Design Study of a Real-Time Resistive-Wall-Mode Identifier using Mirnov Signals for the DIII-D Tokamak*

D. H. Edgell, J. S. Kim, I. N. Bogatu
(FARTECH, Inc, San Diego, CA)

D. A. Humphreys, A. D. Turnbull, E. J. Strait
(General Atomics, San Diego CA)

A. Garofalo
(Columbia University, New York, NY)

and M. S. Chance
(PPPL, Princeton, NJ)

ABSTRACT

Real-time identification and control of the Resistive-Wall-Mode (RWM) are crucial for higher performance operation in present and future tokamaks. Identification of the RWM in a tokamak is difficult due to its slow rotation speed and the fact that its growth rate is comparable to the field penetration rate of the vacuum vessel wall. The mode can grow large enough to dramatically degrade confinement or cause disruption in less than one toroidal revolution of the mode.

A matched filter method of identifying the n=1 RWM component in DIII-D using signals from toroidal and poloidal arrays of Mirnov probes has been developed. Estimations of the time required for data collection and analysis confirms the feasibility of using this method to produce a real-time mode identifier suitable for use in feedback stabilization of the mode on the DIII-D tokamak.

The preliminary design of a real-time RWM identifier for integration with the DIII-D systems will be presented, including data acquisition and analysis hardware.

*Work supported by DOE Grant/Contracts No. DE-FG03-99ER82791, DE-AC03-99ER54463, DE-FG02-89ER53297 and DE-AC02-76CHO3073.

OUTLINE

- Early identification and control of the Resistive-Wall-Mode (RWM) is essential for high-β tokamak confinement but can be difficult
- Mirnov probes inside the vacuum vessel can be used to detect the RWM
- The Matched Filter Method allows identification of the mode (inc. toroidal phase, helicity, poloidal structure) using multiple diagnostics (i.e. Mirnov probes and Saddle loops)
- The matched filter consists of orthogonal vectors of theoretically predicted mode signals which are matched to the actual diagnostic signals.
- A real-time RWM identifier is under-development by FARTECH at DIII-D
- The mode identifier will communicate with the DIII-D PCS but will be a separate data acquisition and analysis entity
- The proposed identifier hardware consists primarily of a DEC alpha processor and dedicated high-sampling rate digitizers connected by a high throughput PCI data bus
- Initial testing of the RWM identifier is scheduled for March 2001 after the DIII-D PCS upgrade.

RWM Early Detection is Essential but Difficult

- Resistive Wall Mode (RWM) is an n=1 pressure driven external kink mode, strongly coupled to the resistive wall unstable when exceeding a β-limit
- Stabilization of the RWM is essential for high-β confinement
- Active control of the RWM requires accurate identification and estimation of mode amplitude and phase before it is too late for control
- Accurate early detection is difficult due to its characteristics

  $\rightarrow$ growth rate comparable to the wall resistive decay/penetration time $\gamma_{RWM} \sim 1/\tau_{Wall}$ equilibrium changes can be significant

  $\rightarrow$ slow or no rotation speed

  $\rightarrow$ can dramatically degrade confinement or disrupt in less than one toroidal rotation

