1. Purpose of Experiments

Include immediate goal of the experiments, scientific importance and/or programmatic relevance. Refer to any relevant program milestones.

The purpose of this experiment is to perform a systematic study of the coupling performances of the LH2 antenna.

The LH2 launcher is based on a novel four-way-splitter concept, which evenly splits the microwave power in four ways in the poloidal direction. The antenna has been designed based on the LH wave linear coupling theory [cite Bramb]. Simulations predict good plasma coupling and a clean N|| spectrum over a wide range of edge density profiles.

Experimental measurement of the antenna-plasma coupling and of the field pattern at the grill mouth is necessary for the validation of the numerical simulation and the assessment of the performance of the LH2 design. These measurements will allow a direct benchmarking of the 4-way-splitter concept to a conventional grill antenna (LH1) under the same operating conditions. These experiments will also provide an indirect comparison with other advanced LH antenna designs such as Multijunctions. Finally, optimizing the antenna coupling not only improves the efficiency of the system, but is also beneficial for reducing the Standing Wave Ratio (SWR) within the antenna structure and the transmission lines, which can lead to RF breakdown across the RF vacuum windows or in the residual gas within the waveguides.

A diagnostic composed of a set of 32 microwave probes [cite Jaquet] was designed to measure the fields in a carefully selected set of the grill waveguides. Coupling can be directly measured from the fields measured by this diagnostic. In addition, under certain circumstances, part of the antenna scattering matrix can be inferred. The probe diagnostic is also part of the Coupler Protection System (CPS).

The coupling efficiency strongly depends on the N|| of the launched wave, the plasma density and the plasma density gradient at the mouth of the LH antenna. The availability of accurate density profiles measurement provided by the C-Mod X-mode reflectometer is important to enable a better understanding of the wave coupling physics in different confinement modes or at high power. Currently, it is common practice to use the ambiguity of the edge density profile to make coupling simulations fit to the experimental measurements. The availability of an accurate density profile measurement eliminates these free parameters and enables a self-consistent validation of the LH coupling codes.

It has been shown that linear coupling theory is invalid at high power operation. It has been conjectured that this is due to the effect of ponderomotive forces on the edge plasma density. However, a definitive theoretical model in this regime is still missing, experimental observations are often contradictory and additional experimental information is therefore essential. The experimental results of this MP using the
microwave probe data will be important at supporting or ruling out the different theories which have been proposed.

Study of long-distance coupling is important for fusion reactors since the distance from the last closed flux surface to the launcher is such that the density at the grill is so low that LH waves are cut off. Finding methods for controlling the electron density in front of the coupler are ultimately needed to obtain good coupling.

2. Background
Discuss Physics Basis of the proposed research. Prior results at Alcator or elsewhere, and any related work being carried out separately.

The LH1 was used during the 2006-2007 and 2008 campaigns. MP464 by G. Wallace was devoted to the optimization of LH wave coupling with LH1. In the 2006 run campaign, ~40% of the klystron power was coupled to the plasma: 3dB loss from klystron to antenna, and an additional ~15% power reflection at antenna, after optimizing the equilibrium of the plasma to be conformal to the shape of the antenna.

Most of current active LH experiments (JET [cite C_Jet1,C_Jet2], Tore Supra [cite C_TS], JT60U [cite C_JT60U]) use multijunction antennas which have been proven to have better coupling efficiency that of “classic” grill antennas. Classic grill antennas from other experiments such as ASDEX [cite C_Asdex] or Alcator-C [cite Micklos _1984] exhibit reflections in the same order of C-Mod, and low reflection shots were achieved when the antenna was flush with the limiters.

The C-Mod coupling results have been explained by means of linear coupling theory codes (such as Brambilla [cite Bramb], ALOHA[cite Aloha] and TOPLHA [cite Topleha]). The density profiles in front of the grill (which previously were not experimentally measured) have been used as a free parameter to fit with the experimental coupling data under different operating conditions. It is important to note that in previous campaigns only the total coupling efficiency has been compared and not the detailed grill waveguide to waveguide coupling. Also for other tokamak experiments, linear theory has been proven to agree with experimental data, after optimizing the edge density profiles in the simulations. In particular, comparisons of the microwave probe coupling measurements from the TeDv experiment with calculations from SWAN code, showed good agreement for low RF power densities at the antenna mouth [cite Jaquet].

