Abstract

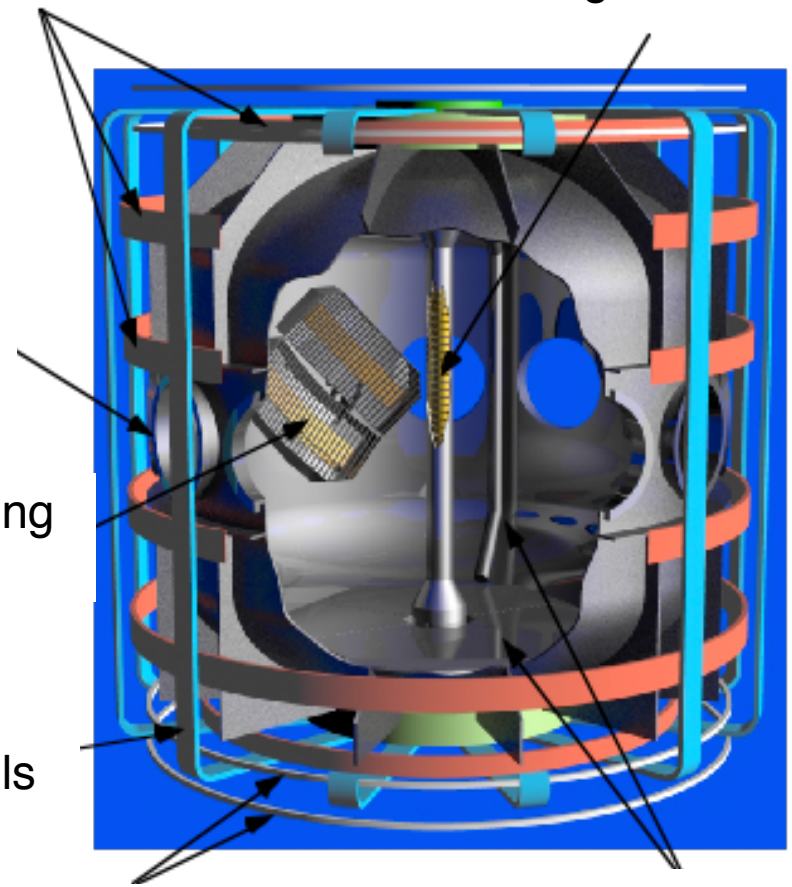
- The details of point source helicity injection as a non-inductive startup technique must be characterized:
  - Is energy confinement dominated by cross-field transport?
  - Is energy confinement dominated by parallel losses (stochastic field lines)?
  - What is the effect of resistively-driven helicity dissipation?

- Develop a Thomson scattering diagnostic for the PEGASUS Toroidal Experiment to aid this characterization:
  - Measure scattered light from incident Nd-YAG laser (λ_{laser}=1064 nm)
  - Light detected by a polychromator system
  - Measure $n_e \sim 10^{19}$ m^{-3} and Te ~ 10 eV – 1 keV
  - ≥10 radial locations, radial resolution ~1.75 cm (fine) and 5 cm (coarse)

Thomson scattering diagnostic needed to explore advanced physics regimes on Pegasus

- Thomson scattering can help diagnose unique physics on Pegasus:
  - n_e and T_e profiles during Taylor relaxation of non-solenoidally generated tokamak-like plasmas
  - Characterization of resistively-driven helicity dissipation
  - High β_T, I_p/I_{TF} plasmas
- Phenomenological scales guide effective diagnostic design
  - Scattering cross-section → guides minimum etendue, detector choice, etc
  - Non-inductive scale lengths → minimum spatial resolution
- Individual components of MPTS system are strongly coupled

PEGASUS is a compact ultralow-A ST



Experimental Parameters

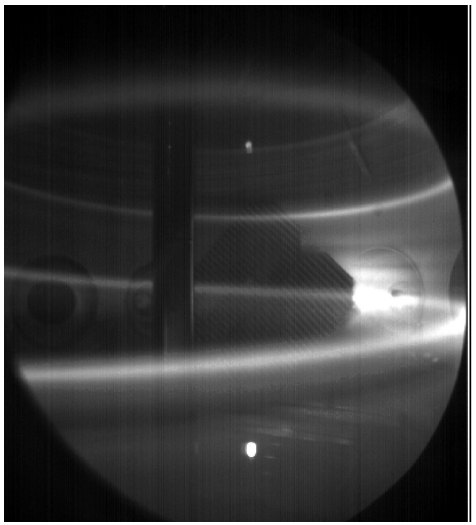
Parameter	Achieved	Goals
A	1.15 – 1.3	1.12 – 1.3
R(m)	0.2 – 0.45	0.2 – 0.45
I_p (MA)	≤ .21	≤ 0.30
I_N (MA/m-T)	6 – 12	6 – 20
RB_t (T-m)	≤ 0.06	≤ 0.1
κ	1.4 – 3.7	1.4 – 3.7
τ_{shot} (s)	≤ 0.025	≤ 0.05
β_t (%)	≤ 25	> 40
P_{HHFW} (MW)	0.2	1.0

Major research thrusts include:

- *Non-inductive startup and sustainment*
- *Tokamak physics in small aspect ratio:*
  - *High-I_N, high-β operating regimes*
  - *ELM-like edge MHD activity`*

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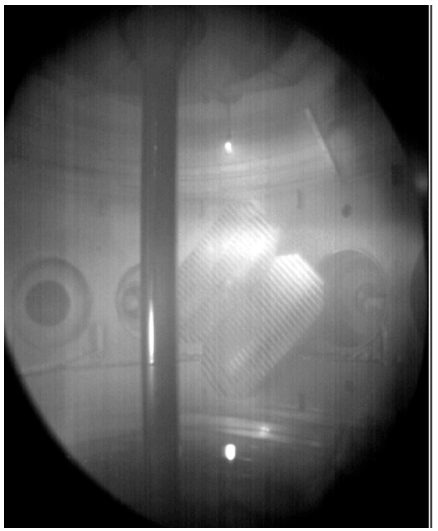
MPTS will measure $n_e(r)$ & $T_e(r)$ during Taylor relaxation of non-solenoidally generated plasmas



Open field line current
M = G

Injected current perturbs vacuum magnetic field

- Dynamics underlying Taylor relaxation will be characterized
- Use shot-to-shot scans with Thomson scattering to obtain detailed n_e and T_e profiles



