Continued Research Through the Next Decade on Existing Tokamaks is Critical to Make Magnetic Fusion a Viable Energy Source

Miklos Porkolab
MIT Plasma Science and Fusion Center

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- Advances in High Temperature Superconducting 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 Greenwald limit
- Particle control

Presentation by Alberto Loarte on ITER R&D Needs

APS DPP Meeting, Chicago, Nov 2010

- R&D is needed in some areas to take decisions on few remaining systems or detailed design choices (timescale 1.5 years from now)
  - ✓ ELM control schemes
  - ✓ Disruption Mitigation schemes with emphasis on runaway suppression
  - ✓ Detailed design of First Wall Panel
- 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 $<n_{DT}>$)
  - ✓ 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

Significant Progress in Theory and Computational Modeling Capability

- Advances in theoretical and computational predictive capability-(SciDAC activity)
  - 3 D nonlinear MHD for bulk plasma stability in progress
  - Gyrokinetic modeling of low frequency turbulence and transport
  - Coupled ray tracing, full wave and Fokker Planck RF codes
  - Edge (pedestal) stability and transport codes under development
  - MHD and now gyrokinetic codes available for Alfven wave stability
  - etc ….
- A new major computational initiative, the FSP has great promise but may take a decade before becoming a useful tool
- Synthetic diagnostics implemented into several codes to validate theory predictions by experiments– quantitative comparisons of experiment and theory for the first time !

Understanding Turbulent Transport in Magnetically Confined Tokamak Plasma is Still Far from Adequate

- Major advances in core turbulence measurements : ITG, TEM, ETG, and Zonal Flow measured in many experiments; however, agreement with gyrokinetic codes (synthetic diagnostic) is "sporadic"
- Progress in measuring edge turbulence by GPI, PCI and RPs; theory and predictive codes based on first principles physics still in infancy ; understanding edge turbulence key to predicting edge pedestal pressure height and thus core fusion performance
- Internal Transport Barrier (ITB) physics investigated but stability not well controlled due to bootstrap current evolution in the steep gradients
- Plasma rotation in RF driven plasmas in the absence of momentum injection can be significant and key to plasma stability (shear flow) and performance but physics not understood
- Transport in electron heated regimes ($T_i < T_e$) needs to be investigated
- **Implications for ITER, FNSF, DEMO, Power Plant**

New Operating Modes Discovered with Attractive Features

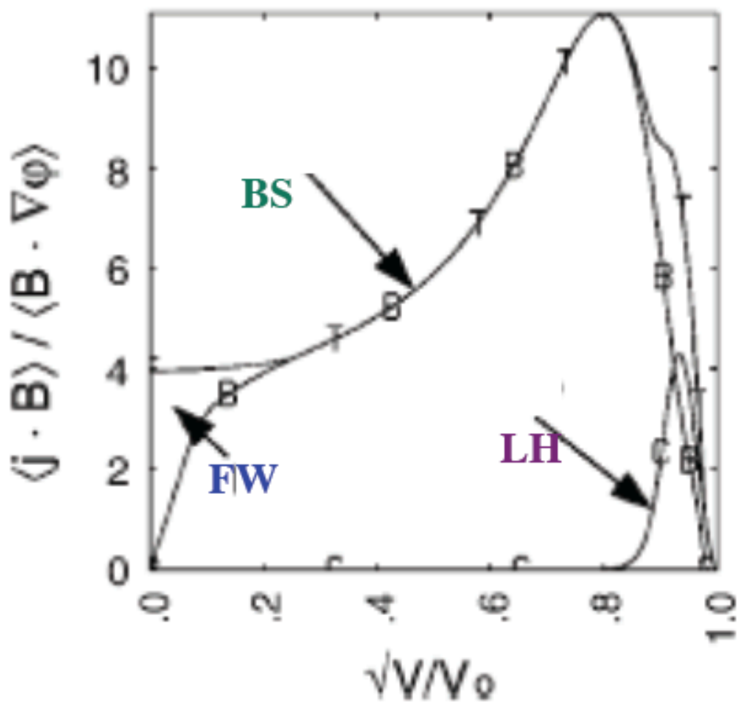
- Promising new confinement regimes discovered beyond ELMy H-mode which mitigate the deleterious effects of sawteeth and/or ELMS: the Hybrid mode, Q-H mode, and I- mode; physics in many cases not understood and extrapolation to ITER and DEMO not clear
- Improved MHD stability by feedback stabilization 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 DEMO or Power Plant ?

