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SIMULATION RESULTS FOR NEW NSTX HHFW ANTENNA STRAPS DESIGN BY USING MICROWAVE STUDIO*

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Abstract— Experimental results have shown that the high harmonic fast wave (HHFW) at 30 MHz can provide substantial plasma heating and current drive for the NSTX spherical tokamak operation. However, the present antenna strap design rarely achieves the design goal of delivering the full transmitter capability of 6 MW to the plasma. In order to deliver more power to the plasma, a new antenna strap design and the associated coaxial line feeds are being constructed. This new antenna strap design features two feed-throughs to replace the old single feed-through design. In the design process, CST Microwave Studio has been used to simulate the entire new antenna strap structure including the enclosure and the Faraday shield. In this paper, the antenna strap model and the simulation results will be discussed in detail. The test results from the new antenna straps with their associated resonant loops will be presented as well.

I. INTRODUCTION

It has been proven that the high harmonic fast wave (HHFW) at 30 MHz can provide substantial plasma heating and current drive for the NSTX spherical tokamak operation[1-5]. However, the present antenna strap design[6] rarely achieves the design goal of delivering the full transmitter capability of 6 MW to the plasma. In order to deliver more power to the plasma, a new antenna strap design and its associated coaxial line feeds are being constructed.

This new antenna strap design features two feed-throughs to replace the old single feed-through design. By relocating the voltage minimum, the antenna enclosure and the Faraday shield can be modified to withstand higher voltage and deliver more power with the same strap voltage distribution. According to the present design, the RF power is going to be launched at both feed-throughs via a full wavelength resonant loop. Ultimately, launching the RF power through two feed-throughs will allow us to reach the design goal of doubling the HHFW power to the plasma.

In the design process, CST Microwave Studio has been used to simulate one complete HHFW antenna structure including the new strap, its enclosure, and the Faraday shield. The simulation configurations and results will be discussed in Sec. II. Test methods and results will be discussed in Sec. III.

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II. SIMULATION CONFIGURATIONS AND RESULTS

In order to determine the propagation speed for this new antenna strap, three different simulation configurations were used.

A. *Complete Configuration and Results*

The side-profile of the simulation model, which is imported directly from the mechanical drawing in STEP, is shown in Fig. 1. It shows the detailed upper and lower feed-through structure with two ceramic vacuum breaks. Also a ceramic post, which is located at the center of the strap to provide some mechanical support, is included in this two-port simulation. The ultimate design goal is to relocate the voltage minimum/virtual ground to this ceramic post. The simulation frequencies were set between 25 MHz and 35 MHz so that we can observe the wave packet propagation through the structure to determine its phase velocity.

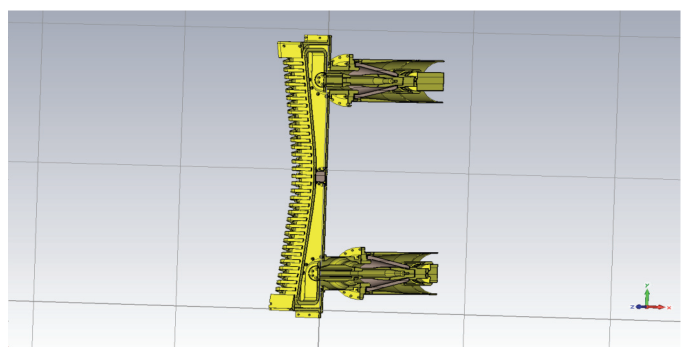

Fig. 1. The side-profile of the simulation model; this is imported directly from the mechanical drawing in STEP.

Since the whole structure is much smaller than one wavelength (10 m at 30 MHz), we had to select 310 lines per wavelength and thus the program size became more than 8 million meshcells. This simulation took more than 24 hours to complete. By closely examining the output and the input wave packet, the time stamp difference at the center of these two wave packets would be the group delay of the structure. Assuming that the group delay dispersion over the 10 MHz bandwidth is negligible, the overall propagation delay at 30 MHz in this simulation is 11.915 ns.

