Correction of 1/1 and 2/2 error field in Wendelstein 7-X via divertor heat load symmetrization

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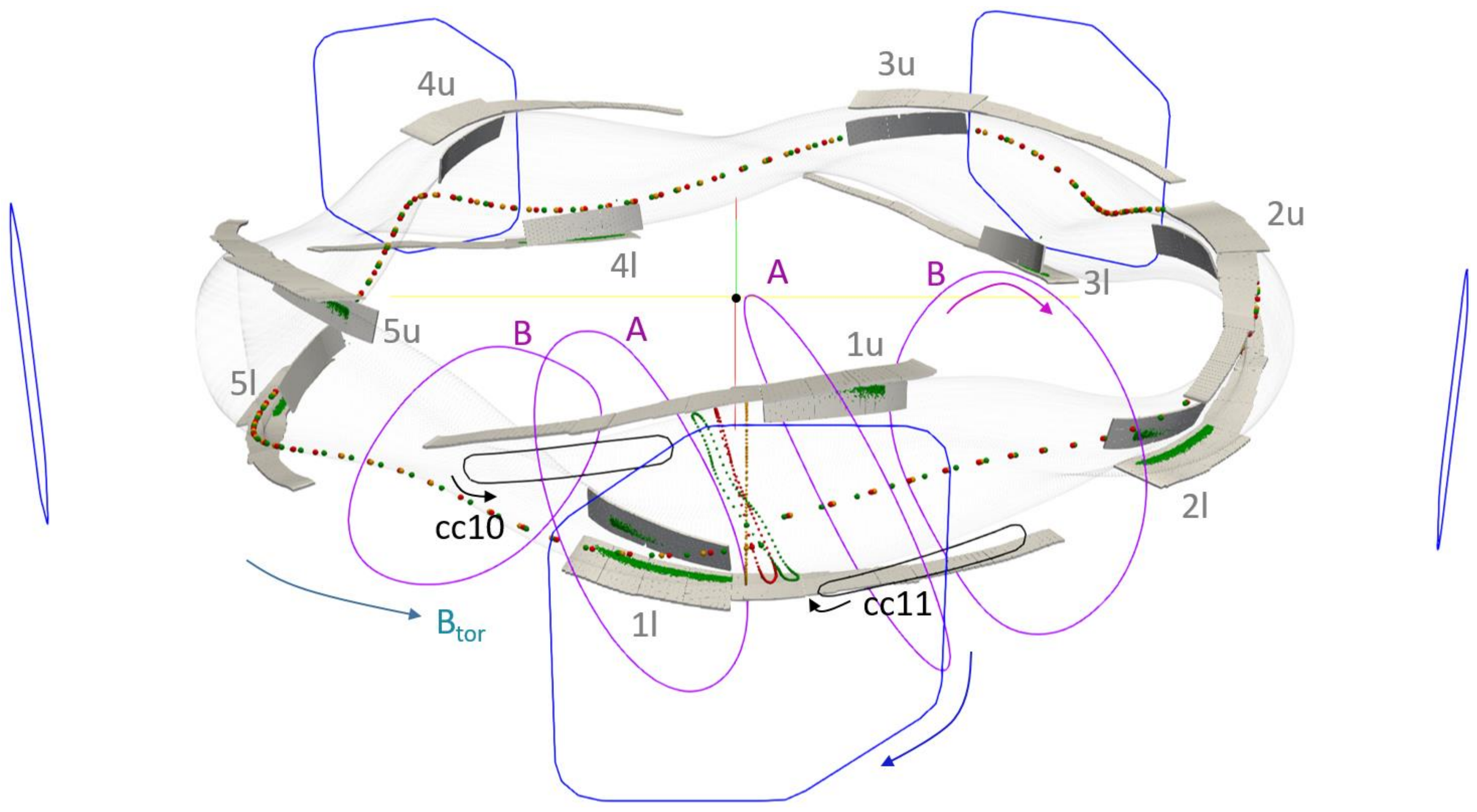
ABSTRACT

