# CHALLENGES FOR PLASMA DIAGNOSTICS IN A NEXT STEP DEVICE (FIRE)

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The physics program of any next step tokamak such as FIRE sets demands for plasma measurement which are at least as comprehensive as on present tokamaks, with the additional capabilities needed for control of the plasma and for understanding the effects of the alpha-particles. The diagnostic instrumentation must be able to provide the fine spatial and temporal resolution required for the advanced tokamak plasma scenarios. It must also be able to overcome the effects of neutron- and gamma-induced electrical noise in ceramic components or detectors, and fluorescence and absorption in optical components. There are practical engineering issues of minimizing radiation streaming while providing essential diagnostic access to the plasma. Many diagnostics will require components at or close to the first wall, e.g. ceramics and MI cable for magnetic diagnostics and mirrors for optical diagnostics; these components must be mounted to operate, and survive, in fluxes which require special material selection. A better set of diagnostics of alpha-particles than that available for TFTR is essential; it must be qualified well before moving into D-T experiments. A start has been made to assessing the potential implementation of key diagnostics for the FIRE device. The present status is described.

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# Good Measurements are Necessary for Understanding Next-Step Plasmas

- Burning Plasma Physics
  - access, explore and understand fusion-dominated plasmas,
  - nonlinear coupling inherent in a fusion-dominated plasma.
- Advanced Toroidal Physics
  - develop and test physics needed for an attractive MFE reactor,
  - couple with burning plasma physics.
- Boundary Physics and Plasma Technology
  - high particle and heat flux,
  - couple core and divertor,
  - fusion plasma - tritium inventory and helium pumping.

# Aspects of Plasma Diagnostics to achieve Burning Plasma Physics Goals in FIRE

- The measurement quality must enable the physics mission to be met;
  - provide the same quality of data as in best present-day devices (with similar specifications to ITER set),
  - provide new information about the alpha-particles.
- High quality, reliable information on many plasma parameters will be used to provide control signals.
- The neutron radiation environment must be considered in design of the diagnostic system.

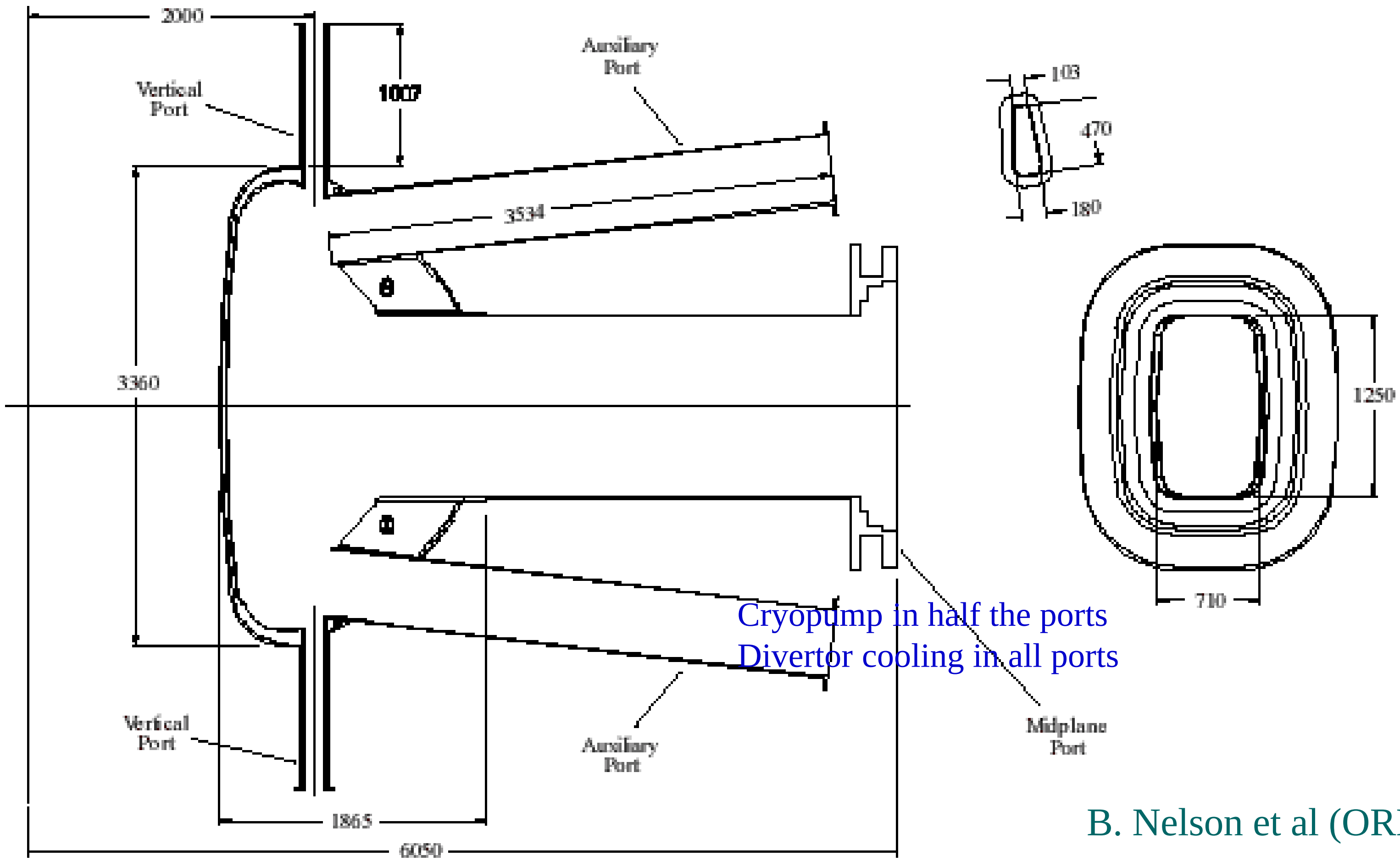
# Examples of Target Plasma Measurement Capability proposed for ITER-FEAT and Relevant for FIRE

| PARAMETER | PARAMETER RANGE | SPATIAL RESOLUTION | TIME RESOLUTION | ACCURACY |
|---|---|---|---|---|
| Plasma current | 0.1 – 17.5 MA | Not applicable | 1 ms | 1% ($I_p$>1 MA) |
| Total neutron flux | $1 \times 10^{14}$ - $1 \times 10^{21}$ n $s^{-1}$ | Integral | 1 ms | 10% |
| Neutron & α-particle source | $1 \times 10^{14}$-$4 \times 10^{18}$ $ns^{-1}m^{-3}$ | a/10 | 1 ms | 10% |
| Divertor surface temperature | 200 - 2500°C | - | 2 ms | 10% |
| Core electron temp-erature profile | 0.5 - 30 keV | a/30 | 10 ms | 10% |
| Edge electron density profile | (0.05 - 3) x $10^{20}$ $m^{-3}$ | 0.5 cm | 10 ms | 5% |
| Radiation profile in main plasma | 0.01 - 1 $MWm^{-3}$ | a/15 | 10 ms | 20% |
| Radiation profile in divertor | ≤100 $MWm^{-3}$ | 5 cm | 10 ms | 30% |

# Simplified List of Measurements for Input to Control Systems

- Fast Plasma Shape and Position Control:
  - Magnetic diagnostics, IR camera, Thomson scattering
- Kinetic Profile Control:
  - Thomson scattering, Interferometer, Reflectometer, ECE, CXRS ($T_i$ and He-ash), neutrons,
- Current Profile, Rotation Control:
  - Magnetic diagnostics, Thomson scattering, MSE, CXRS
- Optimized divertor operation:
  - Interferometry, IR camera, spectroscopy
- Fueling control:
  - D,T monitoring (edge good enough?)
- Disruption prevention (first-wall/ divertor protection):
  - Magnetic diagnostics ($\beta$; MHD), kinetic profile set.

