DIII-D Operations and Facility Plans 2019-2024

by
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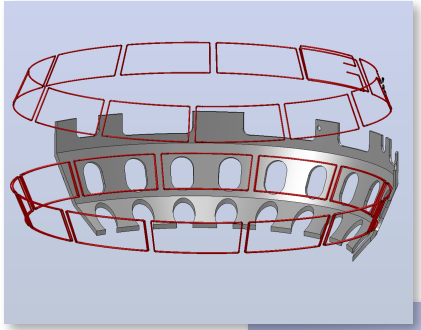
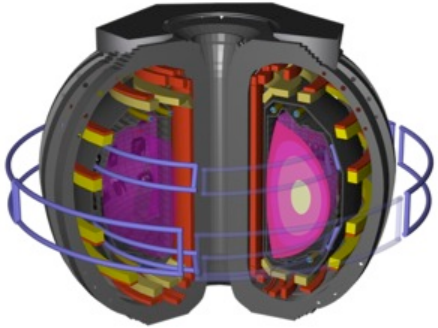
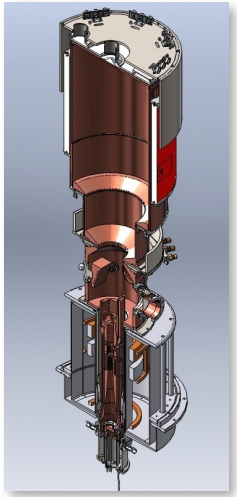
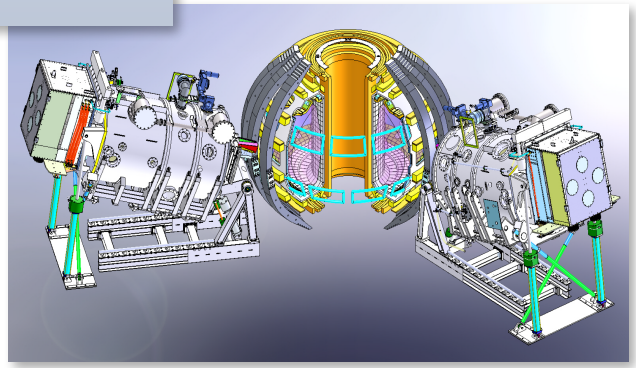
Presented to the
DIII-D Program
Advisory Committee
San Diego, California

April 24-26, 2018





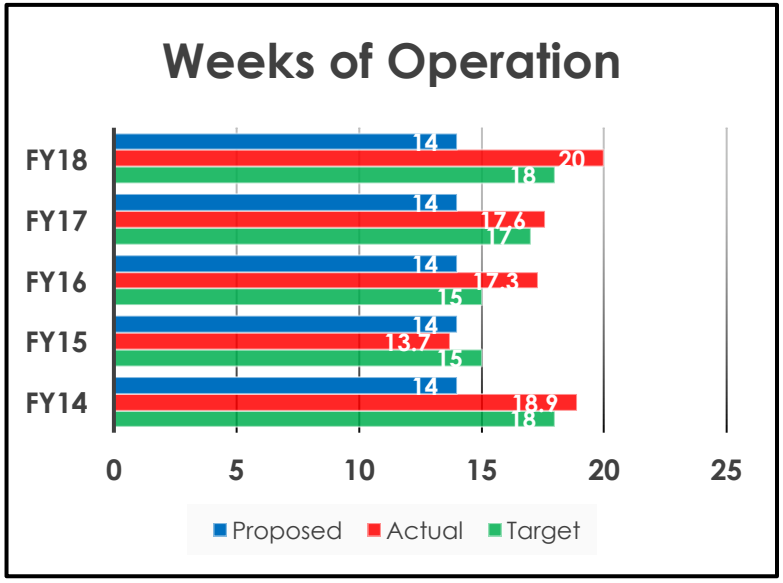


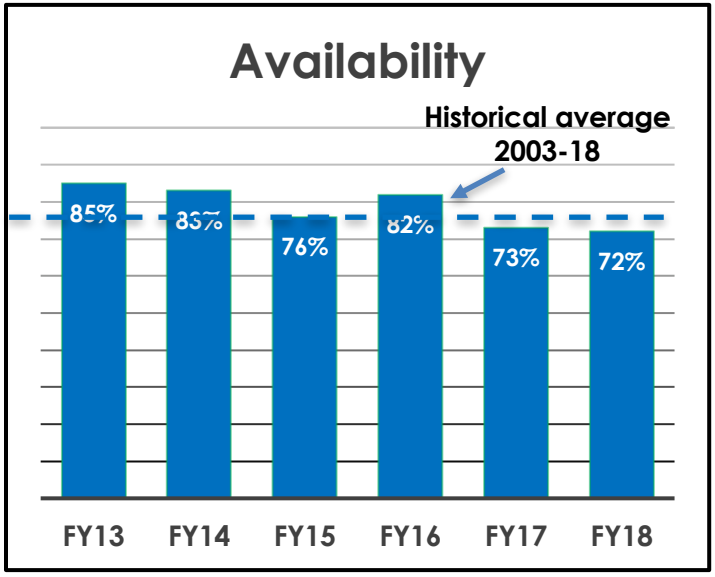


Outline

- **Review of Operational Performance FY14-FY19**
- **Data Systems (7.3), Sustaining Engineering (5.2), and Safety**
- **Major Facility Enhancements FY19 – FY24 (5.1, 5.3)**
- **Summary**

We Have Exceeded the Proposed Weeks of Operation and the DOE Target for Operations in 15 of the Last 16 Years

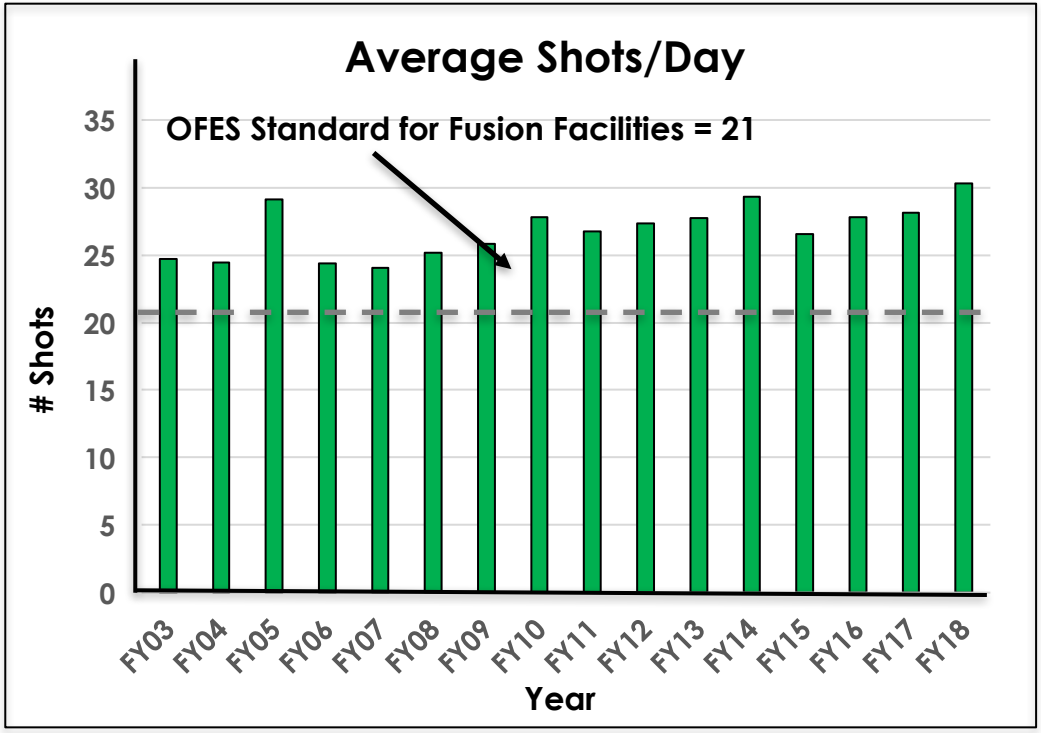




- **Total Proposed: 70 wks; Total Achieved: 76.3 wks**
- **The lower availability in FY17 and 18 highlights the need for increased emphasis on refurbishments**

FY14-FY19

DIII-D Provides a Productive Number of Plasma Shots Per Operational Day



(Note - 2018 thru March 30, 2018)

FY14-FY19

An Extensive Set of New Facility Enhancements Has Been Achieved Concurrent With Our Research Program

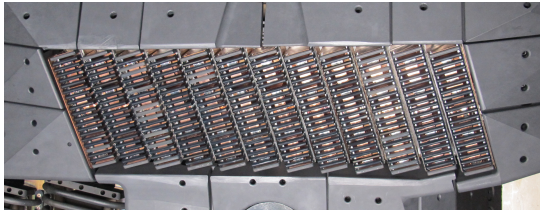
Small Angle Slot Divertor

Tungsten tile inserts

New Generation 1.5 MW Depressed Collector Gyrotron 'Vader'