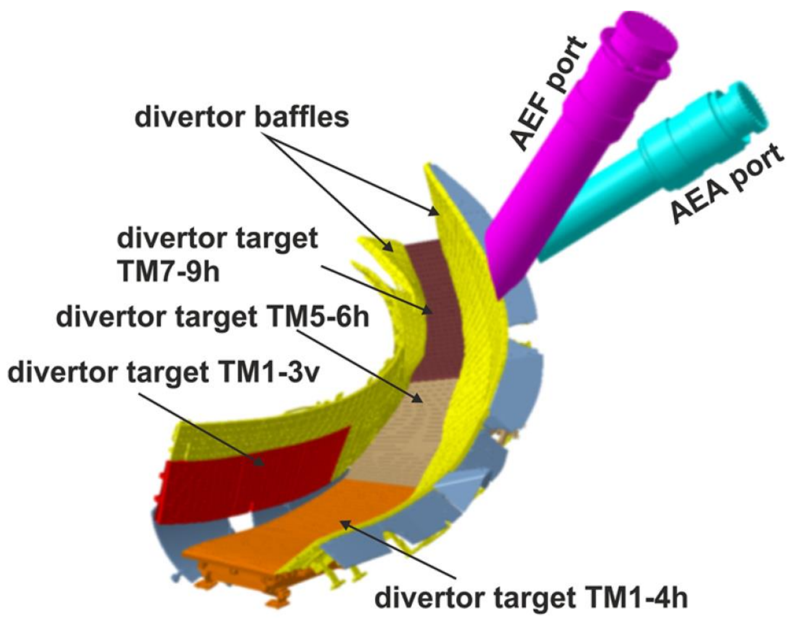
- Correction of the b_{11} error field in W7-X was achieved seven years ago using trim coils, supported by thermocouple measurements and flux surface mapping [1,2].
- With the installation of the new water-cooled divertor, an upgraded infrared diagnostic system [3,4], and the DELVER heat flux calculation code [5], error field correction has been revisited using divertor heat load symmetrization.
- For the first time, correction of the b_{22} error field is achieved through a phase-scan experiment of control coil currents, guided and validated from simulations.

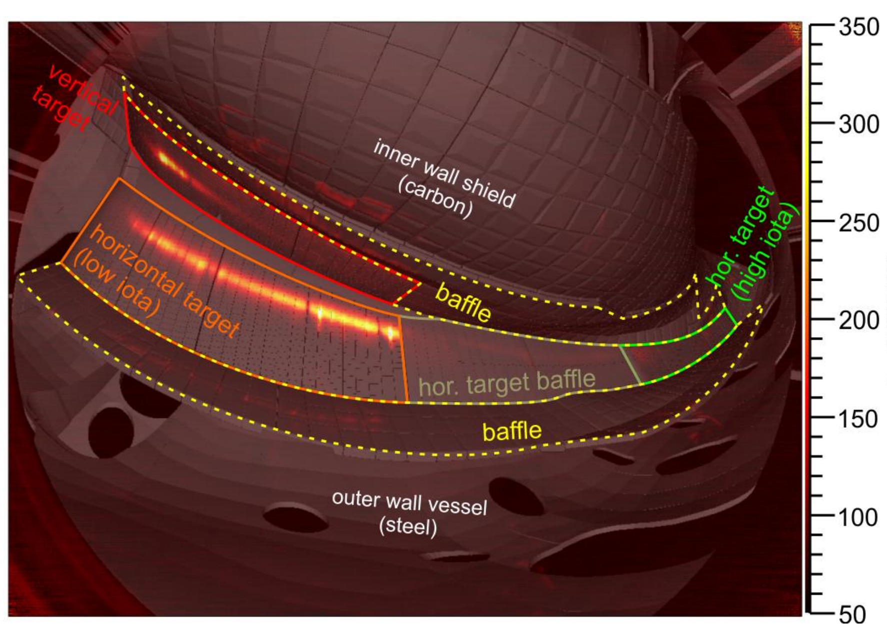
ERROR FIELD AND TARGET HEAT LOADS

- W7-X is designed with a five-fold toroidal modular and an up-down flip symmetry.
- Error field from finite imperfections in coil manufacturing, installation misalignments, electromagnetic deformations, and ferromagnetic materials, can break the symmetry of heat loads on the ten divertor units.
- Five trim coil and ten control coils can be used to correct b_{11} and b_{22} error fields, respectively.



