# High Power Solid-State RF Sources for Accelerator Applications

## An Efficiency Point of View

M. Gaspar

# Solid-State Amplifier Technology Overview

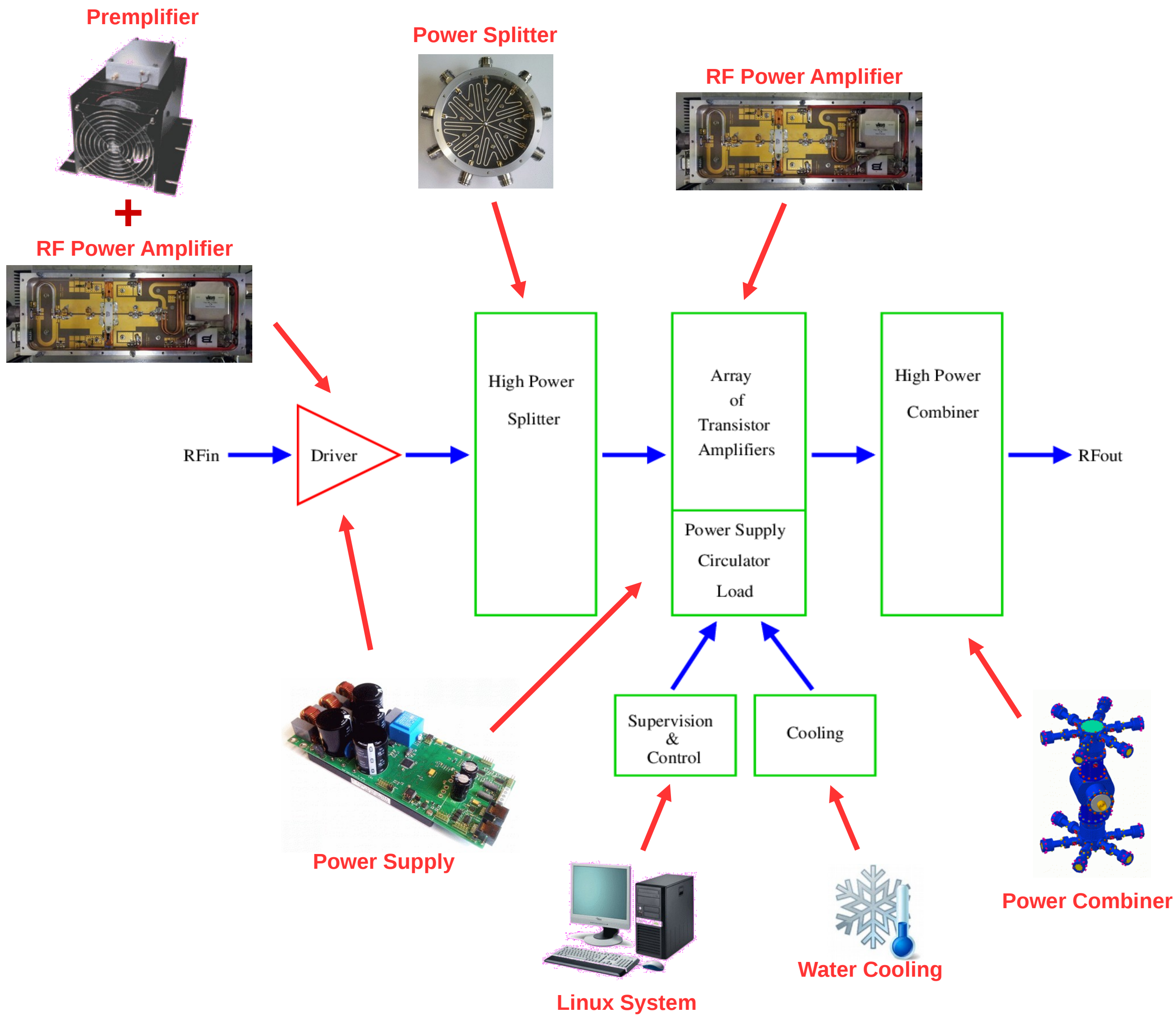
Solid-State Amplifier Technology:

Advantages:

- Modern technology in evolution.
- No high voltage
- No radiation issues
- Price already low and going down.
- Good optimization possibilities
- Redundancy.
- Compact.
- Simple cooling.
- Distributed circulator and load.
- Low phase noise.
- No Vacuum.

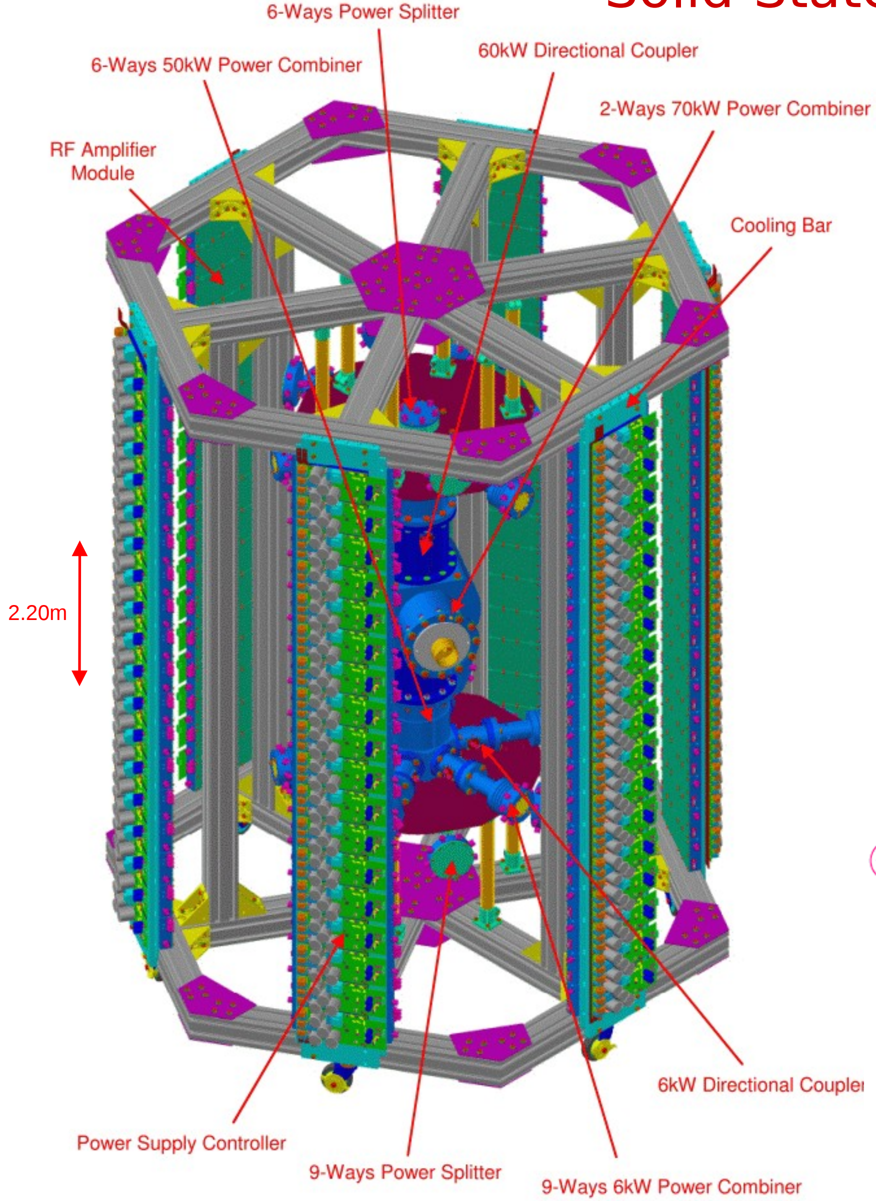
Disadvantages:

