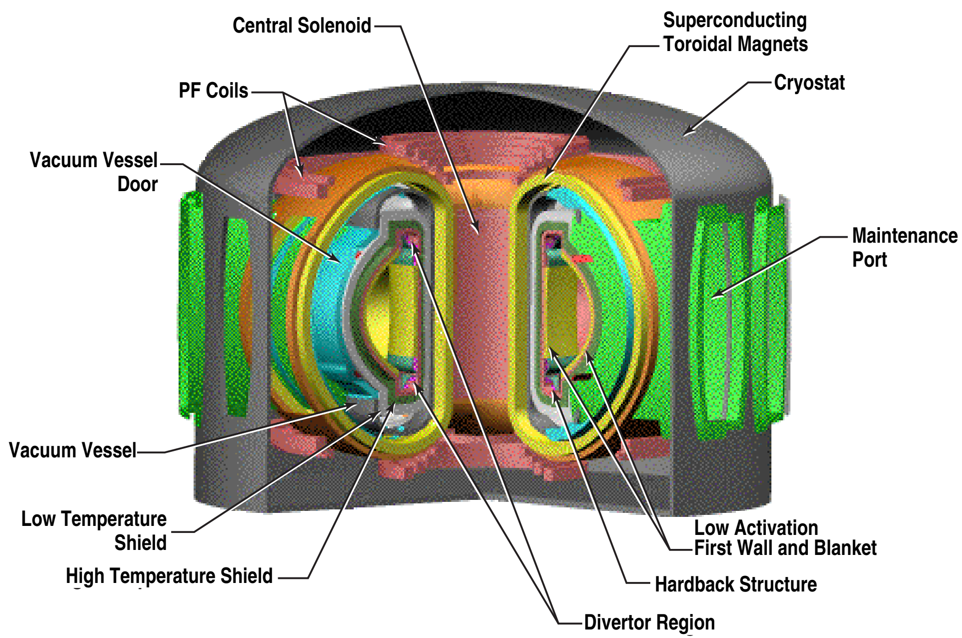
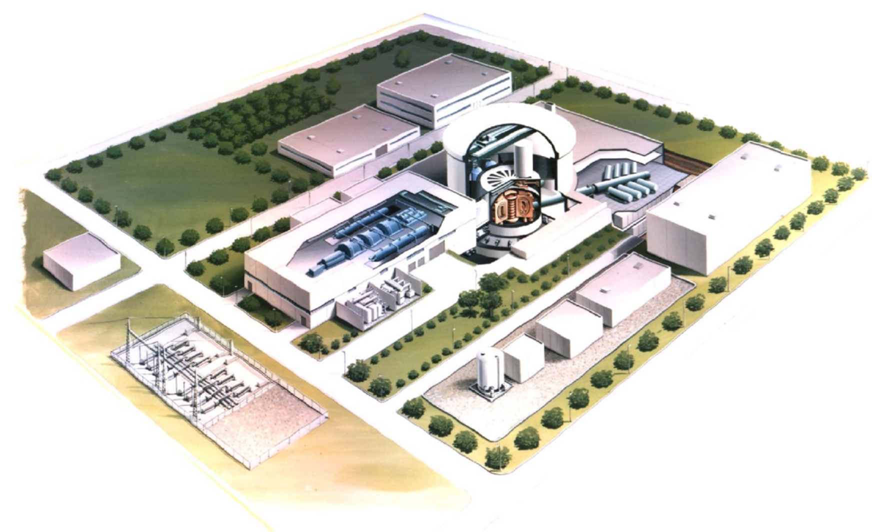
THE ADVANCED TOKAMAK LEADS TO AN ATTRACTIVE FUSION POWER PLANT

- The U.S. ARIES — RS system study



- The Japanese SSTR system study



- Attractive features
  - Competitive cost-of-electricity
  - Steady-state operation
  - Maintainability
  - Low-level waste
  - Public and worker safety

	Conventional	AT
Size, major radius (m)	8	5
COE $/kWhr	~13	~7
Power cycle	Pulsed	Steady state

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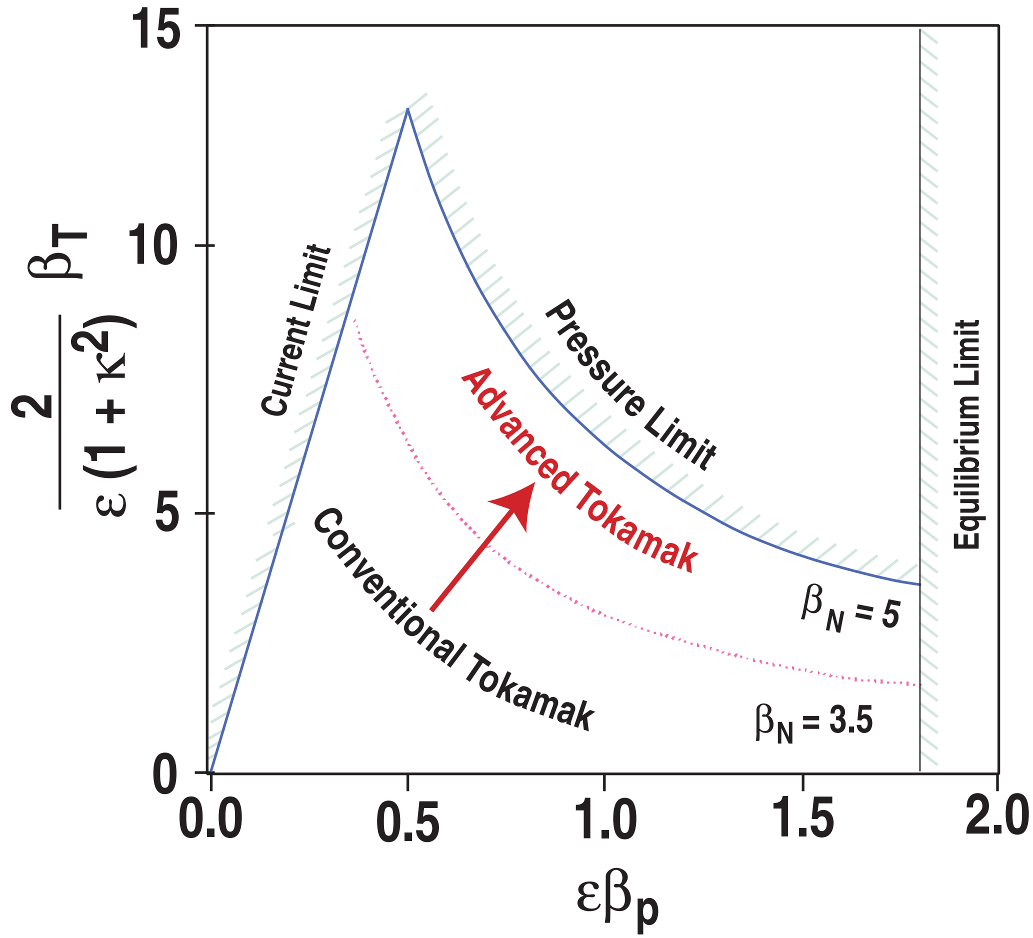
Tokamaks