# Dimensions of FIRE Vacuum Vessel Ports

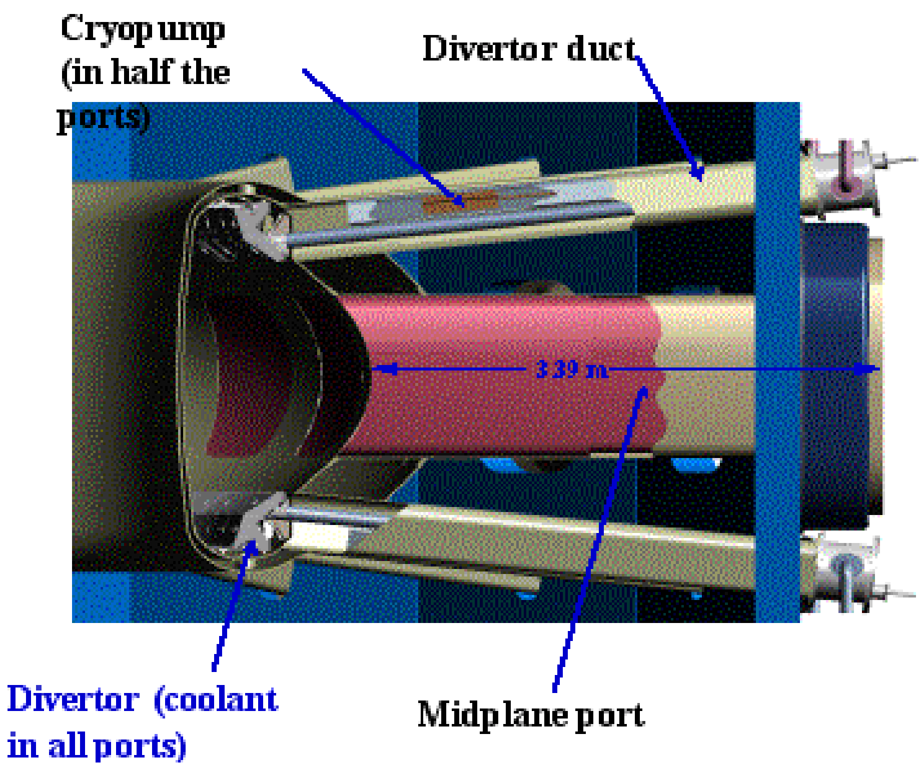



Cryopump in half the ports
Divertor cooling in all ports

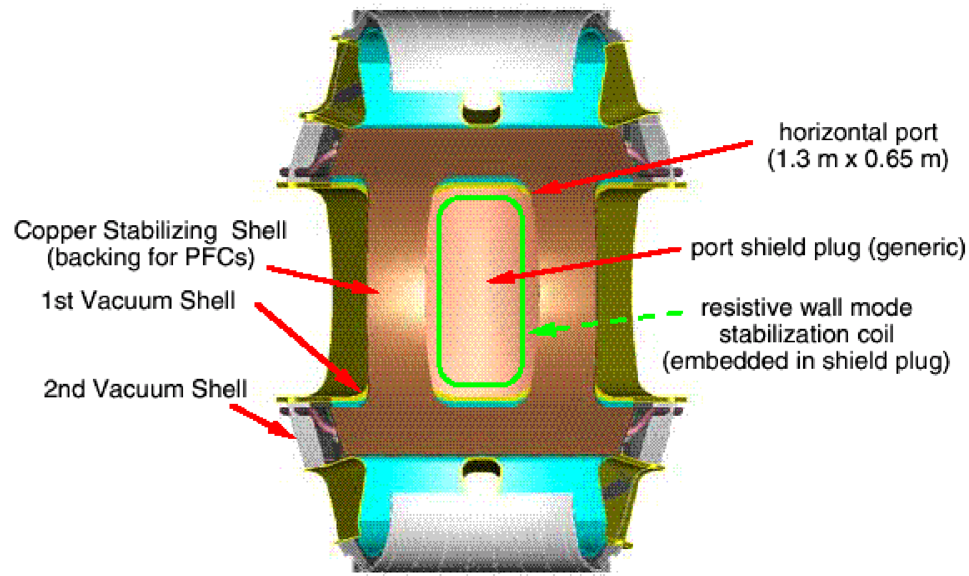
50 x 150 port

B. Nelson et al (ORNL)

# FIRE Port Configuration

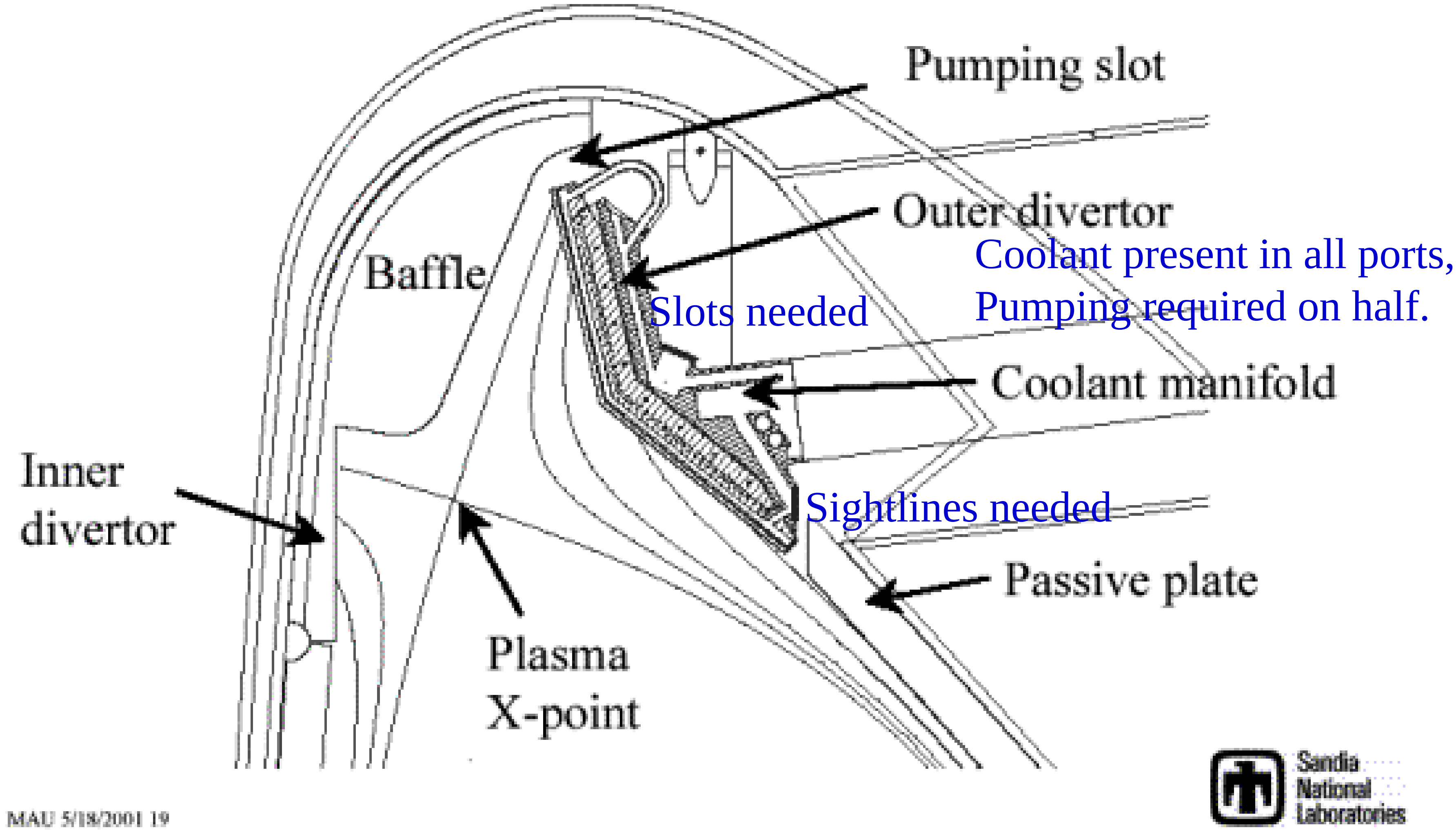



Main port configuration




View of horizontal port plug looking from plasma side

# Access to Divertor is Constrained: Slots Required between Brushes, between Outer Divertor and Passive Plate

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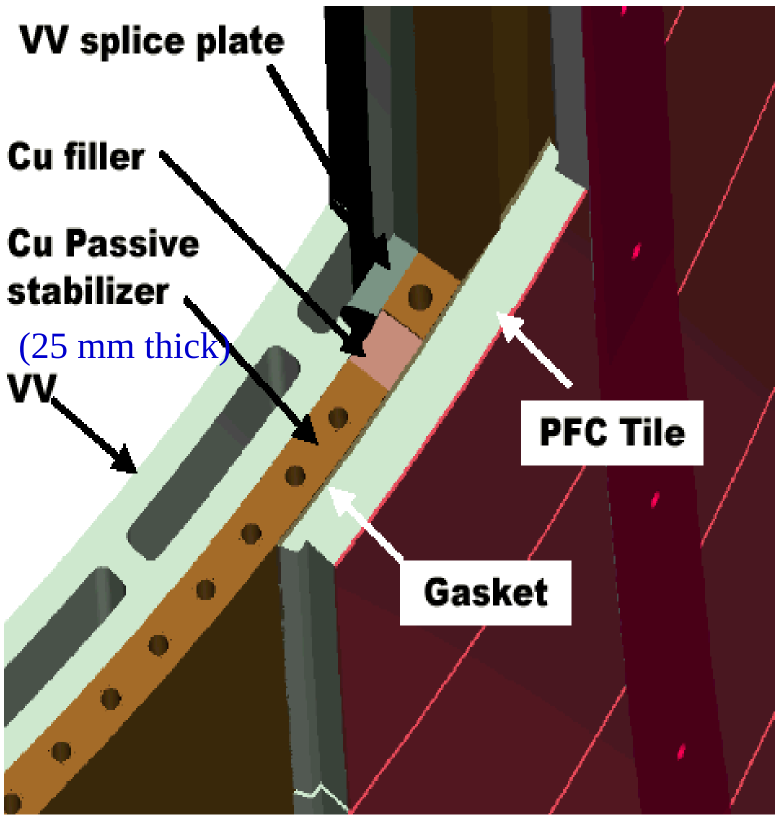
# Mounting Space for Diagnostics is Limited




Inner Wall (no slots shown)

- Magnetic diagnostics will have to be incorporated into slots in passive stabilizer and tiles.
- Position coils, Rogowski coils, diamagnetic loops and high-frequency Mirnov coils to be integrated.
  - Wiring will cross at several locations.
  - Mineral-insulated cable and electrical connections are concern.
- Radiation impact on conductivity of insulators and through nuclear heating.
- Maintenance complexity has to be considered in design.

# Design Issues in Diagnostic Integration

- It is essential to carry diagnostic design along with other in-vessel system designs:
  - Magnetic diagnostics have specific integration needs with the first wall.
  - Sightlines through and past the divertor must be assured (3cm poloidal slot possible by removing row of tungsten brushes; >5cm toroidal gap possible between outer divertor and passive tiles; 5 cm x 15 cm slot in outer divertor to match top port sought.
