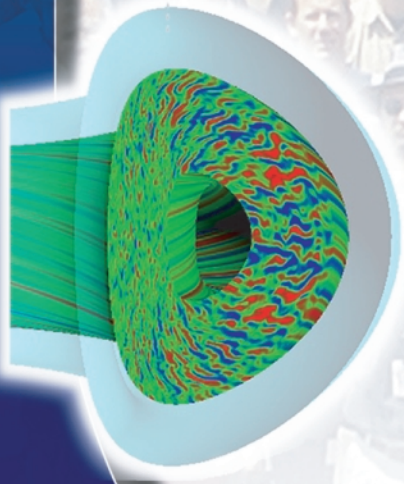


DIII–D Program Overview, Collaborations

by
R.D. Stambaugh

Presented by C. Wong to
US-Japan HHFC/PSI and HPD Workshop
Port Townsend, Washington, USA
July 28-31, 2003

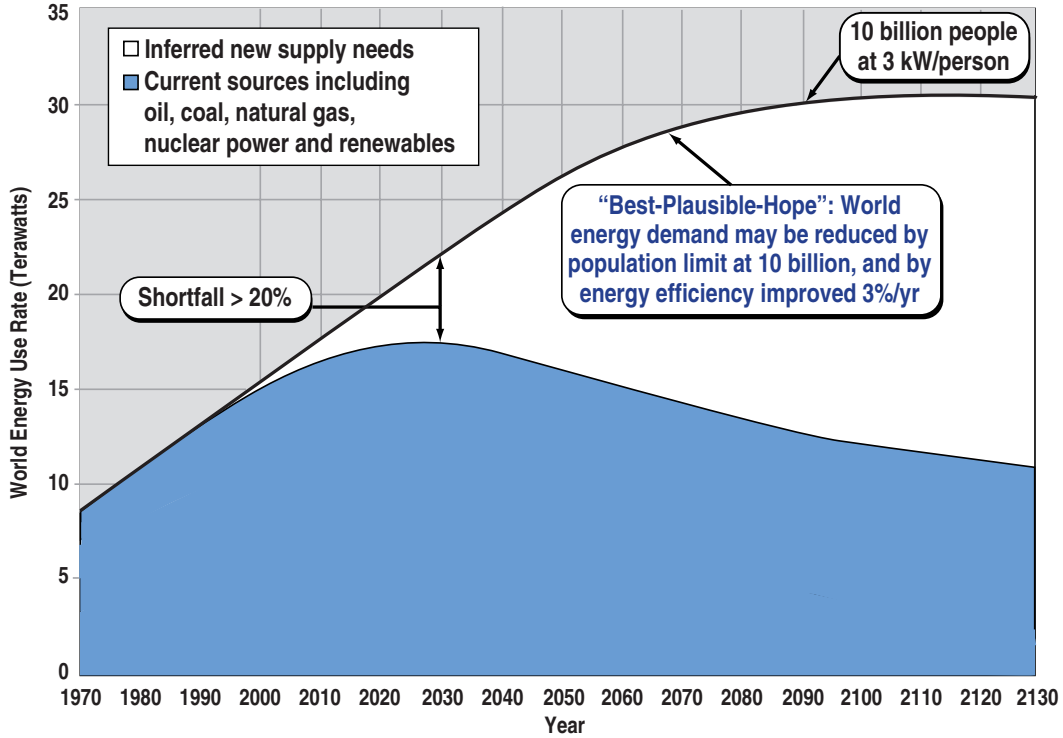
067–03/RDS/wj

Workshop Agenda

DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

THE WORLD NEEDS FUSION ENERGY

- The administration's National Energy Policy document states "Fusion—the energy source of the sun—has the long-range potential to serve as an abundant and clean source of energy. The basic fuels, deuterium (a heavy form of hydrogen) and lithium, are abundantly available to all nations for thousands of years. There are no emissions from fusion, and the radioactive wastes from fusion are short-lived, only requiring burial and oversight for about 100 years. In addition, there is no risk of a meltdown accident because only a small amount of fuel is present in the system at any time. Finally, there is little risk of nuclear proliferation because special nuclear materials, such as uranium as plutonium, are not required for fusion energy. Fusion systems could power an energy supply chain based on hydrogen and fuel cells, as well as provide electricity directly."



Even under "best-plausible-hope" scenarios for population growth and energy demand increases in the developing countries, the world will experience increasingly large short falls in energy supplies, requiring either increased use of current sources or development of new ones.

Adapted from World Energy Council projections

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009-03/RDSrs

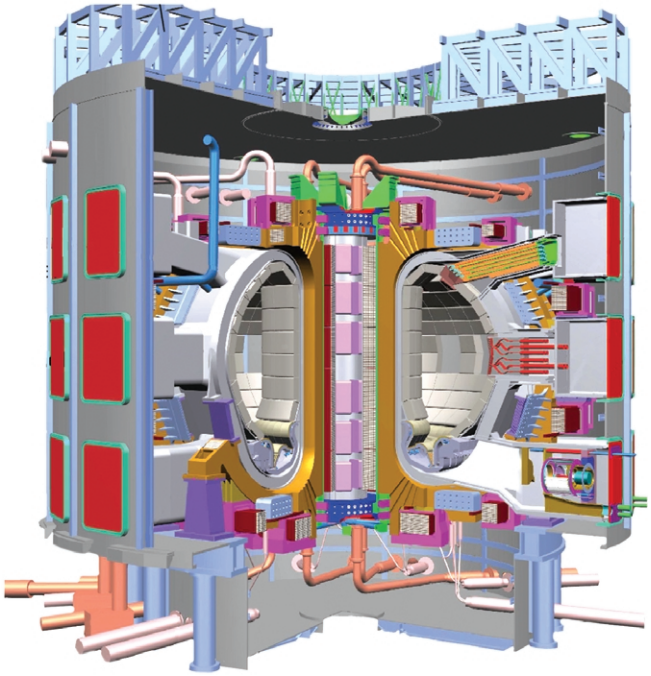
THESE ARE EXCITING TIMES IN FUSION

- **President George W. Bush**

  "The results of ITER will advance the effort to produce clean, safe, renewable, and commercially -available fusion energy by the middle of this century. Commercialization of fusion has the potential to dramatically improve America's energy security while significantly reducing air pollution and emissions of greenhouse gases."

- **Secretary of Energy, Spencer Abraham**

  "By the time our young children reach middle age, fusion may begin to deliver energy independence … and energy abundance …to all nations rich and poor. Fusion is a promise for the future we must not ignore. But let me be clear, our decision to join ITER in no way means a lesser role for the fusion programs we undertake here at home. It is imperative that we maintain and enhance our strong domestic research program … . Critical science needs to be done in the U.S., in parallel with ITER, to strengthen our competitive position in fusion technology."



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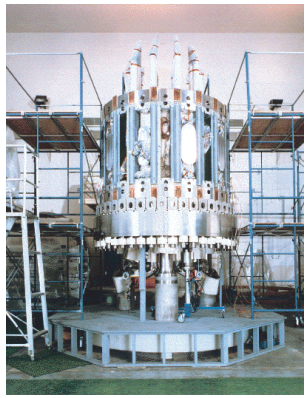
050–03/RDS/ci

