Ion Sources Simulation Program developed at CEA/Saclay

Extraction & Plasma

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Workshop Targets – Ions Sources
06-08 September
GANIL, Caen

Outline

1. **Objective(s)**
2. **Example of Simulations with pentode electrode system (2D & 3D) for SEISM source**
   60GHz ion source at Grenoble
3. **TWISS CODE developed in CEA Saclay**
   Needs and prerequisite
4. **Conclusion**

1. Objective(s)

2 categories of ECR ion sources :

- Highly charged ions sources, I_{ext} = several mA, high electron energy/ high electron density /several charge state/ buffer gas
- Intense light ions sources, I_{ext} = 160mA proton/deuterium, electron energy is useless above 100eV / monocharged / no buffer gas

2 problems on ECR Sources :

- Definition of Plasma : parameters… e-density / e-energy distribution / ion charged state…
- Extraction of particles out of this Plasma, first moment of the beam out of the plasma sheets/meniscus

OBJECTIF : Develop in 2-3 years:

- an extraction code to extracted an ion beam out of a defined plasma **(EXTRACTION code)**
- an simulation of ECR plasma inside our sources **(PLASMA SOURCE code)**

And also the Numeric Tools that will helps to confront simulations to experimental measurements

Existing CODES

3 different codes are :

- Multi-particle
- Handle SSC (rate & @ what position)

AXCEL: Commercial Code

- Fortran code, not really adapted to present machine (many crash) and low statistics
- Field map on axis only
- 2D geometry only (ASCII)
- Plasma with uniform density
- Quick calculation
- No Debugging
- No tool

IBSIMU: **Open source**

- Open source / Linux
- Geometry file DXF or « by bloc » with own Modeler
- Several magnetic maps
- Positive or negative ions plasma (with constant density)
- Quick calculation
- Several tools implemented

OPERA: Commercial Code

- 2D & 3D geometry (.sat file)
- TOSCA : magnetic calculation
- SCALA : electric field calculation coupled on the magnetic nodes & trajectory calculations
- Several plasma emitter (field emission, constant density, Child-Langmuir…)
- Secondary emission

CST OPERA
Promising ion source plasma module, not yet tested

2. SEISM source 60GHz

Example of simulations that LPSC Grenoble group asked us to look after for the SEISM 60GHz ion source :

- Extraction and transport of multi-charged ARGON with pentode extraction system of the **SILHI source**
- Influence of several magnetic configurations on the extracted beam

AXCEL & **Opera** are the 2 codes that we use historically at Saclay

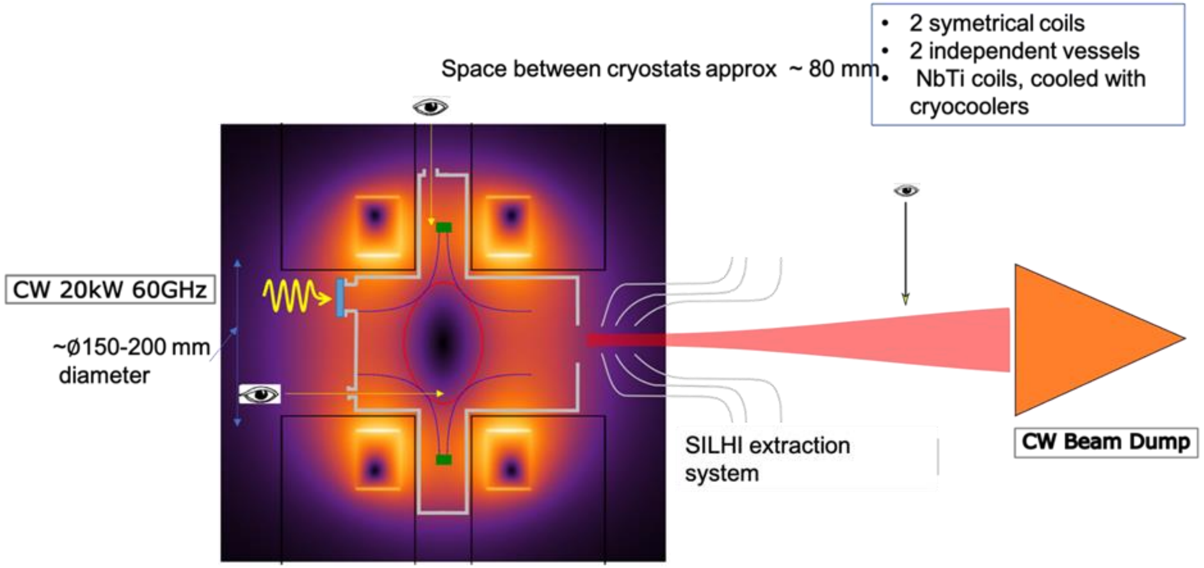
I took time to use **IBSIMU** for the first time

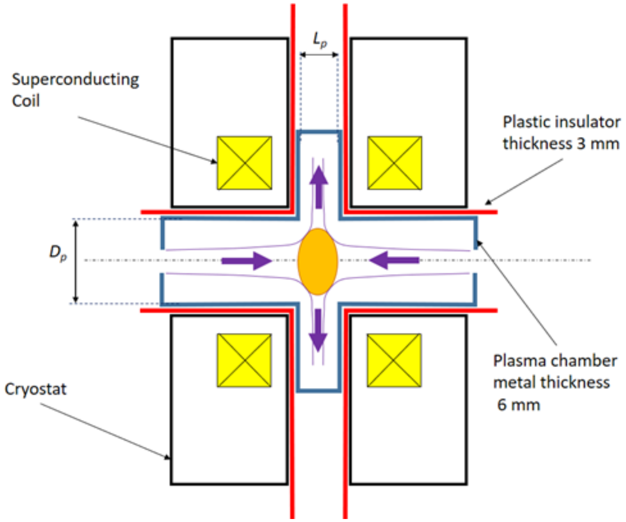
SILHI Pentode extraction system for SEISM source ?

