KlyC: Large signal simulation code for Klystron

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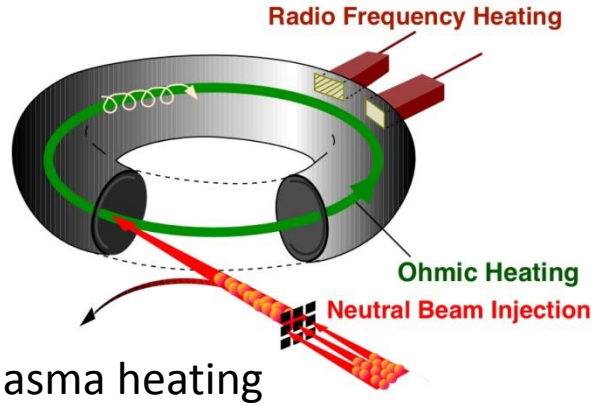
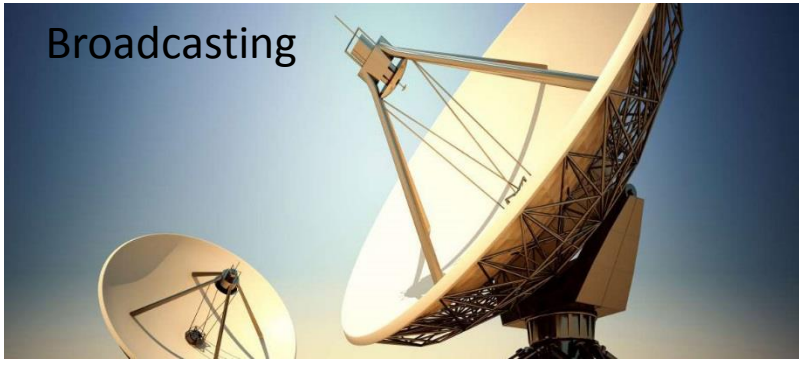
2018/1/24

Areas of Klystron's Applications

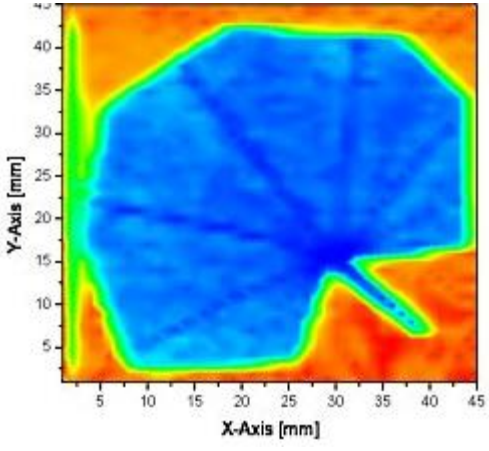


Plasma heating



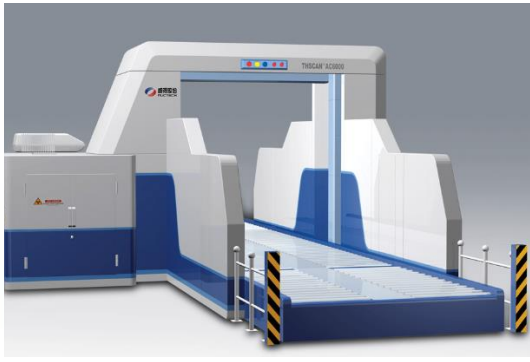
Particle accelerator

Radiation oncology

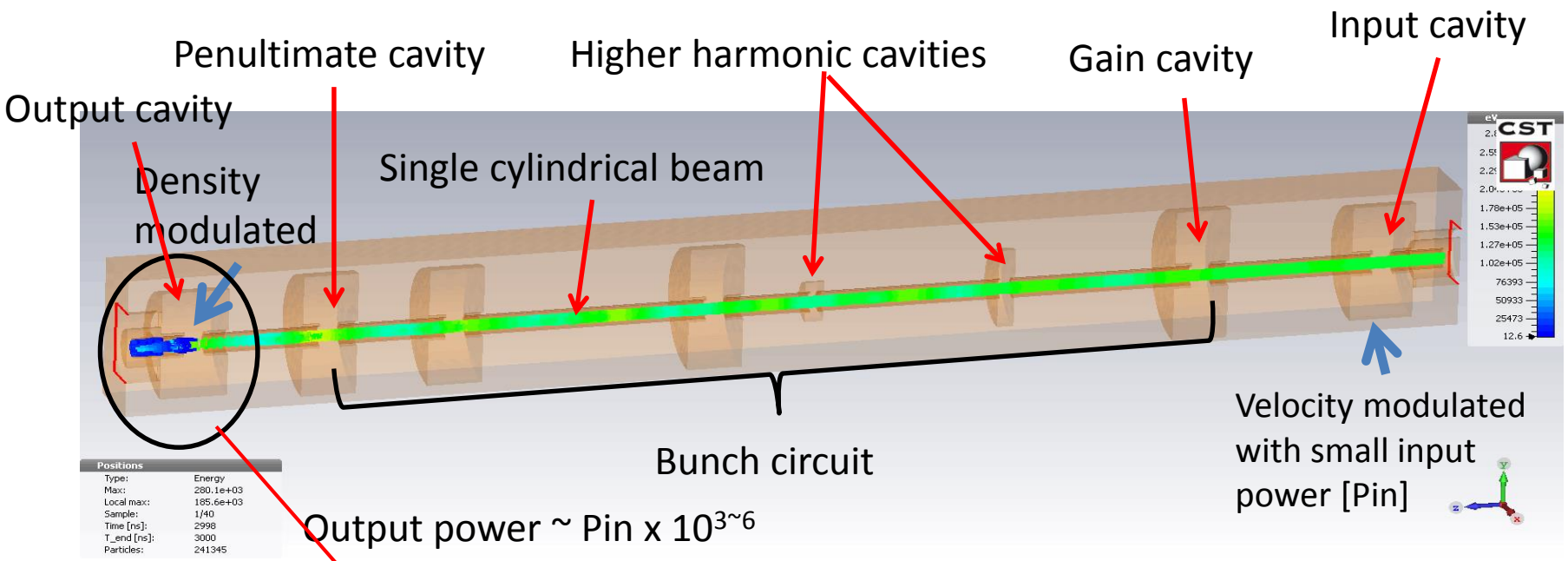


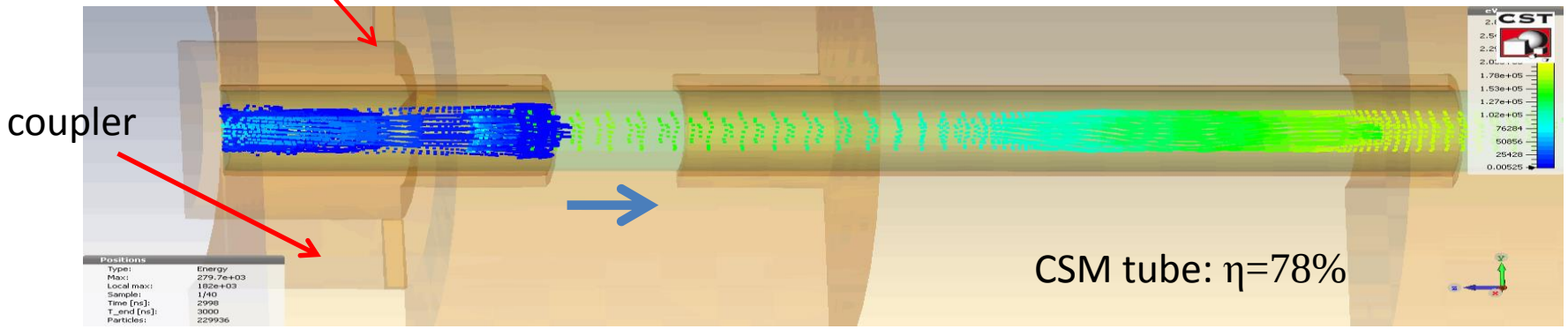
imaging

Security(cargo scanner)



Mechanism and concepts



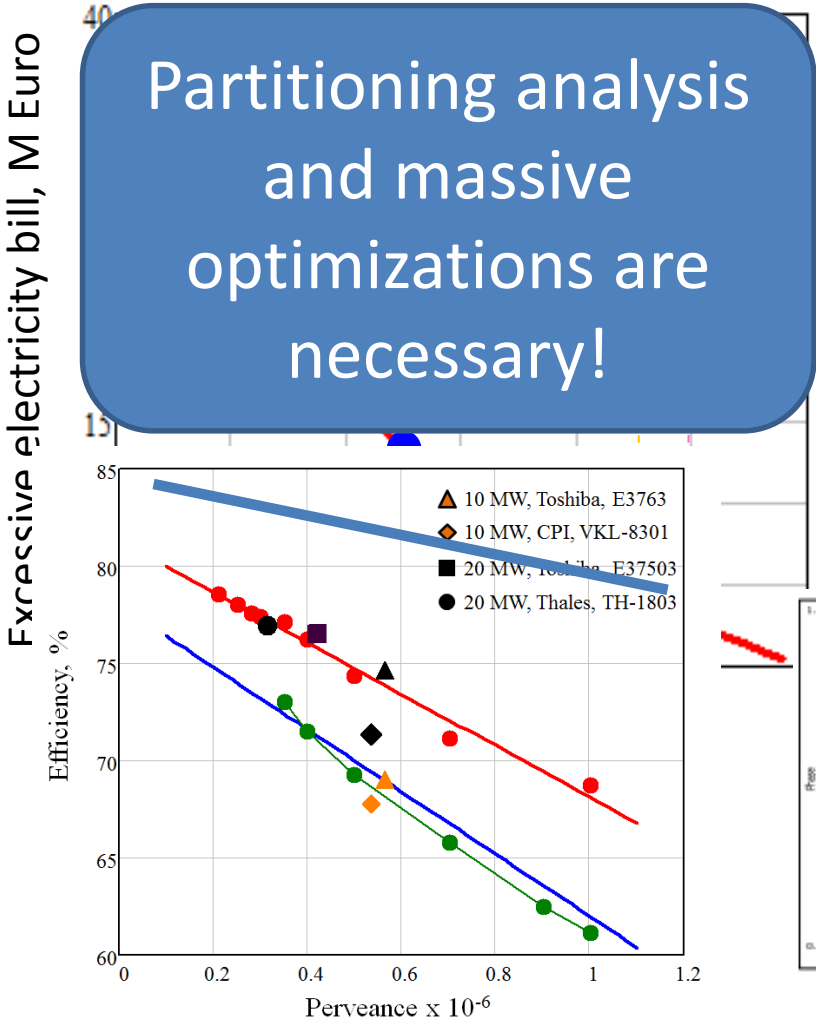


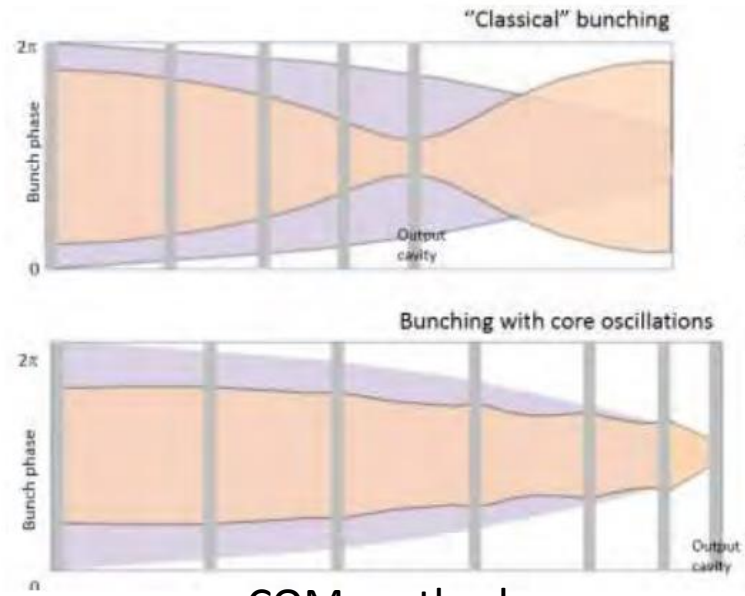
Glossary: Saturation, velocity congregation, Radial stratification

High Efficiency International Klystron Activity lead by CERN

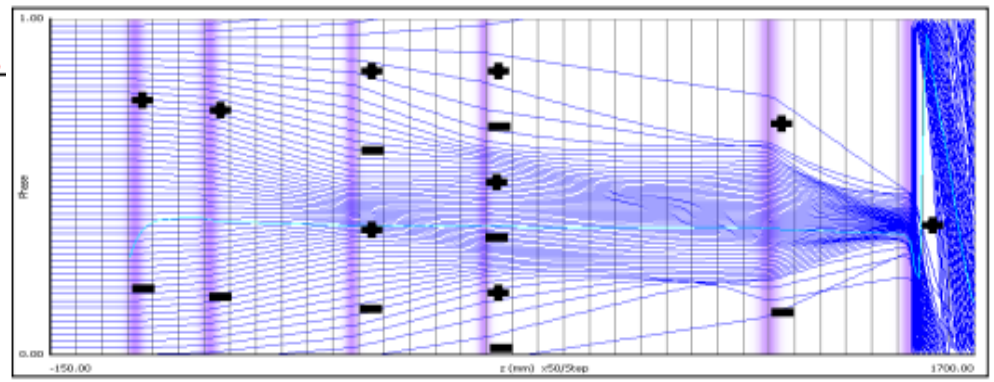
FCC $^{e+e-}$ at 50 Euro/MWh and 5000 hours/year:

Partitioning analysis and massive optimizations are necessary!





