Perspectives on The Development of Fusion Energy: Elements of a Viable Near-Term US Strategy

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Overview

- **Progress in fusion research in the past decade has been extraordinary but key science issues remain that must be resolved with ongoing R&D**
- **Continued research through the next decade on existing US tokamaks with upgraded diagnostic and heating capability is critical for fusion's success**
- **International collaboration is best carried out in parallel with a strong domestic program which tests new ideas, the knowledge base for an effective international collaboration**
- **Advances in technology and materials will be critical to the success of fusion**
- **Workforce development (education) is a critical element for an R&D program with a long term horizon such as fusion**
- **The FY 2012 budget level for the domestic program was a minimum for maintaining a viable US fusion science program but insufficient for development of innovative technologies and better materials**
- **ITER's funding must be additive to the domestic program**

Introduction

- Progress in fusion research in the past decade has been extraordinary but key issues remain to be solved in ongoing experiments to optimize ITER operation
- The scientific basis for an attractive DEMO and power plant is well beyond that required for ITER and remains to be demonstrated in ongoing experiments with upgraded heating power and diagnostics
- Progress in theory and computational science has been impressive but serious gaps remain to predict tokamak performance
- New superconducting tokamaks have a special role in studying long time plasma control, erosion and heat load tolerance but their design parameters may not be adequate to answer key reactor relevant issues
- Advances in High Temperature Superconducting (HTSC) magnets could revolutionize the design of future fusion power plants
- **Graduate education must remain a central element of the program**

More Physics Must be Mastered to Make ITER a Success

"Top 12 risk issues for ITER science"

James W. van Dam, APS Town Meeting, Nov 2010, Chicago

- Disruption mitigation
- H-mode threshold
- ELM mitigation
- Vertical stability control
- Reliable high-power heating
- Divertor performance with W PFCs
- TF ripple effect on performance
- Lack of plasma rotation
- Tritium retention
- Radiative divertor operation
- Achieve densities near the Greenwald limit
- Particle control

Presentation by Alberto Loarte on ITER R&D Needs

APS DPP Meeting, Chicago, Nov 2010

- Development of ITER operational scenarios (non-active to DT) requires R&D to determine plasma behavior and use of baseline systems for its control
  - ✓ H-mode access/sustainment (including I_p ramp-up/down phases)
  - ✓ Access to H ~ 1 from low confinement H-mode and control of P_a (through $\langle n_{DT} \rangle$)
  - ✓ Sustainment of H ~ 1 and relation to ELM control requirements
  - ✓ He and H-mode plasma characterization and control of ELMs
  - ✓ Fuelling of ITER high I_p H-modes : sources vs. pinch and pellet fuelling
  - ✓ Plasma control during confinement transients
  - ✓ MHD control (NTM, sawteeth, RWM, …)
- Continued R&D support by fusion community required to guide outstanding decisions on ITER Baseline systems/detailed designs and for the definition of <u>realizable</u> ITER operational scenarios

New operating modes in tokamaks without ELMs have attractive features

- Promising new confinement regimes discovered beyond ELMy H-mode which mitigate the deleterious effects of sawteeth and/or ELMS: Q-H mode, and I- mode; physics in many cases not understood and extrapolation to ITER and DEMO not clear
- Improved MHD stability by feedback stabilization of RWM and ELM control with external coils demonstrated and may help ITER; but are they reactor (DEMO) relevant ?
- Runaway electrons controlled by massive gas-puff and killer pellets in recent experiments; more studies are needed for ITER and DEMO
- Gas (tritium) retention in the walls in ITER and DEMO is an issue and D gas retention in present day tokamaks with metallic walls under study; what about hot walls (700 C+) like in a Power Plant ?