Source configuration

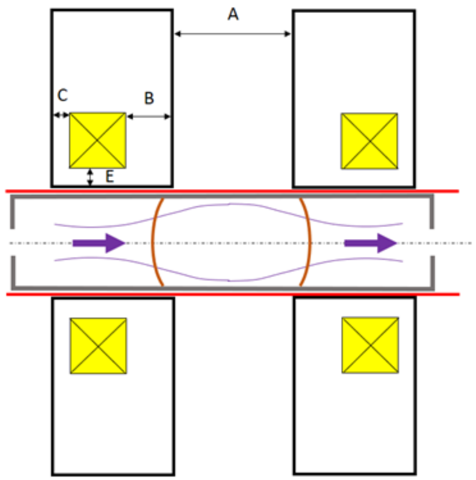
Parameter	Value
Extraction hole diameter	4 mm
High voltage applied to the source	Up to 100 kV
Beam intensity target	100 mA
Min beam current density J_{min}	100 mA/cm^2
Max beam current density J_{max}	500 mA/cm^2
Charge state distribution	Ar1+ → Ar 6+

Charge State	1+	2+	3+	4+	5+	6+
Percentage	14	14	12	12	33	15





two solenoids assembled in cusp



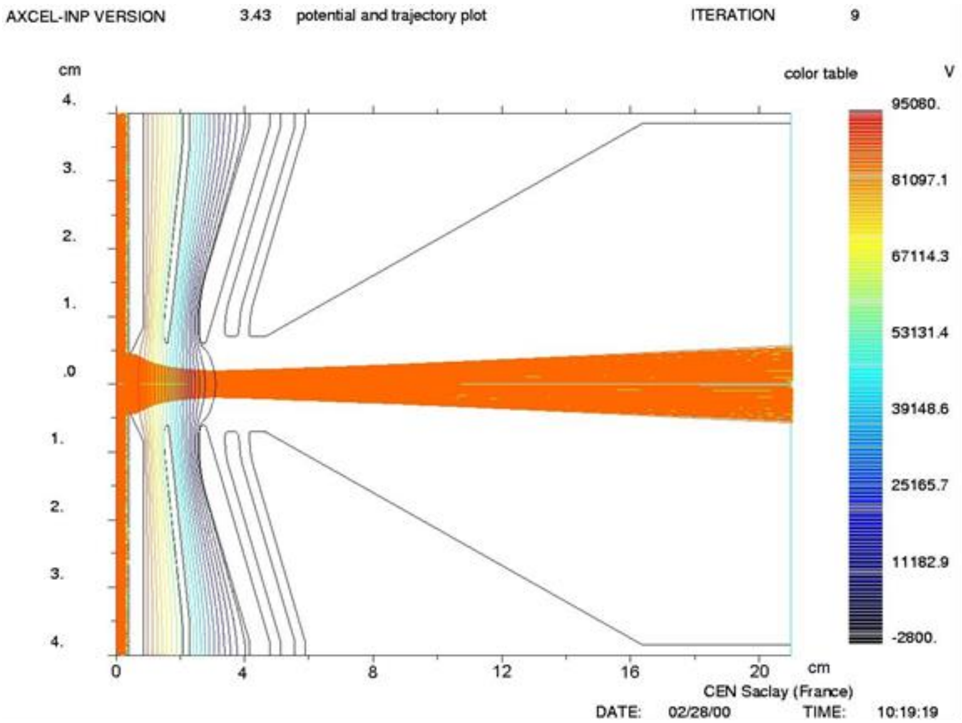
two solenoids assembled in mirror trap

Simulations 2D for SILHI

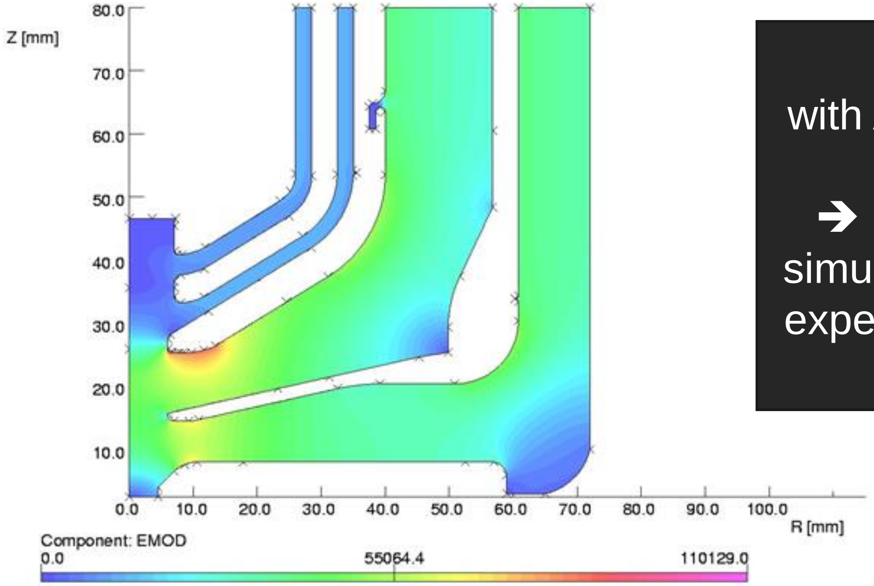
Reference point :

