Proceedings of the Korean Nuclear Spring Meeting
Gyeong ju, Korea, May 2003

Construction of a Resonant Loop with the ICRF Antenna for KSTAR

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Abstract

The antenna of the KSTAR ICRF heating system consists of four current straps, each of which is grounded at the center, and has two coaxial ports, one at each end. The top and bottom ports of each strap are fed by one transmitter. The two ports are connected at tee connector to form a resonant loop, and the coaxial feed line from the transmitter is connected to the tee. One resonant loop with the proto-type antenna is built at the RF test stand in KAERI. It is composed with one current strap, one tee connector and two arms connecting them. Each arm consists of a 6-inch vacuum transmission line, a vacuum feedthrough, a part of pressurized 9-inch coaxial line, and an adjustable phase shifter to cover wide frequency range of 25-60 MHz. Total electrical length is changeable from 45 to 51 m. Many voltage probes and directional couplers are installed to measure RF voltage of the standing wave, power flow and phase difference. Resonant and matching conditions are investigated for various frequencies.

1. Introduction

One of the research objectives of KSTAR(Korea Superconducting Tokamak Advanced Research) tokamak(R_0 = 1.8 m, a = 0.5 m, κ = 2, δ = 0.8, B_T = 3.5 T, I_p = 2 MA, τ_{pulse} = 300 sec) is to perform advanced tokamak research in a high performance regime and to explore methods for achieving a steady-state operation for a tokamak fusion reactor.[1] Heating and current drive using fast wave in the ion cyclotron range of frequencies have been proposed as one of the main features for the advanced tokamak operation of KSTAR. The ICRF(Ion Cyclotron Range of Frequency) system has been developed in KAERI(Korea Atomic Energy Research Institute) for several years.

The KSTAR ICRF system has been designed to operate at any frequency in the range of 25-60 MHz and operate for long pulse length up to 300 seconds. The ICRF system will deliver 6 MW(the power density of 10 MW/m^2) of RF power to the plasma using a single four-strap antenna mounted in a mid-plane port. It will be upgraded to 12 MW with the addition of a second system that is a duplicate of the first. The ICRF system provides heating for the plasmas, centrally peaked current drive, and off-axis current drive using mode-conversion for various operating scenarios over the range of magnetic fields, B_T = 2.5-3.5 T. For B_T = 3.5 T, the frequency of 50 MHz is good for H minority heating or second harmonic heating of D in D majority plasma. The frequency of 38 MHz can be used as an on-axis fast wave current drive scheme for a steady-state operation of KSTAR. With a He^3 minority, operation between 30 MHz and 40 MHz may be possible for He^3 minority heating or off-axis current drive using mode-conversion.

The ICRF antenna[2] consists of four current straps side by side. Each strap is grounded at the center and has two coaxial feed ports, one at each end. Top and bottom ports are connected to form a resonant loop. The loop consists of one current strap, one tee and two arms connecting them. Each arm consists of a vacuum transmission line, a vacuum feedthrough, a part of pressurized coaxial line and an adjustable phase shifter to cover any frequency in the range of 25-60 MHz. The feed line from the 2 MW transmitter is connected to the tee. A schematic of the ICRF system is shown in **Fig. 1**. The capability of changing the current drive efficiency to control the current density profile is provided by changing the phasing between the antenna strap currents during operation. Present antenna design gives k-parallel = 20 m^{-1} for the heating with π phasing and k-parallel = 5~10 m^{-1} for the current drive with $\pi/4$~ $\pi/2$ phasing.[3]

In the design of the resonant loop, the following requirements should be fulfilled;

(1) All transmission lines can withstand the peak RF voltage of 35 kV.
(2) The resonant condition should be satisfied at any frequency between 25 to 60 MHz.
(3) The current capability of 600 A(rms) is required.
(4) All transmission lines including phase shifter should be pressurized with 3 kg/cm^2 N_2.