B. *Upper and Lower feed-through Simulation Results*

Because the upper and lower feed-through are of coaxial line structure with ceramic vacuum breaks on each side, their propagation speed has to be slower than the speed of light in vacuum and thus the delay is still undetermined in the previous simulation. In order to determine their contribution, these two feed-throughs were reoriented to become joined at the strap mounting pieces. As shown in Fig. 2, a thin copper tube is used around the mounting pieces so that the mismatch loss can be reduced in this simulation configuration.

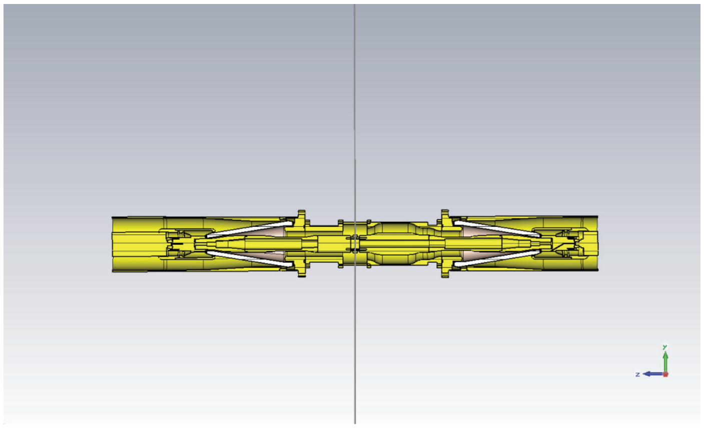

Fig. 2. The side-profile of these two feed-throughs which are reoriented to become joined at the strap mounting pieces.

By using the same simulation conditions and closely examining the output and the input wave packet, the propagation delay at 30 MHz in these two feed-throughs is 5.354 ns. Based on the length, which is 1.349 m (53.1”), in this simulation, the propagation speed in the feed-throughs is 0.84c, where c is the speed of light.

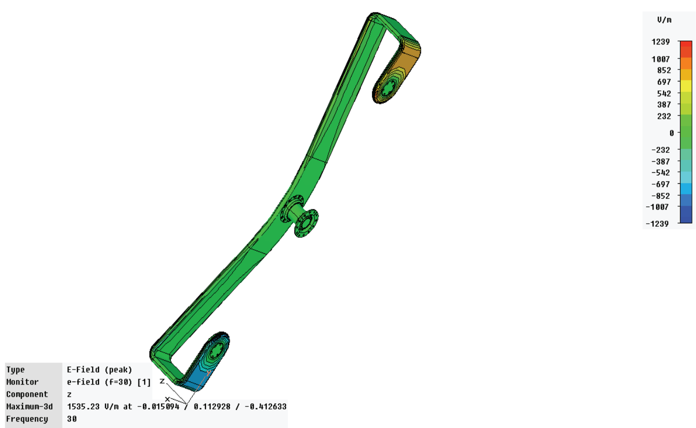

Fig. 3. E-field distribution on the antenna strap; the simulation results indicate that the E-field is always zero at the center of the strap with different phase angles at the input.

C. *Propagation Speed in the Antenna Strap*

By including all the bends in the new antenna strap, the physical length is approximate 1.3 m (51.2”). Since the propagation delay in the antenna strap can be obtained by 11.915-5.354 = 6.561 ns, the propagation speed in the antenna strap is thus ~0.66c. With these data, we can calculate the required coaxial line length from the back plate in order to force the E-field minimum (ideally zero E-field, virtual ground) at the center of the new antenna strap. This length is about 1.25 m (49.2”) with a ceramic vacuum break.

Because Microwave Studio treats the open end as a point source, strong fringe fields at this end would cause great amounts of RF leakage into the vacuum. Note that the vacuum wave impedance is only 377 Ohms. Thus, the simulation results with an open end were very disappointing. This mistake was easily corrected with another quarter wavelength and a short-circuited end. In this case, the overall length for the short circuit coaxial line with the ceramic vacuum break from the back plate becomes 3.75 m (147.64”). As shown in Fig. 3, the simulation results at this length do indicate that the E-field is always zero at the center of the new antenna strap with different phase angles at the input.