SILHI Extraction – Simulation AXCEL / OPERA-2D

Plasma electrode ϕ=9 mm
Potentials : 95 kV / 55 kV / 0 kV / -2.8 kV / 0 kV



Trajectoires



Champ électrique

with AXCEL and OPERA 2D

➔ several years to make simulations converge toward experimental measurements

120 mA extracted @ 95 keV

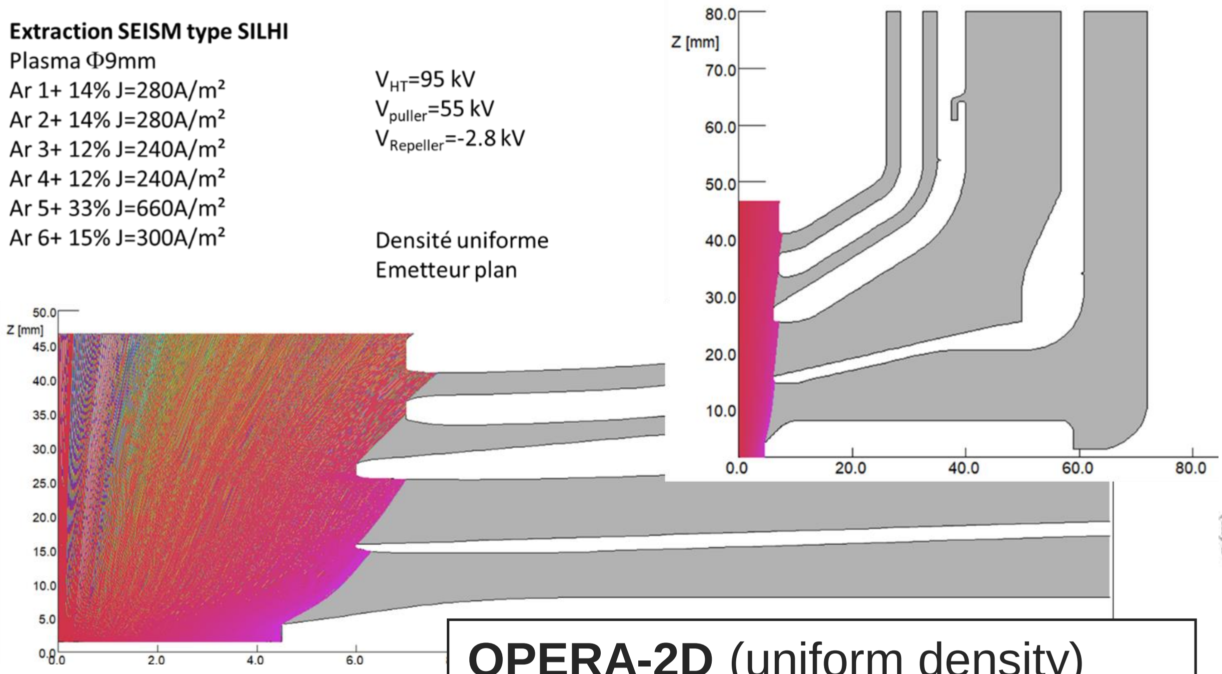
Simulations 2D for SEISM

Argon beam extraction out of SEISM with SILHI geometry (plasma Φ9mm)

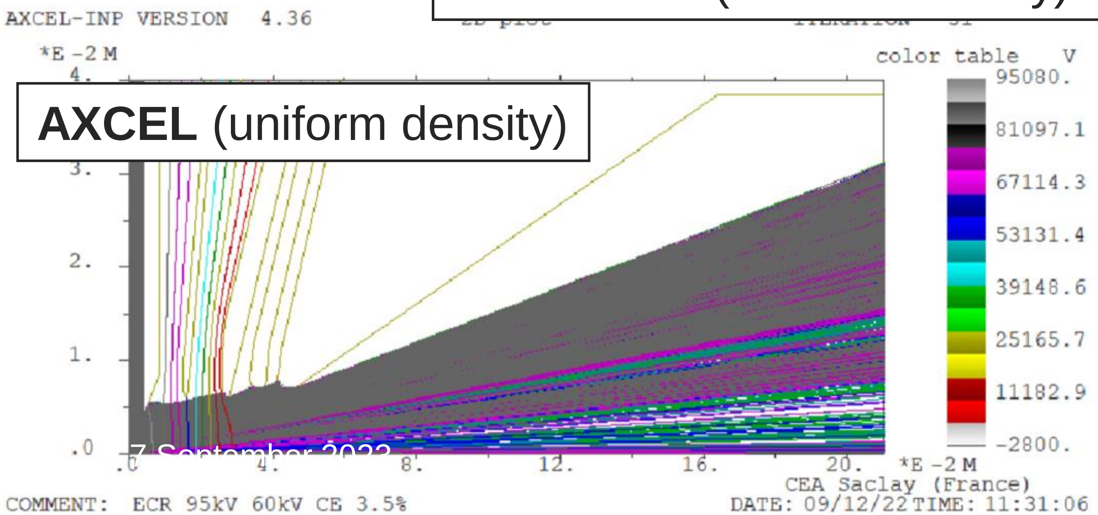
Extraction SEISM type SILHI
Plasma Φ9mm
Ar 1+ 14% J=280A/m²
Ar 2+ 14% J=280A/m²
Ar 3+ 12% J=240A/m²
Ar 4+ 12% J=240A/m²
Ar 5+ 33% J=660A/m²
Ar 6+ 15% J=300A/m²

