FIRE Diagnostics: an Update

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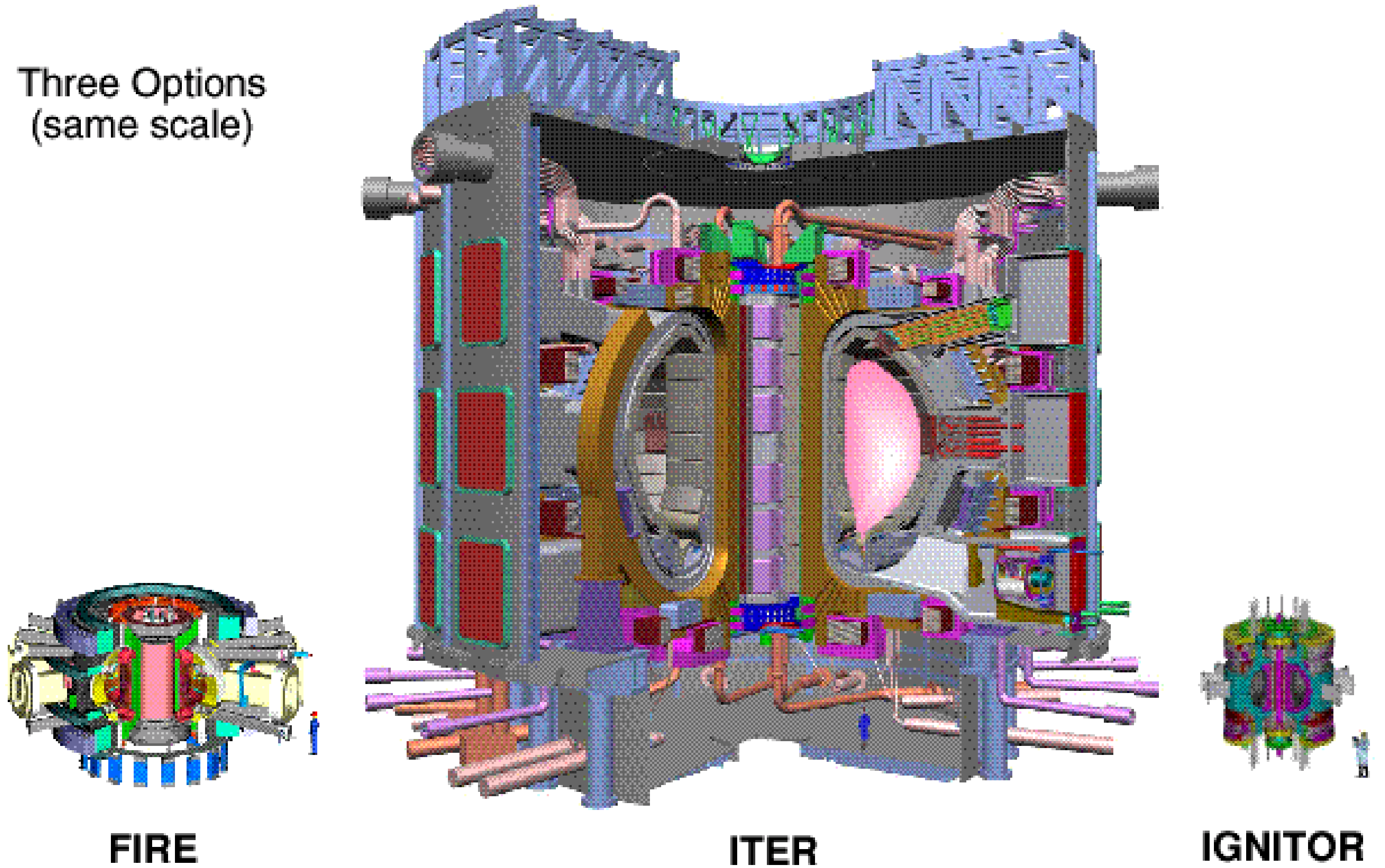
2nd ITPA Topical Group Meeting on Diagnostics

March 4, 2002
General Atomics
San Diego, CA, U.S.A.

Burning Plasma Physics: ITER, FIRE and Ignitor



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Outline

- Reminder of proposed FIRE parameters
- Recent Considerations of Diagnostic Integration
- Assessment Grid for Diagnostics:
  - Diagnostics Integration
  - Physics/Diagnostics

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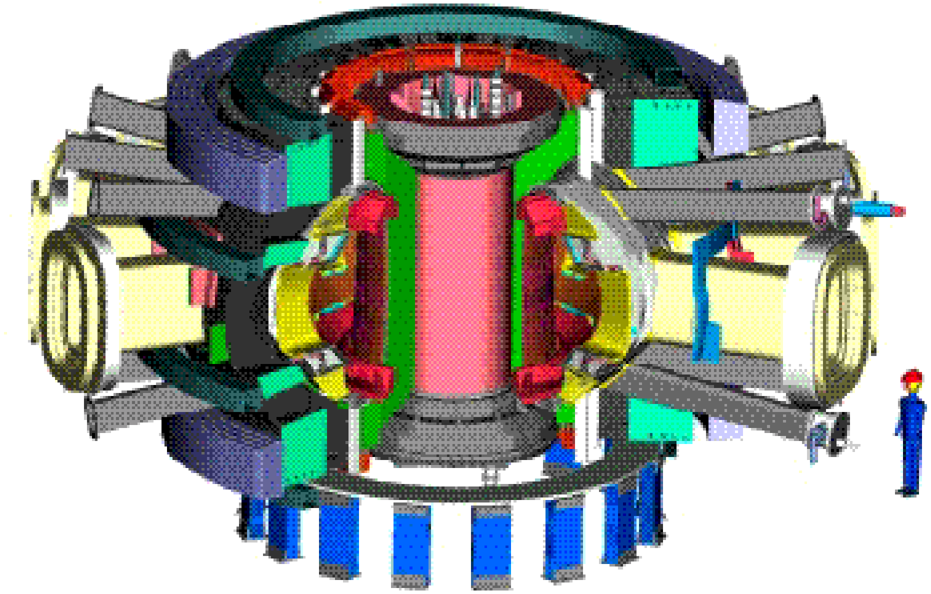
- Proposed Measurement Specifications for FIRE Physics Studies
- Proposed FIRE Diagnostics (table shown at 1st ITPA Meeting)
- Draft Diagnostic Port Assignments

Fusion Ignition Research Experiment

(FIRE)

http://fire.pppl.gov



Design Features

- R = 2.14 m, a = 0.595 m
- B = 10 T
- W_{mag}= 5.2 GJ
- I_p = 7.7 MA
- $P_{aux} \leq$ 20 MW
- Q $\approx$ 10, P_{fusion} ~ 150 MW
- Burn Time $\approx$ 20 s
- Tokamak Cost $\approx$ $375M (FY99)
- Total Project Cost $\approx$ $1.2B at Green Field site.