  - Diagnostic "plugs" for all ports assure diagnostic operation and limit external radiation levels.
  - Potential interferences with water piping for divertor and first wall.

# The Impact of the Neutron (Gamma) Environment

- Special design and materials to be used for in-vessel systems
  - Also prevents the use of many present-day diagnostic components.
- Requirement for thick shielding, penetrated by complex labyrinths.
- Constraint on the use of optical components, especially lenses and fiberoptics.

# Radiation Environment at Selected FIRE locations

| 200 MW DT Pulses | Total Neutron Flux ($n/cm^2s$) | Fast Neutron Flux (E>0.1MeV) ($n/cm^2s$) | Total Gamma Flux ($g/cm^2s$) | Si -Dose Rate (Gy/s) | Total Cumulative Lifetime Dose * (Gy) |
|---|---|---|---|---|---|
| First Wall (Inboard Midplane) | $1.54x10^{15}$ | $1.05x10^{15}$ | $7.56x10^{14}$ | $1.17x10^{4}$ | $3.09x10^{8}$ |
| Behind Tiles (Inboard Midplane) | $1.26x10^{15}$ | $8.00x10^{14}$ | $6.68x10^{14}$ | $7.72x10^{3}$ | $2.08x10^{8}$ |
| Behind TF Coils (Outboard Midplane) | $9.52x10^{8}$ | $3.68x10^{8}$ | $1.41x10^{8}$ | $1.2x10^{-3}$ | 31.1 |
| Behind 1.1 m Port Plug (Outboard Midplane) | $1.01x10^{8}$ | $3.99x10^{7}$ | $7.91x10^{7}$ | $6x10^{-4}$ | 15.1 |
| Behind TF Coils at Top/Bottom | $2.50x10^{10}$ | $9.46x10^{9}$ | $7.71x10^{9}$ | $6.2x10^{-2}$ | $1.63x10^{3}$ |

Mohamed Sawan (U. Wisconsin)

