The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2267-12

Joint ITER-IAEA-ICTP Advanced Workshop on Fusion and Plasma Physics

3 - 14 October 2011

A quest for record high beta in tokamaks

GRYAZNEVICH Mikhail
Culham Centre for Fusion Energy
Abingdon OX14 3DB
UNITED KINGDOM

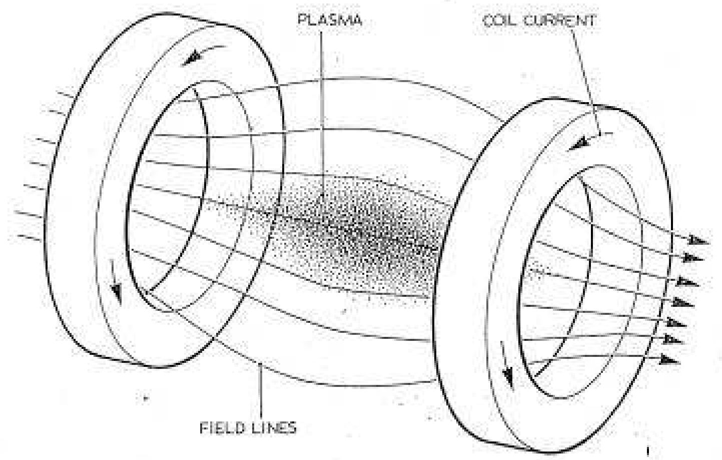
A quest for record high beta in tokamaks

Mikhail Gryaznevich, Alan Sykes

EURATOM/CCFE Fusion Association, Culham Science Centre, Abingdon
Oxon UK OX14 3DB

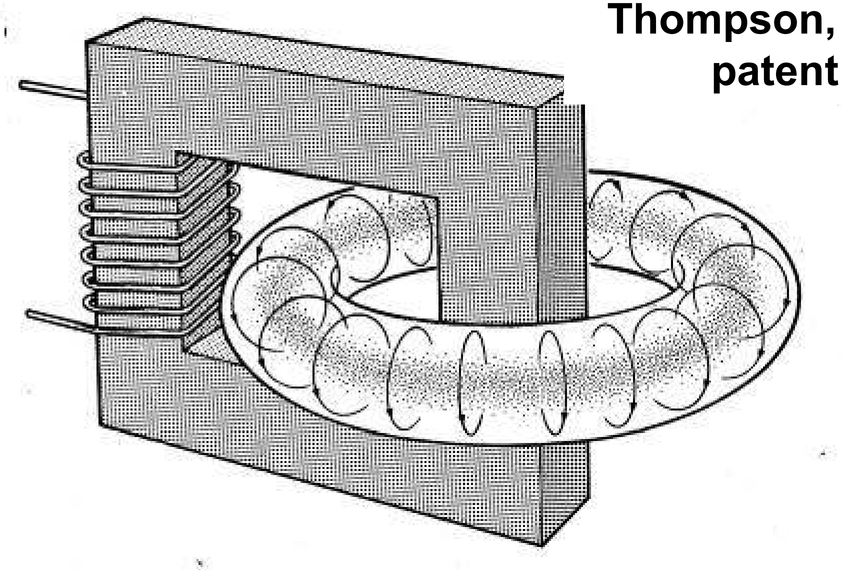
1. Development of the Tokamak
2. Importance of high beta
3. Theoretical studies and scaling laws
4. Beta values achieved
5. Recent developments: 2nd region stability; superconductors

It was first hoped that a Simple Magnetic Mirror would contain a plasma -



- but some plasma escapes from the ends

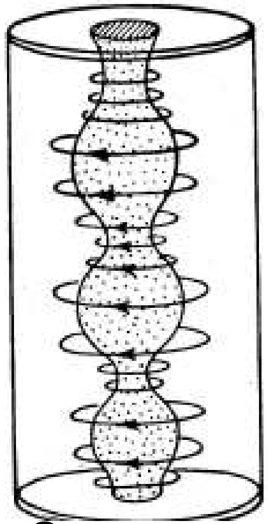
Thompson, Blackman patent 1946



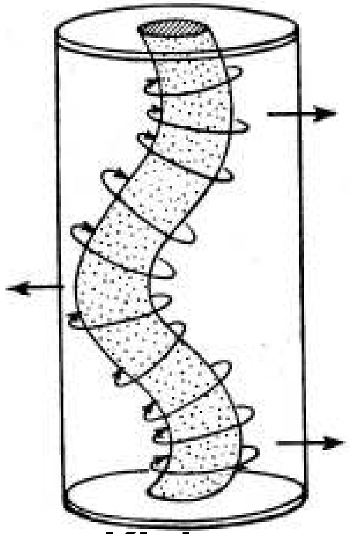
Hence the toroidal pinch:

Toroidal Pinch Studies - 1940's and 1950's

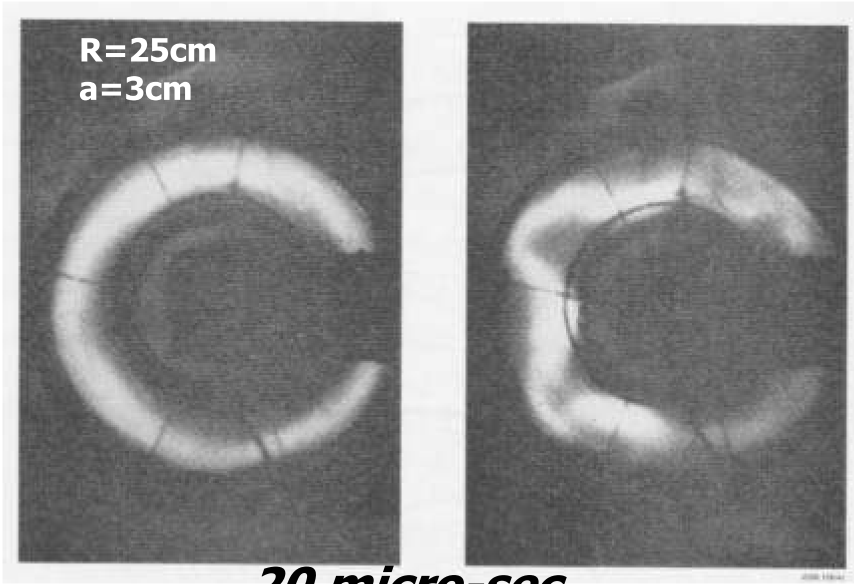
Alan Ware, Stanley Cousins at Imperial College & Aldermaston



Sausage Instability



Kink instability

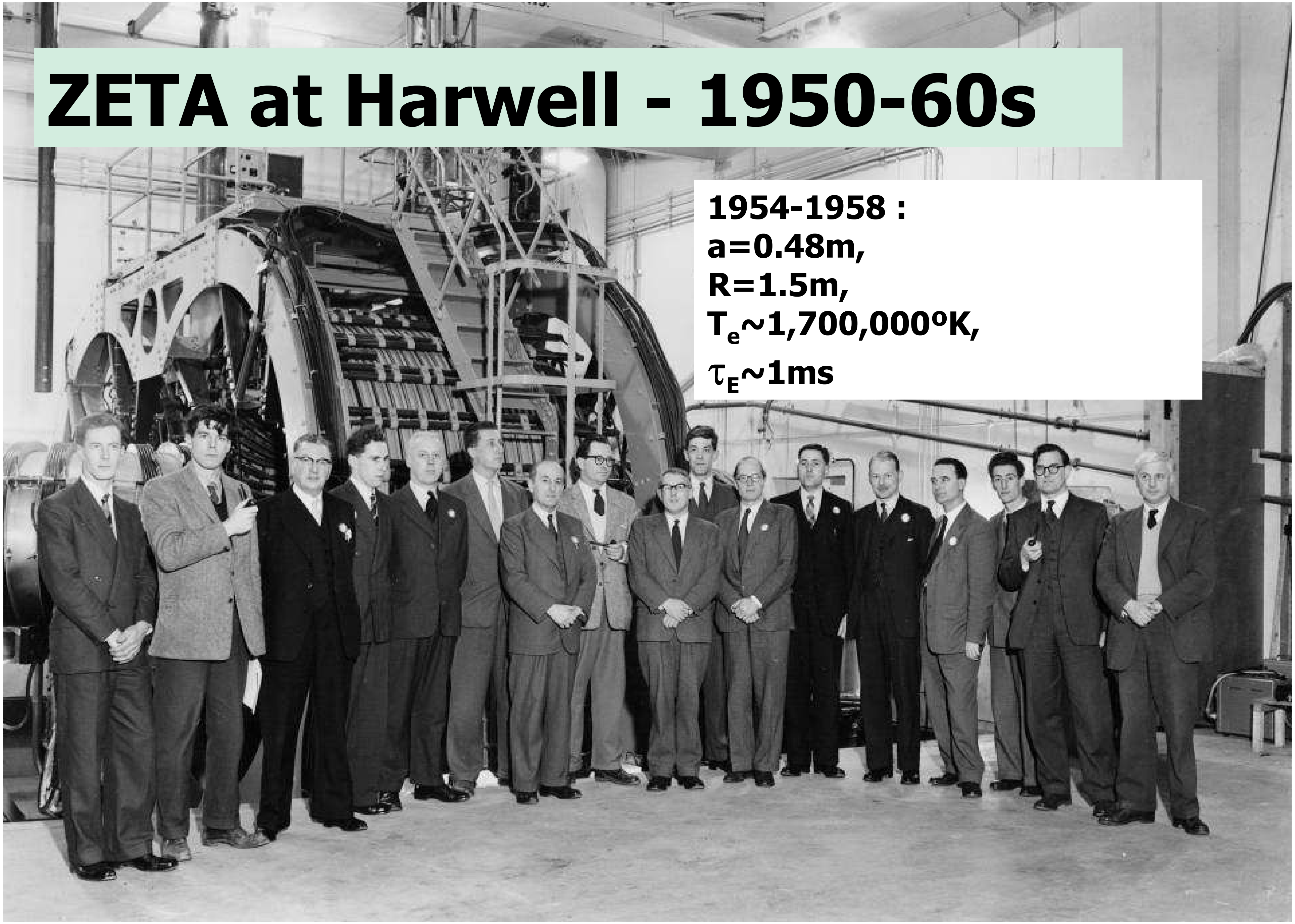


20 micro-sec

First observations of the KINK INSTABILITY

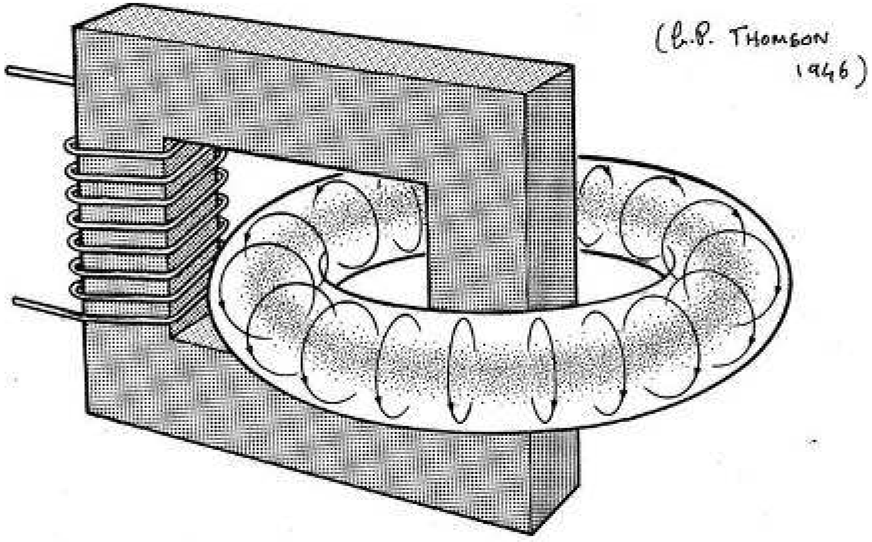
- And in addition to gross instabilities, there were strong micro-instabilities that greatly reduced energy confinement – but steady progress was made..

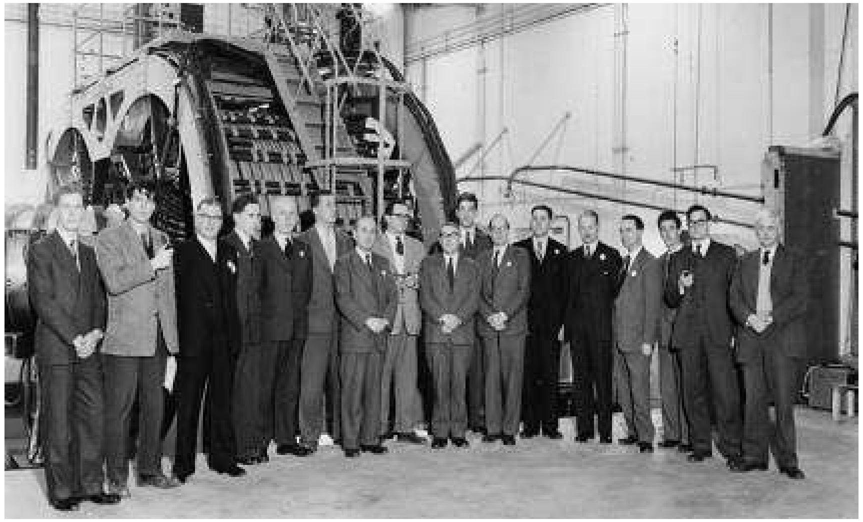
ZETA at Harwell - 1950-60s



1954-1958 :
a=0.48m,
R=1.5m,
T_e~1,700,000ºK,
τ_E~1ms

Vision and reality compared….





Parameters of the Thomson & Blackman Pinch were modest:

R / a = 1.30m / 0.3m, I_p = 0.5MA

classical confinement was assumed :

$\rightarrow \tau = 65$s $\rightarrow T = 500$keV

Hence D-D fusion would be achievable

ZETA at Harwell, 1954-1968, had similar parameters:

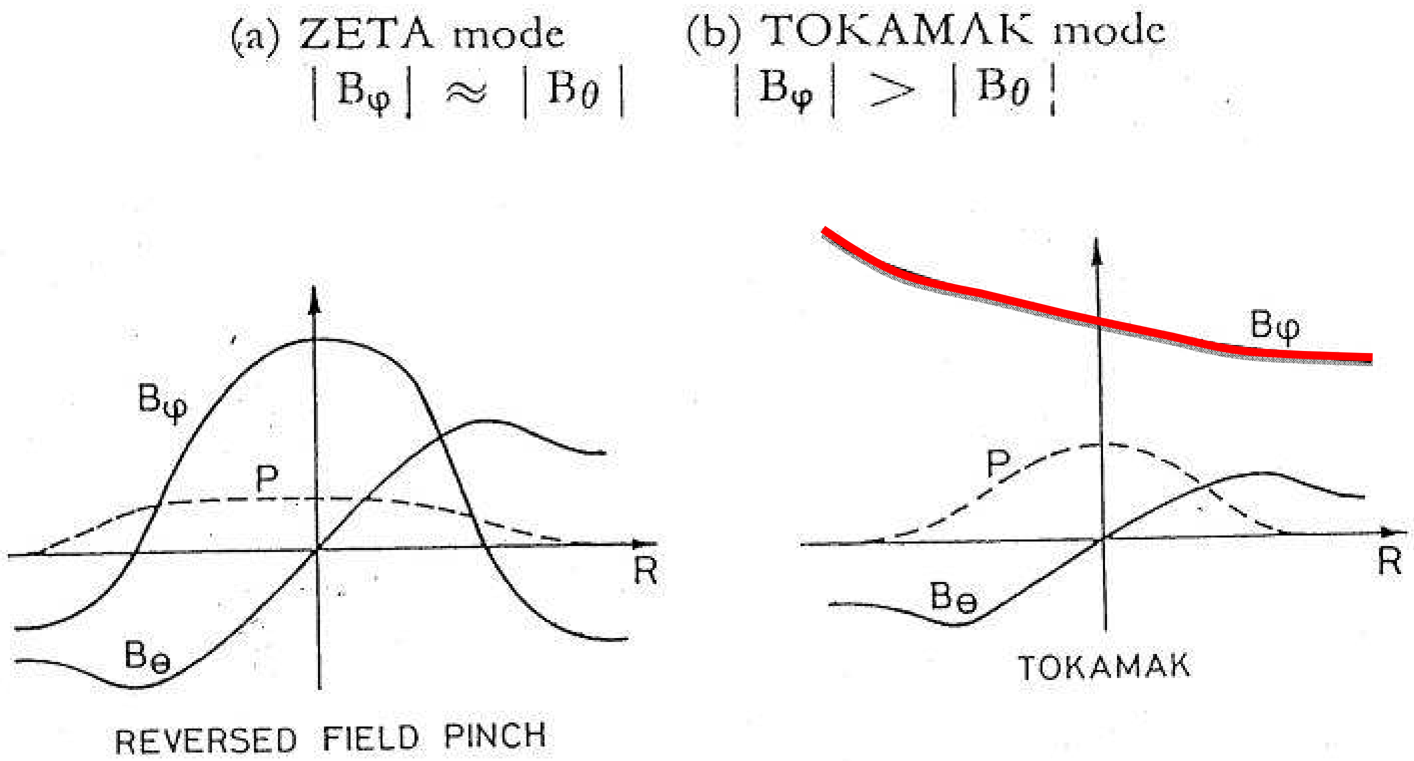
R/a=1.50m / 0.48m, I_p = 0.1 – 0.9MA

Confinement was highly anomalous:

$\tau \sim 1$ms $\rightarrow T \sim 0.17$keV

- Beginning of a long path to fusion energy!

Addition of a small toroidal field in Zeta had improved stability.
Tamm & Sakharov suggested use of a much stronger toroidal field:
hence the first **Tokamaks** (Kurchatov, early 1960's)

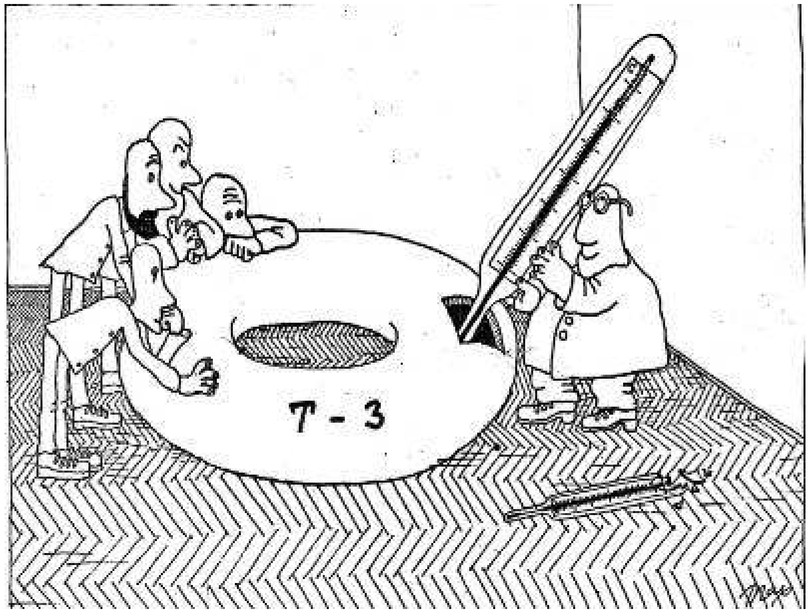


However: to supply a strong toroidal field costs money, both in magnet construction and operating costs. It also increases risks due to the high stored energy.

Beta is the ratio of plasma pressure to magnetic field pressure, and is generally low in tokamaks….

The Tokamak

Claimed to be much hotter than pinches or other devices studied in the Western world. A team of Culham scientists spent a year in Russia, proving this was indeed the case, using Thomson Scattering:



Cartoon by Dr Rasumova's son

The rest of the World began building tokamaks!

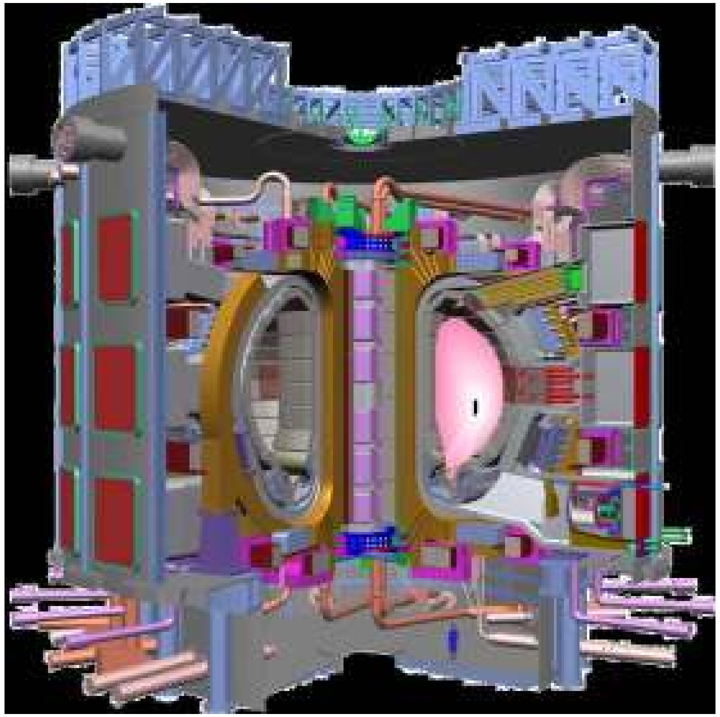
Culham first converted the CLEO device to a Tokamak; then built the TOSCA device. The much larger DITE (Divertor and Injection Experiment) and COMPASS (COMpact ASSembly) tokamaks followed; and then JET, and the START and MAST spherical tokamaks

Developments and improvements of the **Tokamak** have stabilised countless plasma instabilities – kink modes, ballooning modes, tearing modes…and the identification of several key limits – current limit, density limit, beta limit….

