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AUTUMN COLLEGE ON PLASMA PHYSICS

13 October - 7 November 1997

THE SPHERICAL TOKAMAK CONCEPT

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UKAEA Fusion, Abingdon, U.K.

These are lecture notes, intended for distribution to participants.

THE SPHERICAL TOKAMAK CONCEPT

Alan Sykes

ICTP Autumn College on Plasma Physics October 1997

HISTORY

magnetic confinement - pinches - tokamaks - spheromaks - Spherical Tokamaks (STs)

THEORETICAL PROPERTIES OF STs

THE START EXPERIMENT

Overview of START

Summary of results

OTHER STs

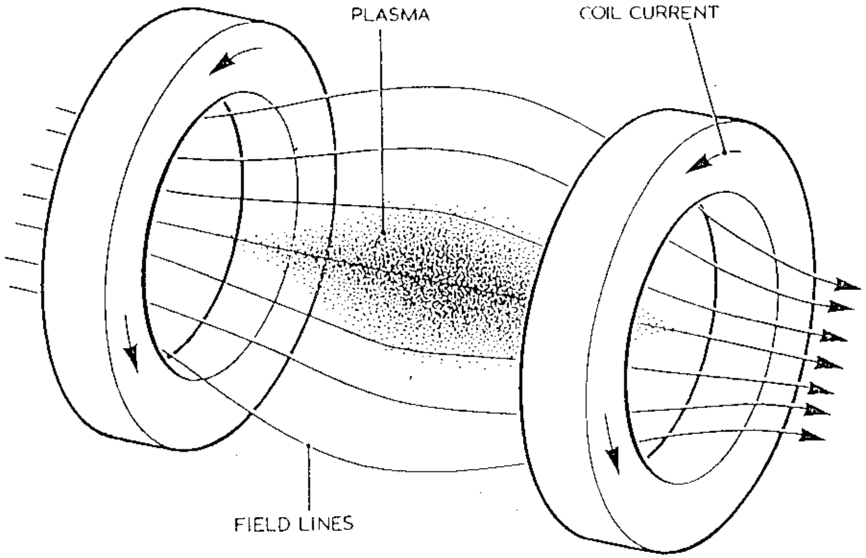
THE FUTURE

- MAST/NSTX; Materials Test Facility?
Power Plant??

UKAEA Fusion

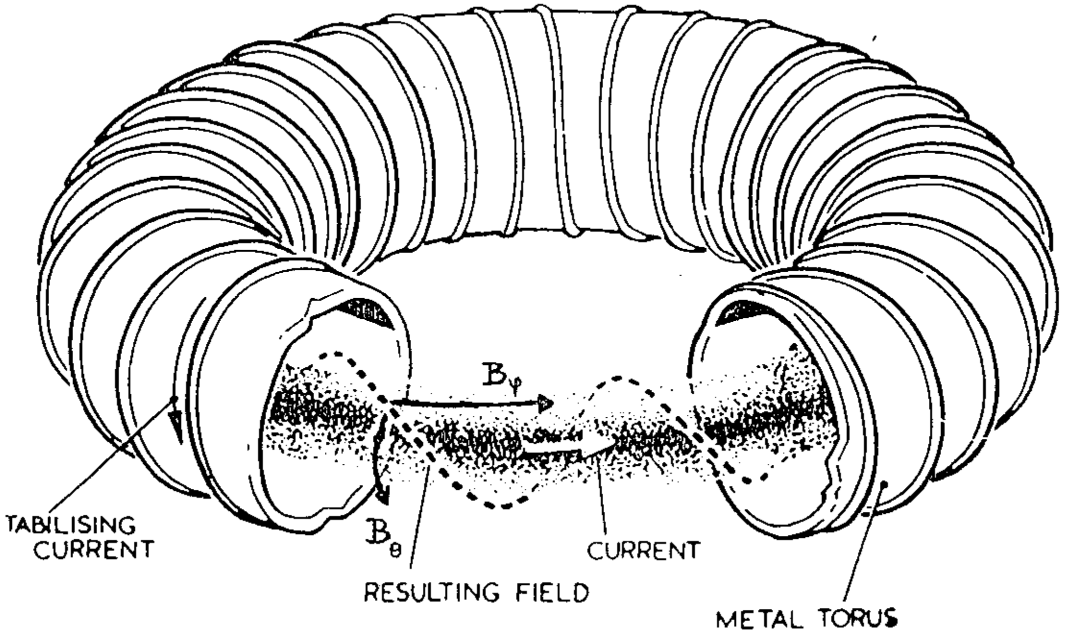
Magnetic Confinement

- to keep the plasma away from walls:
at first, linear pinches or simple mirror devices:



SIMPLE MAGNETIC MIRROR

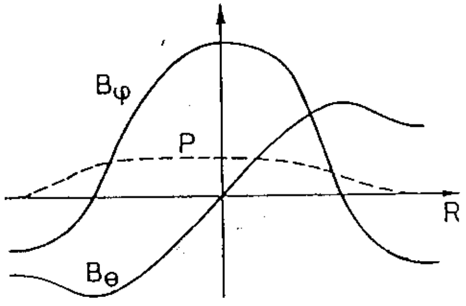
- but some plasma escapes from the ends......



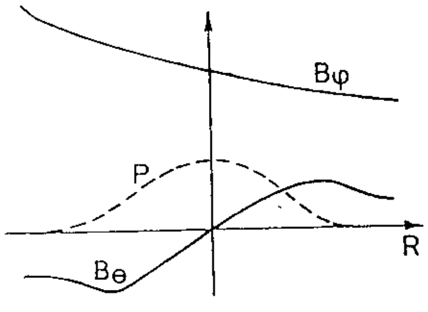
— Toroidal pinch

(a) ZETA mode $|B_\varphi| \approx |B_\theta|$

(b) TOKAMAK mode $|B_\varphi| > |B_\theta|$



REVERSED FIELD PINCH



TOKAMAK

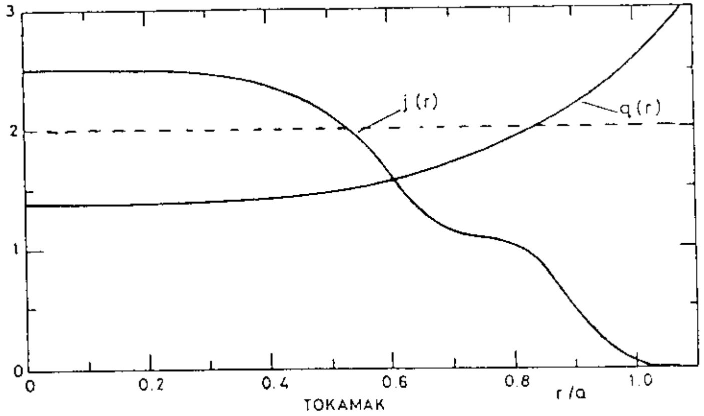
$$\beta \propto \frac{P}{B^2}$$

β large (10 – 30 %)

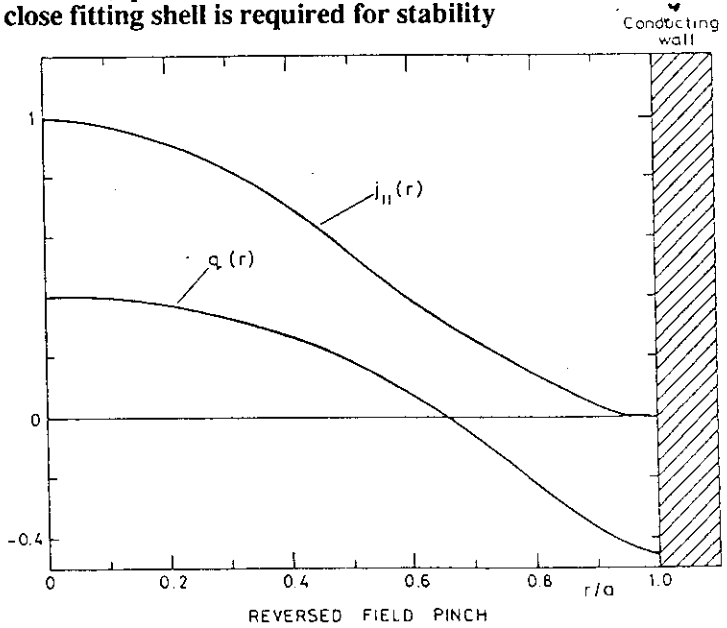
β small (~3%)

Safety factor $q \;\alpha\; \frac{B_T}{B_\theta}$

In a tokamak, (usually) q > 1 and increases outwards:



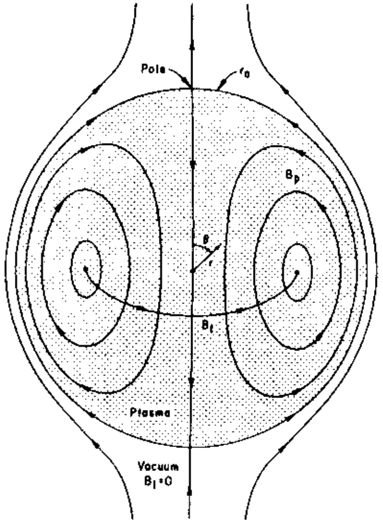
In an RFP, q < 1 and reverses ....
a close fitting shell is required for stability



THE SPHEROMAK (1978)

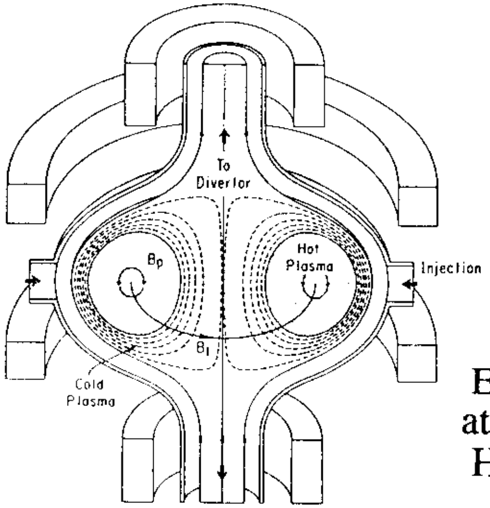
- a tight aspect ratio pinch (no field reversal) with the toroidal field supplied by the plasma alone

Bussac, Furth, Rosenbluth (IAEA Innsbruck 1978)
- connections to Alfven, JBT, Jassby..Ieuan Jones



idealised concept

To make their spheromak (theoretically) stable, they had to squash it...



Reactor proposal

Experiments were begun at Princeton, Los Alomos, Heidelburg, UMIST,......

Unfortunately, spheromak plasmas are generally cold, impure, and prone to tilt and other instabilities.

In 1985 Martin Peng proposed building the STX (Spherical Torus eXperiment) at ORNL..

STX
SPHERICAL TORUS EXPERIMENT

A Feasibility Study for the Spherical Torus Experiment

ORNL/TM-9786

E. A. Lazarus

S. E. Attenberger
L. R. Baylor
S. K. Borowski
R. L. Brown
B. A. Carreras
L. A. Charlton
K. K. Chipley
G. R. Dalton
R. H. Fowler
W. R. Hamilton
T. C. Hender
R. E. Hill
S. P. Hirshman
J. T. Hogan
J. A. Holmes
W. A. Houlberg
S. S. Kalsi
V. D. Lee
P. S. Litherland
D. C. Lousteau
J. N. Luton
J. A. Mayhall
T. J. McManamy
G. H. Neilson
Y-K. M. Peng
J. A. Rome
M. J. Saltmarsh
J. Sheffield
D. J. Strickler
P. B. Thompson
C. C. Tsai
W. L. Wright

In 1986 a convincing summary of the physics changes at tight aspect ratio was published.

FEATURES OF SPHERICAL TORUS PLASMAS*

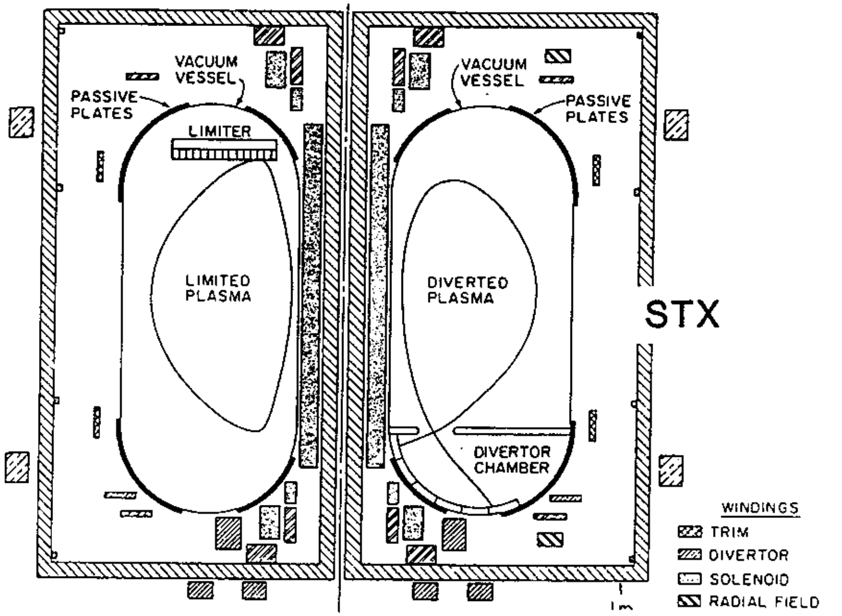
Y-K.M. PENG, D.J. STRICKLER
Oak Ridge National Laboratory,
Oak Ridge, Tennessee,
United States of America

NUCLEAR FUSION, Vol.26, No.6 (1986)

ABSTRACT. The spherical torus is a very small aspect ratio ($A < 2$) confinement concept obtained by retaining only the indispensable components, such as the toroidal field coils, inboard to the plasma torus. MHD equilibrium calculations show that spherical torus plasmas with an edge safety factor $q_a > 2$ are characterized by high toroidal beta ($\beta_t > 0.2$), low poloidal beta ($\beta_p < 0.3$), naturally large elongation ($\kappa \cong 2$), large plasma current with $I_p/(aB_{t0})$ up to about 7 MA$\cdot$mT^{-1}, strong paramagnetism ($B_t/B_{t0} > 1.5$), and strong magnetic helical pitch (Θ comparable to F). A large near-omnigeneous region is seen in the large major radius, bad curvature region of the plasma in comparison with the conventional tokamaks. These features combine to engender the spherical torus plasma in a unique physics regime which permits compact fusion at low field and modest cost. Because of its strong paramagnetism and helical pitch, the spherical torus plasma shares some of the desirable features of spheromak and reversed-field pinch (RFP) plasmas, but with tokamak-like confinement and safety factor q. The general class of spherical tori, which includes the spherical tokamak ($q > 1$), the spherical pinch ($1 > q > 0$), and the spherical RFP ($q < 0$), have magnetic field configurations unique in comparison with conventional tokamaks and RFPs.