* 5TJ DT and 0.5 TJ DD

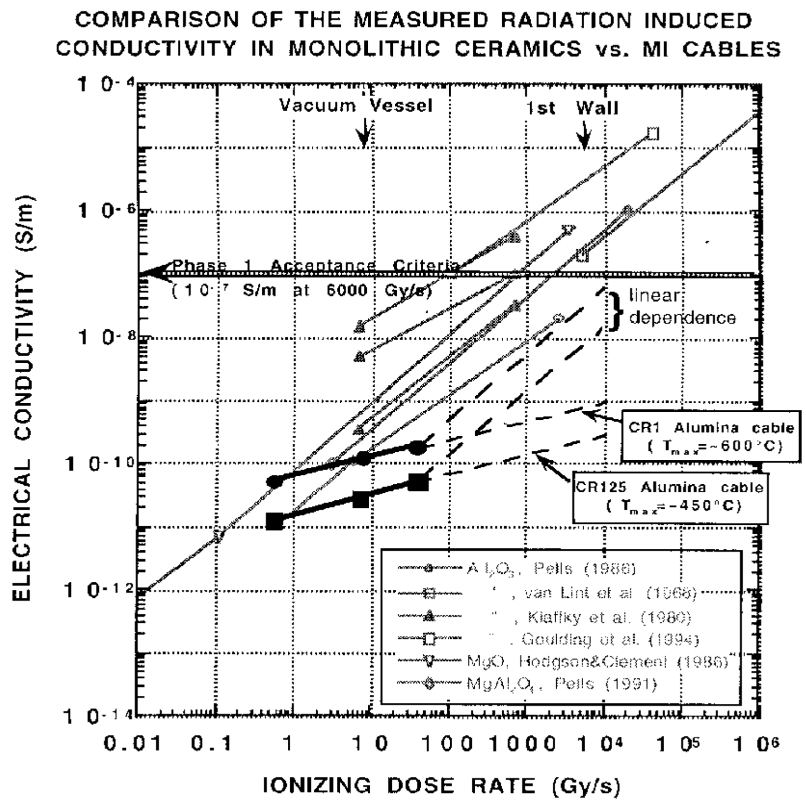
# Radiation Effects on Diagnostic Components

- **Diagnostic Component** **Worst Radiation Problem**

- **Ceramics (and Detectors)** **Electrical (RIC, RIED, RIEMF)**
  - **RIC, and potentially RIEMF, are most severe issue for ceramics and MI cable used in magnetic diagnostics**
- **Fiberoptics (and Windows)** **Absorption, Luminescence, Numerical aperture**
  - **Developments of new doped fibers in progress for reducing absorption,**
  - **Luminescence problem for low-light level signals.**
- **Mirrors** **Mechanical + Neutrals in Surface Modification (near first wall)**
  - **Studies of surface damage impact and of surface preparations in progress.**

# Magnetic Diagnostics: Issues

- Loops, coils, MI-cable must be inside vacuum vessel,
- Maximally unfriendly environment; RIC and RIEMF, temperature, neutral particles,
- Very limited space behind tiles;
  - need grooves in tiles, cladding,
  - potential poloidal locations at vacuum vessel segment boundaries
- Renew R&D program on radiation impact on ceramics/MI cable.

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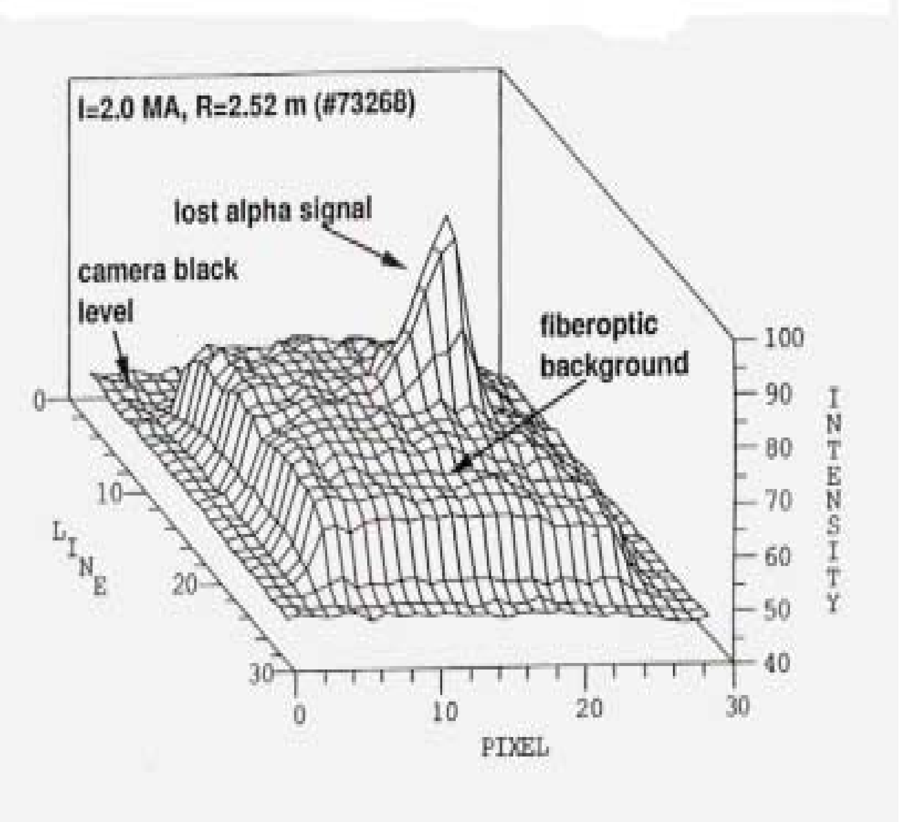
# Luminescence (and absorption) Impact on Measurement

- Lost-α diagnostic on TFTR with fiberoptic outside vacuum vessel.
- TFTR shot at 5MW ($5x10^{-2}$ $MW/m^2$ at first wall.
- Dose at front end of fiber (in shielding)

