HIGH POWER,
WIDEBAND,
SOLID-STATE AMPLIFIERS FOR LEIR AND J-PARC RF SYSTEMS.

Summary

- Overview
- Basic building block
- Hybrid coupler/splitter
- Delay compensated transformers
- An ultra wideband hybrid
- Directional coupler
- 1 kW amplifier
- Use at CERN
- Use at J-PARK

Overview

CERN LEIR machine and J-PARC RCS and Main Ring required driver amplifiers for their grid tubes power stages:

- Frequency range : 0.5 – 6 MHz
- Power 1kW, 4kW and 9kW
- Duty cycle 50% to 100%
- High reliability
- Maintenance ease

Specs well suited for a solid-state modular solution!

Overview

- Since 1993 the CERN PSB accelerating cavities use solid-state drivers built around MRF151G RF mosfets.
- The operation experience (16 units) is very good as no amplifier failure happened in the past (except in case of tetrode ceramic breakdown!)
- The units are installed in a radioactive environment and the integrated dose over the last 14 years is >10k gray.
- No performance degradation has been measured in the operational units.

This unit were the starting point of the new design!

Basic building block

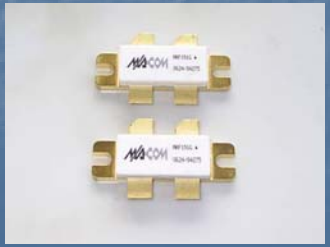
- Class AB for good efficiency and linearity.
- Ability of operating on all load conditions.
- No circulators available for this frequency range so
  - ✓ Full reflected power must be dissipated on the active device.
  - ✓ Load mismatch directly affects the mosfet drain load.

▼

- Single push-pull stage built around an over dimensioned MRF151G double mosfet.
- Device operated at 35V instead of nominal 50V
- Device operated at ~140W instead of nominal 300W

Similar or equivalent devices :

- ✓ D5029UK from Semelab
- ✓ BLF278 from Philips
- ✓ SD2932 from ST
- ✓ SR706 from Polyfet



Basic building block

- At high power, in class B, conduction angle is close to 180 degrees.
- One device provides the full power during half cycle.
- For 140W and 35V supply voltage the drain load and current are then:

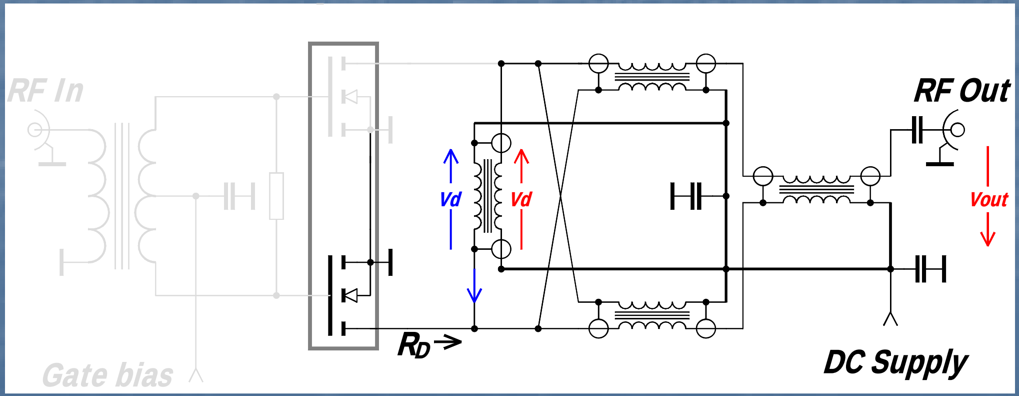
$$R_D = \frac{(V_{DS} - V_{DSS(ON)})^2}{2 \cdot P} = \frac{(35-5)^2}{2 \cdot 140} \approx 3.125\Omega$$

$$I_D = \frac{(V_{DS} - V_{DSS(ON)})^2}{R_D} \approx 10A$$

- Matching achieved with a standard transformer made of coaxial cables wound on a ferrite tore.
- When driven from one drain connection with a 50Ω load:

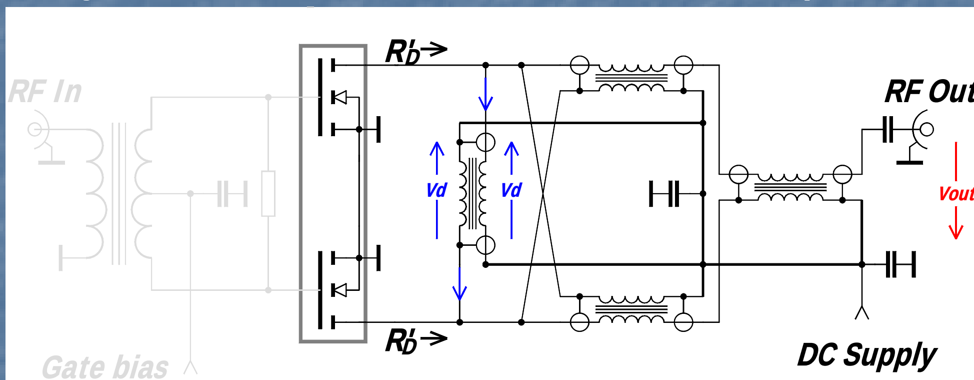
$$n = \frac{V_{OUT}}{V_D} = 4$$

$$R_D = \frac{50\Omega}{n^2} = 3.125\Omega$$



Basic building block

- At low power, in class A, both devices provide power during the whole cycle and are driven in counter phase.



