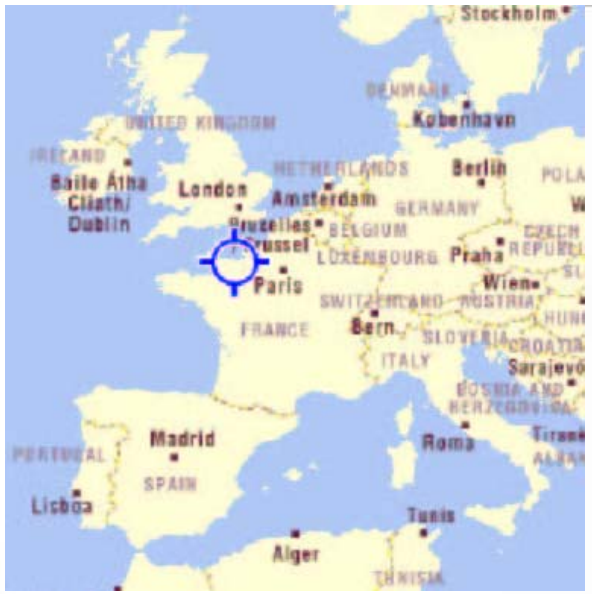
SOLID STATE RF AMPLIFIERS FOR ACCELERATOR APPLICATIONS

Marco Di Giacomo



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- Conclusion

Introduction

Solid state amplifiers are based on transistors instead of vacuum electron tubes as active device.

First RF silicon device: Bipolar Junction Transistor (**BJT**) but :

- thermal runaway => temperature compensated bias circuits
- secondary breakdown => reduced safe operating areas.

Vacuum electron tubes were preferred for medium and high power applications

SS amplifiers were mainly used as driver stages with output CW power up to some hundreds watts at few hundreds MHz.

Introduction

Revolution: Metal Oxide Semiconductor Field Effect Transistor (**MOSFET**)

- BJT patent: 1948 by William Shockley
- Mosfet patent: 1933 Julius Edgar Lilienfeld
  Higher gain, VSWR, lower noise, no drawbacks

But manufacturing only permitted by the development of the **integrated circuit technology**, (1963, Bell Laboratories, Atalla and Khang).

- **70's: Vertical Mosfets** (VMOS)
- **80's:** first UHF low power applications
- **90's:** (**Vertical) Diffusion Mosfets** (DMOS) and **Lateral Diffusion Mosfets** (LDMOS, Motorola).

RF Transistor Applications

RF Power silicon technology has been strongly boosted by several applications, mainly divided in five big sectors:
~1000 M$ in 2008.

Radio Communication


Portable/Mobile Radios
Wireless Data Modem
Wireless Alarm Systems
HF/VHF Marine Radio
RFID & Meter Readers

- *LDMOS Plastic*
- *7.2V ÷ 13.6V*
- *up to 2GHz*


Avionics/Radar & Military Coms


UHF Radar
IFF / Mode-S
Military Comms
DME
TACAN

- *LDMOS Plastic/Ceramic*
- *14V ÷ 36V*
- *up to 1GHz*

Telecom

Base Stations
For
WCDMA/CDMA/GSM

- *LDMOS*
- *28 V*
- *up to 2.2 MHz*

FM-TV Broadcast


FM Radio
VHF TV
UHF Digital TV

- *DMOS et LDMOS*
- *50V ÷ 100V*
- *up to 860 MHz*

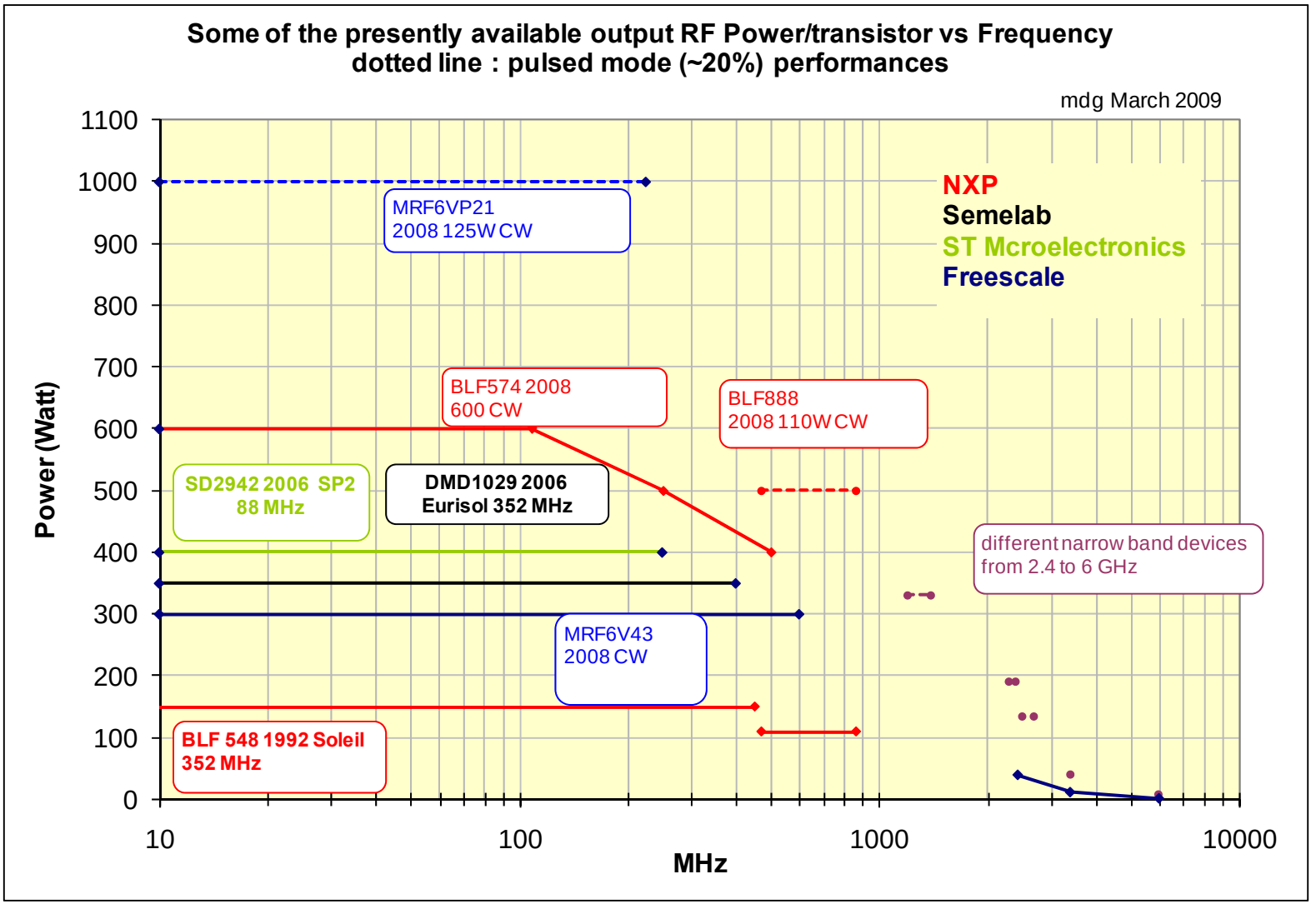
Industrial Scientific Medical


Plasma Generators
Magnetic Resonant Imaging
CO2 Laser Drivers
HF transceivers

- *DMOS*
- *50V ÷ 300V*
- *up up to 200MHz*

Transistor technology

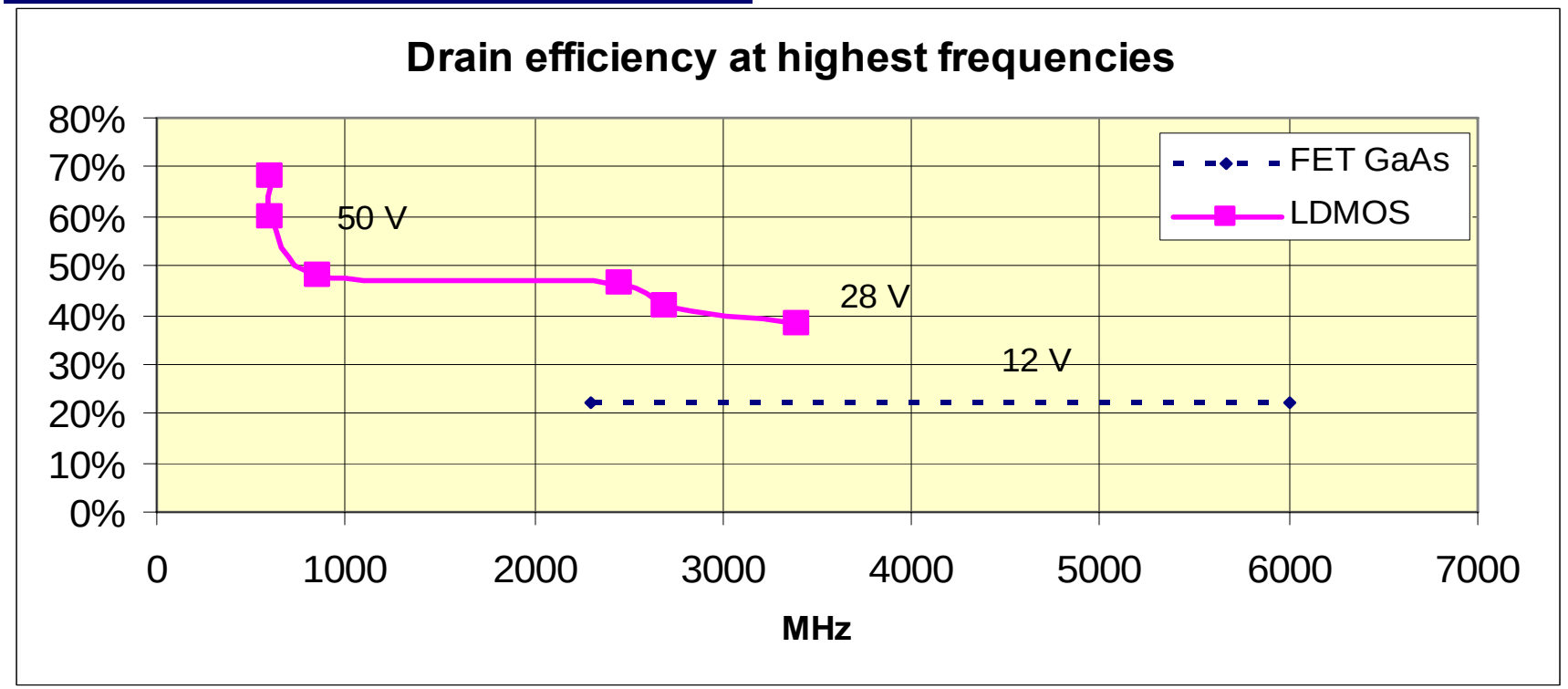
Impressive progress during last 20 years
Today, the whole band for accelerator applications is covered



Transistor technology

Performance issues:
Electrostatic Protections (ESD)
VSWR
Gain
Breakdown Voltage
Efficiency