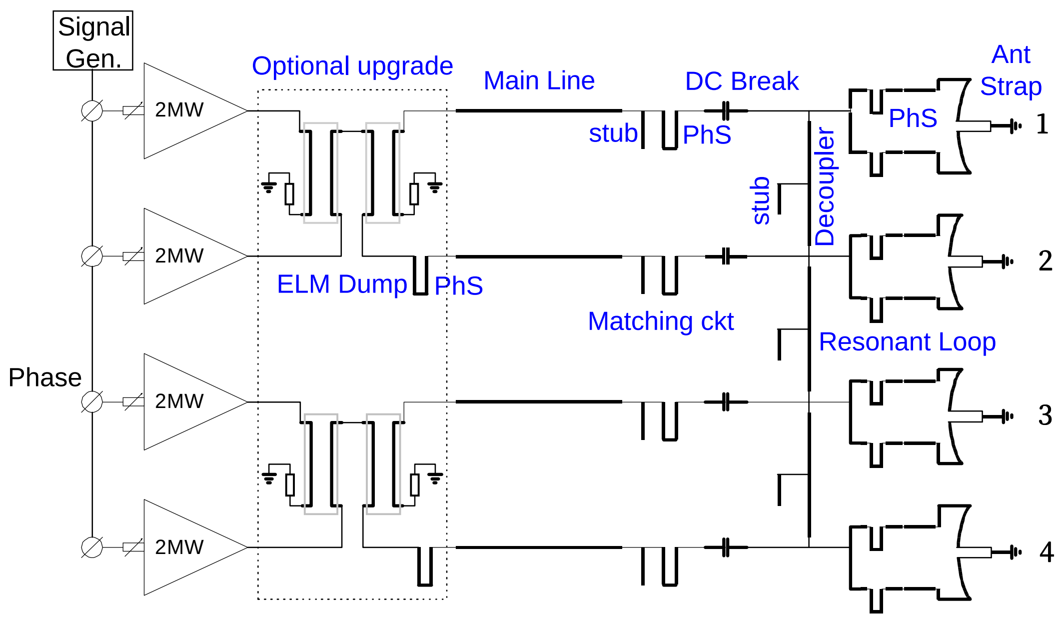

Fig. 1. KSTAR ICRF system schematic.

2. Description of the Resonant Loop

A resonant loop structure as proposed for the KSTAR ICRF system has the general form as shown in **Fig. 2**. It consists of a current strap that is grounded at the center point, the 39Ω 6" vacuum transmission lines from the each strap feeders to the vacuum feedthroughs, and 50Ω 9" resonant loop transmission lines from the vacuum feedthroughs to a tee connector where they are connected to a third line that feeds the power to the system. Phase shifters are included in both the top and bottom sides of the resonant loop transmission lines. They are adjusted to make the loop resonant at the desired frequency in the 25-60 MHz range.

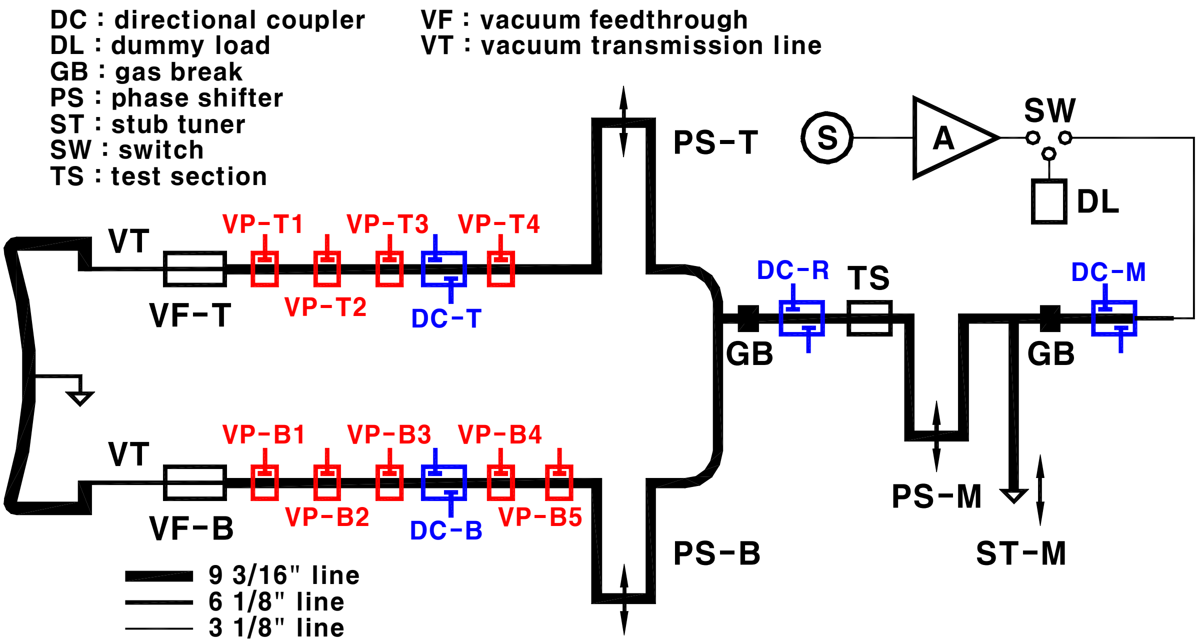

Fig. 2. Schematic diagram of the resonant loop.