History of the 'Spherical Tokamak'

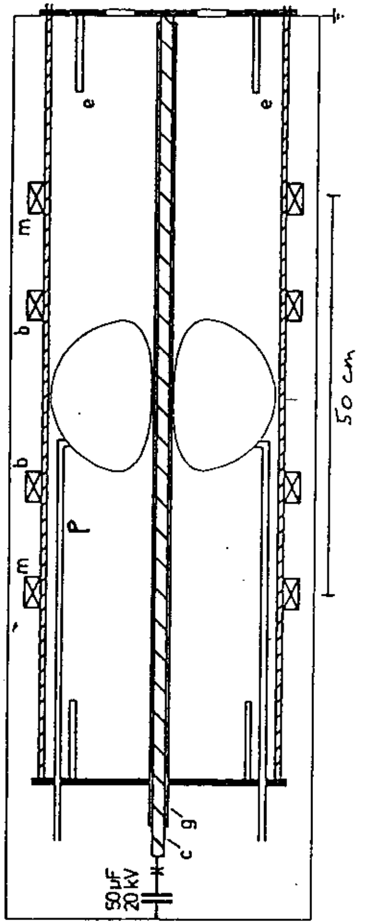
- advocated by Y-K Martin Peng (ORNL) in 1985
- Spherical Tokamak eXperiment (STX) proposed in 1987



PARAMETERS	PERFORMANCE
$R_0 = .45\ m$	$T_e(0) \approx 1\ keV$
$a_0 = .27\ m$	$T_i(0) \approx 1\ keV$
$\kappa \approx 2$	$\bar{n}_e \approx 1 \cdot 10^{20}\ m^{-3}$
$\delta \approx 0.4$	$\langle\beta\rangle \approx 20\ \%$
	(transport and stability)
$B_t = 0.5\ T$	$\beta_p \approx 0.36$
I_p *up to 900 kA*	$q_\psi = 3.5$

- Culham Working Party advocated low A in 1987
- STX abandoned in 1988
- Robinson & Todd design START at Culham
- First plasma in START, January 1991

HEIDELBERG SPHEROMAK EXPERIMENT + TF ROD (HEIDELBERG, GERMANY)



Parameters achieved with 40kA rod current

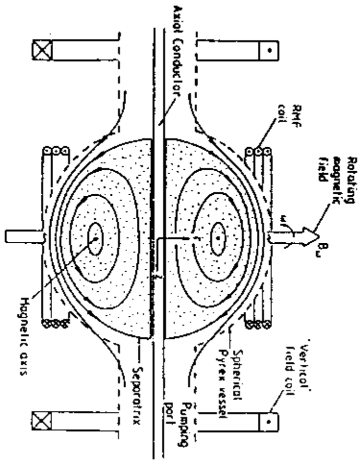
R_0 = 0.07m   a = 0.06m   A = 1.1

I_p = 100kA   t = 0.06ms B_{To} = 0.07T

T_{eo} ~ 20eV

Ref: H Bruhns et al, Nuclear Fusion 27 (1987) 2178

ROTAMAK + TF, LUCAS HEIGHTS AUSTRALIA 1987



R_o = 0.07m   a = 0.064m   A = 1.1

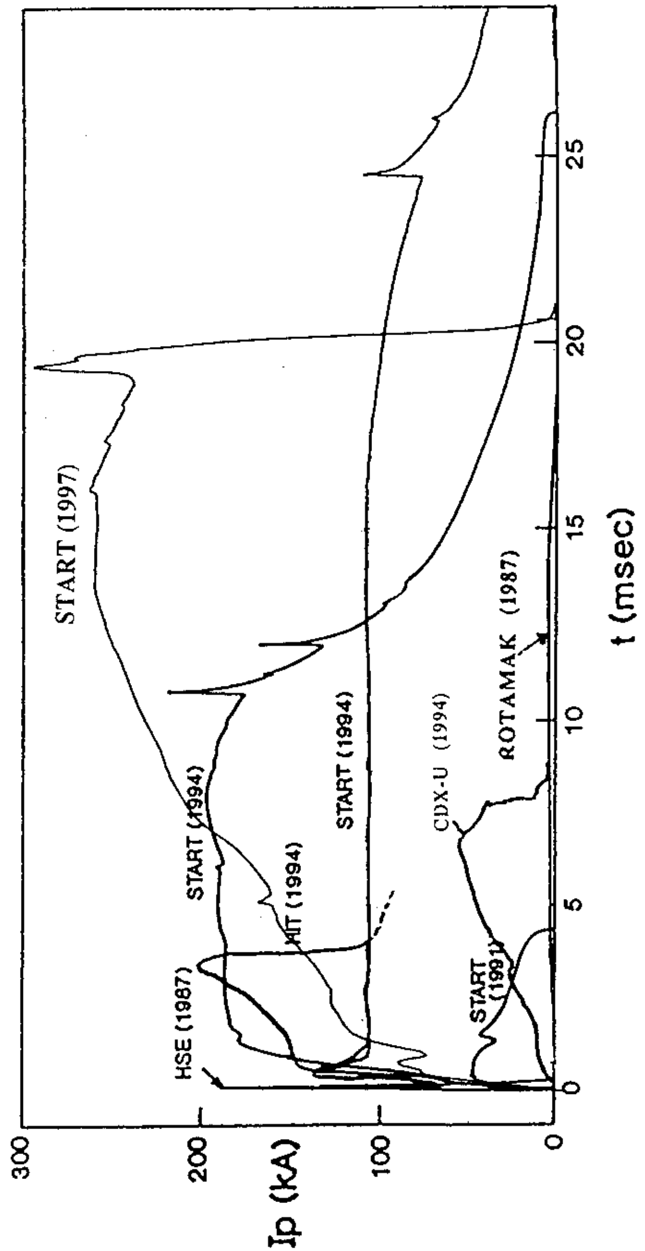
I_p ~ 3kA   t = 20ms B_{To} = 0.02T

$n_{co} \sim 1 \times 10^{19} m^{-3}$ τ ~ 0.005ms

Ref: G A Collins et al, Nuclear Fusion 28 (1988) p255

(same scale)

PROGRESS IN ST DISCHARGES
1987 - PRESENT

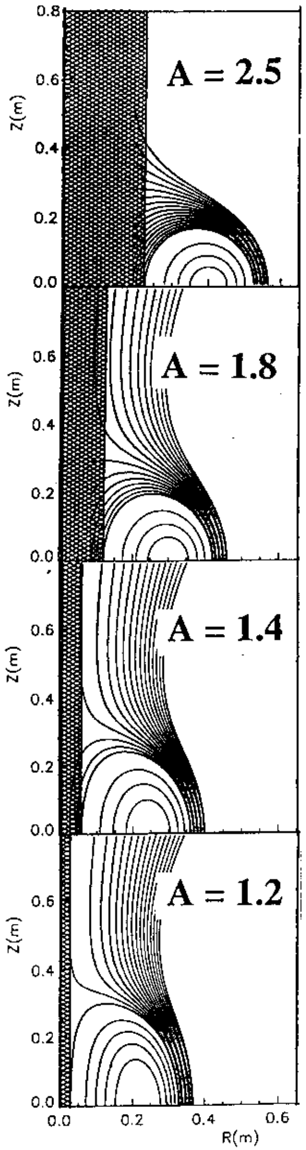


CHANGES IN PHYSICS BEHAVIOUR EXPECTED AT LOW-A

- natural elongation and D-shaping
- high magnetic shear
- trapping raises Ohmic Heating
- trapping affects transport
- bootstrap current - increase or decrease?
- effect on MHD of high toroidicity and high shear: small islands? mode coupling? stabilisation?

Properties of low aspect ratio equilibria

In each example minor radius = 0.15m, and qo ~ 1, qa ~ 8
The vertical field is approximately uniform
Ip chosen to increase with 1/A



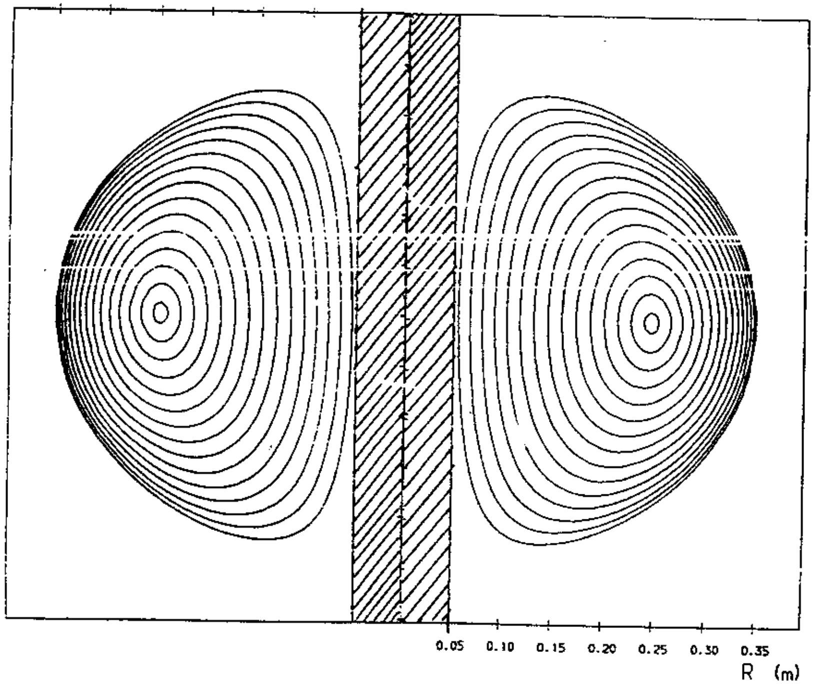
A	I_p (kA)	B_{To}(T)	k	q_ψ	q_{cyl}
2.5	120	1.89	1.1	8.2	5.2
1.8	166	1.22	1.3	8.2	4.0
1.4	214	0.54	1.6	8.2	2.1
1.2	250	0.17	2.0	8.7	0.9

Note that, as aspect ratio is reduced from 2.5 to 1.2:

- **elongation increases naturally from 1.1 to 2.**
- **fraction of exhaust hitting limiter falls from 100% to 1%**
- **Toroidal field required to achieve same q_a for given I_p falls by factor 20.**

HIGH SHEAR AT LOW-A

THE SHEAR IS VERY HIGH, EVEN FOR FLATTISH CURRENT PROFILES: IN THIS MODEL OF THE FLAT-TOP **START** SHOTS, $q_0 = 1.9$ and $q^* = 3.6$, but $q_\omega = 15.2$

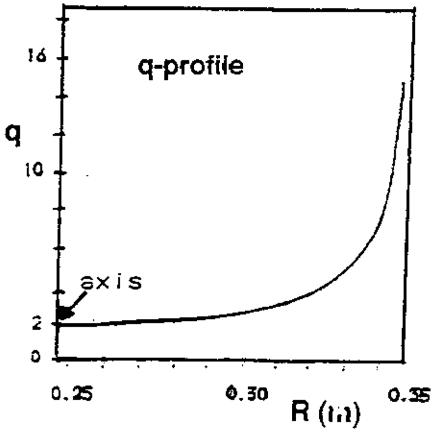


R = 0.20m
a = 0.15m
b = 0.22m

$A = 1.33$
$\kappa = 1.47$

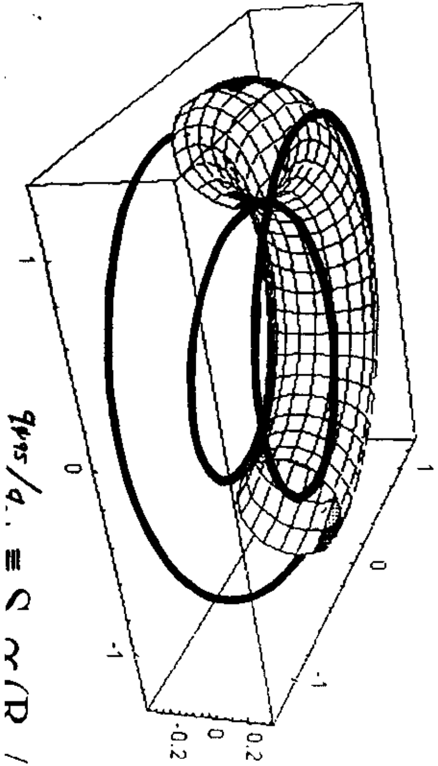
Irod = 480kA
Ip = 100kA

$q_0 = 1.9$
$q_\omega = 15.2$
$q^* = 3.6$



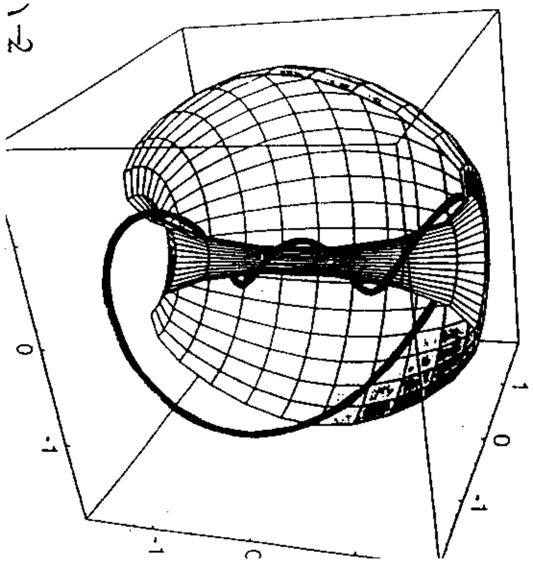
$$\beta_c = \frac{3.5\ I}{a\ B} \sim 4\%$$

Magnetic Field Lines Become Longer in the Stable Region as A is Reduced



A = 3, q = 3

$q_{95}/q_{\cdot} \equiv S \simeq (R\ /a\ - 1)^2$

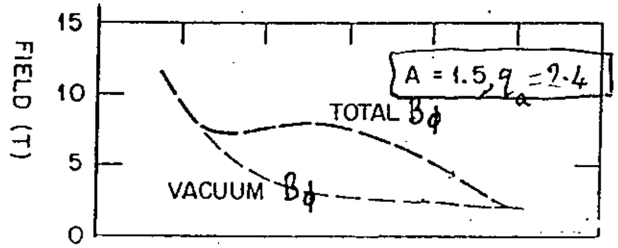


A = 1.25, q = 3

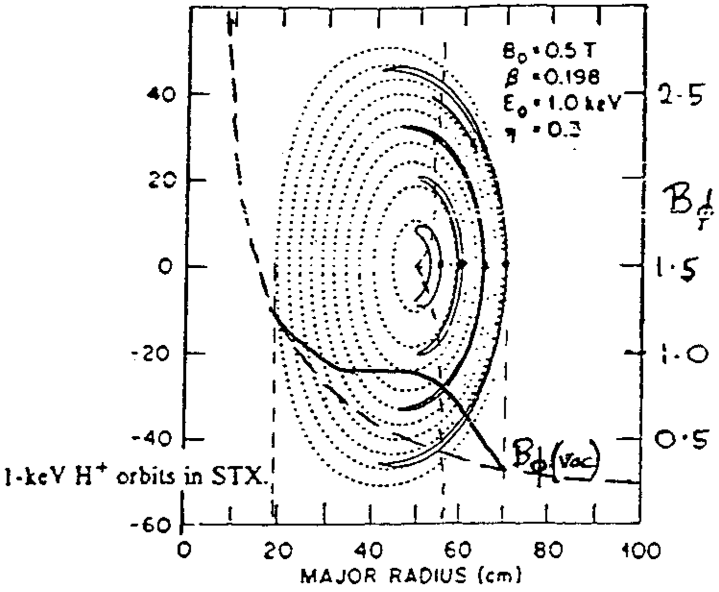
PARAMAGNETISM, PARTICLE TRAPPING AND TRANSPORT

The paramagnetic effect is the increase in toroidal field above the vacuum field.

This can be large at low-aspect-ratio, especially for large Ip / Irod:

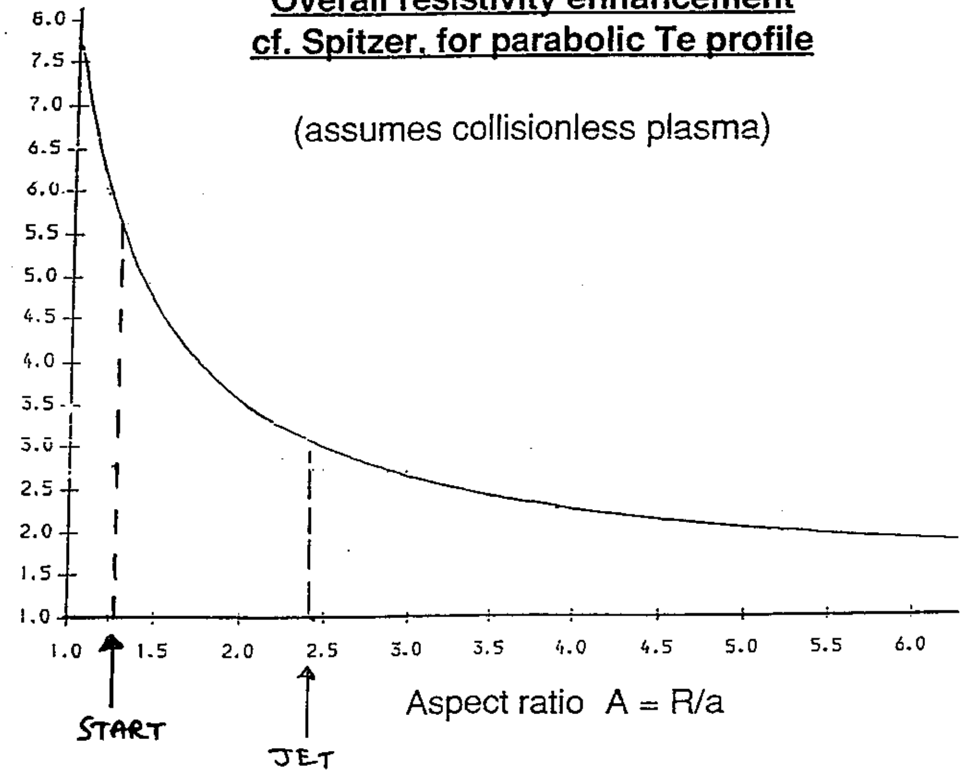


This paramagnetism can lead to the 'omnegeneic effect', in which the |B| contours are nearly parallel to the flux surfaces in the part of the outboard region shown shaded:



This is predicted to produce very narrow banana orbits, and hence confinement may be better than the high fraction of

