RF systems

Francis Perez

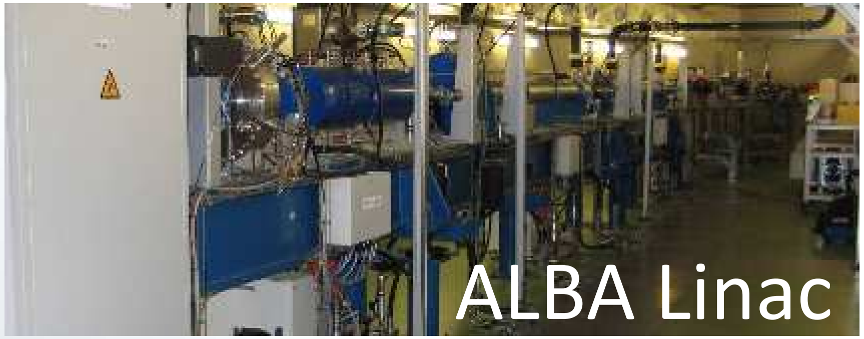
Why we need a RF System?

- To accelerate the beam to high speeds (~c) / high energy
- To restore the energy loss via synchrotron radiation of the stored e^- beam
- To provide a stable energy bucket to the particles to ensure a long lifetime

Why?

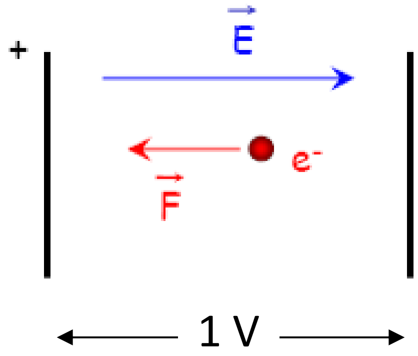
- accelerate the electron beam to high speeds (~c) i.e. high energy

  - in a LINAC:
    - *90 keV to 100 MeV*



  - in a BOOSTER:
    - *100 MeV to 3 GeV*

ALBA case



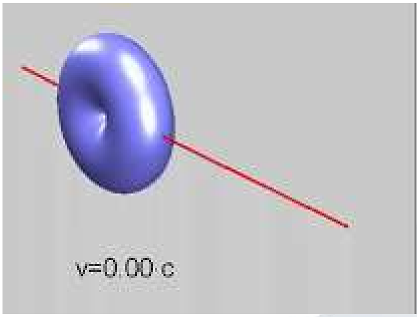
The electrons get an energy of
1 eV

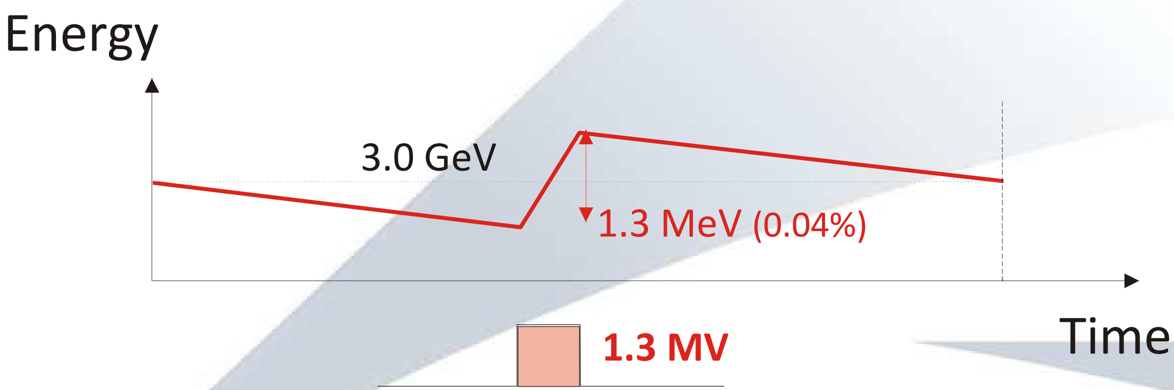
Storage ring energy
3 GeV = 3.000.000.000 eV
for a velocity of
99.9999985% de c

Electrons have to see an accelerating voltage of **three thousands millions Volts**!

Why?

- To restore the energy loss via synchrotron radiation of the stored beam





Cavity Voltage
(if only one cavity)

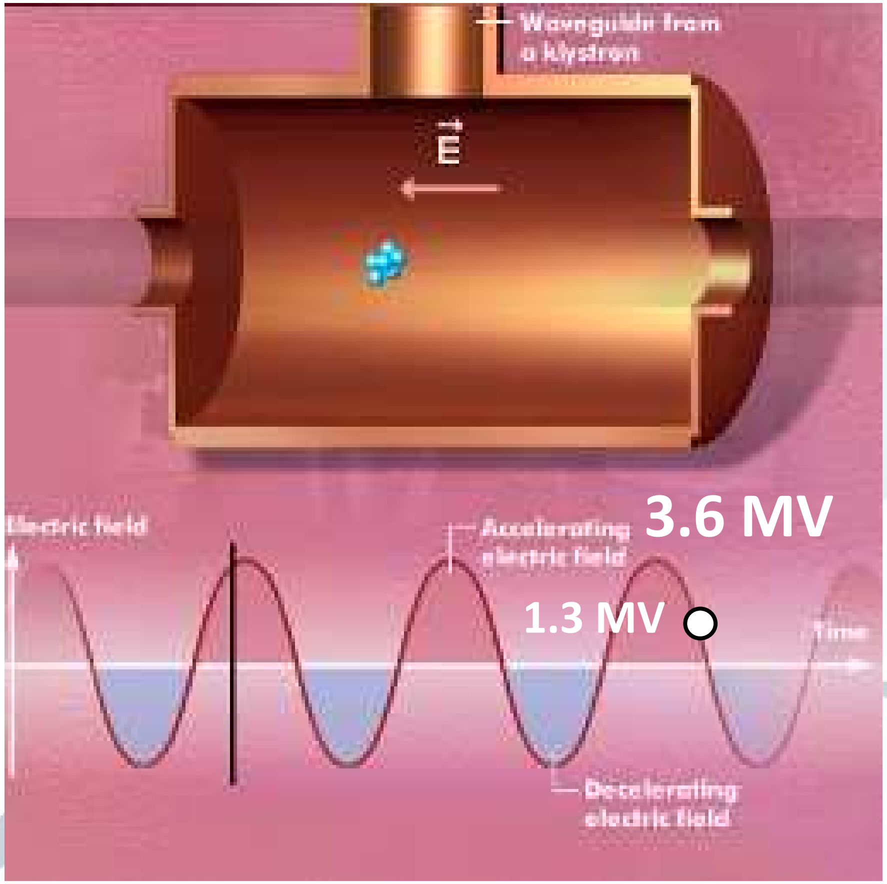
$$U_o = 88.5\ E^4/\rho$$

400 mA
1.3 MeV/turn
→ **520 KW**

ALBA Storage Ring

Why?

- To provide stability, i.e. a stable energy bucket to ensure a long lifetime



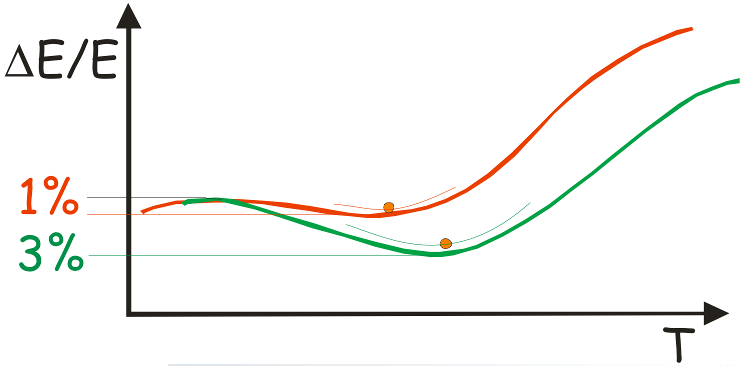
Overvoltage factor:

$q = V_{cav} / U_{losses}$

to have longitudinal focusing

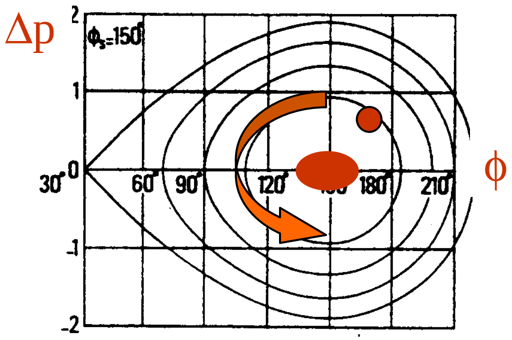
Why?

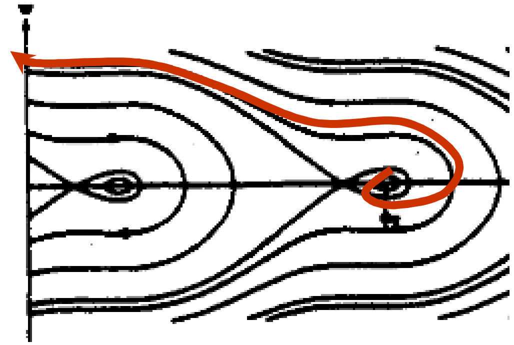
- provide a large stable energy bucket to ensure a long lifetime of the stored e^- beam



High Voltage

Low Voltage





For ALBA SR: 3.6 MV ➡ 3% Energy Aceptance

Why?

inside the RF cavities an electromagnetic field is stored

- and with the use of:

$$\mathbf{F} = q\,\mathbf{E}$$

- it creates a force that:
  - **accelerate** the electrons
  - **stabilize** the movement of the electrons

