Parameter Optimization Studies for a Tandem Mirror Neutron Source

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Attractive Features of Axisymmetric Mirrors

- **“Infinite time” confinement by KAM theorem for some ions, α’s**
- **No Banana Orbits thus No Neoclassical Transport as is min-B Mirrors, Tokamaks, & Stellarators**
- **No Toroidal Curvature so Drift Wave Drive is Weak ($g_{torus}=2c_s^2/R$)**
- **No Plasma Current so No Disruptions**
- **Circular Magnets enable Higher Fields and Mirror Ratios**
- **Plasma Exhaust at Low Power Density Outside the Magnet System.**
- **Potential Direct Energy Conversion and Liquid Molten Salt Blanket**

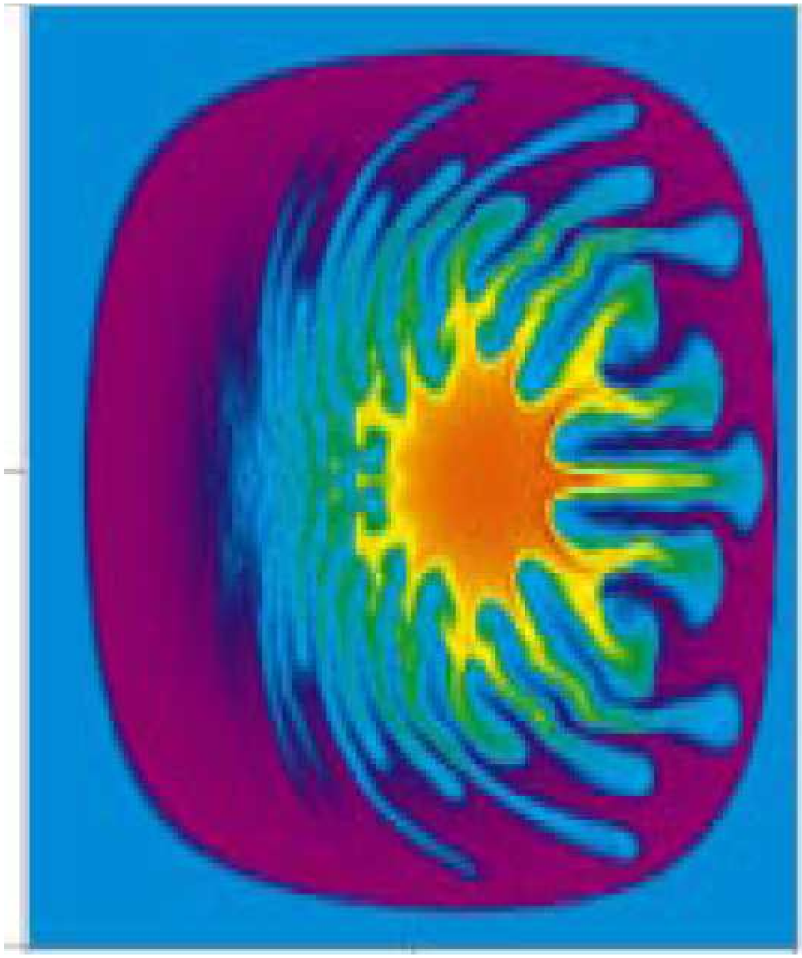
MHD Stability Limits ITER

Chapter 3: MHD stability, operational limits and disruptions

T. C. Hender and 56 additional authors*

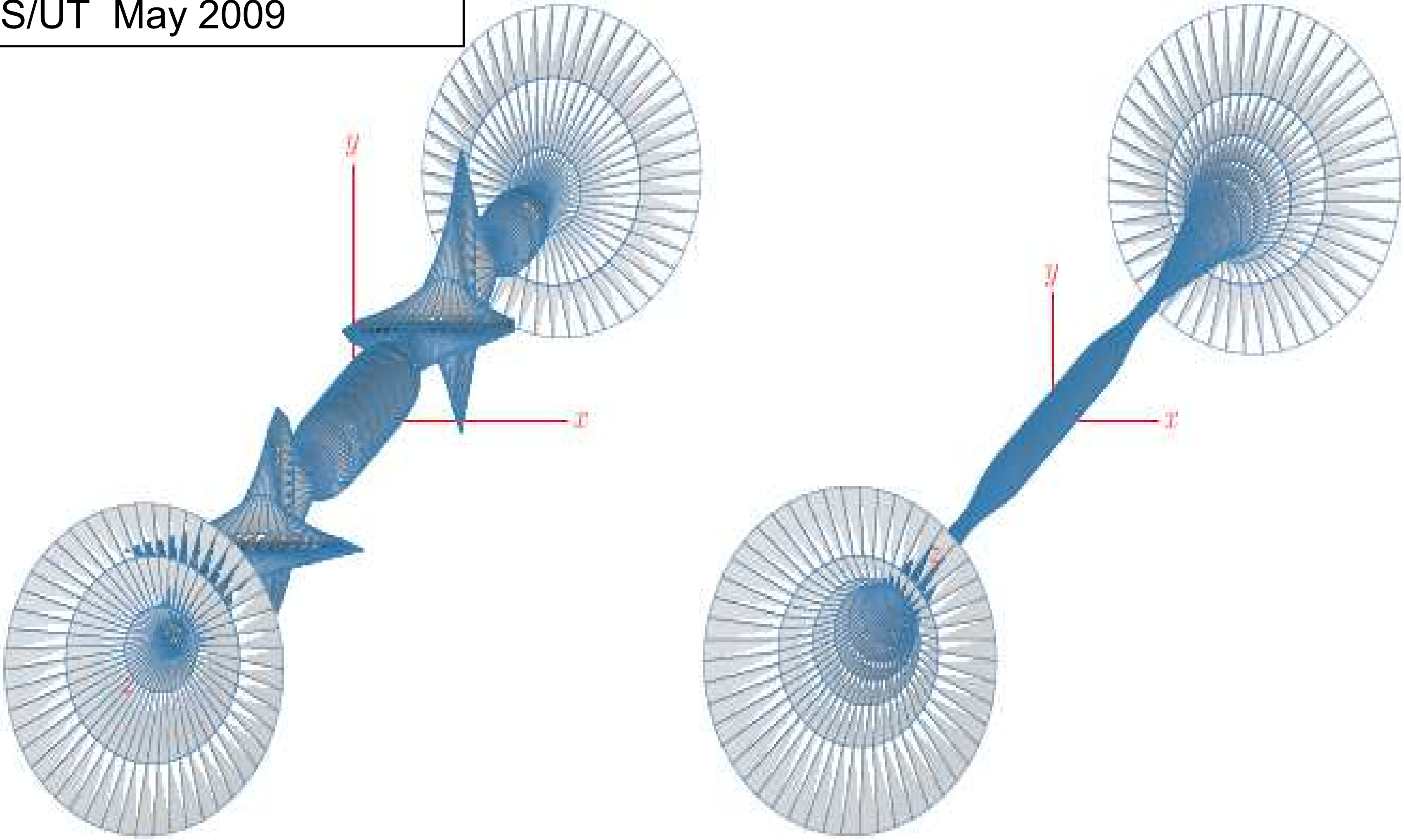
Nuclear Fusion 47, (2007) doi: 10.1088/0029-5515/47/6/S03

Fig. 34 "..disruptions close to the MHD beta limit…ballooning modes…decoupled plasma from magnetic field forming fingers.."