ASIPP 3D Supply

Low Power Helicon Antenna



FY14-FY19

Major Facility Enhancements Completed in FY14-FY19

PACKET

- Low Power Helicon Antenna
- New Power Supply for 3D Studies and Enhanced Shaping (w/ASIPP)
- Small-Angle Slot Divertor
- High-Z (Tungsten) tiles (w/ORNL)
- Rebuild and commissioning of next generation, high power gyrotron
- Disruption Mitigation hardware - 2nd shattered pellet injector (w/ORNL), shell pellet injector (w/UCSD/GA)
- Impurity injectors - Impurity dropper (PPPL), granular injector (PPPL), Laser blowoff (MIT)
- Co-Counter Off-Axis NB – in progress - completion April 2019
- High Power Helicon – In progress – completion in FY20

FY14-FY19

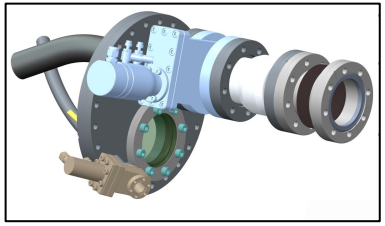
DIII-D Schedule and Facility Upgrades Have Been Responsive to DOE and International Needs

- **Long Torus Opening 3 (w/ CC-OANB) was delayed to provide additional operations time for US program**

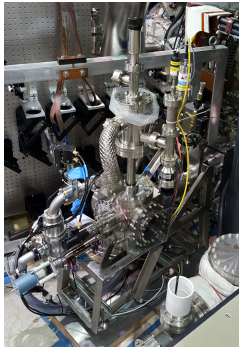
- **Helicon program was delayed to provide increased focus on boundary program**

- **Program for pellet/gas fueling for ELM and Disruption Mitigation was expanded (Pellet pacing, shell pellet, shattered pellet #2, powder dropper, granular injector)**

2nd Shattered pellet



Granular Injector



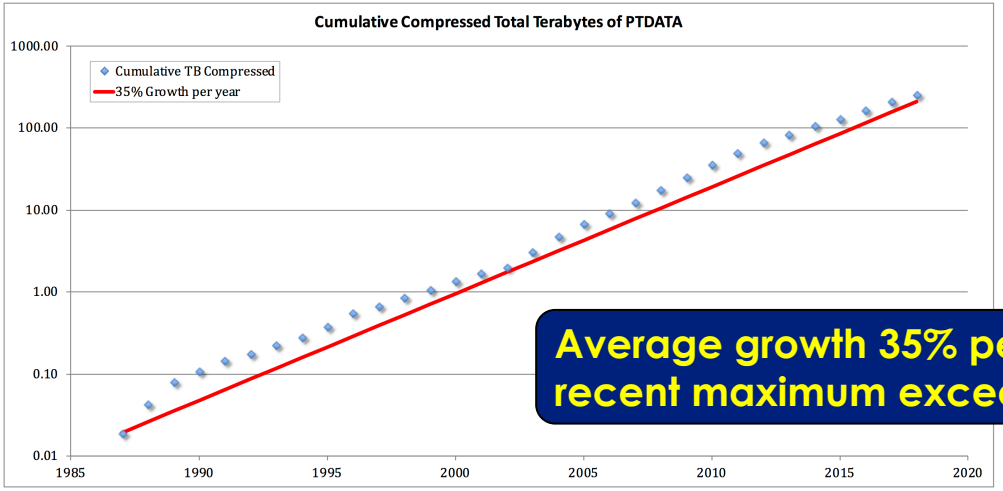
FY14-FY19

Outline

- Review of Operational Performance FY14-FY19
- **Data Systems (7.3), Sustaining Engineering (5.2), and Safety**
- Major Facility Enhancements FY19 – FY24 (5.1, 5.3)
- Summary

Substantial Upgrades and Refurbishments have been Completed for Computing Infrastructure

- **New raw data (PTDATA) storage with greater redundancy**
  - Record ~50TB of data acquired in FY18 for a total of 275TB



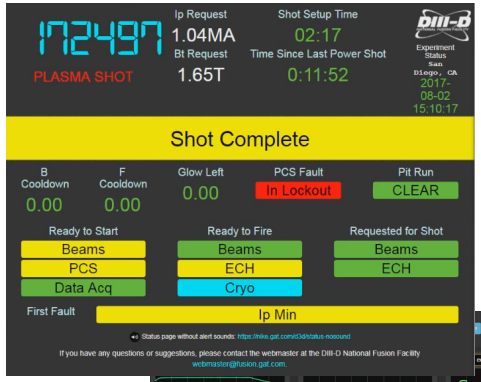
Average growth 35% per year with recent maximum exceeding 50%

- **New analyzed data (MDSplus) storage with greater redundancy**
  - Improve reliability, performance, and increase storage to 60 TB
- **Introduced Object Storage for camera diagnostic data**
  - Provides client/server API for ~380 TB repository

DATA SYSTEMS

Substantial Upgrades and Refurbishments Have Been Completed for Computing Infrastructure (2)

- **Web sites upgraded (~800 users)**
  - New frameworks, new design, and updated content
  - New real-time web-apps for experiment monitoring
- **DIII-D network upgraded**
  - All new core/edge switches (~55)
  - Next Gen Firewall deployed
  - 10 Gb/s reach extended
- **New computational cluster**
  - Substantial boost to 576 cores
  - New fast ZFS-based storage
- **Substantial PCS upgrades**
  - All 12 real-time CPUs now at 64-bit
  - Exclusively 40 Gb/s InfiniBand
- **Numerous DAQ node upgrades**
  - On-track to completely replace CAMAC



DIII-D monitoring web-apps

DATA SYSTEMS

Going Forward, Strong Support for Robust, Flexible and Efficient Data Systems Remains Critical to DIII-D's Success

- **Flexible computing infrastructure that can adapt to changing needs**
  - Data acquisition, instrumentation and control for operation
  - Infrastructure: user support, computing, networking, data storage
  - Support for effective and efficient data analysis
- **Upgrade storage systems to meet demand**
  - Anticipate up to 2.6 PB of raw data (50% increase per year)
- **Next computing cluster design begun after successful FY17 transition**
  - Transition to Red Hat 8 , retain existing file structure & job queue
  - Further acquisition of GPUs and InfiniBand networking as required
- **Expanded Disaster Recovery plan**
  - Geo-replication of critical data with rapid recovery
  - Presently 3 copies of data maintained

DATA SYSTEMS

Going Forward, Strong Support for Robust, Flexible and Efficient Data Systems Remains Critical to DIII-D's Success

- **Improve networking infrastructure to match increased data flow**
  - Expansion of 10 Gb/s connectivity within the LAN
- **Complete deployment of new web application server & new apps**
  - Custom web apps & their databases redesigned/refactored
- **Plasma Control will continued to be modernized to meet needs**
  - Real-time computer upgrades continued at 2 per year
  - GPUs & FPGAs deployed as required to meet experimental needs
- **Data Acquisition Upgrades will continue**
  - As needed for the our technology refreshment cycle (≤ 5 yrs)
  - Higher frequency digitizers as required to support the science
- **CAMAC-free prior to beginning of new 5-year agreement**

Continue to maintain a reliable, flexible, state-of-the-art computer infrastructure to support the needs of the DIII-D community

DATA SYSTEMS

Cybersecurity is an Integral Part of Providing a Secure Environment for Open Collaborative Research

Approach

- **Protect users and their work (data, research and systems)**
- **Protect the network and facility**
- **Be a good and contributing ESnet neighbor**
- **Continuously improve our cyber security practices**
  - Use risk and threat analysis to prioritize our resources and plans

Plans

- **Maintain constant outreach to DIII-D user community on Cybersecurity Awareness**
- **Enhance perimeter security while supporting collaborative services**
- **Complete the networking infrastructure reorganization**
  - Firewall upgrades; Network Access Control (NAC) for all nodes;
  - Full Network Segmentation

DIII-D Has a Strong Maintenance and Refurbishment Program to Maintain a Productive Facility

PREVENTATIVE MAINTENANCE

- 939 pieces of equipment are tracked in PM system
- Approximately 5000 hours of PM performed every 12 months.

