FROM RESEARCH TO INDUSTRY

SOFTWARE TOOLS FOR KLYSTRON DESIGN OPTIMIZATION

Juliette Plouin

CEA, France

www.cea.fr

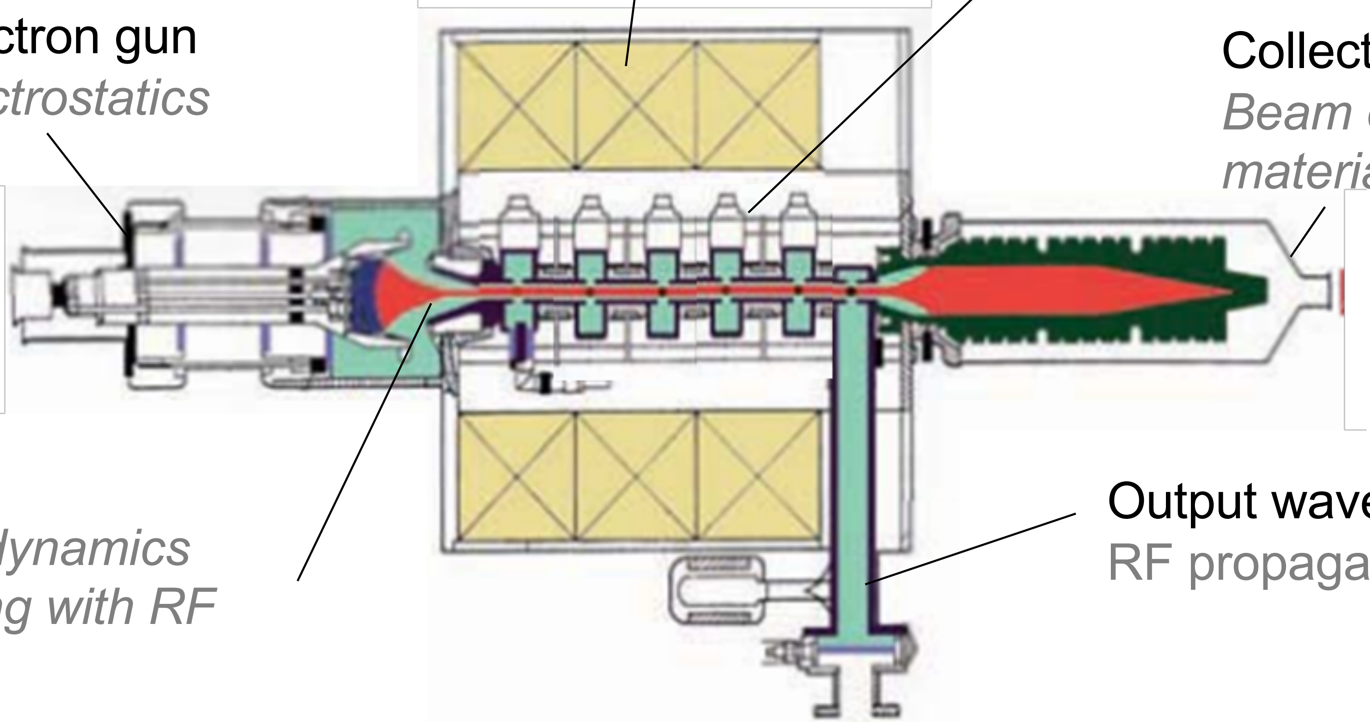
ARIES WORKSHOP ON ENERGY EFFICIENT RF
18/06/2019

SUMMARY

1. How to develop a klystron design?
2. 1D and 2D steady state code
3. 2D and 3D Particle In Cell (PIC) codes
4. Codes results comparison
5. Conclusion

1. HOW TO DEVELOP A KLYSTRON DESIGN?

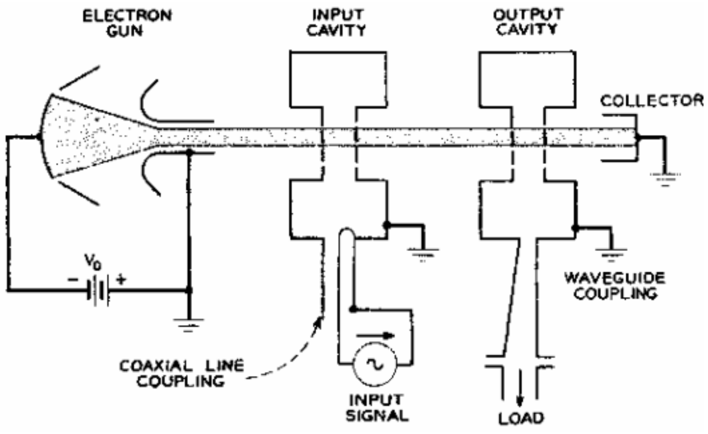
THE KLYSTRON – A COMPLICATED OBJECT…



The design of klystrons has long been a manual process guided by experience...
🖹 Klystrons have been developed since the 1940's, before computers 💻.

SOLVING EQUATIONS…

From very simplified…



Small signal Two-Cavity "Bunching" Theory

$$P_{out} = \frac{1.16 Io}{\sqrt{2}} x \frac{Vo}{\sqrt{2}} = 0.58 I_0 V_0 = 0.58 P_{in}$$

"for the two-cavity klystron, without space charge and with sinusoidal voltage modulation, the maximum efficiency is 58%."

High Power Klystrons: Theory and Practice at the SLAC, **Caryotakis**, 2005

…to full physics

$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$ Lorenz force on electrons

$div\vec{E} = \frac{\rho}{\epsilon_0}$ $\quad r\vec{o}t\vec{E} = -\frac{\partial \vec{B}}{\partial t}$ Maxwell equations

$div\vec{B} = 0$ $\quad r\vec{o}t\vec{B} = \mu_0\vec{J} + \mu_0\epsilon_0\frac{\partial \vec{E}}{\partial t}$

+ Boundary conditions…+ Initial conditions

To each particule…

At each position…

At each instant…

2. 1D AND 2D STEADY STATE CODES

1D CODE : AJDISK

- Combination of analytical formulae and electron dynamics
- Klystron cavities characterized partly by RLC circuits

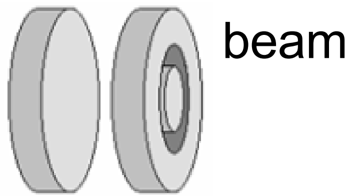
⇨quick assessment of the power and efficiency

Time < 1 mn

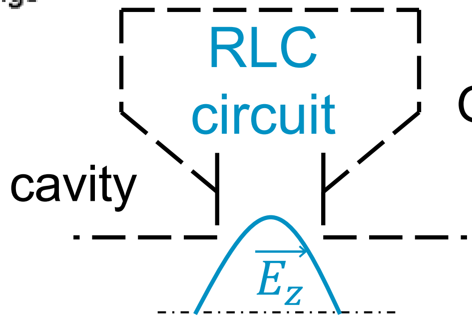
Cavities: R/Q, M, Q_{ext}, Q_0, f_{CAV}, z
Beam: V_k, I_k, r_{beam}
No magnetic field needed

