Development of the ITER synthetic reflectometry diagnostic (REFI)

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REFI - SD reflectometry for ITER

Outline:
- Reflectometry principle
- Workflow of reflectometry SD
- REFI primary simulation results
- Further tasks

Dictionary:

REFI: SD reflectometry for ITER
HFS&LFS: High and Low Field Side reflectometry

SD: synthetic diagnostic - computational module to simulate realistic output signals of a real diagnostic based on plasma and plant parameters

IMAS: Integrated Modelling & Analysis Suite integrated modelling platform to provide managed access to ITER database (experimental & simulation) in a standardized way

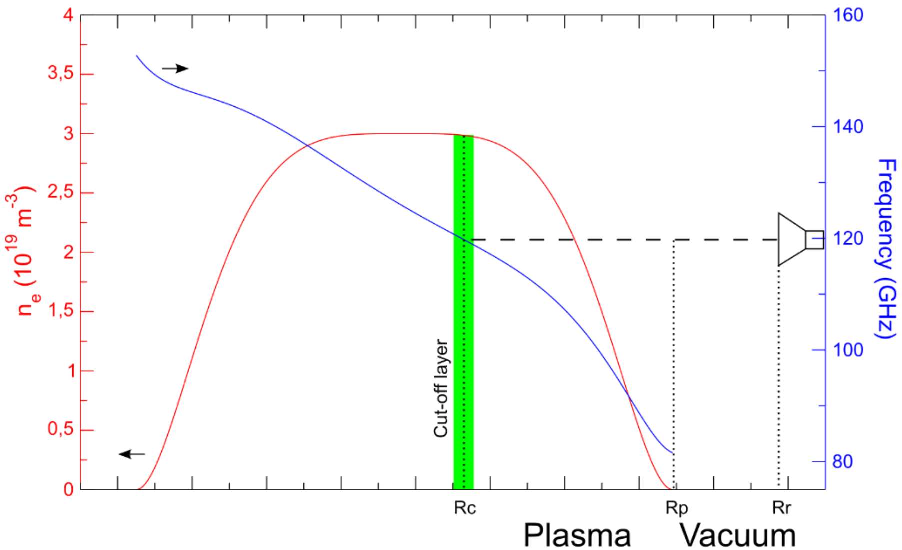
IDS: Interface Data Structures represented in IMAS
More details in Introduction to IMAS by Simon Pinches

Goals:
Apply SD model to time slices from IMAS DB to:
- make a performance assessment [Design (D)]
- predict diagnostics measurements [Physics (P) and Control (C)]

Requirements:
- Accuracy & operational range
- Computational time & time response
- Approximations & assumptions
- Consistency

Reflectometry principle

Radar technique, EM waves reflect from the plasma



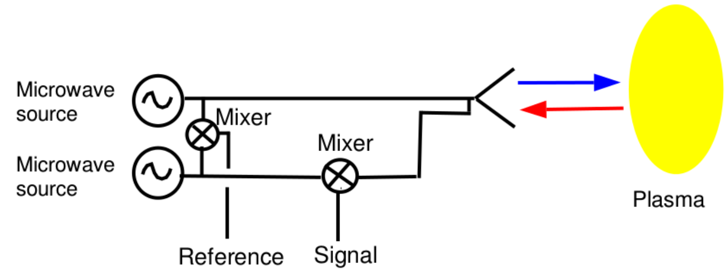
O-mode $E \parallel B$ $N(n_e, T_e)$

X-mode $E \perp B$ $N(n_e, T_e, B)$

$$F_{cutoff} = \frac{1}{2\pi}\begin{cases} \omega_p (O - mode\ cutoff) \\ \left(\sqrt{\omega_p^2 + (\omega_c/2)^2} - (\omega_c/2)\right)(X - mode\ lower\ cut - off) \\ \left(\sqrt{\omega_p^2 + (\omega_c/2)^2} + (\omega_c/2)\right)(X - mode\ upper\ cut - off) \end{cases}$$

$$\omega_p^2 = \frac{4\pi n_e e^2}{m_e}, \quad \omega_c = \frac{eB}{m_e c}$$

n_e profiles: analysis of time required for EM wave with frequency F to travel from antenna to cut-off plasma region and to get back [time-of-flight-delay (TFD) τ]



