Status of ITER diagnostic design and R&D tasks in the EU

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Outline

- Overview of implementation of design and R&D on the diagnostic procurement packages the EU is likely to supply to ITER
- Results from recently completed and ongoing EFDA design and R&D tasks

As usual, this presentation reviews work in the EU specifically directed to ITER diagnostics as part of the **EFDA Technology Workprogramme (TWP)**. It does not cover work in the EU laboratories outside EFDA funding on interesting new diagnostic techniques that may be ITER relevant.

Participating laboratories on EFDA ITER diagnostic tasks (1)

The ITER diagnostic design and R&D work within the EU fusion programme, including ceramics irradiation of components for H&CD and diagnostic systems, is carried out under contract, as part of the **EFDA Technology Workprogramme (TWP)**, at many **Euratom-associated laboratories ("Associations")** by a large number of people (TWP2000–2006):

CEA Cadarache: C. Bruyere, M. Chantant, P. Chappuis, F. Clairet, Y. Corre, P. Defrasne, L. Doceul, S. Droineau, L.-G. Eriksson, C. Gil, D. Guilhem, S. Heuraux, S. Hourcade, M. Lipa, P. Lotte, L. Meunier, P. Moreau, R. Reichle, R. Sabot, S. Salasca, P. Spuig, B. Schunke, P. Stott, E. Thomas, G. Tremblay, J.-M. Travere, J.-C. Vallet, *et al.*

CIEMAT Madrid: E. Blanco, J. Botija, T. Estrada, M. González, T. Hernández, c. Hidalgo, E. Hodgson, A. Ibarra, J. Mollá, A. Moroño, I. Pastor, G. Pérez, J.L. De Pablos, J. Romero, J. Sánchez, P. Tabarés, V. Tribaldos, R. Vila, G. Veredas, *et al.*

CRPP, Lausanne: R. Chavan, A. Encheva, A. Karpushov, P. Marmillod, Y. Martin, J.-M. Moret, A. Perez, D. Testa, G. Turri, H. Weisen

Univ. Basel, Switzerland: G. De Temmerman, L. Marot

DCU, UC Cork: P. McCarthy, C. Nyhan, S. Prunty, M. Spillane

ENEA Frascati: P. Batistoni, L. Bertalot, B. Esposito, L. Giudicotti, G. Maddaluno, D. Marocco, E. Mainardi, L. Petrizzi, *et al.*

ENEA CREATE: R. Albanese, M. Ariola, G. Ambrosino, G. Artaserse, G. Calabrò, V. Coccorese, R. Fresa, C. Morabito, A. Pironti, G. Rubinacci, M. Versaci, F. Villone, *et al.*

ENEA RFX Padova: A. Alfier, M. Bagatin, G. Chitarin, L. Giudicotti, P. Nielsen, S. Peruzzo, R. Pasqualotto, N. Pomaro, M. Valisa, *et al.*

ENEA IFP-CNR Milano: A. Simonetto, G. Gorini, C. Sozzi

FOM Nieuwegein: M. de. Bock, S. Brons, E. Delabie, A.J.H. Donné, A. Goede, M.F. Graswinckel, M. von Hellermann, R. Jaspers, G. van Rooij; TNO: J. Hopman, F. Klinkhamer, B. Snijders; NRG: A. Hogenbirk

FZJ Jülich: W. Biel, G. Bertschinger, G. Czymek, R. Koslowski, L. Litnovsky, M. di Maio, A. Marchuk, O. Neubauer, M. Pap, V. Philipps, A. Pospieszczyk, S. Sadakov, G. Sergienko, R. Sievering, P. Wienhold, *et al.*

Participating laboratories on EFDA ITER diagnostic tasks (2)

FZK Karlsruhe: J. Burbach, I. Danilov, R. Heidinger, A. Meier, U. Fischer

HAS-KFKI Budapest: T. Baross, G. Grunda, S. Kálvin, B. Kardon, T. Kun, B. Mészáros, J. Sárközi, S. Zoletnik

IPP Garching: L. Giannone, G. Haas, A. Herrmann, L. Horton, H. Meister, V. Mertens, I. Radivojevic, G. Raupp, A. Scarabosio, D. Wagner, C. Wittmann, W. Zeidner

IPP.CR Prague: I. Duran, M. Hron, V. Piffl, J. Stöckel

IST Lisboa: L. Cupido, A. Malaquias, M.E. Manso, A. Neto, C. Silva, J. Sousa, P. Varela, *et al.*

