High efficiency klystron technology.
I. Syratchev, CERN

High Efficiency International klystron activity

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Since 2013
High efficiency. How high it could/should be!? 

Personal outlook and challenges in efficiency reach with single beam klystron amplifiers.

Efficiency impact on investment cost

- 'Simple' modulator breakdown cost model
- Fixed RF power and beam perveance

Complimentary technologies

- Multi Beam technology. Reduced voltage and perveance. Cost and efficiency.
- Gated Cathode (triode gun). No HV switches. Modulator cost and efficiency.
- SC or PPM solenoid. System efficiency.
- Depressed Collector. System efficiency
High efficiency! How high it could/should be!?

Efficiency impact on operation cost

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

- 9.3 M Euro (100 MW)
- 10.7 M Euro (37 MW, more than twice the overall RF cryogenic power needs)

FCC $e^+e^-$: CW, 0.4/0.8 GHz, $P_{RF\, total}=100$ MW

ILC $e^+e^-$: Pulsed, 1.3 GHz, $P_{RF\, total}=88$ MW

CLIC $e^+e^-$: Pulsed, 1.0 GHz, $P_{RF\, total}=180$ MW

Pulsed, 0.7 GHz, 92 MW

7th Low Emittance Rings Workshop, CERN, January 2018

I. Syratchev, CERN
State of the art. Commercial MBK (low perveance) tubes with high efficiency.

After 8 decades of development the klystron technology was considered to be saturated. The experimental results from hundred’s of different devices have shown that higher efficiency is associated with lower perveance. Accounting for technological and cost reasons ($\mu K > 0.2$), the 75% efficiency was predicted to be the utmost limit.

Klystron efficiency vs. perveance

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7th Low Emittance Rings Workshop, CERN, January 2018
I. Syratchev, CERN
KlyC: The new (non-commercial) klystron computer code developed at CERN (J. Cai, I. Syratchev).

The success of HE klystrons development strongly depends on availability of accurate 2D/3D computer codes capable of performing massive computer optimizations within a reasonable amount of time.

KlyC is currently undergoing beta-testing with different Labs (CERN, CEA, SLAC and ESS) and industrial partners (Thales, CPI, VDBT and BVERI).
CLIC 20 MW L-band (1 GHz) Multi-beam pulsed klystron.

New/advanced technology

Lower (<60kV) voltage:
- 40 mini-cathodes
- No oil tank (cost)
- Shorter tube (cost)
- Faster switching (efficiency/cost)

Gated mini-cathode:
- No switches (cost)
- Modulator efficiency ~1.0
(+) Improved stability

Permanent Magnets:
- No power consumption
- Potential cost reduction
Vs. SC solenoid:
- More expensive solution

20 MW, 50 Hz, 150 μsec
150 kW

Depressed collector (η=0.5)

New klystron RF circuit (η=0.8)
(+ ) Reduced Collector dissipation (16 kW)

η_{Total} = 0.9

Power from grid:
280 200 MW

η_{Total} = 0.62

180 kV

150 kW + 88 kW

CLIC 20 MW L-band (1 GHz) Multi-beam pulsed klystron.

7th Low Emittance Rings Workshop, CERN, January 2018
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CLIC’k 50 MW X-band (12 GHz) klystron.

09.25 B. Weatherford: ‘HE 50 MW X-band (COM) klystron design progress report’.

A Superconducting Solenoid applicable for X-band Klystrons
A. Yamamoto. CERN/KEK collaboration
Advanced bunching technologies. First method (COM) proposed in 2013 (A. Baikov).

"Classical" bunching

Example of the ‘fully’ saturated bunch in COM tube (Tesla 2D code)

Bunching with core oscillations

Output cavity

77.5%

83.5%
New bunching technologies.
Bunch saturation.

The choice of bunching technology may drive the applicable frequency range and multi-beam options (cost/performance):

<table>
<thead>
<tr>
<th>L-band</th>
<th>S-band</th>
<th>C-band</th>
<th>X-band</th>
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<tbody>
<tr>
<td>CSM/modest MBK</td>
<td>Medical/industrial</td>
<td>Kladistron</td>
<td>Bunching Alignment Collecting, 2.44 m</td>
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<tr>
<td>LHC,FSS,ESS,ILC</td>
<td>BAC/MBK</td>
<td>CLIC, klystron based X-band FEL</td>
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<td>1/6 MW Circular machines &amp; proton linac drivers</td>
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<td>5-10 MW, &lt;60kV</td>
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<td>CLIC, TBA</td>
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<td>10-20 MW High perveance MBK HE tubes (?)</td>
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<td>50+ MW</td>
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133.8 kV, 12.55 A, 1.4 MW at **0.8 GHz**, 80(+)%
Power conversion. Ultimate efficiency reach.

Towards high power klystrons with RF power conversion efficiency in the order of 90%  

A. Yu. Baikov, MPUA, Russia, C. Marrielli, ESS, Sweden, and I. Syratchev, CERN, Switzerland

Ultimate high power conversion efficiency conditions:

- To avoid migration of the electrons from bunch to anti-bunch during deceleration in the output cavity, the incoming bunch with non-zero length should have optimal velocity dispersion: Congregated Bunch, when the leading electrons are slower than the tailing ones.
- Congregated bunch should be gradually transformed at the cavity exit into monochromatic bunch with least velocity.

Fully saturated bunch with optimal congregation can deliver 90(+) RF power production efficiency (in simulations).
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. All together they give 1.75% efficiency reduction.

In ‘real’ tube design efficiency is reduced further:
- bunch saturation (-1%)
- bunch congregation ‘as received’ (-3.8%)

Space charge E-field power flow in the drift tube.
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.
Magnetic focusing (solenoidal) field. Radial beam expansion has little effect (-0.25%) on the RF power production (MAGIC (PIC) simulations).

**Ultimate limit**: reflected electrons generation.

Power conversion efficiency. Limiting factors.
In a low perveance tube, the accumulated effect of all the limiting factors that are inherent to the bunching and deceleration processes may result in 10% efficiency reduction (from 90% to 80%).
Thanks for your attention! I hope I was efficient.