Free boundary equilibrium code CEDRES++

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Introduction

Tokamak design and plasma scenario studies require the development of new performant numerical simulation tools. Free boundary equilibrium codes are mandatory to get an comprehensive description including PF coils related issues. The CEDRES++ code has been improved to match the requierements of such a simulation tools. In parallel, CEDRES++ is being integrated in the ITM platform and gives the possibility to compute equilibrium on every tokamak even on iron core devices like JET or Tore Supra. Moreover, an inverse version of the code allows to find a set of PF coils currents in order to best fit a given plasma shape.

Equations solved

$$L_\mu \psi = j_\varphi \quad \text{with } L_\mu \psi \equiv -\frac{\partial}{\partial r}\left[\frac{1}{\mu r}\frac{\partial \psi}{\partial r}\right] - \frac{\partial}{\partial z}\left[\frac{1}{\mu r}\frac{\partial \psi}{\partial z}\right]$$

▪**In the plasma** (Grad Shafranov)

$$j_\varphi = r\frac{\partial p}{\partial \psi} + \frac{1}{2\mu_0 r}\frac{\partial f^2}{\partial \psi}$$

▪**In the ith PF coil**

$$j_\varphi = \frac{I_i}{S_i}$$

where Si is the surface of ith the coil and Ii the total current

▪**Elsewhere**

$$j_\varphi = 0$$

▪**In the iron** the magnetic permeability μ depends non linearly on the poloidal magnetic field. Elsewhere $\mu = \mu_0$

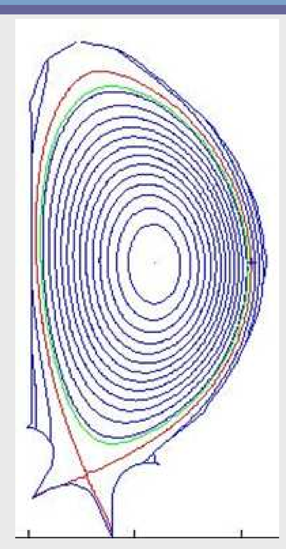
• Boundary conditions: ψ=0 on vertical axis and at infinity

Direct problem

•Compute the solution **ψ** of the **equilibrium** problem using as input PF coils currents, current density profile and Ip

• Numerical method: **P1 finite element** method coupled with **boundary integral method** used to satisfy the condition ψ=0 at infinity

•Non linearities: **Picard or Newton** iterations



ITER equilibrium

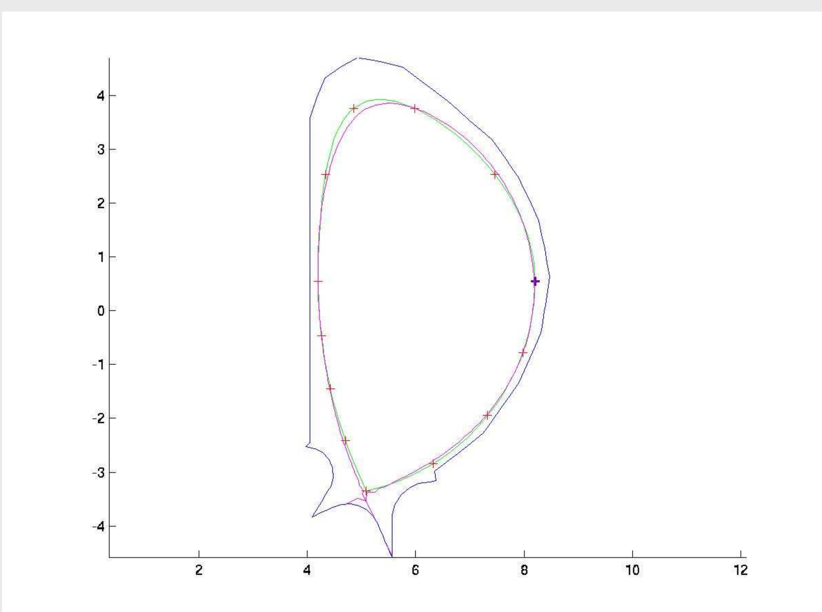
Inverse problem

•Find an optimal **distribution of current in the PF coils** in order to best match a **desired plasma shape**

•Minimisation of cost function J(I, ψ) where the components of the vector I are the currents in the PF coils, and ψ is solution of the equilibrium configuration corresponding to the currents I:

$$J(I,\psi) = \frac{1}{2}\oint_{\Gamma_d} \alpha(M)\left[\psi(M) - \psi(M_0)\right]^2 dl + \frac{1}{2}\alpha_X \int_{V_X} \frac{1}{r}\left|\vec{\nabla}\psi\right|^2 ds + \frac{1}{2}\sum_{i=1}^{m} k_i I_i^2$$

