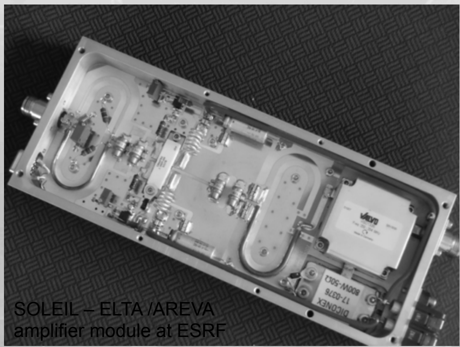
ESRF A Light for Science

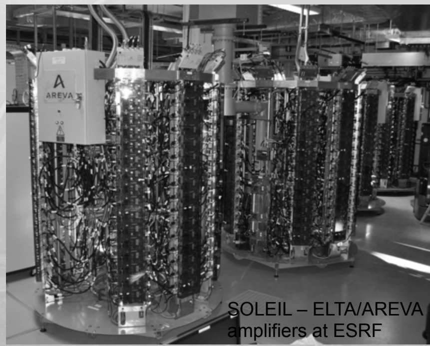
CAS – CERN Accelerator School on Power Converters
Baden, 7 – 14 May 2014

RF Solid State Amplifiers

Jörn Jacob, ESRF



SOLEIL – ELTA /AREVA amplifier module at ESRF



SOLEIL – ELTA/AREVA amplifiers at ESRF

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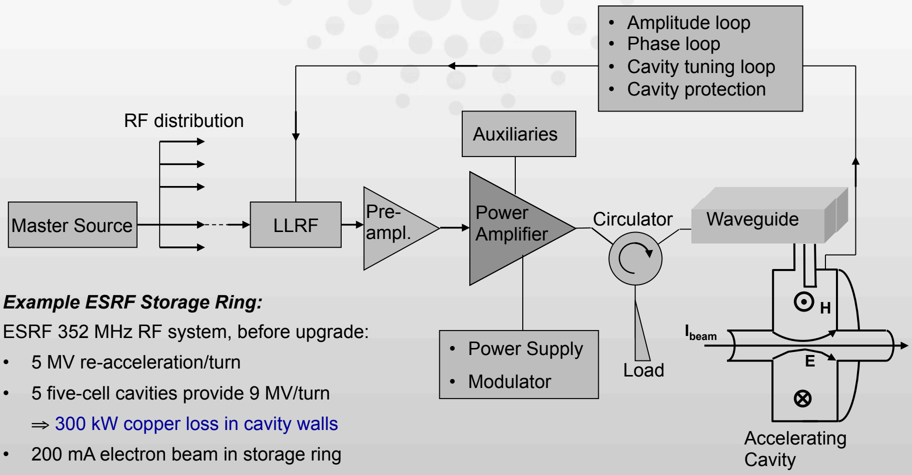
RF transmitters for accelerating cavities



Example ESRF Storage Ring:

ESRF 352 MHz RF system, before upgrade:

- 5 MV re-acceleration/turn
- 5 five-cell cavities provide 9 MV/turn
  ⇒ 300 kW copper loss in cavity walls
- 200 mA electron beam in storage ring
  ⇒ 1000 kW beam power
- RF power from 1.1 MW klystrons

