Commissioning of the Lower Hybrid Current Drive System on Alcator C-Mod


Abstract— A Lower Hybrid Current Drive (LHCD) system has been developed for current profile control of advanced tokamak experiments on Alcator C-Mod. LHCD along with Ion Cyclotron Radio Frequency (ICRF) heating will be used to develop regimes with high confinement, high βn and high bootstrap fraction and extend them to quasi-steady-state conditions. This paper will describe the commissioning and initial operation of the LHCD system that includes a 50kV, 208A pulsed-power supply, twelve 250kW Klystron transmitters, a 96 waveguide launcher and required control, protection and data acquisition systems.

I. INTRODUCTION

UNTIL high-performance high-bootstrap-fraction regimes with fully non-inductive current drive have been produced for pulse durations significantly greater than the resistive diffusion time, dedicated experiments will be required to verify the assumptions used in advanced reactor designs. Lower Hybrid Current Drive (LHCD) experiments on Alcator C-Mod are planned to tailor the current and pressure profiles to reach regimes of high bootstrap fraction (≥ 70%), high βn (∼ 3) and good confinement ( HH ∼ 1–2) [1]. These experiments could help to support the design basis for advanced tokamak reactor designs, at least up to moderate bootstrap fractions (∼ 70%), and provide a basis for advanced operation in ITER. Alcator C-Mod is well suited for the development of advanced tokamak (AT) scenarios due to its internal PF coils which enable the strong shaping required for high βn, sufficient installed ICRF source power to reach high βn at 5 T and cryogenically cooled magnets which allow sustained 5 T pulse durations at up to 5 s (several resistive diffusion times). The existing 8 MW (source) ICRF system and the installed 3 MW (source) LHCD system operating at 4.6 GHz into a single launcher are the tools for the required experiments [2]. With waveguide losses and power density limitations, the maximum delivered LHCD power is expected to be 2 MW. A second phase is planned which will add another launcher and 1 MW of source power. This paper will briefly describe the LHCD system, required calibrations, phase setting and initial commissioning and coupling studies on Alcator C-Mod. Results and plans will also be discussed.

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II. LHCD SYSTEM

A. Transmitters and Power Supply

Three carts with four klystrons each operating at 4.6 GHz and rated 250 kW CW provide 3 MW source power for the LHCD system. A single 50 kV, 208 A power supply is used to power all klystrons. Carts are semi-independently controlled and have a fast Transmitter Protection System (TPS) and programmable logic controller. Critical protection, control and status information is shared between transmitter carts and the high-voltage power supply for coordination of overall control tasks. Klystron window optical arc detection and reverse power fault detection circuits in the TPS provide fast transmitter shutdown while klystron output circulators are rated to handle full reflection at full power for a 5 s pulse. Rectangular waveguide (WR187) operating in TE10 mode is used to connect transmitters to the launcher. Waveguides are pressurized with 10 psig nitrogen at the transmitter and the launcher is separated from the transmitter by DC blocks and pressure windows. The Coupler Protection System (CPS) is designed to monitor 60 forward and 156 reverse power sample points and recognize voltage standing wave ratio faults [3].

B. Launcher

Power is coupled to the plasma by 96 waveguides arranged in 4 rows of 24 waveguides, with each klystron output being split 8 ways into two waveguide columns with 4 waveguides each [4]. Vacuum windows are positioned in front of the cyclotron resonance at 4.6 GHz. The couplers, forward waveguide assembly (FWA) and rear waveguide assembly (RWA) are major launcher subassemblies. (Fig. 1). Note that the RWA two-way splitter, magic Ts and directional couplers are not shown. Four identical aluminum gaskets are used for the RF seal between the RWA and FWA and between the FWA and couplers. Tight control of gasket dimensions is required and careful alignment of the mating waveguides is required to provide adequate gasket compression and to avoid gasket protrusion into the waveguides at the joint.

1) Rear Waveguide Assembly: The RWA is fabricated of 25 stacked plates with four waveguide slots milled into one side of 24 of the plates. Aluminum construction is used for the RWA as it is located well away from the plasma and disruption loads.
are reduced. A two-way splitter with magic Ts, high power mechanical phase shifter, four directional couplers and four E-plane transformers are used to split each klystron output into four feeds for the RWA stacked plates. The final 3 dB splitter is formed by slots in the wall between the top two and bottom two stacked plate waveguides. Measured power split at this splitter is -3.2 ±0.15 dB and loss in the stacked plate waveguides is the same as loss per waveguide in the FWA.

2) Forward Waveguide Assembly: The FWA is similar in construction to the RWA stacked plates except it is made of stainless steel to reduce disruption loads. These plates were copper-plated and polished before assembly. Transmission losses were measured to be about 0.33 dB/m except for two with 0.5 dB/m. These waveguides also include H-plane transformers that transform the 6 cm width of the coupler waveguides to the 4.75 cm width of standard WR 187 waveguides. Flexibility in the location of these transformers is taken advantage of to compensate for additional phase shift caused by the poloidal curvature of the couplers.

