RF Energy Recovery Studies at CERN

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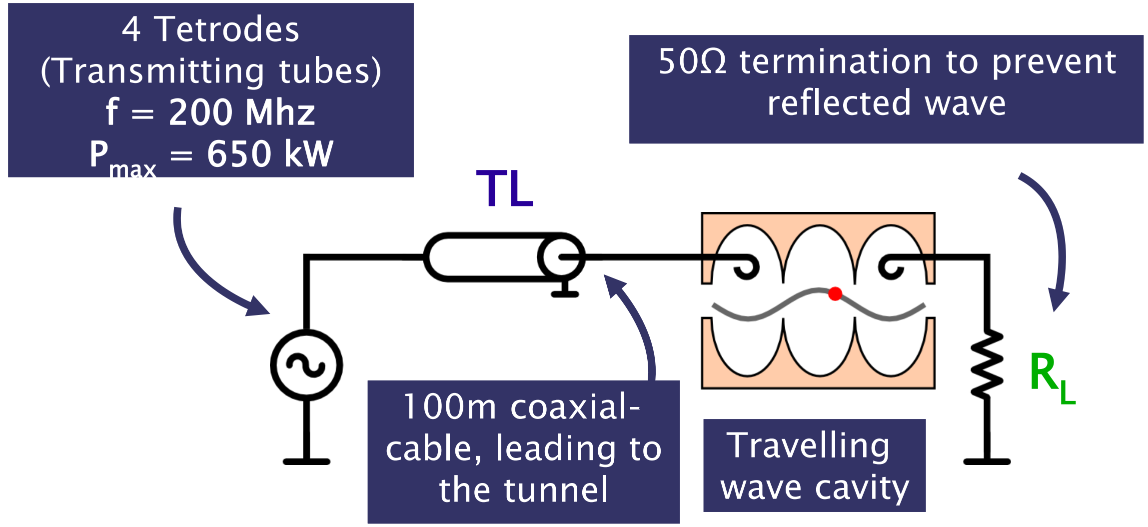
CERN, Geneva

workshop on RF systems design
Uppsala, December 12-14, 2011

Overview – RF energy recovery …

- Motivation
- **Part 1:** … using **rectifiers**
  - Example: the 200 MHz RF-system of the Super Proton Synchrotron (SPS)
  - Prototype
  - Results of pulsed measurements
- **Part 2:** … using **water loads** (150 °C)
  - Conceptual design
  - Simulation and measurement results
- **Part 3:** … using **air cooled loads** (> 600 °C)
  - Conceptual design
- **Part 4:** … using a X-Band Travelling Wave Structure
- Conclusion and Outlook

Introduction



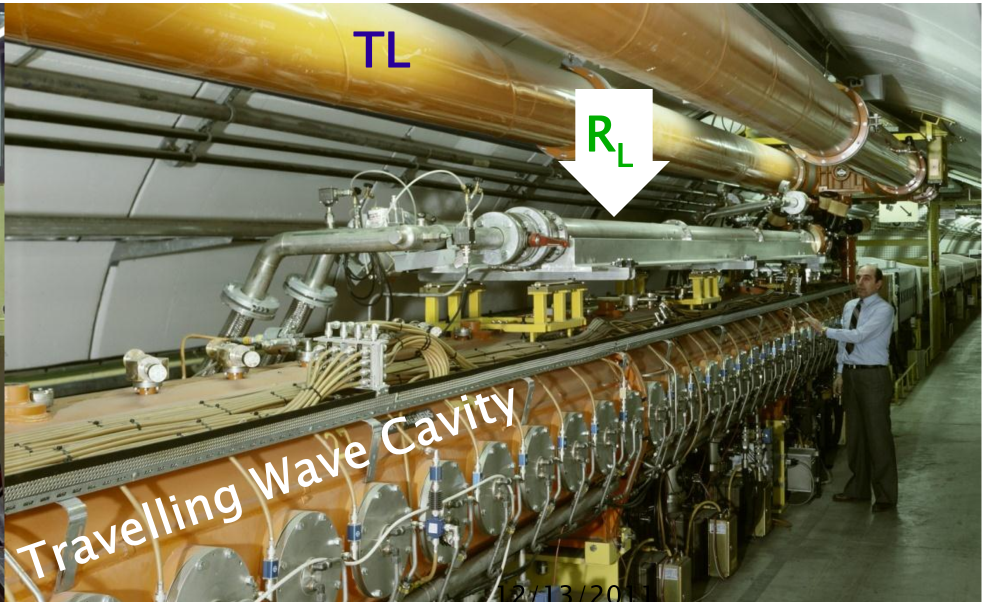
4 Tetrodes
(Transmitting tubes)
f = 200 Mhz
P_{max} = 650 kW

50Ω termination to prevent reflected wave

100m coaxial-cable, leading to the tunnel

Travelling wave cavity

- Can we replace the existing 200 MHz (low temperature) watercooled RF-power loads (R_L) with anything more efficient?



M. Betz, Feasibility Study for High Power RF – Energy Recovery in Particle Accelerators, CERN-THESIS-2010-125

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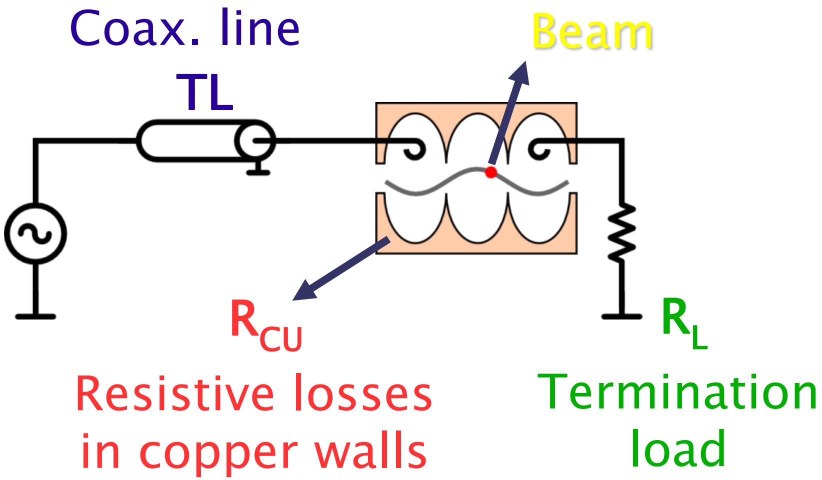
The problem

Power dissipation in termination loads

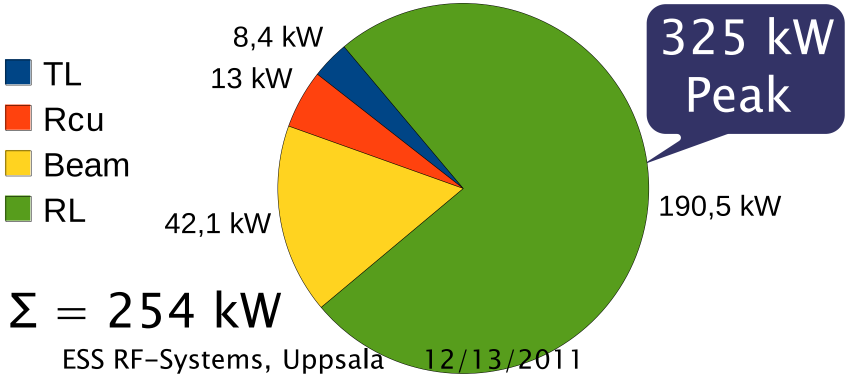
- Average power dissipation in **R_L**: **4 x 190.5 kW**
- Water-cooled termination loads in the tunnel
- This low level (30 – 40 °C) heat is not used but dissipated to the environment by cooling towers on the surface

- Annual:
  - **6.7 million kWh**
  - **~ 450 000 €**

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



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



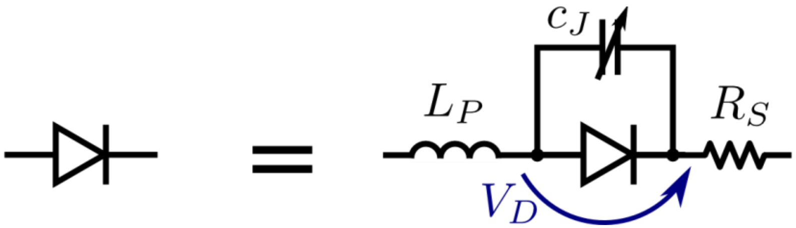
Σ = 254 kW

The solution: a rectifier

M. Betz, Feasibility Study for High Power RF – Energy Recovery in Particle Accelerators, CERN-THESIS-2010-125

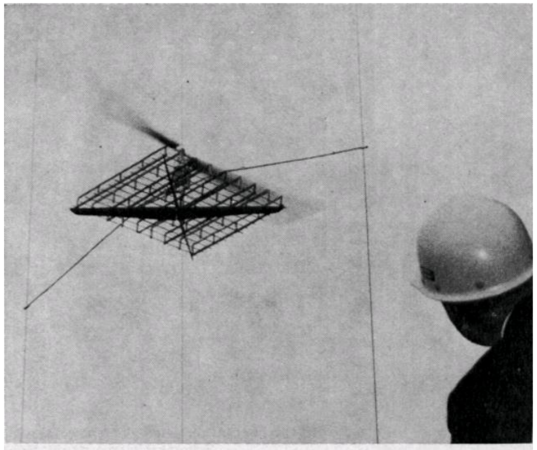
- In principle we just need a reliable RF – power diode which can handle 300 kW CW at 200 MHz
- **However, this does not exist!**

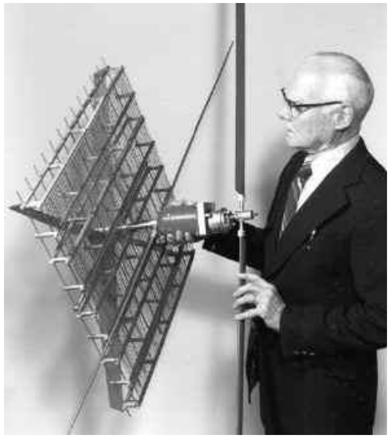
Diode rated for continous operation at 4 kV, 4 kA, 10 cm diameter
From ABB Application Note: Diodes for Large Rectifiers

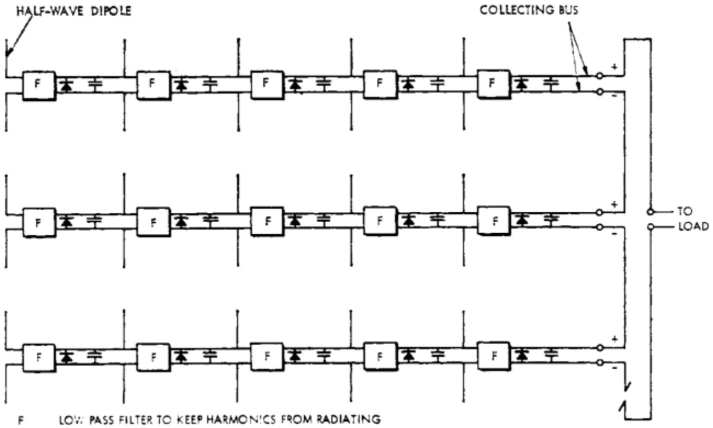


Reverse recovery time in the ms range!

