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MEASURING GAMMA 10 END-LOSS IONS
WITH AN ELIS FROM TMX-U

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Livermore
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MEASURING GAMMA 10 END-LOSS IONS
WITH AN ELIS FROM TMX-U

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ABSTRACT

I spent the period from March 22 to July 10, 1987, at the GAMMA 10 tandem-mirror experiment at the University of Tsukuba in Tsukuba, Japan. The purpose of this extended trip was to install on GAMMA 10 one of the end-loss-ion spectrometers (ELIS) used on TMX-U (Tandem Mirror Experiment-Upgrade) at LLNL and to make plasma measurements there with this diagnostic instrument. This report discusses the considerable planning and preparations that preceded the trip, the actual experience with the ELIS equipment at GAMMA 10, data and results obtained while I was there, GAMMA 10 experimental procedures, the scientific and technical support given me during my stay, and some final comments and suggestions concerning an international exchange such as this one. The data acquired on GAMMA 10 while I was there, along with earlier data, present an encouraging picture of a plasma in a thermal-barrier mode in a tandem-mirror, magnetic-fusion machine.

1. INTRODUCTION

The purpose of this international exchange was to install and operate on GAMMA 10 one of the end-loss-ion spectrometers (ELIS) developed for and used on TMX-U at the Lawrence Livermore National Laboratory. Plasma measurements were made on GAMMA 10 with the ELIS, aiding in the further understanding of tandem-mirror plasmas.

In more detail, purposes of this international cooperation included (a) to demonstrate that expensive equipment can be moved effectively between magnetic-fusion machines in different countries and thus shared, and (b) to help GAMMA 10 personnel in their understanding of tandem-mirror, thermal-barrier-type plasmas.

Under (a), we showed that a large amount of complex equipment can be moved safely a long distance, set up again, and be made to work in a short time. We showed that problems can be solved such as using electrical power of different voltages and frequencies, joining mechanical equipment with different specification systems (i.e., English and metric), and interfacing fiber-optics and water systems with connectors of different specifications.

Under (b), we showed that we can obtain data regularly and reliably over a period of many weeks that help to reinforce and supplement data being obtained by GAMMA 10 diagnostics. We showed that all this can be done in a spirit of cooperation between scientists of different cultures.

We helped GAMMA 10 personnel obtain detailed end-loss data, using an expensive instrument that they certainly could have developed but with considerable time and money. We not only had an instrument already operating but had the self-contained computer data acquisition and analysis system working and able to move with the ELIS.

The ELIS data gave the GAMMA 10 staff, sooner than otherwise possible, more confidence in their good gridded end-loss analyzer (ELA) data and added detail that the ELAs cannot obtain. For example, end-loss-ion spectra are measured with the ELIS at a rate of five per millisecond. Also, the end-loss electrons are easily removed by the magnetic field in the ELIS. Thus, energetic electron bursts do not overlap the ELIS ion spectra. On the other hand, the better sensitivity of the ELAs allows one to observe a smaller level of loss flux (more than a factor of 10 lower) due to the less restrictive acceptance configuration for the ion flux. These characteristics enable the ELIS and ELA measurements to complement one another.

I returned to LLNL with an assortment of GAMMA 10 data, prepared in conjunction with Professor S. Miyoshi, Director of the Plasma

Research Center where GAMMA 10 is located, and Dr. T. Cho. The data are mainly of shots that include ELIS data, although some earlier results are also included for comparison and completeness. Some of these data are described in detail later in this report.

A time schedule for this exchange, from October 1986 to July 1987, is shown in Table 1. It includes several weeks of experimental operation while the ELIS was mounted on GAMMA 10.

A paper discussing this work is being presented at the 29th Annual Meeting of the Division of Plasma Physics of the American Physical Society on November 5, 1987 [1].

References listed at the end of this report include two that describe the ELIS diagnostic instrument [2,3]. Also listed is the GAMMA 10 paper given at the IAEA international meeting in Kyoto, Japan, in November 1986 [4].

2. PLANNING AND PREPARATIONS

Much planning and many preparations were necessary to make this exchange successful. It sounds simple at first: remove the ELIS from TMX-U, pack it up, take it to GAMMA 10, install it, and take data. Then, when one begins to think about the project in detail, one realizes that it is much more complex.

First there was the support stand. The ELIS support structure on each end of TMX-U was bolted onto the end wall of the machine using holes especially drilled for that purpose. It did not seem to be good international relations to arrive at GAMMA 10 and start drilling holes. Thus, we designed and built a free-standing support structure. We were not able to use the old TMX-U support structures at all.

