Modular coil designs for stellarators

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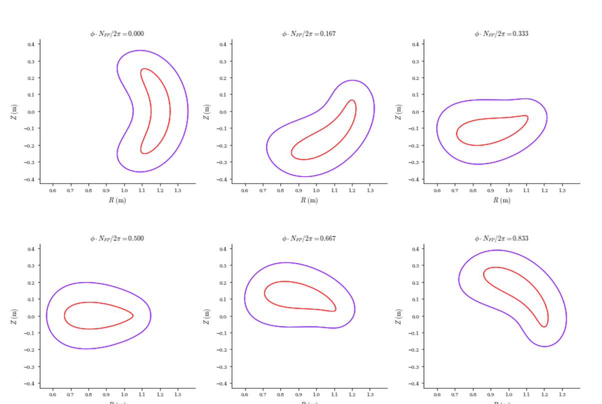
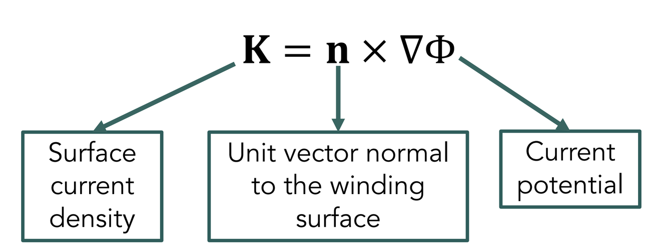
Motivation

- Need for experiments to check plasma performance before building a reactor.
    - Reduced costs.
    - Reduced time of construction.
- Need to study multiple configurations before finding an "optimal" device
    - **Potential solution**: mid-size machine that allows the generation of multiple equilibria.

Background

- Coils for stellarators usually found through surface current distributions $\mathbf{K}$ on a winding surface[1].
- Example:
    - Precise quasi-helically symmetric equilibrium[2].
    - Winding surface generated as an offset surface.

