Abstract

Pegasus Toroidal Experiment
University of Wisconsin-Madison

The capabilities of the Pegasus ST experiment are being extended to better explore very low A plasma behavior. A LabView-based control system drives CAMAC-based waveform generators to produce reference waveforms for pulse-width-modulated feedback control of the coil currents. MHD equilibrium and stability properties are measured by 7 sets of magnetics and a 19-channel SXR array. The internal current profile is constrained by an upgraded soft X-ray tangential imaging system. Pulse height analysis via a silicon drift detector and a Ross filter SXR array provide electron temperatures. A tangentially viewing bolometer array measures profiles of radiated power. A CCD-based visible bremsstrahlung array gives an approximate density profile. SPRED provides an impurity spectrum at 5 kHz via a fast-scanning CCD array. Possible new diagnostics include neutral beam spectroscopy for plasma profiles and a high-resolution SXR array for external kink analysis.

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Motivation

- The PEGASUS project is designed to study near-unity aspect ratio plasmas.
- Multiple upgrades to power supplies and the facility have been installed to improve access to low A, high β_t regime
- New power supplies and infrastructure require development of new control codes and machine interfaces.
- Exploration of this regime requires a modest diagnostic capability for measuring:
  - Equilibrium
  - Stability
  - Plasma Parameters

Overview

Plasma operations rely on machine control and an array of diagnostics:

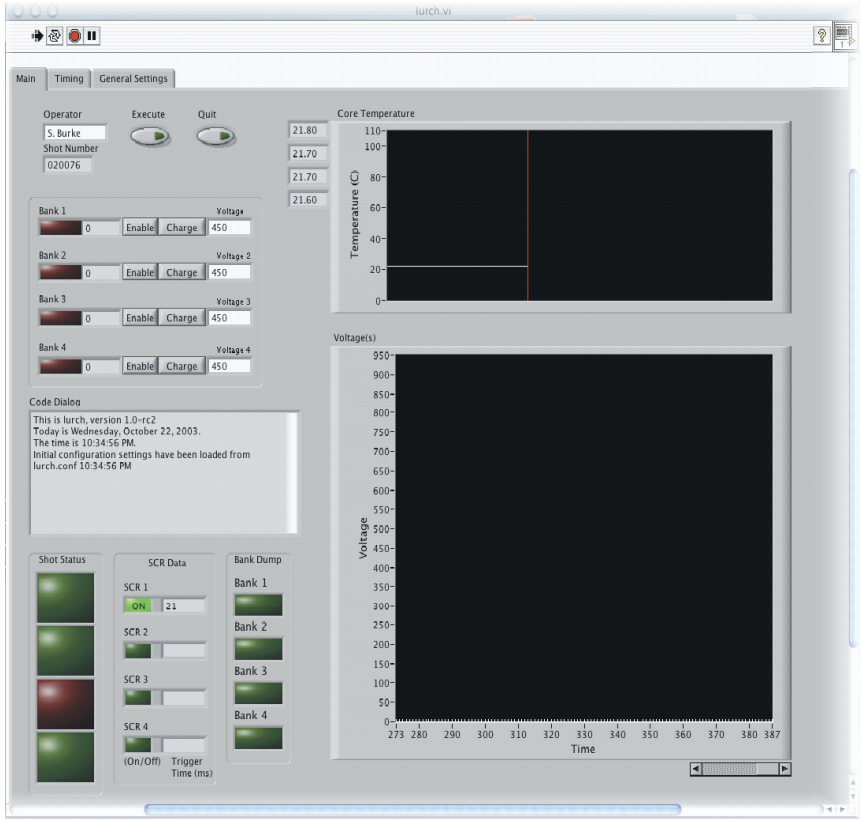
- Machine Ops - Software used to control the machine and power supplies for data acquisition.

- Diagnostics
  - Equilibrium - A full complement of Mirnov coils, a soft X-ray array and a soft X-ray camera.
  - Stability - flux loops, pickup coils, diamagnetic loops and Rogowski coils.
  - Plasma Parameters - Spectroscopy (VUV, Visible Bremsstrahlung), Bolometry, Pulse Height Analysis.

Control Code on PEGASUS

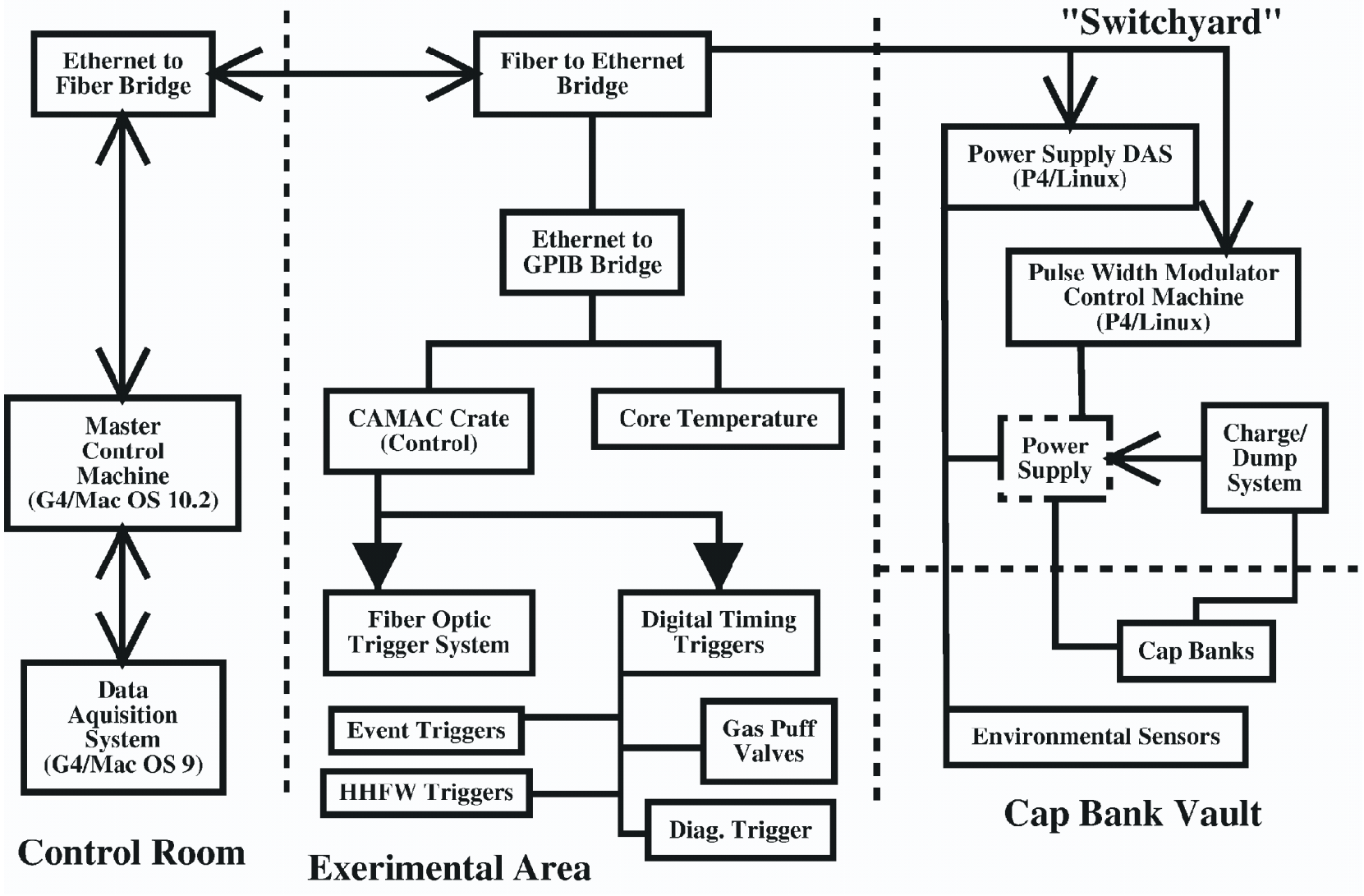
The addition of a new power supply to the experiment warranted a complete redesign of the control code.

