High Power RF

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Overview

- Introduction High Power RF System
- Klystron
- Modulator
- RF Waveguide Distribution

Introduction High Power RF System

- Task:

  Conversion of AC Line Power to Pulsed RF Power and distribution of the Pulsed RF Power to the cavities of the Linear Collider

- Structure:

  Several RF Station consisting of certain components make up the RF System of a linear collider (total RF pulse power:~1-10GW)

  The number of station depends on the maximum power which can be handled reliably by one station (and of course on availablity of components, costs etc)

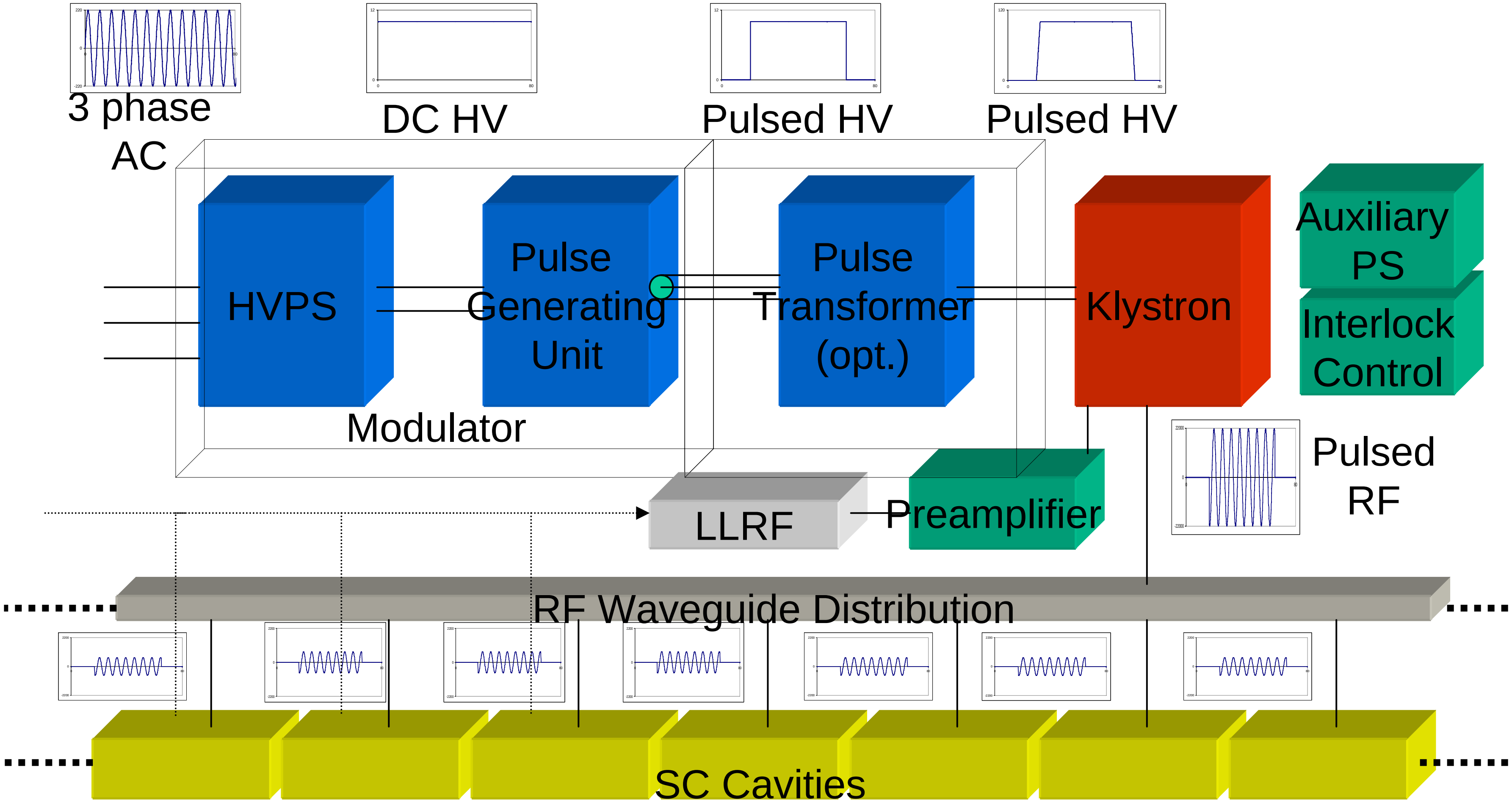
- Pulse Power per Station: ~100kW to ~1-10MW (ILC) to ~100MW (norm. cond. acc.)

- Pulse Width: (~1ms for norm. cond. acc. to) ~1ms (ILC)

- Repetition Rate: ~1Hz to ~10Hz (ILC) ~100Hz(norm. cond. acc.)