Tokamak-like plasma
M > G

Plasma expands inwards to fill the volume while connected to guns

Thomson scattering will aid estimation of resistive helicity dissipation

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

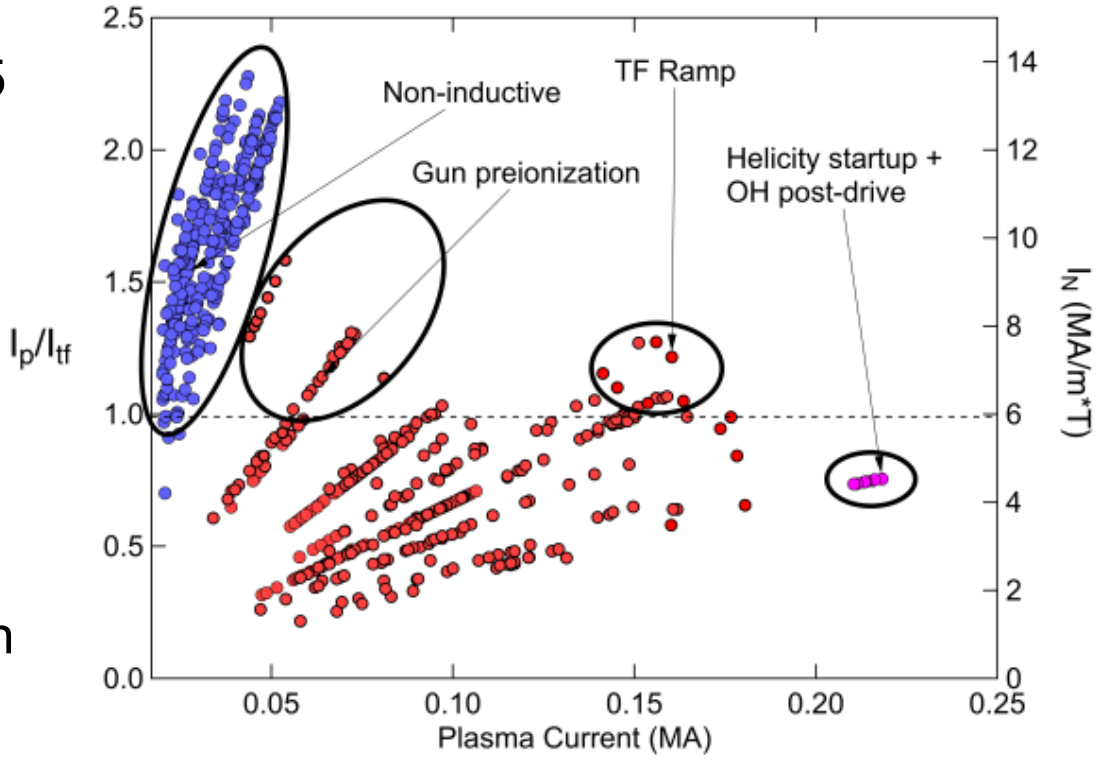
$$\frac{dK}{dt} = -2\int_V \eta \mathbf{J} \cdot \mathbf{B}\, \mathrm{d}^3\mathrm{x} - 2\frac{\partial \psi}{\partial t}\Psi - 2\int_A \Phi \mathbf{B} \cdot \mathrm{ds}$$

- **Resistive Helicity Dissipation**
  - **$\mathbf{E} = \eta\mathbf{J} \rightarrow$** $\eta \approx \dfrac{\pi e^2 m^{1/2}}{\left(4\pi\varepsilon_0\right)^2 \left(kT_e\right)^{3/2}} \ln\left(12\pi n \lambda_D^3\right)$ **(Spitzer)**
  - **Use Thomson scattering to quantify T_e and n_e**
- AC Helicity Injection: $\dot{K}_{AC} = -2\dfrac{\partial \psi}{\partial t}\Psi = 2V_{loop}\Psi$
- DC Helicity Injection: $\dot{K}_{DC} = -2\int_A \Phi \mathbf{B} \cdot \mathrm{ds} = 2V_{inj}B_{\perp}A_{inj}$

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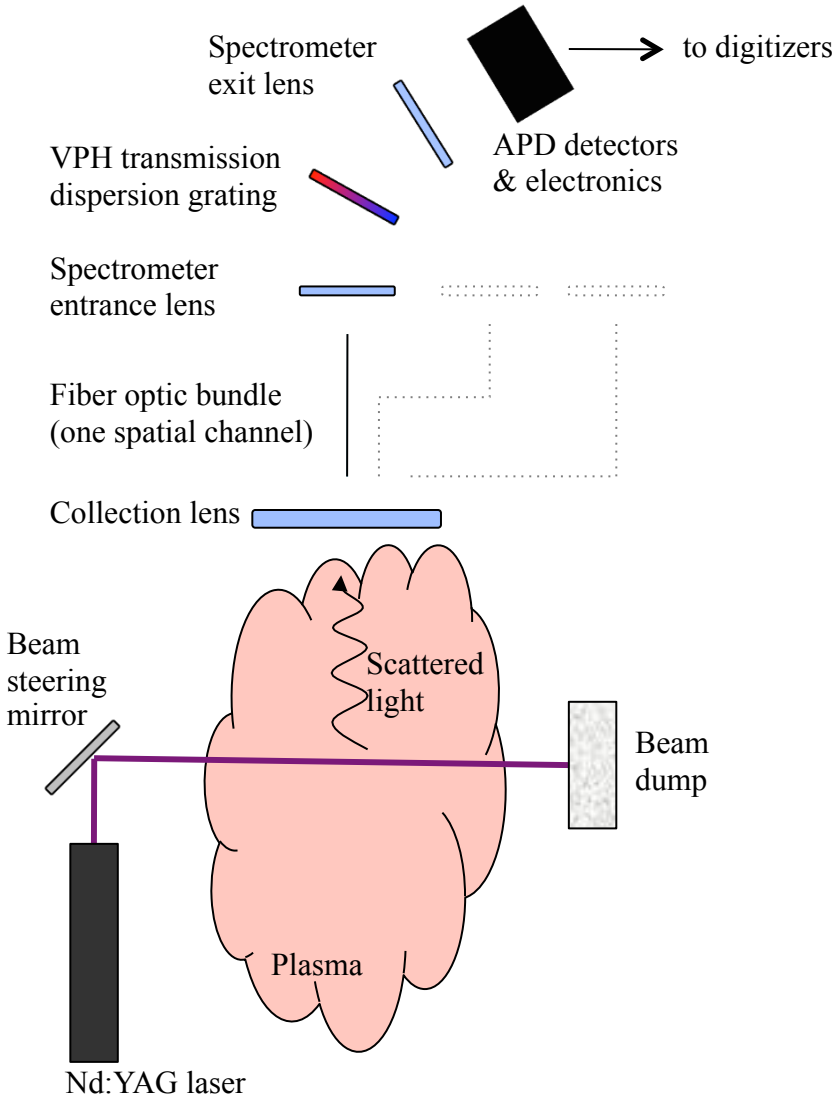
High-β, high I_p/I_{TF} scenarios will be characterized with MPTS

