Equilibrium design for the SUNIST-2 spherical tokamak

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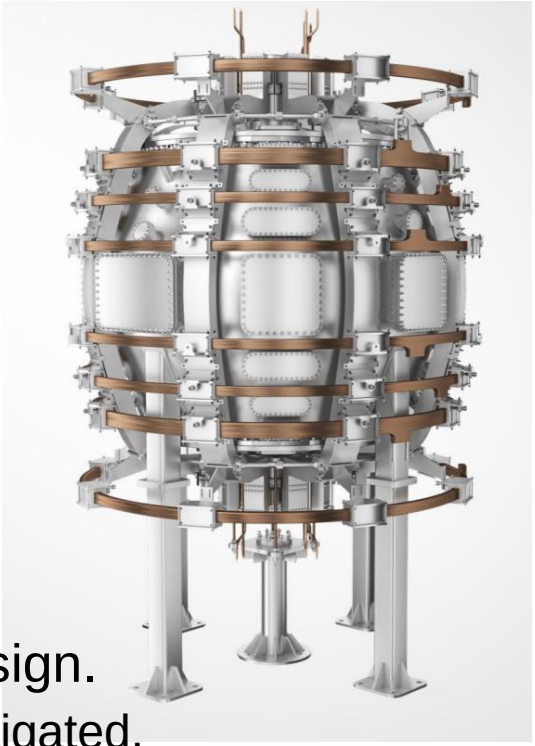
Introduction

- SUNIST-2 a medium size spherical tokamak which is the next generation of SUNIST(Sino-UNIted Spherical Tokamak) [1-2]



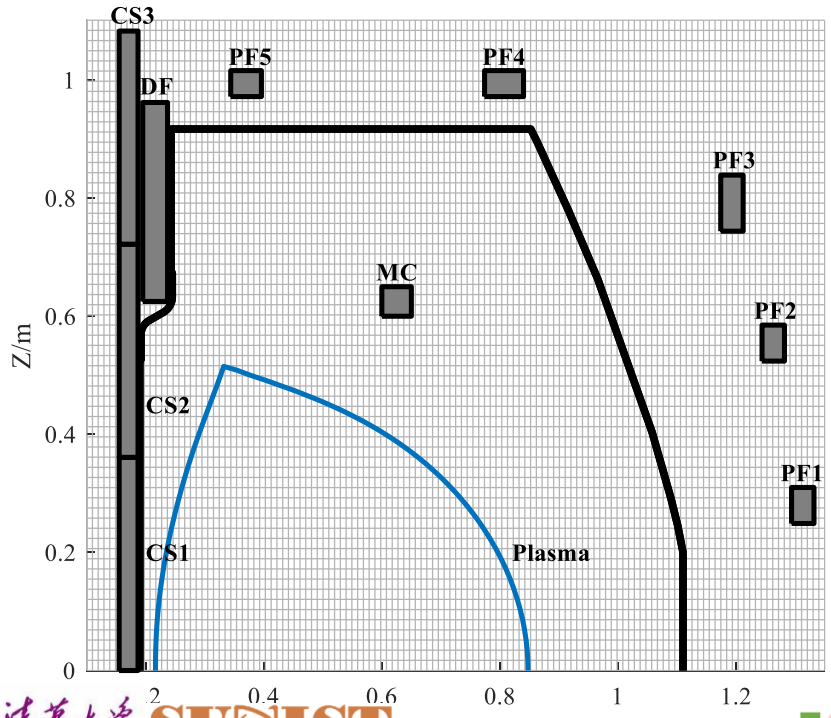
- The main parameters of SUNIST-2
  - Major radius (R_0): 0.525 m
  - Minor radius (a): 0.325 m
  - Aspect ratio : ~ 1.65
  - Toroidal Field at R_0 : < 1 T
  - Plasma current: <500 kA

- Plasma equilibrium is the basis of a tokamak device design.
  - Accessibility of different plasma shapes need to be investigated.
  - To give reference for the design of poloidal field power supply
  - Furthermore, to provide current profile and kinetic profiles for subsequent stability and transport analysis.

Design method

- A free boundary equilibrium(FBE) code is developed based on EFIT[3]
  - Two modes are supported, including equilibrium mode and fitting mode.