- The code executes all shot operations:
  - Monitors core temperature
  - Charging/monitoring of cap banks
  - Programs/triggers timing sequence modules
  - Enables DAS
  - Polls DAS for data
  - Supplies power supplies with a waveform



Above: A screen shot from Lurch, the LabV iew based PEGASUS power testing code.

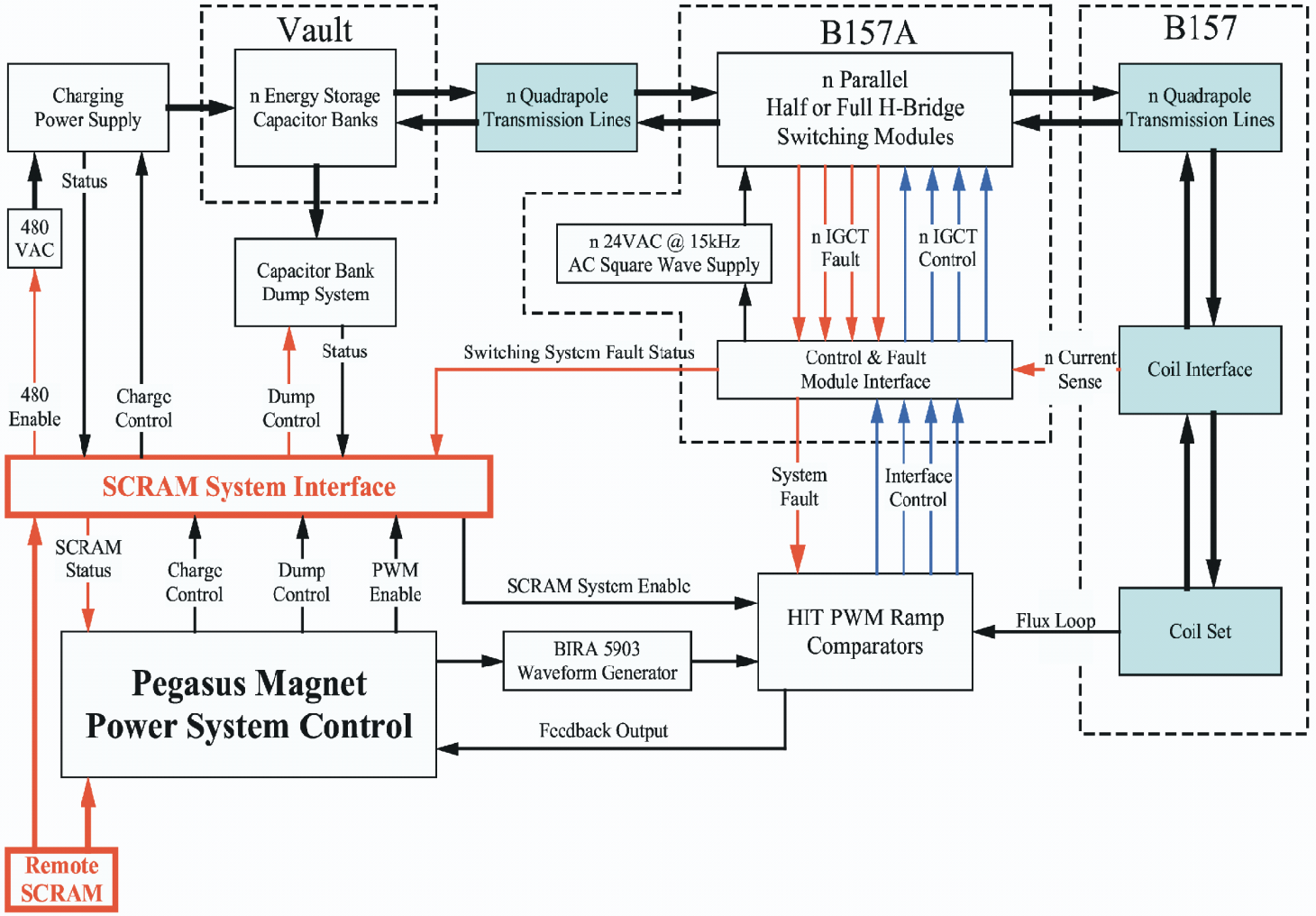
Control System Flow



Power Supply Upgrade

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An upgraded power supply design based upon work done at the University of Washington's HIT Experiment will give PEGASUS programmable magnetic fields.

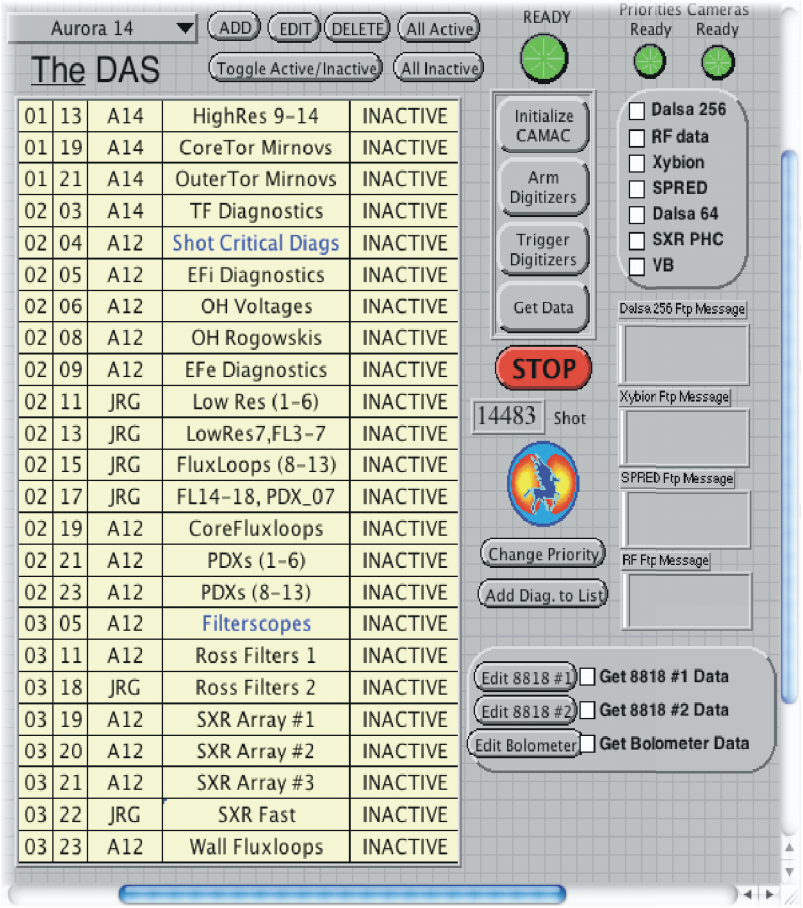


The Data Acquisition System (DAS)

