Diagnostics for FIRE

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

- The diagnostic set should provide the same quality of data as in best present-day devices.
- High quality, reliable information on many plasma parameters will be used to provide control signals.
- New information about the alpha-particles.
- The neutron radiation environment must be considered in design of the diagnostic system.

Outline of Talk

- **Specifications of the measurement goals,**
- **Aspects to be considered in design:**
  - **Port configurations,**
  - **Radiation effects,**
  - **Specific issues for different diagnostic techniques.**
- **Alpha-particle measurement.**

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Examples of Target Plasma Measurement Capability proposed for ITER-FEAT

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	$1x10^{14}$ - $1x10^{21}$ n s^{-1}	Integral	1 ms	10%
Neutron & α-particle source	$1x10^{14}$-$4x10^{18}$ $ns^{-1}m^{-3}$	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%

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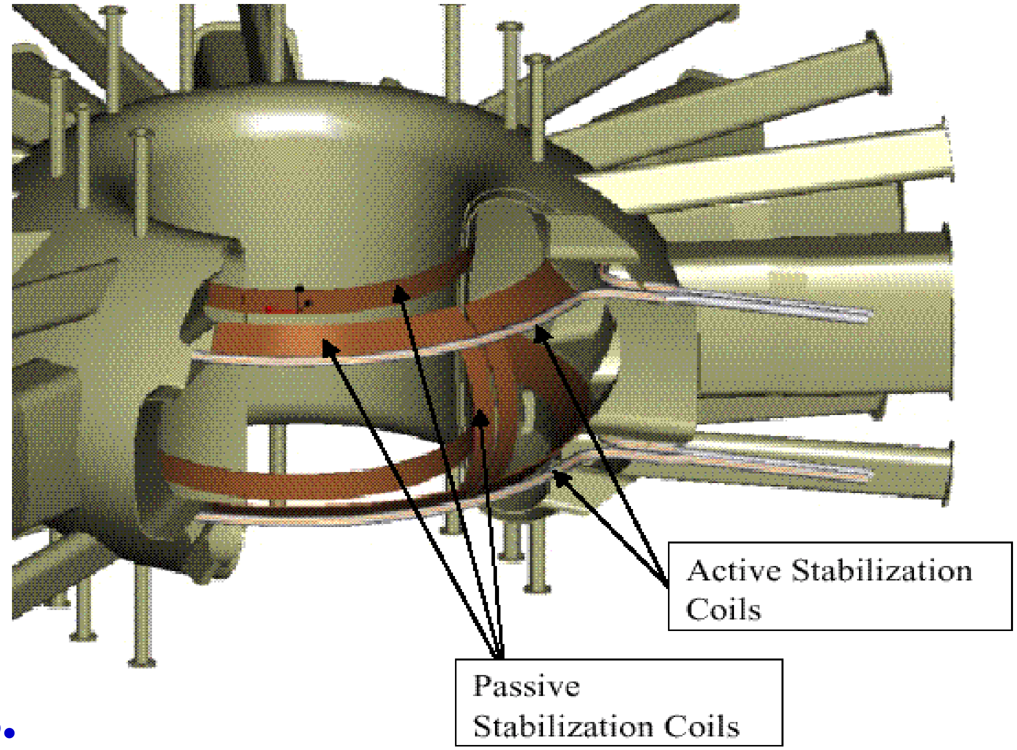
Simplified List of Measurements for Input to Control Systems

- **Fast Plasma Shape and Position Control:**
  - **Magnetic diagnostics, IR camera**
- **Kinetic Profile Control:**
  - **Thomson scattering, Interferometer/Polarimeter, Reflectometer, ECE, CXRS (T_i and He-ash), Neutron Detectors,**
- **Current Profile, Rotation Control:**
  - **Magnetic diagnostics, 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 (β; MHD), kinetic profile set**

FIRE Port Configuration

- Large radial ports with extended necks,
- Very small vertical ports,
- X-point aligned ports to be shared with in-vessel services, and "blocked sightlines", but could be used for divertor sightlines.



