BP8.61:

Design of the IGNITOR Plasma Start-up and Scenarios* G. RAMOGIDA, G. CENACCHI, A. COLETTI, A. CUCCHIARO, ENEA, Italy, F. VILLONE, F. RUBINACCI, CREATE, Italy, B. COPPI, MIT — IGNITOR is a high field, high plasma current compact experiment designed to be first to reach and study ignited plasma conditions. The design is characterized by a high degree of flexibility obtained by mean of a higher number of poloidal coils and a "large" volume available to the plasma relative to the machine overall dimensions. The most advanced operation scenario (11 MA, 13 T) is based on one that involves the optimal filling of the plasma chamber ("extended First Wall configuration"). The double X-point plasma configuration (X- points on the plasma chamber) enables it to reach ignition with a relatively modest amount auxiliary heating and a sufficient magnetic safety factor in the H-regime. This scenario involves a plasma current of 9 MA with the 13 T maximum toroidal field. Other plasma scenarios with reduced performances are based on a 9 T toroidal field and involve plasma currents of 7 or 6 MA, in the extended First Wall or the double X-point configuration, respectively. The plasma start-up phase has been carefully studied and an optimal choice of the poloidal field coils currents has led to obtaining a relatively large area with a nearly null and flat magnetic field, without reducing the available maximum flux swing (up to 36 Wb) from the Poloidal Field coils system.

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Design of the IGNITOR plasma start-up and scenarios*

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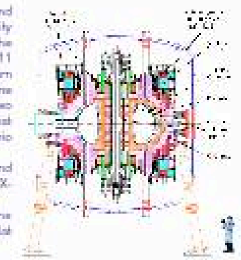
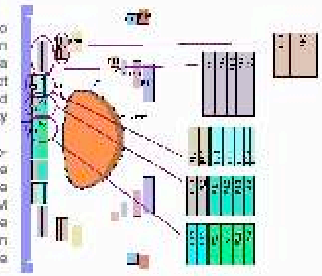
IGNITOR is a high field, high plasma current compact tokamak devoted to reach first and study the burning plasma condition. The design is characterized by a great flexibility obtained by mean of a great number of poloidal coils and a large volume available to the plasma respect to its compact dimensions. The greatest performance plasma scenario (11 MA, 13 T) is based on a limiter configuration that permits the optimal filling of the vacuum vessel but other plasma scenarios have been foreseen to study the burning plasma regime in enhanced confinement modes. The double X-point plasma configuration provide for two field null located just on the vacuum vessel and permit to reach ignition with a modest auxiliary heating and a sufficient safety factor in the H-mode regime. This scenario foresees to reach a plasma current of 9 MA with the 13 T maximum toroidal field.
Other plasma scenarios with reduced performances are based on a 9 T toroidal field and allow reaching a plasma current value of 7 or 6 MA, respectively in limiter or double X-point configuration.
The plasma start-up phase has been carefully studied and an optimal choice of the poloidal field coils currents has allowed obtaining a large area with a nearly null and flat magnetic field, without reducing the great available flux (up to 36 Wb).



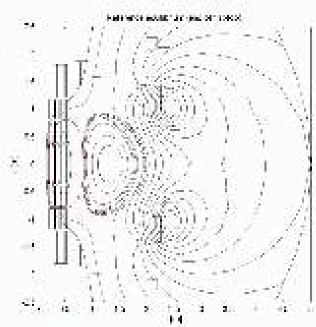
The IGNITOR machine

IGNITOR has been the first experiment proposed and designed to achieve ignition conditions. The machine is characterized by an optimal combination of high magnetic fields (B_T = 13 T) and plasma currents (I_p = 11 MA in the high performance scenario), compact dimensions (R_0 = 1.32 m), tight aspect ratio (A = 2.8) and considerable plasma cross section elongation and triangularity (k=1.83, δ =0.4).
The Poloidal Field Coil (PFC) system of IGNITOR is made of 15 up-down symmetric coil pairs. The central solenoid includes 7 of these pairs (P1 - P8), six pairs of outer coils (P9 – P14) are devoted to the shaping of the plasma and the last two (P15 –P16) constitute the EM active radial press, contributing to the mechanical support of the Toroidal Field Coils. The PFC electrical system provides up-down symmetric currents in all the coils, except for those devoted to the vertical position control (P6+P12).

