SUMMARY OF THE 3RD WORKSHOP ON HIGH POWER RF-SYSTEMS FOR ACCELERATORS

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Abstract

The aim of this workshop was to bring together experts from the field of CW and high average power RF systems. The focus was on operational and reliability issues of high-power amplifiers using klystrons & tubes, large power supplies; as well as cavity design and low-level RF and feedback control systems. All these devices are used in synchrotron radiation facilities, high power linacs and collider rings, and cyclotrons. Furthermore, new technologies and their applications were introduced, amongst others: high power solid state amplifiers, IOT amplifiers, and high voltage power supplies employing solid state controllers/crowbars. Numerical methods for complete rf-field modeling of complex RF structures like cyclotrons were presented, as well as integrated RF-cavity designs (electro-magnetic fields and mechanical structure), using numerical methods.

COMPARISON OF CYCLOTRON RF SYSTEMS TO SYNCHROTRON-, LINAC- & STORAGE RING RF SYSTEMS

What are the Similarities?

- Common design tools for simulation & modeling (e.g.: MAFIA, MWS, EESOF, ANSYS)
- Power couplers, vacuum windows
- Control-, protection- & tuning systems
- Power supplies
- Problem areas: - Voltage breakdowns (sparks)
  - Multipacting

.. And the Differences?

- Frequency range:
  - *Higher f:* Linacs, storage rings:
    ⇒ Cavities are smaller and usually simpler in shape (like pillbox) → simpler to model
  - *Lower f:* Synchrotrons (sweeping f)
- Pulsed RF system operation (only used in cyclotrons for conditioning, testing, etc.)
- Power amplifiers: Klystrons (pulsed & CW); New concepts: IOTs, solid state power amplifiers (kW range)

AGENDA, MAIN TOPICS

The presentations could be classified into the following cathegories, with the contributing institution names given:

- Status Reports, New Projects:
  ESRF, DESY, PSI
- Upgrade Programs, Test Stands
  ELETTRA, ANL
- Operating Experience & Reliability Aspects:
  JLAB, SLAC, ANL
- Power Amplifiers:
  - Improvements, Reliability, MTBF
    ANL, JLAB, PSI
  - New Technologies:
    - New Solid State High Power Amps
      SOLEIL
    - Solid State Amps ⇒ Tubes (IOTs)
      JLAB
- HV- Power supply design: Solid State Fast Power Switch (IGBT) to replace Ignitron
  ANL
- Power Couplers, Vacuum Windows, Tuners
  ANL, CERN
- Modeling of complex RF Structures, New Cavities
  PSI
- Bunchers (operating experience & new)
  GANIL, PSI
- Multipacting, RF Control & Conditioning, RF Diagnostics
  GANIL, PSI, TRIUMF

A SELECTION OF HIGHLIGHTS

A few interesting applications of newer technologies - and first experience with them – were reported. Some conclusions were contradictive: more experience will be required!

RF Power Amplifier Technologies:

- High power (kW- range) solid-state amplifiers
- IOT`s: inductive output tubes

Possible advantages:
Lower costs, better reliability, higher overall efficiency

HV Power Supplies:

- Solid state crowbar systems
- Solid state controllers

Possible advantages:
Increased reliability, no ignitrons needed (→ mercury-free)

RF Cavity Design:

- Field modelling of complex RF structures (complete cyclotron RF systems: multiple dees)
- Complex cavity shapes: RF- field models are integrated with mechanical structure design models

Possible advantages:

- Optimized designs are now possible; in terms of voltage distributions, maximum field gradients, power losses (R_p).
- No 1:1 scale prototypes are needed (!)

A 40 KW SOLID-STATE RF POWER AMPLIFIER

The team of *Partrick Marchand* at the *SOLEIL* synchrotron project proposes to use solid-state amplifier technology extensively for their booster ring (2.75 GeV). The operating frequency is set at 352 MHz, with a projected output power level of 35 kW. [1]
The concept is based on a highly modular design: built-in redundancy should greatly improve reliability, compared to a solution with conventional klystrons.

