{De} is the electron Debye screening length [*Slusher and Surko* , 1980]. Thus, the upper bound on the choice of interrogation wavelengths becomes

$$l_0 \leq 4p \sin(q/2)\, l_{De}$$

For HELIX and RSX (the Reconnection Scaling Experiment at Los Alamos National Laboratory) plasmas, $l_o \leq 1.5$ mm is sufficient to observe collective scattering from electron density fluctuations.

The lower limit on the incident wavelength is constrained by the scaling of the scattered power with incident wavelength,

$$P_s = \tfrac{1}{4} P_0 r_e^2\, l_0^2 (\tilde{n})^2 L_v^2$$

where r_e is the classical electron radius and L_n is the length of the scattering volume [*Luhmann and Peebles*, 1984]. For identical fluctuation amplitudes, scattering volumes, and incident powers, the scattered power from a 1 mm microwave is 100 times larger than the scattered power from 1 00 µm far infrared (FIR) laser and 10,000 times larger than the scattered power from a 10µm CO_2 laser. Thus, for collective scattering experiments, a 1 mW given by a microwave varactor multiplier diode is equivalent to a 100 mW FIR laser and to a 10 W CO_2 laser.

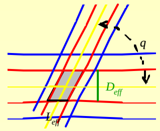
Expected parameters for diagnostic

The scattered signal is mixed with a fraction of the original beam (coherent detection) so that the amplitude and phase of the scattered radiation can be measured using signals that have been transformed into the radio frequency range due to beating of the Doppler shifted scattered radiation with the reference signal.

The scattering volume is defined by the overlap of the incident beam and the antenna beam of the coherent receiver. The dimensions of the scattering volume for the incident and scattered Gaussian beams, with waists w_p =0.721 cm and w_s= 0.393 cm, respectively, is

$$D_{eff} = 2 w_p$$

$$L_{eff} = \frac{2 w_s}{\sin a}$$



These dimensions yield a wave number resolution of

$$s_k = \pm\frac{2p}{k_0 w_s^2}\cos(q/2)$$

For the scattering geometry set by the existing vacuum chamber. The initial scattering angle be at q =64 ° will yield

$$|\Delta\vec{k}| \cong 67\ cm^{-1} \pm 4\ cm^{-1}$$

Assuming P_o ~ 1 mW, the scattered power at q = 64 ° is P_s ~ 1.5x10 $^{-11}$ W assuming a 1% fluctuation amplitude for a typical HELIX density of 10^{12} cm^{-3}.

For a typical detector noise level of 1 x 10 $^{-14}$ W[*Luhmann and Peebles*, 1984], the minimum detectable density fluctuation is n_{min} = 2.5 x 10 ^{8} cm^{-3}, or a 0.03% fluctuation amplitude for a 10 ^{12} cm^{-3} HELIX density.

Future plans are to allow adjustments to the scattering angle of +/- 20 °, which will allow Dk from 48 cm^{-1} to 85 cm^{-1}.

Diagnostic design

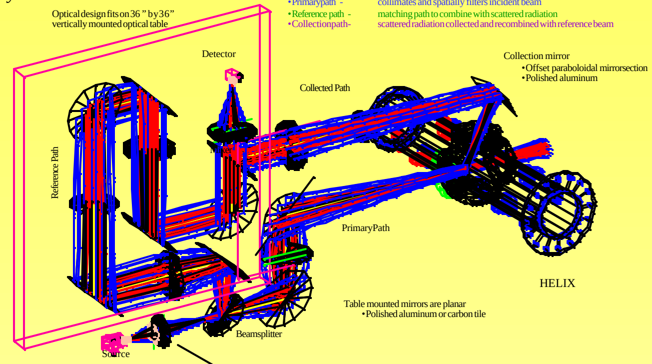
The entire diagnostic is designed to be rugged and portable as it will be used on both HELIX at WVU and RSX at LANL. At RSX, the emphasis will be on the detection and identification of lower hybrid drift instabilities generated during reconnection events.

The source, detector, beamsplitters, and optics (except for the collection mirror) will all be mounted on a single custom, vertically mounted, optical table.

