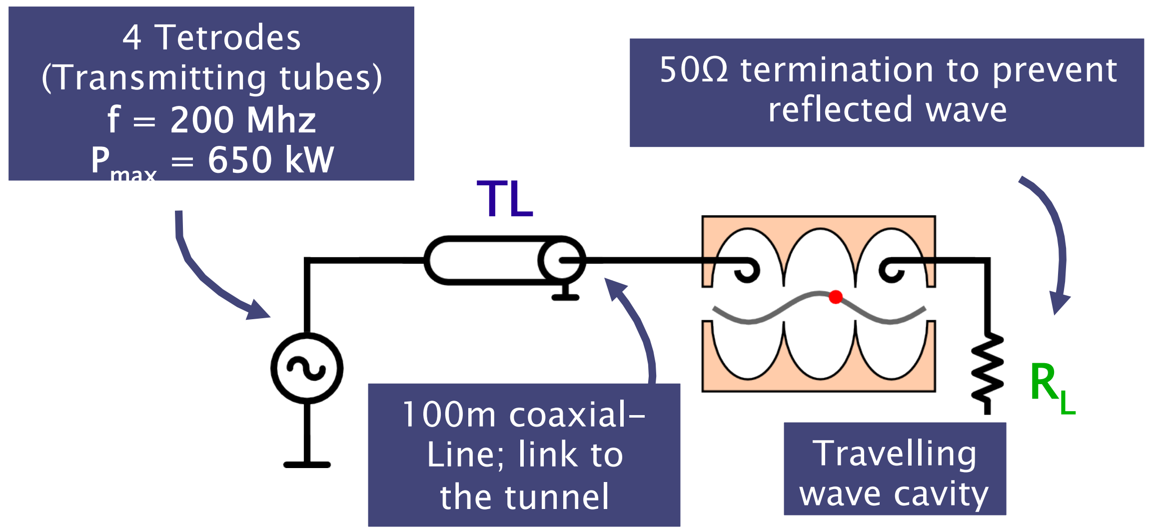
Radiofrequency Energy Recovery Studies at CERN

M. Betz, **F. Caspers**, S. Federmann
CERN

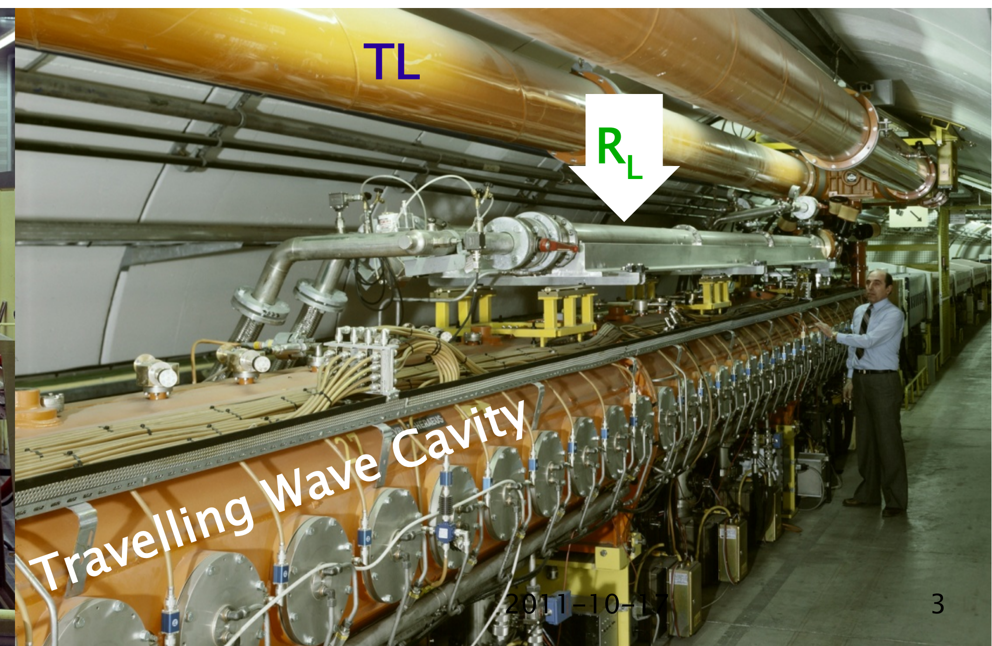
Overview

- Motivation
- **Part 1:** RF energy recovery using rectifiers
  - Example for the 200 MHz RF-system of the Super Proton Synchrotron (SPS)
  - Prototype
  - Results of (short pulse) measurements
- **Part 2:** RF energy recovery using high temperature loads
  - Waveguide absorber
  - Coaxial absorber
  - Simulation and measurement results
- Conclusion and Outlook

Introduction



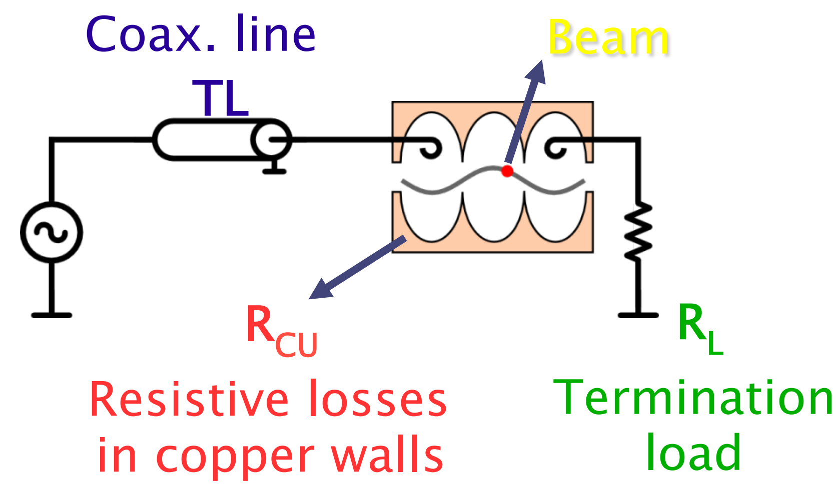
- Can we replace the 200 MHz watercooled RF powerloads (R_L) with something more useful?



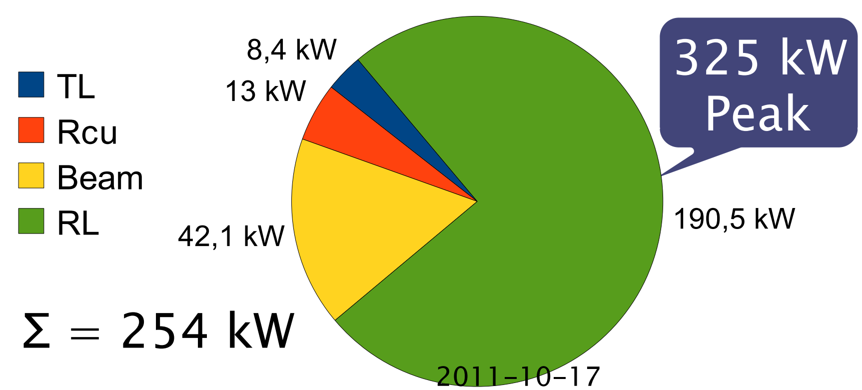
The problem

Power dissipation in termination loads

- Average power dissipation in R_L: 4 x 190.5 kW
- Water-cooled termination loads in the tunnel
- Heat is not utilized and dissipated to the environment by heat exchangers (cooling towers) on the surface
- Annual:
  - **6.7 million kWh**
  - **~ 450 000 €**



Distribution of the average (24 h) Power dissipation per Cavity (there are 4):



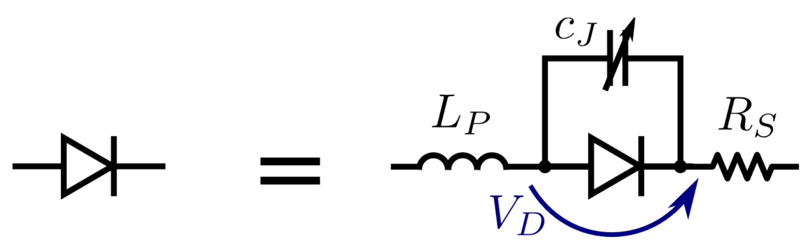
$\Sigma = 254$ kW

We assume: 0.067 € / kWh.
Which is the average energy cost for CERN in Nov. 2009
Source: *http://www.energy.eu/#industrial*

The solution: a rectifier

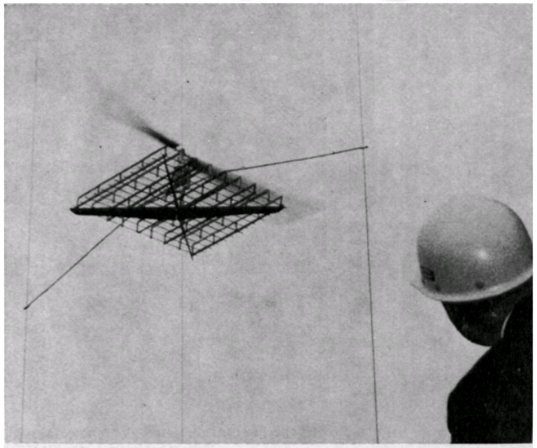
- In principle we just need a reliable RF – power diode which can handle 300 kW CW at 200 MHz
- However, this does not exist!

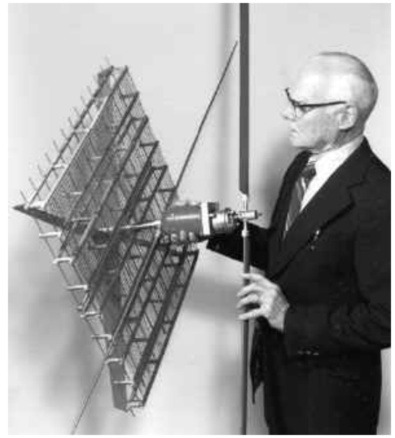
Diode rated for continuous operation at 4 kV, 4 kA, 10 cm diameter
From ABB Application Note: Diodes for Large Rectifiers

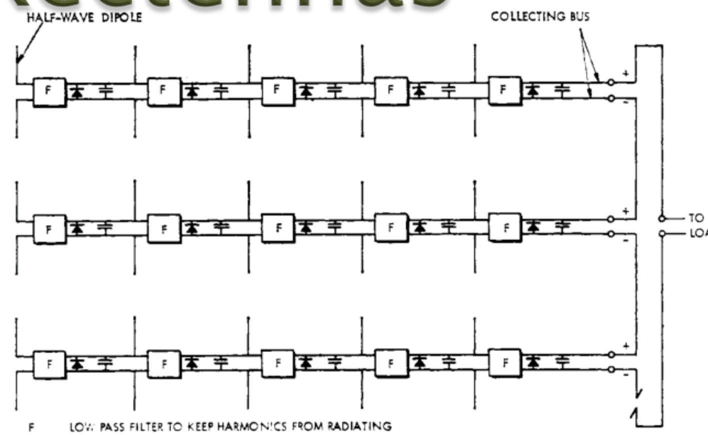


Reverse recovery time in the ms range!
Huge junction capacity

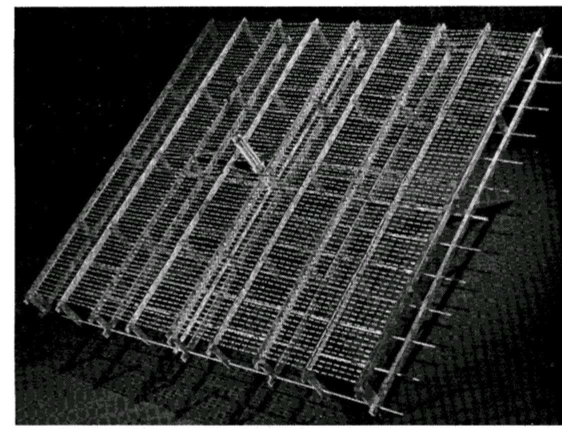
Rectifying antennas = Rectennas







William C. Brown and the first microwave powered helicopter (Massachusetts, 10/1964)



The special “string” rectenna. The array area of four square feet contained **4480 point-contact diodes.** Maximum DC power was **270 W.**

The microwave power transmission demonstration in 1975 at JPL Goldstone Facility. Distance between transmitting and receiving antenna was **1 mile.** Over **30kW** of DC power was obtained from the rectenna with a ratio of DC output to incident microwave power of **0.84.** Part of DC output was used to energize a bank of lights.

