RF Waveguide Distribution

S. Simrock & Z. Geng, 6th International Accelerator School for Linear Colliders, USA, 2011

RF Power Waveguide Distribution (1)

- Distribution of klystron output power to the superconducting cavities

- Protection of the klystron from reflected power

- Control of phase and Q_{ext}

RF Power Waveguide Distribution (2)

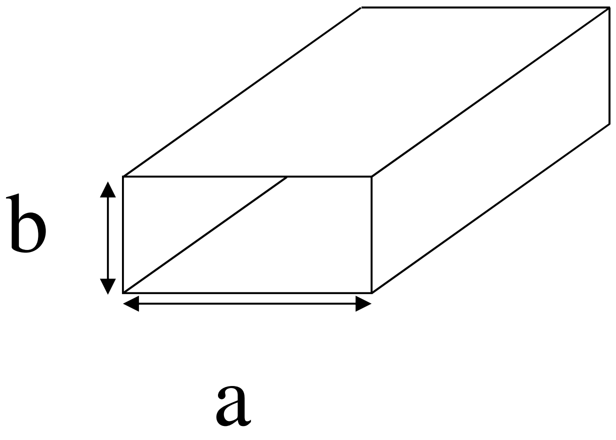
Distribution of RF power is done by:

- Waveguides: high power possible, low loss up to certain frequencies

Other devices which are not used:

- Coaxial lines: power loss is high, heating of the inner conductor or the dielectric material
- Parallel wires: radiation into the environment
- Striplines: breakdown limit at high power is low, in use for low power applications e.g. integrated circuits

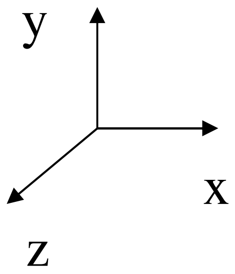
Rectangular Waveguide



Which electromagnetic waves (frequencies, modes) can propagate?

- Start with Maxwell Equation
- Solve wave equation with boundary conditions:

Two types of solutions:



- TE (H-Wave): $E_z=0$ $H_z \neq 0$
- TM (E-Wave): $E_z \neq 0$ $H_z=0$
- The TE and TM waves can be classified due to the number of field maxima in the x and y direction:
  TE_{nm} (H_{nm}) and TM_{nm} (E_{nm})

Cut off wavelength

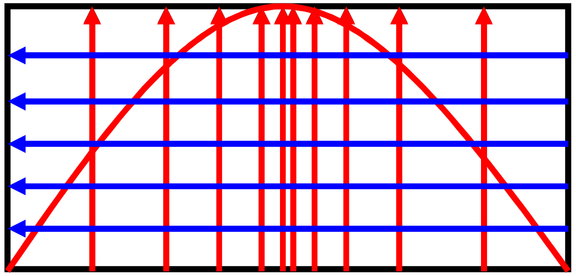
- In a rectangular waveguide only nm- modes below (above) a certain wavelength l_{cnm} (frequency n_{cnm}) can propagate.

$$\lambda_{cnm}=\frac{2}{\sqrt{\left(\frac{n}{a}\right)^2+\left(\frac{m}{b}\right)^2}}$$

$$\upsilon_{cnm}=c\frac{\sqrt{\left(\frac{n}{a}\right)^2+\left(\frac{m}{b}\right)^2}}{2}$$

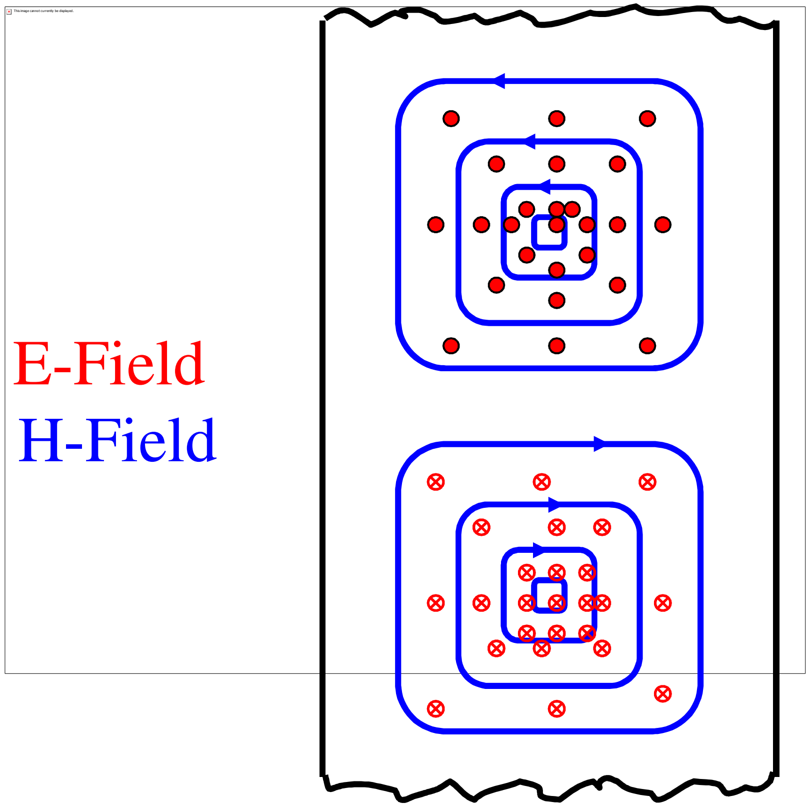
Rectangular Waveguides

- The mode with lowest frequency propagating in the waveguide is the TE_{10} (H_{10}) mode.



Cutoff Frequency:

n_{c10}=c/2a



Waveguide Size for 1.3GHz

- Most common are 2:1 waveguides a=2b, for 1.3GHz the following waveguides would be appropriate

- WR650 (proposed for ILC) a=6.5inch b=3.25inch n_{c10}=908MHz

- WR770 a=7.7inch b=3.85inch
  n_{c10}=767MHz

Attenuation of TE_{10}

- Due to losses in the walls of the waveguides the wave is attenuated.