FIRE vacuum vessel concept

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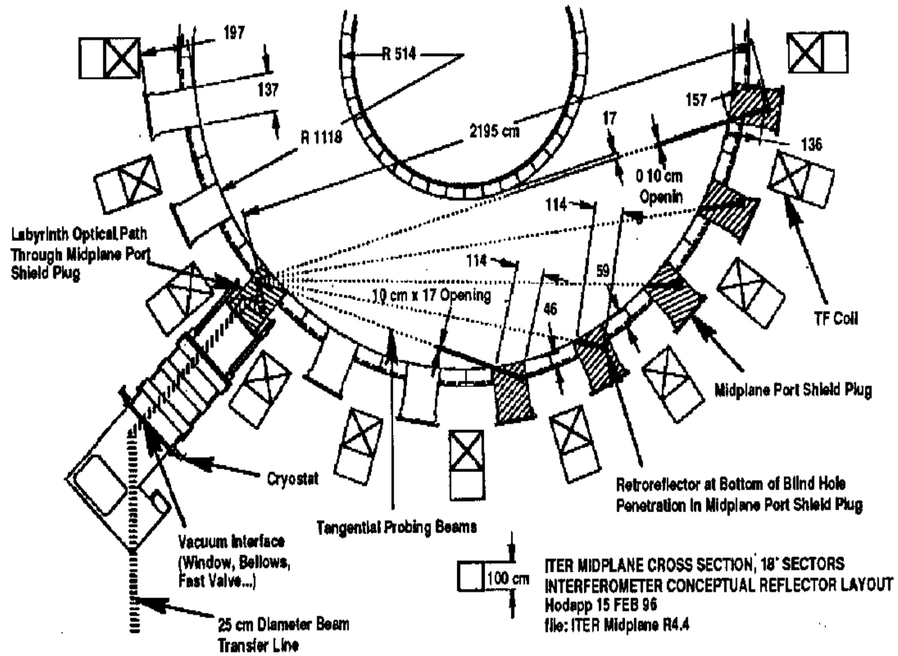
Use of Access Ports

- Extremely good radial access (with shielding),
- Very limited access top and bottom,
- Use top and bottom outer ports for viewing divertors, bolometers, light arrays,
- Use tangential arrangements for interferometry, TS, etc.

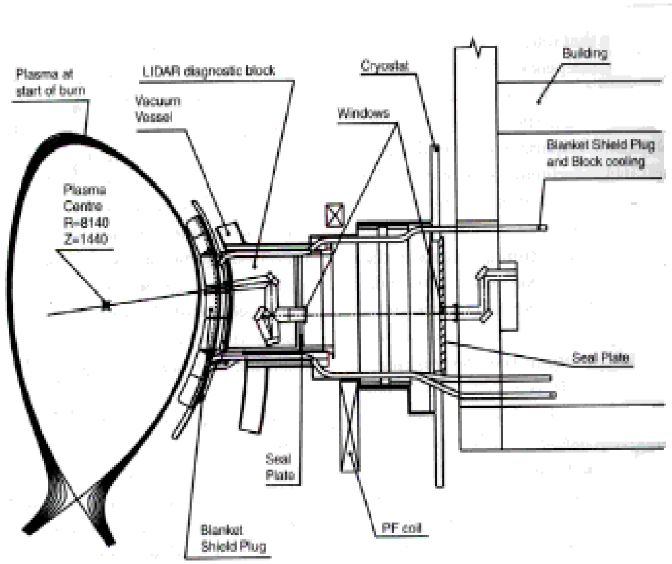


CONCEPT FOR INTERFEROMETER/POLARIMETER FOR ITER

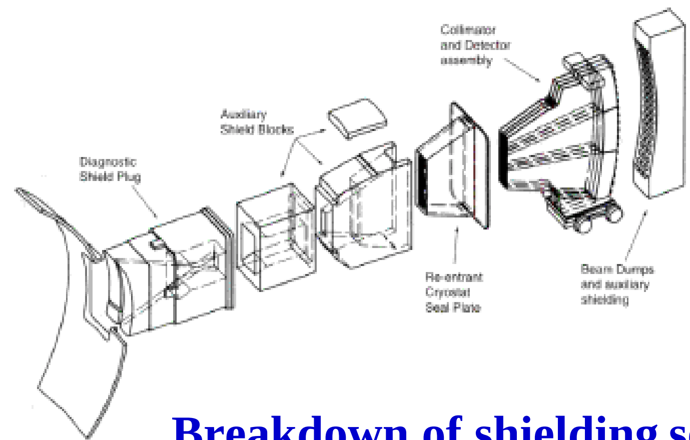
The Impact of the Neutron (Gamma) Environment

- 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.

How does Radiation Impact Use of Ports for ITER?

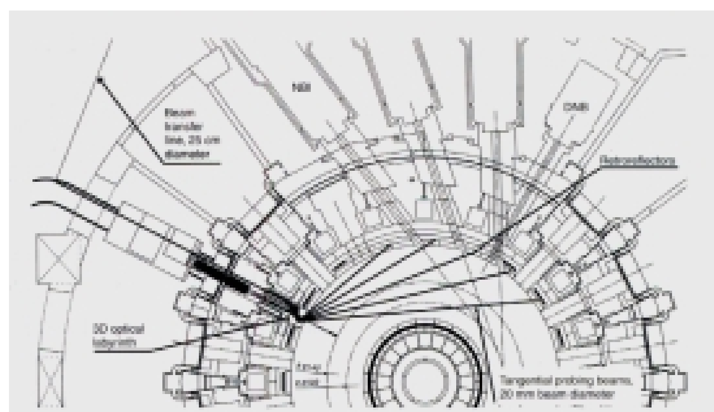


ITER port for LIDAR Thomson scattering



Breakdown of shielding sections for ITER neutron camera

ITER Physics Basis, Chapter 7



Tangential arrangement proposed for interferometer/polarimeter in ITER

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Radiation Effects
(Ceramics (1), Optical components (2), Mirrors (3))

