Torque-aware error field correction for ITER using quasi-symmetric magnetic perturbations

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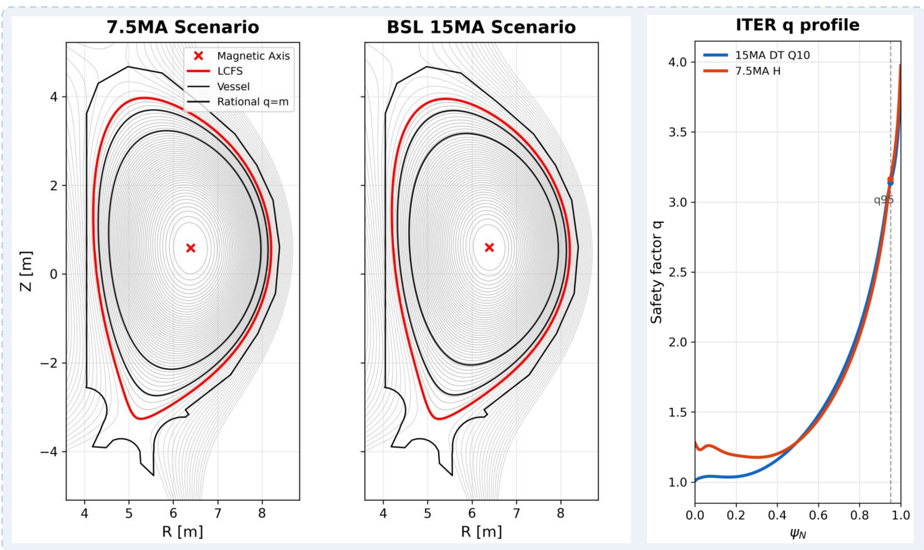
Motivation & objectives

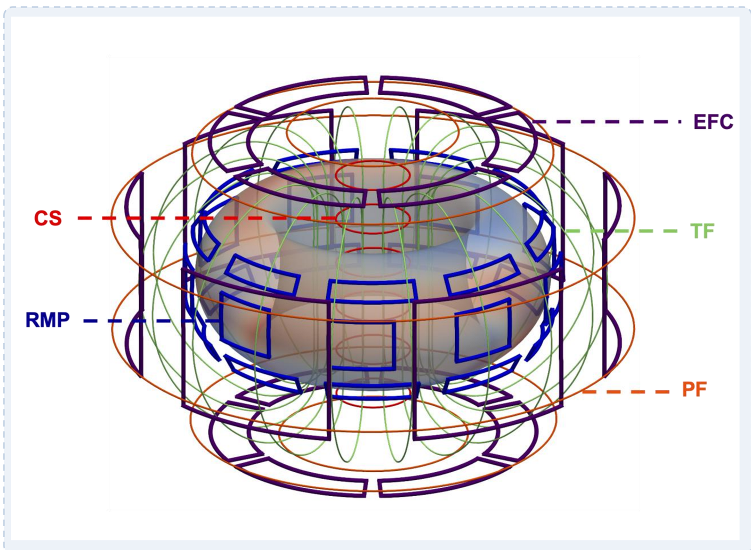
- Intrinsic non-axisymmetric error fields ($\frac{\delta B}{B} \approx 10^{-3} - 10^{-4}$, from PF/TF/CS misalignments) degrade ITER performance — driving resonant field penetration and **locked modes**, and **damping rotation** through NTV torque.
- Conventional error field correction(EFC) minimizes a resonant metric — dominant-mode **overlap** or multi-surface **resonant flux** — effective and essential against disruptive locking.
- But resonant minimization does not uniquely fix the residual 3D spectrum : comparable resonance suppression can leave very different NTV torque.

▶ **We develop a GPEC-based, torque-aware EFC framework for ITER that controls resonance and NTV torque together.**

ITER equilibria & EF sources

- Baseline **15 MA** + reduced-current **7.5 MA** equilibria; **q95 < 4**, dominant n = 1 surfaces at q = 2, 3.
- EF sources = rigid shifts / tilts of PF / TF / CS coils at engineering tolerances; unit perturbations, linear superposition.