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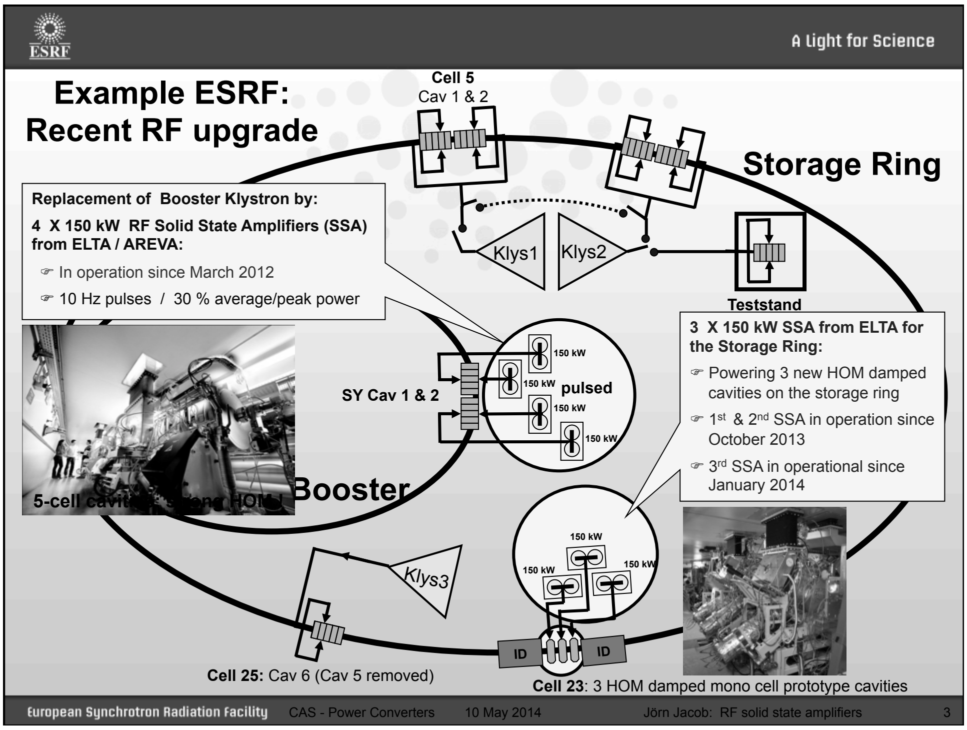
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Example ESRF:
Recent RF upgrade
Cell 5
Cav 1 & 2
Storage Ring
Replacement of Booster Klystron by:
4 X 150 kW RF Solid State Amplifiers (SSA) from ELTA / AREVA:
In operation since March 2012
10 Hz pulses / 30 % average/peak power
Klys1
Klys2
Teststand
SY Cav 1 & 2
150 kW
pulsed
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
Booster
Klys3
ID
Cell 25: Cav 6 (Cav 5 removed)
Cell 23: 3 HOM damped mono cell prototype cavities
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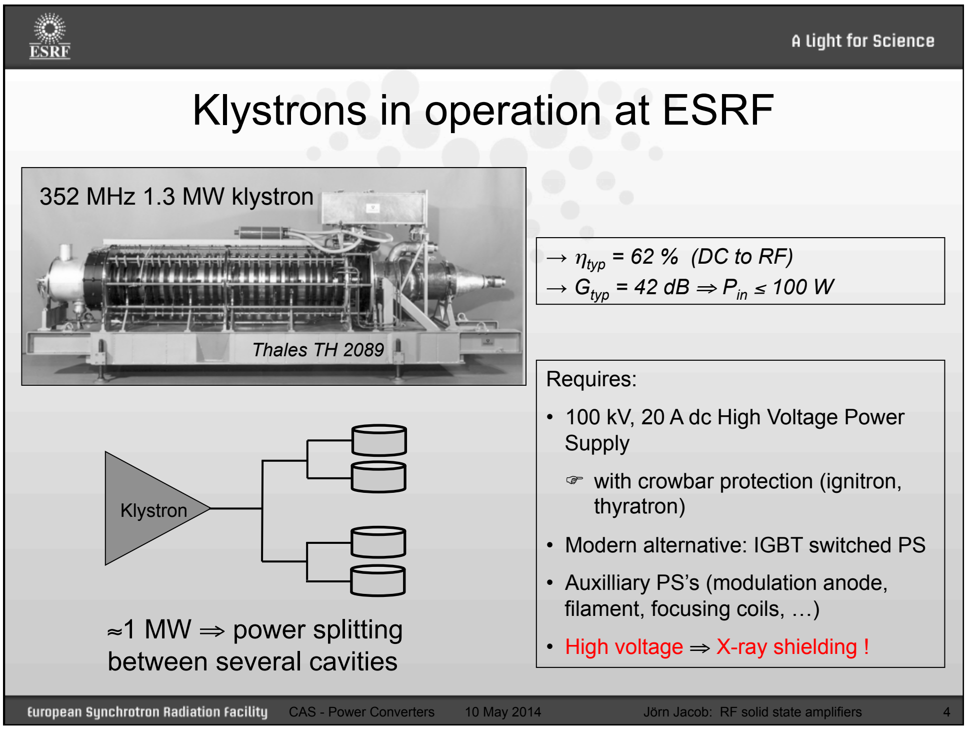
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Klystrons in operation at ESRF
352 MHz 1.3 MW klystron
Thales TH 2089
→ η_{typ} = 62 % (DC to RF)
→ G_{typ} = 42 dB ⇒ $P_{in} \leq$ 100 W
Requires:
• 100 kV, 20 A dc High Voltage Power Supply
with crowbar protection (ignitron, thyratron)
• Modern alternative: IGBT switched PS
• Auxilliary PS's (modulation anode, filament, focusing coils, …)
• High voltage ⇒ X-ray shielding !
Klystron
≈1 MW ⇒ power splitting between several cavities
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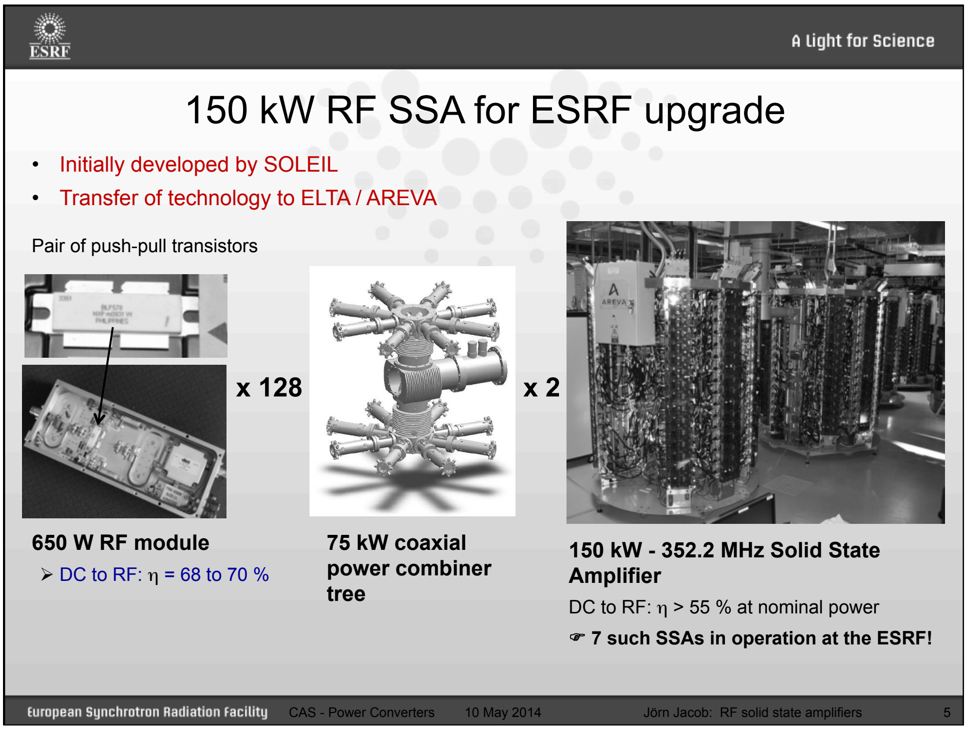
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150 kW RF SSA for ESRF upgrade
• Initially developed by SOLEIL
• Transfer of technology to ELTA / AREVA
Pair of push-pull transistors
x 128
x 2
650 W RF module
➢ DC to RF: η = 68 to 70 %
75 kW coaxial power combiner tree
150 kW - 352.2 MHz Solid State Amplifier
DC to RF: η > 55 % at nominal power
☞ 7 such SSAs in operation at the ESRF!
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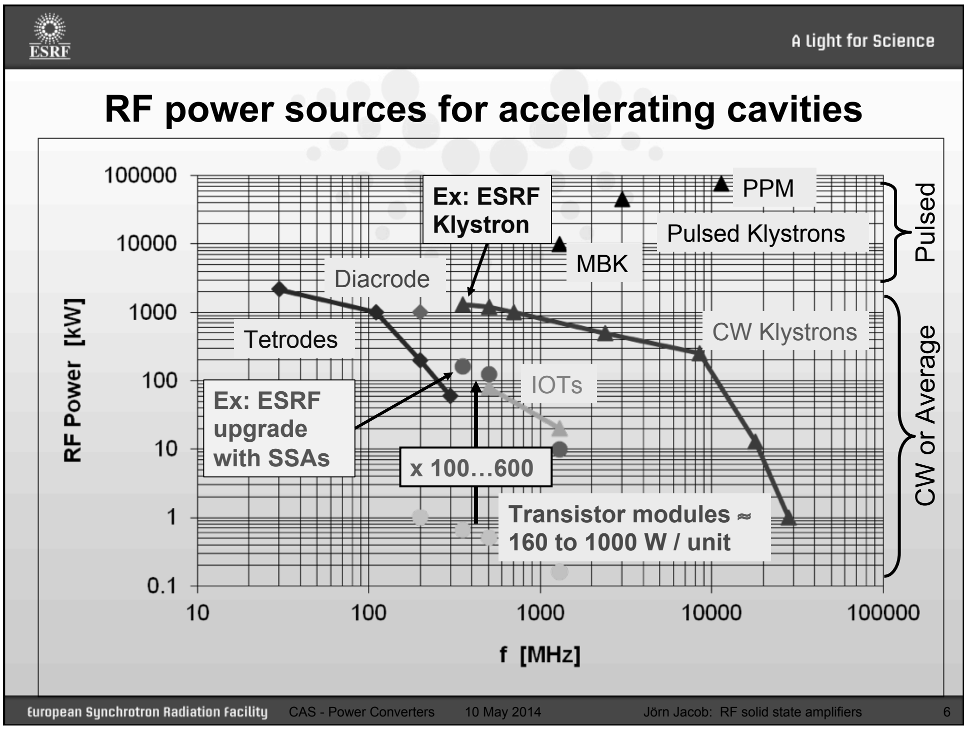
ESRF
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RF power sources for accelerating cavities
RF Power [kW]
100000
10000
1000
100
10
1
0.1
10
100
1000
10000
100000
f [MHz]
Ex: ESRF Klystron
PPM
Pulsed Klystrons
MBK
Diacrode
Tetrodes
CW Klystrons
IOTs
Ex: ESRF upgrade with SSAs
x 100…600
Transistor modules ≈ 160 to 1000 W / unit
Pulsed
CW or Average
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Brief history of RF power amplification