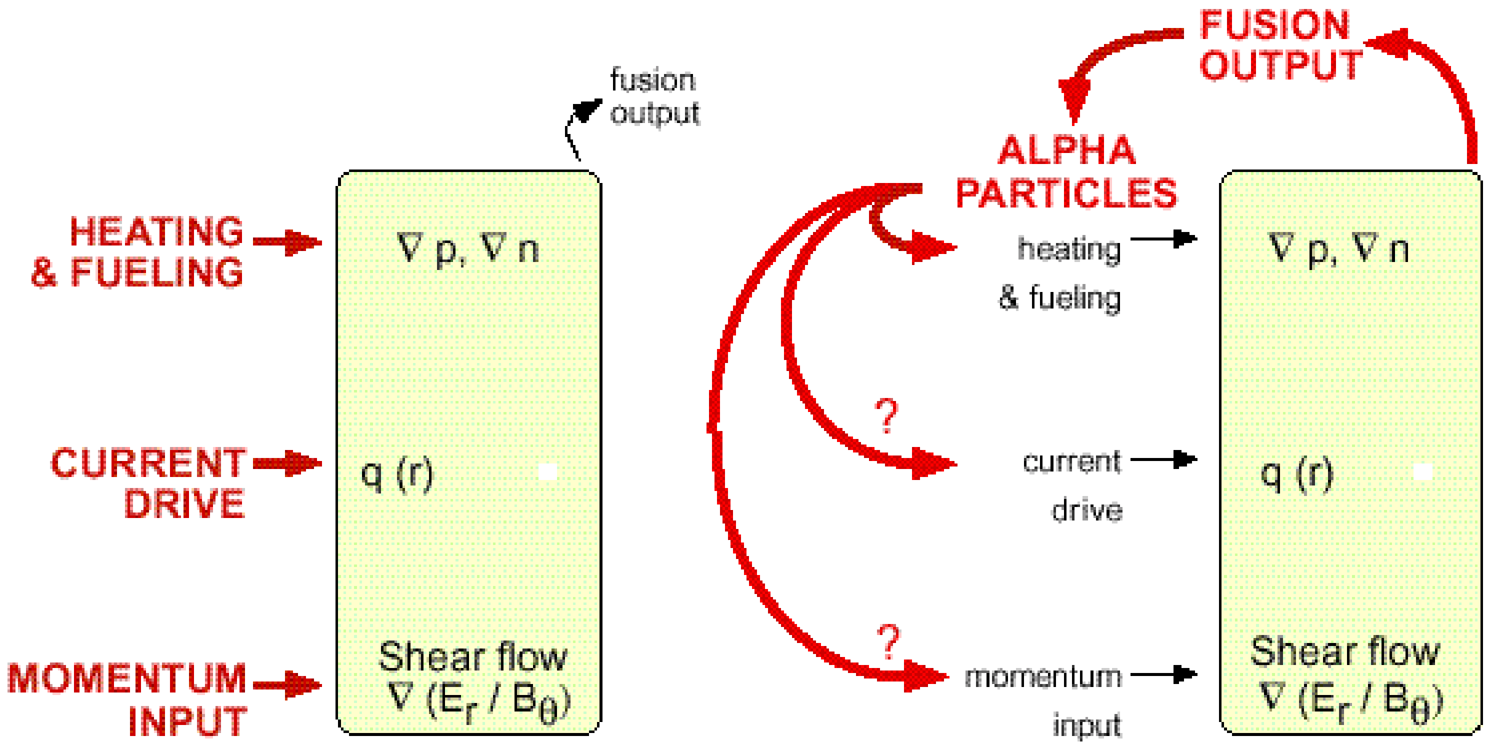
  ~ 30 Gy/s.




Signal observed from scintillator/fiberoptic during TFTR D-T (D. Darrow)

# Measurement of the internal energy source essential as we move from externally-driven to internally-driven plasmas

Present Situation -------> **(JET)** -------> Burning Plasma Device

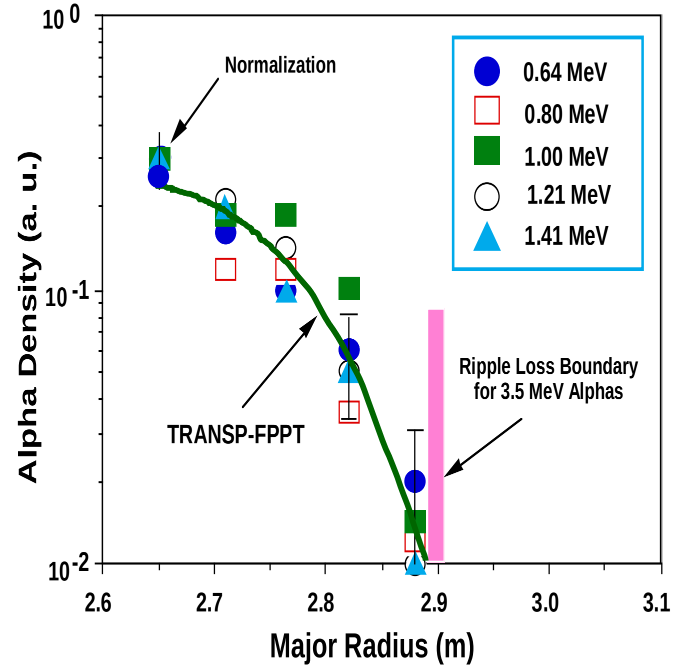



R. Nazikian

# Possible Diagnostics for Alpha-Particle Physics

- Confined α-particle diagnostics (Development required)
  - α-CHERS,
  - Pellet charge-exchange (PCX) for radial distribution,
  - Collective scattering (μwave offers best spatial distribution (& rcfraction), CO2, FIR?),
  - Knock-on neutron,
  - New confined-α detector???
- Escaping fast-ion detectors and IR camera,
- High-frequency Mirnov coils, reflectometry for turbulence studies.

TFTR




- PCX measurement of the trapped alpha density profile in an MHD-quiescent supershot.
- Only the trapped alphas born inside the stochastic ripple boundary for $E_\alpha$ = 3.5 MeV are confined and can slow down to produce the measured profiles.

Fisher et al.

# DRAFT FIRE R&D Proposals

- Irradiation Tests of Materials
  - Evaluation of radiation-induced conductivity (RIC) in selected ceramics and MI cable to define design materials
    - Test coil ceramics to FIRE first-wall flux levels and temperatures,
    - Test MI cable in realistic configurations.
  - Determine cause of radiation-induced emf (RIEMF) with MI cables to prevent signal pollution by significant DC offsets (with EU and Japan).
  - Evaluation of electrical connection techniques for remote handling and insulation properties.
  - Test selected optical fibers for performance in realistic radiation environment at relatively low light-signal levels (with EU, Japan and Russia).

- Development of New or Improved Diagnostic Techniques
  - Develop an Intense Diagnostic Neutral Beam: specification ~125 keV/amu, $1x10^6$ $A/m^2$ in a cross-section of 0.2m x 0.2m at the plasma edge for 1 μsec at 30 Hz repetition rate (LANL started development for ITER R&D).
  - Complete demonstration of fast-wave reflectometry for measuring hydrogen isotope ratios in the core (continuing work started by GA for ITER).
  - Extend the operational range of Faraday-cup based and scintillator-based escaping-α diagnostics to FIRE parameters (U.Colorado/PPPL program through JET).
  - Seek new technique for measuring the confined fast-alphas.

# DRAFT FIRE R&D Proposals (continued)

- Development of New Components/Techniques
  - Continue development of small radiation-hard high-temperature magnetic probes based on integrated-circuit manufacturing techniques.
  - Develop a prototype “plug” to incorporate required tolerances, alignments, assurance of ground isolation, actuation of shutters, etc.
  - Evaluate metallic mirror performance and effects on reflectivity of neutral particle bombardment and nearby erosion (ongoing ITER R&D activity).
  - Develop in-vacuo electrical connection techniques for reliability, remote handling and insulation properties

# Diagnostics proposed for FIRE (1)

| Physics Parameter | Control | Diagnostic Set | Issues and Comments |
|---|---|---|---|
| **Magnetic Measurements** | | | |
| Plasma current | √ | Rogowski Coils | All magnetics inside vacuum vessel |
| Plasma shape and position | √ | Flux/voltage loops | Very high radiation environment and high |
| Shape, position & MHD | √ | Saddle coils (inc. locked-mode) | temperature apply for all magnetics |
| | √ | Discrete Br, Bz coils | Very little space behind first wall/divertor |
| Plasma pressure | √ | Diamagnetic loops | |
| Disruption-induced currents | √ | Halo current sensors | |
| | | | |
| **Current Density Profiles** | | | |
| Current density for most of profile | √ | Motional Stark effect | Requires neutral beam. Two views may give Er |
| | | FIR polarimetry | Most sightlines radial; poor coverage in radial plane |
| Current density in edge | | Li-beam polarimetry | Requires Lithium beam; integration issue |
| | | | |
| **Electron Density** | | | |
| Core electron density profile | √ | Thomson scattering | Tangential laser, imaging view required by small plasma size |
| | | FIR multichannel interferometer/polarimeter | Most sightlines radial; poor coverage in radial plane; tangential polarimeter |
| X-point/divertor density profiles | | Thomson scattering | Design integration into side ports with divertor/first wall |
| Edge, transp. boundary profile | | mm-wave reflectometer | |
| Edge density profile | | Fast-moving probe | |
| Divertor density variation along separatrix | | Multichannel interferometer | Complex integration with divertor/baffle; Dynamic range may make this impossible |
| Divertor plate density | | Fixed probes | RIED may affect probe insulation |

