

Physics issues in spherical tokamaks

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15 November 2003

This work is funded jointly by the UK Department of Trade and Industry, and EURATOM.

Plan of the Talk

What is fusion and why do we need it?

Fusion research at Culham - JET and MAST

Spherical Tokamak concept

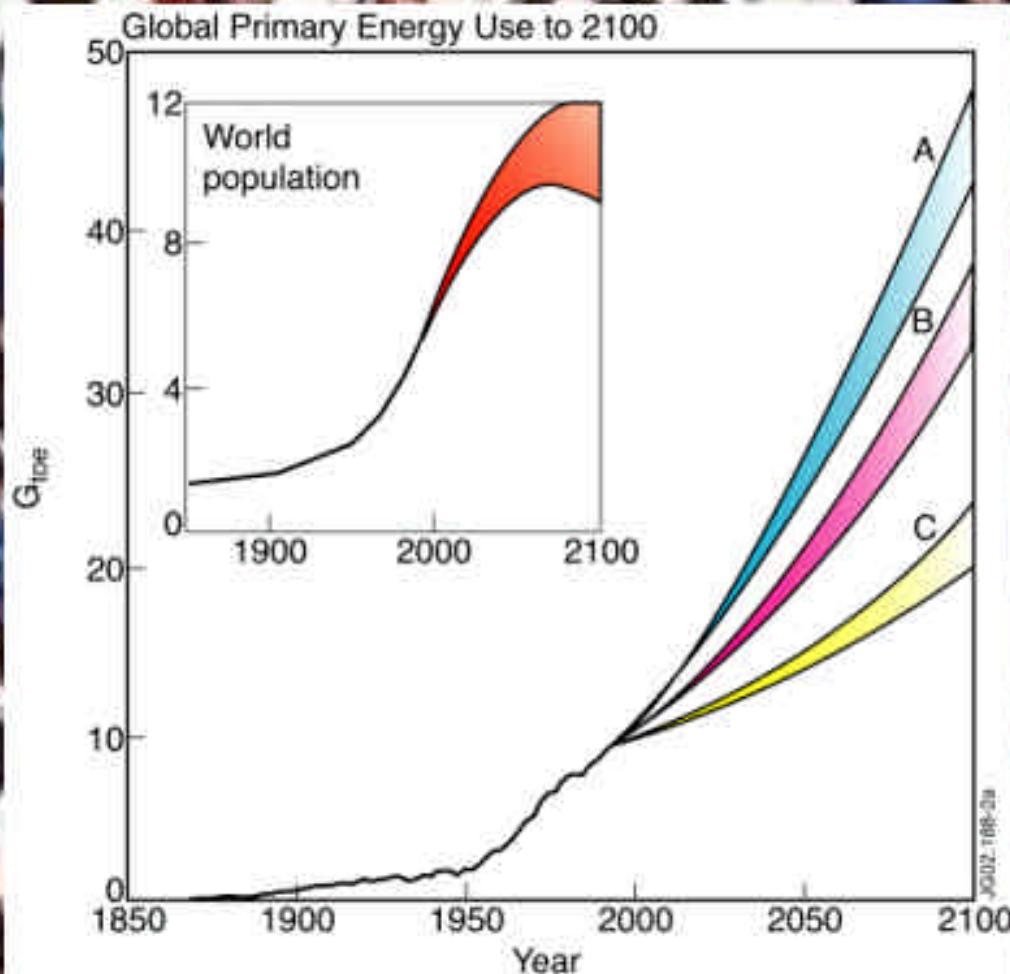
Recent results from MAST

ST route to fusion

World Population Growth

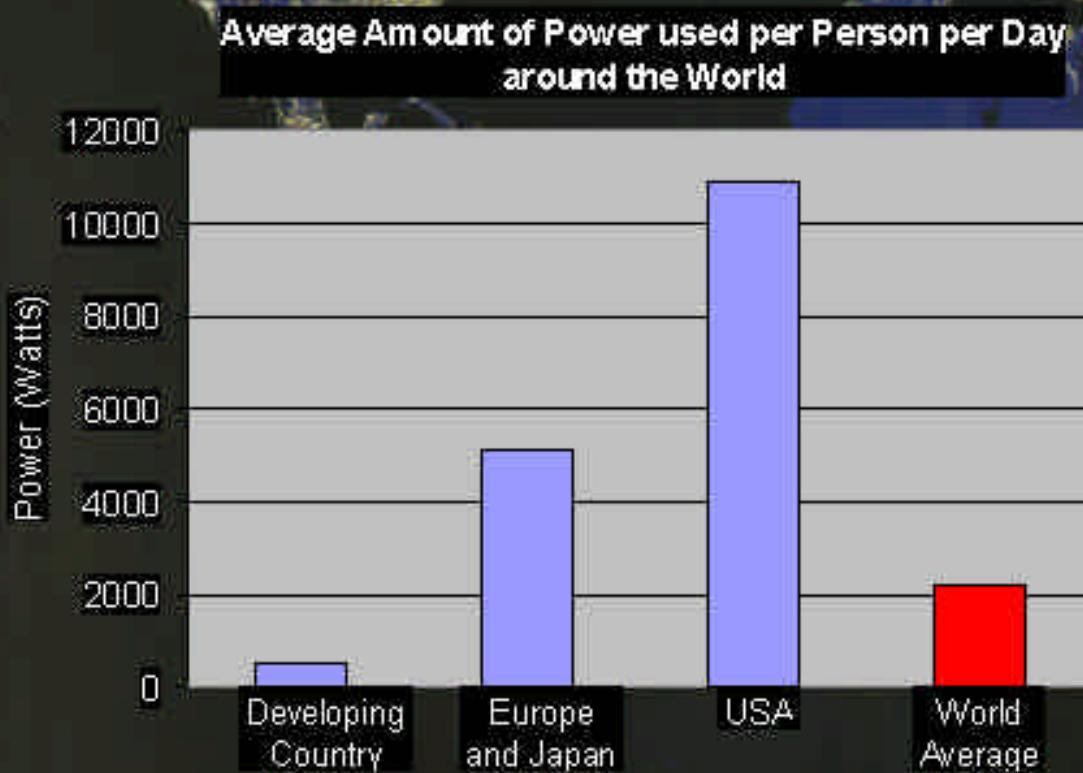
World population
and energy
demand growing
rapidly

Predictions
suggest strong
growth will
continue



Global Energy Demand

Typical energy usage in the developed world is enormous.



World population is almost 6 billion people

Total world power consumption = 11 million million Watts !!!

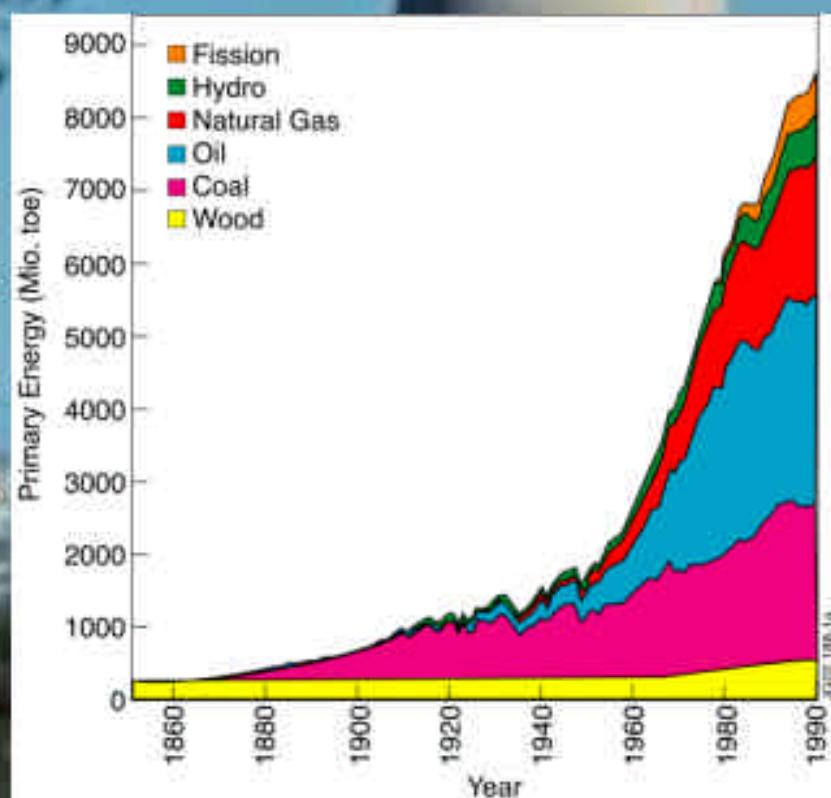
In 50 years, the population will have doubled

Energy usage may have increased by a factor of 2-3



Reliance on Fossil Fuels.

Fossil Fuels are made from decayed plant and animal matter. They can take millions of years to form, so they are not easy to replace.

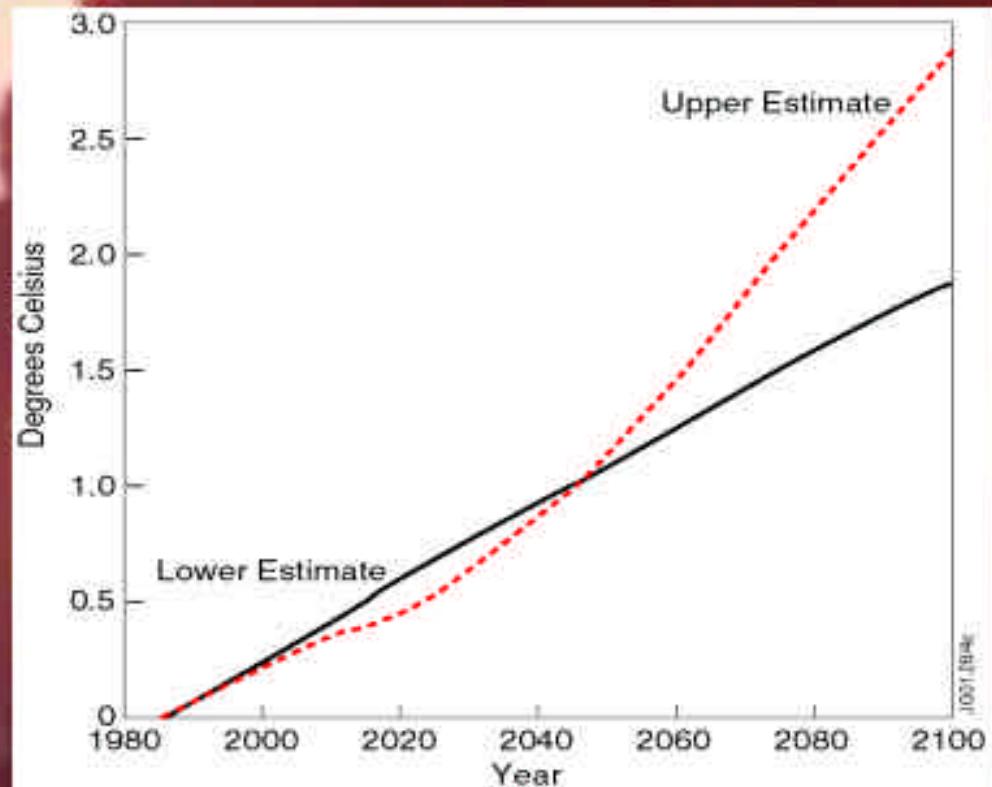


All-world conventional oil production will peak in **5-15 years**

Gas will likely peak around **2020** - World total hydrocarbon shortage perhaps as early as **2010**

Problems with Fossil Fuels

Fossil fuels are currently being burned and lost forever



GLOBAL WARMING due to excessive production of greenhouse gases from power stations

Fossil fuels are essential in the petrochemical and pharmaceutical industries

Significant economic and political impact

Alternative Energy Sources

Nuclear Fission offers a proven alternative but is not without its own problems

Nuclear fission



- Long lived radioactive waste products (many thousands of years) that require transportation and re-processing.
- Public concerns on safety.

UKAEA

Fusion
Furness
Cumbria

Alternative Energy Sources



Renewables (wind, wave, solar, hydro) are the most attractive option at present and offer unlimited and clean energy reserves

However :

- Low energy density.
- Fluctuates in time requiring storage systems.



A 21st Century Solution - FUSION

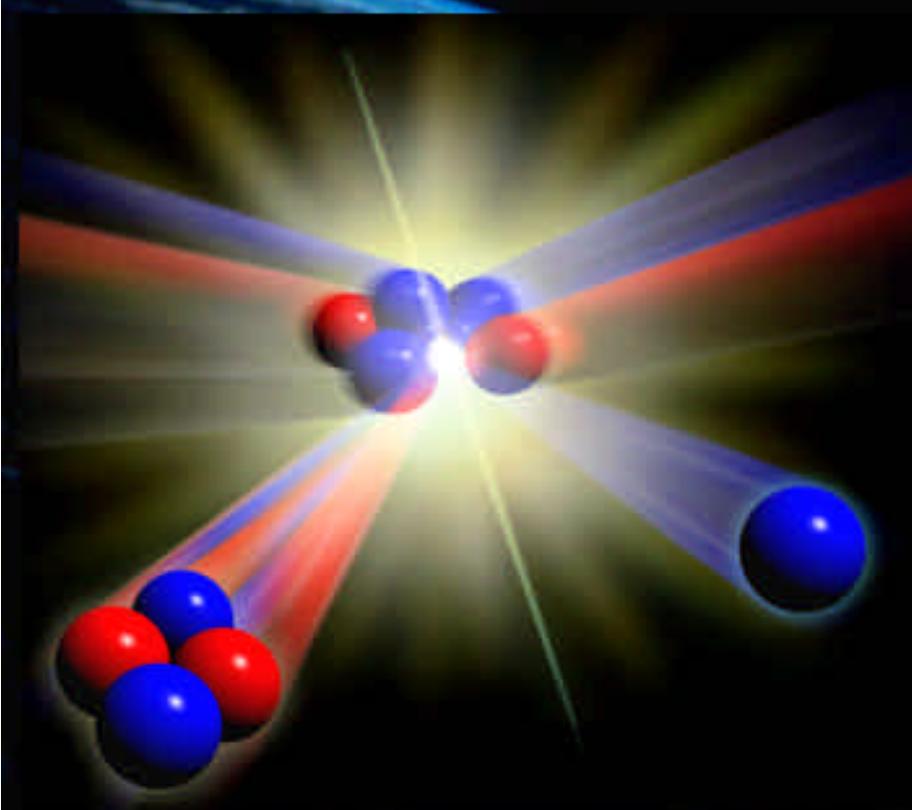
So what is Fusion?

UKALA

Fusion
Working
with Europe

FUSION ...

...occurs when two light nuclei are forced together, producing a larger nucleus



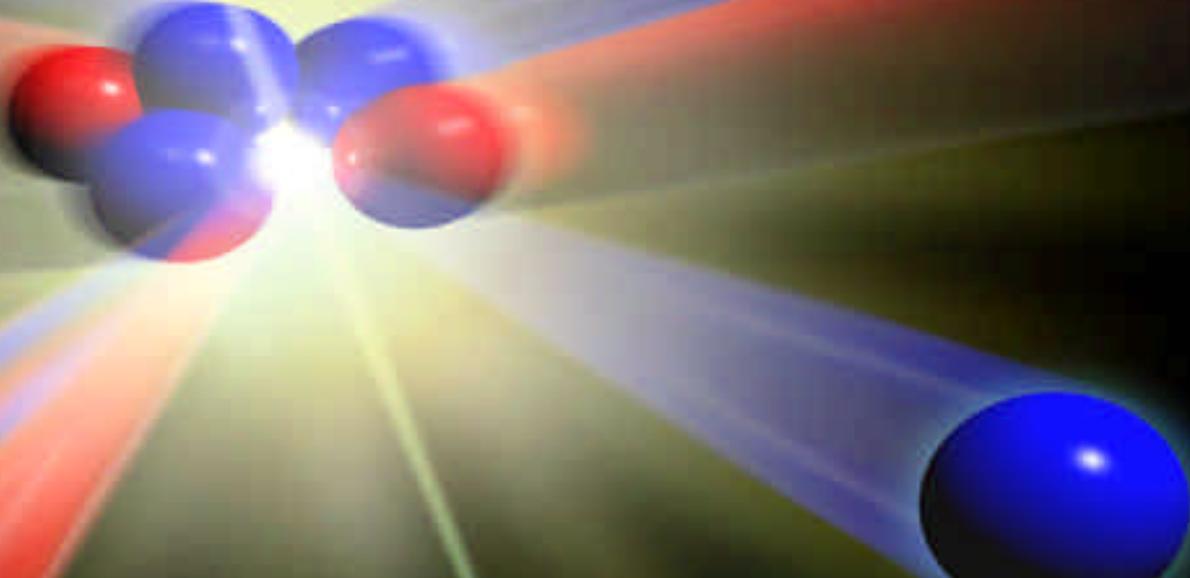
The combined mass of the two small nuclei is greater than the mass of the nucleus they produce

The extra mass is changed into energy

We can calculate the energy released using Einstein's famous equation:

$$E = mc^2$$

1kg of fuel would supply the same amount of energy as 1,000,000 kg of coal!



10 g of Deuterium (from 500 litres of water) and 15g of Tritium produces enough fuel for the lifetime electricity needs of an average person in an industrialised country!!



Advantages of Fusion Power

- Fusion has little or no environmental impact - no Greenhouse emissions
- Fusion does not produce any 'long-lived' radioactive waste
- There is no risk of critical safety events e.g., 'meltdown'
- The fuels are abundant and there is no geographical localisation.
- Deuterium is freely available in



Great Balls of Fire! Fusion in the 21st Century



**Fusion is the Process
Powering the Sun**

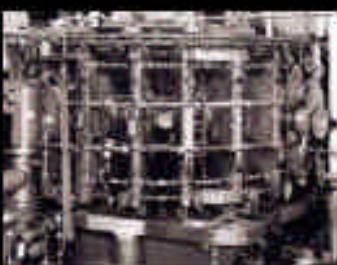
To overcome strong repulsive forces,
fusion nuclei require very high
energies - matter becomes a ...



UKAEA

Fusion
Working with Europe

Magnetic fusion experiments around the world



Fusion research at Culham

Culham is home to ...

