The high-power helicon program at DIII-D: Gearing up for first experiments

B. Van Compernolle

on behalf of

M. W. Brookman[1], C. P. Moeller[1], R. I. Pinsker[1], A. M. Garofalo[1], R. O'Neill[1], D. Geng[1], A. Nagy[2], J. P. Squire[1], K. Schultz[1], C. Pawley[1], D. Ponce[1], A. C. Torrezan[1], J. Lohr[1], B. Coriton[1], E. Hinson[3], R. Kalling[4], A. Marinoni[5], E. H. Martin[6], R. Nguyen[1], C.C. Petty[1], M. Porkolab[5], T. Raines[2], J. Ren[7], C. Rost[5], O. Schmitz[3], H. Torreblanca[8], H. Q. Wang[1], J. Watkins[9], K. Zeller[1]

[1]GA, [2]PPPL, [3]U. Wisconsin-Madison, [4]Kalling Software, [5]MIT, [6]ORNL, [7]U.T. Knoxville, [8]EPFL Switzerland, [9]Sandia

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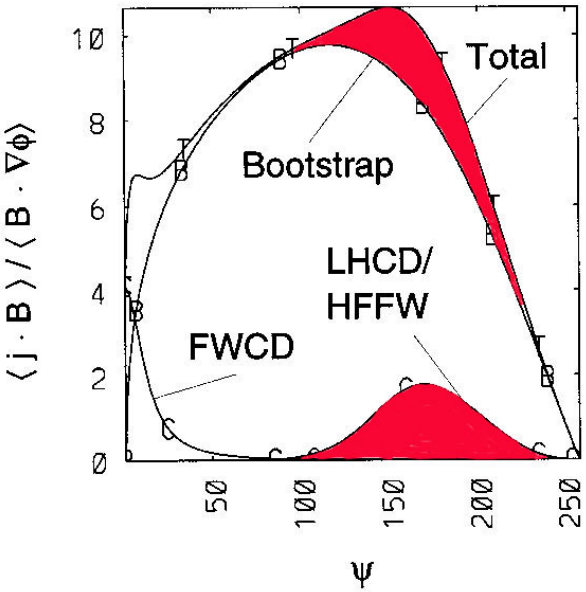
GENERAL ATOMICS

Mid-radius current drive for reactors and for DIII-D

- **Steady-state advanced tokamak reactors require non-inductive current drive in the mid-radius region**

- **DIII-D studying methods for off-axis rf current drive:**
  - Top-launch ECCD (tested 2019 -)
  - Helicon current drive (to be tested 2021 -)
  - Inside-launch LHCD (to be installed 2022 -)

- **Wave absorption for both LH waves, helicon waves via electron Landau damping**
  - Electrons with same parallel velocity as parallel phase velocity of waves gain energy from wave



Jardin, et al.,
Fusion Eng. Des. 1997 (ARIES-RS)

How much power is absorbed and how much current can you drive with it?

Two factors matter:

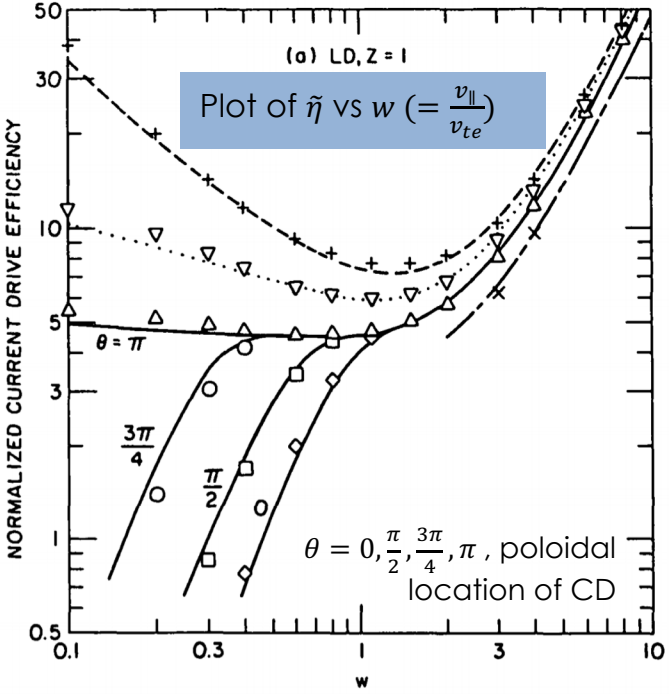
- **How much power is absorbed**
  - Mechanism: Landau damping

$$Im(k_\perp) = \frac{\sqrt{\pi}}{4}\beta_e \xi_e e^{-\xi_e^2} k_\perp G(\omega) \text{ with } \xi_e = \frac{v_\parallel}{v_{te}}$$

- **How much current is driven with the absorbed power**
  - Ehst-Karney efficiency[1] (ratio current density to power density)

$$\eta = \frac{38.4 \times 10^{18}}{\ln \Lambda} \frac{T_e(keV)}{n_e(m^{-3})} \tilde{\eta} \qquad \text{(see fig for } \tilde{\eta}\text{)}$$

- **Key parameter is ratio of electron velocity v_{te} to wave parallel phase velocity $v_{ph\parallel} = \omega/k_\parallel$; $n_\parallel = ck_\parallel/\omega$**
- **Competing effects:**
  - High $\frac{v_\parallel}{v_{te}}$: good CD efficiency, bad absorption
  - Higher density increases absorption, but lowers CD efficiency



Strong function of $\frac{v_\parallel}{v_{te}}$ for $\frac{v_\parallel}{v_{te}} \gtrsim 1$

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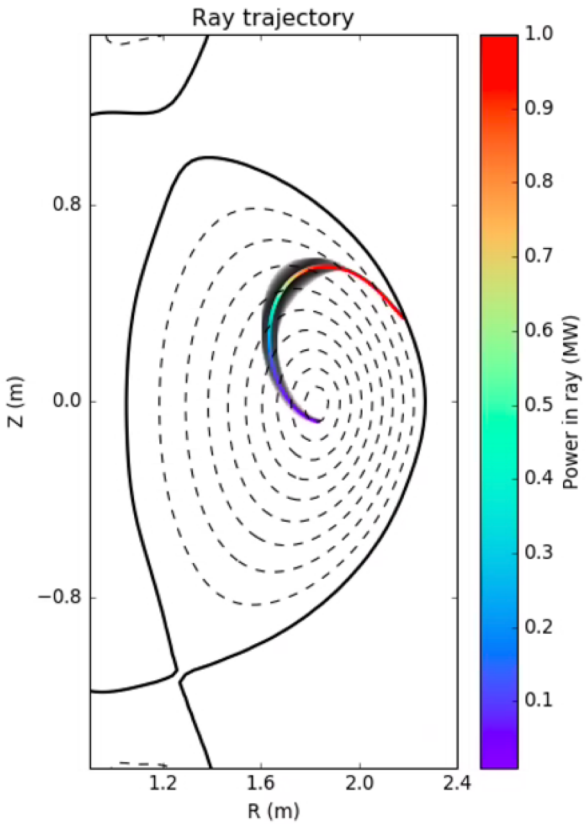
[1]D.A. Ehst and C.F.F. Karney 1991 *Nucl. Fusion* **31** 1933

Helicon current drive for reactors and for DIII-D

- **Helicon waves are fast waves in the lower hybrid range of frequencies (hundreds of MHz for DIII-D)**
  - Can propagate into high density plasmas
  - Propagation is whistler-like, i.e., group velocity more directed along magnetic field
  - Waves slowly spiral radially inwards, gradually deposit energy

- **Prater *et al*[1] examined optimum parameters for DIII-D for helicon current drive in high-performance plasmas**
  - Optimum antenna launched parallel wave number: $n_{\parallel} = 3$, absorption occurs once $n_{\parallel}$ shifts above 4 during propagation
  - Expect 60-70 kA/MW at $\rho \simeq 0.6$ in high-beta plasmas (off-axis H&CD)
  - Expect >100kA/MW in L-mode plasmas (core H&CD)



[1]R. Prater *et al*, Nucl. Fusion 54 (2014) 083024

Requirements of helicon system

- **Requirements:**
  - HHFW in lower hybrid frequency range: **476 MHz** chosen, determined by availability of B-Factory Klystron (BFK) from SLAC
  - Launch at $\boldsymbol{n}_{\parallel} = \mathbf{3}$, optimized for off-axis current drive in DIII-D plasmas
  - **Fast wave polarization**: opt for phased array of strap antennas
  - Drive non-inductive current **either co- or counter**: directed wave propagation, chosen by feeding from either end of antenna
  - **Low-loss** structure -- handle high-power RF

Outline

- **Traveling wave antenna**
  - Principles and design
  - Testing, installation and results
- **RF source and transmission line network**
- **Installed and upcoming diagnostics**
- **Current status and near-term plans**