The three US tokamaks are complementary and well positioned to answer critical fusion R&D questions

- DIII-D is medium size, medium field, with C tiles and NBI and ECRH/ ECCD +HHFW heated with t ~ $\tau_{L/R}$
- C-Mod is compact, high field, with metallic (Mo) tiles and equipped with LHCD and ICRF + FWMC heating/Flow drive with t ~ $\tau_{L/R}$
- NSTX is low aspect ratio, low field, and NBI and HHFW heated with C tiles and lithium coating and operates at high beta

- EU tokamaks are being refurbished with W divertors and/or walls (ASDEX U, JET , and SC TS-Upgrade) to be ITER relevant
- C-Mod only US machine with metallic walls (Mo) and planning hot W divertor to be ITER/DEMO relevant
- EAST and KSTAR in Asia are superconducting with C tiles and early phase of heating and diagnostic development (likely 5 + more years to match maturity of US/EU tokamak science capability)

Progress in theory and computational modeling capability still incomplete

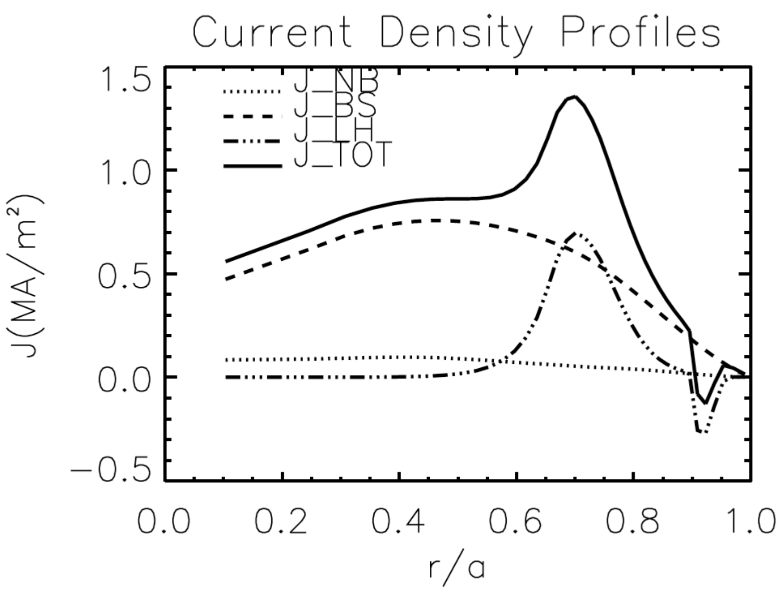
- Advances in theoretical and computational predictive capability-
  - 3 D nonlinear MHD for bulk plasma stability still incomplete
  - Gyrokinetic modeling of low frequency turbulence and transport agree with experiments only in limited operating regimes
  - Coupled ray tracing, full wave and Fokker Planck RF codes disagree with experiments in some regimes (ie, ICRF mode conversion)
  - Edge (pedestal) stability and transport codes still under development
  - MHD and gyrokinetic codes must be validated for Alfven wave stability
  - Steady state scenarios with current drive and bootstrap current needed
  - etc ….
- Synthetic diagnostics implemented into several codes to validate code predictions through experimental cross-check

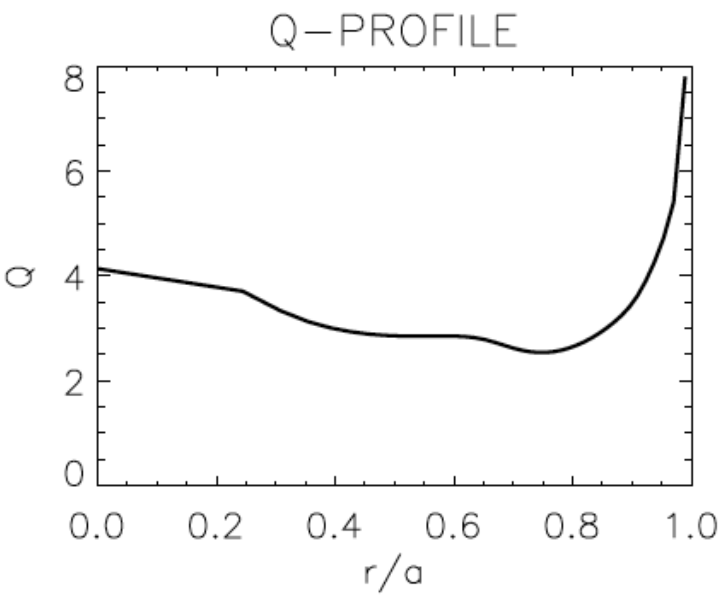
Physics knowledge needed to optimize DEMO performance not in hand and research on existing tokamaks must be continued aggressively

