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RF CURRENT DRIVE ANTENNA

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Paul H. Probert

University of Wisconsin
Department of Nuclear Engineering and Engineering Physics
Madison, WI 53705

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RF Current Drive Antenna (Stacked Stripline Antenna Development)

Abstract

This work represents an attempt to solve a fundamental problem with all coupling devices in tokamaks intended to launch waves in the ion cyclotron range of frequencies (ICRF), that of excessive voltage levels on the launcher and its feed lines. These voltages can lead to impurity problems in the plasma, and they determine the maximum power that can be coupled to the plasma, since it is when arcs caused by this voltage frequently occur that the power must be reduced. The approach taken is to consider an antenna which is composed of many smaller units, each operating at much lower voltages, stacked on end to provide the equivalent functionality of a conventional launcher. The work described herein involved designing, building, and operating such a launcher in the Phaedrus-T tokamak. The results showed that the antenna worked as expected, reducing the voltage dramatically, while still functioning properly, and producing fewer impurity problems and no arcing. A design extrapolating the principles of this idea to reactor-sized tokamaks such as ITER was developed. In addition, a novel decoupling scheme was developed in order to adapt this antenna idea to low frequency current drive schemes.

Introduction

The major part of the results obtained in this project are reported in the paper "Design and Initial Tests of the Stacked Stripline Antenna in the Phaedrus-T Tokamak" which has been accepted for publication in Nuclear Fusion. A copy of that paper is attached to this report. We present in the next few sections some additional results, and especially descriptions of technology developed along the way to achieving our main results. These technology developments include: 1) Development of a high current multiconductor feedthrough, 2) Development of high current matching capacitors, 3) Development of a load-insensitive external decoupling circuit. We describe these briefly below.

High Current Feedthrough

In Fig. 1, we show a rough sketch of the RF antenna geometry in Phaedrus-T. The Stacked Stripline (SSL) antenna in Phaedrus-T was designed for a very low frequency, 7 MHz, due to the nature of the Alfvén wave current drive experiments. This, plus the desire to maintain maximum flexibility, dictated that the resonating capacitors be placed outside the machine's vacuum chamber. This posed a technical challenge, because the circulating current of the antenna's 10 straplets adds up to over 10 kA for normal operation at the few hundred kilowatt level. In order to keep the losses within bounds, the multiple foil feedthrough shown in Fig. 2 as developed. It uses vacuum autoclaved epoxy-fiberglass composite as the sealing material. Despite concerns that this would pose a risk to the vacuum quality, we routinely obtained base pressures of 5×10^{-8} Torr, as good as we obtained before the feedthrough was installed. We note that this feedthrough, using its multiple foil construction, presented an additional inductance in the circuit that was negligible compared to the antenna inductance.

High Current Matching Capacitors

The multiple foil construction of the feedthrough was continued to the matching capacitors, providing essentially an independent connection to each straplet. The inductance of each straplet was about 9 nHy, which implies at 7 MHz a resonating capacitance of 57000 pF per straplet. This is an extremely large capacitance as RF capacitors go, and finding capacitors this large and with inductances small compared to 9 nHy was a challenge. Though the operating voltage was less than 500 volts, the currents were large, upwards of 1000 amperes each. Our first attempt at meeting these requirements was to use commercially available "reconstituted mica" capacitors available from the Cornell Dubilier as kVx brand capacitors. We paralleled 10 such capacitors for each straplet, operating them at 100 amperes each. Unfortunately, their internal construction consisted of a plasma sprayed bond from the foil edges to the leads, and this joint formed a series arc at high currents and destroyed the units after several shots. It became clear that a custom design was necessary.

We built our own capacitors by winding .005 inch thick copper foils sandwiching .003 inch thick polypropylene dielectric, and the leads were formed by directly leading the foils tangentially out from the sides of the rolled units, so that there were no joints to fail.

Fig. 1. Schematic showing the low-field and high-field (SSL) antennas.

RF Feedthrough

$$L_{\text{feed}} \ll 1 \text{ nHy}$$

$$I_{\text{RF}} \sim 10 \text{ kA}$$

$$V_{\text{max}} \sim 300 \text{ V}_{\text{rms}}$$

Fig. 2. Drawing of the high current feedthrough. Two of these units are installed on the Phaedrus-T tokamak to carry over 10 kA of RF current to the SSL antennas.

These units proved to have excellent high current capability, low loss, and very low inductance.

Load Insensitive Decoupling Circuit

Current drive experiments require that adjacent straps in an array be driven at different phases, usually 90° apart, so that a travelling wave of one directionality can be produced. If there is mutual coupling between the straps, this can be difficult, since power is coupled from one strap to the next, interfering with the phase relationships. Originally, the fact that the stripline antenna has low inductance meant that its operating Q would be low. The parameter kQ , the product of the coupling coefficient between adjacent antennas and the Q or quality factor of the antenna (defined as $Q = \omega L/R$ where ω is the frequency, L is the inductance, and R is the total resistance) determines the amount of power transfer between coupled antennas in a current drive array. If kQ is sufficiently less than 1, no decoupling of straps is necessary. Had the loading on the SSL antenna been as high as we expected, no decoupler would have been necessary. Unfortunately the loading was very low, due to the nature of the wave coupling on the high field side of the tokamak. This meant that some sort of decoupling was necessary.