3) Couplers: Each of four couplers consists of 24 waveguides measuring 5.5 x 60 mm in cross-section. They were fabricated from titanium by wire electrical discharge machining and 24 ceramic windows were brazed into each of the waveguides near the end of the coupler that joins to the FWA. Viton seals located between the couplers and FWA form the vacuum seal.

C. Control

Lower hybrid driven current location depends on the launched n|| spectrum, plasma temperature and density profiles. Dynamic control of n|| during the plasma pulse is thus a key consideration, since such capability could eventually be useful in feedback control of the total current profile and in optimizing steady-state performance. Klystron output amplitude and phase control can be realized at the low power klystron input drive level. The LHCD Active Control System (ACS) controls klystron output amplitude and phase, with key components being in-phase and quadrature (I/Q) vector modulators (VM) and I/Q detectors [5]. A single master oscillator split 12 ways provides drive for each klystron through the computer-controlled VM, allowing n|| to be varied from 1.5 to 3 [6]. The oscillator is also used as phase reference, or local oscillator (LO) for I/Q detectors used to monitor the 50 dB intermediate directional coupler (IDC) forward outputs. In open-loop mode the VM I/Q inputs are determined by operator entry of demanded amplitude and phase setpoints to the control computer. I/Q detectors monitor the in-phase and quadrature phase amplitude and phase components at the IDC for each of the 12 klystrons. The closed-loop control programs are designed to compare operator amplitude and phase demand requests in terms of I/Q to the I/Q detector outputs and to calculate error signals used in determining VM setpoint inputs. Closed-loop control should allow variations due to drift in klystron output phase or amplitude, or waveguide heating, to be reduced. Time response for modifying the n|| spectrum during a plasma pulse is designed to be less than 1 ms. Relative phase of the two columns fed by the same klystron can be varied with a high power mechanical phase shifter (MPS) between plasma shots, but this can only be done between plasma shots and requires a cell access. (Fig. 2).

III. CALIBRATIONS

Many calibrations are necessary to allow control, monitoring and protection of the LHCD system. Twelve transmitter forward and reverse power signals, 12 ACS klystron drive signals, 48 RWA directional coupler forward and reverse power signals and 96 rear and front RWA probe reverse power signals must be calibrated. Also, the 12 IDC signals located at the control phase plane are split (forwards) and must be calibrated for control, protection and monitoring in both the ACS and Coupler Protection System (CPS). Due to time constraints, complete calibration of some signals was not possible before commissioning. Combined measurements and calculated estimates were used to provide signal scaling during commissioning for all of the above except the drive and monitor legs, which were carefully calibrated for amplitude and phase using the network analyzer. To produce the spectra at high power it is necessary to have an accurate mapping of the amplitude and phase produced at each of the IDCs vs. the demand settings requested by the operator.

A. Drive Leg Calibrations

Drive leg calibrations are carried out by replacing the master oscillator feeding all VMs with network analyzer port 1. Port 2 is connected to the leg IDC forward outputs used to define the
phase plane between RWA and FWA. The drive legs are non-linear, and ACS programs generate setpoint scans of possible I/Q values and apply them to the VM as amplitude and phase measurements are made. Mapping the demand values vs. the measured values produces a look up table used in calculations that determine I/Q setpoint values. These values are required to produce operator demanded amplitudes and phases at the IDC for each leg over the operating range.

B. Monitor Leg Calibrations

Monitor legs include the IDC forward outputs and I/Q detectors and provide the only system phase monitoring points. A method similar to that used in calibrating the drive legs is used, except that a single calibrated VM and low power test amplifier drive leg is substituted for all drive leg klystrons. The calibrated test drive leg is connected to each monitor leg at the IDC forward output connection point and ACS programs generate setpoint scans of possible test leg amplitudes and phases as I/Q detector outputs are measured. Mapping of the calibrated test drive leg output amplitude and phase values vs. measured I/Q values produces a look up table used to report and scale actual phase and amplitude values at the IDC forward output.

C. Launcher calibrations

Ideally, the launcher would allow adjustment of amplitude and phase of the 12 splitter inputs to produce a constant amplitude and phase plane at the interface between the RWA and FWA. This can only be approximated due to path length variations in the RWA splitter network and any errors in the RWA stacked plate 3 dB power splitter. To calibrate these as closely as possible, shims were inserted in the splitter network to reduce path length effects. Network analyzer measurements were made from IDC input to the interface between RWA and FWA and variations were typically found to be within ± 5 degrees and ± 0.5dB. Residual amplitude and phase variation measurement results were used to calculate Fourier-transformed launch spectra as a function of programmed uniform phase shift progression. Measured residual errors give spectra which are very similar to the spectra produced if a perfectly constant amplitude and phase plane had been formed. The above calibrations and measurements form the basis of phase setting tables generated to simplify experimental setup.