V_{HT}=95 kV
V_{puller}=55 kV
$V_{Repeller}$=-2.8 kV

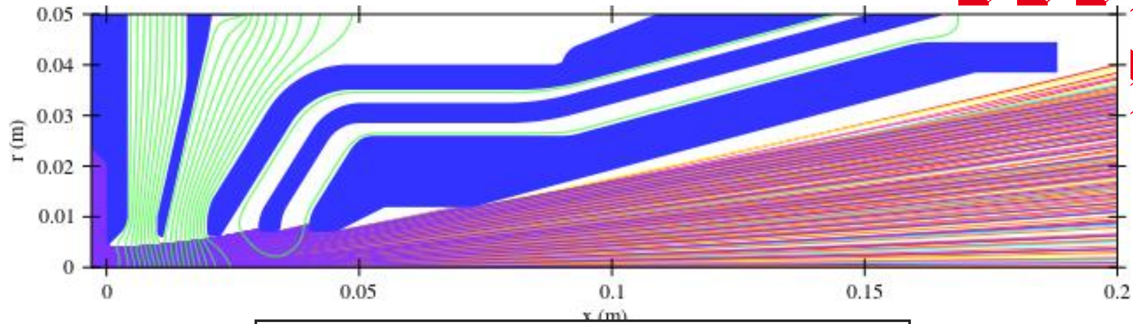
Densité uniforme
Emetteur plan

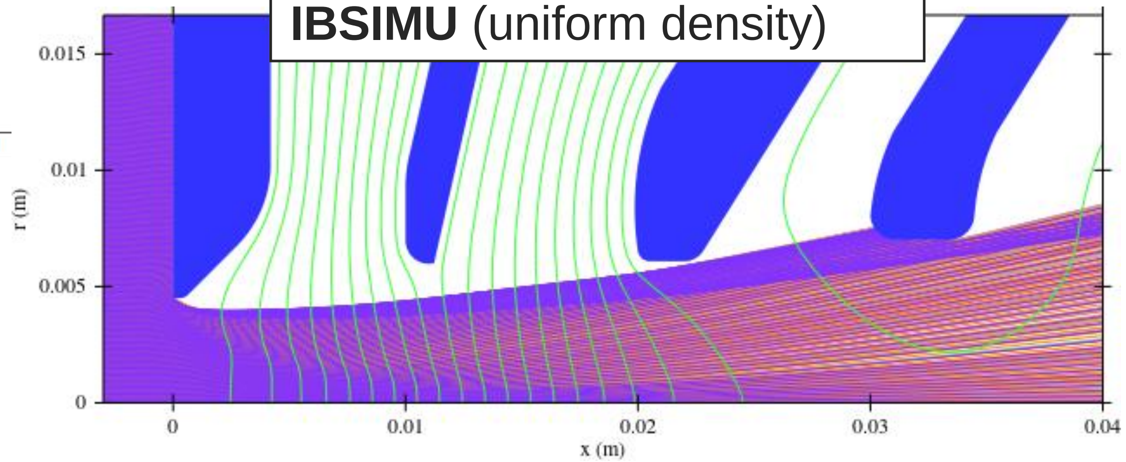


OPERA-2D (uniform density)



AXCEL (uniform density)



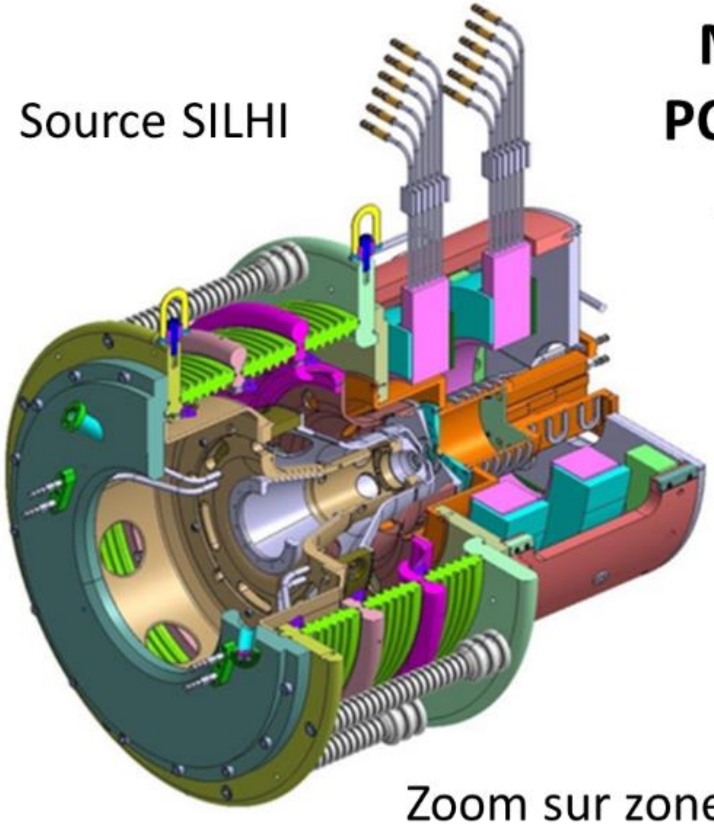


IBSIMU (uniform density)

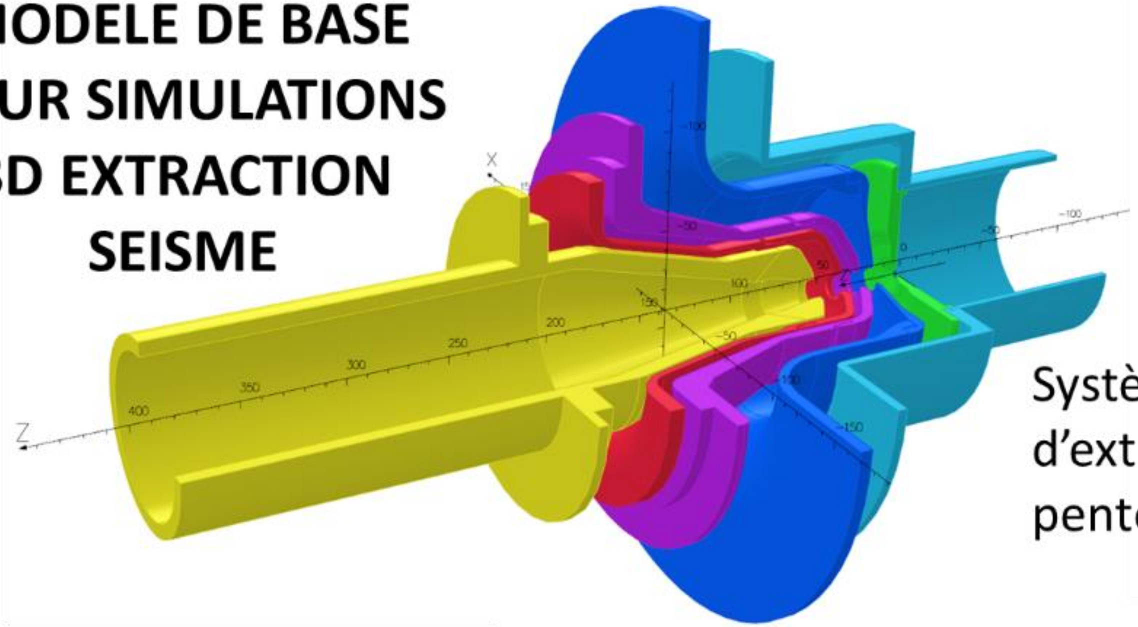
All simulations showed the same result:
➔ Density too high
➔ Divergent beam : explosion
➔ Only 30% Intensity left

Simulations 3D for SILHI (SCALA &OPERA)