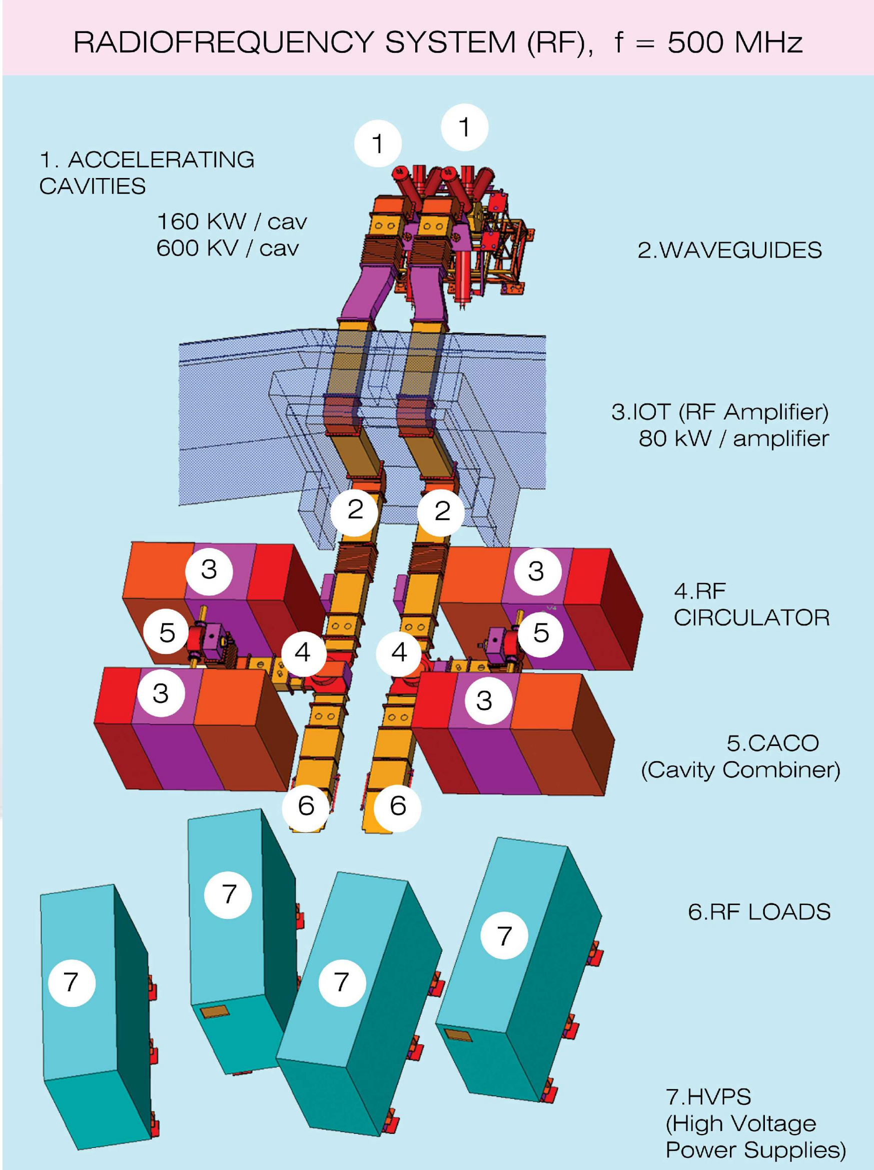
Accelerating structure

Low-level RF control

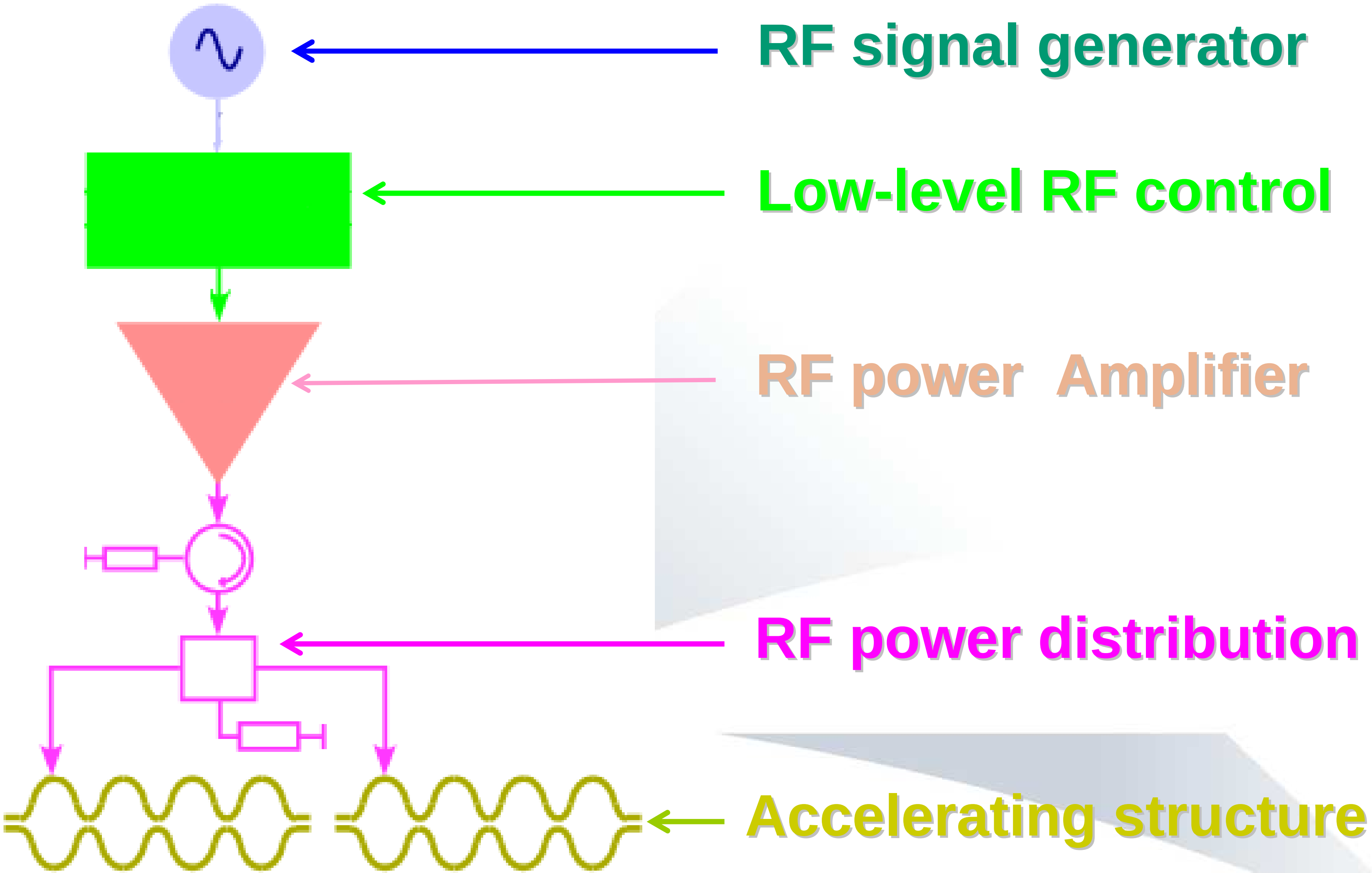
RF power distribution

RF power Amplifier

RF signal generator



ALBA RF scheme

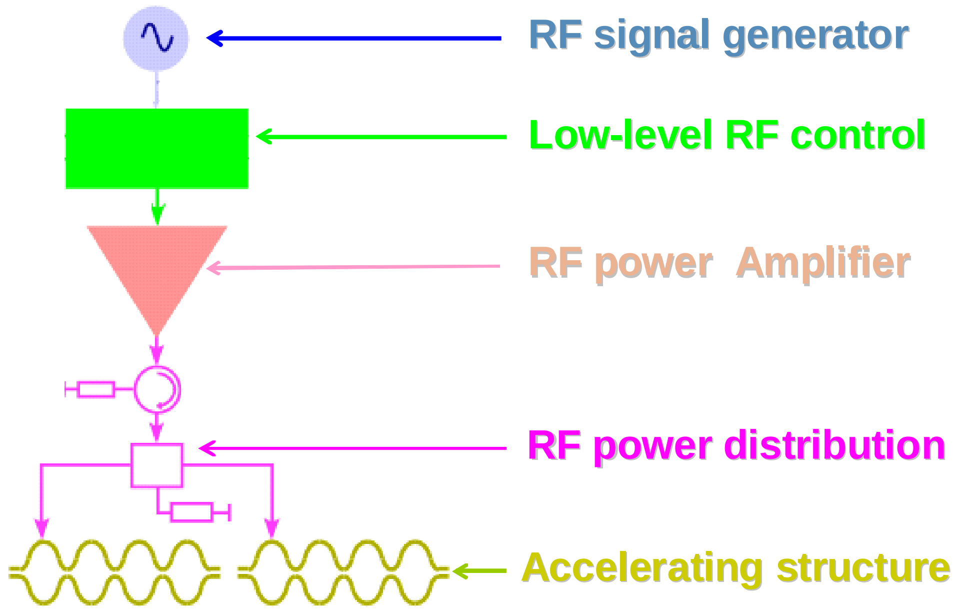

RF signal generator
Low-level RF control
RF power Amplifier
RF power distribution
Accelerating structure

Contents

- Part I: Cavities and waveguide system
- Part II: High Power Amplifiers
- Part III: Low Level RF control (LLRF)

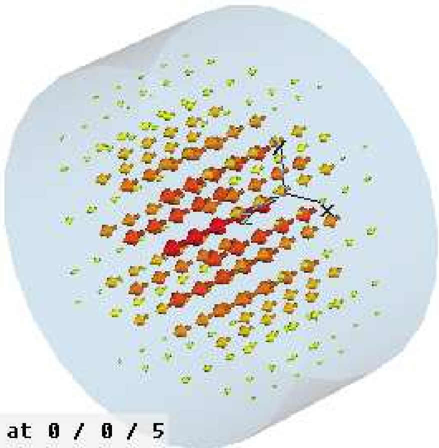
Part I:

Cavities and Waveguide system



Cavity

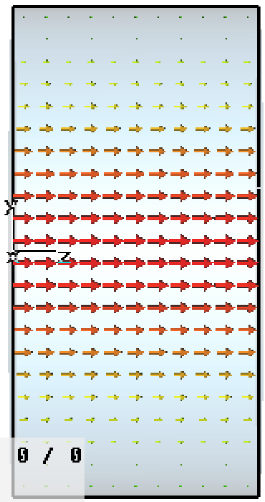
TM_{010} Fundamental resonating mode



Type	E-Field (peak)
Monitor	Mode 1
Maximum-3d	4.61371e+007 V/m at 0 / 0 / 5
Frequency	2.29257
Phase	0 degrees

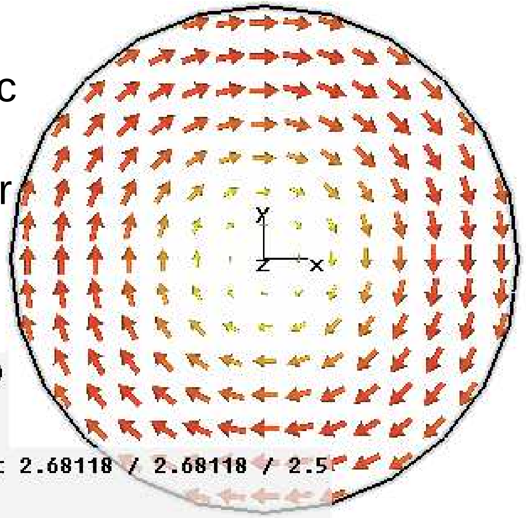
- Electromagnetic RF fields resonate inside the cavity creating Electric and Magnetic Fields

Electric Fields:
Maximum electric field in the axis (electrons path)



Type	E-Field (peak)
Monitor	Mode 1
Plane at x	0
Maximum-2d	4.61371e+007 V/m at 0 / 0 / 0
Frequency	2.29257
Phase	0 degrees

Magnetic Fields: Magnetic field loops around electric field (maximum in the outer part) and causing ohmic heating

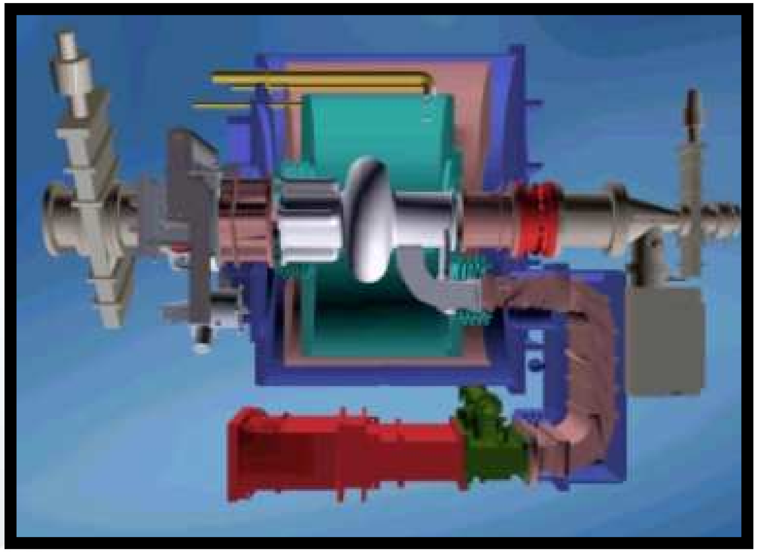


Type	H-Field (peak)
Monitor	Mode 1
Plane at z	2.5
Maximum-2d	77383.3 A/m at 2.68118 / 2.68118 / 2.5
Frequency	2.29257
Phase	90 degrees

** Info from Dr G Burt, Lancaster University*

Cavity

Normal conducting vs Superconducting



Normal conducting vs Superconducting

Quality Factor typical values :

Q = $\sim 10^4$ (NC) $\sim 10^{10}$ (SC)

due to the lowest surface resistance: U ~ 0

$$\frac{R_{SH}}{Q} = \sqrt{\frac{L}{C}} = \frac{1}{\omega_0 C} = \omega_0 L$$

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

$$Q = \frac{\omega_0 U}{2P} = \omega_0 RC = \frac{R}{\omega_0 L}$$

ALBA case

NC cavity				SC cavity		
Total Voltage	**3.6**	**MV**		**Total Voltage**	**3.6**	**MV**
No Cells/IPC	**6**			**No Cells/IPC**	**2**	
Type of cavity	nc			Type of cavity	sc	
Voltage / cell	600	kV		Voltage / cell	1800	kV
R_{shunt}	**3.0**	**MΩ**		**R_{shunt}**	**4500**	**MΩ**
Cavity power	60	kW		Cavity power	0	kW
Beam power/cav	87	kW		Beam power/cav	260	kW
IPC power	147	kW		IPC power	260	kW
Amplifier Power	160	kW		Amplifier Power	300	kW
Total Power	**960**	**kW**	**>>**	**Total Power**	**600**	**kW**

But, all the cryogenics!

