MEMORANDUM: Run Time Guidance for 2024-2025 DIII-D Program

To: DIII-D Team
From: Richard Buttery, Craig Petty, George Sips, Chuck Greenfield.
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Dear DIII-D Team,

We are pleased to provide the Run Time Guidance for DIII-D 2024 and 2025 research program.

Fusion is at a critical juncture in the United States. With recent improvements in capabilities, DIII-D is poised to answer many of the crucial plasma research questions, and indeed is beginning to do so already. This Guidance targets a goal-oriented approach to fusion energy, to close out key research gaps for a Fusion Pilot Plant and ITER. A choice is not made between fusion science and technique development – these happen together, with pursuit of either providing a platform for the other, and both needed if we are to project fusion solutions from DIII-D with confidence.

For FY24-25, critical advances are possible thanks to our new shape and volume rise divertor, which permits us to explore the limits of high pedestal operation in highly shaped plasmas, and access new reactor relevant regimes with greater opacity and energy. This provides a rich seam of exploration for two thrusts called out in this guidance. This is accompanied by record levels of electron cyclotron power in DIII-D to explore plasma scenarios, Advanced Tokamak limits, turbulent transport and stability behavior in both steady state and pulsed FPP scenario, as well as for ITER.

Another tool being pioneered, the new high field LHCD system, offers potential as a highly efficient, high density reactor current drive that can also turbocharge scenarios in DIII-D. Advances in diagnostics such as 2D TS, Lyman alpha, Doppler-free saturation spectroscopy, and a range of turbulence, energetic particle and profile measurement upgrades will enable key physics results, and new pellet tools will take forward fueling and disruption mitigation studies.

The high-level goals for the program in FY24-25 are to close out the most urgent plasma research questions to define viable FPP approaches, to pioneer and test key fusion technologies, and to help resolve the ITER path, particularly as it seeks to re-optimize its timeline for a more rapid trajectory to Q=10. We thus set out thrusts, high priority objectives and allocations to advance this agenda.

Approach to develop Guidance and Allocations
This guidance follows an extensive team-wide consultation across the program, with many well formulated and exciting proposals posed. ***We thank the DIII-D research team and the many further participants that joined this process for their insightful and well thought out ideas.***

These ideas were scrutinized and assessed by the DIII-D Research Council, a representative body of the DIII-D User Board, to identify the highest priority activities and opportunities for consolidation, in the context of strategic goals set out in the DIII-D Five Year Plan for 2024-29. Based on their insights, and after further consultation with the RC and FES, we now issue the following guidance.

A two-year perspective is given to provide the space for initiatives to make major advances in closing out strategic goals. Nevertheless, the guidance for FY25 may be updated in the light of results and progress, following a further Research Council meeting in summer 2024.

All allocations have been made in integer or half day blocks (a day being 8 hours of machine time). Guidance on how contingency time, Director's Reserve, control development and the new category of Standby Experiments will be administered is issued in a separate memo at this time. The category of Low Resource High Output experiments is removed.

Guidance Overview

A summary of the guidance is shown right. For FY24-25 we identify a number of strategic “Thrusts”, each of which aligns with and reports through one of the three DIII-D Research Groups (FPP, Plasma Interacting Technology, ITER). Thrusts are intended to make major advances that close out key questions in a short timescale (by end of 2025). Aspects that merit significant but more generalized effort for longer-range goals are included in general guidance to the Groups. We have sought to avoid prescribing too much time to thrusts, in order to provide space for flexibility and innovation in the Groups. Finally, two Task Forces are established to pursue longer range strategic goals that are multidisciplinary and draw on international participation.

A summary of allocations across groups and thrusts is provided in Table 1. 14 weeks (560 hours, 70 days) of runtime are expected in FY24, with a further 18 weeks (720 hours, 90 days) in FY25. Time is set aside for plasma physics commissioning (startup with shutters open, when key calibration data is taken and physics commissioning of techniques commences), contingency on remaining time (20%), and owed and new **Frontiers Science**.