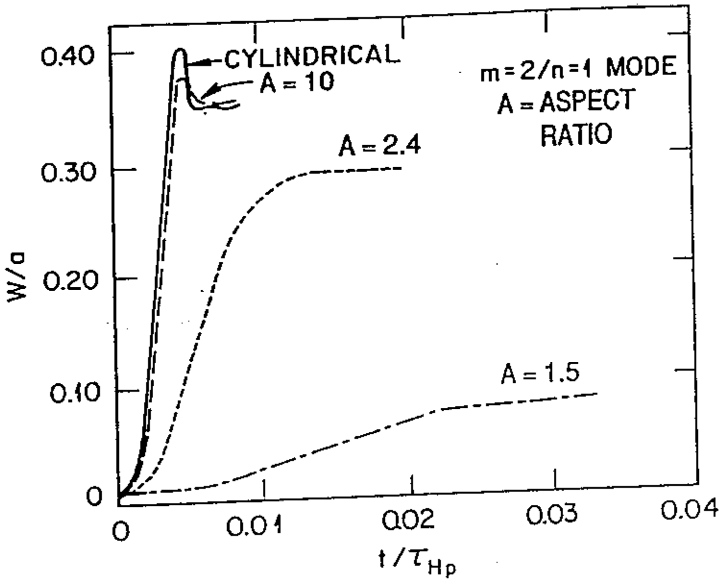
Due to trapping, Ohmic Heating Increases at Low Aspect Ratio

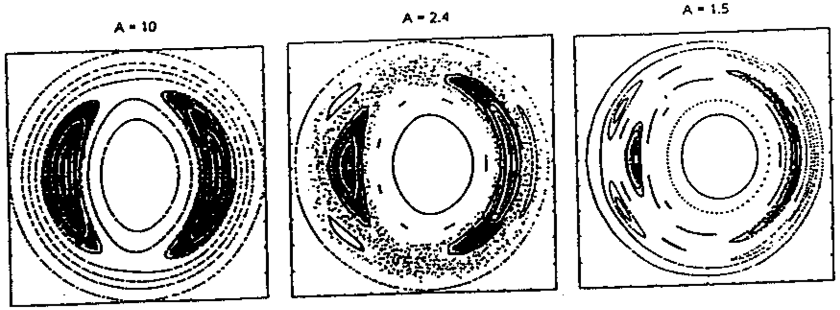


Overall resistivity enhancement cf. Spitzer, for parabolic Te profile

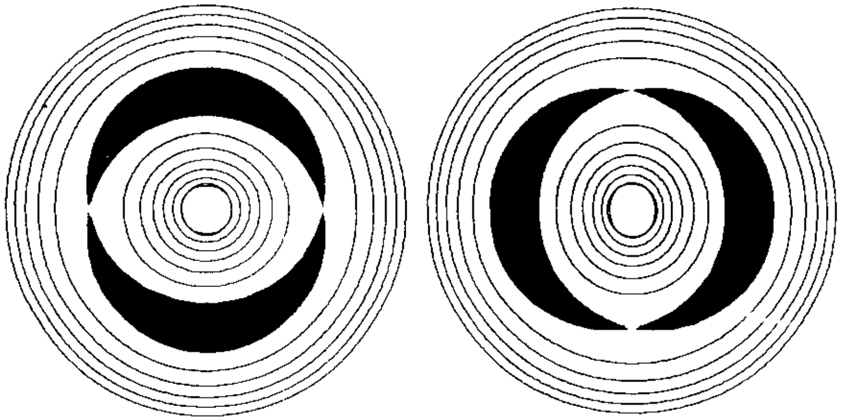
(assumes collisionless plasma)

Island Widths Narrow at Low Aspect Ratio

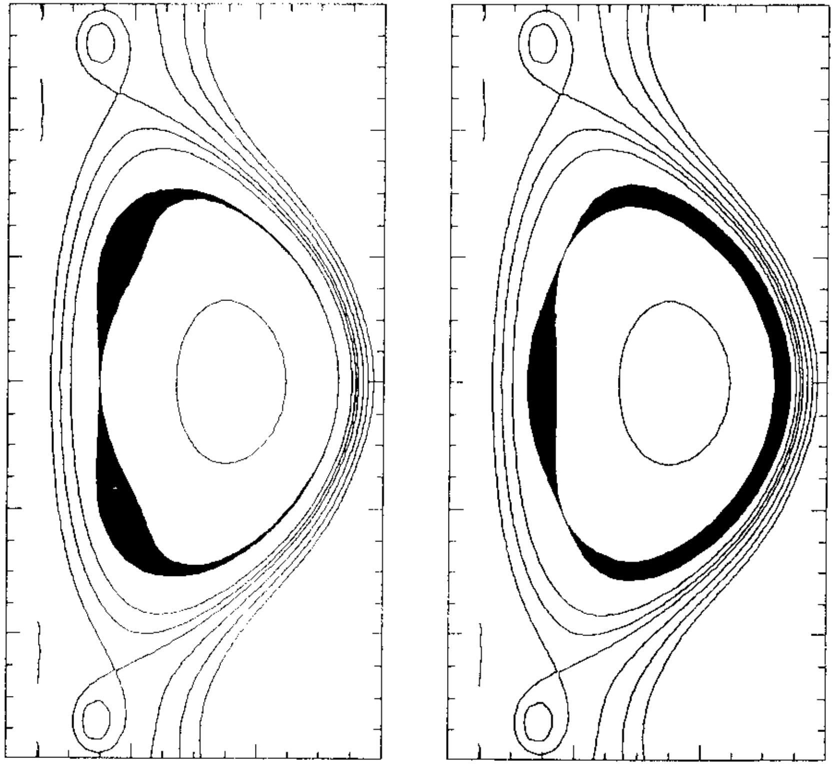




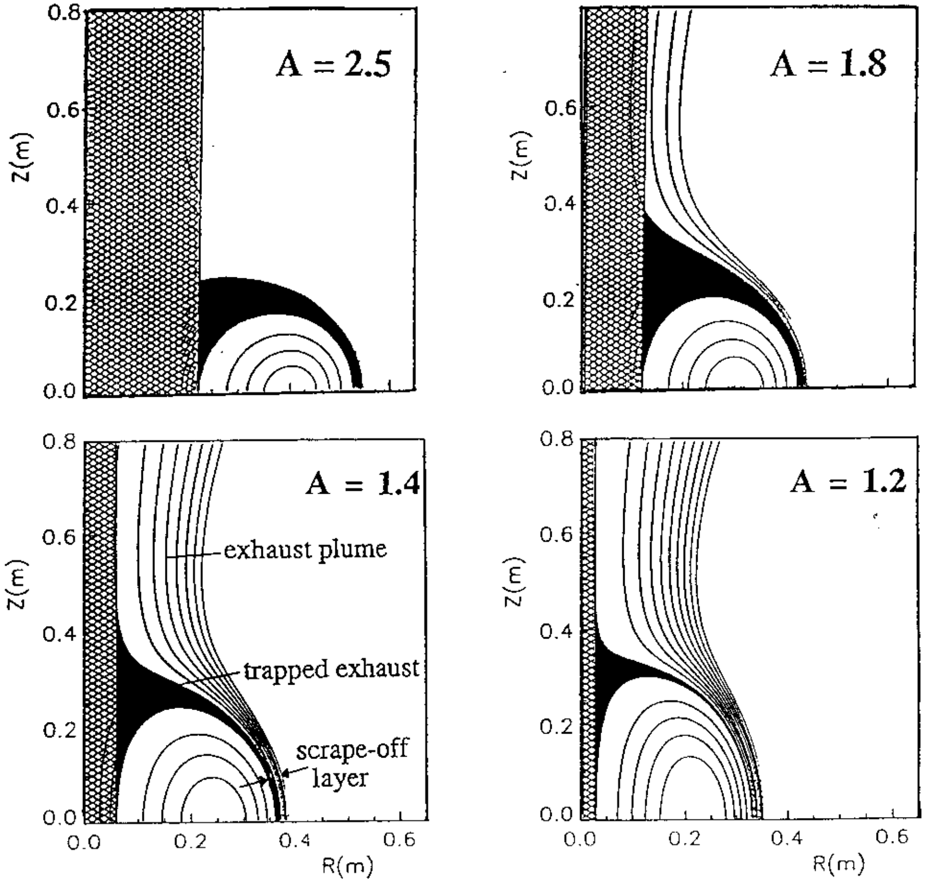
Cylindrical m=2 islands



START m=2 islands



At low aspect ratio, a substantial fraction of the scrape-off-layer (SOL) escapes interaction with the limiter, and forms an exhaust plume



Construction of START 1989-90

To test out the 'spherical tokamak' concept, START was designed in 1988 by Tom Todd and Derek Robinson using spare equipment.

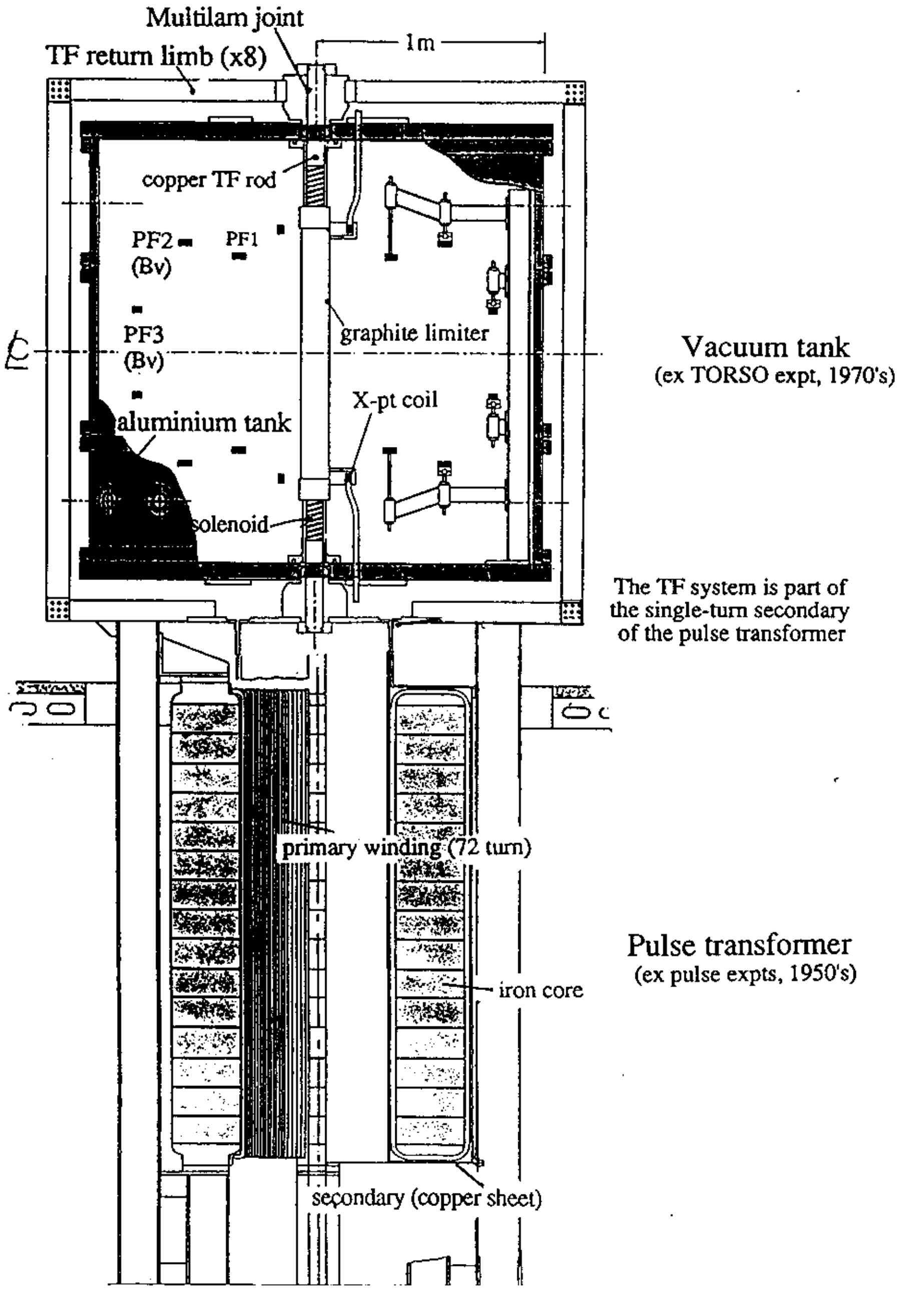
Two novel features were used:

(1) A copper centre rod which was part of the single-turn secondary of a large pulse transformer;

(2) the current was induced around two coils at large radius, then compressed into the required ST configuration.

First plasma was obtained in January 1991

START GENERAL LAYOUT, SEPTEMBER 1995



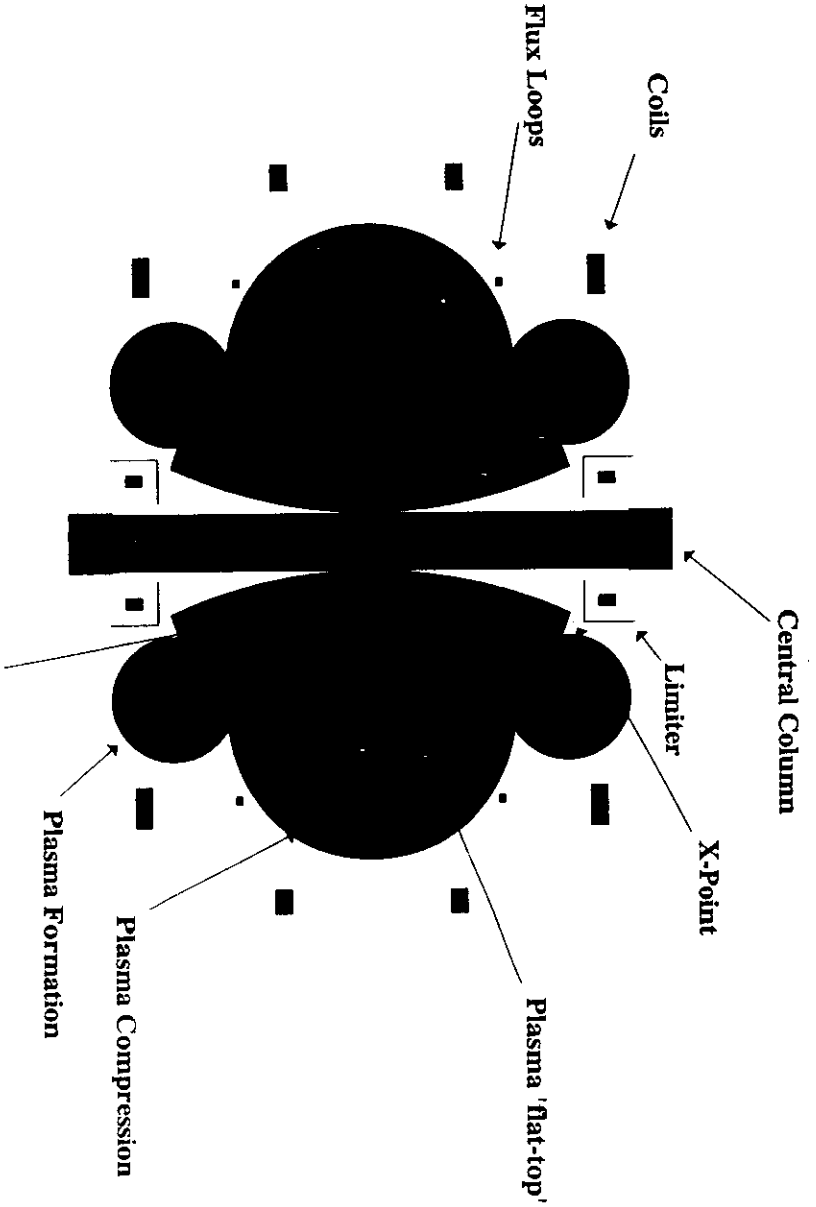
Development of the START facility

First results from START showed well centred, hot plasmas with conventional tokamak features but apparently free from major disruptions.

Plasmas were initially small (R ~ 20cm, a ~ 15cm, κ ~ 1.4), I_p ~ 100kA and discharge time ~ 10ms. Addition of central solenoids (first 20mVs, present 80mVs maximum) has led to plasmas typically R ~ 32cm, a ~ 25cm, κ ~ 1.8, I_p ~ 200kA, discharge time 40ms. Plasma can be of several configurations: limited on the centre column; double-null-divertor (DND) or single-null-divertor (SND).

Ohmic plasmas were studied until 1996 when a 40kV, ≤ 1MW Neutral Beam Injector was installed, on loan from ORNL in USA.

A pellet launcher on loan from Frascati will be installed in late 1997.

