DE LA RECHERCHE À L'INDUSTRIE

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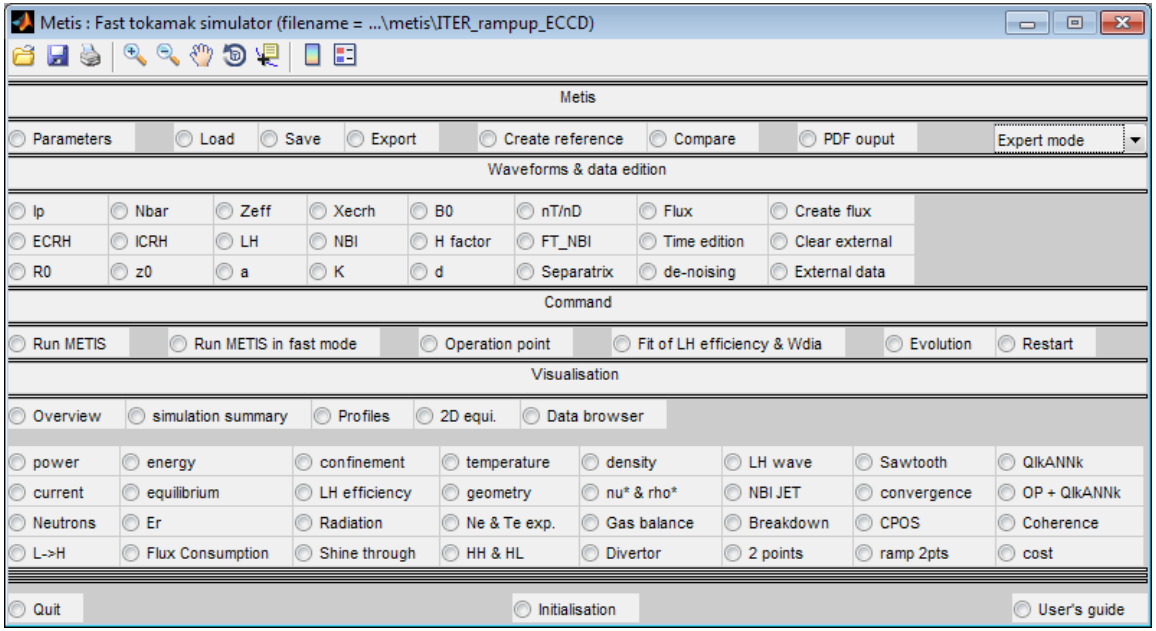
METIS HOWTO



WEDNESDAY, 21 JULY 2021

METIS: A FAST INTEGRATED TOKAMAK MODELLING TOOL FOR SCENARIO DESIGN

- **METIS is a numerical code aiming at fast full tokamak plasma analyses and predictions:**
  - **It combines 0D scaling-law normalised heat and particle transport with 1D current diffusion modelling and 2D equilibria.**
  - **It contains several heat, particle and impurities transport models, as well as heat, particle, current and momentum sources**
  - **It allows faster than real time scenario simulations for reactor simulations.**

- **METIS applications and use cases:**
  - **Tokamaks discharges analysis (WEST, Tore Supra, JET, TCV, DIII-D, EAST, HL2A, COMPAS, …)**
  - **Scenario predictions (JT-60SA, DTT, HL2M)**
  - **Reactor studies (ITER, DEMO, CFETR, …)**
  - **Data provider for other codes (as CRONOS)**
  - **Plasma plant simulator in control workflow**
  - **Students teaching and training**

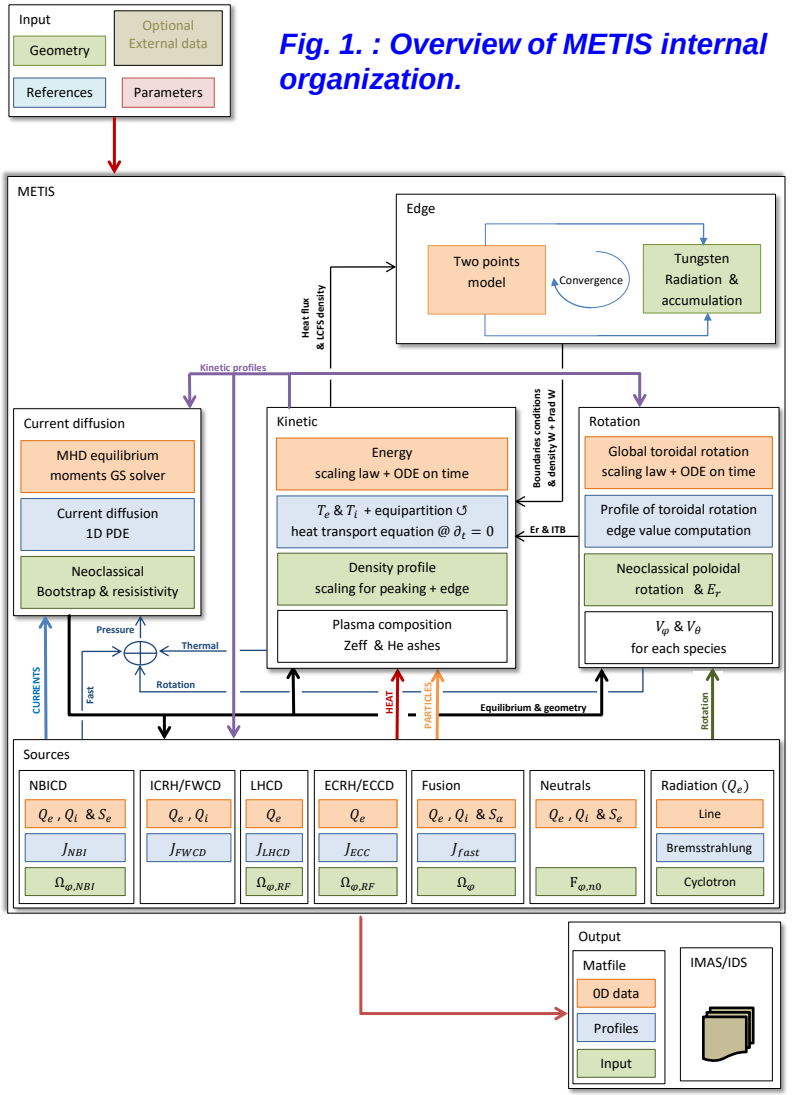


Fig. 1. : Overview of METIS internal organization.

J.F. Artaud et al 2018 Nucl. Fusion 58 105001 (http://iopscience.iop.org/article/10.1088/1741-4326/aad5b1)

FOREWORD

- The goal of this HOWTO is to learn how to run METIS:
  - Connected to database or with scenario generator
  - Compiled or inside Matlab
  - With or without IMAS interface
  - Inside Simulink

- The HOWTO explains what METIS is but does not provide a detailed training on METIS Physics applications

OUTLINE

METIS OVERVIEW

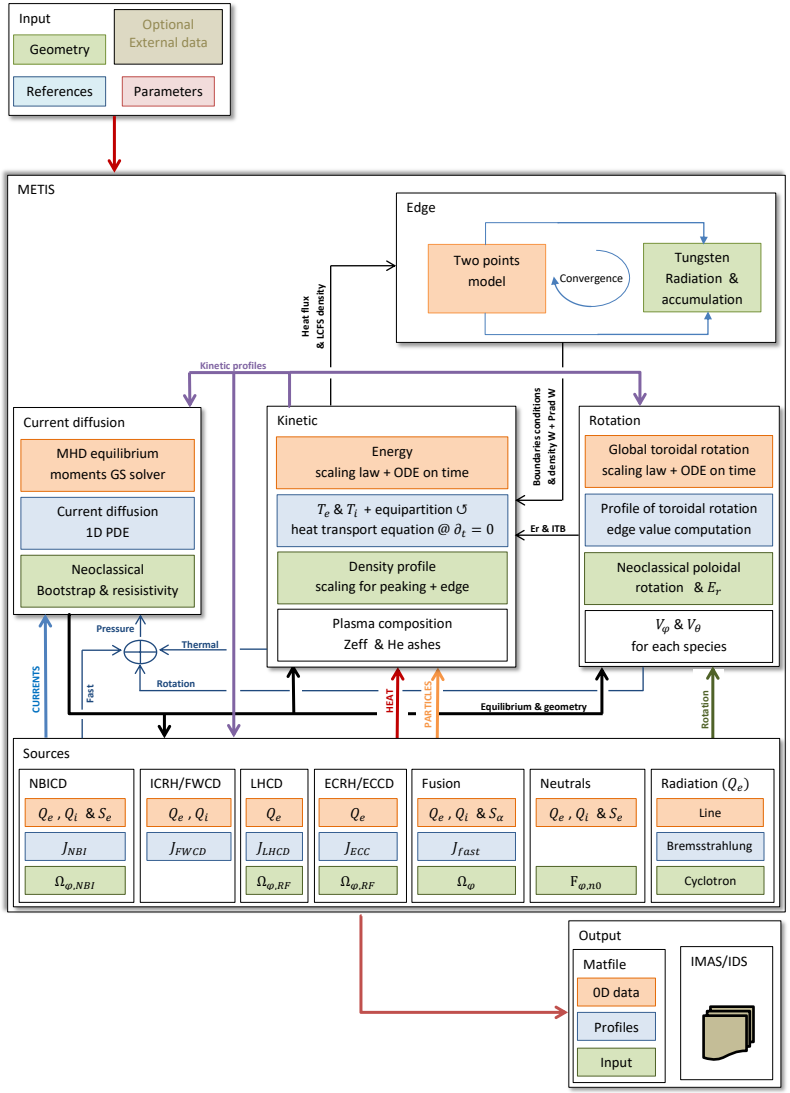
WHAT IS METIS

- **METIS is a fast Integrated Transport Code with simplified assumptions**
- **All parameters of an ITER discharge calculated in 1 minute (300 time slices)**
- **Designed for**
  - **Scenario Design**
  - **Flight Simulator**
  - **First analysis of a discharge**
- **Mixture of 0D and 1.5D equations**
- **Highly convergent computing scheme**
- **Originally part of CRONOS**

MAIN METIS FEATURES

- ✓ **Mixed 1D and 0D equations**
  - ✓ **Current diffusion 1.5D with moment equilibrium**
  - ✓ **Source profiles deduced from simple models**
  - ✓ **Global energy content from 0D ODE (scaling, transients)**
  - ✓ **Temperature profiles : stationary 1D solution, χ scaled to W_{th}**
  - ✓ **All non-linearities solved (dependence of sources on profiles, fusion power, He ash transport)**
  - ✓ **Bootstrap and resistivity :Sauter O. et al 1999 Phys. Plasmas 6 (et non 7), 2834; ibid. 9 (2002)**
- ✓ **Input : Power references, I_P, plasma density, Z_{eff} , LCMS geometry**
- ➢ **Output : all standard 1D and 0D data that you would expect from a transport code**
- ➢ **Global time convergence (wave form relaxation)**

METIS INTERNAL WORKFLOW



METIS has 2 main use cases:

- **Stand-alone full scenario simulation**
  - CRONOS module
  - Matlab function with data base access or UAL connection
  - Standalone runtime (no Matlab license need) with data base access or UAL connection
- **One time step solver in a workflow**
  - Use inside Simulink workflow (simmetis)
  - Use inside Kepler workflow through Matlab actor

METIS DATABASES CONNEXIONS

- Direct connection:
  - Tore Supra / WEST: pre and post shot access (Tslib)
  - JET: MDS+ access to JET data using shared ssh key
  - Compass: dedicated library
  - IMAS & ITM databases: UAL
- Indirect connection:
  - DIII-D: dedicated tool (to be run on DIII-D computers)
  - EAST: dedicated tool (to be run on EAST computers)
  - Asdex-U: still incoming
  - TCV: MDS + access from SPC

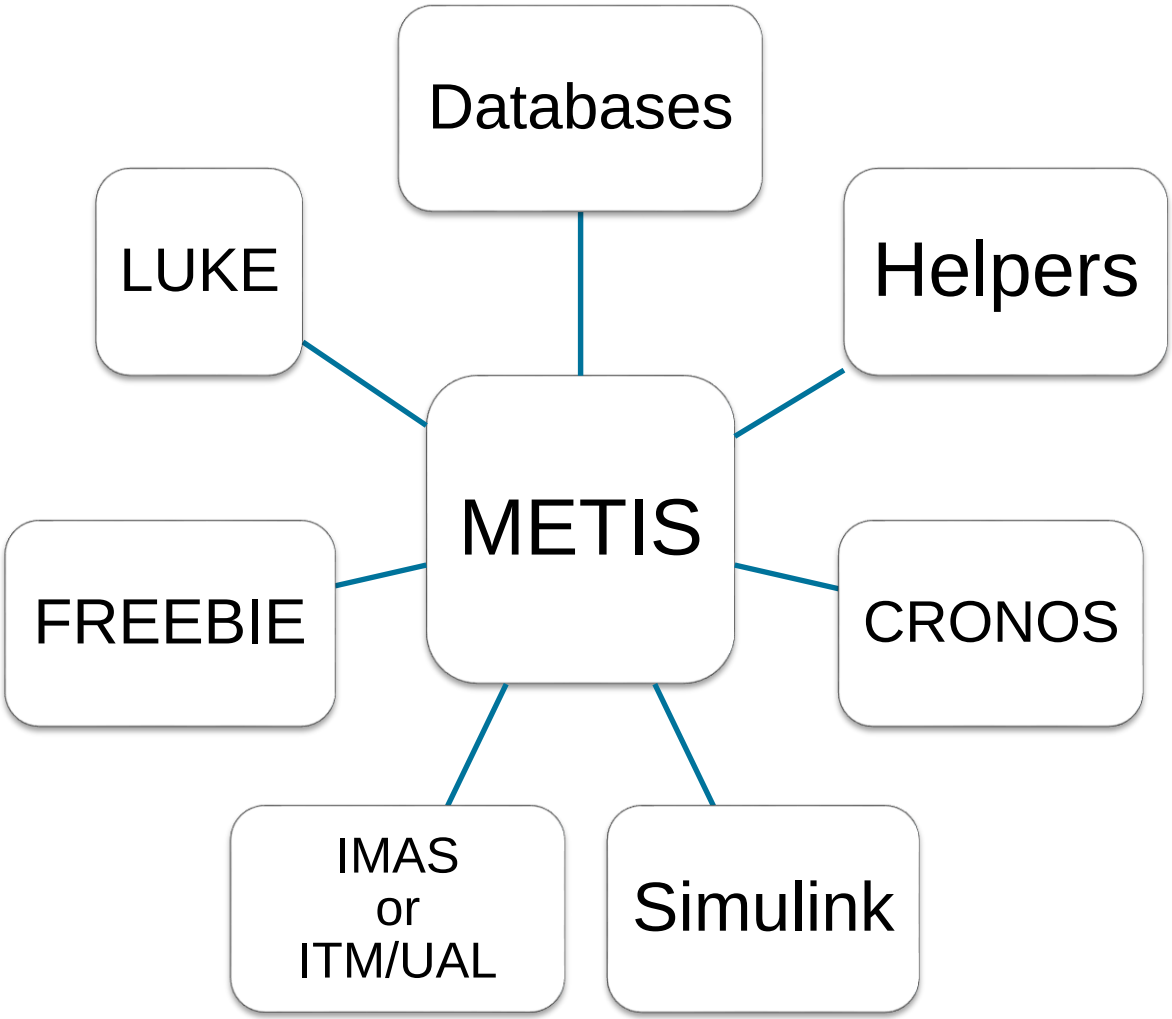
➢ Allows comparison to experimental data.

METIS SCENARIO GENERATORS

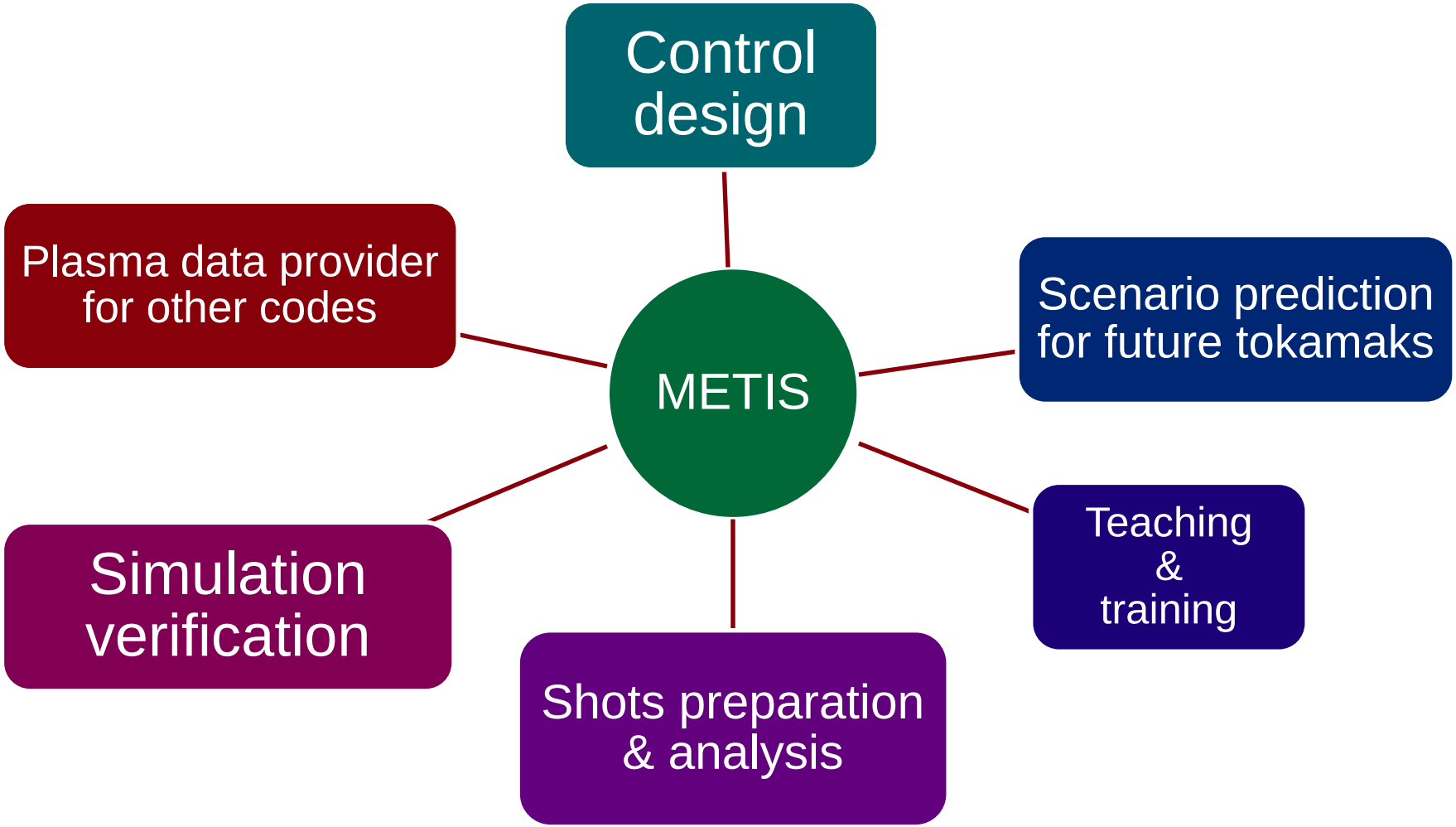
- Tool to prepare a complete scenario ab-initio:
  - Set waveforms and parameters
  - Including ramp-up, flattop and ramp-down
  - Take into account specificity of each device
  - Can be fine tuned from METIS GUI

- Available generators:
  - WEST
  - JT-60SA
  - Reactors (ITER, DEMO, …)

METIS ECOSYSTEM OVERVIEW



METIS APPLICATIONS



LAUNCH METIS

DIFFERENCE BETWEEN VERSIONS

- **METIS as a CRONOS module:**
  - Exchange data between CRONOS↔ METIS
  - Access to more data bases : DIII-D, …
  - Complementary tools : HELENA, NCLASS direct call
- **METIS for IMAS or ITM:**
  - Access to UAL
  - Coupling with Kepler and Python workflow
- **METIS standalone:**
  - Simpler installation
  - Can be called from Simulink
- **METIS runtime (compiled version):**
  - No Matlab license needed (= no Matlab workspace)
  - Work on many OS
    (available for Windows, on demand for Mac OS/X and Linux)

WHERE TO FIND METIS ? (1/4)

- **Pre-installed version:**
  - **On zone intra:**
    any server (but Sirrah is faster)
  - **On zone partenaires IRFM servers:**
    Altair, …
  - **On EUROfusion servers**
  - **ITER servers**

WHERE TO FIND METIS ? (2/4)

- **Source of the code:**
  - **On zone intra and partenaires:**

    /Applications/Metis/metis

  - **On ITER Git server:**

    https://git.iter.org/projects/SCEN/repos/metis

  - **In EUROfusion Gforge server:**

    https://gforge-next.eufus.eu/#/project/metis4itm

WHERE TO FIND METIS ? (3/4)

- **Compiled versions (Windows):**

  – **On Erakis server :**

    C:\Users\JA132999\Documents\Metis64

  – **Request the installer file:**

    send me a email: jean-francois.artaud@cea.fr
    need a license for non IRFM user (but it is free)

  – **First installation:**

    Need to have administrator right for the first installation

WHERE TO FIND METIS ? (4/4)

Pre-installed version:

- **Local PC version :**
  - **Launch: “metisPC64.exe” (Windows 7, …)**
- **Intra & partenaires zone version**
  - **Load module: module load tools_dc**
  - **Launch: /Applications/Metis/metis/metis**

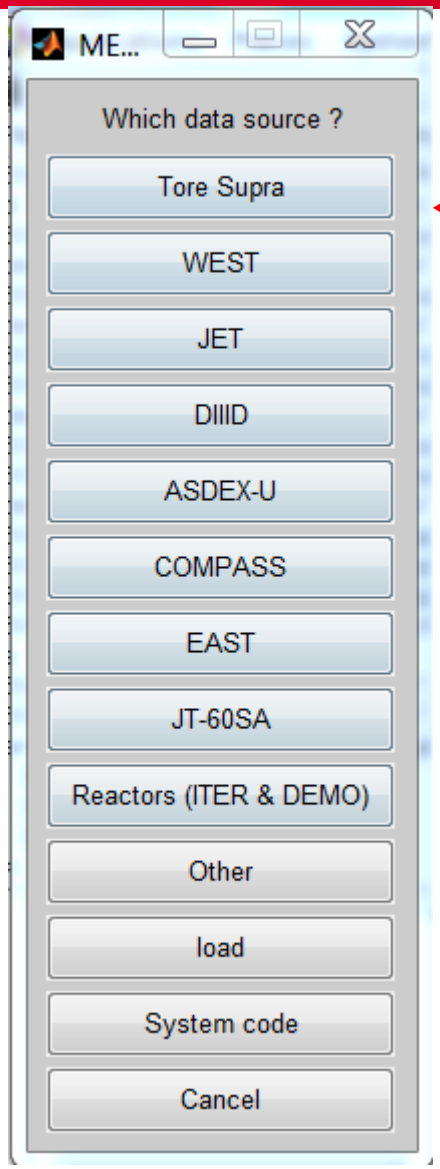
METIS RUN

- **Two ways:**

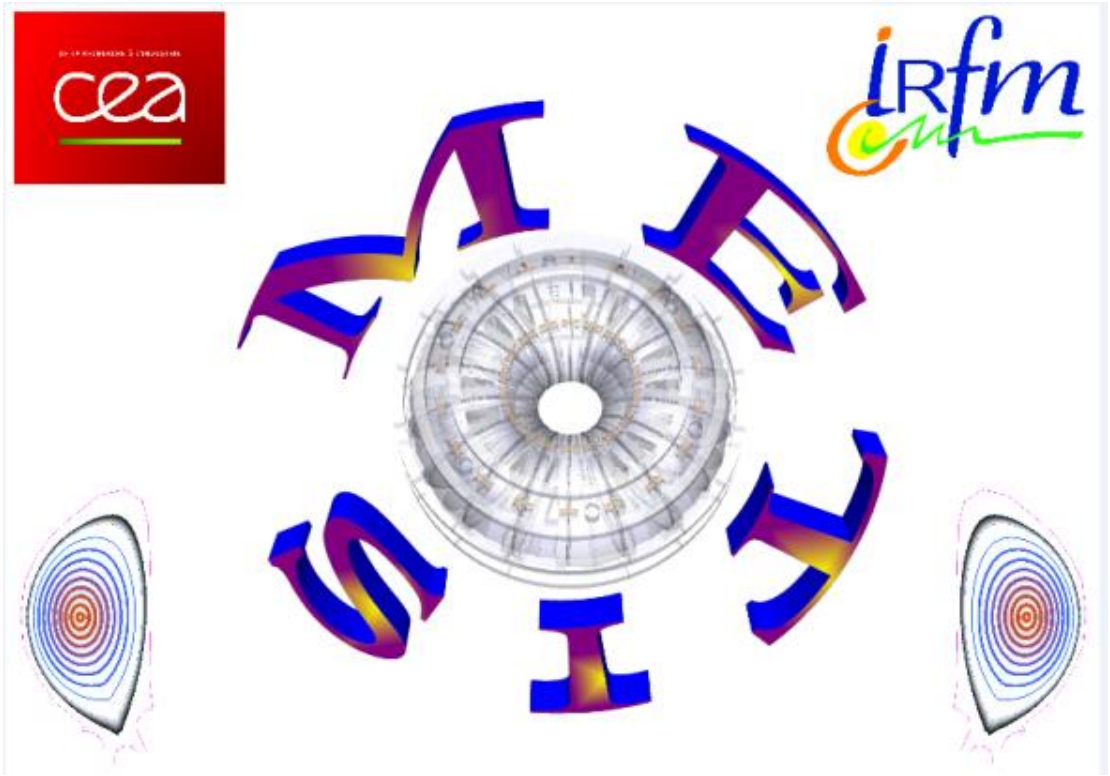
  – **outside matlab : just launch metis script**
  inside directory …/metis4itm/trunk

