RADIO FREQUENCY INSTALLATIONS, COLLABORATIONS, AND PLANS ON THE DIII-D TOKAMAK

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The DIII-D Collaborative Program

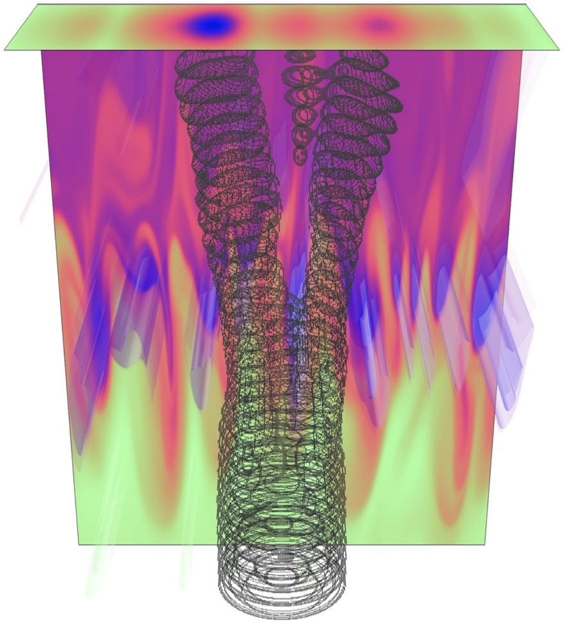
- DIII-D is installing and testing new RF systems at ~1MW:
  - -Helicon
  - -Top Launch EC
  - -Inner wall lower hybrid
  - -Additional gyrotrons
  - -WHAM program at the University of Wisconsin Madison

- It is a major program partly focused on rf systems

- Domestic and international teams including GA, CPI, PPPL, UW-Madison, MIT, ORNL, UCLA, TechX, CompX, ASIPP, and others work together on systems, plasma operations, diagnostics, and codes, contributing to high power collaborative RF research

Some Areas to Pursue with Collaboration

- **We need full wave and beam codes incorporating all relevant physics from launch to deposition –**
  - Evanescence, coupling efficiency, scattering, parametric decay, ponderomotive effects, turbulence modeling, antenna materials modeling need to be captured in a single set of tools
  - These phenomena occur together in a Tokamak environment
  - COMSOL is an example of a powerful code being used
- **The US fusion community is developing an RF-SCIDAC (Scientific Discovery through Advanced Computing) collaboration, working with domestic and international groups and machines**
- **Development efforts are working to establish a single set of predictive tools (capable of multiphysics – heating, AC/DC & RF) and test stand and tokamak data to validate the predictions**
- **Hardware development, including launchers, transmission lines and sources, together with validated modeling development will enable the RF-driven Advanced Tokamak of the future**



3D Full Wave Simulations of complex mm wave propagation through fluctuations are an example of specialist calculations that benefit from collaborations

DIII-D NATIONAL FUSION FACILITY

DIII-D RF Status for Projects and Collaborations

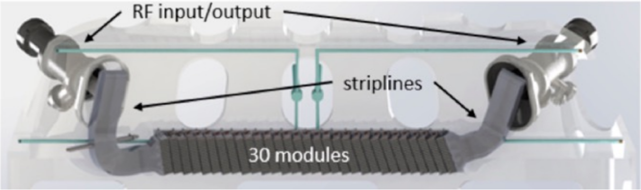
- -HELICON INSTALLATION (ASIPP, SLAC collaborations)
  - -Proposed by Viktor Vdovin of Kurchatov Institute and Ron Prater of GA plus others
  - -Helicon klystron transmission line and antenna installed and initial operations underway
  - -Conditioning the antenna using 1-2 msec pulses 10% duty 5 sec at 100 kW into glow plasmas
- -TOP LAUNCH ECH on DIII-D
  - -One system operational
  - -Second system being prepared for installation in 2021
  - -Third system possible for the 2020 tokamak vent
- -WHAM (Wisconsin High Tc Axisymmetric Mirror project) at the University of Wisconsin-Madison, 8 collaborators including DIII-D, multiple technical applications, project under construction
- -LOWER HYBRID System (PPPL, MIT collaborations)
  - -Preliminary waveguide/launcher grill geometry passed test in DIII-D
  - -Klystron array being installed ex-vessel, waveguide lines being 3D printed
  - -System completion in 2022
- -DIII-D ECH Installation (ASIPP, MIT, PPPL collaborations)
  - -Two gyrotrons operational
  - -One more in test at DIII-D, one delivered, one being completed at CPI, two being repaired at CPI

476 MHz Helicon System was Installed on DIII-D in 2019-2020

- **Antenna is a traveling-wave antenna of comb-line type, a joint project of GA and ASIPP**
  - 30 modular radiating elements, fed only at one end of toroidal array
  - Excites $n_{||}=3$ at 0.48 GHz
  - 12-element low-power prototype tested in 2016 on DIII-D[1]
  - 30 modules of high-power antenna fabricated in 2018-19, half in the US, half at ASIPP (Hefei)
  - Installed in the DIII-D vessel in January 2020
  - High power applied for the first time in December 2020
  - Now being conditioned for operations

[1] R.I. Pinsker, et al., Nucl. Fusion **58** 106007 (2018)

Low-power prototype in DIII-D, 2016



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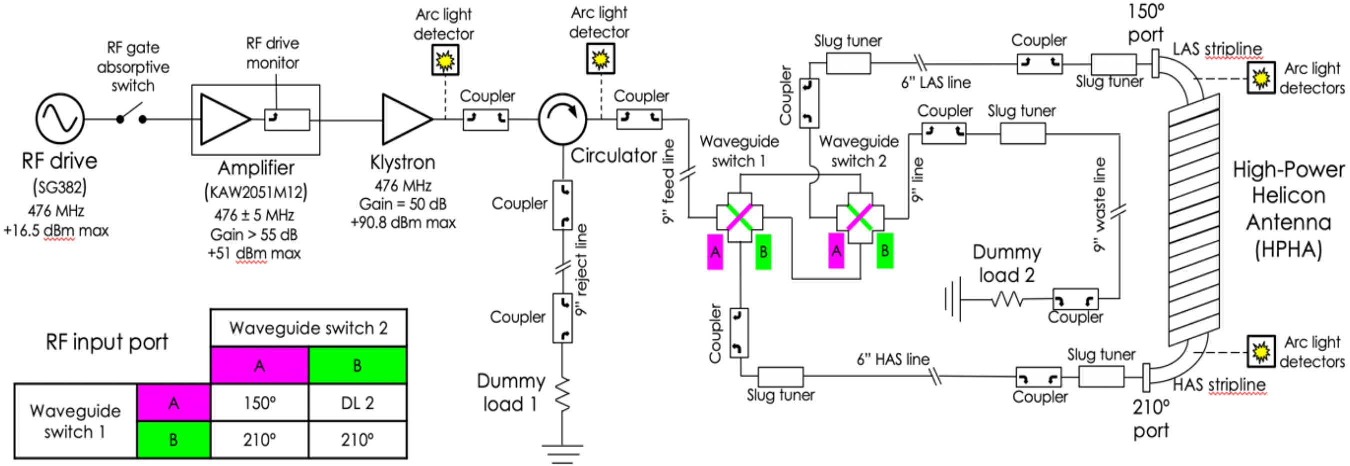
Helicon Installation on DIII-D

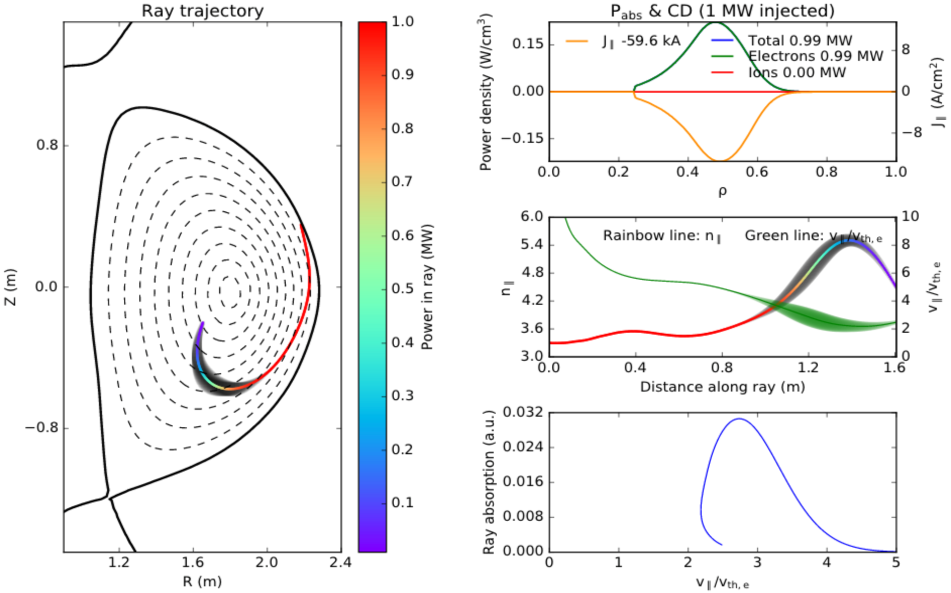


RF input port		Waveguide switch 2	
		A	B
Waveguide switch 1	A	150°	DL 2
	B	210°	210°

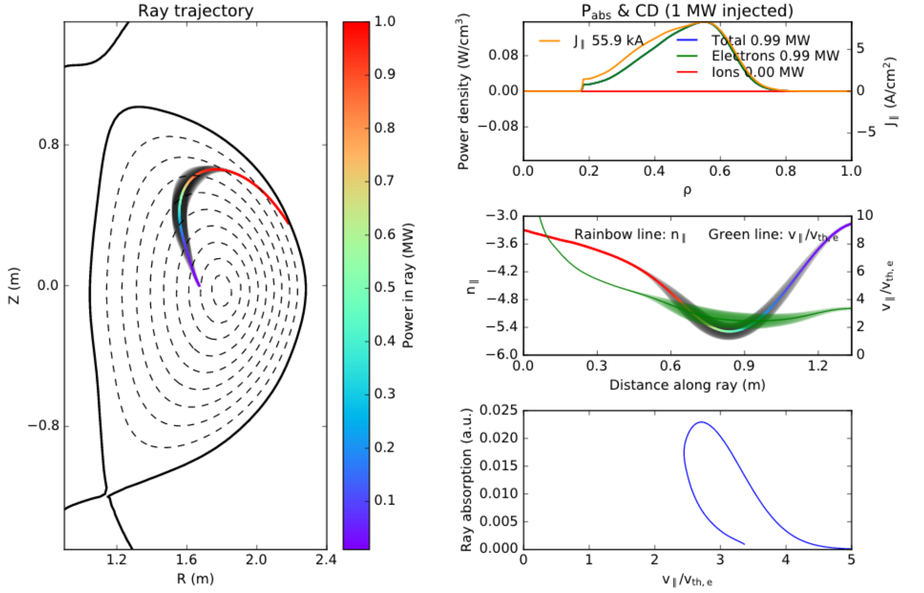
Antenna can be fed from either end, allowing co- and counter-current drive