COM method:



CSM method

Available Simulation tools

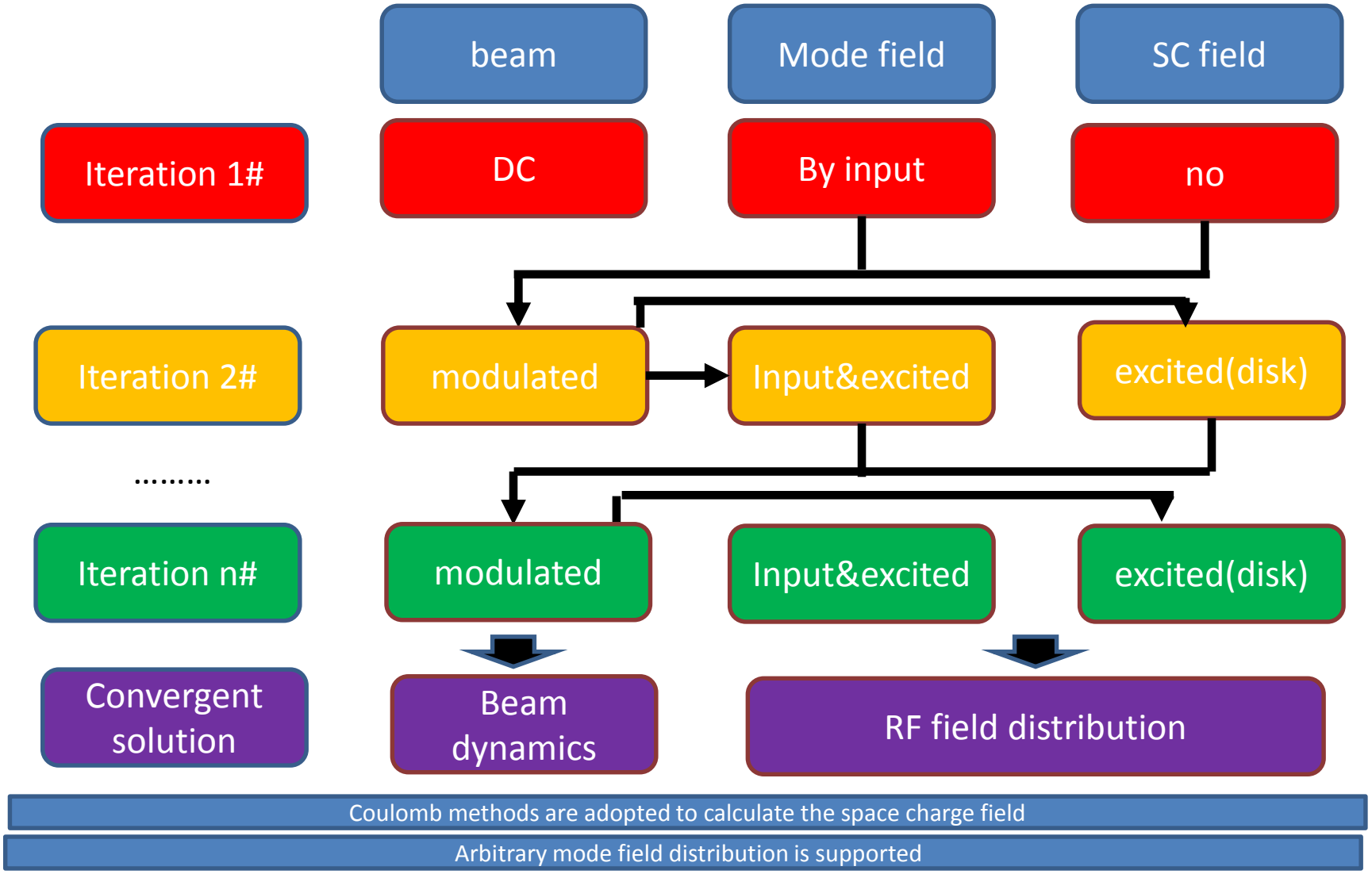
- Disk model: AJDISK,Klys4.5,Dev5,Klypwin
- Discrete model: Tesla, **KlyC**
- PIC:FCI,MAFIA,CST PIC, Magic, GDFIDL, Vorpal (+?)

Of all of them only AJDisk is a non-commercial product.

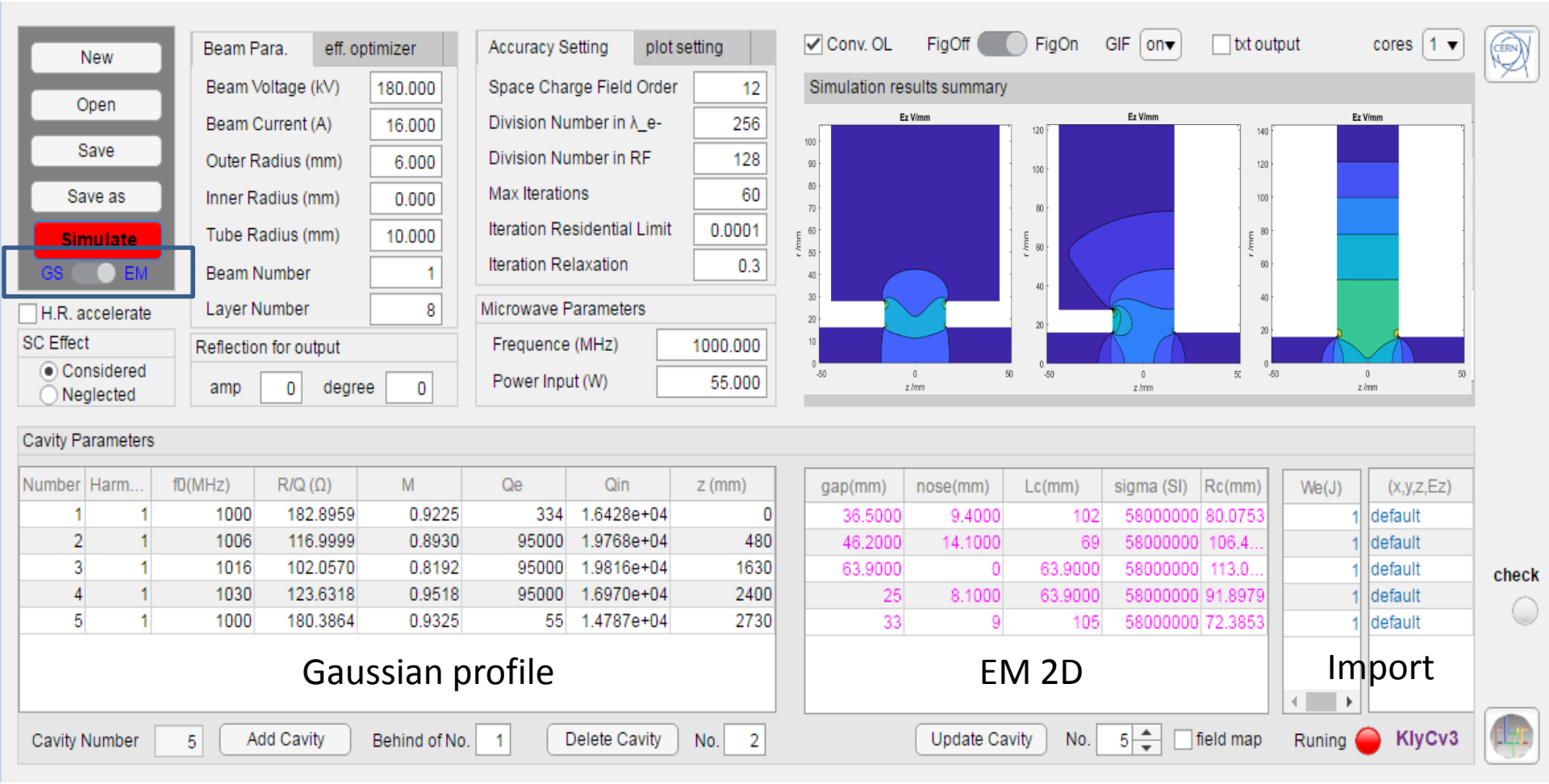
Klyc1D/2D potentials:

1. Free access for the klystron community.
2. Efficiency, much faster (~1/1000) simulation than PIC
3. Precision, 2D simulation are supported ('frozen' beam)
4. Diversity, possible extension to other Klystron's topologies (Multi-gap, Multi-beam, Traveling wave structure etc…)
5. Flexibility, full adapted for special needs (partitioning, bunched beam generation etc.) and versatile output data interface.

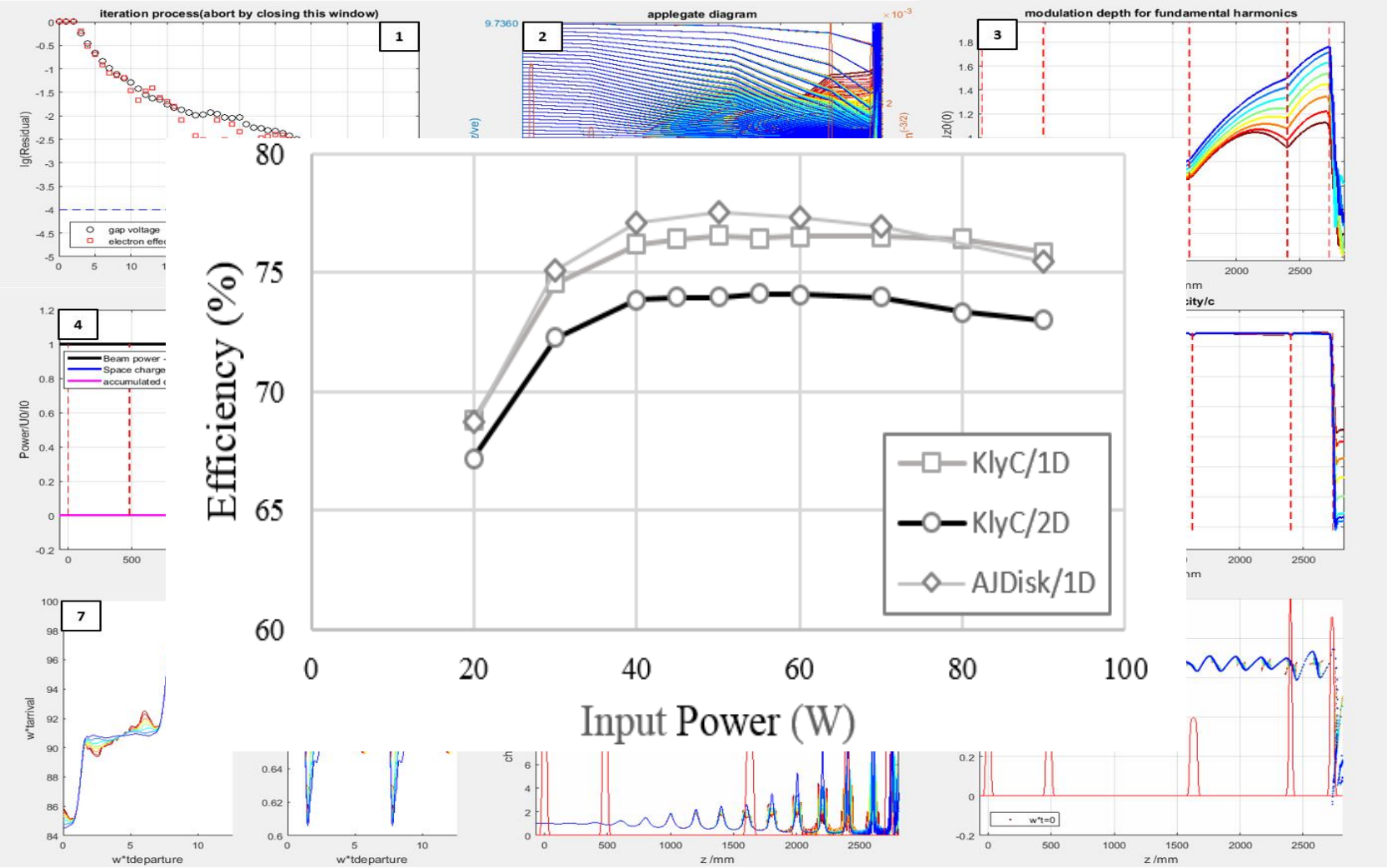
Simplified Algorithm for code “KlyC”