D. *Full Antenna Strap Simulation*

With the above simulation results prescribing the virtual ground (zero E-field) location, we can simulate the whole antenna strap within the resonant loop. First, we can replace the ceramic post with a copper post due to the virtual ground at the center of the antenna strap. This modification can greatly enhance the mechanical strength. Second, two long coaxial lines were added to maintain the resonance at 30 MHz. The top one in Fig. 4 is 3-quarter-wavelength long to the center of the strap; that is 6.25 m long from the back plate to the T-joint. The bottom one is 5-quarter-wavelength long to the center of the strap (11.25 m long in this case). Another 2.75 m long coaxial line was added to the T-joint as the launcher to facilitate the simulation.

In this configuration, the Microwave Studio did complete the simulation and did not complain about “divide by zero” errors when the center of the antenna strap is short-circuited. The simulation results do indicate that the resonance at 30 MHz can be sustained and the H-field in the vicinity of the center of the antenna strap is always maximal (Fig. 5).

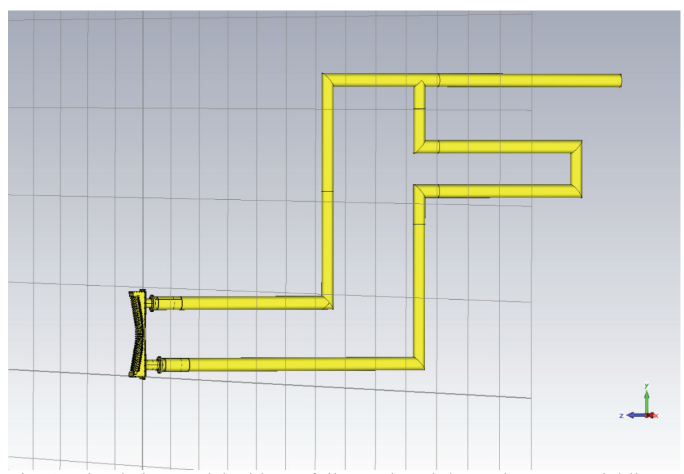

Fig. 4. Simulation model with a 2-full-wavelength loop; the top coaxial line to the T-joint corresponds to 3 quarter wavelengths and the bottom coaxial line to 5 quarter wavelengths.

III. System Installation and Tests

Based on the simulation results, the new antenna straps with upper and lower feed-throughs were built. In order to determine the first quarter wavelength point and complete the full wavelength resonant circuit, two tests have been performed.

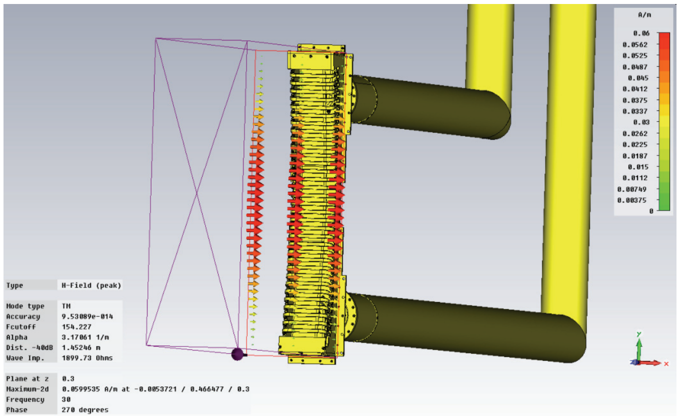

Fig. 5. The simulation results show that the resonance at 30 MHz is achievable and its H-field is always maximal in the vicinity of the center of the antenna strap.

A. *Antenna Strap Measurement*

Prior to the full antenna system installation, the new antenna strap with the copper post and the upper and lower feed-through was tested in situ to determine the first high voltage point from the strap center (the first quarter wavelength point). An HP 4815A Vector Impedance Meter was used for this measurement. The readily available test point under this condition is the end of the top feed-through. A small piece of 6" coaxial line was attached to the end to facilitate the measurement. The meter probe was connected to the coaxial line center conductor with the bottom feed-through being shorted. By dialing the local oscillator of the impedance meter, the highest impedance, which is at the quarter wave resonant frequency, appeared to be between 40 MHz and 44 MHz. This is very close to the simulation results when we translate the propagation delay in the strap (~0.66c) and in the feed-through with a small piece of 6" line (~0.84c).