INTERNAL MIRNOV PROBES CAN DETECT THE RWM

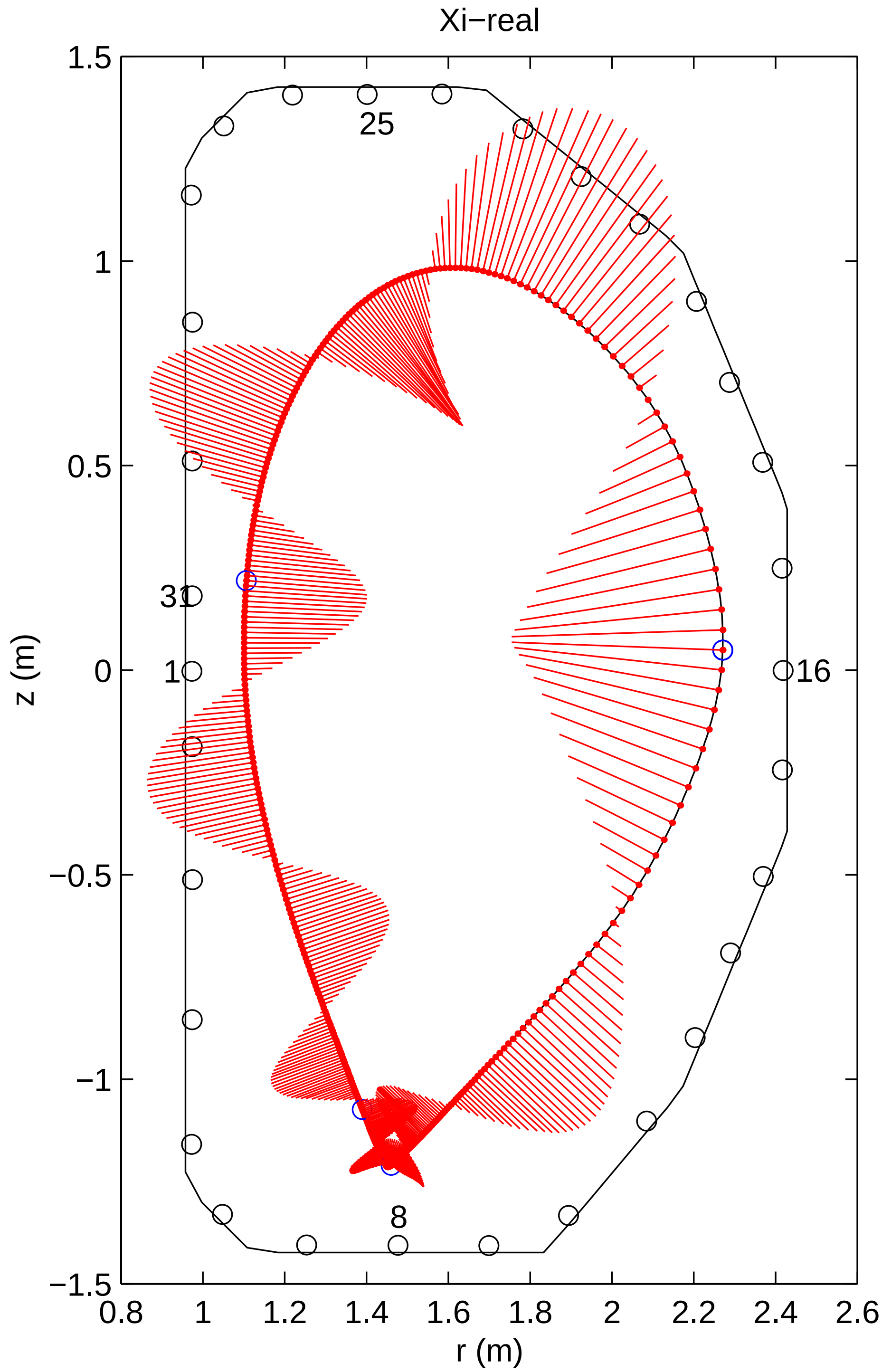
- Currently main RWM diagnostic in DIII-D is Fourier analysis of toroidal outboard-midplane array of six exterior vessel saddle loops (B_r)
  - → limited by vessel penetration time delay and resultant phase lag
  - → little poloidal information is available from saddle loops just off midplane
- RWM can also be detected using high bandwidth Mirnov probes (dB_p/dt)
  - → DIII-D Mirnov arrays contain 11 outboard-midplane probes distributed toroidally plus many probes at poloidally distributed locations
  - → internal location eliminates penetration time delay/phase lag
  - → located closer to mode where perturbed fields larger
  - → probes more noisy and more influenced by equilibrium changes
  - → even spacing of probes has been improved by 3 new toroidal probes
  - → information from poloidal and toroidal probe arrays can be utilized with the matched filter method with potential for good discrimination of RWM from other modes

Construction of Matched Filter Vectors for Identification of RWM from Mirnov Signals

- Matched filter consists of two vectors of Mirnov probe signals predicted for RWM, constructed from stability code (GATO) and vacuum field (VACUUM) analysis using following steps:

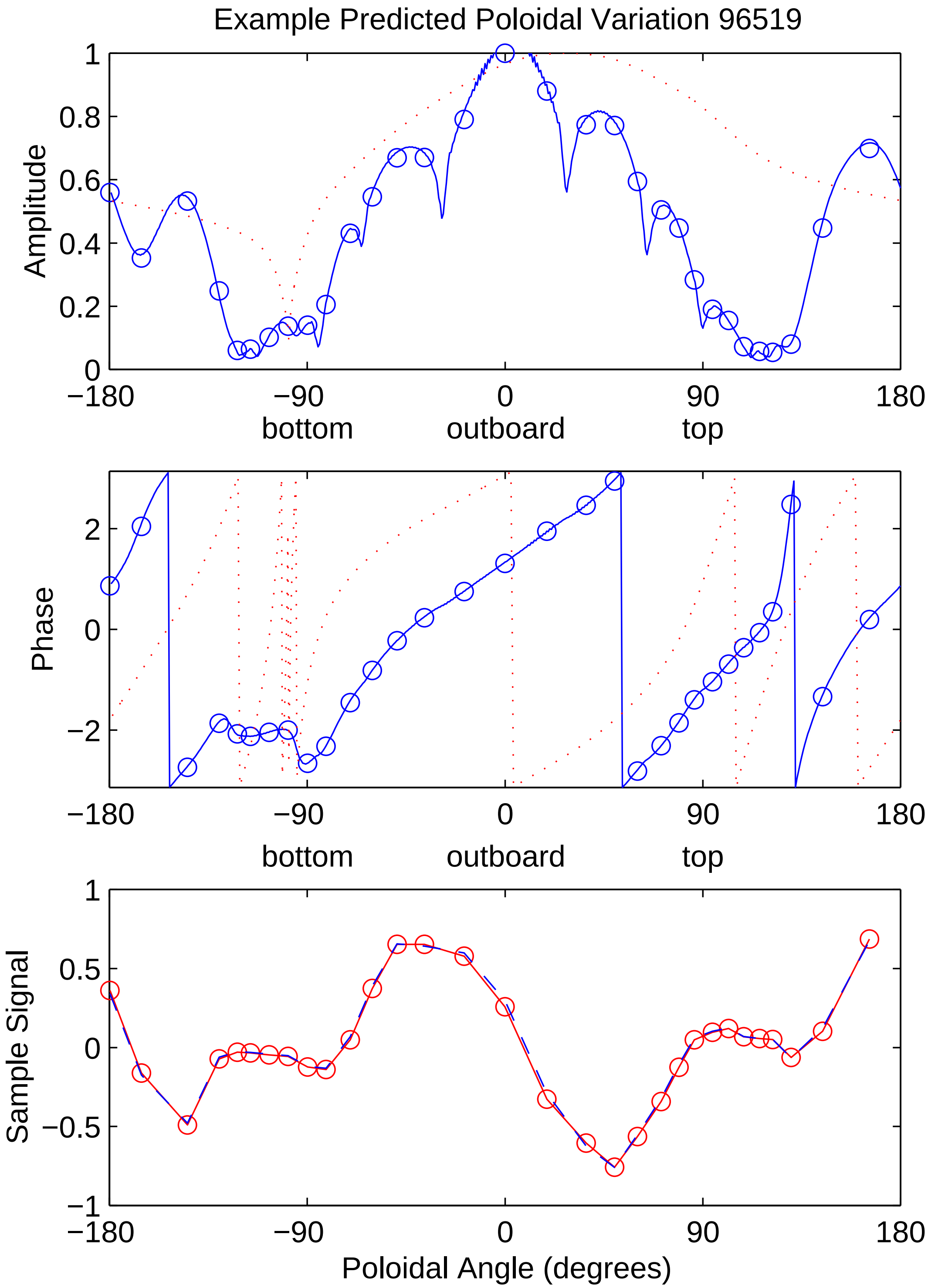
1. EFIT calculates the plasma equilibrium for a poloidal cross-section
2. GATO predicts no-wall ideal kink mode at the plasma boundary:
   displacement $\xi = \xi_r + i\xi$ due to RWM in equal-arc coordinates
3. Displacement mapped to evenly spaced PEST coordinates then decomposed into complex Fourier poloidal components ξ_l and used to predict RWM Mirnov probe signals by VACUUM code
4. Predicted Mirnov probe signals used to create two orthogonal matched filter *poloidal* vectors, 90° out of phase.
5. Mirnov coil predicted signals mapped *toroidally* (n=1) according to Left or Right Helicity to extend the two matched filter vectors to the actual toroidal locations of all the Mirnov probes currently in DIII-D
6. Other Diagnostics (i.e. Saddle Loops, SXR) can in principle be included into the matched filter vectors

GATO PREDICTION OF RWM DISPLACEMENT MAPPED TO PEST



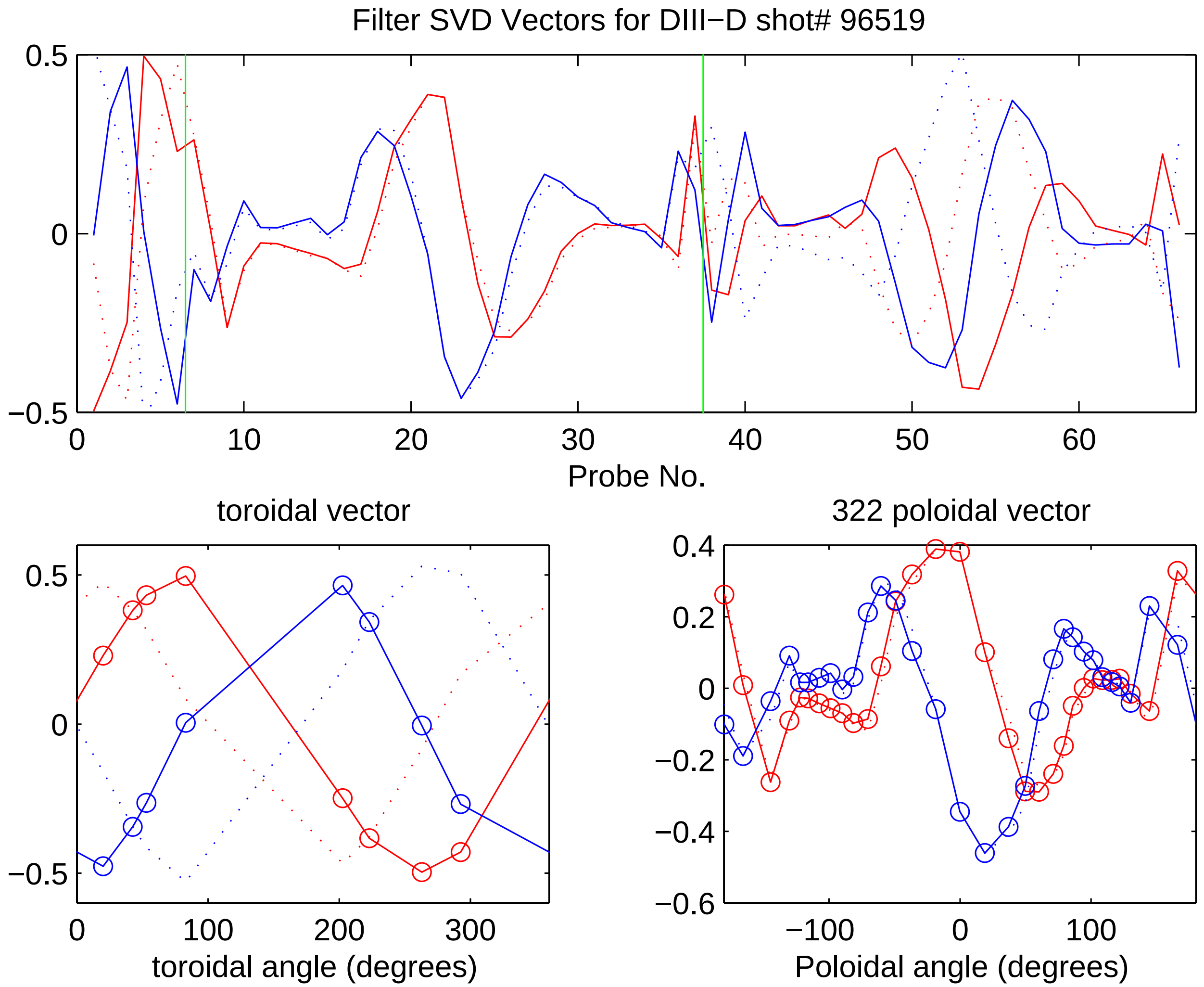
displacement greatly exaggerated for display