- The attenuation constant is:

$$\alpha[dB/m] = 0.2026\, k_1 \frac{1}{b[cm]\sqrt{\lambda\ [cm]}} \frac{\frac{1}{2} + \frac{b}{a}\left(\frac{\lambda}{2a}\right)^2}{\sqrt{1 - \left(\frac{\lambda}{2a}\right)^2}}$$

k_1= 1.00 Ag, 1.03 Cu, 1.17 Au, 1.37 Al, 2.2 Brass

Phase constant and Impedance of TE$_{10}$

$$\beta_g = \sqrt{k^2 - (\pi / a)^2} \quad \text{with} \quad k = 2\pi / \lambda$$

- b_g phase constant of the waveguide wave and k phase constant in free space

$$\lambda_g = 2\pi / \beta_g$$

- l_g is the distance between two equal phase planes along the waveguide and is longer than l

- The impedance Z of the waveguide is

$$Z = \frac{377\Omega}{\sqrt{1 - \left(\lambda / \lambda_{c10} \right)^2}}$$

Power in TE_{10}

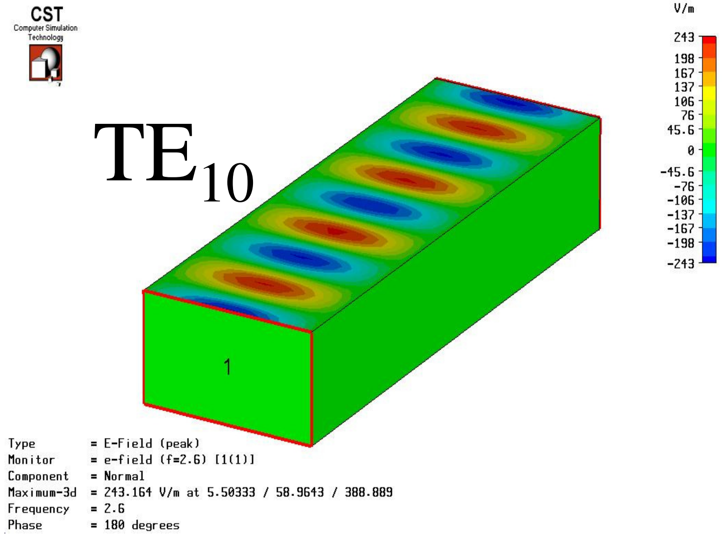
$$P_{RF} = 6.63 \times 10^{-4}\, a[cm]\, b[cm] \left[\lambda / \lambda_g \right] E[V/cm]^2$$

- The maximum power which can be transmitted theoretically in a waveguide of certain size a, b and wavelength l is determined by the breakdown limit E_{max}.

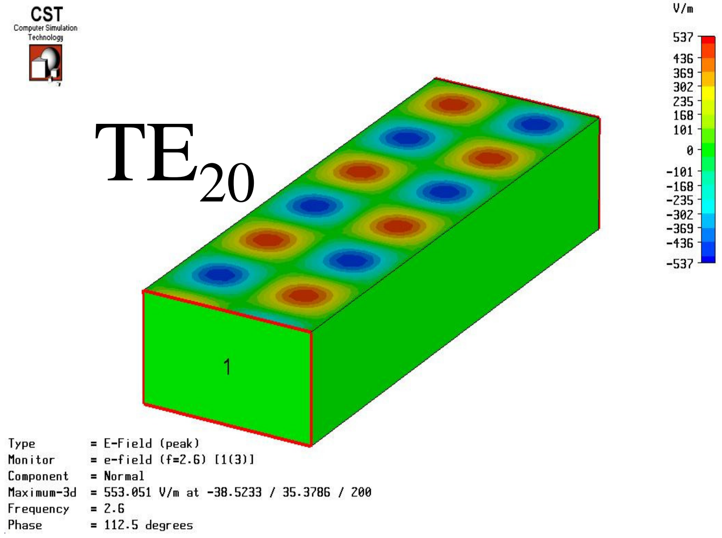
- In air it is E_{max}=32kV/cm and in SF6 it is E_{max}=89kV/cm (1bar, 20°C). Problem with SF6 is that although it is chemically very stable (1) it is a green house gas and (2) if cracked in sparcs products can form HF which is a very aggressive acid.

- The practical power limit is lower, typically 5-10 times lower, because of surface effects (roughness, steps at flanges etc.), dust in waveguides, huminity, reflections (VSWR) or because of higher order modes TE_{nm}/TM_{nm}. These HOMs are also generated by the power source. If these modes are not damped, they can be excited resonantly and reach very high field strength above the breakdown limit.

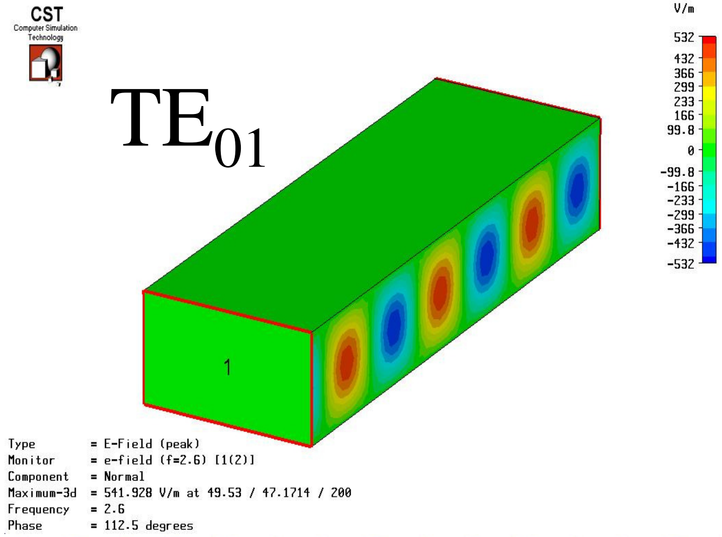
Straight Waveguide (1)



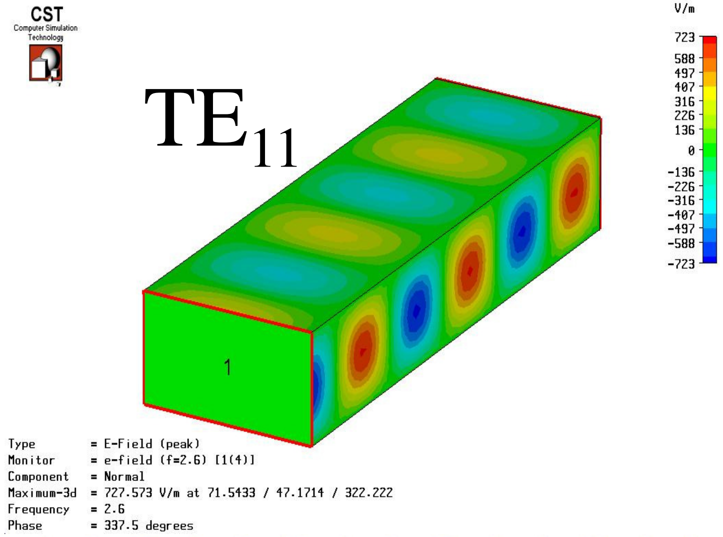
```
Type        = E-Field (peak)
Monitor     = e-field (f=2.6) [1(1)]
Component   = Normal
Maximum-3d  = 243.164 V/m at 5.50333 / 58.9643 / 388.889
Frequency   = 2.6
Phase       = 180 degrees
```



```
Type        = E-Field (peak)
Monitor     = e-field (f=2.6) [1(3)]
Component   = Normal
Maximum-3d  = 553.051 V/m at -38.5233 / 35.3786 / 200
Frequency   = 2.6
Phase       = 112.5 degrees
```