  – **Inside matlab :**
  addpath to metis4itm
  addpath …/metis4itm/trunk
  and launch metis

RUNNING COMPILED VERSION OF METIS



METIS_HELP.pdf	26/02/2013 14:25	Adobe Acrobat D...
METIS_JET_73344	18/05/2017 15:24	Microsoft Access T...
Metis_splash_screen3.png	04/06/2012 14:51	Image PNG
metisPC64.exe	18/05/2017 10:22	Application
MetisPC64.log	19/05/2017 09:33	Document texte



LAUNCH METIS WITH IMAS IRFM SERVERS

How to run it:

1) Source IMAS environment:

   module load tools_dc

2) Select a device:

   imasdb west

3) Launch METIS script (public version):

   /Applications/Metis/metis/metis

LAUNCH METIS WITH ITM/UAL ON GATEWAY

How to run it:

1) Source UAL environment:

   module load imasenv

2) Select a device:

   imasdb west

3) Launch METIS script (public version):

   /afs/eufus.eu/g2itmdev/user/g2jfa/public/metis4itm/trunk/metis

METIS DOCUMENTATION

AVAILABLE DOCUMENTATION

- **In directory “doc” of METIS code (see below)**
- **Main documentation**
  - **Artaud_2018_Nucl._Fusion_58_105001.pdf**
    → Reference paper
  - **Howto_METIS_final.pdf**
    → user guide (this presentation)
  - **METIS_installation_guide.pdf**
    → guide for METIS installation and compilation
  - **description_model_ICRH_Dumont-Vu.pdf**
    → ICRH model details
  - **METIS_Core_edge_coupling_howto.pdf**
    → 2 point model and W source model configuration

AVAILABLE DOCUMENTATION

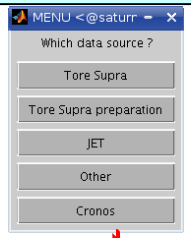
- **In directory “doc” of METIS code (see below)**
- **Parameters documentation**
  - **metis_documentation_for_parameters_standard_mode.pdf**
    → documentation for METIS parameters available in standard mode
  - **metis_documentation_for_parameters_expert_mode.pdf**
    → documentation for METIS parameters
    (all, available in expert mode)

- **Input/output data**
  - **metis_documentation_for_input_data_structure.pdf**
    → description of input data of METIS
  - **metis_documentation_for_output_data_structure.pdf**
    → description of output data of METIS

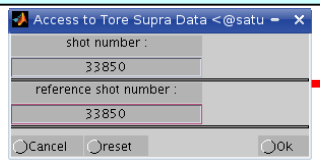
OVERVIEW OF METIS WITH GUI

GUI OVERVIEW

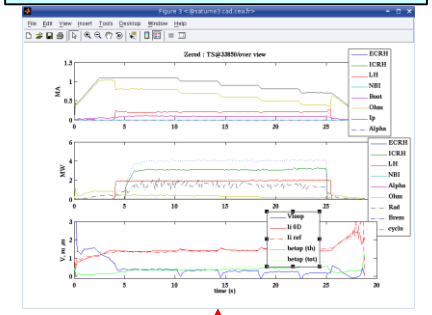
Data source



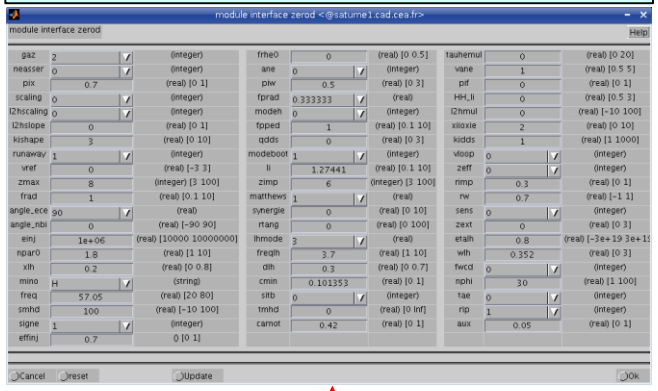
Shot choice



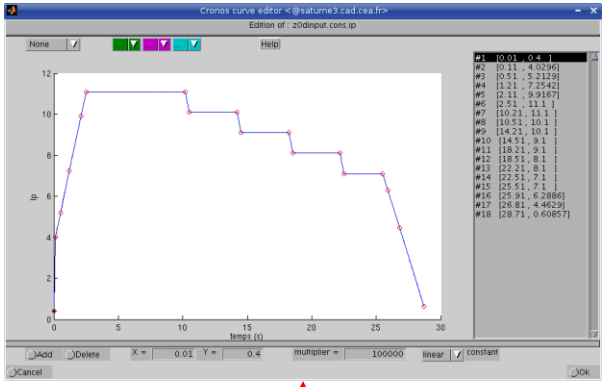
Visualisation



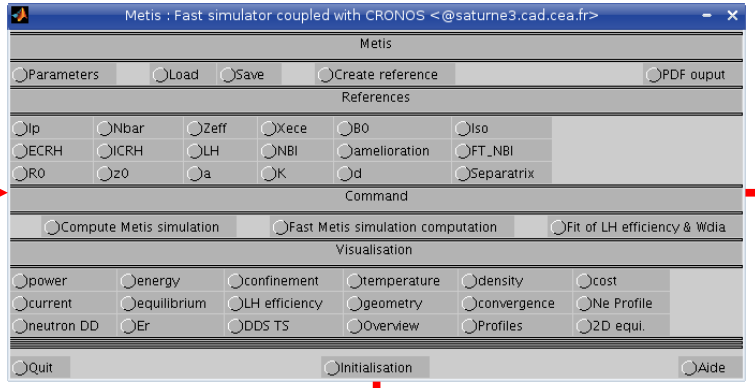
Parameters



References



METIS : main interface



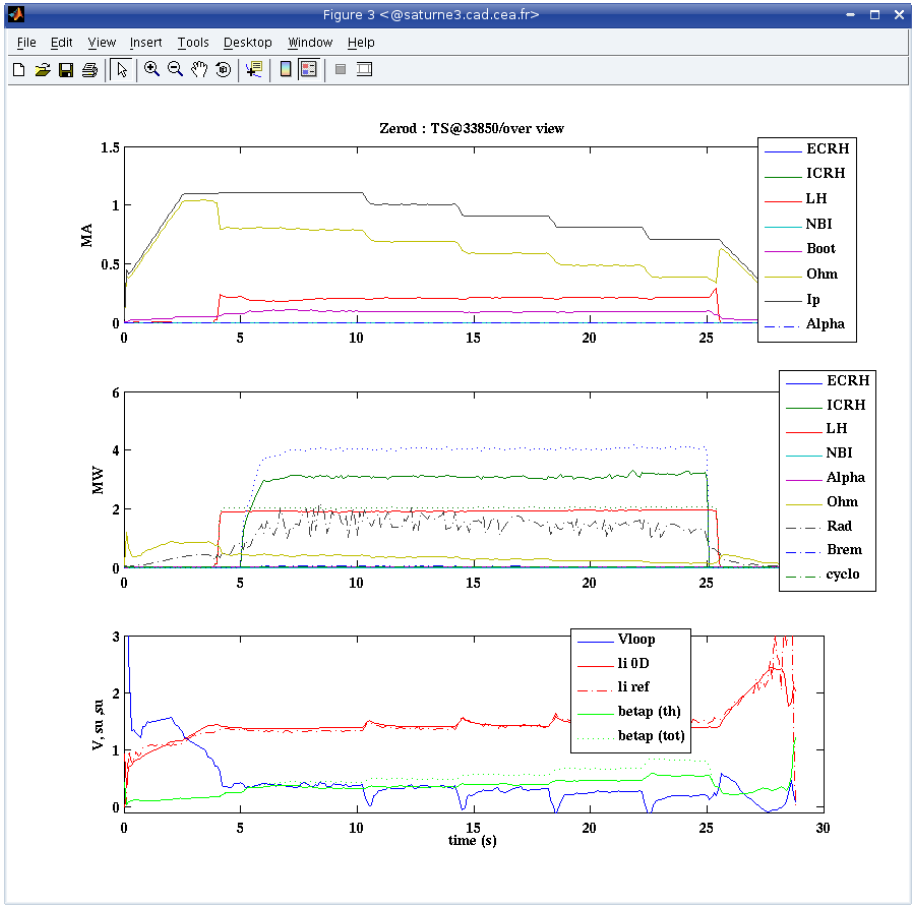
Run (~ 1mn)

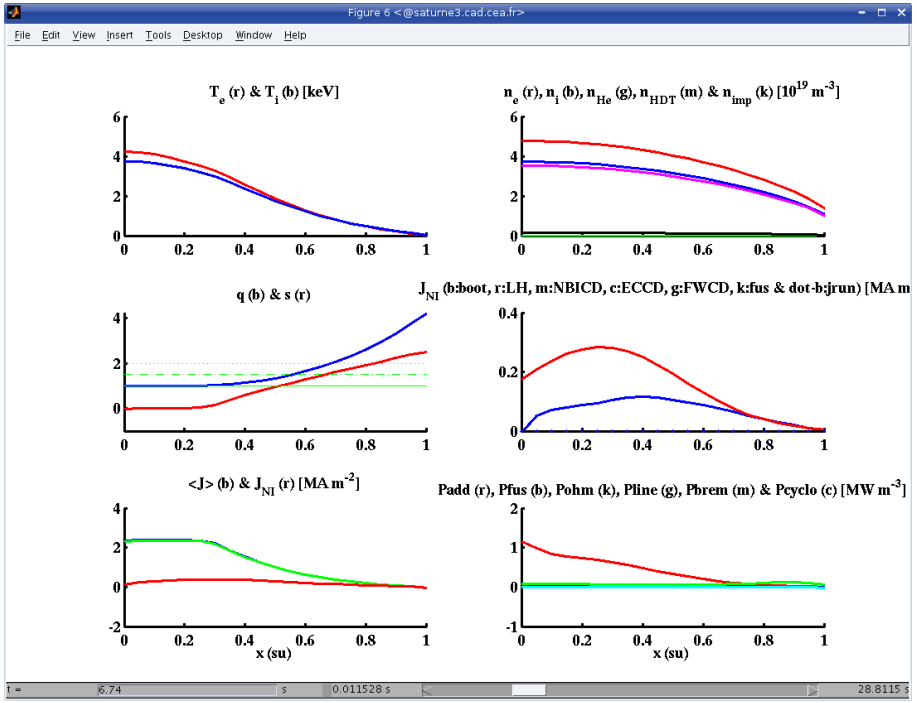
Results

Export to database

METIS OUTPUT EXAMPLE (1/2)

Results: 0D data





Results: profiles

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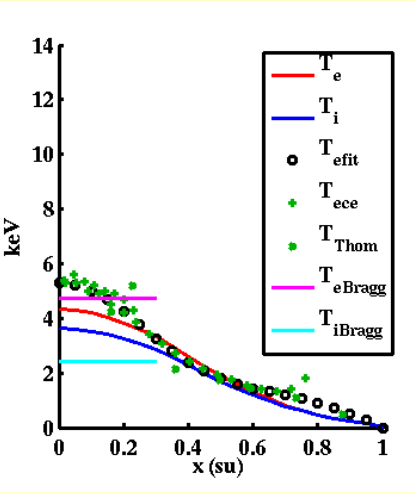
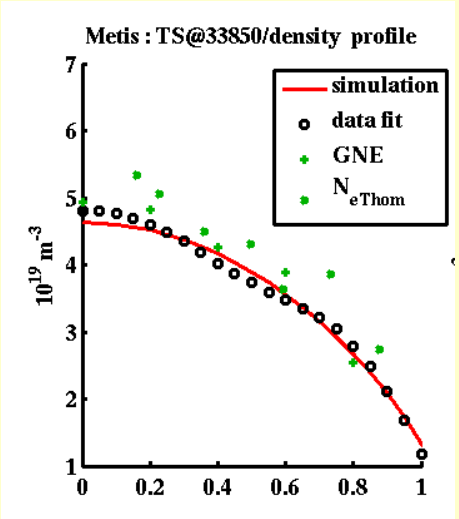
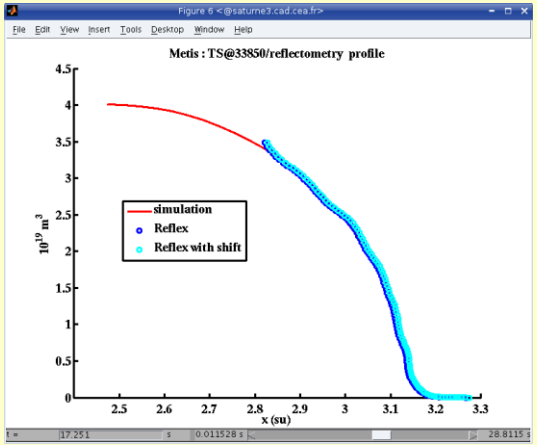
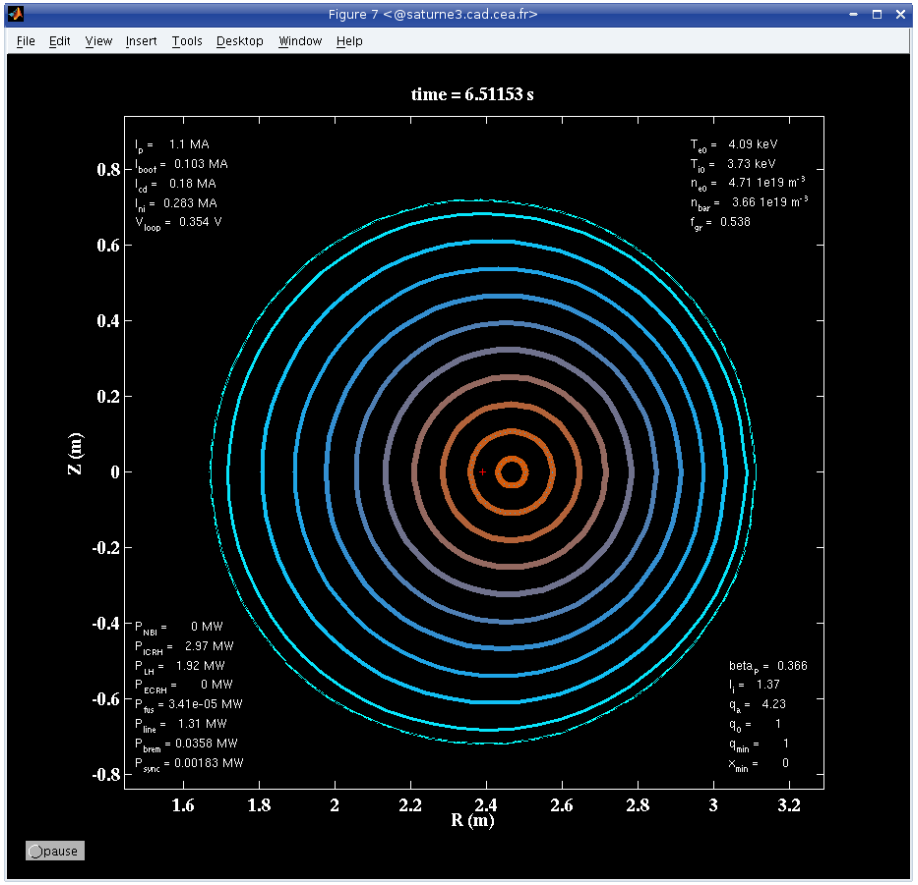
METIS OUTPUT EXAMPLE (2/2)

comparaison with diagnostics data









Internal 2D METIS equilibrium

USE METIS WITH GUI

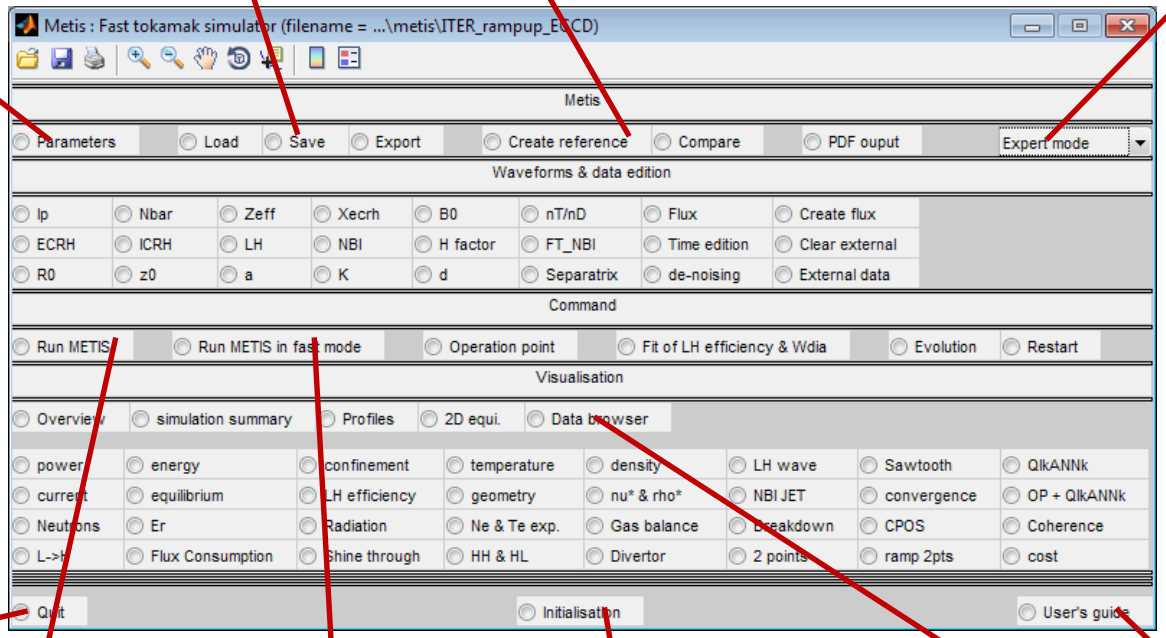
MAIN GUI WINDOWS (1/2)

Edition of simulation parameters

Load & Save simulation

Create reference data set for comparison

Mode switching



Edition references

Pre-defined graphs

Quit METIS

Full simulation (all time slices, to be use for final result)

Fast simulation (selected time slices for overview)

Initialization (create a new simulation)

Data browser (plot any METIS data)

Open METIS manual (need a pdf reader installed)

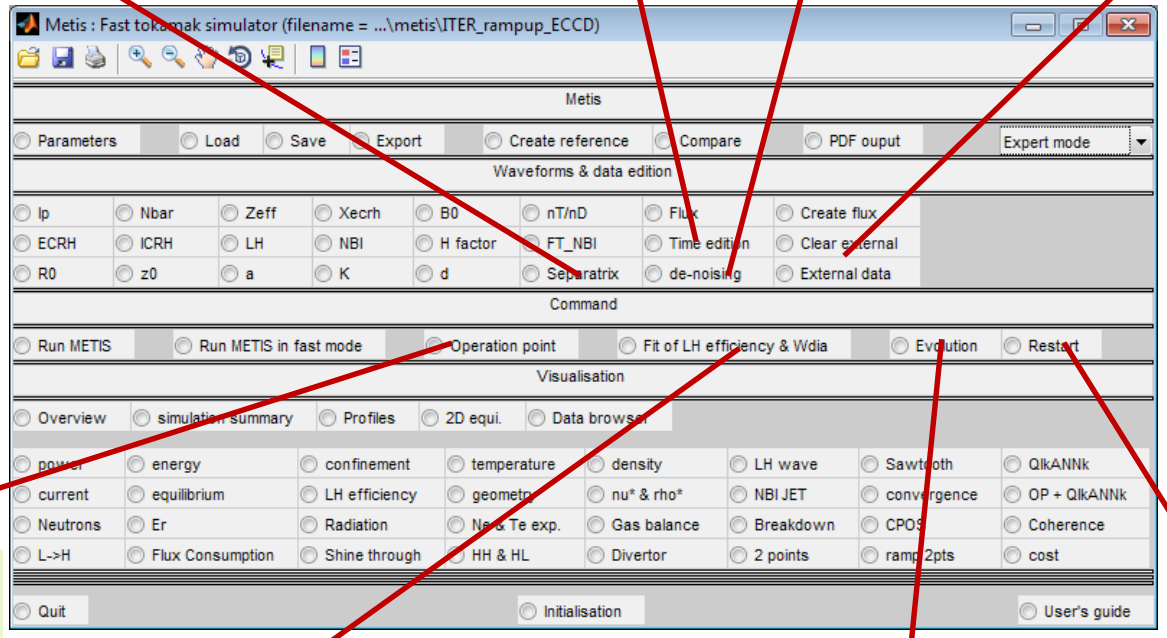
MAIN GUI WINDOWS (2/2)

Generate separatrix (LCFS) with X-point

Noise filter for references

Time resampling (input)

Handle external data (measurement, …)



Edition references

Main graphs

Steady-state fast computation

Fit experimental energy content and search LHCD efficiency (if present)

Run in evolution mode (for testing)

Restart evolution mode (to continue the simulation)

SOME RECIPE FOR A SIMULATION

1. Create or load a data set
2. Edit and modify references
3. Optionally, edit the LCFS (if X-point)
4. Edit and modify parameters
5. Run the simulation in fast mode
6. Visualize results
7. Come back to 2, if changes are needed
8. Run complete simulation
9. Visualize and check results
10. Save results

READ DATA FROM DATABASES

- **From « initialization » :**
  - **Access to databases**
  - **Possibility to create a simulation ab-initio**
  - **Create simulation with scenario generator for WEST, JT-60SA, Reactor (ITER/DEMO)**
  - **Create simulation from SYCOMORE or PROCESS run**
  - **Create a METIS dataset simulation from CRONOS data (if CRONOS available)**
  - **Read METIS input data from IMAS or ITM/UAL**

➢ **Create a new simulation**

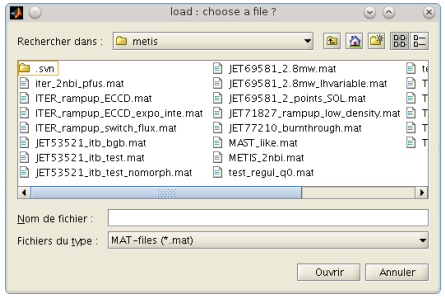
✓ **Data are only in memory : must be saved (after first run) !**

➢ **Menu change depending on context**

LOAD DATA

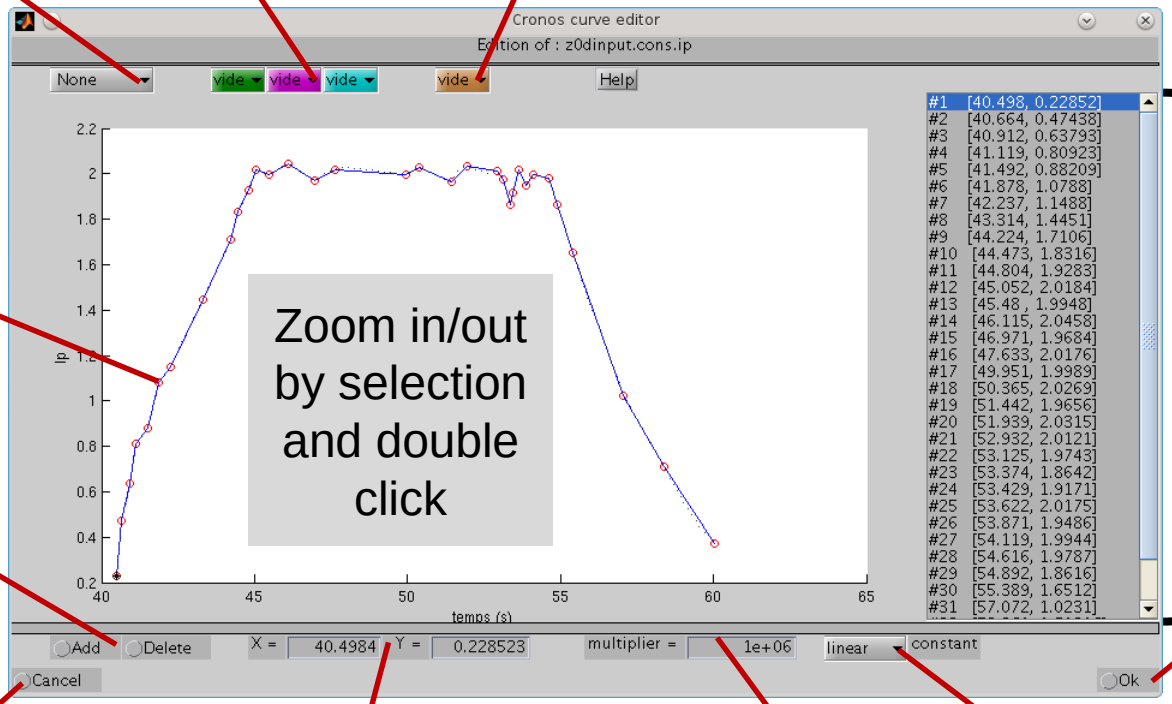
- Button load open a file selector :
  - Just selected a file and open it
- METIS has unified file for input/output
- All METIS files are compatible with new METIS versions (ascendant compatibility)
- Some sample files (used for non-regression tests) are in the directory certification/metis :

…/certification/metis



EDIT REFERENCE

- Time dependent reference can be edited with the help of graphic editor



Grid selector

Superimposes other reference

Add control points of other reference

Graphically editable points (right click for edition menu)

