Energy Confinement and Helicity Dissipation Using Thomson Scattering on the Pegasus Toroidal Experiment

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Abstract

Operating Regimes Unique to the Pegasus Toroidal Experiment:

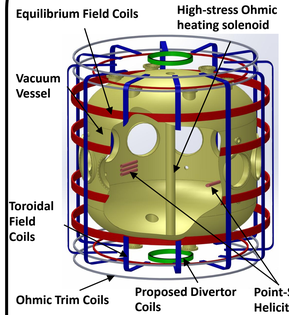
1. **High β, high I_p/I_{TF} at low B_T**
2. **Non-solenoidal startup using point-source DC helicity injection**
3. **Recently identified high-confinement scenario (H-mode?)**

Much interesting physics is accessible through characterization of plasma density and temperature using Thomson scattering:

1. **Measurements for high β equilibrium reconstructions**
2. **Quantification of helicity dissipation during point-source injection**
3. **Dominant energy confinement scaling, and feasibility of scaling startup technique to larger devices**
4. **Confirmation and full exploration of H-mode on Pegasus**

Work supported by US DOE Grant DE-FG02-96ER54375 and the American Recovery and Reinvestment Act

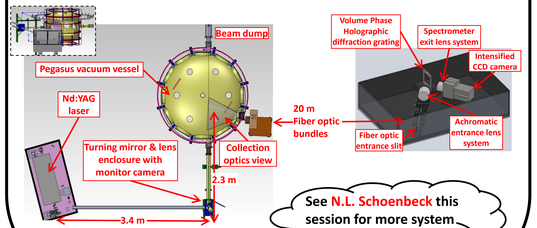
Hardware Overview



Experimental Parameters		
Parameter	Achieved	Goals
A	1.15 – 1.3	1.12 – 1.3
R(m)	0.2 – 0.45	0.2 – 0.45
I_p (MA)	≤ .21	≤ 0.30
I_N (MA/m-T)	6 – 12	6 – 20
RB_t (T-m)	≤ 0.06	≤ 0.1
κ	1.4 – 3.7	1.4 – 3.7
$\int_{shot}$ (s)	≤ 0.025	≤ 0.05
β_t (%)	≤ 25	> 40
P_{HHFW} (MW)	0.2	1.0

Major research thrusts include:

- *Non-inductive startup and sustainment*
- *Tokamak physics in small aspect ratio:*
  - *High-I_N, high-β stability limits*
  - *ELM-relevant edge MHD activity*



See **N.L. Schoenbeck** this session for more system design details

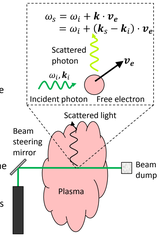
Background

Thomson Scattering

- Thomson scattering = scattering of EM radiation from free electrons
  - Assumes $h\nu \ll m_e c^2$
  - Here, assume incoherent scattering ($k_{inc}\lambda_D \gg 1$)
- Small scattering cross-section requires large photon flux (ex. Laser)

$$\frac{dP}{d\Omega_s} = r_e^2 \sin^2\phi\, c\epsilon_0 |E_i|^2$$

- Scattered photon is Doppler shifted proportionally to electron's velocity, along the line of sight
- Frequency bandwidth of the scattered light is proportional to T_e
  - Dispersion grating used to measure $\Delta\nu = \frac{c}{\Delta\lambda}$



Helicity Dissipation

- **Total helicity in a tokamak geometry:** $K = \int_V (\boldsymbol{A} + \boldsymbol{A}_{vac})\cdot(\boldsymbol{B} - \boldsymbol{B}_{vac}) d^3x$

$$\frac{dK}{dt} = -2\int_V \eta \boldsymbol{J}\cdot\boldsymbol{B}\, d^3x - \frac{2\partial\psi}{\partial t}\Psi - 2\int_A \Phi \boldsymbol{B}\cdot d\boldsymbol{s}$$

- **Resistive Helicity Dissipation**
  - $\boldsymbol{E} = \eta\boldsymbol{J} \rightarrow \eta \approx \frac{\pi e^2 m_e^{\frac{1}{2}}}{(4\pi\epsilon_0)^2 (kT_e)^{\frac{3}{2}}} \ln(12\pi n\lambda_D^3)$ **(Spitzer)**
  - Use Thomson scattering to quantify T_e and n_e
  - These low-density non-solenoidal plasmas present the most challenging conditions for measuring Thomson scattering
- **AC Helicity Injection:** $\dot{K}_{AC} = -2\frac{\partial\psi}{\partial t}\Psi = 2V_{loop}\Psi$
- **DC Helicity Injection:** $\dot{K}_{DC} = -2\int_A \Phi \boldsymbol{B}\cdot d\boldsymbol{s} = 2V_{inj}B_\perp A_{inj}$

Discharge Evolution Limits

- **Helicity balance and Taylor relaxation constrain achievable plasma current**
- Helicity balance:

$$K = \int_V (\boldsymbol{A} + \boldsymbol{A}_{vac})\cdot(\boldsymbol{B} - \boldsymbol{B}_{vac}) d^3x \Rightarrow I_p \leq \frac{A_p}{2\pi R_0(\eta)}(V_{ind} + V_{eff})$$