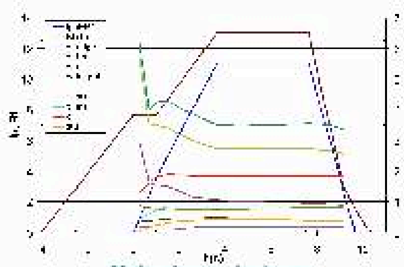


Maximum performance limiter scenario

The IGNITOR maximum performance scenario in the limiter plasma configuration has been adopted as the reference for the design of the machine, setting the features of all the machine systems.
This scenario provides 11 MA plasma current with 13 T toroidal field for a 4s flat-top and has been conceived to effectively achieve the plasma ignition while keeping the safety factor at edge q_ψ well above 3 during the whole plasma evolution, reducing the risk of low-q disruptions and guaranteeing good energy confinement characteristics. To achieve these results the plasma boundaries should match as close as possible the first wall surface during the main part of the scenario.

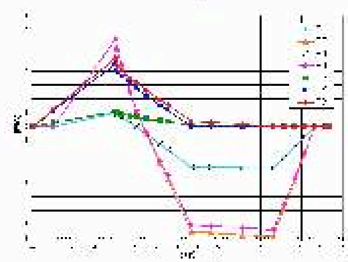


Poloidal flux map and plasma boundary of the equilibrium at the end of flat-top for the IGNITOR maximum performance scenario (I_p = 11 MA, B_T = 13 T, internal inductance l_i = 0.84, β_{pol} = 0.22, R_{axis} = 1.848 m, elongation k = 1.82, triangularity δ = 0.41).

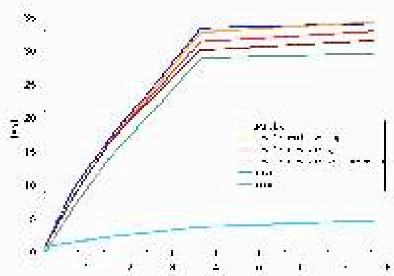


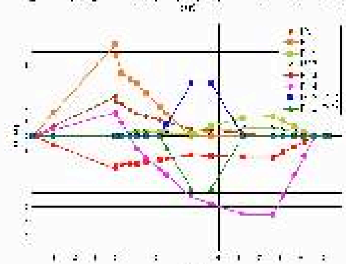
Main plasma features

Maximum performance limiter scenario PFC



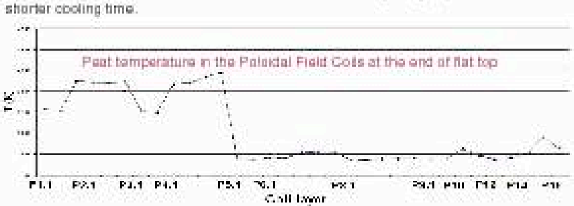
Taking into account the plasma physics requests and the engineering constraints, the Poloidal Field Coil currents waveforms have been optimized, minimizing the current polarity inversion in the shaping coils, putting in series some circuits and smoothing the ramp-up and the ramp down of the currents, in order to reduce the power supply requests. This result has been achieved without degrading the quality of the plasma configuration and without significant reduction of the available poloidal flux, that is maintained enough to balance the plasma flux requirement even without relying on the effect of the bootstrap current.

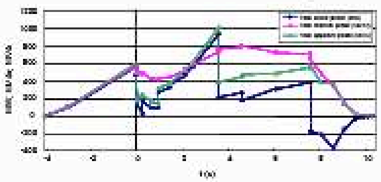


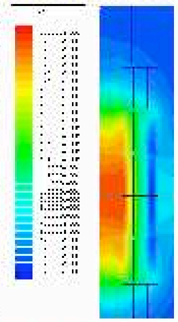


Maximum performance limiter scenario optimization

The IGNITOR scenario is very demanding in terms of current intensities on poloidal and toroidal coils, producing complex mechanical interaction in the load assembly structure and high temperatures in the central solenoid coils: the magnetoresistive effect on the inner coils, due to the high poloidal field, is also relevant in the IGNITOR design. A redistribution of the current density into the coil layers (grading technique) has permitted to homogenize the temperatures inside the central solenoid coils, limiting the peak temperature and stress on them and enabling longer pulse duration and shorter cooling time.

