stellarator news

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NCSX awards major fabrication contracts

The National Compact Stellarator Experiment (NCSX) project has officially moved into its fabrication phase by awarding to industry three contracts to build major components. Following a series of successful reviews, which examined the project's readiness for fabrication from technical, cost, schedule, and management standpoints, the U.S. Department of Energy (DOE) approved the start of NCSX fabrication on September 16, 2004. Immediately thereafter, the project awarded contracts for the vacuum vessel (Fig. 1), the modular coil winding forms (Fig. 2), and the modular coil conductor.

Fig. 1. Computer-generated illustration of the NCSX vacuum vessel.

The key technical review in this process was a Final Design Review, held May 19–20, 2004. It was chaired by Carl N. Strawbridge, Deputy Director of the Spallation Neutron Source project at the Oak Ridge National Laboratory (ORNL), who led a committee of ten experienced fusion engineers. The committee said that the designs of the vacuum vessel and the modular coil winding forms satisfied technical requirements and were ready to proceed with procurement and fabrication. It was noted that the project's manufacturing R&D activities were successful in demonstrating feasible manufacturing processes, qualifying suppliers, and reducing fabrication risks for these critical components. Two DOE project reviews, conducted to examine cost, schedule, management, and procurement issues, were also successful.

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Fig. 2. An actual full-scale NCSX prototype winding form, produced by Energy Industries of Ohio, Inc.

The vacuum vessel will be fabricated by Major Tool and Machine, Inc., of Indianapolis, Indiana. The 11-tonne toroidal vessel, which conforms closely to the plasma, resembles a twisted doughnut in shape. It will be made of Inconel 625, an alloy with high strength, high electrical resistivity, and low magnetic permeability, properties important for NCSX performance. It will be manufactured in three identical segments, which will be joined together by Princeton Plasma Physics Laboratory (PPPL) staff during final assembly of the NCSX to form a closed chamber. Each segment will be fabricated from several 1-cm-thick panels, which will be press-formed and then welded together to form the complete segment. The contract also includes fabrication of the 90 ports that will provide plasma heating and diagnostic access on the completed device. Final delivery is scheduled for November 2005. Major Tool, under a previous NCSX contract, developed the manufacturing process that it will use and demonstrated its capability by fabricating a full-scale prototype sector of the vessel that met all requirements.

The modular coil winding forms will be fabricated by Energy Industries of Ohio, Inc. (EIO), of Independence, Ohio. EIO leads a team of companies that will perform the key manufacturing operations: C.A. Lawton Co. of De Pere, Wisconsin, for pattern making; MetalTek International of Pevely, Missouri, for casting; and Major Tool and Machine, Inc., of Indianapolis, Indiana, for machining. The 18 winding forms will consist of nonmagnetic stainless steel castings with the winding surfaces machined to a tolerance of ±0.5 mm. Six each of three different shapes will be fabricated. The forms have heights up to 2.8 m and weigh approximately 3 tonnes. The first will be delivered in May 2005, and the last in September 2006. Previously, the EIO team carried out an R&D program in which team members resolved key issues and developed the manufacturing plan for the winding forms while developing the prototype shown in Fig. 2.

The conductor will be fabricated by New England Wire Technologies, Inc., of Lisbon, New Hampshire. The order consists of 15 km of insulated copper cable, compacted to meet NCSX dimensional specifications and achieve a high copper fraction. The conductor design is supported by R&D results, which resolved issues associated with fabricating the conductor and with controlling its behavior during the coil winding process. The conductor will be wound on the winding forms at PPPL to produce the completed modular coils.

The NCSX mission is to acquire the scientific and technological knowledge needed for understanding the behavior of a compact stellarator plasma, evaluating its attractiveness as a fusion concept, and advancing the state of the art in three-dimensional analysis of fusion plasmas. The compact stellarator is one of several innovative magnetic fusion plasma configurations supported by the U.S. Fusion Energy Sciences program and has the attractive potential of operating continuously and without plasma disruptions. Also, when extrapolated to a fusion power plant, the compact stellarator is projected to require low operating power compared with that produced by the power plant. The project is led by PPPL and ORNL in partnership and will be operated at PPPL as a national facility for fusion and plasma physics research. Further information about NCSX is available on the project's web site (http://ncsx.pppl.gov/).