The basic building block is a 330W solid-state amplifier module, with its own DC/DC power supply (see Fig. 1). The main power supply is of extremely simple design: basically a line-input 3 phase AC - 6 way rectifier with a rated DC output of 280V/360A.

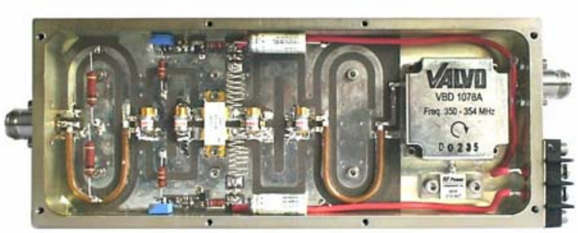

Figure 1: 330 W solid state amplifier module, based on push-pull MOSFETs (Semelab D1029UK05 VDMOS). G_{min} > 12 dB, with circulator in output

18 of these modules, together with their corresponding power supply board (280V/30V DC/DC converter) are mounted on one (of 8) water cooled heat sinks (Fig. 2); for a total of 147 modules & DC/DC converters, to provide a total of 40 kW of RF power.

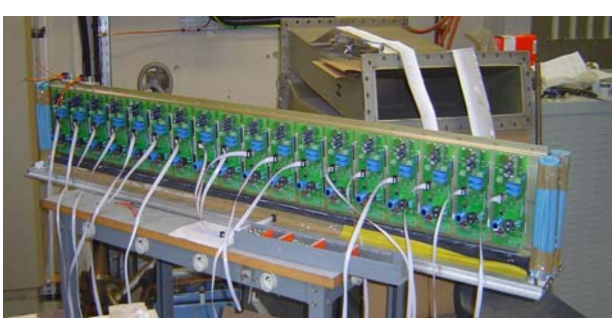

Figure 2: Heat sink (one of eight), with 18 amplifier modules and their corresponding power supplies

The entire structure, including RF signal distribution to inputs of modules and combiners at the outputs of the modules stands about 2m high, with a diameter of approx. 1.6m; it can be seen in Fig. 3.

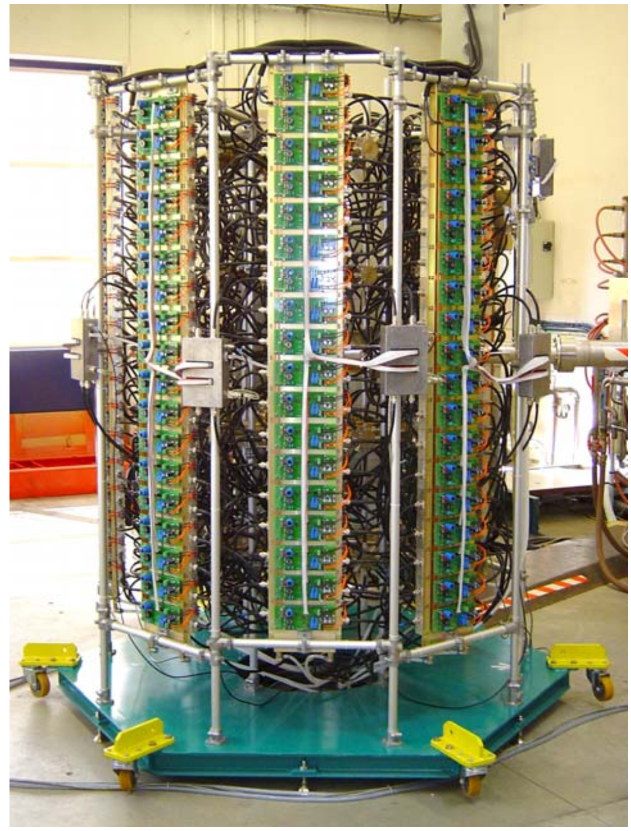

Figure 3: 40 kW/350 MHz solid state amplifier

Advantages:

- Long life time, no high voltage, easy maintenance, (higher reliability?)
- Simple spares, rugged and reliable power combiners and splitters.
- Each amplifier module has circulator at output (fail-safe design).
- Distributed switching power supplies (DC/DC converters).
- Water cooled heat sink acts as a assembly base for amps and PS.
- Monitoring and fail-safe functions included (PLC).
- Lower cost.