- Water-cooled high heat flux divertor units have been in operation since 2023.
- Safe operation is ensured by real-time monitoring of all ten divertor units with wide-angle infrared thermography.
- Heat flux analysis is performed with DELVER (Divertor Energy Load Versatile Estimator), a 3D implicit anisotropic heat diffusion solver that accounts for multi-layer heat transport, water-cooling conditions, and surface layer effects.





COIL CURRENTS FOR ERROR FIELD CORRECTION

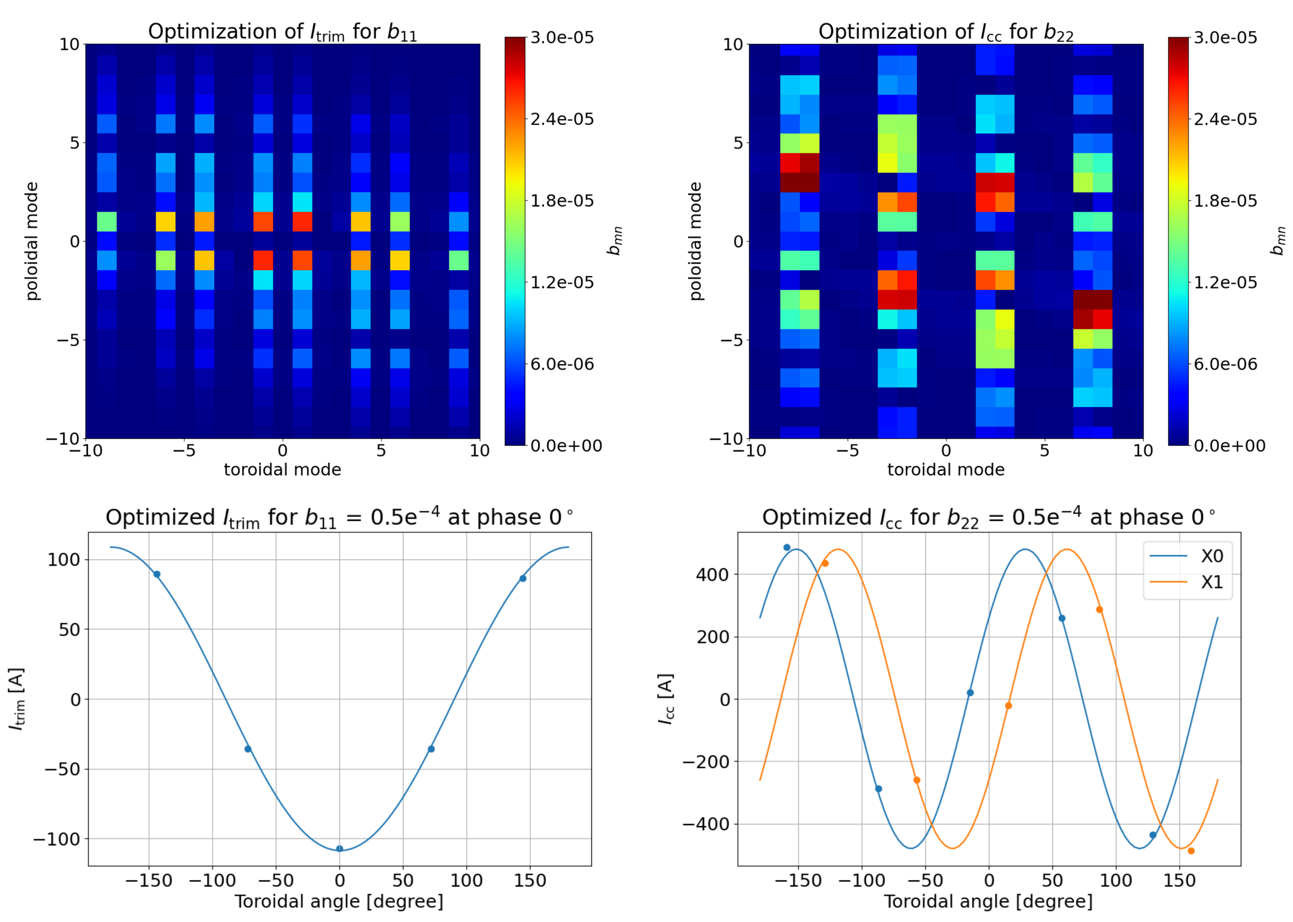
1) Constructing flux coordinates for the last closed flux surface (LCFS):