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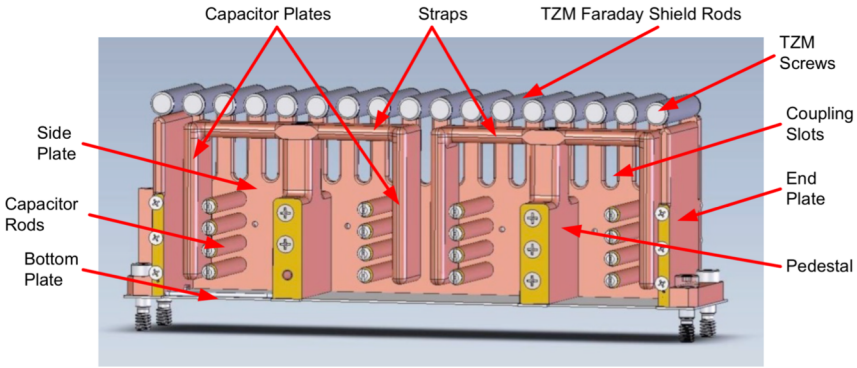
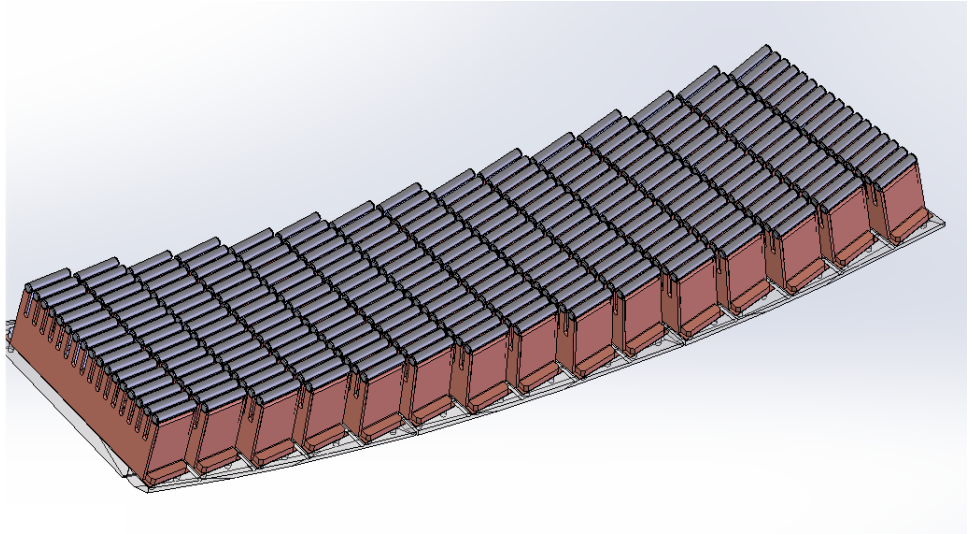
Comb-line traveling wave antenna concept
(Charles Moeller US patent 5289509, 1994)

- **One input port and one output port**
- Power transferred down the array through mutual inductance
- Input impedance determined by mutual inductance – **resilient to changes in plasma loading**, to the extent that plasma-induced changes in mutual are small
- Acts as a bandpass filter with mid-band frequency = 476 MHz
- Each module is essentially a resonant RLC circuit; each module was tuned to same resonant frequency to within ± 0.5 MHz
- **Narrow $n_{\parallel}$ spectrum**



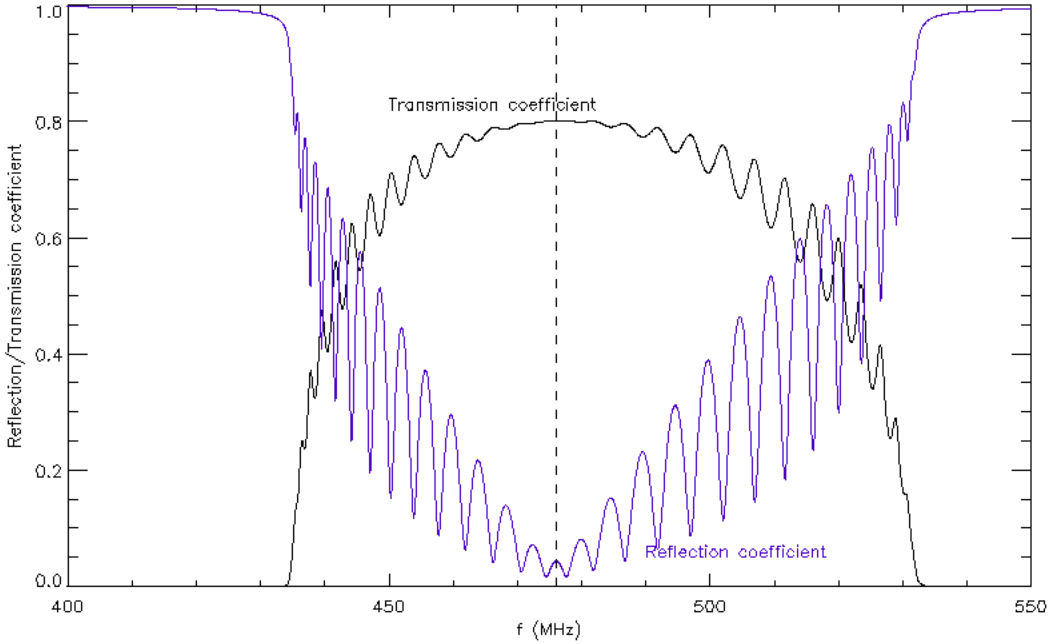
Single module cutaway



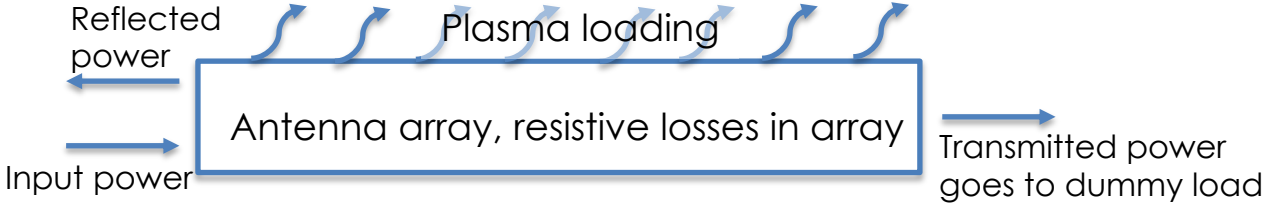
One half of the 30 module array

J. Tooker *et al*, Fusion Engineering and Design **123**, 228 (2017)

Lumped element circuit model (Pinsker – 1996) demonstrates bandpass filter characteristics



- Bandpass width scales with $\frac{\omega_0 M}{L}$
- Transmission coefficient < 1 due to resistive losses and plasma loading
- In real-life measurements, obtain dissipation in antenna from $P_{in} - T - R$



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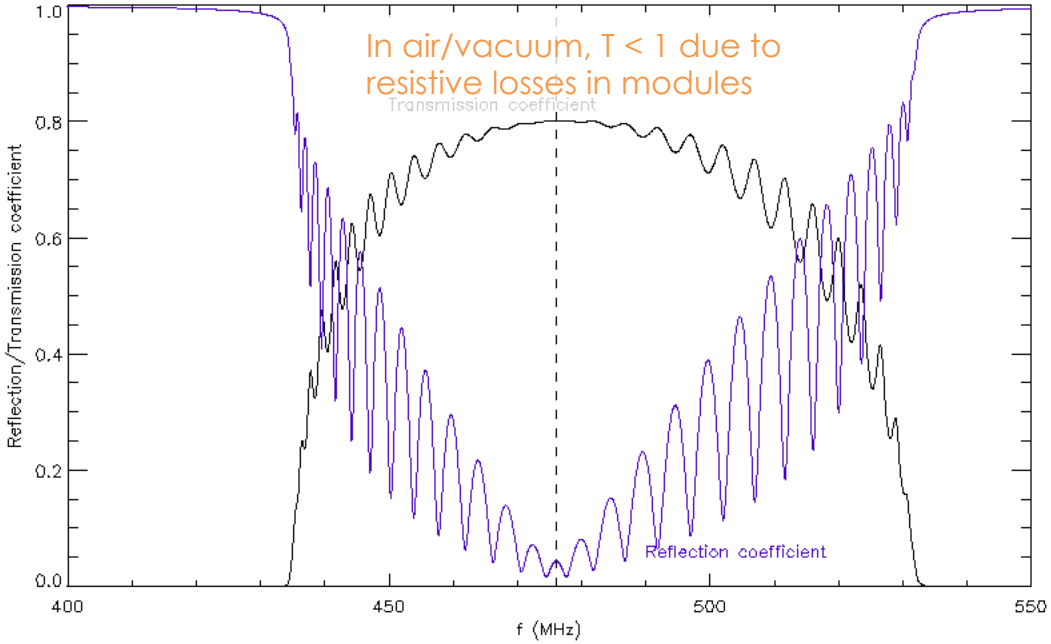

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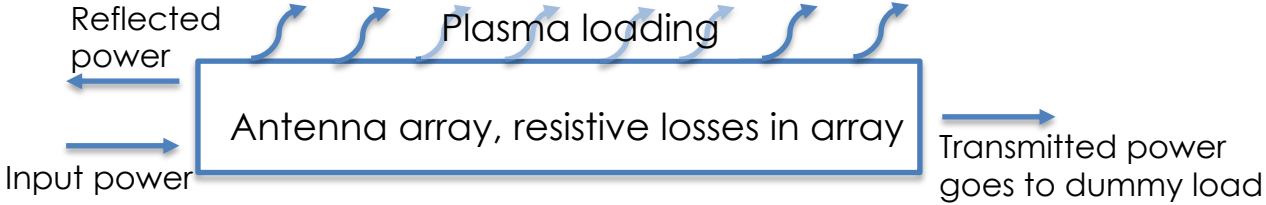