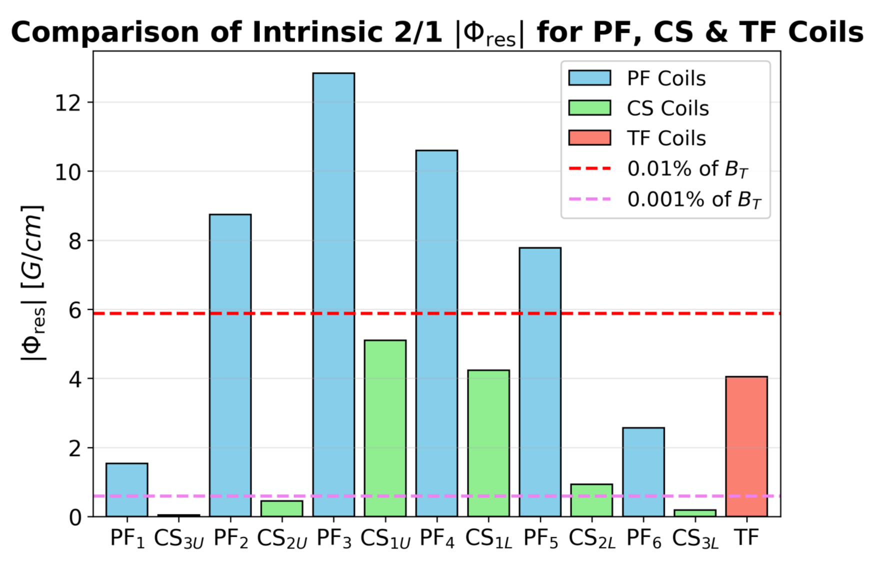


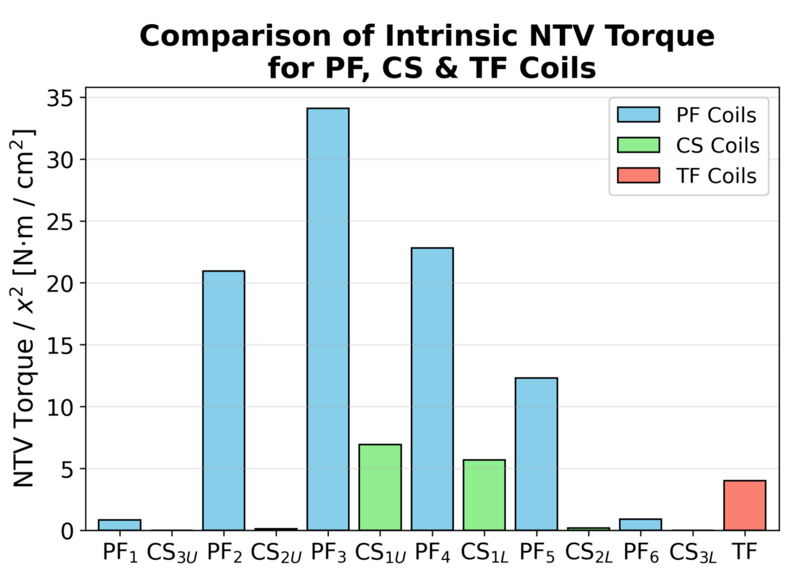


Intrinsic responses

- Per-source resonant flux (left) and NTV torque (right) for unit coil shifts.

