Radiofrequency electromagnetic analysis in the engineering of ITER Electron Cyclotron Heating Upper Launcher

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OVERVIEW

1. **Introduction**
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    - UL Quasi-Optical System
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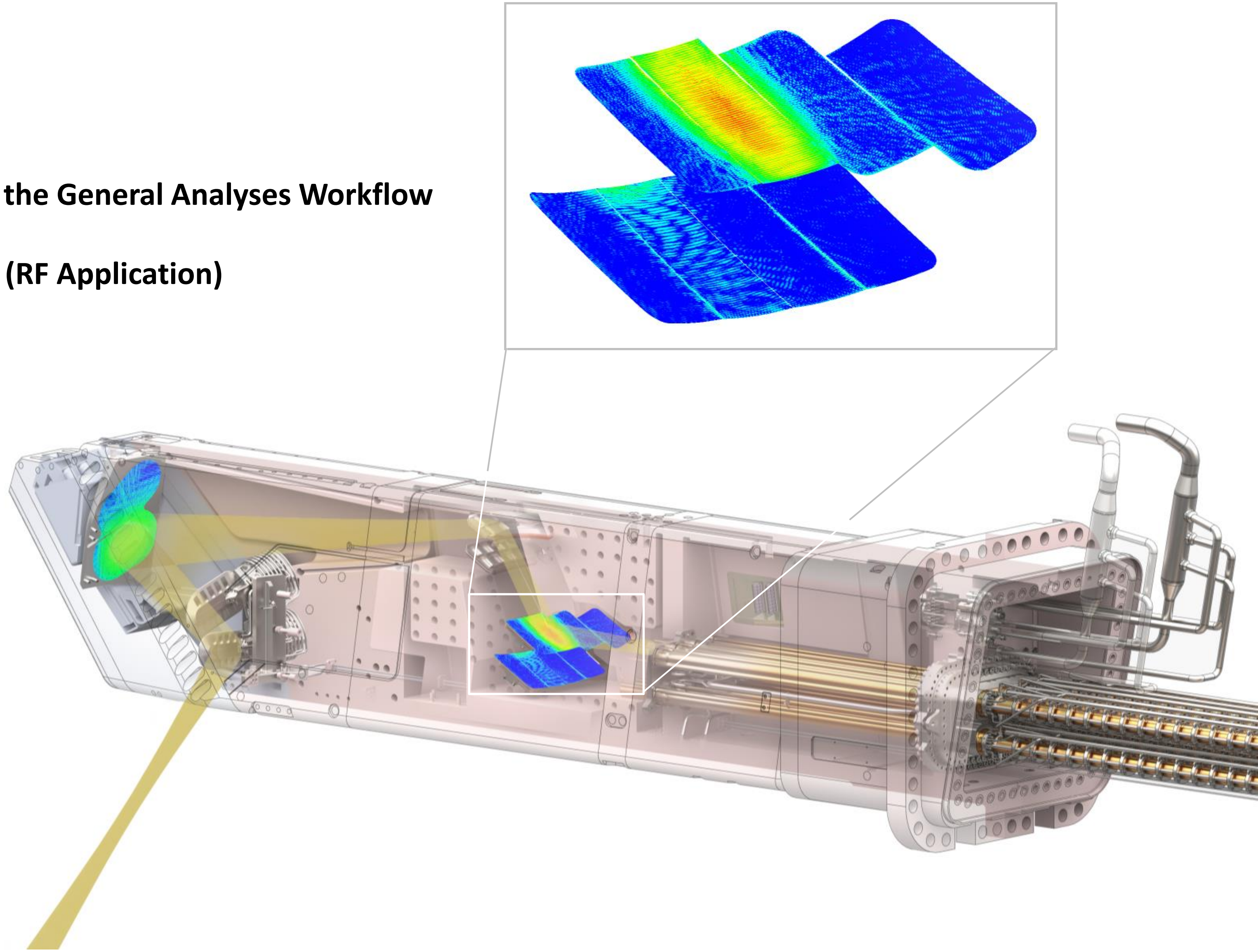
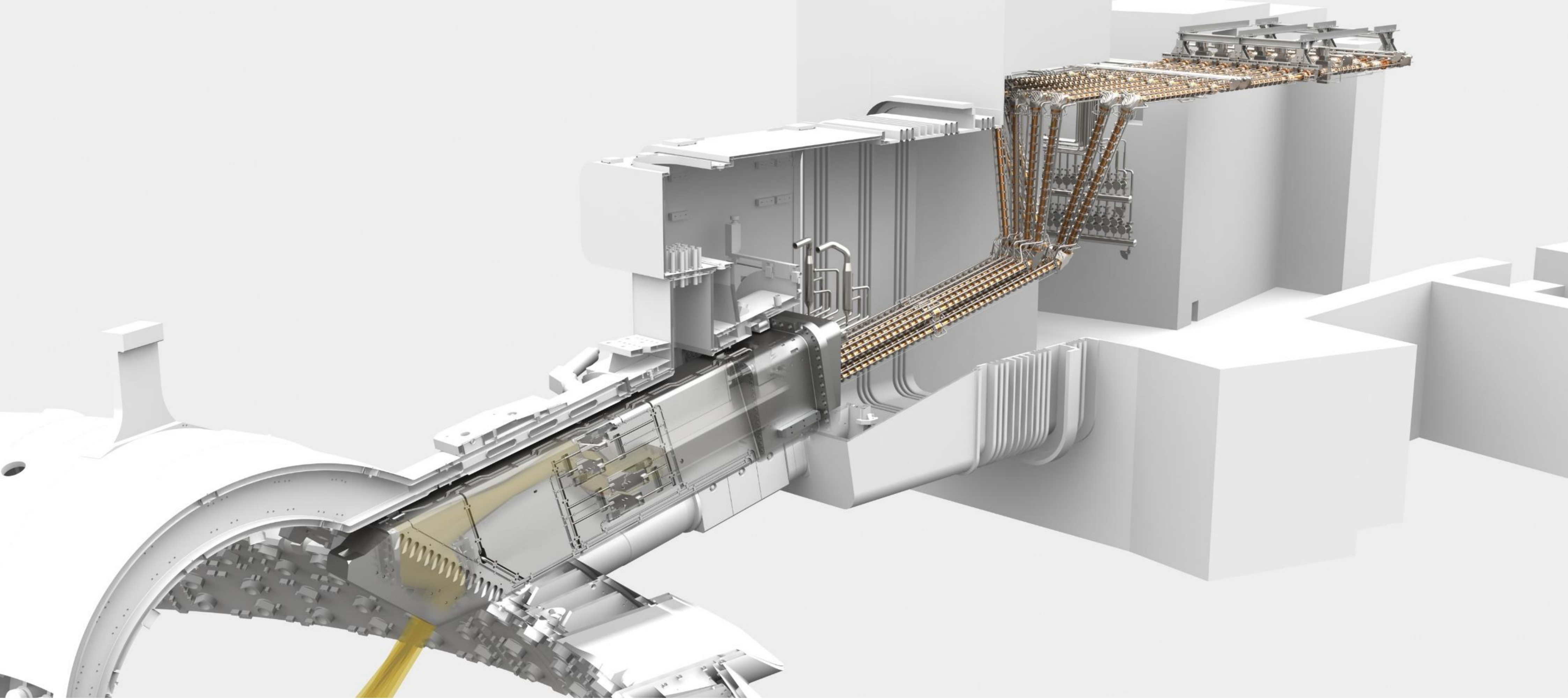
3. **Integration of RF-EM Analyses in the General Analyses Workflow**
4. **Computational Electromagnetics (RF Application)**
5. **Selection of Method:**
    - Main Optical Path Analysis
    - Spillover and Stray Radiation
6. **High Order Modes (HOM)**
7. **Next Steps**
8. **Questions**



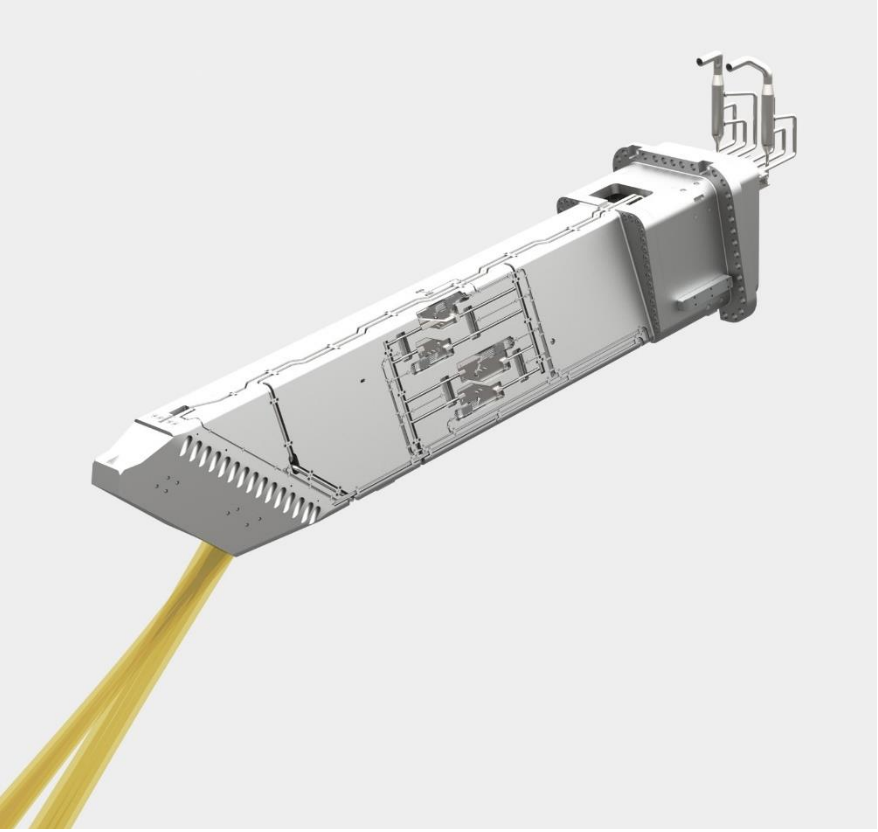
1. INTRODUCTION – ITER ECH SYSTEM

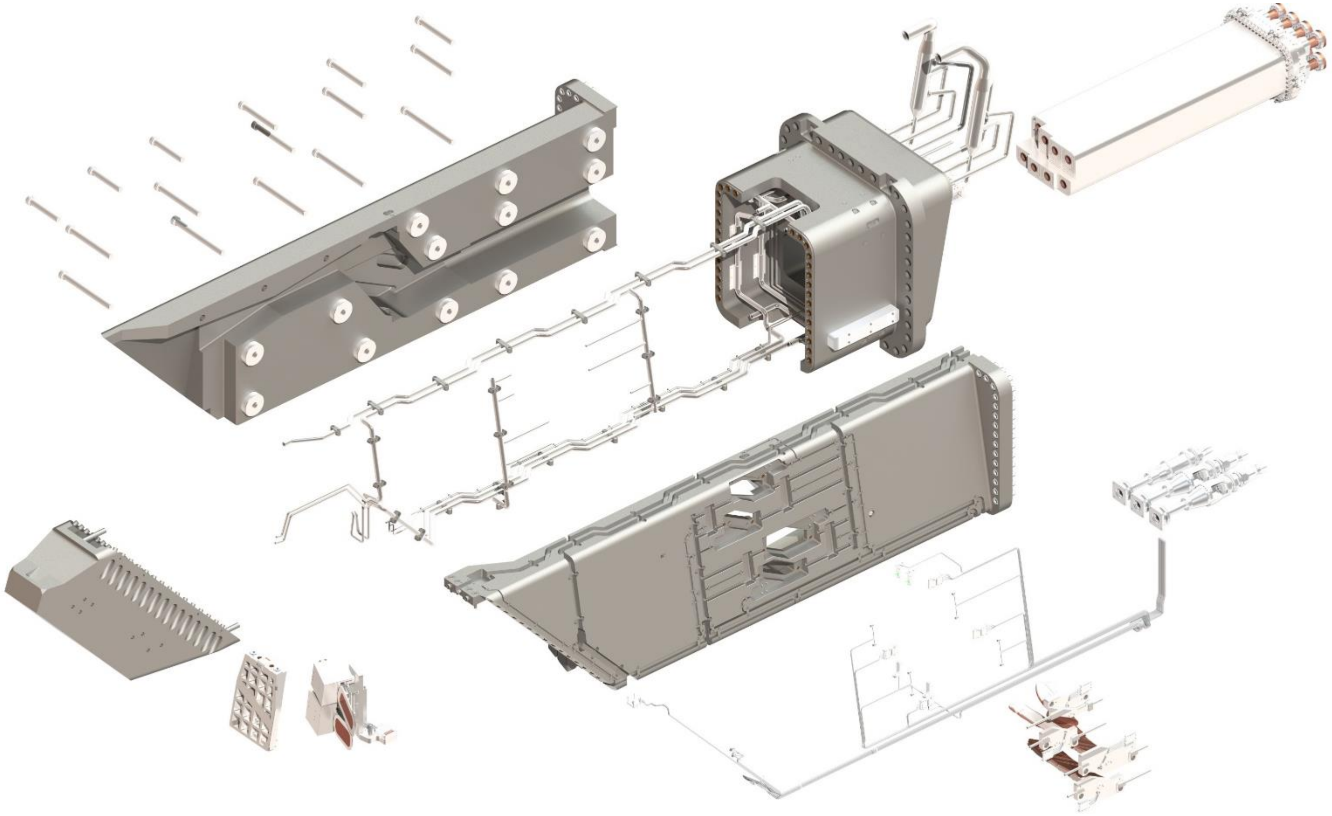
- The **ITER Electron Cyclotron Heating** system provides 170 GHz millimeter-wave heating and current drive to the ITER plasma, contributing to plasma breakdown and burn-through to produce fusion reaction and controlling plasma instabilities.
- Four **Upper Launchers**, together with one Equatorial Launcher, installed in the Tokamak ports, constitute the front-end systems which guide the Electron Cyclotron power to the plasma through a set of mirrors.
- A Consortium formed by IDOM and ALSYMEX has been awarded by F4E with the contract F4E-OMF-1120 for the design finalization, manufacturing, assembly and delivery of the Upper Launchers and Ex-vessel Waveguides of ITER ECH system



1. INTRODUCTION – UPPER LAUNCHER DESIGN

- The Final Design of the Upper Launcher includes the review and rearrangement of the UL mechanical design, as part of an activity that has been called **UL Design Redressing**. The aim was reducing the project risks and costs by means of:
  1) Pursuing more conventional manufacturing techniques to a level affordable for standard industry, mainly for the Upper Launcher Body
  2) The simplification of the assembly process - specially the Upper Launcher Body, the in-vessel piping and electrical equipment.
- In addition, the Upper Launcher Body resulting from this Design Redressing provides an stiff and stable bench for the quasi-optical equipment and can be manufactured with quite accurate tolerances.

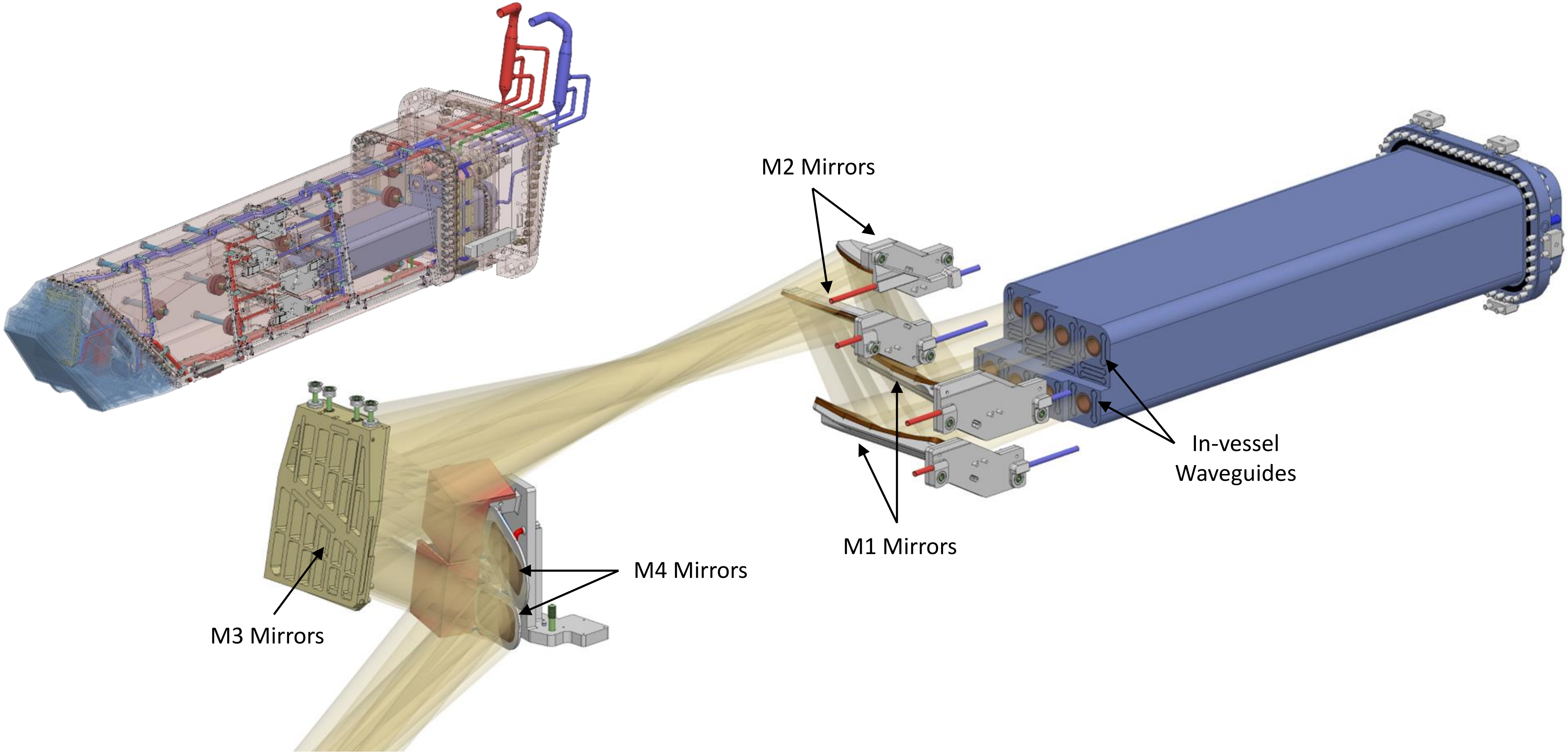




1. INTRODUCTION – UL QUASI-OPTICAL SYSTEM

The quasi-optical system of the Upper Launcher is composed of:

- **8 in-vessel waveguides**, arranged in two rows of 4 waveguides each, which transmit the RF radiation coming from the ex-vessel waveguides to a set of mirrors installed in the Upper Launcher.
- **Fixed mirrors (M1, M2 & M3)**
- **M4 Steering mirrors** which can be oriented in different angles in order to direct the beams to different points in plasma