Disadvantage:

Operating frequency is above that of most cyclotron applications! (but might be relatively easy to extend towards lower frequencies).

Note:

If successful, a 200 kW amplifier, using new LDMOS, consisiting of four 50 kW units is planned. (T. Ruan)

Cost estimates:

The total cost of a 40 kW VDMOS amplifier, including power supplies, circulators, and spare parts is estimated to be < 200 k€.

Cost estimate coefficients: (€/W [RFpower]):

- Amplifier module, including circulator: ~ 1.1;
- Power combiners, splitters: ~ 0.3
- DC/DC converter: ~ 0.6
- Coaxial components and cable: ~ 0.3

Conclusions:

Up to now, a prototype has been tested for over 600 hrs on a dummy load at 35 kW output power (CW). No failure has been observed.

REPLACING SOLID-STATE RF POWER AMPLIFIERS BY IOTs (Inductive Output Tubes) reported by R. Nelson, Jefferson Lab [2]

The RF separator at Jefferson Labs CEBAF machine uses RF copper cavities to deflect beam bunches to different experimental halls. The operating frequency is 499 MHz, and the amplifier used was originally a 1kW solid state design. The amplifiers were configurable: multiple units could be combined: it seemed like a good idea at the time!

So: What were the Reasons to Replace Existing Amplifiers?

Initially, increased beam energy required higher RF power, causing the amplifiers to run near saturation.
This lead to increasingly poor reliability with all-too-frequent failures.
Then, there was the problem of obsolete & virtually unavailable transistors:

- They were "preferred devices" when built!
- At recent failure rates, there was about 6 months worth of devices left!

Hence, the mission became: Replace amplifiers before transistors are depleted!

Amplifier Options: Transistors or Tubes?

- Once bitten… the transistor problem would repeat itself !
- Tubes are more attractive now at higher power (10 kW or more)

Choice: IOT-based Amplifier Proposed and Adopted

- More than adequate power; new amplifiers would be rated at 10 kW or more.
- Essentially an off-the-shelf device (commercial digital communication & analog TV broadcasting).
- Proven reliability in broadcast use.
- Disadvantage: relatively low gain (≈ 23 dB): driver stage required (≈ 200W).

Advantages of Commercial IOTs:

- They are offered by several suppliers, e.g.: CPI (Eimac), EEV, Thales, *Litton.*
- They are used in analog (TV) and digital communication: ⇒ Large market!
- IOTs are reliable devices with a relatively high efficiency of 60% (better than tetrodes or klystrons).
- Operating experience shows average lifetimes of ≈ 35'000 hrs (comparable to klystrons, better than tetrodes).
- Tunable from 470-860 MHz, capable of 30 kW CW.
- Failure mode is usually weak cathode emission; IOT can be re-gunned twice, at about 60% cost of a new IOT.
- Output RF cavities are external to tube; they do not have to be replaced.
- Relatively compact (compared to klystrons); higher efficiency.