Zoom in/out by selection and double click

Selectable list of control points

Add one point or delete selected point

Save new reference

Cancel edition

Editable point coordinates

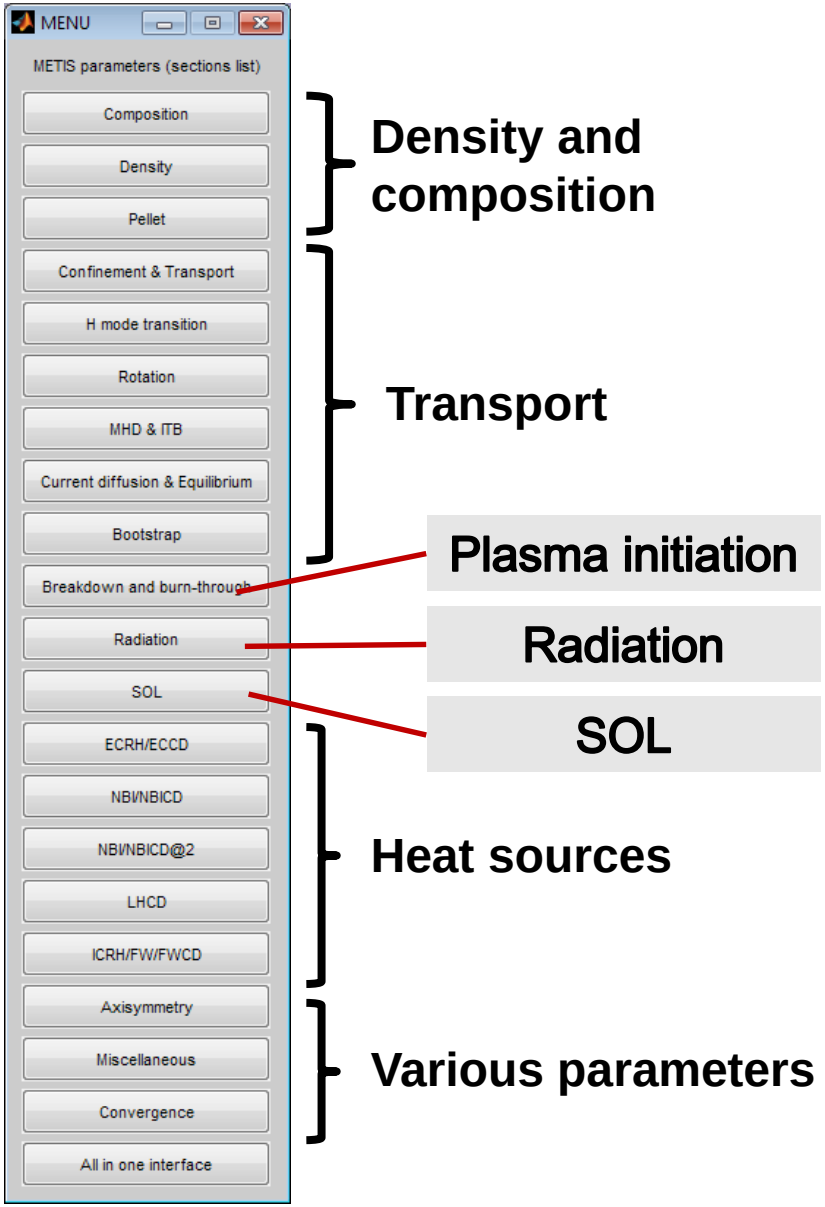
Exponent

Interpolation methods

LIST OF REFERENCES

- Plasma parameters:
  - ip : plasma current
  - flux : edge poloidal flux
  - nbar : line averaged density
  - zeff : line averaged effective charge
  - iso : isotopic plasma composition (n_D/n_T)
  - picrh : ICRH/FW input power
  - plh : LFCD input power
  - pnbi : NBI input power (can open 2 reference editors)
  - pecrh : ECRH input power
  - hmore : enhancement factor
  - ftnbi : NBI composition
  - xece : ECRH maximum deposition position.
- Plasma geometry :
  - a : minor radius
  - R0 : major radius
  - z0 : vertical shift
  - K : elongation
  - d : averaged triangularity
  - b0 : toroidal magnetic field at the major radius
- LCFS generator:
  - More moments
  - Real X-point
  - For given interval of time

EDIT PARAMETERS



- Parameters grouped by topic
- Each button opens a form
- Change the input parameters

RUN METIS

- Main modes:
  - Fast: just to have a look and tune parameters and references
  - Compute: Full computation for final results
  - Fit: Compute energy using measurement (and optionally search for LHCD current drive efficiency)
  - Operation point: One time slice, steady state

- Other modes (for testing):
  - Evolution: test the simulation in evolution mode
  - Restart: restart a simulation in evolution mode

VISUALIZE RESULTS

- At the end of the simulation overview graph is opened.
- Generic graph (0D) : just push the button
  - Power, energy, current, confinement, temperature density, equilibrium, geometry, convergence, …
- 2D plot :
  - equi 2D, Profiles, Er, …
- Specialize graphs :
  - L→ H, Consumed flux, LH wave , …
- Machine dependent graphs :
  - Neutron DD, DDS TS, NBI JET, Ne profile
- Generic data browser and plotter.

DATA BROWSER

Matlab figure menu

0D data

experimental data

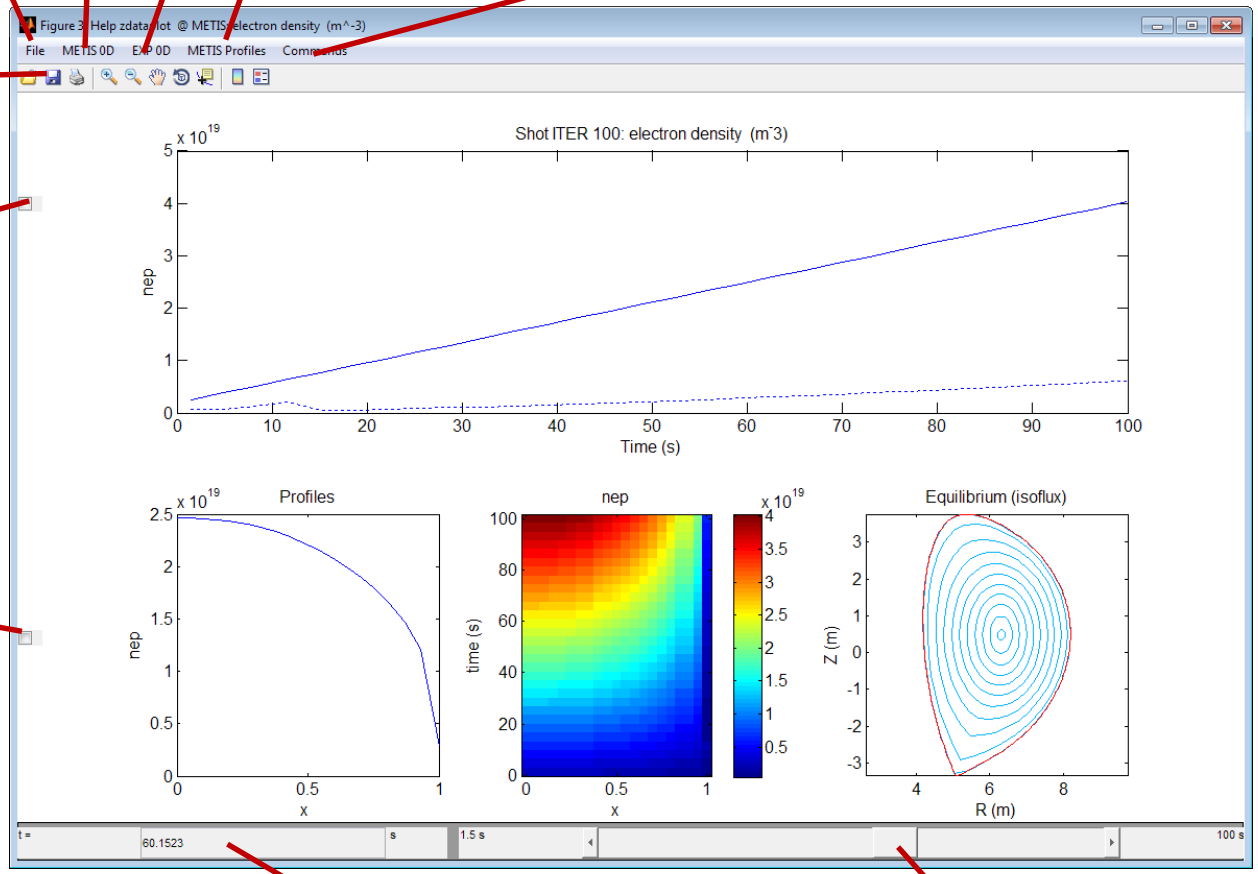
profile data

Graphs options (superimpose, …)

Matlab figure toolbar

time selection With cursor

Memorize profile and superimpose

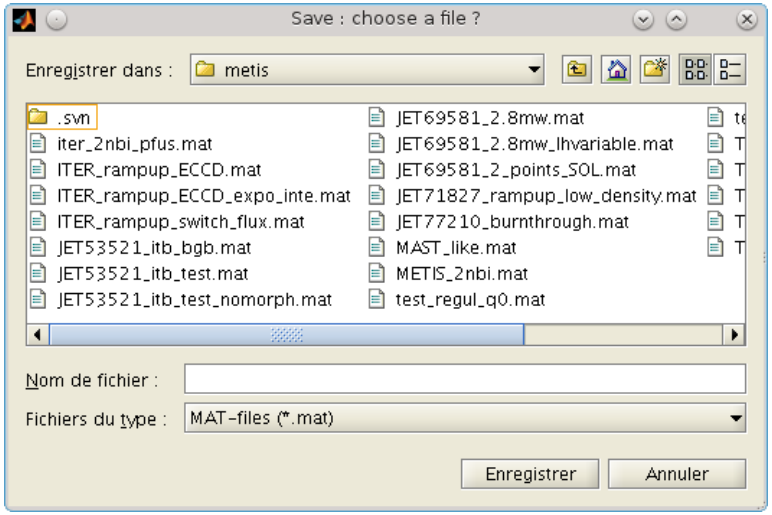


Time (edit field)

Time slider

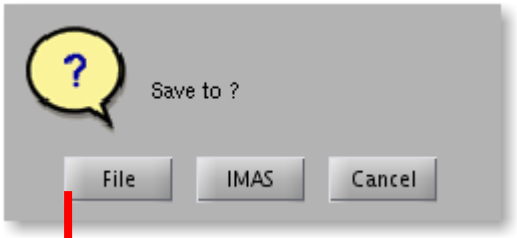
SAVE DATA IN MATFILE

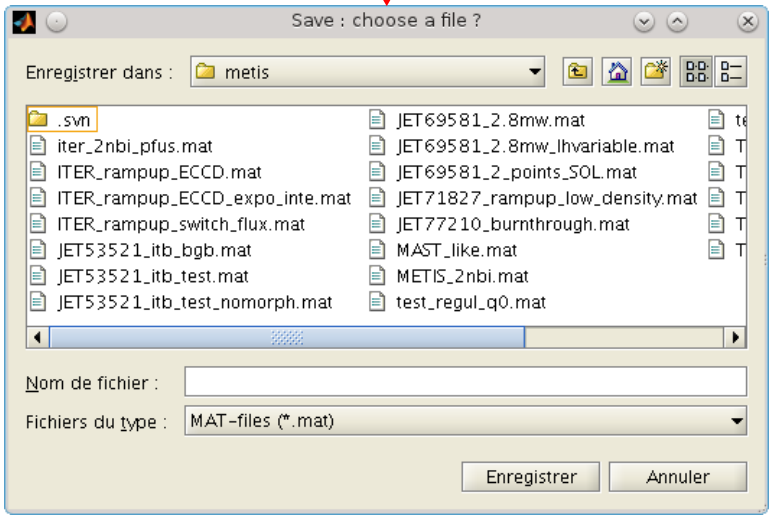
- Button save open a file selector:
  - Just select a file or enter a new name and save it
- METIS has unified file for input/output.

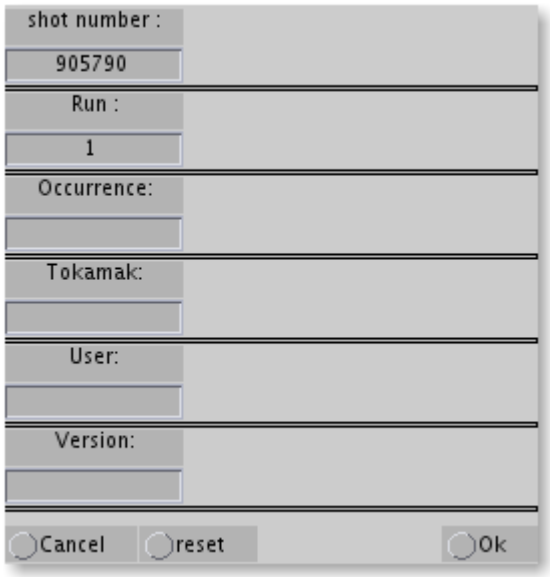


SAVE DATA WITH IMAS OR ITM/UAL

- If IMAS or ITM/UAL is available





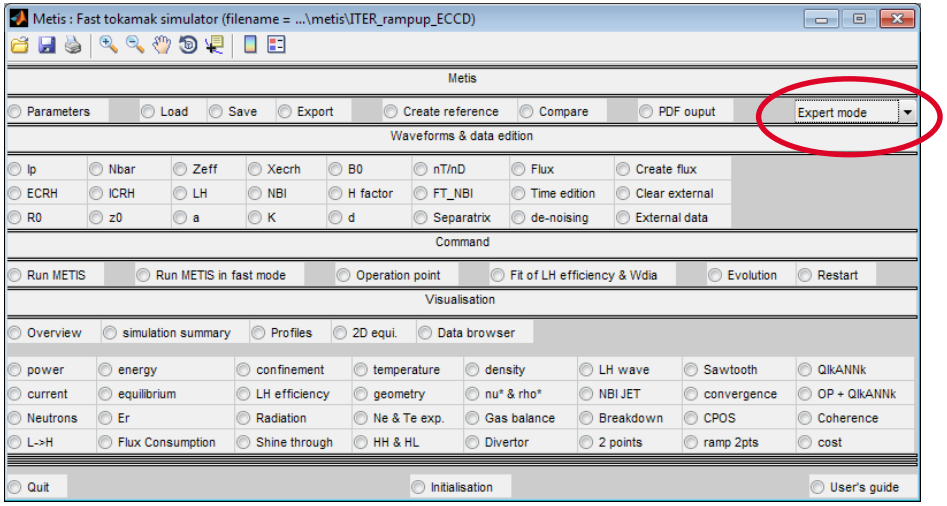


EXPORT DATA IN MATFILE

- Button export:
  - Create IMAS data structure with all requested IDSs and store it in a matfile.
- Internal format depends on Matlab preferences:
  - See command “preferences” in Matlab.

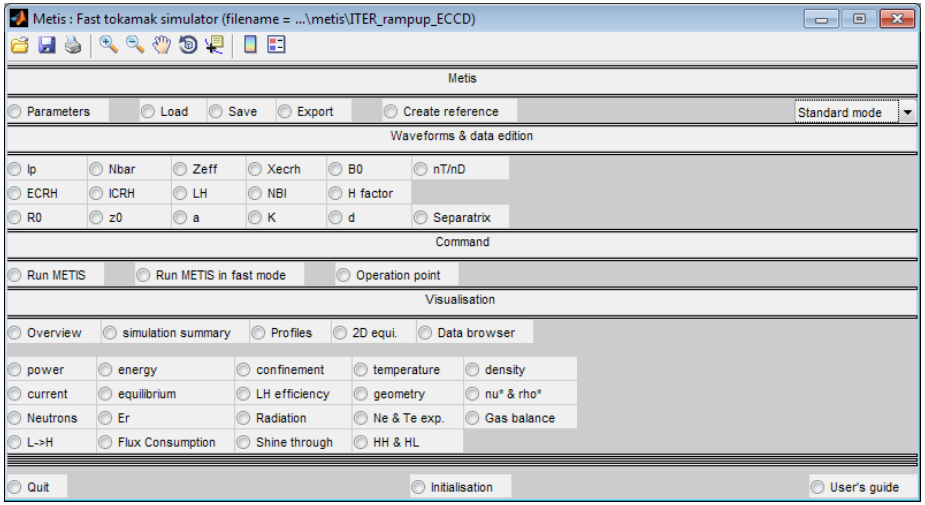
METIS GUI:
EXPERT & STANDARD MODE

GUI HAS 2 MODES: STANDARD AND EXPERT (1/2)



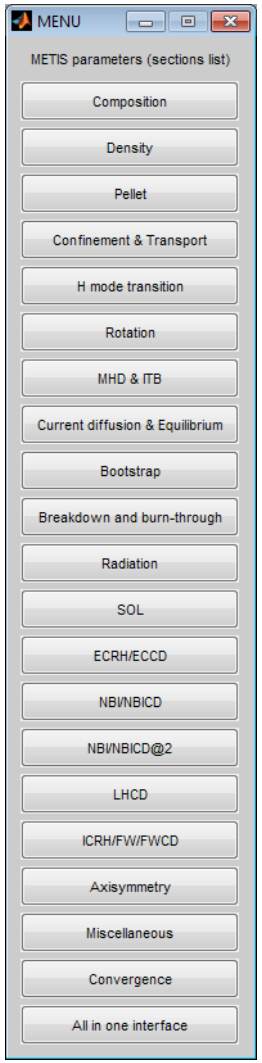
Expert

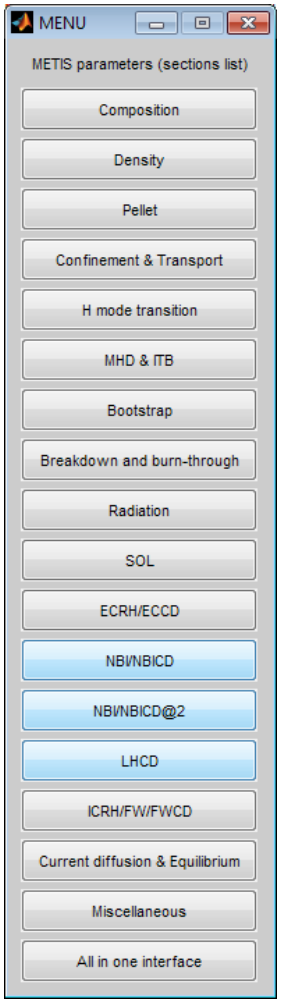
Standard



GUI HAS 2 MODES: STANDARD AND EXPERT (2/2)

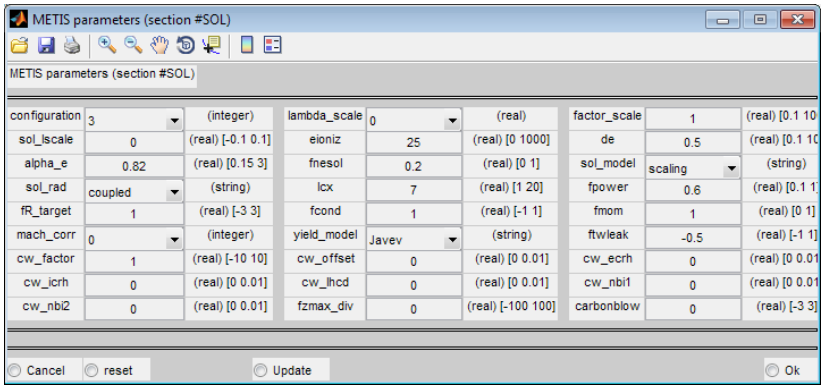
Expert





Standard

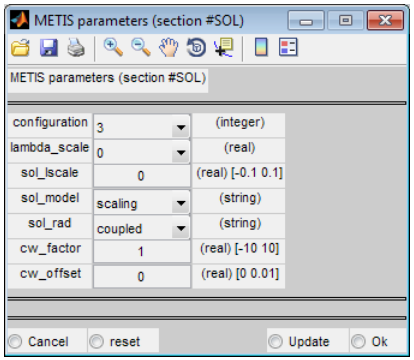
Sections menu



Expert

SOL Parameters
(one example)

Standard

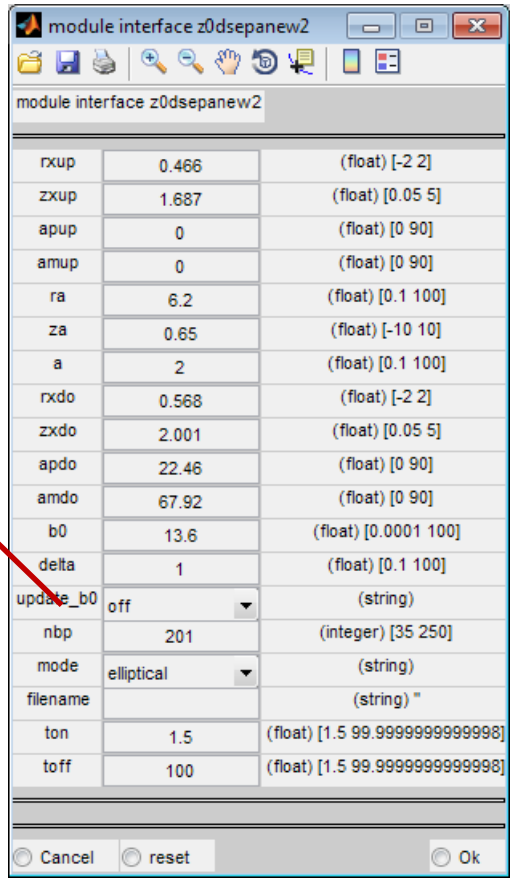


LCFS GENERATOR

LCFS GENERATOR (1/3)

- LCFS parameters:
  - rxup : upper triangularity (normalized)
  - zxup : upper elongation (normalized)
  - apup, amup : upper X-point angles
  - ra : major radius
  - za : vertical shift
  - a : minor raduis
  - rxdo : lower triangularity
  - zxdo : upper triangularity
  - apdo, amdo : lower X-point angles
  - b0 : maximum magnetic field on TF conductor
  - delta : gap between TF and inner plasma point
  - nbp : number points in LCFS
  - mode : interpolation curve type
  - filename : filename of LCFS given by point
  - ton : first time for X-point LCFS
  - toff : last time for X-point LCFS

Update or not B_0



Before and after, use references R, a, K, d

LCFS GENERATOR (2/3)

- LCFS GENERATOR:
  - Override references (R,a,K,d) between ton and toff
  - May re-computes B0 (you must check or reset B0 after)

- If you edit again any R, a, K or d reference:
  - LCFS is reset to moments only
  - You must restart the LCFS design

- Shared by HELIOS/SYCOMORE and METIS:
  - Same set of parameters

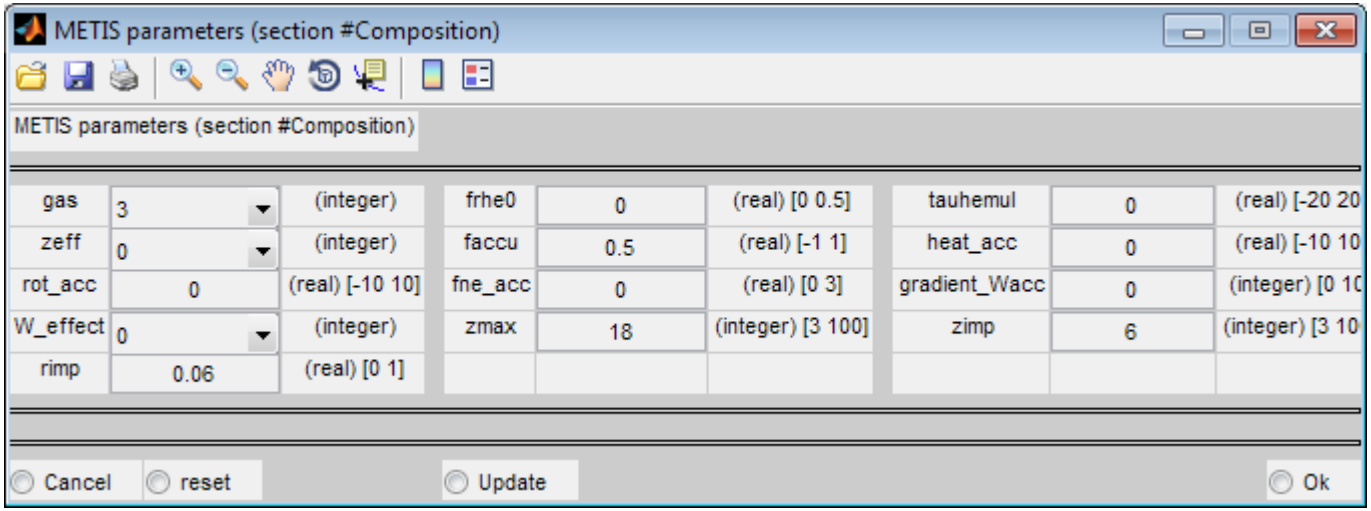
[HELIOS: A zero-dimensional tool for next step and reactor studies, J. Johner, FUSION SCIENCE AND TECHNOLOGY VOL. 59 FEB. 2011]

LCFS GENERATOR (3/3)

- Load a LCFS given by point:
  - Load file pointed by filename field, if field is not empty
  - If filename is invalid or “?”, open a file selector helping to choose the file
  - File must be a matfile containing R vector and Z vector of same length.
  - Override references (R,a,K,d) between ton and toff
  - Override LCFS given by parameters.
- If you edit again any R, a, K or d reference:
  - LCFS is reset to moments only
  - You must restart the LCFS design

