1. Purpose of Experiments

We propose to demonstrate, for the first time, remote (off-site) operation of a tokamak. While engineering control (vacuum, cooling, power supply limits, etc) will remain under local control, physics control (Ip, ne, shape, heating...) will be controlled entirely at the remote site. While the principal purpose for this experiment is to demonstrate remote control, it will be an actual productive physics run. An experiment involving shape control, the reciprocating probe and RF heating would thoroughly exercise C-Mod systems, demonstrate the viability of the concept, and identify any areas in which further development might be necessary.

2. Background

As tokamaks have increased in size, cost, complexity, and performance, there has been a trend towards heavier reliance on remote collaborators controlling diagnostics at the experimental site. Examples of such collaborations are U. Wisconsin – TFTR, U. Maryland – MIT, MIT – TFTR, and LLNL – DIII-D. ITER and TPX will require remote operation not just of diagnostics, but of shape control, heating, etc.

Some issues relevant to remote control of a tokamak have been raised in references [1] and [2]. These include personnel and equipment protection, network security, common user interfaces, and sociological considerations. While the existing collaborations in the diagnostics area will continue to address these issues to some extent, the tokamak community has not yet tried to move control of a machine to a remote location. C-Mod is the first US tokamak capable of such remote operation.

LLNL, as part of their collaboration with General Atomics, is developing a remote control room (the Remote Experimental Site, or RES) which currently supports DIII-D operations with a distributed computations environment. While significant work remains...
to prepare DIII-D for remote operation, the control room itself is sufficiently functional to support C-Mod, and the RES group has invited us to use their facilities.

A collaborative attempt to control C-Mod for a complete run from LLNL will be useful both to anticipate issues that might come up as the LLNL - GA plans proceed, to provide input to currently funded efforts to develop a “collaboratory” concept for remote experimentation, and to provide the first experimental data point to guide the ongoing discussions of ITER and TPX remote control.

The proposed physics experiment will address ITER-relevant divertor physics. Of increasing interest to ITER is whether an auxiliary heated plasma can be sustained when a large fraction (80 -100%) of the power into the SOL is lost by radiation or charge exchange. We have chosen the following for the remote control experiment: For each of a selected set of auxiliary heating powers the central plasma density will be raised from shot to shot to determine under what conditions a dissipative divertor can be sustained. As the central plasma density is increased the radiation in the divertor will increase to dissipate the power that has flowed into the SOL. It is expected that with increasing additional heating powers higher densities will be required to achieve dissipative conditions. Interesting results could be achieved with as little as 1 MW of RF power.

The fallback proposal in case RF heating is unavailable will be MP84, Scrape-off Layer Characterization II.

3.a – Approach, remote operations

While some initial work is required to prepare both MIT and LLNL for this experiment, the actual running of the machine should not be very different from our routine operation. Ideally, the remote physics operator and the engineering operator would face each other via a video-conferencing circuit; in principle, this is the only difference.

(An alternative plan under consideration would identify a Communications Officer in the C-Mod control room, whose responsibility would be to coordinate the interaction of the remote and local physics groups with the local engineering operator. I would like to leave this as a fallback position, and use either IRC or TALK (keyboard-based conferencing tools), with all interested parties (including the EO) participating. The basic question is whether there needs to be a human filter to screen the physics and diagnostics “chatter” from the EO, or whether the EO and the PO can communicate effectively in the presence of other “conversations”. I regard answering this question as an interesting part of the experiment.)

The PO would log into physop via telnet. He would run the Plasma Control System (PCS) on physop as usual, with display set to the remote site; scopes could be run similarly, or using the RPC protocol. RF control would be remote, though tuning would remain local. Four MIT staff (a Session Leader from the Edge group, a Physics Operator from MHD, a representative of the RF group, and one of JAS or TWF) should be sufficient to support the planned physics run and to deal with unanticipated problems at the remote site. Systems support personnel at LLNL will be available as required.
There should be no peculiar personnel or equipment safety concerns. See the Appendix for relevant experience at LLNL.

3.b Approach, physics

The approach is to run a series of discharges with identical magnetic equilibria in the standard lower, single null configuration with different RF powers at different plasma densities. Plasma current would be fixed at 0.8 MA. RF power would varied from 0 to 2.0 MW (or the maximum available). Plasma densities would span the range \( \text{NL}_04 = 0.5 \times 10^{20} \) to \( 2.0 \times 10^{20} \text{ m}^{-3} \). The scanning probe would fire three times at each discharge. Plasma conditions in the divertor would be monitored with the divertor probe array for the onset of detachment. Post-run analysis of the scanning probe and divertor probe data would yield information on the extent of detachment (pressure drop along \( B \)) as a function of density and input power. An important requirement is that the magnetic equilibrium be identical at the scanning probe location for the three scans.