Latvia: M. Antonova, I. Aulika, M. Kalnberga, A. Kalvane, K. Kundzins, M. Kundzins, M. Livins, A. Spule, A. Sternberg, V. Zauls

NASTI/MECT, Romania: B. Constantinescu, A. Danis, D. Dudu, D. Sporea, I. Vata, *et al.*

ÖAW Wien: R. Bittner, H.D. Falter, V. Goloborod'ko, H. Hartmann, K. Humer, G. Pühringer, K. Schöpf, E. Seidl, H.W. Weber, V. Yavorskij

Risø Denmark: H. Bindslev, S. Korsholm, A. Larsen, F. Meo, P. Michelsen, S. Michelsen, S. Nimb, J.R. Pedersen, E. Tsakadze

SCK/CEN Mol: B. Brichard, M. Decréton, A. Gusarov, R. van Nieuwenhove, H. Ooms, W. van Renterghem, L. Vermeeren

Tekes: J. Heikkinen, V. Hynönen, L. Jylhä, J. Koivula, T. Kurki-Suonio, A. Kärkkäinen, A. Oja, W. Schmidt, *et al.*

UKAEA Culham: N. Balshaw, R. Barnsley, M. Beurskens, A. Boboc, P. Carman, N. Conway, M. Cox, A.C. Darke, S. Davis, F. Digby-Grant, P. Dirken, R. Eagle, C. Gowers, M. Loughlin, N. Hawkes, K. Hawkins, P. Karditsas, M. Kempenaars, V. Kiptily, C. Marren, W. Morris, M. O'Mullane, R. Pampin, P. Parsons, A. Patel, K. Patel, R. Pearce, G. Phillips, P. Prior, V. Riccardo, R. Scanell, C. Sowden, M. Stamp, M. Walsh, C. Waldon, B. Walton, Y. Xue, K.-D. Zastrow, *et al.*

VR Stockholm/Uppsala: G. Ericsson, T. Hellsten, T. Johnson, M. Laxåback, M. Kuldkepp, J. Källne, E. Rachlew

Collaborations with institutes outside the EU: Lviv Polytechnic University, Ukraine; IPP NSC KIPT-Kharkov, Ukraine; TRINITI, Troitsk, RF; RRC Kurchatov, Moscow, RF; Ioffe Institute, St. Petersburg; UCSD, San Diego, US

Overview of EFDA tasks on ITER diagnostics (1)

2006 was the first year with a budget that made it possible to implement **tasks on all relevant topics** at the same time:

- The diagnostic procurement packages the EU will supply to ITER
- “Non-costed” diagnostics with EU interest (i.e. diagnostics not yet in the accepted diagnostic set)
- Generic topics (such as port-plug engineering and first mirrors)
- Irradiation testing

The **European Domestic Agency** **“European Joint Undertaking for ITER and the Development of Fusion Energy (‘Fusion for Energy’)”** has been approved on 27 March 2007, and will come into existence in 5–6 weeks from now. Subsequently governing board and director will be appointed, the organization will be set up, staff recruited, and responsibilities transferred from EFDA. **It is expected to become operational in the second half of the year** and form its own strategy and plans**.** **EFDA** will remain in charge of operating JET and on certain **programmatic** topics in preparation for ITER operation and DEMO development.

TWP2006 was the last full workprogramme under EFDA. A small number of urgent tasks will still be implemented under EFDA in the first few months of 2007.

Overview of EFDA tasks on ITER diagnostics (2)

Clusters of EU Fusion Associations have been formed as part of the EFDA TWP2006, charged with the **drawing up of Project Plans** for the full development of most of the EU **diagnostic procurement packages**:

Package	Ports	Diagnostic(s)	Associations involved
PP1	U01&14	**plasma-position reflectometry**	IST, CIEMAT, CEA, ENEA-CNR Milano
PP2	U03	**core-plasma CXRS**	FZJ, FOM, UKAEA, HAS
PP11	E01	**radial neutron camera, equatorial wide-angle viewing system**	CEA, ENEA, CIEMAT, HAS, IST
PP14	E10	**core-plasma LIDAR**	UKAEA, FZJ, FOM, CIEMAT, ENEA-RFX, HAS, IST
PP21	L16	**bolometers, pressure gauges**	IPP, HAS, FZK, CEA, CIEMAT
PP22	L04	**magnetics**	CRPP, CEA, ENEA-RFX, CIEMAT

Aspects that will be addressed as part of the TWP2006 tasks during 2007 are:

- **Identify the scope** of the procurement package and assess **boundaries and interfaces** of the project
- Provide a **detailed description** of the package (later to be developed into the procurement specs)
- Develop a **detailed workplan** for **full implementation** of the package, including
    - **time schedule** and **risk analysis**
    - **definition of design and R&D tasks** (incl. prototyping and testing) that will have to be completed
    - **costing** (hardware, testing, resources, competences, …)

In addition, each cluster will address **urgent design and R&D** on the diagnostics.