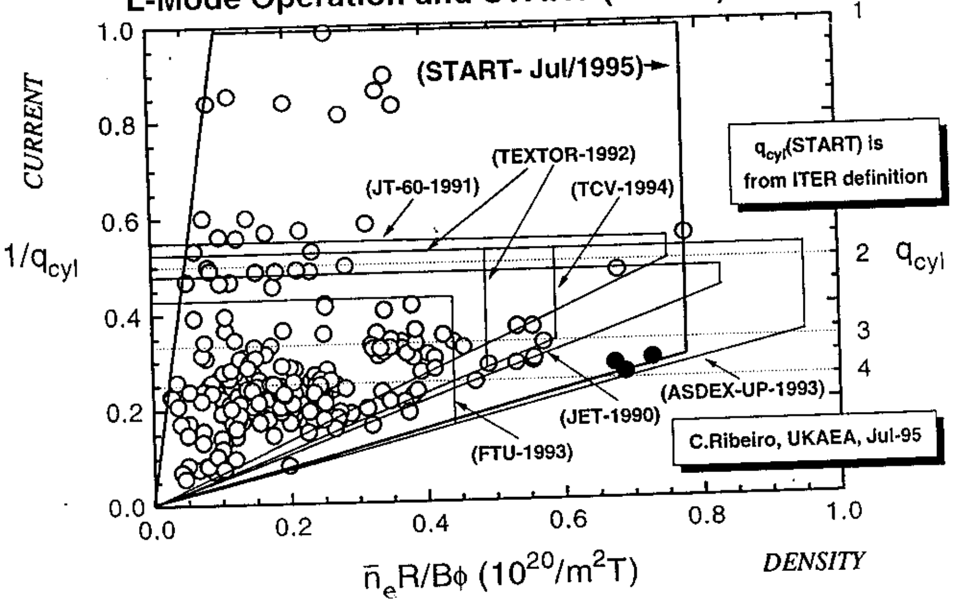


Evolution stages of the START plasma discharge (showing X-point).

File SPDX

The 'operating space' for START is at least as wide as that for conventional tokamaks:

Hugill Diagram for Some Modern Tokamaks in Ohmic L-Mode Operation and START (Ohmic) Results



● = POINTS OBTAINED IN JULY/AUG 1995

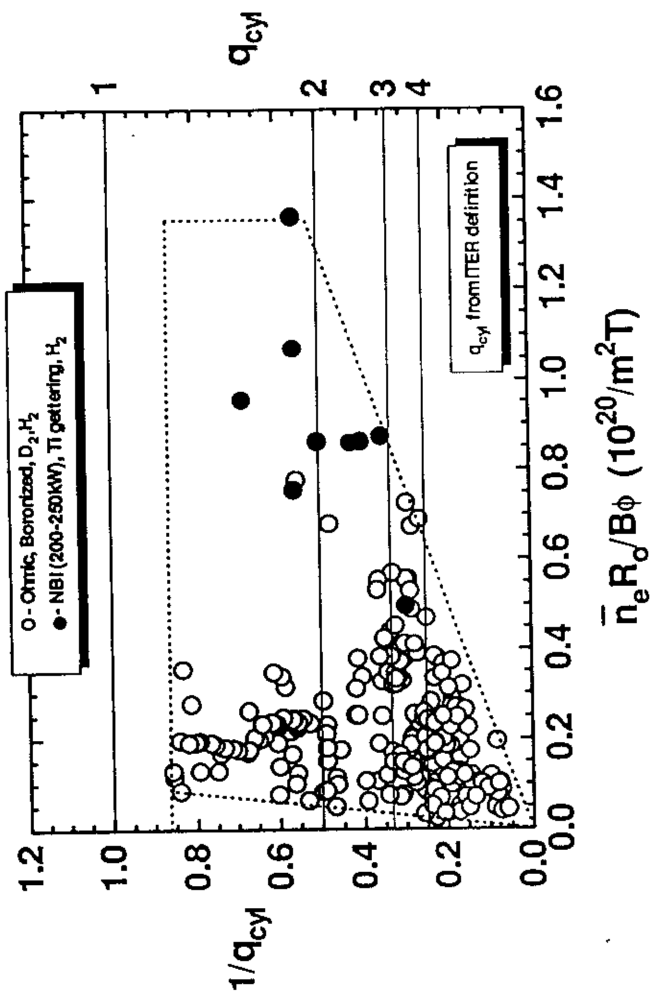
MOREOVER

(1) we are continually extending the boundaries of operation

(2) the boundaries in START are not limited by hard (major) disruptions, but by relatively benign 'Internal Reconnection Events' (IREs) from which the plasma recovers

A 40keV, 0.5MW Neutral Beam Injector (on loan from ORNL) became operational on START in 1996. Present injection is of Hydrogen at up to 30keV.

START Operating Regime



Effects on START Operating Space

Initial attempts to test the effects of extending the operating limits of the START device with NBI have produced very encouraging results. Values of $I_p/N < 10^{-14}$ Am have been achieved

HIGH BETA VALUES ARE EXPECTED IN SPHERICAL TOKAMAKS:

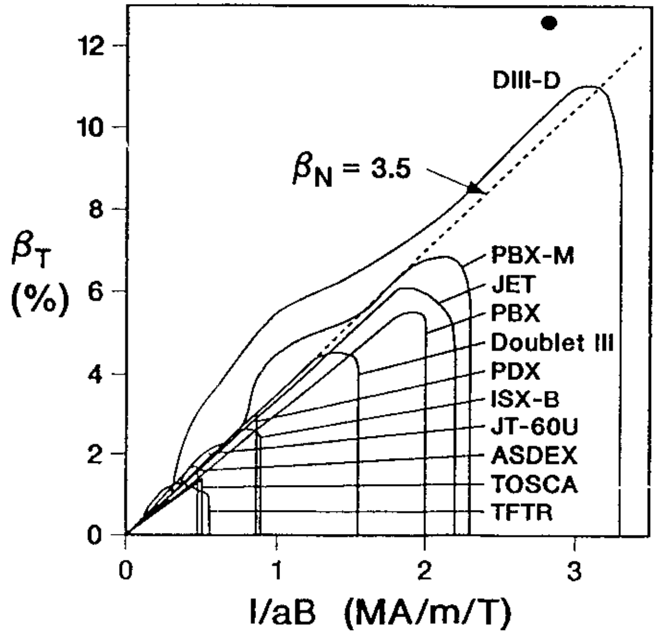
- Theory:

the Troyon limit, $\beta_T = \beta_N.I/aB$, can be written as

$$\beta_T = 5\beta_N.\kappa / Aq_j$$

and high κ, low A are features of the ST

- Experiment:

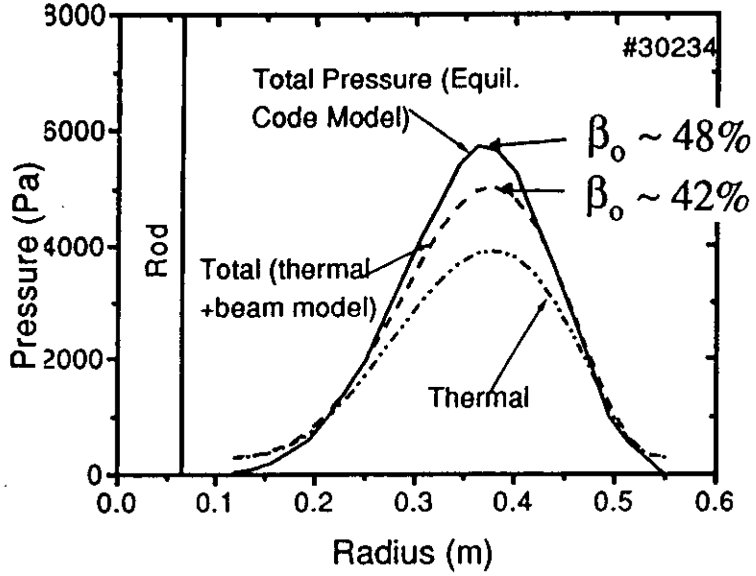


from E.J.Strait, Phys Plasmas 1, 1415 (1994)

For each device, the right-hand limit to operation is the low-q limit $q_s \sim 2$

Large aspect ratio, circular section machines meet this q_s=2 limit at low I/aB and so have low β

PLASMA PROFILES IN START HIGH-β SHOT 30234



Components of total pressure

Previous record central beta value was 44% in DIII-D

UKAEA Fusion

β–Definitions

a) **Volume average total β**

- Most commonly used definition is

$$\beta_T = \frac{\langle p \rangle}{B_0^2 / 2\mu_0}$$

where B_0 is the vacuum toroidal magnetic field at the geometric centre

- Troyon used a full volume averaged β

$$\langle \beta \rangle = \frac{2\mu_0 \int p dV}{\int B_\phi^2 + B_p^2 dV}$$

b)**Central β**

- Using B at the geometric centre R_0:

$$\beta_0 = \frac{p_a}{B_0^2 / 2\mu_0}$$

- Using B at the magnetic axis R_a:

$$\beta_a = \frac{p_a}{B_a^2 / 2\mu_0}$$

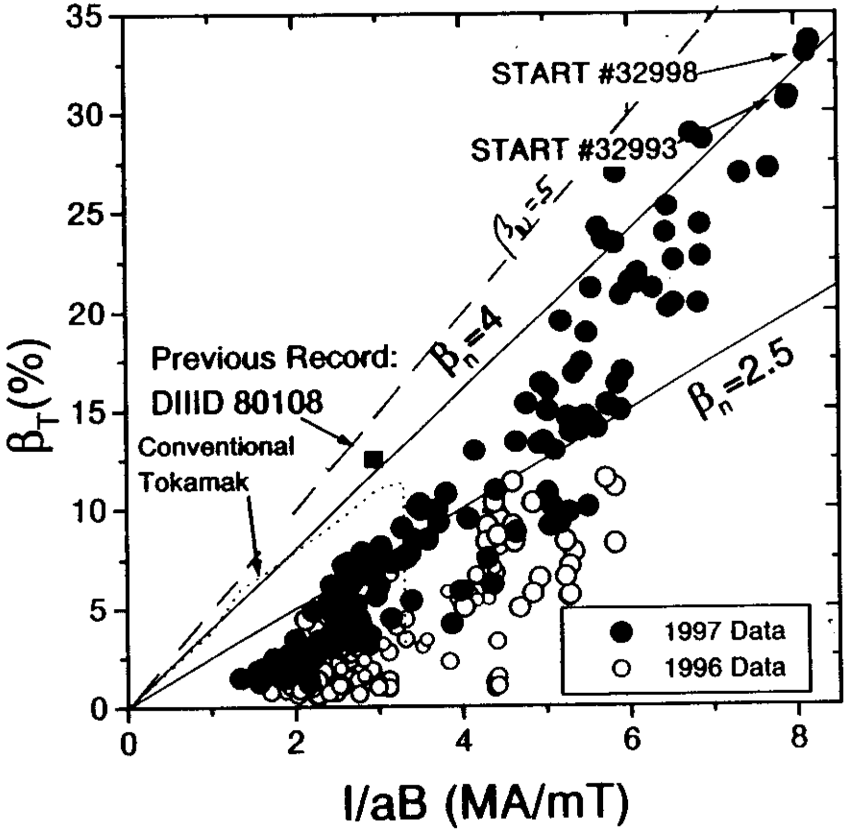
where B_a and B_0 represent the vacuum toroidal field

c)**Reactor β**

$$\beta^* = \frac{\left[\int p^2 dV / \int dV\right]^{\frac{1}{2}}}{B_0^2 / 2\mu_0}$$

Examples (START)	β_T	$\langle \beta \rangle$	β_0	β_a	β^*
#30234(peaked)%	8.5		34	48	
#31832(flat)%	11.5	5.3	33	42	16
#32993(flat)%	31	9.52	>50	>60	36

START Beta Space



β is the ratio of the plasma pressure to magnetic pressure. START results have confirmed predictions that β can be very high in a Spherical Tokamak

([illegible])

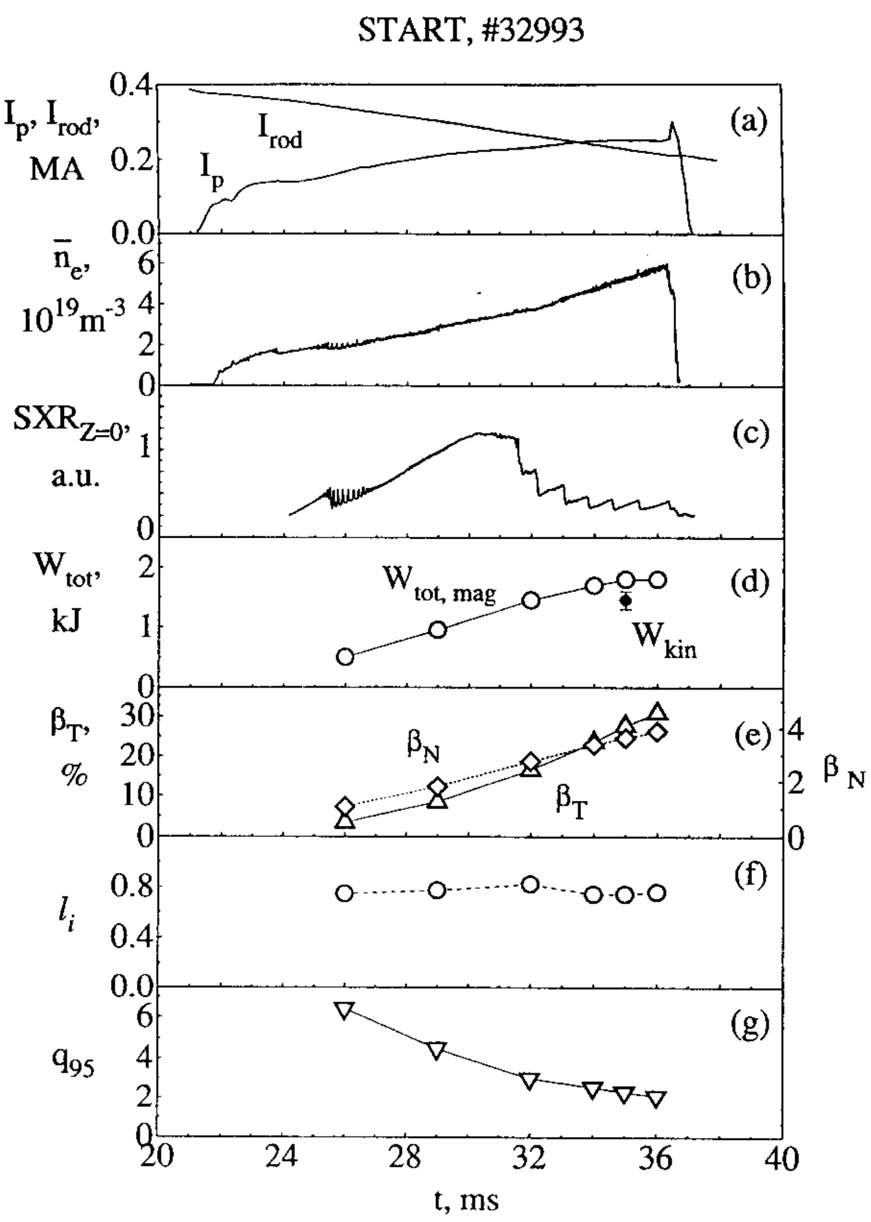
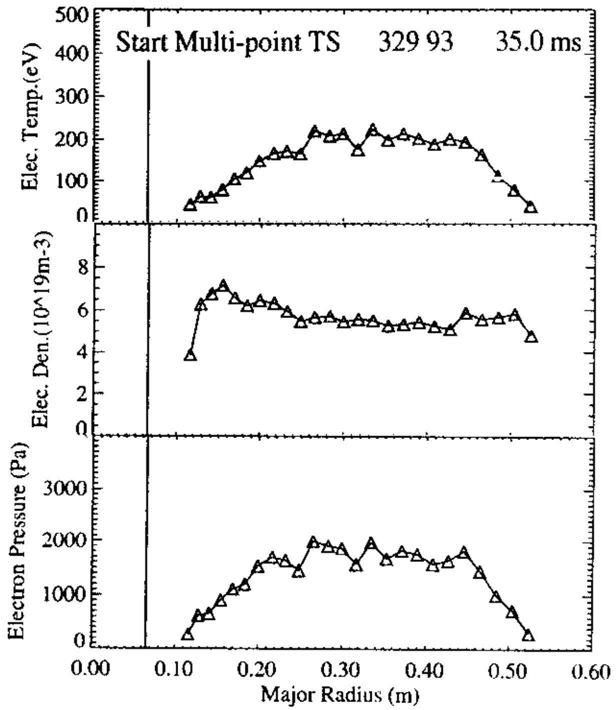


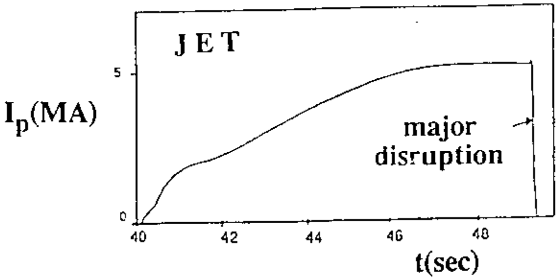
Fig.6. Traces for record high β START shot #32993

