# stellarator news

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## Around the Labs

## Transitions in highly charged ions

In *Stellarator News*, No. 18 (Nov. 1991), Kondo published an article on "the relative calibration of a vacuum ultraviolet spectrometer" that contained information about lines of highly charged titanium ions. At IPP, in collaboration with B. Fricke and G. Blanke from Gesamthochschule Kassel, a full data set of energy levels for all charge states and the elements from Z = 1 to 82 was generated. The basis was the relativistic Hartree-Fock program developed by Desclaux, which was slightly changed by the Kassel group. The full date set includes more than 50,000 energy levels.

This short contribution presents a comparison between the experimental data of Kondo and the calculated results. Table 1 gives the calculated energy levels for Ti XIV, Ti XV, and Ti XVI. Table 2 gives the possible transitions for the different charge states, the corresponding wavelengths, and the differences in the wavelengths and energies of the experimental and calculated data. The difference in wavelength is less than 0.31 nm in all cases. The difference in energy is of the order of 1 eV, which corresponds to an accuracy of $10^{-5}$ in the calculated energy levels.

The best agreement of $10^{-6}$ is obtained for nitrogen-like Ti XVI ions; the largest deviations of $10^{-5}$ occur for transitions of Ti XIV. Not all calculated transitions of Ti XVI are available experimentally. It should be emphasized that the deviations between calculated and experimental values are about the same in the transitions

**Table 1: Energy Levels**

| Ion species | Level | J | Energy (eV) |
|---|---|---|---|
| Ti XIV | $1s^2 2s^2 2p^5$ | 1/2 | 20833.259 |
| | $1s^2 2s\ 2p^6$ | 1/2 | 20735.165 |
| Ti XV | $1s^2 2s^2 2p^4$ | 0 | 19971.604 |
| | $1s^2 2s^2 2p^4$ | 1 | 19972.219 |
| | $1s^2 2s^2 2p^4$ | 2 | 19977.069 |
| | $1s^2 2s\ 2p^5$ | 0 | 19881.587 |
| | $1s^2 2s\ 2p^5$ | 1 | 19883.937 |
| | $1s^2 2s\ 2p^5$ | 2 | 19887.742 |
| Ti XVI | $1s^2 2s^2 2p^3$ | 1/2 | 19007.428 |
| | $1s^2 2s^2 2p^3$ | 3/2 | 19034.948 |
| | $1s^2 2s^2 2p^3$ | 5/2 | 19018.330 |
| | $1s^2 2s\ 2p^4$ | 1/2 | 18962.070 |
| | $1s^2 2s\ 2p^4$ | 3/2 | 18958.185 |
| | $1s^2 2s\ 2p^4$ | 5/2 | 18956.540 |

for a given titanium ion. Therefore, the calculated data set provides useful guidance to the identification of unknown transitions in highly charged ions. Thanks are due to V. Dose for initiating this investigation.