REFURBISHMENTS (Completed under existing 5-yr agreement)

- Motor generator cooling system refurbishments (FY15, FY18-19*)
- Production of spare NB source accelerator parts (on-going)
- Modernization of NB HV Supply and Control System (LCS8, 5&6*)
- Switchgear for PF supplies (FY16-17); line reactor (FY18*)
- CAMAC Control and data acquisition replacement (complete FY19*)
- Primary Vacuum pumps; Vessel Air Bake system*; clean dry air system; water pumps (on-going)

* Scheduled for performance/completion in LTO3

SUSTAINING ENGINEERING

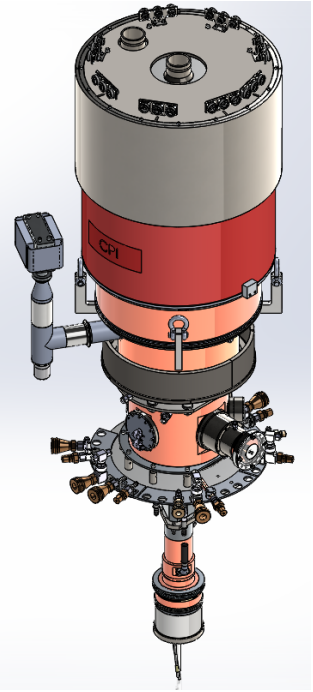
A Major Initiative is Underway to Increase Reliability and Productivity Through a Sustaining Engineering Program

- **Spares (FY18-FY20)**
  - Spares for control circuitry (modernize and spare custom designs)
  - Increase inventory for long lead items: pumps, motors, transformer
  - Install spares for long installation items
- **Replacement**
  - Replace 3 original 1 MW gyrotrons with new CuCrZr collectors for longer life (FY20/21)
  - Helium liquefier (FY20 Delivery)
  - Motor Generator I/O cables (underground) – FY18
  - Other HV cables (FY19)
- **Refurbishment**
  - NB Local Control Stations 5,6 (FY19); NB ion sources (on-going)
  - Motor Generator Cooling System (FY18/19)
  - Helium liquefier (during LTO to improve reliability until replacement)
- **Enhancement**
  - TF reversing switch, access control (FY19/20)

SUSTAINING ENGINEERING

ECH Gyrotron Refurbishment/Repair

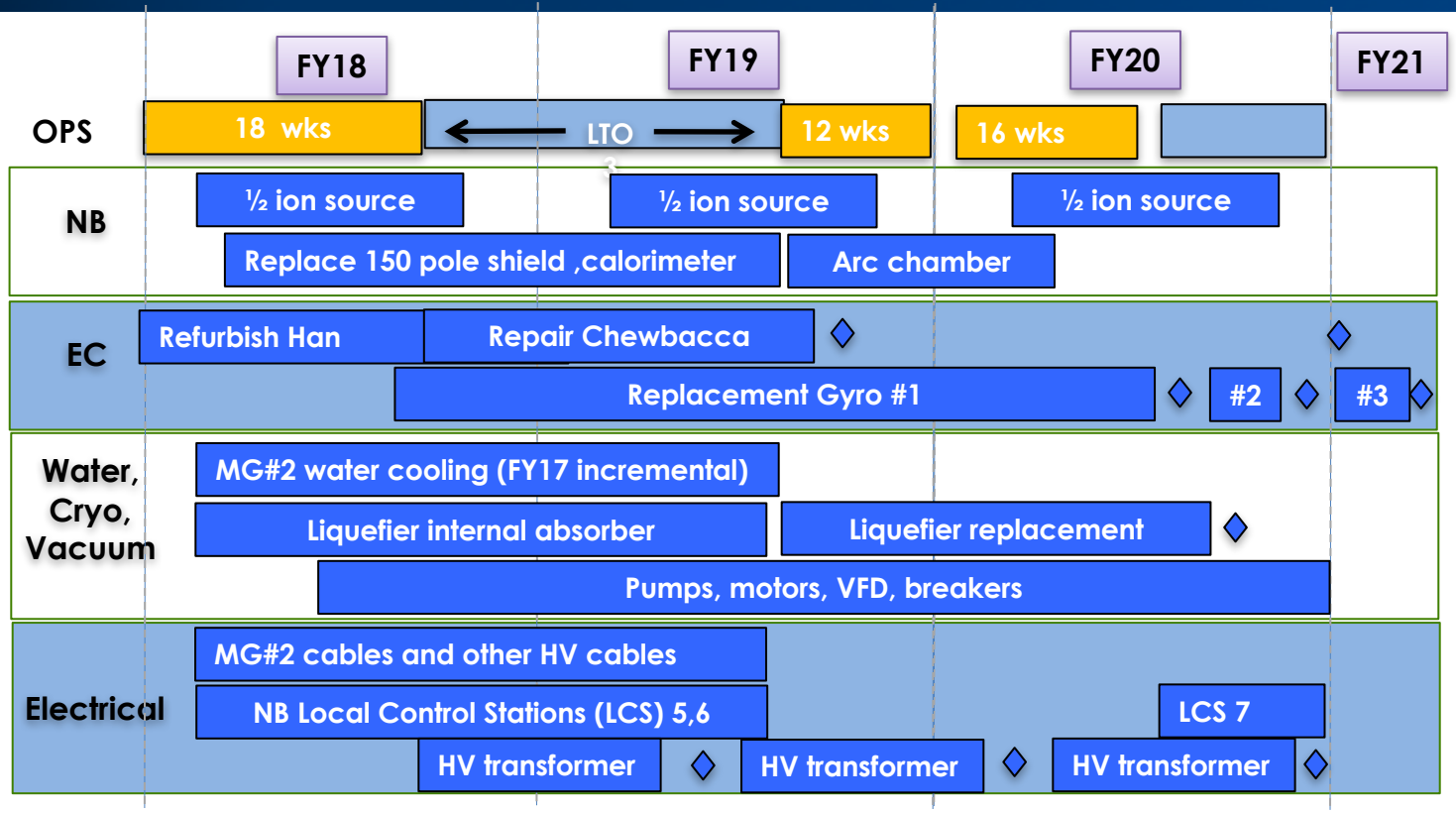
- **Refurbishment of Han (1 MW, non-Depressed Collector) in progress (early FY19 delivery) – upgraded collector and many new parts**
- **Procurement of three replacement 1MW gyrotrons (for 15+ year old gyrotrons) with upgraded collectors is being initiated**
  - Concurrent procurement of three gyrotrons reduces cost 15% compared to procurement of three individually and reduces delivery time
- **Chewbacca (1 MW Depressed Collector) recently developed a vacuum leak; evaluation to occur as soon as possible**



1 MW gyrotron with upgraded collector

SUSTAINING ENGINEERING

Major DIII-D Refurbishments



SUSTAINING ENGINEERING

DIII-D Has A Strong and Effective Safety Program

- **Based on principles of Integrated Safety Management -** fostering a culture of continual improvement with involvement of staff at all levels.
  - 2016 Management and Staff Safety Retreat identified over 100 items that have provided direction for improved safety at DIII-D (Training, procedures, unsafe conditions, unsafe behaviors)
- **We encourage reporting of all incidents, including near-misses**
  - Investigation teams identify both corrective and preventative actions
- **Training of all DIII-D staff (employees, collaborators, students, and post-docs) is carefully tracked and reviewed quarterly**
  - 5668 classes were provided since 2014. Of these 2969 (52%) were instructor led and 2699 (48%) were online. ~1322 class per year.
  - Online training is continuing to increase with the new GA LMS System
- **OSHA recordable incidents have not increased since 2014 and we remain a factor of two below the industry standard**

SAFETY

OUTLINE

- Review of Operational Performance FY14-FY19
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System Capabilities (Start of 5-Year Plan)

Heating and Current Drive (injected power/pulse)

- **NB: 8 sources; 16 MW (4 s) / 19 MW (3 s)**
- **EC: 6 gyrotrons: 4.1 MW (5 s); 8 steerable launchers**

Coils

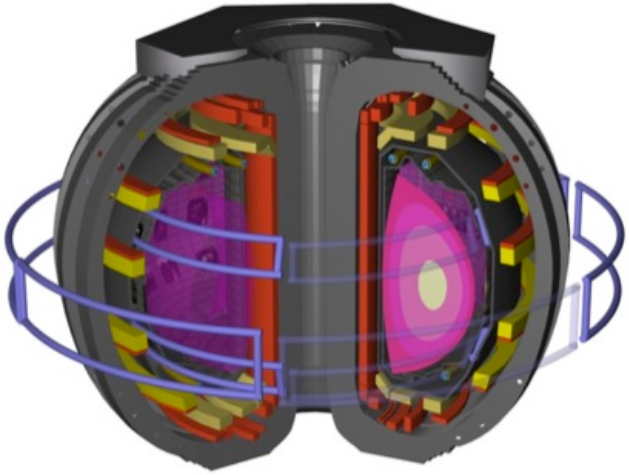
- **18 Poloidal field shaping coils**
- **6 external coils, 12 internal coils**
  - Error field control, RWM feedback
  - ELM control (RMP, NRMF)