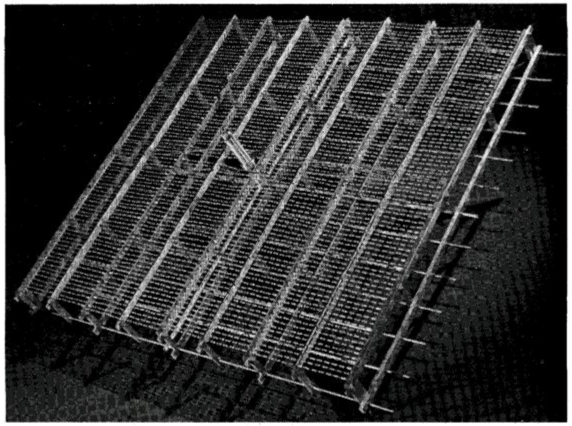
Rectifying antennas = Rectennas



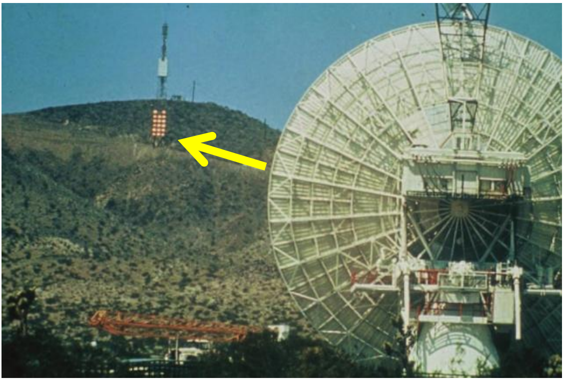




William C. Brown and the first microwave powered helicopter (Massachusetts, 10/1964)



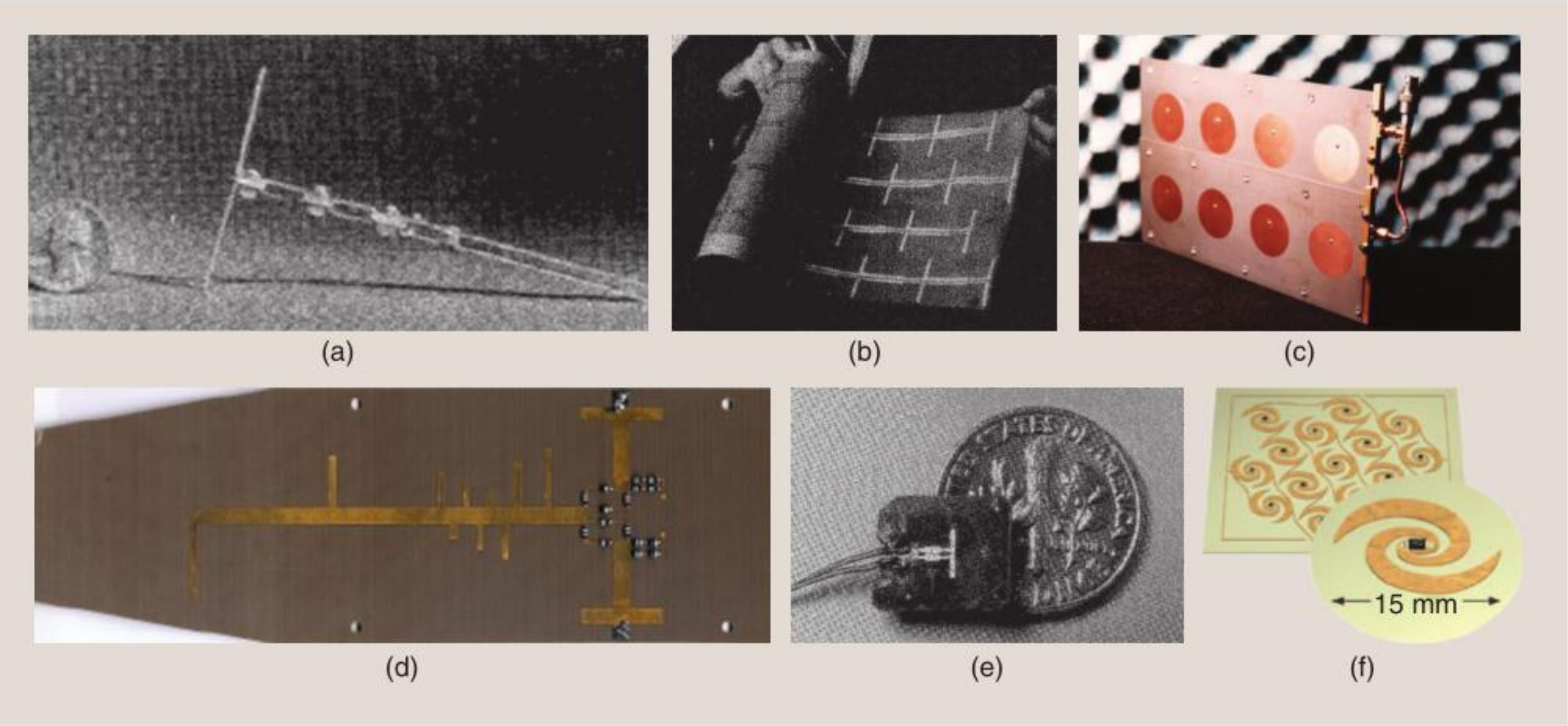
The special “string” rectenna. The array area of four square feet contained **4480 point-contact diodes.** Maximum DC power was **270 W.**



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, SEPTEM

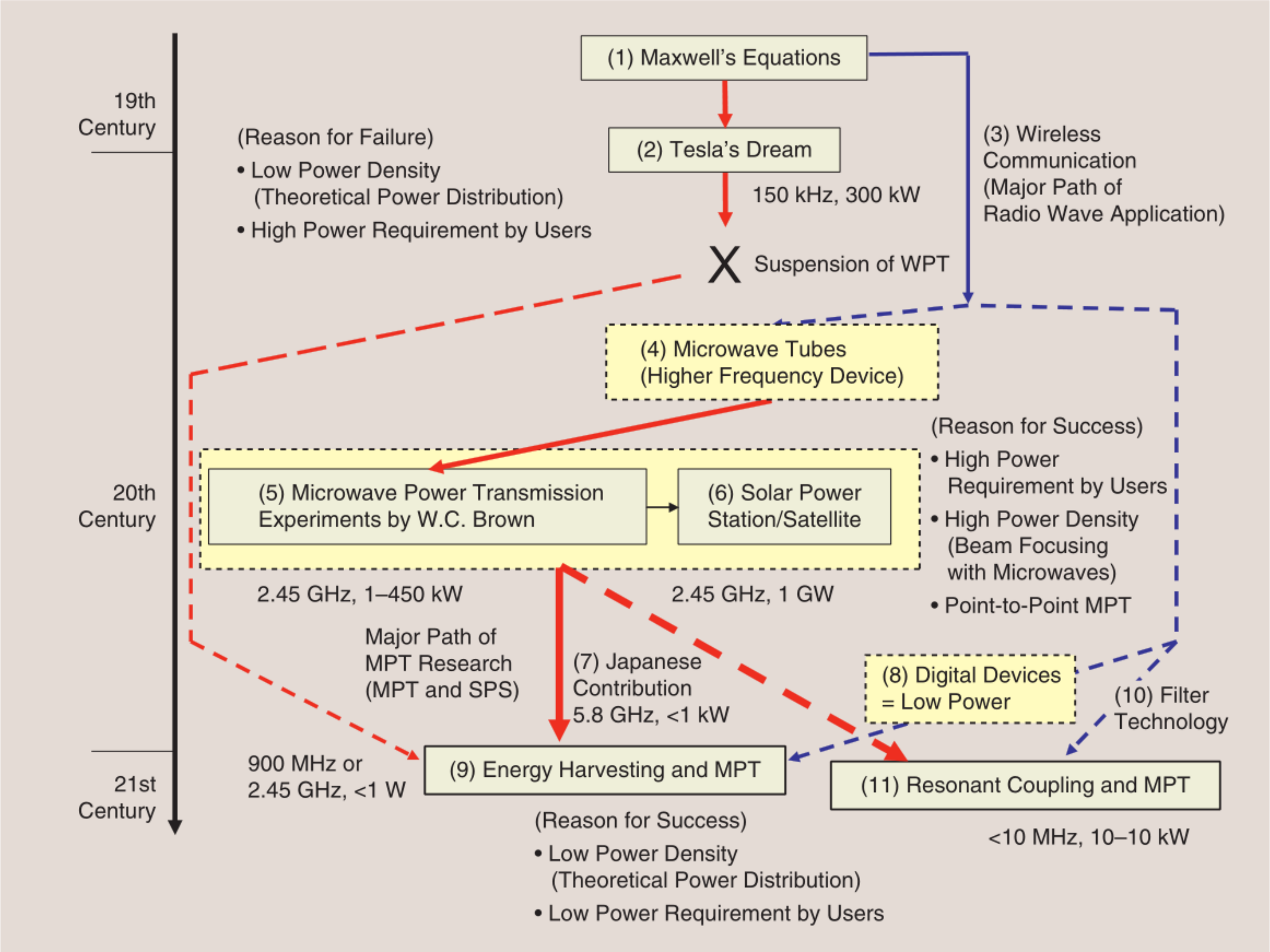
Rectifying antennas = Rectennas


(a) (b) (c)
(d) (e) (f)

Various rectennas

Power Without Wires
IEEE microwave magazine Dec 2011 Supplement

History of wireless power transmission

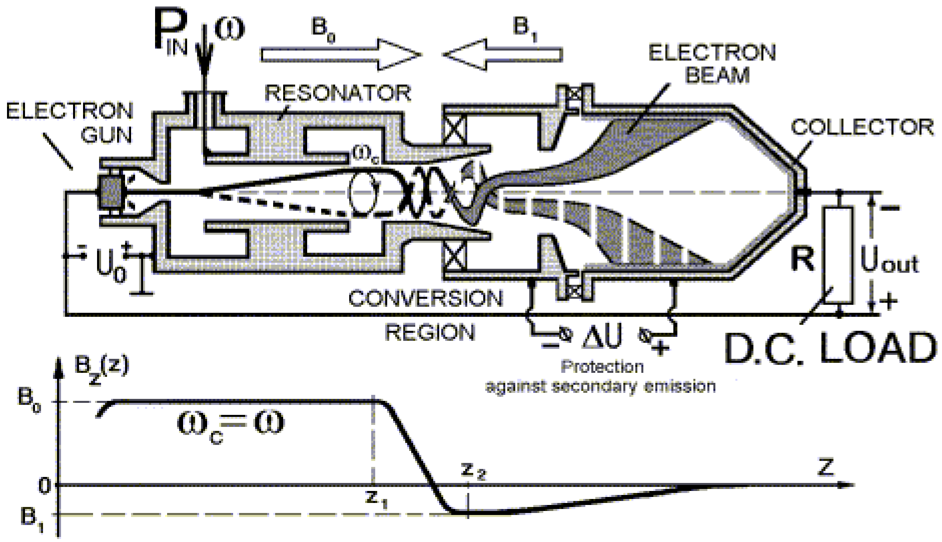


Power Without Wires
IEEE microwave magazine Dec 2011 Supplement

For this slide: SPS = Solar Power Satellite
Elsewhere: SPS = Super Proton Synchrotron

Cyclotron wave converter

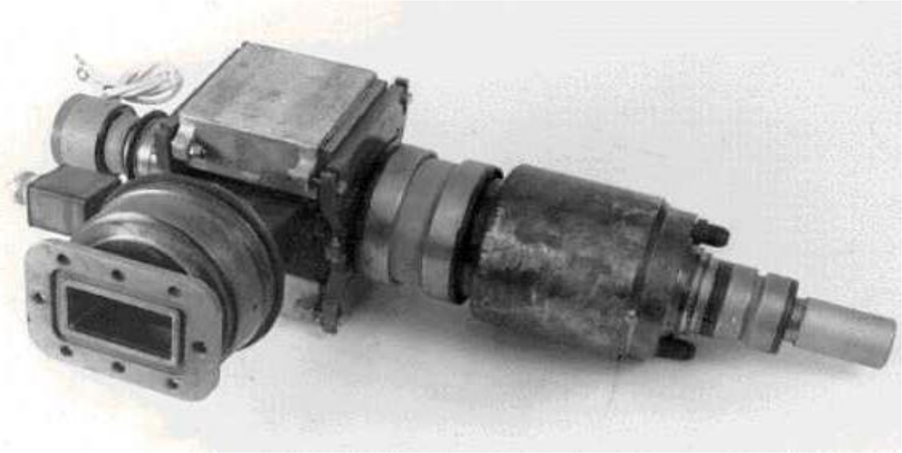
- The Cyclotron Wave Converter (CWC) is a new kind of RF to DC converter, patented by V.A. Vanke in 2003
- Its basic idea is to use RF to accelerate a high current electron beam, then capture the electrons which will generate a DC voltage that can be used technically.