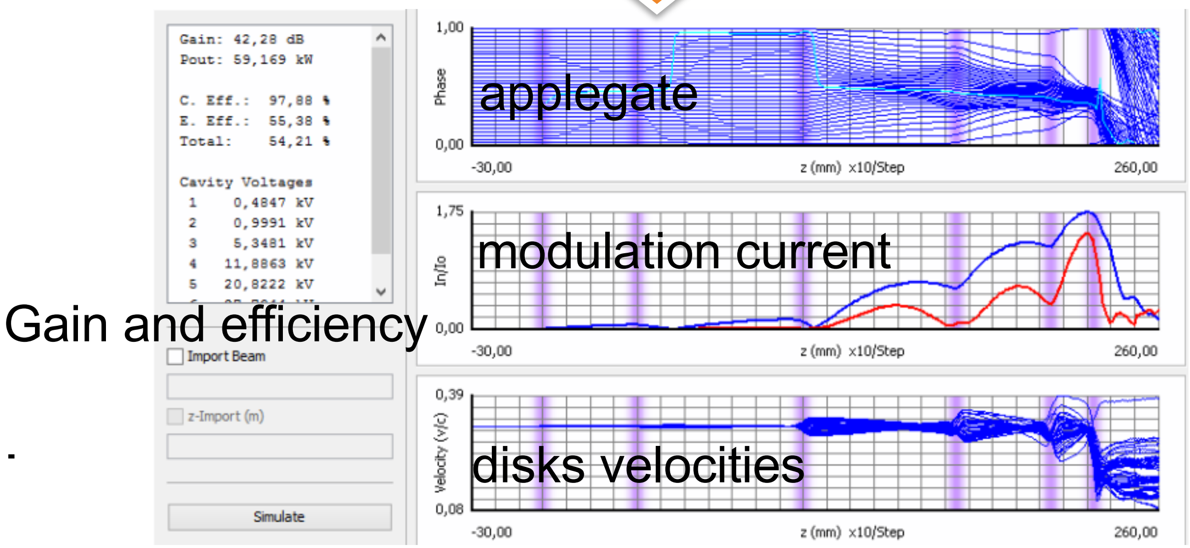
AJDISK (SLAC)

Freely available



Disk & Rings





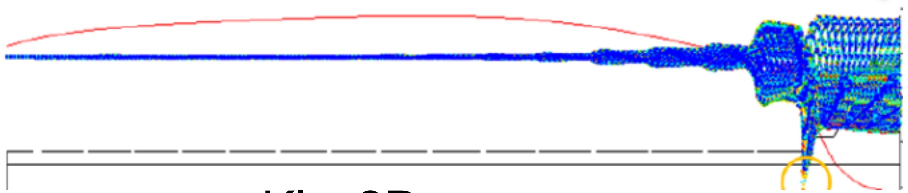
2D CODES : KLYS2D, KLYC, …

- Klystron cavities characterized by lumped circuits (f, R/Q, Q_0, Qext)
- PIC in frequency

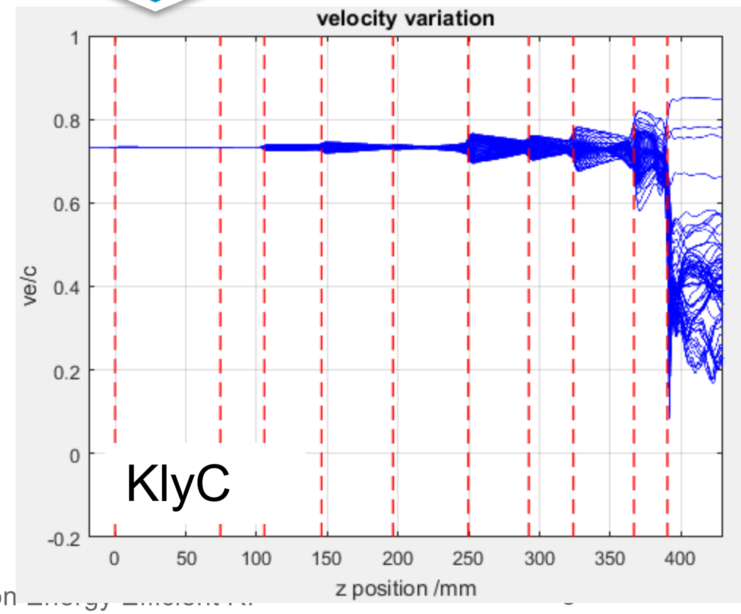
Time ≃ 1 mn

Cavities: R/Q, M, Q_{ext}, Q_0, f_{CAV}, z and geometry (partial)
Beam: V_k, I_k, r_{beam}
Focusing mag. field : B_{z0} or $B_z(z)$

