Electron cyclotron heating and current drive systems on DIII-D

by
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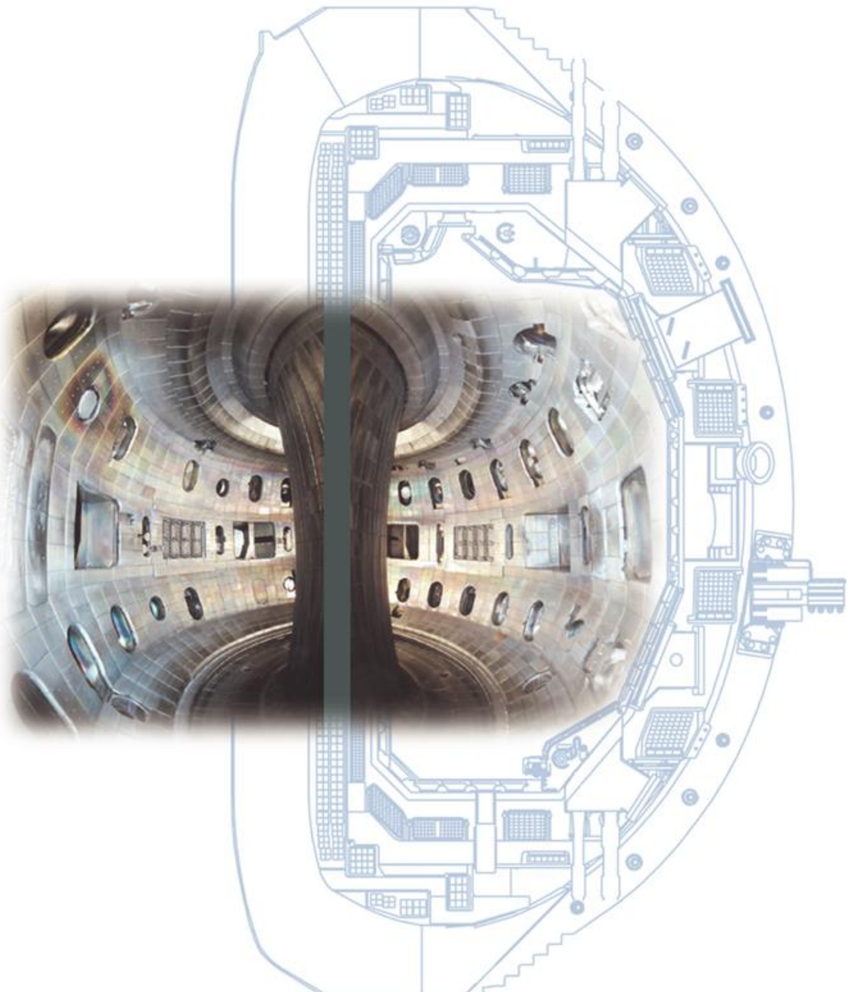

Presented at 21st Joint workshop on electron cyclotron emission (ECE) and electron cyclotron resonance heating (ECRH)

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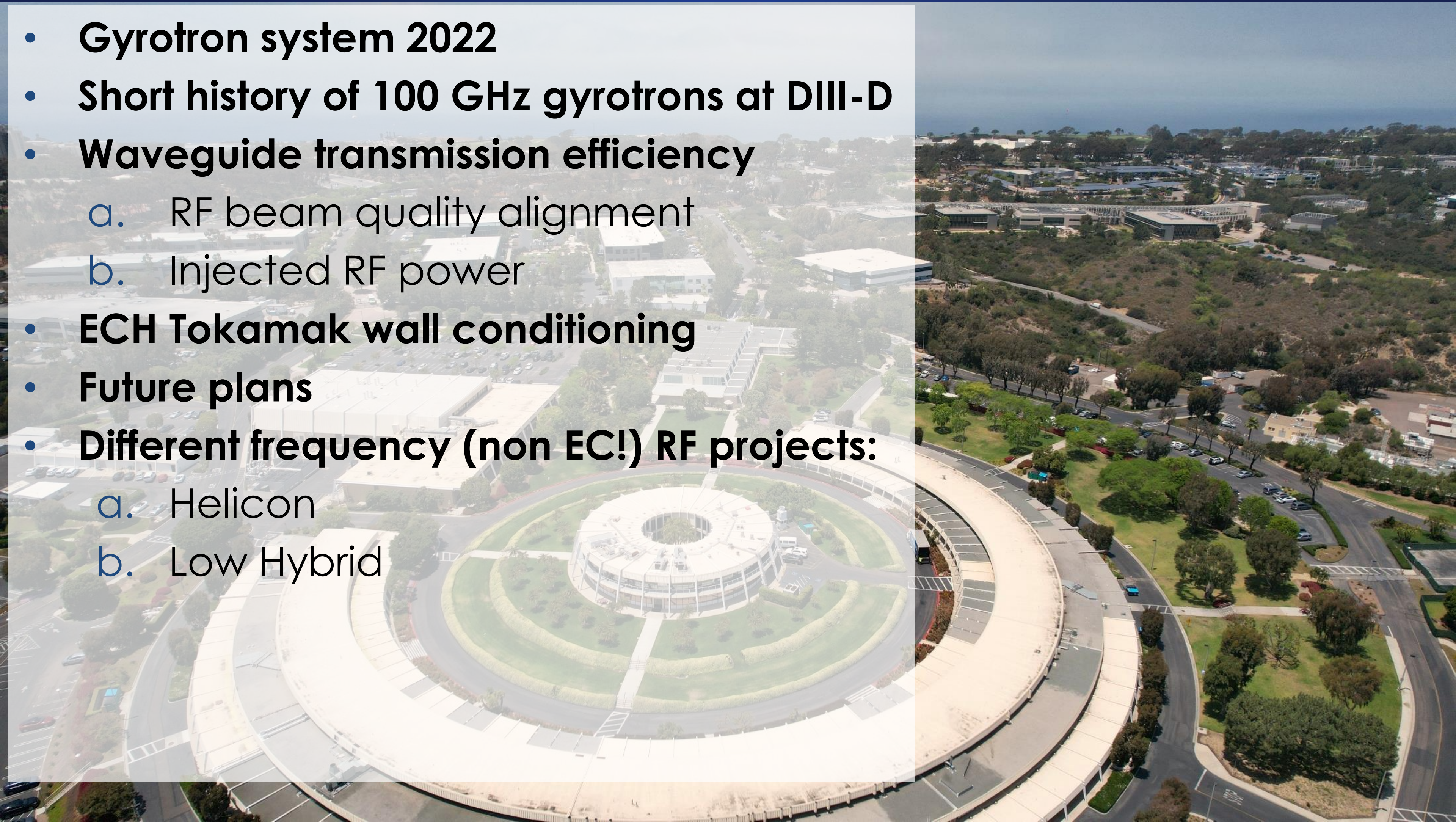
GENERAL ATOMICS

Outline

- **Gyrotron system 2022**
- **Short history of 100 GHz gyrotrons at DIII-D**
- **Waveguide transmission efficiency**
  a. RF beam quality alignment
  b. Injected RF power
- **ECH Tokamak wall conditioning**
- **Future plans**
- **Different frequency (non EC!) RF projects:**
  a. Helicon
  b. Low Hybrid