- In this case each drain is loaded by:

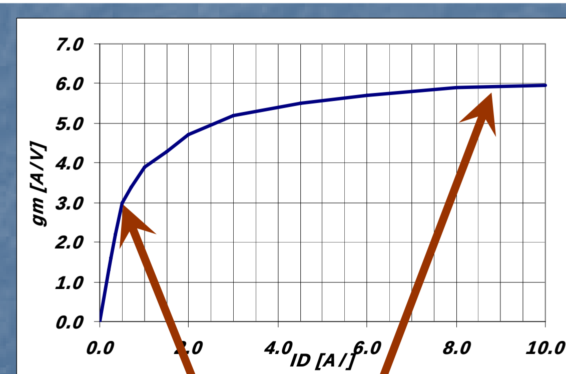
$$R_D' = \frac{50\Omega}{\left(\frac{n}{2}\right)^2} = 2 \cdot R_D = 6.25\Omega$$

- To equalize the mid-band gain at low and high power (class A and class B)

$$G_{V\,A} = gm_A \cdot R_D' \cdot n = gm_A \cdot 2 \cdot R_D \cdot n$$

$$G_{V\,B} = gm_B \cdot R_D \cdot n$$

$$\frac{G_{V_A}}{G_{V_B}} = \frac{gm_A \cdot 2}{gm_B} = 1$$

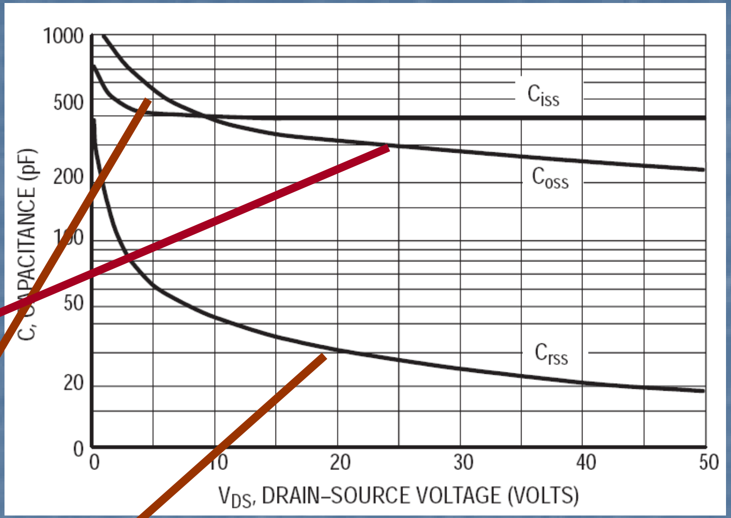


$$gm_A = \frac{gm_B}{2}$$

Basic building block

- Assuming the transformer to be ideal and the mosfet output impedance purely capacitive the high frequency cutoff is:

$$f_c = \frac{1}{2 \cdot \pi \cdot R_D' \cdot C_{OSS}} \approx 85MHz$$

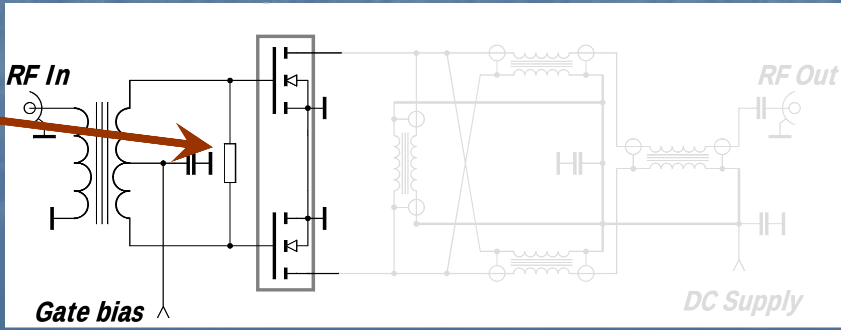


- The gate capacitance is:

$$C_G \approx C_{ISS} + C_{RSS} \cdot (1 + gm_B \cdot R_D) \approx 400\,pF + 30\,pF \cdot (1 + 6 \cdot 3.125) \approx 990\,pF$$

- The input transformer is a balun with 1 to 9 impedance ratio (50Ω to 5.55Ω)