Block diagram of flexible helicon system at DIII-D

Performance Predictions for the Helicon System



Counter Current Drive



Co Current Drive

High Beta Target Plasma

Bart Van Compernolle

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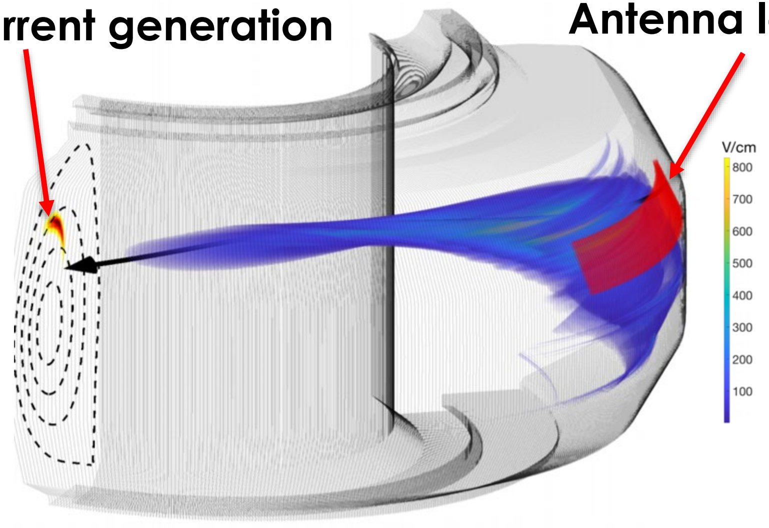
Modeling Efforts are Ongoing at a Number of Institutes to Support the DIII-D Helicon Experiments

- **Collaborators**
  - PPPL
  - Tech-X (Boulder, CO)
  - ORNL
  - GA
  - MIT
  - International collaborators

Modeling helicon excitation, coupling, propagation, absorption and current drive

Absorption and current generation

Antenna launch point



3D full-wave modeling and visualization by ORNL (Lau, et al.)

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DIII-D Helicon Operations

- **First high power Helicon testing has begun and experiments into glow discharge plasmas have begin to measure coupling, deposition, and current drive efficiency. These tests are piggybacked on normal discharge operation in DIII-D at the end of shots.**
- **Diagnostics specifically supporting the helicon operation include**
  - Doppler-free active spectroscopy measuring the near-field electric field
  - Upgraded Phase Contrast Imaging diagnostic for perturbed density measurements in the far field
  - He gas puff
  - Advanced IR cameras and many thermocouples

A goal is to measure the 476 MHz RF waves in the core and edge of the plasma to benchmark modeling

2019 Team Helicon at DIII-D

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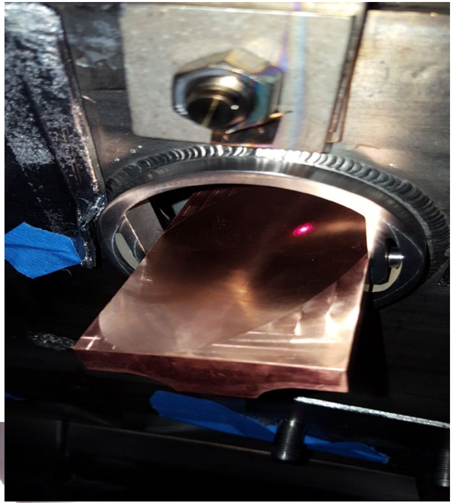
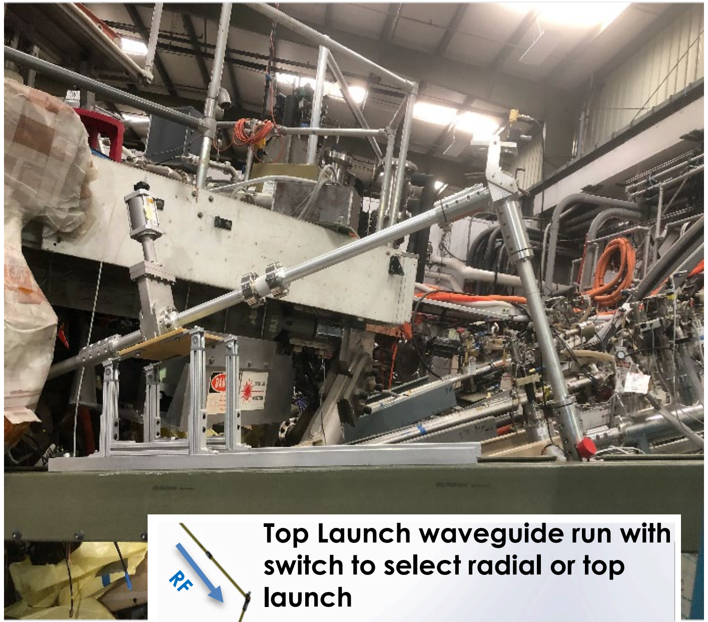
Top Launch ECH

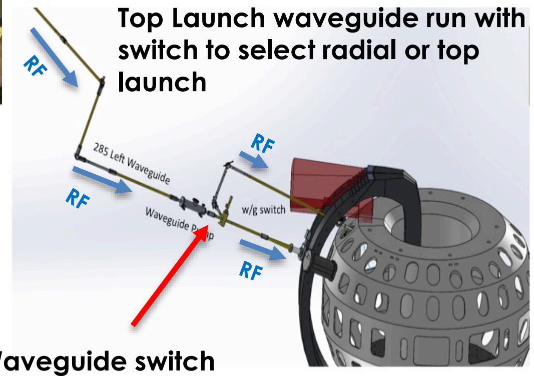
- The Top Launch System is an important new part of the ECH complex and experimental program
- A second system is being designed to be installed on the opposite side of the tokamak
- Physics operation demonstrated significantly increased current drive

Xi Chen



In-vessel fixed turning mirror



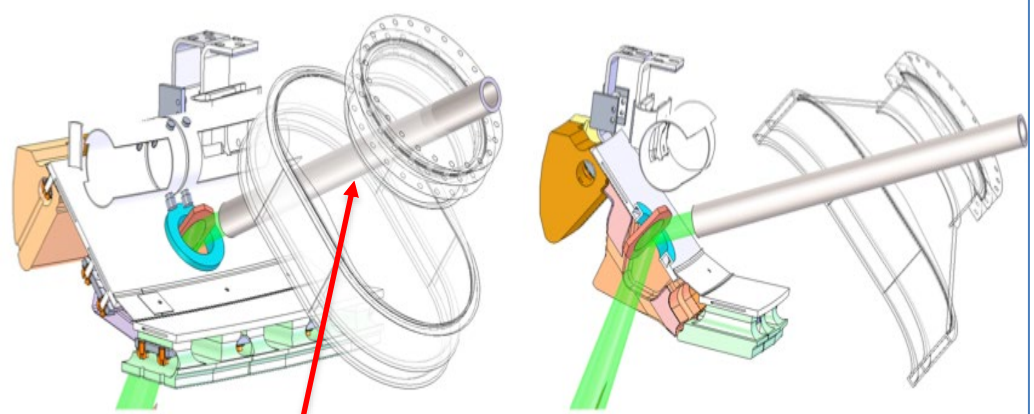


Top Launch waveguide run with switch to select radial or top launch

When switching from radial to Top Launch and back, miter angles change, requiring changes in the waveguide polarizer settings

Waveguide switch

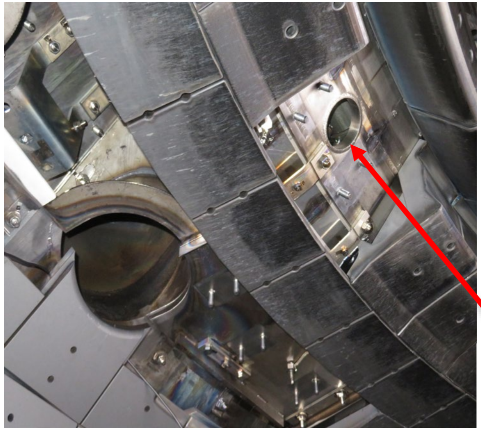
The Top Launch System Increased the RF Current Drive Efficiency
A Second Top Launch System is Being Installed on DIII-D



Corrugated waveguide

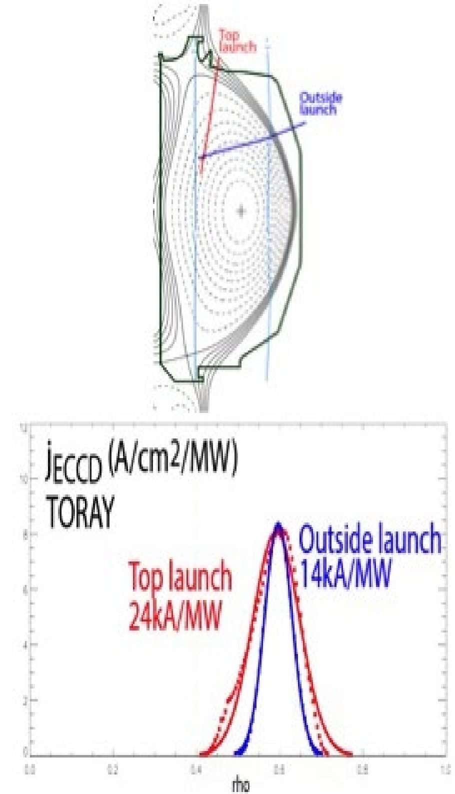
Increased time close to the resonance at higher Doppler shift gives higher current drive than normal radial injection