Source SILHI

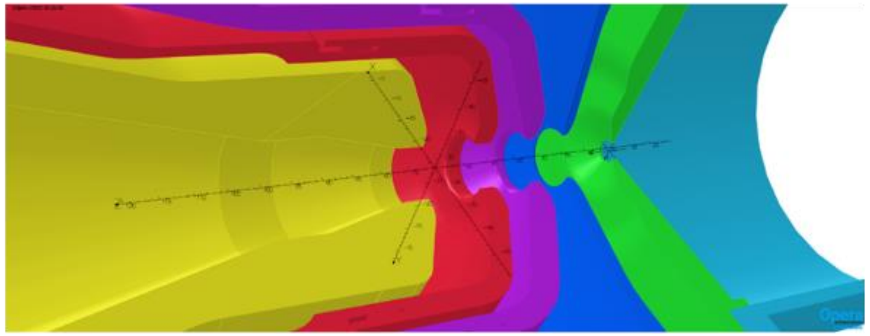


MODELE DE BASE
POUR SIMULATIONS
3D EXTRACTION
SEISME

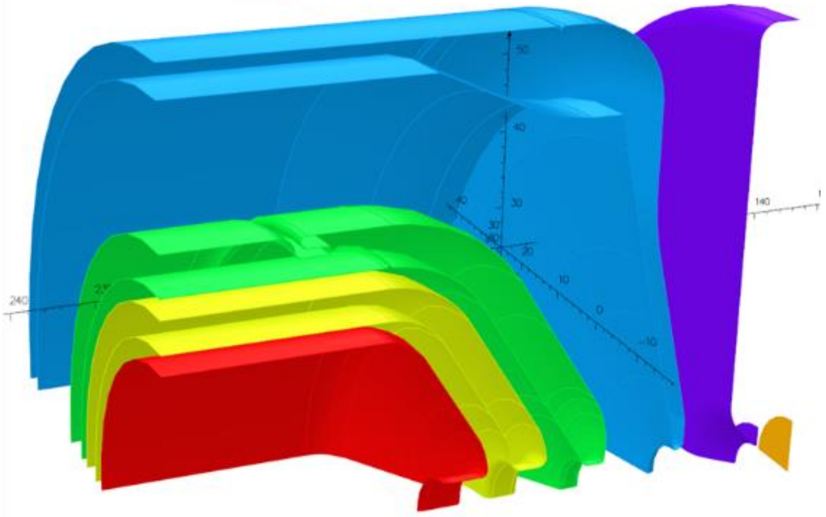


Système d'extraction pentode

Zoom sur zone faisceau



Modèle pour simulations



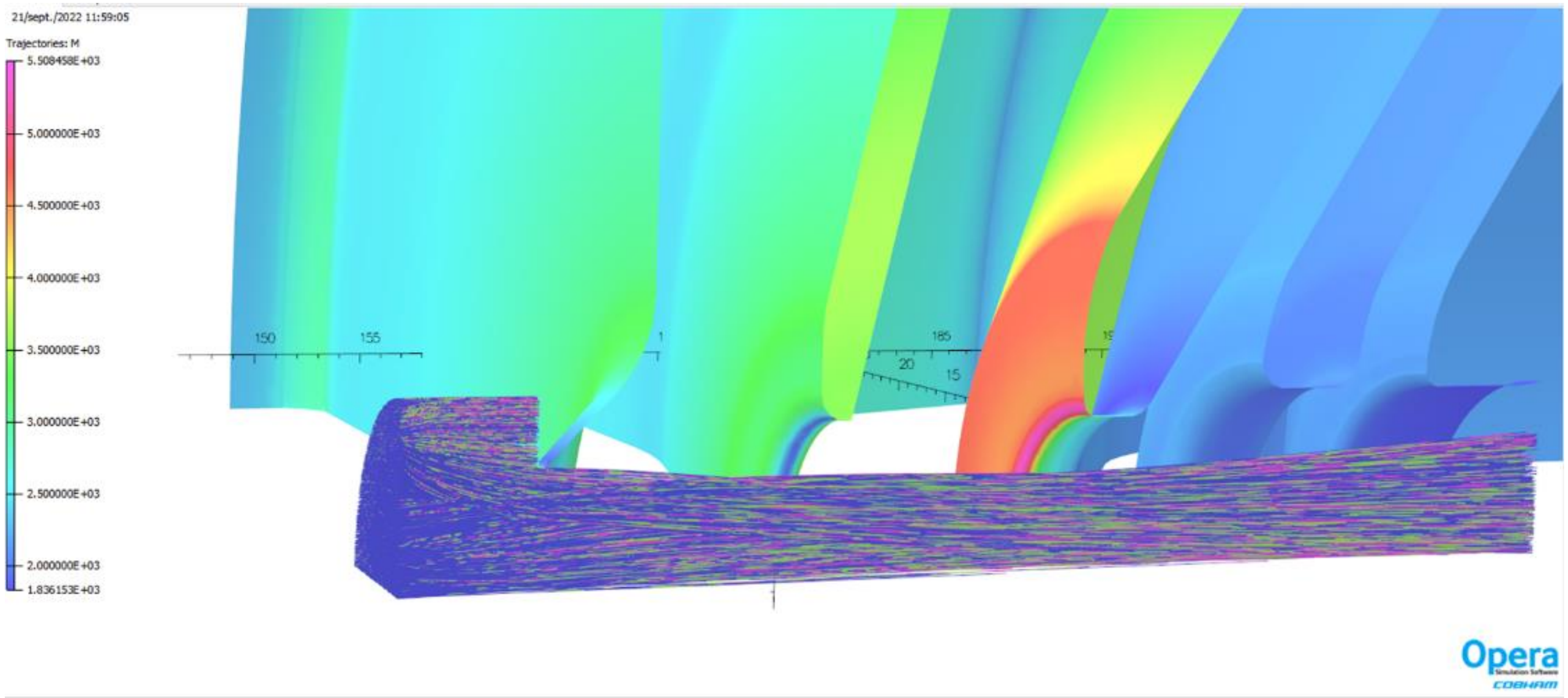
Simulations 3D for SILHI

Reference Point

Extraction SILHI – Simulation OPERA-3D / SCALA

plasma emitor type 103 in SCALA OPERA

Check for SILHI geometry with H^+, H_2^+, H_3^+ :



Paramètres :

Plasma Zone : R=8 mm, DZ=5 mm

Potentials :