For optimal overlap of the reference and collection beams, the reference beam is expanded so as to nearly fill the final lens before the shielded detector.

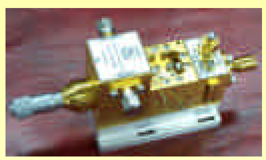
The injection and collection optics are designed so as to pass both the injected and collected beams through the vacuum windows at nearly normal incidence.

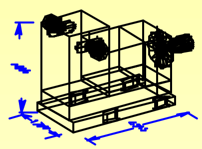
Optical system was designed using ZEMAX optical design software in three parts
- Primary path - collimates and spatially filters incident beam
- Reference path - matching path to combine with scattered radiation
- Collection path- scattered radiation collected and recombined with reference beam



Microwave source

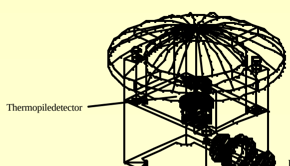
Three-part brass system manufactured by Radiometer Physics GmbH in Meckenheim, Germany.
- The emitter is a Gunn oscillator
  - resonant cavity that can be tuned over a small frequency range,99.5 to 100.5 GHz
- "frequency tripler"
  - second cavity that mode converts to a 299 to 301.5 GHz wave.
- WR-3 fundamental rectangular waveguide to a "potterhorn" antenna
  - horn expands the beam into a cylindrically symmetric TE_{00} mode,
  - quoted power waist, w_0 = 0.19 cm, located in the plane of the horn end.





Beam profile measurement

To optimize alignment and placement of the optical element, the profile of the quasi-optical microwave beam will be measured after each optical element is installed. The measurements will then be compared to the predictions of a Gaussian optics modeling code. To measure the beam profile, a Thermopile detector (model 1SC) from Dexter Research Inc. has been purchased and will be installed in a aperture limited (~1 mm) detector assembly.



Deflector is made of stainless steel with a 1 mm aperture to obtain a spatially resolved beam profile.

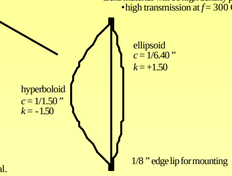
Lens design

Lenses are plano - conic surfaces defined by equation

$$z = \frac{c r^2}{1+\sqrt{1-(1+k)c^2 r^2}}$$

c	radius of curvature reciprocal
k	conic section parameter ($k = -e^2$)
r	distance from optical axis
z	surface depth from front

Lens material will be high density polyethylene (HDPE)
- high transmission at f = 300 GHz



Hyperboloidal and ellipsoidal surfaces are used throughout the design to maintain phase fronts
- hyperboloidal surface to maintain a planar phase front in the denser material,
- ellipsoidal surface is necessary to correct "phase sagging" upon exiting the optically denser material.

Design notes

ZEMAX design was checked with Microsoft Excel to match final mix erposition
- Reference path must match primary plus collection path to within one wavelength to minimize errors due to source frequency drifts

Large beam path design (6.00 " cross-section) allows for better position matching of optical elements
- Primary beam size allows for long 'Rayleigh' length in plasma
- Collection optics dictates spatial and spectral resolution of system
- Large beam cross-section allows for detailed beam profile measurements

Beamsplitter and mixer will use stretched Mylar for maximum and minimum transmission

Eccosorb will be placed between beam paths to minimize stray reflected power
- Absorbs 80 db/cm @ 300 GHz [ALMA Memo #273 "FTS Measurements of Eccosorb MF112 at Room Temperature and 5 K from 300 GHz to 2.4 THz," *G.A. Ediss et al*]

Diagnostic status

- Source is delivered. Beam profile detector is under construction .
- Optical table and vertical mount are on site. Preliminary placement near HELIX is shown above.
- Optical mounting hardware is delivered.
- Lens design is proceeding; material vendors and manufacturers are identified.
- Beamsplitter /Mixer mounting design is in progress.
- Collection mirror and mounting system is still in design phase.
- Detector delivered and preliminary testing complete.