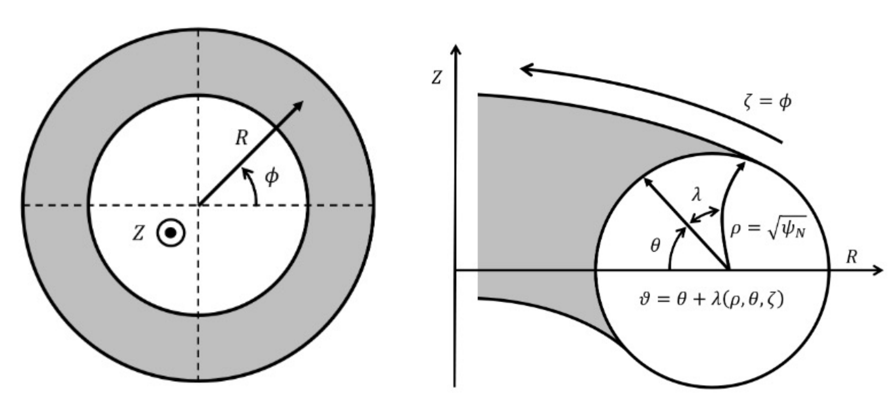


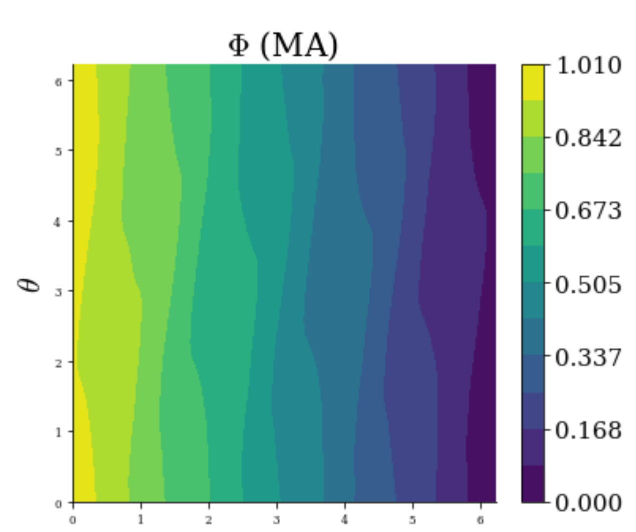


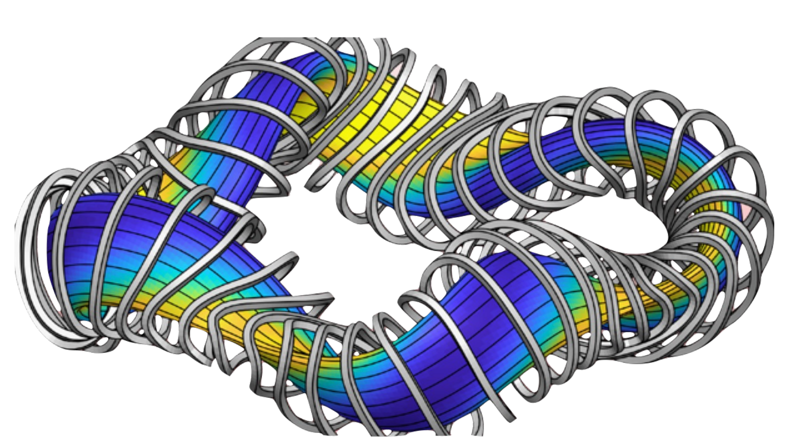
$$\Phi(\theta,\zeta) = \frac{I}{2\pi}\theta + \frac{G}{2\pi}\zeta + \Phi_{sv}(\theta,\zeta)$$

I: Net enclosed toroidal current

G: Net enclosed poloidal current







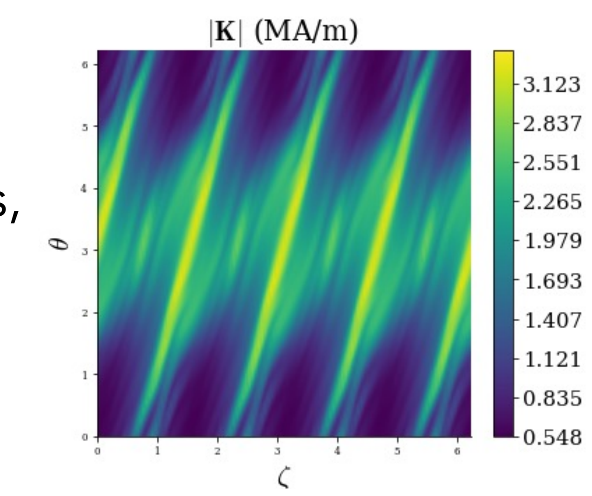
- G guarantees a net toroidal flux in the system.
- Φ_{sv} is used to generate a flux surface $\mathbf{B}\cdot\mathbf{n} = 0$.

DESC Stellarator Code

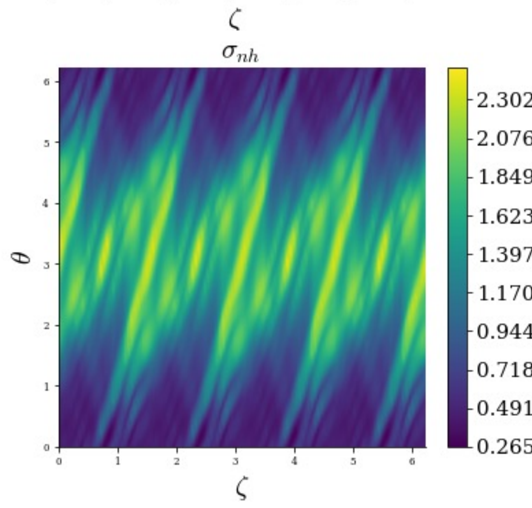
- DESC is an Equilibrium code[3] with enables GPU + Automatic Differentiation capability. REGCOIL[3] algorithm implemented.
- Minimization of $\chi^2_B = \int (\mathbf{B}\cdot\mathbf{n})^2 dS$ becomes a linear least-squares problem with in Φ_{sv} as an unknown, after expanding in Fourier Series (I, G, and winding surface shape are known).
- REGCOIL[5] aids in the search of smooth current density distribution by also minimizing $\chi^2_K = \int \mathbf{K}\cdot\mathbf{K}\, dS'$