Now we had confidence that the 1.25-m position from the back plate should be the first quarter wavelength position for 30 MHz. Because of the available space and the minimum modification in the NSTX HHFW launcher platform, the whole resonant loop at 30 MHz with the new antenna strap can be achieved with one full wavelength instead of two full wavelengths as shown in the previous section. As long as the T-joint is located at the vicinity of the high impedance point from the center of the strap, the resonant circuit should have reasonable Q values to store the energy and deliver the power to the plasma. Hence, the T-joint to the upper feed-through should correspond to one quarter wavelength and to the lower feed-through correspond to three quarter wavelengths in the ideal case. That is 1.25 m and 6.25 m respectively. The typical configuration is shown in Fig. 6.

B. *Antenna Strap System Installation and the Probes*

Due to other physical constraints in the NSTX HHFW area, the exact location of the T-joint to the back plate via the upper feed-through is ~56.75" (1.44 m). Initially the length from the back plate via the lower feed-through to the T-joint was set to 256.75". In order to trim this section to achieve one full wavelength at 30 MHz, voltage probe is used to measure the resonant frequency. This voltage probe was developed to monitor the RF power during the HHFW experiments. The probe itself is a ¼" diameter rod set flush with the coaxial line outer conductor and a female N-connector on the other end. The small cross-section area of the rod is sufficient to provide enough capacitive coupling for the measurement. Typical coupling value for the probe is between -80 dB and -90 dB.

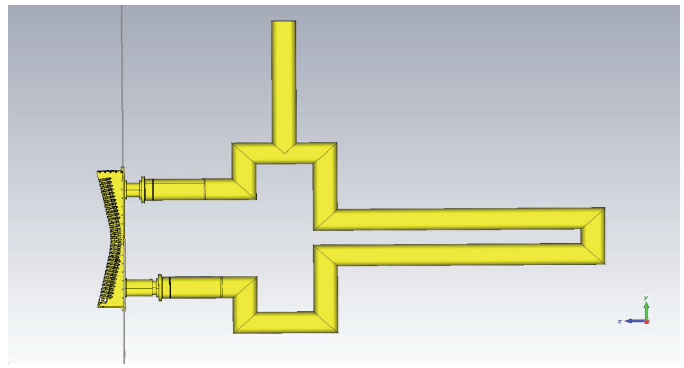

Fig. 6. Typical configuration for the HHFW antenna construction; the whole resonant loop at 30 MHz is one full wavelength in this case due to the available space in the test cell area.

In order to measure the resonant frequency with a network analyzer, two probes are needed. One is the voltage probe and the other is the excitation probe. The top probe is the voltage probe located at the center of a spool piece (5.25" long 6" coaxial line), which is inserted between two 90^{o} coaxial line elbows. As shown in Fig. 6, one elbow is attached to the upper feed-through and the other elbow is attached to the T-joint. The bottom probe is on another spool piece that is directly connected between the lower feed-through and the first elbow. This bottom probe is the excitation probe. It consists of a 100 kΩ resistor and is direct in contact with the center conductor of the coaxial line.

C. *Antenna Strap System Measurement and Modification*

An Agilent E5062A Network Analyzer (300 kHz – 3 GHz) was used to measure the resonant frequency. Since the excitation is in parallel resonant condition (same as the single pole bandpass filter), the resulting coupling ratio is between -90 dB and -100 dB. In order to gain enough equipment sensitivity to do the measurement, the analyzer IF bandwidth was set to 10 Hz and sweeping power to 10 dBm. Typically, the network analyzer front end noise figure is ~40 dB due to the built-in couplers to support full two-port measurements (S11, S21, S12, and S22). With -174 dBm/Hz thermal noise at room temperature and 10 Hz IF bandwidth, the system noise floor is -174 + 10*log(10) + 40 = -124 dBm. In terms of 10 dBm sweeping power, the network analyzer dynamic range in this case is 134 dB. This was enough for us to verify the antenna strap system resonant frequency.

Since the initial cut coaxial line length should be slightly lower than 30 MHz, the analyzer frequency was centered at 30 MHz with 1-MHz span for this measurement. Two port measurement (S21) was performed when the bottom (excitation) and top (voltage) probe were connected to the network analyzer. As soon as the sweeping frequency is close to the resonant frequency, strong coupling will be observed. Depending on the relative positions of these two probes, the peak to average ratio is between 20 dB and 30 dB. The typical test result is shown in Fig. 7.

