Plasma Physics and Fusion Energy

Miklos Porkolab
MIT Plasma Science and Fusion Center

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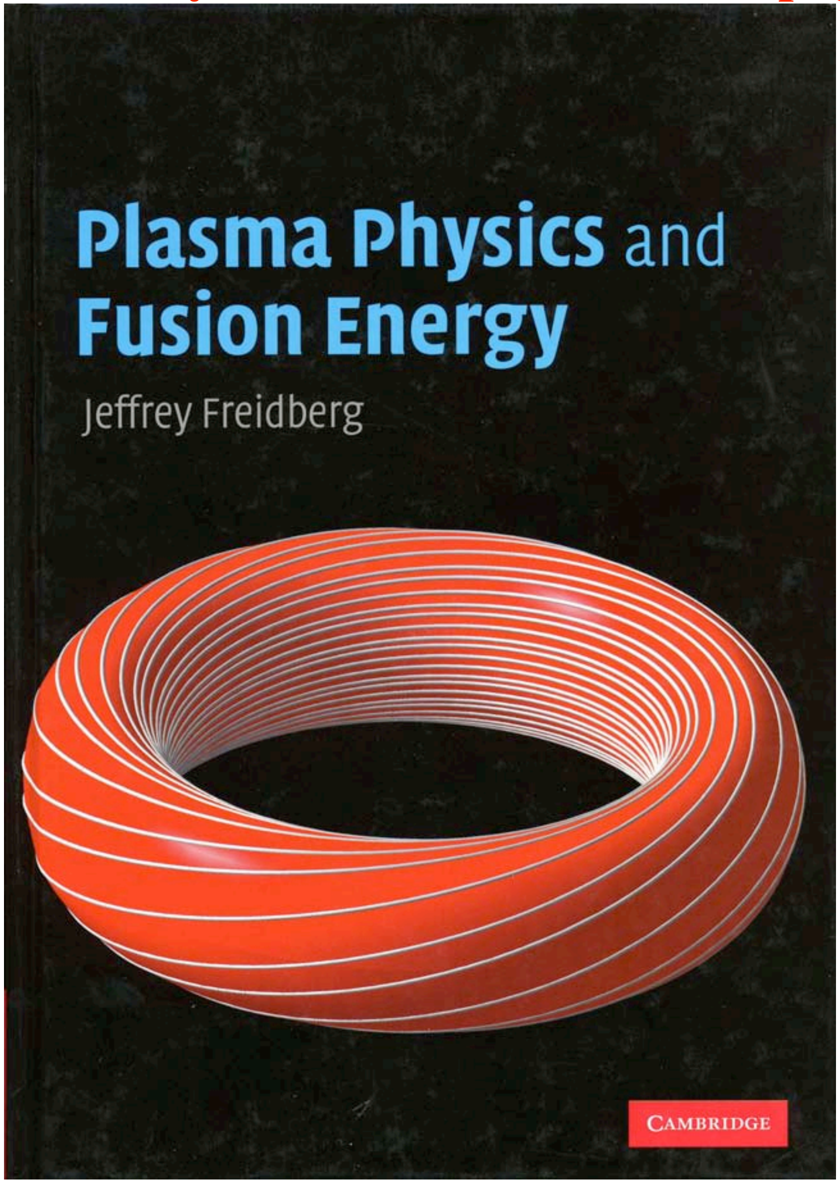
Proposed Title of Miklos' Talk is Actually a Textbook !

- but I have only 18 minutes to cover 671 pages ! -



Introduction

- **Progress in experimental plasma science in the past decade**
- **Progress in theory and computational science**
- **Some requirements to establish the physics basis for DEMO**
- **Advantages of high field tokamaks and research needs for High Temperature Superconductors (HTS)**
- **A possible high field compact experiment to establish DEMO grade plasma physics basis, Plasma Surface Interactions (PSI) physics and chemistry, and wall materials, short of an FNS facility: VULCAN**

Remarkable Progress in this Decade in Understanding the Physics of Magnetically Confined Tokamak Plasmas