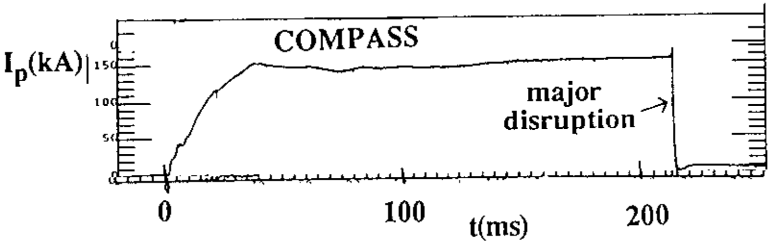
Electron temperature and density profiles for #32993 @ t=35ms, obtained from 30-point Thomson Scattering diagnostic

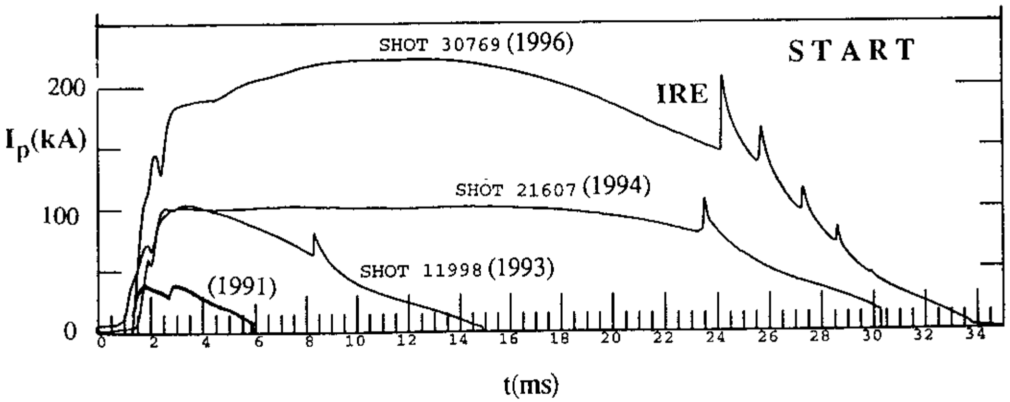


The broad density profile is typical of these high β, low q_{95} discharges. It may result from MHD activity in the plasma centre, or indicate transition to an 'improved' regime

ABSENCE OF CURRENT-TERMINATING MAJOR DISRUPTIONS IN START







- modelling shows that the IRE can be self-stabilising at low aspect ratio

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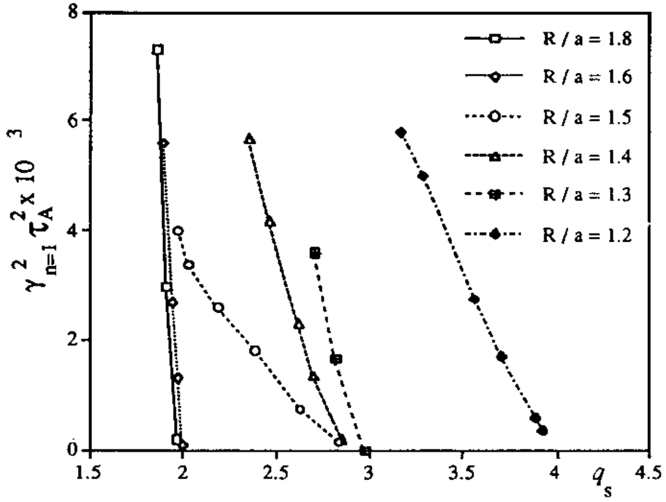
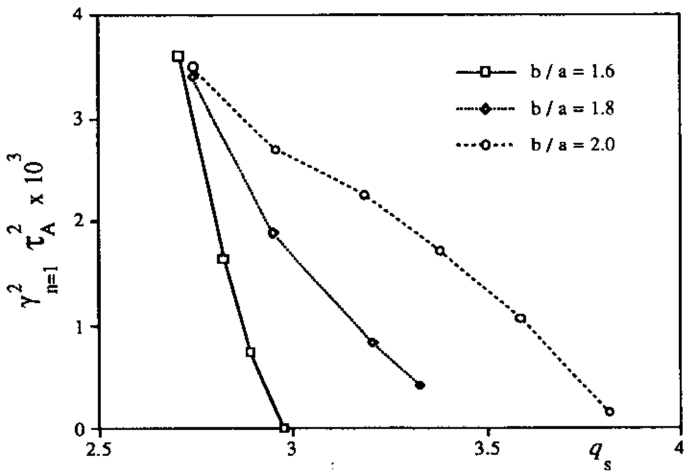
ERATO studies of n=1 kink stability

(Tim Hender)

pressureless model
no wall stabilisation used



$q_s > 4$ is required for stability at A = 1.2
(this plot for elongation k=1.6)

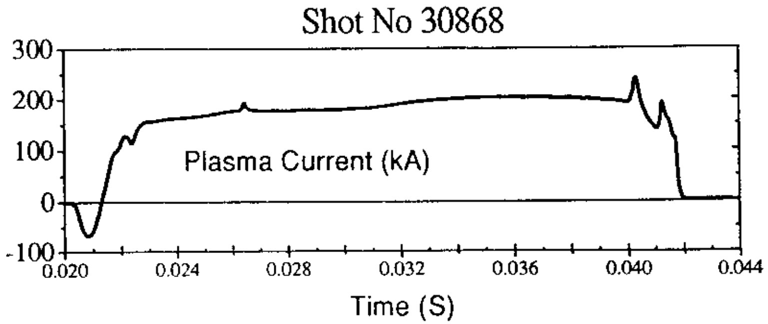


q_s further increases for higher elongations
(this plot for A = 1.3)

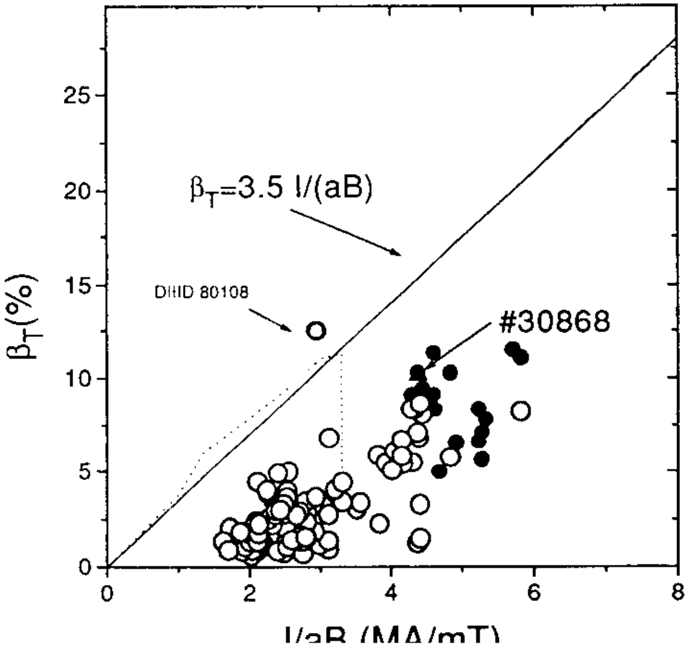
NATURE OF THE LOW-q LIMIT

START has always had its operation space defined by mild internal reconnection events (IREs).

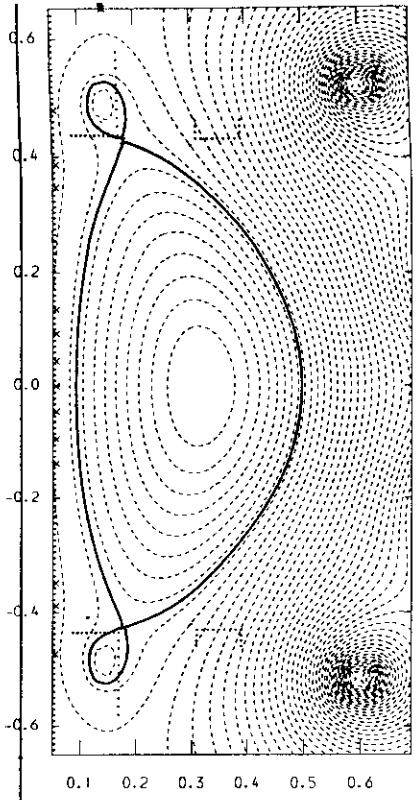
With the present campaign, pushing the low-q limit in the DND plasmas the IREs are more severe:



Many shots near the low-q limit terminate within 2ms (~ confinement time), as shown by ● :



Comparison of typical START and COMPASS equilibria



START

$A = 1.45$

$R = 0.29$ m

$a = 0.20$ m

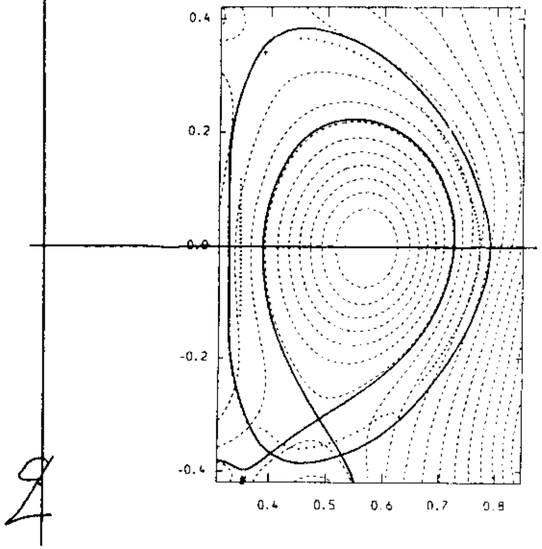
$\kappa = 2.1$

Vol = 0.43 m^3

$B_{To} = 0.34$ T

$I_p = 202$ kA

E = 0.40 kJ



COMPASS

$A = 3.28$

$R = 0.56$ m

$a = 0.17$ m

$\kappa = 1.55$

Vol = 0.45 m^3

$B_{To} = 1.85$ T

$I_p = 172$ kA

E = 2.8 kJ

A remaining uncertainty

- we require high n T τ for ignition.

but $\beta \sim p/B^2$ (defn) and by Troyon, $\beta_{max} \sim I/(aB)$

hence $n\,T\,\tau \sim I\,B\,\tau$

present designs of ST power plant use high I and appeal to high H-factors.

τ is very uncertain: START results show

(1) τ ~ 2 x neo-Alcator
(2) τ ~ Rebut-Lallia
(3) τ > ITER93H (H mode scaling)

- this shows that confinement scalings aren't yet validated at low A

Grounds for optimism :

(i) cleaner, hotter plasmas in MAST (possibly START) may give improved τ as radiated fraction reduces

(ii) H - mode may appear, giving further improvement

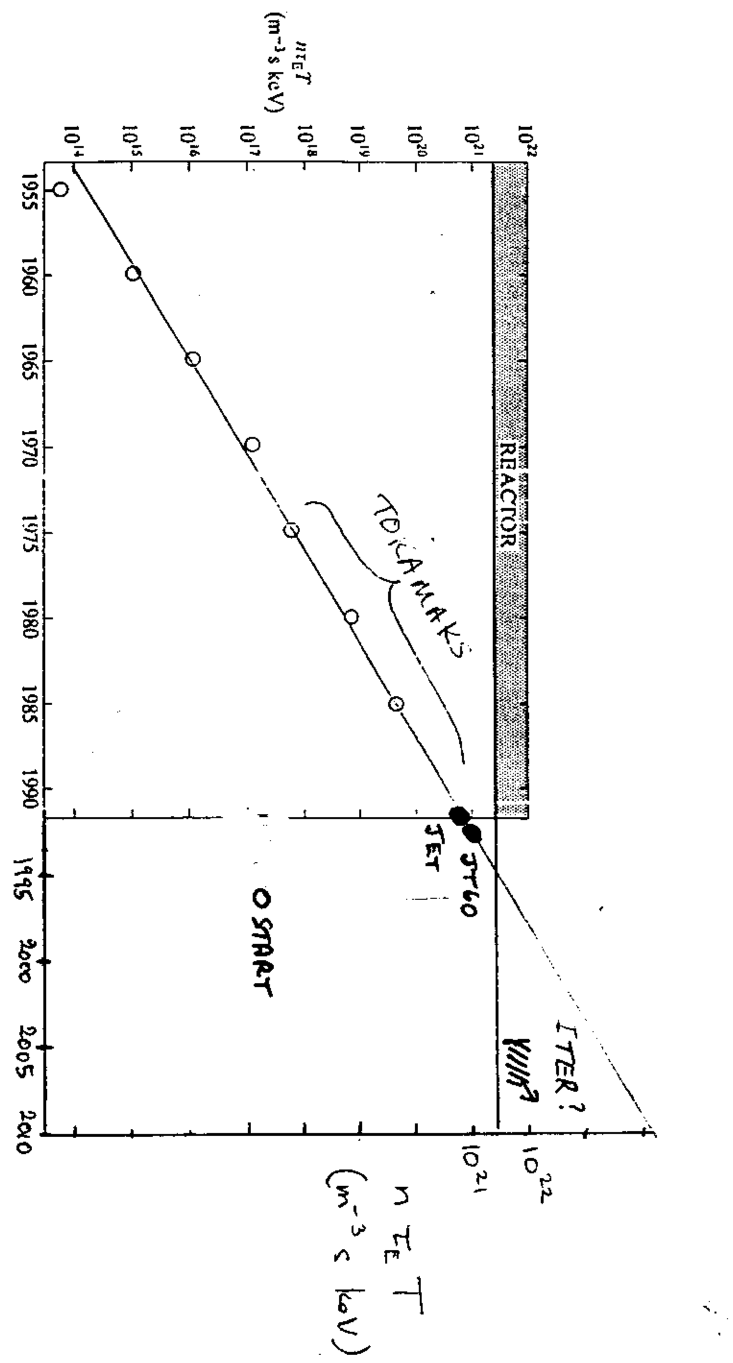


Fig. 1.1.1 In a reactor the product $n\tau_E$ of the ion density and the energy confinement time must be around 1.5–3×10^{20} m^{-3} s and the temperature, T, around 10-20 keV. The required value of the product $n\tau_E T$ is approximately 3×10^{21} m^{-3} s keV (Section 5.1). Progress in improving this product is shown in the figure.

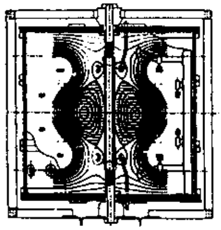
Wesson, 'Tokamaks', 1987

START: $T \sim 0.5$ keV
$n \sim 0.5 \times 10^{20}$
$\tau \sim 0.004$ s
$\rightarrow n\tau_E T \sim 10^{17}$

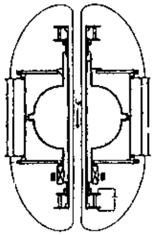
WORLD SPHERICAL TOKAMAK POPULATION

AUGUST 1997

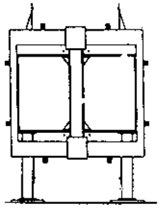
Operational



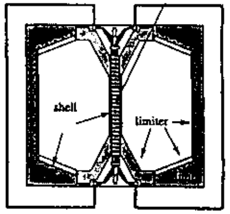
START (1991)



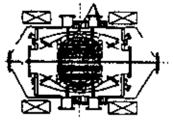
HIT



CDX-U (1994)



T S T
TOKIO, 1995

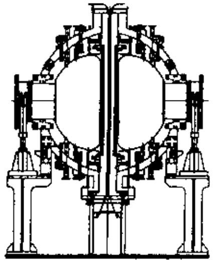


TS-3 ultra low A (1993)

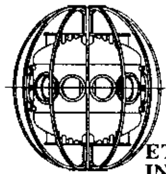
MEDUSA (1994)