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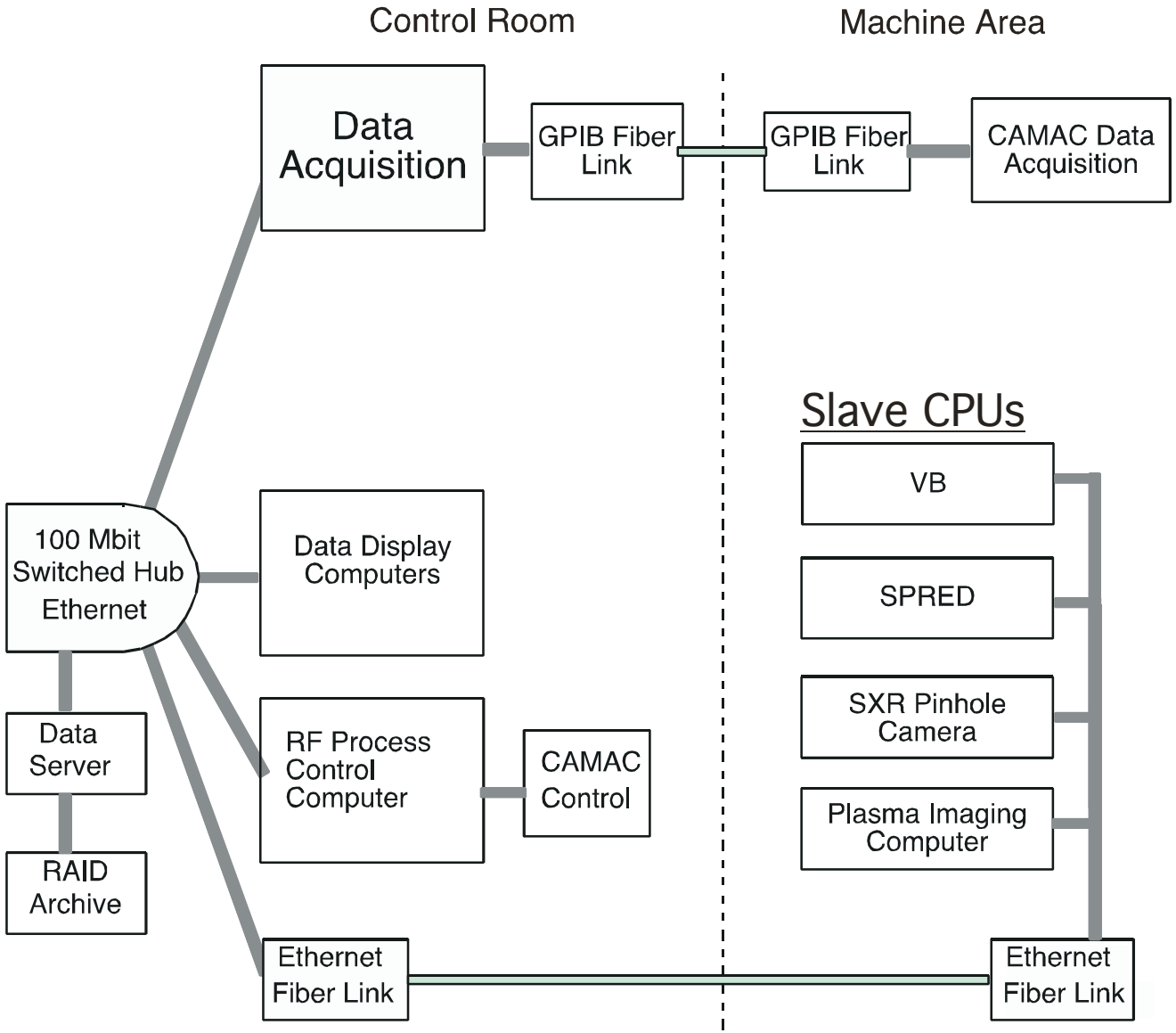
PEGASUS employs a LabView based data acquisition system (DAS) to control CAMAC digitizers and stand alone diagnostic computers.

- The main DAS computer acquires data from selected diagnostics.
- Initial modules on the DAS CAMAC include:
  - Waveform Digitizers
  - Timing Modules
- Slave computers also feed data to the DAS.
  - Visible Bremsstrahlung
  - VUV Spectroscopy
  - SXR Imaging
  - Fast Plasma Cameras
  - Power Supply Diagnostic



Above: A screen shot of main DAS code window.

Data Flow in the DAS



PEGASUS Diagnostics Complement Program Goals

- Plasma Equilibrium and Equilibrium Reconstruction
  - Full array of magnetic diagnostics
    - + Flux loops
    - + Diamagnetic loop
    - + Internal plasma Rogowski
  - Soft x-ray pinhole camera (SXRPHC) to constrain q-profile

- MHD instability analysis
  - Soft x-ray wave array for mode localization
  - Polodial and toroidal Mirnov coils for mode identification

- Diagnostics to Measure Key Plasma Parameters
  - $n_e(r,t)$ and $Z_{eff}(r,t)$ from visible bremsstrahlung (VB) array
  - $T_e(t)$ from soft x-ray pulse height analyzer (SXRPHA)
  - Relative impurity concentration from SPRED
  - Total radiated power from bolometer

PEGASUS Diagnostics

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• Current Diagnostics

Diagnostic	Capability	Measures
Core Flux Loops	(6)	V_L , Φ_{pol}
Wall Flux loops	(6)	Vessel currents
Int. Flux loops	(20)	Φ_{pol}
Rogowski Coils	(2)	I_p
Diamagnetic Loop	(2)	Φ_{tor} / Φ_p
B_p, Mirnov Coils	(56)	B_r , B_z / MHD activity
VUV (SPRED)	central chord	Relative impurity monitor
Filterscopes	central chord	Oxygen, Carbon, VB, D_α
Interferometer	single chord	$N_e l$
High Res. Camera	1000 fps	Plasma shape/position
2-D SXR Camera		Internal Shape/ j(R)
Poloidal SXR Diode Array	(19)	MHD Activity

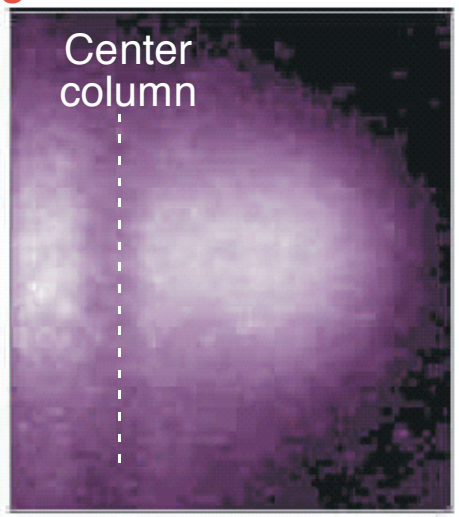
• Near-Future Diagnostics

Diagnostic	Capability	Measures	Status
Tangential PHA	single chord	$T_e(t)$	In Development
Tangential Bolometer Array	~32 chords	P_{rad}	Testing
Ross Filters	4 chords	$T_{e0}(t)$	Testing
Tangential VB Array	~20 chords	$Z_{eff}(R,t)$, $n_e(R,t)$	Testing
DNB		$N_e(R,t)$, $T_e(R,t)$, j(R)	Proposed
EBW Radiometer		$T_e(t)$	Proposed

2-D Soft X-Ray Camera Gives q-profile

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Tangential PHC SXR image



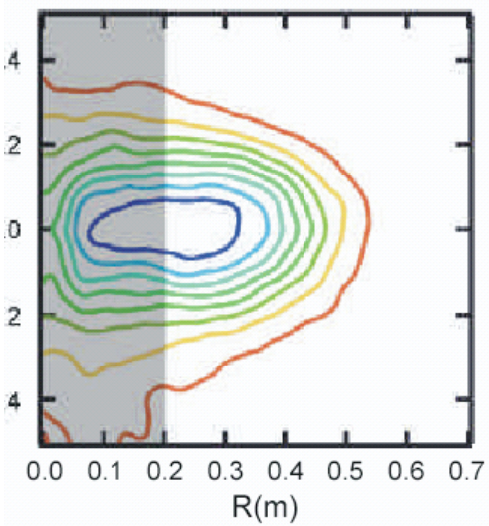
- Image analysis integrated with equilibrium
  - Images soft x-rays
  - Constant-intensity surfaces determined
  - Mapped into flux space
  - G-S equation with SXR constraints
  - Iterate solution until convergence

- Measured q-profile low central shear

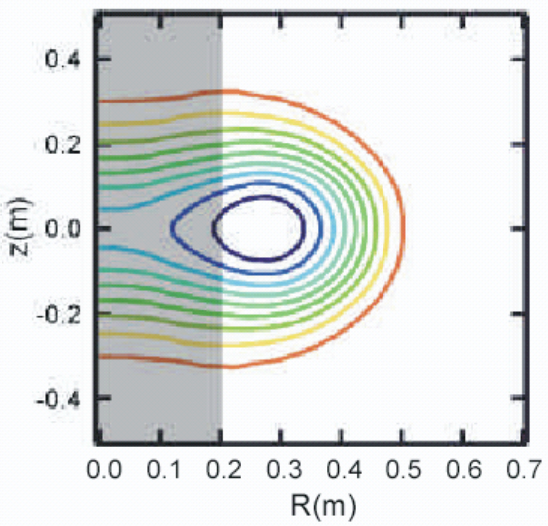
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Image Contours:

Measured

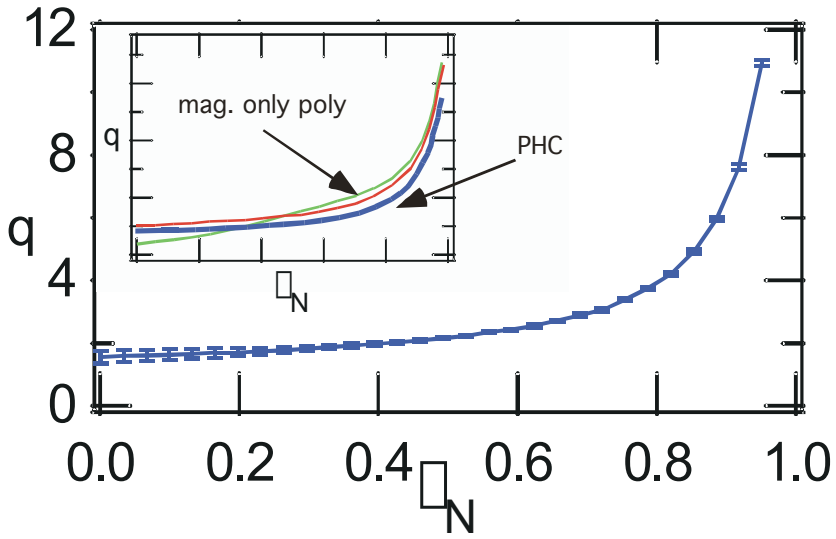


Reconstructed



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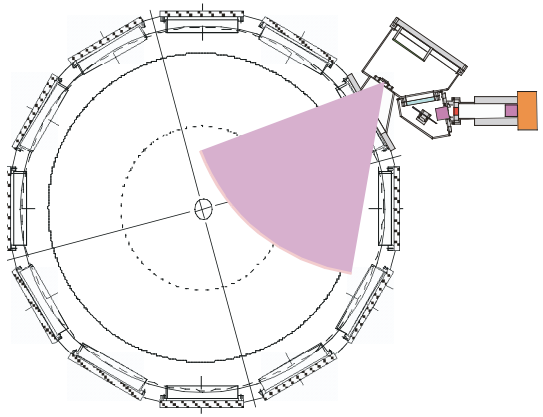
Reconstructed q-profile

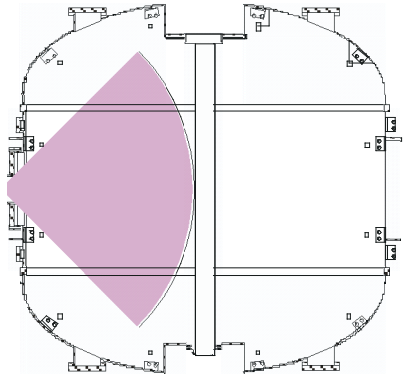


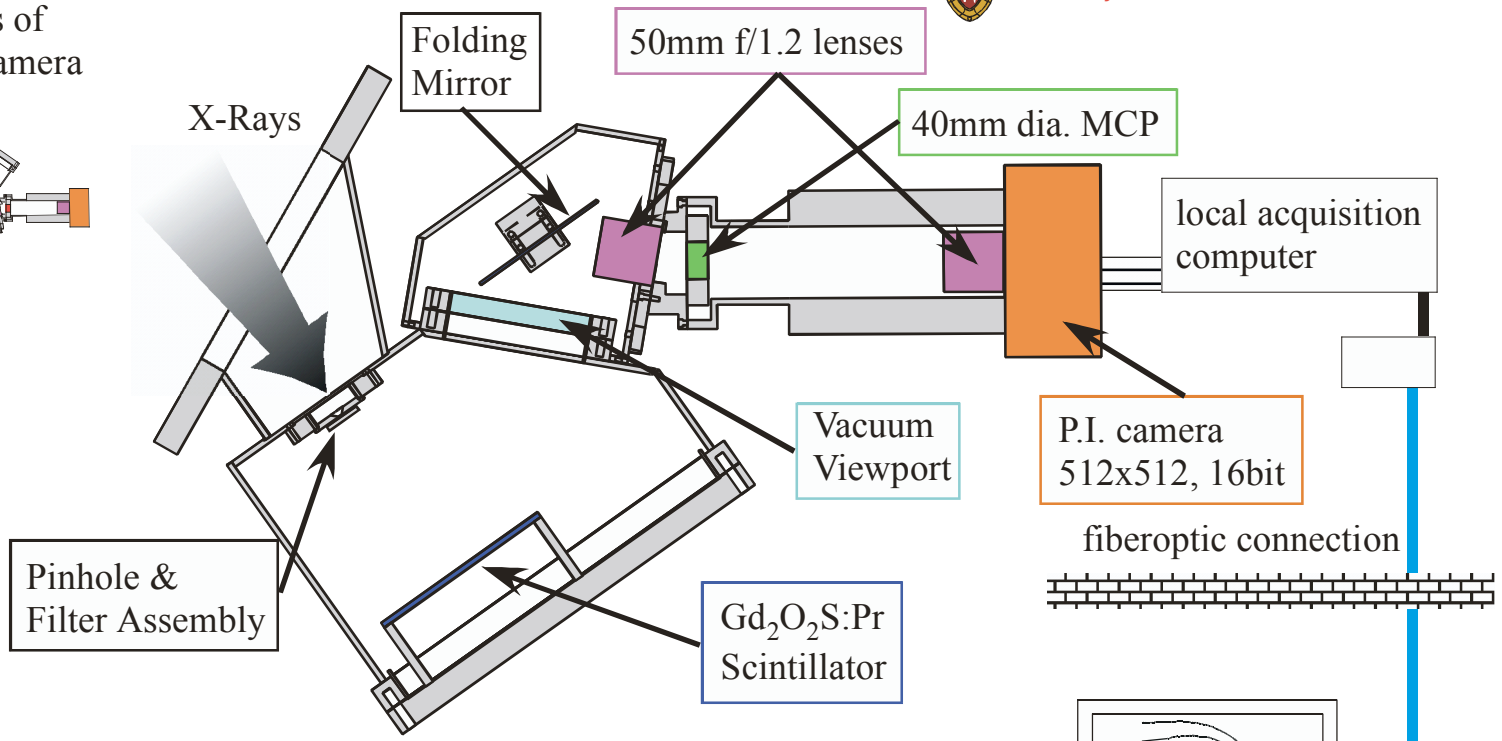
Soft X-Ray Pinhole Camera Diagnostic Layout

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Horizontal and vertical fields of views for the SXR pinhole camera







