Reconstruction of magnetic plasma boundary in tokamaks using low drift integrator measurements and steady state-space modelling on eddy currents in passive structures

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APPLAuSE C5
MT3&4 – LR1

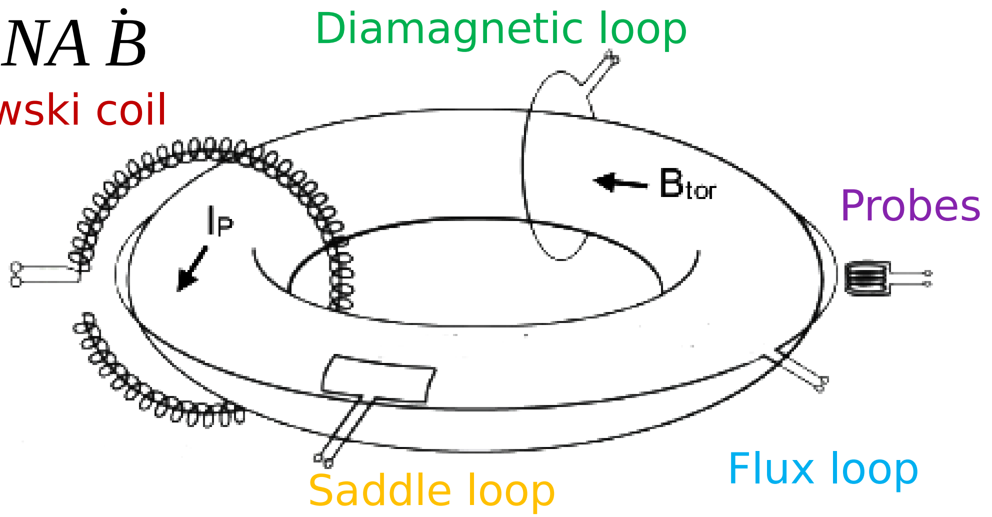
Magnetic diagnostic

$$V_{sensor} = \oint_t \vec{E} \cdot \vec{ds} = -\frac{\partial \phi(t)}{\partial t} = -NA\dot{B}$$

$$\phi(t) = -\int_{t_0}^{t} V(x)\,dx$$

Different coils give us:

- Plasma current (I_P)
- Toroidal loop voltage (U_{loop})
- Plasma energy (W_{dia})
- Plasma beta (β)
- Current distribution ($j(\Psi)$)
- Magnetic fluctuations
- Plasma rotation (V_{rot})
- Plasma position, shape, instabilities

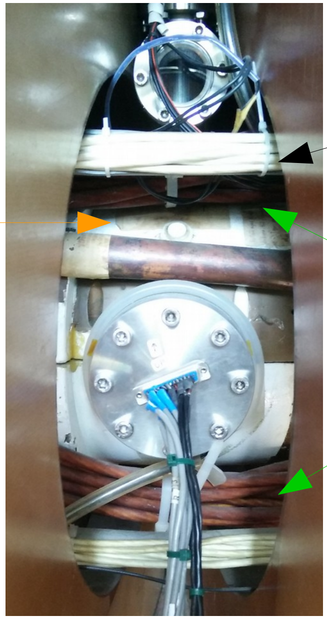


G. Papp – Fusion Research Lecture notes (adapted)

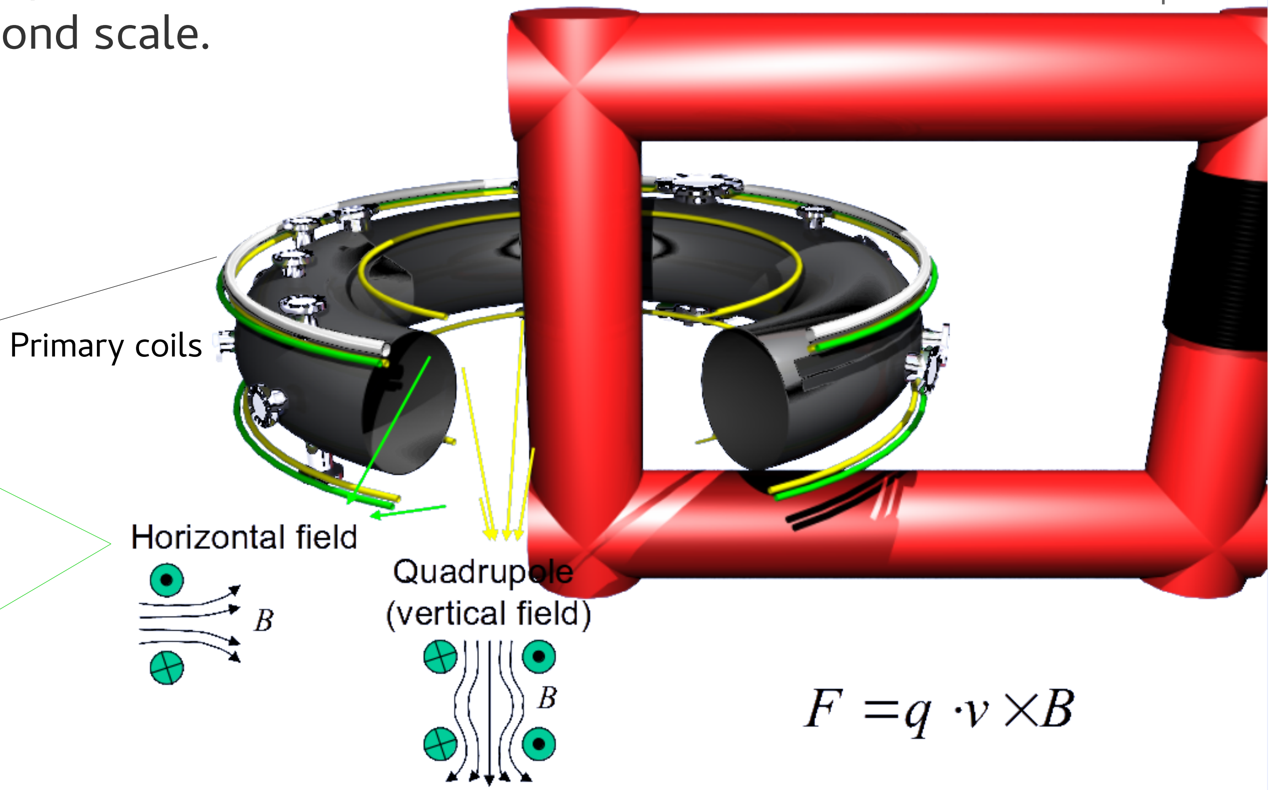
Measure total flux through the enclosed surface

At ISTTOK

The copper shell provides passive instability control by increasing the growth rate of plasma instabilities to the millisecond scale.



