FIRE and its Diagnostics: a Status Report

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for
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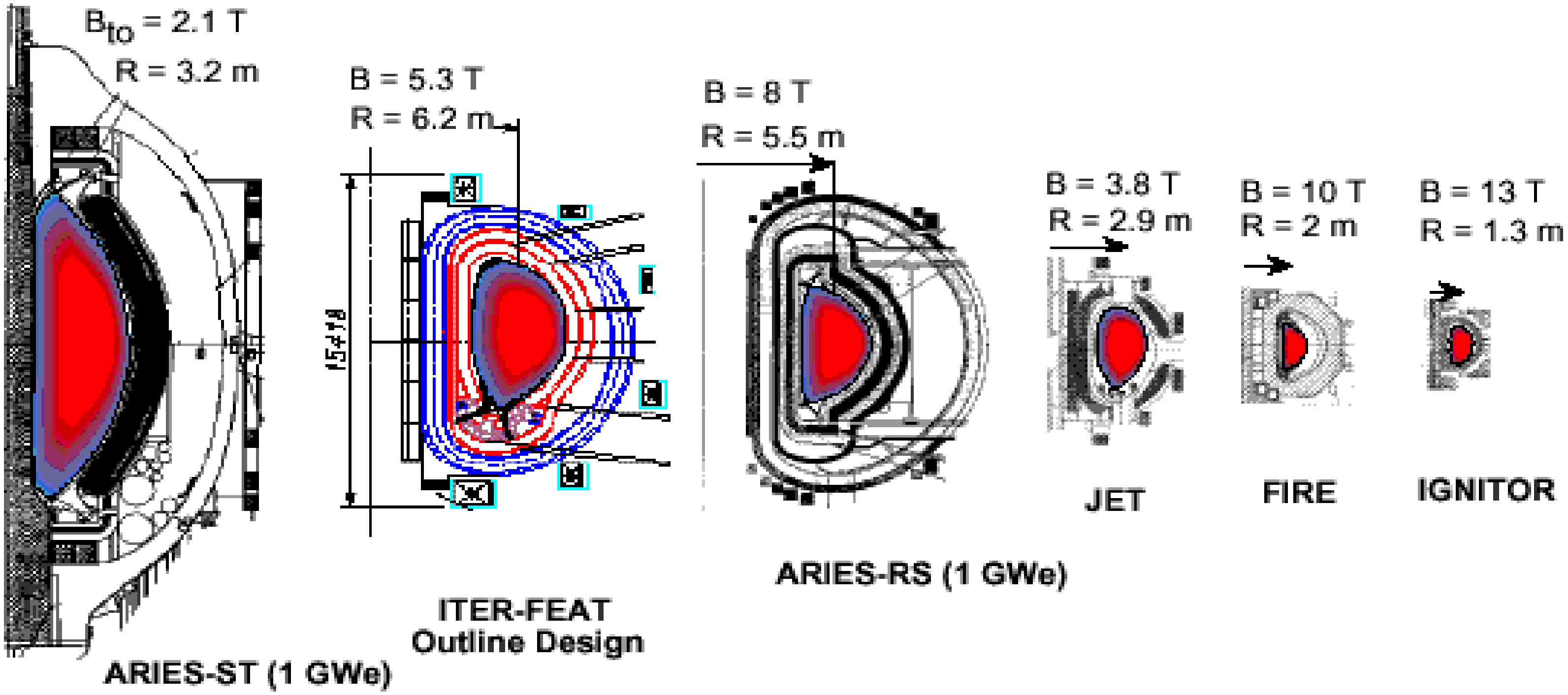
St. Petersburg, Russia

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.

Comparison of Burning Plasma options with JET



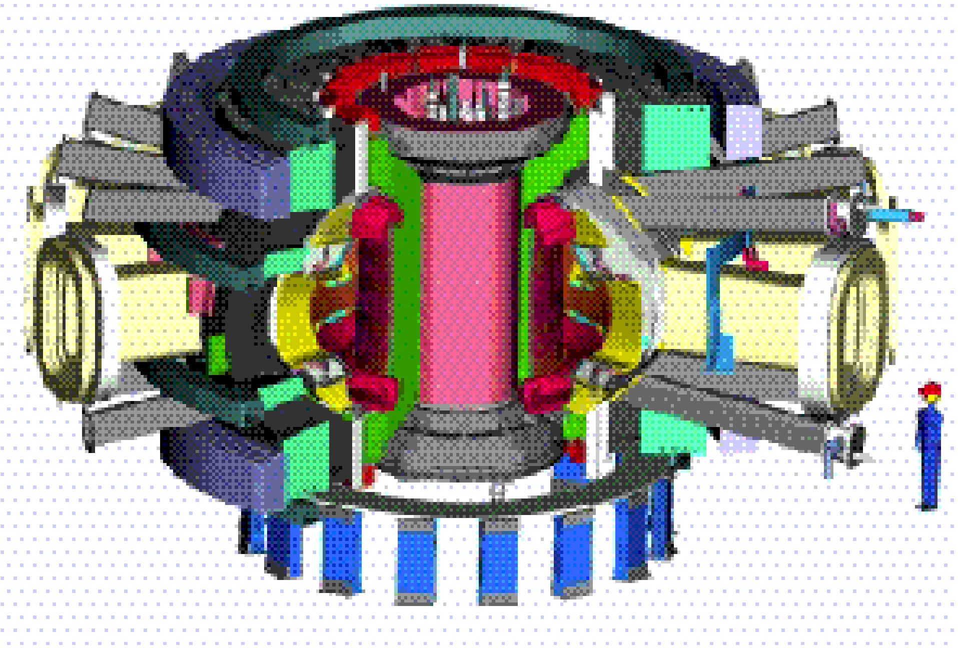
Fusion Power (MW)	**3000**	**500**	**2200**	**16**	**200**	**100**
Burn Time (s), inductive	**steady**	**300**	**steady**	**1**	**20**	**5**

