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SINCLAIR

Surrogate models and sensitivity analysis for simulation of electron guns of high-frequency & high-power amplification devices

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OpenTurns Users' Day #15
10/06/2022

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Contents

1) Context

- Electron amplifier tubes : what are they ?
- Tubes simulations, with a focus on electron gun simulations

2) Sensitivity & Uncertainty studies applied on electron gun simulations

A. Screening with Morris Method
B. Building surrogate models (kriging & polynomial chaos)
C. Global sensitivity analysis with Sobol indices

Works done in collaboration with Phimeca, using Persalys & OpenTurns

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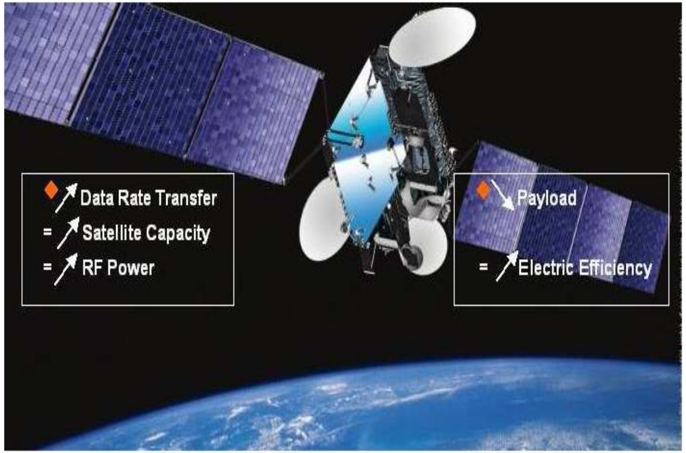
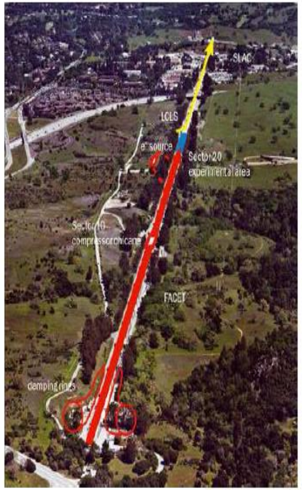
High-Frequency Tubes : High-Power amplifier

Linear beam waves tubes (High-Frequency Waves Amplifier)

- Space Applications (Satellites) and Scientific (Particles Accelerator)

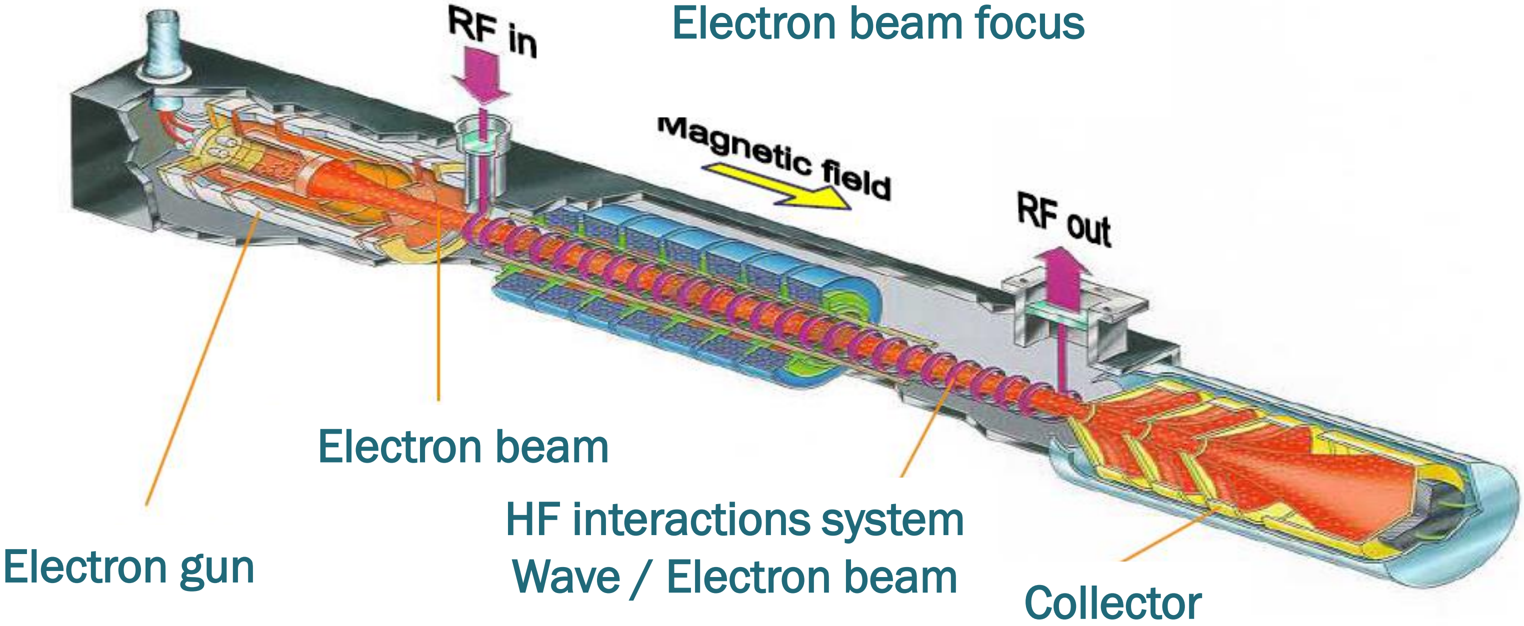


Helix Travelling Wave Tubes, embedded in satellites



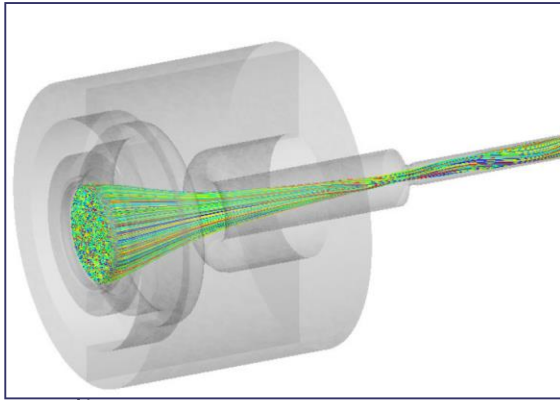
Klystrons embedded in CERN accelerators

High-Frequency Tubes : schematic diagram



Use Case : Electron Gun Simulations (1)