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**Table 2: Transitions**

| Transition | $J \rightarrow J'$ | $\Delta J$ | E (eV) calc. | $\lambda$ (nm) calc. | $\lambda$ (nm) exp. | $\Delta\lambda$ (nm) | $\Delta E$ (eV) |
|---|---|---|---|---|---|---|---|
| **Ti XIV** | | | | | | | |
| $2s\,2p^6 \rightarrow 2s^2\,2p^5$ | $1/2 \rightarrow 1/2$ | 0 | 98.094 | 12.6393 | 12.9440 | 0.3047 | 2.309 |
| $2s\,2p^6 \rightarrow 2s^2\,2p^5$ | $1/2 \rightarrow 3/2$ | 0 | 03.936 | 11.9289 | 12.1986 | 0.2697 | 2.298 |
| **Ti XV** | | | | | | | |
| $2s\,2p^5 \rightarrow 2s^2\,2p^4$ | $1 \rightarrow 0$ | 1 | 87.667 | 14.1426 | 14.2750 | 0.1324 | 0.813 |
| $2s\,2p^5 \rightarrow 2s^2\,2p^4$ | $1 \rightarrow 1$ | 0 | 88.282 | 14.0441 | 14.2130 | 0.1689 | 1.049 |
| $2s\,2p^5 \rightarrow 2s^2\,2p^4$ | $0 \rightarrow 1$ | 1 | 90.632 | 13.6800 | 13.8357 | 0.1557 | 1.020 |
| $2s\,2p^5 \rightarrow 2s^2\,2p^4$ | $2 \rightarrow 1$ | 1 | 84.477 | 14.6767 | 14.8588 | 0.1821 | 1.035 |
| $2s\,2p^5 \rightarrow 2s^2\,2p^4$ | $1 \rightarrow 2$ | 1 | 93.132 | 13.3127 | 13.4609 | 0.1482 | 1.025 |
| $2s\,2p^5 \rightarrow 2s^2\,2p^4$ | $2 \rightarrow 2$ | 0 | 89.387 | 13.8739 | 14.0395 | 0.1656 | 1.076 |
| $2s\,2p^5 \rightarrow 2s^2\,2p^4$ | $0 \rightarrow 0$ | 0 | 90.017 | 13.7734 | | | |
| **Ti XVI** | | | | | | | |
| $2s\,2p^4 \rightarrow 2s^2\,2p^3$ | $1/2 \rightarrow 1/2$ | 0 | 45.358 | 27.3346 | | | |
| $2s\,2p^4 \rightarrow 2s^2\,2p^3$ | $3/2 \rightarrow 1/2$ | 1 | 49.243 | 25.1780 | | | |
| $2s\,2p^4 \rightarrow 2s^2\,2p^3$ | $3/2 \rightarrow 3/2$ | 0 | 76.763 | 16.1516 | 16.1168 | 0.0348 | 0.166 |
| $2s\,2p^4 \rightarrow 2s^2\,2p^3$ | $3/2 \rightarrow 5/2$ | 1 | 60.145 | 20.6142 | | | |
| $2s\,2p^4 \rightarrow 2s^2\,2p^3$ | $5/2 \rightarrow 3/2$ | 0 | 78.408 | 15.8127 | 15.7812 | –0.0315 | –0.156 |
| $2s\,2p^4 \rightarrow 2s^2\,2p^3$ | $5/2 \rightarrow 5/2$ | 0 | 61.790 | 20.0654 | | | |
| $2s\,2p^4 \rightarrow 2s^2\,2p^3$ | $1/2 \rightarrow 3/2$ | 0 | 72.878 | 17.0126 | 16.9740 | –0.0386 | –0.166 |

# High-Performance 140-GHz Gyrotron from IAP Nishny Novgorod successfully tested at IPP Garching

First plasma experiments with 140-GHz ECRH were performed at W7-AS in early 1991 with a prototype 100-kW gyrotron from KfK Karlsrühe. The comparatively low microwave power restricted the experiments to basic physics investigations on wave absorption as well as sophisticated heat wave propagation scenarios. Results were briefly reported in the November 1991 issue of the *Stellarator News*.

As part of a collaboration between IPP Garching and IAP Nishny Novgorod (Russia), a recently developed high-power 140-GHz gyrotron with 0.5 MW, 0.5-s pulse length (alternatively, 0.9 MW, 0.3 s) was delivered to IPP together with a superconducting magnet in autumn 1991. The limitations on the pulse duration are due to the microwave output window design. This gyrotron replaced the KfK gyrotron. The assembly and testing at IPP were supervised by Russian scientists.

This representative of the new generation of gyrotrons provides a number of attractive features: A built-in quasioptical mode converter generates a linearly polarized Gaussian output beam, which can be fed directly to the transmission line. This improvement makes obsolete large and complicated external mode converters, which are necessary for conventional gyrotrons with coaxial mode output. Furthermore, no control anode is implemented in this gyrotron, which allows for a substantial simplification of the high-voltage power supply.

Two major questions to be addressed in the test operation at IPP Garching were thet output power control that can be achieved without a control anode and the reliability of such a system. The robust construction of the tube allowed for full-performance operation (0.5 MW, 0.5 s) within a few days; reliable operation at a duty cycle of 0.002 (typical W7-AS requirement for normal machine operation) was achieved. The output power control is provided by the beam voltage. A power swing from 150 to 550 kW was measured by changing the beam voltage from 60 to 70 kV. Power modulation with frequencies of up to 200 Hz is possible. These results confirm the easy power handling of the tube without a control anode. The frequency limit comes from the existing power supply and can easily be increased. No mode change was observed in this range. Tests of the existing transmission line towards the design limits of 1 MW are possible with the new gyrotron and are presently under way. Involved in the collaboration are the Kurchatov Institute in Moscow, the Russian manufacturer of the tubes, SALUT, the IPF Stuttgart, and the KfK Karlsrühe. Plasma experiments are planned within the present experimental campaign and will address the physics of high-density plasmas with strong electron-ion coupling, as well as the physics of combined ECRH and neutral beam injection.

