MEETING REPORT

SUMMARY OF THE COURSE ON TOKAMAK STARTUP—PROBLEMS AND SCENARIOS RELATED TO THE TRANSIENT PHASES OF A THERMONUCLEAR FUSION REACTOR, ERICE, SICILY, JULY 14-20, 1985

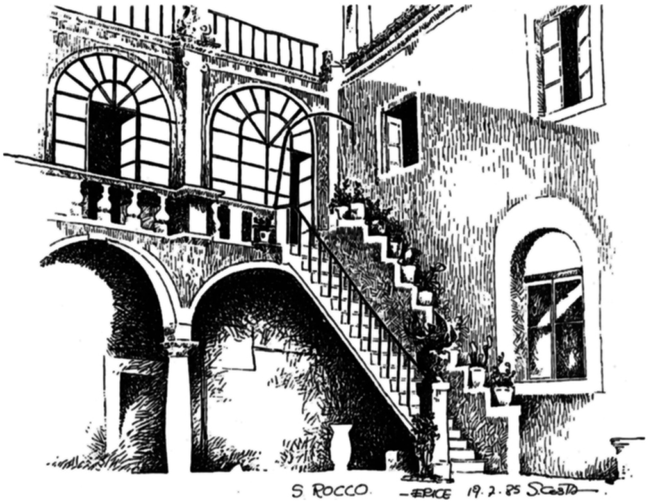
INTRODUCTION

"Tokamak Startup" was the 7th course held under the auspices of B. Brunelli's International School of Fusion Reactor Technology. Since its start in 1972, the school has covered quite a large domain of fusion reactor problems, with the previous six courses devoted to "Stationary and Quasi-Stationary Toroidal Reactors" (1972); "Pulsed Fusion Reactors" (1974); "Tokamak Reactors for Breakeven—A Critical Study of the Near-Term Fusion Reactor Program" (1976); "Driven Magnetic Fusion Reactors" (1978); "Unconventional Approaches to Fusion" (1981); and "Fusion Blanket Technology" (1983).

Fifty participants took part in the 1-week course, which resulted in a very busy event, where the interesting lectures, some very animated discussions, and the many social and cultural events filled the days from early morning to late at night. The course benefited from Erice's unique setting and from the stimulating atmosphere that reigns at the Ettore Majorana Center for Scientific Culture.

The fact that the critical startup and transient phases of a tokamak reactor are now the specific subject of a comprehensive international gathering of fusion specialists seems indicative of the substantial progress made in recent years toward attaining controlled ignition of a nuclear fusion fuel, i.e., toward demonstrating the scientific feasibility of controlled thermonuclear fusion. In fact, the steady-state burning phase has so far attracted most of the attention of fusion physicists and engineers, as it is conceptually more rewarding and theoretically easier to handle. However, as for many large engineering systems—nuclear fission power plants or aerospace crafts, for example—the major issues of design and operation lie often in the startup, shutdown, and power transient phases, rather than at the full load, or at cruising regimes.

The choice of the contributions made for this 1-week course assured as much as possible a comprehensive coverage of the problems inherent in an ignited tokamak reactor, with particular reference to the startup phase.



Plasma issues and conditions on the road to reaching and then maintaining an ignited tokamak plasma were presented and discussed in the two opening lectures, by J. Sheffield and Nermin Uckan. Experimental startup results and experience were illustrated for the two largest tokamaks in advanced operation by A. Tanga and P. R. Thomas for the Joint European Torus (JET), and by D. Mueller for the Tokamak Fusion Test Reactor (TFTR).

Modeling studies and interesting considerations for the startup operation in the next generation of large toroidal machines were presented by F. Engelmann for the Next European Torus (NET) and by N. Fujisawa for the Fusion Experimental Reactor (FER), as well as by O. Gruber for the Axially Symmetric Divertor Experiment (ASDEX) Upgrade. In D. A. Ehst's contribution, a further step was undertaken toward discussing some transient operational aspects of a DEMO reactor. In his contribution, D. Palumbo reminded the participants about the importance of some political and economic constraints in the evolution of these large and expensive programs.

Two problem areas were singled out as being of particular importance for the modeling and the evolution of the startup phase: impurity control and noninductive current drive. The latter subject was presented and discussed at length in nine contributions: four reported on the experimental results in operating experiments—Princeton Large Torus,

F. C. Jobes; PETULA B, D. van Houtte; ASDEX, F. Leuterer; JIPP T-IIU, K. Toi—and five were devoted to proposals of modeling studies for future applications—JET, J. Jacquinot; TORE SUPRA, G. Tonon; DEMO reactor, D. A. Ehst; in addition to the two presentations on NET and FER already mentioned.