But energy confinement τ still anomalous! Empirically, scales approximately (assuming I,n are increased with B_T) as

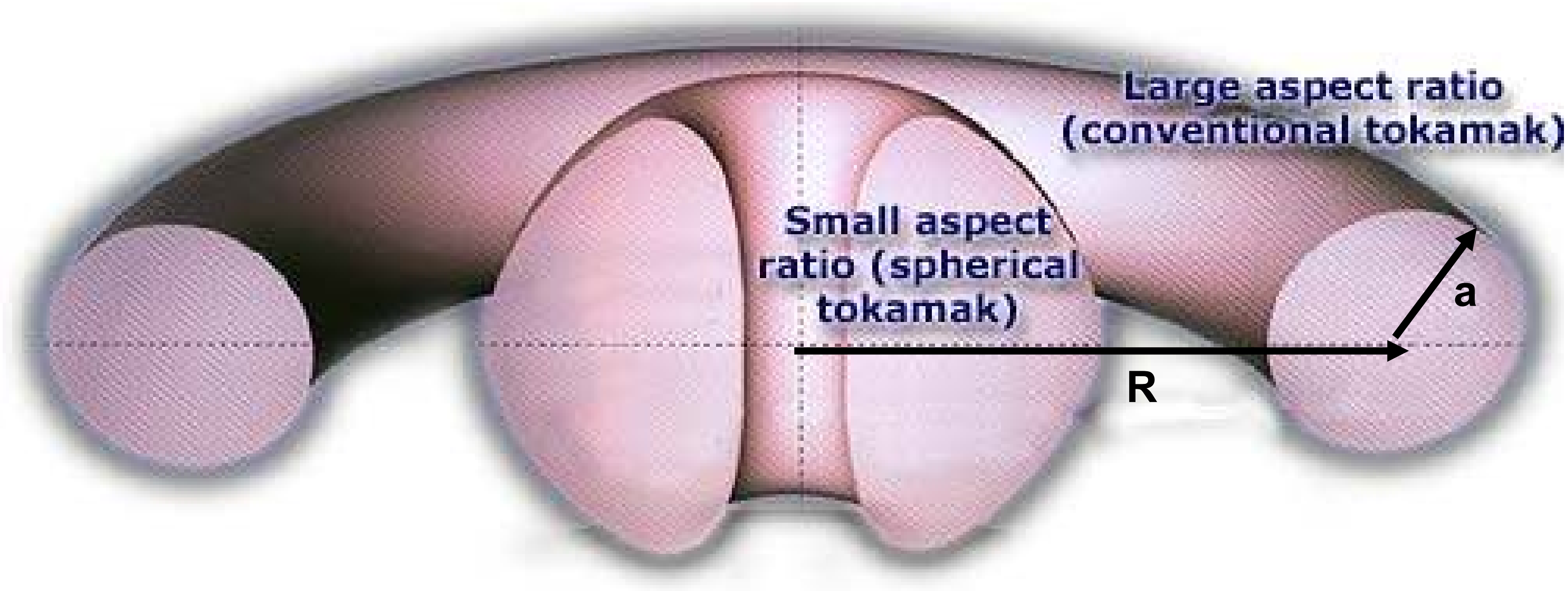
$$\tau \sim R^2 \times B_T^{1.5}$$

– leading to the ITER project
R / a = 6.2m / 2m, Vol ~ 850m^3, I = 15MA,
B_T (at R) = 5.3T, τ ~ 3.5s, T_e ~ 25keV



The large volume of ITER increases the confinement time; and the high I and B help contain the charged ^{4}He particles, which further heat the plasma

Can we improve the tokamak by reducing the aspect ratio?



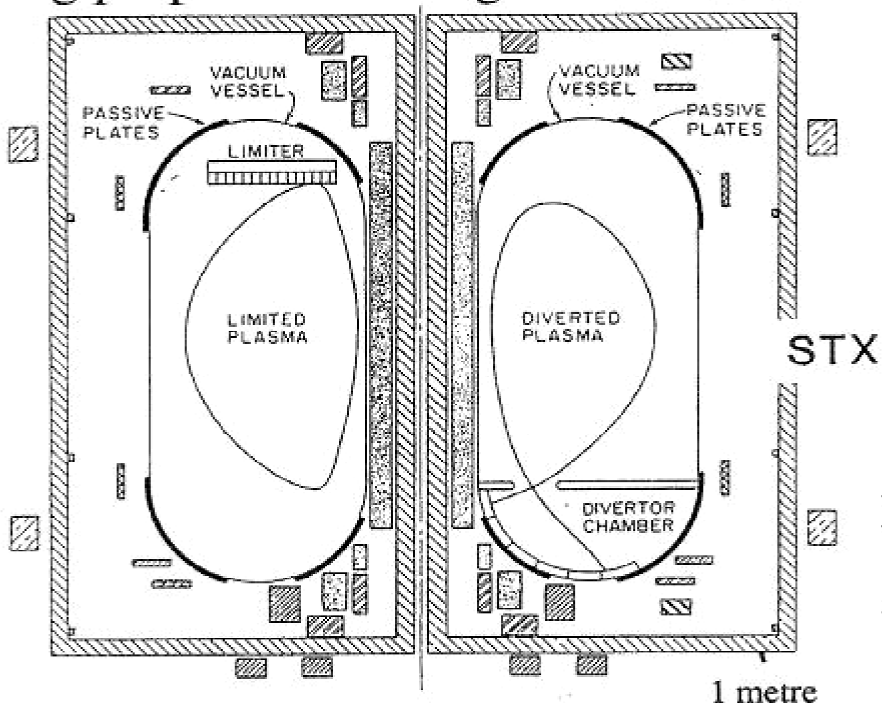
Aspect Ratio = Major radius / minor radius

$$A = R / a$$

History of the Spherical Tokamak (1)

1985 - 7:

- Peng & Strickler [1] published a summary of the physics of low A
- Robinson [2] advocated low A as a means of obtaining RFP efficiency with tokamak stability
- Peng proposed building STX at ORNL



Estimated cost $6M

Aspect ratio A ~ 1.67

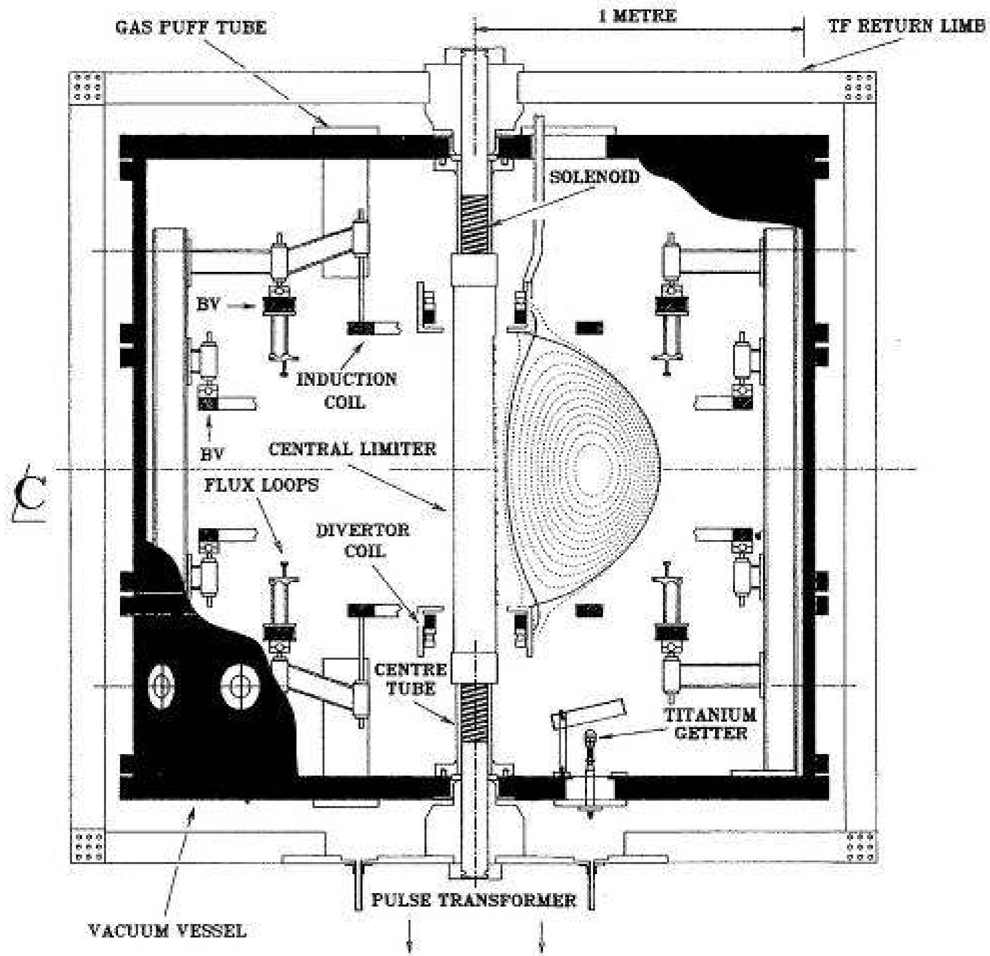
[1] Y-K M Peng & D Strickler, NF 26 769 (1986)]

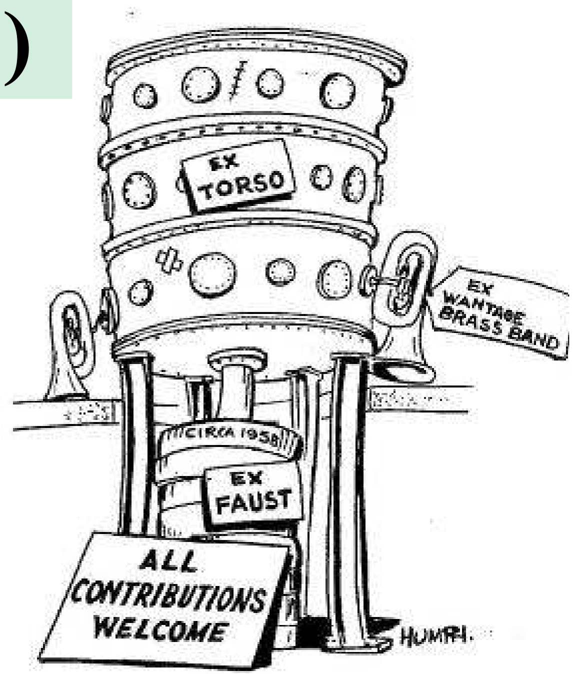
[2] D C Robinson, in Fusion Energy & Plasma Physics, World Scientific Press p601 (1987)

History of the Spherical Tokamak (2)

1988 - 91

- STX abandoned
- Robinson & Todd design low-budget START experiment at Culham





First plasma in START, Jan 1991

Initial build cost ~ £0.1M;

Aspect ratio A ~ 1.25

Concept of low Aspect Ratio..

In the 1980’s it was known that low-A gave high beta, and had low magnetic stored energy.

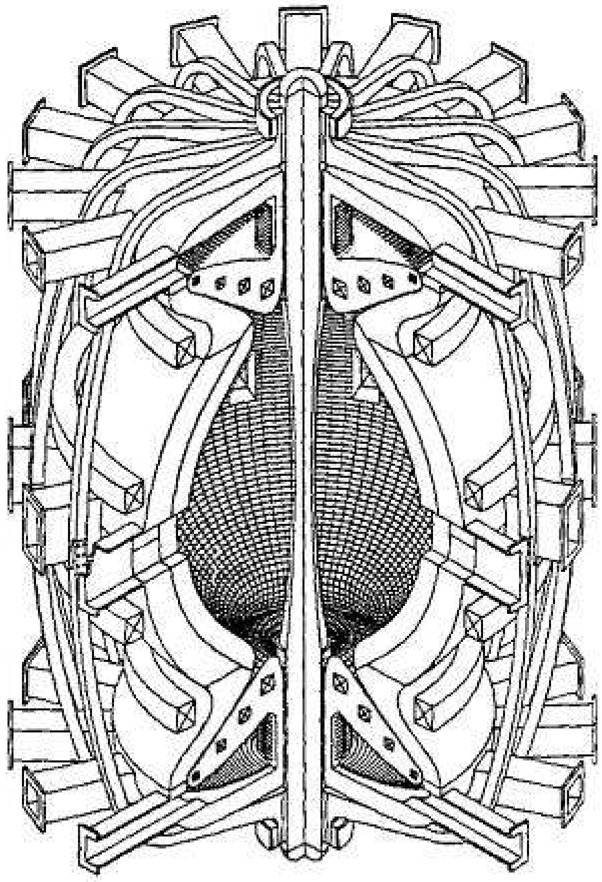
But JET (A ~ 2.4) was considered as ‘tight’ as engineering could permit, given need (in a fusion power plant) for blanket (for tritium breeding), and shield (to protect centre-column windings)

The Peng-Hicks ST reactor concept offered a possible solution:

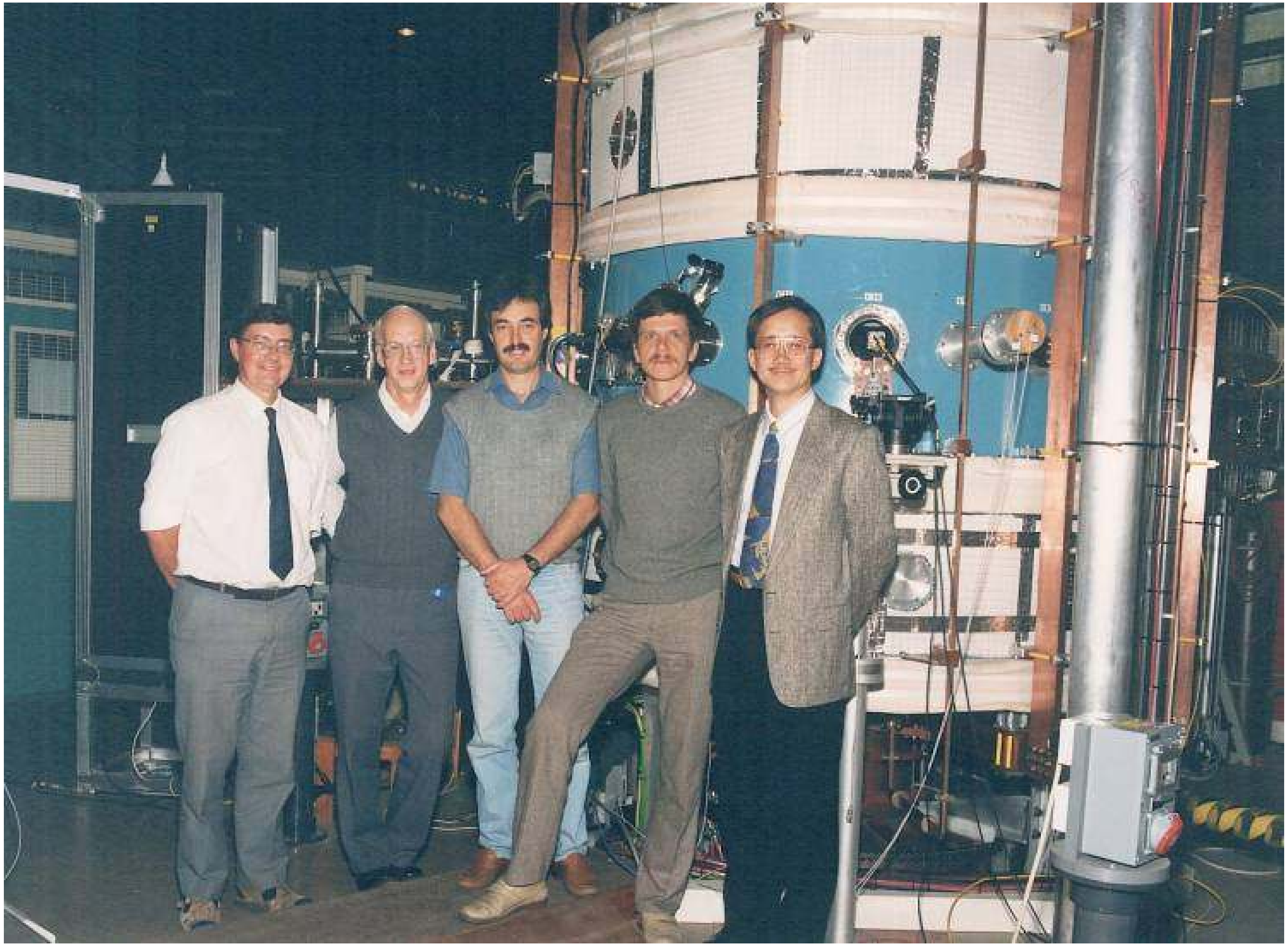
Copper centre column

No blanket (not needed at low A)

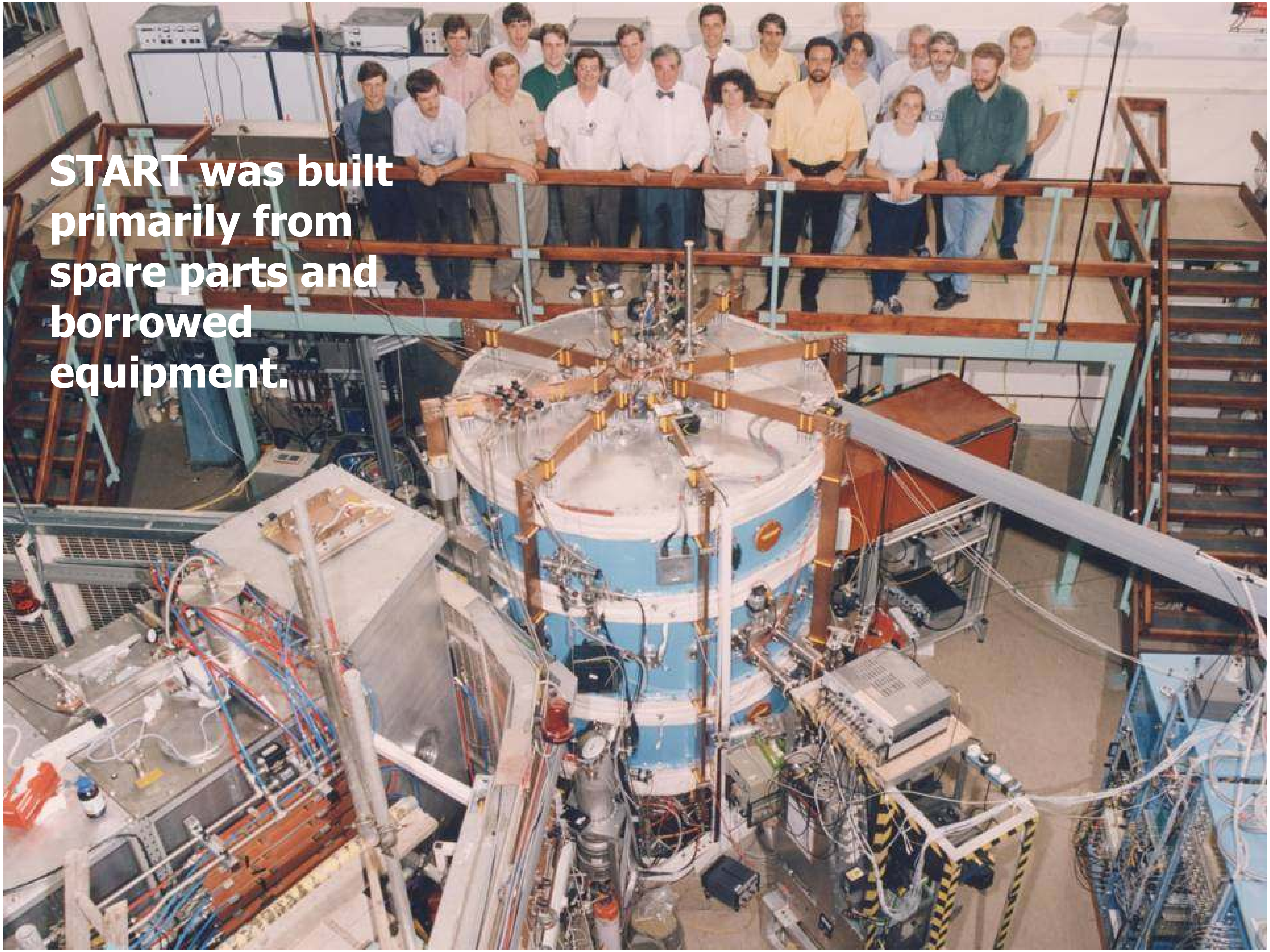
No shield (damage rate low, replace c/col every year or two)



START in operation, 1991



Alan Sykes Dick Colchin Edson Del Bosco Mikhail Gryaznevich Martin Peng


START was built primarily from spare parts and borrowed equipment.