Cost issues
Wafer sizes
Manufacturing process
Thermal conducting plastic packages



GaN couples the high frequency capability of GaAs and the high power and voltage capabilities of Si LDMOS

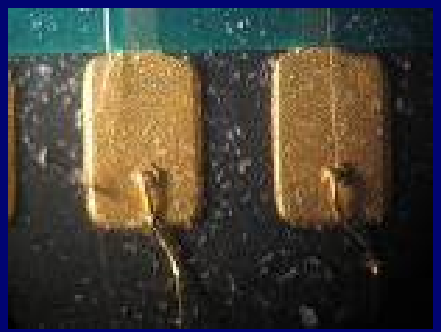
RF power Mosfet manufacturing process

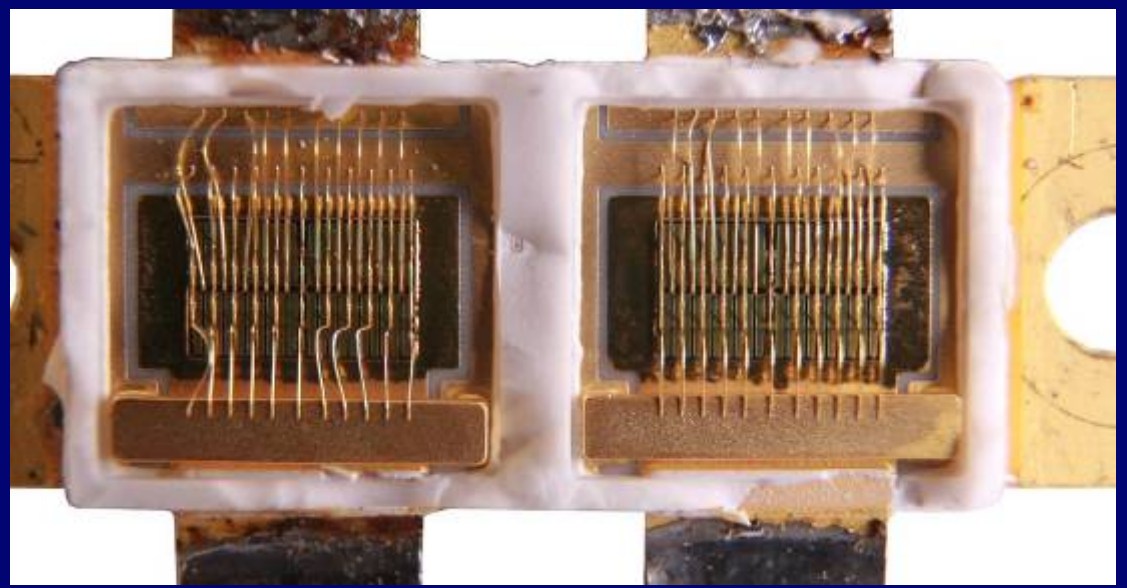
Manufacturing

Small Scale Integration: few thousands of device/wafer
6” and 8” Si wafers (thickness: 0.1 to 0.25 mm)

Process

Diffusing
Sawing
Stratching
Picking
Wire bonding
Closing





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Amplifier Architecture

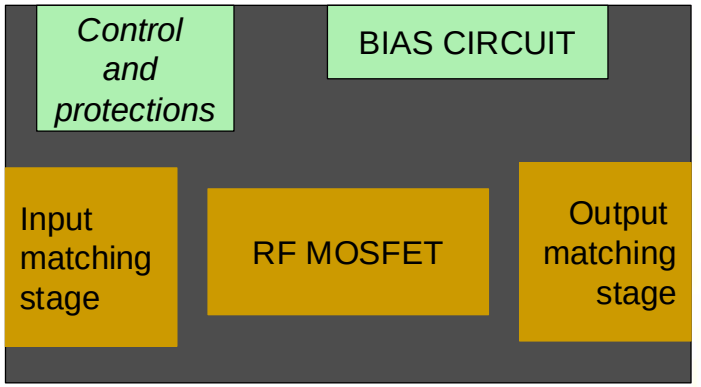
Power Amplifier elementary stage: pallet

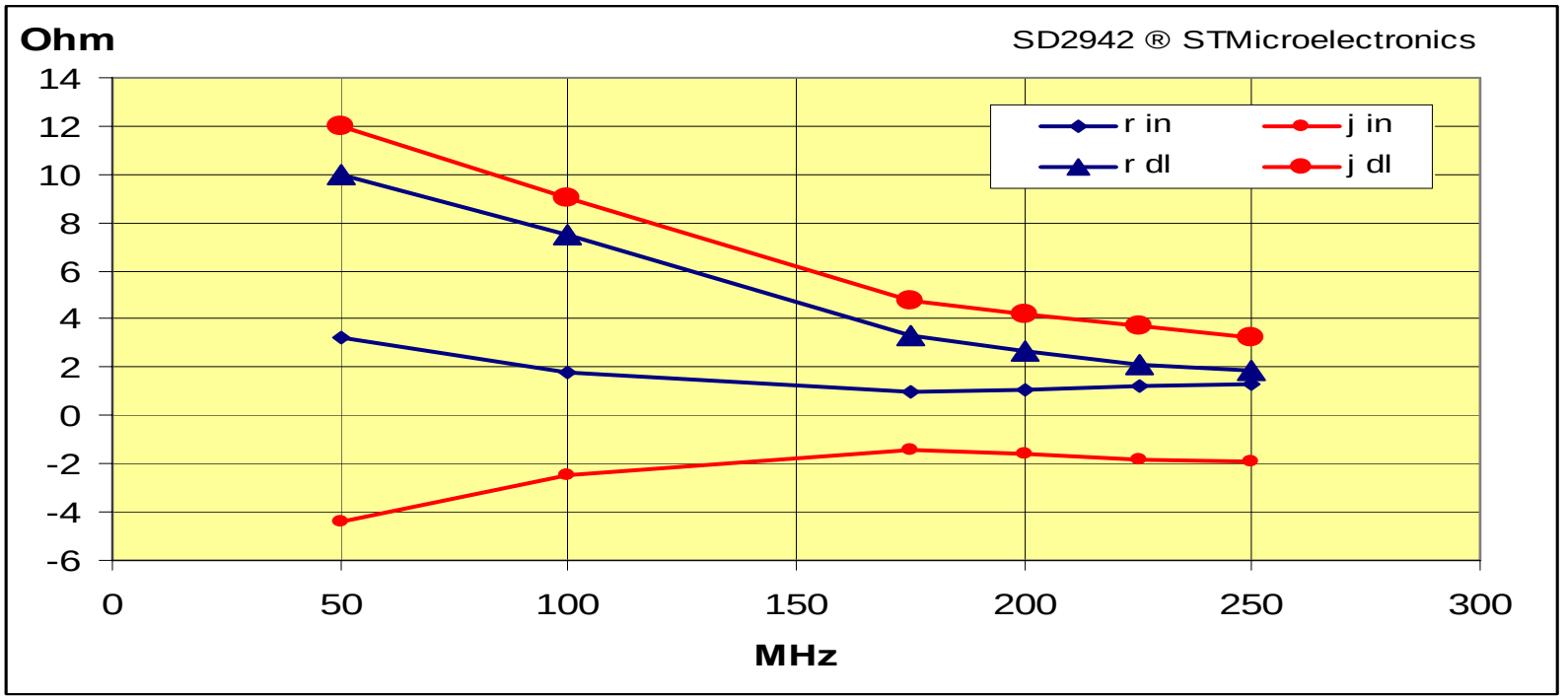
Very low input and output impedances

1 transistor/pallet

Input and output transformers

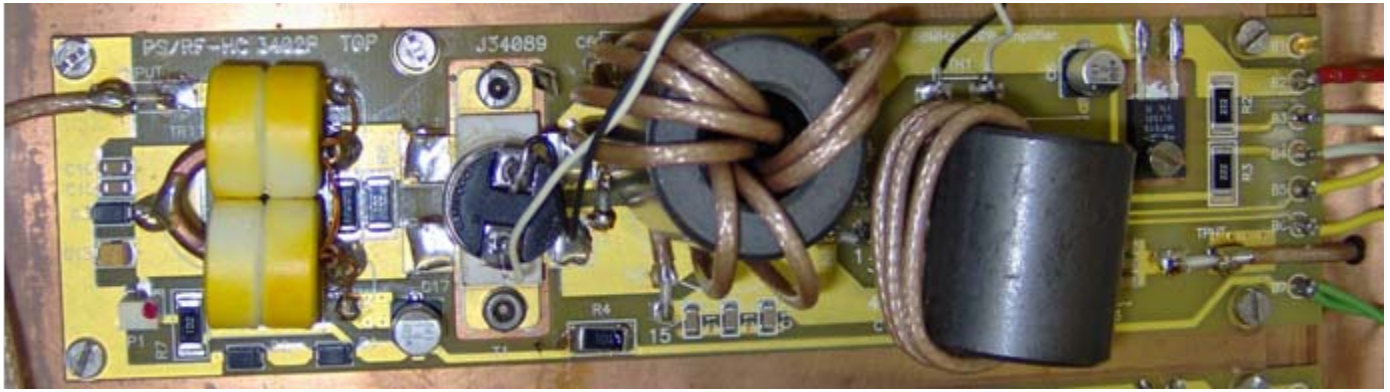
highly th. conducting metallic ground plane



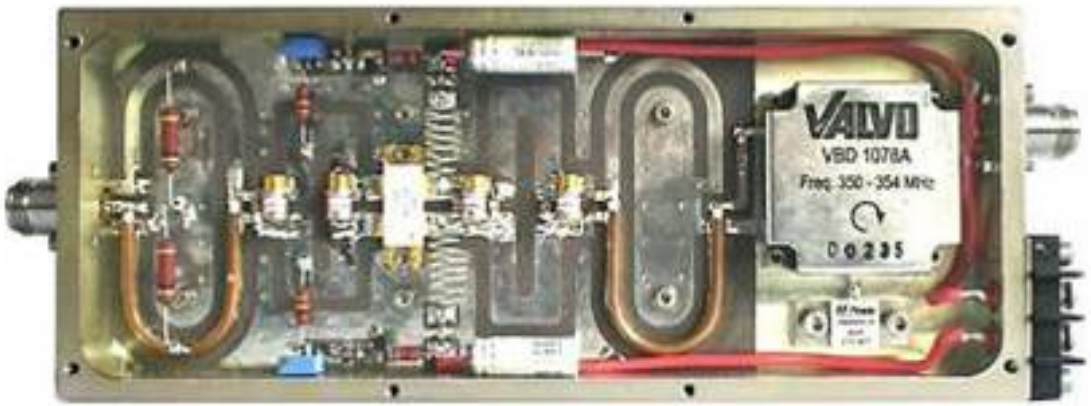


Amplifier Architecture

Pallet Examples



- 140 W pallet –
- 0,5 to 6 MHz
- VSWR>10
  without circulator
- 1 transistors/pallet
- © CERN, M. Paoluzzi