$$f_c = \frac{1}{2 \cdot \pi \cdot \frac{R_G}{4} \cdot C_G} \approx 115MHz$$



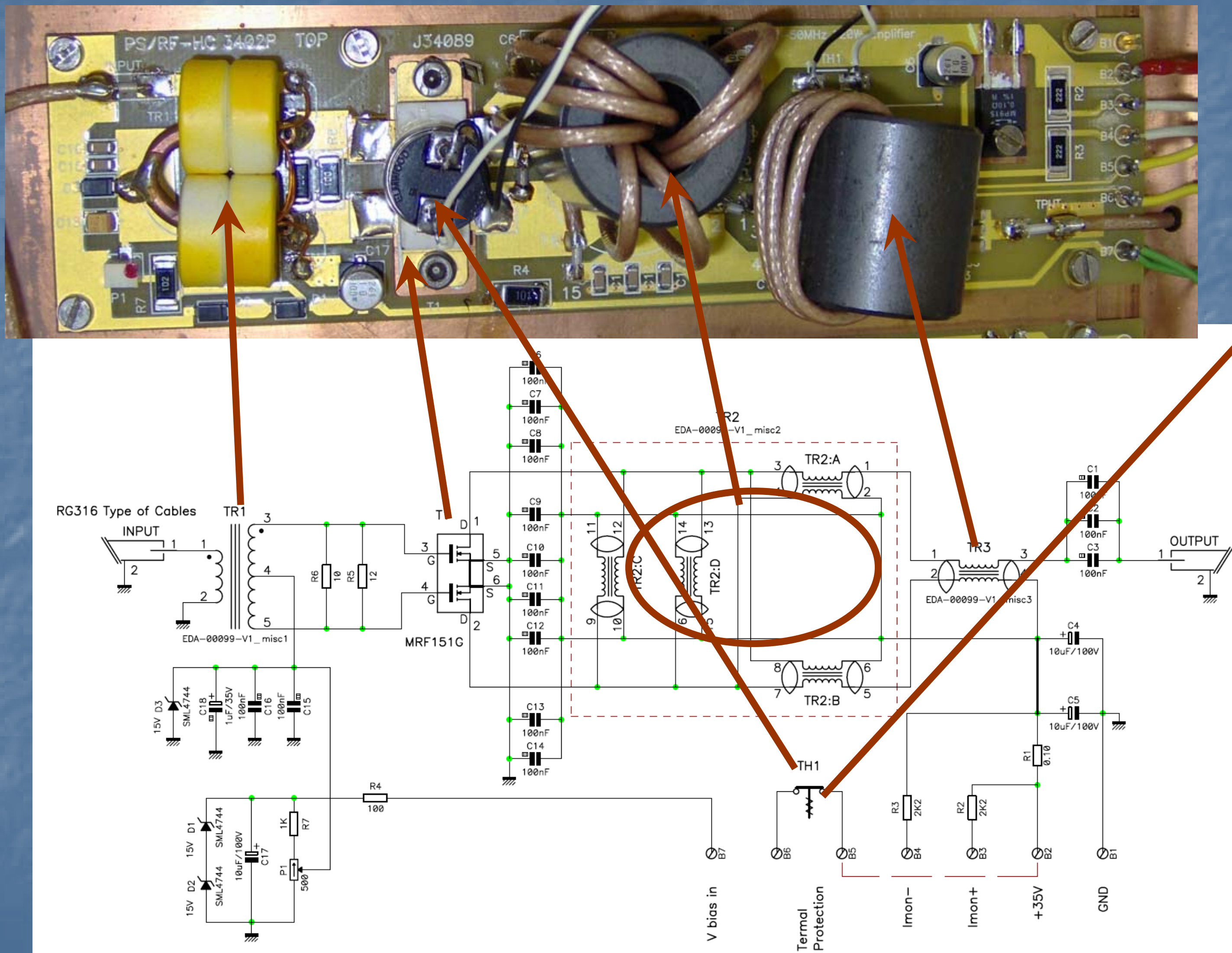
Basic building block

- The output transformer uses 1 tore type 4W620 (Wuerth)
  - ✓ Od=26mm, Id=13mm, H=28.5mm
  - ✓ $S=1.85\ 10^{-4}\ m^2$
  - ✓ $Al \sim 2.8 \mu H/N^2$
- N=4 turns on the balun and N=2 turns for the transformer gives:
  - ✓ B_{MAX}=26.5mT @ 0.5MHz and 140W
  - ✓ $f_L \sim$90KHz

Ferrite saturation typically ~200mT.
CW operation normally possible with B~20-30mT

- The input transformer uses 4 tores type 3E5 (Ferroxcube)
  - ✓ $Al \sim 5 \mu H/N^2$
- N=3 turn on the high impedance side gives:
  - ✓ $f_L \sim$45KHz

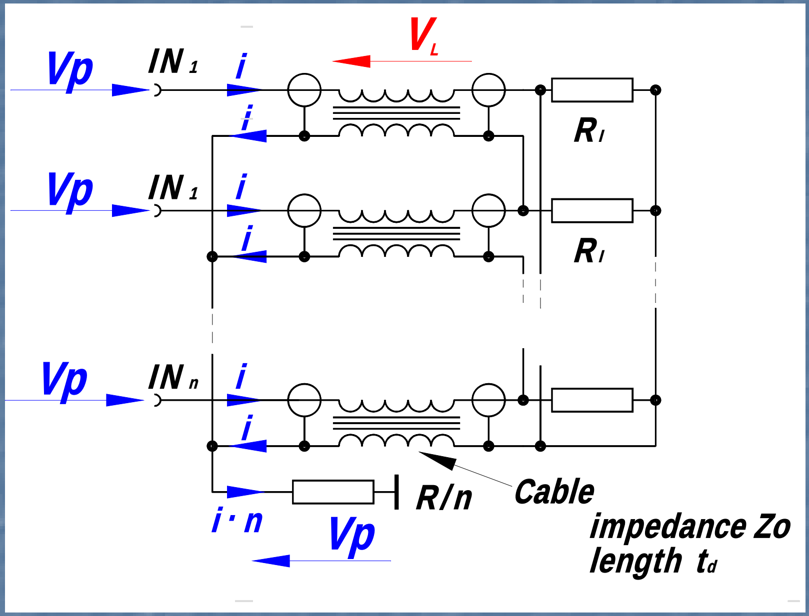
Basic building block



- Thermal protection simply insured by thermal switch glued on the mosfet case.

