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

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Pegasus-III Experiment

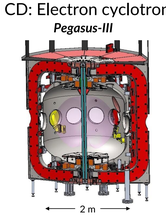
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Pegasus-III: Non-solenoidal Startup

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:

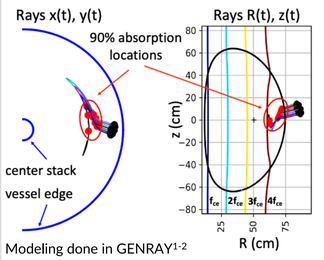
- Current campaign: Local helicity injection (LHI)
- Next campaign: Coaxial helicity injection (CHI)
- In development: Radio frequency (RF) heating and CD: Electron cyclotron (EC) and electron Bernstein wave (EBW)

Major Radius	0.48m
Aspect Ratio	1.22
Magnetic Field	≤ 0.6T
Plasma Current	≤ 0.3 MA
Densities	< 3x10^{19} cm^{-3}
Temperatures	≤ 250 eV



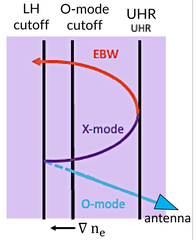
Electron Bernstein Wave Injection

Plasmas in Pegasus-III become overdense at 1×10^{19} m^{-3} for our 28 GHz source. In these scenarios, EBW can be employed for RF heating and CD



Modeling done in GENRAY[1-2]

- EBW propagate via coherent e$^-$ motion: propagate in overdense plasmas and can be absorbed near cyclotron harmonics
- EBW cannot propagate in vacuum: launched via a mode conversion
- Power coupling depends on local B field and density scale length, $L_n = \frac{n_e}{dn_e/dr}$



- Launched O-mode converts to X-mode at LH cutoff ($X = \frac{\omega_p^2}{\omega^2} = 1$) and angular location $N_O^2 = N_{opt\|}^2 = \frac{Y}{1+Y}$ where $Y = \frac{\omega_{ce}}{\omega}$
- O-X transmission coefficient given by Mjølhus eq.[3]

$$T = \exp\left\{-\pi k_0 L_n \sqrt{\frac{Y}{2}}[2(1+Y)(N_{opt\|} - N_\|)^2 + N_z^2]\right\}$$

- X-mode to EBW conversion occurs at UHR layer

When $T_e > 1$ eV and $n_e > 10^{11}$ m^{-3}, plasmas acts as blackbody EBW emitter. Through reverse OXB mode conversion EBW are emitted as RF

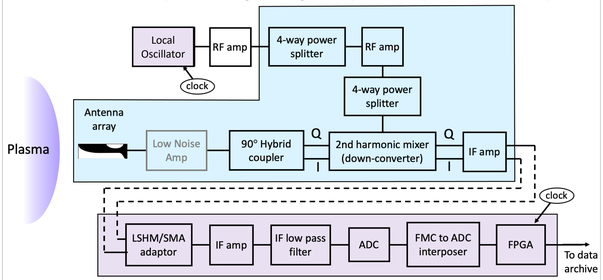
Pegasus-III will make the first EBW emission measurements from LHI plasmas to inform the design of an RF system

The SAMI EBW Emission Diagnostic

The Synthetic Aperture Microwave Imaging Diagnostic (SAMI) - built at University of York[4-8] - will measure EBW emissions from Pegasus-III

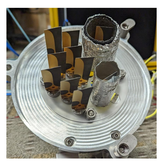
- Previously operated on MAST (2011-2013) and NSTX-U (2016)

SAMI uses phased array interferometry to reconstruct a 2D image of RF emissions from the plasma edge using the aperture synthesis technique[4,9]



SAMI @ Pegasus-III combines analogue "front end" components from SAMI (blue) with digitization "back end" from SAMI-2 (purple) and unique adaptations necessary for Pegasus-III

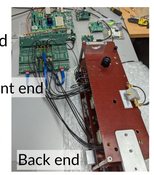
- Hardware procurement, assembly, and testing completed: calibration begun
- Integration into existing Pegasus-III infrastructure is ongoing: universal clock and trigger system, vessel port and appropriate EMI shielding





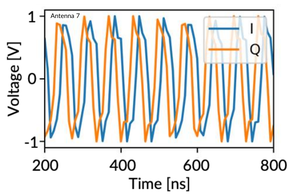
Left: Vivaldi antenna array and testing setup

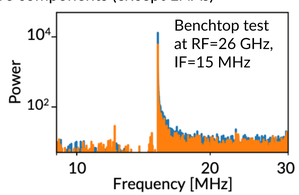
Right: RF and IF signal processing components



Signals from 8 phased-array antennas are split into in-phase (I) and quadrature (Q) signals – necessary for image reconstruction. All 16 channels are digitized simultaneously

- Benchtop testing verified operability of FPGA control firmware, data acquisition software, and all hardware components (except LNAs)





Signal measured by SAMI from horn antenna emitting 25.985 GHz. Thus, a 26 GHz LO gives IF of 15 MHz. FFT shows mode purity of digitized signal.