Outline

- Description of FIRE
  - Mission
  - Main tokamak components
  - Radiation environment
- Diagnostic integration
  - Issues
  - Proposed diagnostics
  - Alpha-particle diagnostics
- Draft R&D proposals
- Final thoughts

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 ≈ 10, P_{fusion} ~ 150 MW
- Burn Time ≈ 20 s
- Tokamak Cost ≈ $375M (FY99)
- Total Project Cost ≈ $1.2B at Green Field site.

Mission:

Attain, explore, understand and optimize fusion-dominated plasmas that will provide knowledge for attractive MFE systems.

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Critical Issues to be Addressed in the Next Stage of Fusion Research

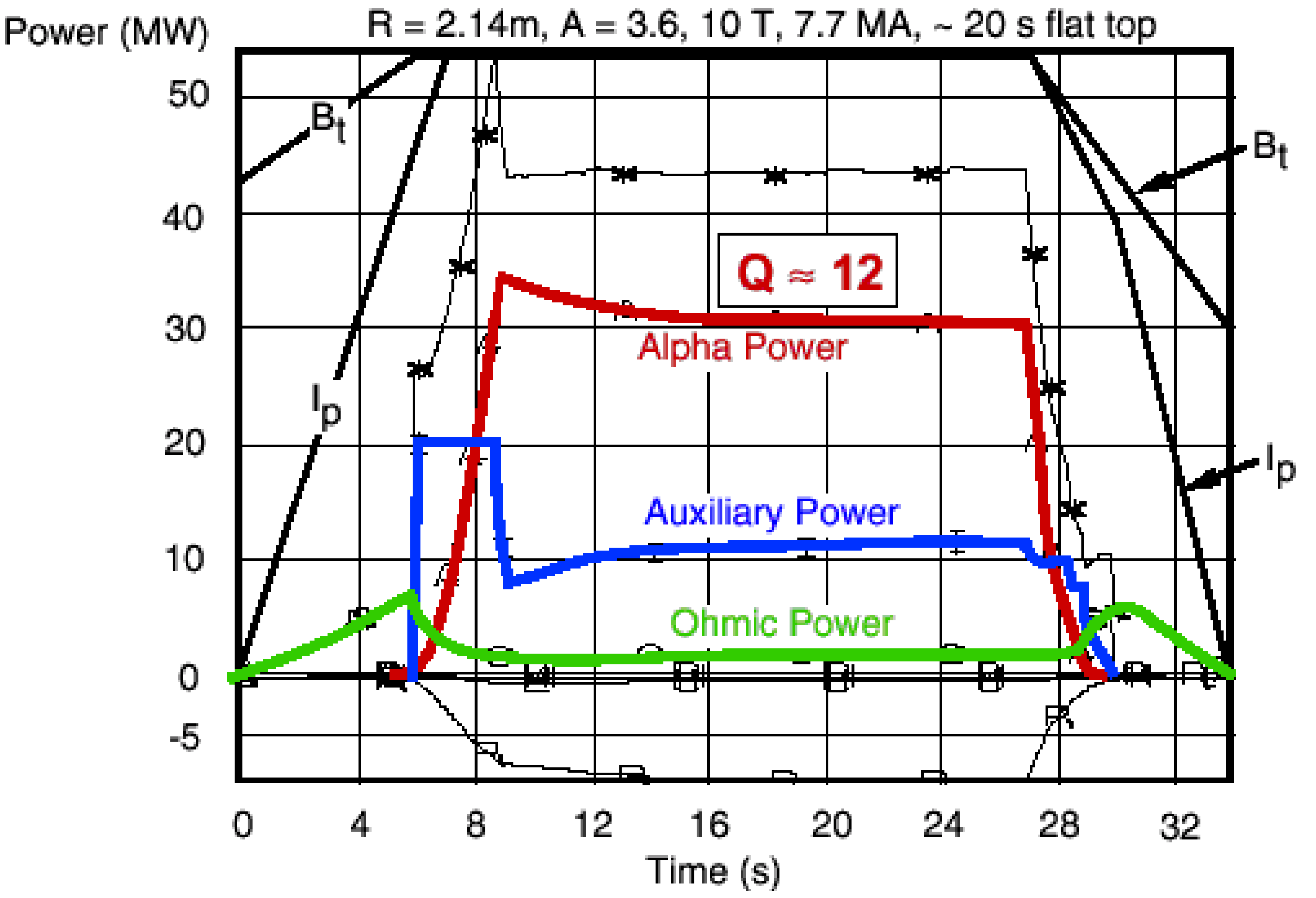
- **Burning Plasma Physics**
  - strong nonlinear coupling inherent in a fusion dominated plasma
  - access, explore and understand fusion dominated plasmas

