RF Solid State Amplifiers

Jörn Jacob, ESRF

SOLEIL – ELTA/AREVA amplifier module at ESRF

SOLEIL – ELTA/AREVA amplifiers at ESRF
RF transmitters for accelerating cavities

Example ESRF Storage Ring:
ESRF 352 MHz RF system, before upgrade:
- 5 MV re-acceleration/turn
- 5 five-cell cavities provide 9 MV/turn
  \[\Rightarrow 300 \text{ kW copper loss in cavity walls}\]
- 200 mA electron beam in storage ring
  \[\Rightarrow 1000 \text{ kW beam power}\]
- RF power from 1.1 MW klystrons
Example ESRF: Recent RF upgrade

Replacement of Booster Klystron by:
4 X 150 kW RF Solid State Amplifiers (SSA) from ELTA / AREVA:
- In operation since March 2012
- 10 Hz pulses / 30 % average/peak power

In operation since March 2012

10 Hz pulses / 30 % average/peak power

3 X 150 kW SSA from ELTA for the Storage Ring:
- Powering 3 new HOM damped cavities on the storage ring
- 1st & 2nd SSA in operation since October 2013
- 3rd SSA in operational since January 2014

5-cell cavities: strong HOM !

3 HOM damped mono cell prototype cavities
Klystrons in operation at ESRF

352 MHz 1.3 MW klystron

\[ \eta_{\text{typ}} = 62\% \ (\text{DC to RF}) \]
\[ G_{\text{typ}} = 42\, \text{dB} \Rightarrow P_{\text{in}} \leq 100\, \text{W} \]

Requires:
- 100 kV, 20 A dc High Voltage Power Supply
  - with crowbar protection (ignitron, thyratron)
- Modern alternative: IGBT switched PS
- Auxilliary PS’s (modulation anode, filament, focusing coils, …)
- High voltage ⇒ X-ray shielding!
150 kW RF SSA for ESRF upgrade

- Initially developed by SOLEIL
- Transfer of technology to ELTA / AREVA

Pair of push-pull transistors

650 W RF module
- DC to RF: $\eta = 68$ to $70\%$

75 kW coaxial power combiner tree

150 kW - 352.2 MHz Solid State Amplifier
- DC to RF: $\eta > 55\%$ at nominal power
- 7 such SSAs in operation at the ESRF!
RF power sources for accelerating cavities

- Tetrodes
- Diacrode
- Transistor modules \( \approx 160 \text{ to } 1000 \text{ W / unit} \)
- CW Klystrons
- Pulsed Klystrons
- CW or Average
- Ex: ESRF upgrade with SSAs
- x 100…600

Ex: ESRF Klystron

Pulsed

RF Power [kW]

f [MHz]
Brief history of RF power amplification

- Early 20th century: electronic vacuum tubes (triodes, tetrodes, …)
  - Typically limited to 1GHz due to finite electron drift time between electrodes
  - Still manufactured and in use today, kW’s at 1 GHz → up to several 100 kW at 30 MHz for applications from broadcast to accelerators (a small 3.5 ... 5 GHz triode for 2 kW pulses, 7.5 W average exists for radar applications)

- 1940’s to 50’s: invention and development of vacuum tubes exploiting the electron drift time for high frequency applications (radars during 2nd world war), still in up-to-date for high power at higher frequencies
  - Klystrons 0.3 to 10 GHz, Power from 10 kW to 1.3 MW in CW and 45 MW in pulsed operation (TV transmitters, accelerators, radars)
  - IOT’s (mixture of klystron & triode) typically 90 kW at 500 MHz – 20 kW at 1.3 GHz (SDI in 1986, TV, accelerators)
  - Traveling wave tubes (TWT): broadband, 0.3 to 50 GHz, high efficiency (satellite and aviation transponders)
  - Magnetrons, narrow band, mostly oscillators, 1 to 10 GHz, high efficiency (radar, microwave ovens)
  - Gyrotron oscillators: high power millimeter waves, 30 to 100...150 GHz, typically 0.5…1 MW pulses of several seconds duration (still much R&D -> plasma heating for fusion, military applications)