- 330 W module
- 352 or 500 MHz, different devices
- 1 transistor/pallet
- 1 circulator/transistor
- © Synchrotron SOLEIL - Ti Ruan

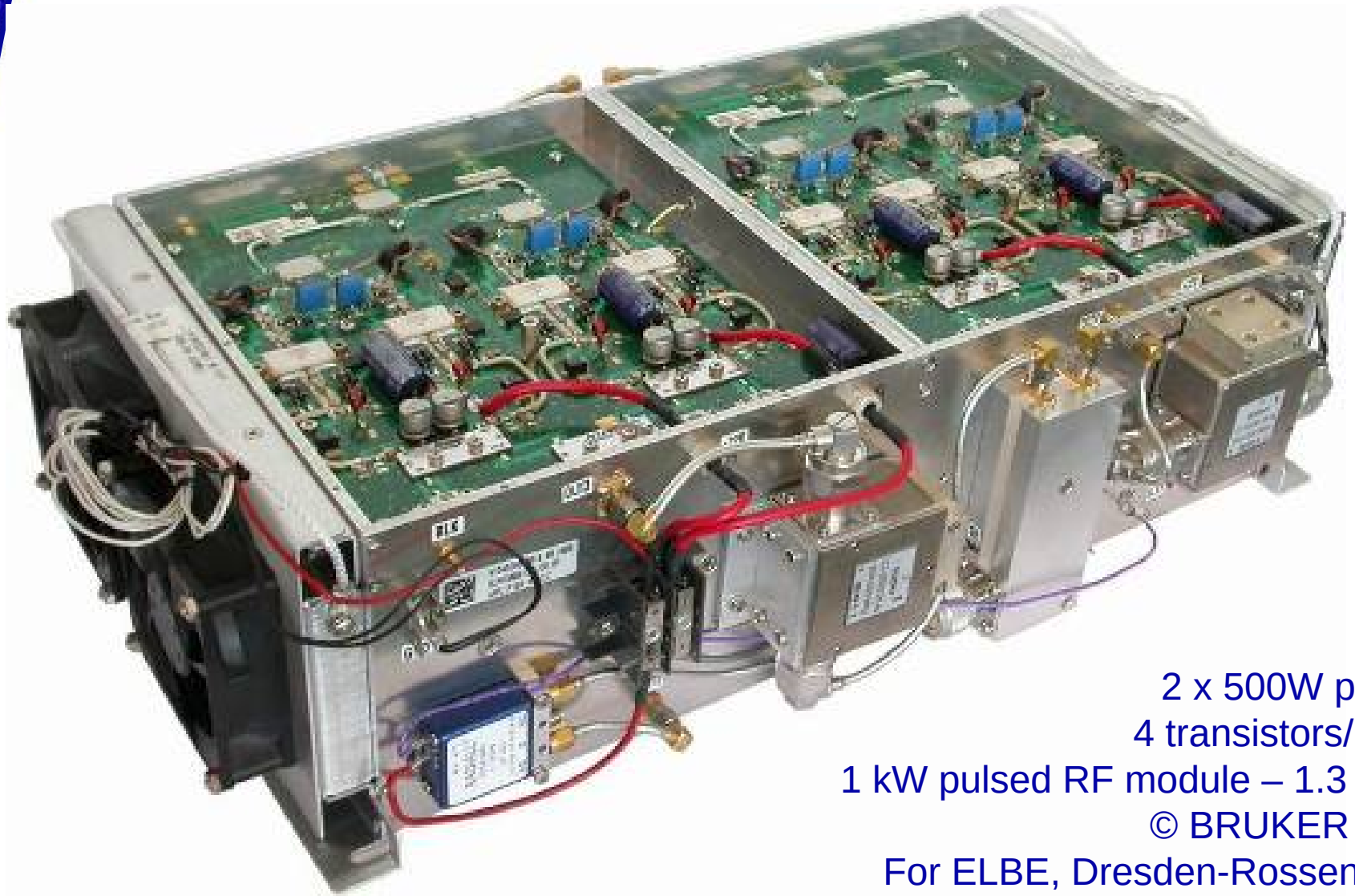
Amplifier Architecture

Pallet Examples

800W pallet
88 to108 MHz
2 transistors/pallet
© DB ELETTRONICA
For SPIRAL2

Amplifier Architecture

Module Examples



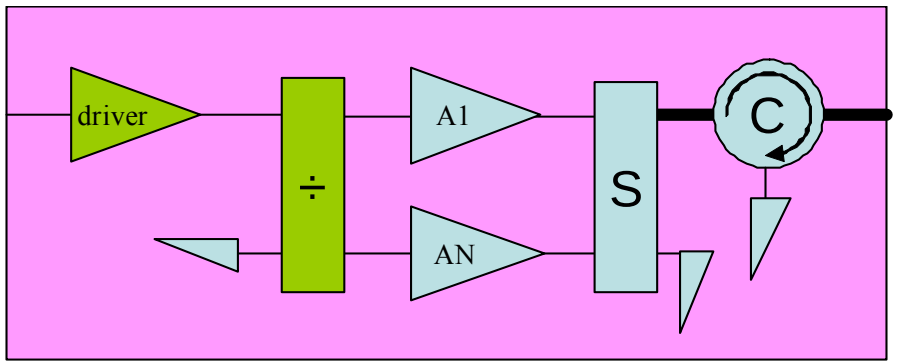
2 x 500W pallets
4 transistors/pallet
1 kW pulsed RF module – 1.3 GHz
© BRUKER 2008
For ELBE, Dresden-Rossendorlf

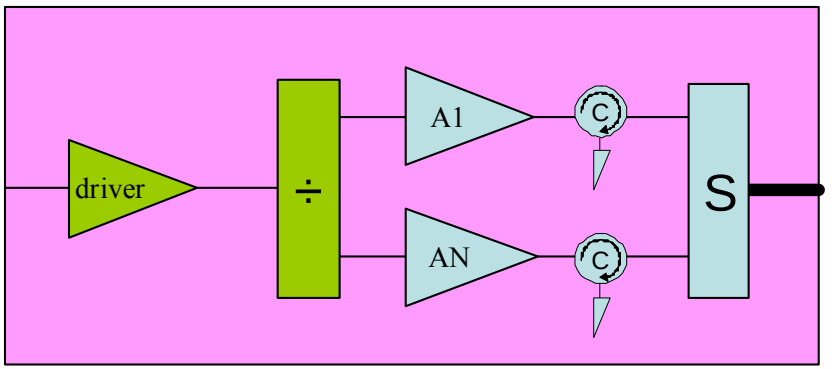
Amplifier Architecture

Splitting/Combining

- Several blocks combined together to obtain higher output power,
  - Arrangement depends on application to fit the required amount of RF power
  - N-way splitters and combiners required

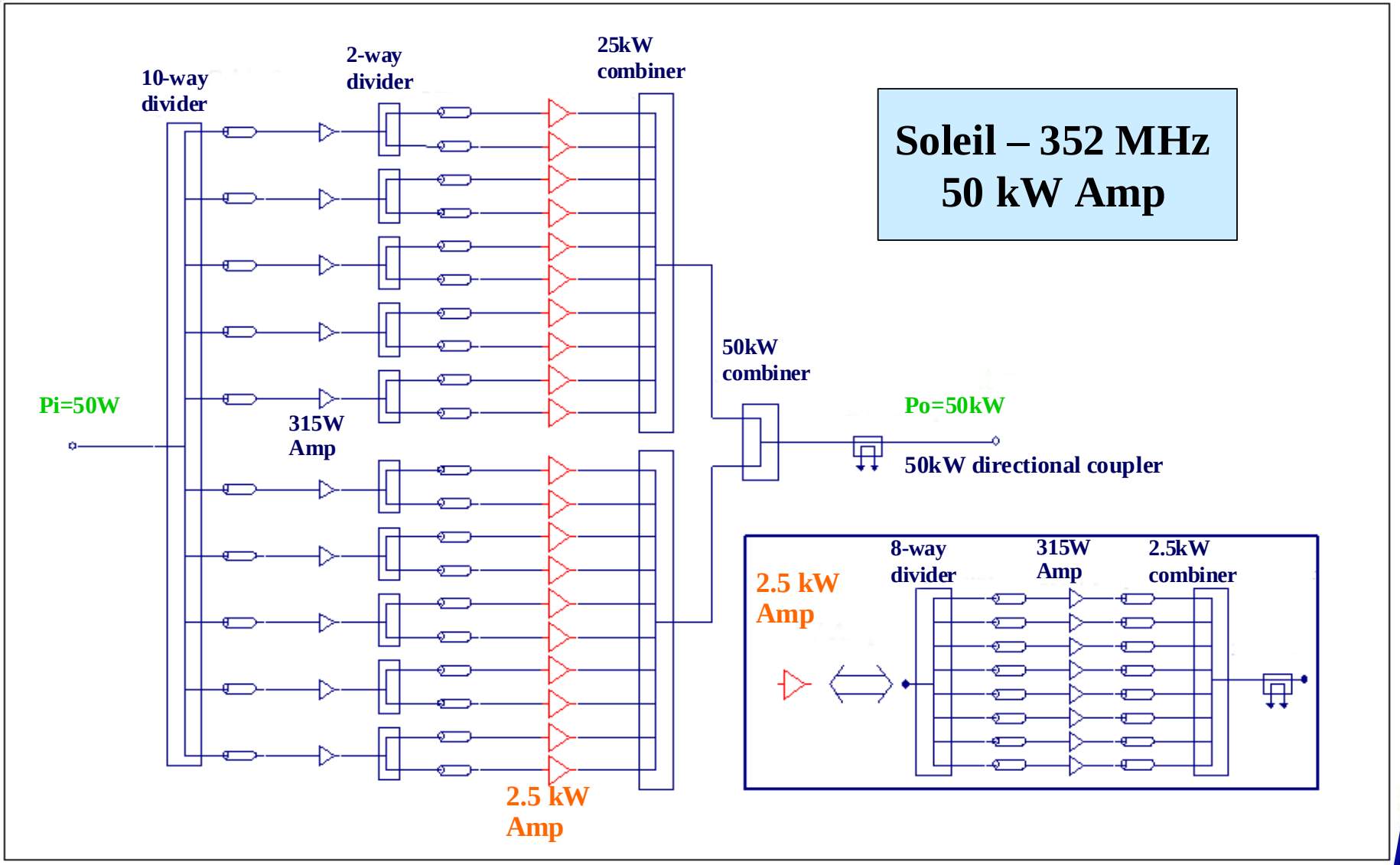
- Management of reflected power required by accelerator applications
  - Isolated dividers and couplers (case1) can be used to avoid oscillations or other phenomena which could bring to the transistor destruction.
  - Circulators can also be used to decouple each amplifier, making it unconditionally stable, and in this case non isolated splitter/combiners can be used (case2).
  - At low frequencies, transistor operated at ~50% of its possibilities





Amplifier Architecture

Combining Arrangement Examples



Amplifier Architecture

Combining Arrangement Considerations

- Any arrangement is possible to fit the single project requirements

- In case of failure of a few transistors, the solid state architecture grants significant amount of power being still available.