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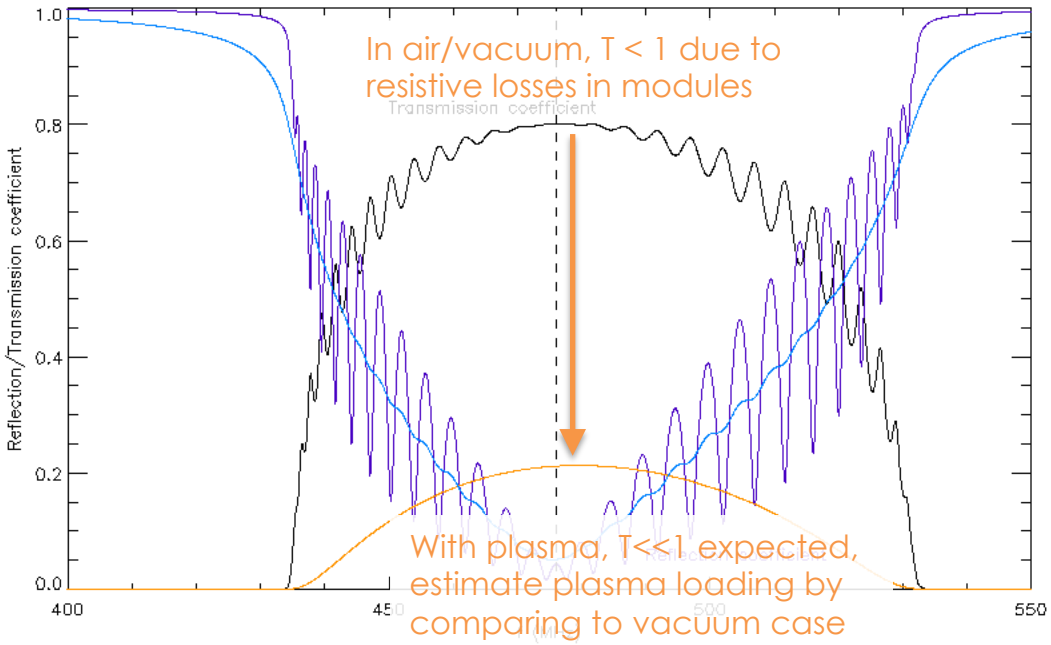

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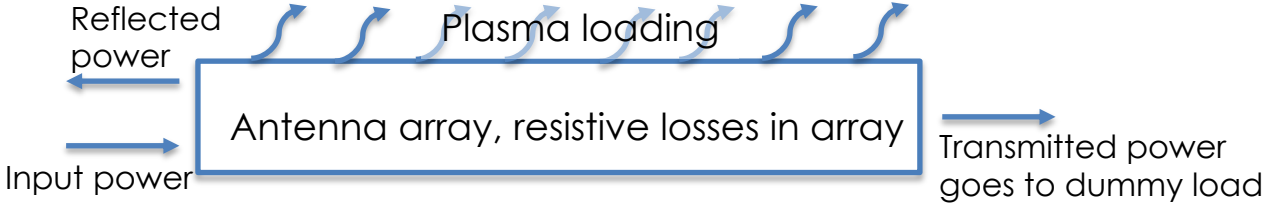

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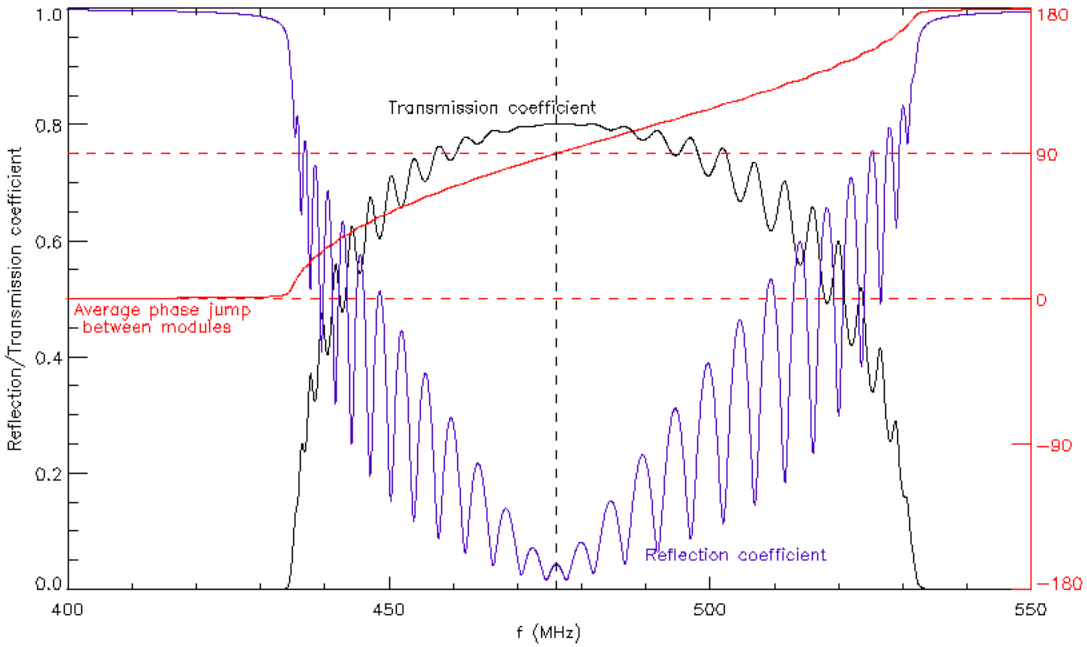

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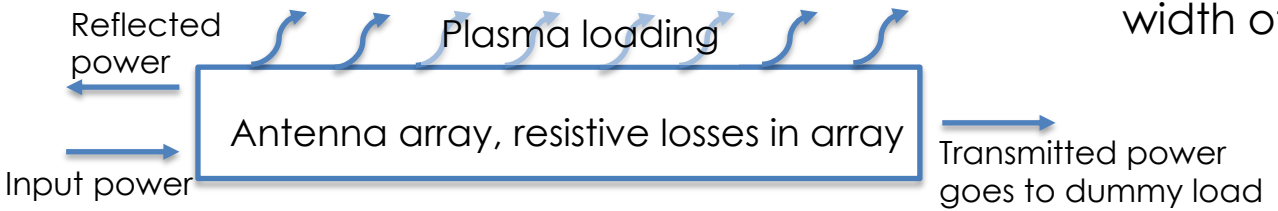
- Transmission coefficient < 1 due to resistive losses and plasma loading
- In real-life measurements, obtain dissipation in antenna from $P_{in} - T - R$
- Antenna phasing varies with frequency, from monopole phasing at low band-edge to pi phasing at high band-edge
- At mid-band, f = 476 MHz, phase jumps between modules is 90°.
- Phase jump combined with the width of the modules sets $n_{\parallel}$ (=3.0)



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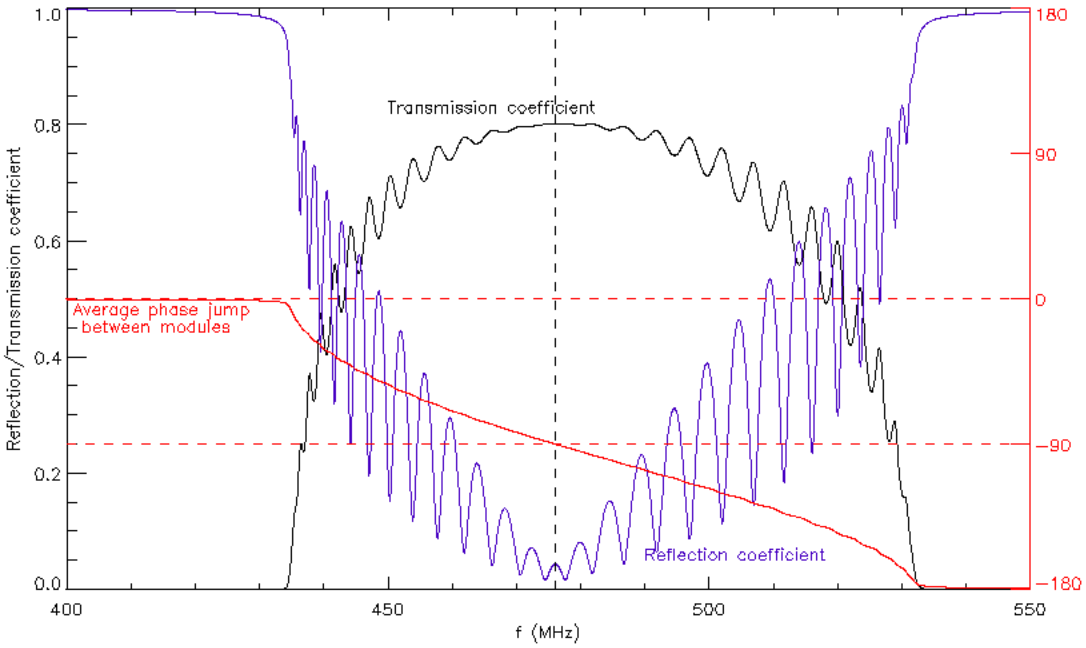