***..ITPA MHD, Disruption and Magnetic Control Topical Group**

Jane Pratt PhD dissertation
IFS/UT May 2009

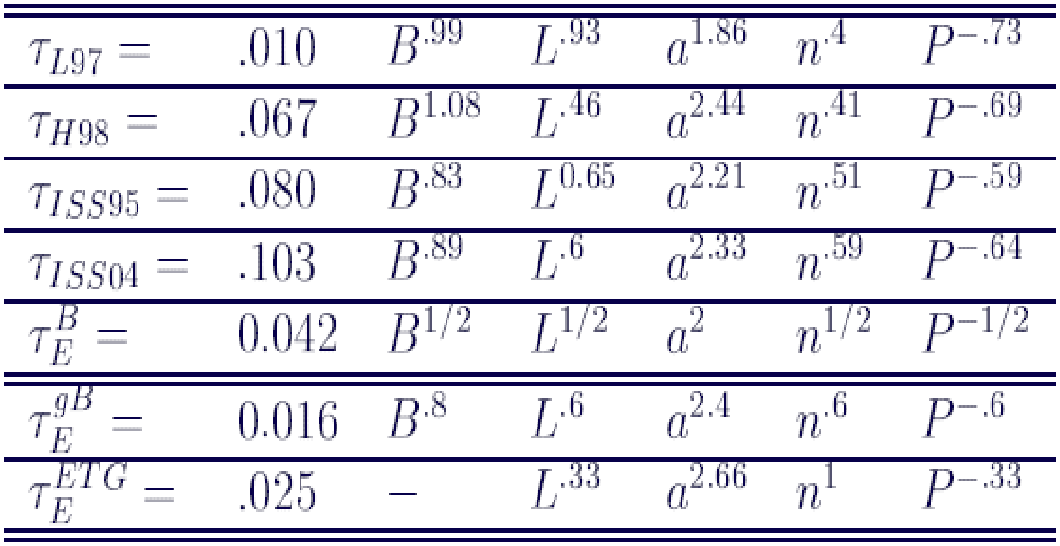


GAMMA-10 flux surface (left). KSTM flux surface (right). Both of these machines have large end tanks for stabilization mechanisms.

15:12:14

Global energy confinement scaling predictions

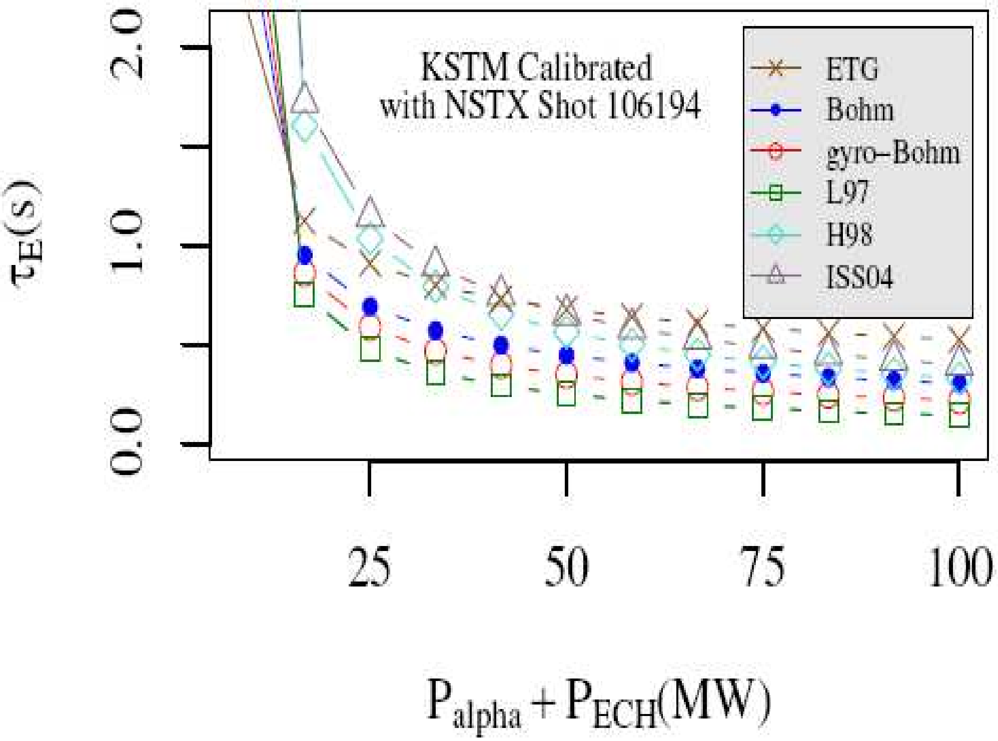
radial losses faster than axial pitch angle scattering losses for
$T_e \geq T_{e,\mathrm{crit}}$