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

But:

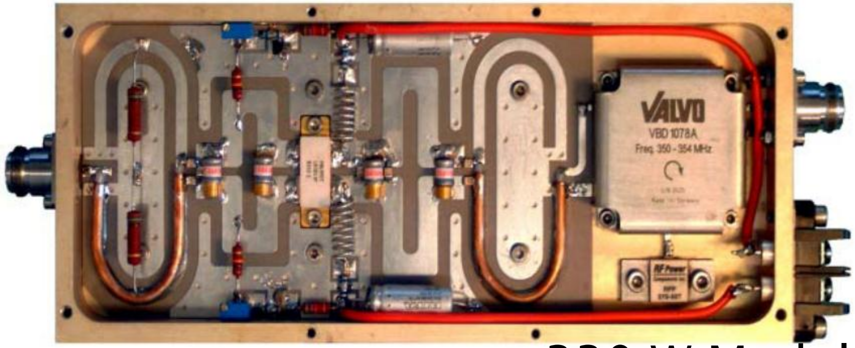
- **A 200 MHz device might be too large (resonant cavity needed)**
- **DC output voltage in the 100 kV range**



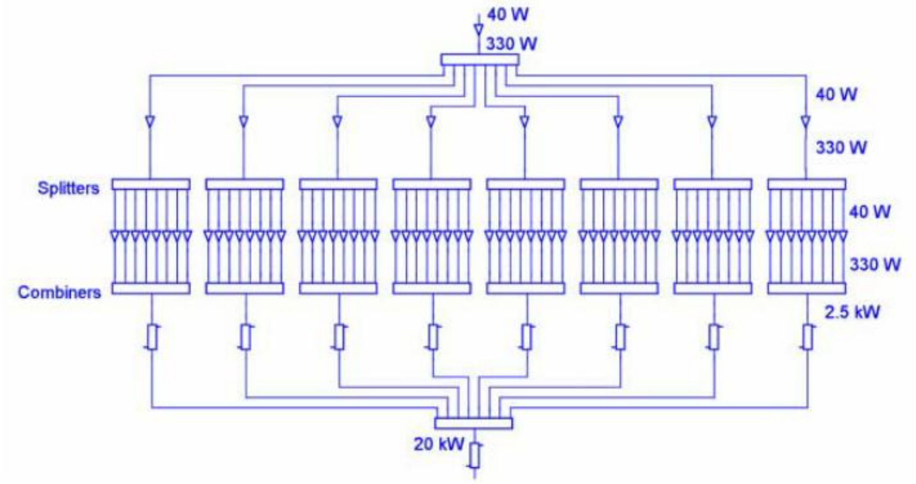
http://jre.cplire.ru/iso/sep99/1/text.html

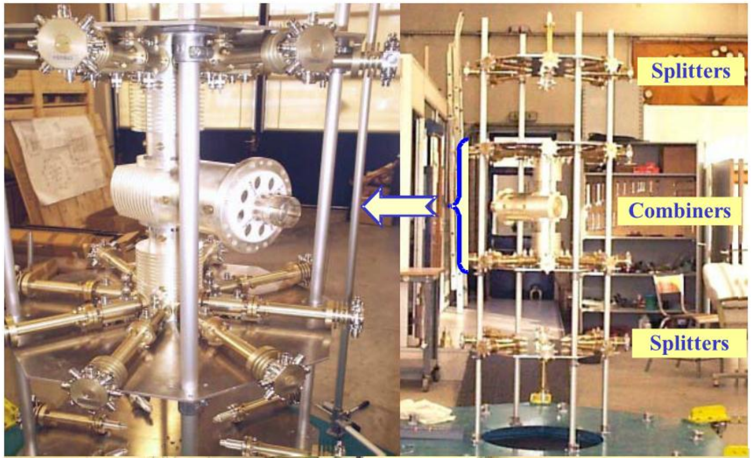
Solid state amplifier at the Synchrotron Soleil:
a large array of amplifiers (35 kW, 325 MHz) For DC to RF conversion

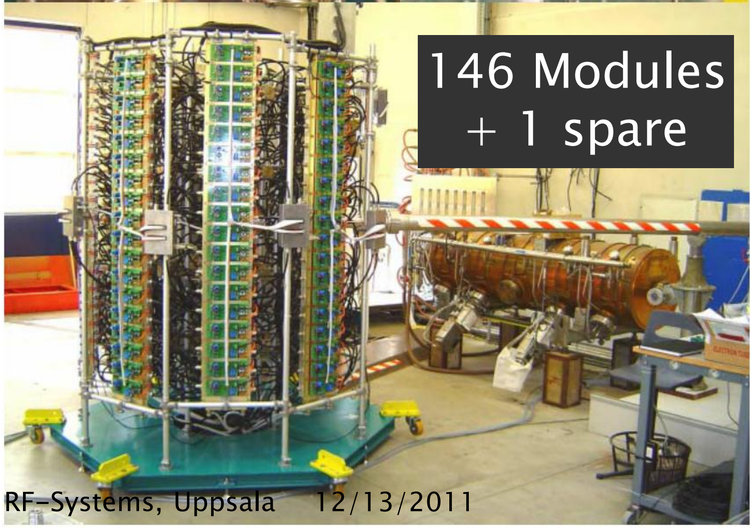
Can we use anything similar for RF to DC conversion, possibly something equivalent to 4 quadrant operation in low frequency power electronics



330 W Module







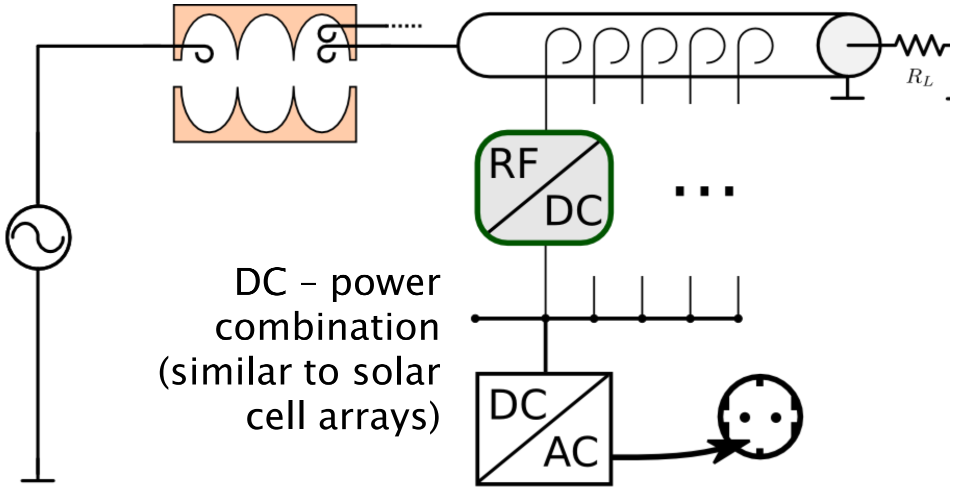
146 Modules
+ 1 spare

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

Energy Recovery concept using solid state technology

Conceptual design for the SPS

M. Betz, Feasibility Study for High Power RF – Energy Recovery in Particle Accelerators, CERN-THESIS-2010-125



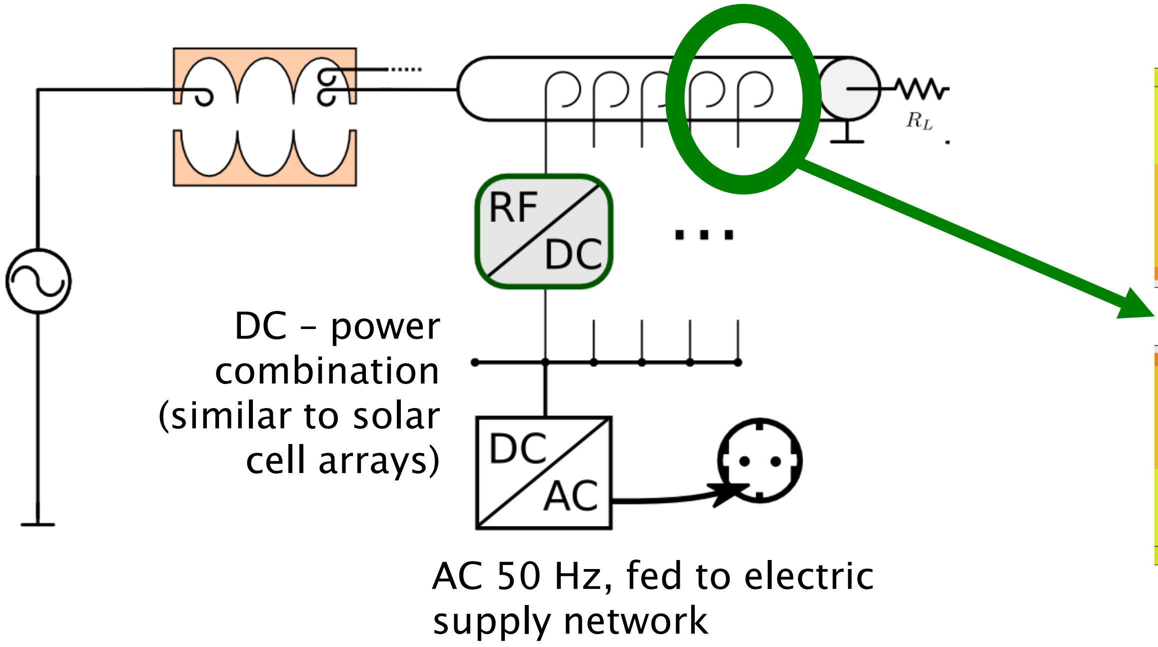
DC – power combination (similar to solar cell arrays)

AC 50 Hz, fed to electric supply network

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 using solid state technology

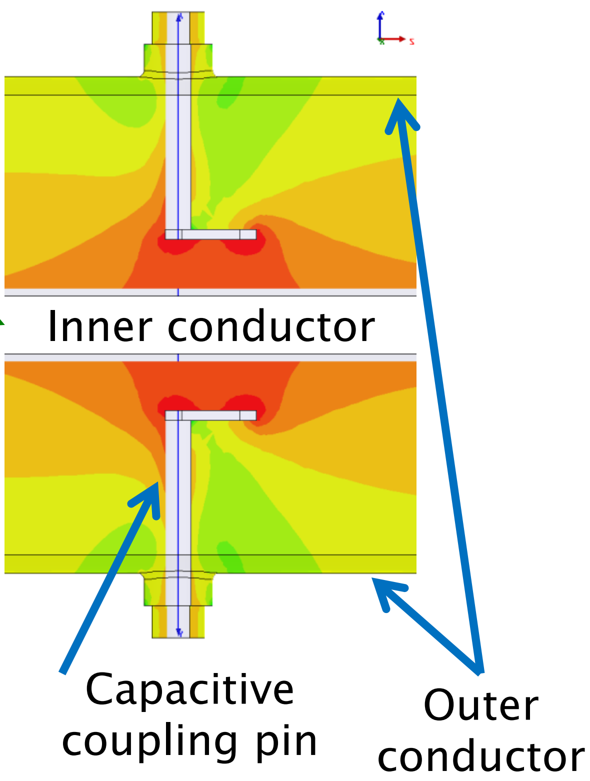
Conceptual design for the SPS



DC – power combination (similar to solar cell arrays)

AC 50 Hz, fed to electric supply network

Coaxial power splitter



Inner conductor

Capacitive coupling pin

Outer conductor

- 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

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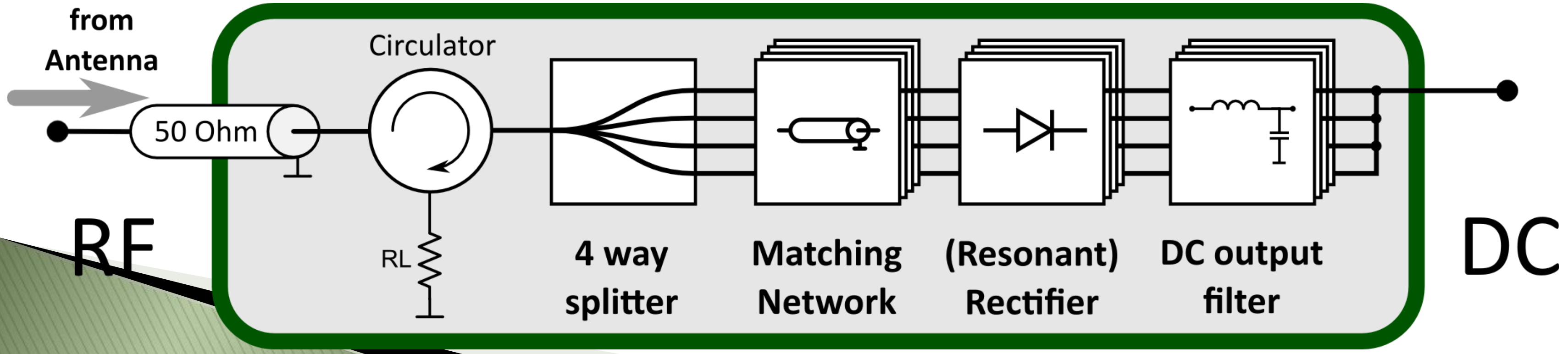
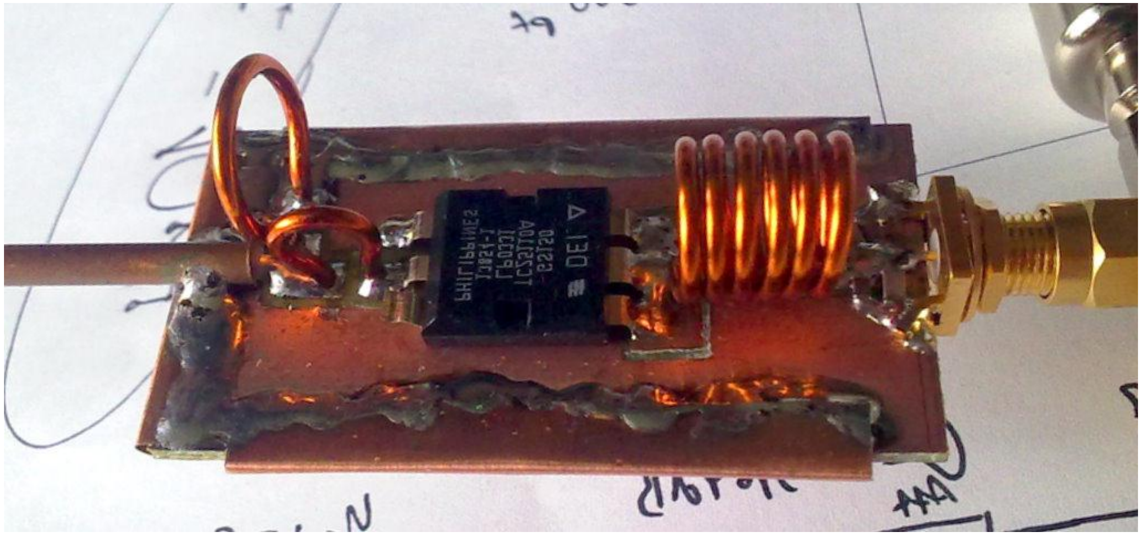
Requirements