- Not enough experience acquired.
- Not well known technology.
- Not enough reliability data.



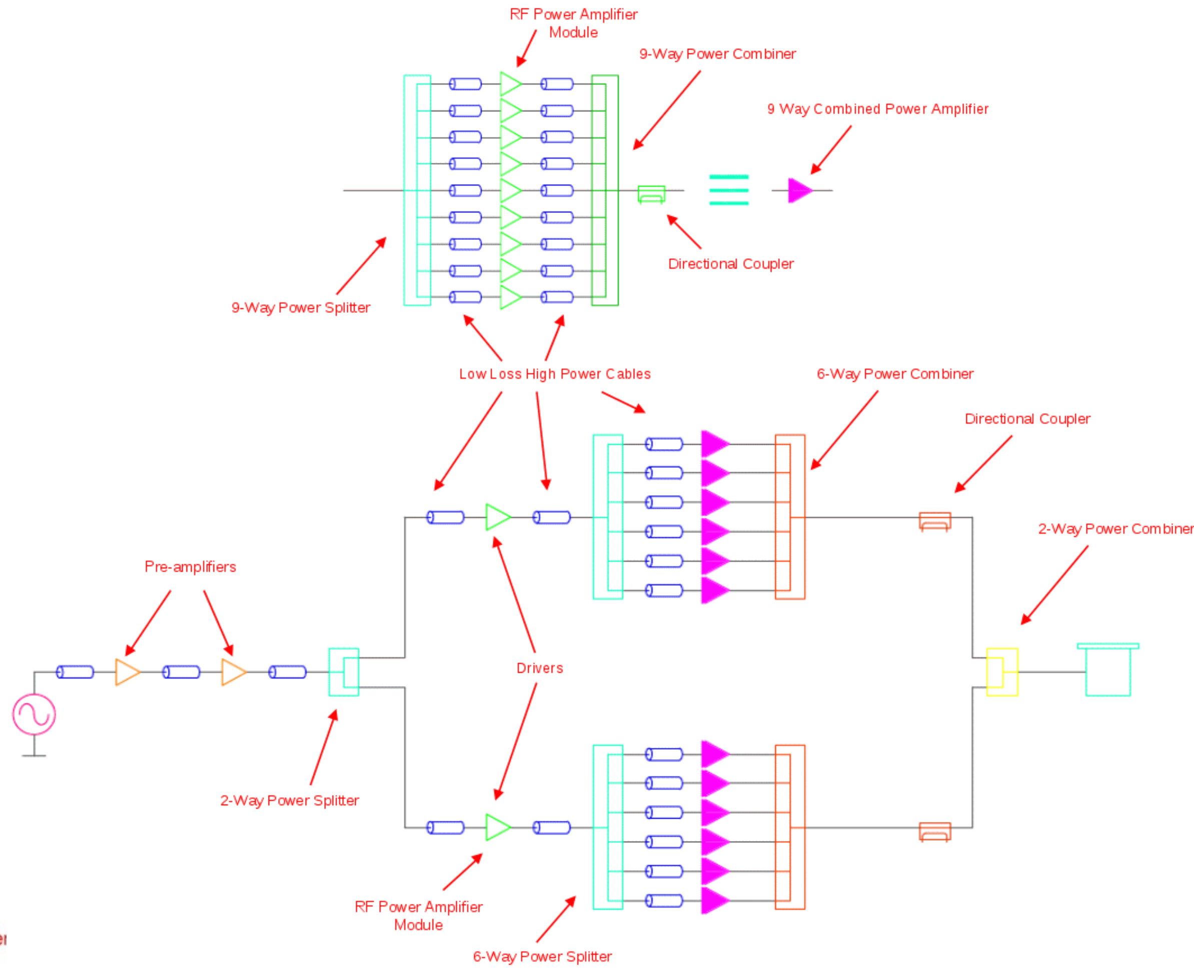

Solid-State Amplifier: Simplyfied Block Diagram

# Solid-State Amplifier System Overview




3D-View of 65kW 500MHz Amplifier System

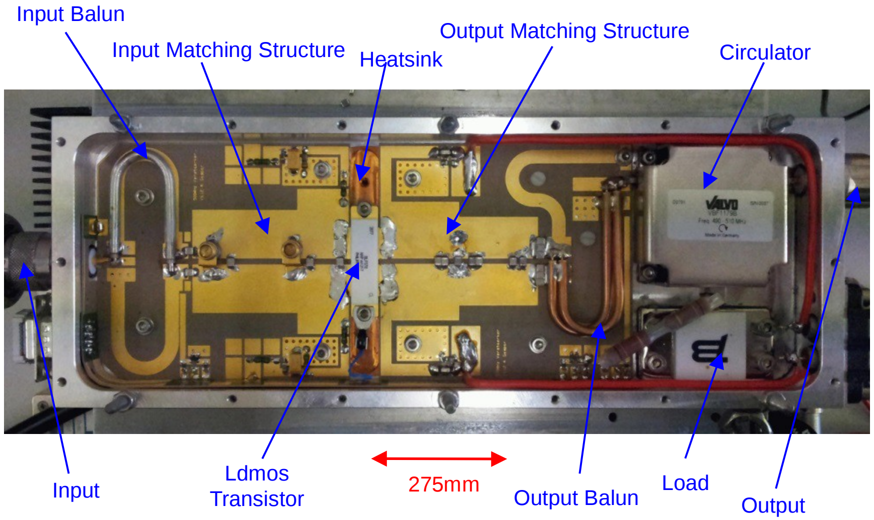
Example of a Real System – PSI 500MHz 65KW Solid State Power Amplifier
Application – Swiss Light Source (SLS)




Block Diagram of 65kW 500MHz Amplifier System