MAIN PARAMETERS FOR FIRST USE

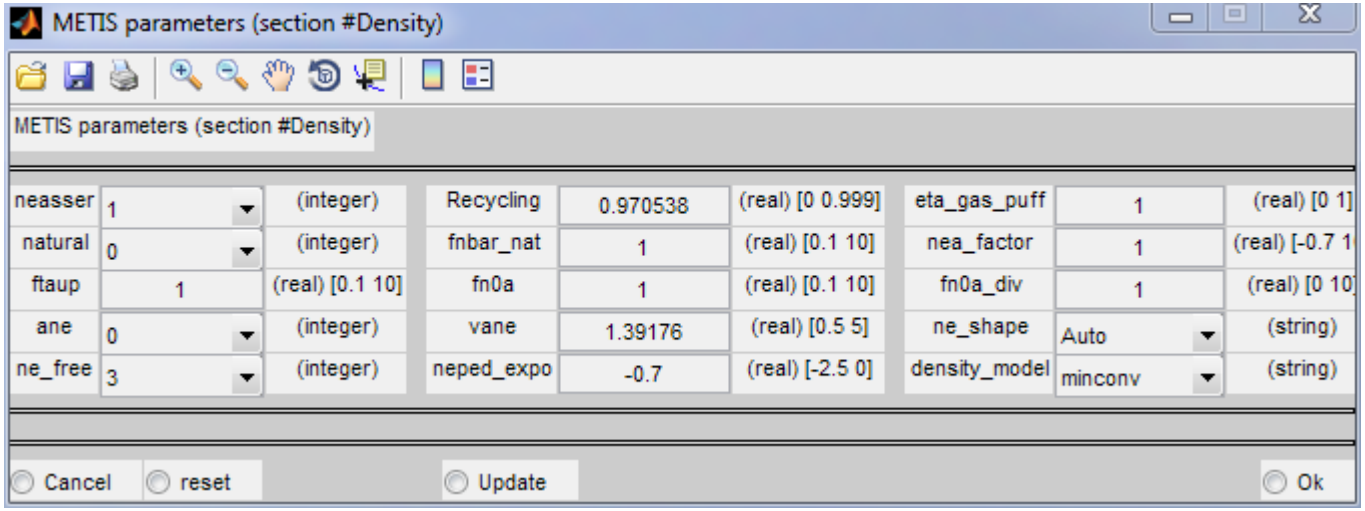
PARAMETERS INTERFACES (COMPOSITION)



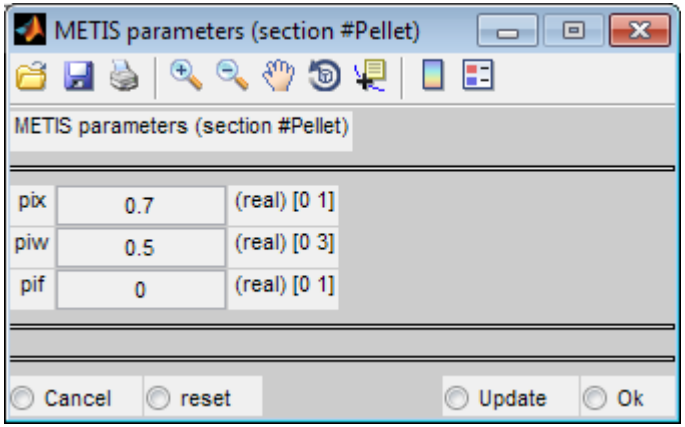
- Main Keys (for first use):
  - gas: main plasma ion species (H/D/He/DT)
  - zimp: charge of light/main impurity
  - zmax: charge of heavy/secondary impurity
  - rimp : density ratio of secondary over main impurity

PARAMETERS INTERFACES (DENSITY)

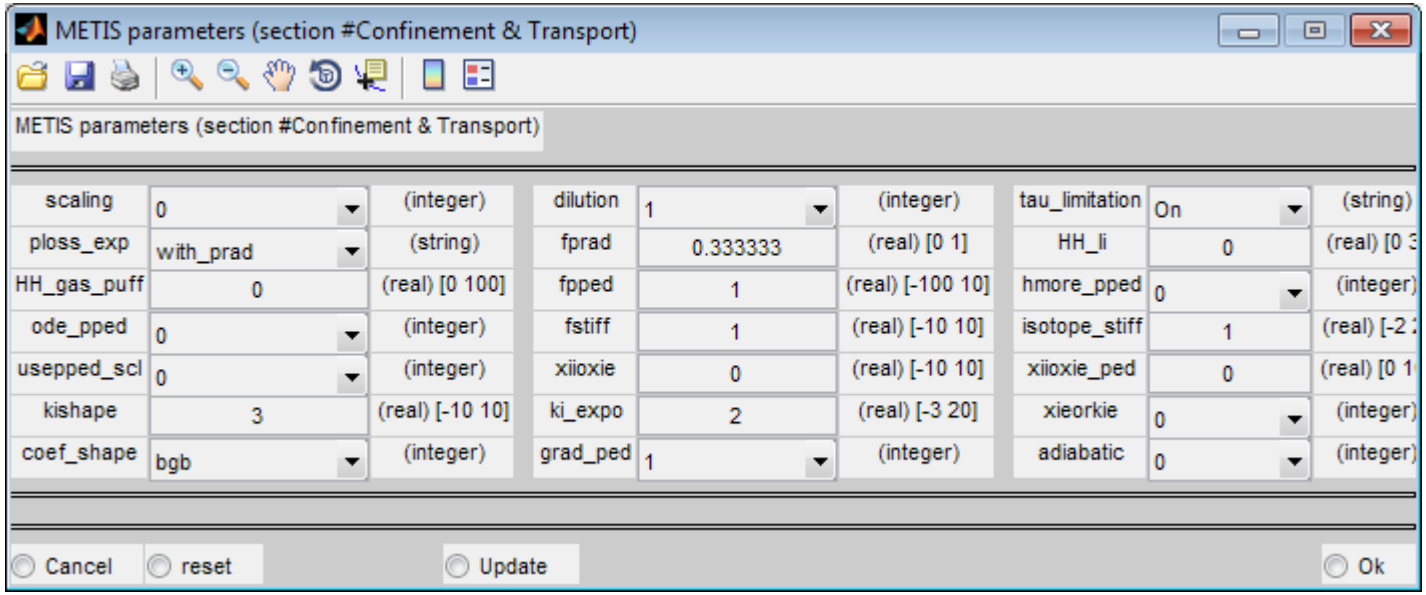
- Main Keys (for first use):
  - ane: model for density peaking factor
  - vane: value of density peaking factor if provided



PARAMETERS INTERFACES (PELLET)

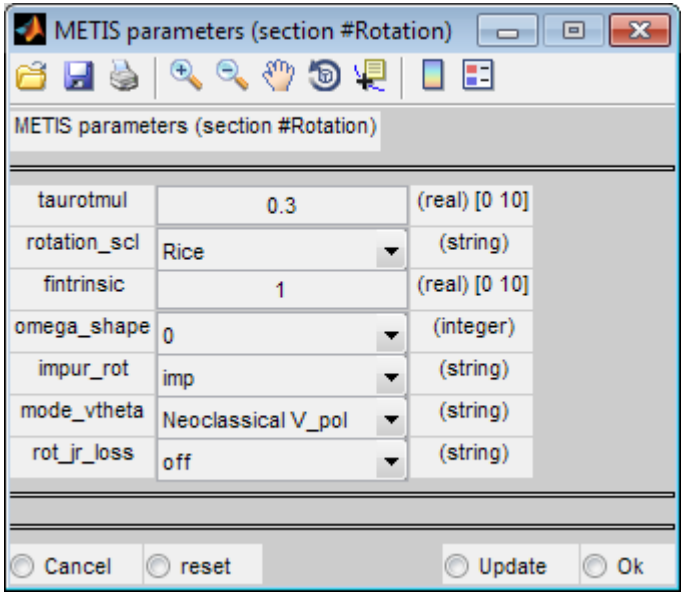


PARAMETERS INTERFACES (TRANSPORT)



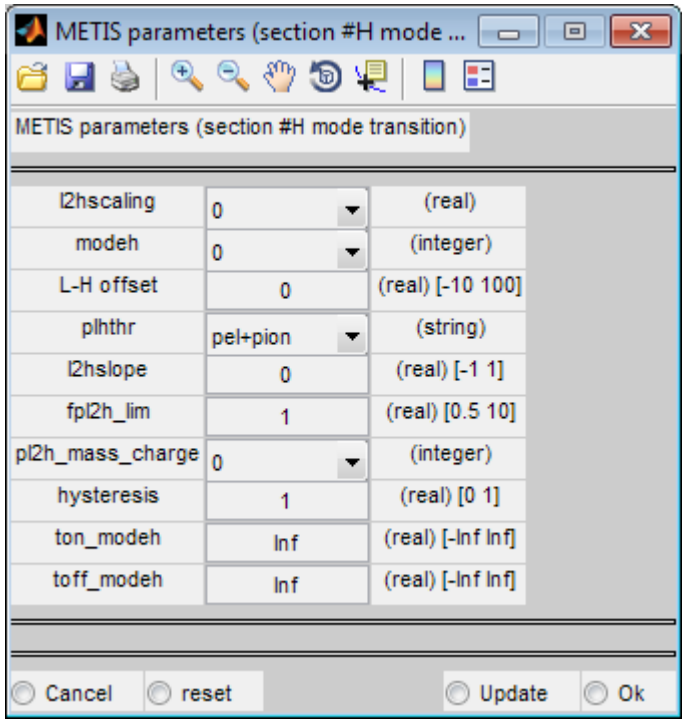
- Main Keys (for first use):
  - scaling: scaling law for energy content choice
  - fpped: pressure at the top of pedestal (factor)
  - usepped_scl: set on scaling for pedestal pressure

PARAMETERS INTERFACES (ROTATION)



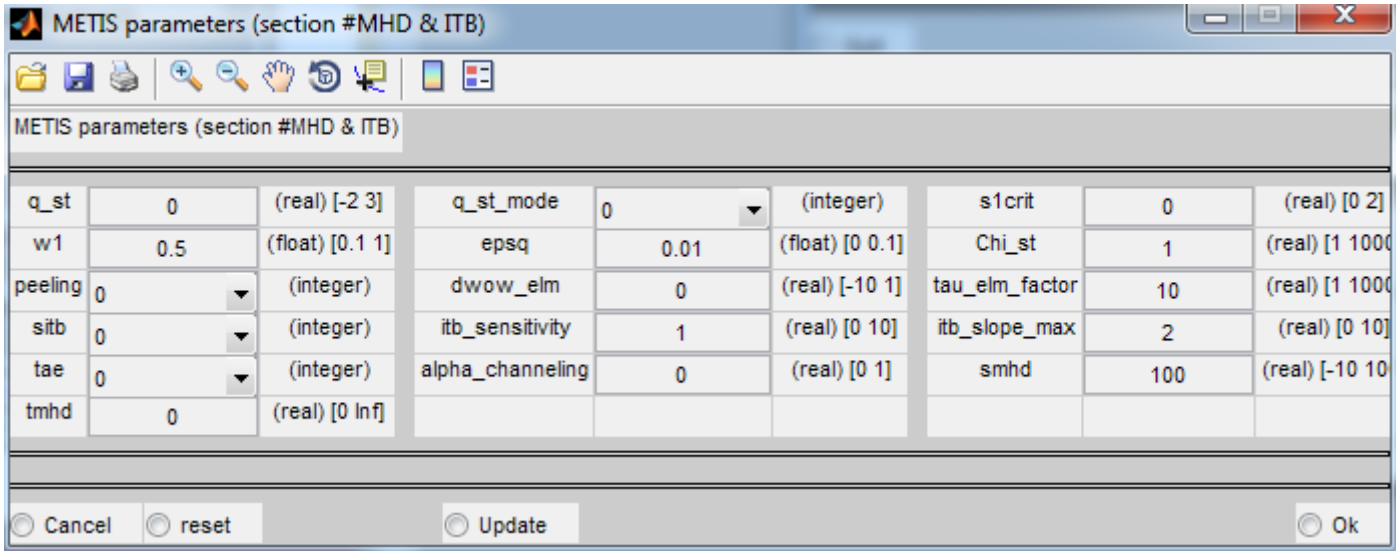
- Main Keys (for first use):
  - taurotmul: τ_φ / τ_E
  - fintrinsic: fraction of intrinsic rotation taking into account

PARAMETERS INTERFACES (H-MODE)



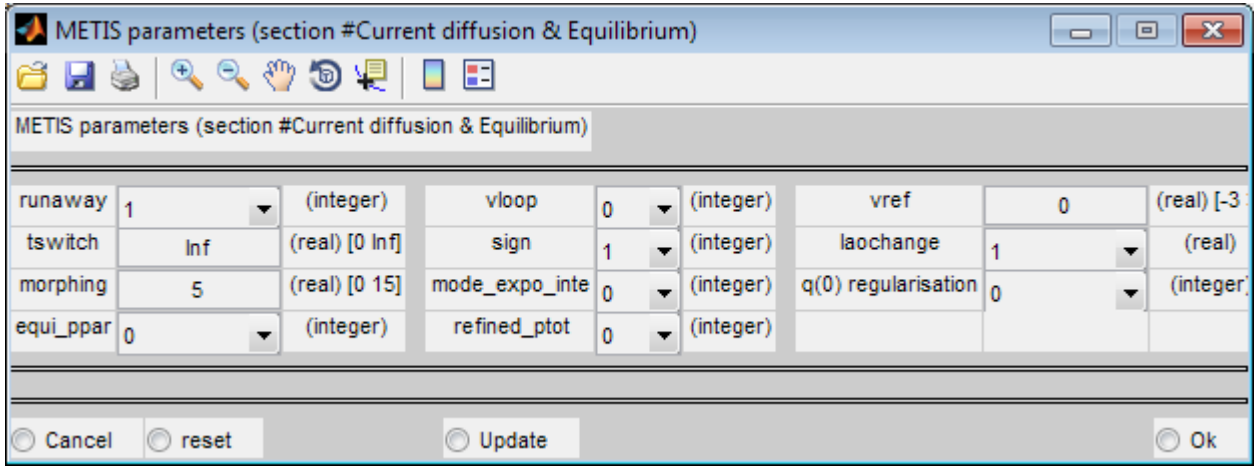
- Main Keys (for first use):
  - l2hscaling: scaling law for L->H transition
  - modeh: allow/force/prevent H-mode transition
  - l2hmul: offset for the transition

PARAMETERS INTERFACES (MHD & ITB)



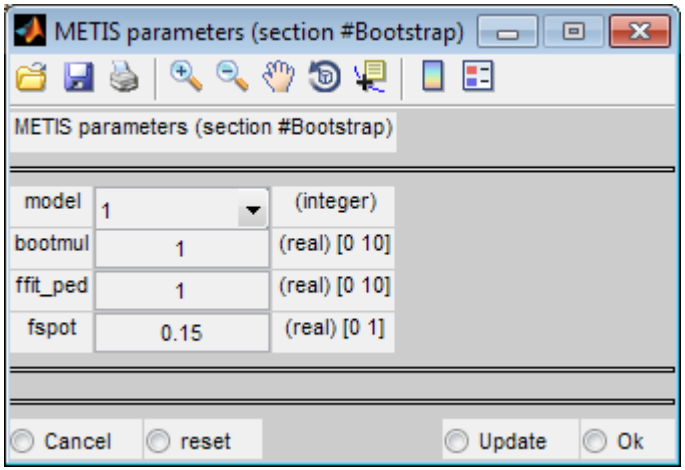
- Main Keys (for first use):
  - q_st: set on sawteeth model
  - Chi_st: effect of sawteeth on transport
  - smhd: limitation of β_N

PARAMETERS INTERFACES (CURRENT DIFFUSION)

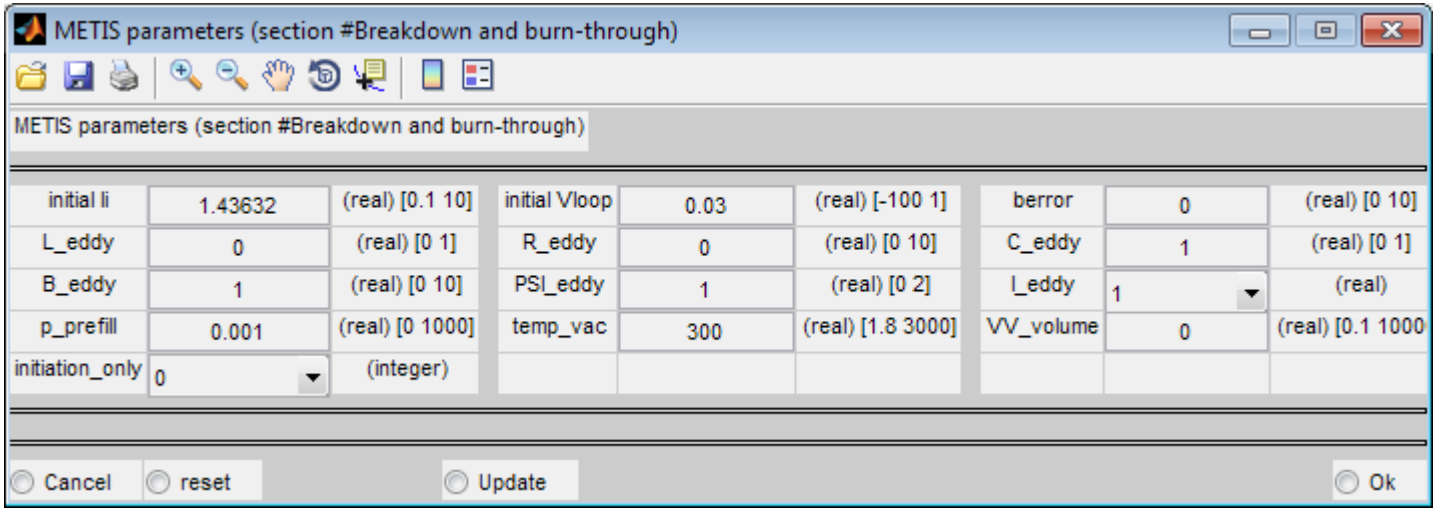


- Main Keys (for first use):
  - runaway: switch on/off runaway model (runaway can be a problem !)
  - signe: sign of Ip * Bphi
  - Cronos_regul: methode to compute safety factor @ magnetic axis

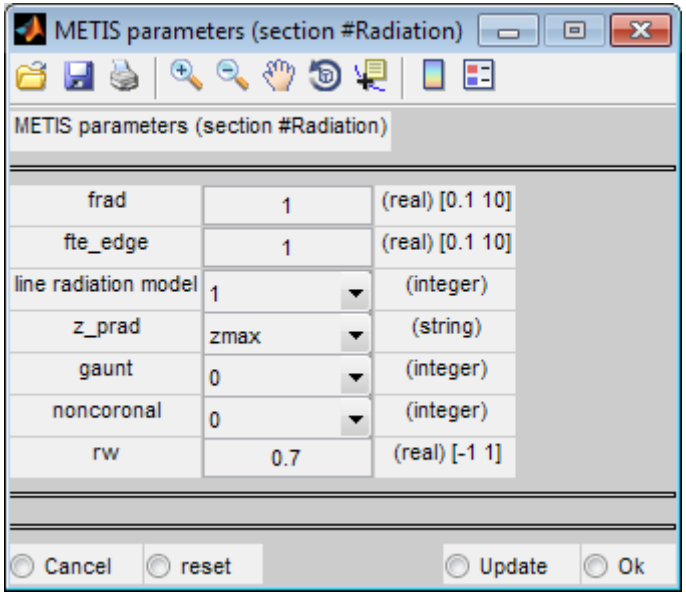
PARAMETERS INTERFACES (NEOCLASSIC)



PARAMETERS INTERFACES (BREAKDOWN)

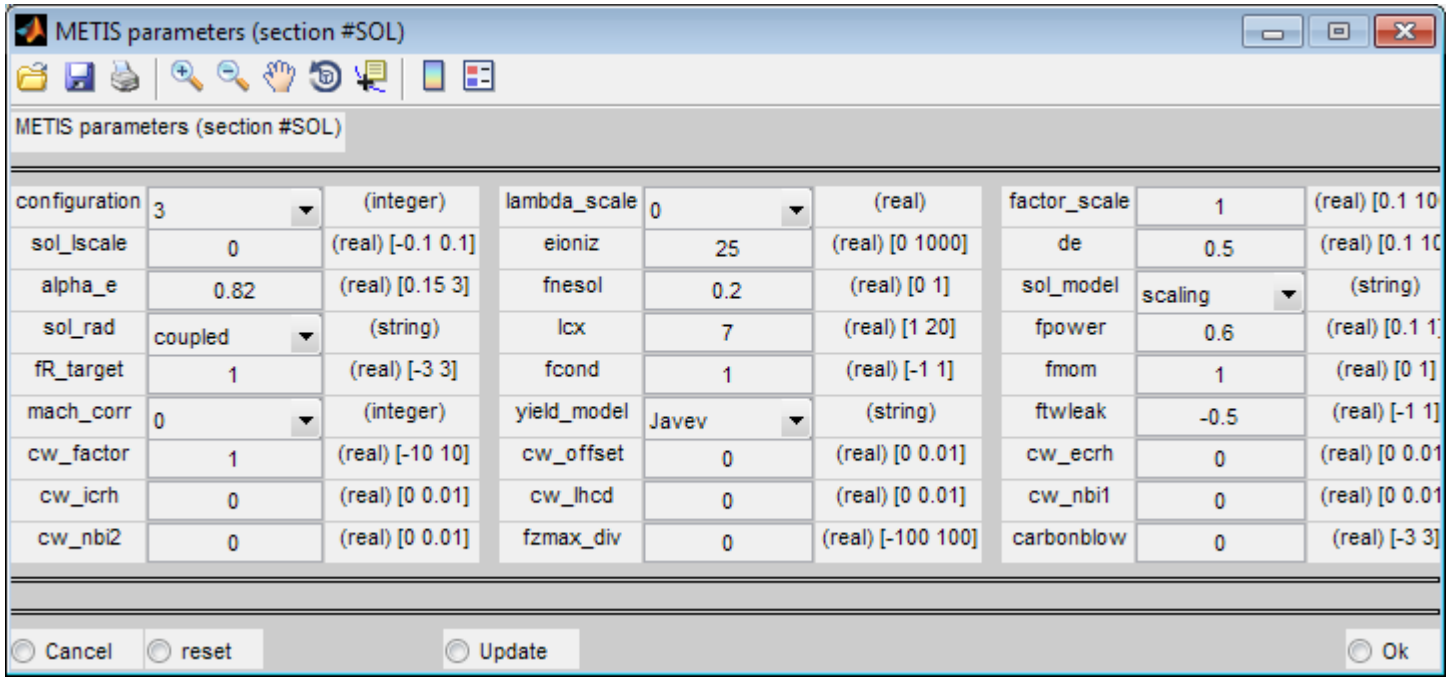


PARAMETERS INTERFACES (RADIATION)



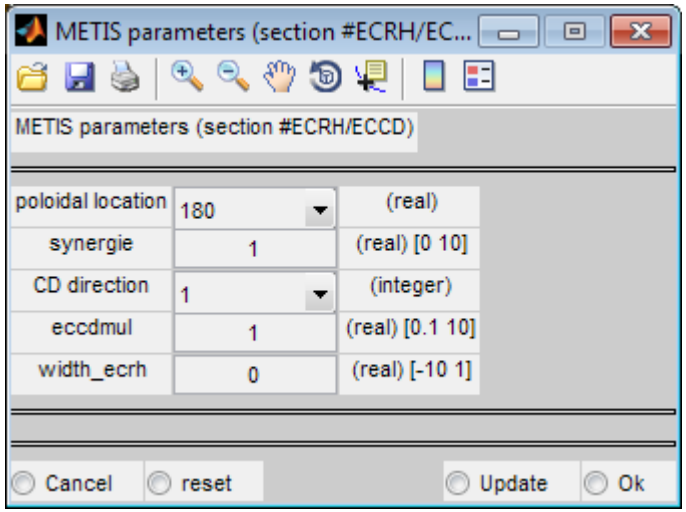
- Main Keys (for first use):
  - frad: factor applied to line radiative power
  - Line radiation model: use Matthews scaling or only cooling rate
  - rw: effective wall cyclotron radiation reflection fraction

PARAMETERS INTERFACES (SOL)



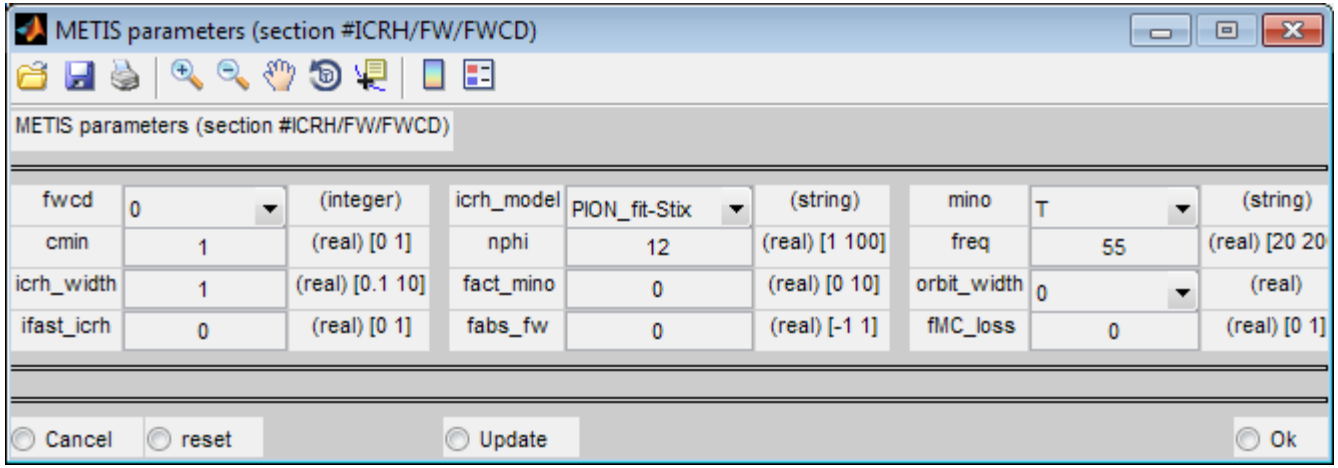
- Main Keys (for first use):
  - configuration: tokamak configuration (poloidal limiter, toroidal limiter, divertor, …)