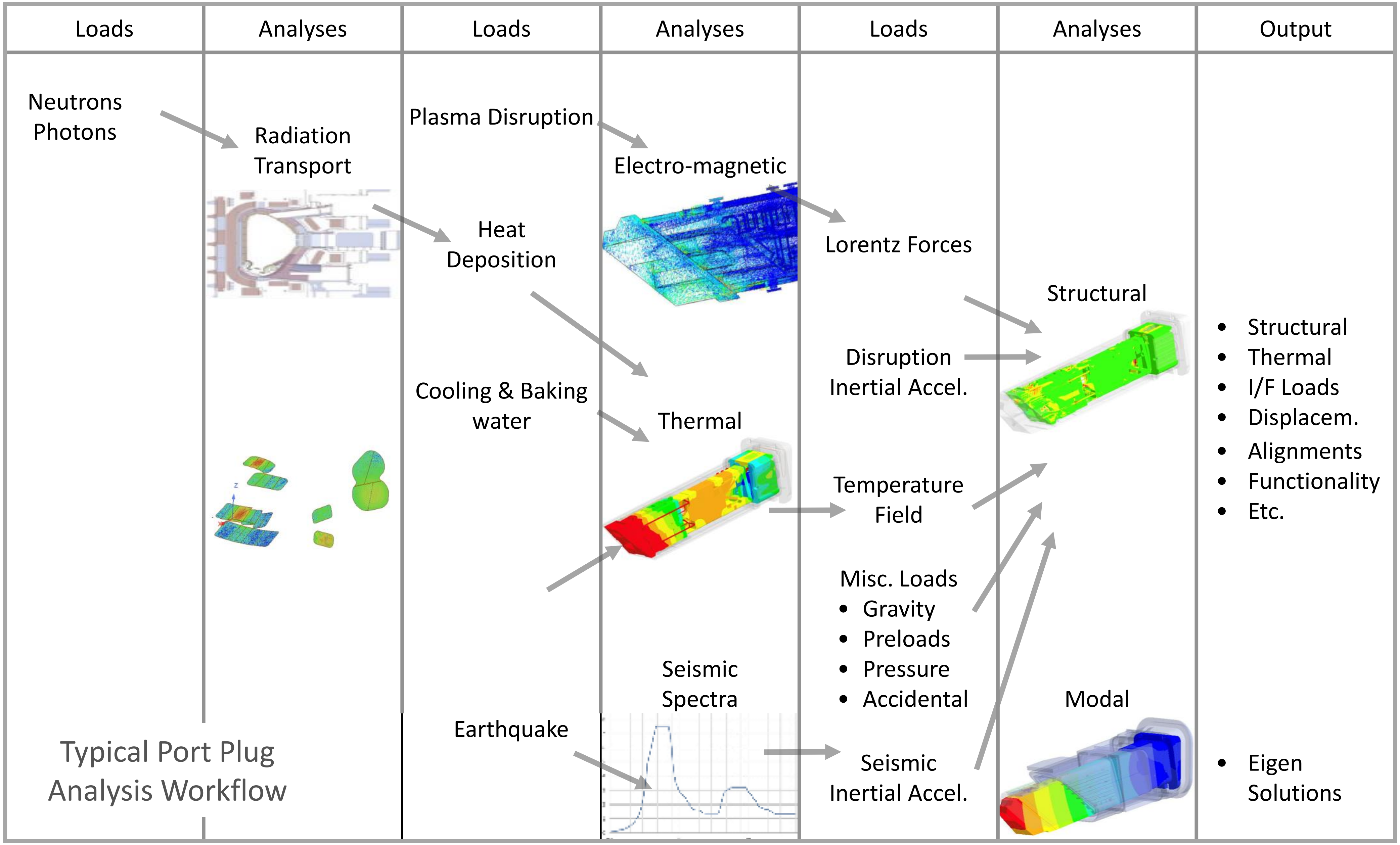
2. PURPOSE

- A key point in the engineering of the Upper Launchers relies in the capability to perform robust, reliable and efficient electromagnetic analysis of the millimeter waves and their interaction with the quasi-optical elements, launcher structures and finally the plasma.

- Special focus has been placed on the integration of this electromagnetic analysis in the end-to-end analysis cycle of the Launcher. The integrated procedure allows coupling the electromagnetic analysis with the thermo-structural analysis, so perturbations of the electromagnetic beams due to mirrors deformation can be accounted for.

- This methodology is aimed to obtain the parameters of the electromagnetic beams injected into the plasma, but also to verify the structural integrity of mirrors and structures against ohmic heating and stray radiation.

3. INTEGRATION OF RF-EM ANALYSES IN THE GENERAL ANALYSES WORKFLOW



Loads	Analyses	Loads	Analyses	Loads	Analyses	Output

Neutrons
Photons

Radiation
Transport

Plasma Disruption

Heat
Deposition

Cooling & Baking
water

Earthquake

Electro-magnetic

Thermal

Seismic
Spectra

Lorentz Forces

Disruption
Inertial Accel.

Temperature
Field

Misc. Loads
- Gravity
- Preloads
- Pressure
- Accidental

Seismic
Inertial Accel.

Structural

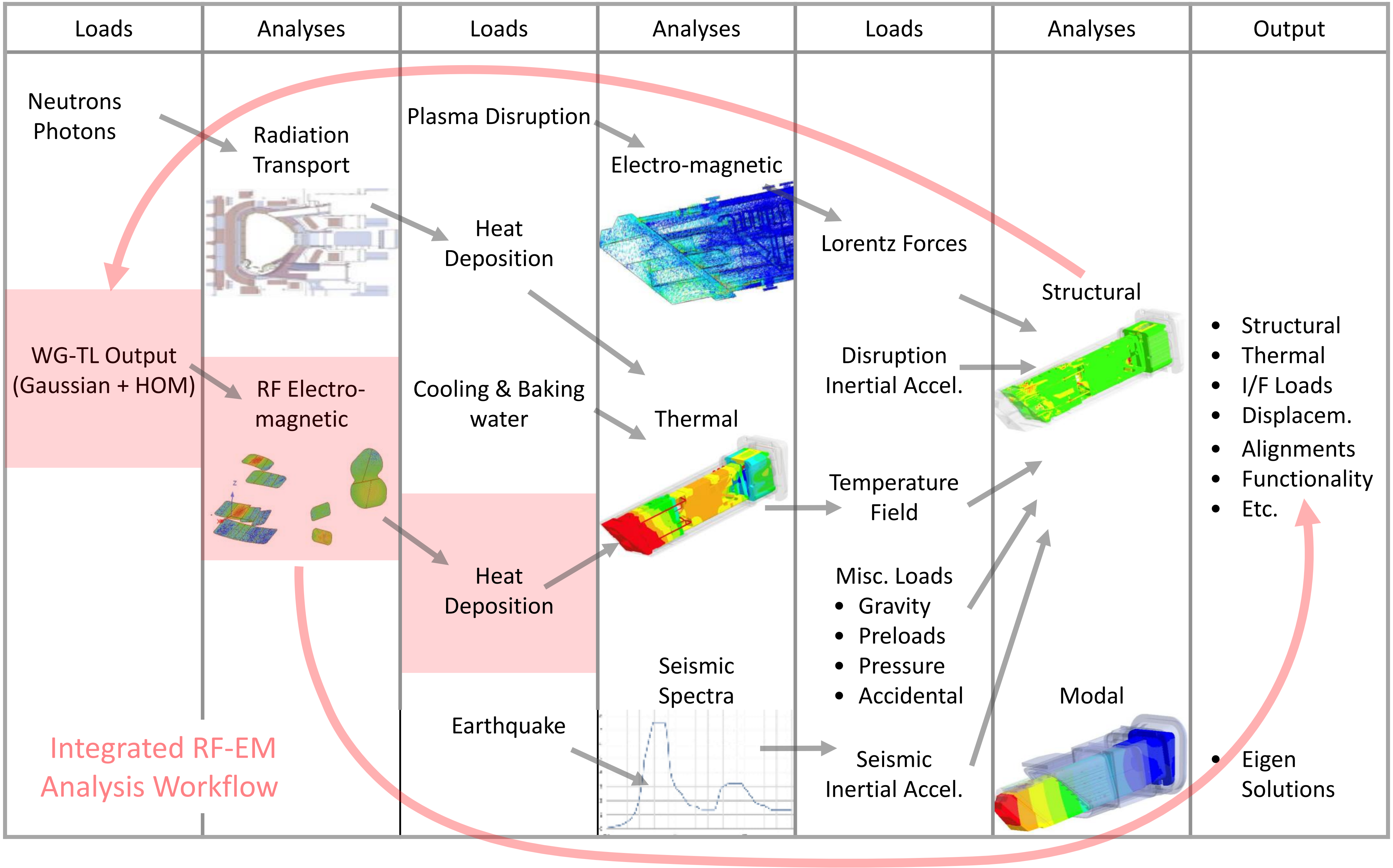
Modal

- Structural
- Thermal
- I/F Loads
- Displacem.
- Alignments
- Functionality
- Etc.

- Eigen
Solutions

Typical Port Plug
Analysis Workflow

3. INTEGRATION OF RF-EM ANALYSES IN THE GENERAL ANALYSES WORKFLOW

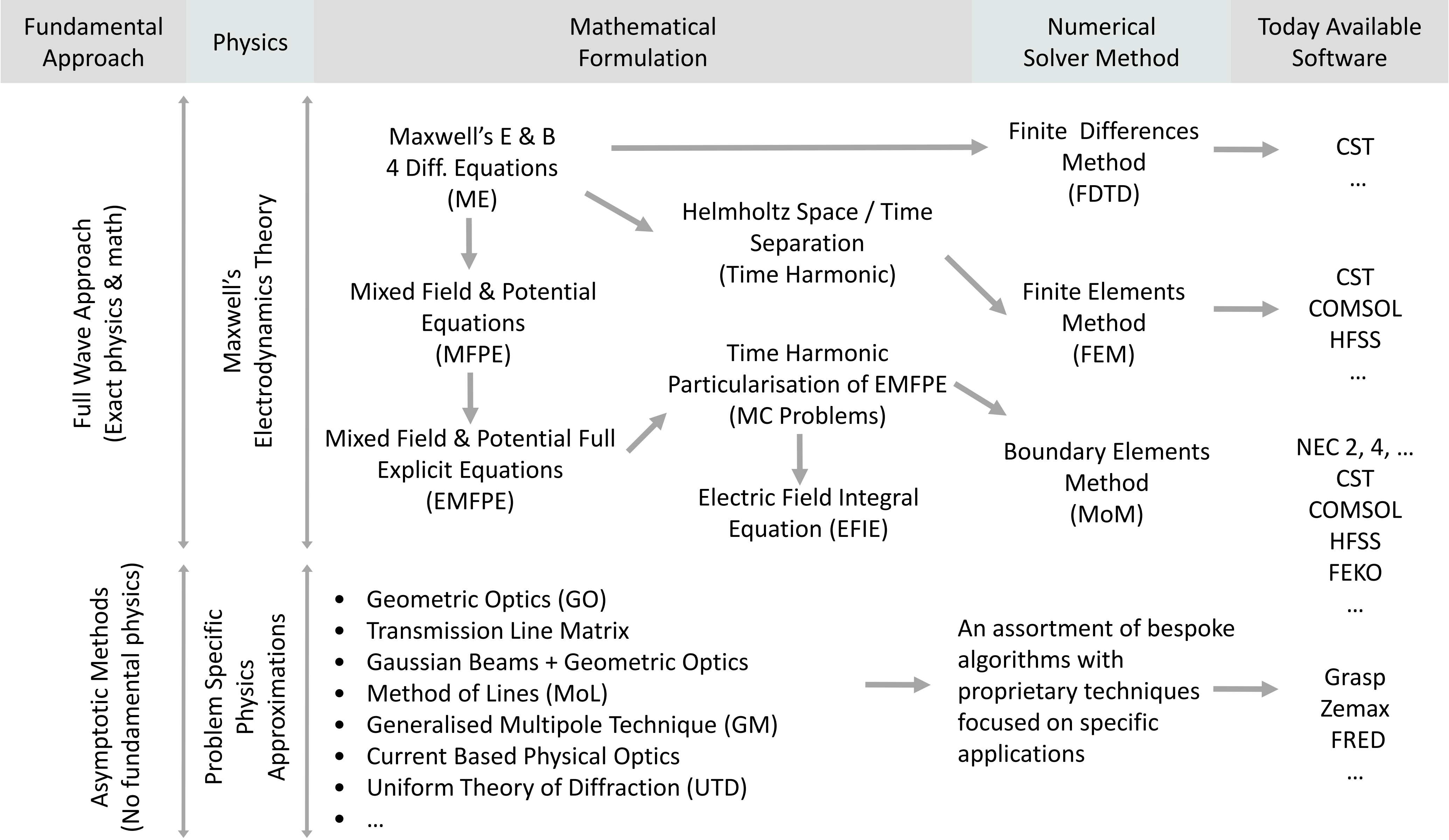


Loads	Analyses	Loads	Analyses	Loads	Analyses	Output
Neutrons Photons WG-TL Output (Gaussian + HOM)	Radiation Transport RF Electro-magnetic	Plasma Disruption Heat Deposition Cooling & Baking water Heat Deposition Earthquake	Electro-magnetic Thermal Seismic Spectra	Lorentz Forces Disruption Inertial Accel. Temperature Field Misc. Loads • Gravity • Preloads • Pressure • Accidental Seismic Inertial Accel.	Structural Modal	• Structural • Thermal • I/F Loads • Displacem. • Alignments • Functionality • Etc. • Eigen Solutions

Integrated RF-EM Analysis Workflow

4. COMPUTATIONAL ELECTROMAGNETICS (RF APPLICATION)

Five levels of abstraction have been considered to select/assess the method candidates for our RF analyses case:



Fundamental Approach

Physics

Mathematical Formulation

Numerical Solver Method

Today Available Software

Full Wave Approach (Exact physics & math)

Maxwell's Electrodynamics Theory

Maxwell's E & B 4 Diff. Equations (ME)

Mixed Field & Potential Equations (MFPE)

Mixed Field & Potential Full Explicit Equations (EMFPE)

Helmholtz Space / Time Separation (Time Harmonic)

Time Harmonic Particularisation of EMFPE (MC Problems)

Electric Field Integral Equation (EFIE)

Finite Differences Method (FDTD)

Finite Elements Method (FEM)

Boundary Elements Method (MoM)

CST
…

CST
COMSOL
HFSS
…

NEC 2, 4, …
CST
COMSOL
HFSS
FEKO
…

Asymptotic Methods (No fundamental physics)

Problem Specific Physics Approximations

- Geometric Optics (GO)
- Transmission Line Matrix
- Gaussian Beams + Geometric Optics
- Method of Lines (MoL)
- Generalised Multipole Technique (GM)
- Current Based Physical Optics
- Uniform Theory of Diffraction (UTD)
- …

An assortment of bespoke algorithms with proprietary techniques focused on specific applications

Grasp
Zemax
FRED
…

4. COMPUTATIONAL ELECTROMAGNETICS (RF APPLICATION)

- Computational electromagnetics (CEM) techniques are used to model the interaction of EM fields and structures using **Maxwell equations**:

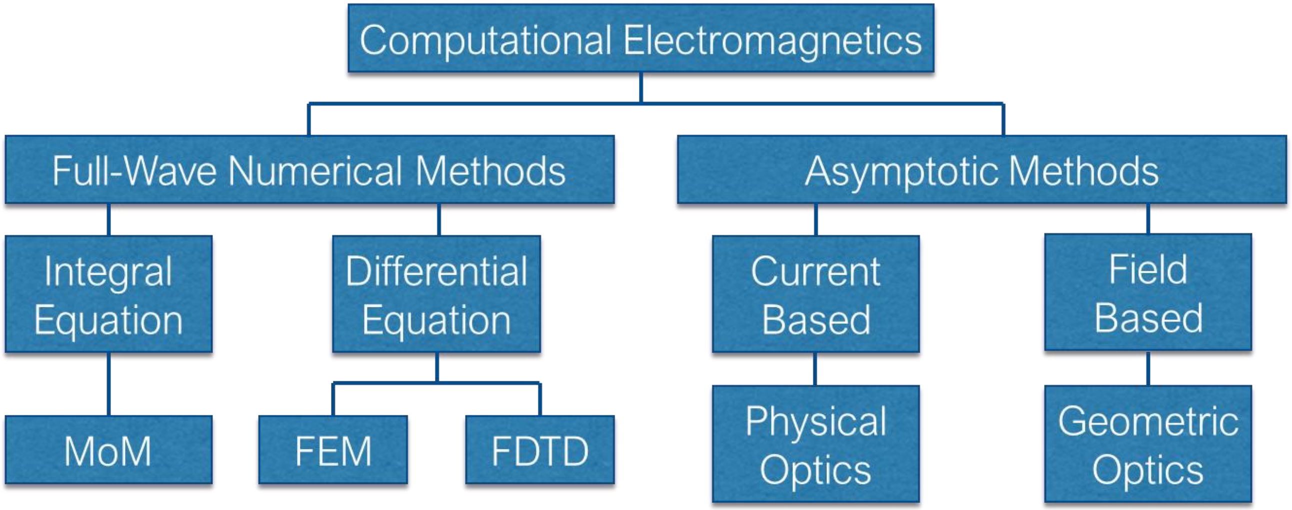
Faraday: $\nabla \times \mathbf{E} = -\partial/\partial t\, \mathbf{B}$

Maxwell-Ampére: $\nabla \times \mathbf{H} = \mathbf{J} + \partial/\partial t\, \mathbf{D}$

Gauss: $\nabla\, \mathbf{B} = 0$

Gauss-Poisson: $\nabla\, \mathbf{D} = \rho$

- As previous shown, there are multiple CEM methods, but most of them can be classified as:
  - ✓ **Full wave numerical methods**
  - ✓ **High frequency/asymptotic methods**
  - ✓ Other methods such as the generalized multipole technique, transmission line matrix, etc.
- In addition, it is possible to use “Hybrid” methods which are a combination of the multiple CEM methods in one analysis, for example FEM+MoM or FDTD+PO.



4. COMPUTATIONAL ELECTROMAGNETICS (RF APPLICATION)

- Inside the **Full-Wave Methods**, there are two classes of numerical solvers for Maxwell's equations:

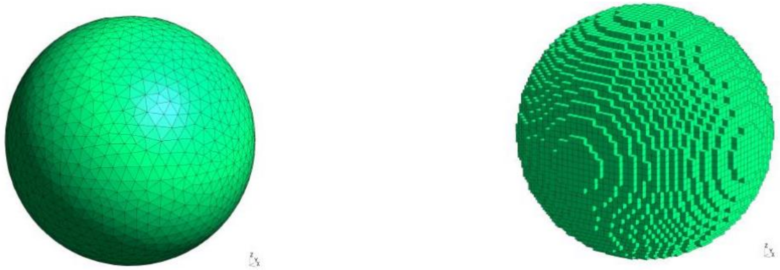
1- Differential equation solver:

- ✓ The unknowns in a differential equation solver are the fields, which permeate all of space, and thus are volumetrically distributed. They usually require a large number of unknowns to represent the whole volume of interest which includes the structure to be analyzed and the surrounding medium (typically called "airbox").
- ✓ The element size is generally a function of the wave frequency, thus modeling the structure and the surrounding medium can lead to large models in some applications.
- ✓ On the other hand, the matrix system associated with a differential equation solver is usually sparse, requiring less storage and less time to solve than a dense matrix system.