KlyC Graphical User Interface



KlyC Graphical outputs



FCC#6. KlyC2D vs MAGIC

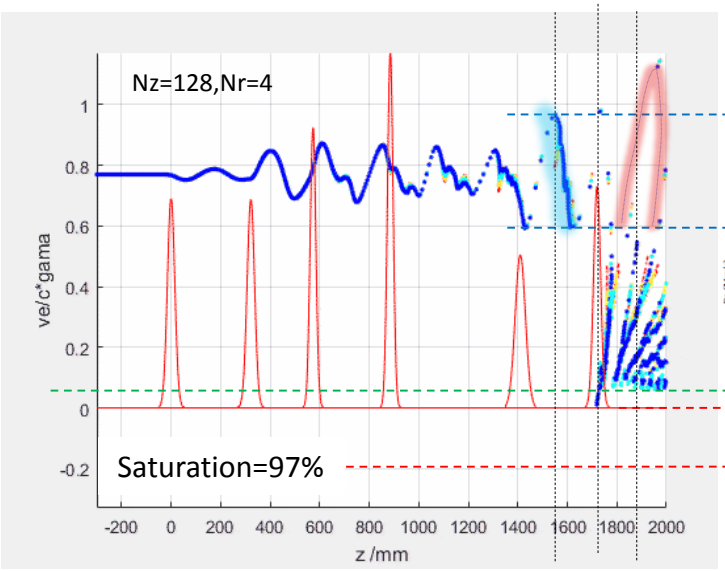
Low beam perveance CSM tube

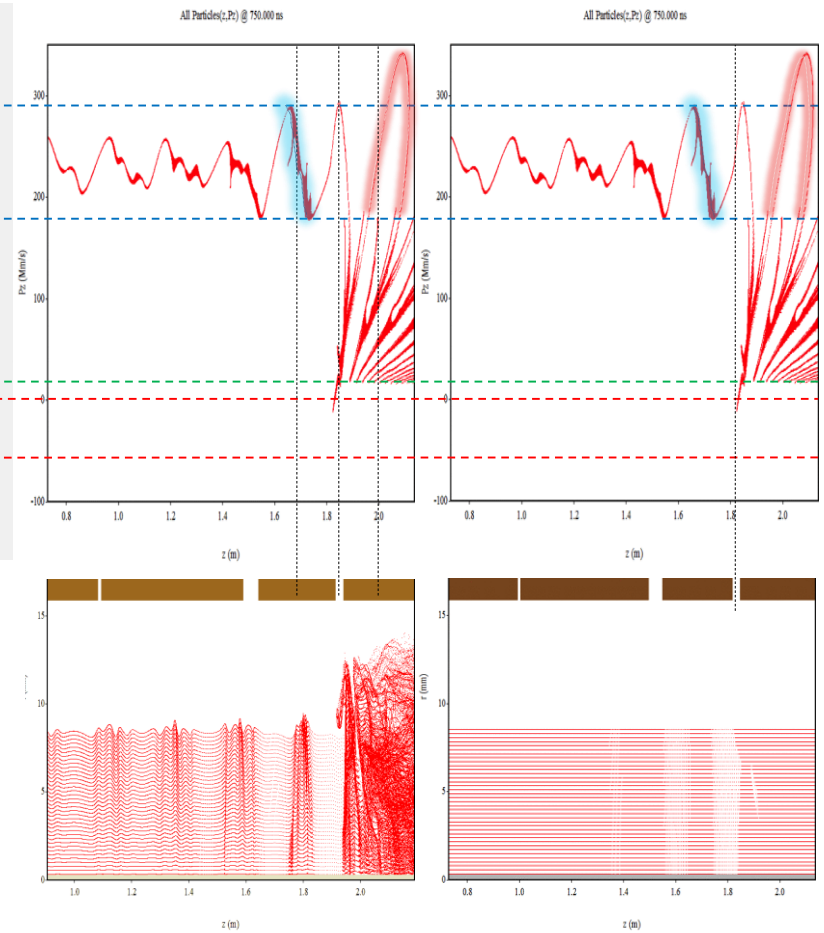
Beam settings :

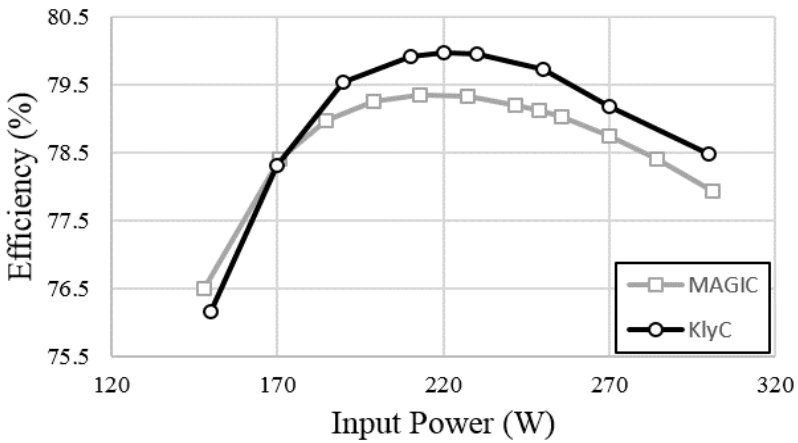
Nz=256,Nr=4, η=79.7%,Tcpu= 20 min

MAGIC (0.07T) **2D**, 79.4% MAGIC (20T) **2D**, 79.6%

Tcpu = 4000 min (~1ooo ns)

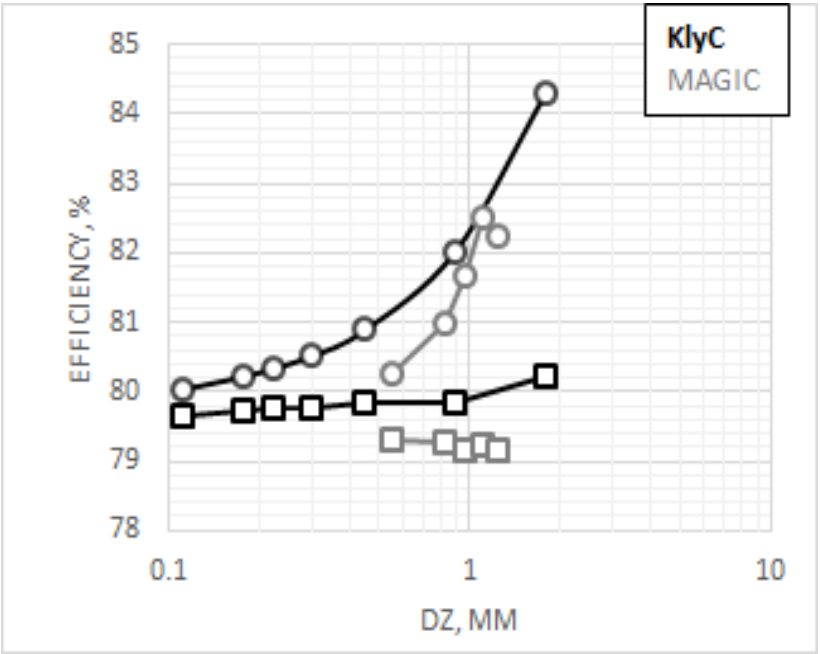


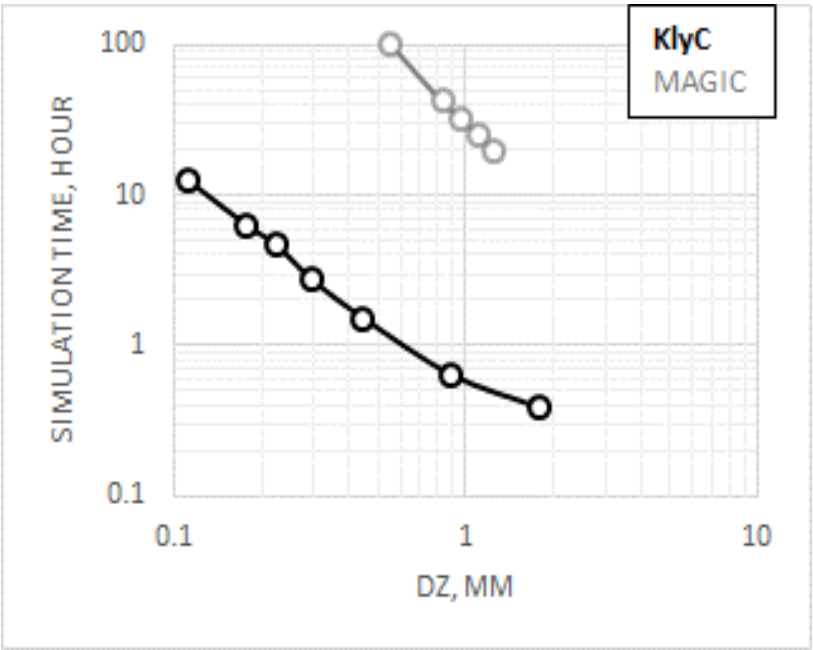




The radial bunch 'expansion' in output cavity (MAGIC2D) practically does not affect efficiency. This validates KlyC2D as an attractive (and fast) tool.

Convergent analysis





$$P_{RFB} = V_0 I_0 - P_{BK} - P_{Ohm} - \Delta P_{SC} + P_{\text{in}}$$

$$\Delta P_{SC}(z) = \iint [J_{z0} \cdot E_{z0} + \frac{1}{2} Re(J_{z1}^* \cdot E_{sz1}) + \frac{1}{2} Re(J_{z2}^* \cdot E_{sz2}) + \cdots] \times 2\pi r dr dz$$

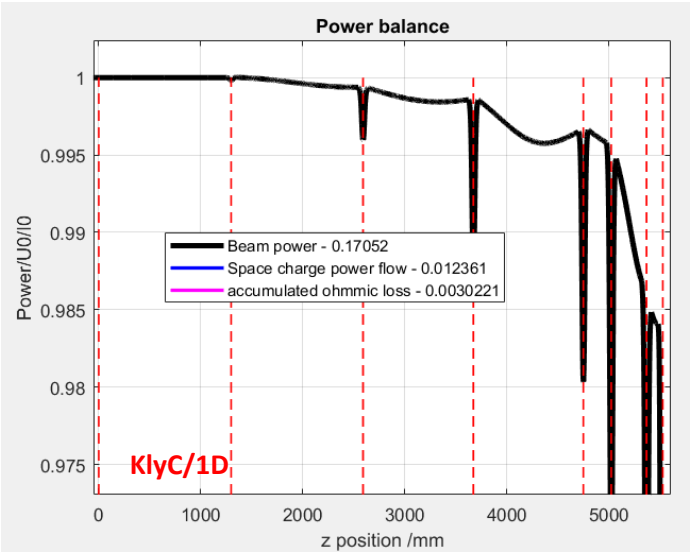
Energy conservation law is abided

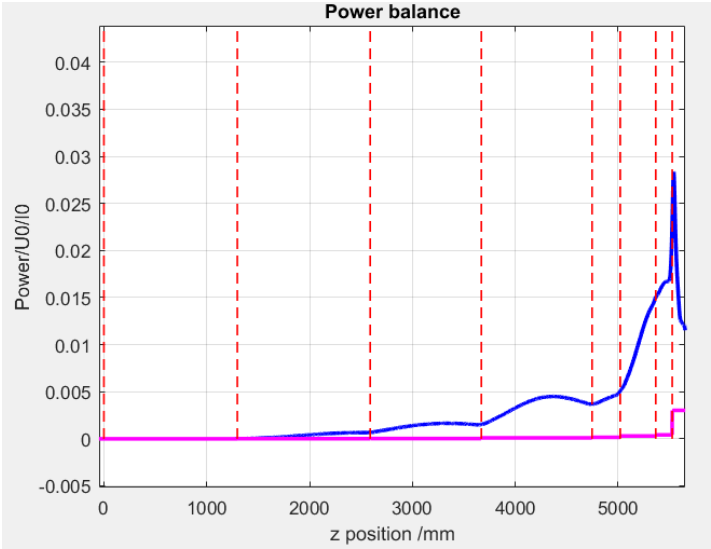
Optimised FCC COM tube

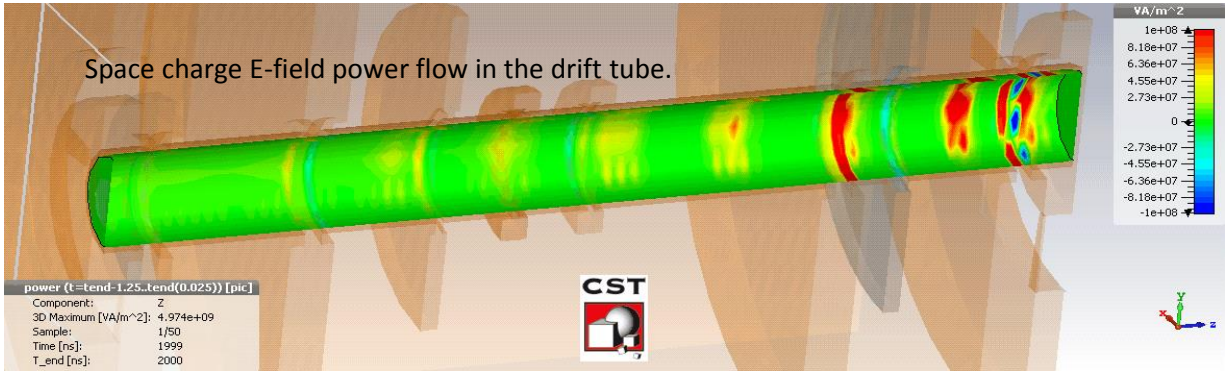
Potential energy in space charge field

Ohmic losses and **"Sabre" effect** . The later one comes from the fractional conversion of the kinetic energy of the non-modulated beam into a) electrostatic energy of the bunched beam and b) differential potential energy of the spent beam.