Disadvantages (for Cyclotron Applications):

- Operating frequency range is *above* that of cyclotrons

Costs:

- Low initial costs: a 30 kW module is < 100 k$

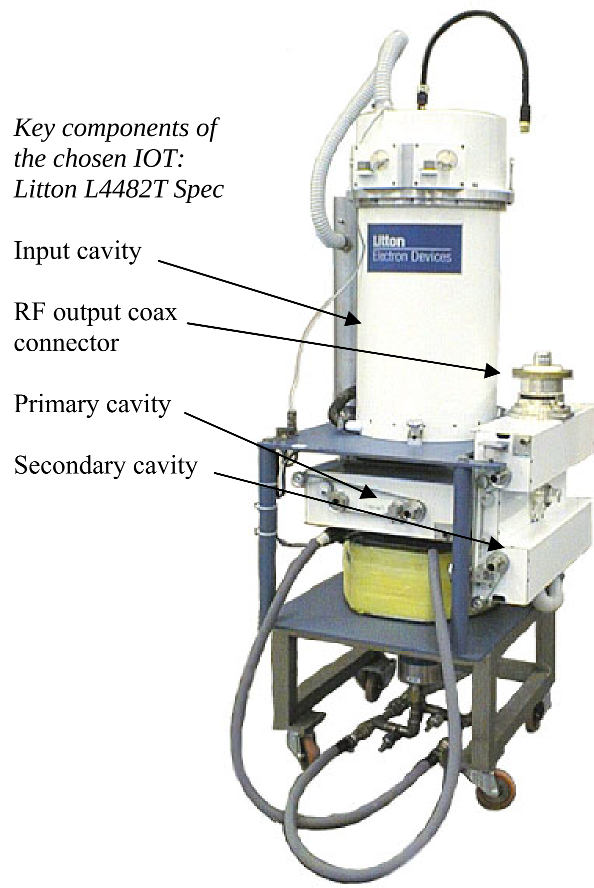

Figure 4: View of 10 kW IOT assembly on trolley (Note compact size, compared to a klystron!)

A 100KV/20A SOLID-STATE FAST SWITCH AND MODULATION-ANODE REGULATOR

T. L. Smith, from the *APS RF group* at *Argonne National Lab* [3], reported on an interesting new concept to avoid some of the problems associated with ignitron crowbars in high voltage power supplies.
Mercury-containing ignitron crowbars are commonly used to protect klystrons from arc damage. When an arc occurs, the crowbar closes and rapidly discharges the energy-storage capacitor.
An alternative way to protect a klystron is to use a switch that *opens* during an arc, using series arrays of **I**nsulated-**G**ate **B**ipolar **T**ransistors (IGBTs).

Choosing Solid-State Series Opening Switches Over a (Parallel Short) Crowbar Configuration Offers the Following Advantages:

- Nearly immediate resumption of operation after an arc, during klystron conditioning.
- Solid–state opening switches use no ignitron crowbars, and therefore contain **no mercury!**
- IGBTs can be much less expensive than vacuum tubes due to expected longer lifetimes.
- Removal of crowbars can significantly lower stresses on upstream power components.
- Opening switches are made with excessive voltage capability, so the switch can operate even if several devices fail (IGBTs always fail shorted).
- Because the energy-storage capacitor does not discharge during an arc, the RF can be turned on again immediately after the arc clears. Under certain conditions, it is possible that the beam may be retained during an arc.

Why the Choice of IGBTs?

The most desirable properties of an ideal switch are:
Fast switching speed, simple drive requirements and low conduction loss.

‘Real’solid-state power switching devices are:
- High power MOSFETs (fast switching)
- BJTs (low conduction loss, but slower)
- IGBTs (fast switching & low conduction loss) Although turn-on speeds are very fast, turn-off (tailing) of the IGBT is slower than a MOSFET. IGBTs have current fall times of around 3 µs

IGBTs can be used as switches as well as regulators, and a modular design allows the use of identical modules and similar driving devices.