I(t) = A(t)cos(φ(t)) and Q(t) = A(t)sin(φ(t))
phase φ= $\tan^{-1}$(Q/I) → density profile & fluctuations

$$\phi(t) = \frac{4\pi F}{c}\int_{R_0}^{R_c} N(F,R)\,\mathrm{d}R - \frac{\pi}{2}$$

$$\frac{\partial\phi(t)}{\partial t} = \frac{4\pi}{c}\left[\frac{\partial F}{\partial t}\int_{R_0}^{R_c} N(F,R)\,\mathrm{d}R + F\frac{\partial}{\partial t}\left(\int_{R_0}^{R_c} N(F,R)\,\mathrm{d}R\right)\right]$$

Measurements

ITER Reflectometry is fully available from PFPO-2

First plasma

H plasma

Commissioning of tokamak core components

Pre-Fusion Power Operation 1 and 2

H, ^{4}He plasmas

Commissioning of main plant systems

H, ^{4}He plasmas

Longer pulses with raise of current and power

Fusion Power Operation

D, DT plasmas

Long pulse operation Q = 10

HFS:

Primary: core n_e profiles, $\delta n_e / n_e$, ELM Density Transient, TAE, MHD

Supplementary: edge n_e profiles,

$\int n_e dl \,/ \int dl$ refractometry – done by K. Afonin

https://git.iter.org/projects/DIAG/repos/refractometer/

LFS:

Primary: edge n_e profiles, $\delta n_e / n_e$, ELM Density Transient, TAE, MHD

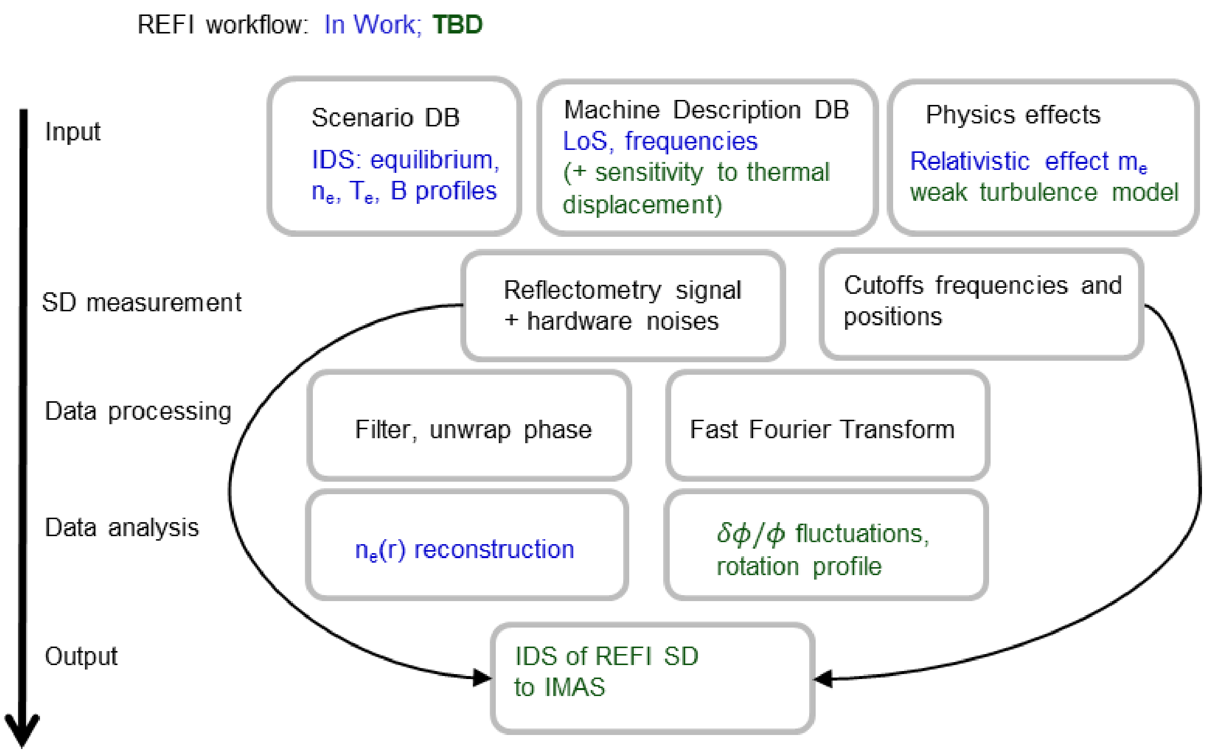
Supplementary: poloidal velocity, $\int n_e dl \,/ \int dl$, core n_e profiles