	First Wall (Gy/s)	Interspace Structure/ Shielding	Outside Vac. Vess. Port (Gy/s)	Fluence
ITER-FEAT (700 MW, 0.8 MW/m^2)	**$4x10^3$** **+ neutrals** →	<---------------> →	**5**	**Issue at 1st wall (long-term damage)** **Few x 0.1 dpa**
FIRE (220 MW, 3.6 MW/m^2)	**$2x10^4$** **+ neutrals** ⟶	<---------------> ⟶	**20**	**Non-issue**
Components	**Magnetics (1) -----** <-------**MI-cable (1)--** **Lost-Alpha** **Retroreflectors (3)** **Thermocouples (1)** **Gauges (1)**	**------>** **Mirrors (3)** **---------------->**	**Windows (2)** **Fiberoptics (2)** **Optical comp-onents ? (2)** **Vacuum-diag.** **Detectors? (1)**	

Numbers are approximate and average

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Radiation Effects on Diagnostic Components

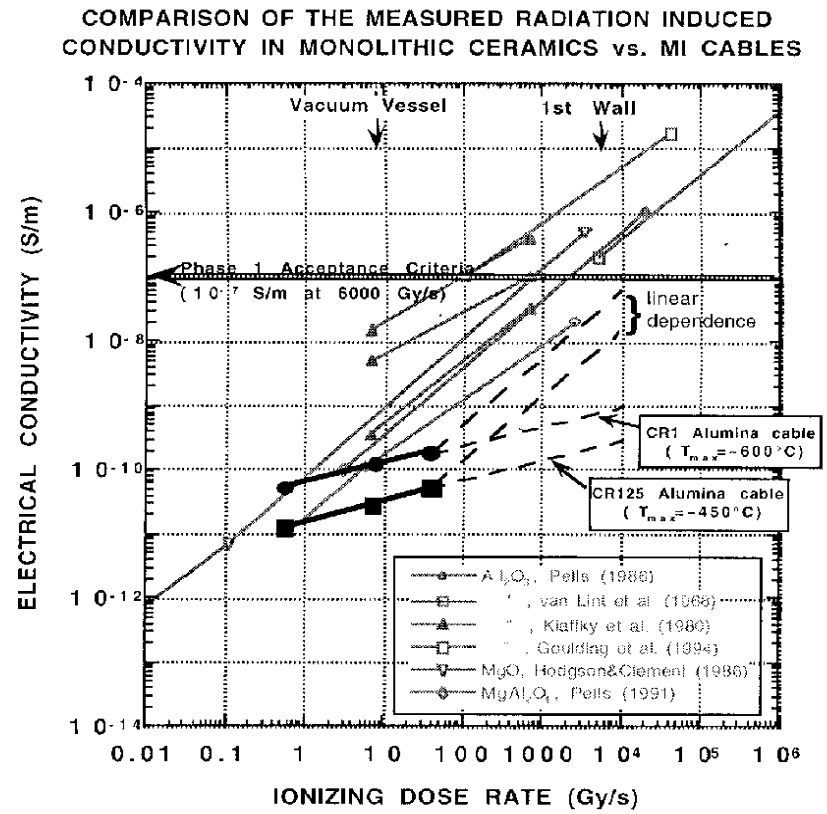
- **Diagnostic Component** | **Worst Radiation Problem**

Diagnostic Component	Worst Radiation Problem
Ceramics (and Detectors)	Electrical (RIC, RIED, RIEMF)
Fiberoptics (and Windows)	Absorption, Luminescence, Numerical aperture
Mirrors	Mechanical + Neutrals in Surface Modification (near first wall)

- **Ceramics (and Detectors)** — **Electrical (RIC, RIED, RIEMF)**
  - Studies of RIEMF in progress for MI-cable used in coils.
- **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