In the vacuum vessel

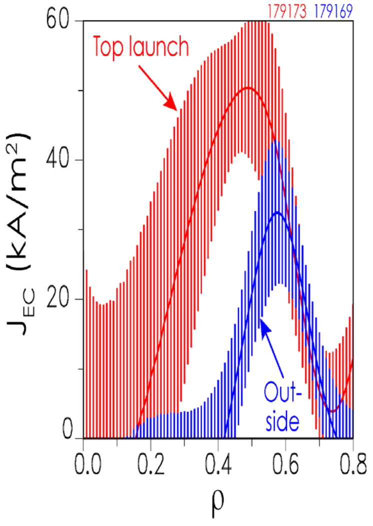


Waveguide access hole in the vessel ceiling near the divertor was a difficult installation location

Initial current drive prediction



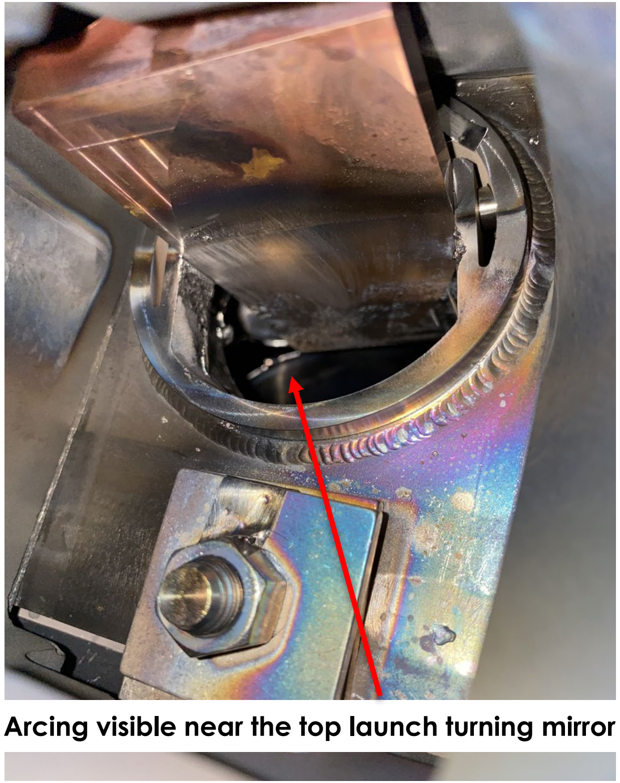
Measured current drive



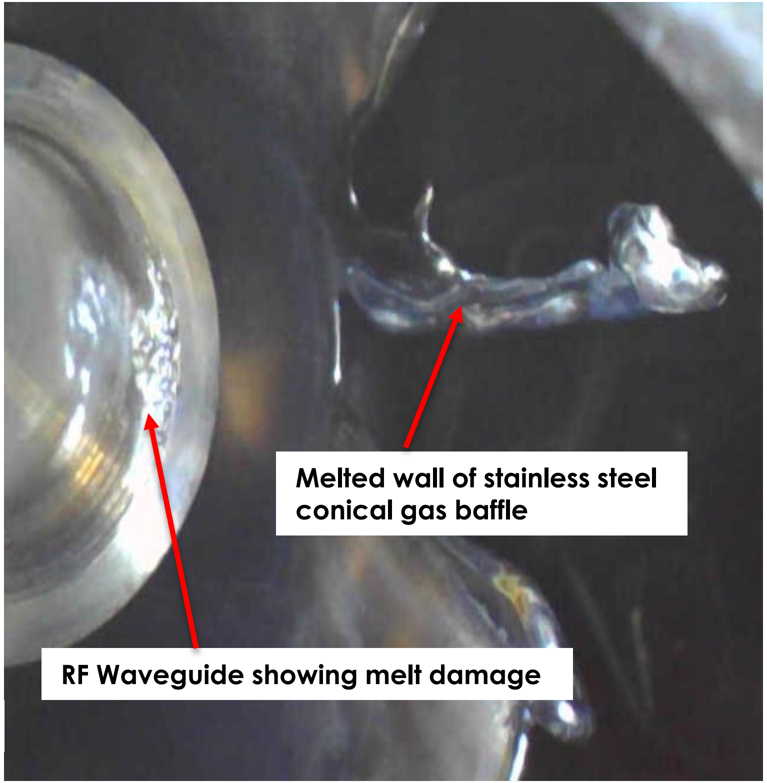
The top launch total current drive is ~2x the outside launch current drive

Xi Chen and Craig Petty

Stray RF in Top Launch Melted the Gas Baffle in the Upper Divertor This Resulted in High Energy Electrons Escaping into the DIII-D Vessel



Arcing visible near the top launch turning mirror



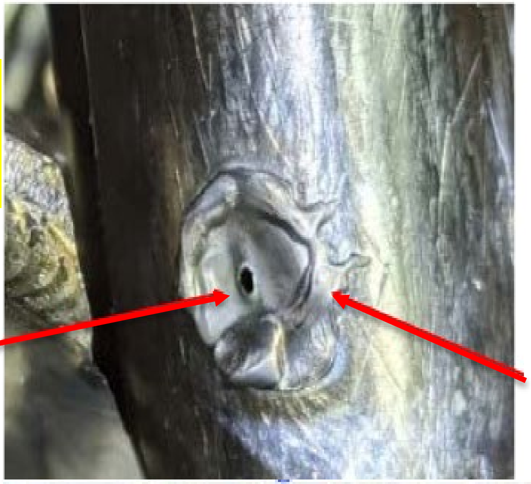
Gas baffle was thin stainless steel with no cooling. A discharge was created by the rf, and electrons followed the magnetic field lines around the tokamak, unfortunately to a water line, which was melted

Electrons Followed B Field from Top Launch to Water Line

- The gas baffle was thin stainless steel
- without cooling
- Discharge at output of ECH waveguide melted baffle in both directions
- This gave a clear path for electrons to
- follow the field and strike the water line
- At least 30 liters of water were removed from the vacuum vessel
- Very clean hole drilled in the line
- > a week of down time

Top Launch operations on temporary hold while gas baffle is rebuilt from graphite

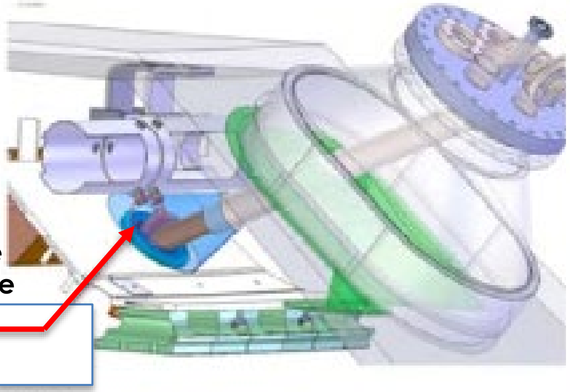
Strike point on water line for electrons originating from top launch location



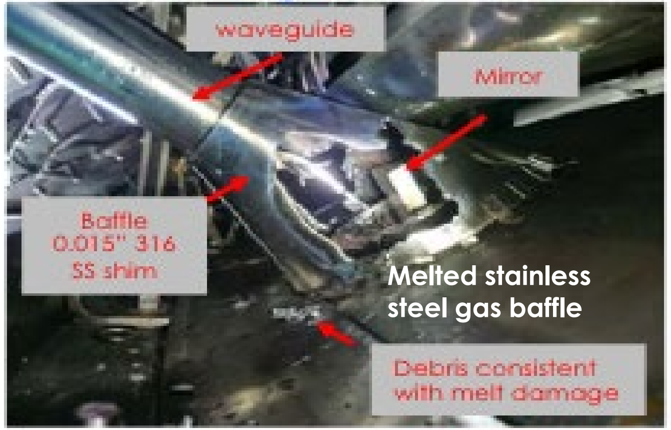
Melted Inconel water line diameter ~3 cm

Next baffle design will use graphite composite- Plastic model has been 3D printed

Water line was relatively far from Top Launch location ~80 deg counter-clockwise but on the same field line as the melt damage in the stainless steel gas baffle



Conical gas baffle intended to reduce gas at end of waveguide



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The University of Wisconsin High Temperature Superconducting Axisymmetric Mirror Collaboration

Wisconsin HTS Axisymmetric Mirror

A Broad-Based International Collaboration-Being Built at Madison Wisconsin

Cary Forest[1], Jay Anderson[1], Jim Anderson[4], Pyotr Bagransky[9], Ted Biewer[7], Mike Clark[1], Luis Delgado-Aparicio[8], Jan Egedal[1], Doug Endrizzi[1], Manaure Francisquez[8], Ammar Hakim[8], Bob Harvey[5], Mykola Ialovega[1], Alexander Ivanov[9], Mi Joung[6], Jeremiah Kirch[1], Grant Kristofek[2], Roderick McNeill[1], John Lohr[4], Elijah Martin[7], Vladimir Mirnov[1], Bob Mumgaard[2], Ethan Peterson[3], Yuri Petrov[5], Jon Pizzo[1], Steve Oliva[1], Charlie Moeller[4], Kunal Sanwalka[1], Oliver Schmitz[1], Mary Severson[1], Bhuvana Srinivasan[8], Danah Velez[1], John Wallace[1], Dennis Whyte[3], Jim Yeck[1]