PARAMETERS INTERFACES (ECRH/ECCD)



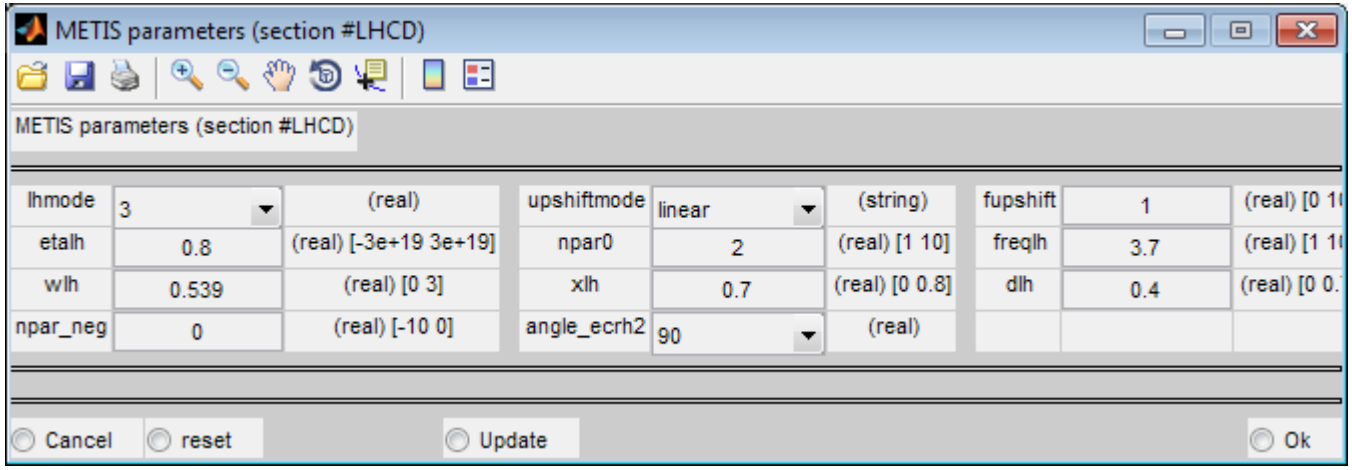
- Main Keys (for first use): all
  - angle_ecrh: poloidal position of absorption
  - sens: co current, perpendicular or counter current

PARAMETERS INTERFACES (ICRH/FW/FWCD)



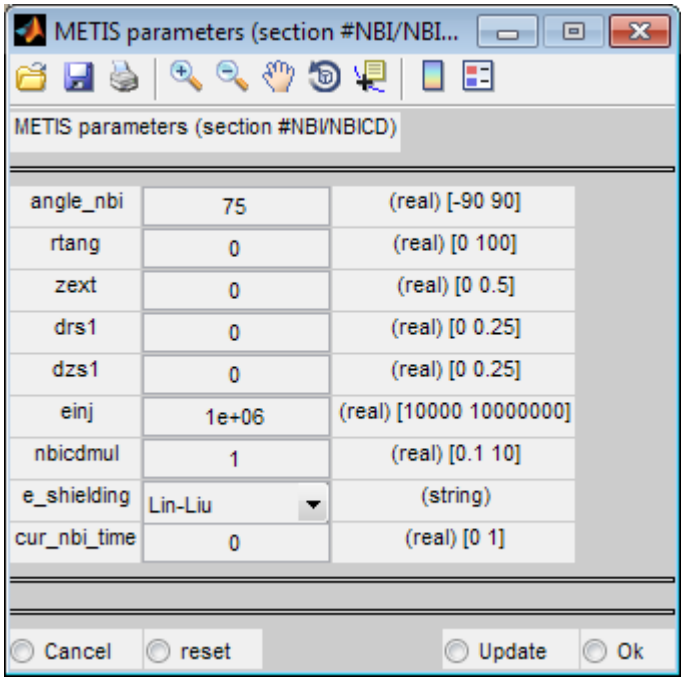
- Main Keys (for first use): all
  - fwcd: selection of heating scheme
  - mino & cmin : type and concentration of minority
  - nphi: toroidal wave number
  - freq : frequency of the injected wave (set to position of deposition)

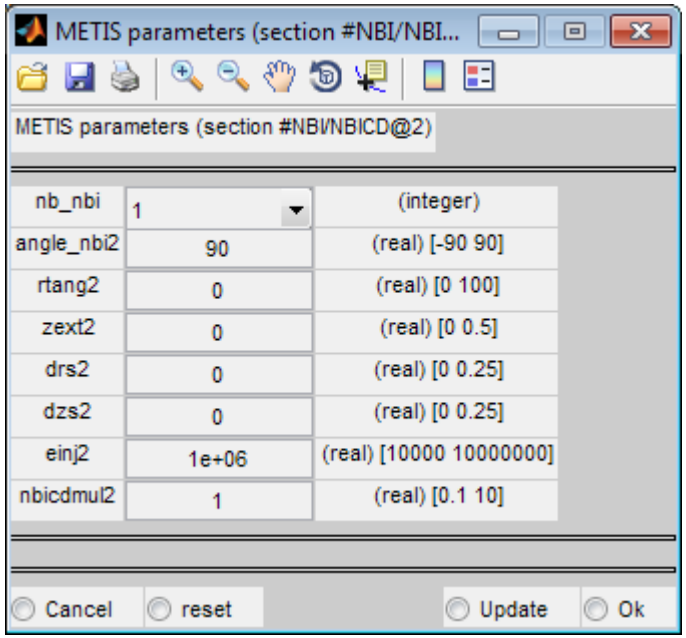
PARAMETERS INTERFACES (LHCD)



- Main Keys (for first use): all
  - Many mode: simpler to start from an example.
  - For Tore Supra can use hard X-rays bremsstrahlung data
  - Internal METIS model must be used cautiously

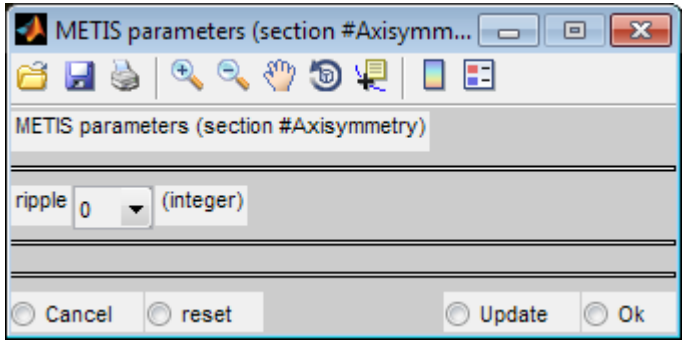
PARAMETERS INTERFACES (NBICD1 & NBICD2)

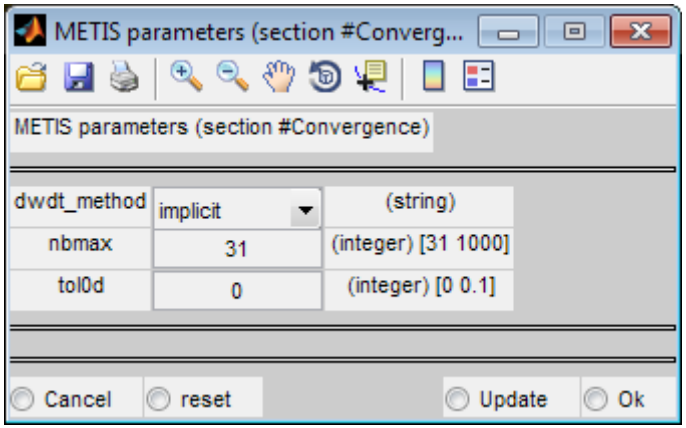


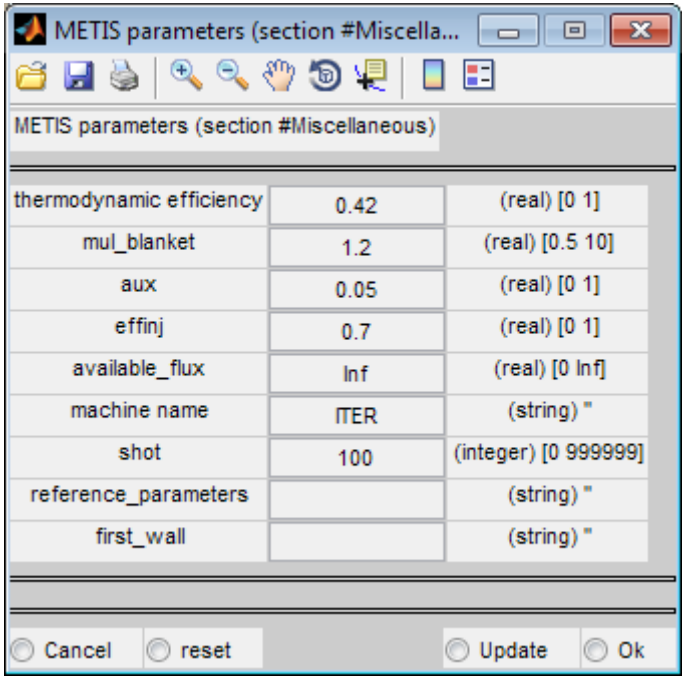


- Main Keys (for first use): all
  - Standard use : provided rtang & set current direction with angle_nbi
  - Set current direction with angle_nbi
    (-90= counter, 0 = perpendiculr, 90 = co)
  - Adjust deposition with zext

PARAMETERS INTERFACES (OTHERS)

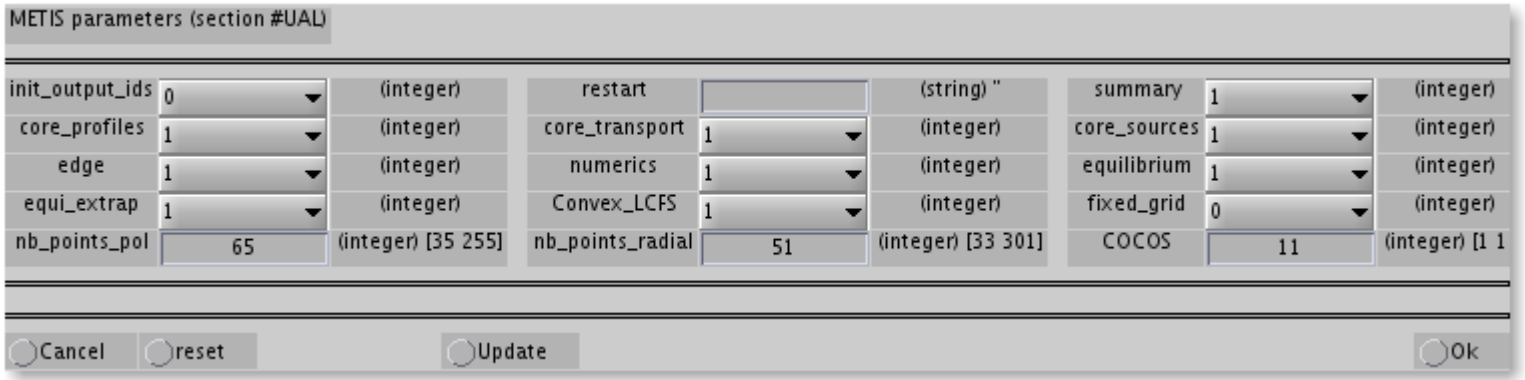


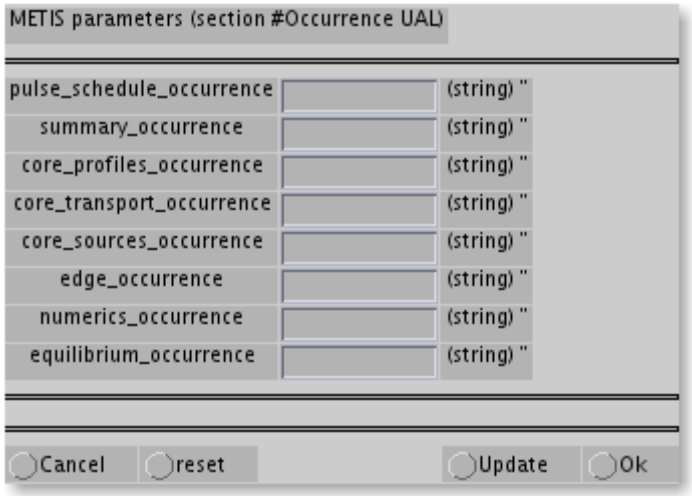




- Main Keys (for first use):
  - shot: shot number
  - machine: machine name
  - reference_parameters : file name of METIS parameters as created with the button “Create reference”. Override METIS internal tuning!

PARAMETERS INTERFACES (IMAS OR ITM/UAL)





INSIDE METIS

HELP AND MANUAL

- METIS is provided with documentation pdf files
  → in directory “doc” where METIS is installed

- In the GUI and in Matlab command line:
  - ✓ Parameters tooltip
  - ✓ Data description

- For evolution mode in Matlab command line:
  - ✓ Simulink help : simmetis, zerodevolution
  - ✓ IMAS help : metis4imas

- For external data used :
  - ✓ external_data_rule_for_METIS.m

MATLAB WORKSPACE (1/2)

- **Standalone METIS data structure:**
  - **Input data: z0dinput**
  - **Output data: post**
    - **post.zerod: 0d data**
    - **post.profil0d: profiles**
    - **post.z0dinput: input data use during simulation**

- **Evolution mode data structure: z0dstruct**

MATLAB WORKSPACE (2/2)

- **z0dinput structure:**
  - **Information:**
    - **z0dinput.info: parameter tooltips**
    - **z0dinput.zsinfo: 0D data descriptions**
    - **z0dinput.profinfo: 1D data descriptions**
  - **Data:**
    - **z0dinput.option: parameters**
    - **z0dinput.cons: references (Ip, powers, …)**
    - **z0dinput.geo: plama geometry**
    - **z0dinput.exp0d: experimental data + LCFS pts**

ADVANCED METIS FEATURES

METIS WITHOUT GUI (1/2)

- METIS commands:
  - metis_load: load and update a simulation
  - metis_save: save a simulation (from workspace)
  - metis_fast: fast simulation (selected time slices)
  - metis_run: full simulation (all time slices)
  - metis_fitlh: search for LHCD current drive efficiency
  - metis_upadate_tests: update non regression tests

METIS WITHOUT GUI (2/2)

- Call METIS functions in a mfile:
  - zerod_init: initialise a simulation
  - zerod_fast: fast simulation (selected time slices)
  - zerod: full simulation (all time slices)
  - zerodevolution: one time step simulation
  - metis4imas: run metis inside IMAS framework
  - metis4itm: run metis inside ITM framework

METIS & EXTERNAL DATA

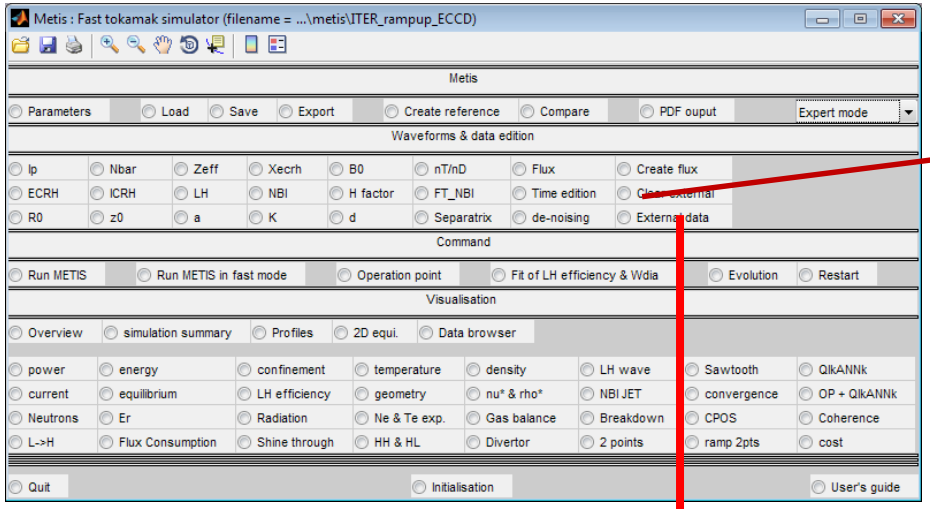
- METIS can use external data for:
  - Heat and current drive sources :
    LHCD, ICRH, ECCD, NBICD, Pline, Runaway
  - Kinetic profiles: Ne, Te, Ti, Ω_φ

- External data override internal METIS computation
- Heat sources are renormalized on references.
- Density is renormalized on $\bar{n}$ reference

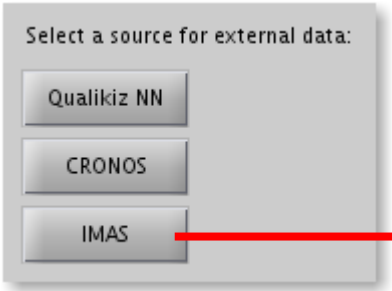
➢ Details available in file:
…/zerod/external_data_rule_for_METIS.m

METIS & EXTERNAL DATA GUI

- METIS GUI for external:



Remove external data
(METIS stops to use external data)



This menu depends on context

METIS IN SIMULINK

METIS IN SIMULINK

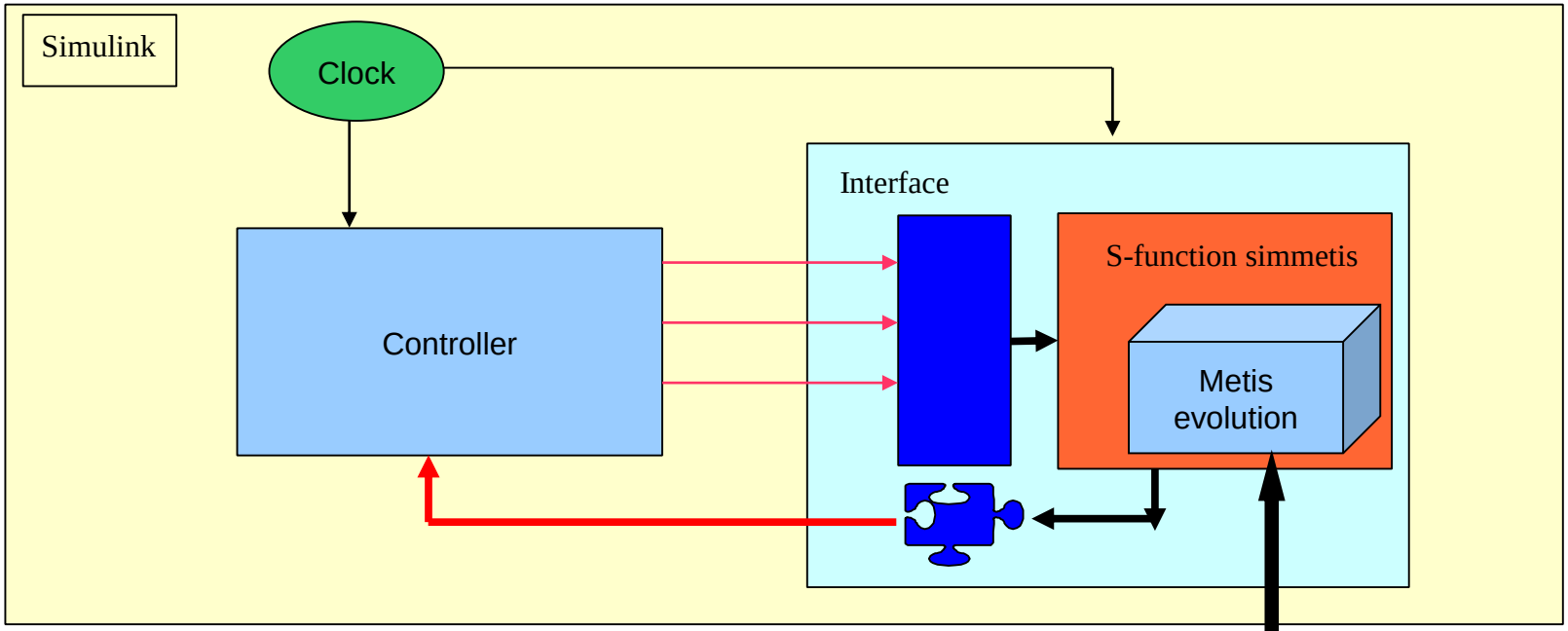
- ✓ METIS call from Simulink = S-function simmetis
- ✓ Standard S-function Input & output

- simmetis use one time step METIS computation: zerodevolution

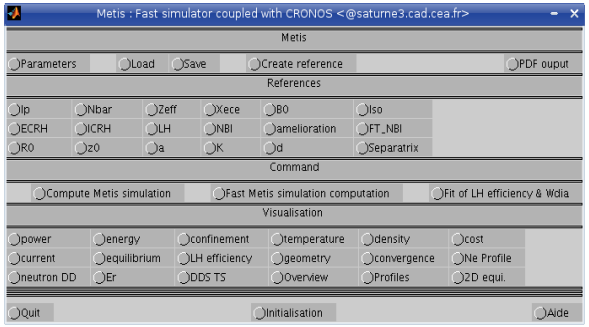
- ➢ Some documentation is written inside functions
  - ✓ help simmetis or help zerodevolution (in Matlab)
  - ✓ S-function documentation :

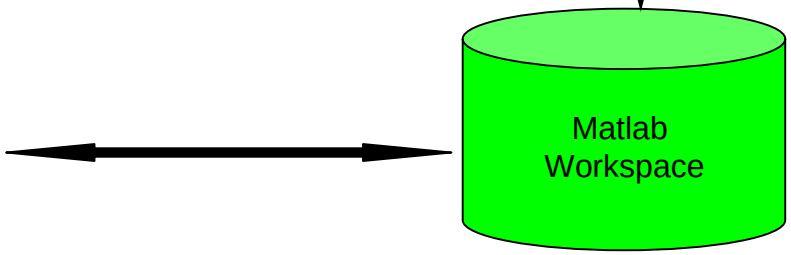
    http://www.mathworks.fr/fr/help/simulink/slref/sfunction.html

METIS EVOLUTION IN SIMULINK



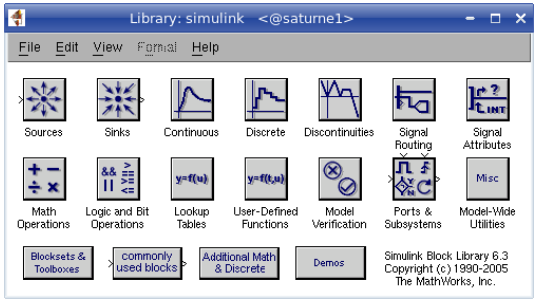
METIS : main interface

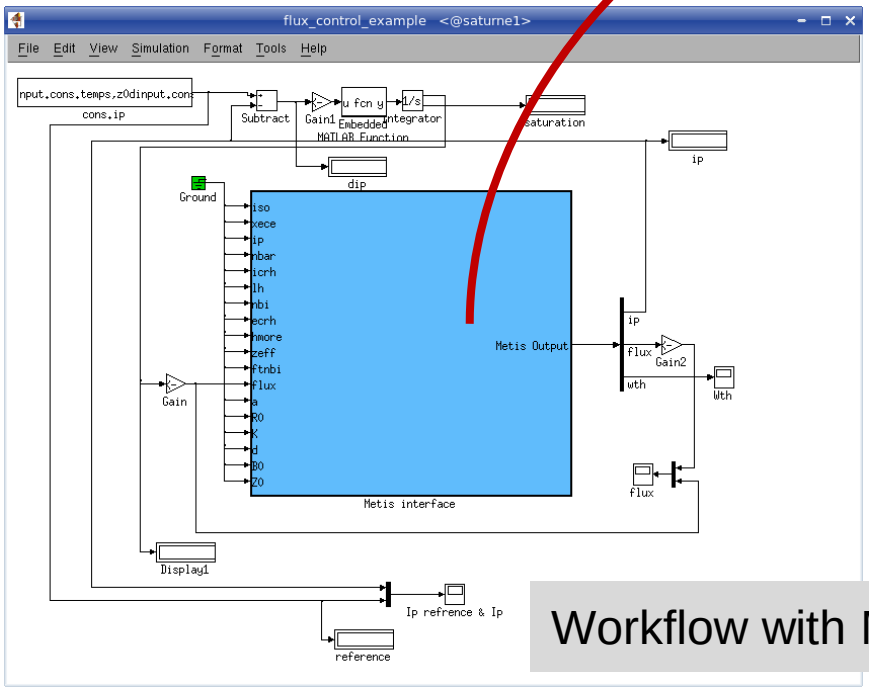


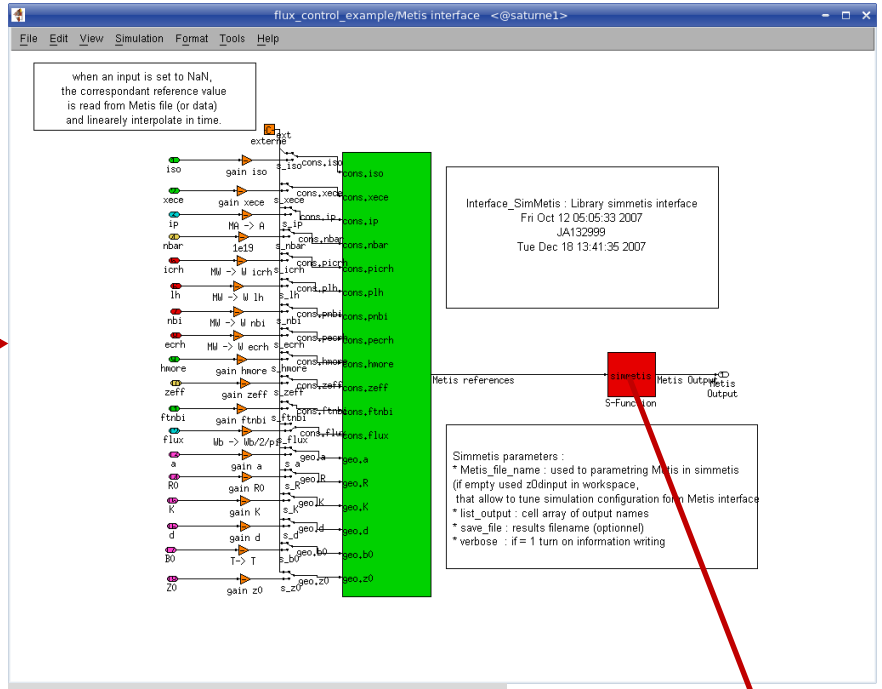


METIS INTERFACE TO SIMULINK

Simulink







Interface to simmetis

S-function simmetis

Workflow with METIS

SAMPLE SIMULINK WORKFLOW

- Sample workflow for simmetis testing (under …/zerod/):
  - test_simmetis.mdl : simple test
  - flux_control_example.mdl : poloidal flux feedback test
- Sample interface between Simulink and simmetis (under …/zerod/):
  - interface_simmetis.mdl : switches, multiplexor + S-function call
- For testing:
  - Launch METIS + load a simulation
  - Open Simulink workflow, tune simulation parameters, and run it