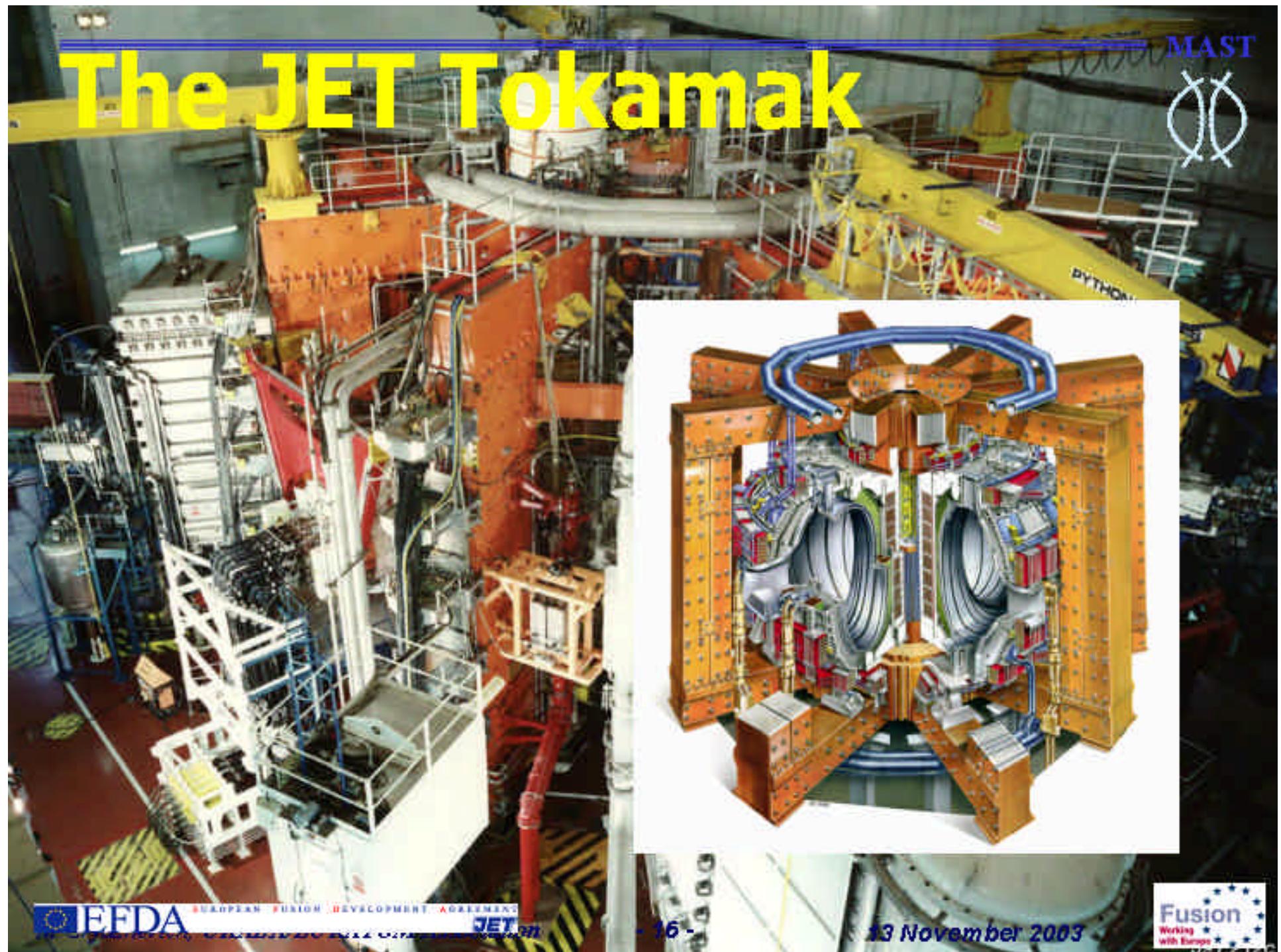
JET - a joint
European tokamak
experiment ...

and **MAST**, the UK's
own spherical
tokamak
experiment

and other scientific
companies

UKAEA

Fusion
Working
with Europe



EFDA

EUROPEAN FUSION DEVELOPMENT AGREEMENT

JET

- 16 -

13 November 2003





JET's achievements

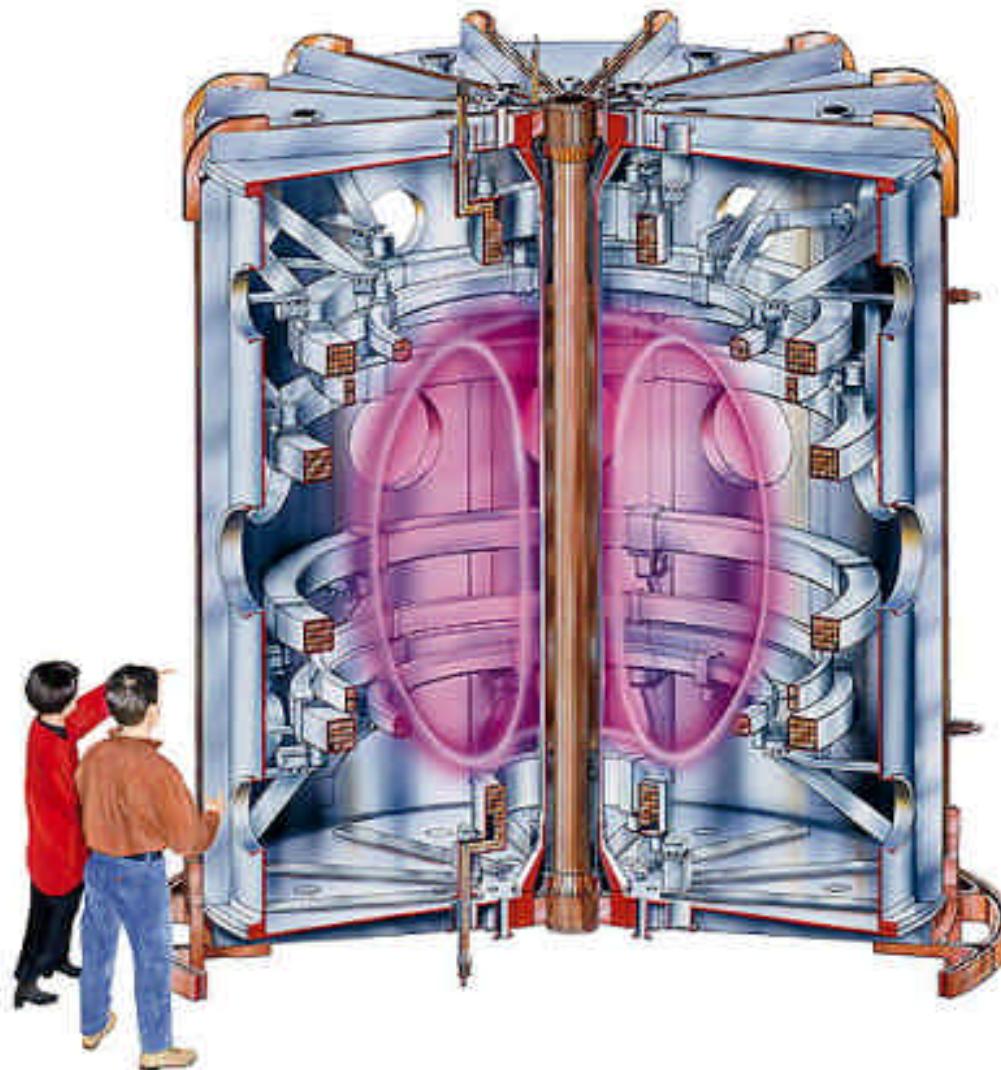
JET is the largest tokamak in the world.

It is the only existing device to use T (as well as D) and observe fusion neutrons.

Robotic technology has proved that remote maintenance of tokamak is possible.



MAST



M. Gryaznovich, UKAEA/EURATOM Association

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13 November 2003



MAST
MAST
Spherical Tokamak





The Future for Fusion Power



When?

1997

**Fusion
Power**

16MW

**Pulse
duration**

~1 second

Q

<1



2015-2020

500-700MW

<30 minutes

>10



~2050

~1500-
2000MW

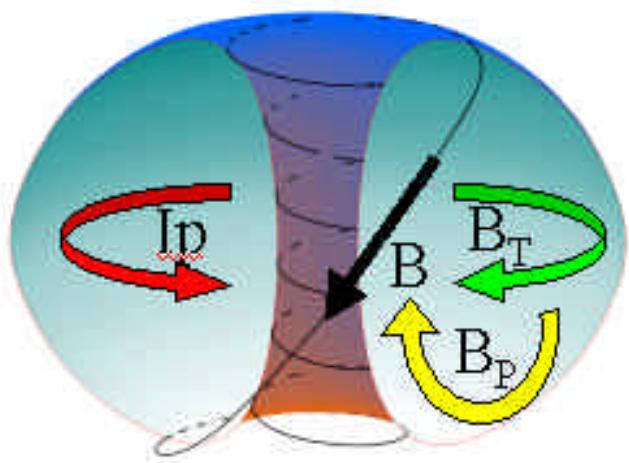
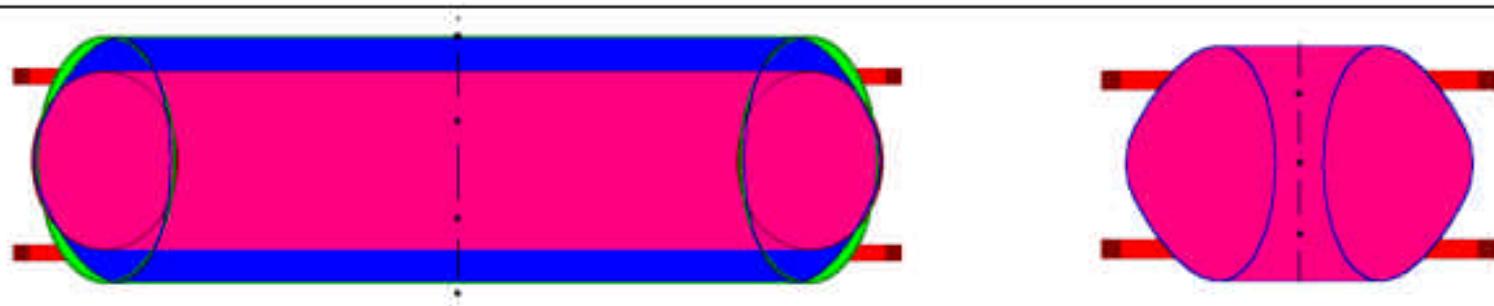
~1 day

~50



What is "Spherical Tokamak"?

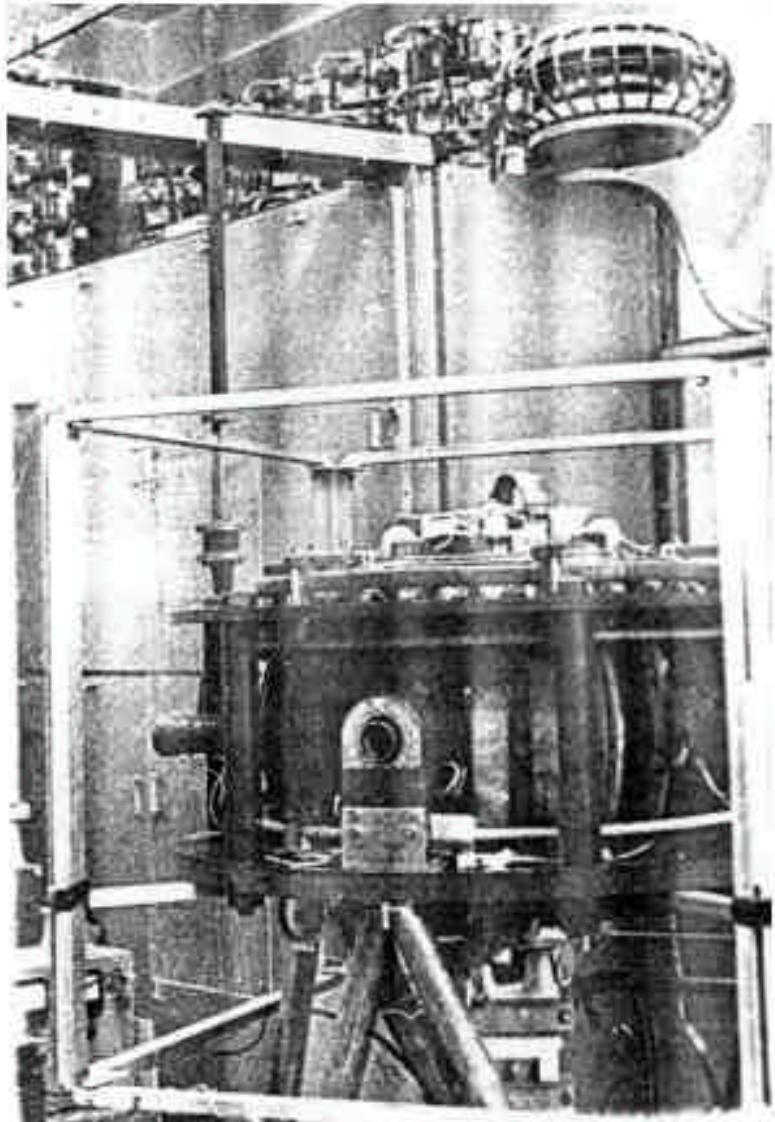
Spherical tokamak ($A=R/a < 2$) is obtained from a conventional one by decrease of major radius to technology limit



- Strong toroidicity increases field line length in high field, favorable curvature region and stabilize interchange modes
- MHD modes kink safety factor increases in ST geometry $q_{edge} \propto (1+\kappa^2) a B_T / I_P A$ and provides high current in low magnetic field
- Strong edge magnetic shear stabilize ballooning modes
- Smaller volume requires less auxiliary heating



GUTTA, IOFFE, USSR (1980-1985)



Vacuum
vessel

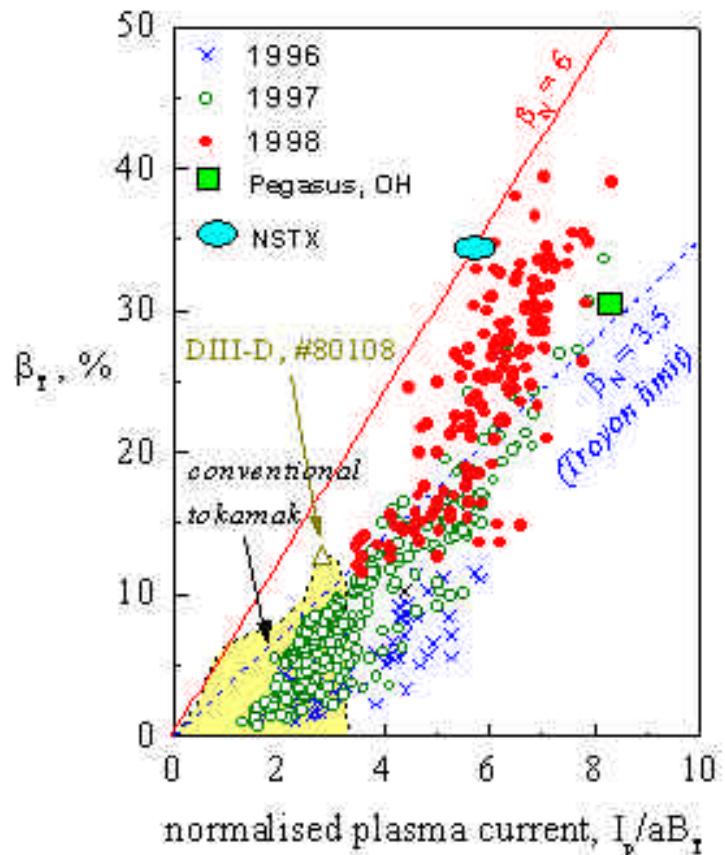
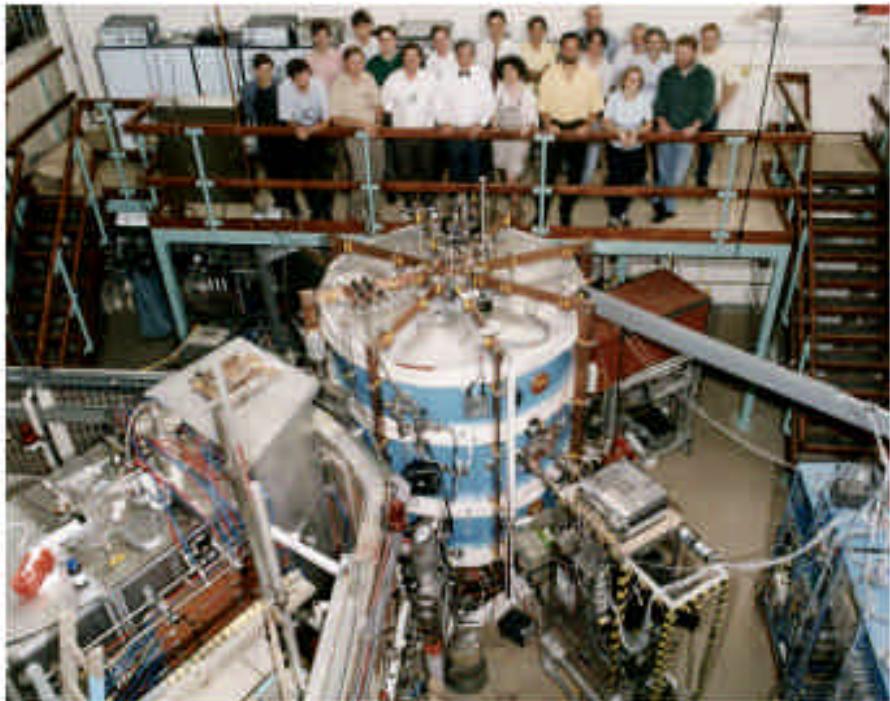
- GUTTA was one of the first attempts to built a spherical tokamak,
G.M. Vorob'ev, Ioffe Institute, 1980

Main parameters:

major radius – $R = 16\text{cm}$,
minor radius – $a = 8\text{cm}$,
aspect ratio – $A \sim 2$,
vessel elongation – $k=2$,
plasma current < 150kA,
toroidal field - 1.5 T



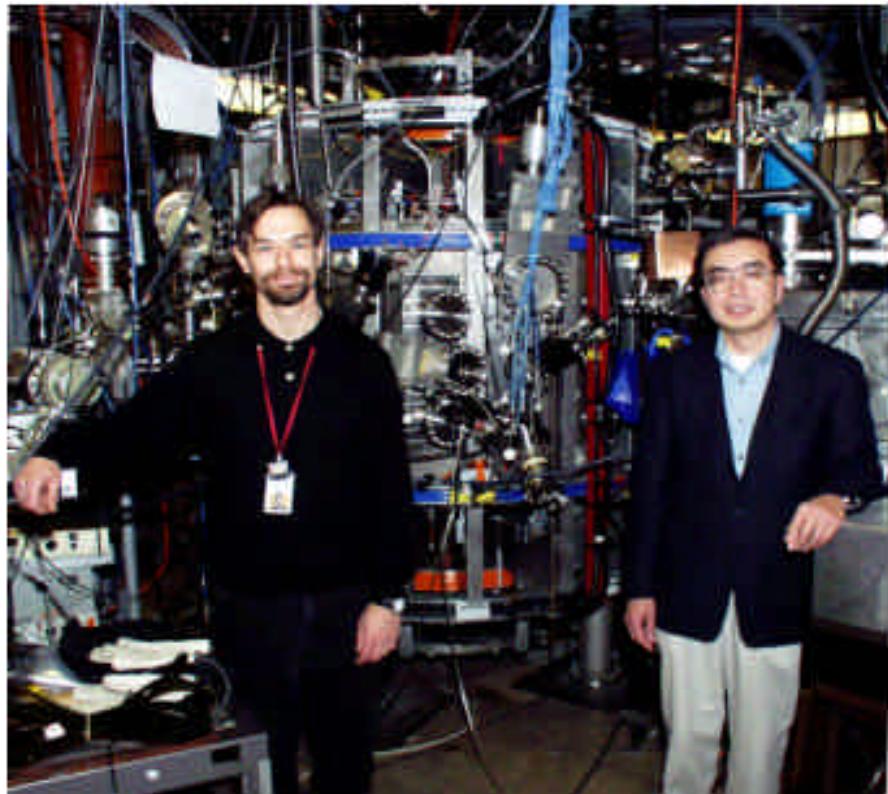
START, UKAEA (1990-1998)



START attained world record tokamak beta values by a combination of high shape factor ($\sim I_p/aB_t$) and high β_N .