- Using helicity startup Pegasus can access $I_N > 5$ at $I_p \sim 0.2$ MA
- As facilities are upgraded, expect to challenge the Troyon limit
- Explore confinement and temperature distributions in these regimes unique to Pegasus



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Thomson scattering occurs when incident EM radiation excites free electrons



- "Thomson scattering" = scattering of EM radiation from free electrons
  - assumes $h\nu << mc^2$
  - here, assume incoherent scattering ($k_{inc}\lambda_D >> 1$)
- Small scattering cross-section necessitates high-energy incident light (i.e. laser)

$$\frac{dP}{d\Omega_s} = r_e^2 \sin^2\phi c\varepsilon_0 |E_i|^2$$

- Collection lens & fiber bundles provide spatially resolved measurements
- Frequency bandwidth of the scattered light is proportional to T_e
  - Dispersion grating used to measure $\Delta\nu = c/\Delta\lambda$
- Small signal levels dictate high-sensitivity, fast detection electronics (ex. APD and fast digitizers)

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Scattered intensities ~μWatts for candidate laser and optical setup

- Preliminary calculations yield scattered intensities of ~8*10^5 total photons
  - Assumes incoherent, non-relativistic scattering
  - Assumes 2J, 10 ns Nd-YAG laser pulse
  - Assumes solid angle of ~0.01 ster per channel
  - For system with 8 spectral channels, ~10^5 photons incident on APD detector (lossless optics)
- Since Pegasus shot times are ~30 ms, will only be able to measure one laser pulse

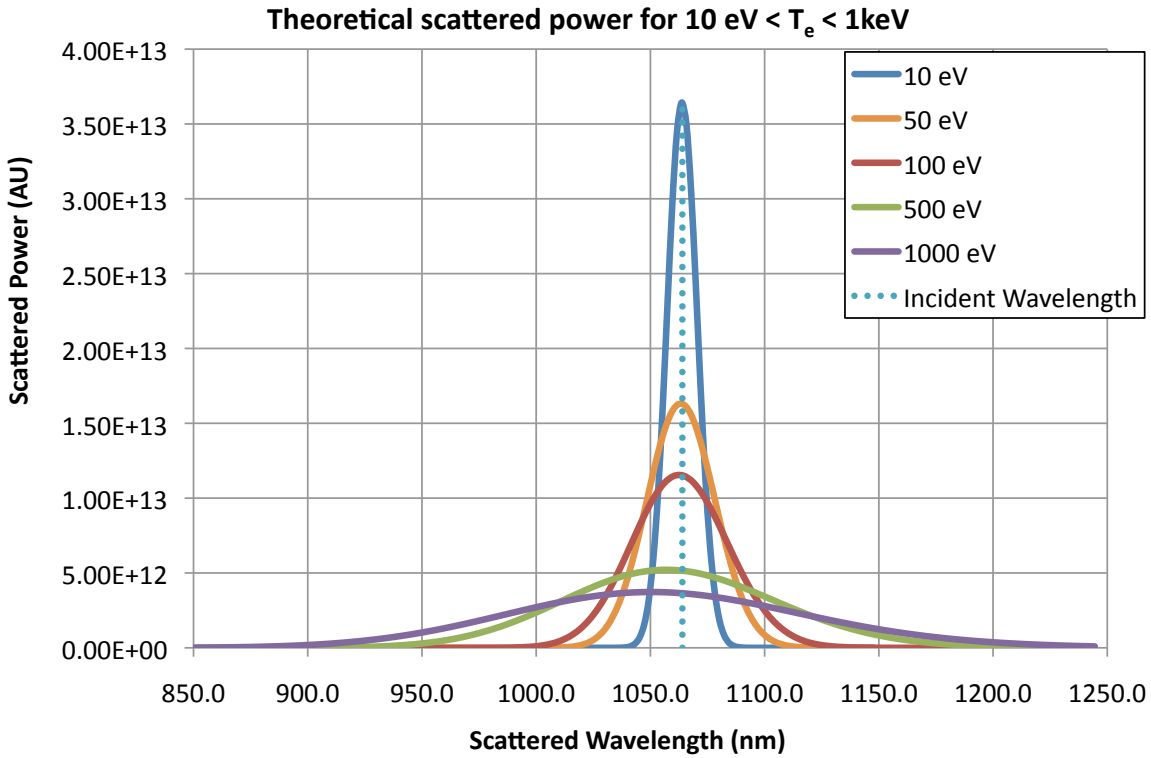
$$
\begin{aligned}
I_{det} &= \frac{E_{laser}}{E_{photon}} \sigma n_e l \frac{\xi}{4\pi} \\
&= E_{laser} \left(\frac{\lambda_{laser}}{hc} \right) \sigma n_e l \frac{\xi}{4\pi} \\
&\approx 2.66 \times 10^{11} \mathrm{s^2/kg} \left(E_{laser} \cdot \lambda_{laser} \cdot n_e \cdot l \cdot \xi \right)
\end{aligned}
$$

Symbol:	Inputs:	
E_{laser}	Laser output energy (J)	2
λ_{laser}	Laser wavelength, λ_m (m)	1.06E-06
n_e	Electron density (m^{-3})	1.00E+19
l	Length of beam for one channel (m)	0.014
ξ	Solid angle subtended by optics	0.01
	Pulse duration (s)	0.00000001
	Output:	
I_{det}	Number of photons incident	79310.77615
	Joules incident at primary wavelength	1.482E-14
	Watts at primary wavelength	1.48E-06

