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AUTUMN COLLEGE ON PLASMA PHYSICS

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The START Spherical Tokamak

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These are lecture notes, intended for distribution to participants.

ICTP Autumn College on Plasma Physics October 1997

The START Spherical Tokamak

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- Introduction
- START layout & construction features
- Results from START
- Future prospects

Acknowledgements

The author acknowledges the many British and international collaborators who have contributed to the success of the START experiment.

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UKAEA Fusion

SPHERICAL TOKAMAKS SHOULD BE SMALLER AND OF SIMPLER CONSTRUCTION THAN THEIR CONVENTIONAL COUNTERPARTS.

EQUILIBRIUM MODELLING SHOWS THAT, IF THEY POSSESS THE SAME STABILITY PROPERTIES, STs WILL REQUIRE AN ORDER OF MAGNITUDE LOWER TOROIDAL FIELD.

EXPERIMENTAL RESULTS ARE NEEDED TO DETERMINE THE STABILITY, CONFINEMENT AND OTHER OPERATIONAL FEATURES OF THE SPHERICAL TOKAMAK.

START WAS THE WORLD'S FIRST DEVICE TO DEMONSTRATE THE PROPERTIES OF HOT SPHERICAL TOKAMAK PLASMAS.

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.

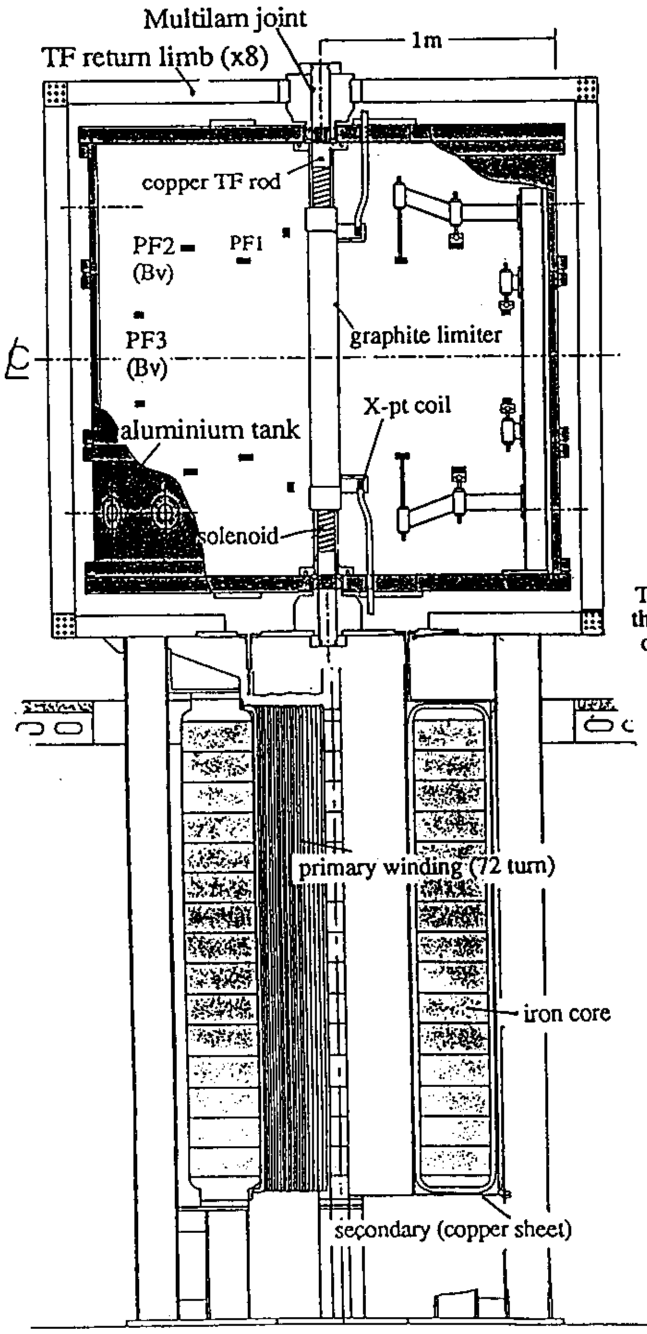
Two novel features were used:

(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



Vacuum tank
(ex TORSO expt, 1970's)

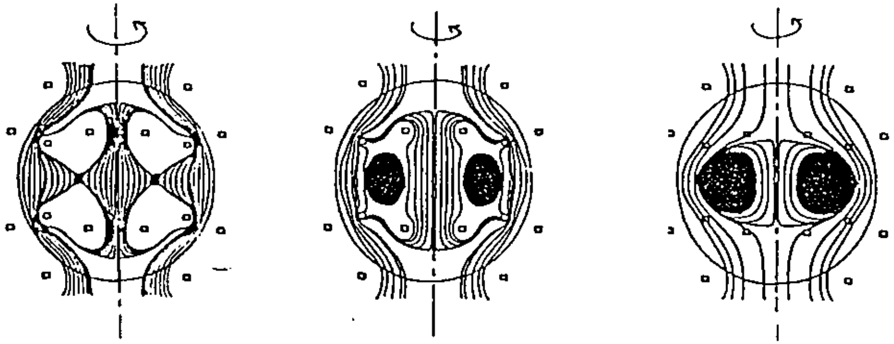
The TF system is part of
the single-turn secondary
of the pulse transformer

Pulse transformer
(ex pulse expts, 1950's)

CURRENT INITIATION AND DRIVE IN STs

Only START uses the induction-compression process, which provides an initial ST plasma without need of valuable Vsecs from the central solenoid. MAST, under construction at Culham, will also use this scheme.

FBX-II at Waseda University, Japan uses flux swings from internal coils to form plasmas, a similar scheme to that initially proposed for START.



Plasma initiation in FBX (Free Boundary eXperiment) II at Waseda University, Tokyo (M. Irie)

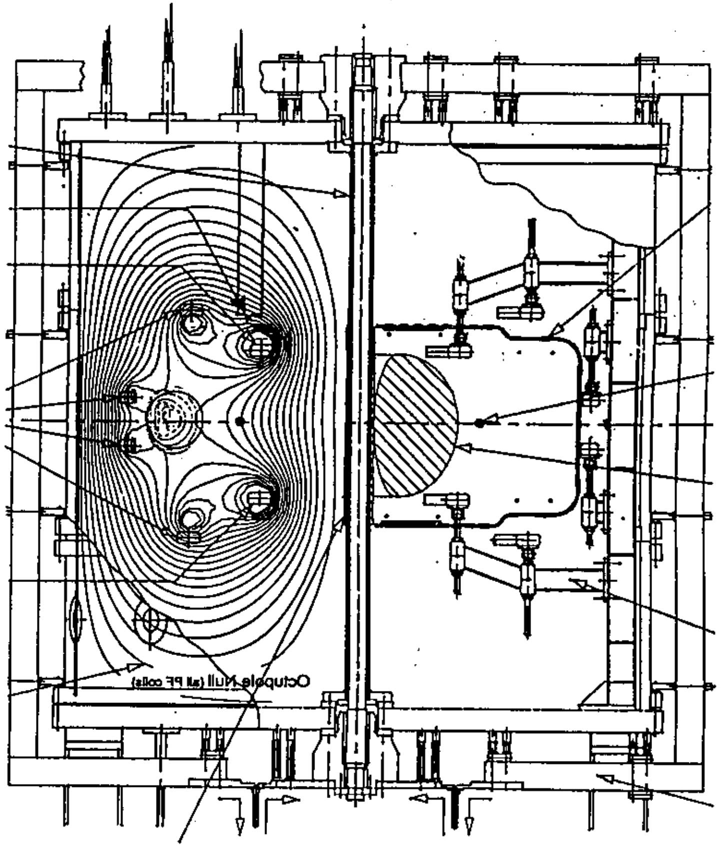
Other STs use a central solenoid, although NSTX (under construction at Princeton) hopes to use Helicity Injection to assist current initiation and drive. High-Harmonic Fast Wave Current Drive is also to be investigated on NSTX.

The most popular means of current drive (and plasma heating) in STs is Neutral Injection, as used by START to obtain its world record β results.

START can also obtain plasmas more conventionally, using the central solenoid - this process is called ‘direct induction’ by the START team.

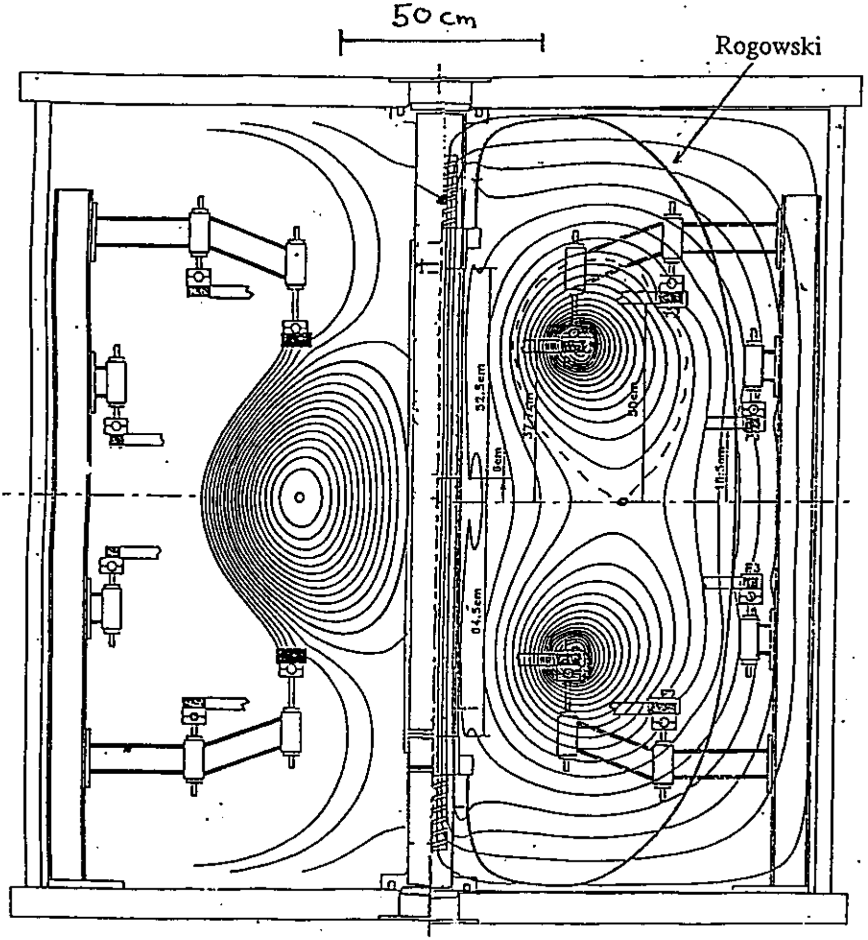
A history of Induction-Compression in *START*

- design featured breakdown in an octopole null at R ~ 60cm



- practice was an observation by MG that swinging the OH coils alone could automatically produce an ST plasma

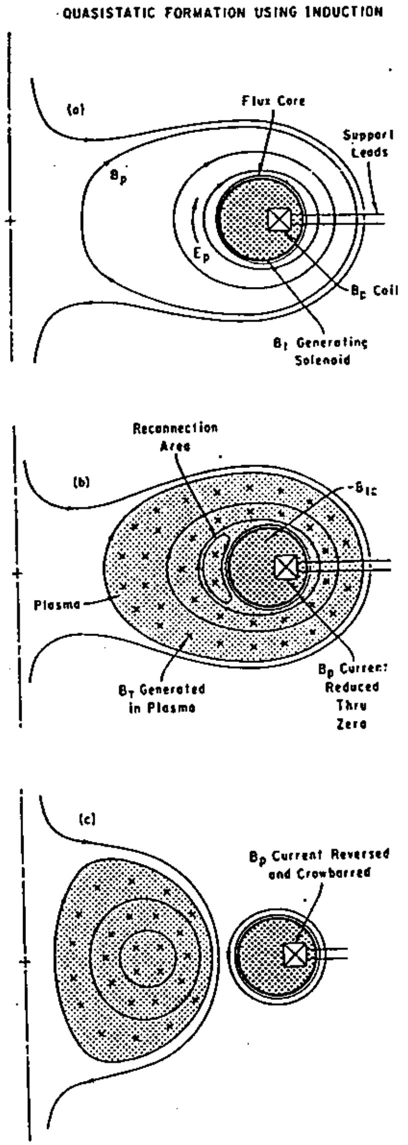
Induction / Compression scheme in START



ompressed plasma $R_0 = 0.30$m, $a = 0.235$m
$A = 1.28$ elongation $k = 1.45$

flux surfaces and null position at moment of breakdown

Induction - Compression in Proto - S1 and S1 spheromaks (Yamada et al, Princeton)



A single induction coil, also contains a solenoid to generate TF

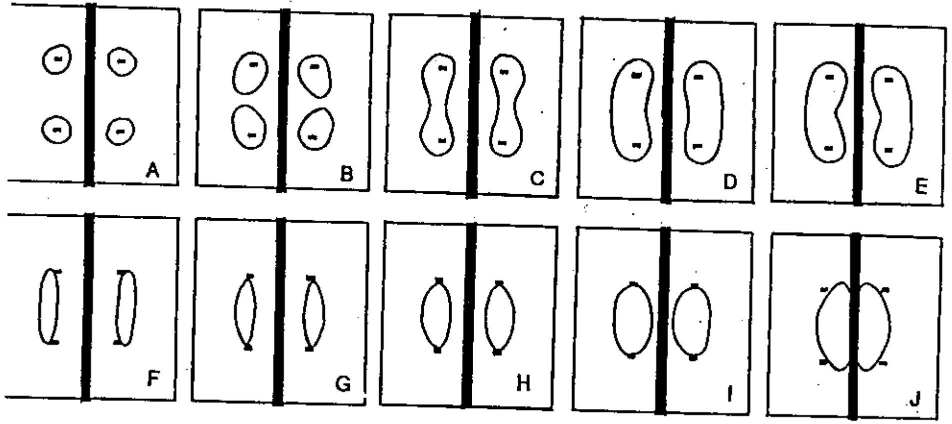
I_{OH} ramps down, plasma forms around coils

external B_v applied to push plasma ring off coil towards axis, aided by reversal of I_{OH}

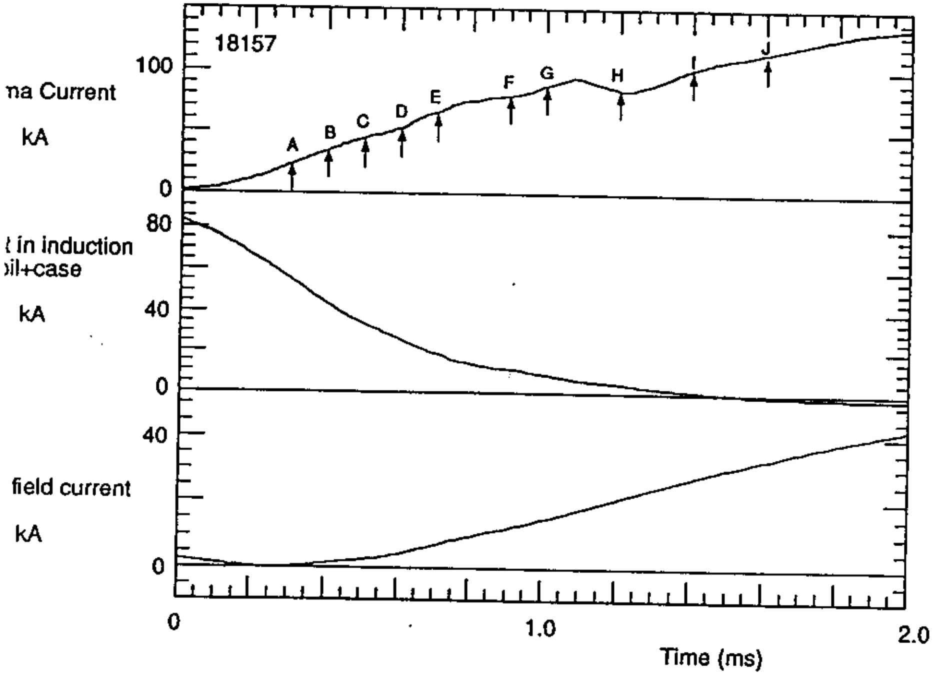
Hence: a very similar process, except one coil not two (so no questions about 'merging' or separate nulls!) and the TF is supplied differently