- 1950’s to 60’s: invention and spread of transistor technology, also in RF
  - Bipolar, MOSFET,… several 10 W, recently up to 1 kW per amplifier, maximum frequency about 1.5 GHz
  - RF Solid State Amplifiers (SSA) more and more used in broadcast applications, in particular in pulsed mode for digital modulation: 10..20 kW obtained by combining several RF modules
  - SOLEIL (2000-2007): pioneered high power 352 MHz MOSFET SSAs for accelerators: 40 kW for their booster, then 2 x 180 kW for their storage ring – combination of hundreds of 330 W LDMOSFET modules / 30 V drain voltage
  - ESRF: recent commissioning of 7 x 150 kW SSAs, delivered by ELTA/AREVA following technology transfer from SOLEIL – combination of 650 W modules / 6th generation LDMOSFET / 50 V drain voltage
  - Other accelerator labs, e.g.: 1.3 GHz / 10 kW SSAs at ELBE/Rossendorf, 500 MHz SSAs for LNLS, Sesame,… more and more up coming projects

ESRF → Example for this lecture
Components of an RF SSA

- **RF input**: 1 W @ 352.2 MHz
- **Transmitter controller / Remote control**
- **Pre-Ampl.**
- **Local control and interlocking**
- **Power Supply AC/DC power converter**
- **Cooling Water**
- **N x RF modules e.g. 256 x 600 W**
- **Power combiner x N**
- **RF output e.g. 150 kW**

1. **Splitter by N**
2. **Drive Ampl(s)**
3. **Power combiner x N**
4. **RF output e.g. 150 kW**
RF amplifier module: **transistor**

SOLEIL / ELTA module for ESRF SSA

- Pair of Push Pull MOSFET transistors in operated in class AB:
  - odd characteristic minimizes H2 harmonic \([\text{Ids}(-Vgs) = -\text{Ids}(Vgs)]\)
- SOLEIL: 30 V drain-source LDMOSFET from Polyfet → 330 W
- Today next generation 50 V LDMOSFET for 1 kW CW at 225 MHz from NXP or Freescale
- For ESRF project: NXP / BLF578 → 650 W / module at 352 MHz
RF power amplification - classes

**Class A:** good linearity, But only $\eta_{\text{max}}^{\text{theor}} \rightarrow 50\%$

**Class B:** $\eta_{\text{max}}^{\text{theor}} \rightarrow 78.5\%$

Push-pull in class B:

In fact push-pull in class AB for less distortion near zero crossing and lower harmonic content

- Gate bias, 0.1 … 0.4 A/transistor without RF

$V_{\text{OUT}} = $ sine wave thanks to **resonant output circuit**
RF amplifier module: RF circuit

Balun transformer:

1200 W Load

Coaxial balun implementation
RF module on SOLEIL/ELTA SSA for ESRF

- Protection of RF module against reflected power by a circulator with 800 W load (SR: 1200 W)
  - No high power circulator after the power combiner!
- Input and output BALUN transformers with hand soldered coaxial lines
- Individual shielding case per module
- Temperature sensors on transistor socket and circulator load
- Performance: 650 W, $\eta = 68$ to 70%, full reflection capability

- RF module mounted on rear side of water cooled plate
- Each transistor powered by one 280 Vdc / 50 Vdc converter (2 dc/dc converters per RF module), installed with interface electronics on front side of water cooled plate
  - SSA powered with 280 Vdc, which is distributed to the dc/dc converters
RF amplifier module: ESRF in house development

Motorola patent

ESRF fully planar design:

- Printed circuit baluns
- RF drain chokes replaced with “quarter wave” transmission lines.
- Very few components left, all of them SMD and prone to automated manufacturing