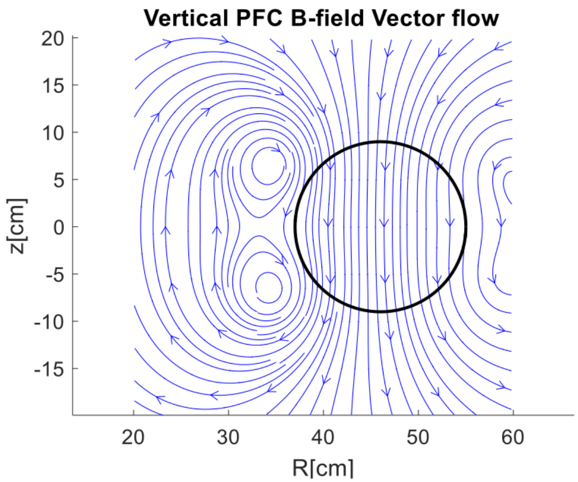
H. Fernandes – ISTTOK Machine Description

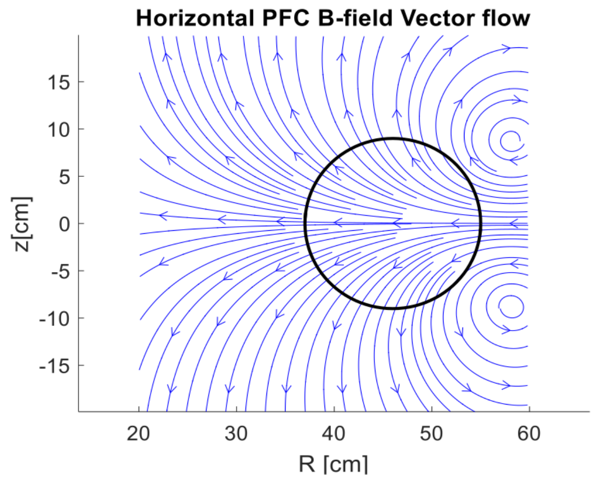


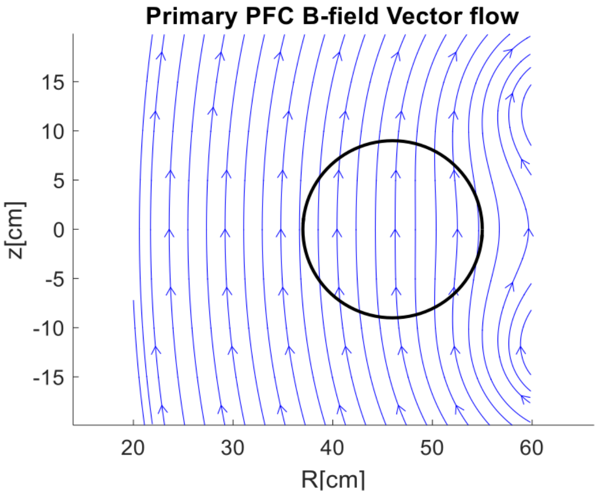
$$F = q \cdot v \times B$$

PF coils signals

We intend to measure the plasma but we also pick up signal from the PF coils that generate and position the plasma