HT 95 kV, Puller 65 kV, RE -3kV

Aperture hole : Φ9mm

Plasma conditions: T=1 eV, V_p=20 V

H^+ J=0,13 A/m²,

H_2^+ J=0.036 A/m²

H_3^+ J= 5.7E-03 A/m²

Not really used in Saclay for design

➔ Error calculation in electrode misalignment

3D Simulations

- Several magnetic configuration on SEISM source
- Study of the bias voltage of electrode on beam extraction
- Influence of T_{ion}, Plasma potential value

Extraction SEISM type SILHI
Plasma Φ9mm
Ar^{1+} 14% J=280A/m²
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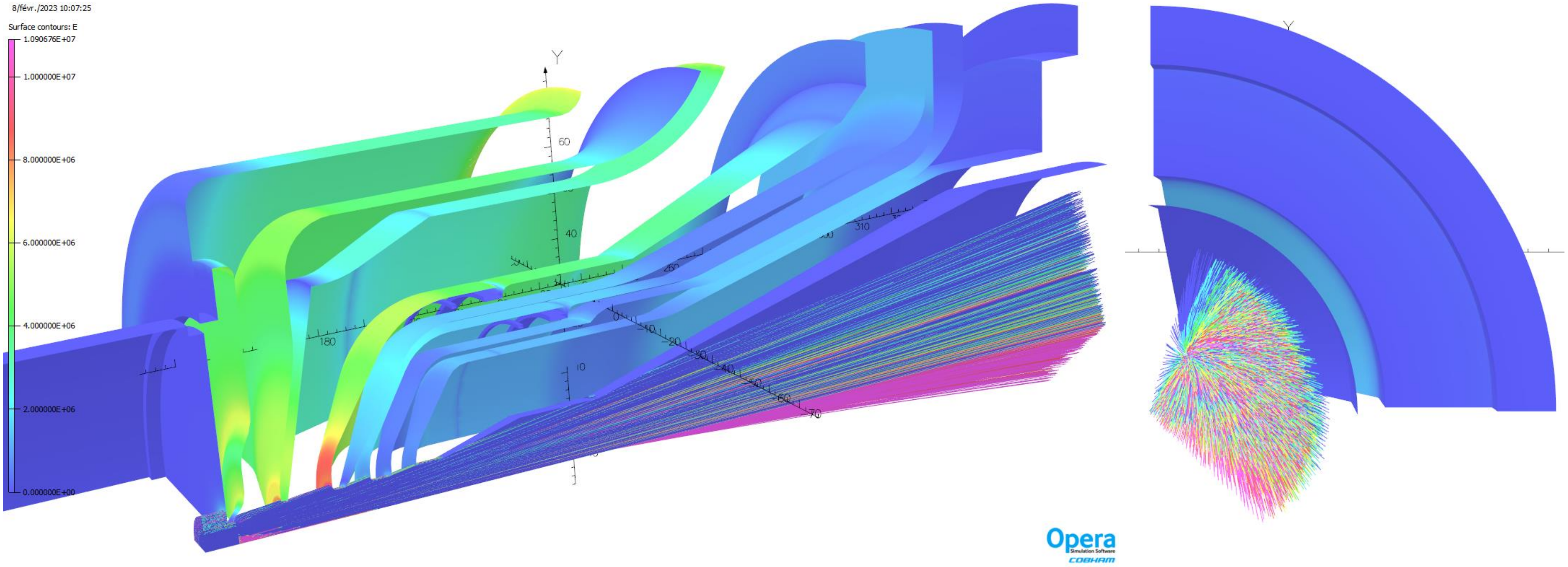


Conclusion on SIMULATIONS for SEISM 60GHz ion Source

With **AXCEL, OPERA** and **IBSIMU**

- I_{TOT}=125 mA total extracted, beam transport to beam dump I_{BD}=40 mA. 66% beam lost on electrodes

➔ Heat up, sparks, electrode deterioration

- No or very few influence of the magnetic field on the transported beam on the **3D simulation**

➔ **The pentode electrode system of the SILHI source not adapted for LPSC SEISM 60Hz ion source Argon beam**

Convergence criteria of simulations **non fully reached**

- OPERA : oscillations ➔ calculation never stops
- AXCEL & IBSIMU : criteria are not fully understood ➔ calculation stop after a defined number of iteration

3. SIMULATION codes in SACLAY
TO DO LIST for the next years

2023

Extraction 1

- 2D Geometry axisymmetric
  - List or points
- Potential lines calculation
- Magnetic field map
- Definition of beam characteristic
- SC and SCC
- Multi-grid & Pusher
- Convergence criteria
- Documentation

2024

Extraction 2

- 3D Geometry
- Analysis TOOL
- GUI Interface
- Collaborations to test the code in various conditions…

Plasma

- 2D axisymmetric
- Physical model
- Collaboration²

2025

Plasma

- Adaptive mesh

a TRACEWIN integration also…?

2D AXISYMETRIC, some Input Parameters

2D axisymetric

- MESH size/ number of trajectories per mesh
- Geometry : DXF import or list of point in ASCII.
- Potential on the electrodes
- Magnetic fiel map in ASCII on axis

BEAM definition:

- beam : Nb part , I_{tot} [A], charge distribution, aperture hole[m], q, m, E0 initial kick; Ti_{Long} et Ti_{trans}
- SCC : yield[%] and position Z_{CE} [m]

Plasma definition:

- R0, Zp radius ans position of the plasma zone
- Te / Tt / Plasma Potential

Calcul :

- Number of iteration, convergence

TOOLS:

- Graph2D
  - Geometry / Trajectory / E and B field lines
  - Emittance (r-r' et z-z') at Z
- Graph1D at a given Z :
  - Profil in R / in R' / charge over masse
  - Have all particles datas along trajectories

Extraction code part of « TWISS »
→TraceWin Ion Source Simulator

Language choice:

- Python for MAIN, graphical interface are easy, plots are nice
- independent packages, easy to share and install
- multiplatform