FEM:

$$\nabla^2 \bar{E}_S + \mathrm{k}^2 \bar{E}_S = 0$$

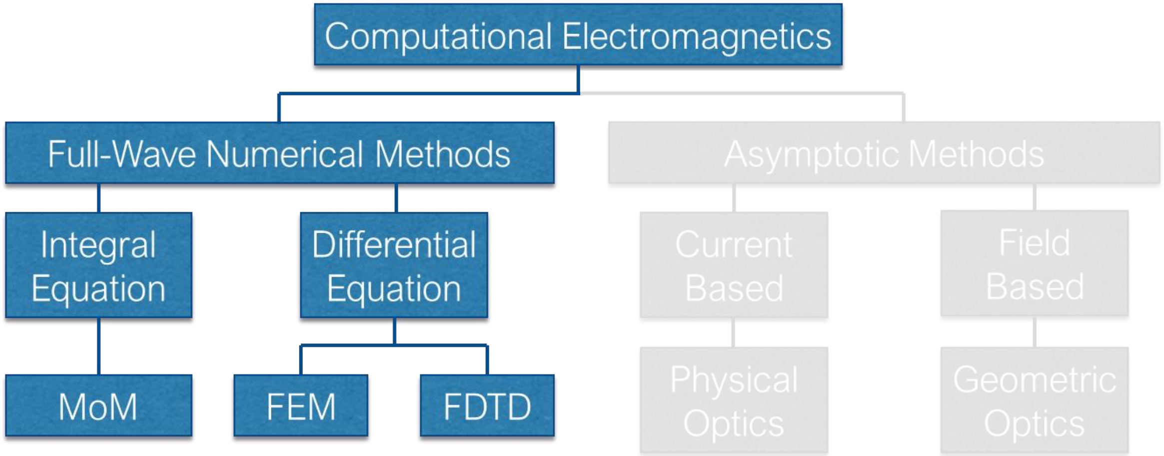
Example of unstructured and structured mesh



FDTD:

$$\frac{\partial \bar{E}}{\partial \mathrm{t}} = \frac{1}{\varepsilon_0} \nabla \times \bar{H}$$

$$\frac{\partial \bar{H}}{\partial \mathrm{t}} = \frac{1}{\mu_0} \nabla \times \bar{E}$$



Computational Electromagnetics

Full-Wave Numerical Methods

Asymptotic Methods

Integral Equation

Differential Equation

Current Based

Field Based

MoM

FEM

FDTD

Physical Optics

Geometric Optics

4. COMPUTATIONAL ELECTROMAGNETICS (RF APPLICATION)

- Inside the **Full-Wave Methods**, there are two classes of numerical solvers for Maxwell's equations:

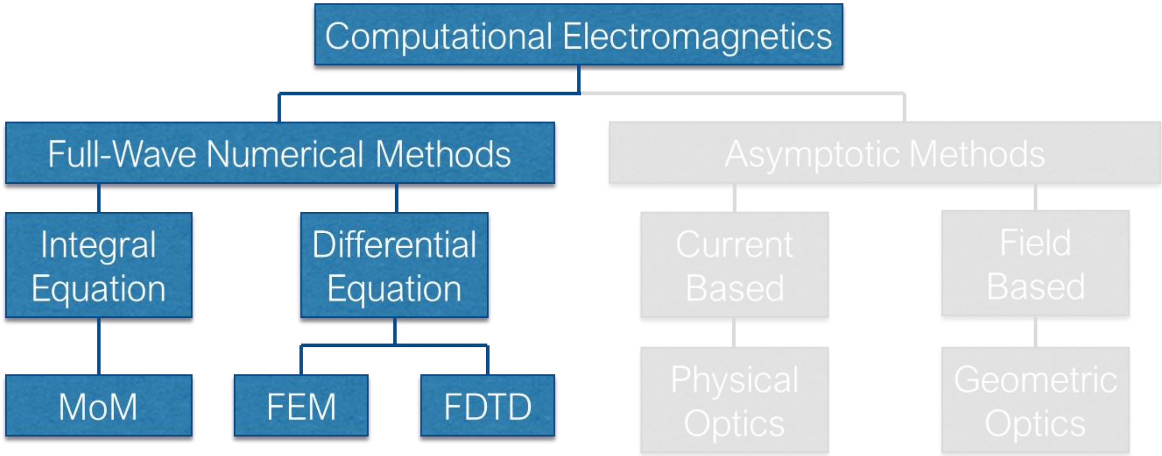
  2- Integral equation solvers

  - ✓ Formulated using Green's functions, i.e. integral equations are derived from Maxwell's equations using Green's function.
  - ✓ The unknowns are surface currents. Thus, there is usually less unknowns as they only appear on the surface of a scatterer, and the matrix systems are generally smaller.
  - ✓ On the other hand, a Green's function connects every current source point on the surface of a scatterer with every other source points, yielding a dense matrix system (can lead to large memory requirements and solution time).

- Both techniques (differential and integral) are exact methods; the error in the numerical solution comes from the discretization.

MoM: Electric Field Integral Equation (EFIE)

$$\begin{cases} \hat{n} \times \mathrm{E}^{\mathrm{inc}}(\mathrm{r}) = \hat{n} \times \displaystyle\int_S \left[\mathrm{j\,k\,\eta\,J}_S(r')\, G(r,r') + \frac{\eta}{\mathrm{jk}} \{\nabla'_{\mathrm{s}} \cdot \mathrm{J}_S(r')\}\, \nabla' \mathrm{G}(\mathrm{r},\mathrm{r}') \right] \mathrm{dS}', \qquad \forall\, \mathrm{r},\mathrm{r}' \in \mathrm{S} \\ G(r,r') = \dfrac{\mathrm{e}^{-\mathrm{jkR}}}{4\pi\mathrm{R}}; \quad R = |r - r'| \end{cases}$$



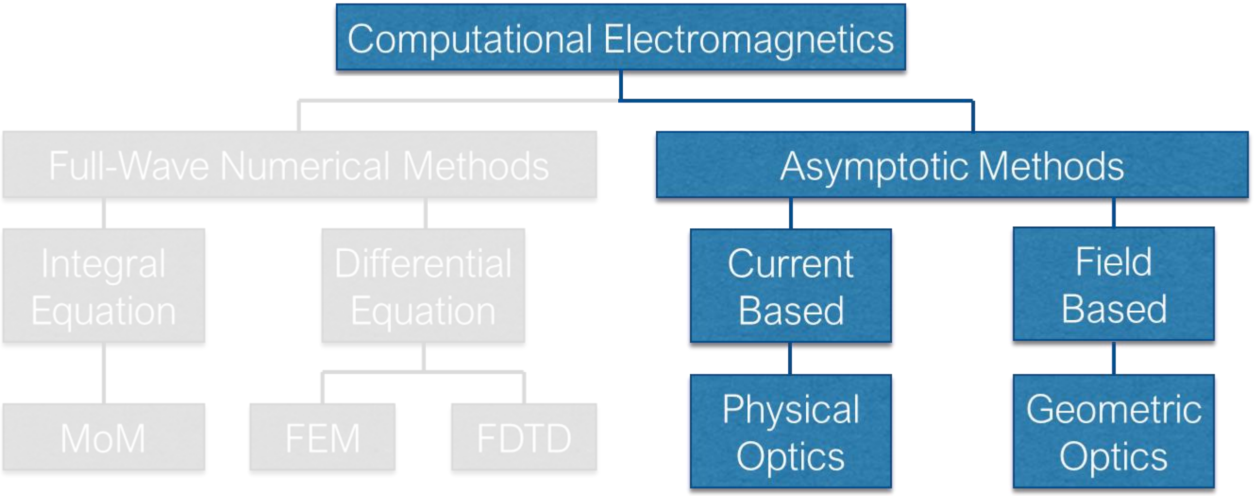
4. COMPUTATIONAL ELECTROMAGNETICS (RF APPLICATION)

- The **Asymptotic Methods** are high frequency methods that are only accurate when the dimensions of the objects being analyzed are large compared to the wavelength of the field, e.g. larger than 10λ.

  1- Physical optics is a current-based method in which the physical optics approximation (i.e. the incident field is treated as a locally plane wave and the reflector surface is perfectly conducting) is used to obtain the current density induced on a surface of a perfect electric conductor (PEC) plane. This method is adequate for large, smooth surfaces with low curvature.

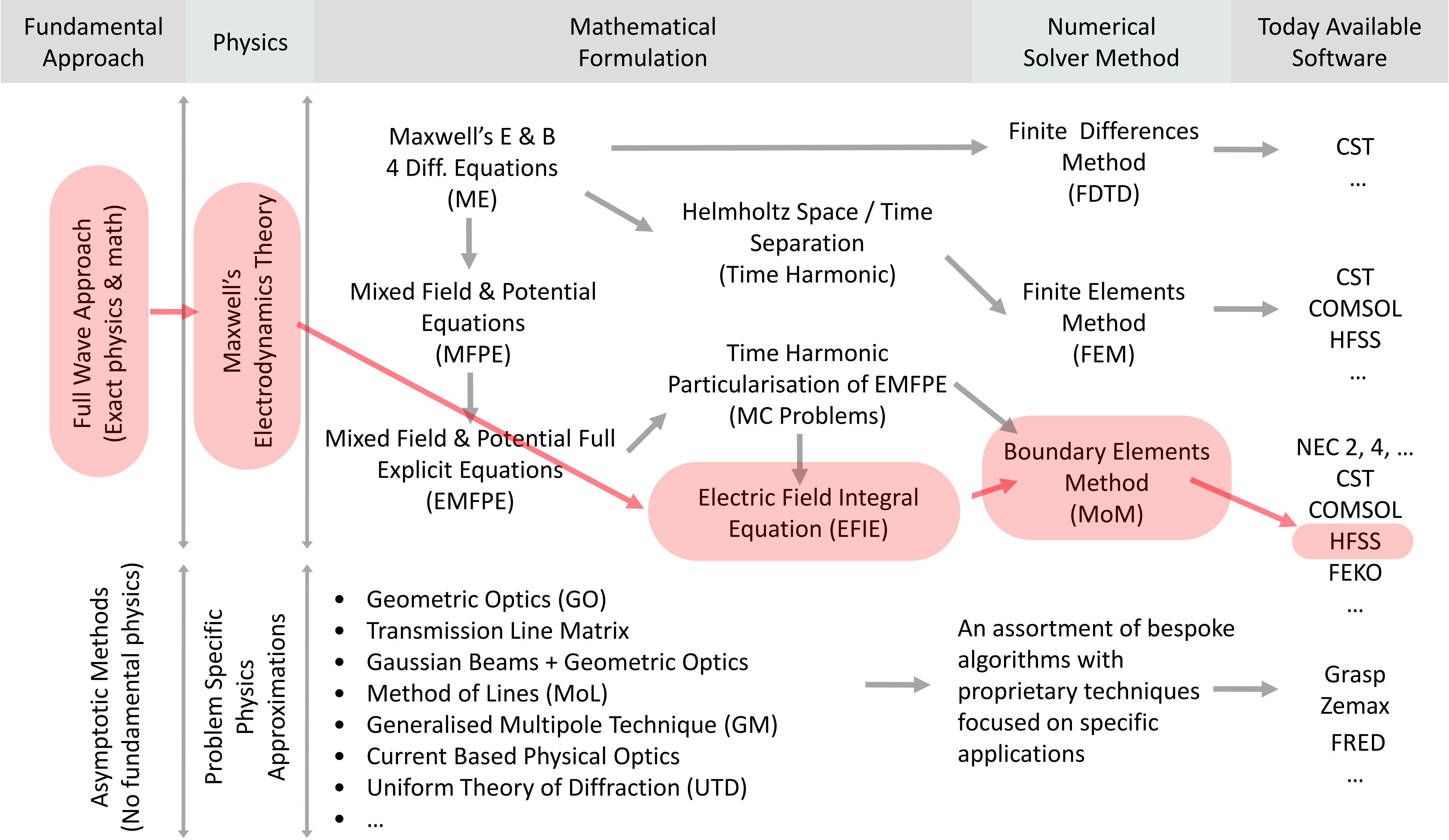
  2- Geometrical optics is a field-based method that describes light propagation in terms of "rays" which are perpendicular to the wave fronts of the actual optical waves.

- Both techniques require of an additional method to compute the contribution due to the diffraction phenomenon.
  - The GO can be complemented with the Geometrical Theory of Diffraction (GTD) or the Uniform Theory of Diffraction (UTD).
  - The PO formulation can be complemented with the Physical Theory of Diffraction (PTD).



5. SELECTION OF METHOD - MAIN OPTICAL PATH ANALYSIS

SELECTION: **HFSS** (from Ansoft, now part of Ansys) with the **IE solver** (integral equation/MoM)



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Boundary Elements Method (MoM)

CST
…

CST
COMSOL
HFSS
…

NEC 2, 4, …
CST
COMSOL
HFSS
FEKO
…

Asymptotic Methods (No fundamental physics)

Problem Specific Physics Approximations

- Geometric Optics (GO)
- Transmission Line Matrix
- Gaussian Beams + Geometric Optics
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An assortment of bespoke algorithms with proprietary techniques focused on specific applications

Grasp
Zemax
FRED
…

5. SELECTION OF METHOD - MAIN OPTICAL PATH ANALYSIS

SELECTION: **HFSS** (from Ansoft, now part of Ansys) with the **IE solver** (integral equation/MoM)

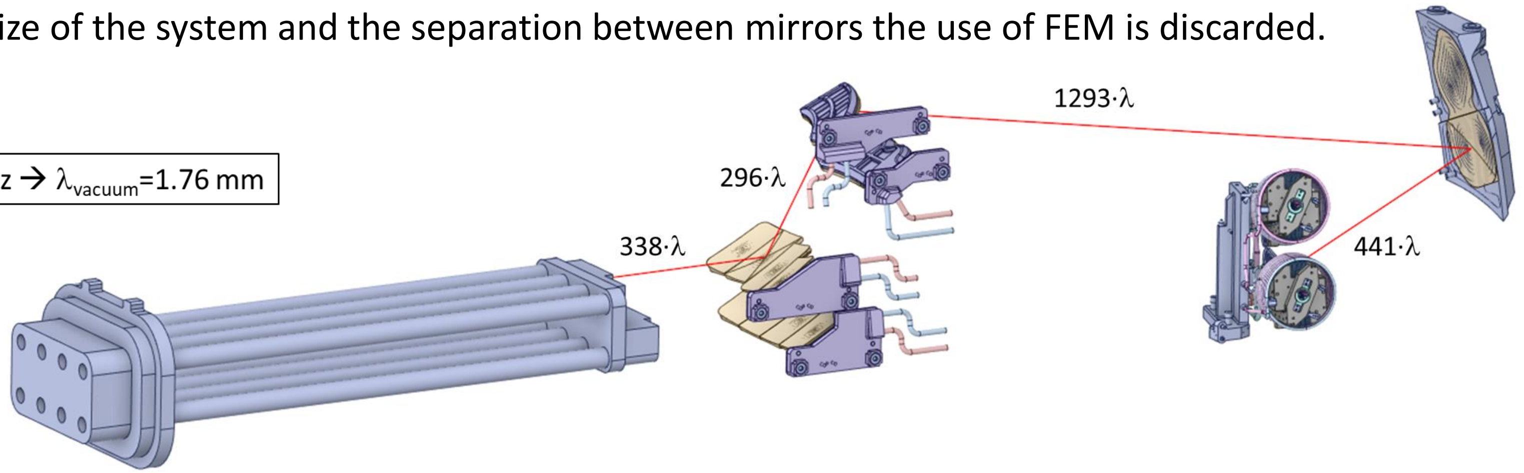
- Full Wave Method. It is an exact method from Physics and Mathematics point of view. (Only natural numerical discretization errors are present and the convergence is consistent and fast)
- MoM Method of Moments (actually Boundary Elements Method BEM) -> Only the field boundaries are modelled and meshed. But all the fields are efficiently obtained by post-processing.
- The method solves for currents (working variable is current density) in scattering surfaces and provides Joule heating readily.
- Good for vacuum and highly conductive surfaces scatterers (reflectors)
- Naturally incorporates the “radiation condition” to free space.
- Numerically efficient. All mirrors + Beam Vault Space and Walls can be solved simultaneously at frequencies as high as 50 GHz. Typically 48h with our computing cluster for the in vacuum full aerial flight with all mirrors and feeds solved full coupled at 50GHz. For higher frequencies, our case, staggered strategies are needed.
- Seamless integration with the *ANSYS* thermal-structural analysis platform (called *ANSYS Workbench*).
  - ✓ Ohmic heating transferred almost automatically to the thermo-structural model: *“Forward Coupling”*
  - ✓ Structural deformations on reflectors transferred automatically to *HFSS:* “Backward Coupling”
- HFSS has several tools to easily link staggered simulations for successive steps of the transmission beam flights.
- Computational cost is low for moderate size reflective surfaces in terms of number of wavelengths (field space not influential), see above, but does not escalates well with frequency ($\mathcal{O}$(f6)). For our case (170 GHz) full simultaneous solution is not possible. But several useful tools are available to solve the our specific case by steps. In our case, backscattering between mirror is negligible.

5. SELECTION OF METHOD - MAIN OPTICAL PATH ANALYSIS

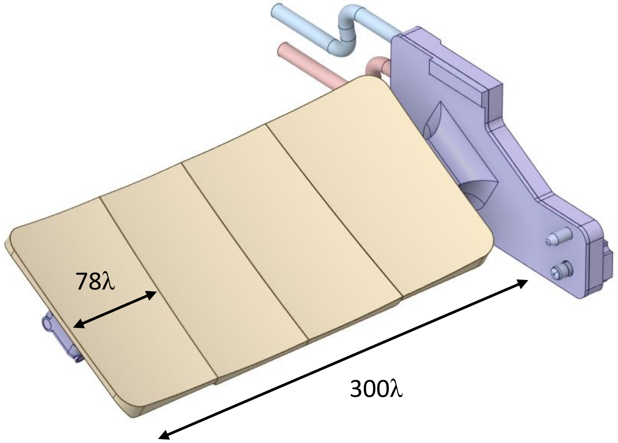
SELECTION: **HFSS** (from Ansoft, now part of Ansys) with the **IE solver** (integral equation/MoM)

- Due to the electrical size of the system and the separation between mirrors the use of FEM is discarded.

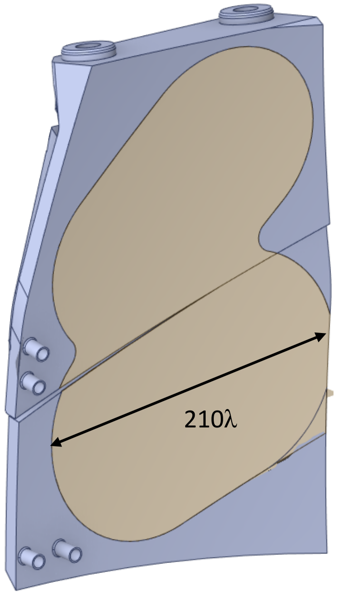
f=170 GHz → λ_{vacuum}=1.76 mm



- In addition, due to the elec. size of each mirror the use of hybrid techniques like FE-BI is also discarded.
- Thus, the **"IE solver" (MoM)** has been used to perform the first analyses of the U. Launcher optical system.