SC RF

Dewar

Valve Box

Turbines

Cavity

Gas reservoir

Cavity

Single cell vs Multicell

Cavity

Single cell vs Multicell

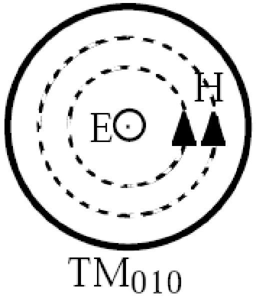
The multicell cavity is highly efficient to transform power in voltage:

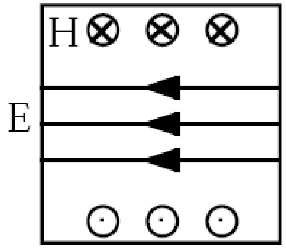
$Z_{cavity} = N \times Z_{cell}$

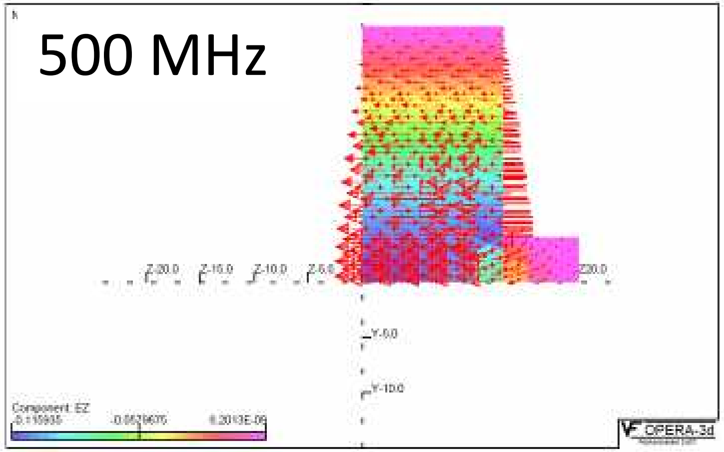
But also the impedance of the HOMs

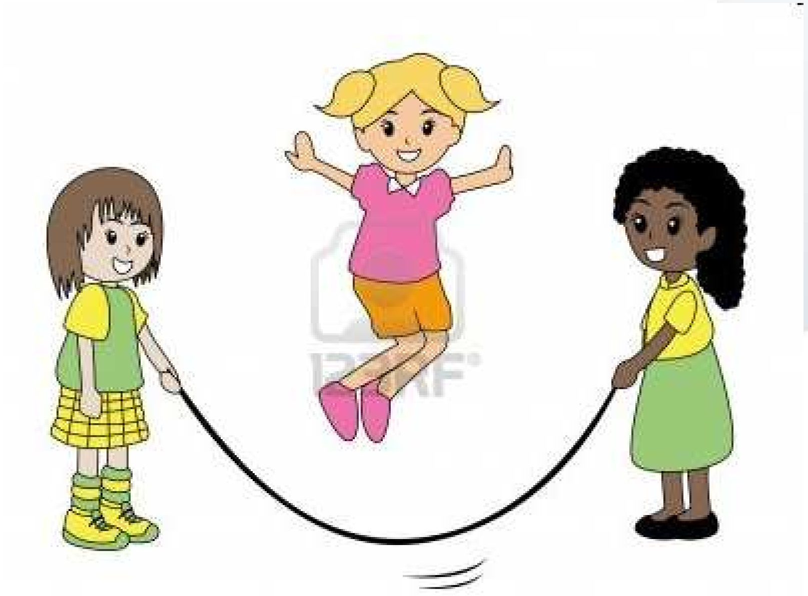
Cavity

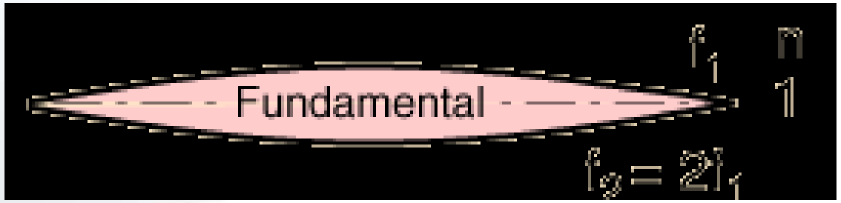
Fundamental Mode:

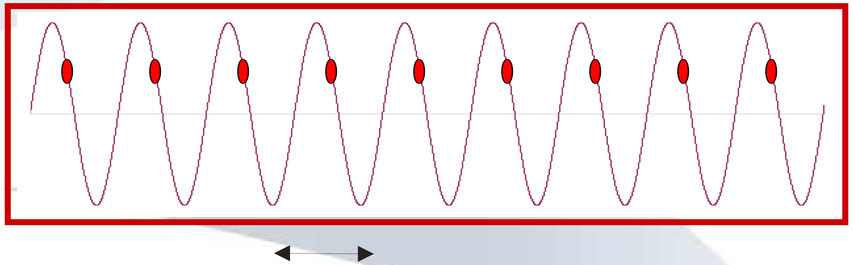








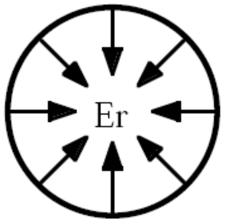




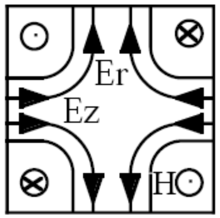
Wavelength = 60 cm

Cavity

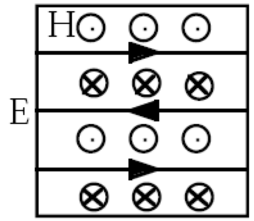
High Order Modes - HOM

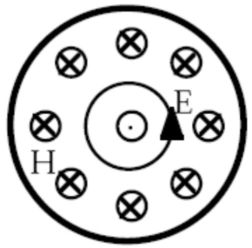


TM011



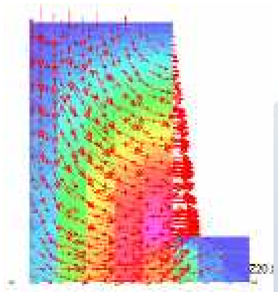
TM020



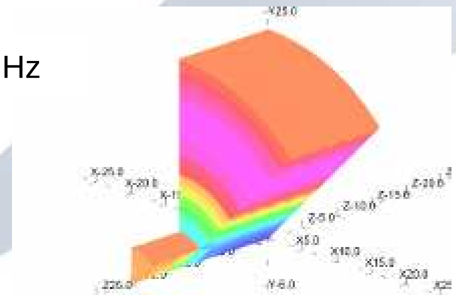


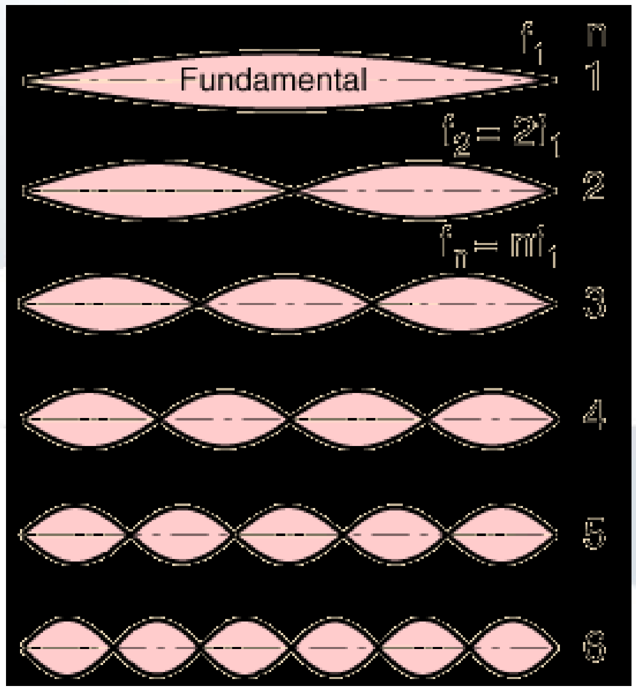
TE011

760 MHz



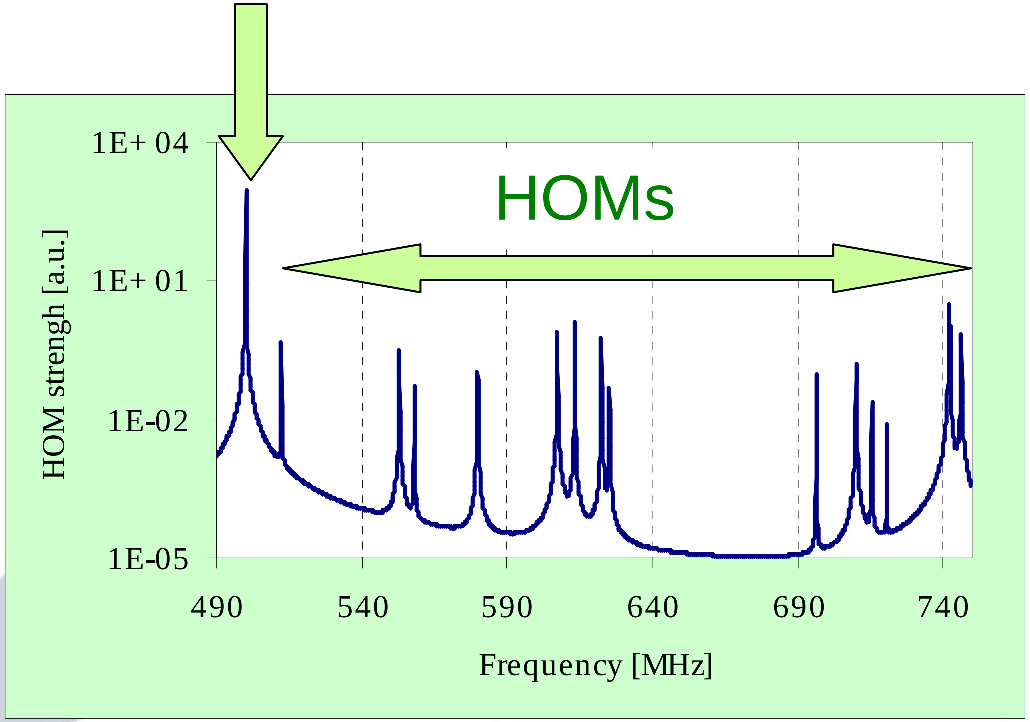
1150 MHz



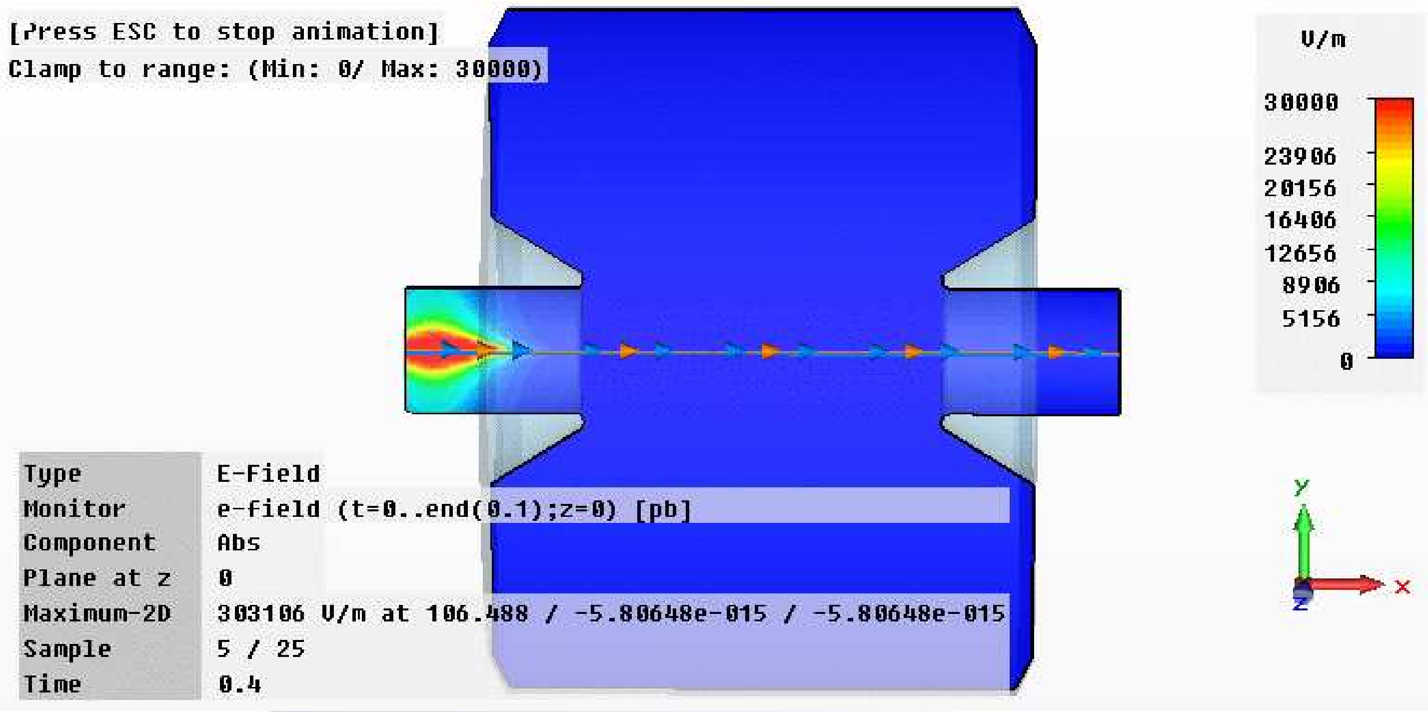


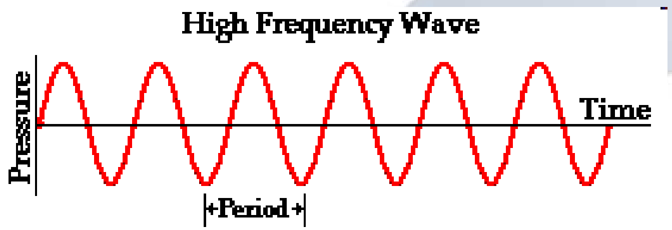
Cavity HOMs

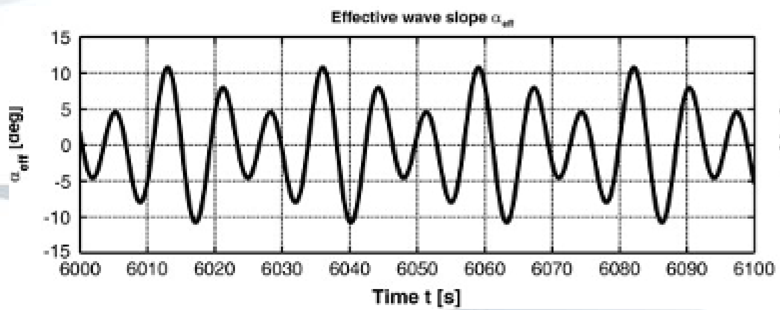
A RF cavity has more than just the
fundamental resonance frequency at 500 MHz



Beam induced HOM power

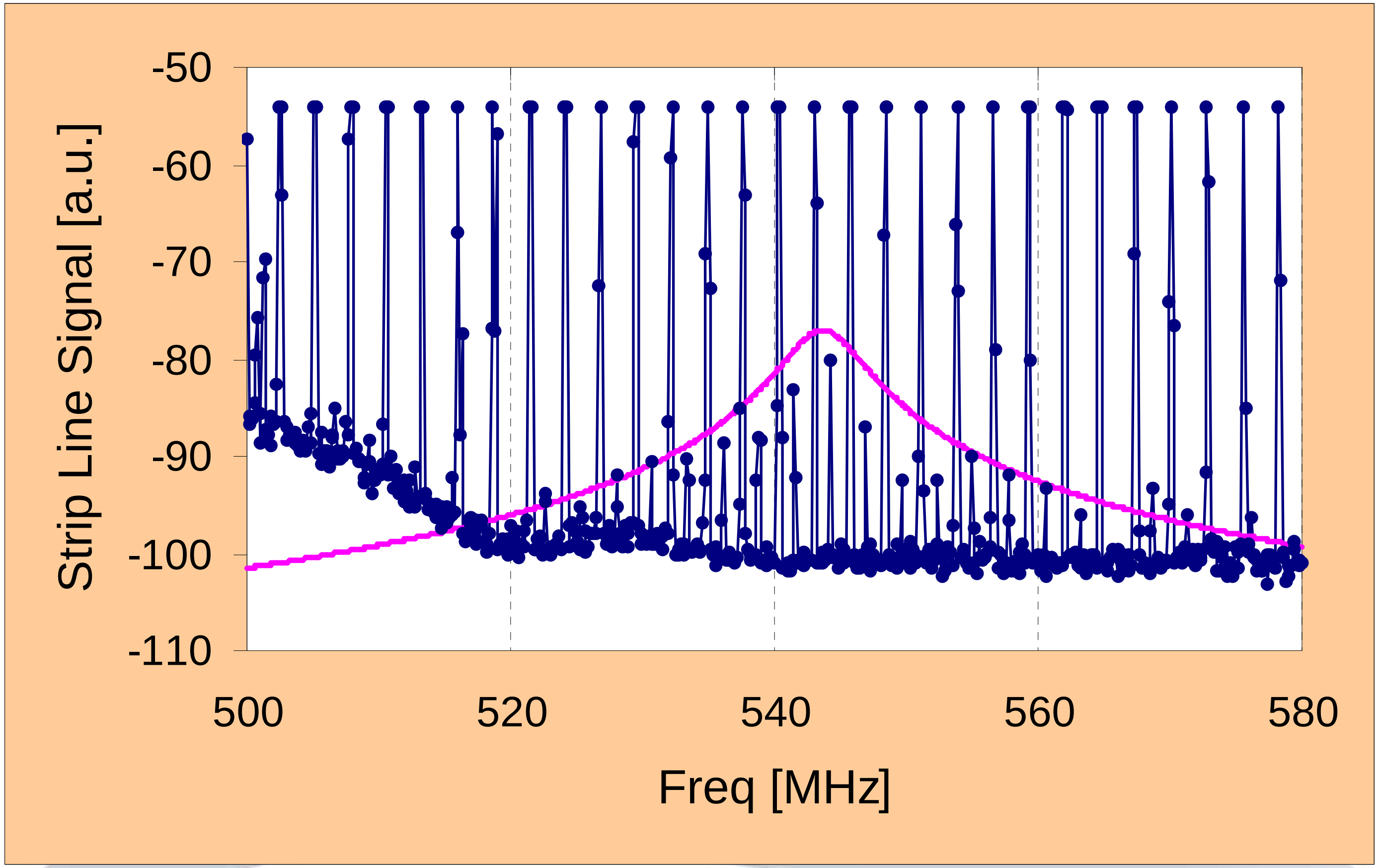






Voltage inside the cavity deforms

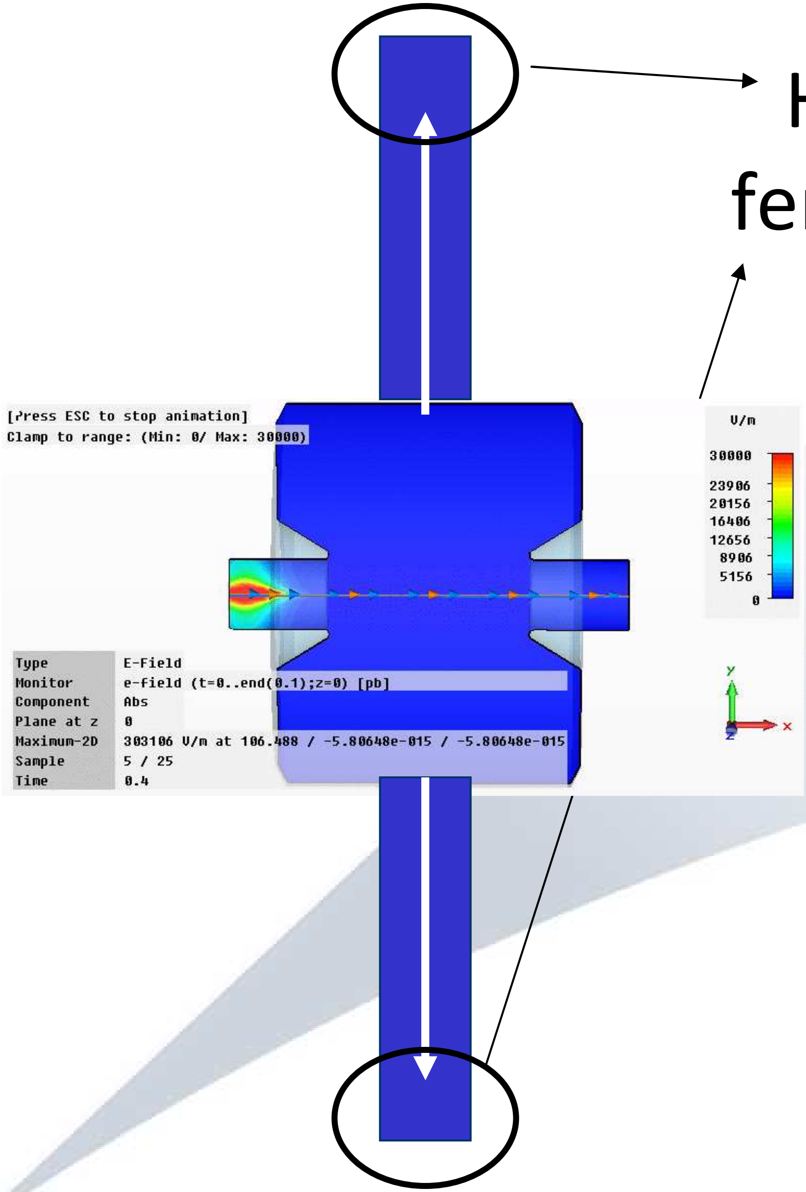
HOM unstability



Beam is unstable around a HOM frequency

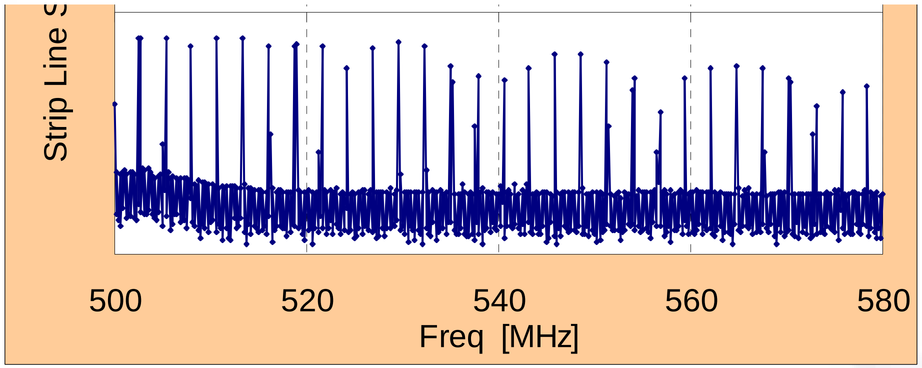
Cavity

Beam induced HOM power



HOM power absorbed in ferrites inside the vacuum…

Beam is stable



Cavity

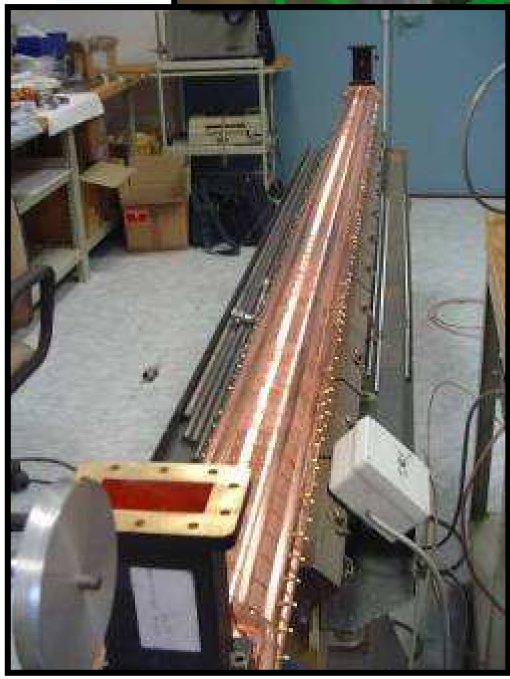
Single cell vs **Multicell**

HOM damping important	HOM damping not so demanding
Normally high current **Storage Rings**	Low current **Injector - Booster**

Cavity

Frequency?