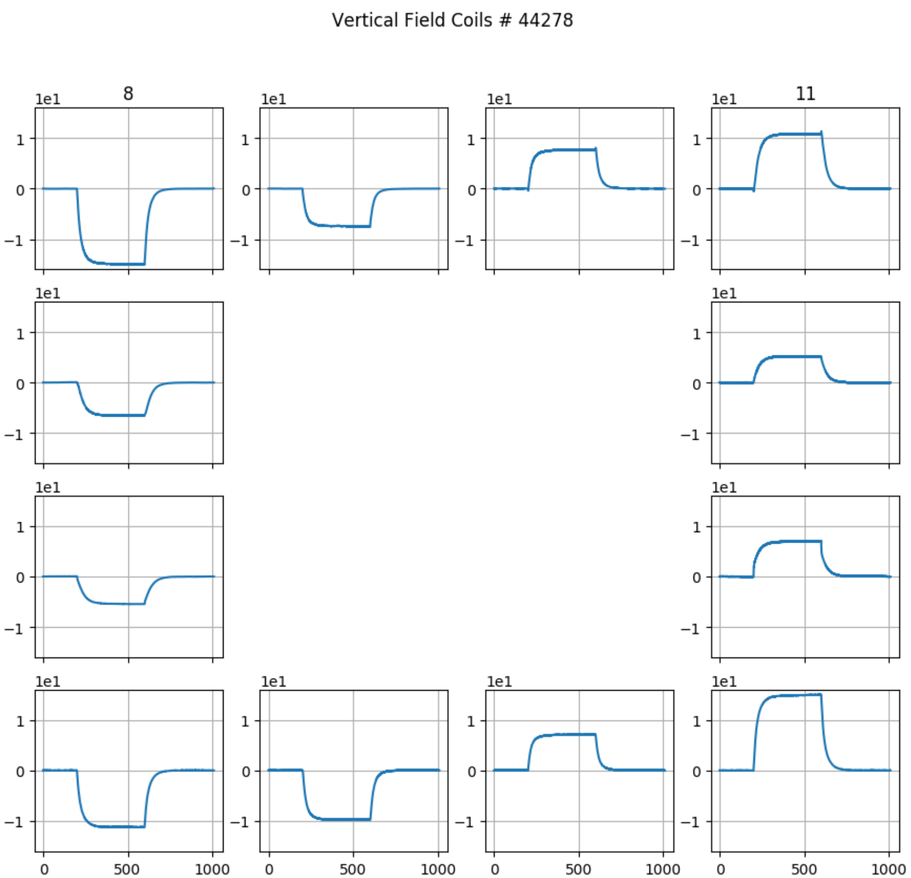


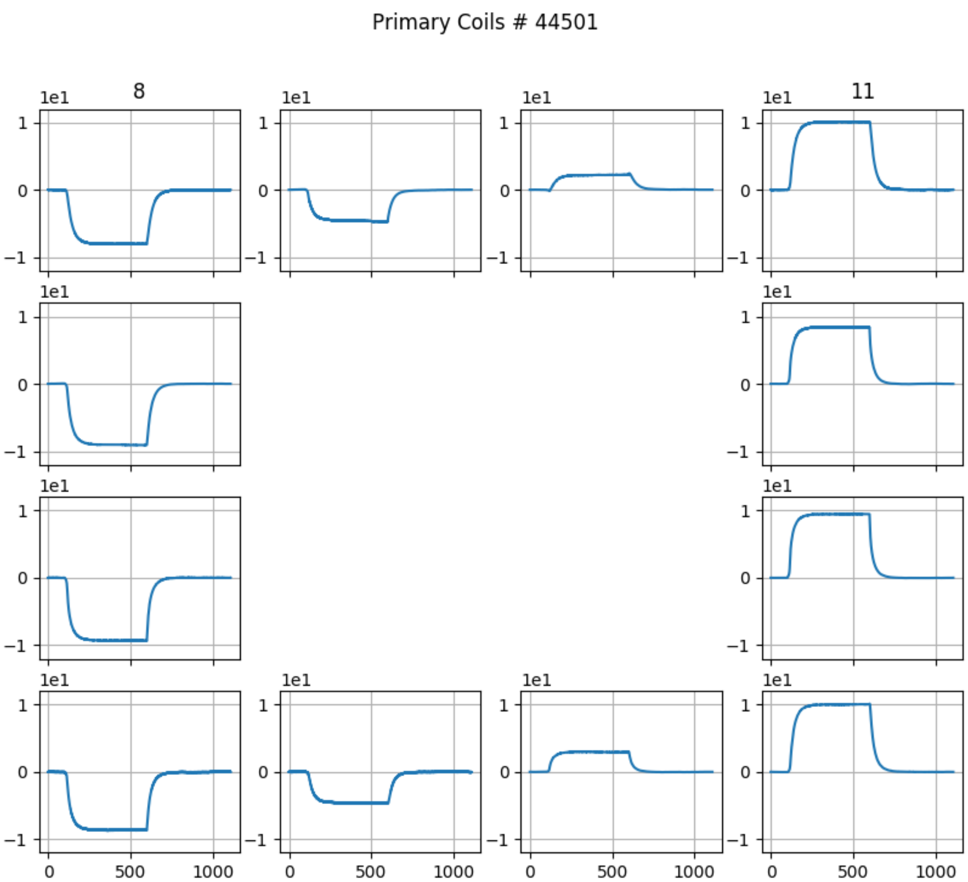


D. Corona

Remove PF coils field in the magnetic signals

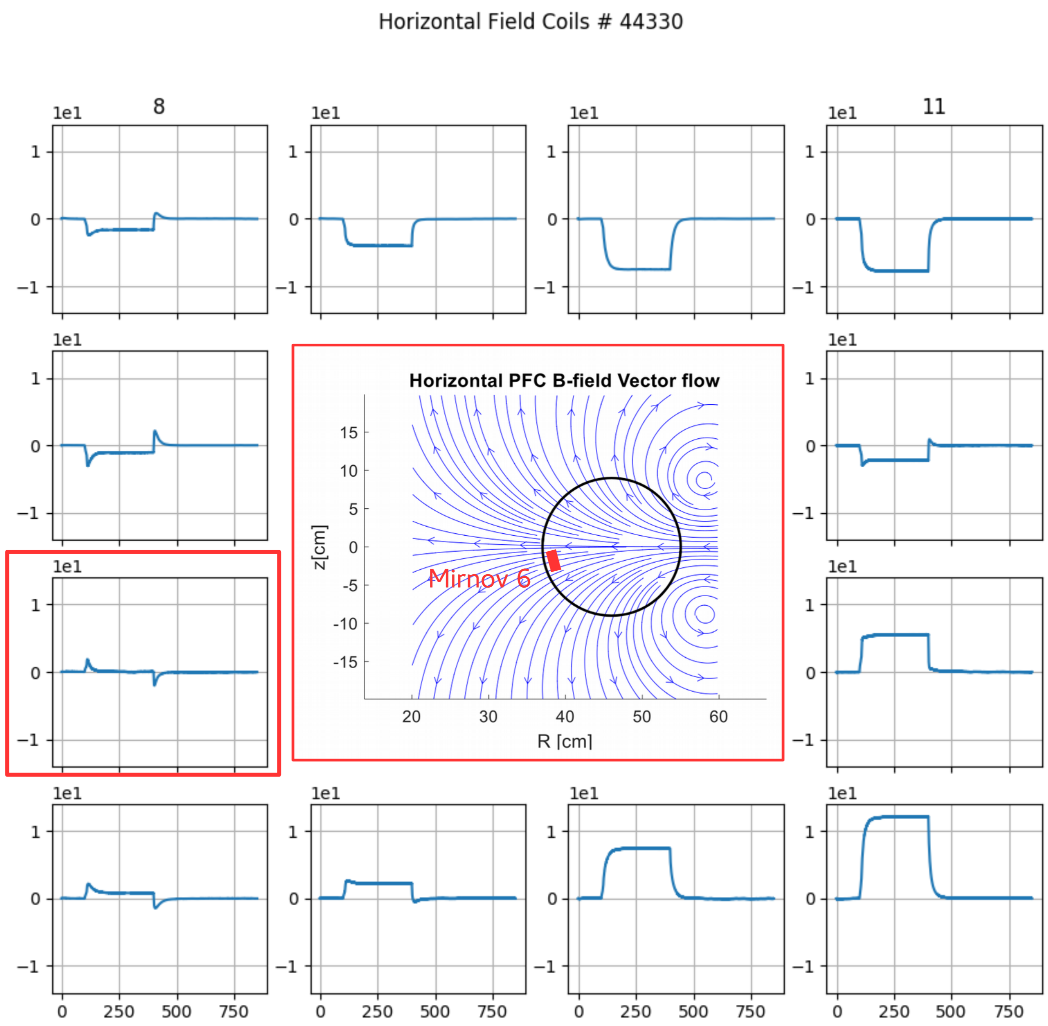
Plasmaless pulse –vertical field and primary





$$\tau \sim 30\, ms$$

Plasmaless pulse – horizontal field coils



Accurate computation of the magnetic field flux

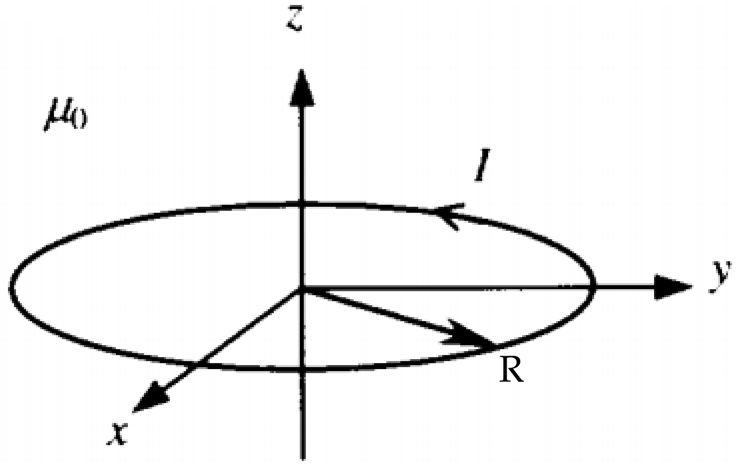
$$\vec{A}(\rho,\phi,z) = \vec{a}_\phi \frac{\mu I R}{4\pi}\oint \frac{\cos\theta d\theta}{\sqrt{z^2+\rho^2+R^2-2R\rho\cos\theta}}$$

$$A_\phi = \frac{\mu I R\sqrt{a+b}}{\pi b}\left[\left(1-\frac{k^2}{2}\right)K(k)-E(k)\right]$$

where K and E are complete elliptic integrals, and

$$a = z^2+\rho^2+R^2$$
$$b = 2R\rho$$
$$k = \sqrt{\frac{2b}{a+b}} = \sqrt{\frac{4R\rho}{z^2+(R+\rho)^2}}$$

Simple Analytic Expressions for the Magnetic Field of a Circular Current Loop, J. Simpson et al., 2012
https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20010038494.pdf



$$B_r = -\frac{2\mu I z}{4\pi\rho\sqrt{z^2+(R+\rho)^2}}\left(K(k)-E(k)\frac{R^2+\rho^2+z^2}{(R-\rho)^2+z^2}\right)$$
$$B_\phi = 0$$
$$B_z = \frac{2\mu I}{4\pi\sqrt{z^2+(R+\rho)^2}}\left(K(k)+E(k)\frac{R^2-\rho^2-z^2}{(R-\rho)^2+z^2}\right)$$

Accurate Formulas for A and B due to Circular Current Loops with Code, K. Nalty, 2012
http://www.kurtnalty.com/ClosedLoopFormulasForAandBwithCode.pdf