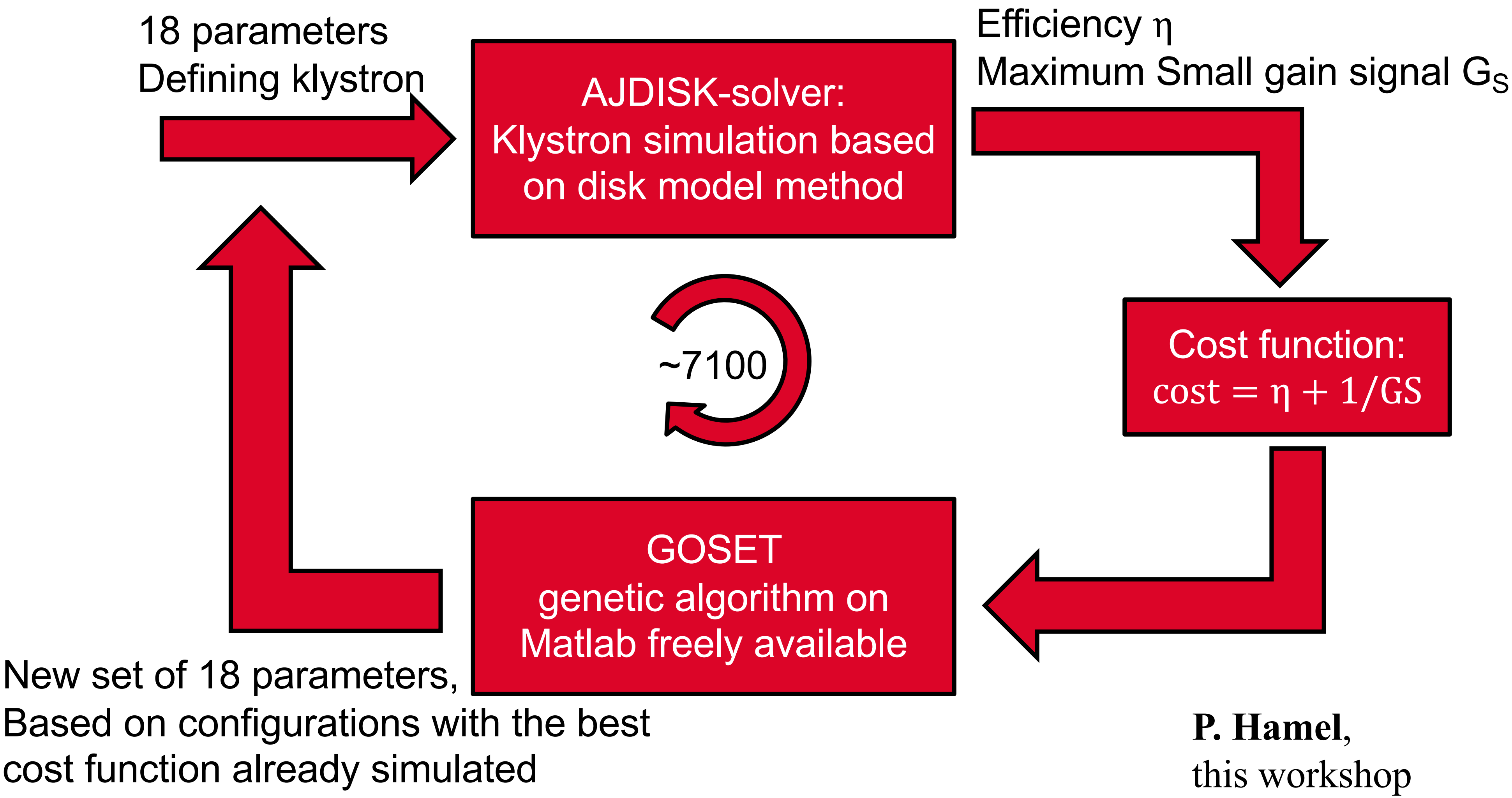
KLYS2D (Thales)
KlyC (CERN)
Klypwin



Klys2D



EXAMPLE OF OPTIMIZATION WITH GENETIC ALGORITHM



P. Hamel,
this workshop

OPTIMIZATION EXAMPLES

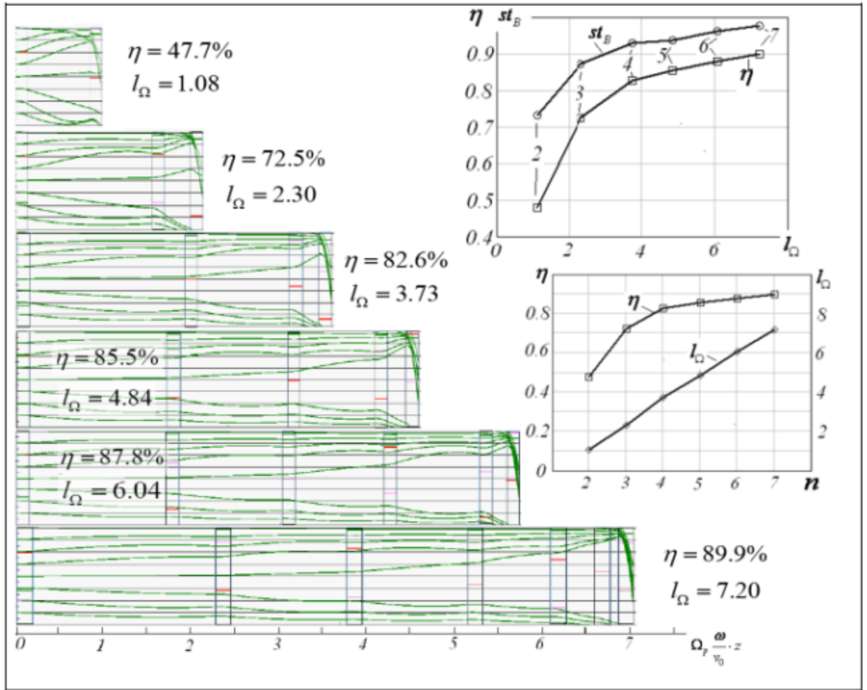


Fig.1. Process of stage-by-stage optimization: η - efficiency, l_Ω-LBL, st_B -bunch saturation, n – number of cavities (stages).

AJDISK with genetic algorithm

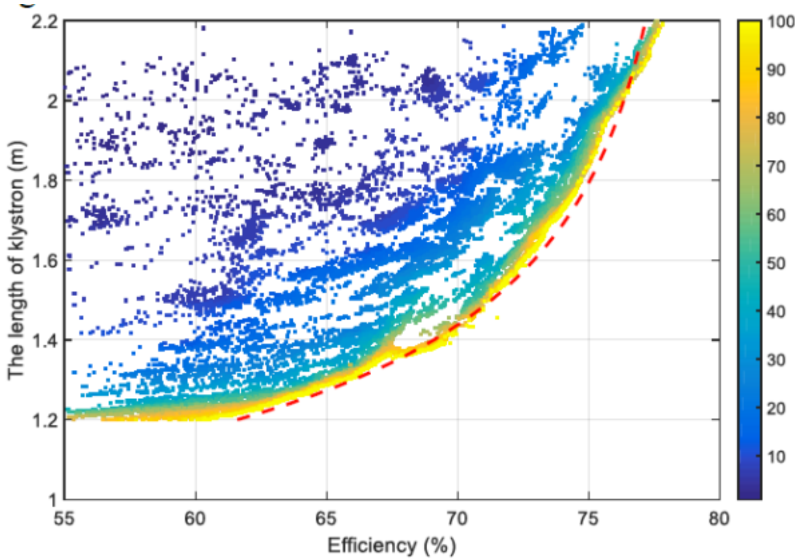


Figure 2: The evolution results for 6-cavity klystron with normal perveance electron gun.

Simulation of High-Efficiency Klystrons with the COM and CSM bunching, Baikov et al., **IVEC2019**

Optimization of klystron efficiency with MOGA, Feng et al, **IPAC2018**

CONCLUSION ON STEADY STATE CODES

Why we use these codes:

They are fast, and allow optimization procedure
They are essential for the development of a klystron
Lab and companies tend to develop their own codes adapted to their specific needs.

Their limits:

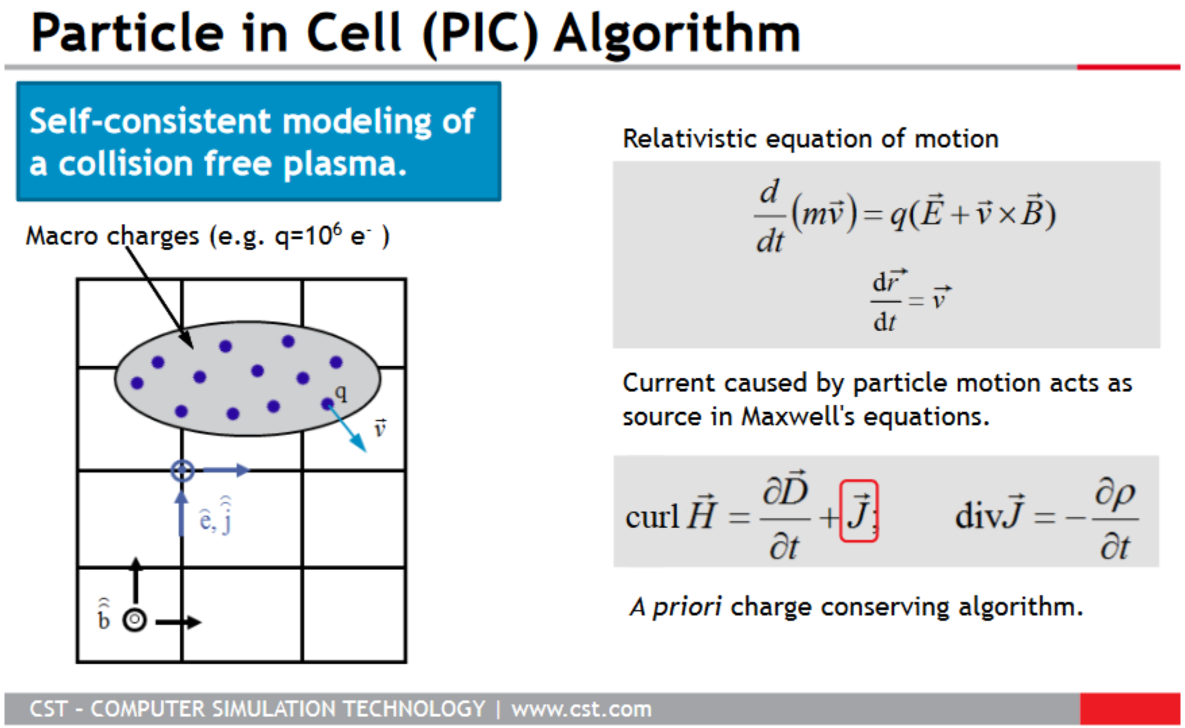
They don't take into account the whole physics and geometry of the klystron
Some of them were developed for conventional klystrons and must be adapted to be valid for new klystron types (COM, BAC, kladistron…)
They cannot predict instabilities