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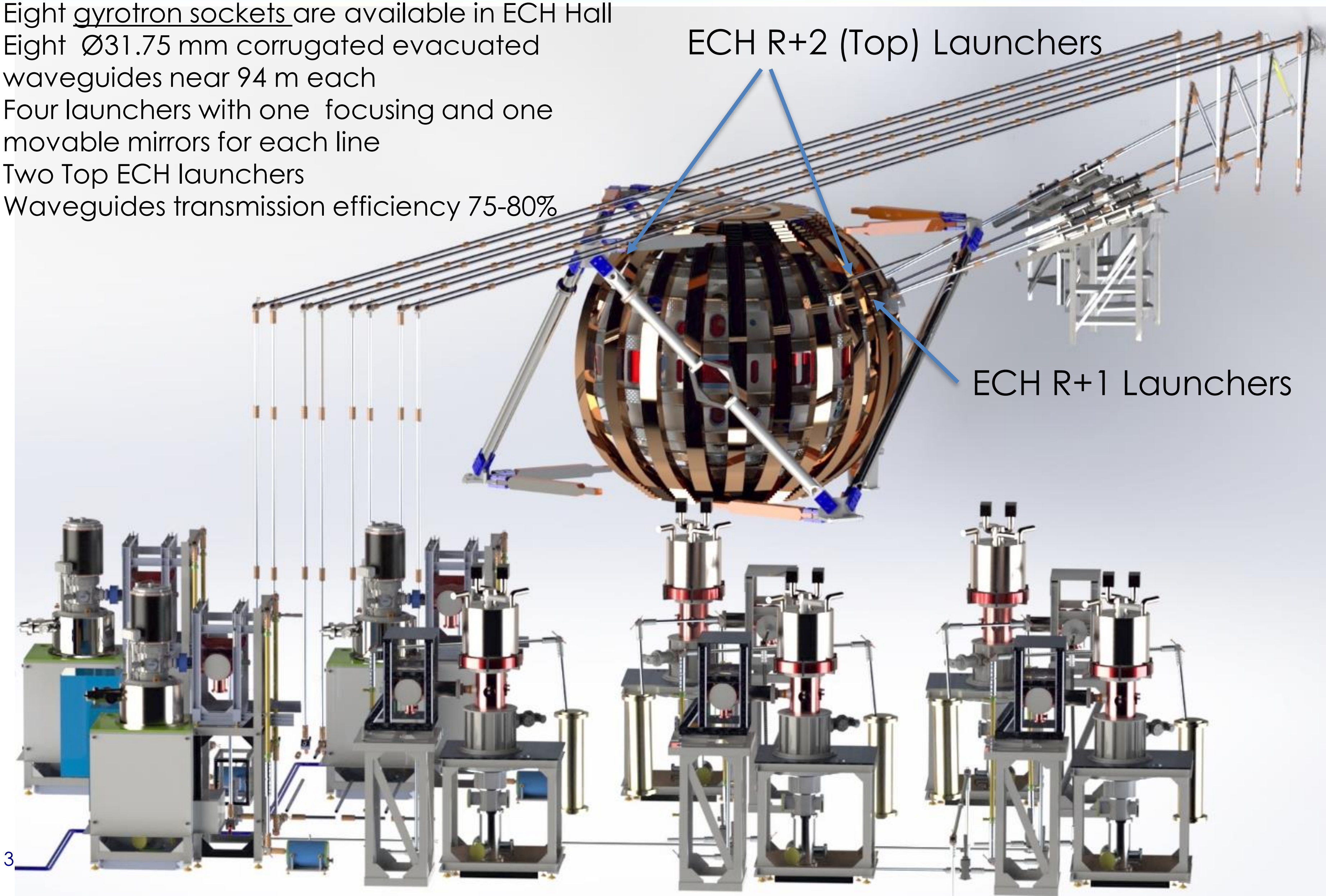
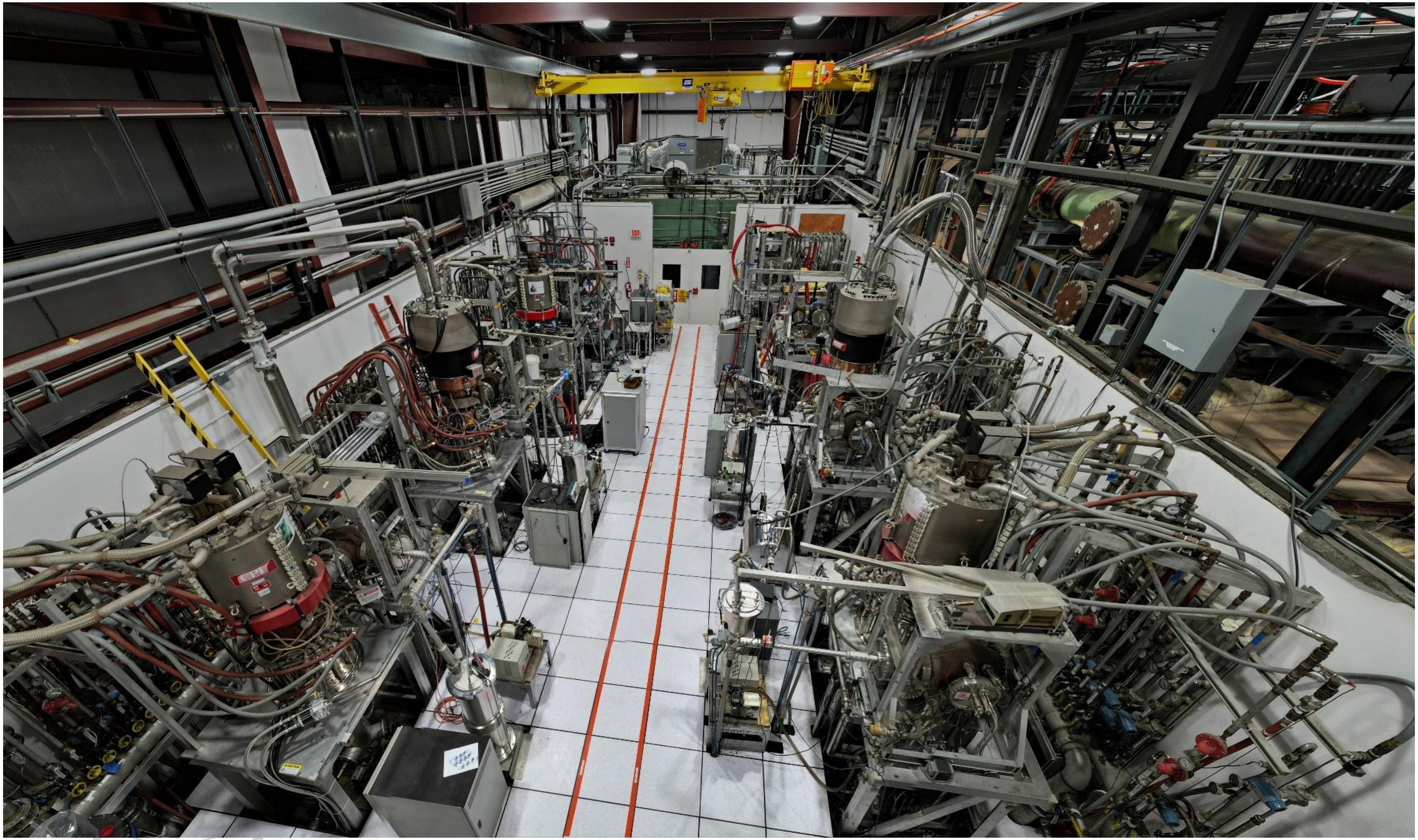
ECH System at DIII-D

- Eight gyrotron sockets are available in ECH Hall
- Eight Ø31.75 mm corrugated evacuated waveguides near 94 m each
- Four launchers with one focusing and one movable mirrors for each line
- Two Top ECH launchers
- Waveguides transmission efficiency 75-80%



Gyrotron Vault 2022



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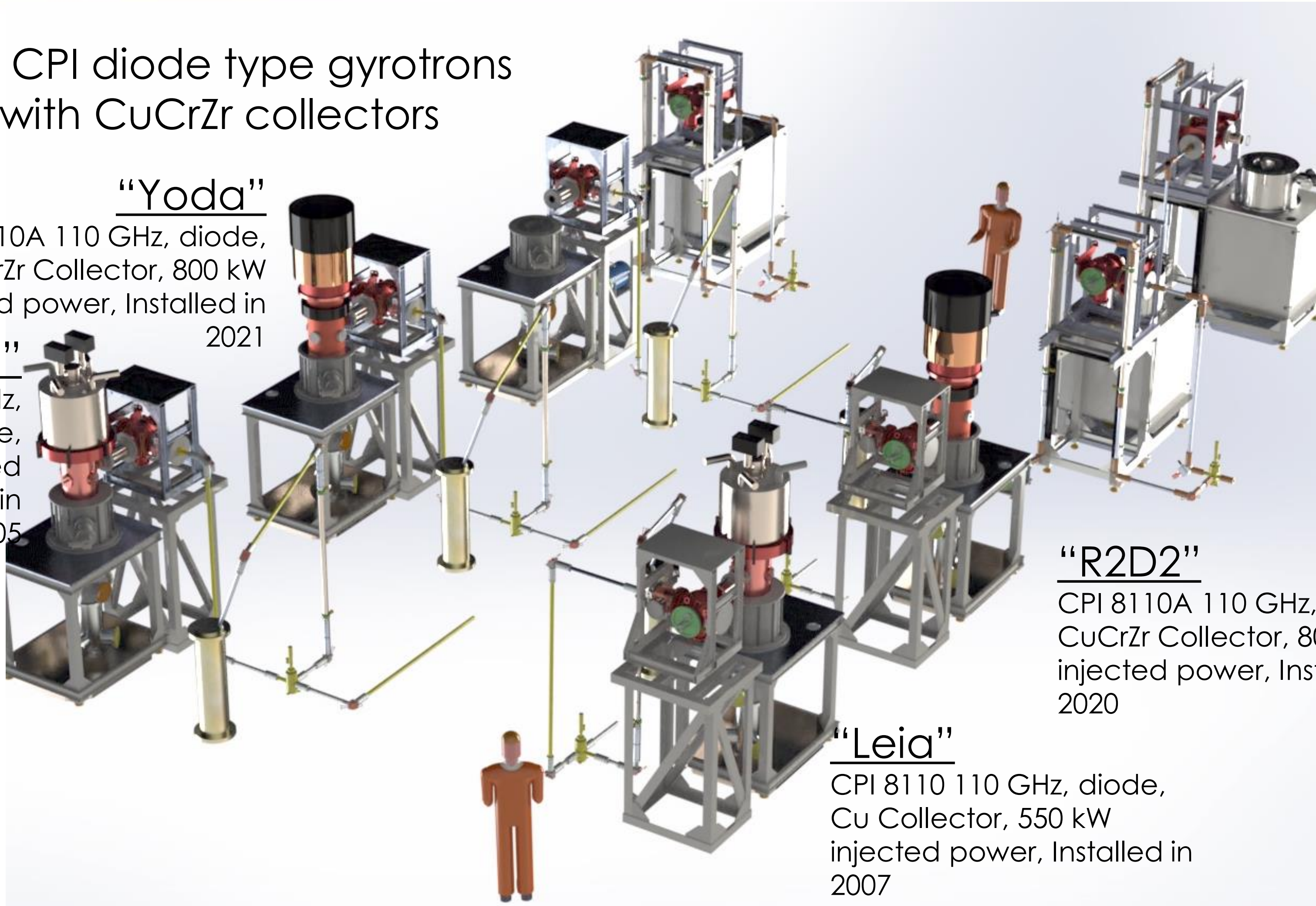
2021 experimental campaign start

Two new CPI diode type gyrotrons
Installed with CuCrZr collectors



"Yoda"
CPI 8110A 110 GHz, diode, CuCrZr Collector, 800 kW injected power, Installed in 2021

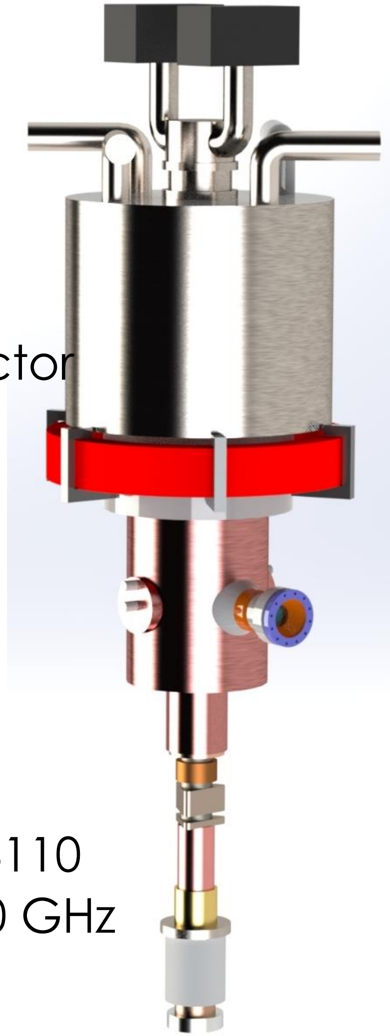
"Luke"
CPI 8110110 GHz, Cu collector, diode, 580 kW injected power, Installed in 2005