(note: the process worked, but spheromak plasmas in Proto-S1 were cold and of very short duration)

Study of the START Induction - Compression process



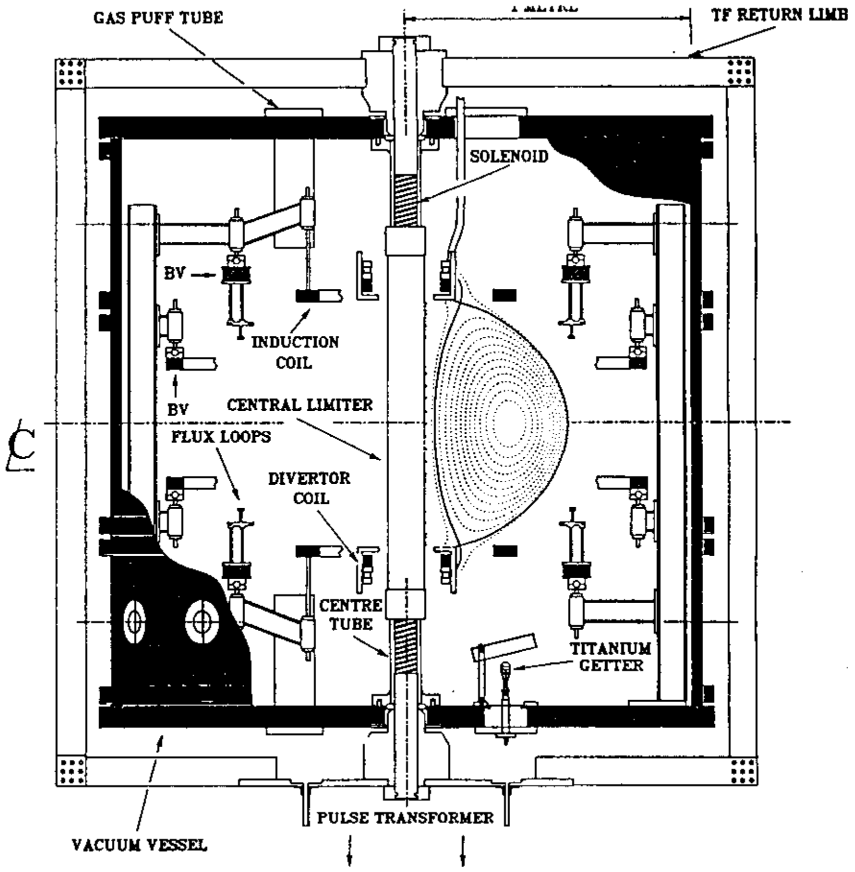
(a) plasma position inferred from CCD images. Letters refer to times shown in (b) below.



(b) waveforms, showing times of CCD images

To optimise the induction-compression in START, the PF coils have been repositioned

for example, the OH coils have been moved in height from ±26cm to ±45cm



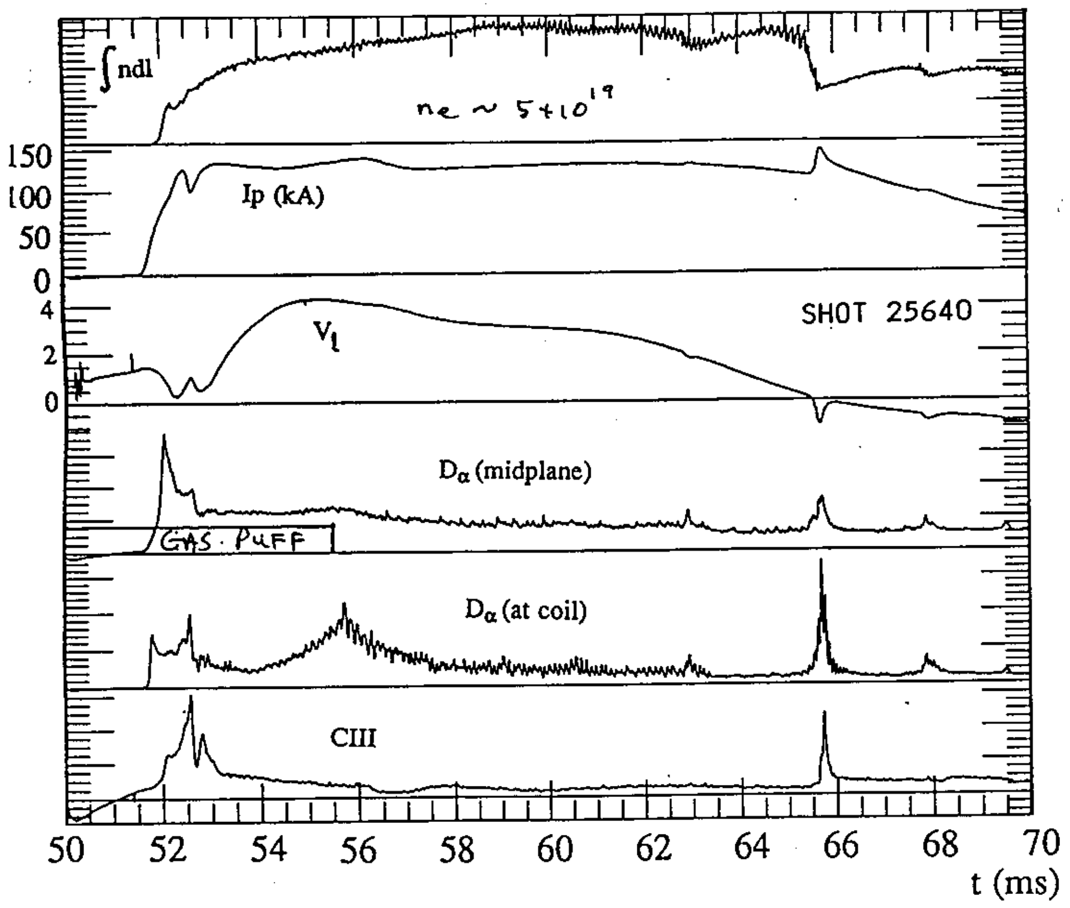
START layout, April 1997

Flux surfaces shown are for TOPEOL reconstruction of high-beta #32993 ($\beta \sim 32\%$)

The 'compression' is now small (say from 40cm to 30cm)

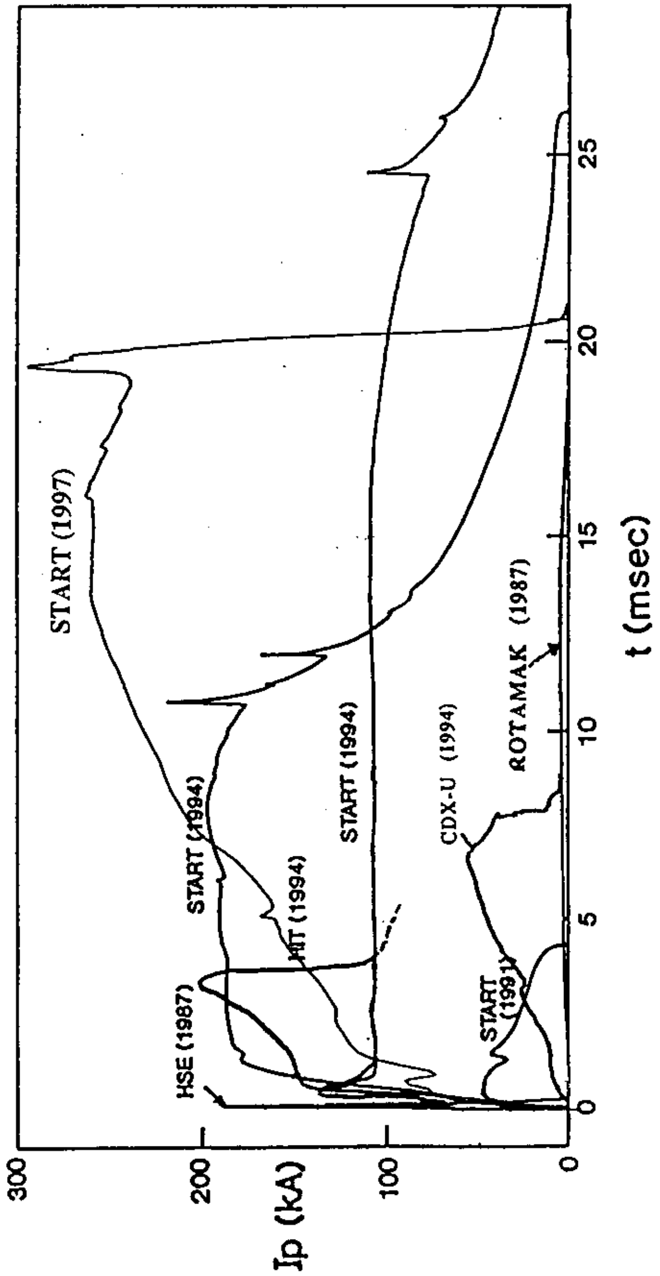
Waveforms for Ohmic START #25640

(Using OH coils to produce DND configuration;
from video shown at 1995 EPS Conf, Bournemouth)

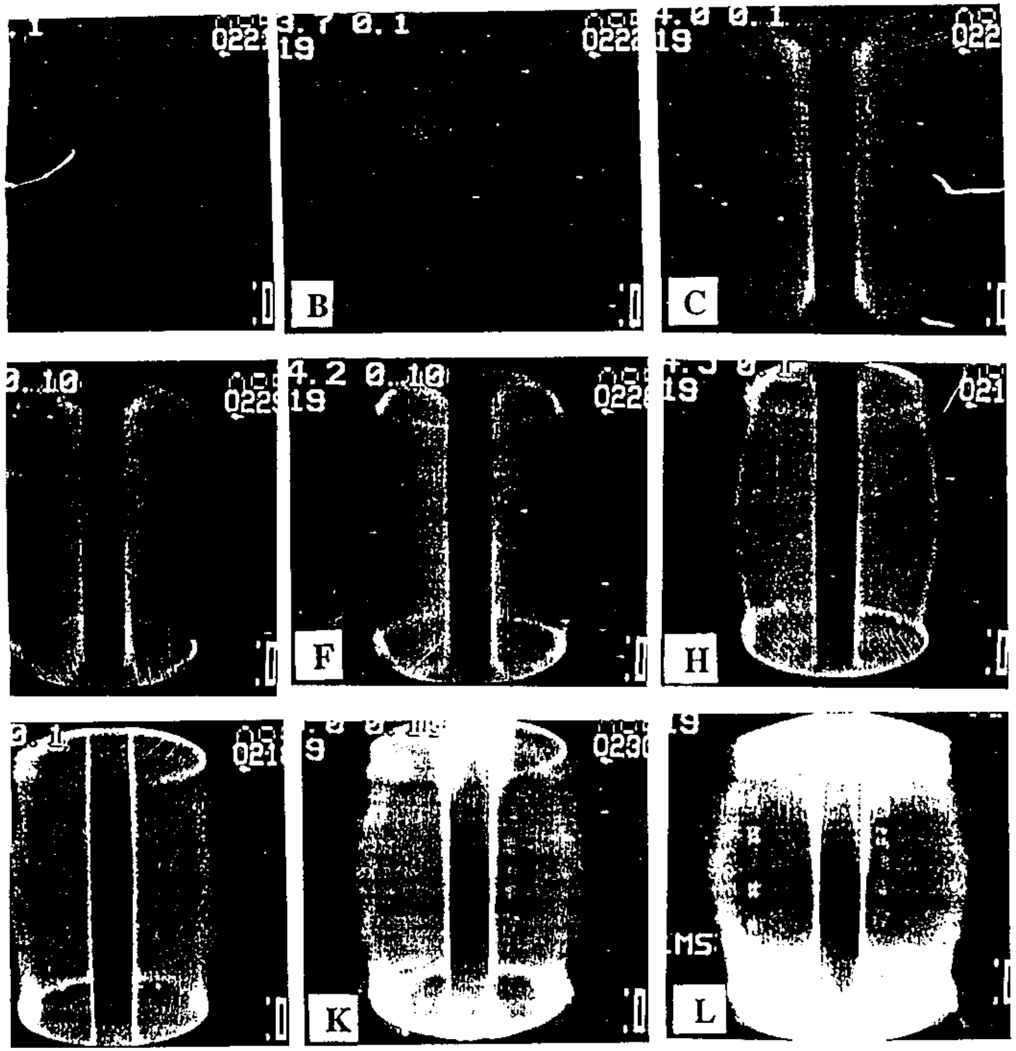


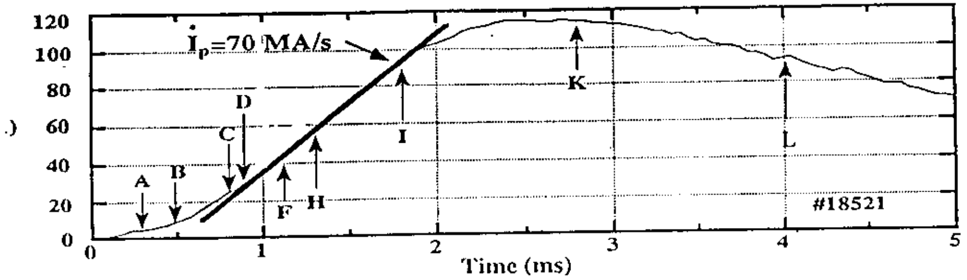
Note:
- increase in density after gas puff stops
- D_α (X-point)
- sudden reduction in D_α (X-pt) at t=63, accompanied by increase in ∫ndl

PROGRESS IN ST DISCHARGES 1987 - PRESENT



Rapid Current Ramp in Elongated lasmas by Direct Induction in START





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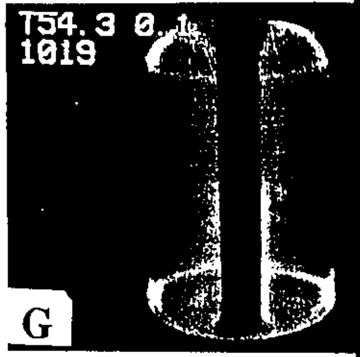
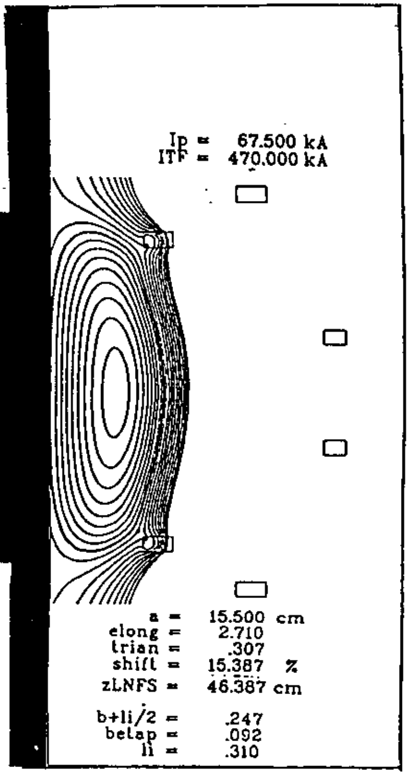
current ramp can produce hollow current profiles and hence very elongated plasmas