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- 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 **S**olid **S**tate **A**mplifiers (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

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Components of an RF SSA

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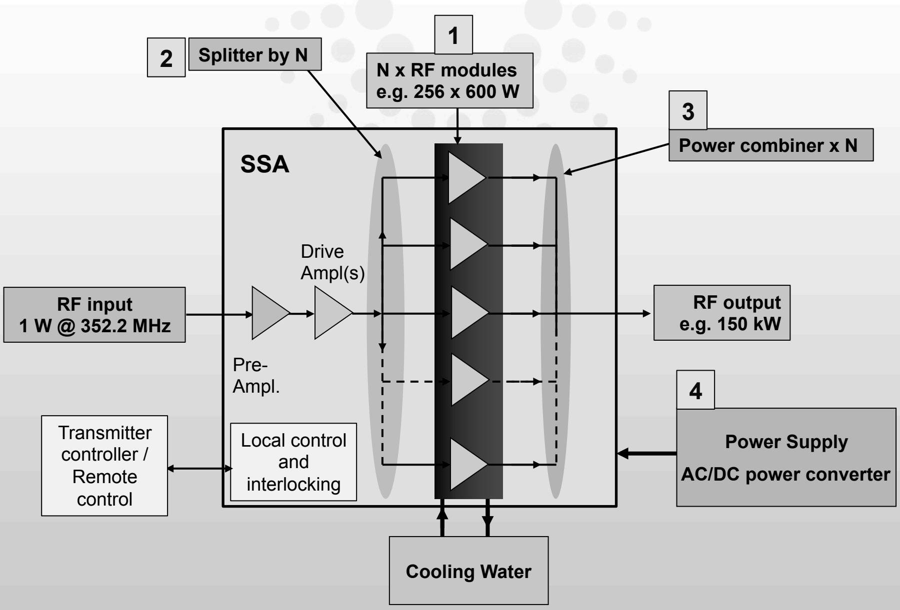

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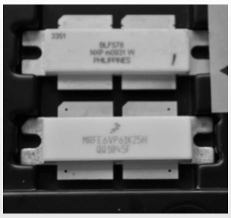
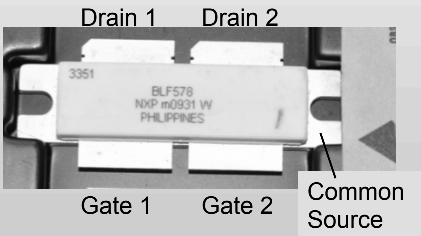
RF amplifier module: transistor

