A Microwave System for Solenoid-Free Startup Studies on Pegasus-III

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Pegasus-III Experiment

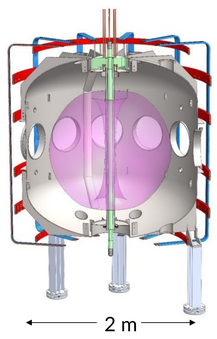
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The Pegasus-III Experiment: dedicated US platform for solenoid-free startup development

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

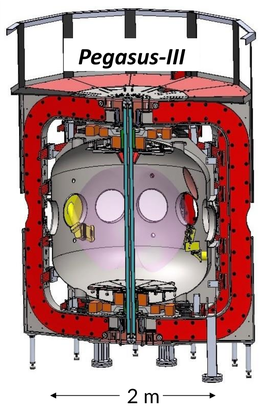
- Compare, contrast, and combine solenoid-free startup concepts in a dedicated facility [1-3]
  - Local helicity injection (LHI)
  - Coaxial helicity injection (CHI), both transient and sustained
  - Microwave assist and sustainment (EBW, ECH, ECCD)
- Goal: develop validated physics and technology basis for MA startup

PEGASUS



Parameter	PEGASUS	PEGASUS-III
I_{TF}	0.288 MA	1.15 MA
N_{TF}	12	24
ψ_{sol} (mWb)	40	0
R_{inner} [cm]	5.5	7.0
TF Conductor Area [cm²]	13.2	72
$B_{T,max}$ [T] at R_0~0.4 m	0.15	0.58
B_T Flattop [ms]	25	50-100
A	1.15	1.18

Pegasus-III

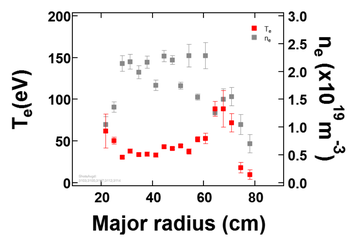


- Significant upgrades performed to provide for this mission
  - Ohmic solenoid removed from system
  - Upgraded TF magnet assembly able to withstand forces of 4x field
  - Active divertor coils
  - Upgraded/expanded power supplies and new stored energy
  - Next generation LHI, CHI, and microwave capabilities
  - Expanded diagnostic set

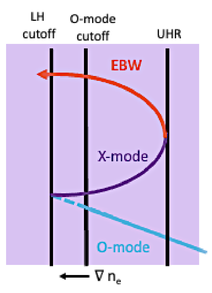
Microwave uses in startup plasmas

- Microwave injection provides various tools for non-solenoidal startup and sustainment of tokamaks
  - Provide auxiliary heating during helicity injection to reduce losses from resistive dissipation
  - Heating and current drive techniques are viable "handoff" candidates for non-inductive ramp-up and sustainment following termination of helicity injection
  - May be suitable for non-solenoidal plasma initiation, ramp-up, and sustainment
- STs are well-suited for electron Bernstein wave (EBW) heating and current drive
  - Low B_T and high n_e characteristics of the ST configuration result in a large volume of plasma that is overdense
  - EBWs can propagate in these plasmas and absorption leads to heating and can also drive plasma current
  - Absorption mechanism is strong cyclotron interaction near a harmonic resonance

Plasmas with high density readily attained in Pegasus-III. Hollow temperature indicates need for heating.

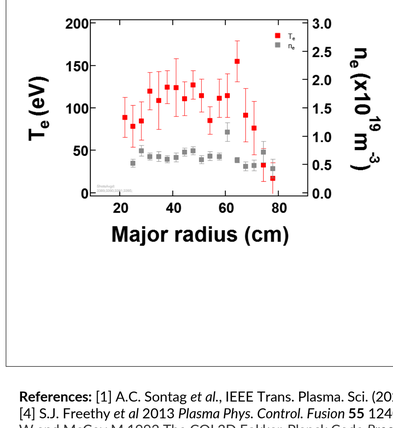


Dispersion relation shown for OXB mode conversion.

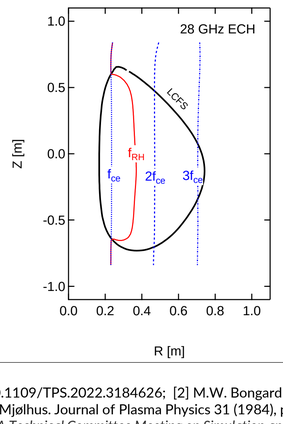


- Over-dense conditions preclude EC wave accessibility to the absorption layer when launched from the LFS of the tokamak
  - During the low-density startup phase, ST plasmas can remain accessible to EC waves and thus heating and current drive scenarios are possible

Plasmas with low density, peaked temperature produced at the beginning of the LHI phase of the discharge.