# Solid-State Amplifier Module Overview

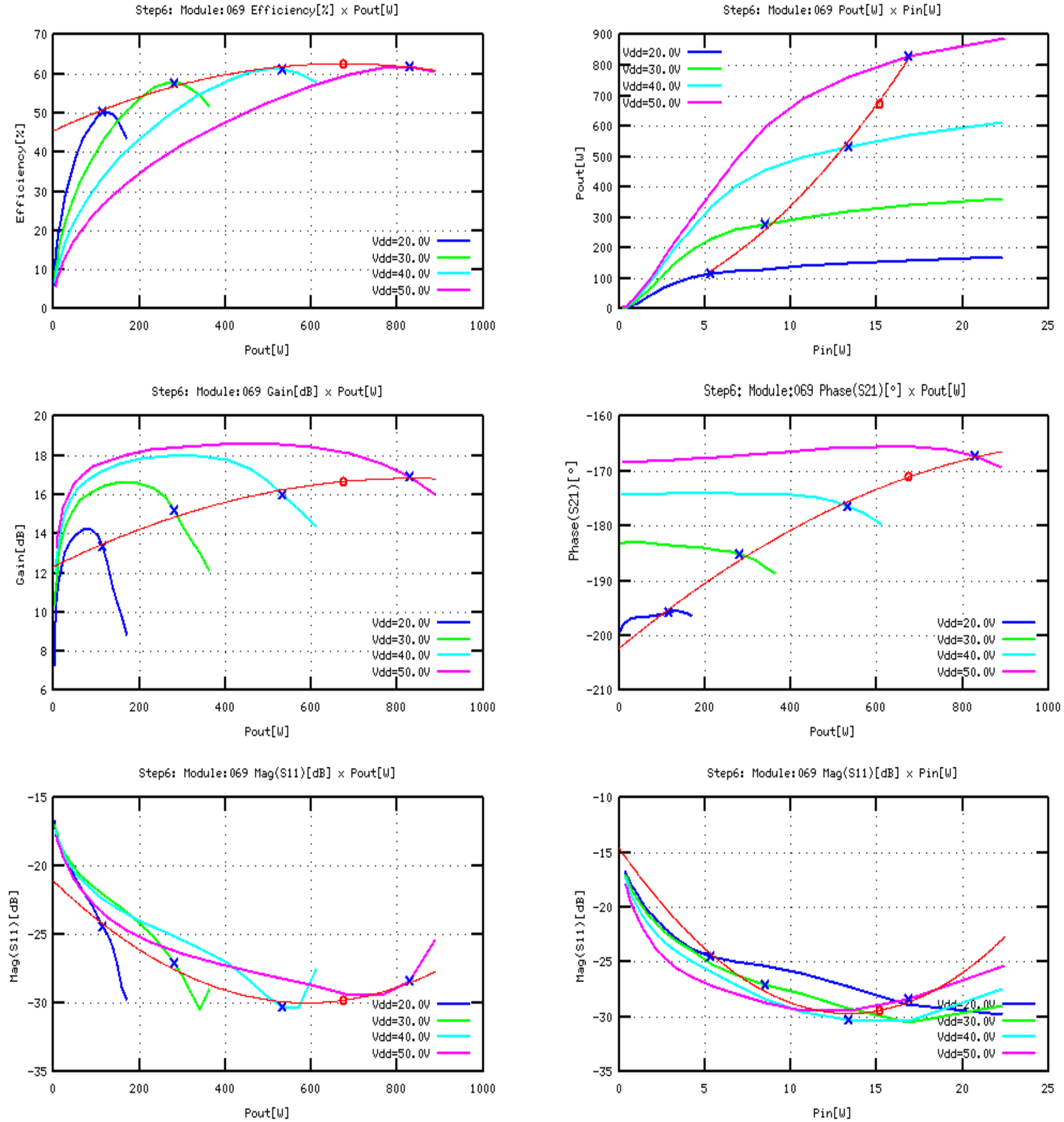
Example design using LDMOS transistor BLF578 500MHz



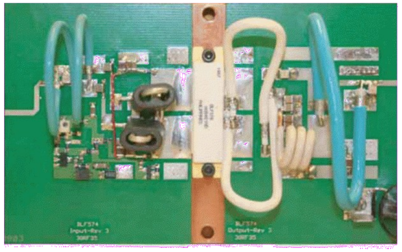

## Typical Performance Parameters (Module 069)

| | Operation (Vdd=48V) | Max (Vdd=50V) |
|---|---|---|
| Output Power (with circulator) | 675W | 890W |
| Gain | 17.7dB | 16dB |
| Efficiency | ~61.1% | 60.6% |

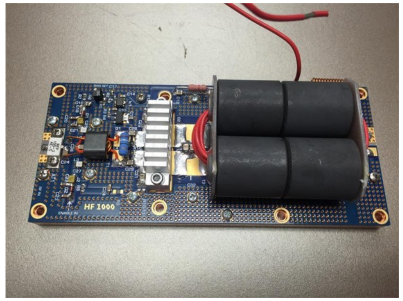
## RF Amplifier Measurement Results – Step 6 - Module 069



