Diagnostics for FIRE

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(and the FIRE Team)

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KSTAR Diagnostics Meeting

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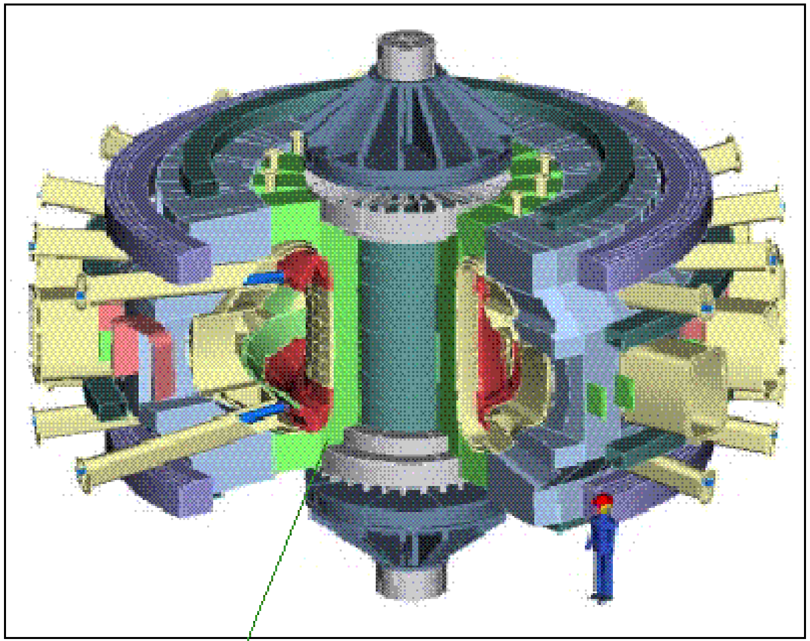
Outline of Talk

- FIRE
  - Mission and objectives
  - Design features
  - Nuclear information
- FIRE Diagnostics
  - Physics perspective
  - Aspects to be considered in design
  - Schedule
  - Provisional list of diagnostics

Fusion Ignition Research Experiment (FIRE)



LN BeCu ("HTS")

Design Goals

- R = 2.0 m, a = 0.525 m
- B = 10 T, (12T)*
- W_{mag}= 3.8 GJ, (5.5 GJ)*
- I_p = 6.5 MA, (7.7 MA)*
- $P_{alpha} > P_{aux}$, P_{fusion} ~ 220 MW
- Q ~ 10, τ_E ~ 0.55s
- Burn Time ~ 20s (12s)*
- Tokamak Cost ≤ $0.3B

  Base Project Cost ≤ $1B

* Higher Field Option

Attain, explore, understand and optimize alpha-dominated plasmas to provide knowledge for the design of attractive MFE systems.

Fusion Science Objectives for a Major Next Step Experiment

- Explore and understand the physics of alpha-dominated fusion plasmas;
  - Energy and particle transport (extend confinement predictability)
  - Macroscopic stability (β-limit, wall stabilization, NTMs)
  - Wave-particle interactions (fast alpha driven effects)
  - Plasma boundary (density limit, power and particle flow)
  - Strong coupling of previous issues due to self-heating (self-organization?)
- Test techniques to control and optimize alpha-dominated plasmas.
- Sustain alpha-dominated plasmas - high-power-density exhaust of plasma particles and energy, alpha ash exhaust, study effects of profile evolution due to alpha heating on macrostability, transport barriers and energetic particle modes.
- Explore and understand some advanced operating modes and configurations that have the potential to lead to attractive fusion applications.

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FIRE General Requirements

R, major radius	2.0 m
a, minor radius	0.525 m
κ95, elongation at 95% flux surface	~1.8
δ95, triangularity at 95% flux surface	~0.4
q95, safety factor at 95% flux surface	>3
Bt, toroidal magnetic field	10 T with 16 coils, < 0.5% ripple @ Outer MP
Toroidal magnet energy	3.7 GJ
Ip, plasma current	~6.5 MA (7.7 MA at 12 T)
Magnetic field flat top, burn time	21 s at 10 T, P_{fusion} ~ 200 MW)
Pulse repetition time	2 hr @ full field
ICRF heating power, maximum	30 MW, 100MHz for $2\Omega_T$, 4 mid-plane ports
Neutral beam heating	None, may have diagnostic neutral beam
Lower Hybrid Current Drive	None in baseline, upgrade for AT phase
Plasma fueling	Pellet injection (≥2.5km/s vertical launch inside mag axis, possible guided slower speed pellets)
First wall materials	Be tiles, no carbon
First wall cooling	Inertial between pulses
Divertor configuration	Double null, fixed X point, detached mode
Divertor plate	W rods on Cu backing plate (ITER R&D)
Divertor plate cooling	Inner plate-inertial, outer plate active - water
Fusion Power/ Fusion Power Density	~200 MW, ~10 MW m-3 in plasma
Neutron wall loading	~ 3 MW m-2
Lifetime Fusion Production	5 TJ (BPX had 6.5 TJ)
Total pulses at full field/power	3,000 (same as BPX), 30,000 at 2/3 Bt and Ip
Tritium site inventory	Goal < 30 g, Category 3, Low Hazard Nuclear Facility

Upgrade to B = 12T and Ip = 7.7MA with a 12 second flat top has been identified.