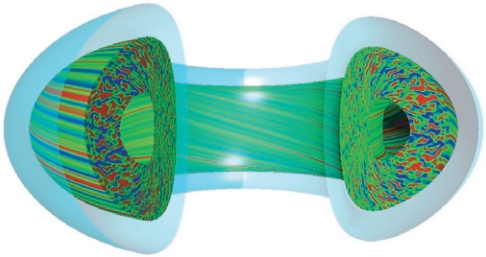
ITER WILL PROVIDE AN ORGANIZING POINT FOR THE WORLD, U.S., AND DIII–D PROGRAMS

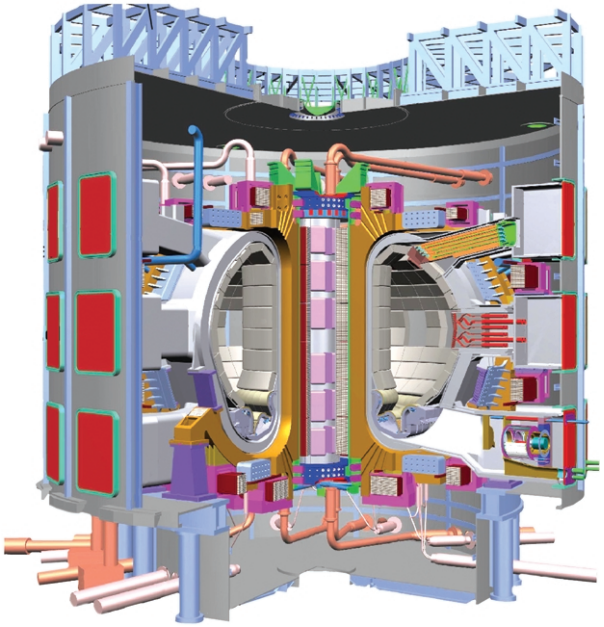
DIII–D Program

Alcator C-Mod



Theory Program





ISOFS

Collaboratory

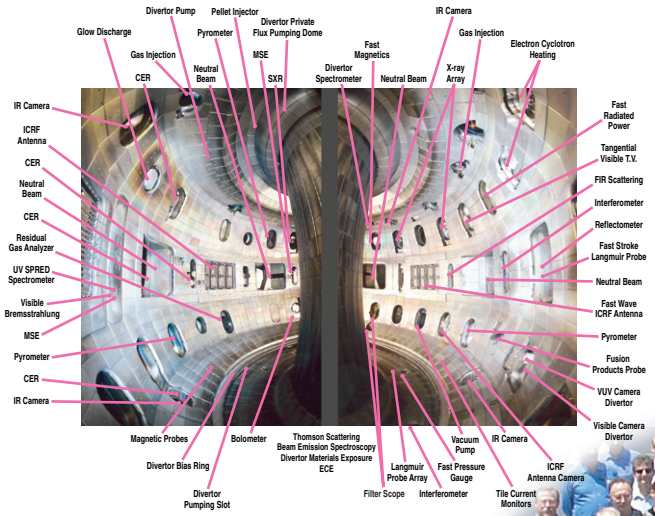
GENERAL ATOMICS

009-03/RDS/rs

DIII–D WILL CONTINUE TO BE A WORLD CLASS PROGRAM AND FACILITY TO CARRY THE U.S. FORWARD TO BURNING PLASMAS

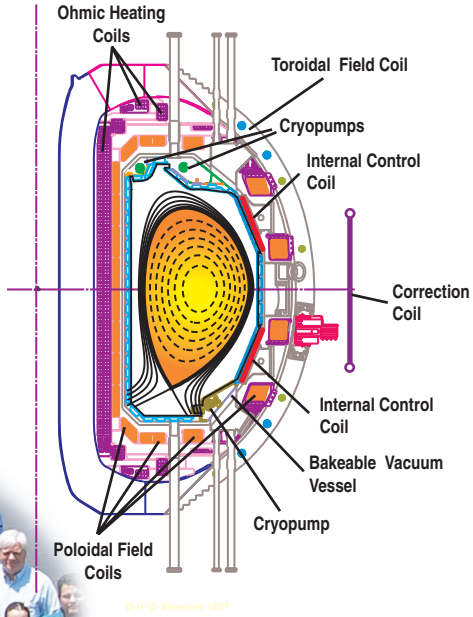
UNIQUE STRENGTHS

Physics Measurements



International Research Team

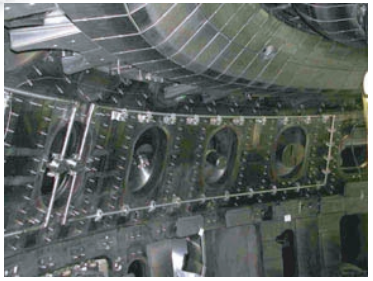
Flexibility



Partnerships and Leadership

- Collaborating Exp.
- ITPA
- TTF
- Theory/Modeling
- Burning Plasmas

Plasma Control



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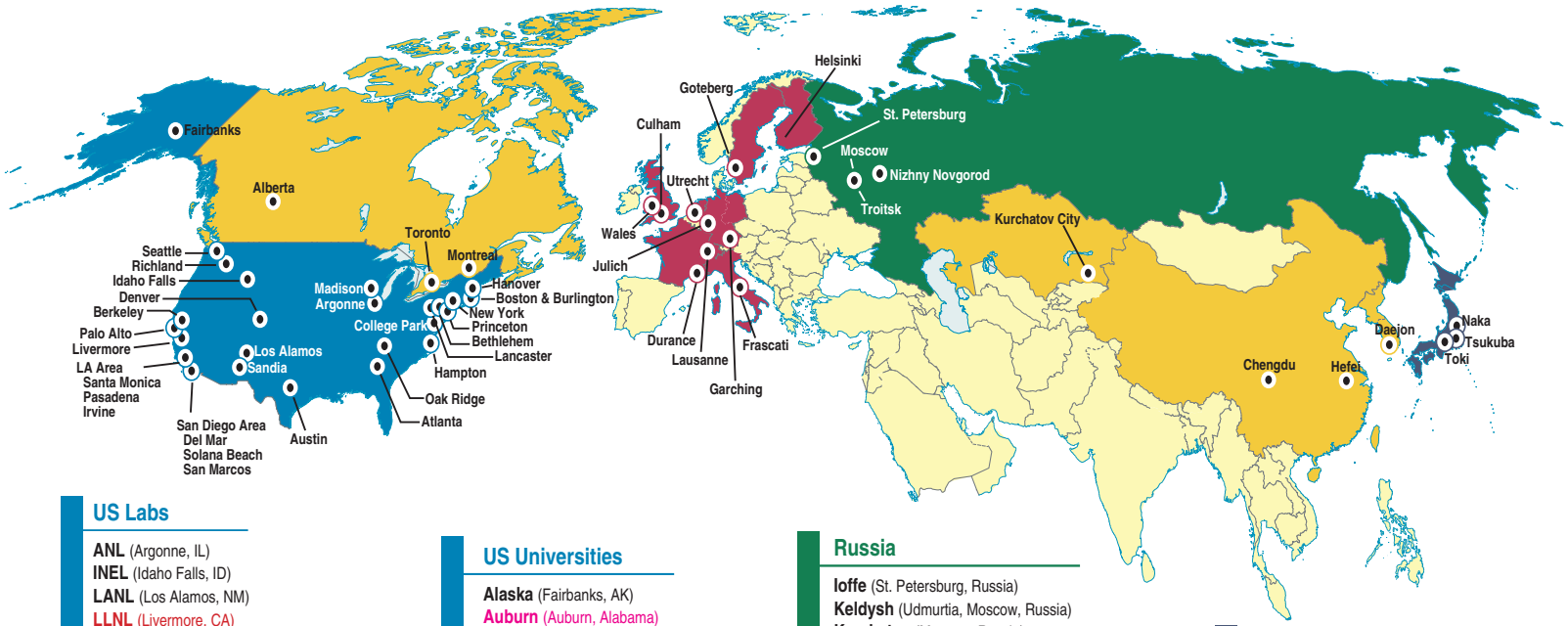
054-03/TST/jy

THE DIII–D INTERNATIONAL TEAM: THE MOST VALUABLE ASSET OF THE DIII–D PROGRAM



US Labs

ANL (Argonne, IL)
INEL (Idaho Falls, ID)
LANL (Los Alamos, NM)
LLNL (Livermore, CA)
ORNL (Oak Ridge, TN)
PNL (Richland, WA)
PPPL (Princeton, NJ)
SNL (Sandia, NM)

US Industries

CompX (Del Mar, CA)
CPI (Palo Alto, CA)
Creare (Hanover, NH)
Digital Finetec (Ventura, CA)
FAR Tech (San Diego, CA)
HiTech Metallurgical (San Diego, CA)
IR&T (Santa Monica, CA)
Orincon (San Diego, CA)
SAIC (La Jolla, CA)
Surmet (Burlington, MA)
Thermacore (Lancaster, PA)
TSI Research (Solana Beach, CA)

US Universities

Alaska (Fairbanks, AK)
Auburn (Auburn, Alabama)
Cal Tech (Pasadena, CA)
Colorado (Boulder, CO)
Columbia (New York, NY)
Georgia Tech (Atlanta, GA)
Hampton (Hampton, VA)
Lehigh (Bethlehem, PA)
Maryland (College Park, MD)
MIT (Boston, MA)
Palomar (San Marcos, CA)
New York U. (New York, NY)
Texas (Austin, TX)
UCB (Berkeley, CA)
UCI (Irvine, CA)
UCLA (Los Angeles, CA)
UCSD (San Diego, CA)
U. New Mexico (Albuquerque, NM)
Washington (Seattle, WA)
Wisconsin (Madison, WI)