MATLAB WORKSPACE (IN EVOLUTION MODE)

- **METIS takes default parameters and references in Matlab workspace**

➢ **METIS GUI still active with Simulink**

✓ **Only active selected references and parameters are override by Simulink data**

- **All METIS internal data copy in Matlab workspace**

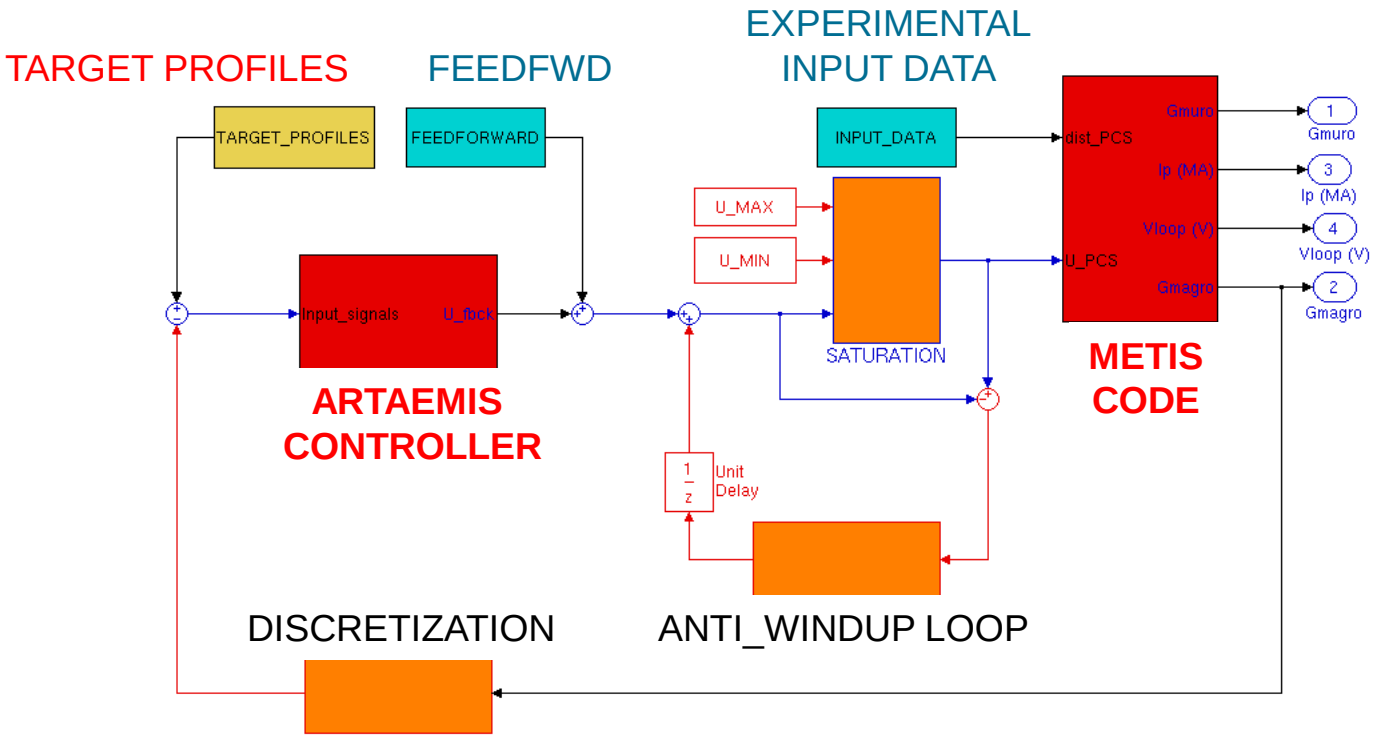
➢ **Simulink can access to any METIS data**

METIS DATA STRUCTURES FOR SIMULINK

- **Last (current time) METIS data are available in Matlab workspace from Simulink:**
  - **zerod_simmetis: 0D METIS data**
  - **profil0d_simmetis: 1D METIS data**
  - **cons_simmetis: references (use by METIS)**
  - **geo_simmetis: geometry (use by METIS)**
  - **sepa_simmetis: if LCFS given by points**

- **More data available in global structure: see simmetis online help**

METIS & SIMULINK USE CASE

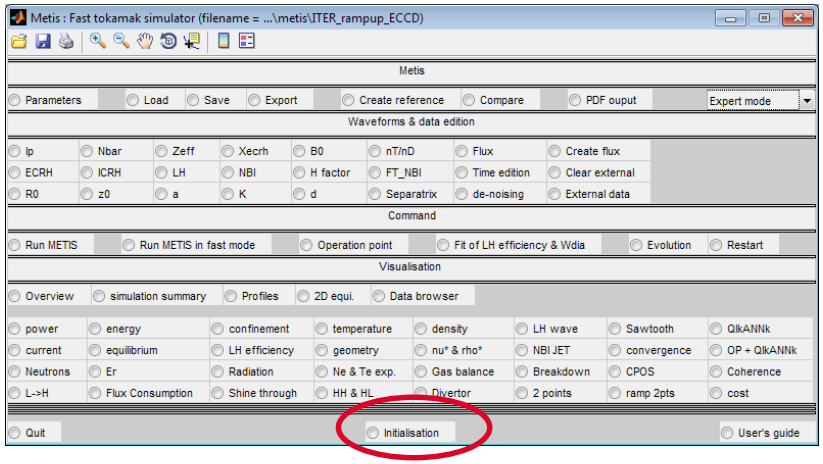


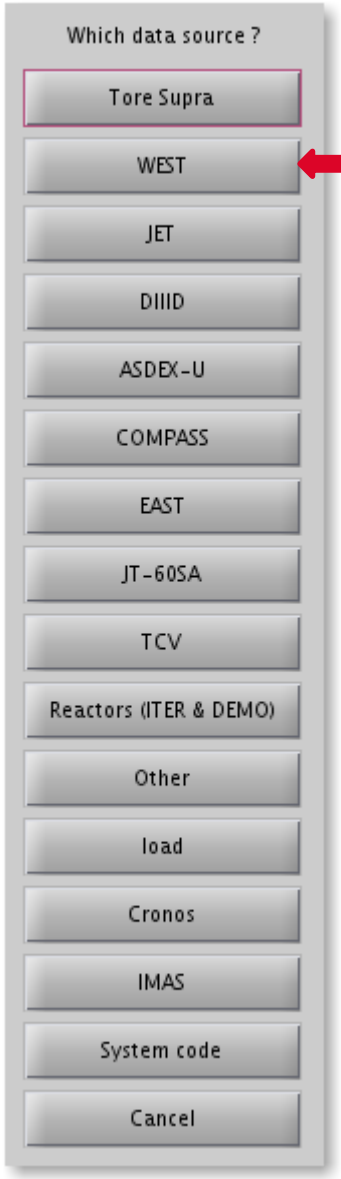
- ✓ Closed loop ARTAEMIS/ METIS simulations to extend control to steady
- ✓ Experimental input data is taken from DIII-D shot

[ITR/P1-20 Integrated Magnetic and Kinetic Control of Advanced Tokamak Scenarios Based on Data-Driven Models D. Moreau et al, 24th IAEA Fusion Energy Conference]

WEST SCENARIO PREPARATION

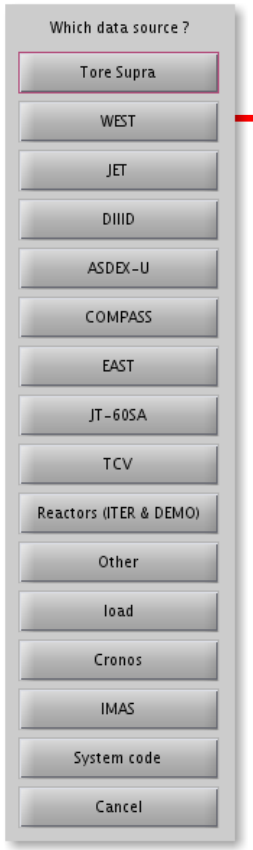
ACCESS TO WEST SCENARIO PREPARATION

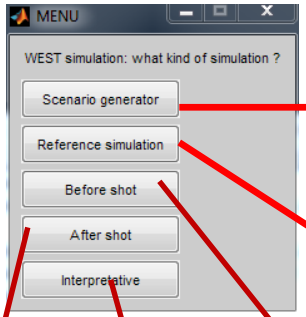


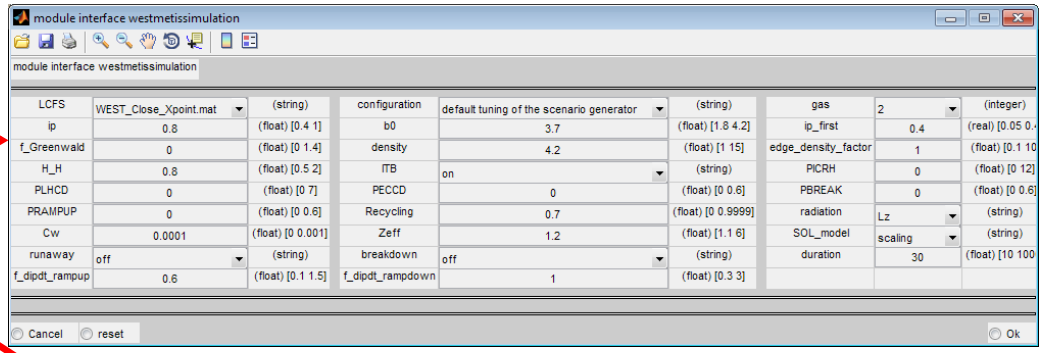


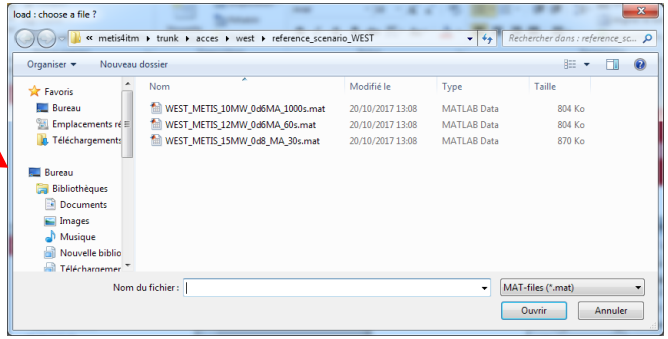
Menu for WEST

METIS INITIALISATION MENU FOR WEST









Prepare an interpretative simulation = After shot + measured profiles & parameters

Read data in ARCAD & IMAS database to prepare a METIS simulation

Read PCS data before shot or to replay a shot as tune in PCS and prepare a METIS simulation

- Menu to choose between:
  - Scenario generator
  - PCS data (before shot)
  - ARCAD data (after shot)
  - Interpretative (use ne,Te,…)

CONSTRAINTS FOR SCENARIO CONSTRUCTION

- Documents :
  - WEST research plan

    (WEST Physics Basis, C. Bourdelle et al 2015 Nucl. Fusion 55 063017)
- Data
  - Snap shots of LCFS from CEDRES++.
  - References WEST simulations

METIS SCENARIO GENERATOR FOR WEST

- We have developed a scenario template generator:
  - Create a full discharge scenario including:
    - break-down & burn through (optional)
    - ramp-up
    - flat-top
    - ramp-down.
  - Pre parametrization with a dedicated GUI.
  - Fine-tuning from METIS GUI.
  - Take into account constraints described in documentation.
  - Actuators are pre-tuned (i.e. LH, ICRH, geometry, …).

WEST SCENARIO GENERATOR GUI

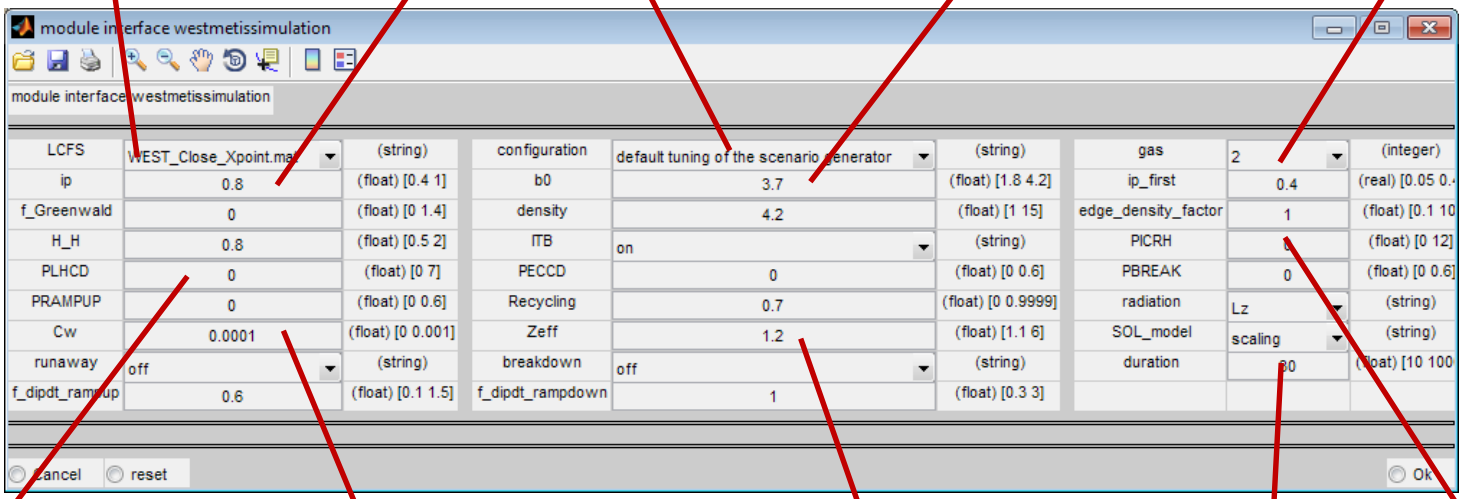
LCFS selection

Reference parameter configuration

Plasma current

Toroidal magnetic field

Plasma composition



LH power

Tungsten contamination

Zeff

ICRH power

Shot duration

SCENARIO GENERATOR PARAMETERS (1/3)

- **LCFS:** LCFS reference from CEDRES++
- **configuration:** initial parameter reference set;

  if = none, use default tuning of the scenario generator.
- **gas:** main gas species: 1 -> H, 2 -> D, 4 -> He
- **ip:** plasma current (MA)
- **b0:** vacuum magnetic field @ R_0 (T)
- **ip_first:** plasma current at time when PCS take control

  of ramp-up rate (MA)
- **f_Greenwald:** Greenwald fraction.

  If set to 0, generator uses density parameter
- **density:** line averaged electron density during flattop ($10^{19} m^{-3}$)

SCENARIO GENERATOR PARAMETERS (2/3)

- **edge_density_factor:** edge density: multiplication factor applied to edge density scaling law:

  if > 0, ne_edge = nea_factor * LCFS_denstity_scaling_law;

  if < 0, ne_edge = abs(nea_factor) * n_bar.

- **H_H:** time confinement multiplication factor during H-mode phase
- **ITB:** allows or not ITB formation (on/off)
- **PICRH:** maximum power for PICRH during flattop (MW)
- **PLHCD:** maximum power for PLHCD during flattop (MW)
- **PECCD:** maximum power for ECRH/ECCD during flattop (MW);

  baseline maximum power is 0 MW.

- **PBREAK:** injected ECRH / ECCD power for assisted breakdown (MW);

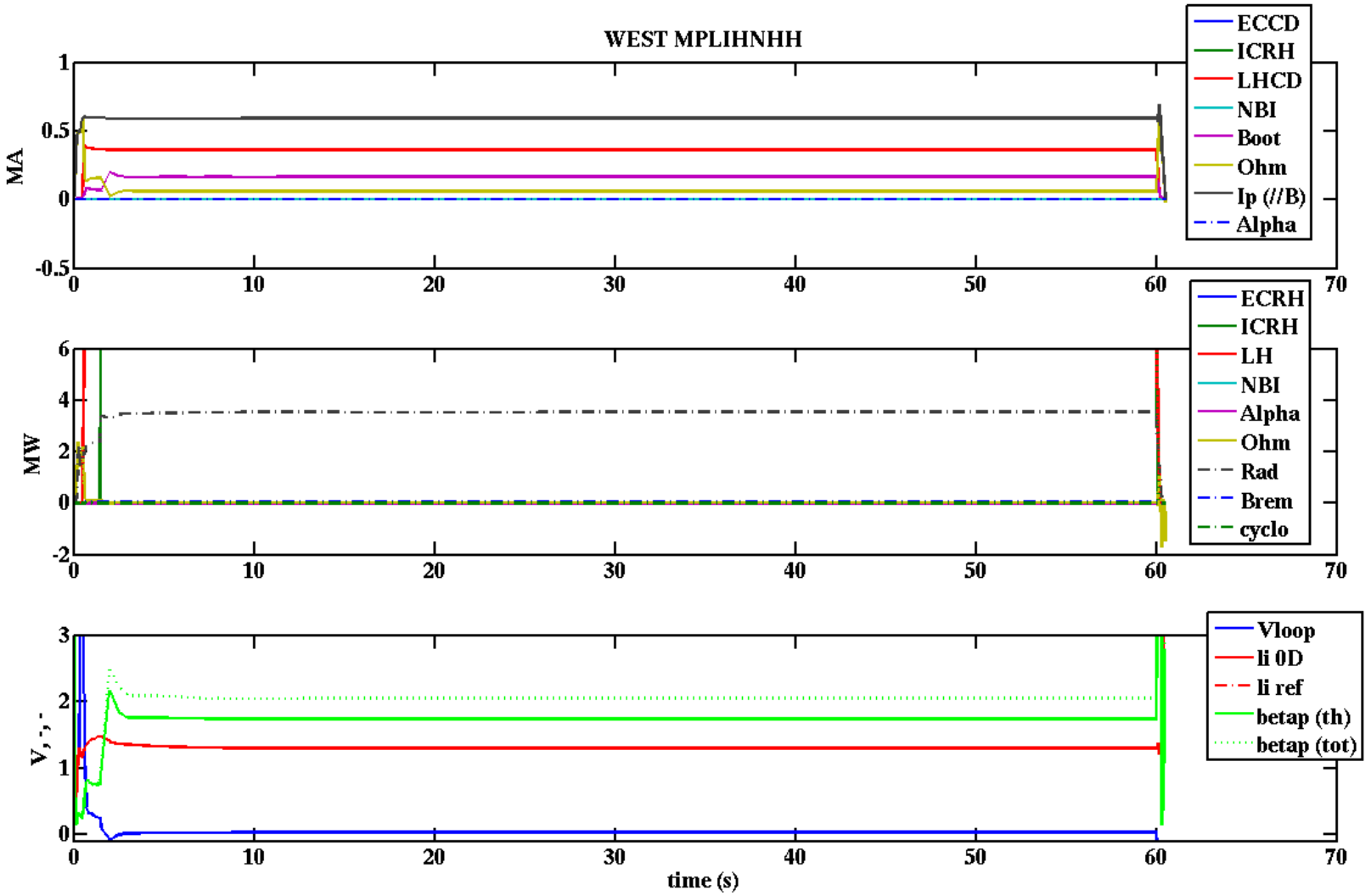
  note that only a small fraction of this power is absorbed;

  baseline maximum power is 0 MW.

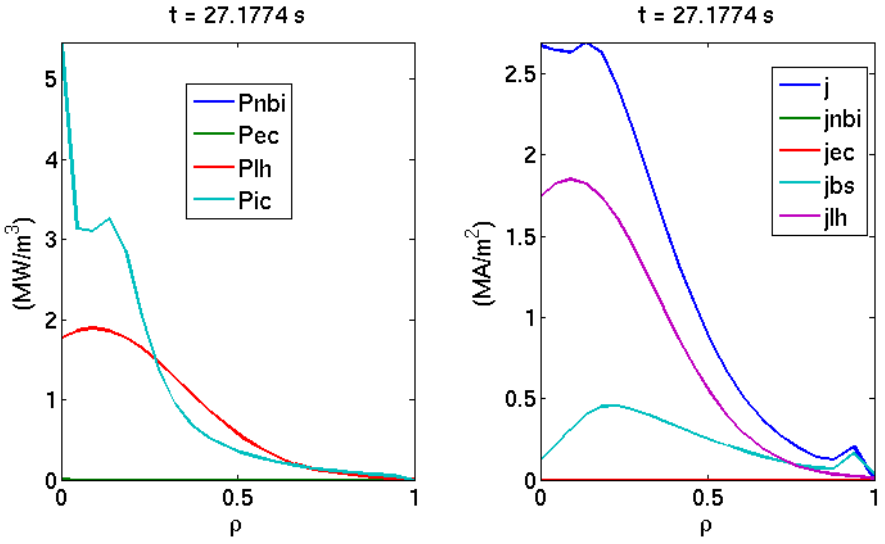
SCENARIO GENERATOR PARAMETERS (3/3)

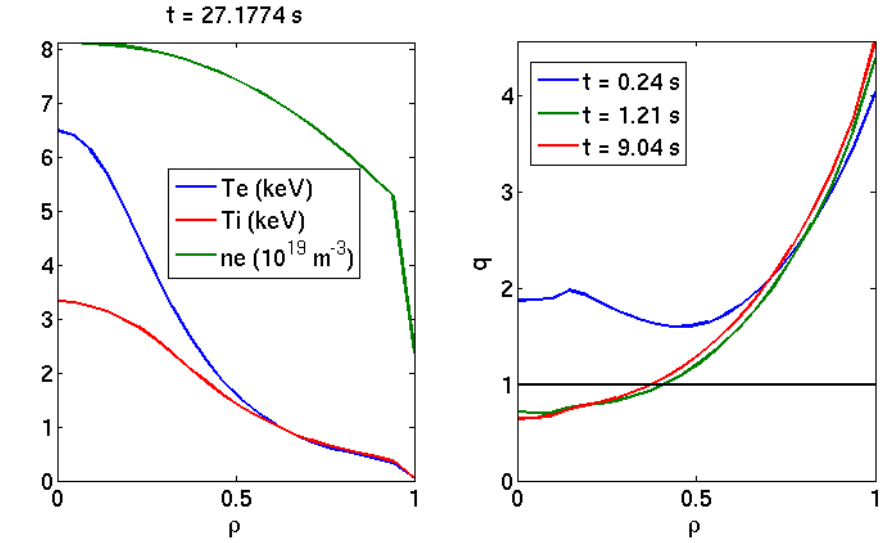
- **PRAMPUP**: ECRH / ECCD assisted ramp-up: power during ramp-up (MW); baseline maximum power is 0 MW.
- **Recycling:** Recycling coefficient
- **radiation:** model for line radiative power in core plasma (Lz = cooling rate or Matthews = Matthews scaling law)
- **Cw:** Tungsten concentration with respect to electron density
- **Zeff:** Effective charge during flattop
- **SOL_model:** scaling law or 2 points model
- **runaway:** allows or not runaway electrons in the discharge (on/off)
- **breakdown:** turn on or off the breakdown model for plasma initiation
- **duration:** shot duration: time of end of flat-top (s)
- **f_dipdt_rampup:** Ramp-up rate (MA/s)
- **f_dipdt_rampdown:** Ramp-down rate (MA/s)

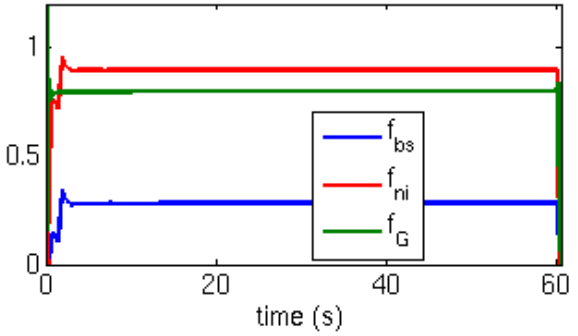
EXAMPLE OF WEST SIMULATION (1/3)

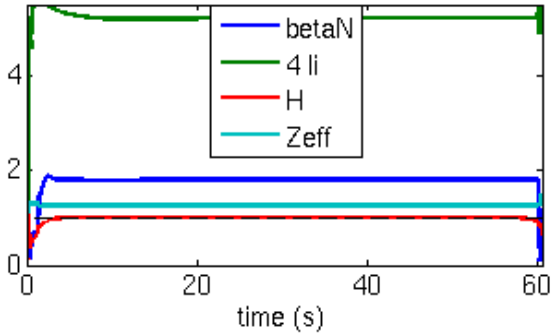


EXAMPLE OF WEST SIMULATION (2/3)