- Significant progress in discovering new confinement regimes which mitigate sawteeth, ELMs, NTMs and metallic impurity injections
- Major advances in understanding transport physics based on turbulence measurements: ITG, TEM, ETG, Zonal Flow, δT_e δB, Edge blobs, δn_e , $\delta\phi$
- Internal Thermal Barrier physics investigated (Beams, RF)
- Strong toroidal plasma rotation seen with RF – a pleasant surprise !
- Understanding of RF physics and current drive extended : ECCD and FWCD theory verified and ICRF mode conversion into ICW verified
- LHCD and ICRF coupling studies at ITER relevant edge conditions underway with gas puff assist (JET, Tore-Supra, DIII-D, C-Mod, AUg)
- Improved MHD stability by feedback stabilization of RWM, ECCD control of NTMs, (DIII-D, AUg) ELM control with external coils (DIII-D)
- Energetic particle driven Alfven Eigenmodes (TAE, RSAE, EPM, etc) measured and impact on transport of fast particles under investigation
- *ITER relevant plasma parameters in hand, but more is needed for DEMO*

Enormous Progress in Theory and Computational Modeling Capability

- Improved computational predictive capability (SciDAC)
  - 3 D nonlinear MHD for bulk plasma
  - Gyrokinetic modeling of turbulence and transport
  - Coupled ray tracing and relativistic FP code for and ECCD
  - RF full wave code developments in ICRF and LHCD
  - Edge (pedestal) stability and transport codes
  - Alven mode turbulence driven by energetic particles and transport underway
- Synthetic diagnostics implemented into codes to verify code predictions by experimental measurements in progress
- Major computational initiative to develop fully integrated modeling capability, the Fusion Simulation Project, or FSP

There is sufficient physics to make ITER a success but much more to learn for DEMO grade plasmas

See review talk by Tim Luce at the 2009 DPP meeting in Atlanta !

DIII-D NATIONAL FUSION FACILITY

Systems Studies Indicate the Performance Gaps from Present-Day Experiments

Present-day experiments need to explore:

- Higher β_N (will close gap in f_{BS} also)
- Higher density
- Improvement in confinement quality does not seem to be a significant need
  - Assumes the scaling is correct for this regime

	JT-60U $f_{NI} \approx 1$	DIII-D $f_{NI} \approx 1$	Slim-CS	EU PPCS	ARIES-AT
β_N	2.4	3.7	4.3	4.0-4.5	5.4
H (98y2)	1.0	1.5	1.3	1.2-1.3	1.7
f_{BS}	0.5	0.65	0.77	0.63-0.76	0.91
q_{95}	4.5	6.3	5.5	4.5	3.2
f_{DL}	0.5	0.5-0.6	0.98	1.5	0.9

ITER will test burning plasma physics with alpha heating but there is a gap to DEMO relevant plasma parameters

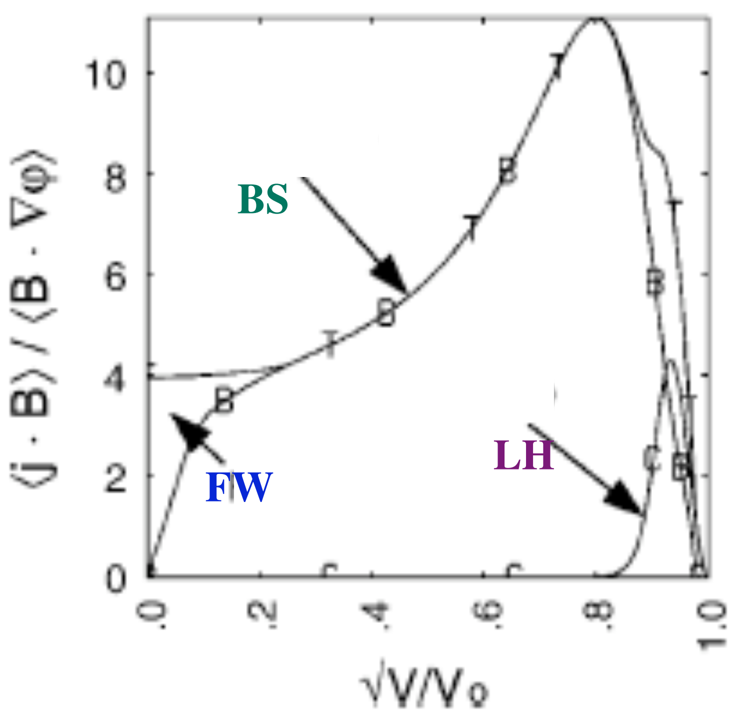
- Q=10 regime at $n_e = 10^{20}$ m^{-3} , B= 5.6 T, for time $t = \tau_{skin} \approx$ 300-500 sec (by CY 2028), low f_{BS}
- Q=4.6 regime with current drive, $f_{BS} \approx 57$ % at $\omega_{pe}^2/\Omega_{ce}^2 = 0.2$ for $t = \tau_{L/R} \approx 3000$ sec at $\beta_N \approx 2.8$ ($P_{NI}/P_{EC}/P_{IC}$ = 33/20/20 MW, LHCD ?) experiment likely delayed until after CY 2030
- Aries-RS/AT (my DEMO models) operate at f_{BS} = 88/91 % at $\omega_{pe}^2/\Omega_{ce}^2 \approx 0.8$ at β = 5.0/9.2% and $\beta_N \approx$ 4.8/5.4 in steady state
- Current drive physics, MHD stability and plasma control more realistic at higher field (Aries-RS at 8 T) than AT at 6 T
- Relevant LHCD physics will be tested at 6-8 T on Alcator C-Mod
- DEMO will be dominantly electron heated by alphas, are there any deviations in transport scaling from NBI ion heated experiments ?