Overview of EFDA tasks on ITER diagnostics (3)

Non-costed diagnostics with EU interest

- Collective Thomson scattering (Risø)
  - o **Results and details presented by S. Korsholm**
- Large neutron spectrometer (VR)
  - o Topics of task: justification, physical and technical feasibility
- Divertor thermography (IPP and CEA)
  - o **Design task** implemented (CEA, TWP2006) to perform an **engineering analysis of the front end casing** and optical study (common to both approaches) and address critical issues on the **fibre-optics approach** (fibre-optic connectors, replaceable fibre mechanism, calibration issues). **Aim** is to be **establish feasibility of the mirror-box** under the divertor dome and to be able to **make a choice between the conventional and fibre-optics approaches** (or a combination).

Overview of EFDA tasks on ITER diagnostics (4)

In-vessel services (PP30) and **thermocouples** (PP22&PP27) are also EU diagnostic procurement packages: "in-vessel services" is handled under generic topics.

Generic topics (1):

- Port engineering (UKAEA, CEA, CIEMAT, IPP, ENEA) **Implemented**
  - Contribution to cross-party diagnostic port-plug engineering task force to develop standard representative upper and equatorial port plugs (port structure)
  - Build expertise required in EU to fulfil our procurement obligations
  - Develop designs and concepts needed for diagnostic integration
- Port-based procurement (UKAEA, TEKES, CEA) **Implemented**
  - Assess implications for the development and procurement organization (e.g. procurement of all EU port plugs central, or distributed per procurement package? Risk? Cost?)
- ITER practice for windows (UKAEA, FZK) **Implemented**
  - The ITER Vacuum Vessel is designed and fabricated based on **developed industrial pressure vessel codes**. **Non-metallic materials such as windows, are generally not allowed in pressure vessel codes**→no applicable exiting industrial standard for the windows ITER requires for diagnostics and H&CD systems. For the ITER licensing, it is necessary to develop an **ITER Practice for non-metallic replaceable window assemblies** that specifies the criteria for the design, the manufacturing, and the testing of these parts and components.

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Overview of EFDA tasks on ITER diagnostics (5)

Generic topics (2):

- First mirrors, including mitigation and cleaning techniques (ongoing FZJ, University of Basel and ENEA-Frascati, new task FZJ, University of Basel, FOM, CEA Saclay)
    - **See report of SWG on mirrors**
- **Fast ions and ITER diagnostics Implemented**
  First results later in this presentation.
- A number of on going tasks from **TWP2005 and earlier workprogrammes** (same topics as implemented in TWP2006)
- EU/RF collaborative tasks on various ITER diagnostics **(ongoing since TWP2005)**
    - **CXRS**
    - **Reflectometry**: joint work on HFS reflectometry mock-up and development of high-performance waveguide feedthroughs/windows
    - **Neutron detectors**: electronics and data-acquisition, radiation hardness of various types of neutron detectors, performance analysis of neutron cameras (tomography)
    - **LIDAR** laser and detector assessment
    - **H_α spectroscopy**: using experimental data on EU machines, and test a prototype ITER spectrometer on TEXTOR
    - **SXR**: vacuum photodiode development and performance analysis
    - Manufacturing methods for large (Ø10 cm) monocrystalline molybdenum **mirrors**
    - Hydrogen loading of large (Ø600 μm) core **optical fibres** (installation complete)

Overview of significant results

Recent results from EFDA tasks:

- **Magnetics sensors**
  - o **Progress on R&D and analysis → next few slides**
  - o Assessment of the effect of plasma noise on the vertical velocity determination. It has been shown, with TCV data (MHD, ELMs, sawteeth), that alternative calculation can minimize the noise propagation. (CRPP)
- **Effect of RF- and NBI-driven fast ions on diagnostics → later slides**
- **Bolometers**
  - o Collimator design to minimize interference from waves (e.g. LH) (CEA)
  - o Second batch of silicon-nitride/platinum bolometers now available (IPP, Univ. Berkeley, HAS)