4. Resources

The primary technical requirement at the remote site is that it have available a sufficient number of medium – high performance workstations, connected to the internet by a high-speed link. A video-conferencing link would also be desirable. The Remote Control Room under development at LLNL meets these requirements. Workstation-based video conferencing hardware (a Silicon Graphics Indy) is operational to provide control room communications. Four additional X-displays are available from 3 dedicated SGI workstations plus an HP X-terminal. An HP9000/750 workstation and a VAX/VMS8600 computer will be dedicated to the operations with additional computations power available as required from Sun compute/file servers in the LLNL User Service Center.

See the Appendix for the current status of our preparations.

4.1 Machine and Plasma Parameters

Give values or range for:

Toroidal Field: 5.3 tesla
Plasma Current: 0.8 MA
Working gas species: deuterium
Density: Line-averaged density from 0.8 to \( 3.0 \times 10^{20} \text{ m}^{-3} \)
Equilibrium configuration: (1) Lower X-point diverted discharge similar to shot 950308011 having strike point locations on the vertical portion of both the inner and outer divertor surfaces. Inner gap and outer gap greater than 1.5 cm. Distance to second separatrix (SSEP on EFIT scope) greater than smallest gap. Maintain constant last-closed flux surface position near the scanning probe location for a minimum of 0.6 seconds.
Pulse length, typical current & density waveforms, etc. 0.6 sec minimum current flattop. Begin current rampdown at 1.0 sec.

4.2 Auxiliary Systems

RF Power, pulse length, phasing: 0 to 2 MW RF power
Pellet Injection (species): none
Impurity blow-off injection: none
Special gas puffing: none
Other: none

4.3 Diagnostics
List required diagnostics, and any special setup or configuration, e.g. non-standard digitization rate.

Standard set of core diagnostics including: Interferometer, ECE, central bolometer array, Visible bremsstrahlung, 2pi bolometer, Moly monitor. Edge diagnostics: Divertor probe array, fast-scanning probe, Reticon arrays viewing $H_\alpha$, divertor bolometer, RF limiter probes, Ratiom gas gauge, Divertor gas gauges.

4.4 Neutron Budget
Estimate the neutron dose rate at the site boundary. Give basis for estimate. (Once some experience has been gained a standard formula will be provided for estimating dose rates.)

Same as previous runs

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.

The shot sequence calls out 28 shots. Assuming 4 shots per hour, we have 7 hours under remote control. If we can take control remotely at 8:00 LLNL time or 11:00 MIT time, this implies a run ending at 6:00 PM MIT time. Therefore an extended run of 10 hours is indicated, which will give us a half hour contingency.

We will plan our initial attempt for Tuesday, March 28, and request an extended (10 hour) run on that day. If we fail due to difficulties with remote control (network failures, for instance) or local (MIT) difficulties with power supplies, etc, we would use March 29 as a backup day, and would accept a normal length run.
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.

The RF group has suggested that we vary rf power at fixed density, rather than density at fixed RF power. This change is under discussion.

Tune up a diverted 0.8 MA plasma with density \( \text{NL} \_04 = 0.5 \times 10^{20} \text{ m}^{-3} \) with specified gaps, strikepoints, and a steady scanning probe target position. This equilibrium will be used for the remainder of the run. Set up scanning probe to fire at .5, .7 and .9 sec. (5 shots)

Take data without RF power for discharges with \( \text{NL} \_04 = 0.5 \times 10^{20} \text{ m}^{-3} \) and \( \text{NL} \_04 = 1.0 \times 10^{20} \text{ m}^{-3} \). Duplicate shots at the same density may be needed in order to readjust the scanning probe insertion depth for changes in the LCFS target. (3 shots)

Program RF power to 0.5 MW for a 0.4 sec pulse length beginning at 0.6 sec. Take data at this RF power for discharges with density ranging from \( \text{NL} \_04 = 0.5 \times 10^{20} \text{ m}^{-3} \) to \( \text{NL} \_04 = 2.0 \times 10^{20} \text{ m}^{-3} \) in steps of \( 0.2 \times 10^{20} \text{ m}^{-3} \) (10 shots)

Program RF power to 2.0 MW (or maximum available) for a 0.4 sec pulse length beginning at 0.6 sec. Take data at this RF power for discharges with density ranging from \( \text{NL} \_04 = 0.5 \times 10^{20} \text{ m}^{-3} \) to \( \text{NL} \_04 = 2.0 \times 10^{20} \text{ m}^{-3} \) in steps of \( 0.2 \times 10^{20} \text{ m}^{-3} \). We may choose to skip over some of the lower density shots on which detachment is not likely to occur. We do need at least one low density shot in order to benchmark the EFIT flux mapping using the attached sheath-limited regime. (10 shots)

Time permitting, program RF power to 1.5 MW (or the appropriate mid range) for a 0.4 sec pulse length beginning at 0.6 sec. Take data at this RF power for discharges with density ranging from \( \text{NL} \_04 = 0.5 \times 10^{20} \text{ m}^{-3} \) to \( \text{NL} \_04 = 2.0 \times 10^{20} \text{ m}^{-3} \) in steps of \( 0.2 \times 10^{20} \text{ m}^{-3} \). Again, we may choose to skip over some of the lower density shots.