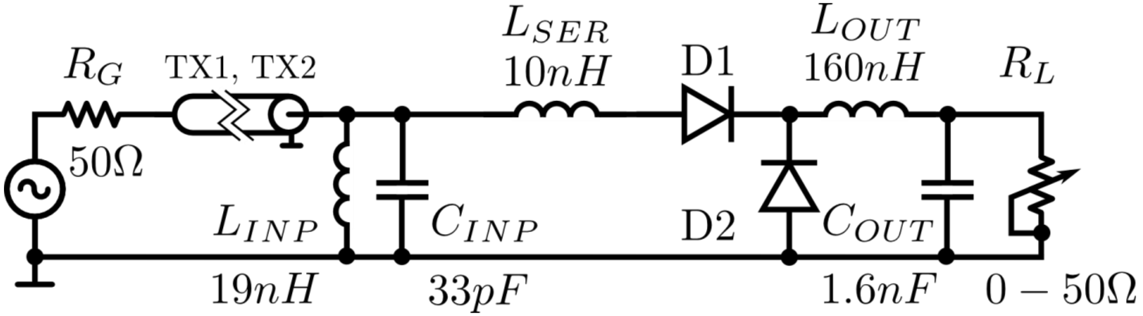
for a single RF/DC Module

Requirement	**Possible Solution**
☐ f_{in} = **200 MHz** (+-2%), P_{in} = **1 kW**	4 resonant Rectifiers, 250 W each
☐ Good 50Ω input match (S_{11} <= -20 dB)	Narrowband matching network
☐ **Failsafe design:** A failure of few individual components shall not lead to a significant disturbance of the SPS operation	**Circulator redirects input power if the rectifier fails partly or completely**
☐ No significant harmonic signals towards the input	



Prototyp 1 of a resonant rectifier





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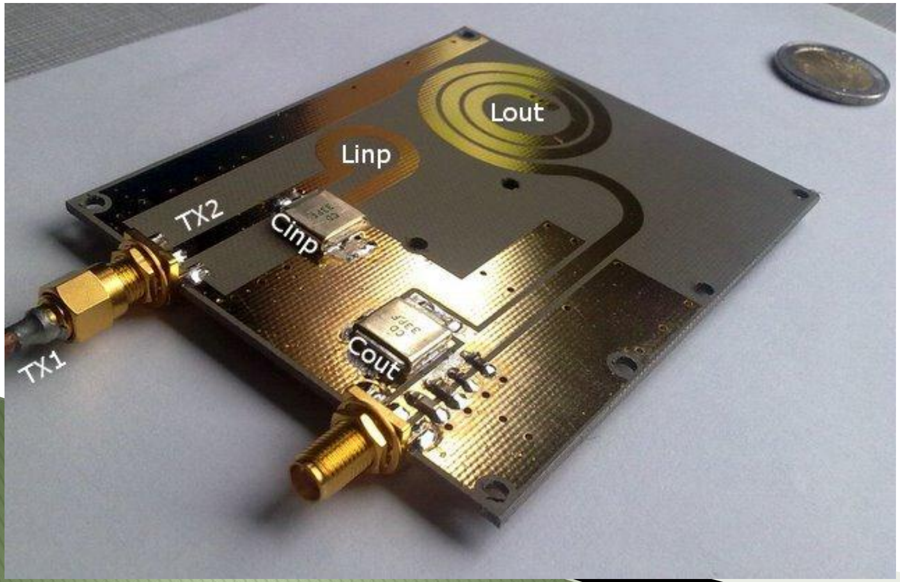
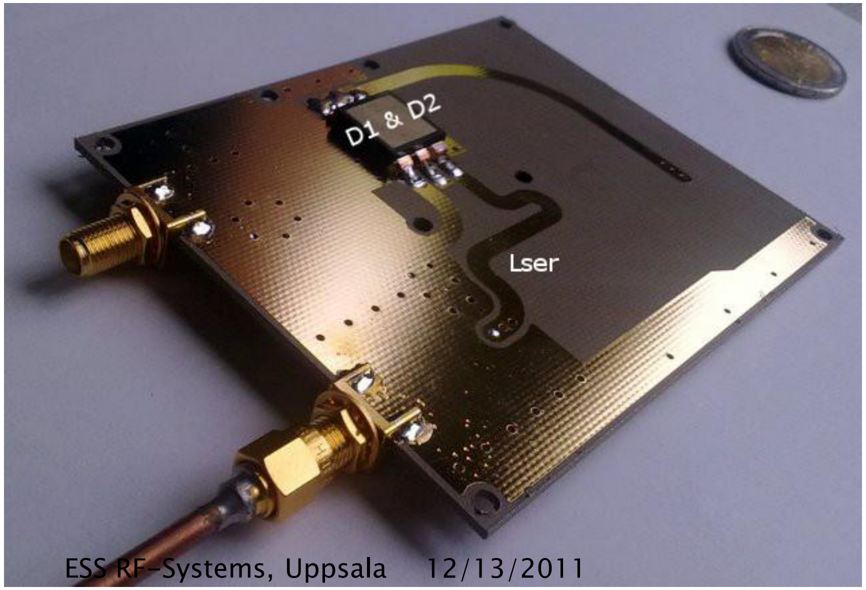
Prototyp 2

with planar inductors

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





Pulsed measurement results

RF to DC efficiency

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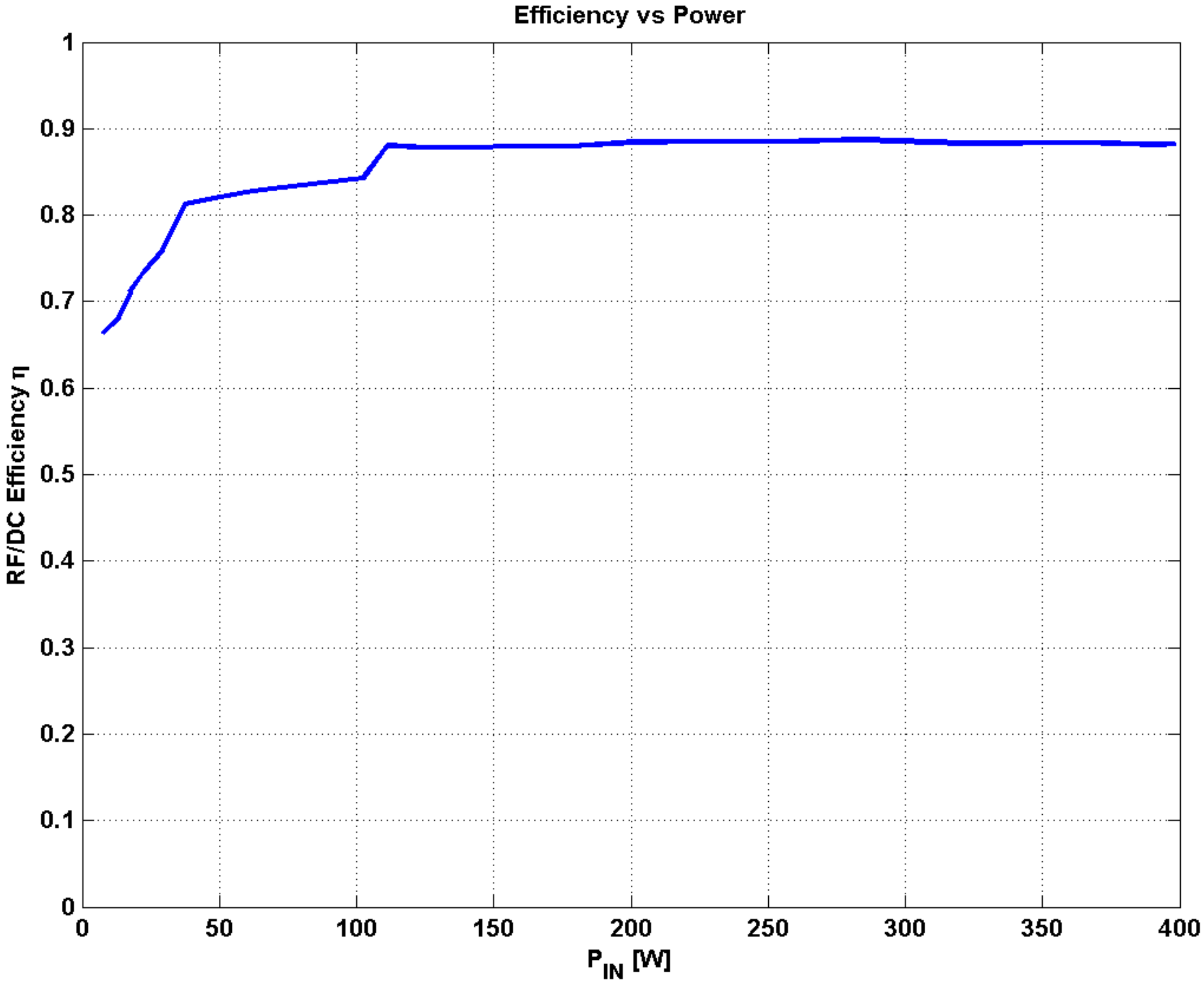


- Pulse length: 1 ms
- Maximum efficiency at:
  - 284 W
  - 88.7 %
- For reduced power we still see a fair efficiency

Summary for this development done 2010 at CERN

Solid State Energy Recovery

M. Betz, Feasibility Study for High Power RF – Energy Recovery in Particle Accelerators, CERN-THESIS-2010-125

- Rectifier with 2 x GaAs (GS150TC25110) diodes
  - Working frequency: 200 MHz
  - Nominal power: 250 W
  - Efficiency: > 85 %
  - Harmonic generation: – 30 dB wrt. input signal

- 4 rectifier units = 1 kW module
- 300 modules = Replacement for one SPS termination load

High power load for RF test bench

Could be used for CW tests of our energy recovery systems

- In our SPS test bench, we have water cooled RF power load to check and validate amplifiers

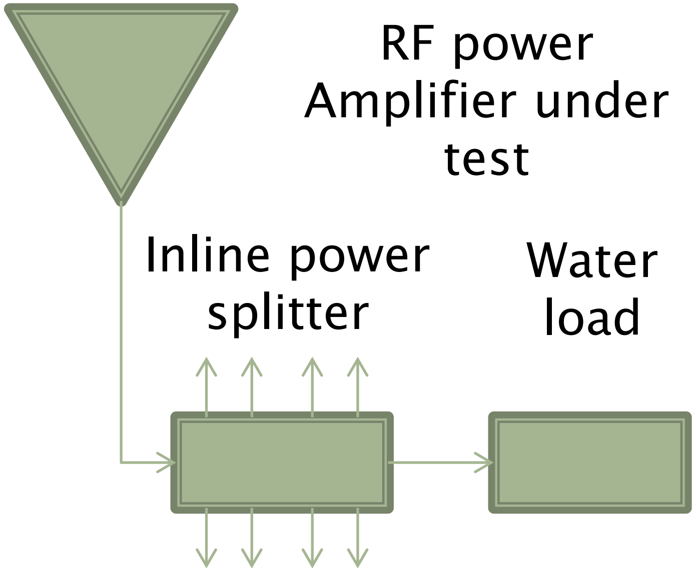
- f = 200 MHz
- Power = 150 kW CW.