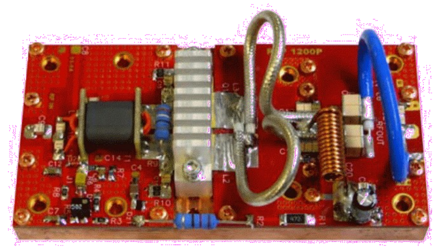
# RF Power Amplifier Module – Typical Implementations



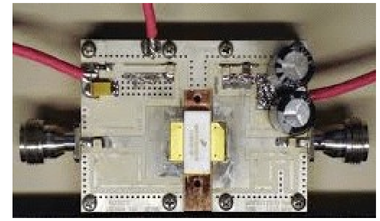
BLF578
Pout=1000W f=88-108MHz Eff=77%



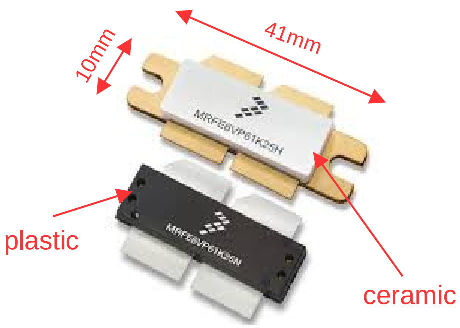
MRFE6VP61K25H
Pout=1100W f=1.5-35MHz Eff=76%



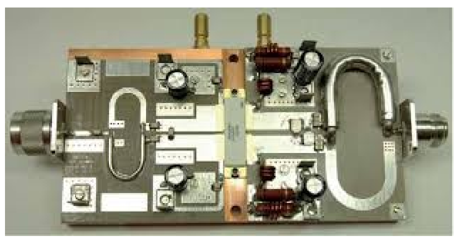
MRFE6VP61K25H
Pout=1000W f=142-150MHz Eff=75%



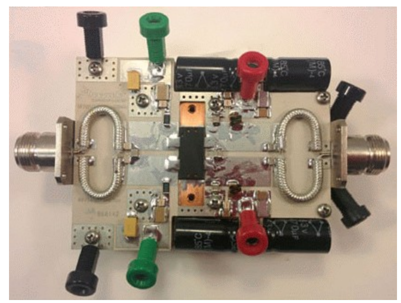
MRF6V12500HS
Pout=500W f=1.2GHz Eff=57%
Pulsed Duty Cicle=20%



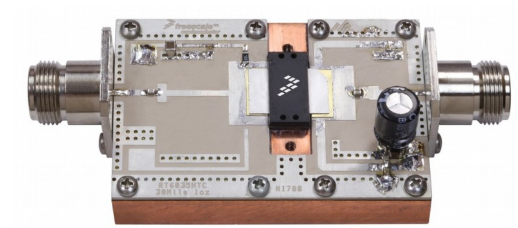

Typical RF Ldmos
Transistor packages



BLF578
Pout=1000W f=352MHz Eff=70%



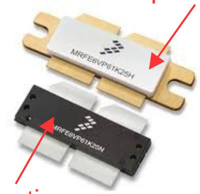
MRF8VP13350N
Pout=350W f=1300MHz Eff=58%

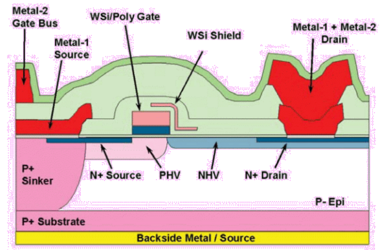


MRF7S24250N
Pout=250W f=2450MHz Eff=55%

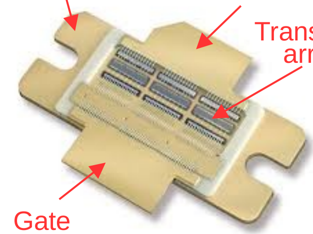
# Present Transistor Technology for High Power Applications

- Packages: plastic (cheaper) and ceramic (traditionaly more reliable).
- Pout=1250W possible today at low frequencies.
- LDMOS is the cheapest technology up to 3GHz. Other technologies coming at high power levels: SiC, GaAs, GaN, etc..
- A packaged device is composed of a large array of transistors all connected in parallel. Ex: BLF578=2x 76 transistors.
- Lower Transistor die temperature → higher output power, gain and efficiency.
- Output and input Impedances (Drain and gate impedances) very low. Balanced configuration higher impedances → lower losses in matching structure → balun needed.
- Single-ended difficult to realize at very high output power due to very low impedance at the output (2 drains in parallel). No Balun needed.
- Large number of transistors have to be stacked to reach high power levels.

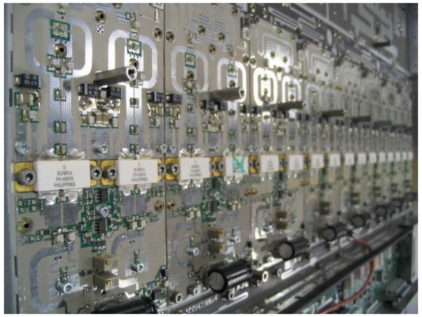



LDMOS device cross-section




LDMOS Device with open package



Array of LDMOS RF amplifiers

Example of transistors available in the market for high power RF application

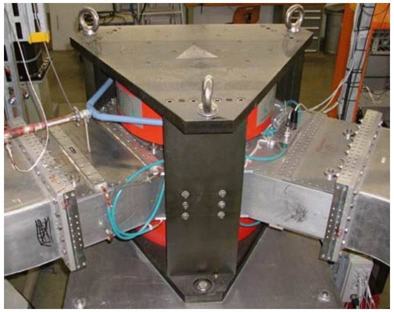
| Transistor | Frequency Range | Efficiency | Max Output Power | Price/Watt (USD/W) | Remarks |
|---|---|---|---|---|---|
| STAC3932F | 0-250MHz | 70% | 580W | 0.16 | •CW (580W)and pulsed (900W). Vdd=100V. |
| BLF188 | 0-200MHz | 65-80% | 1200W | 0.2 | •Wide range of applications. |
| BLF578 | 0-600MHz | 65-80% | 1000W | 0.3 | •Wide range of applications. |
| MRFE6VP61K25H | 1.8-600MHz | 74% | 1200W | 0.25 | •CW and pulsed.<br>•No proven CW performance at f>250MHz. |
| MRF8VP13350N | 700-1300MHz | 58% | 350W | 0.54 (250 pc) | •CW and pulsed.<br>•Internally input matched. |
| MRFE6VP8600H | 700-1300MHz | 50% | 600W | 0.3 | •Pulsed. |
| MRF7S24250N | 2400-2500 MHz | 55% | 250W | 0.6 | •CW and pulsed.<br>•Internally matched. |