# Diagnostics proposed for FIRE (2)

| Physics Parameter | Control | Diagnostic Set | Issues and Comments |
|---|---|---|---|
| **Electron Temperature** | | | |
| Core electron temperature profile | √ | Thomson scattering | Tangential laser, imaging view required by small plasma size |
| | | ECE heterodyne radiometer | |
| | | ECE Michelson interferometer | Provides best calibration for ECE diagnostice |
| X-point/divertor temperature profiles | | Thomson scattering | Design integration into side portswith divertor/first wall |
| Edge temperature profile | | Fast-moving probe | |
| Divertor plate electron temp. | | Fixed probes | RIED may affect probe insulation |
| | | | |
| **Ion Temperature** | | | |
| Core ion temperature profile | √ | Charge exchange spectroscopy | Requires neutral beam |
| | | Imaging x-ray crystal spect. | Full radial coverage would require close-in curved crystal; detector noise issue? |
| | | Neutron camera spectroscopy | Full coverage difficult; spatial res. Poor |
| Divertor ion temperature | | UV spectroscopy | |
| | | | |
| **Plasma Rotation** | | | |
| Core rotation profile | √ | Charge exchange spectroscopy | Requires neutral beam: balanced views for $v\theta$ needed |
| | | Imaging x-ray crystal spect. | Full radial coverage would require close-in curved crystal; detector noise issue? |
| **Relative Isotope Concentration** | | | |
| Density of D and T concentrations in core | √ | Charge-exchange spectroscopy | Requires neutral beam |
| | | Neutron spectroscopy | Can DD neutrons be discriminated from DT and TT neutrons? |

# Diagnostics proposed for FIRE (3)

| Physics Parameter | Control | Diagnostic Set | Issues and Comments |
|---|---|---|---|
| **Radiation** | | | |
| Zeff,visible bremsstrahlung | √ | Visible bremsstrahlung array | |
| Core hydrogen isotopes, low-Z impurities | | Visible filterscopes | |
| Divertor isotopes and low-Z impurities | √ | Divertor filterscopes | |
| Core low-Z impurities | | Visible survey spectrometer | |
| | | UV survey spectrometer | |
| Divertor low-Z impurities and detachment | √ | Multichord visible spectrometer | Very little space to develop sightlines |
| High-Z impurities | | X-ray pulse height analysis | Single sightline, detector noise |
| Divertor impurities | | UV spectrometer | Access issue into divertors |
| Total radiation profile | | Bolometer arrays | Mounting and radiation-hardness of bolometers are challenges |
| Total light image | | Visible TV imaging | |
| | | | |
| **MHD and Fluctuations** | | | |
| Low-frequency MHD | √ | Discrete Br, Bz coils | Very little space behind first wall/divertor |
| | | Saddle coil for locked-mode | |
| | | Neutron fluctuation dets. | |
| High-frequency MHD, TAE, etc. | √ | High-frequency Mirnov coils | HF-coils behind tile-gaps, little space |
| Core density fluctuations | | Mm-wave reflectometers | |
| | | Beam emission spectroscopy | Requires neutral beam |
| Core electron temp. fluctuations | | ECE grating polychromators | |
| | | | |
| **Neutron Measurements** | | | |
| Calibrated neutron flux | √ | Epithermal neutron detectors | Calibration difficult with significant shielding |
| Neutron energy spectra | | Multichannel neutron camera | Difficult to get wide spatial coverage |

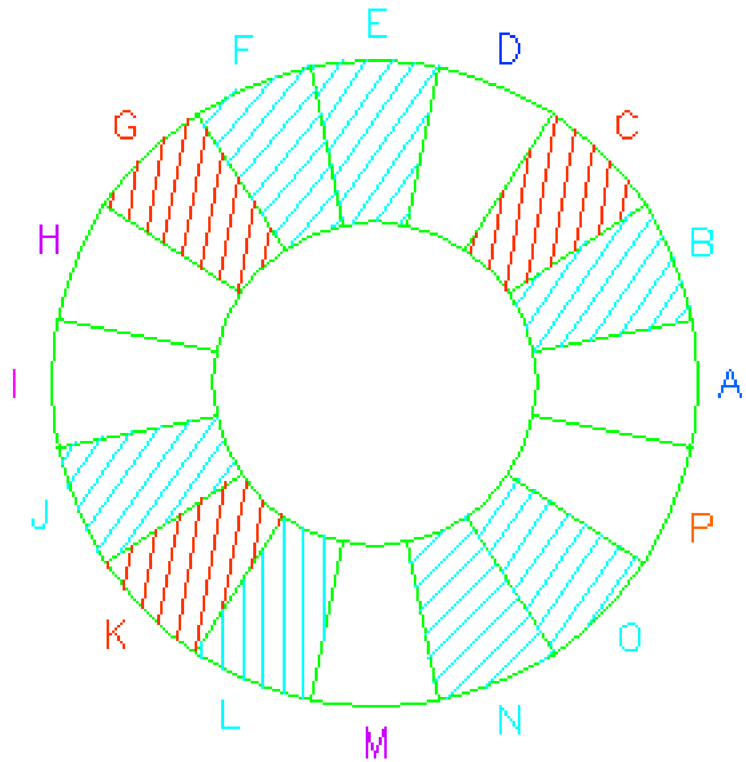
# Diagnostics proposed for FIRE (4)

| Physics Parameter | Control | Diagnostic Set | Issues and Comments |
|---|---|---|---|
| **Alpha-particle Measurements** | | | |
| Escaping alpha-particles/fast-ions | | Faraday cups/scintillators at first wall | Much development needed to handle heat loads and signal transmission |
| | | IR TV imaging | Only gives information about total loss location |
| Confined thermalizing alphas/spatial distribution | | $\alpha$-CHERS | Requires neutral beam, very high throughput optics |
| Confined alpha-particles' energy distribution | | Collective scattering | Need development to optimize wavelength/ spatial resolution; assume mm-wave |
| Spatial redistribution of alphas | | Li-Pellet charge exchange | Needs high-energy repetitive impurity pellet; very difficult access |
| Volume-average alpha-particle energy spectrum | | Knock-on bubble-chamber neutron detectors | Development of detectors required |
| | | Neutron spectrometer | Evaluates knock-on tail above 14 MeV |
| | | | |
| **Runaway electrons** | | | |
| Start-up runaways | √ | Hard x-ray detectors | Inside vacuum vessel; survival with necessary sightlines is issue |
| Disruption potential runaways | √ | Synchrotron rad. detection | Far-forward light cone must be detected |
| | | | |
| **Divertor Pumping Performance** | | | |
| Pressure in divertor gas-box | | ASDEX-type pressure gauges | Concern about RIED affecting operation |
| Helium removed to divertor | | Penning spectroscopy | |