- Average power per Station: ~100kW (ILC)

RF Station Components (1)



RF Station Components (2)

- Modulator:

  HVPS: Conversion of AC line voltage (~400V AC) to DC HV (~1-10kV (100kV))

  Pulse Generating Unit: Conversion of DC HV (~1-10kV (100kV)) to Pulsed HV (~1-10kV (100kV))

  Pulse Transformer: Transformation of Pulsed HV (typ. ~10kV) to higher Pulsed HV (~100kV)
- Klystron:

  Conversion of Pulsed HV (~100kV) to pulsed RF (~10MW)
- RF Waveguide Distribution:

  Distribution of RF power (~10MW) to the cavities (~100kW)
- Other
- Auxiliary PS: Certain voltages for the klystron ion pumps or the klystron solenoid
- Interlock and Controls: Protection and Control
- LLRF: Control of phase, shape and amplitude (other lecture this school)
- Preamplifier: Amplification of ~1mW RF to ~100W RF

TESLA 500 RF Requirements

TDR 2001 (ILC Baseline is similar)

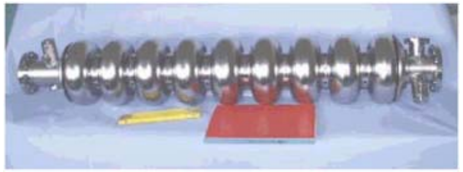
Number of sc cavities: 21024 total

Frequency: 1.3GHz (L-Band)

Power per cavity: 231kW

Gradient at 500GeV: 23.4MV/m

Power per 36 cavities
(3 cryo modules): 8.3MW



Power per RF station: **9.7MW** (including 6% losses in waveguides and circulators and a regulation reserve of 10%)

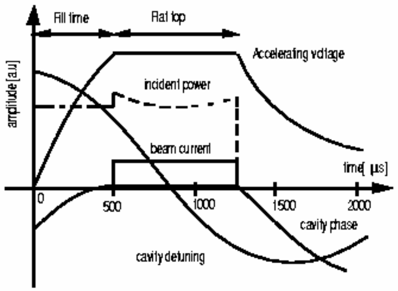
Number of RF stations: **572**

Macro beam pulse duration: 950ms

RF pulse duration: **1.37ms**

Repetition rate: **5Hz**

Average RF power per station: **66.5kW**



For TESLA 800 the number of stations must be doubled. The gradient is 35MV/m.

RF System Components

developed for Tesla and installed at TTF

RF Waveguide Distribution

Klystron

Modulator

Pulse Transformer

Klystron

Possible RF Sources

- Klystron today

Frequency Range:		~350MHz to ~17GHz
Output Power:	CW:	up to ~1.3MW
		Pulsed: up to ~200MW at ~1ms
		up to ~10MW at ~1ms
Klystron Gun Voltage:	DC:	~100kV
		Pulsed: ~600kV at ~1ms
		~130kV at ~1ms

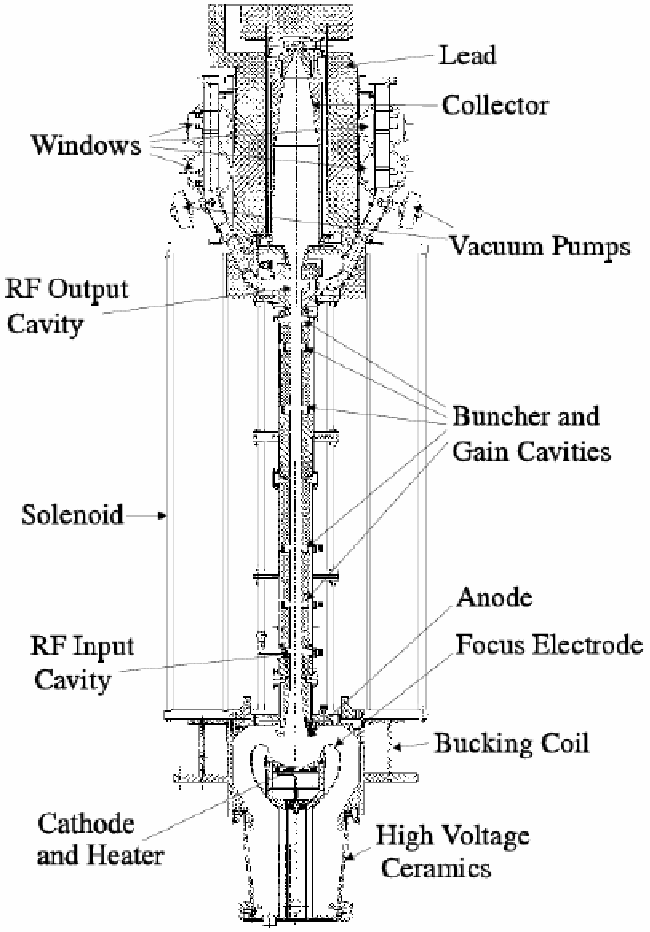
- Tetrode, Triode: Frequency up to ~200-300MHz, ~10kW
- IOT: Frequency up to ~1.3GHz, Power: ~30kW, HOM IOT maybe 5MW in the future
- Gyroklystron: Frequency above ~20GHz, ~10MW
- Gyrotron: Frequency typical 100GHz, ~1MW
- Magnetron: Oscillator, ~10MW
- Travelling Wave Tube, Magnicon, Orbitron, Amplicon etc.