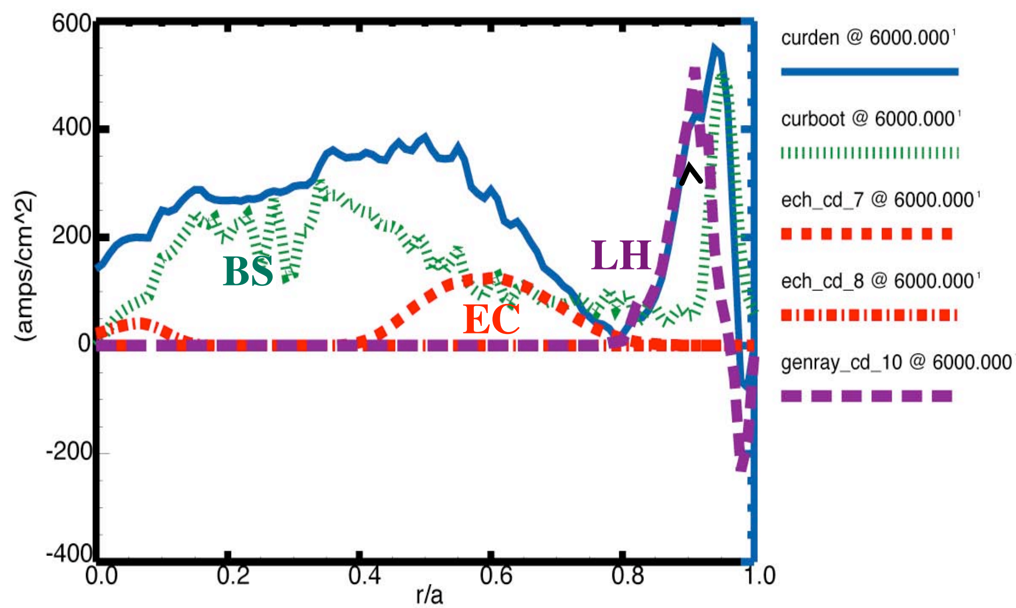
A Combination of RF current drive and BOOTSTRAP current in ARIES AT, RS and FDF, achieve reactor relevant performance

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:

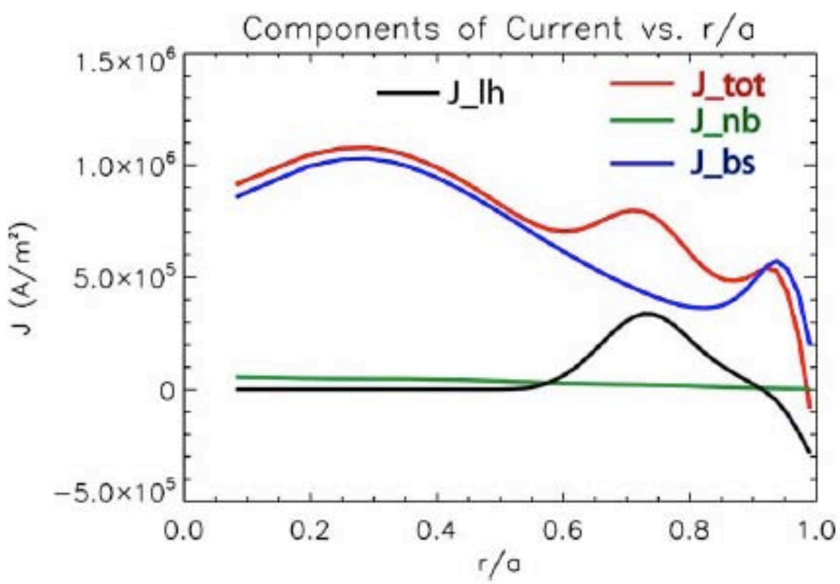
- 50 MW ECCD and 20 MW of LHCD, P_f = 198 MW, Q_{fus} = 2.8
- **f_{BS}= 0.65, (ECCD+LHCD) = 0.35, H_{98Y2} = 1.3, β_N = 3.8**
- (V. Chan, General Atomics, FDF poster GP8 – 2 , 2009 APS-DPP Atlanta)