VACUUM PREDICTIONS OF RWM MIRNOV SIGNALS IN DIII-D



Solid line = VACUUM predictions at DIII-D Wall
Dotted Line = GATO predictions at plasma surface

COMPLETE MATCHED FILTER VECTORS



Solid Lines: two LH helicity matched filter vectors
Dotted Lines: two RH helicity matched filter vectors

Matched Filter Enables RWM Estimation from Toroidal and Poloidal Mirnov Probe Signals

- Matched filter vectors Vs and Vc (analogous to Fourier sin and cos components) can be applied as direct vector dot-product or with generalized inverse (to allow explicit exclusion of selected m=0 equilibrium change vectors):

$$\begin{bmatrix} a_s(t) \\ a_c(t) \end{bmatrix} = \begin{bmatrix} V_s^T \\ V_c^T \end{bmatrix} \vec{B}_{Mirnov}(t) \text{ or } \begin{bmatrix} a_s(t) \\ a_c(t) \\ \vec{a}_{null} \end{bmatrix} = \begin{bmatrix} V_s & V_c & \begin{pmatrix} equilibrium \\ vectors \end{pmatrix} \end{bmatrix}^{-1} \vec{B}_{Mirnov}(t)$$

- EFIT equilibrium current distributions used to calculate the equilibrium change vectors for the following:

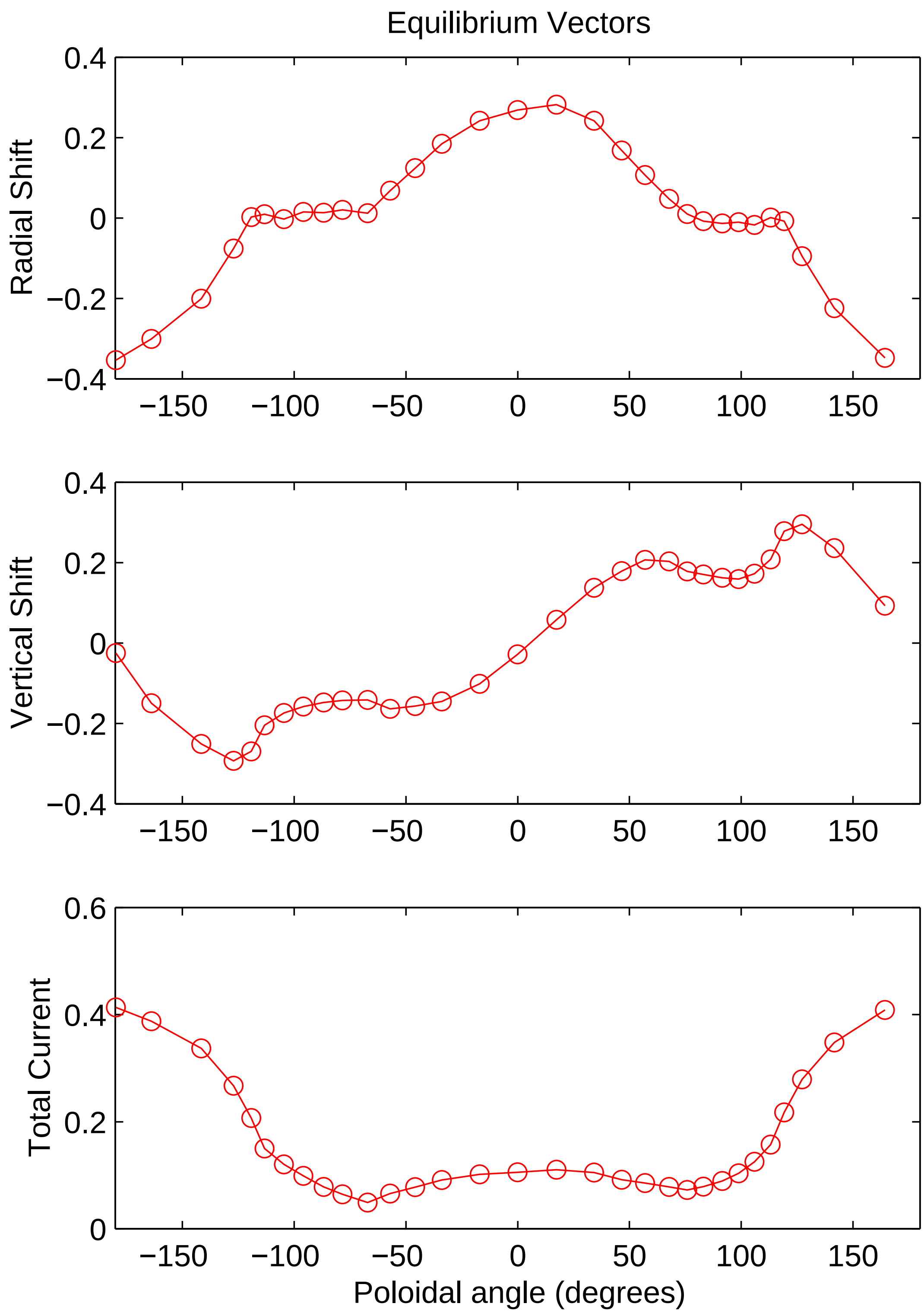
  $\rightarrow$ radial plasma shift

  $\rightarrow$ vertical plasma shift

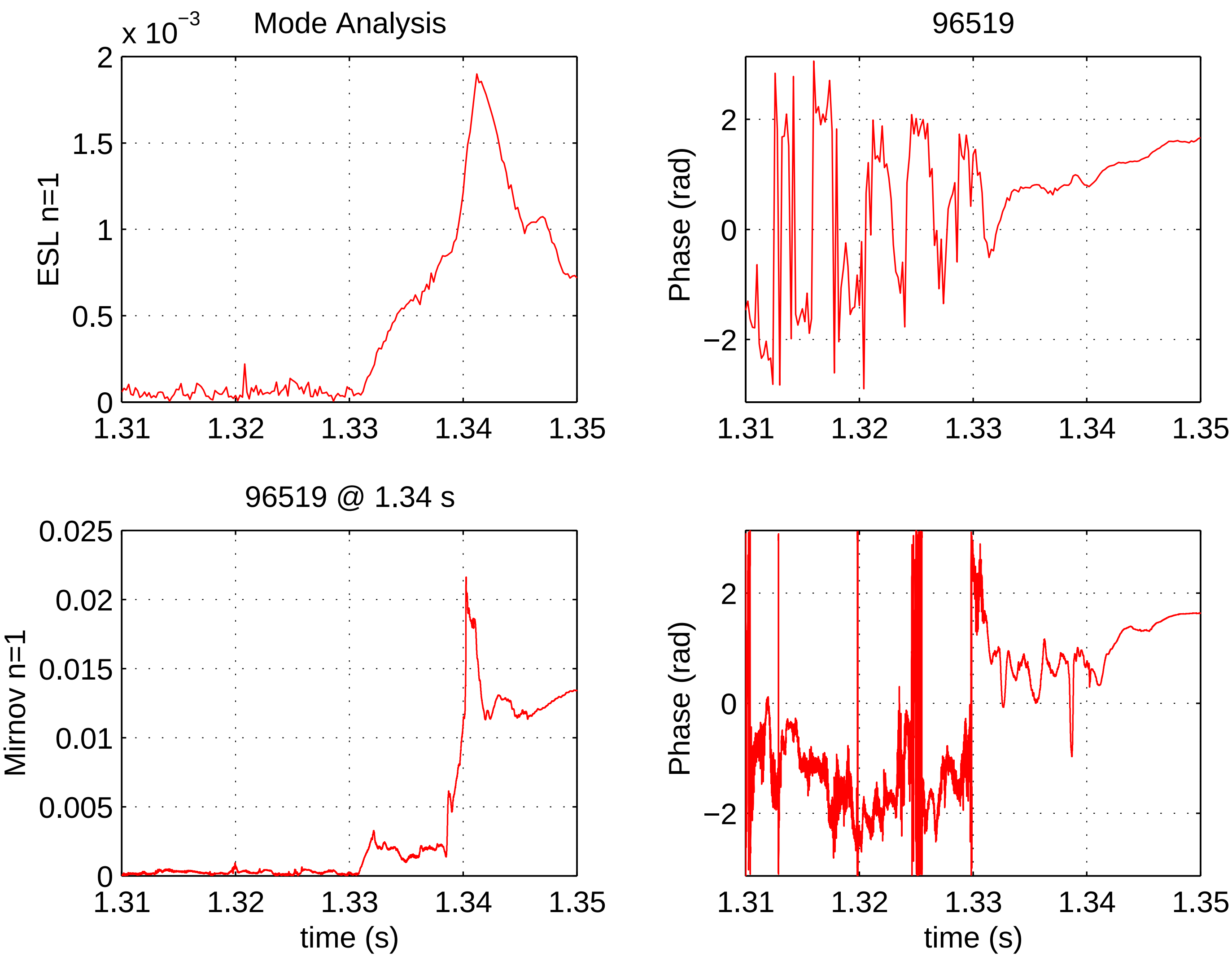
  $\rightarrow$ change in total plasma current