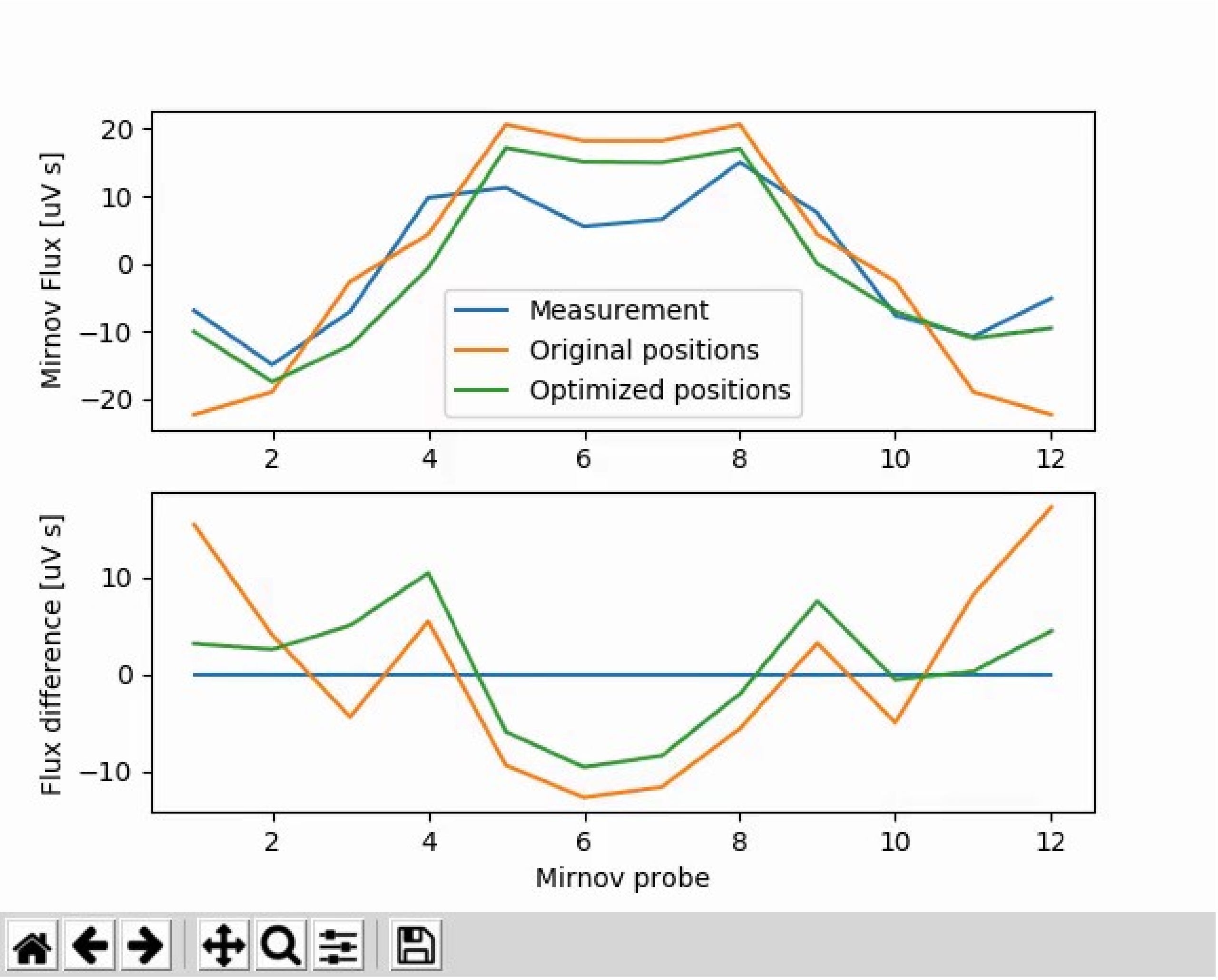
PFC position optimization

12 points, 4-8 (+) DoF
Several possible solutions

Manual 'fitting'

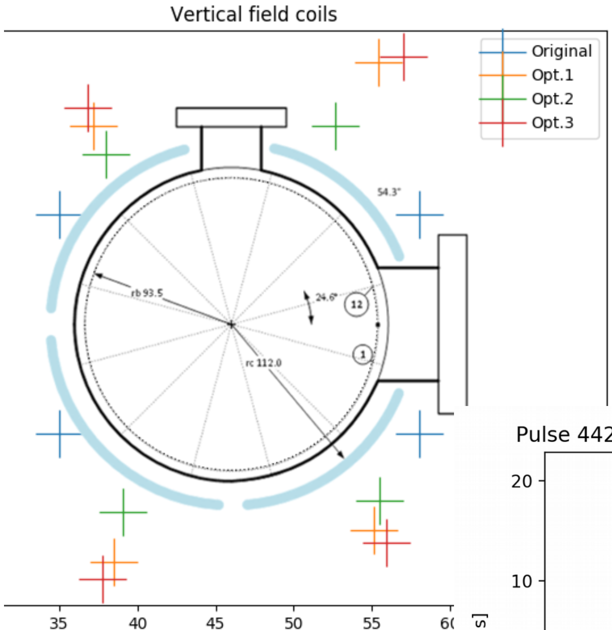
Developed script allows changing:

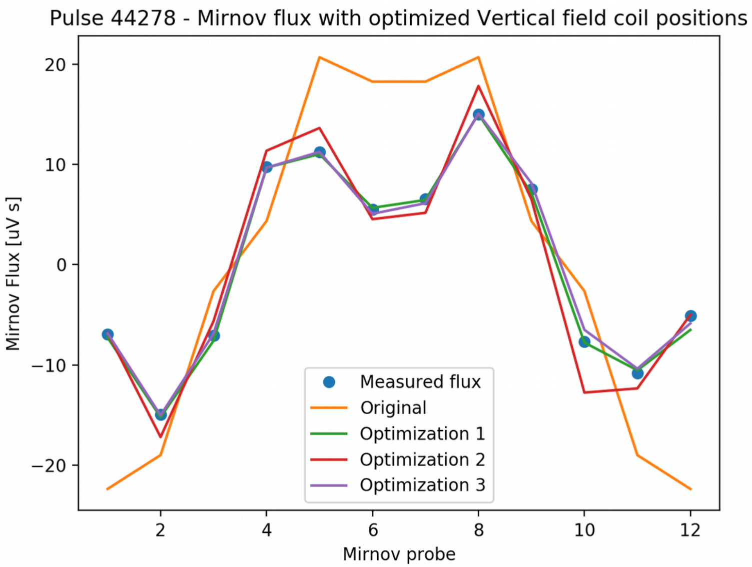
- R and Z coordinate of each coil independently
- Current on the set of coils
- Number of windings
- Empiric gain factor on Bz and Br