- We check 6 x 150 kW and 16 x 35 kW amplifiers per year with a final 12 hours run at full power per amplifier to validate the maintenance work

Some of the RF power amplifier in operation in the SPS

High power load for RF test bench

- The proposal is to insert a power splitter between the amplifier and the power load
- It should demonstrate we are able to extract part of the RF power without disturbing amplifier tests
- We propose to build a 1 dB splitter (26 % in power, i.e. 38.8 kW) in order to demonstrate the feasibility of such a device
- Then we will implement it in our test bench, and make the qualification measurement



RF power Amplifier under test

Inline power splitter

Water load

Extracted RF will be available for other purposes

Part 2:

RF energy recovery using high temperature water 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, Stirling engines, etc.)

Motivation

- Amongst others, 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:
  - Requirement of a **fragile ceramic window** when water is heated directly
  - Usually, fairly **thick ceramic** absorbing layers have to be **braced** to a water cooled metal surface.
  - Issues of different **expansion coefficients** and temperature gradients in the ceramic

Absorbers

- A conceptional design of a high power RF load without any dielectric material is presented. It is an absorber made of metal only (“all metal load”). Essentially a low Q resonator …

- The presented load can sustain high temperatures and high pressures and is even robust against temperature shocks caused by pulsed RF signals.

Absorbers

- The presented load can be connected to ultra high vacuum (UHV) via standard vacuum seals.

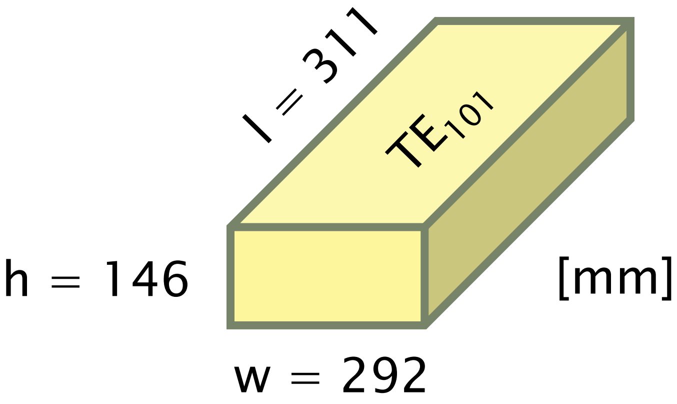
- The transition section between the ambient temperature part and the high power load will be done via a copper plated (thickness: 10 µm) bellows or coaxial line with rather thin stainless steel walls.

- Such bellows ensure good RF properties. It is furthermore capable of bridging the temperature differences from the hot high power load at 100°C – 200°C to the RF feeder line at ambient temperature.

Brainstorming for the ESS 704 MHz loads

- TE_{101} resonator from WR1150 – waveguide
- We need to **minimize the Q-factor drastically**
  - to limit the electric field strength inside and avoid **dielectric breakdown** (for air: 10 kV / cm maximum)
  - to achieve a wider operational **bandwidth**

Specifications		
f	704	MHz
P_{peak}	1,4	MW
P_{avg}	56	kW
S_{11}	< - 20	dB



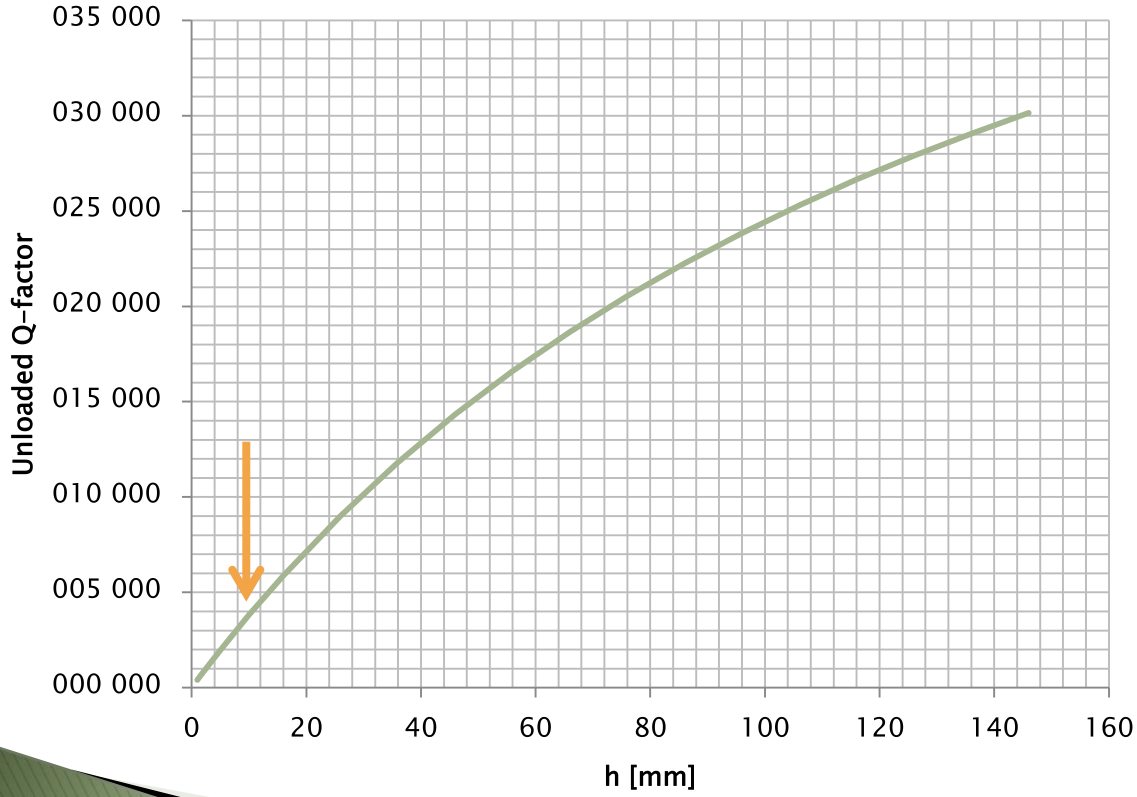
Q_0 = 30 143

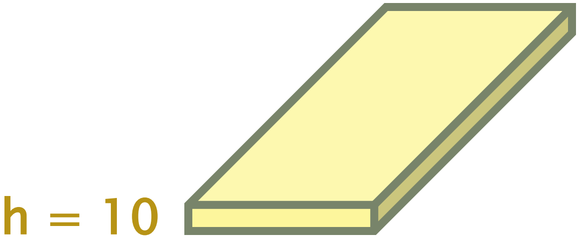
(unloaded Q, for a copper structure)

[mm]

Reduce Q

- By reducing the height!





Q_0 = 3 816

(unloaded Q, for a copper structure)

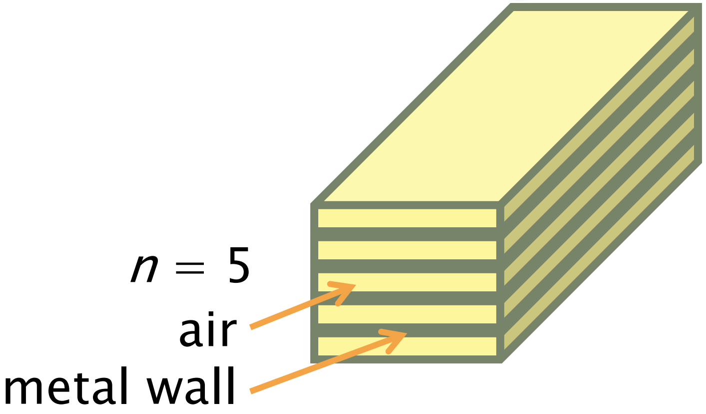
We have gained ≈ factor 10 by modifying the geometry

Still way too high!

Reduce electrical field strength

- Stack several (*n*) structures!
- *n*–times reduced electrical field strength per cell
- Q_0 does not change, compared to a single structure

→ Increased surface area
  - Easier heat transport
  - Less thermal stress on material



Q_0 = 3 816

(unloaded Q, for a copper structure)

Reminder:

The quality (Q) factor of a resonant circuit is defined as the ratio of the stored energy W over the energy dissipated P in one cycle.

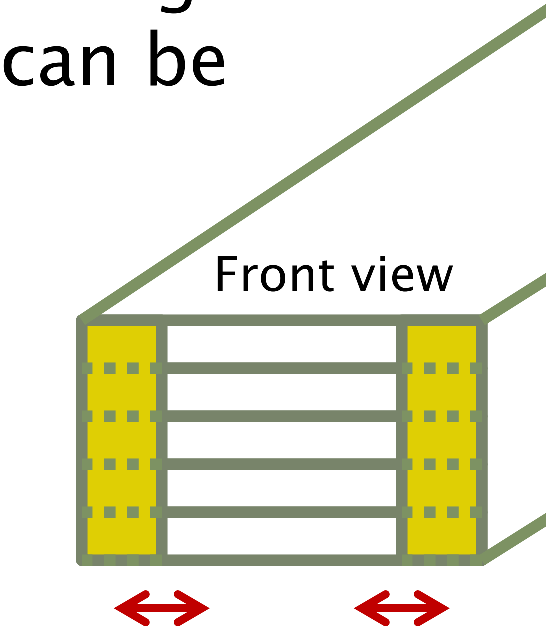
$$Q = \frac{\omega_{res} W}{P}$$

For n resonators in parallel, Q does not change as W and P are proportional to *n*

Coupling to a waveguide

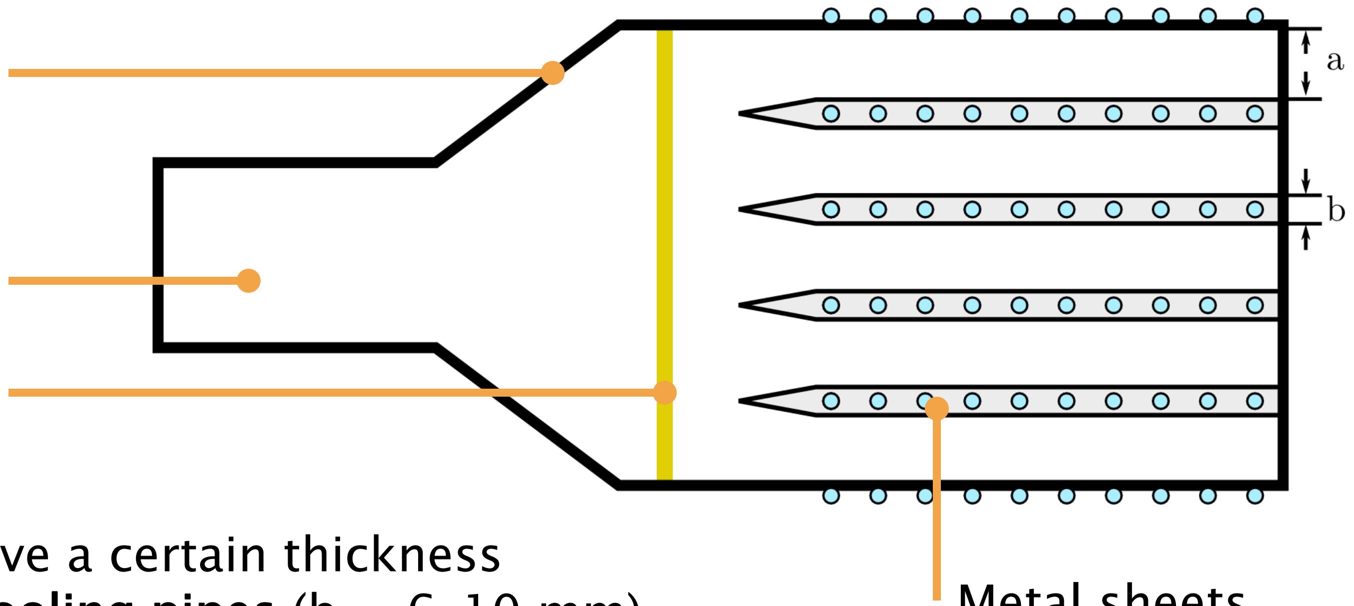
- Critical coupling / impedance matching of the resonator to the input waveguide can be achieved by an iris opening
- The smaller the opening, the weaker the coupling
- For critical coupling we get:

$$Q_{Loaded} = \frac{Q_0}{2}$$



Adjust for critical Coupling
(reflected RF power = 0)