# Diagnostics proposed for FIRE (5)

| Physics Parameter | Control | Diagnostic Set | Issues and Comments |
|---|---|---|---|
| **Machine Operation Support** | | | |
| Vacuum base pressure | √ | Torus ion gauges | On main pumping duct |
| Vacuum quality | | Residual gas analyzer | On main pumping duct |
| Vacuum vessel illumination | | Insertable lamps | To enable initial level of internal inspection |
| | | | |
| **Surface Temperature** | | | |
| First-wall/RF antenna temp. | √ | IR TV imaging | |
| Divertor plate temperatures and detachment | √ | IR TV imaging | |
| | | Thermocouples | |
| | | | |
| **Neutral particle sources for diagnostics** | | | |
| Neutral particle source for core spectroscopy | indirect | Diagnostic neutral beam | Pulsed high power beam required for penetration at ~ 150 keV/amu |
| Lithium source for polarimetry | | High current lithium beam | In development for DIII-D (JET?) |
| Lithium pellet target for confined alpha spatial dist. | | High velocity lithium pellet injector | > 5 km/s, ~10 Hz development needed |

# FIRE Diagnostics:
## Top Port Assignments




A:

B: Magnetics Wiring

C: Illumination

D:

E: Probe Wiring

F: Magnetics Wiring

G: Illumination

H:

I:

J: Magnetics Wiring

K: Illumination

L: Probe Wiring

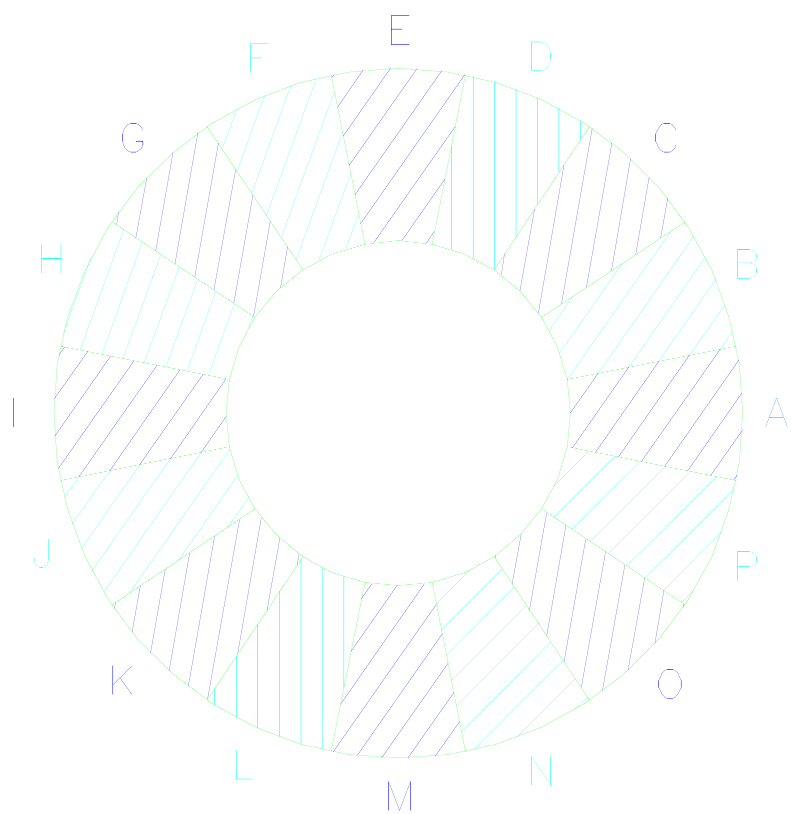
M:

N: Magnetics Wiring

O: FIR Interferometer/Polarimeter

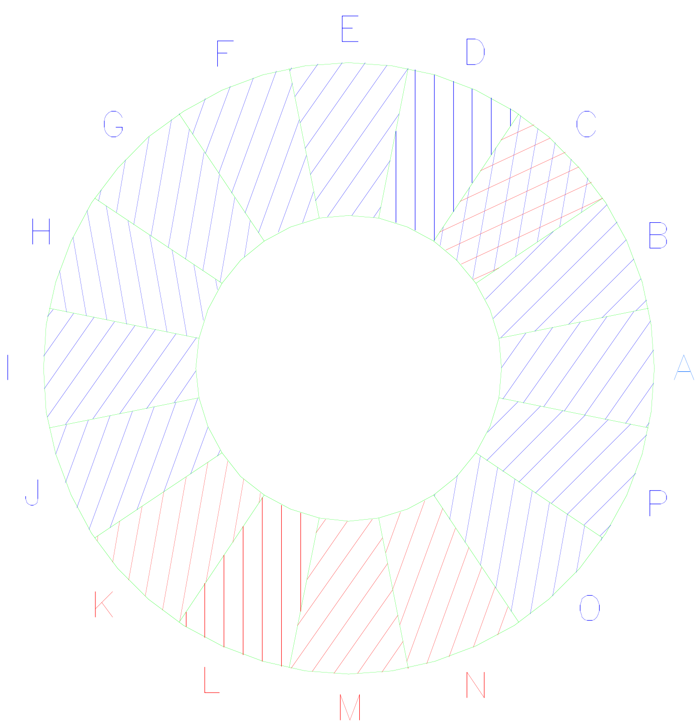
P:

# FIRE Diagnostics:
# Outer Upper Port Assignments




A: Divertor IR TV,
IR TV,
Penning Gauge
B: Divertor Pump/Water
C: Multichord Visible Spectrometer,
Bolometer Array
D: Divertor Pump/Water
E: Divertor IR TV,
IR TV,
Thermocouple Wiring
F: Divertor Pump/Water
G: ASDEX Gauges,
Divertor UV Spectrometer
H: Divertor Pump/Water
I: Rotation CXRS,
Divertor IR TV,
Divertor TV
J: Divertor Pump/Water
K: Bolometer Array,
Separatrix Interferometer
L: Divertor Pump/Water
M: Divertor IR TV,
Divertor TV,
Thermocouple Wiring
N: Divertor Pump/Water
O: Divertor Filterscope,
ASDEX Gauges
P: Divertor Pump/Water