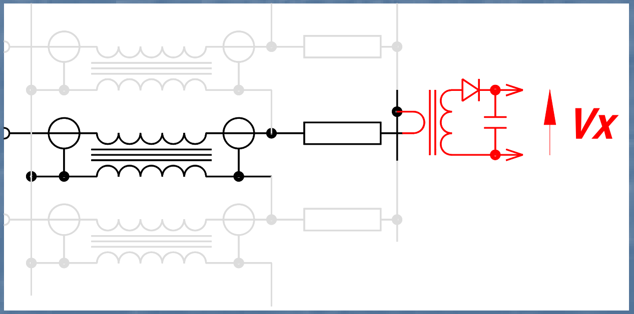
Hybrid coupler/splitter

- Classic hybrid combiner/splitter circuit
- n-ways device
- R_l provides isolation between ports.
- If all ports driven with identical signals
  - ✓ no current through R_l.
  - ✓ $V_L \sim V_{IN} sin(\omega\ t_d)$
- Frequency response limited
  - ✓ notch at $f_n = 1/4t_d$



- Simple detector provides indication of unbalanced drive (or broken module).

Very useful for servicing!



H. Granberg, *Broadband transformers and power combining techniques for RF*, Motorola AN-749

Delay compensated transformer

- In ferrite loaded hybrids and transformers B_{MAX}<20-30mT for CW operation.

$$B = \frac{V}{\omega \cdot S \cdot n}$$

Number of turns

Ferrite cross section

- When combined power get high...
- When extending the low frequency response...

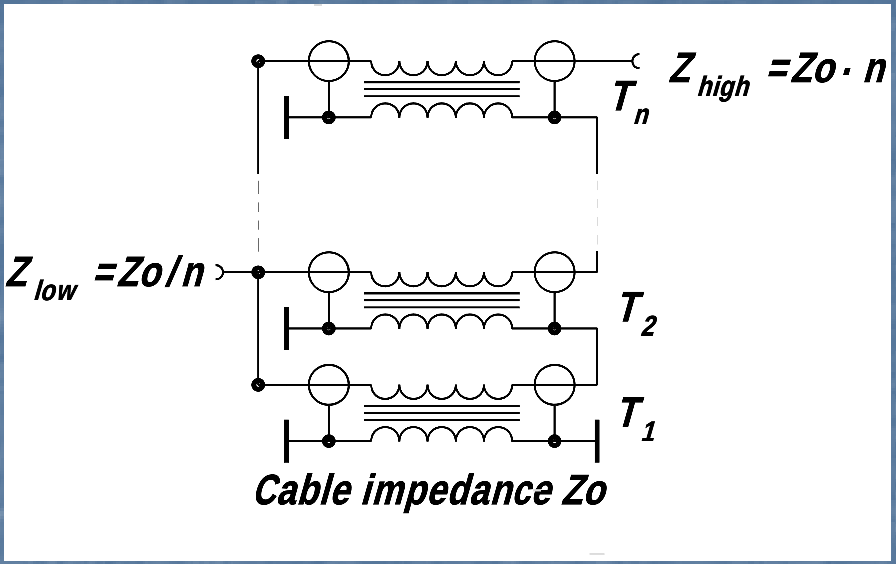
... B_{MAX} limited by increasing the number of turns or the ferrite cross section

- This increases the cable length that affects the high frequency response:

first notch placed at $f_n=1/4t_d$

... the solution is delay compensated devices!

Delay compensated transformer

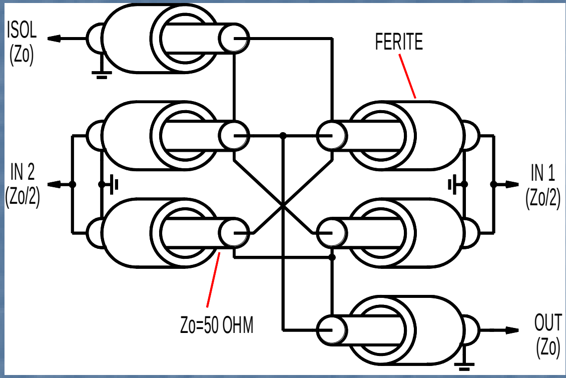


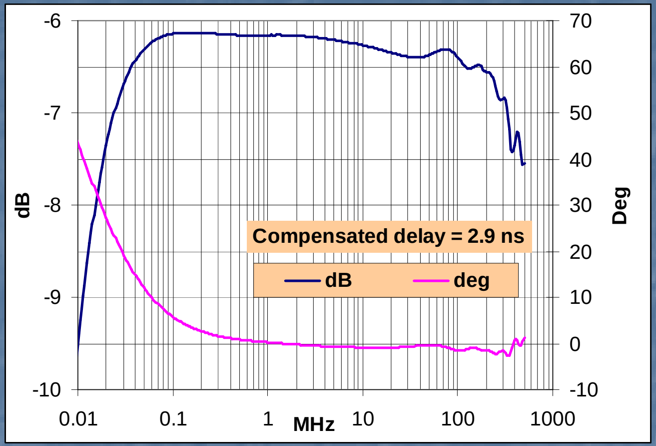
- Cables paralleled on the low impedance side
- Cables in series on the high impedance side.