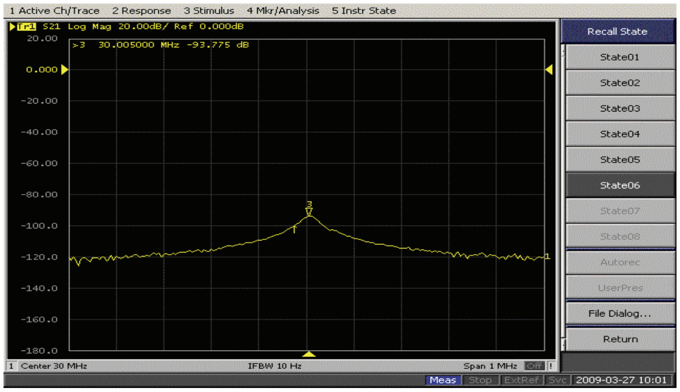

Fig. 7. Typical test result for each antenna loop; it clearly shows in this antenna loop that the resonance at 30.005 MHz is ~30 dB stronger than other frequencies.

After the first measurement, we will have to trim the coaxial lines down to 30 MHz. The logical location for this purpose will be one of the U-shape sections so we do not have to drastically modify the RF coaxial line feeds as shown in Fig. 6. How much to trim down on the coaxial lines relies on the measurement difference from 30 MHz (10 m long wavelength). Note that every 0.1% difference (30 kHz) will have to trim down the lines by 10×0.1% = 0.01 m (0.4"). After few painful iterations of line cutting, flange welding, system reinstallation and measurement, the resonant frequency in this loop will eventually only be off by few kHz.

Also note that the NSTX HHFW system has 12 antenna straps and 6 transmitters. Some caution will be needed during the resonant frequency measurement. This is because each transmitter drives a pair of straps connected with a resonant line length to provide 180^o -phase difference in this pair of straps. There are mutual inductive couplings within the strap pair and with other strap pairs in the antenna array. To minimize these mutual inductive couplings during the measurement, all other straps were shorted near what would be their maximum voltage points (i.e. at the positions of the voltage probes). A long brass rod, which has the same mechanical fitting as the voltage/excitation probe, was used for this purpose.

IV. Conclusions

The new antenna strap featuring two feed-throughs to replace the old single feed-through one was built and installed. Because its structure is symmetrical, we can easily control the E-field distribution so that the antenna enclosure and the Faraday shield can be modified to withstand higher voltage as well as deliver more power for the same strap voltage distribution.

In the design process, CST Microwave Studio has been used to simulate the entire new antenna strap structure including the enclosure and the Faraday shield. The simulation results show that the propagation speed in the new antenna strap is ~0.66c. Since these two feed-throughs include two ceramic vacuum breaks and the associated coaxial lines assembly, their corresponding propagation speed is ~0.84c. With these data, we can calculate the maximum E-field position (the first quarter wavelength at 30 MHz) from the back plate to force the E-field minimum (ideally zero E-field) at the center of the new antenna strap. It is found that the required length is about 1.25 m (49.2") from the back plate including a ceramic vacuum break in the coaxial line.

As soon as the new antenna straps were installed, two tests were used to verify the simulation model. The first test was to find the highest impedance frequency at the upper feed-through. Since this length is shorter than the quarter wavelength at 30 MHz, it is expected that the measurement be in the range of lower 40 MHz. Thus, extra coaxial line is needed to bring the resonance down to 30 MHz. Depending on the construction constraints, the T-joint is placed at the vicinity of this high impedance points at 30 MHz from the center of the antenna strap. The electrical length is roughly one quarter wavelength for the upper feed-through and three quarter wavelengths for the lower feed-through.

The second test was to confirm the resonant frequency for the full wavelength loop. In order to adjust the resonance at 30 MHz, it is required to have a few painful iterations of cutting/trimming the coaxial lines, welding the flanges, and measuring the resonant frequency. When all 12 antenna loops are tuned, some further tunings will be required for the upper stream power splitters.

Acknowledgment

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