Emitted RF Power Measurement

Completed preliminary integration of SAMI into Pegasus-III environment

- Antenna array installed on vessel port, diagnostic relocated to experiment hall and integrated into Pegasus-III trigger & clock system, and data archive



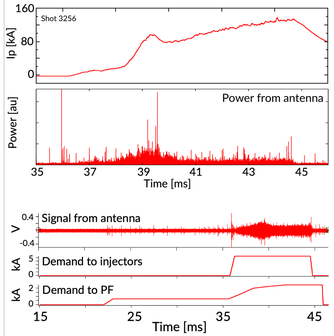


Left: view through SAMI window mounted on 4" nipple to avoid gettering

Right: antenna array installed on port

RF signal power measurement, taken October 2023, are first on-vessel measurement taken with SAMI at Pegasus-III

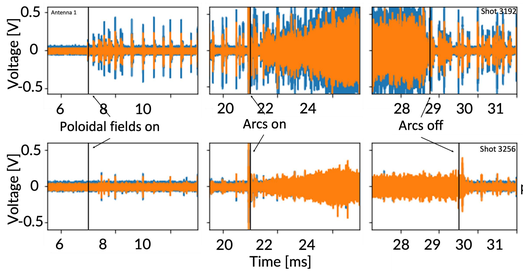
- For full O-X conversion, $\upsilon = 28$ GHz & kT=100 eV, signal strength estimated to be ~3.4mW (5.3 dBm)
- During plasma discharges SAMI measured signals above the 0.3V amplitude necessary for image reconstruction



First measurements made! Next steps to include:

- Complete calibrations for image location, signal power balance, and signal magnitude
- Analyze phase differences and complete first image reconstruction
- Permanent alignment of antenna array: angling may be necessary in case EBW emission windows lie outside current FOV
- Creation of VI and integration into Pegasus-III control code
- Implement additional shielding

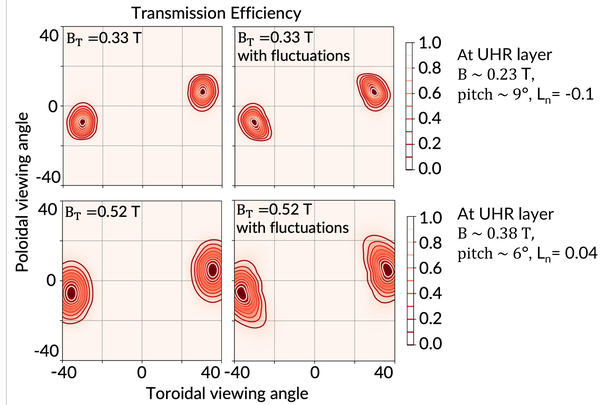
Pegasus-III uses switching power supplies: SAMI must operate in strong EMI environment not present on MAST or NSTX-U. Shielding design is underway



Mode Conversion Window Calculations

High efficiency O-X conversion occurs at two angular locations in plasma edge. Size & location of conversion windows estimated with Mjølhus eq.[3]

- Figures below: window estimates for B_T =0.33 T (top) and 0.52 T (bottom). Figures on right include edge B-field fluctuations as measured on Pegasus



At UHR layer B ~ 0.23 T, pitch ~ 9°, L_n= -0.1

At UHR layer B ~ 0.38 T, pitch ~ 6°, L_n= 0.04

- Angling antennas will allow imaging of window beyond restricted ±20° FOV
- Future modeling to include effects of measured n_e and L_n fluctuations.
- B-field data for equilibrium reconstructions provided by internal magnetics: Hall probe, B-dot coils, flux loops, and Rogowski coil

Progress & Future Work Enabled by SAMI

First steps to operation of SAMI have been completed:

- SAMI has been installed on Pegasus-III with preliminary EMI shielding
- First data on Pegasus-III has been taken, verifying operability of components

Next steps to include:

- Final calibration procedures, EMI shielding, and antenna array alignment
- Analysis of signal phase and image reconstruction of measured data

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**
  - Both low (5x10^{18}) n_e & high (3x10^{19}) plasmas have been produced so far, see [*YP11.00029*] and [*YP11.00040*] for more detail

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]E. Mjølhus. Journal of Plasma Physics 31 (1984), pp. 7–28, [4]S J Freethy *et al* 2013 *Plasma Phys. Control. Fusion* **55** 124010. [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]Zernike F 1938 The concept of degree of coherence and its application to optical problems Physica 5 785–95.