▶ **Resonant ∝ x (misalignment) / NTV torque ∝ x^2**





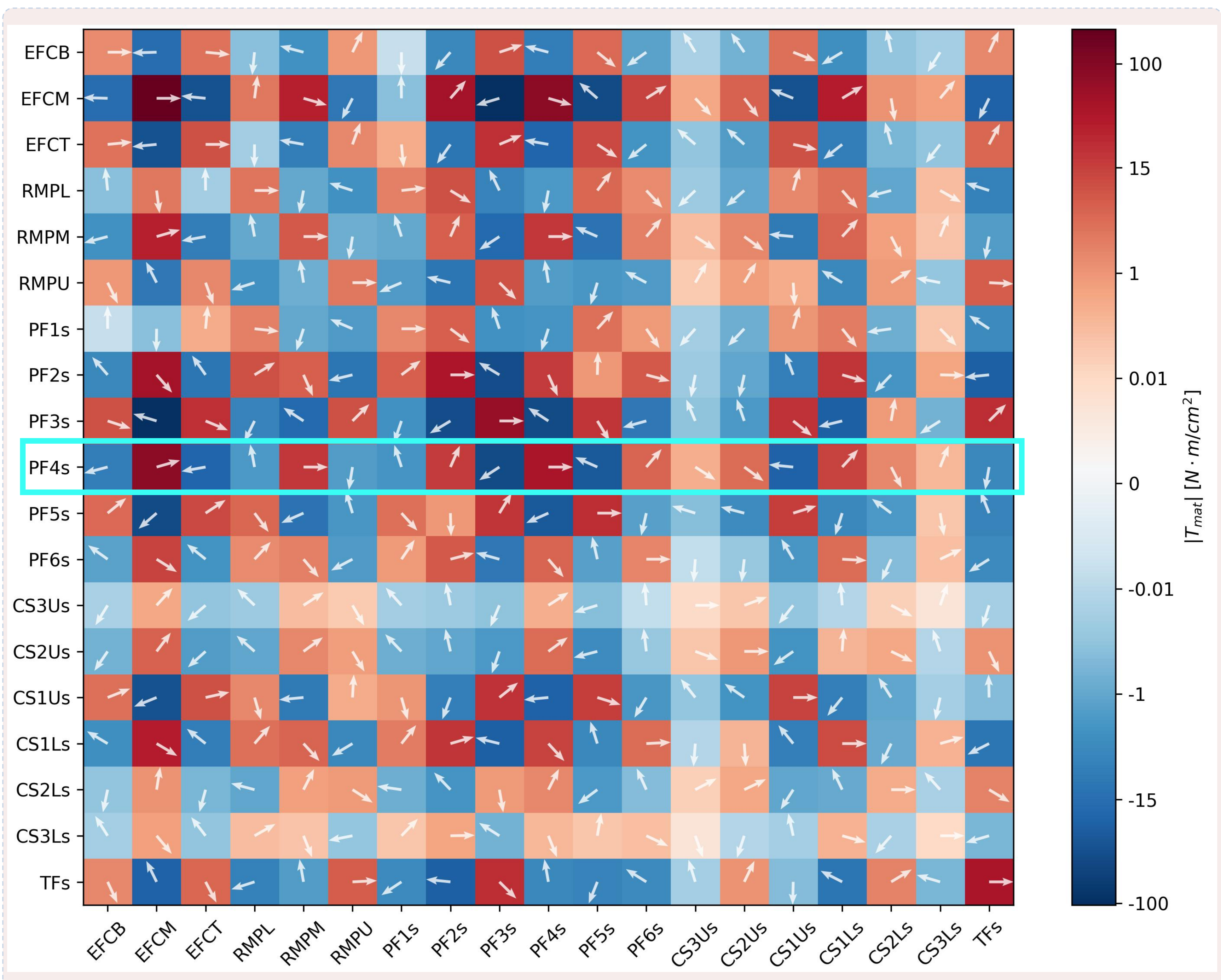
Torque-coupling matrix

- **Integrated torque is quadratic:** $\tau_\phi(\mathbf{I}) = \mathbf{I}^\dagger \mathbf{T}\,\mathbf{I}, \quad \mathbf{I} = \begin{bmatrix}\mathbf{I}_c \\ \boldsymbol{\alpha}\end{bmatrix}$

  Cross-term $\Delta T_{c \leftrightarrow s} \propto 2\,\mathrm{Re}[\,I_c^*\,(M_{cs})_{c,s}\,]$ sets, to leading order, whether coupling is strong enough.

  – Read as an actuator–phase map: Saturation = coupling strength / amp; arrow = correcting phase. (red/blue sign is phase-relative.)

▶ **Strong couplings flag the best coil family + phase before optimization (e.g. EFCM for PF4-shift source).**



Three correction strategies

(i) Overlap-optimal — null the dominant SVD resonant mode (MID-type, single coil family).

$$\min_{\mathbf{I}_c} \left|\mathbf{u}_1^\dagger\,\tilde{\boldsymbol{\Phi}}_r\right|^2 \quad \mathrm{s.t.}\ \|\mathbf{I}_c\|_\infty \le I_{\max}$$

