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Steady-state Operation Requirements of Tokamak Fusion Reactor Concepts

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Abstract
In the last two decades tokamak conceptual reactor design studies have been deriving benefit from progressing plasma physics experiments, more depth in theory and increasing detail in technology and engineering. Recent full-scale reactor extrapolations such as the US ARIES-I and the EC Reference Reactor study provide information on rather advanced concepts that are called for when economic boundary conditions are imposed. The ITER international reactor design activity concentrated on defining the next step after the JET generation of experiments. For steady-state operation as required for any future commercial tokamak fusion power plants it is essential to have non-inductive current drive. The current drive power and other internal power requirements specific to magnetic confinement fusion have to be kept as low as possible in order to attain a competitive overall power conversion efficiency. A high plasma Q is primarily dependent on a high current drive efficiency. Since such conditions have not yet been attained in practice, the present situation and the degree of further development required are characterized. Such development and an appropriately designed next-step tokamak reactor make the gradual realization of high-Q operation appear feasible.

1. Introduction

As experimental fusion installations grow in size and approach reactor conditions it is increasingly important to meet reactor operating requirements. It is already clear that for a next step in tokamak reactor development such as ITER [1] the power supply requirements for steady-state operation will be very high. Considerable improvement is needed towards full-scale reactors.
Without going into the details of a specific reactor conceptual design, one can derive a number of relations that may serve to clarify some rather basic facts. In the considerations presented here it is implied that only steady-state operation would finally be feasible for practical application of any tokamak fusion reactor [2], and that the same would hold for a next step - if considered as an engineering test facility and a relevant DEMO predecessor.
Section 2 deals with the evaluation of the power quality factor Q_p, which denotes the ratio of the gross electric power to the recirculating power needed for reactor auxiliaries. Using that relation, one can, for instance, calculate the ratio of the electric output power to the fusion power needed for its generation, which provides a link with the plasma conditions required for the fusion core of a power station. Fusion power is useful as a reference figure and is needed for introducing the plasma quality factor Q, which is the subject of Section 3. Q - like Q_p - can be expressed in terms of specific or relative quantities, thus appearing independent of absolute dimensions, power etc. Section 4 shows the relation between Q and the energy confinement time for fixed power and reactor geometry. On the basis of typical parameter values for thermal power conversion efficiency, blanket power multiplication, electrical efficiency of

current drive systems and relative auxiliary power requirements one can evaluate a range of necessary Q values for a range of attainable Q_p values for typical relative input parameters. Furthermore, from typical plasma physics parameter values the possible range of γ can be determined, which, in the case of agreement with the first evaluation, gives an indication what consistent combinations of Q and Q_p can be expected. The relative auxiliary power demand for magnetic fusion systems can be very large and has a strong impact in these relations. In Section 5 these important quantities and their interdependence are shown for various reactor design parameter sets and the role of a high current drive efficiency γ is demonstrated. Section 6 concerns the relevance of increasing the Kruskal safety factor by increasing the bootstrap current fraction. Section 7 tackles the possibility of applying high-efficiency steady-state current drive to a next-step pulsed ignition reactor concept. The results are summarized in the conclusions.

2. Electric power quality factor Q_p

The use of this quantity, which is the ratio of the gross electric power to the electric power supply of the reactor itself, provides direct insight into the amount of recirculating and auxiliary power in an electric power station with thermal conversion. The power flow scheme in a DT tokamak fusion reactor as used in, for example, [3], can be described by the following simplified picture (see Fig. 1): 80% of the plasma fusion power (neutrons) enhanced by the blanket reaction multiplication factor f_{bl} appears as heat input to the first wall and blanket thermal conversion system, which is the main conversion system and has the efficiency η_{th}. A part f_p of the pumping power P_p for heat removal also enters into this system. The remaining 20% of the plasma fusion power P_f (alpha particles) together with any additional plasma heating power (such as the power P_{CD} for non-inductive current drive) appears partially (fraction f_r) as radiation to the wall and hence goes to the main conversion system, while the remaining part $(1 - f_r)$ appears as plasma loss power flow, hence as heat input to the divertor thermal conversion system with the efficiency η_{di}. Summing the electric power from the main conversion system and the divertor conversion system yields the gross electric power P_{et}. Recirculating electric power feeds the current drive system (with an electrical efficiency η_{CD}), the cooling system pumping power, and other auxiliaries. The fraction $(1-f_p)P_p$, the auxiliary power P_{aux} and the current drive supply losses are not recovered. The fraction f_r is determined by the ratio of the radiation power to the total heating power. For a steady-state reactor with non-inductive current drive one thus has

$$f_r = (P_{rad}+ P_{sy})/(P_\alpha + P_{CD}) = (P_{rad} + P_{sy})/[P_\alpha (1 + 5/Q)]$$

The gross thermal efficiency $\eta_{tht} = P_{et}/P$ relates the gross electric power to the sum of the main and divertor thermal powers. The overall efficiency η relates the net electric power to the gross thermal power $\eta = P_e/P$.

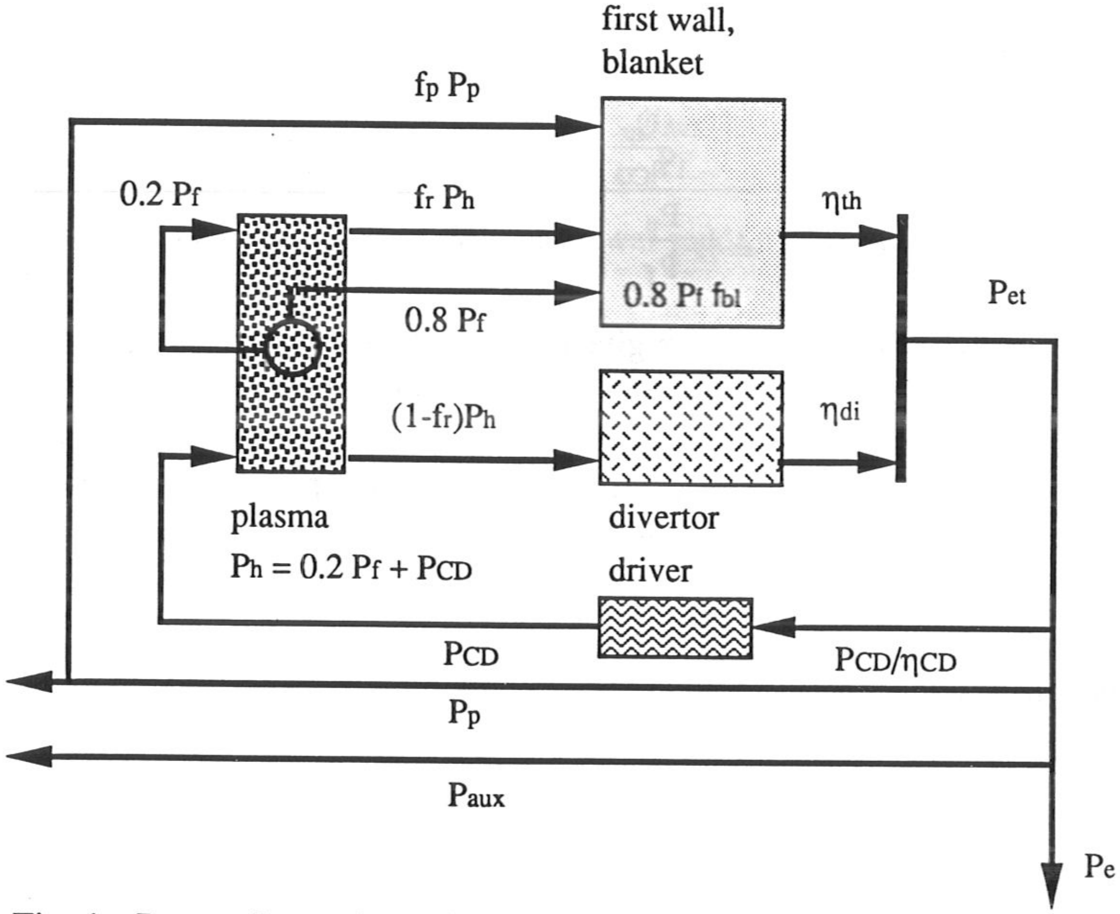

Fig. 1 Power flow scheme in a tokamak fusion power reactor

The scheme in Fig.1 is formulated by means of $Q = P_f/P_{CD}$ and the Q-dependent relative electric power for current drive $P_{CD}/(P_f\,\eta_{CD}) = 1/Q\eta_{CD}$:

$$P = P_{bl} + P_{di} = \left\{\left[0.8\ f_{bl} + 0.2\ f_r\left(1 + \frac{5}{Q}\right)\right] P_f + f_p P_p\right\} + \left\{0.2\ (1 - f_r)\left(1 + \frac{5}{Q}\right) P_f\right\}$$

$$P_{et} = \eta_{th}\left\{\left[0.8\ f_{bl} + 0.2\ f_r\left(1 + \frac{5}{Q}\right)\right] P_f + f_p P_p\right\} + \eta_{di}\left\{0.2\ (1 - f_r)\left(1 + \frac{5}{Q}\right) P_f\right\}$$

$$\eta_{tht} = \frac{\eta_{th}\left\{0.8\ f_{bl} + 0.2\ f_r\left(1 + \frac{5}{Q}\right) + f_p \frac{P_p}{P_f}\right\} + 0.2\ \eta_{di}\,(1 - f_r)\left(1 + \frac{5}{Q}\right)}{\left\{0.8\ f_{bl} + 0.2\ f_r\left(1 + \frac{5}{Q}\right) + f_p \frac{P_p}{P_f}\right\} + 0.2\ (1 - f_r)\left(1 + \frac{5}{Q}\right)}$$

$$Q_p = \frac{P_{et}}{P_{et} - P_e} = \frac{\eta_{th}\left\{0.8\ f_{bl} + 0.2\ f_r\left(1 + \frac{5}{Q}\right) + f_p\frac{P_p}{P_f}\right\} + 0.2\ \eta_{di}\left(1 - f_r\right)\left(1 + \frac{5}{Q}\right)}{\frac{1}{\eta_{CD}\,Q} + \frac{P_p}{P_f} + \frac{P_{aux}}{P_f}}$$

Solving for Q yields

$$Q = \frac{\frac{Q_p}{\eta_{CD}} - \left[\eta_{th}\ f_r + \eta_{di}\left(1 - f_r\right)\right]}{0.8\ f_{bl}\,\eta_{th} + \eta_{th}\ f_p\frac{P_p}{P_f} + 0.2\left[\eta_{th}\ f_r + \eta_{di}\left(1 - f_r\right)\right] - Q_p\left(\frac{P_p}{P_f} + \frac{P_{aux}}{P_f}\right)}$$

For a certain value of Q_p with given data for P_p/P_f and P_{aux}/P_f it is seen that the value of Q would be required to go to infinity, namely for

$$Q_p\left(\infty\right) = \frac{0.8\ f_{bl}\,\eta_{th} + \eta_{th}\ f_p\frac{P_p}{P_f} + 0.2\ \left[\eta_{th}\ f_r + \eta_{di}\left(1 - f_r\right)\right]}{\frac{P_p}{P_f} + \frac{P_{aux}}{P_f}}$$

For $\eta_{th} = \eta_{di}$ one has

$$Q_p\left(\infty\right) = \frac{\eta_{th}\left(0.8\ f_{bl} + 0.2 + f_p\frac{P_p}{P_f}\right)}{\frac{P_p}{P_f} + \frac{P_{aux}}{P_f}}$$

It is obvious that $Q_p\ (\infty)$ mainly depends on the thermal conversion efficiency and the auxiliary power fractions. It determines the level of Q_p that can be attained as an ultimate value for these input parameters.

A normalized representation of Q_p related to $Q_p\ (\infty)$ allows one to identify the impact of the different input parameters on the evolution of Q_p with varying Q. One gets

$$\frac{Q_p}{Q_p\left(\infty\right)} = \frac{Q + \frac{\eta_{th}\ f_r + \eta_{di}\left(1 - f_r\right)}{0.8\ f_{bl}\,\eta_{th} + \eta_{th}\ f_p\frac{P_p}{P_f} + 0.2\ \left[\eta_{th}\ f_r + \eta_{di}\left(1 - f_r\right)\right]}}{Q + \frac{1}{\eta_{CD}\left(\frac{P_p}{P_f} + \frac{P_{aux}}{P_f}\right)}}$$

For $\eta_{th} = \eta_{di}$ one has

$$\frac{Q_p}{Q_p(\infty)} = \frac{Q + \dfrac{1}{0.8\ f_{bl} + f_p \dfrac{P_p}{P_f} + 0.2}}{Q + \dfrac{1}{\eta_{CD}\left(\dfrac{P_p}{P_f} + \dfrac{P_{aux}}{P_f}\right)}}$$

The ratio of net electric power to fusion power reads

$$\frac{P_e}{P_f} = \eta_{th}\left\{0.8\ f_{bl} + 0.2\ f_r\left(1 + \frac{5}{Q}\right) + f_p\frac{P_p}{P_f}\right\} + \eta_{di}\left\{0.2\ (1 - f_r)\left(1 + \frac{5}{Q}\right)\right\} - \left(\frac{1}{\eta_{CD}\, Q} + \frac{P_p}{P_f} + \frac{P_{aux}}{P_f}\right)$$

Furthermore one has for the overall efficiency

$$\eta = \eta_{tht}\frac{P_e}{P_{et}} = \frac{Q_p\left(\dfrac{P_f}{\eta_{CD}\, Q} + P_p + P_{aux}\right) - \dfrac{P_f}{\eta_{CD}\, Q} - P_p - P_{aux}}{\left\{\left[0.8\ f_{bl} + 0.2\ f_r\left(1 + \dfrac{5}{Q}\right)\right] P_f + f_p P_p\right\} + \left\{0.2\ (1 - f_r)\left(1 + \dfrac{5}{Q}\right) P_f\right\}}$$

When written for Q only, this yields

$$\eta = \frac{\eta_{th}\left\{0.8\ f_{bl} + 0.2\ f_r\left(1 + \dfrac{5}{Q}\right) + f_p\dfrac{P_p}{P_f}\right\} + 0.2\ \eta_{di}\,(1 - f_r)\left(1 + \dfrac{5}{Q}\right)}{0.8\ f_{bl} + 0.2\left(1 + \dfrac{5}{Q}\right) + f_p\dfrac{P_p}{P_f}} - \frac{\dfrac{1}{\eta_{CD}\, Q} + \dfrac{P_p}{P_f} + \dfrac{P_{aux}}{P_f}}{0.8\ f_{bl} + 0.2\left(1 + \dfrac{5}{Q}\right) + f_p\dfrac{P_p}{P_f}}$$

If Q went to infinity, one would have

$$\eta(\infty) = \frac{\eta_{th}\left\{0.8\ f_{bl} + 0.2\ f_r + f_p \frac{P_p}{P_f}\right\} + 0.2\ \eta_{di}\left(1 - f_r\right)}{0.8\ f_{bl} + 0.2 + f_p \frac{P_p}{P_f}}$$

$$- \frac{\frac{P_p}{P_f} + \frac{P_{aux}}{P_f}}{0.8\ f_{bl} + 0.2 + f_p \frac{P_p}{P_f}}$$

For $\eta_{th} = \eta_{di}$ one has

$$\eta(\infty) = \eta_{th} - \frac{\left(\frac{P_p}{P_f} + \frac{P_{aux}}{P_f}\right)}{0.8\ f_{bl} + 0.2 + f_p \frac{P_p}{P_f}}$$

This again shows the ultimate level of overall efficiency that is attainable with the input parameters assumed. It is seen that the relative station power requirements can cause a notable reduction of the attainable overall efficiency.