FOCUS OF DIII–D RESEARCH IS ON ADVANCED TOKAMAK PHYSICS

- **Innovative concept improvement of the tokamak concept toward**
  - High power density
    - ★ Improved stability
  - Compact (smaller)
    - ★ Improved confinement
  - Steady state
    - ★ High bootstrap fraction ⇒ high β_p
    - ★ Current drive and divertor optimization
- **A self-consistent optimization of plasma physics through**
  - Magnetic geometry (plasma shape and current profile)
  - Plasma profiles (pressure, density, rotation, radiation)
  - MHD feedback stabilization
- **Ultimate goal is to reduce cast of electricity of a tokamak based power plant**

A COMPACT STEADY-STATE TOKAMAK REQUIRES OPERATION AT HIGH β_N



$$\beta_T \beta_p = 25\left(\frac{1+\kappa^2}{2}\right)\left(\frac{\beta_N}{100}\right)^2$$

$$\beta_N \equiv \beta_T / (I/aB_T)$$

κ = vertical plasma elongation

a = plasma half-width

ε = inverse aspect ratio

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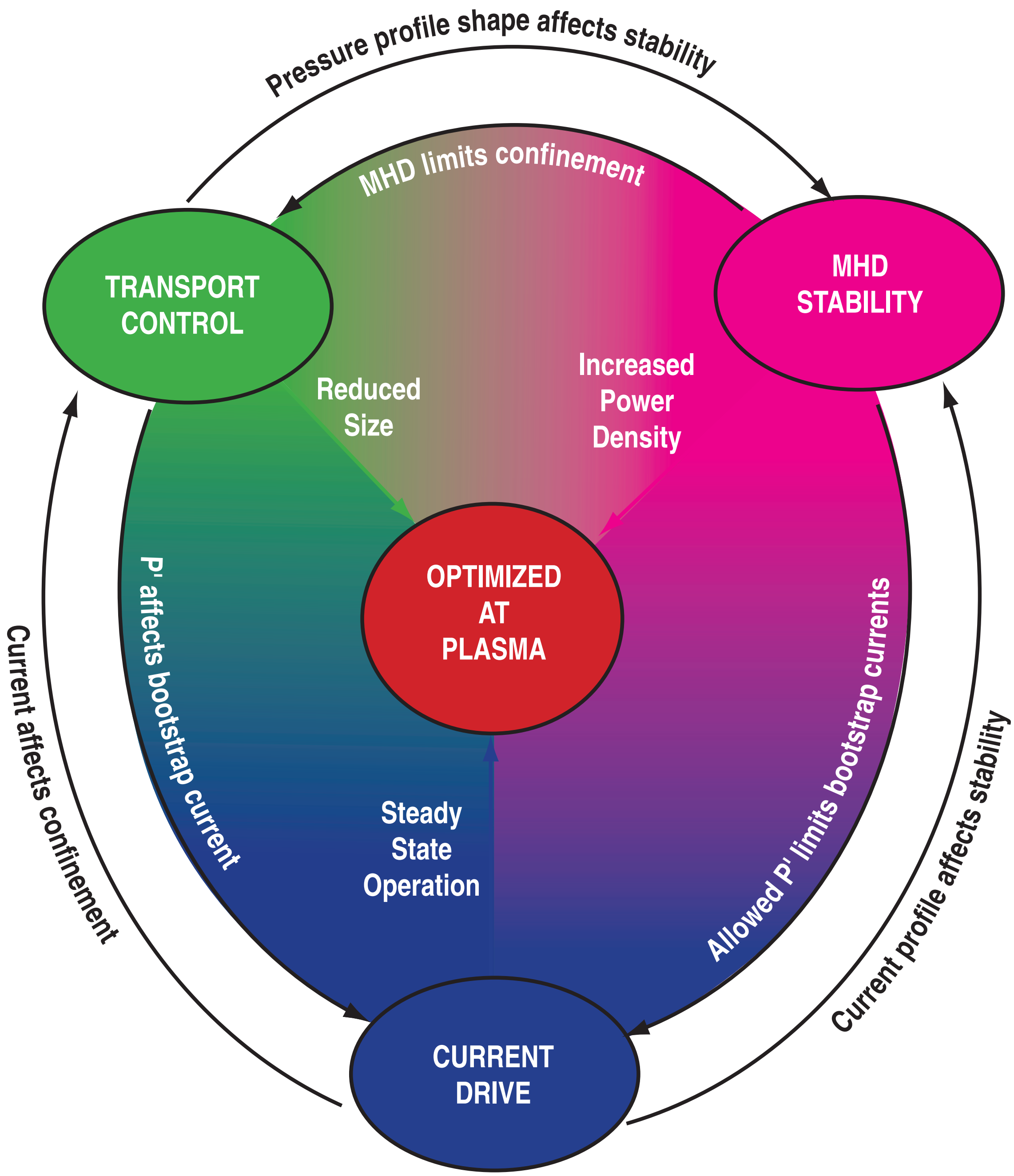
MULTIPLE INTERACTIONS MAKE ADVANCED TOKAMAK OPTIMIZATION A GRAND CHALLENGE