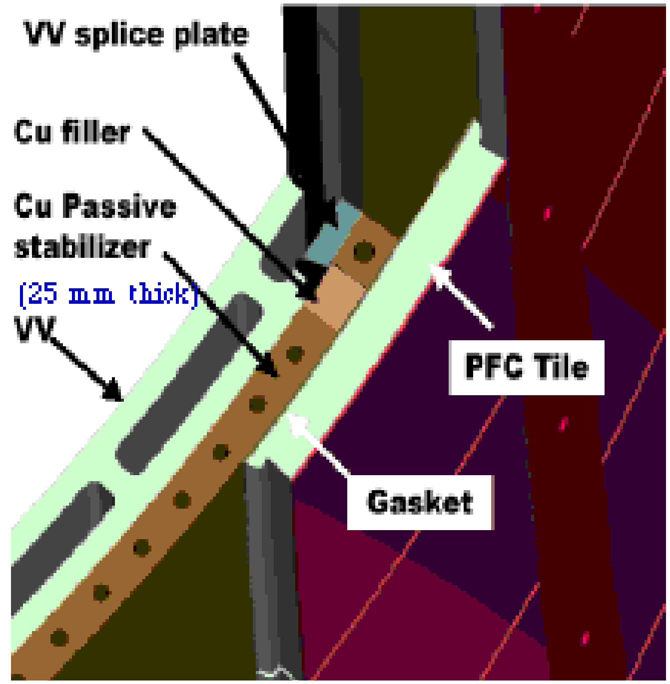
Mission:

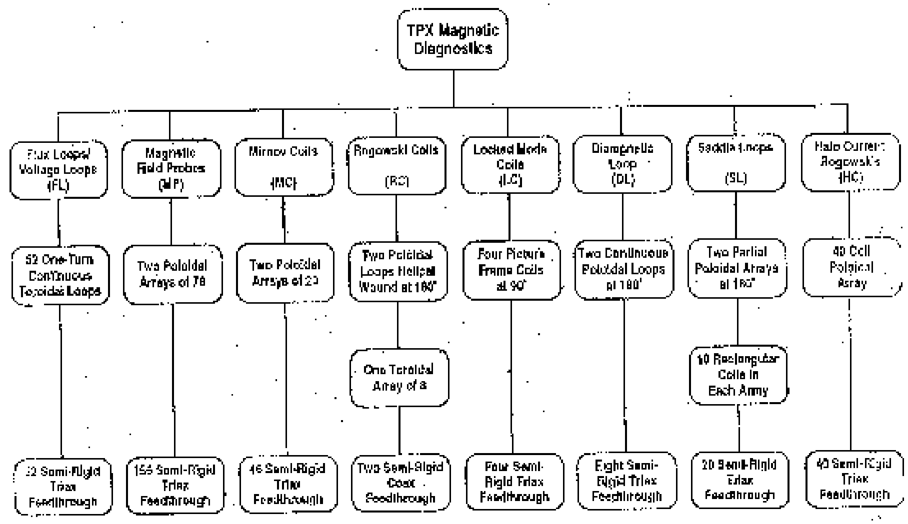
Attain, explore, understand and optimize fusion-dominated plasmas.

Magnetic Diagnostics: Issues

- Slots must be cut in copper to allow field penetration; skin depth at 10 kHz ~0.6mm.
- Very limited space behind tiles;
  - need grooves in tiles, cladding,
  - need clear space between coils and copper (inductance change due to shield can ~ factor 2),
  - eddy currents close to coils will confuse.
- Nuclear heating of alumina of coils ~ 30 Wcm^{-3}
- Fewer coils/loops needed for position control than in TPX because of proximity to LCFS.
- Note: TSC analysis of current penetration into plasma, etc, is only currently under way.

FIRE





TPX: 1993

Radiation Environment at Selected FIRE locations (for 150 MW output)

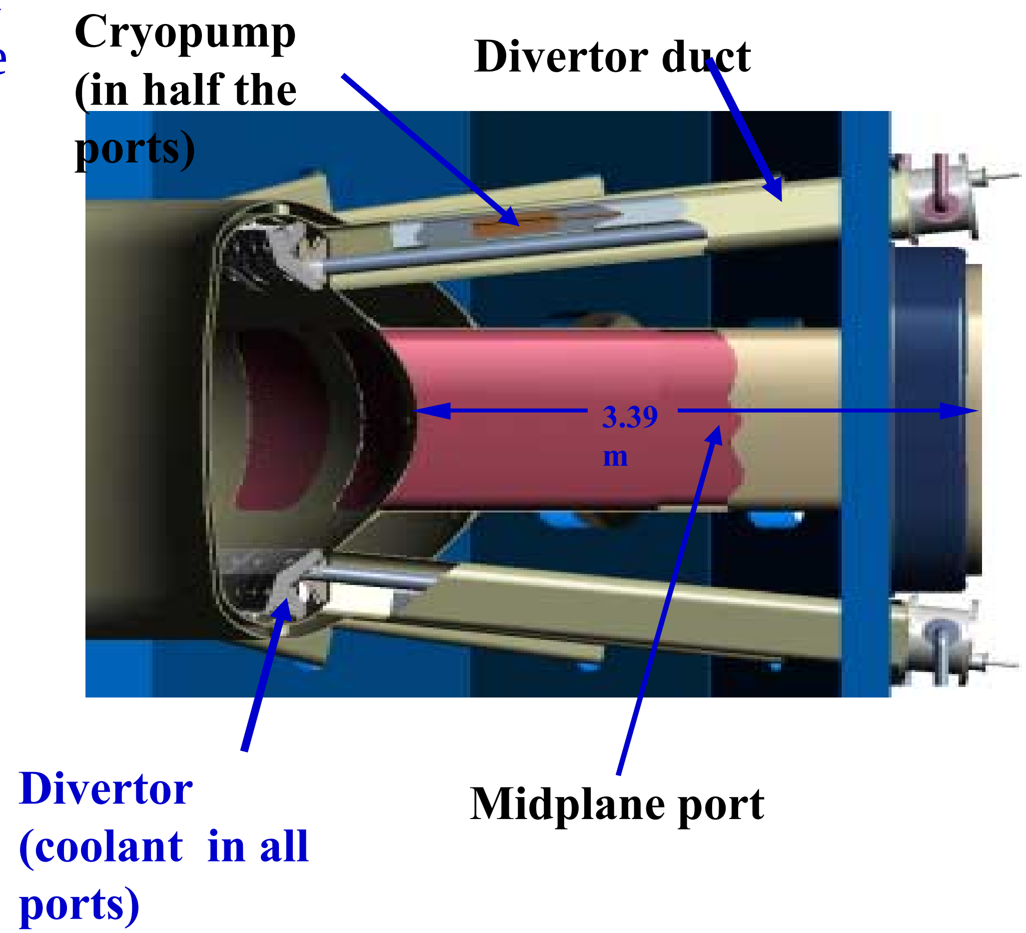
150 MW DT Pulses (1-D Calculation)	Total Neutron Flux (n/cm^2s)	Fast Neutron Flux (E>0.1MeV) (n/cm^2s)	Total Gamma Flux (g/cm^2s)	Si -Dose Rate (Gy/s)	Total Cumulative Lifetime Dose * (Gy)
First Wall (Inboard Midplane)	$1.16x10^{15}$	$7.88\ x10^{14}$	$5.67x10^{14}$	$8.78\ x10^{3}$	$3.09x10^{8}$
Behind Tiles (Inboard Midplane)	$9.54x10^{14}$	$6.00x10^{14}$	$5.01x10^{14}$	$5.79x10^{3}$	$2.08x10^{8}$
Behind TF Coils (Outboard Midplane)	$7.14x10^{8}$	$2.76x10^{8}$	$1.06x10^{8}$	$9x10^{-4}$	31.1
Behind 1.1 m Port Plug (Outboard Midplane)	$7.58x10^{7}$	$2.99x10^{7}$	$5.93x10^{7}$	$5x10^{-4}$	15.1
Behind TF Coils at Top/Bottom	$1.88x10^{10}$	$7.10x10^{9}$	$5.78x10^{9}$	$4.7\ x10^{-2}$	$1.63x10^{3}$

