Tilted Planar Interlinked Coils as a Means of Generating Rotational Transform – Modelling and Experiment

Abstract

- **Tilted planar** Toroidal Field (TF) coils + vertical field (VF) coils can generate a *helical* magnetic field.

- Is this a **generator** or an **amplifier** of rotational transform? Is finite $I_p$ needed?

- Numerical optimization of coil-currents and tilts shows that finite-volume vacuum flux surfaces exist for $I_p = 0$.
  - Takes advantage of analytical expressions for $B$ from circular coil

- Exp. demonstrated in limit-case of 2 interlinked coils: CNT

- More TF coils
  - increase the aspect-ratio
  - reduce eff. ripple, hence trapped particles with non-optimized drifts

- **Goals here:**
  1. Demonstrate generation of rotational transform
  2. Minimize aspect ratio
Earlier Numerical Works, mostly for $I_p \neq 0$
Included generalizations to non-interlinked & non-circular coils

D. Spong ≥2013

D. Spong et al., EPR 2013; A. Clark et al., FED 2014]
18 coil device more axisymmetric than 18 coil tokamak

Needs less $I_p$ than tokamak, for same rotational transform $\rightarrow$ less violent disruptions.
Tilted coils need less current to achieve same transform. Also, have lower effective ripple than equivalent tokamak.

D. Spong et al., EPR 2013; A. Clark et al., FED 2014]
Modeling
Semi-analytic approach to field-line tracing

Analytic expression for magnetic field generated by circular coil,

\[ B_r = \frac{Ca^2 \cos \theta}{\alpha^2 \beta} E(k^2) \]
\[ B_\theta = \frac{C}{2\alpha^2 \beta \sin \theta} [(r^2 + a^2 \cos 2\theta)E(k^2) - \alpha^2 K(k^2)] \]

\[ \alpha^2 \equiv a^2 + r^2 - 2ar\sin \theta \quad k^2 \equiv 1 - \frac{\alpha^2}{\beta^2} \]
\[ \beta^2 \equiv a^2 + r^2 + 2ar\sin \theta \quad C \equiv \mu_0 I/\pi \]

accelerates field-computation (thus, field-line tracing)
by a factor \( \sim 60. \)

Simpson et al, NASA 2001
Optimal coil-currents minimize plasma aspect ratio

Sharp boundaries correspond to island chains exiting LCFS

Aspect ratio \( A \approx 8 \)
Poincare Plots for largest CIRCUS plasma

\[ \phi = 0^\circ \]

\[ \phi = 15^\circ \]

\[ \phi = 30^\circ \]

\[ \phi = 45^\circ \]

TF angle = 46°

\[ \frac{I_{VF}}{I_{TF}} = 1.5 \]

\[ \frac{I_{QF}}{I_{TF}} = -0.5 \]

Plasma volume = 2.05 L
9 coils yield similar cross-sections and aspect ratio $A \approx 12$
12 coils yield similar cross-sections and aspect ratio $A \approx 15$
18 coils yield similar cross-sections and aspect ratio \( A \approx 15 \)
Coil-tilt affects iota profile & plasma volume
Optimizing the coil-tilt nearly doubles the plasma volume

TF angle = 36°
$I_{VF}/I_{TF} = 2.81$
$I_{QF}/I_{TF} = -21.5$

Plasma volume = 3.36 L
6, 9 and 12 coil $I_p=0$ plasmas
15 and 18 coil $I_p=0$ plasmas have large aspect ratios and low transform
Finite $I_p$ results in larger plasmas
Experiment
Interlinking the TF coils

6 interlinked TF coil rims

TF coil rim with axle

Generate 0.0875 T on axis for 2.45 GHz startup, ECH and ECCD
Tilting the TF coils

Tilted interlinked coils mounted on central column.
Tilts and radial locations of coils can be varied

TF supports, adjustable tilt = 34-61° w.r.t. horizontal
Acrylic vessel

Advantages
• High compressive strength
• Transparent to microwaves → easy heating & C
• Transparent to visible light → broad camera view

Disadvantages
High desorption rate

Nonetheless, $P = 2.2 \times 10^{-5}$ torr, sufficient for EC startup.
CIRCUS table-top device at Columbia
[A.W. Clark et al., Fusion Eng. Design 89, 2732 (2014)]
e-beam from filament biased at -100 V

in gas at $10^{-5} - 10^{-4}$ torr follows field line
Rotational transform?
Electron gun can be scanned in 3D, for fine scans of flux surfaces in field-line mapping.

Sliding feedthrough mounted on tiltable bellow.
Summary & Conclusions

- Tokamak-like device with tilted toroidal field (TF) coils needs less plasma current $I_p$ than a conventional tokamak.
- Rotational transform is partly generated by the tilted coils. Can be considered a tokamak-torsatron hybrid.
- Can be operated for $I_p = 0$ (pure torsatron) for optimal TF, VF and QF coil-currents.
- “CIRCUS” (CIRCUlar coil Stellarator) built at Columbia.
- Electron beam in gas used to visualize vacuum field-lines and their rotational transform.
- Scans to be carried out with recent 3D-movable electron gun.
Future work

With present vessel:

• Currently epoxying the coils
• Confirm rotational transform for e-beam initialized on high-field-side, by recently installed filament movable in 3D (1 linear, 2 angular).
• Measure flux surfaces for various radial positions and tilts of coils, and compare with calculations. Identify parameter space where \( I_p = 0 \).
• Introduce deliberate error fields. Measure and compare with calculations.

With future vessel:

• Microwave plasma in new vessel
• Fast-camera studies of plasma formation by EC start-up
• Water cool coils, for longer shots or higher repetition rate

Current Drive:

• Larger plasmas will require \( I_p \neq 0 \). If ECCD not sufficient,
  – Central solenoid, for \( I_p \) generation and Ohmic heating
  – New form of Rotating Magnetic Field CD (RMFCD)
  – Plasma Gunn [as in Proto-CLEO]
New vessel will allow better vacuum.
Coils will be external, cooled. Longer pulses.

Sections of new vacuum vessel: glass cylinders in PTFE wedges.
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