CDX-U, PPPL



First plasma: Oct 1993

achieved

Major radius R (m)	0.34
Minor radius a (m)	0.22
Elongation	< 1.6
Aspect ratio (R/a)	>1.5
Plasma current (MA)	0.1
TF rod current (MA)	0.4
Toroidal field at R (T)	0.2
RF Aux. heating (MW)	0.2
Pulse length (s)	0.025
Plasma volume (m ³)	0.5

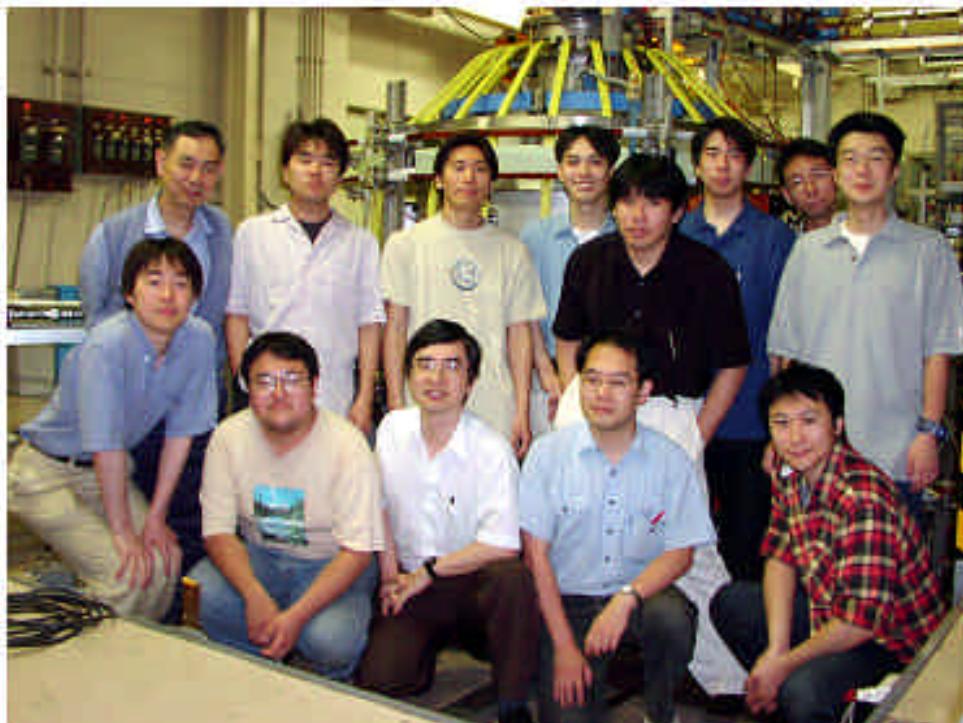
CDX-U is dedicated to a multi-institutional effort to study liquid lithium effects in spherical torus plasmas

*participating institutions: PPPL, Johns Hopkins University,
UCSD, ORNL, SNL, and LLNL*





TST-2, Tokyo



First plasma: Sept 1999

T ST-2 design (achieved)

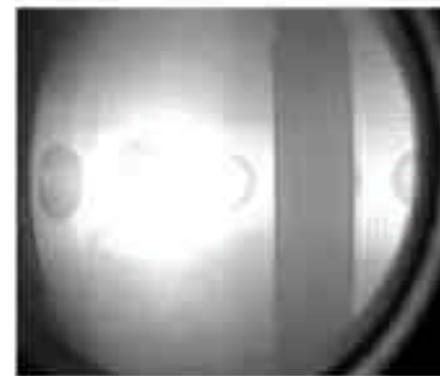
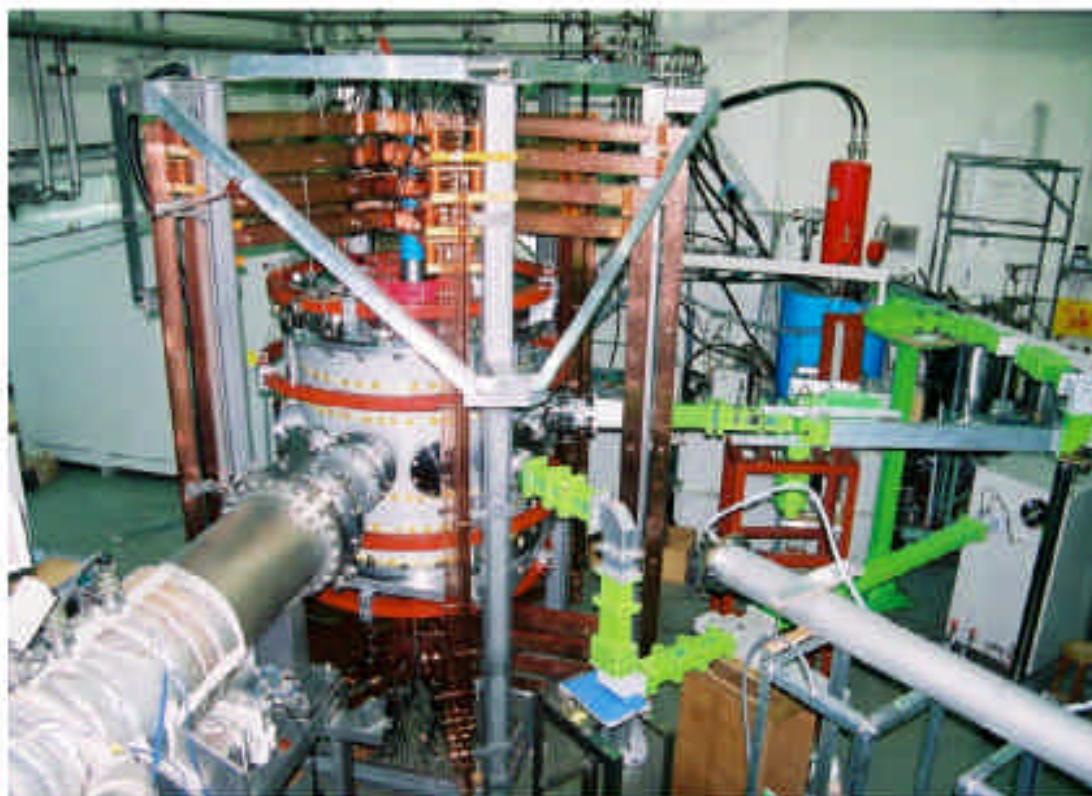
Major radius R (m)	0.36	(0.36)
Minor radius a (m)	0.23	(0.23)
Elongation	< 1.8	(1.8)
Aspect ratio (R/a)	1.6	(1.6)
Plasma current (MA)	0.2	(0.11)
TF rod current (MA)	0.72	(0.38)
Toroidal field at R (T)	0.4	(0.21)
Aux. heating HHFW (MW)	0.5	(0.001)
Pulse length (s)	0.05	(0.1)
Plasma volume (m ³)	0.5	(0.5)

Key research thrusts:

- university research
- RF physics: formation, EBW
- fluctuations and transport

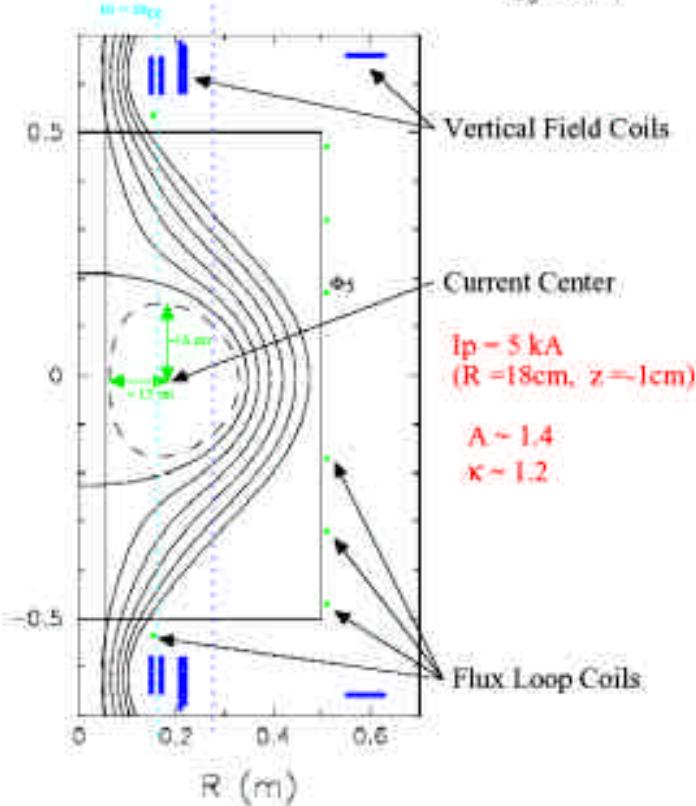


LATE (Low Aspect ratio Torus Experiment) at Kyoto Univ.



$n_e L (R=27\text{cm}) = 2.6 \times 10^{12} \text{ cm}^{-2}$
 $L = 40 \text{ cm} \Rightarrow \bar{n}_e = 6.5 \times 10^{10} \text{ cm}^{-3}$

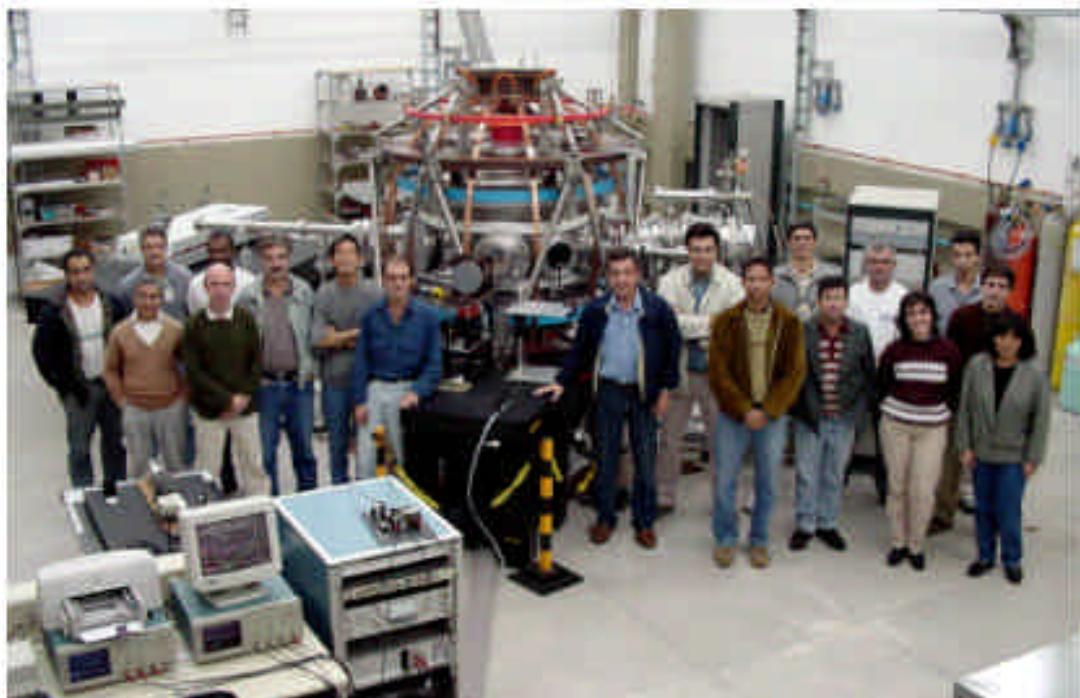
$t = 0.14 \text{ s}$
 $IT = 58.4 \text{ kA}$
 $P_{\text{inj}} = 45 \text{ kW}$



Key research objectives:
non-solenoid start-up and sustainment
EBW heating and current drive



ETE, at INPE, Brazil



First plasma: November 2000.

design (achieved)

Major radius R (m)	0.3	(0.3)
Minor radius a (m)	0.2	(0.2)
Elongation	< 2	(?)
Aspect ratio (R/a)	1.5	(?)
Plasma current (MA)	0.4	(0.03)
TF rod current (MA)	0.9	(0.1)
Toroidal field at R (T)	0.6	(0.067)
Aux. heating	-	
Pulse length (s)	0.1	(0.005)
Plasma volume (m ³)	0.35	(?)

Key research objectives:

- Investigation of parameter space in ohmic regime
- Study of plasma edge physics



GLOBUS-M, St Petersburg



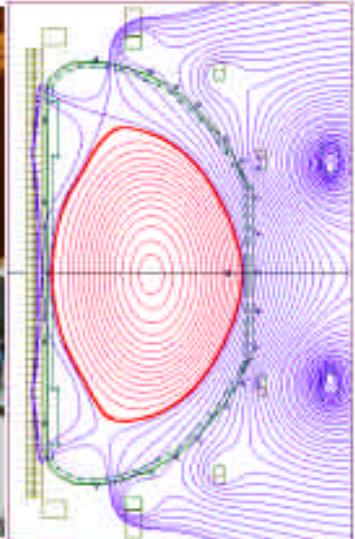
First plasma: November 2000.

design (achieved)

Major radius R (m)	0.36	(0.37)
Minor radius a (m)	0.24	(0.24)
Elongation	2.2	(1.8)
Aspect ratio (R/a)	1.5	(1.5)
Plasma current (MA)	0.5	(0.35)
Toroidal field at R (T)	0.6	(0.35)
Aux. Heating, MW	-	(0.3)
Pulse length(s)	0.3	(0.3)

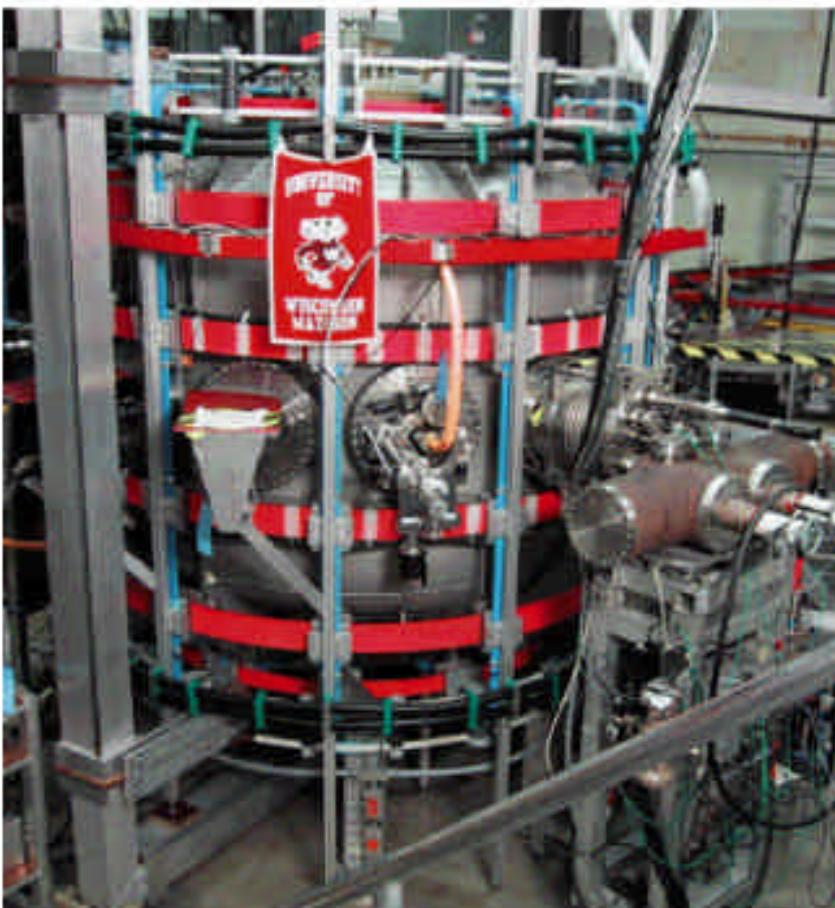
Key research objectives:

- Confinement studies
- NBH, ICRH, EBW, LH studies
- Diagnostics development





Pegasus, University of Wisconsin



Exploration of $A \Rightarrow 1$ regime

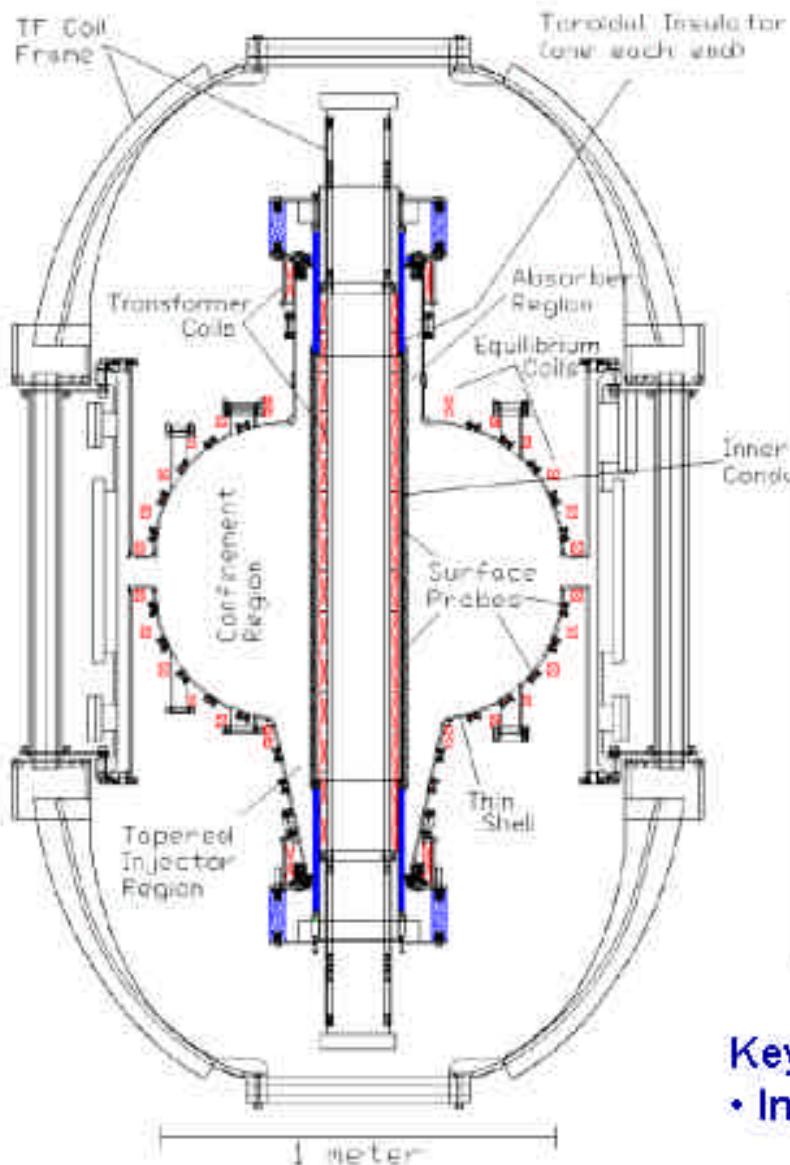
First plasma: June 1999

	design	(achieved)
Major radius R (m)	0.4	(0.45)
Elongation	< 3	(3.7)
Aspect ratio (R/a)	1.1	(1.1)
Plasma current (MA)	0.14	(0.3)
TF rod current (MA)	0.2	(0.225)
Toroidal field at R (T)	0.1	(0.15)
Aux. heating (HHFW, EBW)	-	(?)
Pulse length (s)	0.25	(0.06)





HIT-II, Univ. of Washington, Seattle



- HIT-II Engineering Parameters:

Major Radius R	0.3m
Minor Radius a	0.2m
Aspect Ratio A	1.5
Elongation κ	1.75
Ohmic Flux Available	60 mWb

- HIT-II Achieved Plasma Parameters:

Parameter	Ohmic	CHI
Pulse Length	60 ms	25 ms
Peak Current	200 kA	200 kA
Density \bar{n}_e	$\leq 5 \times 10^{19} \text{ m}^{-3}$	$1-6 \times 10^{19} \text{ m}^{-3}$

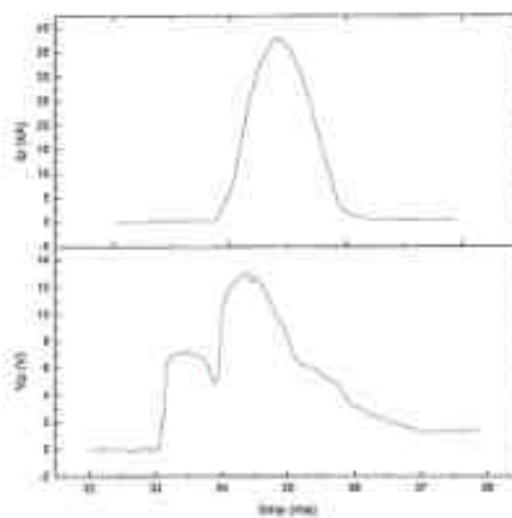
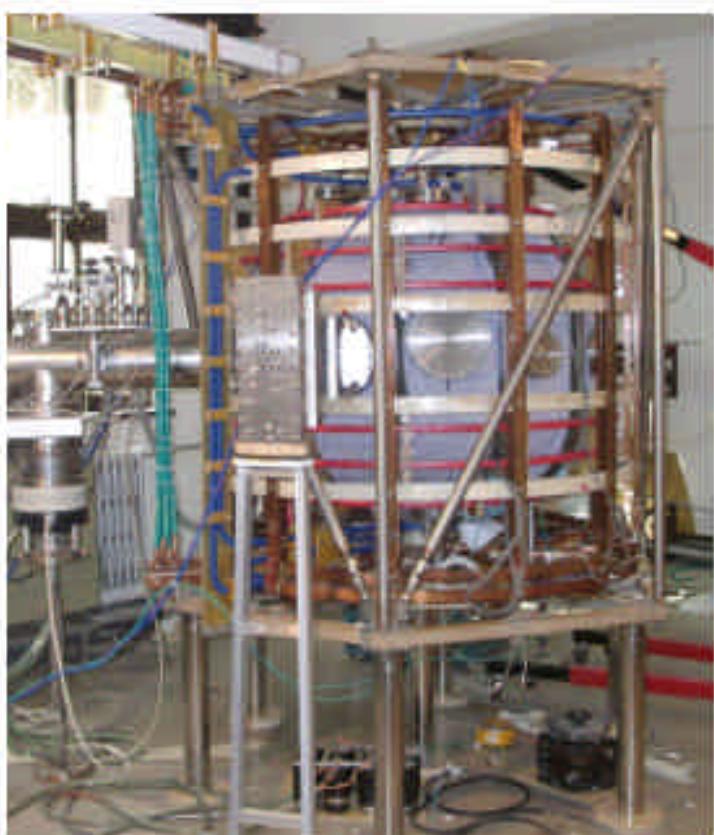
Key research objectives:

- Investigation of coaxial helicity injection



SUNIST

*Institute of Physics, Chinese Academy of Science
Department of Engineering Physic, Tsinghua University
Southwestern Institute of Physics
Institute of Plasma Physics, Chinese Academy of Science*



the first SUNIST plasma on Nov. 4, 2002

Key research objectives:

- Investigation non-inductive current ramp, CHI
- EBW
- core and edge fluctuations study