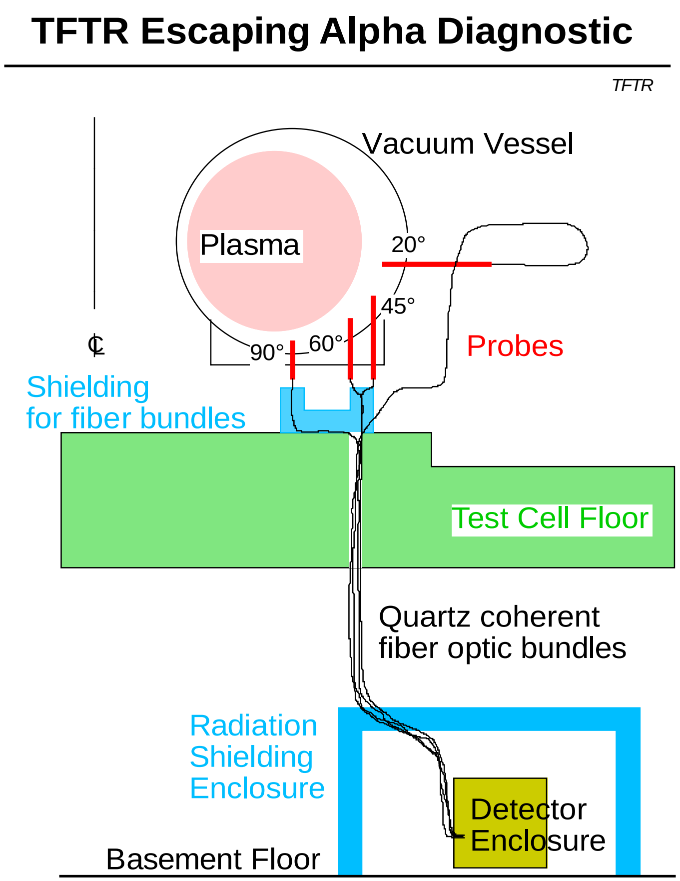
- Loops, coils, MI-cable must be inside vacuum vessel,
- Maximally unfriendly environment; RIC and RIEMF, temperature, neutral particles,
- No in-built protection,
- Renew R&D program on radiation impact on ceramics/MI cable.

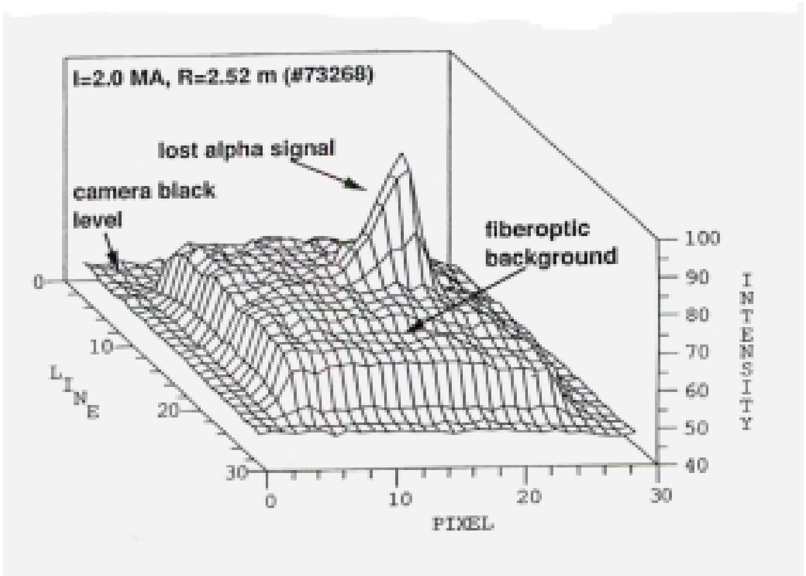


Radiation Effects on Optical Systems

- Radiation discolors/blackens optical components,
- Hence must use reflective optics in high-radiation areas.
- Optical fibers suffer from:
  - Prompt luminescence,
  - Prompt absorption,
  - Long - term absorption damage,
  - Effective change in numerical aperture.
- Running fibers hot only affects the long-term absorption.
- Great disparity in radiation effects on nominally identical fibers.

Luminescence (and Absorption) Impact on Measurement in an α-diagnostic





Darrow, Zweben et al.

Lost-α diagnostic on TFTR with fiberoptic outside vacuum vessel.

TFTR shot at 5MW ($5x10^{-2}$ MW/m^2 at first wall.