Variable conductivity/thickness

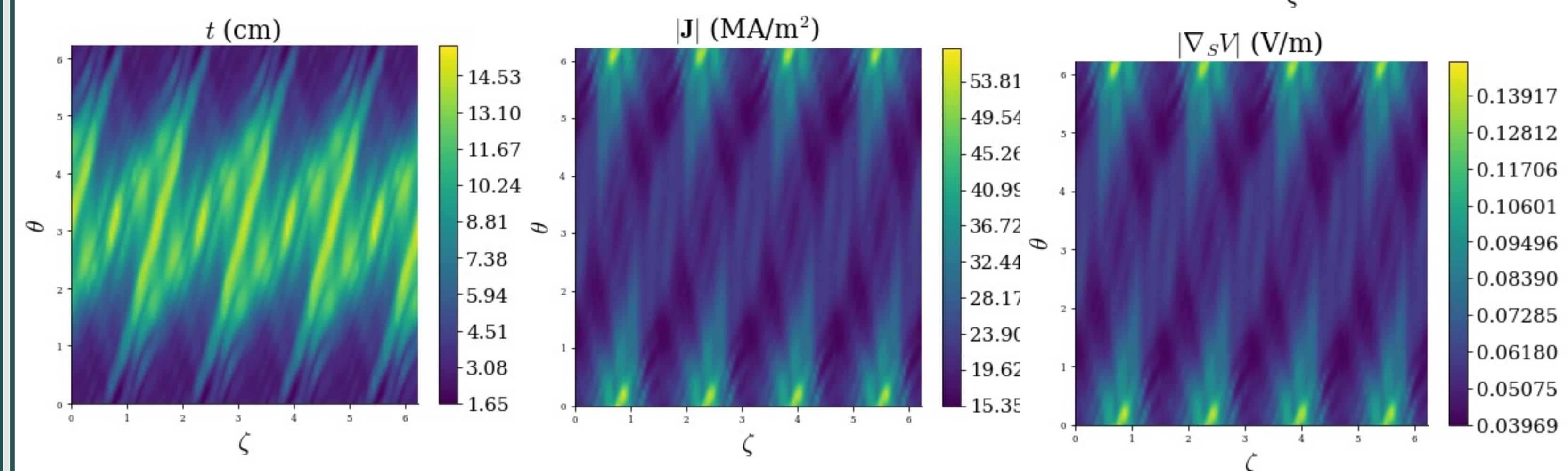
$$\mathbf{K} = \mathbf{n}\times\nabla\Phi = \sigma\nabla_S V$$



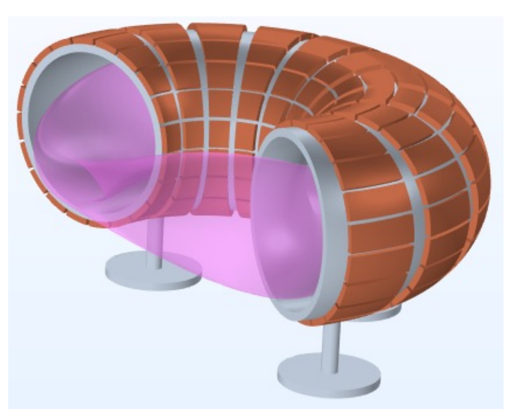
- Instead of finding a discrete set of coils, find distributions of:
    - Variable conductivity σ
    - Voltage distribution V
    - Solutions for PQH



- Results with thickness variation
    - Current density below 50 MA/m^2
        - NCSX design constraints
    - Electric field ~ 100 mV/m
        - ~ 1 kV/m for electric arcing in air.



- Alternative method for conductivity variation: Split the winding surface into patches!

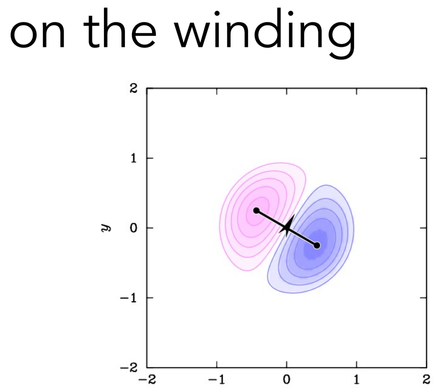


Electric dipoles

- Based on dipole decomposition of incompressible flows[6]:
    - $\nabla_S\cdot\mathbf{K} = \nabla_S\cdot(\mathbf{n}\times\nabla\Phi) = 0$ for any Φ.
    - $\mathbf{K}$ is an incompressible flow on the winding surface!
- Dipole basis for any smooth and closed toroidal surface is known[7]:
- $\{u(\theta,\zeta), v(\theta,\zeta)\}$: isothermal coordinates on the winding surface:

$$ds^2 = \lambda^2(du^2 + dv^2)$$

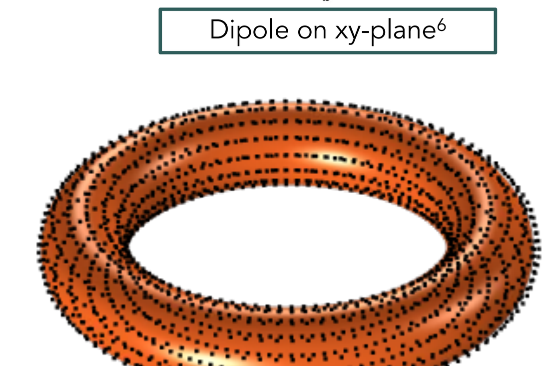
$$F_i = \ln\left[\frac{\upsilon\left(\frac{w-w_{i,1}}{2\gamma}, p_f\right)}{\upsilon\left(\frac{w-w_{i,2}}{2\gamma}, p_f\right)}\right] - \frac{\mathrm{Re}\{w_{i,12}\}}{\gamma\Delta v}w$$