During my December 1986 fact-finding trip to GAMMA 10, I discovered that their crane would not reach close enough to the east end of the machine to lift the ELIS into position. Thus, we built the support structure on heavy-duty wheels. The ELIS could then be mounted on the structure in an area the crane could reach, rolled into position at the east end of GAMMA 10, and jacked up off the wheels on to the support legs.

The ELIS had to be supported at a compound angle, an angle not in either the horizontal or vertical plane. The line of sight was aimed toward the magnetic axis of GAMMA 10 through a port that was 45 deg away from both the horizontal and vertical planes. Also, the entire ELIS spectrometer had to be rotated about 30 deg away from the

vertical so as not to be in the way of the plasma gun mounted on axis. Thus, it was not easy to design the support stand.

We had to fasten the support stand to the GAMMA 10 machine or floor in some fashion, to hold the alignment. We designed three connecting arms that were to bolt to the support stand and extend to the end-tank wall of GAMMA 10. Two were to be fastened to two large lifting eyes on the GAMMA 10 end-tank wall, and the third was to be clamped to the rim of a flange. Also, two outrigger arms were to spread out from the stand to the floor at the sides to provide stability against tipping. These arms were designed to be bolted to the floor if GAMMA 10 personnel had serious concerns about earthquakes, but that was never done.

Differences in electrical power at GAMMA 10 were of a concern: 100 V, 50 Hz instead of the 120 V, 60 Hz in the U.S. We found that most of our equipment had specifications indicating proper operation at 100 V, 50 Hz. No changes were needed to the desktop computer equipment except that we had to take a monitor designed for 50 Hz and we had to reset a switch on the Composite Video plug-in board in the computer. The power supply for the ELIS magnet needed to be modified and recalibrated for 50 Hz, and one jumper had to be changed in the electrical circuit for the mechanical vacuum pump. The specifications for the CAMAC crates that we took stated that they should function at the lower voltage and frequency, and similarly for the rest of the electrical and electronics equipment. In case the equipment worked better at 120 V than at 100 V, we took transformers that could step up the voltage sufficiently.

Hose connectors used at LINL are nonstandard, so I sent the mating connectors to GAMMA 10 ahead of time and they were installed on the water cooling and pumping stand for the ELIS magnet. Thus, our water hoses were easily connected.

As was done on TMX-U, we planned to use at GAMMA 10 two fiber-optics cables between the ELIS at the machine and the desktop computer in the diagnostic area. No other interconnections are needed. This meant going through a set of fiber-optics cables that was already installed between the GAMMA 10 machine and the diagnostic area. The connectors there are different from the ones used on TMX-U equipment, being of Nippon Telephone and Telegraph specifications. I was able to obtain some of these connectors in the U.S. already mounted on fiber-optics cables. We installed TMX-U connectors on the other end of these cables and could then connect our equipment through the GAMMA 10 patch cables.

On GAMMA 10, the hardware was built using metric-system specifications, while the ELIS equipment uses the English system. The one location where planning was needed because of this difference was

where the ELIS coupled to GAMMA 10, at the 6-inch gate valve. Otherwise, we just had to make sure that we took all the English-type nuts, bolts, and tools that we would need.

Besides taking all the mechanical parts and tools that we could visualize needing, we took spares of many of the electronics components. Not only were mechanical and electrical specifications different at GAMMA 10, but the support services to which one is accustomed at LLNL are not all available in the university environment of GAMMA 10. Also, being in another country, it would have been difficult to obtain service and repair parts quickly for much of the equipment. Missing or broken components could have stalled my work at GAMMA 10, so spare parts and chassis had to be obtained and packed. Planning ahead here was essential when we were to be so far from home.

We also planned to have available spare computer equipment in the sense that the other physicist involved in the GAMMA 10 exchange, Dr. Thomas A. Gasper of LLNL, was taking a computer system similar to the ELIS system for his plasma-fluctuation measurements. Thus, if any computer equipment were to fail, we would somehow share the remaining equipment.

We had to plan ahead to obtain an Export License in time so that the equipment could move smoothly and promptly out of the U.S., into Japan, and on to GAMMA 10. Even though DOE in Washington helped me interact with the Department of Commerce there to obtain the license, and we applied for it early, the license was delayed in being approved. However, the schedule was almost kept and the equipment arrived at GAMMA 10 just before it was needed.

So that the large amount of delicate equipment was properly packed, crated, and prepared for shipment on time, we had to coordinate with the LLNL Shipping Department. They prepared packing materials and crates that were reusable because all the equipment had to be returned to LLNL in good condition.

3. EXPERIENCE WITH ELIS EQUIPMENT AT GAMMA 10

In general, our preparations and planning paid off well. The non-metric tools we took were essential. Most of the spare electronics units we took were not needed, but they would have been indispensable if the original units had failed.

