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

B. Van Compernolle
on behalf of
M. W. Brookman¹, C. P. Moeller¹, R. I. Pinsker¹, A. M. Garofalo¹, R. O’Neill¹, D. Geng¹, A. Nagy², J. P. Squire¹, K. Schultz¹, C. Pawley¹, D. Ponce¹, A. C. Torrezan¹, J. Lohr¹, B. Coriton¹, E. Hinson³, R. Kalling⁴, A. Marinoni⁵, E. H. Martin⁶, R. Nguyen¹, C.C. Petty¹, M. Porkolab⁵, T. Raines², J. Ren⁷, C. Rost⁵, O. Schmitz³, H. Torreblanca⁸, H. Q. Wang¹, J. Watkins⁹, K. Zeller¹

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

• How much power is absorbed
  • Mechanism: Landau damping
    \[ \text{Im}(k) = \frac{\sqrt{\pi}}{4} \beta \xi e^{-\xi^2} k G(\omega) \text{ with } \xi = \frac{\nu}{v_{te}} \]
  
• How much current is driven with the absorbed power
  • Ehst-Karney efficiency\(^1\) (ratio current density to power density)
    \[ \eta = \frac{38.4 \times 10^{18} T_e(\text{keV})}{\ln \Lambda} \frac{1}{n_e(\text{m}^{-3})} \tilde{\eta} \text{ (see fig for } \tilde{\eta} \text{ )} \]

• Key parameter is ratio of electron velocity \(v_{te}\) to wave parallel phase velocity \(v_{ph\parallel} = \omega/k_\parallel\); \(n_\parallel = c k_\parallel/\omega\)

• Competing effects:
  • High \(\frac{v_\parallel}{v_{te}}\): good CD efficiency, bad absorption
  • Higher density increases absorption, but lowers CD efficiency

\(^1\)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\textsuperscript{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 $\rho \approx 0.6$ in high-beta plasmas (off-axis H&CD)
  - Expect $>100$kA/MW in L-mode plasmas (core H&CD)

\textsuperscript{1}R. Prater et al, Nucl. Fusion 54 (2014) 083024
• **Requirements:**
  - HHFW in lower hybrid frequency range: 476 MHz chosen, determined by availability of B-Factory Klystron (BFK) from SLAC
  - Launch at $n_{\|} = 3$, 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**
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**
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 $\pm 0.5$ MHz
- **Narrow $n_{||}$ spectrum**

J. Tooker et al, Fusion Engineering and Design 123, 228 (2017)
• 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 $P_{in} - T - R$
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 $P_{in} - T - R$

In air/vacuum, $T < 1$ due to resistive losses in modules

Antenna array, resistive losses in array

Reflected power → Plasma loading → Transmitted power goes to dummy load

Input power
• 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 $P_{in} - T - R$
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 $P_{in} - T - R$.
- 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 $n_{||}$ (=3.0).
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 \( P_{in} - T - R \).
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).
End module cutaway


- 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 $0\pi 0\pi$ 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 $0\pi 0\pi$ 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
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
- LAPD experiment
Modules built half by GA, half by ASIPP and tested/tuned individually

- 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

10 modules on mock-up wall fed by one stripline

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

Initially, substantial reflections found
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
• **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**
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
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
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

• LAPD experiment
Installed diagnostics

18 RF pick-up loops
Installed diagnostics

- 18 RF pick-up loops
- 6 Langmuir probes
Installed diagnostics

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

- 18 RF pick-up loops
- 6 Langmuir probes
- 6 optical arc detectors
- 39 thermocouples
Installed diagnostics

- 18 RF pick-up loops
- 6 Langmuir probes
- 39 thermocouples
- 1 IR camera
- 6 optical arc detectors

IR camera image – part of antenna safety interlocks
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**

• **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