Not for ILC

Klystron Theory

- The klystron principle will be explained
- A basic and simplified theory can be found in the appendix
- Today klystrons or subcomponents of klystrons are designed and calculated making use of different computer codes (Egun, FCI, Mafia, Microwave Studio, Ansys, Magic, special codes developed by klystron manufacturers …)
- PIC codes have been developed recently

Klystron Principle



Example: 150MW,
3GHz S-Band Klystron

- The cathode is heated by the heater to ~1000°C.
- The cathode is then charged (pulsed or DC) to several 100kV.
- Electrons are accelerated form the cathode towards the anode at ground, which is isolated from the cathode by the high voltage ceramics.
- The electron beam passes the anode hole and drifts in the drift tube to the collector.
- The beam is focussed by a bucking coil and a solenoid.
- By applying RF power to the RF input cavity the beam is velocity modulated.
- On its way to the output cavity the velocity modulation converts to a density modulation. This effect is reinforced by additional buncher and gain cavities.
- The density modulation in the output cavity excites a strong RF oscillation in the output cavity.
- RF power is coupled out via the output waveguides and the windows.
- Vacuum pumps sustain the high vacuum in the klystron envelope.
- The beam is finally dumped in the collector, where it generates X-rays which must be shielded by lead.

Klystron Perveance

- Perveance $p = I / U^{3/2}$ (I = klystron current, U = Klystron voltage) is a parameter of the klystron gun determined by the gun geometry (Theory see Appendix)
- Example: THALES TH2104C 5MW, 1.3GHz Klystron U=128kV I=89A $p=1.94*10^{-6} A/V^{3/2}$ (mperveance=1.94)