Plasma Control

- **12 CPUs, 60 GB/sec inter-CPU network**

Divertor/First Wall/Conditioning

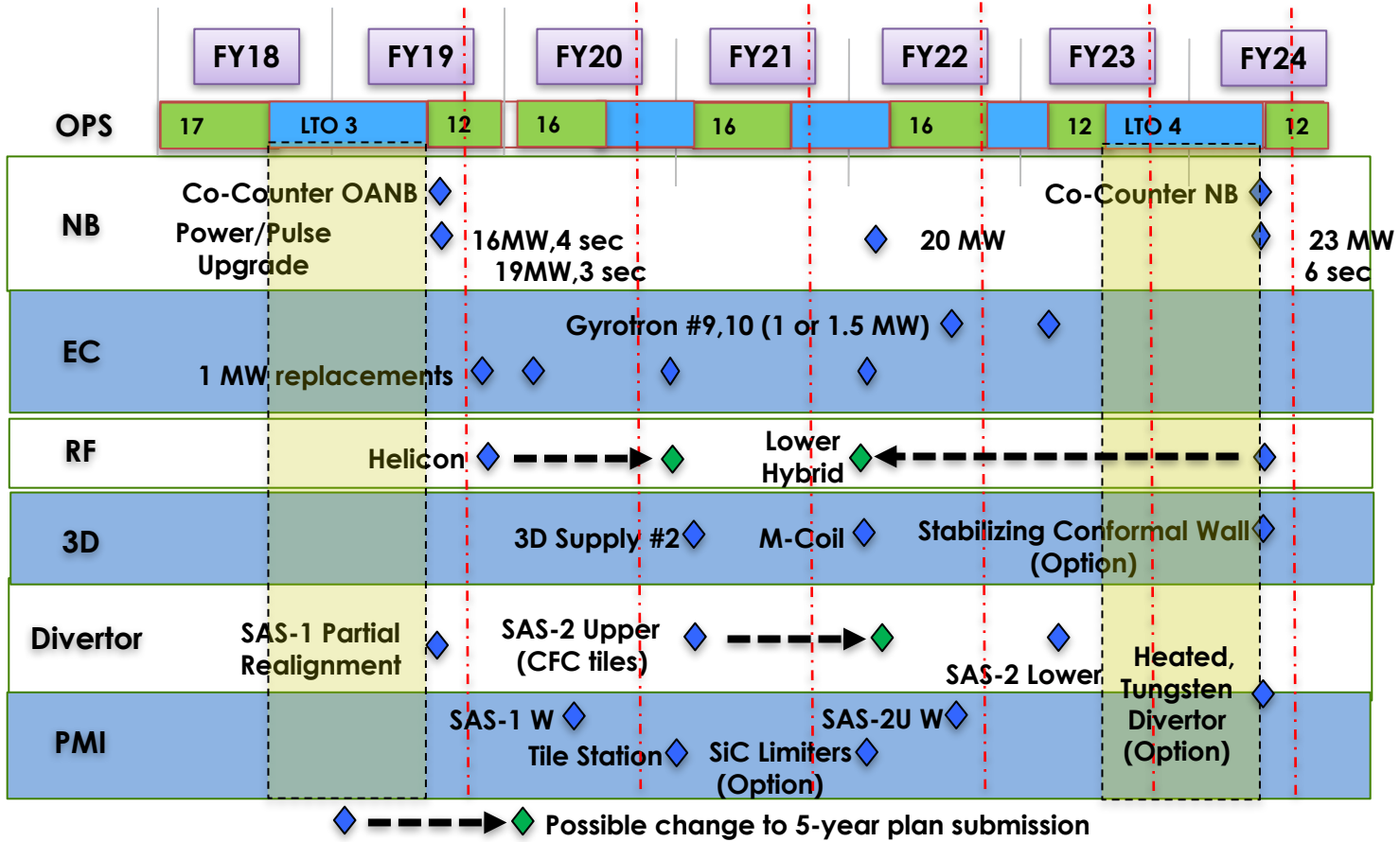
- **3 cryopumps; 15–20,000 ℓ/s**
- **ATJ graphite — 90% coverage; Reduced tile edge heating**
- **350˚C bake, boronization, He glow between shots**



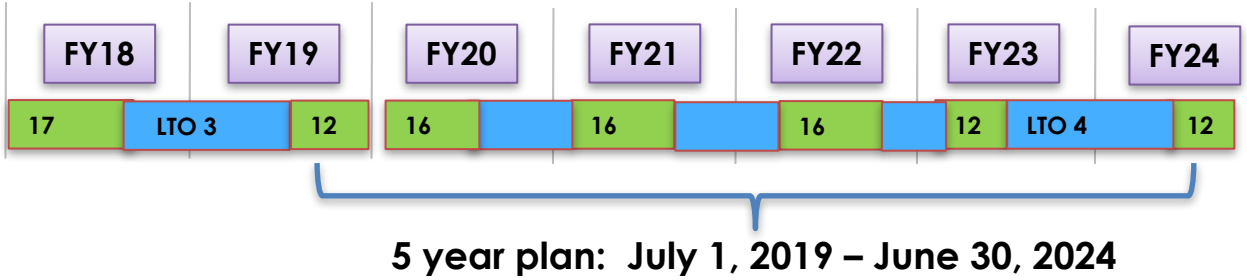
Planned Facility Enhancements Will Strengthen the Steady State AT and Boundary/PMI Programs

	Facility Upgrades	Research Goals
Steady State AT	Expanded EC	Increase Te/Ti; Zero-torque H&CD; Off-axis j(r); NTM stabilization; Perturbative transport
	Helicon/ HFS Lower Hybrid Top Launch EC	High efficiency off-axis current drive
	Co-Counter NB	Increased co- power for high β scenarios Low rotation high β SS scenarios
	NB Pulse/Power Extension	$T \longrightarrow 2\,\tau_R$; Higher β scenarios
Boundary/PMI	New 2D/3D Power Supplies, New 3D coils	Improved divertor shaping RMP and 3D physics
	Divertor Geometry Modification	Heat flux and density control; detachment physics
	Divertor diagnostics	Dissipative physics, SOL flows and momentum, turbulence and transport
	New PFCs – W	Understand sources and develop mitigation techniques

Proposed Major Facility Enhancements FY18 – FY24



73 Weeks of DIII-D Operations are Proposed



- **70 weeks of ops were proposed in existing FY14-FY19 plan**
- **Typical Operating schedule is 8:30 – 5:00 AM; 5 days per week**
- **Higher research productivity has been achieved via a weekly 2 hour plasma control development sessions (5:00 – 7:00 PM)**
- **An Option is proposed to increase Operating time by 70%**
  - Extended hours from 8:30 AM – 5:00 PM to 8:30 AM – 11:00 PM
  - Additional scientific and operating staff will be added to maintain efficient, safe, and scientifically productive operation

Off-Axis Current Drive for Advanced Tokamak Performance Remains Highest Priority

- **Electron Cyclotron Current Drive**
  - Increased power
  - Top Launch
- **High Power Helicon**
- **High Field Side Lower Hybrid**
- **Co-Counter Off-Axis Neutral Beam Current Drive**

OFF-AXIS CURRENT DRIVE

EC Power Remains a Key Element of Research Program – Two Options to Achieve 10 Gyrotron System

- **Purchase most reliable gyrotron compatible with DIII-D EC system**
  - Evaluate performance of new 1.5 MW, 117.5 GHz gyrotron
  - Consider 1 MW gyrotrons for #9-10 and replacement units (#1-4)
- **Completion by early FY23 (FY18 start, 2 yr fab time, 3/year)**
- **Option 1: Purchase (6) 1 MW gyrotrons**
- **Option 2: Purchase (3) 1.5 MW gyrotrons (if and when tube proves reliable) and (3) new 1.0 MW replacement gyrotrons**

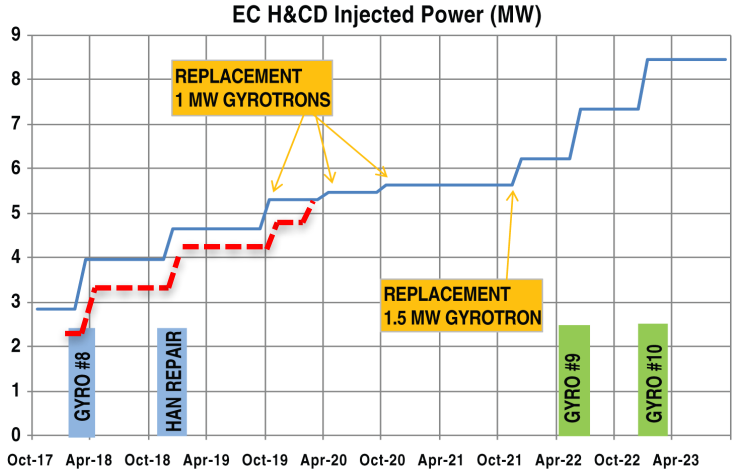
Tube S/N	8110 (old)	8110N (new)	8115 (D.C.)	8117 (D.C.)	Total (MW)
Frequency	110	110	110	117.5	
P- gen/inj (MW)	0.8/0.55	0.9/.65	0.95/.70	1.5/1.1	
Start of 5yr plan	3	1	1(+1)*	1	4.1 MW
Approach 1		7	2	1	7.05 MW
Approach 2		4	2	4	8.4 MW