- **Advanced Toroidal Physics**
  - develop and test physics needed for an attractive MFE reactor
  - couple with burning plasma physics

- **Boundary Physics and Plasma Technology** (coupled with above)
  - high particle and heat flux
  - couple core and divertor
  - fusion plasma - tritium inventory and helium pumping

- **Neutron Resistant Materials** (separate facility)
  - high fluence testing using “point”neutron source

11/2-D Simulation of Burn Control in FIRE* (TSC)



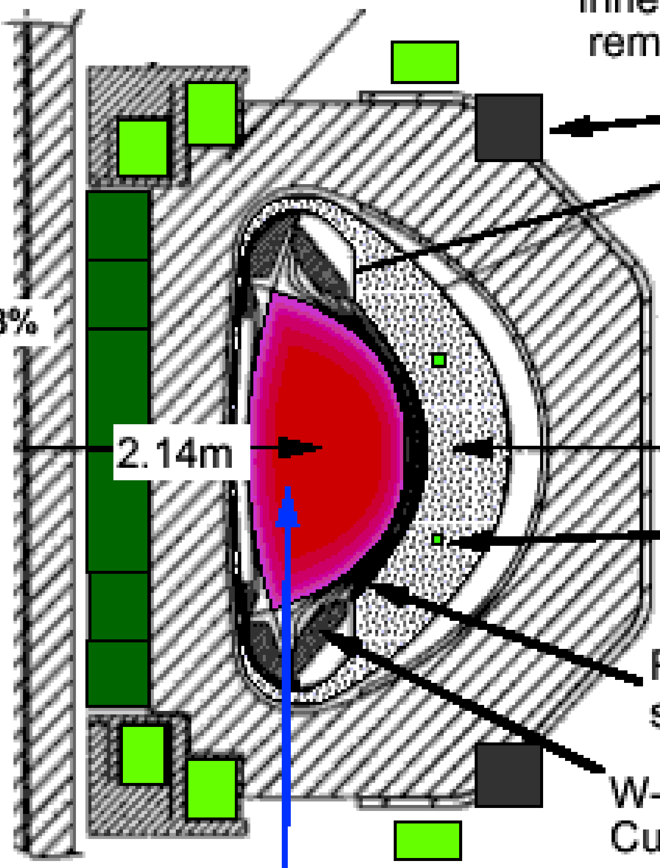
- ITER98(y,2) scaling with H(y,2) = 1.1, n(0)/<n> = 1.2, and $n/n_{GW} = 0.67$
- Burn Time ≈ 20 s ≈ 21 $\tau_E \approx 4\ \tau_{He} \approx 2\ \tau_{skin}$

Q = Pfusion/(Paux + Poh)

FIRE Incorporates Advanced Tokamak Innovations

AT Features

- DN divertor
- strong shaping
- very low ripple < 0.3%
- internal coils
- space for wall stabilizers
- inside pellet injection
- large access ports



Wedged TF Coils (16), 15 plates/coil*
Inner Leg BeCu C17510,
remainder OFHC C10200

Compression Ring

Double Wall Vacuum
Vessel (316 S/S)

All PF and CS Coils*
OFHC C10200

Internal Shielding
(60% steel & 40%water)

Vertical Feedback and Error
Field Correction Coils

Passive Stabilizer Plates
space for wall mode stabilizers

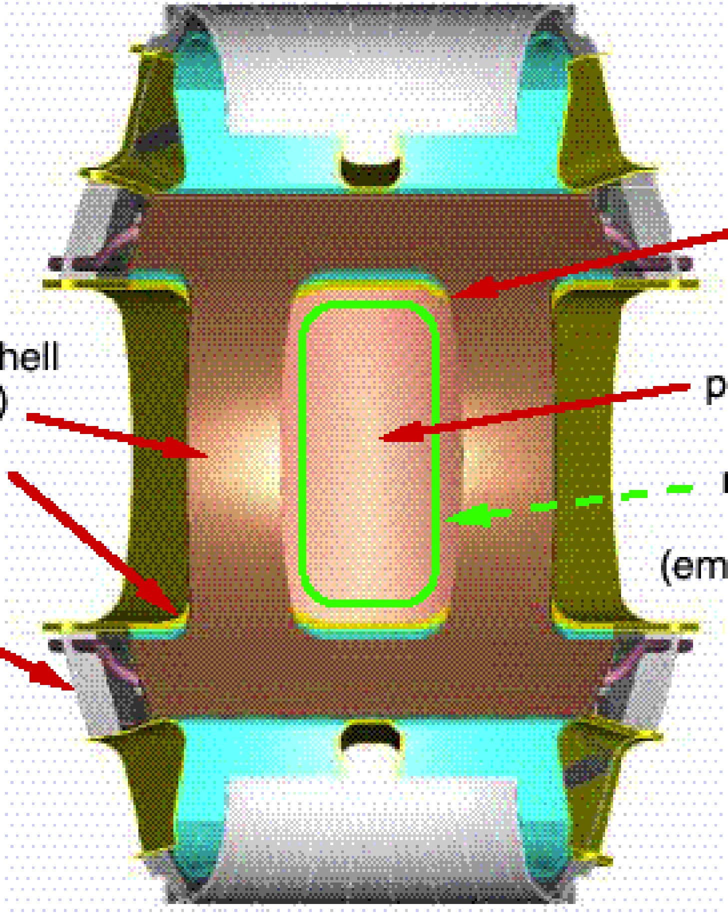
W-pin Outer Divertor Plate
Cu backing plate, actively cooled