- In principle, it is possible to replace a broken module without interrupting the amplifier operation.

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Splitter/Combiners

- Passive, multiport, reciprocal:

=> the same device can be used to divide or combine signals.

- Design based on quarter wave sections of transmission lines :

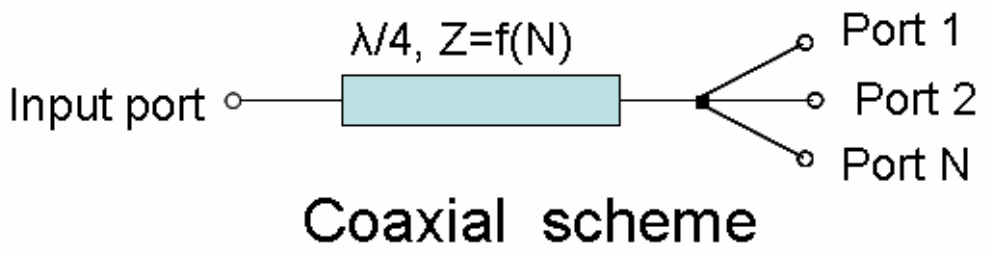
=> narrow band but some tricks exist to wide the operating bandwidth.

- At lower frequencies, they can be realised with lumped elements.

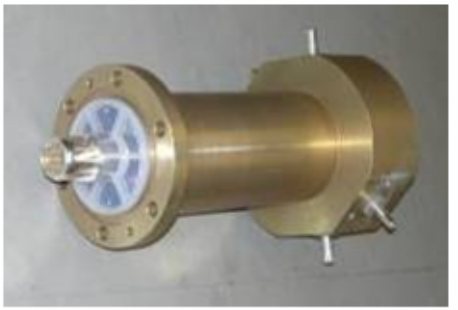
Splitter/Combiners

Y (or star) junction: N Ways

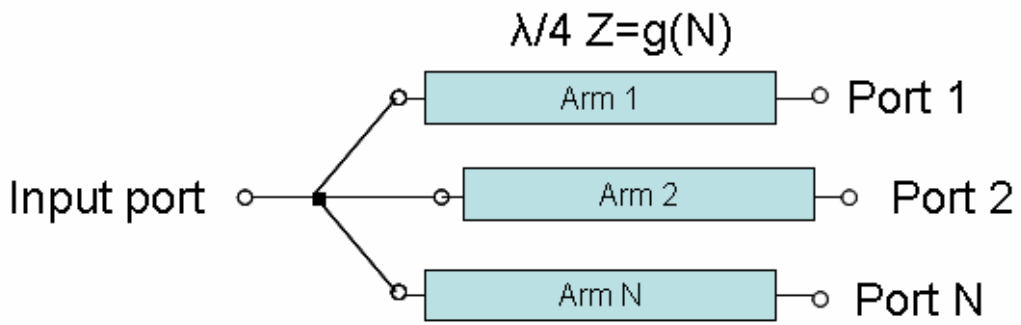
- simplest way to split/combine signals
- two different schemes, well adapted to coax or micro strips
- in-phase signals, no resistor



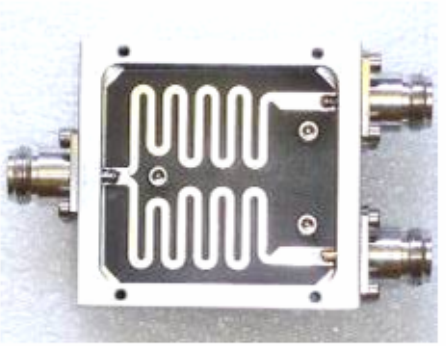
Coaxial scheme



Legnaro 4-ways



Strip line scheme



Soleil 2-ways

Splitter/Combiners

10-way divider

8-way divider

2-way divider

200 kW

100 kW

25 kW

2.5 kW

Splitter/Combiners

The Y junction has the advantages of requiring no resistors and in phase signals, but:

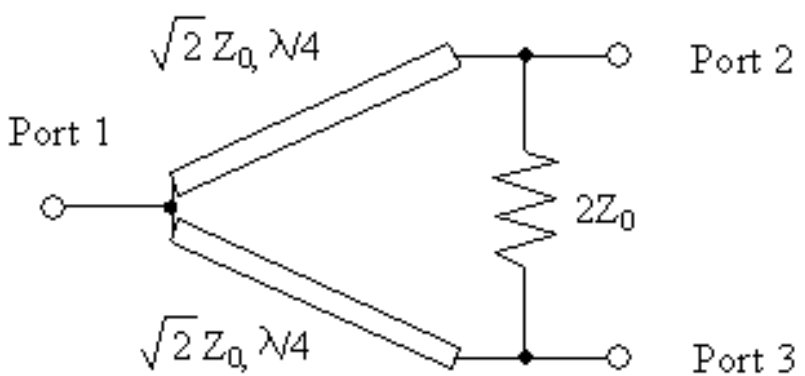
- It doesn't isolate the ports, whose impedance depends on the matching conditions on the other arms.
- It can be used only with unconditionally stable amplifier modules, embedding circulators to decouple direct and reverse powers.

Isolated combiners use one or more resistors to absorb non combined power.

The resistor can be embedded in the network as in the Wilkinson

Splitter/Combiners

Wilkinson: N-Ways



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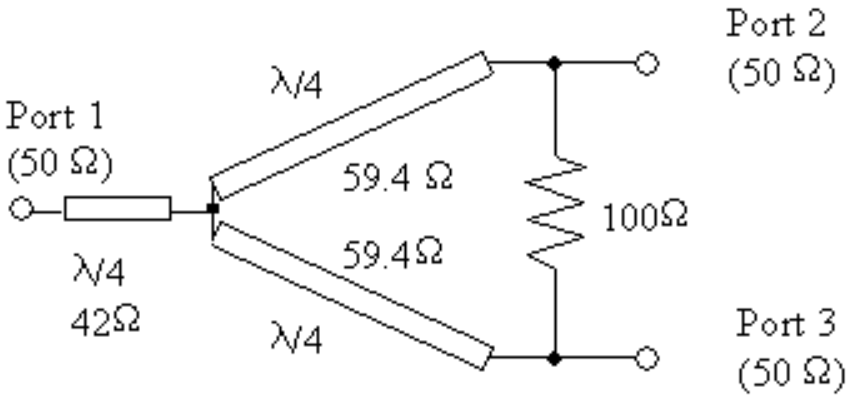

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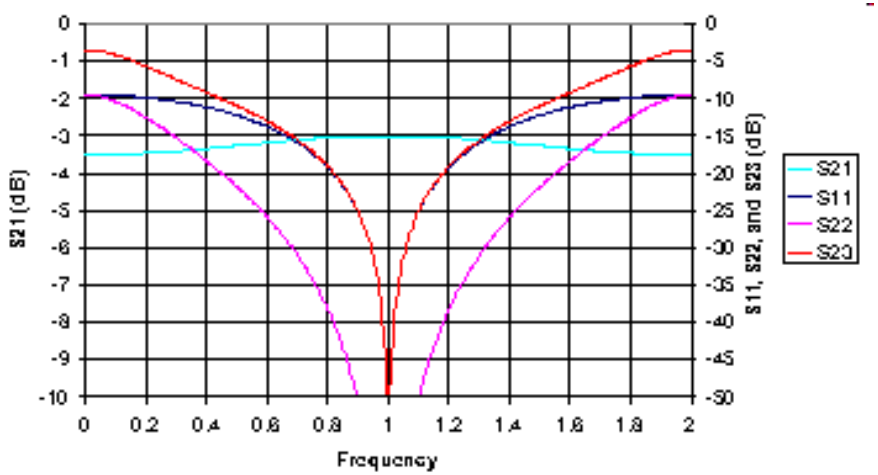
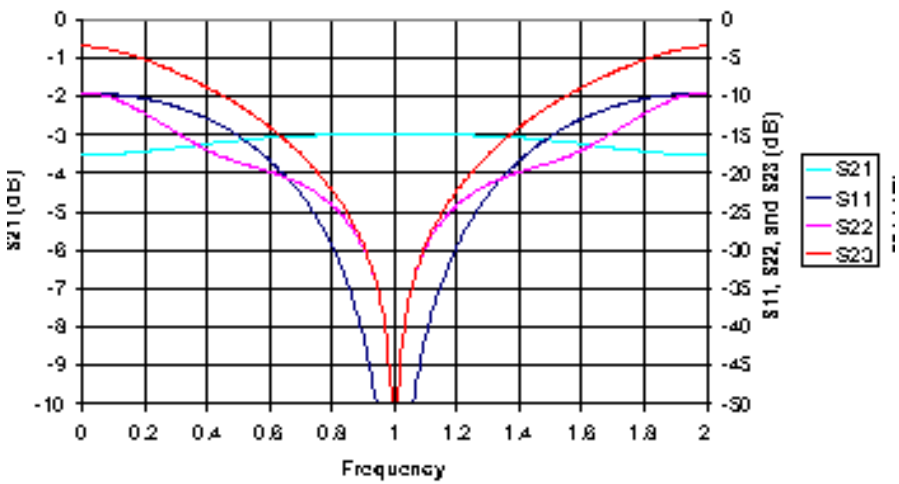




MICROWAVE ENCYCLOPEDIA

Splitter/Combiners

Wilkinson

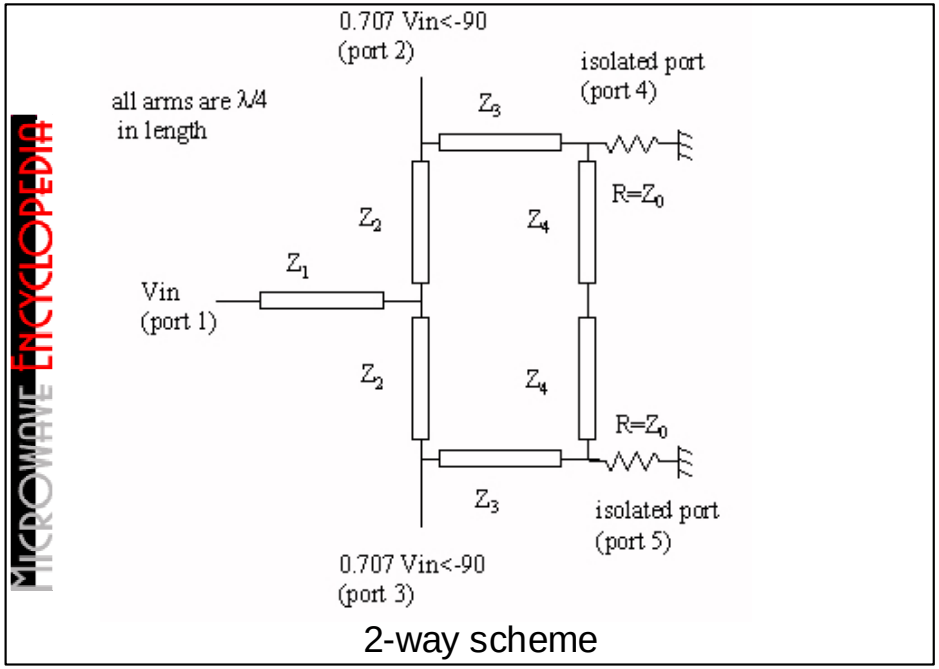
The simplest configuration bandwidth is very narrow but it can be enlarged by placing a transmission line section on the input arm

Resistor has no effect on in-phase and equal amplitude signals but allows the 3 ports to be matched while isolating ports 2 and 3 for different values of phase or amplitude.