M1 lower mirrors

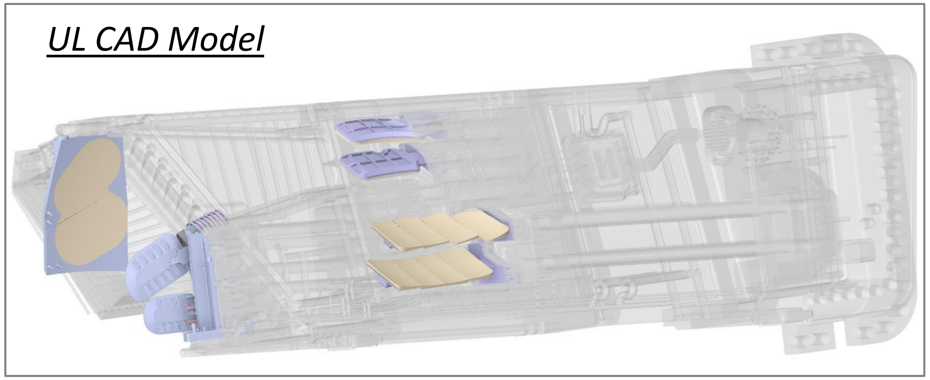


M3 mirrors

5. SELECTION OF METHOD - MAIN OPTICAL PATH ANALYSIS

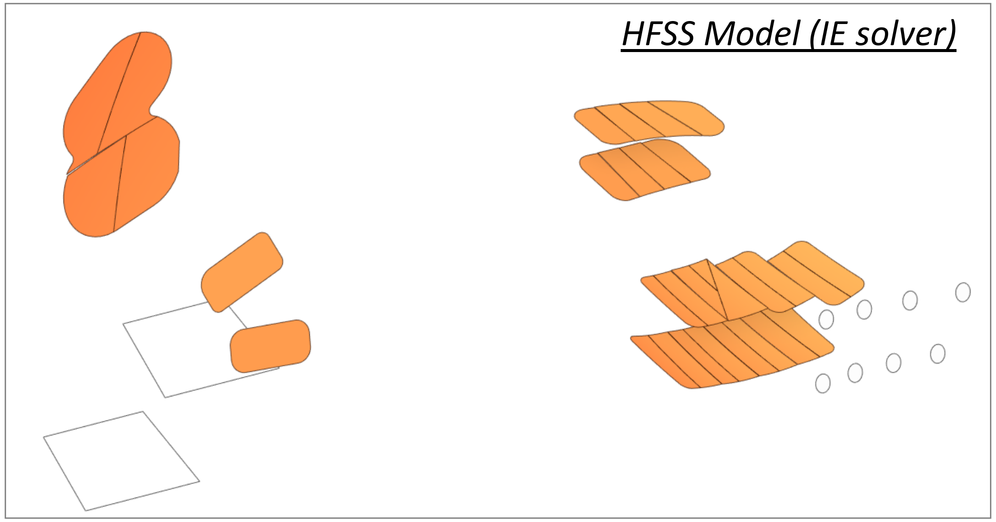
SELECTION: **HFSS** (from Ansoft, now part of Ansys) with the **IE solver** (integral equation/MoM)

- The integral equations solver (IE) uses the **Method of Moments (MoM)** technique to solve for the currents on the surfaces of conducting objects in open regions.
- It is an efficient solution technique for open radiating and scattering of metallic objects. The method allows uniform regions of free space to be removed from the FEM solution (removes the need for an air box to surround metal objects).



UL CAD Model

Scattered surfaces extracted from CAD model

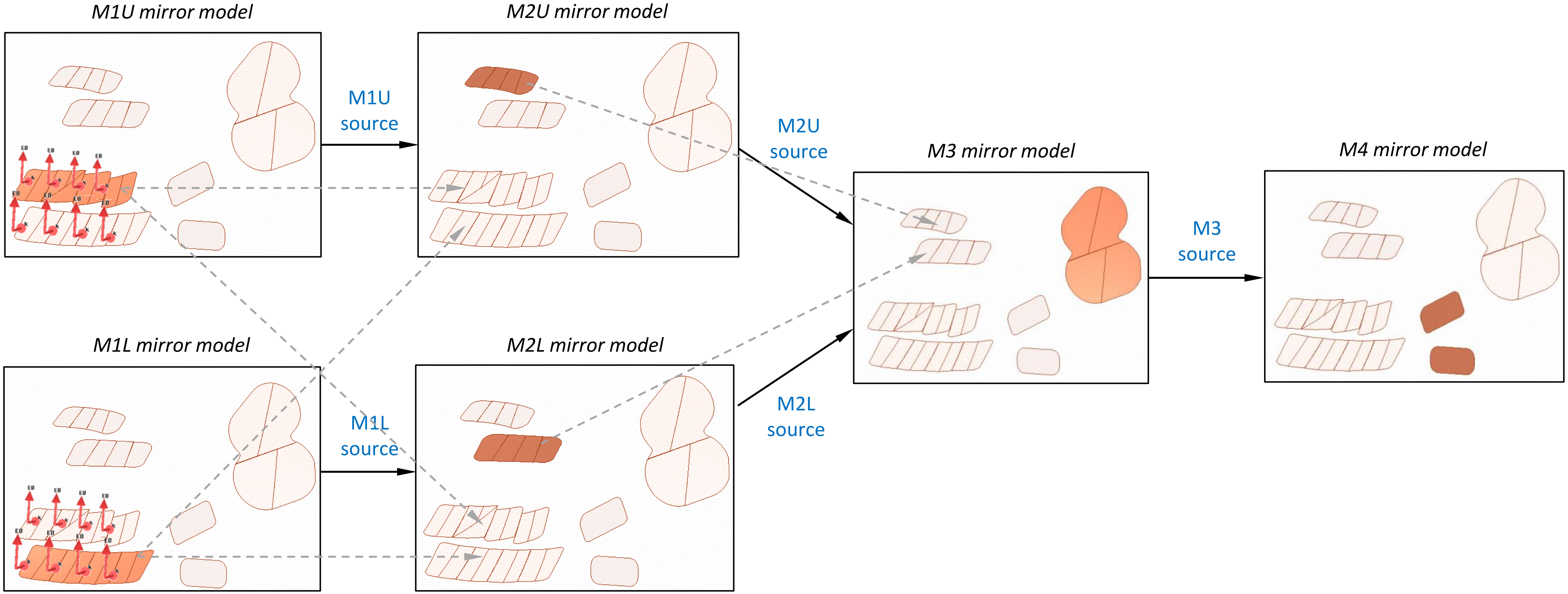


HFSS Model (IE solver)

5. SELECTION OF METHOD - MAIN OPTICAL PATH ANALYSIS

SELECTION: **HFSS** (from Ansoft, now part of Ansys) with the **IE solver** (integral equation/MoM)

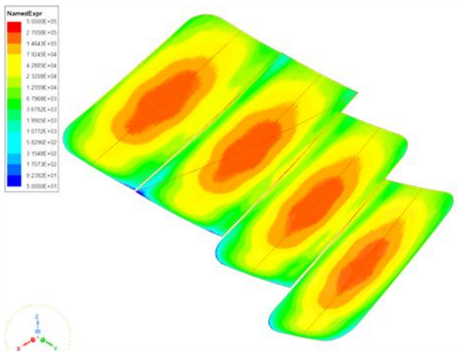
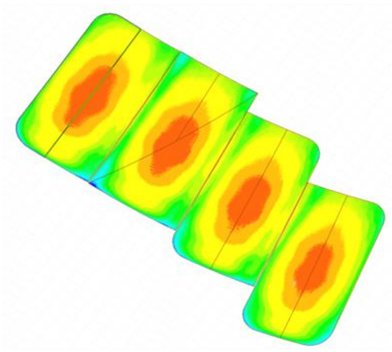
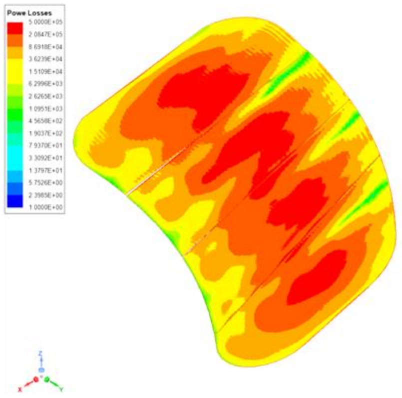
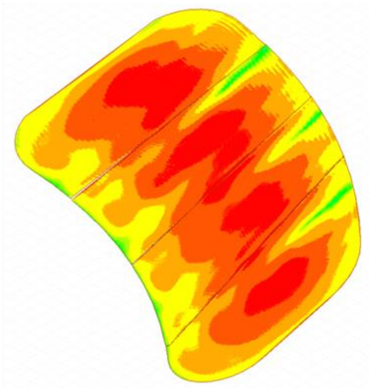
- It is possible to link an *HFSS-IE* analysis as a source in another *HFSS-IE* analysis using a "data link". The source is automatically created in HFSS and the fields are linked to the target *HFSS-IE* analysis
- This creates a one way coupling from source excitation to reflector which can be used in the UL analysis due to the low backscattering from the reflector to source within the optical path.
- Thus, due to the size of the system the analysis could be performed by steps, using the source-target couplings, following the beam reflections.
- This methodology allows for a more detailed modeling of each of the mirrors.



5. SELECTION OF METHOD - MAIN OPTICAL PATH ANALYSIS

SELECTION: **HFSS** (from Ansoft, now part of Ansys) with the **IE solver** (integral equation/MoM)

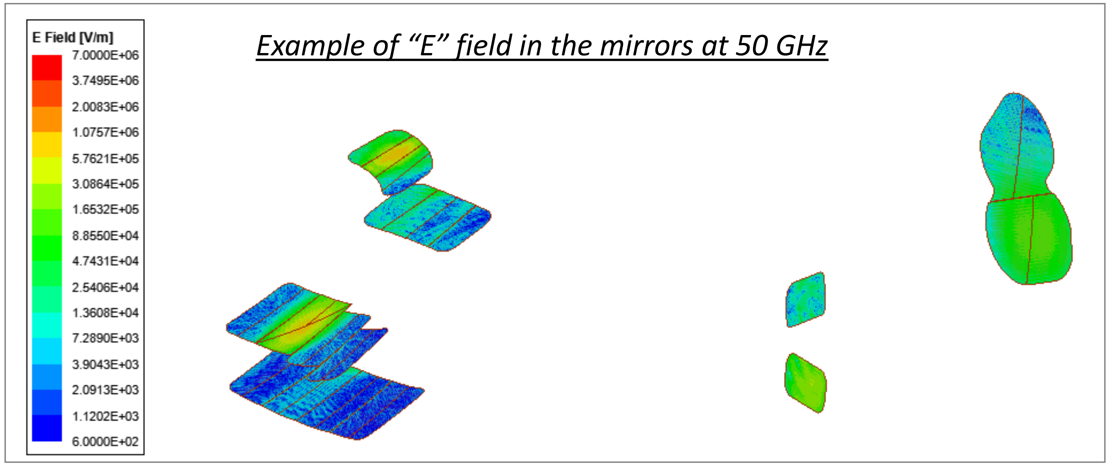
- The stepwise and simultaneous analyses of M1_U to M2_U have been compared in terms of the total heat obtained using both approaches.
- Similar total heat and heat distribution is obtained using both approaches.

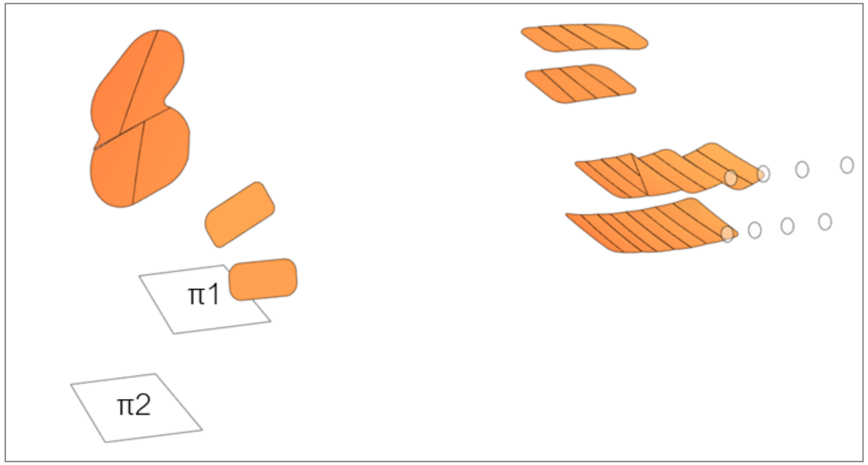
	Stepwise analysis between M1 and M2	Simultaneous M1 and M2 analysis
M1_U	 Q_M1= **7172 W**	 Q_M1= **7103 W**
M2_U	 Q_M2= **6151 W**	 Q_M2= **6087 W**

5. SELECTION OF METHOD - MAIN OPTICAL PATH ANALYSIS

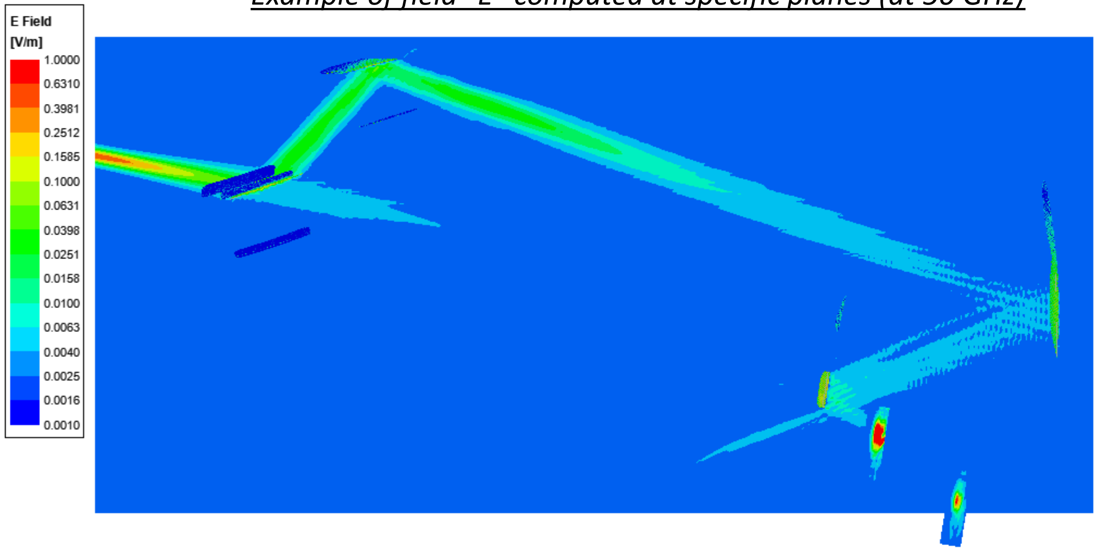
SELECTION: **HFSS** (from Ansoft, now part of Ansys) with the **IE solver** (integral equation/MoM)

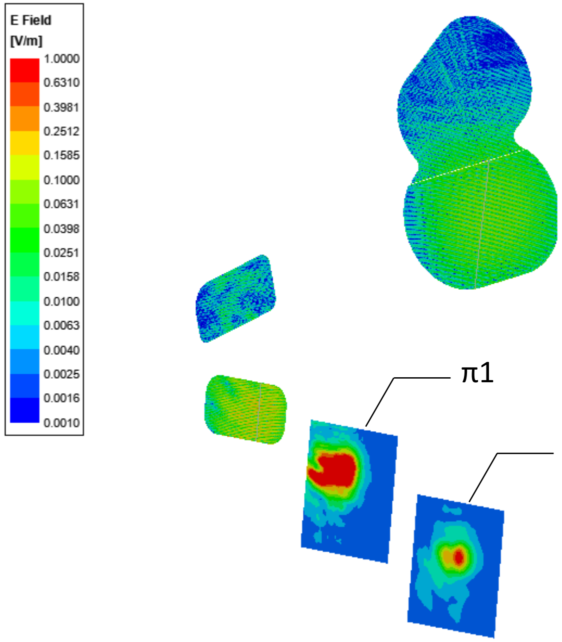
- The currents and fields are calculated in each mirror, and for all input sources defined simultaneously.
- During post-processing it is also possible to calculate the field values in the space between mirrors at specific planes.
- The output beams data at M4 can be obtained two planes (π1 and π2) at the M4 output (plane definition TBD).


Example of "E" field in the mirrors at 50 GHz



Example of field "E" computed at specific planes (at 50 GHz)

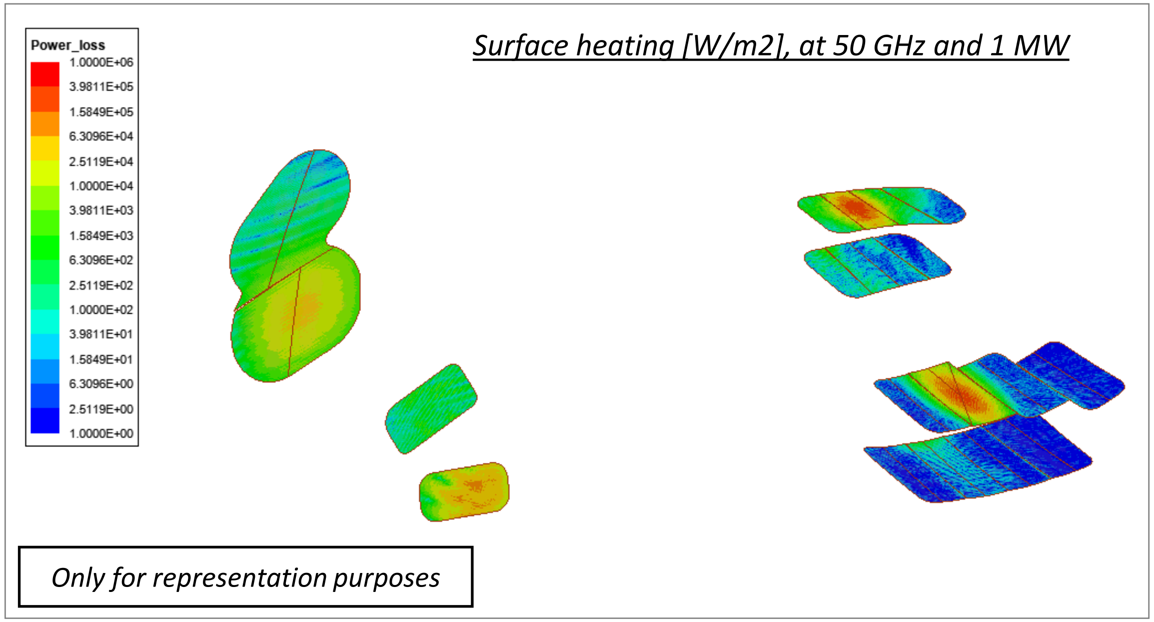




5. SELECTION OF METHOD - MAIN OPTICAL PATH ANALYSIS

SELECTION: **HFSS** (from Ansoft, now part of Ansys) with the **IE solver** (integral equation/MoM)

- The mirror heating [W/m^2] is calculated in HFSS with the “calculator tool”. This methodology has been developed with the ANSYS technical support team.
- The surface heating in each mirror can also be integrated to calculate the total heating in [W].
- A custom python routine is used to prepare the data file, exported from HFSS, for its use in ANSYS Mechanical.