NSTX, Princeton

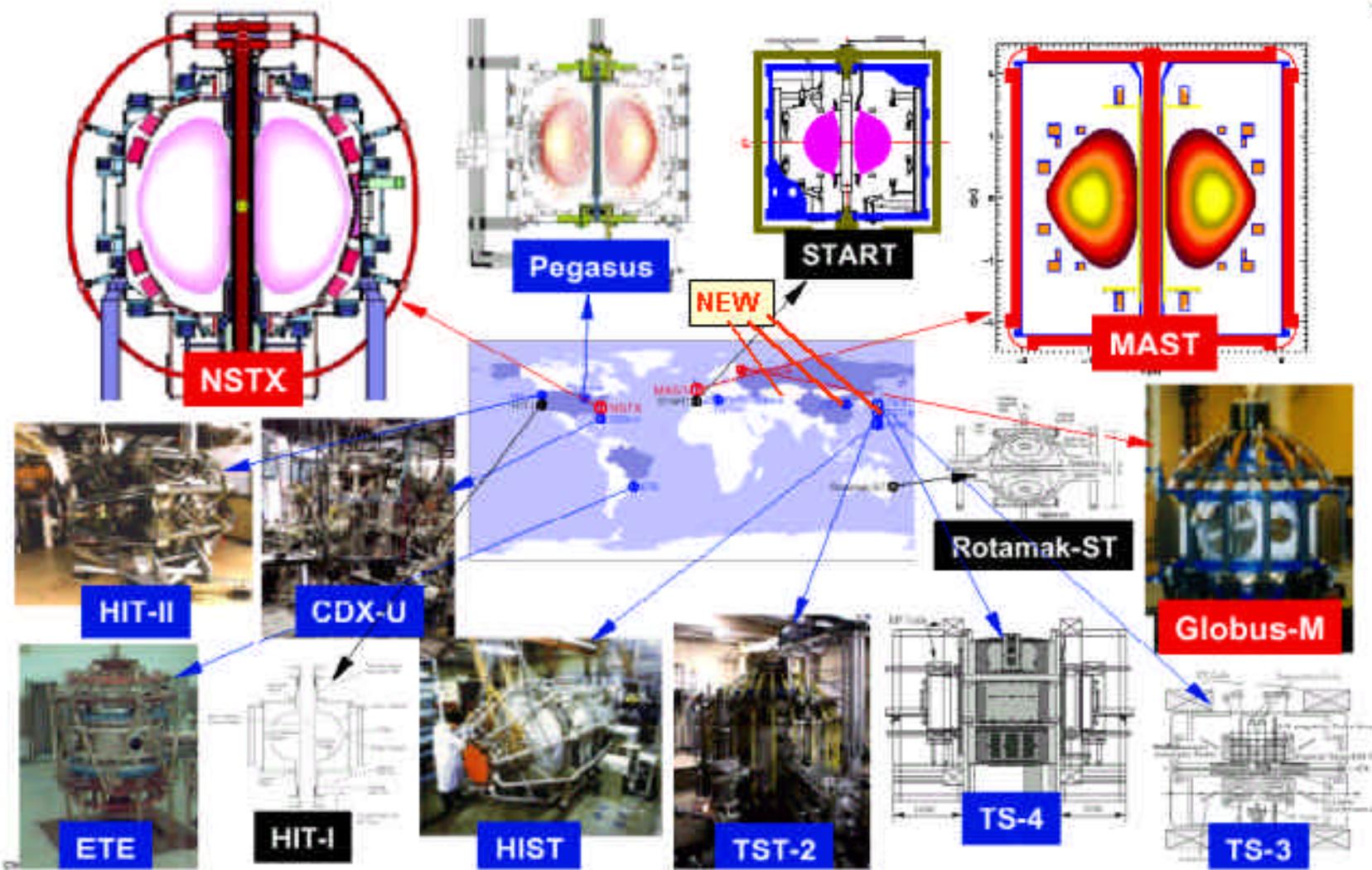


NSTX team, June 2001





A sphere full of Spherical Tokamaks





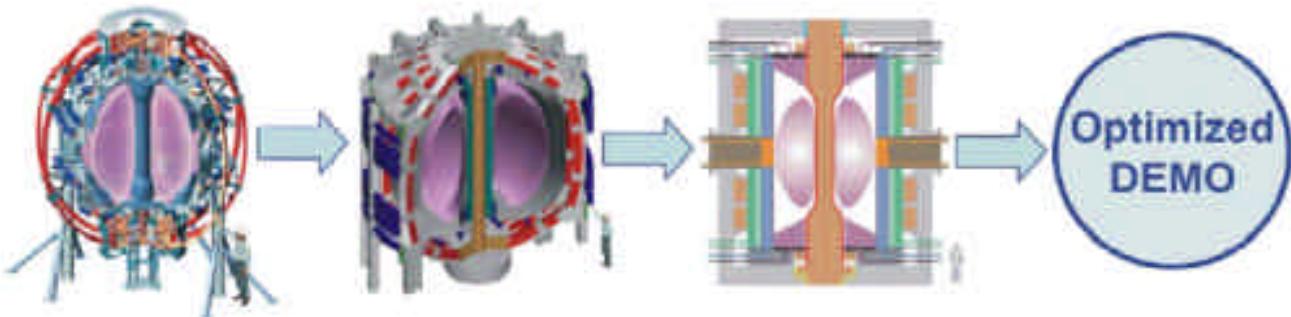
Is the ST a viable route to fusion?

- The ST has a number of promising features, e.g.
 - simpler construction than conventional tokamaks
 - good confinement,
 - low halo currents,
 - high density operation,
 - good stability (particularly at high elongation).
- But questions remain to be addressed by experiments and theory:
 - How does confinement scale?
 - Are there options for handling the exhaust?
 - What is the pressure limit ($\beta_N \sim 6$ already achieved)?
 - Can we demonstrate non-inductive current drive (and start-up)?
 - Fundamental plasma physics at high $\beta \sim 1$
- We are entering an exciting era
 - The role that the ST has to play in the development of fusion should become clear in the next few years



The Benefits of Projected ST Properties Include Potential Cost-Effective PE and CTF Devices

NSTX



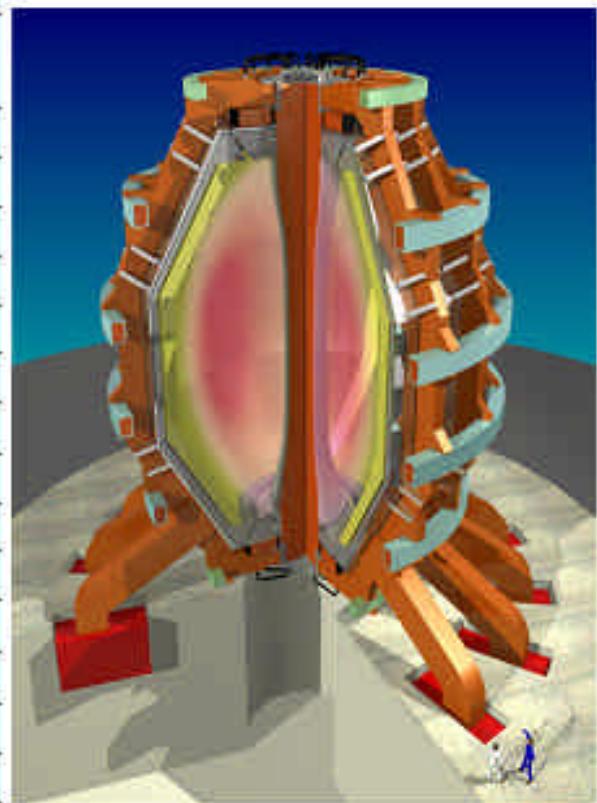
Device	NSTX	NSST	CTF	DEMO
Mission	Proof of Principle	Performance Extension	Energy Development, Component Test	Economy of Fusion Electricity
R (m)	0.85	1.5	1.2	~2.5
a (m)	0.65	0.9	0.8	~1.8
κ, δ	2, 0.8	2.7, 0.6	3, 0.4	~3.4, 0.5
I_p (MA)	1.5	5 – 10	12	~20
B_T (T)	0.3 – 0.6	1.1 – 2.6	2.4	~2
P_{fusion} (MW)	–	10 – 50	≥ 70	~2000
t-pulse (s)	1 – 5	50 – 5	Steady state	Steady state
TF coil	Multi-turn	Multi-turn, LN ₂	Single-turn	Single-turn



ST Power Plant and Material Test Facility Designs

- Several designs of Next Step STs, Volume Neutron Sources and Power Plants based on the ST concept have been proposed during the last ten years:

	Pilot Plant	FDF	FED VNS	VNS	VECTOR-SC	ARIES-ST	ST PP
Q	GA	GA	PPPL	UKAEA	JAERI	ARIES	UKAEA
R, m	1.05	1.12	1.3	0.57	2.8	3.2	3.4
a, m	0.75	0.7	0.93	0.36	1.4	2	2.4
R/a	1.4	1.6	1.4	1.6	2	1.6	1.4
k	2.5	3	3	2.3		3.4	3.2
δ	0.8	0.8	0.6	0.4		0.64	0.55
I_p , MA	15	10.2	10	6.8	19.4	30.8	31
B_t , T	2.8	3.62	2	2.5	5	2.14	1.8
P_{aux} , MW	44	42	45.5	25		70	70
β_N	8.5	4.15	4.65	4.4	6.5	7.5	8.2
β_t , %	62	18	25	34	18	54	59
Wall load	8		2	1.5	9.7	4.1	3.5
$f_{non-ind}$	0.9	0.9	0.5	0.33	0.9	0.99	0.95

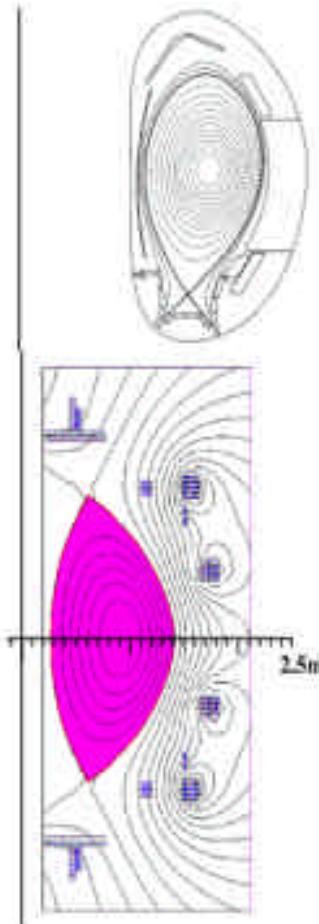


- How these projects are supported by research results from STs?



ST proof-of-principle research - present status

MAST(UK), NSTX, Pegasus, CDX-U, HIT-II (US), Globus-M (RF), ETE(Brazil), TST-2 (Japan) and other STs are providing physics basis for Next Step ST devices and also contribute to ITER



MAST and ASDEX-Upgrade in Europe

	START	MAST	NSTX
R,m	0.35	0.85	0.85
a,m	0.27	0.65	0.68
k	1.5 - 3	2.4 (3)	2.5
I_p, MA	0.31	1.2 (2)	1.5 (1.0)
B_t, T	0.3 - 0.6	0.5	0.45
P_{aux}, MW	1 NBI +0.2 EC	3 NBI (5) + 1 EC (1.5)	5 NBI (5) + 4 FW(6)
t_{pulse}, s	< 0.06	0.65 (5)	0.55 (5)

Red - design values

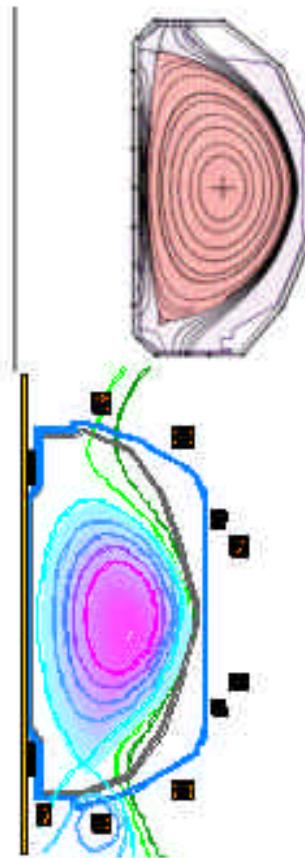
Recent results:

NSTX:

$\beta_t > 30\%$; $\beta_N \sim 6 > \beta_N^{(\text{no-wall})}$; $\beta_{\text{pol}} \sim 1$, $H_{\text{pby2}} \sim 1.8$, $T_e \sim 3.5 \text{ keV}$;

MAST:

$\beta_N \sim 6 > \beta_N^{(\text{no-wall})}$; $\beta_{\text{pol}} \sim 2$, $H_{\text{pby2}} \sim 2$; $T_i, T_e \sim 3 \text{ keV}$; $G > 2$



NSTX and DIII-D in USA

Large STs have similar cross-section and main plasma parameters with conventional aspect ratio tokamaks of similar size



Recent results from MAST, UKAEA

MAST team:

J.Ahn, R.Akers, L.C.Appel, E.R.Arends, K.Axon, C.A.Bunting, R.J.Buttery, C.Byrom, P.G.Carolan, C.Challis, D.Ciric, N.J.Conway, G.F.Counsell, M.Cox, G.Cunningham, A.C.Darke, J.Dowling, M.R.Dunstan, A.R.Field, S.J.Fielding, S.J.Gee, R.S.Gorman, M.P.Gryaznevich, R.J.Hayward, P.Helander, T.C.Hender, M.Hole, M.B.Hood, P.Jones, A.Kirk, I.P.Lehane, B.Lloyd, G.P.Maddison, S.Manhood, R.Martin, G.J.McArdle, H.Meyer, K.McClements, M.A.McGrath, A.W.Morris, S.K.Nielsen, M.P.S.Nightingale, A.Patel, T.M.Rinfold, M.Price, J.Qin, C.Ribeiro, D.C.Robinson, V.Shevchenko, S.Shibaev, K.Stammers, A.Sykes, A.E.E.Tabasso, D.M.A.Taylor, D.Terranova, N.P.J.Thomas-Davies, M.R.Tournianski, A.Thiyagaraja, M.Valovič, M.J.Walsh, S.E.V.Warder, J.Waterhouse, H.Wilson, Y.Yang, S.You, and the ECRH and NBI teams

and to our collaborating Universities and Laboratories:

Imperial College

QUEEN'S UNIVERSITY BELFAST



UNIVERSITY OF STRATHCLYDE
TO GLASGOW



WSL
The Swiss Federal Institute for Forest, Snow and Landscape Research

UNIVERSITY COLLEGE, CORK
Coláiste na hOllscoile Corcaigh



UNIVERSITY COLLEGE DUBLIN
Trinity College Dublin, Royal Irish Academy



AARHUS UNIVERSITET



Inside
MAST

2001





MAST started operating in 2000

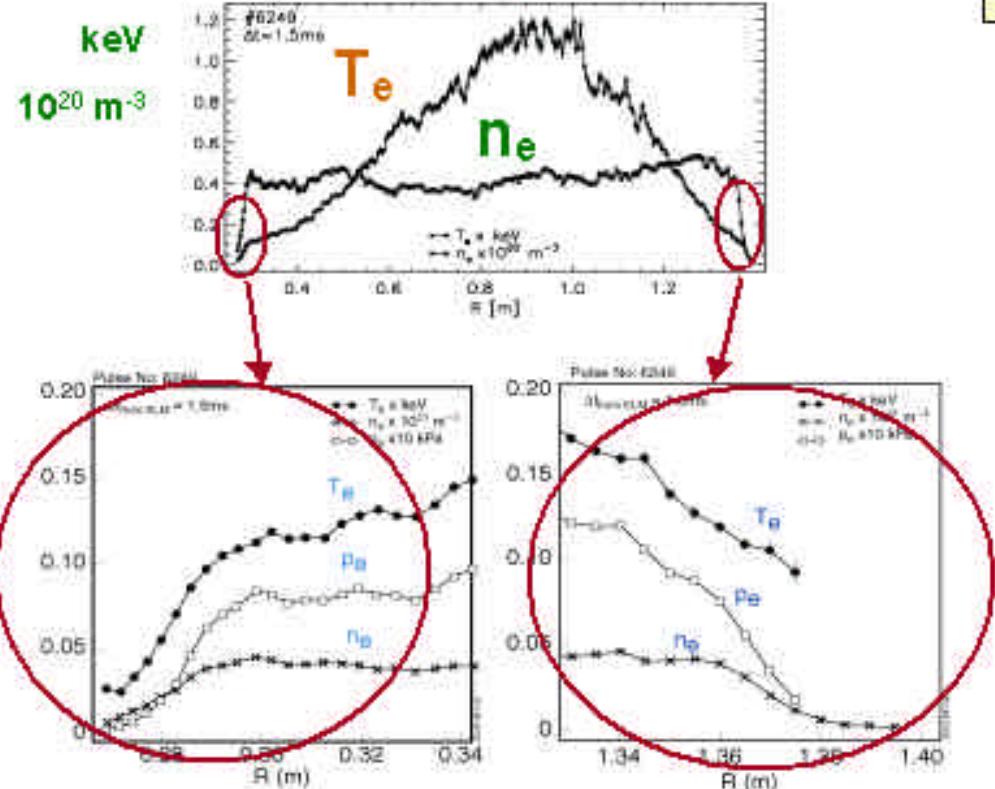
Success of the first three years of physics operations on MAST was based on:

- Comprehensive diagnostics
- Flexibility of Magnetic Configuration
- Reliable operations in H-mode (OH or NBH) and easy H-mode access
- Low MHD and good confinement at high beta

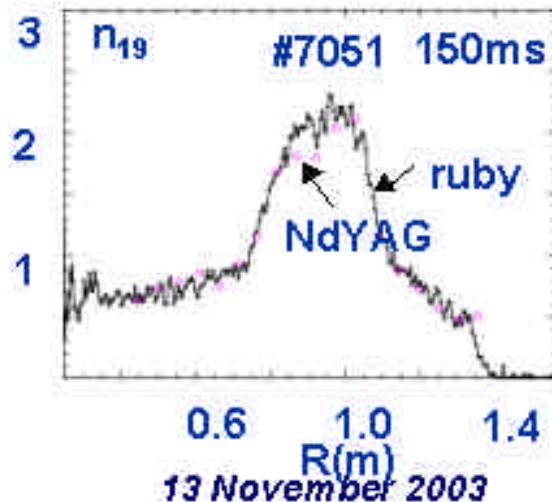
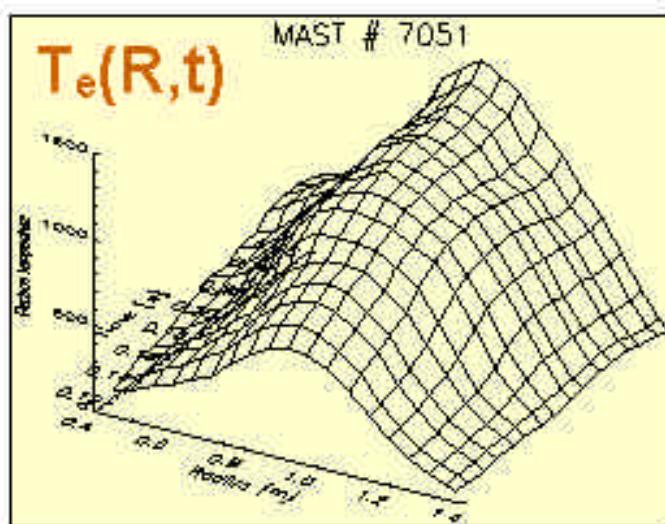


Electron temperature and density measurements: M Walsh E Arends M Dunstan

300pt one (two) time point TS



200 Hz 20 points NdYAG Thomson Scattering



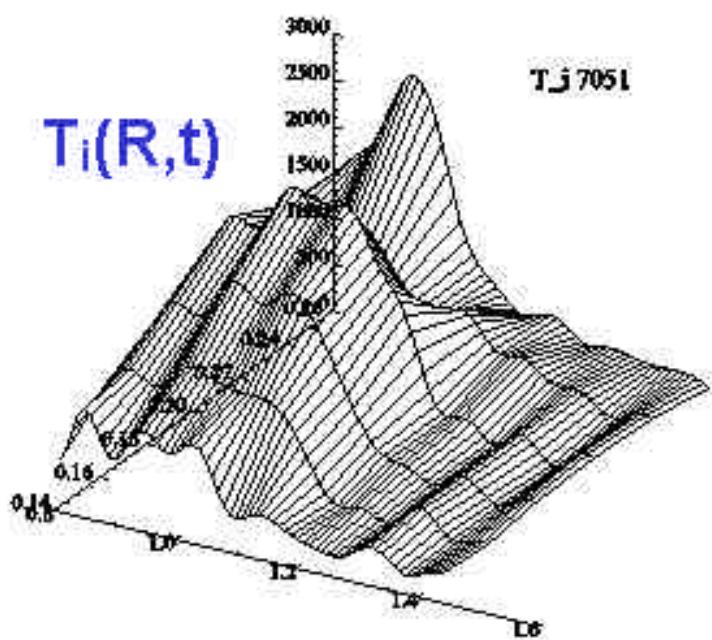
300 point high resolution Thomson Scattering gives i/b and o/b pedestal parameters in a single shot