In KlyC the space charge power flow can be calculated directly:

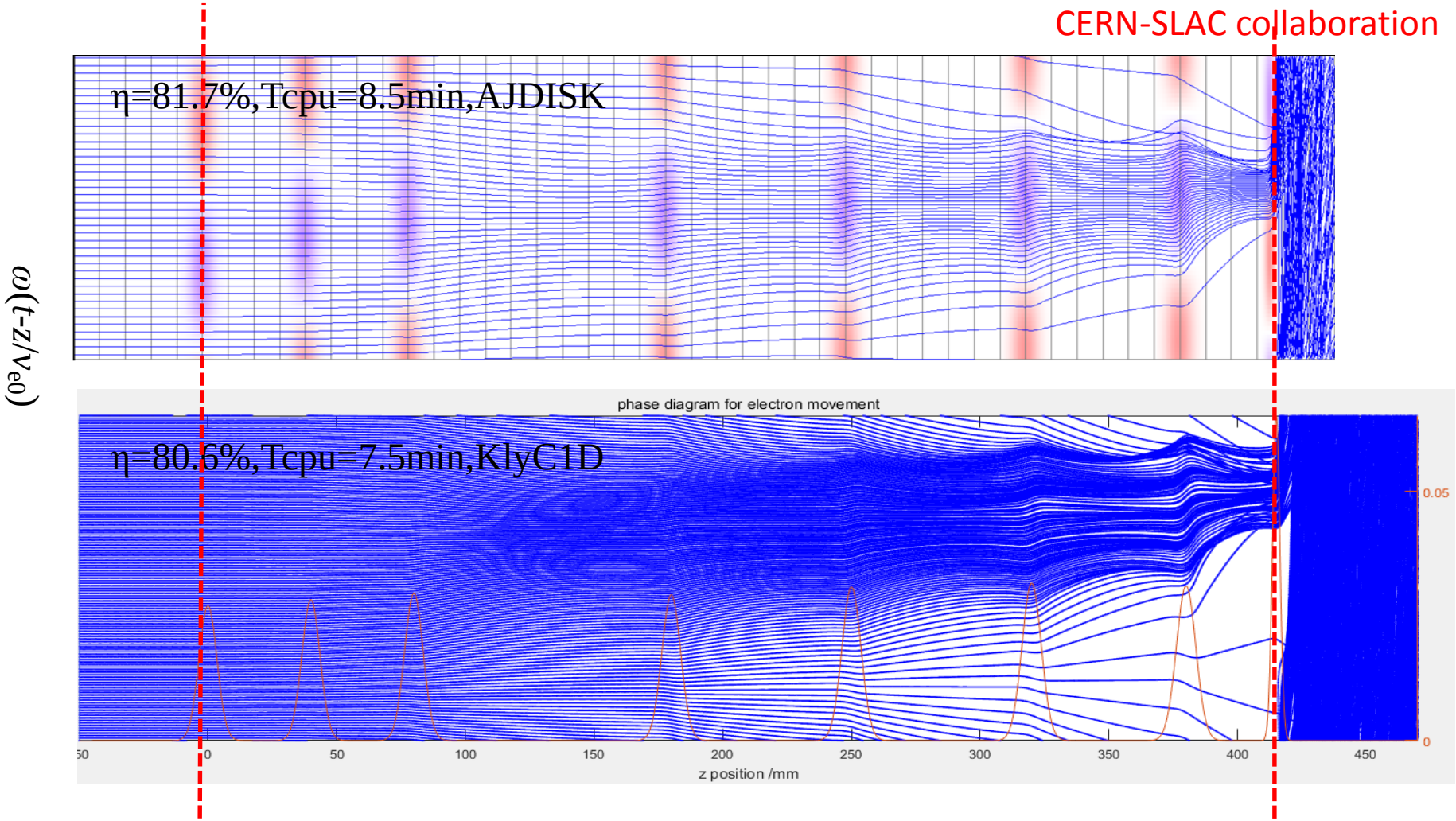




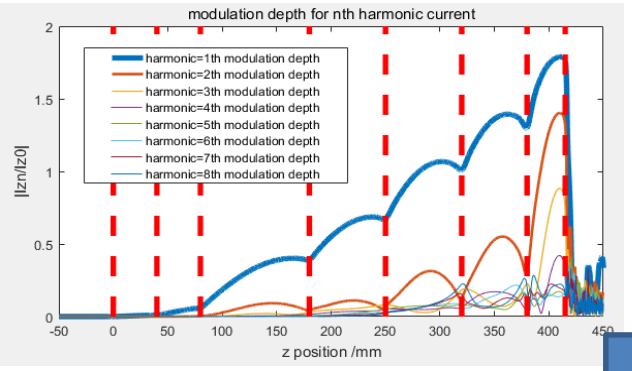


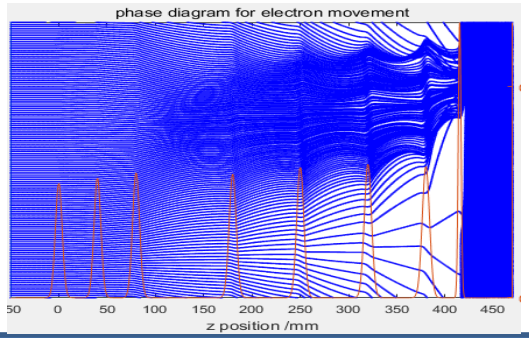
AJDisk vs Kly1D high perveance(1.2μP) HE COM tube X-band 50 MW

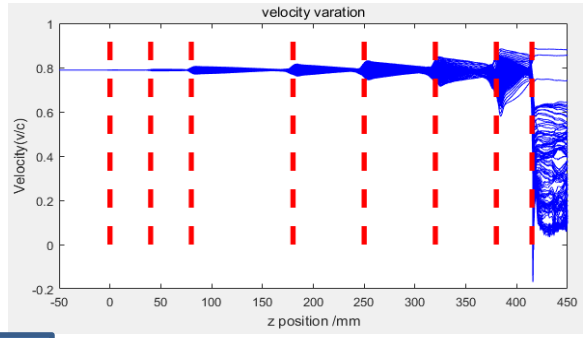
CERN-SLAC collaboration



Klyc2D vs KlyC1D

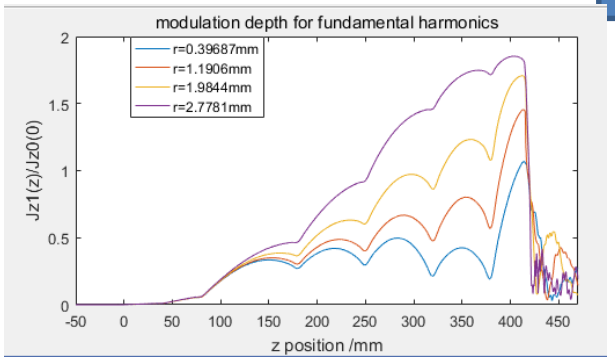


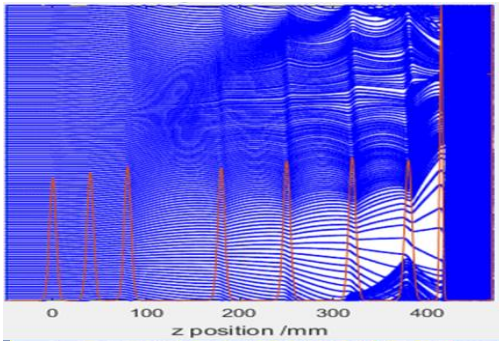


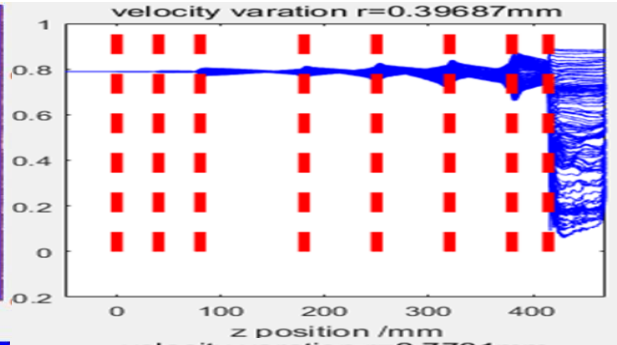


1D

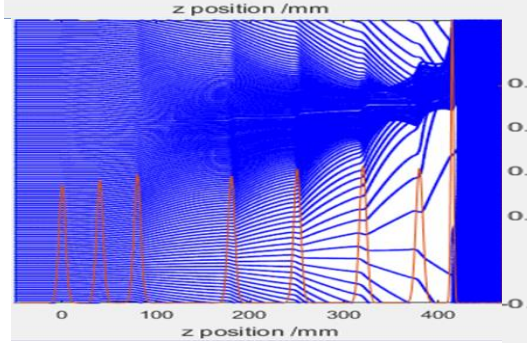
KlyC1D η=80.6% Tcpu=8min

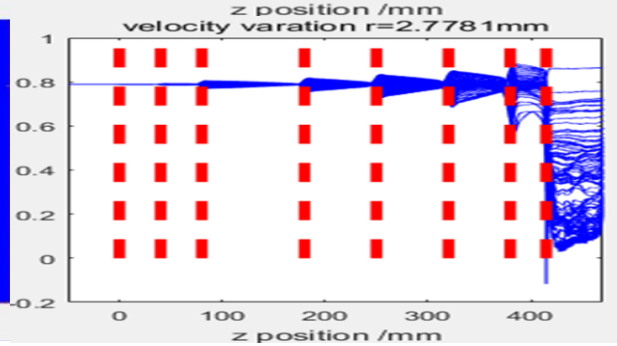






axial





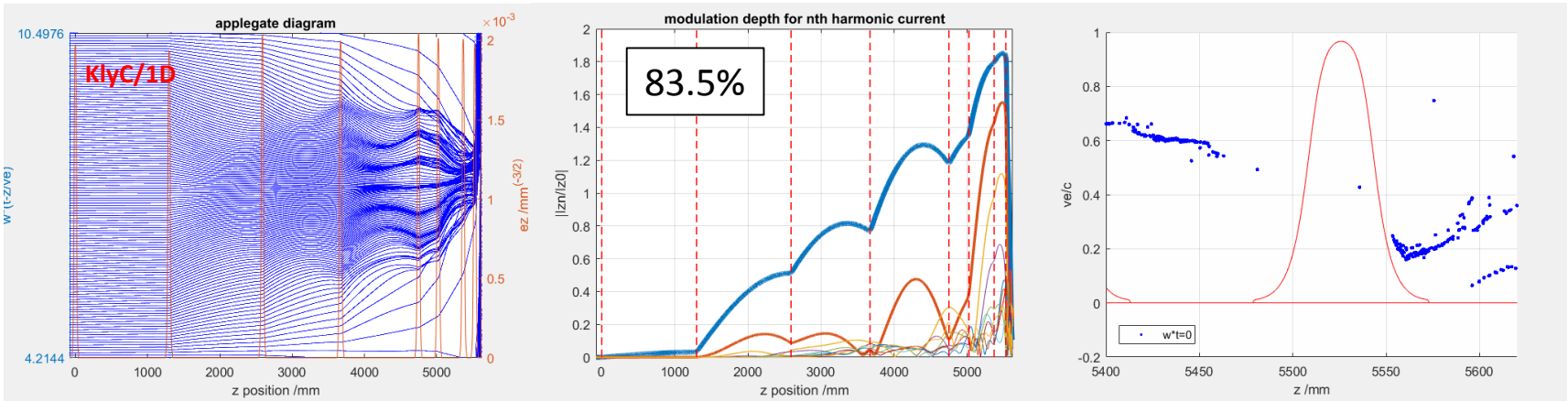
edge

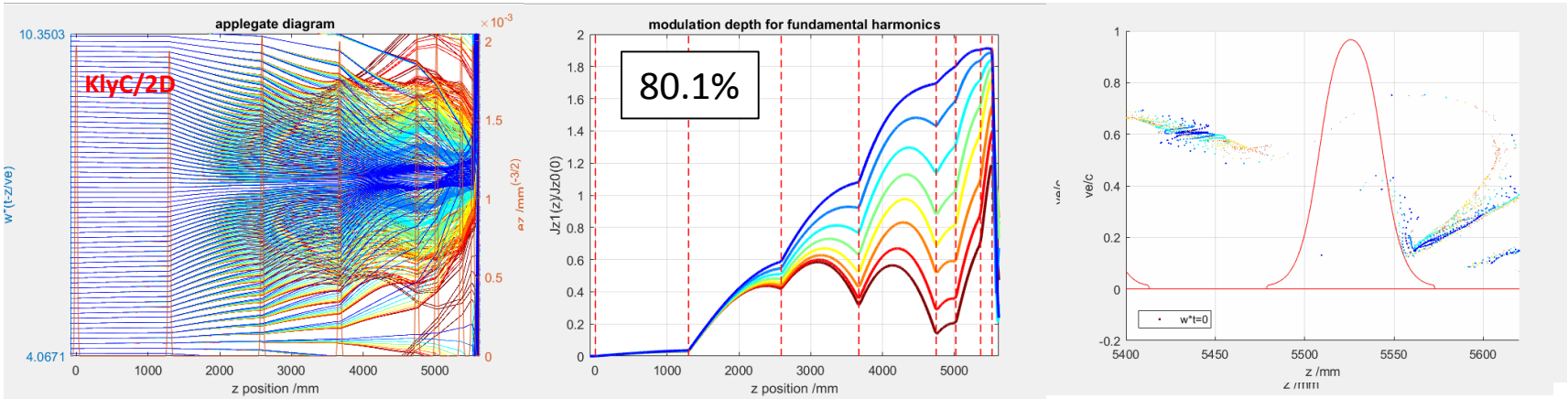
2D stratification effects drops down the efficiency considerably