Vertical field coils optimization

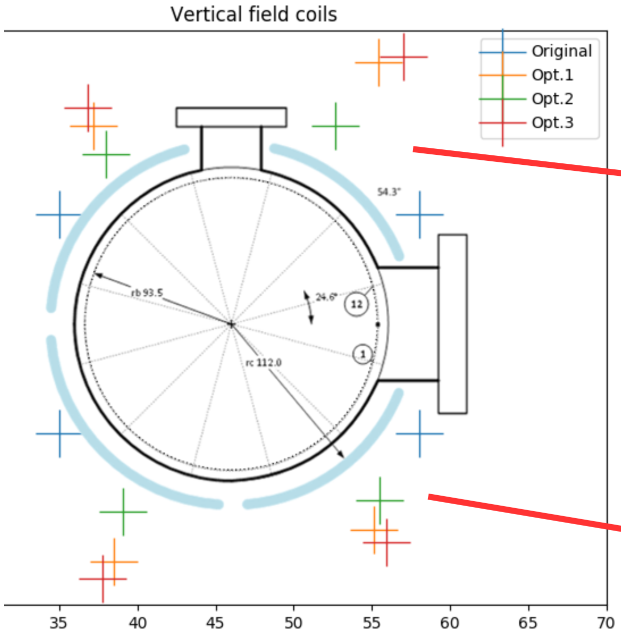
Optim.	R [cm]	Z [cm]	Notes
Nominal	58	-7	5 windings
	58	7	
	35	-7	
	35	7	
1	55,1	-13,2	
	55.4	16.7	
	38.5	-15.2	
	37.2	12.7	
2	55.47	-11.25	0.83 I gain
	52.64	12.68	
	39.05	-12.04	
	38.03	10.89	
3	55.9	-14	1.6 B_R gain
	57.0	17.1	0.8 B_Z gain
	37.8	-16.3	
	36.8	13.8	

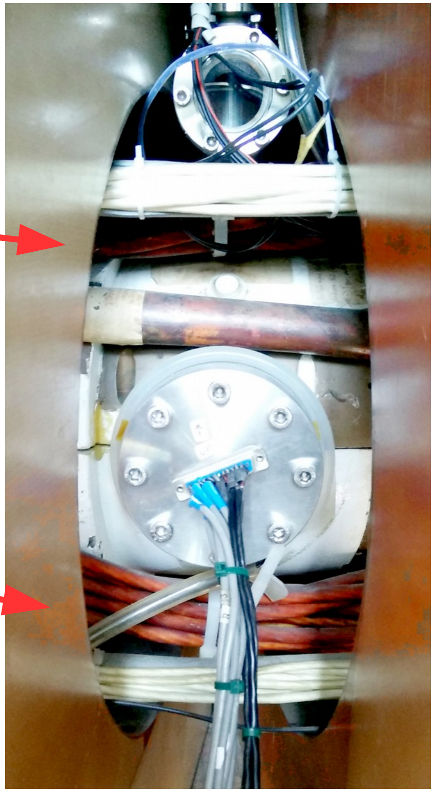




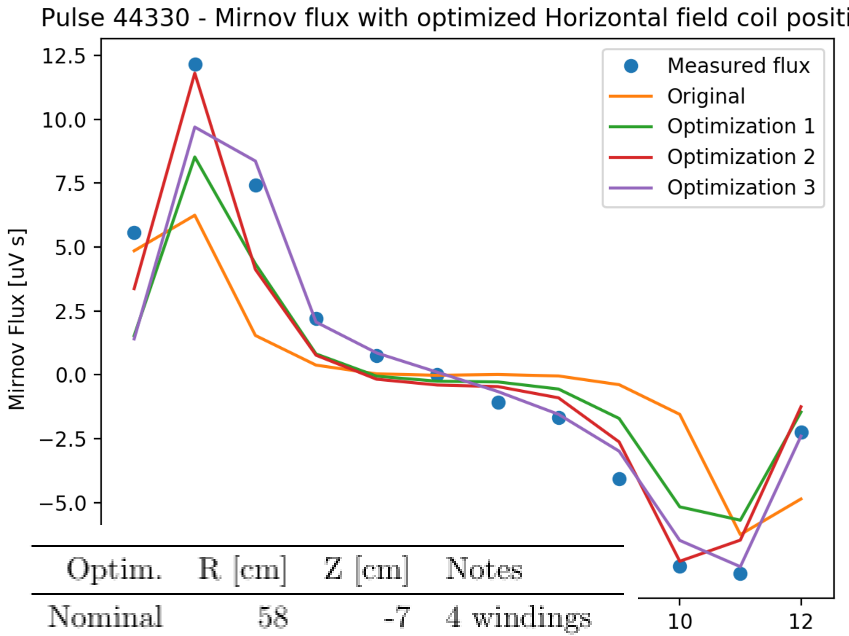
Vertical field coils optimization

Optim.	R [cm]	Z [cm]	Notes
Nominal	58	-7	5 windings
	58	7	
	35	-7	
	35	7	
1	55,1	-13,2	
	55.4	16.7	
	38.5	-15.2	
	37.2	12.7	
2	55.47	-11.25	0.83 I gain
	52.64	12.68	
	39.05	-12.04	
	38.03	10.89	
3	55.9	-14	1.6 B_R gain
	57.0	17.1	0.8 B_Z gain
	37.8	-16.3	
	36.8	13.8	