Beta

Definitions of beta

Importance of beta for fusion

Predictions of beta

Definitions of Beta!

Theoreticians (Troyon, Wesson, Sykes..) used the definition:

$$\langle\beta\rangle = 2\,\mu_o \int p\, dV \Big/ \int B^2\, dV \qquad \text{where } B^2 = B_\theta^2 + B_T^2$$

However (before the advent of EFIT) quantities used in the 'theoretician's definition' were difficult to evaluate, and experimentalists preferred the definition:

$$\beta_T = 2\,\mu_o \int p\, dV \,/\, (V\, B_{To}^2) \quad \text{where V=plasma volume,}$$

and B_{To} is the toroidal field at the plasma major radius in a vacuum shot

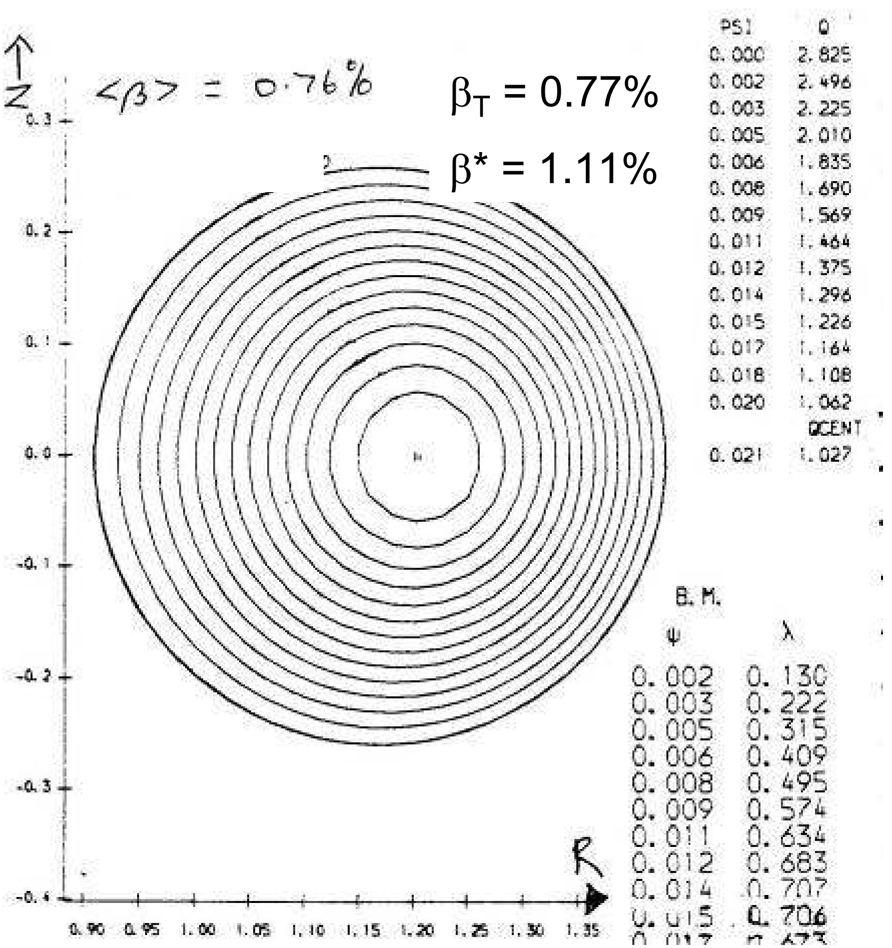
.

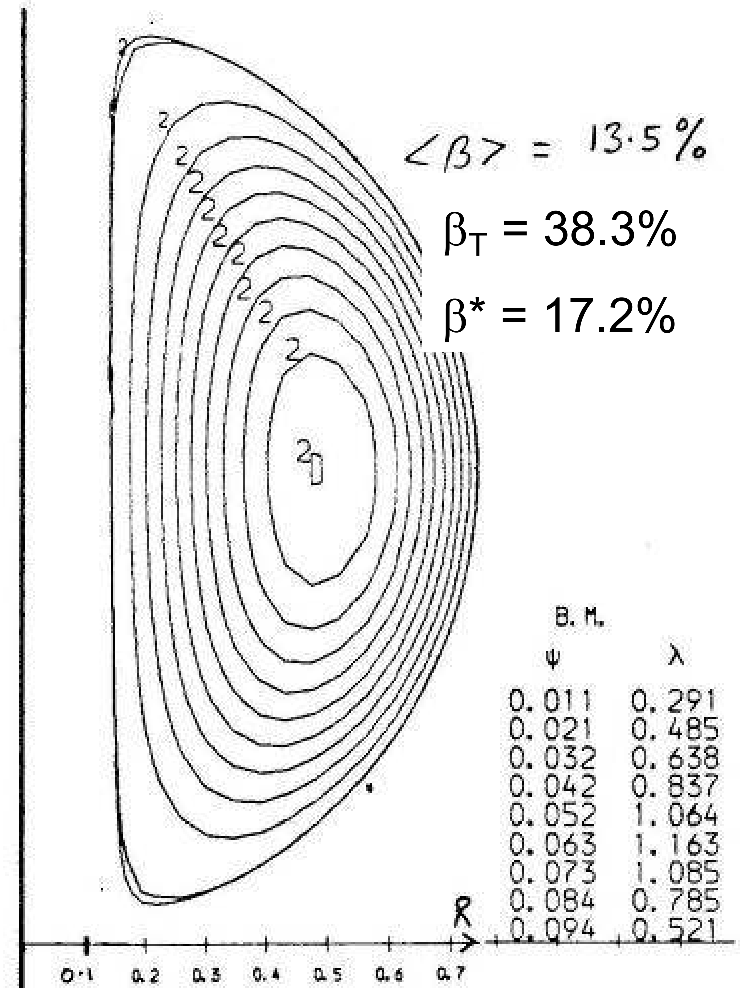
A value relevant to fusion reactor performance is

$$\beta^* = 2\,\mu_o \sqrt{\{ \int p^2\, dV / V \}} \Big/ B_{To}^2$$

For large aspect ratio devices the two main definitions give very similar values; however they are very different at low aspect ratio……

Definitions of Beta (examples – numerical equilibria)





DITE: A=4.5, circular:

$\langle\beta\rangle$ = 0.76% β_T = 0.77%

STX: A=1.7, shaped:

$\langle\beta\rangle$ = 13.5% β_T = 38.3%

Other definitions....

Poloidal beta: $$\beta_p = \frac{2\mu_o \int pdV}{V \langle B_\theta^2 \rangle}$$

where $\langle B_\theta^2 \rangle$ is the average over the last closed flux surface (edge)

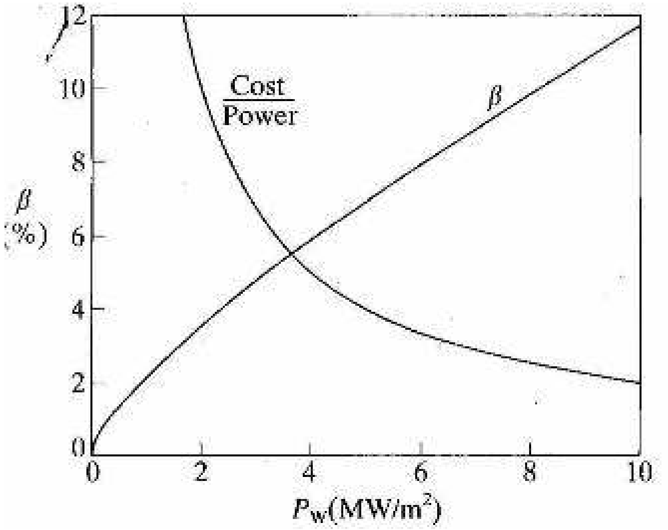
Central beta: $$\beta_o = \frac{2\,\mu_o\, p_o}{B_{To}^2}$$

where B_{To} is the vacuum toroidal field

Why is beta important (1)

$\beta \sim p / B^2$: if β is high, we get maximum plasma pressure for a given field – and field costs money – for build costs of magnets and power supplies, and for electricity costs during operations.

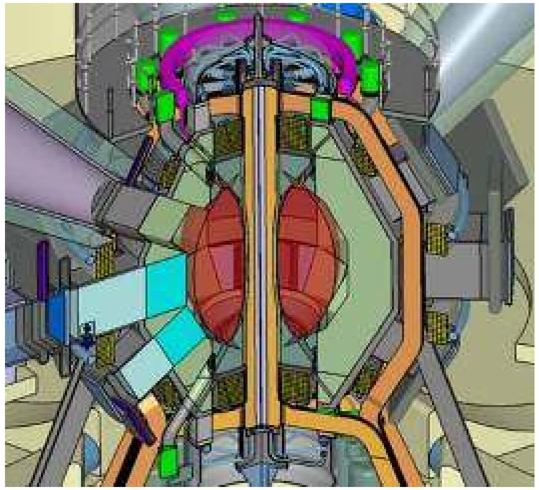
Build costs



For a typical fusion reactor, build cost /power reduces as wall load increases (and β increases). Limits imposed by damage to wall at high P_w, and/or instabilities at high β

(from Wesson, Tokamaks, 1987)

Running costs: e.g. CCFE design for CTF



To produce B_T = 2.5T at Ro = 0.85m requires c/stack current of 10.5MA; to power the TF and PF coils requires 220MW (dissipation being high in copper coils); costing (assuming 1kWh costs 10p, and 50% operation), **£1.6B per year.**

Why is beta important (2)?

β Is the ratio of plasma pressure to magnetic field pressure ~ p / B^2

'Triple product' **$nT\tau$ > 3x10^{21}** (keV, s, m^{-3}) required for ignition

-but p ~ nT, and p ~ β B^2: so triple product ~ β **B^2** τ

Raising β may be more attractive than raising B or τ

Raising B is excellent for fusion output – but costs money (could be reduced by use of superconductors) and is restrained by stress limits.

Raising τ : from the ITER98pby2 empirical scaling:

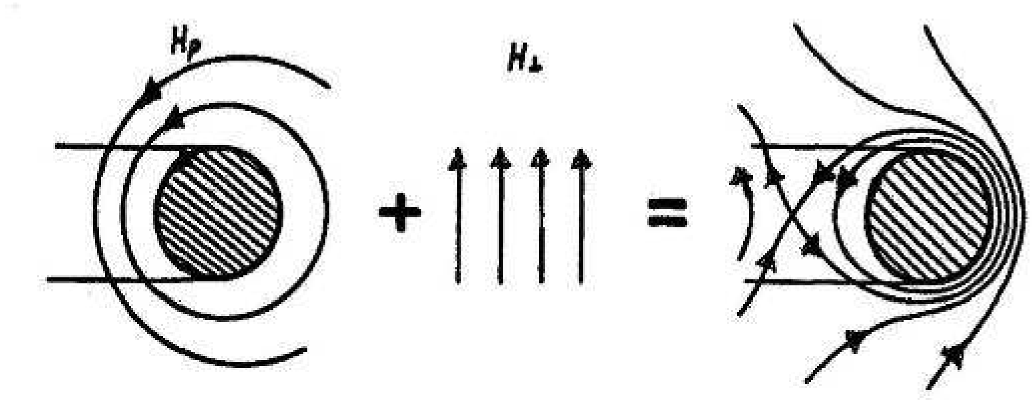
$$\tau_E = 0.0562\, \mathbf{I_p^{0.93}}\, \mathbf{B_T^{0.15}}\, R^{1.97}\, (a/R)^{0.58}\, M^{0.19}\, \mathbf{n_e^{0.41}}\, \kappa^{0.78}\, P\_in^{-0.69}$$

- Each term in **red** can increase approx. linearly with B_T, so $\tau_E \sim R^2 \times B_T^{1.5}$

So apart from raising B_T, τ is best increased by increasing device size – at great cost…

Studies and predictions of beta

It was first thought that beta (both β_p and β_T) would be severely limited for equilibrium reasons:



Mukhovatov & Shafranov, 'Plasma equilibrium in a tokamak', NF 11 (1971) p605

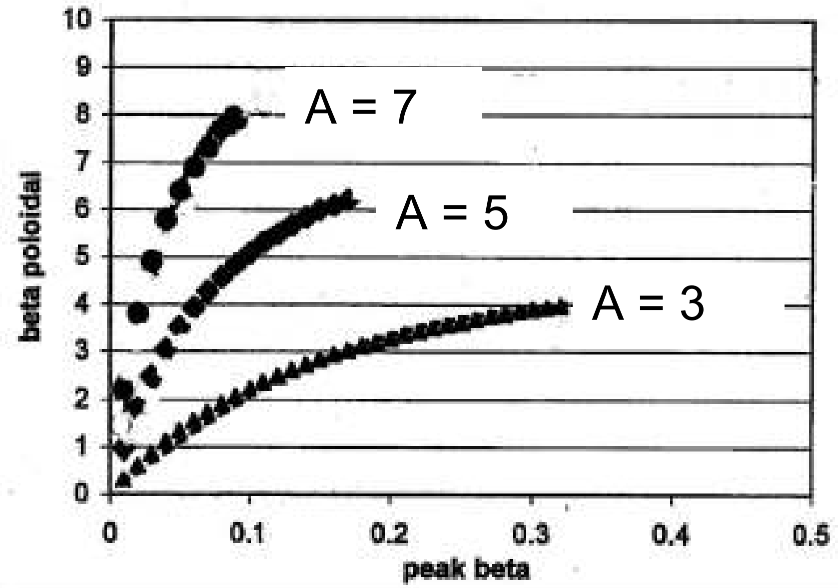
Plasma column (current out of paper) needs vertical field to provide equilibrium; as pressure (beta) increases more vertical field is required to hold plasma

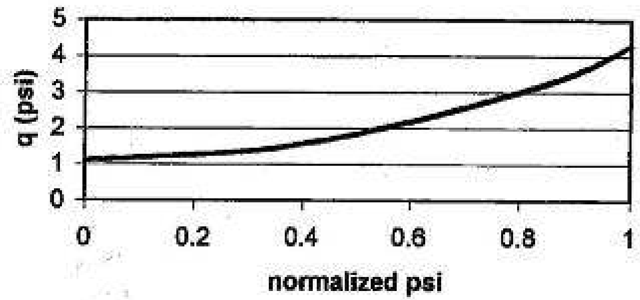
Above a certain limit, seperatrix enters plasma: this limit is $\beta_p \sim A + 0.5$ where A = aspect ratio R/a

Clarke & Sigmar ('High-Pressure flux-conserving tokamak equilibria' PRL 38 (1977) p70) explored the concept (suggested by Mukhovatov & Shafranov) of a 'flux conserving tokamak' whereby strong additional heating could increase pressure whilst 'freezing' in the q-profile

Studies of beta (3)

Later studies [1] showed that the 'flux conserving tokamak' concept could slightly exceed the β_p limit….





For fixed q profile; pressure profile is scaled.

Codes cannot converge beyond β_p **~ A + 1.**

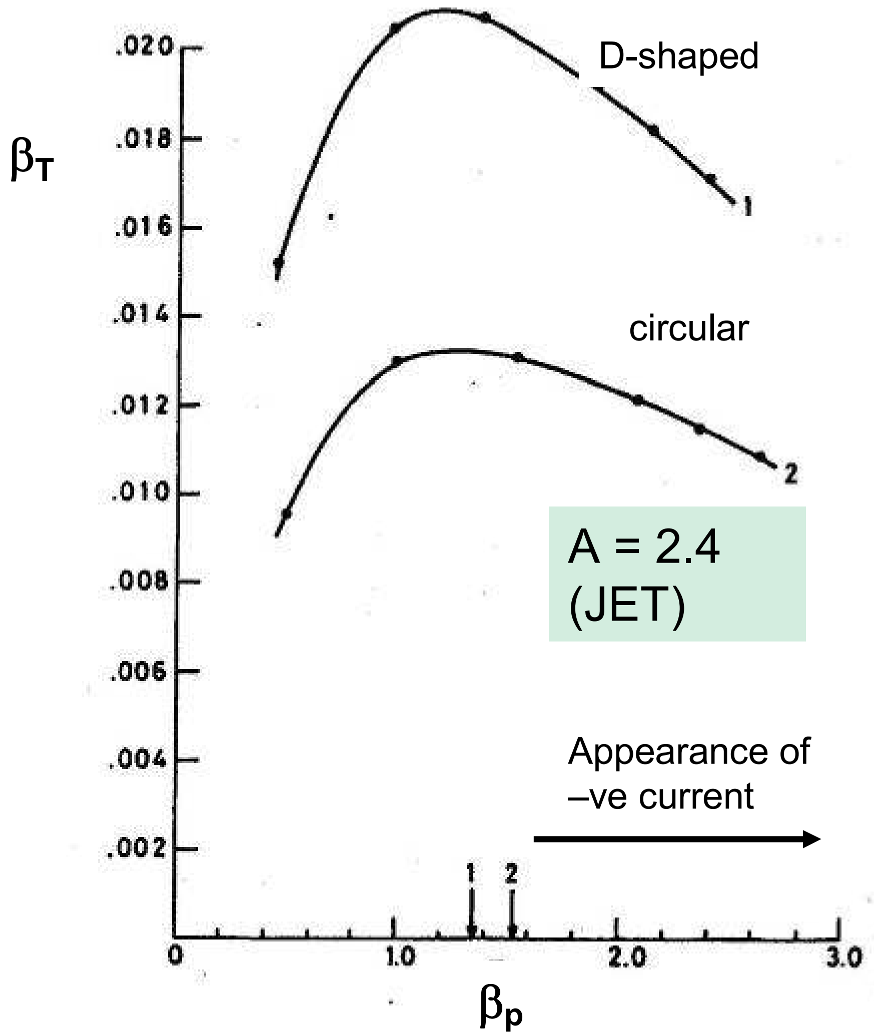
Note 'peak beta' is central beta i.e. $2\mu_o\, p_{peak} / \langle B_o^2 \rangle$ (and so is $> \beta_T$)

Although β_p increases with A, as A increases ratio I/B reduces (to keep q high enough for stability) so peak beta (and β_T) decrease with A

[1] 'Beta-poloidal evolution in fixed – q heating in Tokamaks' Kissick, Leboeuf, Kruger Physics of Plasmas 10 (2003) p1060

Studies of beta (1)

Callen & Dory [1] and Green, Jacquinot, Lackner & Gibson [2] used simple models of current and pressure profiles and found that although β_T begins to increase with β_p (consistent with the simple large-aspect-ratio expression $\beta_T \sim \beta_p\, \varepsilon^2 / q^2$) it later falls, and regions of negative current appear.



[1] Phys Fluids 15 (1972) p1523

[2] 'The scaling of plasma beta in a tokamak' NF 16 (1976) p521

Studies of beta (2)

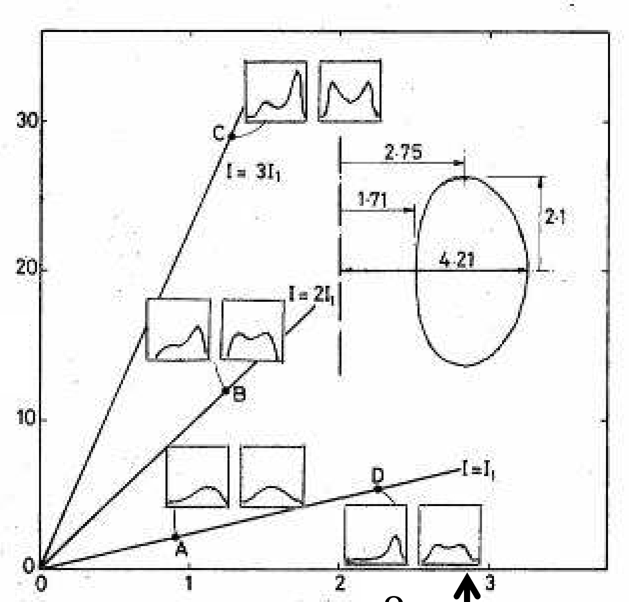
Sykes, Wesson & Cox [1] expressed the R^2 p' and ff' of the Shafranov equation in the form: $R^2p' = \alpha_1 R^2 \psi + \alpha_2 R^2 \psi 2$, $ff' = - \alpha_2 R_o^2 \psi^2 - \alpha_3 \psi^3$

so that $R j_\phi = \alpha_1 R^2 \psi + \alpha_2 (R^2 - R_o^2) \psi^2 - \alpha_3 \psi^3$

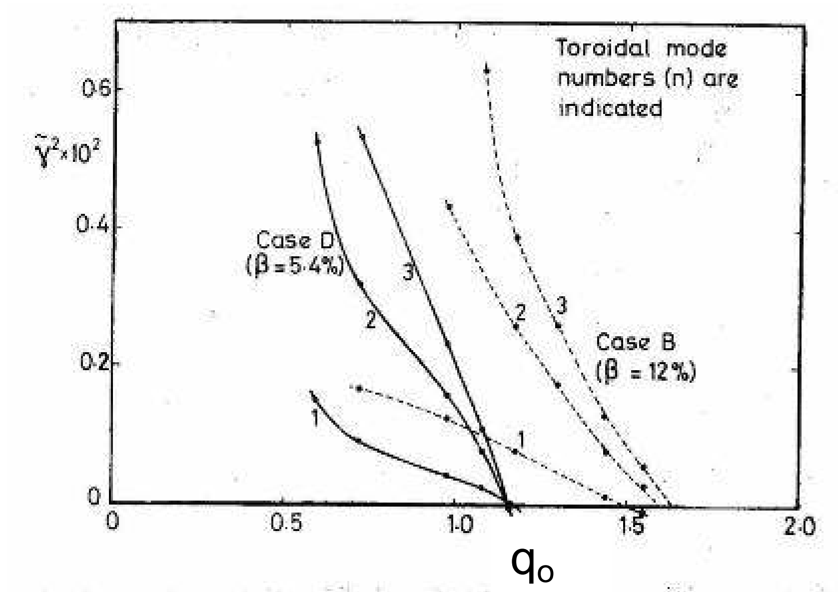
Hence the quadratic term allows exchange of plasma and toroidal field pressure, and the cubic term provides control over q_o.