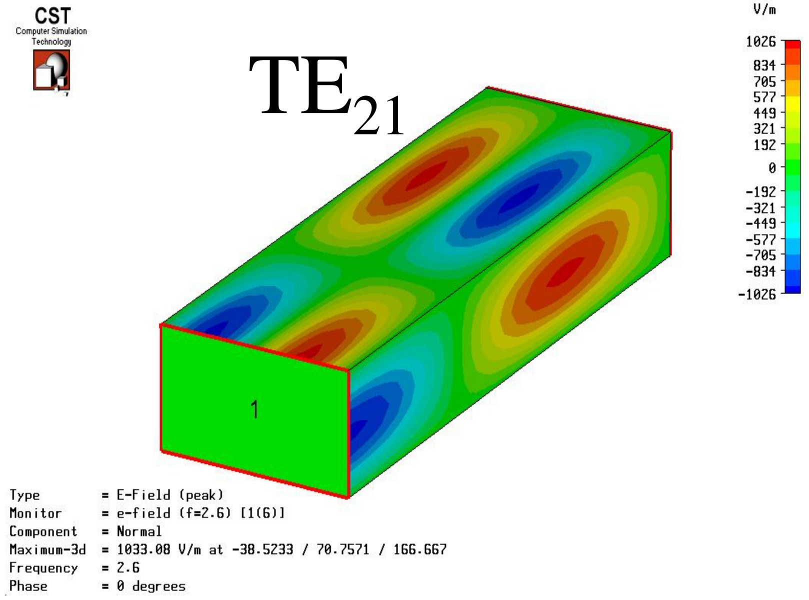


```
Type        = E-Field (peak)
Monitor     = e-field (f=2.6) [1(2)]
Component   = Normal
Maximum-3d  = 541.928 V/m at 49.53 / 47.1714 / 200
Frequency   = 2.6
Phase       = 112.5 degrees
```



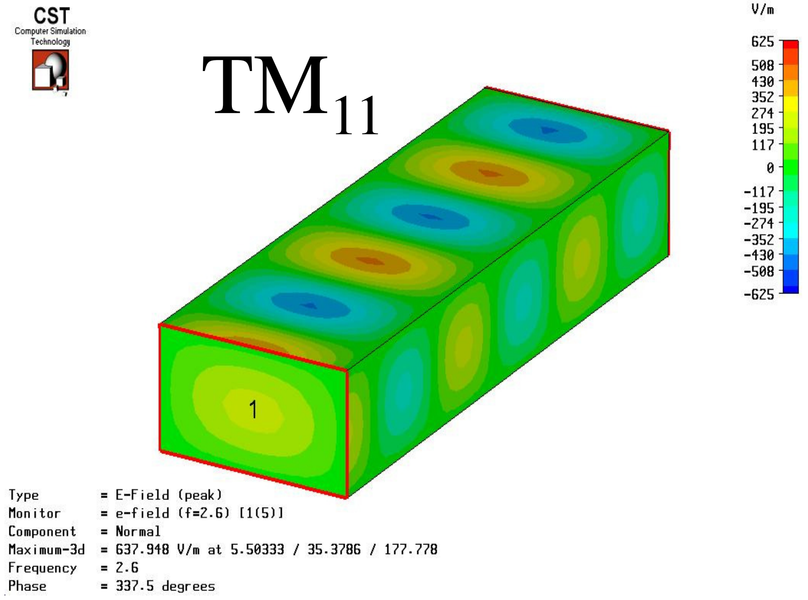
```
Type        = E-Field (peak)
Monitor     = e-field (f=2.6) [1(4)]
Component   = Normal
Maximum-3d  = 727.573 V/m at 71.5433 / 47.1714 / 322.222
Frequency   = 2.6
Phase       = 337.5 degrees
```

Straight Waveguide (2)



TE$_{21}$

```
Type         = E-Field (peak)
Monitor      = e-field (f=2.6) [1(6)]
Component    = Normal
Maximum-3d   = 1033.08 V/m at -38.5233 / 70.7571 / 166.667
Frequency    = 2.6
Phase        = 0 degrees
```

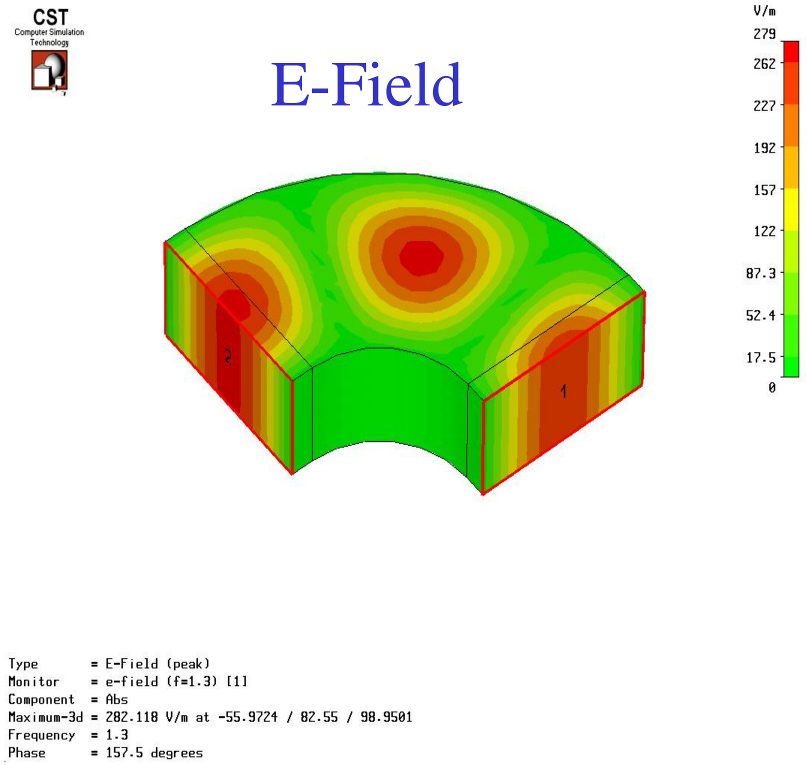


TM$_{11}$

```
Type         = E-Field (peak)
Monitor      = e-field (f=2.6) [1(5)]
Component    = Normal
Maximum-3d   = 637.948 V/m at 5.50333 / 35.3786 / 177.778
Frequency    = 2.6
Phase        = 337.5 degrees
```