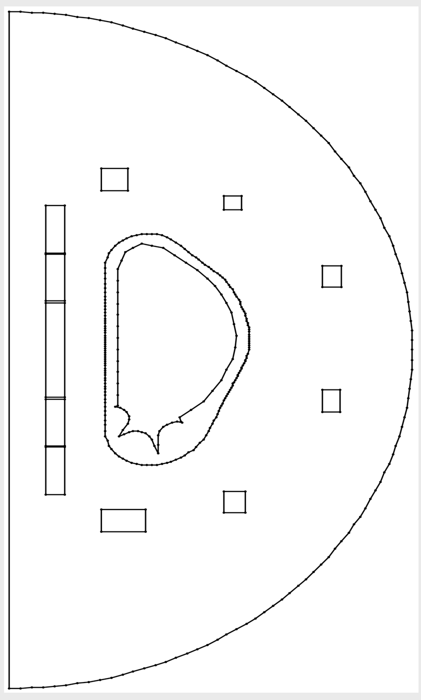
where Γ_d is the desired plasma boundary, Vx is a neighbourhood around the desired X-point position and $\alpha(M), \alpha_x, k_i$ are weights to give more or less importance to the different terms of the cost function

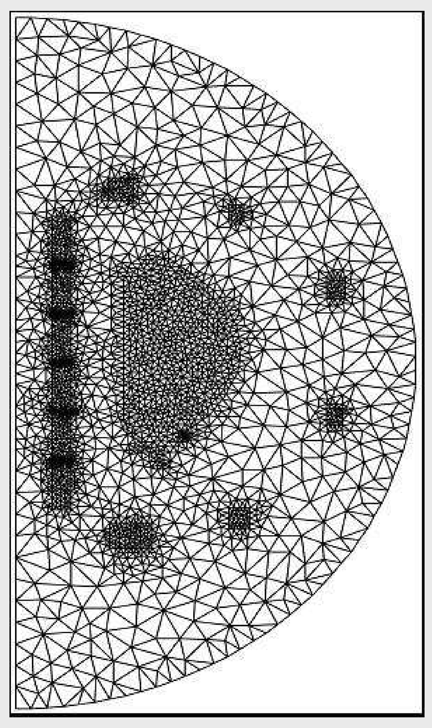


Comparison between the desired plasma boundary (dots and green curve: DINA results) and the plasma boundary calculated by CEDRES++ in inverse mode (pink curve) for the ITER SOB equilibrium.

New developments

Integration of an automatic mesh generator:
The mesh is automatically generated using the machine description. The mesh generator used named TRIANGLE is very fast. A new mesh is created in a few ms.





Current profile density: possibility to give current density profile at discrete points to allow interfacing to a transport solver

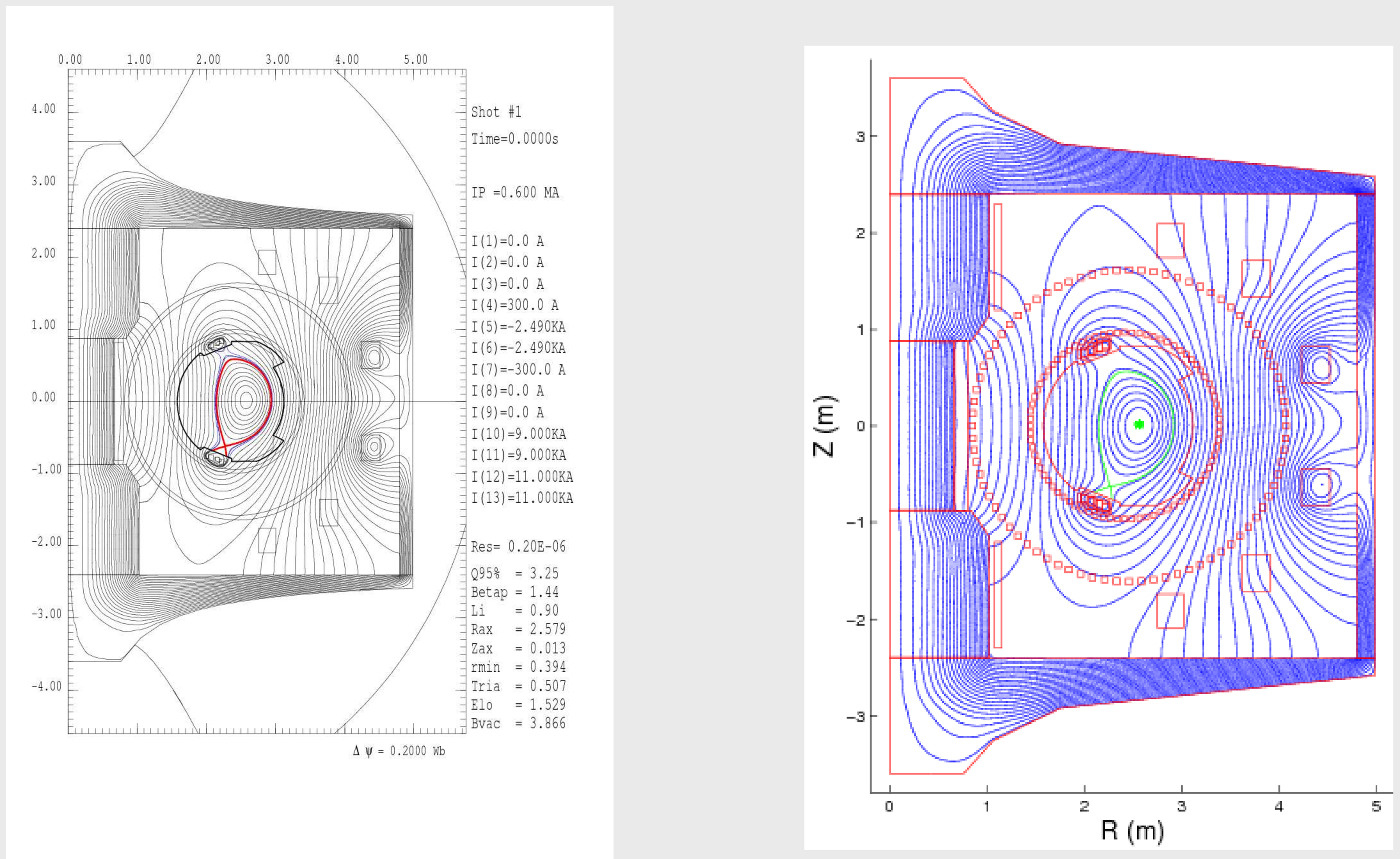
Integration of the iron model: Non linearities treated by Newton or Picard iterations