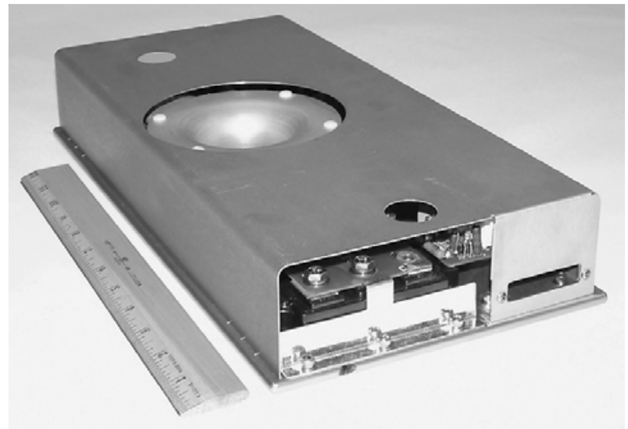

Figure 5: IGBT series switch module, rated at 3.3kV/100A continuous. 36 modules are connected in series to achieve over 100 kV switch capability

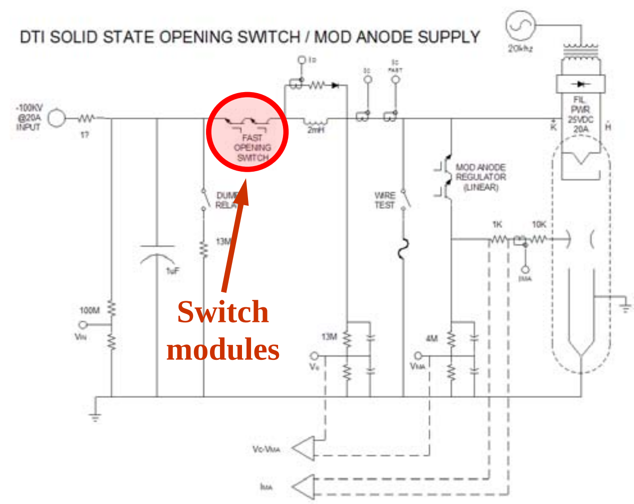

Figure 6: Configuration of IGBT series switch modules in a klystron power supply

Note: For safety, breakers at the input are still required, but will be operated less frequently (only in case of emergency, that is: solid state switch failure)

Conclusions:

- Replacing crowbars and breakers by solid-state switches increases the reliability of power supplies $\Rightarrow$ *this is also a significant advantage in cyclotron RF power supplies.*
- For voltage regulators, IGBTs can be less expensive than vacuum tubes, due to expected longer lifetimes.
- Solid–state opening switches use no ignitron crowbars, therefore: $\Rightarrow$ ***no mercury!***

ADVANCES IN LARGE SCALE ELECTROMAGNETIC MODELING AND INTEGRATED CAVITY DESIGN

M. Bopp, H.R. Fitze, L. Stingelin: PSI

Recently, computers became powerful enough to permit 3D electromagnetic field modeling of complex shapes with large numbers of mesh points (> 1M tetrahedral 2nd order elements). Simulation tools have also been greatly refined and improved.

A typical calculation of eigenmodes with Omega3P (SLAC), solving for 20 modes, takes 45min., with 32 CPUs on an IBM-SP4. Total memory requirement: approx. 120 GB. [4],[7]

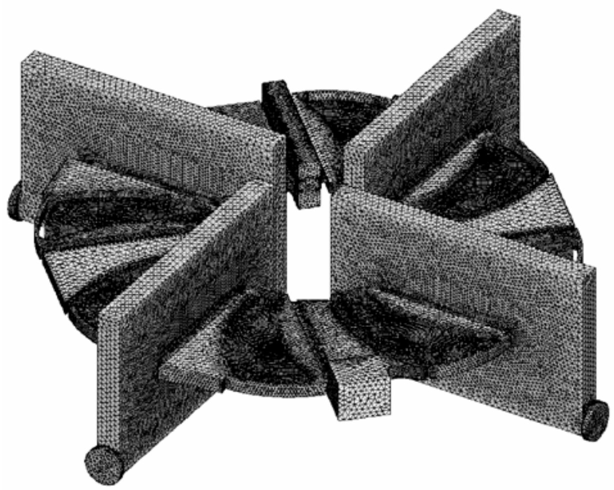

Figure 7: Mesh of RF cavities and vacuum chamber, created with tetrahedral elements, using CUBIT (Sandia Lab) 1.2 M 2nd order elements, 6.9 M degrees of freedom

Parasitic cyclotron modes can now be numerically confirmed, as can be seen in Fig. 8.