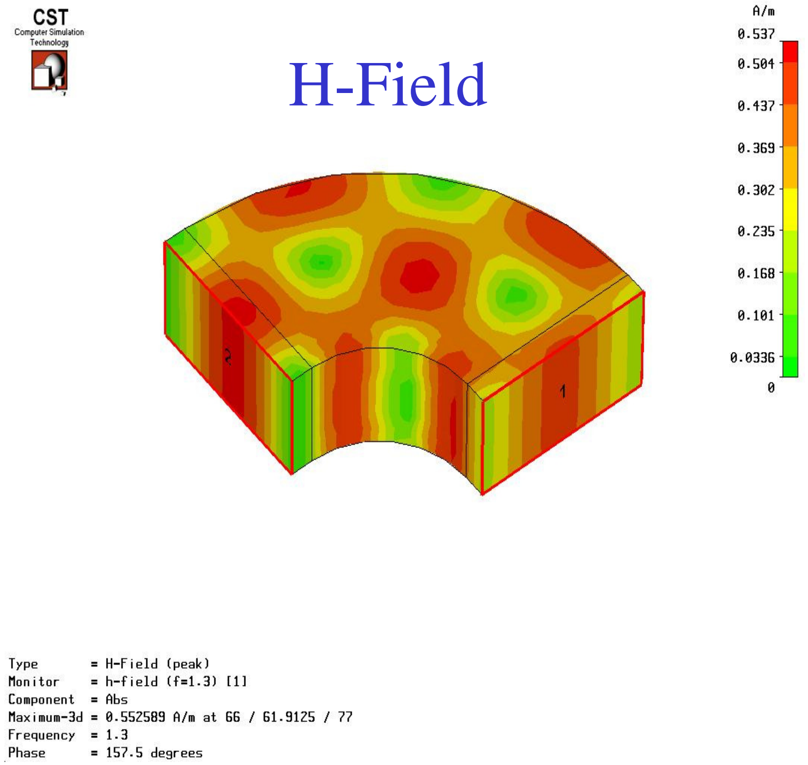
H-Bends

E-Field



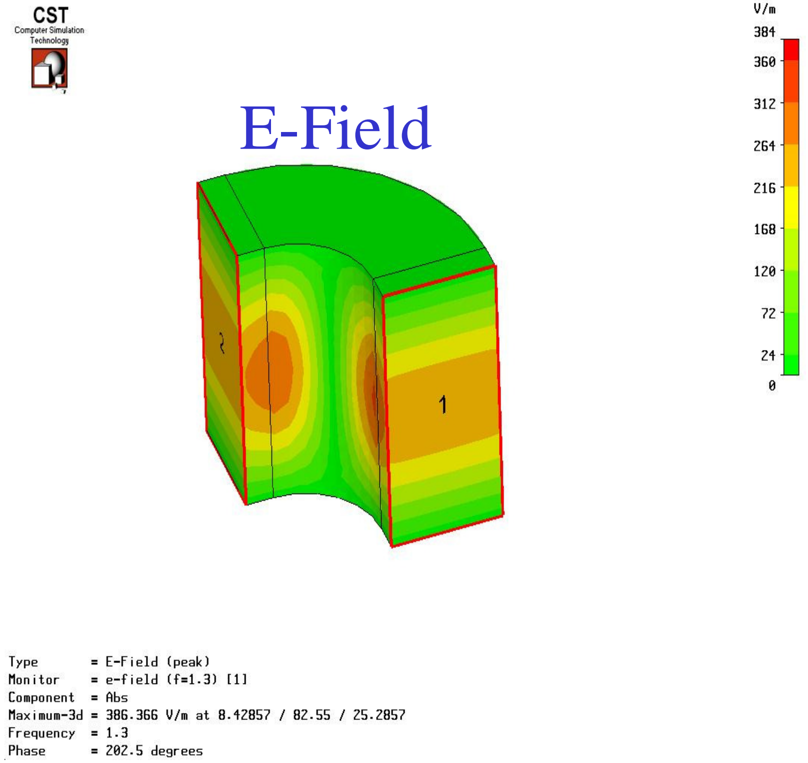
```
Type        = E-Field (peak)
Monitor     = e-field (f=1.3) [1]
Component   = Abs
Maximum-3d  = 282.118 V/m at -55.9724 / 82.55 / 98.9501
Frequency   = 1.3
Phase       = 157.5 degrees
```

H-Field



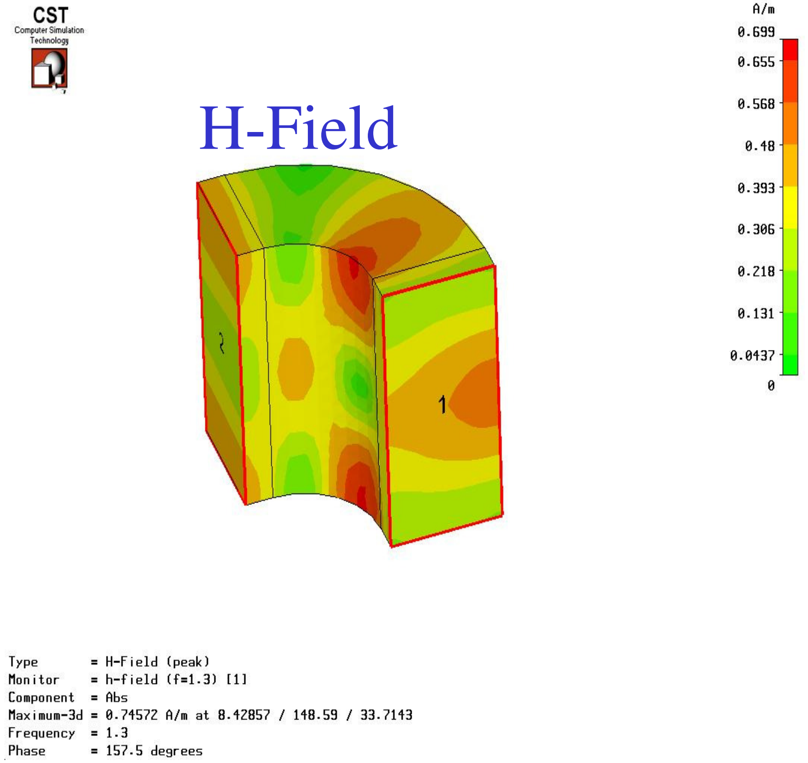
```
Type        = H-Field (peak)
Monitor     = h-field (f=1.3) [1]
Component   = Abs
Maximum-3d  = 0.552589 A/m at 66 / 61.9125 / 77
Frequency   = 1.3
Phase       = 157.5 degrees
```