KlyC2D η=73.9% Tcpu=50min

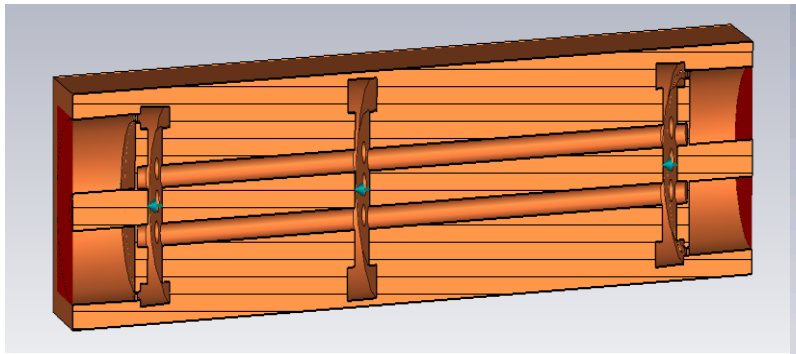
COM tube example

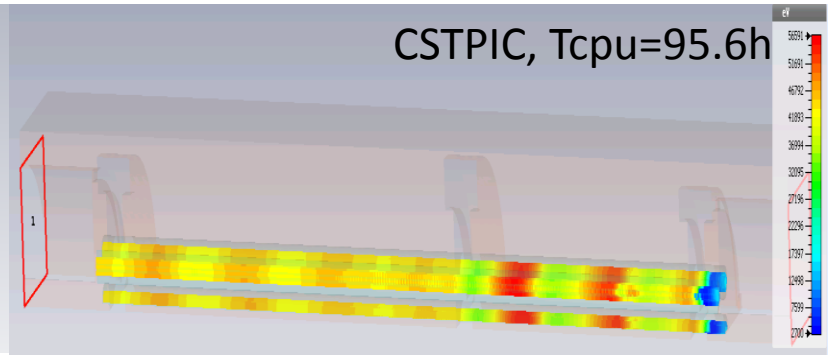
The **Radial Bunch Stratification** is a radial variations of the RF current modulation depth. In a system with axial symmetry with respect to the beam centre, such effect is originated by radial variations of the space charge forces and cavities impedances.



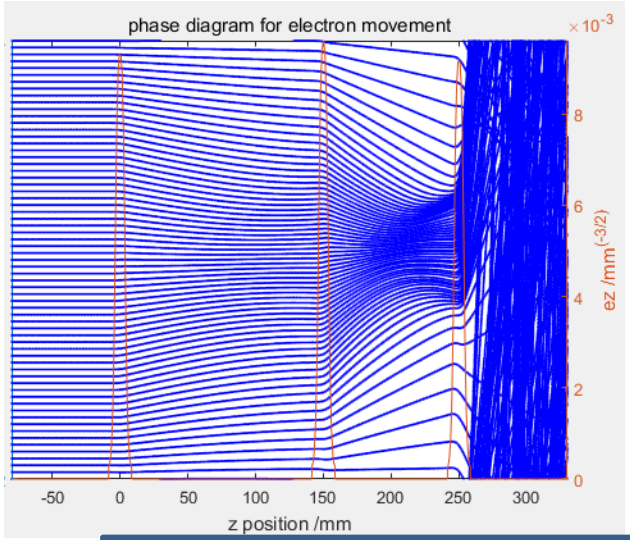


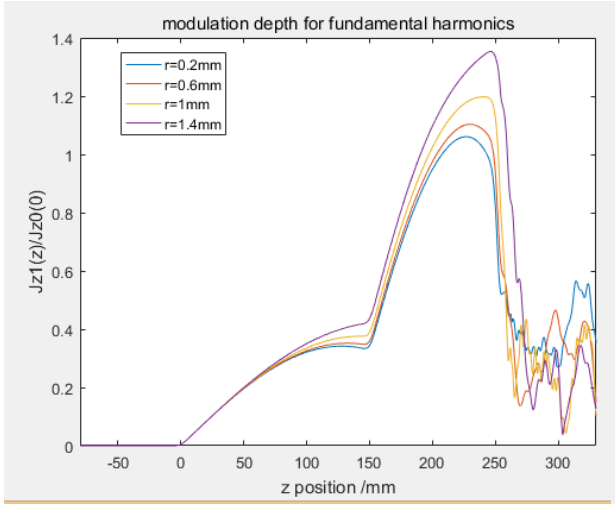
C-band multi-beam Klystron

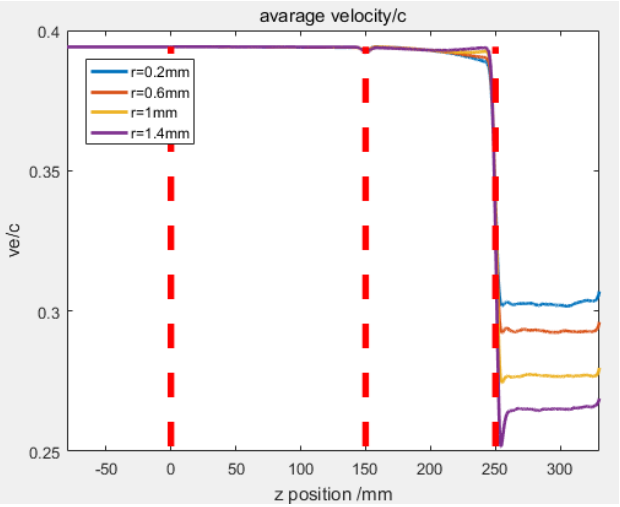




η=50% @ Pin=480W, V0=45kV, I0=4A*8

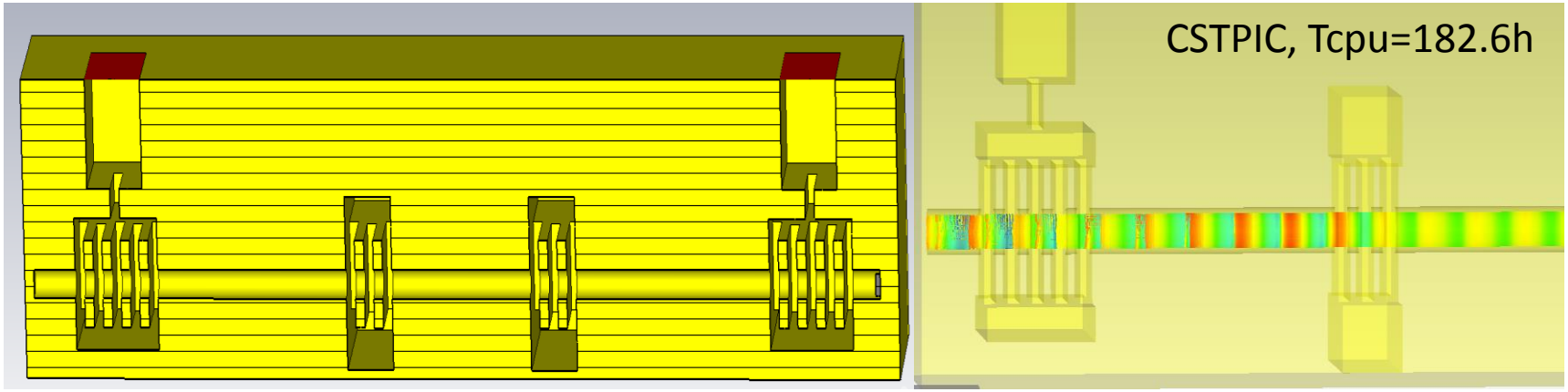


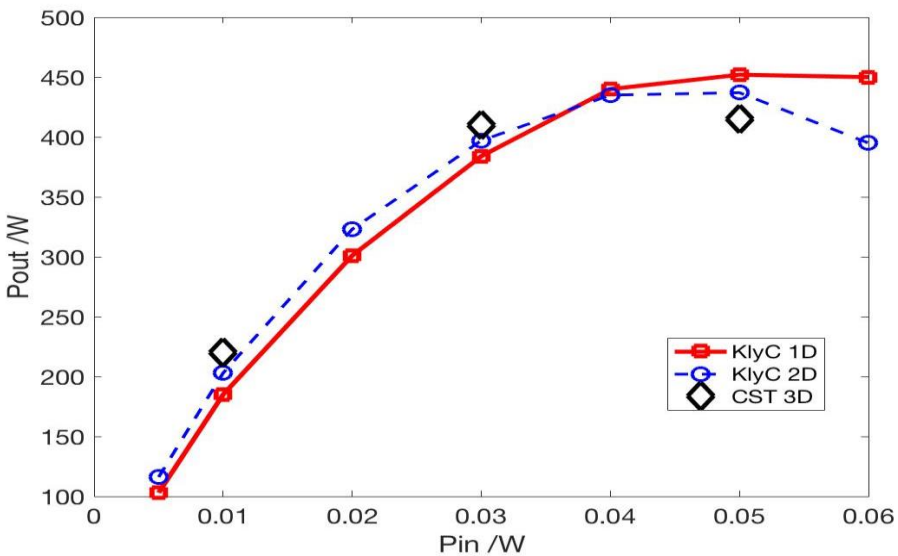




η=52.3% @ KlyC1D, Tcpu=1min; η=51.6% @ KlyC2D; Tcpu=17min;

W-band Extended Interaction Klystron

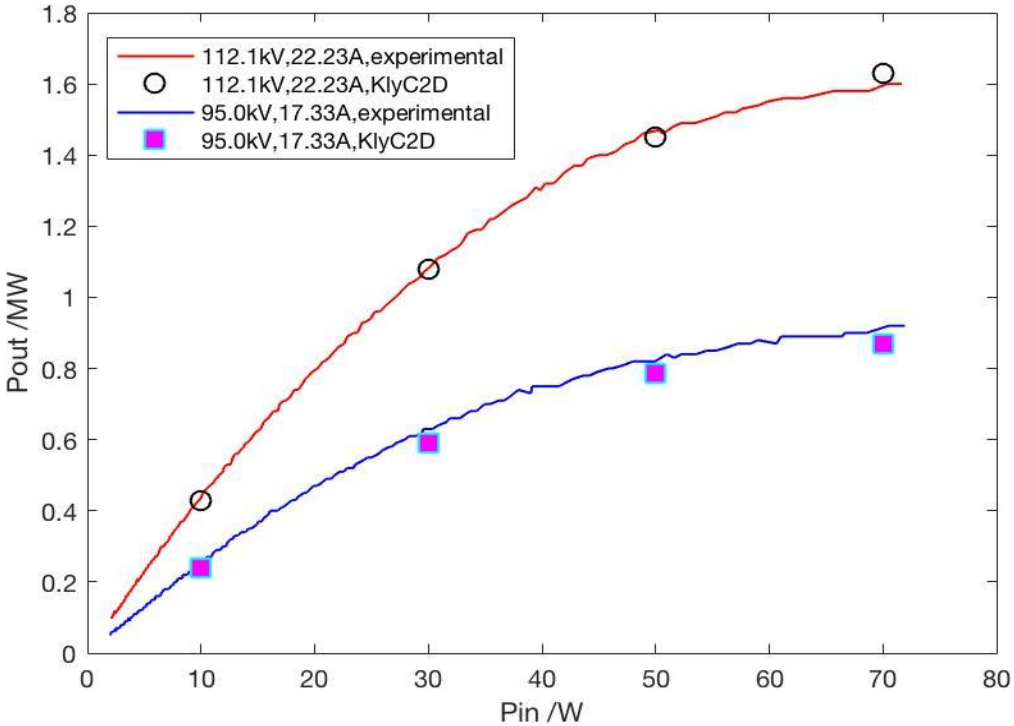




Tcup=0.4min @KlyC1D
Tcup=4min @KlyC2D

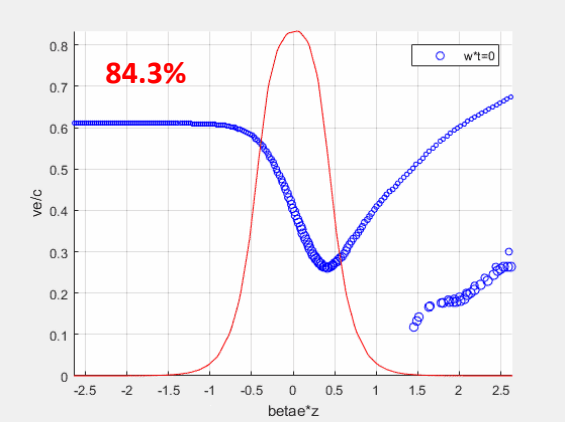
U=17kV,I=0.34A
For low efficiency tube, parallel computation is supported