Resistor is embedded into the network, and must provide a short phase length for the scheme to work.

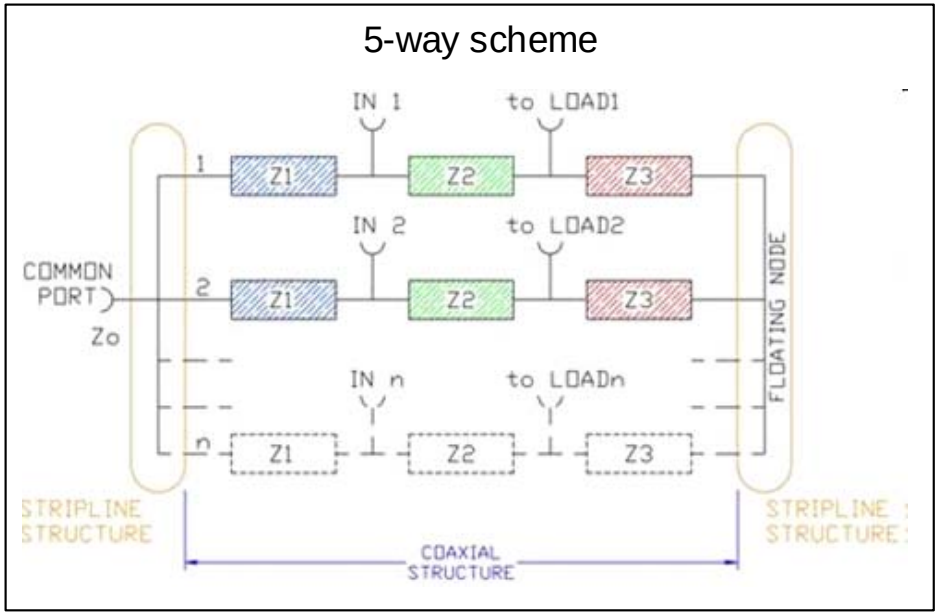
At high power or frequency, the Gysel combiner is preferred.

Splitter/Combiners



2-way scheme

5-way scheme



Gysel: N-Ways

2.5 kW, 5-ways,
211 MHz
©RES INGENIUM

Splitter/Combiners

Gysel

The terminations in a Gysel are equal to Z0, and can be high-power loads.

They can be external to the power splitter as any length of Z0 transmission line can be added between the loads and the splitter.

It is also possible to measure the two resistors in parallel, even if they are grounded to the substrate.

The Gysel scheme is largely used for N-way combiners in the 80 to 200 MHz range of frequency, avoiding the use of circulators on each pallet.

It can be easily realised in microstrip or in in-air structures

Splitter/Combiners

Gysel

3 kW, 4-ways
88÷108 MHz
©DB Elettronica

Splitter/Combiners

-3dB Hybrid: 2-Way
works with 90° phase signals and Zc resistor

20 kW – 88÷108 MHz
-3 dB coupled line 2-way combiner
©DB Elettronica

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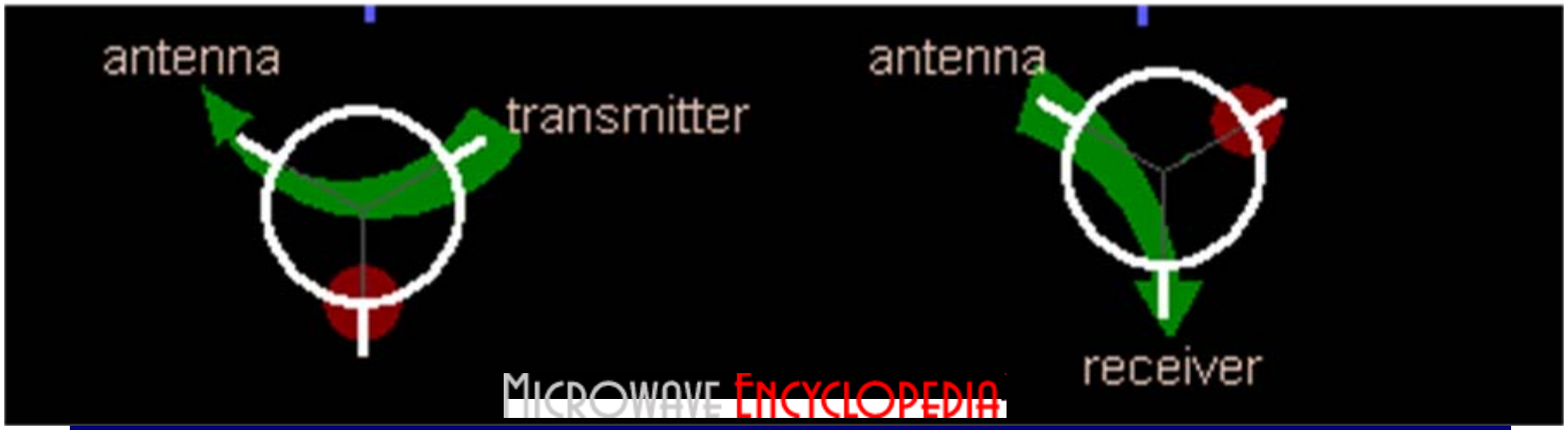
Circulators

Circulators are passive, multiport, non reciprocal devices transferring the power from one port to another in a prescribed order.

3-port circulators are the most common in accelerator application



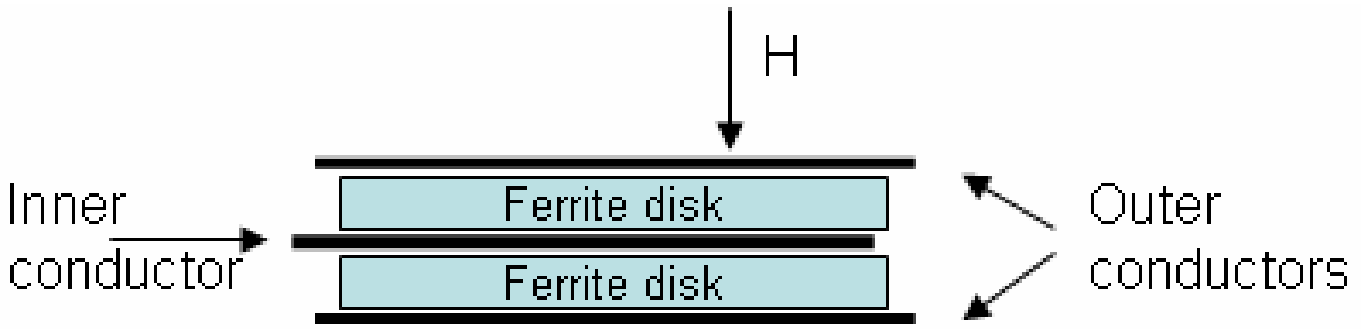
Diplexer application and
Isolator if a dummy load replaces the receiver

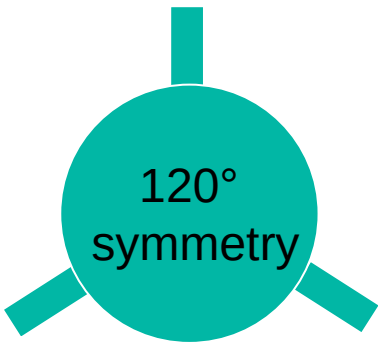
Circulators

Several circulator types exist but

the junction one is the most commonly used as it can be implemented on strip (low power) or in-air (high power) lines as well as on waveguides.

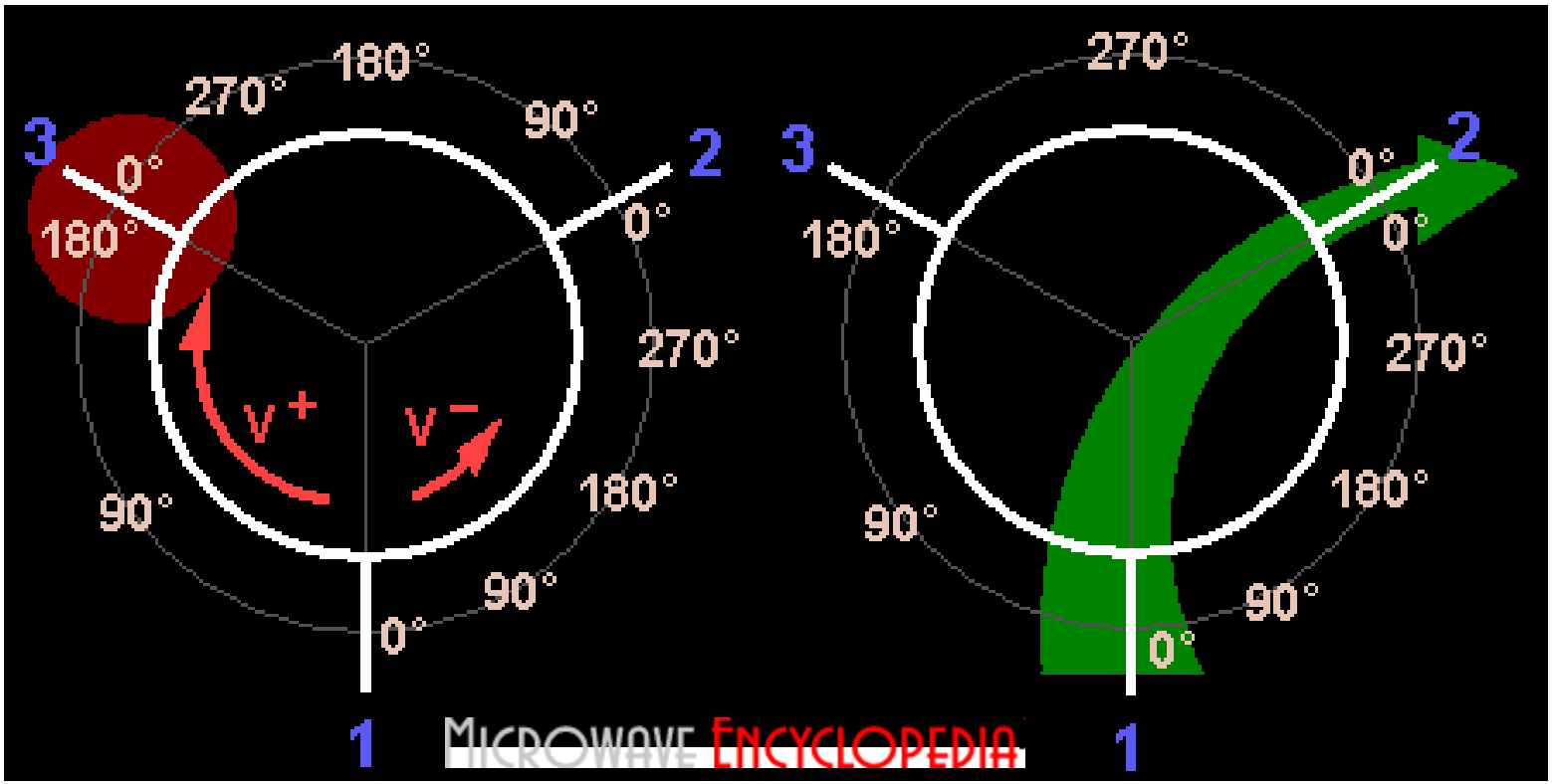
When using coaxial connectors, the 3-plate configuration is normally used, where two plates of ferrite are put between the inner and outer conductors.