Direct and Guided Inside Pellet Injection

*Coil systems cooled to 77 °K prior to pulse, rising to 373 °K by end of pulse.

Potential for Resistive Wall Mode Stabilization System

view of hoizontal port front looking from plasma side



horizontal port
(1.3 m x 0.65 m)

port shield plug (generic)

resistive wall mode
stabilization coil
(embedded in shield plug)

Copper Stabilizing Shell
(backing for PFCs)

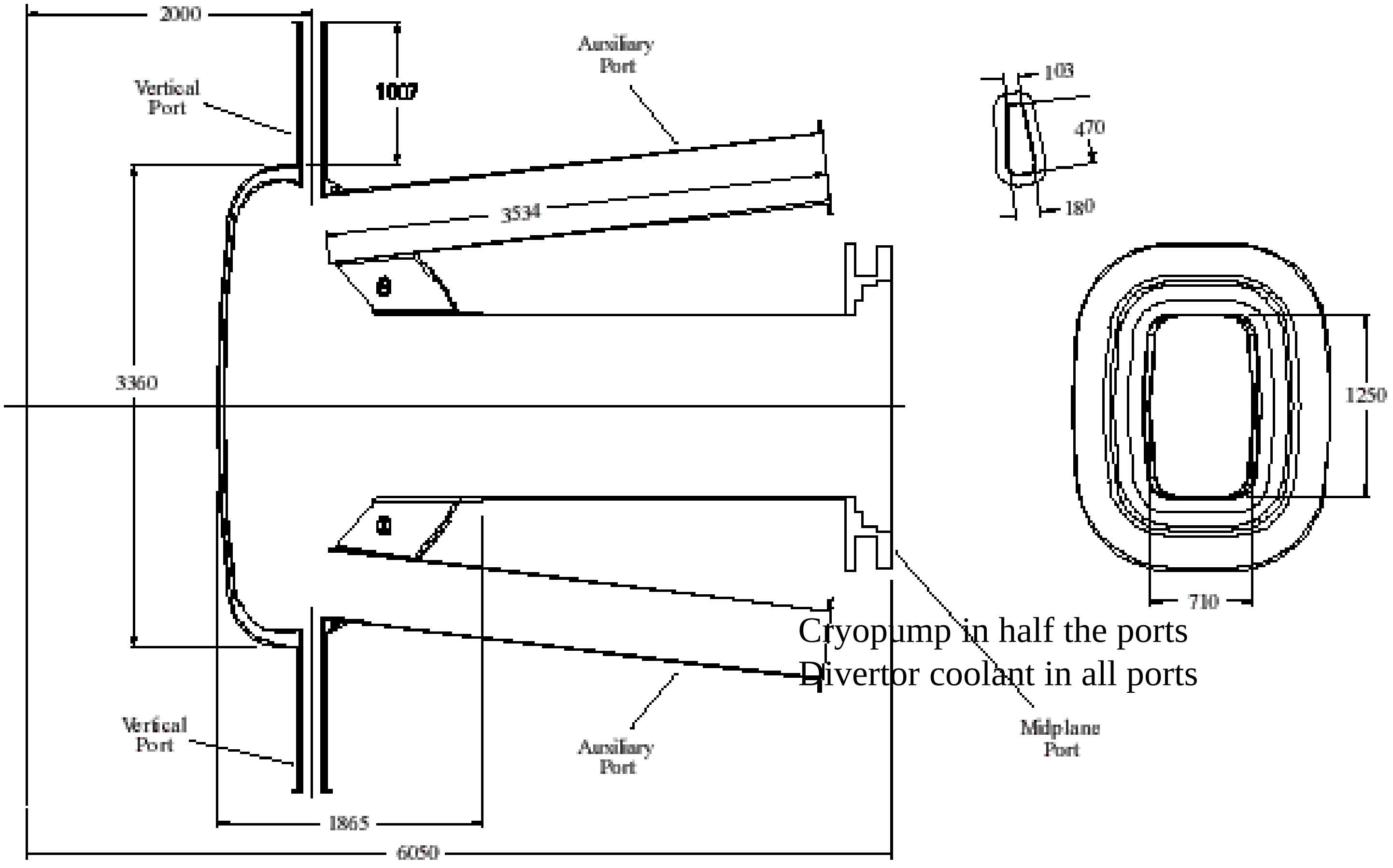
1st Vacuum Shell

2nd Vacuum Shell

Wall stabilization required to attain full Advanced Tokamak potential.