3. Construction of the Resonant Loop

A resonant loop is built at KAERI RF test stand as shown in **Fig. 3**. Electrical length of the top line is about 23 m, and that of the bottom line is 28 m; total electrical loop length is 51 m. The length can be changeable from 45 to 51 m using two phase shifters. The phase shifter is remotely controlled and it can continuously change the phase angle 0 to 90 degree at f=25 MHz, i.e. an electrical length of 3 m. The electric length of the top and bottom lines including two phase shifters is calibrated by measuring phase angle between test section and directional couplers. All transmission lines except the vacuum transmission line are made by 50Ω 9·3/16" coaxial line and they are pressured with high purity N_2 gas to increase standoff voltage. Many voltage probes are installed on the top and bottom lines to measure RF voltage.

Four bi-directional couplers are used to measure forward/reflected powers and phase angle. A test section is installed at entrance of the resonant loop to measure loop impedance, VSWR or attenuation in both directions of the loop and main line, only by opening the device and inserting the measuring adaptor. Several thermocouples are used to monitor the surface temperature of the outer conductor.

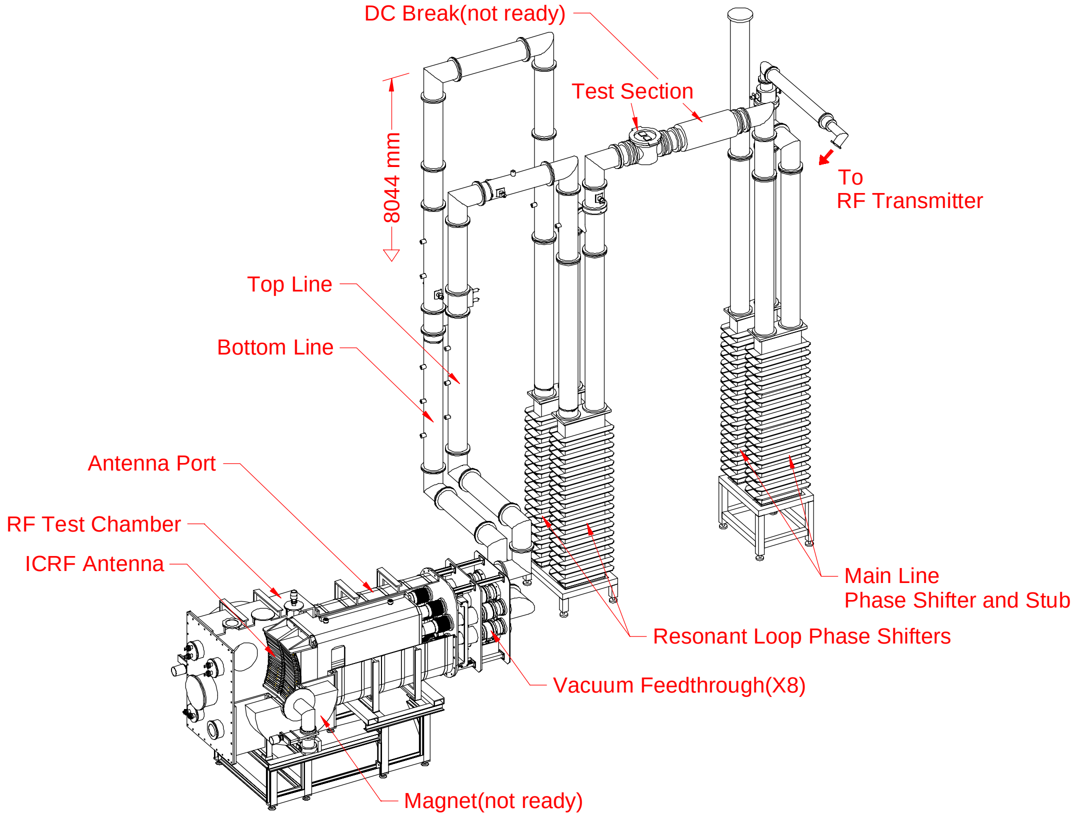

Fig. 3. 3-D view of the resonant loop.