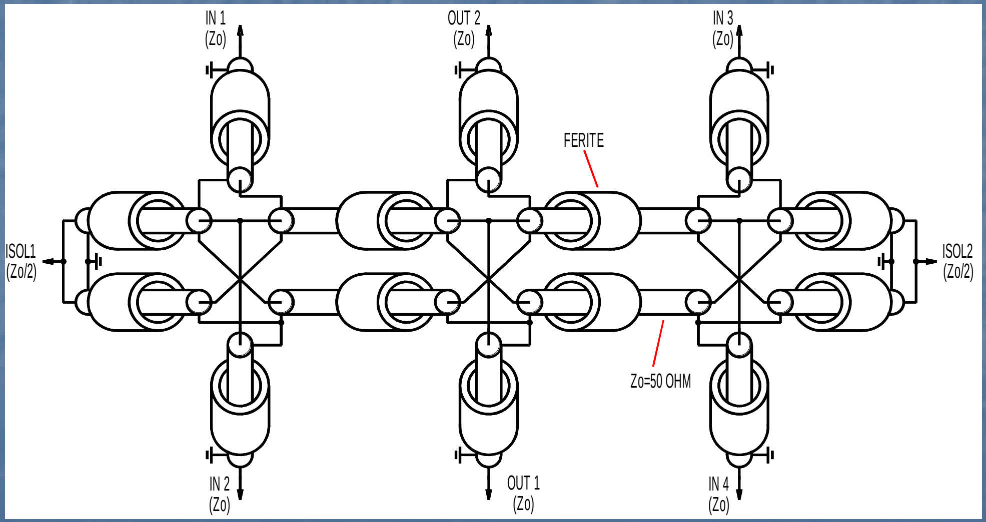
In theory no high frequency limit!

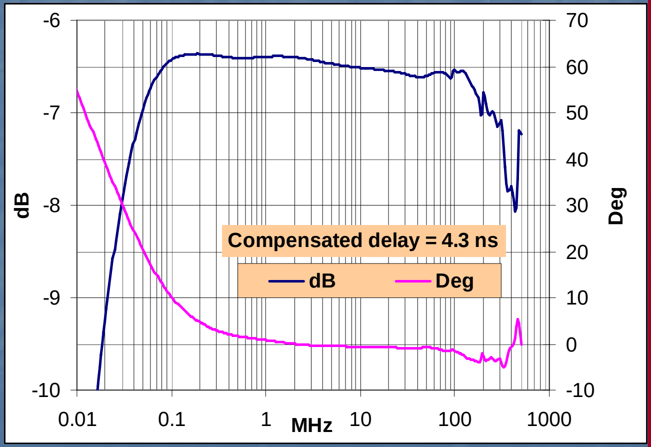
An ultra wideband hybrid

Udo Barabas, *"On an Ultrabroad-Band Hybrid Tee"*,IEEE Transactions on microwave theory and thecniques, vol.MTT-27, no.1, January 1979

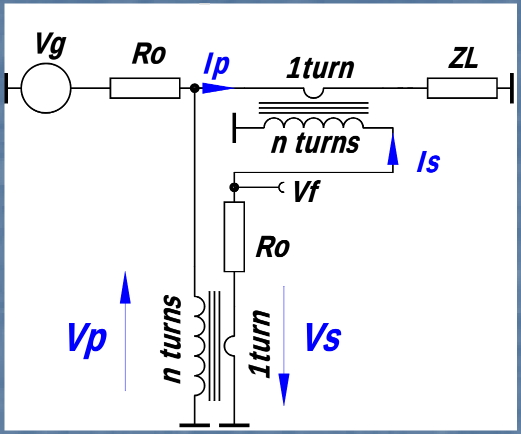








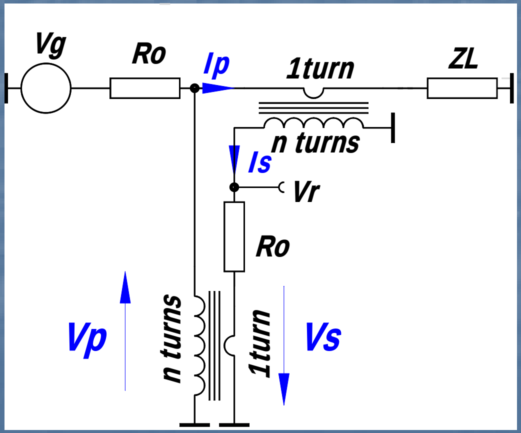
Directional coupler



Assuming the impedance of the 1 turn winding <<Ro and the impedance of the n-turns winding >>Ro then, for any value of ZL:

$$V_F \sim -V_g / n$$

simply proportional to the incident wave

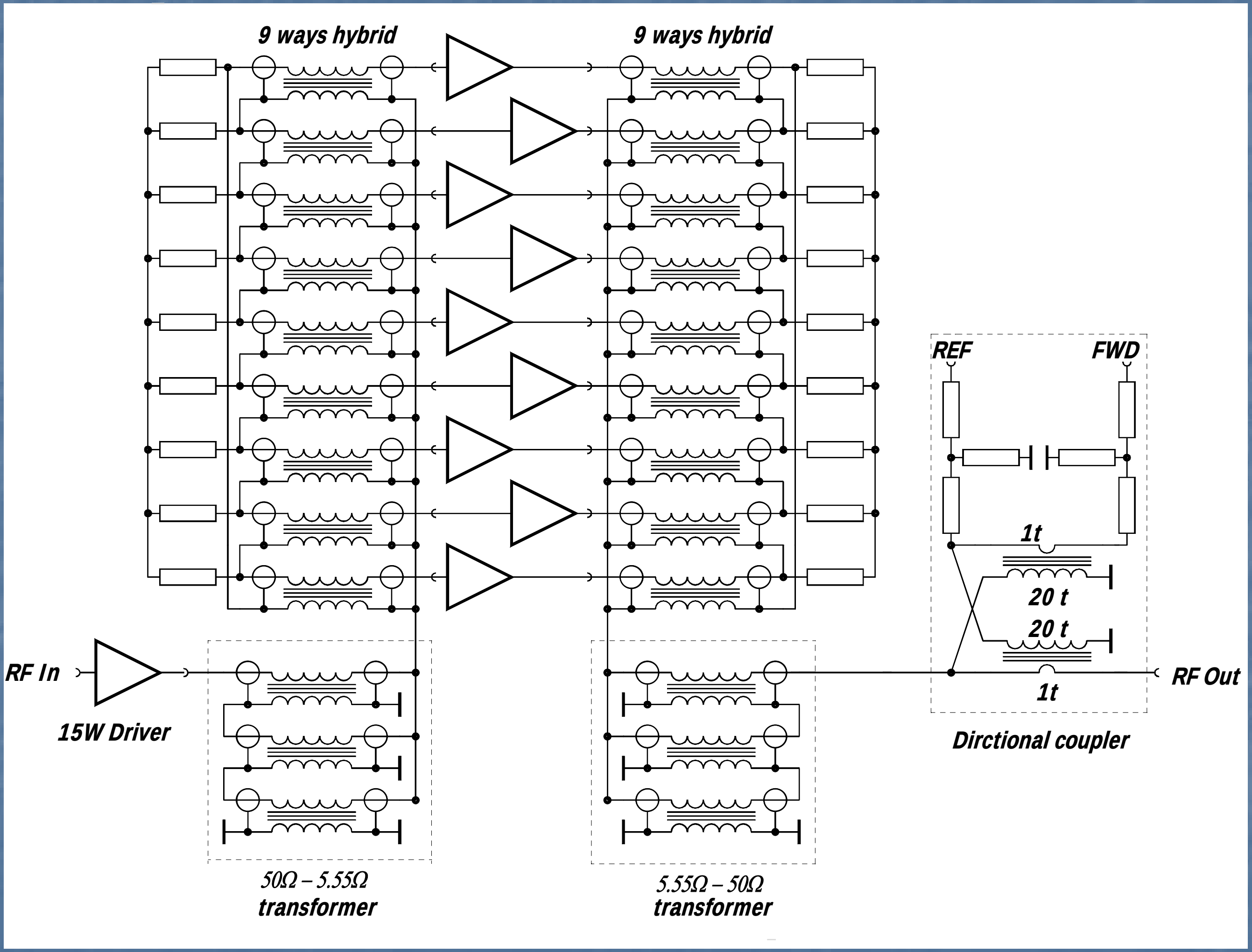


Inverting the current sample direction we get

$$V_R \sim V_F \cdot \left[\frac{Z_L - R_o}{Z_L + R_o} \right] \sim V_F \cdot \rho$$