Concept under development by Columbia Univ. J. Bialek, G. Navratil, C.Kessel(PPPL) et al

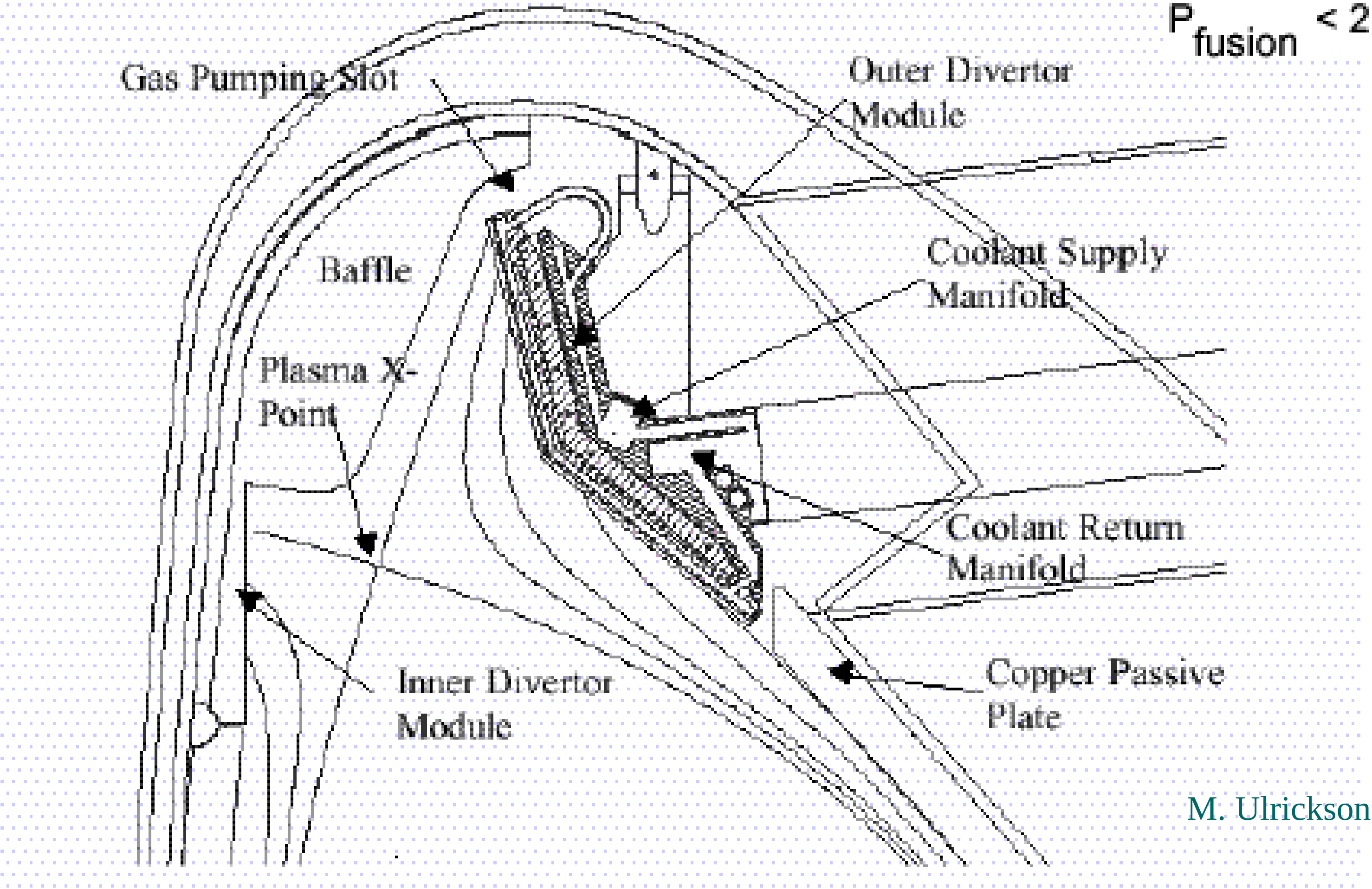
Vessel port configuration



Cryopump in half the ports
Divertor coolant in all ports

50 x 150 port

FIRE's Divertor can handle Attached (<25 MW/m^2) and Detached (5 MW/m^2) Operation



$P_{fusion} < 200$ MW

M. Ulrickson et al. (Sandia)

Reference plan is semi-detached operation with <15 MW/m^2

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	$2.50x10^{10}$	$9.46x10^{9}$	$7.71x10^{9}$	$6.2x10^{-2}$	$1.63x10^{3}$