$\tau_{L97} =$	$.010$	$B^{.99}$	$L^{.93}$	$a^{1.86}$	$n^{.4}$	$P^{-.73}$
$\tau_{H98} =$	$.067$	$B^{1.08}$	$L^{.46}$	$a^{2.44}$	$n^{.41}$	$P^{-.69}$
$\tau_{ISS95} =$	$.080$	$B^{.83}$	$L^{0.65}$	$a^{2.21}$	$n^{.51}$	$P^{-.59}$
$\tau_{ISS04} =$	$.103$	$B^{.89}$	$L^{.6}$	$a^{2.33}$	$n^{.59}$	$P^{-.64}$
$\tau_E^B =$	0.042	$B^{1/2}$	$L^{1/2}$	a^2	$n^{1/2}$	$P^{-1/2}$
$\tau_E^{gB} =$	0.016	$B^{.8}$	$L^{.6}$	$a^{2.4}$	$n^{.6}$	$P^{-.6}$
$\tau_E^{ETG} =$	$.025$	$-$	$L^{.33}$	$a^{2.66}$	n^1	$P^{-.33}$

J. Pratt and W. Horton, Phys Plasmas, 13:042513, 2006.

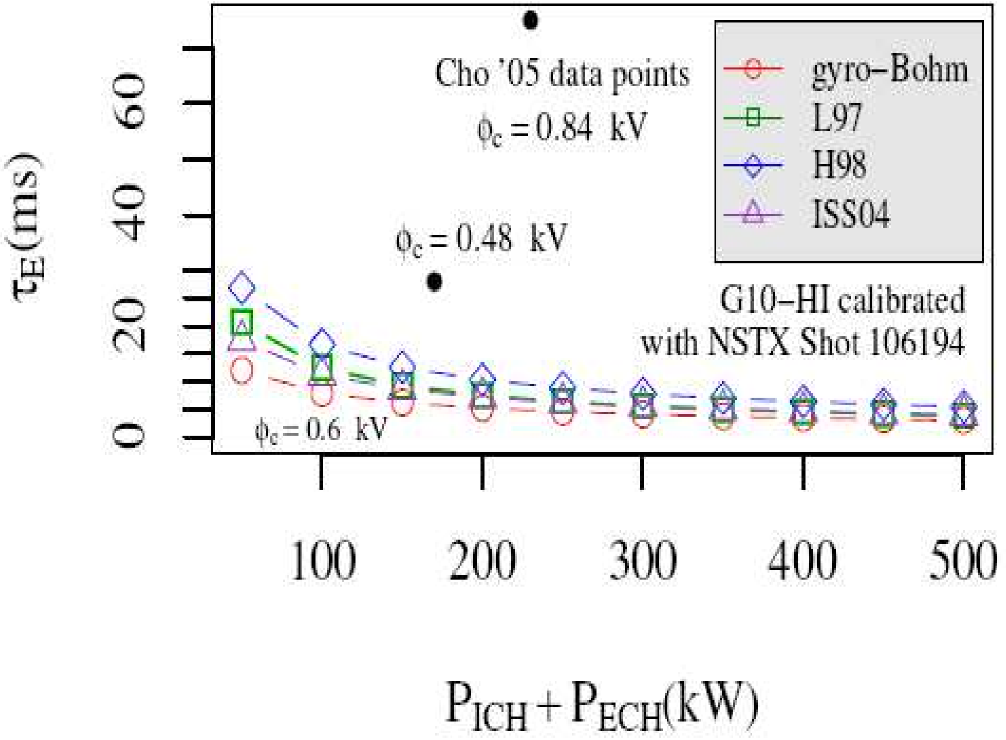
Radial Energy Confinement Times in the KSTM



Predictions for the KSTM machine design. Drift wave scaling laws (Bohm, gyro-Bohm,and ETG) are calculated from formulae for diffusivity and normalized to match the empirical L97 results from NSTX at 3.3 MW of radial power loss.

B.P. LeBlanc, R.E. Bell, S.M. Kaye, *et al.* Confinement studies of auxiliary heated NSTX plasmas. Nuclear Fusion. 44(4), 2004.