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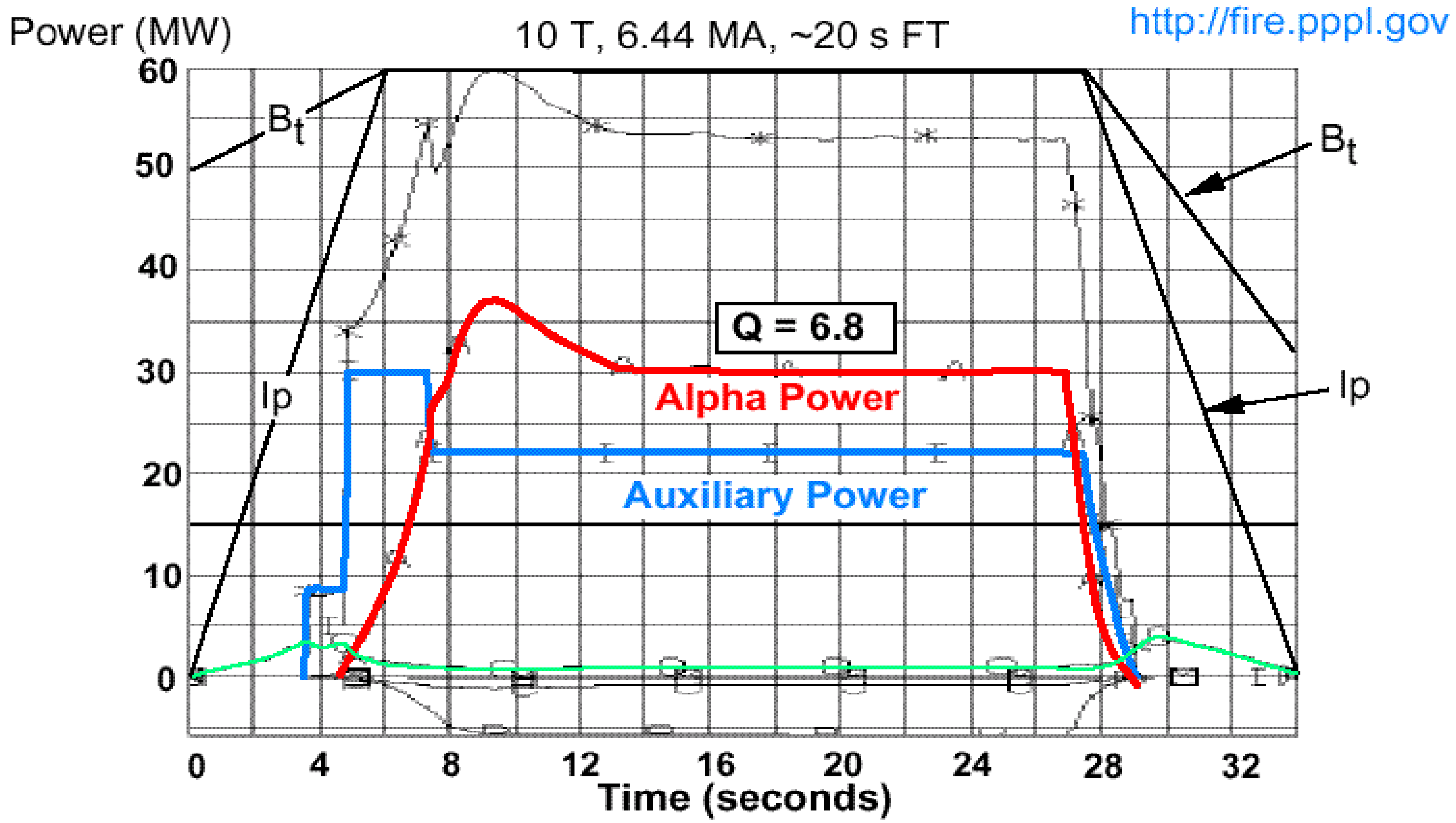
1 1/2-D Simulation of Burn Control in FIRE



- ITER98(y, 2) scaling with H(y,2) = 1.0, n(0)/<n> = 1.25 and n/n_{GW} = 0.59
  - Pulse Duration ≈ 30 τ_E, 6 τ_{He} and ~1.5 τ_{skin}

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FIRE Design Study

- A compact high field tokamak utilizing copper coils pre-cooled to LN temperatures is being evaluated.
- The general configuration was modeled after future advanced reactors (e.g., ARIES-RS and ARIES-AT)
  - Strong plasma shaping $k_{95} \sim 1.77$, $d_{95} \sim 0.40$
  - Double null poloidal divertor
  - Aspect ratio ~ 3.8
  - low ripple $\leq 0.34\%$
- The minimum size (cost) device is being sought, therefore the physics parameter choices were chosen to be in the direction toward moderately enhanced physics performance which is the direction leading to attractive fusion reactors.
- Physics performance projections based on the latest confinement database and scaling relations indicate that FIRE can access fusion dominated conditions, for a significant fraction of points in the data base, at densities well below the Greenwald density with modest profile peaking. (http://fire.pppl.gov and IAEA CN-77 FT-P2/16).

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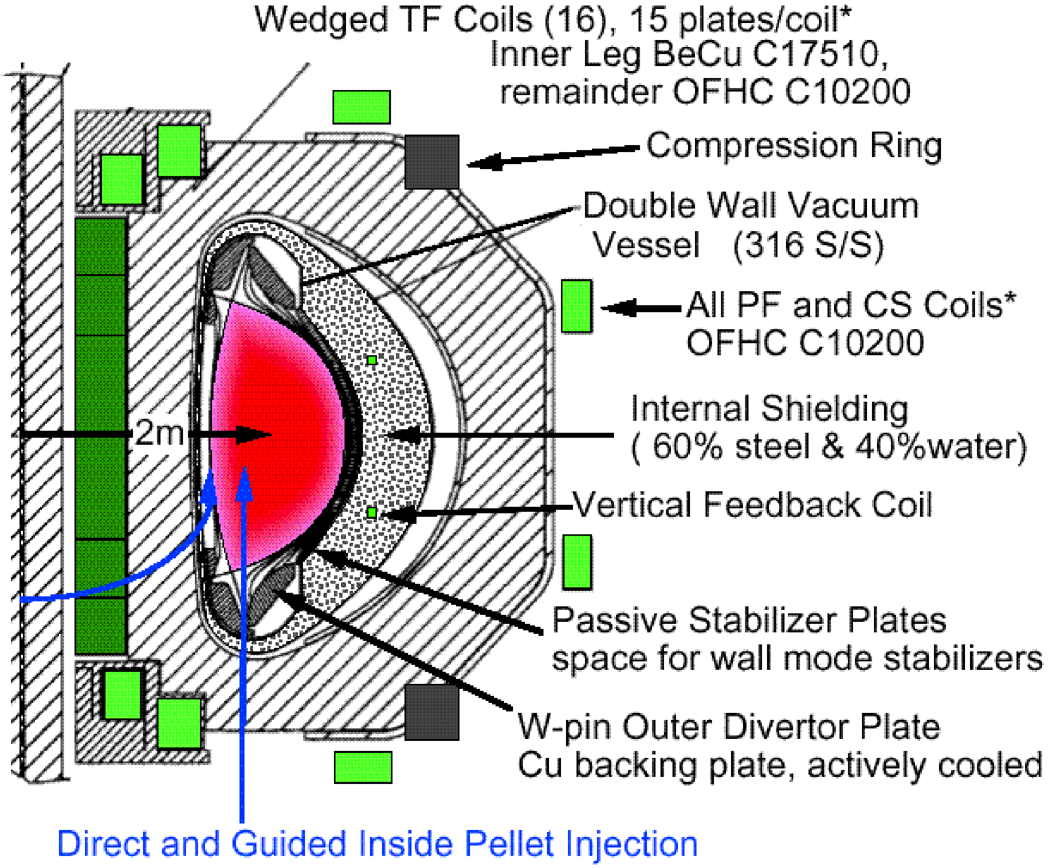
FIRE Design Incorporates Advanced Tokamak Innovations