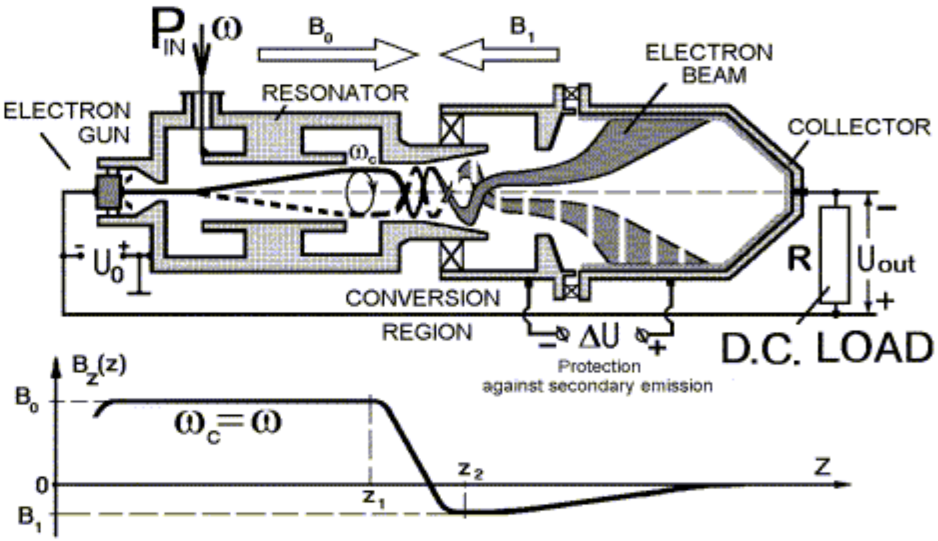
The History of Power Transmission by Radio Waves, WILLIAM C. BROWN,
IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. MTT-32, NO. 9, SEPTEMRER 1984

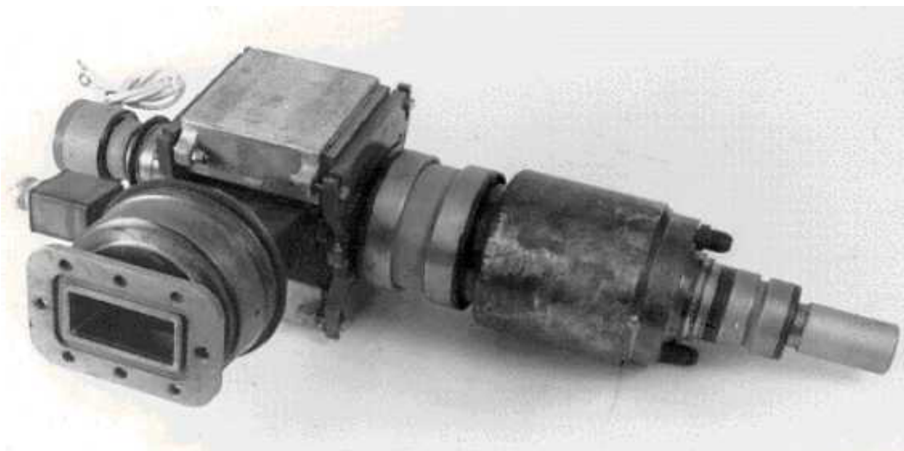
Cyclotron wave converter

- The Cyclotron Wave Converter (CWC) is a new kind of RF to DC converter, patented by V.A. Vanke in 2003
- Its basic idea is to use RF to accelerate a high current electron beam, then capture the electrons which will generate a DC voltage that can be used technically.

- High power handling capability → only a few devices needed for the SPS

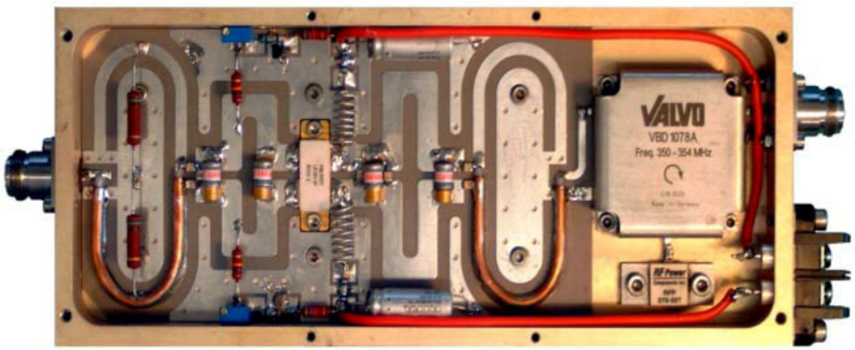
- **A 200 MHz device might be too large (resonant cavity needed)**
- **DC output voltage in the 100 kV range**



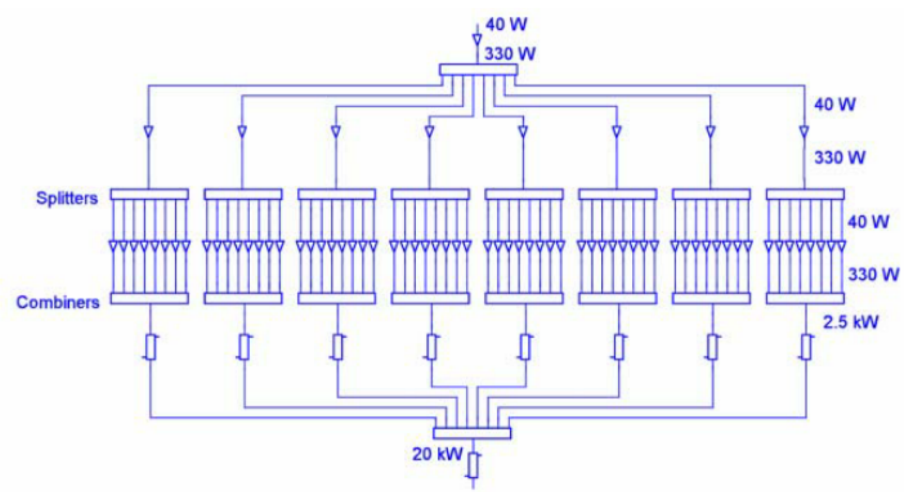


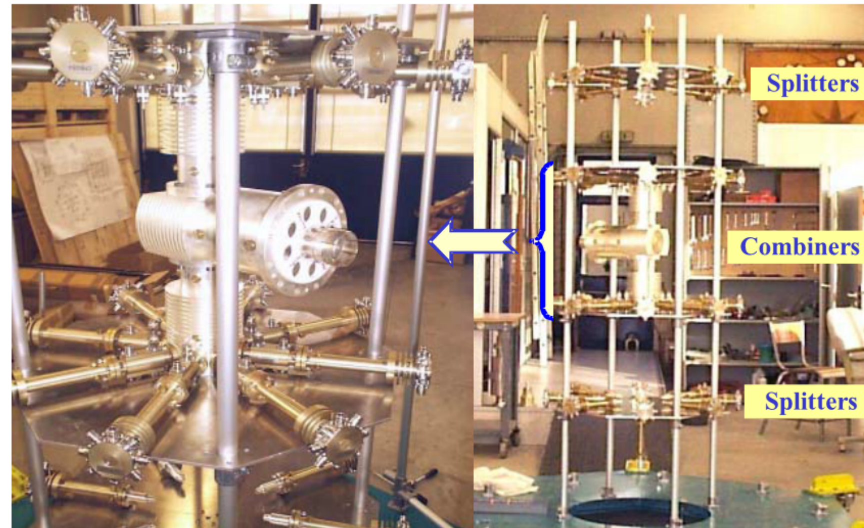
http://jre.cplire.ru/iso/sep99/1/text.html

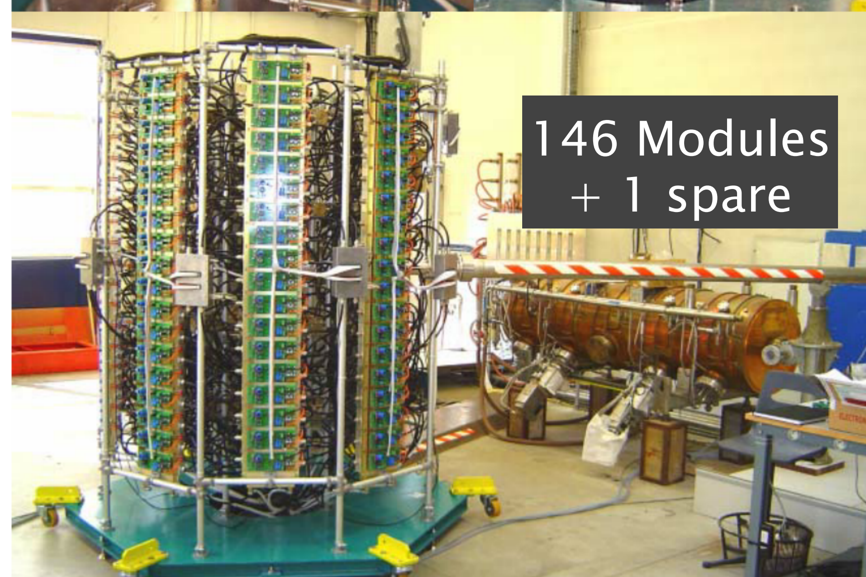
Solid state amplifier at the Synchrotron Soleil:
a big amplifier array (35 kW, 325 MHz)