* 1 gyrotron under repair

ELECTRON CYCLOTRON

1.5 MW Gyrotron Commissioning Continues – High Power Performance is Not Yet Achieved

- **Completed installation of 8th gyrotron system (FY18)**
- **Conditioning and testing of 8th gyrotron underway at DIII-D**
  - Achieved to-date: 900 kW, 1 sec; RF efficiency 27%
  - Efficiency is consistent with 1.3 MW at design parameters of 50 A, 100 kV

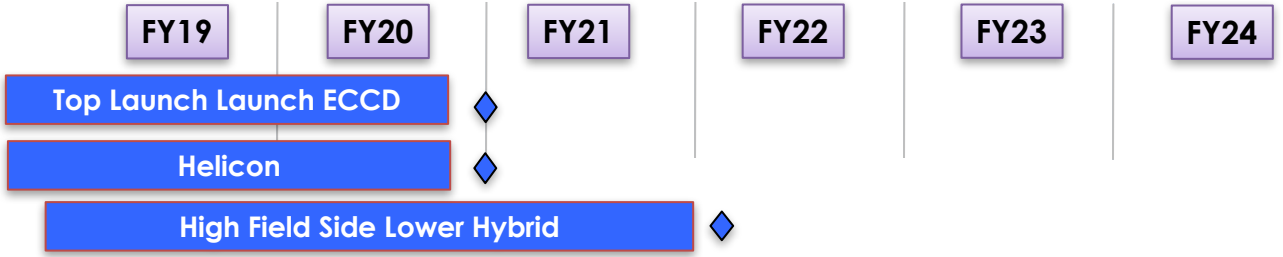


Plot of EC injected power from Five-Year Plan (Option 2)

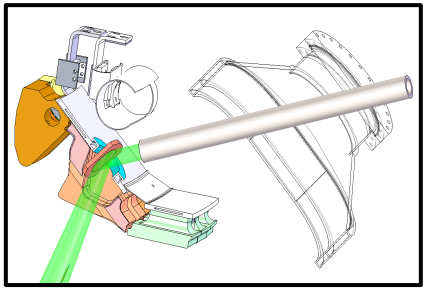
Effect from failure of Chewbacca and its repair

ELECTRON CYCLOTRON

Three Approaches Are Being Considered for Higher Efficiency Off-Axis Current Drive



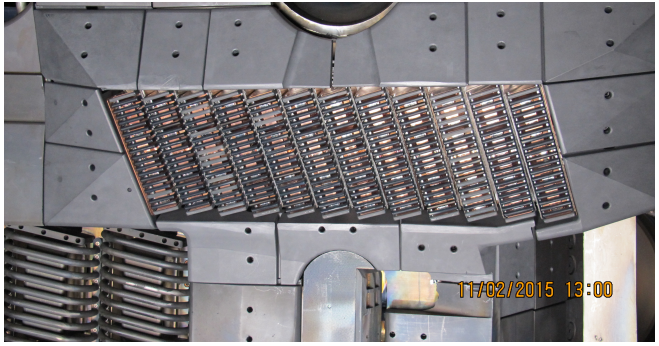
- **Top Launch Launch ECCD**
  - Capable of 110 GHz or 117.5 GHz
  - Uses existing waveguides
  - Developed under GA IR&D
- **Helicon wave antenna (Peak ρ ~ 0.5)**
  - 476 MHz, 1.0 MW injected
- **Lower Hybrid (Inside wall) (Peak at ρ ~ 0.7)**
  - 4.6 GHz, 1-2 MW injected



EC/HELICON/LOWER HYBRID

Helicon (Very High Harmonic Fast Wave) System Will Test Predictions of High Efficiency Off-Axis Current Drive

- **Low power antenna (200 W) installed in September 2015 and operated in October 2015**
- **Experiments with low power antenna obtained key data:**
  - Good rf loading into high performance ELMing discharges achieved
  - Antenna location compatible with high performance discharges
- **Q of high power prototype module increased from 450 to 1200**
- **Project put on hold in FY16 to direct funding to boundary program**

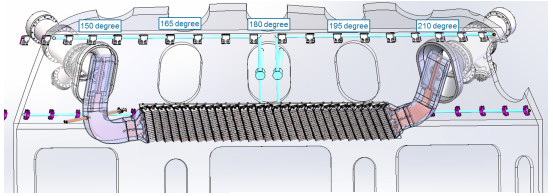


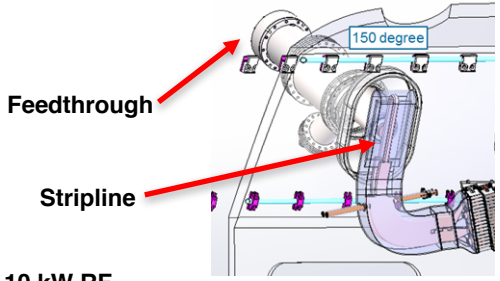
Low power antenna and surrounding tiles

HELICON

Helicon: Progress Made on Resolving Technical Issues Since Restart of Project in Late-FY17

- **Disruption loads:** design and analysis arriving at a viable solution
- **Feedthrough:** use existing feedthroughs from Fast Wave system
  - Remaining: apply TiN coating to mitigate potential for multipactor
- **In-Vessel RF feed:** developed concept for dual stripline with analyses showing acceptable RF performance
  - Remaining: bench test to confirm RF performance
  - Mechanical & thermal design and analyses
- **Multipactor & HV Hold-Off:** testing ¼ module in RF test stand; initial results look promising
  - Remaining: tests with field & TiN coating
  - Test of stripline



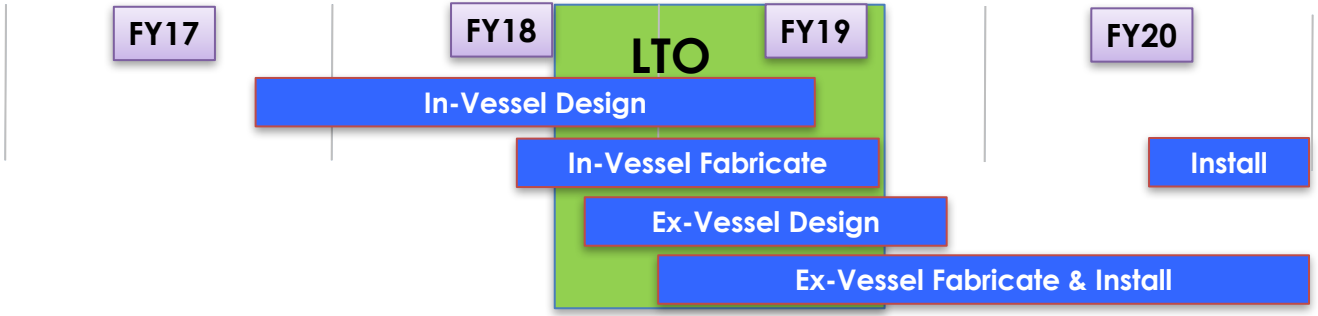


10 kW RF Transmitter

RF Test Stand

HELICON

Resolution of Outstanding Engineering Issues Pushed Installation Beyond LTO into New Cooperative Agreement

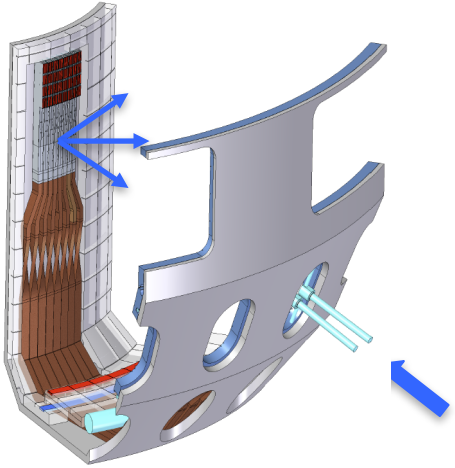


- **SLAC to transfer 476 MHz Klystron and HV supply – preparing a Strategic Partnership Project (SPP) Agreement**
- **Incremental funding received in FY18 may allow earlier completion**
- **Enhanced Collaborations**
  - PPPL – design, fabrication & installation of stripline; procurement of external waveguide components
  - ASIPP – could provide tuned and brazed antenna modules and machined Inconel back-plates
  - KSTAR - developing agreement with SLAC to obtain five klystrons – one is to be loaned to DIII-D in lieu of SLAC transfer