4. Electrical Analysis of the Resonant Loop

For the purpose of modeling the behavior of the strap-transmission line circuit, the current strap is considered as a lossy transmission line with a loss resistance R'[Ω/m] which is due to the power coupled to the plasma. Using a lossy transmission line model, the voltage and current along the resonant loop are calculated for three frequencies, i.e. f=27MHz(FWCD case at B_T=2.5T) , f=38MHz(FWCD case at B_T=3.5T) and 50 MHz(heating case at B_T=3.5T) with R'=6 Ω/m, and the result is shown in **Fig. 4**; x = 0 corresponds to the center-ground point of the current strap. At x = 0.375 m, the current strap connects to the feeding strip which is connected to 39Ω vacuum transmission line at x=0.835. The curves, computed for an initial condition of 1 kA of current flowing at the strap ground, allow the calculation of the maximum voltage in the RF system per unit current in the strap.

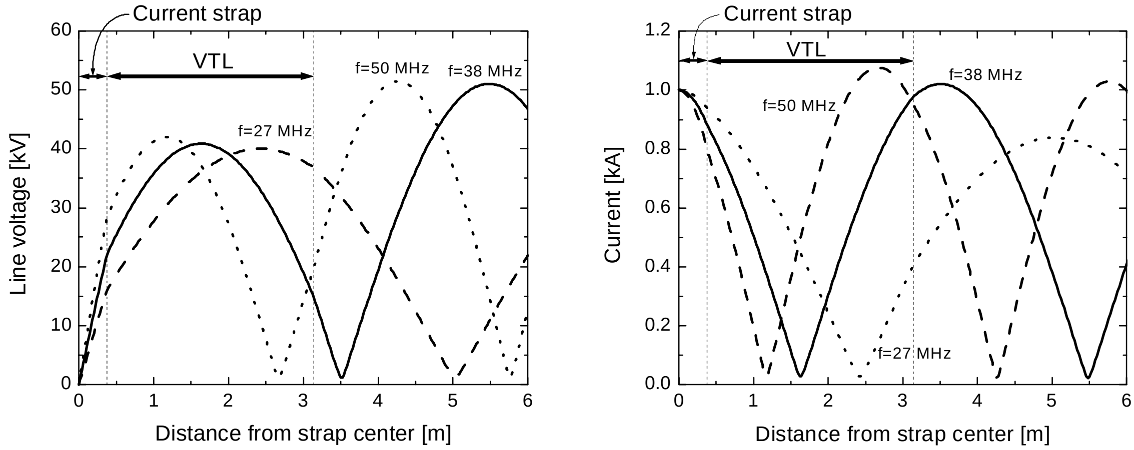

Fig. 4. Voltage(left) and current(right) along the resonant loop.

The operational limit of an RF system is often set by the maximum voltage in the antenna and transmission line system. We have set a limit of V_{per} = 35 kV as the maximum permissible voltage for RF system operation. As there are several tokamaks operating at or in excess of this voltage level at present, this limit should assure reasonably reliable operation of the KSTAR ICRF system. At a given frequency and value of V_{per}, the total power P_{total} that can be delivered to the plasma is determined by

$$P_{total} = \frac{1}{2} R' \ h \ F_{avg} \left(\frac{V_{per}}{V_{max}}\right)^2,$$

where h is the height of current strap which couples power to the plasma, and F_{avg} is the factor used to account for realistic antenna geometry. **Fig. 5** shows the total power coupled to the plasma as a function of loading resistance. It can be seen that the design objective of 6 MW launched at the maximum allowable line voltage of 35 kV requires R' ≥ 5.4Ω/m at 27 MHz, R' ≥ 9.2Ω/m at 38 MHz, and R' ≥ 9.9Ω/m at 50 MHz.

