Development of Efficient Klystrons
Content of talk

- Reasons to improve klystrons efficiency
- Klystron operation principle and limitations
- Ways to achieve high efficiencies
- Simulation of new tubes based on new ideas
- Achieved efficiency of recent prototypes
- Summary
Why we need more efficient klystrons

- RF demand of future large scale particle accelerators (FCC, CEPC, ILC, CLIC, ESS, ...):
  - About 100 MW RF output power
  - Only 10% higher efficiency means several M€ saved per year on electricity bill
  - Operation in the range 0.4-12 GHz

- State of the art klystrons:
  - Few single beam devices deliver above 65% efficiency
  - Multiple beam klystrons (MBK) somewhat higher, but still room for improvement

- Several programs launched in framework of Eucard2 and now ARIES
  - Investigate new ideas with help of modern simulation codes and prototyping
Future large scale accelerators

- **FCC** $e^+e^-$: CW, 0.8 GHz, $P_{RF}$ total = 110 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
- **CEPC** $e^+e^-$: CW, 0.65 GHz, $P_{RF}$ total = 100 MW
- Pulsed, 0.7 GHz, $P_{RF}$ total = 92 MW
Example: FCC RF power consumption for $t\bar{t}$

Eventually, all is converted to waste heat!

Figure of merit: physics results per kWh!
Klystron operation principle

(velocity modulation)

- DC beam passes through input
- Electrons accelerated or decelerated according by the gap voltage
  - Beam is velocity modulated
- Bunches of electrons are formed
  - Beam is spatially modulated
- Output cavity is excited by the bunches
- Power is coupled out to load

- More cavities give better bunching.
  - (Very) Roughly $\frac{1}{4}$ plasma wavelength apart
- Efficiency: $\eta \sim \frac{P_{\text{out}}}{V_c I_b}$ (neglect magnet,...)

![Diagram of klystron operation principle](image.png)
For high efficiency traditionally we chase low permeance by either:

- High voltages
- Low currents (many beams)

For high power both become “unpleasant”.

Performance limited by the slowest electrons

\( \text{must} \) avoid reflecting electrons

Traditional efficiency limited to 80% @ 0.1-0.2ish micropervenance

Non traditional bunching techniques needed to improve efficiency
Why not 100% efficient?

- The simple answer is
  - Imperfect bunching
  - Residual Velocity - energy still in the beam

Bunching monotonic - electrons move to center of bunch

Significant charge outside bunch. Velocities aligned...

Many electrons miss bunch. Significant energy left in bunch!
How to improve efficiency of klystrons?

- **Multi Beam Klystrons:**
  - group many low perveance beams
  - high power, high efficiency (~70% now, >80% with improved bunching)

- **Depressed collectors** (not suited for high power)

- **New bunching techniques:**
  - HEIKA: Core Oscillation Method, Bunch Align Collect, Core Stabilization Method
  - Adiabatic bunching (kladistron)
Multi stage depressed collector

- Decelerate the electrons into the collector to recover energy
- Efficiency increases with number of stages
- Hard to cool electrodes
- Only works in non saturated regime, not suited for high power
- Adds to the complexity and cost of the tube
- Easier to just to design the previous parts better
Improved bunching: Core Oscillation Method

- Bunching split into two distinct regimes:
  - core of the bunch periodically contract and expand (in time) around center of the bunch
  - outsiders monotonically go to the center of the bunch
  - Core experiences higher space charge forces which naturally debunch
  - Outsiders have larger phase shift as space charge forces are small

- Very long, very efficient tubes result.

“Classical” bunching

Core oscillations

traditional approach

Baikov, Marelli, Syratchev, IEEE VOL. 62, NO. 10, OCTOBER 2015
Improved bunching: Bunch Align Collect

- Again based on core oscillations
- Interaction space is wasted “waiting” for space charge forces to debunch.
- A cavity can achieve the same thing in a shorter space by aligning electron velocities
- Structure **half the length** while maintaining efficiency.

