Setup and first operation of the Wendelstein 7-X ICRH matching system

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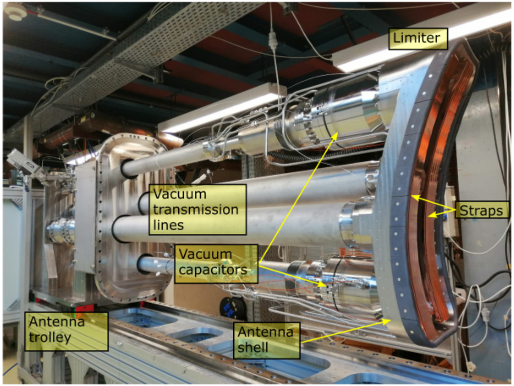
W7-X ICRH system overview

- An **ICRH system** for W7-X[a,b] was assembled and operated as of OP 2.1
- Designed and constructed in collaboration between
  - LPP-ERM/KMS (Belgium)
  - Research Center Jülich (Germany)
  - IPP Greifswald (Germany)
- Frequency range 25 — 38 MHz:
  - 37.5 MHz $\rightarrow$ (H)^{4}He minority heating
  - 25.0 MHz $\rightarrow$ (^{3}He)H minority heating
- Available RF power $\sim$ 1 MW per generator

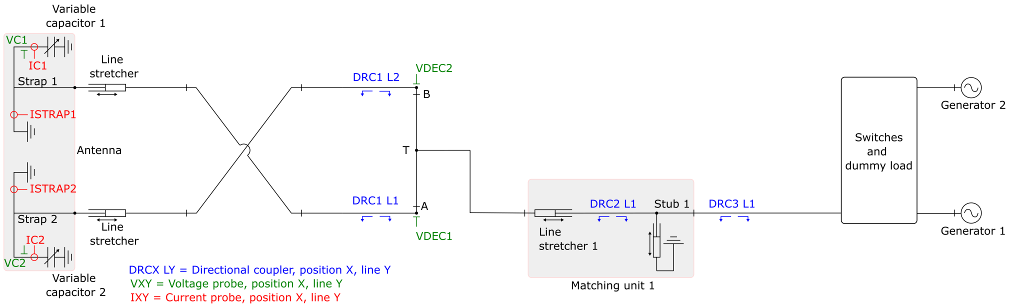
[a] J. Ongena *et al*. AIP Conf. Proc. **2984**, 040003 (2023)
[b] D. A. Castaño-Bardawil *et al*. Fusion Eng. Des. **166** (2021) 112205

- **Main components:** Antenna, transmission lines, matching system, RF generators



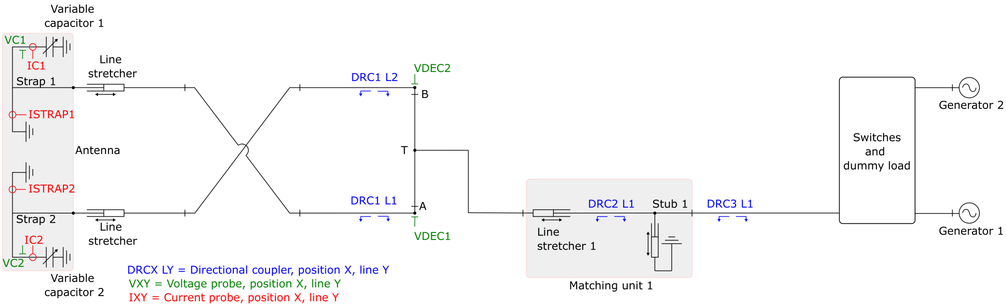
(Image courtesy of D. Castaño-Bardawil)

ICRH system layout (one generator)