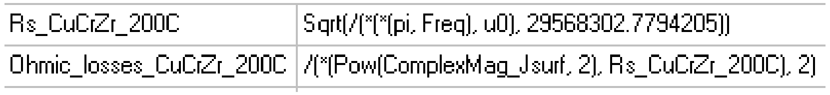
Surface heating [W/m2], at 50 GHz and 1 MW

Only for representation purposes

HFSS calculator expressions

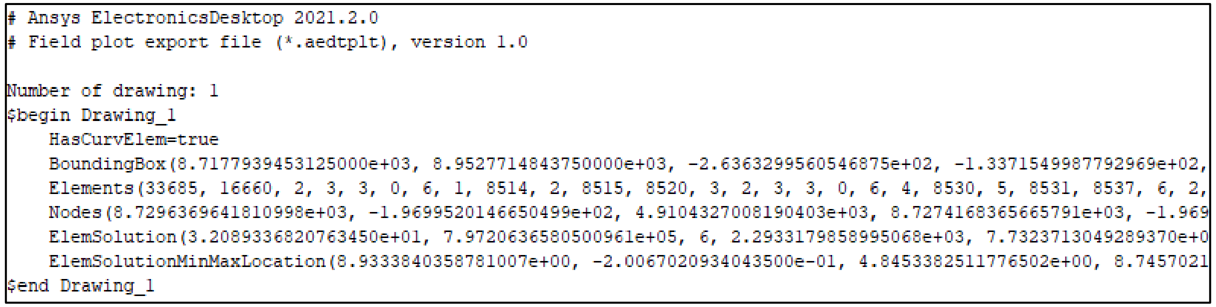
$$P_{avg} = \frac{R_S}{2} \int_{So} |J_S|^2 \, ds$$

$$R_s = \sqrt{\frac{\omega \mu_0}{2\sigma}}$$



Rs_CuCrZr_200C	Sqrt(/(*(*(pi, Freq), u0), 29568302.7794205))
Ohmic_losses_CuCrZr_200C	/(*(Pow(ComplexMag_Jsurf, 2), Rs_CuCrZr_200C), 2)

Export HFSS results to “.aedtplt” file*

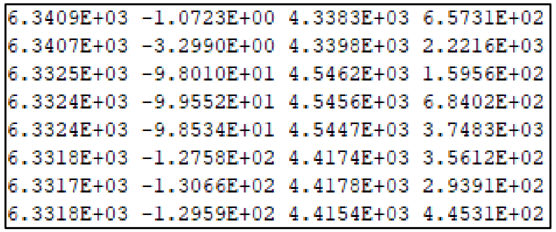


```
# Ansys ElectronicsDesktop 2021.2.0
# Field plot export file (*.aedtplt), version 1.0

Number of drawing: 1
$begin Drawing_1
    HasCurvElem=true
    BoundingBox(8.7177939453125000e+03, 8.9527714843750000e+03, -2.6363299560546875e+02, -1.3371549987792969e+02,
    Elements(33685, 16660, 2, 3, 3, 0, 6, 1, 8514, 2, 8515, 8520, 3, 2, 3, 3, 0, 6, 4, 8530, 5, 8531, 8537, 6, 2,
    Nodes(8.7296369641810998e+03, -1.9699520146650499e+02, 4.9104327008190403e+03, 8.7274168365665791e+03, -1.969
    ElemSolution(3.2089336820763450e+01, 7.9720636580500961e+05, 6, 2.2933179858995068e+03, 7.7323713049289370e+0
    ElemSolutionMinMaxLocation(8.9333840358781007e+00, -2.0067020934043500e-01, 4.8453382511776502e+00, 8.7457021
$end Drawing_1
```

File processing in python routine

Point data for thermal analysis [x; y; z; W/m2]



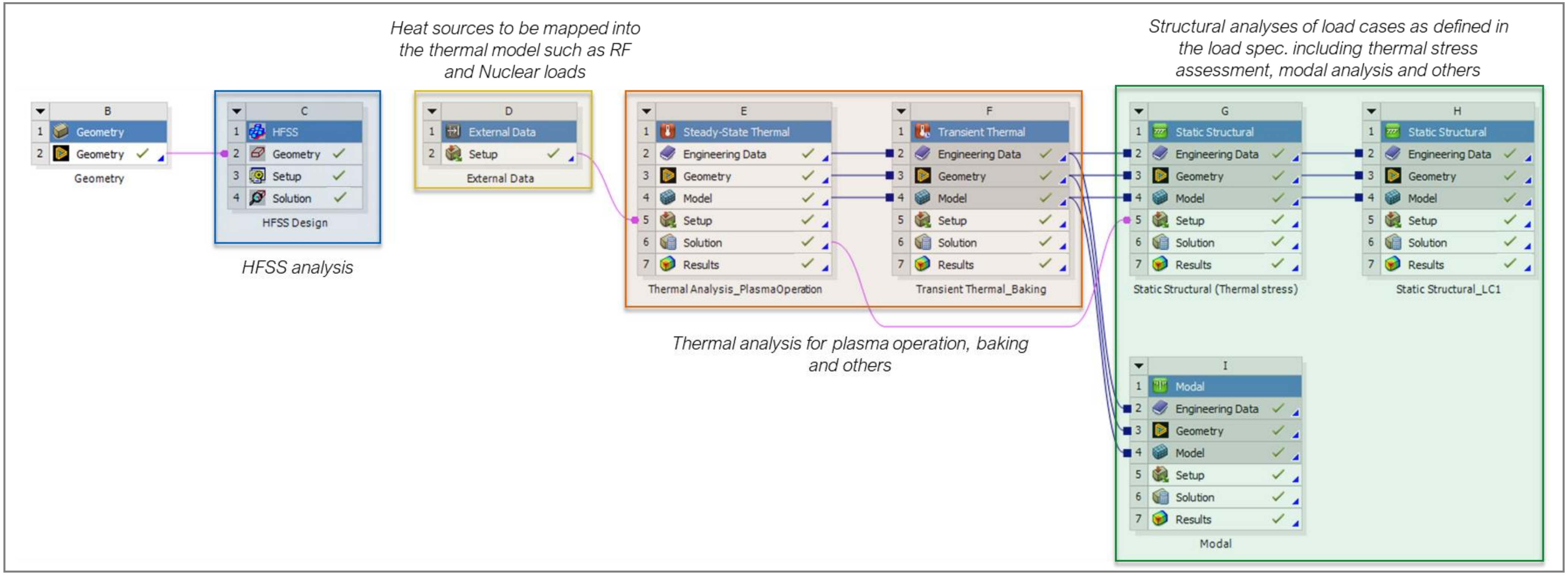
```
6.3409E+03 -1.0723E+00 4.3383E+03 6.5731E+02
6.3407E+03 -3.2990E+00 4.3398E+03 2.2216E+03
6.3325E+03 -9.8010E+01 4.5462E+03 1.5956E+02
6.3324E+03 -9.9552E+01 4.5456E+03 6.8402E+02
6.3324E+03 -9.8534E+01 4.5447E+03 3.7483E+03
6.3318E+03 -1.2758E+02 4.4174E+03 3.5612E+02
6.3317E+03 -1.3066E+02 4.4178E+03 2.9391E+02
6.3318E+03 -1.2959E+02 4.4154E+03 4.4531E+02
```

5. SELECTION OF METHOD - MAIN OPTICAL PATH ANALYSIS

<u>SELECTION</u>: **HFSS** (from Ansoft, now part of Ansys) with the **IE solver** (integral equation/MoM)

- The outputs from the RF analysis are used as a heat source (based on the UL duty cycle) in the thermal analysis.
- The main objectives of the thermal analysis are :
  - 1- Calculation of temperature dependent material properties in the structural analysis.
  - 2- Verification of progressive deformation and cyclic loads.
  - 3- Analysis of thermal deformation.
- Once calculated, the thermal deformations can be saved into a STL file which is then processed in Spaceclaim (ANSYS CAD editor) and imported back into HFSS, as a new geometry, for a new analysis loop.

Example of ANSYS model layout



Heat sources to be mapped into the thermal model such as RF and Nuclear loads

Structural analyses of load cases as defined in the load spec. including thermal stress assessment, modal analysis and others

HFSS analysis

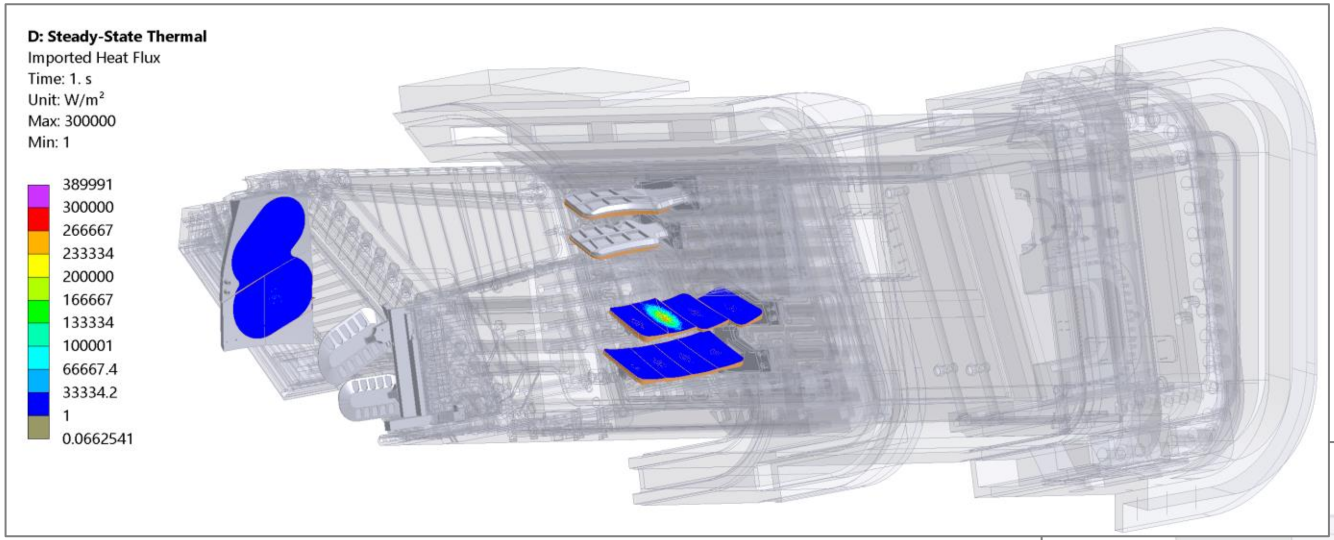
Thermal analysis for plasma operation, baking and others

5. SELECTION OF METHOD - MAIN OPTICAL PATH ANALYSIS

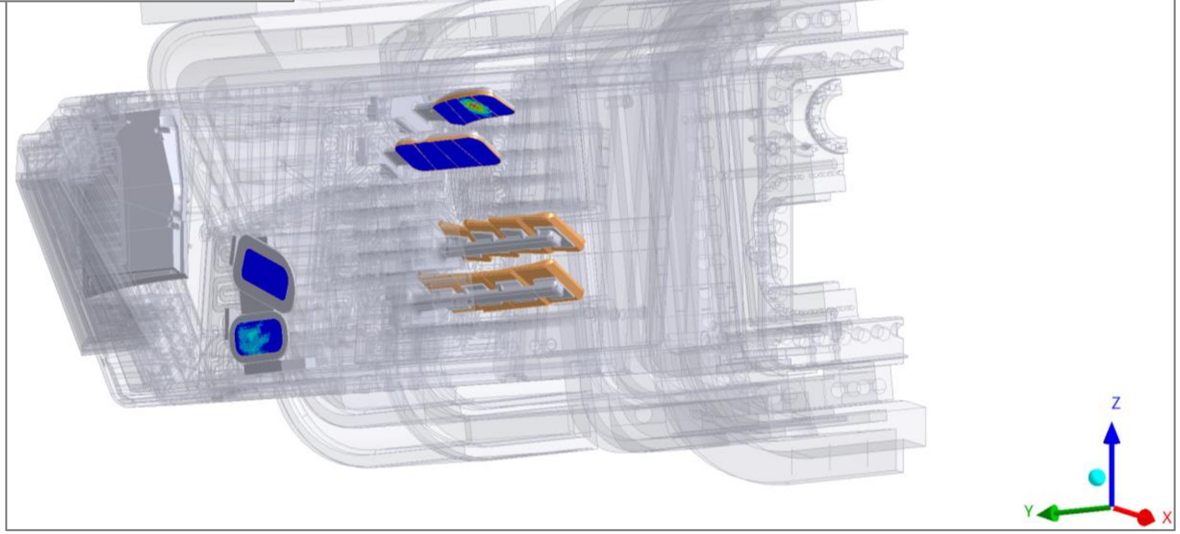
SELECTION: **HFSS** (from Ansoft, now part of Ansys) with the **IE solver** (integral equation/MoM)

- The heat generation is mapped in a coupled thermal-structural FE model with built-in ANSYS tools.
- Other boundary conditions such as nuclear heating, cooling water, radiation, etc. can also be included to model the corresponding cases defined in the Load Specification.

Heat flux from HFSS mapped in the global FE model (view from M1 and M3)

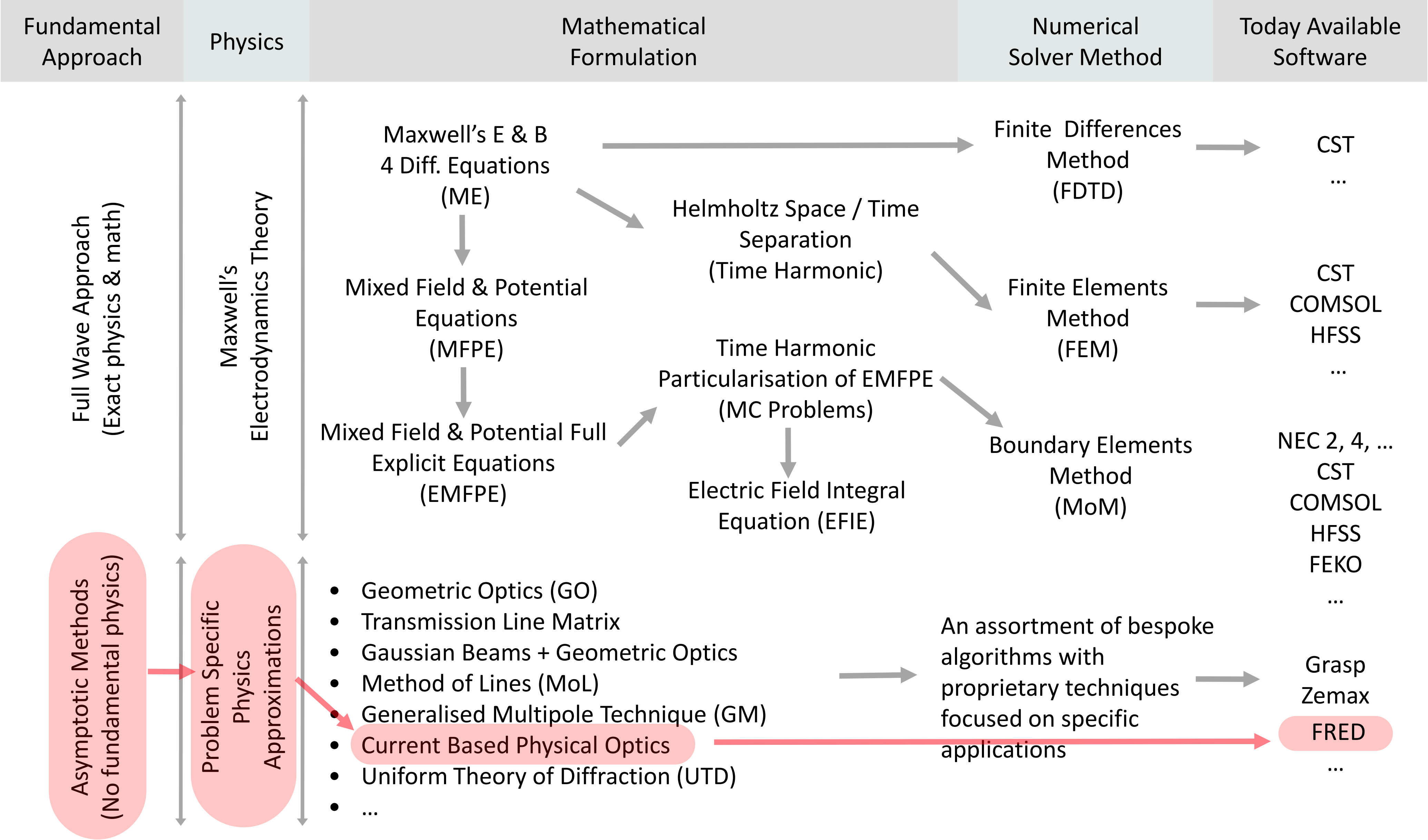


Heat flux from HFSS mapped in the global FE model (view from M2 and M4)



5. SELECTION OF METHOD - SPILLOVER AND STRAY RADIATION

SELECTION: **FRED** Optical Engineering Software (from Photon Engineering), based on **Physical Optics (PO)**



Fundamental Approach

Physics

Mathematical Formulation

Numerical Solver Method

Today Available Software

Full Wave Approach (Exact physics & math)

Maxwell's Electrodynamics Theory

Maxwell's E & B 4 Diff. Equations (ME)

Mixed Field & Potential Equations (MFPE)

Mixed Field & Potential Full Explicit Equations (EMFPE)

Helmholtz Space / Time Separation (Time Harmonic)

Time Harmonic Particularisation of EMFPE (MC Problems)

Electric Field Integral Equation (EFIE)

Finite Differences Method (FDTD)

Finite Elements Method (FEM)

Boundary Elements Method (MoM)

CST
…

CST
COMSOL
HFSS
…

NEC 2, 4, …
CST
COMSOL
HFSS
FEKO
…

Asymptotic Methods (No fundamental physics)

Problem Specific Physics Approximations

- Geometric Optics (GO)
- Transmission Line Matrix
- Gaussian Beams + Geometric Optics
- Method of Lines (MoL)
- Generalised Multipole Technique (GM)
- Current Based Physical Optics
- Uniform Theory of Diffraction (UTD)
- …

An assortment of bespoke algorithms with proprietary techniques focused on specific applications

Grasp
Zemax
FRED
…

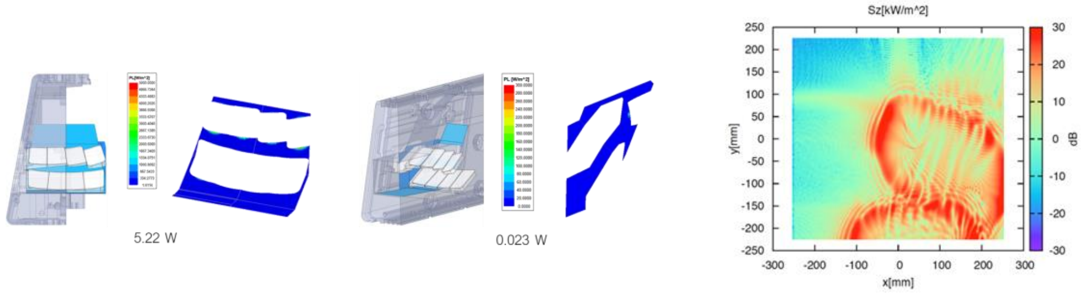
5. SELECTION OF METHOD - SPILLOVER AND STRAY RADIATION

SELECTION: **FRED** Optical Engineering Software (from Photon Engineering), based on **Physical Optics (PO)**

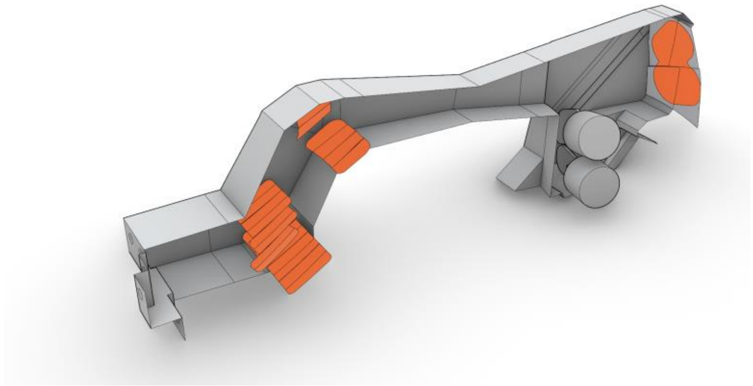
Regarding spillover and stray radiation, the main drivers for the resolution of the problem are:

- Characterization of the source: Pure Gaussian beams generate very low spill over and stray radiation while considering a **“real source”** leads to higher stray radiation → relative low power 2% or less
- Complex cavity: heat distribution and possible hot spot appearance is not obvious due to possible bounces of the waves inside the cavities. **Multi-pass analysis needed.**
- Size of the numerical problem: considering
  - ✓ Whole cavity must be studied to understand the problem. The **electrical size of the problem is many times the wavelength** of the incident wave (1.76 mm)
  - ✓ **Large number of sources** (8x).