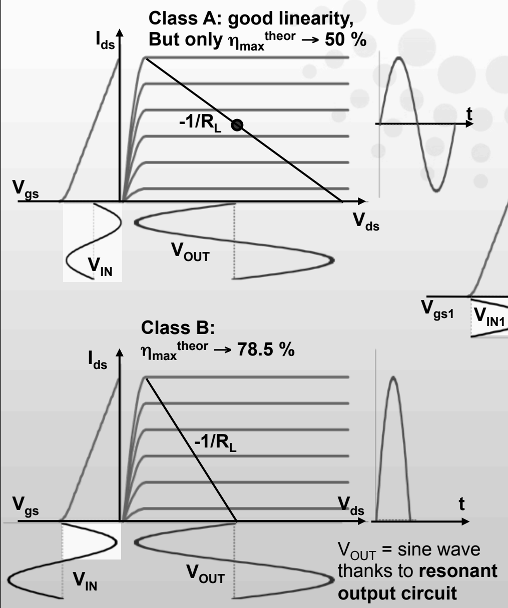


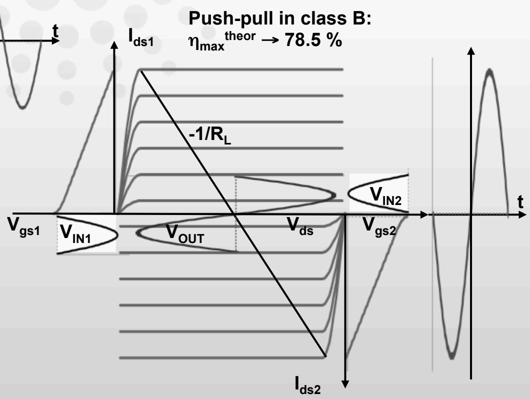
SOLEIL / ELTA module for ESRF SSA

- Pair of Push Pull MOSFET transistors in operated in class AB:
  - odd characteristic minimizes H2 harmonic *[Ids(-Vgs) = -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





- **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

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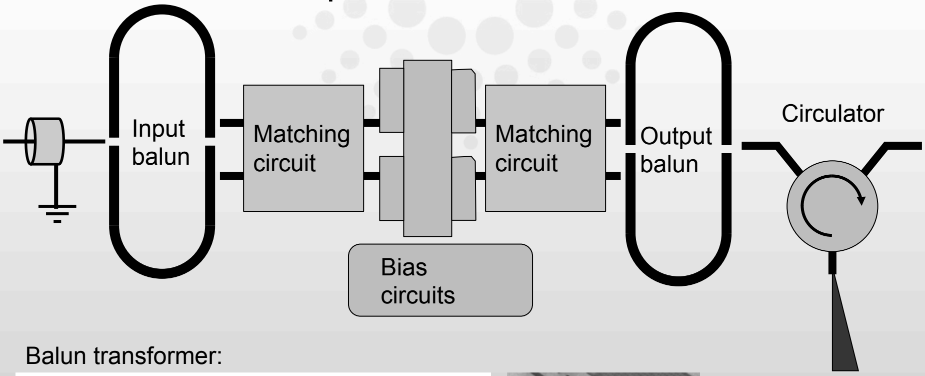
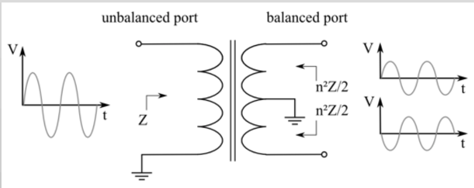
RF amplifier module: RF circuit



Balun transformer:



Coaxial balun implementation

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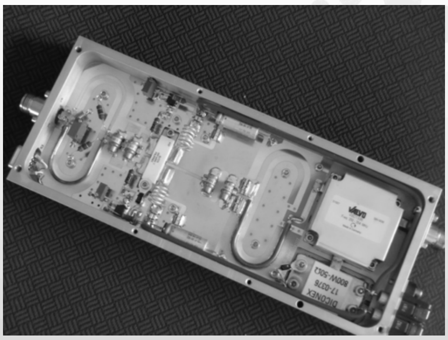
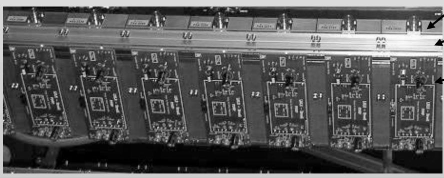
RF module on SOLEIL/ELTA SSA for ESRF



- 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, η = 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

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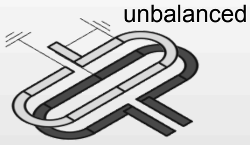
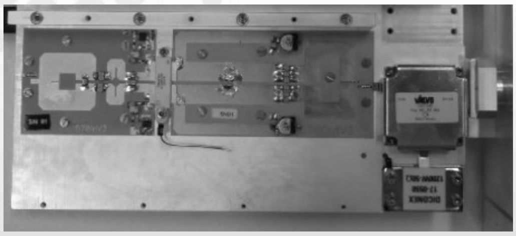
RF amplifier module: ESRF in house development

Motorola patent





ESRF fully planer 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

18 modules incl. output circulator	Average Gain	Average Efficiency
at P_{RF}^{out} = 400 W	20.6 dB	50.8 %
at P_{RF}^{out} = 700 W	20.0 dB	64.1 %

- Still room for improvement
  - ☞ Ongoing R&D
  - ☞ Collaboration with **Uppsala University** for optimization of circuit board