Radial Energy Confinement Times in the GAMMA-10



A variety of energy confinement times adapted to the tandem mirror geometry and GAMMA-10 parameters.

Two data points:

Consistent with low radial loss rates.

Consistent with data presented earlier by R. F. Post showing low radial loss rates compared with torus.

Radial plus End losses define an optimal operating point in parameter space

Optimal Low-Power Heating Parameters for TMR

$$
\begin{aligned}
P_{\mathrm{loss}} &= (\mathrm{radial\,flux})(2\pi a L) + (\mathrm{end\,loss})(\pi a^2 B/B_c) && (1)\\
q_r^e &= (c_B \chi_B + c_{gB}\chi_{gB})\frac{nT_e}{a} && (2)\\
(T_e)_{\min P_{\mathrm{loss}}} &= \left(\frac{c_\parallel}{4c_B}\right)^{2/5}(nZ\Lambda a^2 B)^{2/5} && (3)\\
\left(\frac{1}{\tau_E}\right)_{\min P_{\mathrm{loss}}} &= \frac{(4c_B)^{3/5} c_\parallel^{2/5}}{(4a^2B)^{3/5}} + \frac{c_\parallel^{4/5}(4c_B)^{1/5}(nZ\Lambda)^{3/5}}{(4a^2B)^{1/5}} && (4)\\
&\approx \mathrm{end\,loss} && (5)\\
P_{\min}/n_e &= 1.7\frac{c_B^{1/5} c_\parallel^{4/5}(nZ\Lambda)^{4/5}}{(4a^2B)^{1/5}}(20\% + 80\%) && (6)
\end{aligned}
$$

A Set of "Hand Optimized" Parameters

ATM Reactor

$$\begin{aligned}
\tau_E^* &= 0.1\,\mathrm{s} && (1)\\
W &= \frac{3}{2} n (T_e^* + T_i^*) \pi a^2 L \leq 10^7\,\mathrm{J} && (2)\\
P_{\mathrm{inj}} &\leq 100\,\mathrm{MW} && (3)\\
\pi a^2 B &\leq 12\,\mathrm{m}^2\mathrm{T} = 12\,\mathrm{Wb} && (4)\\
L &\leq 50\,\mathrm{m} && (5)\\
V &= 150\,\mathrm{m}^3\ [\mathrm{cp}\ 700\,\mathrm{m}^3] && (6)\\
p &= 3 \times 10^5\,\mathrm{Pa} && (7)\\
p_{\mathrm{mag}} &= 3 \times 10^6\,\mathrm{Pa} && (8)\\
W_{\mathrm{p}} &\leq 10\,\mathrm{MJ} && (9)\\
n_e \tau_E &= 10^{12}\,\mathrm{s/cm}^3 && (10)\\
Q_{\mathrm{fus}} &\sim 0.1\ \mathrm{to}\ 0.5 && (11)\\
P_{\mathrm{fusion}}/P_{\mathrm{inj}} &\sim 10\,\mathrm{MW}/100\,\mathrm{MW} && (12)
\end{aligned}$$

Tandem Mirror Machine Parameters

Parameter	KSTM	G-10[1]	GDT[2]
r_c	0.3-.6 m	.18 m	0.15 m
L_c	100 m	6 m	6 m
$n_\mathrm{c}(\mathrm{m}^{-3})$	$1-2\cdot 10^{20}$	10^{19}	$2\cdot 10^{19}$
$n_\mathrm{p}/n_\mathrm{c}$	2-10	.1	2
T_e	50 keV	750 eV *	230 eV
T_i	15 keV	6.5 keV $\perp$	8-10 keV
B_{cc}	2-3 T	0.405 T	0.5 T
B_plug	20 T	0.49 T	5 T
$n\tau_E T_\mathrm{i}$ $(\mathrm{m}^{-3}$ s keV)	$1.5\cdot 10^{21}$	$1.\cdot 10^{18}$	$2\cdot 10^{17}$