Circulators

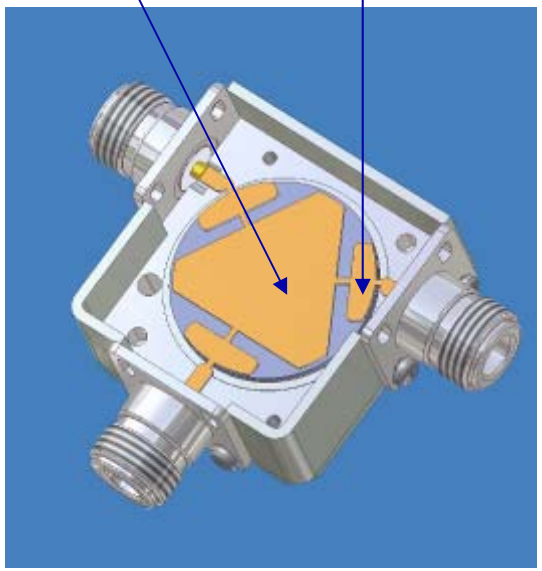
- The line entering each port is split in two equal branches going towards the other two ports (120° symmetry).
- Due to the interaction with the magnetised ferrite, the split entering waves at port 1, have different speeds such as they are in-phase when they arrive at port 2 (where they recombine) and in opposite phase at port 3 where they cancel.

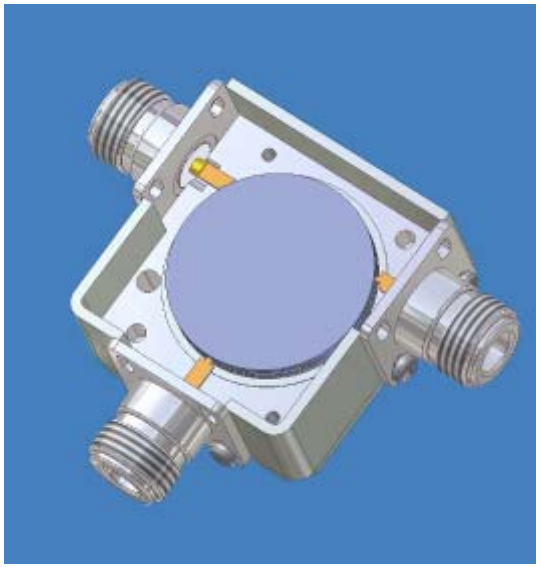


Circulators

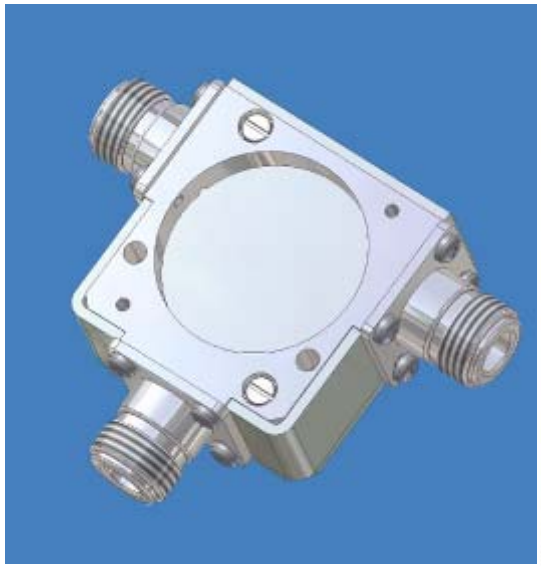
3 plate configuration
Medium power

1) Microstrip inner conductor:
- matching networks
- cavity



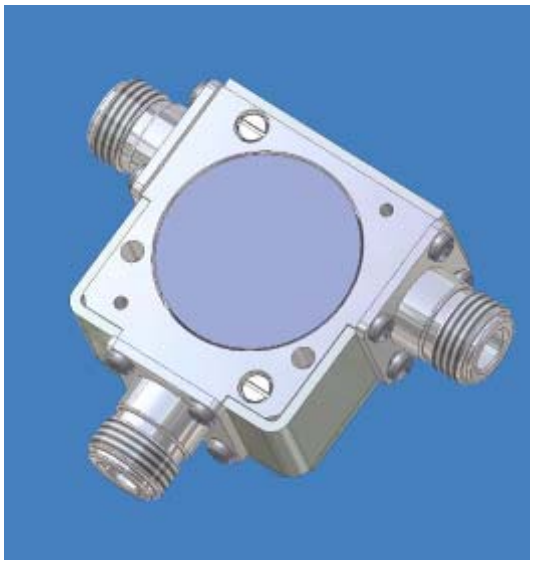


2) Ferrite disk



3) Outer conductor

4) Pemanent magnet disk

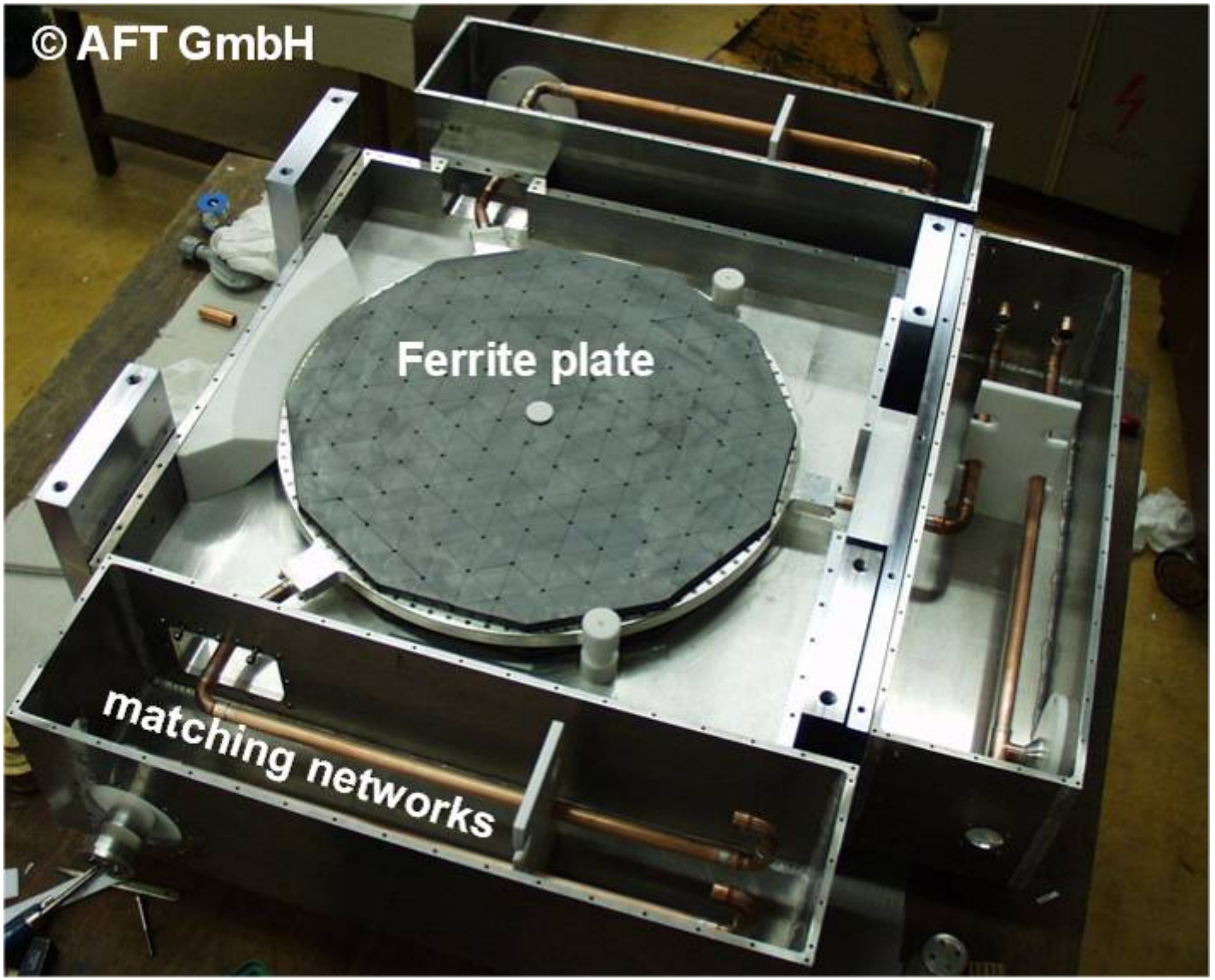


5) Closed package

© VALVO GmbH

Circulators

3 plates - High power: 60 kW, 88 MHz (Spiral 2)