Some experiments [cite Bramb] reported that above a power density threshold of 0.5 to 4 KW/cm^2, the reflection coefficient decreases and becomes roughly independent of the phase between adjacent waveguides. On the contrary, previous experiments on C-Mod [cite Wth] and ASDEX [cite C_Asdex] showed a degradation of the coupling at high power: High power (400kW to 1MW) operation on C-Mod LH1 did not show any apparent trend, even though reflection coefficients are significantly higher (20% to 30%) than at low power. Also, high power coupling seems to have a slight dependency on phasing (90 degrees phasing showing best coupling, followed by 60 and 120 degrees phasing).

To affect matching, the non-linear mechanism responsible for this behavior must be effective in the near-field region. The most plausible cause is the effect of ponderomotive forces acting on the plasma surface, which drives the charged particles toward the weak field area, thus deforming the density profile in front of the antenna. It has been suggested [cite Brambilla] that the ponderomotive force is able to modulate the plasma density in front of the grill. The resulting refractive index modulation (which should be almost independent of the phase since the ponderomotive force depends only on |E|^2) would selectively favor coupling to values of n|| favoring the grill periodicity. Other theories [cite NagaPonder, GonAcc] suggest that the plasma is pushed away under the action of the ponderomotive force and predict an effective shift in the radial direction, thus creating a low density region where LH waves are evanescent and increasing the reflection coefficient.

Coupling of lower hybrid waves to the plasma depends mainly on the edge density. Therefore the distance between the grill and separatrix is a very critical parameter to be adjusted. Experiments on JET and ASDEX showed that good long distance grill-plasma coupling can be maintained when the LH pulse is started while the plasma is near to the grill and then moved away, where otherwise total reflection would occur. This feature improves when the gas valve is near to the grill. Localized gas puffing in JET was used also to improve coupling under the same conditions and it was shown that with increasing LH power, the required gas injection for obtaining good LH coupling is decreasing. Gas injection of deuterated methane
(CD₂) has been found to lead to a smaller increase in electron density in the SOL than D₂ (attributed to the recycling of deuterium), resulting in better LH coupling with D₂ [cite C_JET1]. JET reported the timing of gas injection with respect to when the LH power is applied (0.5 to 1 seconds) is important to allow the gas to diffuse and to be ionized [cite JET_gas_timing].

On C-Mod, localized gas puffing from the Neutral Gas Injection Array (NINJA) was tested at different LH power levels. Despite locally increasing the edge density in front of the LH antenna, the gas puffing system was not found to substantially improve coupling. Long distance coupling experiments with the launcher pulled back 5 mm from the LH limiter showed high reflection even if the density measured by the Langmuir probes was raised well above cutoff. However, variation of the separatrix distance similar to the ASDEX and JET experiments was not performed during the pulse, only D₂ gas was used and effect of timing of the gas puff was not studied.

In several experiments, deleterious cross-talk between LH and Ion Cyclotron (IC) heating schemes is sometimes observed for those ICRH antennae magnetically connected to the LH launcher. For the specific case of C-Mod, the J-port antenna did not substantially interact with the LH1, while the D-port antenna caused a considerable increase in the reflection coefficient, resulting in a trip of the LH system shortly after the ICRF turn-on. The E-port ICRF antenna also caused a degradation of the coupling, although not as pronounced as the D-port antenna. Studies in JET and TS [cite ColasStructure] reported a dependency of the interaction with ICRF phase. In JET, local gas puffing is used routinely to compensate density depletion in front of the LH launcher caused by ICRF.

On C-Mod it was observed that high power LH coupling in H-modes is better (by 5% to 10%) than in L-mode when ICRF is on, for a given density measured by the LH Langmuir probes [cite Wth]. However Langmuir probes are known to be unreliable during ICRF operation. LH triggered H-modes instead show a slight increase of the reflection coefficient. This is in disagreement with what is observed on JET [cite C_JET_Hmode] and JET60-U [cite C_JT60_Hmode], where the edge density drops in H-mode, leading to very high reflection of the wave. In this case, local gas puffing resulted in fixing the problem for JET.