A normalized representation of η related to $\eta\ (\infty)$ allows one to identify the impact of the different input parameters on the evolution of Q_p with varying Q:

$$\frac{\eta}{\eta(\infty)} = \frac{Q + \dfrac{\eta_{th}\ f_r + \eta_{di}\left(1 - f_r\right) - \frac{1}{\eta_{CD}}}{\eta_{th}\left[0.8\ f_{bl} + 0.2\ f_r + f_p \frac{P_p}{P_f}\right] + 0.2\ \eta_{di}\left(1 - f_r\right) - \left(\frac{P_p}{P_f} + \frac{P_{aux}}{P_f}\right)}}{Q + \dfrac{1}{0.8\ f_{bl} + 0.2 + f_p \frac{P_p}{P_f}}}$$

For $\eta_{th} = \eta_{di}$ one has

$$\frac{\eta}{\eta(\infty)} = \frac{Q - \dfrac{\frac{1}{\eta_{CD}} - \eta_{th}}{\eta_{th}\left(0.8\ f_{bl} + 0.2 + f_p \frac{P_p}{P_f}\right) - \left(\frac{P_p}{P_f} + \frac{P_{aux}}{P_f}\right)}}{Q + \dfrac{1}{0.8\ f_{bl} + 0.2 + f_p \frac{P_p}{P_f}}}$$

This indicates that the electric efficiency η_{CD} of the current drive system has an important impact on the Q dependence of the overall efficiency. If Q stays low enough, η may be negative, i.e. despite thermal power conversion there remains a net electric power requirement from the grid, a totally unacceptable situation for a fusion power reactor. For a next-step reactor such as ITER a negative, zero or low net power situation (addition of a power conversion system being assumed) may in fact occur, even though such a reactor has a fusion power level of about 1000 MW. From there it is a long way up to high-power fusion reactors for attaining a net efficiency almost as high as η_{th} and a low recirculating power since the typical station requirements of a magnetic confinement fusion reactor are comparatively large.
The above relations appear all independent of absolute power levels and other reactor parameters. But there are important scale effects such as the tendency of a lower power fraction to be required for auxiliaries when the reactor power level increases.
P_{aux}/P_f and P_p/P_f from existing studies must be expected to be between about 0.18 and 0.13 in the next-step conceptual designs and both to be about 0.03 in the power reactor study, whereas $P_{CD}/(P_f\,\eta_{CD}) = 1/(\eta_{CD}\,Q)$, the relative current drive electric power, varies between 0.46 and 0.04 (!). For DEMO and power reactors $1/(\eta_{CD}\,Q)$ should be about equal to the other auxiliary power fractions (or smaller) in order to keep its impact comparatively low. Another important goal would be a further reduction of the quantities P_{aux}/P_f and P_p/P_f.

In order to demonstrate the various dependences, two pairs of available conceptual reactor parameter sets have been selected, each pair consisting of a next-step reactor and a power reactor. One main difference between the two pairs is the level of current drive efficiency assumed.
Given below for these four reactor design points are the gross and net electric powers P_{et} and P_e, the gross thermal power P (all related to the fusion power P_f), the ratio of the net electric power to the gross electric power, the power Q (Q_p), and the net efficiency $\eta = P_e/P$. Comments are added as required.

For ITER B6 [1] with the input data (conversion cycle data assumed)
$\eta_{th} = \eta_{di} = 0.35$, $f_{bl} = 1.25$, $\eta_{CD} = 1/3$, $Q = 6.522$, $f_r = 0.5$, $f_p = 0.57$,
$P_f = 750$ MW with $P_{aux}/P_f = 0.187$ and $P_p/P_f = 0.127$ one gets
$P_{et}/P_f = 0.499$, $P_e/P_f = -0.274$, $P/P_f = 1.426$, $P_e/P_{et} = -0.550$, $Q_p = 0.645$,
$\eta = P_e/P = -0.192$, $\eta_{tht} = 0.350$.
The auxiliary power $P_{aux} = 140$ MW is very large with respect to the fusion power. Including an electric power for current drive of 345 MW, there is a net power demand from the grid of 206 MW.
The ratio of station power to fusion power required would be 0.773.
If one ignores the fact that ITER B6 cannot be operated with a Q value much larger than 6.5 - because then its plasma power balance can no longer be

fulfilled for the same operating point - a large Q value of 50 would have the following impact with $\eta_{CD} = 0.68$ and $P_{aux}/P_f = 0.187$, $P_p/P_f = 0.127$:
$P_{et}/P_f = 0.452$, $P_e/P_f = 0.110$, $P/P_f = 1.292$, $P_e/P_{et} = 0.242$, $Q_p = 1.320$,
$\eta = P_e/P = 0.085$, $\eta_{tht} = 0.350$.
In this case ITER, apart from covering its own electric power requirements, would generate about 83 MW net power from 969 MW thermal power.
The ratio of station power to fusion power required would be 0.343.
In any case the level of the relative auxiliary power requirements is very high also owing to the low rated power of ITER B6.

It has to be stressed that the thermal conversion efficiency and the blanket multiplication factor assumed are fictitious values since ITER is not envisaged for any thermal energy conversion; these data just illustrate how far the present ITER B6 design concept is from a conceptual energy-supplying reactor. With thermal energy conversion and the rated Q value it would need just about one-third of the power for current drive and auxiliaries additionally from the grid, whereas with a Q of 50 (for which the ITER B6 plasma power balance cannot be fulfilled) and a very large electric efficiency of the current drive system it could supply only a small net power.
The ratio of station power to fusion power required is a very sensitive indicator of any excessive auxiliary power demand in a reactor design.
The ITER B6 case shows that the present level of current drive characteristics achieved is very far from fulfilling power reactor requirements. A next-step reactor concept such as ITER B6 with these characteristics would yield operating data irrelevant to further development.

For the ARIES-I reactor design [3] with the input data
$\eta_{th} = 0.4937$, $\eta_{di} = 0.35$, $f_{bl} = 1.36$, $\eta_{CD} = 0.68$, $Q = 12.682$, $f_r = 0.5$,
$f_p = 0.57$, $P_f = 1991$ MW, $P_{aux}/P_f = 0.0316$ and $P_p/P_f = 0.0773$
one obtains
$P_{et}/P_f = 0.677$, $P_e/P_f = 0.452$, $P/P_f = 1.411$, $P_e/P_{et} = 0.667$, $Q_p = 3.007$,
$\eta = P_e/P = 0.320$, $\eta_{tht} = 0.479$.
With a gross electric power of 1348 MW, a net electric power of 900 MW (only 90% of the power quoted), an electric power of 231 MW for current drive and a pumping power of 154 MW, a total auxiliary power of 63 MW (refrigeration etc.) can be included. For larger P_{aux}, P_e becomes even lower.
The overall efficiency is 32% with a total thermal power of 2809 MW. The gross thermal efficiency is 48%.
The ratio of station power to fusion power required is 0.225.
If ARIES-I could be improved by a current drive system that attains Q = 50, one would obtain (with all other parameters unchanged):
$P_{et}/P_f = 0.652$, $P_e/P_f = 0.513$, $P/P_f = 1.352$, $P_e/P_{et} = 0.788$, $Q_p = 4.709$,
$\eta = P_e/P = 0.380$, $\eta_{tht} = 0.482$.

This would constitute a notable improvement, such that with Q = 50 the net electric power of 1022 MW would come close to that quoted despite some auxiliary power being included here. The gross electric power would be 1298 MW and the electric power for current drive now only 59 MW. The overall efficiency would be 38% with a total thermal power of 2692 MW. The gross thermal efficiency would be 48%. The ratio of station power to fusion power required would be 0.139. It must be stated, however, that in fact such an improvement is impossible for the rated operating point of ARIES-I because the confinement and Q are closely related and because its Goldston confinement enhancement factor over L-mode is already 1.85 (see sec. 4). It should also be noted that the assumed electrical efficiency of the current driver has not been achieved to date, and that nevertheless the reference ARIES-I case needs a very high gross thermal efficiency in order to come up with a net efficiency similar to that of present fission reactors. This is manifested in a value of Q_p of 3.0, which appears extremely low in relation to the case of present light-water fission reactors, which typically have Q_p = 15 - 20. Hence the ARIES-I study shows that a tokamak reactor with low current drive efficiency and high auxiliary power requirements needs an advanced thermal conversion cycle operating at an elevated temperature level in order to cope with a recirculating power fraction of about 33%. The pumping power (although assumed to be partially recoverable) strongly contributes to the auxiliary power requirements. Its rather high level in relation to fission reactors - where it is typically 0.7 - 2.4% of the net electric power for units with 1200 MW_{el} of output power - appears to be due to the more complicated blanket structure in conceptual fusion reactor designs. Another important fusion-specific internal power consumer is the refrigeration system for the magnet systems.

For ETR Alternative [4] with the input data (conversion cycle data assumed) $\eta_{th} = 0.35$, $\eta_{di} = 0.35$, $f_{bl} = 1.25$, $\eta_{CD} = 0.7$, $Q = 22.0$, $f_r = 0.5$, $f_p = 0.57$, $P_f = 1000$ MW, $P_{aux}/P_f = 0.1$ and $P_p/P_f = 0.1$ (estimated) one obtains $P_{et}/P_f = 0.456$, $P_e/P_f = 0.191$, $P/P_f = 1.302$, $P_e/P_{et} = 0.419$, $Q_p = 1.721$, $\eta = P_e/P = 0.147$, $\eta_{tht} = 0.350$.
With a gross electric power of 456 MW, a net electric power of 191 MW, an electric power for current drive of 65 MW and a pumping power of 100 MW, one can include a total of 100 MW of auxiliary power (refrigeration etc.). The overall efficiency is 14.7% with a total thermal power of 1302 MW. The ratio of station power to fusion power required would be 0.265. ETR Alternative, being an attempt to take a direction affording more attractive next-step conceptual parameters, assumes current drive characteristics that would yet have to be realized by development. The current drive efficiency as well as the driver electrical efficiency are very large in relation to present achievements. Despite these favourable assumptions, ETR Alternative remains at a rather large recirculation power fraction owing to its comparatively low

fusion power level. Similarly to ITER B6, but to a lower degree, it shows the disadvantage of large internal power requirements.

For the EC R2 study (European Reference Reactor) [5] with the input data $\eta_{th} = 0.40$, $\eta_{di} = 0.40$, $f_{bl} = 1.25$, $\eta_{CD} = 0.7$, $Q = 33.516$, $f_r = 0.5$, $f_p = 0.57$, $P_f = 3050$ MW, $P_{aux}/P_f = 0.0262$ and $P_p/P_f = 0.0328$ one gets $P_e/P_{et} = 0.796$, $P_e/P_f = 0.398$, $P/P_f = 1.249$, $P_{et}/P_f = 0.499$, $Q_p = 4.914$, $\eta = P_e/P = 0.319$, $\eta_{tht} = 0.400$.
With a gross electric power of 1523 MW, a net electric power of 1213 MW , an electric power of 130 MW for current drive and a pumping power of 100 MW, one can include a total of 80 MW of auxiliary power (refrigeration etc.) .The overall efficiency is 31.8% with a total thermal power of 3808 MW. The gross thermal efficiency is 40%.
The ratio of station power to fusion power required is 0.102.
EC R2, despite the benefit of a high power level, still assumes about twice the current drive efficiency of present achievements, a fraction of the bootstrap current that is beyond the most optimistic scaling known to date, and a driver electrical efficiency much larger than hitherto possible.

Table 1 Comparison of parameters that impact on Q_p and η_{th}

		ITER B6	ARIES-I	ETR Altern.	EC R2
P_f	[MW]	750	1991	1000	3050
η_{th}	[%]	35	49.4	35	40
η_{di}	[%]	35	35	35	40
f_{bl}		1.25	1.36	1.25	1.25
η_{CD}	[%]	33.33	68	70	70
Q		6.52	12.68	22.0	33.5
f_r		--	0.5	--	--
f_p		0.57	0.57	0.57	0.57
$1/Q\eta_{CD}$		0.460	0.116	0.065	0.043
P_p/P_f		0.127	0.077	0.100	0.033
P_{aux}/P_f		0.187	0.032	0.100	0.026
Q_p		0.645	3.007	1.721	4.914
η_{tht}	[%]	35.0	47.9	35.0	40.0
η	[%]	-19.2	32.0	14.7	31.9
P_e/P_f		-0.274	0.452	0.191	0.398
P/P_f		1.426	1.411	1.302	1.249

The above examples show the critical impact of the internal station power (needed for current drive, first wall and blanket cooling pumps, magnet refrigeration, power supply etc.) in the tokamak reactor power balance. This strongly underlines that, in order to attain the usual overall power efficiencies also in fusion reactors with their large auxiliary and pumping power (compared with fission reactors [6]), a very large plasma Q value is called for and has to be included in the design, as well as possibly a high blanket multiplication factor and advanced power conversion data, with favourable impact of large unit power.
For convenience of comparison Table 1 gives some parameters for the above four conceptual reactor designs.

3. Plasma power quality factor Q

It has been pointed out that with other input data fixed an increase in Q could strongly improve the reactor performance of existing point designs, provided enough margin is available for still meeting the stationary plasma power balance when Q is increased. The plasma physics basis for high Q is therefore considered. One can show that $Q = P_f/P_{CD}$ can be expressed independently of any power level, plasma current or reactor geometry, but only in terms of specific global plasma parameters (volume averages) such as the basic current drive efficiency of the specific driver system, the bootstrap current fraction, the plasma elongation, the safety factor, the dilution factor, the Murakami parameter, the plasma temperature and the pertaining fusion reaction cross-section:

$$Q = \frac{\pi^2}{10} \frac{\gamma_0}{1 - \frac{I_B}{I}} k \frac{q}{f(k)} \left(\frac{n_{DT}}{n_e}\right)^2 C_{\sigma E_f} M T_{10}^2$$

with the neoclassical bootstrap fraction being defined by [7]

$$\frac{I_B}{I} = 3.373 \frac{g k q \sqrt{A}}{C_{fa} f(k)}$$

while a more recent evaluation by Fujisawa [8] indicates approximately

$$\frac{I_B}{I} \approx 10.2 \left[\frac{g k q \sqrt{A}}{C_{fa} f(k)}\right]^{1.3}$$

The range of Q values for ITER B6 and ARIES-I , ETR Alternative and EC R2 has already been indicated in the previous section, namely 6.52, 12.7, 22.0, and 33.5, respectively. The corresponding current drive efficiencies γ_0 and

bootstrap current fractions I_B/I are 0.45, 0.314, 1.50, and 0.70 MA/MWm^2 and 0.29, 0.57, 0.26, and 0.50, respectively.
For f(k) (a function of triangularity and elongation) and C_{fa} one has [9]

$$f(k) = \frac{1 + \left(1 + 2\,\Delta^2 - 1.2\,\Delta^3\right) k^2}{2} \quad ; \quad C_{fa} = 1 + 0.2\,(T_{10} - 0.37)$$

The equation for Q shows a strong dependence on temperature ($C_{\sigma E_f} T_{10}^2$ has an approximate overall T_{10}^2 characteristic, see List of Symbols), and thus large Q seems to require a large plasma temperature, everything else given, such that the transition from typically 10 keV, as for ignition reactor designs, to 20 keV, as for steady-state reactor cases, could imply an increase in Q by a factor of almost four. As shown in [15], however, the plasma operating range in the $n_e(T_{10})$ plane of a reactor with noninductive current drive - for a given reactor configuration, given γ_o and a fixed enhancement factor for a certain energy confinement scaling (see sec. 4) - is limited to below a certain temperature level. Under these conditions the most important path towards a larger plasma Q is thus to achieve an essential improvement of the basic current drive efficiency γ_o itself. On the basis of a certain divertor model [15] one can also show, that the density has to stay above a certain range, which also restricts the temperature range.

There is a very strong incentive to notably larger current drive efficiency for much larger Q than available today, as shown in secs. 2 and 5. This calls for practical development of novel current drive methods with high efficiency. An improvement of γ by a factor of 6 to 8 above what is achieved today (hence $\gamma > 3.0 - 4.0$, including the bootstrap contribution, which should not exceed about 0.7 to maintain the possibility of profile control by RF current drive) is an important goal to aim at, as has been shown above. Theory indicates that current drive efficiencies in that range may well be within reach.
Theoretical work [11, 12] indicates that the achievable current drive efficiency for compressional Alfvén wave current drive could attain

$$\gamma_A = 6.278\,\frac{T_{10}\sqrt{\dfrac{5\,g\,f(k)}{q\,A}}\,(\alpha_T + 1)(\alpha_n + \alpha_T + 1)^{1/2}\left(1 - \dfrac{I_B}{I}\right)}{Z_{eff}\left(1 + \dfrac{Z_{eff}}{2}\right)(\alpha_n + 1)\,q_\psi\,A^{3/2}\,f_{CD}}\left[1 + \frac{Z_{eff}}{2}\,f(\rho_s)\right]$$

for $f(\rho_s) = 1 - 3\rho_s + 4(\rho_s)^2$, $\rho_s < 0.5$ and with

$$f_{CD} = \int_0^{\rho_s} \frac{\rho \, d\rho}{\left\{1 - \rho^2\right\}^{(1.5\,\alpha_T - 0.5\,\alpha_n)} \left(A^{1/2} - \rho^{1/2}\right)^3} \qquad \text{with } \rho_s \approx \sqrt{\left(1 - \frac{I_B}{I}\right)\frac{1}{q_\psi}}$$

It can be shown that the prediction for a next step reactor would be about $\gamma_A = 1.1$ for usual values: $T_{10} = 1.5$, $Z_{eff} = 1.7$, $g = 0.03$, $f(k)/q = 1.1$, $A = 4$, $q_\psi = 3.0$, $\alpha_T = 1.0$, $\alpha_n = 0.5$, and $I_B/I = 0.3$. Taking into account the bootstrap enhancement the overall γ would be accordingly larger.
A typical γ scaling to date for fast and lower hybrid waves reads [3]

$$\gamma = 0.174\, T_{10}^{0.77} \left(1 + 28.66 \frac{g\, f(k)}{q\, A}\right) = 0.174\, T_{10}^{0.77} \left(1 + 5.732\, \beta\right)$$

Clearly, this relation does not lead to current drive efficiencies required for the realization of large Q values (with the above input data one obtains $\gamma = 0.37$). From the above equation for Q it follows that there is an obvious limitation on the attainable product $C_{\sigma E_f} M T_{10}^2$ due to the density and the beta limits for a steady-state current drive operating point. From

$$\left(\frac{n_{DT}}{n_e}\right)^2 M\, C_{\sigma E_f} T_{10}^2 = 4\, p_f \frac{M}{n_e^2} = 4\, p_f \frac{R}{B\, n_e}, \text{ hence } Q = 0.4\, \pi^2\, \gamma_o\, k \frac{p_f M}{n_e^2} \frac{\frac{q}{f(k)}}{1 - \frac{I_B}{I}}$$

it is seen that a large Q value corresponds to large plasma fusion power density, with M as a relative upper limit for density (while the divertor conditions impose a lower density limit). The plasma fusion power density increases with reactor power (with a strong impact of the plasma power balance for a certain energy and particle confinement scaling [15]). Since p_f is proportional to $(n_e T_{10})^2$, a large plasma temperature enhances Q in any case.
When comparing the values of $p_f M/(n_e)^2$ for the four cases the first three turn out to be almost equal (1.33, 1.42, 1.59 and 4.71, respectively). The values of the term $kq/f(k)$ (1.98, 3.08, 1.74, and 1.56, respectively) somewhat contribute to the different Q values. The large Q for ETR Alternative is based on a high-efficiency driver with $\gamma_o = 1.5$ yet to be developed. The largest Q noted for EC R2, apart from its large fusion power density assuming a Troyon coefficient of 0.04, is also based on a high-efficiency driver with $\gamma_o = 0.7$ yet to be developed, and on a large bootstrap fraction not fully covered even by the scaling from [8].