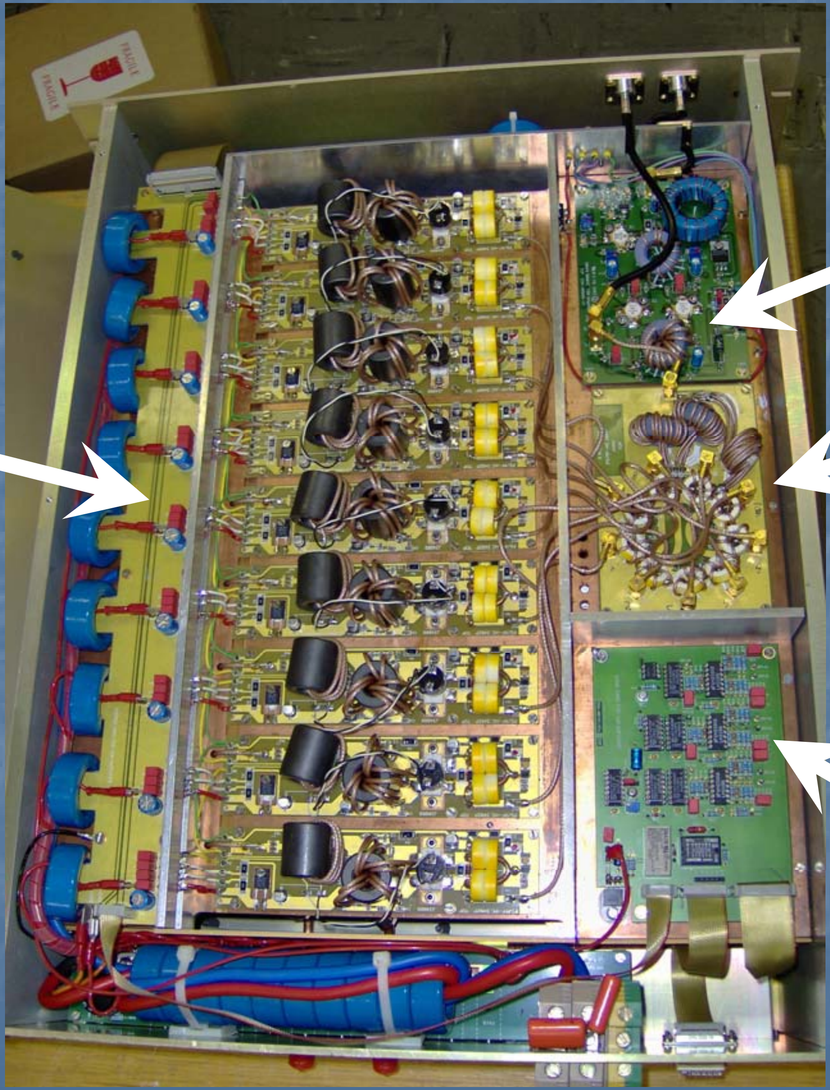
thus proportional to the reflection coefficient.