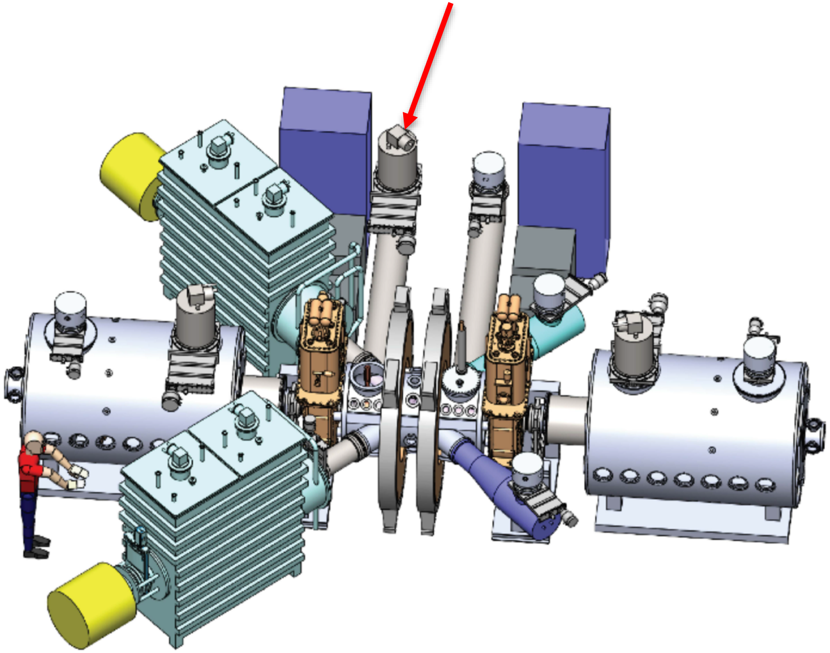
[1] University of Wisconsin-Madison
[2] Commonwealth Fusion Systems
[3] MIT
[4] General Atomics
[5] CompxCo
[6] KSTAR NFRI
[7] ORNL
[8] Virginia Tech/PPPL
[9] Budker Institute

Name/Conference/Date

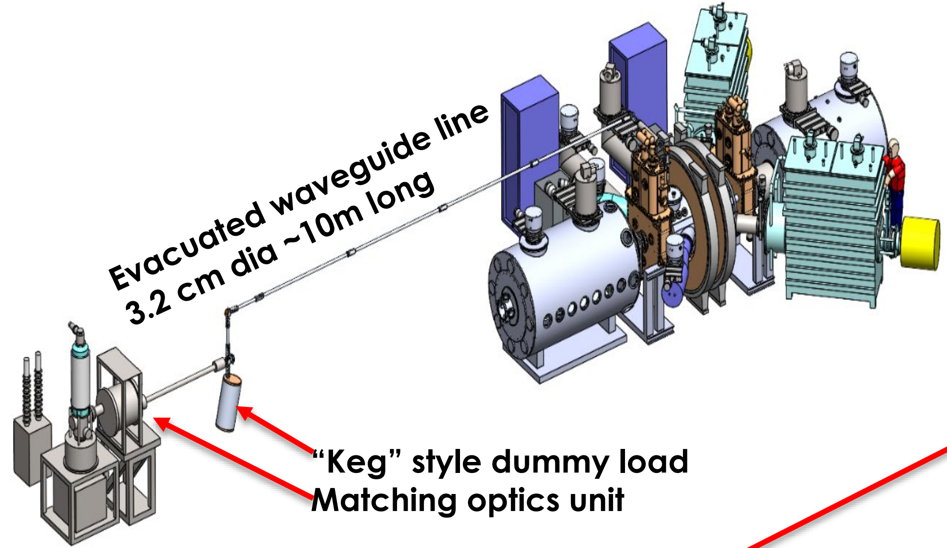
Engineering design nearly complete

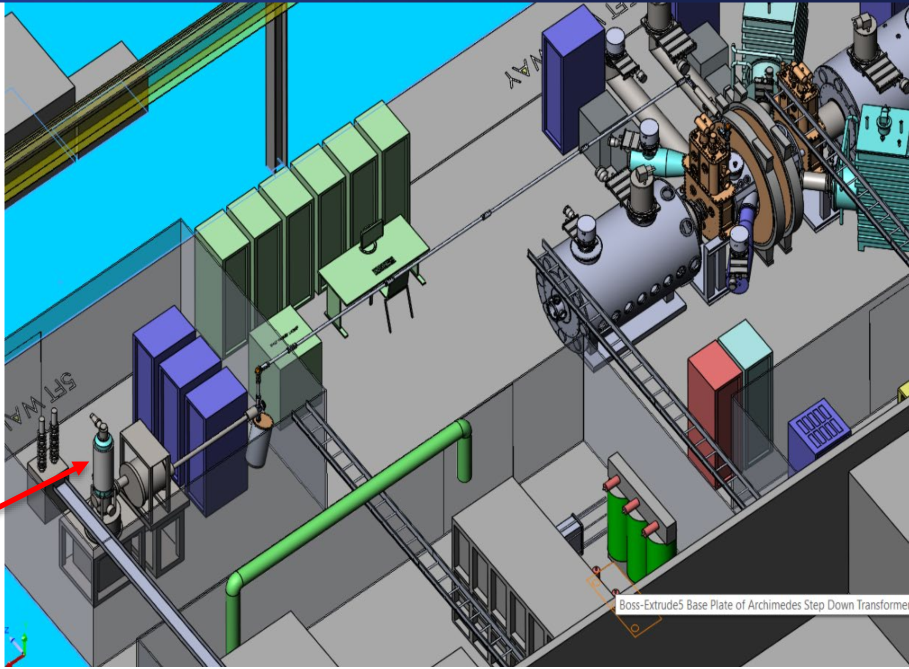
- Central coils will be pulsed copper
  - Repurposed from W7-AS stellarator
    - Power supply to leverage 4 @ 100 V, 5 kA units in UW storage
  - Considered LTS, HTS and MgB_2
  - Major factors: cost, liquid helium, diagnostic access
- Iterated with two informal design reviews utilizing BINP
  - Larger diameter central vessel implemented
  - Larger end cells
  - Addressing issues with operation of NBI in strong B
- 1st NBI will use MST beam with new grids to change focal length and use neutralization tank from TAE system
- Conceptual design of ECH transmission line and launcher
  - In collaboration with General Atomics
  - Gyrotron operations expertise, helium reliquefier loan
  - Vendor for ECH transmission line components

Gycom Centaur Gyrotron
110 GHz, .6 MW, 2 sec pulses
Saw service at DIII-D and KSTAR



ECH Installation Layout

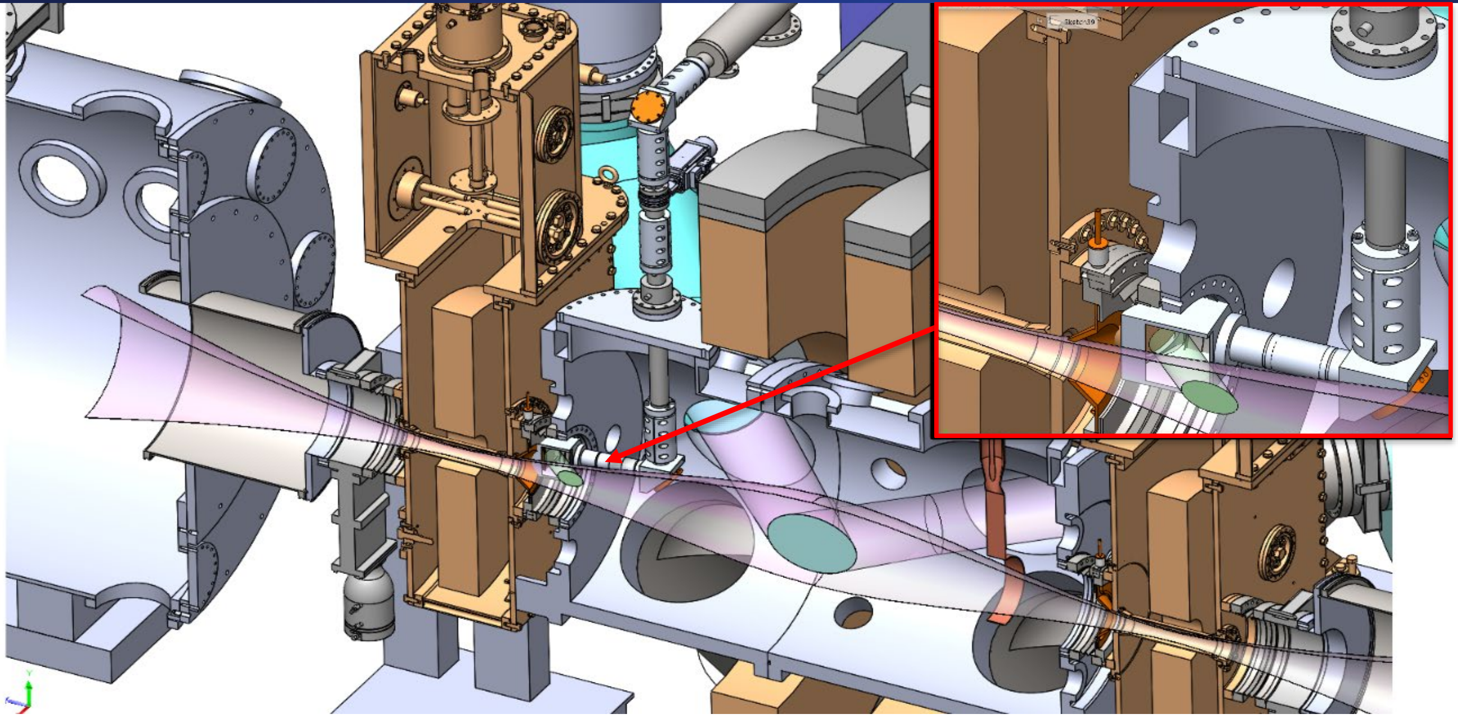




WHAM Installation

Goals:
High T_e with sustained MHD stability
In-situ ion acceleration with high power rf
Predicted improved confinement
Initial operation 2021-2024

RF Heating at a Mirror Point

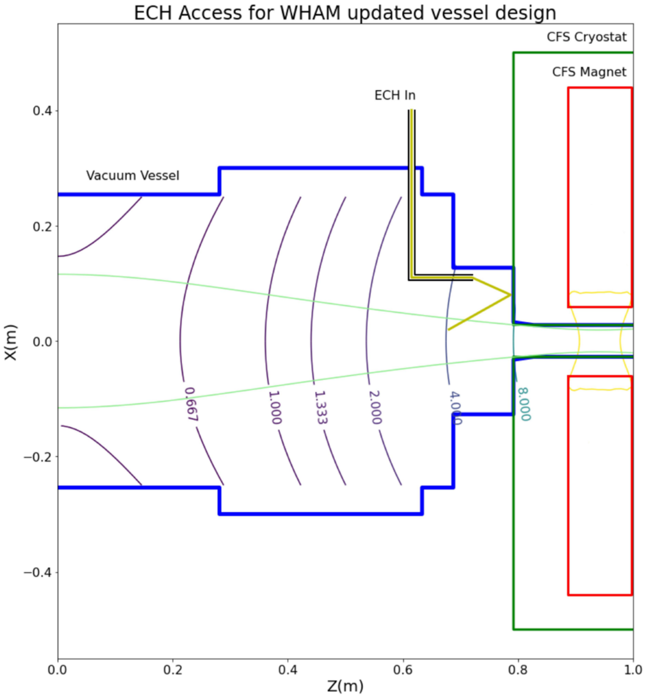


RF Heating beam directed at one mirror point

Split waveguide at the resonance prevents arcing in the guide

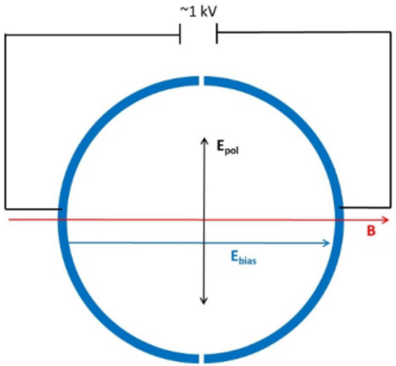
High Temperature Superconductor magnet produces 1.2 T field
Copper shim coils provide field correction

ECH launch to target 4 T contour; technical challenges abound. Previously solved problem by GA experts.