A listing of the Q-relevant parameters for the above reactor designs is given below. The respective theoretical Alfvén wave current drive efficiency is shown in parenthesis in order to visualize the potential of different configurations in this respect. Comments on the parameters are added as required.

ITER B6 $A = 2.79$, $\gamma_o = 0.45$, $I_B/I = 0.29$, $M = 0.79$, $k = 2.0$, $T_{10} = 2.0$, $g = 0.03$, $n_e = 0.64$, $f(k) = 2.88$, $q = 2.85$, $p_f = 0.69$, $Q = 6.5$, $Z_{eff} = 2.20$, $C_{\sigma Ef} = 3.70$, ($\gamma_A = 1.07$).
This reactor concept stays with the present current drive efficiency and roughly with the neoclassical bootstrap prediction. The plasma density and the Murakami parameter are low, such that the divertor conditions for a certain model can barely be met (see [15]). Also the fusion power density is very low.

ARIES-I $A = 4.5$, $\gamma_o = 0.314$, $I_B/I = 0.57$, $M = 0.81$, $k = 1.6$, $T_{10} = 2.0$, $g = 0.032$, $n_e = 1.62$, $f(k) = 2.14$, $q = 4.12$, $p_f = 4.60$, $Q = 12.7$, $Z_{eff} = 1.62$, $C_{\sigma Ef} = 3.70$, ($\gamma_A = 1.62$).
With respect to the current drive efficiency and the Murakami parameter the same holds as for ITER B6. The bootstrap fraction is enhanced in keeping with the large Kruskal safety factor. The elongation appears relatively low.
Q remains at a level that is not relevant to a reactor. The fusion power density is large, and the level of the toroidal field is extremely high (see Table 2) and far exceeds the present large magnet technology status.

ETR Alternative $A = 3.66$, $\gamma_o = 1.50$, $I_B/I = 0.26$, $M = 1.0$, $k = 1.98$, $T_{10} = 1.67$, $g = 0.03$, $n_e = 1.21$, $f(k) = 2.83$, $q = 2.48$, $p_f = 2.32$, $Q = 22.0$, $Z_{eff} = 1.66$, $C_{\sigma Ef} = 4.30$, ($\gamma_A = 1.25$).
This conceptual parameter set was devised in order to show that on the basis of improved current drive efficiency one can obtain an improved next-step design that otherwise stays within the present plasma physics guidelines as established for ITER assuming the first stability regime. As seen from Table 2, the assumption on the status of large magnet technology keeps close to that made for ITER.

EC R2 $A = 3.79$, $\gamma_o = 0.7$, $I_B/I = 0.5$, $M = 1.24$, $k = 2.25$, $T_{10} = 2.0$, $g = 0.04$, $n_e = 1.45$, $f(k) = 3.14$, $q = 2.17$, $p_f = 6.60$, $Q = 33.5$, $Z_{eff} = 1.54$, $C_{\sigma Ef} = 3.70$, ($\gamma_A = 2.59$)
The bootstrap current fraction quoted for EC R2 is covered neither by the above neoclassical relation nor by a more recent one also shown. The current drive efficiency quoted assumes an improvement of the present values by a factor of about two, a weaker, but similar extrapolation when compared with ETR Alternative. The ETR conceptual parameter set assumes a Troyon coefficient exceeding the present predictions and results for the first stability regime, while the Kruskal safety factor appears extremely low. Among the

four reactor concept parameter sets considered here EC R2 assumes the highest Murakami parameter. The fusion power density is larger than for ARIES I, the level of the toroidal field is lower in comparison, in keeping with the lower q-value (see Table 2), but still exceeds present large magnet technology.
(For units see List of Symbols.)
The critical density limit according to a recent model [16] is just about fulfilled for ITER B6 and ETR Alternative and is met with ample margin by ARIES-I and EC R2.

Table 2 Comparison of reactor parameters and those that impact on Q

		ITER B6	ARIES-I	ETR Altern.	EC R2
P_f	[MW]	750	1991	1000	3050
R	[m]	6.00	6.53	5.28	5.31
a	[m]	2.15	1.45	1.45	1.40
A		2.79	4.50	3.66	3.79
k		2.00	1.60	1.98	2.25
I	[MA]	18.9	10.9	14.4	16.6
B	[T]	4.85	13.0	6.38	6.22
B_{max}	[T]	11.2	23.8	12.7	14.9
γ_o	[A/W m^2]	0.46	0.31	1.5	0.70
I_B/I		0.29	0.57	0.26	0.50
$\gamma_o/(1-I_B/I)$		0.65	0.72	2.03	1.40
M	[10^{20} T m^{-2}]	0.79	0.81	1.00	1.50
T_{10}	[10 keV]	2.00	2.00	1.67	2.00
n_e	[10^{20} m^{-3}]	0.64	1.62	1.21	1.45
n_{ecrit}	[10^{20} m^{-3}]	0.60	2.28	1.24	2.44
g	[T m/MA]	0.03	0.032	0.03	0.04
f(k)		2.88	2.14	2.83	3.14
q		2.85	4.12	2.48	2.17
q_ψ		3.90	5.40	3.10	3.38
f_{HGO}		1.75	1.85	1.71	1.41
τ_E	[s]	2.36	1.27	1.80	1.20
p_f	[MW m^{-3}]	0.69	4.60	2.32	6.60
Q		6.52	12.68	22.0	33.5
Z_{eff}		2.20	1.60	1.66	1.54

Clearly, γ_o and I_B/I remain the main drivers for an increase in Q beyond the quoted values. An increase of the Troyon coefficient at low q to the level

assumed for EC R2 does not seem to be attainable according to the recent results from DIII-D reported in [10].
For convenience of comparison Table 2 gives some parameters for the above four reactor conceptual designs (reference case always).

4. Plasma Q and energy confinement

If a certain reactor design and a given plasma operating point is taken for which Q is not at the confinement limit, a possible increase in Q over the rated value can be determined in the following way.
The plasma power balance reads approximately (alpha power and current drive heating power compensated by plasma losses, bremsstrahlung and impurity radiation and synchrotron radiation)

$$(P_\alpha + P_{CD}) = P_l + (P_{rad} + P_{sy})$$

The plasma loss power is given by

$$P_l = W_{th}/\tau_E$$

the current drive power by $P_{CD} = P_f/Q$

For a fixed fusion power in a given reactor geometry, the plasma operating point thus being maintained, the confinement time τ_E has to be varied so as to compensate for any change in Q. (A change of Q affects P_{CD} and hence P_l only.) Thus, changing from a status with Q_o and τ_{Eo} to a new one with Q and τ_E requires

$$P_f/Q - P_f/Q_o = W_{th}/\tau_E - W_{th}/\tau_{Eo}$$

Global power scaling laws for τ_E generally take the form

$$\tau_E = f_H C_{\tau E} / (P_l)^\alpha$$

For Goldston scaling τ_{EGO} one gets:

$$C_{\tau E} = 0.037 (A_i/1.5)^{0.5} I R^{1.75} k^{0.5}/ a^{0.37} \quad \text{with } \alpha = 0.5$$

In order to take into account the energy confinement scaling at lower temperatures as well, one can apply the following relation for the overall τ_{Et}:

$$\tau_{Et} = \frac{1}{\sqrt{\frac{1}{\tau_{Eneo}^2} + \frac{1}{\tau_{EGo}^2}}}$$

with $$\tau_{Eneo} = 0.07\ n_e\ a\ q\ R^2$$

The enhancement factor f_H over L-mode confinement will have to change when the energy confinement time has to be varied. (It is, however, not yet clear how to do this. But confinement control is a prerequisite in any case.) For steady-state operation it can be assumed that on the basis of Goldston scaling f_H would be 1.65 - 1.85 at the ELMy steady-state confinement limit. Hence, if for a certain reactor design f_{Ho} is lower than about 1.75, the Q value may be increased above Q_o, provided a larger current drive efficiency can be attained.
For Goldston scaling combined with neoclassical scaling (see above) one has

$$Q = \frac{Q_o}{1 - Q_o \frac{W_{th}}{P_f}\left[\sqrt{\frac{1}{\tau_{Eneo}^2} + \frac{W_{th}^2}{C_{\tau E}^4 f_{Ho}^4}} - \sqrt{\frac{1}{\tau_{Eneo}^2} + \frac{W_{th}^2}{C_{\tau E}^4 f_H^4}}\right]}$$

Evaluation of this relation for ITER B6, ARIES-I, ETR Alternative and EC R2 shows the typical situation of each of these design points. Generally, for a certain reactor operating point there is always a possibility of operating at a lower Q than the rated one, but a larger Q value could only be attained if the design has a sufficient confinement margin. Among the cases considered such a margin is only found for EC R2. In all cases the dependence $Q(f_H)$ is very steep near the operating point. The expression

$$f_{H\infty} = \frac{1}{C_{\tau E}}\left[\frac{W_{th}^2}{\left(\sqrt{\frac{1}{\tau_{Eneo}^2} + \frac{W_{th}^2}{C_{\tau E}^4 f_{Ho}^4}} - \frac{P_f}{Q_o W_{th}}\right)^2 - \frac{1}{\tau_{Eneo}^2}}\right]^{1/4}$$

describes how near to f_{Ho} (and hence how steeply) Q could rise to infinity, provided Goldston confinement scaling is assumed. The corresponding data for ITER B6, ARIES-I, ETR Alternative, and EC R2 are listed in Table 3.
Figure 2 shows the $Q(f_H)$ characteristics for the four reactor design points with respect to the assumed average confinement limit of about $f_H = 1.75$ for Goldston scaling. The operating points are indicated. For comparison a modified version of ITER Case A1 as discussed in sec. 7 is indicated as well.

Table 3 Parameters for evaluation of Q vs. f_H and ultimate f_H for Q = ∞

	f_{Ho}	Q_o	W_{th}[MJ]	P_f[MW]	$C_{\tau E}$[sMW$^{0.5}$]	τ_{Eneo}[s]	$f_{H\infty}$
ITER B6	1.75	6.52	604	750	22.1	9.88	2.48
ARIES-I	1.85	12.7	632	1991	15.3	28.8	2.24
ETR Altern.	1.71	22	383	1000	15.6	8.44	1.96
EC R2	1.41	33.5	594	3050	19.5	8.69	1.57

Whereas ITER B6 and ARIES-I rely on a very low current drive efficiency comparable to present values, ETR Alternative and EC R2 anticipate a future development of new current drive methods leading to higher efficiency and hence larger Q. The value of the current drive efficiency strongly determines the reactor design point for minimum-outlay next-step reactors close to the confinement limit. In the case of ITER B6 the design cannot cope with a Q increase later on. ETR Alternative indicates that also a next-step reactor can be designed to work with high Q near the confinement limit. The EC R2 curve illustrates that compact full-scale reactor designs for notably larger than minimum next-step power can utilize high-efficiency drivers without getting to the confinement limit at all: $f_H(\infty) = 1.57 < 1.75$.

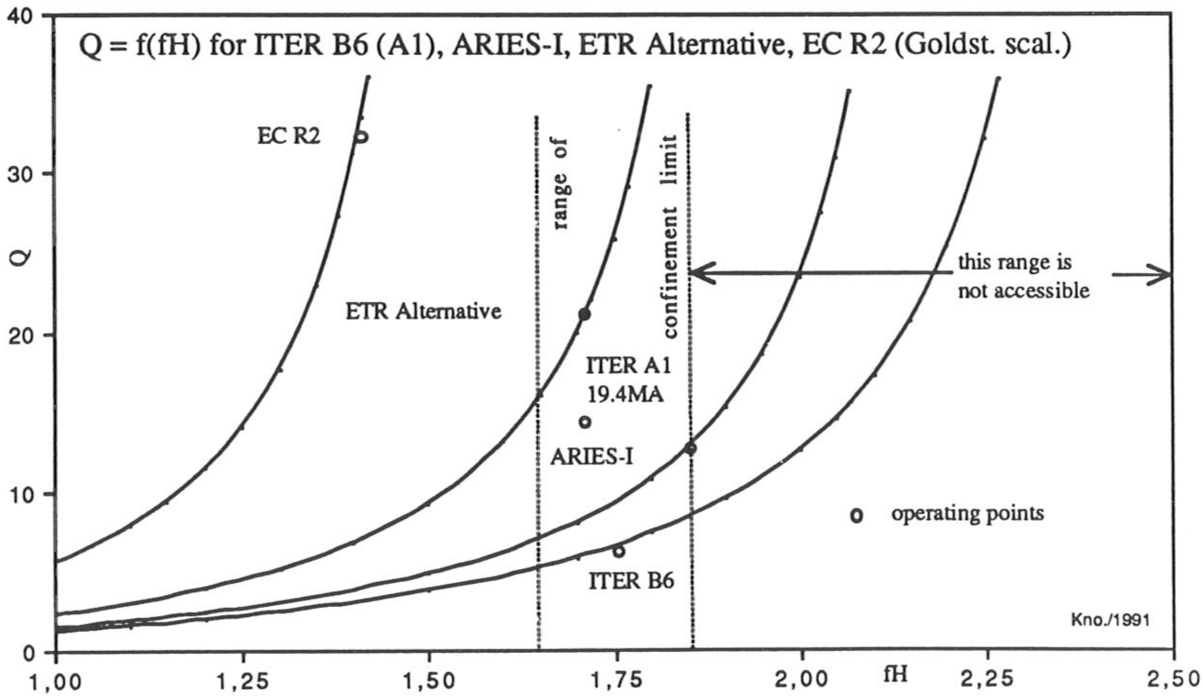

Fig. 2 Q versus confinement enhancement factor for different reactor designs

The curves for ETR Alternative and EC R2 demonstrate that large Q is associated with a strong Q sensitivity to f_H variat-ions. (See also Figs. 3 to 6 with the operating points and the confinement limits shown versus the pertaining Q.)
For the slope of $Q(f_H)$ one finds

$$\frac{dQ}{df_H} = Q^2 \frac{2\, W_{th}^3}{P_f\, C_{\tau E}^4\, f_H^5} \frac{1}{\sqrt{\dfrac{1}{\tau_{Eneo}^2} + \dfrac{W_{th}^2}{C_{\tau E}^4\, f_H^4}}} \approx Q^2 \frac{2\, W_{th}^2}{P_f\, C_{\tau E}^2\, f_H^3}$$

The values for the four cases at their respective operating points are 15.8, 43.7, 115 and 244, which quantifies the above observation on the steepness of $Q(f_H)$. A tough control situation may generally arise for steady-state tokamak reactors at very large Q values (when it is just known how to control f_H).
The above approximate expression can further be shown to be equal to

$$\frac{dQ}{df_H} \approx Q^2 \frac{2\, W_{th}^2}{P_f\, C_{\tau E}^2\, f_H^3} = Q^2 \frac{160}{f_H^3} \frac{\left(1 + \dfrac{n_i}{n_e}\right)^2 q^2}{\left(\dfrac{n_{DT}}{n_e}\right)^2 [f(k)]^2} \frac{1}{B^2\, A^{0.74}\, R^{0.76}}$$

$$= Q^2 \frac{3990}{f_H^3} \frac{\left(1 + \dfrac{n_i}{n_e}\right)^2}{\left(\dfrac{n_{DT}}{n_e}\right)^2} \frac{a^{1.24}}{(I\ A)^2\, A^{1.5}}$$

Hence the slope of $Q(f_H)$, apart from depending on Q^2, is also inversely proportional to $(B/q)^2$, which reinforces the arguments for using a higher field and a lower q level in fusion reactor designs, in this case for reducing the slope for any given Q etc. The alternative expression above shows that a large product IA, a large aspect ratio, a large value of f_H (below about 1.75!) and a small minor plasma radius serve the same purpose.
Application of alternative confinement scalings and different f_H limits can somewhat change the picture, but not the basic relation between the plasma quality factor and the confinement requirement.