D. MINENNA

For parallel calculations : Code part can be run in C++

N. PICHOFF

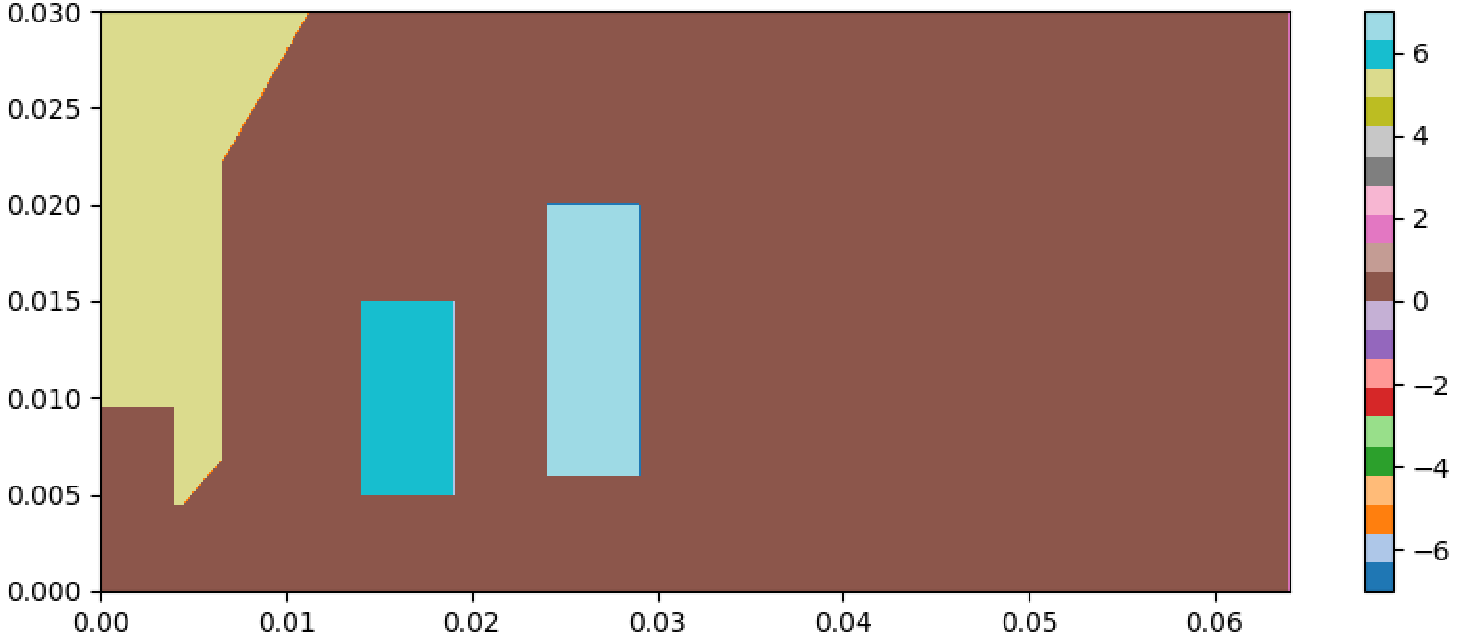
First attempt
How to manipulate geometry

.ECF file with list of points

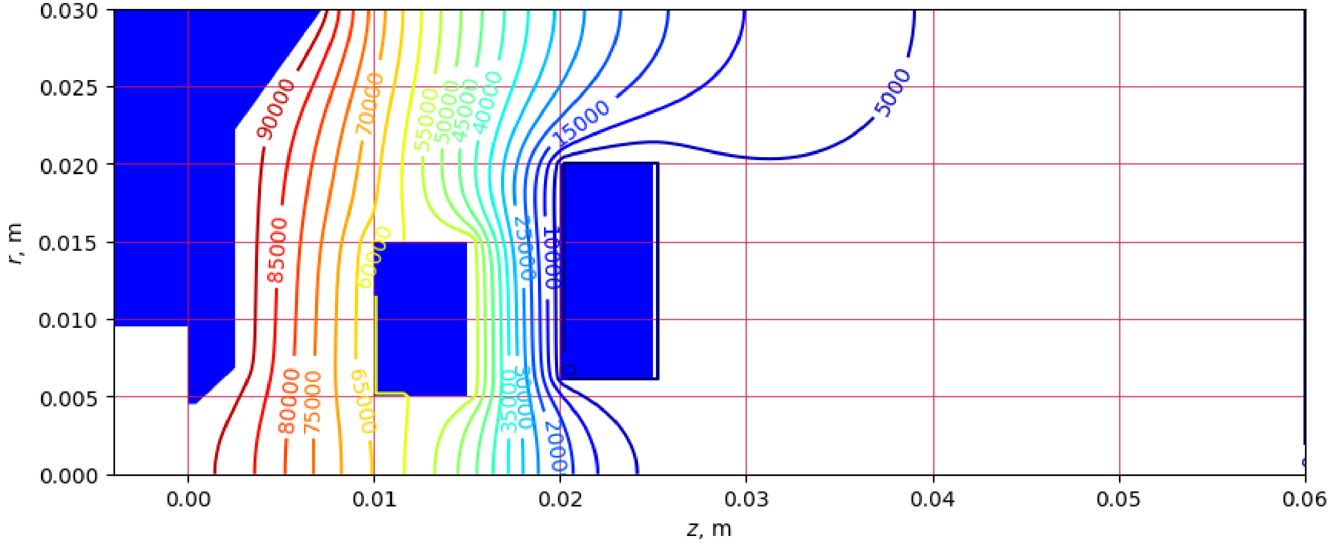
EP	
-5,	9.5
-5,	71
7.24,	71
7.24,	35.2
2.55,	22.2
2.55,	6.85
0.45,	4.5
0,	4.5
0,	9.5
-5,	9.5
end	