3. Approach

Describe the methodology to be employed; explain the rationale for the choice of parameters, etc. Describe the analysis techniques to be employed in interpreting the data, if applicable. If the approach is standard or otherwise self-evident, this section may be absorbed into the Experimental Plan.

In usual LHCD C-Mod discharges the plasma-antenna distance tends to be smaller near the midplane. For common LSN (USN) discharges the lower (upper) part of the grill is usually farther from the plasma than the upper (lower) part. The density at the grill usually reflects the equilibrium asymmetry. Optimization of the plasma equilibrium to be conformal to the shape of the launcher helps at least in two ways. First, for a given plasma-launcher distance, the various rows are then likely to have a similar reflection coefficient. This is very important especially for 4-way-splitter based antennas, because such matching reduces poloidal unbalance and maximizes the power coupled to the plasma. Secondly, since the plasma flux reaching the limiters is poloidally homogenized, it allows to operate with a smaller distance between the grill and the separatrix.

The very first shots will be devoted to study the dependency of coupling to the shape of the plasma. A lot of attention will be given to optimize the shape of the plasma to fit the launcher profile, the goal being to even the coupling among the four rows of the grill. The shots which gave the best coupling from MP464 are a good starting point. The effectiveness of the shape optimization can be quantified by measuring the variation in the reflection coefficient from the probes installed in columns 8 and 9.

From figure 1 one can see that coupling efficiency strongly depends on the density profile at the mouth of the LH antenna. Also, since numerical simulations predict the LH2 to be sensitive to poloidal non-uniformities, these will be forced by shaping of the plasma. To study coupling as a function of the SOL density profile, the radial positioning of the launcher behind the limiters, gas puffing, and radial movement of the plasma column will be used. The X-mode reflectometer will be used to measure the actual density profile in front of the launcher at three poloidal locations. Using a linear density model, a crude estimate of the density and its gradient can be inferred by means of the Langmuir probes of different length (1mm and 2mm) mounted at the grill mouth.
It is also worth pointing out that at high density coupling tends to become insensitive to perturbation in electron density which could happen for example during ELMs, during gas puffing, or during high density striations which have been observed in front of the LH1 grill during high power operation [cite Wth].

Sweeping the phase while keeping all plasma parameters constant can be used to deduce the density profile in front of the launcher, under the assumption that linear theory holds true. Figure 2 shows the expected average LH2 reflection coefficient as a function of the antenna phasing. The density profile in front of the grill can be inferred by fitting the measured coupling data to the linear coupling theory model the density profile in front of the grill (for a linear model: density, scale length and vacuum gap). Figure 3 shows a plot of RMS error of the fitting procedure if an ideal linear density profile with ne0=9E17 [m^-3] and =15E-3 [mm] was to be measured. For this example a phase scan between 50 and 145 degrees has been considered (thus keeping the reflection coefficient always within acceptable limits). The plot gives an idea of the sensitivity of this method. The average density profile can be inferred by considering the average reflection coefficients of the whole antenna. However, for the specific case of LH2, this technique can be used to deduce the density profiles at four poloidal locations using measurements from the RF probes located on columns 8 and 9 of the LH2. Measurements from the Langmuir probes and the X-mode reflectometer will be used to check the validity of the phase scan method. If successful, this technique could be routinely used to infer density profile in front of LH antennas (also in other tokamaks) and could be the building block for a phase feedback control system which minimizes reflection.

When all the waveguides are energized the antenna reflection coefficient can be evaluated. The grill scattering matrix may be measured by energizing one waveguide at a time and measuring the reflection.
(self term) and coupling to all other waveguides (non diagonal terms) when they are loaded with a matched load. Under the assumption of a purely toroidal magnetic field, poloidal coupling is negligible and part of the scattering matrix of the bottom waveguides of the antenna can be directly measured. This is done by powering either column 8 or 9 (which are fed by a single klystron and have probes installed) and measuring the coupling to bottom waveguides. These shots are expected to have high reflection due to the absence of phasing. Disabling the CPS and operating at low power with short pulses is required.