Russia

Ioffe (St. Petersburg, Russia)
Keldysh (Udmurtia, Moscow, Russia)
Kurchatov (Moscow, Russia)
Moscow State (Moscow, Russia)
Triniti (Troitsk, Russia)
Gycom (Nizhny Novgorod, Russia)

European Community

Cadarache (St. Paul-lez, Durance, France)
Consorzia RFX (Padua, Italy)
Culham (Culham, Oxfordshire, England)
Frascati (Frascati, Lazio, Italy)
FOM (Utrecht, The Netherlands)
IPP (Garching, Germany)
JET-EFDA (Oxfordshire, England)
KFA (Julich, Germany)
Lausanne (Lausanne, Switzerland)
Chalmers U. (Goteberg, Sweden)
Helsinki U. (Helsinki, Finland)
U. Naples (Naples, Italy)
U. Strathclyde (Glasgow, Scotland)
U. Wales (Wales)

Japan

JAERI (Naka, Ibaraki-ken, Japan)
JT-60U
JFT-2M
Tsukuba University (Tsukuba, Japan)
NIFS (Toki, Gifu-ken, Japan)
LHD

Other International

Australia National U. (Canberra, AU)
ASIPP (Hefei, China)
KAIST (Daegon, S. Korea)
KBSI (Daegon, S. Korea)
National U. (Taiwan)
Nat. Nucl. Ctr. (Kurchatov City, Kazakhstan)
SWIP (Chengdu, China)
U. Alberta (Alberta, Canada)
U. Toronto (Toronto, Canada)

DIII–D
NATIONAL FUSION FACILITY
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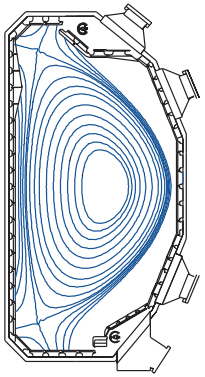
050-03/RDS2/rs

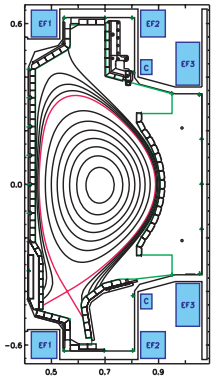
DIII–D WORKS WITH OTHER WORLD TOKAMAKS TO RESOLVE CRITICAL ISSUES FOR ITER AND ADVANCED TOKAMAKS



DIII–D

DIII–D

- *AT* physics-high β
- Wall stabilization
- Transport focus
- ECCD/ECH
- NBI/FW
- All carbon wall
- High δ divertor
- Disruption mitigation



C–MOD

ALCATOR C–Mod

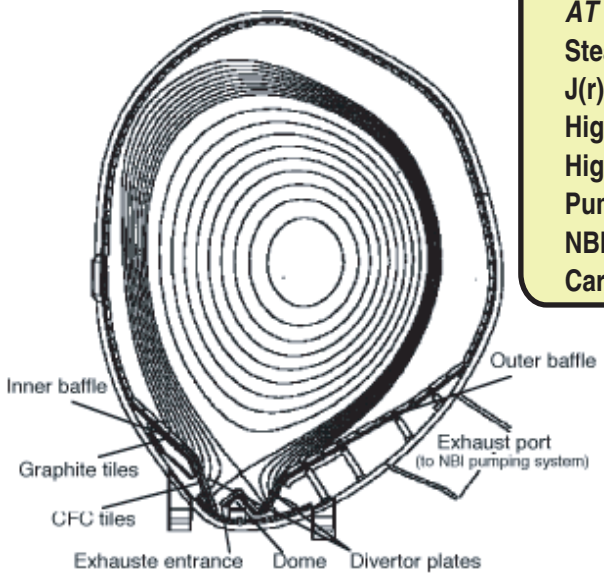
- High field
- High density
- LHCD/ICRF
- Dissipative divertor
- Moly walls

JET

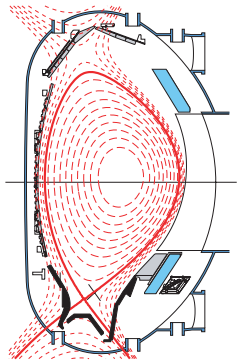
- DT physics
- High performance
- Dimensionless scaling
- NBI/ICRF/LHCD
- ITER validation
- Carbon/beryllium

JT–60U

- *AT* physics
- Steady-state
- J(r) control
- High performance
- High bootstrap
- Pumped divertor
- NBI/LH/EC
- Carbon



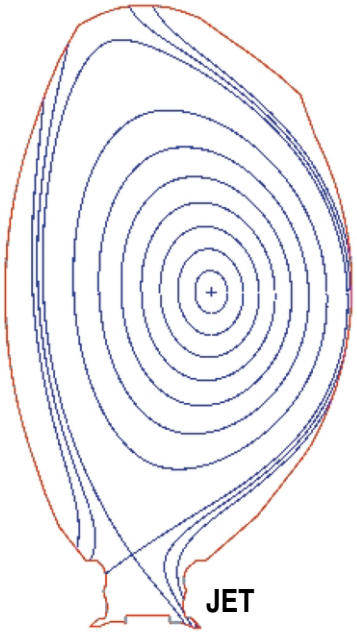
JT–60U



ASDEX UPGRADE

ASDEX-UPGRADE

- Power and particle control
- ITER coil configuration
- ITER hybrid
- ECCD/ECH
- NBI/FW
- Tungsten/carbon
- ELMs



JET

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COLLABORATION AMONG WORLD TOKAMAKS PROVIDES REQUIRED BREADTH IN PHYSICAL CHARACTERISTICS

	I_p (MA)	Paux (MW)	B_T (T)	R (m)	a (m)	κ	δ	Special Features
Elongated								
JET (EC)	5.0	40	3.4	3.000	1.5	1.6	0.35	DT, ICRF, LHCD, C and Be
JT–60U (Japan)	5.0	50	4.4	3.000	0.7	1.8	0.3	Negative ion NB, EC
DIII–D (US)	3.0	27	2.2	1.670	0.67	2.5	1.0	Flexible shape, RWM, EC
C–Mod (US)	2.0	8	9.0	0.670	0.21	1.8	0.4	High magnetic field, rf heated, Mo PFC
ASDEX-Upgrade (Germany)	1.6	18	2.7	1.65	0.5	1.6	0.15	Divertor physics, W and C PFC, off-axis NBI
TCV (Switzerland)	1.2	4.5	1.4	0.875	0.24	3.0		EC, strong shaping
Tore Supra (France)	1.7	9	4.5	2.250	0.7	1.0	0	Circular, long-pulse (CIEL) limiter, superconducting
TEXTOR (Germany)	0.8	8	3.0	1.750	0.48	1.0	0	Circular, dynamic ergodic divertor

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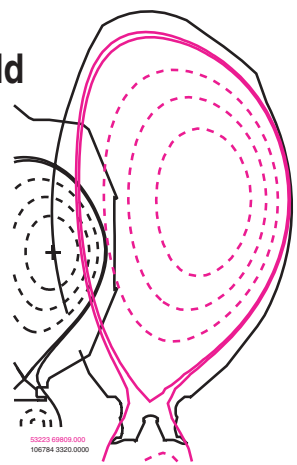
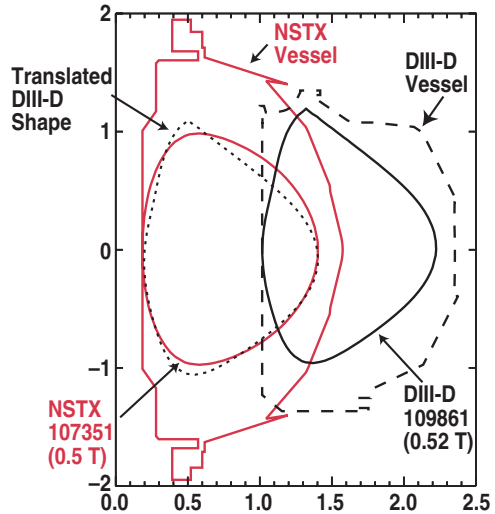
COLLABORATIVE EXPERIMENTS COORDINATED BY IEA/ITPA ENABLES PHYSICS VALIDATION IN SUPPORT OF ITER