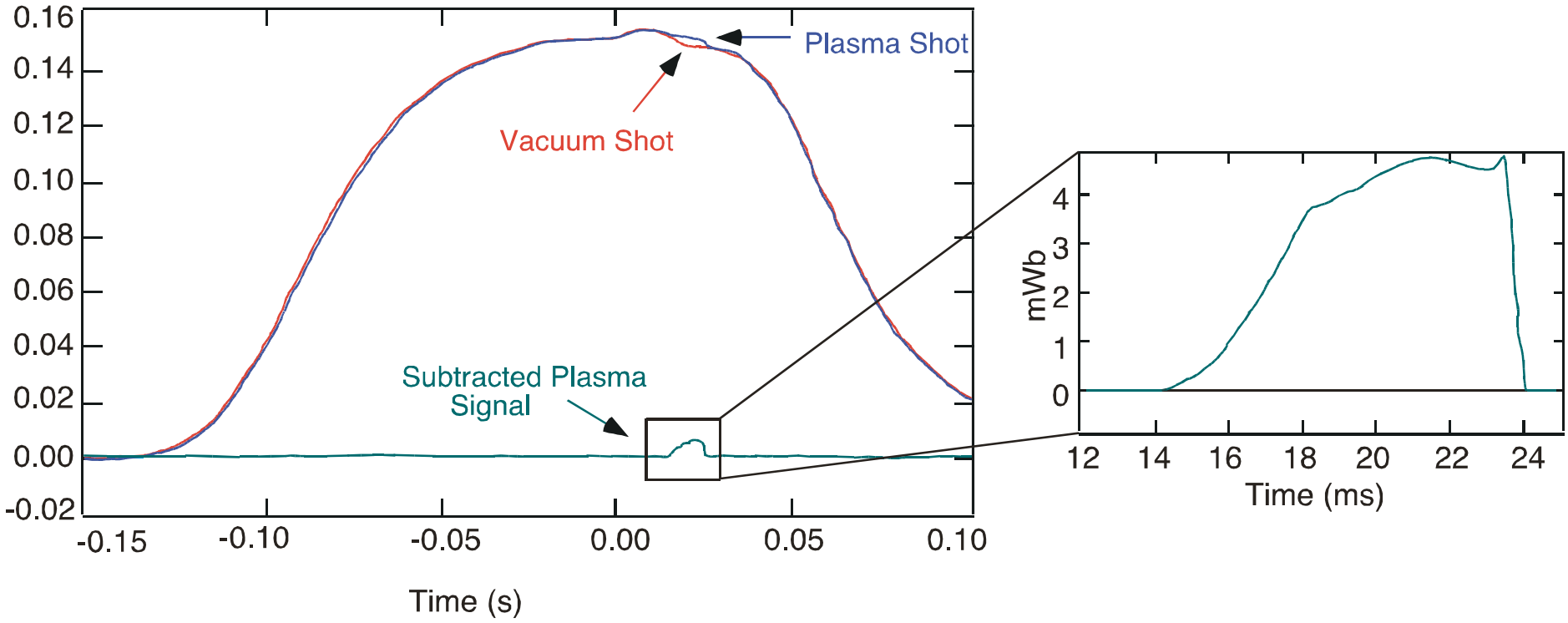
SXR pinhole camera hardware schematic

- Upgrading system to increase SNR
  - Bypassing image intensifier
  - Improving coupling optics to CCD
  - Examining scintillator/detector replacements

Diamagnetic Loop Used to Constrain Pressure

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- For PEGASUS, ΔB_{tor} due to plasma is relatively large.
  - Alignment to ±1mm is adequate.

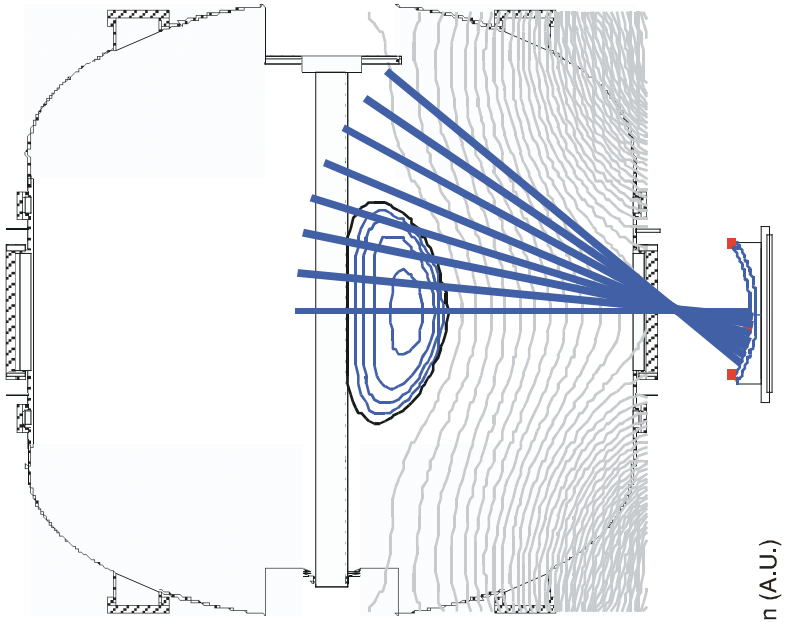


- A compensation loop is used to remove signal noise due to TF switching transients

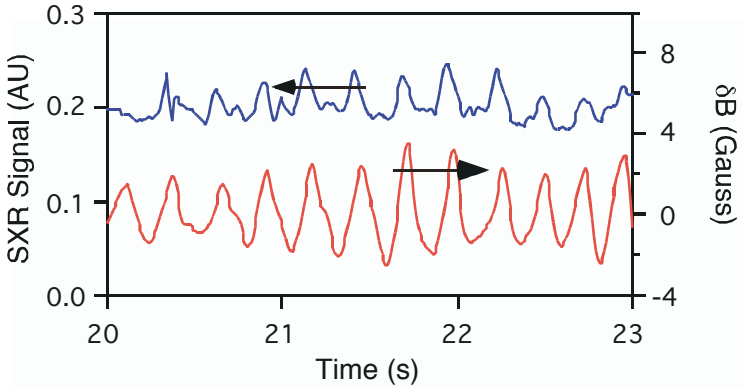
Soft X-Ray Array for MHD Analysis

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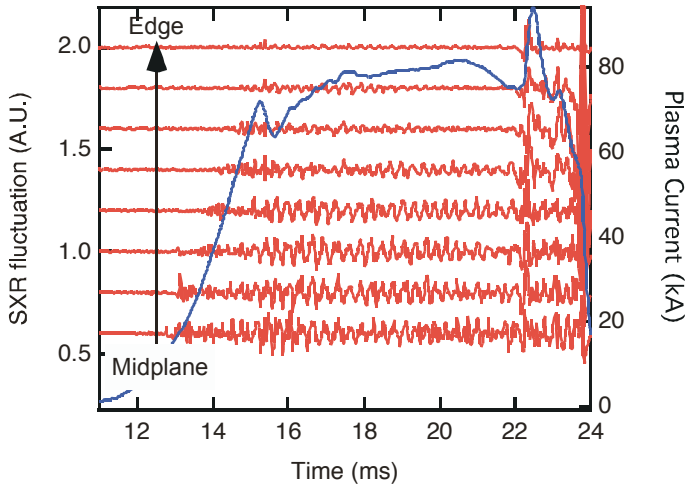
- 19 channel poloidal array of photodiodes (courtesy of PPPL)
  - External kinks observed and correlate with the visible camera images
  - 2/1 covers large portion of the plasma
  - 5 mil Be filters are used to get rid of most of the edge radiation
  - Ni filters will be used next spring to kill off the edge radiation completely