Examples of addressed questions:

1. **Design:** Measurement of edge density down to ~1e18 m^{-3} for the ICRF coupling R cutoff density location
2. **Physics**: L-H transition characterization (pedestal formation, steep gradients)
3. **Control**: Advanced plasma control, on-line $n_e(r)$

REFI workflow

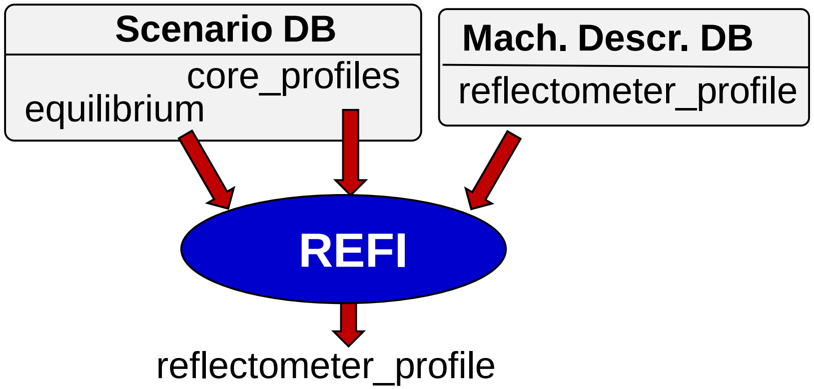
Modules in Python (signal simulation, analysis, incorporation)



Use case: Diagnostic performance

- Simulating diagnostic as accurately as possible
- Diagnostic raw & analyzed data generated for all time points of an input scenario
- Results stored in IMAS as diagnostic output of that scenario
- Calculation time allowed to take a while, error estimates as accurate as possible

IMAS SD models



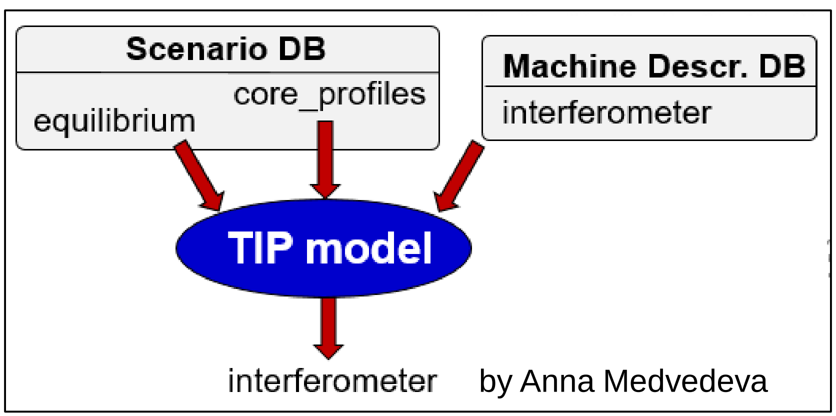
Input IDSs from Scenario DB:
equilibrium, n_e, T_e, B core profiles

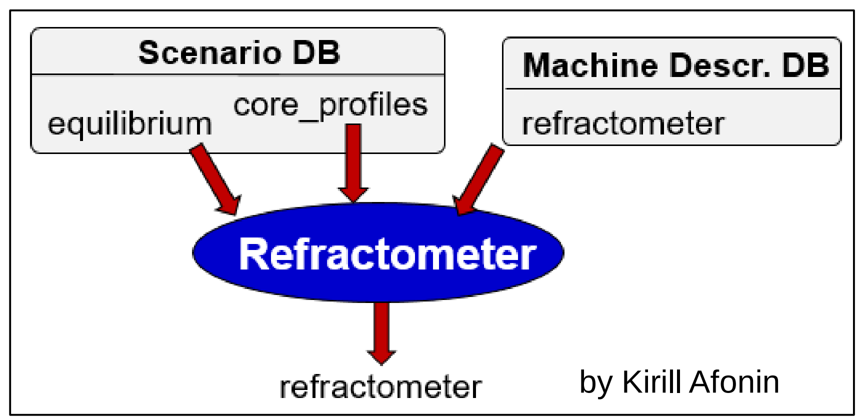
Input IDSs from Machine Description DB:
LoS, frequencies
(+ sensitivity to thermal displacement)