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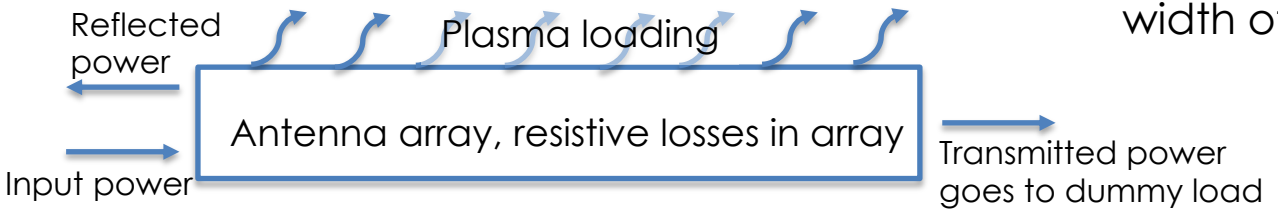
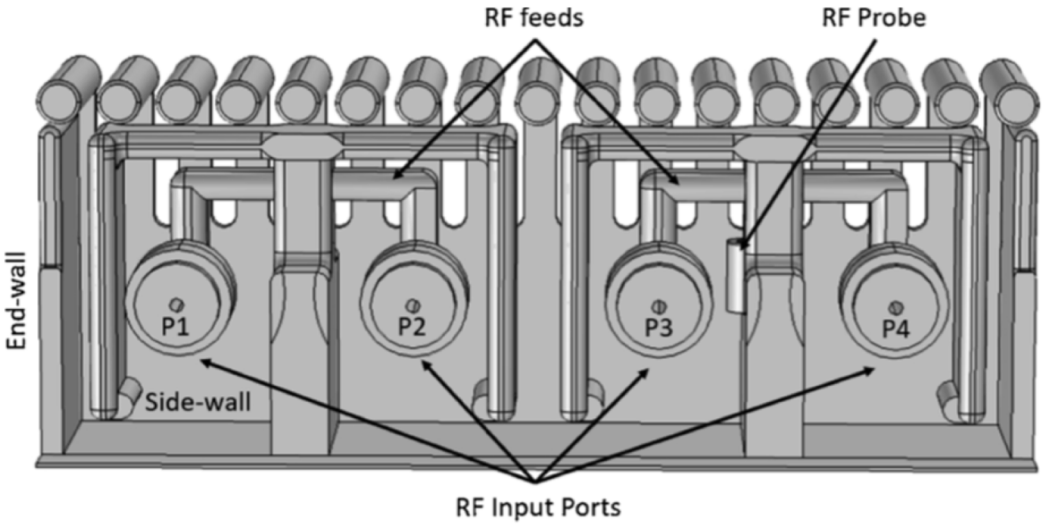


Power fed into array from specialized end-modules

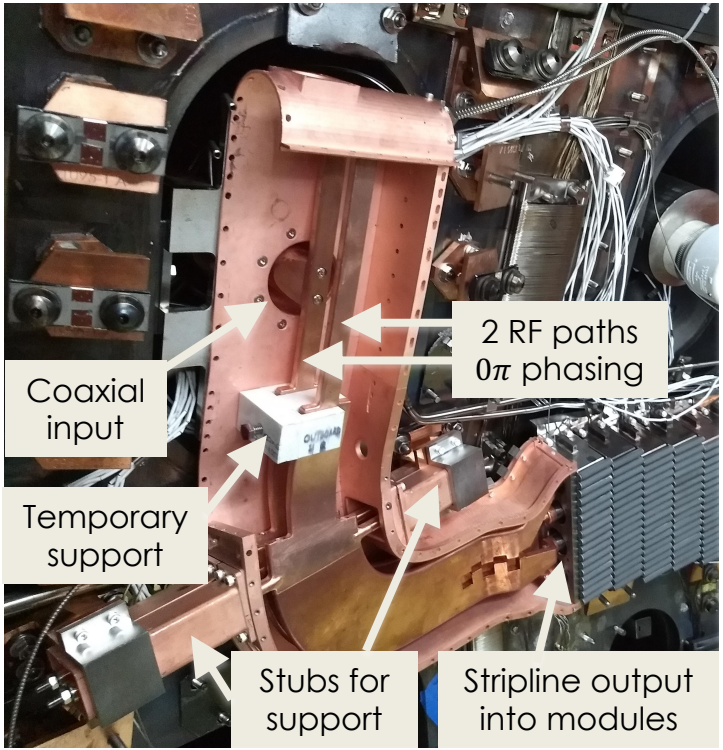


End module cutaway

H. Torreblanca, *et al,* Fusion Engineering and Design 146 (2019) 626–630

- End-modules have four coupling straps – RF feeds
- Need to be fed with equal power
- To ensure unidirectional current flow on top straps, input straps need to be fed with $0\pi0\pi$ phasing
- Can be fed with 4 separate coaxial feeds for testing, or with stripline (final install)

Stripline feeds are critical, complex component of system



- Antenna array fed from either end by stripline
- Coaxial input
- Stripline has two RF paths, each split in two → 4 equal-power outputs with $0\pi0\pi$ phasing as input to the antenna array end-module
- Complex 3D structure intended to 'hug' the vessel wall
- Certain parts are 3D printed Inconel, coated with copper

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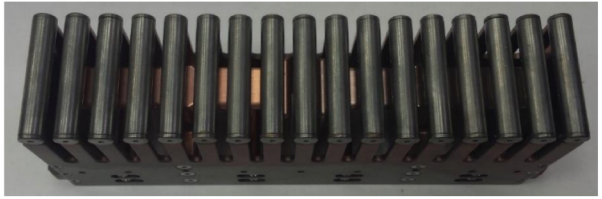
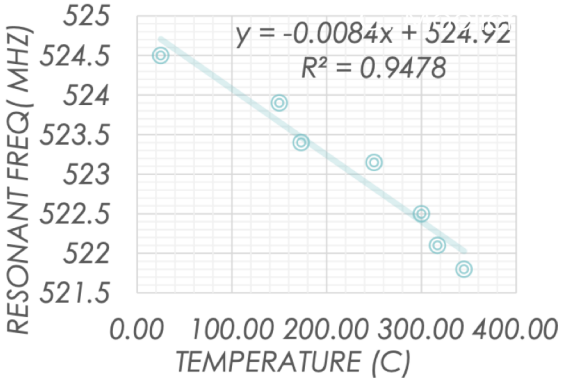
- **LAPD experiment**

Modules built half by GA, half by ASIPP and tested/tuned individually



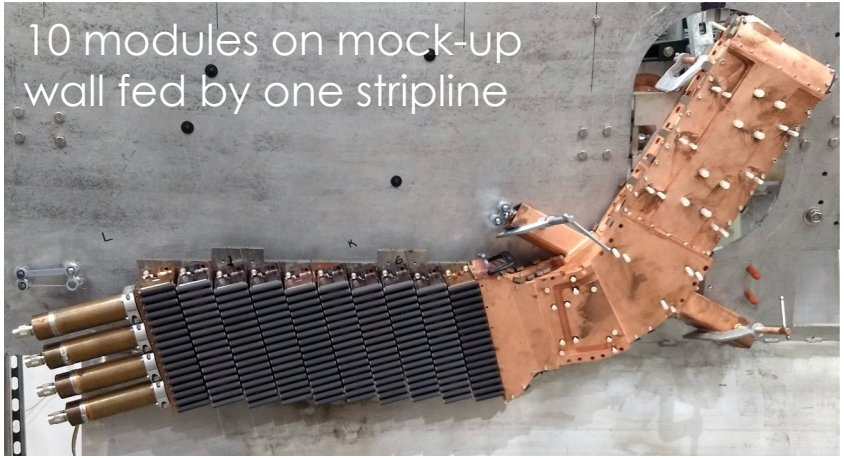
Above: Prototype antenna module, 1 of 18 built by ASIPP
Below: temperature dependence with heating in vacuum oven

- **Module prototypes produced in Hefei & San Diego – consistently tuned to 525 MHz** (Test setup upshifts the resonant frequency)
- **Thermal response evaluated by team - prototype was heated in a vacuum oven, producing a 2.4 MHz change in resonant frequency @ 330 C – as expected from thermal expansion**
- **Antenna bandwidth is sufficient to allow this**



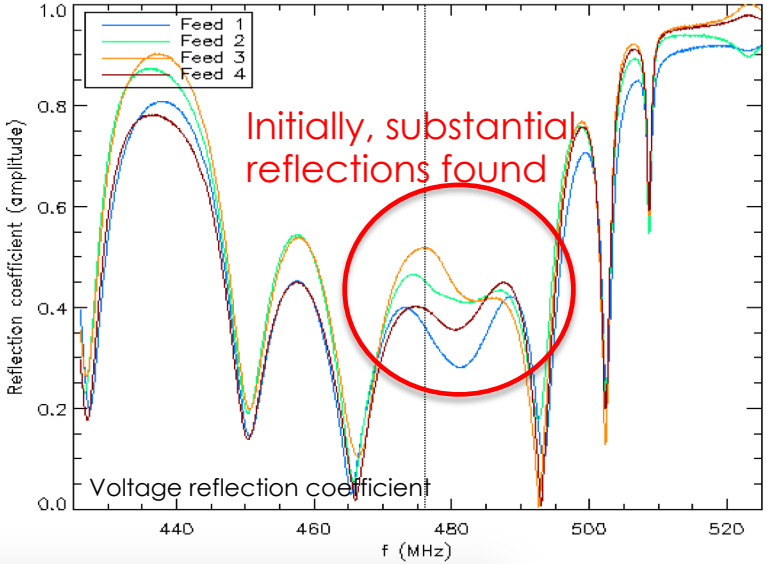
Extensive bench testing done during Summer/Fall 2019

- Tests with 5, 10, 15, 20, 30 modules
- Flat on bench, and on curved backplates
- With and without stripline
- Established optimization procedures, gained experience for in-vessel install



30 modules on back plates

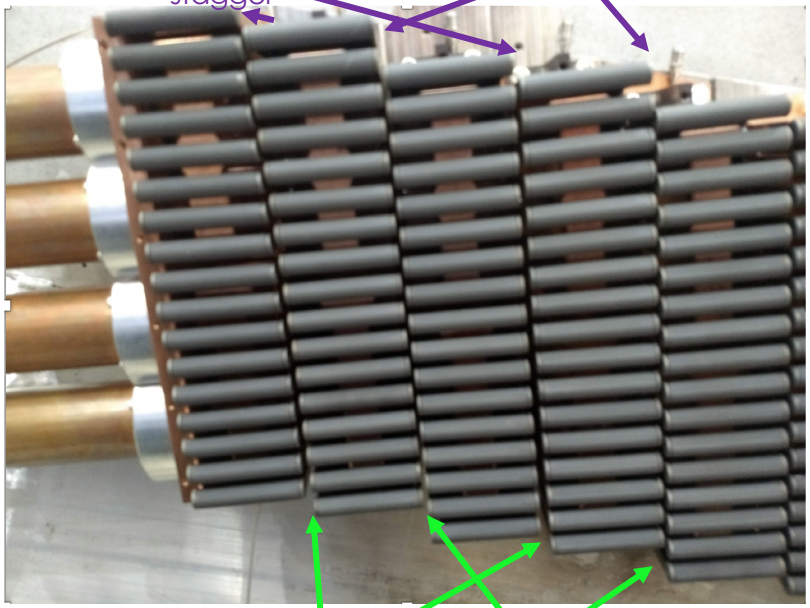
Issue with large reflected power seen in bench testing



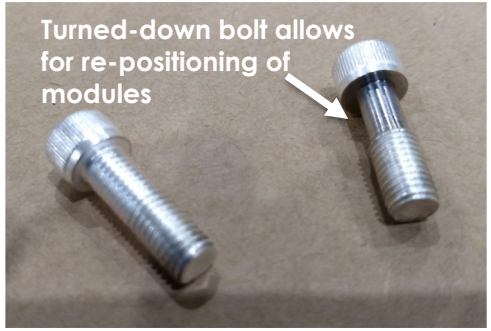
- Antenna modules tilted to match magnetic field pitch
- Substantial reflected power seen near mid-band frequency
- On the order of ~15-20% of input power
- Initially not clear what the cause was

- Extensive bench testing done to investigate effect of non-overlapping modules, alternating stagger, done flat on the bench (no curvature), and on curved backplates

Bench testing led to optimization procedure that removed large reflected power

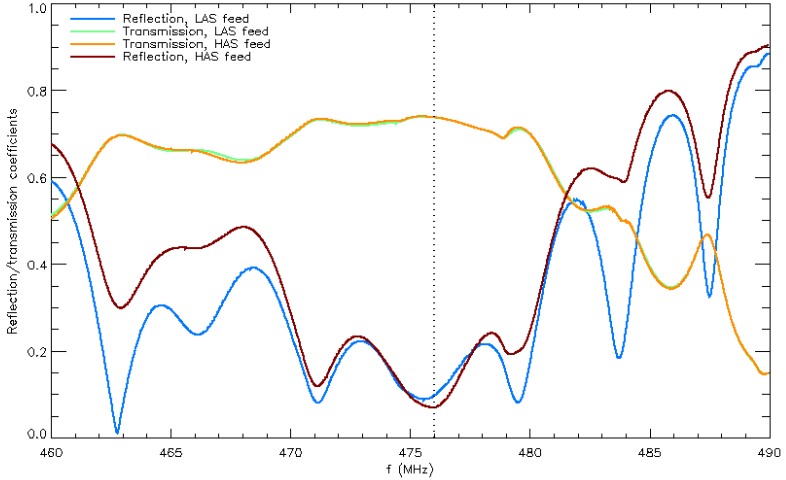


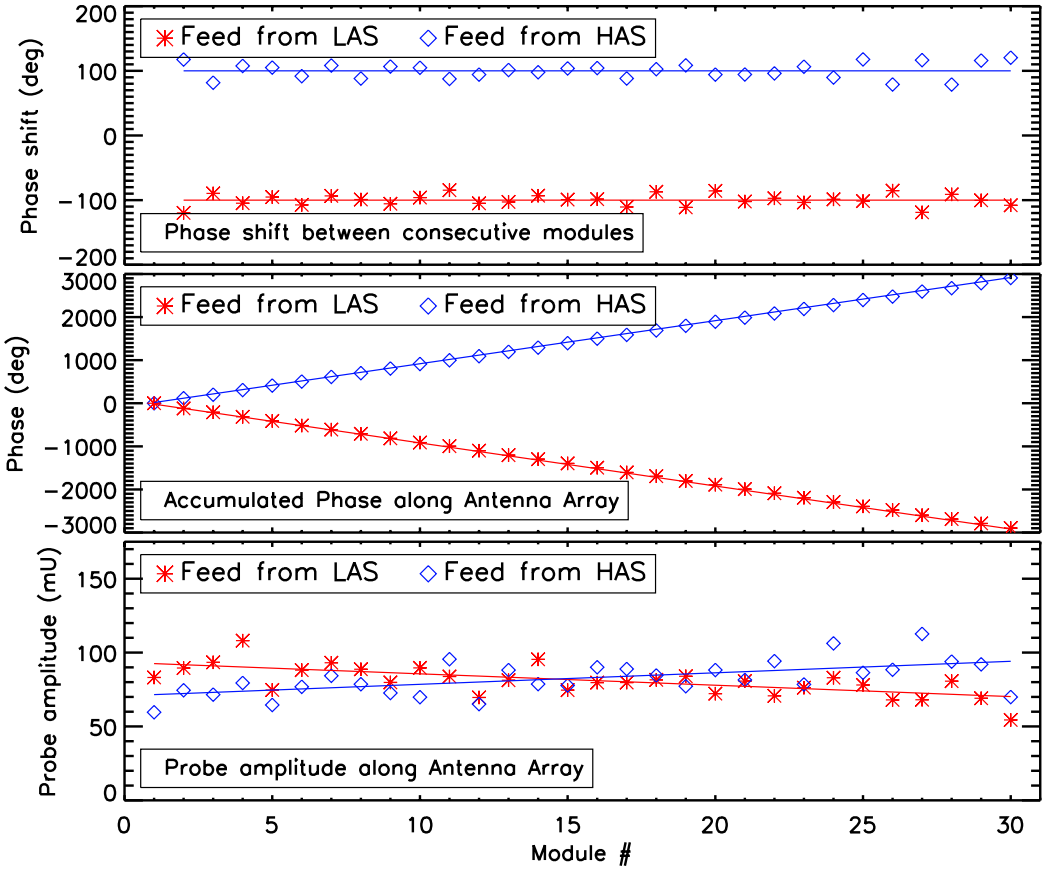
- Layout of modules: uneven staggering introduces unwanted 2-module periodicity
- Correct for this by re-positioning modules slightly in the toroidal direction (left-right)
- Effectively creating a more uniform mutual coupling between pairs of modules
- **Big improvement in reflection coefficient**
- Also improved phasing between modules



Installed antenna meets design target

- Low reflected power (~1%) at 476 MHz, stays <4% in 10MHz band
- Dissipated power in each module is 1.45% of incident power on module
- Phase shift between modules uniform along array
- Amplitude decays steadily from injection point, with only small variations
- No evidence of standing modes
- Equally good results feeding from either end





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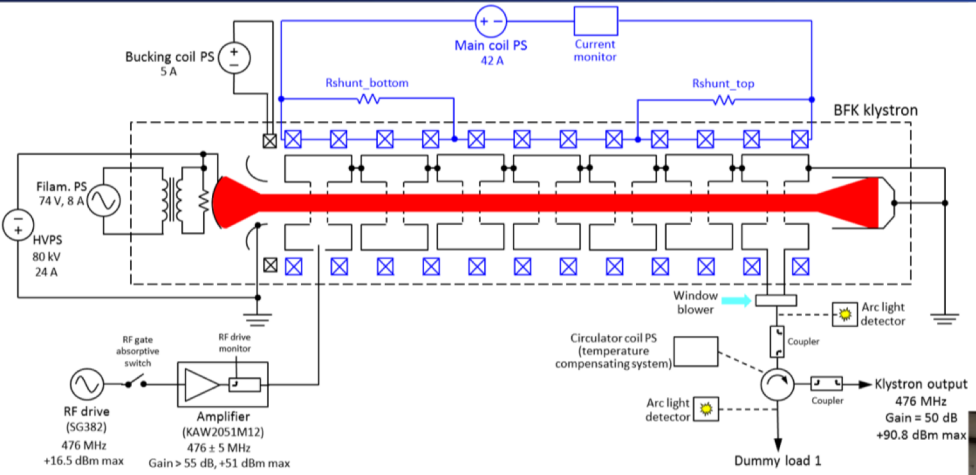
RF source is a 1.2 MW klystron at 476 MHz



B-factory klystron, obtained from SLAC

- 476 MHz, 1.2 MW RF output power
- Highly tuned with 7 RF cavities, 1dB bandwidth of ±1.5 MHz
- 60% efficiency

- Control software updated to allow for pulsed mode
- Amplitude modulation possible by modulation of RF input power or modulation of electron beam voltage

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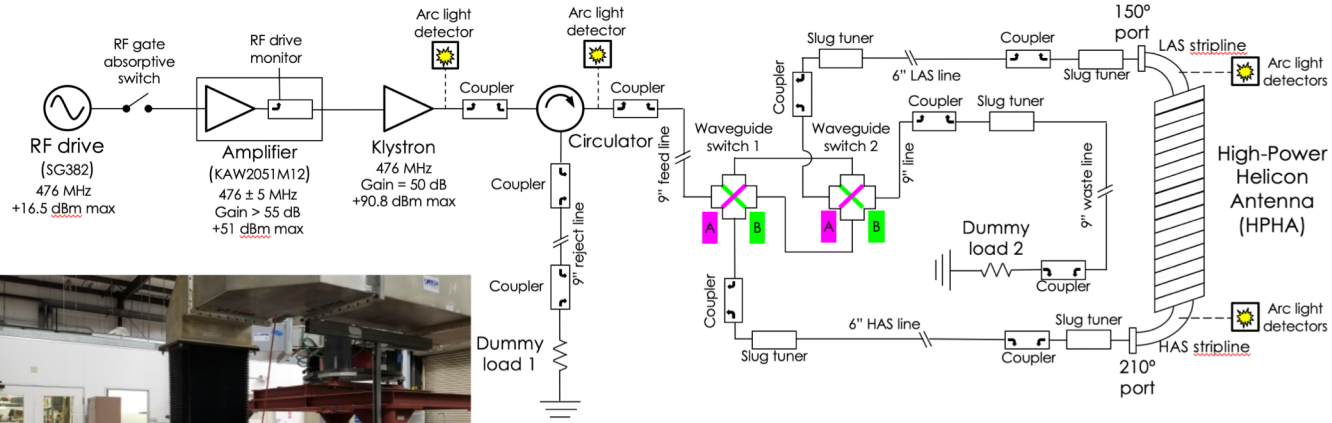
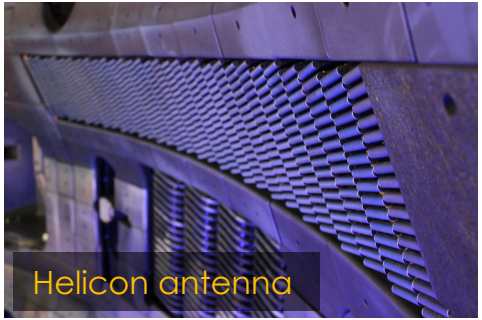
Transmission line network enables powering either end of antenna, or dummy load

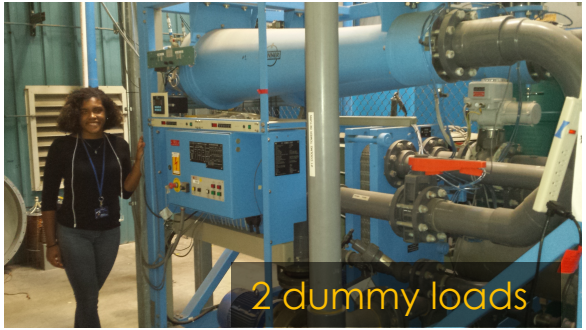
- Repurposed 9" and 6" coaxial line
- Repurposed coaxial dummy load

- New 4-port waveguide switch
- Waveguide circulator from SLAC




Helicon antenna


Klystron and circulator above it


2 dummy loads


4-port waveguide switch (MEGA)

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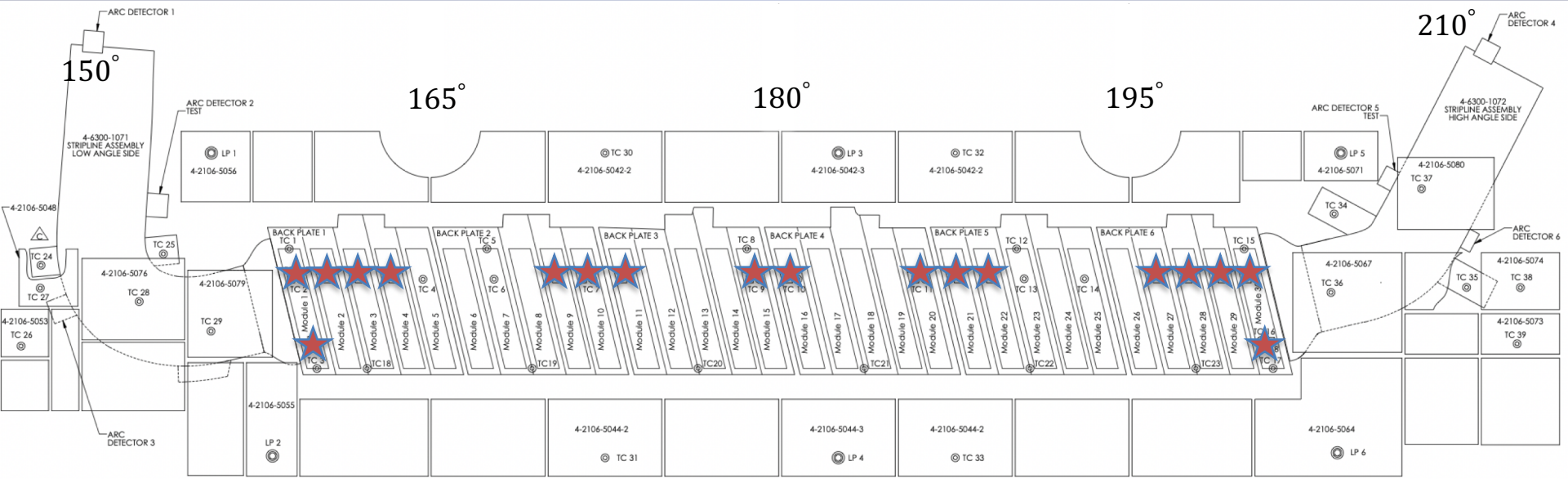
Installed diagnostics



★18 RF pick-up loops

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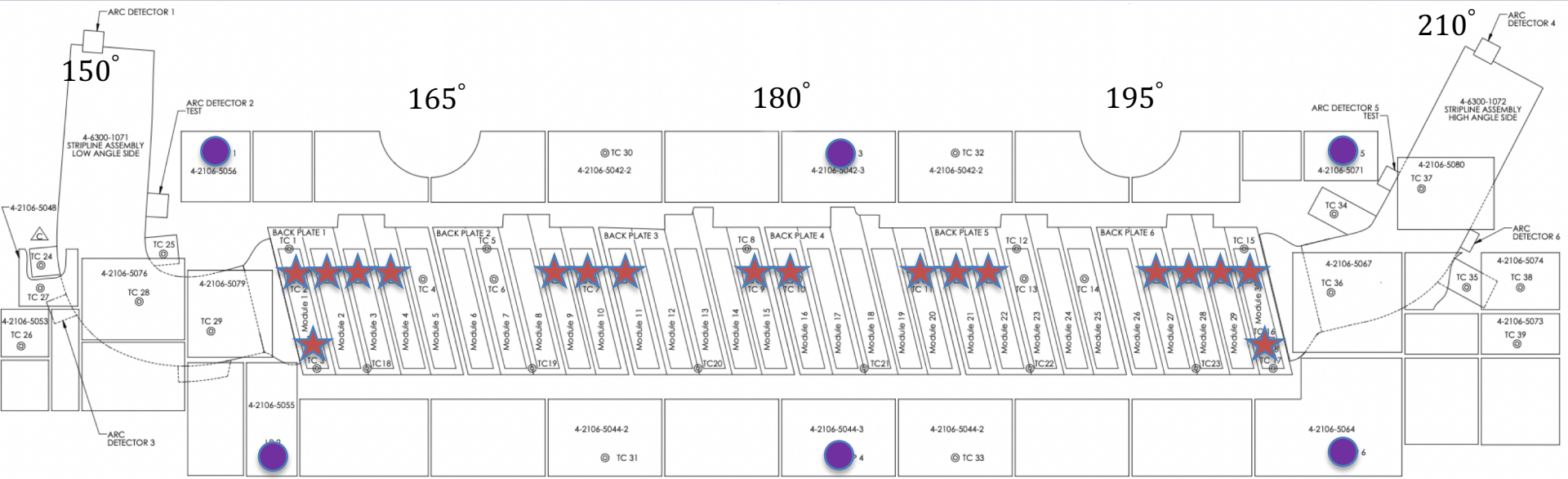
Installed diagnostics



★18 RF pick-up loops ● 6 Langmuir probes

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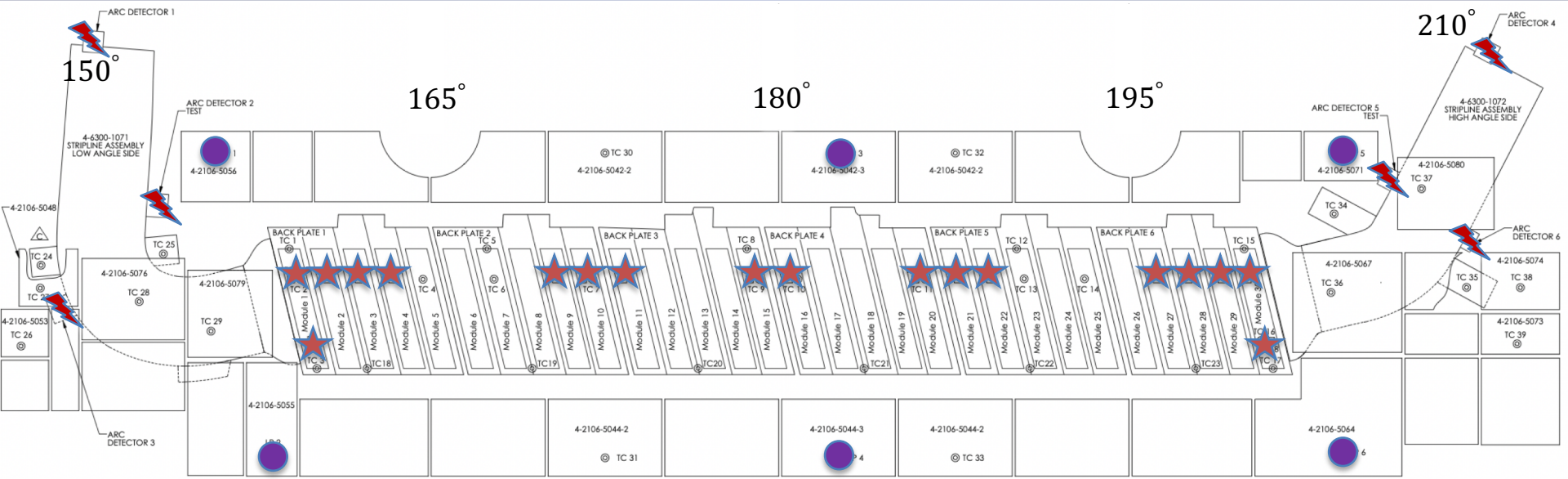
Installed diagnostics



18 RF pick-up loops 6 Langmuir probes 6 optical arc detectors

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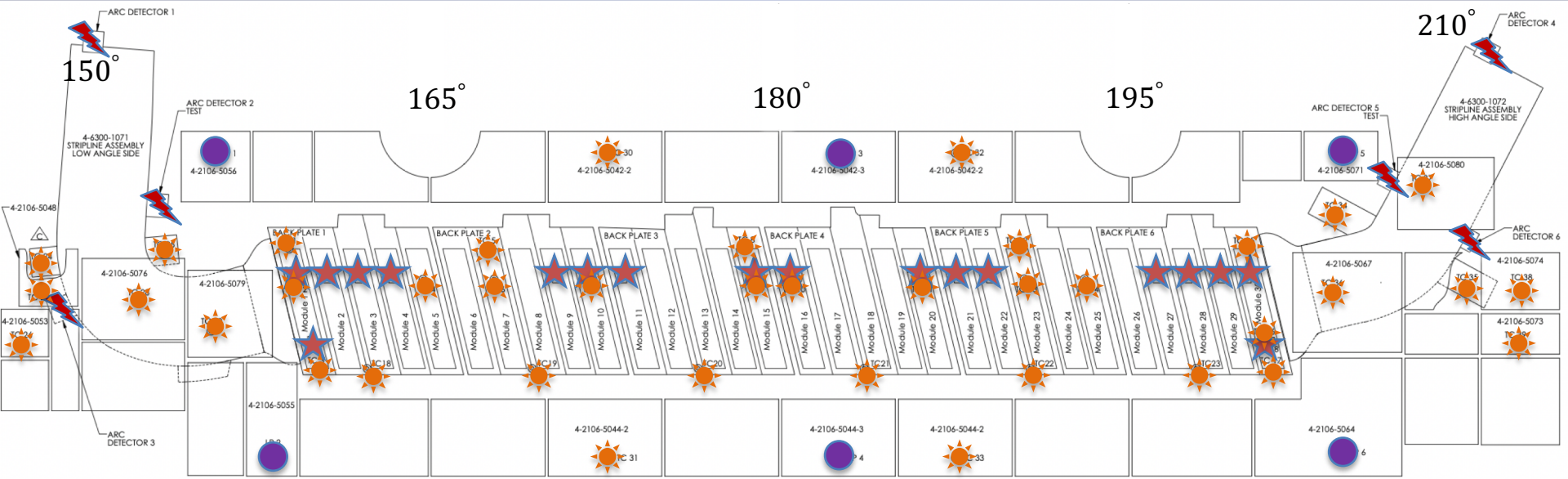

18 RF pick-up loops

6 Langmuir probes

6 optical arc detectors

39 thermocouples

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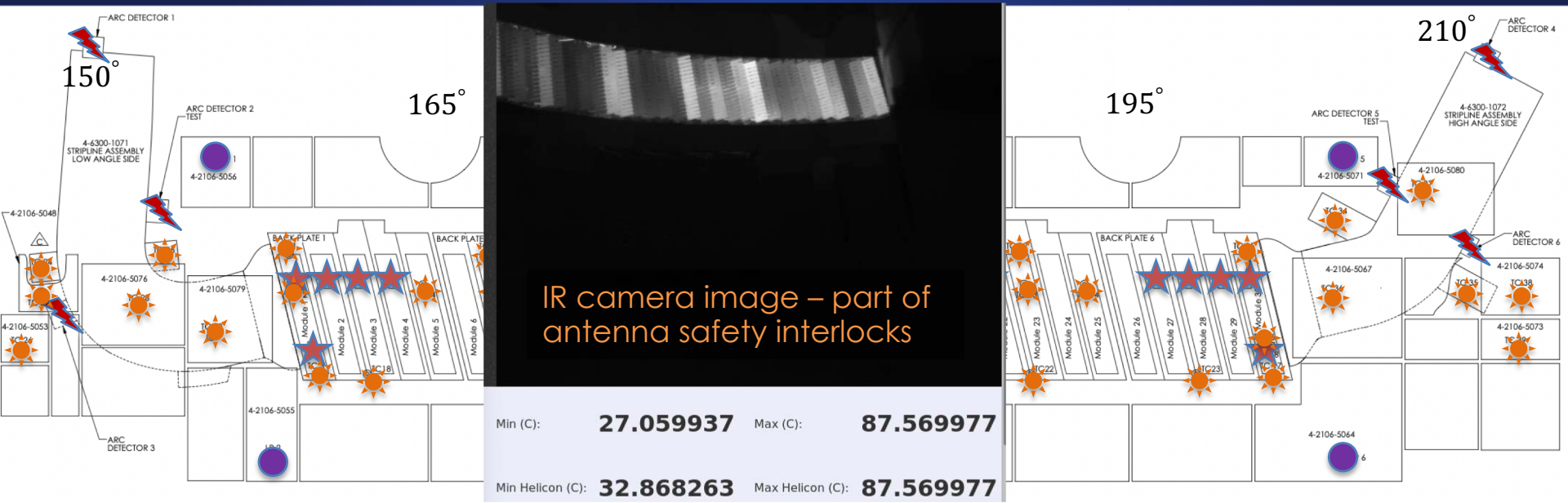

18 RF pick-up loops

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39 thermocouples

1 IR camera

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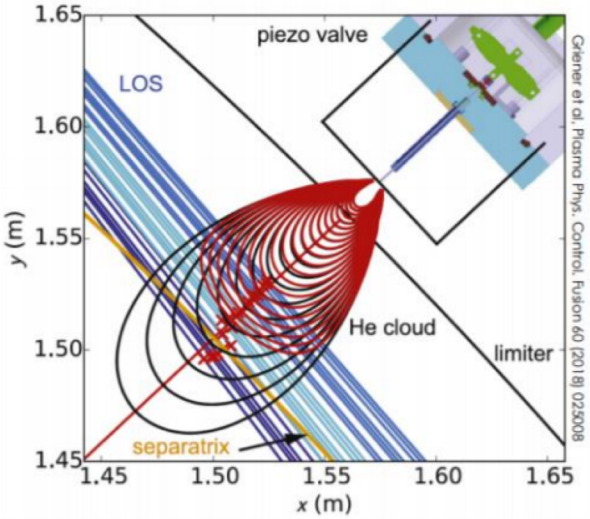
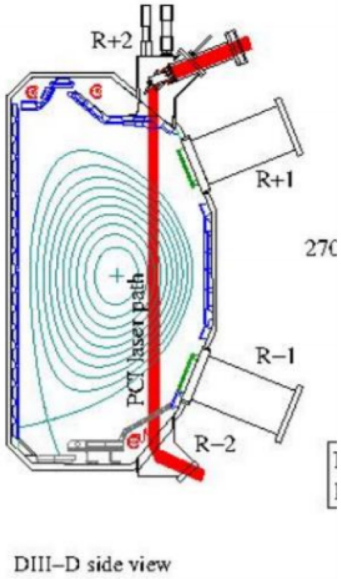
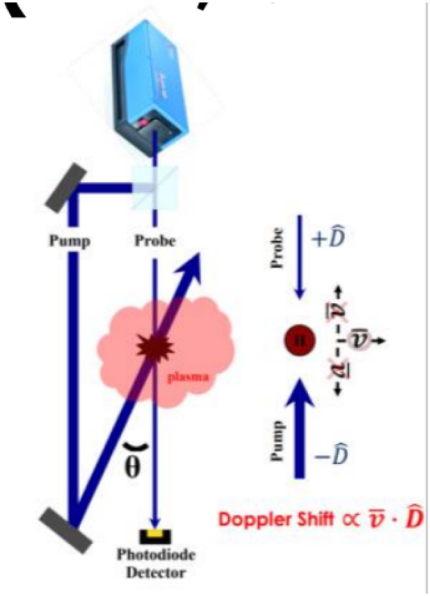
Planned additional diagnostics will enable detailed physics studies



Density profile measurement through **He-beam neutral emission line ratios**
E. Hinson, O. Schmitz (U. Wisconsin – Madison)



Far-field wave measurements - **Phase Contrast Imaging (PCI)** – A. Marinoni, C. Rost, M. Porkolab (MIT)

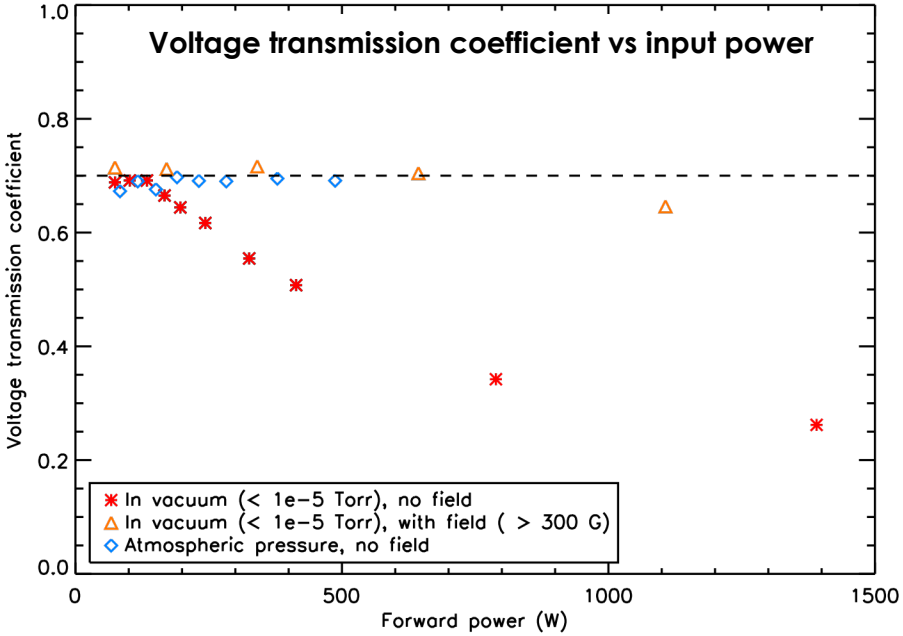


Near-field wave electric field measurements – **Doppler Free Saturation Spectroscopy**
E. H. Martin - ORNL

Outline

- Traveling wave antenna
  - Principles and design
  - Testing, installation and results
- RF source and transmission line network
- Installed and upcoming diagnostics
- **Current status and near-term plans**

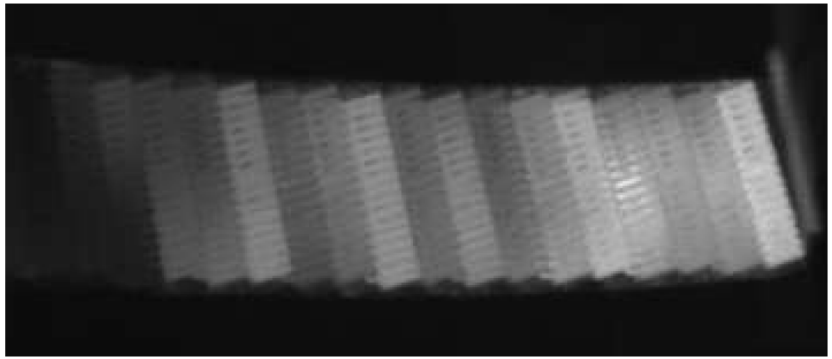
Moderate power tests in vacuum show onset of multipactoring



- Power scan shows nonlinearity starting at ~150 W input power in vacuum, i.e., power is not flowing through array as in linear regime → drop in transmission coefficient
- No such nonlinearity observed at atmospheric pressure
- Attributed to the onset of multipactoring in antenna

- Later tests with magnetic field show that fields greater than 200G greatly improve on multipactoring in modules

Conditioning at 5kW shows improved RF power flow through array

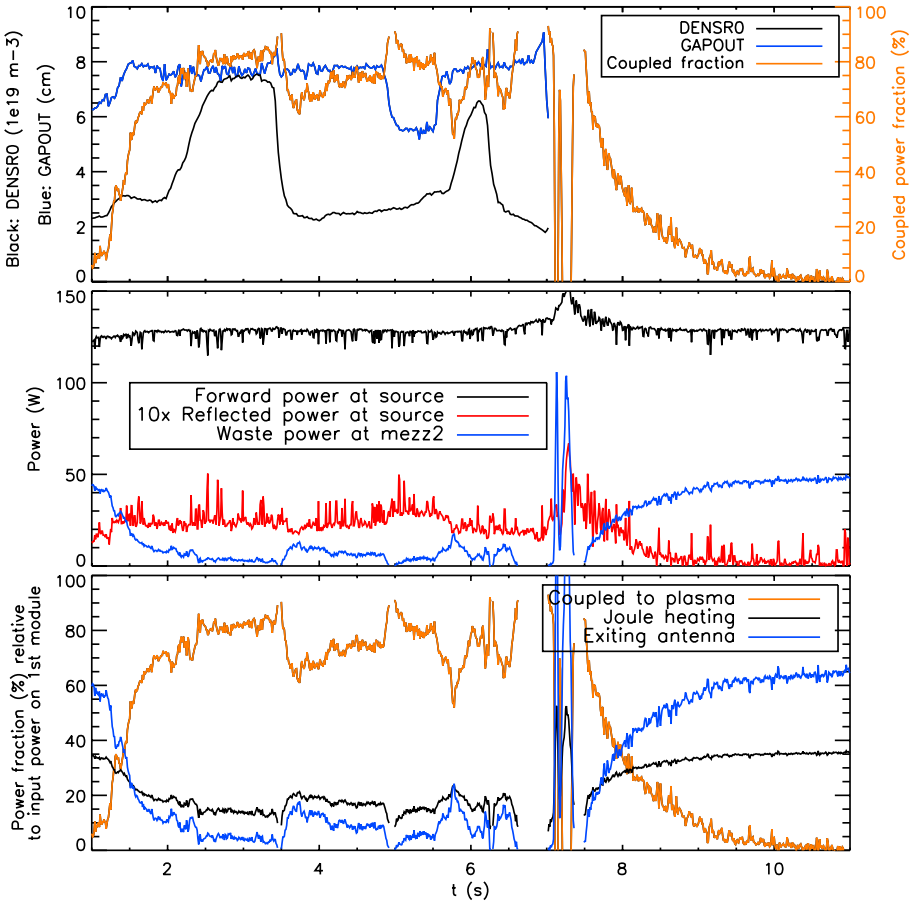


- System tests were performed with 5kW source, while klystron commissioning was in progress
- Various diagnostics checked out and verified/calibrated at up to 5kW
- At 5kW of input power, IR camera images show power initially stopped at first module.
- Power spreads out further down array as modules condition

Preliminary tests into plasma show strong coupling of RF power to the plasma

- **Strong RF power coupling to plasma, >80%** of power incident on first module
- Reflected power less than ~4%, **resilient** to LH/HL transitions and variations in proximity of plasma
- Coupled power responds both to density changes during LH/HL transitions, and to changes in GAPOUT

- Results consistent with previous results with low-power prototype antenna
  R.I. PINSKER et al, Nucl. Fus. 58 (2018) 106007



Current status and near-term plans

- Klystron conditioned up to **1MW RF output** – as of Dec 2020
- **Antenna conditioning** with klystron started early 2021
- **First planned high-power plasma experiments** (May - June 2021):
  - Coupling studies at high power under various plasma conditions
  - Core H&CD in L-mode plasmas
  - Off-axis H&CD in H-mode plasmas

- **Simulation efforts** ongoing – AORSA (C. Lau - ORNL), VPic (A. Pankin, D. Smithe - Tech-X), COMSOL (C. Lau - ORNL, GA group) and Petra-M (E.H. Kim, S. Shiraiwa – PPPL, GA group)

Conclusions

- **DIII-D helicon system completed**
- **Novel comb-line traveling wave antenna behaves as expected**
  - Low reflected power across 10 MHz band
  - Good directionality
  - No evidence of standing modes in array
- **Initial antenna tests at moderate power encouraging**
- **MW klystron conditioned, antenna conditioning started**
- **First high-power experiments coming soon**