1 kW amplifier



1 kW amplifier

DC distribution and filtering

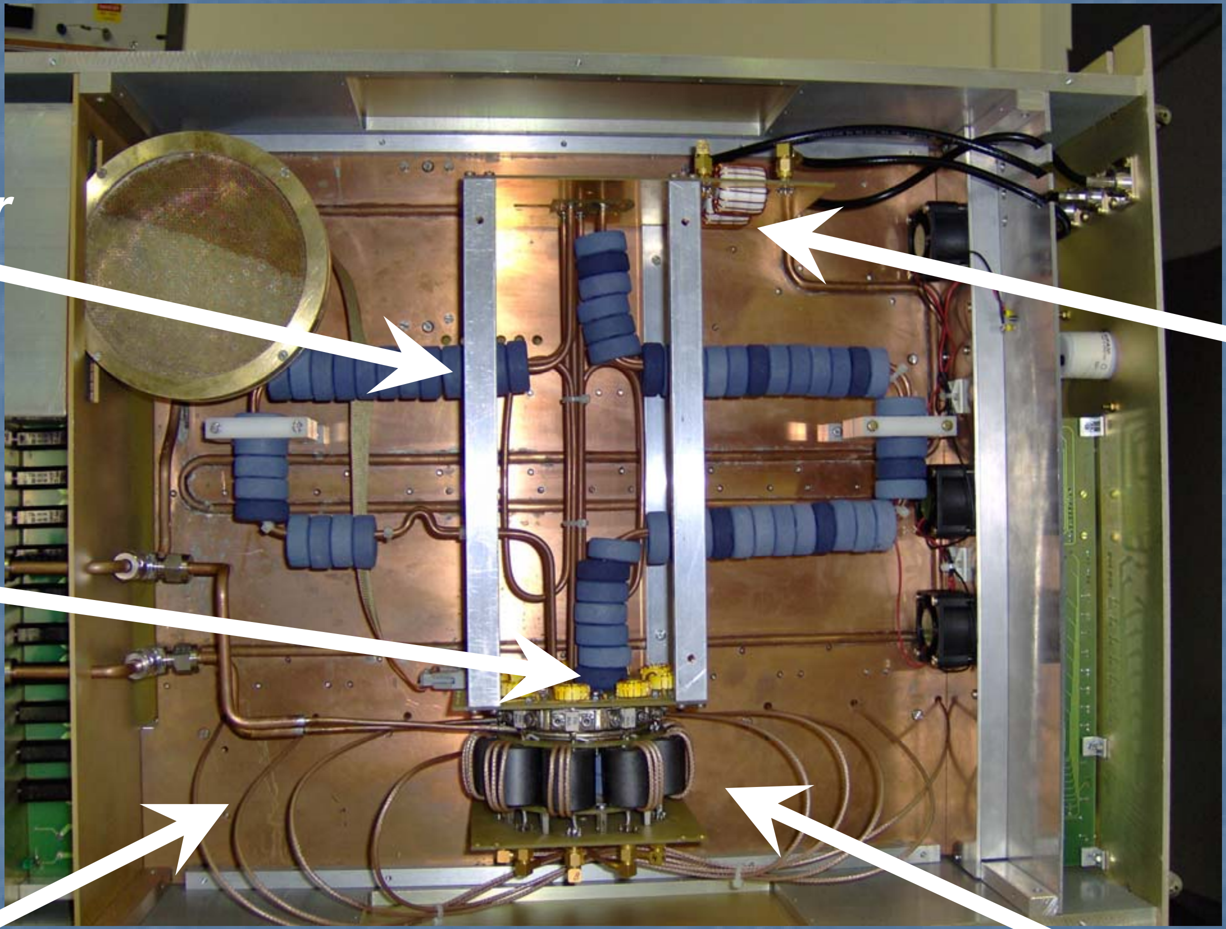


15W Driver

9 ways splitter

Survey electronics

1 kW amplifier



5.55Ω – 50Ω transformer

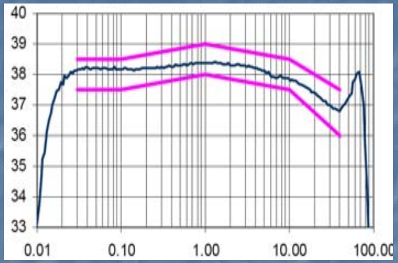
Directional coupler

Unbalance detectors

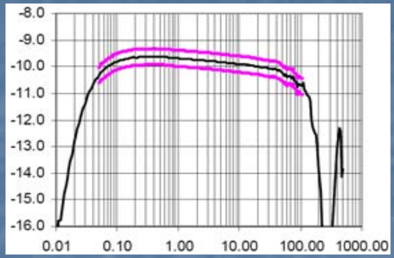
Water cooled copper plate

9 ways combiner

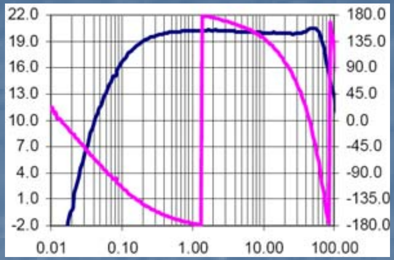
1 kW amplifier



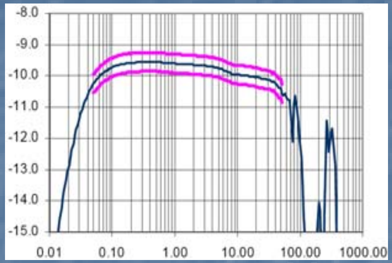
15W driver



9 ways splitter

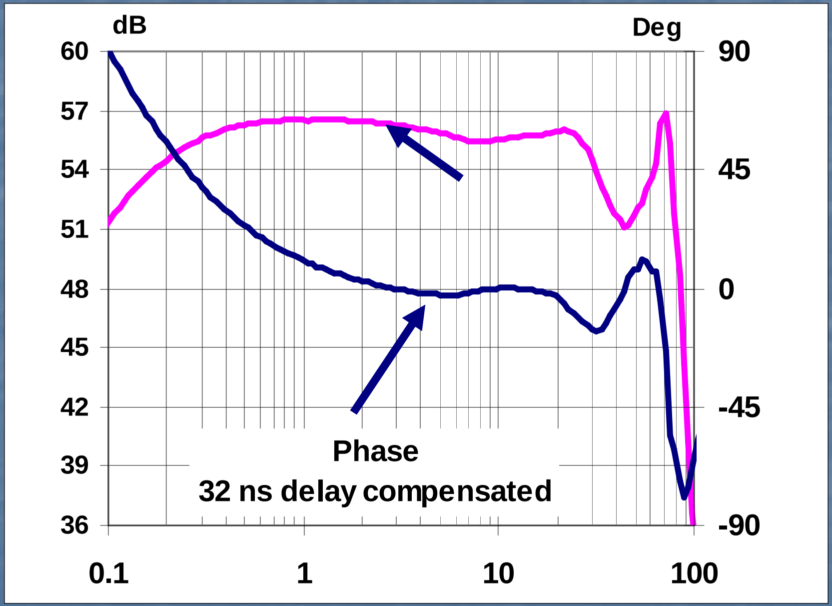


140W module



9 ways combiner (in splitting mode)

-3dB Bandwidth	**0.2 - 10 MHz**
-1 dB Bandwidth	**0.5 – 5 MHz**
Gain	**58 dB ±1.5 dB**
Output power at 1 dB compression	**>1 kW**
Harmonic distortion	**<-15 dBc @ Pout 1 kW** **<-18 dBc @ Pout 500 W**
Gain linearity	**±1 dB**
Input impedance	**50 Ω VSWR 1.1:1 max**
Load impedance	**50 Ω , no damage when operated with any load.**
Protections	**Overtemperature** **Overcurrent**
Monitoring	**RF Drive input (-26 dB)** **Output Forward Power (-46dB)** **Output Reflected Power (-46dB)** **Driver and final stages DC current** **140W modules power balance**
Power requirements	**35 V 100 A DC**
Cooling	**Water**



1 kW amplifier

CERN LEIR

- Six 1kW units have been produced for CERN use in LEIR machine

- 4 in use without troubles for 2 years (2 spares)

J-PARC

- For J-PARC more than 100 1kW units have been manufactured.
- Units combined to get 4 kW and 8 kW.
- For 8 kW, nine units have been combined to achieve the required power also in case of failure of 1 unit.
- In 2007, 70 units have been operated for 3 months without troubles.
- This means a total of ~1000 MRF151G have been installed and tested.
- More than 600 MRF151G where operated.
- No failure occurred until now.
- Additional production of 40 more 1kW units planned.

Thanks to Dr. Chihiro Ohmori for the information and pictures!

J-PARC


Main Ring - 4 kW assemblies

1 kW unit #94


Rapid Cycling Synchrotron
8 kW assemblies