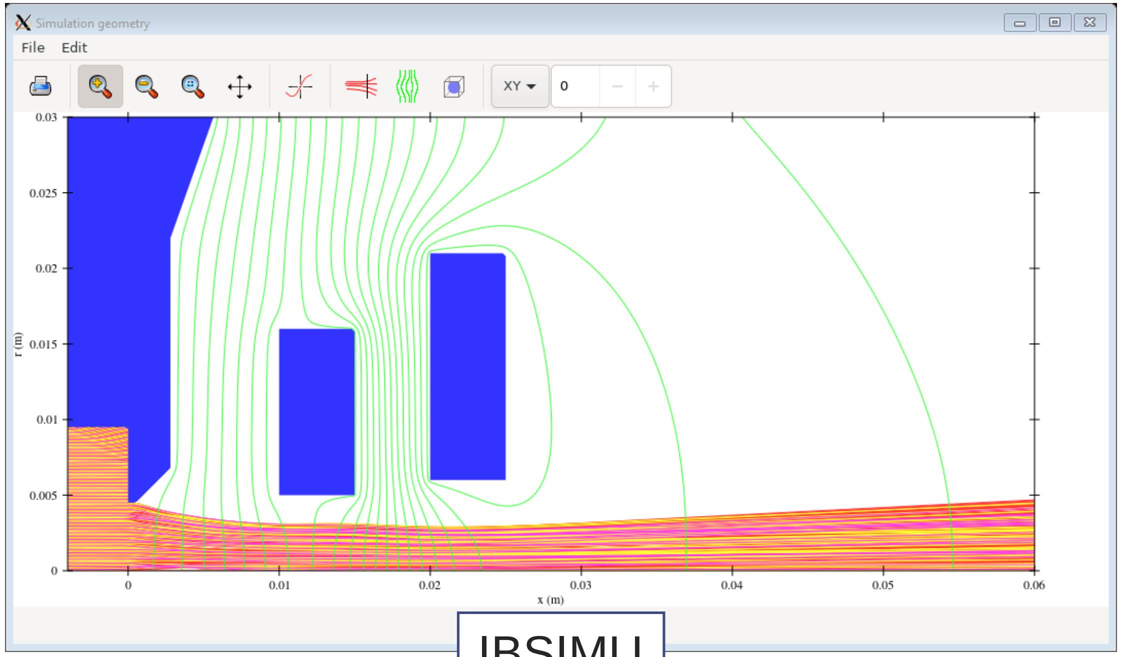
PULLER	
10,	5
10,	15
15,	15
15,	5
10,	5
end	

MASSE1	
20,	6
20,	20
25,	20
25,	6
20,	6
end	



TWISS code, Potential calculation





IBSIMU

- Poisson solver for potential calculation on the mesh grid ➔ OK
- Pusher is written ➔ in debugging phase
- Beam Diagnotics are ready
- Documentation is made in parallel with the code conception

Documentation

Enies
0.1

Search docs

FOR USERS
- Definition of electrodes
- 2D Cylindrical Poisson Solver

FOR DEVELOPERS
- Simu class
- Electrodes from Simu class
- Plotter for the Simu class
  - meshplot()

Plotter for the Simu class — View page source

Plotter for the Simu class

enies.Simu.meshplot(*self, id: int, key: str, plot: str = 'pcolormesh', **kwargs*)→ subplot

Mesh plotter

Example

Simple plot of the mesh.

```
simu.meshplot(0,"V",
                plot="contour",
                # plot="pcolormesh",
                edgecolors = 'grey',
                electrodes=True,
                cmap='plasma',
                grid=True,
                savefig="ElectrodePot.png",
                )
```

Parameters:
- **id** (*int*) – Mesh id
- **key** (*str*) – Variable wanted
- **plot** (*str, optional*) – Plot option. Defaults to "pcolormesh".
- ****kwargs** (*List of properties*) –
  - grid (str): Defaults to True.

Returns: matplotlib.pyplot figure.

Return type: plt.subplot

Previous

Enies
0.1

Search docs

FOR USERS
- Definition of electrodes
- 2D Cylindrical Poisson equation

FOR DEVELOPERS
- Simu class
- Electrodes from Simu class
- Plotter for the Simu class
- MultigridZR

Gauss Seidel method — View page source

Gauss Seidel method

In vacuum and far from the boundaries

At node i, j, in vacuum (node $n = 0$), we have the order 1 finite difference

$$\frac{1}{r_{i,j}}\frac{V_{i,j+1}-V_{i,j-1}}{2\delta r}+\frac{V_{i,j+1}-2V_{i,j}+V_{i,j-1}}{\delta r^2}+\frac{V_{i+1,j}-2V_{i,j}+V_{i-1,j}}{\delta z^2}=-\frac{\rho_{i,j}}{\epsilon_0}$$

or

$$\frac{V_{i+1,j}}{\delta z^2}+\frac{V_{i-1,j}}{\delta z^2}+\frac{\delta r^2+2r_{i,j}\delta r}{2r_{i,j}\delta r\delta r^2}V_{i,j+1}+\frac{2r_{i,j}\delta r-\delta r^2}{2r_{i,j}\delta r\delta r^2}V_{i,j-1}+\frac{-(2\delta z^2+\delta r^2)}{\delta z^2\delta r^2}V_{i,j}=-\frac{\rho_{i,j}}{\epsilon_0}$$

Therefore, we have the following equation

$$V_{i,j}=\frac{1}{C}(F-DV_{i+1,j}-GV_{i-1,j}-HV_{i,j+1}-BV_{i,j-1})$$

with

$$F=-\frac{\rho_{i,j}}{\epsilon_0}$$
$$C=\frac{-(2\delta z^2+\delta r^2)}{\delta z^2\delta r^2}$$
$$D=\frac{1}{\delta z^2}$$
$$G=\frac{1}{\delta z^2}$$
$$H=\frac{\delta r^2+2r_{i,j}\delta r}{2r_{i,j}\delta r\delta r^2}$$
$$B=\frac{2r_{i,j}\delta r-\delta r^2}{2r_{i,j}\delta r\delta r^2}$$

Jacobi Method

At time k, we have

$$V_{i,j}^{(k)}=\frac{1}{C}\left(F-DV_{i+1,j}^{(k-1)}-GV_{i-1,j}^{(k-1)}-HV_{i,j+1}^{(k-1)}-BV_{i,j-1}^{(k-1)}\right)$$

Gauss-Seidel Method

More efficient and need only one matrix. At time k, we have

$$V^{(k)}=\frac{1}{C}\left(F-DV^{(k)}-GV^{(k-1)}-HV^{(k)}-BV^{(k-1)}\right)$$

4. Conclusion(s)

The work just started (mid 2023)

Lot of intermediate steps to control the validity of the code results and

- confront it to another code (potential calculation for example)
- or experiments (this will be mainly at the end with beam)

Code progress are done in parallel with its libraries and documentation