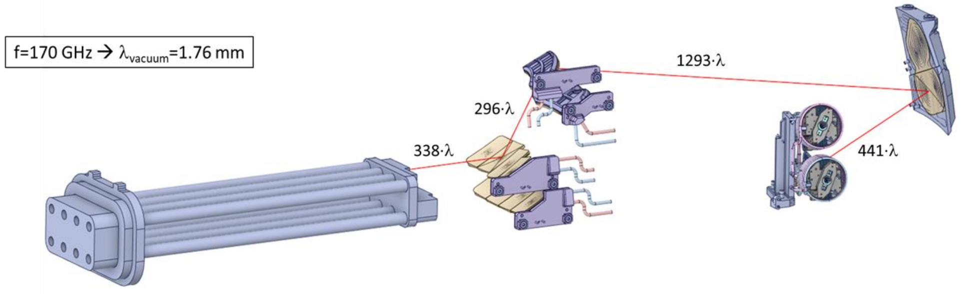
-



Effects of real source



Complexity of the conduit



Electrical size

5. SELECTION OF METHOD - SPILLOVER AND STRAY RADIATION

SELECTION: **FRED** Optical Engineering Software (from Photon Engineering), based on **Physical Optics (PO)**

Based on the points listed in the previous slide, the problem cannot be solve using a full-wave numerical method like (MoM, FEM, FDTD) as least not at such a high frequency. Therefore, alternative methods must be evaluated:

Engineering budget	Full-wave limited frequency	Asymptotic methods
Following the work already done in the past, an assignment of the stray loads can be done. Some details might be missing but it might be considered to be a conservative approach	An alternative solution that could provide representative results is using full wave methods at lower frequencies, that are providing an stray maps that is afterwards factored. This method might require some correlation with simple cases	They are approximated methods that can be used at high frequencies when the electrical size of the problem is large. Several methods are available, they are well suited for the stray power analysis
SPECIFIC TOOL HAS BEEN DEVELOPED TO EVALUATE QUALITATIVELY THE STRAY POWER	For early analysis and back-up solution	Three methods have been evaluated. FINALLY "FRED" HAS BEEN SELECTED

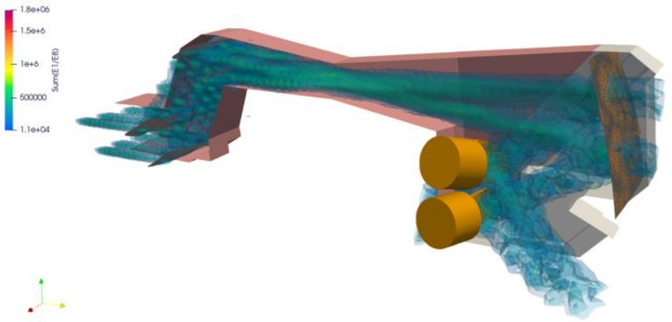
5. SELECTION OF METHOD - SPILLOVER AND STRAY RADIATION

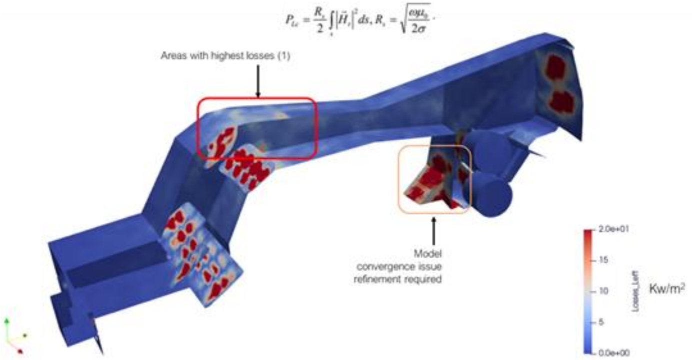
SELECTION: **FRED** Optical Engineering Software (from Photon Engineering), based on **Physical Optics (PO)**

Three of these asymptotic methods have been studied in parallel:

SELECTED OPTION ⇩

SBR + (Shooting and Bouncing Rays), implemented in HFSS

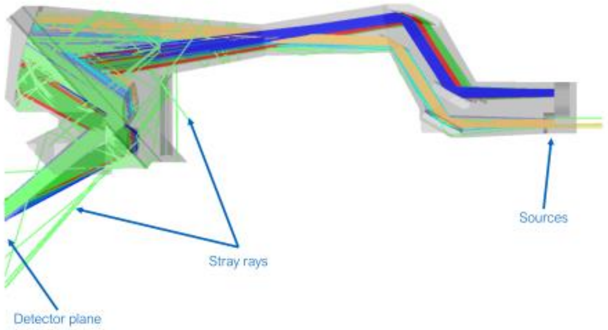


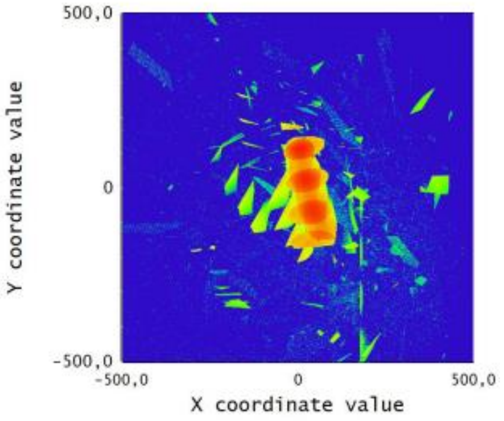


$$P_{Lc} = \frac{R_s}{2}\int_s \left|\vec{H}_t\right|^2 ds, R_s = \sqrt{\frac{\omega\mu_0}{2\sigma}}.$$

Powerful but still unpractical from computational point of view. Well suited to solve the propagation problem but not optimized to evaluated the losses

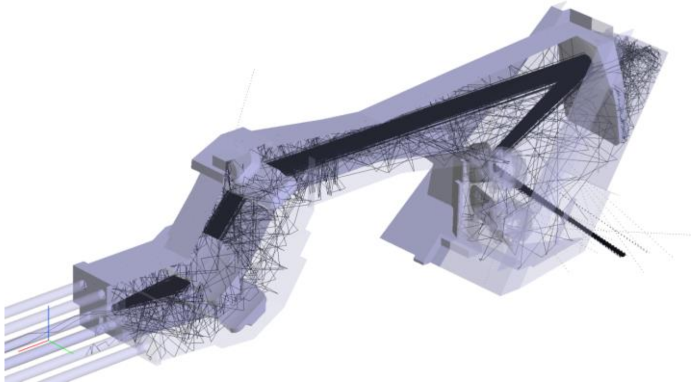
Physical Optics propagation using **ZEMAX**

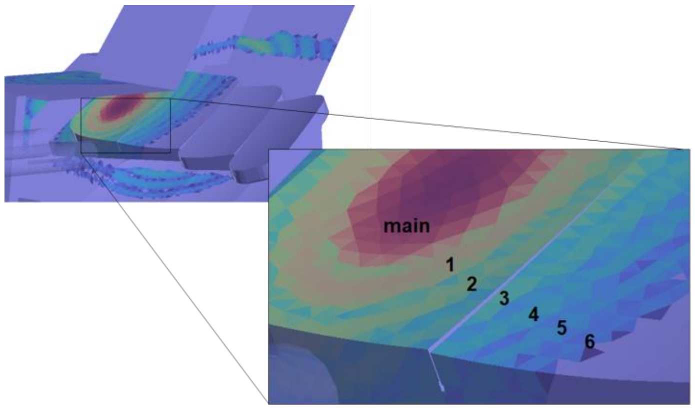




Good capabilties, but less flexible for management of geometry and postprocessing

Physical Optics propagation using **FRED**





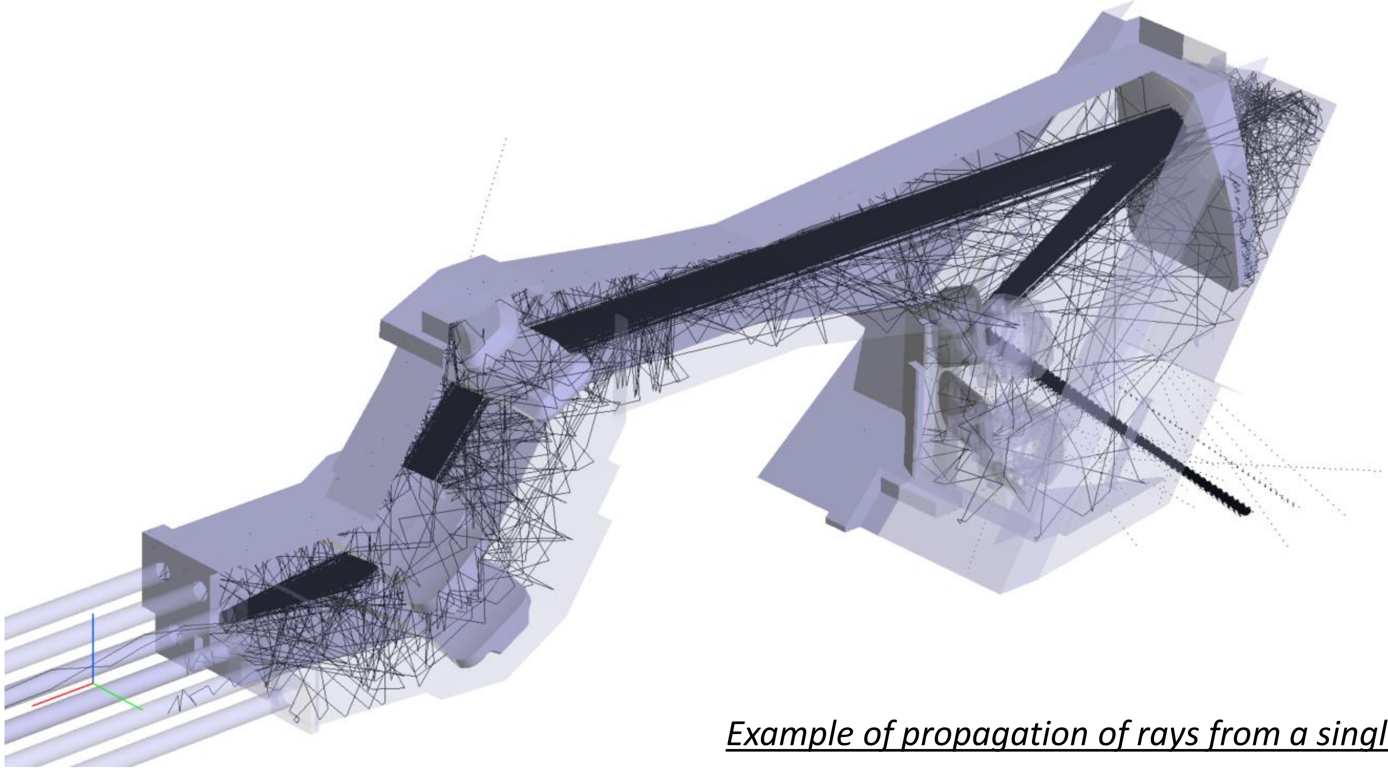
Good capabilties, very flexible on geometry management & post-processing.

5. SELECTION OF METHOD - SPILLOVER AND STRAY RADIATION

SELECTION: **FRED** Optical Engineering Software (from Photon Engineering), based on **Physical Optics (PO)**

From these tools and based on the preliminary checks performed FRED seems to be the most suited for the analysis of the specular reflection of the spillover radiation taking into account:

1. Multiple reflections of each ray.
2. Power absorption based on the wall material.
3. Possibility of using the real HE11 and HE11+LP11 sources.



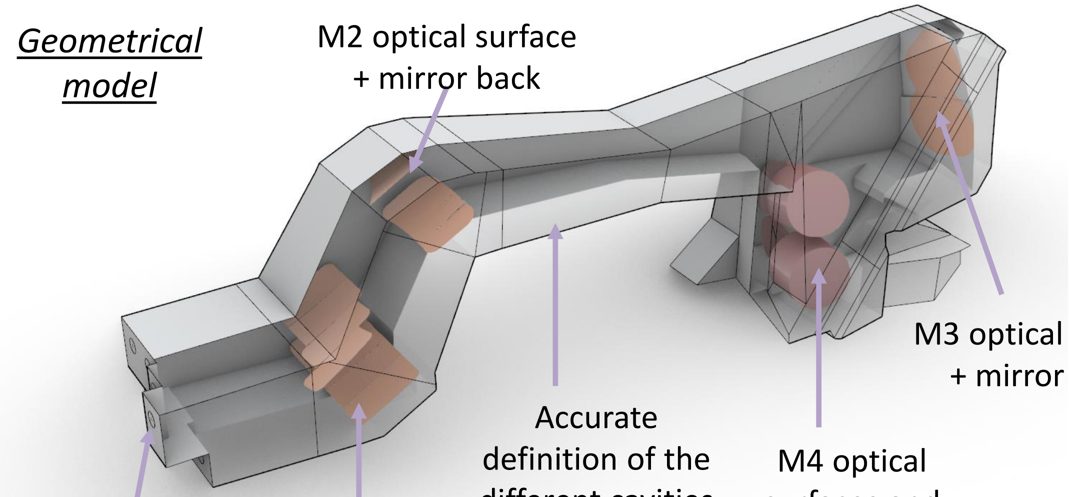
Example of propagation of rays from a single waveguide

5. SELECTION OF METHOD - SPILLOVER AND STRAY RADIATION

SELECTION: **FRED** Optical Engineering Software (from Photon Engineering), based on **Physical Optics (PO)**

Initial example. One “real source” (HE11): 10^9 rays → computational time 1 hour approx.

Geometrical model



M2 optical surface + mirror back

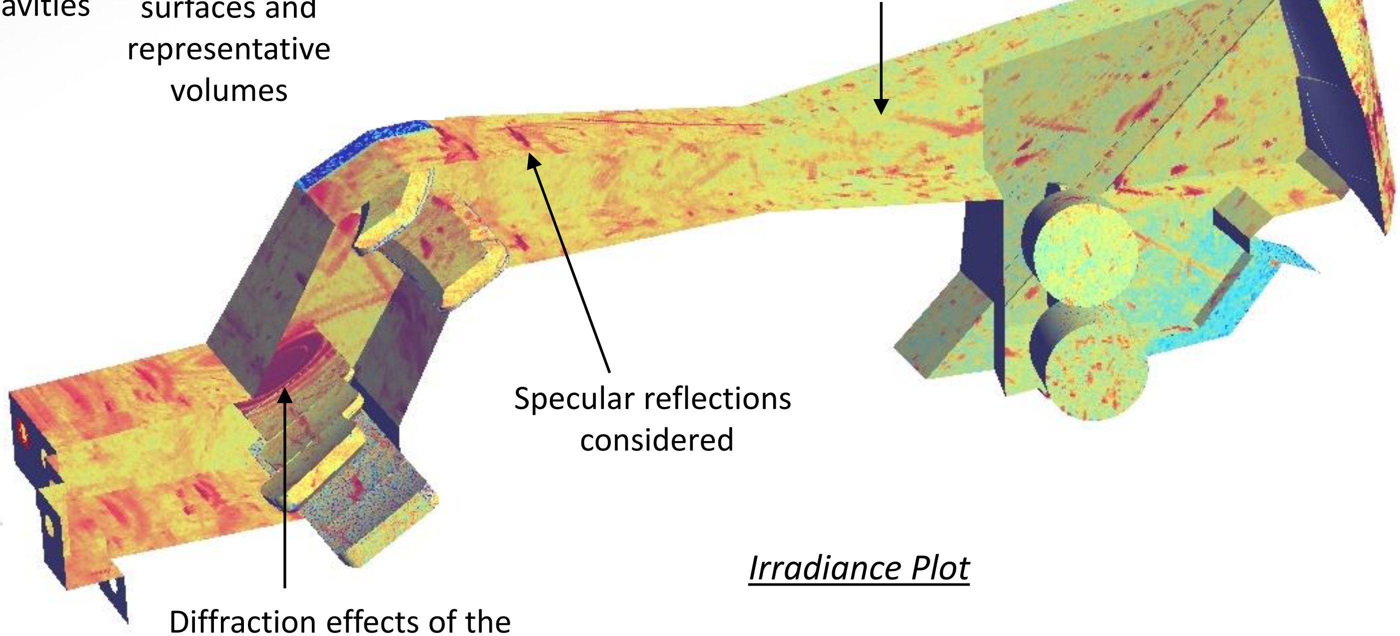
M3 optical surface + mirror back

Accurate definition of the different cavities

M4 optical surfaces and representative volumes

Accurate position of the source outlets

M1 optical surface + mirror back



Multipass. Diffuse propagation considered

Specular reflections considered

Diffraction effects of the source are considered

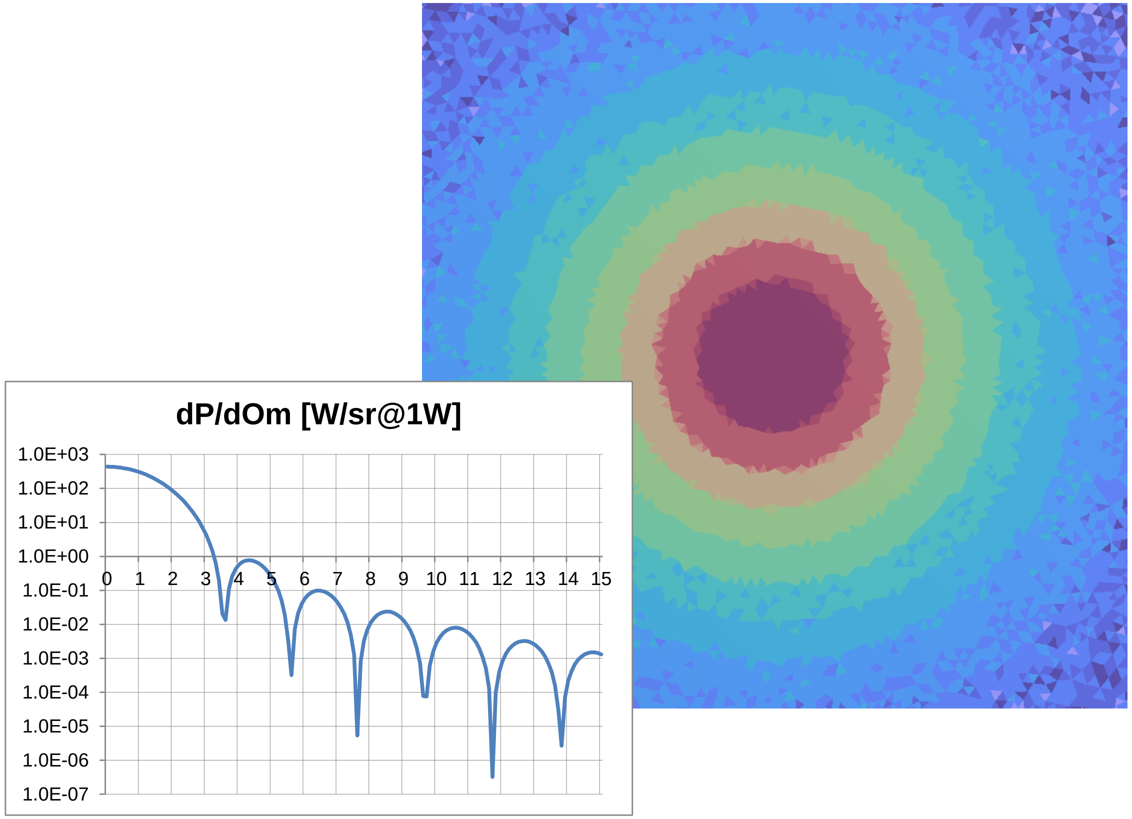
Irradiance Plot

5. SELECTION OF METHOD - SPILLOVER AND STRAY RADIATION

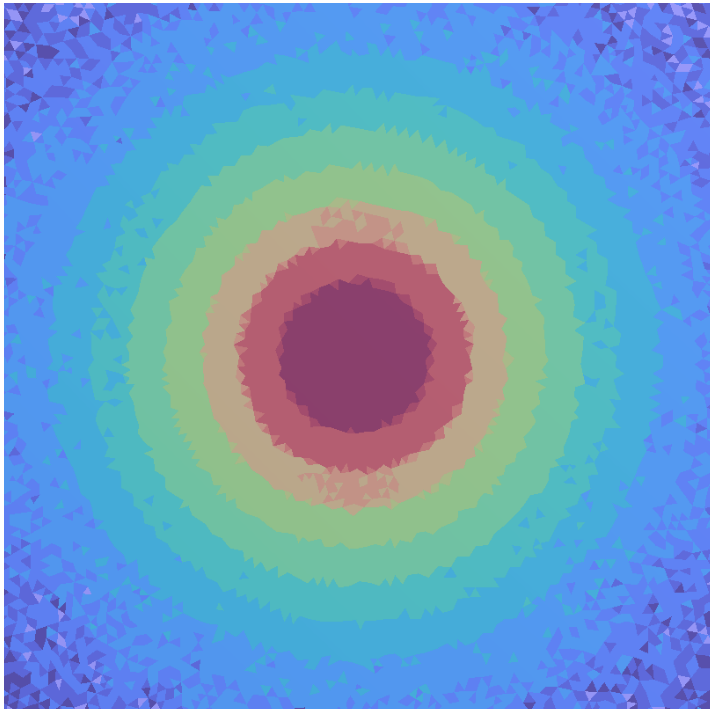
SELECTION: **FRED** Optical Engineering Software (from Photon Engineering), based on **Physical Optics (PO)**