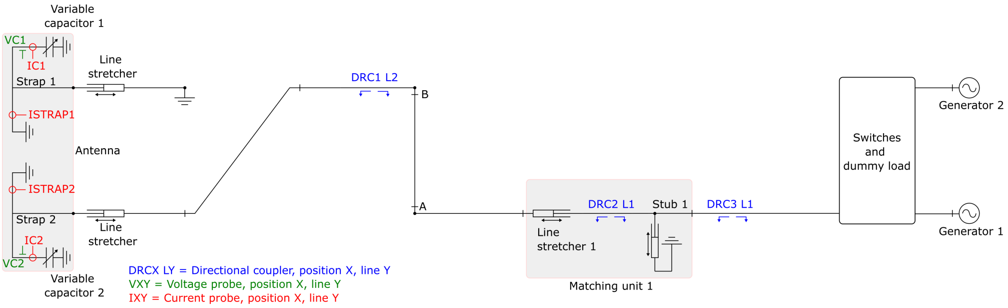
- **One generator, two straps** $\rightarrow$ $(0, \pi)$ or $(0, 0)$ phasing, at 25.0/37.5 MHz (advanced phasing modes later...)
- **Tuning capacitors** allow current distribution control ($\rightarrow$ antenna spectrum) and **pre-matching**
- **Matching system** compensates antenna/generator impedance mismatch
  - Line stretcher + shorted stub (trombones, Dielectric 9” 3/16 EIA transmission lines)
- Configuration being commissioned for OP 2.2

ICRH system layout (one generator)



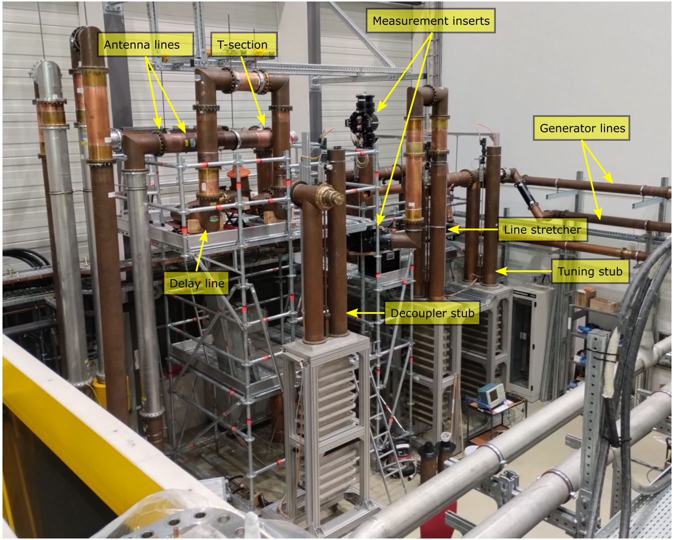
- **Complex system** → requires detailed diagnostics:
  - DRC1: antenna input power and reflection coefficients → antenna tuning and pre-matching control
  - DRC3: generator line power and reflection coefficients → matching control
  - DRC2: Backup of DRC3 → matching control
  - Antenna voltage and current probes → current distribution and spectrum

ICRH system layout (OP 2.1)



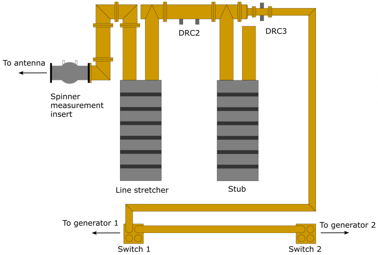
- Tests in vacuum with $P_{FWD} \sim 0.01 - 10$ kW revealed unstable behavior on line 1, power-dependent matching $\rightarrow$ problem traced to broken capacitor on strap 2
- Therefore: **one generator, strap 2 only** at 37.5 MHz
- Strap 1 shorted and both capacitors at maximum separation to minimize risk of discharge
- (Capacitor 1 eventually failed high voltage test)

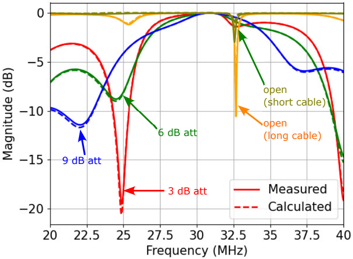
ICRH system layout

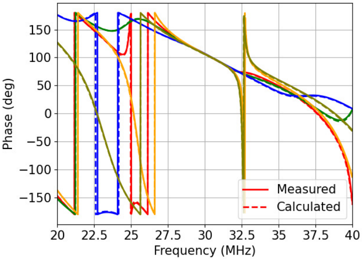


Matching system modeling

- RF measurements of individual components allow to build **numerical model of the matching system**
- **Aim 1:** de-embed measurement section matrices to calibrate directional couplers
- **Aim 2:** compute matching solutions during antenna operation
- Model successfully validated by one-port and two-port measurements