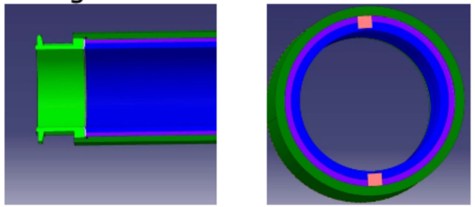


Passing the resonance: Longitudinally-split electrically-biased waveguide

- Principle described in patent application by C Moeller (1986)
- Experience from DIII-D and DITE on design and operation
- Need to electrically isolate the two halves from each other and the unit from surroundings
- Cooling of WG is probably needed (while preserving electrical isolation)
- Performance as circular corrugated WG due to split and isolation at end points uncertain [modelling and prototyping needed]



Schematic of split electrically biased waveguide



CTS CAD design of split electrically biased waveguide

EXCERPT FROM KORSHOLM ITER CTS NOTES

Gycom 110 GHz Centaur gyrotron installation in magnet completed- Superconducting magnet with LHe reservoir level maintained using helium reliquifier

Clockwise from bottom left:

Cryomagnet placed on oil tank.

Gyrotron in crate before lift.

Preparing tilt to vertical.

Lift w/ forklift & boom: bridge crane too low.

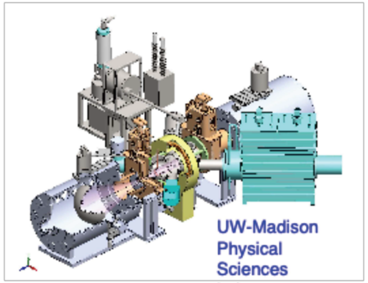
Oil tank moved via air bearings under suspended tube.

Tech 2 Market: private investment envisioned

2020 | 2024 | 2028 | 2032 | 2036 | 2040

Notional time line

WHAM → WHAM-EP



*W*isconsin *H*TS *A*xisymmetric *M*irror

Breakthrough physics thru ARPA-E BETHE program.

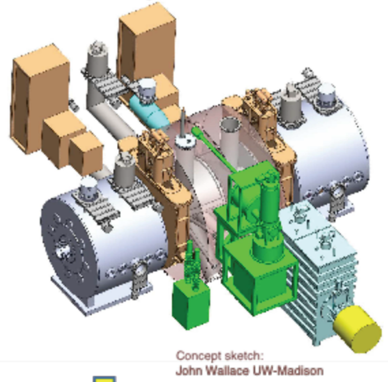
High power 110 GHz ECH

High Te with sustained MHD stability

High power rf: In-situ ion acceleration

Improved confinement $n\tau \propto \langle E_i \rangle^{3/2}$

*E*xtended *P*ulse or *E*nd *P*lug



Handoff to industry

Single-mirror source: 'n flux set by heating power + plasma performance.

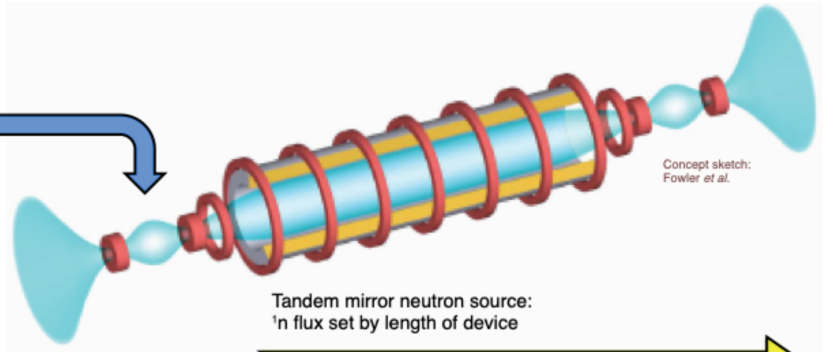
BEAT

*Break**E**ven **A**xisymmetric **T**andem*

2x WHAM-EP

HAMMER

*H*TS *A*xisymmetric *M*agnetic *M*irror *E*xperimental *R*eactor



Tandem mirror neutron source: 'n flux set by length of device

Applicatons accessible with increasing flux

Imaging, testing | Large scale radioisotope production | Nuclear waste remediation | Fission/ Fusion hybrid driver

WHAM-VNS

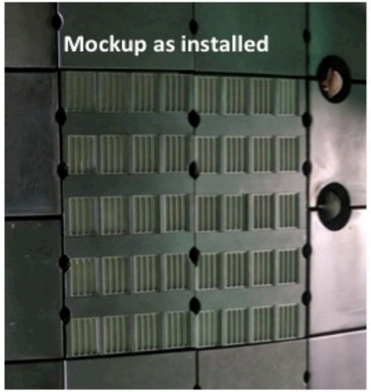
***WHAM V**olumetric **N**eutron **S**ource:* Apply WHAM high Te, high ion energy results for fusion neutron source.

MIT Lower Hybrid Collaboration on DIII-D

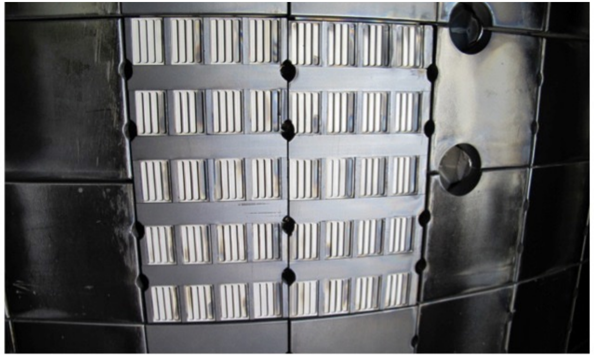
New Lower Hybrid System in Process of Testing and Installation

Mockup antenna installed in DIII-D to assess impact of high-Z (TZM moly) materials on center post on plasma operations

- Demonstrate that the HFS LHCD coupler will not interfere with DIII-D operations
  - Initial characterization of plasma material interaction
  - Characterize local molybdenum source and thermal load
- Mock-up is located same vertical position as planned coupler, at different toroidal angle – mock-up at 292-300°, actual will be around 15 deg
- TZM area is ~identical to proposed coupler
  - TZM structure ~1 mm behind carbon protection limiters



Post-test operations check showed the mockup to be in excellent condition

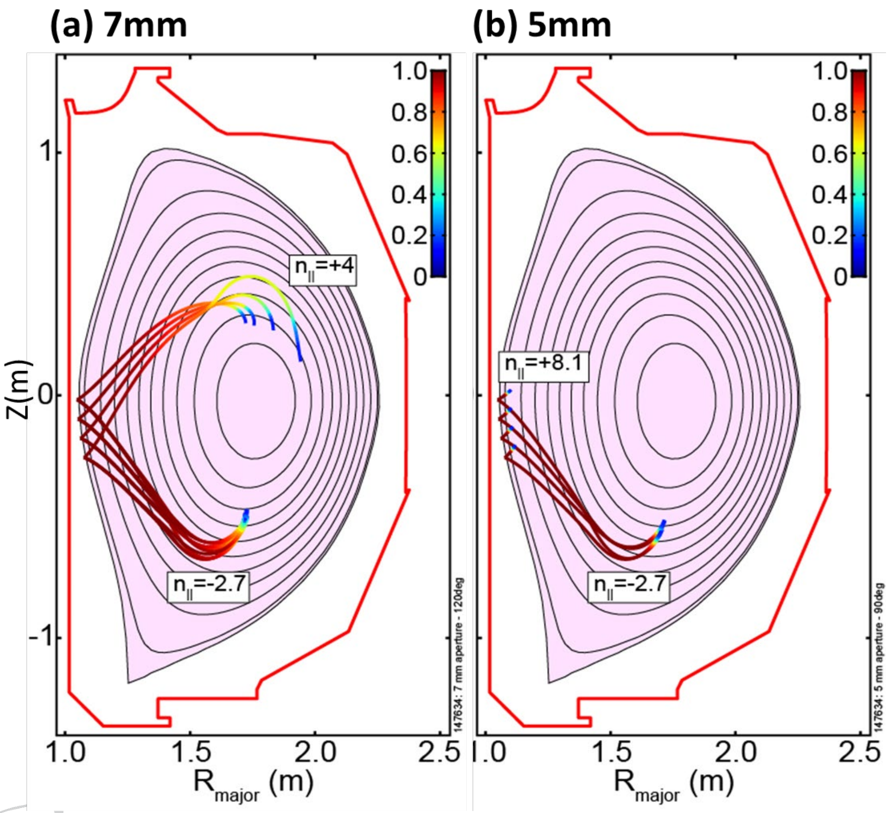


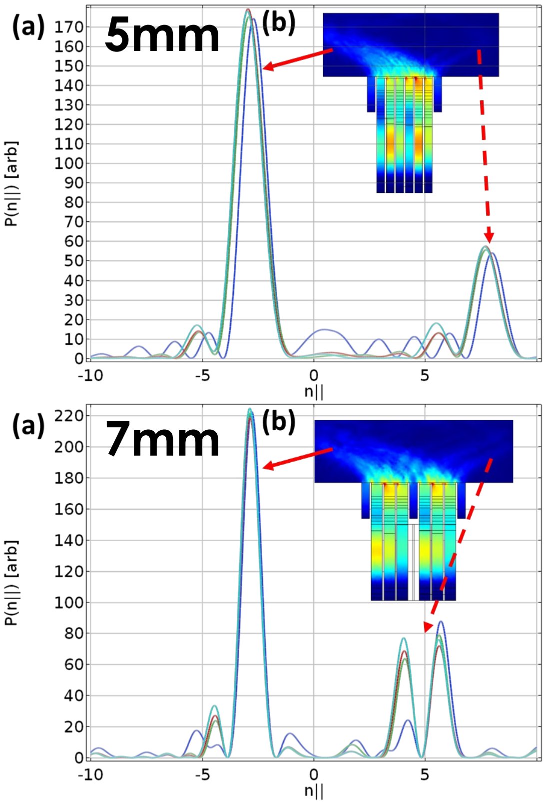
-High efficiency steady state non-inductive current drive is the goal
-Ex-vessel work underway with beginning installation of klystrons and transmission systems