- FRED allows to use default sources such as laser beam, point source, etc. and also custom sources.
- HE11 source data can be converted to a specific input format and imported into FRED.
- Following this methodology it is also possible to introduce the HE11+LP11 specific sources.
- The polar angle has been trimmed to 15 degrees to reduce the number of rays traced.

HE11:



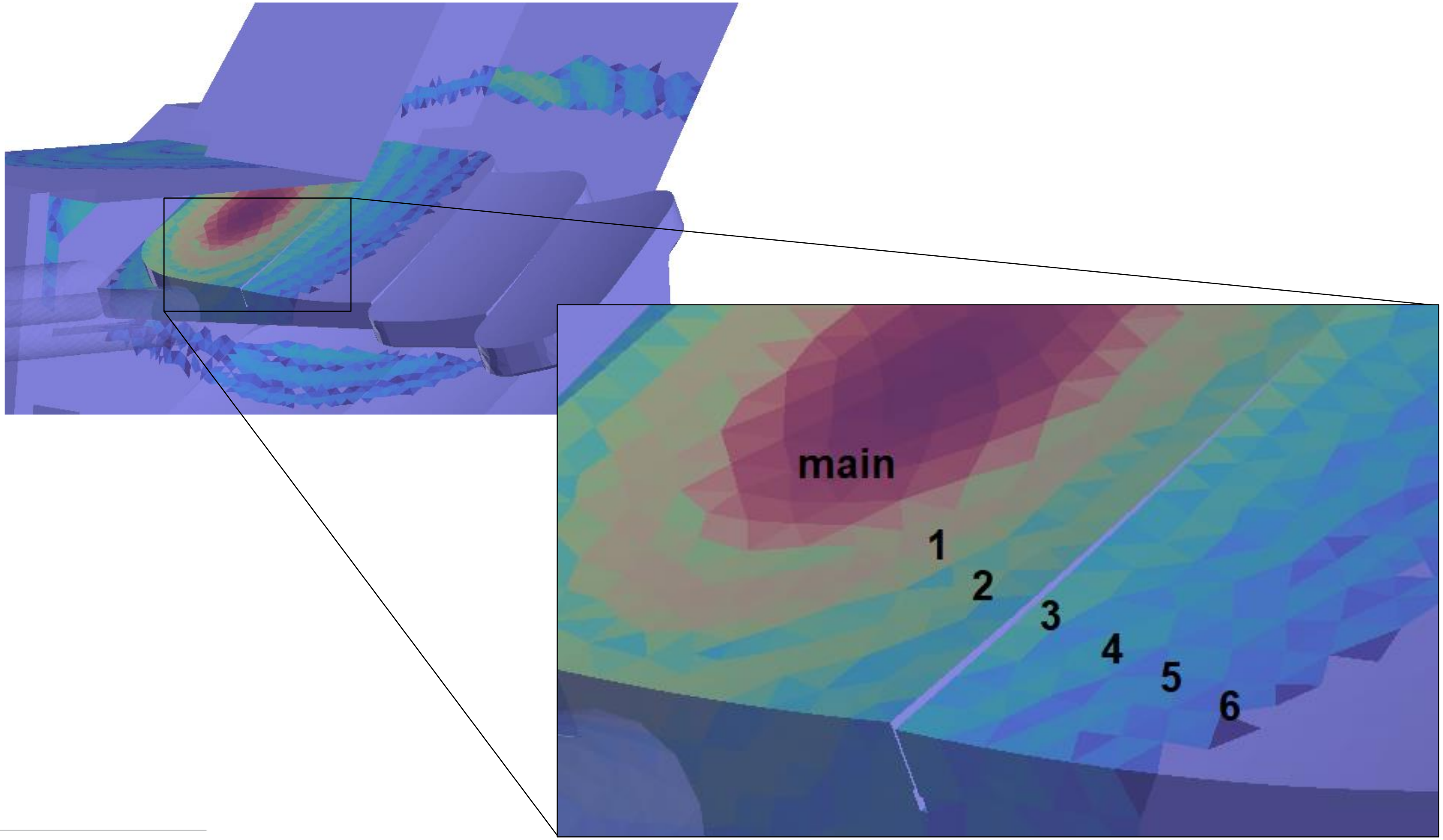
HE11+LP11:



5. SELECTION OF METHOD - SPILLOVER AND STRAY RADIATION

SELECTION: **FRED** Optical Engineering Software (from Photon Engineering), based on **Physical Optics (PO)**

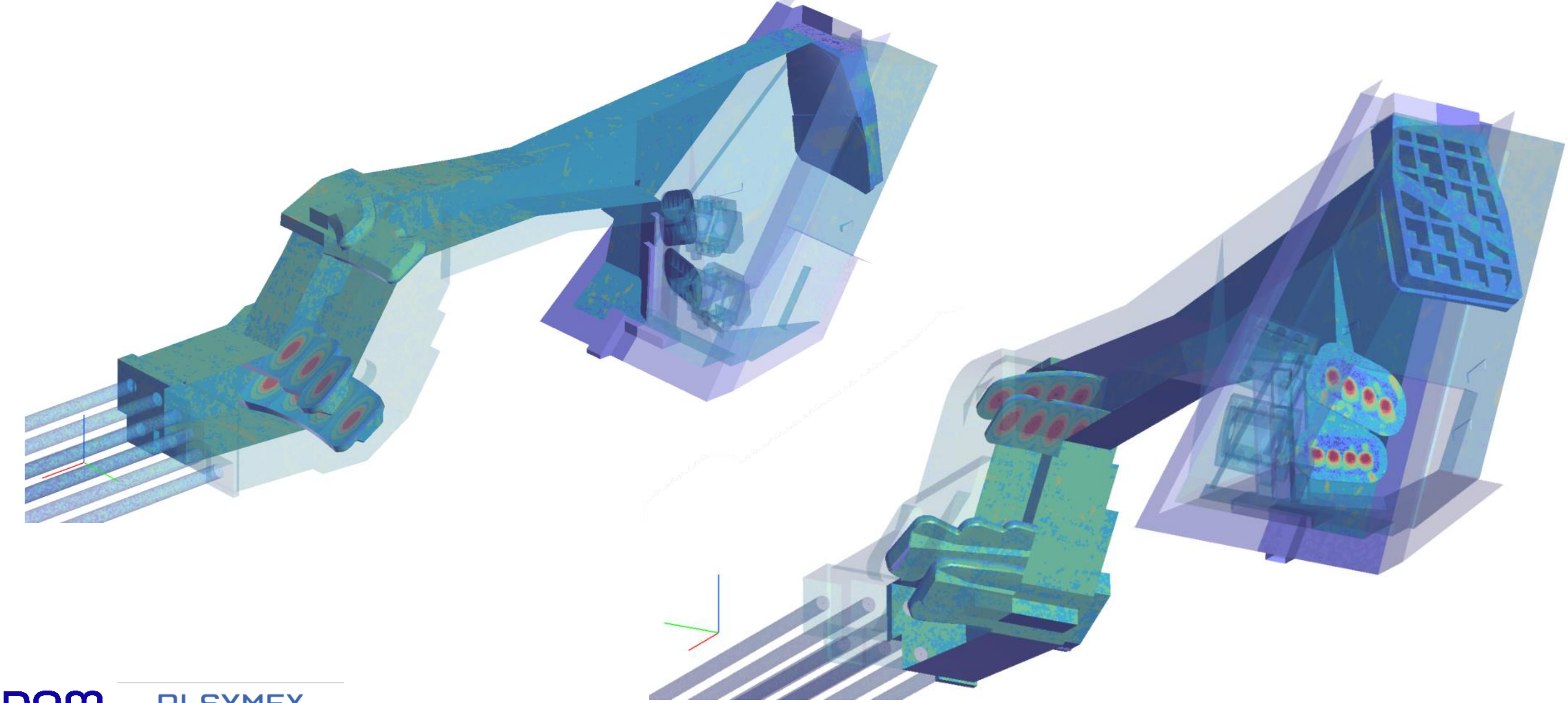
- The analysis accounts for the reflection of all the inner surfaces and their corresponding material properties (surface resistance).
- The stray radiation in the UL is driven by the radiation pattern sidelobes in the waveguide open end, and this is accounted for in the input source. Once the rays are launched they are considered as uncoherent light (which is considered appropriate in case of stray light).



5. SELECTION OF METHOD - SPILLOVER AND STRAY RADIATION

SELECTION: **FRED** Optical Engineering Software (from Photon Engineering), based on **Physical Optics (PO)**

- In order to calculate the power density in the all the UL components walls, the CAD model is meshed and imported in FRED as a faceted body (similar to an STL file). The components can be imported in multiple files to easily account for different materials and to allow for an agile modification of a specific subcomponent if needed.
- Once the analysis is completed, the results can be exported in a .csv file which can then be mapped to the ANSYS Thermal analysis model.
- The preliminary results obtained so far are consistent with the expected beam propagation, although further model verification is on-going.



6. HIGH ORDER MODES (HOM)

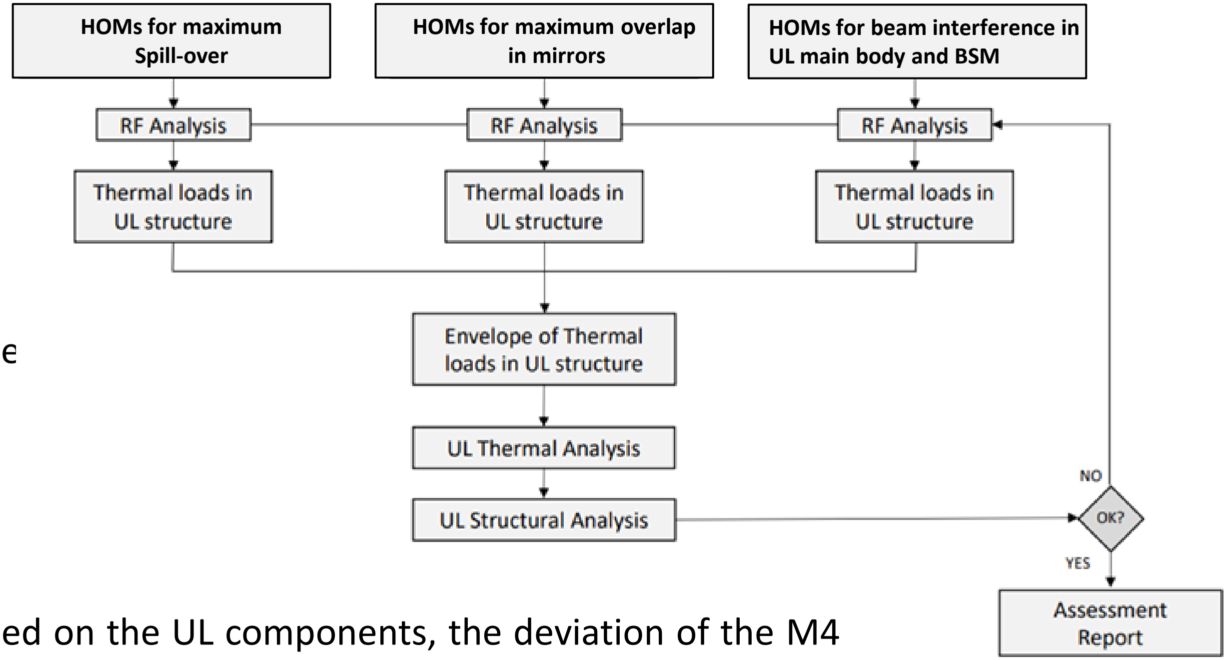
- The **High Order Modes (HOM)** are modes in the RF transmission lines with larger propagation constant than the intended operation mode: in this context LP11 as opposed to HE11 (LP01).

- The fundamental problem when dealing with HOMs is that, even though the beam shape is already specified, the direction of the offset and the angle are not known and it can be different for each waveguide. This can become in an stochastic problem so…

It is essential to find a simple and robust way to characterize the HOMs

- In this sense, the HOM configurations to be considered should be limited to a reduced number of enveloping cases.

- The enveloping HOM configurations to be considered should be the ones that maximize:
  - ✓ Spillover
  - ✓ Beams Overlap in mirrors
  - ✓ Interaction of Beams with UL Main Body and surroundings of Blanket Shield Module (First Wall) aperture



HOMs for maximum Spill-over

HOMs for maximum overlap in mirrors

HOMs for beam interference in UL main body and BSM

RF Analysis

Thermal loads in UL structure

Envelope of Thermal loads in UL structure

UL Thermal Analysis

UL Structural Analysis

OK?

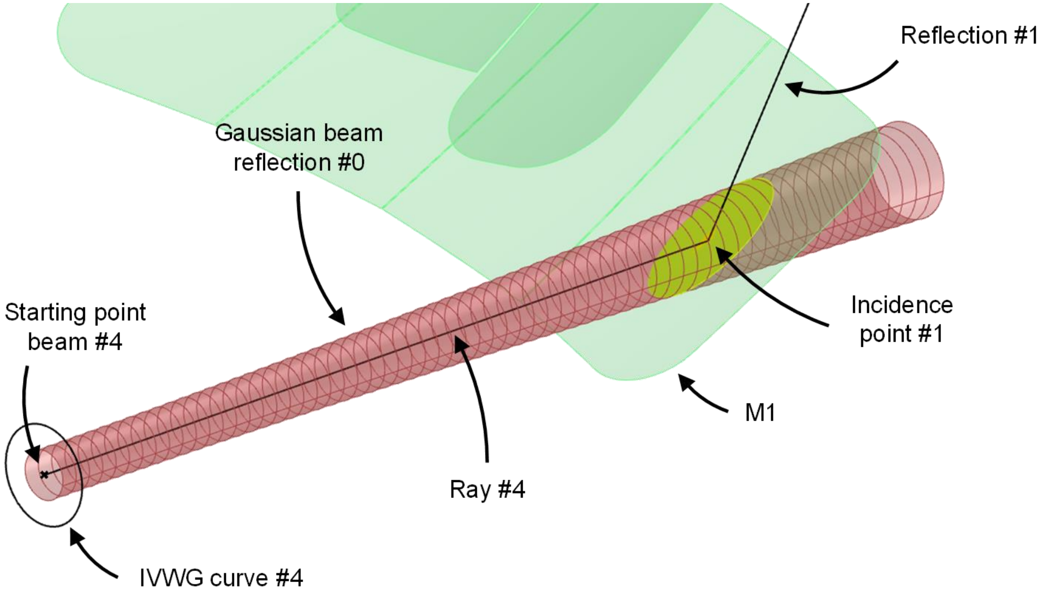
NO

YES

Assessment Report

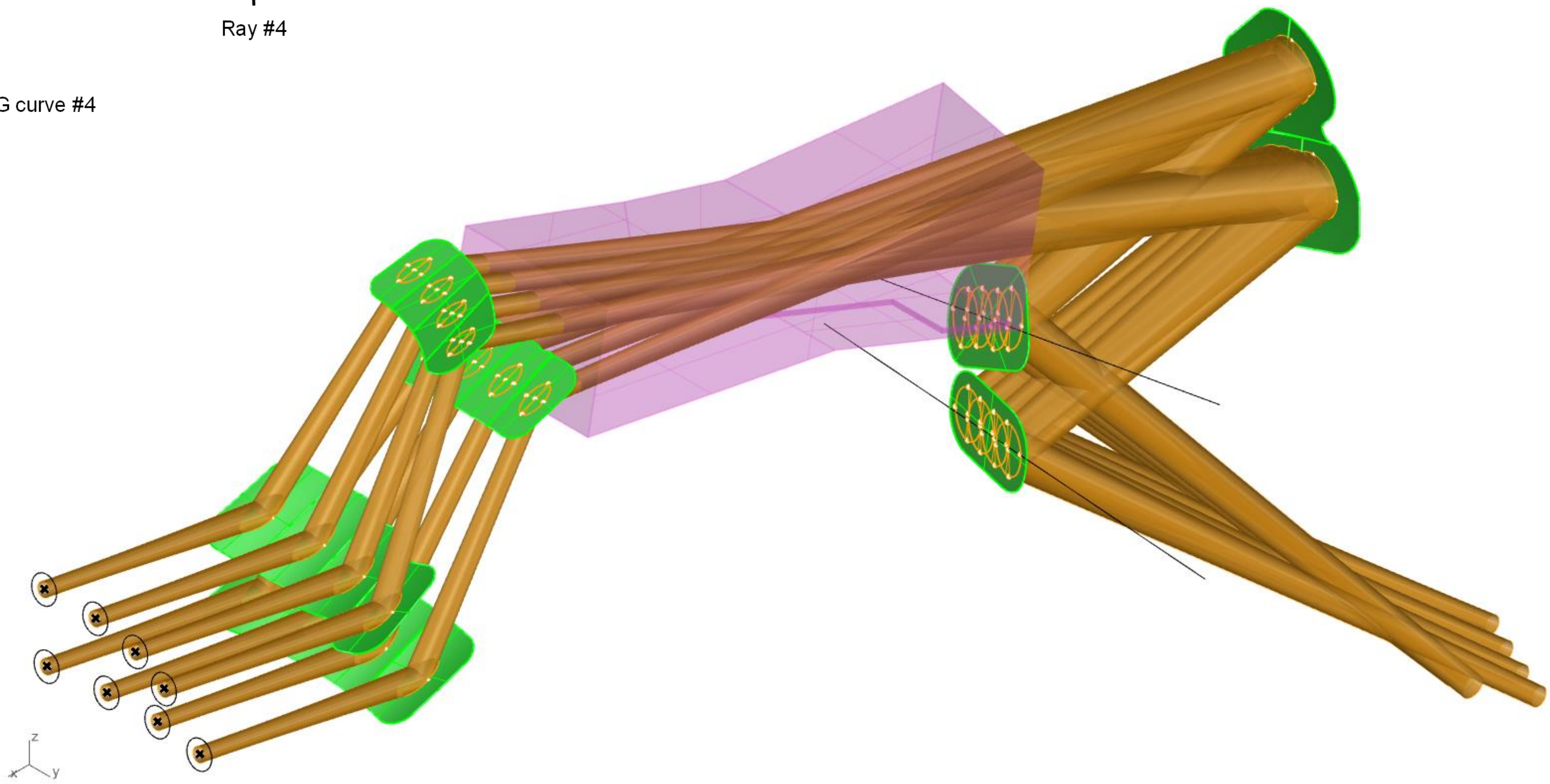
- Apart from increasing the thermal loads produced on the UL components, the deviation of the M4 output beams by effect of the HOMs will also affect to the plasma performance, so a set of HOM configurations (12+12 cases) will be also analysed by ray tracing methods in order to obtain the incidence points and k-vectors at M4 for the plasma performance analyses