Spectral range ~800 – 1050 nm for Pegasus operating scenarios

- Pegasus plasmas typically 100 eV < T_e < 1 keV

- Increased spectral resolution needed for low temperatures:
  - T_e = 100eV → ~ 5 nm/ch
  - T_e = 1000eV → ~ 40 nm/ch
  - If possible, 8 spectral bins used to define lower-half Gaussian in each case



Based on: J. Sheffield, Plasma Phys., Vol 14, 783-791 (1972)

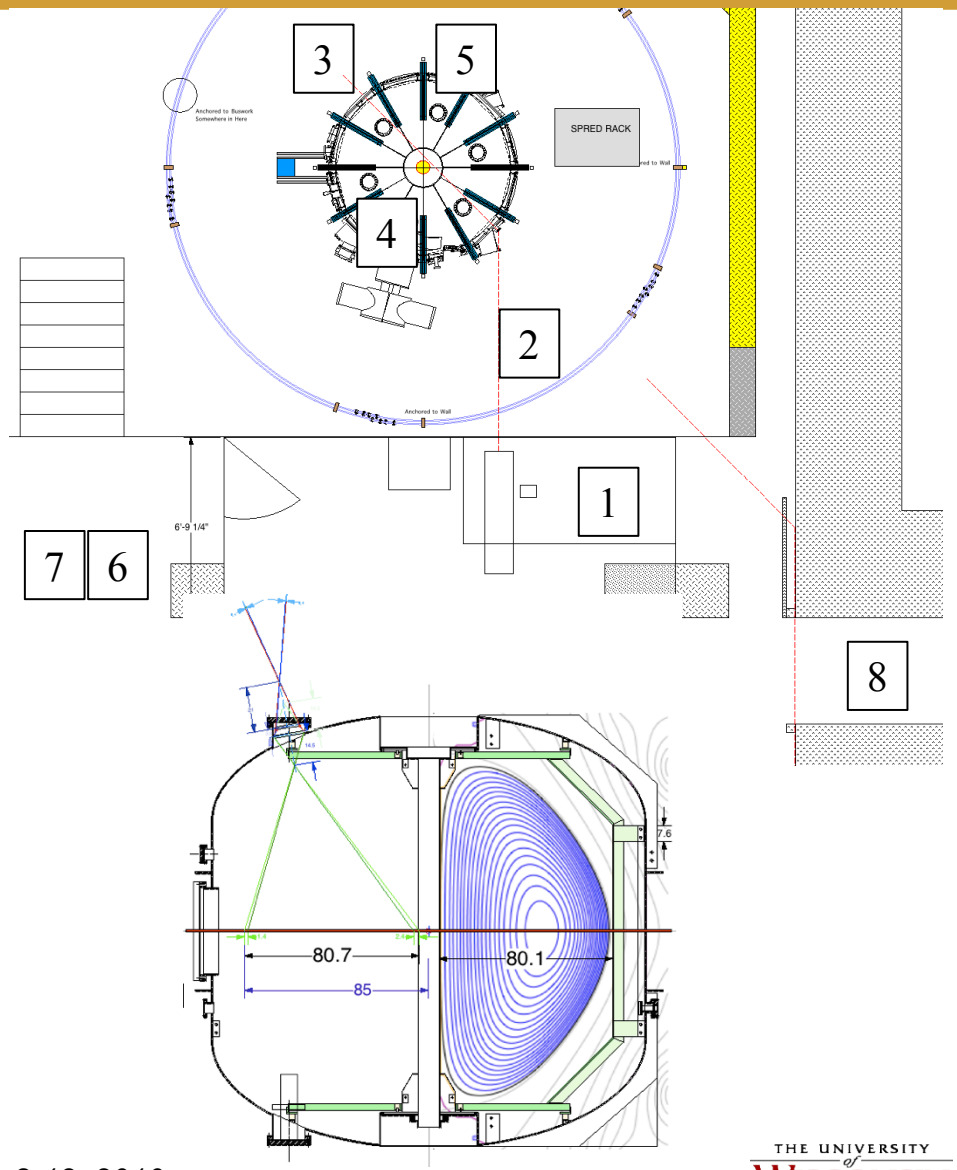
- Predictions assume 90° average scattering angle with ~10^{-2} solid angle
  - Relativistic effects evident in shift of central wavelength at T_e = 1 keV

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Design method divides entire system into coupled subassemblies

Subassemblies include:

1) Laser & laser room
2) Beamline housing
3) Beam Dump
4) Viewing Dump
5) Collection Optics
6) Fiber Optics & spectrometers
7) Data Acquisition
8) Control Code & SCRAM systems interface
9) Safety Overall



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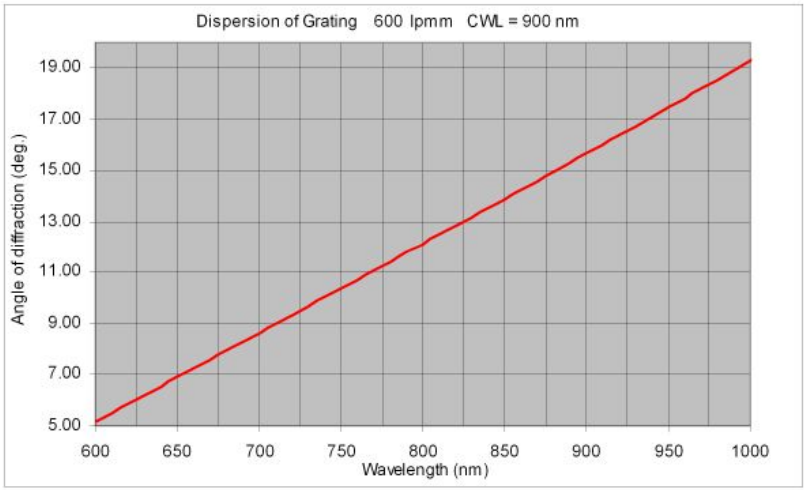
Laser specifications balanced between commercial availability and physics needs

Specification	Value	Determining factors
Output Energy	≥ 2000 mJ	Scattered intensity fraction
Divergence	≤ 0.5 mrad	Desired spatial resolution, component damage thresholds
Pointing stability	≤ 50 μrad	Beam line
Pulse length	≥ 10 ns	Availability at desired power
Repetition Rate	≥ 10 Hz	Shot duration; availability
Jitter	≤ 500 ps	Time resolution
Beam diameter	8 – 15 mm	Availability
Polarization ratio	≥ 90%	Scattering dependence
Energy stability	± 2 %	Availability; repeatability; Intensity resolution