Output IDSs:
$n_e(r)$; $\delta\phi/\phi$

Modelled diagnostic or signal:
HFS and LFS reflectometers

Synthetic Diagnostic Integration Data Analysis IDA

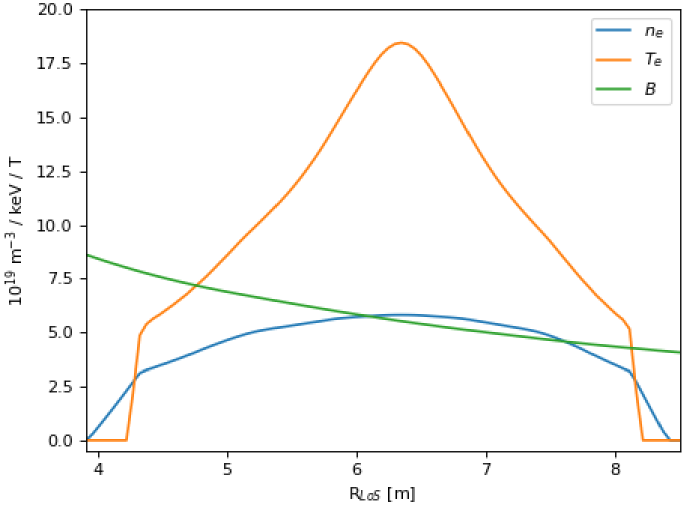


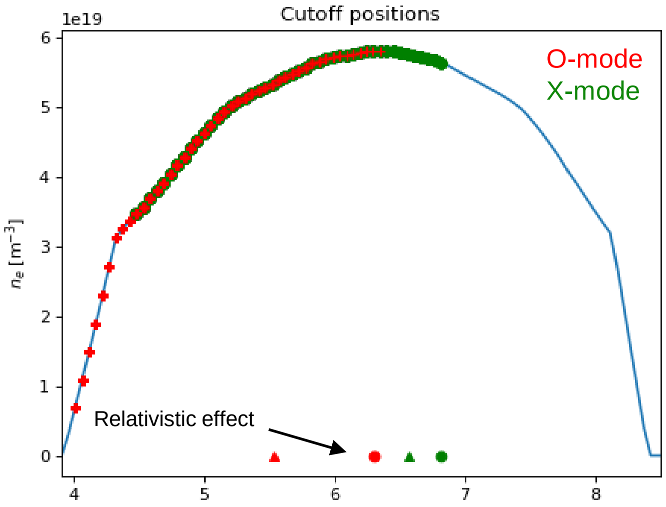


IDM: 4RPFVL by Mireille Schneider

HFS REFI intermediate simulation results

Input: Discharge
134173, run 106, time slice 97.3 s
L-mode + H-mode DINA-JINTRAC





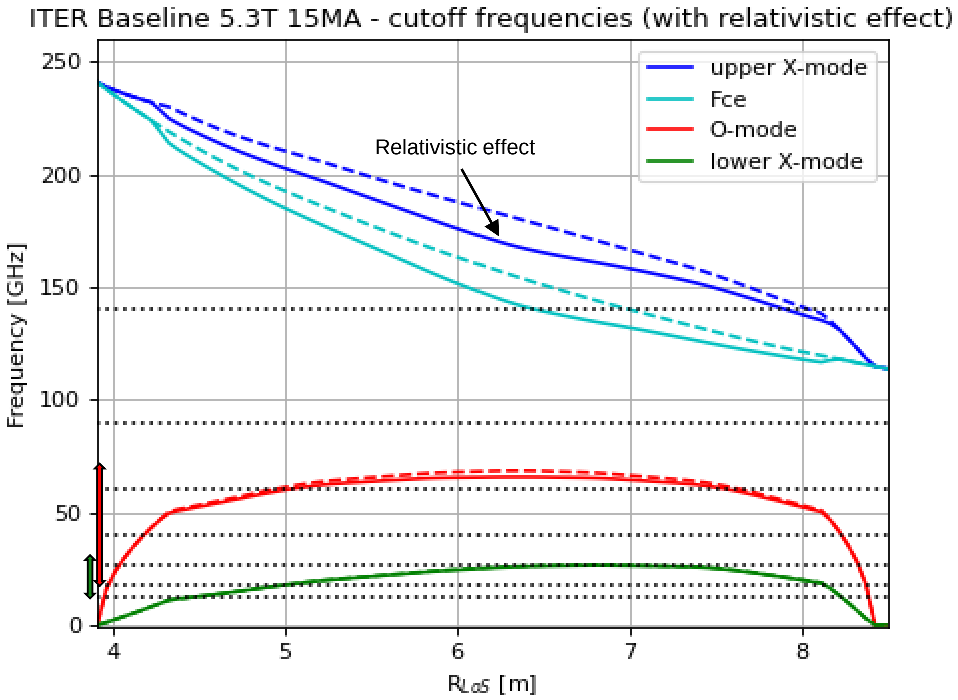
Geometry

$R_{antenna}$: 3.8012 m
$Z_{antenna}$: 0.0528 m

Frequency bands

O-mode GHz
F: 90 - 140
E: 60 - 90
U: 40 - 60
Ka: 26.5 - 40
K: 18 - 26.5
Ku: 12 - 18
X-mode