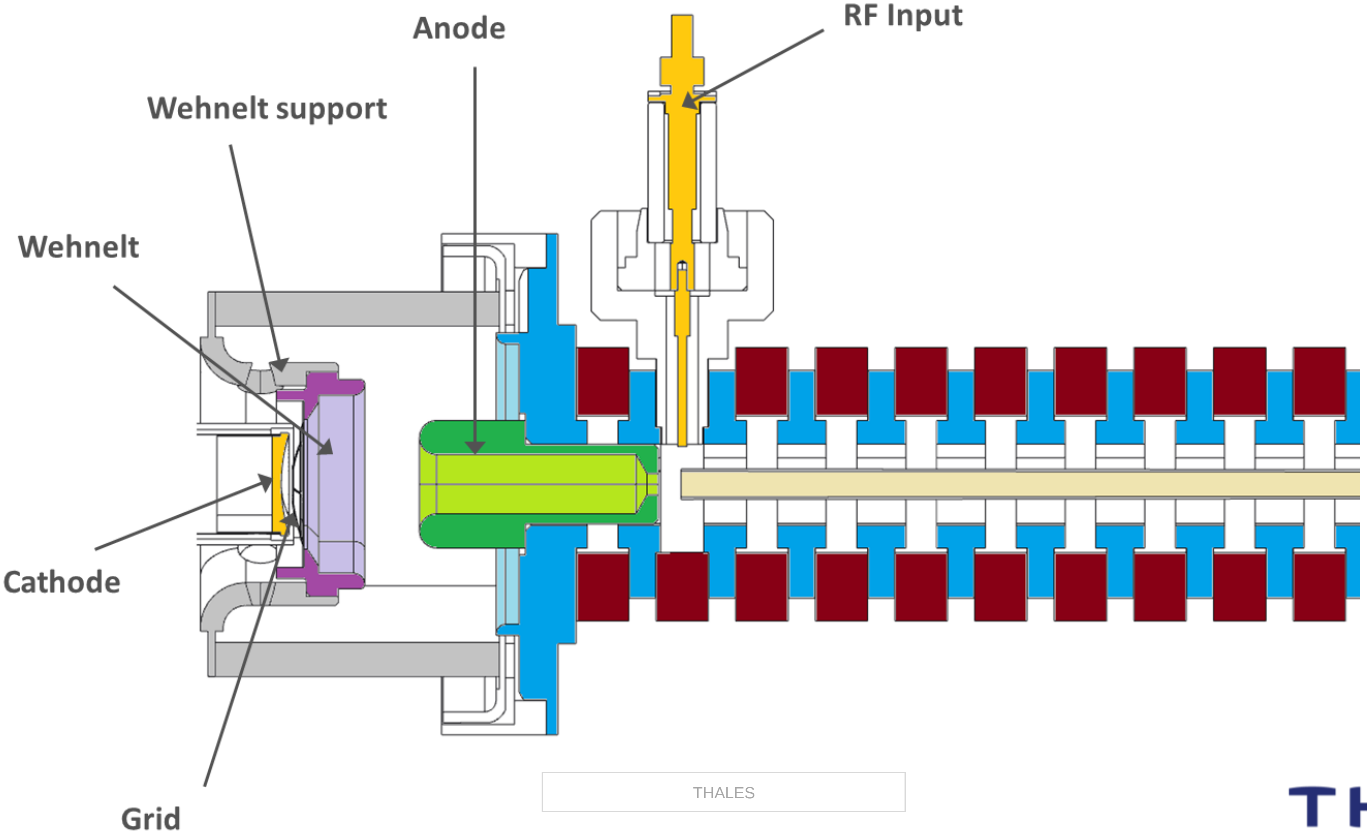
Modelling electronic optics for electron gun



- **Voltage gaps between cathode and anodes**
  - Electric field force acting on beam electrons
  - Electric field modified by electrons' charge
- **Electrons' emission from cathode**
  - Computing total emitted current by cathode value
- **Particles' beam motion to interaction line**
  - Computation of electromagnetic field which acts on particles motion
  - Electrons propagation between cathode and anodes, and then beyond
- **Solve a coupled system**
  - **Poisson's equation (which gives electric field locally modified by electrons) → Finite elements method**
  - **Vlasov's equation (which governs particles motion with Lorentz's force) → Method PIC**

Use Case : Electron Gun Simulations (2)

Schematic view of electron gun (study case)



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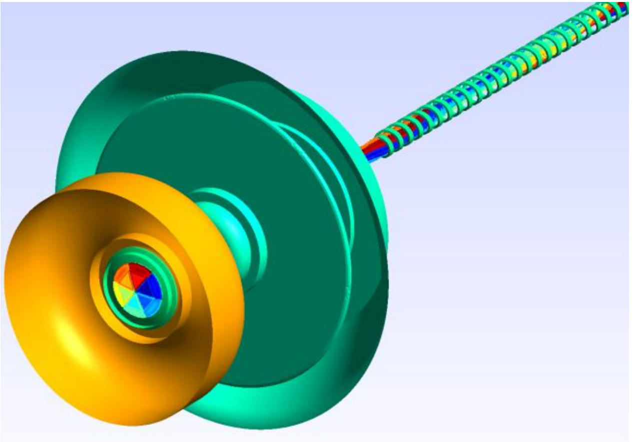
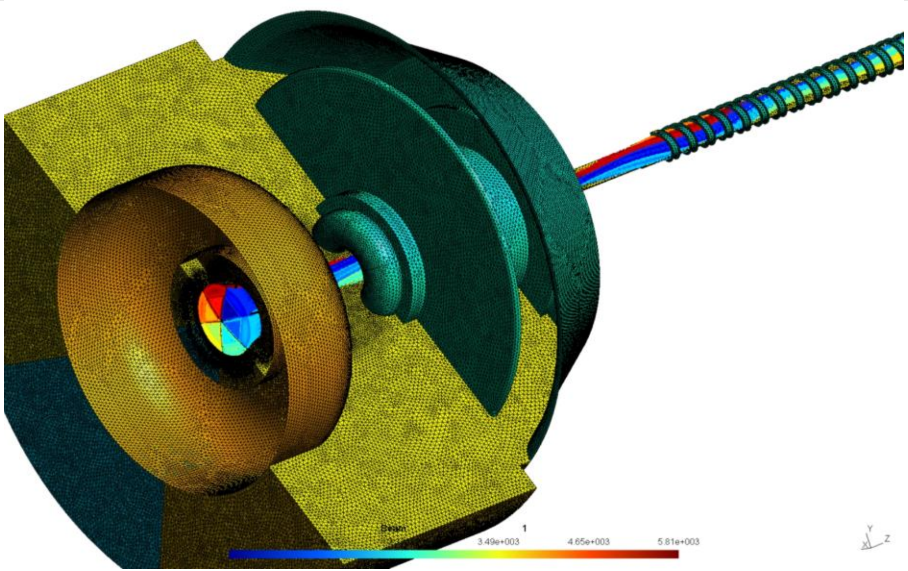
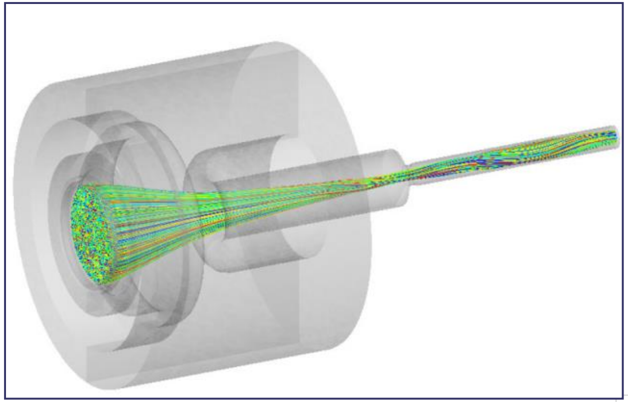
Use Case : Electron Gun Simulations (3)