Fortunately, the equipment problems were minor ones and easily circumvented: (a) A set of clearance holes on the flange that joined the ELIS to GAMMA 10 had to be enlarged. The size was correct on our

original drawing, but the holes had been drilled incorrectly and no one at LLNL had noticed it. (b) My limited experience with the ELIS vacuum-pumping system was compensated for by GAMMA 10 staff members who knew that type of system well. Also, there was a service representative in Tokyo who could give advice and assistance on the pumping system. (c) Two of the fiber-optics cables that we took did not seem to work after the shipping; however, because we had taken double the number actually needed, we still had one spare of each type throughout our stay. (d) One LeCroy 8212 32-channel amplifier unit was noisy and had to be replaced. That still left us with a spare of this vital component, which was never needed.

The 50-Hz, approximately 100-V electrical power caused only minor problems. All the computer equipment worked well, including the monitors. We did not regularly use the step-up voltage transformers that were taken. After some startup difficulties, the equipment worked satisfactorily with the near-100-V power. Some of the equipment tended to blow fuses when using a step-up transformer, possibly because the GAMMA 10 power was actually somewhat more than 100 V. The voltage for the ELIS vacuum-pumping system needed to be increased to get the system started when the mechanical pump was cold, but then the transformer had to be removed before the system would run steadily and reliably. The few changes needed to run our equipment at 50 Hz had been made at LLNL, and there seemed to be no problems in this regard.

The fiber-optics cable arrangement worked well. We connected to the GAMMA 10 fiber-optics patch cables that were laid between the machine and diagnostic areas. One pair of our cables ran in the machine area from the cable patch panel to the CAMAC crate at the ELIS. The other pair ran in the diagnostic area from the cable patch panel to the ELIS CAMAC crate that connected to the computer system. Even with the added junctions in the fiber-optics cabling system, the communication between the ELIS and its upstairs computer was good.

Besides the two fiber-optics cables between the GAMMA 10 machine room and the diagnostic area, our only other connection between upstairs and downstairs was a coaxial cable for the shot timing trigger that originated in the diagnostic area. I put an isolation transformer in the circuit near the F'IS equipment to avoid any ground-loop problems. Some occasional false triggers occurred until a 5-times attenuator was inserted into the circuit. Then the triggering worked reliably.

The extra effort we put into designing and building the large support stand for the ELIS was worthwhile. It functioned well in supporting the ELIS, when rolling it into position, and when using the various adjusting bolts to obtain the correct height and alignment angle. The clearance between the ELIS equipment and the east concrete

wall was as planned so that personnel could go past without great difficulty. Making the stand extra sturdy paid off, not only because it supported the ELIS well but also because there was a lot of climbing around on it during the early period on GAMMA 10 (even after the ELIS was aligned).

The connecting arms between the support stand and GAMMA 10 seemed to function satisfactorily as did the outrigger arms on the sides that added stability in general and especially in case of earthquakes. Within four days after our final alignment and attachment to GAMMA 10, we had a moderately strong earthquake. No shifting of position was observed then or after three smaller earthquakes within the next three weeks.

Because of the connecting and outrigger arms that we took, we were able to use the attachment locations already on GAMMA 10 and did not have to drill new holes in the machine or floor. After we removed the ELIS, the only evidence of our stay were four ink circles on the floor that were drawn around the support feet to show if any shift occurred in the ELIS position. There had been no shift during the three months that the ELIS was attached to GAMMA 10.

Once we were under way, the ELIS equipment operated very reliably. This included the vacuum system, which ran constantly for over two months without incident. During a typical week's run, the ELIS magnetic and electric fields held steady for up to 84 h with essentially no adjustment. This was a different mode of operating than on TMX-U, where we turned off the equipment overnight. We did, however, turn off the equipment over the weekend, which was standard GAMMA 10 policy.

In Figs. 1 and 2, we show photographs of the ELIS. Figure 1 shows the ELIS at the side of GAMMA 10 being prepared to be rolled into position, and Fig. 2 shows it mounted on the east end of GAMMA 10.

Figures 3 and 4 are schematic drawings of the ELIS equipment used at GAMMA 10. Figure 3 shows the equipment that was located at the east end of GAMMA 10, while Fig. 4 shows the electronics equipment used between the ELIS on GAMMA 10 and the ELIS computer system in the diagnostic area. The sets of equipment in the two separated areas were connected by the two fiber-optics cables only.