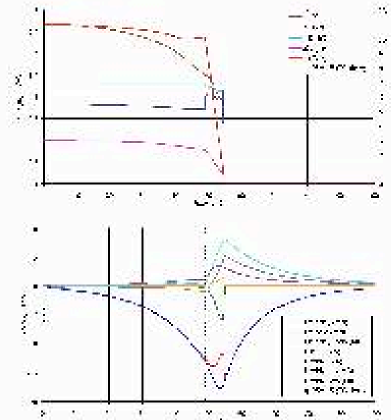






Poloidal magnetic field in the central solenoid region at the end of flat top

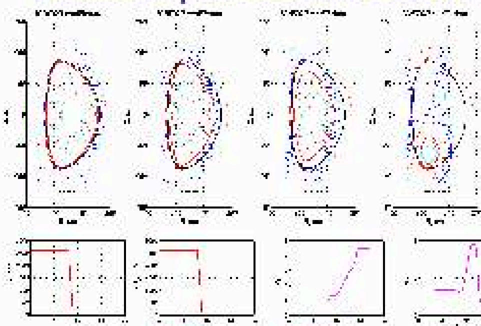
Maximum performance limiter scenario VDE



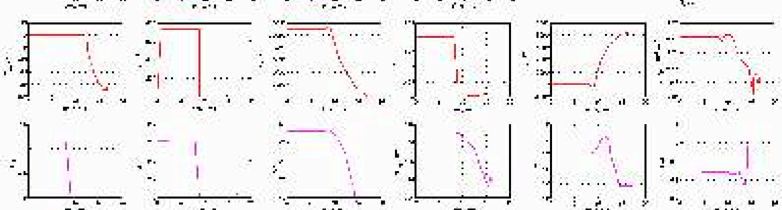
Due to the large thermal and magnetic energy and to the very fast time involved, the plasma disruptions in IGNITOR can expose the mechanical structure to very severe loads and represent one of the main concerns in the engineering of the machine. Cause of the vertical intrinsic instability of the elongated plasmas the most dangerous disruptions occur when a sudden onset of some instability causes a fast change in plasma equilibrium and position that brings the plasma out of the operating range of the active control system.

The most dangerous plasma disruption analysed is a downward Vertical Displacement Event (VDE), modelled by the MAXFEA code simulating a loss of control at the end of flat-top in the maximum performance limiter scenario (Ip=11 MA, Bt=13T). This disruption begins with a slowly decreasing current due to flux conservation consequent to the plasma shrinking during the first phase of the VDE. When the safety factor at the plasma edge goes below 2 a rapid loss of thermal energy occurs, next followed by a fast current decay (a plasma current quench with a linear decay rate of 2 MA/ms has been assumed). This phase is accompanied by some halo currents onset in the vessel structure. The results of this simulation have been used as input data for the electromagnetic and stress analyses, that have shown the correct dimensioning of the vessel and the support structures.

Maximum performance scenario major disruption

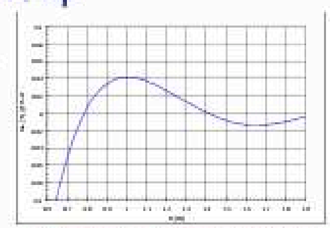


A major disruption, occurring in the maximum performance limiter scenario has been simulated with the DINA code, including the onset of poloidal halo currents in the vessel.