ANSYS ENVIRONMENT
- GEOMETRY MODELING
- MESHING
- PARAMETERS SETTINGS
- ACT

Use Case : Electron Gun Simulations (4)

Quantities of interest :

- Total current emitted by cathode
- Electron beam shape :
  - External radius of electron beam, as a function of longitudinal abscissa
  - Radius minimum which characterizes beam waist
- Body currents intercepted on metallic pieces (to minimize in order to maximize performances)

Many random input parameters

- Geometry characteristics (manufacturing tolerances & bias)
- Issues about concentricity/alignment of assembly components
- Voltages values applied on cathode, anodes
- Magnets characteristics

Purposes : confirm technicians' observations / focus efforts on compliance with tolerances of specific parts

Novelty : Ansys Coupling Model

Persalys

Ansys WorkBench project related with a parametric model

Ability of batch runs of this Ansys project with a specific command file (similar to python script)

In this way, Persalys can :

- Load Ansys WorkBench project and recognize automatically all inputs/outputs parameters chosen by user in this project
- Execute Ansys coupling model
  - Generate an Ansys command file
  - Ansys batch run
  - Recover Ansys computation results
- This allows within Persalys to achieve on-shot computation or full DOE computations

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PHIMECA
L'ingénierie responsable

Persalys

A- Screening with Morris method (1)

First model was including 44 uncertain input parameters

- 42 geometry characteristics + 2 electric parameters
- Modelled with distribution laws : uniform, normal or lognormal

Purpose : reduce uncertain input parameters' number in order to build easier surrogate models

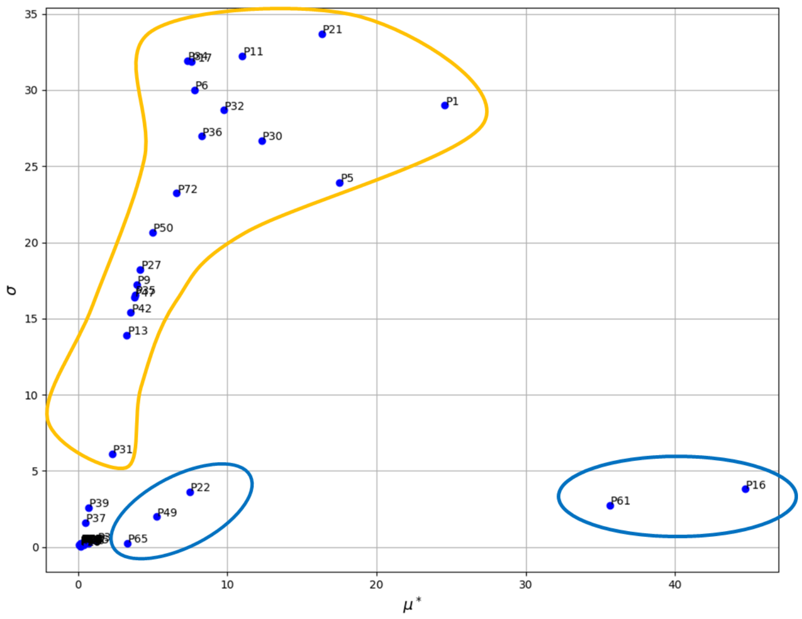
Execution of a Morris' Design of experiments of 900 simulations/points (computation duration : 6 min)

A- Screening with Morris method (2) : Results

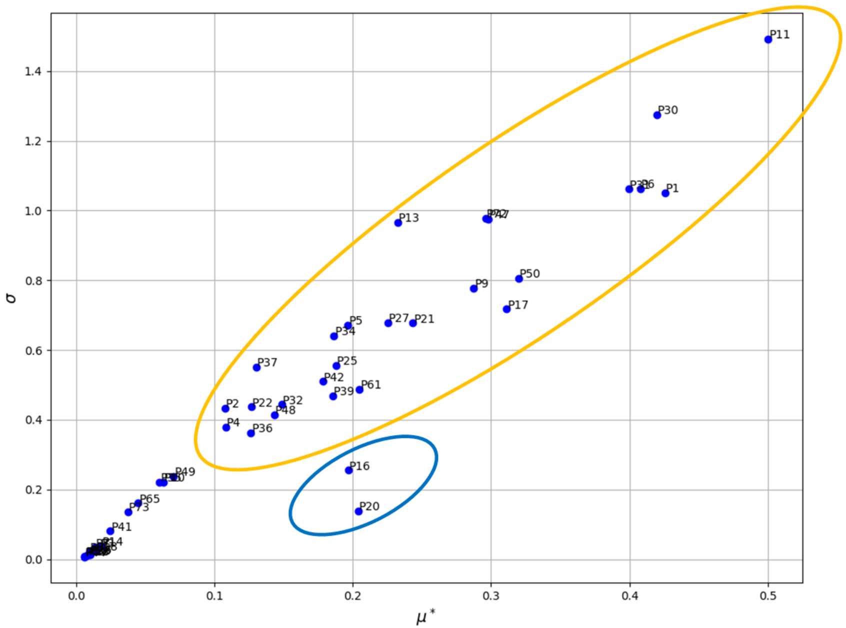
Sort of most influential inputs, common with all studied results