Other results from EFDA tasks are presented in:

- Reflectometry → **SWG**
- Radiation effects → **SWG**
- CXRS → **SWG**
- X-ray crystal spectroscopy → **SWG**
- Magnetics → **G. Chitarin**
- CTS → **S. Korsholm**

Magnetics (1)

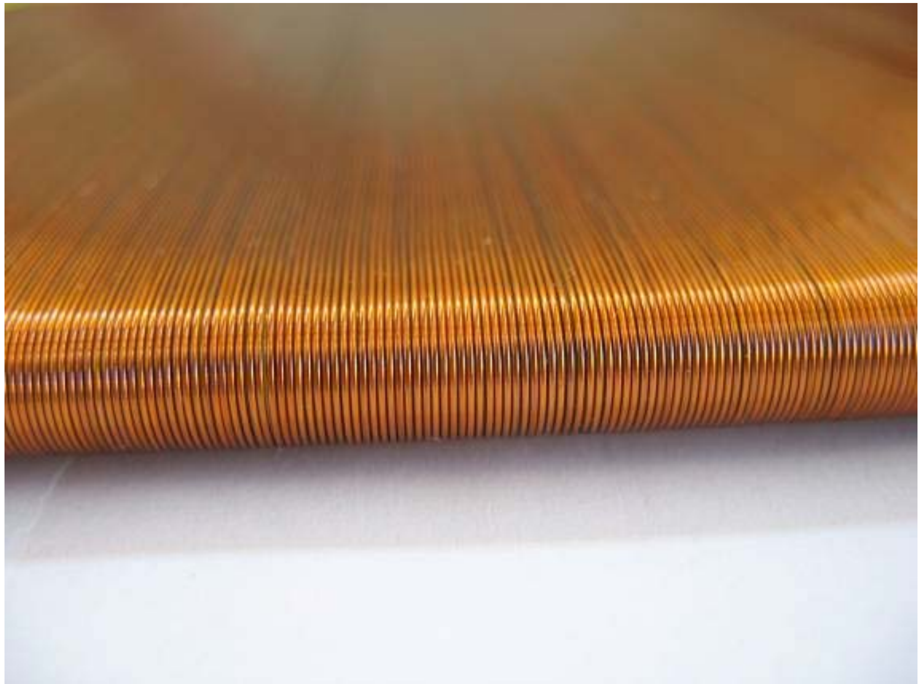
Since TWP2004: comprehensive tasks on **ITER magnetics diagnostics**.

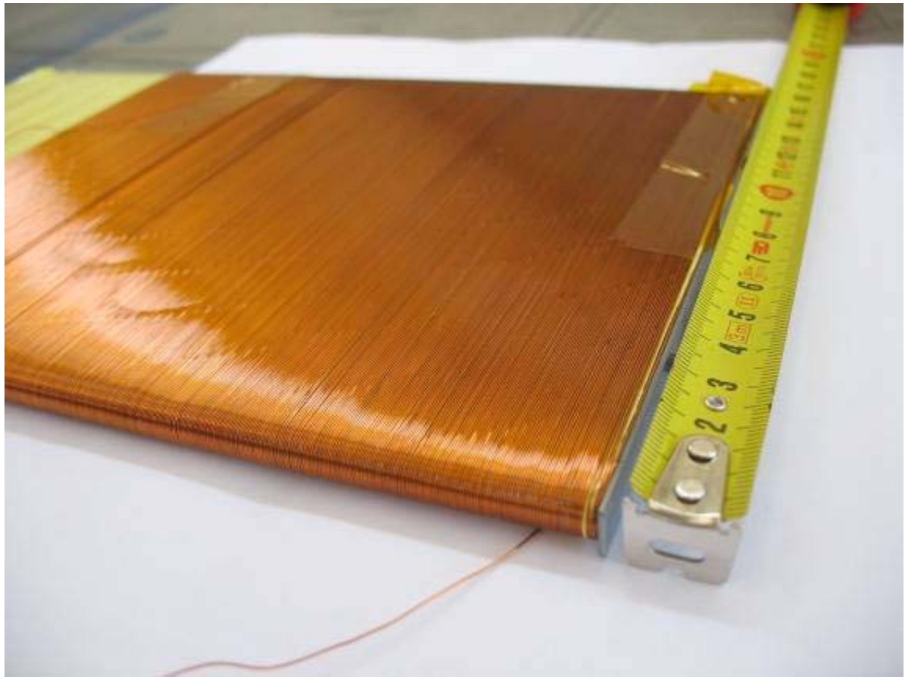
Main present topics:

- **Sensor design and R&D** for the wide range of sensors. **R&D ongoing on**:
  - o **In-vessel coils** (RFX) → **Presentation by G. Chitarin**
  - o **Ex-vessel coils (CEA)**
  - o **Rogowski coils** (CEA) (**11th ITPA**) and **fibre-optic current sensor** (CEA, SCK-CEN) → **presentation by B. Brichard**
  - o **High-frequency coils** (CRPP);
  - o **Steady-state sensors**: Hall probes (IPP.CR & Lviv-group), micromechanical magnetometers (force balance) (Tekes), colossal magneto-resistive effect (CIEMAT).
- **Development of** specifications for EM and vacuum-movement **models** to assist engineering and performance analyses (CRPP)
- **Performance analysis** of equilibrium and gap reconstruction
- **Assessment of the effect of plasma noise on the vertical velocity measurement**
- **Fast magnetic measurements** (high-frequency coils, MHD saddles) and diamagnetic flux measurement (CRPP)

Magnetics (2): Ex-vessel coils

Tangential coils are the most difficult: **2 m^2 effective area** required, with space envelope between outer VV vessel and thermal shield **8 x ~150 x 250 mm^3** (and shorter in areas of high curvature)





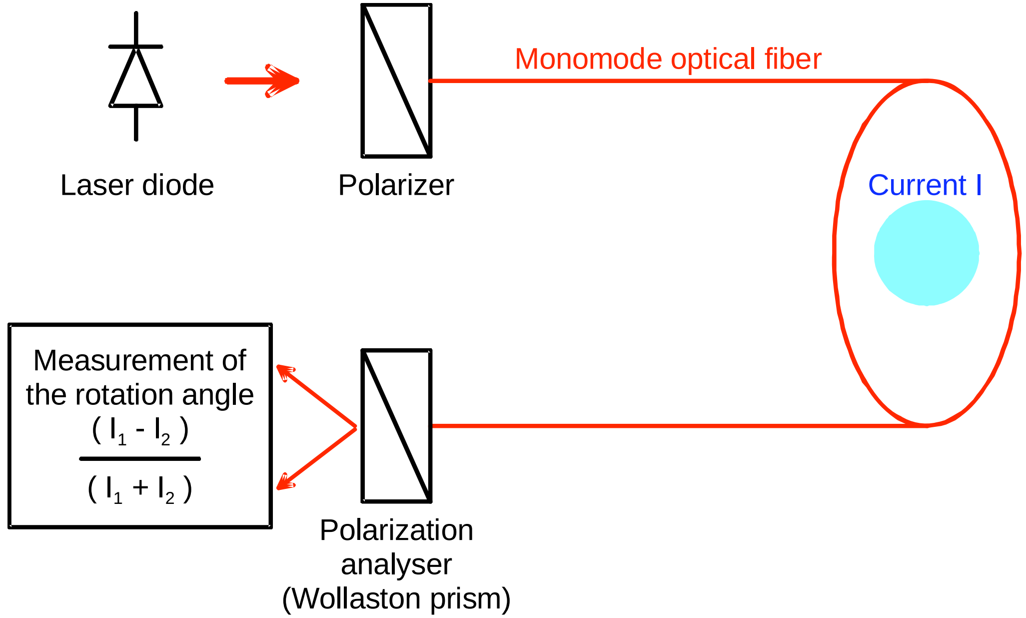
Prototype of the ex-vessel tangential coil located in area of large VV curvature.

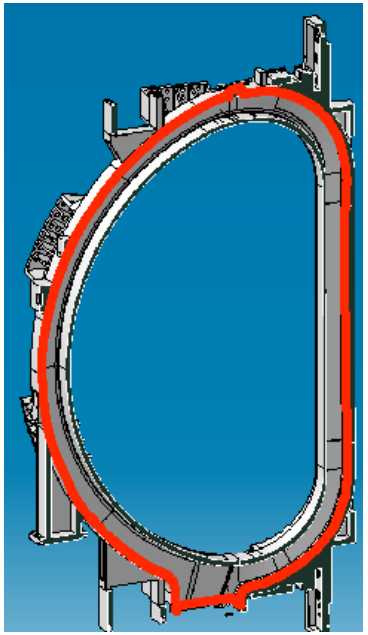
Enamelled wire (∅0.35 mm seems feasible) wound on a ceramic former 650–700 turns/layer