Klystron Output Power

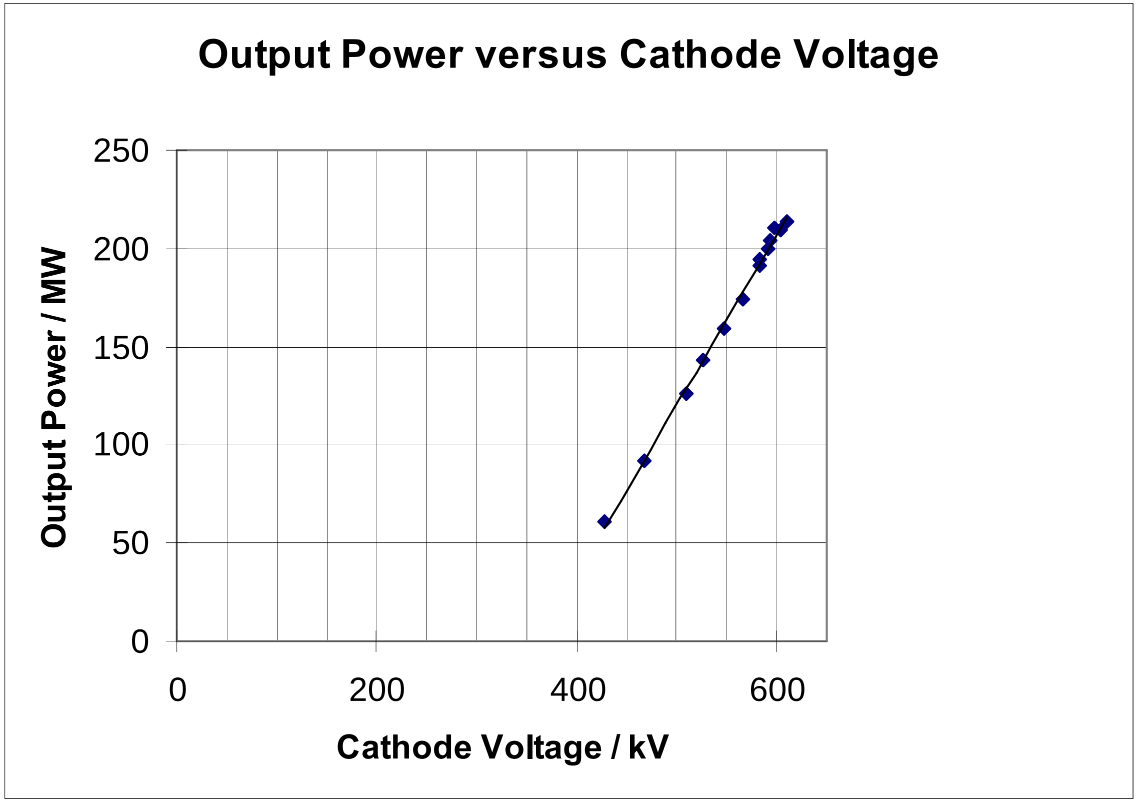
$$P_{RF} = \eta P_{Beam}$$

$$P_{Beam} = UI$$

$$P_{Beam} = pU^{5/2}$$

$$\eta = \eta(U) \propto U^{>0}$$

$$P_{RF} \propto U^{>5/2}$$



Example: RF output power of a 3GHz (S-band) klystron as function of the voltage

Klystron Efficiency

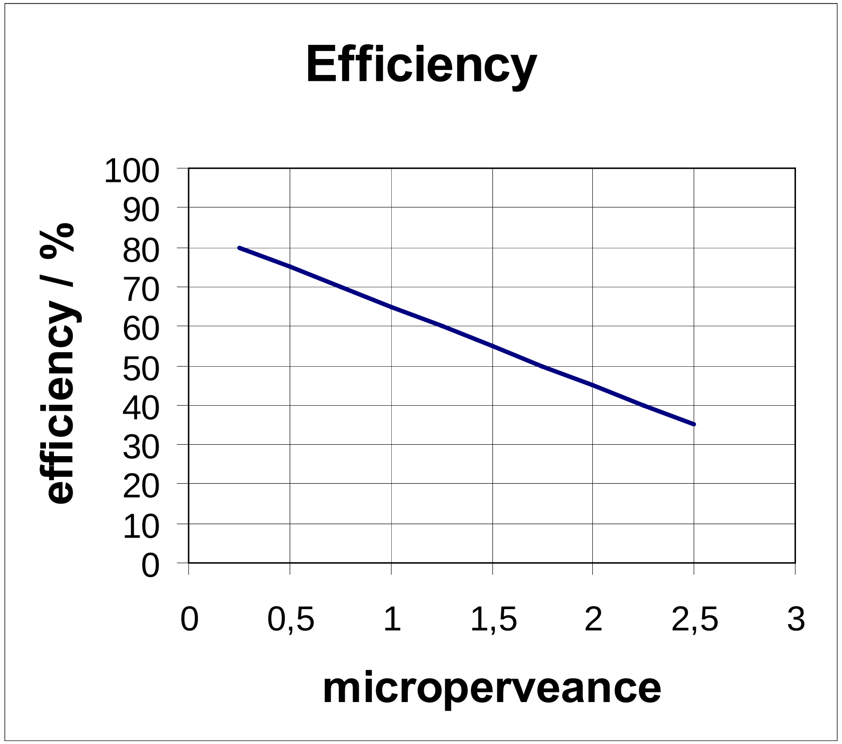
- Efficiency of a klystron depends on bunching and therefore on space charge forces

- Lower space forces allow for easier bunching and more efficiency

- Decreasing the charge density (current) and increasing the stiffness (voltage) of the beam

  increase the efficiency

- Higher voltage and lower current, thus lower perveance would lead to higher efficiency



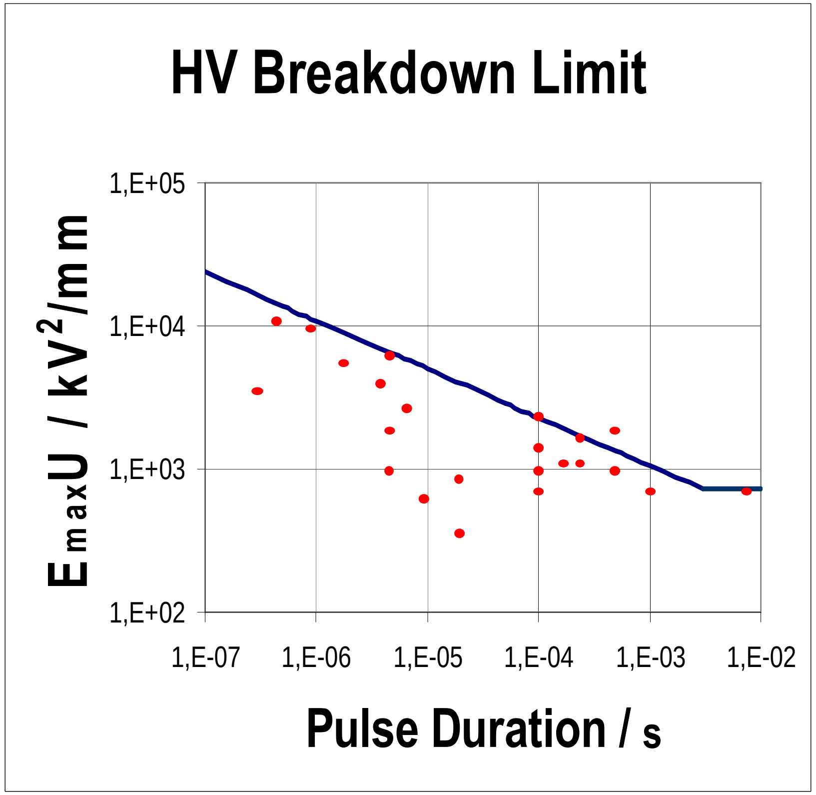
Rule of thumb formula from fit to experimental data

$$\eta = 0.85 - 2 \times 10^{5} \times p$$

Klystron Gun Breakdown Limit

- Disadvantage: higher voltage increase the probability of breakdown

- The breakdown limit EU depend on the pulse duration



$$E_{max} \times U = 100 \times \tau^{-0.34} \left(kV \right)^2 / mm$$

Multibeam Klystron

Idea

Klystron with low perveance:
=> High efficiency but high voltage
Klystron with low perveance and low high voltage
⇒ low high voltage but low power

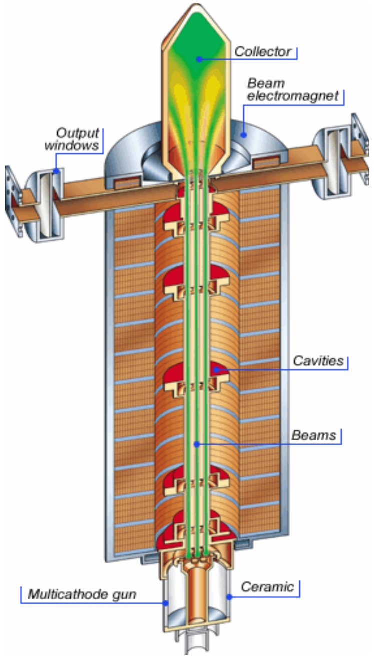
Solution

Klystron with many low perveance beams:
=> low perveance per beam thus high efficiency
low voltage compared to klystron with single low perveance beam

