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Plenary discussion: Vacuum tubes

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Vacuum tubes (tetrodes, IOT, klystrons…) are used since the 50's to provide high power RF for very different type of accelerator particles. With the emergence of new accelerator projects very energy hungry like CLIC, ILC, FCC-hh(ee) ($\mathcal{O}$(100 MW)), increasing the power conversion efficiency from outlet by 10% only would help save substantial amount of electricity, and thus contribute to the overall effort to diminish power consumption with the goal of reaching sustainable energy.

In the context of this ARIES workshop, the different options of improving efficiency of vacuum tube type RF sources were addressed in several dedicated talks.

- ***IOT:***
    - IOTs are still very solid candidates for reliable and efficient RF power sources. E. Montesinos did summarize years of stable operation for CERN SPS, and C. Marelli did report on an excellent joint R&D development with industrial companies (L3, Thales-CPI) of a 1.2 MW 704 MHz MB-IOT that could have been an option for RF power source for ESS high beta elliptical cavities.
- ***Klystrons:***
    - Simulation tools for klystron optimization:

      J. Plouin gave an overview of the various codes used to optimize the design of klystron architecture (mainly interaction line), from fast 1D-2D steady-state codes to time consuming but much more realistic 2D-3D Particle in Cell codes. At present, even PIC codes in time domain fail to predict correctly spurious oscillations observed in "high efficiency" prototypes build recently based on Bunch-Align-Collect method (SLAC S-band 5045 retrofit) or adiabatic bunching (kladistron based on 5 GHz TH2166). J.-Y. Raguin presented an interesting glimpse on his fast 1D PIC code he is developing at PSI, which, once fully debugged and operational, could be complementary to 2D KlyC code (CERN) to speed up klystron optimization. C. Marelli showed that many real life issues have to be considered on top of the design obtained by the 2D-3D PIC codes in order to get a realistic simulated klystron efficiency (which may add up to a total loss of 5 to 10% efficiency): ohmic losses, power dissipated in the auxiliary power supplies, non-ideal output match, HV risetime in pulsed systems, power overhead for regulation, …
    - Design studies of high eff. Klystrons:

      J.C. Cai presented two ongoing design studies for high efficiency klystrons in the X-band range for the CLIC project. One at 8 MW to be used to condition CLIC cavities in the X-BOX test stands, and one at 50 MW envisaged for the "klystron based "380 GeV initial CLIC stage. The 8 MW version, using COM method and output coupler optimization is predicted to reach 60% eff (vs. 45% for existing Toshiba tube), and the 50 MW version plans to reach about 70% efficiency. P. Hamel showed another design study going on in the framework of the ARIES WP4, to develop a X-band klystron at about 30 MW that could be used for the Compact Light project, and which combines COM and adiabatic bunching ideas. At the present stage of the study, an efficiency of 70% is predicted, but more simulations are needed to guarantee avoiding spurious oscillations.

- Power dissipated in focusing magnet:

A key issue for the X-band klystrons developed above for CLIC or a Compact Light source, is that they will be operated in pulse mode at very small duty cycles. In this case, the average power dissipated by the interaction line is small, and the energy budget of the klystron at the power outlet can be quickly dominated by the focusing magnet if a conventional warm magnet is used. A. Yamamoto presented a design of a cry-cooled solenoid for the 50 MW CLIC klystron option, which reduces the power consumption by a factor 10 compared to warm. But that may not be enough to really benefit from the efforts made to increase the interaction line efficiency, and use of permanent magnets for klystron beam focusing has to be envisaged.

- Modulators:

C. Martins presented a lengthy but successful R&D for a “compact” SML modulator allowing to provide 660 kVA HV to 4 ESS 704 MHz klystrons simultaneously, reaching thus the goals of reducing cost and minimizing footprint.

The following points were proposed at the plenary discussion on vacuum tubes:

1) ***Overview of vacuum tube types****:*

- ***Tetrodes****: not much addressed, but will need to rely on them for the next decades. Hope for SSPA to eventually take over.*
- ***MB-IOT****: successful, but no solid data for lifetime. How to make it mature? Who will fully validate technical choices?*
- ***CERN IOT*** *experience (@Alba, RAL …): requires very systematic procedures and preventive maintenance, but IOT itself has acceptable lifetime (35kH+); Lifetime in operation of smoothing capacitors >> lifetime on shelf ?!*
- ***Magnetrons:*** *the community should at least validate or discard the idea, based on relevant tests to be conducted.*
- ***Klystrons and modulators****: what about the LLRF request to work correctly below saturation? Rise time losses in pulsed operation: can we switch RF on when voltage is at 90%? (with additional phase FF ….); Nice development of SML modulator 660 kVA (JEMA) for ESS.*

2) ***High-efficiency Klystrons****:*

- *Where do we stand?*
- *What should we concentrate on? …*
- *How to best include industry – win/win…*
- *What method for which application? (COM, BAC, CSM, kladistron…)*
- *Multi-gap output cavity – advantages and disadvantages. How to proceed to fully validate?*
- *Superconducting solenoid vs permanent magnet focussing?*
- *Spurious oscillations in “EuCARD-2” tube – understood?*
- *All these simulation codes – benchmarking them against each other.*
- *Efficiency limits: have we included everything?*

PLENARY DISCUSSION:

The plenary discussion was driven by two main questions: which vacuum tubes are best suited for future demanding high-power RF accelerator projects, and what is the roadmap to fully validate the new concepts of improving vacuum tube efficiency and make them mature in time for their deployment on the presently discussed projects like ILC, FCC, CLIC, Compact Light, …

- Choice of vacuum tube type

  Ignoring SSPA discussed in the other session, the present consensus is that only IOT and klystrons remain good contenders for high power RF sources today. We will have to live with the existing park of tetrodes for the next decade, SSPA will eventually take over.