5. Q_p, relative electric and thermal power, current drive and overall efficiency

One can illustrate the above findings by plotting Q_p, P_e/P, $\eta = P_e/P$ and $\gamma_o/(1-I_B/I)$ versus Q for ITER B6, ARIES-I, ETR Alternative, and EC R2. This provides an insight into the importance of large Q for different types of reactor designs and the required current drive efficiency for attaining large Q at the operating point. Assuming a certain confinement scaling (Goldston scaling is taken here) and a maximum value of the enhancement factor f_H allowed for steady-state operation (an average value of $f_H = 1.75$ being assumed), one can also see the margin available for a possible improvement in Q within that confinement limit. Naturally, for next-step conceptual designs Q will be near the value consistent with the confinement limit, but it is possible to design a next-step reactor for both high Q and f_H close to 1.75. For power reactor design points - if properly chosen - the confinement limit would allow even larger Q values than may be achievable with practical high-efficiency drivers and than may be necessary for overall efficiency. The ARIES-I study shows, however, that even a power reactor design point with a low current drive efficiency may exceed the confinement limit [3].

The following figures are ordered according to their sequence in Fig. 2, i.e. in the direction from larger to lower values of f_H. In all cases the respective nominal reactor geometry, plasma operating point, and hence fusion power, are kept the same throughout the respective diagrams.

Figure 3a shows the curves for ITER B6 (1990). Up to Q = 20 there is a strong reduction in net electric power supply from the grid. The ratio of the net electric power to the gross thermal power (η) starts to saturate at about Q = 20 as well. Q_p is very low throughout. At Q = 20 it reaches a value of 1 (self-sufficient zero output power reactor). Owing to the large relative auxiliary power no practical increase in Q can make ITER B6 (1990) a reactor with any notable net electric power output. The confinement limit is at the operating point and no Q increase is acceptable.

Figure 3b supports this picture by showing that at the operating point about 70% of the gross electric power (to be generated if ITER B6 is fitted with a power conversion system) is additionally needed from an external supply. The γ_A limit would allow Q values of up to about 15.5 (not accessible).

Figure 4a indicates that for ARIES-I (1989) there is a strong increase in net electric power up to Q = 20 and a further increase even beyond Q = 50. The ratio of the net electric power to the gross thermal power (η) starts to saturate at about the same Q = 20. Q_p still considerably increases well beyond Q = 50, which means, that, for example, the recirculating and waste electric power fraction still reduces from 27% to 21% between Q = 20 and Q = 50. The corresponding overall current drive efficiency $\gamma_o/(1-I_B/I)$ would have to increase from 1.15 at Q = 20 to 2.89 at Q = 50. This is about 1.6 to 4.0 times the level attainable with the present current drive methods ($\gamma_o = 0.5$ with $I_B/I = 0.3$) at low q. Since, however, the confinement limit is already exceeded at the operating point, only a Q of about 10 would be tolerable, beyond which a Q increase is not acceptable. Figure 4b shows that with increasing Q the gross thermal power decreases well beyond Q = 20, which also entails a decrease in gross electric power. Since, however, the utilization of electric power improves with

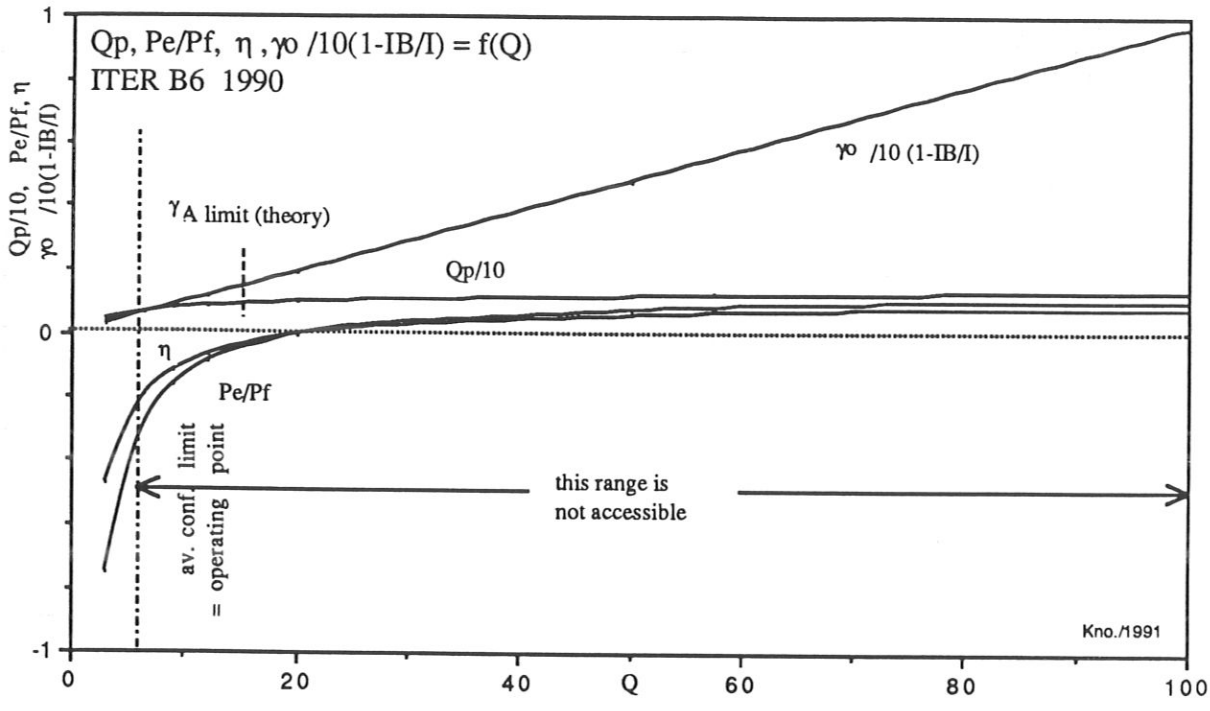

Fig. 3a Q_p (electric power Q), net electric power/fusion power, fusion power/ thermal power (η) and $\gamma_o/(1-I_B/I)$ vs. plasma Q for ITER B6 (1990)

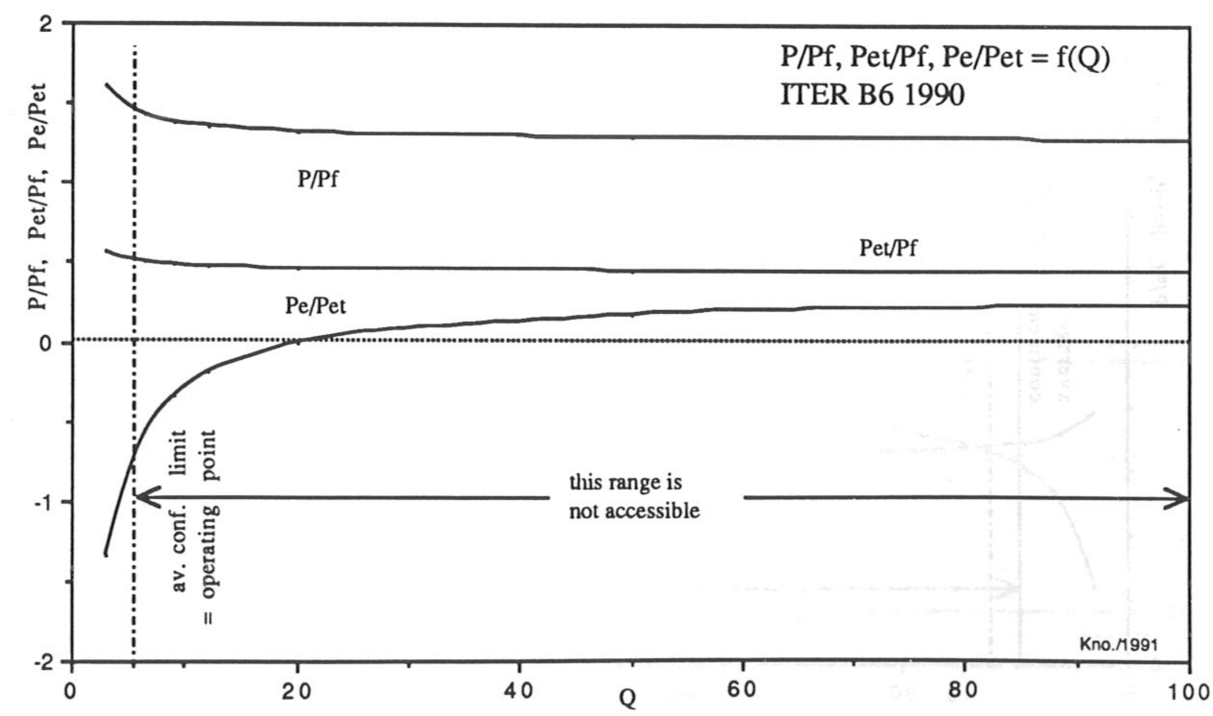

Fig. 3b Gross thermal power/fusion power, gross electric power/fusion power and gross/net electric power vs. plasma Q for ITER B6 (1990)

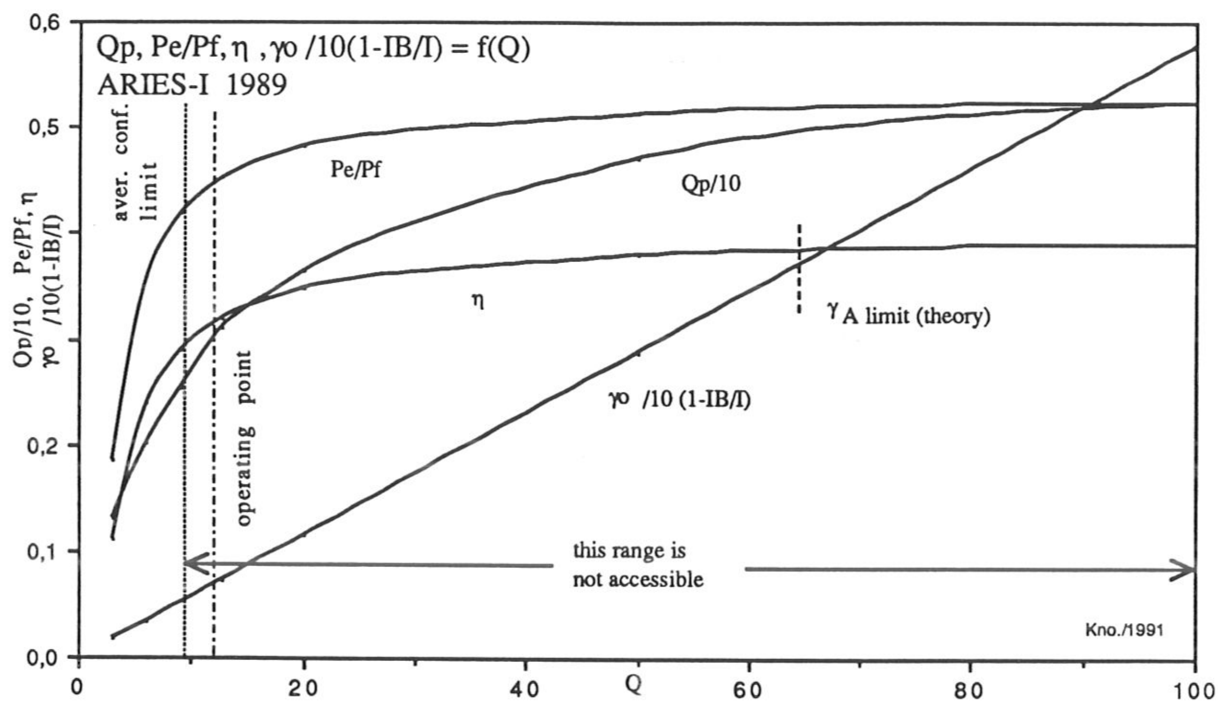

Fig. 4a Q_p (electric power Q), net electric power/fusion power, fusion power/ thermal power (η) and $\gamma_o/(1-I_B/I)$ vs. plasma Q for ARIES-I (1989)

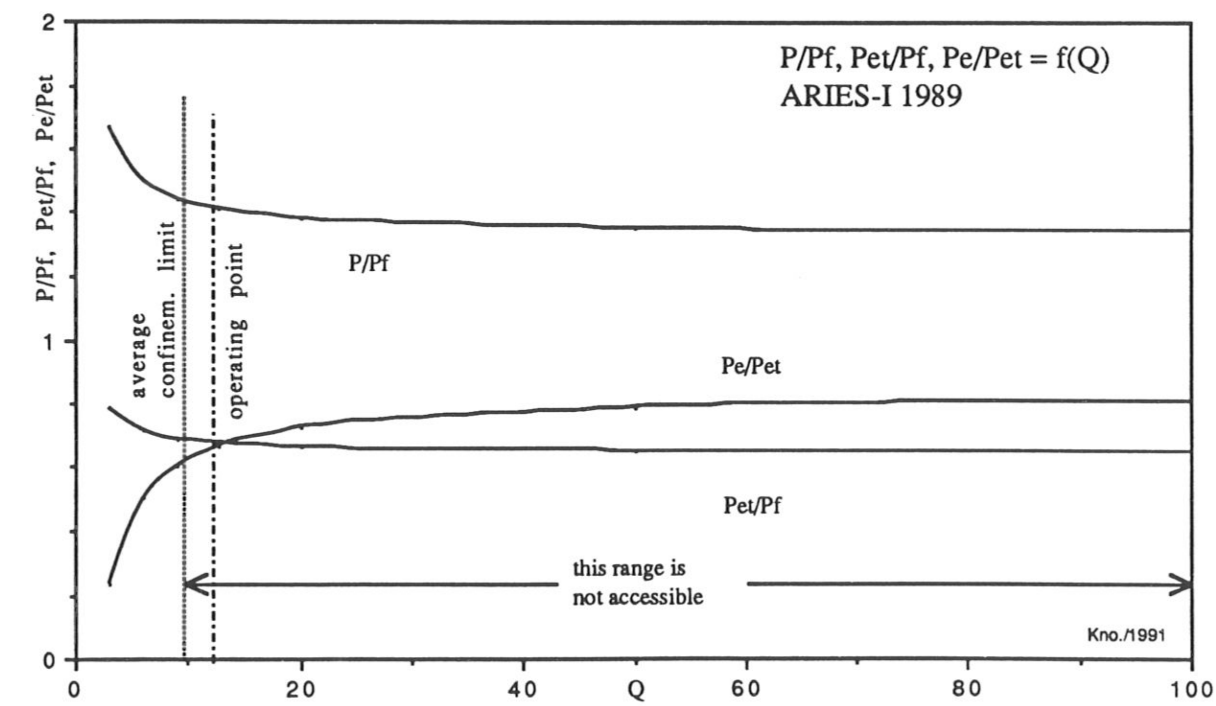

Fig. 4b Gross thermal power/fusion power, gross electric power/fusion power and gross/net electric power vs. plasma Q for ARIES-I (1989)

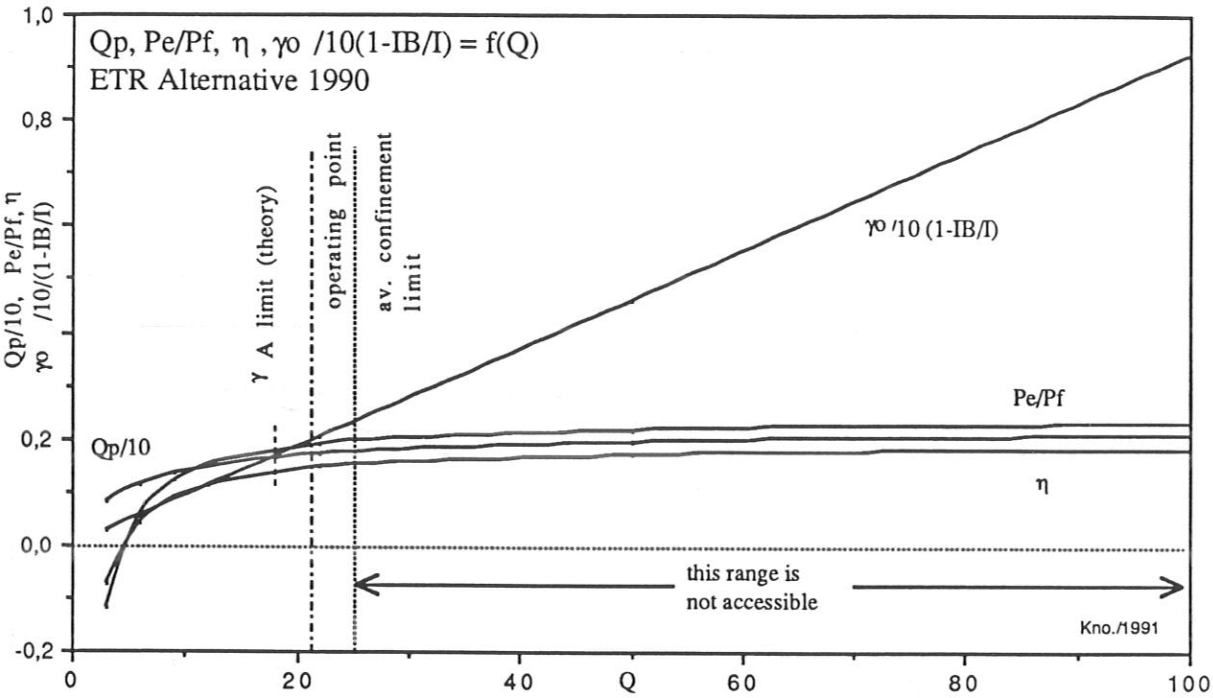

Fig. 5a Q_p (electric power Q), net electric power/fusion power, fusion power/ thermal power (η) and $\gamma_o/(1-I_B/I)$ vs. Q for ETR Alternative (1990)