Output:



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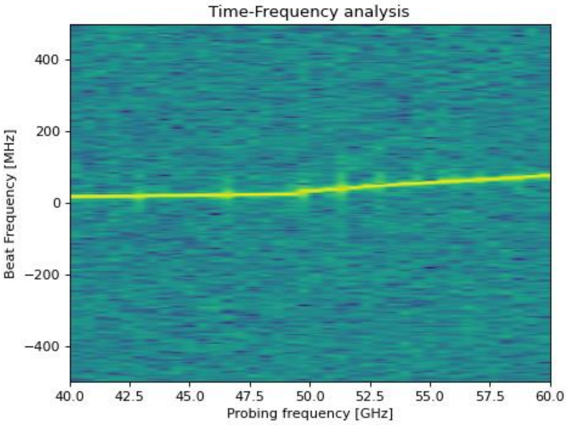
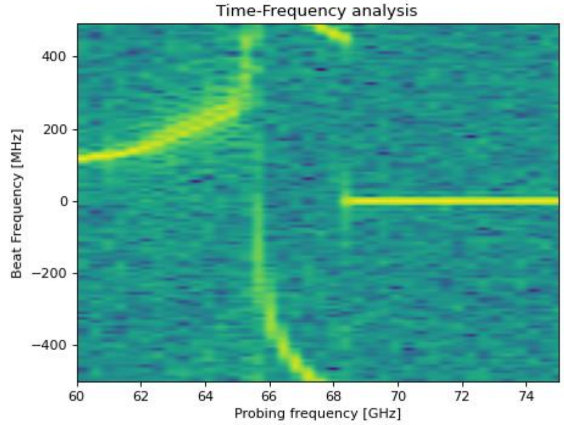
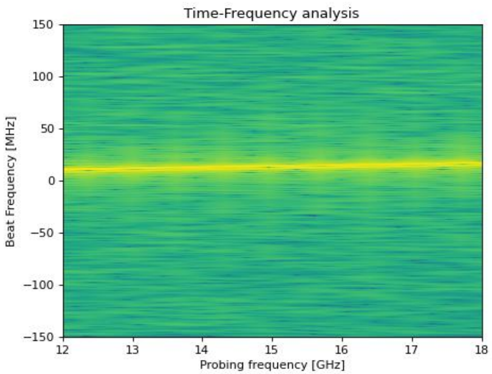