The arrangement of the probes is shown in figure 4 and allows a direct measurement of : \( S_{8,2} \), \( S_{8,4} \), \( S_{8,6} \), \( S_{8,8} \), \( S_{8,9} \), \( S_{8,11} \), \( S_{8,13} \), \( S_{8,15} \) or \( S_{9,2} \), \( S_{9,4} \), \( S_{9,6} \), \( S_{9,8} \), \( S_{9,9} \), \( S_{9,11} \), \( S_{9,13} \), \( S_{9,15} \). If the magnetic field is purely toroidal then the scattering parameters among equally distant waveguides should be equal. Comparing the falloff of the coupling as a function of the distance between waveguides to the predictions of linear coupling theory models will give direct information on the plasma surface impedance.

At first it may seem that the 4-way-splitter design does not allow a direct measurement of scattering parameters, since the impedance at the feeding end of each of the grill waveguides is not a matched load. However, in the LH2 antenna, not a single waveguide but a whole 4-way-splitter is energized at a time. The splitters were designed so that if the plasma load is the same on all rows, and the same power goes into the grill waveguides, then no power is reflected back to the plasma (this design choice was taken to keep the fields inside of the grill waveguides as low as possible). This is effectively similar to having waveguides which present a matched load. Simulation results proving the validity of this method are shown in figure 5. In the experiment, measurement of the forward power in the waveguides will indicate how well this condition is met.

![Figure 4: Probes arrangement: RED (singly fed klystron probes), BLUE (doubly fed klystron probes), GREEN (dummy column probes), ORANGE (not connected probes)](image)

The arrangement of the probes is shown in figure 4 and allows a direct measurement of : \( S_{8,2} \), \( S_{8,4} \), \( S_{8,6} \), \( S_{8,8} \), \( S_{8,9} \), \( S_{8,11} \), \( S_{8,13} \), \( S_{8,15} \) or \( S_{9,2} \), \( S_{9,4} \), \( S_{9,6} \), \( S_{9,8} \), \( S_{9,9} \), \( S_{9,11} \), \( S_{9,13} \), \( S_{9,15} \). If the magnetic field is purely toroidal then the scattering parameters among equally distant waveguides should be equal. Comparing the falloff of the coupling as a function of the distance between waveguides to the predictions of linear coupling theory models will give direct information on the plasma surface impedance.

![Figure 5: Forward and reflected wave in the D row waveguides when only the 8th 4-way-splitter is energized. The forward power is very low in all of the waveguides besides column 8. The measured reflected wave agrees with the magnitude of row 8 of the grill scattering matrix.](image)

It is not clear if we can expect the performance of the antenna to improve or degrade at high power. This is especially true for the C-Mod 4-way-splitter based antenna, for which density profile changes on one row
can affect the power output in the others. There is a possibility of self-regulation feedback. This hypothesis would require a study of how high power coupling depends on antenna phasing and plasma density on C-Mod. The microwave probes may be used as a tool to effectively investigate the causes of non linear coupling at high power. In fact, if ponderomotive effect results in a shift of the density profile, then we can expect to see the phase of the reflected waves increase with power. If this is observed, the phase sweep technique could be used to infer the density profile in front of the grill at different power levels. We can instead expect a more complicated dependency of the phase of the reflected waves, if the ponderomotive force results in density modulations in front of the grill. In this case the finite element COMSOL code (which is able to model non-uniformities of the plasma) will be used to interpret the experimental data.

First, we investigate the effects of long distance coupling by radial displacement of the plasma column. Good long distance coupling is expected if the LH pulse is started while the plasma is near to the grill and then moved away. Effectiveness of this technique can be evaluated by reversing the process and start the LH pulse while the plasma is far from the grill and then moved closer. Some amount of hysteresis is expected, also depending on the power level. Localized D₂ gas puffing from the NINJA system will then be used to increase the density in front of the launcher. The effect of timing of gas injection with respect to LH power will be investigated. In subsequent shots, injection of the same amount of gas from the main gas valve should be used to assess whether change in coupling is indeed a local effect. LH coupling measurements at high power in H-mode and I-mode can be collected in piggybacking of other experiments, provided that injection of low power LH waves is allowed.

