Installation and commissioning of an ion temperature diagnostic on the Pegasus-III spherical tokamak

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Pegasus-III Experiment

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Non-solenoidal startup on Pegasus-III

GOAL: investigate the fundamental physics of solenoid free in spherical tokamaks and develop power plant relevant technologies

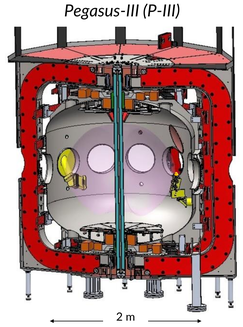
Pegasus startup systems:

- Local Helicity Injection (LHI)[1]
- Coaxial Helicity Injection (CHI)[2]
- Microwave heating and sustainment[3,4]

[1]M.W.Aslin et al., JP12.00066; [2]T.N. Teirney et al., JP12.00070; [3]J.K Peery et al., JP12.00072; [4]J.A. Goetz et al., JP12.00073

Pegasus-III Parameters	
Major Radius	0.48 m
Aspect Ratio	1.22
Magnetic Field	0.6 T
Plasma Current	0.3 MA
Density	~10^{19} cm^{-3}
Electron Temperature	~50 eV

Pegasus-III (P-III)



LHI produces anomalously ion heating

- Pegasus experiments found anomalously high ion temperatures in LHI heated plasmas
  - Magnetic reconnection results in ion heating
- Impurity ion energy spectrometer
  - Local ion temperatures around ~250 eV
  - ~5x greater than electron temperature
- Perpendicular T_i scales with local potential well from reconnection [1]

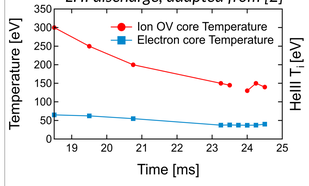
$$\Delta T_i \propto \Delta\Phi = \frac{I_{inj}\sqrt{2eV_{inj}}}{2\mu_0 e^2\sqrt{m_e}}$$

- Ion temperature found to scale with injector current and voltage

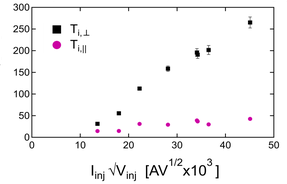
$$\Delta T_i \propto I_{inj}\sqrt{V_{inj}}$$

- Bulk ion energy yet to be directly measured in Pegasus

Core impurity and electron temperature LHI discharge, adapted from [2]



Perpendicular and parallel ion temperature of HeIII, adapted from [1]



Analyzing neutral particles to recover ion energy distribution

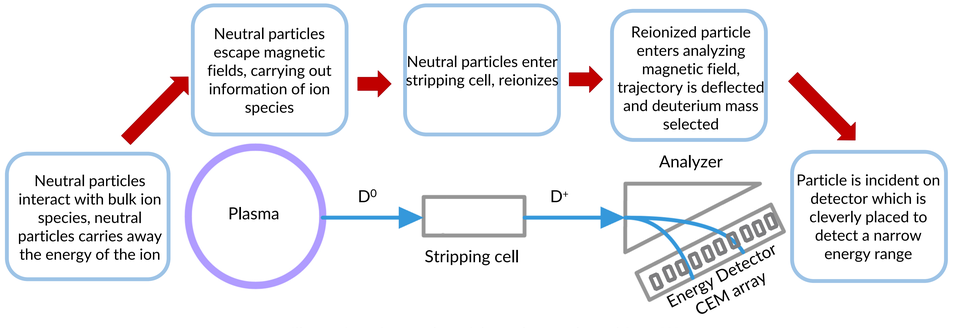


Illustration of neutral particle analyzer, adapted from [3]

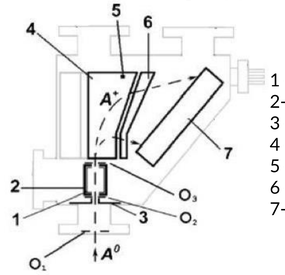
- Channel Electron multipliers (CEM) measure flux of particles as a function of time
  - Distributed such that each detector sensitive to certain energy range
- Surface of CEM biased
  - Secondary electrons are emitted on collisions
  - Electron multiplication amplifies signal
- Pulse mode allows for counting of particles incident on CEM

Cross section of CEM [4]

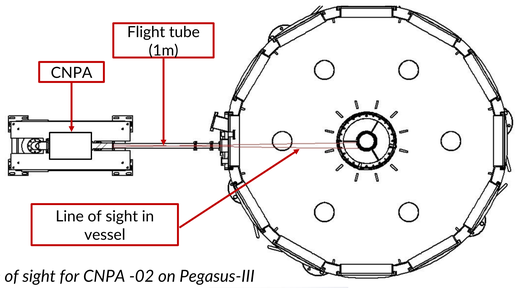


Deployment of compact neutral particle analyzer for Pegasus-III operations

CNPA-02 Internal Diagram [5]