- NC 100 MHz MAXlab
- SC 352 MHz SOLEIL
- NC 500 MHz ALBA
- NC 800 MHz SPS - CERN
- SC 1.3 GHz EU-XFEL
- NC 3 GHz Linacs
- …



Cavity

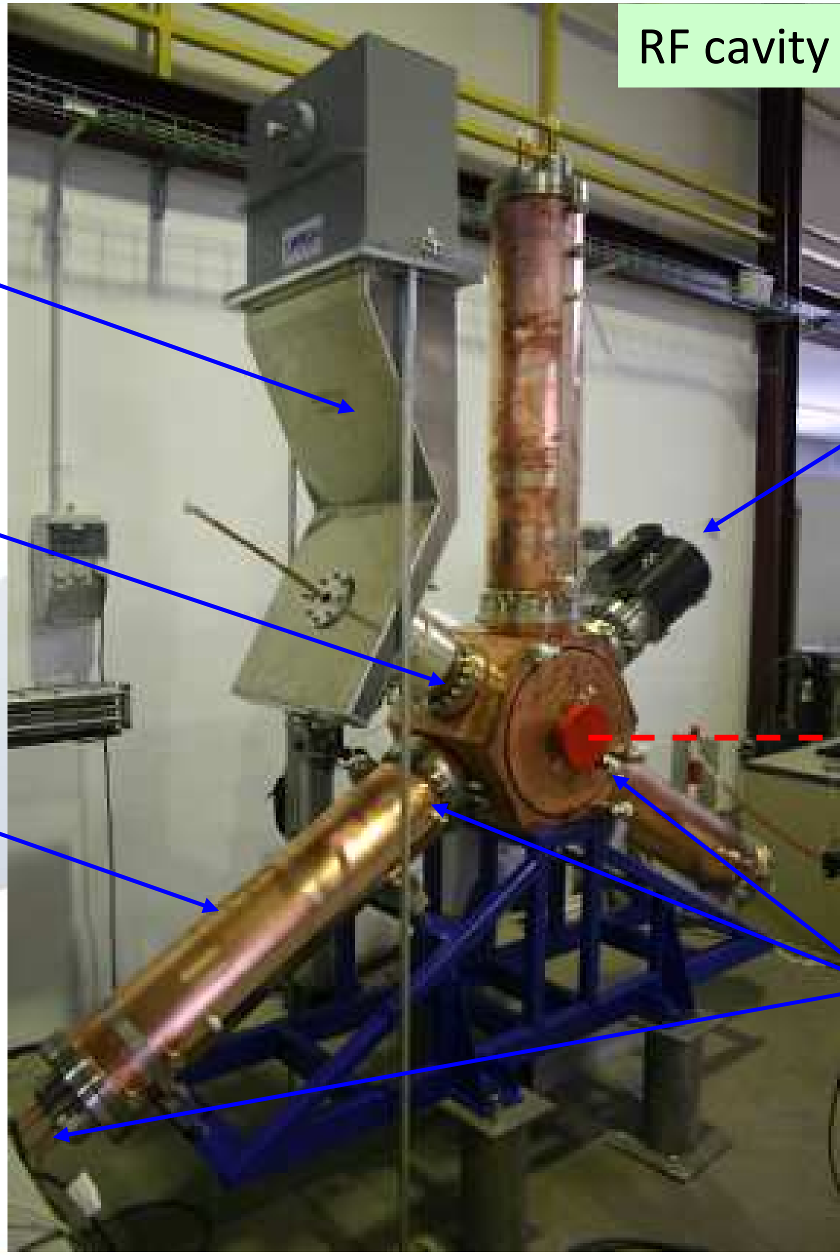
The choice will depend on the application, on the kind of accelerator:

Linear → Single particle passage
Circular → Multi particle passage

Acceleration (booster)
Storage (light source)
Collider
....

⇨ **Decided case by case, but look what others did!**

Parts of a cavity

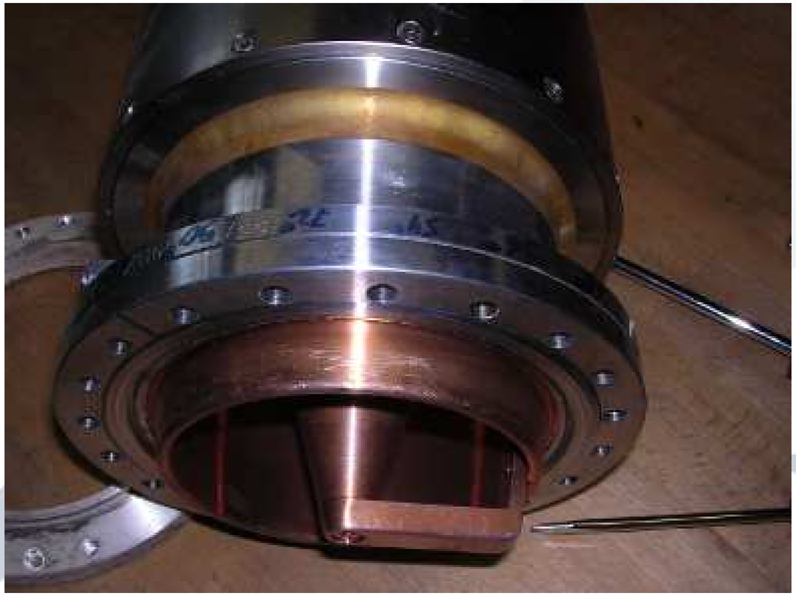


RF window - coupler

Couple the transmission line with the cavity to transfer the power. Coupling can be:

Magnetic (Inductive)

Electric (Capacitive)



Example of a magnetic coupler

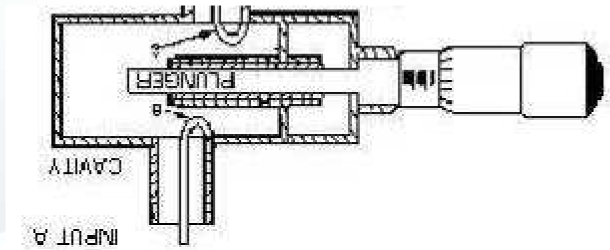
Frequency Tuner

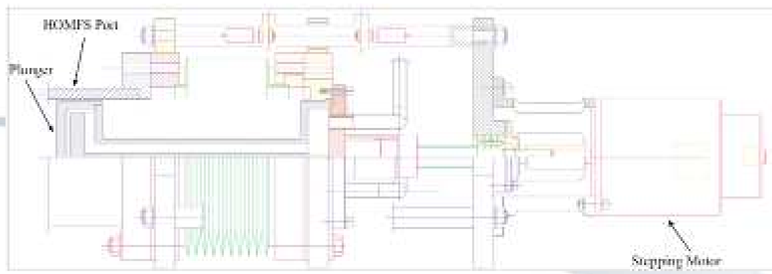
Changes the resonant frequency of the cavity by changing the volume.