Figures 5 and 6 are samples of data obtained once the ELIS equipment was mounted on GAMMA 10 and was operating. Figure 5 shows the H⁺ end-loss spectrum as a function of time during a shot (a plasma-cleanup shot, not a thermal-barrier-type shot) that was taken soon after the gate valve between the ELIS and GAMMA 10 was opened for the first time. Figure 6 shows the analyzed potential data versus

time for that shot.

4. GAMMA 10 DATA AND RESULTS

I brought back from GAMMA 10 plasma data for several shots. Most of the data were obtained and analyzed while I was there, but some data are from the GAMMA 10 Group's earlier best "IAEA" shots (referring to their good results presented at the November 1986 Kyoto IAEA meeting).

These data present an encouraging picture of a plasma in a thermal-barrier mode in a tandem-mirror, magnetic-fusion machine, and I will refer to the data in these terms in this report. I did not bring back with me answers to all the questions that the U.S. fusion community might ask. But others have visited the GAMMA 10 experiment and have heard reports by GAMMA 10 Group members at conferences, so they may be able to fill in the gaps in my information and knowledge themselves.

Typically, the data consist of potential measurements at various axial locations versus time during a plasma shot as well as supporting measurements and information. Potential measurements were made with the ELIS, gridded ELAs, and heavy-ion beam probes measuring near the central-cell midplane and in the thermal-barrier region at the east end of the machine. (The ELIS was mounted on the east end so it would be near the second beam probe.)

The thermal-barrier period of a shot is that period when the measured east beam-probe potential is less than the central-cell beam-probe potential, and both of these are less than the peak plug potential as measured by the ELIS and ELA (all measurements adjusted to the same radius). This is the axial potential profile we would expect when a thermal barrier is formed.

Figure 7 shows the potential data for one of the shots with the deepest thermal barrier obtained while I was at GAMMA 10. There, the criteria just given are satisfied during the shot-time period of about 60 to 67 ms. Figures 8 and 9 show potential data for two shots with less deep thermal barriers, also obtained while the ELIS was mounted on GAMMA 10. The timing of the power sources for these three shots is shown in Fig. 10.

Other data suggesting a thermal-barrier-type plasma include the east-plug electron temperature higher than the central-cell electron temperature, i.e., isolation of the electrons in the two regions. The central-cell electron temperature is measured by electron-cyclotron emission, and the plug electron temperature by x rays. The plug

electron temperature can be several hundred eV higher than the central-cell electron temperature during the thermal-barrier period.

The central-cell line density tends to increase during the thermal-barrier period while the H-alpha source signal (which varies with plasma production) remains constant or decreases slightly and the plasma radius tends to decrease. Thus, the central-cell density and the ion confinement time appear to increase during the thermal-barrier period.

The GAMMA 10 staff puts much importance on the results plotted as Φ_c versus Φ_b , where Φ_c (the ion confining potential) is the difference between the outer peak potential and the central-cell potential, and Φ_b (the thermal-barrier or electron-confining potential) is the difference between the central-cell potential and the barrier potential. These quantities are defined graphically in Fig. 11(b), which is similar to the first figure in Ref. 4. Figure 12 shows a Φ_c versus Φ_b plot obtained by combining the data of Figs. 7 through 9, which include ELIS data. The linear behavior shown in this figure is supported by theory [5,6]. The GAMMA 10 staff believes the ion-confining potential must continue to increase with the barrier depth, as shown in Fig. 12, in order to scale to larger machines.

An important correction to the ELIS and ELA data is the adjustment of their potential results from their radial position of 4.3 cm (mapped to the central-cell midplane) to the magnetic axis. Without this correction, these potential values are not clearly higher than the central-cell beam-probe potential measurements (at $r = 0$) during the thermal-barrier period. The GAMMA 10 staff has evidently done much careful work determining this correction factor. The beam probe in the east barrier region can measure the radial variation of the potential [$\Phi(r)$] by sweeping across the radius. Arrays of ELA detectors and the movable ELAs can measure $\Phi(r)$ inward to about a 2.4-cm central-cell radius and still allow the plasma guns at both ends of the machine to fire and start up the plasma. By using a plasma gun at only one end, they can still form a thermal-barrier plasma; then a movable ELA can be positioned all the way to the axis during a scan. An ELA detector plate mapped to the central-cell midplane has a projected radial extent there of 6 mm, so the spatial resolution is good.

The $\Phi(r)$ results obtained with these different methods appear to be consistent and provide data from the axis to large radii. The $\Phi(r)$ values of the beam-probe data are naturally lower than for the ELA data during thermal-barrier conditions but there is a constant factor between them as a function of radius (when mapped to the central-cell midplane). That is, their shapes are the same. When combined, these results give a correction factor of about 1.38 during

the thermal-barrier period and about 1.20-1.25 just before and after that period. Typical $\Phi(r)$ results are plotted in Fig. 13. These data show that during the time the ELIS was monitoring ion end losses on GAMMA 10, the $\Phi(r)$ profile obtained with an ELA array was consistent with similar profiles taken in 1986.