- Key mechanism to develop physics basis for next step burning plasmas (ITER)
- National and International coordination through IEA/ITPA is working
  DIII–D FY2003 → 18 topics (23/53 days)

JET/DIII–D
NTM Threshold



NSTX/DIII–D Alfvén Instabilities



Planned collaborations

- JT-60U
  - Steady-state, high performance
- JET
  - AT/ITB, hybrid scenarios
  - RWM and NTM
  - RF and rotation
  - Pedestal physics, QH-mode
  - Disruption mitigation
- ASDEX
  - RWM and NTM
  - Pedestal physics, QH-mode
  - Hybrid scenarios
- TCV
  - H–mode
- C-Mod
  - Pedestal
  - SOL
  - NTM
- NSTX
  - Alfvén modes
  - Transport
- HBT-EP
  - RWM

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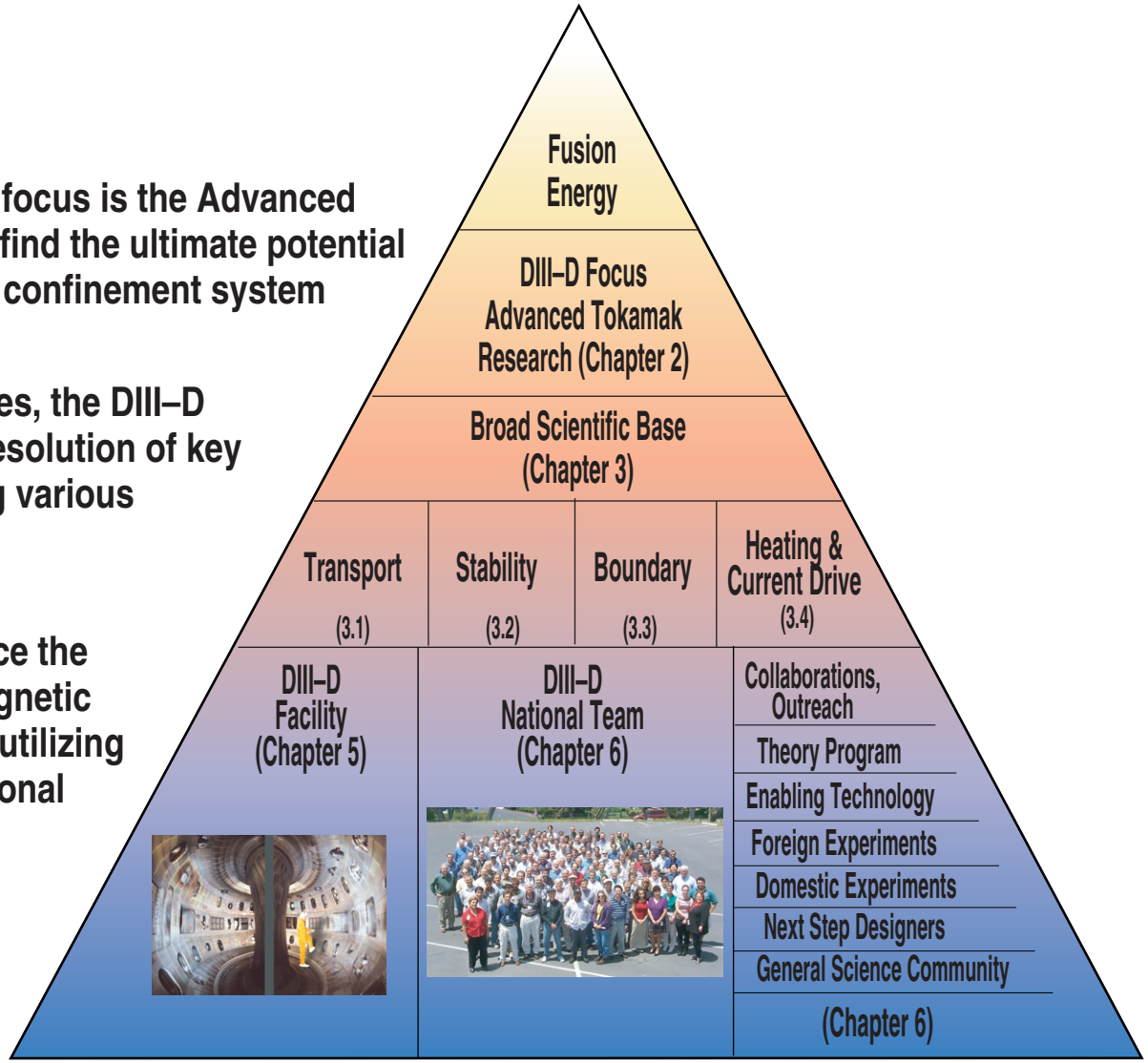
ITPA TOPICAL: PHYSICS GROUP PROPOSALS, NOVEMBER 2002

Proposal Title	Devices	FY2003 Experiment Time
β scaling of confinement in ELMy H–modes	All available devices, **DIII–D**, JET, NSTX, AUG, JT–60U	1 day
Improving the condition of global ELMy H–mode and pedestal databases	All available devices	
Development of hybrid scenario demonstration discharges	AUG, **DIII–D**, JET, JT–60U	2 days
Development of steady-state demonstration discharges	AUG, **DIII–D**, JET, JT–60U	~4
High-performance operation with $T_e \sim T_i$	AUG, **DIII–D**, JET, JT–60U	0 to 1
ITB operation with no external momentum input	AUG, C–Mod, DIII–D, JET, JT–60U	
Improved physics understanding of QDB/QH–mode operation	AUG, **DIII–D**, JET, JT–60U	3 days
Improved understanding of β-limits with ITB operation	AUG, **DIII–D**, JET, JT–60U, NSTX	2 to 3 days
Dimensionally similar ITB scaling experiments	AUG, JET	
Simulation and modeling support for T–10 turbulence studies	T–10	
Understanding of pedestal characteristics through dimensionless experiments	JET, JT–60U	
JET/DIII–D pedestal similarity studies	**DIII–D**, JET	1 day
Comparative MHD analysis and predictive modeling of Type 1 and Type II ELMy H–mode	AUG, JET, JT–60U	
Stability analysis with improved edge treatment	AUG, **DIII–D**, JT–60U	Study to be completed
Dimensionless identity experiments with JT–60U Type II ELMy H–modes in DIII–D	DIII–D, JT–60U	0 days
Impact of ELMs on the pedestal and SOL (effect of aspect ratio)	AUG, **DIII–D**, MAST, NSTX	0.5
Parameter similarity studies (L–H transition, EDA)	AUG, C–Mod, JET	
Parameter similarity studies Quiescent H–mode regimes	AUG, **DIII–D**, JET, JT–60U	0.5
Scaling of Type I ELM energy loss	**DIII–D**, JET, JT–60U and others	0.5
Tritium codeposition	AUG, C–Mod, **DIII–D**, JET, TEXTOR, Tore Supra	2 days
Parallel transport in the SOL	AUG, **DIII–D**, C–Mod, JET, JT–60U	1
Pressure and size scaling of gas jet penetration for deposition	AUG, C–Mod, **DIII–D**, JET, JT–60U	1 day
Joint experiments on resistive wall mode physics (lack of experiment time)	AUG, **DIII–D**, JET, NSTX	0.5
Joint experiments on neoclassical tearing modes (including error field effects)	AUG, **DIII–D**, JET	1 day
Neoclassical tearing mode physics — aspect ratio comparison	AUG, DIII–D, MAST, NSTX	0 day
Comparison of sawtooth control methods for neoclassical tearing mode suppression	AUG, **DIII–D**, JET	1 day
Error field sideband effects for ITER	**DIII–D**, JET	1 day
Preparation of ITER steady-state scenario	AUG, **DIII–D**, JET, JT–60U	~4 day
Preparation of ITER hybrid scenario	AUG, **DIII–D**, JET, JT–60	2 days

DIII–D MISSION: ESTABLISH THE SCIENTIFIC BASIS FOR THE OPTIMIZATION OF THE TOKAMAK APPROACH TO FUSION ENERGY PRODUCTION

- **DIII–D National Program goals**
  - The DIII–D Program's primary focus is the Advanced Tokamak thrust that seeks to find the ultimate potential of the tokamak as a magnetic confinement system
  - Where it has unique capabilities, the DIII–D Program will undertake the resolution of key enabling issues for advancing various magnetic fusion concepts
  - The DIII–D Program will advance the science and technology of magnetic confinement on a broad front, utilizing its extensive facility and a national research team