E-Bends



E-Field

```
Type        = E-Field (peak)
Monitor     = e-field (f=1.3) [1]
Component   = Abs
Maximum-3d  = 386.366 V/m at 8.42857 / 82.55 / 25.2857
Frequency   = 1.3
Phase       = 202.5 degrees
```



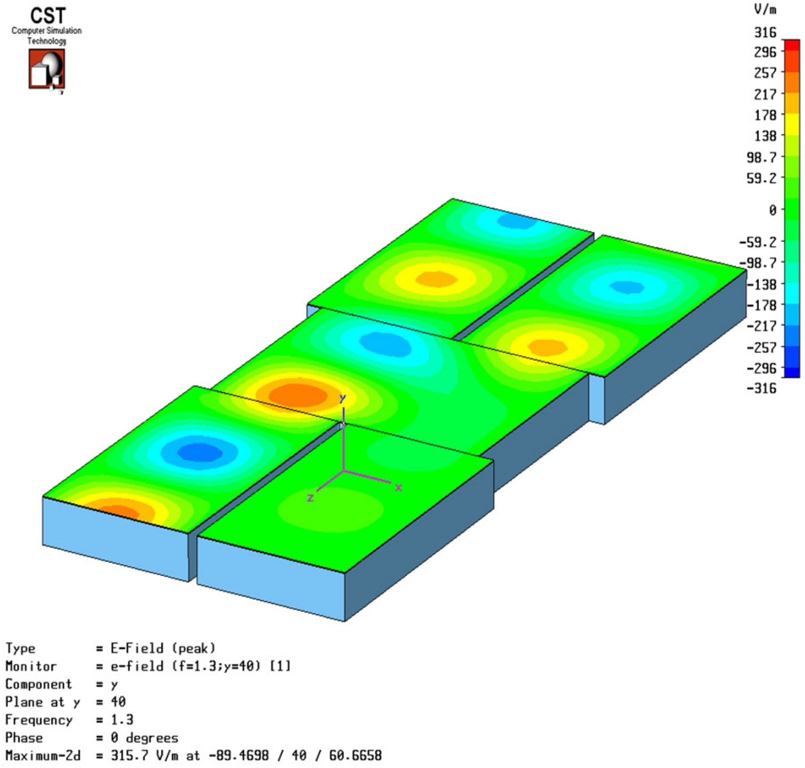
H-Field

```
Type        = H-Field (peak)
Monitor     = h-field (f=1.3) [1]
Component   = Abs
Maximum-3d  = 0.74572 A/m at 8.42857 / 148.59 / 33.7143
Frequency   = 1.3
Phase       = 157.5 degrees
```

Power Coupler

- Power Coupler are used to couple out a certain amount of power from a main waveguide arm

- Hybrids, Magic Tees, Shunt Tees, Series Tees might be used

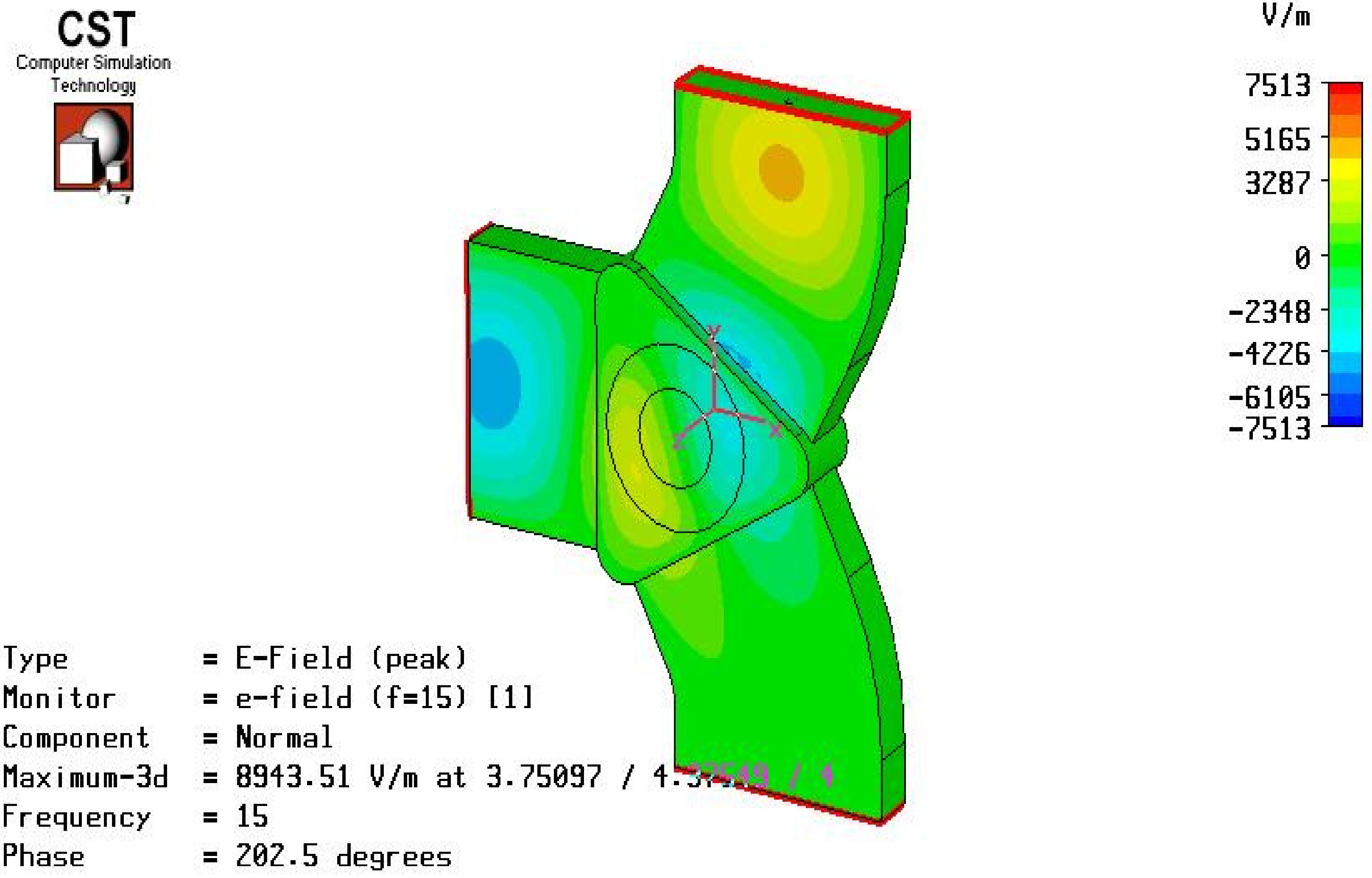


```
Type          = E-Field (peak)
Monitor       = e-field (f=1.3;y=40) [1]
Component     = y
Plane at y    = 40
Frequency     = 1.3
Phase         = 0 degrees
Maximum-2d    = 315.7 V/m at -89.4698 / 40 / 60.6658
```