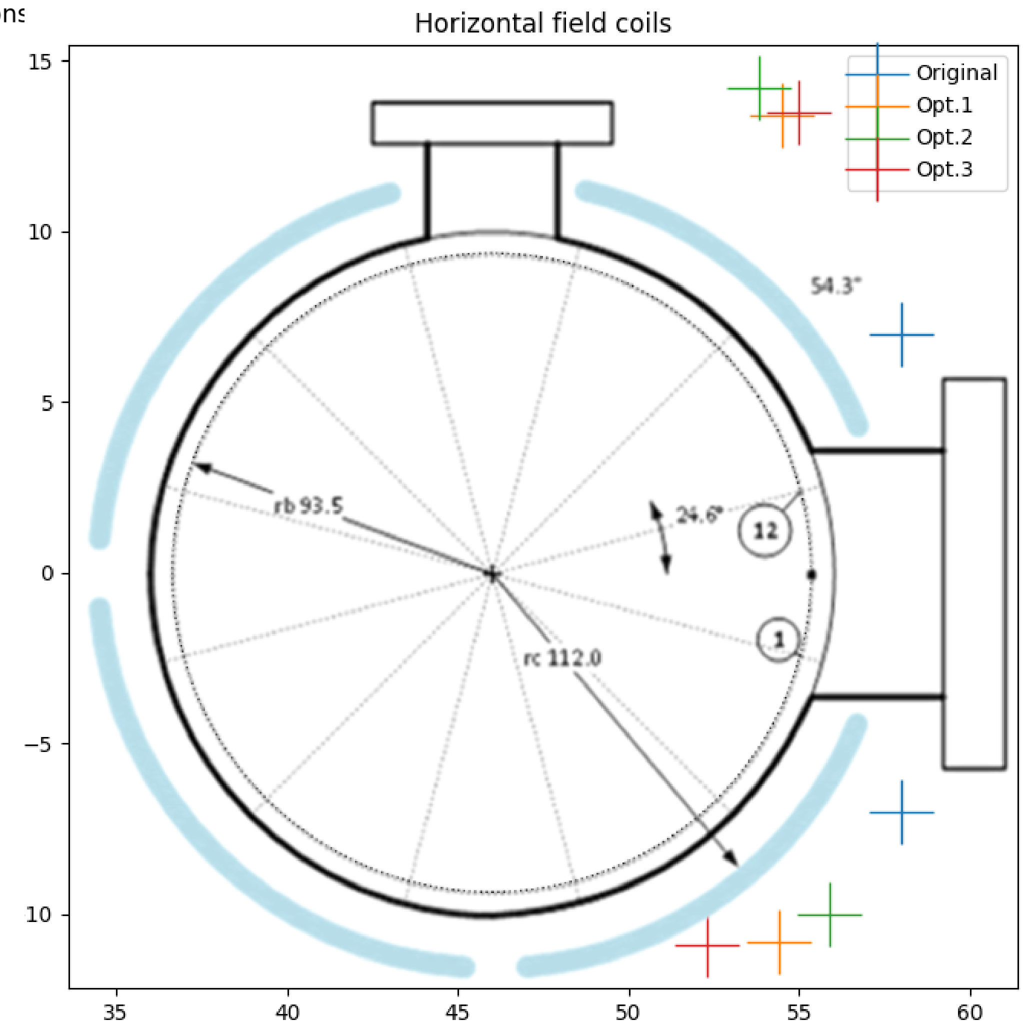




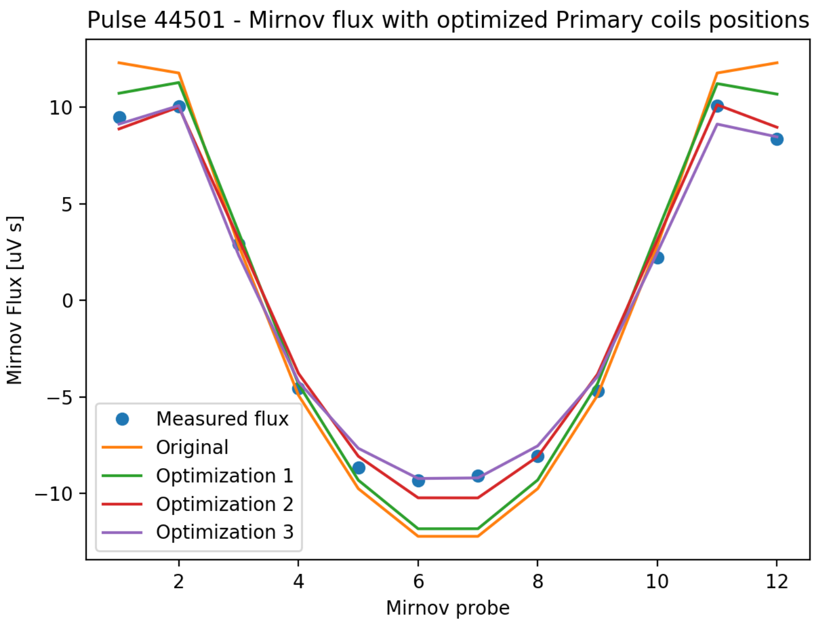
Horizontal field coils optimization



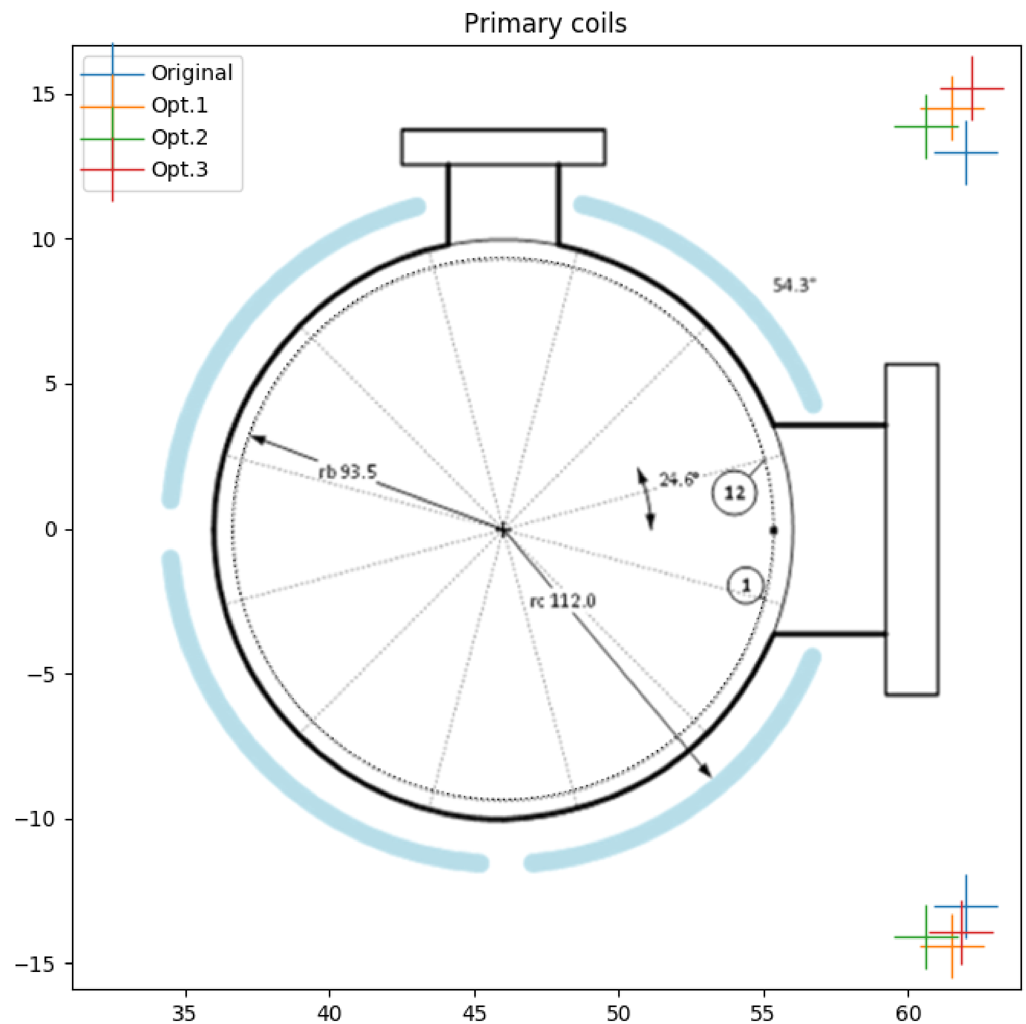
Optim.	R [cm]	Z [cm]	Notes
Nominal	58	-7	4 windings
	58	7	
1	54.4	-10,8	
	54.5	13.4	
2	55.9	-10.0	1.324 I gain
	58.8	14.6	
3	52.3	-10.9	1.6 B_R gain
	55.0	13.5	0.8 B_Z gain
			0.91 I gain



Primary coils optimization



Optim.	R [cm]	Z [cm]	Notes
Nominal	62	-13	14 windings
	62	13	
1	61.5	-14.4	
	61.5	14.5	
2	60.6	-14.1	0.842 I gain
	60.6	13.9	
3	61.8	-13.9	1.6 B_R gain
	62.2	15.2	0.8 B_Z gain