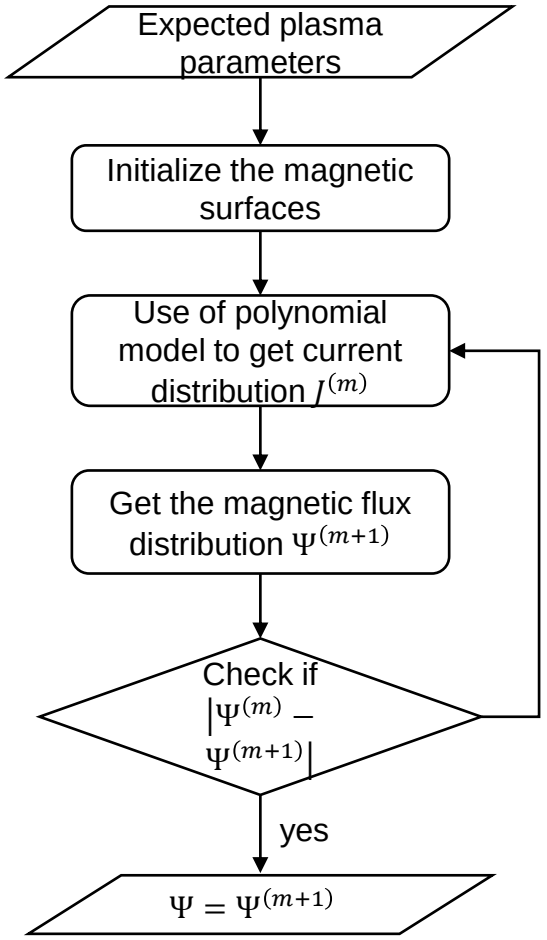
Mode	Problem type	Inputs	Outputs
Equilibrium	Forward equilibrium	$plasma\ shape, p', FF'$	$\psi(R,Z), I_a$
Fitting	Backward/Reconstruction	Mag. measurements	$\psi(R,Z), p', FF', I_a$



- The two modes share the same
  - Picard iteration scheme
    - $j_\phi^{t+1}(R,Z) = -\frac{\Delta^*\psi(j_\phi^t)}{\mu_0 R}$
  - Rectangular grid
    - Easy for spatial difference
- Are different in
  - Current profile models adopted
    - Polynomial or GAQ model[4]
  - The way how plasma toroidal current is updated
  - …

Design method

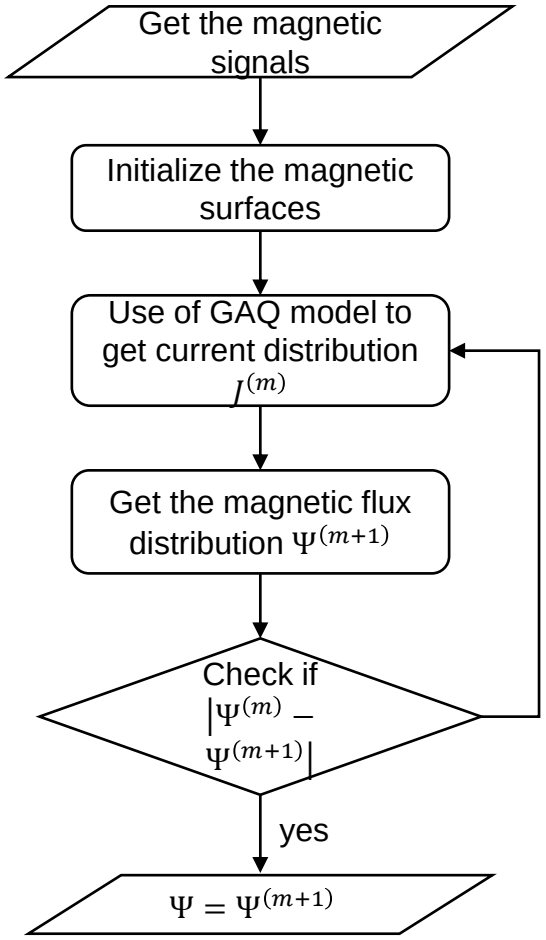
- The equilibrium mode
  - Can be used to reconstruct the plasma from magnetic diagnostic signals



- The problem solved is in fact to find $x = \psi(R, Z)$ to minimize the following cost function
  - $L = \left|\left|\overrightarrow{\psi_b} - \psi_{b0}\right|\right|$
- Under the constrain
  - $\Delta^*\psi = -R\mu_0(j_\phi + j_a + j_v)$ in the computational region and $j_\phi = Rp' + \frac{1}{\mu_0 R}ff'$
  - Other constraints C_{other} like axial safety factor, etc.
- It's important to note that
  - Usually a guess of the poloidal field coil currents will help the algorithm to converge to the more desired equilibrium.
    - In this sense, we say by increasing the fitting weights of coil currents the corresponding plasma shape can be given.
  - ψ_{b0} can be given as a fixed value or adjusted in the iteration depending on our goal, such as to minimize the coil currents or get a zero-sum of coil currents.