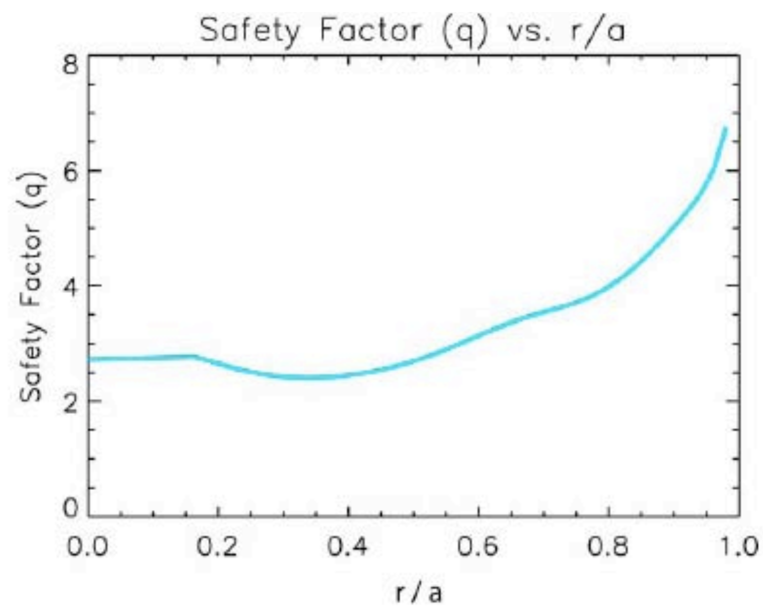




ATBX being revisited and upgraded to 8 T with DEMO relevant plasma parameters and LHCD current drive

M. Porkolab, P.T. Bonoli, J. Schultz, et al, IAEA Conf., Yokohama, 1998)





T_{e0} (keV)	P_{LH} (MW)	I_{LH} (MA)	γ_{LH} (A/W/m^2)	I_P (MA)	f_{BS}	P_{NB} (MW)	I_{NB} (MA)
30	40	1.21	0.22	12.3	0.87	10	0.43

At r/a= 0.75, n_e= 1.3x10^{20} m^{-3}, T_e= 10 keV

Physics knowledge needed from existing tokomak research to match DEMO performance (Aries RS, AT) not in hand

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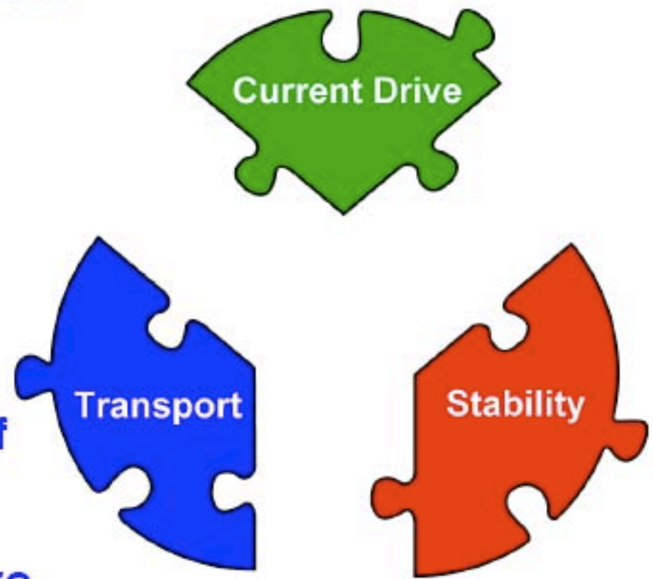
T. Luce

Insights from Studying the Individual Elements Need To Be Integrated Into the Steady-state Scenario