Stability to n=1,2,3 internal modes was predicted for $\langle\beta\rangle$ = 5.4% for JET current of 4.8MA, requiring q_o >1.15; and 12% for 9.6MA, requiring q_o > 1.6. (B_{To} = 3.5T)

$\langle\beta\rangle$



β_p



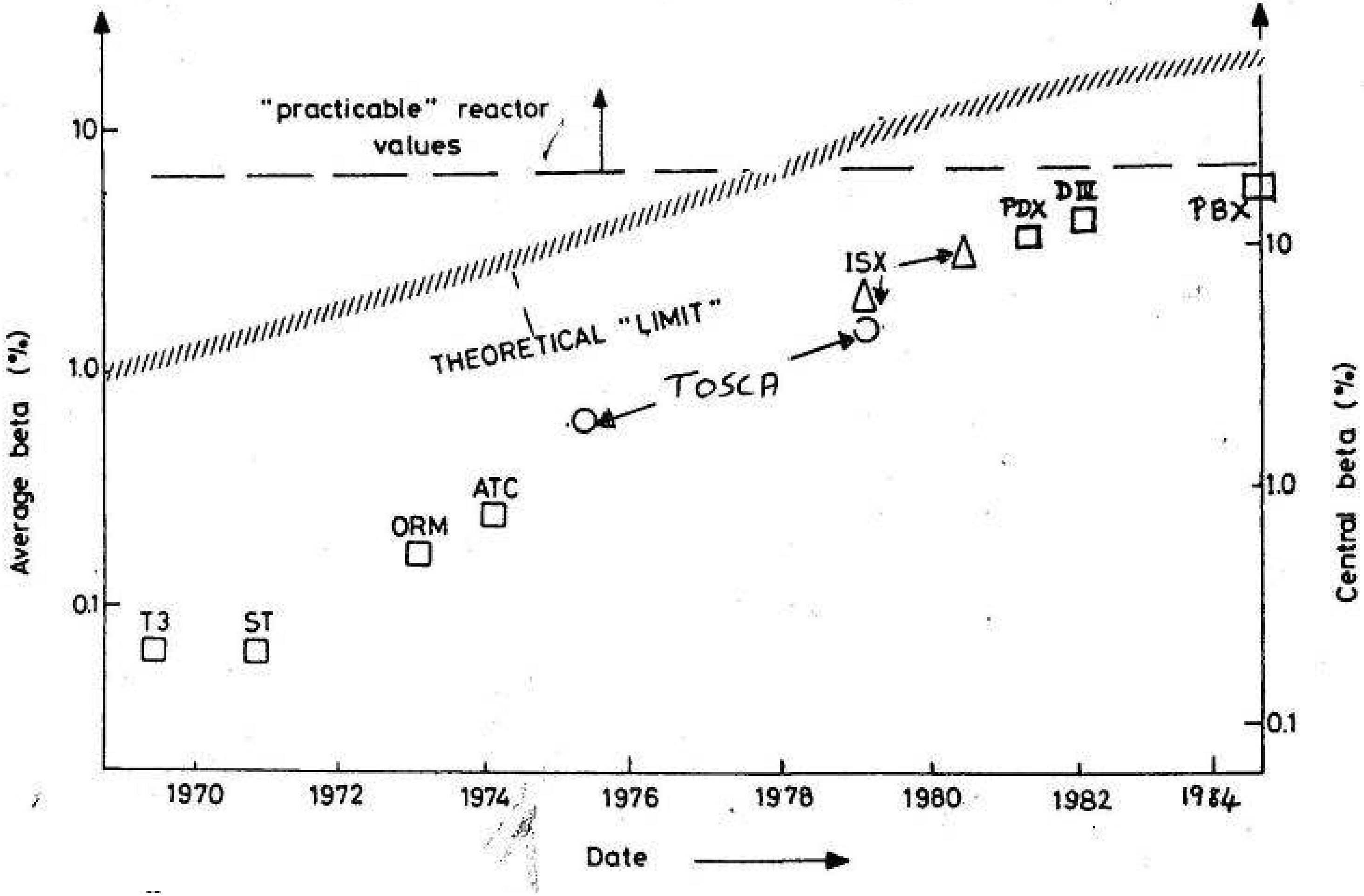
q_o

Note: β_p < A + 0.5 limit not exceeded

[1] *'High-β tokamaks' PRL 39 (1977) p757*

Studies of beta (4)

- As seen by the TOSCA group, c 1981



Limits to beta

After concerns due to the equilibrium limit on β were removed, simple equilibrium modelling predicted high values of beta.

However the max beta is limited by (many!) forms of MHD, including:

Surface kink modes (around qedge = 2,3,4…) MUST be avoided…plasma rotation (helped by NBI injection) can be stabilising (next slide)

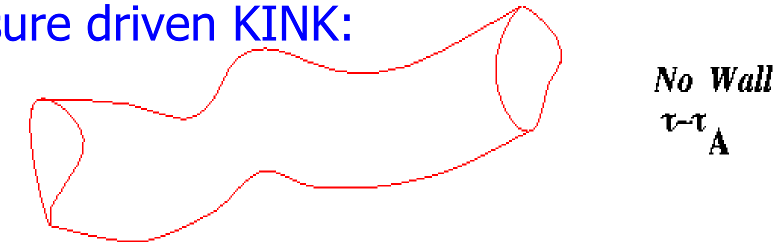
However there are many other ideal MHD and resistive MHD instabilities, some of which can be benign..

Kink modes can be stabilised by plasma rotation…..

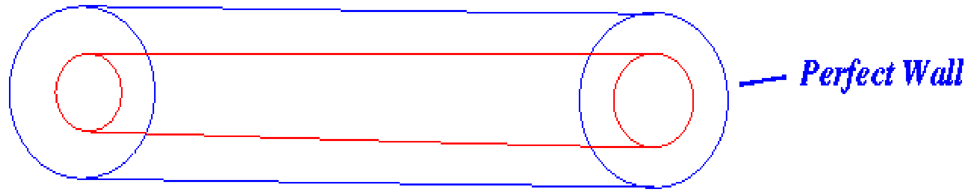
- Above “no wall” kink limit:
  - Kinks will occur
  - …send flux through wall
  - …slowed to wall time
- Rotation makes wall seem perfect

(Above the “with wall” limit fast kink disruptions will occur)

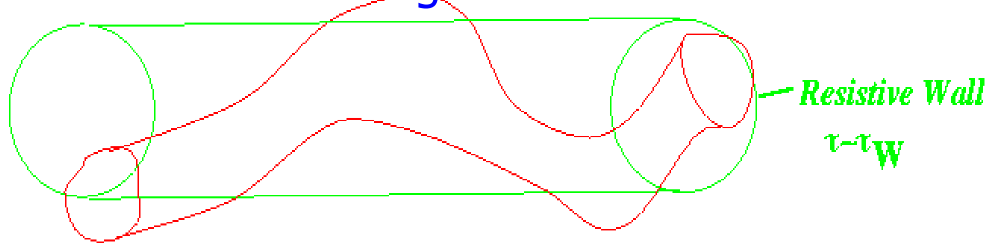
Pressure driven KINK:



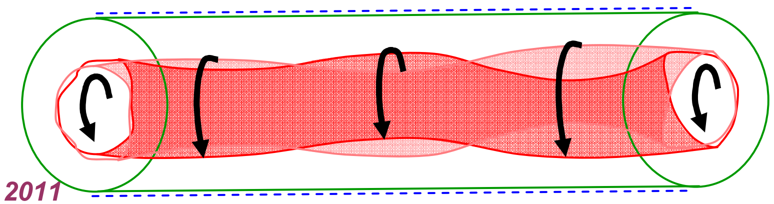
A close enough wall can stabilise it:



Real wall slows it’s growth:



Rotation prevents wall penetration
- mode sees perfect wall:



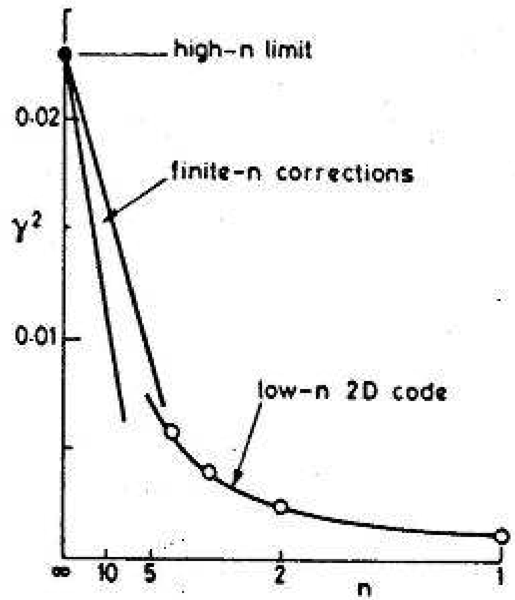
What limits beta ? (continued)

Internal ideal pressure driven modes (n = ∞ being the most restrictive);

Resistive ballooning modes;

Tearing modes (TMs) on q=2,3,.. and 3/2, 4/3.. surfaces; 2/1 worst; forms islands, which can be self-stabilising as their growth lowers j' at the resonant surface

Neo-classical tearing modes (NTMs): pressure flattened in TM island, which removes bootstrap current, driving island to larger size



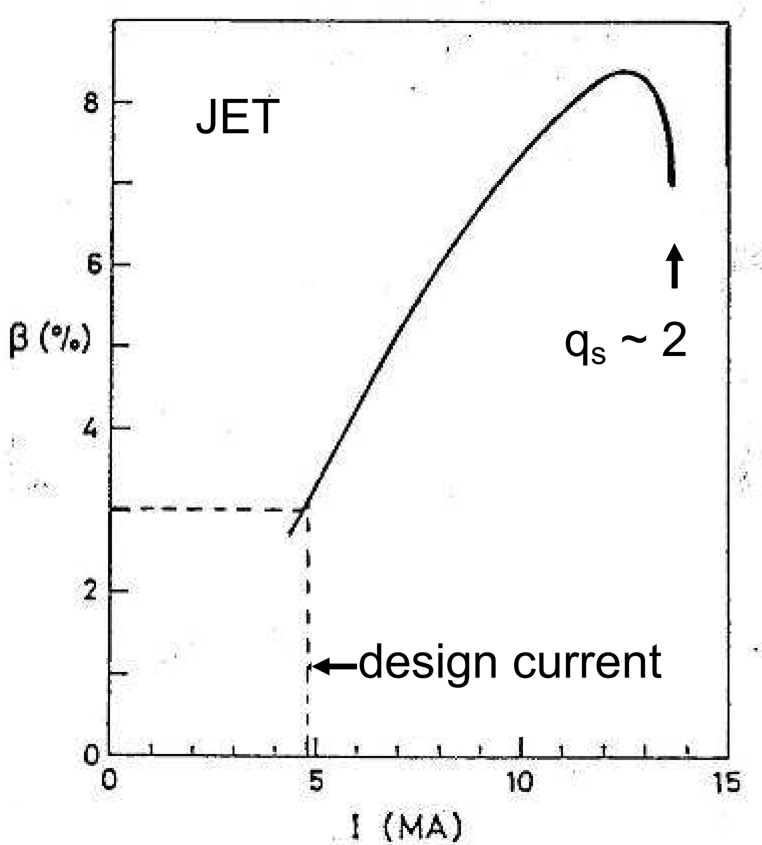
Not all these modes are catastrophic; for example, high-n ballooning instability may act to locally reduce pressure, the plasma evolving to a nearby stable profile.

But they all have to co-exist – the re-adjustments caused by one instability may de-stabilise another, possibly with catastrophic results.

Large islands slow down the plasma rotation so that a suface kink can penetrate an imperfect wall ….

Early scaling laws for beta

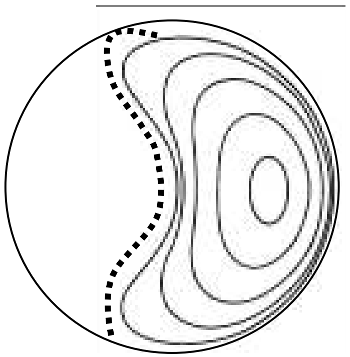
1) $\beta \sim 1/A$ Friedberg & Haas (1973)
2) $\beta \sim E$ (elongation) Friedberg & Haas (1974)
3) $\beta \sim 1/A$ and also E if sufficient triangularity: PEST results, 1977
4) $\beta \sim I_p$ derived by Wesson, 1981 based on results by Bernard, 1980 (see Fig)
5) $\beta \sim 10(1+E^2) / (A\, q_{cyl})$ Rutherford " a crude fit to low-q ideal MHD stability calcs" (1982)
6) $\beta = 7.8E^{(1 + 0.014(q_s-1))} / [q_s^{0.54} (A-1)^{0.76}]$ optimised to high-n ballooning stability by Tuda, 1982
7) $\beta = 27\, E^{1.2} (1 + 1.5\delta) / [A^{1.3}\, q_s^{1.1}]$ Bernard 1983



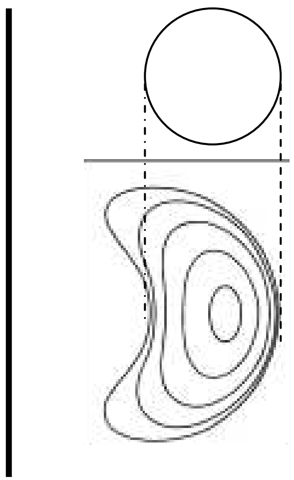
Interpretation of Bernard's results by Wesson, predicting $\beta \sim I_p$ until q_s=2, and β = 3% for JET operation at 3.5T, 4.8MA

Digression: magic beans!

Early scaling laws for beta were confused by the apparent high-beta properties of the bean shaped plasma.



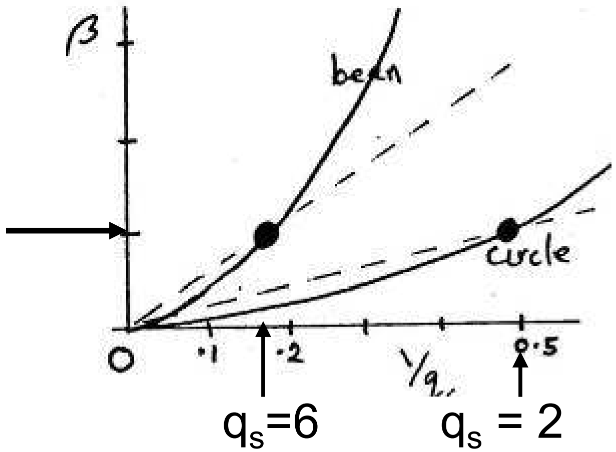
Reason 1: If for this high-beta plasma in a circle section tokamak, $\langle\beta\rangle$ is evaluated over the bean-shaped (dashed) area, a higher value is obtained: for the omitted area contains large B^2 contributions which reduce the circle value.



Reason 2: for the same current and minor radius a, the bean would have say q_s=6 if the circle had q_s=2.

We now know that, for the same I,a,B, β - limits are the same in both cases (but the bean can have higher I).

Since it was once expected that $\beta \sim 1/q_s^2$, it was thought that for the same q_s, β (bean) = 9 x β (circle), whereas β_{max} (bean) = 3 x β_{max} (circle)



Aachen conference 1983 (1)

Sykes, Turner & Patel [1] optimised pressure profiles to marginal stability to high-n ballooning modes, and found for a wide range of shapes (circles, D's, backward D's, ellipses, beans) and a wide range of aspect ratios (1.5 - 4.5), the max. beta was given by

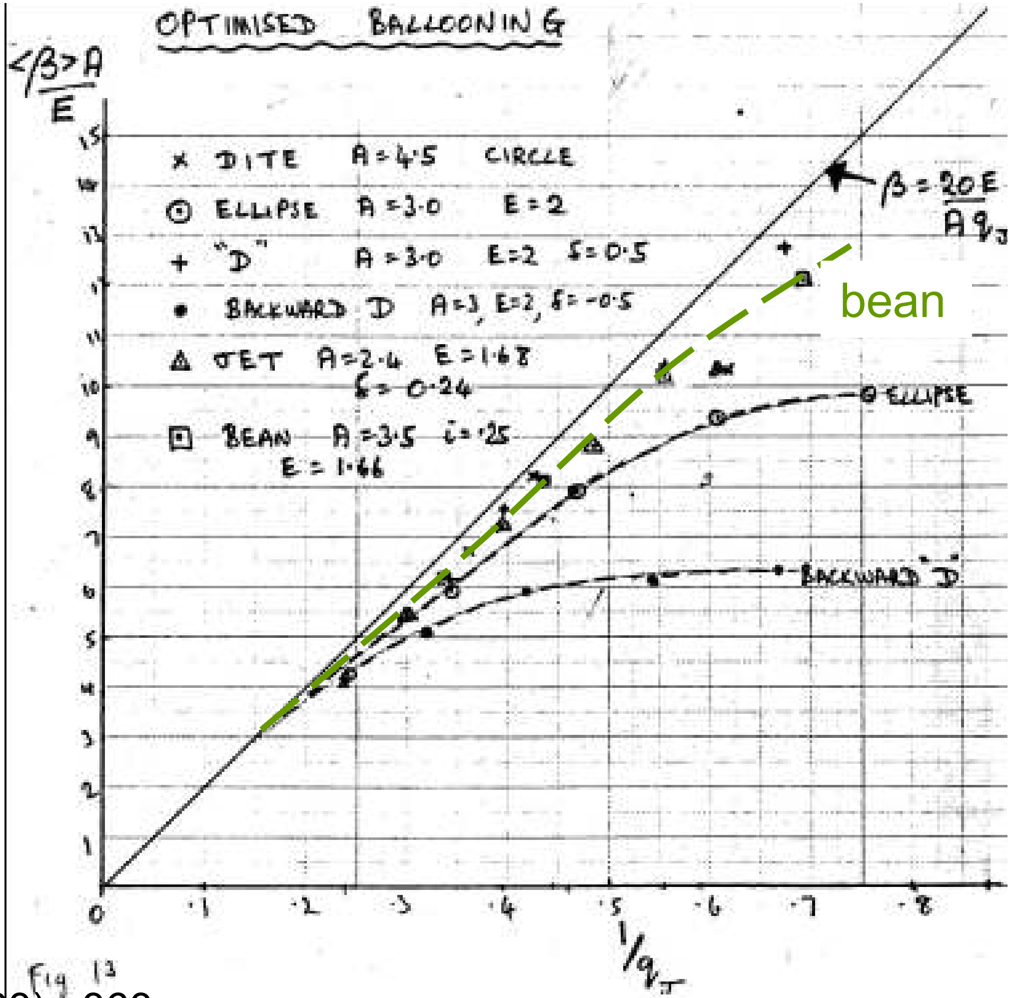
$\langle\beta\rangle = 20\ E / [A\ q_J]$

where $q_J = 2\ B_{To} / [\ \mu_o\ R_o\ I_p\ /\ \text{area}]$

-Provided there was sufficient triangularity δ.