Direct problem validation

•The validation of CEDRES++ based on a benchmark with DINA and Proteus equilibrium codes is in progress.

• Good agreement between CEDRES and DINA on the ITER inductive scenario

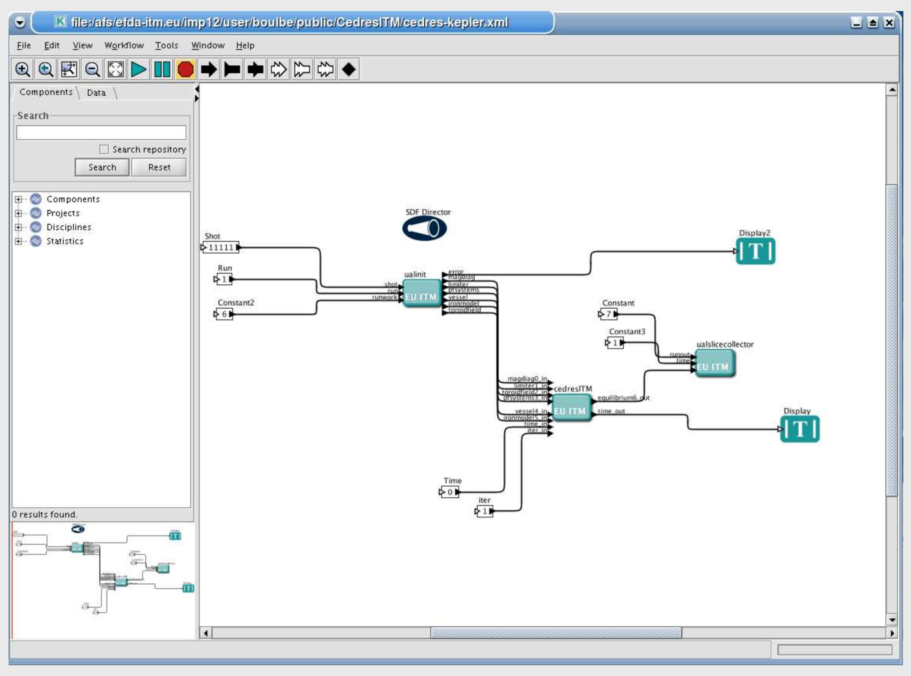
• Validation of the iron model with Proteus: good agreement on the first test case



Poloidal flux map calculated by PROTEUS (left) and CEDRES++ (right) for a Tore Supra Divertor Tungsten reference equilibrium

ITM integration

• CEDRES-ITM version avalaible as a GForge project
• Kepler actor avalaible



•Perspectives

• Development of an evolutive version of CEDRES++ including circuit equations and diffusion of induced currents in vaccuum vessel currently being tested (with G. Selig)
• Next step: coupling the evolutive version with the transport code CRONOS (preparing coupling to the ETS)