⇒ Reduced fabrication costs

<table>
<thead>
<tr>
<th>18 modules incl. output circulator</th>
<th>Average Gain</th>
<th>Average Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>at $P_{\text{RF}}^{\text{out}} = 400$ W</td>
<td>20.6 dB</td>
<td>50.8 %</td>
</tr>
<tr>
<td>at $P_{\text{RF}}^{\text{out}} = 700$ W</td>
<td>20.0 dB</td>
<td>64.1 %</td>
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- Still room for improvement
  - Ongoing R&D
  - Collaboration with Uppsala University for optimization of circuit board
Components of RF SSA

1. N x RF modules e.g. 256 x 600 W

2. Splitter by N

3. Power combiner x N

4. Power Supply
   AC/DC power converter

- RF input 1 W @ 352.2 MHz
- Pre-Ampl.
- Drive Ampl(s)
- Local control and interlocking
- Cooling Water
- RF output e.g. 150 kW

Transmitter controller / Remote control
Power splitters for the RF drive distribution

SOLEIL stripline splitters, using $\lambda/4$ transformers

N x splitter:
Length = $\lambda/4$
Z = $\sqrt{N} \times 50 \, \Omega$
Wilkinson splitter for the RF drive distribution

3 x splitter:
Length = $\lambda/4$
$Z = \sqrt{3} \times 50 \, \Omega$

Addition of resistors to absorb differential signals without perturbing the common mode, thereby decoupling the connected outputs from each other

Implemented on the prototype SSA under development at the ESRF
Components of RF SSA

1. \( N \times \text{RF modules e.g. 256 \times 600 W} \)

2. Splitter by \( N \)

3. Power combiner \( \times N \)

4. Power Supply
   AC/DC power converter

- RF input
  1 W @ 352.2 MHz

- Transmitter controller / Remote control

- Local control and interlocking

- Coolant Water

- Drive Amplifier(s)
Coaxial combiner for SOLEIL/ELTA SSA at ESRF

75 kW coaxial power combiner tree with

- λ/4 transformers like the splitters but used in reverse
- Coaxial diameter adapted to power level:
  - EIA 1"5/8 for 6 kW power level (8 x 650 W)
  - EIA 6"1/8 for 40 kW (8 x 5.2 kW)
  - EIA 6"1/8 for 80 kW (2 x 40 kW)

Each RF module is connected its 6 kW combiner by means of a 50 Ω coaxial cable:

→ 256 coaxial cables for 650 kW full reflection, with tight phase (length) tolerance

- EIA 9”3/16 for 160 kW (2 x 80 kW)
- 150 kW SSA

18 May 2014
ESRF - R&D of SSA using a cavity combiner *

For 352.2 MHz ESRF application:

- 6 rows x 22 Columns x 600 … 800 W per transistor module

\[ \Rightarrow 75 \ldots 100 \text{ kW} \]

- More compact than coaxial combiners

\[ \beta_{\text{waveguide}} \approx n_{\text{module}} \times \beta_{\text{module}} \gg 1 \]

- Easy to tune if \( n_{\text{module}} \) is varied

- Substantial reduction of losses \( \Rightarrow \) higher \( \eta \)

Strongly loaded \( E_{010} \) resonance

- Modest field strength
- Cavity at atmospheric pressure
- 1 dB - Bandwidth \( \approx 0.5 \ldots 1 \text{ MHz} \)

* Receives funding from the EU as work package WP7 of the FP7/ESRFI/CRISP project
ESRF-R&D of SSA using a cavity combiner

Prototype with 18 RF modules x 700 W:
- Successfully tested at 12.4 kW, \( \eta = 63\% \)
- 75 kW prototype with 22 wings in construction

Direct coupling of RF modules to the cavity combiner:
- No coaxial RF power line
- Very few, sound connections
- 6 RF modules are supported by a water cooled “wing”
- The end plate of the wing is part of the cavity wall with built on coupling loops
- One collective shielding per wing
- Less than half the size of a 75 kW tower with coaxial combiner tree
Components of RF SSA