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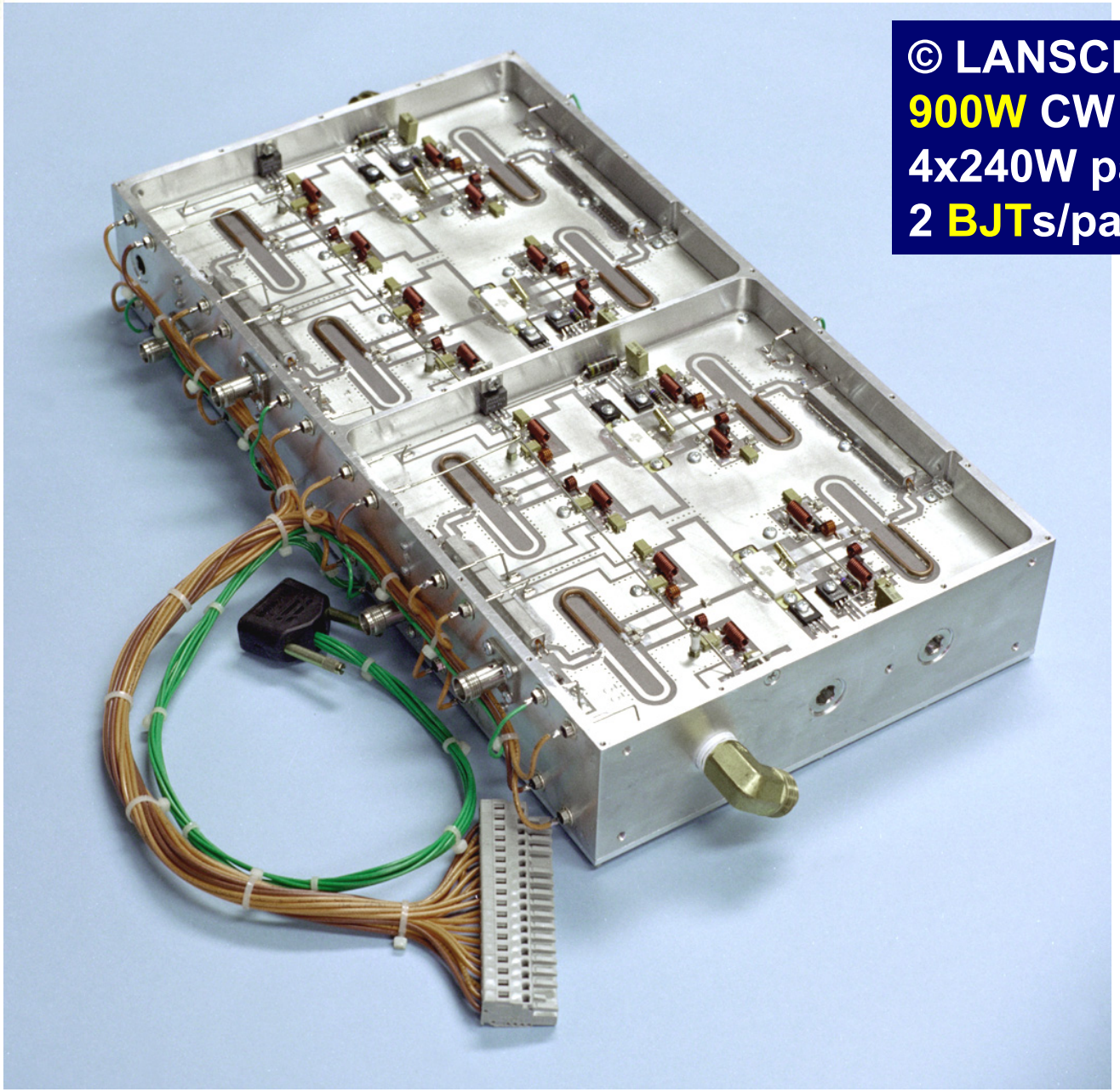
Applications

Solid state amplifiers have been built or are foreseen for very different applications, let me choose the following examples:

(Italic: not yet in operation: under construction or foreseen)

- Master generator amplifier: Lansce … (‘94, BJT, 0.9 kW, 805 MHz)
- NC ion injectors: CERN, JPARK, GSI, … (LF, up to several kW)
- Ions SC linac: Atlas, Alpi, *SPIRAL2 2, FRIB* … (up to tens of kW)
- Protons, Deuteron SC Linacs: *Saraf, Eurisol* … (up to tens of kW)
- Light sources : SOLEIL, *LNLS, SLS* … (up to hundreds of kW)
- …… and many others.

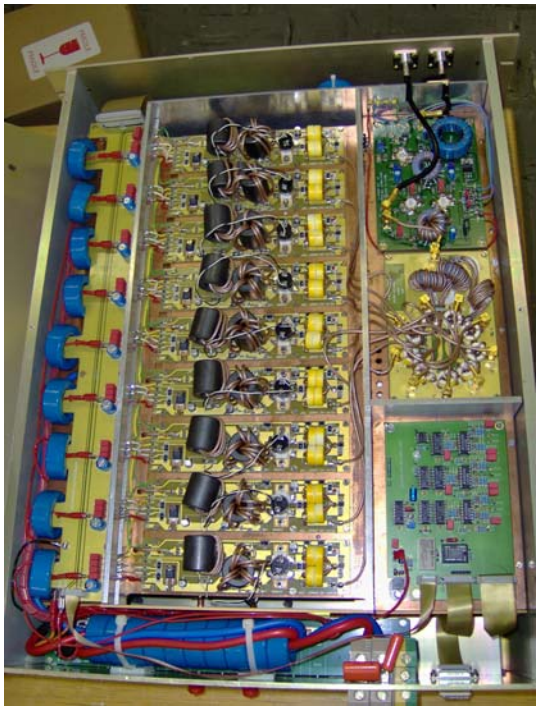
Applications



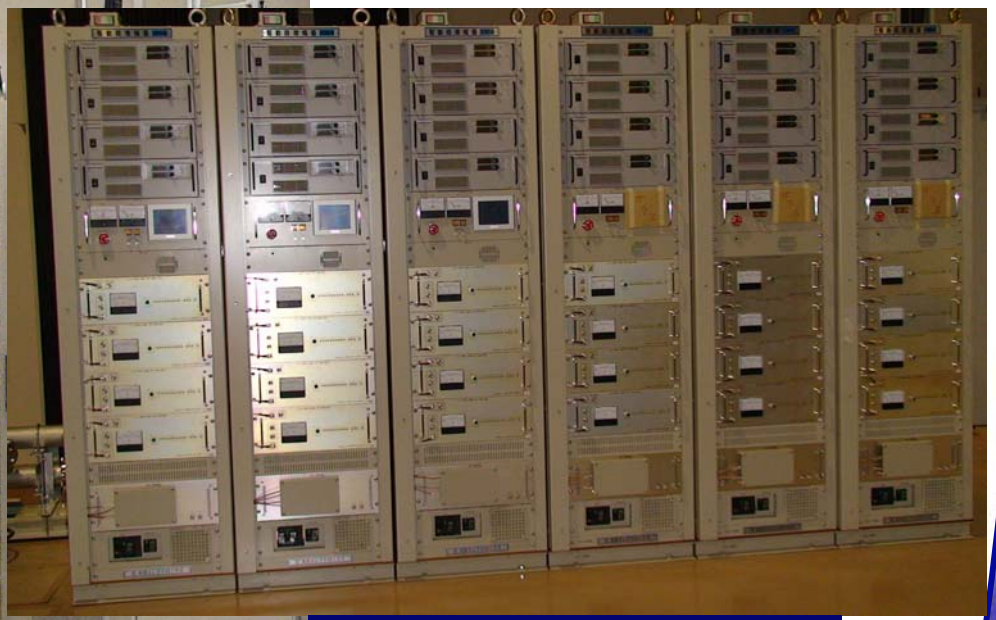
© LANSCE 1994, J.Lyles
900W CW module – 805 MHz
4x240W pallets
2 BJTs/pallet

Applications

CERN LEIR AND J-PARK : 0,5 – 6 MHz, no circulators
1 kW racks 9 pallets/rack
up to 8 kW amplifiers



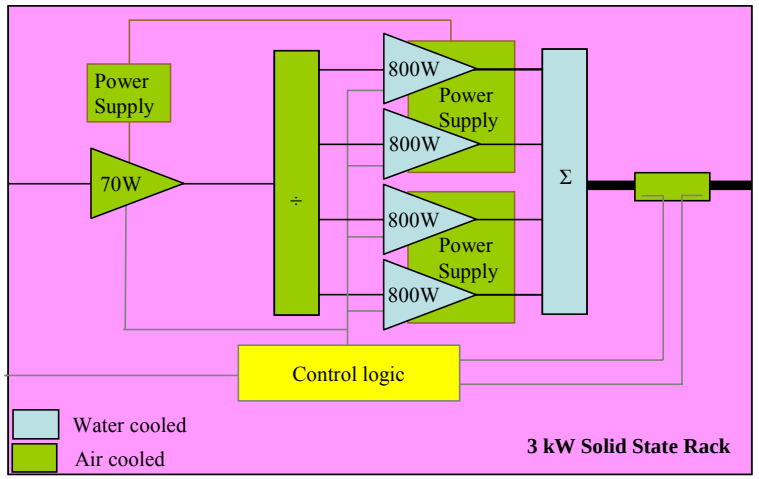
CERN DESIGN 1 kW rack (© M. Paoluzzi)

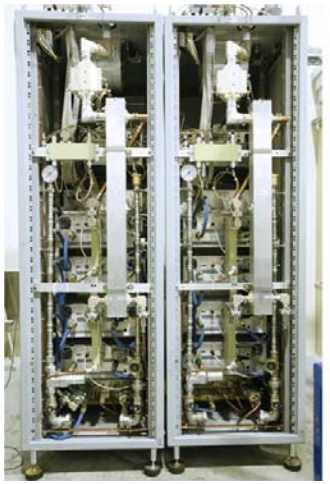


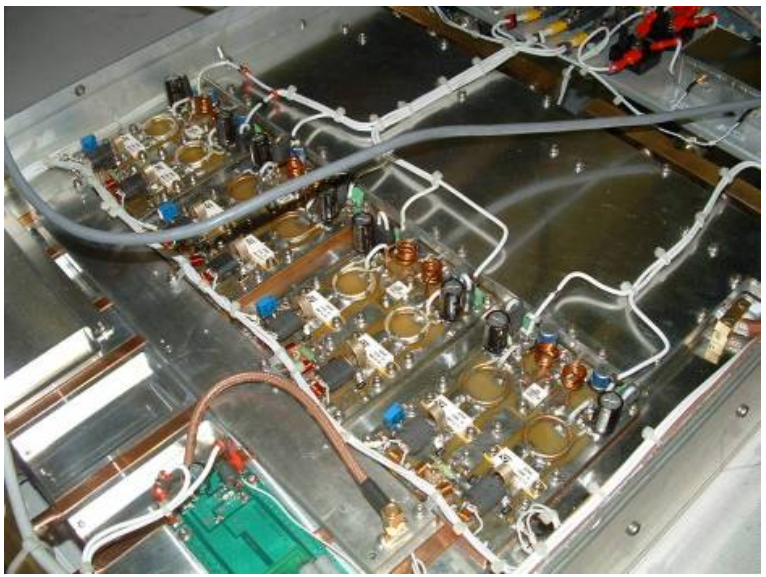
J-PARK : 8 and 4 kW units
(Thanks to Dr C. Ohmori)