* 5TJ DT and 0.5 TJ DD

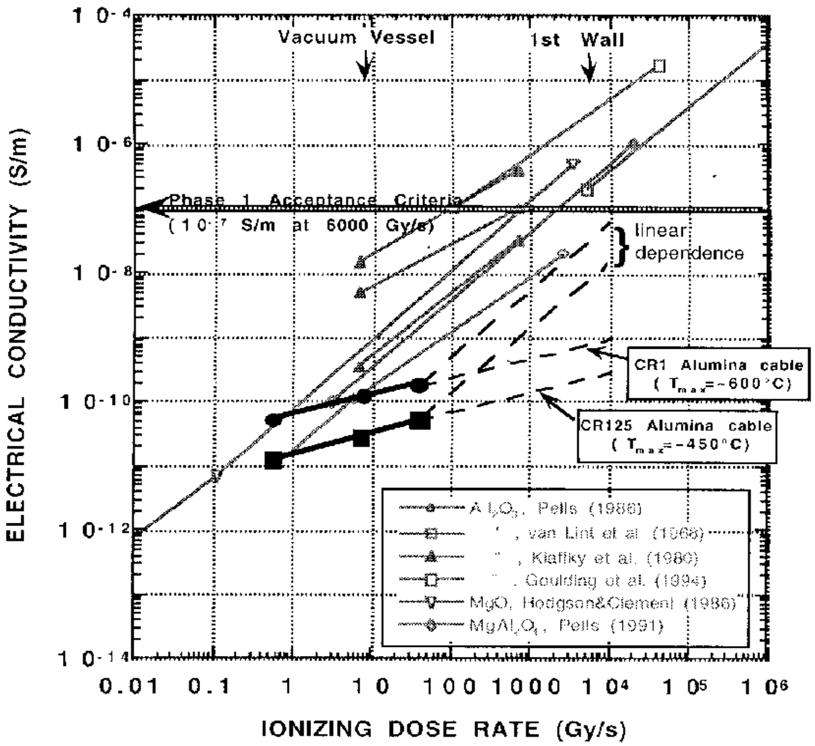
Mohamed Sawan (U. Wisconsin)

Diagnostic Integration Design Issues

- 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.

Magnetic Diagnostics: Issues

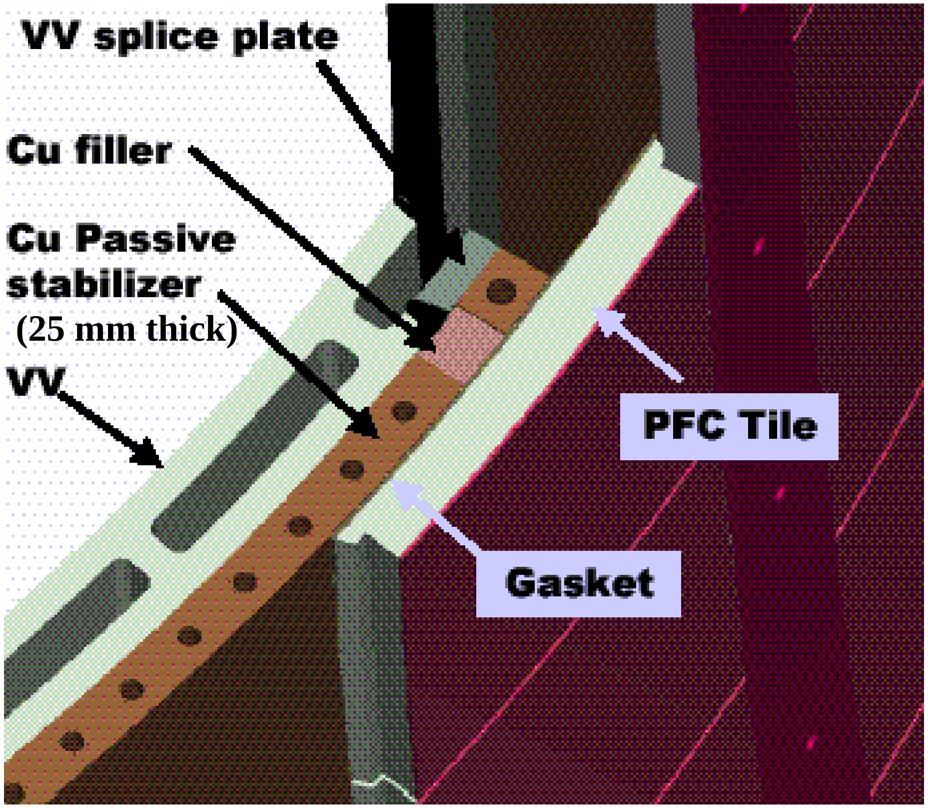
- Loops, coils, MI-cable must be inside vacuum vessel,
- Maximally unfriendly environment; RIC and RIEMF, temperature, neutral particles,
- Very limited space behind tiles;
  - need grooves in tiles, cladding,
  - potential poloidal locations at vacuum vessel segment boundaries
- Renew R&D program on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



COMPARISON OF THE MEASURED RADIATION INDUCED CONDUCTIVITY IN MONOLITHIC CERAMICS vs. MI CABLES

Zinkle et al.