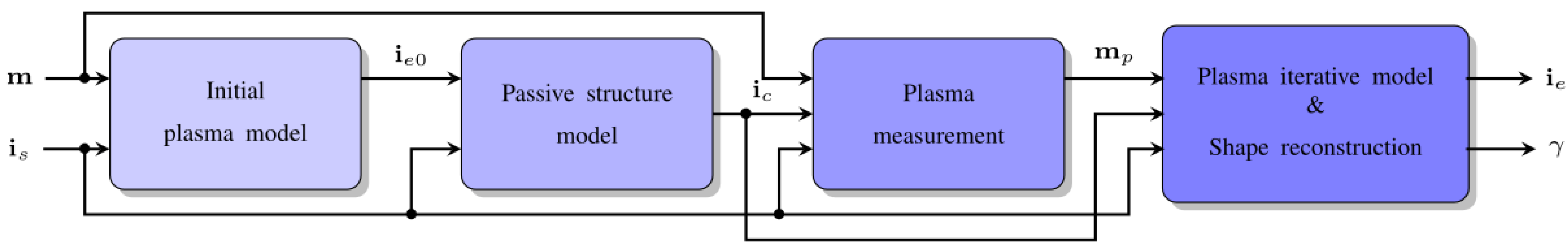
LTI model for axisymmetric structures

Modeling the eddy currents on the passive stuctures

Finding an optimized location of discrete current filaments that would fit the magnetic data

1. Filamentary model of the plasma
2. Computation of a filamentary model of the currents on the passive structures
3. Correction of the error field on the magnetic measurements
4. Reconstruction/contol algorithms

m - magnetic measurements
i_s - active coil currents
i_c - eddy currents
i_e - plasma model
γ - shape parameters



A. Cenedese, et al. - Model-Based Approach for Magnetic Reconstruction in Axisymmetric Nuclear Fusion Machines (2018)

LTI model implemented

$$\dot{\Psi}_c = -R_c M_{cc}^{-1} \Psi_c + Rc M_{cc}^{-1} M_{cs} i_s$$

$$i_c = M_{cc}^{-1} \Psi_c - M_{cc}^{-1} M_{cs} i_s$$

$$\dot{\Psi}_c = A \Psi_c + B i_s$$

$$i_c = C \Psi_c + D i_s$$

$$L_{i,j} = 2\pi R A_\varphi(R, z)$$

$$L_c = \mu_0 R(ln(8R/a)) - 2 + Y/2$$

$$\rho = 1.68 \cdot 10^{-8}\ \Omega\mathrm{m}^{-1}$$

Interactive script for filament position optimization

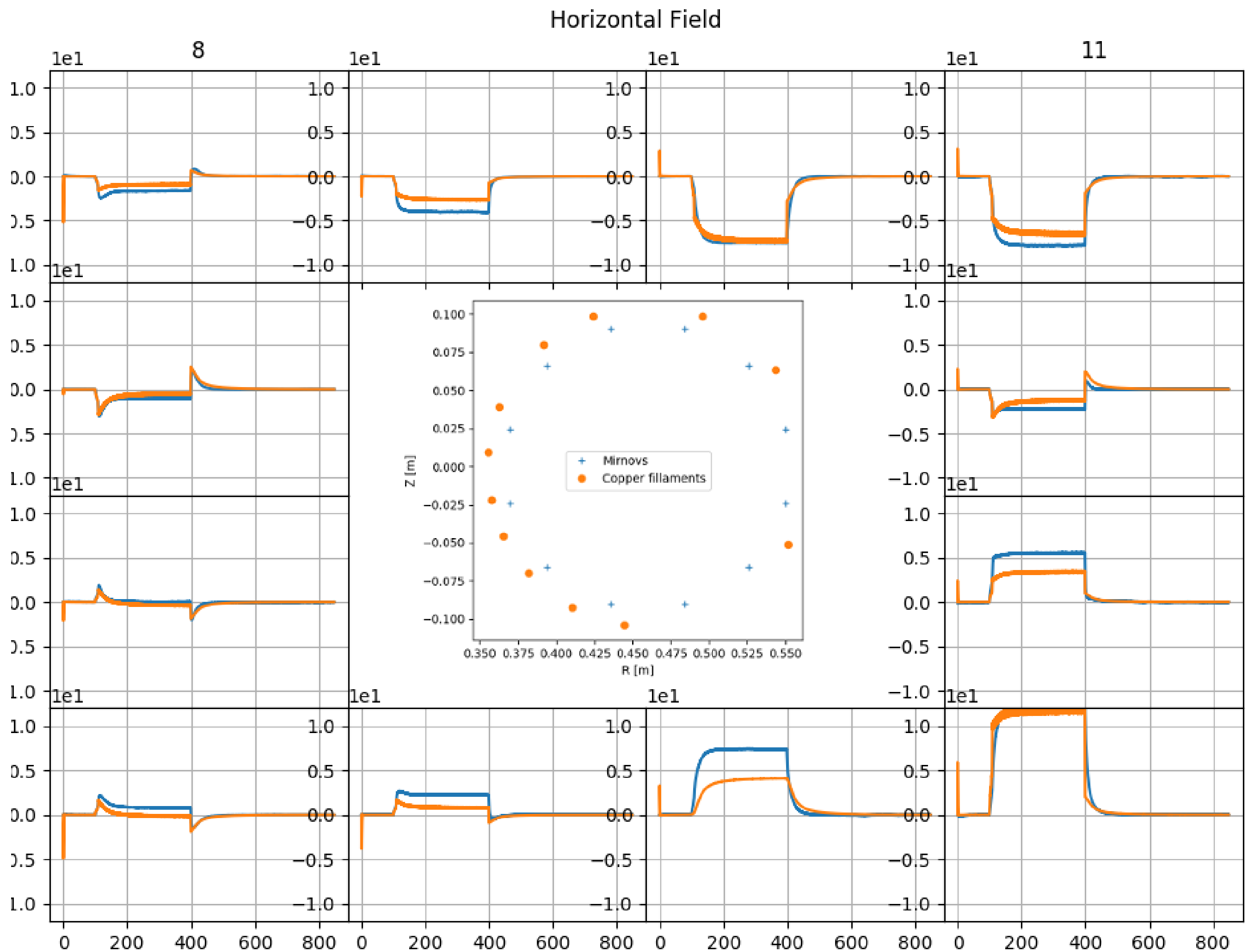
Interative script

a=10 mm;