Cross section of the structure



Taper to gain height (reduce elect. field strength)

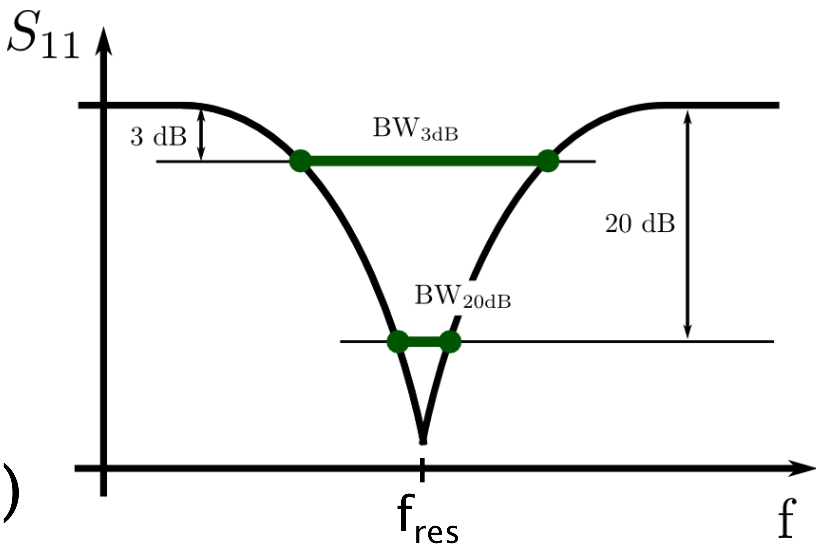
WR1150 waveguide

Iris

Metal sheets with cooling pipes

- The sheets must have a certain thickness to accommodate **cooling pipes** (b = 6–10 mm)
- Trade-off: thicker sheets = higher field strength (unless geometry is changed)
- The metal sheets will be made from **copper** (high thermal conductivity) but **coated with a metal**, having low electrical conductivity and high permeability

Operating bandwidth



- The frequency range where S_{11} = –20 dB is defined as operating bandwidth $BW_{20\ dB}$
- $BW_{20\ dB} \approx f_{res}\ /\ (\ Q_{Loaded}\ \cdot\ 10\ )$
  - The **resonant frequency** (f_{res}) of the load **drifts with** its **temperature**, depending on the thermal expansion coefficient of its material
  - Critical point ... → Hunting for the lowest possible Q

Choosing the optimum coating material

Q values have been derived from an analytical formula [1]

Material	Elect. Cond. σ [S/m]	Rel. permeab. M_r	Q_0	Q_L
Copper	$59,6 \cdot 10^6$	1	3816	1908
Nickel	$14,3 \cdot 10^6$	≈ 6	763	382
Iron	$10,0 \cdot 10^6$	≈ 40	**247**	**124**
*** Stainless steel**	$1,5 \cdot 10^6$	≈ 6	**247**	**124**

A good coating candidate material is Iron with a very thin protective layer of Nickel on a copper core

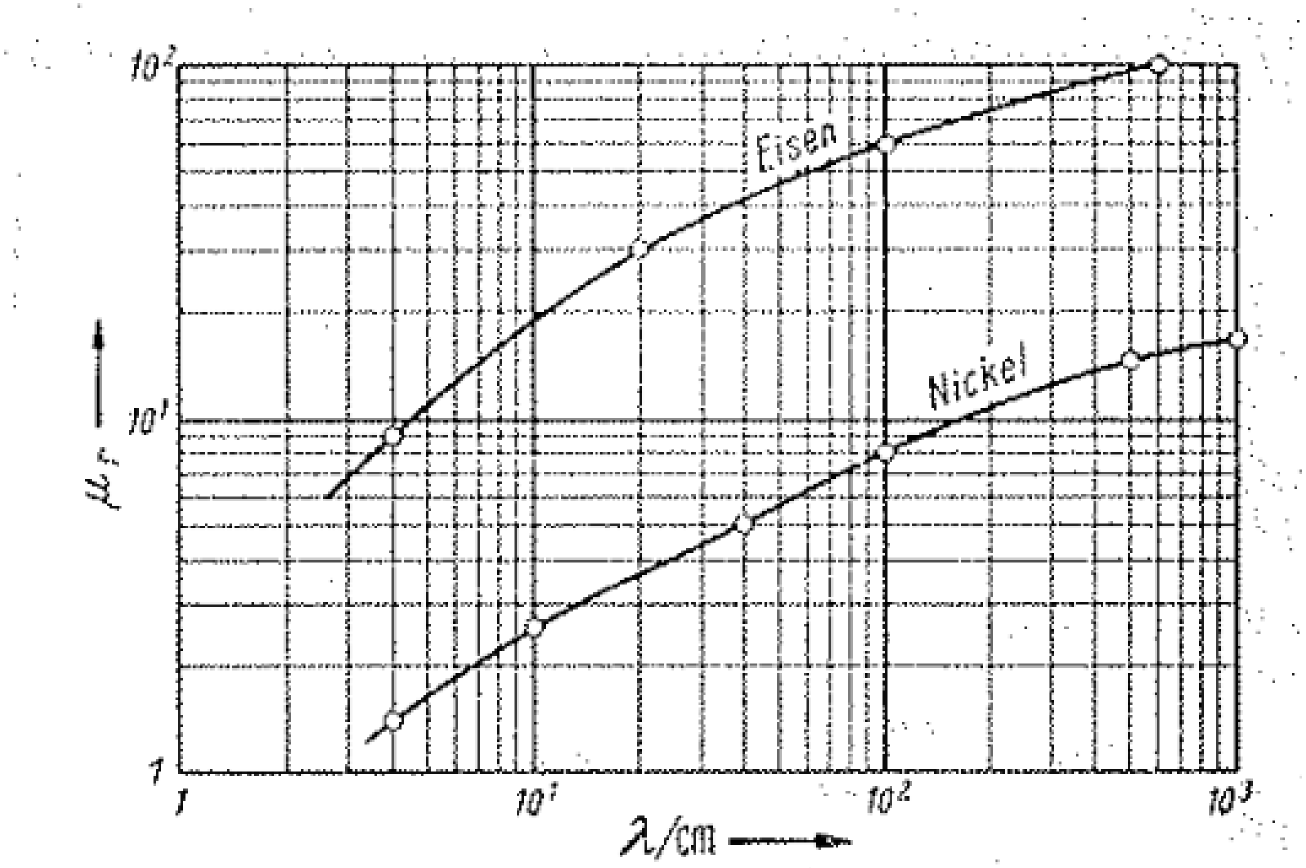
[1] David Pozar, Microwave Engineering, 2nd edition, Wiley, New York, NY, 1998

http://en.wikipedia.org/wiki/Electrical_resistivity_and_conductivity#Resistivity_of_various_materials

http://en.wikipedia.org/wiki/Permeability_(electromagnetism)#Values_for_some_common_materials

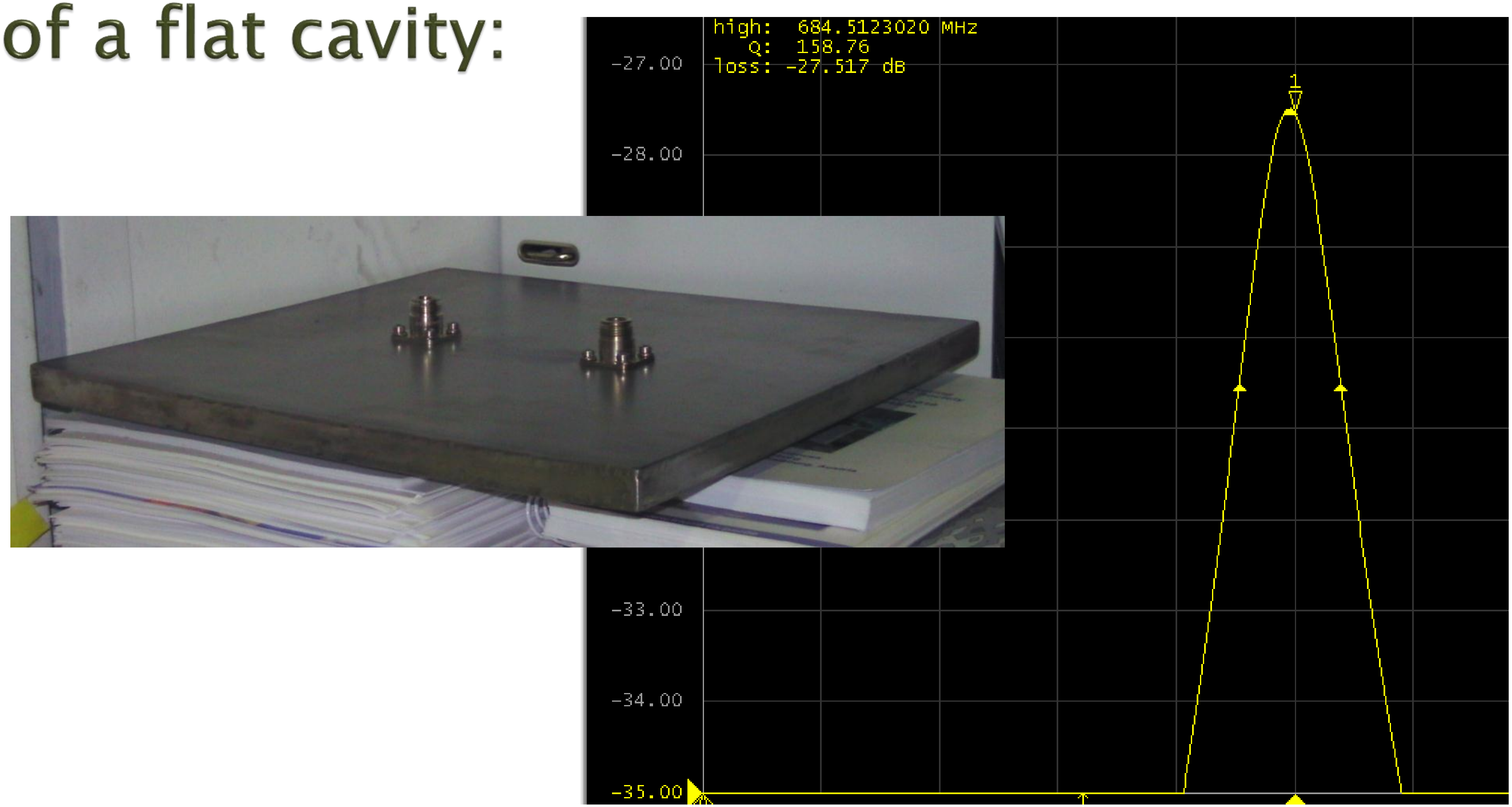
* = Can not be coated electro-chemically

Relative permeability of Iron and Nickel at high frequencies



Meinke Grundlach, Taschenbuch der Hochfrequenztechnik, dritte Auflage, p. 3

Measurement setup for the first prototype of a flat cavity:



We measured Q0 ≈ 160, loaded QL ≈ 80. This is still way too high!