* 5TJ DT and 0.5 TJ DD

Mohamed Sawan (U. Wisconsin)

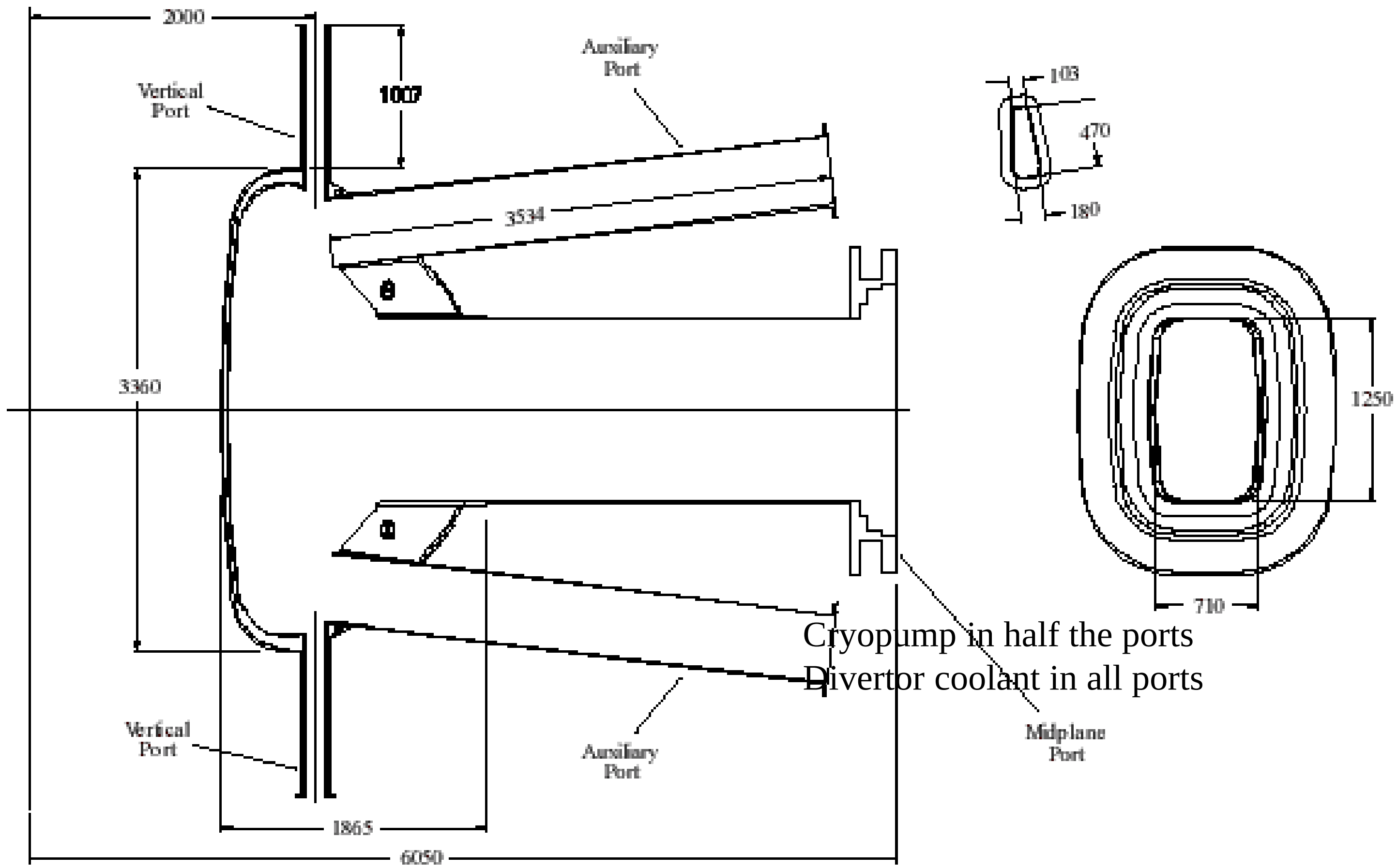
Diagnostic Use of FIRE Ports

- Design goal of device is limit radiation outside dewar so that access is possible within few hours.
- Design philosophy for diagnostic installation must be same as for ITER.
- Neutronics calculations made with 1.1 m shield plugs. Radiation levels at outer end similar to those for ITER.
- One 100mm. dia.straight penetration at mid-plane almost doubles neutrons outside tokamak.
- Hence most diagnostics must be designed with 4 90°bends to reduce streaming ~4 orders of magnitude.
- Because of narrow ports and intermingling of diagnostic sightlines, very thorough neutronics analysis will be required.



- Divertor structure does not provide same degree of shielding as in ITER.

Vessel port configuration



Cryopump in half the ports
Divertor coolant in all ports

50 x 150 port

Evaluation of FIRE Diagnostics:

Support the Mission of the Experiment?

- 1) Mission is to "Attain, explore, understand and optimize fusion-dominated plasmas that will provide knowledge for attractive MFE systems".
  - Measurements must provide the same capability for physics interpretation of plasma behavior as provided in the best operating tokamaks plus the capability for measuring the alpha-particles from birth to demise. Effort must be concentrated on fast-ion physics and the ability to control the plasma behavior through transitions between different confinement modes.
- 2)Which modes can the diagnostics cover?
  - Diagnostics are being conceived with sufficient spatial and temporal resolution (in the appropriate locations) to allow measurement in all the anticipated confinement regimes.

Evaluation of FIRE Diagnostics:

Flexibility and Redundancy?

- 1) What are the planned redundant systems/measurements?
  - There is little redundancy between different techniques for measuring the same plasma parameter because of different physics in the techniques or different sensitivities.
  - The magnetic diagnostics will have full redundancy to compensate for their inaccessibility.
  - There will be no or little redundancy built into the other diagnostics' interfaces with the tokamak; at a later time purchase of spare sources or detectors for specific diagnostics associated with plasma control should be considered.
- 2) What fraction of access exists for future development in diagnostics?
  - Up to a final design assessment (~ 4 years from start) there is considerable flexibility.
  - After that, and assuming diagnostics keeps ownership of 12 radial ports, ~ 20% would be available. But note that the accessibility will be very dependent on the access demands of the diagnostic.