- Reducing to 20 inputs (19 geometry characteristics + 1 electric parameter)

Morris - Elementary effects for P54 - Beam characteristics CurrentAll [mA]



Morris - Elementary effects for P55 - Beam characteristics BeamWaist R95 [mm]



B- Building surrogate models (1)

Second model with 20 input parameters

Execution of several design of experiments (DOE)

- Different algorithms used, including 200, 400 and 1000 computations/points

Graphical analysis of results got with these DOE (histograms, boxplots)

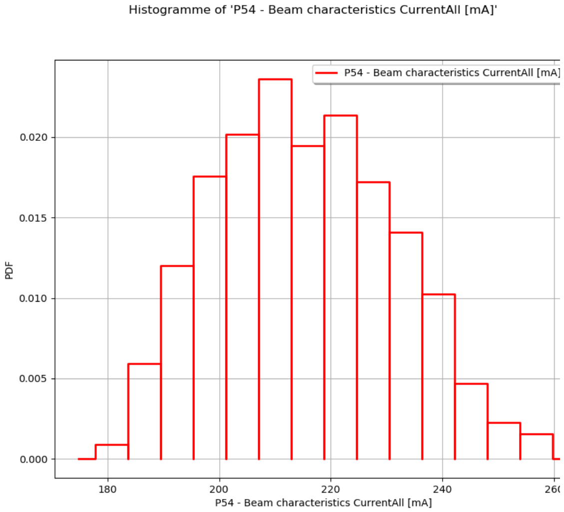
Surrogate models building (kriging and polynomial chaos expansion)

- For result : total current emitted by cathode Ik
- For result : min of electron beam radius R95
- For result : body intercepted current on grid Ihg

B- Building surrogate models (2)

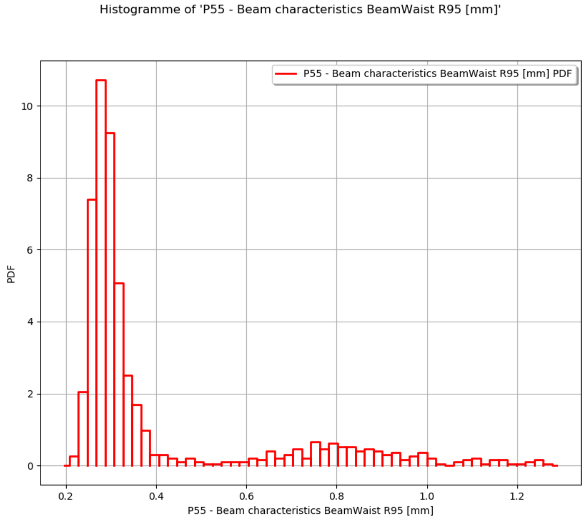
Graphical analysis of these DOA results (histograms)

DOE of 1000 points – LHS with simulated annealing algorithm, criterion C2



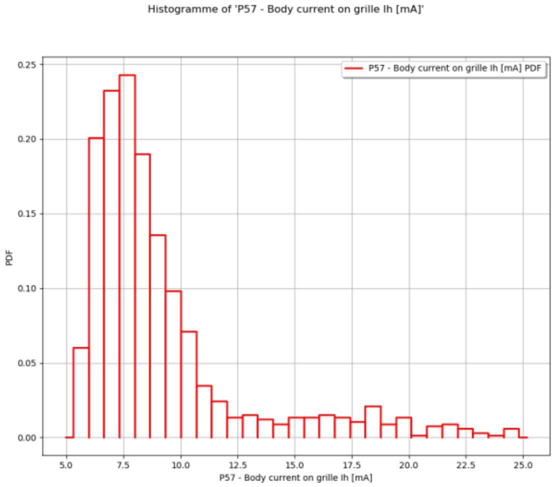
For total current emitted by cathode Ik

CV ≈ 7.5%



For min of electron beam radius R95

CV ≈ 57.8%



For body intercepted current on grid Ihg

CV ≈ 39.4%

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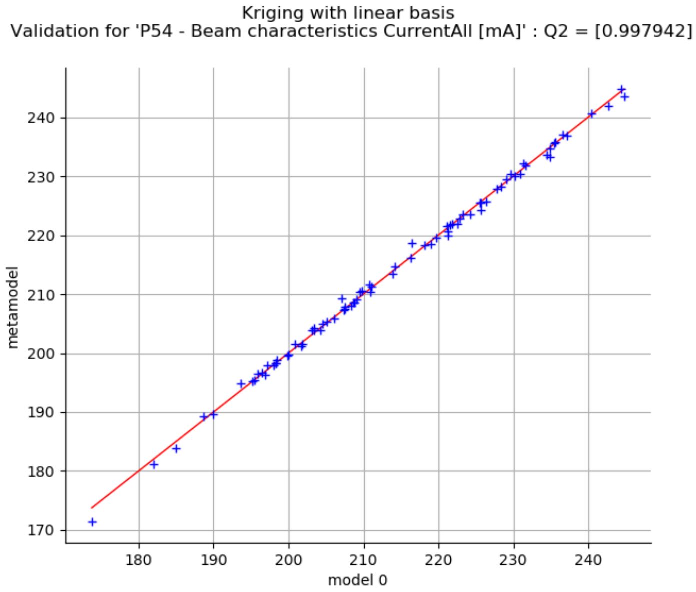
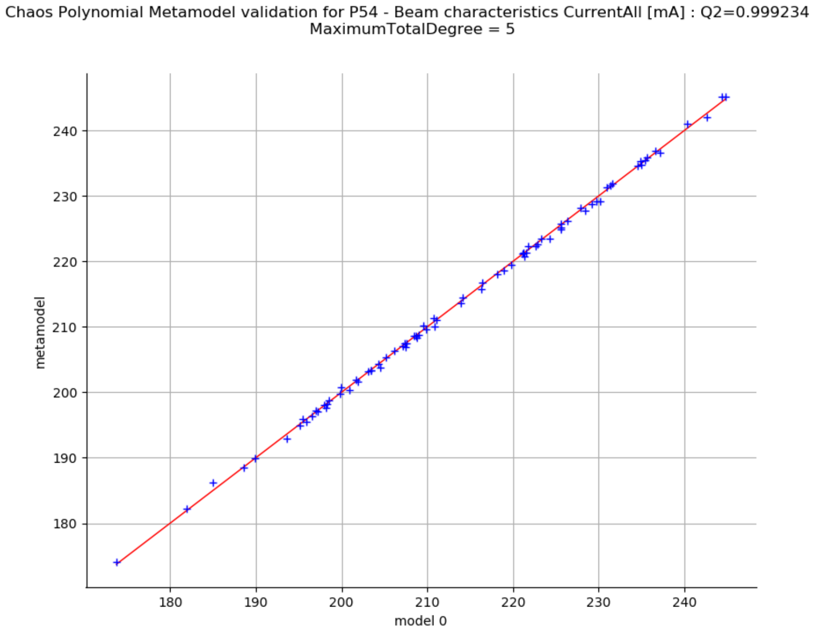
B- Building surrogate models (3)