CCD image of highly elongated plasma

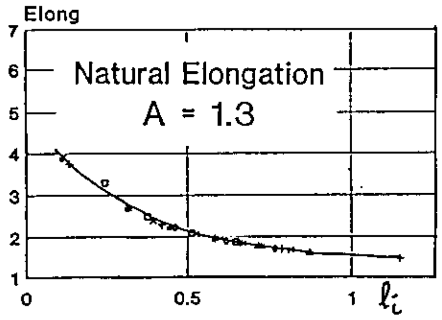
18607 at t = 24.3ms

R_0 = 22cm, a = 15.5cm, k = 2.9

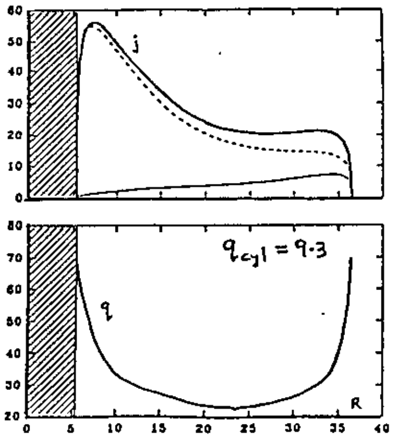


DEPS reconstruction

a = 15.5, R = 22, k = 2.7

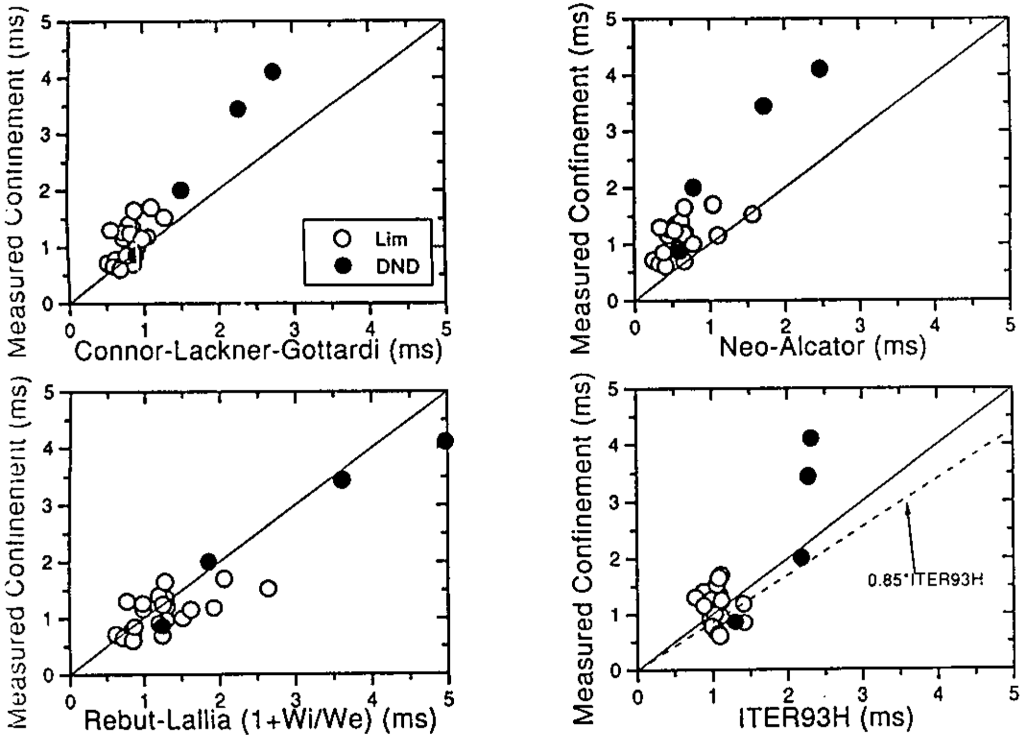


Elongation vs. li in uniform vertical field at A = 1.3 (from equilibrium code)



START OH confinement data, compared with various scaling laws (EPS Bournemouth, 1995)

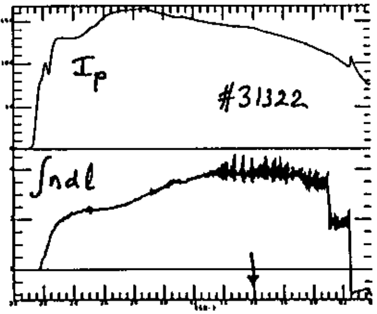
The DND discharges (solid dots) were obtained using the induction coils (radius 35cm) as X-pt coils, and so had aspect ratio A ~ 1.6

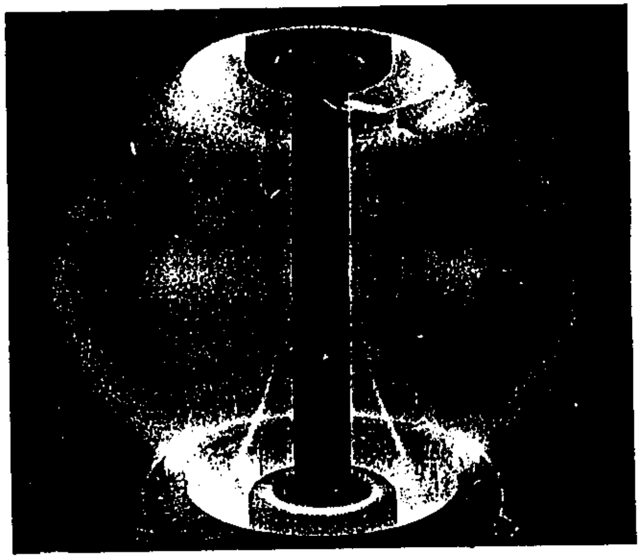


The proper X-pt coils were fitted in Oct 95, and vacuum conditions and plasma condition were poor until the recent vacuum break (Nov 96).
OH discharges were poor - cold, hollow Te profiles, radiating cores etc.

'Radiating Core' in START

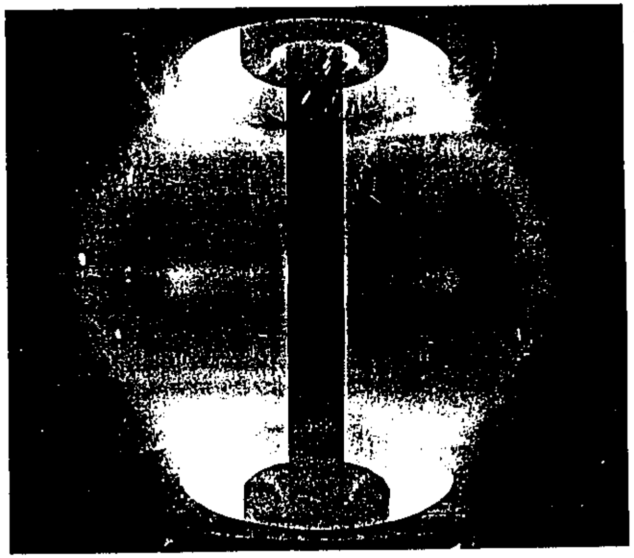
35mm photos of DND START plasmas, September 1996





 # 31322
t = 36ms

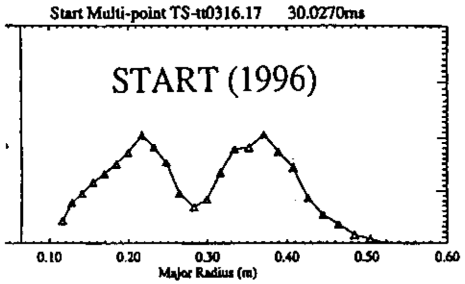
Two possible sources of impurities are contact with the steel OH coil cases, and impurities from the leaks in the upper X-point coil (fixed in the Oct-Nov 96 vacuum break).

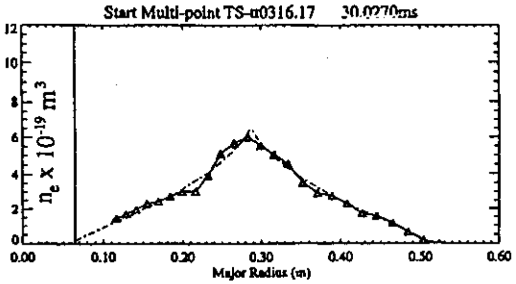


# 31323
t = 38ms

Impurity contamination on START

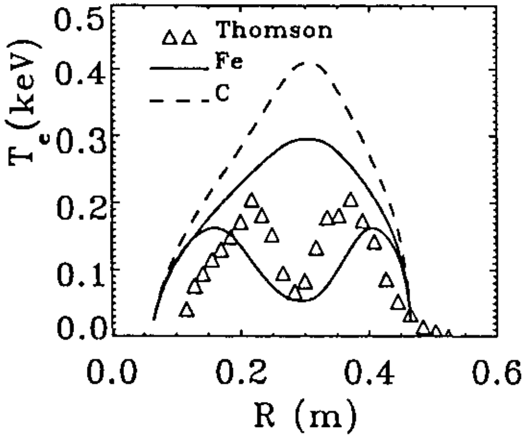
In 1996, hollow T_e profiles were often observed in OH discharges:

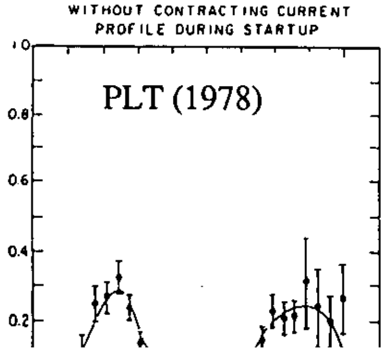




Modelling suggests that this could be caused by influx of high-Z impurities, probably from contact with a steel diagnostic coil on the OH coils:

ASTRA model (Colin Roach), assuming Zeff = 3.5 produced by 0.4%Fe (full lines), or 17%C (dashed line).



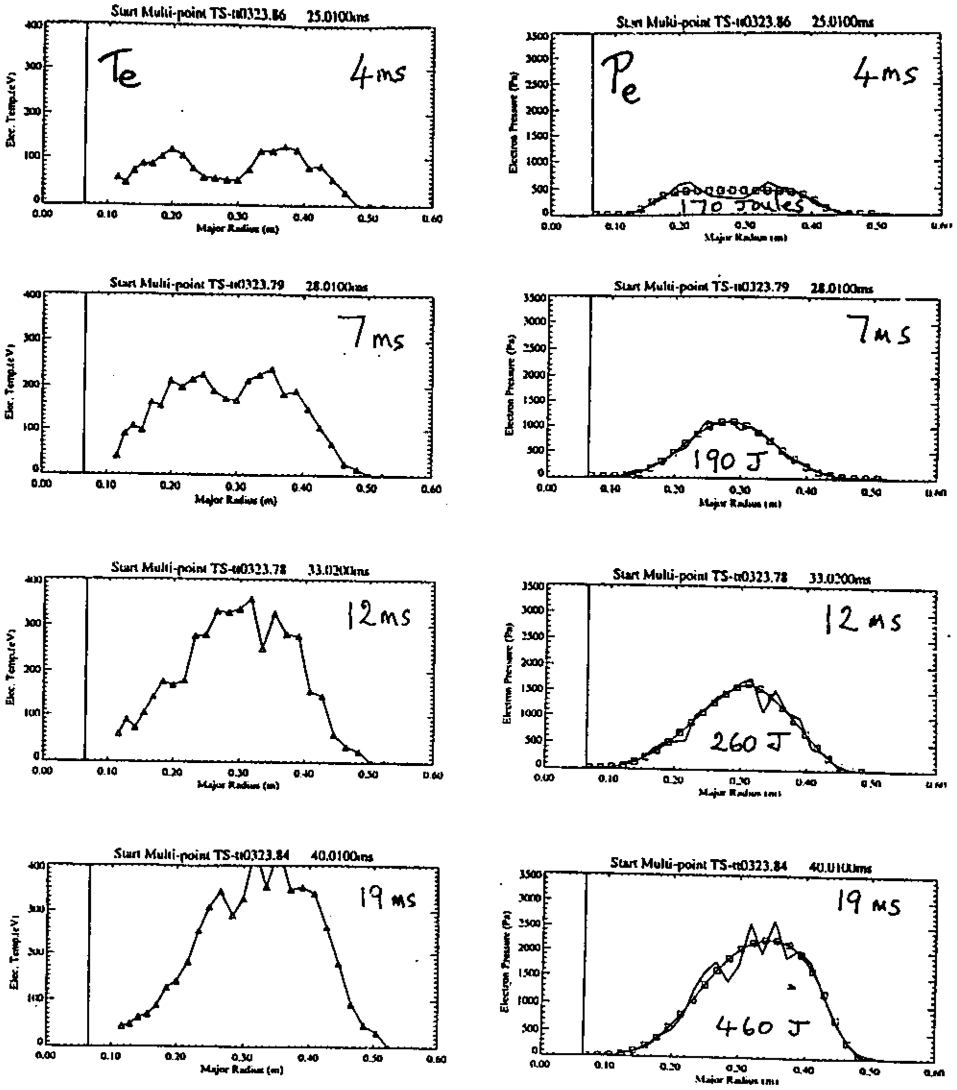


- similar problems occured in PLT (Hawryluk, Nucl.Fus. **19**,1307 (1979)

Action: move coils to keep plasma away from OH coil cases; shield steel rogowski case in graphite.