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Toroidal rotation of protons and impurities in the TJ-II stellarator

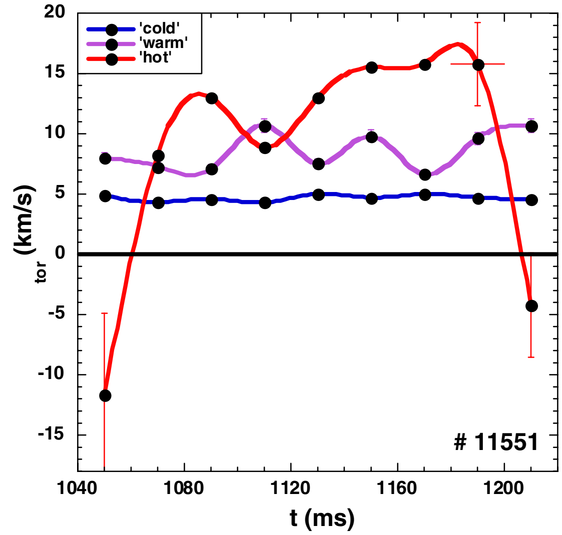
Passive emission spectroscopy has been used to measure the toroidal rotation velocities of protons and impurities in discharges created in the TJ-II stellarator with electron cyclotron resonance heating (ECRH) only and with combined ECRH/unbalanced tangential neutral beam injection (NBI) heating. TJ-II is a helical magnetic axis stellarator located at Asociación EURATOM-CIEMAT in Madrid, Spain.

The impurity toroidal rotation was measured by determining the line shift of selected impurity lines (C V 2270.89 Å, He II 4685.7 Å, C III 2296.871 Å), while proton rotation was deduced from the analysis of H_α emission; in all cases the plasma line emission was monitored through a central plasma chord tangential to the magnetic axis. For these measurements, we used a 1-m spectrometer equipped with an intensified silicon photodiode array (700 active pixels) to record the spectral line shapes with moderate time resolution (~15–30 ms), limited mainly by the photon flux available in these clean boronized discharges. The plasma emission was relayed by means of 1-mm-diam fibers to the spectrometer, which was fitted with a 1200-line/mm grating to provide a reciprocal dispersion of ~7.9 Å/mm, thereby providing a wide spectral range (200–900 nm). Note that for a toroidal line of sight, the chord integration length is limited to a short part of the plasma because of the strong helical rotation of TJ-II.

A novel system was developed to perform absolute real-time wavelength calibration. It consists in a 2-m quartz fiber with two branches, one collecting the plasma emission and the other relaying the emission from a hollow cathode lamp with Ne I, Cd I, and Cd II reference lines. The measurements were made at a toroidal position well away from the neutral beam injector in order to avoid light contamination from its beam.

The analysis method used was based on a three-component Gaussian fitting of the H_α spectral line at 6562.8 Å, corresponding to the different particle populations across the plasma minor radius: a "cold" peripheral component representing boundary hydrogen atoms, a "warm" component due to hydrogen atoms residing in an intermediate zone (~0.4–0.7), and a "hot" component corresponding to hydrogen atoms in the plasma core. In contrast, a one-component Gaussian fitting was sufficient for impurities, as their emission is better localized than that of hydrogen.

The first toroidal rotation results suggest that the protons have a wide range of toroidal velocities that depend on the effective radius. In the following examples, positive and negative values correspond to the co-magnetic and counter-magnetic field directions, respectively.



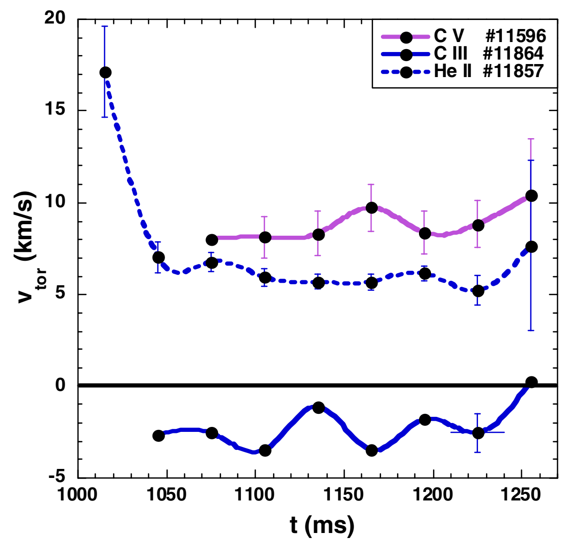
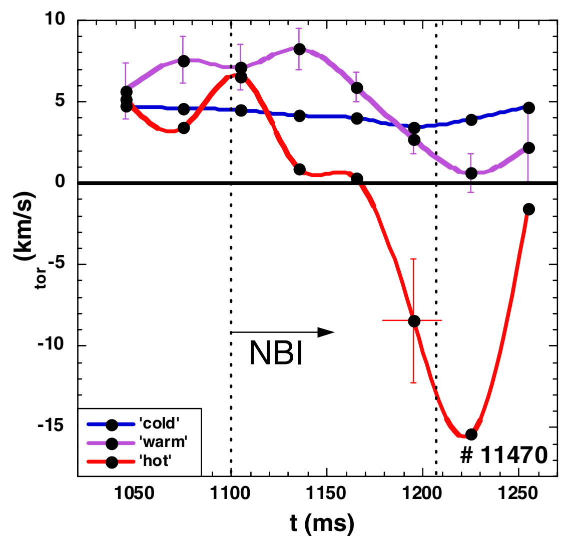