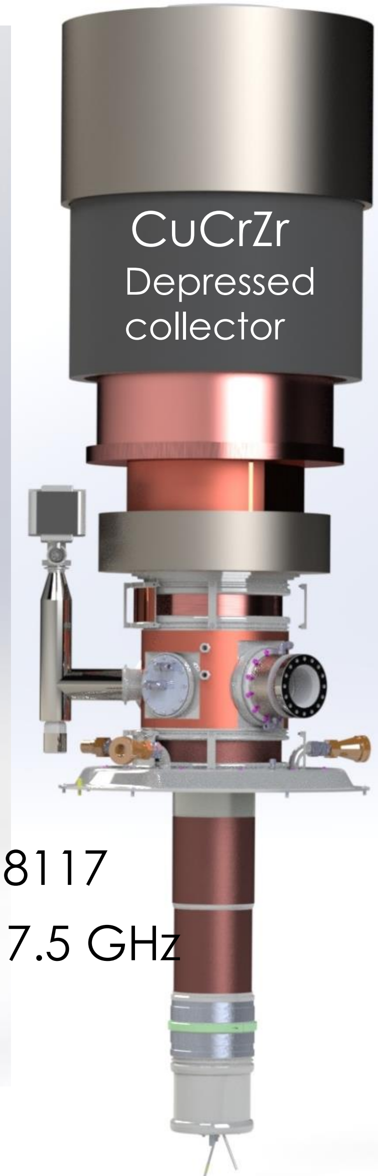
"R2D2"
CPI 8110A 110 GHz, diode, CuCrZr Collector, 800 kW injected power, Installed in 2020

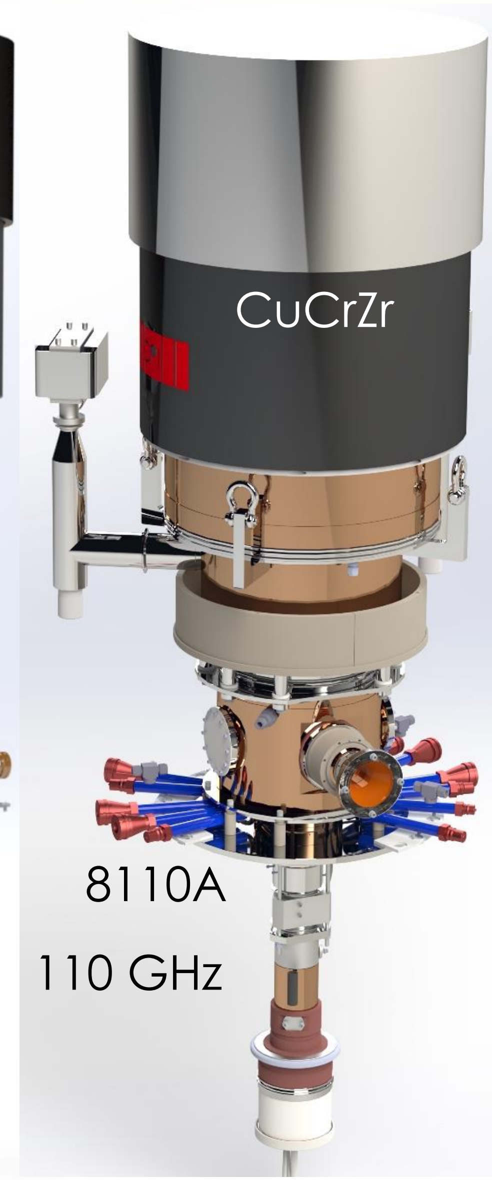
"Leia"
CPI 8110 110 GHz, diode, Cu Collector, 550 kW injected power, Installed in 2007

Four 1 MW class gyrotrons with total injected ECH power 2.7 MW

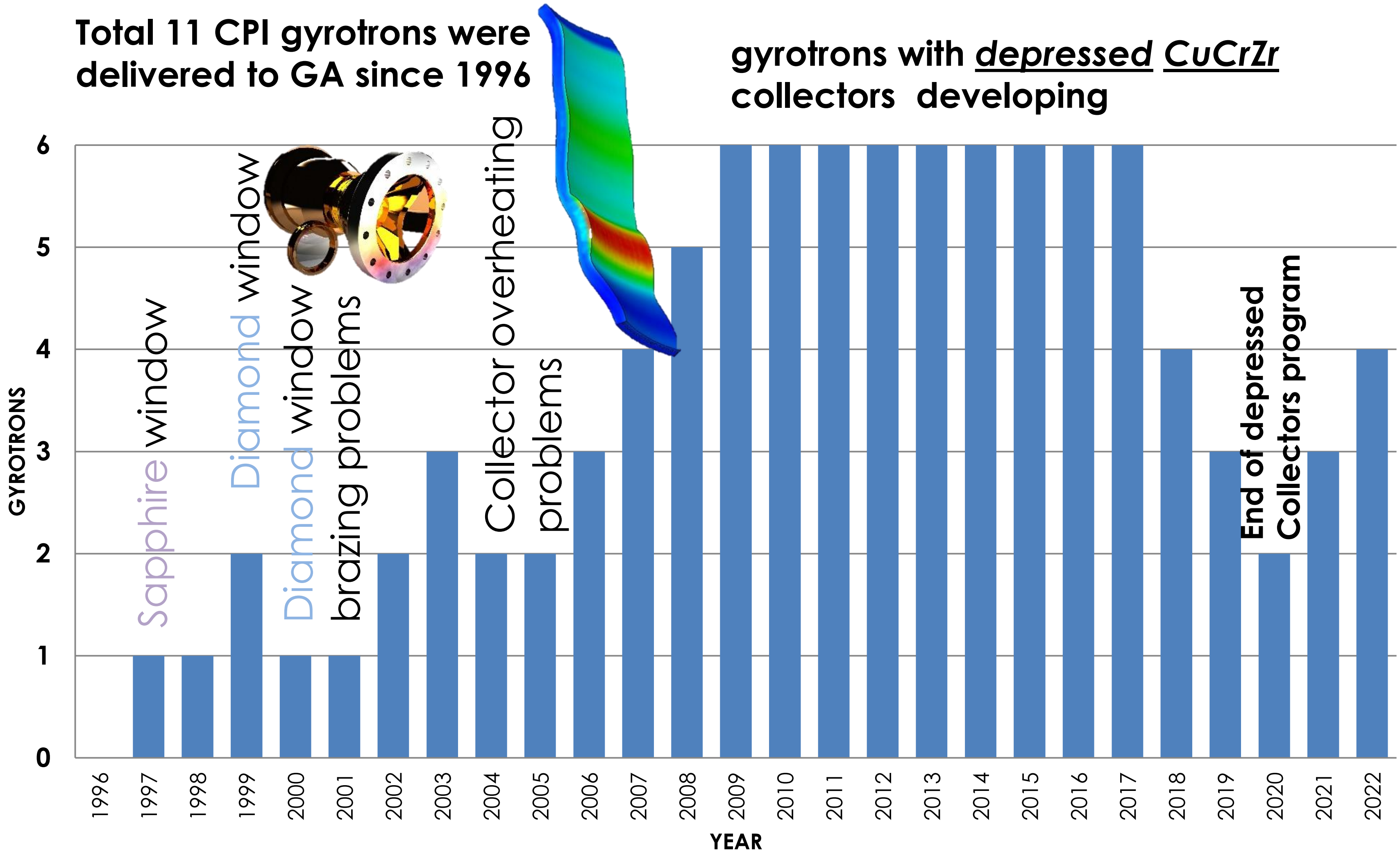
Four types of CPI gyrotrons for DIII-D







History of CPI 110 GHz 1 MW class gyrotrons on DIII-D



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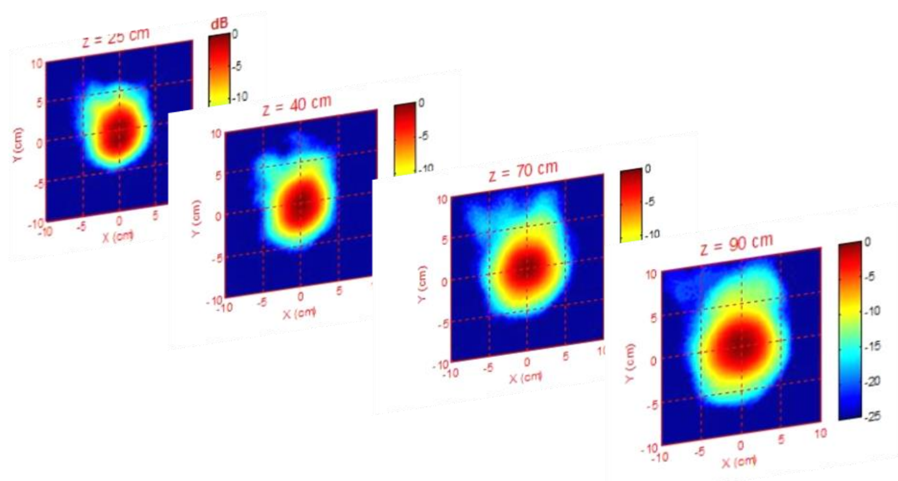
Transmission Efficiency of the Waveguide Lines