SXR View of a plasma



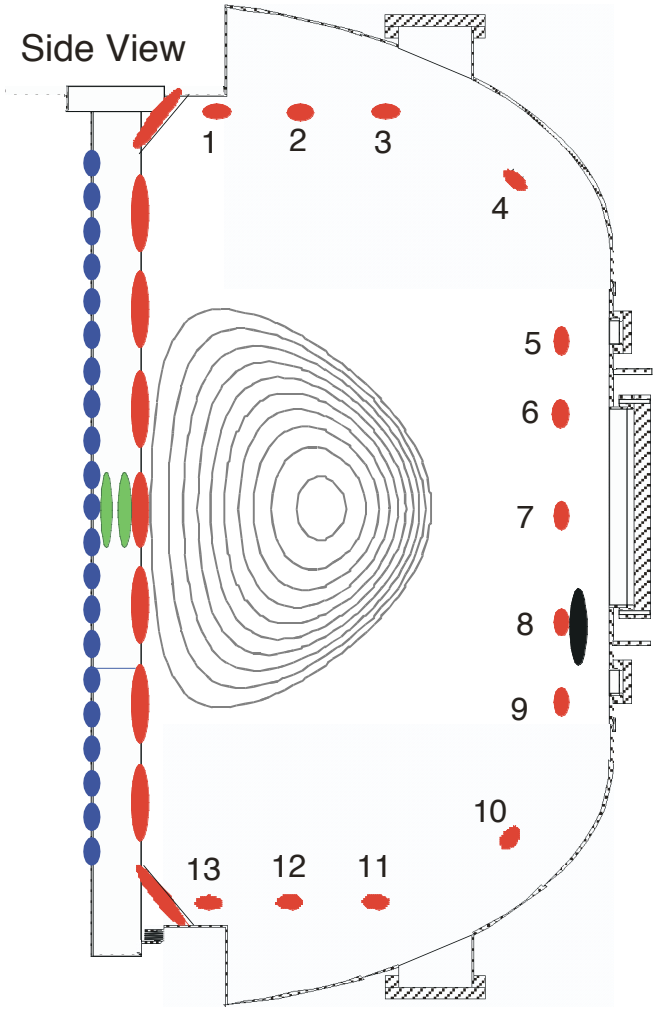
Correlation between Mirnovs and SXR

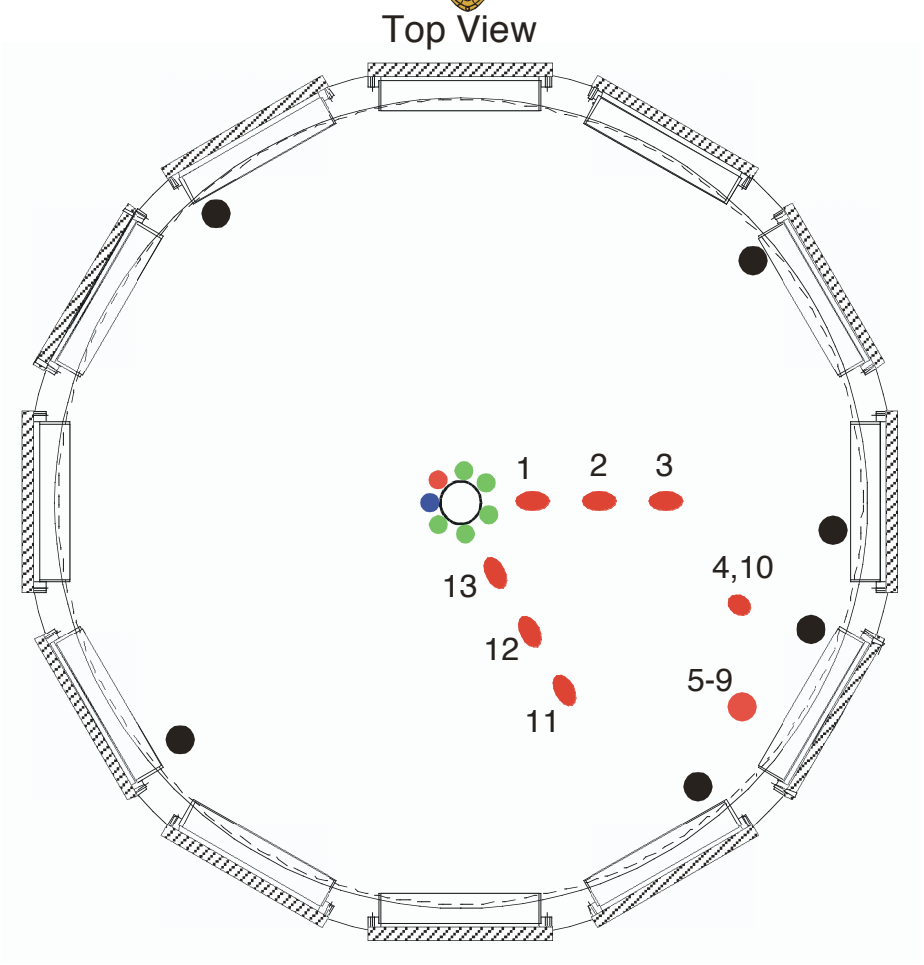


Large spatial extent of oscillations

Schematic Layout of Mirnov Coils

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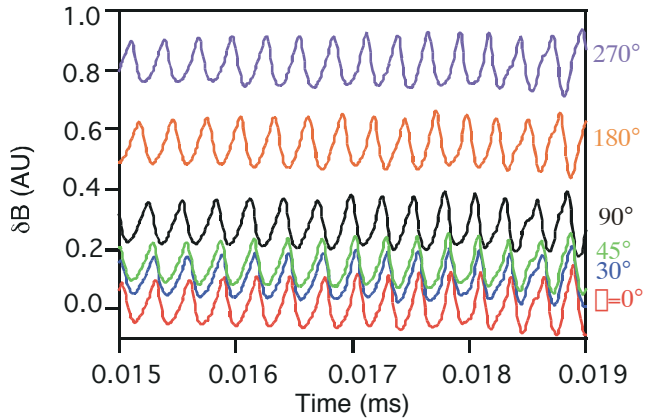


- "High-Res" Core Mirnov Coils (21)
- Poloidal Mirnov Coils (22)
- LFS Toroidal Mirnov Coils (6)
- HFS Toroidal Mirnov Coils (7)

Mirnov Coils Allow Full Mode Identification

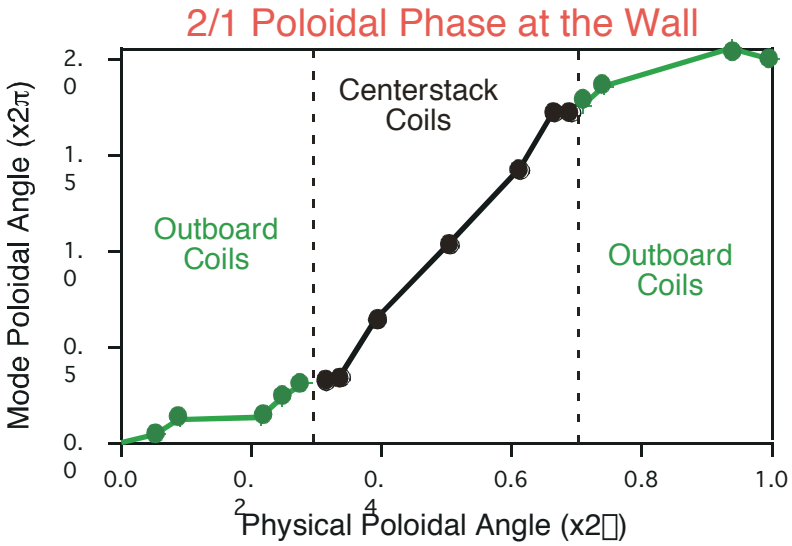
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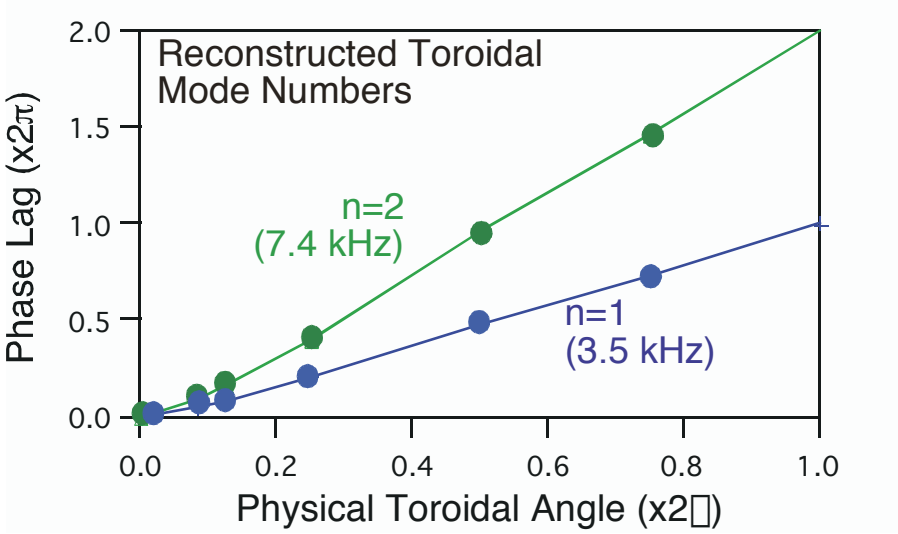
- The 6-coil LFS toroidal array is used to obtain values of n
  - Uneven coil spacing allows for resolution up to n=12



Toroidal Mirnov Signals

- Spectral techniques are used to extract resonant frequencies and phase delays
  - Cross-power gives spectrum
  - Cross-phase gives phase shift