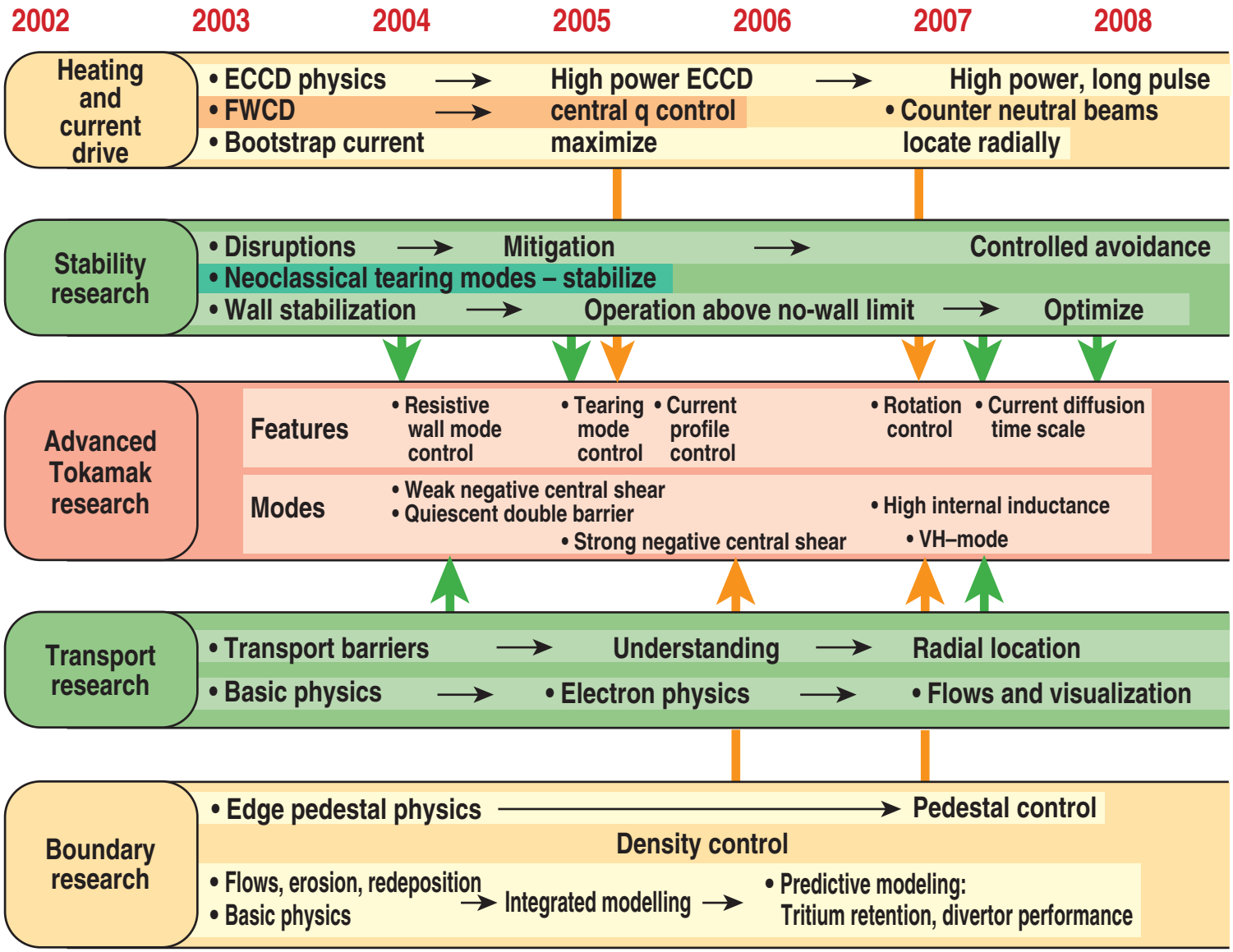


"The knowledge gained is the program's enduring contribution"

DIII–D NATIONAL FUSION FACILITY

009-03/TST/JY

IN OUR OVERALL RESEARCH PLAN, TOPICAL SCIENCE AREAS DEVELOP FUSION SCIENCE BASE AND CONTRIBUTE TO ADVANCED TOKAMAK FOCUS



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NATIONAL FUSION FACILITY
SAN DIEGO

067–03/RDS/wj

WE HAVE THE OPPORTUNITY IN THIS DECADE TO MAKE THREE MAJOR ADVANCES

1. Advanced Tokamak physics basis for steady-state operation of ITER, CTF, and DEMO
   - The building blocks of AT physics are in place or close-at-hand
   - The path to AT performance appears open on all fronts. Integration is key
2. An understanding of the basic mechanisms of transport from turbulence
   - Our last remaining science area to achieve predictive code capability
   - Improved computational capabilities and diagnostics needed
3. An understanding of the physics of mass transport in the SOL and divertor regions and develop techniques to affect and control the flows of particles around the boundary of divertor plasmas

NOW IS THE TIME TO SEIZE THESE OPPORTUNITIES

THE DIII–D PROGRAM IS IN A VERY STRONG POSITION FROM ACCOMPLISHMENTS IN THE LAST FIVE-YEAR PERIOD (1999–2003) TO ENTER THE NEXT ONE (2004–2008)

Status	Needs (04–08)
The building blocks of AT physics are in place or close-at-hand	
— Wall stabilization looks like it will work	Audio amplifiers
— Neoclassical tearing mode stabilization with ECCD works	Six long-pulse gyrotrons
— Successful disruption mitigation technique is available	Massive gas puff mods
— Current profile control demonstrations have started (ECCD physics)	ECCD (9 MW, 10 s), FWCD (6 MW, 10 s)
— Enhanced confinement states are numerous	Counter beamline
— ELM-free regimes exist (C–Mod and DIII–D)	Counter beamline
— Necessary density control methods have been shown	Pump for high δ DN
— New era of plasma control is starting	Continue development
The technology needed has been proven	
— 1 MW, long-pulse gyrotrons work	Replace GYCOM with CPI
— Six gyrotron EC system in place	Eight gyrotrons (9 MW, 10 s)
— Restarting FW operation	Upgrade ABB units
— Upper divertor provides adequate SN density control	Pump for high δ DN
— I–coil system expected to be adequate for RWM stabilization is done	Audio amplifiers
ITG modes control ion transport	High k diagnostics, BES, counter beam
High density dissipative divertor works	Divertor CER/DNB quartz microbalance

DIII–D NATIONAL FUSION FACILITY

Green = World Leader Blue = at forefront

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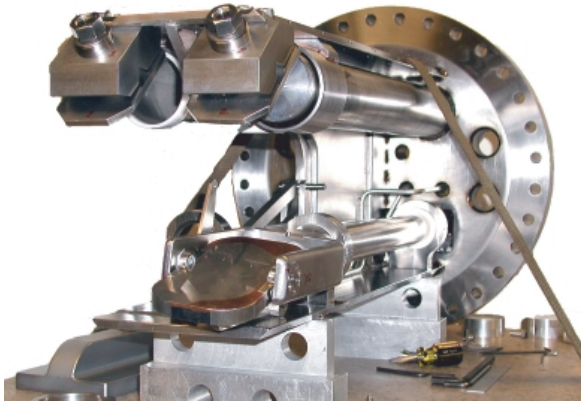
THE DIII–D ELECTRON CYCLOTRON HEATING (ECH) UPGRADE TO 6 MW PROJECT IS NOW COMPLETE !