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GENERAL ATOMICS

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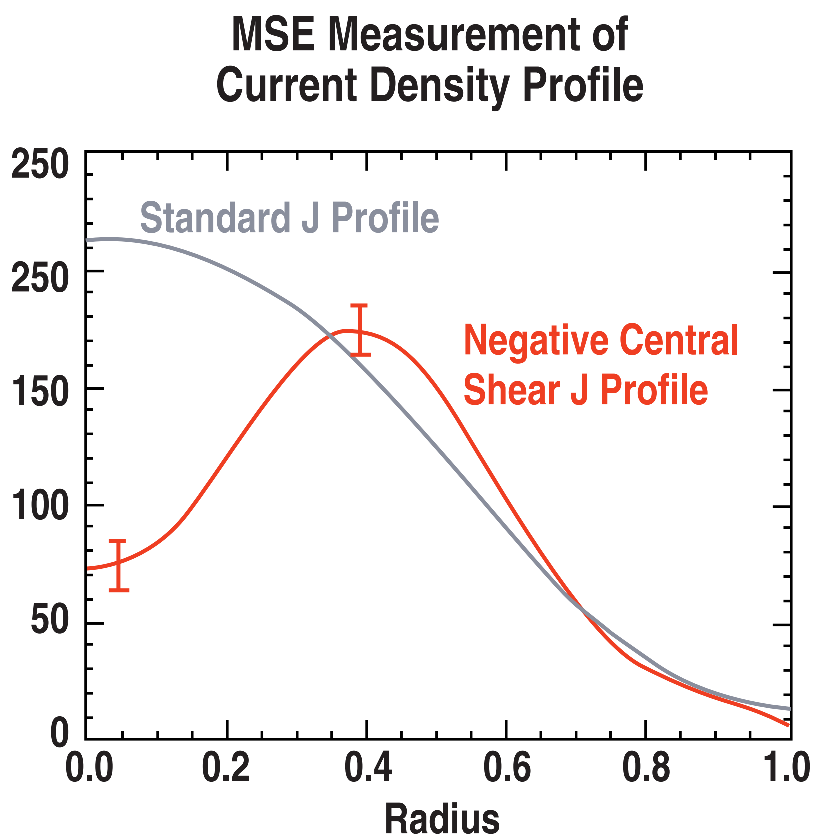
ADVANCED TOKAMAK RESEARCH REQUIRES EXTENSIVE SET OF DIAGNOSTICS

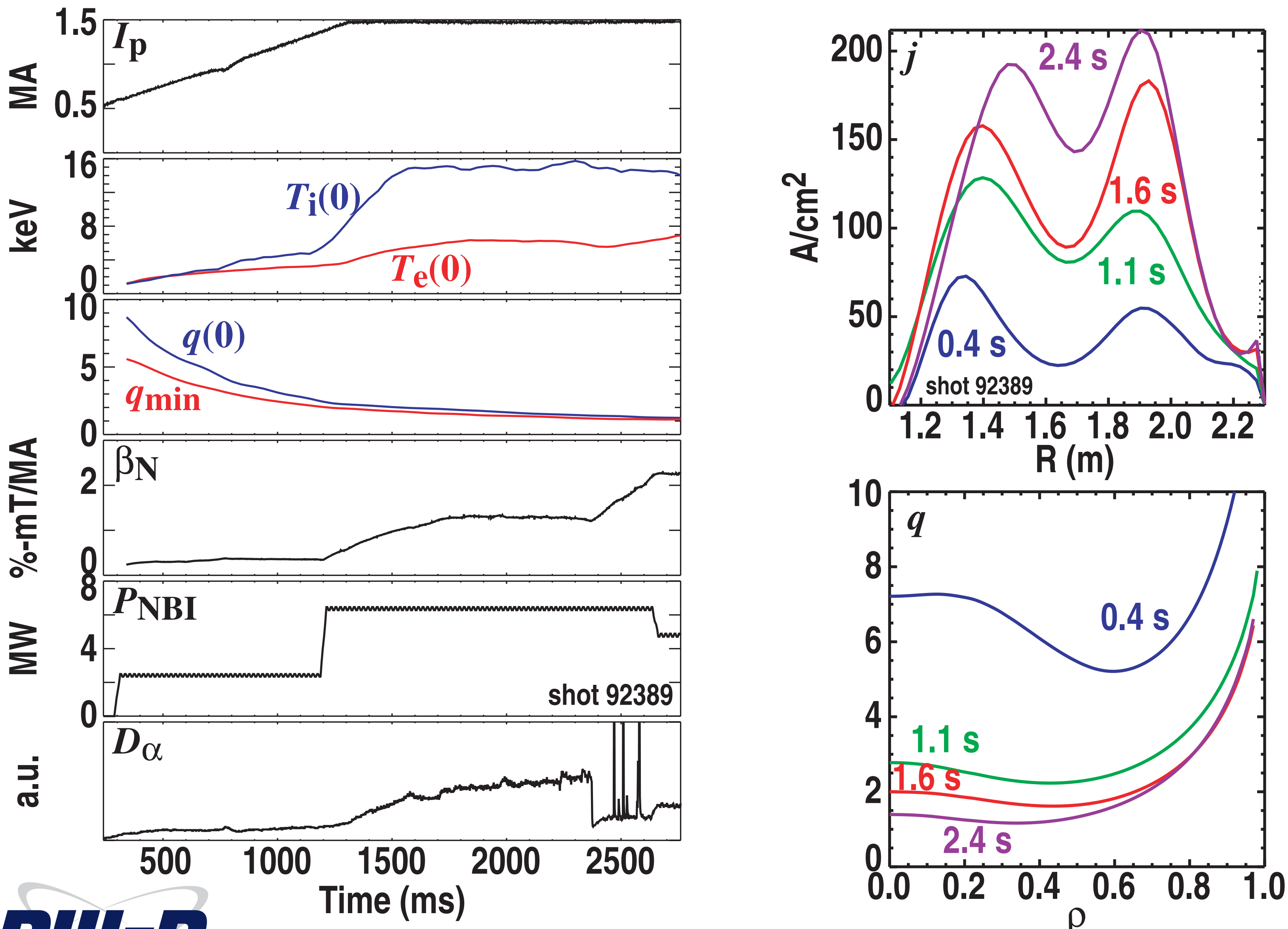
- Control of profiles require detailed measurements
- Optimization of performance requires physics understanding
- Complete J(r, t) measurement
- Complete pressure profiles
- MHD structure
- Turbulence characterization

