Emission Measurements of EBW for Development of a Microwave Heating System on the PEGASUS-III Experiment

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PEGASUS-III Experiment

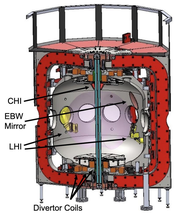
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PEGASUS-III: Non-Solenoidal Startup Experiment

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

- Local helicity injection (LHI): at high I_p & B_T and longer pulse length
- Coaxial helicity injection (CHI): Transient and sustained
- 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	< 2x10^{19} cm^{-3}
Temperatures	≤ 250 eV



RF provides power plant relevant enhancement to startup tools

PEGASUS-III provides multiple scenarios to explore synergistic effects between DC helicity injection and RF techniques:

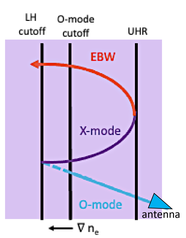
- Applicability of RF in seeding plasmas via pre-ionization
- T_e(r=0) heating during LHI to reduce resistive losses and increase CD efficiency
- Post HI use of ECH for subsequent heating, CD
- EC heating in post-CHI decay phase to increase T_e for NBI sustainment
- Handoff to ramp-up, sustainment following HI startup

Emission measurements to explore unknown effects of LHI current streams on RF injection physics!

Electron Bernstein Wave (EBW) Heating and CD

Plasmas in PEGASUS-III can become overdense, reflecting EC waves. In these scenarios, EBW can be employed for RF heating and CD

- Overdensity occurs at 1x10^{19} m^{-3} for our 28 GHz source
- EBW propagate in overdense plasmas, are absorbed near cyclotron harmonics
- EBW cannot propagate in vacuum: are launched via mode conversion scheme such as OXB, and emitted thermally through the reverse process
- Power coupling between modes depends on local magnetic field and density scale length



- O-mode wave launched obliquely into plasma
- O-X conversion at LH cutoff: $X = \frac{\omega_p^2}{\omega^2} = 1$
- Angular location given by $N_{O\parallel}^2 = N_{opt\parallel}^2 = \frac{Y}{1+Y}$ where $Y = \frac{\omega_{ce}}{\omega}$
- X-B conversion at UHR layer: $X + Y^2 = 1$
- Window size determined by n_e scale length $L_n = \frac{n_e}{dn_e/dr}$

[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]Harvey R W and McCoy M G 1992 *The CQL3D Fokker-Planck Code* (National Technical Information Service no. DE93002962). [4]J. Preinhaelter and V. Kopecky,, J. Plasma Physics, 10, part 1, pp.1-12, (1973). [5]Freethy, S. "Synthetic aperture imaging of BXO mode conversion". PhD thesis. University of York, 2012. [6]E. Mjølhus. Journal of Plasma Physics 31 (1984), pp. 7–28. [7]Freethy, S. *Synthetic aperature imaging of B-X-O mode conversion* PhD thesis (2012), [8]Brunner, K. *FPGA-based High Performance Diagnostic for Fusion* PhD thesis (2017), [9]Thomas, D. *Phased array imaging of two dimensional Doppler microwave backscattering from spherical tokamak edge plasmas* PhD thesis (2016), [10]Huang, B. *Development of FPGA controlled diagnostics on the MAST fusion reactor* PhD thesis (2013).

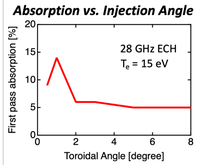
Modeling Results Show Feasibility of 28 GHz EBW and EC for Heating on PEGASUS-III

3D ray-tracing code GENRAY[1,2] by CompX was used to calculate propagation and absorption of O-mode, X-mode & EBW

- GENRAY uses predicted equilibrium generated by PEGASUS code (KFIT), n_e and T_e profiles
- OXB mode conversion for EBW modeling is handled analytically[4] in GENRAY
- Outputs couple to the Fokker-Planck code CQL3D[3] to calculate driven current

ECH X2 Modeling Shows Path to High Absorption During HI

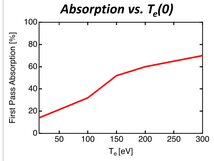
Absorption vs. Injection Angle



Peak 15% first pass absorption estimated for $T_e(0) = 15$ eV

- Results shown for single ray launch
- Launcher at z = 5.5 cm, θ_{pol} = 15°, ϕ_{tor} = 1°
- Applicable to CHI targets

Absorption vs. $T_e(0)$

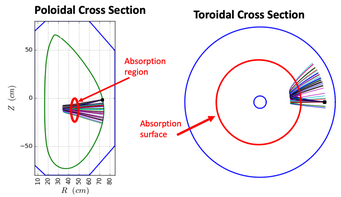


First pass absorption reaches 70% as $T_e(0)$ increases to 300 eV

- Existing LHI targets start at T_e = 100 eV, may improve at higher B_T

Efficient ECH power absorption in core demonstrated for underdense HI plasmas

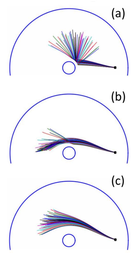
Poloidal Cross Section **Toroidal Cross Section**