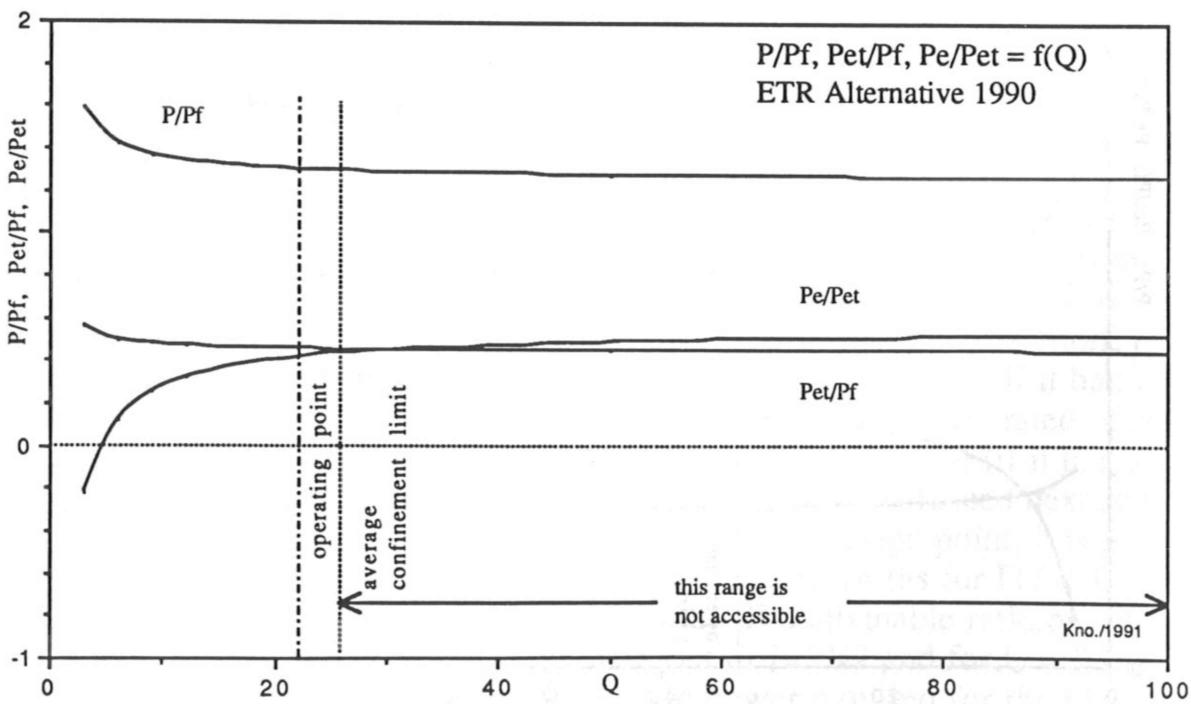

Fig. 5b Gross thermal power/fusion power, gross electric power/fusion power and gross/net electric power vs. plasma Q for ETR Alternative (1990)

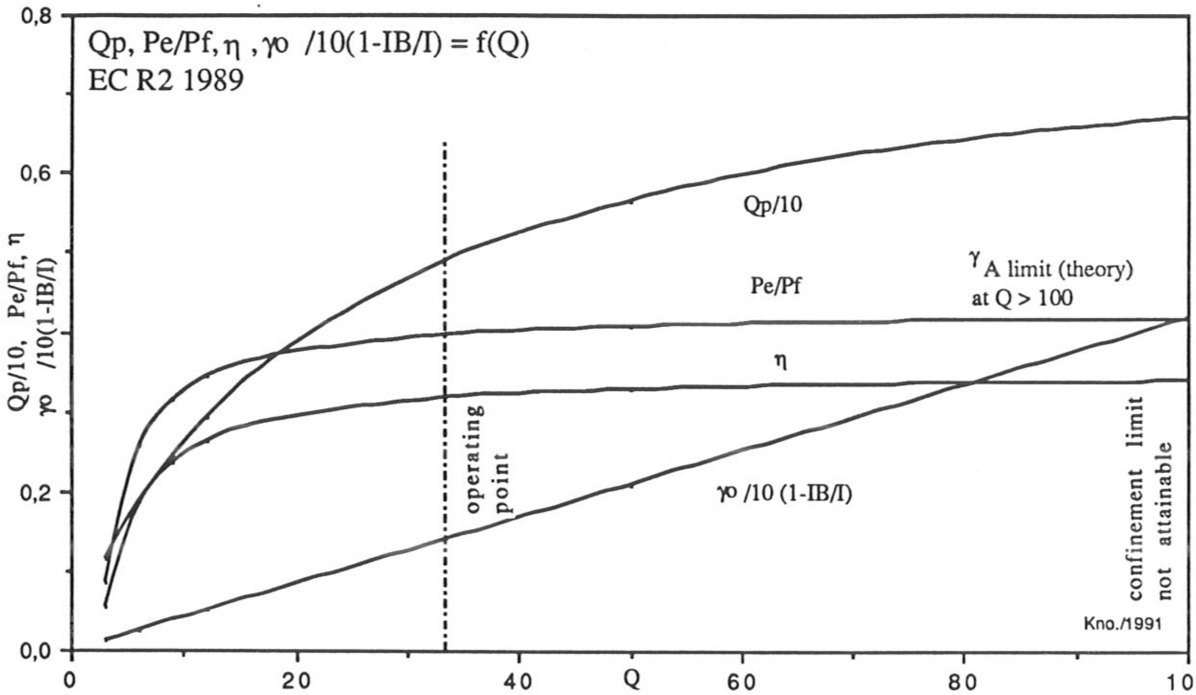

Fig. 6a Q_p (electric power Q), net electric power/fusion power, fusion power/ thermal power (η) and $\gamma_o/(1-I_B/I)$ vs. plasma Q for EC R2 (1989)

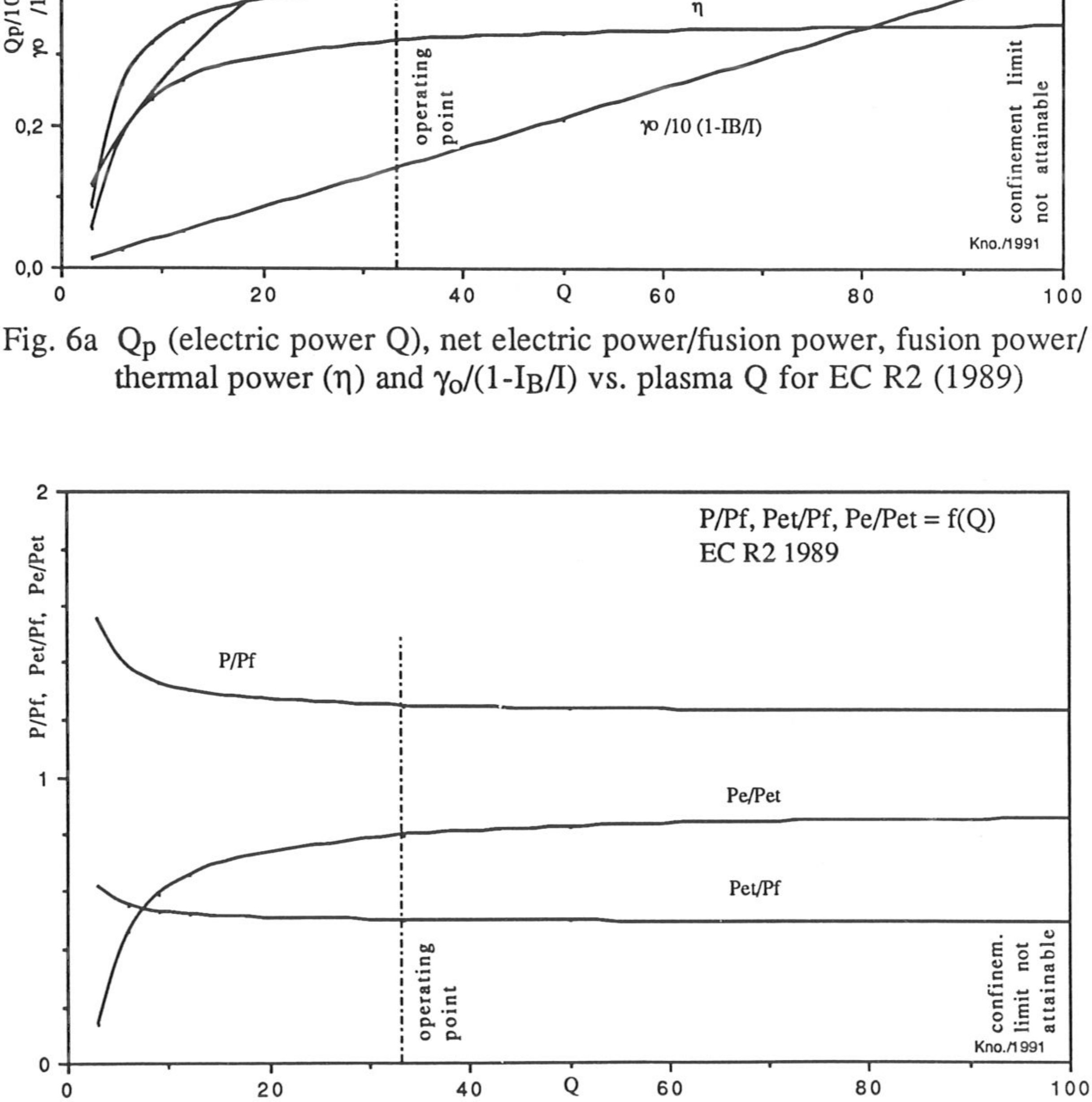

Fig. 6b Gross thermal power/fusion power, gross electric power/fusion power and gross/net electric power vs. plasma Q for EC R2 (1989)

increasing Q, the most efficient operating scenario (largest η) would be found for large Q. Q_p attains about 3, and at the confinement limit it is somewhat less. The (inaccessible) γ_A limit would occur only at a rather high value of Q = 65. Figure 5a shows the corresponding curves for ETR Alternative, a different reactor design concept for a next step including larger current drive efficiency and taking advantage of high Q for the operating point, which is still somewhat below the confinement limit. The traces in general are similar to those of the above figures, but owing to the relatively low fusion power the auxiliary power fractions are rather large and this leads to a limitation of the overall efficiency (if ETR Alternative is completed with a power conversion cycle) to below 20%. Nevertheless, in this case net electric power could be generated. This demonstrates that tokamak fusion reactors are bound to tend towards large units not only because of the plasma confinement scaling but also owing to the decreasing power fraction required for the cooling pumps and the other auxiliaries, irrespective of the current drive power, as the reactor power increases. Whereas in the first two cases (ITER B6 and ARIES-I) the current drive efficiency is low, ETR Alternative anticipates a large current drive efficiency $\gamma_o = 1.5$ ($I_B/I = 0.26$) to be attainable. Such a value could perhaps be achieved by development, for which there is promising theoretical background. Q_p attains about 1.7. γ_A would allow Q values of up to 18.3 (lower than assumed). Figures 6a and 6b refer to a full-scale power reactor design point with about three times the fusion power of ETR Alternative. While the traces are generally similar to the above figures, it can be seen that a further increase of Q would be possible since the confinement limit is well above a situation with $Q = \infty$. Q_p still increases well beyond Q = 50. Thus, instead of the anticipated value of $\gamma_o = 0.7$ ($I_B/I = 0.5$), one could aim at $\gamma_o > 2.0$ ($I_B/I = 0.3$), which would about double the Q value at the operating point and bring Q_p up to well above 6. The γ_A limit (assuming $I_B/I = 0.5$) leads to Q = 124 for EC R2. Comparing Figs. 3 to 6 gives a good overview of reactor design points between the next step and a power reactor. The theoretical limit of the current drive efficiency γ_A (and Q) for compressional Alfvén wave current drive is shown for comparison. It is of particular interest for next-step reactor definition. Whereas for ITER B6 the maximum attainable net electric power (if it had a blanket suited to power conversion) is close to nil, ARIES-I at the rated operating point attains an overall efficiency of 32%. ETR Alternative (if it had a blanket suited to power conversion) can be considered as a balanced next step after the JET generation of devices. Like any next-step design point, it is a minimum-size device for the input assumptions, and hence (as for ITER B6) the operating point is near the confinement limit. The attainable ratio of net electric power to fusion power is about half that of EC R2 and for Q = 22 the ratio of the gross electric power to the electric power required for the plant is 1.7. Such a situation appears acceptable for an experimental reactor.

The EC R2 full-scale power reactor, based on less advanced technology assumptions than ARIES-I, attains an overall efficiency of 32% for Q = 33.5 or 33% at Q = 50, which in this case is well within the confinement limit. For Q = 33.5 one has $Q_p = 4.9$. This still means a recirculating and loss power of 20%, a large figure in comparison with light-water fission reactors of the same output power, for which it is typically 5 - 7%.
Figure 7 provides a comparison of the four reactor design points in terms of $\eta = f(Q_p)$ with the nominal respective operating points indicated. An almost universal curve shows the increase in overall efficiency with increasing Q_p. The difference between the design-specific curves at large Q_p is mainly due to different figures for the thermal conversion efficiency and the station power requirements, including current drive, as shown in the following equation, which derives from the relations shown in sec. 2:

$$\eta = \frac{(Q_p - 1)\left\{\left(0.8\ f_{bl} + f_p \frac{P_p}{P_f}\right)\eta_{th} + \left[\eta_{th}\ f_r + \eta_{di}\,(1 - f_r)\right]\left[0.2 - \eta_{CD}\left(\frac{P_p}{P_f} + \frac{P_{aux}}{P_f}\right)\right]\right\}}{\left(0.8\ f_{bl} + f_p \frac{P_p}{P_f}\right)\left[Q_p + \eta_{CD}\,(1 - f_r)\,(\eta_{th} - \eta_{di})\right] + Q_p\left[0.2 - \eta_{CD}\left(\frac{P_p}{P_f} + \frac{P_{aux}}{P_f}\right)\right]}$$

It should be noted that, if the conversion efficiencies of the main and divertor power system are the same ($\eta_{th} = \eta_{di}$) and if $\eta_{CD} = 0.2/(P_p/P_f + P_{aux}/P_f)$, the relation simplifies to read

$$\eta = \eta_{th} \frac{Q_p - 1}{Q_p}$$

This reveals one main difference between the η traces in Fig. 7, namely that due to different values of η_{th}. (The above condition for η_{CD} cannot be fulfilled, however, for power reactor designs like ARIES-I and EC R2.) For power reactors the overall efficiency and the power quality factor should be as large as possible. Figure 7 shows that with increasing fusion power the level of the overall efficiency and Q_p strongly increases between 750 and 3050 MW.
The overall current drive efficiency, which is also shown, can contribute essentially to enhancing the overall efficiency and electric power quality factor. Figure 8 shows the dependence of the overall efficiency on the plasma Q for the same four reactor designs, again with the rated operating points indicated. While the representation versus Q_p clearly shows the possibility of enhancing the overall efficiency, Fig. 8 indicates that, in order to achieve this by increasing the current drive efficiency, the increase has to be strong. The margin for reducing the other station power requirements typical of the respective reactor power levels has to be checked, but it may turn out not to be large. It is interesting to note that EC R2 attains the same overall efficiency despite the