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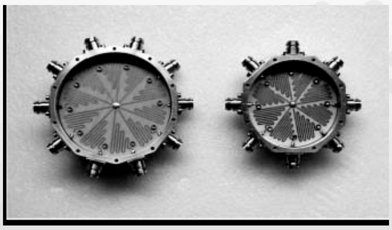
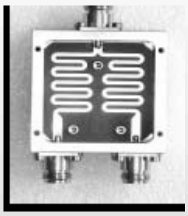
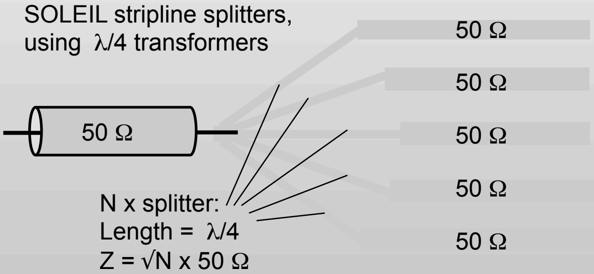
Power splitters for the RF drive distribution





SOLEIL stripline splitters, using λ/4 transformers



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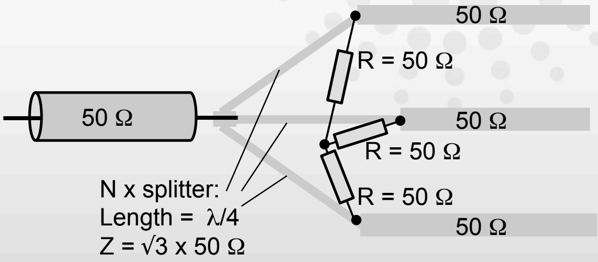
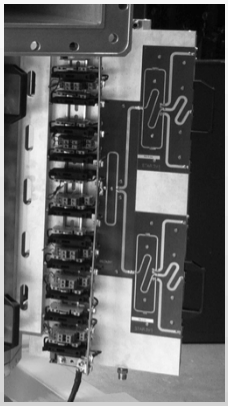
Wilkinson splitter for the RF drive distribution





Implemented on the prototype SSA under development at the ESRF

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

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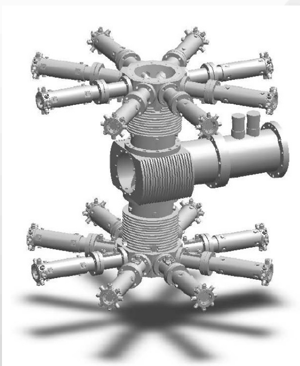
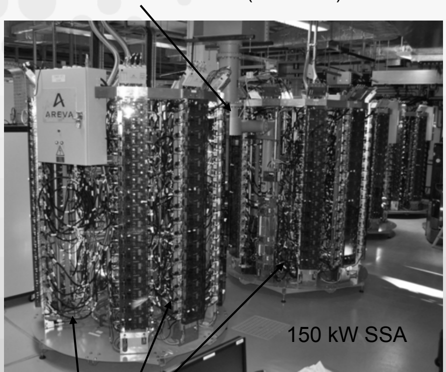
Coaxial combiner for SOLEIL/ELTA SSA at ESRF



x 2

➢ EIA 9"3/16 for 160 kW (**2** x 80 kW)



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

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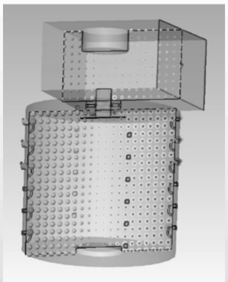
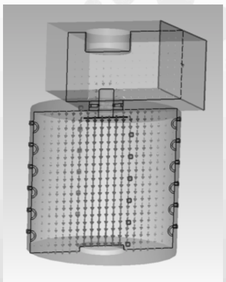
ESRF - R&D of SSA using a cavity combiner *



H field

Homogenous magnetic coupling of all **input loops**



E field

Strong capacitive coupling to **the output waveguide**

For 352.2 MHz ESRF application:

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

  ⇒ **75 … 100 kW**
- More compact than coaxial combiners

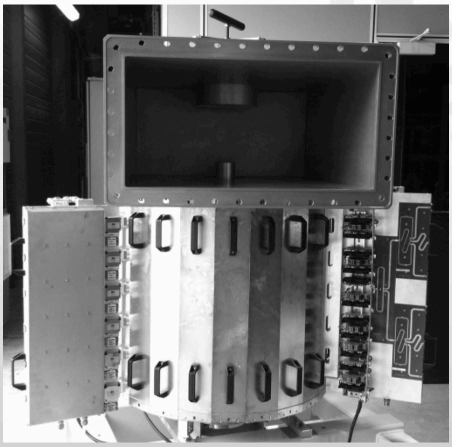
  $\beta_{waveguide} \approx n_{module} \times \beta_{module} >> 1$
- Easy to tune if n_{module} is varied
- Substantial reduction of losses ⇒ higher η

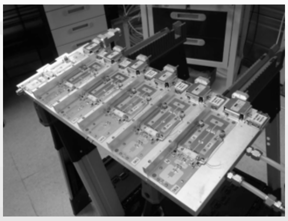
Strongly loaded E_{010} resonance

- Modest field strength
- Cavity at atmospheric pressure
- 1 dB - Bandwidth ≈ 0.5 … 1 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