Calibrations of the various potential measurements are of course very important when comparing the results of the different measurements. Data obtained by the ELIS and an ELA were generally in good agreement. The sets of ELIS and ELA raw data at $r = 4.3$ cm in Figs. 7 through 9 are examples. The agreement between diagnostics from opposite sides of the Pacific Ocean is reassuring. Careful calibrations of the beam-probe measurements (central-cell and east barrier) have been made at GAMMA 10 in the past. Also, much effort had evidently been made earlier producing various types of plasmas and comparing the beam-probe and ELA results. Some plasma conditions were such that the potentials measured by the different diagnostics should have agreed, and apparently they did.

For me, not being well acquainted with the calibration data, the results from our running on GAMMA 10 are more meaningful when the potential data from the various diagnostics are plotted before and after as well as during the thermal-barrier period of a shot. Then, one can see that the relative values of the measured potentials vary in a reasonable way during a shot.

Figure 7 is an example. There, early in the shot [when the plasma is produced by the plasma guns and the barrier electron-cyclotron heating (ECH)], the east-barrier potential appears slightly higher than the central-cell potential and is near the peak potential measured by the ELIS and ELA. That is, this axial potential profile is characteristic of the profile expected for a conventional tandem mirror. This potential profile is quite different from the profile later in the shot, during the thermal-barrier stage.

In Fig. 9, the potentials vary somewhat differently during the shot. A thermal barrier is again obtained, now during the 61- to 65-ms period. But near the end of the shot, the central-cell potential is approximately equal to the peak potential measured by the ELIS and ELA, and all these values are above the east-barrier potential. That is, the axial potential profile appears to be maximum in the central cell and to fall off toward the ends of GAMMA 10, not a tandem-mirror situation.

An important observation is that of "plugging" during the thermal-barrier period, that is, the drastic decrease of ion end losses. Plugging is a consistent behavior in the GAMMA 10 data. The deeper the thermal barrier, the less the amount of end loss and the harder it is to measure the peak potential with the ELIS and ELA. In

most of the data obtained during my stay at GAMMA 10, there was occasional ELIS end-loss signal during the thermal-barrier time. Some ELA data usually existed, too. Thus, we were able to obtain peak-potential measurements. Where the ELIS had the advantage of no ambiguity due to electron bursts (the magnetic field of the spectrometer cleanly separates the electrons from the ions), the ion signals were smaller than those of the ELA because of the more stringent acceptance criterion of the ELIS. Thus, combining the two sets of results enhances the final data.

I asked the GAMMA 10 group if they had data relating the barrier depth to the hot-electron fraction in the barrier and to the barrier-filling rate. They said that these parameters are interrelated and are not simple to sort out. The measured hot-electron fraction in GAMMA 10 under good thermal-barrier conditions is about 30%.

There were two special concerns that I had about the effect of the ELIS on GAMMA 10: (1) whether the large volume of iron represented by the ELIS would adversely affect the GAMMA 10 plasma, and (2) whether ELIS gases would adversely affect the sensitive GAMMA 10 vacuum conditions. There is no evidence that either was a problem. ELA radial profiles agreed with those previously measured without the ELIS present (see Fig. 13, for example). Good agreement was obtained between the ELIS and ELA potential data, as noted above, and thermal-barrier plasmas could still form. There was no noticeable deterioration from earlier GAMMA 10 operation with the ELIS present that might not be explained by other factors.

Two differences in the GAMMA 10 and TMX-U ELIS data are especially noticeable. One is the difference in the D⁺ end-loss signal. The ELIS separates and measures both H⁺ and D⁺ end losses. In TMX-U, we ran a D⁺ plasma but often used hydrogen gas for the diagnostic pump beams. Although the principal end loss was D⁺, there was always a certain fraction of H⁺. GAMMA 10 runs an H⁺ plasma and all ion end loss observed by the ELIS was H⁺, with no D⁺ visible.

The second difference is the behavior of the measured potential at the beginning of the shot. In TMX-U, we started the plasma buildup from low density with ECH. As the plasma density increased from zero, the potential started high, soon dropped to a low level, and then began to increase again. In GAMMA 10, the initial plasma is formed by plasma guns and is of high density and low energy. The potential starts out very low and increases from there, similar to the TMX-U increase after the initial potential drop.