Design method

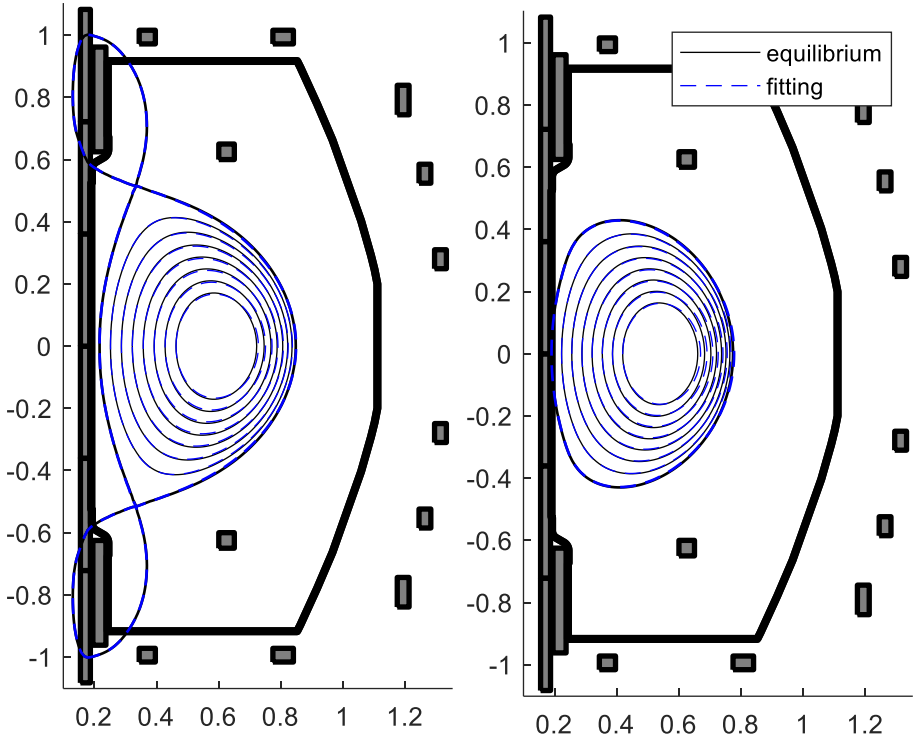
- The fitting mode
  - Can be used to evaluate the coil currents needed to sustain different plasma shapes



- The problem solved is in fact to to find $x = \psi(R, Z)$ to minimize the following cost function
  - $L = \left|\left|\overrightarrow{\psi_m} - \psi_{m0}\right|\right|$
- Under the constrain
  - $\Delta^*\psi = -R\mu_0(j_\phi + j_a + j_v)$ in the computational region and $j_a = Rp' + \frac{1}{\mu_0 R} ff'$
  - Other constraints C_{other} like topological constraint, etc.
- It's important to note that
  - All the constraints need to be formulated as a linear relationship with the polynomial coefficients.
    - Such as the signals from flux loops, magnetic probes, diamagnetic loops, and axial safety factors.
  - Vertical shift instability are stabilized via an extra free parameters[5].

Self benchmarking

- We reconstructed the equilibrium based on synthetic signals obtained from predesigned limiter and double null configurations.