Evolution of a 200kA START Ohmic discharge, Jan 1997

Following the Oct-Nov 96 vacuum break *(leak in upper X-point coil repaired; coils moved closer together to give smaller, higher power density plasmas with increased clearance between SOL and steel OH coil cases)* plasma conditions in Ohmic discharges were much improved



electron temperature and pressure profiles obtained from 30-point

The ORNL neutral beam injector

Installed at Culham during 1995

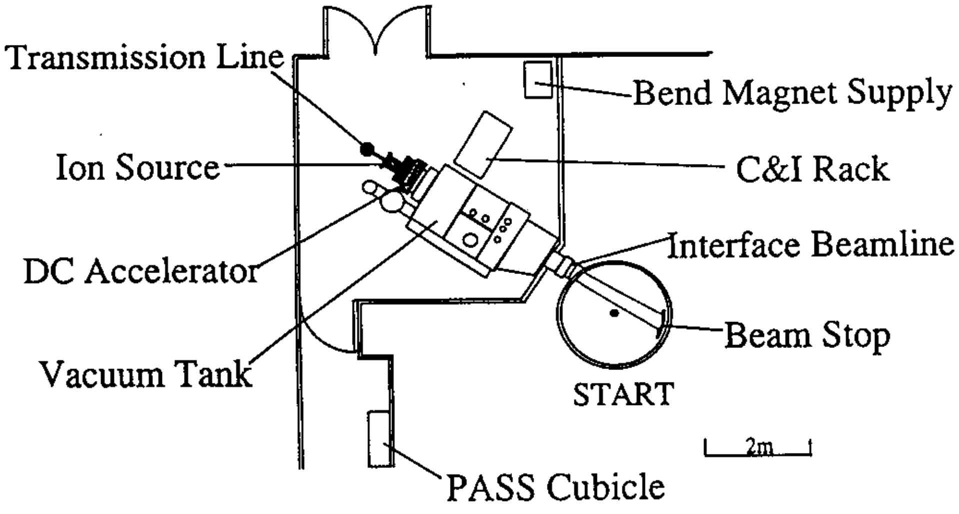
1996: injection of 200 - 400 kW @ up to 30keV

$H \Rightarrow H$; $H \Rightarrow D$; $D \Rightarrow D$

1997: injection of up to 550kW @ ~ 30keV, $H \Rightarrow D$

A getter pump was installed in May 1997: this has increased the max. NBI power available up to ~ 1MW

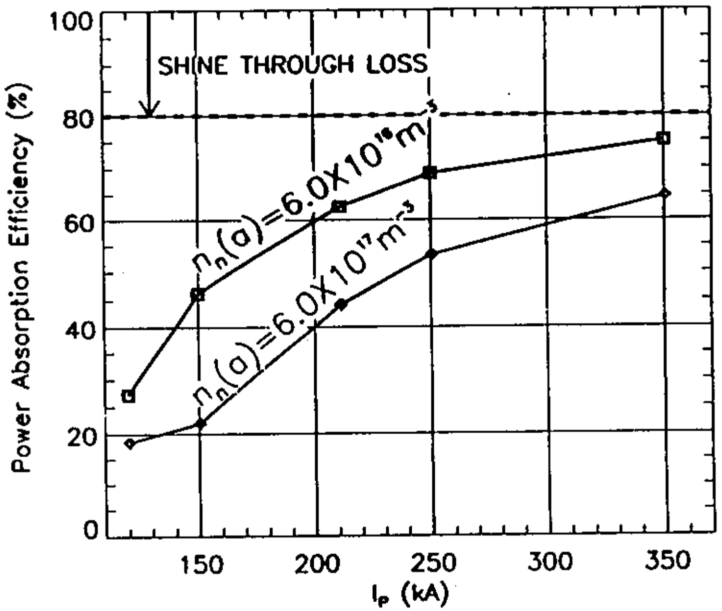
- Modelling of power absorption efficiency
- Observations of electron and ion heating



START Neutral Beam Injection Geometry

Modelling of P_{NBI} absorbed by plasma

- this depends on density (shine-through losses) and on I_p and edge neutral density (orbit losses)



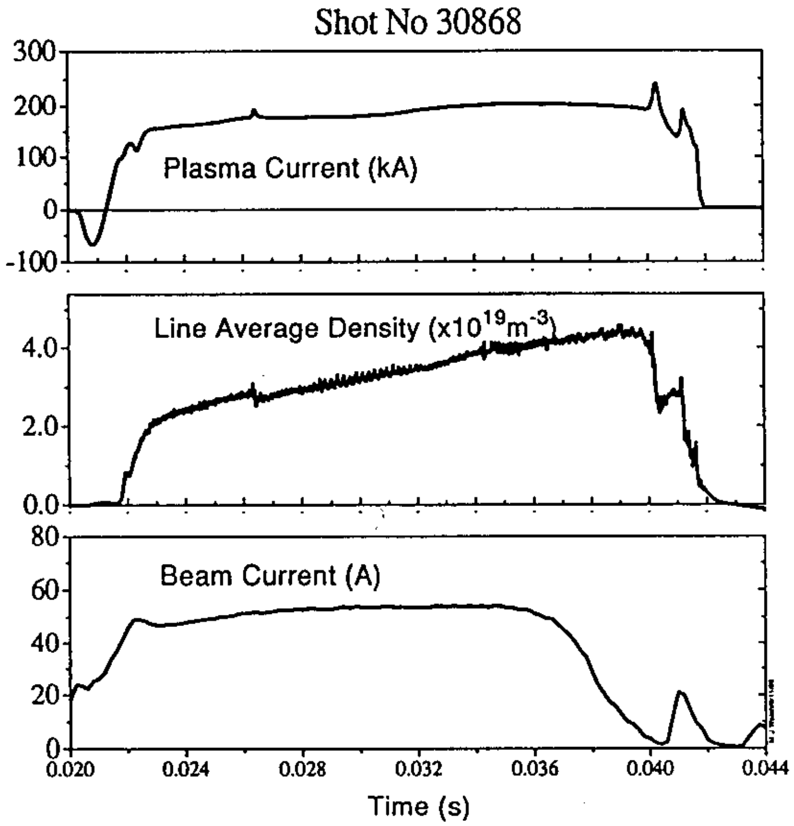
Power absorption efficiency for conditions representative of high β shots 32993, 33005.

These curves asume $\bar{n}_e = 3.5 \times 10^{19}\ m^{-3}$; shine-through losses reduce to 7% for $\bar{n}_e = 6 \times 10^{19}\ m^{-3}$

Example of NBI heating : START shot 30868

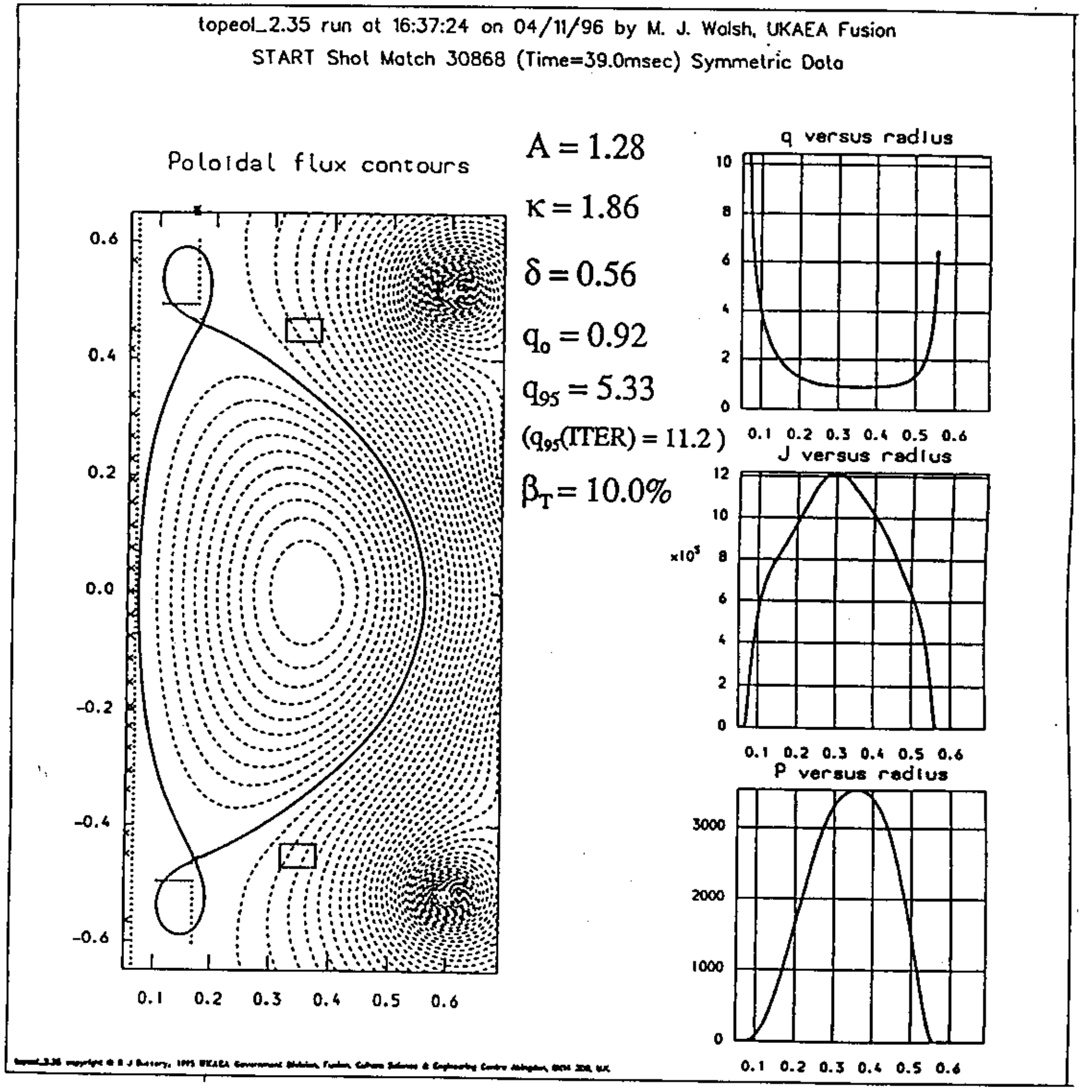
$P_{NB} \sim 400kW \pm 100kW$ (i.e. $P_{NB} \sim P_{OH}$)

(1) experiment waveforms



Example of NBI heating : START shot 30868

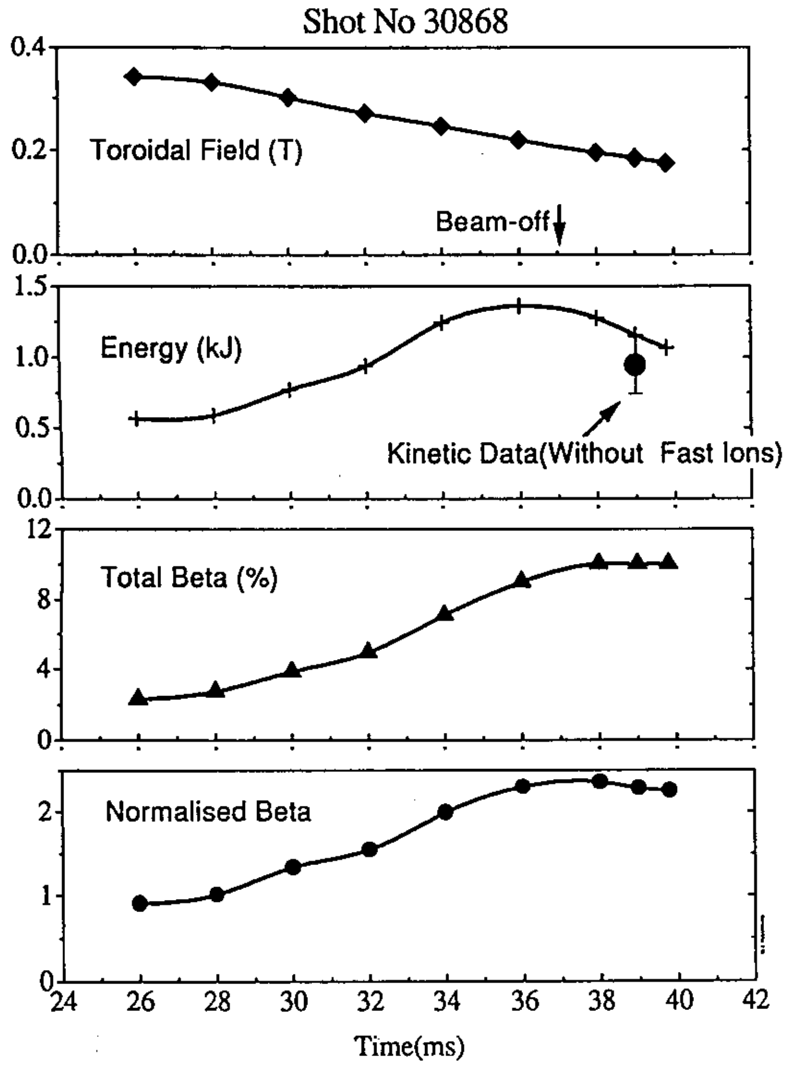
(2) equilibrium reconstruction at time 39ms, using TOPEOL



Fitting to centre column Bv coils, flux loops, diamagnetic signal, TS data

Example of NBI heating : START shot 30868

(3) results: time evolution of total plasma energy, total beta and normalised beta



In this discharge, total beta values of $\beta_T > 10\%$ and normalised beta of $\beta_N \sim 2.4$ were attained

The physics of START plasmas

selected topics:

Energy confinement

[heating and confinement; comparison with scaling laws for Ohmic and auxiliary heated discharges]

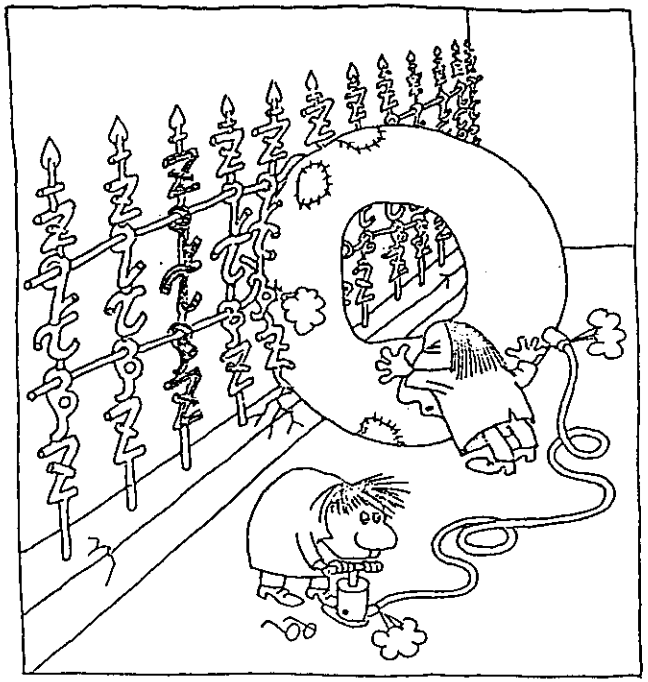
High β properties

[comparison with Troyon limit for highly shaped discharges: achievement of record values $\beta_T \sim 10\%$ in Ohmic plasmas, > 30% in NBI plasmas]

MHD properties

[m = 1 islands, snakes, sawteeth; m = 2 modes; Internal Reconnection Events; major disruptions]

Energy Confinement



The Spherical Tokamak offers exciting possibilities:

- high ExB shear to provide transport barrier, suppress micro-turbulence [1,2]

- at high β , reversed processional drift should stabilise trapped particle drift waves [3]

- at high β, true magnetic well in |B| appears [4]

BUT τ_E is difficult to measure in START, and theoretical insight is confused because START is fairly collisional

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[1] Stambaugh R et al, 1997, Proc of 4th International Symposium on Fusion Nuclear Technology (Tokyo) submitted to Fusion Engineering & Design

[2} Dorland W, invited paper 1997 APS

[3] References in Roach C M et al 1995 Plasma Phys. Control. Fusion 37 p679

[4] Palumbo D 1968 Nuovo Cimento 53 507

Ion and electron profile diagnostics

T_e, n_e, T_i and V_ϕ are measured

20 chord Doppler spectrometer:
- Lines of sight normally configured for equatorial plane
- Use C^{6+} line @ 529.1nm, both with and without NBI
- Deconvolve line-integrated signals to find radial profiles
- $T_i(r)$ and $v_\phi(r)$, typically every 2ms