Note that substituting for q_J, the STP expression is

$\mathbf{\langle \beta \rangle = 4\ I_p / (A\ B_T)}$



[1] Sykes, Turner, Patel CFPP (Aachen) (1983) p363

Aachen conference 1983 (2)

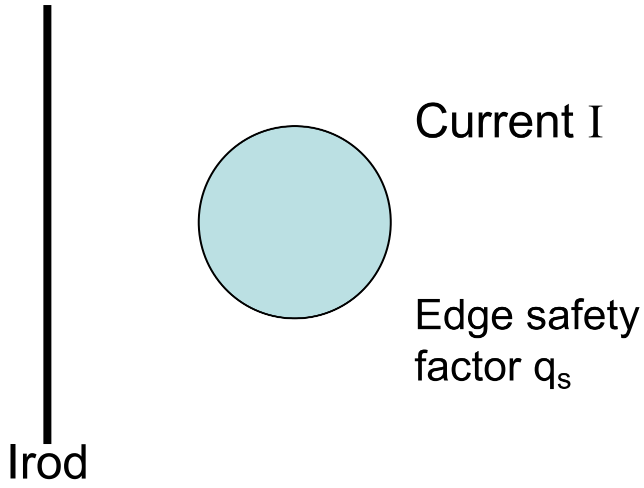
Troyon & Gruber performed low-n mode studies on ERATO of JET and INTOR, including a test of high-n stability, and derived:

$$\mathbf{< \beta > = 2.8\ I_p / (aB_T)}$$

although S-T-P and T-G are identical in form, the Troyon expression has a lower coefficient because (a) profiles are not optimised to marginal stability (b) a further condition of low-n stability is imposed.

Why is $\beta_{lim} \sim I$?

It may seem surprising that β limits should be linear in I, apparently in conflict with the following thought experiment:



If we double the rod current and hence the toroidal field B, q_s (proportional to B) will double, and β (proportional to $1/B^2$) will quarter.

This suggests that $\beta \sim 1 / q_s^2$, i.e. that $\beta \sim I^2$ rather than I.

The explanation is that

(a) We are saying that β **LIMITS** are $\sim I$, not β values per se

(b) Suppose in the above example that initially q varied from 1 to 3. After doubling B, q will adjust itself to be 1 to 6 (not 2 to 6), giving extra shear which permits an increase in β

A simple model

Wesson** provided an analytic explanation of why limiting $\beta \sim I$:

Maximise $\beta = 4\mu_o \int_0^a p \, r \, dr \quad / \, (a^2 B^2)$

Using the ballooning mode stability diagram shown in Fig 1,
Where $s = r/q \; dq/dr$ and
$\alpha = - 2\mu_o R q^2 / B^2 \; dp/dr$

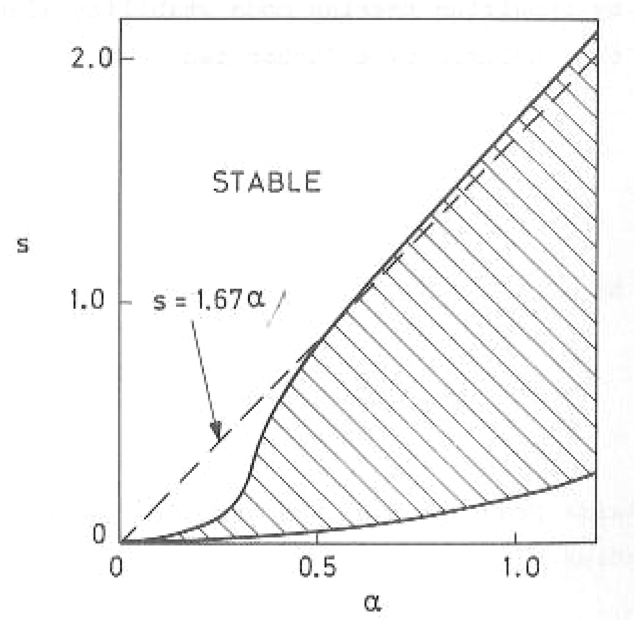
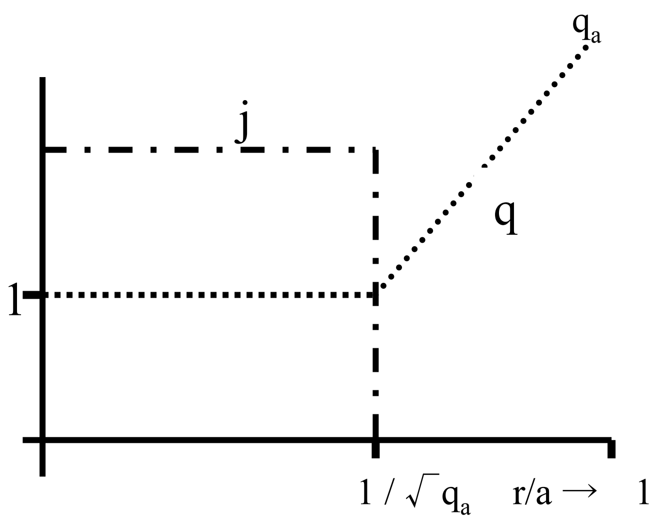


Fig. 1 Ballooning mode stability diagram.



Approximating by the expression $s = 1.67\alpha$, β is maximised by the top hat current profile shown in Fig 2

** Wesson & Sykes, 1984

A simple model (cont'd)

Wesson found that both the approximation and a full optimisation gave $\beta = 28\, a/(R\, q_a)$, equivalent to β **= 5.6 I / (aB)**

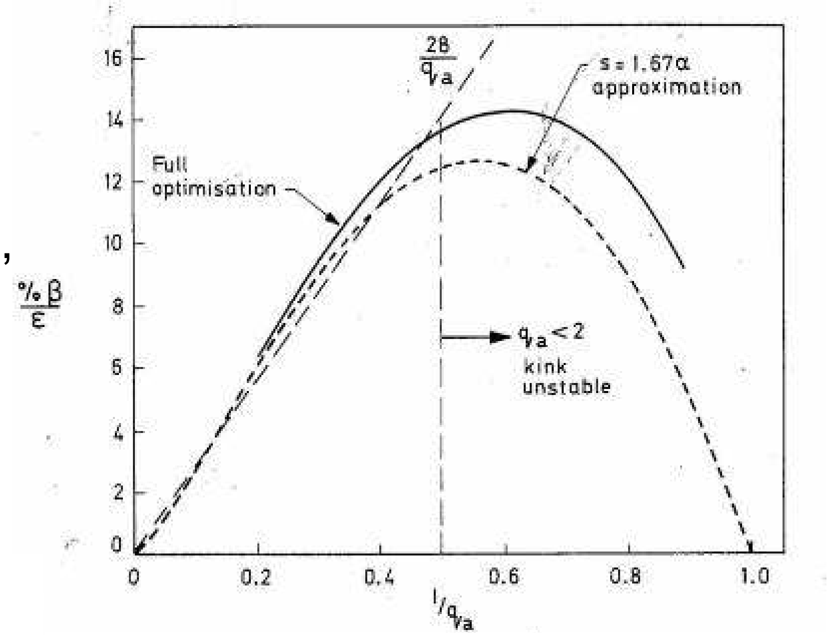


Fig 3 *Max. β as a function of q_a*

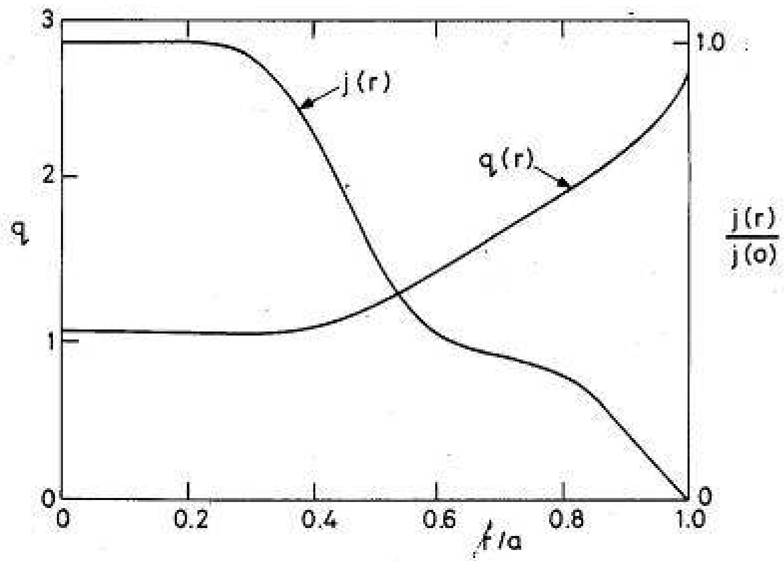
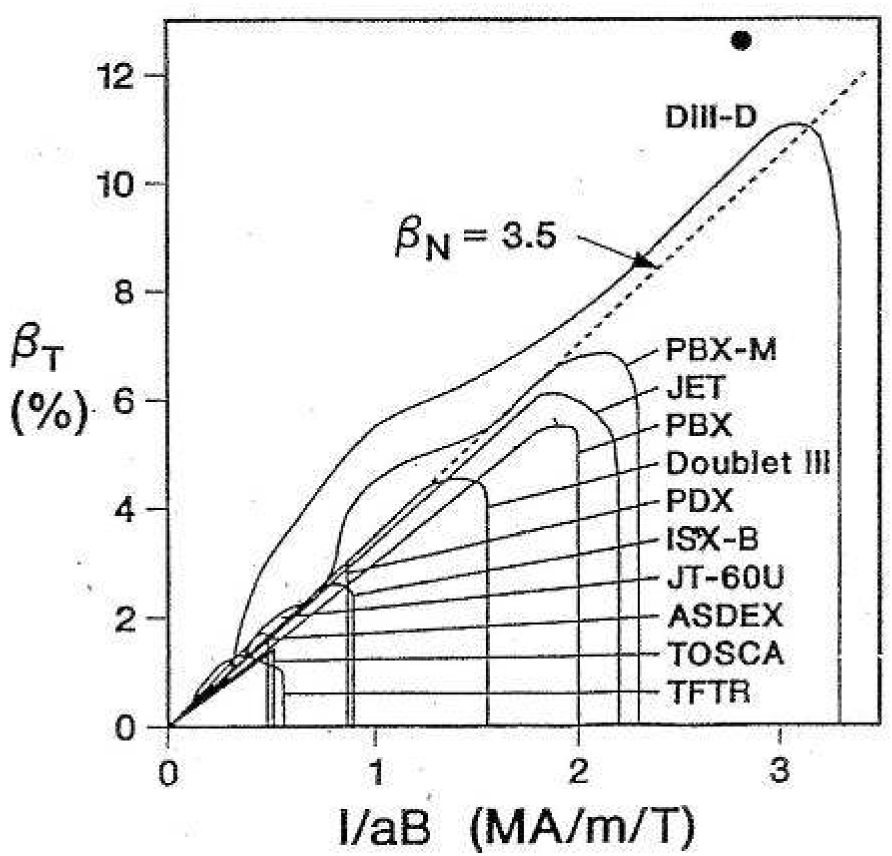


Fig 4 *current profile stable to tearing modes*

Using more realistic current profiles (rather than the 'top hat') reduced the coefficient, and a profile stable to tearing modes (shown in Fig 4) had a reduced coefficient of β **= 2.8 I / (aB)**

Beta in world tokamaks - 1993

(from Ted Strait's invited Paper at 1993 APS conf)

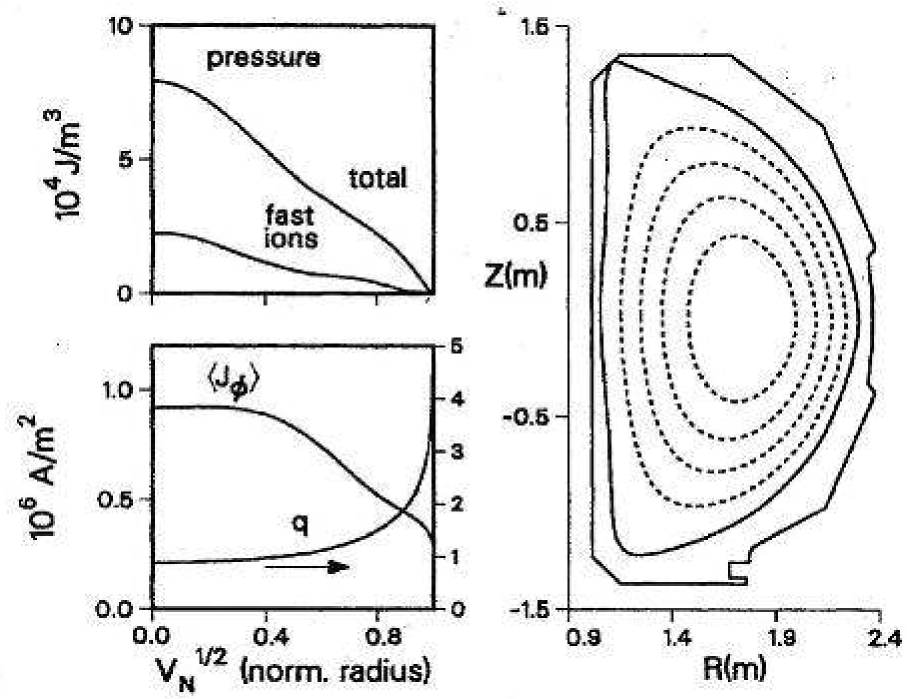


For each tokamak, the right-hand limit to operation is the onset of the low-q limit at $q_a \sim 2$

Large A, circular section machines (eg TFTR) meet this limit at low I/aB and so have low β

The peak JET beta of ~6% is for I_p=2MA, B_T=1.3-1.0T (ramped down), using 10MW of NBI heating (Huysmans et al, PPCF 34 (1992) p487)

DIII-D set the record



“Plasma rotation essential… resistive wall modes appear only when the rotation velocity approaches zero” [1]

This beta is:

< ideal stability limit assuming perfect conducting wall

> (by 30%) than if no wall

DIII-D #80108: β_T = 12.5% = 4.3 I/(aB)

q_{95} = 2.5 l_i = 0.71 B_T = 0.8T I = 1.5MA

(Note: standard parameters are B_T=2.2T, I_p=3MA)

[1] ‘Wall stabilisation of high beta tokamak discharges in DIII-D’ E.J.Strait et al, PRL 74 (1995) p 2483

Predictions of beta for JET

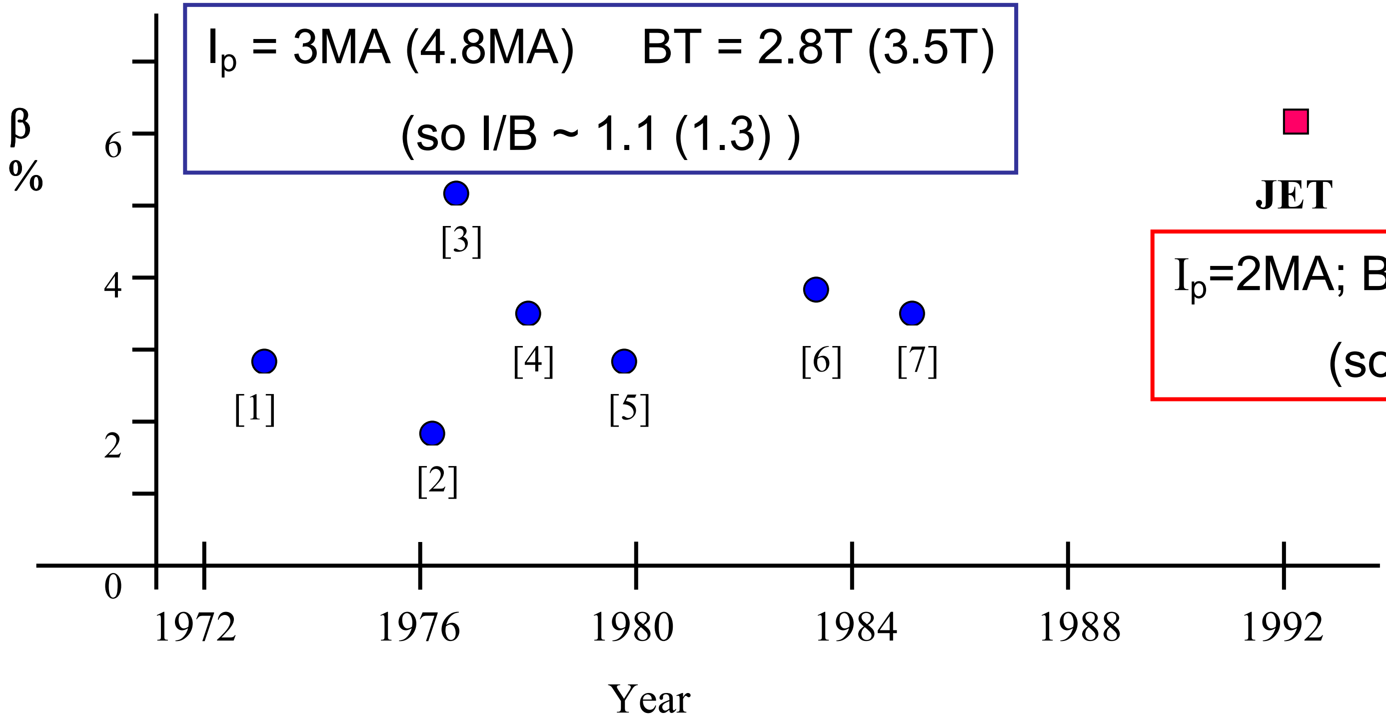
Original JET baseline parameters were B_T = 2.8T, 3MA, 'extended performance' was 3.5T, I_p =4.8MA; peak plasma current was 7MA.

Initial plasmas were very large, ~ 100m^3; later SND ones (introduced to get H-mode) were 80m^3.

This large volume, high field and high current gave JET very high energy confinement time…and predictions of a high beta limit..

However JET was relatively low-powered for its size - 22MW of NBI for 100m^3 of plasma volume – so the β-limit was only reached at low current

Predictions of beta for JET (cont'd)



I_p=2MA; B_T = 1.3 →1.0 T

(so I/B ~ 2)

[1] Wesson & Sykes IAEA Tokio 1974 (low-n & kink)

[2] Green, Jacquinot, Lackner, Gibson NF 16 (1976) p521

[3] Sykes, Wesson, Cox PRL 39 p 757 1977 (low-n, found unstable to surface kinks)

[4] Sykes & Turner IAEA Innsbruck 1978 (lown, high n, ?surface kinks)

[5] Wesson (from Bernard) all low n modes (using ERATO)

[6] Sykes, Turner, Patel Aachen conf (high n, low n)

[7] Saunemann (using ERATO) LRP263

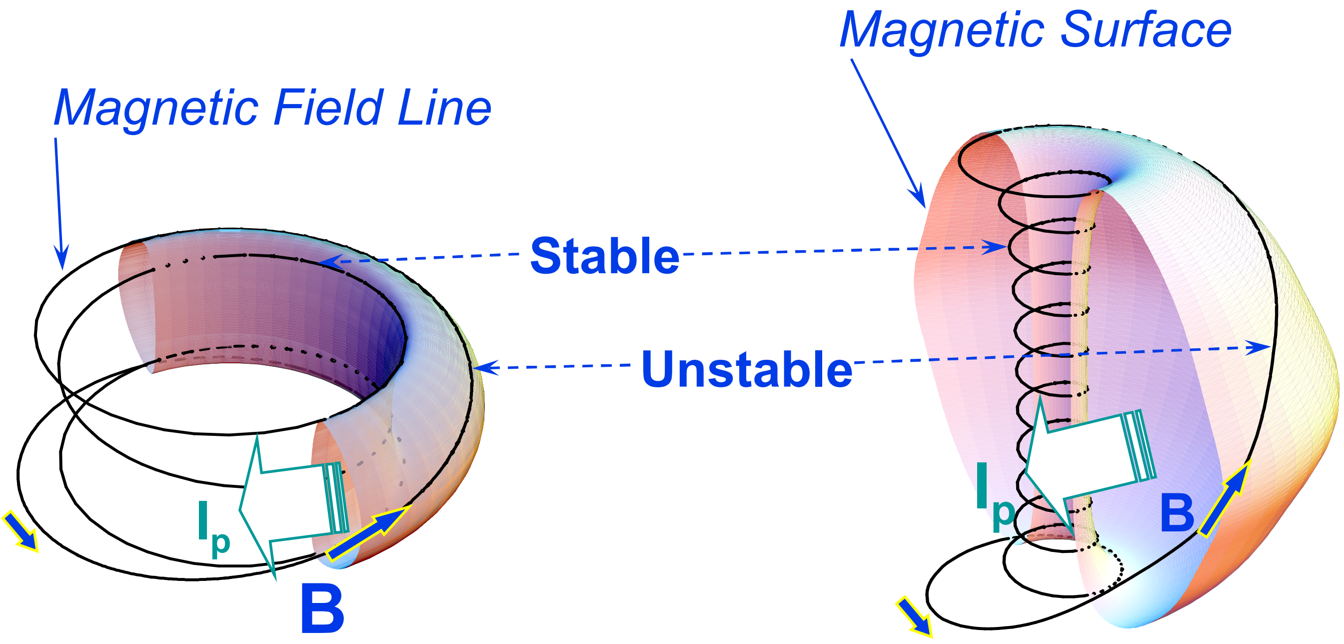
Predictions mostly
in <β>
Expt in β_T

β values can be much higher in a shaped low-A device…

In an ST, field lines spend most time in the high TF region near the centre…..