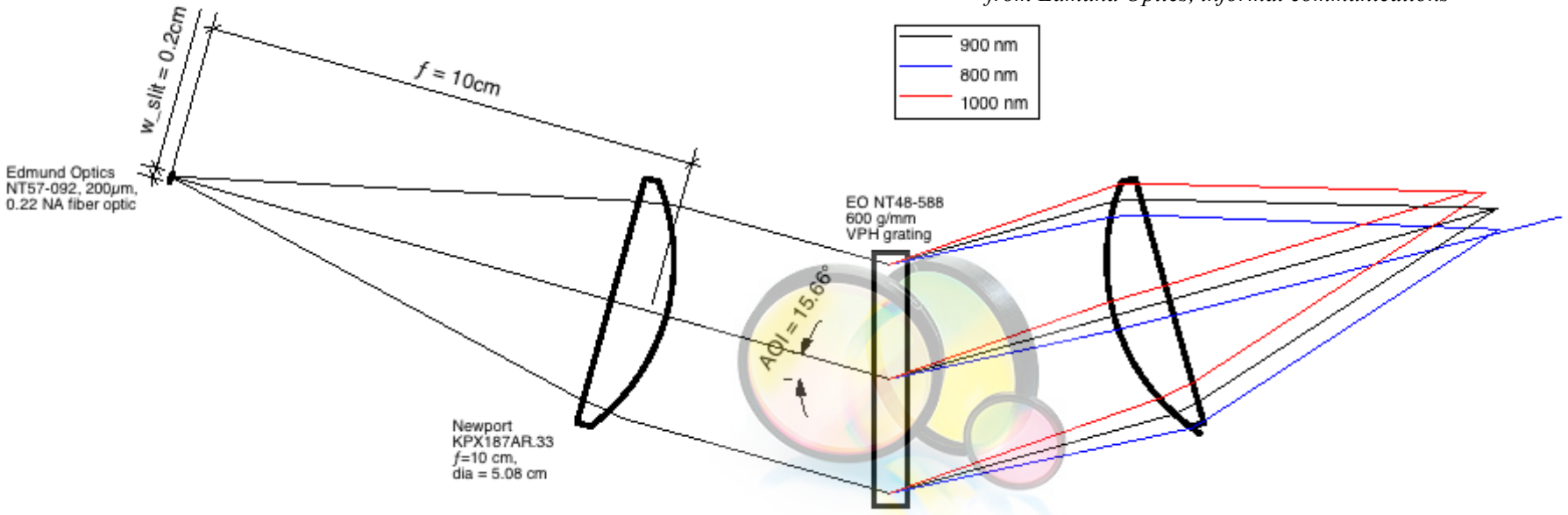
- Identify tolerable limits due to physics needs and layout constraints
- Reliable, "turn-key" operation of laser desired
  - Nd:YAG used extensively for MPTS in plasmas
  - Operate in steady-state firing mode to obtain maximum stability
- Implement design with consideration for possible future upgrades:
  - Additional spatial points
  - Multiple laser passes
  - Multiple time points per shot

Dispersive system employs volume phase holographic grating technology

- F/2 optics
- Off-the-shelf 2” dia. VPH gratings available from Edmund Optics
- Simple off-the-shelf PCX lenses (Newport) used for modeling
  - Revise to reduce chromatic aberrations for final design