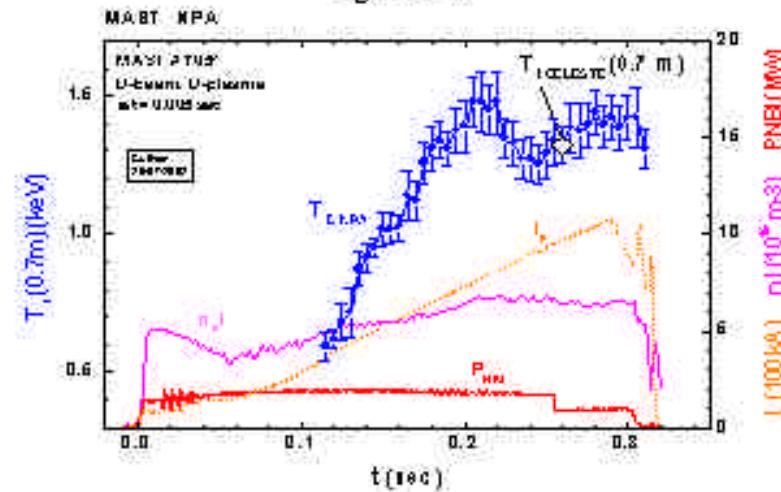
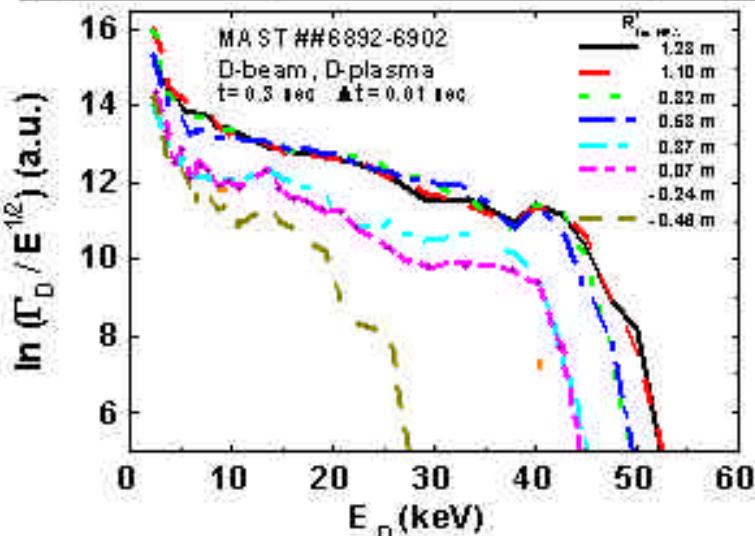
Ion temperature and fast ion energy measurements:

N Conway F Chernishev M Tournianski

$T_i(R,t)$, $V_f(R,t)$
**Charge Exchange
Radiation (CXR) 20 chords**



$T_i(t)$ Scanning neutral particle analyser (PPPL)

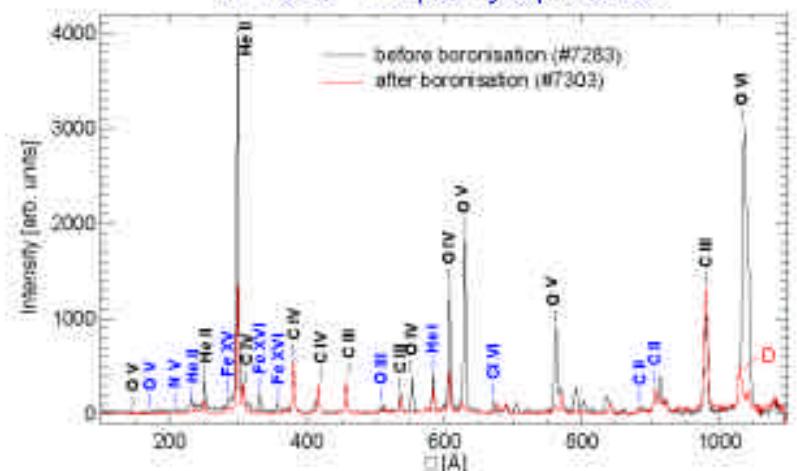




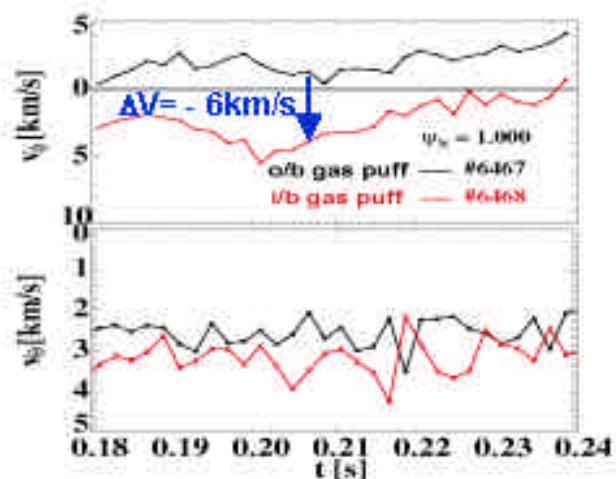
Impurities, rotation and Z_{eff} measurements:

A R Field, N Conway, H Meyer, I Lehane, A Patel, M J Walsh

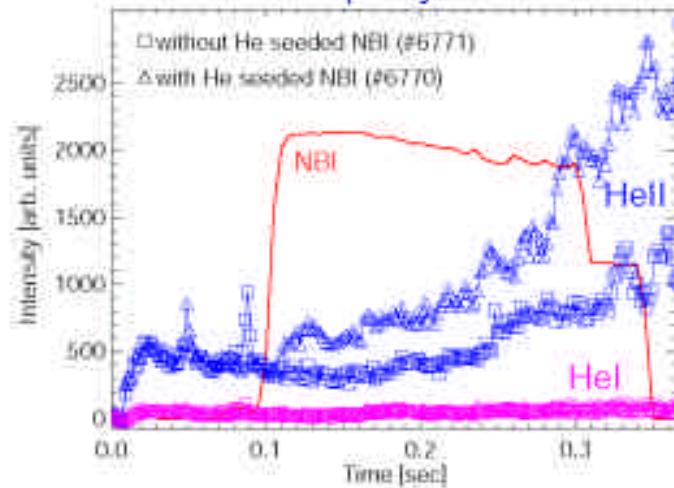
SPRED - impurity spectrum



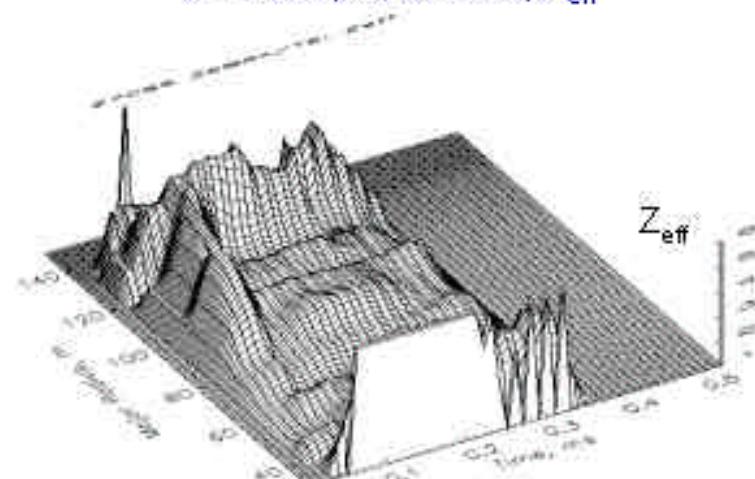
He II Doppler (20 chords) CELESTE



SPRED - fast time absolutely calibrated impurity radiation



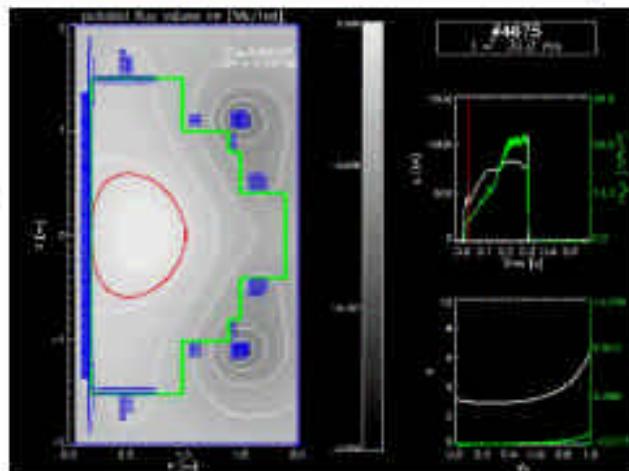
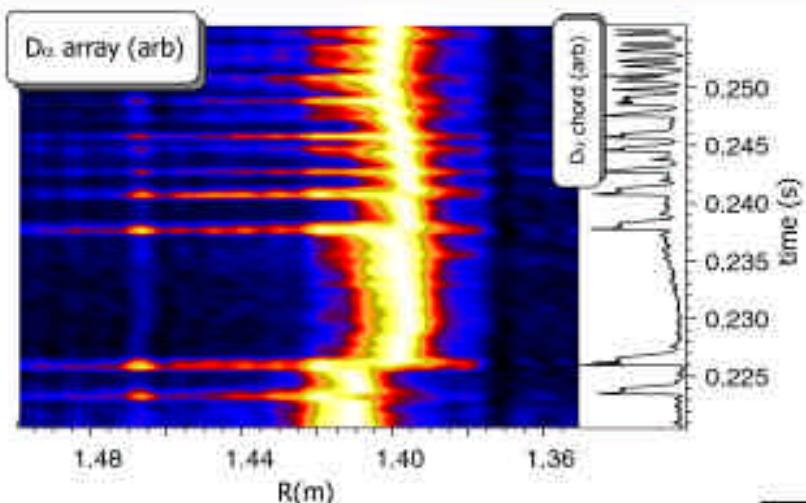
ZEBRA (200 chords) Z_{eff}



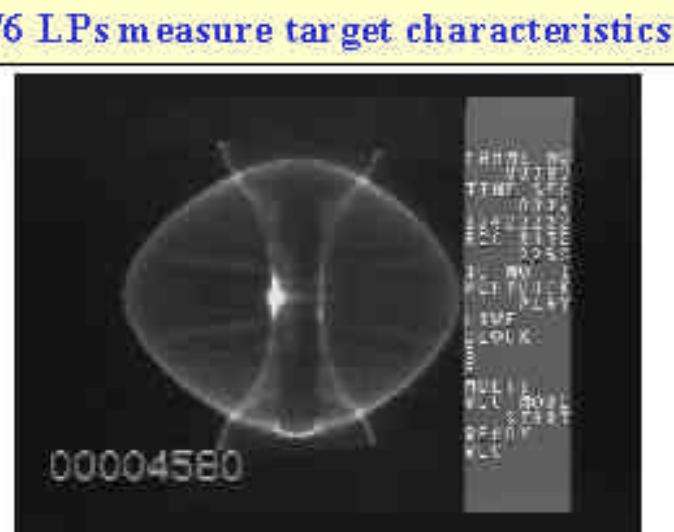


Visible and infrared emission measurements and LP:

M Price, J Dowling, G Counsell, A Kirk, M Tournianski



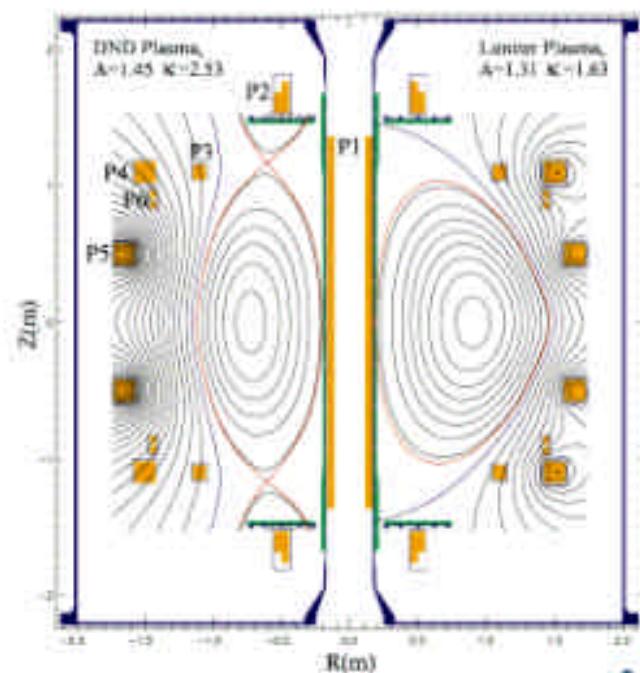
IR power video, divertor ribs



High speed video, up to 25000f/s

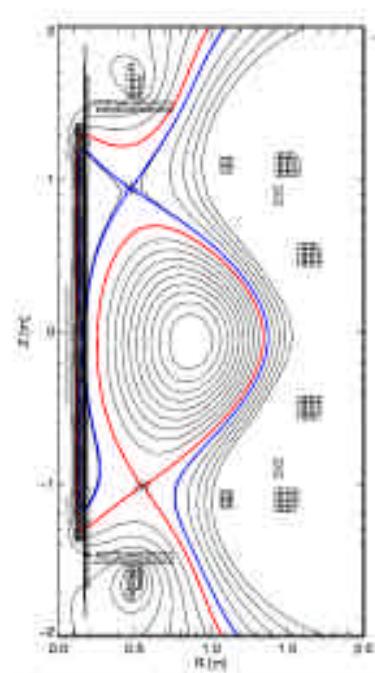
Flexibility of Magnetic Configuration:

Divertor configurations in MAST:

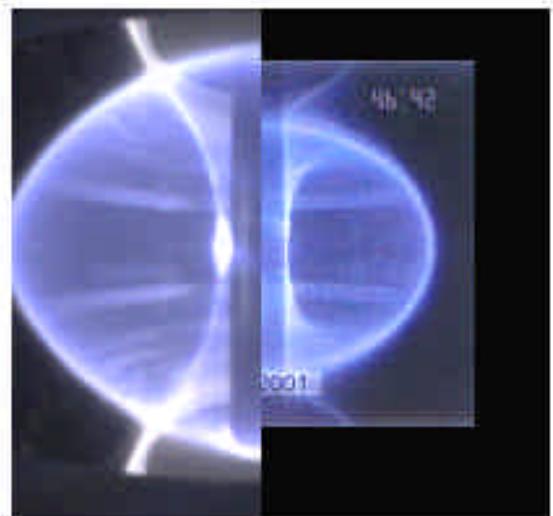
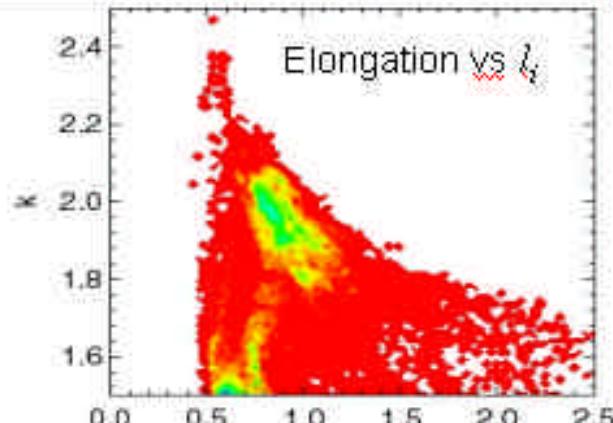


Double-Null
Divertor (DND)

Limited, or Natural
Divertor (ND)



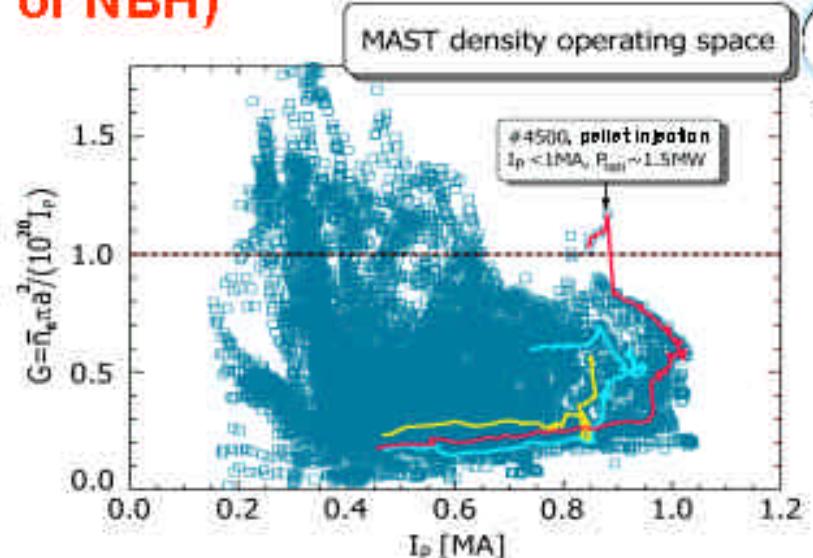
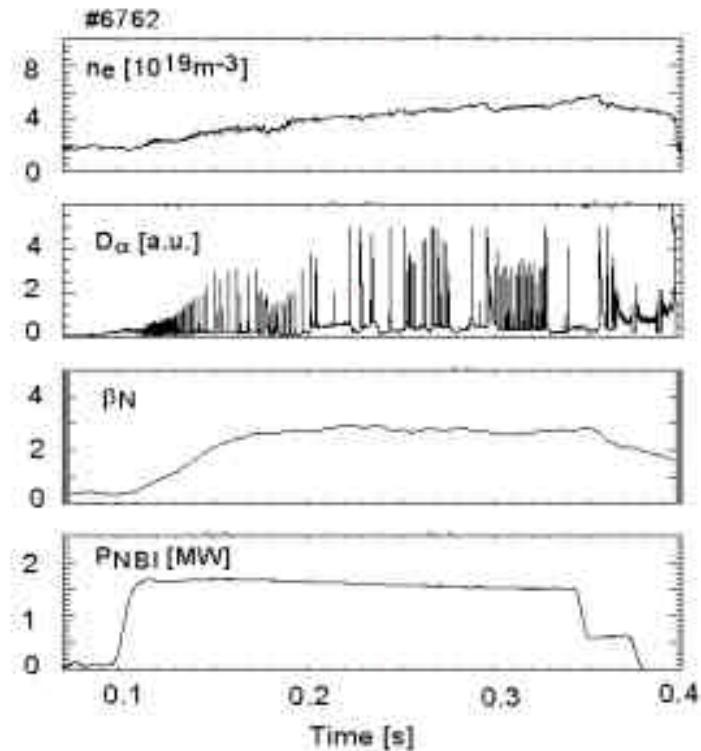
SND plasmas can be produced
G Cunningham, H Meyer



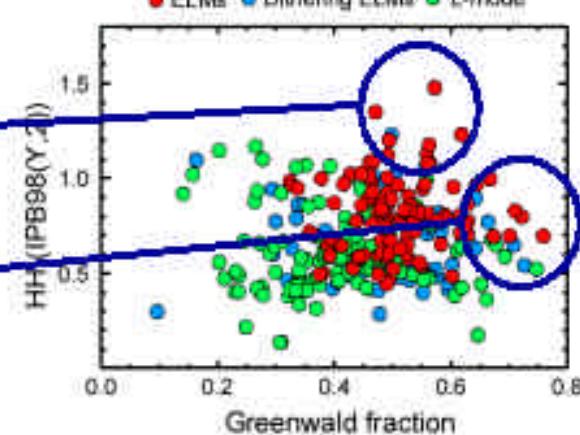
H-mode in DND and
Natural Divertor plasmas



Reliable operations in H-mode (OH or NBH) and easy H-mode access:



HH(IPB(y,2)) up to 1.5 in ELMy H-mode (EFIT data)
ELMy H-mode with G up to 0.8

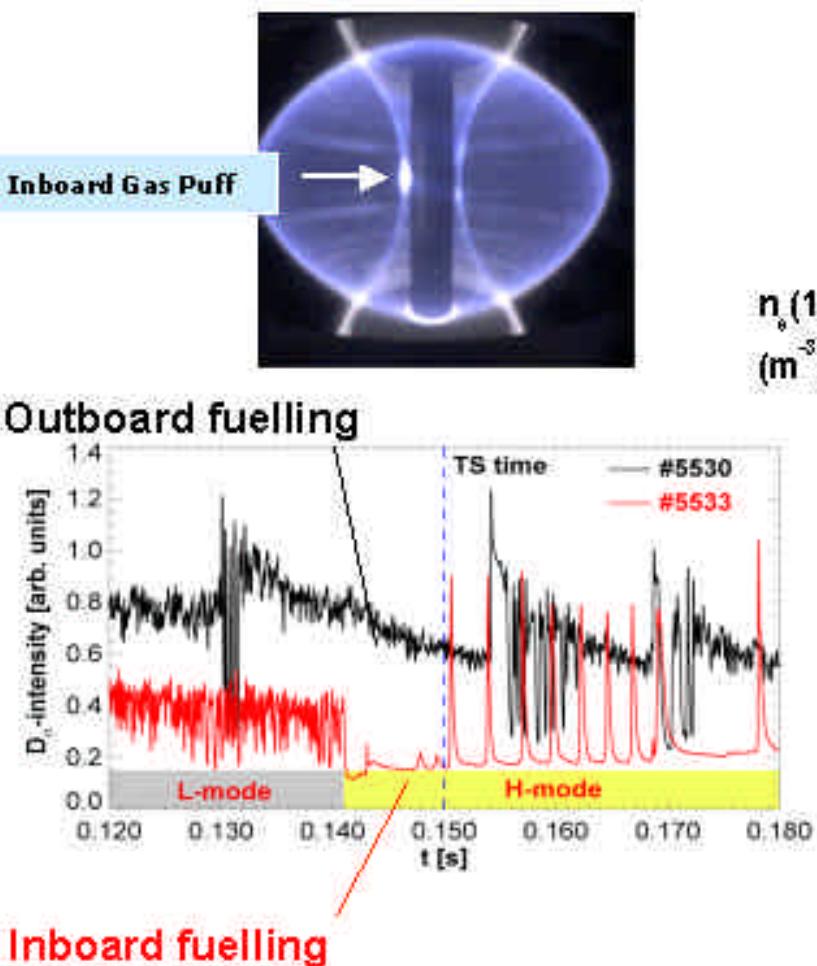


Sustained H-modes platform for studies:
 $\beta_N \sim 3$, $H_H \sim 1$, $n_e/n_{Gr} \sim 0.5$ sustained
for ~ 220 ms ($> 5\tau_F$), $W_{kin} \sim W_{max}$, $W_{fast} \sim 10\%$
M Valovic

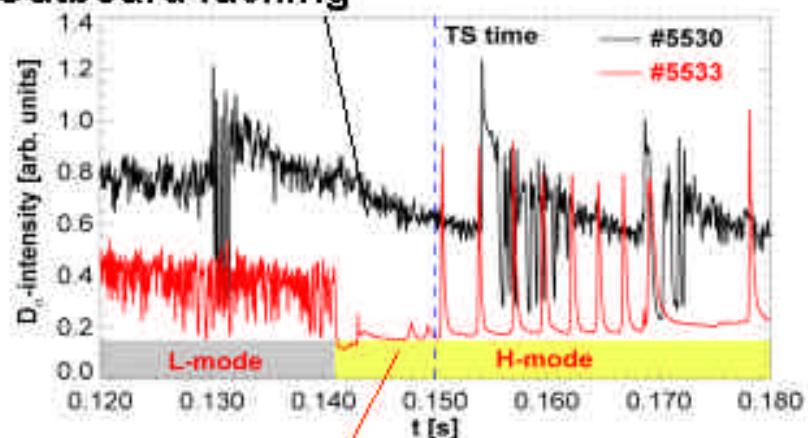
Good performance at high density
G F Counsell



**Inboard midplane fuelling
improves H-mode access:
A Field**



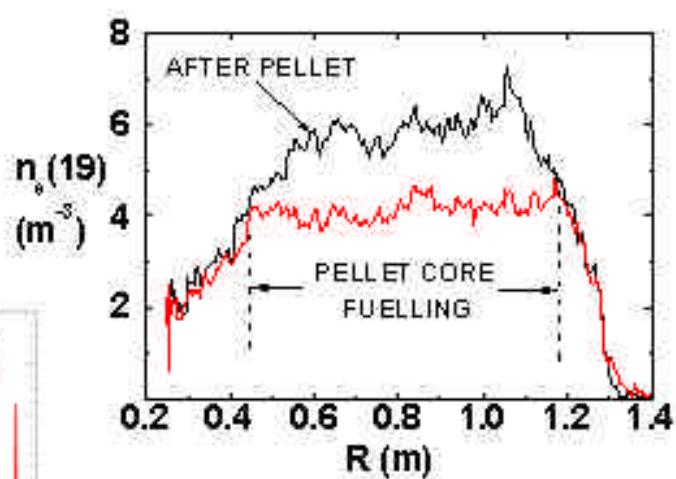
Outboard fuelling



Inboard fuelling

M Gryaznevich, UKAEA/EURATOM Association

**Pellet injection provides
internal fuelling in H-mode:
K Axon, C Ribeiro, S Shibaev**



8-pellet Risø gas gun injector (used on RTP, FOM);
3 pellet sizes: $0.5, 1, 2 \times 10^{20}$ atoms of deuterium
Pellet velocity 300 - 1200 m/s

Initial estimates of fuelling efficiency ~ 50%

Main Results and Questions in Heating & Confinement studies

- H-mode Access
- H-mode Confinement
- Internal Transport Barriers

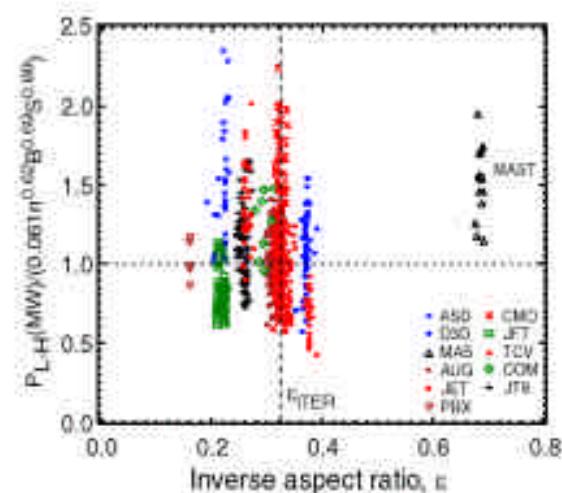
**From START to MAST:
can we achieve good confinement and
high beta simultaneously?**



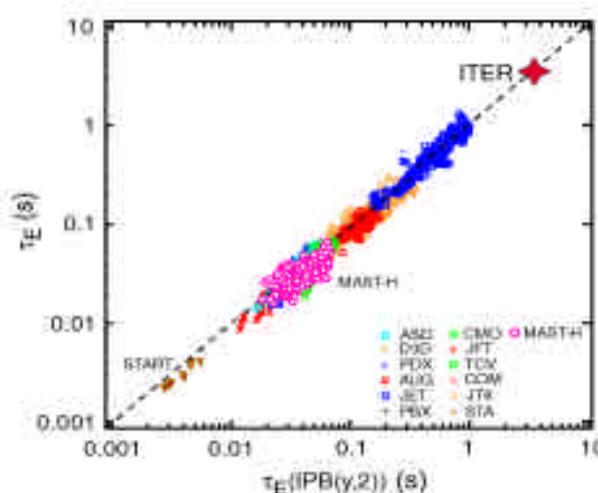
H-mode confinement

Data-sets of power threshold and energy confinement of ELM_y H-mode from MAST have been assembled

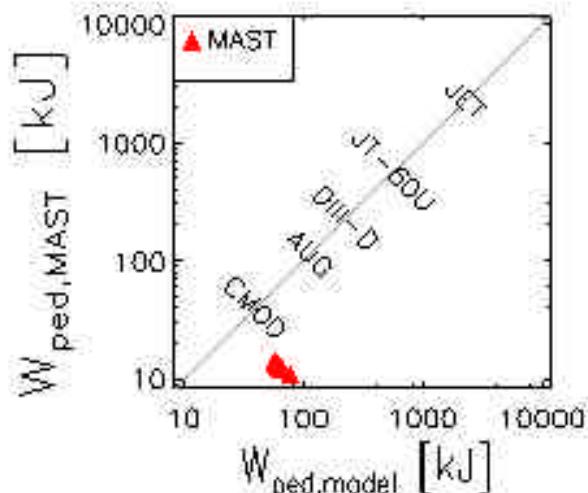
Comparisons with international scalings (at moderate betas) show that:



MAST data is ~ 1.5x above scaling



MAST data agrees with scaling



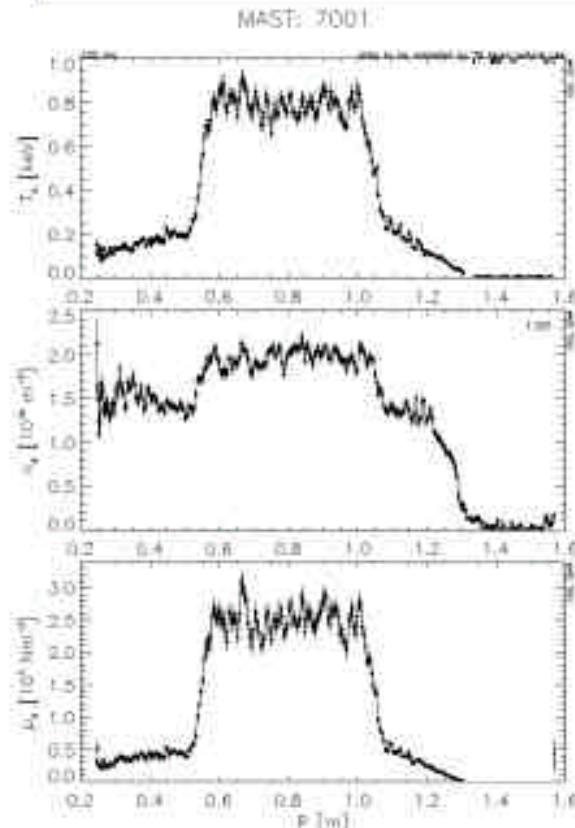
MAST data is much below scaling

- MAST introduces a weak positive ϵ -dependence in the L-H power threshold
- MAST data is consistent with the global IPB98(y,2) scaling but supports a stronger aspect ratio dependence
- MAST indicates a quadratic R/a-dependence for pedestal energy scaling

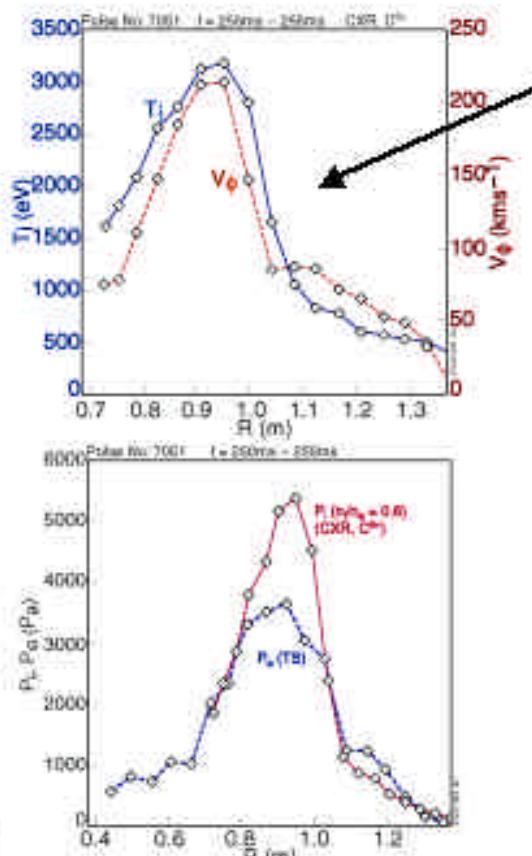


Internal Transport Barriers: Alternative ?

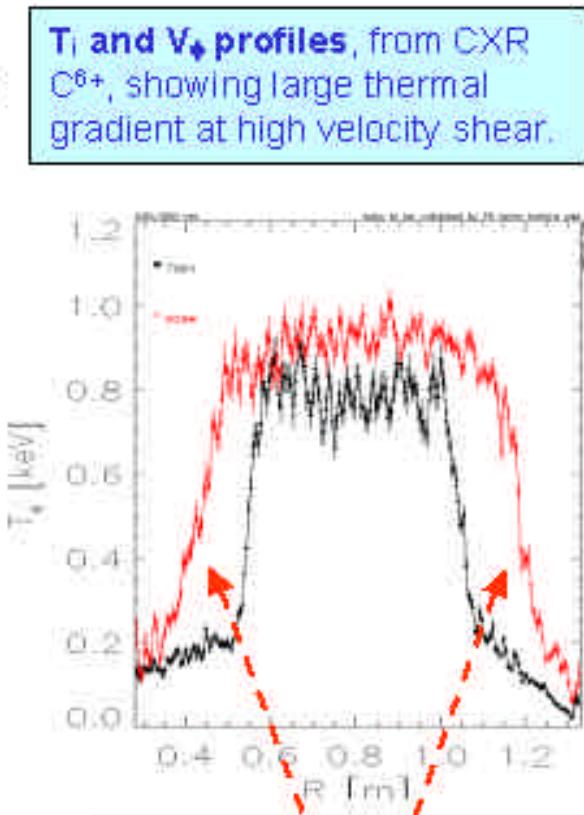
Combination of current ramp and NBI produced steep ion and electron pressure gradients in the plasma core



Electron temperature, density and pressure profiles, showing **very steep gradients**



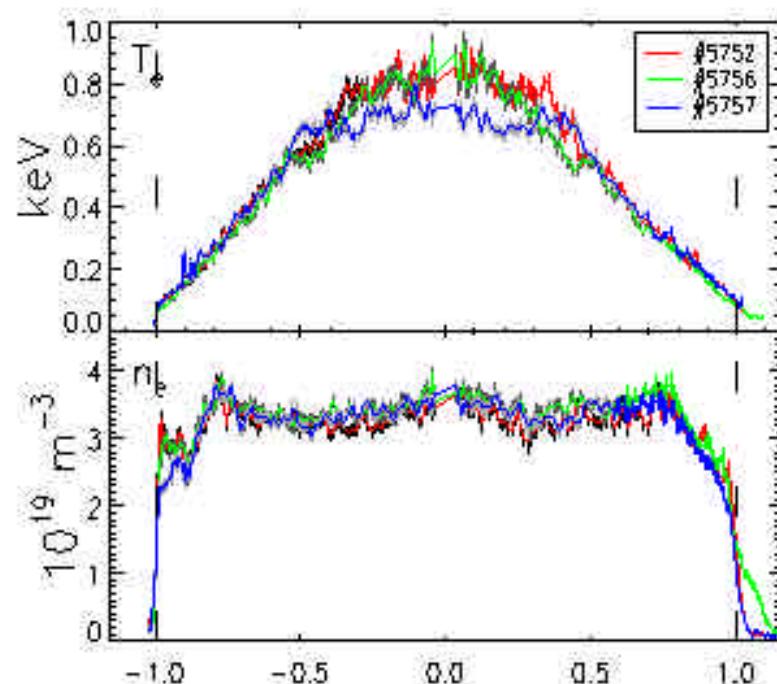
ITB observed both in ions and electrons



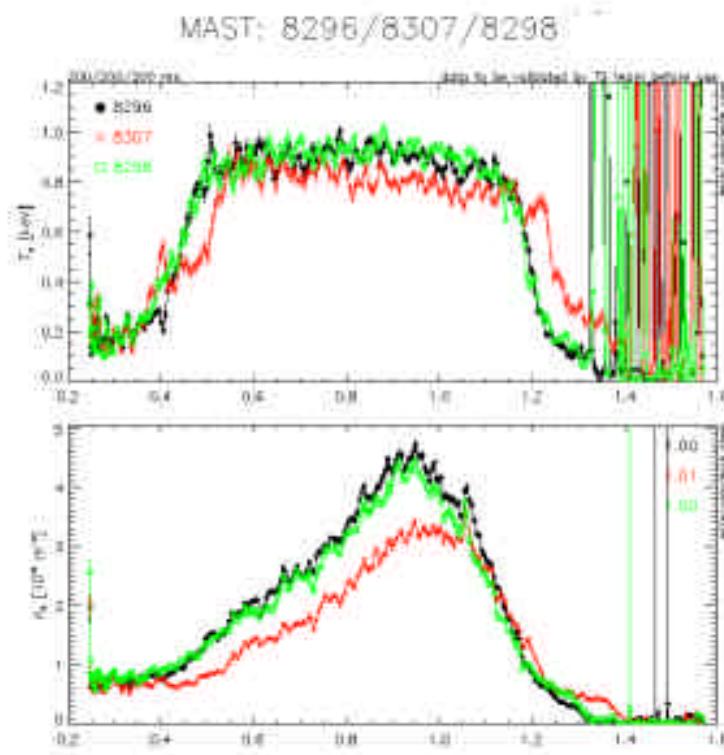
Broader ITBs observed recently



Towards the ST Reactor Operation Point Regime:



Typical H-mode:
peaked T_e , broad n_e



Broad ITB:
broad T_e , peaked n_e

Main Results and Questions in High Beta & Stability

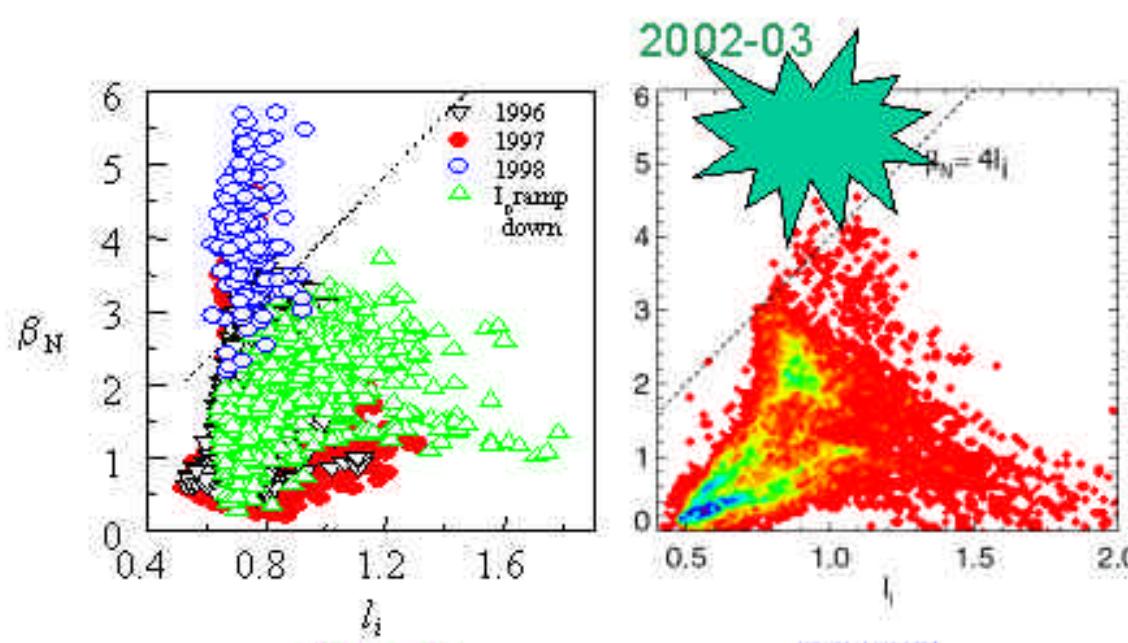
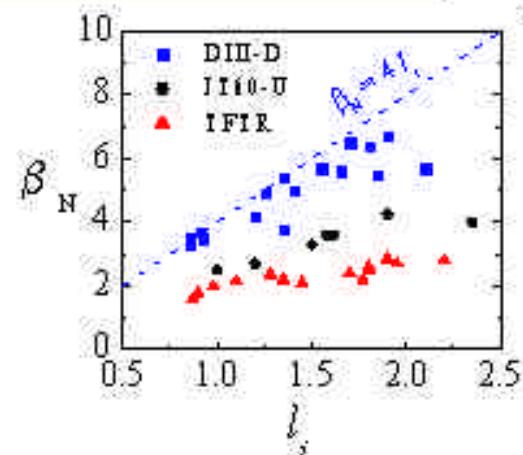
- Good Confinement at High Beta
- Good Stability at High Beta
- Avoidance of Neo-classical Tearing Modes

**From START to MAST:
do we see beta limit, "hard" or "soft"?**



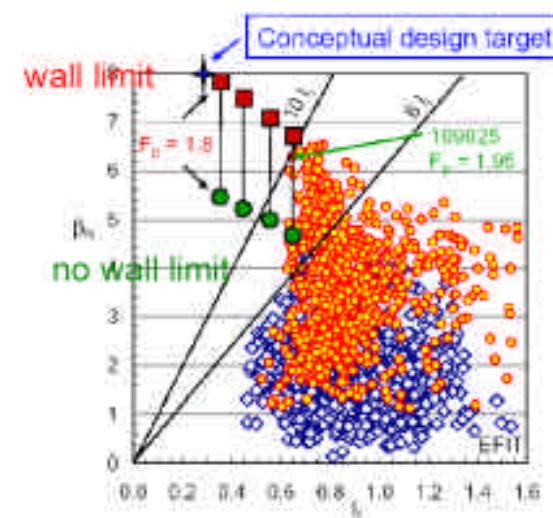
Route to high betas in STs: Limits

Unlike in conventional aspect ratio tokamaks, an empirical $\beta_N \leq 4l_i$ limit has not been justified in STs