In our conventional strap antenna, we use a technique pioneered by Majeski (referenced in the paper at the end of this report) in which opposite mutual inductances are included in series with the antenna straps inside the vacuum chamber. This technique, however, cannot be applied to the stacked stripline antenna due to its multiple straplet nature and its extremely low operating inductance. We needed to use decoupling elements which were electrically located on the transmitter side of the first matching capacitors. We therefore employed the simplest circuit, shown in Fig. 3a. A series coupling transformer was placed as shown, followed by an additional external matching circuit composed of C_E and L_E . This circuit, after suitable calculation and adjustment, could provide decoupled operation in a limited fashion. A problem we discovered, however, was that the decoupling only worked at one particular value of plasma loading. It could not, for instance, be adjusted for decoupling in vacuum and then be expected to perform properly with plasma present. Analysis of the circuit equations showed why: the first matching circuit, consisting of L_A , the antenna inductance, and C_A , the resonating capacitors, inverts the loading resistance of the antenna. That is, for low loadings the impedance seen looking into the parallel combination of the antenna and the first matching capacitor is high, and for high loadings it is low. Thus the current through the decoupling transformer is not in strict proportionality to the current through the antenna, and there can be no hope of load independent decoupling.

The solution to this problem is to put the decoupling transformer before another matching section, so that there are 2 inversions in the loading impedance. The current through the decoupler will always be in the same proportion to the antenna current, and load independent decoupling is achieved. This is shown in Fig. 3b. This decoupler was built and found to perform perfectly. The series capacitance C_D is to resonate out the leakage inductance of the decoupler. Physically, the transformer L_D consists of about 30 inches of twisted RG-8 center conductor, having a mutual impedance of about 12 ohms and a

a)

b)

Fig. 3. Decoupler circuits. a) The simplest, first attempted circuit. This circuit did not allow load-independent decoupling. b) A variation on a) in which the decoupler is located before 2 resonating stages, so that there is no load inversion.

coupling coefficient of .6. We designed the matching circuit by writing a program in the IDL language which can solve for all the circuit parameters given experimentally generated impedance data. In Fig. 4 we show the results of a typical impedance matrix generated by the antenna without the decoupler, and in Fig. 5 the same data is shown for the case when the decoupler is present. In Fig. 5 the data at later times (after about 200 ms) is in vacuum. By examining the off-diagonal terms in the impedance matrix, one can see that the decoupling remains small both for vacuum and plasma. The small variation in real and imaginary parts of the impedance matrix was discovered to be due to a phase shift in the coupling due to the plasma, which is beyond the ability of an inductive decoupler to compensate exactly. Fig. 6 shows the results of that analysis, which shows that the phase shift is proportional to the Alfvén time for transiting between straps. We note that such a phenomenon might be useful as an edge density diagnostic.

Z Matrix Shot 69578

no dec

Fig. 4. Z matrix measurements for the circuit of Fig. 3b but with no decoupler and no series capacitor C_D . There is no tokamak plasma present. The large values for Im Z₂₁ and Im Z₁₂ represent the mutual inductance of the antenna, as seen through the matching network.

Z Matrix Shot 69584

Fig. 5. Z matrix measurements for the circuit of Fig. 3b, with plasma present until a time of about 200 ms.

Fig. 6. Analysis of the phase of the coupled signal from one strap to another, showing that the time delay is proportional to the Alfvén time.

Design and Initial Tests of a Low Voltage Stacked Stripline Fast Wave Launcher in the Phaedrus-T Tokamak

P.H. PROBERT, S.P. OLIVA, and G.R. WINZ, Department of Nuclear Engineering and Engineering Physics, University of Wisconsin-Madison, Madison, Wisconsin, United States of America, D.J. HOFFMAN, J.B.O. CAUGHMAN, and W.L. GARDNER Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States of America

Abstract

A new type of antenna for launching waves in the ion-cyclotron frequency range in toroidal plasma devices has been developed and tested in the Phaedrus-T Tokamak. This antenna, a stacked stripline, generates a radio frequency (RF) magnetic field similar to that of a conventional strap antenna but develops voltages 2 orders of magnitude less, and can operate without a Faraday shield. In comparison tests with a conventional strap antenna at a power level of 60 kW, the RF induced density rise and the impurity production (as indicated by soft x-ray and loop voltage increases) were reduced by a factor of 3. In addition it was demonstrated that capacitive loading effects were reduced or eliminated in comparison to those observed on a conventional strap antenna operated without a Faraday shield, and in operation of a pair of SSL antennas at 90° phase small current drive effects were observed.

Introduction

In almost all toroidal plasma devices where radio frequency (RF) power is applied in the ion-cyclotron frequency range (ICRF), the power is coupled to the plasma by launching a fast magnetosonic wave (B_{rf} parallel to B_0 , the equilibrium plasma confining magnetic field). The device which generates this wave is almost always a set of conducting straps in the poloidal direction, subtending 30 to 90 degrees of poloidal angle, and usually separated from the plasma by a Faraday shield structure which serves to reduce the exposure of the plasma to the high voltages usually present on the antenna.

These high voltages are a result of the inductance L of the antenna, which represents a reactance ωL (where ω is the RF frequency) many times larger than the resistive load R_{plasma} due to the plasma. Though this scheme has been remarkably successful in heating present day tokamak plasmas and in conducting current drive experiments, there are several technical shortcomings which are related to this excessive inductive reactance and the resulting high voltages which limit the applicability of ICRF power to next generation tokamak designs such as ITER, IGNITOR, and reactors in general:

- 1) The Faraday shield is subject to damage by disruptions and erosion and is difficult to maintain remotely.
- 2) The power density available through a given antenna is usually limited by voltage standoff, and improvements in power density can greatly simplify the machine design.