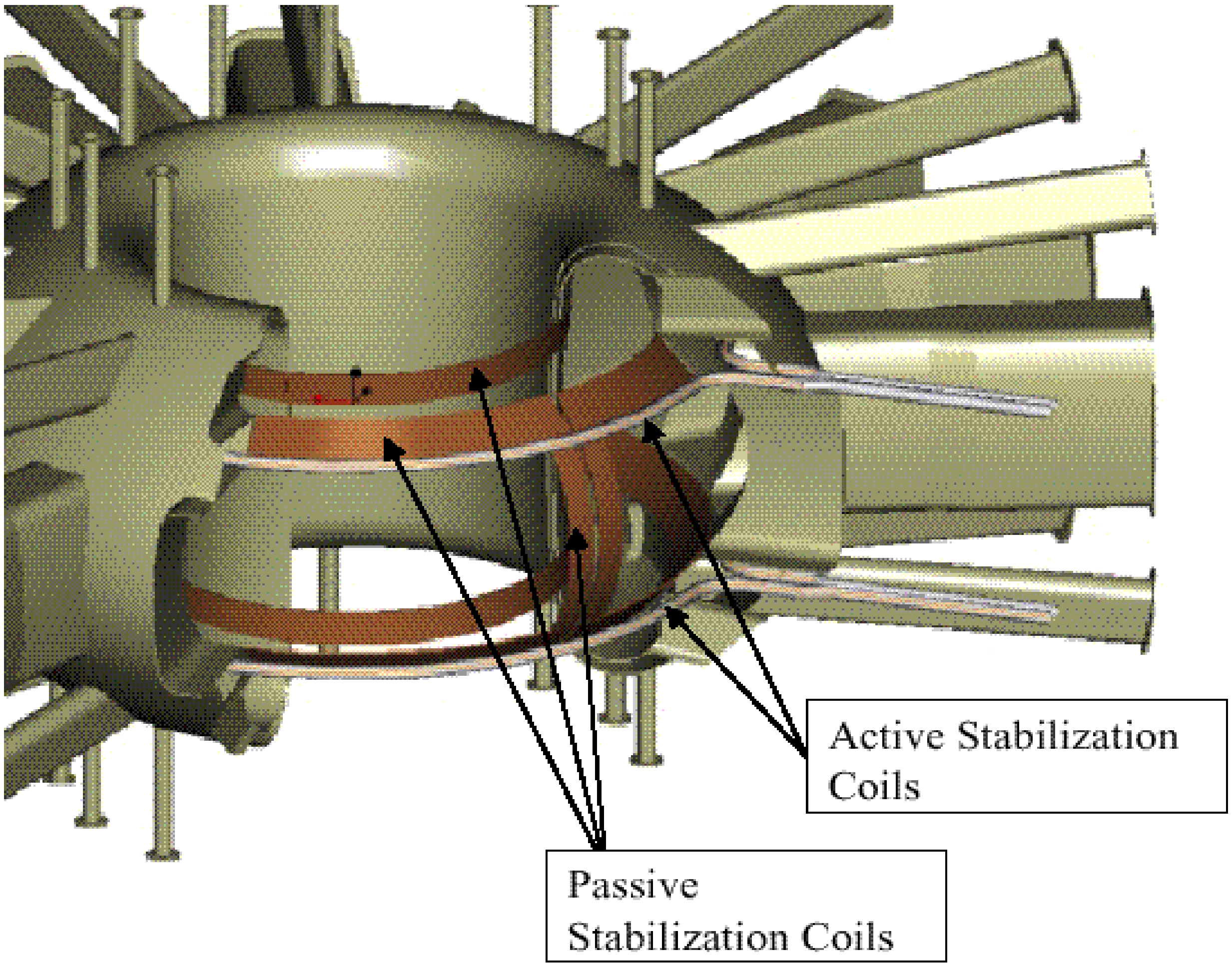
AT Features

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



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

FIRE would have Good Access for Diagnostics and Heating



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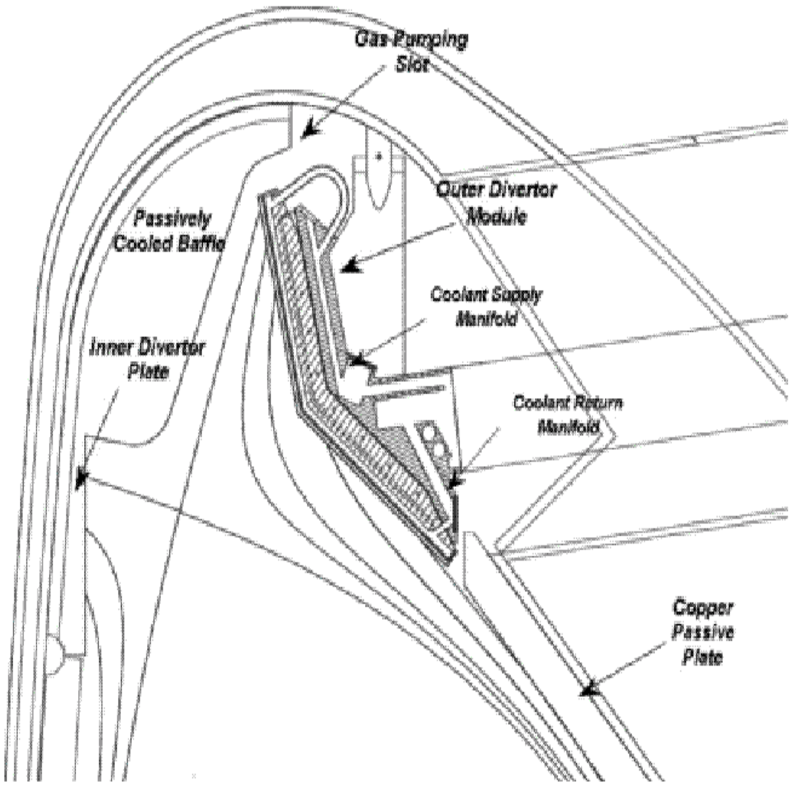
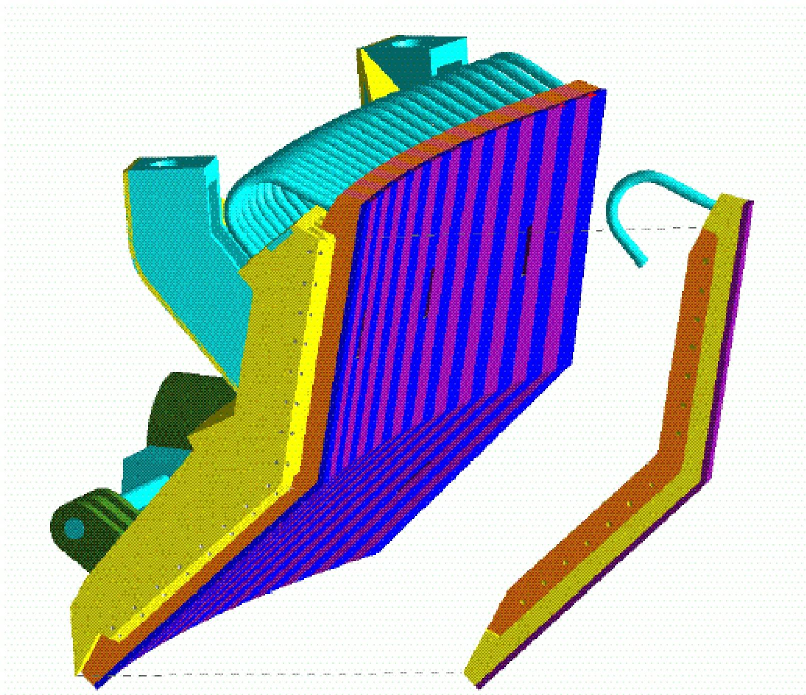
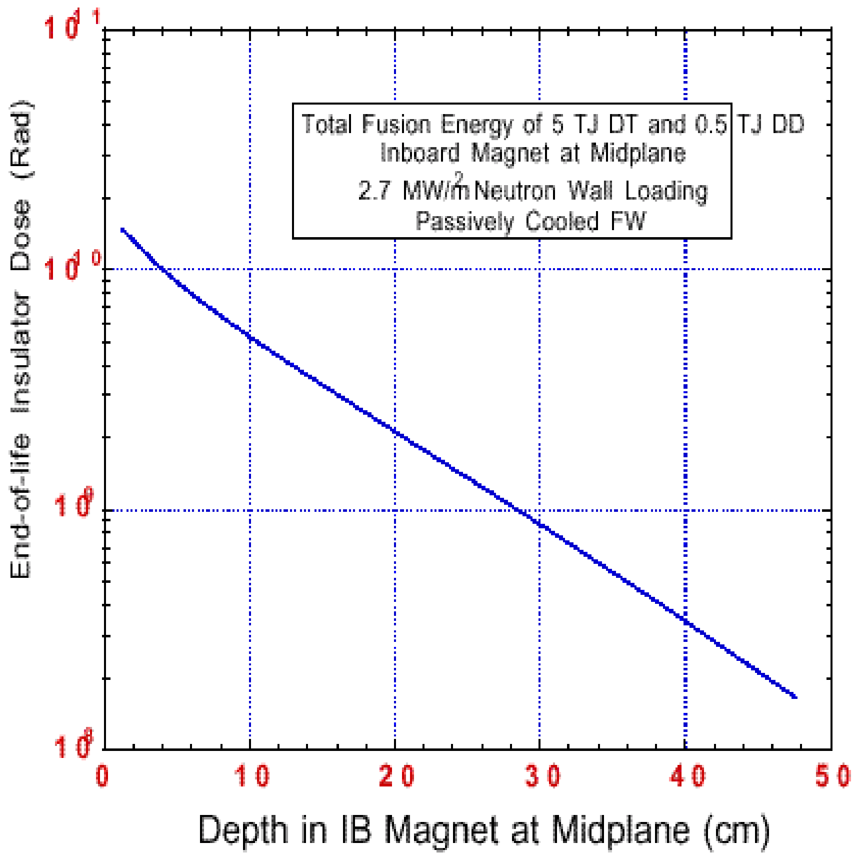
The FIRE Divertor

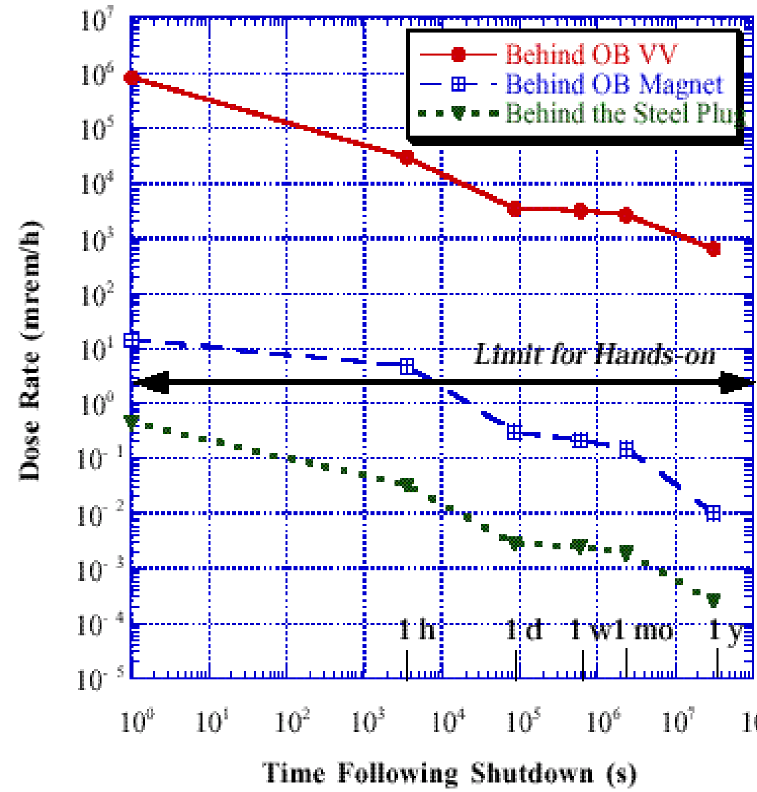




Key Nuclear Radiation Data



Radiation dose at inboard magnet



Biological dose rates at the midplane as a function of time following shutdown

FIRE Neutron Wall Loading and Radiation Dose at Different Poloidal Locations outside Vacuum Vessel

	Total VV thickness (cm)	Neutron wall loading (MW/m^2)	Peak Insulator Dose Rateoutside VV (Gy/s)
IB midplane	5	2.7	4.82×10^3
IB Z= 60 cm	5	2.4	4.28×10^3
OB midplane	57	3.6	3.43
OB Z= 90 cm	45	2.7	11.8
Divertor	12	1.8	

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U. Wisconsin

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Radiation Effects
(Ceramics (1), Fiberoptics (2), Mirrors (3))
(Windows)

	First Wall (Gy/s)	Interspace Structure/ Shielding	Outside Vac. Vess. Port (Gy/s)	Fluence
ITER-FEAT	$4x10^3$ + neutrals →	<----------------> →	5	Issue (long-term damage) Few x 0.1 dpa
FIRE	$2x10^4$ + 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 components ? (2) Vacuum-diag. Detectors? (1)	

Numbers are approximate and average

K. M. Young 21 September 2000

For Diagnostic Components	Worst Radiation Problem
• Ceramics (and Detectors)	Electrical (RIC, RIED, RIEMF, TSC)
• Fiberoptics (and Windows)	Absorption, Luminescence, Numerical aperture
• Mirrors	Mechanical + Neutrals in Surface Modification

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Role for the Plasma Measurements

- 1) Provide data for physics studies for the evaluation of plasma performance in D,
- 2) Provide input for real-time plasma control systems,
- 3) Provide first evaluation of plasmas where alpha-particle heating dominates.