3. 2D AND 3D PARTICLE IN CELL (PIC) CODES

PARTICLE IN CELL CODES

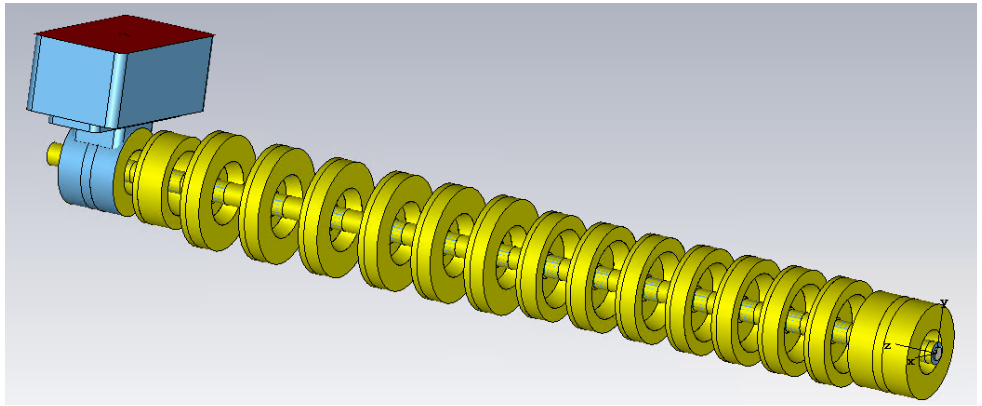
The particle-in-cell (PIC) solver, which works in the time domain, can perform a fully consistent simulation of particles and electromagnetic fields

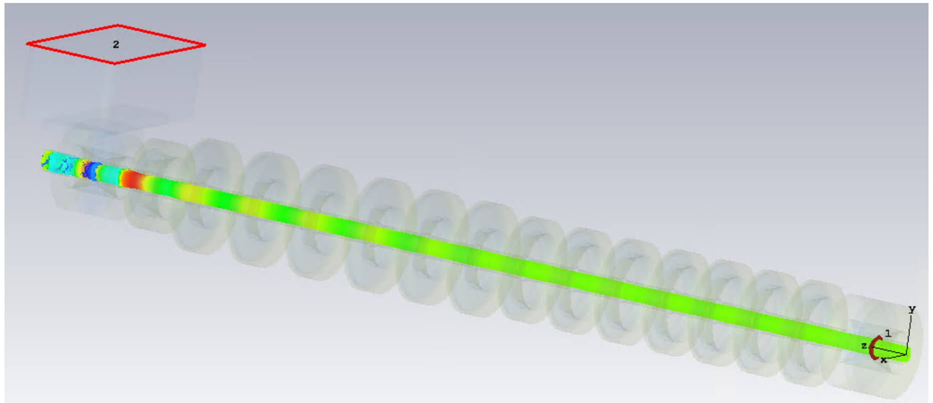
- Integration of the equations of motion.
- Interpolation of charge and current source terms to the field mesh.
- Computation of the fields on mesh points.
- Interpolation of the fields from the mesh to the particle locations



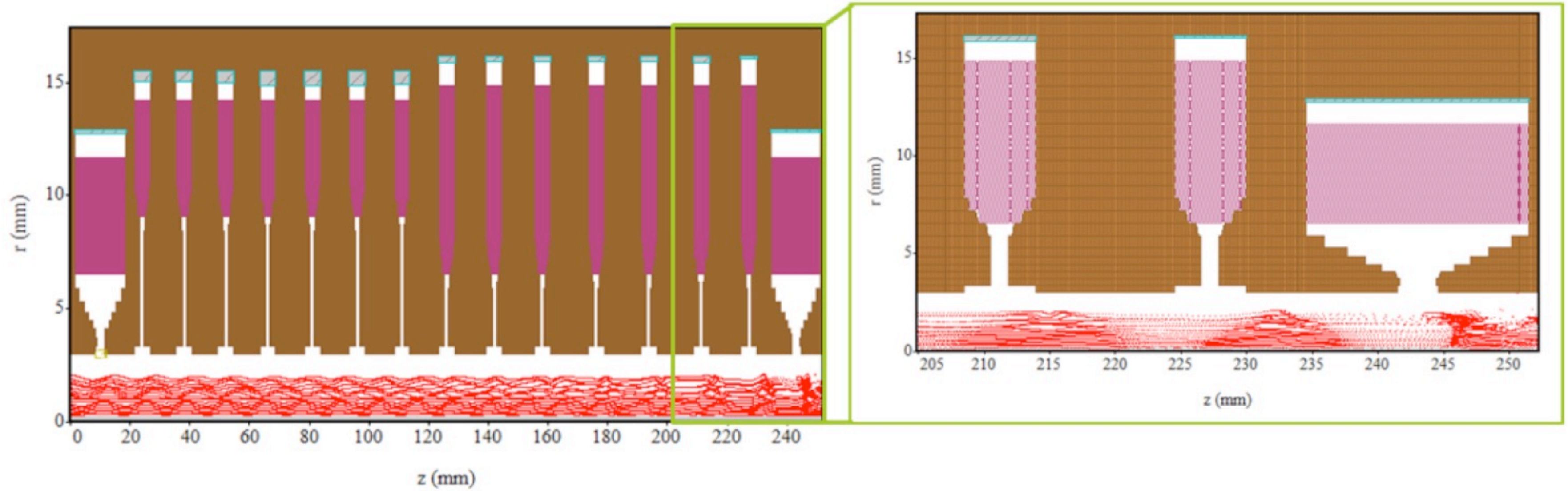
PIC CODES : CST AND MAGIC

CST (Dassault Systems)



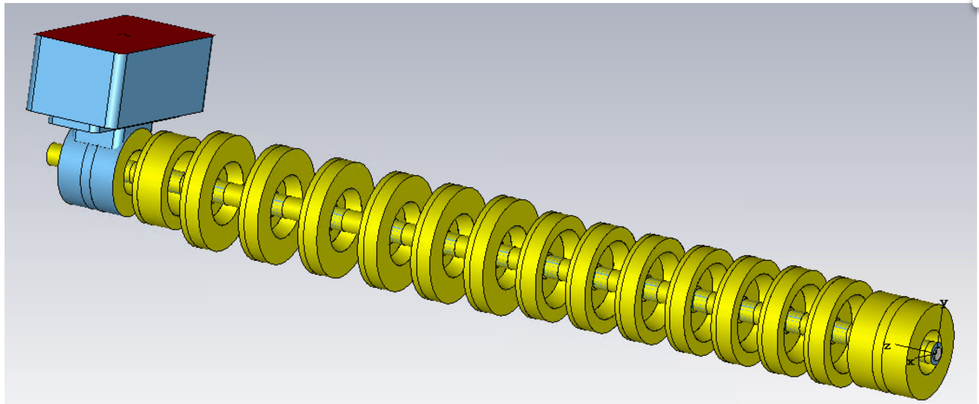


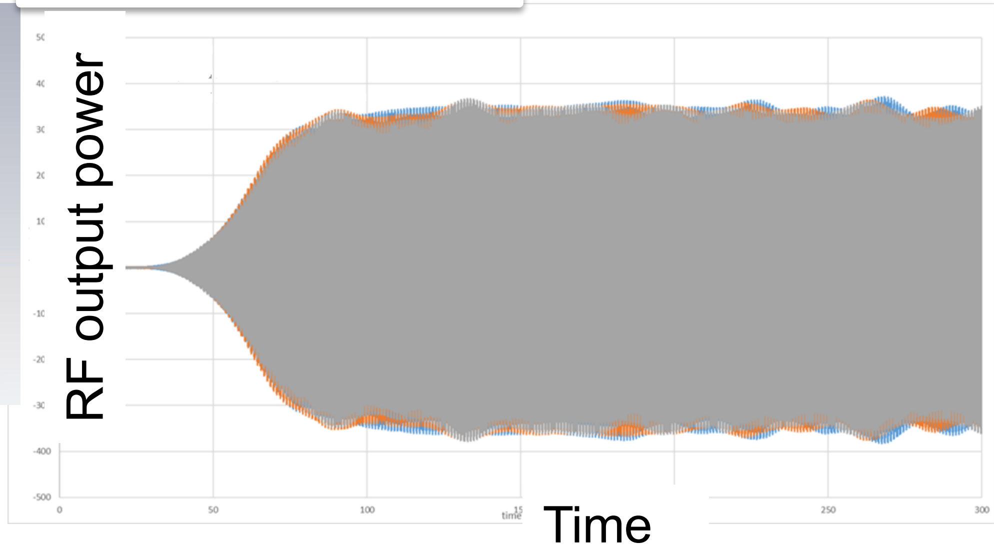
MAGIC 2D (Orbital ATK/Northrop Grumman)