3) The radiation sensitivity and fragility of ceramic insulators and the design of the feedlines and matching circuits in a reactor environment are technical problems made more difficult at high voltages.

4) The finite wavelength, and the capacitive nature of the Faraday shield (which reduces the wave speed along the strap) results in non-uniform current distributions along the strap. To reduce this effect requires more complex strap geometries [1].

The above considerations are ample motivation for pursuing antenna designs which offer lower voltages. In the experimental program on Phaedrus-T, where the emphasis is on low frequency ($\omega < \omega_{ci}$, where ω_{ci} is the ion cyclotron frequency) current drive, we are motivated to find a new antenna design by the following considerations:

1) In this frequency range, where we expect to couple to the shear Alfvén resonance by exciting an evanescent fast wave, the loading resistance is very low. This leads to large antenna currents for a given power, and subsequently large inductive voltages on the antenna.

2) ICRF in small tokamaks usually leads to severe problems with RF induced fuelling and impurity production, some of which are related to the antenna voltage. The predominant candidate for the cause of the fuelling and impurity release is sheath rectification of induced RF voltages [2, 3], but we find that even with no Faraday shield and insulating limiters, there is still a considerable amount of RF induced fuelling. Capacitive coupling from the high voltage on the straps is suspected as the cause for a least some of this remaining effect.

3) For reasons related to the physics of the low phase velocity Alfvén wave current drive scheme, we are motivated to launch the waves from the high field side.

These reasons include the following: 1) There is some controversy concerning the effect of electrons trapped in the toroidally induced magnetic mirror [4] which might severely reduce the efficiency of current drive which takes place on the low field side. By driving a current from the high field side, we may be able to experimentally resolve this controversy. 2) The nature of the Alfvén resonance surface is such that it approaches the magnetic axis on the high field side of the machine, and so a high field side launch may allow more central current drive. As on most tokamaks, space is limited on the high field side of Phaedrus-T, so we require a design with low voltage so that the gaps necessary for voltage standoff do not take up too much space.

4) The low loading resistance, as mentioned in item 1), makes it difficult to get an efficiency, defined as the ratio of power not dissipated in the antenna or reflected back to the transmitter to the total power, greater than 60 to 70% with conventional strap antennas.

These considerations have led us to the design presented here, the Stacked Stripline (SSL) Antenna. Though it is relevant to reactors and large tokamaks it has immediate relevance to our experiments. We present in the next section the details of our tokamak experiment.

The Phaedrus-T Tokamak

Phaedrus-T is a mid-sized tokamak with parameters as given in Table I. The focus of our experiments has been on ICRF current drive, especially in the regime $\omega < \omega_{ci}$, and in the

range of wave phase velocities such that $v_{\text{phase}} < v_{\text{the}}$ (where $v_{\text{phase}} = \omega/k_z$, k_z being the wavenumber in the z direction, and $v_{\text{the}} = (kT_e/m_e)^{1/2}$, the thermal speed of the electrons).

We have used extensively two versions of a conventional strap antenna in these studies.

The antenna conditions we typically encounter are given in Table II.

The antenna in these studies is a conventional strap antenna with a strap width of 2.54 cm, 60 degrees poloidal extent, backplane to strap spacing about 6 cm, and strap to plasma spacing of 2 cm. We use 2 such straps spaced toroidally 14 cm apart, driven with a relative phase of, for example, 90° for current drive or 180° for Alfvén wave heating, and the mutual inductances are cancelled using a decoupling transformer built into the return leads of the straps [5]. We currently use no Faraday shield, and use insulating Boron Nitride antenna limiters. Studies with this and similar configurations have explored ways of reducing the effect of the antenna on impurities and fuelling by the use of insulating antenna limiters [6] and the heating of the electrons with Alfvén waves [7].

Low Voltage Antennas

The quintessential low voltage antenna concept is the Folded WaveGuide (FWG) antenna [8]. Fig. 1 shows a schematic representation of the antenna. This concept generates a B_z at the plasma by exposing the partially shorted end of a folded waveguide containing a standing wave to the plasma edge. Experiments on a test antenna have shown that the voltages can be 100 times less than those generated by Faraday shielded strap antennas[9]. The only significant drawback of this design is that the frequency is restricted to be above some minimum value related to the dimensions of the waveguide, in practice limiting the use of FWG antennas to large and/or high field tokamaks. Variations on the concept were

then invented to remove this frequency restriction, namely the folded stripline and, the subject of this paper, the stacked stripline.