Circulator (1)

- A circulator is a device, which has an input port (1), output port (2) and load port (3). If power is entering (1) it is transfered to port (2), but if power is entering (2) it is tranfered to (3) and than absorbed in a load.
- The ciculator protects the RF source from reflected power.
- Circulators make use of ferrite material in the waveguide which is pre-magnetized by an external magnetic field.
- The interaction of the H-vector of the RF field with the permanent magnets of the ferrites are responsible for the directive properties of a ciculator.
- The height in a circulator is reduced due to the ferrite plates. Therefore the breakdown limit and thus the power capability is reduced. In a WR650 waveguide and air it is ~500kW.

Circulator (2)



```
Type          = E-Field (peak)
Monitor       = e-field (f=15) [1]
Component     = Normal
Maximum-3d    = 8943.51 V/m at 3.75097 / 4.37549 / 4
Frequency     = 15
Phase         = 202.5 degrees
```

Loads

- Loads absorb the power generated by an RF source
- Absorbing material can be ferrite, SiC or water.
- The amount of power reflected by a load is described by the VSWR defined as

$$VSWR = \frac{|E_f| + |E_r|}{|E_f| - |E_r|} = \frac{1+\rho}{1-\rho}$$

and

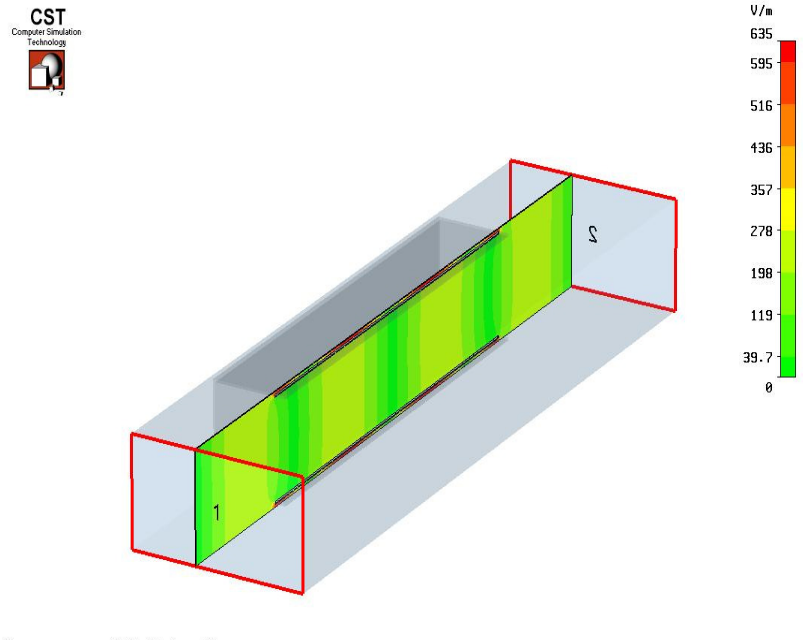
$$\rho = \frac{Z_L - Z}{Z_L + Z}$$

With Z waveguide impedance of the waveguide and Z_L load impedance

Phase Shifter

- By adjusting the dimensions of the waveguide e.g. the width a changes and therefore the phase constant changes.

$$\beta_g = \sqrt{k^2 - (\pi / a)^2}$$



```
Type         = E-Field (peak)
Monitor      = e-field (f=1.3;x=-b) [1]
Component    = Abs
Plane at x   = -21.15
Frequency    = 1.3
Phase        = 90 degrees
Maximum-2d   = 634.757 V/m at -21.15 / 0 / 64.6887
```

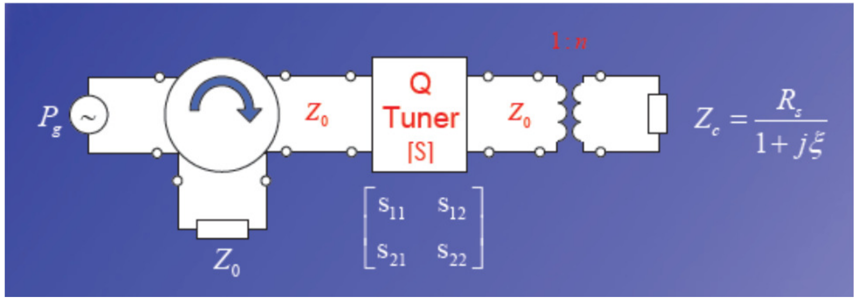
Adjustment of Q_{ext} (1)

- The RF power required for a certain gradient of a superconducting cavity depends on the beam current and coupling between the cavity and waveguide.

- The coupling with the cavity may be changed by variation of Q_{ext}.

- The Q_L seen by the cavity is determined by the $Q_{unloaded}$ and Q_{ext}. Q_{ext} is given by the load impedance Z_0 plus variable coupling to this load.

- The Q_{ext} can be adjusted by tuners like stub tuners, iris tuners, E-H tuners etc.



Adjustment of Q_{ext} (2)

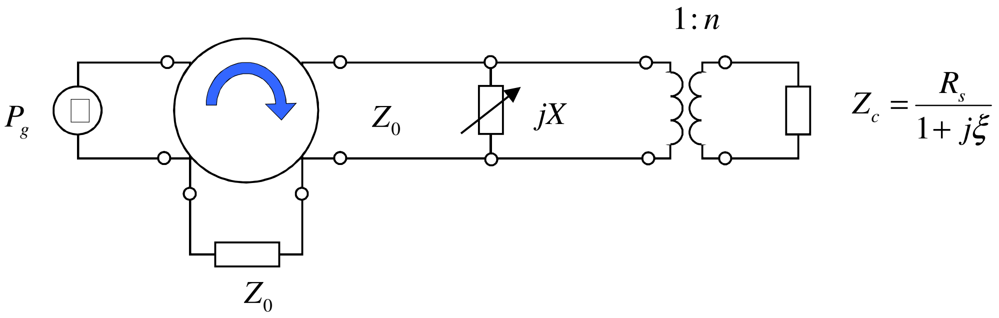


Figure 1: *Equivalent circuit of cavity powered through a circulator with the variable obstacle (no moving along waveguide)*