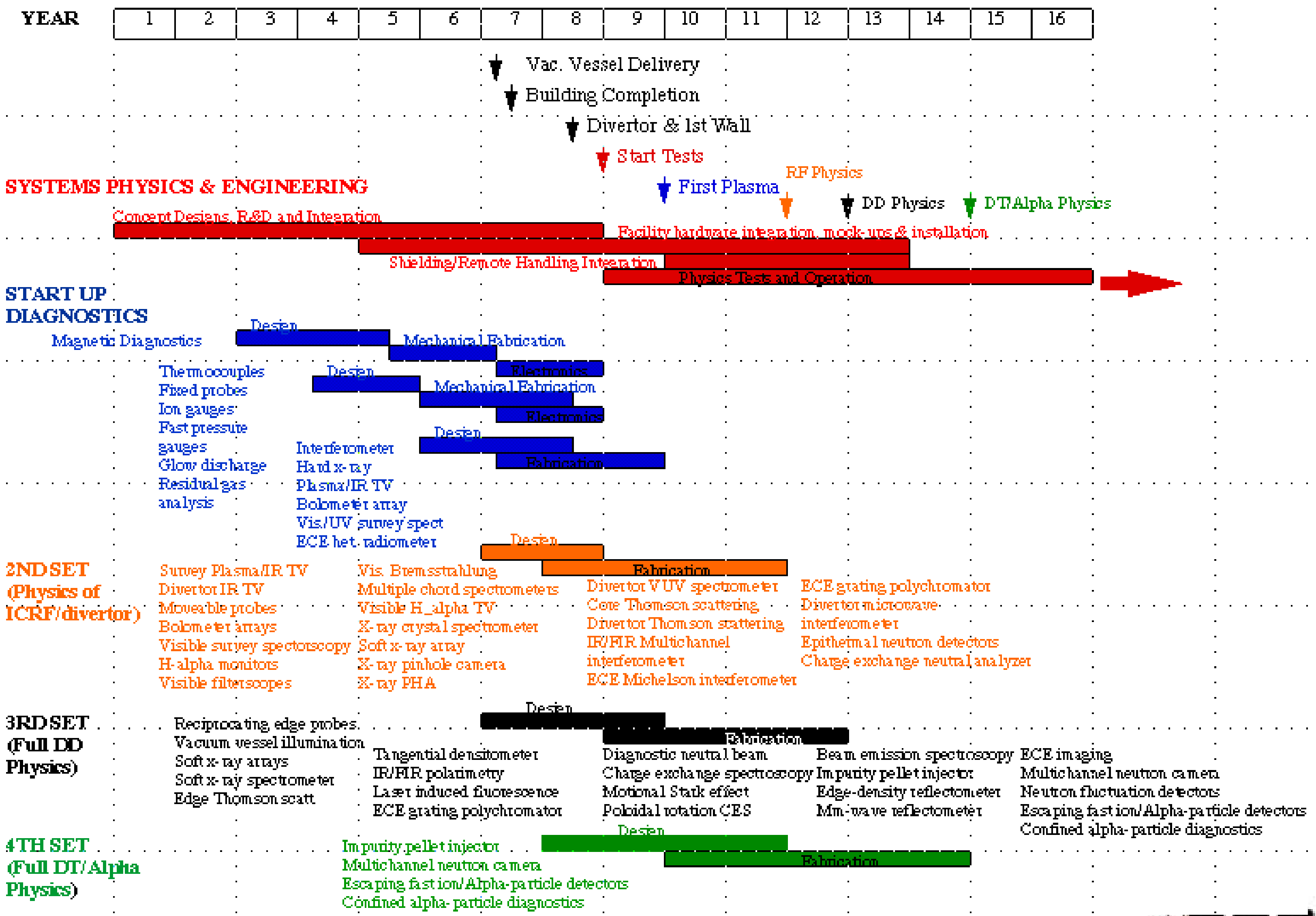
Evaluation of FIRE Diagnostics:

Installation Schedule

- The draft schedule for installation of FIRE diagnostics is shown next.
  - Schedule was developed prior to a clearly defined physics program.
  - All alpha-particle diagnostics are available for testing on fast ions during D-operation.

- Different requirements for H/D/T operation.
  - It is anticipated that the same type of port plug arrangement, with diagnostic labyrinths, will be used for all phases of the operation.
  - Since the main H-operation will probably happen first, there may be unused ports which could be left without shield plugs for easy access.
  - D-operation will provide sufficient neutrons that the shield plugs must all be installed.
  - T-operation requires all diagnostics with vacuum extensions to be shielded and to be integrated into the tokamak vacuum system.

FIRE Diagnostics Schedule (Rev 0; Sept 1999)



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Evaluation of FIRE Diagnostics:

R&D Required

- Irradiation Tests of Materials
  - Evaluate radiation-induced conductivity (RIC) in selected ceramics and MI cable to define design materials.
  - Determine cause of radiation-induced emf (RIEMF) with MI cables to prevent signal pollution by significant DC offsets.
  - Develop and evaluate 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.
- 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 msec at 30 Hz repetition rate.
  - Extend the operational range of Faraday-cup based and scintillator-based escaping-α diagnostics to FIRE parameters.
  - Seek new technique for measuring the confined fast-αs.
- Development of New Components/Techniques
  - Continue development of small rad-hard high-temperature magnetic probes based on integrated-circuit manufacturing techniques.
  - Evaluate metallic mirror performance and effects on reflectivity of neutral particle bombardment and nearby erosion (ongoing ITER R&D activity).

Evaluation of FIRE Diagnostics:

Diagnostics - New Opportunities

- 1) New diagnostics that would benefit from FIRE:
  - All α-particle diagnostics will benefit from this experiment because of the relatively improved signal strengths.
  - Application of diagnostics in control, particularly those measuring parameter profiles, will be thoroughly tested.
  - Capability to model very high density tokamak plasmas with strong central heating.
  - (Note: since a reactor will use a much smaller set of diagnostics, this device will provide clear guidance on the diagnostics necessary for its control.)
- 2) What are the items/issues related to diagnostics that can be addressed uniquely?
  - Plasma parameter surveys could be run to assess the α-diagnostic capabilities.
  - Effectiveness of integration of the diagnostics under realistic reactor conditions.

Evaluation of FIRE Diagnostics:

Physics requirements for the diagnostics

- 1) What are the physics requirements for the diagnostics?
  - A draft tabe of the proposed measurement specifications is attached.

- 2) What are the physics justifications for diagnostics?
  - The physics justifications for ITER have been recently prepared for review by the ITPA Working Groups. The FIRE justifications are similar.
    - Since the requirements for physics studies are generally more severe than for control, the needs for spatial and temporal resolutions are comparable for the two devices.
    - FIRE does not have a very long-pulse requirement.

Evaluation of FIRE Diagnostics:

3) Systems planned for measuring:

- A 5-page table is attached, giving the full planned set.
  - It is expected that the whole set will not be able to be implemented because of competition for space or difficulty of implementation.
- Temperatures/core/boundary
  - Thomson scattering (core, x-point, divertor), ECE, fast-moving probe.
  - Charge exchange spectroscopy (with diagnostic beam), imaging X-ray spectroscopy, neutron camera spectroscopy; UV spectroscopy in divertor.
- Densities/core/boundary
  - Thomson scattering (core, x-point,divertor), FIR multichannel interferometer/polarimeter, reflectometer (boundary), probes in divertor, multichannel interferometer in divertor
- Flows/rotations/core/boundary
  - Charge exchange spectroscopy, imaging x-ray spectroscopy, edge probe.
- Fields/currents magnetics/core/boundary
  - Rogowski, Flux/voltage loops, saddle coils, discrete coils, diamagnetic loops, halo current sensors; motional Stark effect (with diagnostic beam), FIR polarimetry, Li-beam polarimetry (edge).
- Fluctuations/core/boundary
  - ~300 kHz Mirnovs, mm-wave reflectometers, beam emission spectroscopy (with diagnostic beam), ECE grating polychromators.