CURRENT PROFILE CONTROL IS A KEY TO ADVANCED TOKAMAK



- Better core confinement
- High bootstrap; good alignment ⟹ steady state
- Better core stability
  - High-n ballooning
  - Low-n tearing
- Better edge stability
  - Second stability access control

MSE MEASUREMENTS ALLOW DETERMINATION OF CURRENT DENSITY AND q PROFILES IN I_p RAMP EXPERIMENTS



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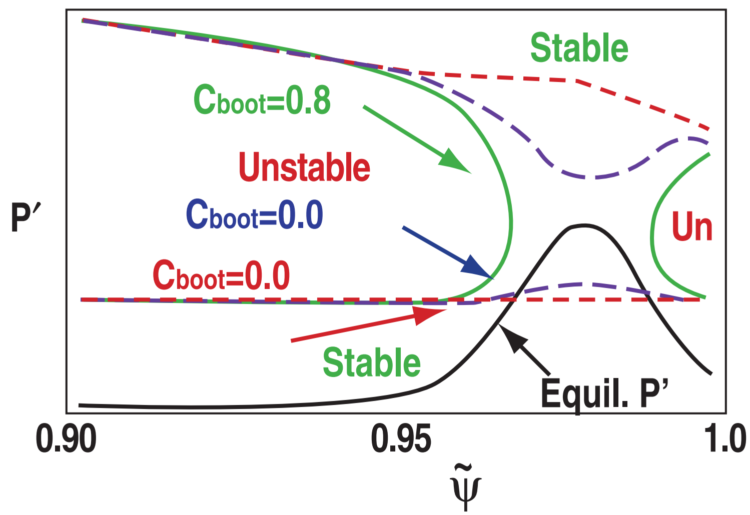
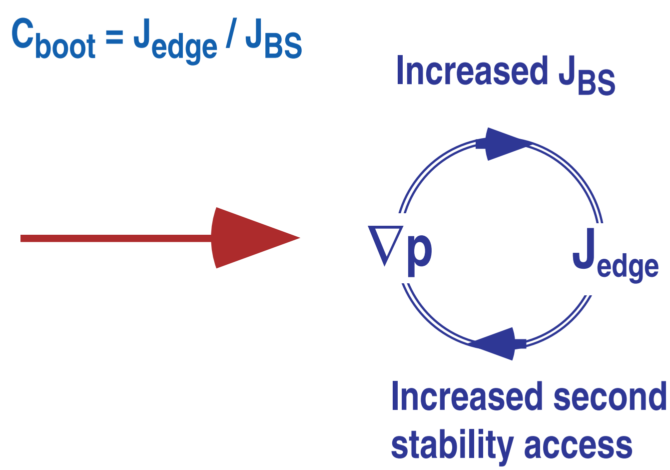
CURRENT PROFILE CONTROL ON DIII–D IS CRITICAL KEY TO AT EFFORT — CONTROL REQUIREMENTS AND CAPABILITIES ARE EVOLVING

- Measurement J(r) — MSE diagnostic
  - Continuous improvement in spatial resolution and accuracy
- Modeling and stability analysis generate optimized current profile
  - High bootstrap → steady state
- ECCD program to develop localized actuator
- Real time measurement of q_0 — MSE and magnetics — 2000

- Central J(r) control — ECCD — 2001
- Real time EFIT calculations — MSE and magnetic — 2001
  - Complete equilibrium available for control
- Edge current measurement — 2001
- Edge current control — 2002
  - Realtime edge current measurement
  - Actuators, gas puff, edge heating . . .
- Non thermal electron distribution function measurement 2002