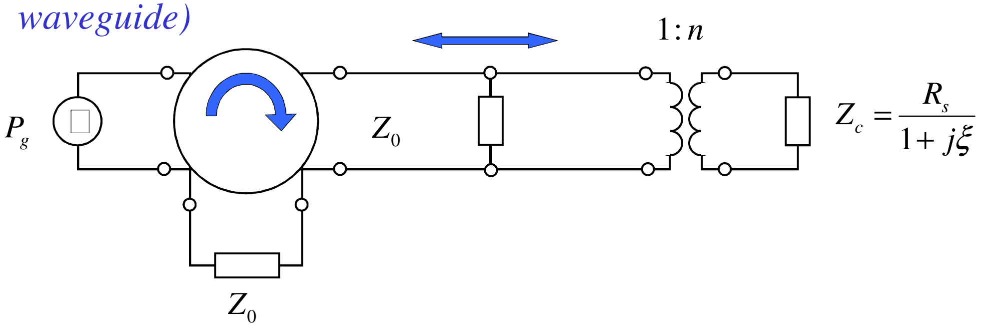
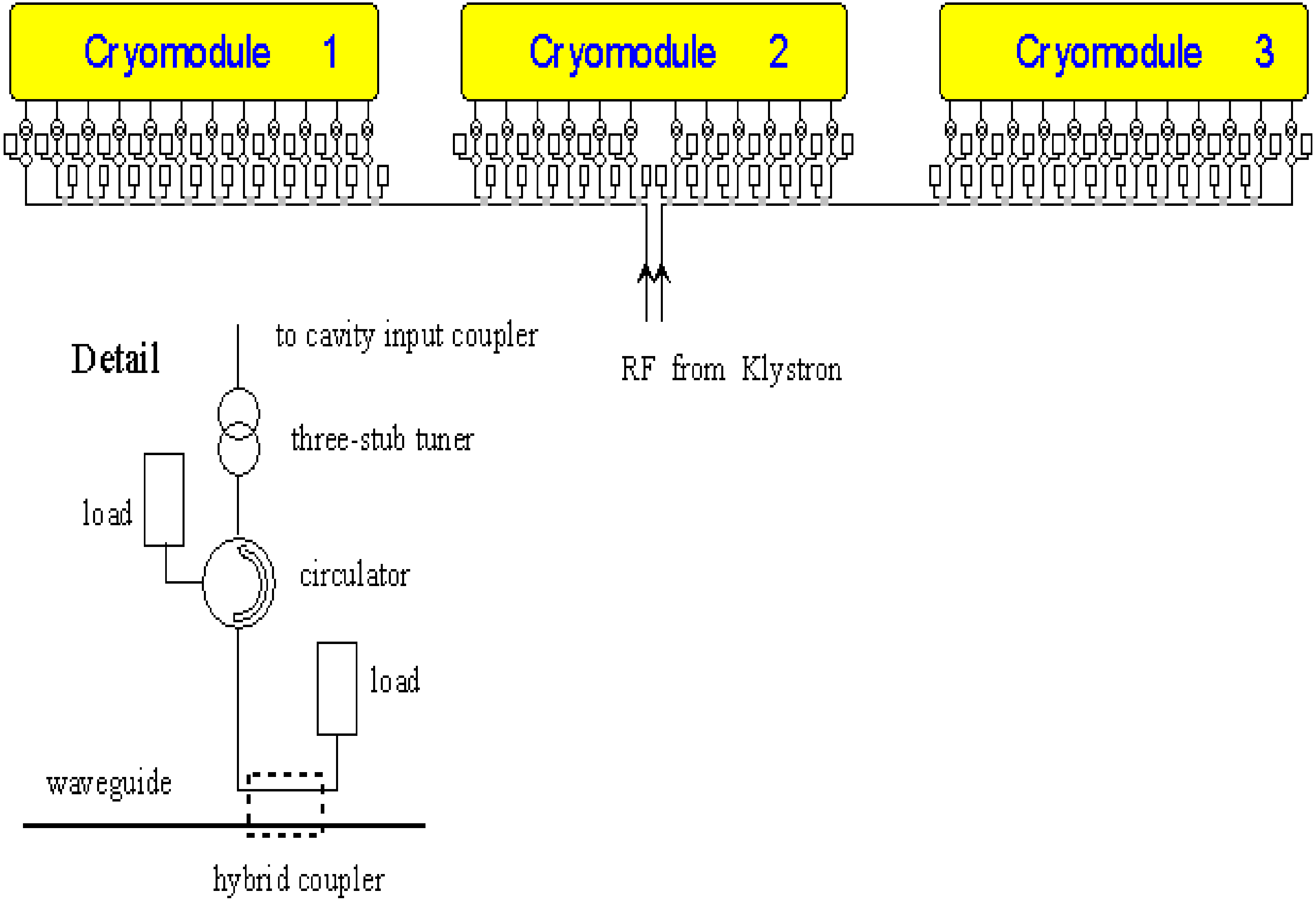


Figure 2: *Equivalent circuit of cavity powered through a circulator with the fixed obstacle moving along waveguide*