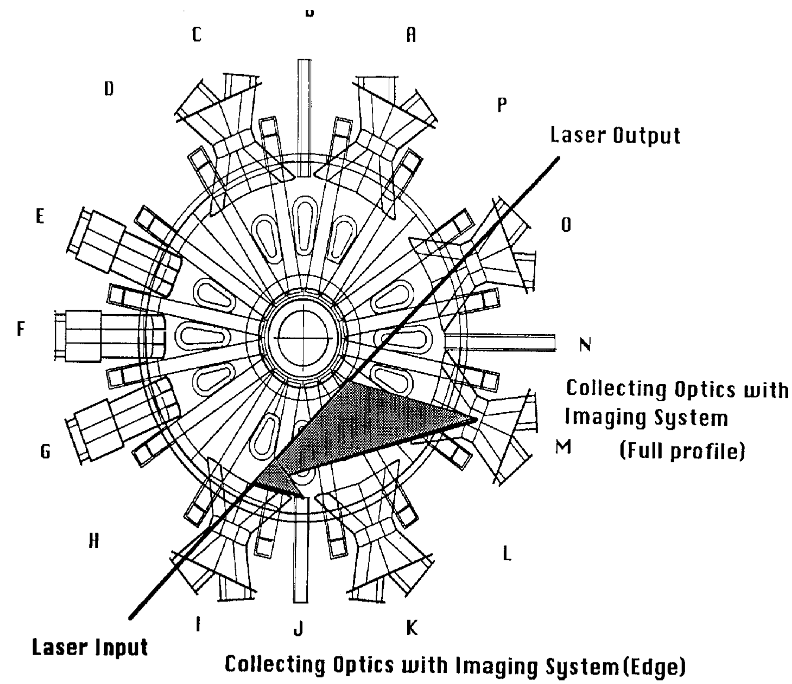
Dose at front end of fiber ~ 30 Gy/s

Issues for other Individual Systems

- Good spatial resolution diagnostics like x-ray diodes, bolometers, CCD cameras susceptible to failure in radiation background,
- Low-light level spectroscopic measurements susceptible to radiation noise, absorption (calibration!)
- Magnetic field, density range affect choice of microwave diagnostics,
- Auxiliary heating technique affects diagnostics.

Thomson Scattering: Issues

- Imaging system required for spatial resolution (cannot use LIDAR),
- Optical systems need shielding,
- Difficult sightline arrangement; will have to use tangential laser beam, view from nearby port, with close front-end mirror.



KSTAR Concept for TS

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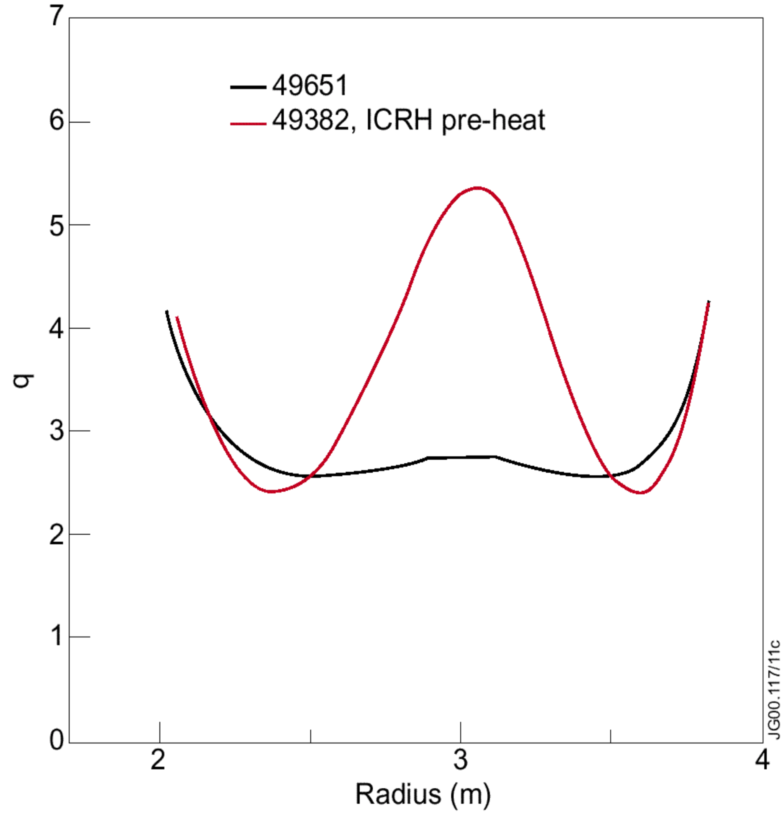
Good Profile Diagnostics currently Require a Neutral Beam

- $T_i(r)$, $v_f(r)$, $v_q(r)$, $q(r)$, $n_{HE\text{-}ash}(r)$, $(E_r(r))$,
- Good poloidal rotation needs opposing views; not possible,
- Diagnostic beam near-radial; penetration at ~100keV/amu problematic,
- Diode beam, $5x10^9$W for <1ms for CXRS?
- MSE prefers > 300 keV/amu.



MSE q-profiles in the target phase of two JET Optimized Shear discharges. The q-profile for shot 49651 is typical for JET OS plasmas. Shot 49382 had LHCD and ICRF in the pre-heat as well as the beams and it shows a strongly reversed q-profile (Stratton, Hawkes, et al.)