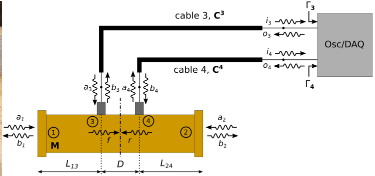


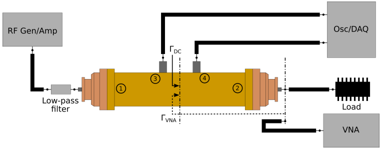


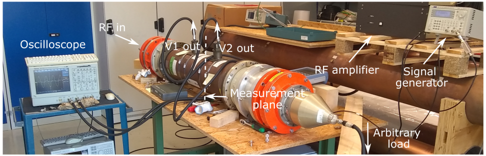


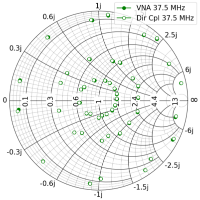
Directional couplers on test stand

- Directional couplers: **main diagnostic** $\rightarrow \Gamma = V_{rfl}/V_{fwd}$, power, $|V|$ and $|I|$ on transmission line
- Calibration matrix obtained from 4-port measurement and used to measure various test loads





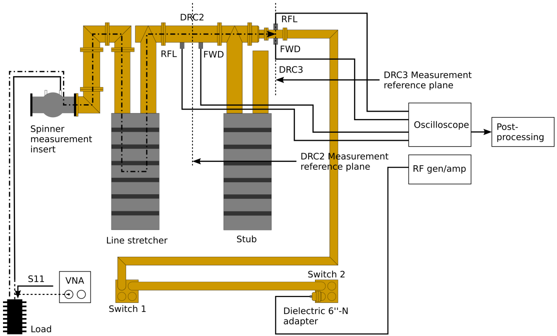




- Good results achieved independent of $|\Gamma|$: average errors in magnitude and phase $\lesssim 1.0\%$

Directional couplers *in situ*

- DRC sections tested again after integration into matching system



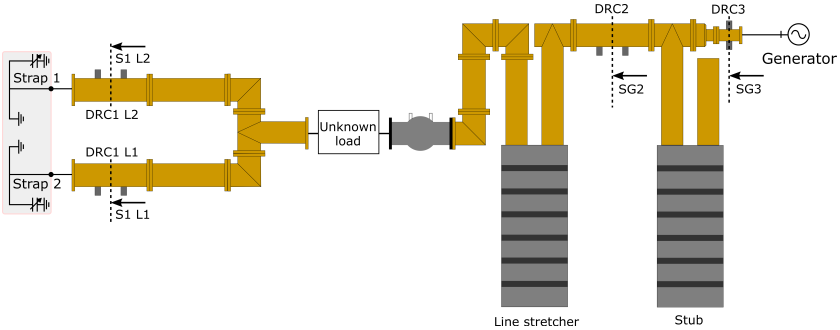
- Using the test stand calibration matrices results in degraded accuracy:

Section	$\Delta(\|\Gamma\|)$	$\Delta(\Phi(\Gamma))$
DRC2 stand	$0.4 - 0.5\%$	$0.5^\circ - 0.7^\circ$
DRC2 *in situ*	$2.2 - 2.4\%$	$4.7^\circ - 6.5^\circ$

- Reason: misalignment of central conductor after integration (± 1 mm shift $\rightarrow$ ± 0.5 dB in coupling)
- Conclusion: do calibration *in situ*
- Measurement section matrices de-embedded using the **model** $\rightarrow$ accuracy improved

Section	$\Delta(\|\Gamma\|)$	$\Delta(\Phi(\Gamma))$
DRC2 *in situ*	$1.1 - 1.8\%$	$3.4^\circ - 5.5^\circ$