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# Diagnostics Improvements for Transport Study in CHS

## A scanning mirror VUV spectrometer

A normal-incidence VUV spectrometer was rearranged to measure spatial profiles of various impurity line emissions by the use of a rotating mirror placed far above one of the top ports of the CHS device. The rotating mirror consists of eight individual mirrors made of platinum-coated glass on a octagonal rotor. The rotation frequency can be varied from 0 to 3000 rpm, and the radial emission profile can be measured every 2.5 ms at the highest speed. In routine operations, line emission profiles are obtained every 10 ms. A timing marker can give the absolute position of the vertical observation chord with a resolution better than 5 mm. In order to eliminate spurious signals from wall reflection, the surface of the wall facing the observation chord was covered by cylinders coated with a special black dye except for a region on the inner wall of the vacuum chamber that may be contacted by the plasma.

By observing line emissions localized near the plasma edge, we can accurately determine the plasma boundary. In addition, by observing line emissions with enough intensity in the central region of the plasma, we can determine the magnetic axis location. For example, the finite beta effects on the magnetic axis shift and on the plasma boundary shift can be monitored every 10 ms during a complete NBI discharge.

Figure 1 shows a sample of line emission profiles for H I (Lyman $\alpha$) and Ti XII in a discharge with NBI and a tungsten limiter. Because of the availability of this fast scanning capability, particle transport study using transient phenomena, especially for impurities, is in pro-

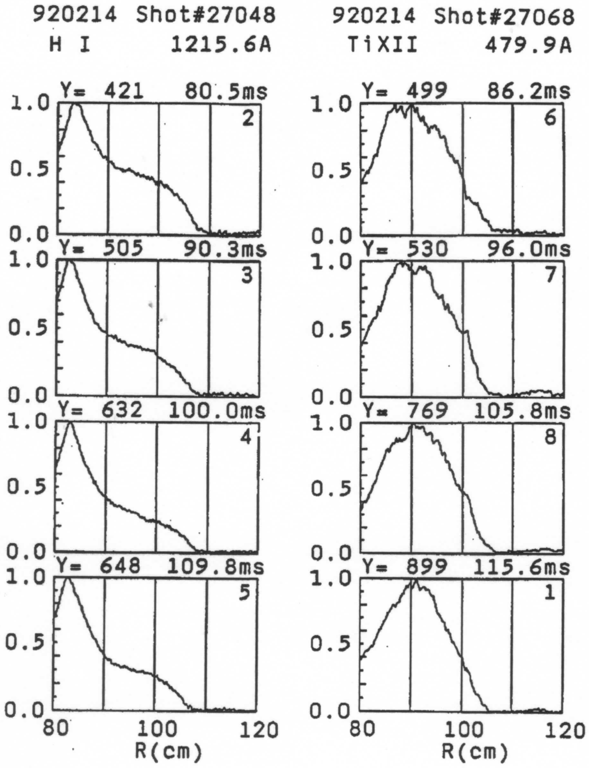

**Fig. 1.** Radial emission profiles for H I (Lyman $\alpha$; left) and Ti XII for NBI discharge with a tungsten limiter. The profiles are taken every 10 ms.

gress. Impurity accumulation, density peaking, and a transient increase in plasma stored energy associated with a reduction of edge neutrals have been observed in the reheat phase of high-density NBI plasmas. Similarity to the tokamak IOC mode is under discussion. Improvement of the understanding of radiative collapse is also expected.

## Laser-induced fluorescence for neutral hydrogen measurements

In order to study particle transport, an understanding of the behavoir of neutral hydrogen is essential. Because of the low aspect ratio of CHS, the last closed flux surface is very close to, or touches, the inner wall of the torus, depending on the magnetic configuration.