MIT PPPL DIII-D collaboration

Andrew Seltzman MIT

Lower Hybrid RF Trajectories Depend on Launcher Geometries Targeting Intermediate rho for Current Drive





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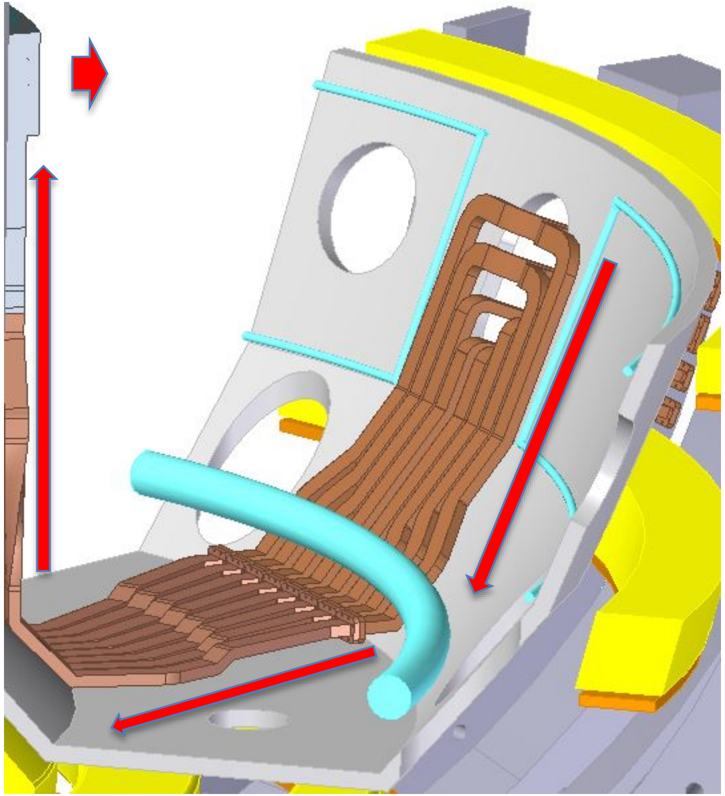
Andrew Seltzman MIT

Waveguide Routing for the Lower Hybrid System

- Restricted mechanical access on central column
- Waveguide feeds enter on outboard side and pass under first wall tiles
- Multijunction and power divider located on central column
- Poloidal power divider initially modeled after CMOD design



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Lower Hybrid CW Klystrons Being Installed

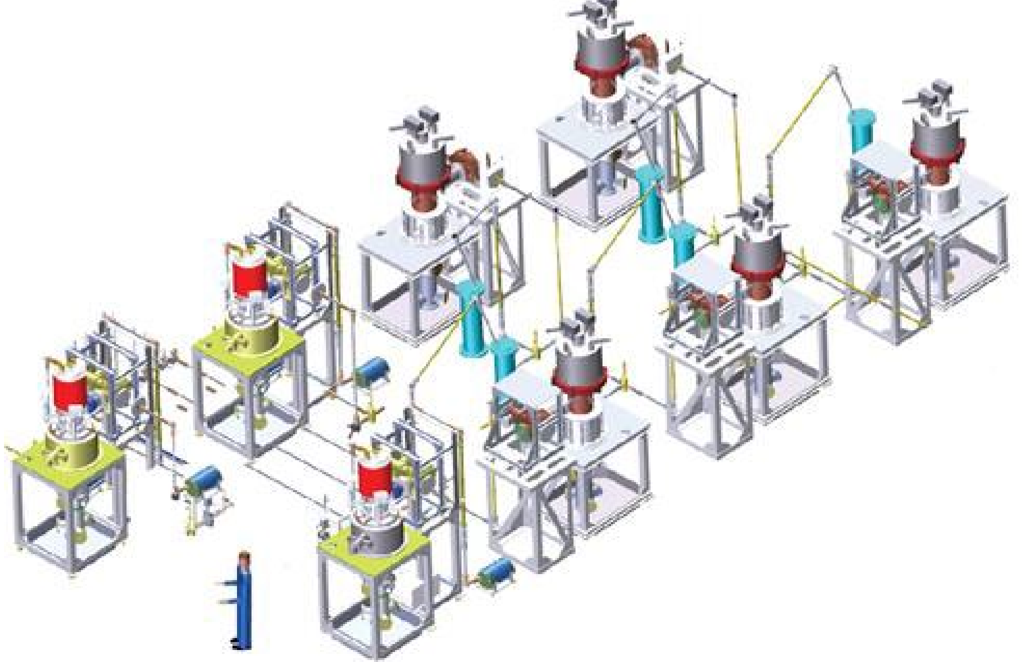
- **Initially 8 waveguide launchers and klystrons**
  - CPI VKC-7849B klystrons
  - Operating frequency 4.6 GHz
  - Drive power 0.68 W
  - Cathode Voltage 45 kV DC
  - Cathode Current 12.1 A
  - Maximum RF output power per klystron 263 kW
  - Solenoid current 32 ADC

- **DIII-D In-vessel installation scheduled to begin May 2021 for 2022 operation**
  - Klystron installation underway
  - Control station established

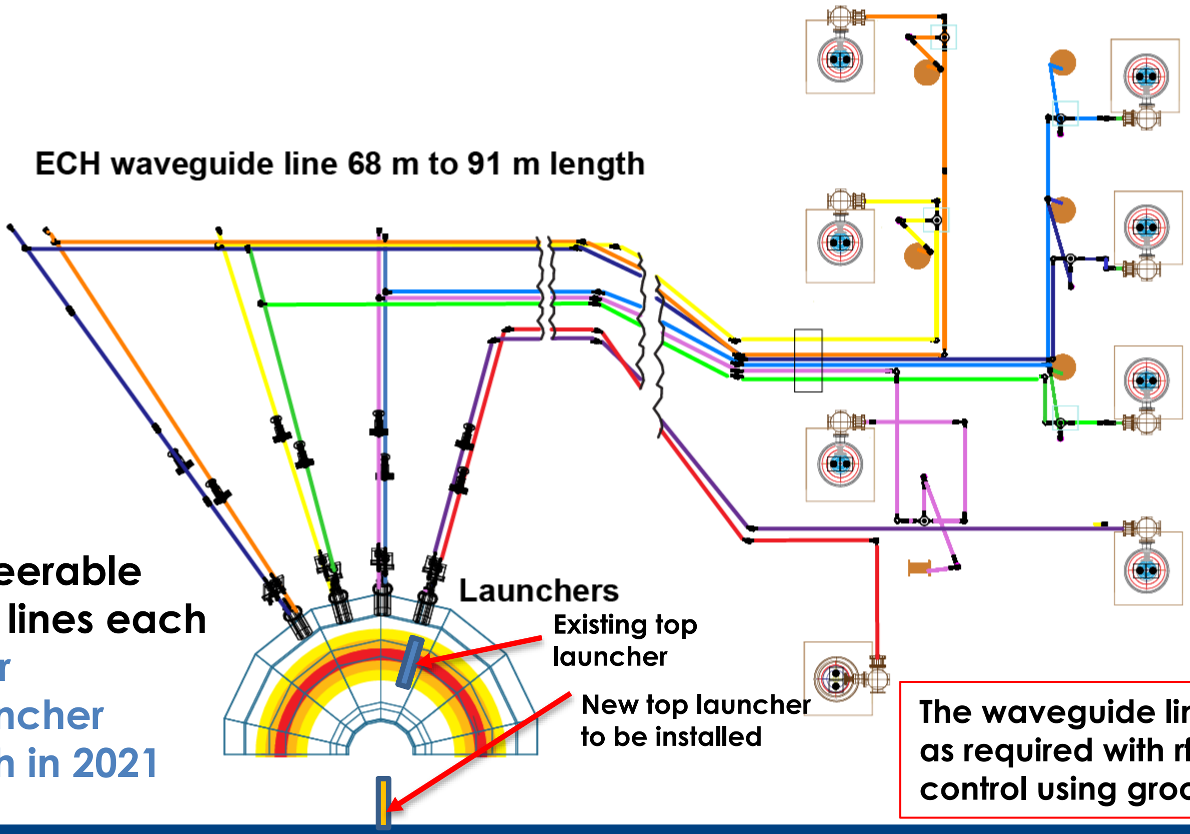
Klystron installation underway outside DIII-D radiation shield wall

DIII-D Gyrotron Status: Two Operating- More on the Way

- The EC Systems are flexible, allowing placement of gyrotrons in different sockets, connection to different launchers and high voltage power supplies-previous maximum 6 gyrotrons operating at one time-some failures
- All eight sockets can be used for Diode Gyrotrons, only three of the sockets for Depressed Collector tubes
- Latest group of 3 new gyrotrons are all diode tubes with CuCrZr collectors
- Two depressed collector tubes at CPI for repair of leaks



Gyrotron Power Routing in 2020



Launchers:

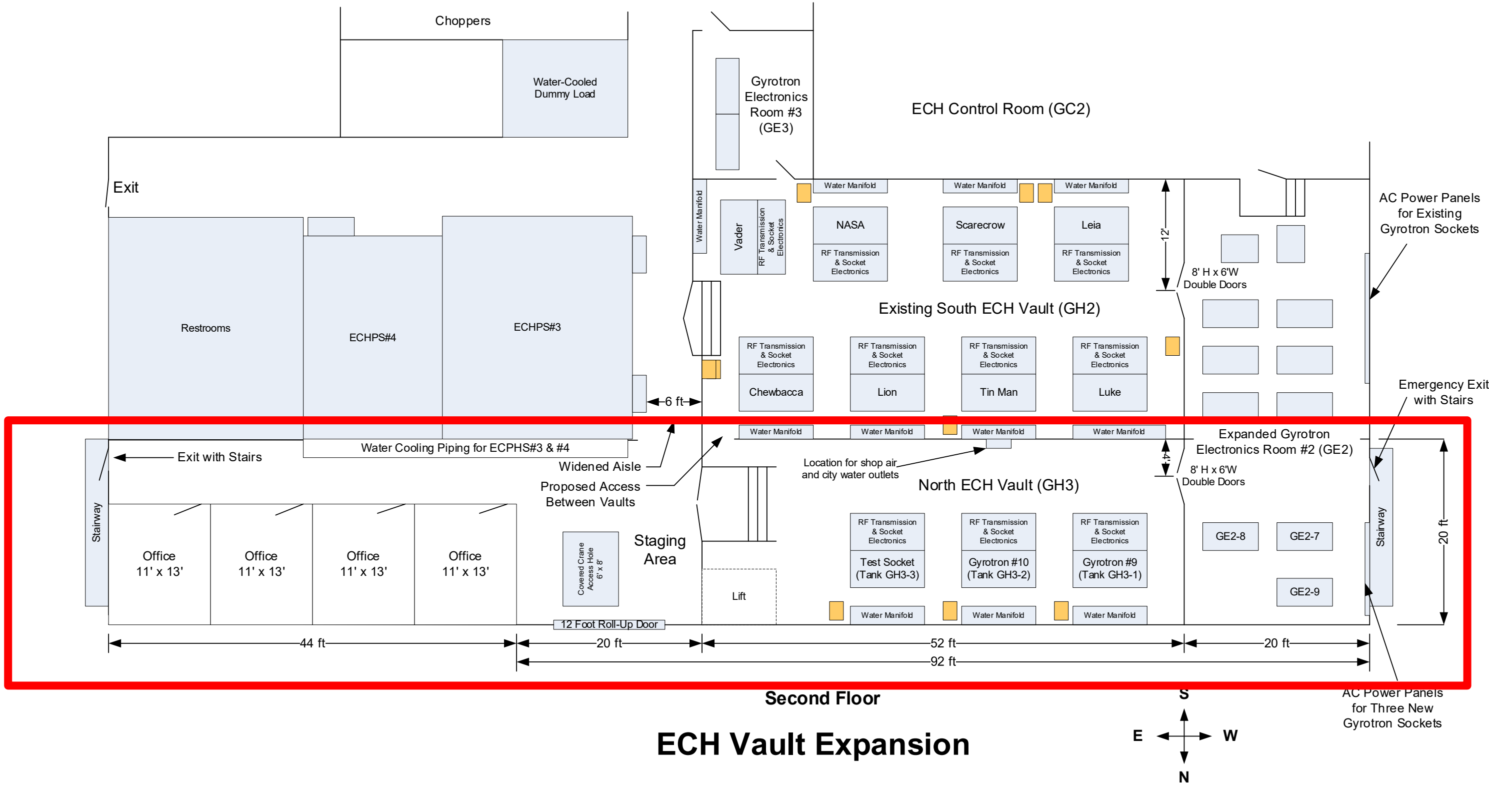
- 4 midplane steerable Launchers with 2 lines each
- 1 top launcher

  1 new top launcher at 90° azimuth in 2021

Eight gyrotron sockets in Gyrotron vault-
HV power at 100 kV from outside with tetrode mod/reg supplies in the building controlling voltage to gyrotrons

The waveguide lines can be rerouted as required with rf beam polarization control using grooved miter mirrors

ECH Building Expansion Will Have Additional Gyrotron Sockets



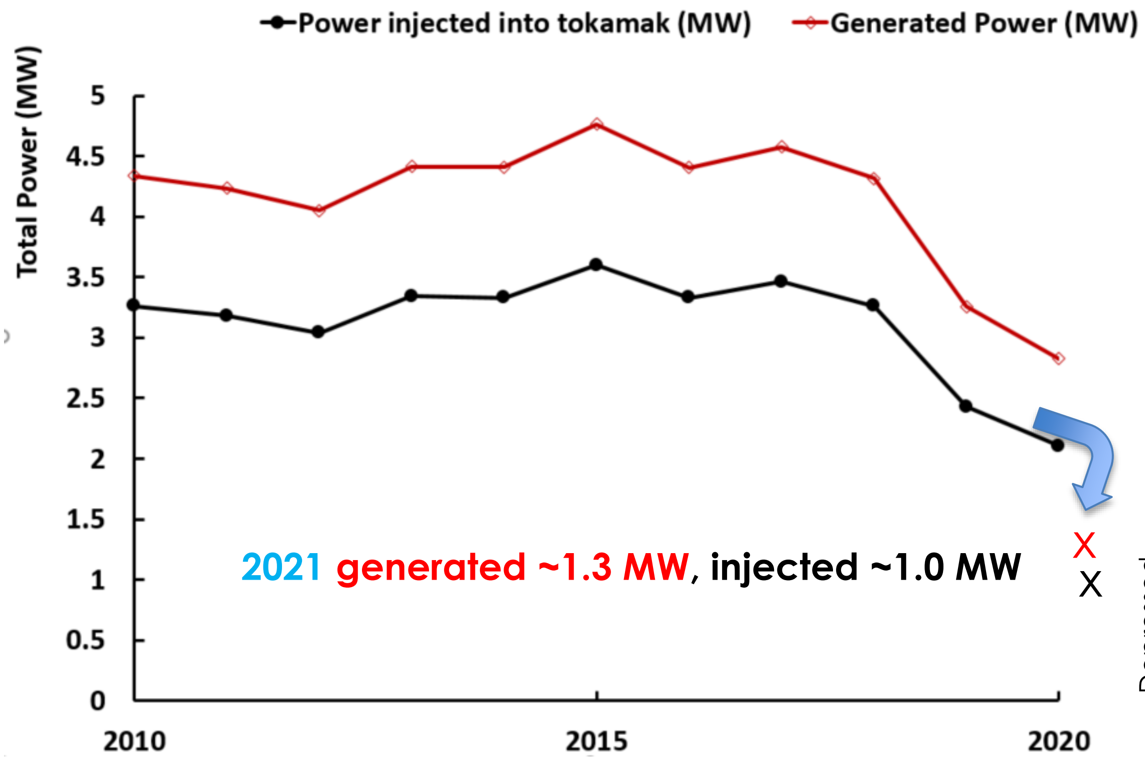
Building expansion for:

- Offices
- Sockets 9&10
- Test socket
- Electronic racks

Ground floor:

- PS5
- Future PS's

Gyrotron Status in 2020 - ECH Power Evolution 2010 - 2020



8 different gyrotrons during this period:

Diode tubes

Lion: 2010 – 2013

Scarecrow: 2010 – 2018

Tinman: 2010 – 2020

Leia: 2010 – 2020

Luke: 2010 – 2020

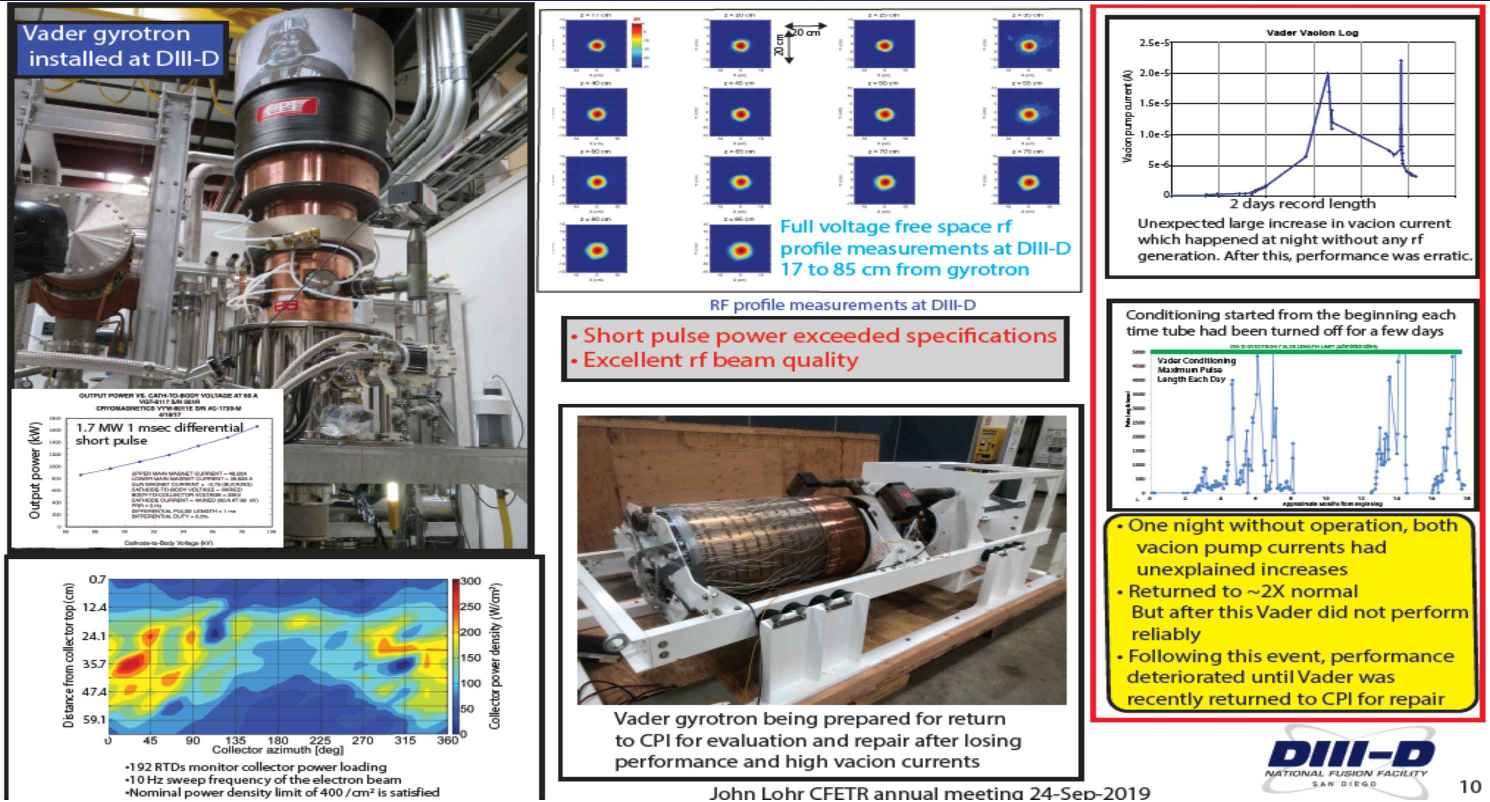
Depressed collector tubes

Chewbacca: 2014 – 2019

NASA: 2014 – 2020

Vader: 2018 – 2019

Gyrotron Performance and Problems



Very small vacuum leaks, usually due to a leak in a braze joint, can require months of transfer and repair time to recover