CPI Gyrotron

- Scope: add three long-pulse diamond window 110 GHz 1 MW class gyrotrons to the existing three gyrotron system

- All three gyrotrons have now been operated at GA in 5 s long pulses at the full rated voltage of 80 kV, full rated current of 40 A, and with 1 MW of rf power generated at 110 GHz

- This achievement brings to completion a major element of work in the DIII–D program. In that time, we have procured, built, installed, and brought into an operational state:
  - A new building addition to house the new EC equipment
  - Three new CPI gyrotrons and their superconducting magnets
  - Two new high voltage (-80,000 V) and current (80 A) gyrotron power supplies
  - Electrical and cooling water systems for the gyrotrons
  - An entirely new control system for the gyrotrons
  - Two more transmission line runs from the gyrotron vault to the DIII–D tokamak
  - Numerous EC components such as beam interface units, dummy loads, etc.
  - Three new fully steerable EC launchers (PPPL)



ECH Launcher

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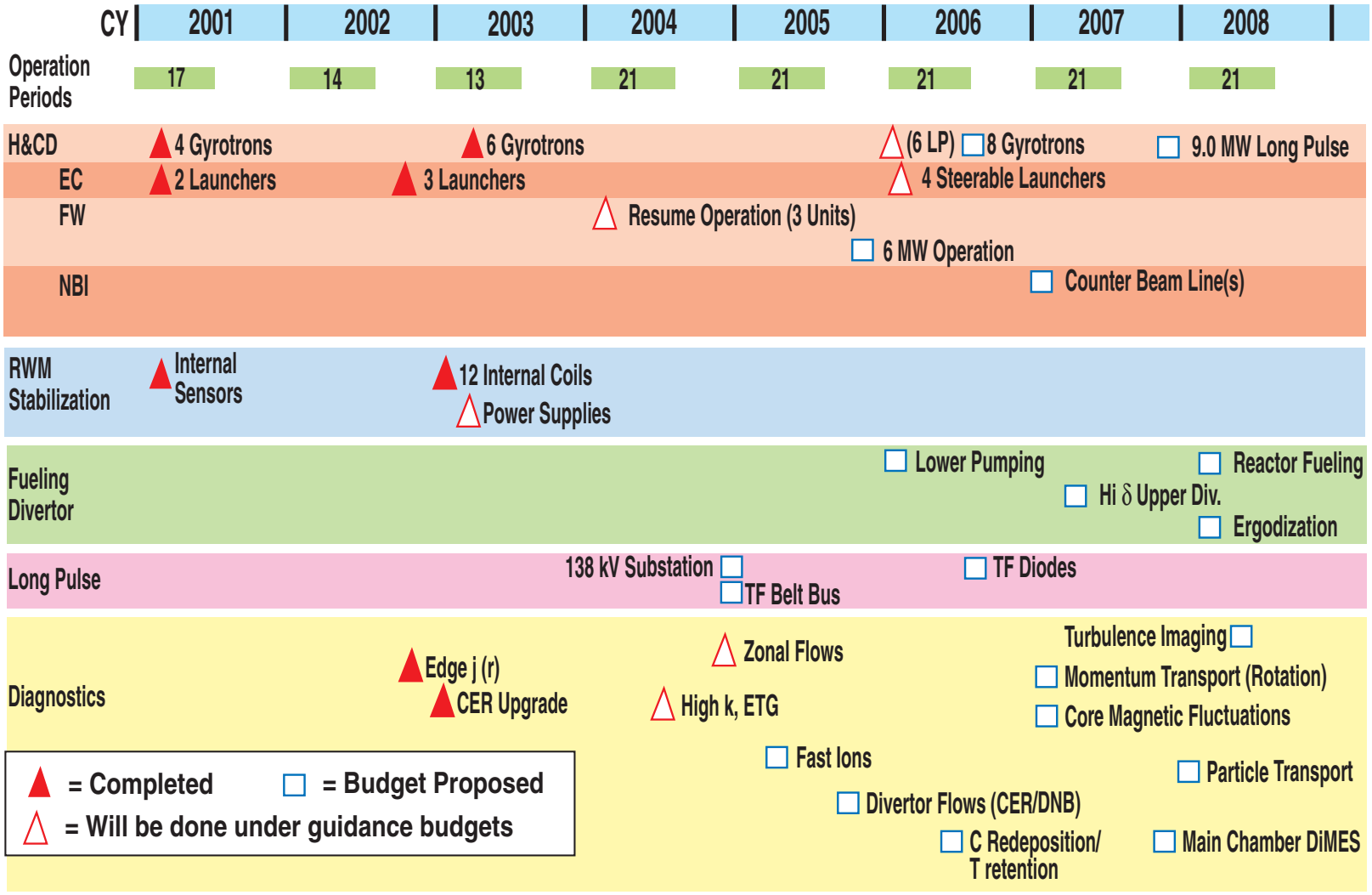
DIII–D NEEDS INCREASED FACILITY CAPABILITIES TO SEIZE THE OPPORTUNITIES FOR FY04–08



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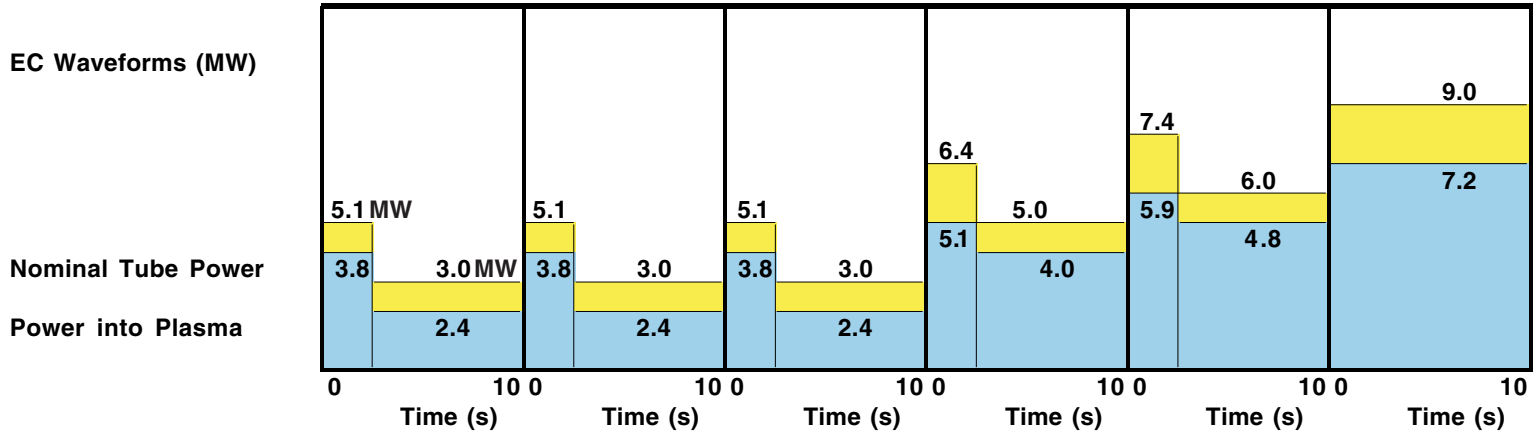
PROPOSED EC SCHEDULE

		CY02	CY03	CY04	CY05	CY06	CY07
≤2 s	GYCOM #1	0.7 MW, 2s					
	GYCOM #2	0.7 MW, 2s					
	GYCOM #3	0.7 MW, 2s					
≤10 s	CPI-P1	1.0 MW, 10s					
	CPI-P2	1.0 MW, 10s					
	CPI-P3	1.0 MW, 10s					
	CPI-P4				1.0 MW, 10s		
	CPI-P5				1.0 MW, 10s		
	CPI-P6				1.0 MW, 10s		
	CPI-DC1						1.5 MW, 10s
	CPI-DC1						1.5 MW, 10s