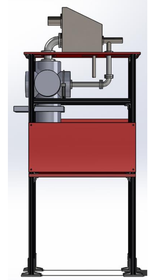
1 - Gas stripping cell (He)
2- Stripping cell magnetic shield
3 - Visible and UV light shield
4 - Analyzing magnet
5 - Hall probe
6 - Electrical deflector (selects deuterium)
7- Channel Electron Multipliers



Line of sight for CNPA -02 on Pegasus-III

	FAMU-CNPA functioning parameters [6]
Time resolution	20 kHz
Energy resolution	7%-16% ($\Delta E/E_{ch}$)
Energy range	0.34-5.2 keV
Spatial resolution	Line integrated

- CNPA will be installed on a midplane radial port
- Integrated line of sight accounts for the full plasma radius
- Neutral particles collimated in flight tube and stripping cell
  - Limiting apertures in the flight tube minimize background signal
- Robust support structure to maintain midplane view
  - Vacuum and auxiliary operational equipment
- Vacuum system designed to pump out from two ports
  - Minimizes helium entering Pegasus-III
- Gas flow controlled by MV-112 piezoelectric gas leak valve
  - Pulsed gas flow to minimize helium entering Pegasus-III
- Energy range calibrated for 0.1-2keV ions
- CEM spatial distribution affects energy resolution
  - Higher resolution for high energy ions



CNPA designed stand



CNPA deployment stand

Estimating ion temperature from flux distribution

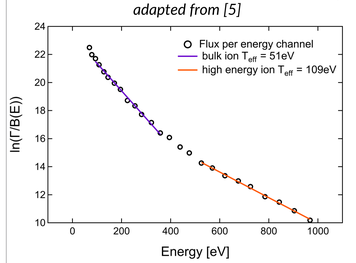
- Assuming a parabolic ion density and neutral density profile
- Assuming a Maxwellian ion energy distribution $f_i(E,l) = A\exp(-c\frac{E}{T_i})$
- Flux of neutrals from the plasma columnated into CNPA is [5]

$$\Gamma_{ch} = f_i \int_0^L n_a n_i < \sigma_{cx} v_{ia} > dl = B(E) exp(-c\frac{E}{T_i})$$

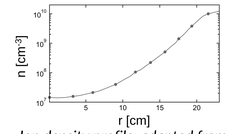
- Ion temperature found from energy and flux per channel

$$T_i = \frac{E_{max} - E_{min}}{\ln\left(\frac{\Gamma_{min}}{B(E_{min})} \Big/ \frac{\Gamma_{max}}{B(E_{min})}\right)}$$

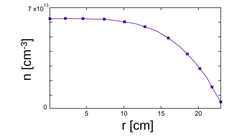
Ion temperature distribution as a bi-Maxwellian, adapted from [5]



Neutral density profile, adapted from [5]



Ion density profile, adapted from [5]



Summary

- Magnetic reconnection associated with LHI current drive results in auxiliary ion heating
- High temperatures measured in impurity ion channel
- Bulk ion temperature expected to correlate to impurity ion temperature
- Compact Neutral Particle Analyzer to be deployed on Pegasus-III
  - Direct measurement of ion temperature distribution
- Allows for resolution of bulk ion temperatures and high energy features
  - Energy range and resolution sufficient for use on Pegasus-III
- Deployment for Pegasus-III takes advantage of radial midplane port
  - Line of sight fully intersects plasma radius
- Vacuum and gas puffing system designed to minimize helium entering Pegasus-III
- Analysis of data relies on understanding of neutral particle density
  - Modeling of Pegasus-III neutral density

References:
[1] M. G. Burke, J. L. Barr, M. W. Bongard, R. J. Fonck, E. T. Hinson, J. M. Perry, J. A. Reusch, and D. J. Schlossberg, Continuous, edge localized ion heating during non-solenoidal plasma startup and sustainment in a low aspect ratio tokamak, Nucl. Fusion **57**, 076010 (2017) **[2]** J. D. J. Schlossberg, G. M. Bodner, M. W. Bongard, M. G. Burke, R. J. Fonck, J. M. Perry, and J. A. Reusch, Noninductively Driven Tokamak Plasmas at Near-Unity Toroidal Beta, Phys. Rev. Lett. **119**, 035001 (2017). **[3]** I. H. Hutchinson, *Principles of Plasma Diagnostics*, 2nd ed (Cambridge University Press, Cambridge ; New York, 2002). **[4]** *Dr. Sjuts Optotechnik GmbH - Channel Electron Multipliers and Complete Measurement Systems*. https://www.sjuts.com/CEMModels_Arrays.html. **[5]** E. D. Menzonlin, Neutral particle analyzer measurements on the SSPX spheromak |Review of Scientific Instruments | AIP Publishing, Rev. Sci. Instum. (2007). **[6]** Ioffe Physical-Technical Institute of the Russian Academy of Sciences, St. Petersburg, Compact Neutral Particle Analyzer CNPA-05-2: Technical Description and Instruction Manual, 2010.

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