	Gyrotron	Total # Miters	Measured HE_{11}(%)	Measured Loss MOU %	Measured Transmission w/g %	Estimated transmission w/g %	Power at DIII-D (kW)
VGT - 8110 S/N 106	Leia	9	94	7	81	84	570
VGT - 8110A S/N 108	R2D2	9	80	4.5	79	84	640
VGT - 8110 S/N 104	Luke	10	85	7.5	78	82	625
VGT - 8110A S/N 107	Yoda	10	82.1	3	80	82	740

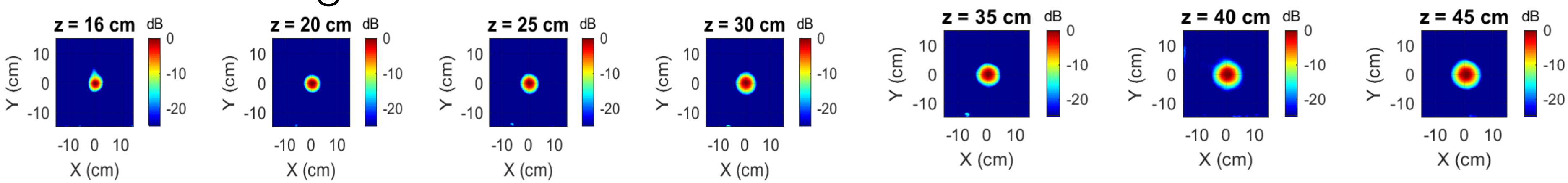
Free space RF beam measurements

- Efficiency of waveguide transmission lines depends on quality of the RF beam at the input to waveguide
- The RF beam of the gyrotron was measured in free space with infrared camera (IR).
- Results obtained were used for phase retrieval calculations, MOU mirror parameters, spool piece

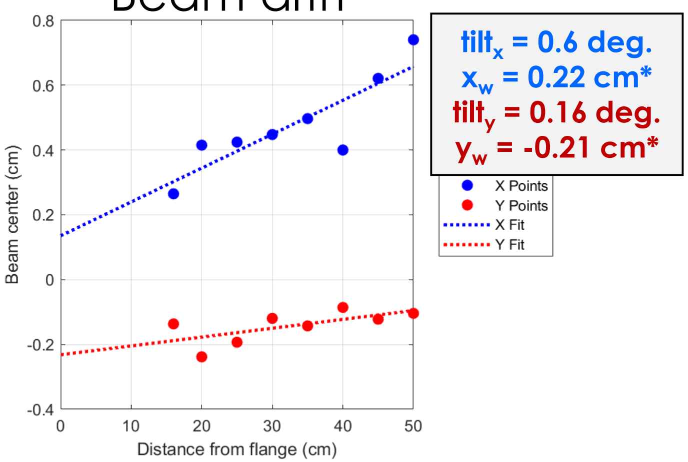


RF beam characterization in free space

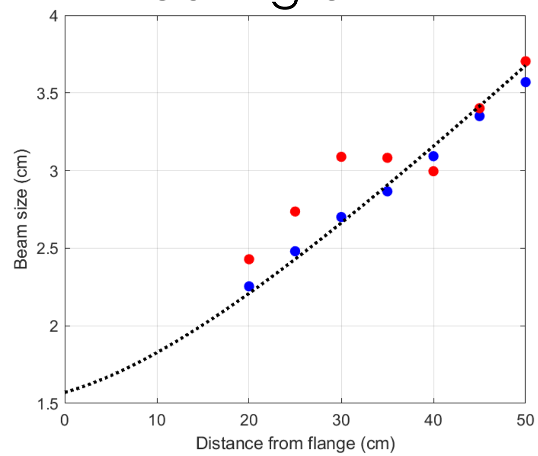
IR images of RF beam at different distances from the window



Beam drift

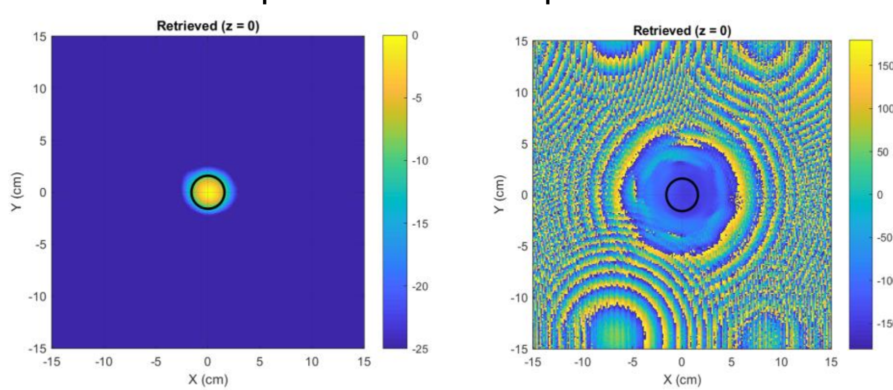


Beam growth



Result of these measurement was used in design of MOU mirror and spool piece

Amplitude and phase retrieval



- **Match to ideal Gaussian beam at gyrotron window = 96.7%**
- **Includes amplitude and phase**

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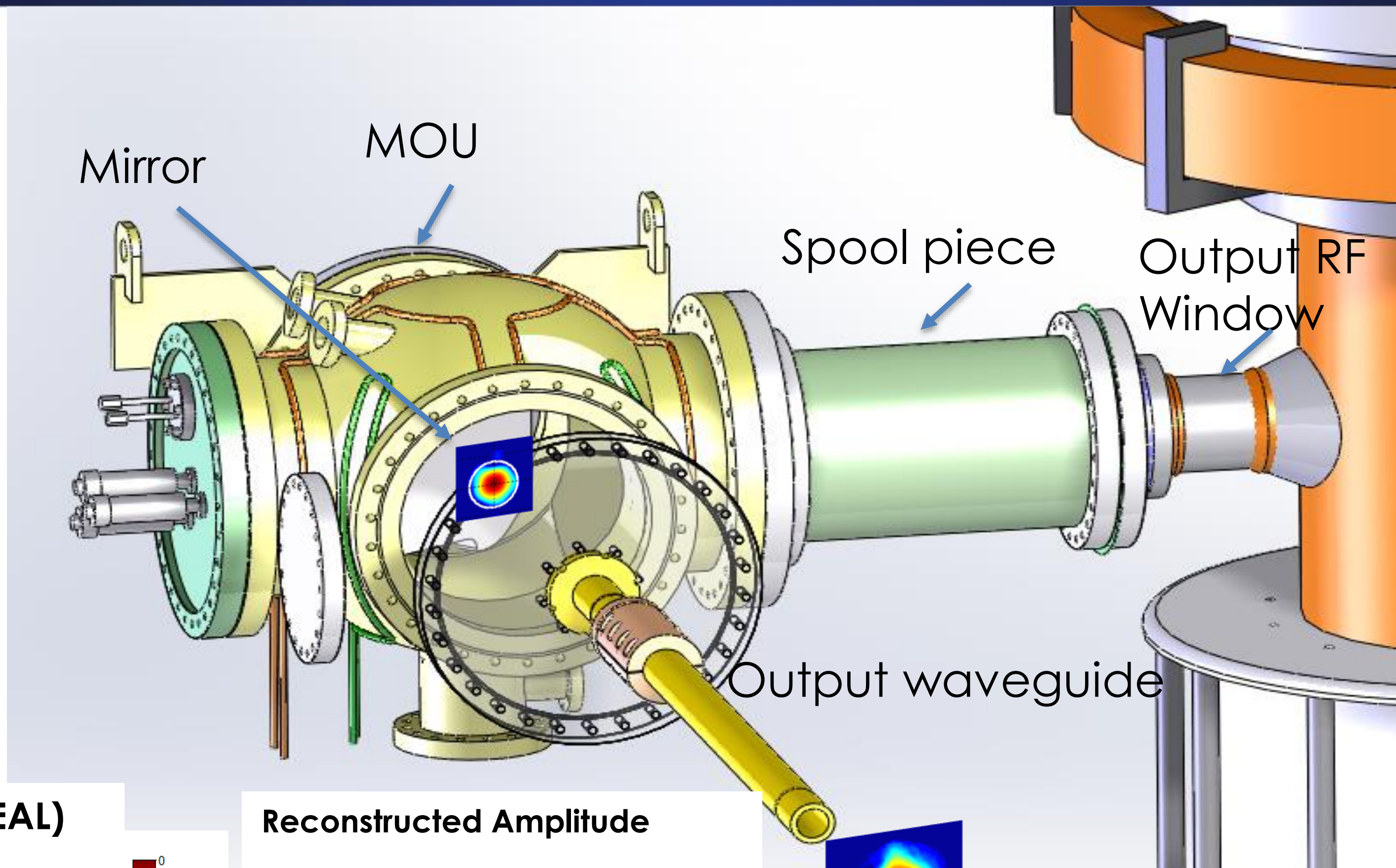
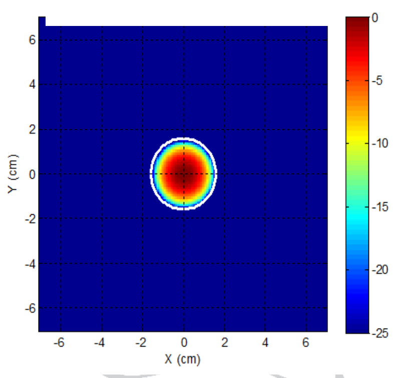
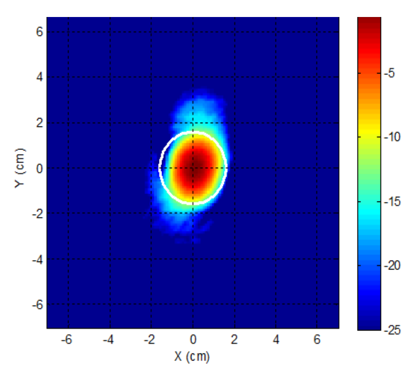
Aligning the RF beam Into waveguide input