Evaluation of FIRE Diagnostics:

Systems planned for measuring (2)

- Fusion products/lost/confined
  - Epithermal neutron detectors, multichannel neutron camera,
  - Lost-α detectors, IR TV imaging, α-CHERS (with diagnostic beam), collective scattering (FIR), Li-pellet charge exchange, knock-on bubble detectors.
- Wall parameters
  - IR TV imaging, thermocouples
- Fluxes/radiation/particles/neutrons
  - Visible bremsstrahlung array, visible filterscopes, divertor filterscopes, visible survey spectroscopy, UV survey spectroscopy, multichord visible spectrometer for divertor, x-ray PHA, UV spectrometer in divertor, bolometer arrays, visible TV imaging,

    epithermal neutron detectors.

Evaluation of FIRE Diagnostics:

Diagnostics capability, resolution, coverage and calibration

- 1) Requirements which are not presently achievable:
  - Insufficient design to make definitive statements,
  - Specific concerns include;
    - Resolution requirement of q(r), for AT control,
    - Core measurements of T_i, rotation with neutral beam,
    - Imaging x-ray system for T_i, because of γ-generated noise in detector,
    - Ability to measure the radiation profile with sufficient resolution by bolometry,
    - Lost-αs with space limitations.
- 2)Which diagnostic uncertainty could lead to compromising mission success?
  - None obvious at this time.
- 3) Which calibration issues could compromise diagnostic ability to reach planned physics requirement?
  - All optical techniques requiring calibration through the whole system, including the front-end mirror, will be challenging.
  - Calibration is a major issue in each case, but cannot be addressed until the diagnostics are further into design.

Evaluation of FIRE Diagnostics:

Environment Issues for Diagnostics

- 1) Which effects are expected to be significant on diagnostic performance?
  - The radiation environment completely changes the interface of all diagnostics with the tokamak. This can strongly impact spatial resolution, range of coverage for many diagnostics.
  - Radiation-induced conductivity and emf(?) will impact design and choice of materials of magnetic diagnostics.
  - All optical signals have to pass through labyrinths with reflecting optics inside the vacuum vessel. The first mirror may have serious problems with neutral particle bombardment. Fiberoptics outside the shield plug must still be either specially selected and/or shielded to minimize background effects on low-level light signals.
  - Actuators and detectors must be selected to minimize noise/damage.

Evaluation of FIRE Diagnostics:

Environment Issues for Diagnostics (2)

- 2) Accounting of environmental issues in choice and design of diagnostics:
  - There was concern that x-ray diagnostics would not be feasible because of the γ-background but new detectors have been developed. The x-ray imaging for T_i profiles needs analysis because of vertical slot in shielding.
  - Since no detailed design has been done, it is only possible to say that many designs of the tokamak interfaces are expected to be similar to ITER designs. The radiation undoubtedly affects available spatial resolutions.
  - Sensitive detector arrays such as those for bolometry and fluctuations using x-rays cannot be installed without major shielding, so losing spatial resolution. X-ray system is not included for FIRE.

Fire Measurement Specifications (Draft: 1/16/02)

(prepared in style used by ITER Group)

MEASUREMENT	PARAMETER	CONDITION	RANGE or COVERAGE	ΔT or ΔF	ΔX or Δk	ACCURACY
1. Plasma Current	I_p	Default	0 – 1 MA	1 ms	Integral	10 kA
			1 - 8.0 MA	1 ms	Integral	1 %
		I_p Quench	8.0 – 0 MA	0.1 ms	Integral	30 % + 10 kA
2. Plasma Position and Shape	Main plasma gaps, Δ_{sep}	I_p > 1 MA, full bore	-	10 ms	-	0.5 cm
		I_p Quench	-	1 ms	-	1 cm
	Divertor channel location (r dir.)	Default	-	10 ms	-	0.5 cm
		I_p Quench	-	1 ms	-	1 cm
	dZ/dt of current centroid	Default	0 – 100 m s^{-1}	0.1 ms	-	0.05 m/s (noise) + 3% (absolute)
3. Loop Voltage	V_{loop}	Default	0 – 30 V	1 ms	4 locations	5 mV
		I_p Quench	0 – 500 V	0.1 ms	4 locations	10 % + 5 mV
4. Plasma Energy	β_p	Default	.01 – 1	1ms	Integral	5 % @ β_p =1
		Thermal Quench	.01 – 1	0.1 ms	Integral	~ 30 %
5. Radiated Power	Main Plasma P_{RAD}	Default	TBD –.2 GW	10 ms	Integral	10 %
	X-point / MARFE region P_{RAD}	Default	TBD – 0.2 GW	10 ms	Integral	10 %
	Divertor P_{RAD}	Default	TBD – 0.2 GW	10 ms	Integral	10 %
	Total P_{RAD}	Disruption	TBD – 20 GW	1 ms	Integral	20 %
6. Line-Averaged Electron Density	$\int n_e\, dl / \int dl$	Default	$1 \cdot 10^{18} – 1 \cdot 10^{21}\ m^{-3}$	1 ms	Integral	1 %
		After killer pellet	$8 \cdot 10^{20} – 2 \cdot 10^{22}\ m^{-3}$	1 ms	Integral	100 %
7. Neutron Flux and Emissivity	Total neutron flux		$1 \cdot 10^{14} – 1 \cdot 10^{20}\ ns^{-1}$	1 ms	Integral	10 %
	Neutron / α source		$1 \cdot 10^{14} – 5 \cdot 10^{18}\ nm^{-3}s^{-1}$	1 ms	a/10	10 %
	Fusion power		0.01 – 0.25 GW	1 ms	Integral	10 %
	Fusion power density		0.1 - 20 MW m^{-3}	1 ms	a/10	10 %
8. Locked Modes	$B_r(\text{mode})/B_p$		$10^{-4} – 10^{-2}$	1 ms	(m,n) = (2,1)	30 %
9. Low (m,n) MHD Modes, Sawteeth, Disruption Precursors	Mode complex amplitude at wall		TBD	DC – 10 kHz	(0,0) < (m,n) < (10,2)	10 %
	Mode – induced temperature fluctuation		TBD	DC – 10 kHz	0,0) < (m,n) < (10,2) Δr = a /30	10 %
	Other mode parameters		TBD	DC – 30 kHz	Integral	10 %