HELICON

Inside Wall Launch Lower Hybrid System Will Test Predictions of High Efficiency Off-Axis Current Drive

- MIT will be technical lead
- Klystron and HV supply exist at MIT
- Viability of centerpost antenna is being evaluated with mockup antenna installed April 9



WR187 waveguide feeds inside launch antenna

Klystron Assembly
8-16 @ 250 kW each

High voltage supply

LOWER HYBRID

Implementation of the Inside Launch Lower Hybrid System Will Be Split Between GA and MIT

GA Responsibility

- Vessel Tiles (Floor and Centerpost)
- Vessel Feedthrough for waveguides
- Water cooling pad (pumps, tank, ac power, resin beds, piping)
- HV cabling (50 kV cables, 480 Vac)
- DC Power supply site prep (6 MW breakers, cabling, concrete pad)

MIT Responsibility

- High voltage power supply (50 kV)
- Klystrons (8 in phase 1), (8 in phase 2); Klystron controls
- Waveguide transmission lines from klystron to vessel
- All in-vessel hardware associated with transmission line

- Proposed for FY23-24 installation. Increased funding in early years may permit moving installation forward to FY20-21

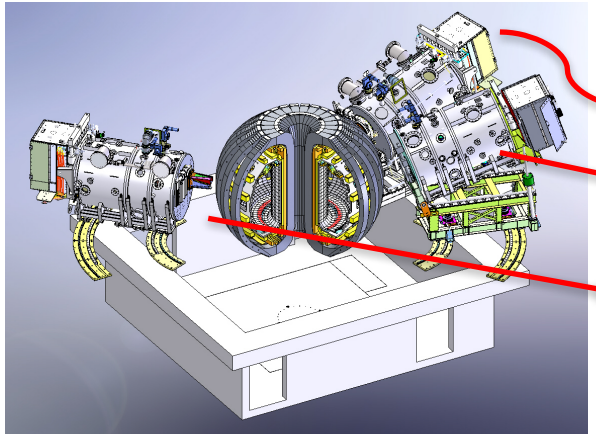
LOWER HYBRID

Two Phase Beam Upgrade Doubles Off-Axis Power, Increases Co-Power and Enables Full Co- and Balanced Injection

FY16 | FY17 | FY18 | FY19 | FY20-22 | FY23 | FY24

210 Co-counter OANB #2
Fixed off-axis angle + co/counter adjustable

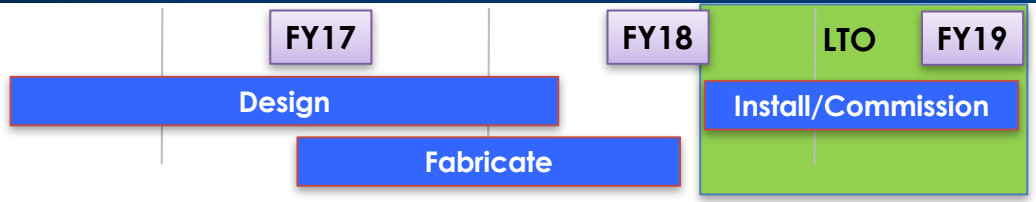
30 co-counter #2
Co/counter adjustable only

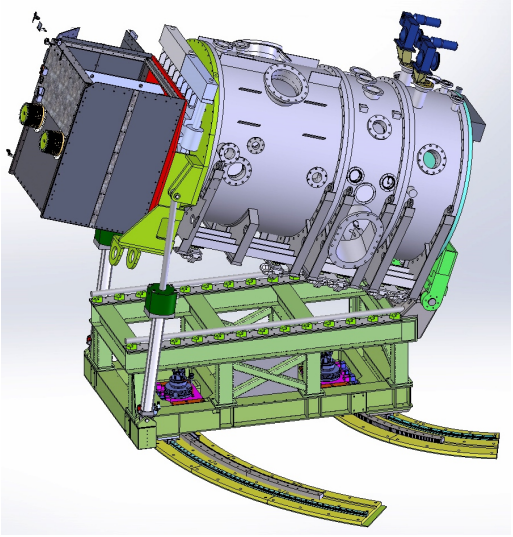


	Off-Axis	Co-Power	Balanced
Present	4 MW	14 MW	10 MW
Phase 1- 210 beam	9 MW	19 MW	10 MW
Phase 2 – 30 beam	9 MW	19 MW	19 MW

CO-COUNTER OANB

Phase 1: 210 Co-Counter Off-Axis Beam is on Schedule to be Completed at End of LTO3 (April 2019)





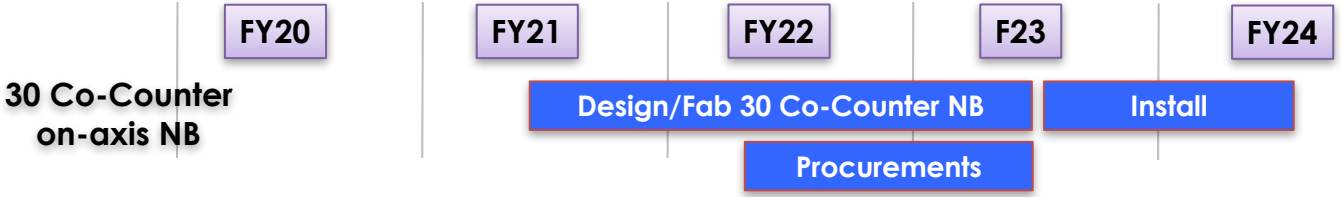
- All designs are 95% complete
- 78% of procurement is in progress(minimum slack time of 61 days for items in fabrication)

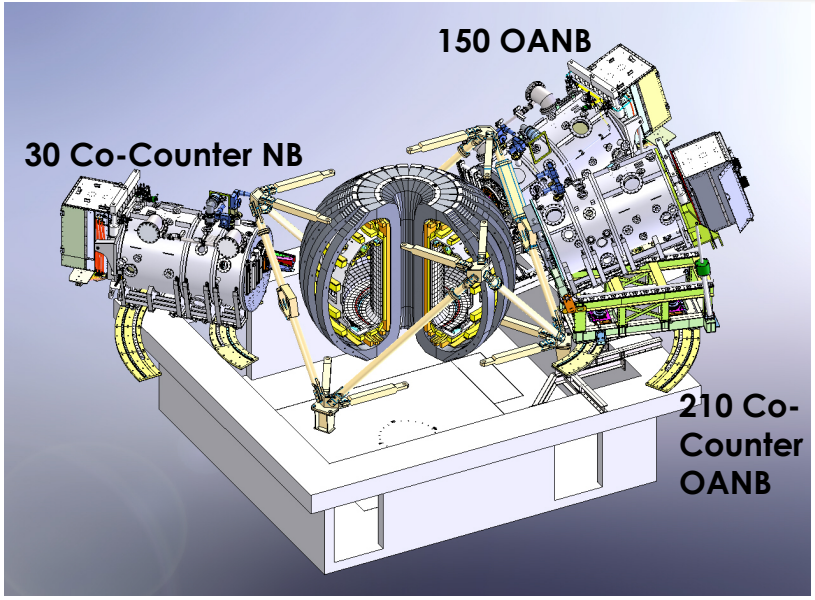
Beam Duct

Beam stand

CO-COUNTER OANB

Phase 2: Add Co-Counter Capability to On-Axis 30° Beamline to Provide Full Power Balanced Injection





- Co-counter mechanism uses 210 design
- Horizontal beam reduces seismic loads
- Geometry relative to pit concrete structure and anti-torque structure involves design issues from both previous movable beam designs.

