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ELECTRON CYCLOTRON EMISSION IMAGING OF ELECTRON CYCLOTRON RESONANCE ION SOURCE PLASMAS*

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Abstract

A new imaging system for electron cyclotron resonance ion sources (ECRIS) has been designed and is being built. This K- and Ka-band camera will extract localized measurements of absolute energy and relative number density for ECRIS plasma electrons by imaging their electron cyclotron emission (ECE) spectra, as the frequency, shape, and strength of the ECE harmonics correlate directly with the local magnetic field, electron energy, and plasma density. The design of the overall quasi-optical system will be presented, including novel ceramic optics for the radial viewports of the Cyclotron Institute's ECRIS and metamaterial mirrors with electronically controllable reflectivity. Spatial resolution sufficient to distinguish important plasma regions and temporal resolution sufficient to study dynamic plasma processes is expected.

INTRODUCTION AND MOTIVATION

A non-disruptive, high spatial resolution, general-purpose diagnostic tool that can measure the energy distribution of the magnetically confined plasma electrons in electron cyclotron resonance ion sources (ECRIS) would be highly useful for investigating and monitoring ECR plasmas. Many plasma diagnostics exist, but extracting electron population parameters from current diagnostics generally relies upon making assumptions about certain correlations between different plasma regions or certain interactions in the electron and ion populations. Direct diagnostics such as Langmuir probes are also not necessarily practical for use in an ECRIS while generating beams for particle accelerators. It would greatly assist routine particle accelerator operations and ECRIS modeling efforts if the ECRIS electron energy distribution was known during routine use, especially given that the myriad of parameters contributing to practical ECRIS plasmas are generally not known to sufficient accuracy a priori.

As some ECRIS plasma electrons are known to be both in cyclotron motion and mildly relativistic, we can expect those plasma electrons to exhibit electron cyclotron emission (ECE). Furthermore, if we assume the electrons in a particular region of the plasma interact sufficiently to produce local Maxwellian populations, the shape of the ECE spectrum from that region will correlate directly and distinctly to an electron temperature in that region [1]. Measuring such a spectra in an ECRIS is complicated, however, by the wide spread of cyclotron frequencies in the min-B magnetic field configuration. ECE spectra observed from ECRIS by simple line-of-sight measurements overlap into a nearly continuous spectrum [2].

The split hexapole design of the conventional 6.4 GHz ECRIS at the Cyclotron Institute allows for radial access ports, which in turn have enabled a novel solution to the problem of studying the ECE of ECRIS plasmas. This paper will discuss an imaging system design capable of simultaneously capturing the ECE spectra from various regions of the plasma.

CAMERA DESIGN

The ECE harmonics expected for the 6.4 GHz ECRIS primarily fall into the K/Ka-band. In order to spatially resolve the origin of ECE signals in the plasma, a novel K/Ka-band microwave imaging system has been designed that consists of ceramic optics, metamaterial quasi-optical elements, and superheterodyne receiver electronics.

The primary optics will be placed under vacuum inside an access pipe for the radial plasma chamber port. These optics will transport the ECE signal from the plasma chamber to an exit vacuum window, where the signal can be routed by secondary optics through air to the data capture tower located beyond the ECRIS x-ray shielding and safety fence (Fig. 1).

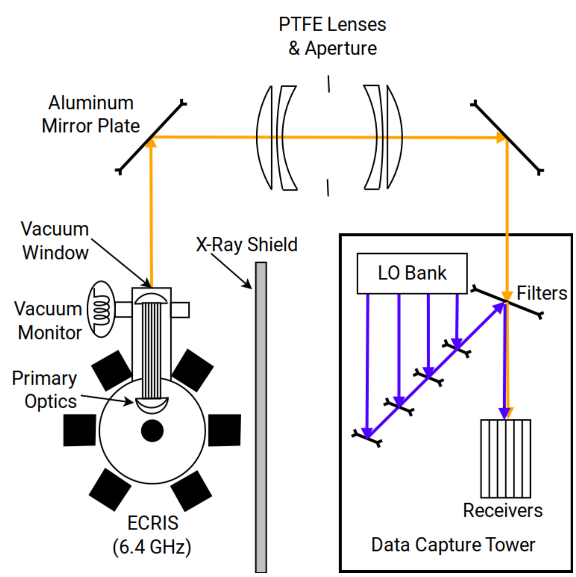

Figure 1: Camera layout (not to scale).