Time in Days	**FY24**	**FY25***
Time available	**70**	**90**
Physics commissioning	10	3
Contingency (20%)	12	17
Frontiers (owed 24, new 25)	2	4
PhD Runtime	2.5	3.5
Control Preparation	2	2
Directors Reserve	3.5	6.5
FPP Group		
Thrust: Shape rise diverto	6	6
Gen FPP time	6	13
Plasma Interacting Technology Group		
Thrust: Materials	3	3
Thrust: LHCD	3	3
Gen PIT time	5	7
ITER Group		
Thrust: EP turbulence	2	3
Thrust: Opacity	3	5
Gen ITER time	5	7
Task Forces		
Hybrid DIII-D/KSTAR	2	4
High betap	3	3

**FY25 allocations may be revised at end of FY24*

PhD time: 12 half-days are set aside for PhD students. Research Division is directed to organize a process to allocate this ahead of the main run selection. This does not preclude students also receiving runtime in main selections. Further, PhD runtime should be encouraged to support main research goals, while main research areas should support students well, helping to maximize deliverables for their thesis.

Control development (CD) for selected experiments: 8 half-days are set aside to be allocated by control group to address the most challenging control preparation needs of the main experiment selection. This is not considered low resource time. It is separate from control research and will be allocated in half day blocks. Proposals should identify CD needs. Needed CD not in this 8 half-days must be built into regular shot plans with Group Leaders adapting time allocations accordingly.

Director’s Reserve and Standby Time: Ten days are held back in Director’s Reserve. Five of these will be set aside for new proposals later, to respond to developments in the field. The rest will be allocated to Standby Experiments in half day increments – <u>an additional resource available to all groups and thrusts</u> for activities that use a greatly reduced set of tokamak systems, but advance on main program goals. The process for bidding standby time is outlined in a parallel memo to this note. Any owed or additional Torkil Jensen Award time will be taken from the DR category

This leaves 92 days of experiment time to address the Guidance below. Groups and thrusts are free to make a two-year plan, but there will be flexibility to make or remake selections for FY25, as FY24 completes. Note also that additional possibilities to advance main goals through Standby Experiments, PhD studies, control development, and Director’s Reserve with suitably imaginative proposals. Thrusts can be established within existing Topical Science Areas or with additional structures and/or leaders. Experiment leadership opportunities should be allocated with eye to fostering <u>personnel development and equitably addressing diversity in the program.</u>

Fusion Pilot Plant (FPP) Group

FPP Group is directed to pursue goals toward pulsed and steady state fusion pilot plants, with foundational work and targeted initiatives as follows.

A **Shape Rise Divertor Thrust** is initiated with 12 days allocated to commission, validate models of, and test the limits with, the new shape rise divertor which permits operation with very high triangularity, and increased plasma volume and current. In addition to basic commissioning and characterization of divertor operation, work should test the models that predicted improved pedestal access and divertor behavior. A major emphasis should be placed on pushing and assessing the limits of plasma operation in this configuration, particularly with respect to pedestal pressure and density, as well as for integration of ELM free/mitigated and radiative divertor operation, while also assessing the impact on core performance and transport, and the possible use and role of fueling.

It is noted that further work on **opaque pedestal and density limits** is called out in a Thrust in ITER Group, in which FPP members should engage, and where FPP goals should play a significant role.

Using general group time, FPP Group should explore the physics of **high density divertor** operation, and critical issues of divertor design and detachment, and isolation of core and edge. In particular, work should assess radiation front stability and impurity dynamics, core plasma isolation and the role of divertor leg length, and study density driven phenomena at high power, alongside wider crucial divertor science questions.

In the core, FPP Group is encouraged to exploit improved heating and current drive tools **to assess stability limits and transport of high q_{min} steady state cores**, complementing proposed work on integrated advanced core solutions in the high β_P Task Force (below). For **pulsed FPP** cores, some limited time is appropriate for testing and adapting regimes in large bore configurations, with a view to accelerating such work in the future. Note that there is significant overlap of FPP scenario development with the task forces, and significant benefit is expected from work proposed in the thrusts associated with the SVR divertor and high opacity, as well as the KSTAR Task Force.

It is noted that further work toward **core-edge integration** and **ELM mitigation** is called out in the Task Forces and ITER guidance below. Additionally, interesting proposals were noted on **impurity transport** – these were well received, and although there is insufficient time available for a major thrust in its own right on these issues, significant possibilities exist for relevant work in the high opacity thrust, and some additional runtime is possible in general FPP Group time.

Finally, it is vital to advance **FPP control** with scheme preparation, offline and some online studies. A specific effort and outreach to potential stakeholder should be made by the control topical science area. It is noted that a lot can be done and is needed short of actual plasma runtime, in preparation of control schemes, and with DIII-D PCS infrastructure testing. Significant research personnel effort should be devoted to this. Work should include studies of reactor-like limited diagnostic measurements, synthetic diagnostics and limited actuators. Work may also include development of advanced controllers such as ML/AI tools to manage plasma state, and anticipate and respond to plasma events. A responsible person or people should be appointed to coordinate FPP control.