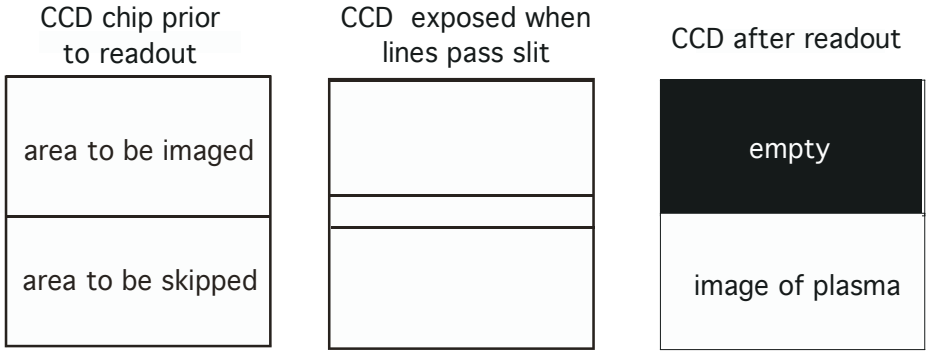


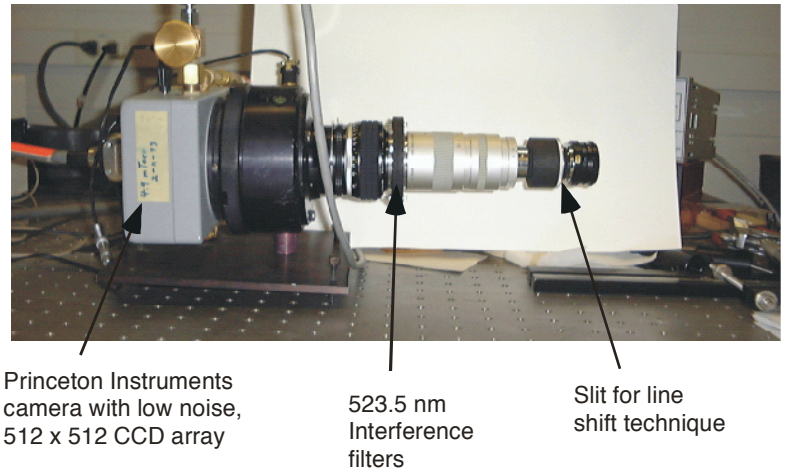


Visible Bremsstrahlung Camera Gives $Z_{eff}(r,t)$ or $n_e(r,t)$

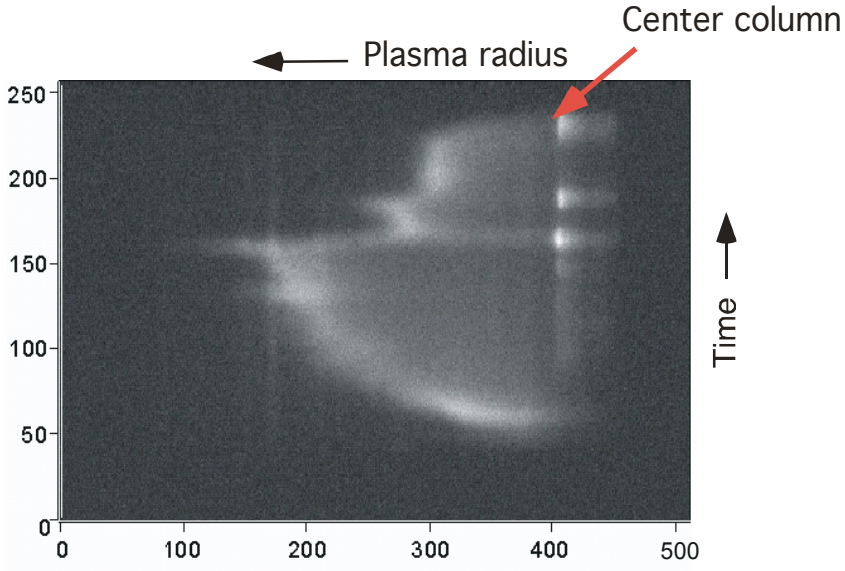
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- Initial testing successfully demonstrates diagnostic operation





- Line shift technique collects images of the plasma midplane as a function of time
- Each data point is 12 pixel rows on CCD
  - ~80 ms per line
  - ~1 ms temporal resolution



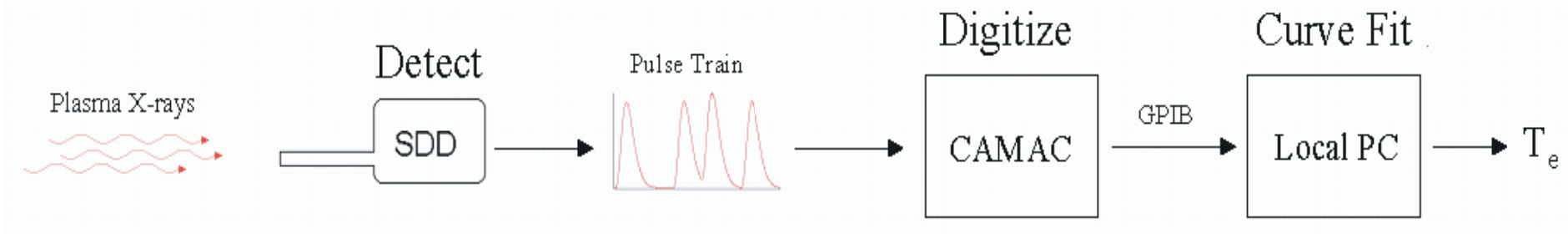
- Noise sources identified and resolved
- Upgrading diagnostic for next run cycle
  - Larger filters for increased throughput
  - Photometric calibration of entire optical system
  - D_2 gas valve being moved outside field of view

SXR Pulse Height Analyzer for $T_e(t)$

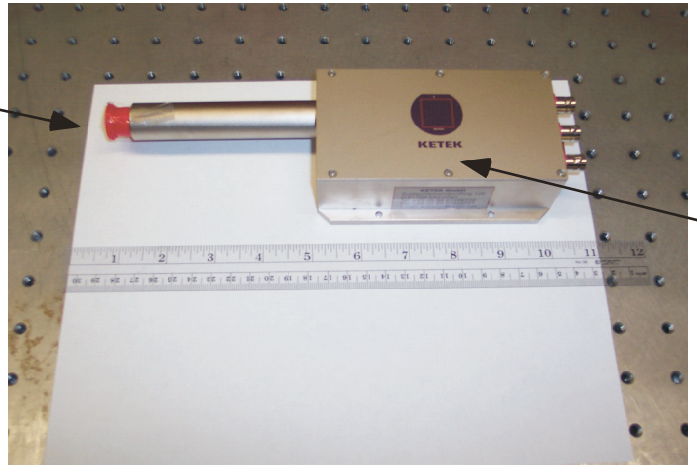
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- Silicon drift detector (SDD) based PHA
  - Δt ~1 ms; 20 total time points
  - Shot to shot midplane scanning for radial profiles

- SXR spectrum >1 keV analyzed to find $T_e(t)$
  - Low noise, 5 mm^2, SDD detects at rates >200,000 photons/sec
  - CAMAC DAS digitizes pulse shaper output
  - Curve-fitting routine extracts data in the pulse pileup region



Vacuum isolated
SDD with on-chip
Peltier cooling



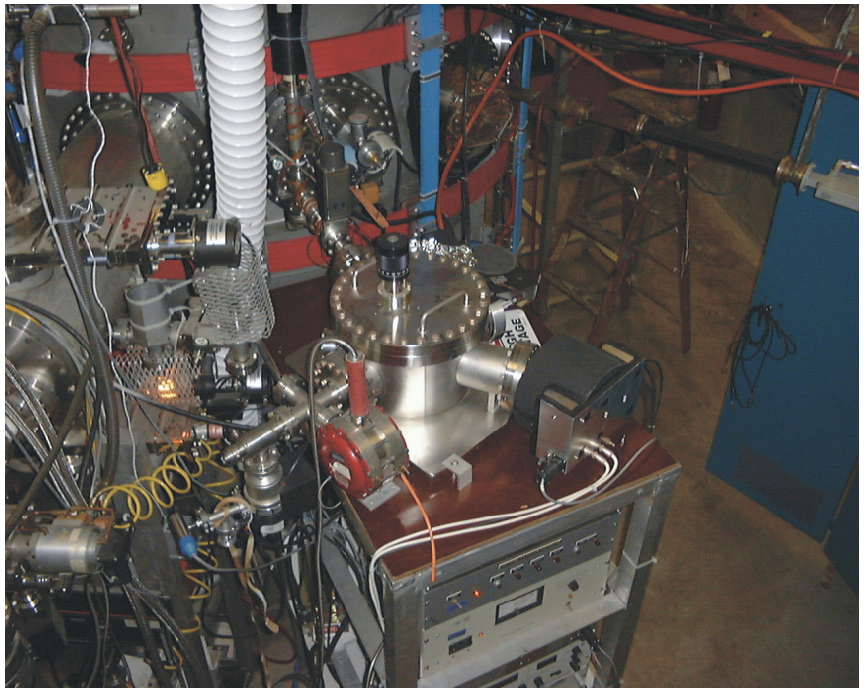
Housing for:
- Pre-amplifier
- Pulse shaper
- Temperature control
- Power supply