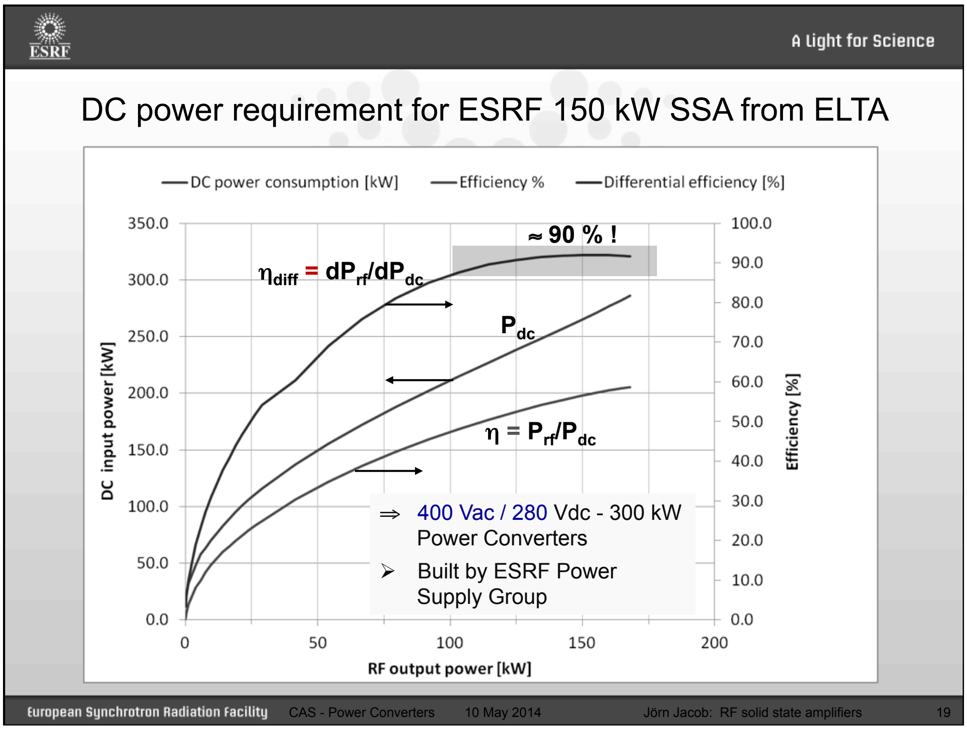
Prototype with 18 RF modules x 700 W :

☞Successfully tested at **12.4 kW**, **η = 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**


ESRF
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DC power requirement for ESRF 150 kW SSA from ELTA
DC power consumption [kW]
Efficiency %
Differential efficiency [%]
≈ 90 % !
ηdiff = dPrf/dPdc
Pdc
η = Prf/Pdc
DC input power [kW]
Efficiency [%]
RF output power [kW]
⇒ 400 Vac / 280 Vdc - 300 kW Power Converters
➢ Built by ESRF Power Supply Group
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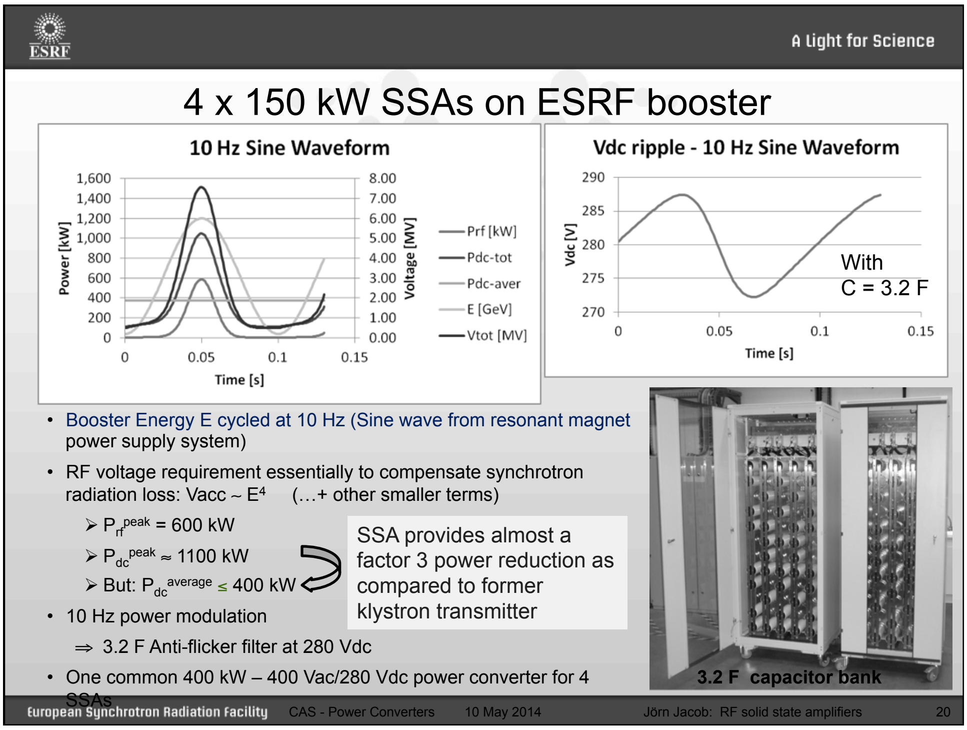
ESRF
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4 x 150 kW SSAs on ESRF booster
10 Hz Sine Waveform
Power [kW]
Voltage [MV]
Time [s]
Prf [kW]
Pdc-tot
Pdc-aver
E [GeV]
Vtot [MV]
Vdc ripple - 10 Hz Sine Waveform
Vdc [V]
Time [s]
With C = 3.2 F
• Booster Energy E cycled at 10 Hz (Sine wave from resonant magnet power supply system)
• RF voltage requirement essentially to compensate synchrotron radiation loss: Vacc ~ E⁴ (…+ other smaller terms)
➢ Prf peak = 600 kW
➢ Pdc peak ≈ 1100 kW
➢ But: Pdc average ≤ 400 kW
SSA provides almost a factor 3 power reduction as compared to former klystron transmitter
• 10 Hz power modulation
⇒ 3.2 F Anti-flicker filter at 280 Vdc
• One common 400 kW – 400 Vac/280 Vdc power converter for 4 SSAs
3.2 F capacitor bank
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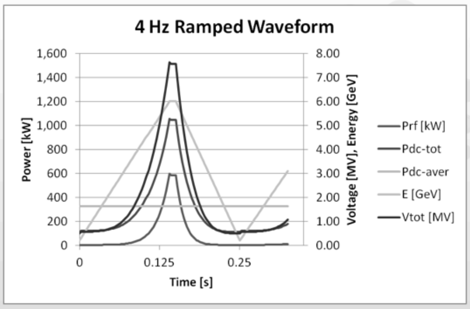
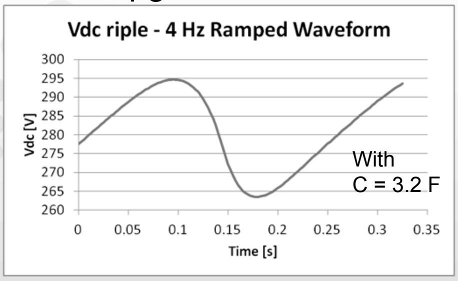
Planned ESRF booster upgrade