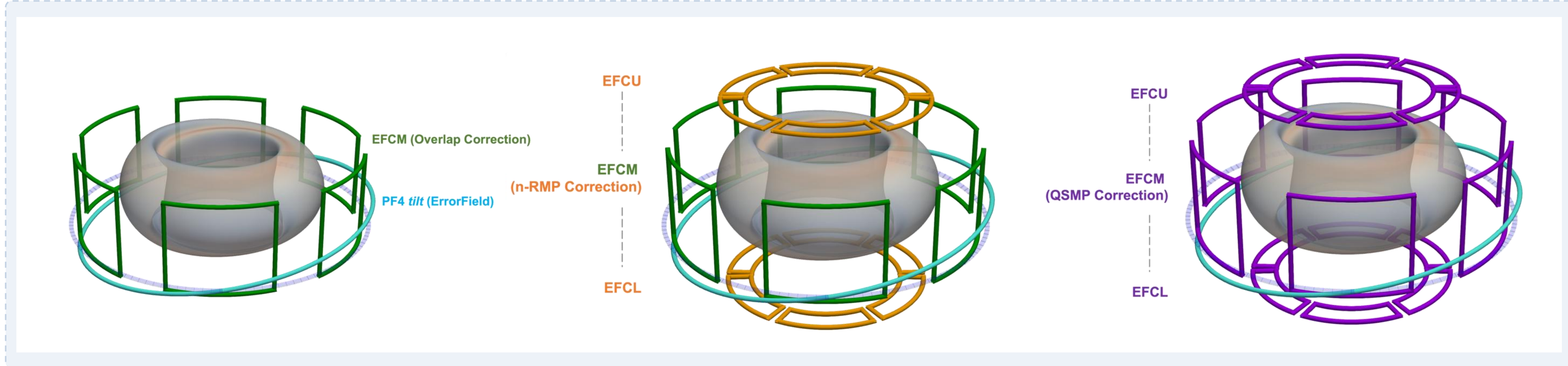
(ii) Resonance-optimal — minimize total residual resonant flux on q = 2, 3.

$$\min_{\mathbf{I}_c} \left\|\tilde{\boldsymbol{\Phi}}_r\right\|_2^2 \quad \mathrm{s.t.}\ \|\mathbf{I}_c\|_\infty \le I_{\max}$$

(iii) QSMP — minimize NTV torque

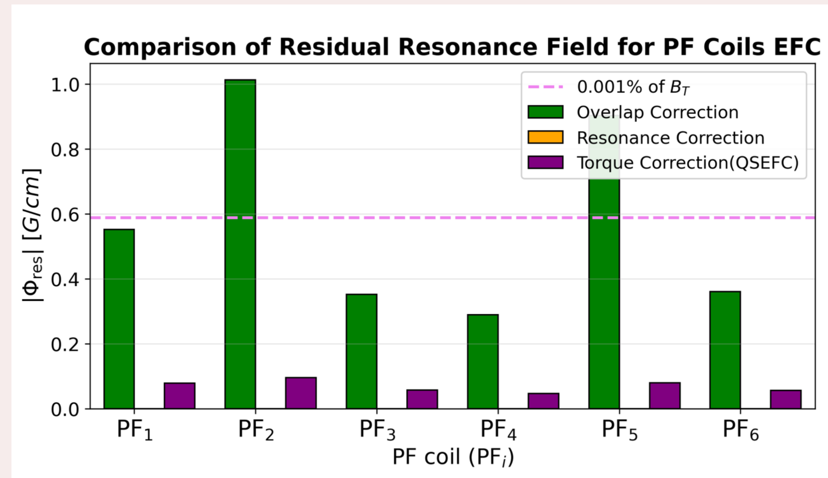
– Cap = threshold-like safeguard; torque = continuous penalty within the feasible region.