Validation of RF Physics Nearly Complete; but Demonstration of Profile Control is Still Scarce

- Validation of ECH and ECCD nearly complete; as expected, heating and current drive (CD) is efficient in the plasma core but CD efficiency drops rapidly at r/a > 0.6
- ECCD control of NTMs shown to be effective and extrapolate favorably to ITER; but what about DEMO or a power plant ?
- ICRH should be efficient and cost effective in ITER and DEMO; however, antenna coupling through the edge plasma remains a challenge
- LHCD in tokamaks is the most efficient CD technique for profile control but still needs varification in AT regimes; however, antenna coupling through the edge plasma in ITER and DEMO a challenge
- RF wave penetration into the core of STs remains a challenge
- **ITER will test plasma physics in alpha heated regime but significant extrapolations remain in both physics and materials to steady state Advanced Tokamak versions of DEMO/Reactor**

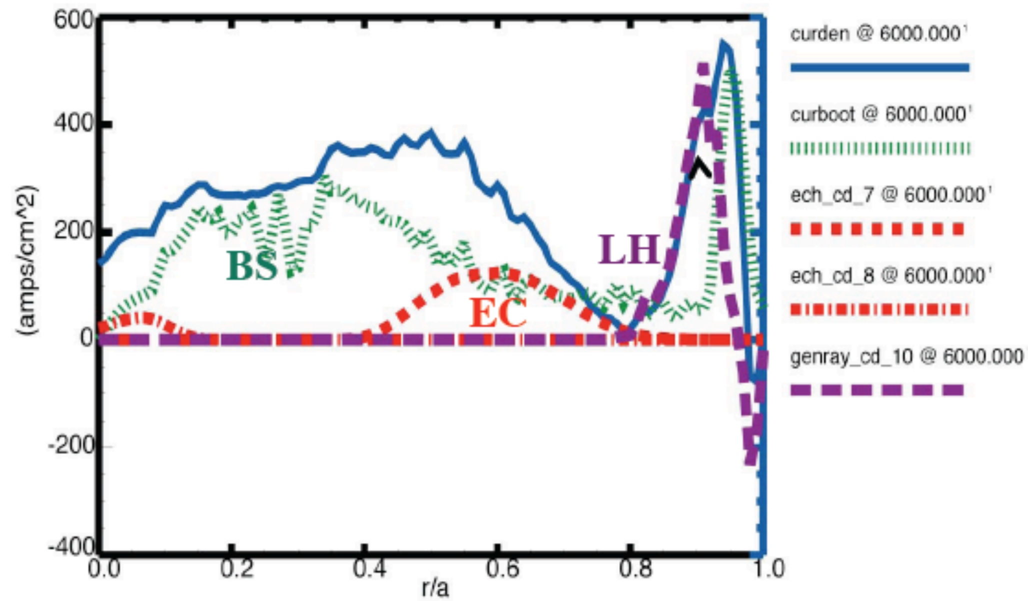
A Combination of RF current drive and BOOTSTRAP current in ARIES AT, RS and FDF, achieve reactor relevant performance

Current profiles in Aries AT :
F. Najmabadi et al, FED **80**, 3-23, (2006) **H_{98Y2} = 1.7, β_N = 5.4, f_{BS}=0.91, LHCD = 0.09, P_{LH} = 40 MW, P_{FW} = 10 MW (or P_{EC})**



Current profiles in FDF:

- 50 MW ECCD and 20 MW of LHCD, P_f = 198 MW, Q_{fus} = 2.8
- **f_{BS}= 0.65, (ECCD+LHCD) = 0.35, H_{98Y2} = 1.3, β_N = 3.8**
- (V. Chan, General Atomics, FDF poster GP8 – 2 , 2009 APS-DPP Atlanta)