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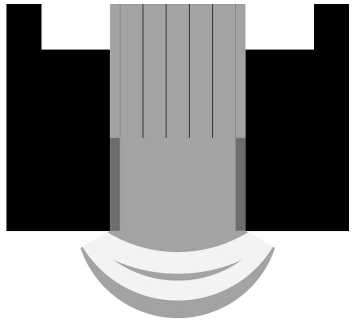

Figure 2: Dielectric structure of the primary optic inside the radial port.

Primary Optics

The main optic (Fig. 2) is a cemented stack of alumina and PTFE lenses that protrudes from the radial plasma chamber port approximately 1/2". The space occupied by this cemented lens is well removed from the plasma flutes and the ECR heating shell, and care has been taken to minimize RF heating. The cemented lens focuses ECE from the central plane of the plasma into the entrance of a 5x5 array of alumina-filled, 0.125" square waveguides. The exit face of the waveguide array will be bonded to an exit lens sitting below the vacuum window which allows for the ECE image to be transmitted into air outside the ECRIS.

Alumina and PTFE were chosen as optical materials due to their flat dispersion curves and low loss tangents across the K/Ka-bands. Alumina's high index of refraction (n = 3.1) also allows for a particularly important trick: diffraction in the 3/4" radial ports would normally destroy any usable image at our frequencies of interest, but once the port is filled with alumina diffraction can be made negligible. PTFE increases the performance of the primary optic by suppressing total internal reflections (increasing the numerical aperture) and diminishing Fresnel reflection. A microwave-absorbing lining is also employed to reduce unwanted stray reflections and cavity modes inside the radial port.

The initial design of the primary optical stack was improved iteratively through ray-tracing with the BEAM4 open-source software package [3] and finite-difference-time-domain (FDTD) simulations of Maxwell's equations with the MEEP open-source software package [4]. The finalized design simulations show good separation of ECE signals from different plasma regions into corresponding waveguides (Fig. 3). The resolution of the optics is Rayleigh-limited at the low end of their operating frequency range (approx. 17 GHz).

Signal Preparation

The ECE signal beam will be passed through a quasi-optical beamsplitter arrangement (Fig. 4) of electronically variable reflective surfaces (EVRS), which are metamaterial mirrors designed for this project and formed by an array of resonators interconnected with resistive silver ink traces and PIN diodes (Fig. 5). The purpose of the PIN diodes is to provide a resonance-clamping AC impedance to the EVRS cell when the array is biased by the proper DC current. Simulations of EVRS supercells in MEEP have shown this clamping behavior for electromagnetic waves at oblique incidences (Fig. 6) and have also shown the EVRS are largely transparent across all other frequencies in the K/Ka-band. A set of EVRS with different resonant frequencies can therefore be stacked to create a broadband mirror with electronically selectable frequency transmission notches.

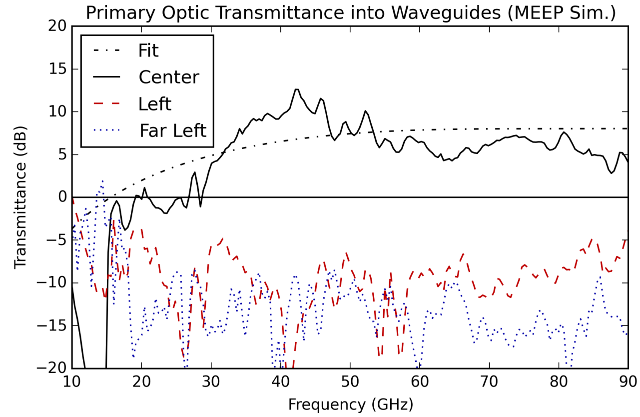

Figure 3: Simulated transmittance of an electromagnetic point source at the center of the plasma chamber into the waveguide array.

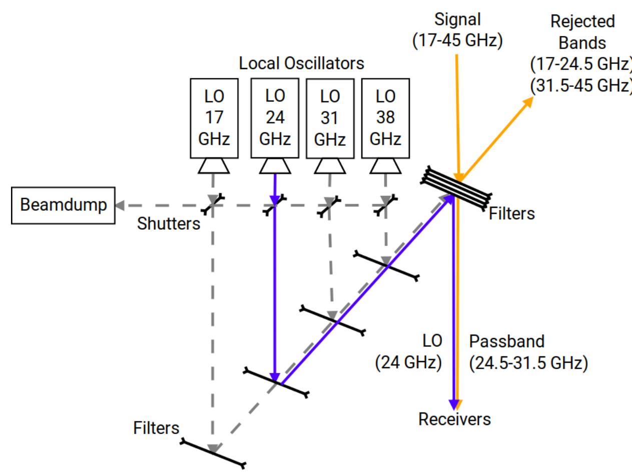

Figure 4: Quasi-optical signal bandpassing scheme.