Stacked Stripline Fundamentals

The SSL antenna is most readily derived by simply breaking up a conventional strap antenna into a lot of short straps all stacked up in series but fed in parallel, as shown in Fig. 2. It generates B_z almost identically to that of a conventional strap antenna (if all the feed currents are in phase and equal). If the number of "straplets" is N then the input current $I_{ssl} = N I_{strap}$, and the impedance (reactive or resistive) scales such that $Z_{ssl} = Z_{strap} / N^2$. This is if the other dimensions of the antenna, such as the width and the backplane to strap distance, remain the same. In our case it we have taken the opportunity to make the SSL much wider than the strap it replaces, so that the inductance is yet further reduced. This opportunity is provided by the lower voltage and relaxed voltage standoff requirements. One might take caution that the periodic nature of the SSL structure in the poloidal direction might introduce a large ripple in the field. In fact such a "bumpiness" has been reported in the case of the FWG [9]. However, it is easy to show that such a ripple is significant only when the width of the antenna is not much larger than the straplet spacing. Define the straplet aspect ratio to be $\alpha = w / \Delta y$ where w is the SSL width and Δy is the period in the poloidal direction. Then if $\alpha \gg 1$ the the ripple in the field is small.

The design of the sidewall of the SSL antenna is important to the fields generated by the antenna. In Fig. 2 we see a version of an SSL with conducting sidewalls, and in Fig. 3 the sidewalls are open. The fields from an antenna with conducting sidewalls are different

from those without the sidewalls because the return current, which must flow from the bottom of the antenna to the top in opposition to the main current on the straplets, will flow along the closed sidewalls, closer to the face of the antenna. The configuration shown in Fig. 2, most reminiscent of the FWG design and with closed sidewalls, has return currents flowing as shown in the same plane as the main current on the face of the antenna. As shown in the next section, this has an impact on the fields and the k spectrum of the antenna.

Fields From a Test Antenna

A small test antenna was constructed from copper foil so that the RF magnetic field could be measured. The test antenna dimensions are: antenna depth (minor radial extent) 5 cm, antenna width (toroidal extent) 12.5 cm, antenna height (poloidal extent) 30 cm, number of straplets 12.

The plots of B_z vs z and B_z vs x shown in Figs. 4 and 5 were made with a 6 mm diameter pickup coil, with a large (1 m square) conducting backplane directly under the antenna. In Fig. 4 we also show, as calculated from Bio-Savart integrations of model antenna currents, the B_z vs z of a conventional strap antenna of similar dimensions in the x and y directions, but of .0254 m extent in the z direction for the conventional strap (as is the case in Phaedrus-T) and the B_z vs z of a sheet current model of the SSL. The sheet current model of the SSL does not include the individual straplets but rather approximates the SSL by modeling it as one conventional strap with the same x , y , and z extents as the whole SSL, neglecting the contributions from all the straplet feed and return elements except the ones at the top and bottom (the extremes in the y direction). This is a good approximation

because all the other feed-return elements occur in closely spaced pairs which approximately cancel each other. In Fig. 5 we show the x dependence from these models along with the experimental data for the SSL with no sidewall. From these plots we can make the following conclusions: 1) The B fields of the SSL are well approximated by the sheet current model. The major discrepancy is that the B_z vs z plots show that the current in the actual antenna is not uniform in the z direction but crowds slightly to the edges. We can expect, therefore, that the other components, B_x and B_y , will be readily calculable from the model or can be assumed to be nearly identical to those of a regular strap, albeit of a wider extent in the z direction in the present case. In the comparison of the two SSL variants, one with an open sidewall and one with a closed sidewall, we note the following:

- 1) There are evidently large return currents flowing in the sidewalls near the face of the antenna.
- 2) Though we don't have B_z vs x plots for the case with the closed sidewall, we can infer that the field decays more rapidly with increasing x than the antenna with the open sidewall. This is because the open sidewall antenna, with a single return current parallel to the main current but shifted in x , is predominantly a dipole source. The closed sidewall antenna, with two return currents on either side at the face of the antenna, is more like two opposing dipole sources closely spaced, giving rise to a larger quadrupole component.

In Fig. 6 we show the k_z spectrum of B_z as calculated from the SSL data of Fig. 4. In these plots we highlight the differences between the SSL antenna with open sidewalls (dotted lines) and closed sidewalls (solid lines). The presence of the return currents on the face of the antenna with the closed sidewall forces the field reversals to occur much closer

to the main lobe of the antenna, and this increases the high k_z content of the antenna spectrum.

The Phaedrus-T SSL Antenna

As stated earlier, for reasons having to do with current drive and trapped electrons, we needed an antenna which could be mounted on the high field side of Phaedrus-T. In this region, there is a gap between the plasma and the vacuum vessel wall allowing an antenna of only 5 cm of thickness in the minor radial direction. The design chosen was such that this space was taken up almost entirely by straplets, with the feed lines at the rear being made of .13 mm thick copper foils soldered to the straplets and leading poloidally away from the antenna to feedthroughs at the top of the machine above the major axis. The relevant dimensions of this antenna are as follows: antenna depth (minor radial extent) 5 cm, antenna width (toroidal extent) 15 cm, antenna height (poloidal extent) 60 degrees (about 30 cm), number of straplets 10.

The feed lines are arranged in the form of closely spaced parallel plate transmission lines. Each straplet has two 12.7 cm wide copper foils, a supply and return, connected to it. The collection of 10 foils, plus one extra ground foil, are all insulated from each other with Kapton sheet, and the whole bundle is wrapped in a copper foil shield. The thickness of this bundle is about 6 mm. This feed transmission line design provides a reactance small compared to that of the antenna, and introduces losses much smaller than the plasma loading by distributing the high currents over a large cross-section of copper. The thickness of the foils, .13 mm, is about 4 skin depths at 5 MHz. This antenna, built with a curved backplane to fit into the Phaedrus-T vacuum chamber, is shown in Fig. 7.