Fig. 1. Temporal evolution of the toroidal rotation velocities of protons (top) and impurities (bottom) for typical ECRH discharges. Positive values indicate the co-magnetic field direction.

In the top portion of Fig. 1, the first results of proton rotation obtained from an ECRH discharge are presented. If the Doppler shift of the line center is interpreted as a pure rotation, the cold component exhibits a rotation of 4.7 km/s in the magnetic field direction. The warm component shows a rotation which is a factor of 2 greater than that of the cold component, whereas the hot component reaches toroidal rotation values of about 14 km/s. Results for three different impurity ions from several similar discharges, with exposure times of 30 ms, are plotted in the bottom of Fig. 1. The toroidal rotation velocity of the C V line, belonging to a plasma zone about ρ = 0.5, is similar to that of the H_α warm component (8 km/s). Another bulk impurity, the He II ion, displays similar behavior along the discharge plateau, where the velocity is typically about 6 km/s (±0.4 km/s) in the co-magnetic field direction. Finally, analysis of the C III ion, which resides near the boundary, revealed that this impurity rotates in the counter-magnetic field direction with velocities of between –3 and –5 km/s.



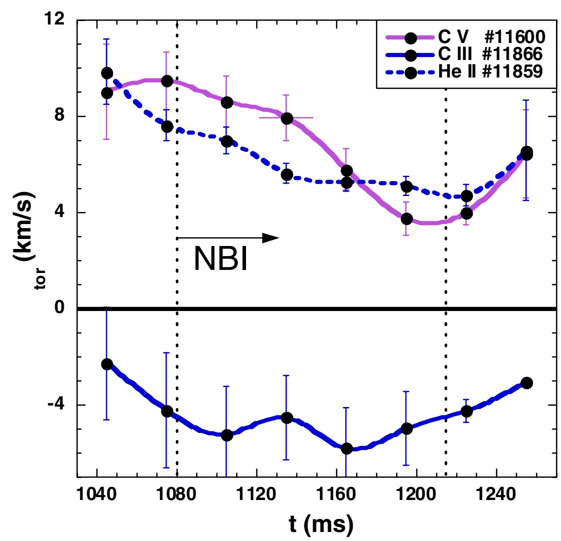


Fig. 2. Temporal evolution of the toroidal rotation velocities of protons (top) and impurities (bottom) along a plasma created by ECRH and sustained (between the vertical broken lines) by both ECRH and NBI. Positive values indicate the co-magnetic field direction.

The top portion of Fig. 2 shows the typical toroidal rotation behavior of the main plasma ions during NBI, which takes place between the dashed vertical lines. At the start of the discharge the rotation values are typical of ECRH conditions, but once NBI begins, the toroidal velocities of the warm and hot H_α components are reduced. This is more dramatic for the hot component and is probably associated with the increased line-averaged electron density and with the peaking of the electron density profile (which is normally flat or hollow for ECRH). Also, the maximum diminution of toroidal rotation depends strongly on the final electronic density; i.e., the higher the density, the lower the final rotation. Moreover, the hot component in the plasma center changes its direction to the counter-magnetic field direction. In contrast, no significant changes are observed at the plasma boundary, where the rotation velocity of the cold component remains similar to that during ECRH.