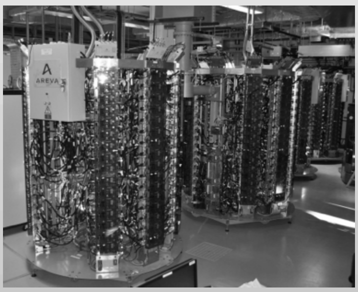
- Implementation of **4 Hz ramped DC magnet power supplies** as alternative to 10 Hz resonant system:
  - Goal: easier bunch cleaning in the booster for future top up operation of the storage ring
  - Back up for 25 years old booster power supplies
- 2 five-five cell RF cavities (two RF couplers each) → **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 : $P_{dc}^{average}$ 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



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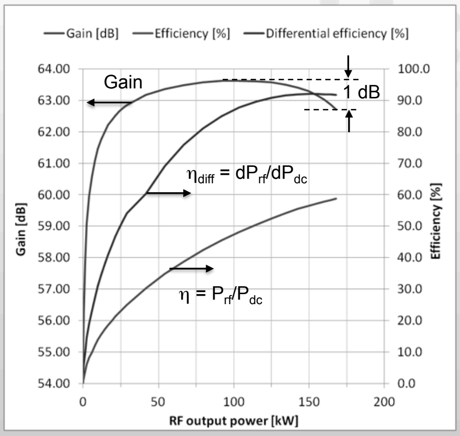
SSA gain/power, harmonics – CW &pulsed operation



Efficiency / gain curve of 150 kW ELTA SSA at ESRF

- Specified efficiency easily met:
  - ✓ η > 57 % at 150 kW = P_{nom} (spec: 55 %)
  - ✓ η > 47 % at 100 kW = 2/3 P_{nom} (spec: 45 %)
- Gain compression < 1 dB at P_{nom} = 150 kW
  - ☞ Gain curve and P_{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 μs)
  - ➢ Transient gain increase up to ≈1.3 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: H2 < -36 dBc, H3 < -50 dBc
- Spurious sidebands / phasenoise:
  - ➢ < 68 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 $f_{synchrotron}$

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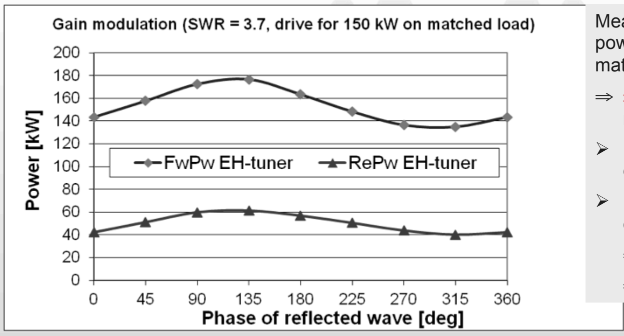
Operation on mismatched loads



Measurement with constant RF input power level, giving 150 kW on matched load:

⇒ ± 20 kW on FwPw, i.e. **gain modulation**

➢ Partially intrinsic to non directive coaxial combiner tree

➢ Partially due to imperfect circulators on RF modules:

⇒ modulation of load impedance

⇒ RF module gain modulation

Specification:

- SWR = 3.7 → P_{refl} / P_{fwd} = 50 kW / 150 kW, all phases (☞ EH – tuner)
- Full reflection at all phases specified and tested for 80 kW (movable short circuit)

Test results:

✓ **Reflected power well absorbed by circulator loads on RF modules**

➢ But: gain modulation ⇒ for some phases: SWR=3.7 test limited to 140 kW and short circuit test limited to 60 kW by overdrive protection

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ESRF — A light for Science

Problem: load mismatch & a few RF modules OFF

Power combiners: not directive and mismatched inputs:

⇒ Each RF module sees reverse power from:

1. Reflection from itself (almost 100 % reflection)
2. Power coupled from all other modules (sums up to almost the power of 1 module
3. Power from external mismatch, equally redistributed to all RF modules

- Normally, when all RF modules have same amplitude and phase, 1 and 2 cancel out ⇒ only power 3 from external mismatch remains: harmless
- However, when some modules are OFF (or in default) they see the **vector sum of 2 and 3**, which can exceed the 650 W of a single module (up to 1700 W for SWR=3.7 at P_{nom}).
  - ⇒ This can lead to destruction of the output circuit of the RF module, limited to 1200 W by the circulator load !