Vader is our first 1 MW gyrotron operating at 117.5 GHz

Its CuCrZr collector is a difficult material to braze

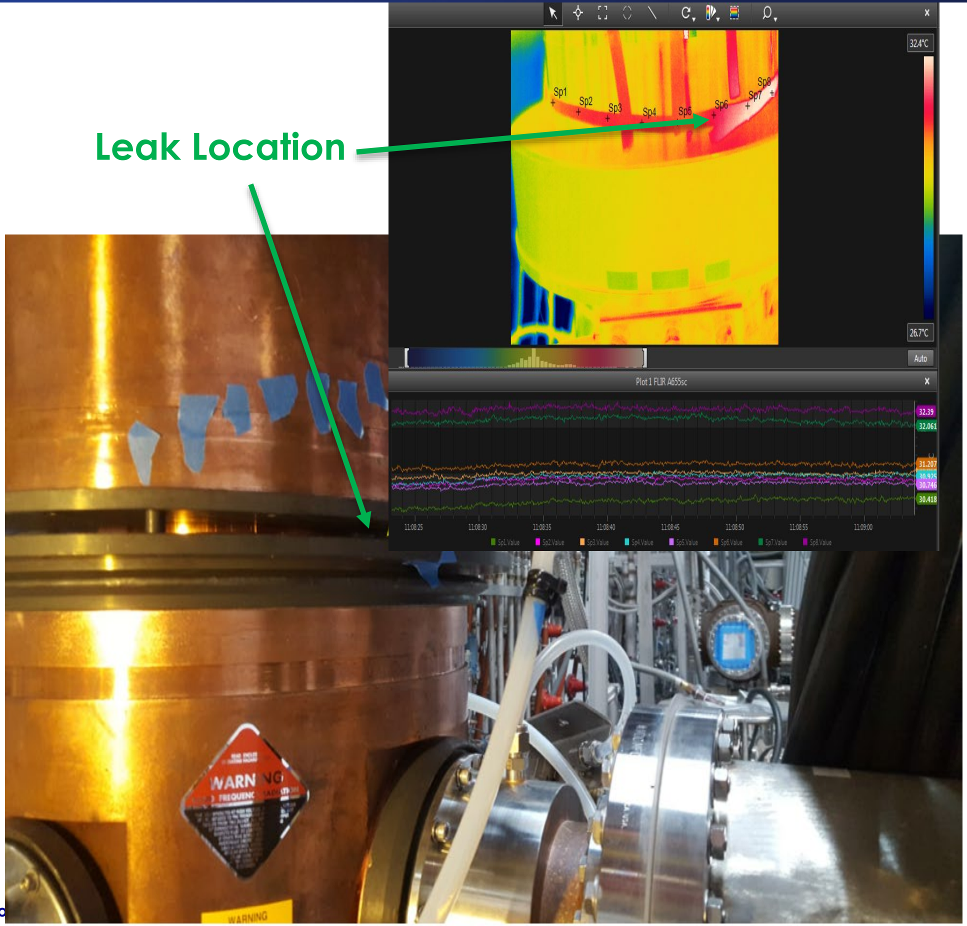
DIII-D Vader Gyrotron Vacuum Leak

Vader developed a leak which was traced to asymmetric heating of the collector support due to electron beam gun misalignment with respect to the magnetic field

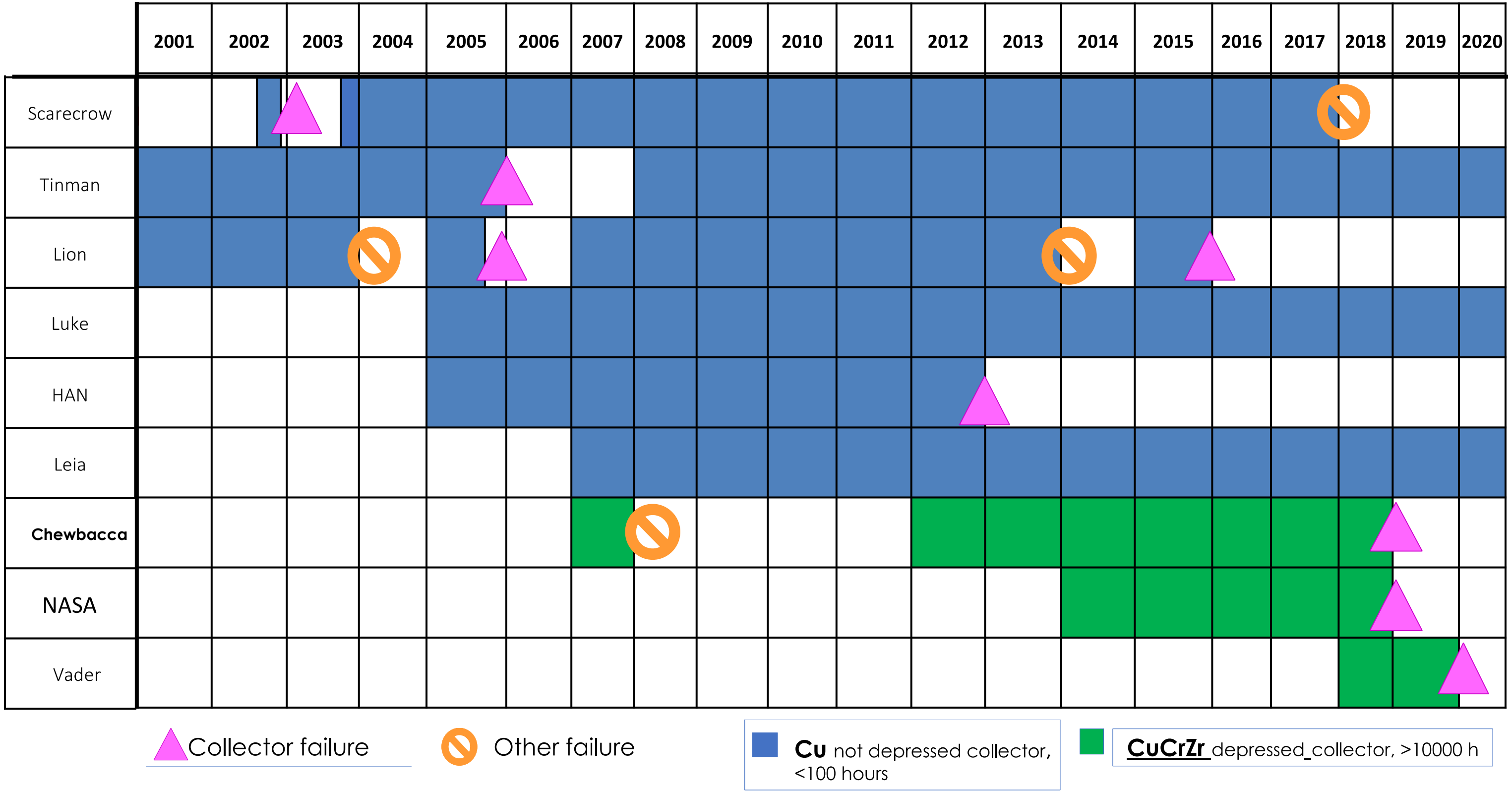
It was possible to affect the gyrotron internal pressure using Torrseal vacuum sealant at a suspect location tagged by an array of thermocouples

Vader is currently at CPI for repair

CuCrZr material used for this collector is difficult to braze but it is being introduced as a material for high heat load applications



Status in 2020 - 20 year history of CPI gyrotrons at DIII-D



CuCrZr collectors are predicted to have a lifetime of >100,000 on/off operational cycles and > 10,000 hours of operation at 10 Hz collector sweep frequency. their main problems are related to the difficulty of brazing the material.

Thank You *US-PRC MFC Workshop 2021*

60 GHz 200 kW
1990s

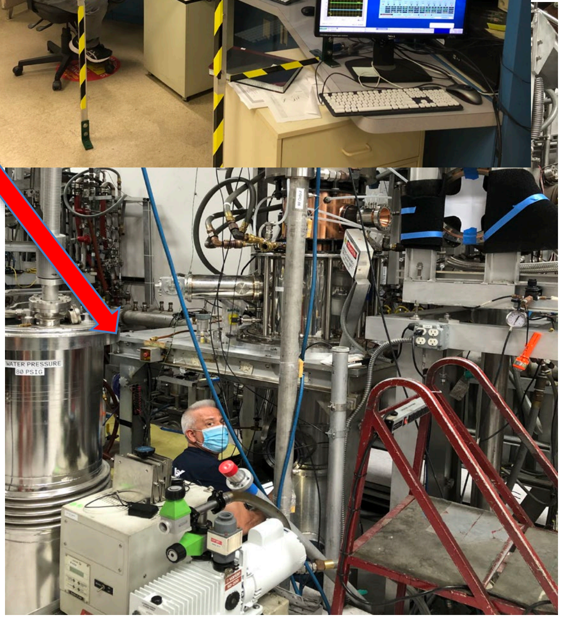
110 GHz 1MW
gyrotron *Yoda*
2021

100 kV tetrode
modulator

ECH control room
Gyrotron operations
and Helicon control

In the trenches
under gyrotron *R2D2*

Gyrotron vault



DIII-D
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