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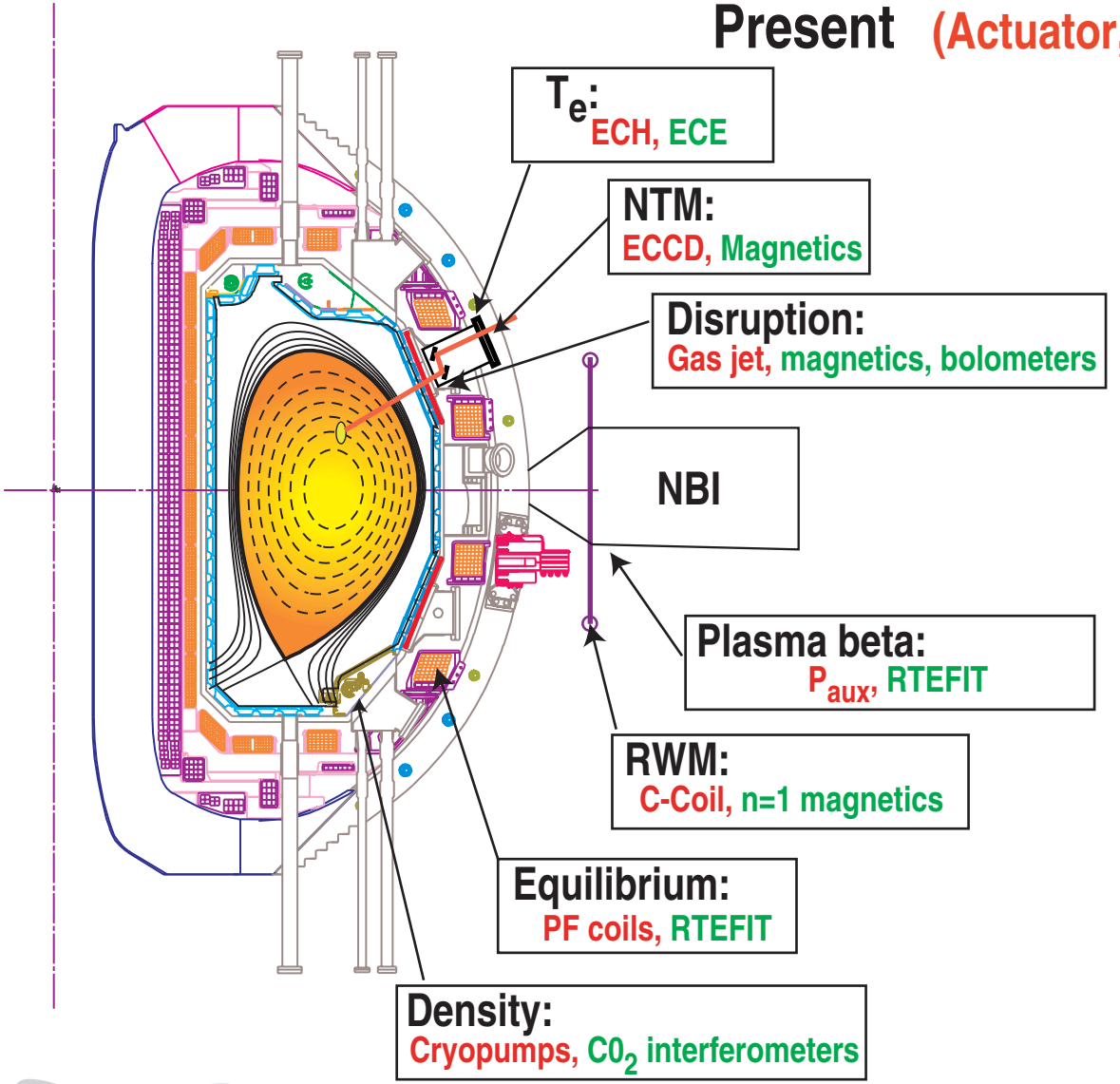
A NEW ERA IN PLASMA CONTROL: KEY TO THE DIII–D AT PROGRAM

Present (Actuator, Sensor) **Planned**



Integrated control:
Validated models
Expanded PCS

Current profile control:
ECCD/FWCD, MSE

Optimized RWM control:
I-Coil
Expanded magnetics

Disruption detection, correction, mitigation:
MHD regulation — PCS
Expanded magnetics

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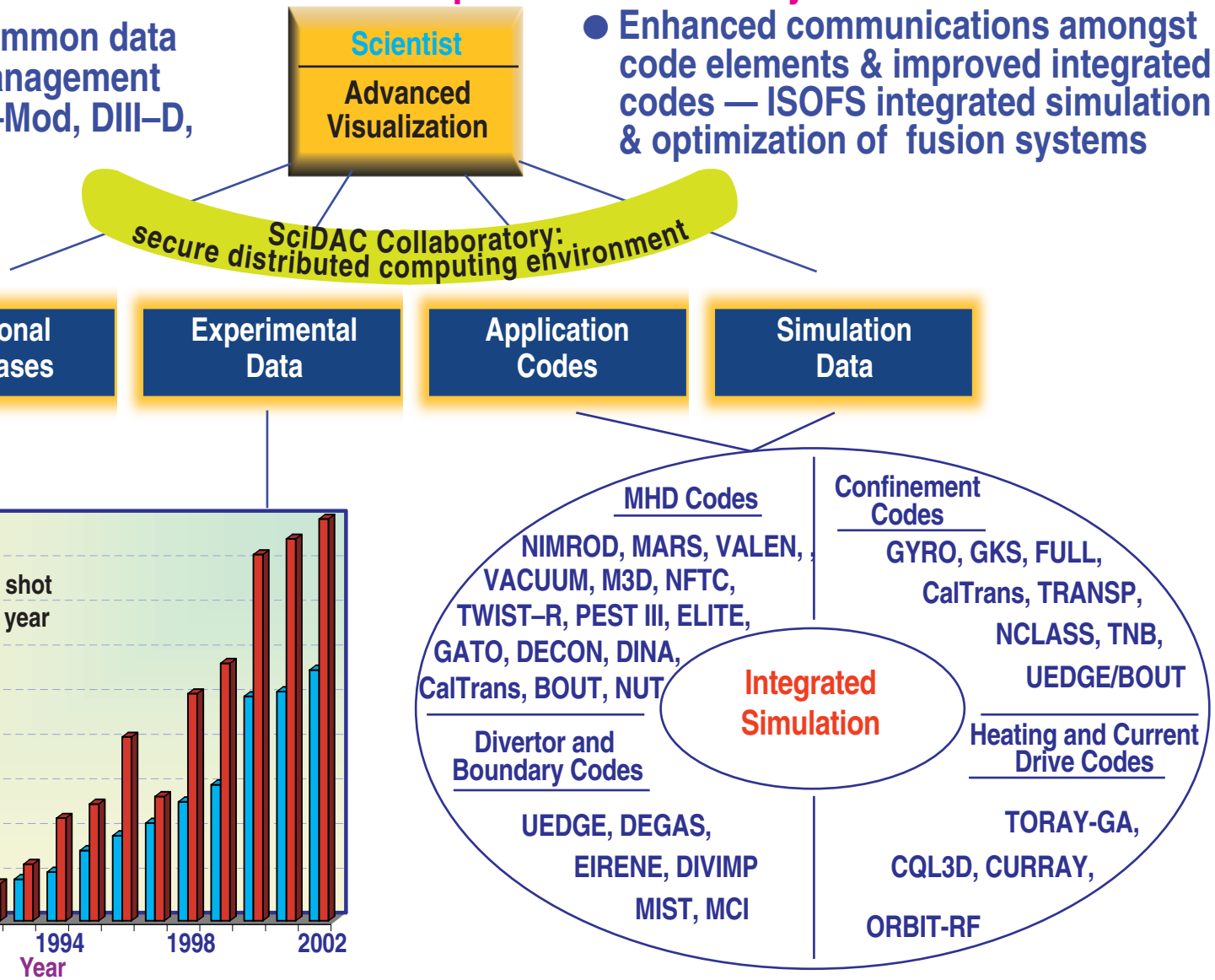
DATA, ANALYSIS TOOLS, AND MODELING CODES ARE EMPOWERING DIII–D SCIENTISTS (Worldwide) TO ADDRESS CRITICAL ISSUES

— The connection between experiment and theory —

- MIT MDSPlus: a common data acquisition and management system (Alcator C–Mod, DIII–D, NSTX, JET, TCV)
- Enhanced communications amongst code elements & improved integrated codes — ISOFS integrated simulation & optimization of fusion systems



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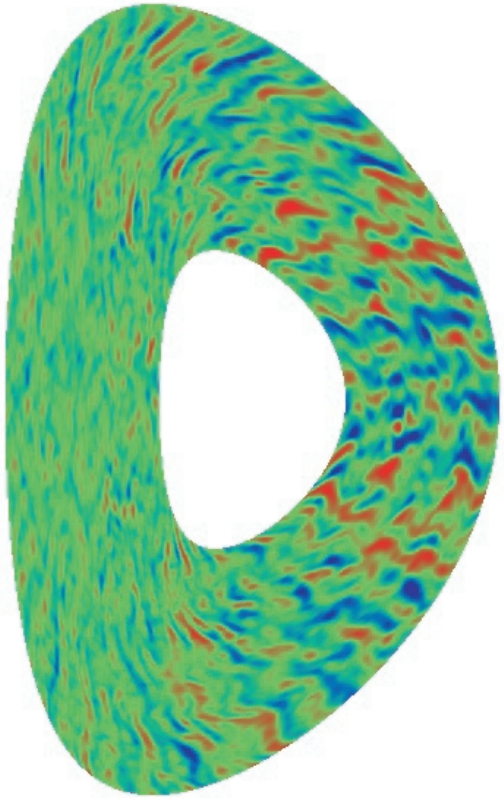
THE DIII–D PROGRAM PLANS A FOCUSED EFFORT ON UNDERSTANDING TURBULENT TRANSPORT TOWARD MEETING LONG RANGE IPPA GOALS