Example of Advanced Tokamak Demo Current Profiles

(ATBX, Porkolab et al, IAEA, Yokohama, 1998, FTP/13)

- B_T=6.25 T, n_e= 2x10^{20} m^{-3} R=5.60 m, a=1.75 m, Ip = 12.0 MA
- P_{LH} = 60 MW, P_{NBI} = 20 MW, Q_{DT} = 10.5, f_{BS}= 0.71, β_N = 2.8





Reactor like ARIES RX/AT:

n_e= 2.8x$10^{20}$$m^{-3}$, B_T=8 T, f_{BS} = 0.9, P_{LH} = 40 MW

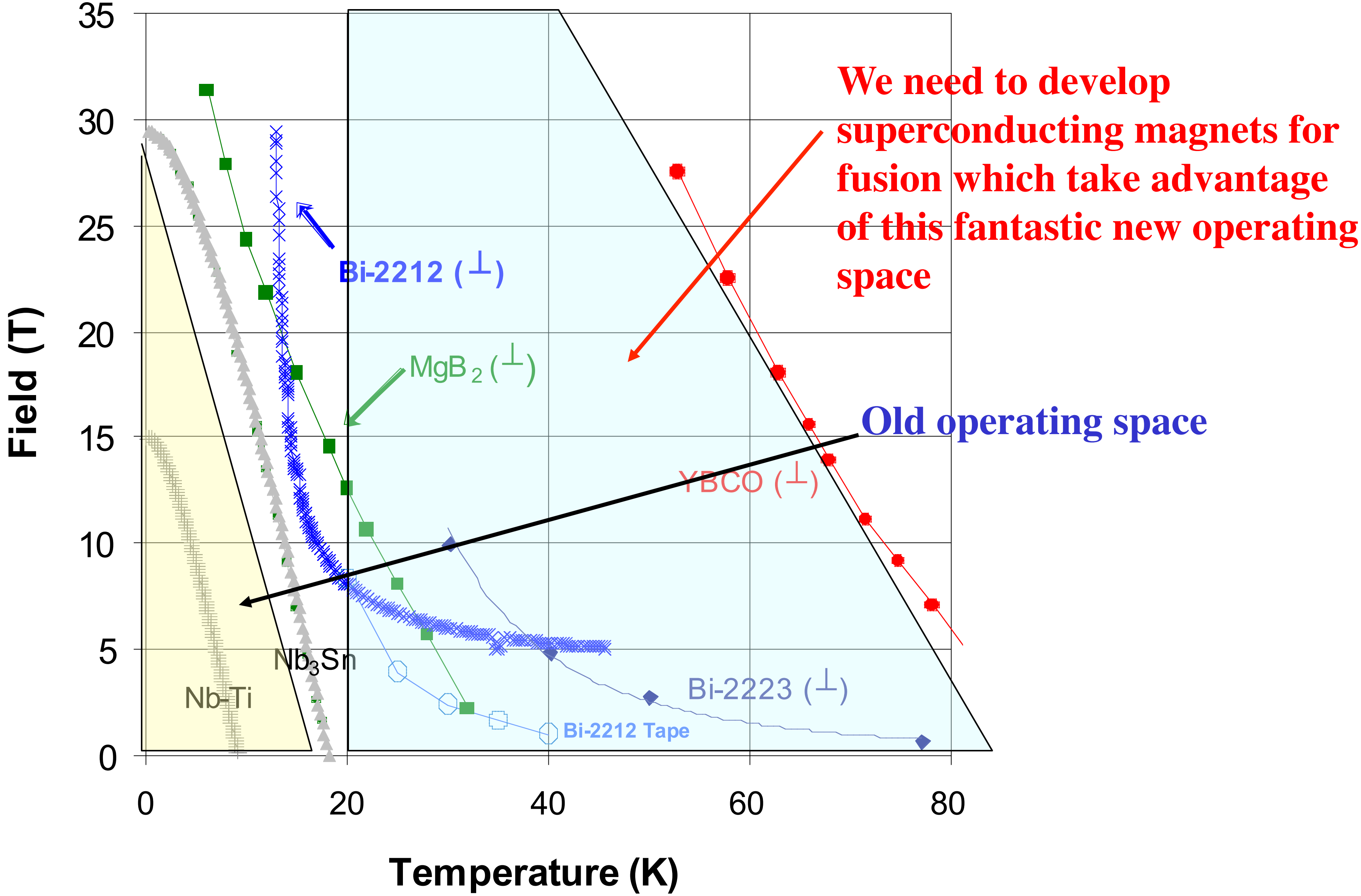
Higher Magnetic Field is a Winner

Fusion Power Density: $P \sim \beta^2 B_T^4 = (\beta/\varepsilon)^2(\varepsilon B_T^2)^2$

- Higher B-field (say16 T at the coil, 8 T on-axis) would reduce some key physics constraints and would increase reliability and availability
- Adequate plasma current for good confinement at somewhat higher q_{95}
- Higher efficiency for off-axis RF current drive in RS plasmas
- More stable MHD operation
- Should revisit Aries RS studies with more realistic current drive scenarios and modern plasma physics (realistic edge-pedestal parameters) while also adopting the higher thermal efficiency (0.59) in Aries AT versus 0.46 in RS
- **High Temperature Superconductors (HTSC) could revolutionize magnetic fusion**