NSTX

(cartoon Courtesy Martin Peng)



Conventional Tokamak
(safety factor q = 4)

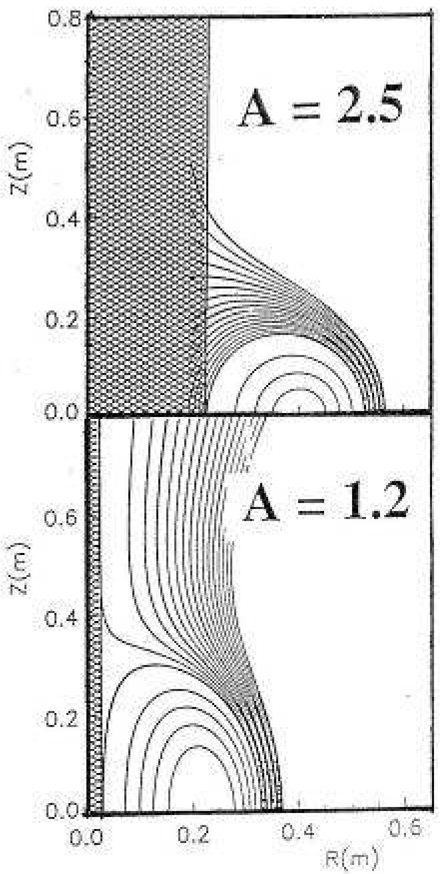
Spherical Tokamak
(safety factor q = 12)

This leads to many differences in ST plasma parameters and properties

STs require much lower toroidal field, and exhibit 'natural' elongation:

In each case, minor radius = 0.15m, and I_p = 100kA

Profiles and toroidal field B_{T0} chosen to give $q_o \sim 1$, $q_a \sim 8$



A	B_{T0}(T)	k	q_ψ	q_{cyl}
2.5	1.58	1.1	8.2	5.2
1.2	0.07	2.0	8.7	0.9

As aspect ratio is decreased from 2.5 to 1.2, the toroidal field required to achieve the same q_a for a given I_p falls by a factor 20

$$q = 1/2\pi \int B_\varphi / (RB_\theta)\, ds$$

At low A, B_φ is large over much of the surface AND B_θ is small near the 'points'

This means that for a given B_T plasma current can be MUCH larger……. Note that β (max) is proportional to I_p

β values in STs are high, due to increased shear and the higher current made possible by the increase in edge q

The large A 'cylindrical' expression for q_s is

$q_s = 5\, a^2\, B / (R\, I)$

This has been modified to apply accurately to ITER geometry:

$q^*_{(ITER)} = 5a^2B/(RI) \times [1 + k^2(1+2\delta^2-1.2\delta^3)]/2$

With an expression for $q^*_{95(ITER)} = q^*_{(ITER)} \times (1.17-0.65/A) / (1-1/A^2)^2$ (1)

For lower A, we have derived an expression from numerous numerical equilibrium studies over a variety of plasma shapes, and including double-null and divertor plasmas, deriving:

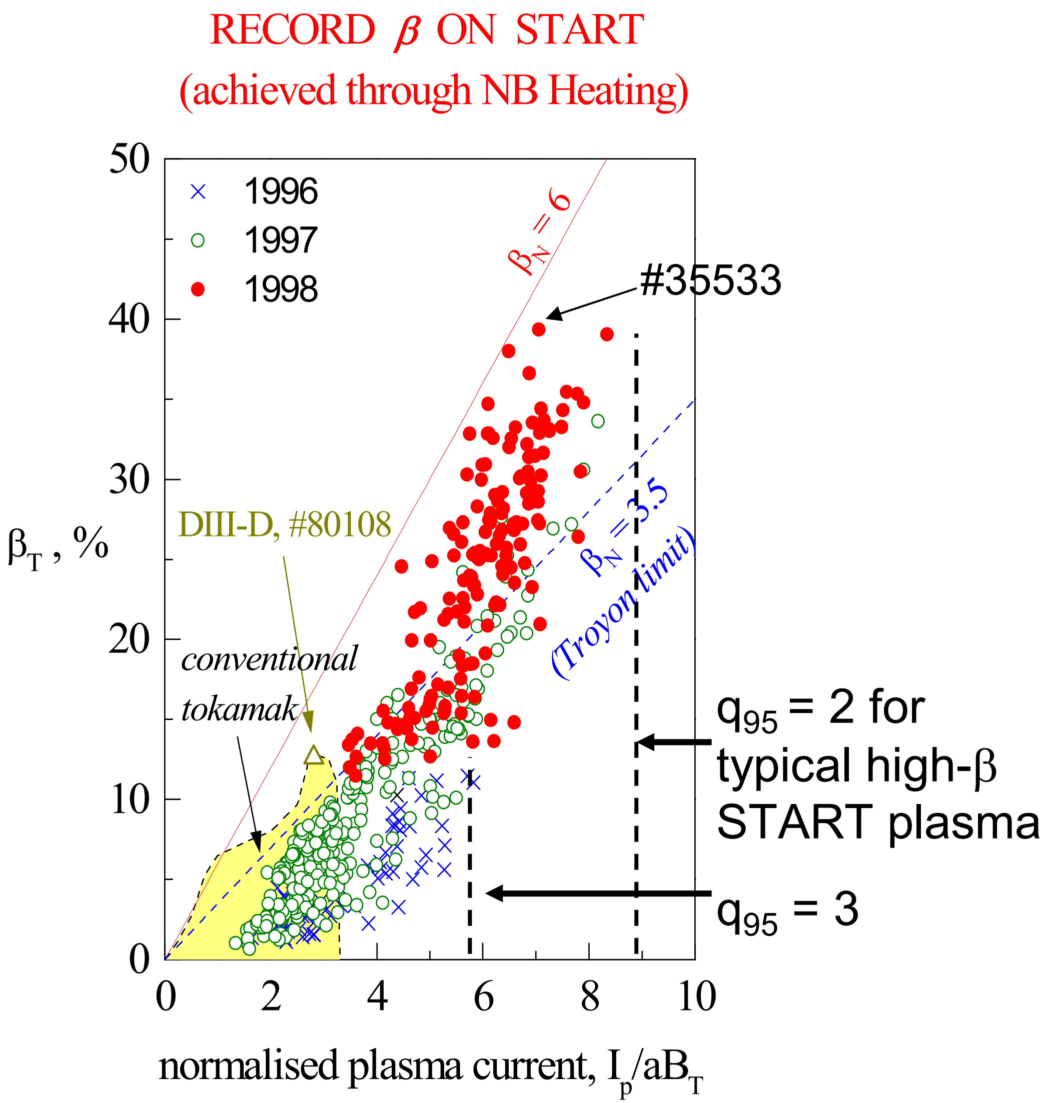
$$q_{95\,(ST)} = c\, q^*_{(ITER)} \sqrt{[A / (A-1)]} \qquad (2)$$

where c=1.17 for limiter plasmas, 0.9 for DND plasmas

Example 1, JET: R=3, a=1.25, A=2.4, k=1.6, δ=0.25 limiter, at q_{95}=2.5 gives (using (1)) $\beta_{max} = 4\, I / (aB) = 10\%$

Example 2, START: (#35533) R=0.31, a=0.23, A=1.35, k=1.77, δ=0.6, I=0.245MA, B_{To} = 0.15T, and $\beta_{\mathbf{expt}}$ =40%, corresponding to 5.5 I / (aB). Eqn (2) for DND gives q_{95} = 2.58.

START achieved record beta values



#35533

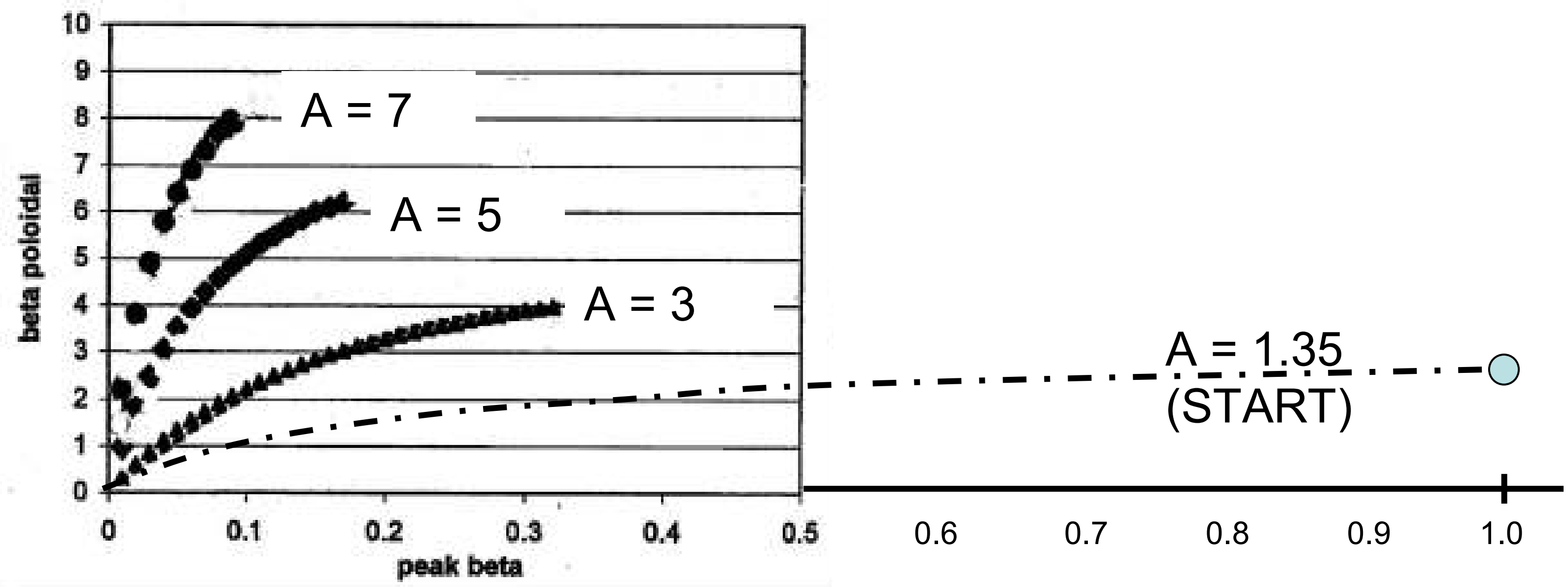
R=0.31 a = 0.23 A=1.35 κ=1.8
I_p = 0.245MA B_T=0.15T δ=0.6
β_T=40% <β> ~ 17.5%

β_o ~ 100% (half thermal, half fast ion) [1]

[1] *'Neutral beam heating in the START spherical tokamak'* *R.J.Akers et al, NF 42 (2002) p122*

Return to studies of beta…

The ‘flux conserving tokamak’ concept ….

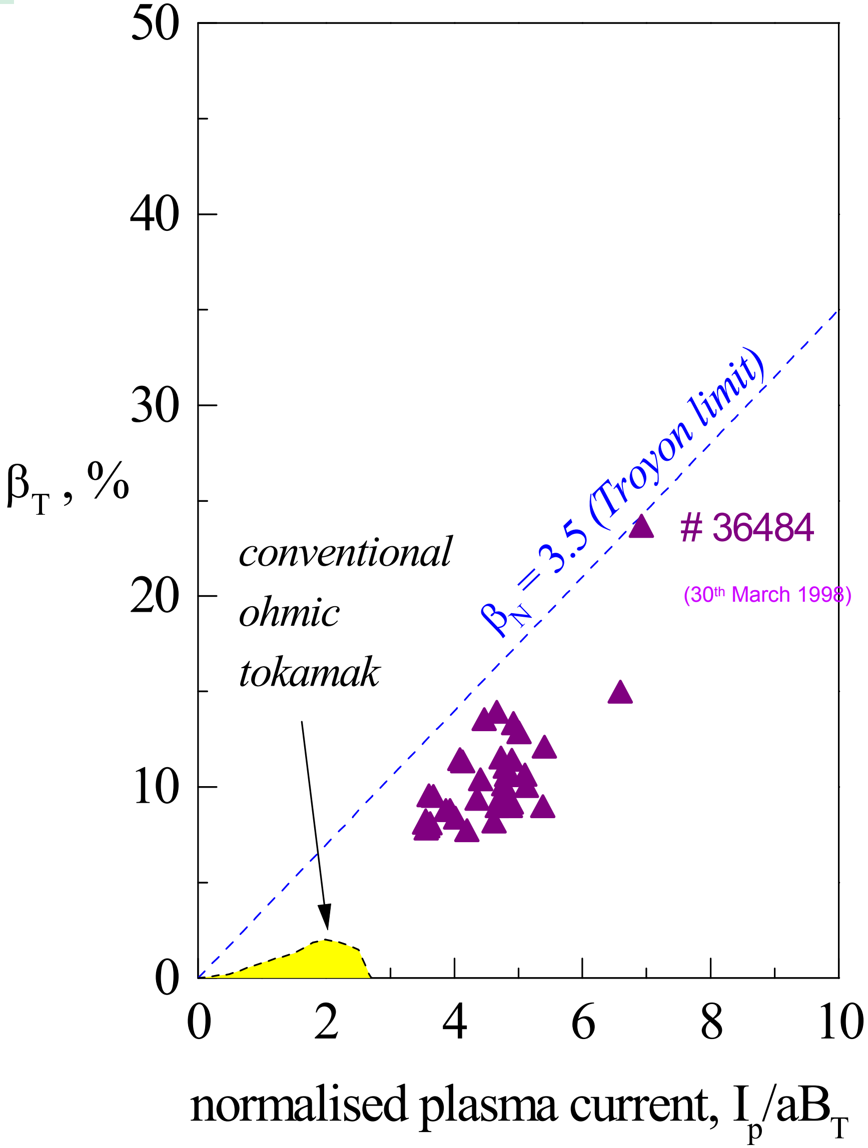


Note ‘peak beta’ is central beta i.e. $2\mu_o\, p_{peak} / \langle B_o^2 \rangle$ (and so is > β_T)

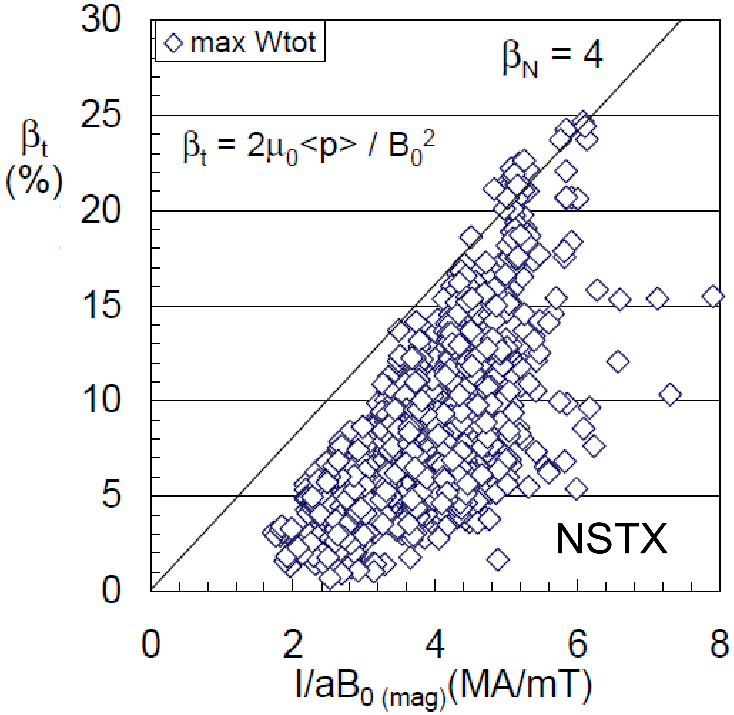
START achieved record beta values (2)

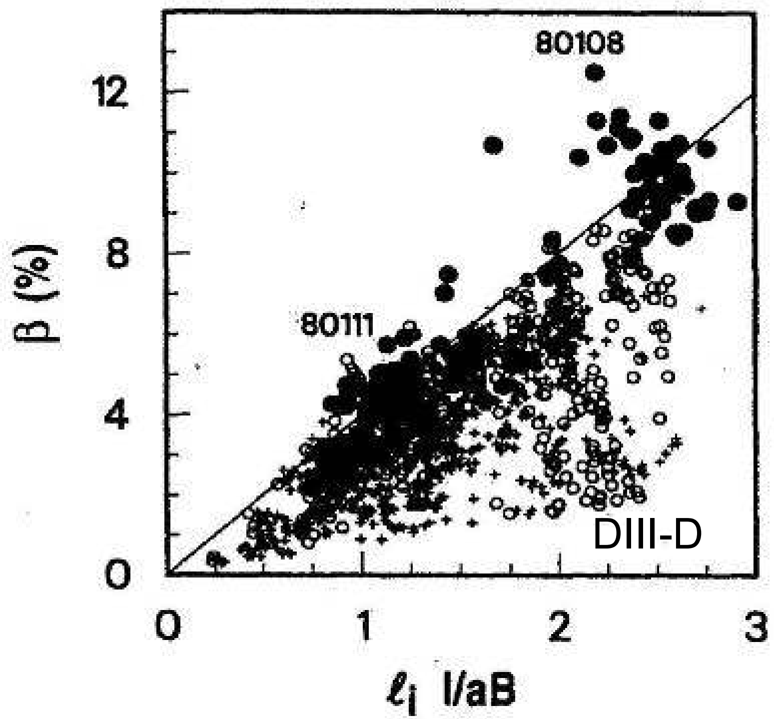
The record high value of 22% was achieved on the last day of START operations – using higher current and with continuous Ti gettering!

RECORD OHMIC β ON START
(achieved through self-heating)



Further sources of confusion!





Bo = vacuum B_T at magnetic axis? Which falls due to Shafranov shift as β increases

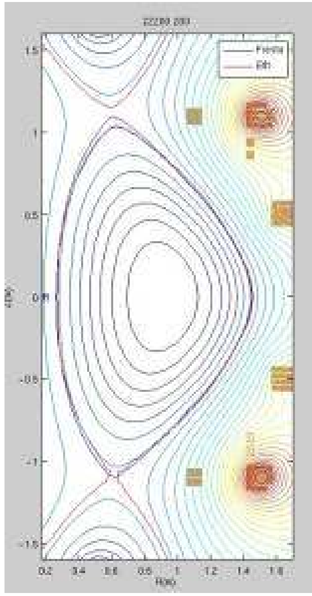
Internal inductance li is small for flat current profiles, large for peaked ones. Although increasing peakedness can raise β it has many confusing effects…

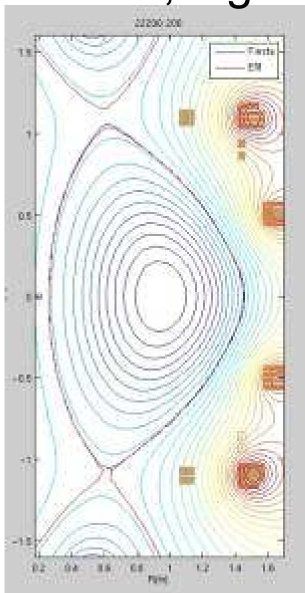
NSTX results from Steve Sabbagh et al, 2001 APS

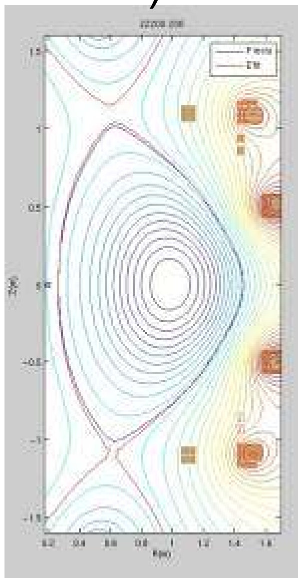
DIII-D plot from Strait et al PRL 74 (1995) p2483

Effect of varying li: MAST equilbria

All plots have same plasma and coil currents: just current shape is varied (low li, flat current; high li, peaked current)





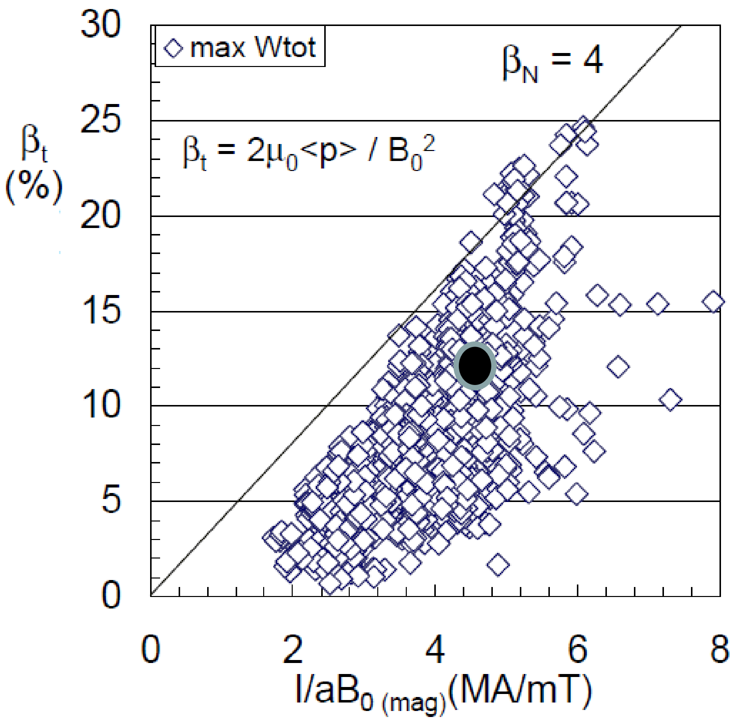


Dave Taylor

li(2)	0.65	0.98	1.51
qo	3.87	1.61	0.86
κ	1.85	1.77	1.69
δ(0.5)	**0.28**	**0.17**	**0.12**