5. GAMMA 10 EXPERIMENTAL PROCEDURES

Vacuum conditions in GAMMA 10 are considered of utmost importance. This concern caused some delay in opening the gate valve between GAMMA 10 and the ELIS and thus in obtaining ELIS data. First, some changes were made to the ELIS vacuum system to reduce the amount of gas that would enter GAMMA 10. A conductance-limiting orifice was installed and the vacuum-system manifold was baked. An auxiliary pumping system was used each time before the gate valve was opened, to further reduce the outgassing. With these changes, no apparent adverse effect on GAMMA 10 vacuum or plasma was noticed when the gate valve was opened, and we proceeded to thermal-barrier shots.

To obtain the deepest thermal barriers, the vacuum conditions must be just right. Standard machine operation while I was at GAMMA 10 was 4-1/2-d/wk, 24-h/d running. During the first 24 h or so of a week's run, the walls are conditioned with "discharge-cleaning" plasma shots. Then the sequence is changed to the standard thermal-barrier-type operation, and plasma shots are taken at regular 15-min intervals. Breaks in this schedule are avoided because the regular shot cycle helps condition the walls. The GAMMA 10 staff tries to operate all week with the same machine input power and other machine conditions. They believe they obtain the best plasmas this way because the same wall regions are being bombarded during the running. Thus, the walls clean up better and less gas is knocked off during a shot.

For the best GAMMA 10 thermal-barrier data (1986), a shot cycle of 15 min was more effective than one of 12 min. By continually taking shots (in 1986), there would be periods as the vacuum conditions changed slowly (over a day or two) when a series of "best" shots would be obtained. Such information should help in developing future tandem-mirror machines.

A liquid-helium cryogenic pumping system will soon be installed on GAMMA 10. This improvement should make the vacuum conditions more controllable.

In obtaining their results, the GAMMA 10 staff does careful, patient, and thorough experimentation. They are willing to make the commitment and put in the time and effort to obtain as good results as possible. When necessary, they will spend several weeks of running doing calibrations.

Their deepest thermal barriers were not obtained while I was there even though a serious attempt was made. Problems with the gas-puffing system and a new gyrotron during this period may account for the more limited results. When they measured their deepest barriers, in the spring and fall of 1986, they could obtain these results consistently. Thus, they could do $\Phi(r)$ scans and take many

shots to accumulate ELA potential data during the plugging time.

The run that took place while I was at GAMMA 10 was the first thermal-barrier-type run since the Kyoto IAEA meeting. Between that time and my arrival in March, their experimentation had been oriented toward obtaining data for student theses. Many students help with the GAMMA 10 experiment, and the mutual interaction seems beneficial to both sides.

6. GAMMA 10 SUPPORT

The support at GAMMA 10 for the ELIS was good. They wanted to make a success of this international collaboration as much as we at LLNL did. All along, they provided the manpower and other support that was needed. This exchange was a considerable effort and expense for them as well as for LLNL.

A lot of GAMMA 10 manpower was expended in unpacking and installing the ELIS, in getting the ELIS vacuum system working properly, and in making the changes to the ELIS vacuum system so that it would be more compatible with the GAMMA 10 vacuum. All this included help from the three GAMMA 10 technicians and from graduate students.

Some machine-shop work needed to complete the installation was promptly provided. The nearby University Main Machine Shop did three small jobs for us, including fabricating two non-metric machine screws that I had forgotten to take. These jobs were done promptly even though the shop obviously had a long waiting list. The machine-shop foreman appeared to want to help the visitor from the U.S. The larger job of fabricating two connecting vacuum-manifold spools (for the ELIS vacuum modifications requested by GAMMA 10) was done within a week by a machine shop near Tokyo.

A water cooling and pumping system was purchased for the ELIS magnet with GAMMA 10 funds. It was very reliable and will be used on a diagnostic neutral beam at GAMMA 10 later on.

Some equipment at the east end of GAMMA 10 was modified and shifted to accommodate the ELIS. An enlarged screened hole in the PPC (plasma potential control) plates was installed. A new spool and 6-in. gate valve were installed on the port to be used by the ELIS. An ELA was shifted to another port to avoid conflict with ELIS equipment. The support for the east plasma gun was changed from a floor mount to an overhead mount so the large ELIS support stand would fit.

GAMMA 10 personnel took care of the ELIS operation during the evening and early morning hours. This freed me for a 10- to 12-h

shift during the day when I could more effectively interact with the GAMMA 10 staff and handle nonroutine ELIS matters. Fortunately, the ELIS ran steadily and reliably most of the time so that minimum attention was needed during the night hours.