HTS Make Higher Magnetic Fields Accessible

L. Bromberg, J. Minervini



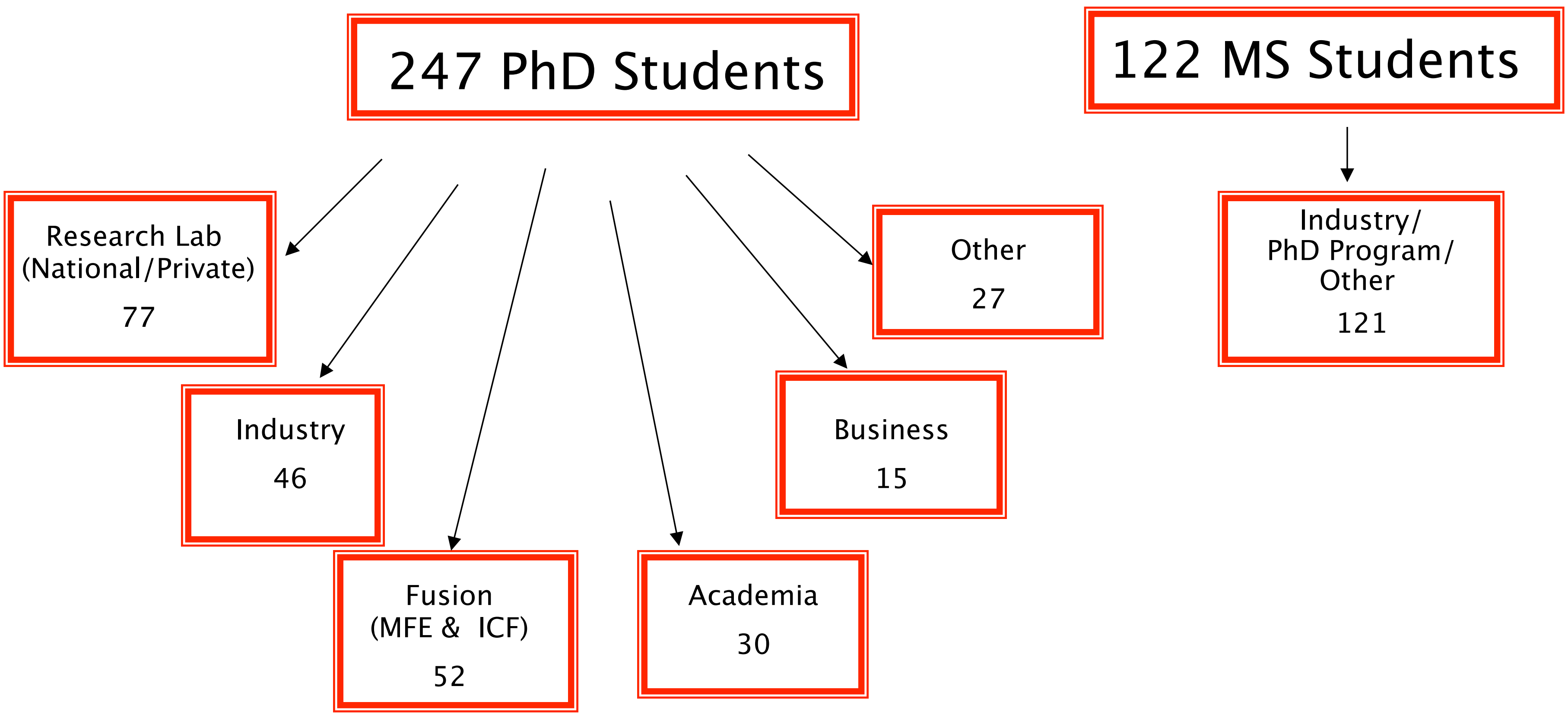
HTS is potentially a "*game-changer* " for Fusion

- ➢ Higher magnetic field
- • Peak field limited by structure, not by superconductor
- ➢ Increasing operating temperature (avoiding 4 K operation)
- • Decrease refrigerator requirement due to cryostat loads, electrical dissipation
- ➢ Jointed coils/demountable magnets-ease of maintenance
- • Design with wide access for installation, removal of components and repair as needed
- ➢ Materials exist today, at costs that are not prohibitive
- ➢ R&D is required specifically for fusion applications:
- ✧ Radiation effects on superconductor and insulating materials
- ✧ Cable construction
- ✧ Magnet cooling
- ✧ Joints

Educational Program at MIT in fusion and plasma physics: an example of scientific manpower training