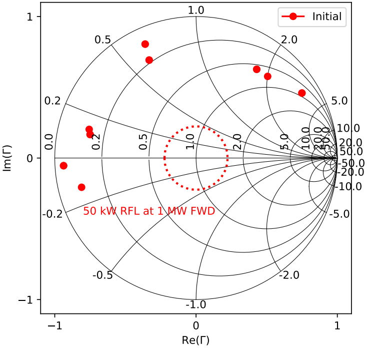
Matching procedure

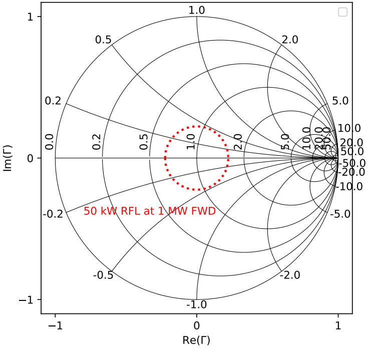


- No feedback operation possible (arcing danger) $\rightarrow$ **feed-forward procedure:**
  1. RF pulse to measure S_{G2}/S_{G3} at DRC2/DRC3 $\rightarrow$ determine load by de-embedding (for OP 2.2 reconstruction available from DRC1 as well)
  2. Vary line stretcher and stub lengths until predicted $|S_{G3}| < \epsilon_{tol}$ **(Bang-Bang algorithm)**, set trombones to resulting positions
  3. RF pulse to confirm S_{G3} at DRC3, repeat if necessary

Matching system tests

- **Procedure tested** on a variety of artificial loads + antenna in vacuum vessel





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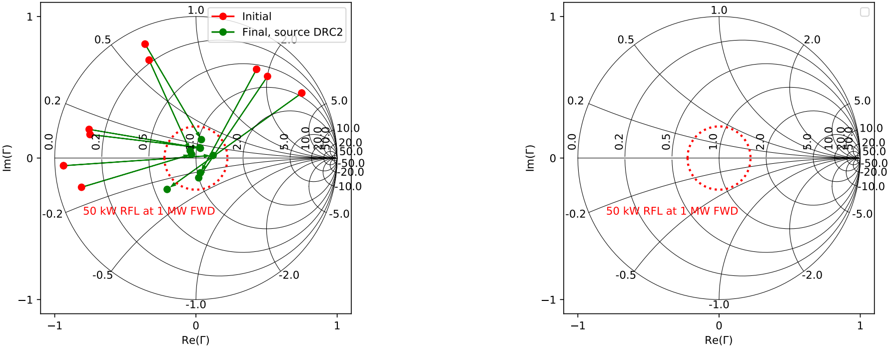

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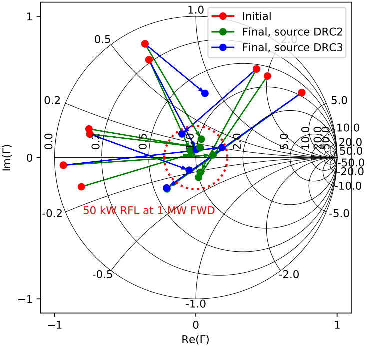

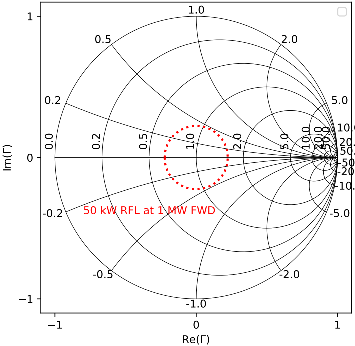

- For high |Γ| cases, **accuracy seems to depend on starting positions** → hypothesis: mismatched line stretcher

Matching system tests

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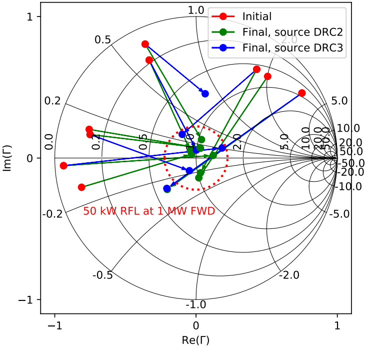
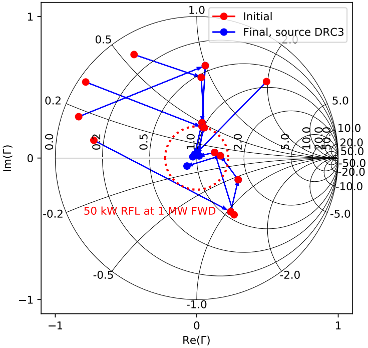
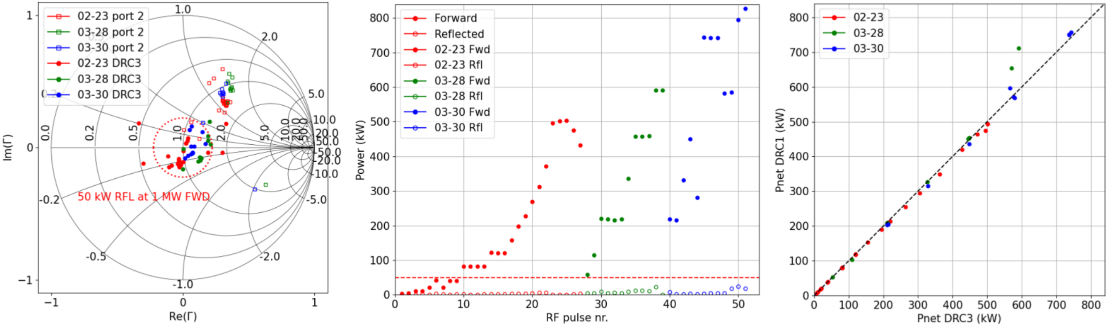