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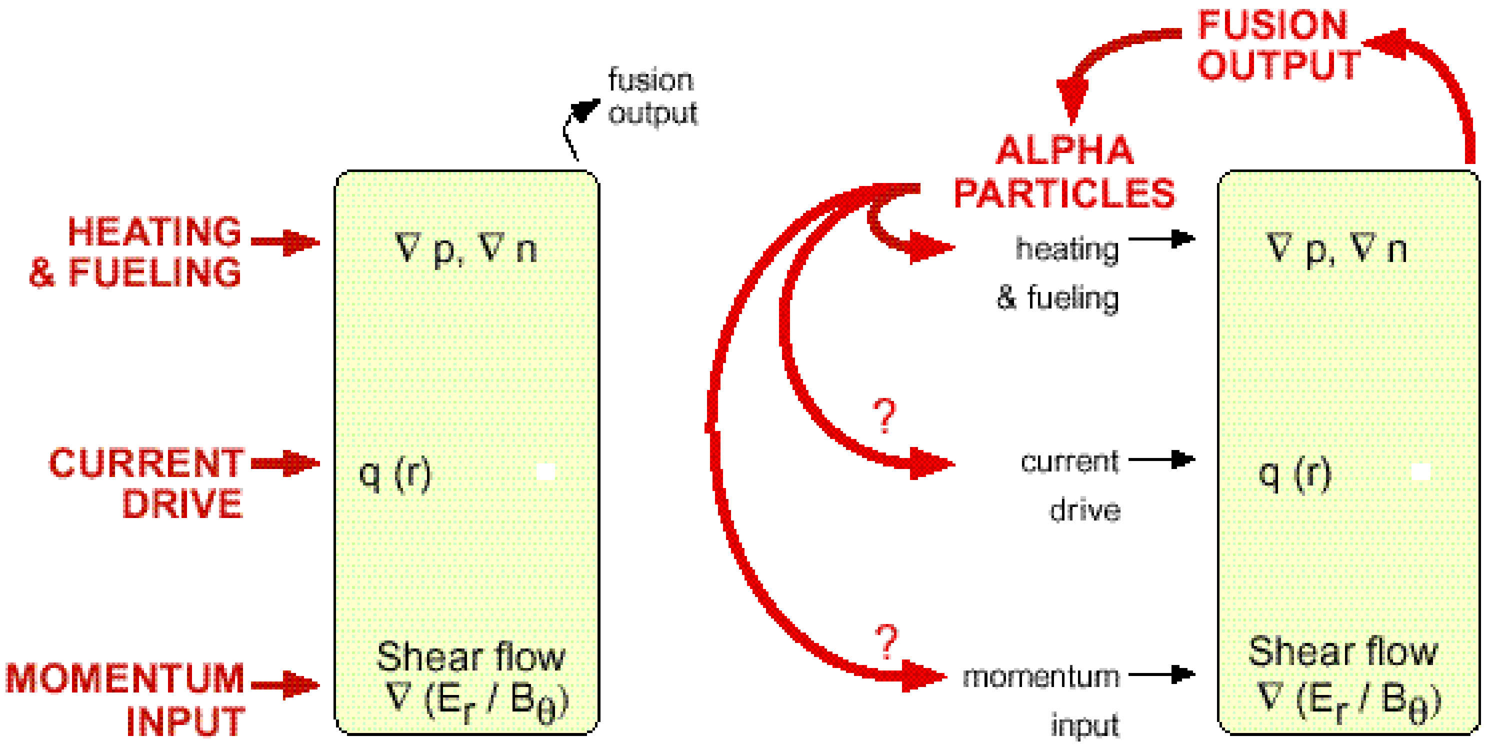
Issue: Can we Confine Alphas, Minimize Wall Loading and Apply them to Heat and Maintain Advanced Confinement Regimes?

Present Situation ->FIRE Physics Studies -> Burning Plasma



R. Nazikian

FIRE Presents a Range of Challenging Physics Issues for Fusion-dominated Plasmas (following JET-EP)

- **Thermalization and plasma heating**
  - Maintenance of confinement regimes with central self heating
- **Classical Orbit Effects**
  - Anomalous diffusion of supra-thermal ions in AT regimes
- **MHD Interactions and induced loss**
  - Resonant interaction with MHD, effects on stability and particle loss (Sawteeth, Fishbones, ELMs, KBMs, …)
- **Collective Fast Ion Driven Instabilities**
  - Gap modes (Alfven Eigenmodes), Energetic particle modes,
  - Ion Cyclotron range of frequency, ICE
- **External Control of fast ion distribution**
  - Effect on rotation, ash accumulation, heating efficiency
- **Diagnostics for confined and lost fast ions**

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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, Reflectometer, ECE, CXRS (T_i and He-ash), Neutrons Detectors,**
- **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 (b; MHD), kinetic profile set**

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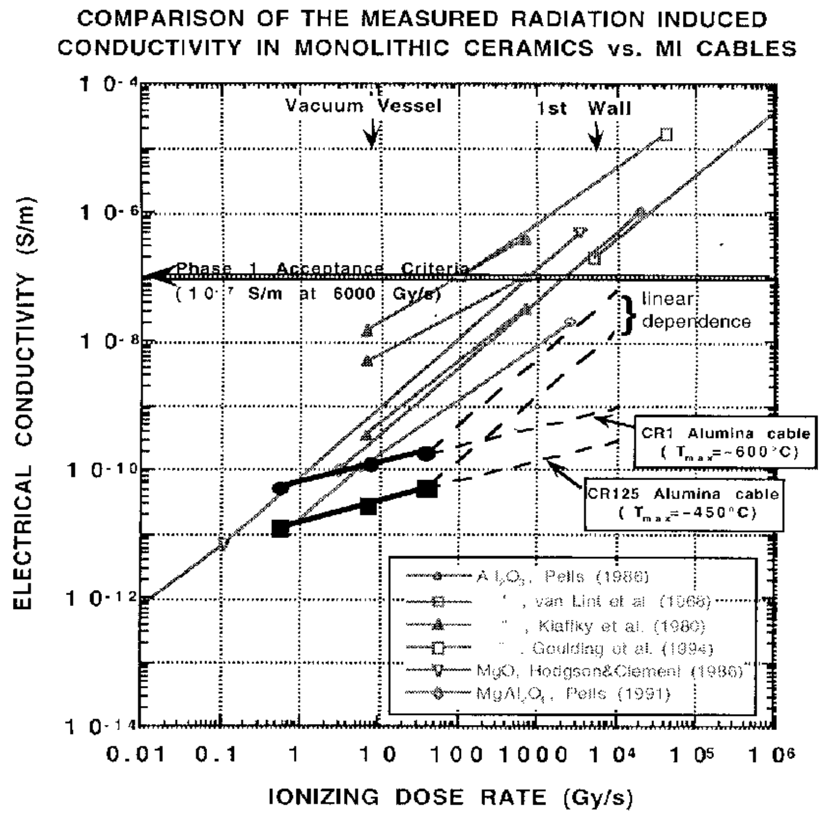
Magnetic Diagnostics: Issues