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I.A. Guzilov, IVEC 2014 proceedings
Power conversion efficiency issues

- 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 certain velocity dispersion:
    Congregated Bunch, when the leading electrons are slower than the tailing ones.
  - For the full deceleration, the congregated bunch should be gradually transformed at the cavity exit into monochromatic bunch with least velocity.

\[ \frac{I_1}{I_0} = 1.75 \]

- quick optimisation

\[ 89.4\% \]
New bunching technologies on one slide

133.8 kV, 12.55 A, 1.4 MW at 0.8 GHz, 80(+)%

Core Oscillations Method (5.75 m)

Bunching Alignment Collecting, 2.44 m

High Efficiency International klystron Activity

HEIKA

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Core Stabilization Method

CSM_23B1, 1.72 m

CSM_2L3B3, 1.88 m

CSM_23B1, 1.72 m
HEIKA/HEKCW working team:
I. I. Syratchev (CERN)
II. C. Lingwood (Lancaster)
III. G. Burt (Lancaster)
IV. D. Constable (Lancaster)
V. V. Hill (Lancaster)
VI. R. Marchesin (Thales)
VII. Q. Vuillemin (Thales/CERN)
VIII. A. Baikov (MUFA)
IX. I. Guzilov (VDBT)
X. C. Marrelli (ESS)
XI. R. Kowalczyk (L-3com)

16 beams MBK cavity
R/Q = 22 Ohm/beam

FCC HEKCW Tube

Tube parameters:
- 1.5MW
- 800 MHz
- Voltage: 46 kV
- Total current: 36A
- Efficiency: >80%
- N beams: 16
- μK/beamx10^6 : 0.213
- N cavities: 8
- Cathode loading: 2 A/cm^2
- Beam radius: 3 mm
  - Filling factor 8 mm
- Length: 2.3 m
- Beam circle radius: 75 mm
- Solenoid field (2x): 600 G
- Solenoid radius: 150 mm
- Collector: common
  - Nominal load: 170 kW
FCC HEKCW Tube: Simulated COM version 8

COM tube. 8_04_XX series of 10 optimised tubes.

Frequencies scattering

Drifts scattering

Replacing cylindrical beam by hollow beam efficiency is further increased up to 86%

BRS effect is almost mitigated!

FCC week 2017, Berlin, Germany.

C. Marchand - Energy for Sustainable Science - Magurele

23/11/2017

I. Syratchev, CERN
FCC HEKCW Tube: Simulated CSM second gen.

CSM tube. Second Generation. Tube length 1.72 m at 0.8 GHz.

Saturation curve (MAGIC 2D)
The first commercial VDBT S-band MBK tube employing the new BAC bunching technology:

- Frequency: 3 GHz
- 40 beams
- Permanent Magnets focusing system
- Low voltage: 52 kV
- Peak power: 7.5 MW
- Target Efficiency: ~70%
- Pulse length: 5 microsecond
- Repetition rate: 300 Hz
- Average power: 30 kW
Expected efficiency from simulations:
1. Efficiency 77%. (1D) Klys4.5, Original company code used to optimise the tube.
2. Efficiency 69.9%. (1D) KlypWin (A. Baikov). The code used by HEIKA study for the basic design and optimisation of high efficiency klystrons.
3. Efficiency 65.74%. (2D) KLYS2D is the code used at Thales.

All codes predicted higher efficiency of the device compared to 48% of original KIU-147A tube.

Measured efficiency on two tubes: 59% and 64%
SLAC 5045: S-band BAC demonstrator

- Retrofitting a 5045 S-Band with BAC
- 60 -> 80MW
- 4 more cavities
- Plug compatible (needs new solenoid)
- Original 5045: 45% +BAC -> 55% expected
  - Measured 54%, but only with narrow 100 ns pulses; Oscillations from higher harmonics at 3.5 ms
TH1803 CLIC L-band MBK

- **TH1803 Multi-beam Klystron for CLIC (CERN)**
  - 1GHz 20 MWp 150kWa @150µs
  - 10 electron beams @ K= 0.35 µperv per beam
  - 6 coaxial cavities with one on 2nd harmonic
  - 20.6 MWp @150µs demonstrated at factory with $\eta > 70\%$
    - 146.5 kV x 191.2 A
    - average power limited by beams losses in output drift tubes
Another MBK by Toshiba

- If ILC project is approved, it is required to raise the tube efficiency more to save the total power dissipation.
  - Classical way: recent improvement of Toshiba for CLIC MBK ~ reached to 70%
  - HEIKA way: recent approach to raise the efficiency
    - Budget is not approved but try to pursue the way.