# The Circulator

A key component with non negligible limitations


Drop-in Circulator – Typical Features

| | |
|---|---|
| Insertion Loss | **0.2dB (4%)** |
| Isolation | **23dB (0.5%)** |
| Total Loss | **~4.5%** |
| Price (estimated) | **~0.1USD/W** |



Large Circulator – Typical Features

| | |
|---|---|
| Insertion Loss | **0.05dB (1.1%)** |
| Isolation | **26dB (0.25%)** |
| Total Loss | **~1.35%** |
| Price (estimated) | **~0.5USD/W** |

## Important Features:

Protects the amplifier against reflected power.

Increases combiner isolation between ports → improving amplifier stability.

## Limitations:

Non ideal insertion loss and isolation → power losses → system efficiency degradation.

### Drop-in Circulators:

Advantages:

Lower Price/W.

One device per power amplifier module. Redundancy. Failure affects minimally the whole amplifier.

Disadvantages:

Higher Insertion loss, lower Isolation, higher efficiency degradation.

Large number of circulators used.

### Large High Power Circulators:

Advantages:

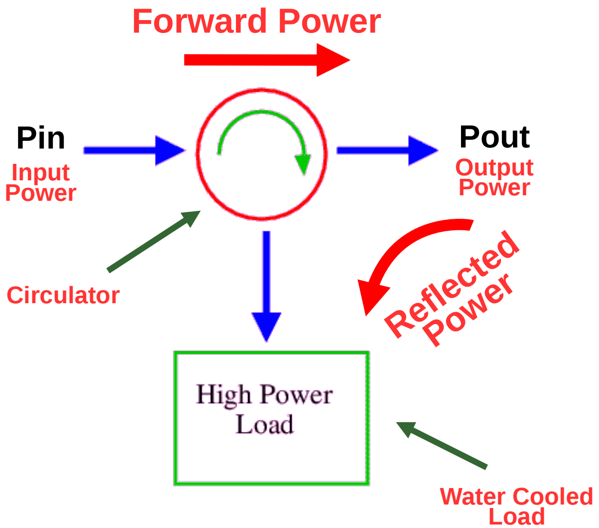
Only one device required.

Lower Insertion loss, higher Isolation, lower efficiency degradation.

Disadvantages:

Higher Price/W.

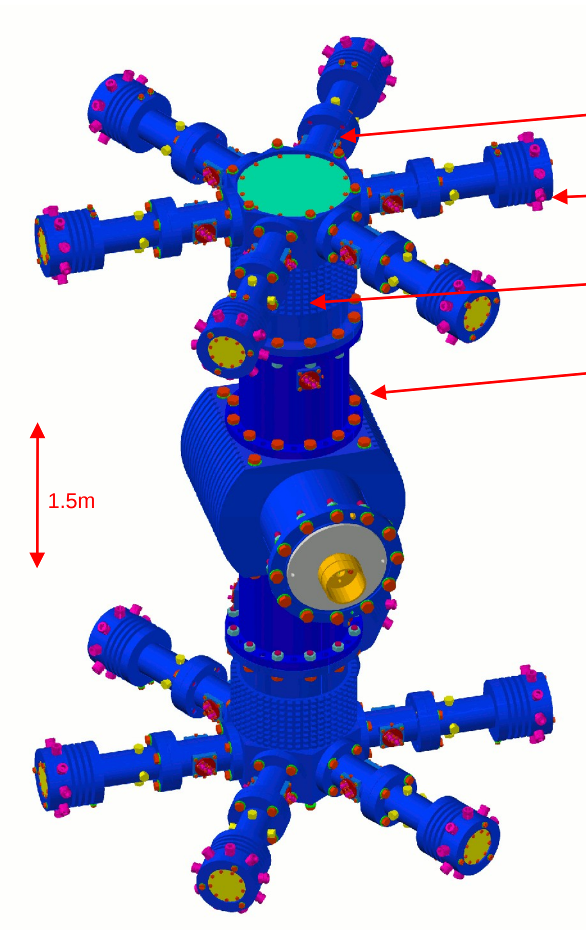
Failure stops the whole amplifier.



# Output Power Combiner








3D View – Complete Combining Structure

Example: Output Power Combiner of the PSI 500MHz 65KW Solid State Power Amplifier

## High Power Combiners – Typical Performance Parameters

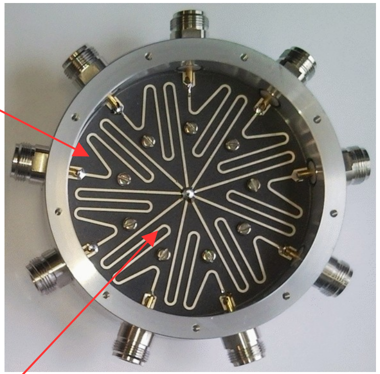
| Combiner Type | Insertion Loss (Typical) | Efficiency | Loss | Remarks |
|---|---|---|---|---|
| Coaxial (Quarter Wavelength) | -0.03dB | 99.3% | 0.7% | Only available at high frequencies. Large size. Very low losses. |
| Transformer | -0.08dB | 98% | 2% | Only available at low frequencies. Efficiency dependent on materials and construction technique. |
| Cavity | -0.17dB | 96% | 4% | Early Development Phase. |

The efficiency of the combiner has a direct influence on the system efficiency and the system output power as it is placed after the last amplification stage.