→ Electrical break down in air

→ Temperature related drift of resonance frequency

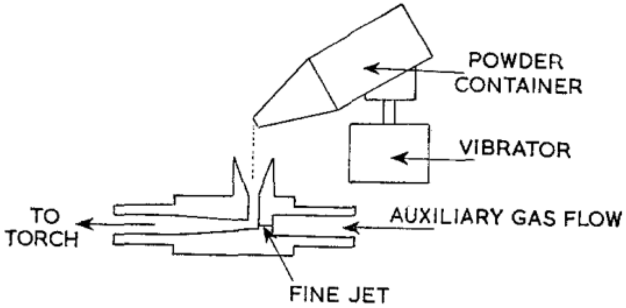
Further means to reduce Q

- Apply a very **thin** ferrite coating (150 - 300 μm)

- The thermal expansion coefficient of ferrite differs from its metal carrier
  - The reason why conventional ferrite loaded structures can not be used for high temperature operation
  - The ferrite will get brittle and crack

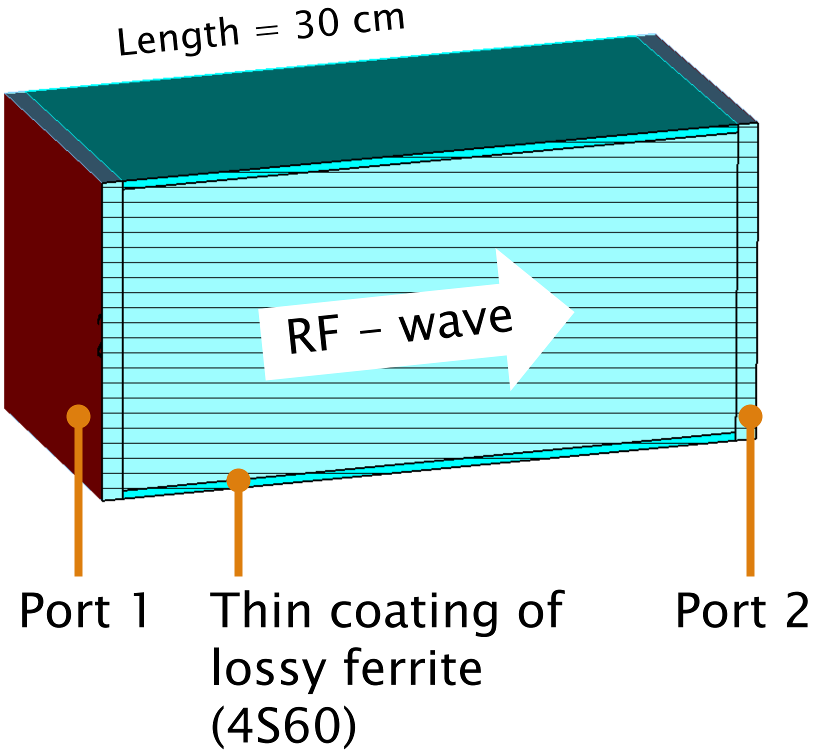
- This is not an issue for very thin ferrite coatings!

- The coating can be applied by plasma spraying [1]



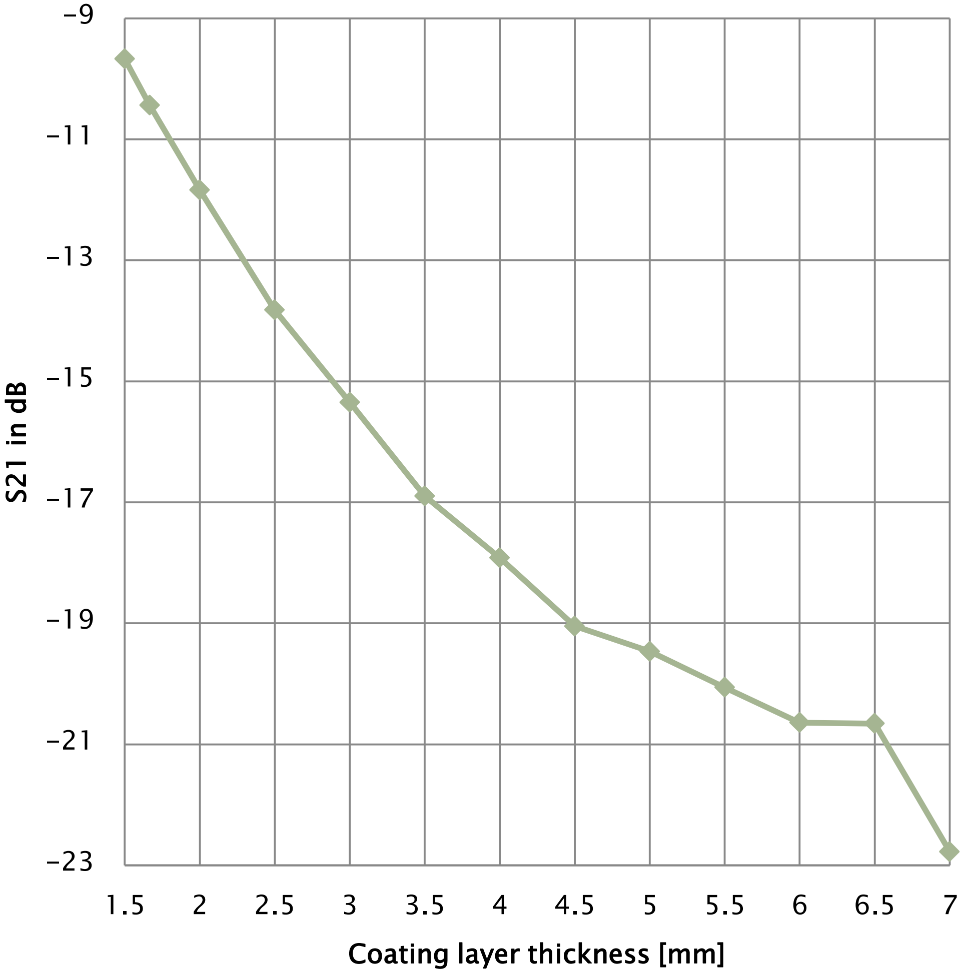
[1] I. PREECE, C. W. D. ANDREWS, Plasma spraying of ferrites, JOURNAL OF MATERIALS SCIENCE 8 (1973) 964-967

Attenuation of a coated, 30 cm long WR-1150 waveguide



Simulating thin coating layers (below 1.5 mm) gets increasingly difficult as a very dense calculation mesh is needed.

Results of a Microwave Studio simulation (Transient solver, at least 3 meshcells along the depth of the coating layer)



We can extrapolate Q from the simulation results

- For a coating layer of **d = 1.5 mm** the simulation predicts an attenuation of **9.7 dB** for **30 cm** length
- → 32 dB / m → α = 3.7 Neper / m

- If the ferrite layer is much thinner than the skin depth (which it is, in our case), the attenuation is proportional to the amount of ferrite in the waveguide. **We can scale linearly**.

- We **approximate** for **d' = d/10 = 150 µm**
- → 3.2 dB / m → α = 0.37 Neper / m

The Q-factor of a resonator made from waveguide can be determined by:

$$Q_0 = \frac{\pi}{\lambda_r \alpha}$$

Where $\lambda_r = 0.62$ m is the wavelength inside the waveguide

We get $Q_0 = 13.6$ for the standard-size waveguide

With a thin waveguide we can reduce Q_0 by another factor of 10.

Travelling wave operation

- Reducing the quality factor below **$Q_0 = 13.6$** with thin waveguides would allow us to build travelling wave loads by making the structure long enough (but still < 1 m)

- No resonating structure, no enhancement of the electric field strength, no problems with electric breakdown

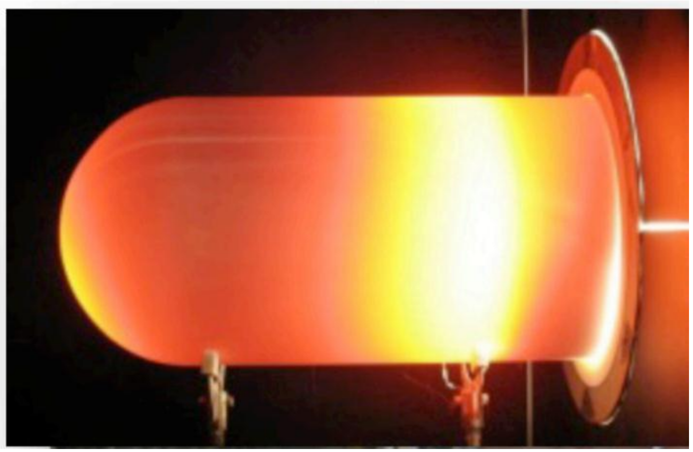
- A prototype of a cavity with plasma sprayed ferrite coating is in preparation in collaboration with:
  - RWTH Aachen University, Institut für Oberflächentechnik
  - Ferroxcube Germany

Part 3:

RF energy recovery using air cooled ceramic foam loads

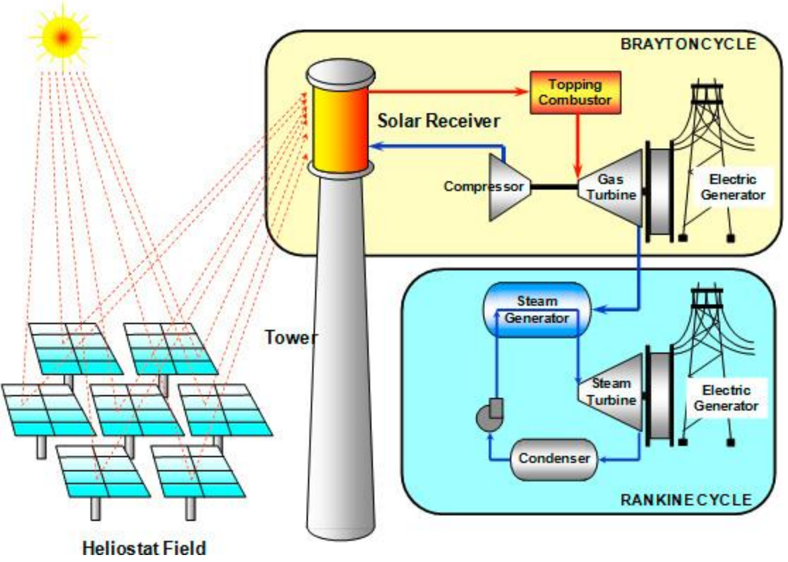
Air cooled RF load with ceramic foam

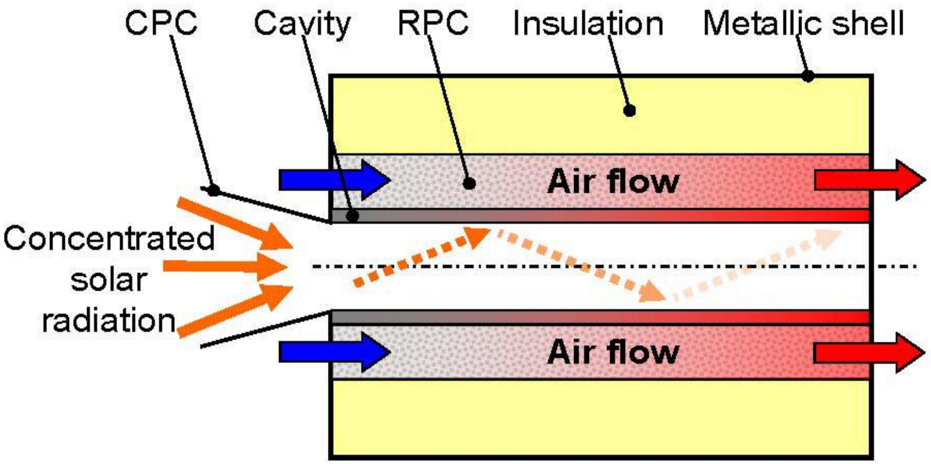
- The solar energy absorber concept by I. Hischier [1] inspired us to this new kind of very high temperature air cooled RF load



[1] I. Hischier, Development of a pressurized receiver for solar-driven gas turbines, 2011 Diss. ETH 19723