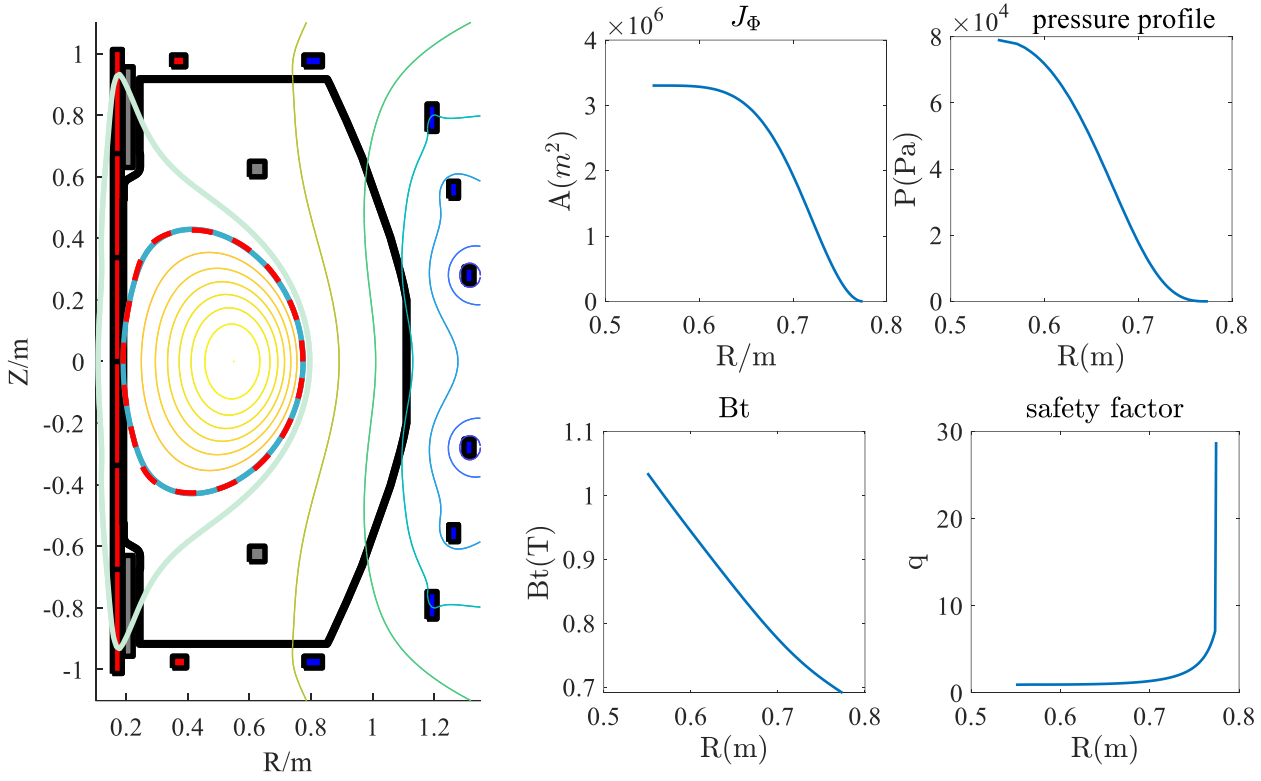
- Synthetic signals include
  - 30 flux loops
  - 75 magnetic probes
  - Rogowski coils measuring the current of the plasma and the poloidal field coils

		I_p kA	a_p m	R_p m	δ	κ	l_i	β_p
div.	equil.	500.0	0.32	0.53	0.634	1.63	1.304	0.75
	fit.	500.2	0.32	0.53	0.634	1.63	1.355	0.74
Lim.	equil.	500	0.29	0.48	0.238	1.47	1.219	0.625
	fit.	500	0.29	0.48	0.243	1.46	1.260	0.617

- The reconstructed equilibrium agrees well with the designed ones.

Designed equilibrium configuration

- The limiter configuration



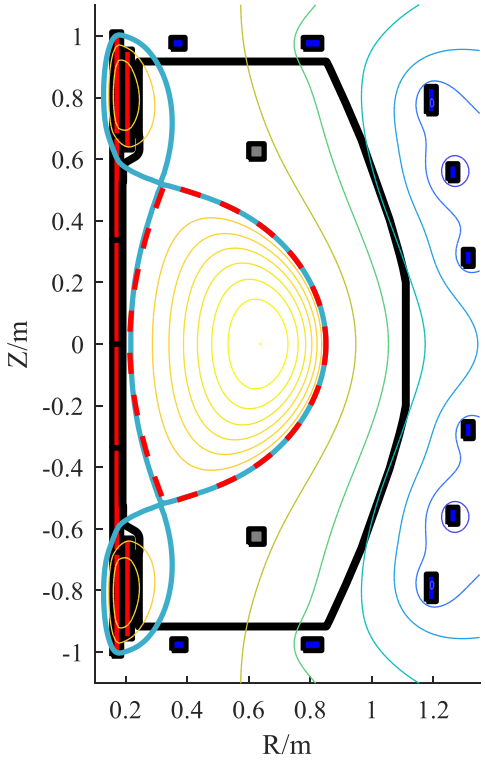
Plasma parameters:

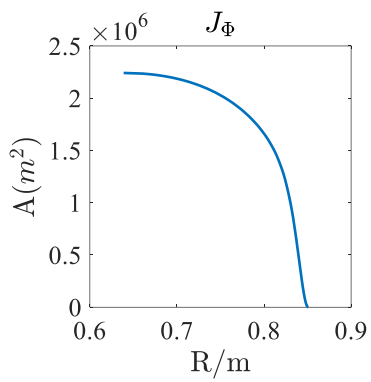
$$I_P = 500kA$$
$$\beta_p = 0.34$$
$$\beta_t = 2.6\%$$
$$\beta_N = 1.34$$
$$li = 1.12$$
$$q_{axis} = 0.95$$
$$q_{out} = 6.84$$
$$W_{plasm} = 17.62kJ$$
$$r_{maxis} = 0.52m$$
$$z_{maxis} = 0$$
$$Vol = 1.159m^3$$
$$a = 0.292m$$
$$\delta = 0.237$$
$$\kappa = 1.461$$

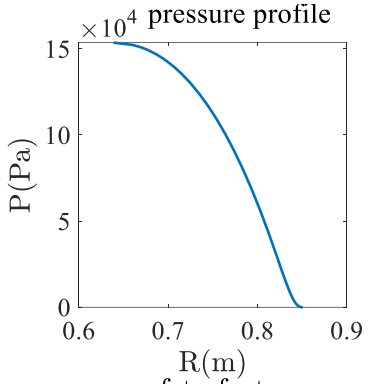
- All the external field coils except DF and MC are utilized
- The coil currents are shown in the table at the final page of the presentation.

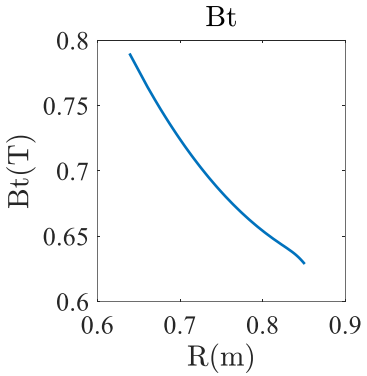
Designed equilibrium configuration

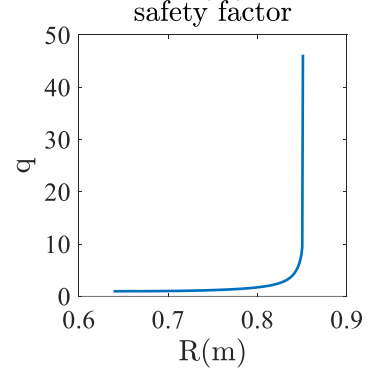
- The double null divertor configuration