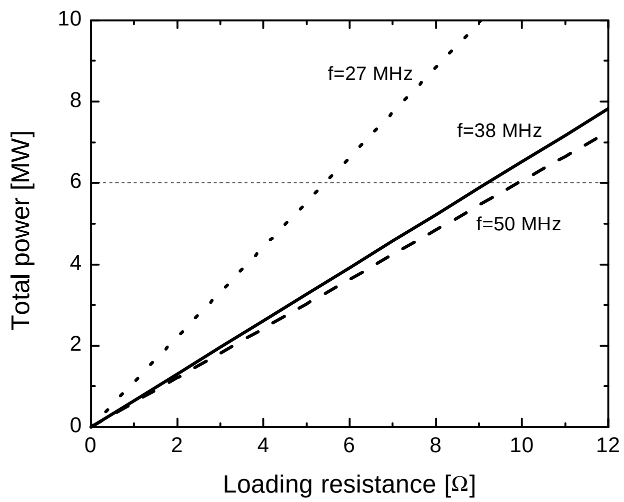

Fig. 5. Total power coupled to the plasma.

For a given frequency, total electrical length of the loop should be equal to $N \cdot \lambda$ to be resonant, with the current in the top and bottom halves of the current strap flowing in the same direction. To make the phase difference between top and bottom current straps as small as possible, the tap point, w is set to approximately $\lambda/4$, where the loop impedance, Z_{loop} is maximum. Loop impedance means the impedance seen by the main transmission line at its connection to the resonant loop. **Figure 6** shows the resonant frequency as a function of the bottom side length for several N's, and top line length for N=5, at which the difference between the top and bottom line lengths is $\lambda/2$. There are some frequency ranges at which the loop is not resonant, but all frequency range can be covered by changing some parts of the line with a longer line. **Figure 7** shows the loop impedance as a function of distance from the strap center along the top-line at the frequency of 30 MHz with bottom-line distance of 27 m. At the resonant frequency of 30 MHz, real part of the loop impedance becomes maximum at the top line distance of ~22 m. The minor difference between the distance and electrical length in **Fig. 6** is caused by the phase velocity of β=0.607 on the strap. **Figure 8** shows the maximum loop impedance as a function of the plasma loading, which is the impedance that should be matched with a transmitter using the matching circuit.

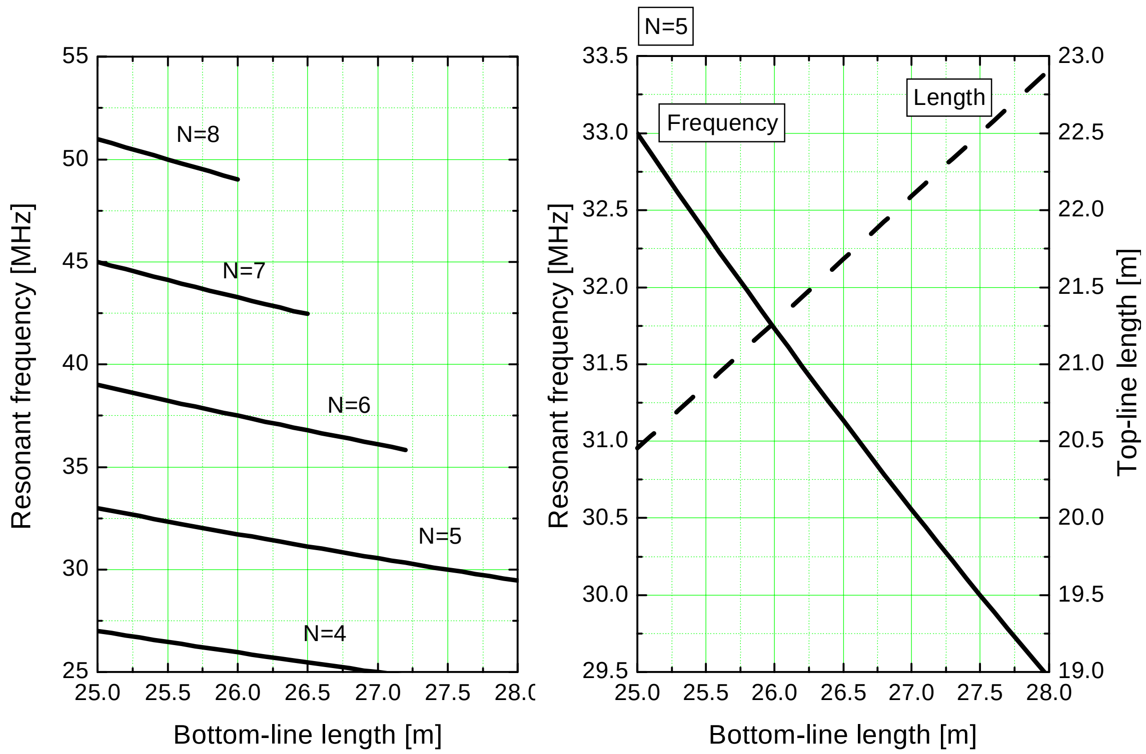

Fig. 6. Resonant frequency(left), and top-line length vs bottom-line length.