Since this antenna is a low voltage design, it is operated without a Faraday shield. In order to make sure that the RF magnetic field produced by the antenna is polarized parallel to the tokamak field, many tokamaks use a canted Faraday shield design. We achieved the same result by giving the straplets a 4.6 degree tilt to align them with the tokamak equilibrium magnetic field. The purpose of doing so is to reduce impurity influx caused by sheath rectification of RF voltages induced in loops which consist of short magnetic field lines which intersect different Faraday shield elements (or, in this case, straplets)[2]. Since we are comparing the SSL antenna here to a conventional antenna for which we have attempted to solve this problem by eliminating the Faraday shield, tilting the straplets probably allows for a fairer comparison. We point out that the SSL design allows for this polarization control more easily than a conventional strap which, though equipped with canted Faraday shield blades, is almost always built with the strap itself in the poloidal direction.

In order to prevent plasma from impinging on the antenna, we employ limiters of the same minor radius as the main graphite limiter (a circular, full poloidal ring, baked, and located 120° toroidally from the antenna) but adjacent to the antenna and located on both sides. The toroidal separation of these local limiters from the edges of the SSL antenna was 15 cm. For our conventional strap antenna, these limiters are of insulating boron nitride [5]. For the SSL antenna, we used a slotted graphite design.

High Current Feedthrough

Each straplet must carry a current equal to the strap antenna it is replacing. When these currents are combined in parallel, a current of NI_{strap} must be supplied. This presents

several problems for the feedthrough. If the current is concentrated into one conductor to simplify the feedthrough, the resistive losses become too great. This is because the loading impedance which these resistive losses must be compared to is down by a factor of $1/N^2$. Also, any inductive reactance introduced by the feedthrough, even if held to a few $nH\Omega$, will dominate over the antenna reactance and raise the system voltage unacceptably (though such increases in voltage would not be felt by the plasma, they increase the voltage rating required of the matching capacitors).

Two solutions to this problem are possible. In a large or high field tokamak, where the dimensions are large and/or the frequency is high, it is easy to design sufficient resonating capacitance into the antenna structure inside the vacuum chamber, so that the current which must flow through the feedthrough is reduced by a factor of about Q , where Q is the quality factor $\omega L_{\text{strap}} / (R_{\text{plasma}} + R_{\text{strap}})$, a number which is at least 10 for most situations. This reduction in current required is due to the resonating capacitors supplying all of the strap current which is out of phase with the antenna voltage (reactive current) leaving only the in-phase portion to flow through the feedthrough.

In our machine, the solution is to bring the multiple foil set of parallel plate lines out of the vacuum chamber as is, by constructing an epoxy sealed feedthrough. The copper foils are sandwiched between layers of .5 mm thick 3M Scotchply 1003 pre-impregnated epoxy fiberglass material. This assembly was cured in a vacuum autoclave at 330F to minimize inclusion of gas and gas bubbles in the epoxy. The inductive reactance introduced by the feedthrough is negligible, and resistive losses are of the same low value as in the transmission line itself.

Fields from SSL Antenna in the Tokamak

Extensive field measurements in the tokamak have not yet been made. We have, however, used a pickup coil to measure the field inside each straplet and at the surface of each straplet. These are plotted in Fig. 8. These measurements were made with the resonating capacitors mentioned below connected, with the antenna inside the vacuum chamber but with no plasma present, and with the antenna excited at low power at a frequency of 7 MHz. We note that there is some non-uniformity to the field structure. This can be understood in terms of the mutual coupling between the straplets. The current divides so as to provide more current to the center straplets because the induced voltages from neighboring straplets cancel some of the inductive voltage drop. The end straplets have fewer neighbors, and so they get less current. This effect may be beneficial by reducing the amount of poloidal harmonics in the antenna spectrum. If it were desired to keep the currents strictly equal, one could insert small series inductances in some of the straplet circuits in order to equalize the currents, or perhaps the straplet geometries themselves could be slightly altered.

An interesting effect was noted by observing the ratio of the field inside a straplet to the field on the surface on the outside of the straplet. Before mounting the antenna in the machine, this ratio was 10. This can be seen as the proportion of the feed current which elects to flow on the inside of the straplet, taking the lowest inductance path, to that flowing on the outside, where it produces B_z at the antenna surface. When the antenna was mounted in the chamber, this ratio dropped to 5 (more current flowed on the outside, near the plasma region). The presence of the conducting vacuum chamber reduces the

inductance of the current path on the outside of the straplet, allowing the current there to increase. Alternatively, one can see that placing the antenna's backplane against a conducting surface restricts the return flux to half the space it would otherwise have, and since the current on the surface of the antenna is proportional to the return flux there, it must increase. We also note that the large non-uniformity in the B_z fields inside the straplets is not seen on the surface. The return flux distributes itself more smoothly over the surface of the antenna.

Loading Measurements

After installation in the tokamak, the SSL was tuned to resonate at a frequency of 7 MHz by connecting capacitance in parallel. A pi network matching circuit was added to match the impedance to a generator, and low power signals were applied during normal plasma shots. During these shots the phase and magnitude of voltages on the antenna and in the matching circuit were measured, allowing us to calculate the impedance presented to the antenna by the plasma. The impedances we describe here are referred to the point on the feedthrough just outside the tokamak vacuum vessel where we connect all the straplets in parallel and connect the resonating capacitors. The traces shown in Fig. 9 show the reactive and resistive parts of this impedance as a function of time. Near the end of the shot the plasma decays and the vacuum loading can be seen. The impedances shown have been calculated from the raw data using measured values of the matching circuit properties, including resistive losses in the matching capacitors and stray inductances in the capacitor leads. The resistive part shown after the plasma is gone is partly due to the

resistance of the copper feeds, but roughly half is due to dissipation in the stainless steel of the tokamak chamber walls.