— As part of a community-wide effort, in concert with TTF —

- Lead goal is predictive understanding of transport (FESAC goal 1.1)
  - Five-Year Objective: Advance the scientific understanding of turbulent transport, forming the basis for a reliable predictive capability in externally controlled systems

⇒ For the first time, codes contain essential physics needed for meaningful comparison with experiment

  - New diagnostic measurements essential for this comparison



Fusion SciDAC
Computing Initiative

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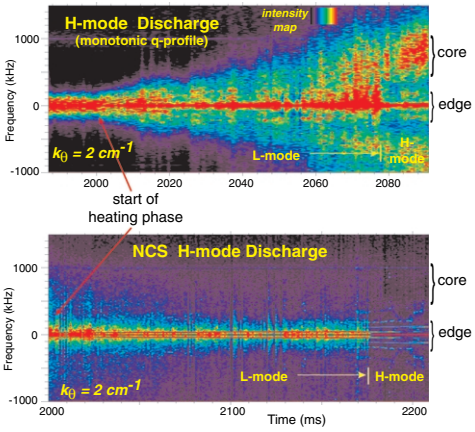
ALL DIII–D TURBULENCE MEASUREMENTS ARE CARRIED OUT BY UNIVERSITY COLLABORATIONS

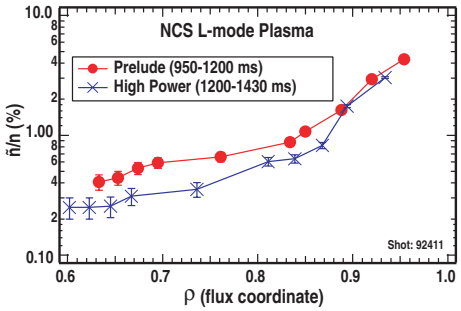
- **FIR scattering – UCLA**
  - Survey instrument covering entire plasma radius
  - Good time and wavenumber resolution
- **BES (Beam Emission Spectroscopy) – U. Wis.**
  - Spatially resolved with ability to provide profiles
  - Absolute measurement of turbulence levels
- **Reflectometry – UCLA**
  - Radial correlation length of the turbulence
  - Relative ñ with high spatial and temporal resolution
- **Phase contrast imaging – MIT**
  - Ability to measure density fluctuations
- **Electron cyclotron emission – U. Texas/U. Md.**
  - Electron temperature fluctuations
- **Fast edge probes – UCSD**
  - Localized edge turbulence



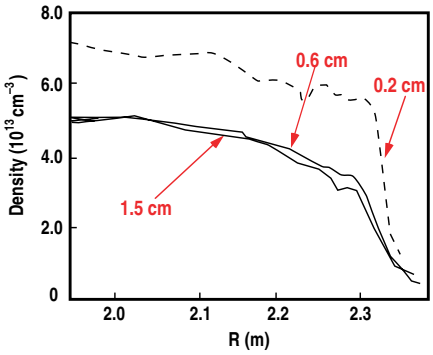
FIR scattering data

L– and H–mode

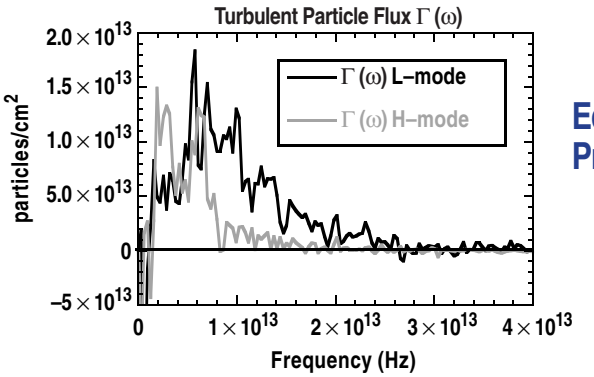
NCS L– and H–mode



Turbulence level from BES system



Correlation length from reflectometer



Edge Probe

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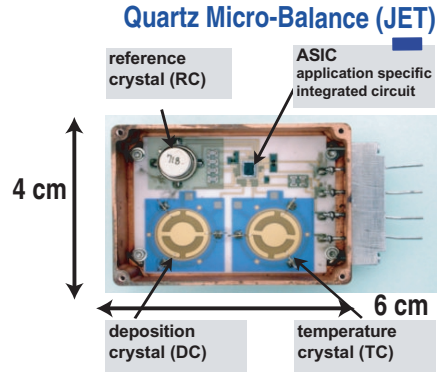
BOUNDARY PHYSICS: UNDERSTAND MASS TRANSPORT

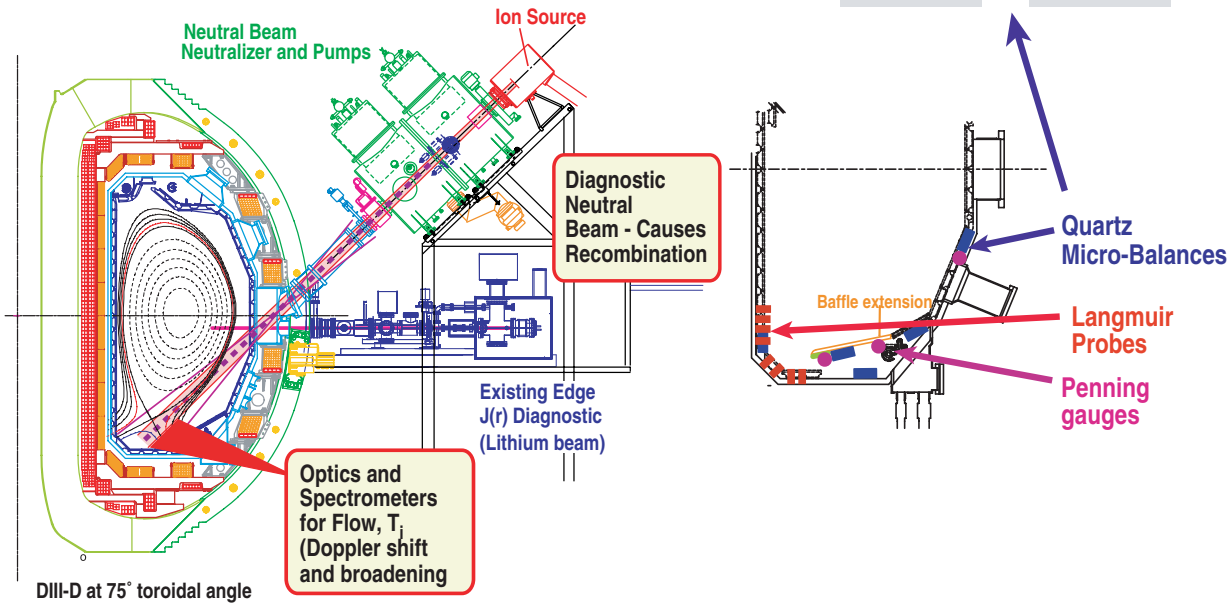
- **FESAC/IPPA 5-Year Objective: Advance the capability to predict detailed multi-phase interfaces at very high power and particle fluxes**

- **DIII–D Goal**

  Understand the physics of "mass transport" in the SOL, plasma chamber and develop techniques to affect and control the flows of particles around the boundary of divertor tokamaks

- **Applications: radiative divertor, T co-deposition problem**
  - Measure particle sources, sinks and flow channels
    - ★ In-situ diagnostics
  - Erosion, redeposition
    - ★ ELMs
  - Integrated boundary modeling, divertor plate to the pedestal top
    - ★ Quantify tritium retention
    - ★ Devise mitigation





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MAJOR FUSION OBJECTIVES ARE WITHIN OUR REACH IN THIS DECADE

- The physics basis for advanced operating modes in ITER (500 MW for one hour or even steady state)
  - Will enable the first phase of ITER to focus on advanced, long-pulse modes, moving much of the currently envisioned Phase 2 into Phase 1
- An understanding of the basic physical mechanisms of transport from turbulence
- An understanding of the physics of mass transport in the SOL and divertor