6. HIGH ORDER MODES (HOM)



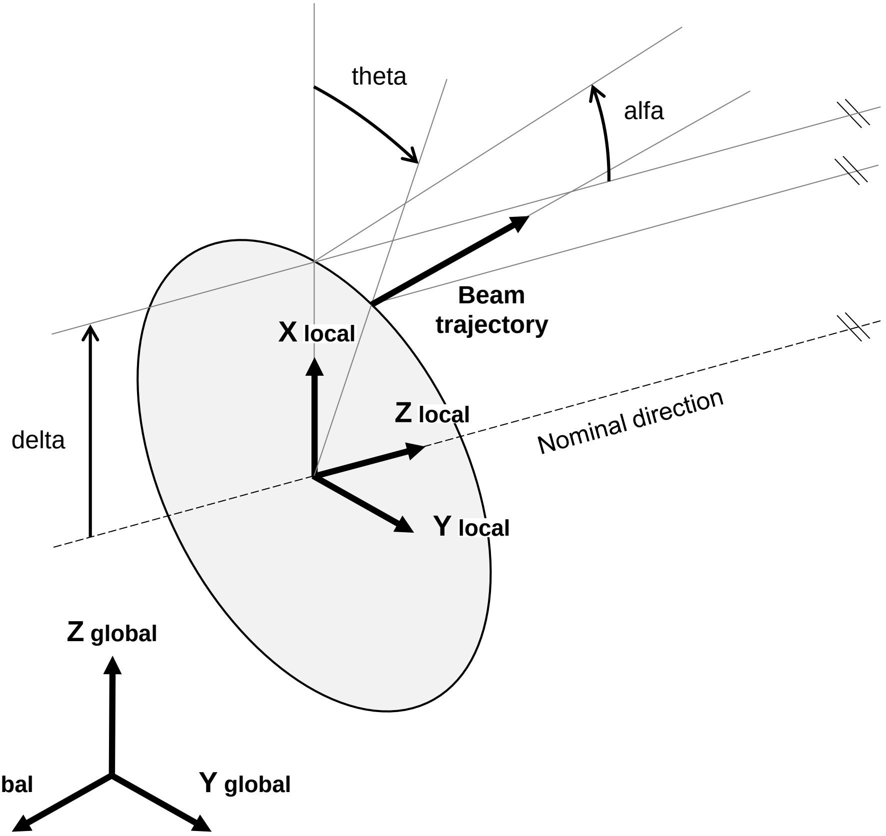
A **parametric model** has been developed in *Rhino/Grasshopper* to assess qualitatively the worst-case HOM configurations. The results of this analyses will be further analyzed in other software tools (e.g. *FRED*).

The main advantage of *Rhino* is that the calculations are very fast, so thousands of HOM configurations can be tested in a short amount of time. All the analyses are based on geometries and automated in *Grasshopper*.

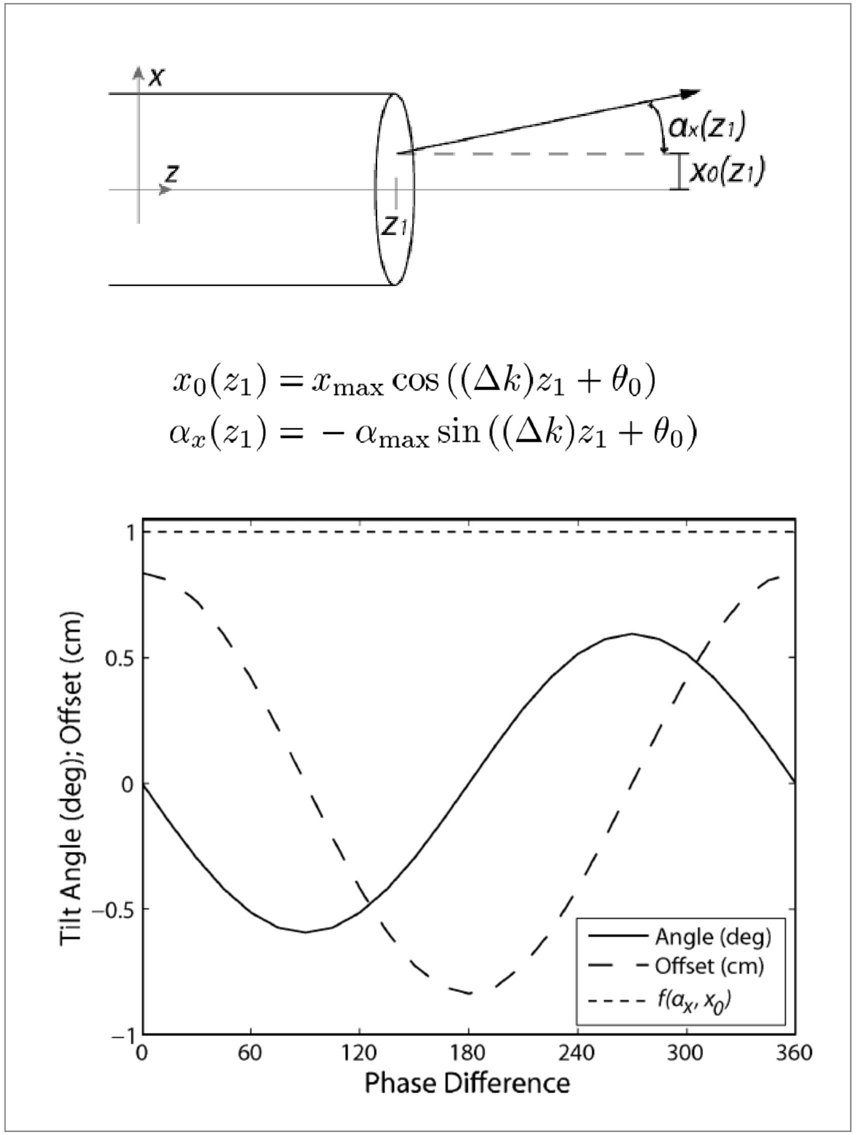


6. HIGH ORDER MODES (HOM)

- The beam deviations due to HOMs can be characterized by:
  - ✓ Real HE+LP mode (multiple combinations)
  - ✓ Combination of three parameters: delta, alpha and theta
- The program allows to set multiple values to these parameters, and all the possible combinations are analysed.
- The alpha and delta variation are 90deg out of phase, thus when one is maximum the other is cero.



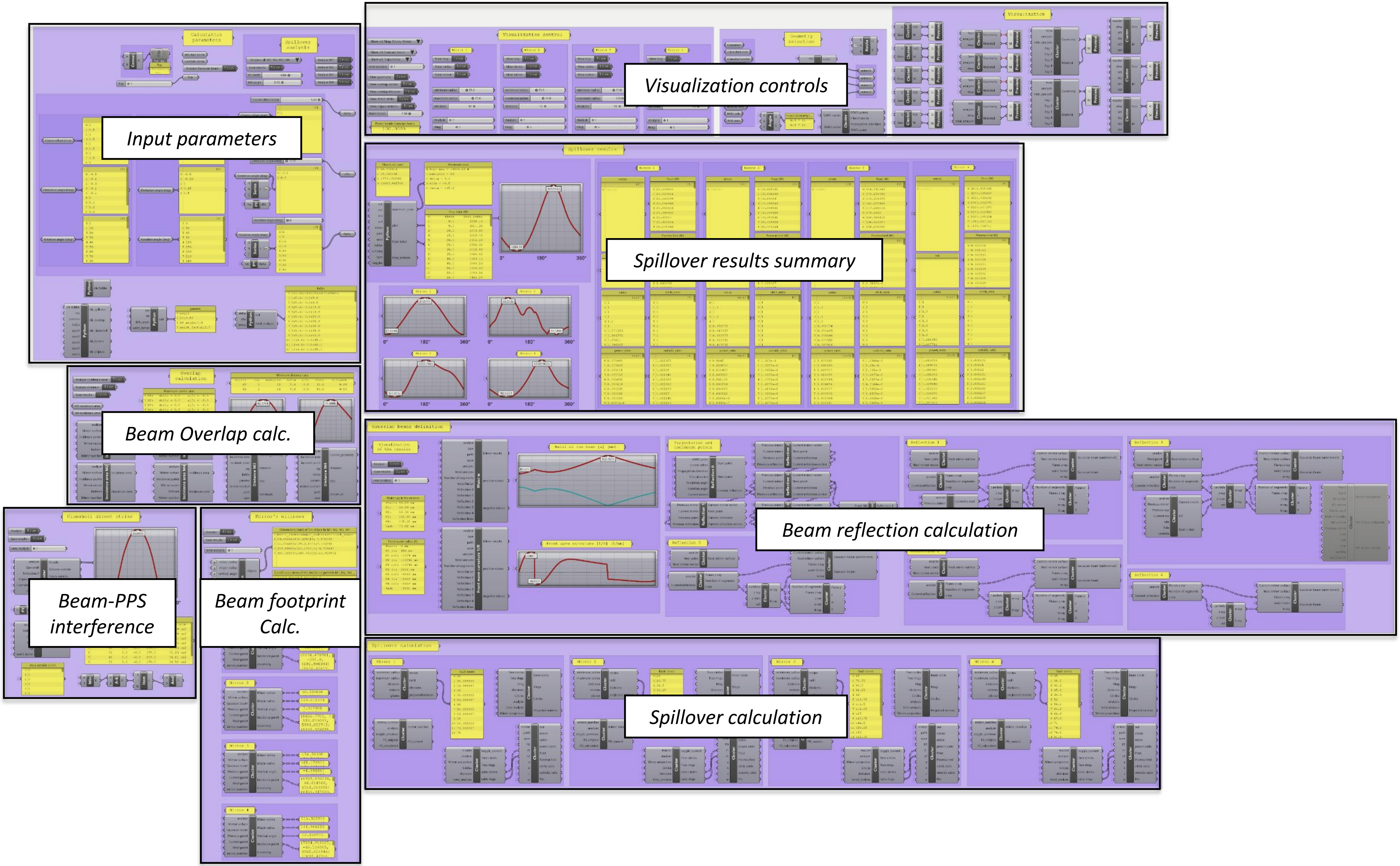
Linearly Polarized Modes of a Corrugated Metallic Waveguide (Kowalski, E.J., et al)



$$x_0(z_1) = x_{\max}\cos\left((\Delta k)z_1 + \theta_0\right)$$
$$\alpha_x(z_1) = -\,\alpha_{\max}\sin\left((\Delta k)z_1 + \theta_0\right)$$

6. HIGH ORDER MODES (HOM)

Overview of *Grasshopper* Model Controls



Visualization controls

Input parameters

Spillover results summary

Beam Overlap calc.

Beam reflection calculation

Beam-PPS interference

Beam footprint Calc.

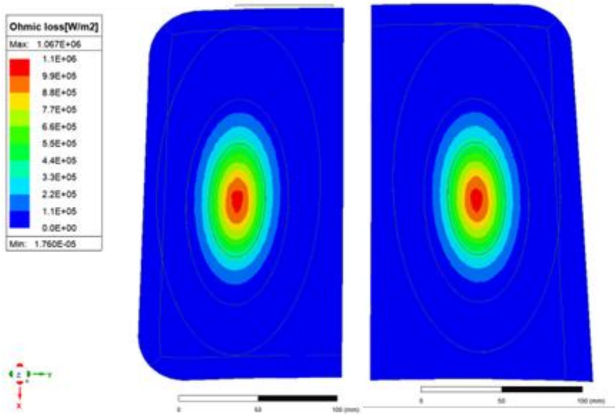
Spillover calculation

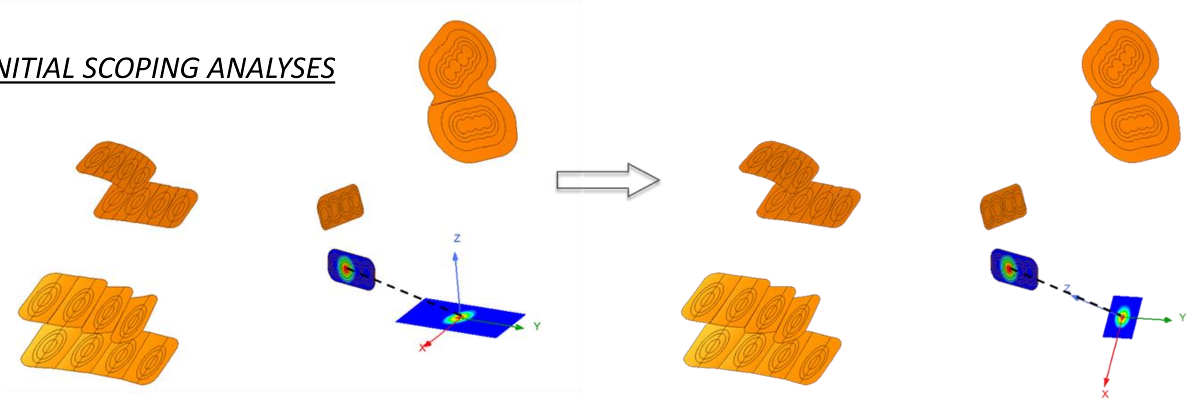
7. NEXT STEPS

- With the RF EM methodology already defined, the next step is to put it into practice to perform the Final Design RF Analyses and obtain the required inputs for plasma performance verification (beam parameters at the M4 output) and the generated thermal loads to be considered for the structural integrity assessment.
- The Final Design analyses are just about to be launched, but some initial scoping analyses (including a complete analysis loop with mirrors nominal and deformed shape) have been already performed in order to confirm the adequacy of the proposed methodology and verify that there are no show stoppers to continue with the detailed definition of the Upper Launcher Redressed Design.

__SOME OUTPUTS FROM INITIAL SCOPING ANALYSES__

__M1U Ohmic loss (undeformed shape)__

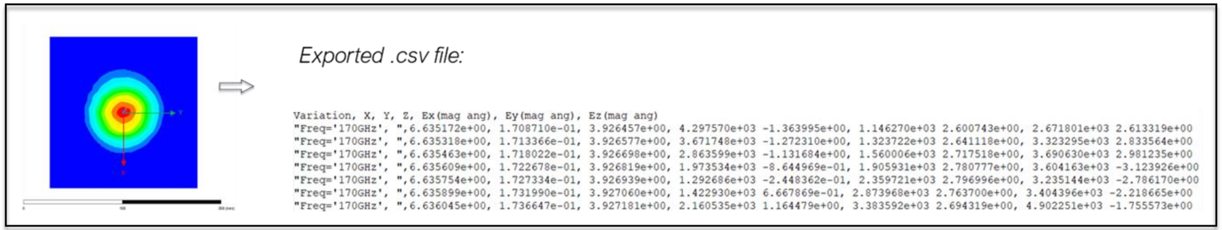




Plane:
P = (6650, 100, 3900) mm
n̂ = global coordinates

__M4 output k-vectors__

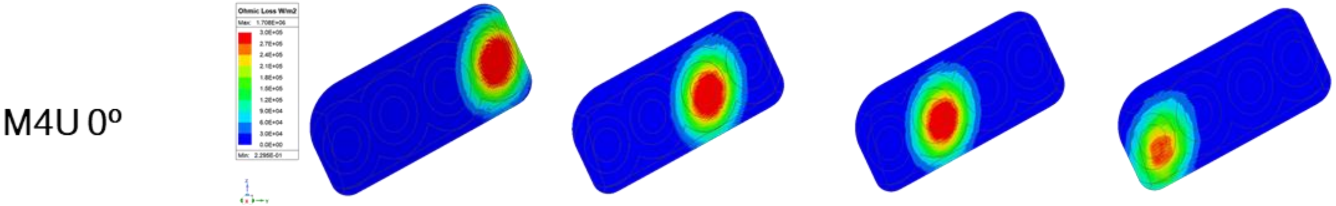
Plane:
P = beam centre at Z=3900 mm
n̂ = propagation vector ($\hat{k}$)



Exported .csv file:

```
Variation, X, Y, Z, Ex(mag ang), Ey(mag ang), Ez(mag ang)
"Freq='170GHz', ",6.635172e+00, 1.708710e-01, 3.926457e+00, 4.297570e+03 -1.363995e+00, 1.146270e+03 2.600743e+00, 2.671801e+03 2.613319e+00
"Freq='170GHz', ",6.635318e+00, 1.713366e-01, 3.926577e+00, 3.671748e+03 -1.272310e+00, 1.323722e+03 2.641118e+00, 3.323295e+03 2.833564e+00
"Freq='170GHz', ",6.635463e+00, 1.718022e-01, 3.926698e+00, 2.863599e+03 -1.131684e+00, 1.560006e+03 2.717518e+00, 3.690630e+03 2.981235e+00
"Freq='170GHz', ",6.635609e+00, 1.722678e-01, 3.926819e+00, 1.973534e+03 -8.644969e-01, 1.905931e+03 2.780777e+00, 3.604163e+03 -3.123926e+00
"Freq='170GHz', ",6.635754e+00, 1.727334e-01, 3.926939e+00, 1.292686e+03 -2.448362e-01, 2.359721e+03 2.796996e+00, 3.235144e+03 -2.786170e+00
"Freq='170GHz', ",6.635899e+00, 1.731990e-01, 3.927060e+00, 1.422930e+03 6.667869e-01, 2.873968e+03 2.763700e+00, 3.404396e+03 -2.218665e+00
"Freq='170GHz', ",6.636045e+00, 1.736647e-01, 3.927181e+00, 2.160535e+03 1.164479e+00, 3.383592e+03 2.694319e+00, 4.902251e+03 -1.755573e+00
```

__M3U Ohmic loss (deformed shape)__



THANKS FOR YOUR ATTENTION

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