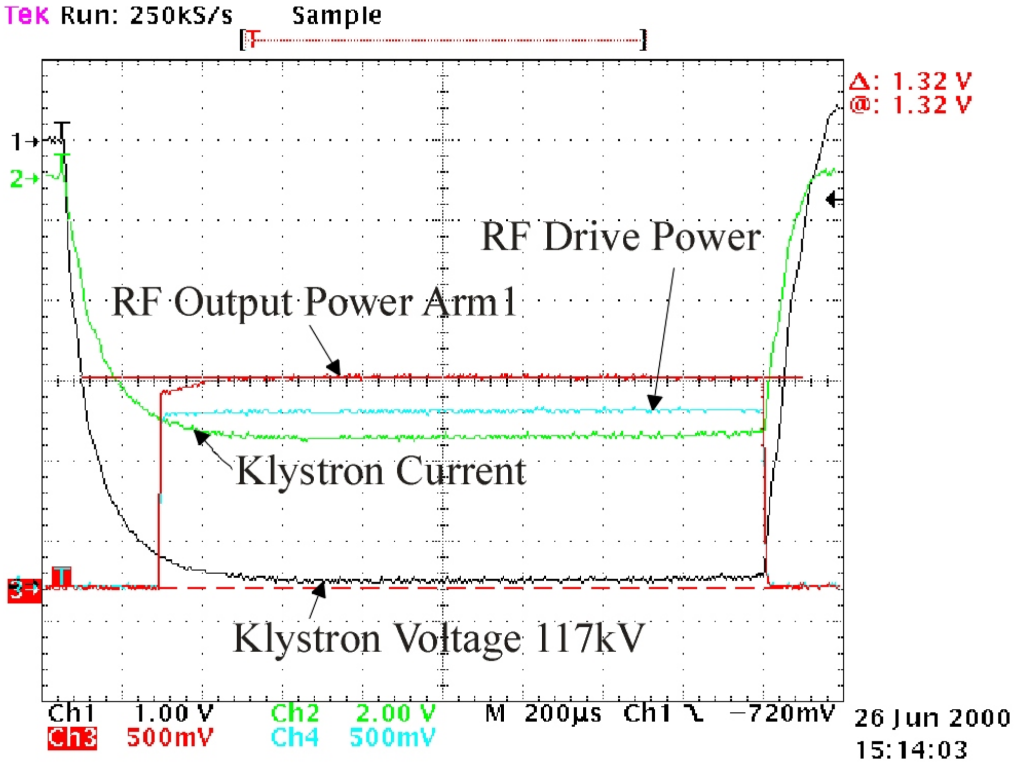
Multi Beam Klystron THALES TH1801 (1)

Measured performance

Operation Frequency: 1.3GHz
Cathode Voltage: 117kV
Beam Current: 131A
mperveance: 3.27
Number of Beams: 7
Cathode loading: 5.5A/cm^2
Max. RF Peak Power: 10MW
RF Pulse Duration: 1.5ms
Repetition Rate: 10Hz
RF Average Power: 150kW
Efficiency: 65%
Gain: 48.2dB
Solenoid Power: 6kW
Length: 2.5m
Lifetime (goal): ~40000h