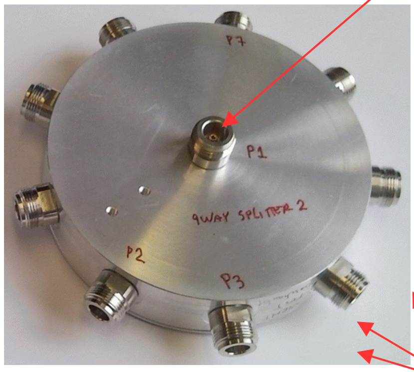
# Input Power Splitter

Typical Microstrip Line Design
(Example for fc=500MHz)

Low loss substrate



RF input




9 RF outputs

Quarter wavelength transformers symetrically placed

Microstrip Splitter – Typical Features

| | |
|---|---|
| Frequency (Center) | **500MHz** |
| Bandwidth (-20dB) | **~10%** |
| Insertion Loss | **0.06dB (1.4%)** |
| Isolation | **20dB** |
| Total Loss | **~1.4%** |
| Maximum Power | **700W (Tested)** |

Wideband operation possible using ferrite transformers at low frequencies up to 100MHz.

Bandwidth decreases as the number of channels increases.

Splitter losses affect minimally the system efficiency as they are placed before the last amplification stage.

Narrowband operation helps to protect the amplifier system against excitation outside the accepted frequency range.

# Efficiency Improvement

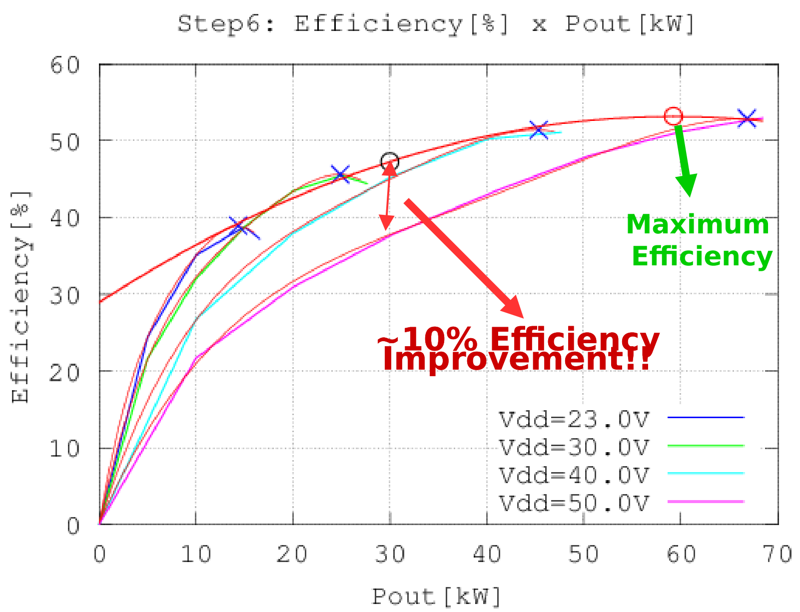
## Overview of Solid-State Amplifier Components and possible efficiency improvement

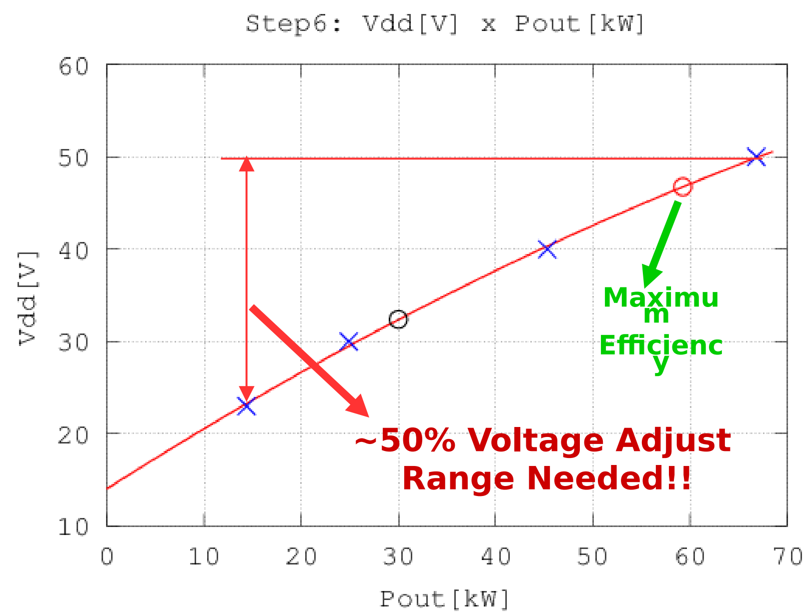
| Component | Efficiency | Loss | Possible efficiency improvement | Remarks |
|---|---|---|---|---|
| Transistor | 50% (1.3GHz – 250W)<br>60% (500Mhz – 1kW)<br>70% (250MHz – 1kW)<br>80% (50MHz - 1kW) | 20%-50% | • Maximum Vdd increase.<br>• Ron reduction.<br>• Improve device cooling. | • Efficiency is frequency dependent.<br>• Technological advance will further improve the efficiency.<br>• Switching amplifiers can have Eff>90% at low frequencies (f<30MHz). |
| Circulator | 96% (500MHz – 1kW)<br>98.8%(350MHz-1MW) | 4%<br>1.2% | • Reduction of circulator leads.<br>• Better cooling.<br>• Reduction of material losses. | • Efficiency is frequency dependent.<br>• Circulator removal further improves the efficiency, but: no amplifier protection against reflection, degraded stability and worse output combiner channel isolation. |
| Balun | 99.5% (coax 500MHz)<br>98% ( PCB 500MHz) | 0.5%<br>2% | • Reduction in coax cable losses.<br>• Improvement in printed implementation. | • Coax Balun – Very low losses, cheap.<br>• Printed Balun – High losses, early development phase.<br>• Single-ended topology supresses balun but output matching structure has higher losses due to lower transistor output impedance. |
| Matching structures | 99% (PCB 500MHz) | 1% | • Reduction in capacitor losses.<br>• Reduction in PCB losses.<br>• Increase of transistor output impedance. | • Output matching structure has strong influences in the system efficiency and reliability.<br>• Technological advance in capacitor technology (mica and ceramics) will further improve the efficiency and power handling. |
| Power Supply | 89%-95% | 5%-11% | • Advances in Mosfet technology.<br>• Higher switching frequency.<br>• Reduction of the connection path from power supply DC output to RF power amplifier. | • Eff=95%-98% already available in some special cases.<br>• Difficult to obtain high efficiency and wide voltage adjustment range.<br>• Wide voltage adjust range is important for efficiency optimization at any RF output power lower than the maximum. |
| Driver and preamplifier | ~45%<br>Preamplifier - class AB<br>Driver – class A | 55% | • Operating point optimization. | • Preamplifier and driver give around 1% system efficiency degradation.<br>• No considerable efficiency improvement expected from operating point optimization. |
| High power coaxial cables | 99% | 1% | • Reduction of cable length.<br>• Direct connection (cable suppression) | • The suppression of high power cables is an alternative to reduce the cable losses. But flexibility in maintenance is also lost. |
| Cooling system | - | - | • Cooling liquid temperature reduction.<br>• Improvement of cooling liquid.<br>• Improvement of heatsink cooling capabilities (higher turbulence). | • Reduction of the temperature of cooling liquid has strong influences in transistor efficiency and gain. The lower the temperature the higher the system efficiency. |