Porkolab_FPA_2010

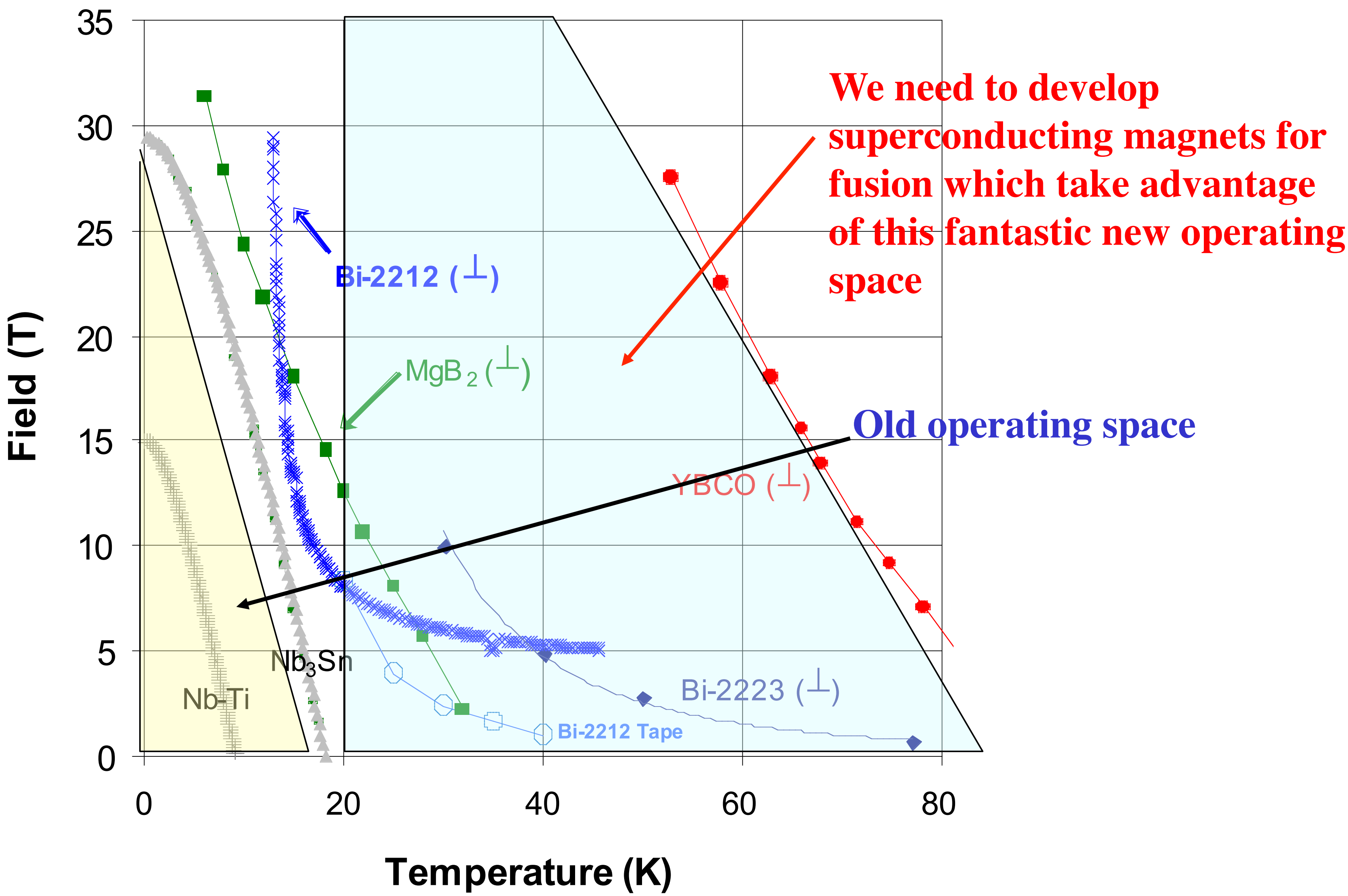
Higher Magnetic Field is a Winner

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 [$B_T(0)$=8T] with more realistic current drive scenarios and pressure profiles while also adopting the higher thermal efficiency (0.59) in Aries AT [B(0) = 6T] versus 0.46 in RS
- High Temperature Superconductors (HTS) beyond SC technologies used in ITER and ARIES could revolutionize magnetic fusion

HTS Make Higher Magnetic Fields Accessible

L. Bromberg, J. Minervini, MIT PSFC



HTS Implications for Fusion

L. Bromberg, MIT PSFC

- Increasing magnetic field
  - Peak field limited by structure, not by superconductor properties
- Increasing operating temperature (avoiding 4 K operation)
  - Decrease refrigerator requirement due to cryostat loads, electrical dissipation
- Jointed coils/Demountable magnets
  - Design with wide access for installation, removal of components and repair as needed (key applications for Fusion Nuclear Science Facilities)

Need a HTS Development Program for Fusion

- Magnet technology for use in HTS magnets needs to be developed
- HTS offers a unique opportunity in fusion applications
  - ✧ Refrigeration of joint losses decreased because of operation at temperatures 40-60 K
  - ✧ Low electrical power requirements, good for long operation
  - ✧ Demountable, good for access (however, require external support structure)
  - ✧ 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

Summary

- Much physics remains to be done on existing tokamaks in order to optimize ITER operation
- For DEMO and for Fusion Power Plant must expand plasma parameters beyond ITER (density by a factor of 3 and magnetic field by 1.5) with significant impact on actuators such as heating and current drive, as well as materials (hear talk later by D. Whyte from MIT)
- Advanced Tokamak (AT) physics (pressure and CD profile control) must be demonstrated at reactor relevant fields (B =6-9 T) and densities (n_e= 2.6x$10^{20}$$m^{-3}$)
- High Temperature Superconductor technology could revolutionize future magnetic fusion development