330 W Module



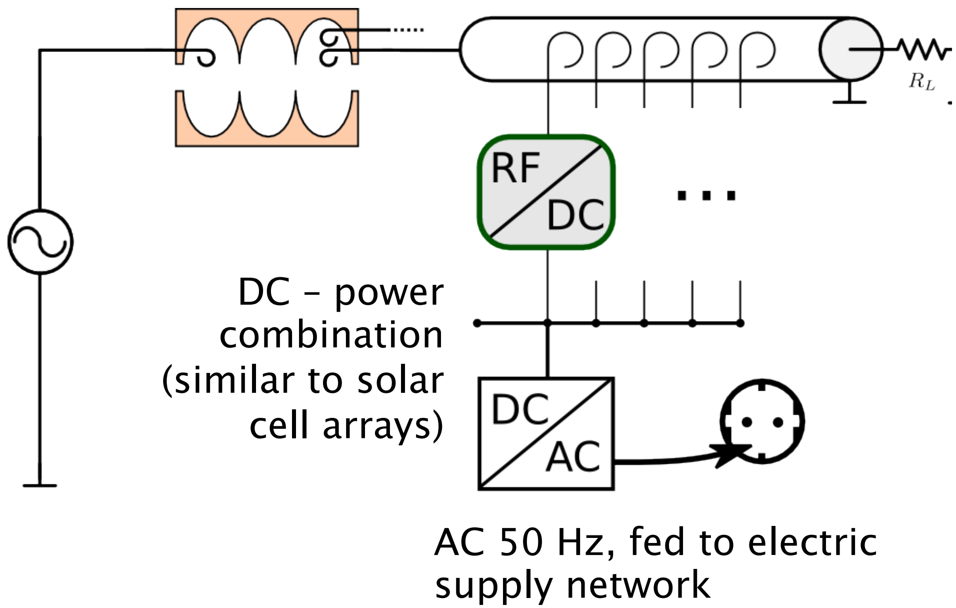




P. MARCHAND et. al.; HIGH POWER (35 KW AND 190 KW) 352 MHZ SOLID STATE AMPLIFIERS FOR SYNCHROTRON SOLEIL; EPAC 2004

Energy Recovery concept

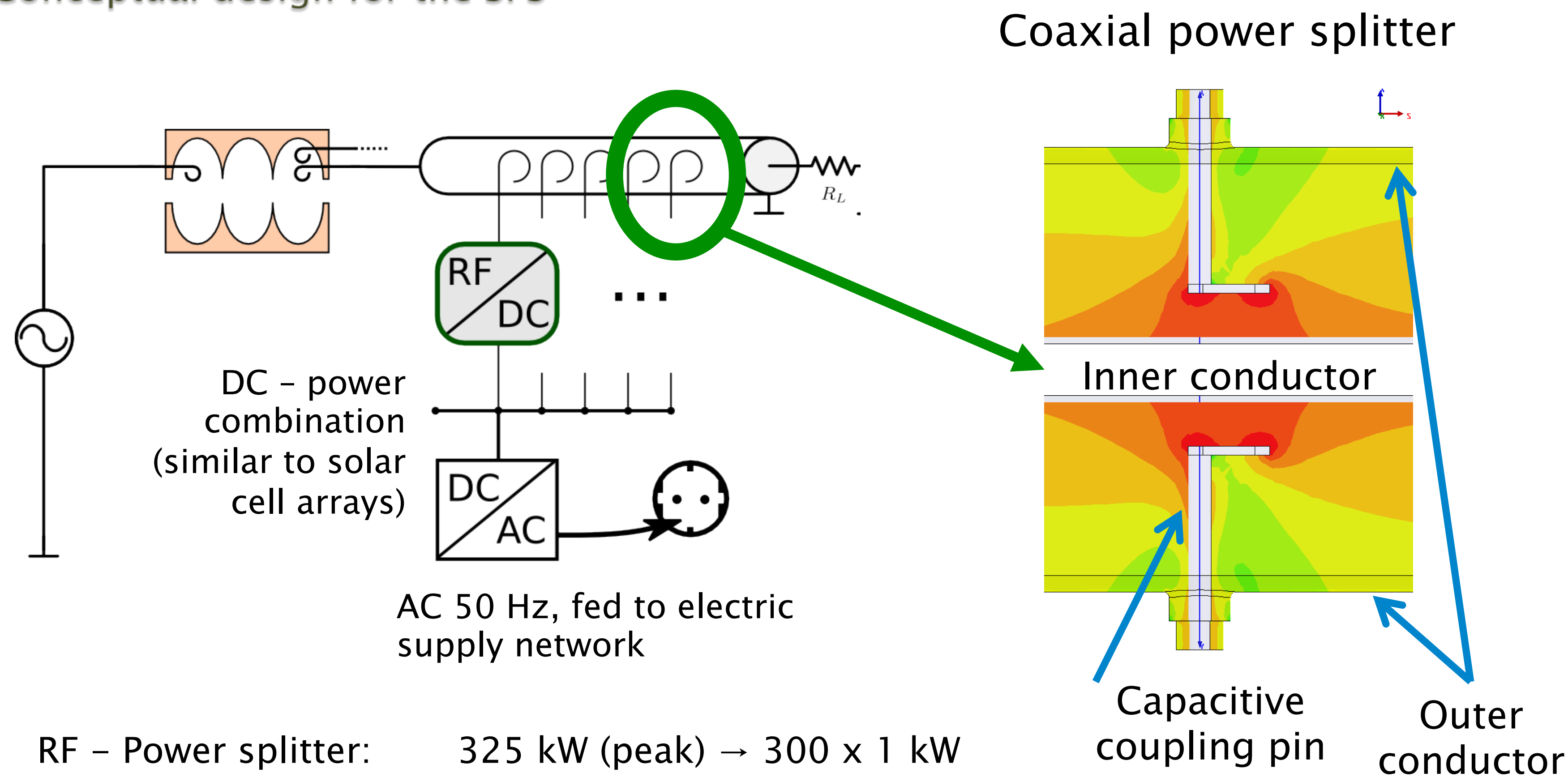
Conceptual design for the SPS



- RF – Power splitter: 325 kW (peak) → 300 x 1 kW
- 300 x RF/DC Modules
- DC – Link: DC power of individual module outputs is combined
- DC to AC (50 Hz): e.g., with commercial photopholtaik power converters

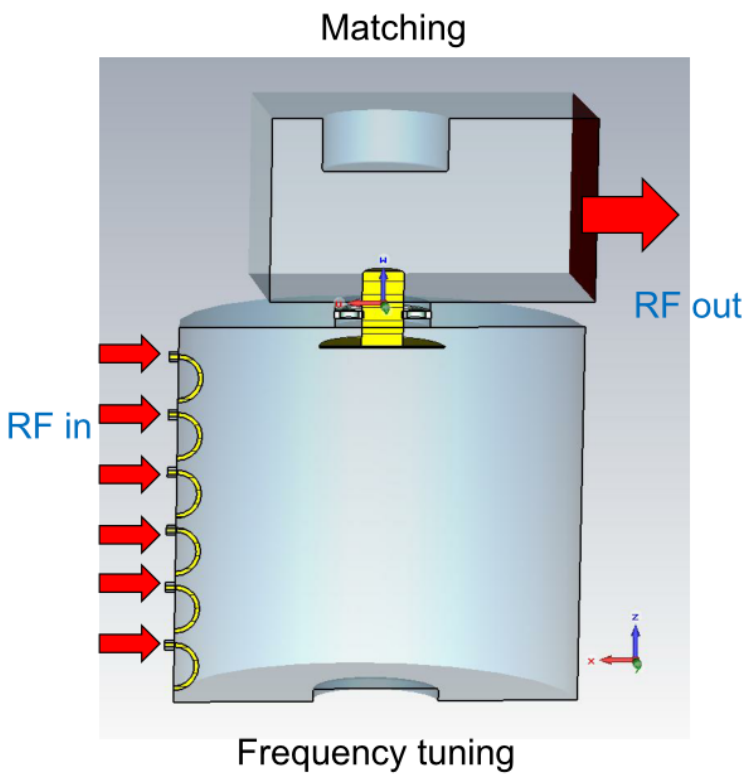
Energy Recovery concept

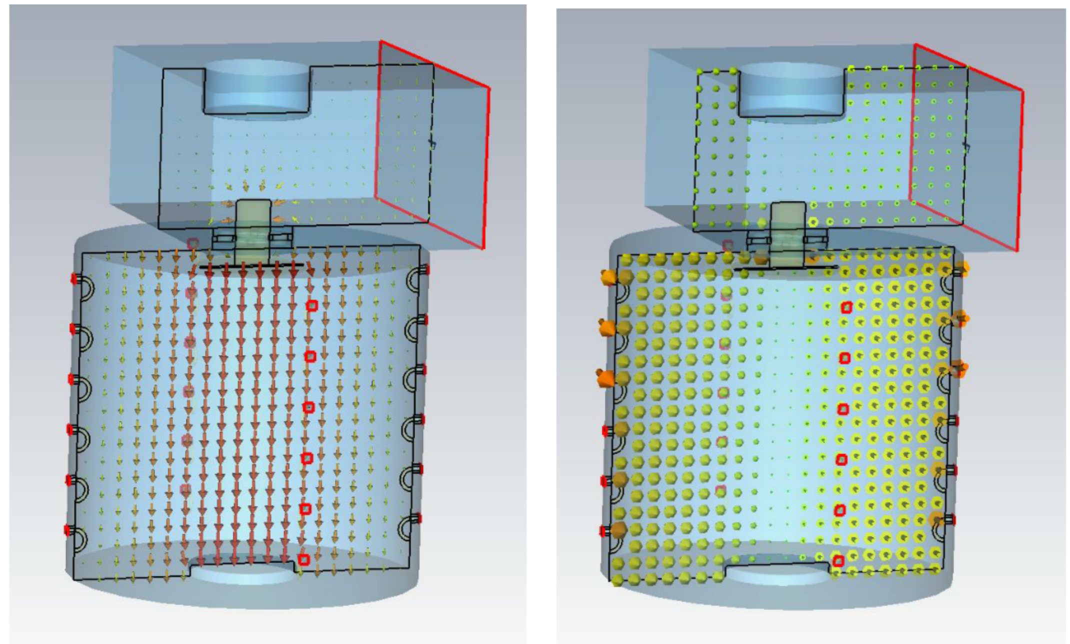
Conceptual design for the SPS



- RF – Power splitter: 325 kW (peak) → 300 x 1 kW
- 300 x RF/DC Modules
- DC – Link: DC power of individual module outputs is combined
- DC to AC (50 Hz): e.g.,like with commercial photo-voltaic power converters

Related structure:
Cavity type power splitter / combiner





E010 mode E-field H-field

Cavity combiners for transistor amplifiers
M.Langlois, J.Jacob, J.M. Mercier;
2010 Sixth CW and High Average Power RF Workshop

Requirements
for a single RF/DC Module

Requirement

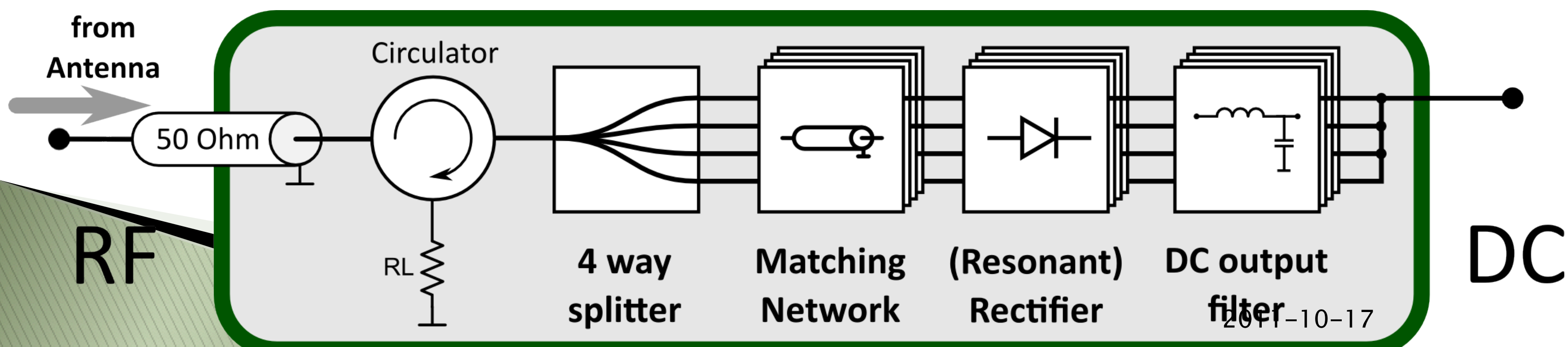
- f_{in} = **200 MHz** (+−2%), P_{in} = **1 kW**
- Good 50Ω input match (S_{11} <= −20 dB)
- **Failsafe operation:** Failure of a few individual components shall not lead to a significant disturbance of the SPS via mismatch of the load. In the worst case the dummy loads of the circulators must take the power
- No significant harmonic signals towards the input