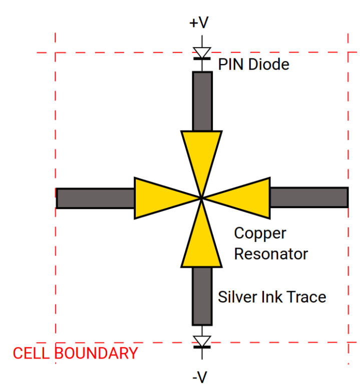

Figure 5: EVRS cell conceptual diagram.

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The EVRS beamsplitter stack greatly simplifies bandpassing the signal, and back-illumination of the beamsplitter stack (Fig. 4) also allows for a known local oscillator (LO) frequency to be overlaid onto the passband signal beam. As soon as the combined beam of passband signal and LO is received by a broadband antenna, it can be immediately passed into a mixer diode for frequency down-conversion.

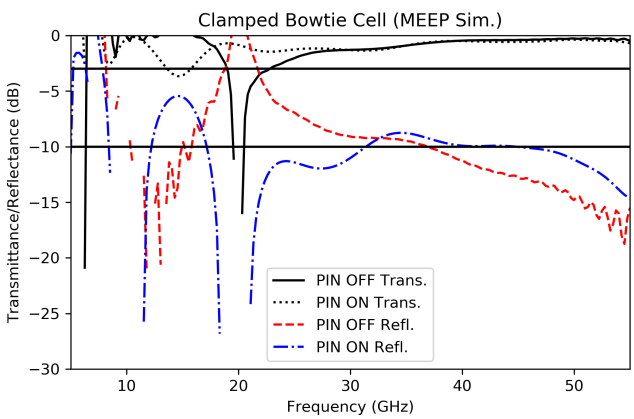

Figure 6: Simulated response to oblique electromagnetic waves by EVRS with lattice parameter a=5.5 mm.

Receiver Electronics

A 5x5 array of broadband antennas will immediately shunt the optically-processed signal into mixer diodes. This will convert the K/Ka-band 17-45 GHz signal into a 0-8 GHz signal that can be easily handled by conventional microstrip electronics. In order to eliminate the rolling shutter effect, the mixers will feed into 25 independent superheterodyne receiver circuits that step down the signal frequency further until it can be digitized by integrated 12-bit, 250 MS/s analog-to-digital (ADC) converters. Finally, in order to maximize the frame rate, the ADC samples will be transmitted to the data capture computers (DAQ) by 25 independent USB 3.1 connections. The maximum data rate for the imaging system is expected to be 100 Gbit/s.

The imaging system will have several operating modes for arbitrary frame rates and partial spectral coverages. The EVRS power supply switching, voltage monitors, and superheterodyne receiver controls will all be tied to a handful of microcontrollers so that the operation of the entire system can be monitored and reconfigured by the DAQ over USB.

COMPONENT DEVELOPMENT

An anechoic chamber with turntables is being assembled for testing the frequency response of each optical component at various angles of incidence. The device-under-test (DUT) and receiver microwave horn will have independent angular positioning, and a 12.4 GHz network analyzer equipped with step-up and step-down mixers will sweep through the entire design band of 17-45 GHz to log the S_{21} scattering parameter for the DUT. This will generate a frequency response curve for every optical component and implicitly create a calibration curve for the final system assembly.

3D-printed PLA optical mounting hardware was developed while access to the lab was limited during the Spring of 2020. The use of entirely plastic frames for mounting most optical elements will greatly reduce paraxial reflections that can otherwise cause significant self-interference in the microwave signal.

INITIAL PLANNED MEASUREMENTS

Once the full imaging system has been assembled, the first measurement that will be attempted is a comparison of the relative electron temperature in the ECR plasma core and in the ECR heating shell during steady-state ECRIS operation. If that proves successful, high frame rate observations of the ignition and afterglow processes will be made.

REFERENCES

[1] G. Bekefi, *Radiation Processes in Plasmas*. New York, NY: John Wiley and Sons, Inc., 1966.

[2] R. Geller, *Electron Cyclotron Resonance Ion Sources and ECR Plasmas*, Bristol, UK: CRC Press, 1996.

[3] Stellar Software, *Beam Four*. Berkeley, CA: Stellar Software, 2015. https://www.stellarsoftware.com/

[4] A. Oskooi, D. Roundy, M. Ibanescu, P. Bermel, J.D. Joannopoulos, and S.G. Johnson, "MEEP: A flexible free-software package for electromagnetic simulations by the FDTD method," *Comput. Phys. Commun.*, vol. 181, pp. 687-702, 2010. doi:10.1016/j.cpc.2009.11.008