Building surrogate models : kriging or polynomial chaos expansion

For total current emitted by cathode Ik

- DOE 200 points : Q2 ≈ 0.98-0.99 for kriging / Q2 ≈ 0.95-0.99 for PCE
- DOE 400 points & 1000 points : Q2 > 0.99 for both surrogate model types





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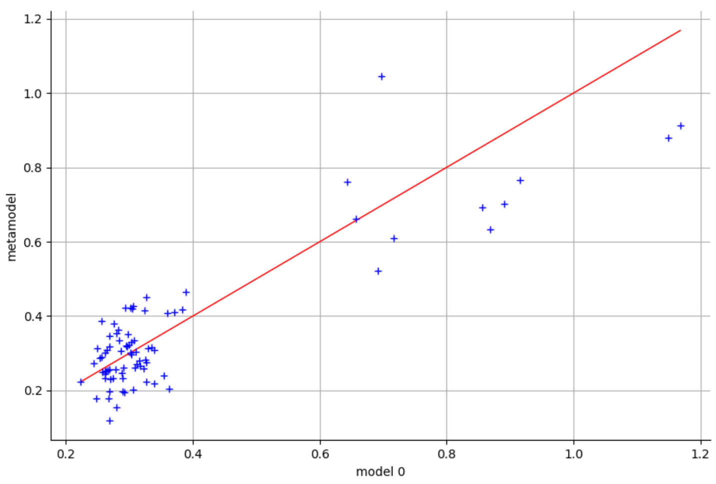
B- Building surrogate models (4)

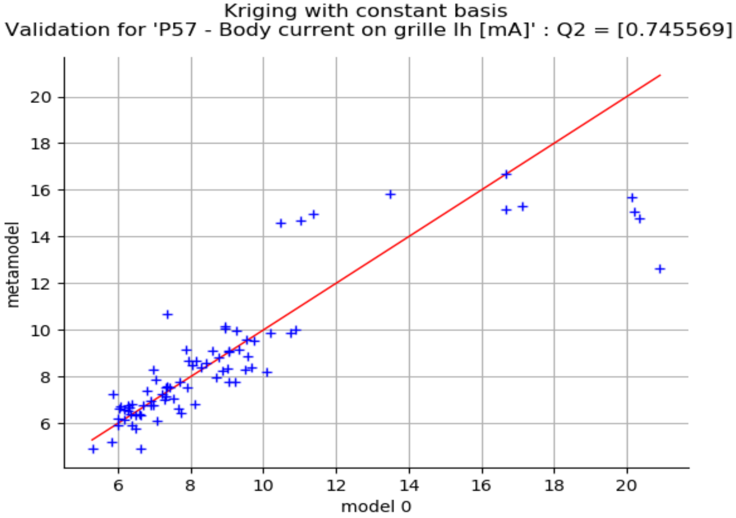
Building surrogate models : kriging or polynomial chaos expansion

For min of electron beam radius R95 & body intercepted current on grid Ihg

- Q2 : sometimes < 0, improved by increasing points number in DOE
- DOE 1000 points : Q2 ≈ 0.5-0.75 for kriging & Q2 ≈ 0.4-0.8 for PCE



PCE for min of electron beam radius R95



Kriging for body intercepted current on grid Ihg

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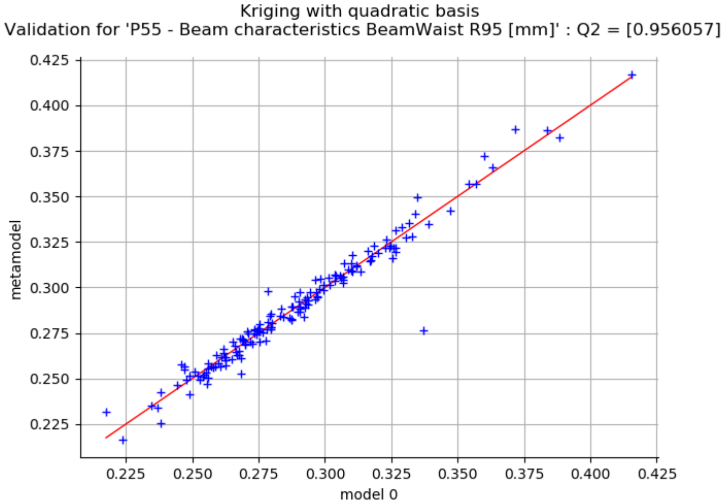
B- Building surrogate models (5)

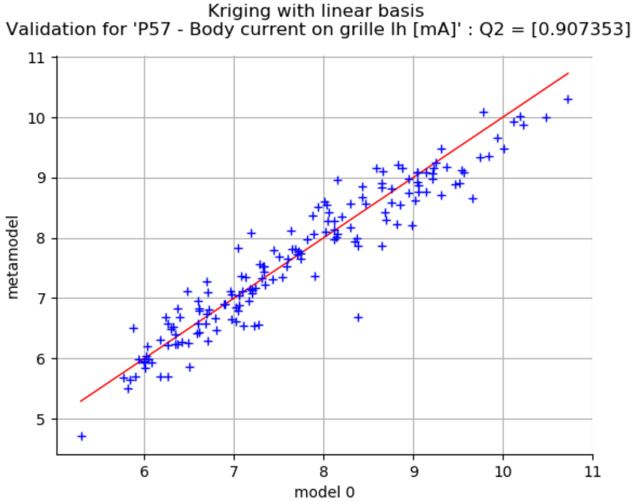
Building surrogate models : kriging or polynomial chaos expansion

For min of electron beam radius R95 & body intercepted current on grid Ihg

- Tests of classification methods with **otmixmod** (DOE 1000 points)
  - → no improvements (Q2 ≈ 0.3-0.6)
- Data filtering from DOE 1000 points (take off cases with results > thresholds)
  - → improvements ! (Q2 ≈ 0.8-0.95)