- Changes in the equilibrium current distribution shape (elongation, etc.) not yet taken into account with equilibrium vectors

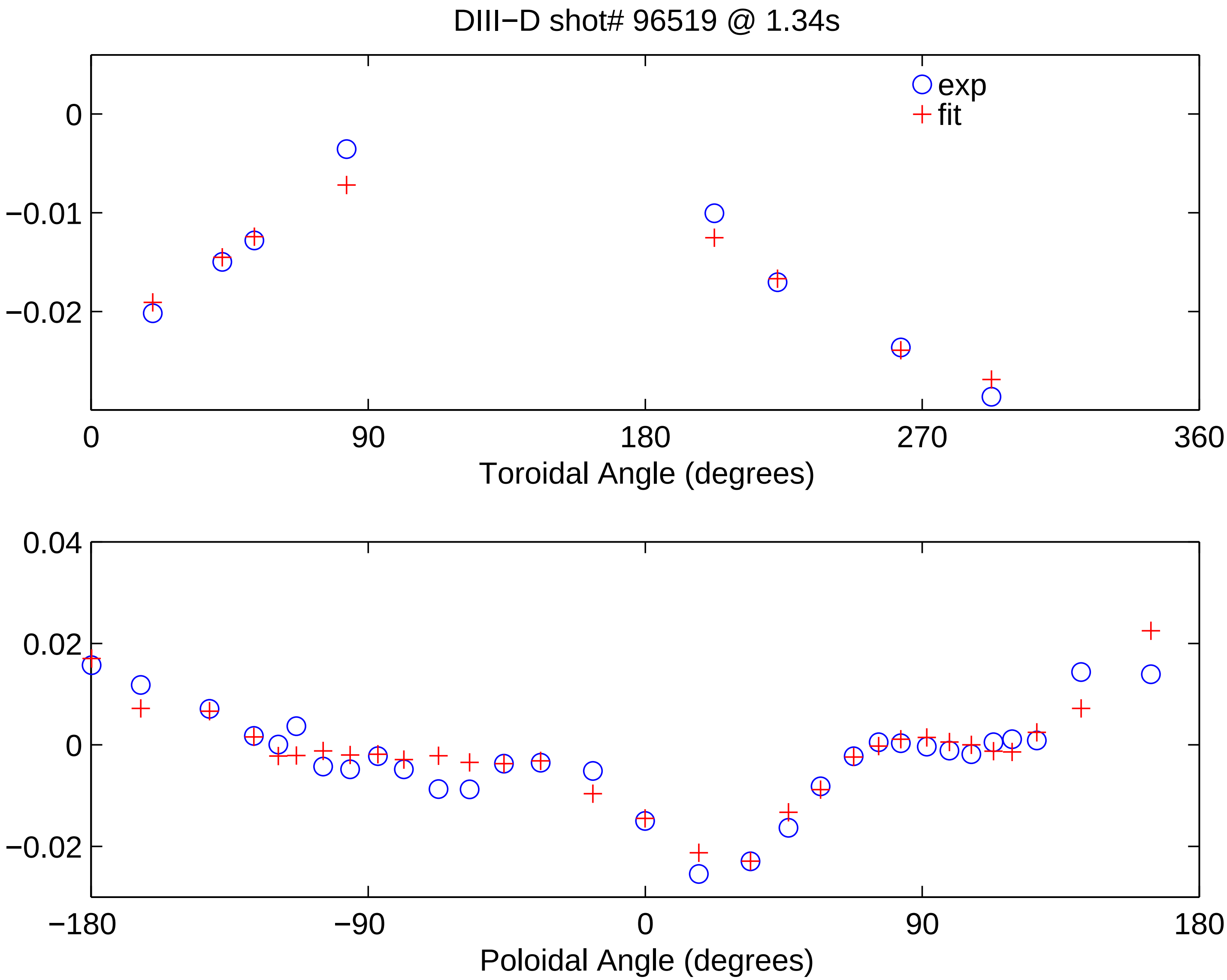
EQUILIBRIUM VECTORS



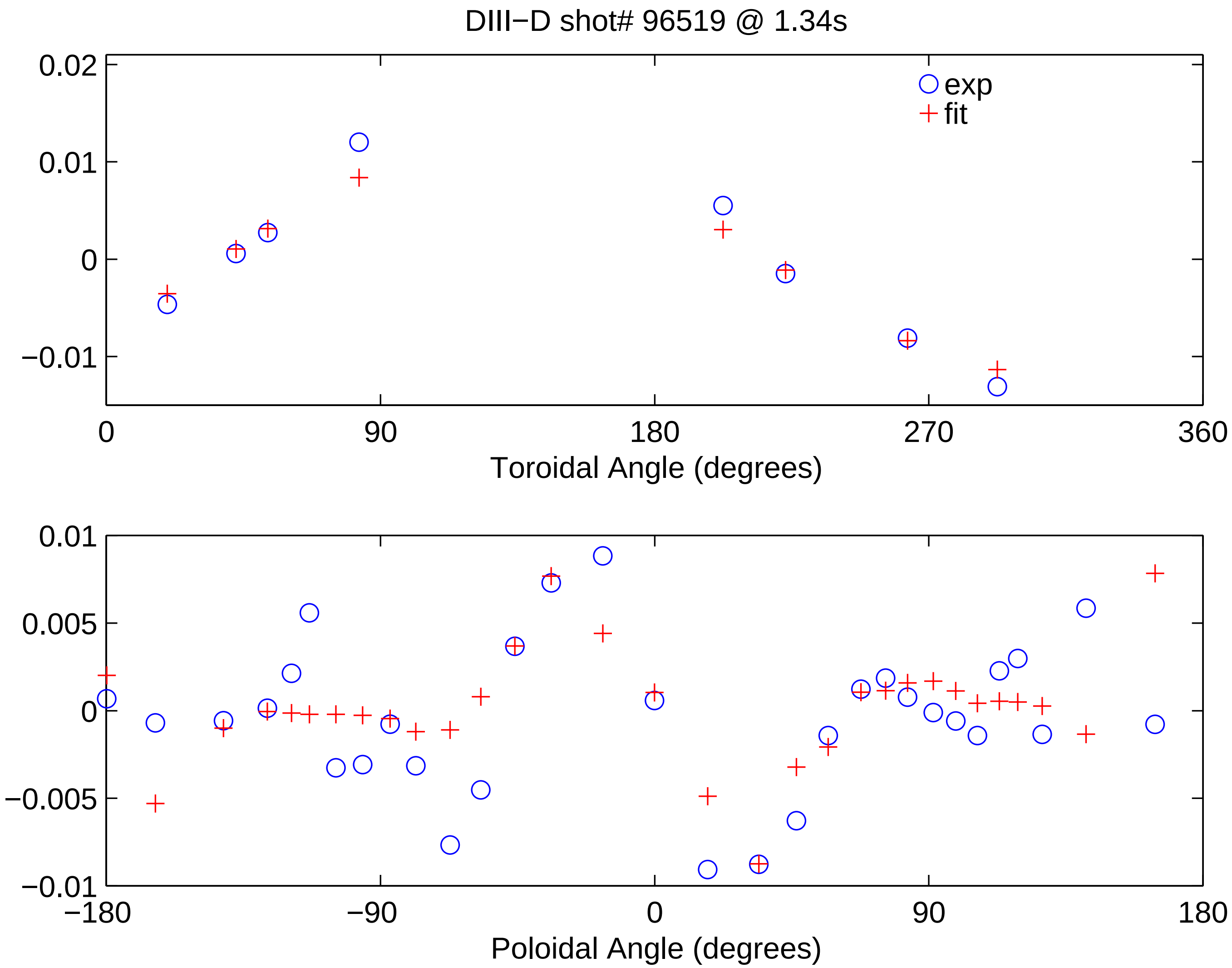
COMPARISON OF EXTERNAL SADDLE LOOP n=1 AND MIRNOV PROBE MATCHED FILTER ANALYSIS



MATCHED FILTER FITS EXPERIMENTAL DATA WELL



Reconstruction With Equilibrium Fit Removed Shows Mode Structure



Requirements for RWM Real-Time Detection

- Commercial Off-the-Shelf (COTS) components
- Compatibility with ongoing DIII-D Plasma Control System (PCS) upgrade

  → same processor (DEC Alpha)

  → same operating system (Linux)

  → same programming language (C)
- Detection time should be less than 1/5 of the maximum growth rate ~400μs

  → Mode Estimation Calculations (<90 μs) after data acquisition and mode control calculation/execution overhead
- This detection speed should be achievable using off-line calculated matched filter vectors for the expected plasma equilibrium

  → equilibrium changes can be accounted for using real-time EFIT and vector parameterization vs. equilibrium parameters (e.g. elongation)

- Data Acquisition Requirements
  - → Sampling Rate: 1 MHz, fast enough for accurate numerical integration
  - → Total Channels: initially 32 but expandable up to 64
  - → Total Memory: 1.28 GB RAM (16bits@1MHz x 10s discharge = 20 MB per channel) maximum, plus memory for calculations and integrated data channels
- Digitizers will be placed on same PCI bus as processor to minimize data acquisition delays by avoiding PCS network data flow(25+ μs) and using direct-memory access (DMA)

MAJOR COMPONENTS OF RWM IDENTIFIER

- All components will be chosen to maximize compatibility with PCS upgrade and new PCS data acquisition/communication software.
- **Processor:** DEC Alpha 21264, 667 MHz

  → inexpensive, flexible, fast clock speed

  → 80-100 MB/s PCI bus with Direct-Memory Access (DMA)

  → 3 open PCI bus slots required + 1 ISA/PCI slot for network card

  → 2 GB RAM required for data channels and calculations
- **Operating System:** Linux