- For high $|\Gamma|$ cases, **accuracy seems to depend on starting positions** $\rightarrow$ hypothesis: mismatched line stretcher
- Antenna in VV also tested, multistep matching possible if first iteration not successful

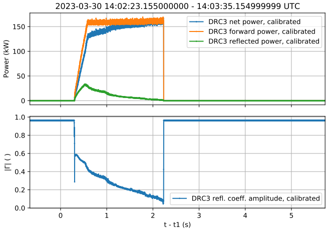
Operation on stable plasma

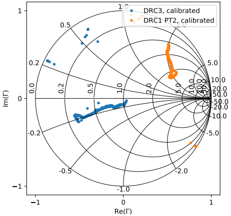


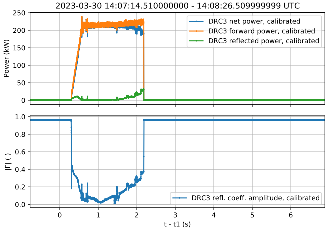
- **Successful matching** in all pulses: $P_{RFL} < 50$ kW
- However: rather high strap loading, $R_L \sim 10 - 20\ \Omega \rightarrow$ not very difficult to match (pre-matching?)
- $\Phi(\Gamma) \sim 40^\circ - 50^\circ$ on port 2 $\rightarrow$ capacitor fixed, voltage antinode shifted away from port (suboptimal)
- Excellent agreement between DRC1 and DRC3 diagnostics

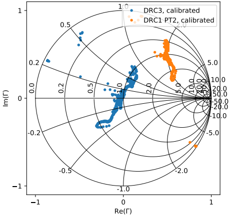
Operation during plasma startup experiments

- **Loading changes significantly** → compute solution for selected time window, iterate

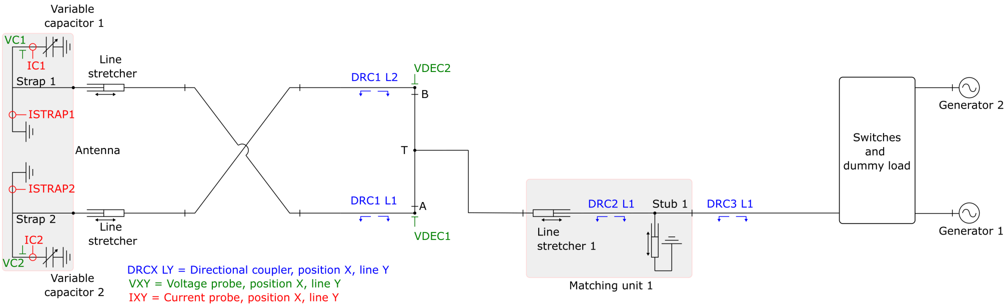








System upgrades for OP 2.2



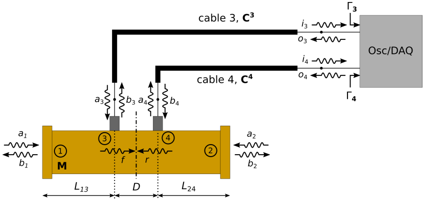
- DRC1-L1, DRC2 integrated into DAQ and tested
- Matching solutions available from DRC1, DRC2, DRC3 (selected by user)
- Capacitor voltage probes and strap current probes calibrated *in situ*, integrated into DAQ and tested
- Available **phase measurements**: strap-to-strap, capacitor-to-capacitor and strap-to-capacitor
- **Capacitor tuning procedure** demonstrated