1. N x RF modules e.g. 256 x 600 W
2. Splitter by N
3. Power combiner x N
4. Power Supply
   AC/DC power converter

RF input
1 W @ 352.2 MHz

Pre-Ampl.
Drive Ampl(s)

Local control and interlocking

RF output
e.g. 150 kW

Cooling Water

Transmitter controller / Remote control

Jörn Jacob: RF solid state amplifiers
10 May 2014
DC power requirement for ESRF 150 kW SSA from ELTA

\[ \eta_{\text{diff}} = \frac{dP_{\text{rf}}}{dP_{\text{dc}}} \]

\[ \eta = \frac{P_{\text{rf}}}{P_{\text{dc}}} \approx 90 \% ! \]

⇒ 400 Vac / 280 Vdc - 300 kW Power Converters

➢ Built by ESRF Power Supply Group
- Booster Energy $E$ cycled at 10 Hz (Sine wave from resonant magnet power supply system)
- RF voltage requirement essentially to compensate synchrotron radiation loss: $V_{acc} \sim E^4$ ($\ldots$ + other smaller terms)
  - $P_{rf}^{\text{peak}} = 600$ kW
  - $P_{dc}^{\text{peak}} \approx 1100$ kW
  - But: $P_{dc}^{\text{average}} \leq 400$ kW
- 10 Hz power modulation
  - $\Rightarrow$ 3.2 F Anti-flicker filter at 280 Vdc
- One common 400 kW – 400 Vac/280 Vdc power converter for 4 SSAs

SSA provides almost a factor 3 power reduction as compared to former klystron transmitter

With $C = 3.2$ F
Planned ESRF booster upgrade

- Implementation of **4 Hz ramped DC magnet power supplies** as alternative to 10 Hz resonant system:
  - Goal: easier bunch cleaning in the booster for future top up operation of the storage ring
  - Back up for 25 years old booster power supplies
- 2 five-five cell RF cavities (two RF couplers each) → **4 five-cell RF cavities** (single RF coupler):
  - Same RF voltage with 1 SSA/cavity in fault out of 4 ⇒ redundancy for frequent topping up
  - Alternatively: 40 % more RF voltage for same RF power as before
- **Consequence of new 4Hz waveform for the RF SSA’s:**
  - Slight reduction of: \( P_{dc}^{\text{average}} \) by 12 %
  - Twice as much Vdc ripple for 3.2 F ⇒ Must double anti-flicker capacitances at 280 Vdc
Main specifications and acceptance tests for RF Solid State Amplifiers

example: ESRF 150 kW RF SSA from ELTA
SSA gain/power, harmonics – CW & pulsed operation

- Specified efficiency easily met:
  - $\eta > 57\%$ at $150\,\text{kW} = P_{\text{nom}}$ (spec: 55\%)
  - $\eta > 47\%$ at $100\,\text{kW} = \frac{2}{3} P_{\text{nom}}$ (spec: 45\%)

- Gain compression $< 1\,\text{dB}$ at $P_{\text{nom}} = 150\,\text{kW}$
  - Gain curve and $P_{\text{nom}}$ adjusted by means of load impedance on RF module

- Avoid overdrive conditions
  - High peak drain voltage can damage the transistor
  - Overdrive protection interlock

- Short pulses (20 $\mu$s)
  - Transient gain increase up to $\approx 1.3\,\text{dB}$
  - Risk of overdrive
  - Overdrive protection needs to be adjusted carefully

- Requested redundancy → operation reliability:
  - All specifications met with up to 2.5\% i.e. 6 RF modules OFF (becoming faulty during operation)