On **Negative Triangularity,** the campaign in FY23 achieved terrific results, with NT established to offer significant potential for an FPP. Momentum should be maintained with creation of a **Topical Science Area** to analyze and discuss past results, consider NT-FPP perspectives, develop future DIII-D's NT plans, and pursue crucial further experiments. With much data obtained recently, a thrust level of effort is not proposed for FY24-25, but it is anticipated that some general FPP Group time will be needed for critical reference cases for the NT campaign and crucial control development.

Plasma Interacting Technology (PIT) Group

The new PIT Group is intended to ramp up efforts at DIII-D into technologies with an explicit goal of resolving reactor compatible techniques. This program builds and may expand upon many areas of traditional DIII-D excellence, such as disruption mitigation, materials research and innovative heating and current drive. But it also seeks to expand into further reactor-relevant fields such FPP diagnostics, pellet fueling, and other innovative components and approaches. There is an explicit mandate reach out to the wider fusion community to identify new program elements – either novel components of existing fields or even entirely new opportunity areas.

Building this program requires significant outreach with a range of stakeholders to draw in and develop mutual understanding. Major parts of this program can and should be achieved beyond the simple allocation of runtime – in the development of concepts and ideas, and components that can be tested offline or in piggyback. Nevertheless, significant parts of this work do need runtime. Two key areas are identified for Thrusts below, but significant general PIT Group time is allocated to develop underlying technologies and approaches, and PIT Group is encouraged to use some of this for imaginative new studies and research lines. We start with the thrusts:

A **Thrust on FPP Candidate Wall Materials** is initiated to assess a wide range of materials options championed by the community to assess key plasma interaction properties such as erosion, heat flux resilience, retention issues and plasma compatibility. This work should be conducted in close collaboration with the materials community, extending in particular to private sector fusion needs, and pursuing alignment with any pertinent FES 'Centers' created during the period. The objective is to obtain crucial qualifying or other data to enable the U.S. community to resolve key tests and challenges of materials and inform down-selections for an FPP. Six days are allocated.

A **Thrust on High Field Side LHCD** should pursue the development of this system to high power. This will involve substantial effort in startup, physics commissioning and piggyback time throughout FY24 and FY25, but 6 days of runtime are initially allocated to provide dedicated commissioning, characterize antenna coupling behavior and develop broad current profile for high performance and AT operation. Substantial efforts in startup and piggyback are expected, and run coordinators should seek to exploit opportunities for piggyback commissioning on an opt-out basis, with some compromise or risk to experiment goals that can be recovered through contingency time. While the FY24 milestone targets 300kW into plasma, a concerted and sustained effort is expected through FY24 and FY25 to reach of the order of 1MW as soon as possible, to facilitate both exploitation in FY25 as a current drive source and enable key testing of the LHCD physics. The need for additional runtime will be kept under review, and may be allocated from Director's Reserve.

In addition, **PIT Group** should use general run time to address a wide range of goals toward PIT development with a further 12 days allocated. This is expected to seek out innovative new ideas and approaches, and particularly to interface to private sector fusion needs as a potential new customer, while addressing other high priority ongoing programs. In particular:

- **Disruption mitigation research** represents a crucial, world-leading, vitally needed field of research on DIII-D. Reflecting the long-range effort and priority being provided at DIII-D, a thrust level of effort is identified with at least six days directed into the field, to emphasize testing of new FPP-relevant actuators such as sabot launch, RF and Li-coated shells.
- Any further data needed to assess **helicon** as a viable and effective system for efficient off axis current drive for an FPP should be taken in FY24, in preparation for a review by the end of 2024 into helicon's role and potential for an FPP and DIII-D. Additional conditioning time for helicon may also be needed, with a similar approach to LHCD expected (though less time).
- Further work on **real time wall conditioning** / coating is encouraged, with many good ideas noted, but a thrust level effort not possible within runtime constraints this year. Nevertheless, key new techniques should be tested with a view to motivating future studies. It may also

become important to pursue any urgent ITER questions, although it is noted Director's Reserve is available if / as these emerge later.

- The program should be open to **testing new technologies, diagnostics and other components**, including **liquid metals**. Particular attention should be paid to concept that arise from initiatives on FPP design, such as work from the new DOE Centers or the private sector, with a goal for DIII-D to provide crucial testing data for US FPP goals.
- **FPP control development** with reactor relevant actuators and diagnostic approaches should also be pursued, but time here is accounted under FPP Group (see guidance there).