In all these contributions particular attention was paid to the relevant technical consequences. For example, the review by M. F. A. Harrison on impurity control was followed by four contributions on related technical aspects: pump limiters by K. H. Finken, wall protection by K. J. Dietz, plasma position control by U. Seidel and by E. Coccorese. Finally, E. Salpietro reviewed the technological implications of startup and current transients on the design of electromechanical components in a NET-type machine.

The conclusions on the various results and points of view presented at the course were drawn at two panel sessions chaired by G. Briffod ("Noninductive Current Drive") and M. F. A. Harrison ("Impurity Control"), and in the concluding session chaired by R. S. Pease.

TOKAMAK OPERATION PHASES

The operation of an ignited thermonuclear tokamak plasma encompasses two main phases—startup and burn—each with its own physical and technological problems. Actually, in a complete cycle, these two phases are followed by the shutdown, and then by a dwell time, before the cycle is repeated again. The former, however, is essentially the time inverse of the startup phase, and during the dwell time technical problems must be handled that are quite different from those discussed at Erice.

The startup phase can be divided into some three to five subphases: (a) plasma formation and current initiation; (b) current rampup (low and medium temperature range); (c) heating and fueling toward ignition (and reaching the burn working point).

The way the plasma current is driven in a tokamak reactor—either by inductive or noninductive means—has a strong impact on the operation scenarios that can be envisaged; hence, it also strongly influences the technological problems and their solutions.

Plasma Formation

The very first moments of a tokamak startup, plasma formation and current initiation, can well be described by the classical ionization and discharge theory, and, as shown by JET and TFTR, can relatively easily be managed in large tokamaks. In this respect, it is important to have low stray fields (of order 0.01 T) and good mastery of the magnetic control field B_V. Experience shows that a toroidal electric field of ~1 V/m is needed during this subphase, thus requiring a loop voltage of typically 35 V in NET.

At the end of this subphase, the tokamak configuration is formed and the plasma current in a large device reaches a level of ~0.1 MA. Then the plasma is heated by the rapidly increasing current through the radiation barrier, attaining an electron temperature of ~0.1 keV. During this period (which actually belongs already to the beginning of the rampup phase), the loop voltage has to remain at its maximum value, the plasma density should not exceed $\sim 5 \times 10^{18}$ m^{-3}, and the impurity concentration must be low to ensure a positive power balance.

Conditioned, clean vacuum chamber walls are required, as otherwise uncontrollably large quantities of gas (and impurities) can be released from them in the early stages.

Experimental evidence, particularly from JET and TFTR, indicates that a modest (<2%) concentration of low Z impurities (e.g., carbon) is harmless, provided that the filling density is not too high (5×10^{18} m^{-3}). The presence of higher Z impurities (e.g., from Inconel, aluminum, etc.) can quench the plasma, due to excessive radiation losses. A combination of controlled gas puffing and carefully prepared boundary surfaces will result in an adequate filling procedure. In conclusion, the plasma formation phase should not present serious problems for the future large tokamaks.

Inductive Current Rampup

In ramping up the current to the multimegampere region, the main problems concern the rate at which the current is raised, the associated volt-seconds flux loss, and the simultaneous density rampup (required to avoid disruptions).

The current rise cannot be too short, or otherwise the turbulence due to incipient skin effect may be too large. Also, the variation of the control field B_V (required to control the plasma position) may become too fast (enticing problems in the power control units, in the superconducting coils, and in the thick blanket structures of fusion reactors). The rise time cannot be too long either as the volt-seconds used may become too large (as a result of resistive losses).

In present experiments 5 MA have been reached (JET) with a current rise of ~1 MA/s without prohibitive flux loss or other particular problems, a result that is near satisfactory in view of NET/FER applications. Consequently, this subphase will last typically 20 s, during which the 8-MA current and the expected 3-keV temperature level is reached; it is also where a D-shaped plasma configuration has to be formed.

One could remark that comparable (time-inverse) problems may arise in the shutdown phase. In particular, here the current and density rampdown tend to adjust automatically (when the time scale is reasonably slow), as if the loss of current and the loss of plasma were linked.

Startup in both JET and TFTR has demonstrated that high Z impurities (e.g., nickel, iron, etc.) can be deleterious, at least in the early phases of rampup. Such impurities may be more acceptable toward the flattop regime of ohmic discharges, especially if they are progressively introduced, e.g., as a consequence of sputtering. However, operational experience has demonstrated that there is a significant likelihood of transient release of impurities by processes such as arcing. It therefore seems desirable to reduce the risk of plasma disruption by ensuring that plasma/wall contact be limited to low Z surfaces during limiter operation. It is also desirable to minimize the oxygen impurity content. A convenient criterion is that impurity radiation at early current flow should not exceed ~80% of the input power.