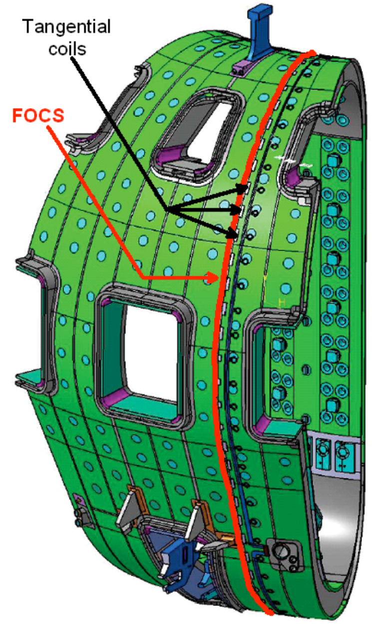
An alternative design with copper track on an insulting matrix appear is also still being pursued as a back-up solution and prototyping is being initiated. Kapton envisaged as substrate; radiation effects?

Magnetics (3): fibre-optic sensor

External Rogowski to measure plasma and VV currents (shown at last ITPA meeting) → additionally **fibre-optic current sensor** explored







Based on Faraday Effect in birefringent optical material (e,g, silica), i.e. proportional to magnetic field due to the enclosed current. Single-mode fibre. Advantages:

- Insensitive to electromagnetic interference
- Large dynamic range (DC to a few MHz)
- No signal drifts as no integrators
- High-speed measurements
- Operation in harsh environment (to be verified for ITER)
- Electrically passive device
- Optical fibers are easily and conveniently interfaced to long distance

→ **presentation by B. Brichard**

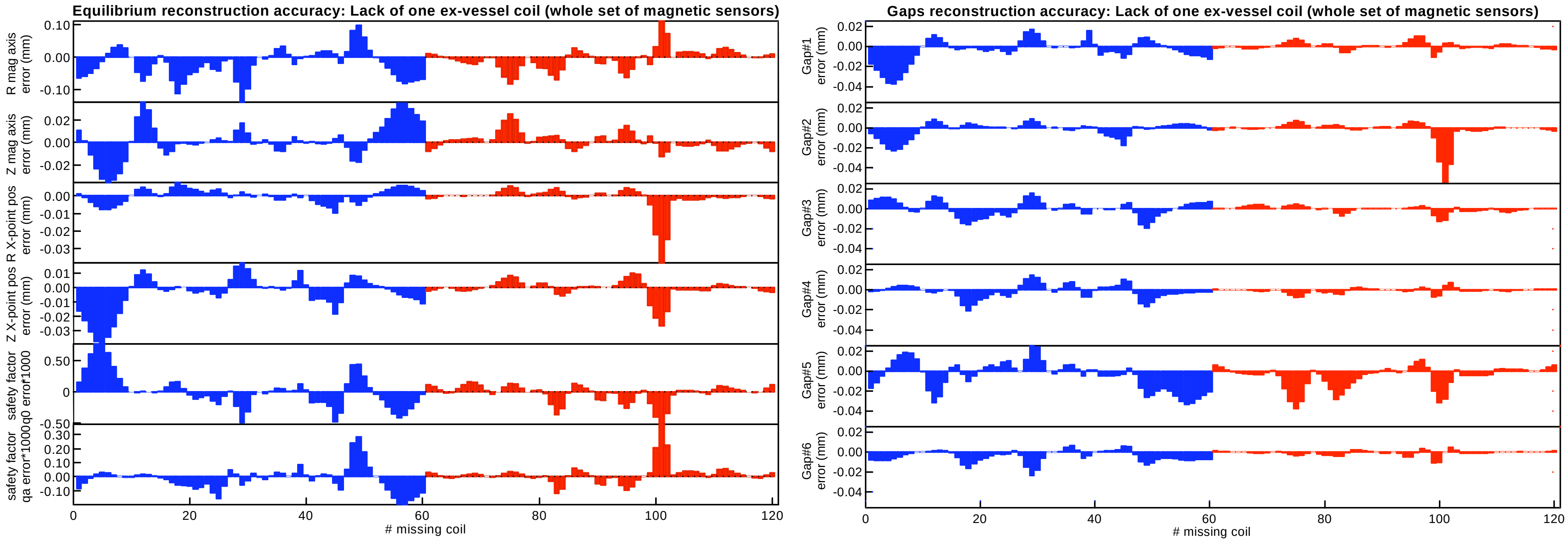
Possible paths:

- Integrated with external Rogowski in TF-coil casing (left) → operation at cryogenic temperature uncertain and difficult electrical&optical connectors?
- Separate on outer VV skin (right). Radiation level ok for IR fibre (1.3-1.5µm), although Verdet constant decreases with λ.