A similar qualitative dependence is observed for bulk impurities, as shown in the bottom portion of Fig. 2. The C V rotation values are in good agreement with those of the warm proton component, although the latter fall to values closer to zero than the former (in these cases the discharges were not quite identical). The trend of He II is similar to, but not the same as, that of C V. This is because the He II is not localized at the same radius as C V. The most external impurity, C III, is unaffected by NBI, and its behavior is typical of ECRH.

Preliminary estimates suggest that the radial electric field contribution along with bootstrap current could account, at least qualitatively, for the toroidal rotation behavior and direction.

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Extended abstracts

Physics of the geometry-related detachment stability in W7-AS

To appear in *Nuclear Fusion* in December 2004

Island-divertor experiments in the last operational period of the Wendelstein 7-AS (W7-AS) stellarator showed that a stable detachment requires sufficiently large islands and field-line pitch [1], which correspond to a sufficiently large plasma-to-target distance Δx and a sufficiently small connection length L_c respectively. In order to understand the underlying physics, a detailed transport analysis has been performed with the three-dimensional (3D) edge transport code EMC3-EIRENE [2, 3]. It shows that under detachment conditions the radiation distribution in the island scrape-off layer is highly sensitive to the island geometry. At detachment transition, the radiation layer leaves the divertor plates shifting towards the *X*-points located just in front of the targets, independent of the configuration geometry. However, with increasing plasma density at the separatrix, n_{es}, the radiation distribution bifurcates, forming one of two distinct patterns depending on the geometry (Fig. 1). For stable configurations, as found experimentally for larger Δx and smaller L_c, the radiation zone gradually shifts poloidally away from the divertor region towards the *X*-points located at the inboard side of the torus. When n_{es} is increased further, the radiation zone spreads poloidally around the *X*-points to form an extended radiation belt at the high-field side. A concomitant slow radial inward shift leads finally to a penetration of the radiation belt into the confinement region, which defines the density limit for stable detachment. In contrast, for unstable configurations (smaller Δx or larger L_c), an intensive and strongly localized radiation is established in the divertor region.

The density range in which a detached radiation layer stays outside the last closed magnetic surface is much smaller than that for the inboard-side radiation case. However, during the penetration phase into the core, the radiation zone shifts to the inboard side and also forms a radiation pattern that is almost identical to that of the stable-detachment case. The appearance of an intense radiation zone at the inboard side of closed flux surfaces has been observed experimentally in deeply detached plasmas [4, 5]. The physics leading to the experimentally observed unstable detachment state is governed by an instability driven by the recycling neutrals penetrating into the core [6]. This is demonstrated by a linear stability analysis using the 3D simulation results. The growth rate of the instability is directly related to the neutral screening efficiency, which, in the divertor radiation case, is too low to limit the growth of the recycling flux entering the core. Decreasing the edge density has a stabilizing effect. These results are in good agreement with the experiments.

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[4] H. Thomsen et al., Nucl. Fusion **44**, 820 (2004).

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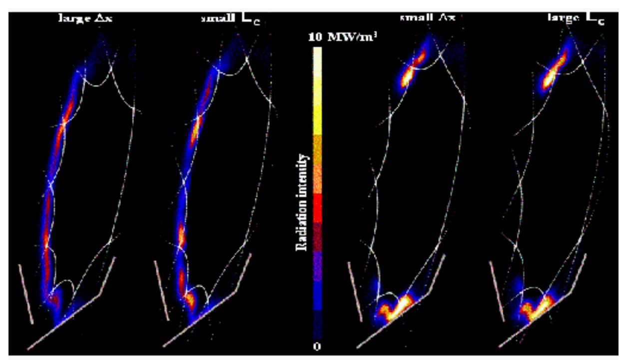

Fig. 1. Two typical radiation patterns identified by the code. Left: Inboard-side radiation for large Δx and small L_c. Right: Divertor radiation for small Δx or large L_c.

Characterization of the island divertor plasma of W7-AS in the deeply detached state with volume recombination

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Divertor detached plasmas have been studied extensively, both experimentally and by modeling, in tokamak configurations. For helical configurations, Wendelstein 7-AS (W7-AS) with island divertors presents the first opportunity to study those detached regimes.