Current must be sustained in steady-state using minimal external sources

- Key metric: $f_{BS} > 0.6$



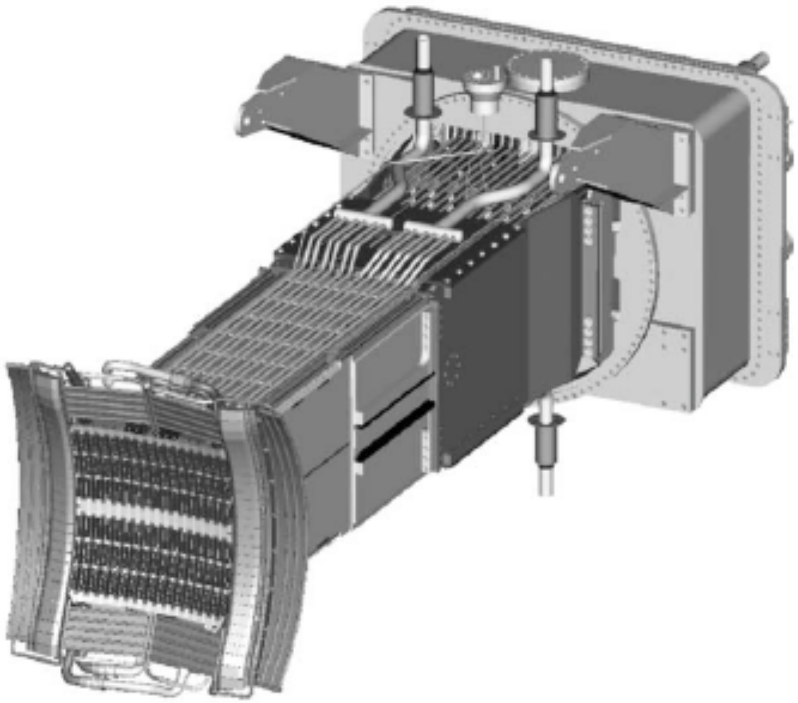
Strong interaction of transport and the current profile ties together the pressure and current profiles through the bootstrap current at high f_{BS}

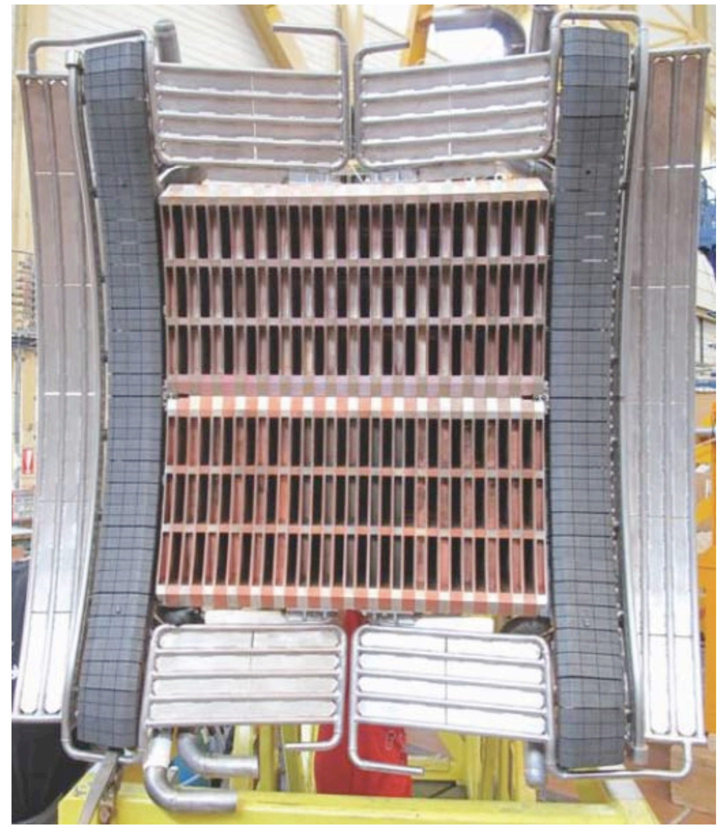
Broad pressure and current profiles are needed for wall stabilization to achieve pressures required for high fusion power and bootstrap current

- Key metric: $\beta_N > 3.5$

ITER ¼ antenna size prototype LHCD PAM antenna has been built and is being tested in Tore Supra (P. Bibet concept, 1995)