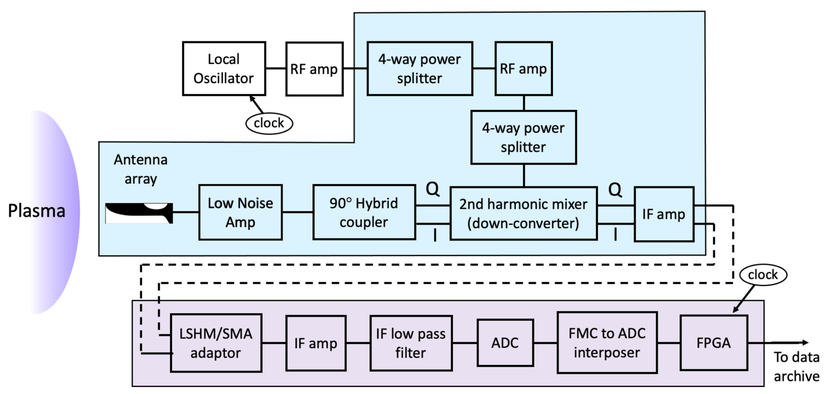
EC harmonics at 28 GHz in a Pegasus-III B_T = 0.6 T plasma with the density profile to the left showing access to the 2nd and 3rd harmonics.



EBW emission diagnostic

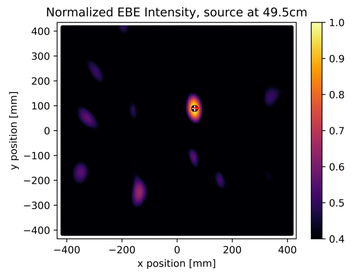
- Measurement of EBW emission (EBE) identifies mode conversion windows for efficient EBW coupling by estimating the desired location for wave deposition
- A synthetic aperture microwave imaging (SAMI) diagnostic will be used to measure EBE from Pegasus-III
  - Developed & built at University of York, used on MAST & NSTX-U [4]
- SAMI uses phased array interferometry to reconstruct a 2D image of microwave emission from the plasma edge using an aperture synthesis technique

Block diagram of the SAMI diagnostic showing analog components (blue) and data acquisition (purple) with Pegasus-III adaptations.

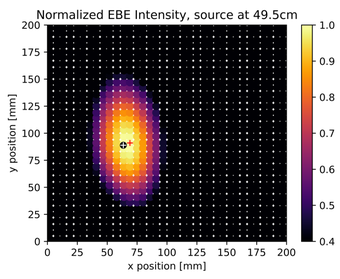


- First steps for operation of SAMI on Pegasus-III completed
  - Integrated into clock and trigger infrastructure
  - Installed with sufficient mitigation of noise from switching power supplies
  - Preliminary data taken verifying operability of components
  - Calibration procedures and antenna array alignment ongoing
  - Analysis of signal phase, image reconstruction of measured data beginning
- Laboratory testing and phase calibration of the 8 receiving antenna array to be used on Pegasus-III performed
  - Reconstructions of calibration data done
  - Beam forming technique is used for aperture synthesis
  - Applied to a movable source antenna on a defined grid
  - 1 MHz bandwidth centered on IF = 15 MHz is used

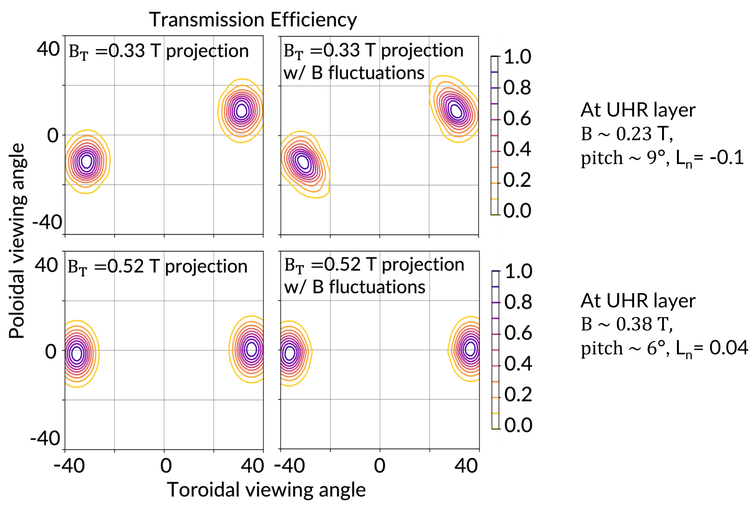
Reconstructed image of an emitting antenna located at x = 63.5 mm , y = 88.9 mm