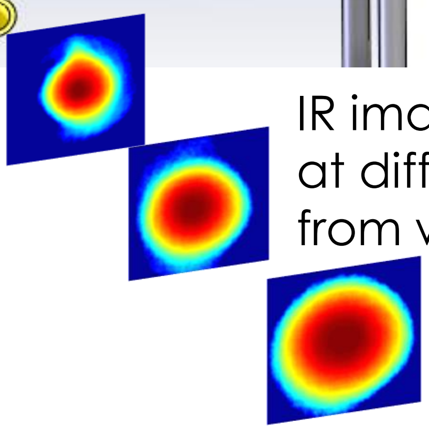


HE$_{11}$ (IDEAL)



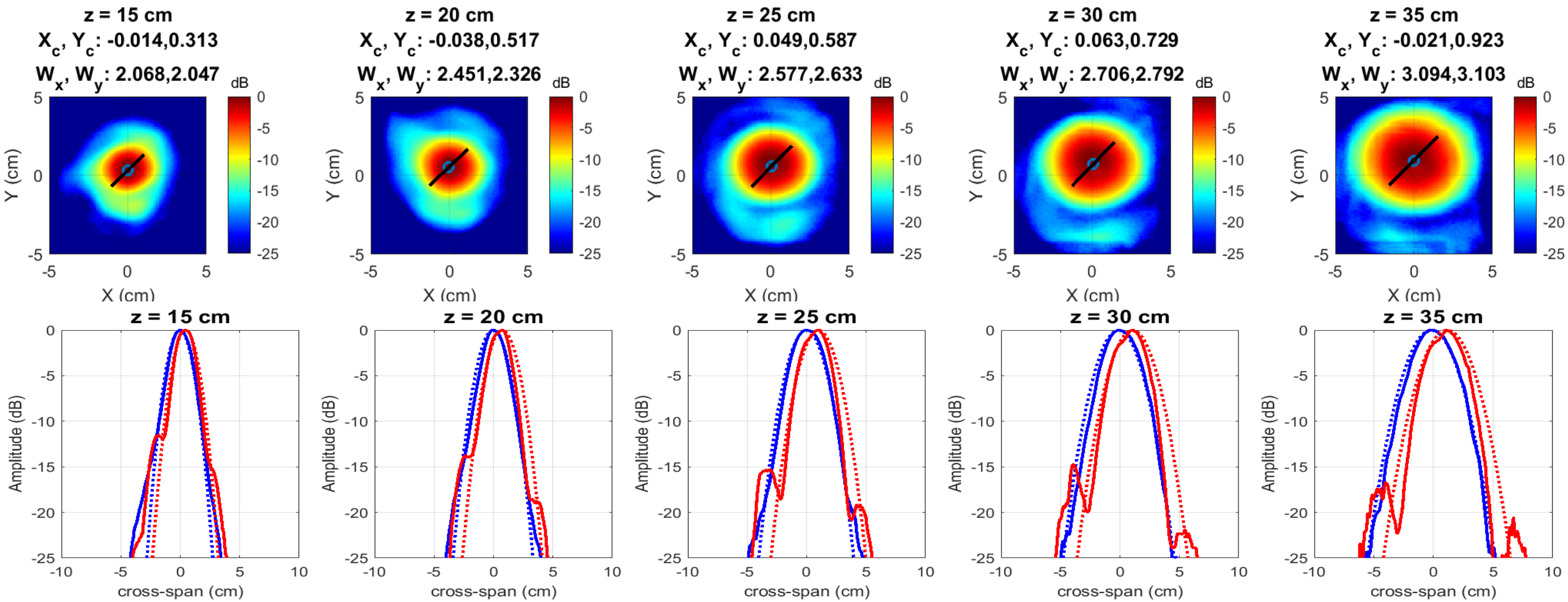
Reconstructed Amplitude

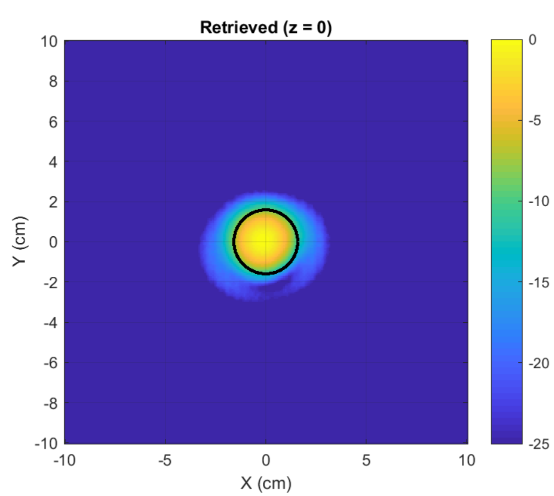


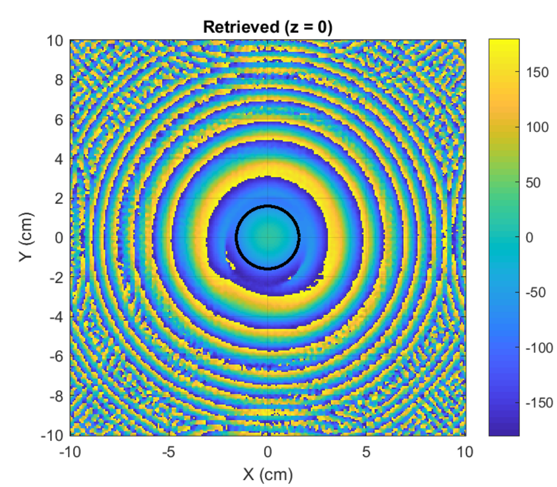


IR images of RF beam at different distances from waveguide output

Typical IR RF beam measurements

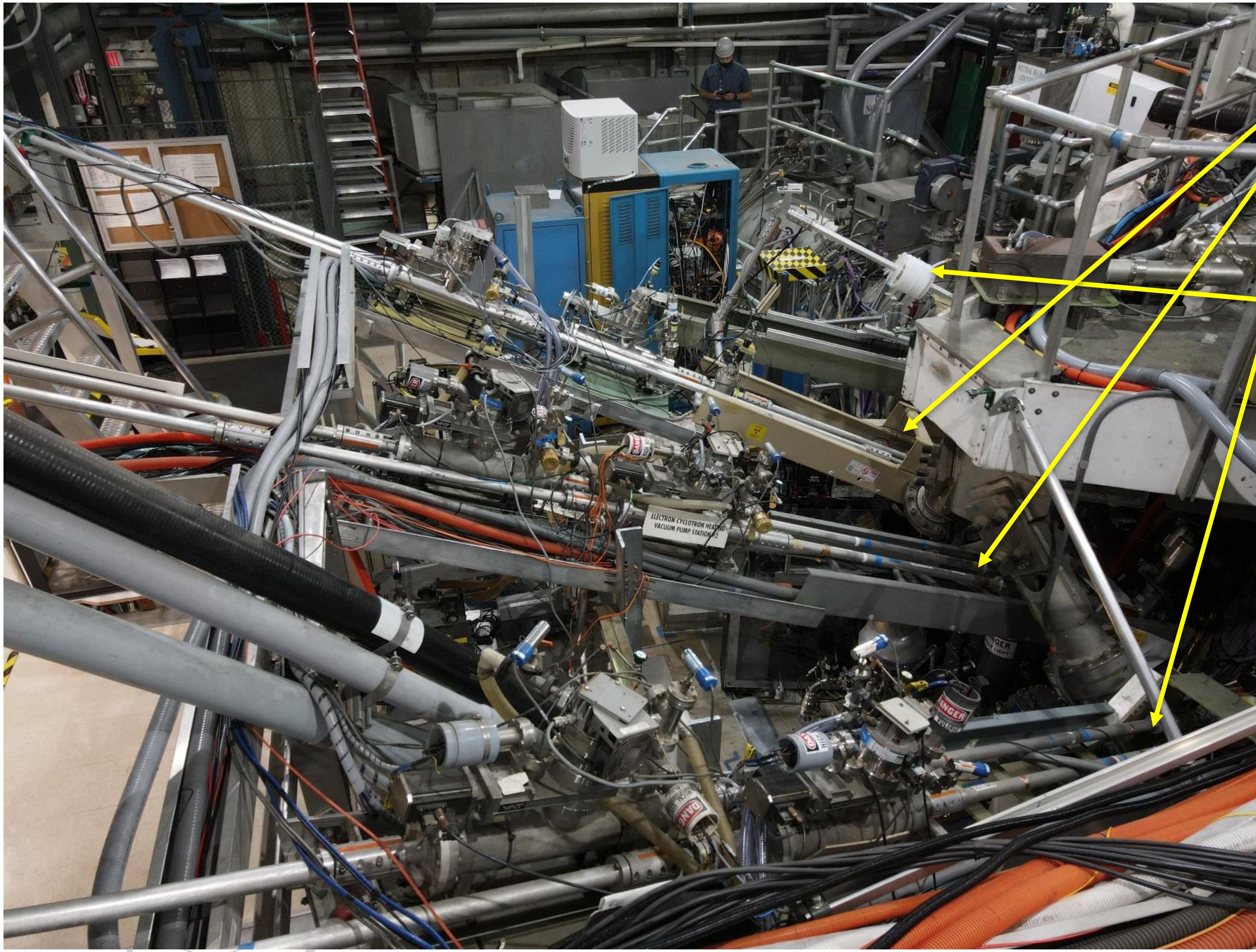






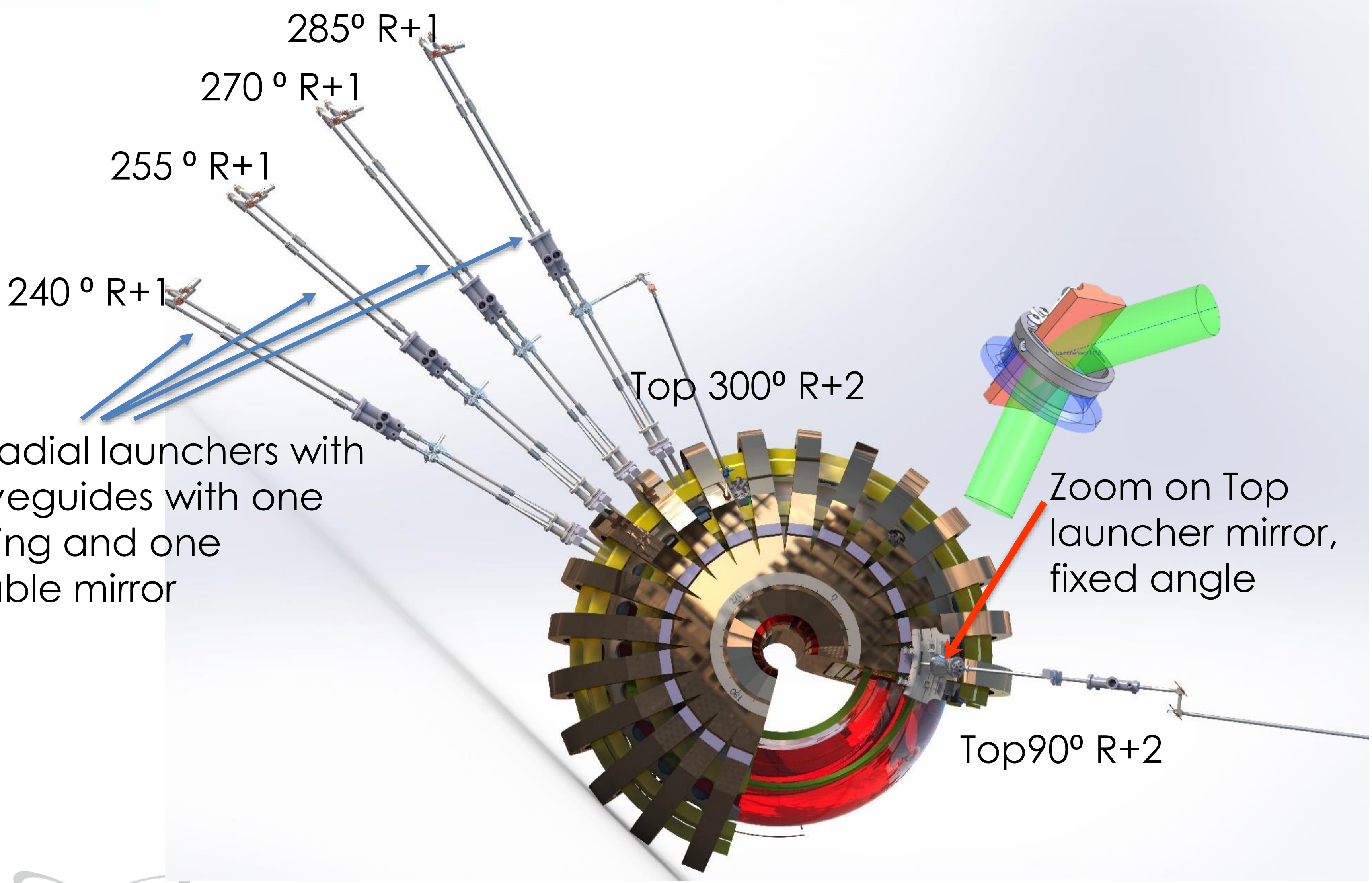
Amplitude and phase match to HE11 82.1%

ECH Launchers on DIII-D