Inductive startup scenarios for conceptual reactors such as the International Tokamak Reactor (INTOR) and NET are based on the concept of operation with a limiter during ionization, current initiation, and the early stages of current and density rampup. The plasma conditions expected are comparable to those presently experienced in the ohmic phases of JET and TFTR.

A poloidal divertor configuration can be formed only when a significant fraction of the plasma current is flowing and it appears that a low Z limiter must be accepted during the early stages of startup. It is advantageous to form the divertor configuration as soon as possible during the rampup phase and, because of the extended rampup time, this appears to be somewhat easier to achieve with noninductive current drive. Present concepts of the divertor to be employed during the heating and burn phases are based on a tungsten (or comparable heavy refractory metal) target; as this assures high recycling conditions within the divertor there is, however, a presently unresolved problem of contamination of the low Z limiter with divertor target material.

Noninductive Current Rampup

Radio-frequency (rf) current rampup offers the experimental advantage of extending the performances of existing apparatus and of achieving slow rampup without loss of volt-seconds in any inductive core. It can show noticeable volt-second savings for a NET/FER type of reactor and offers the prospect of continuous operation of a tokamak. The disadvantages are that it cannot be used for fast rise of current and it may be expensive in terms of additional equipment. So far, although there are indications of current drive from the neutral beam and from electron cyclotron wave injections, only the lower hybrid (LH) range radiation has been effective in establishing high currents.

Steady-state current drive, current rampup, and transformer recharge have been tested by means of LH waves in many tokamak experiments and in a wide range of plasma parameters: density (10^{18} to 10^{20} m^{-3}), magnetic field (up to 10 T), current (up to 400 kA). Currents have been ramped up to 250 kA. Currents of 400 kA have been maintained on flat top with LH drive powers of the order of several hundred kilowatts.

For practical applications to the burn phase of a DEMO reactor, LH current drive efficiencies as obtained in today's experiments are still too low by at least a factor of 5. In fact, the best results (so far obtained) give a driven current over rf power efficiency of $I/P \simeq 0.12 \times 10^{20}/(nR_0)$ (A/W, m^{-3}, m), which would imply prohibitive rf power levels (hundreds of megawatts) to drive the necessary currents of typically 10 MA. Progress can be expected by optimization of wave and plasma parameters, and/or by electron temperature increase. In any case, results by other methods are urgently required.

On the other hand, startup assisted by rf waves might be advantageous, as it could reduce induced loop voltage requirements during the early stages by providing plasma formation and heating as well as possibly current initiation. Both electron cyclotron and LH waves have been used for this purpose, mainly in small experiments, with electron cyclotron waves having a somewhat broader data base for plasma formation and heating, but so far only LH waves have been demonstrated to be effective for current initiation.

Of importance for future applications is the possibility of current profile shaping and stability control through rf radiation. Disappearance of $q = 1$ sawteeth has been reported, as well as stabilization of $m = 2$ modes in LH-driven discharges. Better control of rf-generated current profiles could have strong impact on plasma stabilization and β-limit; such a control is envisaged on JET by means of ion cyclotron resonance heating (ICRH) in the mode conversion regime with low $N_{\parallel}$ (≤ 2).

The rate of rampup of an LH-driven current is limited by the available rf power. This is optimized by performing current rampup in low-density plasmas (typically $\bar{n} \sim 3 \times 10^{18}$ m^{-3}).

The relatively slower rampup (with respect to inductive drive) permits early formation of the divertor. Minimization of impurities by divertor action is predicted to be strongly dependent on attainment of powerful localized recycling, which is dependent on the balance between the nonradiated power density flowing to the divertor and the particle density at the separatrix of the scrape-off plasma. To attain a suitable balance, it will be necessary to tailor the heating power to the time-dependent density limit (at the plasma edge) during the rf heating phase.

The general impression was that there appear to be no insuperable problems of impurity control during startup of a NET/INTOR device but that noninductive current drive at low plasma density incurs a high risk of plasma contamination.

Heating Phase

The problems of heating and fueling the bulk plasma to temperatures and densities of thermonuclear interest were excluded as a main topic from this course. Nevertheless, on various occasions, the heating processes and their consequences came up in the presentations and discussions.

Heating by neutral beams, ion cyclotron waves, LH waves, and electron cyclotron waves is presently being applied in many tokamak experiments. An rf method would be preferred for the NET/FER devices because the equipment for wave power generation can be placed far away from the nuclear core of the device. Fueling to a density of 10^{20} m^{-3} can be done by gas puffing, to be supplemented by pellet injection if density profile control or fast density rise is required.