Possible Solution

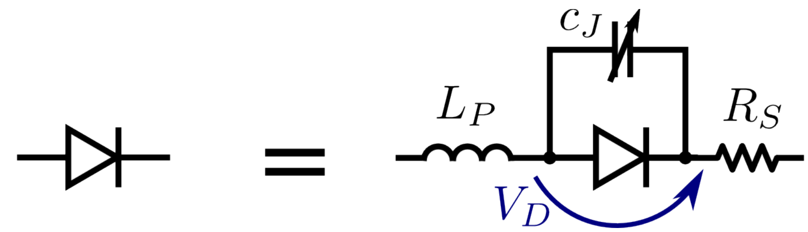
4 resonant Rectifiers, 250 W each

Narrowband matching network

Circulator redirects input power if the rectifier fails

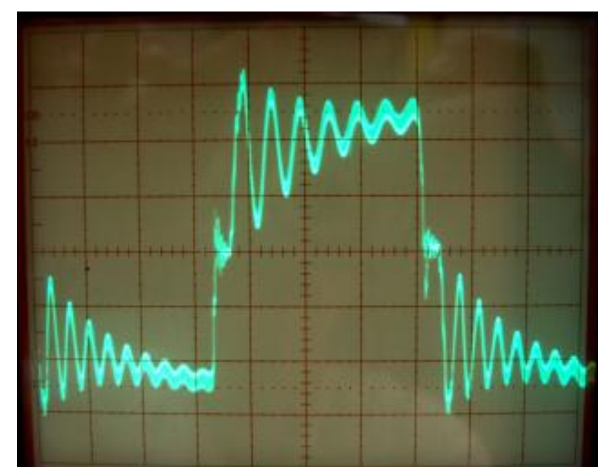


Schottky Diodes
in RF – applications



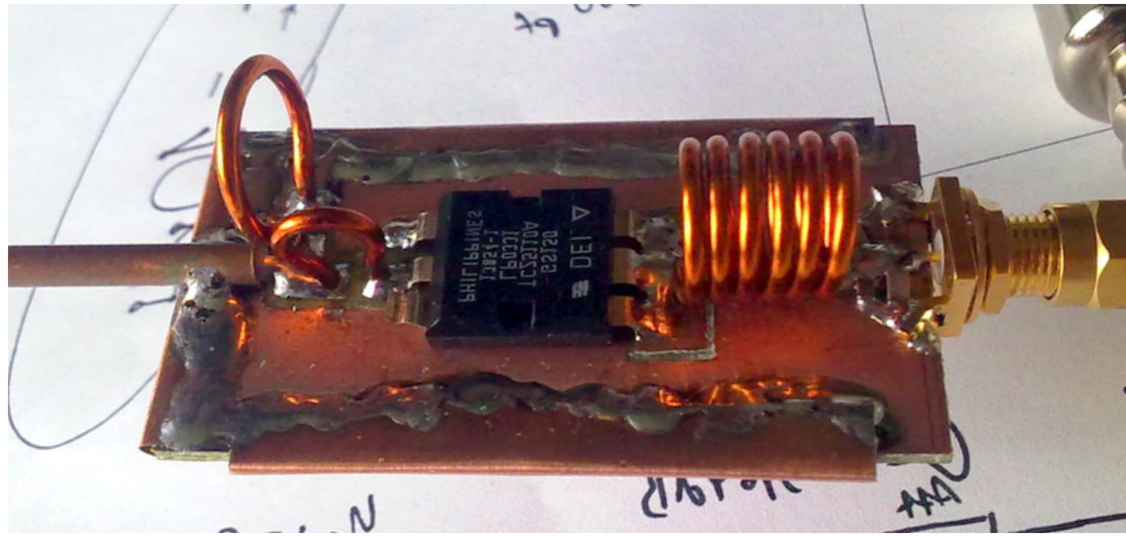
- Junction capacity c_J
  - Non-linear dependency on V_D
  - Significant reactive charging / discharging current
  - e.g., $C_J = 100$ pF
    → 8 Ω reactance at 200 MHz
    → the diode looks like a short circuit in a 50 Ω system

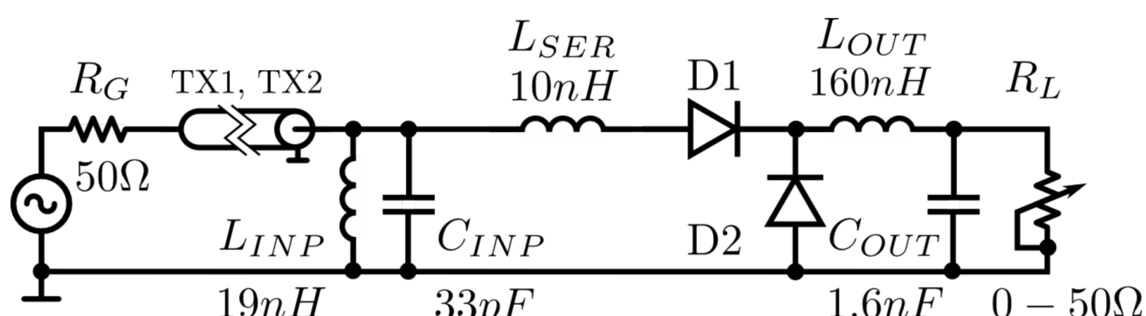
- Package inductivity L_P
  - Constant
  - Originates from package pins & circuit traces
  - Forms a resonant circuit with c_J
    → **Ringing**



For details see:
Design Concepts for RF-DC conversion in particle accelerator systems; M. Betz, F. Caspers, A. Grudiev
Proceedings of IPAC'10, Kyoto, Japan

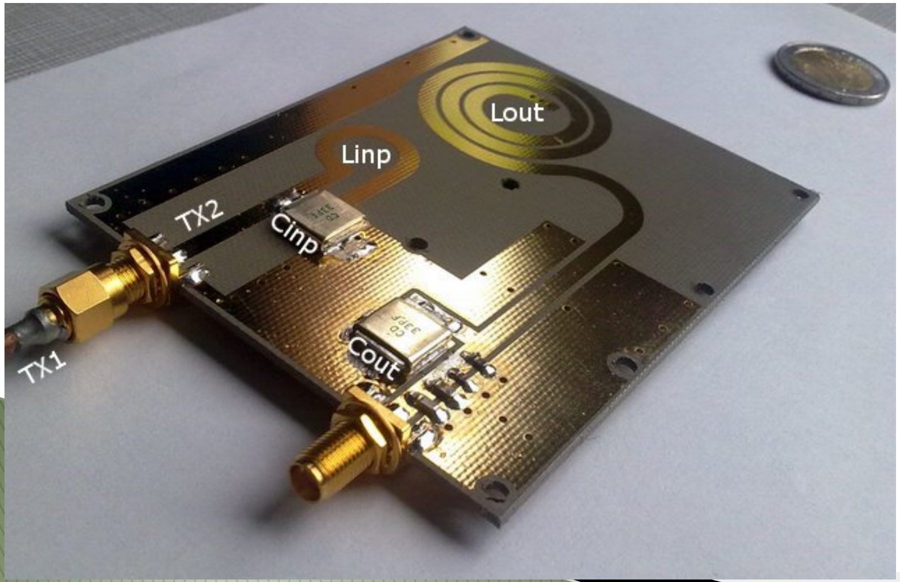
Prototyp 1 of a resonant rectifier

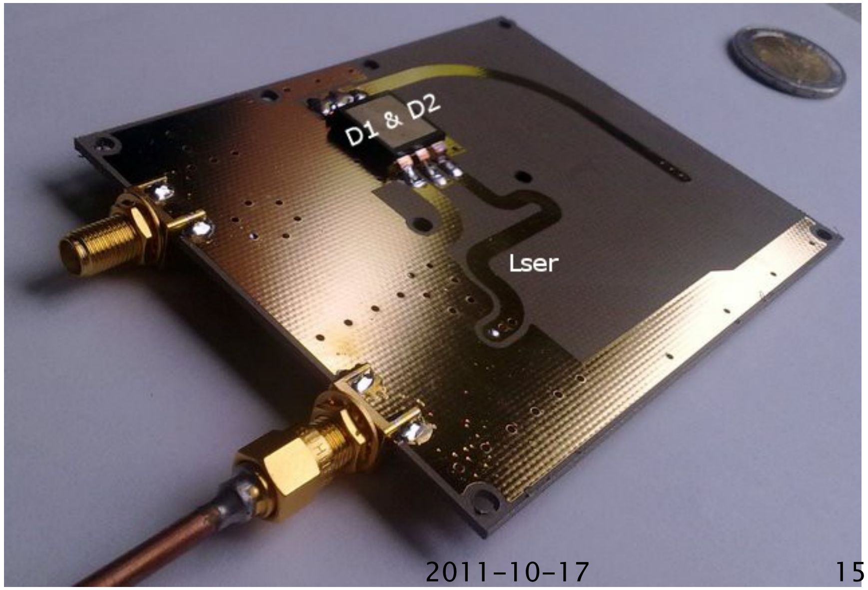




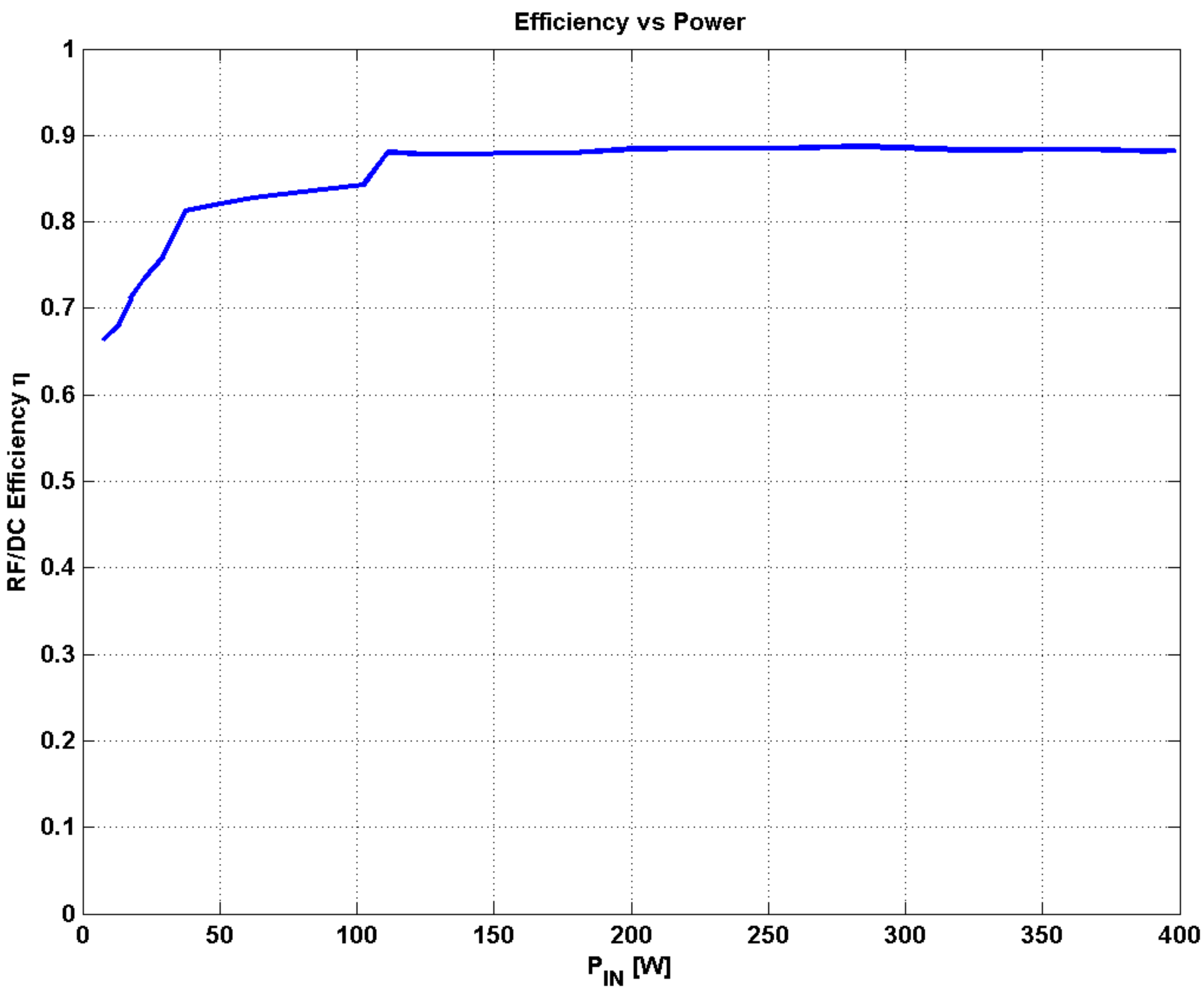
Prototyp 2
with planar inductors

- Same circuit
- Planar inductors
  - Bigger surface area (better cooling, less losses)
  - Better reproducibility
  - Easier to produce in large numbers