Dipole on xy-plane[6]

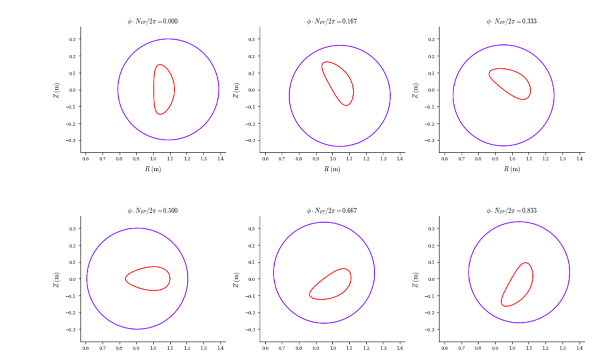
$$\Omega = \mathbf{w}_v + i\mathbf{w}_u = \frac{F'(w)}{\lambda} \qquad \chi_i = \mathrm{Re}\{F_i\}$$

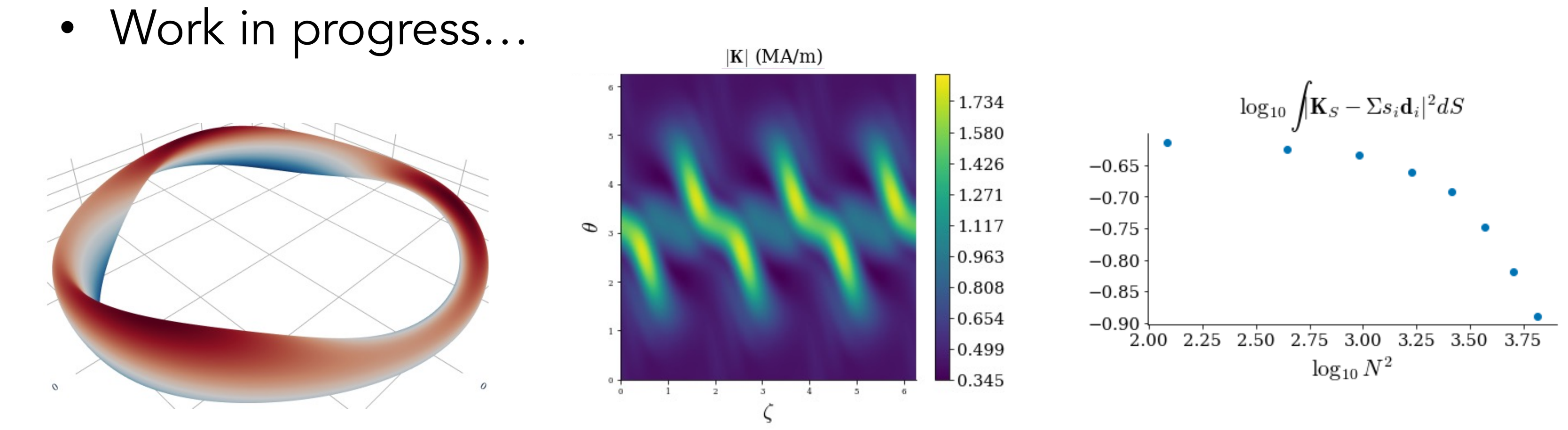
$$\mathbf{w} = \frac{1}{\lambda}\hat{\boldsymbol{n}}\times\tilde{\nabla}\chi(s) \qquad w = u + iv$$



Electric dipoles

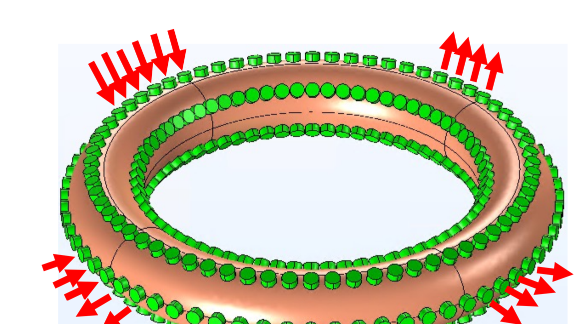
- Results on a quasi-axisymmetric equilibrium (R. Jorge).
- Dipoles can generate the total current required to generate the equilibrium.
- Winding surface generated to fit two different stellarators inside the same vacuum vessel.
- Work in progress…