Measurements in the 2007 campaign [cite Wth] detected Parametric Decay Instability (PDI) waves at 4.6GHz ± 30 MHz having -10dB amplitude with respect to the pump wave (ne=1.5E20). We expect this wave to be coupled to the LH launcher waveguides. Detection of the PDI signal from the microwave probes array may allow measurement of the PDI wave N\text{TOROIDAL} and N\text{POLOIDAL} mode numbers. An initial assessment of the probes PDI signal level should be done by directly connecting a spectrum analyzer to one of the probes cables (possibly one of the A6 probes, or a dummy column probe). Since PDI level increases exponentially with density and grows linearly with injected power, high density high power operation will be needed. If detection of PDI by microwave probes is successful, in upcoming run campaigns measurement of the PDI forward and reflected wave in the LH launcher waveguides could be achieved by a modification of the current microwave diagnostic electronic which will require an heterodyne detection scheme.

4. Resources

4.1 Machine and Plasma Parameters

- Toroidal Field: 5.4 T
- Plasma Current: 800 KA
- Working Gas Species: D₂
- Density: n₀ 1e19 – 1e20 m⁻³
- Boronization: NO
- Equilibrium configuration: 1070413005 (conformal shape)
  1080108008 (high triangularity shape)
  1080320017 (typical LH1 shape)

4.2 Auxiliary Systems

- ICRF Power, pulse length, phasing: E-port, 0.5s, 00, 0pi
- LHCD Power, pulse length, phasing: 200kW to 1MW, 0.02 0.5 s, 0 to 180
- Pellet Injection (species): NO
- Impurity blow-off injection: NO
- Diagnostic Neutral Beam: NO
- Special gas puffing: NINJA LH_B and LH_D capillaries
- Cryopump: Preferable
- Non-axisymmetric Coils: NO

4.3 Diagnostics

- LH microwave probes
- LH Langmuir Probes (swept mode)
- LH visible camera

June 16, 2010
5. Experimental Plan

5.1 Run sequence Plan

Specify total number of runs required, and any special requirements, such as consecutive days, no Monday runs, extended run period – 10 hours maximum – etc.

Two run days are required. The first day will cover low power LH wave coupling experiments which do not require high performance plasmas. Coupling experiments requiring high power and high performance plasmas will be done the second day of the MP.

5.2 Shot sequence plan

For each run day, give detailed specification for proposed shot sequence: number of shots at each condition, specific parameters and auxiliary systems requirements, etc. Include contingency plans, if appropriate.

DAY 1

1. Verification of new launcher:
   1. **Conformal equilibrium:** Low power (200 kW) pulses, with launcher radial position at 1.0mm. Any antenna phasing is fine. Start with equilibrium from 1070413005 and change equilibrium trying to minimize poloidal coupling asymmetries. [4-8 shots. Could be done during conditioning MP]
   2. **Shaping:** Long (0.5 s) low power (200 kW) pulse, with launcher radial position at 1.0mm. Any antenna phasing is fine. Target \( n_{04} \) densities of 4E19. Start with conformal equilibrium and increase triangularity so to have plasma closer to rows B and C. Vertical displace the plasma to force the plasma to be closer to row A first, and row D after. [4-8 shots. Could be done during conditioning MP]
   3. **Benchmark of linear theory:**
      1. **Density sweep:** Long (0.5 s) low power (200 kW) pulse, with launcher radial position at 1.0mm and conformal equilibrium. For 70, 90, 145 degrees phasing, smoothly increase \( n_{04} \) density during LH pulse in three steps: 0.5E19-4E19, 3E19-7E19 and 6E19-1.1E19 m\(^{-3}\). Repeat with radial position of the launcher at 2.0mm. [6-9 shots]
      2. **Increasing radial gap:** Long (0.5 s) low power (200 kW) pulse, with launcher radial position at 1.0mm and conformal equilibrium. For 70, 90, 145 degrees phasing, smoothly displace the plasma radially from grazing the LH limiter to -1cm. [3-6 shots]
      3. **Phase scan technique:** Long (0.5 s) low power (200 kW) pulse, with launcher radial position at 1.0mm and conformal equilibrium. Steady density at \( n_{04}=4E19 \). Smoothly sweep the phase from 50 to 145 degrees 5 times during each shot. Radially displace the plasma from -1.0cm to grazing in 5 discrete steps. Target \( n_{04} \) densities of 2E19, 4E19, 6E19. Disable CPS. Repeat with radial position of the launcher at 2.0mm. [6-9 shots]
      4. **Scattering matrix measurement:** Short (10ms) very low power (100 kW) pulses with low duty cycle (25%), 6 segments. Segments 1 and 4 power all the grid with 90 degrees phasing. Segments 2 and 5 shoot power only from column 8. Segments 3 and 6 shoot power only from column 8. Launcher radial position at 1.0mm, target \( n_{04} \) densities of 4E19 and conformal equilibrium. Disable CPS. [2-4 shot]

