KlyC: Large signal simulation code for Klystron

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Areas of Klystron’s Applications

- Radar
- Plasma heating
- Broadcasting
- Particle accelerator
- Collider for High energy physics
- Security (cargo scanner)
- Radiation oncology
- Imaging
Mechanism and concepts

- Velocity modulated with small input power $[\text{Pin}]$
- Density modulated
- Bunch circuit
- Output power $\sim \text{Pin} \times 10^3\sim 6$

Glossary: Saturation, velocity congregation, Radial stratification

CSM tube: $\eta=78\%$

Input cavity
Penultimate cavity
Higher harmonic cavities
Gain cavity
Output cavity

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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!

Efficiency, %

Excessive electricity bill, M Euro

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”

Iteration 1#
- Beam
- Mode field
- SC field

Iteration 2#
- DC
- By input
- no

Iteration n#
- modulated
- Input & excited
- excited (disk)

Convergent solution
- Beam dynamics
- RF field distribution

Coulomb methods are adopted to calculate the space charge field
Arbitrary mode field distribution is supported
KlyC Graphical User Interface

Gaussian profile

EM 2D

Import
KlyC Graphical outputs

Diagram showing various plots and graphs related to efficiency and input power.
The radial bunch ‘expansion’ in output cavity (MAGIC2D) practically does not affect efficiency. This validates KlyC2D as an attractive (and fast) tool.
Convergent analysis

\[ P_{RFB} = V_0 I_0 - P_{BK} - P_{Ohm} - \Delta P_{SC} + P_{in} \]

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

Energy conservation law is abided
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:

Space charge E-field power flow in the drift tube.
AJDisk vs Kly1D high perveance (1.2µP)
HE COM tube X-band 50 MW

η=81.7%, Tcpu=8.5min, AJDISK

CERN-SLAC collaboration

η=80.6%, Tcpu=7.5min, KlyC1D

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Klyc2D vs KlyC1D

KlyC1D $\eta=80.6\%$ $T_{cpu}=8$ min

KlyC2D $\eta=73.9\%$ $T_{cpu}=50$ min

2D stratification effects drops down the efficiency considerably
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;

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W-band Extended Interaction Klystron

CSTPIC, $T_{cpu}=182.6h$

For low efficiency tube, parallel computation is supported

$T_{cpu}=0.4min \, @KlyC1D$
$T_{cpu}=4min \, @KlyC2D$

$U=17kV, I=0.34A$

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Thales tube TH2180

A. Leggieri made comparison between TH2180 experimental data and KlyC simulations
KlyC1D vs CST (3D) PIC benchmarking

Gaussian ‘classical’ bunch

Magnetized beam, $B_z = 20T$

$84.3\%$

Gaussian ‘classical’ bunch

$82.8\%$

Bz = 0.07T (CSM tube)

$84.5\%$

Fully saturated ‘rectangular’ bunch

$84.7\%$

Magnetized beam, $B_z = 20T$

$84.7\%$

(bouncing electrons)

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PIC simulations confirm that 90% efficiency is within reach for the fully saturated bunch with appropriate congregation.
Power conversion efficiency. Limiting factors.

Fully saturated bunch

Optimised congregation → Linear congregation → Stratified bunch with linear congregation

FCC COM tube

90.1%

88.70%

84.20%

CST MWS

82.6%

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Eff. Optimizer in KlyC

<table>
<thead>
<tr>
<th>Beam Para.</th>
<th>eff. optimizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>delta f/f</td>
<td>0.01</td>
</tr>
<tr>
<td>delta z /mm</td>
<td>20</td>
</tr>
<tr>
<td>separation /mm</td>
<td>30</td>
</tr>
<tr>
<td>-dQe/Qe</td>
<td>0.2</td>
</tr>
<tr>
<td>+dQe/Qe</td>
<td>0.2</td>
</tr>
<tr>
<td>eff. LB</td>
<td>0.3</td>
</tr>
<tr>
<td>ve/c. LB</td>
<td>0.1</td>
</tr>
<tr>
<td>Max Ev.</td>
<td>50</td>
</tr>
<tr>
<td>Individual</td>
<td>30</td>
</tr>
</tbody>
</table>

- Global: genetic algorithm
- Local: pattern search
- S band, perv. = 1.9μP
- 3 days for optimization

3 days for optimization

Global evolution process (abort by closing this window)

45% 67%
Thanks for your attention!
Ka-band sheet beam Klystron

\( \eta = 35.7\% \), \( T_{cpu} = 27s \)

\( U = 100kV, I = 100A \)

\( \eta = 35.6\% \), \( T_{cpu} = 46s \) @KlyC 1D

\( \eta = 35.6\% \), \( T_{cpu} = 6.3\text{min} \) @KlyC 2D

Sheet beam in drift tube
320GHz folded waveguide TWT

$N_p = 100$
$T_{cpu} = 16h$
$U = 15.1kV$
$I = 5.6mA$

$T_{cpu} \sim 0.5 \text{min} @ \text{KlyC1D}$
$T_{cpu} \sim 4 \text{min} @ \text{KlyC2D}$

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Power conversion efficiency issues.

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

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.”

\[
\eta = \frac{1}{2} \frac{I_1}{I_0} \left( \frac{E_{\text{min}}}{E_0} \right)^{1/2}
\]

(1)

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