1 metre

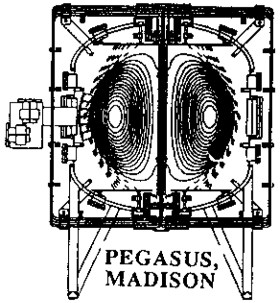
Under Construction



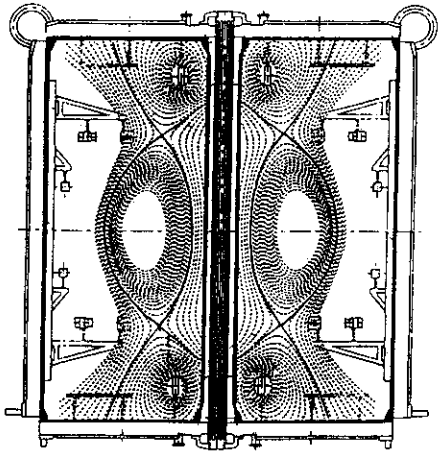
GLOBUS-M,
IOFFE

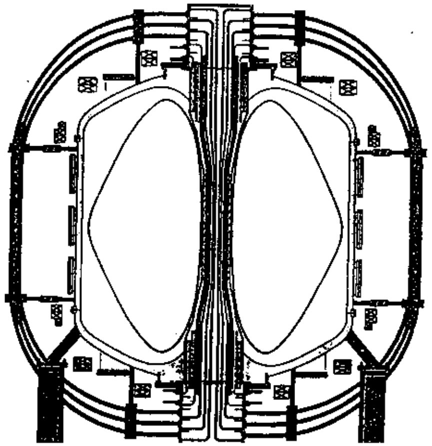


ETE,
INPE



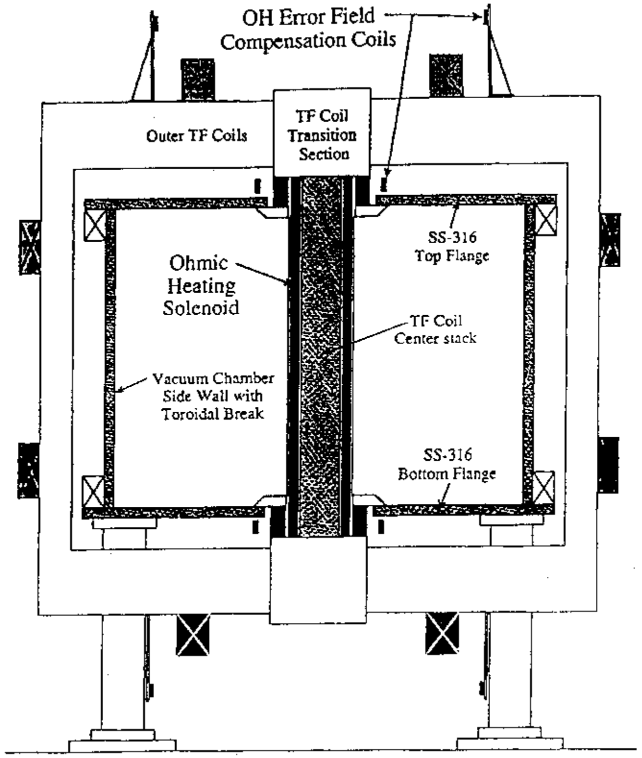
PEGASUS,
MADISON





CDX-U
(PPPL, USA)

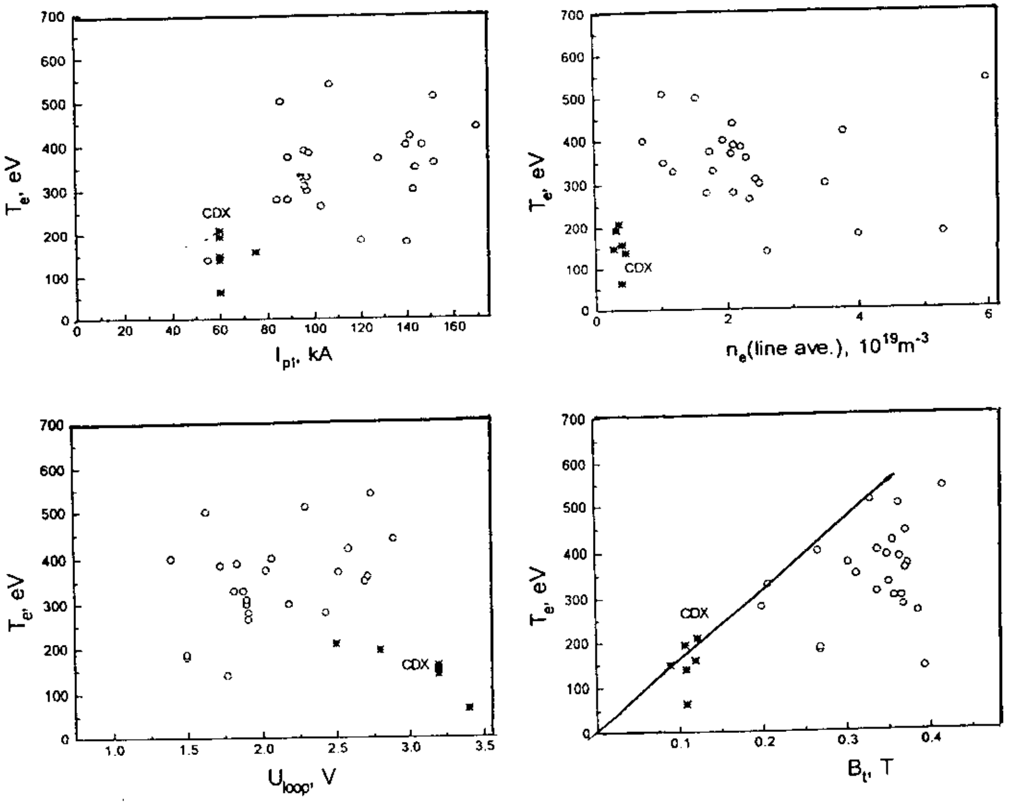
DC Helicity injection : new central solenoid now operational



	design	achieved (June 1994)	1996
Plasma Current	≤ 100kA	30kA	100 kA
Minor radius	= 24cm	20	
Elongation	≤ 1.5	1.3	
Major radius	= 33cm	32	
Aspect ratio	= 1.4	1.6	
Toroidal field (Steady-state)	= 0.17T	0.1T	0.13T

Dependence of central electron temperature on I_p, n_e, V_{loop}, B_T for Ohmic plasmas in START and CDX-U

(M.Gryaznevich,1996)

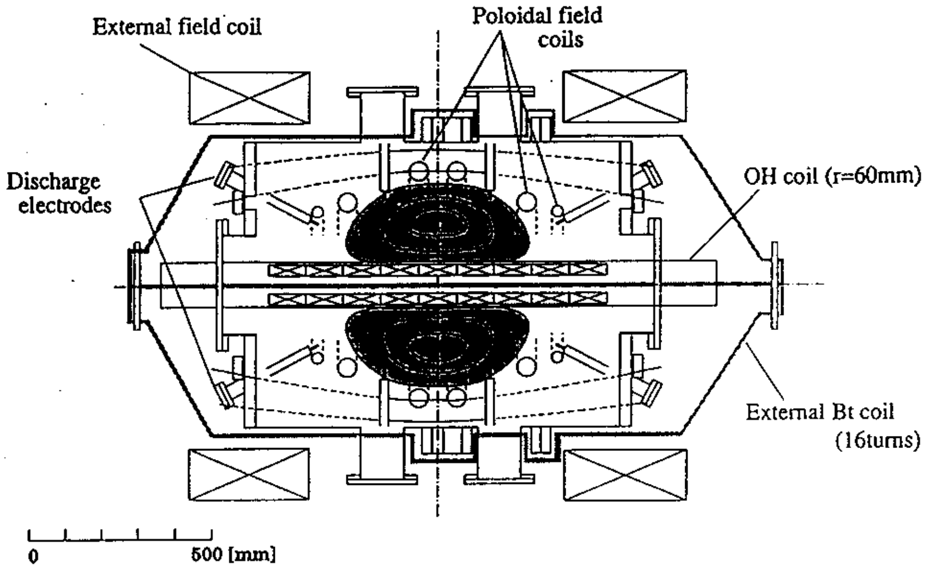


Note 1) CDX-U operates at low density (for pre-ionisation reasons)

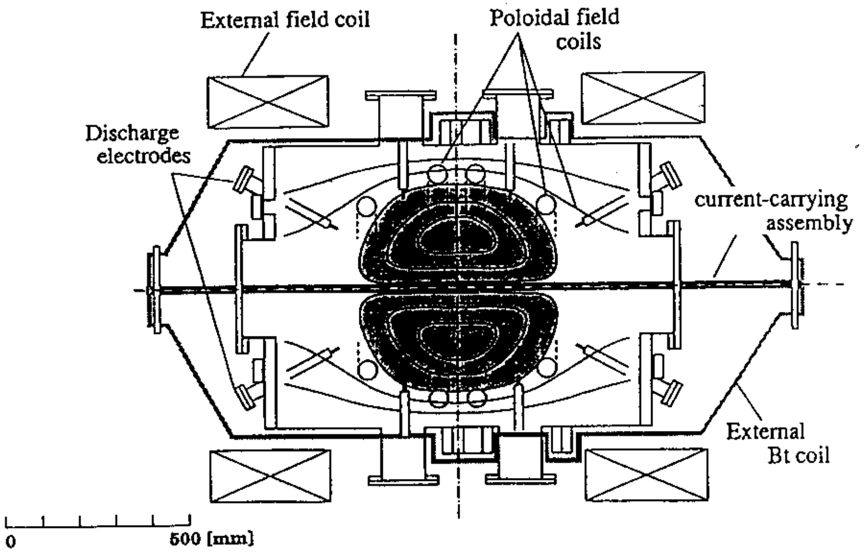
2) maximum $Te_o \propto B_T$

TS-3 : original low-A form (1991-3)

(Tokyo, Japan)



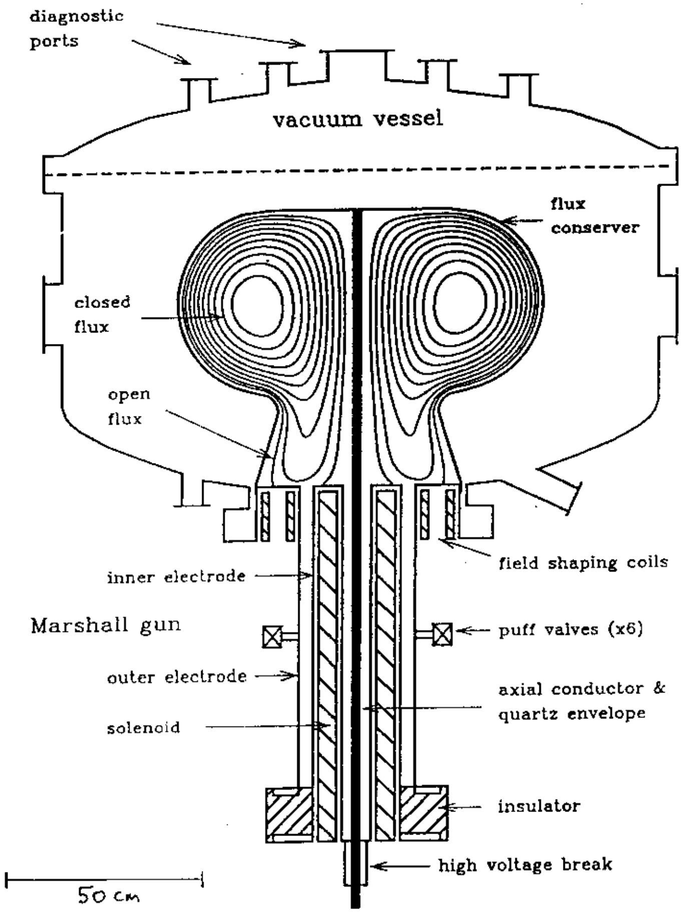
TS-3 : ultra-low-A (1993 →)



Ref : Y Ono et al, Phys. Fluids B 5 (1993) p3691

SPHEX 'RODOMAK'

UMIST, UK



SPHEX 'RODOMAK'

$R_o = 0.23m$ $a = 0.22m$ $A = 1.05$

$I_p \leq 200kA$ $t \sim 0.7ms$ $B_{To} = 0.045T$

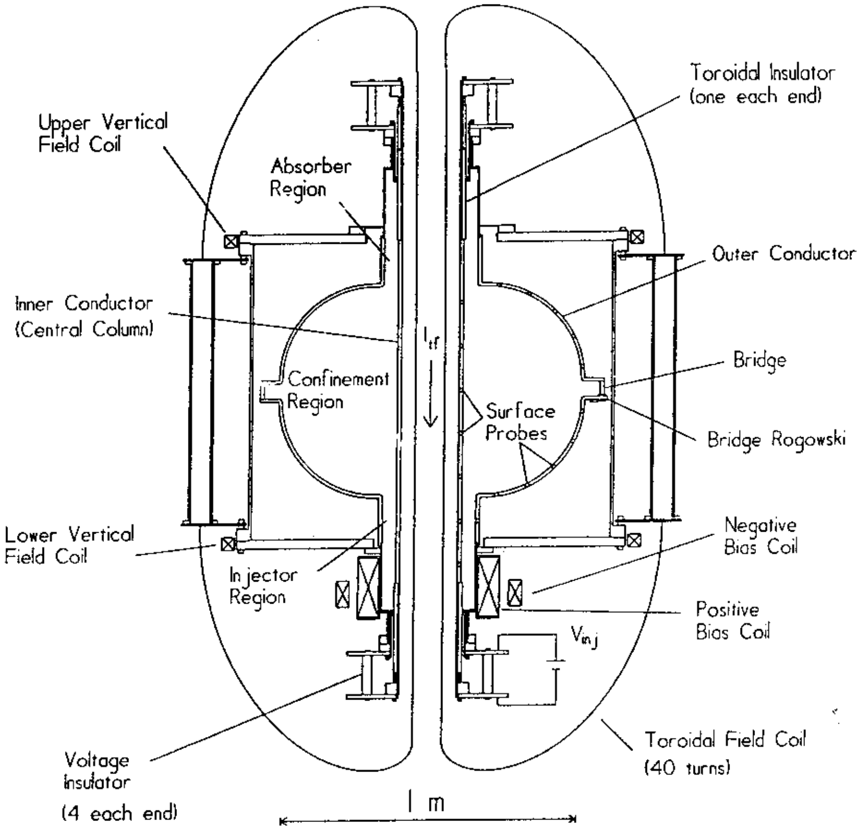
$T_{eo} \sim 30eV$ $n_{eo} \sim 3 \times 10^{19} m^{-3}$ $T_{io} \sim 30eV$

$\tau_E \sim 0.010ms$

Ref: P K Browning et al, Phys. Rev. Lett. 68 (1992) p 1722

HIT (Helicity Injected Tokamak)

Seattle, USA



Parameters achieved

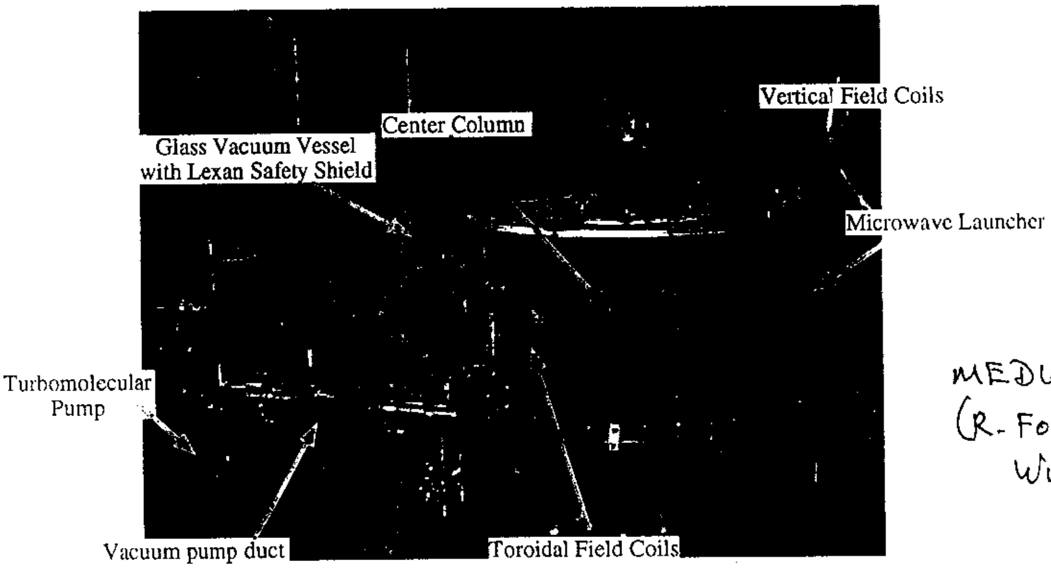
$R = 0.3m$ $a = 0.2m$ $A = 1.5$

$B_0 = 0.46T$ $t = 6ms$ $I_p =$ ~~150~~kA 250

$n_{eo} \sim 6 \times 10^{19} m^{-3}$

Ref B A Nelson et al, Phys Rev Letts 1994

TOKAMAK COILS, MECHANICAL AND VACUUM ASSEMBLIES



MEDUSA
(R. Fonck et al,
Wisconsin)