$$\sum_{mn}\{R_{mn}, z_{mn}\}e^{i(m\iota+sn)\varphi}, \ \varphi_g = \varphi + \sum_{mn}\varphi_{mn}e^{i(m\iota+sn)\varphi}$$

2) Calculating Fourier spectra for the perturbation fields produced by individual coils:

$$b_{mn} = \frac{1}{rR_0B_0}\cdot\left(\vec{B}_{pert}\cdot\left[\frac{\partial\vec{r}}{\partial\theta}\times\frac{\partial\vec{r}}{\partial\varphi}\right]\right)_{mn}$$

3) Employing an optimization algorithm to determine current combinations that achieve target modes while suppressing unwanted harmonics.



- Target mode:

  $b_{mn} = A\cdot e^{i\varphi_g}$

  $A = 0.5 \cdot 10^{-4}$

  $\varphi_g = 0^\circ$

- Sidebands exist, but not resonant with $\iota = 1$. Thus, minor effects on 5/5 islands.
- Optimal coil currents can be fitted by $cos\varphi$ for trim or $cos2\varphi$ for cc coils, with unique correlation to the b_{mn} phase.

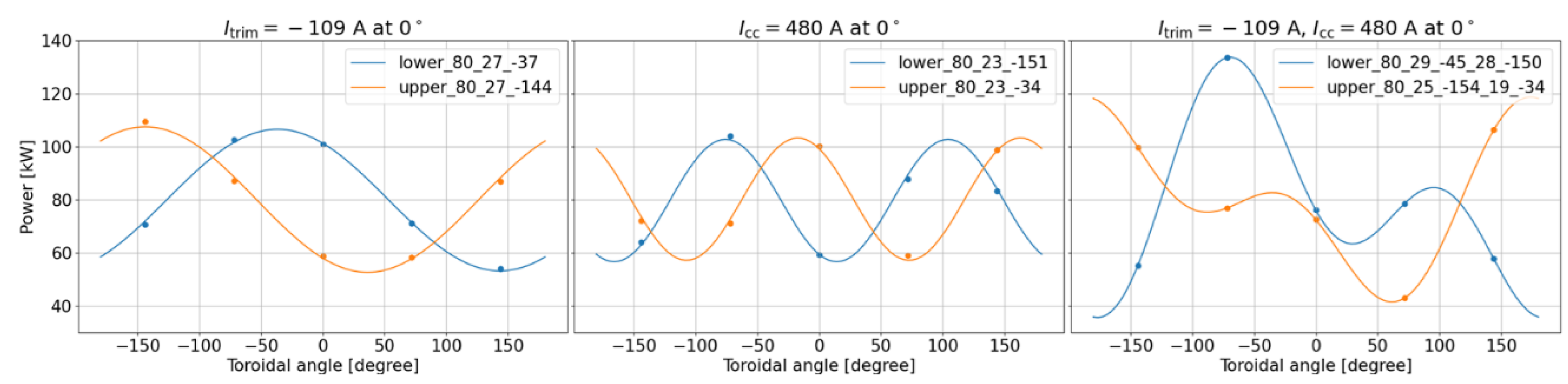
CONCLUSION AND REFERENCE

- Divertor heat loads from all ten divertor units are used for error field correction.
- Simulation establishes a direct link between coil current waveform and perturbation fields, guiding the design of phase-scan experiment.
- Divertor load distributions can be expressed as superpositions of cosine functions, reflecting combined effects of b_{11} and b_{22} fields.
- Experiments achieve the highest level of heat load symmetrization when both b_{11} and b_{22} error fields are corrected, with qualitative agreement from simulations.