The development of relationships and plans for expansion of new areas are particularly important for PIT. This can include run time but, in many cases, should also include significant offline work in developing approaches, testing on DIII-D infrastructure, and later piggyback testing once a technique is ready, as well as collaborative work at related facilities if possible. It is anticipated that such programs take time to ramp up and see though to application in live plasma situations. While DIII-D should pursue this as rapidly as possible, effort in FY24-25 is laying the groundwork for future expanded programs. Promising new ideas are also eligible for Directors Reserve, once they are ready for testing in plasma.

ITER Group

Substantial effort was undertaken in FY22-23 to address a range of issues for ITER, with a major task force to developing scenarios for the early phases of ITER and providing crucial insights to its operation and control, while a JRT provided key insights into non-ELMing scenarios, and significant work was undertaken on disruption mitigation, ELM control, machine learning prediction, disruption free protocol and NTM physics. There were many good ideas for continuation of this work. However, with ITER's hardware plans and timeline now being evolved, this changes the balance of the program necessary on DIII-D, with some aspects becoming less urgent, while other critical questions on ITER's hardware choices, research phases and approach may be very urgent. The DIII-D programmatic response to ITER need will thus evolve.

First and foremost, the DIII-D ITER Group should liaise with the ITER team **to understand the most critical questions pertaining to the convergence of ITER's new research plan and facility choices**. This will likely involve key questions pertaining to basic scenarios, control, and behavior in Deuterium vs non-activation phases. It is noted that there are good foundations for a thrust to develop ITER scenarios with more electron heating and control, though precise plans will need to be evolved for the new context of a tungsten wall and revised research phases. A specific thrust is thus not allocated, but instead a significant amount of ITER Group's 12 days of general time is available and a substantial fraction of this should be set aside to meet this goal. It would be wise for ITER Group to hold back some of this allocation (e.g. FY25 allocations), for later-emerging urgent issues, while pursuing efforts in the ROF and with ITER to determine FY24 priorities for general ITER Group time.

Further requests for substantial program time are noted (and represent good ideas from effective work areas), though these are somewhat less urgent owing to the delays to ITER's approach now emerging. Thus, Guidance seeks to take this opportunity to address some foundational issues, while maintaining momentum on critical tasks with the remainder of general ITER Group time, noting also pertinent work in the Task Forces. In particular:

A **Fast Ions, Turbulence and Alfvén Waves Interaction Thrust** is identified, with 5 days allocated. Studies should explore and resolve the foundational non-linear interactions between these phenomena with a view to resolving predictive models for ITER and an FPP in order to resolve how to regulate and optimize performance in a burning plasma.

A **High Opacity and Density Operation** Thrust is created with 8 days of operation to understand and push the physics and limits of opaque plasma conditions in the pedestal and core. This should assess the role of **transport on plasma profiles with low neutral penetration depths**, isolating turbulence, pinch and fueling effects utilizing DIII-D's unique neutral particle and fluctuation diagnostic and H&CD capabilities. Mechanisms that explain and extend the **density limit** in the pedestal and core should be tested against new theoretical models and nonlinear simulations. The role of impurity transport should be assessed as time permits. **A reach goal is to develop transport optimized profiles for high performance and density solutions as targets for core-edge integration.** Work should target ITER & FPP goals, and engaged members of FPP Group as needed.

The **Disruption Free Protocol** and **NTM research** are making good progress, and the increase in ECH in FY24-25 provides further opportunities to develop integrated control for ITER. For the DFP, work should continue to exploit a wide range of approaches on a "piggyback with opt-out" basis, which provides the breadth and realistic conditions to hone effective techniques. Nevertheless, some dedicated ITER time may be needed to test key principles where precisely controlled measurements are needed for **key tearing physics** measurements or critical facets of **integrated control**.

- It is vitally important that hardware and computing resources be prioritized to resolve real time equilibrium and ECCD steering capabilities in support of this work.
- A report is requested on the efficacy and progress toward disruption free operation that is possible with these techniques by the end of FY25.

Non-ELMs and ELM mitigated scenarios. Major progress was made over the last two years with the JRT and associated experiments. Focus should turn to analysis and publications in this area. Nevertheless, some ITER Group time may be appropriate to address critical questions, not least behavior at increased density and opacity with advanced pedestals. Plans should be coordinated with European researchers as part of a new joint EU-US ELM-free working group just agreed. It is also noted that thrusts on FPP area will provide additional useful reference data here.