(Courtesy T. Hoang)





TORE SUPRA

The ITER prototype passive-active (PAM) launcher installed in Tore Supra and operations began;
Results outstanding after second day of commissioning
0.45 MW coupled for 4.5 second with low reflectivity

Higher Magnetic Field is a Winner

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

To $\vec{B}$ or not to be … (to quote Jeff Freidberg)

- Higher B-field (say16 T at the coil, 8 T on-axis) would reduce some key physics constraints and would increase reliability and availability in DEMO
- Higher current drive efficiency for off-axis LH current drive
- Seed current drive with ECCD at 230 GHz is feasible (Temkin)
- Lower β, more stable MHD operation
- Should revisit Aries RS studies with new current drive tools

  and modern plasma physics (in particular, edge-pedestal codes) while adopting advanced heat transfer properties from Aries AT
- High temperature SC magnet technology is improving rapidly and demountable joints could revolutionalize DEMO designs

ReNew Theme II - Thrust 7 Conclusions: Develop High Temperature Superconductors (HTS) and novel magnet innovations to advance fusion research

J. Minervini, L. Bromberg, MIT and the Thrust 7 Team

- HTS is potentially a *'game changer'* for fusion devices in several respects:
  - *high performance, demountable magnets*
  - *high reliability, availability and maintainability*
  - *acceptable cost*
- Flexible experimental scale devices
- Steady-State tokamaks
- Stellarators, and other 3-D magnetic configurations
- Synergism with other DOE and scientific programs:
  - High Energy Physics
  - Superconductivity for Electric Systems
  - High field NMR
  - Medical (MRI, Proton Radiotherapy)

VULCAN - A NEW CONCEPT FOR AN 8 TESLA SUPERCONDUCTING TOKAMAK TO STUDY PSI

MIT is leading a consortium of interested universities to propose a modest size steady state tokamak for Plasma Surface Interaction (PSI) studies and wall materials research with hot walls (> 500 C) at DEMO relevant plasma conditions but in a non-DT plasma

**D. Whyte, P.T. Bonoli, L. Bromberg, A. Hubbard,
B. Lipschultz, J. Minervini et al, and collaborators**

MIT PSFC

Vulcan Physics & Engineering Scoping Study Properly Links Core Plasma to PSI/boundary (D. Whyte)

	ARIES*	FDF	Vulcan	*Why?*
R (m)	5.2-5.5	3.2	1.25	*Minimize PFC surface area & P_{heat}*
$A \equiv R/a$	4.0	3.5	4.0	*Similarity*
P_h/S (MW/m^2)	0.85-1.1	0.87	0.9	*Global power exhaust for CD / PSI*
Δt	yr	weeks	arbitrary	*Integrate PSI at CTF/DEMO timescales*
B (T)	6-8	6	6- 8	*Similarity of CD & Edge physics* *Demountable SC coils --> maintenance*
n (10^{20} m^{-3})	1.7-2.3	2.4	1.5 - 4	*Access large range of non-inductive scenarios over wide density range for edge exploration & similarity*
P_{CD} / $P_{heat,ext}$	~ 1	~ 1	~ 0.2 - 1	
$\nu_N{}^*{}_{SOL}$ a)	0.25-0.38	0.27	0.12 - 0.36	*SOL collisionality*
$n_{20}{}^{2/7}$ R	40-90	54	4 - 170	*Match divertor plasma T and n*
Upstream $q_{//}$ (GW/m^2)	3-5	3.9	~ 4-5	*SOL T similarity & heat removal*

** Range for RS to AT*

a): Stangeby upstream separatrix figure of merit for achieving conduction limited divertor: $n L_{//} / T^2 / 1.5x10^{17}$

Summary and Conclusions

- Rapid growth of science base of magnetically confined plasma
- ITER is essential to provide the missing alpha physics
- DEMO will need plasma physics parameters well beyond ITER and must be obtained in parallel from our existing base program, with possible upgrade of our facilities and likely one or two new facilities
- Plasma physics in Aries RS (8 T) is achievable and the physics and engineering design should be revisited and updated
- High temperature SC magnet technology is progressing rapidly and we should invest more aggressively in this area for fusion applications
- Fusion relevant Materials Science and Fusion Nuclear Science technologies must be developed in parallel, and not at the expense of plasma physics at the present state of knowledge
- To ensure uninterrupted future progress, continued education of students must be a key element of the fusion program