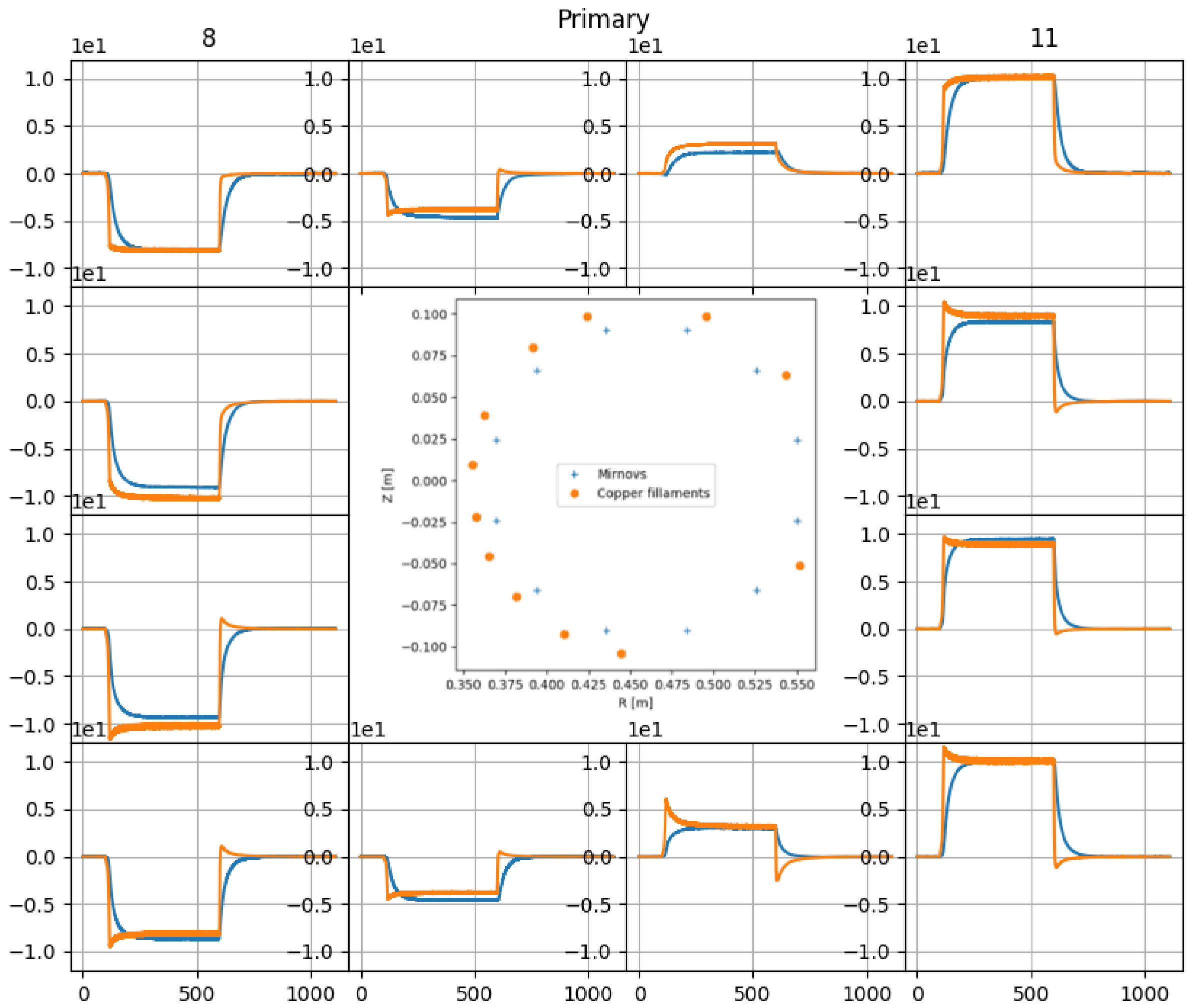
12 filaments

Interactively change the angle of the each filament, observing the efect on the 3 closest mirnovs

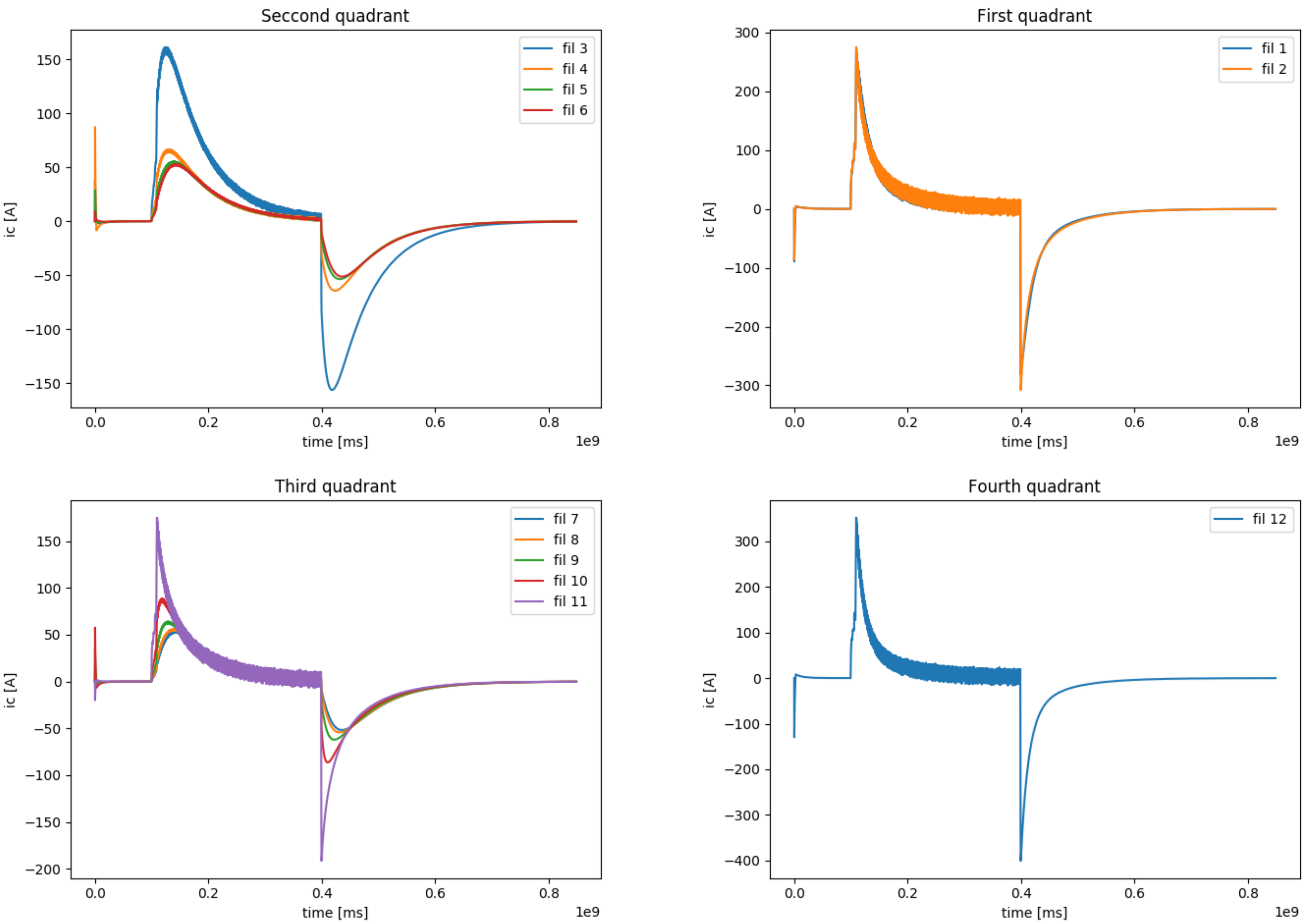
Allowed angles:
[20, 70], [110, 175], [180, 265], [275, 340]



Interactive script for filament position optimization



Interactive script for filament position optimization



Conclusions and future work

Implemented model relies on the active coils positions for the mutal indutance between the filaments and PFCs and is therefore essential to have low uncertenty.

Measurements on the PFC **actual positions** in order to reduce the number of DoF.

Missalignments or misscalibration on the mirnov coils can not be rulled out, effective area.

Modeling of the **iron core** for correction of the field on HFS

Copper shell **not** axisymetric

A precise computation of the external and error magnetic flux on the mirnov coils is needed in order to apply boudary reconstruction algorithms or to use the Mirnov coils for active control or plasma boundary reconstruction.