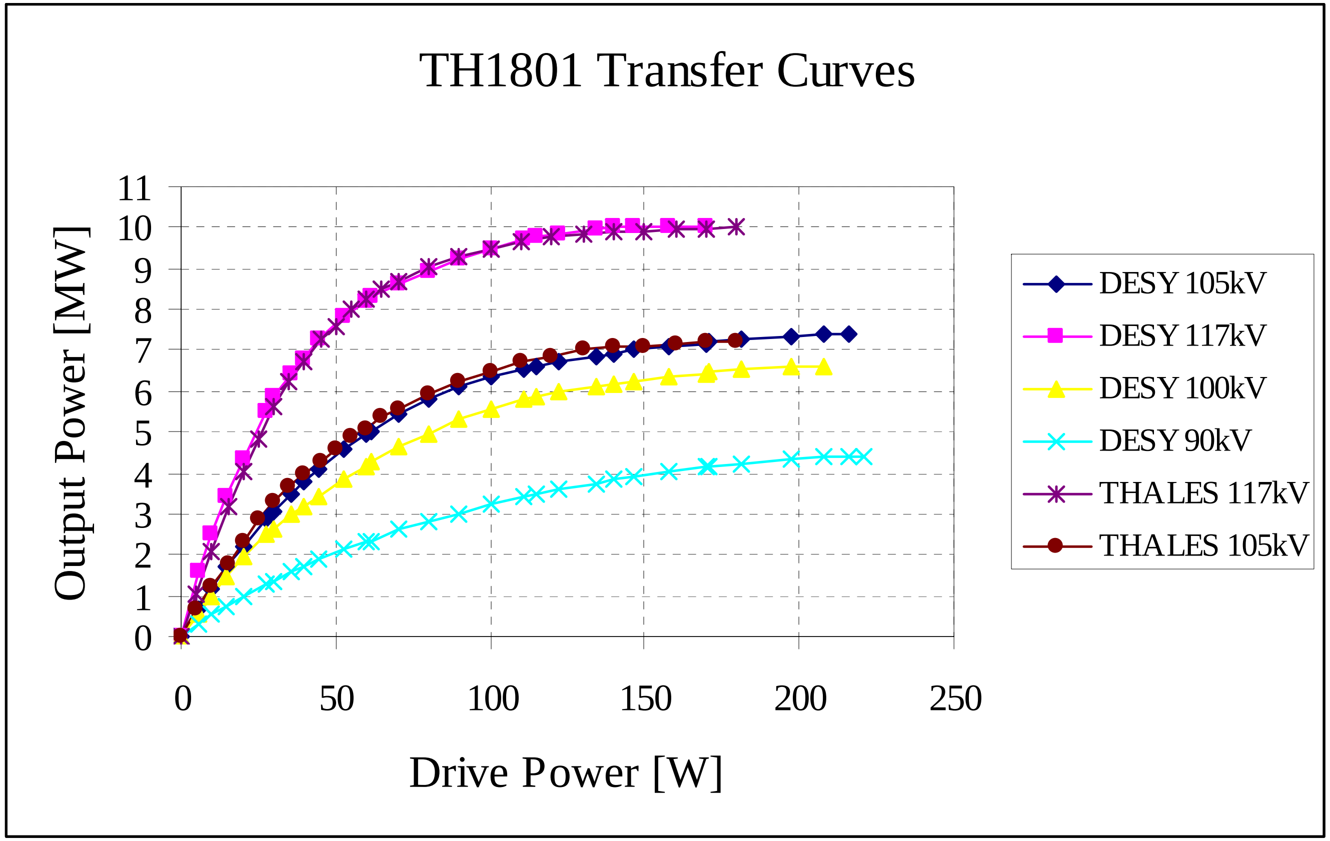


Multi Beam Klystron THALES TH1801 (2)



Pulse Waveforms of a Klystron (Voltage, Current, RF Drive Power, RF Output Power)

Multi Beam Klystron THALES TH1801 (3)

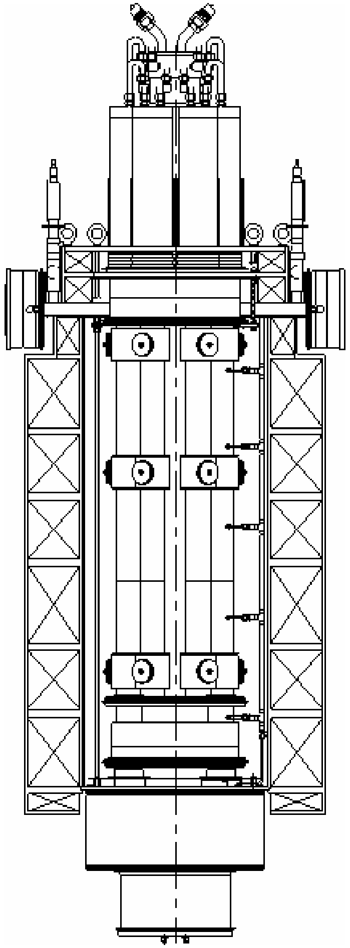


Transfer Curves: RF output as function of RF drive power with klystron voltage as parameter

Multi Beam Klystron CPI VKL-8301(1)

Design Features:

- 6 beams
- HOM input and output cavity
- Individual intermediate FM cavities
- Cathode loading: <2.5A/cm^2 lifetime prediction: >100000h



Drawing of the Klystron

Multi Beam Klystron CPI VKL-8301 (2)

Specified Operating Parameters

Peak Power Output		10	MW (min)
Ave. Power Output		150	kW (min)
Beam Voltage		114	kV (nom)
Beam Current		131	A (nom)
mperveance		3.40	
Frequency		1300	MHz
Gain		47	dB (min)
Efficiency		67	% (nom)
Cathode Loading		2.0	A/cm^2
Dimensions	H,**Ø:**	2.3 by	1.0 meters
Weight		2000	lbs