CST EXAMPLE

Time: tens of hours



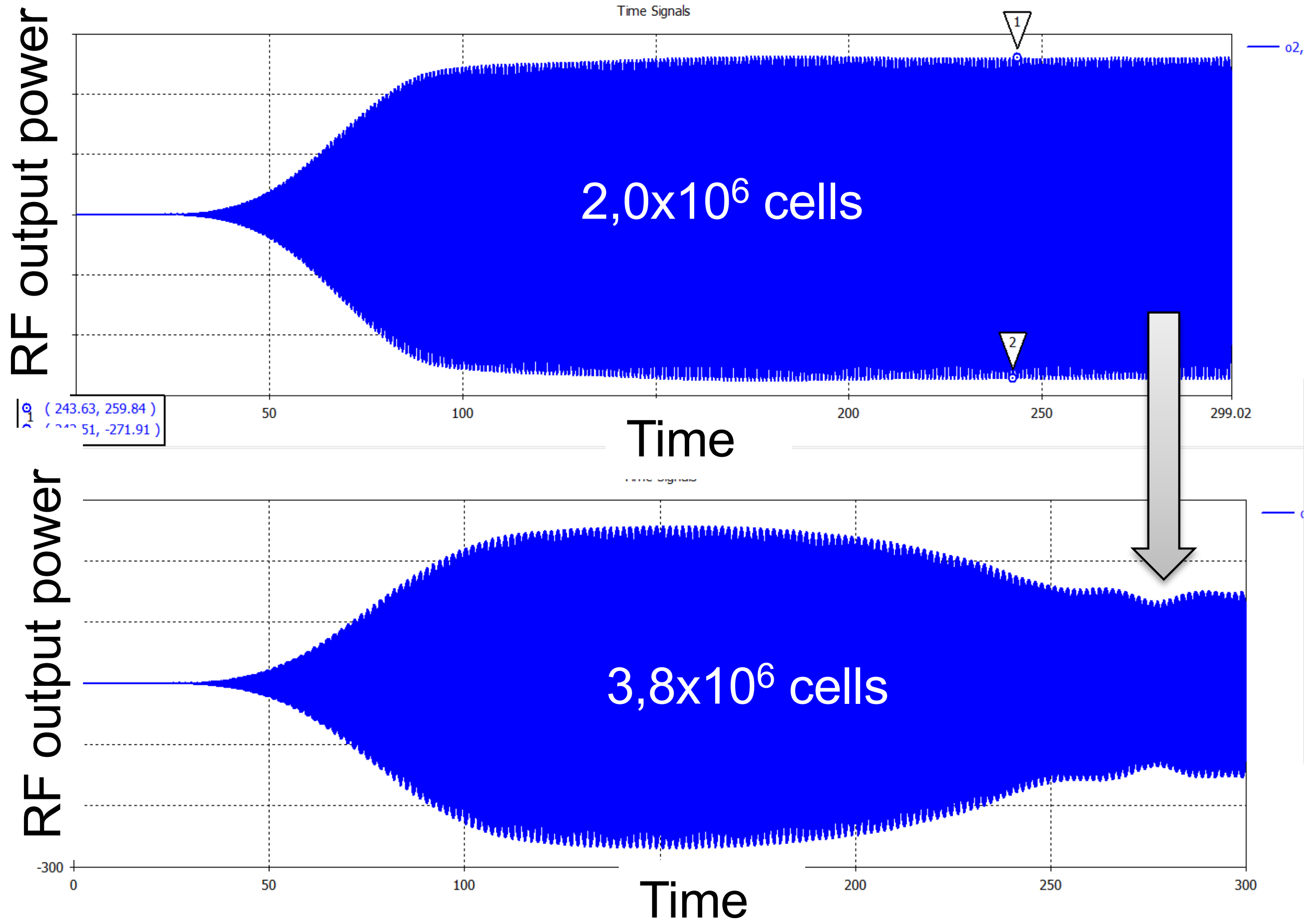


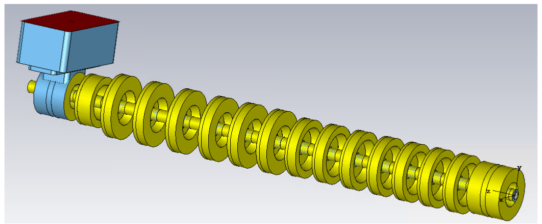
To do list

- Cavity tuning to get expected frequencies
- Mesh adaptation for results convergence
- Numerical noise: must be damped with artificial absorption
- RF signal injection: antenna, waveguide…
- Find input power giving maximal efficiency

The klystron calculated performances can be very sensitive to all these parameters…

NUMERICAL PROBLEM EXAMPLE WITH CST





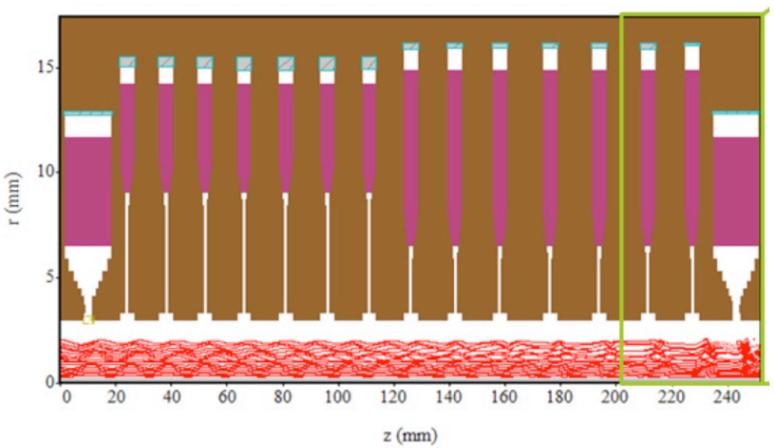
Mesh size increases…
and klystron stability is lost!

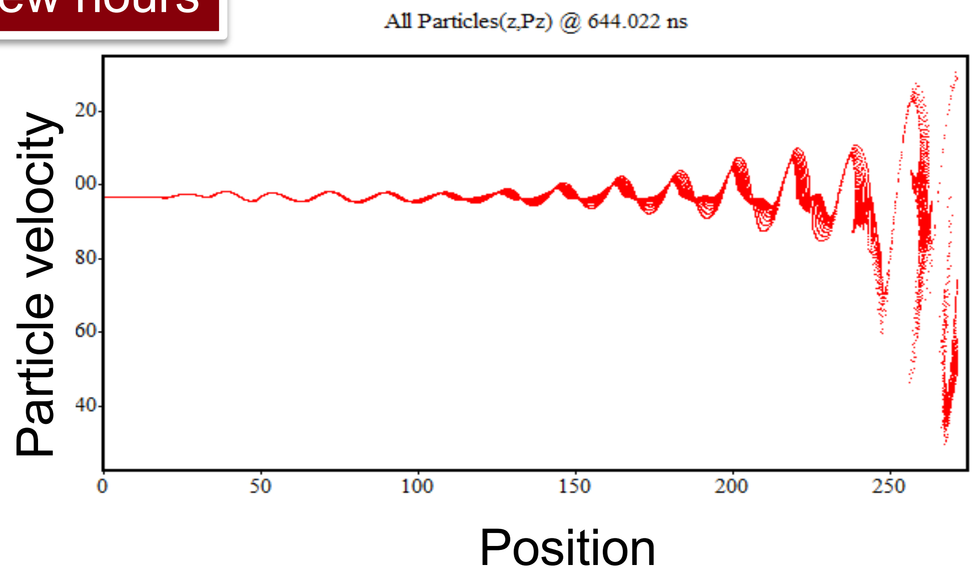
This was due to a numerical problem wich as now been solved