30 point single-pulse Thomson scattering system → $T_e(r)$ and $n_e(r)$

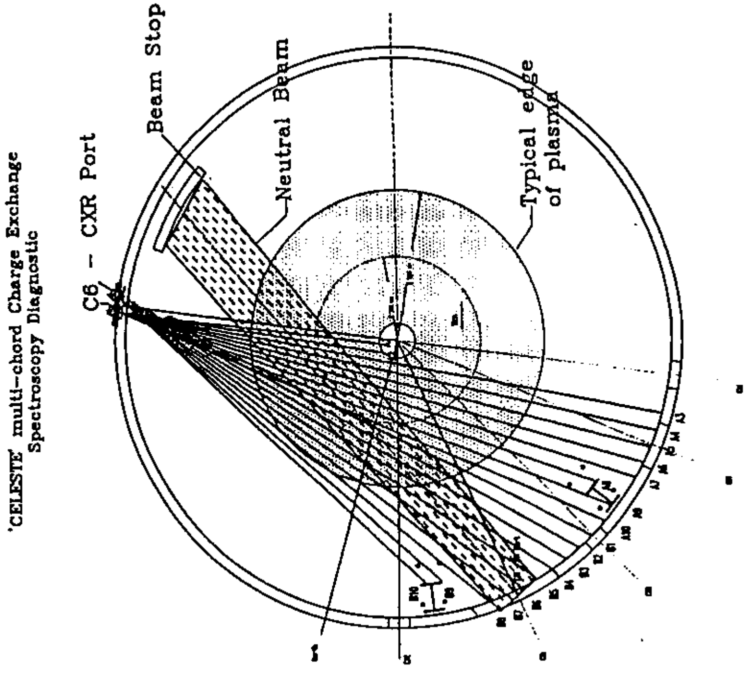
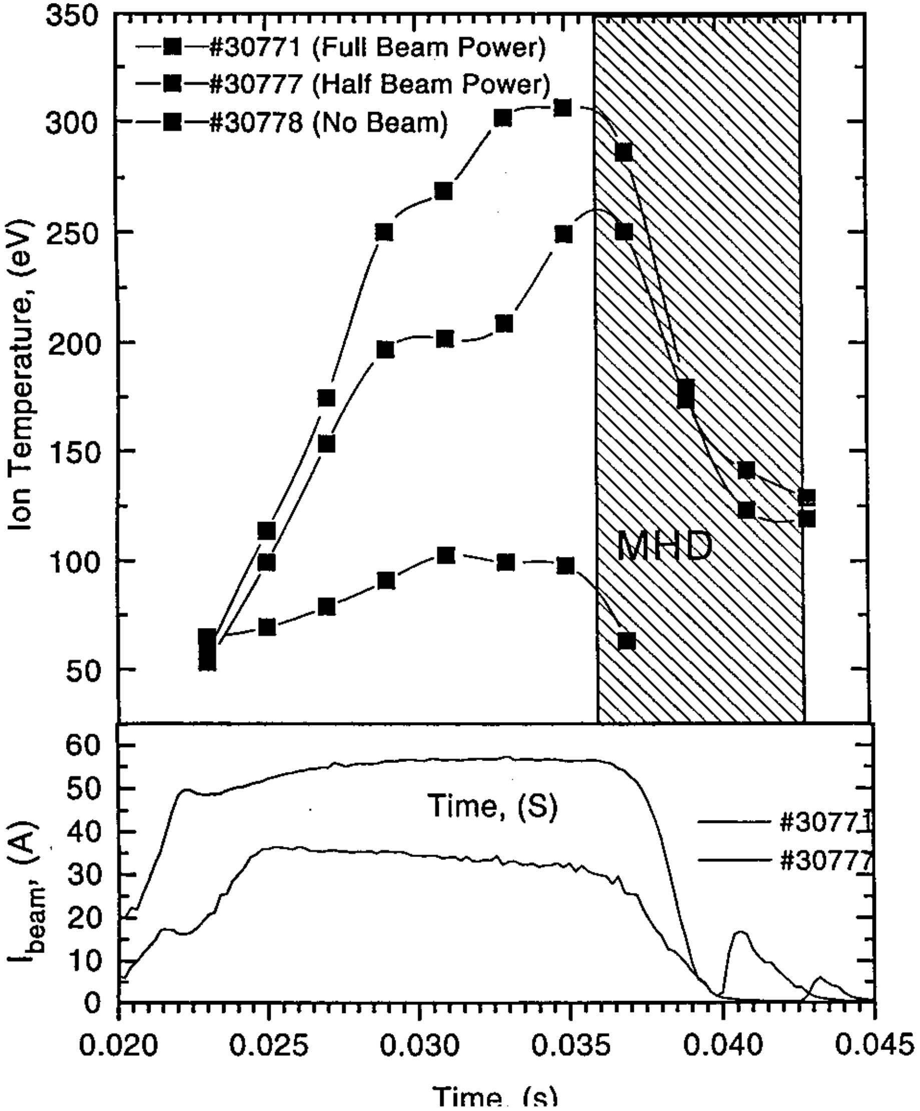


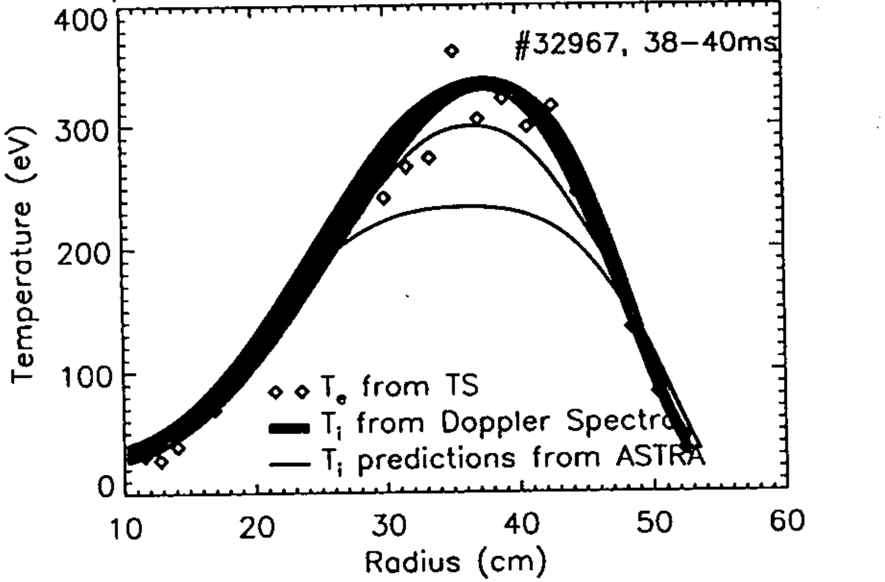
Figure 1: Plan view of the START midsection, showing the lines of sight for the Doppler spectrometer. These are composed of two independent sets, each with 10 chords, and use f/2 collection optics and fibres.

THE EFFECT OF NBI HEATING ON START IS MOST OBVIOUS ON THE IONS:



Ion Temperature for Different NBI Power
(START #30771,#30777,#30778)
CELESTE-1

In NBI heated discharges, ion temperature profiles (obtained by the CELESTE Charge-Exchange diagnostic)[1] are found to be very similar to the electron temperature profiles (measured by Thomson Scattering).



Comparison of Electron and Ion temperature

Also shown are the results of the ASTRA modelling for this discharge, which shows good agreement, and indicates that **the ion energy confinement is approximately neoclassical[2].**

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[1] P G Carolan et al, Rev. Sci. Instr, 68 No 1 part II, 1997 p 1015

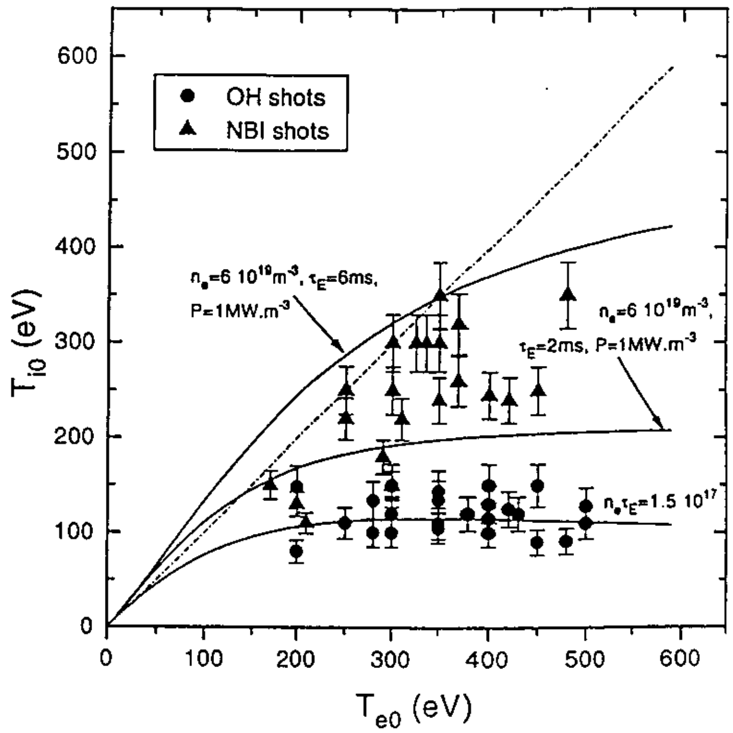
[2] P G Carolan et al, 1997 EPS Conf Berchesgaden

Measured central ion temperatures are plotted against central electron temperatures

Also plotted are *calculated* central on temperatures, based on the ndicated values for the energy confinement time and density, and a simple 0D calculation.

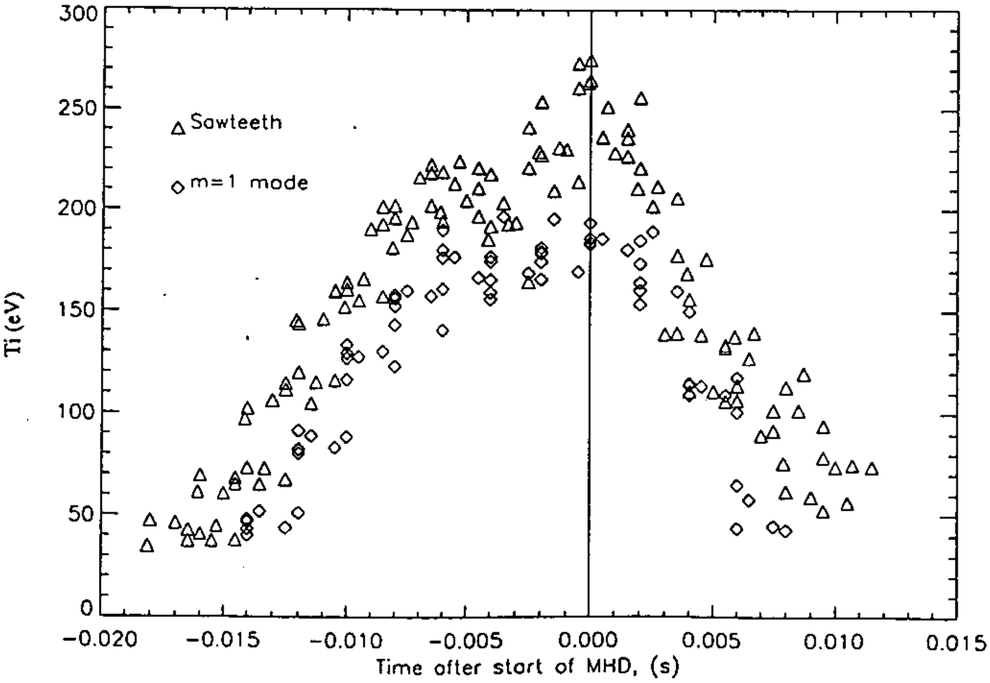
The auxiliary heating power density assumed is approximately correct or all the measurements shown.

This data implies an ion energy confinement time of the order of 4ms, about 50% more than the total energy confinement time.



Sawteeth and MHD activity

During high-β NBI plasmas, sawteeth and low m,n modes have a similar effect on the ion energy confinement, as shown in Fig. 10 (below). T_{i0} falls quite rapidly, and it is estimated that the ion confinement time falls to ~ 1ms.



This result may be merely the consequence of enhanced transport due to the large-scale MHD, but it is consistent with recent modelling[1] which shows that the ion neoclassical confinement reduces dramatically at the high densities and low toroidal fields typical of these high-β discharges.

[1] Yuri Dnevstrovsky, private comm. Oct 1997

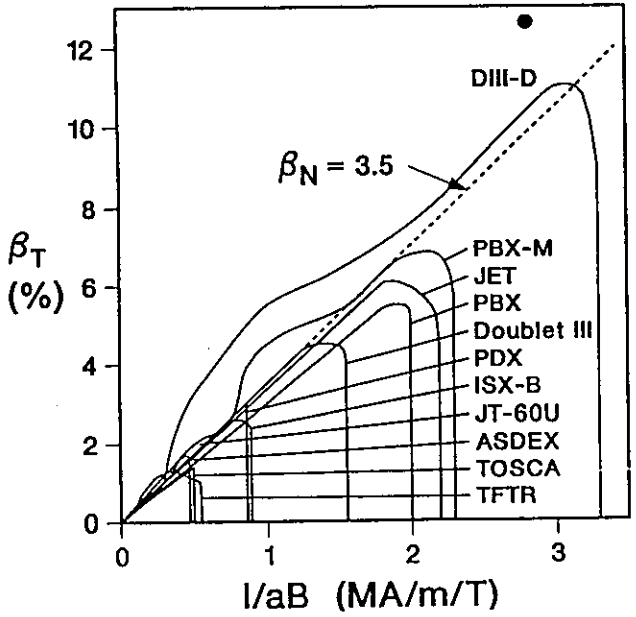
HIGH BETA VALUES ARE EXPECTED IN SPHERICAL TOKAMAKS:

- Theory:

the Troyon limit [1] , $\beta_T = \beta_N . I/aB$, can be written in the form [2] $\beta_T = 5\beta_N . \kappa / Aq_j$

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 $q_s \sim 2$

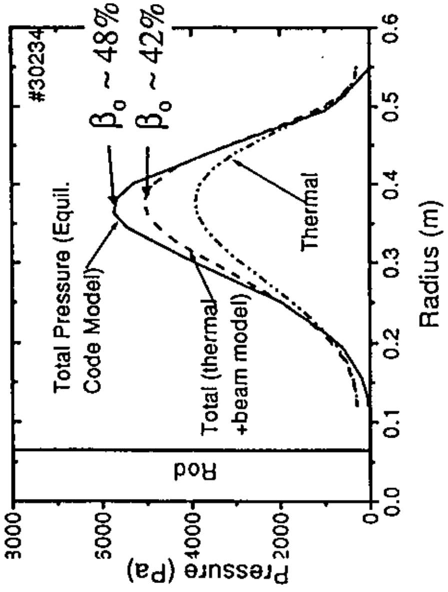
Large aspect ratio, circular section machines meet this q_s=2 limit at low I/aB and so have low β

[1] F.Troyon et al, Plasma Physics & Controlled Fusion,26,(1984) p209

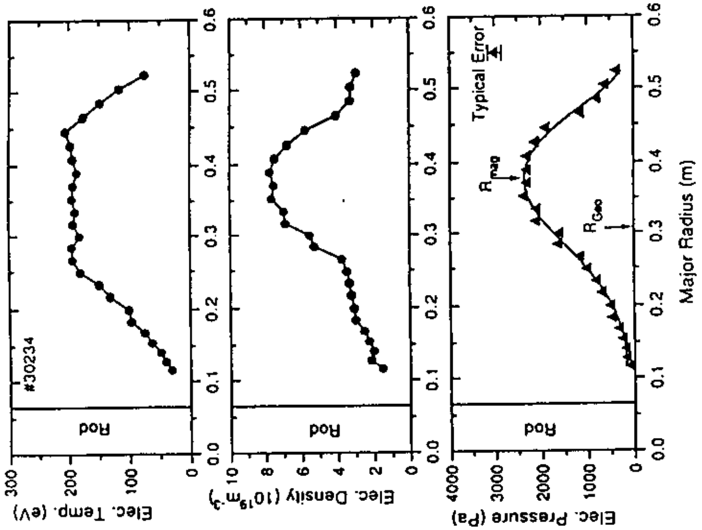
[2] A Sykes, M F Turner & S Patel, in Proc. of 11th EPS, Aachen, 1983