Two main types

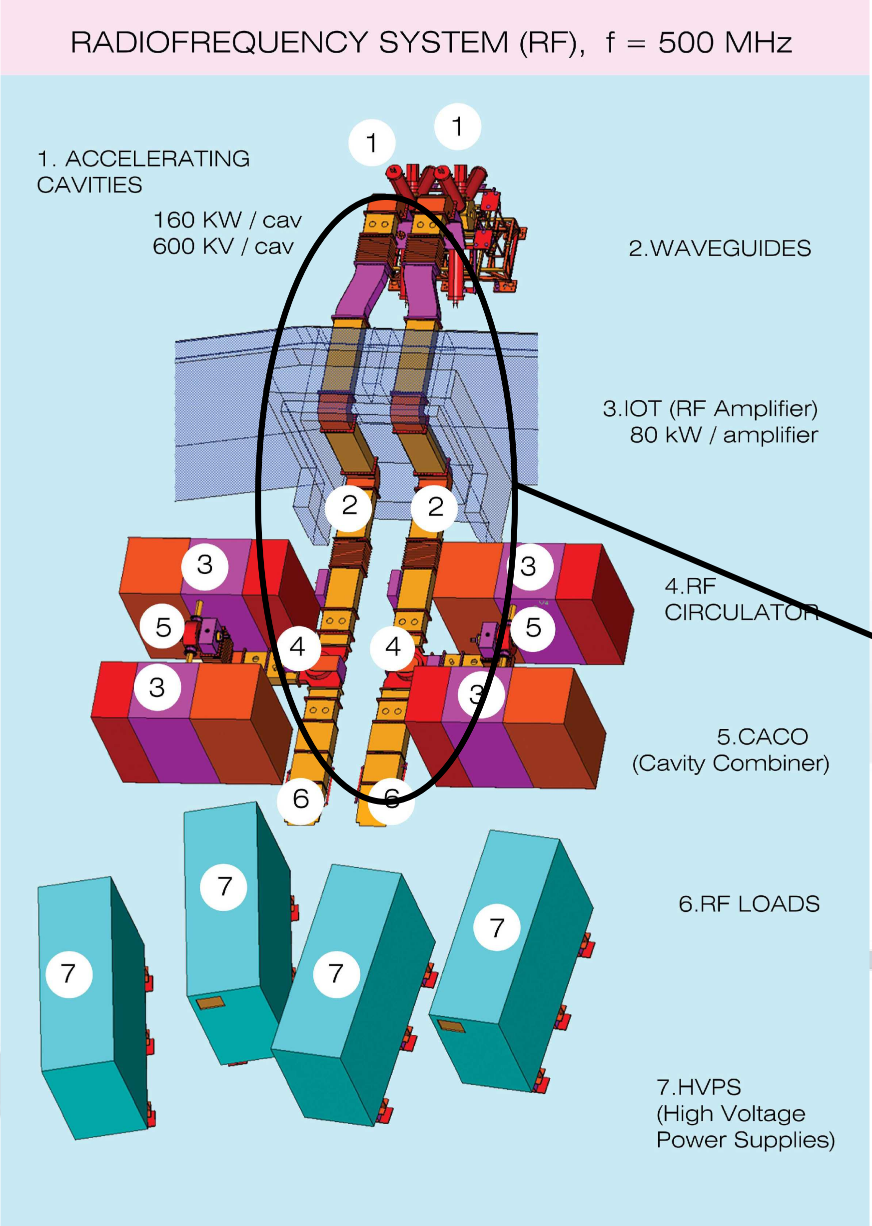
By deformation

By pungler





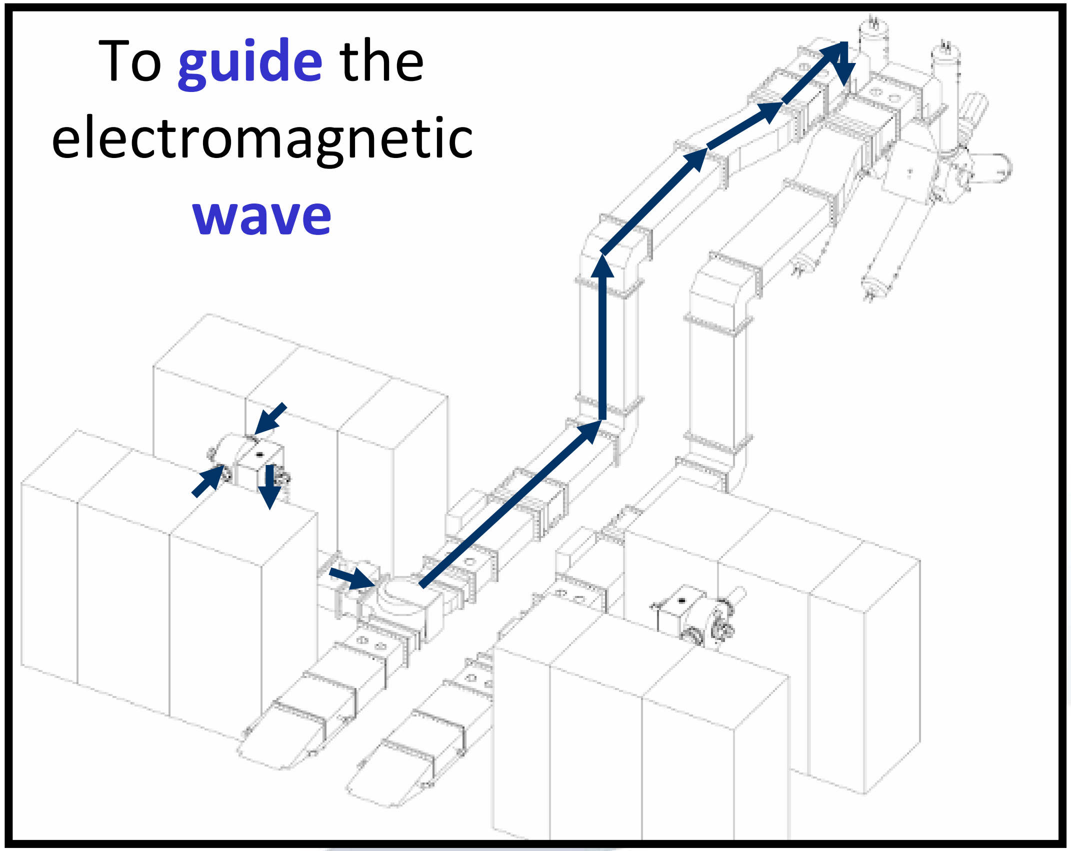
RF transmission system



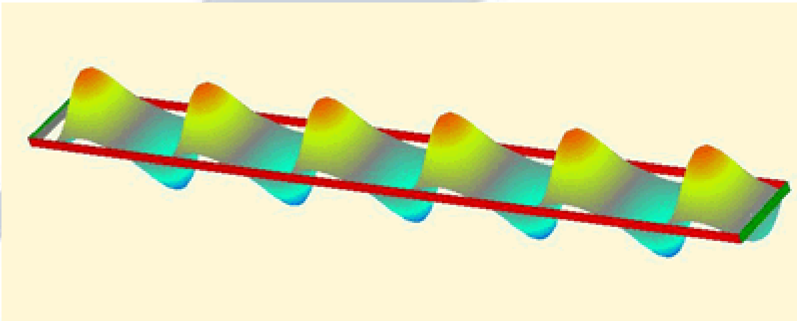
To **guide** the electromagnetic **wave**

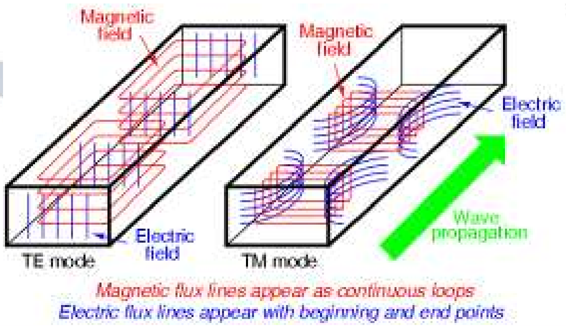
Waveguide system

To **guide** the electromagnetic **wave**



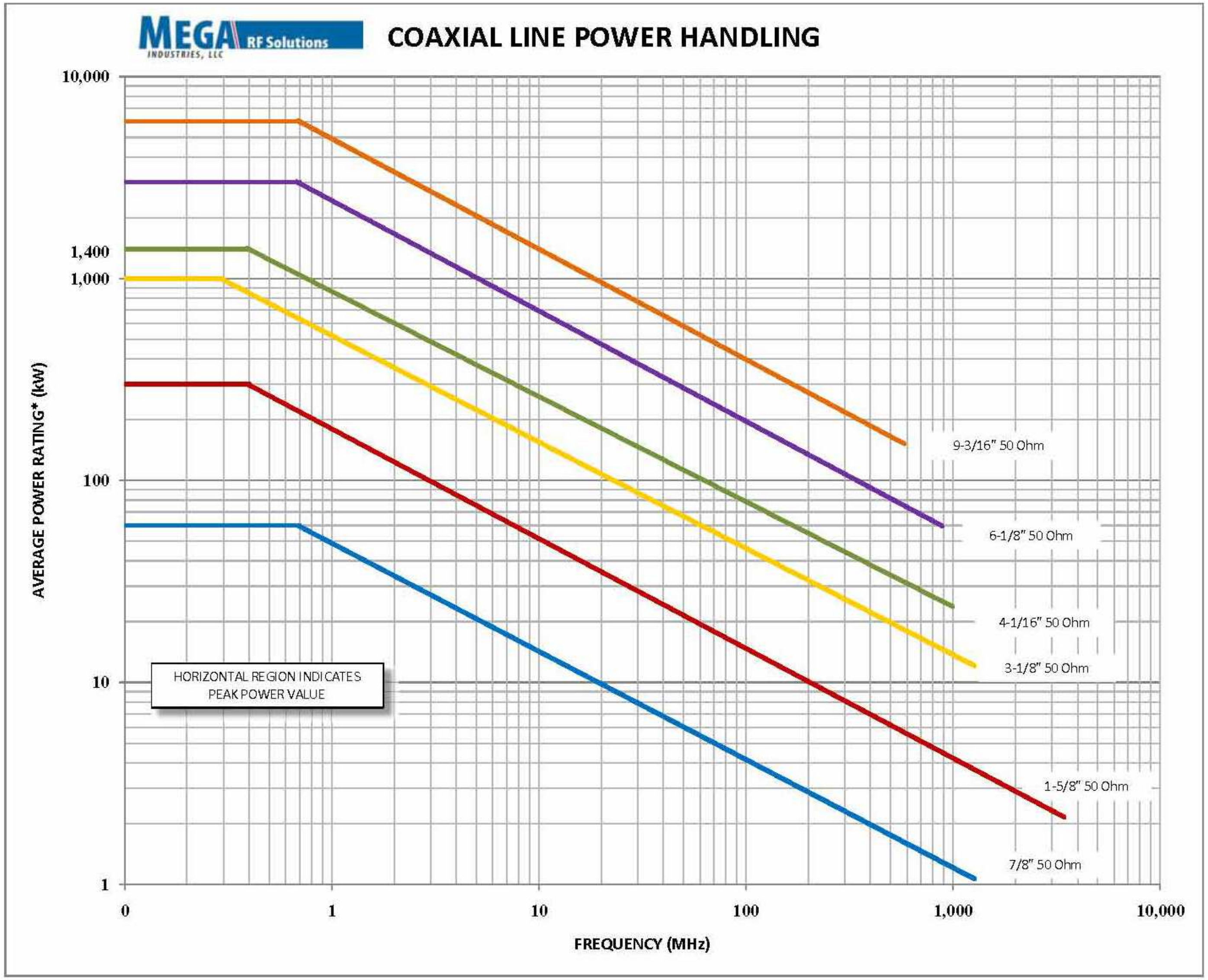
- Combiners/Splitters
- Circulator
- Load
- Waveguide Elements
- Transitions

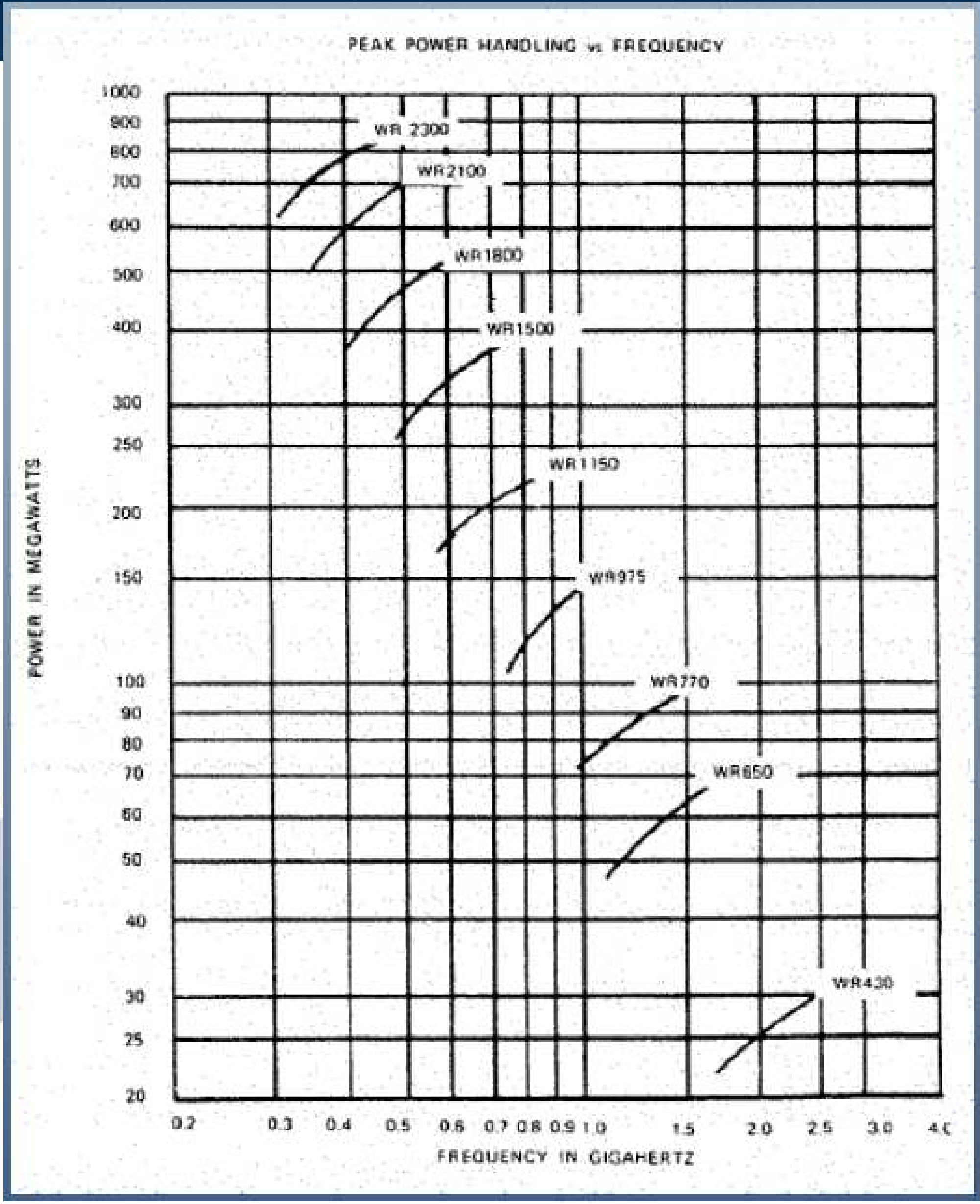




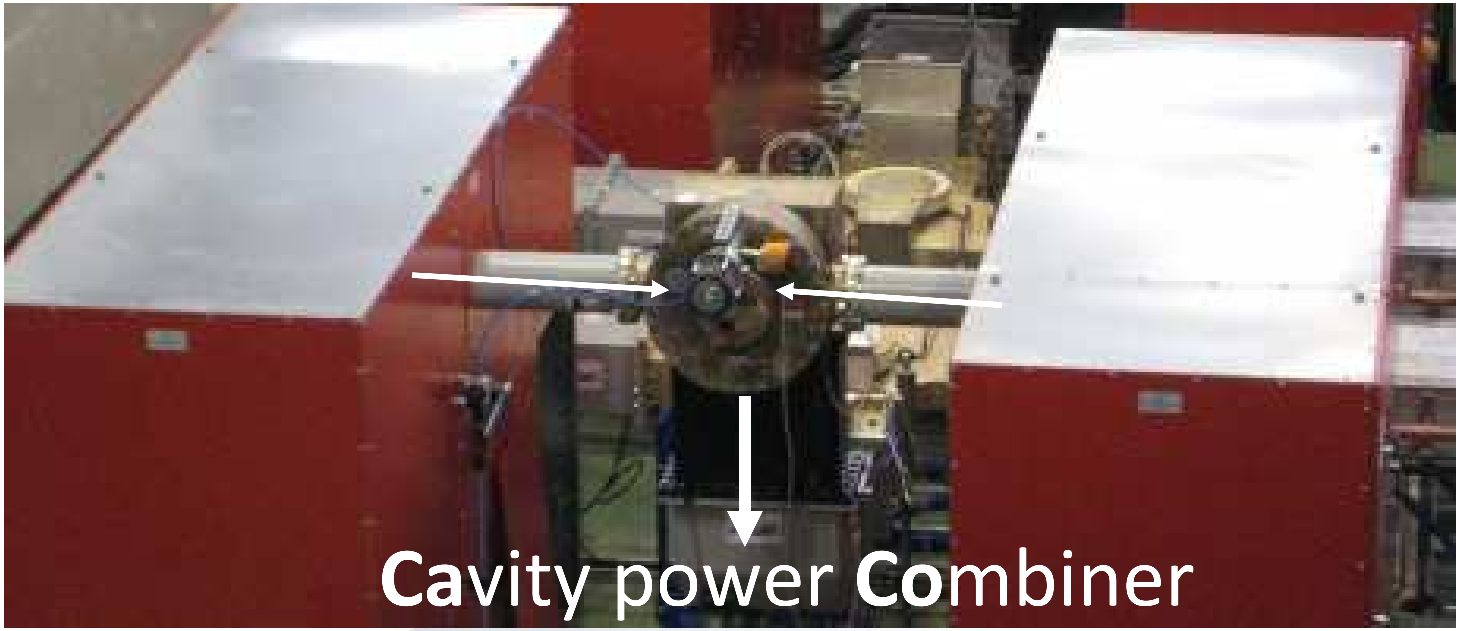
Coaxial vs. Waveguides

- **Coaxial lines**
  - frequency range: 0...10 GHz
  - largest practical size: 350 mm for outer conductor, 150 mm for the inner conductor
  - power rating: for CW operation at 200 MHz: 1 MW
  - low-pass line, upper frequency limit given by moding
  - relatively high attenuation
  - power limited by inner conductor (high field => thermal load)
  - in general easier to handle than waveguides
- **Waveguides**
  - frequency range 0.32...325 GHz (standard guides)
  - largest practical size: 590 mm x 298 mm
  - power rating: 150 MW peak at 310 MHz
  - low attenuation
  - bandpass, low frequency cut-off determined by dimension