CO-COUNTER NB

Increasing Power/Pulse Length for AT and Boundary Research Requires NB and Vessel Hardware Changes

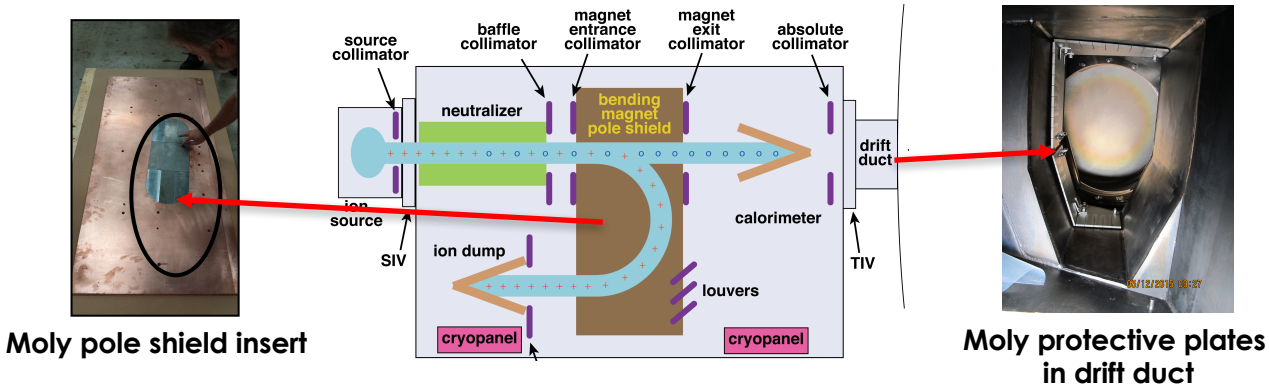
TARGET NB Power/Pulse: 16 MW/4 sec upgraded to 23 MW/6 sec

- **Neutral Beam – design for 3.2 MW, 6 second capability**
  - Upgrade internal collimators, enlarge source aperture
  - Replace calorimeters, upgrade magnet pole shields (PPPL)
- **High Voltage Systems - increase from 81 to 93 kV (2.5 MW to 3+ MW)**
  - Refurbish HV components; upgrade isolation in arc supplies and source housing
  - Improve input DC voltage regulation (w/PPPL)
- **First Wall – increase from 75 MJ to 180 MJ (30 MW/6 sec)**
  - Tile Thermal Upgrade

POWER/PULSE

Proven Designs for Addressing NB Power and Pulse Limits Are Being Incorporated into All Beamlines

- **Drift duct protective plates have been installed in all beamlines**



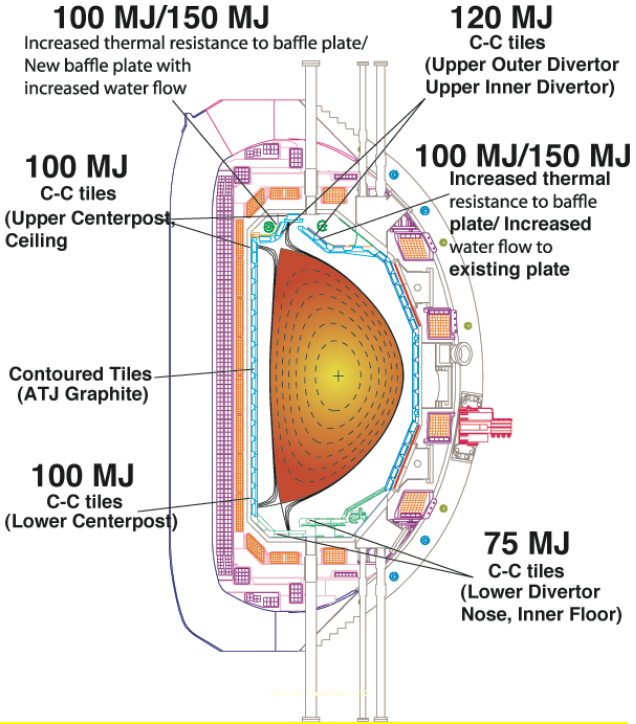
- **Designs for beamline internals are completed and partially installed:**
  - Magnet pole shields (design complete; 330 installation completed)
  - Internal collimators (design complete; 150 installation completed)
  - Calorimeters (design complete - PPPL)
  - Increase source aperture (5 sources completed)
- **HV system upgrade required to enable operation up to 93kV**

NB POWER/PULSE

Planned PFC Modifications Will Accommodate 150 MJ

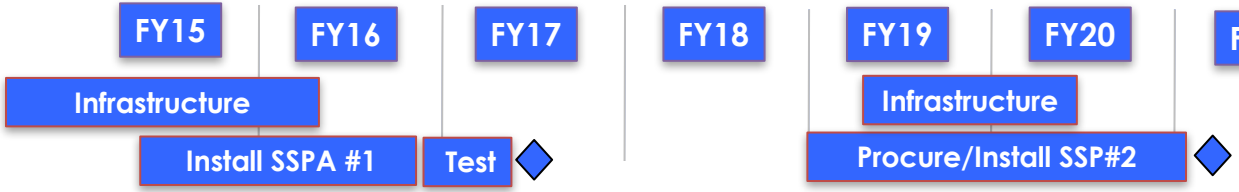
- **CFC tiles replace ATJ graphite**
  - 75 MJ < E < 100 MJ — 360 tiles
  - 100 MJ < E < 150 MJ — 168 tille
- **Moving beyond 150 MJ requires some combination of:**
  - Improved water cooling (SAS-2U)
  - Increased radiation above 30%
  - Increased SOL flux expansion
  - Improved real-time monitoring
- **Coordinate with boundary plan**
  - Lower divertor (FY20)
  - Upper divertor w/ SAS-2 in FY21
  - Centerpost (w/ HFS Lower Hybrid)

Present thermal limits



PULSE EXTENSION/FIRST WALL

New Power Supply Through ASIPP Collaboration Significantly Enhances 3D Control and 2D Shaping



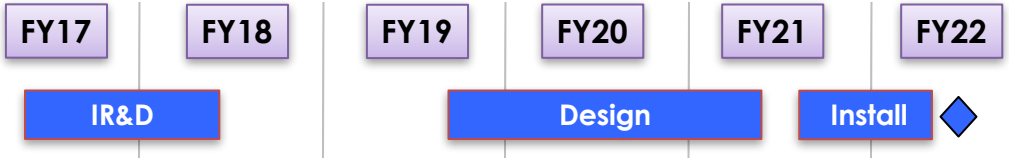
- **SSPA#1 commissioned and in routine use**
  - 6 modules @ 2.7 kA, 450V
- **Supplies provide:**
  - Greater flexibility for 3D magnetic spectra
  - Improved 2D shaping capabilities for new divertor and ITER research
- **Procurement of 2nd supply and infrastructure will begin in FY19 for late FY20 installation**
  - Transformer and Flexible patch panel for 2nd supply already installed.

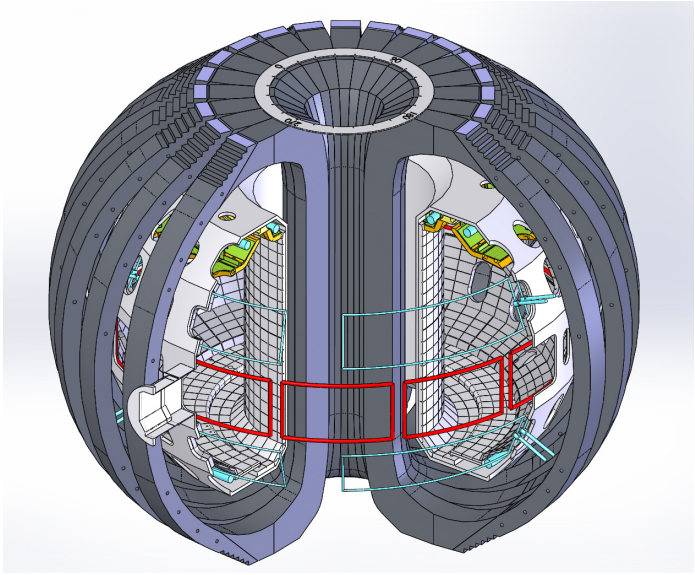
Power Supply (FY17)

Patch Panel (FY16)

POWER SUPPLIES

New 12 Coil Array of Internal Coils on Midplane (M-Coil)

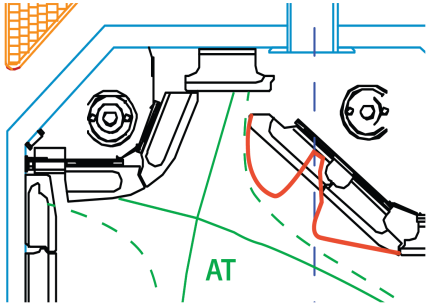




- Multi-turn coils (4 turns)
- 2.7 kA/turn to match new power supplies
- Wind coils in-vessel to reduce fab/install time and to improve coil reliability

INTERNAL COILS

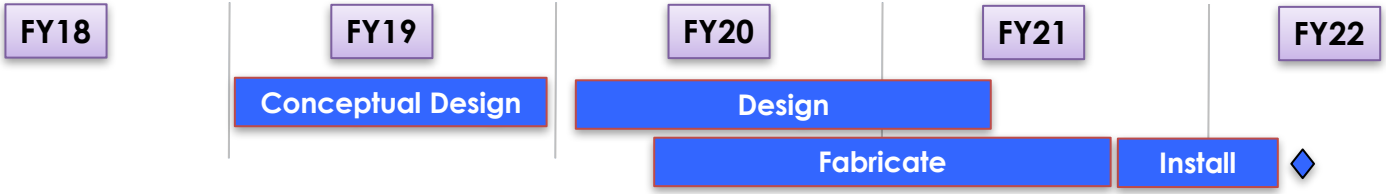
Divertor/Wall Modifications in FY19-24 Will Enable Study of Slot Divertor With Pumping and Integration with AT Core