DAY 2

5. **Coupling at high power**

1. **Power sweep:** Long (0.5 s) pulse, with launcher radial position at 1.0mm and conformal equilibrium. For 70, 90, 145 degrees phasing, linearly increase power from 200 kW to 1MW. Target \( n_{04} \) densities of 4E19 and 1E20. [6-9 shots]
   2. **Phase scan at different powers:** Long (0.5 s) pulse, with radial position at 1.0mm and conformal equilibrium. Linearly increase power from 200 kW to 1MW throughout the shot. Oscillate phase between 80 to 100 degrees (triangular waveform, 30 full oscillations). Target \( n_{04} \) densities of 4E19. [2-4 shots]
6. Coupling at long distance
   1. **Gas puffing:** Long (0.5 s) high power (1 MW) pulse, with launcher radial position at 1.0mm and conformal equilibrium. 90 degrees phasing. Puff 5 psi D$_2$ from NINJA capillaries starting 0.75, 0.5, 0.25 and 0.0 seconds before LH turns on. Once best timing is found, repeat shot with 2.5mm and 5.0mm radial position of the launcher. [5-9 shots]
   2. **Increasing radial gap:** Long (0.5 s) high power (1 MW) pulse, with launcher radial position at 1.0mm and conformal equilibrium. For 90 degrees phasing, smoothly displace the plasma radially from grazing to -1cm. Repeat with best NINJA settings from previous point. [3-6 shots]

7. Coupling, with ICRF: Long (0.5 s) high power (1 MW) pulse, with launcher radial position at 1mm, 90 degree phasing and conformal equilibrium. Turn on 1MW E-port ICRF antenna while LH is already on, and change ICRF phasing from 00 to 0π. Repeat with D$_2$ gas puffing from NINJA with best conditions found in point 9. [4-8 shots, if time allows. May be chances for collecting data without NINJA puffing in piggyback]

PIGGYBACK
8. **PDI feasibility study:** High power (~1 MW) pulses. High density (e.g. nl_04=1E20) and high field. Equilibrium matching limiter shape is preferable. [Piggybacked to LHCD in high density regime MP]
9. Coupling H and I modes: Low power (200 kW) pulses, with launcher radial position at 1mm. Equilibrium matching limiter shape is preferable.

6. Anticipated Results
Discuss possible experimental outcomes and implications. Indicate if the program may be expected to lead to publications, milestone completions, improved operating techniques, etc. Indicate if the experiments are intended to contribute to a joint research effort, an ITER request, or an external database.

Verification of LH2 and microwave diagnostic design. Benchmarking of 4-way-splitter design concept. The outcome of this MP has important implication for the LH3 launcher to be installed on C-Mod. Validation of LH wave coupling codes with known density profile from X-mode reflectometer. Direct measurement of the grill scattering matrix.

Prove feasibility of measuring the density profile in front of the LH antenna by means of phase scan technique. This technique will ultimately show if evanescent region is required for agreement between coupling codes and experimental results. If successful, could be routinely used to infer density profile. Comparison with X-mode reflectometer density profile may point out that other physics is going on.

Microwave probes offer unique opportunity to study high power coupling in detail and compare to existing theories. Further verify if localized gas injection methods works on C-Mod for improving long distance coupling and presence of ICRF.

7. References
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