EBW Emission Measurements for Development of a Pegasus-III RF System

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66th Annual Meeting of the APS Division of Plasma Physics, Atlanta, GA, Presentation JP12.00072, 8 October 2024

Work Supported by US DOE Grant DE-SC0019008

Pegasus-III Experiment

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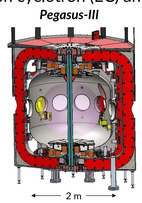
For more information:

Pegasus-III: Non-solenoidal Startup

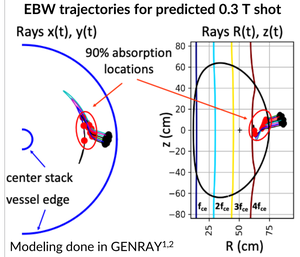
Pegasus-III Mission: Solve the plasma startup challenge by comparing, contrasting and investigating synergistic effects of non-solenoidal current drive (CD) techniques using power plant relevant technology:

- Current campaign: Local helicity injection (LHI)
- Next campaign: Coaxial helicity injection (CHI)
- In development: Microwave heating and CD: Electron cyclotron (EC) and electron Bernstein wave (EBW)

Major Radius	0.48m
Aspect Ratio	1.22
Magnetic Field	≤ 0.6T
Plasma Current	≤ 0.3 MA
Densities	< 3×10^{19} cm^{-3}
Temperatures	≤ 250 eV

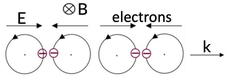


Electron Bernstein Wave Injection



For our 28 GHz source, plasmas become overdense at 1×10^{19} m^{-3}, prohibiting EC propagation. Instead, EBW can be employed

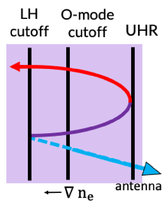
- EBW propagate via coherent e-motion[3]

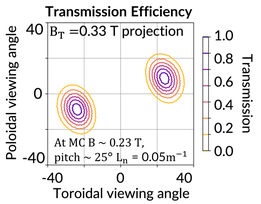


- Can propagate in overdense plasmas and be absorbed near EC harmonics

EBW cannot propagate in vacuum and are launched via OXB mode conversion scheme

- Launched O-mode converts to X-mode at LH cutoff
- X-mode to EBW conversion occurs at UHR layer
- Power coupling between modes depends on B field and density scale length, $L_n = \frac{n_e}{dn_e/dr}$





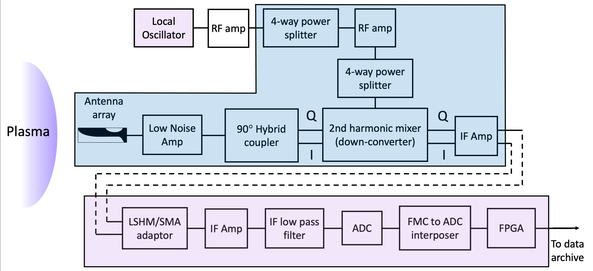
When $T_e > 1$ eV and $n_e > 10^{11}$ m^{-3} the plasmas acts as blackbody EBW emitter.

- Through BXO MC, EBW are emitted
- OX conversion occurs at two angular locations in plasma edge
- Size & angular location of MC windows are estimated with analytical equation.[4]

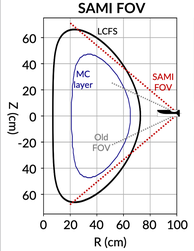
The SAMI EBW Emission Diagnostic

The Synthetic Aperture Microwave Imaging Diagnostic (SAMI) - built at University of York[5-9] - will measure EBW emissions from Pegasus-III

- Previously operated on MAST (2011-2013) and NSTX-U (2016)
- SAMI @ Pegasus-III combines analogue components SAMI from (blue) with digitization system from SAMI-2 (purple) & unique adaptations for Pegasus-III



- FPGA-based digitizers allows measurement throughout shot duration
- RF bandwidth of 18-40 GHz is measured before down-conversion; after, a 0.5-50 MHz bandwidth is digitized





- 8 Vivaldi antennas used in SAMI antenna array. Non-uniform layout optimized for sidelobe suppression
- SAMI has an 80° field of view horizontally and vertically
- Previous window on 4" nipple limited FOV. New window w/ internal shutter recovers full FOV

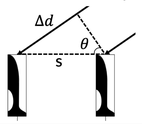
Hardware assembly, testing, installation, and integration into Pegasus-III infrastructure has been completed!

- New port location, mounting structure, & antenna plate
- Noise mitigation: relocation to shielded RF rack



Next step is measurement and image reconstructions of EBE from LHI plasmas

SAMI uses phased array interferometry to reconstruct a 2D image of emissions from plasma edge [9,10]