START

MAST

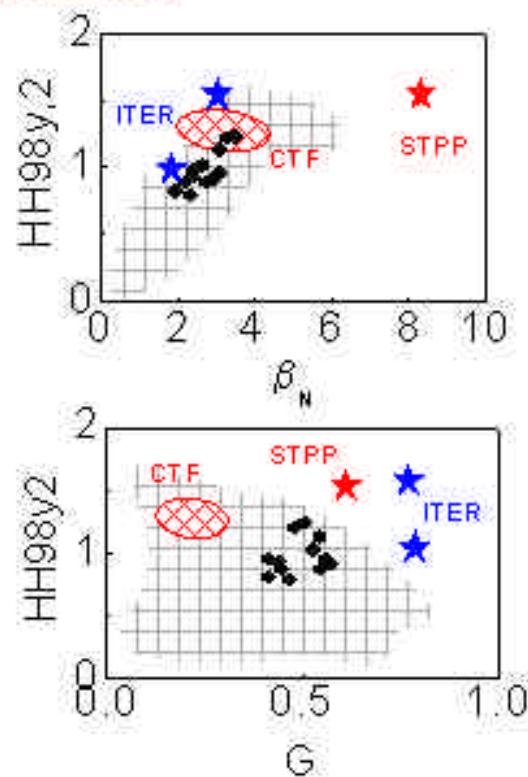
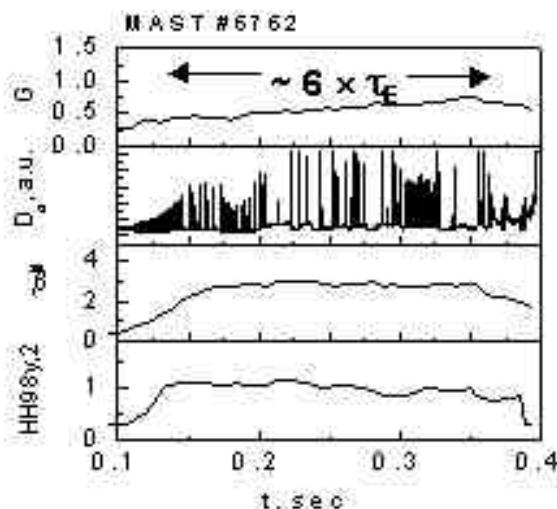
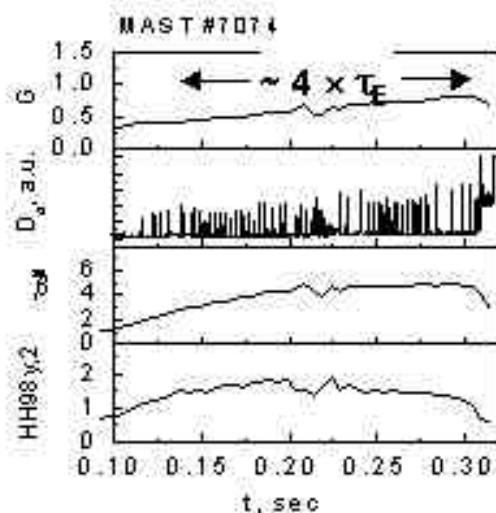


NSTX



Contribution to the baseline ST scenario

High beta sustained for several confinement times:



Many of parameters required for ST Component Test Facility have been achieved simultaneously

However, access to operating point of the ST Power Plant is a challenge for future experiments

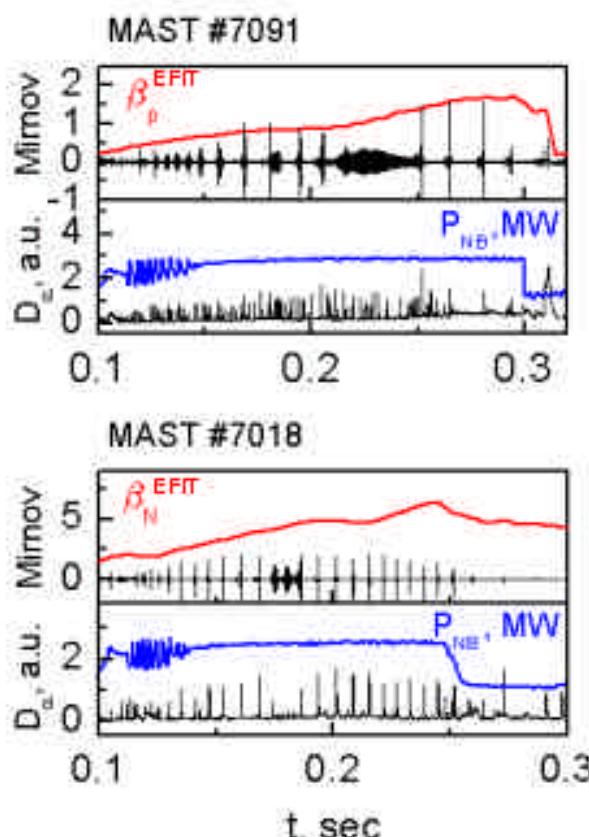
MAST operating space with future ST and ITER parameters (dots - kinetically validated data with low FP component and $-0.05 \leq (dW/dt)/P \leq 0.35$)
H Wilson, M Valovic



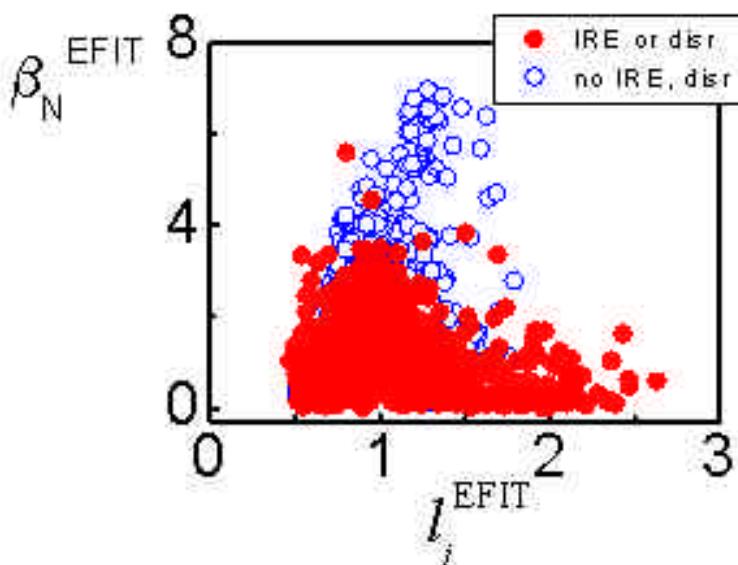
Beta Operating Space

High beta discharges have low MHD activity:

MHD activity is low at high beta:



Highest beta discharges on MAST had no disruption, little MHD and were limited mainly by operational constraints (i.e. position control, NB duration, etc.)



Scope for higher β_N by using less pressure peaked H-mode discharges

Main Results and Questions in SOL, Exhaust & ELMs studies

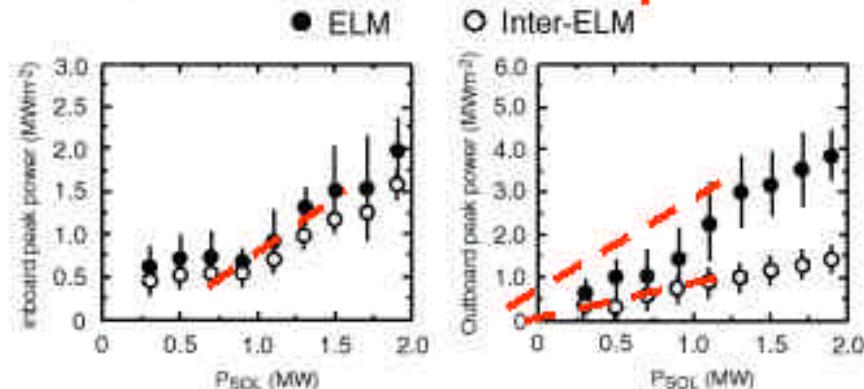
- Divertor Power Loading & ELMs
- Divertor Biasing
- Halo Currents

From START and MAST towards Next Step:
can STPP operate with ELMs in DND?

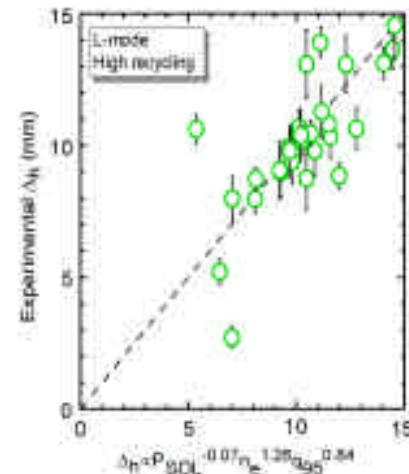


Exhaust in Next Step ST

- ST geometry \Rightarrow most heat goes to the outboard divertor leg (95% in MAST L-mode)
- Power load and SOL width: **Extrapolate from MAST?**



Power load linear with P_{SOL} (justification?)

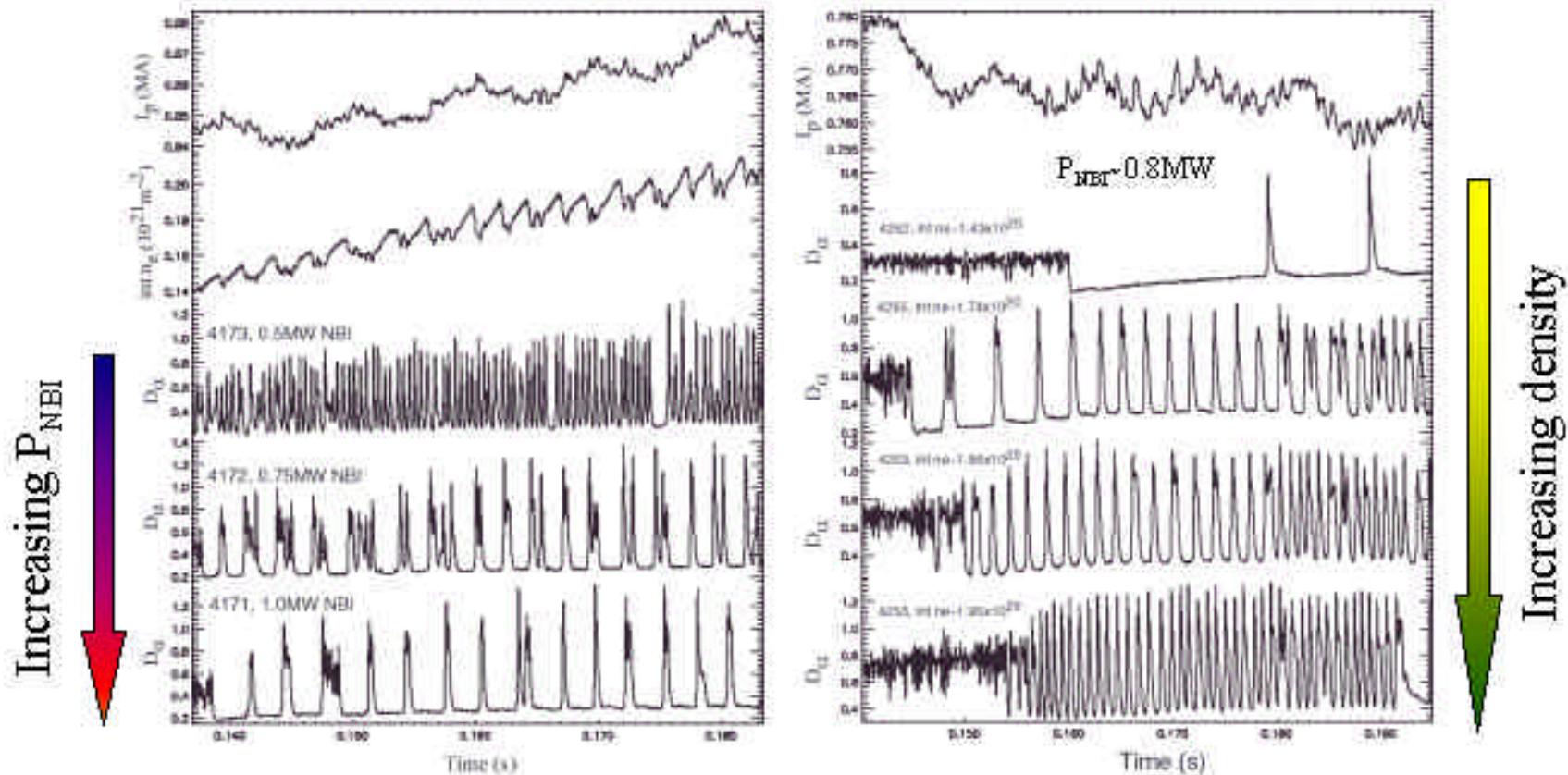


SOL width scaling
(collisionality? dimensionless?)

- Or take a scaling for the SOL width based on resistive interchange mode turbulence:
 - ~28mm (3.3mm) SOL width at outboard (inboard) divertor
 - assume 50% radiated power
 - outboard loading: ~40MWm⁻² (10^0 angling of divertor plate)
 - inboard loading: ~26MWm⁻² (5^0 angling of divertor plate)



Power efflux & impact of ELMs

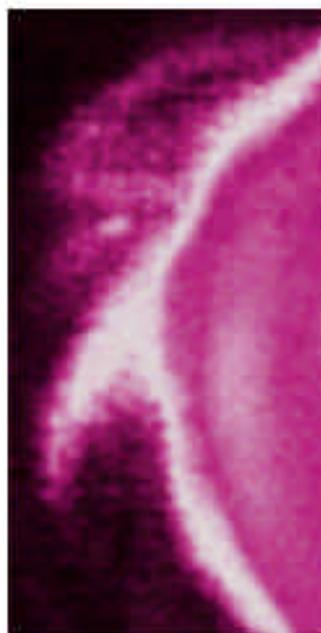


Characteristics of H-mode operation in MAST resemble those of type-III ELMs in conventional aspect ratio devices

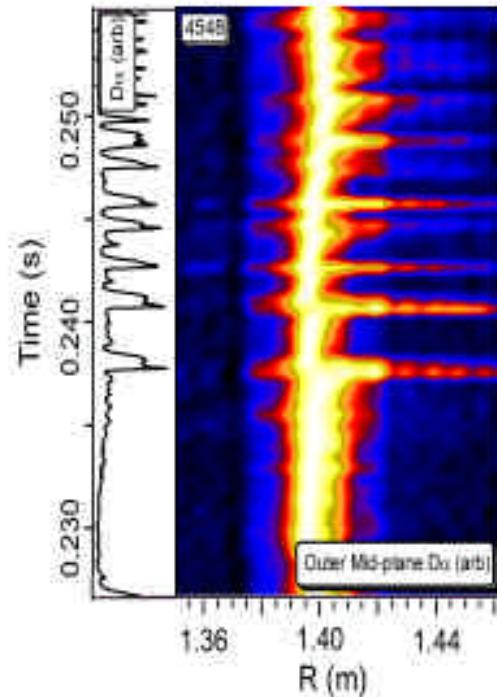


ELM effluxes far into SOL

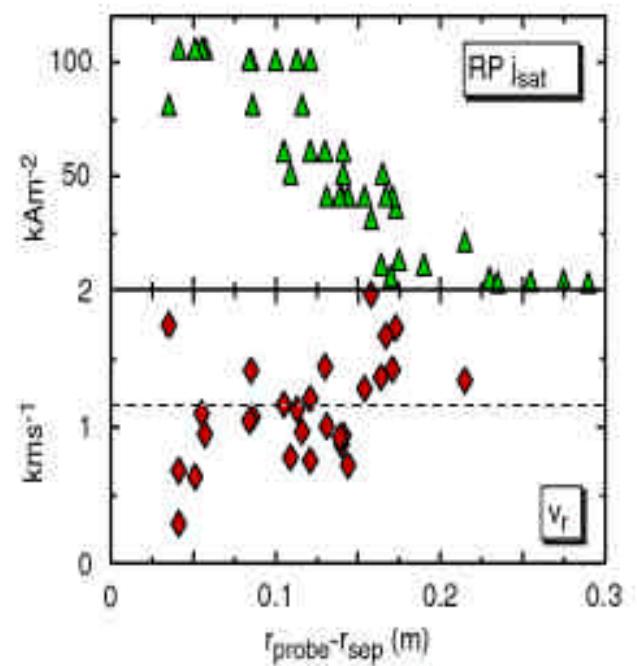
ELM effluxes extend up to 30cm beyond separatrix at outboard side



Plasma edge
on START
(L-mode)



Linear D_α camera
shows outboard
expansion of ELMs

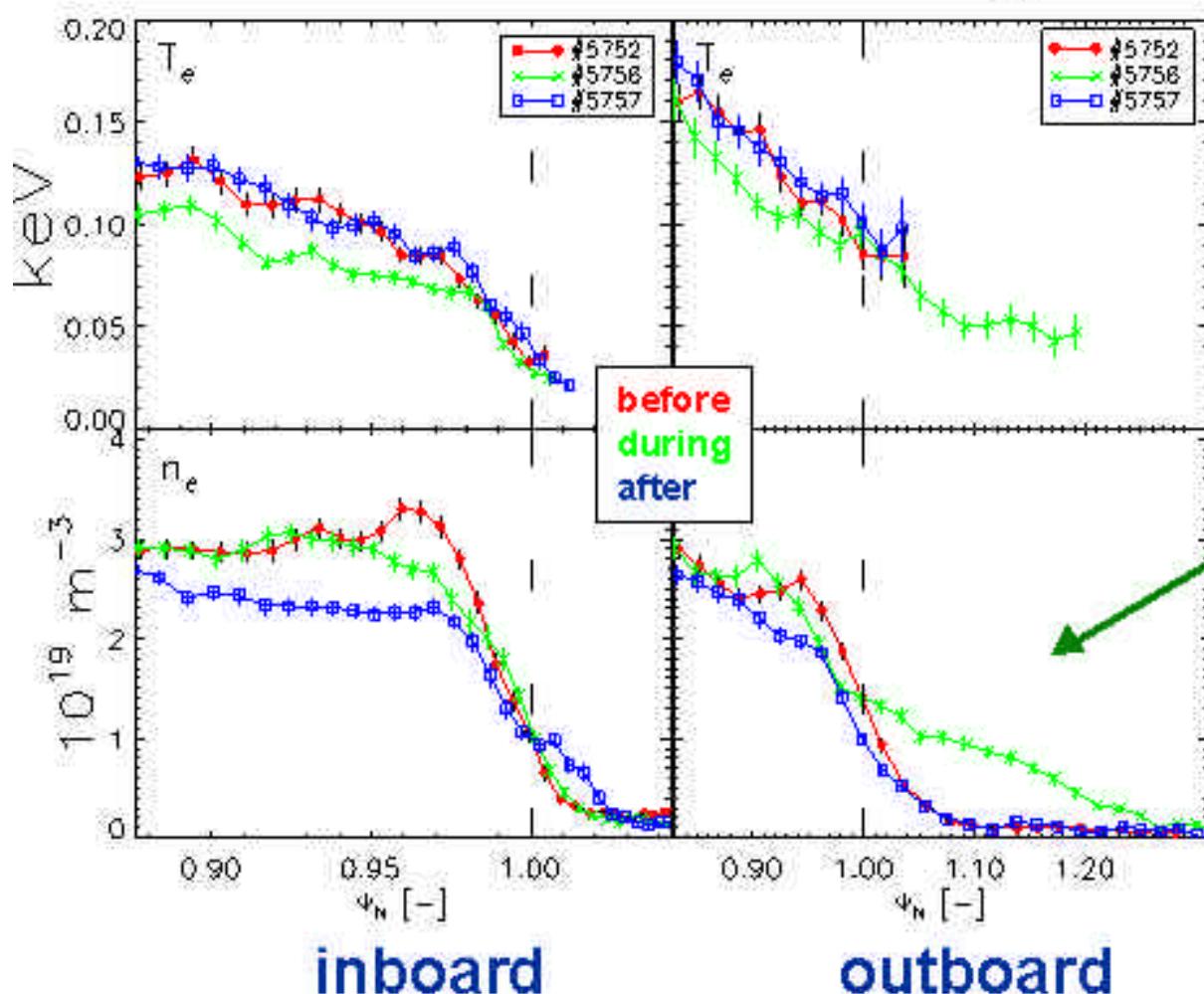


Radial expansion of
outboard localised
structure at $\sim 1\text{km/s}$
"ballistic" mechanism ?