- Below is the example of CLIC 1GHz MBK in Toshiba

Simulation and test results

In the courtesy of Toshiba presented at 2016 Jap. Accl. Meeting
CEPC: BAC single beam klystron study

Strategy to manufacture tube in China

Current Status
- Mechanical design of test tube
- Coaxial window design to manufacture and test
- Director requests us to have more than 80% efficiency, and 2.5D simulation will be desirable using FCI, Magic and CST
- Manufacturing infrastructure such as backing and exhausting furnace is needed

Ajdisk: 74%

- Longer interaction region
  -> Bigger furnace required
- MBK as alternative design
- How to increase efficiency in Linear region?
- Possibility to collaborate with company other than China.........

S. Fukuda Talk in IAS2017
It appeared, that HE klystron (for the fixed perveance) requires higher integrated voltage in the output cavity.

Thus a new design will be needed. It also can limit the high RF peak power performance.

CERN/SLAC agreement has been signed for a new full optimisation of the tube (paper study).

<table>
<thead>
<tr>
<th></th>
<th>XL5</th>
<th>XL5/HE</th>
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<tbody>
<tr>
<td>Voltage (kV)</td>
<td>400</td>
<td>290</td>
</tr>
<tr>
<td>Current (A)</td>
<td>312</td>
<td>186</td>
</tr>
<tr>
<td>Power (MW)</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>40</td>
<td>73(80)</td>
</tr>
<tr>
<td>Last gap voltage (kV)</td>
<td>270</td>
<td>440</td>
</tr>
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Kladistron: CLIC X-band adiabatic bunching

A Kladistron (KI-adi(adiabatic)-stron) is a high-efficiency klystron with a large number of cavities (at least twice as many as in a classical klystron).

CLIC Project needs a 12GHz-high-efficiency klystron, with a microperveance of 1.5 A.V^-3/2. Our preliminary AJDisk results show a higher efficiency than what we can expect from a klystron with such a high microperveance.

20 cavities – 12GHz
μP = 1.5 A.V^-3/2
Efficiency 78 % (AJDisk simulation)
Length 285 mm

Antoine Mollard – IVEC 2017
Kladistron: TH2166 5 GHz retrofit simulation

Our kladistron simulation results reach an efficiency of six points above TH2166 simulation results. The electron bunching and the beam current growth are also smoother.
Kladistron: TH2166 5 GHz retrofit prototype

16 cavities interaction line
(6 cavities for original TH2166)

TH2166 cavity shape

Low-coupling cavity shapes

- Tube sealed, and now in baking
- Tests postponed to 2018
SLAC depressed collector klystron study

Energy recovery in depressed collector of the klystron operating in pulsed mode.
Jeff NEILSON

Spent beam energy recovery concept:

- Pulsed energy recovery concept has been experimentally proven with excellent agreement.
- The energy recovery technology is ideally suited for ultrashort pulse (<300ns) RF sources.
- Accelerator stewardship funding will make technology commercially available within two years

Mark Kemp, Aaron Jensen, Gordon Bowdon, Erik Jongewaard, Andy Haase and Jeff Neilson

CLIC workshop, January 2016, CERN
C. Marchand - Energy for Sustainable Science - Magurele

I. Syratchev 23/11/2017
Optimum klystron design/frequency

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

- **L-band**
  - CSM/modest MBK
  - LHC, FSS, ESS, ILC
  - 1/6 MW

- **S-band**
  - Medical/industrial
  - BAC/MBK
  - 5-10 MW, <60kV

- **C-band**
  - High perveance MBK HE tubes (!?)
  - 10-20 MW

- **X-band**
  - Kladistron
  - CLIC, klystron based X-band FEL
  - COM/single beam
  - 50+ MW

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FCC week 2017, Berlin, Germany.
C. Marchand - Energy for Sustainable Science - Magurele

23/11/2017
Future high energy particle accelerators need in the 100 MW RF power for beam, which means up to 200 MW at outlet with conventional klystrons (50% efficiency).

This is a key candidate topic for energy saving, and triggered numerous recent studies to increase efficiencies above 80%.

These efforts, conducted inside collaborations like HEIKA and programs like Eucard\(^2\), lead to construction of several different prototypes which validate the concepts and reach up to 70%.

Reaching >80% still needs more studies and work. ARIES has an ongoing funded program for 4 years (WP4, task 2).