Passive conductor is also heat sink



- Copper layer required to prevent large temperature gradients in VV due to nuclear heating, PFCs
- Passive plates are required in most locations anyway
- PFCs are conduction cooled to copper layer
  - Reduces gradient in stainless skin
  - Extends pulse length

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

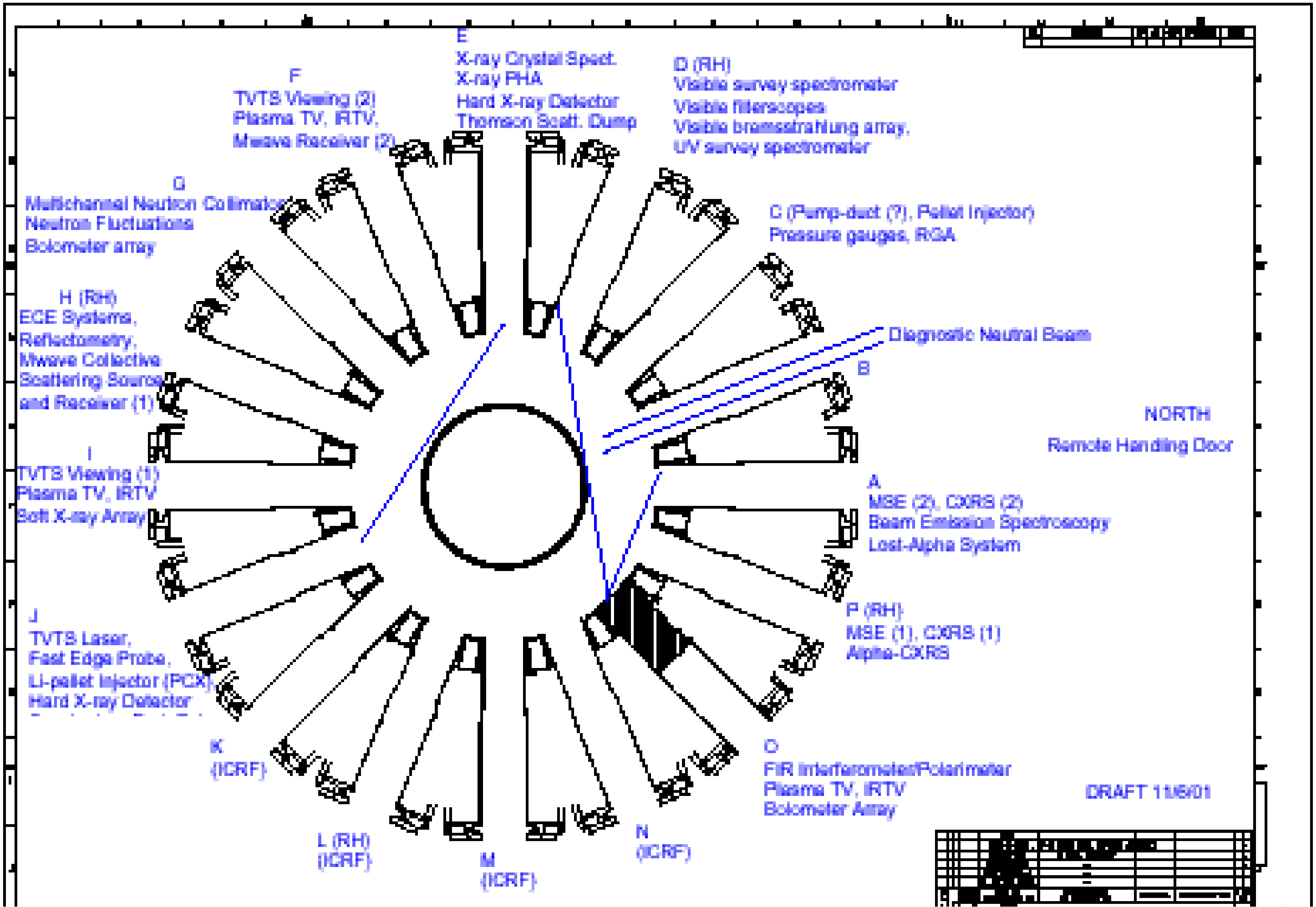
Diagnostics proposed for FIRE (4)

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		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