The last phase of startup is the reaching of ignition and the transition to the working point. This transition requires control of the burn temperature. A further critical issue anticipated for this transition phase is the impact of magnetohydrodynamic phenomena and in particular of the so-called sawteeth activity on plasma behavior, which is expected to lead to very demanding control problems. All in all, the inductive startup of a NET-type device will last ~30 s.

Additional heating methods as used in the present large tokamaks (JET/TFTR) have still to progress some way, before the heating levels needed in ignited tokamaks (NET/FER) will successfully be established. During the burn phase the heating will be due to alpha-particle emission from the fusion reactions. This heating process can partly be modeled with neutral beam injection experiments.

In TFTR, additional heating by neutral injection was (at mid-1985) in the power range up to 6.3 MW. In JET, ICRH operating at up to 5 MW increased the temperature by 1 to 2 keV to a total of up to 4 keV. In conditions when the limiters and walls of JET had been freshly carbonized, heating by ion cyclotron resonance frequency (ICRF) did not increase the relative concentration of impurities. There are indications that heating becomes difficult when metallic impurities are present. In the case of diverted plasmas in ASDEX, there is evidence that impurity release is peaked at the major radius corresponding to the ICRF deposition zone. Thus, optimum impurity control is likely to be achieved when this radius coincides with the throat of the divertor.

Burn Phase

During the burn phase (which should last from 200 to 1000 s), the control of the plasma temperature and the fusion power are among the major issues. The value of the loop voltage during burn, important for the volt-second consumption, is estimated to be in the range of 0.07 to 0.1 V if the plasma resistivity is collisional.

Many of the operating conditions anticipated for NET and FER are being approached in the major operating tokamaks (JET/TFTR). This is true, for example, for the plasma current, the dimensions, the temperatures, and the impurity content (Z_{eff}), for which the best values so far achieved all lie within a factor of <2 of what will presumably be needed in an ignited tokamak. On the other hand, the parameters that still diverge significantly are, e.g., the poloidal beta, the particle density, the $n\tau$ parameter.

Even if Z_{eff} lies within reasonable range (in TFTR), means to control the impurity content require particular attention in the long burning times considered for the ignited tokamaks. Studies such as NET/INTOR and FER indicate that it seems feasible to operate divertor targets at a peak power load of ~ 5 MW/m^2. The operational lifetime of a bonded tungsten/copper target structure is then expected to be limited by cyclic thermal stress. In the divertor of a power reactor, the peak loading could be enhanced by a factor 3 to 5. While there are various structures that can accept very high power loads (for example, the nose structure of the space shuttle), these are limited by a short cyclic lifetime. The most profitable approach is likely to be a compromise between reduction in power load (by means of radiation), reduction in the number of operational cycles, and improved technology of heat extraction.

To sustain the long burn time in a tokamak, quasi-steady hybrid scenarios are considered both in NET and particularly in FER. In these scenarios, the plasma current is kept approximately constant, while the fusion burn is in a pulsed operation. The plasma current is driven inductively by a transformer during the burn, and the transformer is recharged between consecutive burns, while maintaining the plasma current by an rf current drive method. This quasi-steady-state operation scenario also has many engineering advantages, such as a reduced number of pulses, which leads to a reduction of thermal and mechanical stress fatigue and of magnetic energy loss during transfer from the poloidal field coils to the energy storage system.

The low plasma density presently envisaged for noninductive current drive during transformer recharging implies that adequate recycling can be established within the divertor.

CONCLUSIONS

While the total pulse length in the NET/FER tokamak generation (with all its consequences) should be much longer than in preceding devices (of order 1000 s), the startup conditions will be relatively close to those obtained in the presently operating large devices. On the basis of the experience gained in JET, TFTR, and other large tokamaks, one could conclude that the plasma formation and inductive current rampup (including impurity control in these substages) are not likely to present serious problems when extended to the large tokamaks of the future.

Noninductive current drive is still too inefficient by at least a factor of ~ 5 to be of interest in the burn phase of NET/FER or the DEMO reactor. Instead, noninductive current drive in the context of a hybrid operation scenario is considered to be useful in assisting the current initiation (to save inductive volt-seconds) and, possibly, for maintaining the current during transformer recharging (while during the burn the current is driven inductively). However, in these noninductive current drive phases, which are necessarily operated at relatively low plasma densities, there is a high risk of plasma contamination.

Then, reaching the steady burn phase implies, of course, mastering the physical and technical problems of heating, containing, and controlling the thermonuclear plasma—but these were not main topics of discussion at this course.

The proceedings of this course will be published in book form by Plenum Press in early 1986.

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