At the end of the experimentation with the ELIS at GAMMA 10, several GAMMA 10 staff members and students helped remove the ELIS, dismantle it, and crate it up for shipment back to LLNL. This work took about three days and included packing auxiliary items such as electronics and computer equipment. We also packed the electronics and computer system used by Dr. Thomas A. Casper during his concurrent visit to GAMMA 10.

7. FINAL COMMENTS AND SUGGESTIONS

It was important to prepare well for this exchange because we had only one opportunity to obtain data with the ELIS on GAMMA 10. Thus, the equipment had to work correctly the first time. Extensive modification, repair, and service support was not easily obtainable.

It was advantageous bringing to GAMMA 10 essentially a stand-alone, operating, diagnostic system, including the computer equipment for data acquisition, handling, and analysis. Our only physical connections to the GAMMA 10 equipment were at the gate valve and supporting arms between the ELIS and GAMMA 10 and at the timing-trigger chassis. Being completely independent of the GAMMA 10 data acquisition and analysis system helped us carry out the project successfully. We could do our work without disturbing the rest of the experimentation, and interact when we combined the results from the analyzed ELIS data with GAMMA 10 processed results. Using our own data acquisition, handling, and analysis programs on our computer system, programs that had been developed for TMX-U and extensively used there, we were able to acquire and analyze data sooner than we otherwise could have done. This was the efficient and practical way to carry out the project.

I needed considerable time to prepare for the exchange with GAMMA 10. Getting the equipment assembled, operating, and ready to ship took more time than I had estimated. Much planning was needed so that we would have in Japan the proper tools, supplies, support stand, other equipment, and spare parts needed to prepare the ELIS for operation and to keep it working. Paperwork and other planning details took much time. Fortunately, my other commitments were minimal during this period of several months so I was able to prepare properly.

Along with the time involved to prepare, the cost was also more than expected. A lot of equipment was involved. Expenditures were necessary to prepare the equipment, to crate it for shipping, and to

transport it. The support stand was a major expense. It had to be designed and built, and it served its purpose well. With the expended time and effort, the project was able to be carried out to completion. Cutting corners could have reduced the effectiveness of the exchange.

The equipment arrived safely at GAMMA 10 after its long trip across the Pacific Ocean and proved to be satisfactory to do the job. The packing and shipping were done well. Nothing was damaged. Even the sensitive computer equipment (including hard disks) and other electronics arrived safely at GAMMA 10. The packing materials and wooden crates were saved, and all were used for shipping the equipment back to LLNL.

My 5-d fact-finding trip to GAMMA 10 in December was very worthwhile. The information exchange during that short trip was good. Based on what I learned on that trip, I was able to properly prepare for the actual exchange. It would have been difficult, if not impossible, to work out all the details from long distance (phone and mail). When outside equipment is involved in an exchange, I strongly advise a short preliminary trip.

The schedule for the ELIS at GAMMA 10 turned out to be a good one. We began unpacking and preparing the ELIS for GAMMA 10 during a week when there was no scheduled running or other major activity on the machine. (The staff was preparing for and then attending a conference.) Thus, manpower and the crane were available for the ELIS. Then came a short up-to-air period when the ELIS viewing hole inside GAMMA 10 was enlarged and the ELIS was aligned using a laser to aim at a calculated point along the magnetic axis inside GAMMA 10. Regular GAMMA 10 work such as regettering was also accomplished during that period. We then worked out the ELIS vacuum-compatibility problems while GAMMA 10 cleanup shots were in progress. Thus, the ELIS was ready to take data by the time the GAMMA 10 vacuum conditions were good enough to start serious thermal-barrier operation.

By extending my stay at GAMMA 10 an additional three weeks beyond the departure date originally planned, we were able to take ELIS data until GAMMA 10 was ready to come back up to air and regetter. (GAMMA 10 personnel were also able to take additional plasma-fluctuation data during this period because Dr. Casper left his equipment operating, even though he needed to return to LLNL on schedule.) Thus, removing the ELIS equipment from GAMMA 10 and preparing it and the other equipment for shipping worked in well with the overall GAMMA 10 schedule. The 3-wk extension also meant that we did not have to shut down GAMMA 10 to remove the ELIS during the more limited time that two visitors from the TARA experiment at MIT were present.

Officially, the equipment was not a loan to GAMMA 10 but was equipment taken over with me to use and then return to LLNL when I did. Thus, I needed to stay at GAMMA 10 as long as the equipment remained.

In any other exchange involving outside equipment, it would be wise to coordinate the schedule as well as possible with the plans of the host institution. This is not always feasible because of the complexity of a magnetic-fusion machine. But, a smooth meshing of schedules can certainly reduce frustration on both sides. Flexibility in the visitor's schedule, especially concerning the date for returning home, can help as it did in my case. Cooperation in this matter by the visitor's home institution and by DOE can certainly ease the situation.