World record β values have been obtained - first, record central β (June 1996[1])

PLASMA PROFILES IN *START* HIGH - β SHOT 30234



Components of total pressure



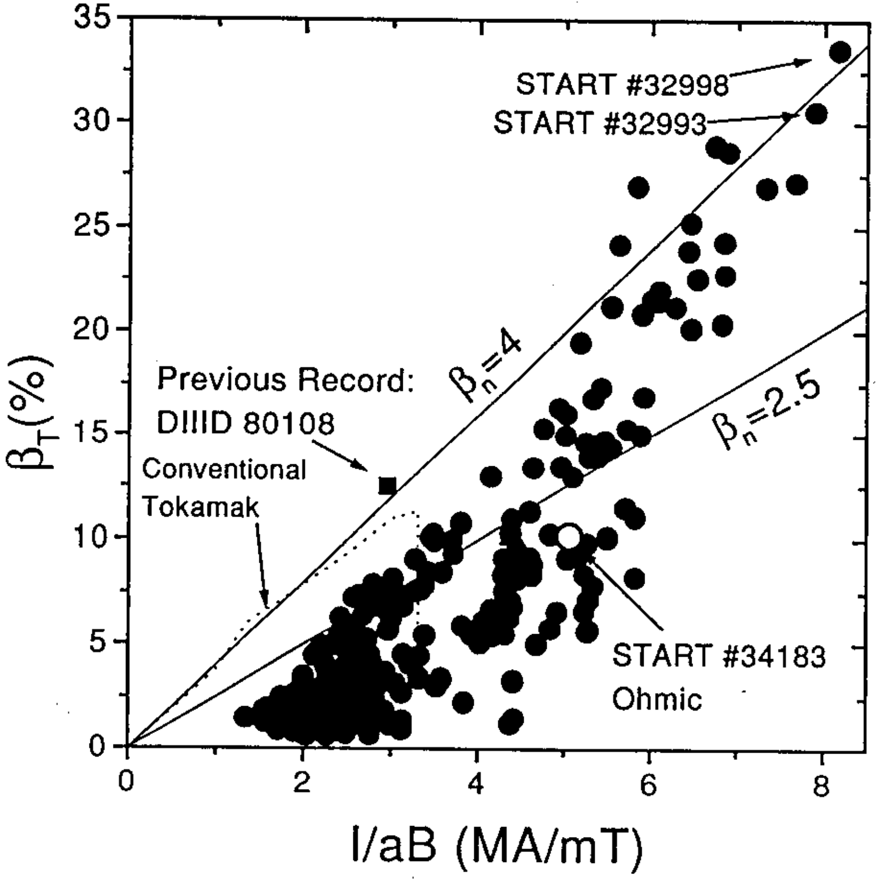
Electron temperature, density and pressure profiles from 30-point Thomson scattering

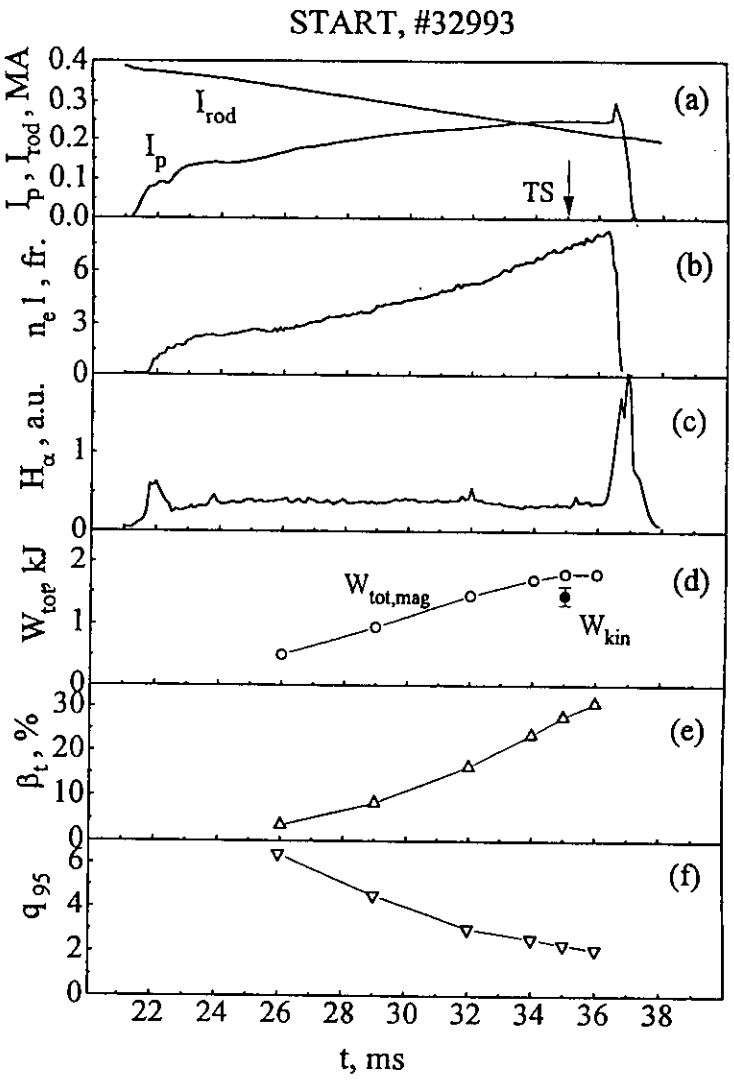
[1] M J Walsh et al, Proc. 21st EPS conf (Kiev) 1996

Record volume average β, $\beta_T = 34\%$ (March 1997[1])

The Ohmic beta β_T value of 10% is also a tokamak record

[1] A.Sykes, Proc 22nd EPS Conf (Berchtesdagen) 1997, to appear in PP& CF





Waveforms for high-beta START #32993.
At t = 36ms, I_p/I_{rod} =1.2 and β_T = 30%

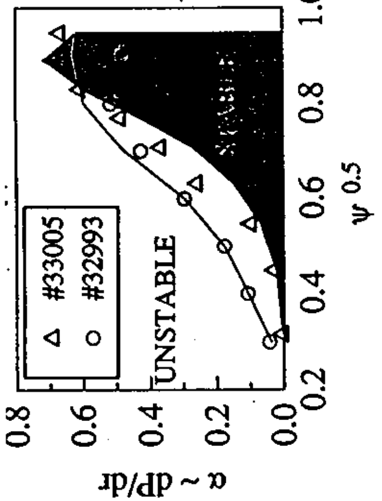
W_{tot}, β_T and q_{95} values from equilibrium reconstruction (TOPEOL, EFIT codes), consistent with kinetic data (TS, CX) obtained at t=35ms (fast ion component, not included, estimated at 0.3kJ)

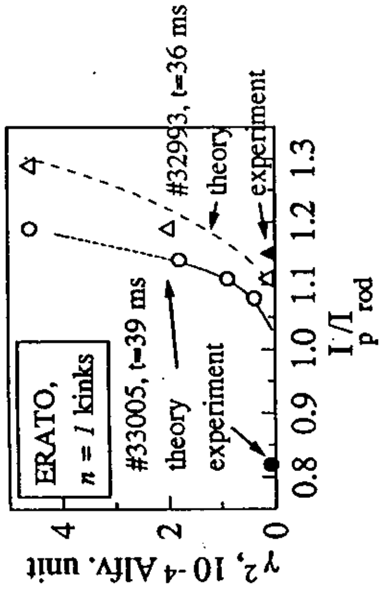
STABILITY ANALYSIS

for the two examples :

#32993 reaches $\beta_T \sim 31\%$, $\beta_N \sim 4$, $q_{95} \sim 2.3$

#33005 reaches $\beta_T \sim 24\%$, $\beta_N \sim 4$, $q_{95} \sim 2.8$





Both shots are close to marginal stability to high-n ballooning modes

ERATO modelling (using similar equilibria) predicts #33005 to be stable to external modes; #32993 unstable

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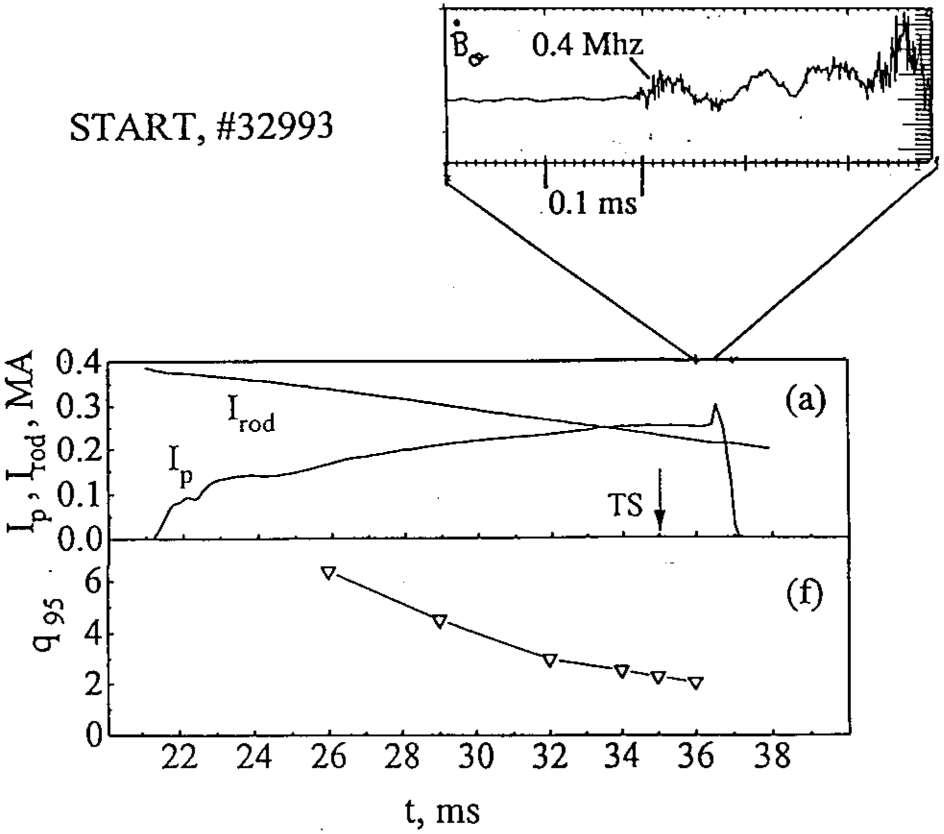
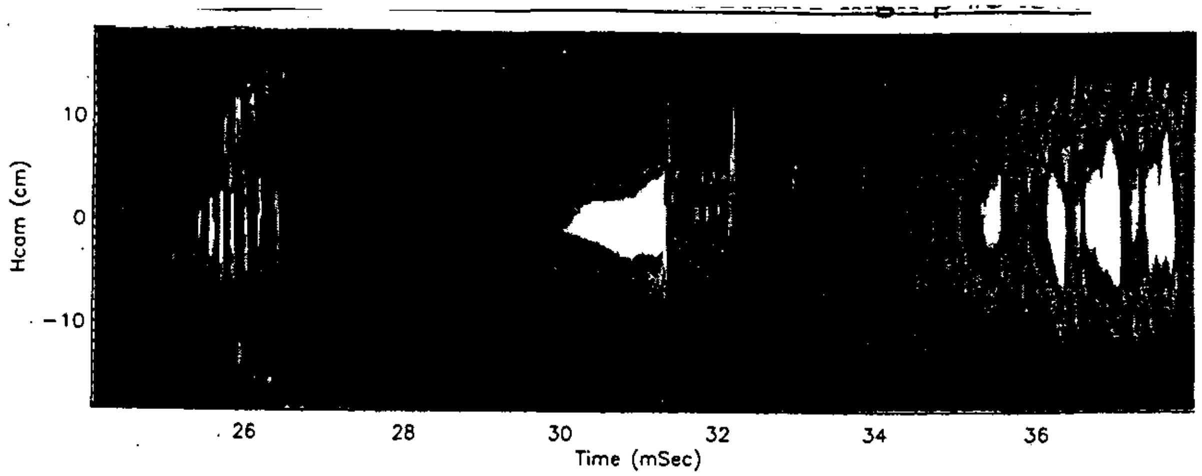
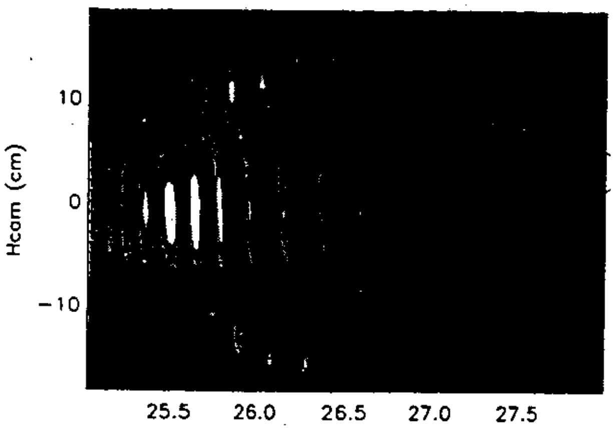
Low n MHD activity (~ 10kHz) is observed on the centre-column Mirnov coils for ~ 0.3ms prior to the IRE / termination:

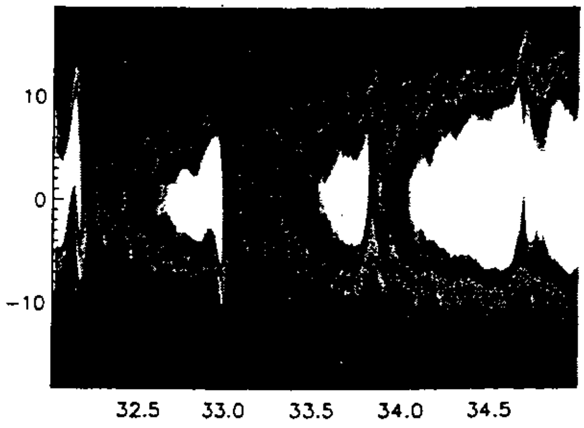


Equilibrium reconstruction indicates $q_{95} \sim 2.3$ at this time



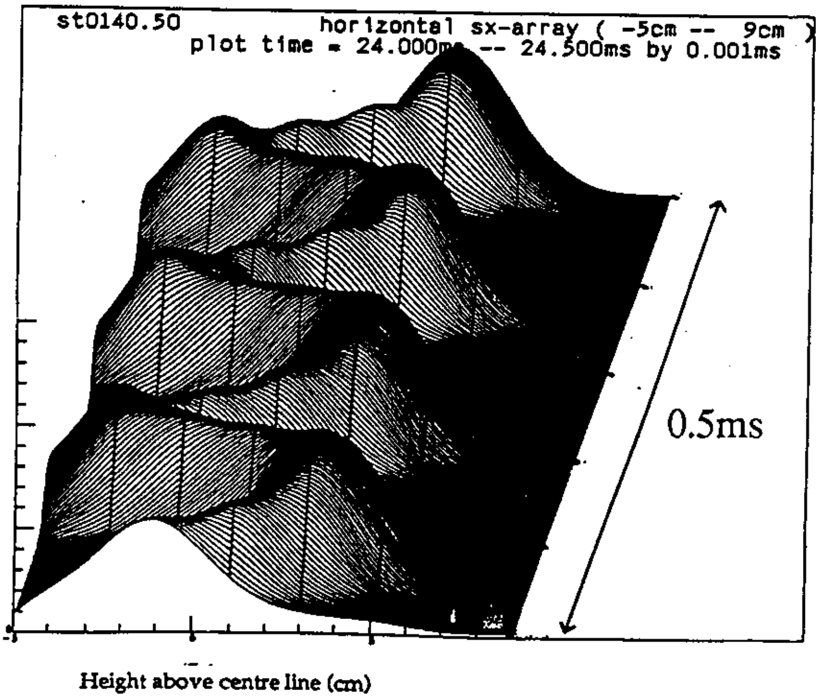


m = 2 islands appear when q_0 falls below 2



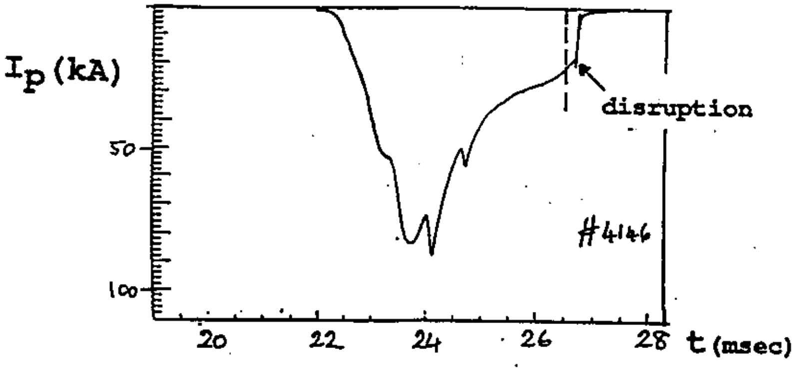
m = 1 sawtooth activity begins when q_0 falls below unity