- Results confirm earlier b_{11} correction [2] (seven years ago) despite different diagnostics and divertor components, and validate simulation predictions for the b_{22} field performed previously based on flux surface mapping results [1].
- Findings indicate long-term stability and mechanical integrity of the W7-X magnetic coil system.

[1] S. Bozhenkov *et al.* NF 60 026004 (2019)
[2] S.A. Lazerson *et al.* *PPCF* 60 124002 (2018)
[3] M. Jakubowski *et al.* *RSI* 89 10E116 (2018)
[4] J. Fellinger *et al.* *FED* 203 114413 (2024)
[5] S. Thiede Master's thesis, Uni. Greifswald (2023)
[6] Y. Feng *PPCF* 64 125012 (2022)

PERTURBATION FIELD EFFECT ON HEAT LOADS

- EMC3-Lite [6] is used with parallel electron heat conduction and perpendicular heat diffusion terms: $\nabla\cdot(-\kappa_e\nabla_\parallel T - \chi n\nabla_\perp T) = 0$, with Bohm sheath boundary condition.
- $T = T_i = T_e = 100$ eV, $n = n_i = n_e = 1\cdot10^{19}$ m^{-3}, $\chi = \chi_i + \chi_e = 1$ m^2/s, $P = 800$



- b_{11} perturbation leads to a target heat load waveforms in $a_0 + a_1cos\varphi$.
- b_{22} perturbation leads to a target heat load waveforms in $a_0 + a_2cos2\varphi$.
- Apply both $b_{11}$and b_{22}, the heat load waveforms are mostly superimposed.
- Fitting will fail with stronger $b_{mn} > 1\cdot10^{-4}$, or strongly reduced $\chi < 0.1$ m^2/s. Both increasing asymmetry level such that certain targets receiving almost no loads.