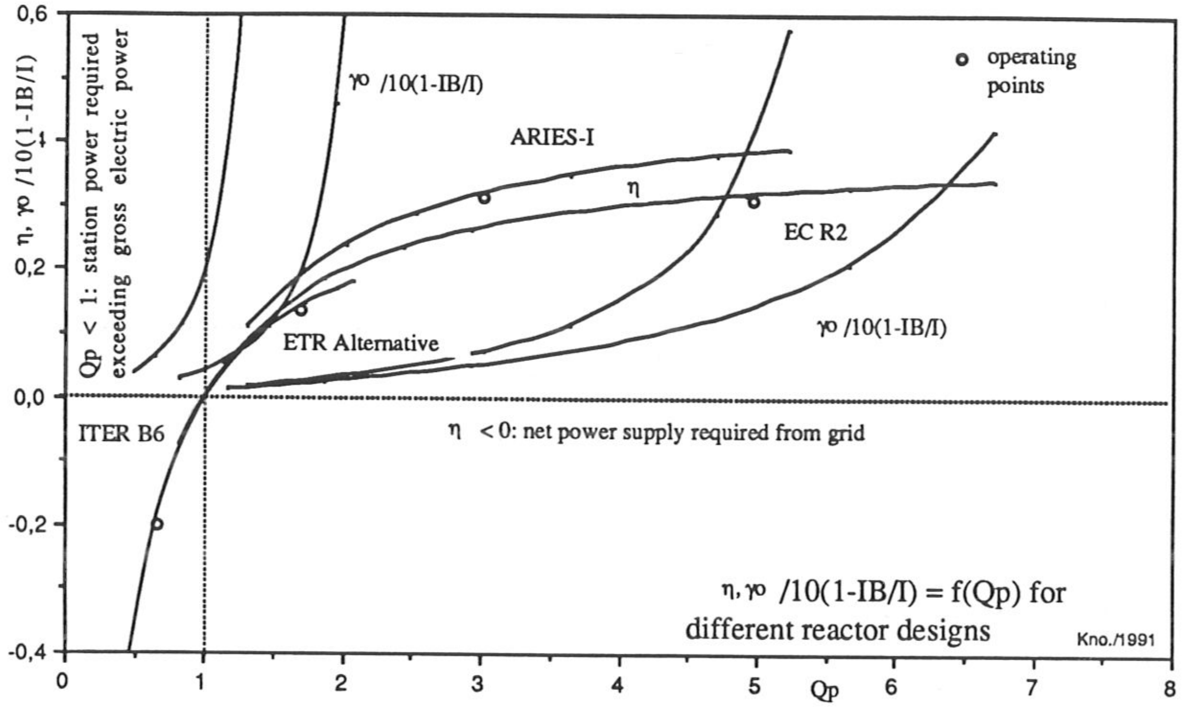

Fig. 7 Overall efficiency and current drive efficiency vs. $\bar{Q}_p$ for ARIES-I, ITER B6, ETR Alternative, and EC R2

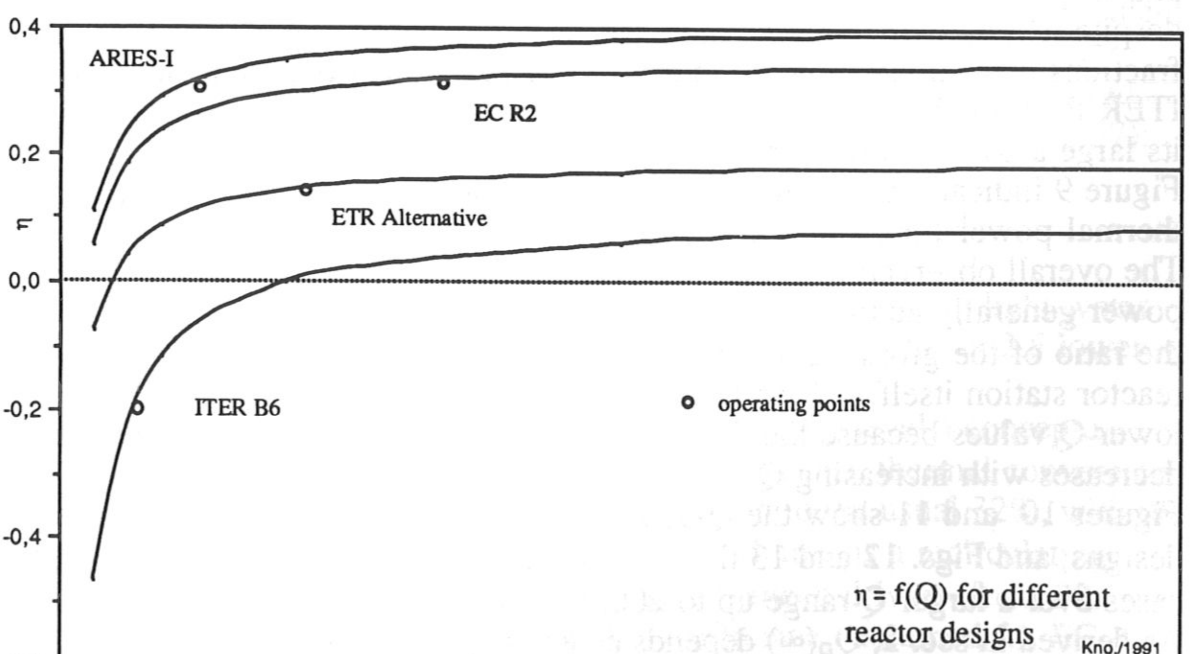

Fig. 8 Overall efficiency vs. Q for ARIES-I, ITER B6, ETR Alternative, and EC R2

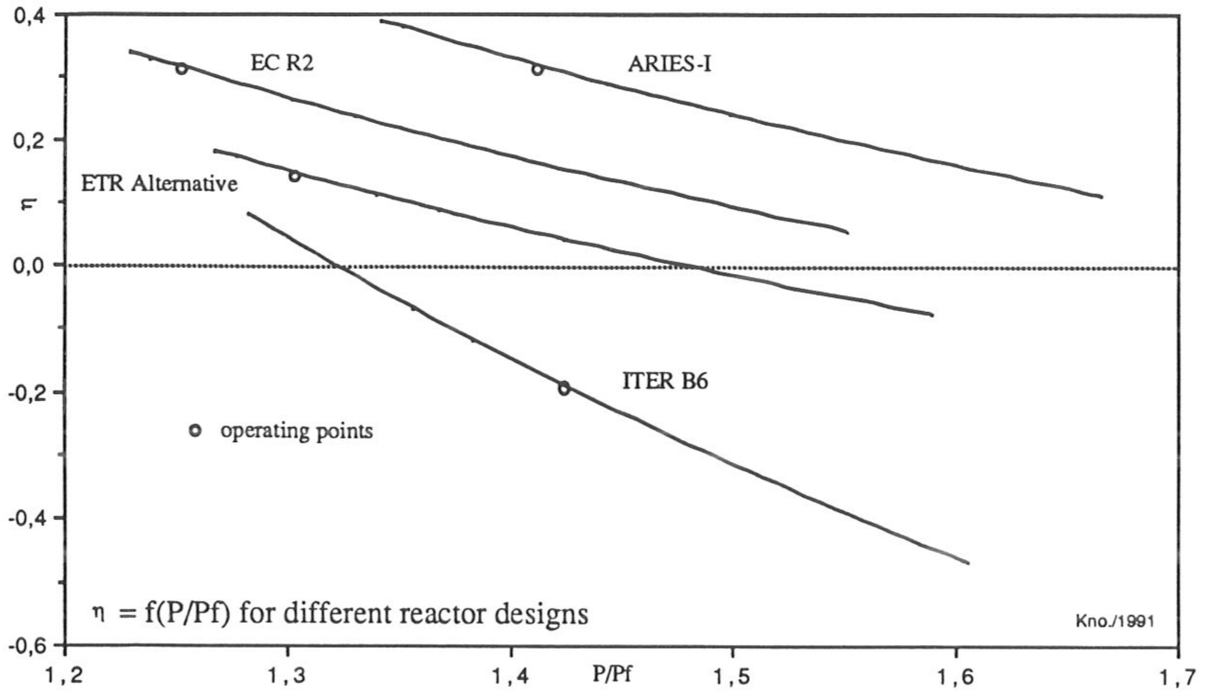

Fig. 9 Overall efficiency vs. relative thermal power for ARIES-I, ITER B6, ETR Alternative, and EC R2

lower thermal conversion efficiency in relation to ARIES-I because its Q value and its power are higher. The curve for ETR Alternative essentially shows that despite its relatively large Q value the lower power level and hence the larger fractions of auxiliary power requirement lead to a low overall efficiency.
ITER B6 provides an extreme example of negative overall efficiency owing to its large auxiliary power fractions and its low Q.
Figure 9 indicates the increase in overall efficiency and the decrease in gross thermal power for rising Q.
The overall observation is that the overall efficiency and the electric output power generally attain their highest level at rather large Q values, where Q_p, the ratio of the gross electric power to the required electric power for the reactor station itself, still notably increases. The overall efficiency saturates at lower Q values because the thermal power (for constant fusion power) decreases with increasing Q.
Figures 10 and 11 show the Q-dependence of Q_p and η for the four reactor designs, and Figs. 12 and 13 the relative values $Q_p/Q_p(\infty)$ and $\eta/\eta(\infty)$, in all cases over a larger Q range up to 200. Note the limits shown in Figs. 3a to 6a. As derived in sec. 2, $Q_p(\infty)$ depends essentially on $(P_p/P_f + P_{aux}/P_f)$, and hence gets larger as the reactor power increases; $\eta(\infty)$ increases mainly owing to increasing η_{th}, but diminishes with increasing $(P_p/P_f + P_{aux}/P_f)$.

The Q-dependence of the relative quantities $Q_p/Q_p(\infty)$ and $\eta/\eta(\infty)$ is strongly influenced by the quantities $1/[\eta_{CD}(P_p/P_f + P_{aux}/P_f)]$ and $[1/(\eta_{CD}\eta_{th}) - 1]$, respectively. For $\eta/\eta(\infty)$ the quantity $(P_p/P_f + P_{aux}/P_f)$ is important as well.
A large value of $1/[\eta_{CD}(P_p/P_f + P_{aux}/P_f)]$, hence low η_{CD} and a low value of $(P_p/P_f + P_{aux}/P_f)$, leads to a shift of large $Q_p/Q_p(\infty)$ in the direction of large Q values. This can be seen directly when comparing the sequence of the values of $\eta_{CD}(P_p/P_f + P_{aux}/P_f)$: 0.140 (ETR Alternative), 0.105 (ITER B6), 0.074 (ARIES-I) and 0.041 (EC R2) with the sequence of the $Q_p/Q_p(\infty)$ curves in the direction of increasing Q. Similarly, as $[1/(\eta_{CD}\eta_{th}) - 1]$ becomes larger the $\eta/\eta(\infty)$ curves are shifted towards larger Q and lower $\eta/\eta(\infty)$. The sequence of the values of $[1/(\eta_{CD}\eta_{th}) - 1]$, namely 1.98 (ARIES-I), 2.57 (EC R2), 3.08 (ETR Alternative) and 7.57 (ITER B6), describes the sequence of the $\eta/\eta(\infty)$ curves.
Hence for Q_p to become large, $(P_p/P_f + P_{aux}/P_f)$ should be as low as possible, and $\eta_{CD}(P_p/P_f + P_{aux}/P_f)$ should be as large as possible, so that simultaneously $(P_p/P_f + P_{aux}/P_f)$ has to be low and η_{CD} large. As can be seen from the $Q_p/Q_p(\infty)$ curve for EC R2, high-power reactors need very large Q values to attain satisfactory levels of $Q_p/Q_p(\infty)$. Only then can full benefit be derived from minimizing $(P_p/P_f + P_{aux}/P_f)$.
For η to become large within the frame set by η_{th}, $[1/(\eta_{CD}\eta_{th}) - 1]$ should be as low as possible, which calls for large η_{th} and again large η_{CD}.
The other parameters f_p and η_{di} lead to some refinement, but do not essentially impact on these tendencies.
Thus, the requirement of large Q values can be derived from the requirements of large Q_p and large η. If, for instance, for a large fusion power reactor $(P_p/P_f + P_{aux}/P_f) = 0.025 + 0.025 = 0.05$ and $\eta_{CD} = 0.7$ could be achieved, one would get the following values ($\eta_{th} = \eta_{di} = 0.35$, $f_{bl} = 1.25$, $f_p = 0.57$):

$$Q_p(\infty) = 8.500,\ \eta(\infty) = 0.309 \text{ for } Q = \infty \text{ and}$$
$$Q_p(100) = 6.665,\ \eta(100) = 0.297 \text{ for } Q = 100,$$
$$Q_p(50) = 5.498,\ \eta(50) = 0.286 \text{ for } Q = 50.$$

The values for Q = 100, when compared with those for existing light-water fission reactors, are somewhat lower in η, but at least a factor of 2.5 lower in Q_p.
As demonstrated by the EC R2 study, at the 1200 MW_{el} level a conceptual steady-state tokamak fusion reactor requires an advanced thermal conversion cycle with $\eta_{th} = 40\%$ to bring the net efficiency up to the usual 32%, with the Q_p value, however, still remaining at 4.914, which means a recirculating power of 20.3%. When Q is raised - with an advanced driver - from 33.5 to 100 (which implies tripling the current drive efficiency assumed for EC R2 or quintupling the present best current drive efficiency; in fact, with a bootstrap fraction according to [8] this would mean a basic current drive efficiency

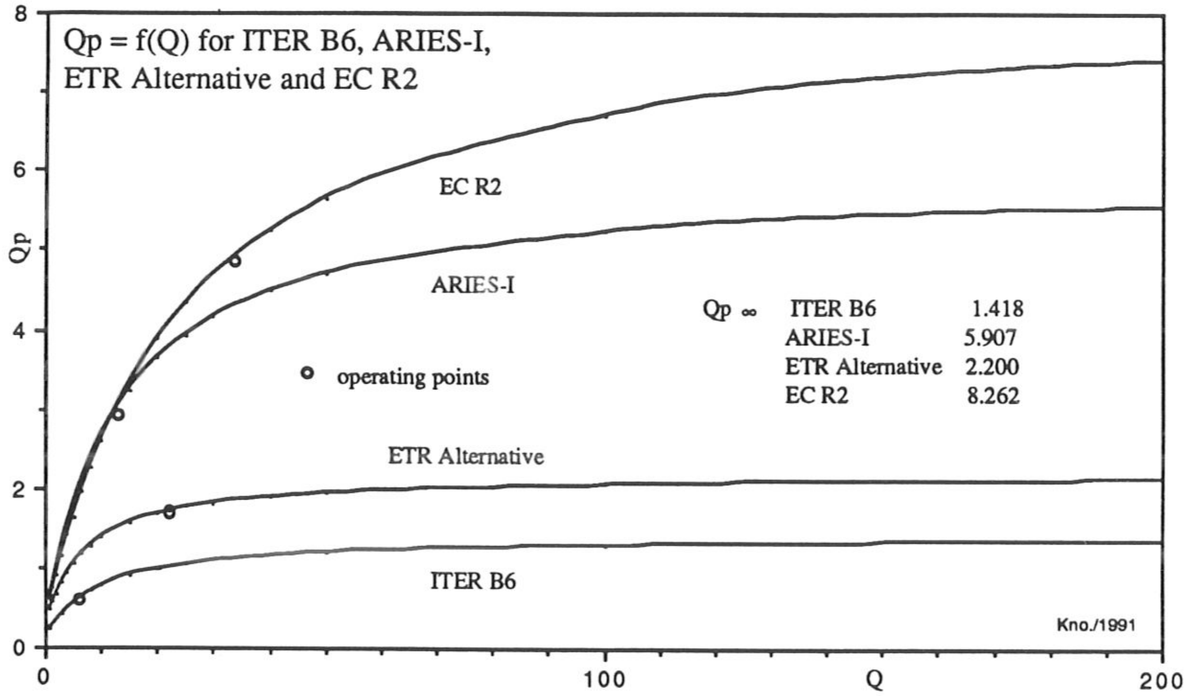

Fig. 10 Q_p (electric power Q) vs. plasma Q for ITER B6, ARIES-I, ETR Alternative and EC R2