DETAILED EDGE PROFILES PLAY CRITICAL ROLE IN PERFOMANCE AND LONG TERM HEALTH OF DISCHANGES





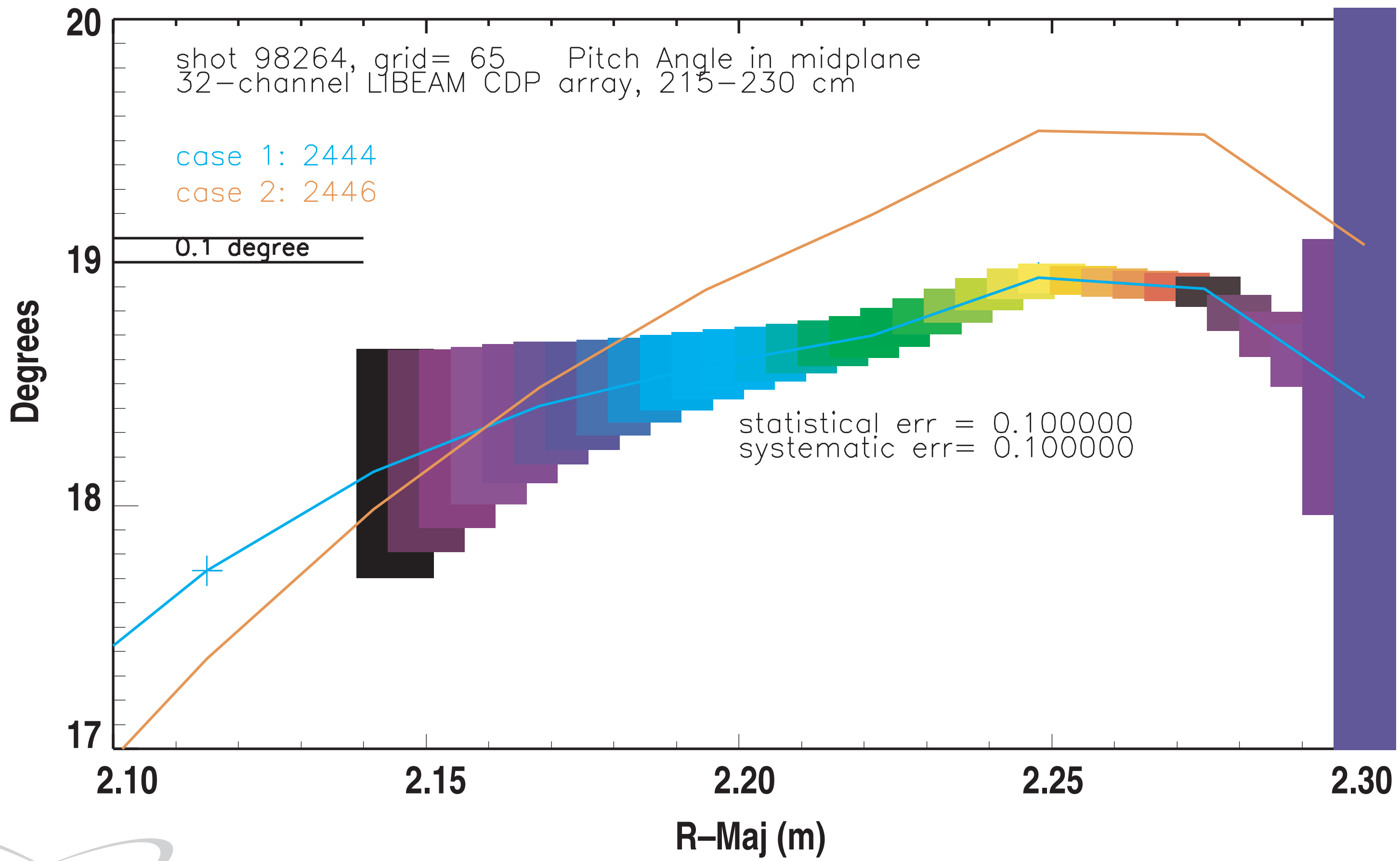
- The improved confinement from the edge transport barrier leads to large P′ and large J_{edge} which often drive MHD instabilities, terminating the discharge or reducing the performance, endangering divertor
- Control second stability access will reduce edge P′ and amplitude of ELM perturbation.

MSE DIAGNOSTIC ON DIII–D HAS LIMITATION AT EDGE DUE TO E_r AMBIGUITY. NEW EDGE CURRENT DENSITY PROFILE DIAGNOSTIC UNDERWAY ON DIII–D

- Goal is to resolve small differences in edge j(r) that are thought to inhibit or promote second stable access
- Method is based on precision Zeeman Polarimetry of injected Lithium Beam to specify B_{pol} components
  - 32 channels, r = 0.7-1.0. Utilizes mothballed LIBEAM accelerator, leverages MSE polarimetry experience, prior TEXT/ASDEX diagnostics
  - Quantum system exhibits no Stark mixing, no E(r) ambiguity to measurement
  - Small diagnostic beam + large excitation rate yields good signals and spatial localization. Penetration is adequate for edge measurements
- Construction and installation are underway
  - Should be debugging in December, with a few channels operational
- Zeeman splitting is small, Li beam penetration is limited

Addition of 32-channel array results in good discrimination of first and second stable cases

- **Conservative case-- late H-mode, high pedestal density. Boxes represent radial and pitch angle errors for each array element**



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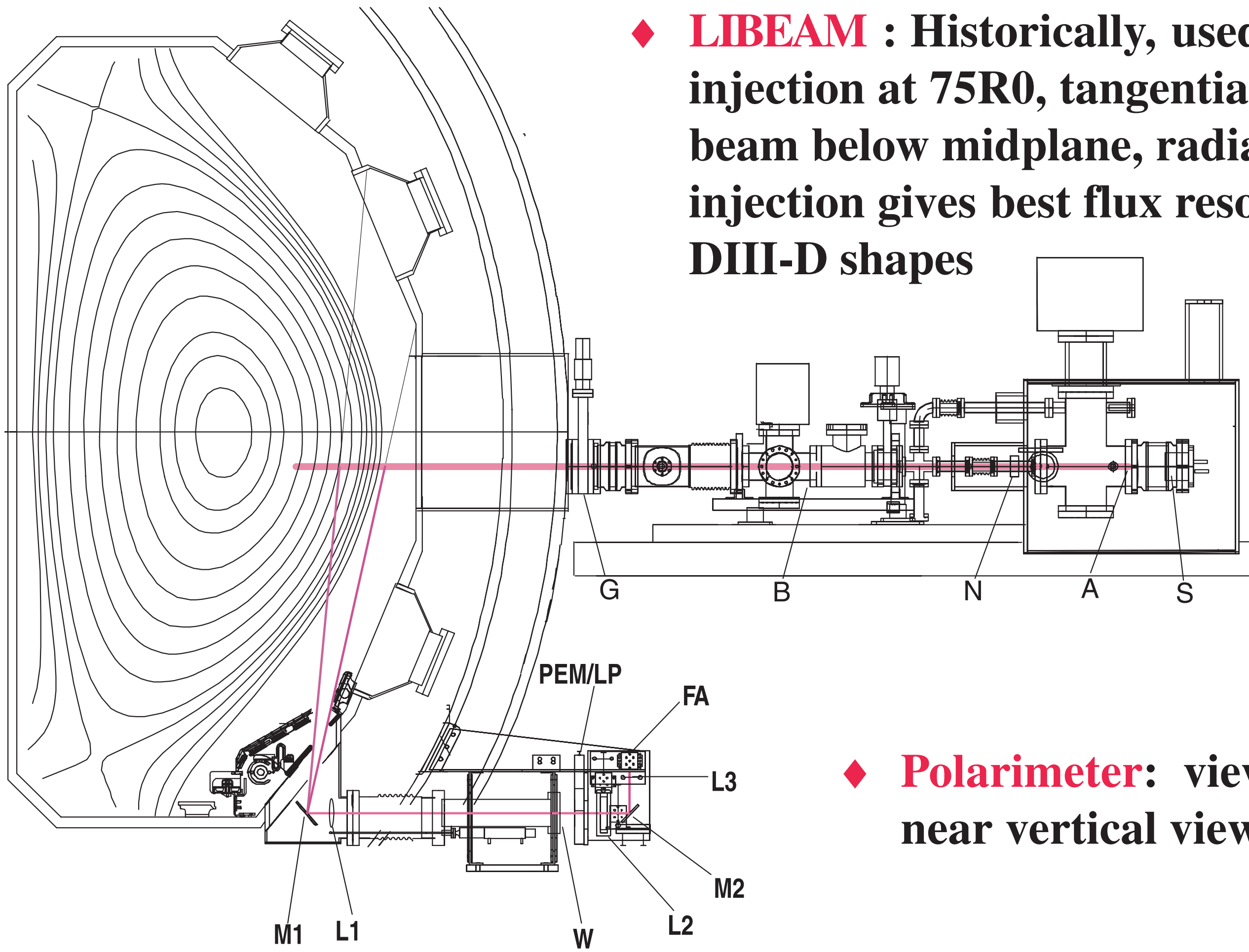
Radial injection of Li and vertical viewing gives good spatial resolution for most DIII–D shapes

