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GENERAL ATOMICS

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ABSTRACT

The gyrotron complex on the DIII-D tokamak now comprises six 110 GHz gyrotrons with injected power greater than 3 MW. The system is in regular use at DIII-D for a wide variety of plasma physics experiments. Several additional experiments related to gyrotron technology and photovoltaic conversion have been undertaken.

The gyrotron complex on the DIII-D tokamak [1] now comprises six 110 GHz gyrotrons. Five of these tubes have demonstrated 1 MW pulses 5 s in length and one, probably limited by a problem at the cathode, has generated 750 kW for 5 s pulses. Initial factory testing demonstrated about 600 kW at 10 s pulse length for all 5 of the high performing tubes. Typical peak injected rf power during DIII-D physics experiments has been 3.25 MW with 6 gyrotrons, 5 of which were generating 4 s pulses and one, which had not completed conditioning, 2 s pulses. The rf beams can be directed anywhere in the tokamak upper half plane with full control of the toroidal injection angle for co- and counter-current drive and of the elliptical polarization at the injection point. The maximum injected rf energy for a single tokamak pulse has been 12.1 MJ.

The system is extremely versatile, as indicated by the transport experiment summarized in Fig 1. All six gyrotrons were modulated with two groups of three while having their power deposited at two slightly different locations in the plasma. The modulation phase difference between the two groups was exactly 180°, but the total injected power was carefully adjusted to remain constant. This periodically rocked the gradient of $T_e(r)$ as shown in the figure, permitting a study of only the effects of changing the gradient with no other complicating factors. This experiment took advantage of the accurate control of the power deposition, the small region of absorption yielding high power densities $\sim 3\ \mathrm{kW/cm^3}$, the precise control of the output power of each gyrotron and the ability to modulate the tubes independently.

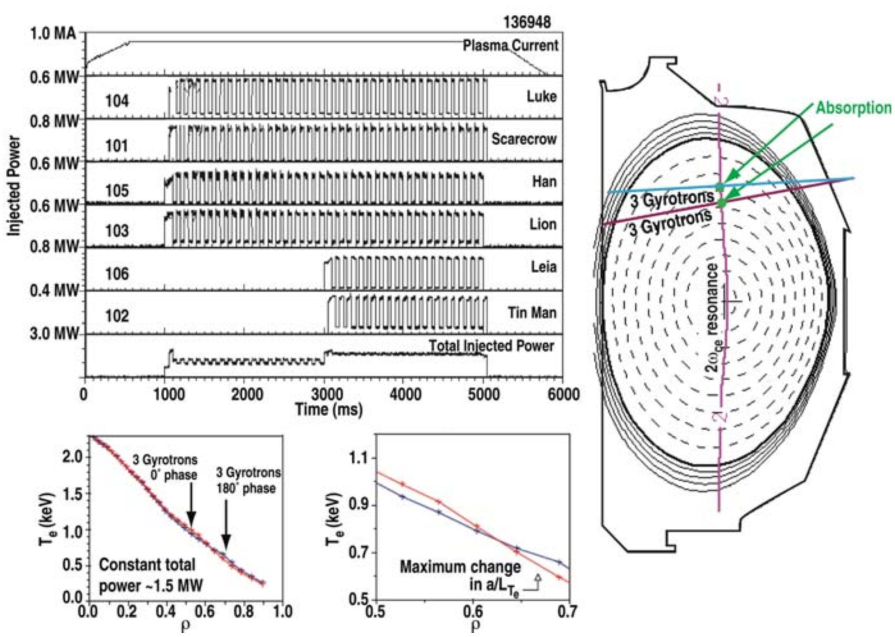

Fig. 1. Modulated rf power deposited out of phase at two nearby locations permitted a detailed transport experiment to be performed with simplified analysis. Modulation was at 20 Hz and the two groups of gyrotrons were modulated out of phase but with equal injected power for the two groups. The temperature gradient was rocked about the point between the two absorption locations.

Other recent ECH/ECCD experiments on DIII-D for which the system is indispensable have included suppression of neoclassical tearing modes, edge localized mode control, creation of H-mode plasmas without momentum or particle injection, collisionality studies, and breakdown for plasma startup and ECH assisted plasma startup without using the tokamak central solenoid. The system is routinely available as a tool to achieve desired $j(r)$ profiles, for plasma heating to delay flux penetration and to provide a means of finding a trajectory leading to steady state plasma operation.

A number of experiments using the gyrotrons, but unrelated to fusion research have been performed. For example, the system has been used to flash anneal amorphous silicon leading to efficient formation of crystalline silicon in an effort to increase the photovoltaic conversion efficiency at low cost [2]. This resulted in excellent crystals, Fig. 2, which may serve as nucleation sites for mass production.