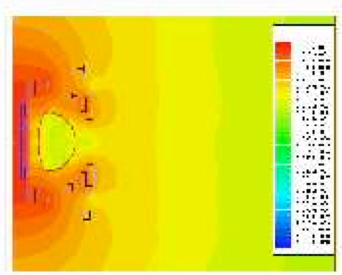


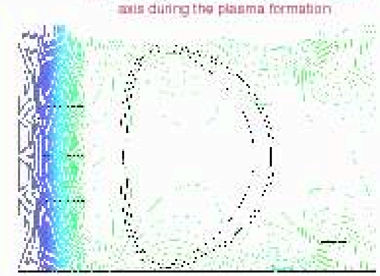
Plasma start-up

The plasma start-up was carefully studied, with the aim of balancing the plasma flux requirement with the engineering constraints. A outer null field point at R=1.412 m has been adopted in the scenari but a inner null field point has been also investigated. About 30 V are available during the 50 ms of the plasma breakdown phase. The compliance with all the structural engineering constraints has been verified with the ANSYS code.



Vertical magnetic field along the equatorial axis during the plasma formation





Extended flat-top limiter scenario

The IGNITOR extended flat-top scenario in the limiter plasma configuration provides the basic configuration for an operation with reduced electrical and cooling requirements. The poloidal flux available permits also operation with an extended plasma flat-top duration, much longer than the currents diffusion time.

This scenario provides 7 MA plasma current with 9 T toroidal field with a plasma flat-top of about 10s. The safety factor at edge q_ψ is kept well above 3 during the whole plasma evolution, reducing the risk of low-q disruptions and guaranteeing good energy confinement characteristics.

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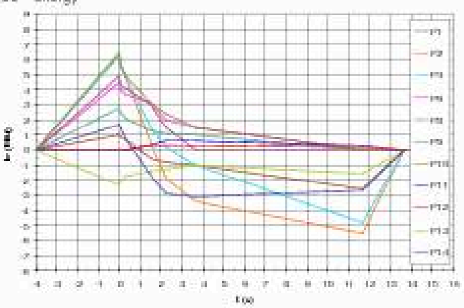
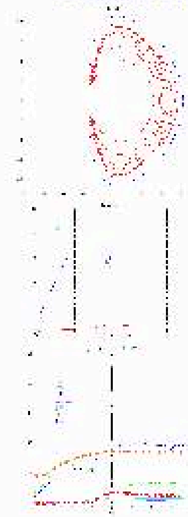
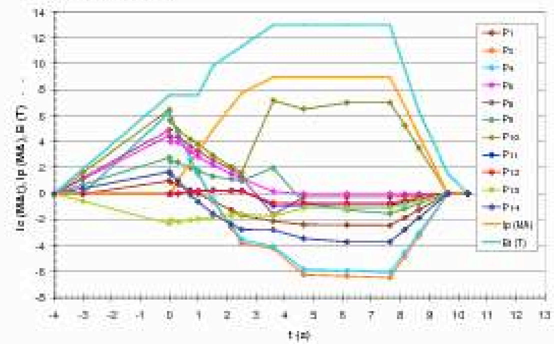


Maximum performance double null scenario



The IGNITOR maximum performance double X-point scenario gives the possibility to access H-mode, with an high current and a safety factor at edge q_ψ above 3. To fulfil these goals the plasma is optimized to fill almost all the vacuum vessel, with two simmetric X-points close to the vessel itself. This simmetric configuration also permits to use, at their maximum performance, the first wall, the load assembly and and the electric systems that have been designed and optimized for the limiter configuration.

This scenario provides 9 MA plasma current with 13 T toroidal field with a plasma flat-top of 4 s.



Sub-ignited double null scenario

The IGNITOR sub-ignited scenario in the double X-point plasma configuration provides the basic configuration for an operation with reduced electrical and cooling requirements in H-mode.

This scenario provides 6 MA plasma current with 9 T toroidal field with a plasma flat-top longer than 4s. The safety factor at edge q_ψ is kept well above 3 during the whole plasma evolution, reducing the risk of low-q disruptions and guaranteeing good energy confinement characteristics.

The plasma is optimized to fill almost all the vacuum vessel, with two simmetric X-points close to the vessel itself. This simmetric configuration also permits to use, at their maximum performance, the first wall, the load assembly and and the electric systems that have been designed and optimized for the limiter configuration.

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