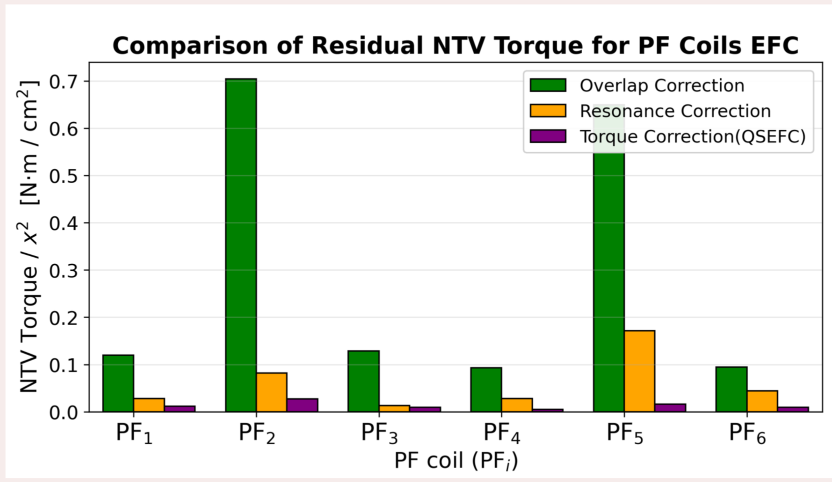
$$\min_{\mathbf{I}_c} T(\mathbf{I}_c, \boldsymbol{\alpha}) \quad \mathrm{s.t.}\ \left\|\tilde{\boldsymbol{\Phi}}_r\right\|_2 \le \Phi_{\mathrm{cap}},\ \|\mathbf{I}_c\|_\infty \le I_{\max}$$



Resonance vs torque — key result

- Residual resonance(left): all three strategies reach the axisymmetric reference → all locking-safe.
- Residual NTV torque(right): resonance-focused solutions leave large, non-negligible residual torque. QSMP stays low.



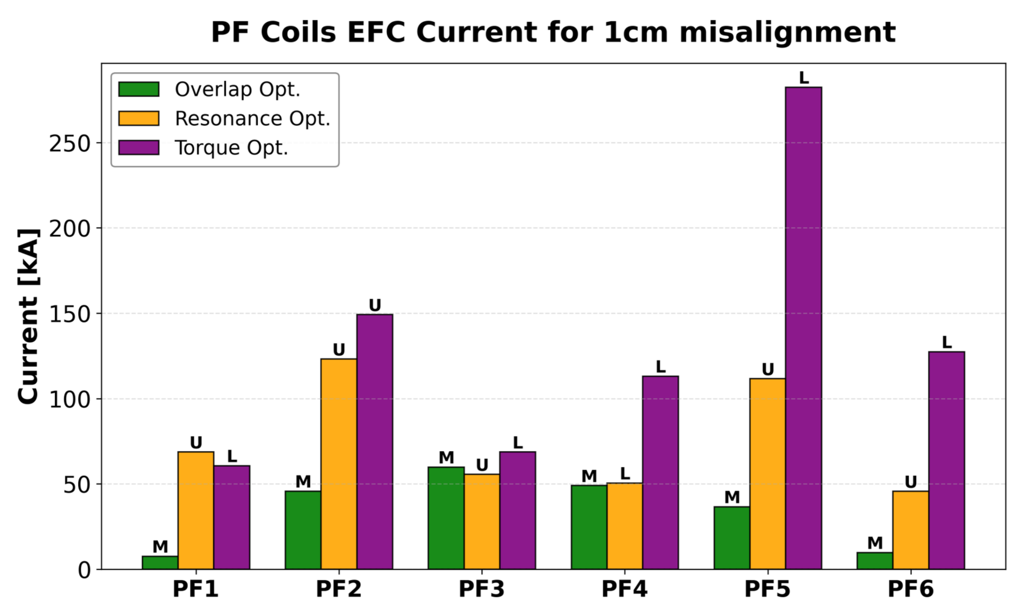


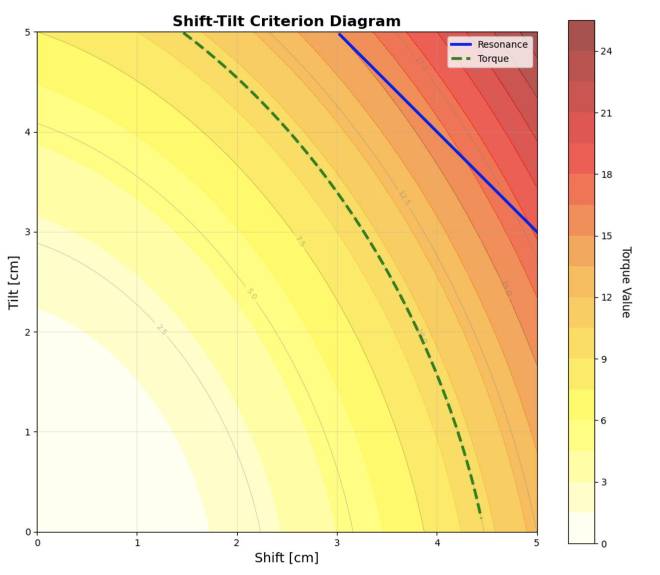
▶ **Suppressing resonance does NOT guarantee suppressing torque — QSMP is the ultimate strategy that keeps both residual resonance and torque low.**