5. Summary

A resonant loop with total electrical length of 51 m is constructed, and its resonant condition is investigated. For the future work, high power rf test will be performed to study standoff capability of the resonant loop. This work was supported by the Korea Ministry of Science and Technology under KSTAR Project Contract.

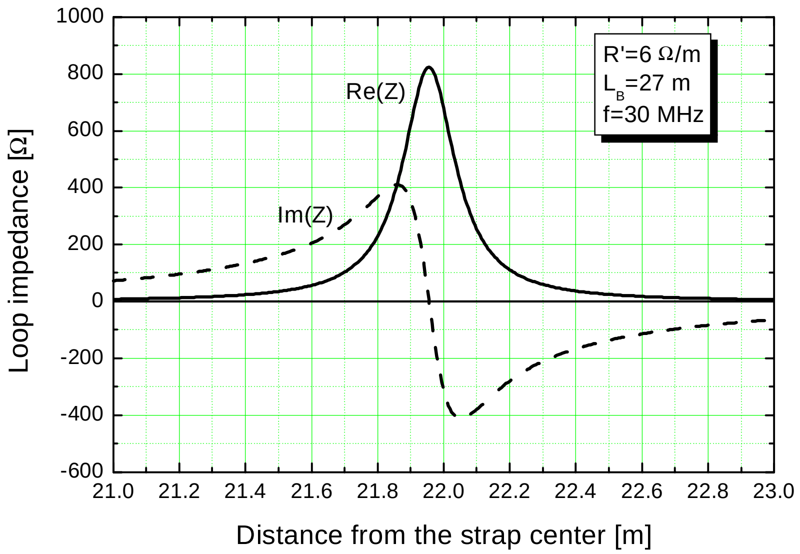

Fig. 7. Real and imaginary of the loop impedance as a function of top-line length at frequency of 30 MHz with bottom-line length of 27.5 m.

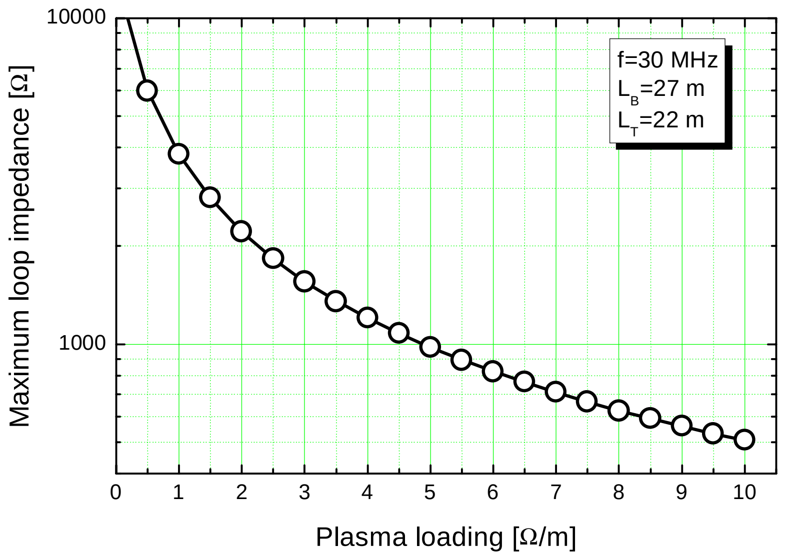

Fig. 8. Maximum loop impedance as a function of plasma loading.

Reference

[1] G.S. Lee et al., *Nuclear Fusion* **40** (2000) 575.
[2] Y.D. Bae, C.K. Hwang, and B.G. Hong, *Fusion Engineering and Design* **65** (2003) 1.
[3] C.K. Hwang, B.G. Hong, and D. Swain, *Fusion Engineering and Design* **45** (1999) 127.