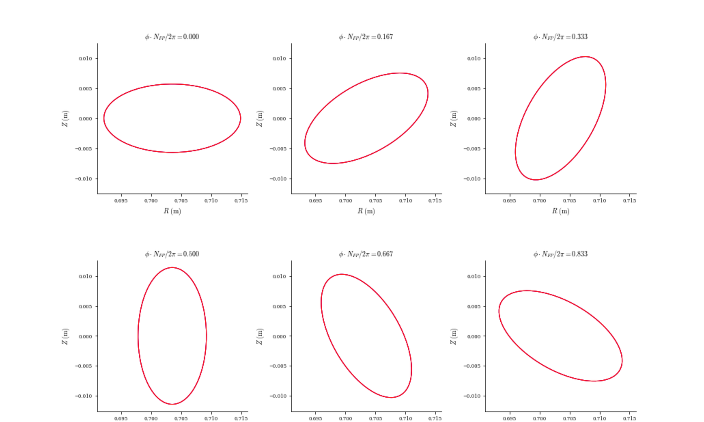


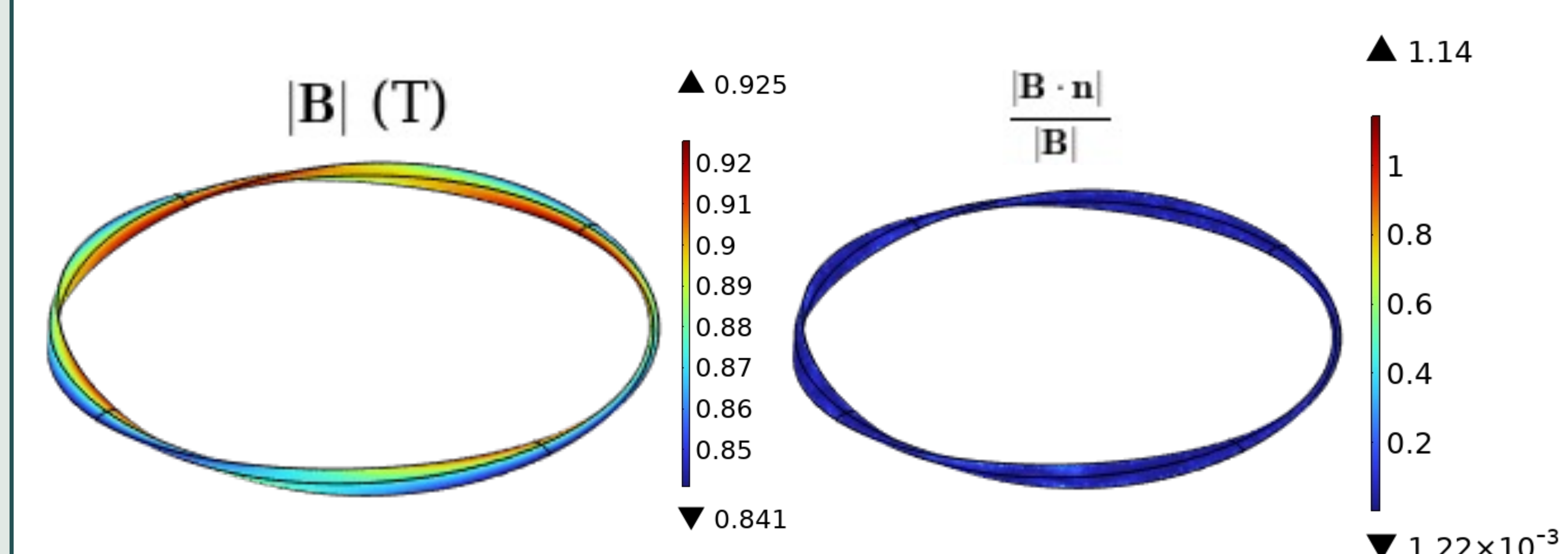


Sources and sinks of current

- Sinks and sources of current on a matrix of wired plugged into the winding surface.
- Sinks and sources are used to cancel the $\mathbf{B}\cdot\mathbf{n}$ component generated by a net poloidal current in the winding surface.
- Solutions for a simple stellarator (rotating ellipse).







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