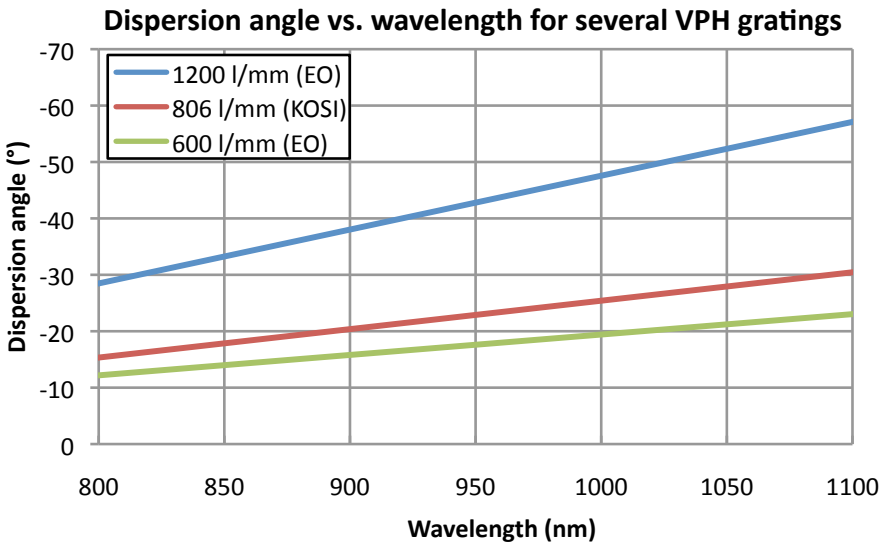


from Edmund Optics, informal communications

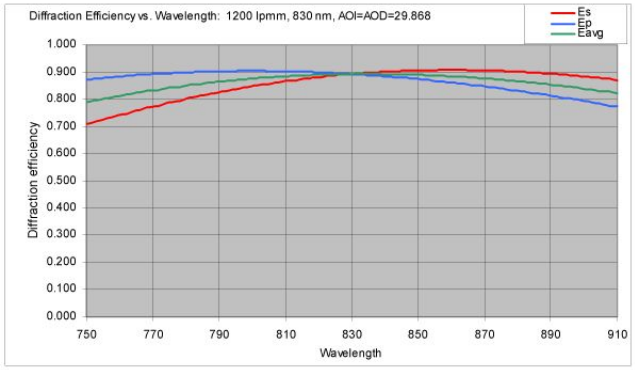


Grating dispersion can be customized to provide desired spectral resolution

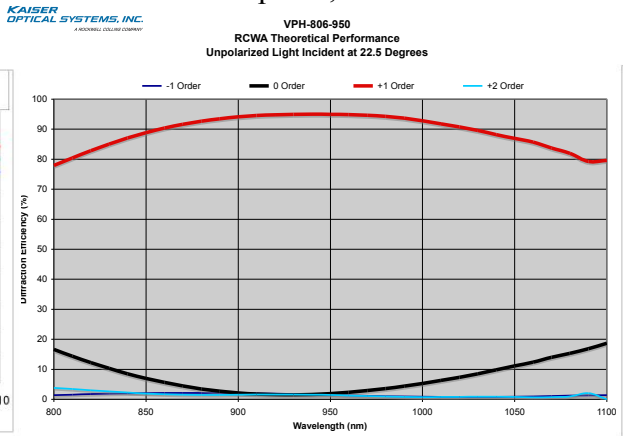
- At low temperatures, need high spectral resolution (~5nm/ch)
  - Implies use of higher dispersion grating for given image plane size, ex. 1200 l/mm
- At high temperatures, need lower spectral resolution
  - Implies use of low dispersion grating for given image plane size, ex. 600 l/mm
- Efficiency >80% desired across spectral range



Edmund Optics, 1200 l/mm

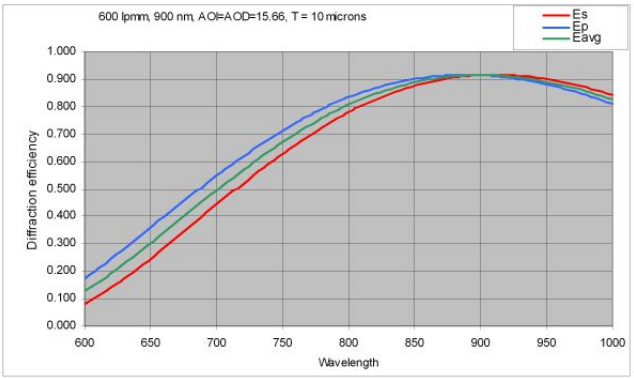


Kaiser Optical, 806 l/mm



J. Arns
Printed 10/19/10

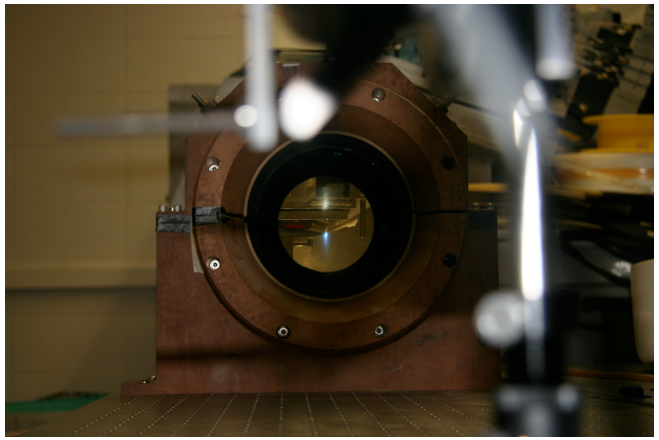
Edmund Optics, 600 l/mm

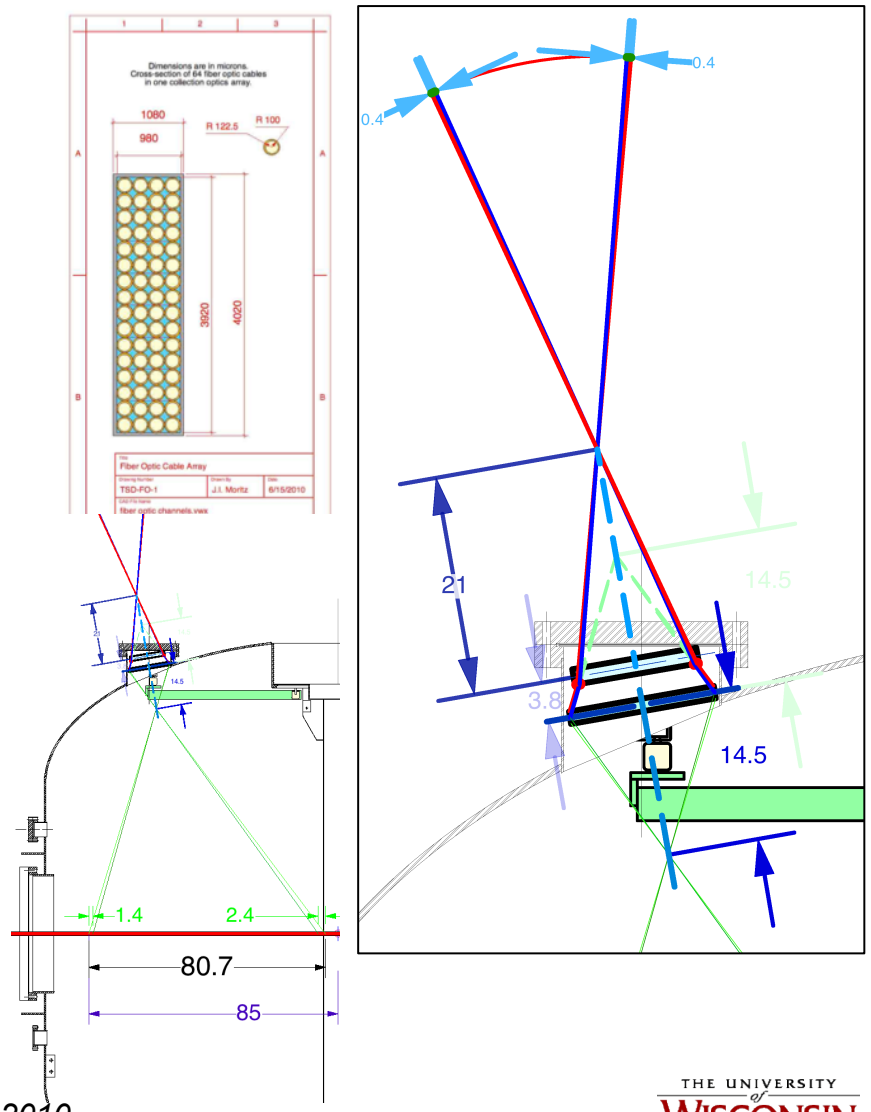


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Collection optics may employ Petzval design to minimize aberrations

- Laboratory optical characterization presently underway
- System designed for 1.4 cm radial resolution in plasma core, 2.6 cm radial resolution near edge
- Etendue calculated to be ~0.23 mm^2 ster for least-favorable setup
- Possibly re-commission TS-1 spheromak optics