Solar Thermal Combined-Cycle Power Generation



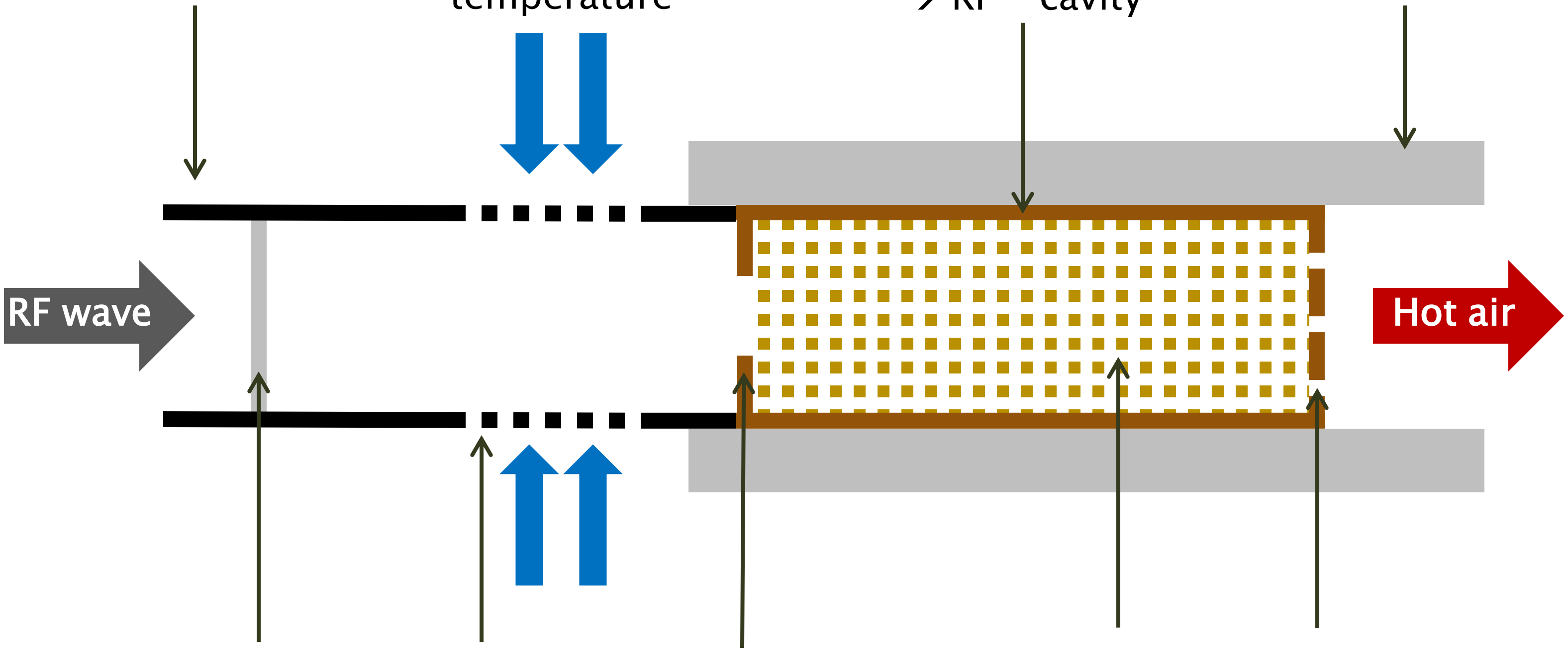


Air cooled RF load with ceramic foam

- We suggest a porous ceramic foam made from Silicon Carbide (SiC) in a metal enclosure
- The ceramic foam has rather high electric losses at microwave frequencies
- The foam is cooled by pressurized air
- The outlet air temperature may be > 800 °C and thus of practical value
- **The ceramic is NOT brazed to the metallic enclosure but just in loose contact**
- This is like the concept of using fire clay bricks in a domestic stove (except for the RF losses)

Air cooled RF load with ceramic foam

Cross section of a Standing wave structure



Standard waveguide (e.g., WR-1150)

Pressurized air at ambient temperature

Metal enclosure at high temperature (> 800 °C) → RF - cavity

Thermal insulation

Air tight RF window

Perforation serves as RF tight air inlet

Iris for standing wave operation

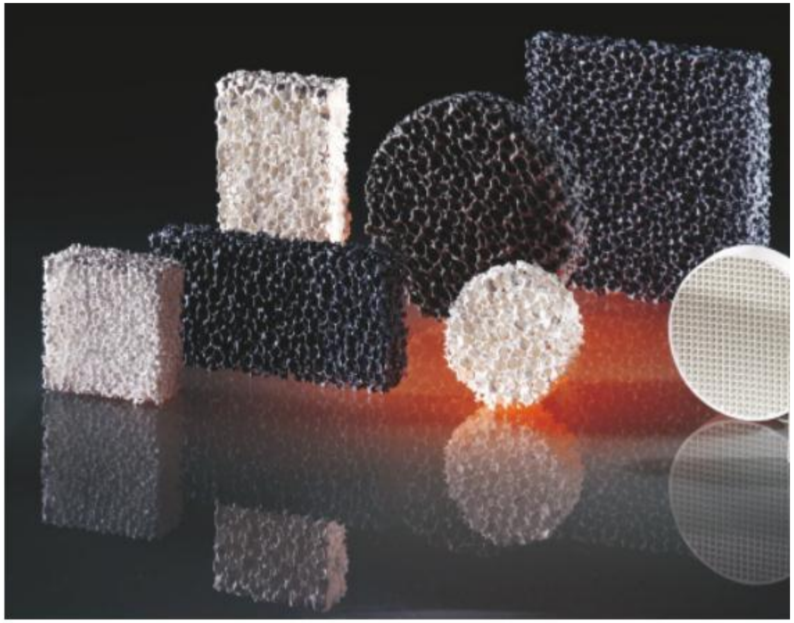
ceramic foam with high RF losses

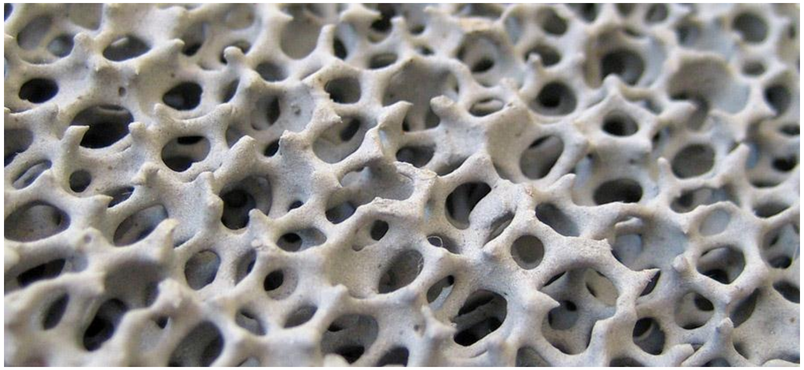
Perforation serves as RF tight air outlet

Length $= 0.5 \dots 2\ \lambda_0$
Height $= 0.5 \dots 1\ \lambda_0$

Air cooled RF load with ceramic foam

- **SiC foam** is widely used in metal casting applications
- Molten metal is guided through the foam to filter out impurities and to control fluid flow
- Different shapes, sizes and porosities are commercially available
- Maximum temperature for SiC: 1 550 °C





http://www.hofmann-ceramic.de
http://www.frank-landmesser.de

Part 4:

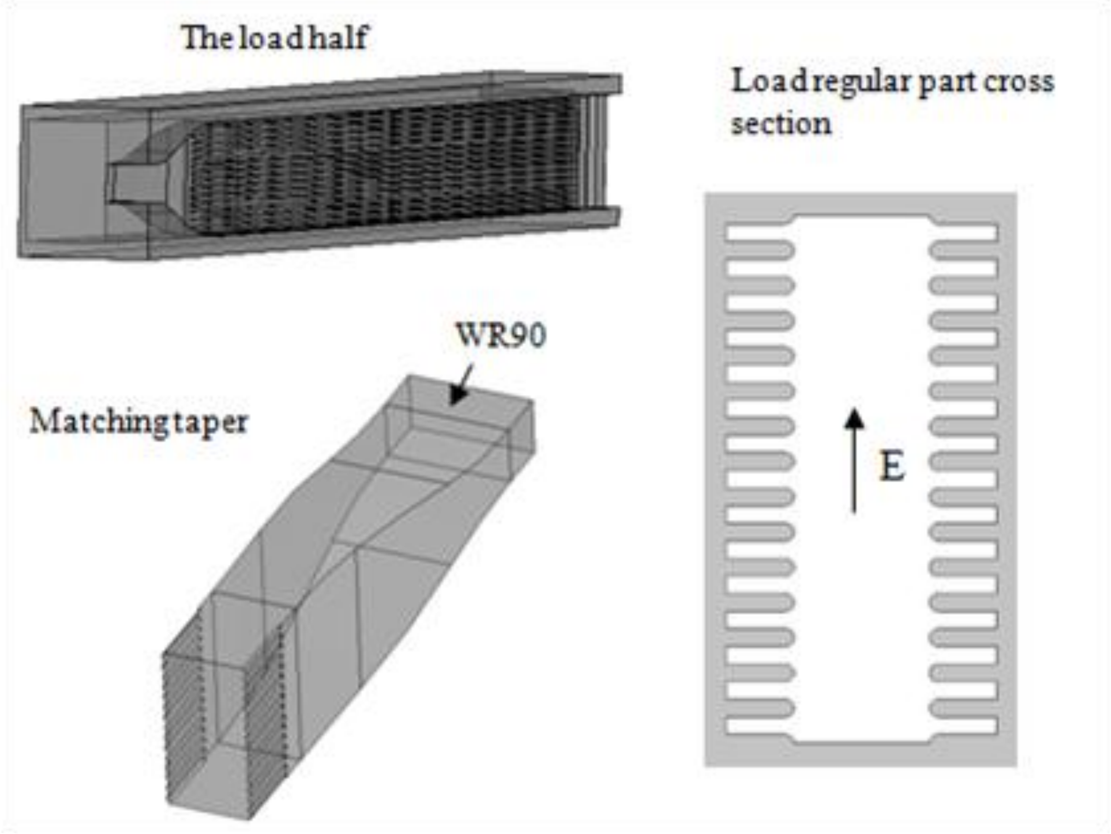
X-Band Travelling Wave Structure

X-Band Travelling Wave Structure

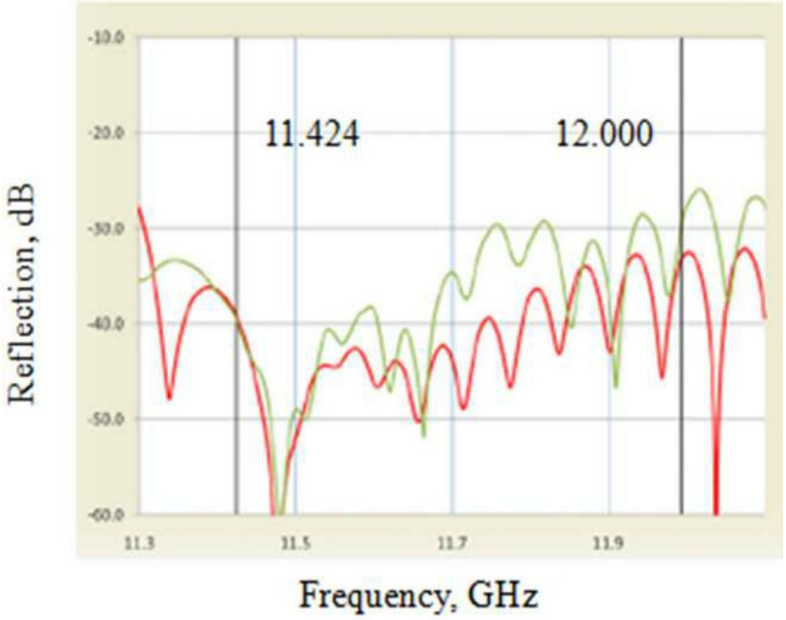
- X-band RF load built from magnetic (μ = 6) stainless steel (SS430)
- Concept based on the classical approach of a regular waveguide operated close to its cut-off frequency
- waveguide with special cross-section – central gap width about half the waveguide width, cut-off frequency about 20% higher than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

- Note that the concept of a thin, plasma sprayed layer of ferrite can also be applied to this structure to reduce the electrical field strength

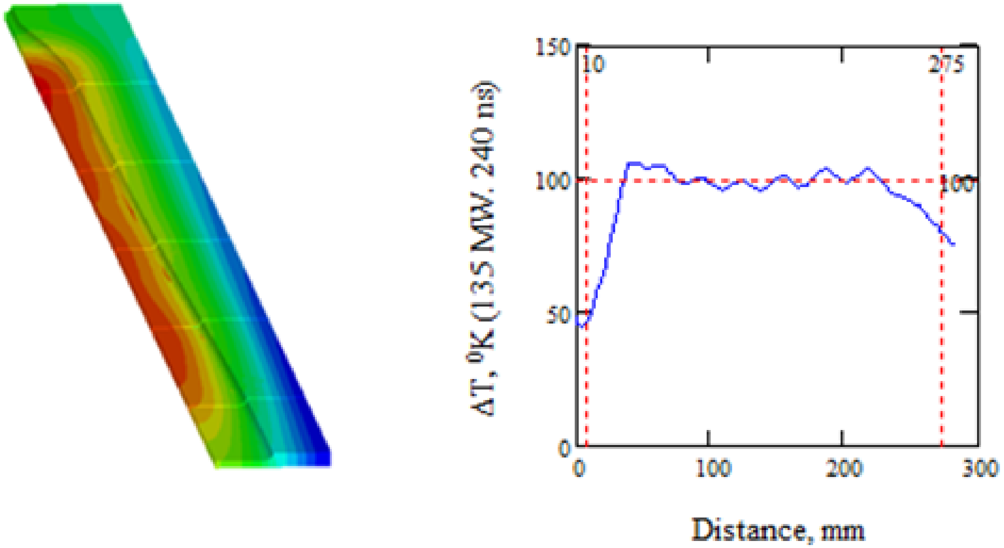
X-Band Travelling Wave Structure



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 60 MW peak RF power at 11.424GHz [1]

[1] S. Matsumoto, T. Higo, I. Syratchev, G. Riddone, W. Wuensch: High Power Evaluation of X-band High Power Loads, CERN-ATS-2010-217, October 2010

Conclusions

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

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

Thanks for your attention.

Any questions?