Auxiliary slides

Directional couplers on test stand

- Directional couplers: main diagnostic $\rightarrow \Gamma = V_{rfl}/V_{fwd}$, P_{fwd}, P_{rfl}, P_{net}, $|V|$ and $|I|$ on transmission line

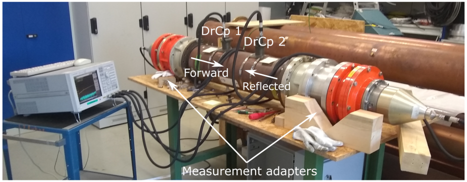
- Calibration matrix **C** obtained from the de-embedded 4-port measurement section:

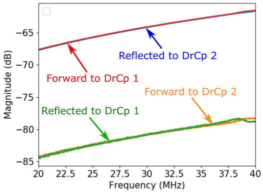


- **C** includes cables, filters, DAQ/DSO input matching

$$\begin{bmatrix} f \\ r \end{bmatrix} = \mathbf{C} \begin{bmatrix} i_3 \\ i_4 \end{bmatrix}$$

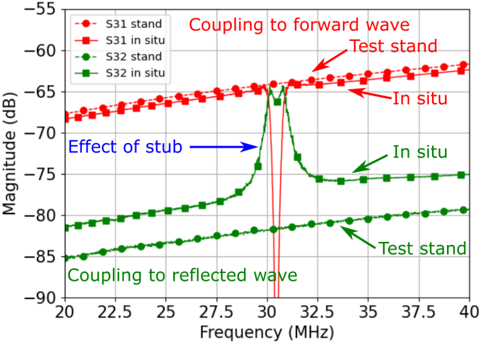
- On some measurement sections, directional couplers intentionally detuned to have the opposite coupling signal above NA noise floor





Directional couplers *In situ*, pt. 2

- Change in sensor coupling clearly seen in the de-embedded matrices



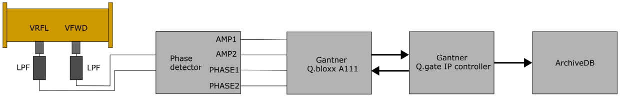
- **After recalibration, DRC2 and DRC3 performance improved** (but did not reach test stand accuracy)

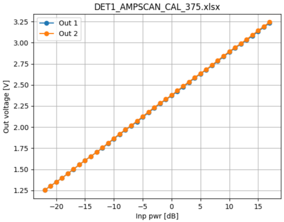
Section	Cal. data	$\Delta(\|\Gamma\|)$	$\Delta(\Phi(\Gamma))$
DRC2	From test stand	2.2 — 2.4%	4.7° — 6.5°
DRC2	From *in situ*	1.1 — 1.8%	3.4° — 5.5°
DRC3	From test stand	1.1%	1.6° — 2.7°
DRC3	From *in situ*	0.7 — 1.5%	0.7° — 1.6°

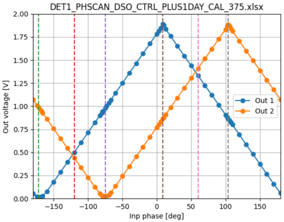
- DRC1-L1 and L2 also calibrated *in situ*
- DAQ chain also calibrated (demodulators, phase detectors, etc)

DAQ chain calibration

- AC signals from directional couplers feed into **analog demodulators and phase detectors**
- DC output of the detectors is digitized by **Gantner Q.bloxx A111** measurement modules, and sent via Ethernet to ArchiveDB through Gantner Q.Gate IP Controller modules
- DRC1/2/3 use custom-built phase detectors provided by IPP Garching (dynamic range -40 to +23 dBm)