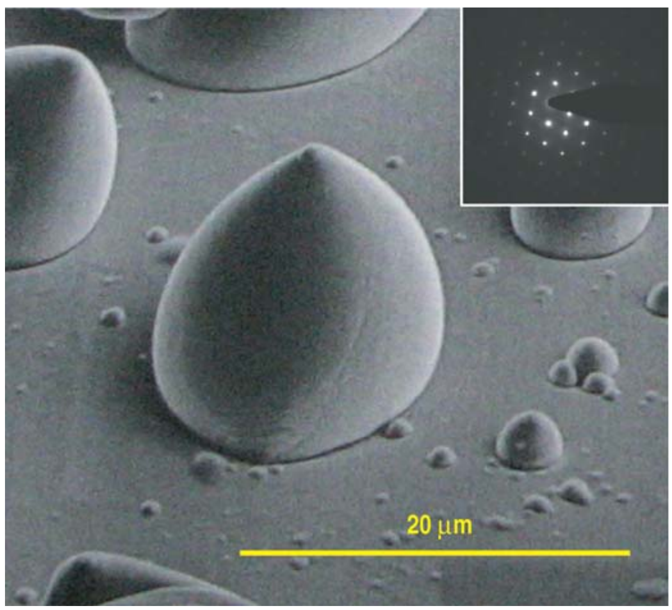

Fig. 2. Flash annealing of amorphous silicon by 110 GHz rf power resulted in excellent silicon crystals to improve photovoltaic conversion efficiency at low cost. The inset is the spatial scattering distribution from transmission electron microscopy showing the single quality of the crystalline solids produced with msec pulses at 110 GHz.

In studies of gyrotron technology, spectroscopic measurements are being performed on the light emitted through the diamond gyrotron output window to attempt to identify the source of gas evolved during the conditioning process. During conditioning in preparation for operations, low frequency parasitic emission has been observed on several tubes. One gyrotron has exhibited two different types of low frequency parasitic oscillation, one associated with reflected electrons between the gun and the cavity and the other apparently connected with electron trajectories in the collector. These have different characteristic frequencies below 100 MHz and different dependence on the gyrotron operating parameters and are being investigated further.

Transmission line efficiency is important for high power gyrotron installations, particularly as steady state operation becomes necessary for the next generation of long pulse confinement devices. The DIII-D beam transport system has measured efficiency of ~ 75% for 90-100 m transmission line length [3], with about -1 dB loss occurring in the first several meters of the lines, apparently due to mode conversion at the injection point. A series of experiments is being performed to understand the mode conversion, which is believed to be due to small angular misalignments, much less than 1°, of the rf beam at the input to the waveguide system. Alignment is performed by analyzing the free space propagation of the rf beam exiting the gyrotron, placing the beam axis on the optical axis of the transmission line and then slightly adjusting the alignment by tilting the focusing mirror in the Matching Optics Unit (MOU). Losses for the $HE_{1,1}$ mode due to mode conversion at miter bends are well understood theoretically but the additional -1 dB loss, probably due to these small misalignments, remains to be reduced.

Tetrode modulators are used for all the gyrotron systems at DIII-D. The tetrodes are configured so that two groups of two gyrotrons are operated in parallel from one tetrode and the remaining two gyrotrons are each connected to individual tetrodes. The nonlinear loads presented by the gyrotrons have sometimes resulted in voltage control instabilities in the pairs operated from one modulator. This has been mitigated by reducing the tetrode gain. The output power of the gyrotrons can be square wave modulated at up to about 5 kHz either with pre-programmed waveforms or using real time feedback on plasma parameters derived from diagnostics with command signals routed to the gyrotrons by the DIII-D plasma control system. The system reliability has increased to about 90% defined by meeting the requested performance of individual gyrotrons during tokamak pulses.

Future plans for the system include: increasing the number of gyrotrons from six to eight, with new power supplies, transmission lines and launchers for the additional tubes; increasing the accuracy and speed of the remote control aiming capability; installation of real time control of the injection geometry using the DIII-D plasma control system; development of a real time calibrated injected power determination for DIII-D; and installation of a k-spectrometer to measure the mode purity in the waveguide lines leading to an improved technique for alignment of the rf power at the waeguide injection point.

REFERENCES

[1] John Lohr, *et al*., Fusion Sci. Tech. **48**, 1226 (2005).

[2] F. Liu, *et al*., Adv. Mater, DOI 10.1002/adma.200900157 (March 2009).

[3] M. Cengher, *et al*., Proc. 15th Joint Workshop on ECE and ECRH, J. Lohr, ed., World Scientific, Singapore (2009).

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