Three radial launchers with 6 waveguide and **one top launcher are** on this image

ECH Launchers at DIII-D (cont.)



Four radial launchers with 8 waveguides with one focusing and one movable mirror

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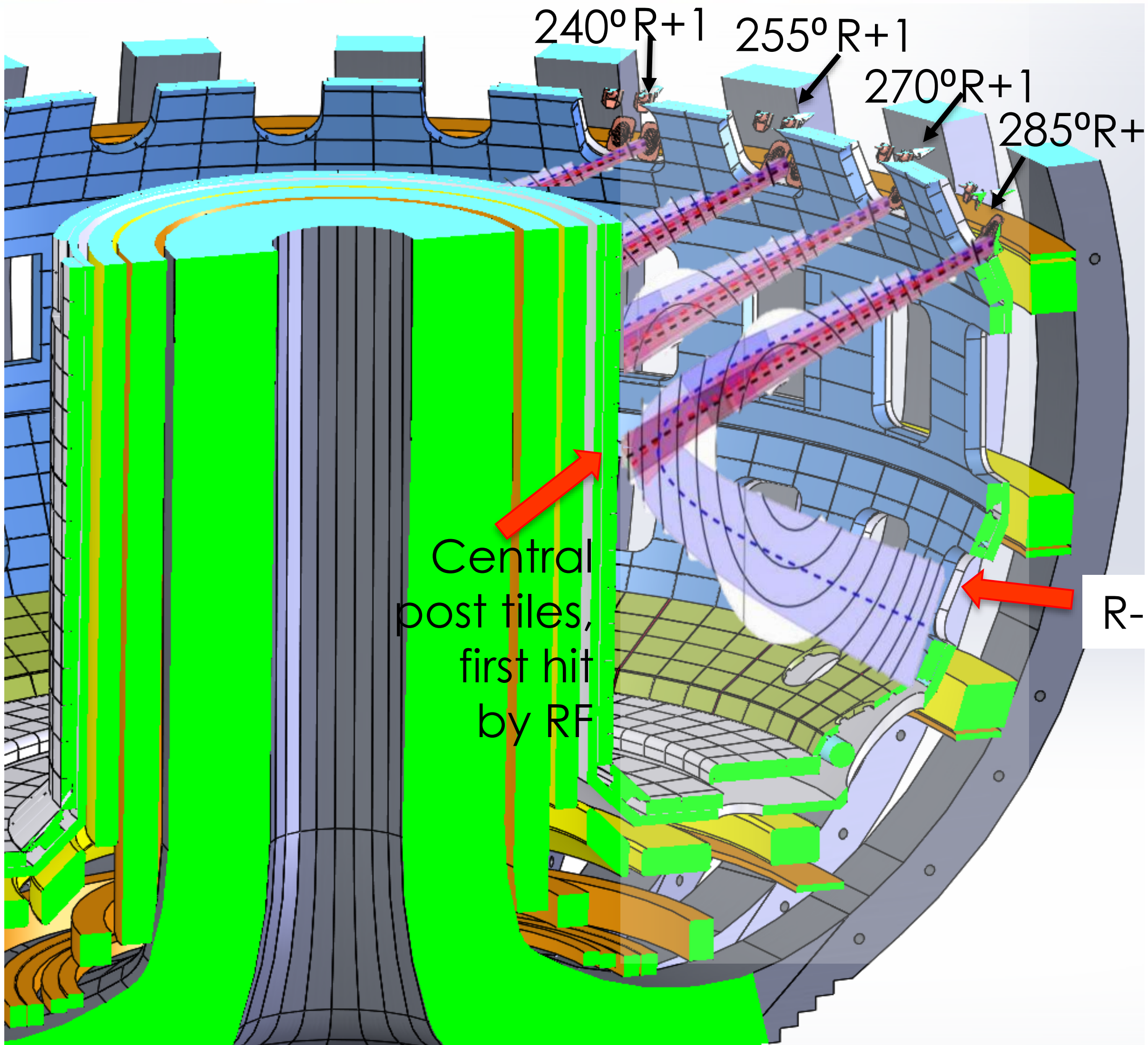
Extend EC injection into vacuum

- IR camera "observes" ECH with wide band of interaction
- Data on Bolometers measurements
- Modest torus pressure rise during ECH
- **Good vessel conditioning**