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The GAMMA 10 group members were very helpful and friendly throughout my long visit. In particular, both Dr. T. Cho and Dr. Y. Nakashima of the GAMMA 10 professional staff spent considerable time on the ELIS during various stages of its interaction with GAMMA 10. Their work was important in making the exchange a profitable one. I am grateful to Professor Miyoshi for his hospitality and patience during the 3-1/2 months that I was at GAMMA 10. I hope that he feels, as I do, that it was a beneficial interaction.

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Table 1. Schedule for ELIS-GAMMA 10 international scientific exchange.

Date	Event
1986	
October 1	Detailed planning for exchange begins.
November 29 to December 5	Fact-finding trip to GAMMA 10 to make arrangements and to work out details.
December 8	Planning begins for long-lead-time items such as support stand and special fiber-optics cables.
1987	
January 12	List of equipment planned for use in Japan is sent to DOE in Washington for forwarding to Department of Commerce for Export License approval.
February 2	West ELIS removed from TMX-U and preparations begin for shipping it and its auxiliary equipment.
March 4	Eight large wooden crates of equipment packed and ready for shipping.
March 6	Export License issued. Shipment for Japan leaves LLNL.
March 19	Shipment arrives at GAMMA 10.
March 21-22	J. H. Foote travels to Tsukuba.
March 24	Unpacking of ELIS equipment begins.
March 27	First vacuum pumpdown of ELIS, at side of GAMMA 10.
April 3	ELIS mounted on east end of GAMMA 10 and aligned.
May 1	Allowed to open vacuum gate valve between the ELIS and GAMMA 10. Data are obtained on the next shot and from then on until end of the run.
June 27	End of GAMMA 10 run.
June 29	Repacking of ELIS equipment begins.
July 3	Shipment leaves GAMMA 10 for LLNL.
July 10	J. H. Foote returns to U.S.

1. ELIS mounted on its support stand, being prepared to roll into position at GAMMA 10.

2. ELIS mounted on the east end of GAMMA 10.

3. Schematic drawing of the ELIS equipment located near the east end of GAMMA 10.

4. Schematic drawing of the electronics used between the ELIS on GAMMA 10 and the ELIS computer system in the diagnostic area.

GAMMA 10 H+ Scale 100 Time 50.00ms Step .2 Base 3 8 May 1987 Shot 4333

5. The ELIS H+ end-loss spectrum as a function of time during a shot (a plasma-cleanup shot, not a thermal-barrier-type shot) taken soon after the gate valve between the ELIS and GAMMA 10 was opened for the first time. The plot on the left shows the magnitude of the escaping ion current.

6. Analyzed potential versus time for the data shown in Fig. 5.

7. Potential data for one of the shots with deepest thermal barrier obtained while the ELIS was mounted on GAMMA 10. Solid squares show the east-barrier potential, upper solid circles show the central-cell potential, and upper open squares and circles show the peak plug potential. (The vertical rectangles are like the open squares except that their height more nearly represents the uncertainty in the corrected potential measurement.) The two lowest plots show differences in these potentials (ϕ_c and ϕ_b , discussed in Sec. 4). Also described in Sec. 4 is the radial-position correction to the ELIS and ELA data (from 4.3 cm to the axis).

8. Same as Fig. 7 except that in this shot the thermal barrier was not as deep.

9. Same as Figs. 7 and 8 except that in this shot the thermal barrier was even more shallow.

10. Timing of the power sources for the shots of Figs. 7 through 9.

11. (a) GAMMA 10 magnetic-field and plasma configuration, showing locations of heating sources (NBI -- neutral-beam injectors, MPD gun -- magneto-plasma-dynamic gun).
- (b) GAMMA 10 axial profiles of (top) magnetic-field strength (showing locations of heating sources and key diagnostics); (middle) thermal-barrier potential; and (bottom) corresponding density and electron temperature.

	ELA	ELIS
44306	●	○
45589	◆	◇
46616	■	□

12. Plot of ion-confining potential Φ_c versus the thermal-barrier (electron-confining) potential Φ_b , combining data from three representative shots (see Figs. 7 through 9) obtained while the ELIS was on GAMMA 10.

13. GAMMA 10 ELA data showing plasma potential versus radius [$\Phi(r)$] mapped to the central-cell midplane. The data represented by the circles and triangles were obtained in 1986 using a movable ELA, with plasma guns firing at both ends or one end, respectively. The data represented by the squares were obtained with an ELA array on a single shot during the period that the ELIS was mounted on GAMMA 10.