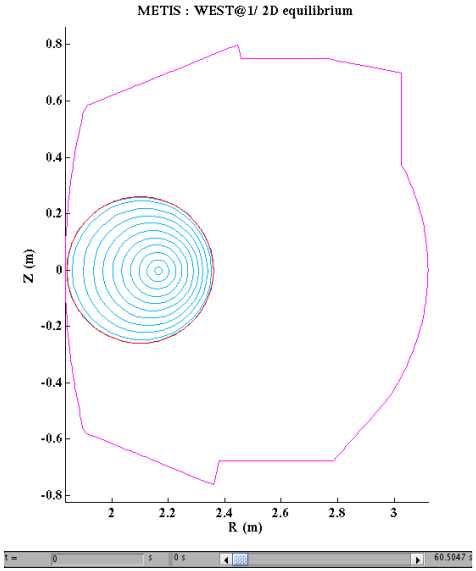


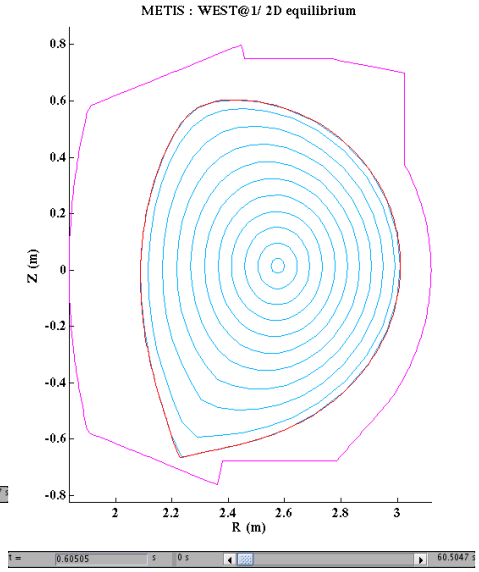


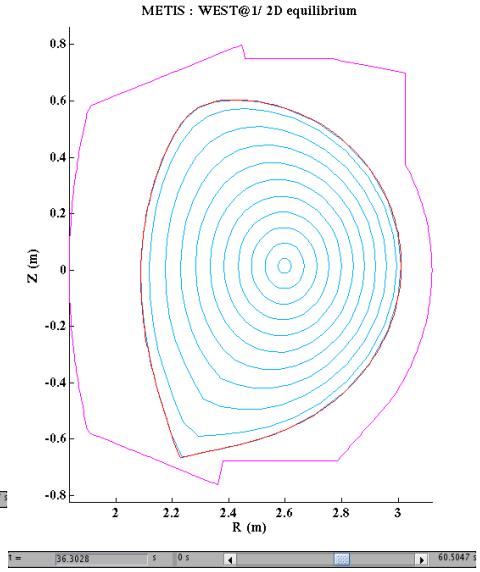


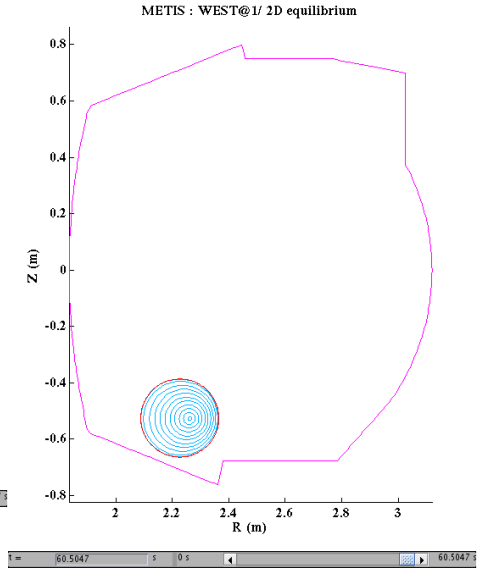


EXAMPLE OF WEST SIMULATION (3/3)



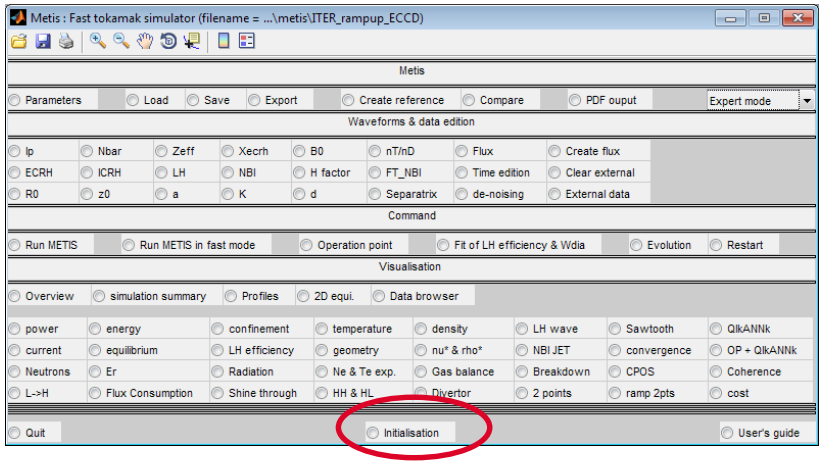


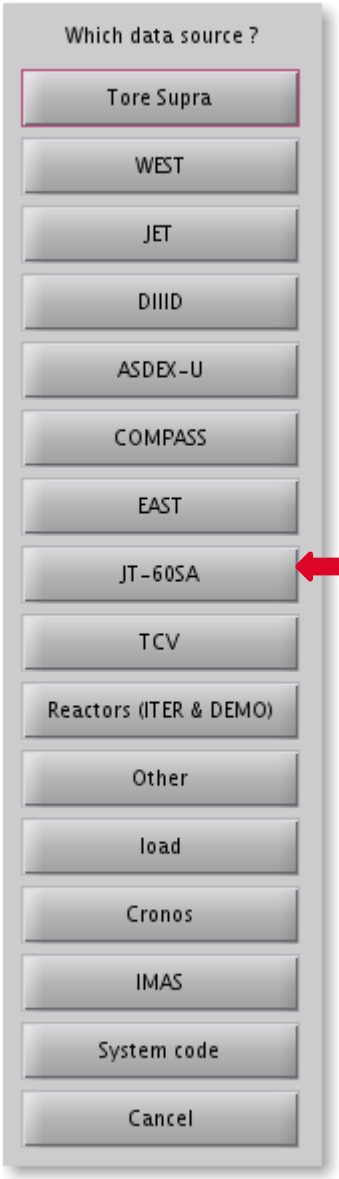




JT-60SA SCENARIO PREPARATION

ACCESS TO JT-60SA SCENARIO PREPARATION

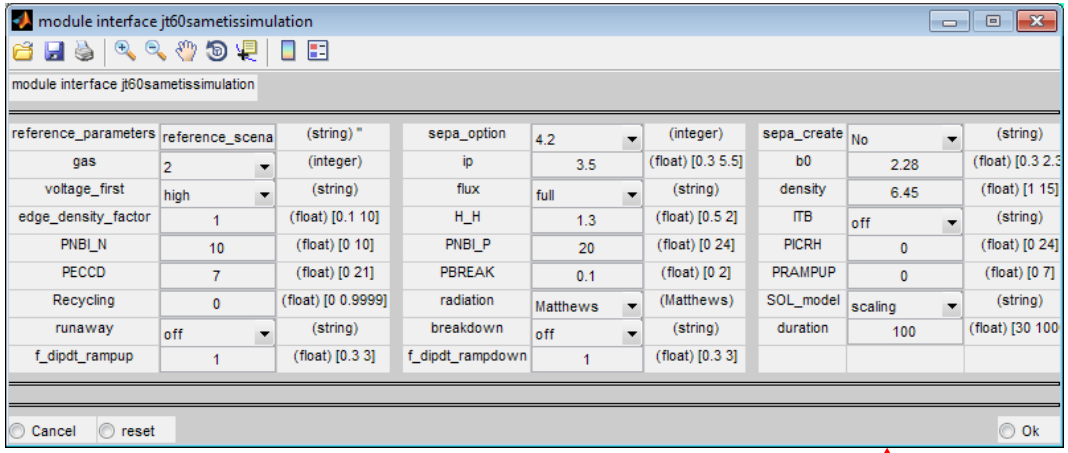


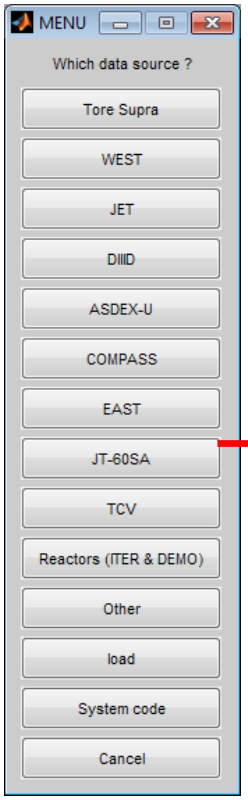


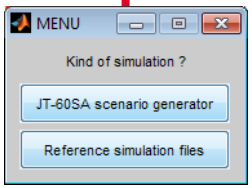
Menu for JT-60SA

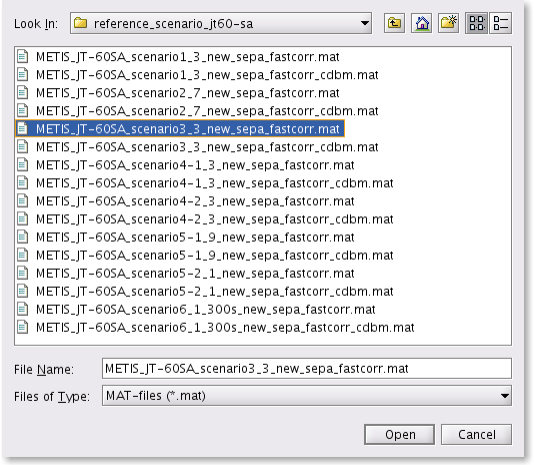
METIS INITIALISATION FOR JT60-SA

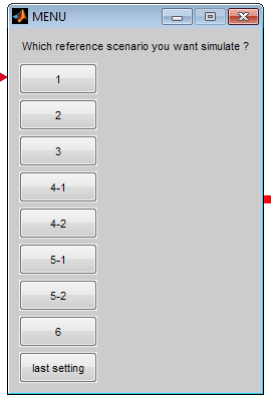
- Added menu to choose between:
  - reference scenario files
  - scenario generator











RAMP-UP AND RAMP-DOWN CONSTRAINTS

- Documents :
  - JT-60SA Research
  - Development of operation scenarios for plasma breakdown and current ramp-up phases in JT-60SA tokamak , H. Urano et al, Fusion Engineering and Design 100 (2015) 345–356
  - Simulation of plasma current ramp-up with reduced magnetic flux consumption in JT-60SA, T Wakatsuki et al, Plasma Phys. Control. Fusion 57 (2015) 065005 (12pp)
- Data
  - Snap shots of LCFS during scenario 2 from CREATE team.

METIS SCENARIO GENERATOR FOR JT60-SA

- We have developed a scenario template generator:
  - Create a full discharge scenario including:
    - break-down
    - burn through
    - ramp-up
    - flat-top
    - ramp-down.
  - Pre parametrization with a dedicated GUI.
  - Fine-tuning from METIS GUI.
  - Take into account constraints described in documentation.
  - Actuators are pre-tuned (i.e. NBI geometry, …).

SCENARIO GENERATOR PARAMETERS (1/4)

- **sepa_option:** reference scenario for LCFS parametrisation (JT-60SA Research Plan, Version 3.3, 2016, March)
- **sepa_create:** if = Yes, use LCFS provided by CREATE team (available for scenario 2); if = No, use LCFS generated by the program
- **gas:** Plasma composition: main gas species: 1 -> H, 2 -> D, 4 -> He
- **ip:** plasma current (MA)
- **b0:** vacuum magnetic field @ R_0 (T)
- **voltage_first:** Plasma initiation: burn through Vloop: high or low (H. Urano et al, Fusion Engineering and Design 100 (2015) 345-356)
- **flux:** available flux from pre-magnetisation: half CS current or full CS current (H. Urano et al, Fusion Engineering and Design 100 (2015) 345-356)
- **density:** line averaged electron density during flattop ($10^{19}\ m^{-3}$)

SCENARIO GENERATOR PARAMETERS (2/4)

- **edge_density_factor:** multiplication factor applied to edge density scaling law:

  if > 0, ne_edge = nea_factor * LCFS_denstity_scaling_law;

  if < 0, ne_edge = abs(nea_factor) * n_bar

- **H_H:** time confinement multiplication factor during H-mode phase
- **ITB:** allows or not ITB formation (on/off)
- **PNBI_N:** maximum power for NNBI during flattop (MW)
- **PNBI_P:** maximum power for PNBI during flattop (MW)
- **PICRH:** Optional ICRH source; maximum power for PICRH during flattop (MW);must be 0 by default (this source can be used for scope studies)
- **PECCD:** maximum power for ECRH/ECCD during flattop (MW); baseline maximum power is 7 MW

SCENARIO GENERATOR PARAMETERS (3/4)

- **PBREAK:** injected ECRH / ECCD power for assisted breakdown (MW); note that only a small fraction of this power is absorbed
- **PRAMPUP:** ECRH / ECCD assisted ramp-up: maximum power at the end of ramp-up (MW): power increases in time depending on density and plasma current
- **Recycling:** Recycling coefficient
- **radiation:** model for line radiative power in core plasma

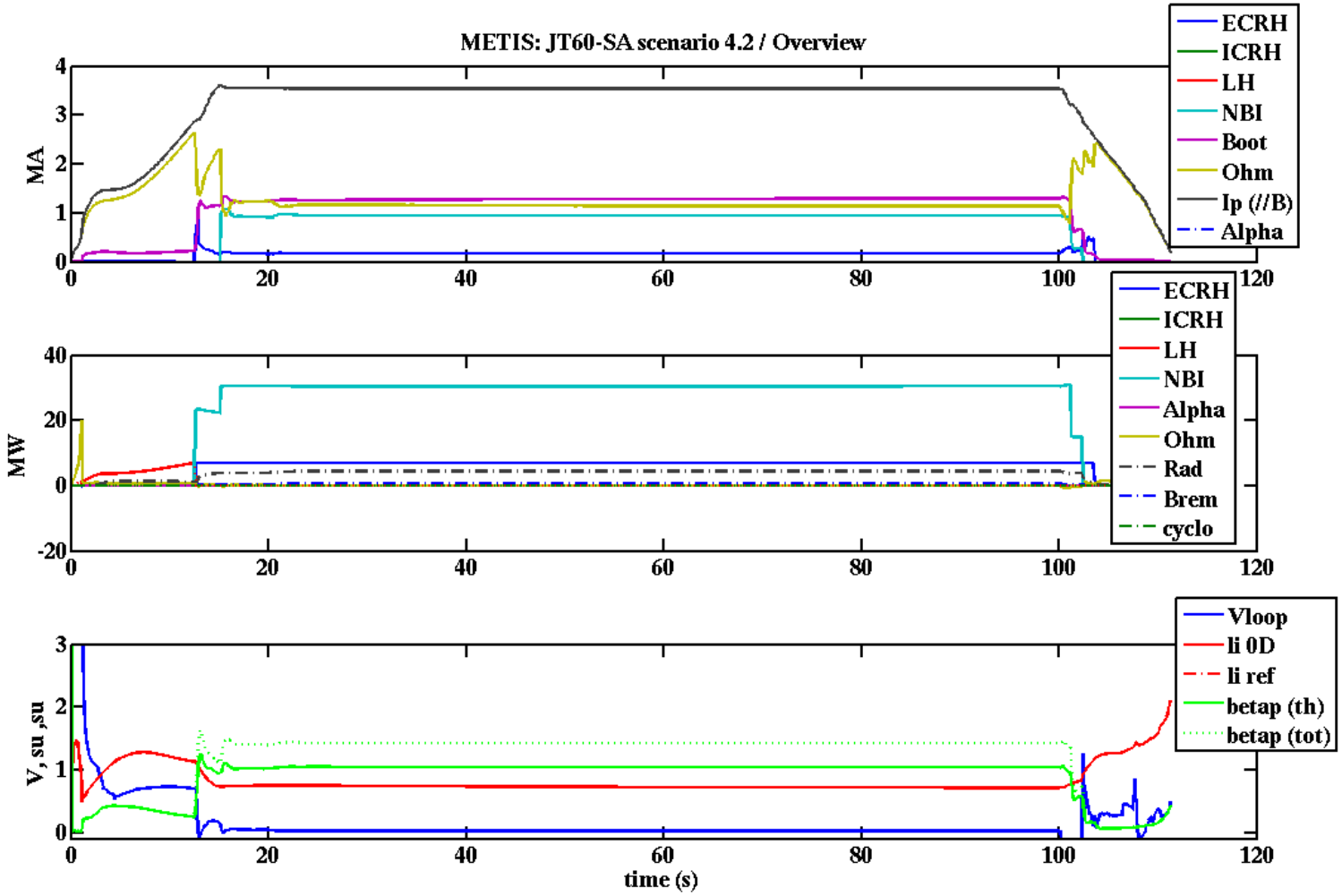
  (Lz = cooling rate or Matthews = Matthews scaling law)
- **SOL_model:** scaling law or 2 points model
- **runaway:** allows or not runaway electrons in the discharge (on/off)
- **breakdown:** turn on or off the breakdown model for plasma initiation
- **duration:** shot duration: time of end of flat-top (s)

SCENARIO GENERATOR PARAMETERS (4/4)

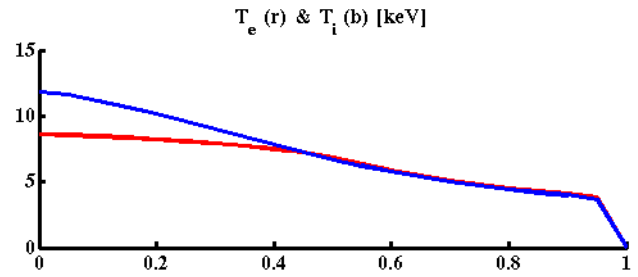
- **f_dipdt_rampup:** Ramp-up rate; multiplication factor applied to dIp/dt for plasma current ramp-up with respect to reference case
  (H. Urano et al, Fusion Engineering and Design 100 (2015) 345-356)
- **f_dipdt_rampdown:** Ramp-down rate; multiplication factor applied to dIp/dt for plasma current ramp-down with respect to reference case
  (H. Urano et al, Fusion Engineering and Design 100 (2015) 345-356)

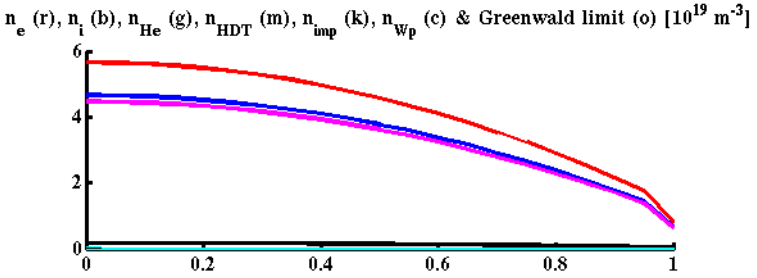
- **reference_parameters:** file name that contains Parameters that will overwrite user defined Parameters (if empty, it is not used)

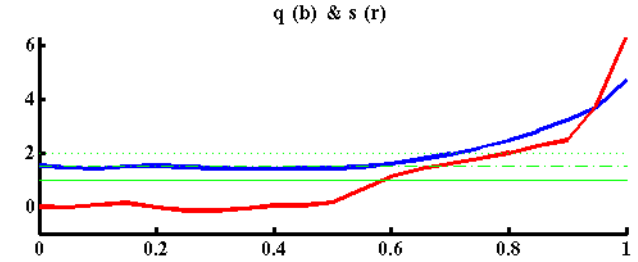
ONE EXAMPLE: SCENARIO 4.2

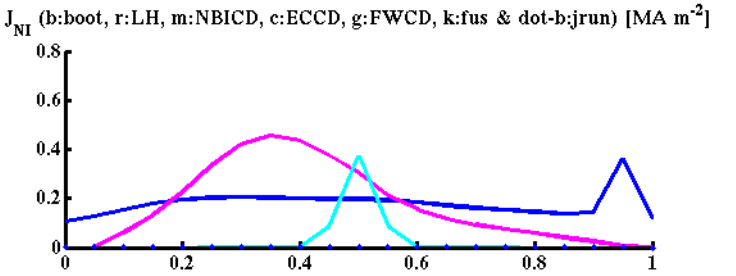


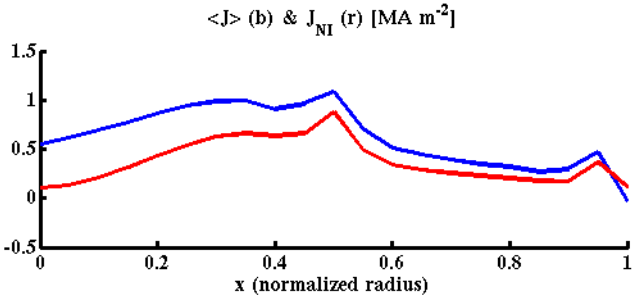
ONE EXAMPLE: SCENARIO 4.2 (2/3)

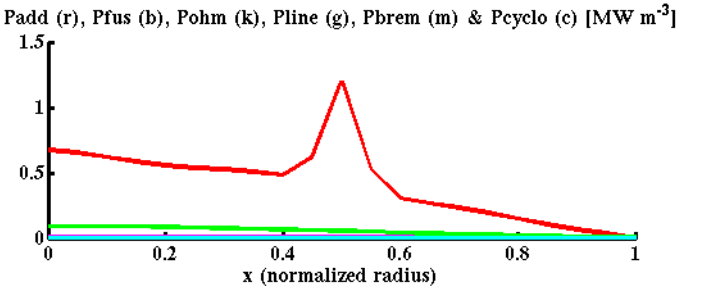




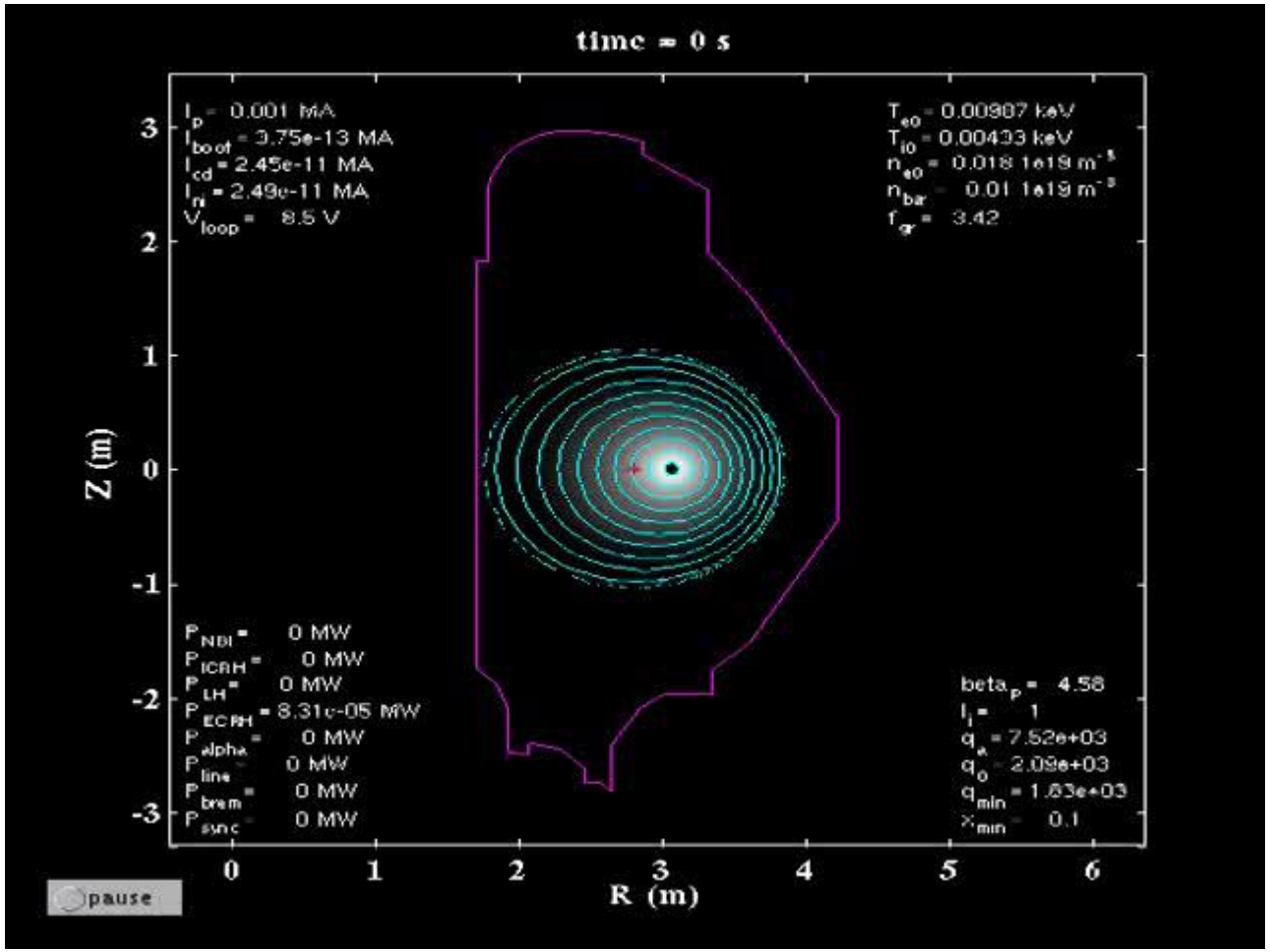








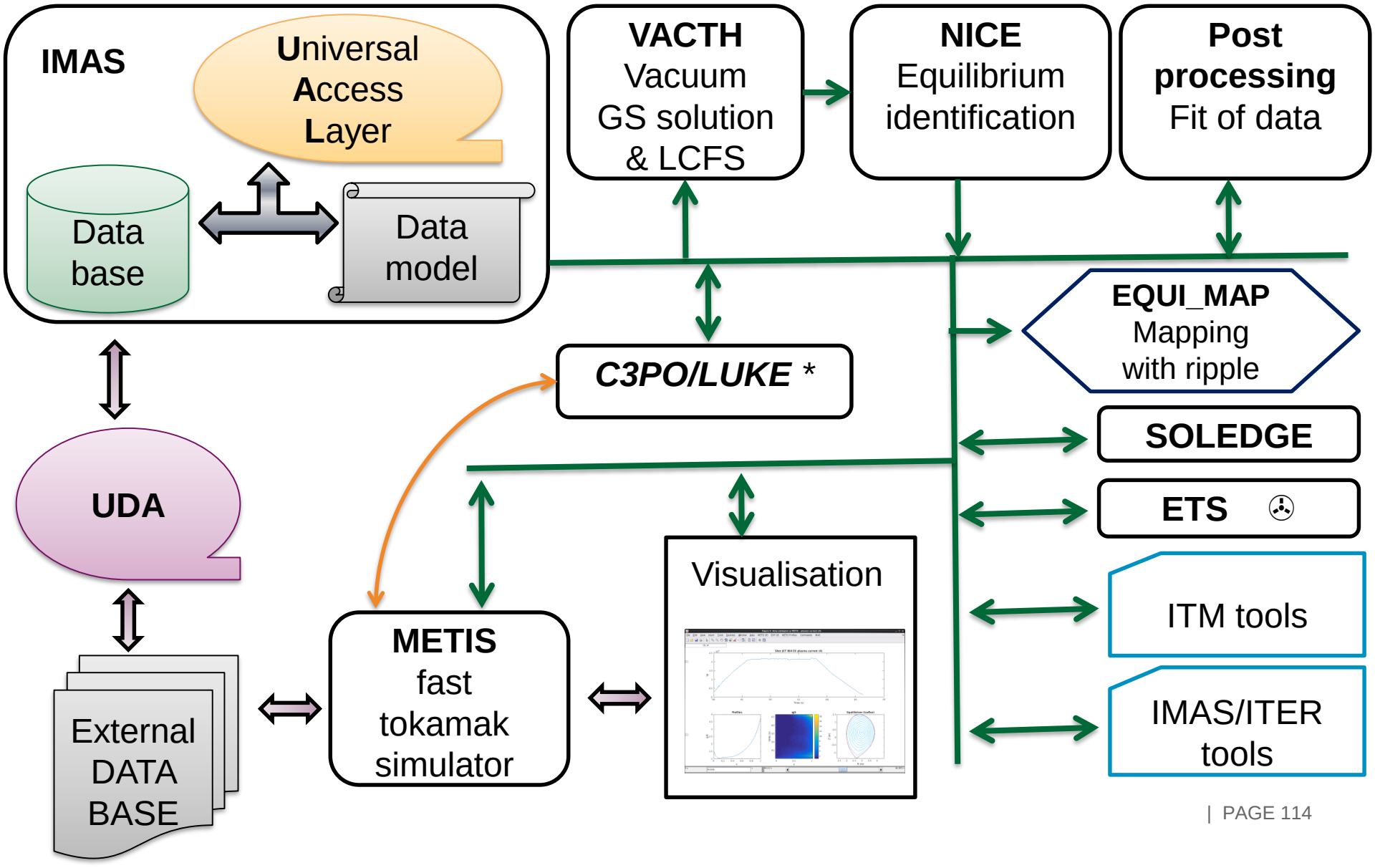
ONE EXAMPLE: SCENARIO 4.2 (3/3)