# FIRE Diagnostics:
# Radial Port Assignments

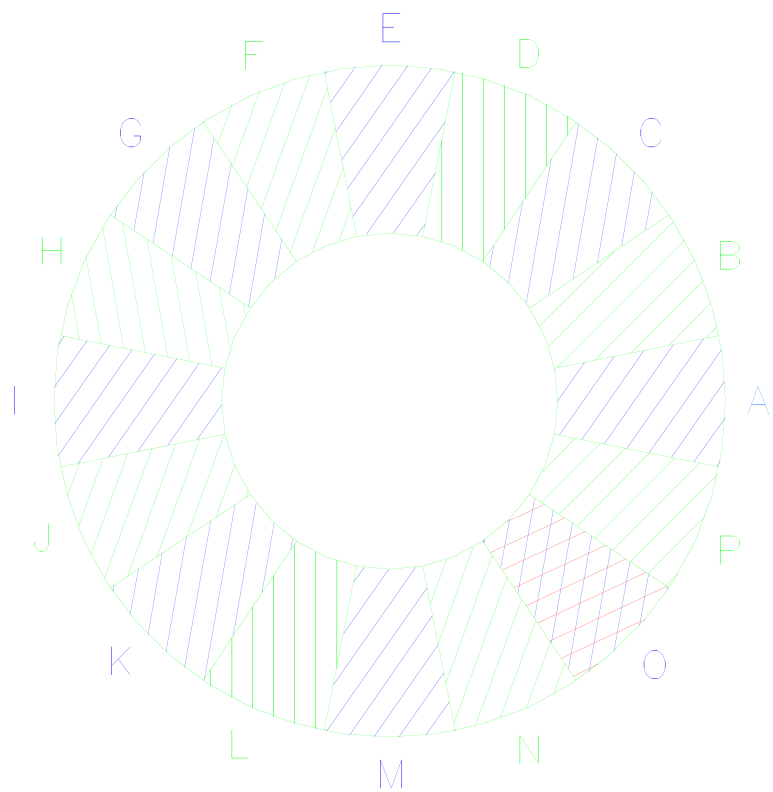



Blue: Diagnostics Components
Orange: Diagnostics-provided Services
Red: Auxiliary Systems
Green: Services

A: MSE (2),
CXRS (2),
Beam Emission Spectroscopy,
Lost-α System
B: Diagnostic Neutral Beam
C: Pump Duct,
Pellet Injector,
Ion Gauges,
RGA
D: Visible Survey Spectrometer,
Visible Filterscopes,
Visible Bremsstrahlung,
UV Survey Spectrometer
E: X-ray Crystal Spectrometer,
X-ray PHA,
Hard X-ray Detector
TVTS Dump
F: TVTS Detection
Plasma TV,
IR TV,
MM-wave Receiver
G: Neutron Camera,
Neutron Fluctuation Detectors
Bolometer Array
H: ECE Systems,
Reflectometers,
MM-wave Collective Scattering Source and Receiver,
Magnetics Wiring

I: TVTS Detection,
Plasma TV,
IRTV
Soft X-ray Array
J: TVTS Laser,
Pellet Charge Exchange,
Li-Pellet Injector,
Hard X-ray Detector
Synchrotron Rad. Detector
K: ICRF Launcher
L: ICRF Launcher
M: ICRF Launcher
N: ICRF Launcher
O: FIR Interferometer/ Polarimeter,
Plasma TV,
IR TV,
Bolometer Array
P: MSE (1),
CXRS (1),
α-CHERS

# FIRE Diagnostics:
# Outer Lower Port Assignments

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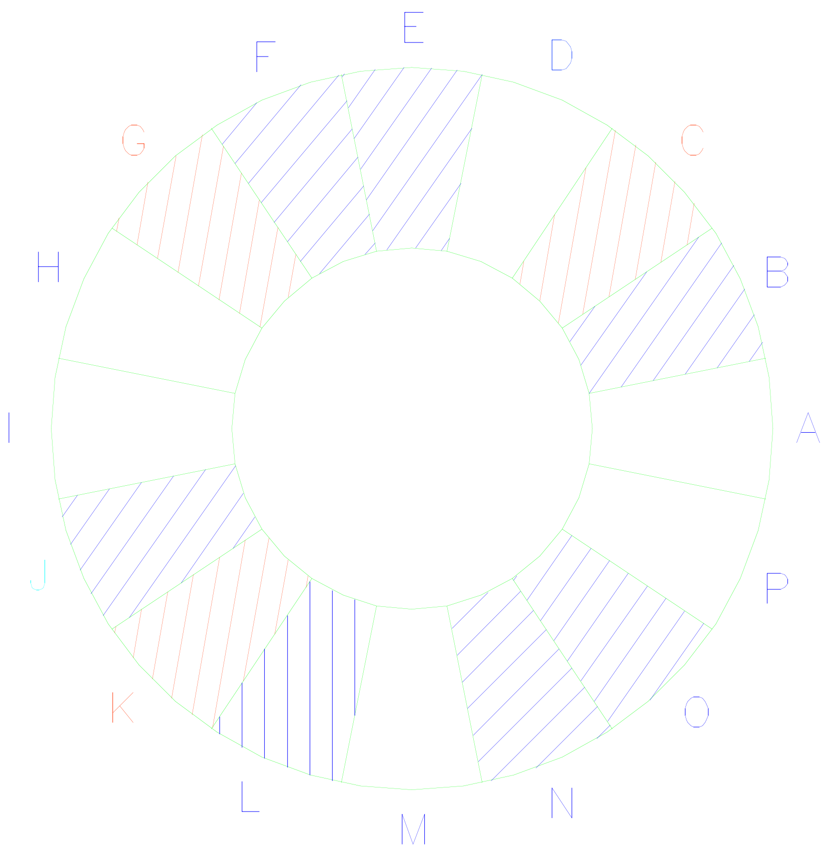
C: Multichord Visible Spectrometer,
Bolometer Array
D: Divertor Pump/Water
E: Divertor IR TV,
IR TV,
Thermocouple Wiring
F: Divertor Pump/Water
G: ASDEX Gauges,
Divertor UV Spectrometer
H: Divertor Pump/Water
I: Rotation CXRS,
Divertor IR TV,
Divertor TV
J: Divertor Pump/Water
K: X-point Thomson Scattering,
Bolometer Array
L: Divertor Pump/Water
M: Divertor IR TV,
Divertor TV,
Thermocouple Wiring
N: Divertor Pump/Water
O: Divertor Filterscope,
ASDEX Gauges,
Inside-Launch Pellet
P: Divertor Pump/Water

# FIRE Diagnostics:
# Bottom Port Assignments




A:
B: Magnetics Wiring
C: Illumination
D:
E: Probe Wiring
F: Magnetics Wiring
G: Illumination
H:
I:
J: Magnetics Wiring
K: Illumination
L: Probe Wiring
M:
N: Magnetics Wiring
O: FIR Interferometer/Polarimater
P:

# Some Final Thoughts

- Significant detailed design and analysis is required to determine the real access capability for diagnostics:
  - The small size, high field, high density FIRE plasma provides some measurement difficulty relative to the ITER-FEAT device,
  - The determination of the spatial resolution required for some measurements has to await some conceptual design. Even “standard” measurements like $n_e$ and $T_e$ may not meet stringent spatial-resolution requirements for ITBs,
  - Interaction with shielding and internal hardware must be designed,
  - Reliability and maintainability of in-vessel diagnostics is necessary goal.
- A diagnostic beam is essential for control and physics: profiles of q, ion temperature, rotation, He-ash, slowing-$\alpha$s, and possibly $E_r$ require it.
- Microwave scattering has been adopted for measurement of confined-$\alpha$s: TEXTOR data shows promise. Development of new techniques should be encouraged.
- Development of a technique for measuring the escaping-$\alpha$s is necessary; test should be done on JET-EP.

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