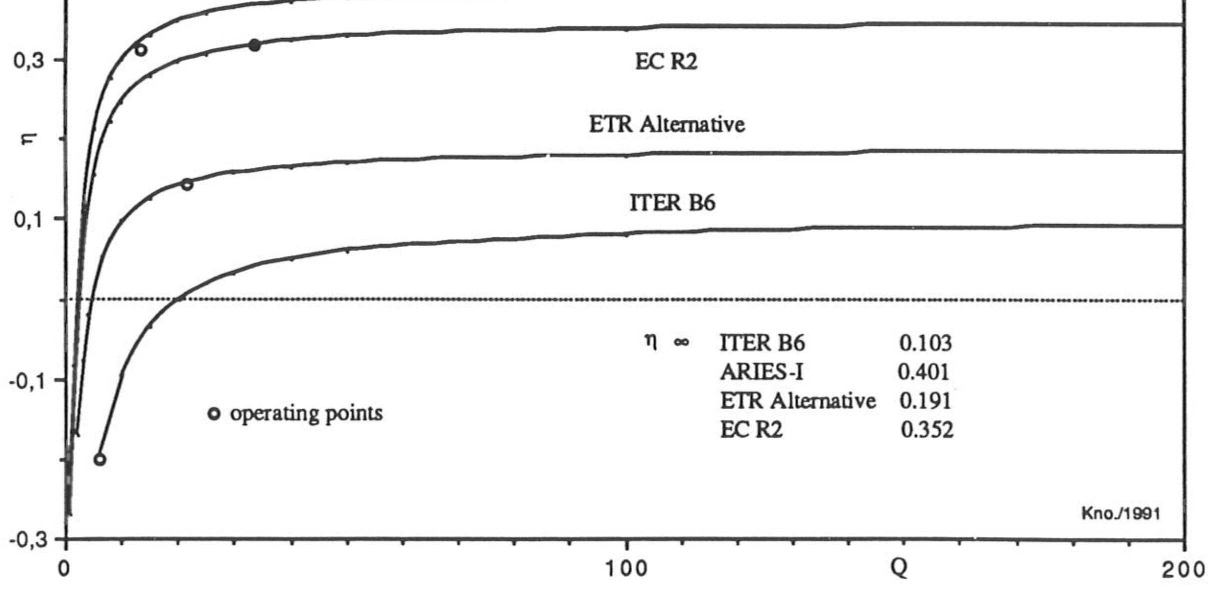

Fig. 11 η (overall efficiency) vs. plasma Q for ITER B6, ARIES-I, ETR Alternative and EC R2

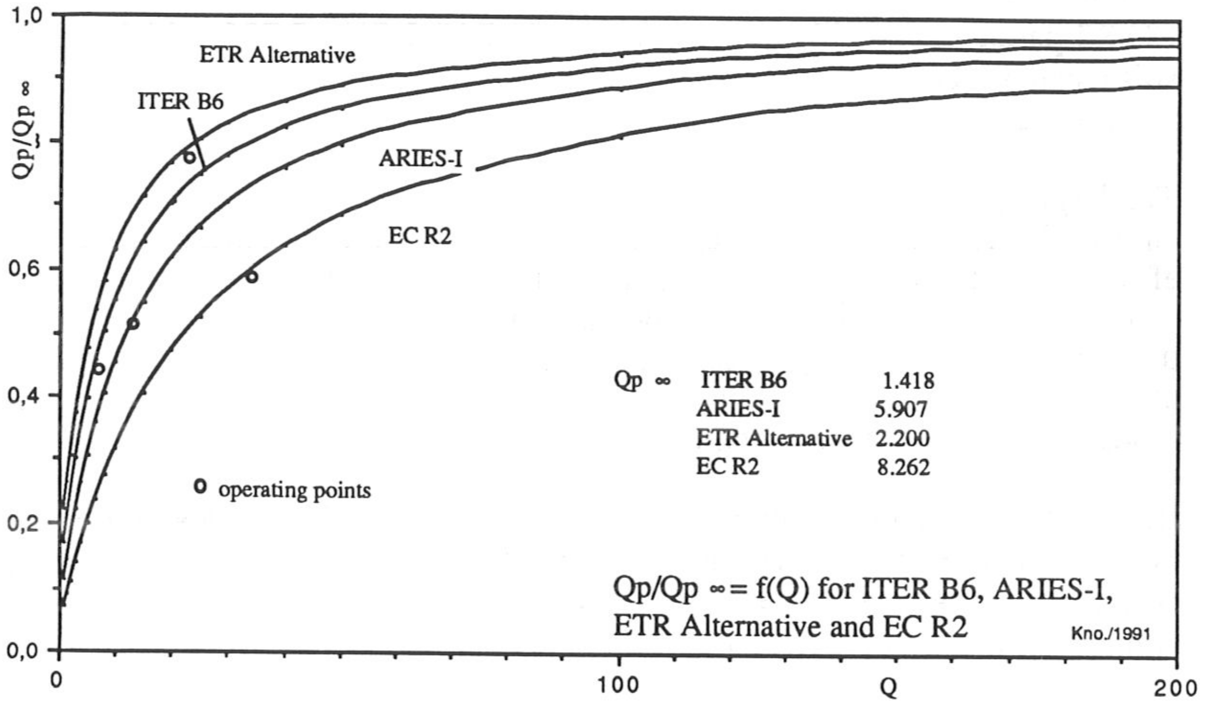

Fig. 12 Qp/Qp(∞) (relative electric power Q) vs. plasma Q for ITER B6, ARIES-I, ETR Alternative and EC R2

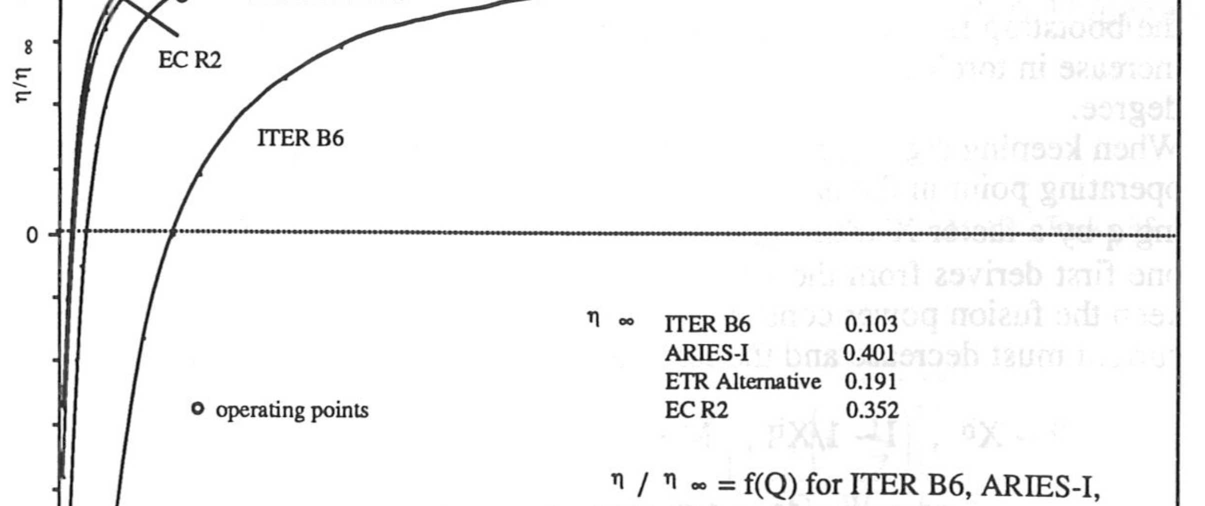

Fig. 13 η/η(∞) (relative overall efficiency) vs. plasma Q for ITER B6, ARIES-I, ETR Alternative and EC R2

of 2.4 A/Wm^2 or about six times the present best current drive efficiency, which would be theoretically attainable with compressional Alfvén wave current drive, for which $\eta_{CD} = 0.7$ would have to be proved as well), the EC R2 parameters would improve to $\eta = 34\%$ and $Q_p = 6.706$, which would still mean a recirculating power of 14.9% (at least twice as large as in a fission reactor station).

The large Q values obviously required appear attainable once high-efficiency current drivers have been developed. Already the value of current drive efficiency anticipated for EC R2 is roughly a factor of two larger than what can be achieved to day and the bootstrap fraction anticipated in keeping with the low q (Kruskal safety factor) assumed is not supported by present scalings, as mentioned above. ETR Alternative anticipates an even larger efficiency but a moderate (neoclassical) bootstrap fraction.

Besides the operational advantages of large Q visualized in the above figures, the reduction of the wall heat load at high Q for a given neutron wall load according to $(P_\alpha + P_{CD})/P_\alpha = (1+5/Q)$ is an important argument for large Q values and hence for large current drive efficiency.

6. Compensation of low current drive efficiency by a large Kruskal safety factor corresponding to a large bootstrap current fraction

An alternative possibility of achieving an overall increase in Q for a given (low) current drive efficiency - as indicated by, for example, Perkins et al. [10] and Kikuchi [13] - by increasing the Kruskal safety factor (which also increases the bootstrap fraction; see equations in sec. 3) requires a corresponding increase in toroidal field and hence cannot readily be exploited to a sufficient degree.

When keeping a given reactor configuration the same, maintaining the plasma operating point in the $n_e(T_{10})$ plane, hence also the fusion power, but increasing q by a factor X while γ_o could change by a factor Y and Q by a factor Z, one first derives from the Kruskal and the Troyon equations that in order to keep the fusion power constant with a fixed Troyon coefficient, the plasma current must decrease and the toroidal field has to increase, so that

$$B \sim X^b \ , \quad I \sim 1/X^i \ , \quad M \sim 1/X^b , \quad \gamma_o \sim Y \ , \quad Q \sim Z \quad \text{with } b + i = 1$$

Taking $q = q_o X$, $\gamma = \gamma_o Y$ and $Q = Q_o Z$, one obtains the following relation for Y (using the neoclassical bootstrap relation [7] shown in sec.3):

$$Y = \frac{Z\left[1 - \frac{I_B}{I}\right]}{X^b\left[1 - \left(\frac{I_B}{I}\right)_o\right]} = \frac{Z\left[1 - 3.373\ \frac{k\ g\ q_o\ \sqrt{A}}{C_{fa}\ f(k)}\ X\right]}{X^b\left[1 - 3.373\ \frac{k\ g\ q_o\ \sqrt{A}}{C_{fa}\ f(k)}\right]}$$

Consistency under the above assumptions requires that b = 0.5.
Keeping γ_o constant (Y = 1), one obtains for the relative increase in Q due to the enhancement of the bootstrap current at higher q

$$Z = \frac{X^{1/2}\left[1 - 3.373\ \frac{k\ g\ q_o\ \sqrt{A}}{C_{fa}\ f(k)}\right]}{1 - 3.373\ \frac{k\ g\ q_o\ \sqrt{A}}{C_{fa}\ f(k)}\ X}$$

With typical parameters and q_o = 2.5 the neoclassical bootstrap fraction is about 0.3 (0.44 from [8]). Hence one can write as an approximation for orientation

$$Z = \frac{0.7\ X^{1/2}}{1 - 0.3\ X}$$

which indicates that for X = 1.5 the plasma quality factor Q may increase by a factor of about 1.6, for X = 2 by a factor of about 2.5.
A further condition deriving from the plasma power balance requires a change in the confinement enhancement factor since the plasma current changes and also because the synchrotron radiation power changes owing to its field dependence. Hence the following power balance equation holds:

$$P_f/Q - P_f/Q_o = W_{th}/\tau_E - W_{th}/\tau_{Eo} + P_{sy} - P_{syo}$$

For Goldston scaling the f_H condition for Y = 1 reads (with $C_{\tau E}$ and τ_{Eneo} as defined above - see sec. 4)

$$f_{Hq} = \frac{X^{1/2}\ W_{th}^{1/2}}{C_{\tau E}\left\{\left[\sqrt{\frac{1}{\tau_{Eneo}^2} + \frac{W_{th}^2}{C_{\tau E}^4\ f_{Ho}^4}} - \frac{P_{syo}}{W_{th}}\left(X^{5/4} - 1\right) - \frac{P_f\left(1 - \frac{1}{Z}\right)}{Q_o\ W_{th}}\right]^2 - \frac{1}{\tau_{Eneo}^2\ X^2}\right\}^{1/4}}$$

$$P_{syo} = 0.001\ k^{1/4}\sqrt{\frac{1+k^2}{2}\ \frac{R}{a}}\ \sqrt{n_e}\ (B\ a\ T_{10})^{5/2}$$

This expression implies a wall reflectivity of $r_b = 85\%$. The dependence on reflectivity is sqrt(1-r_b) [14]. (To include any OH heating power , a further expression in the square bracket of the equation for f_{Hq} would be required: + $(P_{OHo}/W_{th})(X-1)$, which derives from the B^2-dependence of P_{OH}.)
On the basis of the values in Table 3 f_{Hq} is shown in Table 4 for X = 1.5 and 2.0. The values of P_{syo} are also listed.

Table 4 Goldston enhancement factors: reference cases for Y = 1, requirements when increasing q by 1.5 and 2.0

	f_{Ho}	$f_{Hq}(1.5)$	$f_{Hq}(2.0)$	Z(1.5)	Z(2.0)	P_{syo}[MW]	$(I_B/I)_o$
ITER B6	1.75	2.36	2.96	1.54	2.39	8.34	0.29
ARIES-I	1.85	2.76	-----	3.63	-----	75.00	0.57
ETR Altern.	1.71	2.20	2.64	1.49	2.18	7.40	0.26
EC R2	1.41	1.85	-----	2.45	-----	12.33	0.50

In all cases in Table 4, already an increase of q by 50% leads to a violation of the assumed average confinement limit of $f_H = 1.75$ (see sec. 4). EC R2 comes closest to allowing $X \leq 1.5$ considering the plasma power balance, but the associated increase in toroidal field would lead to a maximum field of 18 T (X = 1.5) (see Table 2).
A further comment on input assumptions is the following: If for the rated Q of EC R2 a combination of the neoclassical bootstrap fraction of 31% (instead of 50%) together with a basic current drive efficiency of 1.11 A/Wm^2 (instead of 0.7 A/Wm^2) is taken, $f_{Hq}(1.5)$ stays at 1.85 and Z(1.5) becomes 2.50 instead of 2.64 (see Table 4). The impact of the composition of $\gamma = \gamma_o/(1-I_B/I)$ is weak.
Evaluations of the above relations as shown by the data in Tables 3 and 4 indicate that (in the first stability regime) the alternative of low current drive efficiency together with large q is much less attractive than the combination of high current drive efficiency and low q for fixed fusion power and configuration, because under these constraints (with neoclassical bootstrap scaling)

- increasing q leads to larger toroidal field and hence larger device outlay for the same fusion power, apart from engineering limits that may be exceeded;
- increasing q easily leads to violation of the confinement limit deriving from the associated reduction in plasma current, especially for reactor concepts below the power reactor level;
- a factor $X \leq 1.5$ is, for example, just marginally possible for a full-scale power reactor concept like EC R2 (see Table 4). The associated increase of the bootstrap current fraction in this case leads to $I_B/I \leq 0.75$, which may be beyond the level permitted when additional non-inductive current drive for current profile shaping and control is required;

- enhancing the bootstrap current fraction by increasing q would introduce a further sensitive dependence of the operating conditions on the bootstrap mechanism in addition to the general $Q(f_H)$-dependence (see sec. 4) deriving from the steady-state plasma power balance;
- while ARIES-I is close to the confinement limit anyway, the remaining reactor concepts except EC R2 cannot tolerate a substantial increase of q since they are already in the confinement limit range (see Fig. 2);
- since a desirable basic γ value would be > 2 A/Wm^2 (which is well covered by theoretical predictions for compressional Alfvén wave drive in a higher power reactor concept), the attainable overall γ values at increased q (from the larger bootstrap fraction for larger q) with existing drivers fall a factor of > 2 short of becoming competitive; assumption of other scalings for the energy confinement time will somewhat modify the results, but the tendencies will remain similar. (Goldston scaling is rather close to the recent so-called quiescent H-mode scaling, pending definition of a scaling for H-mode operation with ELMs.)