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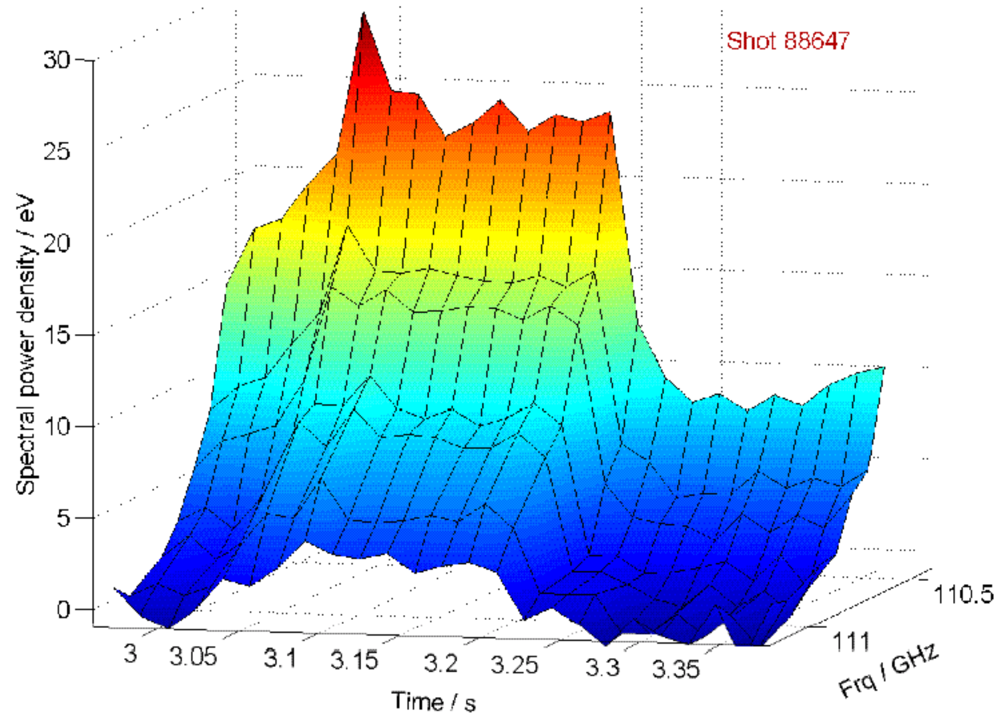
Divertor Diagnostics

- Divertor diagnostics must relate to the physics goals of the device
  - Needs strong modeling interaction,
  - Important for impurity, fueling and ash measurements, tritium accountability,
  - Need validated control schemes.
- Detachment monitoring.
- Survivability of position and shape measurements.

Diagnostics for Alpha-Particle Physics

- Lost fast-ion detectors and IR camera,
- α-CHERS,
- Collective scattering (CO_2, ?),
- Li-pellet, fast neutral particle analyzer,
- Knock-on neutron,
- New confined-α detector???
- High-frequency Mirnov coils, reflectometry.



Fast-ion spectra from Collective Scattering in TEXTOR (Bindslev, Woskov et al.)

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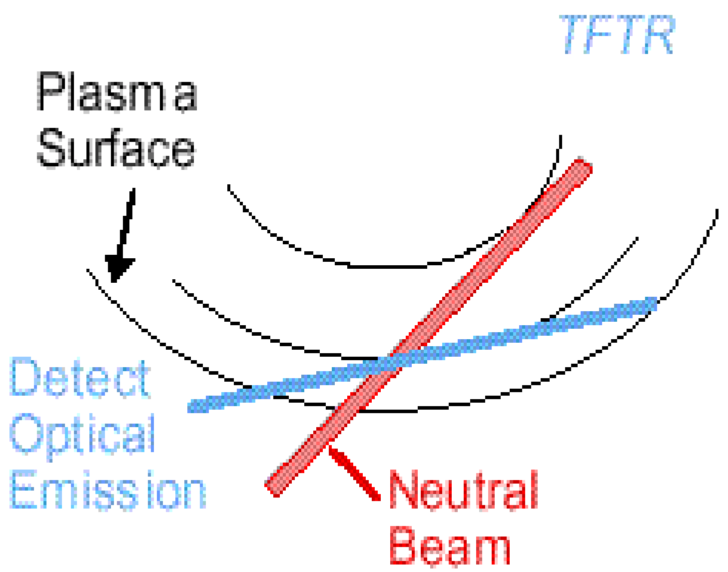
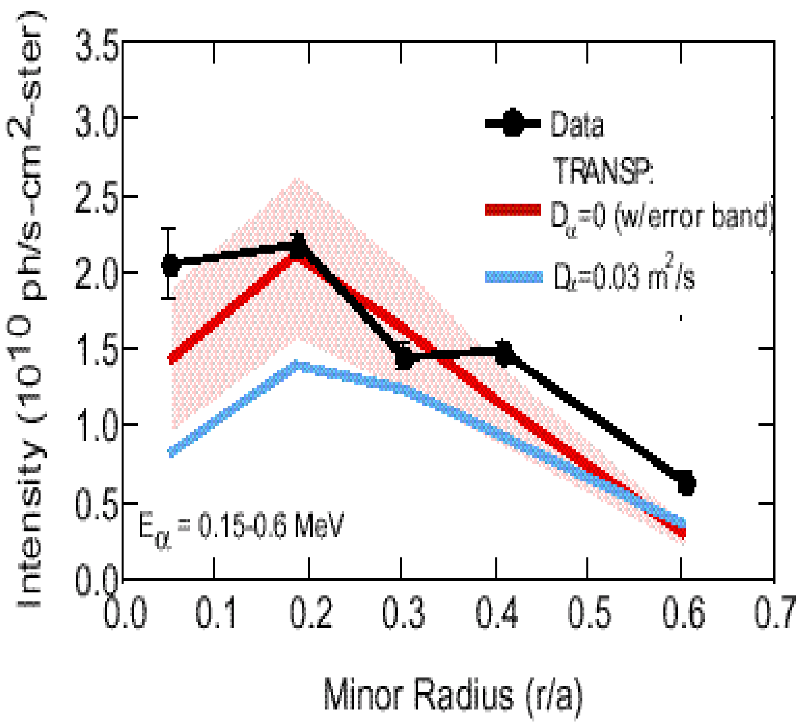
Alpha-Chers can Provide Absolute Measurement of some Confined Alphas