Similar measurements made on the conventional strap antenna, operated without a Faraday shield, have always shown a larger inductive reactance with plasma than in a vacuum. We have taken this to be a sign that there is significant parasitic capacitive loading of the straps by the plasma. Modelling has indicated that about 20 pF of capacitance from the bare strap to the plasma edge is sufficient to account for the increased inductive reactance observed. The measurements shown in Fig. 9 for the SSL antenna show a slight reduction in the inductive reactance with plasma, and we conclude from this that the parasitic capacitive loading is reduced, as one would expect with the much lower voltage levels on this antenna.

The ratio of the reactance to the resistive loading for the SSL antenna in Phaedrus-T, at 7 MHz, gives an operating $Q \approx 30$, whereas under identical conditions the Q of the strap antenna is much higher, $Q_{\text{strap}} \approx 150$. Besides the issue of voltage, this may have implications for current drive. When closely spaced sets of antennas are operated from separate RF power supplies, with the phase controlled so as to produce travelling waves, there is a power transfer between antenna elements proportional to $(kQ)^2$ where k is the coupling constant (arising from the mutual inductance). Though this can be eliminated with external circuitry, we see that the SSL antenna holds out the possibility that, by having lower Q , the power transfer might be small enough that external decoupling circuitry could be eliminated.

In an effort to find the best operating regime for Alfvén wave current drive, we measured the antenna loading as a function of frequency and toroidal magnetic field. To do this, the resonating capacitors were removed and the antenna was connected with all the straplets in parallel, through a series 50 ohm resistor, to a wideband 100 Watt amplifier which was swept in frequency from 2 to 8 Mhz. The magnitude and phase of the voltages on either side of the 50 ohm resistor were measured, from which the complex impedance could be calculated. The results of these measurements are shown in Fig. 10. These measurements are in contrast to theoretical predictions of large loading spikes expected from the contributions of global Alfvén waves [10] for our experimental conditions. The loading due to the Alfvén continuum, which theoretically couples to the B_z field of a fast wave launcher such as this antenna through mode conversion processes [11, 12, 13] is probably what is observed, and the fact that we see a rising loading at the lowest magnetic fields in Fig. 10b would then reflect the fact that the Alfvén resonance surface is moving to the edge, closer to the antenna. The main implication of this data for us is that the loading is poor no matter what the conditions and poses strict demands on the efficiency of the antenna.

High Power Operation

After the low power measurements, we performed a series of shots where power levels of up to 100 kW were applied to the SSL antenna and, for comparison purposes, to the strap antenna. Nearly identical conditions of toroidal magnetic field, gas, and machine conditioning (especially the time since the last boronization, which reduces impurities and fuelling) were maintained. We operated only 1 strap of the conventional strap antenna on

the low field side and only one unit of the SSL antenna, a configuration equivalent to zero phase operation of a pair of antennas, that is, a condition likely to generate the most impurities and fuelling. The traces of density, soft x-rays, RF power, and loop voltage during these shots are shown in Figs. 11 (SSL antenna) and 12 (Strap Antenna). The soft x-ray signal is chiefly an indicator of the impurity level since it is sensitive to vacuum ultraviolet line radiation. The RF power traces shown here are the net coupled power, with copper and capacitor losses and reflections subtracted. We see that the density rise and soft x-ray increases due to the RF are reduced by a factor of 3 for the SSL antenna. The possibility that the rise of the soft x-ray signal might be due to plasma heating can be discounted, based on the following considerations: 1) The only clear evidence of heating in RF experiments on Phaedrus-T with the conventional strap antenna are when the operation is at higher power levels (100 kW or more) and when 2 straps are excited at 180° phase [7]. 2) The primary indications of such heating are a marked drop in loop voltage, which, as shown in the data in Figs. 11 and 12, is not present here. Though much more experimentation has yet to be done, we clearly find an improvement in the density rise and impurity production with the SSL antenna. Although conditions are identical in most respects, we must point out that the SSL is mounted on the high field side, whereas the strap antenna is on the low field side.

Finally, in a final test in this series of experiments the power was pushed up further, to establish what limits there might be, and a level of 100 kW was reached before arcing problems in the resonating capacitors developed. The voltage and current traces for these shots are shown in Fig. 13. We see that a peak current of 6000 amperes was reached, and

this with an input voltage of under 300 volts. This is in sharp contrast to the strap antenna, which for an equivalent current (600 A RMS) the input voltage is 18 kV (RMS). We note that we can only roughly verify the scaling of the impedance $Z_{ssl}=Z_{strap}/N^2$. In these experiments the strap loading was $.3 \Omega$ whereas the SSL loading was $.8 \text{ m}\Omega$. The SSL loading is a factor of 3.75 below the scaling (here $N^2=100$), which we believe is due to excessive losses in the strap antenna due to capacitive coupling to the edge plasma. It may be, however, that the differences between high and low field side operation, as mentioned in the previous paragraph, can be blamed for the differences in loading.