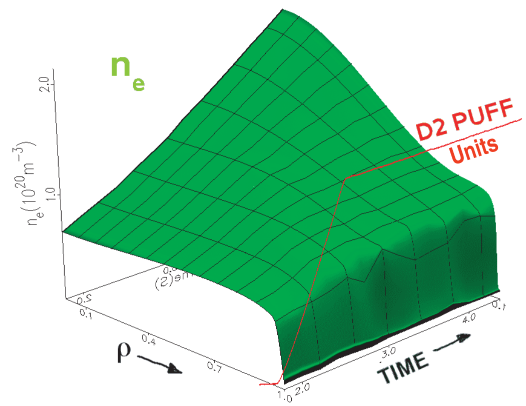
- **LIBEAM : Historically, used near-radial injection at 75R0, tangential view. Now, beam below midplane, radial and horizontal injection gives best flux resolution for most DIII-D shapes**

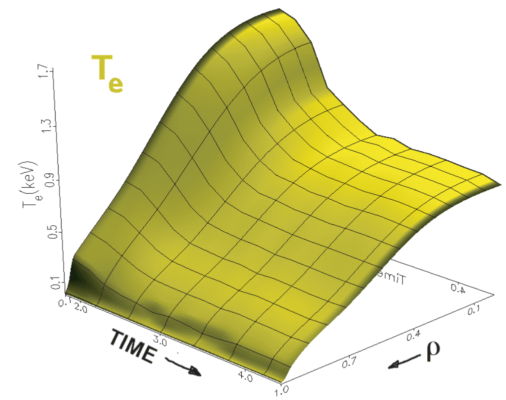


- **Polarimeter: view from below, near vertical viewchord fan**

PRESSURE PROFILE MEASUREMENTS ON DIII–D (TOKAMAKS) ARE A SUCCESS STORY

- Detailed T_e (r,t), n_e (r,t) via Thomson scattering, reflectometry
- Detailed T_i (r,t), [v_ϕ (r,t), E_r (r,t)] via change exchange spectroscopy
- Complete time dependent profiles (1–20 ms resolution) with cm resolution throughout the plasma routinely available
- Demsonstrates temperature being able to integrate results from many diagnostics into a single analysis code
- Next step is pressure control
  — Need real time mesurements
  ★ Modification of data acquisition
  ★ Integration into actuator control





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NEW DIAGNOSTIC MEASUREMENTS NEEDED TO UNDERSTAND NON-IDEAL MHD INSTABILITIES

- Techniques to measure the internal structure of rotating and non-rotating MHDmodes with toroidal mode number n in the range of 1 to 5. These are the key modes for kink and resistive wall mode work. Two and three dimensional reconstructions of mode structure are needed

- Techniques to determine the mode structure of the moderate to high toroidal mode number modes (n = 10–30) which contribute to ELMs
  - Multiple Imaging systems
    - ★ ECE
    - ★ X–ray cameras
    - ★ BES

- Methods of accurately measuring the edge current density in the outer 20% of the plasma. This is crucial determining whether the edge plasma has access to the second-stable regime for balloning modes
  - Multiple MES (co, counter beams)
  - Li beam (see left)

- Measurements of the fast ion pressure profile in the plasma core. This is needed to find the contribution of the fast ion pressure to the total pressure for equilibrium and stability calculations as well as for determining the contribution to fast-ion driven instabilities
  - Scattering

- Measurements of the local B_T internal to the plasma, the ff´ term in the equilibrium calculations and the stability calculations based on those equilibria
  - O–mode and X–mode reflectometry