Charge Exchange between fast beam ions and slowing-down Alphas



- $0 \leq D_\alpha \leq 0.03\ m^2/s$

No data taken in TFTR during neutron pulse.
Improved optical design should provide time-resolved measurements of alpha distribution

Stratton, Fonck et al.

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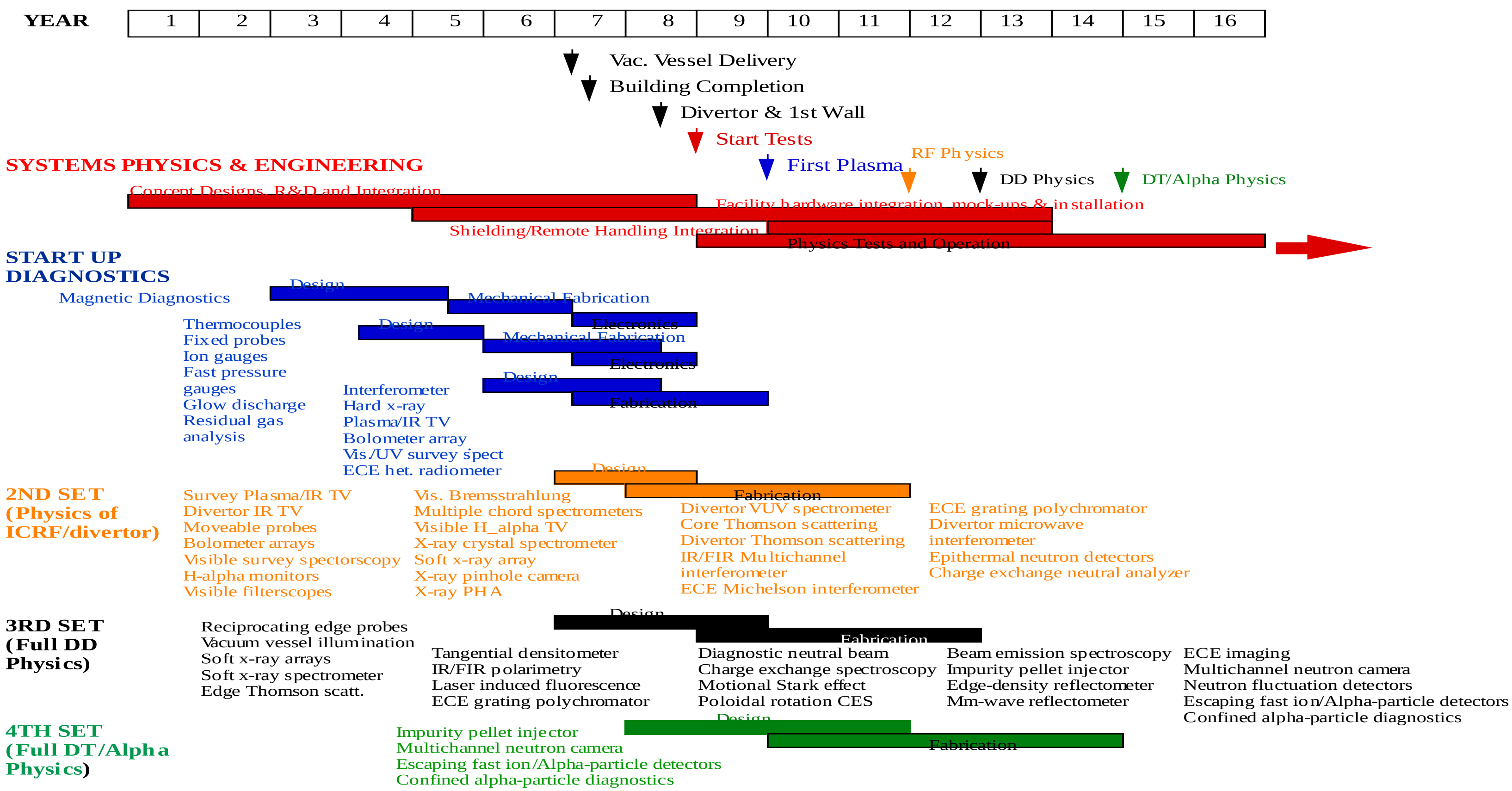
FIRE: Diagnostics Schedule