Thales tube TH2180

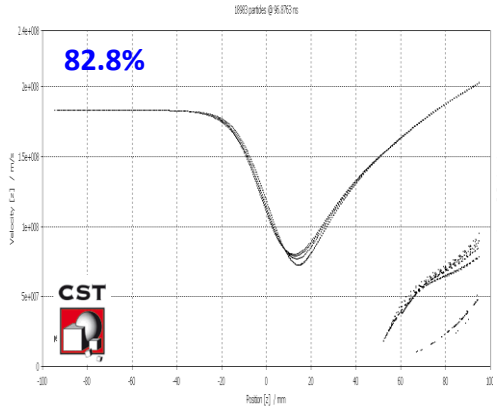


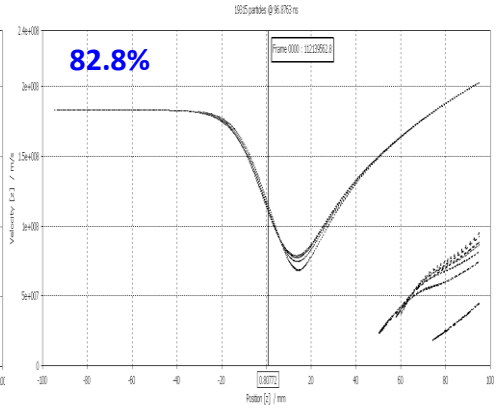
A. Leggieri made comparison between TH2180 experimental data and KlyC simulations

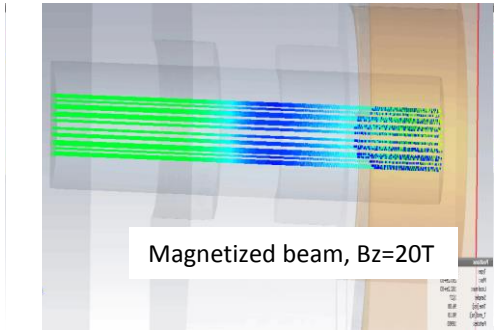
KlyC1D vs CST (3D) PIC benchmarking (monochromatic bunch)

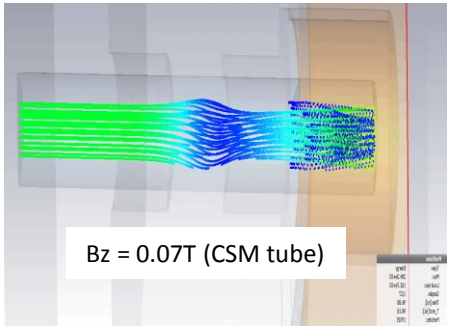


Gaussian 'classical' bunch

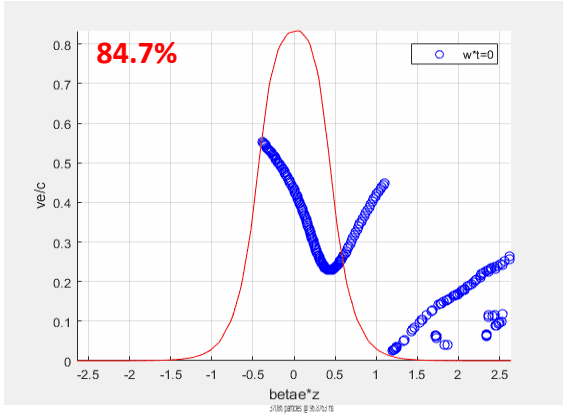


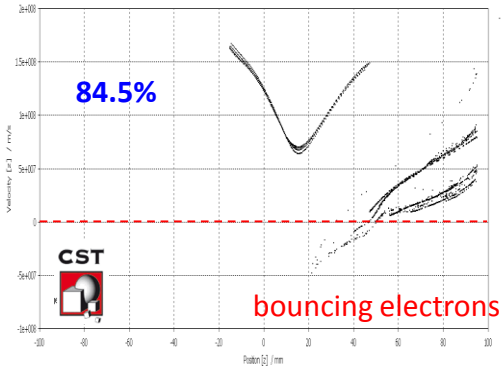


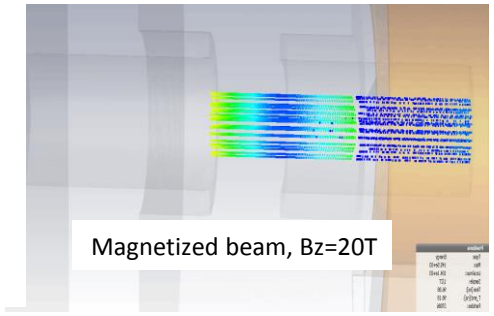




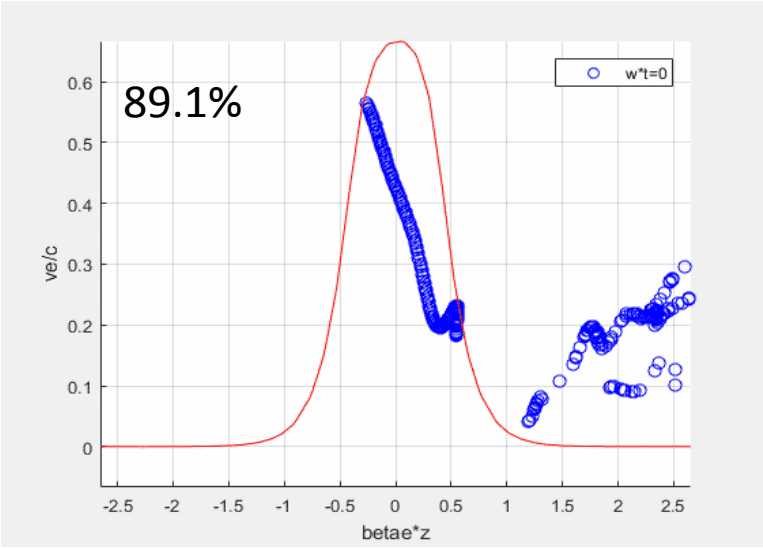
Fully saturated 'rectangular' bunch



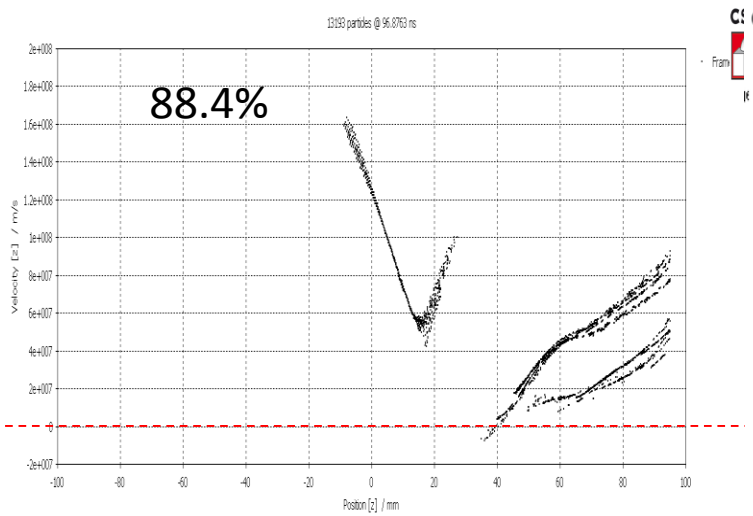


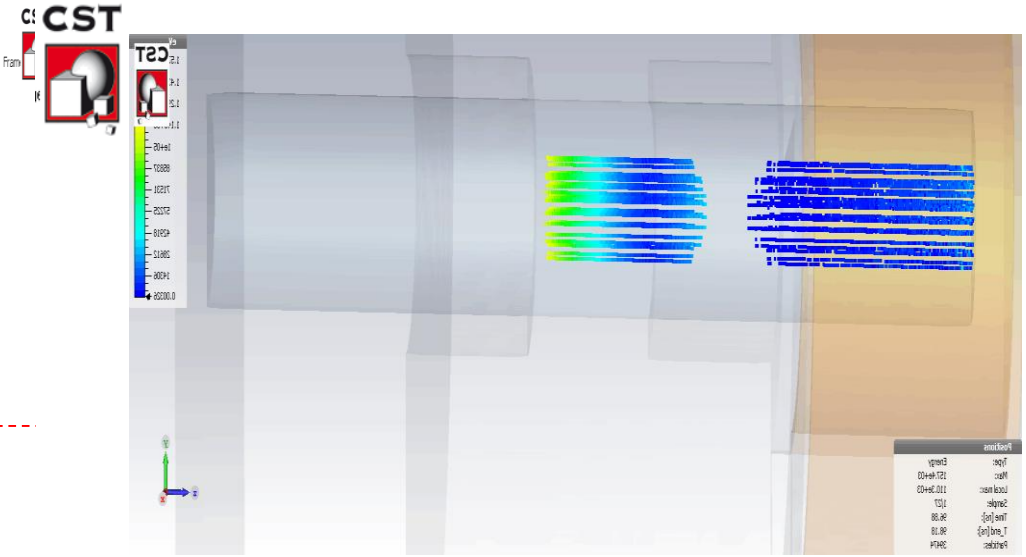


KlyC1D vs CST (3D) PIC benchmarking (congregated bunch)



PIC simulations confirm that 90% efficiency is with reach for the fully saturated bunch with appropriate congregation.



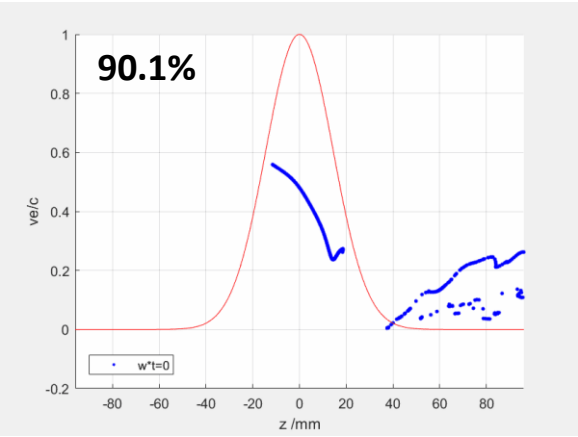


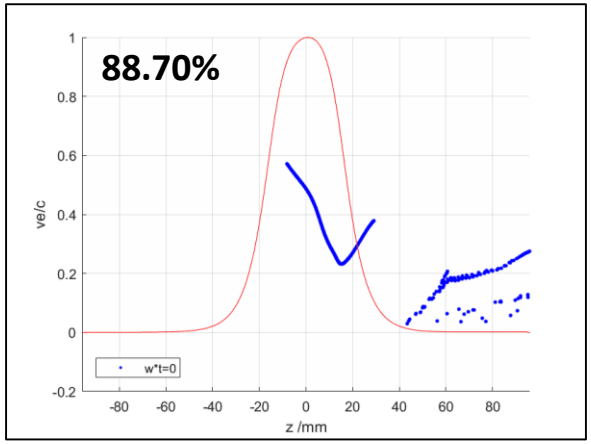
Power conversion efficiency. Limiting factors.