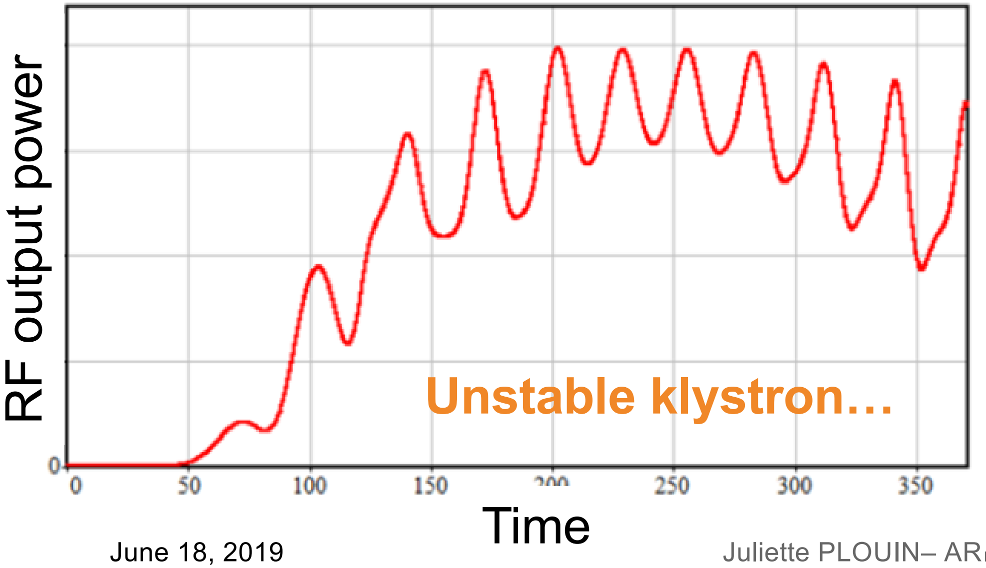
- Check and re-check the validity of your results.
- Discuss with code developers!

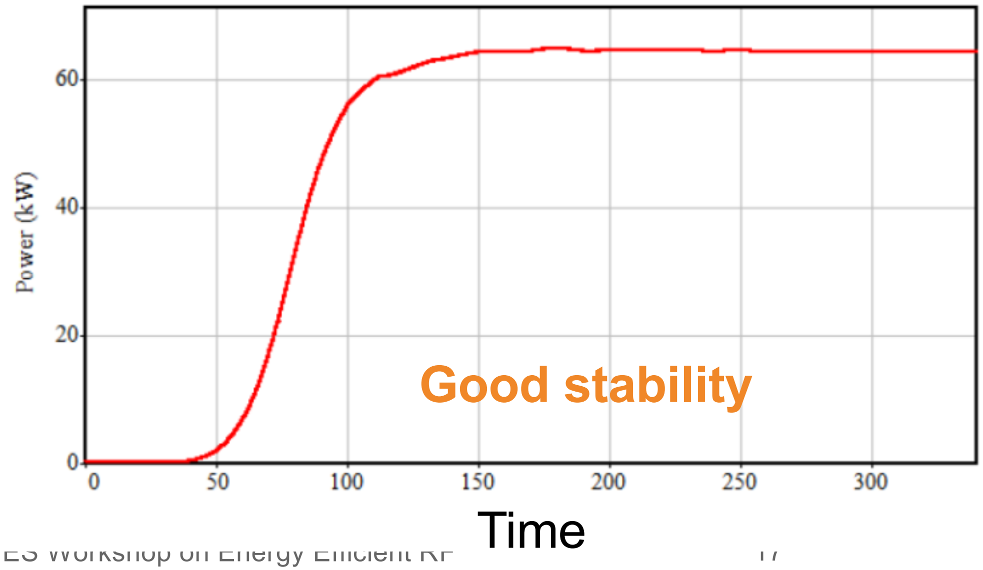
MAGIC 2D EXAMPLES

Time: few hours







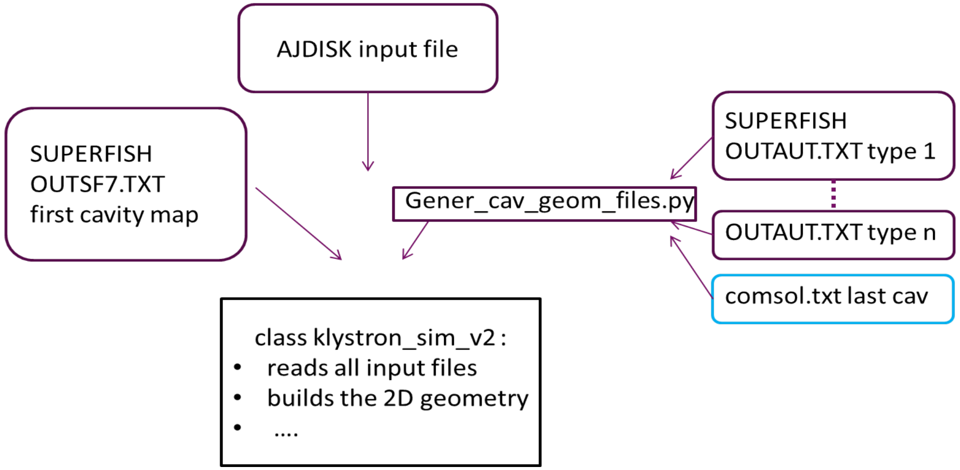


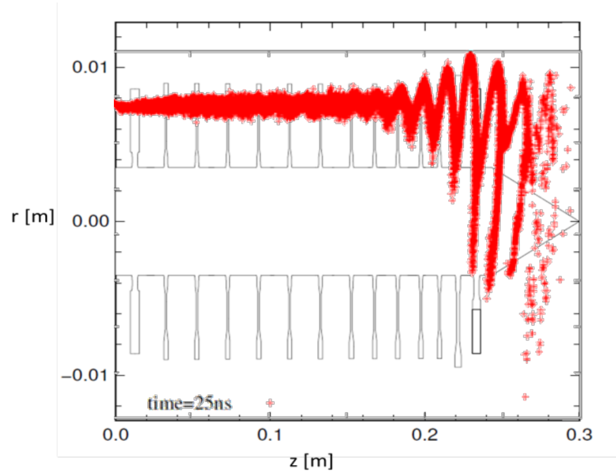
OTHER PIC CODES

GDFidL : work was done on klystron but doesn't seem to have been continued

Warp is an extensively developed open-source PIC code designed to simulate charged particle beams with high space-charge intensity. It has been developed at Lawrence Berkeley National Laboratory, CA, USA. It's a free and open source code.