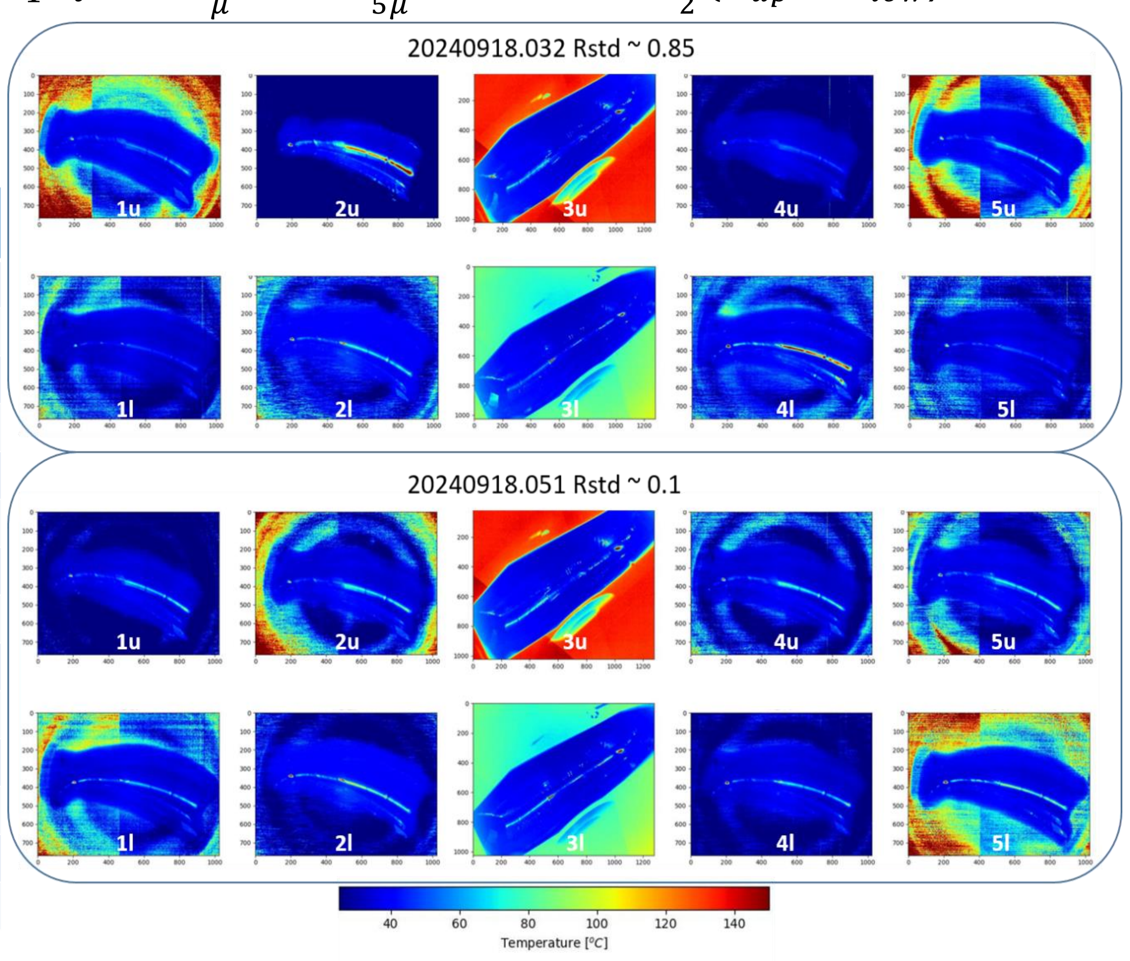
PHASE-SCAN EXPERIMENT

- Discharges all run with 1.8 MW heating power, and line-integrated electron density of $2\cdot10^{19}$ m^{-2}, with each probing a specific phase of perturbation field, while the amplitude for both b_{11} and b_{22} is fixed at $0.5\cdot10^{-4}$, from previous studies [1,2].
- Relative standard deviation (Rstd) of integral divertor is used to quantify the symmetry level: $\mu = \frac{1}{5}\sum_{t=1}^{5}P_t$, $R = \frac{\sigma}{\mu} = \frac{\sqrt{\sum_{t=1}^{5}(P_t-\mu)^2}}{5\mu}$, $Rstd = \frac{1}{2}(R_{up}+R_{low})$