IV. PHASE SETTING

To control the $n_||$ spectrum each waveguide’s characteristic phase shift must be considered in determining launcher phasing. Klystron phasing required for a desired phase at the phase plane is determined by subtracting the measured FWA front end phase from the measured IDC phase and then adding to the desired phase. Row A was chosen as the reference for phase control so, for example, the calculated klystron 1 phasing uses row A measurements to set the phase for columns 1 and 2, rows A-D. Phase differences between adjacent columns driven by the same klystron are minimized by using row A calibrations when setting the MPS. Ideal and approximate phasing methods were tested during commissioning.

A. Ideal Phasing

With ideal phasing the MPS are set to match the phase change from column to adjacent column, requiring adjustment of both klystron phasing and MPS for desired phasing. The wave is launched in either the current drive (CD) or counter current drive (CCD) direction by changing the phase rotation.

B. Approximate phasing

Approximate phasing is used to avoid the 45 minute delay required for experimental cell access to change the MPS. With this method, ideal phasing is approximated by leaving the MPS in a set position and adjusting the klystron phase demand. The MPS are commonly set to 90 degrees with current drive phase progression. Approximate phasing typically gives less power in the primary peak with loss increasing as the deviation from 90 degrees increases. With the low losses expected for most cases, the time saved using the approximate phasing method makes its use acceptable [7].

V. COMMISSIONING

A. Installation and Initial Tests

The coupler was installed on Alcator C-Mod during February and early March of 2005. (Fig. 3). Initial testing included successful checks of synchronization of the ACS, transmitter and LHCD data system operation with Alcator C-Mod shot cycles. Due to time constraints, drive leg calibrations were only done at 35kV klystron beam voltage. Although this would eventually limit going to higher power testing, other findings proved to limit this as well. The CPS worked as designed, but could not be used to protect the coupler since high reflected power was observed on pulses without waveguide arcs and low reflected power was observed on pulses with waveguide arcs. Thus, for the remainder of the commissioning period the CPS was bypassed and procedural limits were put on the test power and pulse lengths to limit possible coupler damage due to arcing.

B. First Measurements

First measurements of the reflection coefficient were made as a function of phase progression and density at the launcher mouth. Forward and reverse powers at 48 directional couplers located just before the E-plane transformers feeding the RWA were measured and their ratios were used to form reflection coefficients. (Note that direct calibration of these 96 signals during the initial commissioning was not accomplished and error bars could be as high as 20%). These measurements, made at very low applied power in the range of 200 kW total, were averaged to determine a single global reflection coefficient. Dependence of the global reflection coefficient as a function of phase and density at the launcher mouth as a parameter is shown in Fig. 4. During measurements the MPS was fixed at ± 90 degrees, where the + sign corresponds to the CD direction, the - sign to the CCD direction. A uniform phase progression occurs only at 90 degrees. Densities measured by six Langmuir probes embedded in the launcher face at launcher positions 1,3, and 5 mm (distance from launcher to limiter) vary over
the launcher face and are in the ranges $2.5 - 3.5 \times 10^{18}$, $0.8 - 1.3 \times 10^{18}$ and $2 - 3 \times 10^{17} \text{m}^{-3}$ respectively. Good coupling efficiency was obtained at relatively high density at the couplers ($\sim 3 \times 10^{18} \text{m}^{-3}$) and at optimal current drive phasing (90 degrees). Unfortunately, initial LHCD experiments had to be terminated due to interaction of the titanium couplers with hydrogen that led to loss of material from the couplers.

VI. IMPROVEMENTS AND PLANS

During commissioning the ACS operator programs were changed to allow more straightforward klystron amplitude and phase setting. The new programs allow fast setup of conditioning and experiment amplitude demand waveforms for each klystron and include operator entry of shot length, start and end power, pulse period and pulse duty cycle parameters. The programs also allow the operator to easily set up the phase demand settings for a range of experiments based on the calibrations and calculated ideal or approximate phasing requirements. A different approach to detecting arcs and protecting the launcher is required, and work has started on a method of detecting third harmonic signals during arcs which will require only two protection circuits for all waveguides. Other methods are being considered as well. Having the front probe forward output signals and rear probe forward output signals recorded was determined to be useful, so more monitoring channels are being added. To gain operating experience, commissioning was started with shorts instead of loads at the rear of the RWA. Loads were determined to be necessary for optimal operation of the RWA stacked plate 3 dB splitters. These loads have been designed and are being built. Adding switched dummy loads after the IDC will save much time in drive and monitor leg calibrations and system troubleshooting, and these have been added and are to be remotely controlled. Based on commissioning experience, programs to partially automate drive leg and monitor leg calibrations have been written and are being tested. Since experiments require frequent launcher position change, a system is being designed to allow remote positioning capability. Most importantly, fabrication of stainless steel couplers to replace the unplated titanium couplers damaged during commissioning is well underway.

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REFERENCES