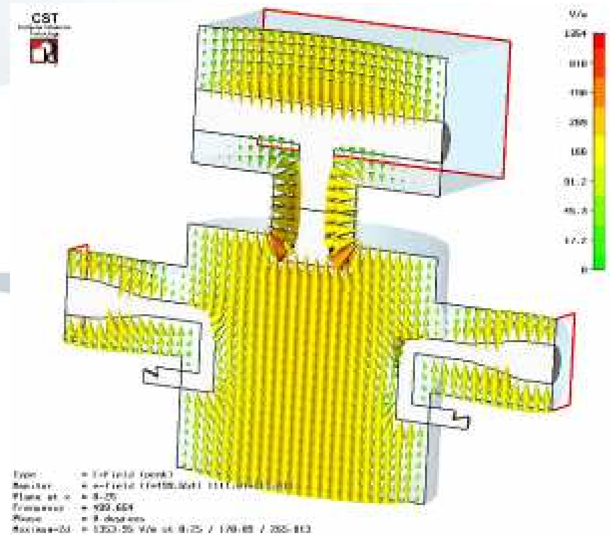

MEGA RF Solutions
INDUSTRIES, LLC
COAXIAL LINE POWER HANDLING
10,000
1,400
1,000
100
10
1
AVERAGE POWER RATING* (kW)
0
1
10
100
1,000
10,000
FREQUENCY (MHz)
9-3/16" 50 Ohm
6-1/8" 50 Ohm
4-1/16" 50 Ohm
3-1/8" 50 Ohm
1-5/8" 50 Ohm
7/8" 50 Ohm
HORIZONTAL REGION INDICATES
PEAK POWER VALUE


PEAK POWER HANDLING vs FREQUENCY
POWER IN MEGAWATTS
FREQUENCY IN GIGAHERTZ
WR 2300
WR2100
WR1800
WR1500
WR1150
WR975
WR770
WR650
WR430
1000
900
800
700
600
500
400
300
250
200
150
100
90
80
70
60
50
40
30
25
20
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.5
2.0
2.5
3.0

Combiner / Splitter

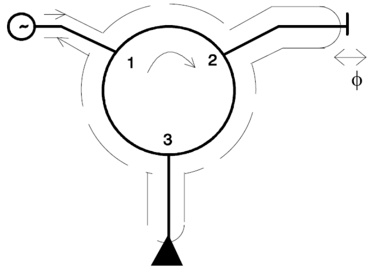


Combines, add, the
power of two or more
amplifiers

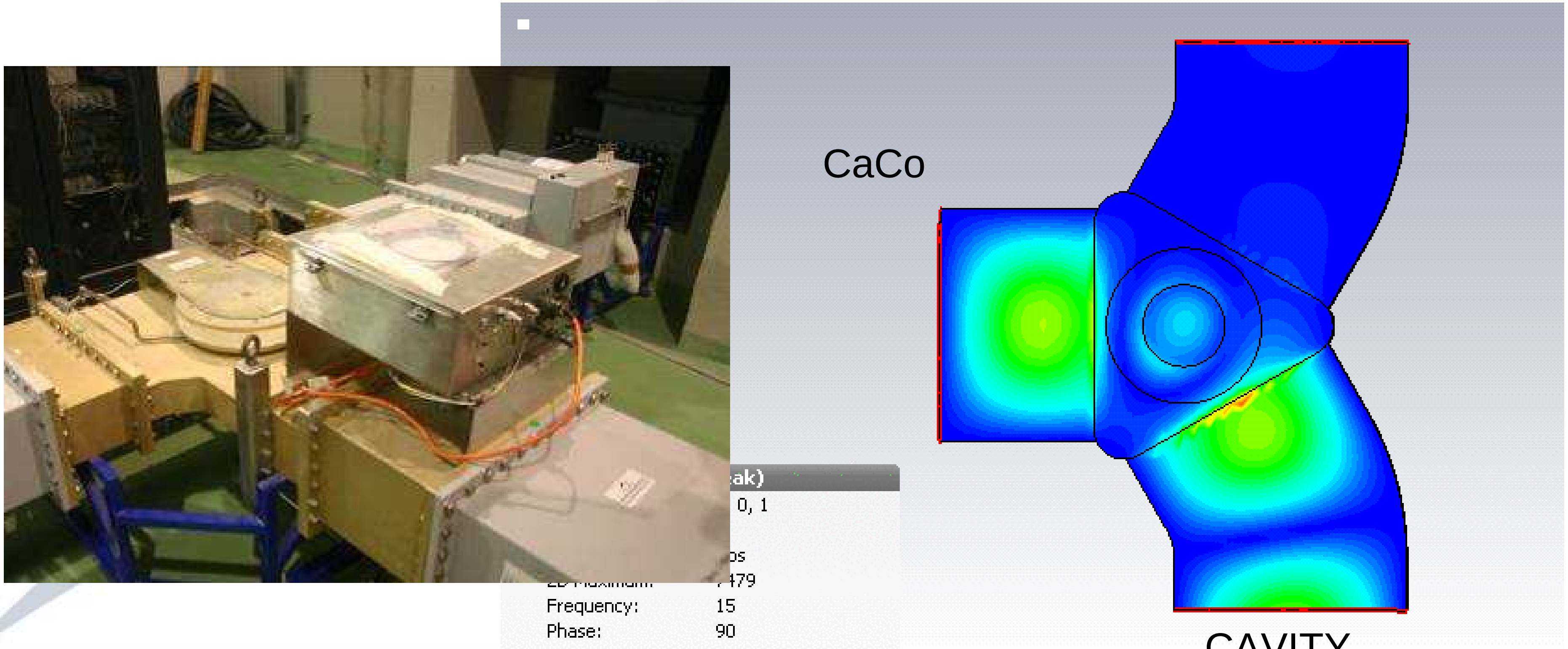


Circulator

It is like a *roundabout*, RF waves should always circulate around in a given direction, and always take the 1st exit