After formation sawteeth and occasionally snakes indicate $q_0<1$



Absence of the 'major disruption' at low-A

Conventional major disruptions can be produced in the late stages of a START discharge, as shown in the Ip / time plot:

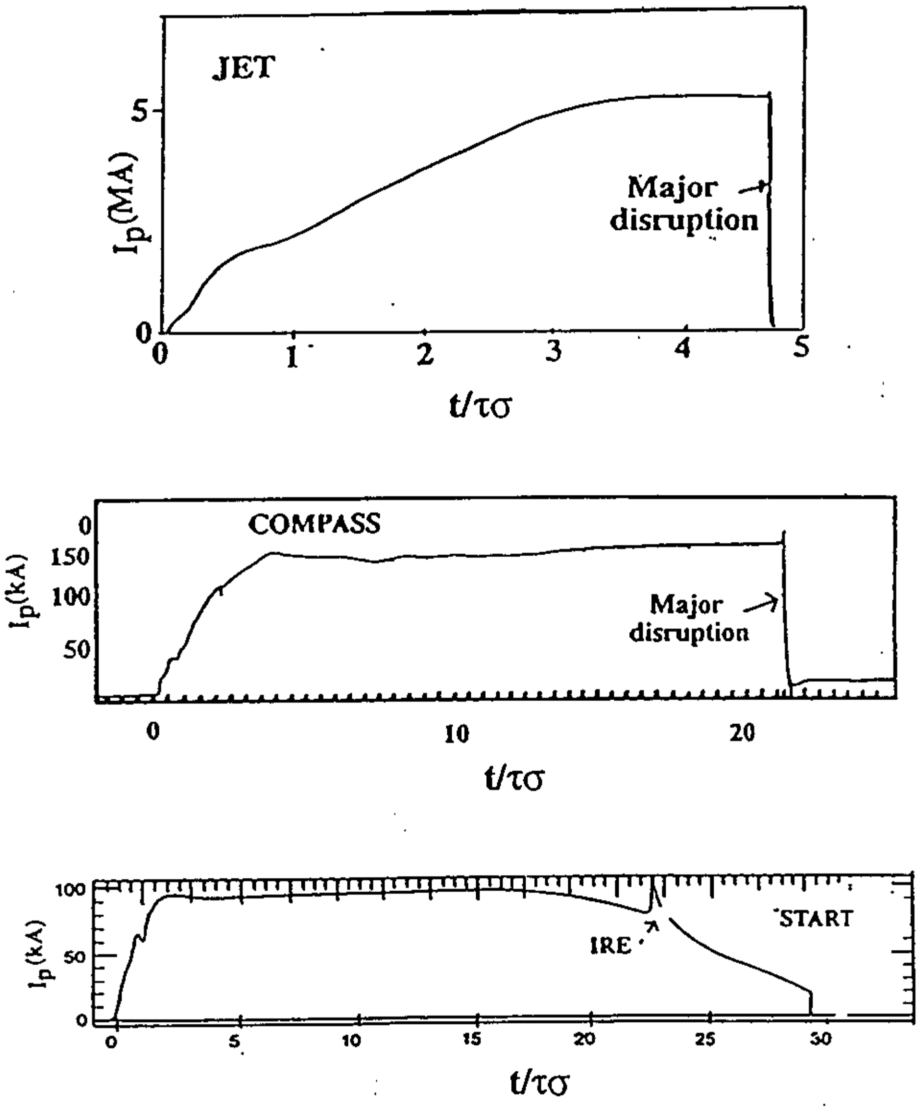


However these disruptions are only observed in START when the current column has shrunk so that the aspect ratio has increased to A ~ 2. In this example, the plasma is seen to have aspect ratio A = 2.25 just before the disruption:

#4146, t=26.5 msec

CCD image (retouched!)

If it can be verified that this is a general result, it will be a significant advantage of the Spherical Tokamak.

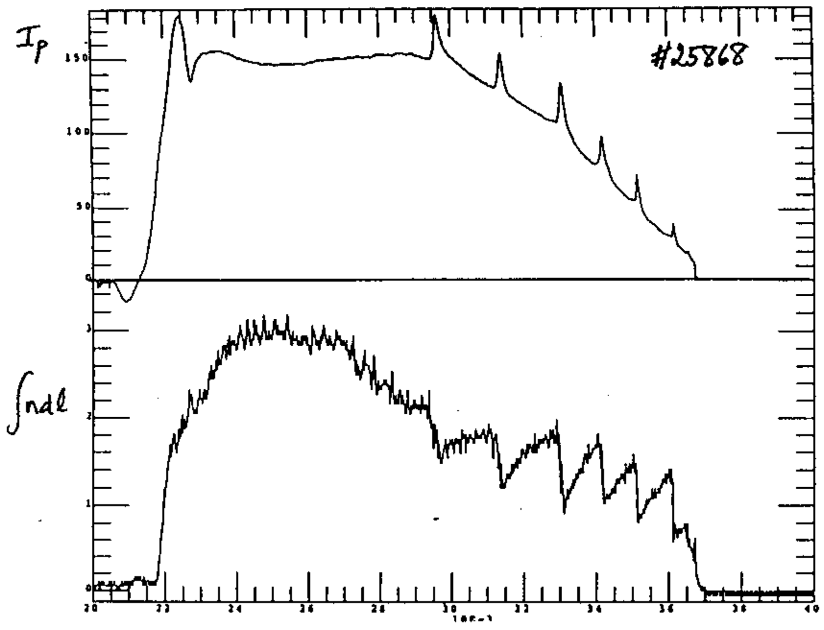


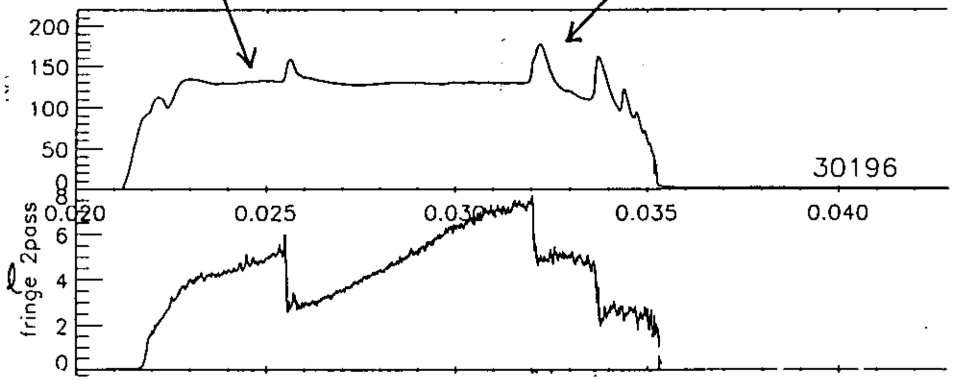
'Major disruptions in the conventional non-circular tokamaks, JET and COMPASS-D, and the internal reconnection events in START for pulse lengths normalised to the field diffusion time (τσ).

'Internal Relaxation Events' (IREs) in START

can occur under many circumstances...

q_a too low....




Too rapid a density rise, and/or severe limiter contact

density too high

IREs in START

- similar events seen in CDX-U and MEDUSA

what are they?

- probably rapid growth of an m=2 island on the q=2 surface

when do they occur?

- typically when q_0 first falls below 2; or when a density limit, or q limit is reached. An IRE usually occurs when the loop voltage reverses late in a discharge

what is observed?

- a sudden increase (10-20%) in plasma current, accompanied by an increase in elongation

what can be measured?

- TS profiles show a fall in β_p (typically x 0.5), an increase in l_i (typically x 2/3)

conjecture

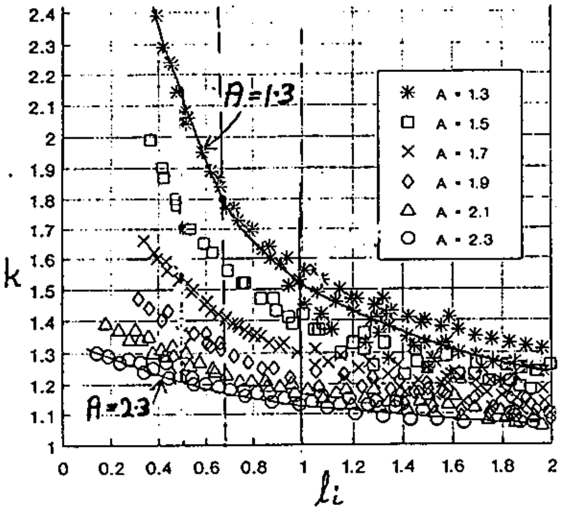
- the IRE is the first stage of a 'major disruption' (rapid current termination) which is commonly seen in tokamaks.

However in the first 4 years of START operation, no rapid current terminations were seen. Why?

Why were no major disruptions observed on START ?

reason 1: flattening of the current profile (lowering li) produces a large increase in elongation k **at low** A(but only a small increase for conventional A).

Since $q_{95} \sim (1 + k^2)$ this produces an especially large increase in q_{95} at low A



reason 2: At conventional aspect ratio A, the total plasma inductance is dominated by the external component Lext and so does not reduce significantly when li reduces at an 'IRE'.

However at low A, Lext is comparable to li and itself reduces as elongation k increases (Hirschman & Nielsen): so the total plasma inductance falls appreciably at an IRE.
This produces a much larger current 'spike' at the IRE which increases the outwards hoop force, countering the inward contraction in major radius seen at conventional A.

Hence in START, little or no reduction in major radius occurs, and there is little or no increase in interaction with the inner limiter

Compare START & JET assume in both, $q_o = 0.92$ and $l_i = 1$

START (110kA)	JET (1.6MA)
$\frac{I_{ROD}}{Ip} = 4.5$	$\frac{I_{ROD}}{Ip} = 23$
$q^* = 4.7$	$q^* = 2.8$
$q_{95} = 9.8$	$q_{95} = 3.1$
$q_\psi = 19$	$q_\psi = 3.5$
A = 1.26(initially)	A = 3.1(initially)

What happens to key parameters when we reduce l_i and βp, to simulate an IRE?

changes in key parameters if βp, $l_i \rightarrow \frac{\beta_p}{2}, \frac{2l_i}{3}$

are, for the helicity conservation model,

	START	JET
R	× 0.97	× 0.91
a	×0.965	× 0.7
∴ A	×1.02(to1.28)	× 1.3 (to 4)
k	× 1.12	× 0.99
Ip	× 1.09	× 1.03
q_o	× 1.8 (to 1.7)	× 1.3 (to 1.2)
q_{95}	× 1.13(to 11.1)	× 0.6 (to 1.9)

HENCE this example of an IRE event would:
increase q_{95} in START
decrease q_{95} in JET

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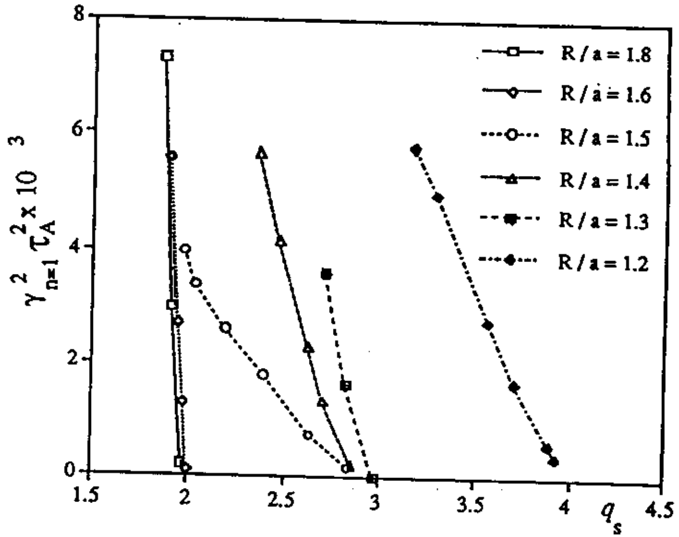
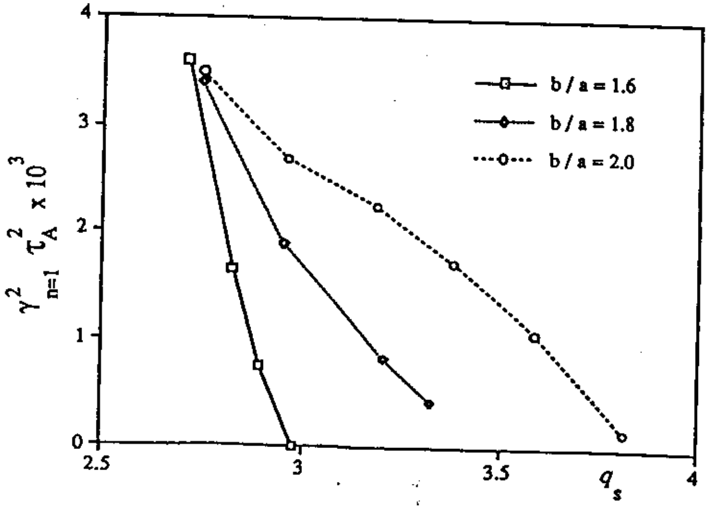
studies of n=1 kink stability

(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)