Current Drive Operation

The above experiments were performed using a single antenna element. To perform current drive experiments, we connected the pair of SSL antennas to separate matching circuits and then to independent transmitters. This has been done in our current drive experiments with the conventional strap antenna in which we have found evidence of current drive [14]. The details of the matching process are somewhat different, especially in the decoupling circuitry. The conventional antenna has decoupling mutual inductances in the ground return leg of each strap [5]. Such an arrangement was not practical for the SSL, so a circuit was developed which incorporated the decoupling into the matching circuits external to the vacuum tank. When the SSL was operated with 90° relative phase between the currents in each unit, at a power level of up to 75 kW coupled power, we observed small loop voltage changes. The results of these experiments, and of similar experiments at higher power using the conventional strap antenna, are shown in Fig. 14. In Fig. 14a we show the loop voltage behavior for typical shots using both the

conventional strap and the stacked stripline antennas. Also shown are fitted curves to illustrate the meaning of the transient and steady state voltage dips. The fitting function is, during the RF pulse, a transient part which decays exponentially, the amplitude of which is called the "transient voltage dip", and a constant part called the "steady state voltage dip."

In Fig. 14b we plot the power dependence of these loop voltage changes. The current drive efficiency, defined as the slope of the steady state dip with power, appears to be similar for the two antennas. Likewise, the transient part scales in a similar fashion. The meaning of the transient and steady state parts has been related to the presumed minor radius at which the current drive is taking place [15].

These preliminary experiments have shown that the current drive efficiency seems to be comparable to that of the conventional strap antenna, and thus validates the SSL as a functional RF coupler. Experiments to find the optimum experimental conditions for current drive, and to increase the power, are underway at the time of this writing.

Stacked Stripline Design for Large Fusion Devices

We note that the detailed antenna design used for our experiments on Phaedrus-T is not suitable for use in a large fusion device, especially a reactor. Although the voltages are much reduced, the high current feedthrough would be cumbersome and unreliable and would probably introduce unacceptable losses. It turns out, however, that the high current feedthrough can be eliminated in a large machine, and the SSL antenna concept can be very simple. This is due to the fact that the higher frequency and larger size of a reactor design makes it very easy to incorporate the resonating capacitance inside the antenna. In fact, this capacitance is easily provided by what would normally be considered parasitic

capacitances from the feed line to ground. We present here a simple, approximate design to illustrate the concept.

We take for operating conditions a scenario for the ITER tokamak wherein ion heating at ω_{CD} is applied at a frequency of 43 MHz [16]. We copy the antenna dimensions from ref. 16: a total strap length in the poloidal direction of 3 m, a strap width w of .4 m. In ref. 16 the strap width was .2 m, but the width of the Faraday shield was at least .5 m. Since we are replacing strap and Faraday shield with the SSL, we choose to fill some of the width formerly occupied by the Faraday shield with SSL straplet width to keep the inductance low. We use a strap to backplane distance d of .25 m, which is the same as the distance from backplane to Faraday screen as in ref. 16. For our calculations we use simple formulas, such as that the inductance of a straplet is $L = \mu_0 h d / w$ where h is the feed to return conductor spacing, w is again the straplet width, d is the length of the straplets in the minor radial direction (the same as d mentioned above), and μ_0 is the free space permeability. We have found that this formula is accurate to 10% for the Phaedrus-T antenna's measured inductance. The losses are computed using the room temperature inconel conductivity of about 1×10^6 S-m and taking into account the skin effect. We do not take into account the slightly greater losses due to current crowding near the edges of the conductors. The design we have arrived at is shown in Fig. 15 and described in Table III. The resonating capacitance per straplet is provided entirely by the 1 cm gaps from the hot-side of the straplet to ground. We note that the unloaded Q is fairly high for this design (although we have not taken into account losses due to currents induced elsewhere in the machine). This good efficiency is a result of the close proximity of the resonating

capacitance to the antenna's inductance, minimizing the distance over which the circulating current must flow. Thus, even with bare inconel as the antenna material the losses are negligible. The loading due to the plasma that we have used is also copied from ref. 16, a value of $5 \Omega/\text{m}$. We chose 30 as the number of straplets in order to get the resonating capacitance to work out using 1 cm gaps. One can vary this value to get lower voltages at the expense of some complexity and structural rigidity. This design produces a voltage of about 6600 volts RMS at the feed line for a power of about 3 MW. Whether this is acceptable is a matter for further study. We suspect that the voltage that exists on the Faraday shield rods of a conventional Faraday shielded antenna is comparable to this, and so it is probably acceptable to operate this SSL antenna without further shielding. The input resistance of the antenna, we note, is given approximately by $R_{\text{in}} = Q^2 R_{\text{strap}} / N^2 = 13.8 \Omega$ where N is the number of straplets, Q is the loaded quality factor, and R_{strap} is the single strap loading, here 15Ω . We see that the impedance presented to the input transmission line is in a comfortable range for coaxial lines, and the low voltage can be maintained and the VSWR can be held low. It is likely that a design could be produced in which there were no ceramic insulators inside the reactor vessel. Further, since the straplets are short and well supported, it is likely that this design can tolerate high disruption forces.