# Efficiency Optimization

## Psi 500MHz 65kW Solid-state High Power Amplifier

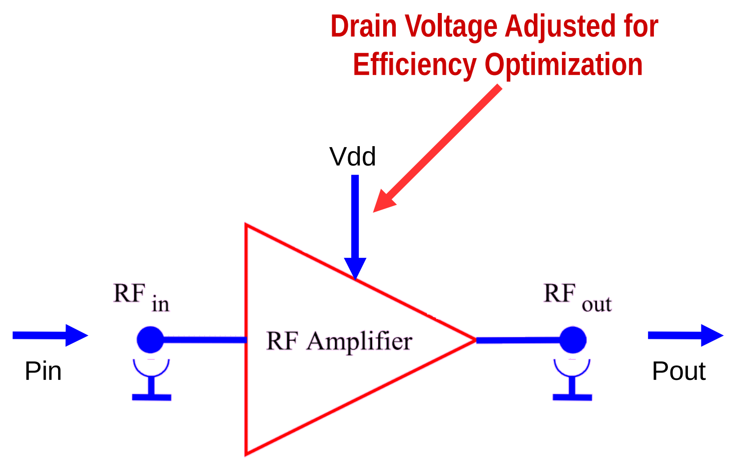
SSPA Example: Efficiency optimization at 30kW (black marker) and Maximum Efficiency Operation (red marker)



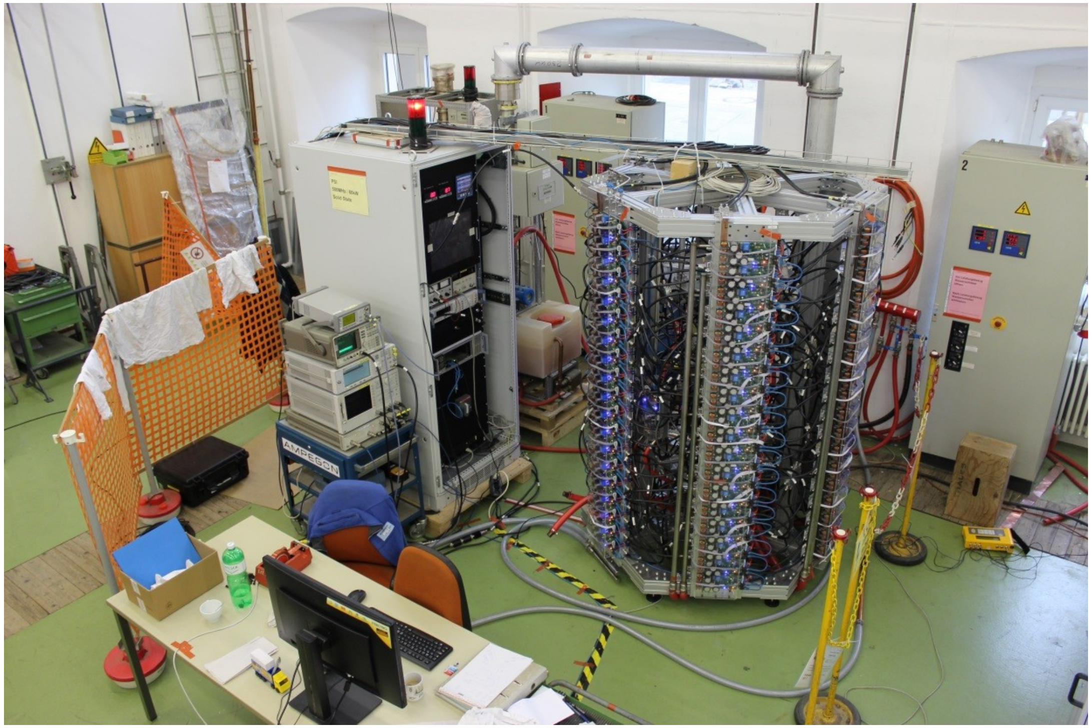




**Comparison: Klystron Amplifier (incl. accessories) vs. SSPA (with efficiency optimization)**

| | Booster (pulsed) Duty cicle:50% | | Storage Ring (CW) Beam current: 400mA | |
|---|---|---|---|---|
| | Klystron Amplifier: BO | SSPA 1x65kW System | Klystron Amplifier: SR3 | SSPA 2x65kW System |
| Pout | 36kW | 36kW | 100kW | 100kW |
| Efficiency | 11.2% | 46.5% | 40% | 52% |

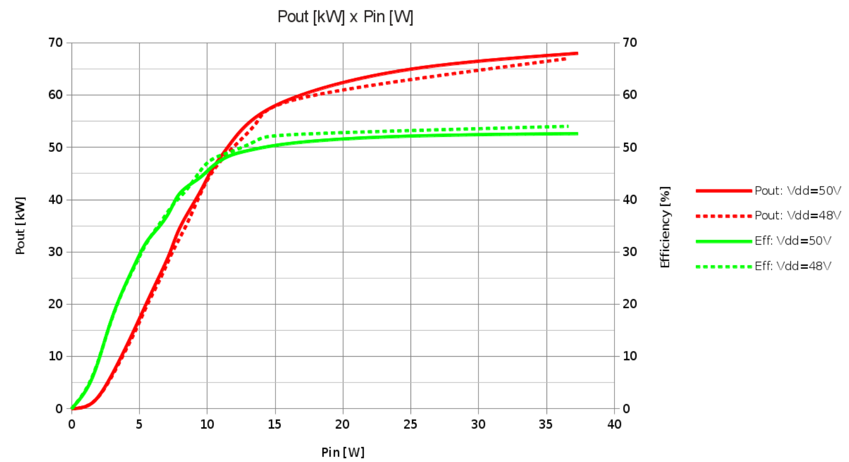


# Example Performance Results of a Complete System



65kW 500MHz Amplifier System in Operation.