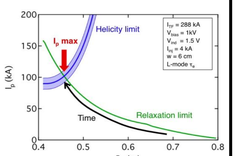
where: $V_{eff} \approx \frac{\eta_{inj} A_{inj} B_{\theta,inj}}{\Psi} V_{bias}$

- Taylor relaxation of a force-free equilibrium:

$$\nabla\times\boldsymbol{B} = \mu_0\boldsymbol{J} = \lambda\boldsymbol{B}, \text{ where } \lambda_p \leq \lambda_{edge}$$

$$\Rightarrow \frac{\mu_0 I_p}{\Psi} \leq \frac{\mu_0 I_{inj}}{2\pi R_{inj} w B_{\theta,inj}}$$

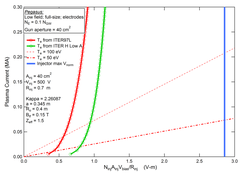
$$\Rightarrow I_p \leq f_G \left[\frac{\epsilon A_p t_{TF} I_{inj}}{2\pi R_{inj} w}\right]^{\frac{1}{2}}$$

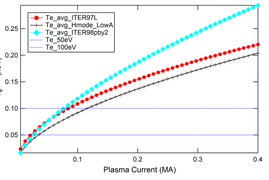


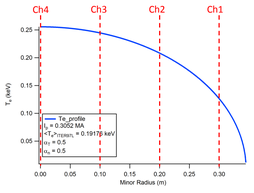
Assumes:
Driven edge current mixes uniformly in SOL
Edge fields average to tokamak-like structure

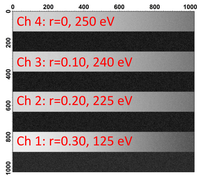
$I_{p,max}$ occurs at intersection of helicity and relaxation limits

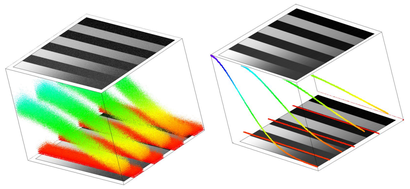
Predictions for Non-Solenoidal Plasmas

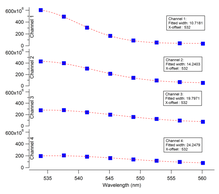






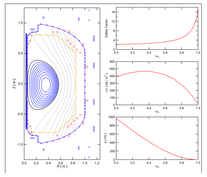






High Performance Plasma Predictions

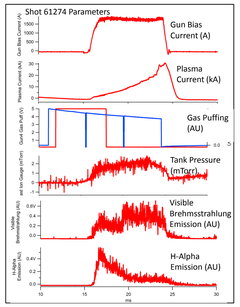
- Thomson scattering can help constrain equilibrium reconstructions of high-performance discharges
- Multiple spatial points spanning plasma radius, at single time point
- Provides useful boundary conditions for time-evolving equilibrium reconstructions

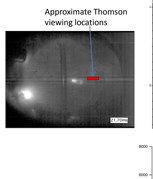


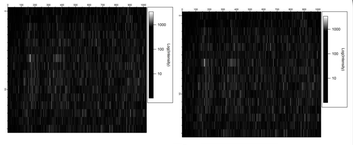
Equilibrium Parameters
Shot 61222, 28.67 ms

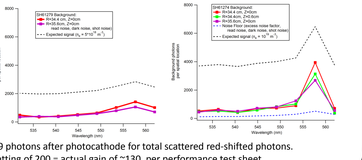
I_p	124 kA	R_0	0.315 m
β_t	0.027	a	0.266 m
ℓ_i	0.57	A	1.19
β_p	0.17	κ	1.6
W	1033 J	δ	0.36
B_{T0}	0.164 T	q_{95}	10.3

Initial system operation & "first light" images









- Assume 4819 photons after photocathode for total scattered red-shifted photons.
- Use II gain setting of 200 = actual gain of ~130, per performance test sheet
- Use CCD QE of 0.9
- 4819*130 * 0.9 = 56823 e- in CCD

Data Analysis

1. Check for on-chip binning, or desired software binning
2. Subtract dark image
3. Chop up image into spatial channels, if not already on-chip binned
4. Chop up image into spectral bins, if not already on-chip binned
5. Normalize image to account for:
   a) Wavelength mapping based on VPH grating used
   b) Wavelength sensitivity of grating
   c) Wavelength sensitivity of camera & flat-field correction
   d) Camera vignetting
   e) Overall system throughput accounting for collection geometry, collection lens, fibers, grating, ICCD
   f) Output # photons at collection lens
6. Fit with simple Gaussian fits
7. Determine temperatures from FWHM of fits using maximum likelihood fitting

Calibration Procedures:

- Spectral alignment accomplished using calibrated pen lamp sources
- Spatial alignment accomplished via in-vessel activities
  - Backlight fibers
  - Pulse attenuated laser
  - Use a scatter plate at intersection to fine-tune alignment
- Temporal alignment accomplished via measurement and calculation
  - Measure delays through cabling
  - Fine-tune timing using weak stray laser light signal