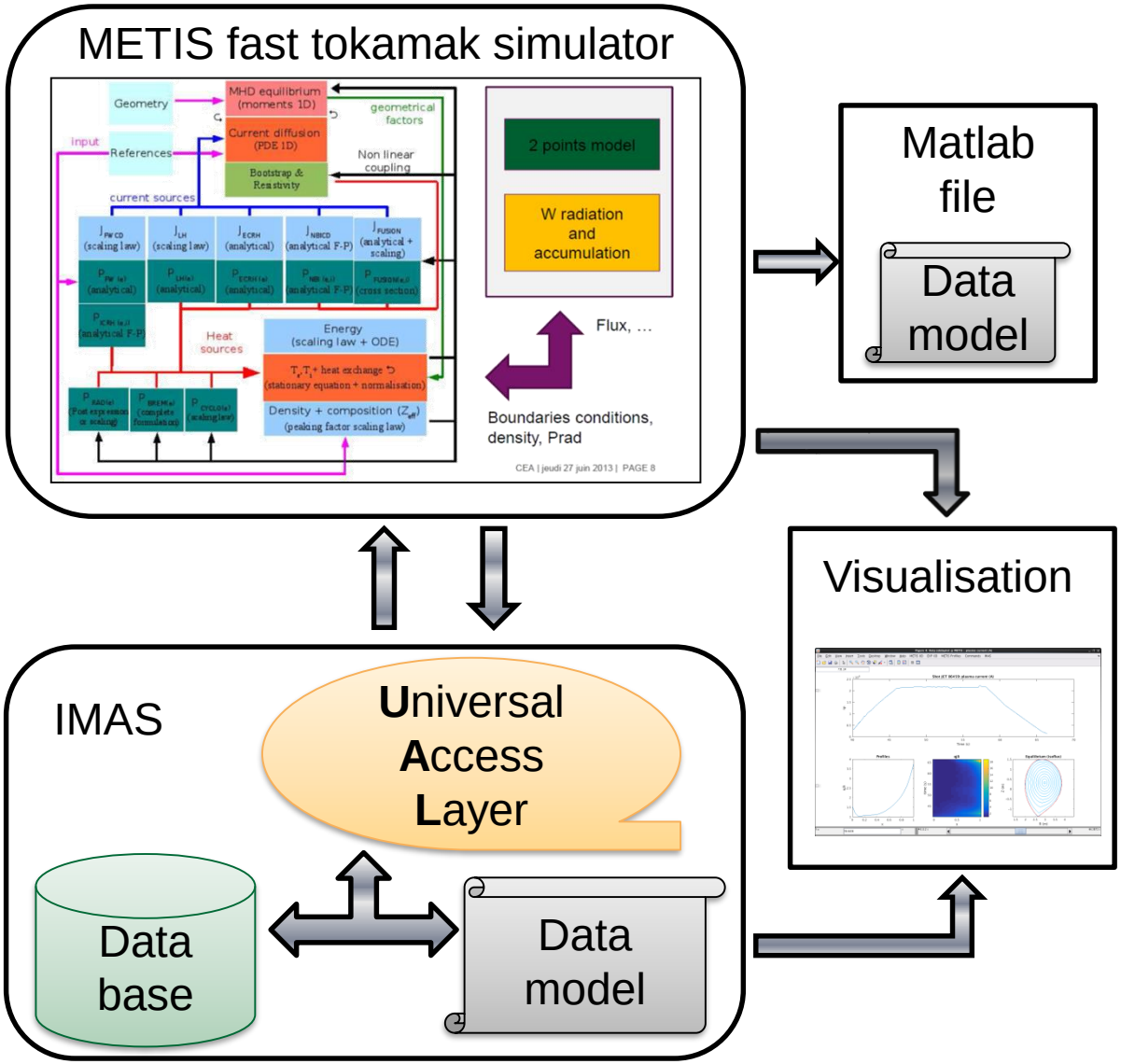
Time is not linear in this video !

METIS AND IMAS

IMAS MODELING ARCHITECTURE FOR WEST



METIS IS CONNECTED TO UAL



- Allows to call ITM or IMAS tools using METIS data set.
- Ready for analysis shot data, mixing both experimental data (fitted by ProfileMaker) and METIS prediction
- IDSs:
  - Core_profiles
  - Core_sources
  - Core_transport
  - Equilibrium
  - Pulse_schedule
  - Summary
  - Dataset_description
  - transport_solver_numerics

METIS IS CONNECTED TO IMAS UAL (2/3)

- **METIS & IMAS**
  - METIS is a fast tokamak plasma simulator.
  - IMAS is the modelling infrastructure for ITER (data model + access layer named UAL).
  - METIS can, both, read data from and write data into IMAS UAL.
  - METIS can use data provided by other tools connected to IMAS infrastructure.
  - METIS can export Matlab file (matfile) containing image of ITER data model for standalone use.
  - METIS can display, for comparison purpose, both METIS native data and IMAS data.

METIS IS CONNECTED TO IMAS UAL (3/3)

- **New capability interests for METIS:**
  - Modelling shots from data read directly into IMAS coming from machines not directly linked to METIS.
  - Analysing shot data mixing both experimental data (fitted by ProfileMaker) and prediction (example: current diffusion) for data consistency.
  - Feed IMAS data base (starting with ITER simulations) to provide data to others codes under IMAS infrastructure.
  - Export IMAS formatted structures in a matfile.

METIS4MAS OVERVIEW

metis4imas.m = interface UAL ⇔ METIS

- ✓ **Drives METIS (call methods)**
- ✓ **Handles input coming from Kepler and provides information to Kepler**
- ✓ **Reads and converts input IDS data**
- ✓ **Maps IDSs data and writes in database**

Remark:

use imasdb command under Matlab to set the default user, machine and version that will be used by metis4imas later.

METIS4IMAS INPUT

shot = shot number.

run = run number for this.

occurrence = input IDS scenario occurrence in Kepler (default = 0).

Method = METIS command (see below).

time = time scalar or vector for which METIS must be run. If empty, read all time slices of the IDS and use IDS vector time as input.

codeparam_filename = codeparam (see below).

interpolation_methode = interpolation method used for data extraction (see UAL user guide).

METIS4IMAS METHODS

- test = test the function (use test data and create IDSs).
- auto_test = complete test of metis4imas (whole functions)
- full = whole shot computation, full METIS mode
- fast = whole shot computation using fast METIS mode
- Init = initialization of the evolution mode of METIS.
- one_time = compute plasma evolution for on time step.
- read = read UAL data and return in Matlab structure

- <filename> = load a METIS simulation and create associated IDS Matlab data structures.

Codeparam contains:

- all standard METIS parameters
- UAL specific parameters that allow to control which IDS are written (+ occurrence choice)

Sources of codeparam:

- XML string
- XML file
- Input IDS pulse_schedule (if codeparam empty)
- Default values if not specified (no input IDS pulse_schedule & codeparam empty)
- Matlab structure (for testing only)

METIS4IMAS OUTPUT

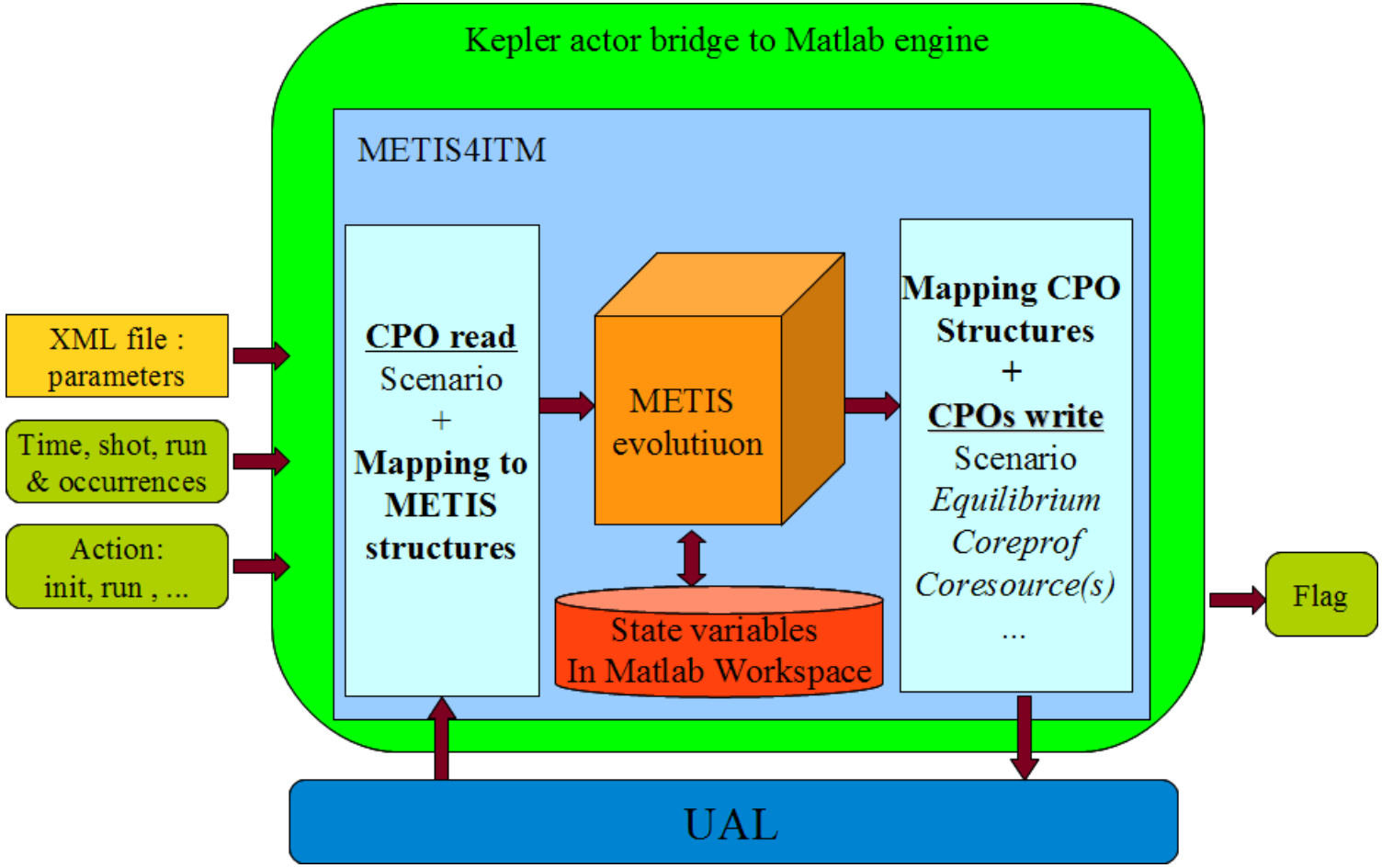
Standard output:

- err_flag = error code, must be = 0 if no error
- output_data = Matlab structure containing the counterpart of IDSs structures in Matlab compatible format.

METIS internal state:

- stored in appdata IMAS_Z0DSTRUCT
- allows to access to any METIS data and return it in Kepler

METIS ACTOR (IMAS & ITM)



METIS INTERNAL RUNAWAY MODEL

METIS MODEL FOR RUNAWAY ELECTRONS

➢ METIS have already a simplified model for runaway

- Total current is predicted:
  0D model for total runaway density/current
  [H. Smith et al, Physics of Plasma 13 (2006) 102502]
- Current density shape given by seed shape
  (with exponential dependence):
  [F. Sourd, Phd, Université de Provence, 2004]
- Taking into account as a source in current diffusion solver of METIS

➢ Mainly use for ramp-up:

Change of effective resistivity during ramp-up

METIS & QUALIKIZ NEURAL NETWORK

QUALIKIZ NEURAL NETWORK PREDICTION

- Qualikiz neurak network:
  - Neural network interpolation of Qualikiz
  - 10D version in METIS:
    limited capabilities, consider results with wariness

- Run as a post processing of METIS:
  - Compute electron density and temperature and ion temperature
  - Predicted profiles can be used as METIS external data

Ref: J. Citrin et al 2015 Nucl. Fusion 55 092001

K. L. van de Plassche et al Phys. Plasmas 27, 022310 (2020); doi: 10.1063/1.5134126

SOLVER = POWER BALANCE

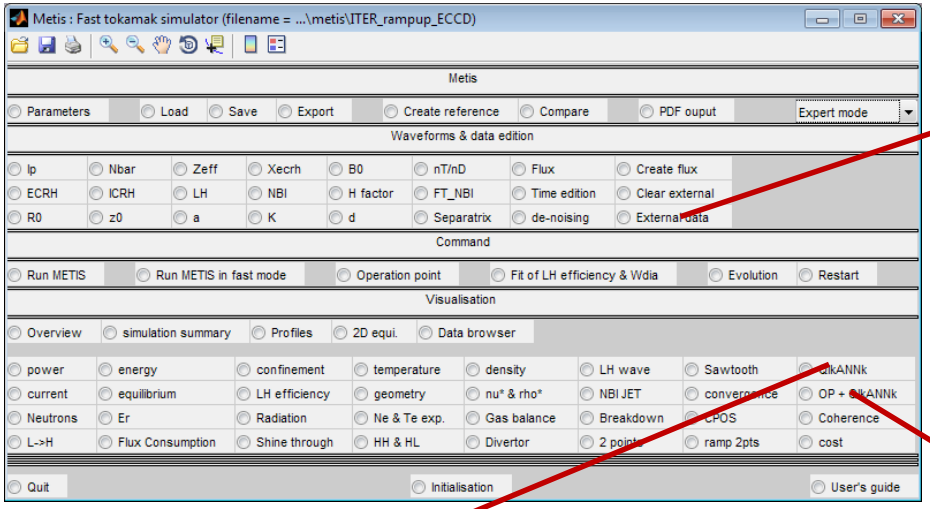
- Search for solution that equals flux computed from sources and from closure formula (transport coefficients).
- Steady state solution
- The solver uses simulating annealing for optimization/convergence (quite fast, very simple to implement, robust and no need of derivatives)
- Sources are got from Metis
- Equilibrium is got from Metis
- Neoclassical ion heat transport is computed using Chang-Hinton formula (ref: Tokamak, Wesson). It is added to Qualikiz NN flux.
- Ware pinch computed in Metis is added to particle pinch computed by Qualikiz NN
- Equipartition heat term (electron/ion energy transfer by collision) is updated in the convergence loop

OPTIONAL TRICKS

- A factor can be applied to ion neoclassical heat transport
- Electron heat diffusivity can be clamped above some fraction of ion neoclassical heat diffusivity
- Particle diffusivity can be clamped above some fraction of ion neoclassical heat diffusivity
- Fast particle effect can be included using JETTO trick (reduction of $\frac{R\nabla T_i}{T_i}$ as $\frac{W_{th}}{W}$)
- Flux ratio (ion/ electron or electron/ion) can be limited to some given value
- Threshold shift can be taken into account
- Time dependence can be mimicked by multiplying flux computed from sources by:

$$\frac{P_{loss} - \frac{dW_{th}}{dt}}{P_{loss}}$$

TWO MODES: FULL SCENARIO OR SELECTED TIME SLICE



External data menu with item QUALIKIZ. Allows to select between Ne, Te and Ti

Full scenario prediction

Selected time slice

Remark: in selected time slice, a loop of convergence is performed between Qualikiz neural network prediction and METIS. Ne, Te and Ti are predicted by Qualikiz neural network and METIS predicts all other quantities.

METIS: OTHER FEATURES

METIS HELPERS

- External codes interfaced to METIS

➢ Call for one time slice

➢ Tuning or validation of METIS models

✓ Available helpers:

  – HELENA/NCLASS: bootstrap current

  – Qualikiz neural network: (Te, Ti & Ne)

METIS IN CRONOS

- Originally METIS was a module of CRONOS
  - CRONOS data set can be used to prepare a METIS simulation
  - METIS simulation can be used to fulfil a CRONOS data set
- Integration is complete between CRONOS GUI and METIS GUI
- Useful to check a CRONOS simulation
- Use to prepare CRONOS simulation for future tokamak
- Allows to rapidly run a module of CRONOS from a METIS simulation.

FEEQS.M/NICE-METIS

- FEEQS.M (FBE) and METIS have been coupled
  = full tokamak simulator for scenario and controller design

✓ METIS: fixed boundary solver for FEEQS.M

✓ FEEQS.M provided LCFS + moments to METIS

✓ Interfaced to Simulink

LUKE/C3PO/R5X2 TOOL

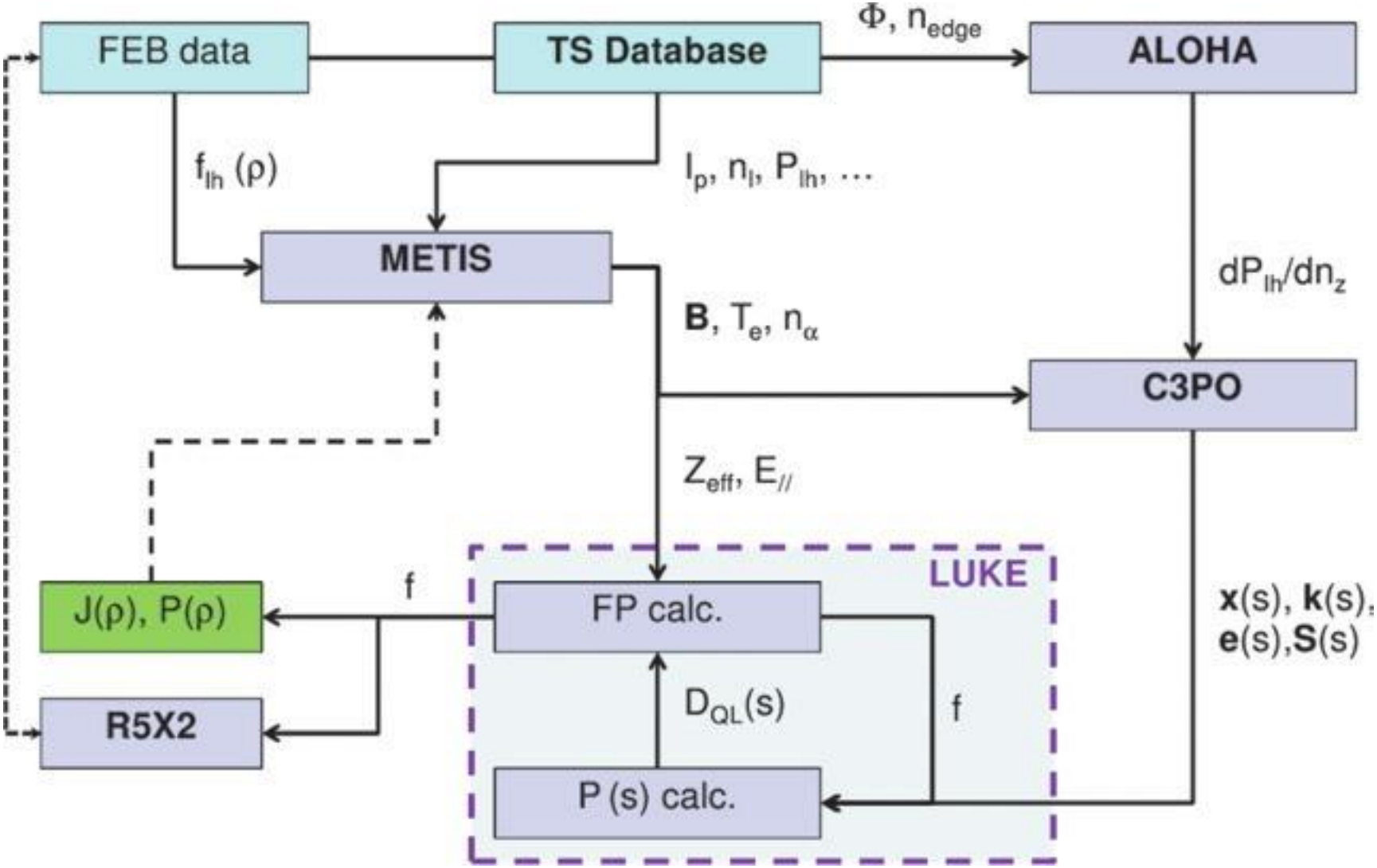
- C3PO/LUKE module compute sources from RF electron resonant waves:
  - LHCD
  - ECCD
- C3PO: ray-tracing code
- LUKE: relativistic Fokker-Planck solver
- R5X2: synthetic diagnostic for fast electron bremsstrahlung

[Y. Peysson et al, Plasma Phys. Control. Fusion, 54:045003, 2012]

[Y. Peysson and J. Decker, Calculation of rf current drive in tokamaks, CEA/IRFM,Association Euratom-CEA, 2007]

[Y. Peysson and J. Decker, Physics of Plasmas, 15, 2008].

LUKE/METIS COUPLING

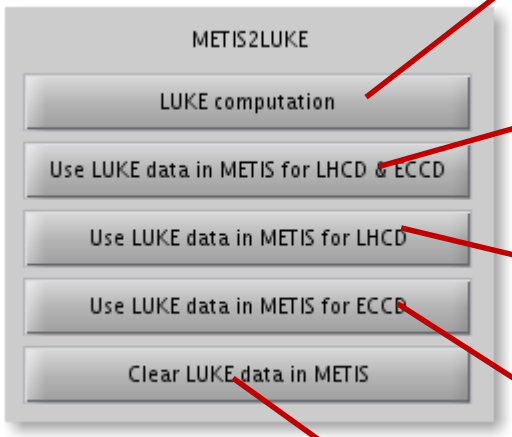


METIS/LUKE USE CASES

- ✓ METIS provides core plasma data to LUKE/C3PO (kinetic profiles and MHD equilibrium)
- ✓ LUKE provides LHCD and ECCD sources to METIS
- ✓ LUKE will provide runaway current to METIS that in return will provide $E_{//}$

[E. Nilsson et al 2013 Nucl. Fusion 53 083018 doi:10.1088/0029-5515/53/8/083018]

METIS/LUKE GUI (MAINTENANCE IN PROGRESS !)



Prepare LUKE data from METIS simulation and call LUKE interface

Use LUKE results in METIS as external data for LHCD and ECCD

Use LUKE results in METIS as external data for LHCD

Use LUKE results in METIS as external data for ECCD

Remove LUKE data from external data used by METIS

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