Klystron class developed at CEA for Warp (interfaces with superfish and AJDisk)





Conclusion in 2015: "*Warp shows high potentiality to simulate the klystron as built without any assumption, but a deeper knowledge of the code is still needed.*"

CONCLUSIONS ON PIC CODES

Why we use these codes:

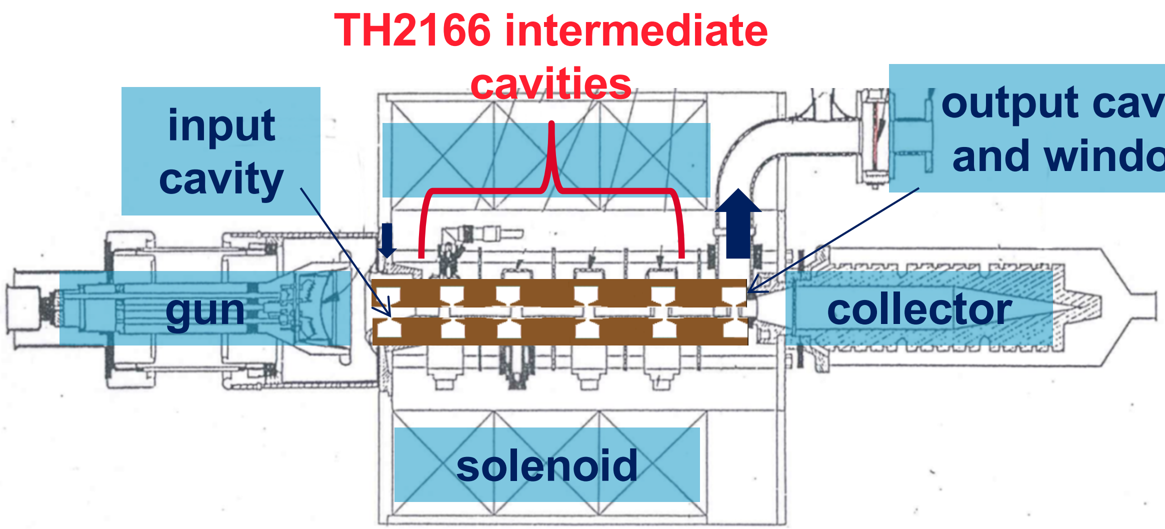
Their agreement with geometry and physics of klystrons is much higher.
They allow verification of the klystron performances after optimization
These codes are developed and sold by private companies, are maintained, and propose technical support (CST people are very active in the microwave tubes community)

Their limits and difficulties:

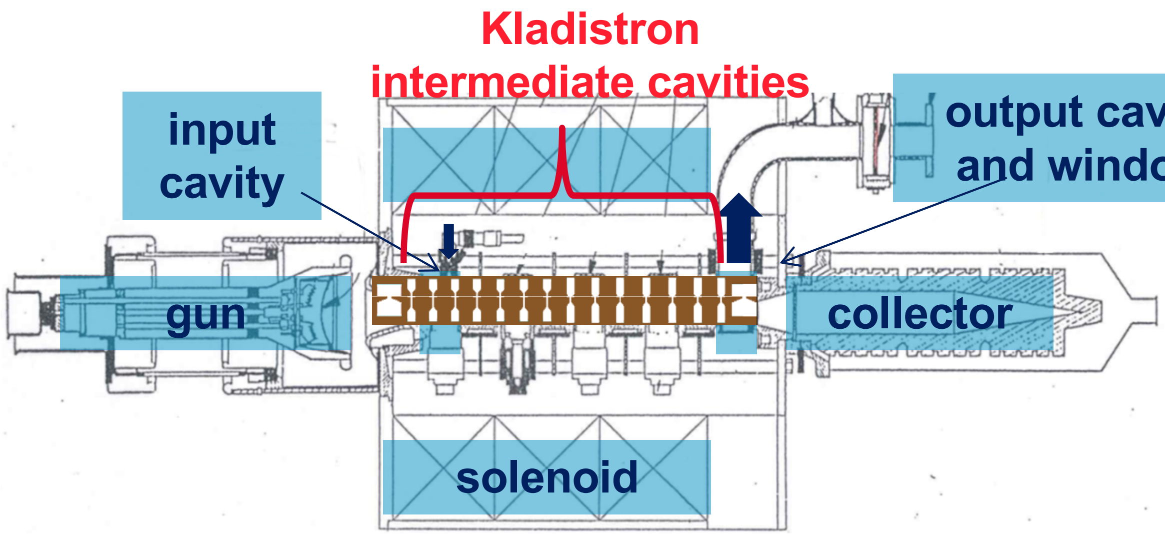
They are time consuming, and are not fitted for optimization procedure.
They require good knowledge of their operation to avoid fake results.

4. CODE RESULTS COMPARISON

Thales TH2166 klystron - 6 cavities



CEA/Thales kladistron - 16 cavities



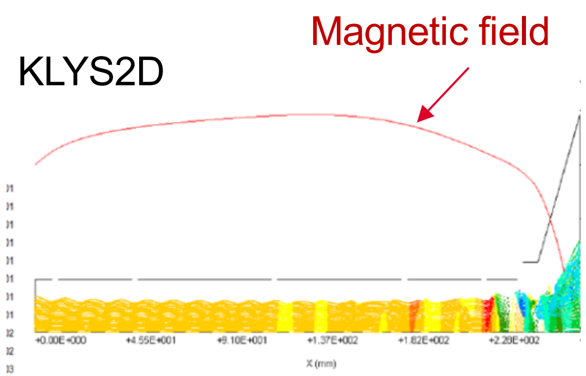
During EUCARD², a kladistron operating in the C-band (5 GHz) has been designed and manufactured, from the design of the existing Thales klystron TH2166 in view of increasing efficiency.

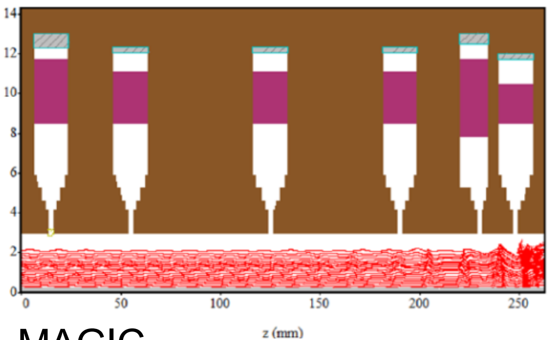
Same elements

COMPARISON BETWEEN CODES FOR TH2166

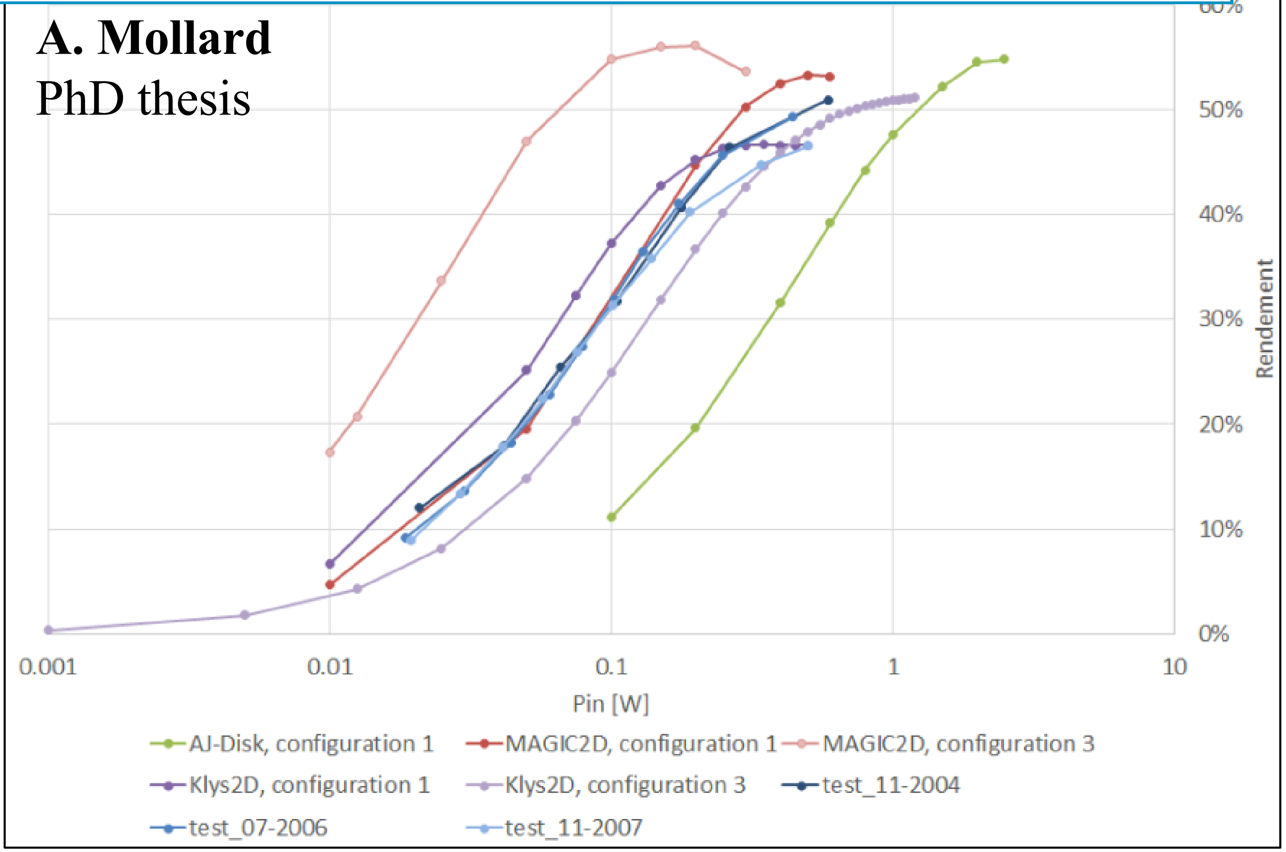
Configurations	Initial beam	Magnetic field
1	Laminary	Uniform
3	From Optic2D (Thales code for electron gun)	Real values