MEASUREMENT	PARAMETER	CONDITION	RANGE or COVERAGE	ΔT or ΔF	ΔX or Δk	ACCURACY
10. Plasma Rotation	V_{TOR}		1 – 100 km s^{-1}	10 ms	a/30	30 %
	V_{POL}		1 – 50 km s^{-1}	10 ms	a/30	30 %
11. Fuel Ratio in Plasma Core (D-T Operation)	n_T/n_D	r/a < 0.9	0.1 – 10	100 ms	a /10	20 %
12. Impurity Species Monitoring	O, C rel. conc.		$1{\cdot}10^{-4} – 5{\cdot}10^{-2}$	10 ms	Integral	10 % (rel.)
	Be rel. conc.		$1{\cdot}10^{-4} – 5{\cdot}10^{-2}$	10 ms	Integral	10 % (rel.)
	Be influx		$4{\cdot}10^{16} – 2{\cdot}10^{19}\ s^{-1}$	10 ms	Integral	10 % (rel.)
	Cu rel. conc.		$1{\cdot}10^{-5} – 5{\cdot}10^{-3}$	10 ms	Integral	10 % (rel.)
	Cu influx		$4{\cdot}10^{15} – 2{\cdot}10^{18}\ s^{-1}$	10 ms	Integral	10 % (rel.)
	W rel. conc.		$1{\cdot}10^{-6} – 5{\cdot}10^{-4}$	10 ms	Integral	10 % (rel.)
	W influx		$4{\cdot}10^{14} – 2{\cdot}10^{17}\ s^{-1}$	10 ms	Integral	10 % (rel.)
	Extrinsic (Ne, Ar, Kr) rel. conc.		$1{\cdot}10^{-4} – 2{\cdot}10^{-2}$	10 ms	Integral	10 % (rel.)
	Extrinsic (Ne, Ar, Kr) influx		$4{\cdot}10^{16} – 8{\cdot}10^{18}\ s^{-1}$	10 ms	Integral	10 % (rel.)
13. Z_{eff} (Line-Averaged)	Z_{eff}		1-5	10 ms	Integral	20 %
14. H-mode: ELMs and L-H Transition Indicator	ELM D_α bursts	Main Plasma	-	0.1 ms	One site	-
	ELM density transient	r/a > 0.9	TBD			
	ELM temperature transient	r/a > 0.9	TBD			
	L-H D_α step	Main Plasma	-	0.1 ms	One site	-
	L-H Pedestal formation (ne, Te)	r/a > 0.9	-	0.1 ms	-	TBD
15. Runaway Electrons	E_{max}		1 –20 MeV	10 ms	-	20 %
	$I_{runaway}$	After Thermal quench	(0.05 – 0.7) $\cdot I_p$	10 ms		30 % rel
16. Divertor Operational Parameters	Maximum surface temperature		200 – 2500°C	2 ms	1 cm	10 %
	Real-time net erosion		0 – 3 mm	1 s	1 cm apart	0.2 mm
	Gas pressure		$1{\cdot}10^{-4}$ – 5 Pa	50 ms	Several points	20 % during pulse
	Gas composition	A = 1-100 ΔA = 0.5	TBD	1 s	Several points	20 % during pulse
	Position of the ionisation front		0 – 0.3 m	1 ms	2 cm	-

MEASUREMENT	PARAMETER	CONDITION	RANGE or COVERAGE	ΔT or ΔF	ΔX or Δk	ACCURACY
17. First Wall Visible Image & Wall Temperature	1st wall image		TBD	100 ms	1 mm	-
	Wall surface temperature		200 – 1500°C	10 ms	1 cm	20°C
18. Gas Pressure and Composition in Main Chamber	Gas pressure	Between & during pulses	$1 \cdot 10^{-7}$ – 20 Pa	1 s	Several points	20 % during pulse
	Gas composition	A = 1-100 ΔA = 0.5	TBD	10 s	Several points	50 % during pulse
19. Gas Pressure and Gas Composition in Divertor Ducts	Gas pressure	Between & during pulses	TBD	100 ms	Several points	20 % during pulse
	Gas composition	A = 1-100 ΔA = 0.5	TBD	1 s	Several points	20 % during pulse
20. In-Vessel Inspection	Wall image		100 % coverage of first wall and divertor	-	1 mm	-
21. Halo Currents	Poloidal current	In disruption	0 – 0.2 I_p	1 ms	Locations TBD	20 %
22. Toroidal Magnetic Field	B_T		2 – 12 T	1 s	2 locations × 2 methods	0.1 %
23. Electron Temperature Profile	Core T_e	$r/a < 0.9$	0.5 – 15 keV	10 ms	a/30	10 %
	Edge T_e	$r/a > 0.9$	0.05 – 5 keV	10 ms	0.5 cm	10 %
24. Electron Density Profile	Core N_e	$r/a < 0.9$	$3 \cdot 10^{19}$ – $1 \cdot 10^{21}$ m^{-3}	10 ms	a/30	5 %
	Edge N_e	$r/a > 0.9$	$5 \cdot 10^{18}$ – $1 \cdot 10^{21}$ m^{-3}	10 ms	0.5 cm	5 %
25. Current profile	q(r)	Physics study	0.5 - 5	10 ms	a/30	10 %
			5 – TBD	10 ms	1 cm	0.5
	r(q=1.5,2)/a	NTM feedback	0.3 – 0.9	10 ms	2 cm	2 mm
	$r(q_{min})/a$	Reverse shear control	0.3 – 0.7	1 s	2 cm	2 mm
26. Zeff Profile	Z_{eff}	Default	1-5	100 ms	a/10	10 %
		Transients	1-5	10 ms	a/10	20 %
27. High frequency macro instabilities (Fishbones, AEs, turbulence)	Fishbone – induced perturbations in B,T,n		(m,n) =(1,1)	0.1 –10 kHz	1 cm	-
	AE Mode – induced perturbations in B,T,n		n = 10 - 50	10 –300 kHz	1 cm	-
	High frequency turbulence	Correlation	-	10 –300 kHz	1 cm	-
28. Ion Temperature Profile	Core T_i	$r/a < 0.9$	0.5 – 15 keV	100 ms	a/10	10 %
	Edge T_i	$r/a > 0.9$	0.05 – 5 keV	100 ms	1 cm	10 %