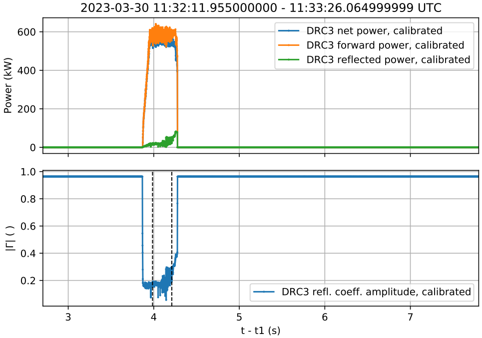


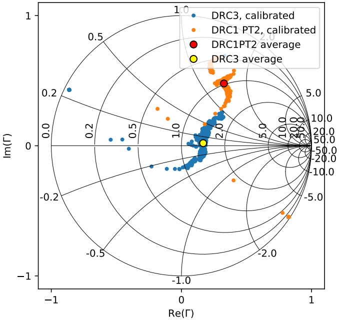


- DRC0: log demodulator built by M. Vervier (LPP-ERM/KMS), no phase detection

ICRH matching calculator

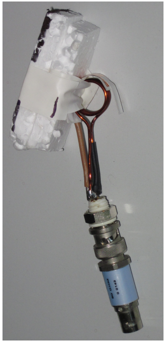
- **Custom software** provides info on ICRH system, compute and visualize matching solutions
- Written in Python, uses PyQt5 for the GUI
- Allows the user to:
  - Read raw data from ArchiveDB → apply calibration → compute physically meaningful data
  - Compute derived data (loading resistance, voltage distribution…)
  - Compute matching solutions for a selected time window
- **Routinely used during OP 2.1** (single strap), now upgraded for two-strap operation

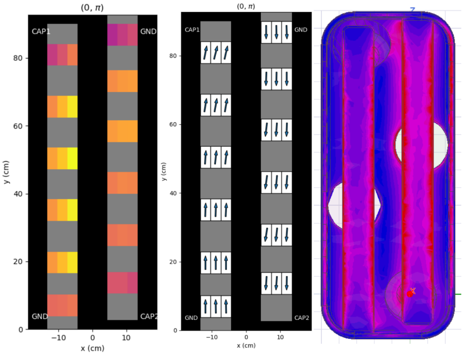




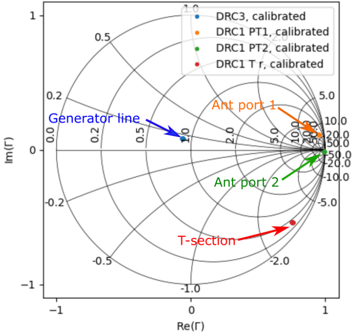
System upgrades for OP 2.2

- **Antenna tuning:** voltage max on antenna ports $\rightarrow$ strap currents "poloidally uniform" $\rightarrow$ minimize k_y
- Before antenna in VV: direct measurement of strap current with B-field probe (but no access to port Γ's)
- After antenna in VV: measurement of port Γ's under power using DRC1 (but no current measurements yet)


B-field probe



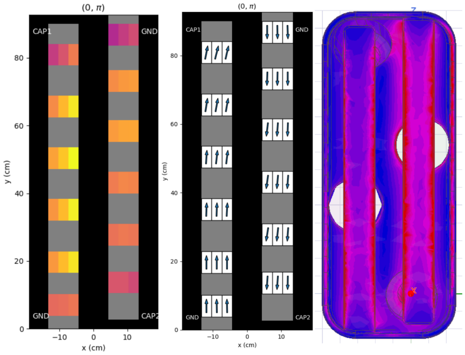
25 MHz (0, π) direct measurement



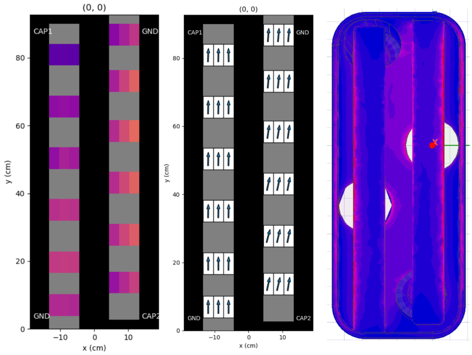
25 MHz (0, π) via DRC1

System upgrades for OP 2.2

- **Antenna tuning:** voltage antinode on feeding ports $\rightarrow$ strap currents "poloidally uniform"
- Before antenna in VV: direct measurement of strap current with B-field probe (but no access to port Γ's)



25 MHz (0, π)



25 MHz (0, 0)

System upgrades for OP 2.2

- **Antenna tuning:** voltage antinode on feeding ports $\rightarrow$ strap currents "poloidally uniform"
- After antenna in VV: measurement of port Γ's under power using DRC1 (but no current measurements yet)