Expanded view with the center (red) vs. the emitter location (black) showing agreement within measurement uncertainties



- High efficiency O-X mode conversion occurs at two angular locations in plasma edge
  - Size & location of mode conversion windows depends on density gradient & magnetic field pitch, estimated with Mjølhus equation [5]
- Figures below show window estimates for B_T =0.33 T (top) and 0.52 T (bottom). Figures on right include edge B-field fluctuations (≤ 40%) as previously measured on Pegasus

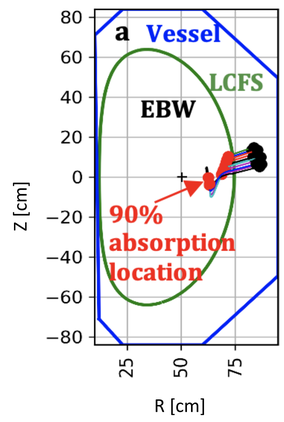


- SAMI will be used to identify mode conversion windows in HI plasmas
  - During active injection with plasma fluctuations
  - After injection when tokamak plasma is decaying
- Measurements will inform further scenario development

Modeling of EBW and EC deposition

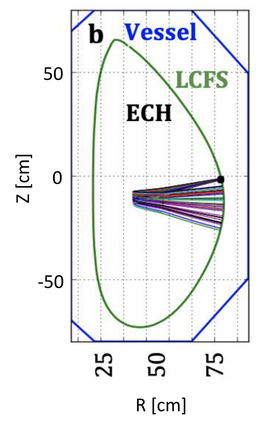
- Examine feasibility and attractiveness of heating and current drive using a 28 GHz source
  - Simulation using predictive equilibrium modeling - Pegasus-III geometry and plasma parameters
  - Coupled to GENRAY [6] raytracing
- Assessment of feasibility of heating in two scenarios
  - After completion of LHI which requires EBW coupling to relatively high-density plasma
  - During LHI or CHI with EC coupling into relatively low-density plasmas

GENRAY calculation of OXB mode conversion in post-LHI plasma



- GENRAY simulation results, including OXB analytic coupling calculations identifying the ideal launch angle shown for a post-LHI target plasma with n_e = 1x10^{19} m^{-3}, T_e = 150 eV, and B_T = 0.4 T.
- Demonstrates full absorption of EBWs near ρ ~ 0.6–0.8, corresponding to absorption near the 3rd harmonic.

ECH deposition in low-density CHI plasma



- Initial GENRAY simulation results of second harmonic (X2) ECH launch into a simulated T-CHI/low density LHI plasma shown with n_e = 3 x 10^{18} m^{-3}, T_e = 150 eV and B_T = 0.4 T.
- Modeling shows the feasibility of 28 GHz X2 ECH in Pegasus-III at its full capacity to provide core heating in plasmas following helicity injection as well as during active LHI drive.

Summary

- Microwave system on Pegasus-III will allow direct tests of synergies between HI and microwave injection methods for both startup and ramp-up scenarios
- SAMI will be used for first measurements of EBE from HI plasmas
  - Identify operational windows for effective use of EBW for heating & current drive both during and post helicity injection
- Determine if magnetic turbulence and density fluctuations impact EBW-based heating and current drive schemes
  - Develop scenarios during and post helicity injection
  - Exploration of optimal plasma conditions for mode conversion and optimal antenna launch angle
- Modeling using GENRAY and the CQL3D [7] Fokker-Planck code to assess the viability of EBW and EC methods under these plasma conditions
- Scenario development and modeling inform microwave system requirements and launcher design

References: [1] A.C. Sontag *et al.*, IEEE Trans. Plasma. Sci. (2022), doi: 10.1109/TPS.2022.3184626; [2] M.W. Bongard *et al.*, IEEE Trans. Plasma. Sci. (2022), doi: 10.1109/TPS.2022.3165694; [3] Reusch *et al.*, IEEE Trans. Plasma. Sci. (2022), doi: 10.1109/TPS.2022.3171510; [4] S.J. Freethy *et al* 2013 *Plasma Phys. Control. Fusion* **55** 124010; [5] E. Mjølhus. Journal of Plasma Physics 31 (1984), pp. 7–28; [6] A.P. Smirnov, R.W. Harvey, and K. Kupfer, A General Ray-Tracing Code GENRAY, *Bulletin of the American Physical Society* **39** 1626; [7] Harvey R W and McCoy M 1992 The CQL3D Fokker-Planck Code *Proc. of the IAEA Technical Committee Meeting on Simulation and Modeling of Thermonuclear Plasmas, Montreal, Canada (IAEA, Vienna, 1992)*

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