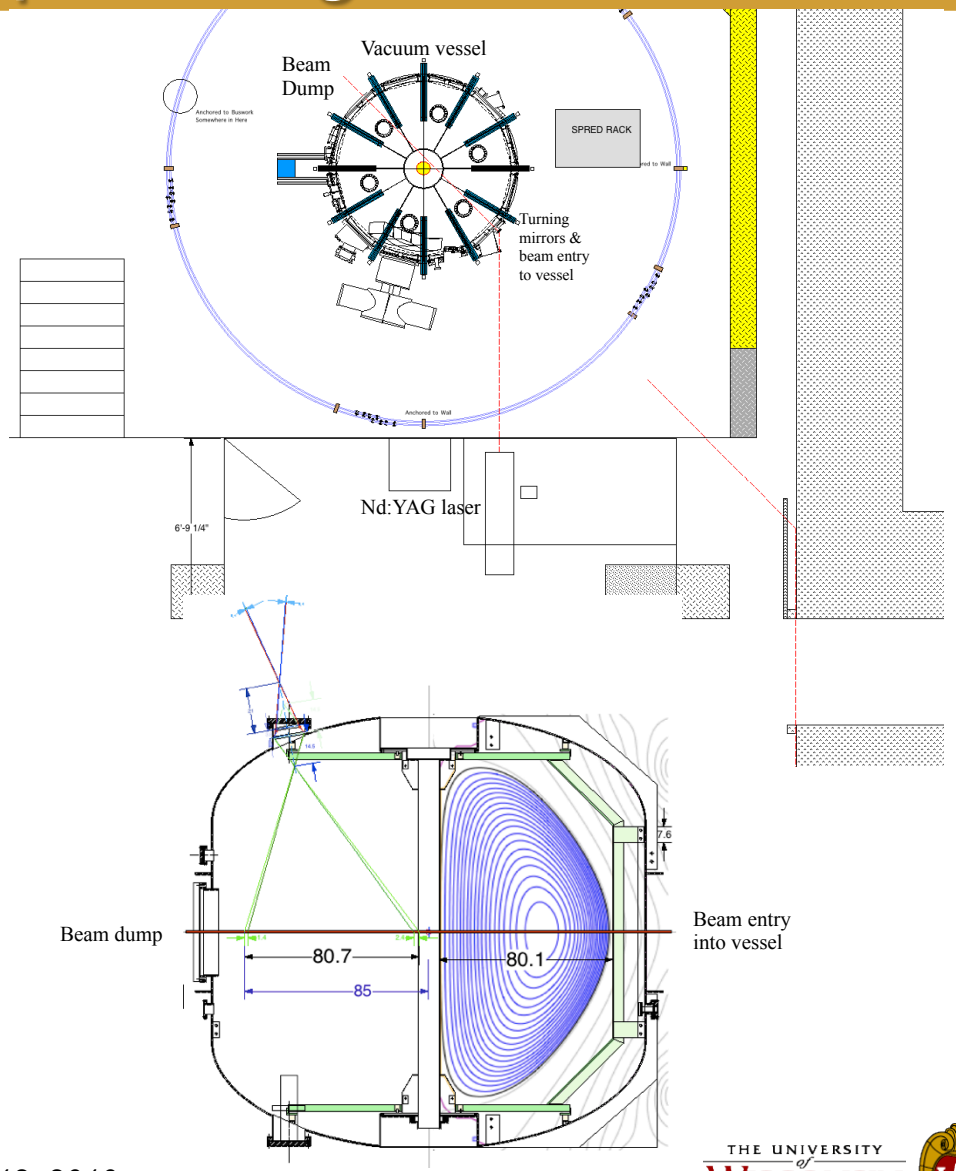




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Beamline optimized for simplicity and shortest path length

- Position laser head close to vacuum vessel
  - ≤ 2 turns in beamline
  - Total beam path length≈ 5 m
  - Vibration-isolated mounting
  - Environmentally controlled, dedicated "laser" room
- Monitor alignment with digital cameras at turning mirrors
  - Remote-controlled actuators may be used for inter-shot beamline tuning
- Horizontal beam through plasma; vertical viewing
- Beam dump
  - Use absorbing glass plates for power reduction
  - Terminate with razor blade array to minimize reflections