Kriging for min of electron beam radius R95



Kriging for body intercepted current on grid Ihg

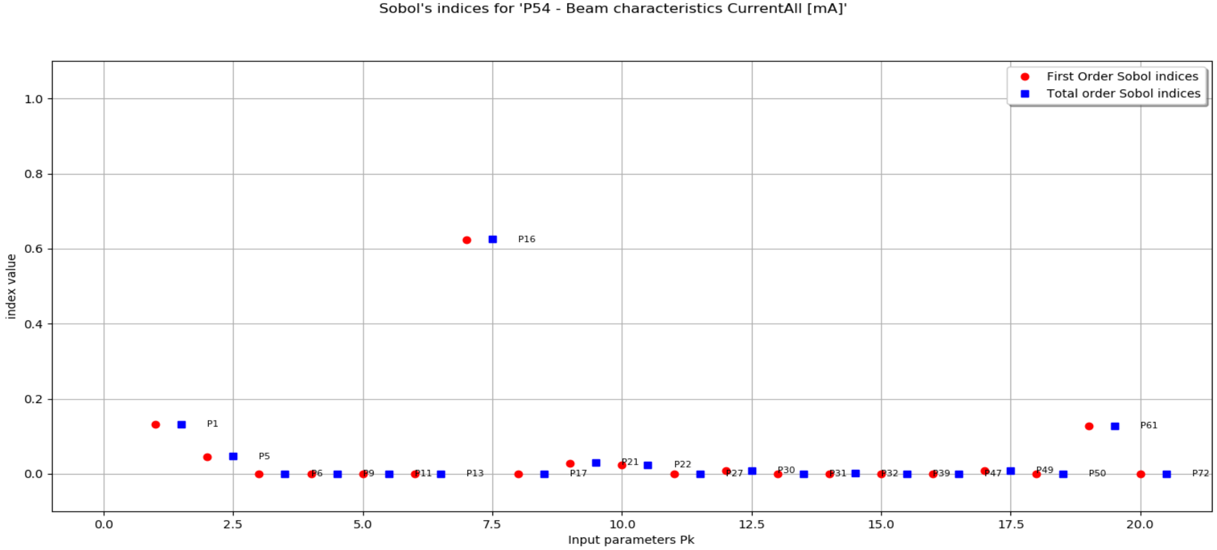
C- Global sensitivity analysis (1)

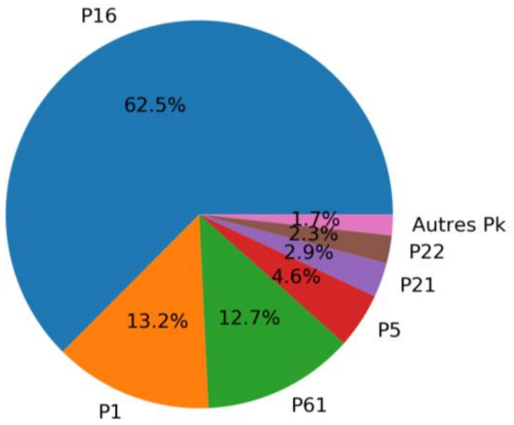
Determination of Sobol indices with surrogate models

Full DOE 1000 points

For total current emitted by cathode Ik

- Total and 1[st] order indices very close; $1 - \sum S_i \approx 0.003$ very close to 0;
- **>> few interactions between parameters**
- **>> input parameter P16 is predominant**





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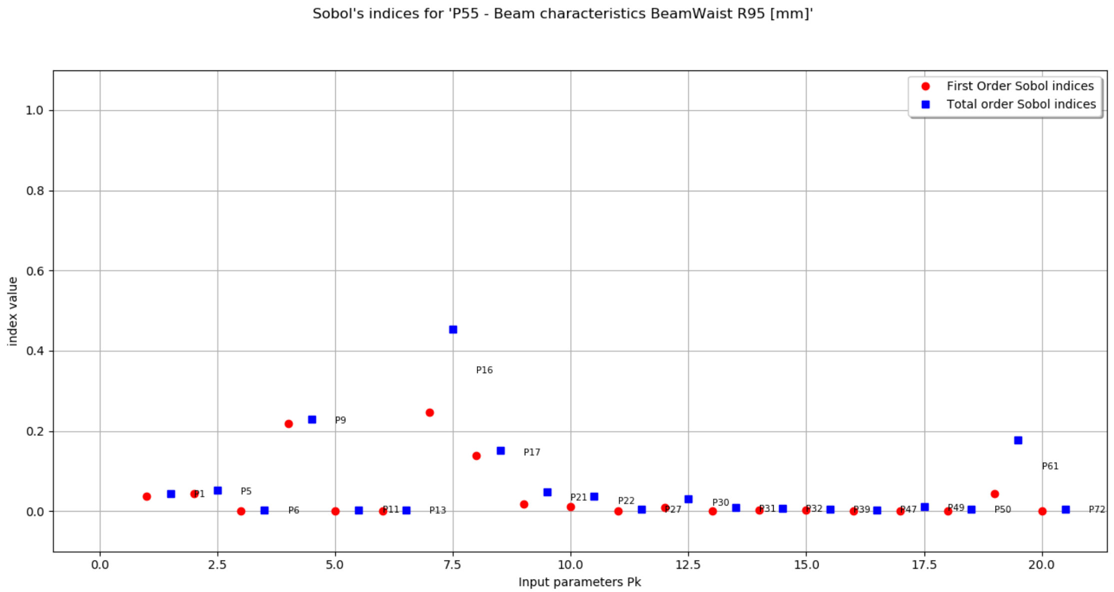
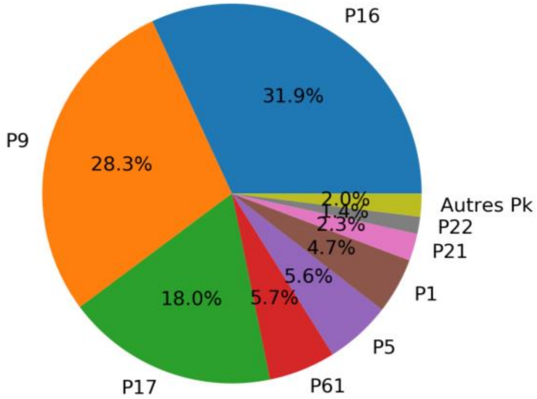
C- Global sensitivity analysis (2)

Determination of Sobol indices with surrogate models

DOE 1000 points filtered

- **For min of electron beam radius R95**
  - Total and 1st order indices different; $1 - \sum S_i \approx 0.23$;
  - **>> interactions between inputs acting on variability**