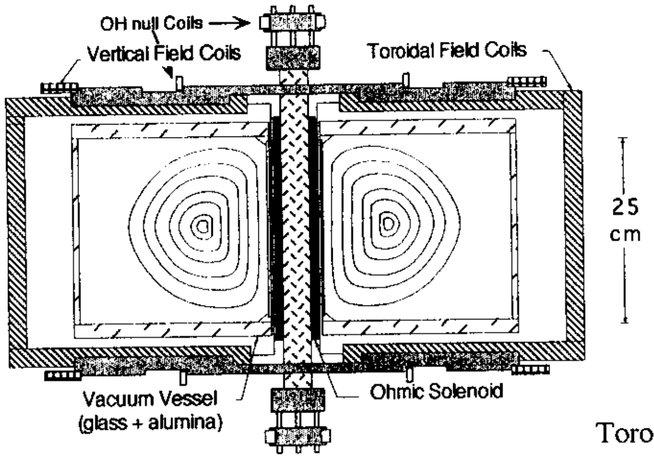
Tokamak Design Issues:

- Very high electromechanical stresses supported by rigid mechanical structure
- Glass cylinder supports atmospheric stress of 12,700 pounds of force
- Tensile stress on conductor in central drive solenoid within a factor of 2 of the plastic deformation limit of copper
- State-of-the-art turbomolecular vacuum pump system for extreme cleanliness

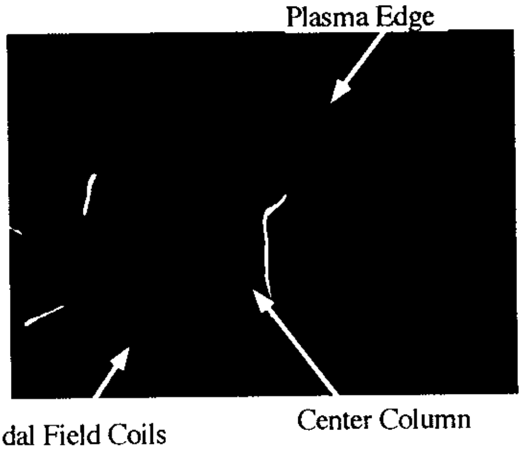
MEDUSA: A LOW-ASPECT-RATIO TOKAMAK AT UW

Design plasma paramters for MEDUSA:

Minor radius = 8 cm
Major radius = 12 cm
Plasma current = 20 - 60 kA
Max. toroidal field = 0.4 Tesla
Max. Pulse length = 5 msec



Machine Schematic



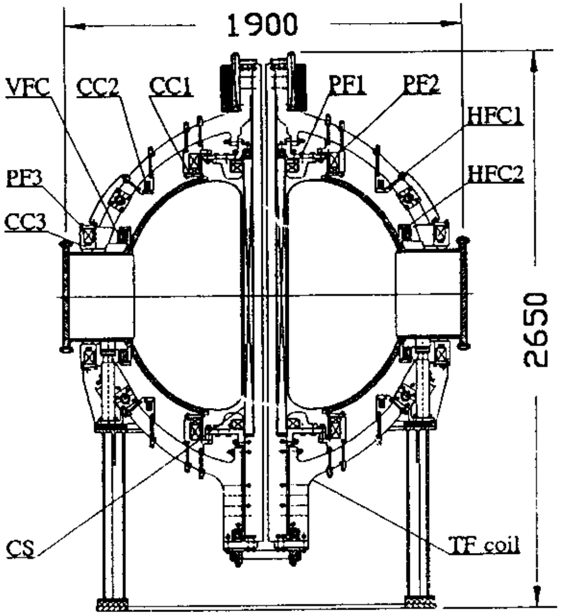
High-speed TV Camera Picture of Plasma in MEDUSA

- Technology development testbed for PEGASUS experiment
- Sophisticated experimental facility built with part-time undergraduates with no funding
  - Mostly surplus and home-made components

GLOBUS - M Spherical Tokamak

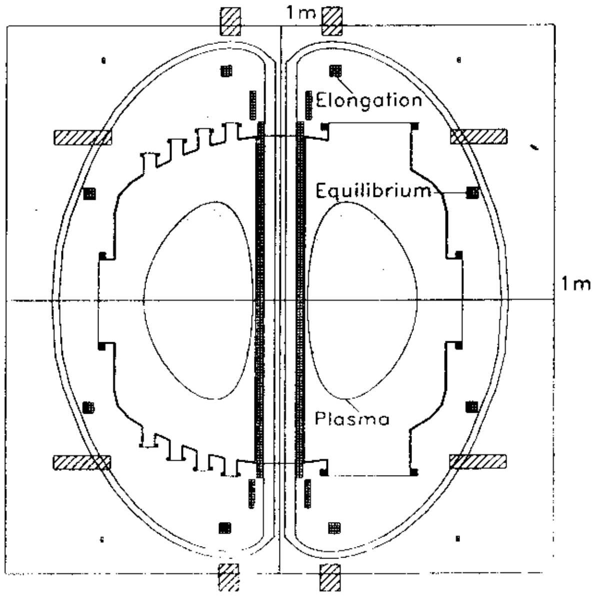
Ioffe Institute, St Petersburg

status: under construction



GLOBUS-M Basic Parameters

Plasma major radius, R	0.36 m
Plasma minor radius, a	0.24 m
Aspect ratio, R/a	1.5
Plasma vertical elongation, k	1.5 - 2.2
Plasma triangularity, δ	~ 0.2
Plasma current I_p	0.3 MA
Toroidal magnetic field, B_T	0.5 T
Plasma shaping factor, $S=I_p q_\psi/aB_T$	25
Pulse length	0.3 sec
Auxiliary heating power	~ 1 MW
Weight of tokamak	~ 5 Ton

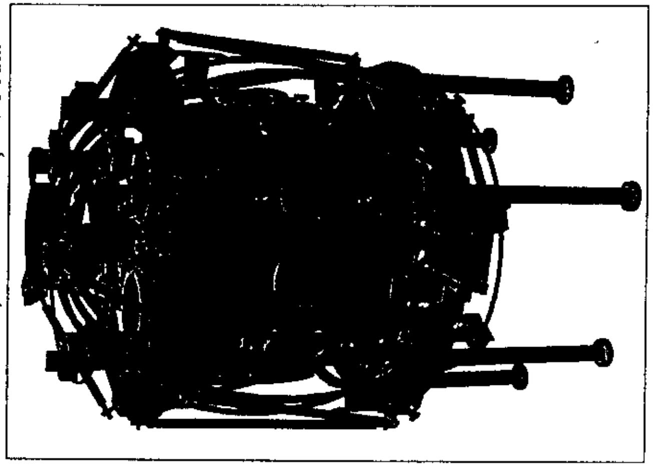


The ETE Spherical Tokamak Experiment
(Experimento Tokamak Esférico)

G. O. Ludwig, M. C. R. Andrade, L. F. W. Barbosa, P. R. P. Barreto, E. Del Bosco, J. G. Ferreira, A. Montes, C. S. Shibata, M. Ueda.

INPE, Brazil

status: under construction

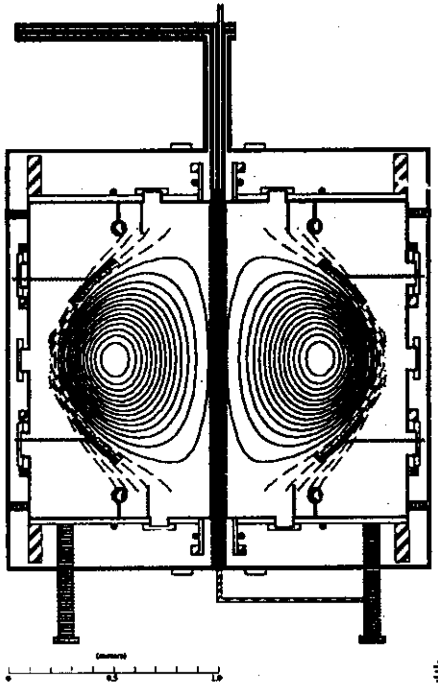


Major radius $R_0(a)$	0.30 m
Aspect ratio $A=R_0(a)/a$	1.5
Elongation κ(a)	1.6 - 1.8
Triangularity δ(a)	0.3
Toroidal magnetic induction B_0	0.4 T
Toroidal plasma current $I_T(a)$	0.22 MA

Laboratório Associado de Plasma
Instituto Nacional de Pesquisas Espaciais
12201-970 - São José dos Campos, SP, Brazil

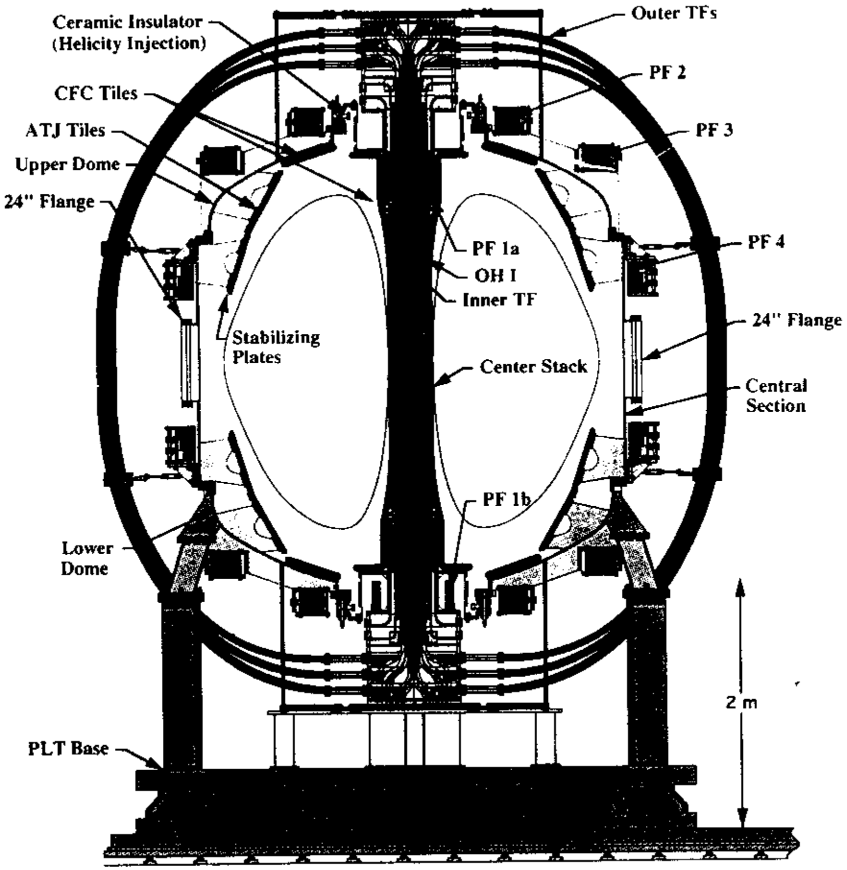
'PEGASUS' is the large scale successor to 'MEDUSA' and is now under construction at Madison, Wisconsin USA by Ray Fonck's team

The PEGASUS Toroidal Experiment



from the University of Wisconsin Department of Nuclear Engineerinng and Engineering Physics, a proposal for a ...

NSTX



NSTX (National Spherical Torus eXperiment)

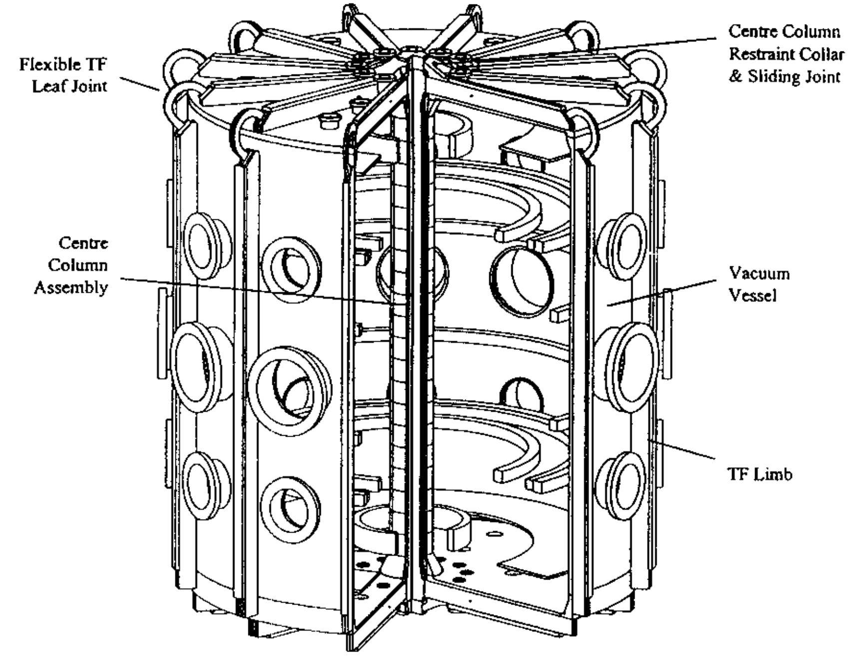
PPPL USA

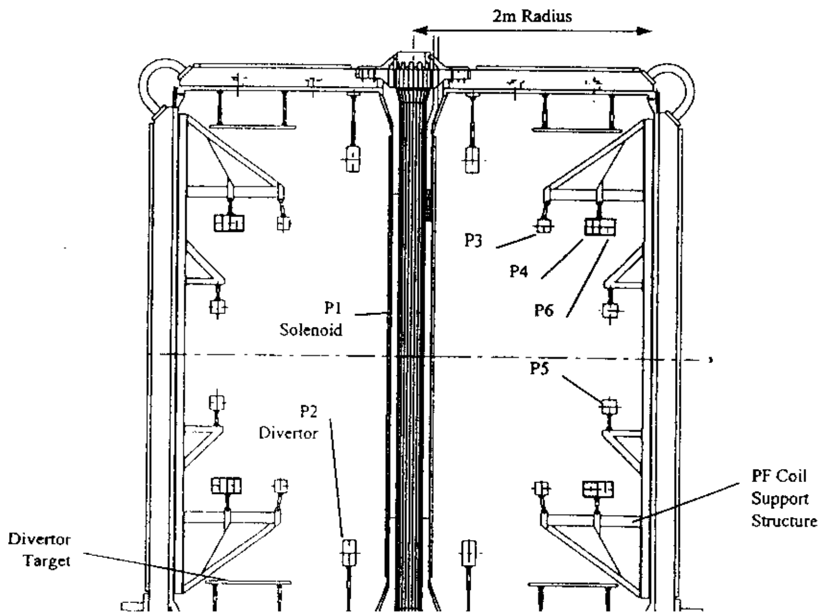
status: under construction
(first plasma scheduled for April 1999)

MAST (Mega-Amp Spherical Tokamak)

UKAEA Culham

status: under construction
(first plasma scheduled for Sept 1998)

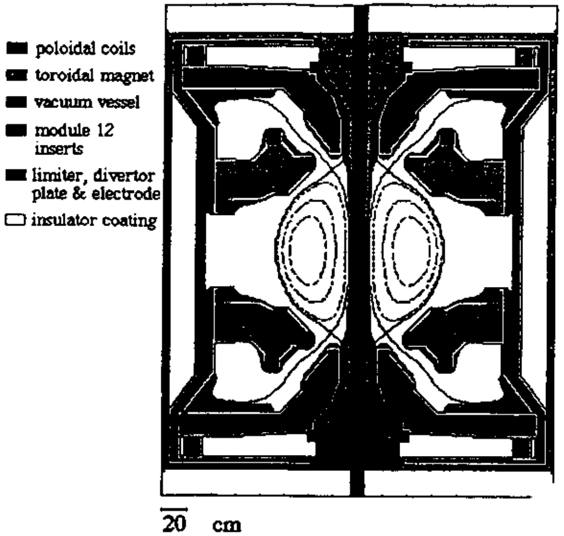




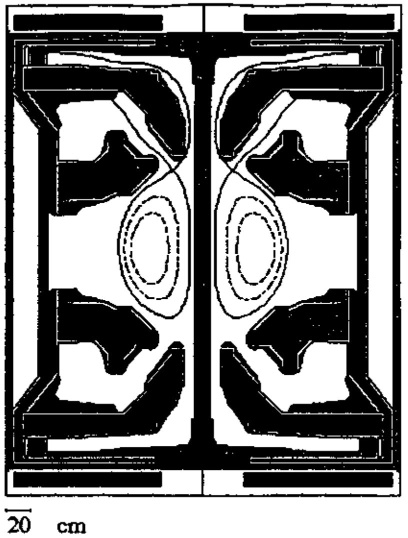
PARAMETERS OF FEW SELECTED MODERN AND NEAR FUTURE SPHERICAL TOKAMAKS

	CDX-U Princeton	START Culham	ETE San Paulo	GLOBUS-M S.Petersburg	MAST Culham	NSTX Princeton
R (m)	0.32	0.2÷0.4	0.3	0.36	0.7	0.8
a (m)	0.3	0.15÷0.3	0.2	0.24	0.5	0.55
A	>1.4	>1.2	1.5	1.5	1.4	1.45
I (MA)	0.09-0.2	0.1÷0.3	0.2-0.4	≤0.5	1-2	1-2
B (T)	0.1	<0.5	0.4-0.8	0.62	0.6	0.5
τ_{f-t} (sec)	0.01	>0.01	0.015	0.1	0.5	1-5
Aux. Heating	0.2 MW HHFW	0.3 MW NBI	-	1-2 MW ICRH, LH	5 MW NBI	5 MW NBI, HHFW