Experimentally, good confinement has been obtained with an inward-shifted magnetic axis where the plasma is wall-limited. In this case, strong recycling of the neutral hydrogen occurs at this inner wall area, at eight locations around the torus. So far, we have prepared many observation chords for $H_\alpha$ emission measurements. A toroidal detector array is arranged to monitor toroidal symmetry at eight toroidal positions corresponding to the toroidal pitch number. Two poloidal detector arrays have been used to measure poloidal emission profiles. One observes vertically ( 34-channel TV CXRS for ion temperature profile measurement is used by tuning the wavelength to the $H_\beta$ line) where the plasma is touching the inner wall in the case of wall-limited configurations. The other observes horizontally (16 channels) from the inside port of the torus where the plasma has a horizontally elongated cross section and is detached from the wall in any configuration. In addition to these observations, two new techniques have been applied. One is a calibrated TV camera with an $H_\alpha$ optical filter, which was used to see the toroidal and poloidal expansion of the recycling area near the inner wall. The other is a laser-induced fluorescence (LIF) method to measure the neutral hydrogen profile in the core plasma. The laser was tuned to $H_\alpha$ and injected horizontally from the outer port along two chords at the meridian plane and at one chord shifted 10 cm down, and three observation volumes for each chord were chosen so that neutral penetration could be accurately evaluated. These results were compared with the neutral simulation code DEGAS. Analysis of these data for understanding particle transport is under way. These experiments are carried out in collaboration with Kyushu University.

## A fast lithium neutral beam probe

The role of edge confinement is considered to be important for global confinement in a toroidal plasma. In order to study it, a fast lithium neutral beam probe has been prepared to measure the edge density profile. This probe is complementary to a thermal lithium beam probe already installed for edge fluctuation studies. A neutral lithium beam with an energy 8 kV and a beam current of several tens of microamperes is injected into the plasma from the outside port where the plasma is horizontally elongated. The beam diameter is typically 20 mm (FWHM).

Visible light emission from the lithium atoms (6708 Å) by electron-impact collision is collected by a camera lens and led into a photomultiplier tube through an optical interference filter. The radial resolution is 10 mm in the present optics arrangement. Because of the rather wide bandwidth of the optical filter (15 Å), the desired amount of background light cannot be eliminated, so a phase-sensitive detection technique is used. Time resolution is typically 3 ms at present.

Two methods for the determination of local electron density are used to cover the density range from $10^{11}$ to $10^{13}$ $cm^{-3}$. For the low-density region where the beam attenuation is negligible, a gas scattering method is used in

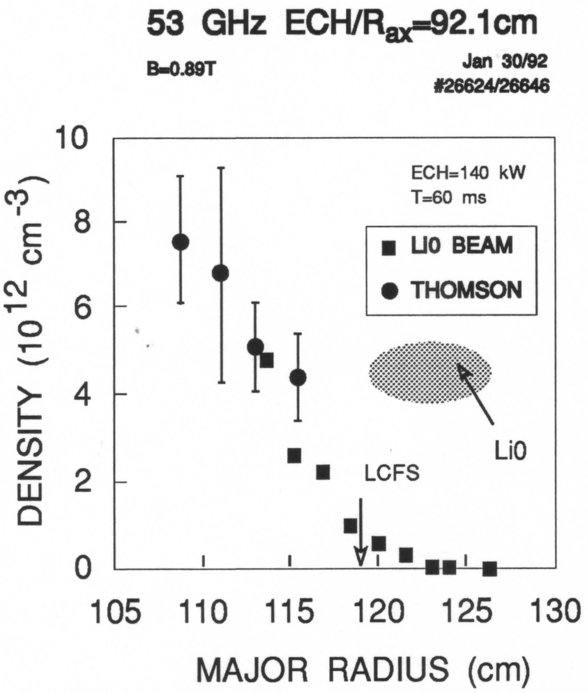

**Fig. 2.** Typical edge density profile for ECH plasma. Thomson scattering data are also shown for comparison, indicating good agreement.

which the CHS vacuum chamber is filled with helium gas at constant pressure, and a lithium beam with the same parameters used in the plasma experiment is injected. By comparing the visible light emission intensities from the plasma and from this helium gas, the electron density is derived using the excitation cross sections for the two atomic processes. For the higher density region where the beam is strongly attenuated, a density reconstruction method is used in which various atomic processes for the beam attenuation are taken into account. This beam probe system, although it only has a single channel at the moment, has been successfully applied to various modes of operation from low-density ECH plasmas to high-density NBI plasmas. A typical edge density profile is shown in Fig. 2 which also shows Thomson scattering data at the same flux surfaces, taken 67.5 degrees (toroidally) away from the lithium probe.

The results from the latter two new diagnostics will be reported at the 10th International Conference on Plasma-Surface Interactions in Controlled Fusion Devices at Monterey, CA, USA.

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