* T_e to be confirmed

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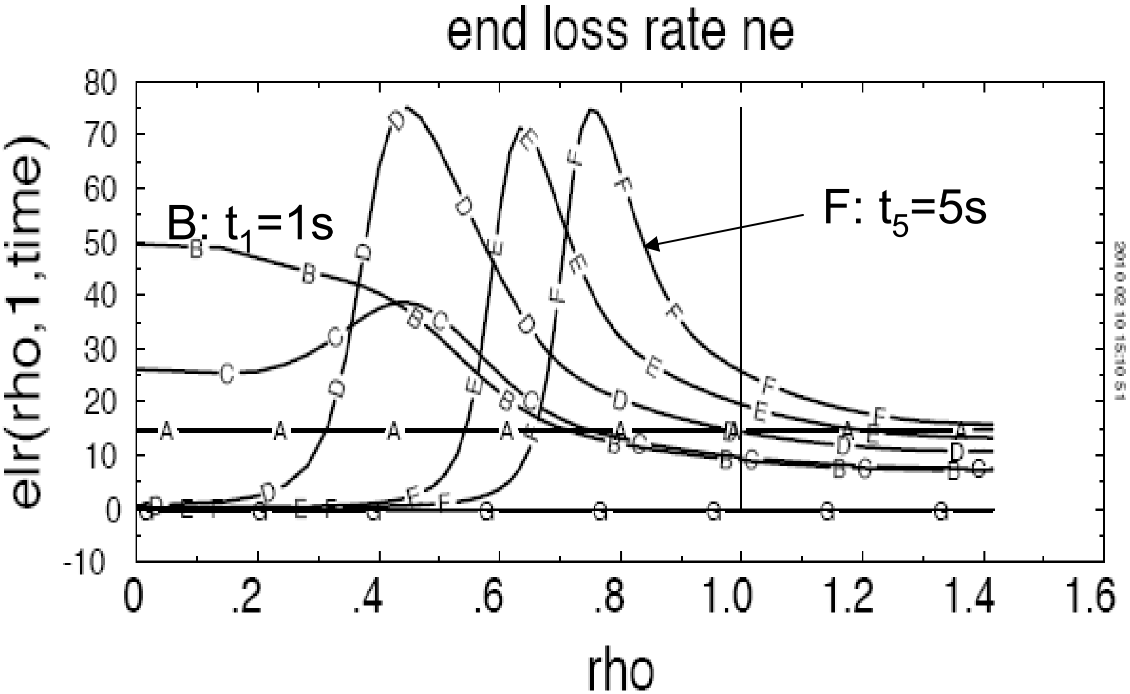
[1] Cho, private communication, Dec. 2006

[2] A. V. Anikeev et al., Phys Plasmas 4, p.347 (1997) and Ivanov ATM Workshop presentation, LBL, Sept 2008.

GDT Parameters from
Ivanov, Beklemishev, Kruglyakov, Bagryansky, et al.
to appear in Fusion Science and Technology

- R_p=0.07m L_c=7m B_{cc} =0.28T B_{max}=10T
- N_c=1.5X10^{19}/m^3 T_e≤250ev T_i ~10keV
- n_e tau$_E$ 6X10^{17} s/m^3
- tau$_E$ ~ 2ms and tau-drag ~4ms
- Reported low radial losses due to novel nonlinear electrostatic barrier from m=1 mode in central cell. Beklemishev et 2009.