The fallback proposal in case the RF heating is unavailable will be MP84, Scrape-off Layer Characterization II.

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, or an external database.

This is a first attempt at remote control of a tokamak. If it is successful, we will have experimentally demonstrated the viability of the idea. We hope to prepare sufficiently that even failure will be interesting and yield useful data to guide a next attempt. In any event, we will contribute an experimental data point to the (so far) theoretical discussions of remote tokamak control. In the realm of divertor physics, the results of these experiments will allow us to determine the range in plasma density and total input power over which detached divertor conditions can be maintained.
7. References


Appendix

Status as of 3/9/95

1. Video Link. The LLNL group is in the process of setting up a new SGI. Initial attempts to set up a link have revealed that their video software does not match their operating system. They can receive us, but cannot transmit. Mark London is assisting them. We have moved our SGI (macon) to the C-Mod control room. (As of evening of 3/8/95, we have made a 2-way connection to llnl. Audio response was quite acceptable; video was 2-10 frames per second, depending on how we set the bandwidth. We had only 30 minutes of tests before their system went down for some scheduled maintenance, but initial results were promising.)

There is an ongoing debate about how to use the video link. I suggest we defer this decision at least until the proposed meeting on Monday, March 20.

2. Software. The MDS Scope and PAD utilities have been ported to the LLNL HP; no obvious problems have been seen.

We have made some modifications to IRC (Internet Relay Chat) and for several days have run a ”server” on macon. This program allows a conversation between several people. Tom has written a utility which injects state information into the conversation. We have used IRC over the past week or so to coordinate tests of the llnl/mit video connection. (To join the conversation, ”$ run IML$ROOT:IRC.EXE” and type “/join #cmod”).

A similar tool (VMS Phone) was used during a run as the communications link between the physics op and the engineering op. Both parties (Horne and Silva) found this a convenient communications method. We hope to use IRC during the run to allow anybody in either control room to interact with the operators.

We have done some experimenting using macon to test various IDL procedures (PCS and the Efit movie) when the display is set to a unix computer. No problems have been detected. Testing these tools is a high priority on our initial visit.

3. Network Security. I would like to claim that running the machine remotely cannot increase risks compared to running it locally. This claim is based on the fact that machine access and current limits are enforced via local PLC’s not hooked to the net; the only way to influence them is to go through the local engineering operator.

Tom Casper makes the following comments:

This is the same way we ran our free electron laser connected to MTX. For this case we had VMS systems talking to the PLC’s and the PLC’s did the real time control and machine safety. We had a UNIX/Xwindows-based expert program which served as the physics interface to the FEL control system for tuning and operations which communicated to the VMS world with interprocess communications, basically RPC’s. This system ran for 2-3 years without any problems (other than the normal problems of an experiment).
Since several of us will be logging into remote computers often over the next few weeks, the issue of “password sniffers” operating on nodes that don’t usually see our network traffic should be considered. Probably it’s sufficient for those of us who’ve been ‘exposed’ to change our passwords after the run.

3. Telephones. We’re considering setting up some speaker-phones. Tom Casper is checking on this at LLNL. Someone (Maybe Martin Greenwald?) should take care of our end.

4. Protocols. I don’t see any obvious difficulties here. We’re used to operating with communications between physics and engineering being funneled through the PO and EO. If a tool such as IRC is used, then all parties can look back at all the communication that’s occurred in the last couple of shots; the conversation can be logged automatically if desired. Horne is scheduled as PO on 3/16 and will attempt to use IRC then to communicate with the EO.

5. “Documentary.” The opinion has been expressed that we should try to film (with camcorders) some of the activity during the run. At the MIT end this should be relatively straightforward; at LLNL there may be perceived security issues. If it’s to happen there Tom Casper will have to set it up. Josh has agreed to be the camera operator at llnl – if things go well he’ll have nothing else to do; if he’s busy then we’re in trouble and don’t want to film. We need to identify a camera operator at the C-Mod end.

6. Preliminary Trip. Tom Fredian and Steve Horne will be at LLNL March 13-14. Josh will assist us from MIT in establishing a video connection and dealing with whatever problems we encounter. We will eavesdrop on the run and, if things go well and the PO for that run is co-operative, attempt to load a single shot. We would also appreciate it if the physics operator for that run (and anyone else who is interested) try using the IRC tool to keep us informed.

7. After Fredian and Horne return we should schedule a meeting to discuss any last-minute issues. We still have to decide exactly how to use the video-conferencing tools, for instance.