FIRE DIAGNOSTICS SCHEDULE: REVISION 0 1 SEPTEMBER 1999

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Development Concerns

- What are impacts of high-field, highly shaped, high-$n_{e,}$ high radiation, RF-only on diagnostics selection and development?
  - Radiation "hardness" of diagnostic components?
  - Lifetime of plasma-facing mirrors, other optical elements?
  - Reliability of magnetic diagnostics?
  - ECE/reflectometry functionality?
  - Interferometry refraction/wavelength?
  - Use of bolometry, x-ray techniques?
  - CXRS and MSE techniques; capability for diagnostic neutral beam(s)?
  - Confined alpha-particles?

Physics Input Needed prior to detailed Diagnostic Design

- Will the new physics need the same high resolutions as now in U.S.?
- What input will be needed for control systems?
- What is needed for fluctuation (turbulence) measurement?
- What level of detail is needed about the α-particles?

Provisional List of Diagnostics (1)

- Magnetic Measurements
  - Rogowski Coils, Flux/voltage loops, Discrete Br, Bz coils, Saddle coils, Diamagnetic loops, Halo current sensors, Hall effect sensors
- Current Density Profiles
  - Motional Stark effect with DNB, Infrared polarimetry
- Electron Density and Temperature
  - Thomson Scattering, ECE Heterodyne Radiometer, FIR interferometer, Multichannel Interferometer, ECE Michelson interferometer, ECE Grating Polychromator, Millimeter-wave Reflectometer
- Ion Temperature
  - Charge Exchange Spectroscopy with DNB, X-Ray Crystal Spectrometer, Charge Exchange Neutral Analyzer (edge)
- Visible and Total Radiation
  - Visible Survey Spectrometer, Visible Filterscopes, Visible Bremsstrahlung Array, Bolometer Arrays, Plasma TV and Infrared TV
- Ultra Violet and X-Ray Radiation
  - UV Survey Spectrometer, Hard X-ray detectors, Soft x-ray Spectrometer, X-ray pulse height analysis

Provisional List of Diagnostics (2)

- MHD and Fluctuations
  - Mirnov Coils, Locked-mode coils, Soft x-ray array, Beam emission spectroscopy, Millimeter wave reflectometer, Collective scattering
- Particle Measurements and Diagnostic Neutral Beam
  - Epithermal Neutron detectors, Multichannel Neutron Collimator, Neutron Fluctuation detectors, Diagnostic Neutral Beam
- Charged Fusion Products
  - Escaping Alpha Particle detectors, IR TV (shared with total radiation), Collective Scattering (CO_2?), α-CXRS, Knock-on neutron detectors
- Divertor Diagnostics
  - Divertor IR TV, Visible Hα TV, UV Spectrometer, Divertor Bolometer Arrays, Multichord visible spectrometer, Divertor Hα monitors, ASDEX-type Neutral Pressure Gauges, Divertor Thomson Scattering, Penning Spectroscopy, Divertor reflectometer
- Plasma Edge and Vacuum Diagnostics
  - Thermocouples, Fixed Edge Probes, Fast Movable Edge Probes, Torus Ion Gauges, Residual Gas Analyzers, Glow Discharge Probes, Vacuum Vessel Illumination

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Conclusions

- A compact advanced copper-coil tokamak, like FIRE, can make major contributions to fusion science studies leading ultimately to fusion energy,
- but significant challenges for **diagnostics**
  - radiation and other environmental impacts on components,
  - demand for fine spatial resolution profile data for control,
  - alpha-physics diagnostics: alpha-particles and their impact,
  - limited funding.