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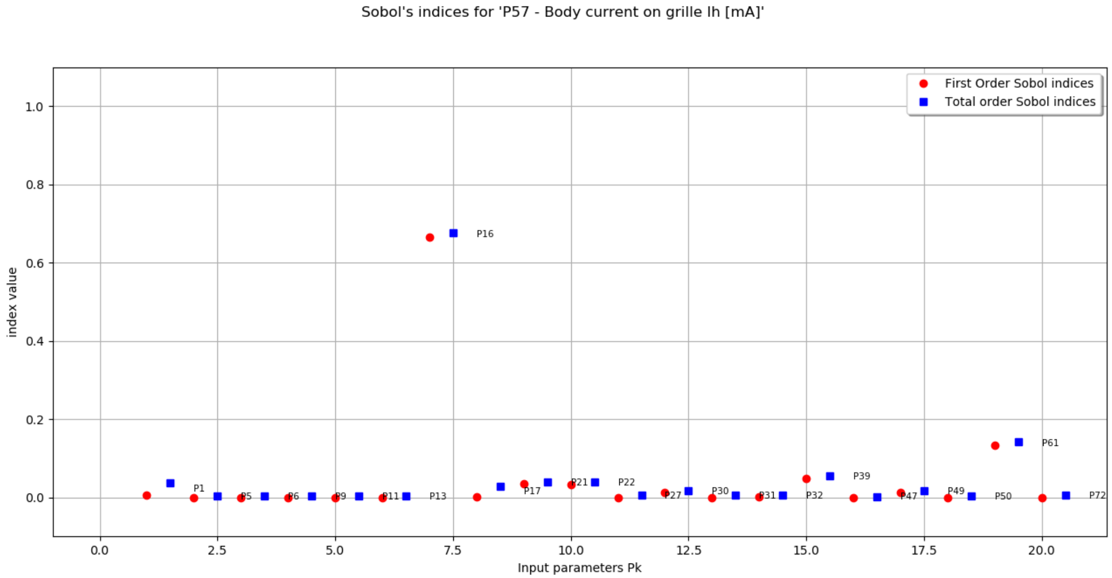
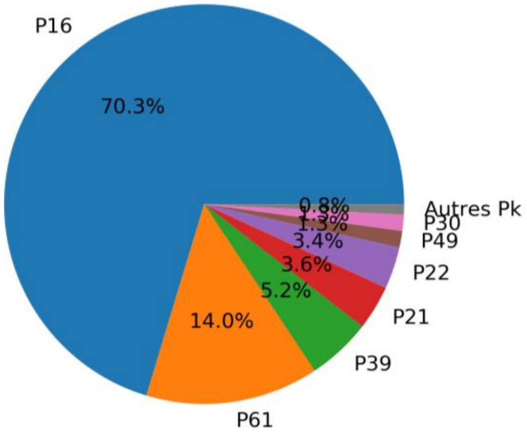
C- Global sensitivity analysis (3)

Determination of Sobol indices with surrogate models

DOE 1000 points filtered

- **For body intercepted current on grid Ihg**
  - Total and 1st order indices very close; $1 - \sum S_i \approx 0.05$ very close to 0;
  - **>> few interactions between parameters**
  - **>> input parameter P16 is predominant**





Conclusions & Perspectives

Sort most influential input parameters

- One parameter « P16 » with major influence
- 3 to 5 parameters with secondary influence

To be continued :

- Central tendency and dispersion measures
- Apply process on another electron gun configuration (without grid)
- Take into account external magnetic field applying on electron beam (variabilitity of magnets geometry and physical characteristics)

Thanks for your attention !

Some questions ?

Some suggestions ?

Appendix : Most influential input parameters

For total current emitted by cathode Ik

P16 - Plane_WehneltGrille.LCathodeGrilleWehnelt [mm]
P1 - Plane_Cathode.HConcavite [mm]
P61 - potential grille wehnelt potential [V]
P5 - Plane_Anode.LCathodeAnode [mm]
P21 - Plane_WehneltGrille.RintAxe [mm]
P22 - Plane_WehneltGrille.EpaisSupportG [mm]