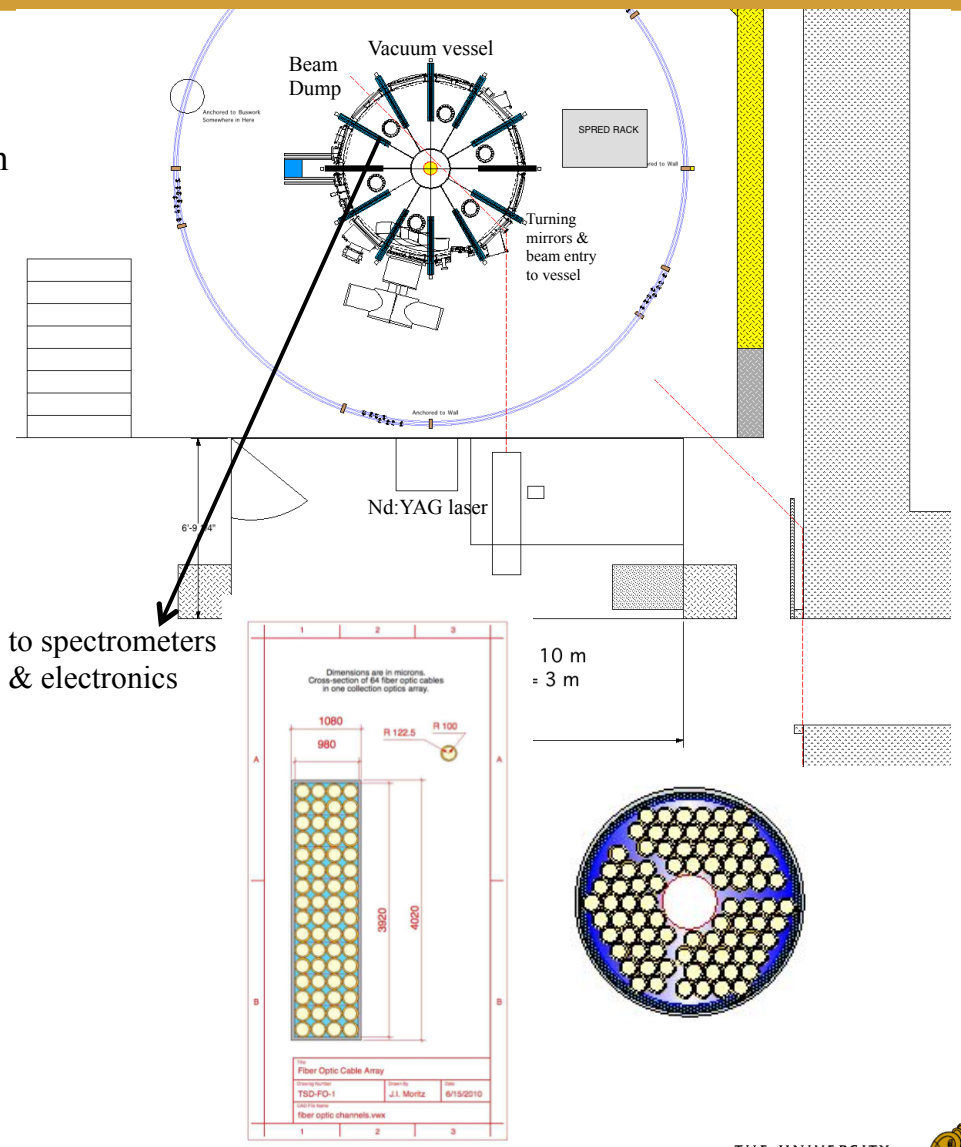


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Close-packed fiber bundles transport signal to remote spectrometers & electronics

- For signal transmission in NIR, use fused silica optical fiber
  - Optimized for transmission from 700-1200 nm
  - NA up to 0.22 readily available (25.4° acceptance)
  - Core diameters ≥ 50 μm
  - Attenuation ~ 8 dB/km over spectral band

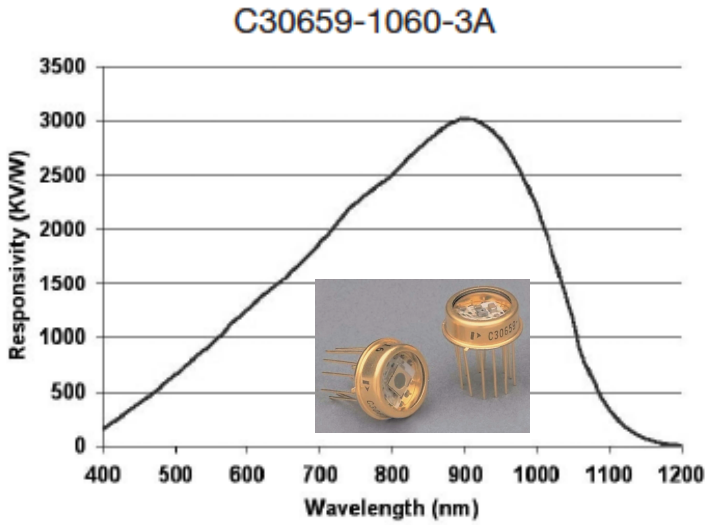
    Very low losses for lengths ≈ 30 m
- High packing fraction and matched fiber-detector geometries maximize collected light fraction
- Spectrometers remotely located to allow easy accessibility
  - Available during shot; minimal interruption to operations
- Electronics remotely located to reduce stray noise effects
  - Pegasus experimental area heavily affected by power supply switching noise
  - Optically transmit MPTS signal out of area



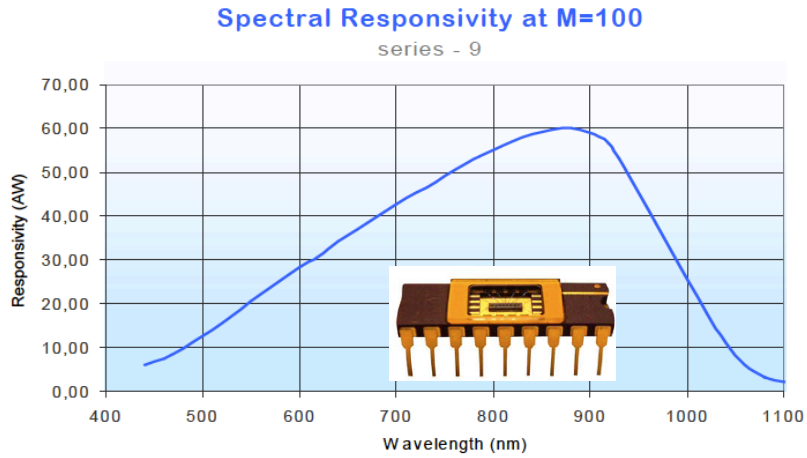
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Avalanche Photodiodes (APD) will be used to detect scattered light

- Many MPTS systems use Perkin-Elmer C30659-1060-3A
  - Large area (3 mm diameter)
  - Relatively high responsivity
  - Coating optimized for 1064 nm
  - 65° half-angle of acceptance



- Alternate concept is an APD linear array
  - For dispersion-grating based instrument, wider spectral bands map to wider physical dimension
  - Detector array placed directly in spectrometer output plane and individual elements grouped together to form desired spectral bin "size" (ex. (5) elements @ 0.65x0.2 mm each)
  - Practicality depends on customizability of multi-element APD arrays with small element separations



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Summary

- Design of a new Thomson scattering diagnostic for the Pegasus Toroidal Experiment is underway
- This diagnostic will be used to characterized physics regimes unique to Pegasus:
  - Taylor relaxation of non-solenoidally generated tokamak-like plasmas, the role of resistively-driven helicity dissipation in these plasmas, and also high β_T, I_p/I_{TF} plasmas
- Initial predictions yield feasible scattered intensity and distribution estimates
- Diagnostic design guided by consideration of physical scale sizes
  - Laser specifications, system throughput, and optical characteristics
- Novel Volume Phase Holographic (VPH)-based MPTS system proposed
  - If details yield unrealistic constraints, consider pre-existing GA-based filter polychromator method
- Digitization scheme presently being investigated
  - Ideally digitize at rate faster than background variation, but not necessarily at ~GHz (for 10 ns pulse)
  - Characteristic timescale and intensity for background variations during HI discharges must be estimated

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