Conclusions

We have developed and installed a new type of fast wave launcher in the Phaedrus-T tokamak, the Stacked Stripline antenna, which operates at greatly reduced voltages compared to conventional strap antennas. Initial tests show reduced impurity generation

and RF induced fuelling and showed some small current drive effects similar to those observed with the conventional strap antenna. Loading measurements were conducted at low and high power, and showed that capacitive coupling effects present on the unshielded strap antenna were reduced or eliminated. A high current RF feedthrough was developed in order to handle the much greater RF currents necessary to feed the antenna, and though it contained epoxy sealing materials it was not found to create impurity problems in the tokamak operation. The design of the SSL antenna is found to scale favorably to larger tokamaks, where resonating capacitance is easy to incorporate inside the vacuum chamber and neither large voltages or currents need to be carried accross the seals.

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Table I Phaedrus-T parameters

Toroidal Field	.9 T
Plasma Current	100 kA
Major Radius	.92 m
Minor Radius	.26 m
Line Averaged Density	$2 \times 10^{13} \text{ cm}^{-3}$
Electron Temperature	500 eV

Table II Typical conventional strap antenna operating conditions

RF Power	300 kW (150 kW per strap)
Ohmic Power	150 kW
Frequency ($\omega/2\pi$)	7 MHz
Inductive Reactance (ωL)	30 ohms
Plasma loading (R_p)	.2 ohms
Strap Resistance (R_s)	.12 ohms
Strap Current (I_s)	600 A rms
Antenna Voltage ($I_s\omega L$)	18 kV rms
Voltage due to plasma (I_sR_p)	120 V rms.

Table III Parameters of SSL design for ITER 43 MHz operation

Frequency	43 MHz
Material Conductivity (Inconel)	1×10^6 S-m
Equivalent Strap Loading	15 Ω
Antenna Height (poloidal)	3 m
Antenna Width (toroidal)	.4 m
Antenna Depth (minor radial)	.25 m
Straplet Current	447 A
Resonating Capacitance (per straplet)	250 pF
Straplet Inductance	55 nHy
Voltage (feedline)	6600 VRMS
Power	3 MW
Loaded Q	28.8
Unloaded Q	912

Figure Captions

Fig. 1. Schematic representation of the folded waveguide antenna. When assembled, the front mask shown is bonded and connected electrically to the waveguide structure. The waveguide is operated as a resonator, the front face being the location of a short (voltage minimum, current maximum).

Fig. 2. The Stacked Stripline antenna. Here strip transmission lines are operated as separate TEM resonators, all in the same phase.

Fig. 3. A Stacked Stripline antenna with the sidewalls cut back so as to modify the k spectrum of the field.

Fig. 4. B_z fields vs z of test antennas and model calculations. The measurements are taken at $x=1.5$ cm and at $y=0$, the midplane of the antenna. The x,y,z coordinates are shown in Fig. 3, and they are all 0 at the center of the front surface of the antenna. The sheet current model and conventional strap are calculations as discussed in the text.

Fig. 5. B_z field vs x of the test SSL antenna without the sidewall and of the calculations for the sheet current model and conventional strap as discussed in the text. Here $y=0$, $z=0$, the center of the antenna.

Fig. 6. Power spectra of the test antennas, with and without sidewalls. These were obtained by Fourier transforming the data shown in Fig. 4.

Fig. 7. The Phaedrus-T SSL antenna, two of which have been installed, side by side, in Phaedrus-T. The straplets have been given a 4.6 degree tilt in the y-z plane to align with the total field of the tokamak equilibrium.

Fig. 8. The B_z field measured inside the straplets and on the surface facing the plasma (though the measurements were not taken with plasma present, they were made with the antenna installed in the tokamak vacuum chamber).

Fig. 9. Low power loading measurements taken during a plasma shot.

Fig. 10 a) Loading resistance measurements vs toroidal field B_t and frequency, plotted as a surface plot. The density was $1 \times 10^{19} \text{ m}^{-3}$ (line averaged) and the gas species was hydrogen. b) The same data, but plotted as conventional plots.

Fig. 11. Data from several diagnostics during a shot with power applied to the SSL antenna.

Fig. 12. Data taken under nearly identical conditions as in Fig. 11 except that the RF power was applied to the conventional strap antenna.

Fig. 13. Antenna data during a high power shot into tokamak plasma, showing the high current, low voltage nature of the SSL antenna.

Fig. 14. Current drive results using both the conventional strap antenna and the SSL antenna. a) Loop voltage trace for the conventional antenna at a power level of about 280 kW and for the SSL antenna at 73 kW. Also shown are fitted functions as described in the text. Here the RF was on from 100 to 150 ms. b) The power dependence of the loop

voltage dips for both antennas, showing that the SSL results lie roughly on the same line as the results for the conventional (LFS meaning Low Field Side) antenna.

Fig. 15. Example SSL antenna design for ITER 43 MHz operation. This is a simplified side view of a structure much like that shown in Fig. 7. Here, however, there is a single feed conductor A which connects all the straplets in parallel. Resonating capacitance is provided by the 1 cm gaps to ground and by the extra plate B. The grounded backplane box is shown by C. The dimension d is 25 cm, the straplet period p is 10 cm.

Fig 1

Fig. 2

Fig 3

Fig 4

Fig 5

Fig 6

Fig. 7.

Fig. 8

Fig. 9

Fig 10 a)

Fig. 10 b

Fig. 11

Strap Antenna

Fig. 12

Shot 46303

Fig 14 a)

Fig 14 b)