Economy & low-risk transfer

correcting current generally rises in the order **overlap → resonance → QSMP**

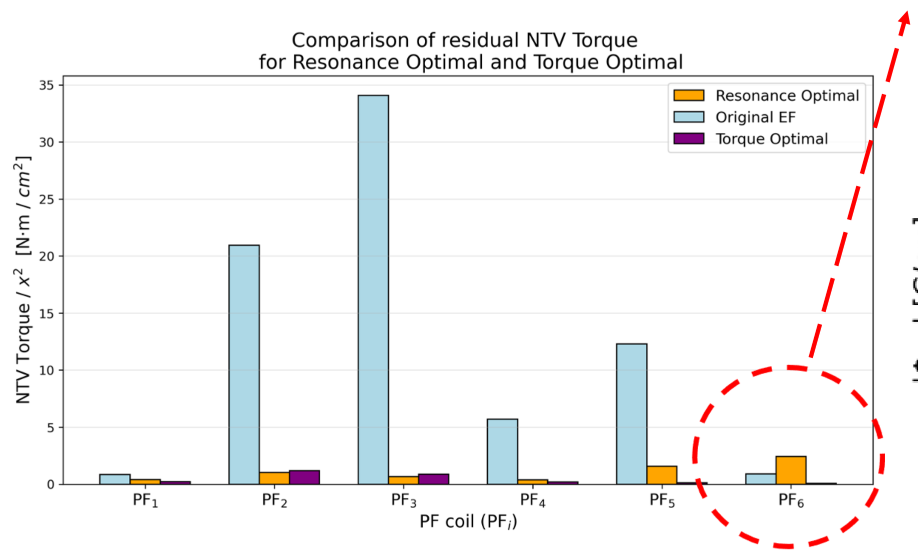
— bulk correction by the strong coil, peak current set by weakly-coupled fine-tuning coils

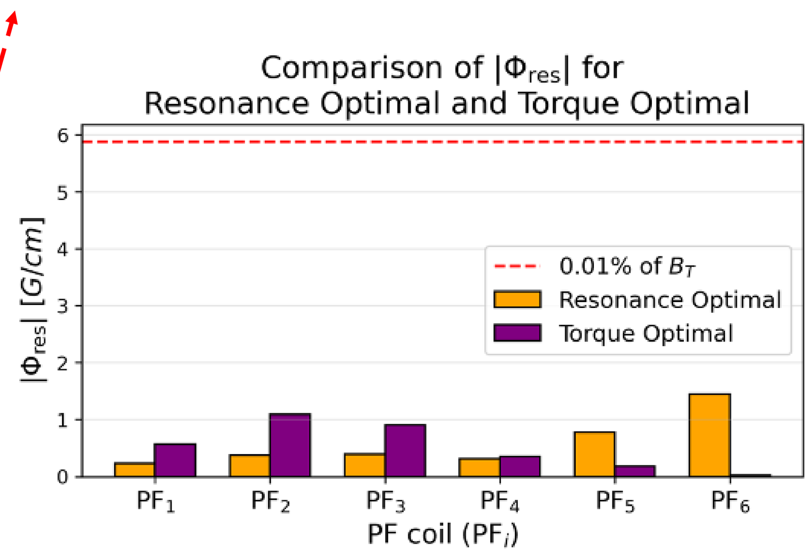




Optimize at 7.5 MA (avoids disruptive 15 MA scans), apply directly to 15 MA without re-optimization.

▶ **Torque scales quadratically vs resonance linearly → equilibrium mismatch is amplified in the torque channel.**





Conclusions

- Torque-coupling matrix makes torque-aware EFC actionable (provenance → actuator + phase).
- Resonance-focused EFC is not transport-robust**; QSMP gives order-of-magnitude torque reduction** with competitive resonance control.

▶ **Robust under current scaling → practical ITER protocol; even more critical for DEMO.**

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