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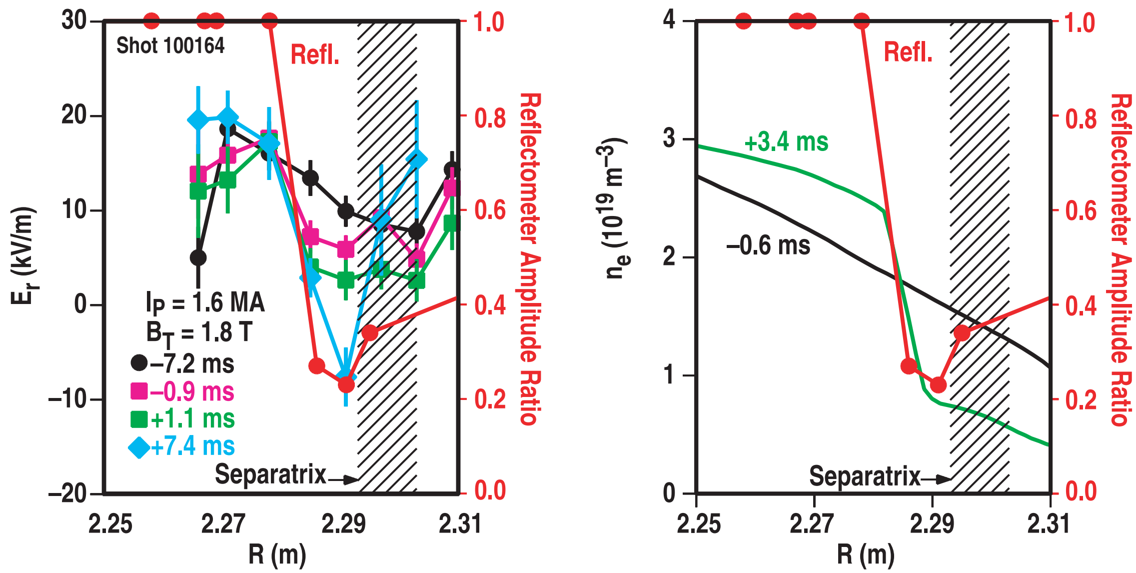
STEADY-STATE TOKAMAK WILL REQUIRE SOME EXTENDED CURRENT DRIVE — DIII–D HAS FOCUSED ON ELCTRON CYCLOTRON CURRENT DRIVE (ECCD)

- Bootstrap current may provide most of the current but some external drive will be required
  - — Control of detailed profile for performance optimization
- DIII–D has plans for 6–10 (megawatt class) gyrotrons as ECCD
- MSE measurements provide J (r,t)
  - — No velocity space information
  - — Single channel pulse height system on DIII–D provides single line of right measurement
- f_e (v, r, t) information is required to
  - — Understand ECCD physics
  - — Validate models
  - — Understand transport of non thermal electrons
- Hard x-ray camera is leading candidate for DIII–D
  - — Detectors and viewing geometry straight forward
  - — Interpratation of data is issue
  - — Other options?

ADVANCES IN TRANSPORT RESEARCH IN RECENT YEARS HAVE LEAD TO IMPROVED GLOBAL CONFINEMENT AND IMPROVED UNDERSTANDING

Internal transport barriers have improved tokamak performance

Model of E×B shear stabilization of turbulence has been used to explain H–mode transport barriers



E_r and density profile evolution during an H–mode transition along with the density fluctuating levels, E_r well (steep gradient in E_r) correlation with drop in fluctuation levels

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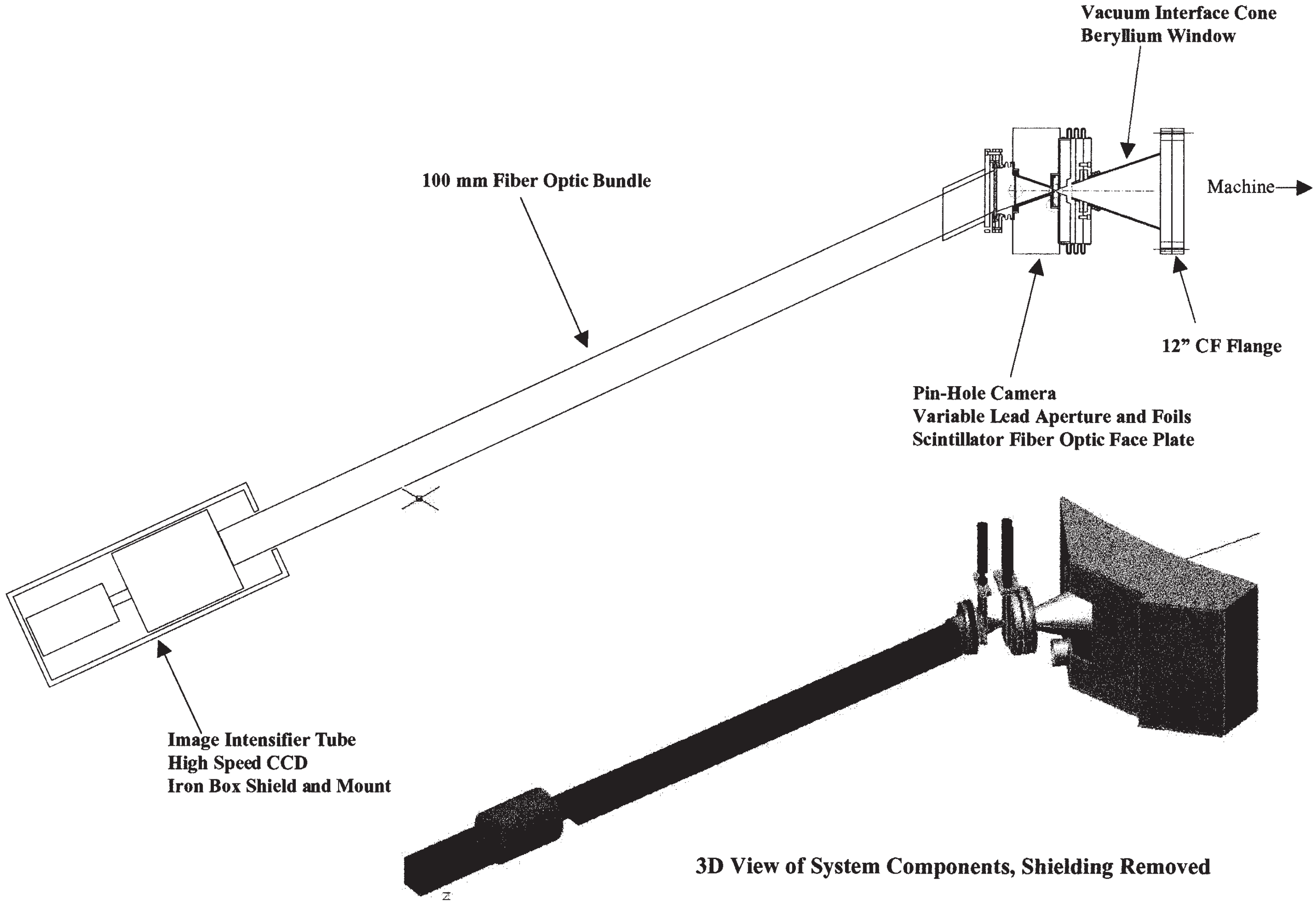
MEASUREMENTS NEEDED TO ADVANCE UNDERSTANDING OF TRANSPORT