‘Internal Reconnection Events’ (IREs) in START

Natural Divertor (limited on centre column) plasmas -
⇒Oct 1994

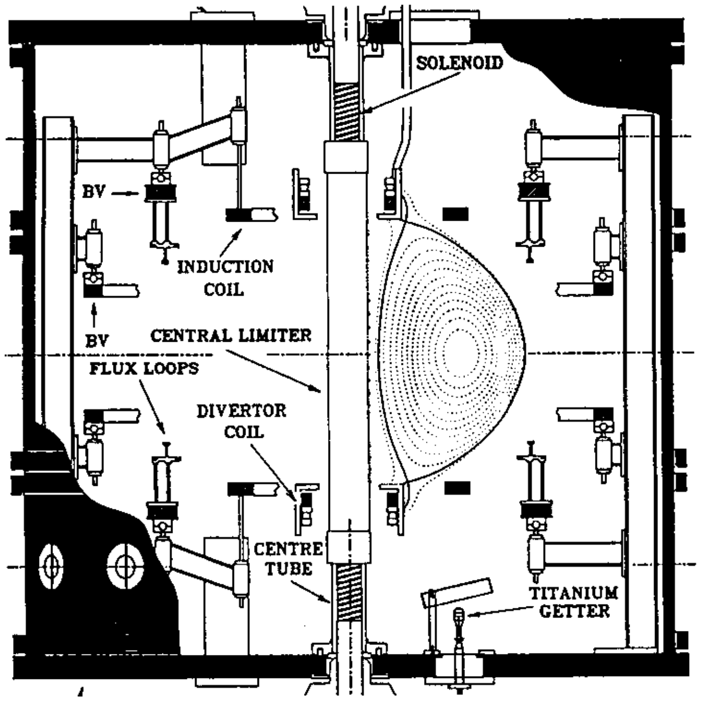
- no disruptions seen in low-A plasmas

X-pt coils fitted at $z =$ 54cm: Oct 94

- some disruptions seen

X-pt coils moved in to $z =$ 49cm: Oct 96

- many disruptions seen



START layout, April 1997

Flux surfaces shown are for TOPEOL reconstruction of

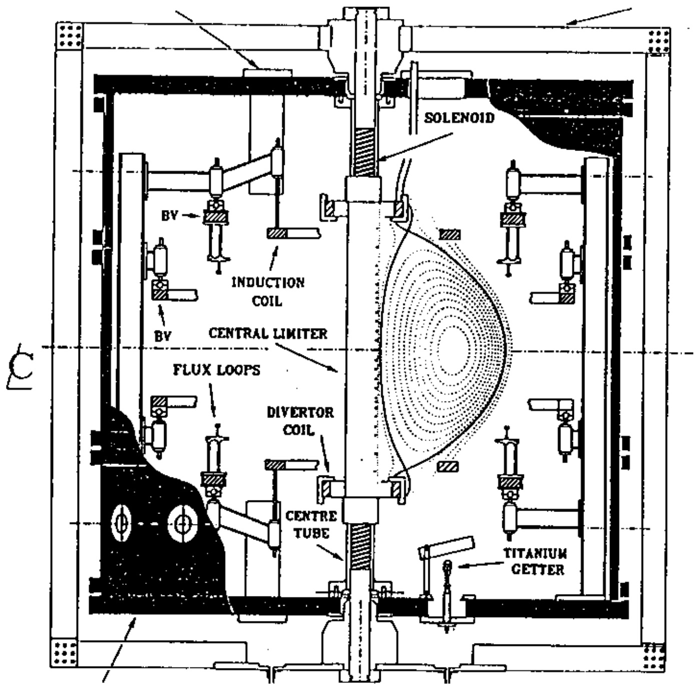
IREs and DISRUPTIONS

Modelling of the IRE has shown (R.Akers et al, Montreal IAEA conference) that the reduction in internal inductance l_i during an IRE raises the plasma elongation and, at low aspect ratio, raises edge safety factor q - thus acting to improve stability.

This work was for ‘natural’ i.e. limited plasmas.

For the present DND plasmas in START, problems may arise:

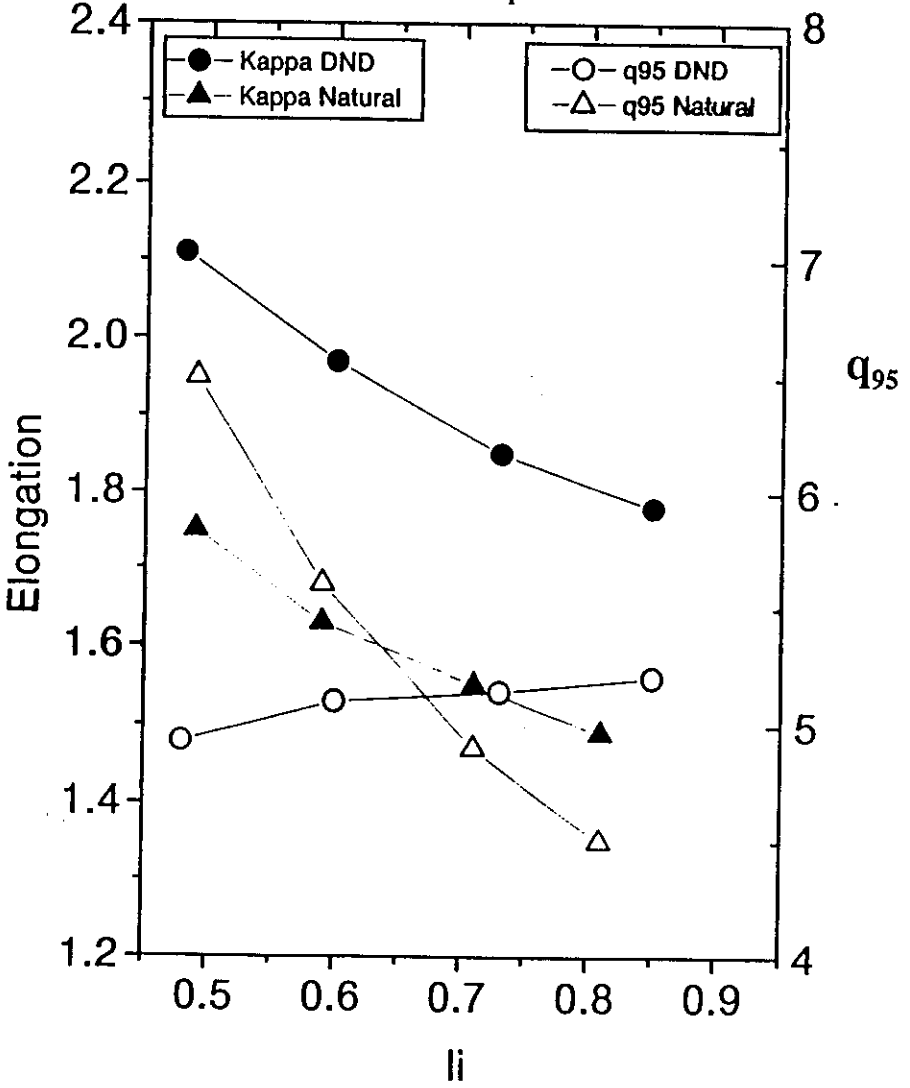
(a) the X-points are close to the coils - increasing elongation could cause the plasma to interact heavily



(b) in these DND plasmas, if the X-point remains fixed, increasing elongation evidences itself by a narrowing of the plasma shape and an increase in aspect ratio - which lowers edge q.

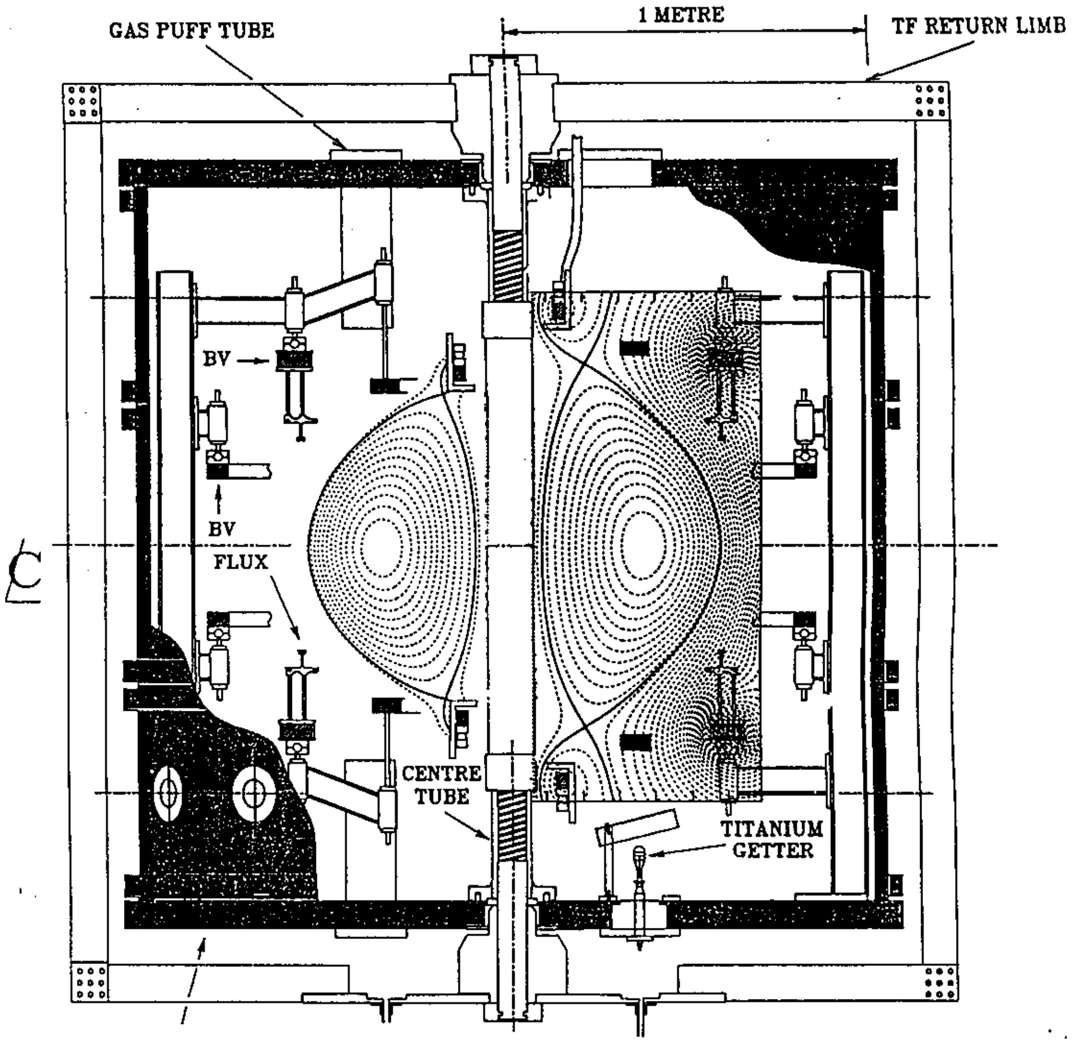
DND and naturally limited plasmas can behave differently in IRE-like events:

TOPEOL equilibrium studies, for typical START parameters, holding I_p and R_o fixed.



As l_i is reduced, q_{95} rises in a limited plasma, but falls for the DND configuration presently used in START.

CONFIGURATION (DEC 97??)



PRESENT (June 97)

X-pt coils : z = ±49cm
(originally, at 54 cm until Nov 96)
OH coils: z = ± 45cm

plasma shown is #32993
$I_x \sim 26$kA, $I_p \sim 250$kA, k=1.8
R=32.5 cm, vertical 'clearance' ~1cm
$q_{95} \sim 2.3$, $I_N \equiv I/aB \sim 8$, $\beta = 32\%$, $\beta_N = 4$
plasma Vol ~ 0.55m^3

PROPOSED

X-pt coils : z = ± 65cm
OH coils: z = ± 55cm

plasma shown has:
$I_x \sim 60$kA, $I_p \sim 250$kA, k=2.03
R=33.3 cm, vertical 'clearance' ~9cm
$q_{95} \sim 2.3$, $I_N \equiv I/aB \sim 10$, $\beta = 52\%$, $\beta_N = 5.2$
plasma Vol ~ 0.65m^3

Comparison of *START* and *MAST*

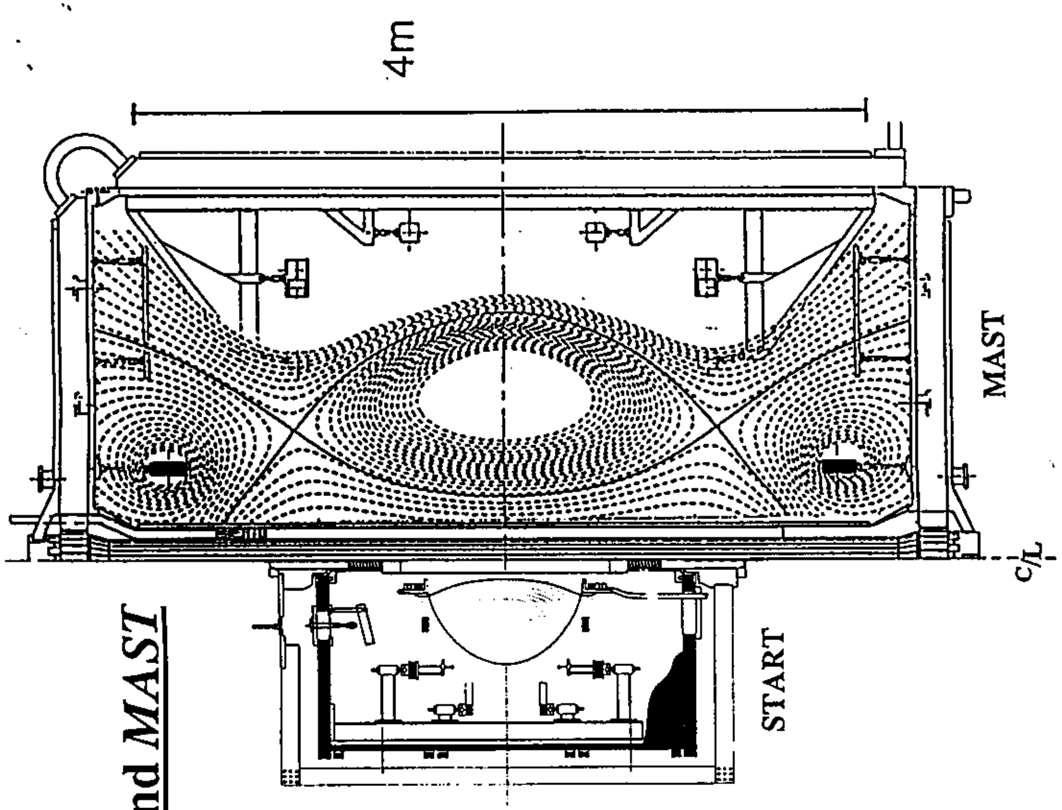


Table 1 Physics Parameters

Parameter	START	MAST
Plasma Current	260 kA	1-2 MA
Toroidal Field	0.32 T	0.63 T
Major Radius	0.32 m	0.7 m
Minor Radius	0.26 m	0.5 m
Aspect Ratio	≥1.25	≥1.3
Elongation	≤3	≤2.5
Flat Top Time	~40 msec	~0.5-1.0s
Heating Power	~500 kW	~5 MW

Table 2 Engineering Parameters

Parameter	START	MAST
TF System	Single turn	24 turns
TF Rod Current	≤500 kA	≤2.2 MA
Vessel Diameter	2 m	4 m
Vessel Height	2 m	4.4 m
Bakeout Temp	50°C	~200°C
Solenoid Flux	~0.08 Vs	≥1 Vs
Design Life	-	10^5 cycles
Pulse Repeat	~5 mins	~10 mins

FUTURE OF THE ST

- **continue physics studies**
  - extension of tokamak database
  - elucidate mechanisms of trapping, mode coupling, disruption avoidance etc.
- **larger, MA - size experiments needed**
  - confirm and extend present results
  - to enable confident predictions for Materials Test Facility (MTF) or Spherical Tokamak Reactor (STR)