  - Magnetrons have been discussed as a cheap alternative option, being used heavily in microwave ovens, but they are very difficult to phase lock, being quite noisy by nature, and also suspected to not last long, because of strong loading with electrons. It is felt that the community should make a final decision based on definitively concluding tests, but who is willing to take time for that?
  - IOT's have regained some interest, as they have decent MTBF (10 to 12 kh in CW, higher in pulsed mode, up to 35 kh), and also due to development of multibeam IOT for ESS. Even if this MB-IOT option has been discarded by ESS for now, due to lack of solid data for lifetime, Stéphane Bethuys (Thalès) argues that they may become interesting for (medium?) high-beta cavities at power levels of 700 to 800 kW at a later stage of ESS.
  - Klystrons remain one of the preferred choice for very high power RF sources (> 1 MW) given their quite low price and reliability, but SSPA will become contenders when their efficiency will improve, and their foot print reduce.
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- Improve vacuum tube efficiency: design, prototyping, maturation of new solutions…
  - Design using new concepts:

    The first method used to improve efficiency of klystrons (and IOT as well) has been to spread the beam over several interaction lines, reducing thus the microperveance of each individual beam, and hence allowing to increase its efficiency: this is the multi-beam klystron design. Since 2013, some innovative concepts of improving the bunching of the beam, and thus optimize extraction of RF at the output cavity and consequently improving efficiency have been proposed in the framework of the HEIKA collaboration: BAC (bunch-align-collect), COM (core optimization method) and CSM (core stabilization method). It is now common consensus that COM are better suited for X-band, while CSM are adapted to tubes below 1 GHZ, because it allows for shorter tube length.

    A plethora of 1D to 3D simulation codes exist to integrate these new concepts in the conception of new tubes, but it is felt that there is still some effort to be made to benchmark them together, and most important as has been shown by Chiara to correctly account for all small effects that can reduce efficiency at the end.

  - Prototyping of new concepts:

    Simulations may have improved, nothing replaces building prototypes to test the feasibility to improve efficiency of tubes with the new bunching techniques cited above. Most efforts done so far, or underway, consist in retrofitting an existing tube, as it is cheaper to start from an existing tube, and just replace the interaction line cavities, keeping the gun, the output cavity, the collector and the focusing magnet. However, for some high-power tubes (like retrofitting SLAC X5 tube for 50 MW at 12 GHz), the improved bunching results in higher electrical fields at the output cavity, which needs thus to be replaced by a multi-gap cavity. Only fabricating such a multi-gap cavity and testing it on a retrofitted tube will allow to validate this new concept. Also, two recent retrofits (SLAC 5042 in S-band by BAC method, and Thales 2166 in X-band by adiabatic bunching) have been hampered by spurious oscillations which prevents from obtaining even initial tube efficiency, and are not yet fully reproduced by existing simulations.

- Maturation of new concepts:

  In all these efforts to build prototypes for high efficiency tubes, industry must be involved (and is most of the time), but the recurrent problem is to obtain funding in a win/win solution. Such an effort is underway at CERN to improve efficiency of LHC klystrons operating at 400 MHz, together with Thales. Once funding issue is solved, and a prototype successfully tested, there remains the problem of maturation, that is long term reliability of the new concepts. This problem has shown up after successful fabrication and test of a MB-IOT for ESS, and may reoccur for CERN as well. Part of the problem comes from the fact that RF tubes used in accelerators originate from space and military where they have been tested extensively over long-time ranges, while nearly nobody wants to take the risk of jeopardizing a new accelerator project by not well enough proven technology. It should nevertheless been reminded that synchrotrons like SOLEIL and ESRF took the risk to switchi from tubes to solid state for their choice of RF sources.

- Operate close to saturation:

  An alternative way to gain some efficiency is to operate the tube near saturation (about 90%). This leaves less margin to adjust the amplitude of the RF signal due to beam loading effects, but modern LLRF techniques experienced at DESY allow to cope up.

For sake of completeness, here are E. Jensen’s notes on plenary hot topic discussion (partly incorporated and expanded above, can be removed from final report)

- **IOT’s**:
  - MB-IOT may become interesting for medium-beta cavities, at power levels of 700 to 800 kW at a later stage of ESS (Stéphane).
  - Applications also in broadcast
  - MTBF of about 10 kh, maybe 12 kh in CW. MTBF different in CW and pulsed operation
  - Possible issues with ceramic (Armel)
- **Magnetrons**:
  - Phase control devilish
  - Life-time issue suspected (strong loading with electrons) – same with CFA’s
- **Klystrons**:
  - LLRF overhead necessary for large beam loading.
  - DESY has good experience operating at 90% of saturation.
  - COM design better suited for X-band, CSM good for below 1 GHz.
  - Juliette: don't narrow down choices now - at this time, diversity is good.
  - Jörn: could we think of a "test-kit" to quickly test different HE Klystron proposals?
  - Juliette: CEA did something similar for the kladistron tests.

CONCLUSION:

Several innovative concepts of improving efficiency of high-power tubes have come up in the recent years (multi-beam, improved bunching), some of them tested successfully (or not) on prototypes, but they are still considered by the accelerator community as too immature to deploy them on a wide scale as RF power sources.