Possible Radial Port Layout for FIRE



K.M.Young 14 Nov. 01

1st ITPA Diagnostics, St. Petersburg, Russia

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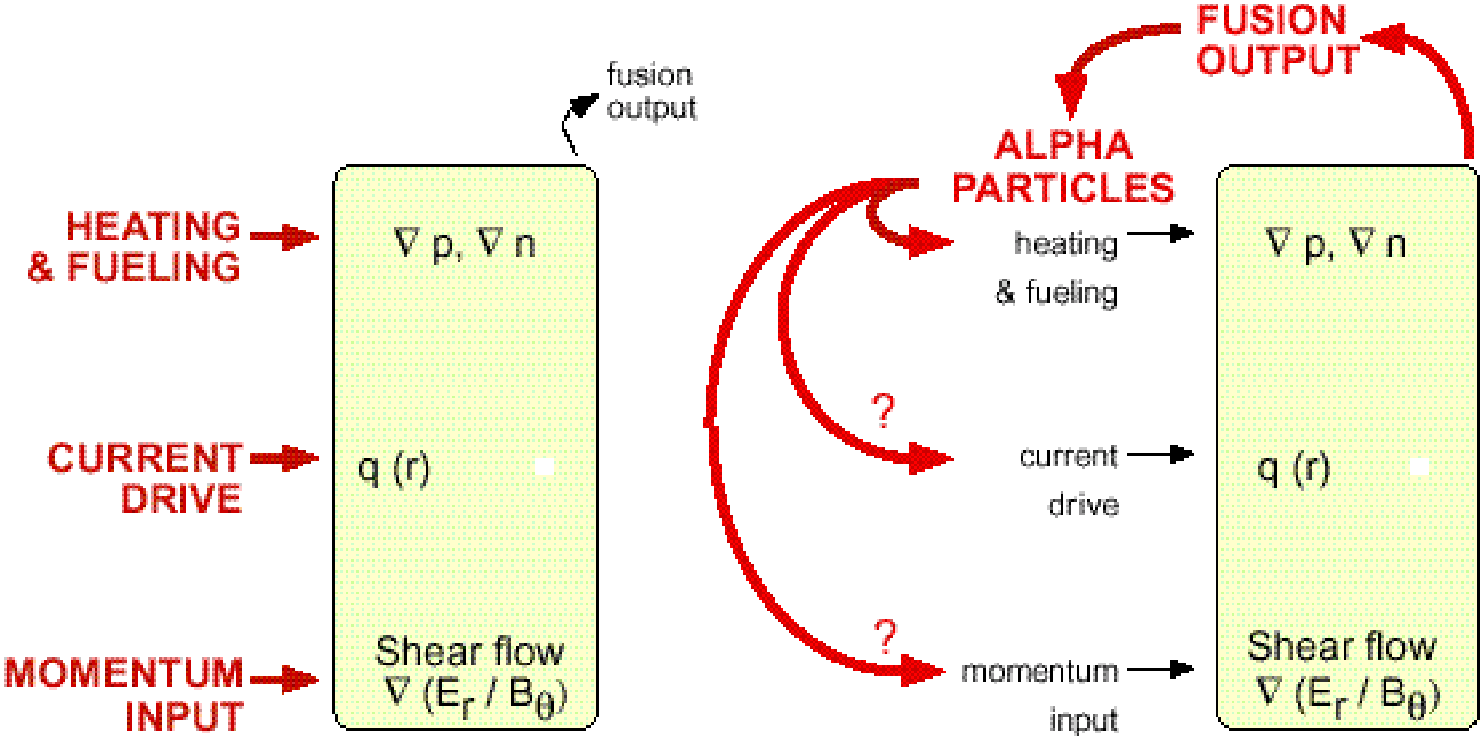
Measurement of the internal energy source essential as we move from externally-driven to internally-driven plasmas

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

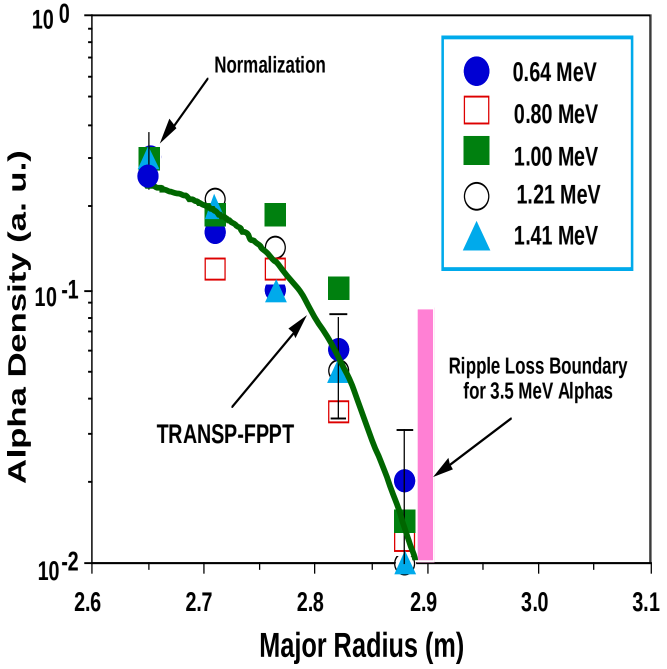


R. Nazikian

Diagnostics for Alpha-Particle Physics

- Lost fast-ion detectors and IR camera,
- 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???
- High-frequency Mirnov coils, reflectometry.

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_α = 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 (continuing work which involved GA and ORNL) .
  - 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 (continuing work done for ITER) .
- 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 rad-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

Some Final Thoughts

- The small size, high field, high density FIRE plasma does provide 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 requirements for ITBs.
- A diagnostic beam is essential for control and physics: profiles of q, ion temperature, rotation, He-ash, slowing-αs, and possibly E_r require it. A short pulse beam does not permit BES fluctuation measurement.
- Microwave scattering has been adopted for measurement of confined-αs: TEXTOR data shows promise. Development of new techniques should be encouraged.
- Development of a technique for measuring the escaping-αs is necessary; test should be done on JET-EP.
- Polarimetry for support of core q measurements is probably not possible, but edge-q using polarimetry of a Li-beam may be possible.