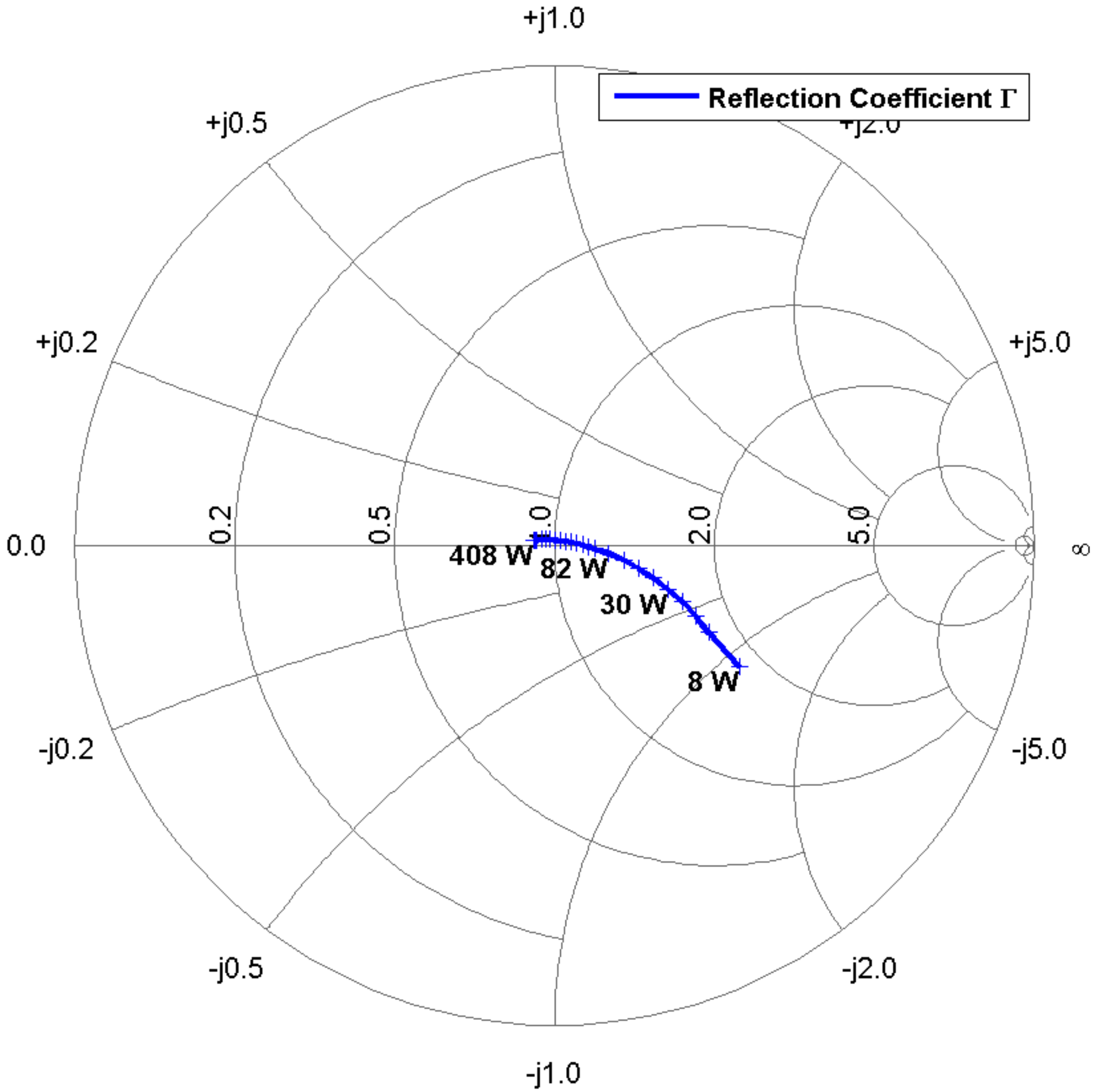
Measurement results
RF to DC efficiency



- Maximum efficiency at:
  - 284 W
  - 88.7 %
- For reduced power we still see a fair efficiency

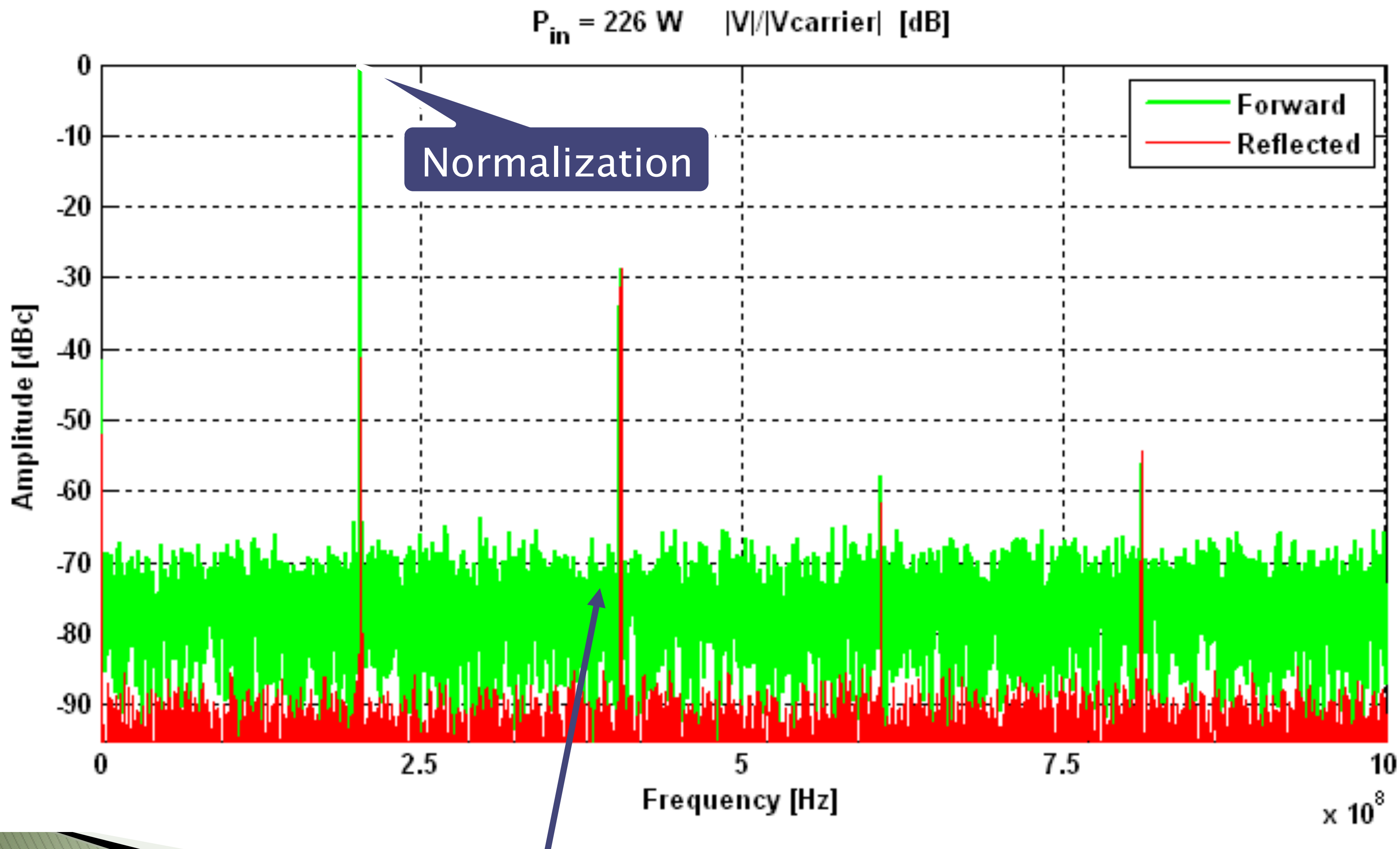
Measurement results

Reflection coefficient



- At low input powers:
  - Capacitive behaviour
  - C_J becomes significant
- Best input match at:
  - 225 W

Measurement results
Harmonic radiation



First harmonic is attenuated by 30 dB

Conclusion
Solid State Energy Recovery

- Rectifier with 2 x GS150TC25110 diodes
  - Working frequency: 200 MHz
  - Nominal power: 250 W
  - Efficiency: > 85 %
  - Harmonic radiation: – 30 dB

- 4 x rectifiers = 1 kW module
- 300 x modules = Replacement for one SPS termi-nation load

Part 2:

RF energy recovery using high temperature loads

Motivation

- Conventional RF power loads produce cooling water at **low pressure** and **moderate temperature**
  - This kind of energy is **barely usable**

- We propose RF loads producing cooling water above **150 °C** at up to **100 bar** pressure which is **technically usable**
  (Domestic heating, steam turbines, Stirling engines, etc.)

- 2 concepts will be discussed:
  - Narrowband waveguide absorbers
  - X-Band travelling wave structures

Motivation

- Two types of high power RF loads are used so far:
  - Loads heating up water directly
  - Absorbing materials on water-cooled surfaces

- Difficulties occur for both, such as:
  - Use of fragile ceramic windows when water is directly heated
  - Application of the material layers on water cooled metal surfaces which is often a complex and critical procedure
  - Absorbing materials and metal have different thermal expansions which can lead to inhomogeneous heat transfer if not properly attached

Absorbers

- We present two designs of high power RF loads without any dielectric material. One is a waveguide absorber, the other one a coaxial absorber. Both are made of stainless steel ("all metal loads").

- These models are not only rather cheap but also very stable structures. They can take high temperatures and high pressures and are even robust against temperature shocks caused by pulsed RF signals.

- They are not critical in handling (no delicate pieces) and radiation hard.