- Loops, coils, MI-cable must be inside vacuum vessel,
- Maximally unfriendly environment; RIC and RIEMF, temperature, neutral particles,
- No protection like ITER blanket.



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.

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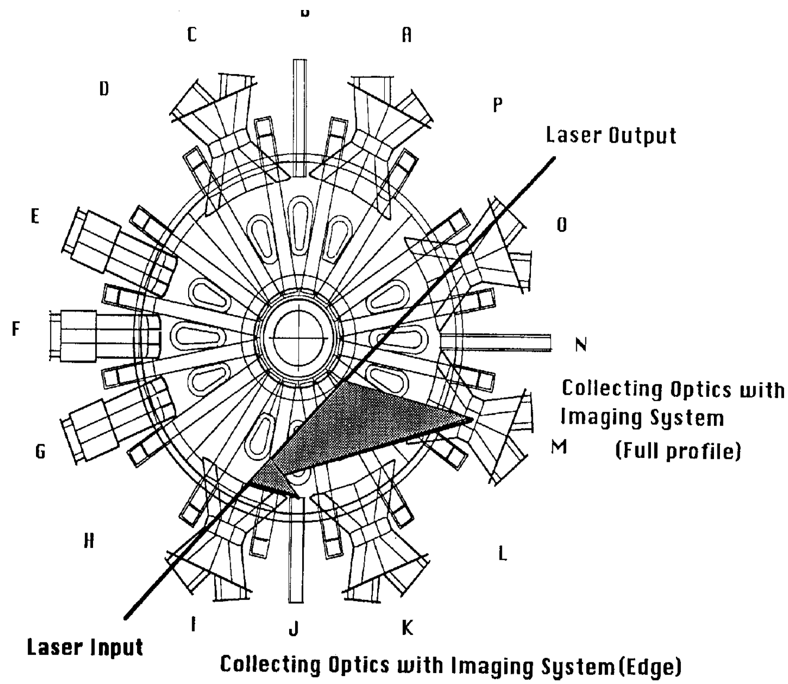
Thomson Scattering: Issues

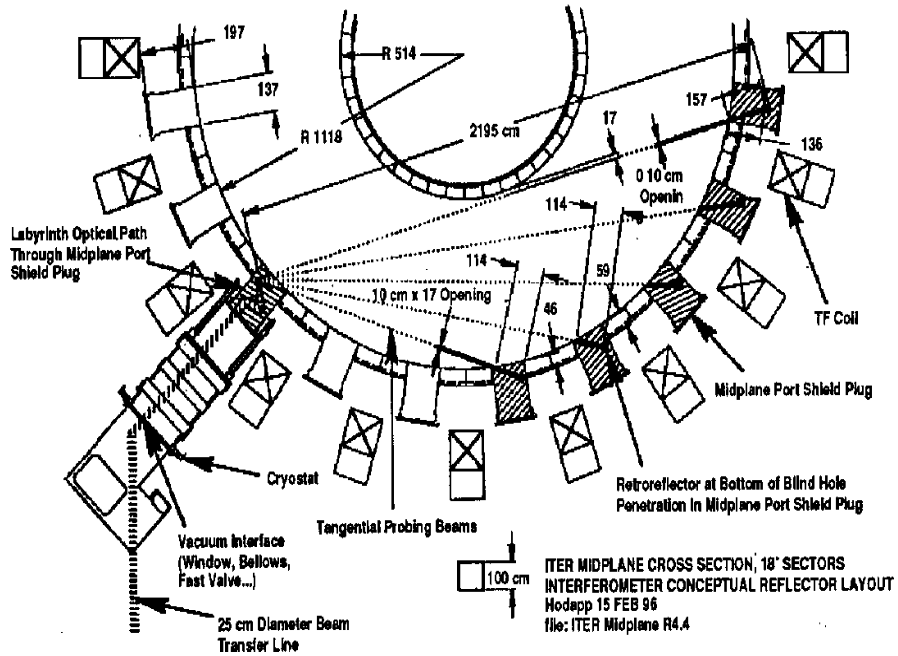
- Imaging system required for spatial resolution (cannot use LIDAR),
- Optical systems need shielding,
- Difficult sightline arrangement; will have to use tangential laser beam, view from nearby port, with close front-end mirror.



KSTAR Concept for TS

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

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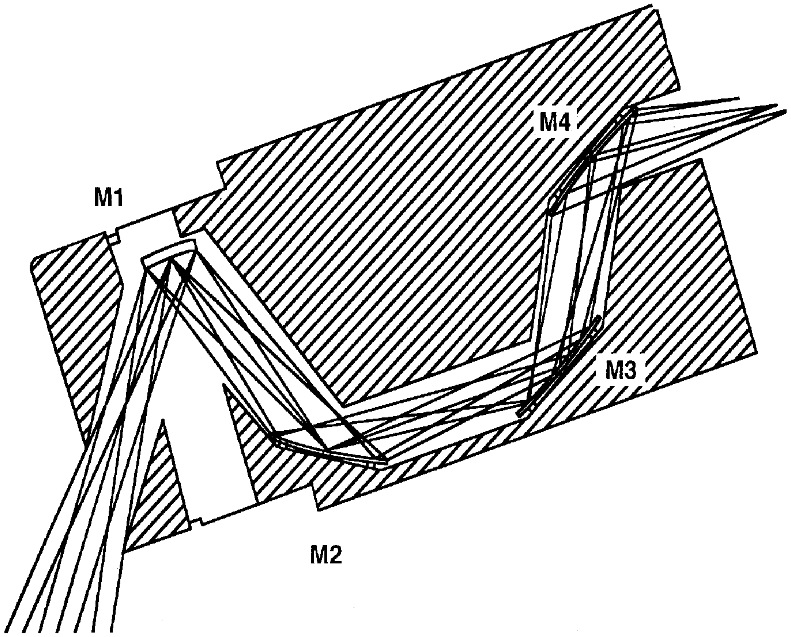
Measurements which presently need a Neutral Beam

- $T_i(r)$, $v_f(r)$, $v_q(r)$, $q(r)$, $n_{HE\text{-}ash}(r)$, ($E_r(r)$),
- Good poloidal rotation needs opposing views; not possible,
- Diagnostic beam near-radial; penetration at ~100keV/amu problematic,
- Diode beam, $5\text{x}10^9$W for <1ms for CXRS?
- MSE prefers 3 - 400 keV/amu.