Should additional requests be made from ITER, there are the possibilities to allocate additional Director's Reserve, or redirect from some of the above priorities. The ITER group is requested to reach out to the ITER team directly and to US ITER efforts to identify such issues, ensure technique and codes are optimized for ITER deployment, and personnel are more directly engaged in and aware of ITER in readiness for deeper ITER engagements for future U.S. roles in ITER.

Task Forces

Two Task Forces are established for FY24-25 to lever international partnerships.

Long Pulse Tungsten Compatible Steady State Scenarios Task Force

A joint activity is initiated between the DIII-D and KSTAR programs to develop high performance scenarios suitable for steady state regimes in ITER and an FPP, which are compatible with long pulse metal wall conditions, and integrate required control and mitigation of transients and heat flux. This activity is intended as an equally balanced partnership with run time allocated on both facilities and a joint team collectively developing plans, leading experiments and analyzing data on both facilities.

Six days from DIII-D are allocated over FY24-25 to start this exciting program for DIII-D to establish potentially KSTAR compatible scenarios, with suitable control and mitigations. A parallel program on KSTAR is expected which will explore control development and scenario implementation, and extension to longer pulse length. Work may also involve exploitation of complementary capabilities of DIII-D and KSTAR to resolve particular physics questions behind projection of techniques. This work is expected to be principally based on the hybrid scenario approach, with the main focus on the core-edge integration and long pulse elements, compatible with maintaining high performance.

This work is intended as the start of a potentially longer-range partnership as techniques are developed and iterated between the facilities. This work should also integrate with, and lever as far as possible, work by US funded PIs on the KSTAR facility (though does not assert any direction over those separately funded DOE initiatives). Focus should also be given to ensuring strong interaction with both ITER preparation and needs, and also FPP/DEMO activities. Other pertinent facilities (e.g. WEST) can and should be folded into this partnership, as opportunities arise

Integrated High β_P Scenario Task Force

The immensely successful work under the previous DIII-D/EAST Task Force will be evolved to further target progress toward more advanced higher performing steady state regimes for ITER and FPP that address complementary challenges to the DIII-D/KSTAR Task Force. This work focuses on highly advanced 'high β_P' or 'high q_{min}' scenarios, where advanced current profiles and other techniques offer potential for improved configurations with higher β_N limits, stabilized turbulence at low rotation, and avoidance of tearing resonances, as well as higher bootstrap fraction operation.

Work is expected to interface to and lever international partners, with efforts to coordinate with other programs including joint experiments (including on collaborative facilities), joint leadership and joint publications. It is particularly desirable for this work to include parallel efforts and engagement with the EAST program, as well as potential expansion to other facilities such as KSTAR and JT-60SA, within the parameters of the pertinent international coordination agreements and facility operational and access arrangements.

Efforts in FY24-25 should target expansion of the performance limits and projective understanding of these regimes in pressure and density, utilizing current drive and shaping tools to extend in β and bootstrap fraction, while ensuring suitable ELM and heat flux mitigated, and low torque scenarios. Goals are to pioneer steady state regimes for ITER that are compatible with day 1 heating systems, and to develop promising candidate scenarios for net electric regimes in FPP. Six days are allocated.

Final Remarks

In executing this program, it is noted that DIII-D now has goal-oriented Groups to provide decision making and prioritization focus. Topical focus and interest groups are maintained in the Topical Science Areas, each formally located under one of these Groups, but expected to provide support and even coordinate experiments in any of the Groups as needed to achieve Group scientific goals.

Consider next steps, the program will now undertake a Research Opportunities Forum, with breakout sessions to determine the selection in early 2024. The primary goal of this process is to identify and prioritize experiments for the first 14 weeks of operation. Nevertheless, research groups may also sketch out their experimental plans for 2025, though noting FY25 allocations may be adjusted after the Research Council meeting in summer 2024. Exchanges of time allocations between years, between research groups are permissible through mutual agreement if this facilitates a more productive sequence. Run coordinators should track accounting of run time against the categories allocated in this guidance.

Further to the goal-oriented approach set out in our five year plan, Groups should track advances in TRL level, both in considering and projecting TRL advances in run selections made, in experiment proposals and miniproposals drafted, and later in tracking their progress as studies execute, to report progress at the end of FY24 and FY25.

Finally, it is noted that a campaign style approach was highly productive for the Negative Triangularity campaign in FY23. It may be more effective in some cases to collect experiments of a thrust or particular topic into 1-2 week blocks, so that they can be interleaved for technique development and thinking time, and rapid transitions can be made between studies to get the best for all experiments in a thrust or area.