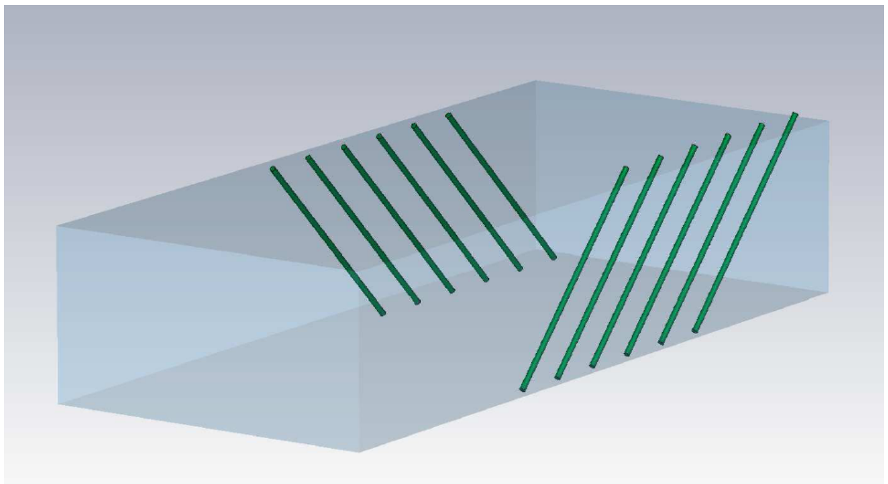
- Both use metal tubes and hence they can be water cooled (energy recovery possible – principle of a pressurized water heat exchanger).

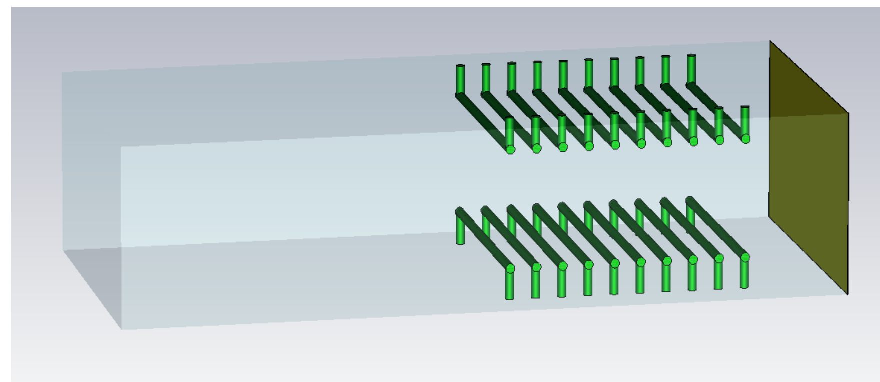
Absorbers

- The loads shown here may be connected to ultra high vacuum (UHV) via standard vacuum windows at normal temperature. No high temp. loads in UHV!!!
- The hot – cold transition between a normal waveguide or coax line and the high power load will be done via a copper plated (plating thickness: 10 µm) bellows or coaxial line with very thin wall (wall thickness = fraction of mm).
- Such a bellows ensures good RF properties. It is furthermore capable of bridging the temperature differences from the hot high power load at >200 deg C to the RF feeder line at ambient temperature.

Waveguide absorber

- Two different structures were investigated:

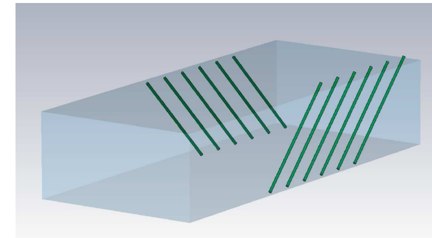


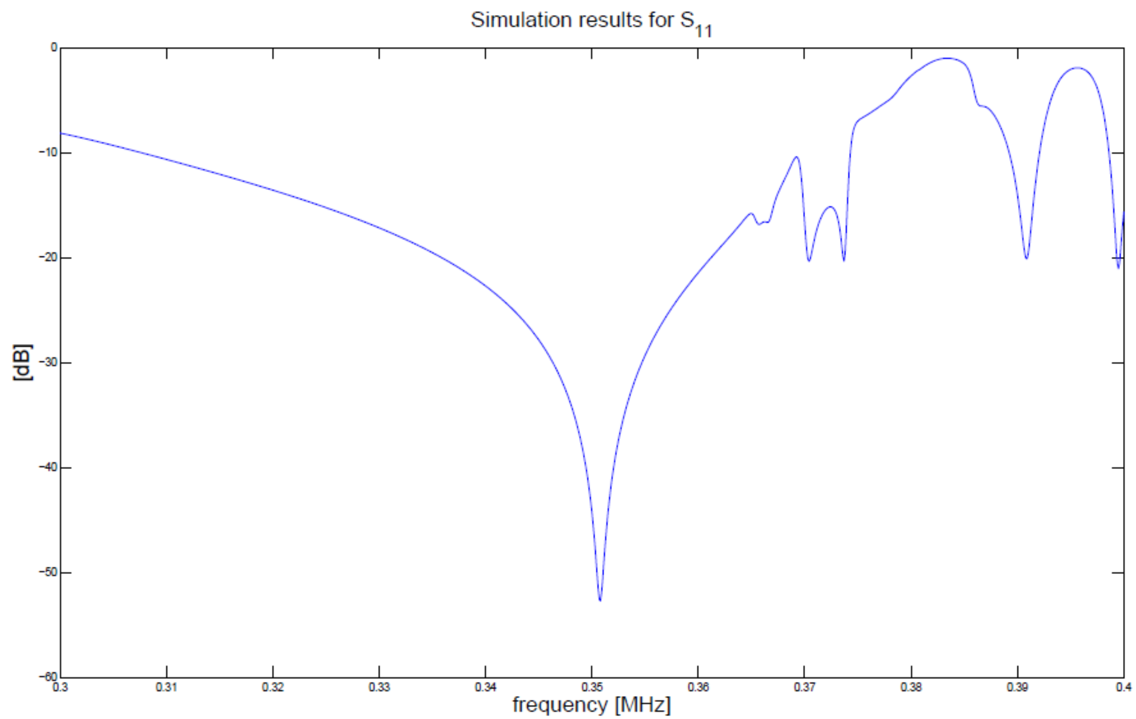


- For absorber I (left) a test model was built and measured
- Absorber II (right) only simulations are available

Waveguide absorber – Simulation results

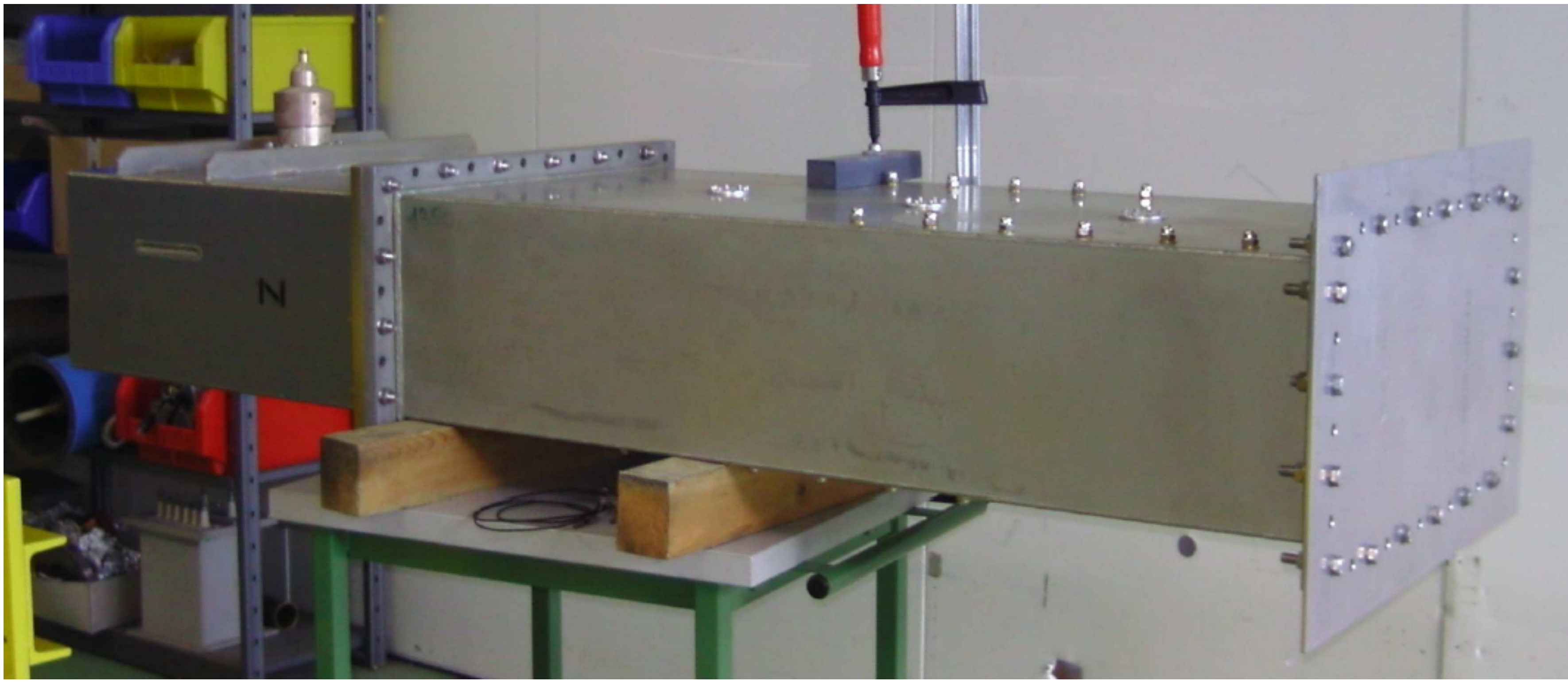
- Absorber I:





Waveguide absorber – Prototype

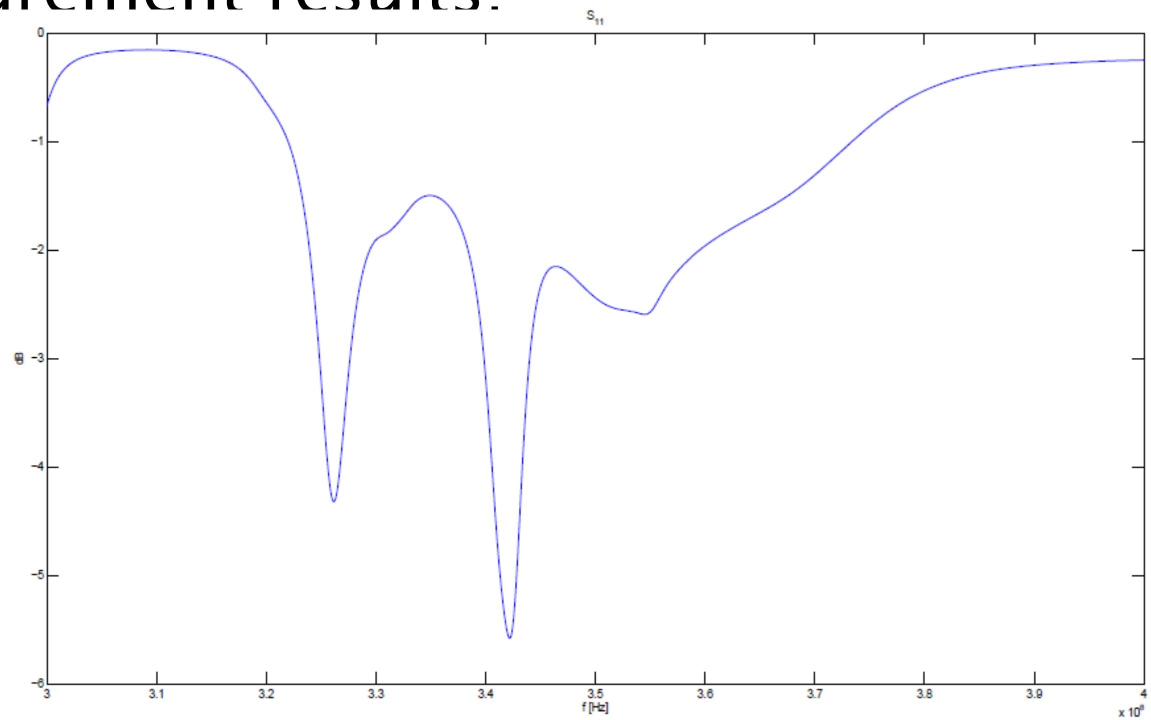
- Measured model (absorber I):



- Threaded rods of size M10 were used.