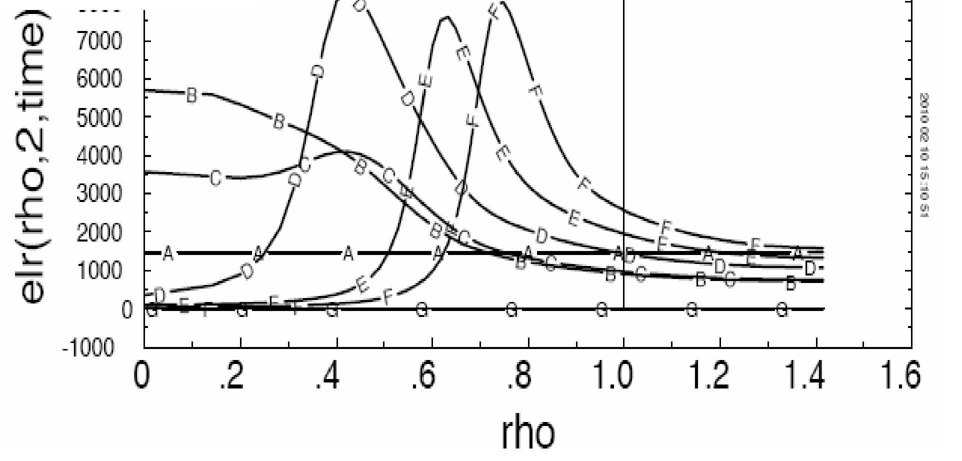
Time evolution of End losses



B: t_1=1s

F: t_5=5s

As core plasma heats up the end losses move to a cylindrical shell at edge.



Burning core plasma with natural outer shell divertor into expander cell.

MHD Stability from Kinetic Stabilizer

- Berk and Pratt show that a kinetic stabilizer can give stabilizing factor that is 5 times the unstable central cell contribution.
- Use a deuterium beam a nearly parallel to the expander field giving large stabilizing pressure gradient and the correct ambipolar potential for KSTM operation.

IFS Preprint being prepared: Idea proposed by Post in UCRL-JC130404, 1998 and developed by D. Ryutov

Optimizing System Parameters

Example: Solar Wind Driver Magnetosphere-ionosphere System

Parameter vector $\mu = (\mu_1, \mu_2, \ldots, \mu_n)$, $n = 18$ (see Spencer and Horton, 2007, JGR)

GA=genetic algorithm to optimize performance over $d = 20$ dimension vector space with physical bounds

ATM System

$\mu = (a_c, L_1, L_2, L_3, B_1, B_2, B_3, P_{\mathrm{ECH}}, P_{\mathrm{nb}}, \theta_{\mathrm{nb}}, E_b, \ldots)$, 15-20 parameters

$\mu_* = (L_1/a, L_2/L_1, L_3/L_1, \rho_*, \nu_*, \beta_*, M_1, M_2, \ldots)$, 10 dimensionless parameters over specific physical bounds

Maximize P_{fus} or Q_{fus}, minimize β or W_{pe} or P_{inj}

Focused Neutron Beams – Spin-Polarized D-T Fuel

- enhanced fusion yields from SPIN polarized D and T nuclei produced by Optical Pumping of the gas. [4]
- The new linear Tandem Mirror facility would allow the testing of key qualitatively new aspects of the fusion system that are difficult and thus have not been, and are unlikely to be, carried out in toroidal systems due to the θ If instead the D nuclei are spin polarized across B there is a peaking of the neutron spectrum along the magnetic field.

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_0}{2\pi}\left[\frac{3}{4}a\sin^2\theta + \left(\frac{2}{3}b + \frac{1}{3}c\right)\left(\frac{1+3\cos^2\theta}{4}\right)\right] \tag{1}$$

- For D and T polarized parallel to the magnetic field $a = 1$ and $b = c = 0$ and the distribution is given by $\sin^2\theta$. For D and T nuclei polarized perpendicular to the magnetic field then $c = 1$ and the distribution is $\sim 3\cos^2\theta$.

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[4] R. M. Kulsrud, H. P. Furth, E. J. Valeo, and M. Goldhaber, Phys. Rev. Lett. **49**, 1248 (1982).

Conclusions and Plans

- Tandem mirrors have significantly lower fluctuations and radial transport. Pratt and Horton, 2006, Post 2007.
- The KSTM design is simple and elegant quadrupole anchored tandem mirrors demonstrating MHD stability.
- MHD stability can be achieved with a kinetic stabilizer design.
- Ongoing work (Pratt and Berk, 2009) suggests that trapped particle modes may have slow growth rates or even be stable if sufficient warm plasma in the expanders.
- National Instruments FPGA and LabVIEW for quick prototyping of key control components

Feedback control of T_e with ECH and Thomson Scattering proposed to NSF/DoE Oct 2009

- Toshiba has blue-prints for basic TM architecture with circular coils and no linked fluxes or currents.

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