When the line-averaged density exceeds a critical value in the high-density H-mode, the plasma detaches from the island divertor of W7-AS. The critical value of line-averaged density increased with heating power. The observed detachment is partial (i.e., the plasma remains attached at some locations, while it is detached completely from the majority of tiles) and is found to be quasi-stationary for many confinement times. Up to 90% of the absorbed power is radiated, with the radiation being edge-localized and asymmetrically distributed poloidally. The spectroscopic characteristics of this deeply detached plasma have been reported in this recently published paper, which also includes strong evidence for volume recombination. The visible hydrogenic radiation from the downstream plasma is dominated by Balmer series spectral lines up to $n = 12$. Detailed analysis of these Balmer spectra indicates very high densities and low temperatures in the region close to divertor tiles. Figure1 is an artist's sketch of this detached state. The analysis once again underlines the importance of three-dimensional modeling. An initial comparison is made with latest results from EMC3-EIRENE modeling.

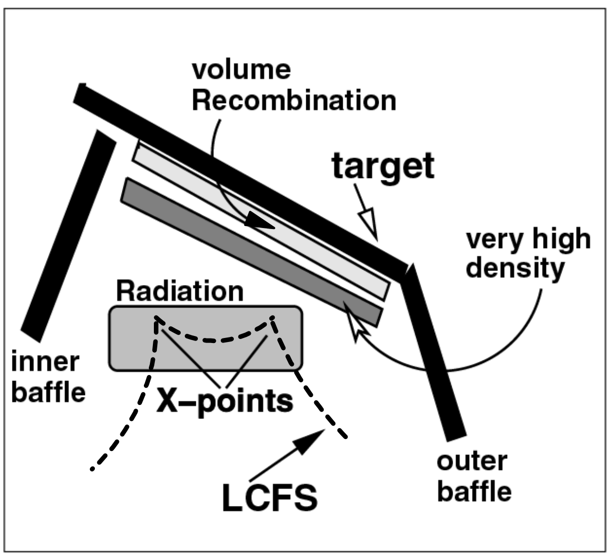

Fig. 1. Rendering of the scrape-off layer region with the plasma in the quasi-stationary, deeply detached state.

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Meetings

The plenary and oral presentations from the 16th ANS Topical Meeting on the Technology of Fusion Energy, held September 14–16 in Madison, Wisconsin, have been posted at

http://fti.neep.wisc.edu/tofeorals

"W7-X Progress"
M. Gasparotto, V. Erckmann, W. Gardebrecht, Th. Rummel, F. Schauer, M. Wanner, L. Wegener, and the W7-X team
http://fti.neep.wisc.edu/tofeprogram/oral/O-I-1.2.pdf

"Recent Progress in the Design, R&D, and Fabrication of NCSX"
NCSX Team
http://fti.neep.wisc.edu/tofeprogram/oral/O-I-1.5.pdf

"Helical Fusion Power Plant Economic Studies"
T. J. Dolan, K. Yamazaki, and A. Sagara, NIFS
http://fti.neep.wisc.edu/tofeprogram/oral/O-I-4.6.pdf

"Exploration of Compact Stellarators as Power Plants: Initial Results from ARIES-CS Study"
Farrokh Najmabadi and the ARIES Team
http://fti.neep.wisc.edu/tofeprogram/oral/O-II-1.1.pdf

"Reactors With Stellarator Stability And Tokamak Transport"
P. R. Garabedian, L.-P. Ku and the ARIES Team
http://fti.neep.wisc.edu/tofeprogram/oral/O-II-1.2.pdf

"Optimization of Stellarator Reactor Parameters"
J. F. Lyon, Oak Ridge National Laboratory
http://fti.neep.wisc.edu/tofeprogram/oral/O-II-1.3.pdf

"Attractive Design Approaches For a Compact Stellarator Power Plant"
A. R. Raffray, L. El-Guebaly, S.Malang, X. Wang, and the ARIES Team
http://fti.neep.wisc.edu/tofeprogram/oral/O-II-1.4.pdf

"Benefits of Radial Build Minimization and Requirements Imposed on ARIES Compact Stellarator Design"
Laila El-Guebaly, R. Raffray, S. Malang, J. Lyon, L. P. Ku, and the ARIES Team
http://fti.neep.wisc.edu/tofeprogram/oral/O-II-1.5.pdf

"New Superconductors for Fusion Magnets"
David Larbalestier and Peter Lee
http://fti.neep.wisc.edu/tofeprogram/oral/O-III-1.4.pdf

"Ceramic Breeder Blanket for ARIES-CS"
A. R. Raffray, S. Malang, L. El-Guebaly, X. Wang, and the ARIES Team
http://fti.neep.wisc.edu/tofeprogram/oral/O-II-5.6.pdf