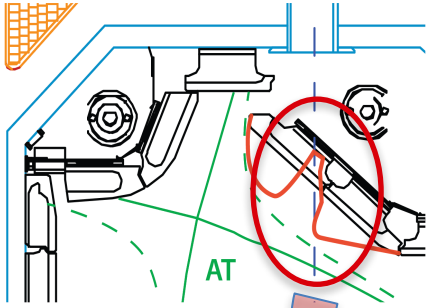


- SAS 1 – (FY17) Tested Small angle slot concept separated from main divertor
- Partial re-alignment of tiles scheduled for FY18-19 will better align the slot with the toroidal field (offset from the centerpost by 3 mm)

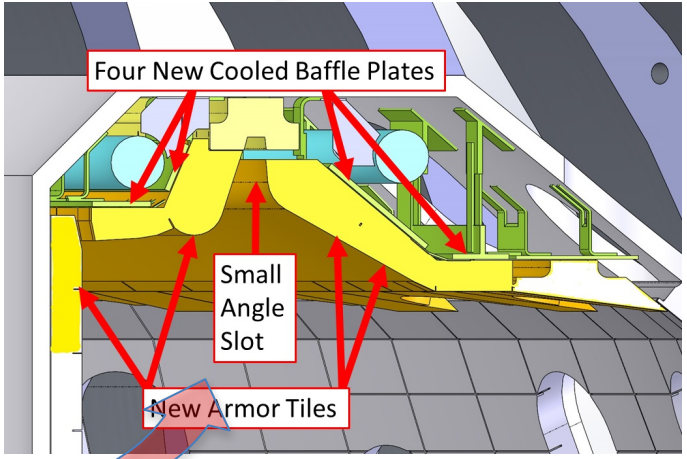
BOUNDARY

Divertor/Wall Modifications in FY19-24 Will Enable Study of Slot Divertor With Pumping and Integration with AT Core





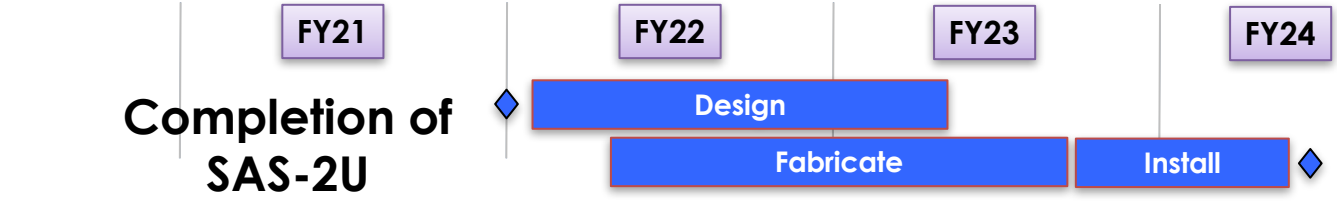
SAS IIU (FY21/22)

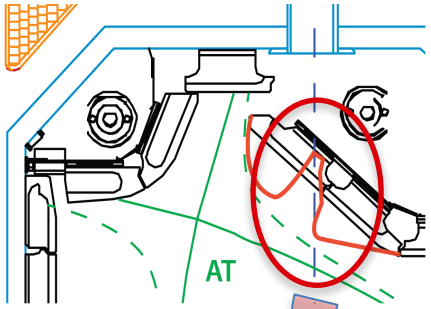


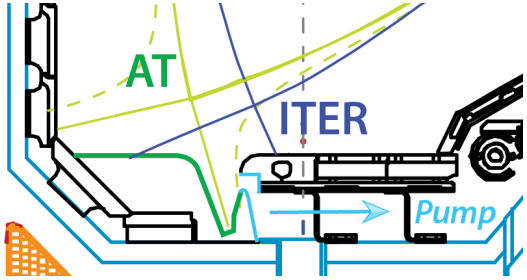
- **SAS 2U – slot will become primary upper divertor region with pumping**

BOUNDARY

Divertor/Wall Modifications in FY19-24 Will Enable Study of Slot Divertor With Pumping and Integration with AT Core





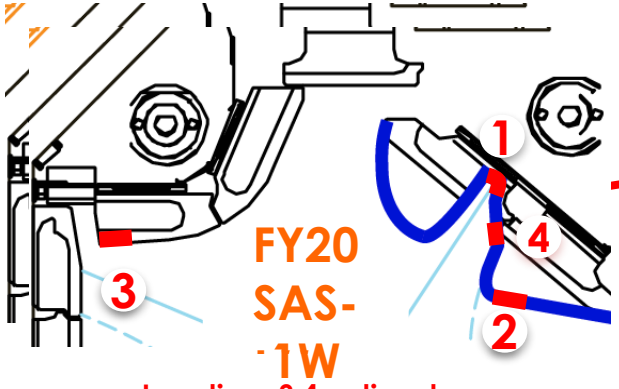


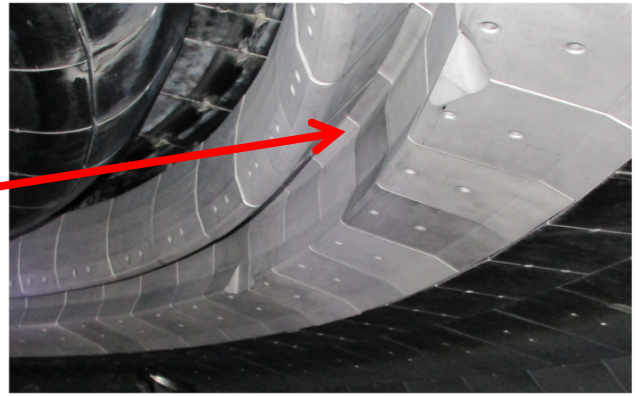
SAS IIL (FY24)

- **SAS 2L – (FY24)**
  - Full integration of SAS concept with double null AT discharges

BOUNDARY

New High Z tiles in SAS-1 Slot Will Enable Study of High Z Leakage from a Closed Divertor



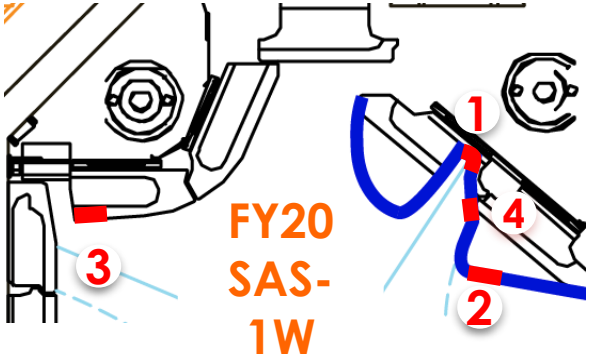


New Upper SAS divertor (120° - 195°)

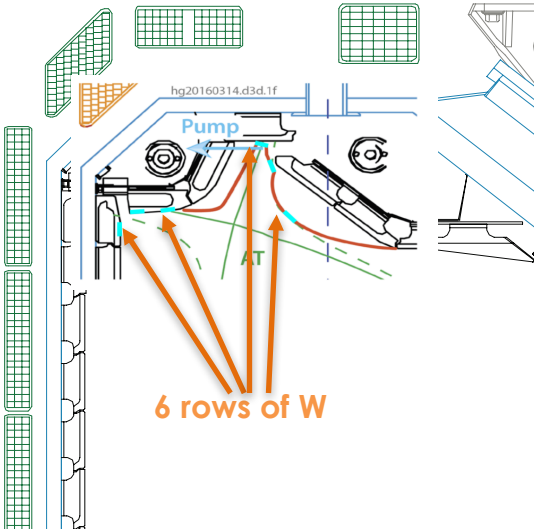
- Up to 4 rows of Tungsten tiles (inserts or coating) will be installed in FY20 for 2 week campaign.
- Isotopic coating of W-182 provided by ORNL
- Natural tungsten (mixed isotopes) can be achieved by coating graphite or Moly inserts

BOUNDARY/PMI

New High Z tiles in SAS-1 Slot Will Enable Study of High Z Leakage from a Closed Divertor



Similar studies are planned for SAS-2U (FY23)



BOUNDARY/PMI

Proposed Enhancements Comprise an Exciting Plan That Provides New Capabilities For All Major Research Thrusts

- The DIII-D program has met its operational goals and provided world-class upgrades and a safe, productive facility for the US and World fusion community
- An enhanced Sustaining Engineering program is proposed to maintain high reliability and productivity
- Proposed upgrades coupled with new diagnostics will provide new capabilities needed by the proposed research program to explore and gain understanding of new regimes