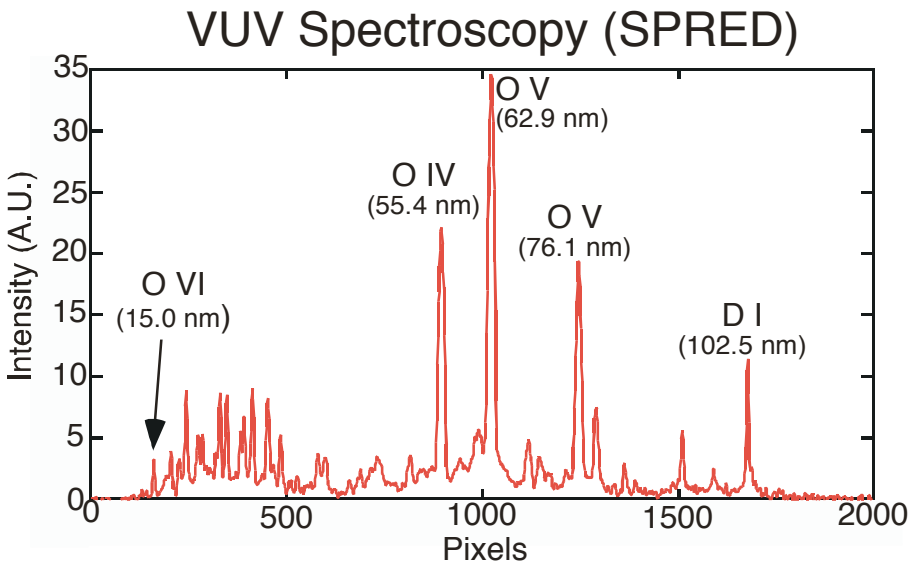
Relative Impurity Concentrations Using SPRED

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- SPRED VUV Survey Spectrometer
  - 10 - 110 nm spectral range measured simultaneously
  - Single radial view of plasma
  - VUV - visible image intensifier/convertor lens coupled to 1-D camera

- New high-speed, 1-D imaging detector increases resolution
  - 2048 pixel 1-D camera (DALSA CL-C6)
  - Up to 4.8 kHz sample rate

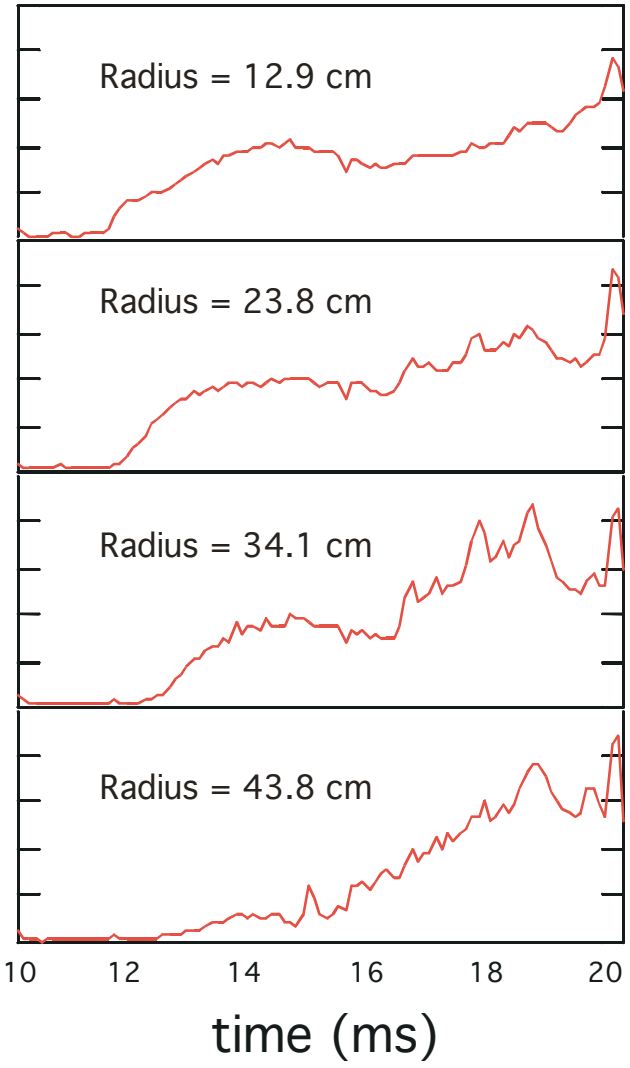




Bolometer Arrays to Measure Total Radiated Power

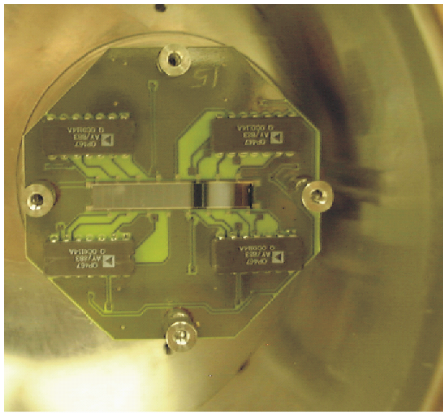
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- Two 16 channel AXUV photodiode arrays to cover core and edge of plasma

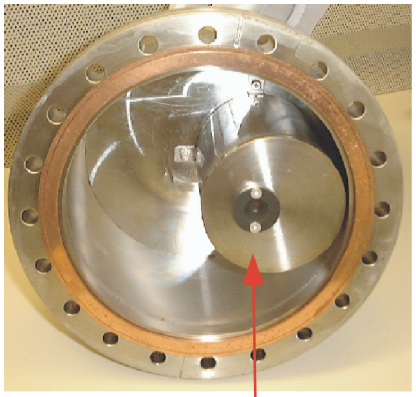


Center

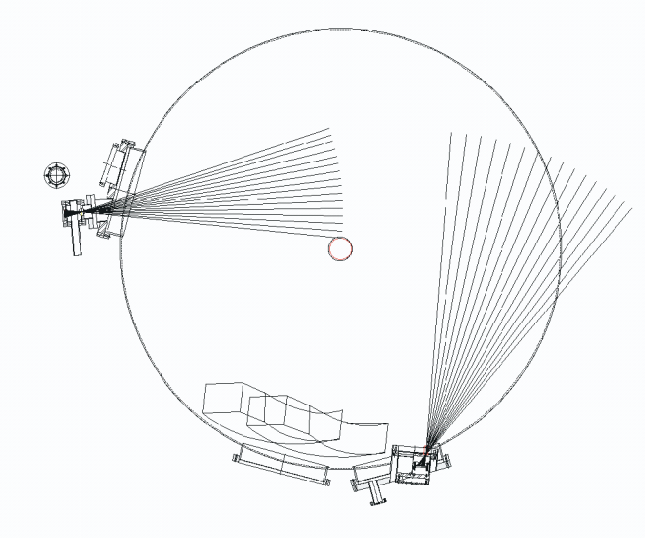
Edge



Diodes and pre-amp assembly



Pinhole imaging aperture



Fields of view in plasma give full midplane coverage

Summary

The PEGASUS control system and diagnostic set are reasonably complete:

- Machine Ops
  - Control Code
  - Data Acquisition Software
  - Remote controlled power supply diagnostic
- Equilibrium Diagnostics
  - Mirnov coils
  - Soft X-Ray Imaging
- Stability Diagnostics
  - Rogowski coils and flux loops
  - Diamagnetic loops
- Parameter Diagnostics
  - VUV, VB Spectroscopy
  - Bolometers
  - SXR PHA
  - SXR imaging for j(r)
  - Fast plasma imaging
  - Ion spectroscopy (planned)

Reprints