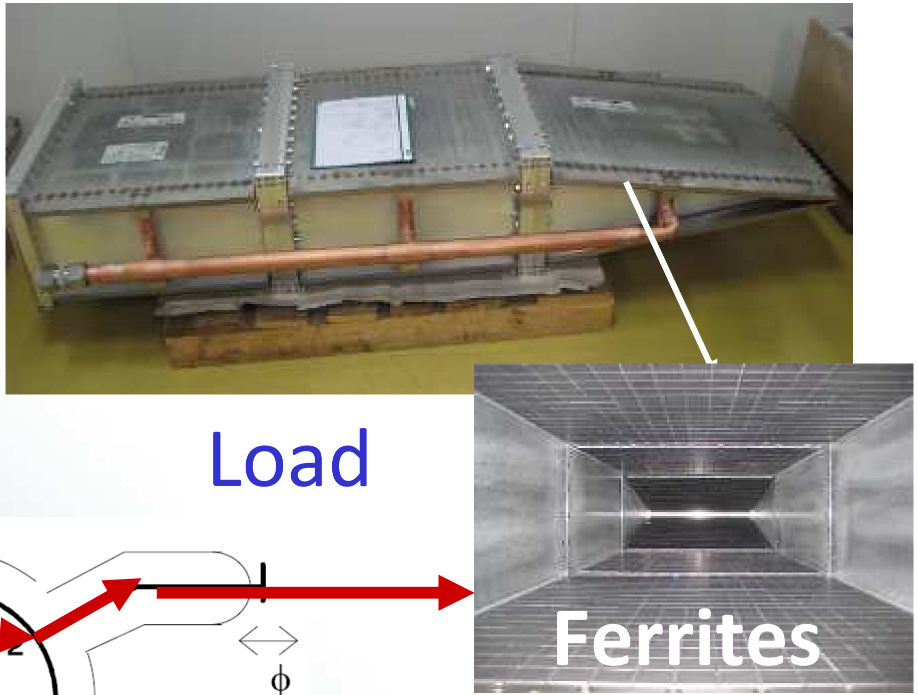
LOAD

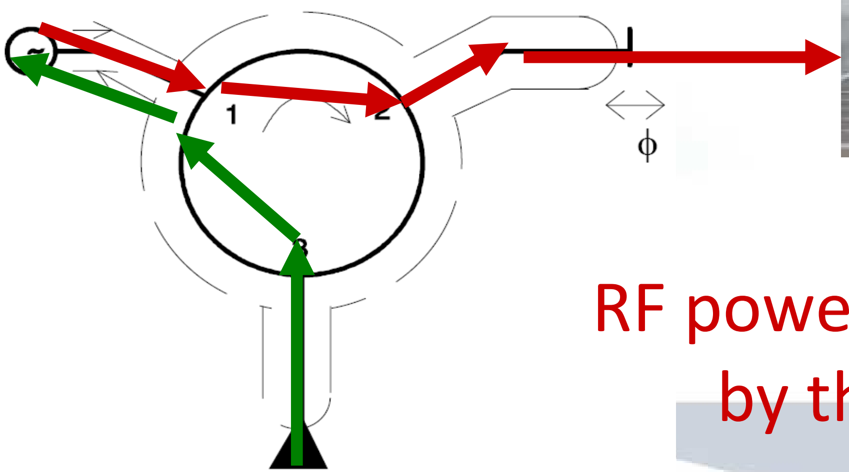


CAVITY

Circulator & Load

It isolates the amplifiers from the behaviour of the cavity





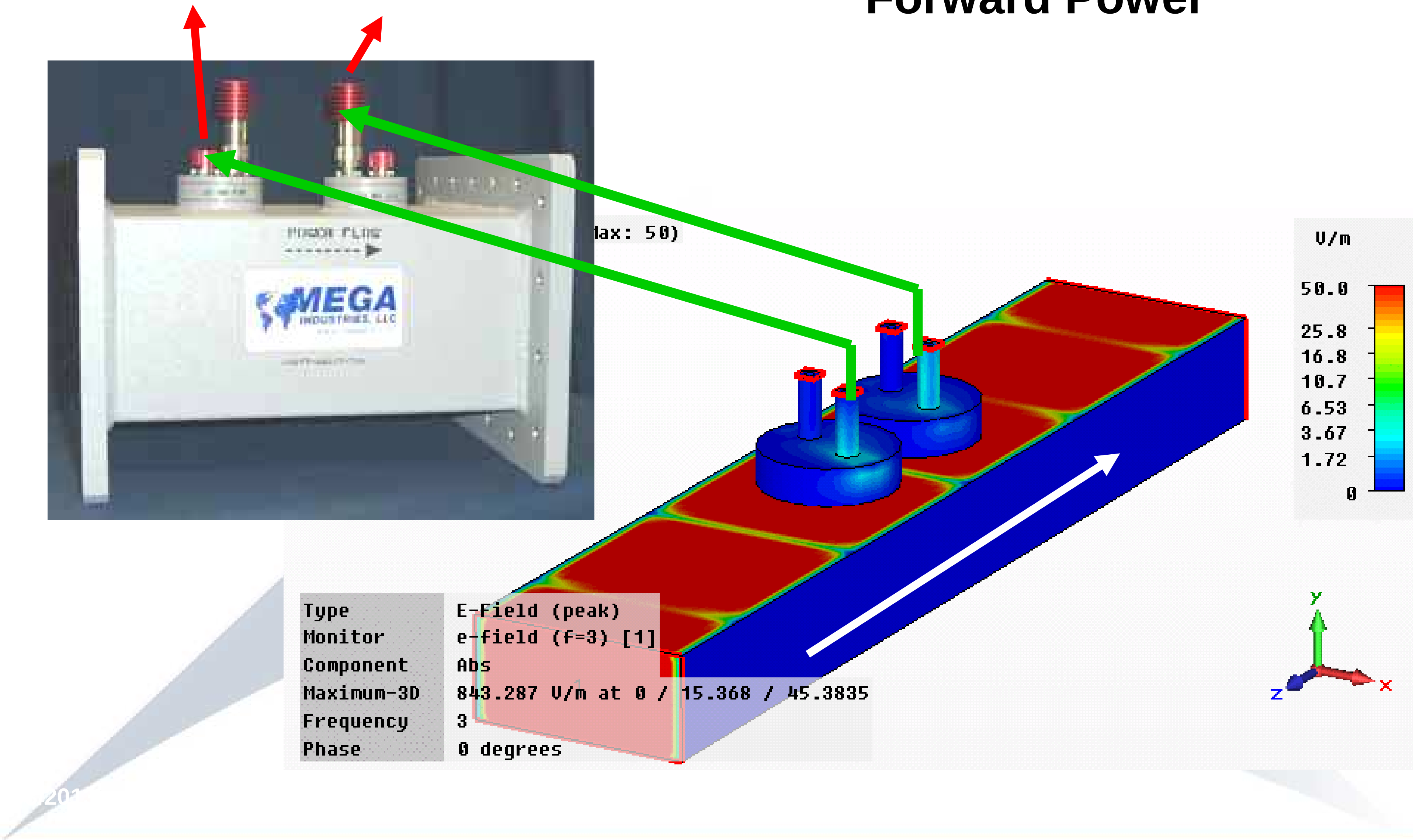
RF power absorbed by the load

Bidirectional Couplers

Forward power measurement

Dissipated load

Forward Power

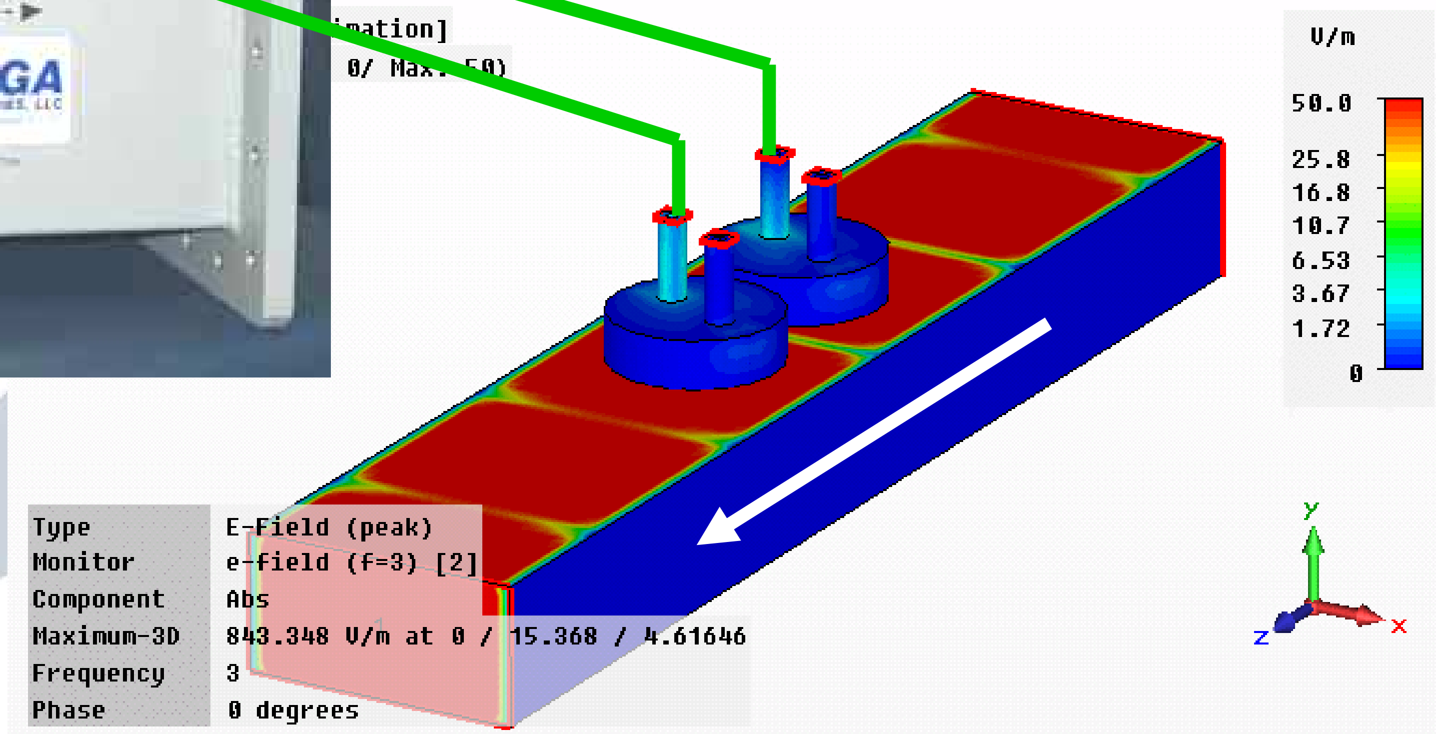


Bidirectional Couplers

Dissipated load

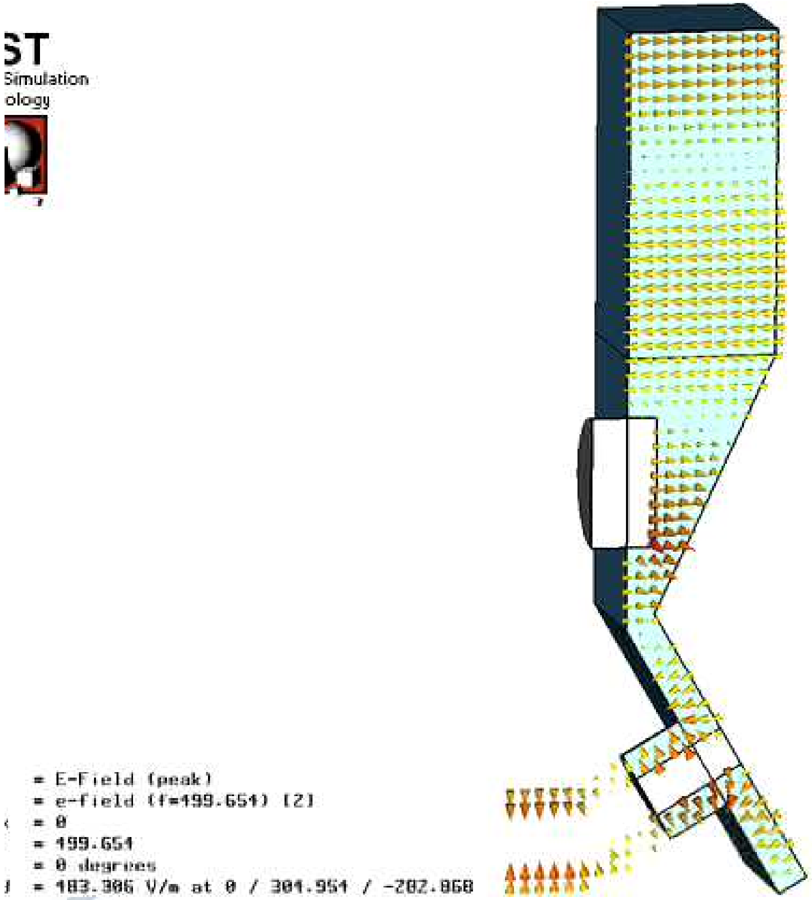
Reverse power measurement

Reverse Power



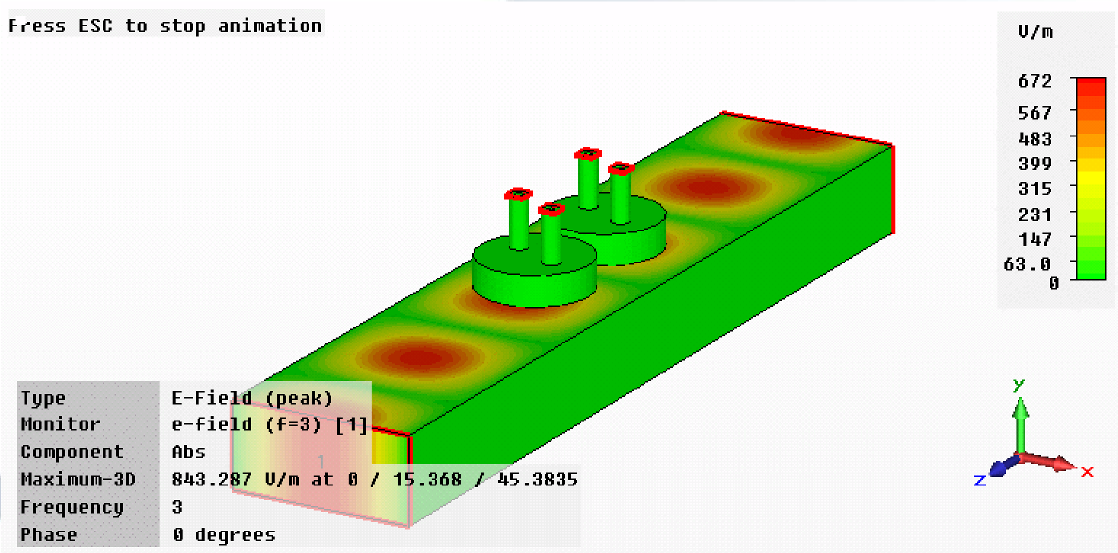
Transitions

Feed the RF power
into the cavity



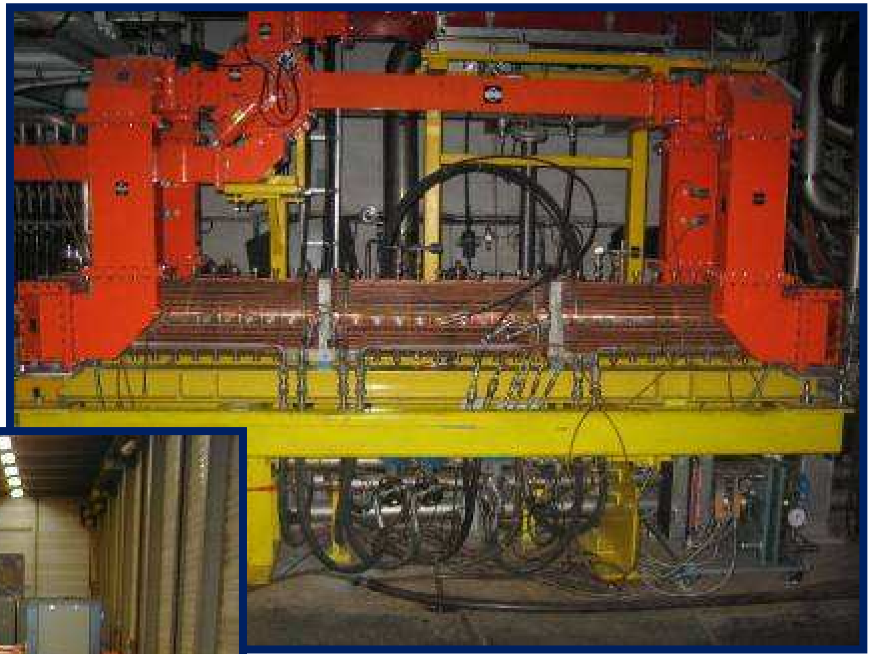
Other components

Rectangular Waveguide (WR1800 for 150 kW cw):



Like a LEGO

Many configurations



From CERN

Thank you

Questions?