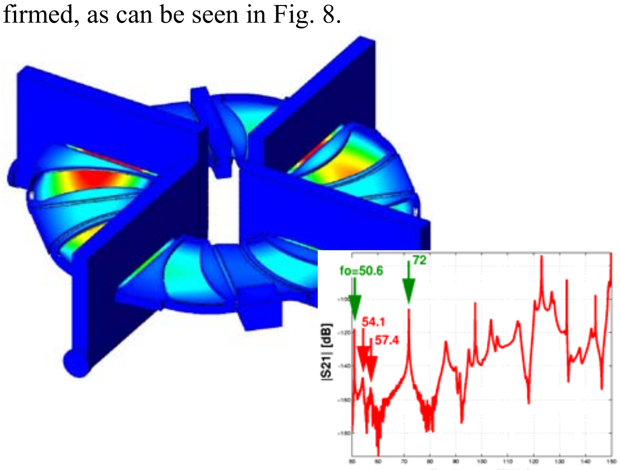

Figure 8: E- field of simulated 54 MHz mode, and measured spectrum (Network analyzer data)

Beam-cavity interactions can also be investigated, the excitation of higher order modes in cavities and vacuum chambers can be analyzed and verified. [4]

Mechanical Cavity Design, Illustrated on Cyclotron Cavity for the PSI Ring Cyclotron [5]

Mechanical cavity design is performed using FEA (finite element analysis) simulation (ANSYS) to answer the following questions:

- Inner dimensions of the cavity under vacuum: ⇒ operating resonance frequency
- Frequency drift (thermal, atmospheric pressure)
- Temperature distribution (for cooling system layout)
- Frequency tuning range
- Effect of manufacturing tolerances

Applying sequential coupled field analysis [7], we arrive at crucial values for:

- Inner dimensions of the cavity in air ⇒ necessary for manufacturing!
- Frequency drift (tuning system)
- E- and H- field distribution ⇒ acceleration gap voltage profile, heat flux distribution
- Resonance frequency in air
- Unloaded Q-value (Q_0)

The procedure yields a *deformed* RF geometry, which represents the *operating* geometry. [6], [7]

From the magnetic field distribution we derive the heat flux distribution, and ultimately arrive at the temperature distribution at 500 kW RF power, as can be seen in Fig. 9.

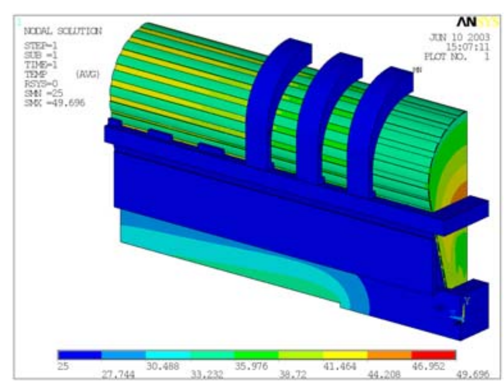

Figure 9: Temperature distribution in 1/8th cavity model

REFERENCES

[1] P. Marchand, T. Ruan, SOLEIL: 3rd Workshop On High Power Rf-Systems For Accelerators 2004, & private communication
[2] R. Nelson, JLAB: 3rd Workshop On High Power Rf-Systems For Accelerators 2004, & private communication
[3] T. L. Smith et al., APS/ANL: 3rd Workshop On High Power Rf-Systems For Accelerators 2004, & private communication
[4] L. Stingelin, PSI: this conference, code 20P06
[5] H. R. Fitze et al., PSI: this conference, code 18B3
[6] M. Bopp et al.: 22nd CAD-FEM Users meeting, Nov. 10-12, 2004, Dresden, D
[7] PSI Scientific & Technical Reports: 2001 - 2003