Magnetics (4): equilibrium reconstruction

Performance assessment of equilibrium reconstruction capability (CEA and CRPP)

- Expansion of work earlier done by ENEA-CREATE (TWP2002)
- Uses EFIT-ITM. A database of equilibria is being pursued: so far a limited range
- **Assessment of missing ex-vessel coils** (**figure⇓**), the noise level and integrator drift



Simulation with all sensors (in-vessel coils, divertor, flux loops and ex-vessel coils). Error due to suppression of one ex-vessel coil assessed: **blue tangential** (1-60), **red radial** (61-120)

Right-hand figure: R_{mag}, Z_{mag}, R_X, Z_x, q; left-hand figure: gap 1-6. All in mm.

Fast-ion effects on diagnostics (1)

RF and NBI driven fast ion modelling and **assessment of impact on diagnostics**:

(1) can the fast ions be diagnosed?

(2) does the presence of fast ions affect the performance of the diagnostic for other purposes?

- **Content:**
  - o RF modelling (PION and SELFO codes) (CEA, VR-KTH, TEKES)
  - o NBI modelling (ASCOT and Fokker-Plack code in Constant-of-Motion space (ÖAW, TEKES, Risø)
  - o Diagnostics:
    - Neutron cameras (ENEA-Frascati)
    - Neutron spectrometry (VR-Uppsala, ENEA-CNR Milano)
    - Gamma measurement (UKAEA)
    - CTS (Risø)
- **Limitations**:
  - o The scope of the task is limited, looking at **first-order effects**: will fast ions generated by expected heating scenarios be diagnosable or affect the determination of other plasma parameters, such the fusion alphas?
  - o The input profiles of ASTRA are not necessarily consistent with the heating simulated.
  - o The codes used have certain limitations. Effects on the velocity distribution function other than from RF and NBI heating separately are not taken into account (e.g. not the possible alterations by RF interacting with fast NBI ions, nor a self-consistent analysis with fusion alphas).

Fast-ion effects on diagnostics (2): status

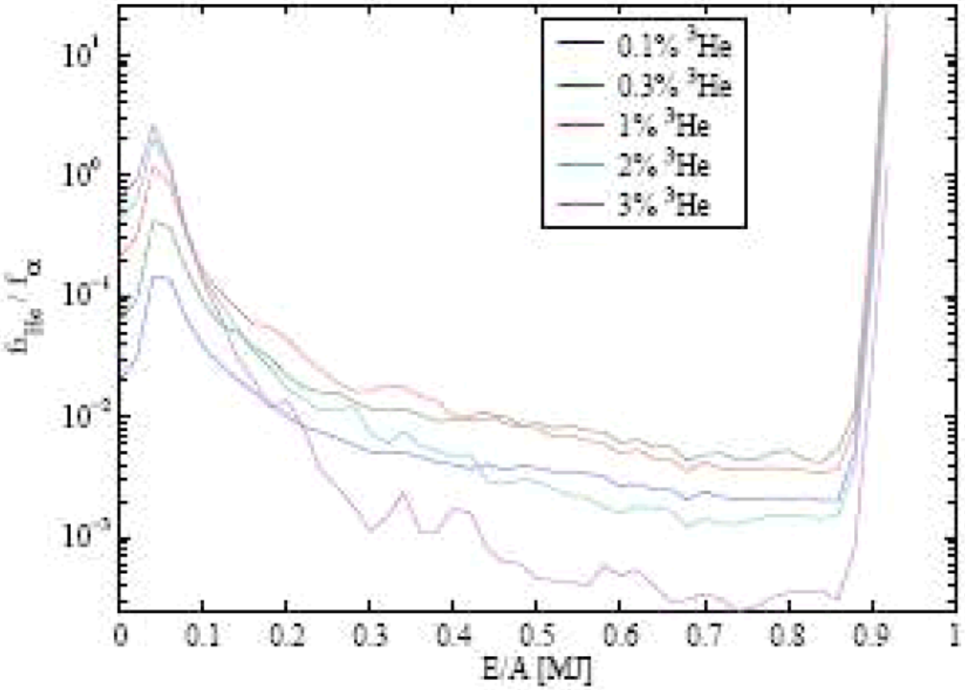
- **Scenarios selected** (L.-G. Eriksson *et al.*):
  - o **Plasma scenarios** 2 (standard H mode) and 4 (steady-state with ITB) will be simulated. The other scenarios are in between. Also **start-up scenarios** should be investigated, as the fast-ion effects are likely to be more pronounced.
  - o **HNB scenario**: 33-MW, 1-MeV D-beam.
  - o **RF scenario**:

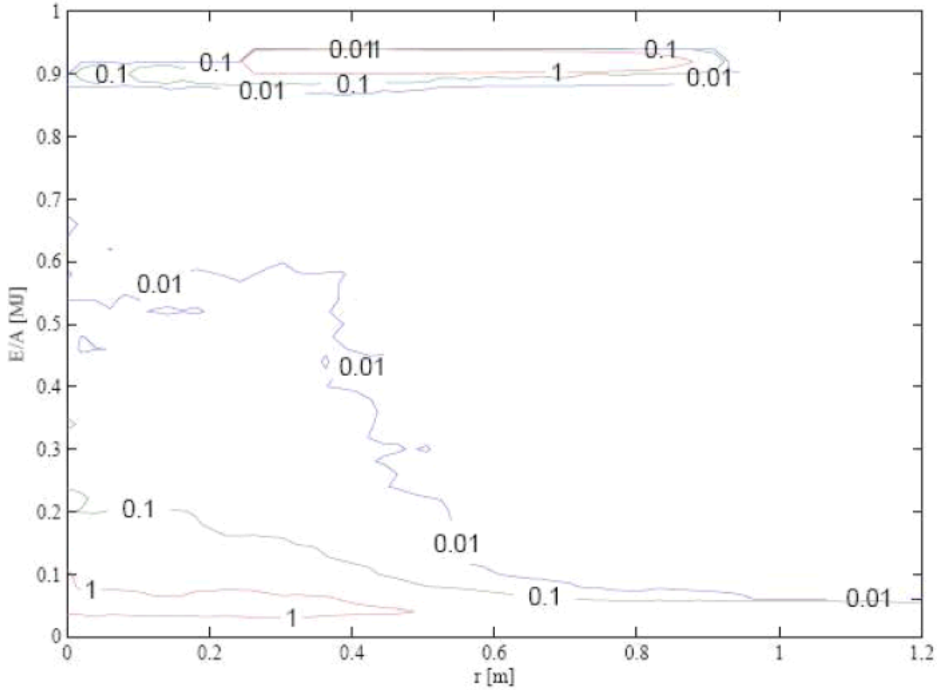
Resonance	Frequency (MHz)	Description	Comment
$\omega = 2\omega_{cT}$	53	**Main scenario** The **second harmonic T absorption** can be combined with ^{3}He minority absorption to increase ion heating fraction in the start-up phase of an ITER plasma (e.g. ~3% ^{3}He)	**Main candidate for significant effects. Scan for ^{3}He concentration.** NBI and RF species different→no interaction
$\omega = \omega_{cHe\text{-}3}$	45	Minority current drive near the q = 1 surface	Modest fast ion population expected (off axis resonance leading to low power density)
$\omega = 2\omega_{cD}$	50	Minority D heating	Limited interest because for **tritium-rich plasma** and parasitic absorption by alpha particles and Be
FWCD	56	Fast Wave Current Drive	little fast ion production expected

- **The interfacing of RF&NBI modelling codes with the diagnostic codes has been agreed.** E.g. transfer of full distribution functions to diagnostic codes, or determining diagnostic quantities directly from the modelling codes.

Fast-ion effects on diagnostics (3): example

Preliminary result from RF modelling with SELFO (M. Laxåback)





Ratio f_{3He}/f_α integrated over entire plasma as a function of normalized energy *E*/*A* for 16 MW RF power and a scan of ^{3}He concentrations.

Ratio f_{3He}/f_α as a function of minor radius and normalized energy *E*/*A* for 1% ^{3}He concentration and 16 MW RF power → ^{3}He exceeds alphas for ~0.05 MeV.

Conclusions:

- Overall, the fast ^{3}He and T densities are much lower than the α density. An exception is in the centre of the plasma at large minority concentrations and energies around *E*/*A* ≈ 0.05 MeV.
- RF heating should not seriously affect the ability of CTS to diagnose the global α particle distribution function, although locally (in space and velocity space) fast-ion contributions could be significant.