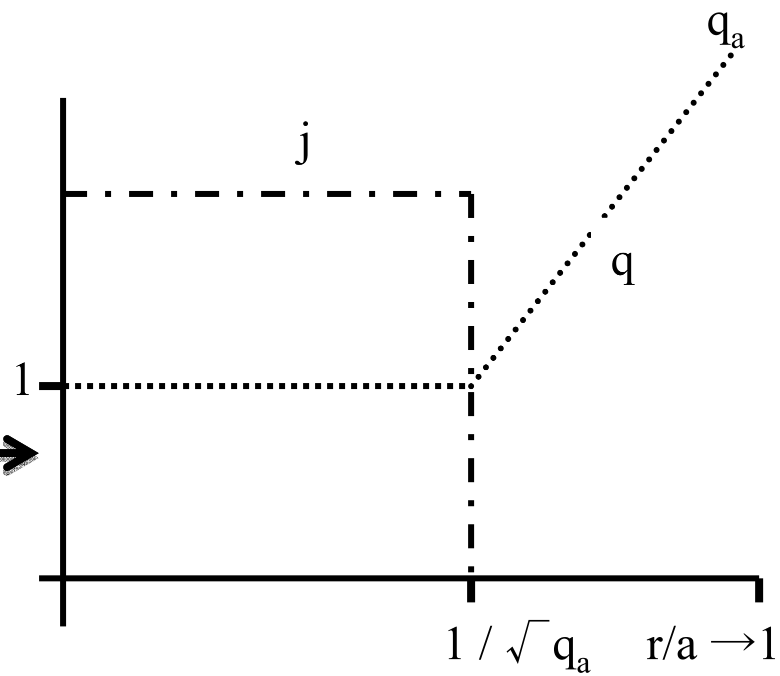
The high li case will sawtooth; loses triangularity in the interior; has ~15% reduced q_{95} (so will reach the q = 2 limit sooner)…

Optimum li



At any point, it may be possible to increase β by increasing li PROVIDED sawteeth or internal modes or tearing modes are not destabilised, and the edge q value does not become close to 2, 3, etc…

To give highest β, the optimum q-profile is
- subject to other stability requirements



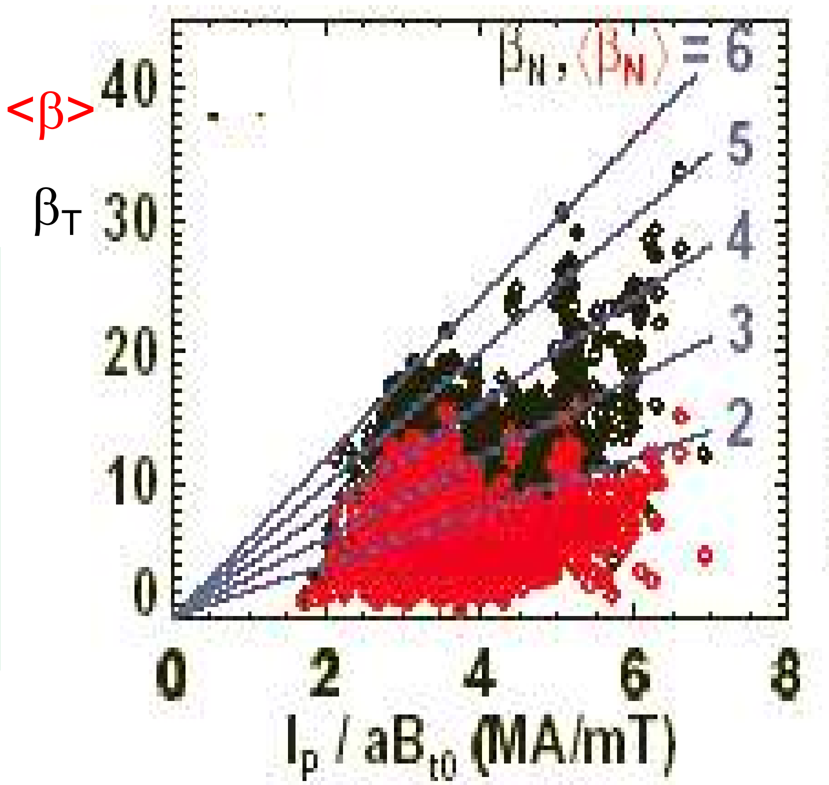
Comparison of <β> and β_T in NSTX

the THEORETICIANS defn of < β > uses the integral of $B_T^2 + B_\theta^2$ over the plasma volume. However the Sykes – Troyon scalings are commonly used to represent β_T evaluated using just B_{To} evaluated at the geometric centre. This gives similar results at high aspect ratio – but at low A, < β > can be less than one-half β_T…..!

The difference is most marked at high I, where B_θ becomes high.

So, expt data for STs is NOT well represented by Sykes-Troyon scalings if their definition of <β> is used (falling below expectations at high current), but well fitted if the 'wrong' experimentalist's defn is used!

Explanation: life is harder for the plasma at high I due to onset of other instabilities – reducing <β> below Sykes-Troyon. But at high I β_T exceeds <β>, countering this reduction.



*β_T (black) and **<β>** (red) achieved on NSTX, from Synakowski UCRL-JRNL-202468 2004*

Power / volume is important…

	Volume (m^3)	Heating (MW)	H / V	Max β_T attained
JET	100 (SND:80)	22	0.2 (0.25)	6%
MAST	8	3	0.4	15%
DIII-D	25	20	0.8	12.5%
START	0.5	1	2	40%

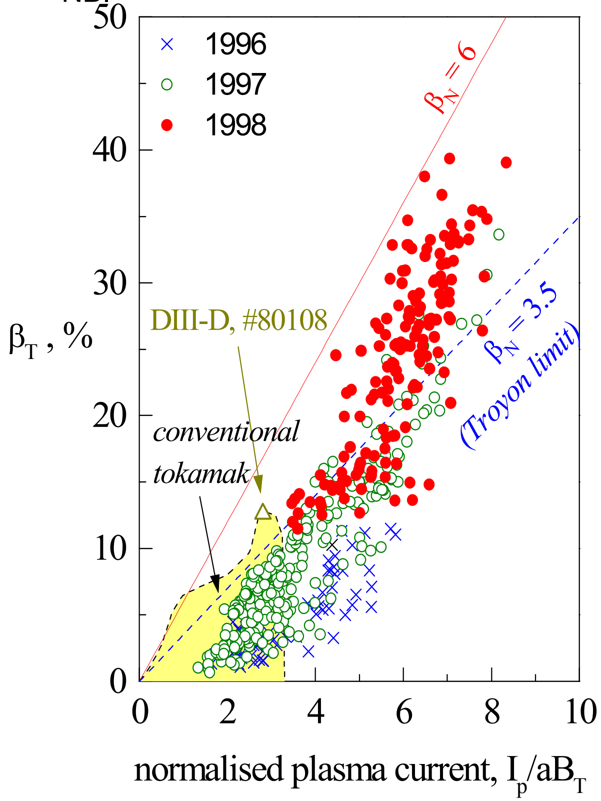
JET and DIII-D attained their highest beta values at LOW toroidal field and plasma current, so that their heating suffices to reach the pressures required

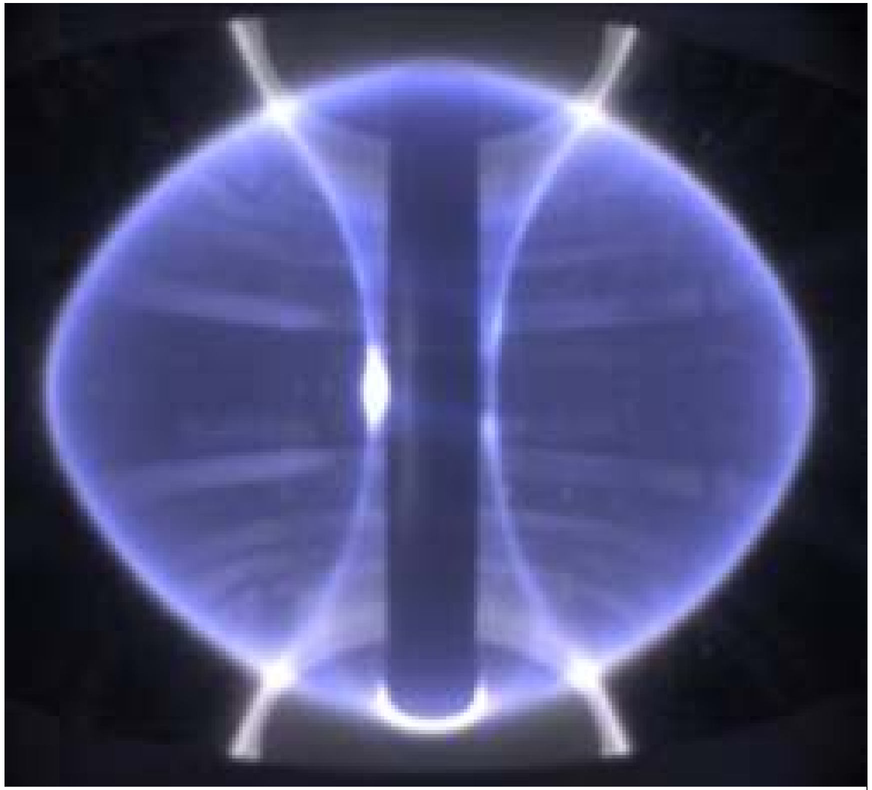
START obtained 40% by having high NBI/vol; raising I_p AND lowering B_T

high beta values could be achieved on MAST?

START: A~ 1.31, κ ~ 2, δ ~ 0.8

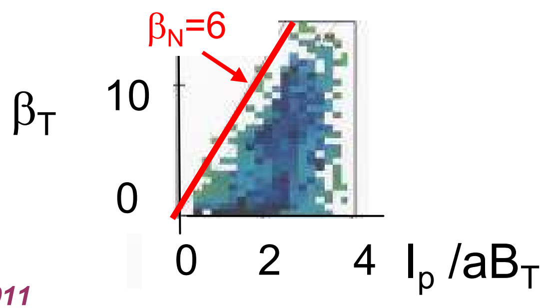
P_{NBI} = 1MW plasma vol ~ 0.6m^3





MAST: A~ 1.36, κ ~ 1.75, δ ~ 0.44

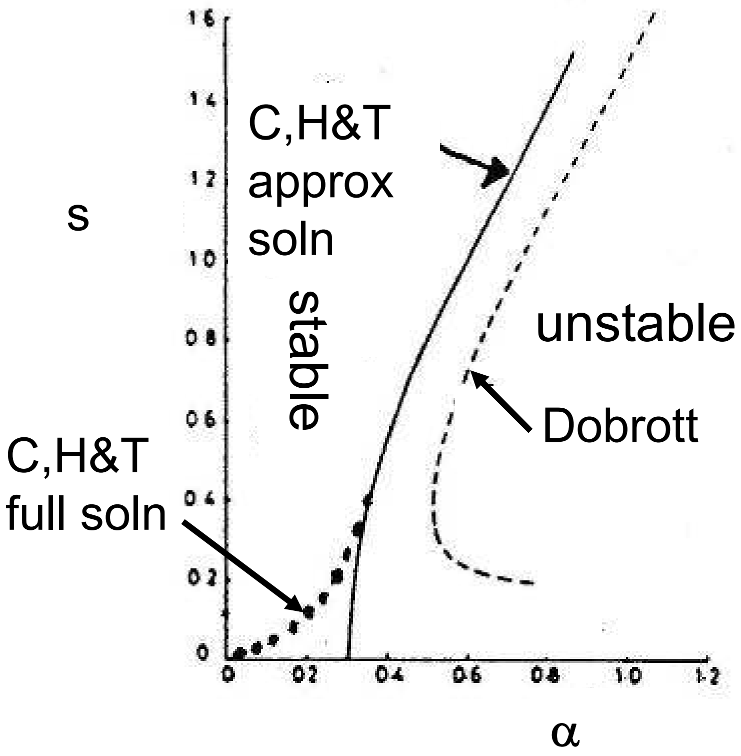
P_{NBI} ~ 3MW plasma vol ~ 10m^3

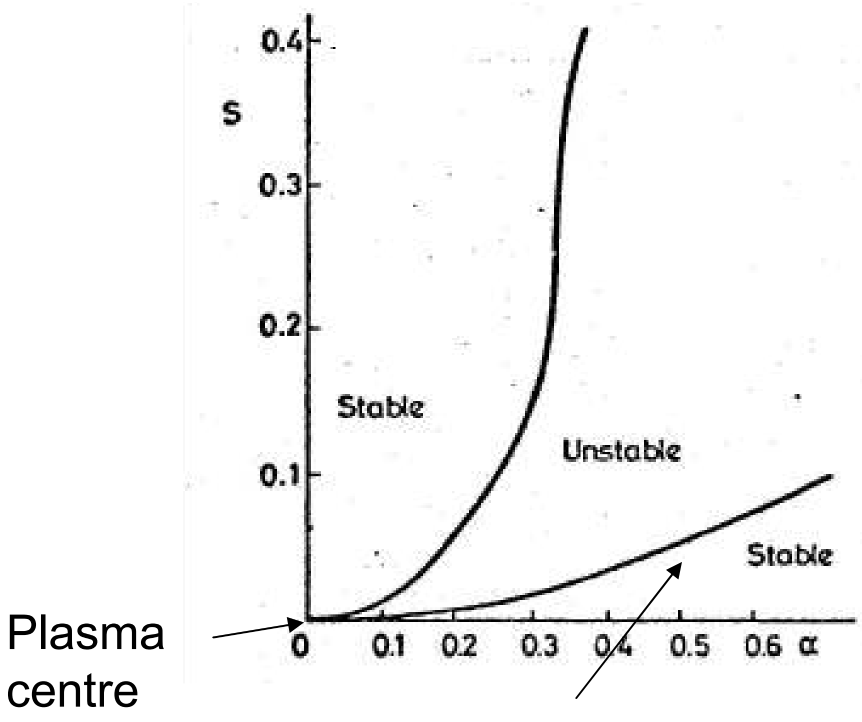


Reducing B_T in MAST could provide high beta

A second region of stability?

The high-n ballooning mode stability diagram for 'typical' plasma equilibria with $q_o = 1$ is shown (s = r/q dq/dr ~ shear, α ~ pressure gradient)



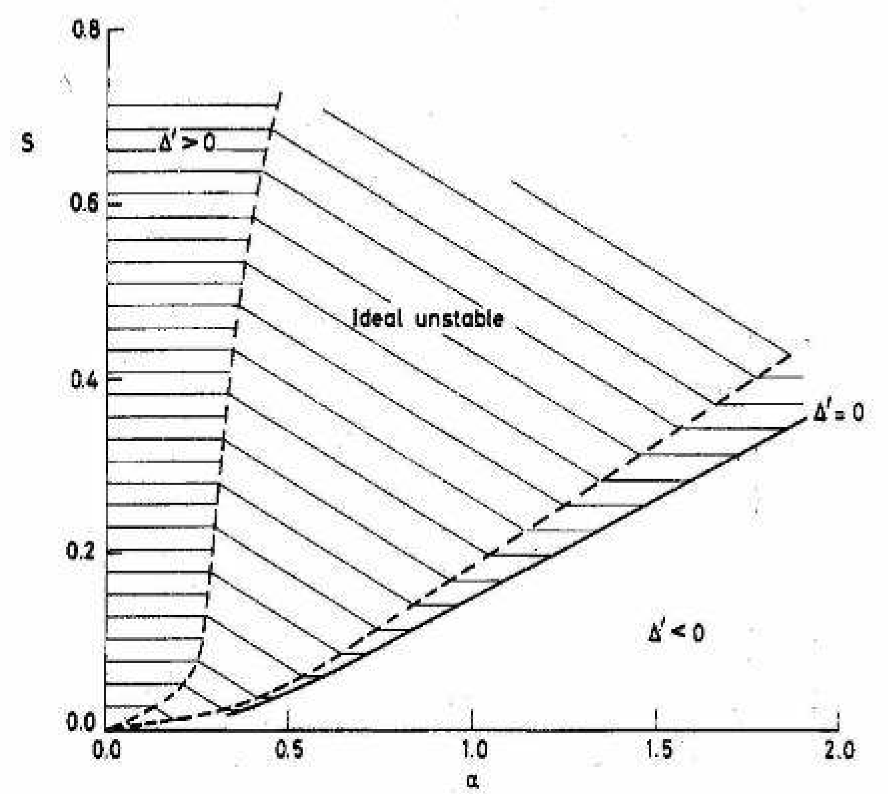


Progress- Connor, Hastie & Taylor developed earlier work by Coppi and Dobrott…

[1] *Connor, Hastie, Taylor PRL 40 (1978) p396*

A second solution of the ballooning equations was observed by Marion Turner – but at first, was considered inaccessible.

The second region aroused great interest…



s – α diagram: diagonal shading = unstable to ideal b.m.
Horizontal shading: unstable to resistive b.m.

Resistive ballooning modes have much lower growth rates than ideal modes – so can only have effect in regions of ideal stability

It was found [1] that all the first region of stability was in fact unstable to resistive b.m. (could this be the cause of anomalous transport?) – but the 2nd region was mostly stable….

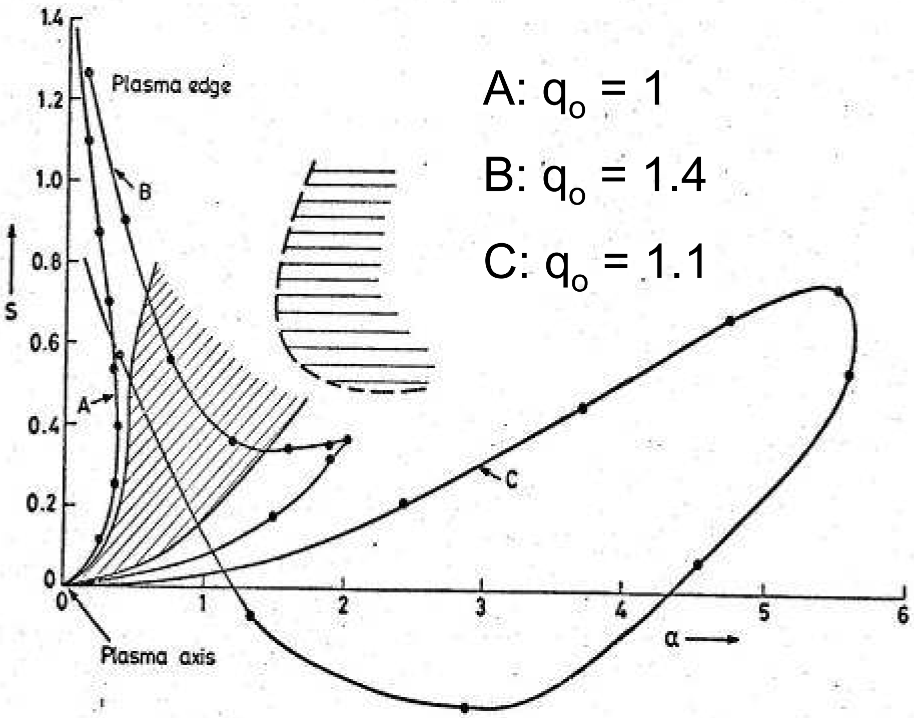
[1] Sykes, Bishop & Hastie PPCF 29 (1987) p 719

A second region of stability (2)

However, if q_o can be raised, the ideal unstable region can become detached [1] , allowing access to higher pressure gradients….

Raising qo above unity was a new concept in 1979 – but is a common technique now.

J J Ramos extended the Troyon-Sykes scaling to include higher q_o [2] and noted that access was improved by high shaping (high triangularity) and low aspect ratio



A: q_o = 1

B: q_o = 1.4

C: q_o = 1.1

[1] 'A stable route to the high β_p regime' A.Sykes, M F Turner EPS Conf Oxford 1979

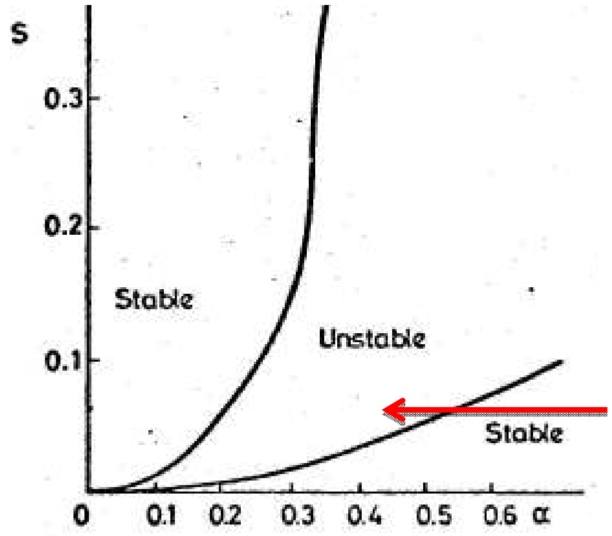
[2] J J Ramos Phys Fluids B 3 (8) 1991 p2247

A second region of stability (3)

So far we have considered access to 2nd stability near the **plasma centre**, by reducing shear by raising q_o.