Idea of this experiment was to effective clean up Tokamak vacuum chamber

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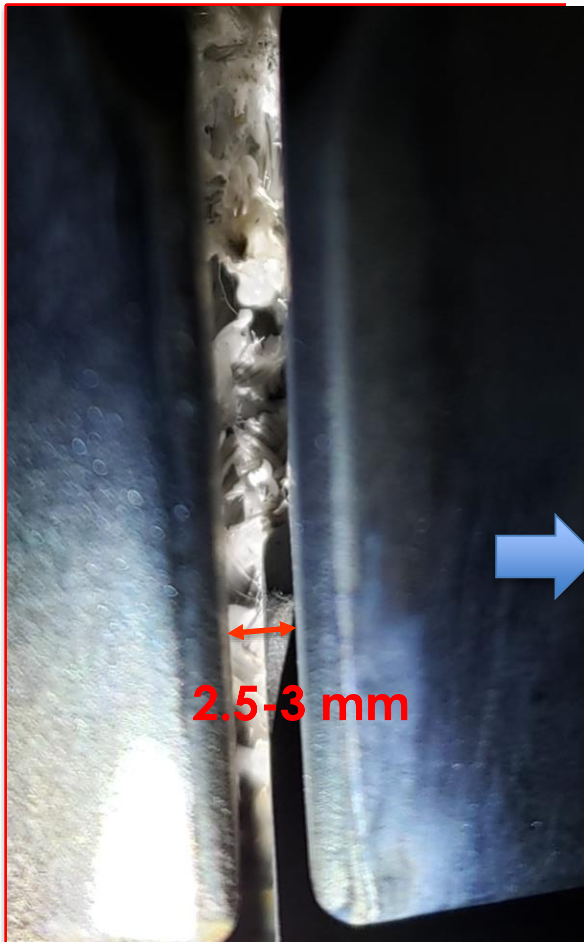
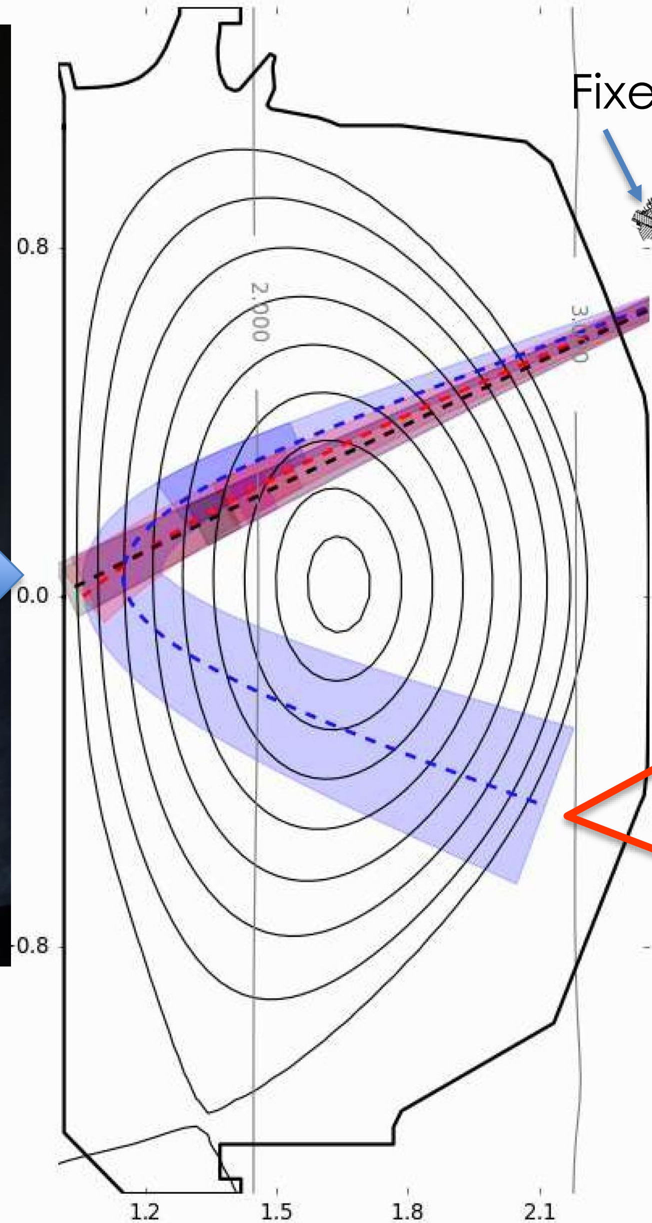
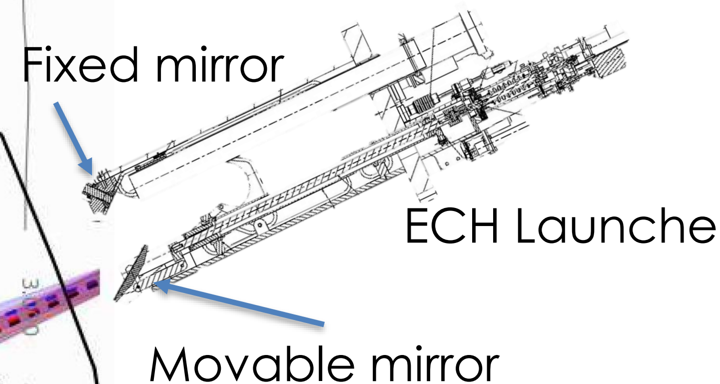
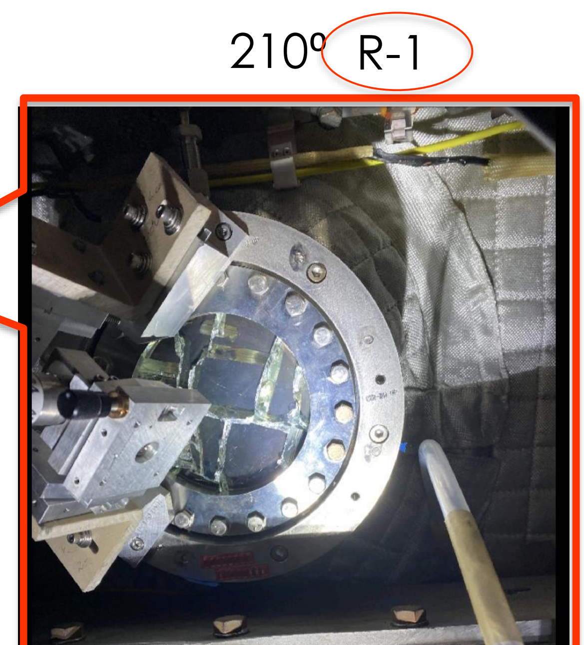
Lessons from empty camera ECH injection



NEXTEL isolation melts and forms gla
examples from areas between and
the center post areas in **direct view**







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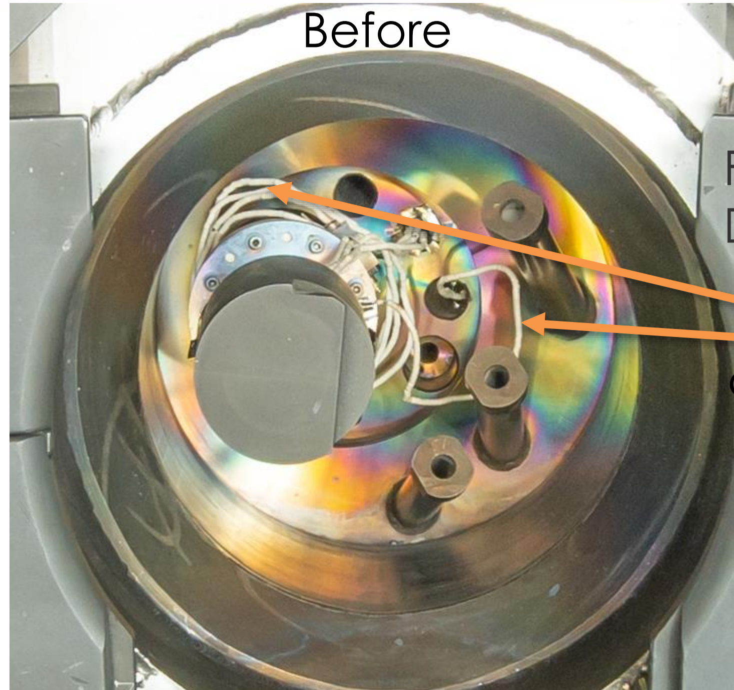
Lessons from empty camera ECH injection (cont.)

No damages were observed on the wall carbon tiles and covered diagnostics, but….

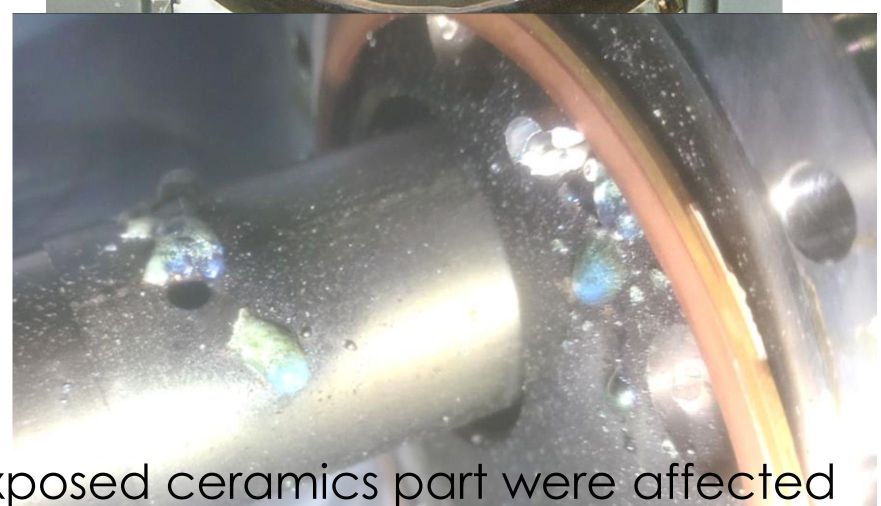


255⁰ R-1

Fast Ion Loss Detector(FILD)