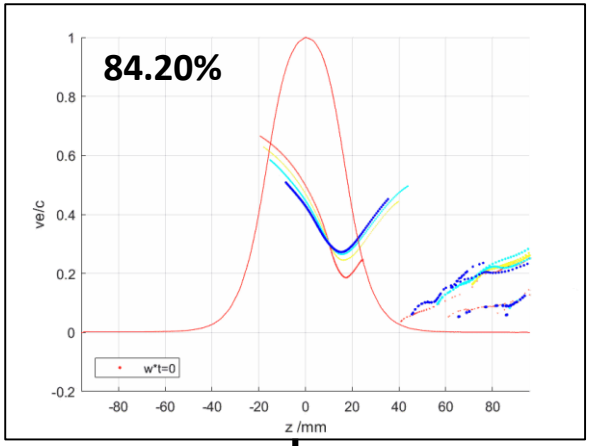
Work From Z.N. Liu

Fully saturated bunch

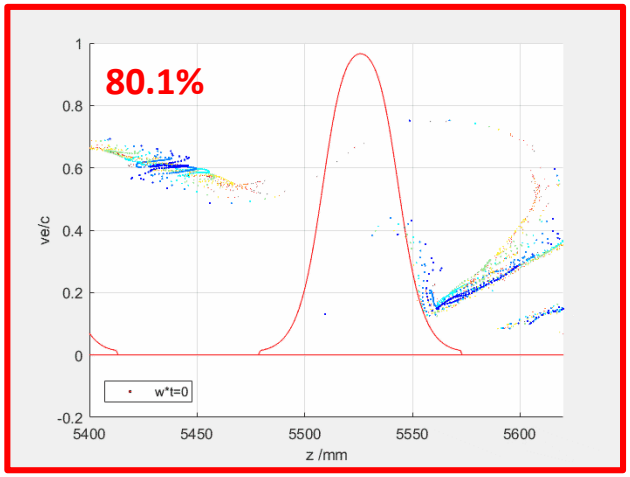
Optimised congregation → **Linear** congregation → **Stratified** bunch with linear congregation