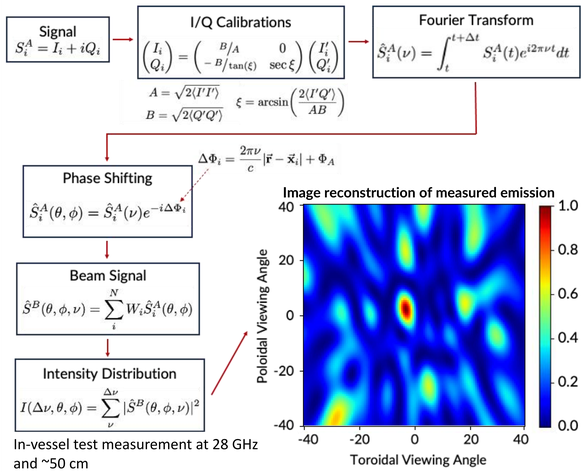


- Incident angle (θ) is calculated from phase difference (ϕ) for wavelength (λ) and separation distance (s):

$$\sin(\theta) = \frac{\Delta d}{s} = \frac{\cos(\phi)}{s}\lambda$$

Image Reconstructions: Beam-Formation

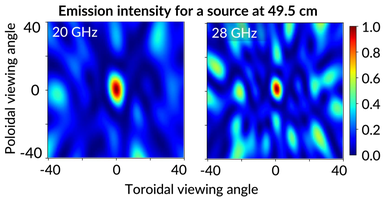
SAMI uses the Beam-Forming technique to create image reconstructions[9]:



In-vessel test measurement at 28 GHz and ~50 cm

The Beam-Forming technique has multiple advantages over other options:

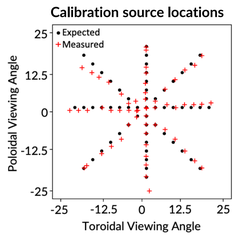
- Pros: Found to perform better than Fourier Inversion, can be implemented in near-field, straightforward mathematics, used by SAMI-2 team at York
- Cons: More computationally taxing than other options (Fourier inversion, Matrix inversion)



Appearance of sidelobes due to finite grid in computational domain - are brighter and more numerous at higher f

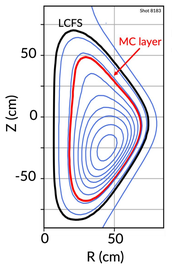
Hardware phase shift calibrations and location measurements are complete:

- Measurements were taken on a plane at 49.5 cm from antenna array: MC layer is expected at 40-60 cm depending on n_e profile
- Measured vs expected locations for 28 GHz source show good agreement

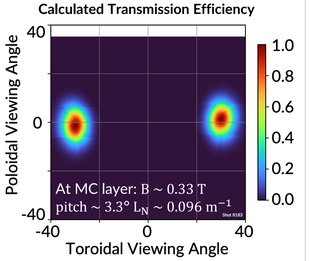


Modeled EBW Injection in 0.6 T Plasmas

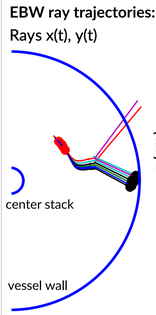
EBW transmission efficiency and MC window locations calculated[3] for a recent 0.6 T Pegasus-III shot

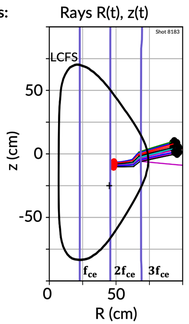


Equilibrium reconstruction of 0.6 T shot

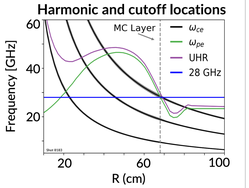


Modeling of EBW injection with the ray-tracing code GENRAY[1,2] shows propagation and absorption near EC harmonic in the plasma core





- Typical Pegasus-III plasmas with modest temperatures & hollow profiles may benefit from microwave heating in plasma core



Progress & Future Work Enabled by SAMI

Steps to bring SAMI into an operable state have been completed:

- First true power measurement from plasma – identified need for LNAs
- Hardware calibrations have been completed and on-vessel tests have verified operability of all components, and image reconstruction routine
- Reinstallation on-vessel with EMI shielding on new port to allow full FOV

Measurement of EBW emissions from Pegasus-III will allow:

- Characterization of EBW emission during and post helicity injection
- Exploration of effects of LHI current streams and n_e fluctuation on emission
- Exploration of optimal plasma conditions for mode conversion and optimal antenna launch angle for future RF system
- **Assessment of feasibility of EC and EBW heating and CD on Pegasus-III**

Reprints available at https://pegasus.ep.wisc.edu/technical-reports.

References: [1]Smirnov A P, Harvey R W and Kupfer K 1994 A General Ray-Tracing Code (GENRAY) *Bulletin of the American Physical Society* **39** 1626. [2]Smirnov A P and Harvey R W 2003 *The GENRAY Ray Tracing Code* (Del Mar, CA: CompX no. CompX-2000-01). [3]Laqua, 2007, [4]Electron Bernstein Wave Heating and Diagnostic"[4]E. Mjølhus. Journal of Plasma Physics 31 (1984), pp. 7–28, [5]Freethy, S. *Synthetic aperature imaging of B-X-O mode conversion* PhD thesis (2012), [6]Brunner, K. *FPGA-based High Performance Diagnostic for Fusion* PhD thesis (2017), [7]Thomas, D. *Phased array imaging of two dimensional Doppler microwave backscattering from spherical tokamak edge plasmas* PhD thesis (2016), [8]Huang, B. *Development of FPGA controlled diagnostics on the MAST fusion reactor* PhD thesis (2013). [9]S J Freethy *et al* 2013 *Plasma Phys. Control. Fusion* **55** 124010. [10]Zernike F 1938 The concept of degree of coherence and its application to optical problems Physica 5 785–95.