General SOLUTIONS:

- Limit the power reflection (interlocks)
- Over-dimension the output circuit of the module, including cable, circulator and load
- Or add a high power circulator and load at the output of the SSA

ESRF 150 kW SSAs (no high power circulator)

- Booster: no problem thanks to pulsed operation
- Storage Ring (CW):
  - Modification of combiner tree to create destructive interference between power from neighbouring modules on 1st combiner and all other RF modules of the system (proposed by SOLEIL team).
  - Circulator load increased from 800 W to 1200 W

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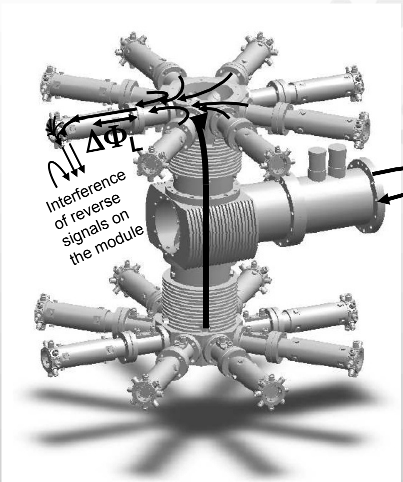
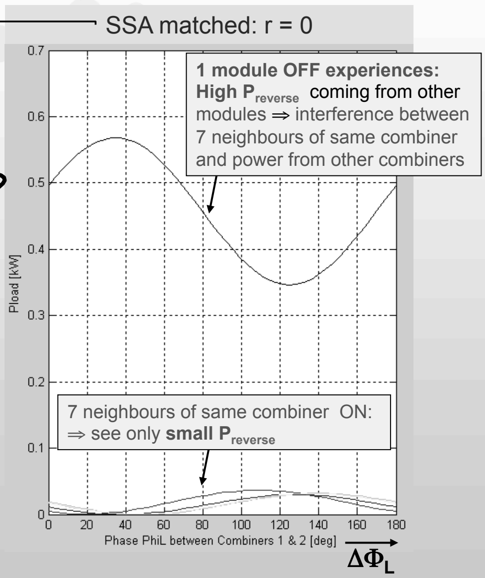
Adjustment of phase between 1st and 2nd 8x-Combiner stages





☞ $\Delta\Phi_L$: proposed by SOLEIL for the SSA of the storage ring

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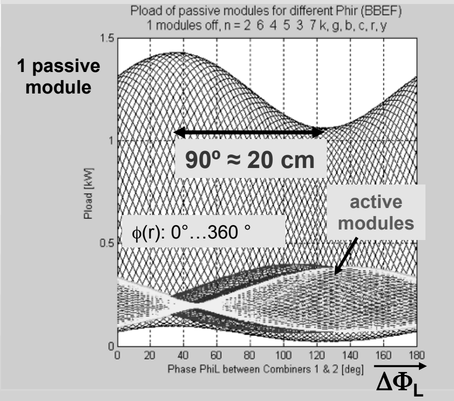
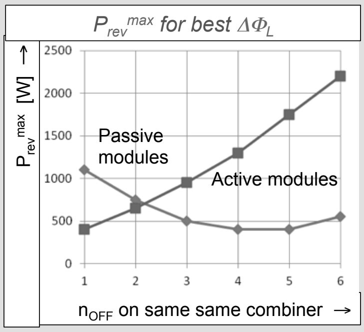
Adjustment of phase between 1st and 2nd 8x-Combiner stages

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





☞ Not more than 3 modules OFF on the same combiner !

- 1 module OFF: depending on $\Delta\Phi_L$ the circulator load receives
  - P_{rev}^{max} = 1400 W for worst $\Delta\Phi_L$
  - P_{rev}^{max} = 1100 W for best $\Delta\Phi_L$
- Active modules receive the remaining power: maximum of 400 W for best $\Delta\Phi_L$

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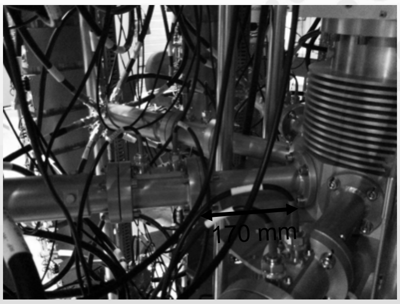
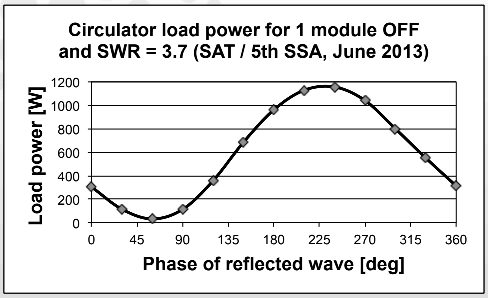
Successful reduction of maximum reverse module power





- Under worst specified conditions with SWR = 3.7 (150 kW forward and 50 kW reflection), the maximum load power was successfully reduced from 1700 W to 1200 W by prolonging the first combiner stage by 170 mm.
- This was implemented on the 3 SSAs of the ESRF storage ring
- This cannot be applied to a cavity combiner with its symmetric arrangement.

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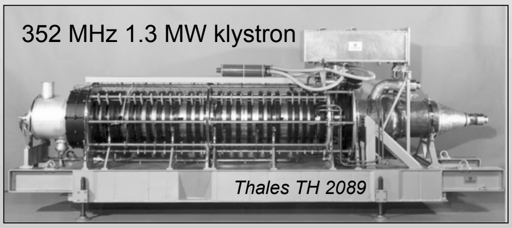
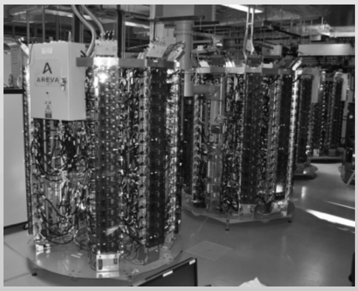
Conclusion
Short comparison Klystron / SSA





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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

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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.
- Many thanks also to the SOLEIL RF team, P. Marchand, R. Lopez, F. Ribeiro, to the ELTA team, mainly J.-P. Abadie and A. Cauhepe, and to my RF colleagues at the ESRF, in particular: J.-M. Mercier and M. Langlois. Their contributions constitute the backbone of this lecture.

Ti Ruan at the 13th ESLS RF meeting at DESY in 2009

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