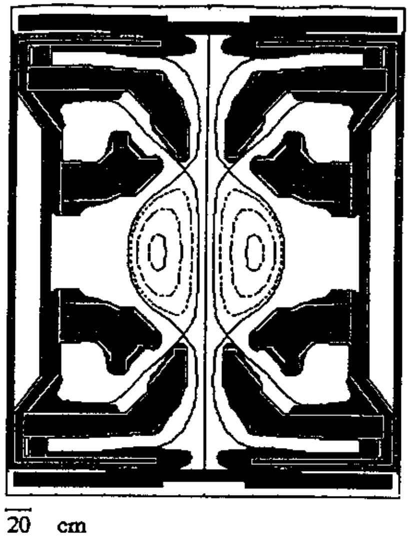
SPHERA (Spherical Plasma for Helicity Relaxation Assessment) was proposed by Alladio, Micozzi and Pieroni et al at Frascati. This large device (Ip up to 2 or 3 MA) is designed to study several aspects of ST formation:



"conventional" ohmic solenoid



Helicity injection



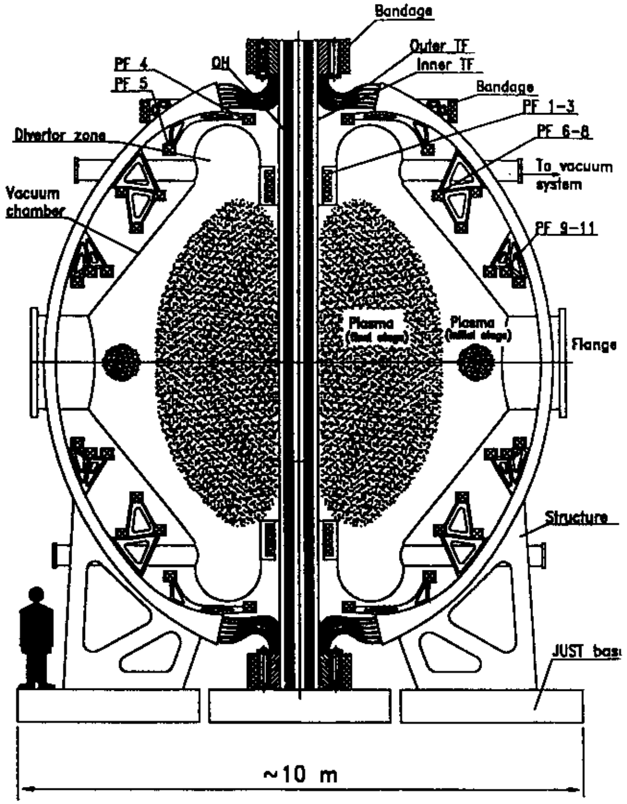
Central screw pinch to provide TF (0.38MA 'rod' current)

JUST

Russia

status: proposal

Joint Upgrated Spherical tokamak



JUST preliminary parameters

Plasma major radius, R [m]	1.7
Plasma aspect ratio, A	1.5
Plasma minor radius, a [m]	1.13
Plasma elongation, k_{95}	2.5
Plasma safety factor, q_{95}	3.3
Toroidal magnetic field on axis, B_t [T]	1.34
Toroidal plasma beta, β_t [%]	27
Plasma current, I_p [MA]	14
Auxiliary heating power, P_{aux} [MW]	15
Fusion power, P_{fus} [MW]	40

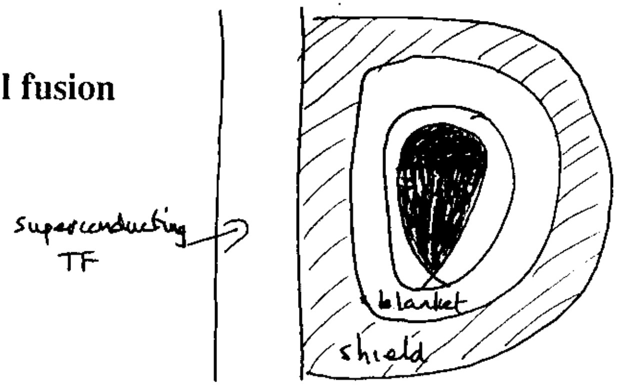
THE FUTURE:

STs as D - T { Materials Test Facility
Power Plant

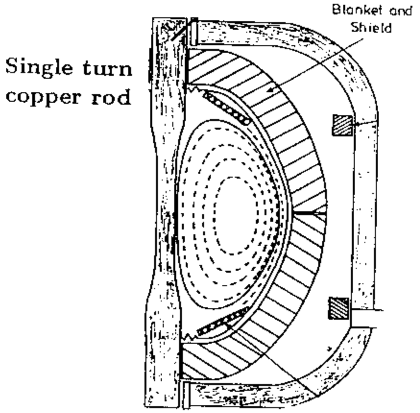
Assume the physics works out OK
(confinement, stability, start-up, current drive, bootstrap fraction, wall materials...)

there remains THE CENTRE COLUMN PROBLEM:

Conventional fusion power plant e.g. ITER:



Peng's solution
(Peng & Hicks, 1990 SOFT conf)

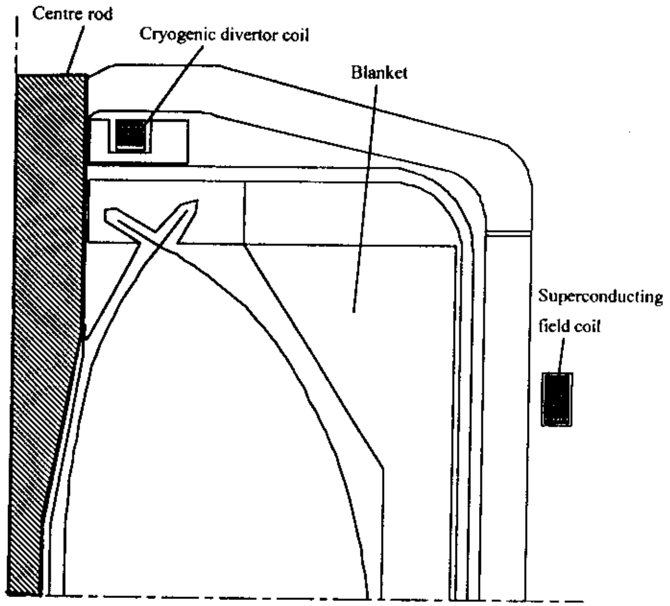


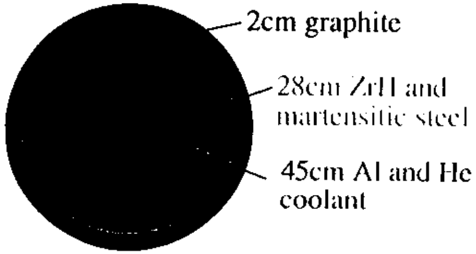
- replace copper rod when radiation damaged (1 - 2 years)
- sufficient lithium-tritium breeding area without central blanket, provided A < 1.6

Novel centre-post designs are being investigated

e.g. Bond & Hender, UKAEA Culham:

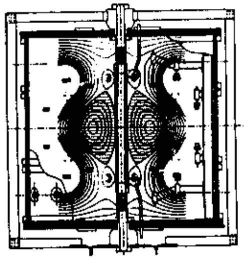
ST Power Plant Cryogenic Centre Post



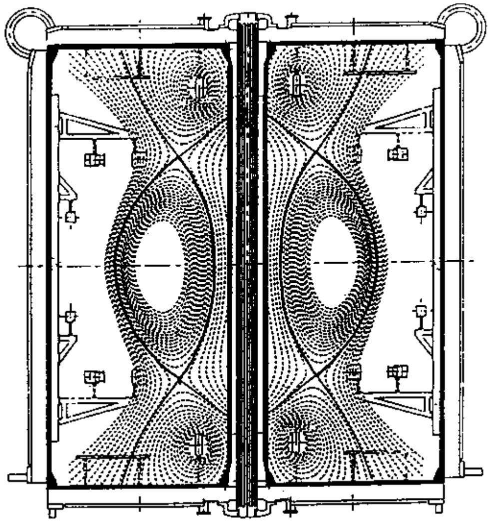


- Al runs at ~30k, resistive loss only 6MW, but needs 100MW cryo plant
- Al column suitable for shallow burial after 100years
- Shileding may be such that column never needs

CULHAM SPHERICAL TOKAMAK PROGRAMME

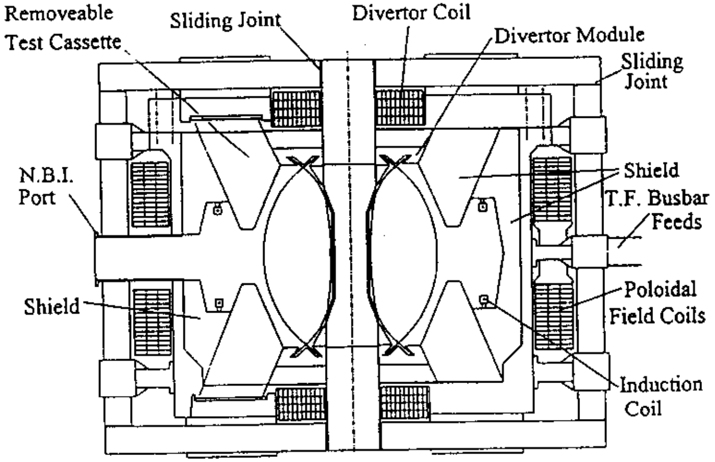


START
(Operational)



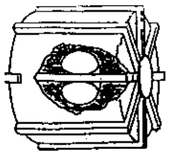
MAST
(Under construction)

0 1 m
Scale

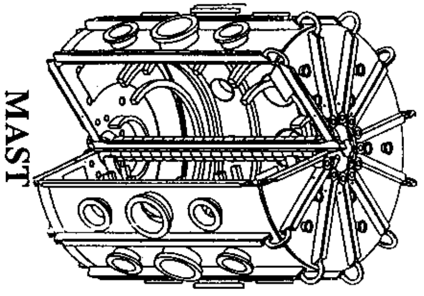


CTF
(Component Test Facility)
(design)

THE ST ROUTE TO FUSION POWER

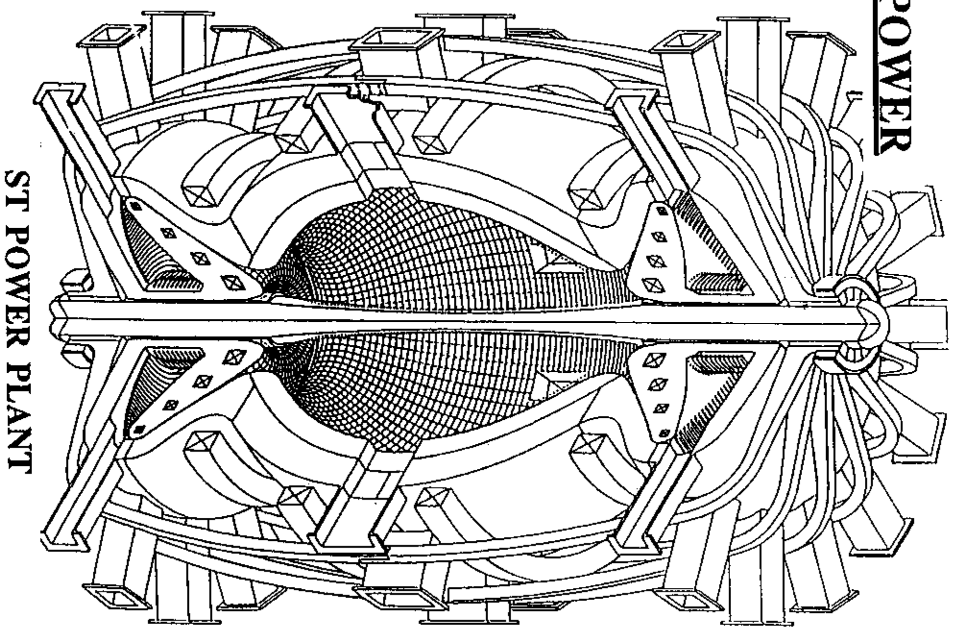


START

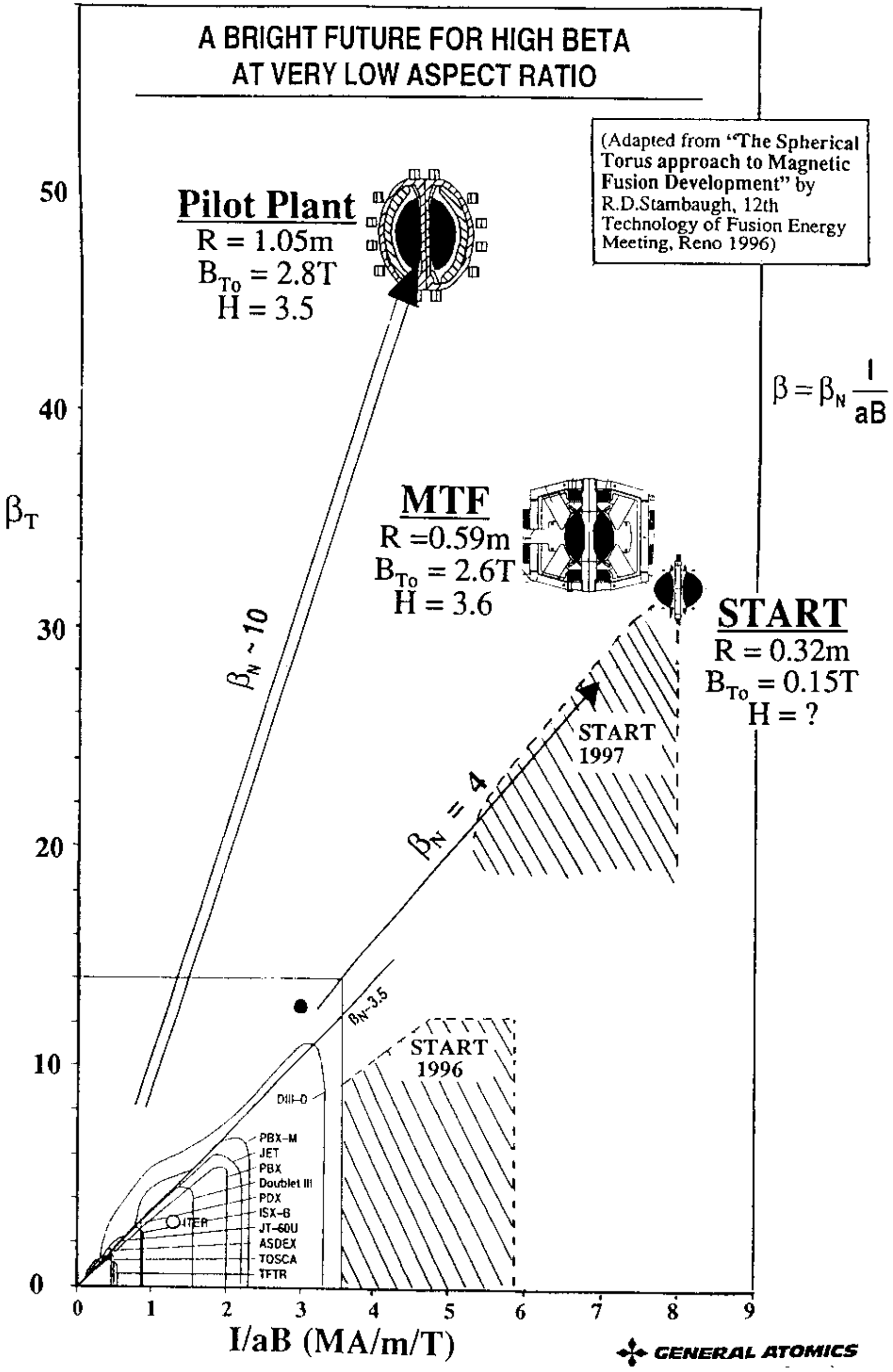


MAST

0 1 2 3 4 5
metres



ST POWER PLANT



A BRIGHT FUTURE FOR HIGH BETA AT VERY LOW ASPECT RATIO

(Adapted from "The Spherical Torus approach to Magnetic Fusion Development" by R.D.Stambaugh, 12th Technology of Fusion Energy Meeting, Reno 1996)

CONCLUSIONS

Results from the small spherical tokamaks presently operating continue to be encouraging -

- natural plasma elongation and shaping, good vertical stability
- wide operating space
- confinement equal to (or exceeding) usual tokamak scalings
- resilience to hard disruptions
- very high β observed, supporting theoretical predictions

⇒ further study of the ST concept is required - in particular on the larger, purpose-built mega-amp size devices now under construction