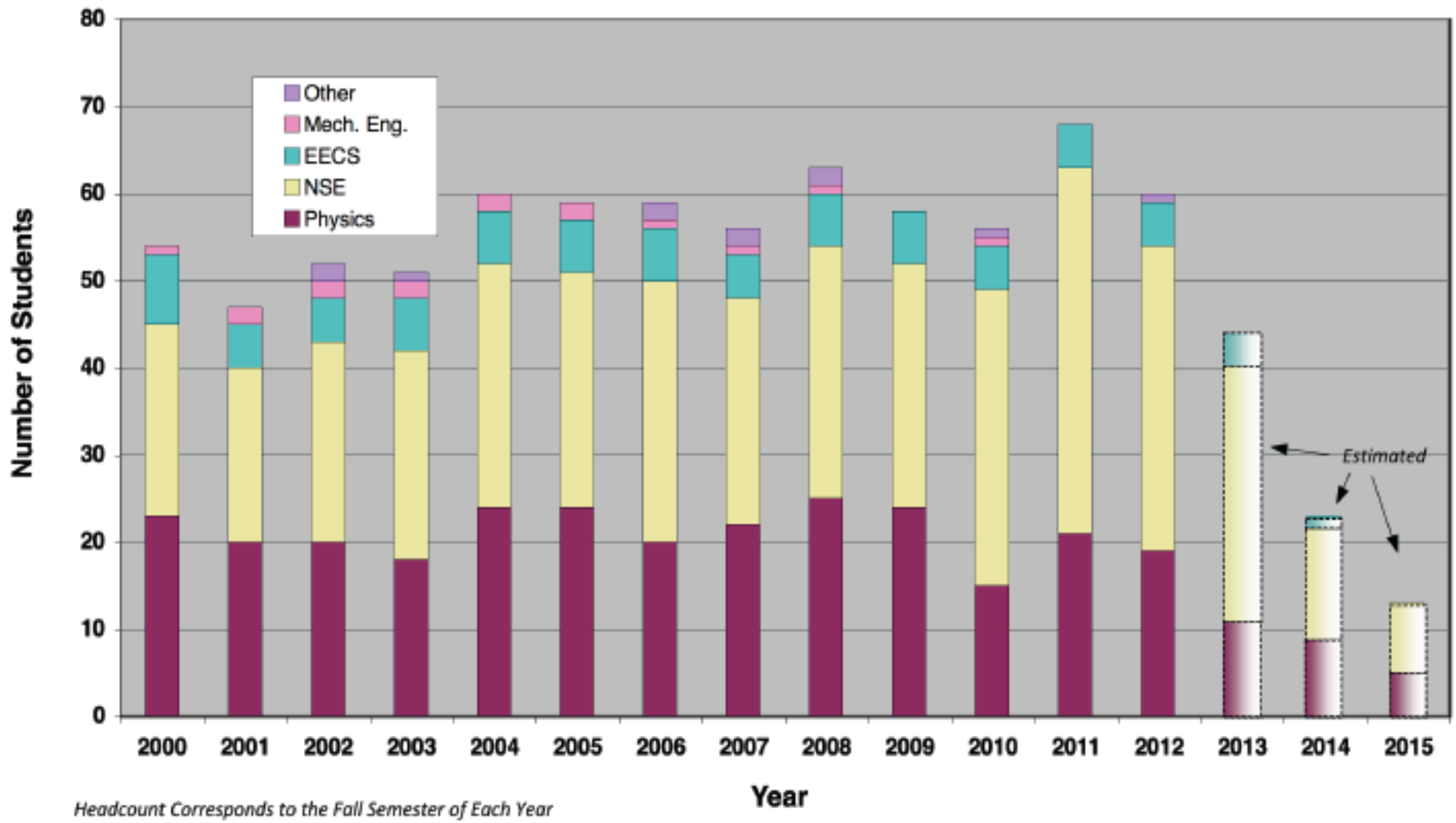
- Program in 5 different departments, with majority of students in Nuclear Science and Engineering, Physics, and EECS
- Totally integrated into MIT academic programs and life
- Wide range of courses offered and taught by 6 full time professors plus Senior Scientists and emeritus professors
- Thesis supervision with additional Senior Scientists
- Easily employed over the years, with majority in National Labs
- With proposed budget cuts, in FY 2013, academic program faces near destruction in spite of two recent hires at the Assistant Professor level in NSE

Employment Status of MIT PSFC PhD/MS Students Beyond Graduation (1980-2012)



Total Number of Graduate Students at the PSFC, by Year

Massachusetts Institute of Technology



Summary

- To maintain a viable fusion science program in the US, a minimum budget at the FY 2012 budget is necessary ($300 M, maintain operation of the 3 facilities, maintain university programs and maintain a viable theory and computational science program; it is still not sufficient to fund a viable fusion technology program)
- The proposed FY 2013 budget level of $250 M is a way to marginalize the US fusion science program, leading to massive loss of scientific manpower, setback of graduate students education and loss of US scientific leadership in fusion
- The third budget based on ITER role-off is likely not before the end of this decade and does not allow for needed funds for innovative technology and materials development and/or construction of a new domestic fusion facility