CONCEPT FOR MSE OPTICS LABYRINTH FOR ITER

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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.

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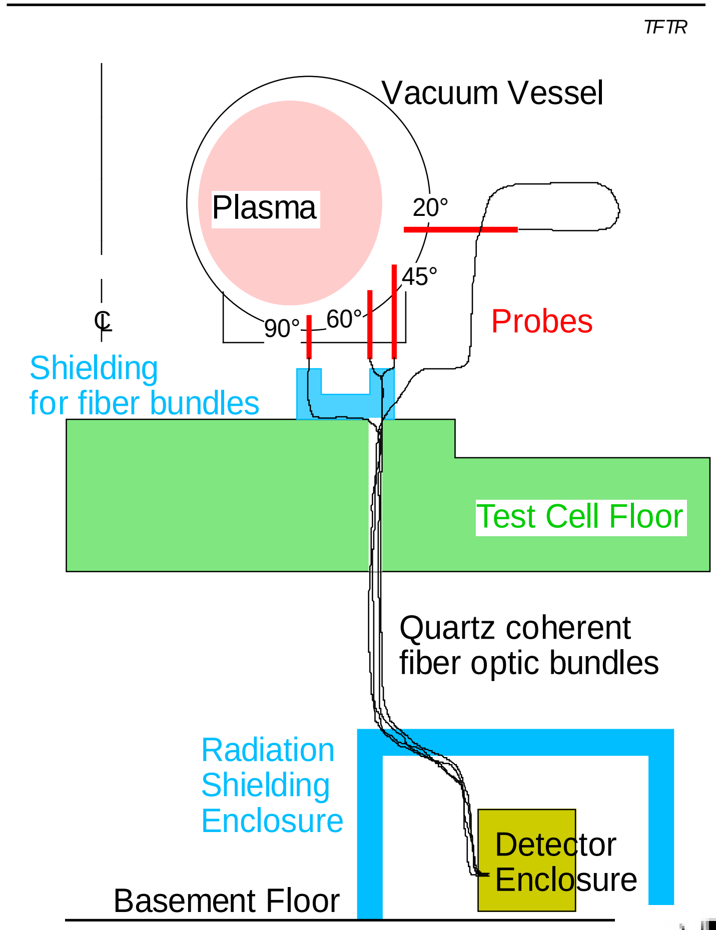
Diagnostics for Alpha-Particle Physics

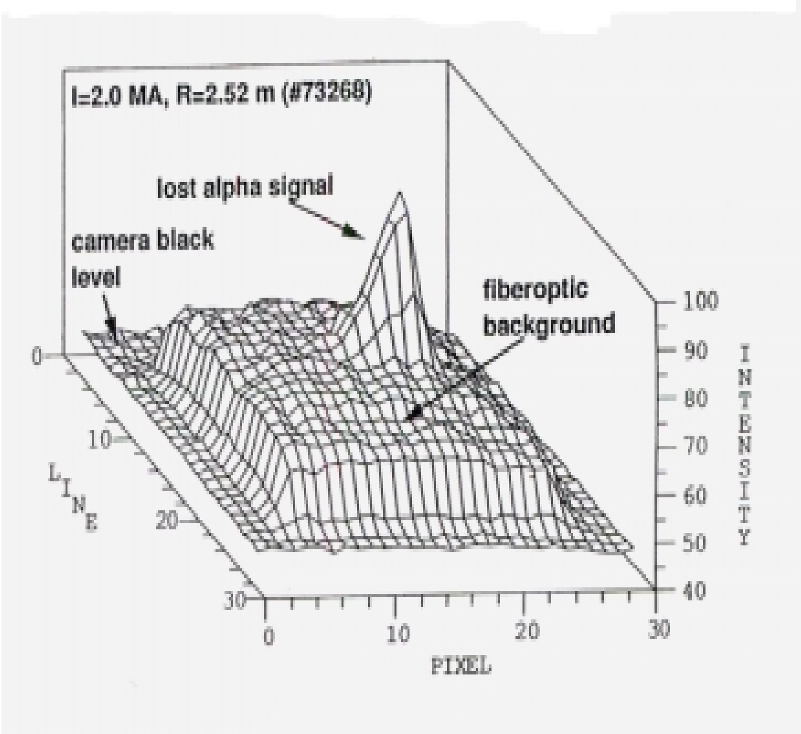
- Lost fast-ion detectors and IR camera,
- α-CHERS,
- Li-pellet, fast neutral particle analyzer,
- Collective scattering (CO_2?),
- Knock-on neutron,
- New confined-α detector?
- High-frequency Mirnov coils, reflectometry.

TFTR Escaping Alpha Diagnostic



Luminescence (and absorption) Impact on Measurement

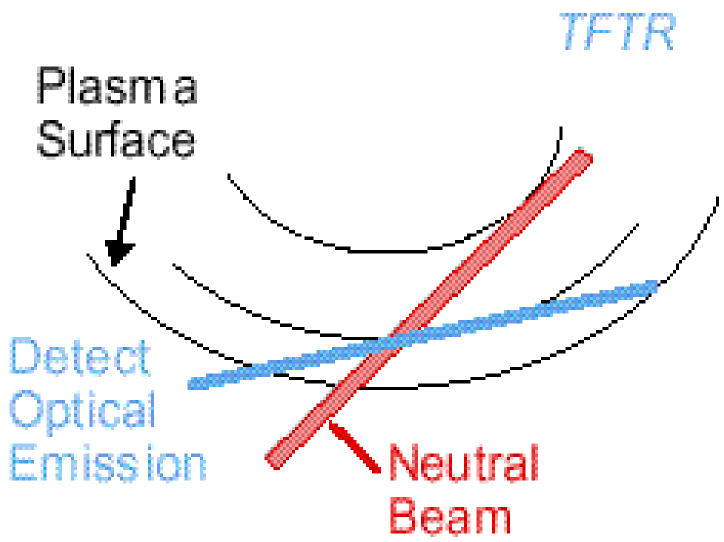
- Lost-α diagnostic on TFTR with fiberoptic outside vacuum vessel.
- TFTR shot at 5MW (5×10^{-2} MW/m^2 at first wall.
- Dose at front end of fiber (in shielding) ~ 30 Gy/s