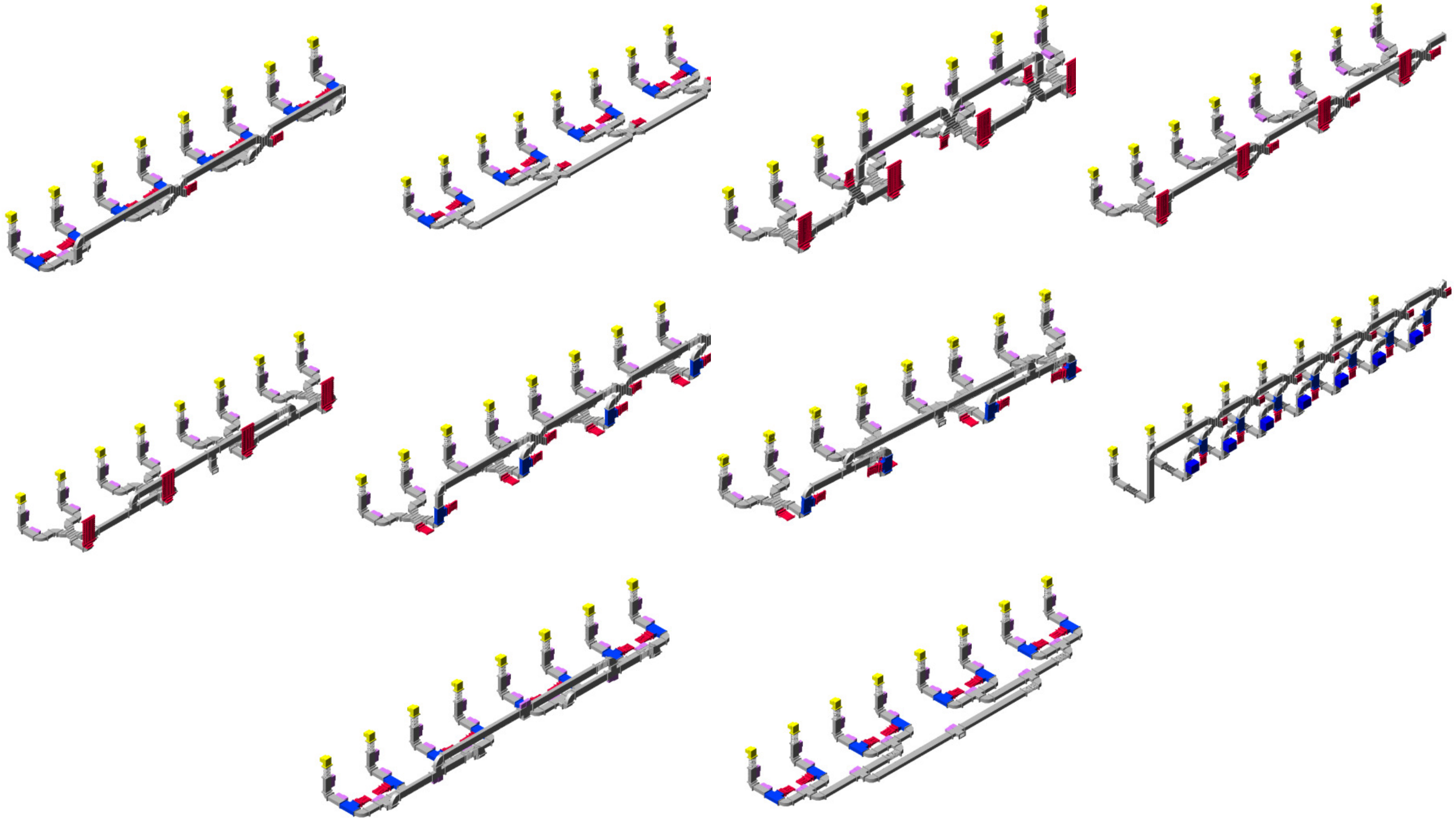
Linear Distribution System (1)

- For TESLA a linear distribution system has been proposed
- Equal amounts of power are branched off from the main RF power waveguide
- Circulators in each branch protect the klystron from reflected power
- Stub tuners allow adjustment of phase and Q_{ext}, for the XFEL inductive iris tuners are proposed
- Alternative schemes have been proposed

Linear Distribution System (2)



Alternative waveguide distribution schemes



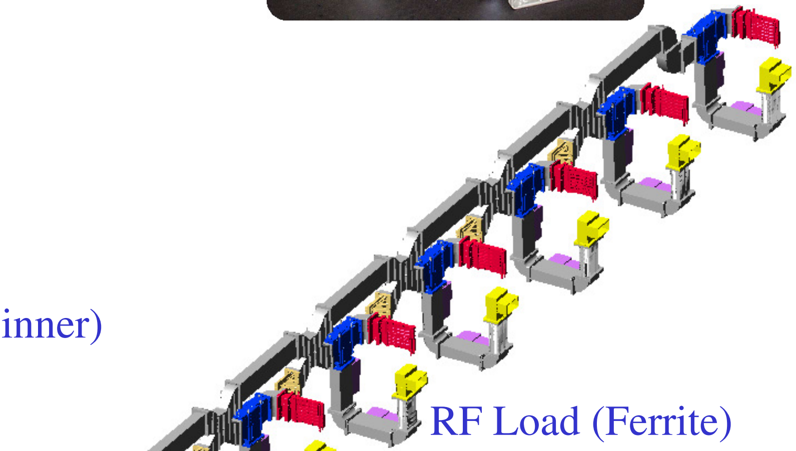
RF Waveguide Components

3 Stub Tuner (IHEP, Bejing, China)

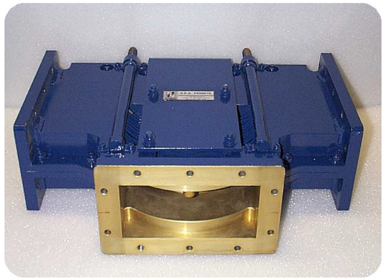
Changing phase, degree	±60
Impedance matching range	1/3Z_w ÷ 3Z_w
Max power, MW	2

* Z_w – waveguide impedance

E and H Bends (Spinner)



Circulator (Ferrite)

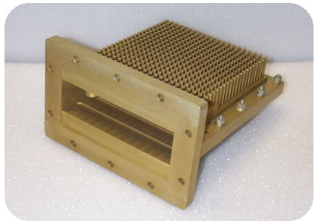


Type	WFHI 3-4
Peak input power, MW	0.4
Average power, kW	8
Min isolation at 1.3 GHz, dB	>30
Max insertion loss at 1.3 GHz, dB	≤0.08
Input SWR at 1.3 GHz (for full reflection)	1.1

Hybrid Coupler (RFT, Spinner)

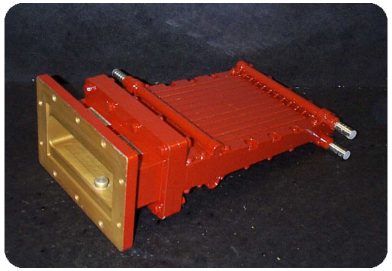
Directivity, dB	≥30
Return loss, dB	≥35
Coupling factor, dB (due to tolerance overlapping only 13 different coupling factors instead 18 are nessesary)	12.5; 12.0; 11.4; 10.7; 10.1; 9.6; 9.1; 8.5; 7.8; 7.0; 6.0; 4.8; 3.0
Accuracy of coupling factor, dB	±0.2

RF Load (Ferrite)



Type	WFHLL 3-1
Peak input power, MW	1.0
Average power, kW	0.2
Min return loss at 1.3GHz, dB	32÷40
Max VSWR at 1.3 GHz	≤1.05
Max surface temperature, ΔT °C (for full average power)	50
Physical length, mm	230

RF Load (Ferrite)



Type	WFHL 3-1	WFHL 3-5
Peak input power, MW	2.0	5.0
Average power, kW	10	100
Min return loss at 1.3 GHz, dB	32÷40	32÷40
Max VSWR at 1.3 GHz	<1.05	<1.05
Max surface temperature, ΔT °C (for full average power)	20	30
Physical length, mm	385	850

RF Waveguide Distribution Status

- New high power waveguide components for 1.3GHz have been developed in cooperation with industry or are standard of the shelves components
- Operation experience of 10 years from TTF
- Development of integrated components has been started (e.g. circulator with integrated load) to allow faster and more reliable installation