- Power margin paid with efficiency: must be dimensioned carefully

- Harmonics: $H_2 < -36\,\text{dBc}$, $H_3 < -50\,\text{dBc}$

- Spurious sidebands / phase noise:
  - $< 68\,\text{dBc}$ at 400 kHz (from DC/DC PS’s, harmless)
  - Compare klystron -50 dBc from HVPS ripples at 600 Hz, 900 Hz, 1200 Hz, … moreover close to $f_{\text{synchrotron}}$
Adjustment of phase between 1\textsuperscript{st} and 2\textsuperscript{nd} 8x-Combiner stages

\[ \Phi_L : \text{proposed by SOLEIL} \]

1 module OFF experiences:

High $P_{\text{reverse}}$ coming from other modules $\Rightarrow$ interference between 7 neighbours of same combiner and power from other combiners

7 neighbours of same combiner ON:

$\Rightarrow$ see only small $P_{\text{reverse}}$

when SSA matched: $r = 0$
Adjustment of phase between 1\textsuperscript{st} and 2\textsuperscript{nd} 8x-Combiner stages

Additional interference with reflection for mismatched operation: |r| = 1/\sqrt{3} \quad (ESRF spec)

- 1 module OFF: depending on $\Delta \Phi_L$ (and on reflection phase) the circulator load receives up to
  - $P_{\text{rev}}^{\text{max}} = 1500$ W to 1700 W for worst $\Delta \Phi_L$
  - $P_{\text{rev}}^{\text{max}} = 1100$ W for best $\Delta \Phi_L$
- Active modules receive the remaining power: maximum of 400 W for best $\Delta \Phi_L$
  $\Rightarrow$ Successful implementation of best $\Delta \Phi_L$ and 1200 W loads on the SSA for the SR, which are operated in CW

$\triangleright$ NB: not necessary on booster, operated in pulsed mode (800 W loads tested above 2000 W pulsed RF)
Transient reflections for pulsed cavity conditioning

*Computation: amplitude*

- SSA tested with 20 μs /150 kW pulses at full reflection
- Fast interlock for $P_{\text{refl}} > 150$ kW
- Interlock on low pass filtered signal for $P_{\text{refl}} > 50$ kW
Conclusion
Short comparison Klystron / SSA

352 MHz 1.3 MW klystron

Thales TH 2089
RF SSA as alternative to klystron: Pros & Cons

+ No High voltage (50 V instead of 100 kV)
  + No X-Ray shielding
  + 20 dB less phase noise

+ High modularity / Redundancy
  ➢ SSA still operational with a few modules in fault (but not if driver module fails)
  ⇒ Increased reliability

− More required space per kW than a tube,
  ➢ But it is easier to precisely match the power to the requirement
  ➢ Cavity combiners → reduced SSA size

• Durability / obsolescence:
  ➢ Klystron or other tube: OK as long as a particular model is still manufactured, but problematic in case of obsolescence, development costs of new tubes too high for medium sized labs
  ➢ SSA: shorter transistor product-lifetime, however guaranteed availability of comparable, possibly better transistors on the market ✶ requires careful follow up!

+ Easy maintenance, if there are sufficient spare parts available
  • Investment costs:
    − Still higher price per kW than comparable tube solutions
    + But SSA technology is progressing ✶ e.g. expected cost reduction with ESRF planar module design and compact cavity combiner
    + Prices for SSA components should sink
    + Prices for klystrons have strongly increased over the last decades

+ Low possession costs:
  + ESRF spec: Less than 0.7 % RF modules failing per year, most easy to repair
  + so far confirmed by short ESRF experience

• SSA/tubes: Comparable efficiency, must be analyzed case by case
  + Reduced power consumption for pulsed systems (e.g. Booster), thanks to possible capacitive filtering of the DC voltage
Acknowledgments

• Tribute to **Ti Ruan** who past away in March 2014.

In the early 2000’s **Ti Ruan** initiated the design and the implementation of high power SSA’s combining hundreds of transistors for larger accelerators. He is the father of the big SSA’s implemented at SOLEIL, ESRF and many other places around the world.

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