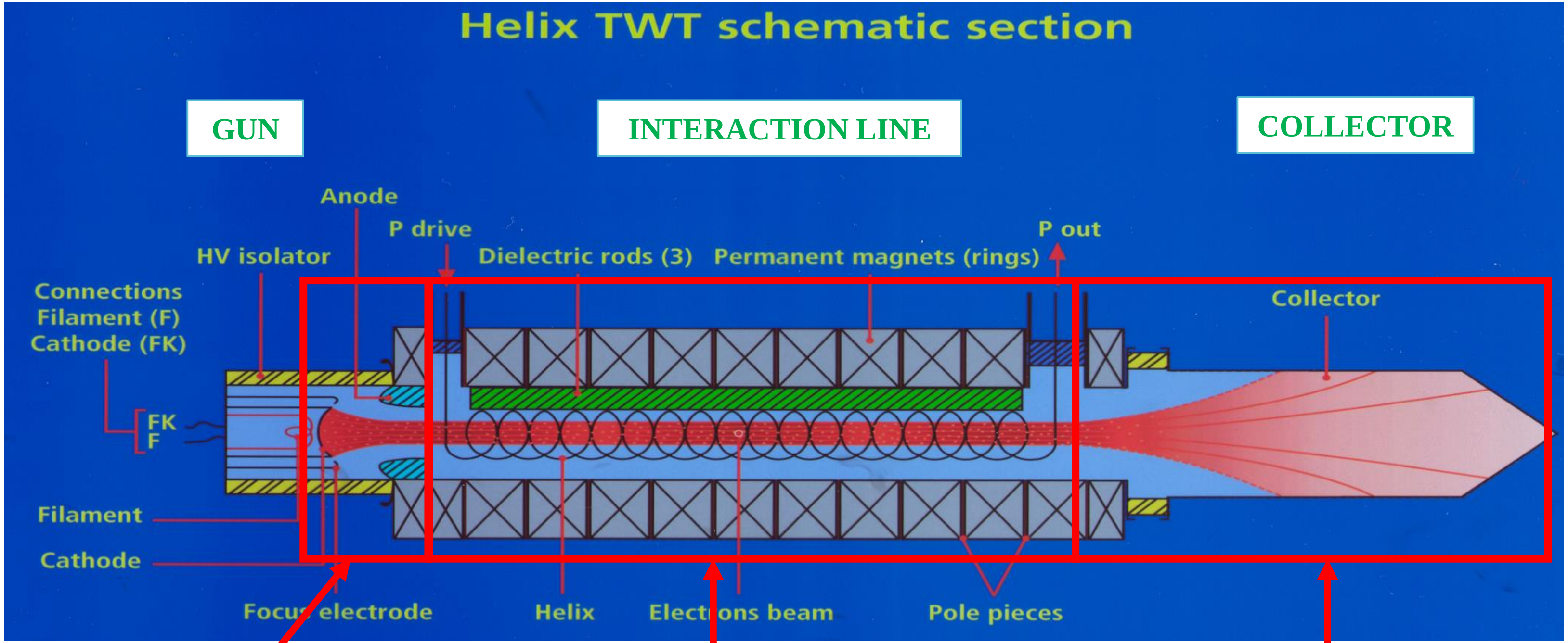
For min of electron beam radius R95

P16 - Plane_WehneltGrille.LCathodeGrilleWehnelt [mm]
P9 - Plane_Anode.AParallelisme [degree]
P17 - Plane_WehneltGrille.RDecentrageGW [mm]
P61 - potential grille wehnelt potential [V]
P5 - Plane_Anode.LCathodeAnode [mm]
P1 - Plane_Cathode.HConcavite [mm]
P21 - Plane_WehneltGrille.RintAxe [mm]
P22 - Plane_WehneltGrille.EpaisSupportG [mm]

For body intercepted current on grid Ihg

P16 - Plane_WehneltGrille.LCathodeGrilleWehnelt [mm]
P61 - potential grille wehnelt potential [V]
P39 - Plane_GrilleShape.Rint2 [mm]
P21 - Plane_WehneltGrille.RintAxe [mm]
P22 - Plane_WehneltGrille.EpaisSupportG [mm]
P49 - Plane_WehneltGrille.AngleWehnelt [degree]
P30 - Plane_WehneltGrille.HconcaviteGrille [mm]

Context : Tubes simulations : 3 physics phenomena



2D/3D Tools
Focalisation
(Emission + Transport)

2D/3D Tools
Gain & Efficiency
(Interaction)

2D/3D Tools
Collector performance
(Transport + Re-emission)

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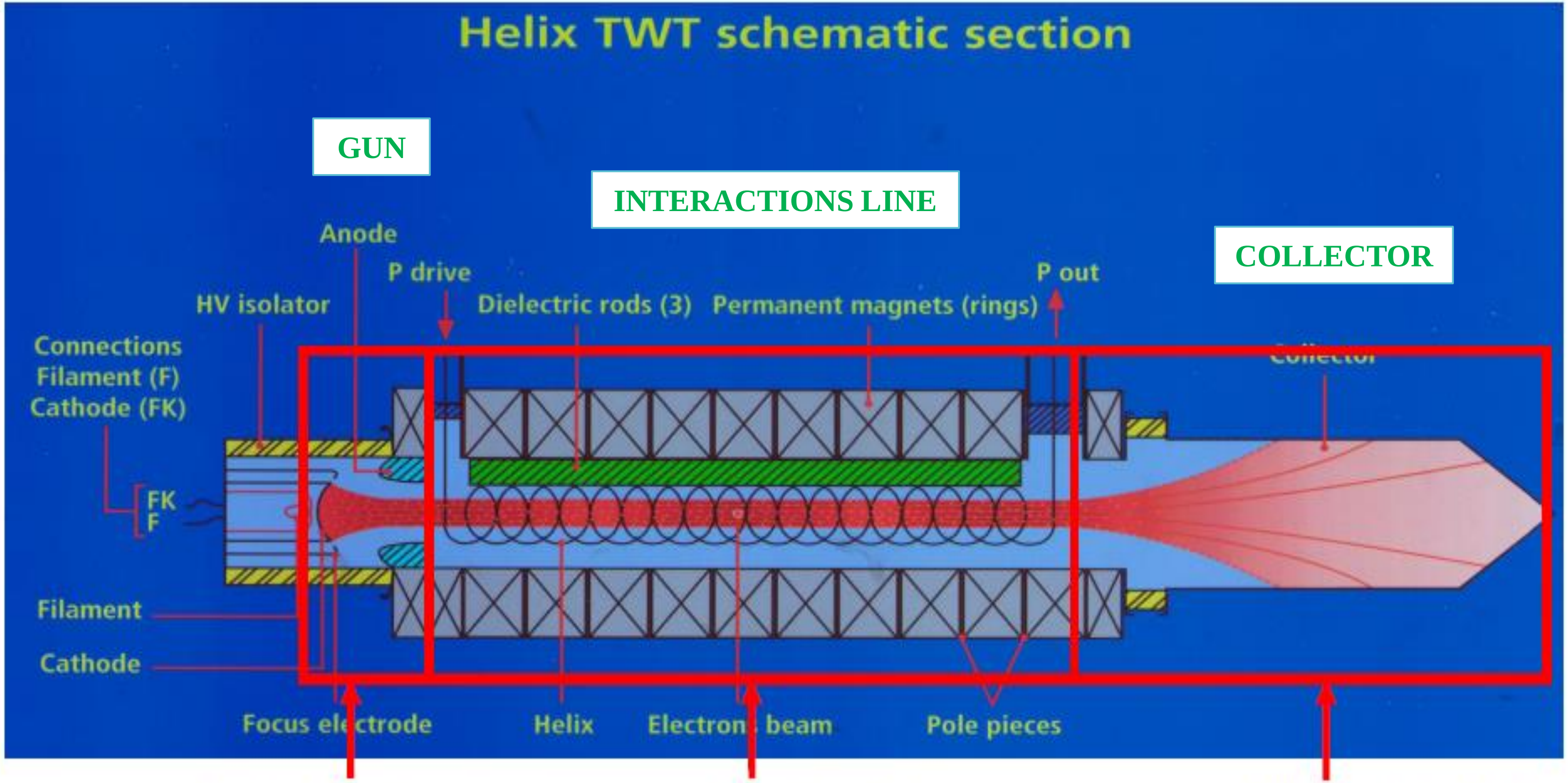
Context : Tubes simulations : 3 physics phenomena



Gun Optic Codes
Emiss Laws + Beam Transp
PIC, Poisson

Interaction Codes
Cold Param + Space charge + Beam Transp
PIC, Poisson, Helmoltz, Maxwell

Collector Optic Codes
Re-Emiss Laws + Beam Transp
PIC, Poisson