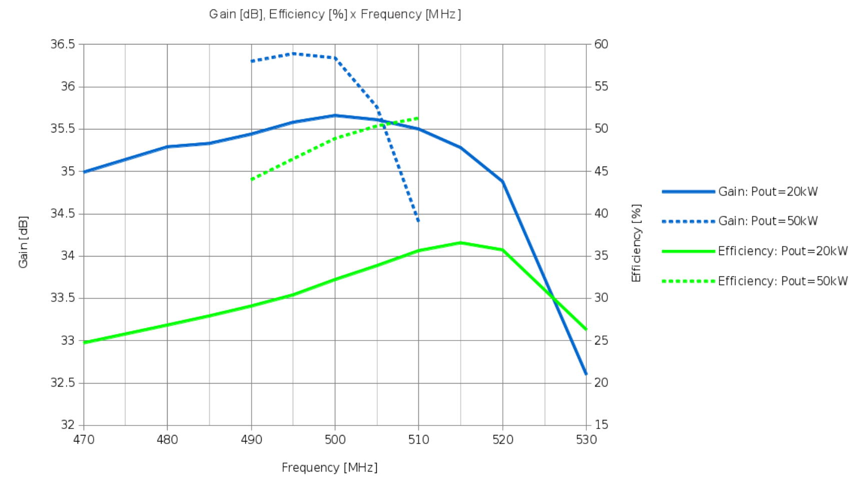
## The PSI 500MHz 65KW Solid State Power Amplifier




Full 65kW Amplifier System Measurement Results:
Pout and Efficiency vs Pin

## 65kW 500MHz Amplifier System Performance: Maximum Output Power

| Vdd[V] | Pout[kW] | Pmains[kW] | Efficiency[%] | Pin[W] |
|---|---|---|---|---|
| 48 | 67 | 124 | 54 | 36.6 |
| 50 | 68 | 129.2 | 52.6 | 37.3 |

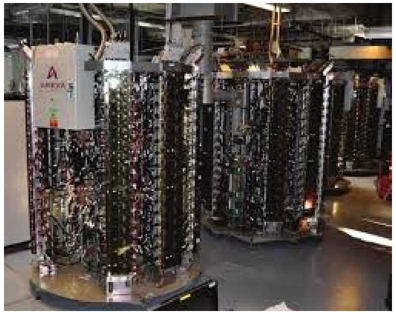



Full 65kW Amplifier System Measurement Results:
Pout and Efficiency vs Pin

# Comparison of Some Available Complete Systems

| Developper | Frequency | Output Power (max/op) | CW/Pulsed | Rise/Fall Time | Pulse Width | Rep. Rate | Efficiency | Remarks |
|---|---|---|---|---|---|---|---|---|
| PSI | 500MHz | 72kW/65kW | CW/Pulsed | 45ns/45ns | 0-100% | - | 54% (max @ 64kW)<br>47.8% (30kW,Optim.) | Efiiciency measured from mains input to RF output (includes all components). |
| ESRF (Areva) | 352MHz | 75kW/70kW | CW/Pulsed | - | - | 1Hz/<br>10Hz | 57%/55% | CW. AC-DC external converter (Eff=90%) not included in efficiency performance. Expanded to 150kW. |
| SOLEIL | 352MHz | 35kW/30kW | CW/Pulsed | - | - | - | 50% | CW. Probably AC-DC external converter not included in efficiency performance. Expanded to 180kW. |
| LNLS | 472MHz | 32kW/25kW | CW | - | - | - | 57% | CW. Particle accelerator. Expanded to 50kW. |
| Cryoelectra | 72.8MHz<br>118MHz<br>500MHz | 150kW/115kW<br>32kW/16kW<br>75kW/45kW | CW<br>CW<br>CW | -<br>-<br>- | -<br>-<br>- | -<br>-<br>- | 57.2%<br>45.9%<br>50.5% | Particle therapy. Efficiency can be optimized. No circulator.<br>Light source.<br>Light source. |
| ELBE<br>Sigmaphi/Bruker | 1300MHz | 18kW/16kW | CW/Pulsed | 20ns/60ns | 0.5-6ps<br>40-100us | 13MHz<br>1-100Hz | 47% | Material research.Price<10$/W@1300MHz. |
| R&K | 1.8MHz<br>509MHz<br>1300MHz | 60kW(pep)<br>20kW<br>16kW | CW/Pulsed<br>CW<br>CW/Pulsed | -<br>-<br>10ns/10ns | -<br>-<br>- | -<br>-<br>- | 56%<br>?(Linear)<br>36% | Accelerator application.<br>Forced air and water cooled.<br>Forced air and water cooled. |
| Tomco | 350MHz<br>700MHz | 10kW<br>10kW | CW<br>CW | -<br>- | -<br>- | -<br>- | 55%<br>45% | Particle accelerators. CW. Expandable to 110kW.<br>Particle accelerators. CW. Expandable to 80kW. |
| Siemens<br>ESS/Siemens | 72.5MHz<br>352MHz | 18kW<br>48kW | CW<br>Pulsed | -<br>- | -<br>3ms | -<br>14Hz | 75%<br>60% | Proton therapy.<br>European Spallation Source. Expandable to 400kW (Siemens R&D). |

SOLEIL Amplifiers



ESRF Amplifiers

LNLS Amplifiers

# Thank you