MEASUREMENT	PARAMETER	CONDITION	RANGE or COVERAGE	ΔT or ΔF	ΔX or Δk	ACCURACY
29. Core Helium Density	n_{He}/n_e	r/a < 0.9	1 – 20 %	100 ms	a/10	10 %
30. Confined Alphas	Energy Spectrum	Energy resolution TBD	(0.1 – 3.5) MeV	100 ms	a/10	20 %
	Density Profile		$(0.1 – 4)\cdot 10^{18}$ m^{-3}	100 ms	a/10	20 %
31. Escaping Alphas	First wall flux	Default	$1\cdot 10^{-2}$– 2 MW m^{-2}	100 ms	a/10 (along poloidal direction)	10 %
		Transients	$1\cdot 10^{-1}$– 20 MW m^{-2}	10 ms	TBD	30 %
32. Impurity Density Profile	Fractional content, Z<=10	r/a < 0.9	0.5 – 20 %	100 ms	a/10	20 %
		r/a > 0.9	0.5 – 20 %	100 ms	2 cm	20 %
	Fractional content, Z>10	r/a < 0.9	0.01 – 0.3 %	100 ms	a/10	20 %
		r/a > 0.9	0.01 – 0.3 %	100 ms	2 cm	20 %
33. Fuel ratio in the edge	n_T/n_D	r/a > 0.9	0.1 – 10	100 ms	Radial integral	20 %
	n_H/n_D	r/a > 0.9	0.01 – 100	100 ms	Radial integral	20 %
34. Neutron Fluence	First wall fluence per pulse		0.1 – 50 MJ m^{-2}	10 s	TBD	10 %
35. Impurity and D,T Influx in Divertor	Γ_{Be},Γ_W		10^{17} – 10^{22} at s^{-1}	1 ms	1 cm	30 %
	Γ_D,Γ_T		10^{19} – 10^{25} at s^{-1}	1 ms	1 cm	30 %
36. Plasma Parameters at the divertor targets	Ion Flux		10^{19}-10^{25} ions s^{-1}	1 ms	0.3 cm	30 %
	n_e		10^{18} – 10^{22} m^{-3}	1 ms	0.3 cm	30 %
	T_e		1eV –1 keV	1 ms	0.3 cm	30 %
37. Radiation Profile	Main Plasma P_{RAD}		0.01 – 1 MW m^{-3}	10 ms	a/15	20 %
	X-point / Marfe region P_{RAD}		TBD – 300 MW m^{-3}	10 ms	a/15	20 %
	Divertor P_{RAD}		TBD – 100 MW m^{-3}	10 ms	5 cm	30 %
38. Heat Loading Profile in Divertor	Surface Temperature		200 – 2500°C	2 ms	3 mm	10 %
	Power load	Default	TBD – 25 MW m^{-2}	2 ms	3 mm	10 %
		Disruption	TBD – 5 GW m^{-2}	0.1 ms	TBD	20 %
39. Divertor Helium Density	n_{He}		10^{17} – 10^{21} m^{-3}	1 ms	-	20 %
40. Fuel ratio in the Divertor	n_T/n_D		0.1 – 10	100 ms	integral	20 %
	n_H/n_D		0.01 – 100	100 ms	integral	20 %

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MEASUREMENT	PARAMETER	CONDITION	RANGE or COVERAGE	ΔT or ΔF	ΔX or Δk	ACCURACY
41. Divertor electron parameters	n_e		$10^{19} - 10^{22}$ m^{-3}	1 ms	2 cm along leg, 3 mm across leg	20 %
	T_e		0.3 –200 eV	1 ms	2 cm along leg, 3 mm across leg	20 %
42. Ion Temperature in Divertor	T_i		0.3 –200 eV	1 ms	2 cm along leg, 3 mm across leg	20 %
43. Divertor Plasma Flow	V_p		TBD – 10^5 ms^{-1}	1 ms	2 cm along leg, 3 mm across leg	20 %
44. n_H/n_D Ratio in Plasma Core	n_H/n_D		0.01 – 100	100 ms	a/10	20 %
45. Neutral Density between Plasma and First Wall	D/T influx in main chamber		$10^{18} - 10^{20}$ at $m^{-2}s^{-1}$	100 ms	Several poloidal and toroidal locations	30 %

NOTE: FIRE is double-null device with two divertors. The determination of which measurements will be duplicated in the divertors has not been decided.

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 vθ 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)

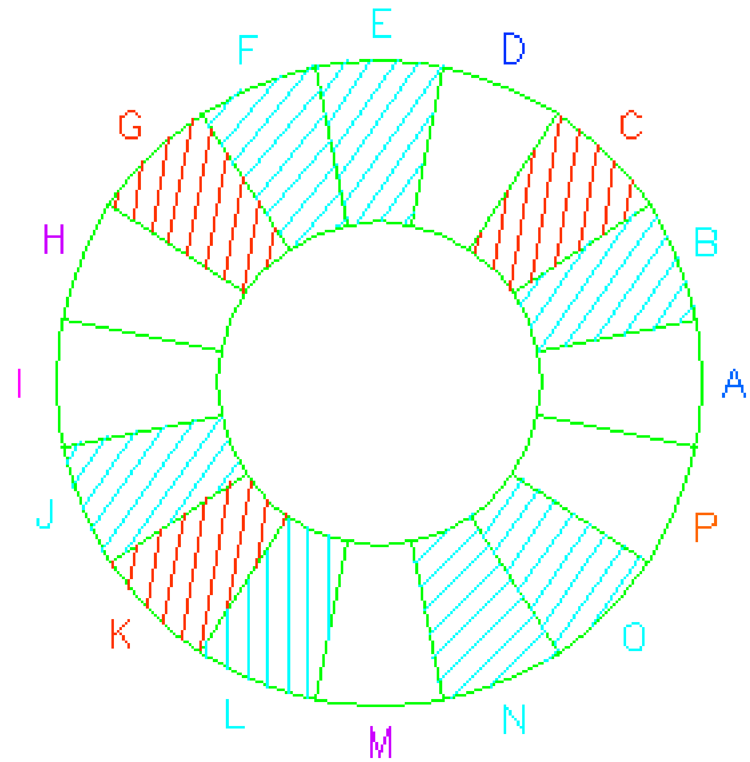
Physics Parameter	Control	Diagnostic Set	Issues and Comments
Alpha-particle Measurements			
Escaping alpha-particles/fast-ions		Faraday cups/scintillators at first wall	Much development needed to handle heat loads and signal transmission
		IR TV imaging	Only gives information about total loss location
Confined thermalizing alphas/spatial distribution		α-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

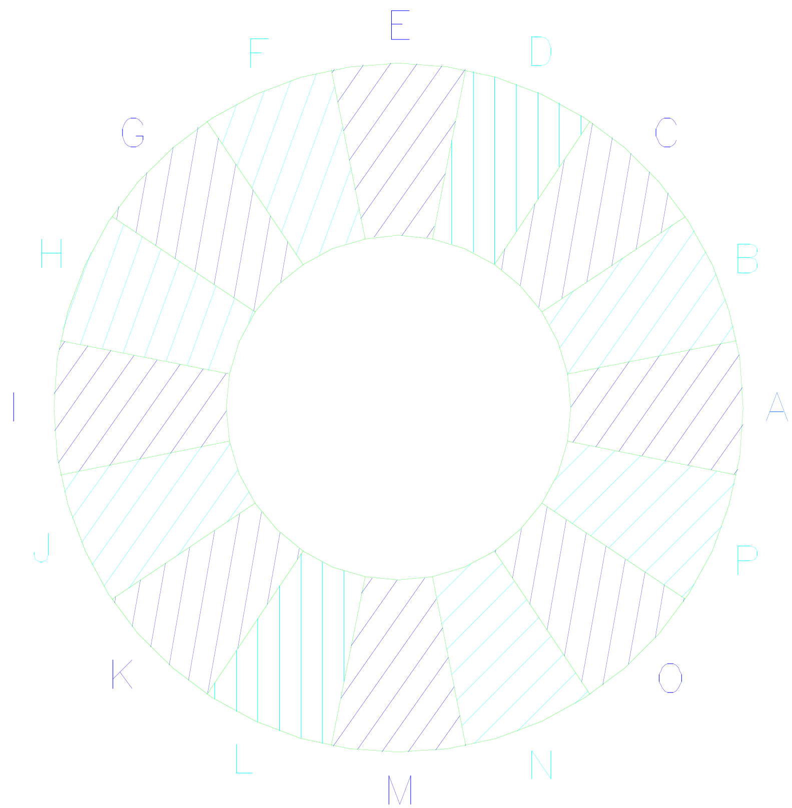
M:

N: Magnetics Wiring

O: FIR Interferometer/Polarimeter

P:

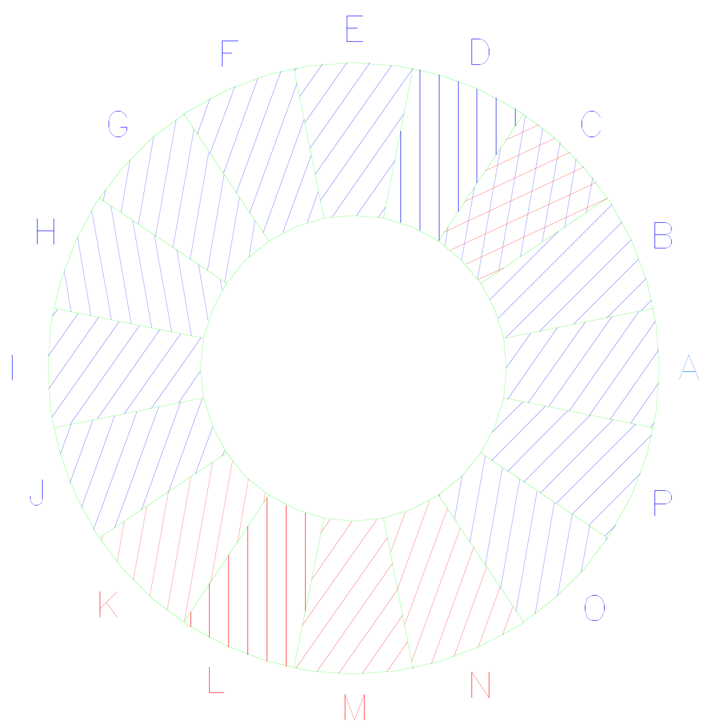
FIRE Diagnostics:
Outer Upper Port Assignments



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

PPPL PRINCETON PLASMA PHYSICS LABORATORY

FIRE Diagnostics:
Radial Port Assignments

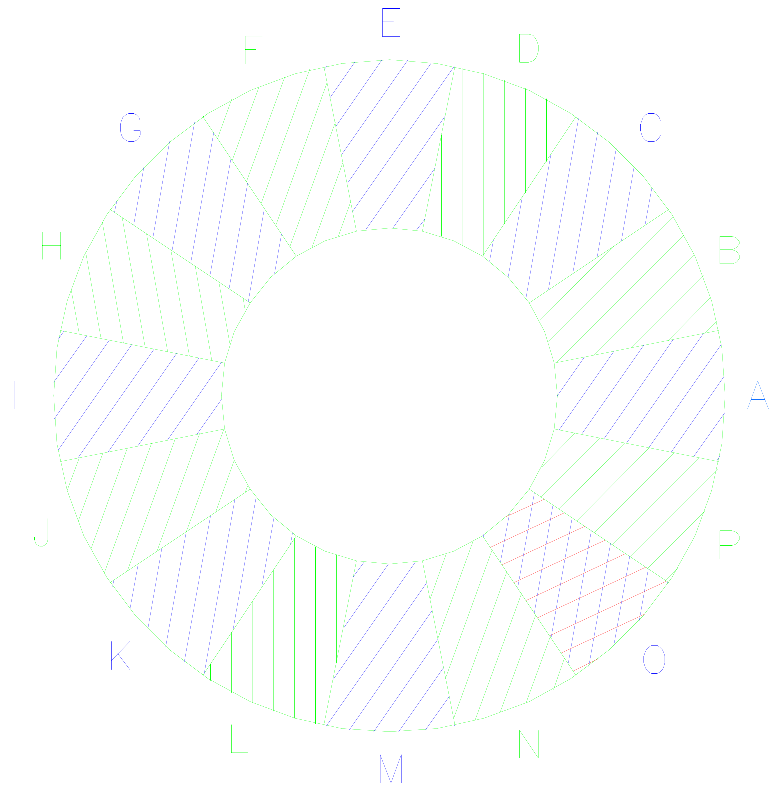


Blue: Diagnostics Components
Orange: Diagnostics-provided Services
Red: Auxiliary Systems
Green: Services

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

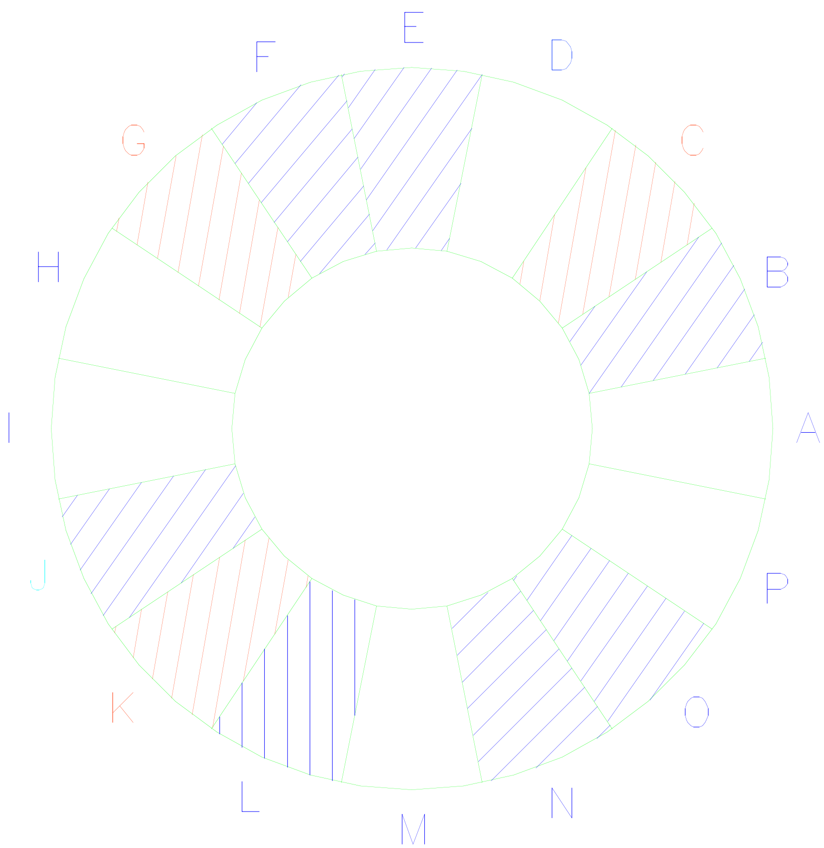
I: TVTS Detection,
Plasma TV,
IRTV
Soft X-ray Array
J: TVTS Laser,
Pellet Charge Exchange,
Li-Pellet Injector,
Hard X-ray Detector
Synchrotron Rad. Detector
K: ICRF Launcher
L: ICRF Launcher
M: ICRF Launcher
N: ICRF Launcher
O: FIR Interferometer/ Polarimeter,
Plasma TV,
IR TV,
Bolometer Array
P: MSE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

FIRE Diagnostics:
Outer Lower Port Assignments



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: 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: