WPSA General Meeting - Integrated Data Analysis and Validation

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IDA for Nuclear Fusion

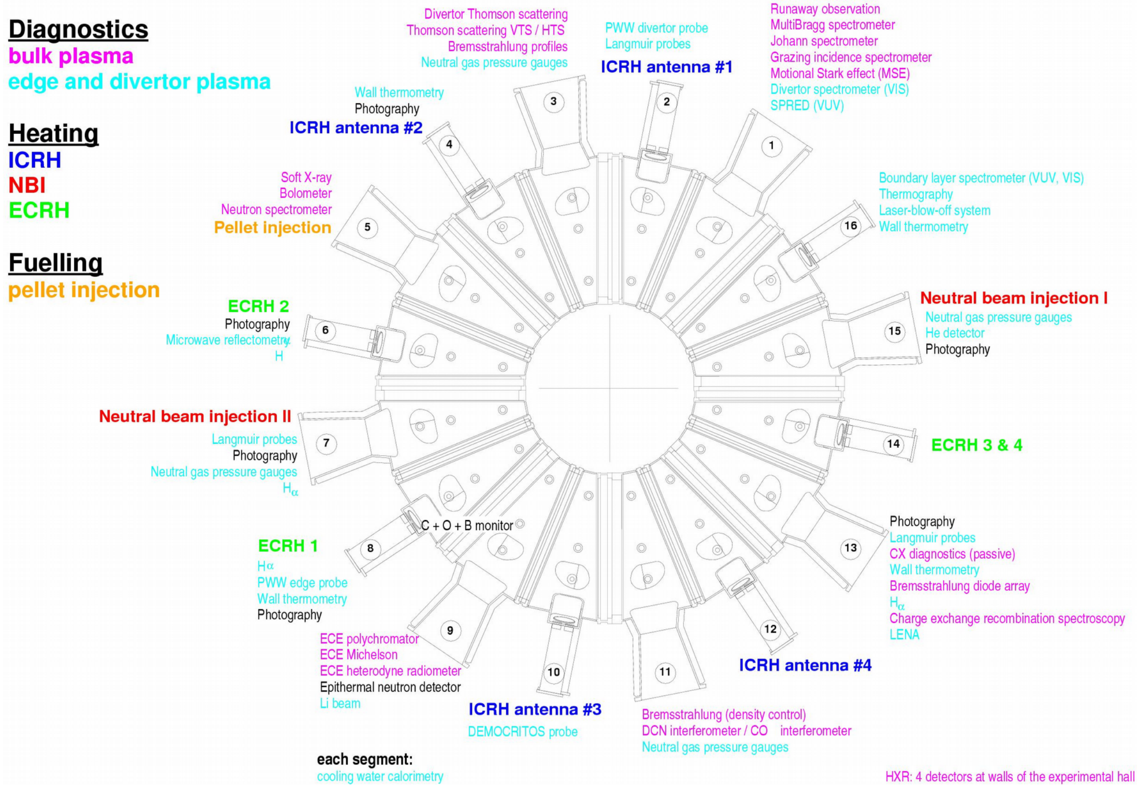
Scientific exploitation of fusion devices crucially depends on the reliability of measurements

Different measurement techniques for the same quantities → redundant and complementary data

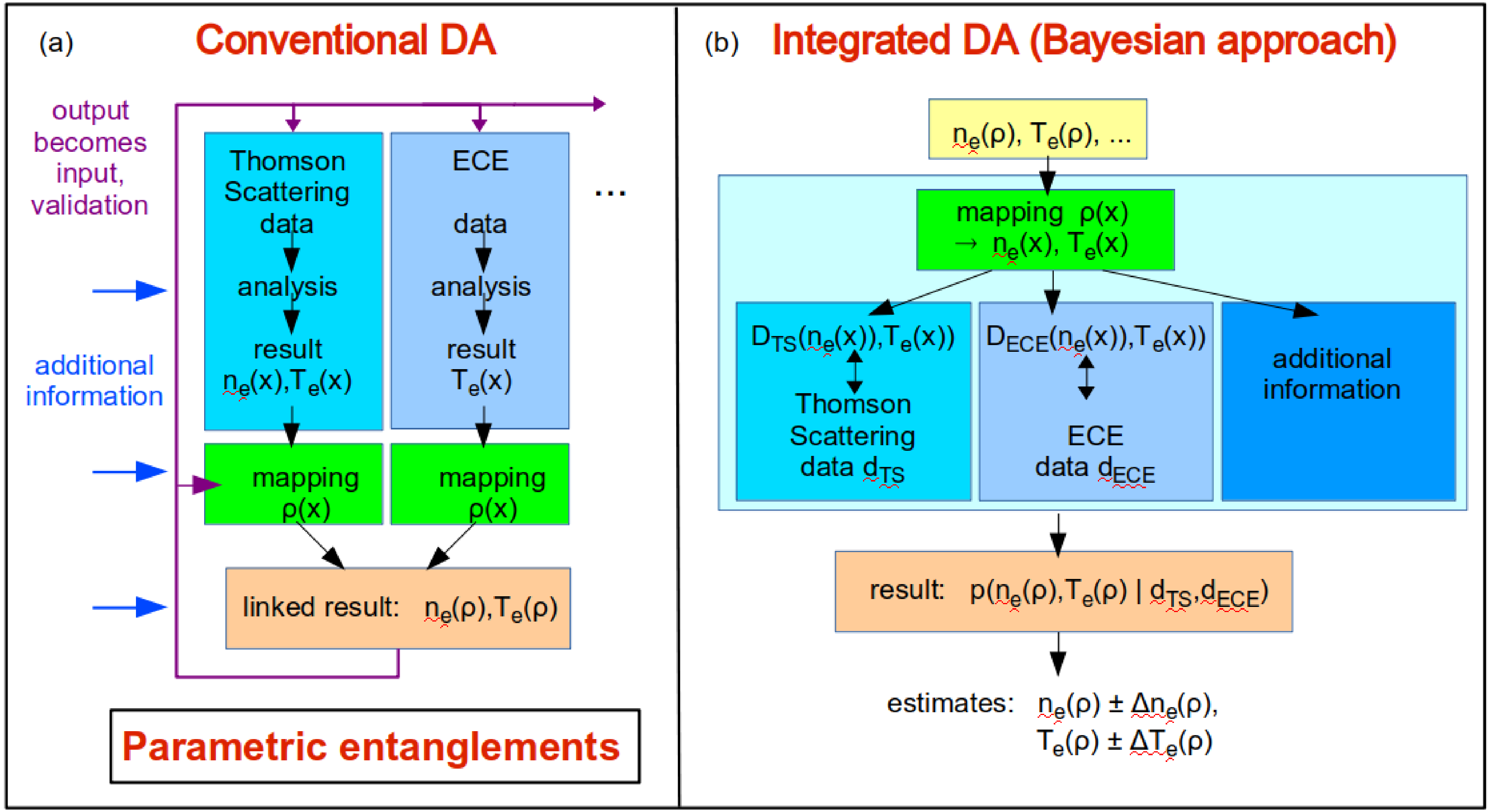
Coherent combination of measurements from different diagnostics

Goal:

- replace combination of results from individual diagnostics
- with combination of measured data
  → one-step analysis of pooled data



Conventional vs. Integrated Data Analysis



Conventional vs. Integrated Data Analysis (cont.)

Drawbacks of conventional data analysis: iterative

- (self-)consistent results? (cumbersome; do they exist?)
- difficult to be automated (huge amount of data from steady state devices: ITER, ...)
- information propagation? (Single estimates as input for analysis of other diagnostics?)
- error propagation? (frequently neglected: underestimation of the uncertainty)
- data and result validation? (How to deal with inconsistencies?)
- often backward inversion techniques (noise fitting? numerical stability?)
- result: estimates and error bars (sufficient? non-linear dependencies?)

Probabilistic combination of different diagnostics (IDA)

✔ uses only forward modeling (complete set of parameters → modeling of measured data)
✔ additional physical information easily to be integrated
✔ systematic effects (inconsistency) → describe with (nuisance) parameters; identify and resolve inconsistencies
✔ unified error interpretation → Bayesian Probability Theory
✔ result: probability distribution of parameters of interest incl. all dependencies

IDA offers a unified way
of combining data (information) from various experiments (sources)
to obtain improved results

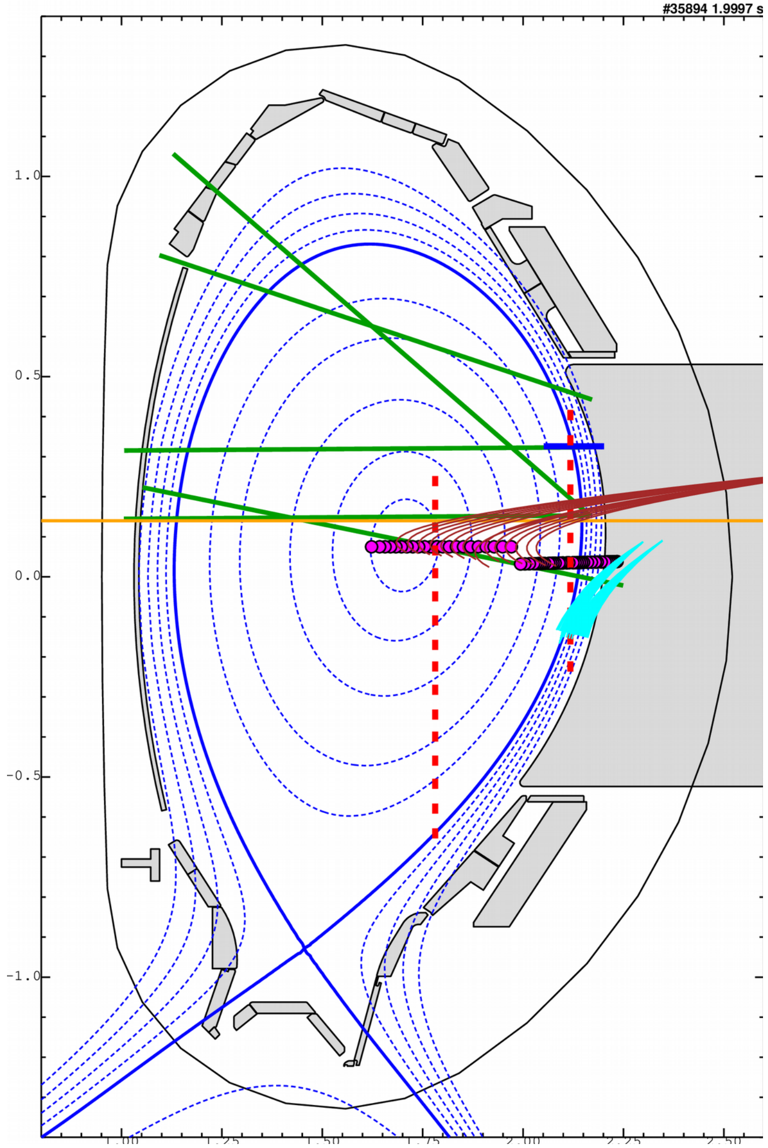
IDA at ASDEX Upgrade

multi-diagnostic profile reconstruction: n_e , T_e

- Lithium beam impact excitation spectroscopy (LIB)
  collisional radiative model → $n_e\ (T_e)$
- Interferometry measurements (DCN) → n_e
- Electron cyclotron emission (ECE)
  ECRad: Electron cyclotron radiation transport → $T_e\ (n_e)$
- Thomson scattering (TS) → n_e , T_e
- Reflectometry → n_e
- Beam emission spectroscopy → $n_e\ (Z_{eff})$
- Thermal Helium beam spectroscopy → n_e , T_e

- Equilibrium reconstructions for diagnostics mapping
  (*IDE*: kinetic Grad-Shafranov solution coupled with current diffusion)

A lot of dependencies and uncertainties:
We need a probabilistic approach!

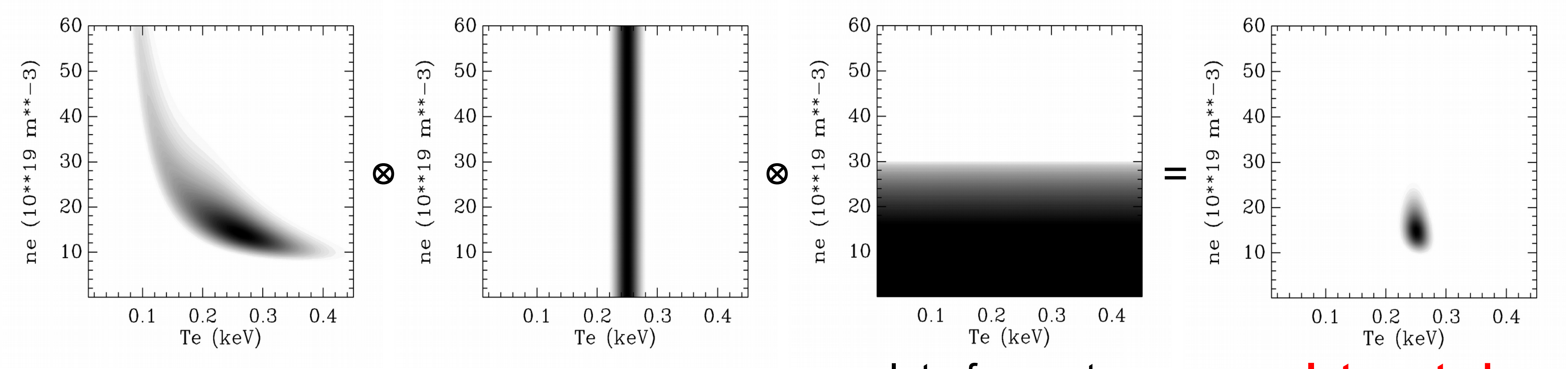


IDA: Probabilistic approach

Combination of a *set* of diagnostics

- n_e … electron density
- T_e … electron temperature

R. Fischer, A. Dinklage, E. Pasch, PPCF 2002, PPCF 2003



Thomson Scattering

Soft-X-ray

Interferometer Operation

Integrated Result

Probabilistic framework

IDA for Nuclear Fusion

Bring together different diagnostics/diagnosticians/theoreticians with redundant/complementary/modeling data

- Probabilistic modeling of individual diagnostics (forward models, likelihoods for all kind of uncertainties)
- Probabilistic combination of different diagnostics (multiply pdfs, unified error analysis, error propagation)
- Probabilistic combination with prior / modeling information

- Redundant data:
  - more reliable results by larger (meta-) data set → reduction of estimation uncertainties
  - detect and resolve data inconsistencies (reliable/consistent diagnostics) using standardized error/uncertainty treatment

- Complementary data:
  - resolve parametric entanglement
  - resolve complex error propagation (non-Gaussian)
  - synergistic effects (exploiting full probabilistic correlation)
  - automatic *in-situ* and *in-vivo* calibration (transient effects, degradation, …)
  - advanced data analysis technique

    → improvements in modeling (ECE) and diagnostics hardware (LIB)

Further Applications of IDA

W7-AS: n_e , T_e : TS, interferometry, soft X-ray

R. Fischer et al., PPCF, 45, 1095-1111 (2003)

W7-X: non-Maxwellian electron energy distribution function: visible emission spectrum

n_e , $T_{e/i}$, impurity densities, flows: TS, X-ray imaging

n_e , T_e : TS, interferometry, helium beam

Z_{eff} : bremsstrahlung spectra

D. Dodt et al., J. Phys. D: Appl. Phys., 41:205207, 2008.
A. Langenberg et al., RSI, 90(6), 063505 (2019)
S. Kwak et al., arXiv:2103.07582, 2021
S. Kwak et al., RSI, 92:043505 (2021)

MST RFP: T_e : TS, soft X-ray

Z_{eff} : soft X-ray, CXRS

L. M. Reusch et al., RSI, 85:11D844, 2014.
M.E. Galante et al., NF, 55:123016, 2015.

TJ-II: n_e , T_e : TS, interferometry, reflectometry, Helium beam

B. Ph. van Milligen, et al., RSI 82, 073503 (2011)

JET: n_e : LIB

n_e , T_e : LIDAR, interferometry

fast-ion distributions : velocity-space tomography of fast-ion D-alpha spectroscopy, collective TS, gamma-ray and neutron emission spectrometry, and neutral particle analyzers.

D. Dodt, et al., P-2.148, EPS 2009
O. Ford, et al., P-2.150, EPS 2009
M. Salewski et al., FST 74:23–36, 2018.

ITPA Diagnostic TG: SWG IDAV

Integrated Data Analysis and Validation (IDAV) specialist working group

- founded: 01.01.2020
- Rainer Fischer (chair, IPP Garching, Germany)
- Keisuke Fujii (co-chair, Kyoto University, Japan)
- Simon Pinches (co-chair, IO)
- Topic:
  - ITER provides many measurements coming from multiple diagnostics systems and this information will be used for machine control and safety as well as physics studies.
  - SWG working to develop self-consistent data validation procedures (profiles, error bar estimates…) for key ITER measurement parameters (density, ion and electron temperature, current and q-profile, Zeff, wall condition, etc.)
  - integrating all measurements to optimize information available for ITER operations, control and safety.
- started developing a modular IDA tool box for present and next generation fusion devices using a modern language

IDA Basic Implementation for ITER, JT-60SA, ...

Integrated Data Analysis: basic implementation in python

- open source license
- working implementation on https://git.iter.org
  - being completely modular
  - to be compatible with any fusion device (ITER:IMAS, ...)
  - diagnostics: Thomson scattering, ECE and interferometry, ...
  - likelihoods (data uncertainty): Gaussian, Cauchy (outlier robust), …
  - multi-fidelity forward models / synthetic diagnostics
    - ECE: $T_{rad} = T_e$ vs radiation transport modeling $T_{rad}(T_e, n_e)$
    - real-time vs offline analysis
  - flexible parameterisation of, e.g., profiles: splines, GPR, ...
  - priors: smoothness, positivity, physical modeling, ...
  - results and their uncertainties:
    - MAP solution (probability maximum and width)
    - MCMC sampling methods (explore full probability space)

```
.
├── run_ida_sample.py
└── lib
    ├── core
    │   ├── likelihoods
    │   ├── optimizers
    │   └── IDA
    └── diagnostics
        ├── base
        ├── aug
        │   ├── ECE
        │   ├── INTF
        │   └── TS
        ├── iter
        └── jt60sa
```

IDA for JT-60SA: Status, plan and goal

Present status:

1) The adaption of a generic IDA code package to JT-60SA diagnostics has been specified, starting with commissioning diagnostics.
2) Continuation of IDA(ITER) code development (ITER IMAS, diagnostics forward modeling)

Plan (to be agreed):

1) start with commissioning diagnostics (PO-1):
   - interferometry → n_e
   - soft-X ray → $T_e(n_e,Z_{eff})$
   - visible spectroscopy → $Z_{eff}(n_e,T_e)$
2) augment with PO-2 synthetic diagnostics:
   - Thomson scattering → n_e,T_e
   - ECE → $T_e(n_e)$

Benefits of IDA approach:

1) same IDA as for ITER
2) mutual development for various devices
3) mutual development for similar diagnostics

4) diagnostics inter-dependencies resolved
5) probabilistic parameter space exploration (MCMC)
   → to characterize diagnostics to be commissioned
6) unified uncertainty quantification of data and parameters
7) addtl. information: positivity (n_e, T_e), Z_{eff}>=1, modeling, ...
8) (nuisance) parameters, e.g. calibration and uncertainty
9) easily to be augmented with further diagnostics...

Goal: IDA for physics exploitation in 2025

IDA for JT-60SA: Commissioning diagnostics

1) n_e : 2-colour CO_2 laser interferometry $\int n_e \, dl$

and polarimeter $\sim \lambda^2 \int n_e B_{t,\parallel} \, dl$

2) $T_e(n_e, Z_{eff})$: Line-integrated soft-X ray bremsstrahlung intensity $\sim \int n_e^2 \sqrt{T_e} Z_{eff} \, dl$

3) $Z_{eff}(n_e, T_e)$: Visible spectroscopy, bremsstrahlung intensity $\sim \int g_{ff}(Z_{eff}, T_e, \lambda) \frac{n_e^2 Z_{eff}}{\sqrt{T_e} \lambda^2} \exp(hc/\lambda T_e) \, dl$

Parametric entanglements

IDA for JT-60SA: Technicalities

IDA ingredients (QST support needed):

1) measured data and an exploration and quantification of statistical and systematic errors (calibration)
2) physical (forward) model for the data/diagnostic
3) outlier robust method optionally (likelihood)
4) prior/modeling information

IT:

1) Platform: EURO*fusion* Gateway cluster or QST server at Naka
2) preferred data-dictionary and access-layer? (IMAS is already implemented)
3) python infrastructure

Proposed collaboration:

1) Contact persons: H. Tojo (QST), K. Fujii (Kyoto Univ.), R. Fischer (IPP), D. Stieglitz (IPP), G. Falchetto (CEA)
   (1st meeting 10 Dez 2020)
2) Manning (IPP): 12pm/year (postdoc);
3) Visits: short visit 1-2 weeks in the initial phase, longer visit possible to be discussed at a later stage