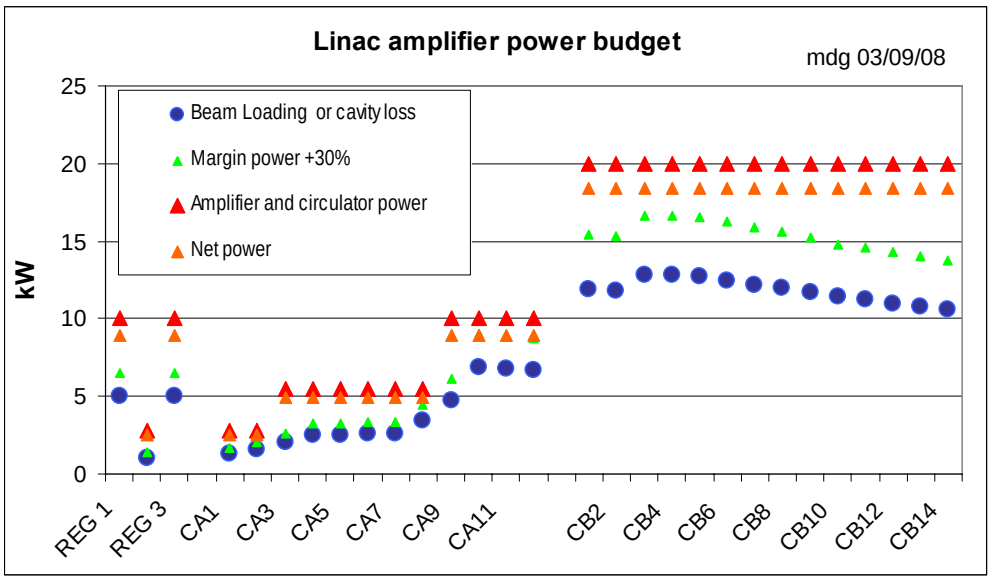
Applications

SPIRAL2: 88 MHz, ion, high current SC driver (5mA)
20 kW amplifiers prototype (© DB Elettronica)
(2x10 kW cabinets, 8x2.8kW racks









380 kW total installed power

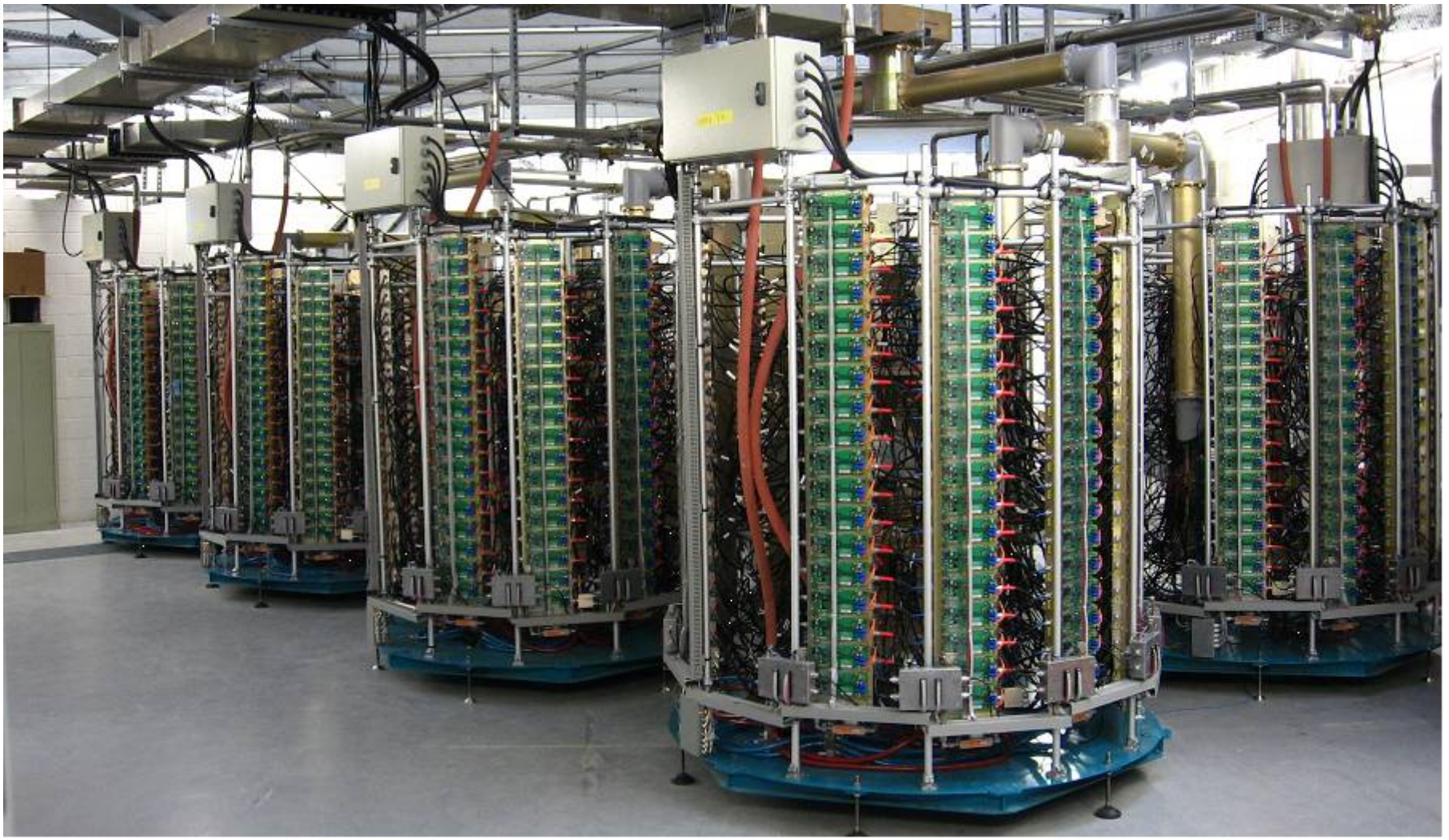
Applications

EURISOL driver: 352 MHz, proton SC linac
10 kW prototype amplifier
10 kW cabinets, 36x350W modules, circulators embedded
INFN/LNL © Fabio Scarpa

SC DRIVER REQUIREMENT		
MHz	**Amp kW**	**Total kW**
176	5, 10	690
352	25	900

Applications

Synchrotron SOLEIL: (Ti Ruan)
352 MHz, 180 kW amplifiers; 4x45 kW towers
35kW + 4x180 kW installed



Contents

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- Solid State Technology
  - Historical Introduction
  - Commercial Applications and available devices
  - RF power Mosfet manufacturing process
- Solid state amplifier architecture
- Splitter/Combiners
- Circulators
- Accelerator applications
- **Conclusion**

Conclusion

Today, the whole range of frequency for accelerator applications is covered at very competitive prices and performances.

Several industrial applications push the development of solid state RF devices in a very large range of frequencies: up to 3.7 GHz.

Tube prices increase (when their manufacture is not simply stopped) as the market is falling down.

Operating advantages vs tubes

- absence of high biasing voltages
- longer life times **(more than 80000 hours at LANL or CERN)**
- easier and quicker maintenance,
- possibility of reduced power operation in case of failure,
- fit ≠ power levels inside the same project, with one elementary brick.
- Stable gain with aging

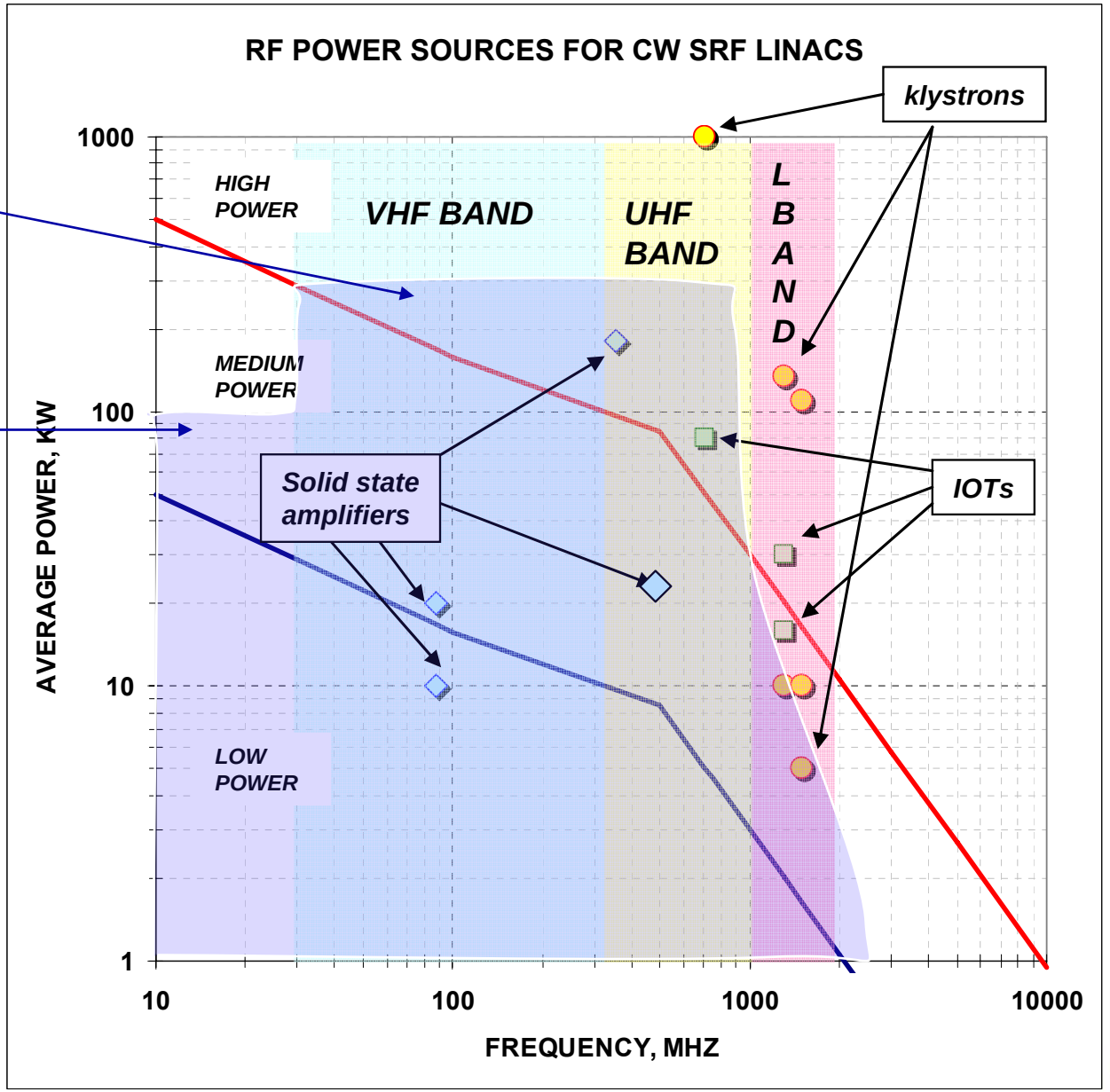
Reliable and efficient operation up to 200 kW at 350 MHz has already been proved. Similar levels at 500 MHz are already planned (PSI, …).

Conclusion

Next future

Circulators and transistors available

“NO” circulators



Original diagram by S. Belomestnykh: RF systems for CW SRF linacs, Linac08

Thank you for your attention

References

- **Publications of people listed in the acknowledgements and available on the JACoW website.**
- **Transistor manufacturers websites**
- **Wikipedia and Microwave Encyclopediae**

Sorry for not talking at all about power supply schemes and operation monitoring issues.

RF Transistor Applications

Industrial, Scientific, Medical Applications

- Industrial laser
- Nuclear magnetic resonance (NMR)
- Plasma generator for semiconductors
- Plasma generator for display panels
- Spectroscopy
- RF heating

RF Power Device Market