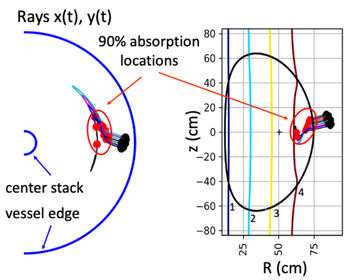
Initial ray tracing for B_T = 0.375 T, toroidal launch angle scanned across 5°, 10° and 15°

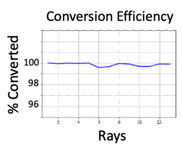
- 0% First pass absorption for 3rd, 4th harmonics
- Steerable injection may provide CD

Scan of EC toroidal launch angle



Localized EBW (OXB) absorption for $B_T = 0.40$ T





Modeling demonstrates 28 GHz is a suitable frequency for an RF system on PEGASUS-III

- EBW and EC waves couple to plasma with high absorption efficiency over a range of B_T
- Central power absorption available from EC in low density and EBW in overdense plasmas

$n_e \leq 1.2\text{x}10^{19}$ m^{-3} used

Modeling demonstrate localized EBW absorption possible over PEGASUS-III B_T range and increases with field

Summary: Modeling and Emission Measurements Aid Development of RF System

Measurement of Mode-converted EBW emissions from PEGASUS-III will allow:

- Characterization of EBW emission during and post HI
- Verification of transmission window locations
- Exploration of optimal plasma conditions for mode conversion
- Optimization of antenna launch angle for future RF system
- Exploration of effects of LHI current streams and n_e fluctuations

Assessing feasibility of EC & EBW heating, CD on PEGASUS-III

Near term goals of program include RF assisted startup:

- Post heating of helicity injection plasmas (EC → EBW)
- Synergistic improvement of LHI plasmas via heating
- Comparative test of HI methods

RF auxiliary heating and CD enables long-term campaigns

- Synergistic effects for improving helicity injection CD
- Plasma handoff/sustainment with RF driven currents
- Pure RF startup: EC initiation and current channel formation

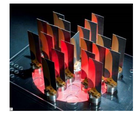
Poster available online at https://pegasus.ep.wisc.edu/

Measurement of EBW Emissions from LHI Plasmas

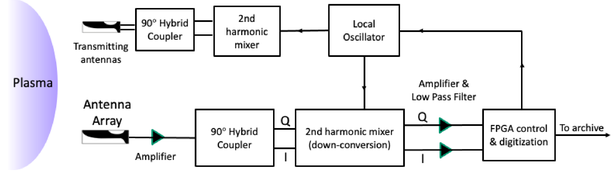
Emission Diagnostic Built at University of York[7-10] to be deployed at PEGASUS-III

Synthetic Aperture Microwave Diagnostic (SAMI) measures mode converted EBW emissions

- Previously operated on MAST and NSTX-U
- Uses synthetic aperture interferometry and 2D Doppler Backscattering to measure B-field pitch, plasma edge current density, and turbulence characteristics during active operation



Display of Vivaldi antennas used in SAMI



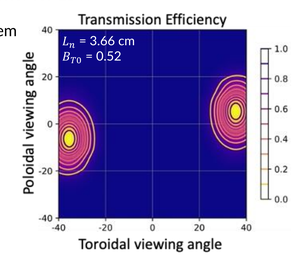
First measurements of EBW emitted from LHI driven plasmas will be made on PEGASUS-III

- When $T_e > 1$ eV and $n_e > 10^{11}$ m^{-3} plasma acts as blackbody emitter for EBW
- EBW are emitted from plasma via BXO mode conversion
- Emission measurements will inform design of PEGASUS-III RF system

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

Using the Mjølhus equation[6] size and location of OX transmission windows estimated for B_T= 0.52T

- Plasma parameters calculated from projected equilibrium
- At cutoff layer B ~ 0.38 T, B pitch ~ 6°
- Windows of 70% transmission ~8 cm wide



Update and deployment on PEGASUS-III of the SAMI diagnostic began in early 2022

- Hardware procurement, assembly and installation: new FPGA boards and local oscillator chip
- Integration into existing PEGASUS-III infrastructure: Data archive system, universal clock system, vessel port installation

Experimental Equipment for RF System Currently Under Design

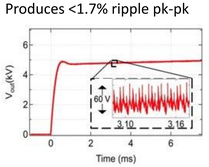
Hardware for RF system:

- 28 GHz, 200 kW Varian gyrotron with launcher located near midplane on vessel LFS, lent by HSX
- 80kV-8A power supply built by PEGASUS-III group option under consideration



28 GHz Varian Gyrotron

Produces <1.7% ripple pk-pk





Additional diagnostics provide tools to investigate RF injection into HI plasmas

- Thompson Scattering diagnostic to measure n_e and T_e profiles
- Hall probe, Mirnov coils, flux loops, and Rogowski coil will provide B-field data for equilibrium reconstructions – mode conversion modeling
- Sniffer probe to look for evidence of stray radiation during RF injection
- Future: X-ray diagnostics to study localized EBW current drive