Gradients during ELMs

Three similar H-mode discharges



non-conductive loss:
 $\langle n_e \rangle \Delta T_e \ll \langle T_e \rangle \Delta n_e$

outboard tail during ELM

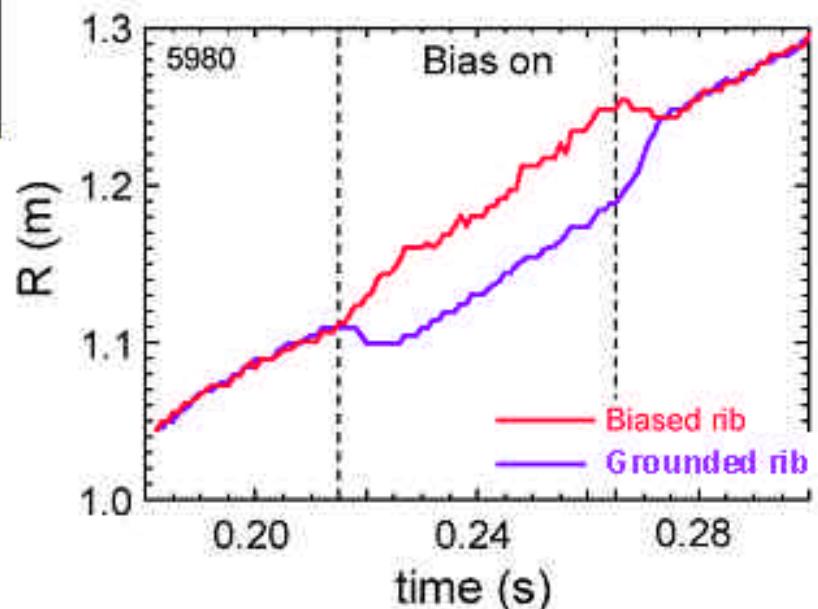
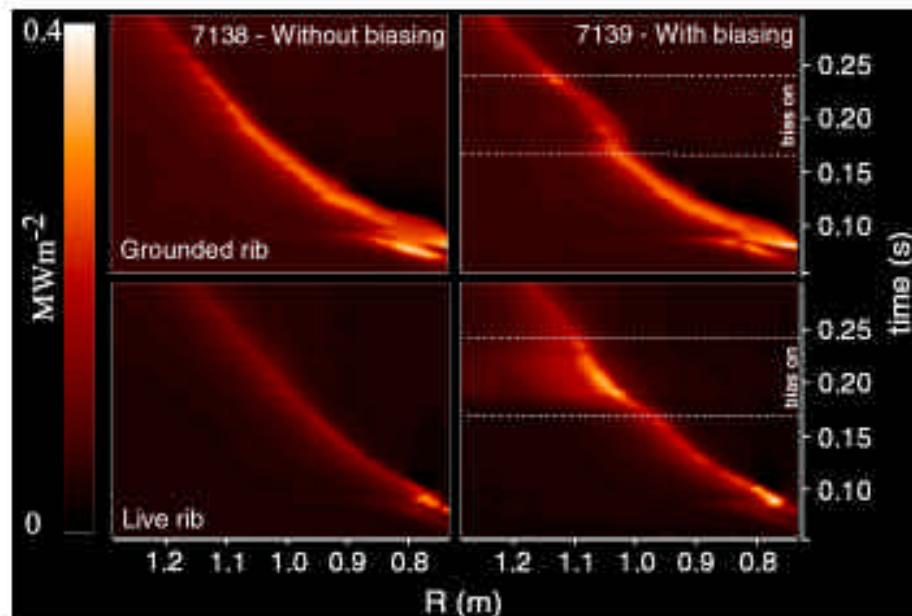
Density and T_e profiles
before and during ELM
show formation of
outboard tail



Toroidally Asymmetric Divertor Biasing

Initial divertor biasing experiments show promising effects

G F Counsell



Strike point movement in accordance with theory

Applications to Next Step using self-biasing of components (different materials, angled tiles etc.)



Main Question still remains:

Is the ST a viable route to fusion?

Main SS issues:
formation
sustainment
exhaust

- Basics of Operational Power Reactor Regime



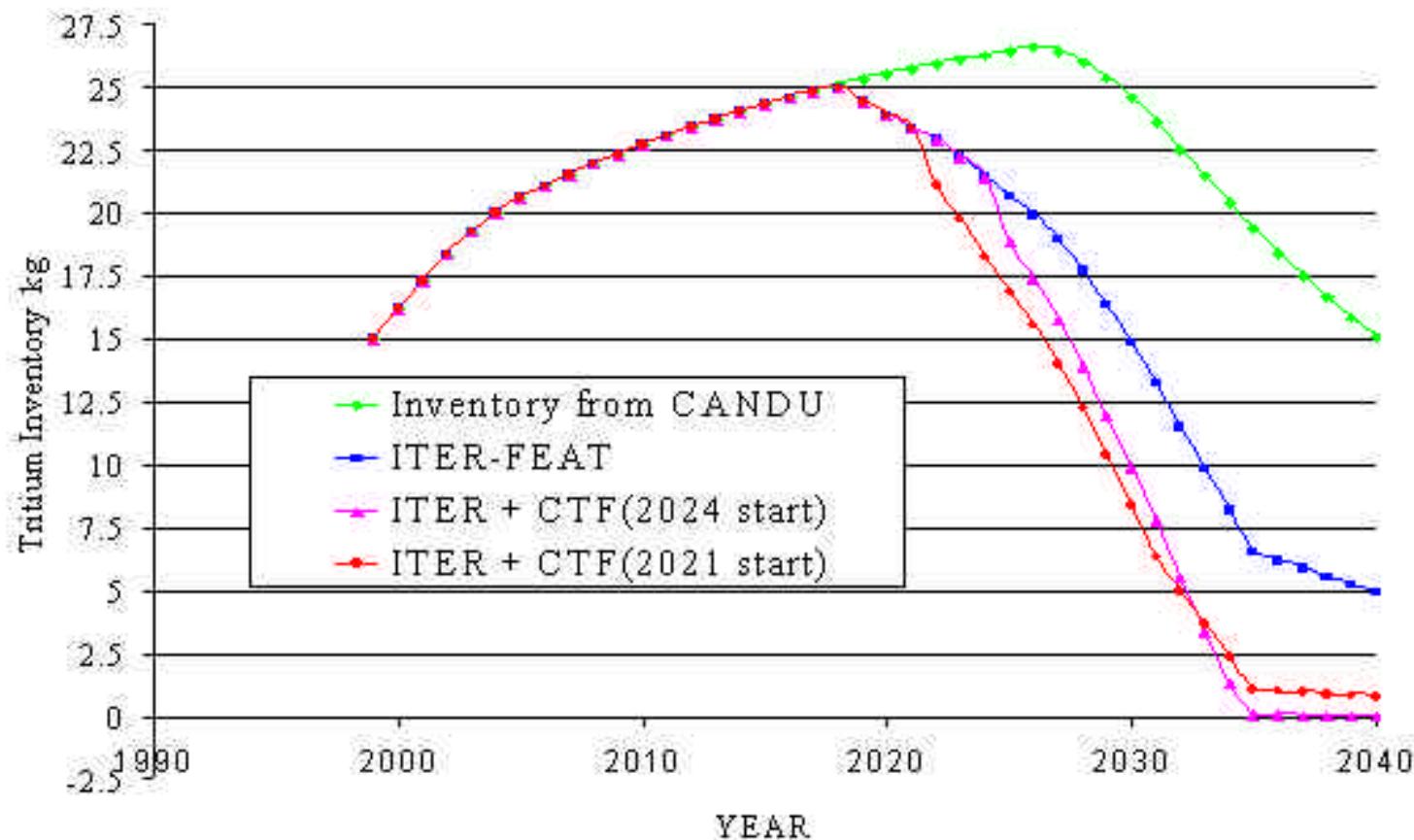
Fuel Resources: Availability of Tritium

The tritium availability can be estimated from the production rate, consumption rate and decay rate with the following assumptions:

- The only significant source of T is from extraction plant at Darlington, Canada.
- Candu reactors shutdown in mid 1990's are not re-started.
- Operation of Candu reactors is not extended beyond 40 year life.
- No further Candu reactors are built.
- No T is available from irradiating T production units in commercial reactors.
- No T is available from military sources.
- ITER-FEAT starts in 2004, 10yrs construction, 20yrs operation.
- CTF operation starts 2024 for 10 yrs, 40MW at 40% availability.



Fuel Resources: Availability of Tritium

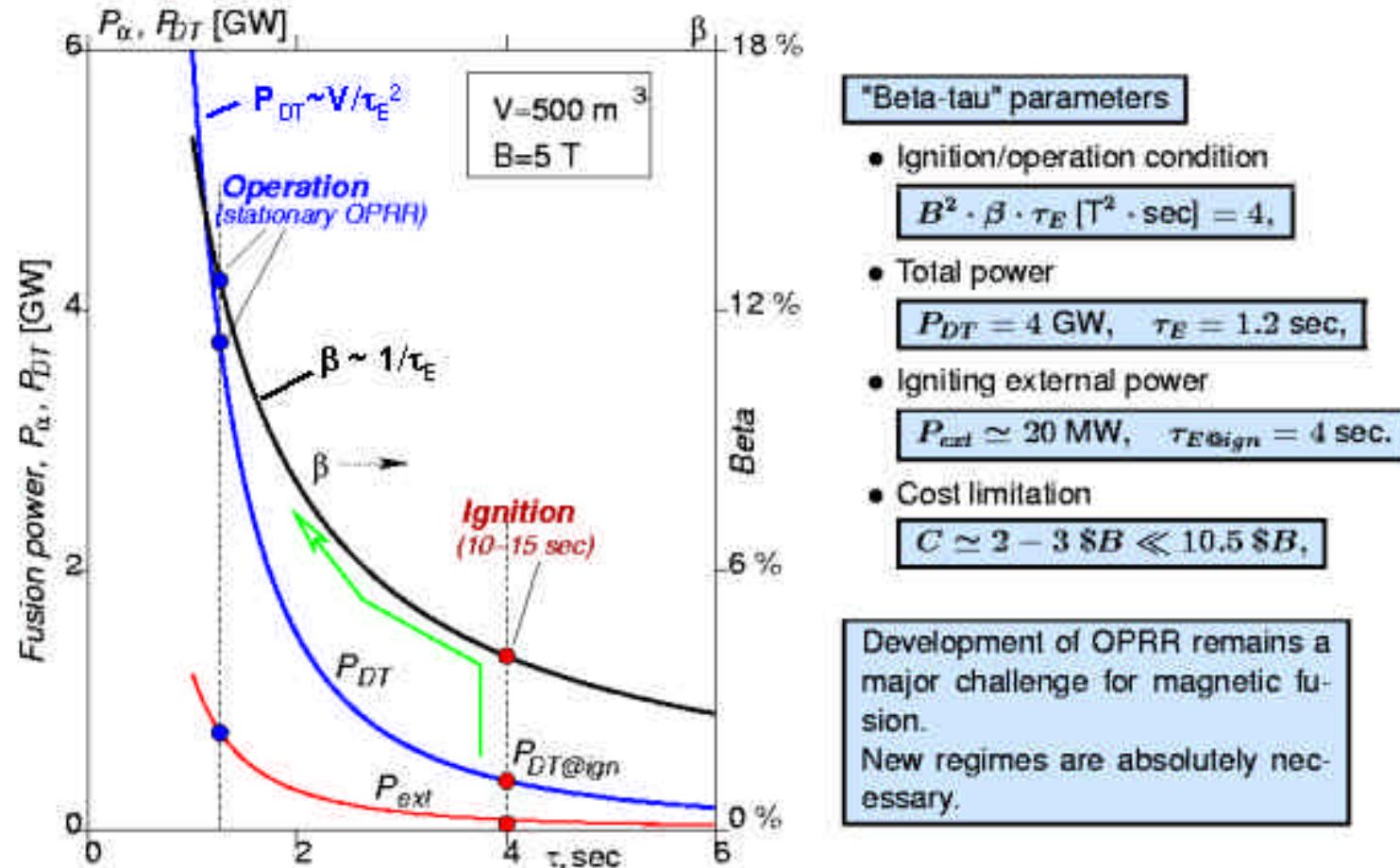


- We need to account for Tritium
- Spherical Tokamak - smaller volume - less fuel!



OPRR and Ignition are two distinct plasma regimes.

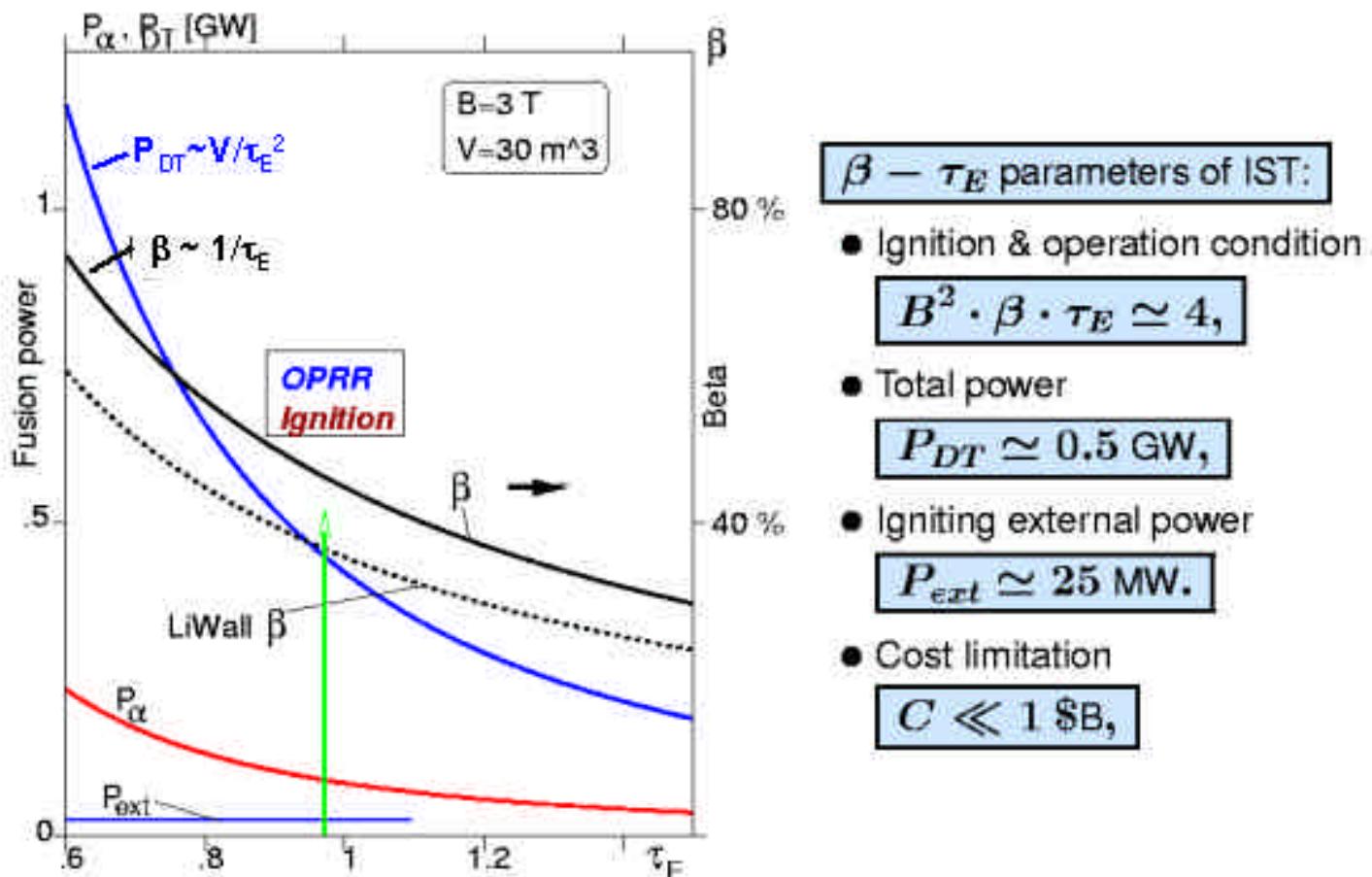
Ignition requires high τ_E , operation requires high β .





Ignited ST is a research mini-reactor

Spherical Tokamaks are unique in merging OPRR and Ignition Phase



Ignited ST is a practical approach for development of OPRR, FW and TC



Conclusion and Plans



e

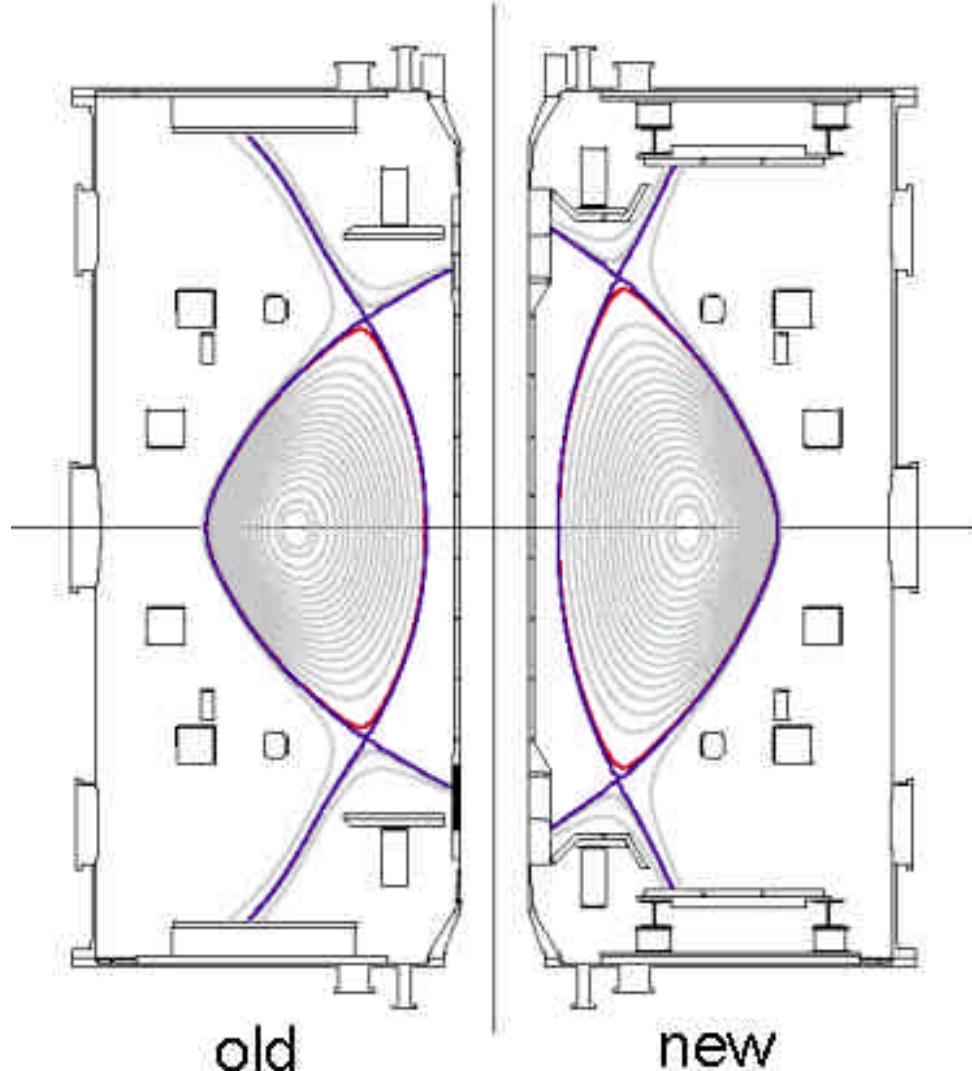
Challenges: understand the new physics of high beta and low aspect ratio and integrate it to expand the limits of ST

What New Physics?

- “Anomalous” ion heating: “too good” ion confinement, $\chi_i < \chi_{neq}$ - do we need revision of neoclassics formulas? ITG suppressed?
- Neoclassics effects when plasma is dominated by trapped particles: bootstrap current, high resistivity, etc.
- Cross-field transport enhanced: role of geometry, rotation
- no-wall limit exceeded without a wall: role of rotation, viscosity, etc.
- Wide AE gaps in ST: does “the quantity” change “the quality”?
- “Disruption resilience” - new look
- Equilibrium: steady-state helical equilibrium observed - consequences?
- RF heating: new opportunities or problems? EBW



2003-2004: MAST Improved Divertor (MID) and new solenoid



The design features:

- Controllable inboard gas puff
- Larger footprint for inner SOL strike points
- Smaller flat section of P2 armour, to ease H-mode access
- Longer solenoid & 10cm higher P2 coils/plates to aid high k studies



Conclusions

MAST data are making important contributions to key physics R & D issues for ITER, as well as helping to establish the viability of the ST concept

Considerable advances in areas relevant to the physics basis for operations in next-step STs (*start-up, current ramp, stability, confinement, current sustainment and exhaust issues*)

Together with the extensive array of high quality diagnostics on MAST, these results provide an excellent platform for further input to key ITER physics studies and issues of specific relevance to the viability of the ST concept