- Techniques for two dimensional turbulence visualization. In the studies of the dynamics of neutral fluids (e.g. water), the ability to visualize the flows has led to fundamental advances in understanding; being able to do the same for plasmas would almost certainly pay similar dividends
- Methods of determining the nature of the basic modes included in the theories. Transport theories are couched in terms of various micro-turbulence modes such as the ion temperature gradient mode, trapped electron mode, electron temperature gradient mode. etc. We need to devise definitive tests to determine if these modes are actually present and if their properties really match those given by theory
- Techniques for determining what drives electron transport, especially in plasmas where $E \times B$ shear has reduced ion thermal diffusivity to neoclassical levels. One part of this question is whether magnetic fluctuations play any role in tokamak transport
- Direct measurements of zonal flows
- Techniques to determine whether large events (e.g. avalanches) play a significant role in tokamak transport. This is especially important to determine in plasmas in reduced transport regions
- Techniques to demonstrate quantitatively that fluctuation-driven transport is big enough to play a role in the plasma core

HARD X-RAY CAMERA “COMPACT” SYSTEM COMPONENTS OVERVIEW



3D View of System Components, Shielding Removed

DIII-D HARD X-RAY CAMERA

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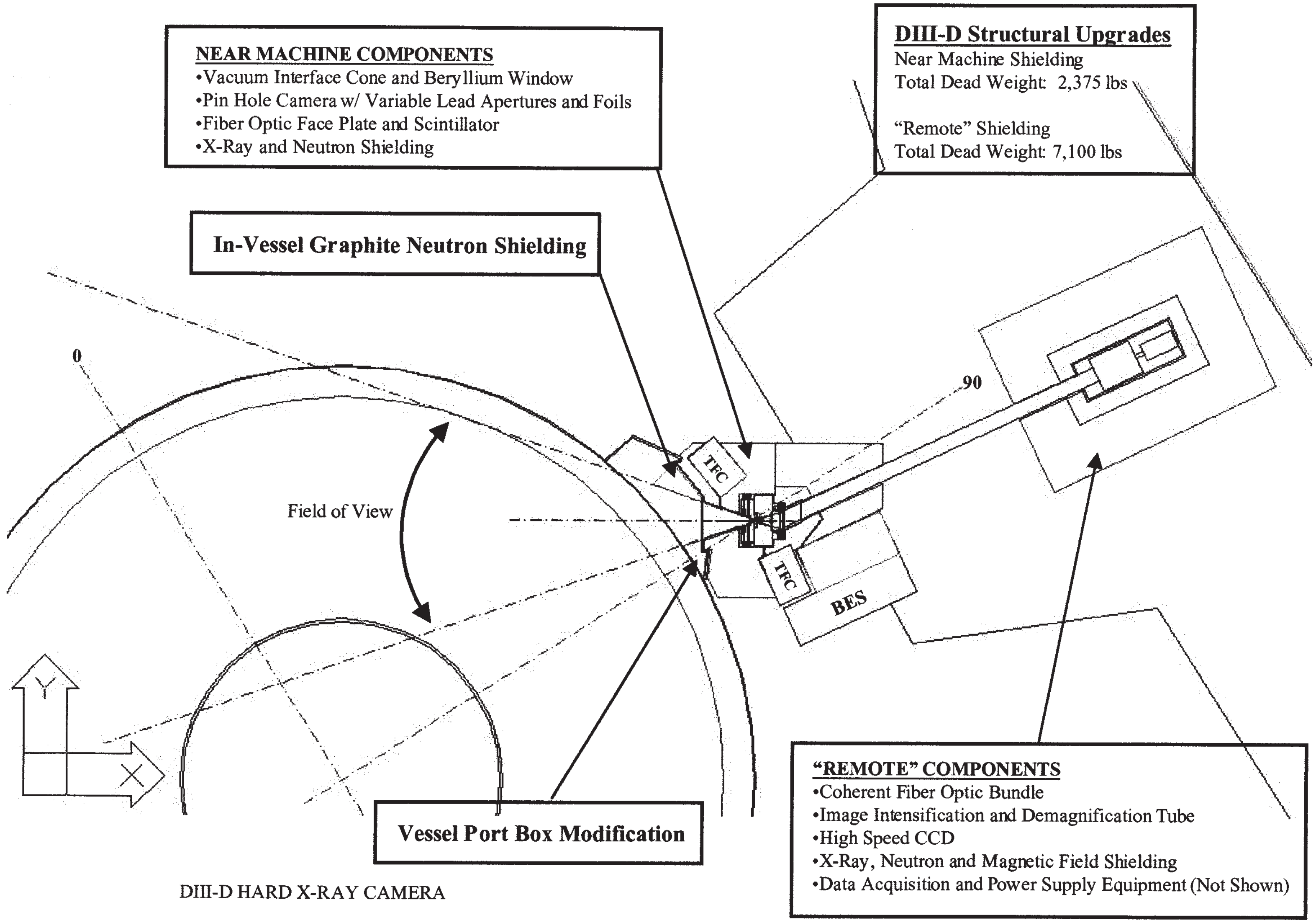
HARD X-RAY CAMERA DESIGN SYSTEM OVERVIEW



DIII-D HARD X-RAY CAMERA

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SUMMARY

- Advanced tokamak research has significant new diagnostic requirements
- Optimization and control of current and pressure profiles place stringent requirements on diagnostic measurements
- There is still a need for new measurements to understand transport and turbulence
- DIII–D program is looking for new techniques, technology and players to meet the diagnostic needs of the DIII–D advanced tokamak research program