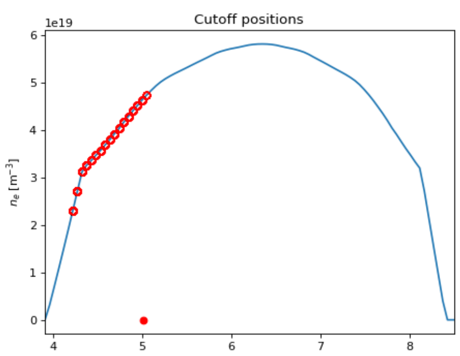


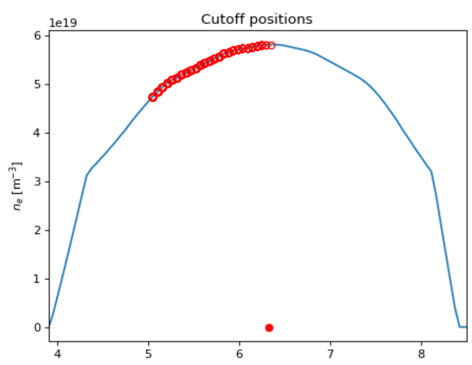


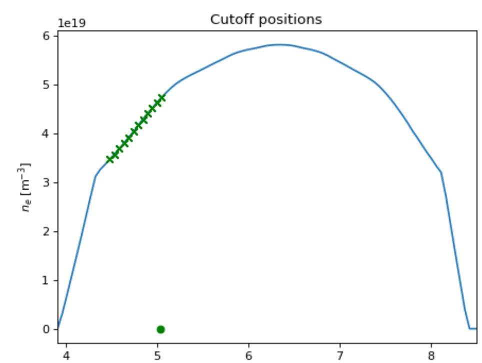
τ_{sweep} = 5 μs

- Beat frequency → tof delay → radial locations
- Probing frequency → density

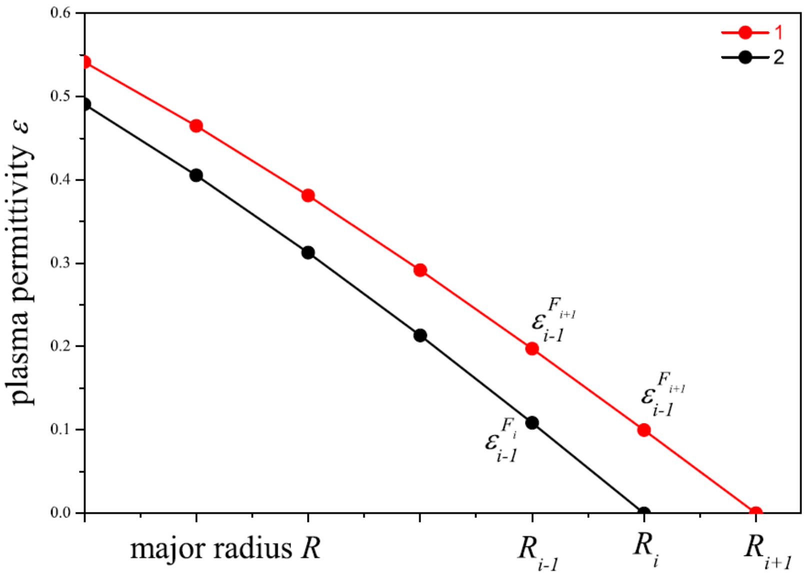
$$\Delta\varphi_i^{i+1} = 2\pi f_i^{i+1}(t_{i+1} - t_i)$$







D. Shelukhin et al. Rev. Sci. Instrum. **89**, 094708 (2018)

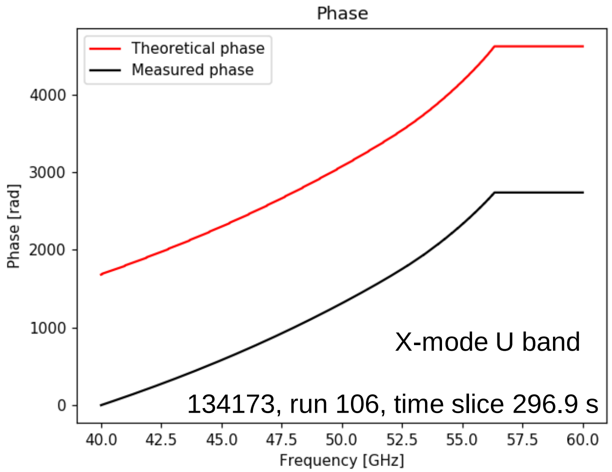


Plasma permittivity profile →
linear approximation between the radial positions of the reflections at probing frequencies

$$\varphi_i = 2 \cdot \frac{2\pi F}{c} \cdot \int_{R_0}^{R_i} \sqrt{\varepsilon(r,F)}dr + \frac{\pi}{2}$$

$$= \frac{\pi}{2} + \frac{4\pi F}{c} \sum_{j=0}^{i-1} \left[\int_{R_j}^{R_{j+1}} \sqrt{k_j^{j+1} \cdot r + b_j^{j+1}} dr \right]$$

$$k_j^{j+1} = \frac{\varepsilon_{j+1} - \varepsilon_j}{R_{j+1} - R_j}, b_j^{j+1} = \varepsilon_j - k_j^{j+1} \cdot R_j$$



Similar to Bottolier-Curtet and Ichtchenko algorithm

Conclusions and perspectives

- Synthetic reflectometry diagnostic REFI is being developed
- Assessment of the HFS reflectometry signals is ongoing

To do:

- Add module for the LFS REFI
- Check performance and coverage of SDs across DB
- Density profile reconstruction
- Incorporate SD and IDS to IMAS
- Check consistency (analysis in different plasma scenarios, simulations, comparison with experimental data)

International Reflectometry Workshop IRW15
8 – 10 June 2022 at ITER, France

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