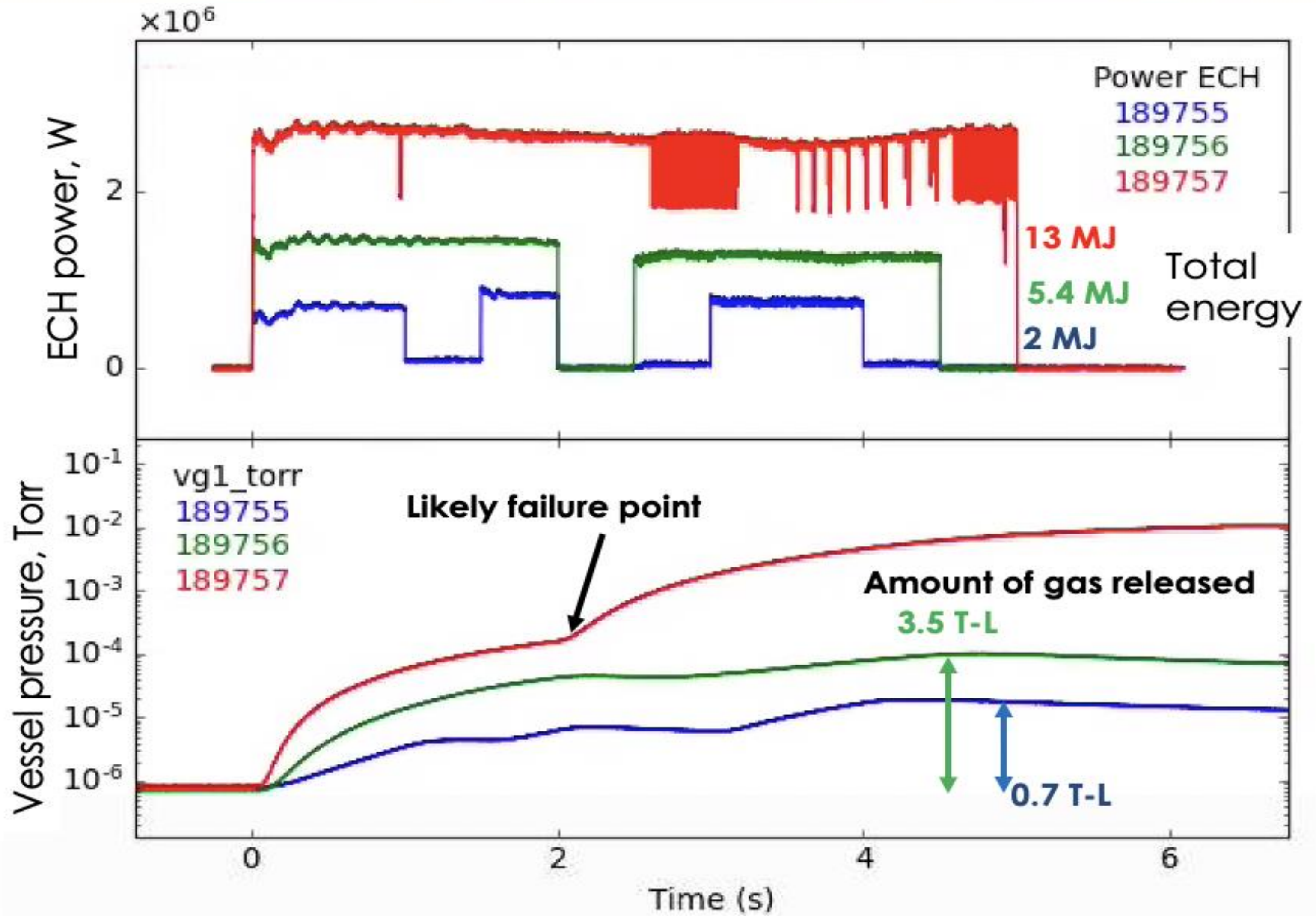
ceramic beads

Glazed ceramic beads after ECH empty vessel injection



All direct exposed ceramics part were affected

Tokamak wall conditioning effect



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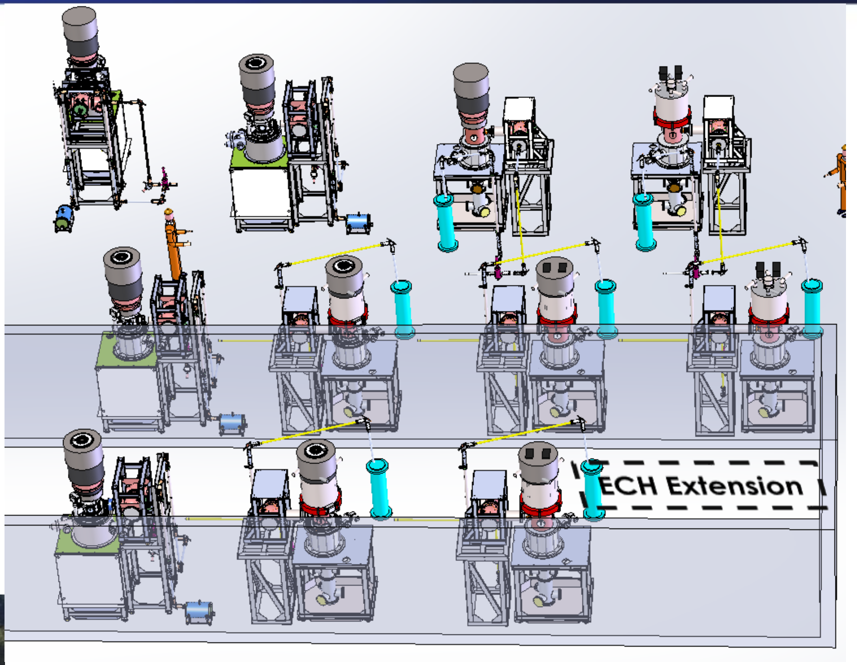
Future plan



2022- two110 GHz CPI gyrotron installation
2023-two next 110 GHz CPI gyrotrons delivery
2024-three more new gyrotrons installation

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SUMMARY

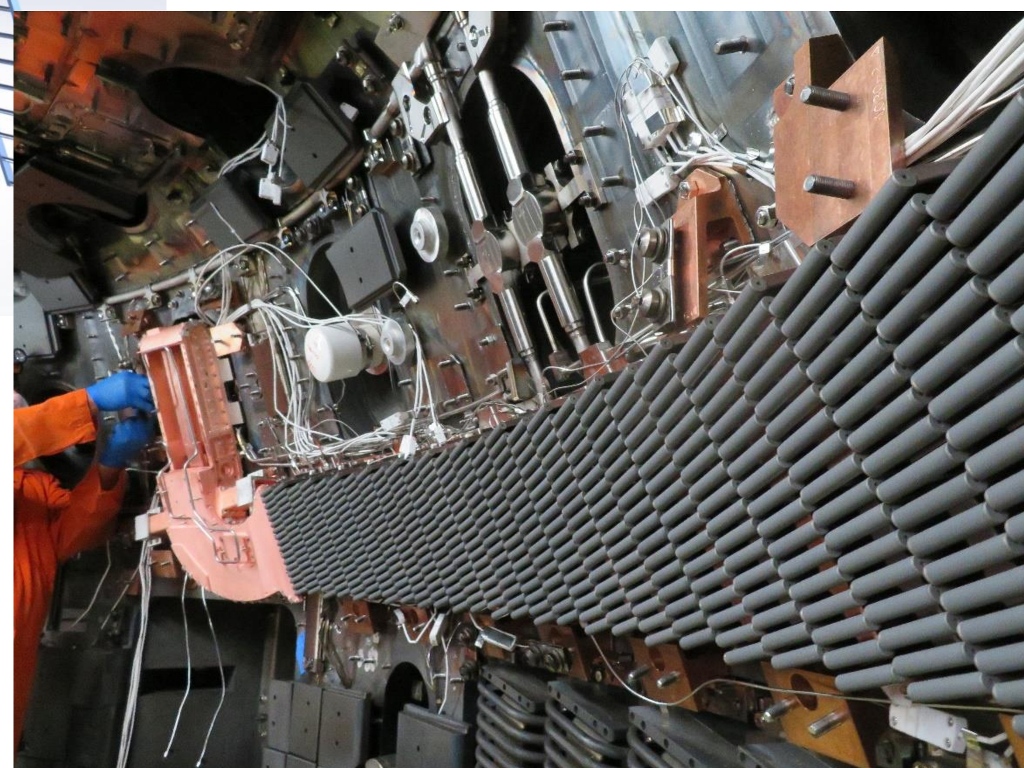
- The DIII-D Gyrotron system provided EC power for various experiments during the 2021-2012 campaign, with up to 2.7 MW injected from 4 gyrotrons
  - Pre-ionization
  - ECCD On-axis and Off-axis to reach steady-state conditions
  - EC power to sustain low and high density scenarios
  - EC conditioning of tokamak internal surface
- Six years of experience operating CPI depressed collector gyrotrons has demonstrated lower than expected efficiency and less reliability than non-depressed collector gyrotrons
- GA order four new non-depressed, CuCrZr collector gyrotrons from CPI. Two of them installed and operating now
- New extension building for additional gyrotron stand near completion. Three additional gyrotrons should arrive in 2023

Helicon Current Drive

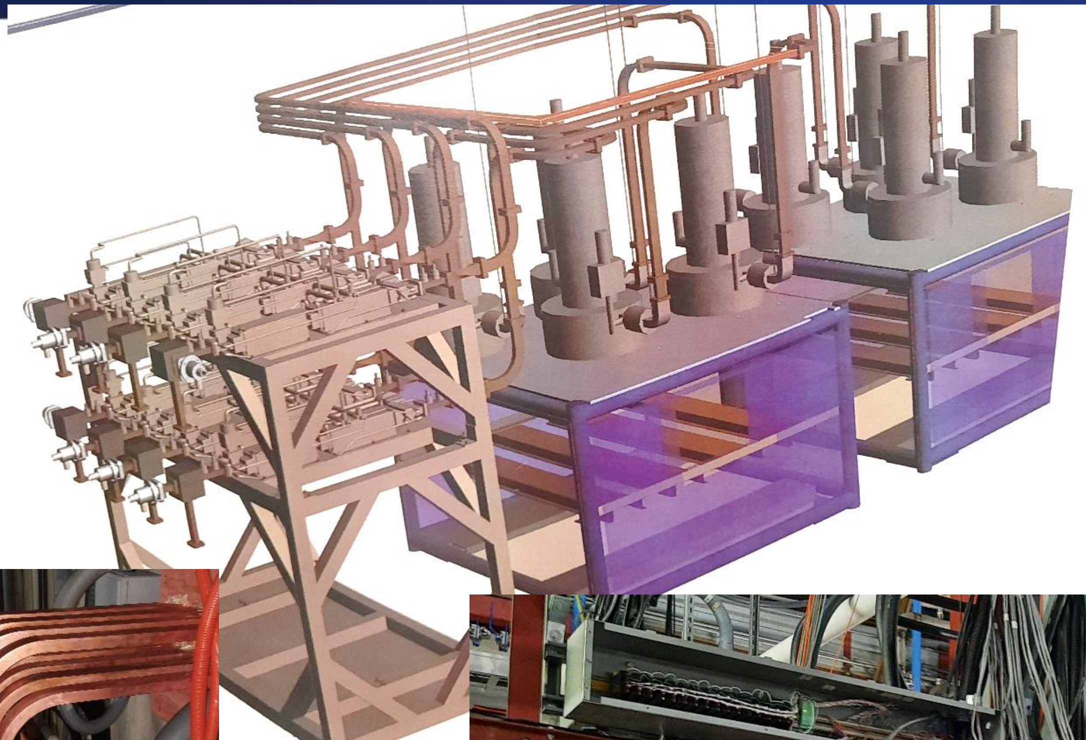
Klystron SLAC 1
Power 1.2 MW
Frequency 476 MHz
Tested 1.25 MW into D/L

300 kW power coupled to plasma demonstrated in 2021

Helicon Antenna



High Field Side Launch Lower Hybrid Current Drive



8 CPI Klystrons
200 kW each
4.6 GHz frequency