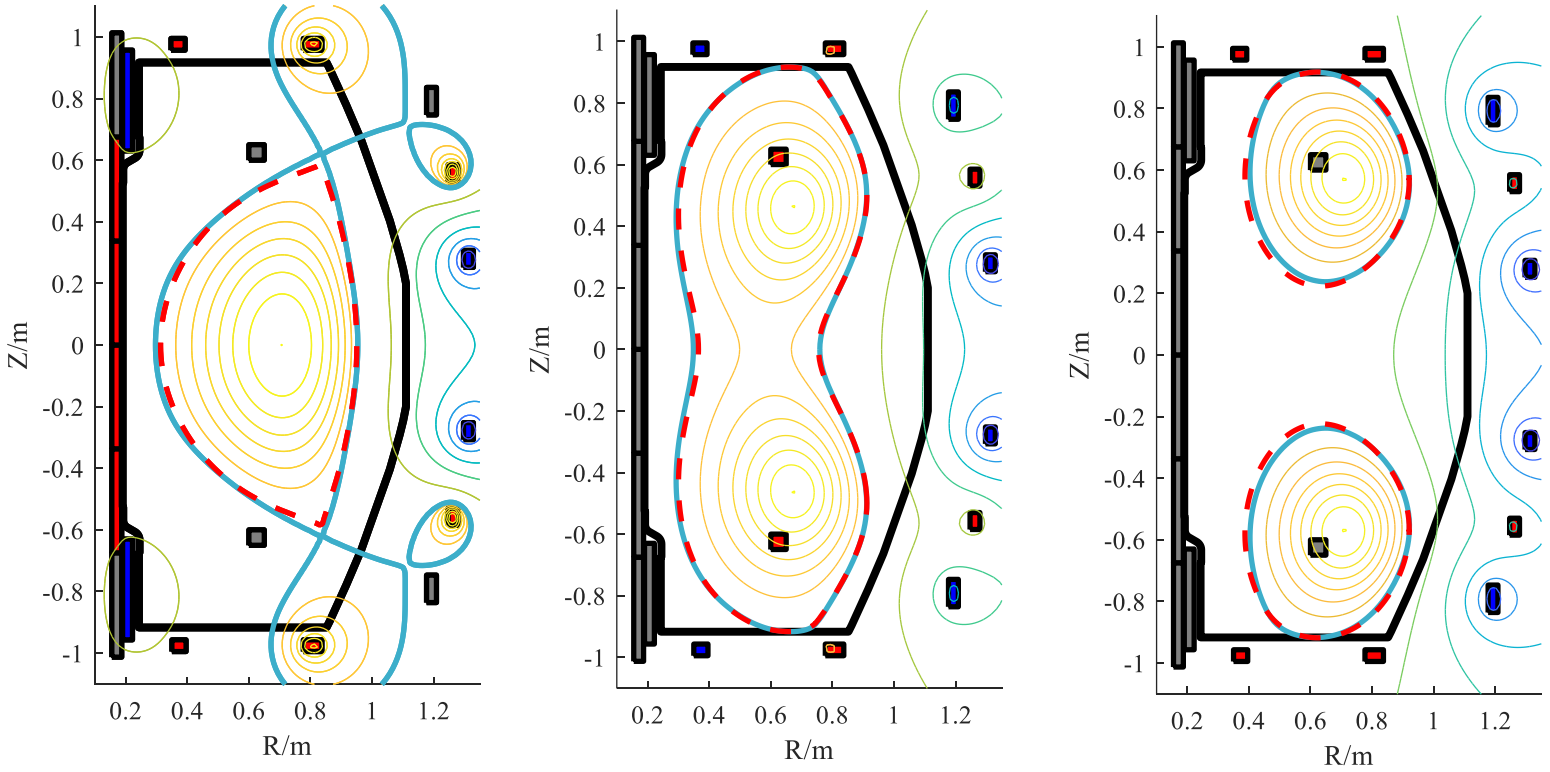
Plasma parameters:

$I_P = 500kA$
$\beta_p = 0.754$
$\beta_t = 4.1\%$
$\beta_N = 2.63$
$li = 1.31$
$q_{axis} = 0.95$
$W_{plasm} = 37.4kJ$
$r_{maxis} = 0.604m$
$z_{maxis} = 0$
$Vol = 1.51m^3$
$a = 0.32m$
$\delta = -0.63$
$\kappa = 1.64$

- All the external field coils except MC are utilized
- The coil currents are shown in the table at the final page of the presentation.

Other configurations

- The double null with negative triangularity, doublet, and droplet configuration



- The double null with negative triangularity has higher confinement[6]
- The doublet and droplet configurations will serve for merging compression of SUNIST-2

The coil currents needed

- The current loads needed of different coils for various configurations

Configurations	CS1 kA	CS2 kA	CS3 kA	DF kA	MC kA	PF1 kA	PF2 kA	PF3 kA	PF4 kA	PF5 kA
limiter	96.1	1.9	1.1	0	0	-71.3	-65.7	-56.0	-37.8	17.4
Double null(positive triangularity)	205.2	235.5	650.5	161.1	0	-61.9	-98.8	-66.6	-52.7	-7.5
Double null(negative triangularity)	189.9	198.6	0	-228.5	0	-188.5	121.6	0	43.71	4.6
Doublet	0	0	0	0	0	-38.0	-6.7	-2.15	6.0	1.59
Droplet	0	0	0	0	0	-35.6	11.9	-41.1	0.2	19.7

- The plasma current in these five configurations are all 500 kA.
- The double null configuration with negative triangularity has higher requirements for the diverter field coils, PF1 coils and PF2 coils.

Summary

- FFB is developed in MATLAB environment and used to design the equilibrium of SUNIST-2 device.
- The self benchmarking between equilibrium mode and fitting mode shows that the code is accurate.
- The current poloidal field coils allows a variety of different magnetic configurations.
  - Including limiter, double null with positive triangularity, negative triangularity, droplet and doublet configurations.
- The next work will focus on the equilibrium configuration optimization
  - Investigate more suitable equilibrium configuration to **reduce the coil load**
  - To carry out the **discharge simulation** to simulate the current evolution of current in the external coils.

Reference and acknowledgements

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