It was conjectured in [1] that edge current gradients possible in divertor tokamaks may lower the shear at the **edge of the plasma** – permitting access to a 2nd region there – possibly the H-mode.

Later work [2] explored bifurcated temperature profiles and L-H modes; and a full theory of coupled peeling-ballooning modes giving an explanation of L-H transition and ELMs was developed in [3].



However, as cautioned in [3], if in H-mode, the effect of entering the nearby region unstable to ballooning modes is likely to cause a catastrophic effect (increased turbulence lowers α and causes deeper instability) – as indeed observed with ELMs.

[1] 'Resistive ballooning modes and the second region of stability' A Sykes, C M Bishop & R J Hastie PPCF 29 1987 p719

[2] 'Bifurcated temperature profiles and the H-mode' C M Bishop, NF 27 (1987) p1765

[3] 'Access to second stability region for coupled peeling-ballooning modes' H R Wilson & R L Miller PoP 6 (1999) p873

The quest for Ignition in STs

To date, STs have been at low toroidal field, and have successfully exploited the ability to obtain high plasma current.
Can we build a high field ST?
Can STs make fusion devices?

'Triple product' for ignition: $nT\tau > 3\mathrm{x}10^{21}$ (keV, s, m^{-3})

-but $p \sim nT$, and $p \sim \beta B^2$: so triple product $\sim \beta \mathbf{B^2} \tau$

Raising β : easy at low aspect ratio!
Raising B : difficult at low aspect ratio (see next slide)
Raising τ : favours large devices

Comment: the famous high beta values in DIII-D, JET and START have all been achieved at LOWER than usual values of B!

Raising B

Doubling the toroidal field in any device:
-Enables current I_p to be doubled (same stability q)
-Hence density limit doubled (Greenwald limit ~ n)
-Temperature T increases ($\sim B_T^{0.8}$ in Ohmic plasmas)
-Confinement $\tau \sim B_T^{1.5}$ (approx) through B, I, and n
- hence max $nT\tau$ increases by factor 8 or more!

BUT peak B_T is limited by stress on the magnet, and temperature rise.

If we assume that stress, temp. rise ~ (copper area)$^{-1}$ in centre stack, we have max(Irod) = c r^2 where r = radius of centre rod, $r = R_o(1 - 1/A)$
We can fix the constant c by data from the ultimate high-field copper tokamak (still incorporating a solenoid) namely IGNITOR: where R_o = 1.43, B_{To} = 13, a=0.5 (hence A = 2.86). Since B_{To} = 0.2*Irod / R_o , Irod = 93MA (incidentally giving a field of 20T at the edge of the copper centrestack).
Hence c=108 and we have an expression for maximum toroidal field:

$B_{To} / R_o = 21.5 (1 - 1/A)^2$ for copper TF coils at aspect ratio A

Raising B (cont'd)

$$B_{To} / R_o = 21.5 (1 – 1/A)^2 \qquad [1]$$

Implies that max B_T increases with size; and decreases at low aspect ratio. Some examples for copper TF with solenoid:

Device	Ro	A	B_{To} (expt)	B_{To}(max) from [1]
START	0.32m	1.28	0.3T	0.33T
MAST	0.85m	1.35	0.5T	1.2T
MAST-U	0.85	1.5	0.8T	2T
IGNITOR	1.43m	2.86	13T	13T
JET	3m	2.4	4T	11.7T**

** limited by max. permissible field 20T at edge of conductor

At low A, max TF is limited by stresses produced by the solenoid. Using a smaller solenoid both reduces stress and allows use of more copper for TF. In fusion devices neutron damage will greatly reduce stress limits, unless space for shielding…

minimising magnet dissipation costs

Two approaches:

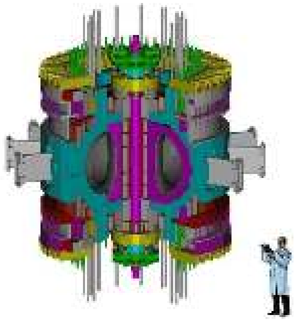
1) Improve beta so that the required plasma pressure (and hence fusion power) can be obtained for a lower magnetic field.

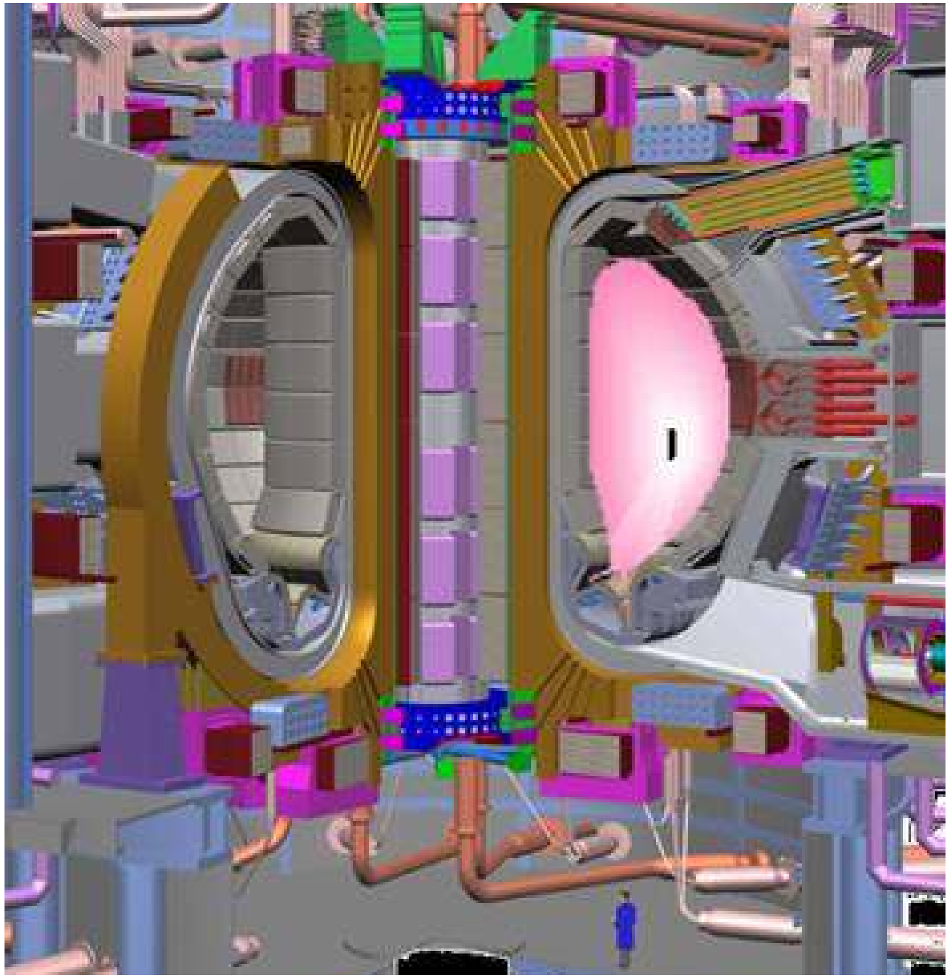
2) Use superconducting magnets.

   Most recent long-pulse tokamak designs or proposals (including ITER) feature low-temperature superconducting magnets. These are costly to make, and the cryostat and cryoplant are costly and inconvenient, but running costs are greatly reduced.

Note: superconducting TF magnets may not be practical in STs as limited space for cryostat and shielding!

Raising toroidal field B_T: two approaches:



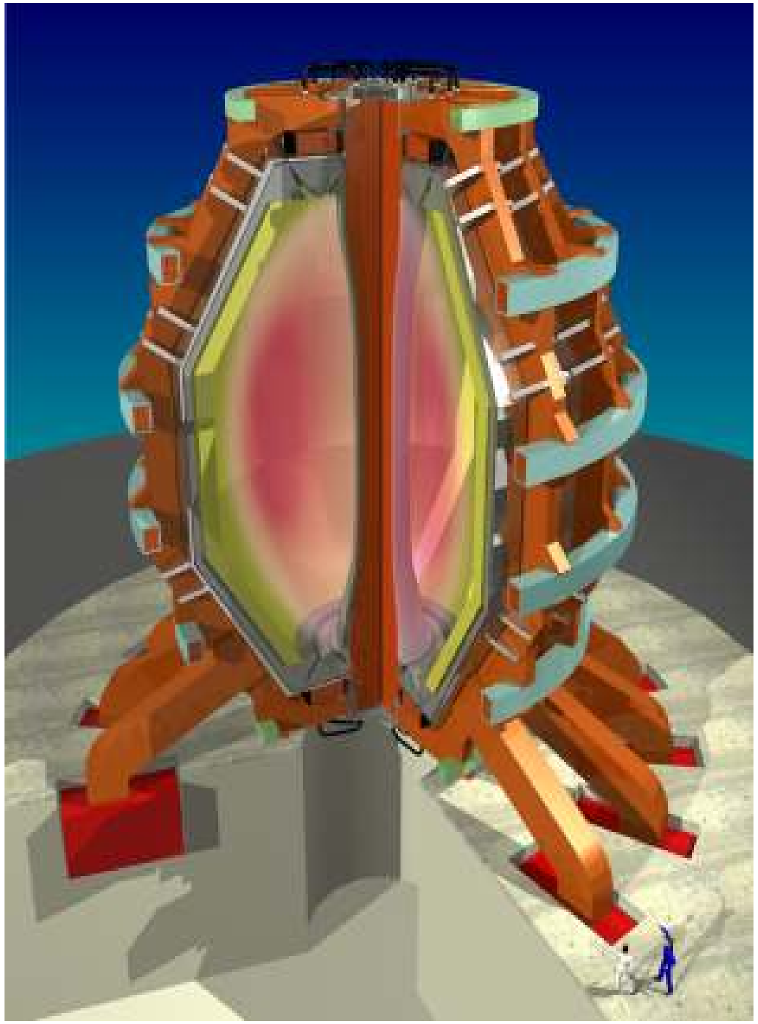


IGNITOR: The TF magnet is copper. It is designed to give the max possible field for short pulses. The field at the edge of the copper is 20T, field at Ro (1.3m) = 13T.

ITER: the TF magnet is LTS (Nb3Sn) in steel casing. It uses a small part of the central stack. There is a large central solenoid to power long pulses. The LTS conductor max field is 11.8T; field at Ro (6.2m) = 5.3T

ST Power plant - general features

Design driven by need to produce ECONOMICAL fusion power



$R/a = 3.4/2.4$m; $k = 3.2$

$I_p = 31$MA, $B_t = 1.8$T

$\beta_N = 8.2$, $P_{fusu} = 3.5$ GW

$Q = 50$, $P_{wall} = 3.5$MW/m^2

$f_{non\text{-}ind} = 0.95$

copper single-turn TF,
replaced at intervals
when neutron damaged

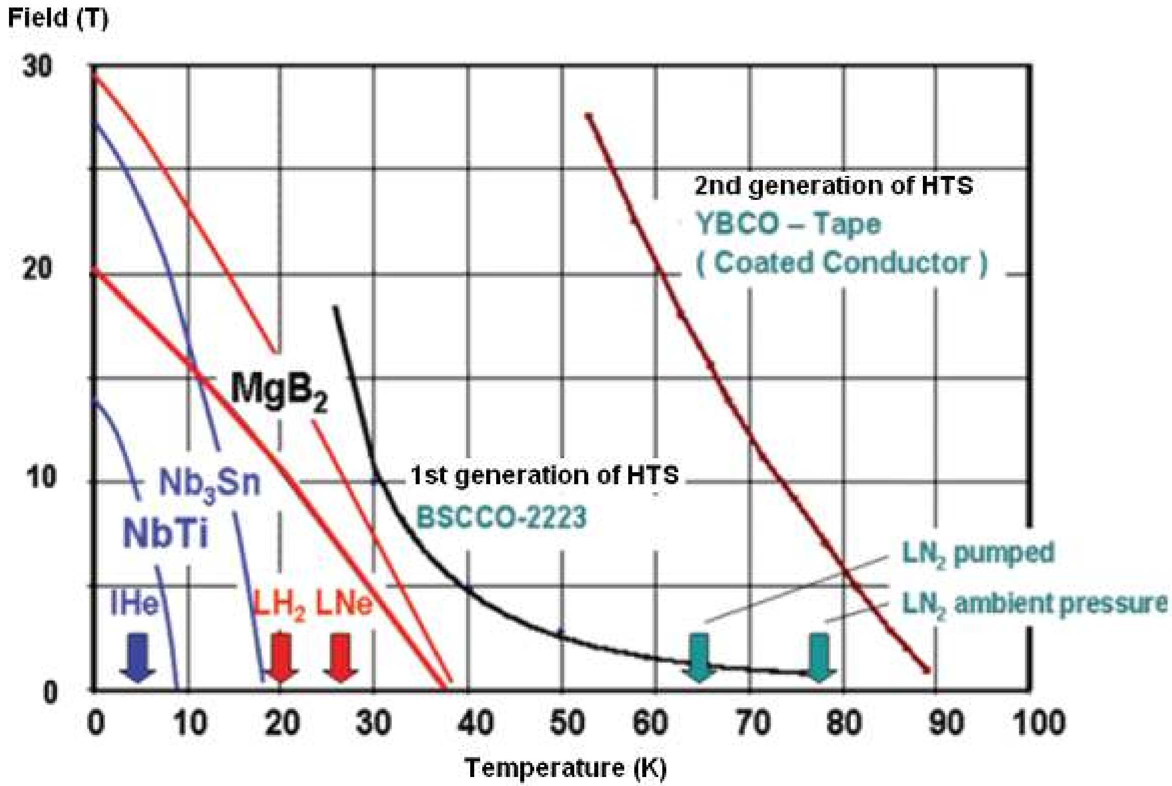
Very high $\beta \sim 59\%$;
low field; large size

Physics: *Wilson et al, NF 2004*
Engineering, *Voss et al ISFNT 2000, 2002*

New ideas – High Temperature Superconductors (HTS)

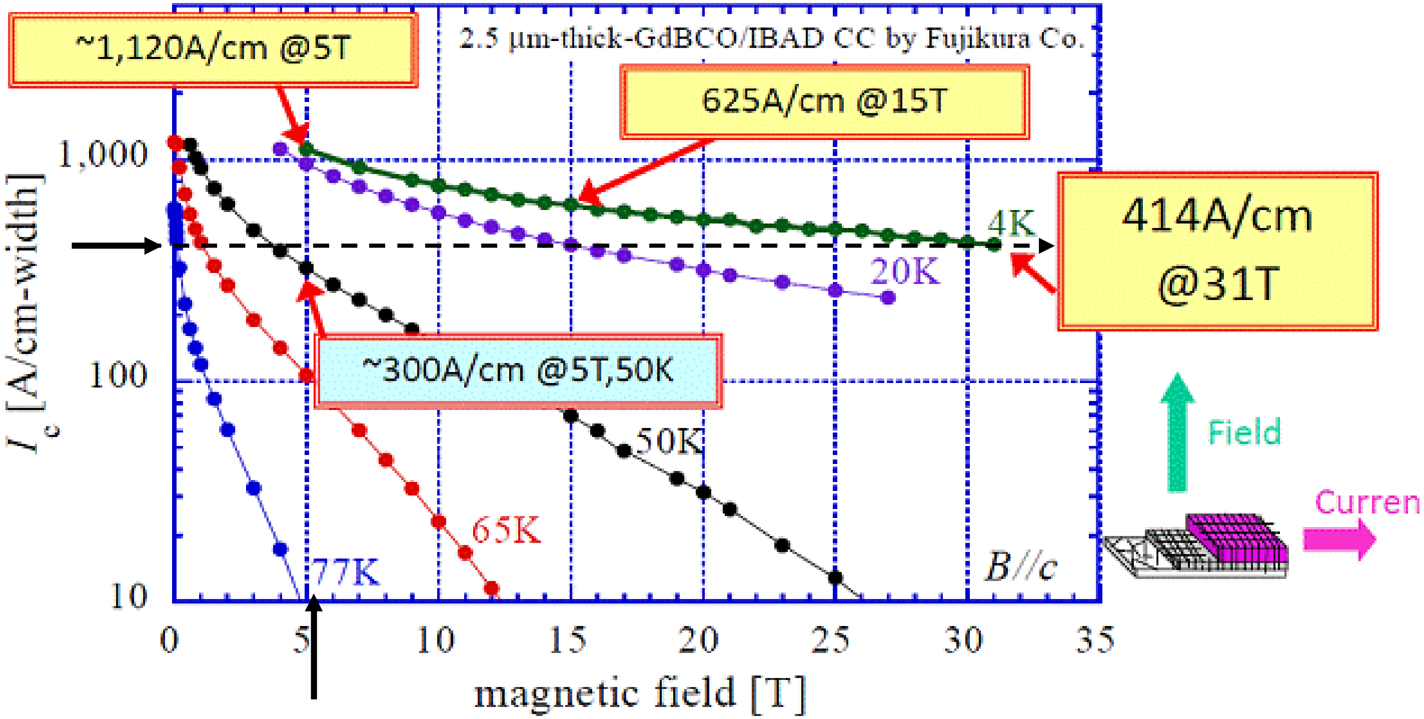
The recent development of 'High Temperature' superconductors could have far-reaching application.

At first, these were just thought to be a more convenient form of LTS in that they give similar performance but at around 77K (liquid nitrogen) rather than 4K (liquid helium) temperatures. (Note however that nitrogen is unsuitable in a neutron environment as radioactive C14 is produced.)



Properties of HTS…

operated at low temperature, HTS appears to offer much higher performance



Example 1: moving vertically, in a field of 5T HTS tape can transmit 10A at 77K, but 300A at 50K and 1100A at 4K

Example 2: moving horizontally, the HTS tape can pass 400A in a field of <1T at 77K, but 400A in a field of 30T at 4K

Potential of passing much higher currents AND operation at higher fields than LTS, and better neutron tolerance(?)

Conjecture: HTS in an ST?

Just possibly, the high-current carrying properties of HTS (when run at LTS temperature!) will enable an HTS TF magnet (with sufficient neutron and thermal shielding, space for cryostat and steel support structure) to be made for an ST – increasing TF, and reducing c/col losses

- Leading to an efficient ST power plant.

Summary

The tokamak has brought high performance – at a cost of providing high magnetic fields.

Despite early concerns about equilibrium and stability limits, beta (ratio of plasma pressure to magnetic field pressure) CAN be high enough for Fusion Power Plants to be viable in a variety of formats

- but it is difficult to make the process economic!

The advent of superconductors brings added complexity but higher efficiency; possibly the recent advances in 'High Temperature Superconductors' (perhaps operated at low temperature!) may increase the efficiency and expedite the dream of Fusion Energy.

Acknowledgements

- To my many colleagues on the beta trail, both old and new, theoretical and experimental; and especially those who have provided advice or material for this talk (or who are about to!)

Raising B (cont'd)

$$B_{To} / R_o = 21.5 (1 - 1/A)^2 \qquad [1]$$

Implies that max B_T increases with size; and decreases at low aspect ratio.
Some examples for copper TF with solenoid:

Device	Ro	A	B_{To} (expt)	B_{To}(max) from [1]
START	0.32m	1.28	0.3T	0.33T
MAST	0.85m	1.35	0.5T	1.2T
MAST-U	0.85	1.5	0.8T	2T
SCFNS	0.5m	1.67	1.5T	1.7T
IGNITOR	1.43m	2.86	13T	13T
JET	3m	2.4	4T	11.7T**
ITER	6.2m	3.1	5.3T	13.5T**

** limited by max. permissible field 20T at edge of conductor

At low A, max TF is limited by stresses produced by the solenoid. Using a smaller solenoid both reduces stress and allows use of more copper for TF

Aachen conference 1983 (1)

Sykes, Turner & Patel optimised pressure profiles to marginal stability to high-n ballooning modes, and found for a wide range of shapes (circles, D's, backward D's, ellipses, beans) and a wide range of aspect ratios (1.5 - 4.5), the max. beta was given by

$\langle\beta\rangle = 20\ E / [A\ q_J]$

where $q_J = 2\ B_{To} / [\ \mu_o\ R_o\ I_p / \text{area}]$

-Provided there was sufficient triangularity δ.

Note that substituting for q_J, the STP expression is

$\mathbf{\langle \beta \rangle = 4\ I_p / (A\ B_T)}$

Using ITER expression for q_{95}, for Ro=3, k=1.6, B_T=3.5T, max beta in JET is when q_{95}=2 at I = 10.5MA and is β = 9.8%