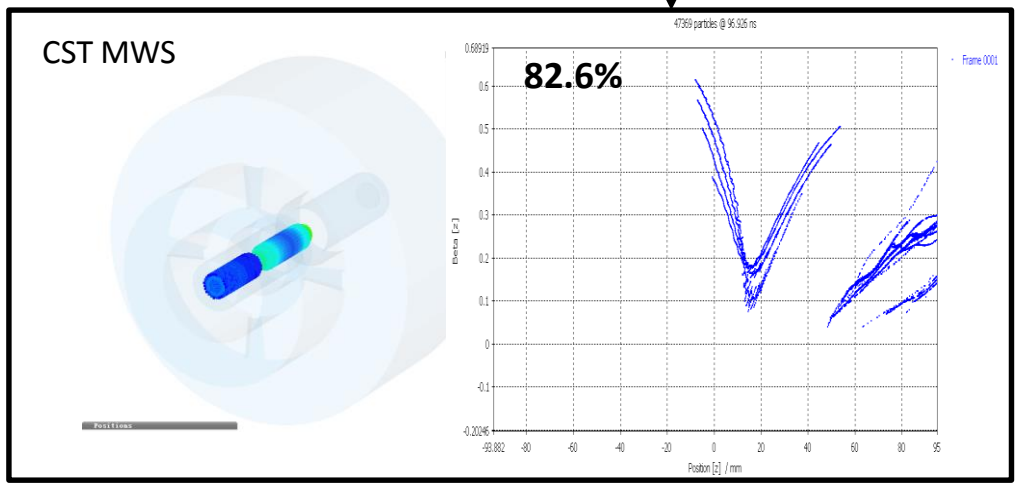




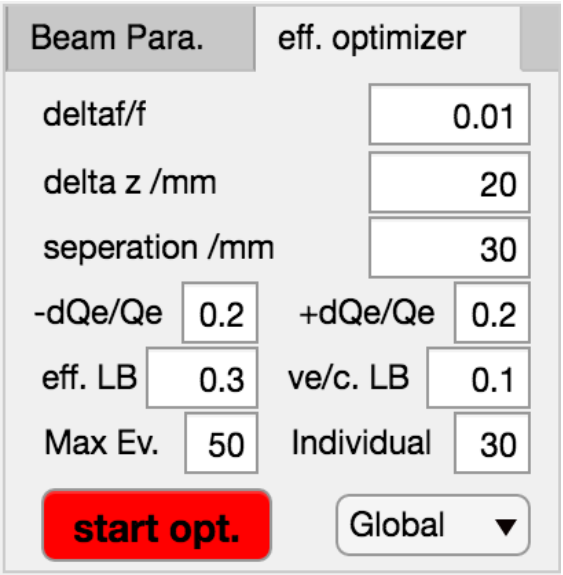


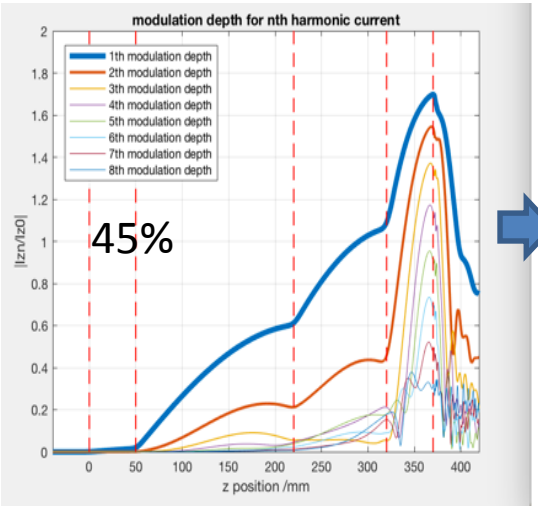
FCC COM tube

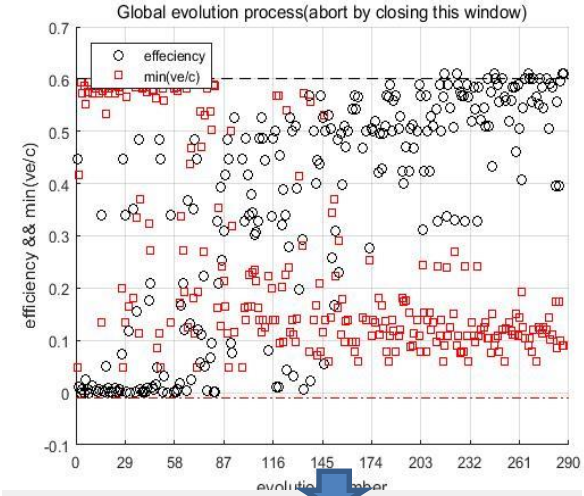


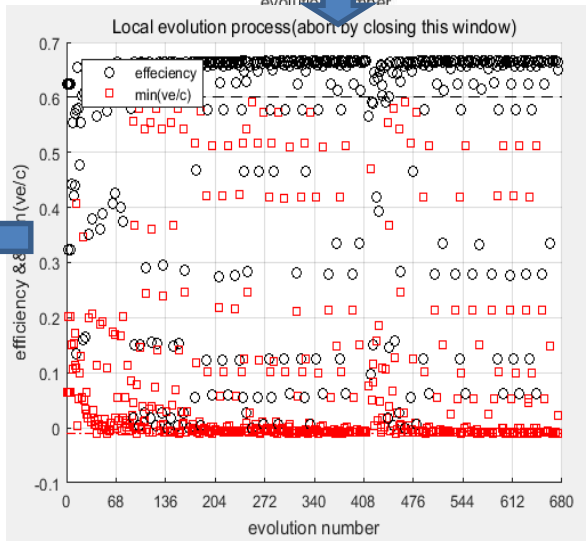


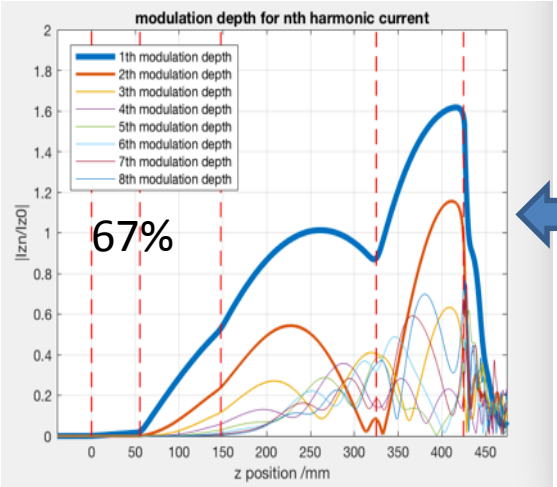
Eff. Optimizer in KlyC











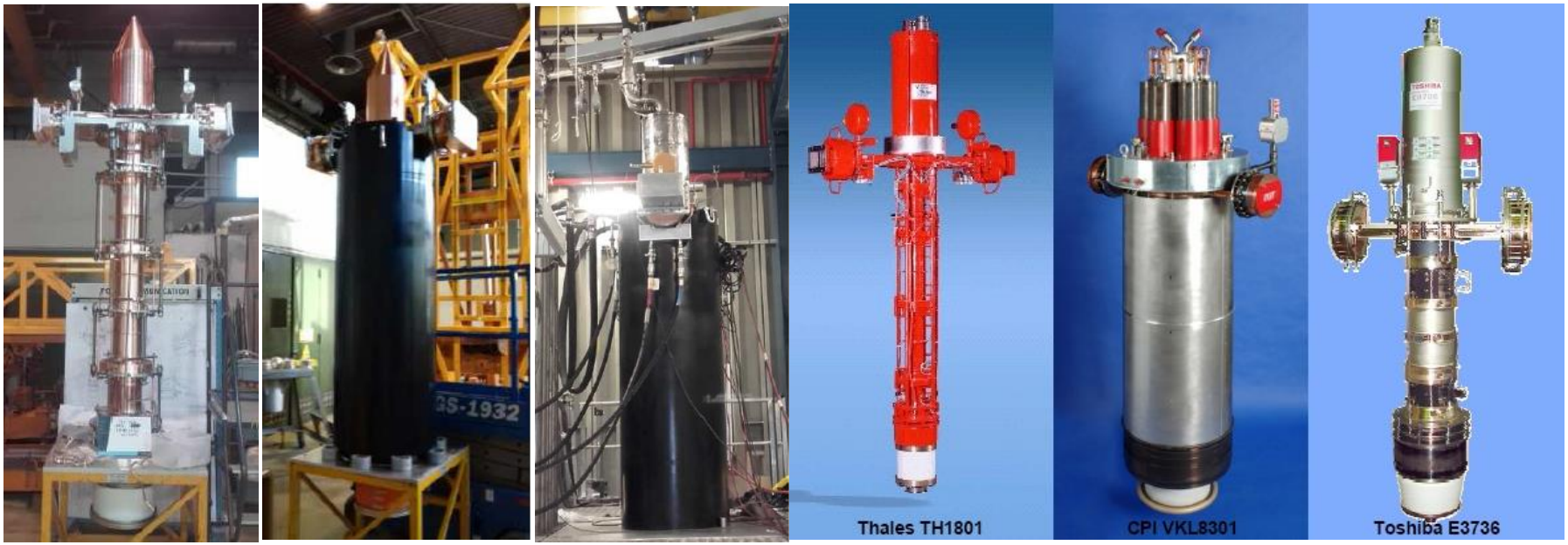
Global: genetic algorithm

Local: pattern search

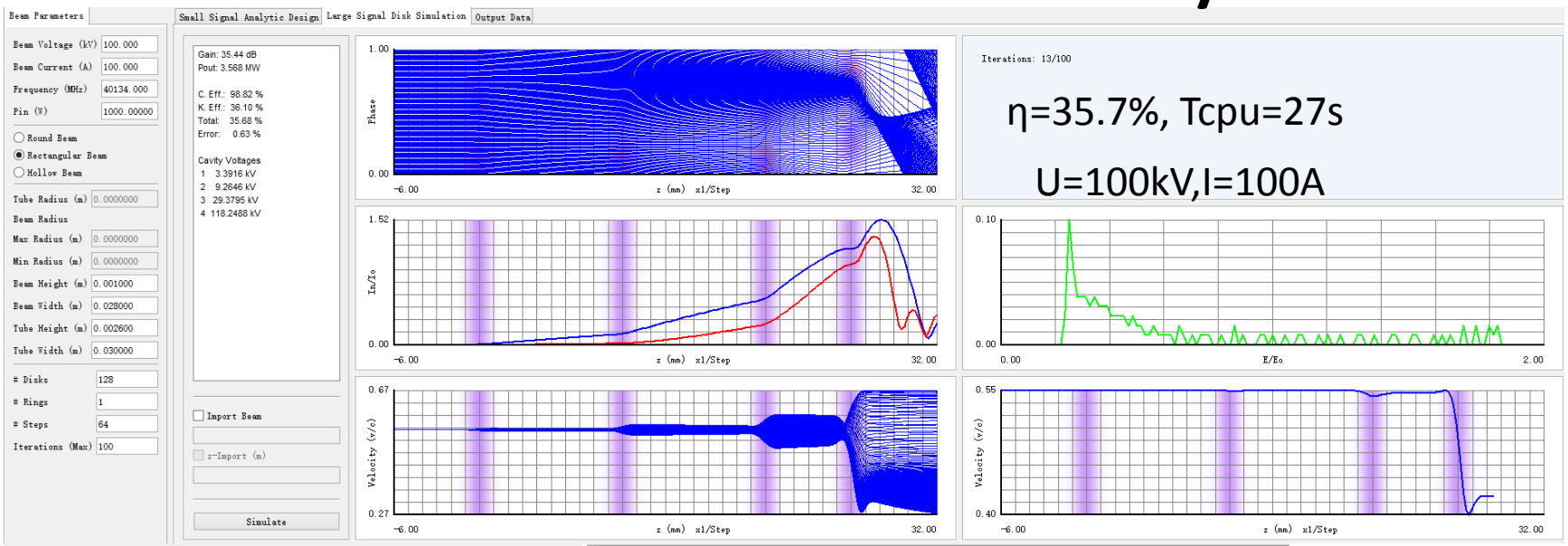
S band, perv.=1.9μP

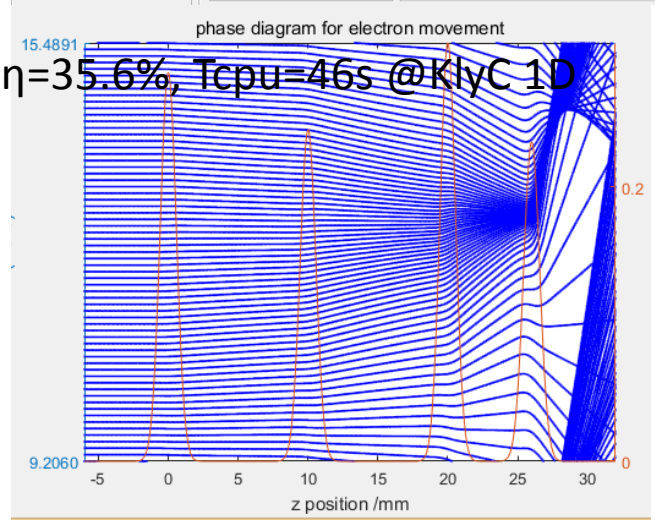
3 days for optimization

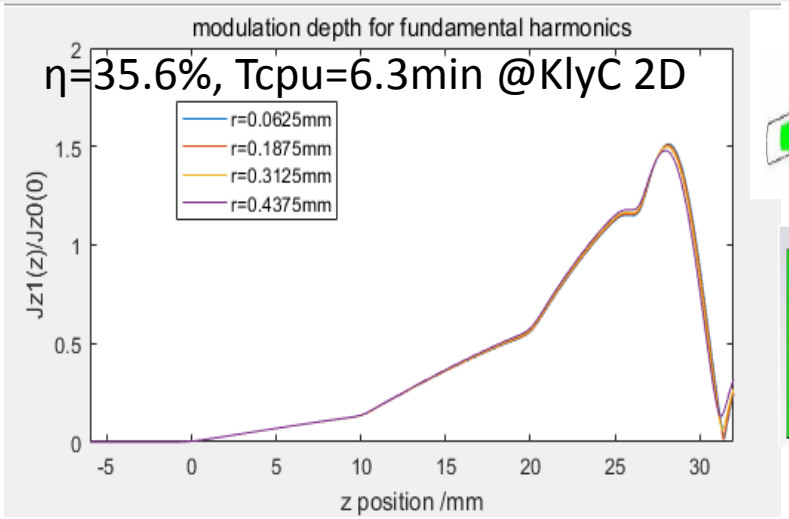
Thanks for your attention!

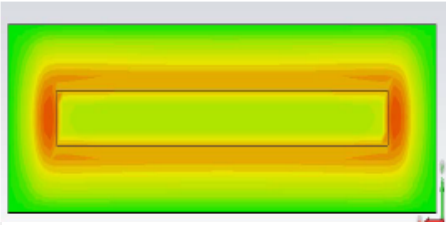


Ka-band sheet beam Klystron



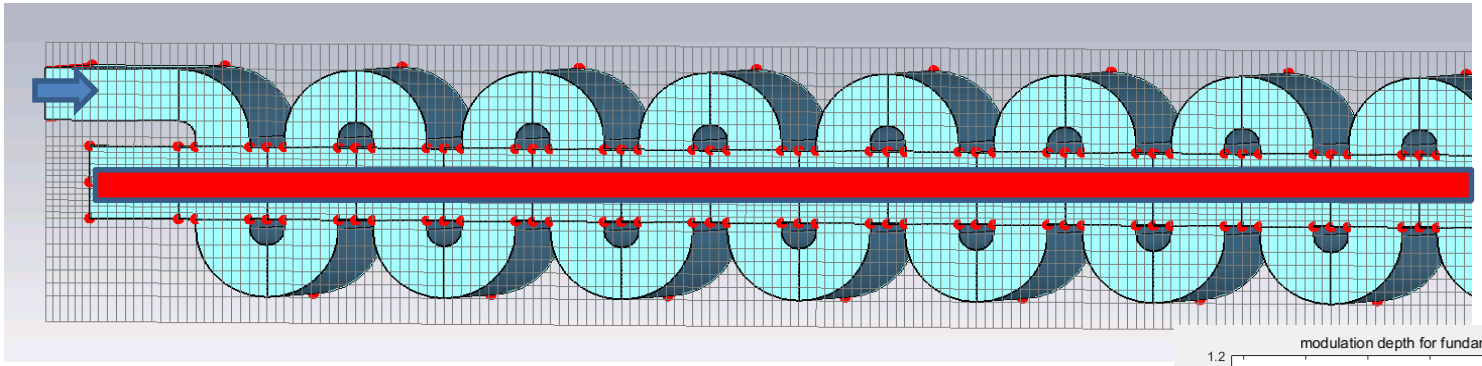






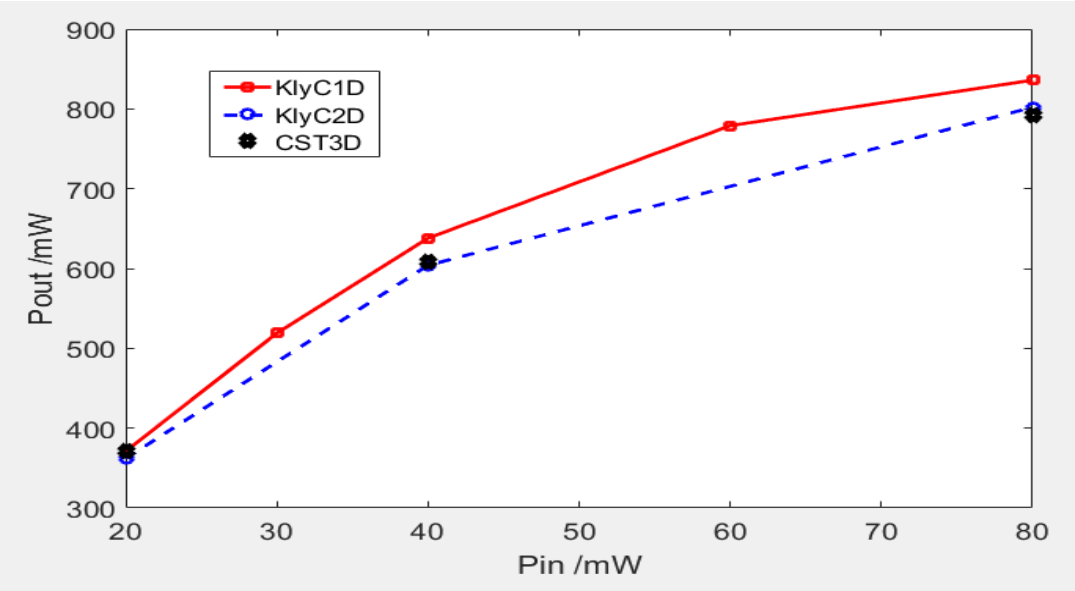
Sheet beam in drift tube

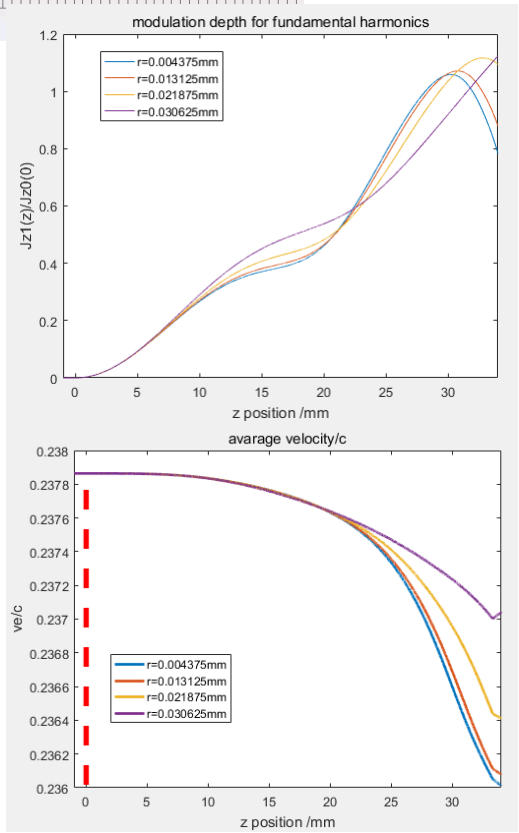
320GHz folded waveguide TWT



Np=100
Tcpu=16h

U=15.1kV
I=5.6mA

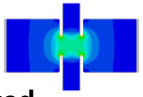




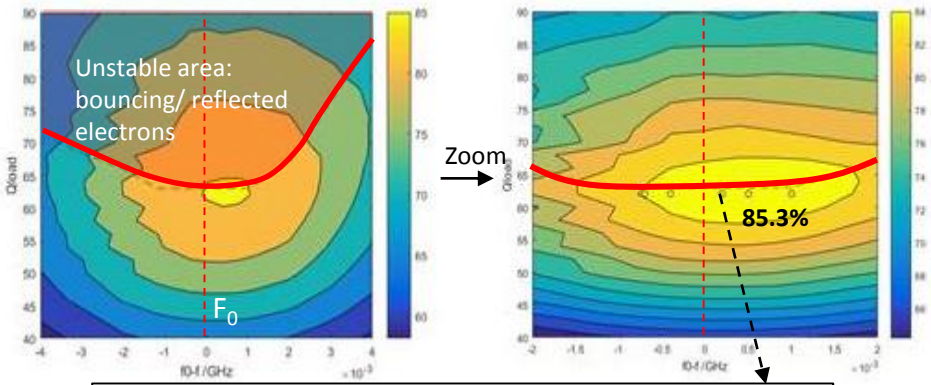
Tcpu~0.5min @KlyC1D Tcpu~4min @KlyC2D

Power conversion efficiency issues.

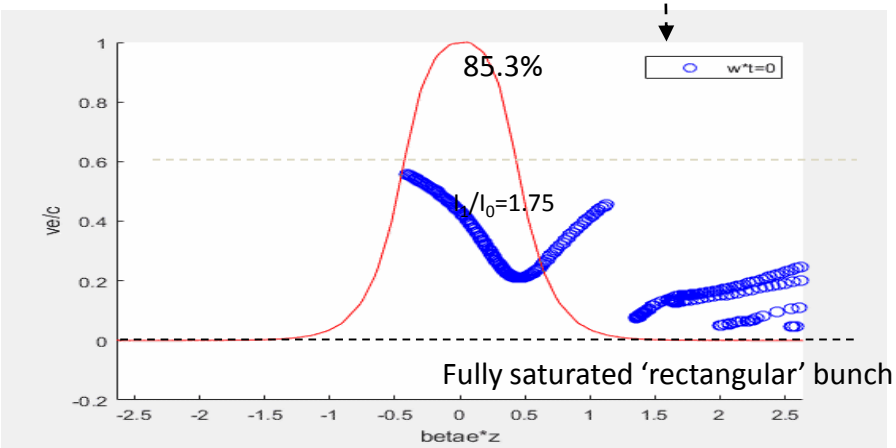
Example: power extraction efficiency from the bunched beam with I_1/I_0=1.75 and $E_{min}=E_0$ (monochromatic bunch) at the output cavity entrance. **The beam and cavity parameters were taken from FCC COM tube.**



Output cavity F-Q_{Loaded} phase space. **Fully saturated bunch** 1D simulations with KlyC1D



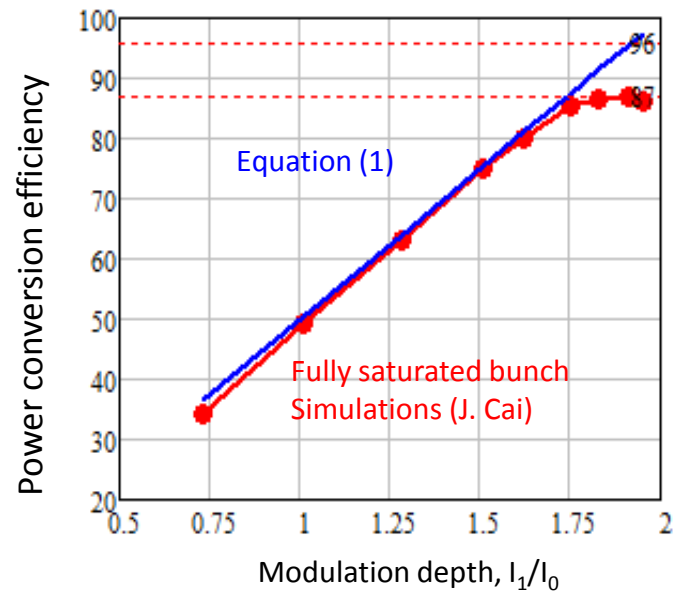
Bunch deceleration in the output cavity **F=1.00025xF_0**



From the klystron text book:

"For the bunch entering output cavity, the good bunching (i.e., a high fundamental harmonic of the beam current) can only yield high conversion efficiency when the energy spread in stream is small."

$$\eta = \frac{1}{2}\frac{I_1}{I_0}\left(\frac{E_{min}}{E_0}\right)^{1/2} \qquad (1)$$



In a 'classical' approach, the highest power conversion efficiency with fully saturated bunch does not exceed **87%**.