Waveguide absorber – type I

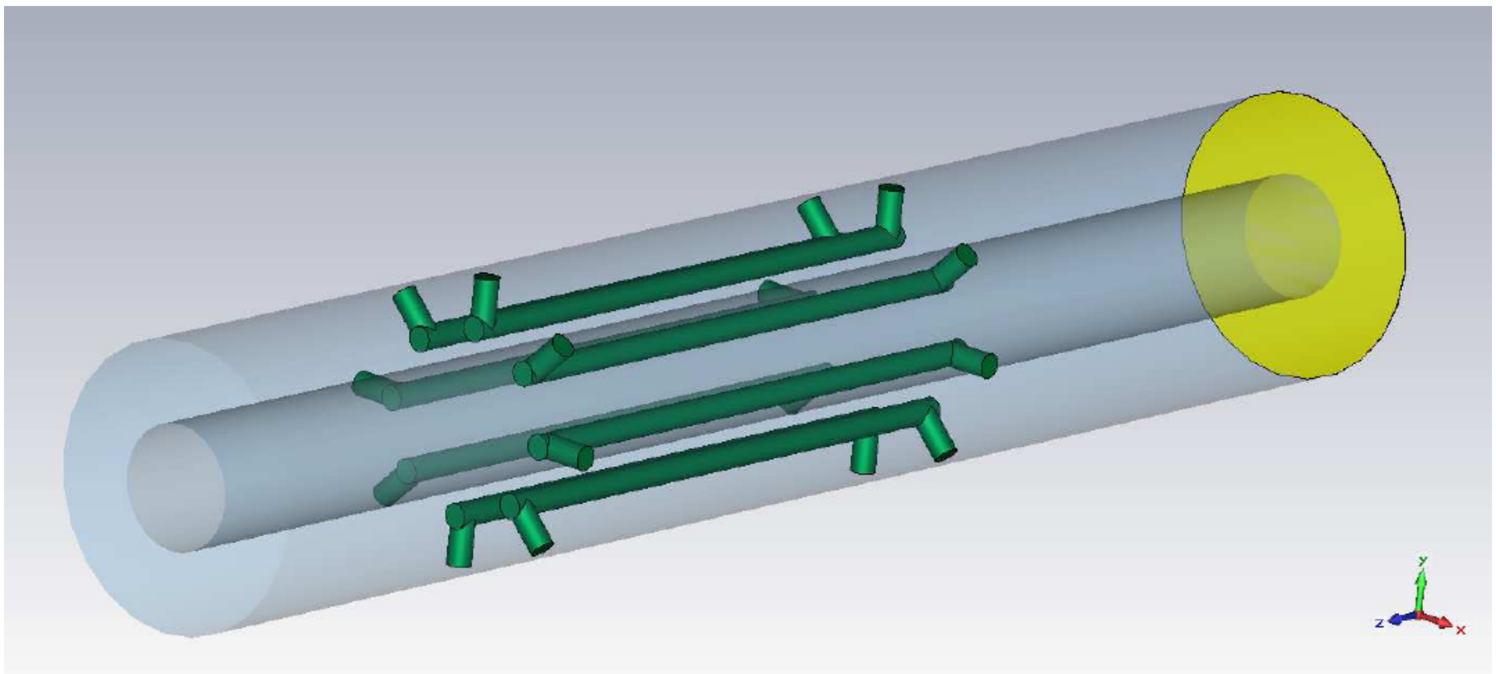
- Measurement results:



- The problem: Q value of used structure was too low -> usage of threaded rods not feasible

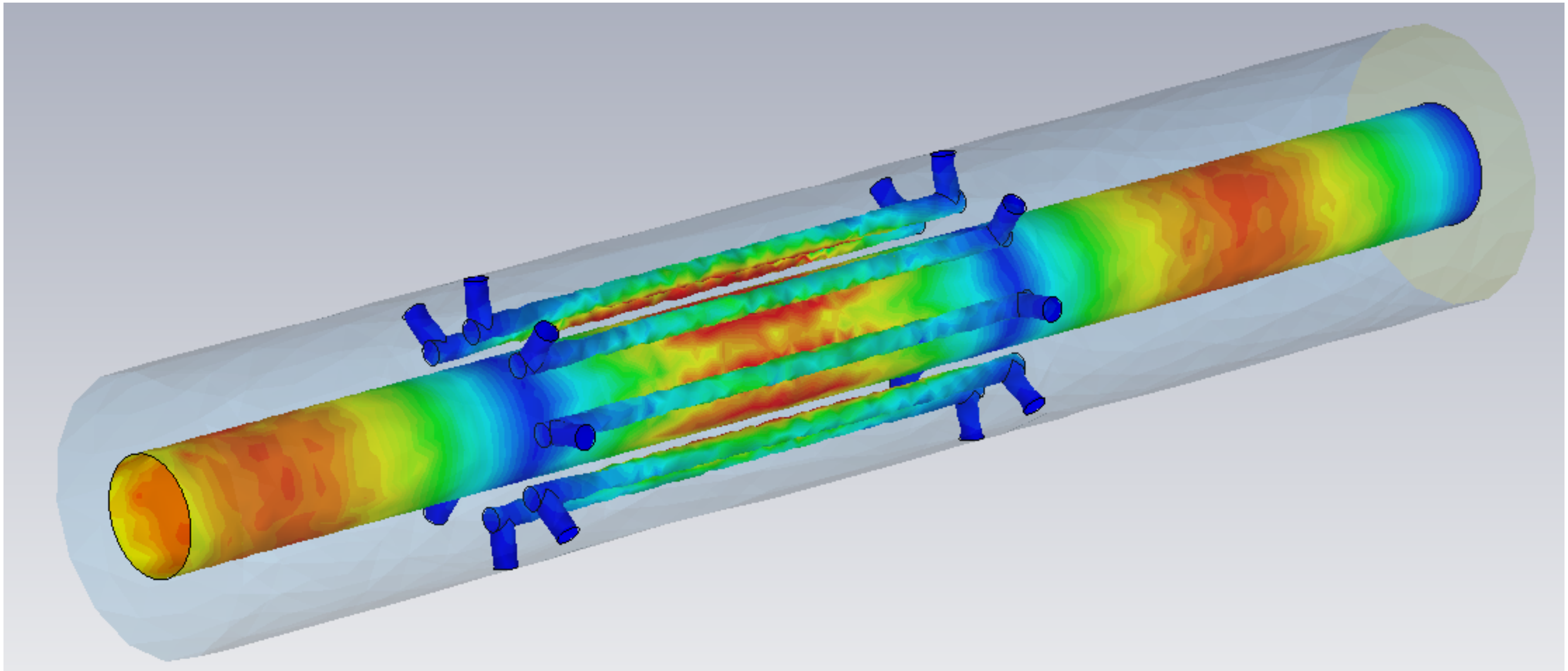
Coaxial absorber

- 2m of coaxial line (Dimension: SPS feeder lines; inner diameter of outer conductor: 345mm, outer diameter of inner conductor 150mm)
- 8 Metal rods symmetrically grouped around inner conductor
- Line shortened at lambda-half (measured from end of rod)



Coaxial absorber

- Coupling is achieved via electric field (surface current causes resistive losses):



Coaxial absorber – Simulation results

- 2 different distances of rods from outer conductor were investigated: 50 and 60mm
- Results for both cases in summary:

	diameter of rods [mm]			
μ	**15**	**20**	**30**	**35**
1	-11.7	-14.2	-12.9	-5.8
5	-19.2	-14.7	-5.2	-2.5
10	-12.2	-10.1	-3.8	-1.9
25	-7.6	-6.4	-2.6	-1.3
50	-5.6	-4.8	-1.9	-1

50 mm distance

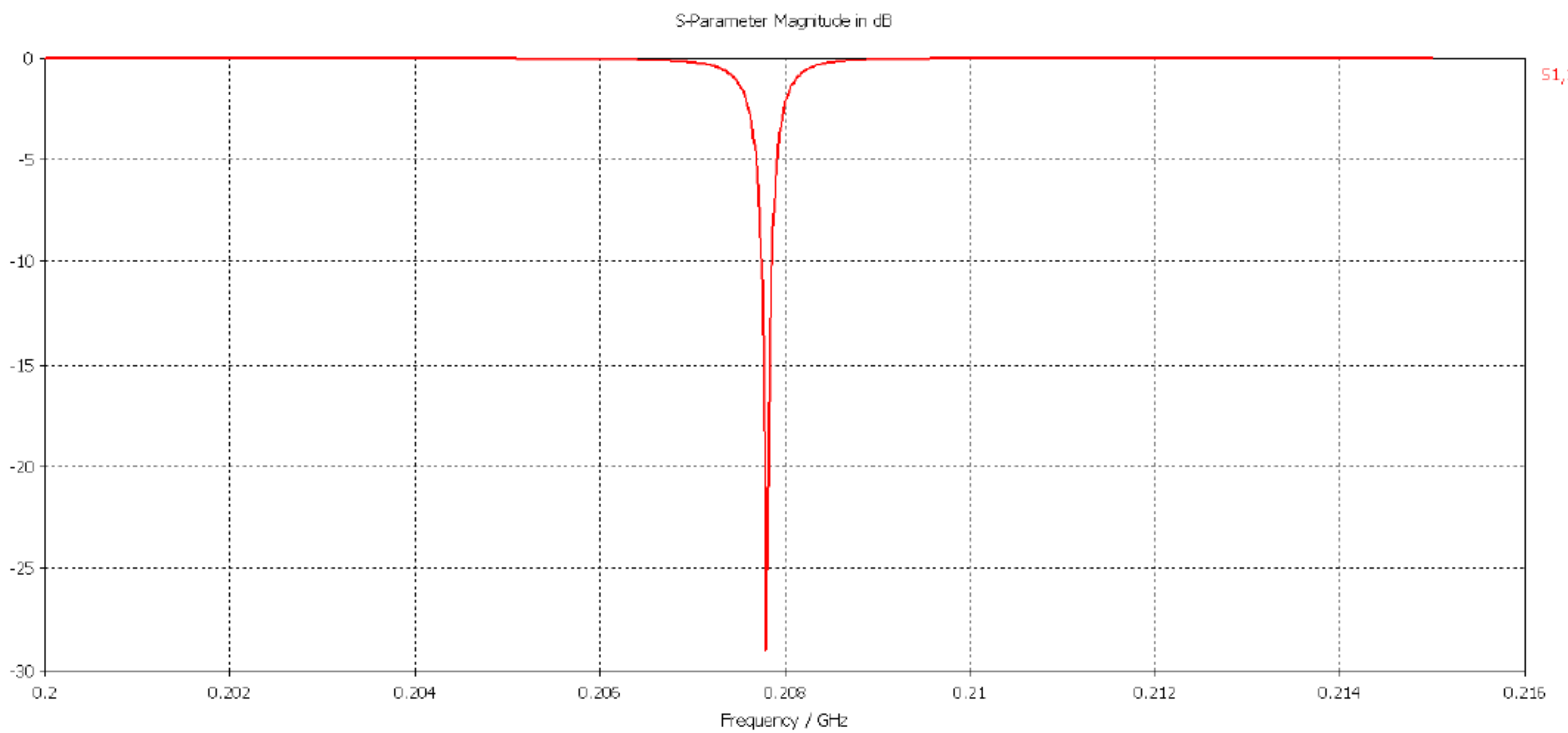
	diameter of rods [mm]			
μ	**15**	**20**	**30**	**35**
1	-6.5	-8.4	-29	-10.9
5	-17.3	-30.9	-8.7	-4.5
10	-47.3	-18.9	-6.1	-3.3
25	-14.1	-10.3	-4	-2.3
50	-9.7	-7.3	-3	-1.7