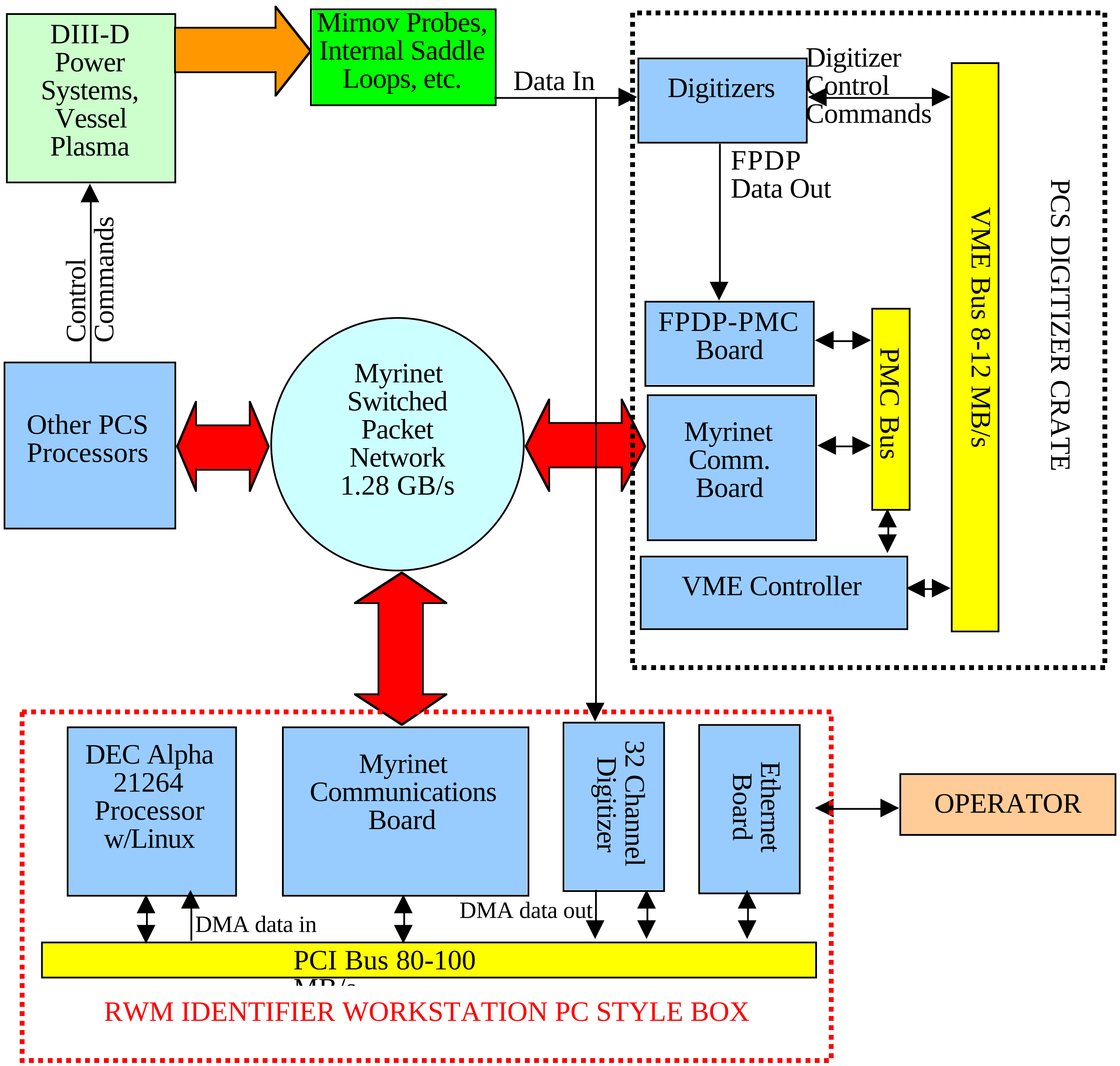
  → inexpensive

  → open-source

  → real-time use with DIII-D under development

- **Inter-processor Communications:** Myrinet switched packet network
  - → 1.28 GB/s, used to send mode amp/phase to PCS, shared with all other PCS channels
  - → onboard Direct-Memory Access (DMA)
  - → open architecture
- **Digitizers (1 or 2):**
  - → 32 channels, anti-aliasing filters
  - → ~1 MHz sampling rate, simultaneously sampled
  - → PCI bus format for high-throughput DMA with processor
- **Diagnostics** Available for Matched Filter Calculations
  - → 41 Mirnov Probes (11 Toroidal array, 31 Poloidal Array)
  - → 30 Internal Saddle Loops (6 on midplane, 24 off midplane)
  - → 6 External Saddle Loops
  - → Possibly SXR, etc. in future
  - → best 32/64 diagnostics for RWM calculations will be used

PRELIMINARY RWM IDENTIFIER DESIGN



SUMMARY

- Mirnov Probes can be used to identify the Resistive Wall Mode
- The matched filter method along with the use of probes at multiple toroidal *and poloidal* positions allows determination of the mode structure, including phase and helicity
- Matched filter method allows the integration of diverse diagnostics (i.e. Mirnov probes, Saddle loops, SXR etc.) into a single mode identification algorithm.
- Real-time mode identification (< 400 μs) should be possible using commercial-off-the-shelf (COTS) components incorporated into the DIII-D Plasma Control System (PCS) Upgrade
- A real-time RWM identification system is proposed for DIII-D consisting primarily of a dedicated DEC Alpha processor and 32 channel digitizer connected by a PCI data bus.
- Initial testing of the real-time RWM identification is planned for March 2001 with the scheduled PCS Upgrade