Electromagnet

Solenoid Power	4	kW (max)
Coil Voltage	200	V (max)
Weight	2800	lbs

Klystron during construction

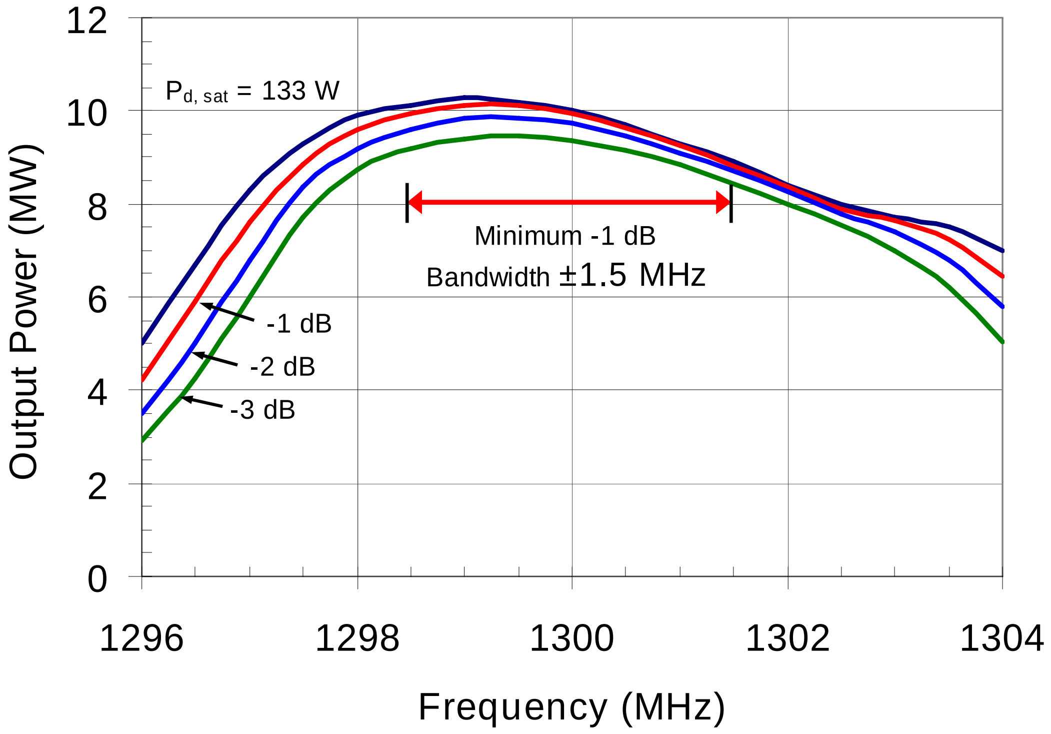
Multi Beam Klystron CPI VKL-8301 (3)

Measured Operating Parameters at CPI at 500ms pulsewidth

Peak Power Output	10	MW
Ave. Power Output	150	kW
Beam Voltage	120	kV
Beam Current	139	A
mperveance	3.34	
Frequency	1300	MHz
Gain (saturated)	49	dB
Efficiency	60	%
Beam Transmission		
DC, no RF	99.5	%
at Saturation	98.5	%

Klystron ready for shipment

Klystron CPI

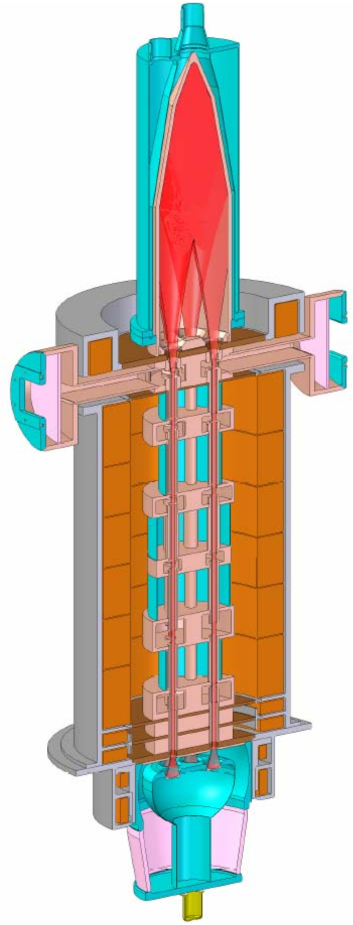


Output power as function of frequency

The TOSHIBA E3736 MBK (1)

Design Features:

- 6 beams
- Ring shaped cavities
- Cathode loading: <2.1 A/cm^2



Design Layout

The TOSHIBA E3736 MBK (2)

Measured performance

Voltage: 115kV

Current: 135A

mperveance: 3.46

Output Power: 10.4MW

Efficiency: 67%

Pulse duration: 1.5ms

Rep. Rate: 10Hz

Klystron ready for shipment

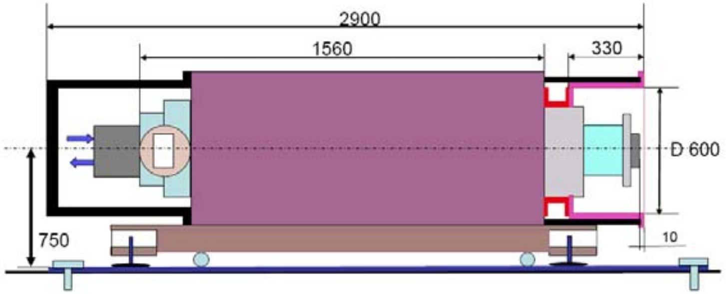
Horizontal Klystron

- Horizontal klystrons are already in use e.g. the LEP klystrons at CERN or the B-factory klystrons at SLAC

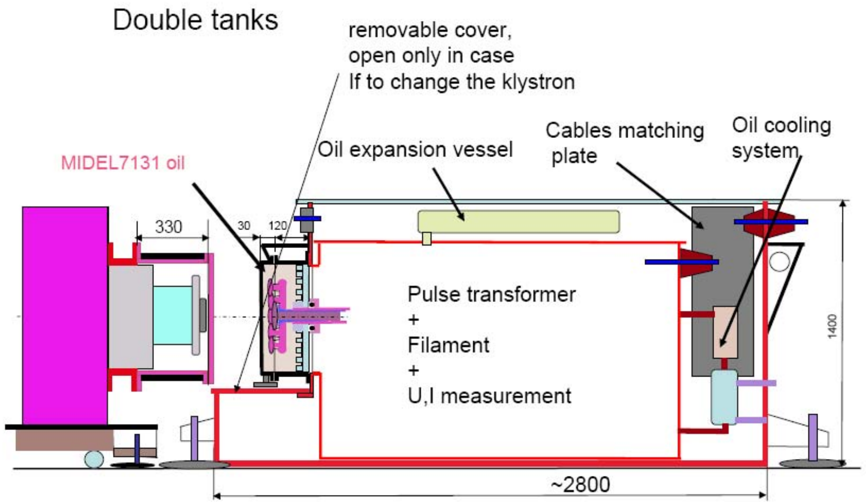
Aspects

- Space in tunnel
- Transportation of klystron and pulse transformer in the tunnel
- Exchange of the klystrons
- Ease of interchange of different types of klystrons to pulse transformer tank and to waveguide distribution system
- X-ray shielding
- Oil leakage