7. Steady-state operation at high γ of a reactor designed for pulsed ignition

For a next-step reactor designed mainly for pulsed ignition operation such as ITER Case A1 one may consider steady-state operation with high current drive efficiency instead of pulsed operation with inductive current drive.
The possible operating regime attainable is characterized below by means of the data set of ITER Case A1 [1]. Related questions such as operation at a relatively large density which may be close to or even beyond a density limit are not tackled here. With the data of ITER Case A1 the equivalent (ohmic) current drive efficiency is $\gamma_o = 58.56$, which is considerably higher than anything to be expected for steady-state non-inductive current drive. Hence, introducing steady-state current drive for the plasma operating point of ITER Case A1 is equivalent to a very strong increase in current drive power over the pulsed ohmic power level. One can approximately clarify the situation by writing the steady-state plasma power balance (neglecting the synchrotron radiation, which is low anyway at the ITER Case A1 operating point), keeping the operating temperature fixed and relating everything to the Case A1 reference point. Initially, it is assumed that the plasma density and the plasma current could be changed away from the reference operating point. A confinement power law proportional to $I\,P^{-0.5}$ is assumed. One has for the plasma power balance

$$P_{\alpha o}\left(\frac{n_e}{n_{eo}}\right)^2 + P_{CDo}\,\frac{n_e}{n_{eo}}\,\frac{\gamma_o}{\gamma}\,\frac{I}{I_o} - \frac{W_{tho}\left(\frac{n_e}{n_{eo}}\right)^2}{\tau_{Eo}\left(\frac{f_H}{f_{Ho}}\right)^2\left(\frac{I}{I_o}\right)^2} - P_{rado}\left(\frac{n_e}{n_{eo}}\right)^2 = 0$$

Replacing $P_{\alpha o}$ and P_{rado} with the reference point power balance, one obtains

$$P_{CDo}\,\frac{n_{eo}}{n_e}\,\frac{\gamma_o}{\gamma}\,\frac{I}{I_o} - \frac{W_{tho}}{\tau_{Eo}\left(\frac{f_H}{f_{Ho}}\right)^2\left(\frac{I}{I_o}\right)^2} - P_{CDo} + \frac{W_{tho}}{\tau_{Eo}} = 0$$

which leads to the following approximation for f_H/f_{Ho}

$$\frac{f_H}{f_{Ho}} = \frac{I_o}{I}\left[\frac{1}{\left(\frac{I}{I_o}\,\frac{\gamma_o}{\gamma}\,\frac{n_{eo}}{n_e} - 1\right)\frac{P_{CDo}\,\tau_{Eo}}{W_{tho}} + 1}\right]^{1/2}$$

Bearing in mind the strong change in γ anticipated, one clearly sees that a variation of the plasma density cannot compete with the γ variation. Only the plasma density and current could be reduced in practice which for the density would lead to some reduction of the enhancement factor required, whereas for a reduction in current the enhancement factor would have to increase. The strong anticipated reduction in γ leads to a reduction of f_H if nothing else is changed. For the same plasma operating point, however, a reduction of the current is possible - with g and q increasing inversely proportionally to the current - up to the limit where the reference value of f_H is reached again. Keeping first the plasma density and current constant and inserting the reference values for ITER Case A1, one gets

$$\frac{f_H}{f_{Ho}} = \left[\frac{1}{0.0175\left(\frac{\gamma_o}{\gamma} - 1\right) + 1}\right]^{1/2}$$

Assuming now a basic current drive efficiency of $\gamma = 1.5$ as anticipated for ETR Alternative (see sec. 3), one gets $f_H/f_{Ho} = 0.775$, which agrees within 2% with a more accurate evaluation [15]. The pertaining current drive power is 89 MW, which means Q = 12.1. Since the operating temperature for ITER Case A1 is 10 keV as compared with 20 keV for ITER Case B6 (see sec. 3) and since the density and plasma current are higher, a more than threefold anticipated increase in current drive efficiency in relation to ITER Case B6 only leads to less than doubling of Q in relation to ITER Case B6. The current drive power is reduced by 23% only.
Some improvement of Q is possible within the confinement enhancement as assumed for ETR Alternative when the plasma current is reduced while the fusion power, plasma temperature and density are kept constant by increasing both the Troyon coefficient and the safety factor q inversely proportionally to the plasma current. The above general relation for f_H/f_{Ho} states that for the

above data f_H could return to approximately $f_{Ho} = 1.71$ when the plasma current is decreased by about 12.4%. A more accurate evaluation shows that 11.7% plasma current reduction leads to a Goldston confinement enhancement factor of 1.71 as for ETR Alternative, the case for comparison. The required current drive power is still 74 MW, which corresponds to Q = 14.6.
A list of the Q-relevant parameters (see sec. 3) for this case reads
ITER A1 (19.43 MA): A = 2.79, $\gamma_o = 1.50$, $I_B/I = 0.22$, M = 1.51, k = 2.0, $T_{10} = 1.0$, g = 0.023, $n_e = 1.22$, f(k) = 2.84, q = 2.73, $q_\psi = 3.75$ $p_f = 1.00$, Q = 14.59, $Z_{eff} = 1.66$, ($\gamma_A = 0.62$).
This also shows that the assumed current drive efficiency is by far not covered by the theoretical prediction for compressional Alfvén wave current drive.
Figure 2 (sec. 4) shows the operating point of ITER A1 (19.43 MA), which still appears well below ETR Alternative.
For ITER A1 (19.43 MA) with the input data (see sec. 2, conversion cycle data assumed)
$\eta_{th} = \eta_{di} = 0.35$, $f_{bl} = 1.25$, $\eta_{CD} = 1/3$, Q = 14.59, $f_r = 0.5$, $f_p = 0.57$,
$P_f = 1080$ MW with $P_{aux}/P_f = 0.130$ and $P_p/P_f = 0.088$
one obtains
$P_{et}/P_f = 0.462$, $P_e/P_f = 0.0379$, $P/P_f = 1.319$, $P_e/P_{et} = 0.0822$, $Q_p = 1.090$,
$\eta = P_e/P = 0.0288$, $\eta_{tht} = 0.350$.
The auxiliary power $P_{aux} = 140$ MW is very large with respect to the fusion power. For a required electric power for current drive of 222 MW there is a possible net power input to the grid of 31 MW.
The ratio of station power to fusion power required would be 0.424.
Comparison with ETR Alternative (see sec. 3) shows that the latter - based on the same anticipated current drive efficiency - has a considerably larger margin in respect of plasma density and comes much closer to the current drive efficiency theoretically predicted for compressional Alfvén wave current drive.
Assuming the same electric efficiency of the current driver as taken for ETR Alternative (and for EC R2), namely $\eta_{CD} = 0.7$ - everything else unchanged - one gets for ITER Case A1 (19.43 MA) = ITER A1 mod.:
$P_{et}/P_f = 0.462$, $P_e/P_f = 0.146$, $P/P_f = 1.319$, $P_e/P_{et} = 0.316$, $Q_p = 1.461$,
$\eta = P_e/P = 0.110$, $\eta_{tht} = 0.350$.
The ratio station power to fusion power required would be 0.316.
The important impact of the driver electrical efficiency for the overall efficiency is clearly demonstrated.
The net power input to the grid could be 157 MW in this case (deriving from a fusion power of 1080 MW), as compared with the value of 191 MW (deriving from a fusion power of 1000 MW) for ETR Alternative. Some data for the latter two cases are collected in Table 5.
Thus, the comparison between ITER Case A1 (19.43 MA, increased g and q) and ETR Alternative confirms the following arguments in favour of higher plasma temperature and higher toroidal field for steady-state reactors:

Table 5 Comparison between ITER Case A1 (19.43 MA) and ETR Alternative

		ITER A1 mod.	ETR Altern.	remarks
P_f	[MW]	1080	1000	about equal
T_{10}	[10 keV]	1.00	1.67	
n_e	[10^{20} m^{-3}]	1.22	1.21	equal
n_{ecrit}	[10^{20} m^{-3}]	1.17	1.71	
Q		14.6	22.0	
γ_o	[A/W m^2]	1.50	1.50	equal, extrapol.
I_B/I		0.22	0.26	
f_{HGO}		1.71	1.71	equal
I	[MA]	19.4	14.4	
P_{CD}	[MW]	74.0	45.5	
A		2.79	3.66	
V	[m^3]	1083	431	
B	[T]	4.85	6.38	
B_{max}	[T]	11.2	12.7	
q_ψ		3.75	3.10	
g		0.023	0.030	
M	[10^{20} m^{-2} T]	1.51	1.00	
W_{th}/τ_E	[MW]	231	212	
γ_A	[A/W m^2]	0.62	1.25	for comparison
Q_p		1.461	1.721	
η	[%]	11.0	14.7	
η_{CD}	[%]	70	70	equal, extrapol.

- the greater margin in density both in terms of the Murakami definition and according to a more recent model [16] that interprets the tokamak density limit n_{ecrit} as a radiation limit;
- the possible access to overall current drive efficiencies more than three times larger than the present ones without the necessity of the bootstrap fraction approaching 80% (which would be associated with very high toroidal field);
- hence the potential to attain Q values in future power reactors that follow the requirements of economic competition with existing reactors;
- the possibility of exploiting both the beta and density limits at an appropriate level, which for a given configuration defines the largest fusion power attainable.

8. Conclusions

It has been confirmed that a large Q value is of paramount importance for steady-state tokamak power reactors and their predecessors that are needed in a step-wise approach towards full-scale reactor conditions. A large Q value, apart from reducing the thermal wall loading with respect to the pertaining neutron wall load, reduces the impact of current drive power on the overall efficiency by reducing the amount of circulating power (in relation to a low-Q case). Since the station power requirements in a fusion reactor are relatively large, but are a reducing fraction of, for example, the fusion power as the latter increases, and since the current drive power contributes essentially to the total station power requirements, Q and the driver electrical efficiency must increase particularly for large power reactors. For steady-state operation of a next-step reactor an adequately large Q value and a large driver electrical efficiency are essential in order not to arrive at a plasma power balance that is dominated by the power input from non-inductive current drive, and in order to avoid excessive supply.

A large value of Q can be attained predominantly by a large basic current drive efficiency of the driver system, enhanced by a certain bootstrap fraction when operating at the largest plasma temperature accessible under current drive conditions. The role of the bootstrap fraction should not be overestimated, since at bootstrap current fractions close to 1 the power balance would very strongly depend on the bootstrap mechanism. This would come in addition to the strong sensitivity of the plasma power balance in the relation between Q and the required confinement capability for a given plasma operating point in a given reactor configuration. The increase of the Kruskal safety factor for compensating a low basic current drive efficiency by increasing the (neoclassical) bootstrap current fraction, instead of aiming at a larger current drive efficiency, is shown not to be a viable option for the implied increase in magnetic field and the stringent limitations imposed by the plasma power balance.

The present drivers do not satisfy the ultimate requirements, and for a next-step reactor they entail a large power supply and a huge amount of plasma heating power for a steady-state plasma operating point even at high temperature, which means that steady-state operation would be far from the ignited burn condition.

As an example, the Q value of 6.5 of ITER 1990 (Case B6) means that 77 % of the alpha power is additionally introduced into the plasma. This is not reactor-relevant. There is no way either to make such a device at least conceptually a net electric power source despite its thermal power of about 1070 MW (if treated as a power reactor). Comparison of ETR Alternative and ITER A1 with reduced plasma current, with steady-state current drive being assumed, shows the importance of combining an enhanced (but restricted) plasma temperature,

a high toroidal field, a large current drive efficiency and a high driver electrical efficiency.
A next reactor step can be designed for large Q prior to development of the pertaining high-efficiency driver, and with a proper parameter choice it can be operated at reduced power with a less efficient driver in a preliminary phase. It is also possible to design a next-step reactor for a low current drive efficiency, provided enough confinement margin is built in from the beginning. Then, later operation with a high-efficiency driver is possible according to the interdependence of Q and the confinement time in a specific reactor configuration.

The arguments on current drive efficiency involve the plasma power balance and technical aspects for near-term reactors, while for power reactors recirculating power and overall efficiency are issues of concern. Figure 14 is an attempt to generally visualize both the technical (electric power $Q = Q_p$) and the plasma-related (confinement enhancement beyond the L-mode) aspects of the topic. For the same data as in Fig. 2, which is restricted to Q values < 40, it indicates the essential differences in the four designs considered here. The low current drive efficiency assumed for ITER B6 (which also assumes a low driver electrical efficiency) and ARIES-I is an essential reason for the low performance of the two cases in terms of recirculating power, whereas the assumption of a notable increase in current drive efficiency and of high driver

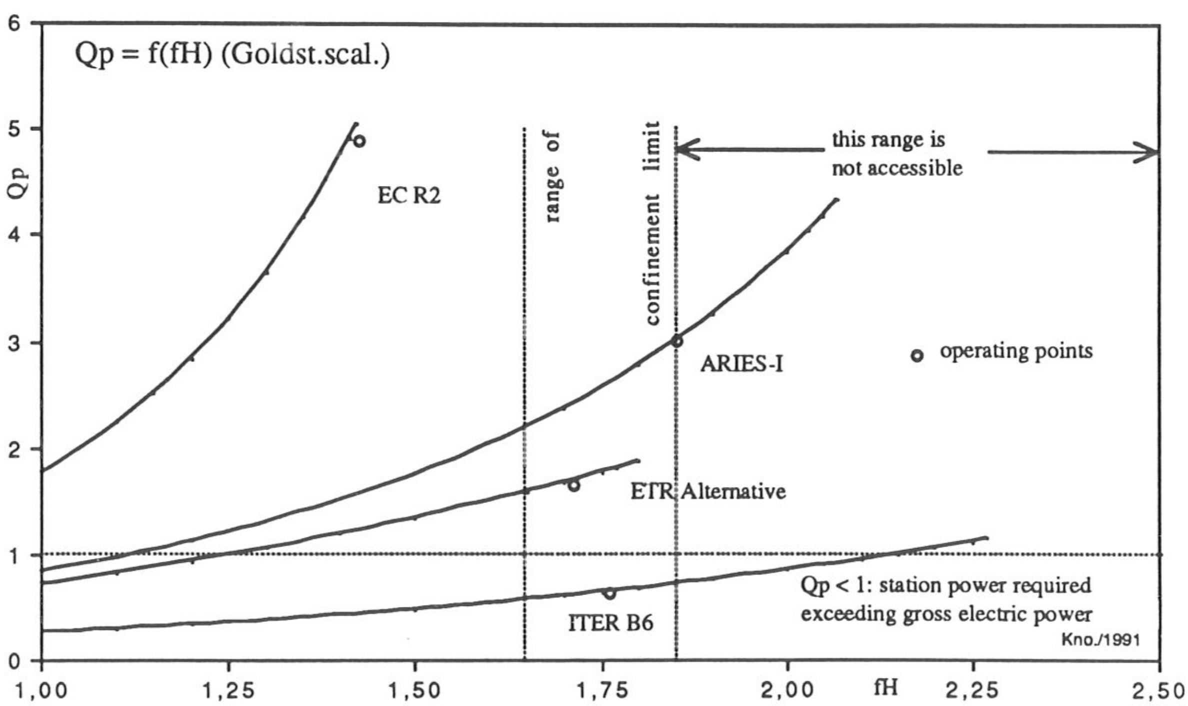

Fig. 14 Electric power Q (Q_p) vs. the confinement enhancement factor f_H for ITER B6, ARIES-I, ETR Alternative and ECR 2

electrical efficiency for ETR Alternative and EC R2 (supported by a larger fusion power level in both cases) leads to a remarkable improvement of Q_p within the usual frame for the plasma energy confinement.
As shown by checking on existing conceptual design studies, it is not possible to arrive at relevant next-step reactor and satisfactory power reactor steady-state operating parameters on the basis of the present current drive efficiency and driver electrical efficiency. An ultimate improvement in current drive efficiency by a factor of about 6 is necessary (such a factor theoretically appearing to be possible at the EC R2 level, especially if a larger than neoclassical bootstrap fraction would be attainable), while the driver electrical efficiency should be improved up to the level of > 70%.
The above results underline the necessity of developing very efficient high-γ non-inductive drivers for making steady-state next-step tokamak reactors accessible and maintaining high-power tokamak reactors as a relevant option.

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List of Symbols

a	[m]	minor plasma radius
k		plasma elongation
R	[m]	major plasma radius
A		aspect ratio: R/a
B	[T]	toroidal field on plasma axis
$f(k)$		function of k and triangularity
q		current-q (~ Kruskal parameter q_ψ)
M	[10^{20} T^{-1} m^{-2}]	Murakami parameter
g	[T m MA^{-1}]	Troyon coefficient
C_{fa}		beta enhancement by fast alphas ($\beta_{tot}/\beta_{therm}$)
n_e	[10^{20} m^{-3}]	electron density (volume average)
n_{ecrit}	[10^{20} m^{-3}]	critical electron density [16]
n_{DT}/n_e		relative fuel density
T_{10}	[10 keV]	plasma temperature (volume average)
$C_{\sigma Ef}$	[10^{-42} MW m^3 keV^{-2}]	4*fusion power/[volume*$(n_{DT}T_{10})^2$]
τ_E	[s]	plasma energy confinement time
f_H		confinement enhancement factor
τ_{EGO}	[s]	Goldston energy confinement time
τ_{Eneo}	[s]	neoclassical energy confinement time
W_{th}	[MW]	thermal plasma energy
γ_o	[MA MW^{-1} m^{-2}]	current drive efficiency ($I_B/I = 0$)
γ_A	[MA MW^{-1} m^{-2}]	Alfvén wave current drive efficiency ($I_B/I = 0$)
I_B/I		bootstrap current fraction
Z_{eff}		effective impurity number
Q		plasma power quality factor: P_f/P_{CD}
P_f	[MW]	fusion power
p_f	[MW m^{-3}]	fusion power/volume
P_α	[MW]	alpha power
P_{CD}	[MW]	current drive power into the plasma
P_{rad}	[MW]	bremsstrahlung and impurity radiation
P_{sy}	[MW]	synchrotron radiation
f_r		$(P_{rad} + P_{sy})/(P_\alpha + P_{CD})$
ELM		edge-localized mode (plasma operating state)
Q_p		electric power quality factor: $P_{et}/(P_{CD}/\eta_{CD} + P_p + P_{aux})$
P	[MW]	gross thermal power

P_{bl}	[MW]	1st wall/blanket thermal power
P_{di}	[MW]	divertor thermal power
P_{et}	[MW]	gross electric power
P_e	[MW]	net electric power
P_p	[MW]	electric power for pumping the cooling circuits
f_p		fraction of electric pumping power converted
P_{aux}	[MW]	auxiliary electric power except pumping and current drive power
f_{bl}		blanket power multiplication factor
η_{th}		thermal conversion efficiency: 1st wall/blanket
η_{di}		thermal conversion efficiency: divertor
η_{tht}		gross thermal efficiency: P_{et}/P
η		overall efficiency P_e/P
η_{CD}		electrical efficiency: current driver system