KLYS2D



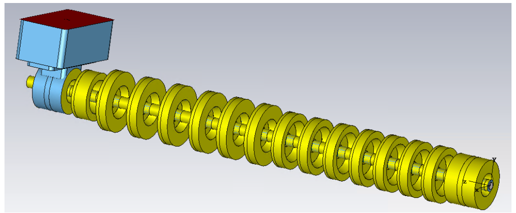


MAGIC

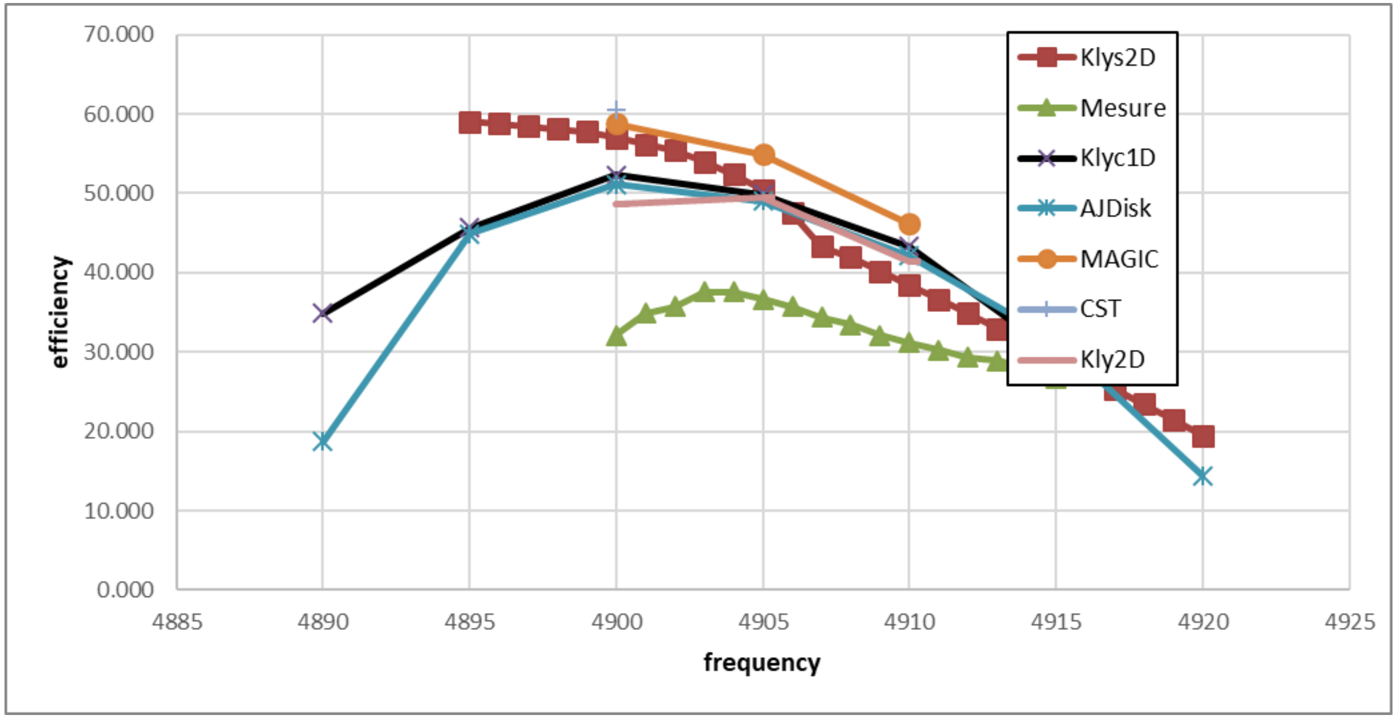


Efficiency spread [45-55%] depending on code AND configuration

COMPARISON BETWEEN CODES - KLADISTRON



CST



P. Hamel courtesy

- Efficiency spread [50-60%] depending on code simulation
- The measured efficiency is lower than expected
  - this point is presently explored with retro-simulations
  - spurious oscillation has been observed

HOW TO PREDICT SPURIOUS OSCILLATION ?

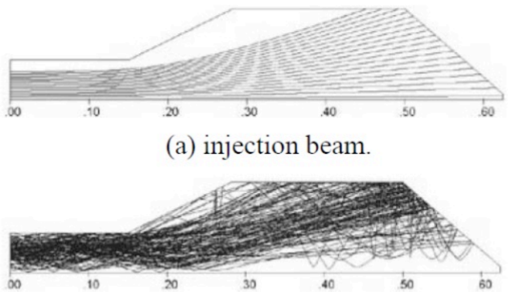
Spurious oscillation in klystrons can occur when:

- **Backstreaming electrons** turn in resonance in the interaction lines
- **Monotron** oscillation is excited

- In principle, these phenomena cannot be simulated with the steadystate codes (even if the conditions – high gain for example- can be predicted).
- In principle, these phenomena can be simulated in PIC codes

However, the conditions leading to such oscillation can be very tricky

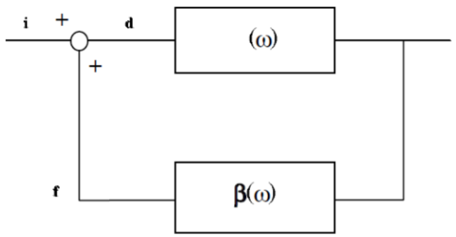
Up to now, I didn't find a paper showing that a spurious oscillation measured in a klystron was properly generated by a PIC code. ⇨ **Still this is an issue.**



(a) injection beam.

(b) backstreaming electrons.

Fig. 7: Trajectories of the injection beam and backstreaming electrons in klystron #1.



Example of dedicated simulations of electrons reflected from a collector, responsible of spurious oscillation

Instability caused by backstreaming electrons in klystron, **Fang**, APAC, 2001

CONCLUSION

- No code will be a perfect representation of a klystron reality, and this has never stopped the fabrication of good klystrons.
- The development of codes has allowed the study of more complicated, subtle interaction lines.
- Those last years, new efficient bunching methods could be developed (COM, BAC, kladistron,…) and start to give good experimental results
- Systematic optimization techniques, in particular with genetic algorithms, are probably a promising tool for the future
- The complete simulation of a klystron in 3D is now possible, and helps a lot for checking some issues, but is not a turnkey solution.