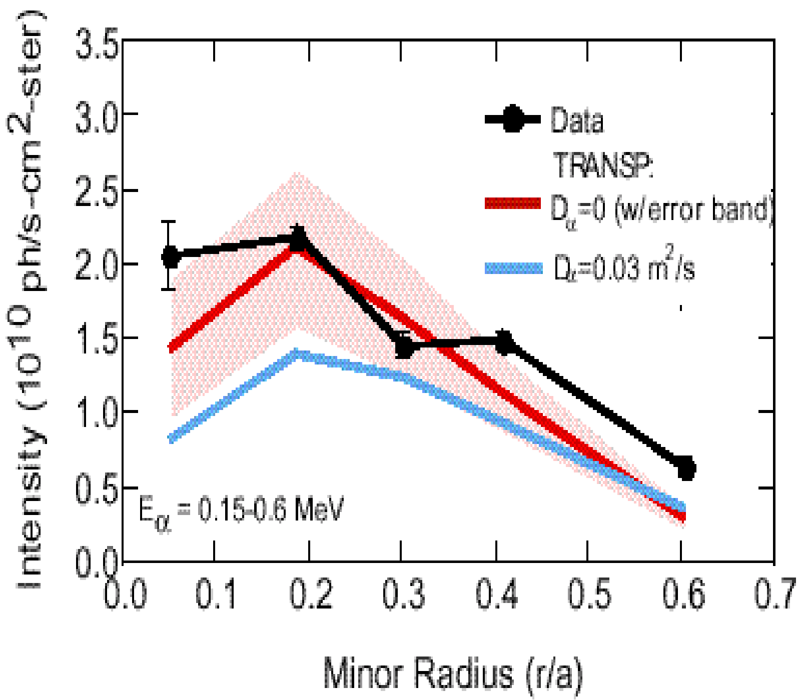
Signal observed from scintillator/ fiberoptic during TFTR D-T

D. Darrow

Alpha-Chers can Provide Absolute Calibration of Confined Alphas



Charge Exchange between fast beam ions and slowing-down Alphas



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

Improved optical design should provide valuable time-resolved measurements of alpha distribution

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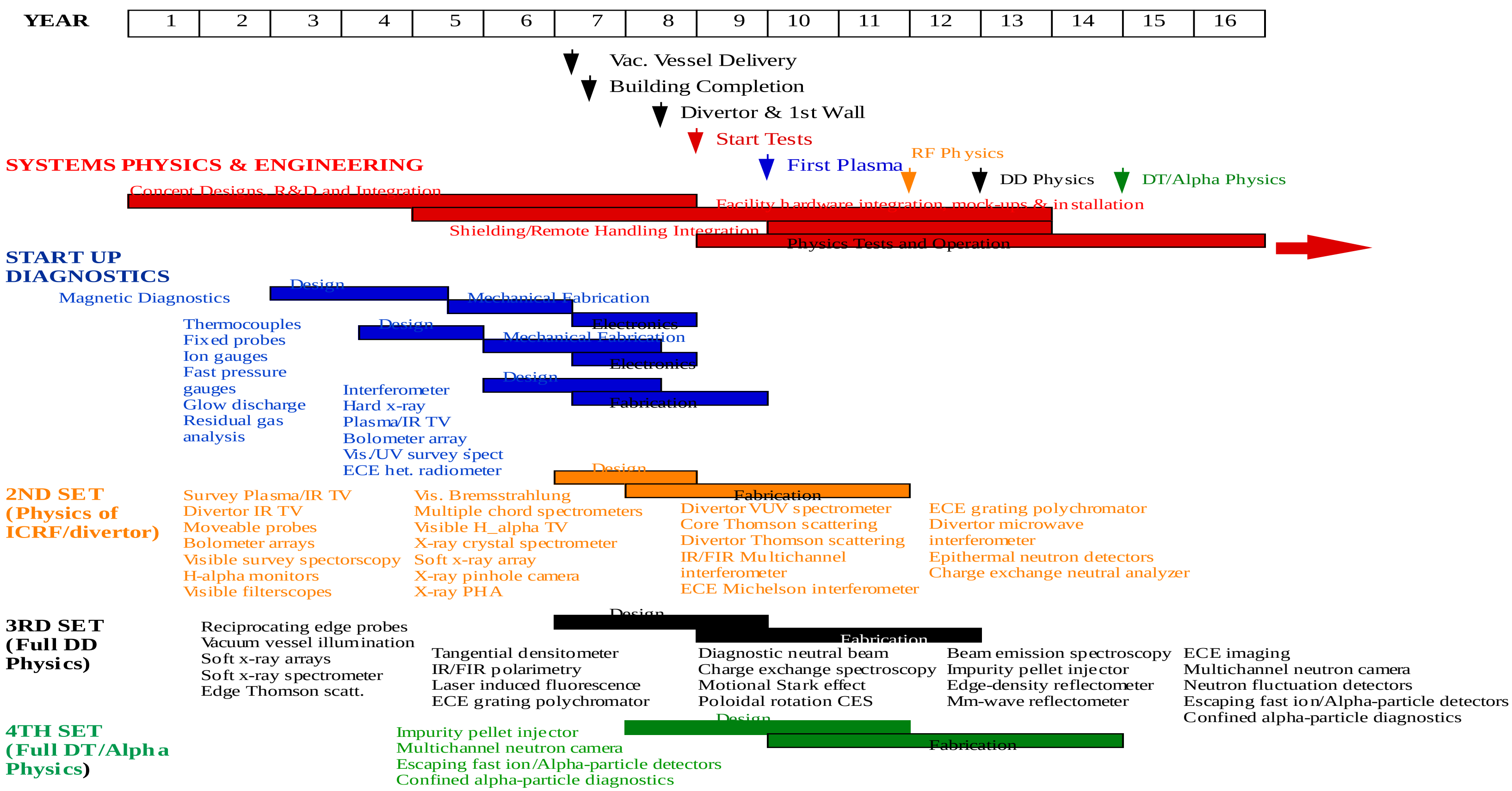
FIRE: Diagnostics Schedule



FIRE DIAGNOSTICS SCHEDULE: REVISION 0 1 SEPTEMBER 1999

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R&D Concerns

- What are impacts of high-field, highly shaped, high-n_e, high radiation, RF-only on diagnostics selection and development?
  - Reliability of magnetic diagnostics?
  - Lifetime of plasma-facing mirrors, other optical elements?
  - ECE overlap?
  - Interferometry refraction/wavelength?
  - Functionality of x-ray systems?
  - CXRS and MSE techniques; capability for diagnostic neutral beam(s)?
  - Inside-launch reflectometry?
  - Confined alpha-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

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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 (CO2?), 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.