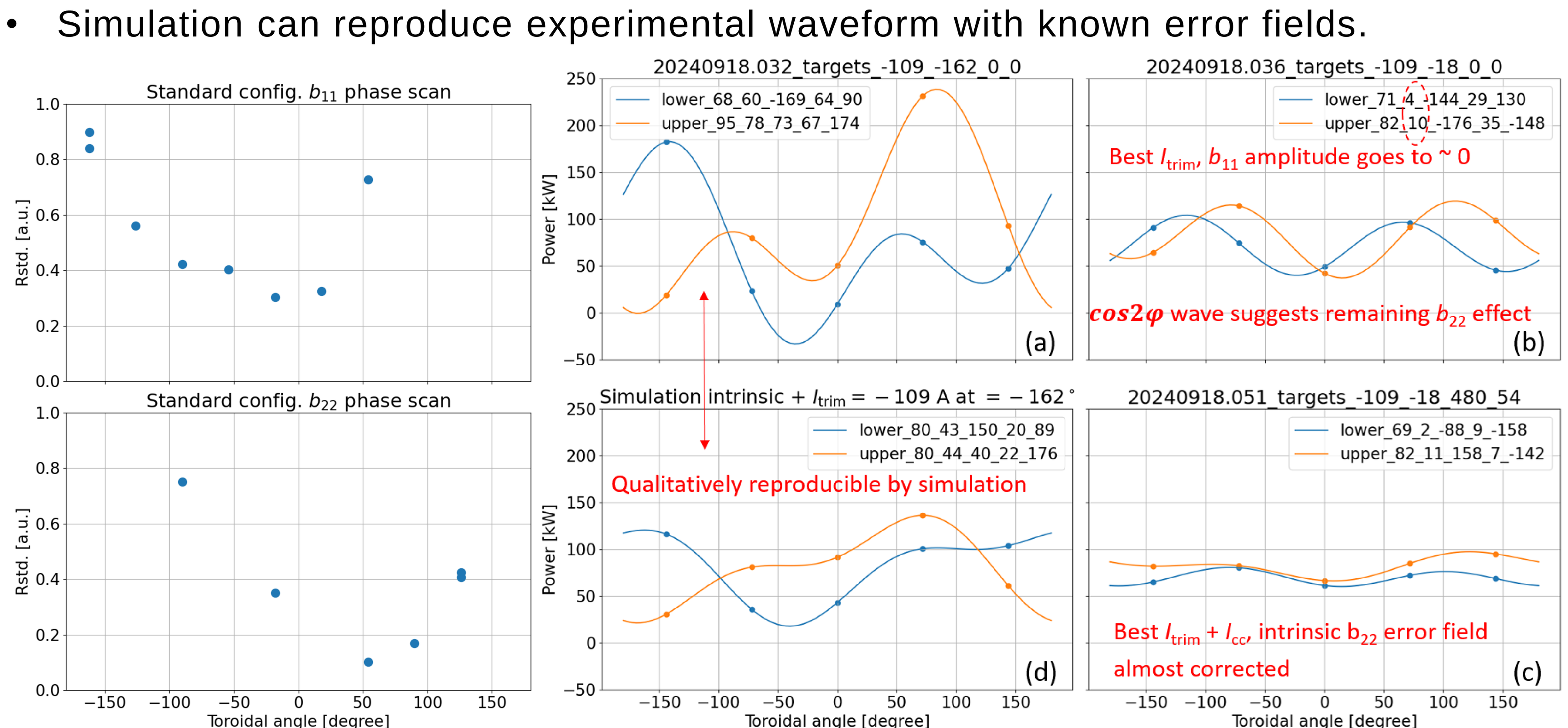
TABLE 1. Phase scan experiment performed on 20240918. Table includes program ID, amplitude of the coil current waveform, and the relevant phase of the produced b_{11} and b_{22} perturbation fields.

20240918.0XX

PID	I_{trim} [A]	φ_{b11} [°]	I_{cc} [A]	φ_{b22} [°]
31	-109	-162	0	0
32	-109	-162	0	0
33	-109	-126	0	0
34	-109	-90	0	0
35	-109	-54	0	0
36	-109	-18	0	0
41	-109	18	0	0
42	-109	54	0	0
50	-109	-18	480	126
51	-109	-18	480	54
54	-109	-18	480	126
57	-109	-18	480	-90
58	-109	-18	480	-18
59	-109	-18	480	90



- Rstd valley provides confidence, indicating intrinsic b_{11} at $\varphi_g = -18^\circ + 180^\circ = 162^\circ$, b_{22} at $\varphi_g = 54^\circ - 180^\circ = -126^\circ$ ($\varphi_g$opposite to the correction field).
- With b_{22} correction, Rstd reduces to ~ 0.1 from ~ 0.3 obtained with b_{11} correction.
- Simulation can reproduce experimental waveform with known error fields.



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