60 mm distance

- We chose 30mm rods with mu=1 for reasons of mechanical stability and facility of production

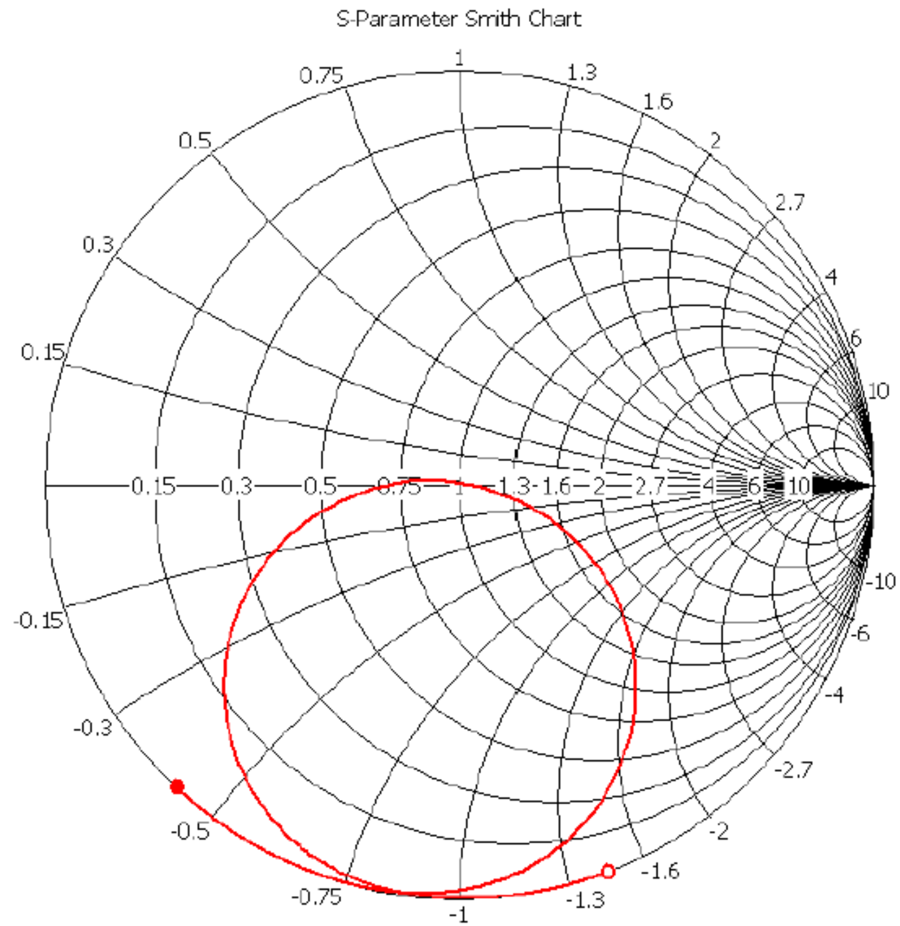
Coaxial absorber – Simulation results

- Reflection coefficient for the chosen model:



Coaxial absorber – Simulation results

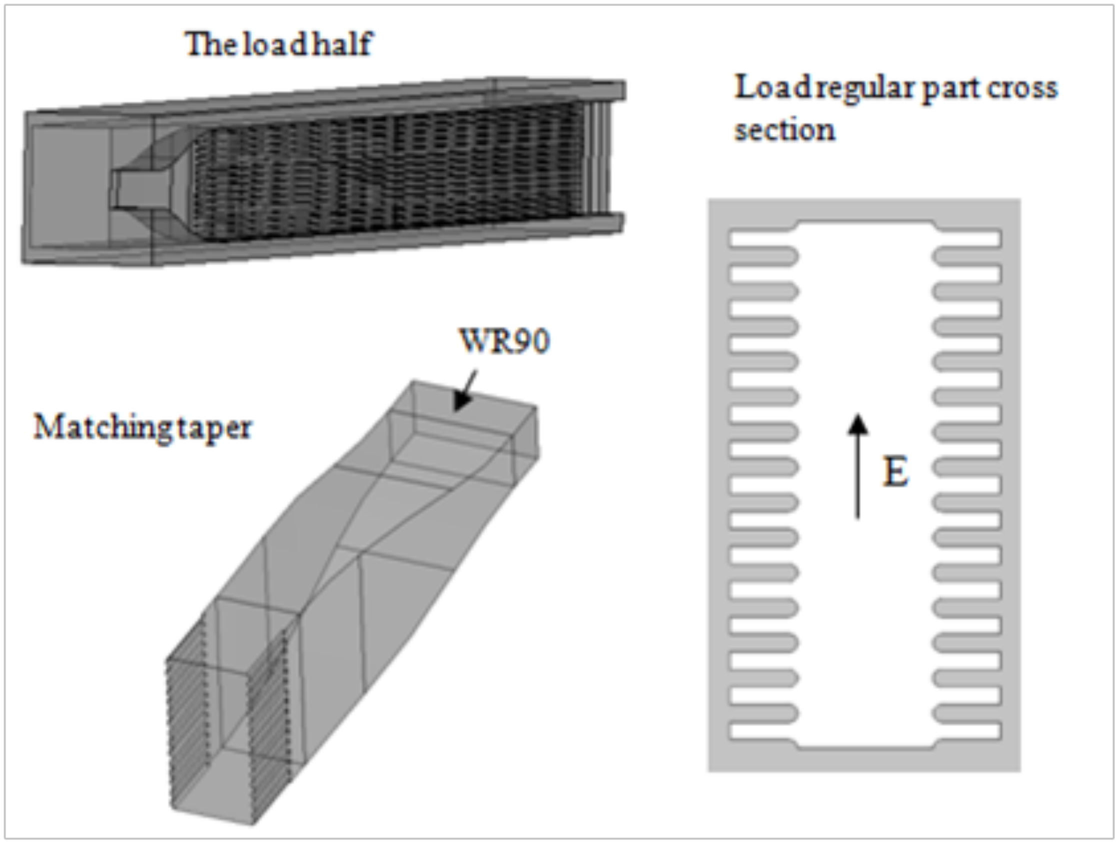
- Resonance displayed in the Smith chart. As can be seen we have nearly critical coupling.



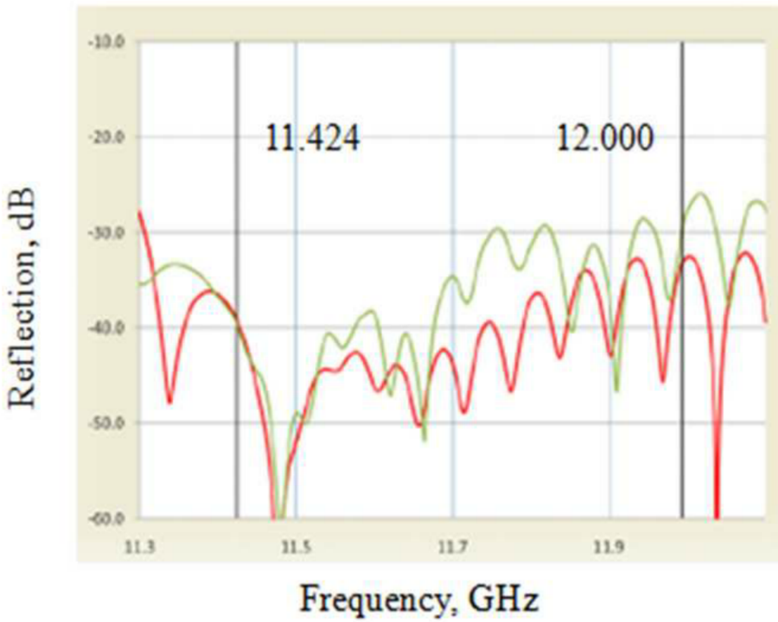
X-Band Travelling Wave Structure

- X-band RF load built from magnetic ($\mu = 6$) stainless steel (SS430)
- Concept based on the classical approach of a regular waveguide operated close to its cut-off frequency
- waveguide with special cross-section – central gap width about half the waveguide width, cut-off frequency about 20% higher than that of a standard rectangular waveguide of the same width

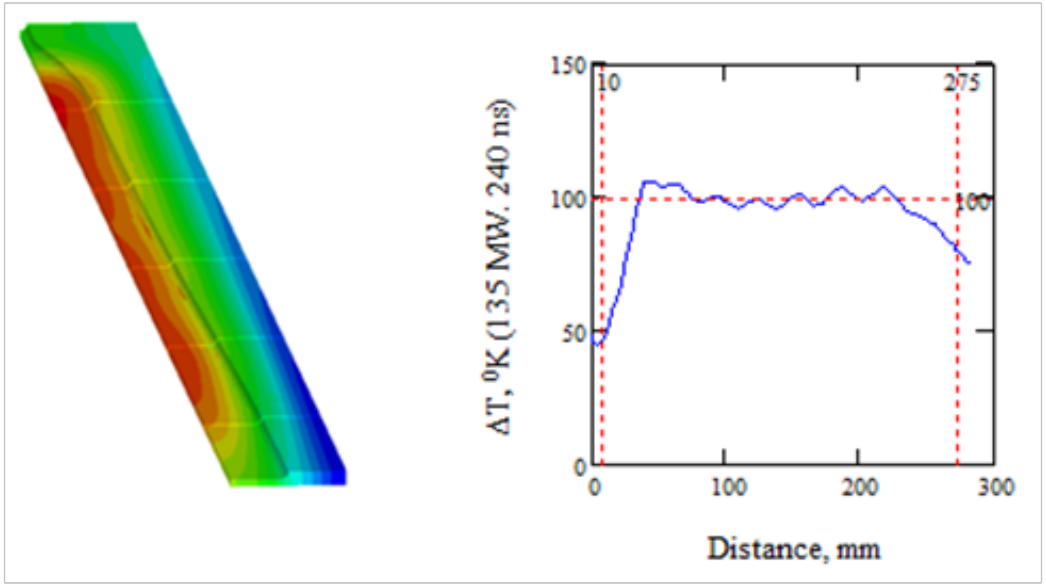
X-Band Travelling Wave Structure



X-Band Travelling Wave Structure



Measured (red) and calculated with HFSS (green) reflections in the typical load



The magnetic field distribution on the quarter geometry of the single period tapered part is shown left. The pulsed heating profile along initial load length is shown right

X-Band Travelling Wave Structure

- Benefits:
- Reduction of the electric and magnetic surface field concentration while maintaining high enough RF losses along the line, even when operating far above cut-off
- All benefits mentioned in former section
- special tapering of the wedges provide constant heat load distribution for almost 20 cm along the initial load length

- About 50 of such loads have been built and successfully tested up to 60MW peak RF power at 11.424GHz

Conclusions

- Direct conversion from RF to DC is the most efficient way of RF energy recovery. However, also the most complex one. We have done a a small step in this direction.

- High temperature loads could be closer to practical realization, their cost should be smaller. However their efficiency is fundamentally limited by Carnot's theorem.

Outlook

- **Waveguide absorber**: more systematic simulations are necessary (currently in progress)
- **Coaxial absorber**: a reasonable looking conceptual solution was found wrt mechanical properties and electrical performance
- Simulation results are promising.
- A prototype is needed for confirmation of our simulation results.

Thanks for your attention.