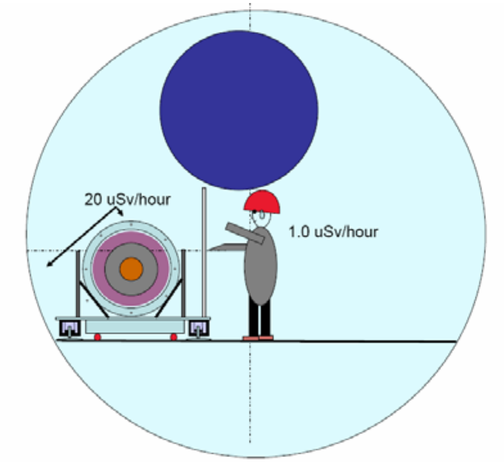
Horizontal MBK



Horizontal MBK



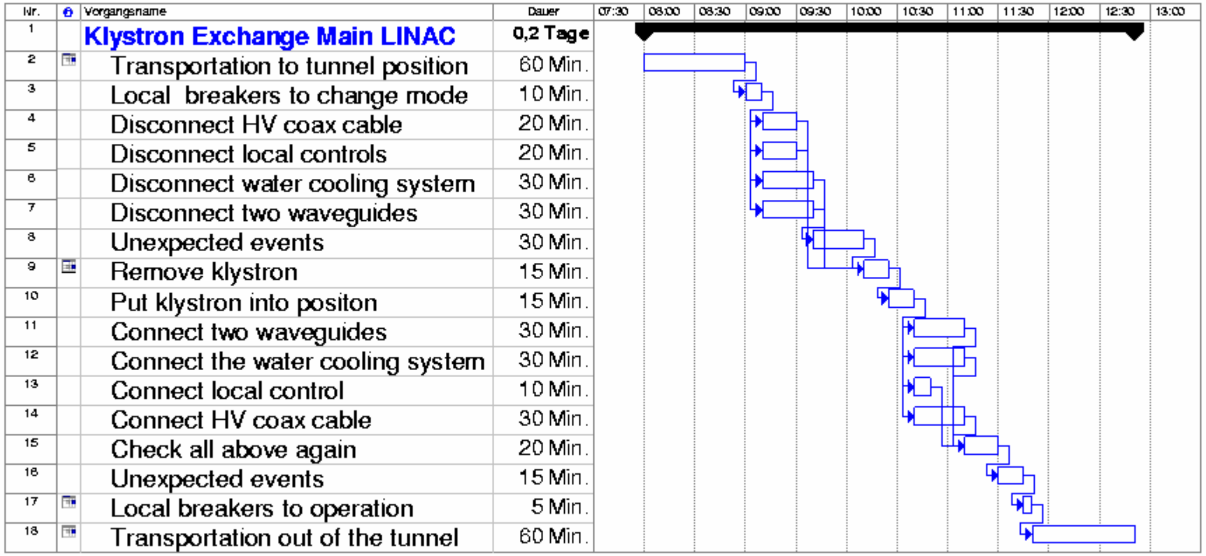
MBK gun and pulse transformer



X-Ray shielding

Klystron Replacement for the TESLA Linear Collider

- The klystron lifetime will be determined most likely by the cathode lifetime since other klystron components are operated at a moderate level
- With a klystron lifetime of 40000h and an operation time of 5000h per year 8 klystrons must be replaced during a monthly access day
- An overhead of 12 klystrons will be installed, therefore no degradation of accelerator performance is expected between two access days
- Teams of 3-4 people will exchange a klystron within a few hours; klystrons will be equipped with connectors (HV, controls, cooling, waveguides) which allow fast exchange of a klystron in the tunnel



Nr.	ℹ	Vorgangsname	Dauer
1		**Klystron Exchange Main LINAC**	**0,2 Tage**
2	▤	Transportation to tunnel position	60 Min.
3		Local breakers to change mode	10 Min.
4		Disconnect HV coax cable	20 Min.
5		Disconnect local controls	20 Min.
6		Disconnect water cooling system	30 Min.
7		Disconnect two waveguides	30 Min.
8		Unexpected events	30 Min.
9	▤	Remove klystron	15 Min.
10		Put klystron into positon	15 Min.
11		Connect two waveguides	30 Min.
12		Connect the water cooling system	30 Min.
13		Connect local control	10 Min.
14		Connect HV coax cable	30 Min.
15		Check all above again	20 Min.
16		Unexpected events	15 Min.
17	▤	Local breakers to operation	5 Min.
18	▤	Transportation out of the tunnel	60 Min.

Modulator

Modulator Types (1)

Hard Tube / Series Switch Modulator

Pro:

- Very simple circuit diagram

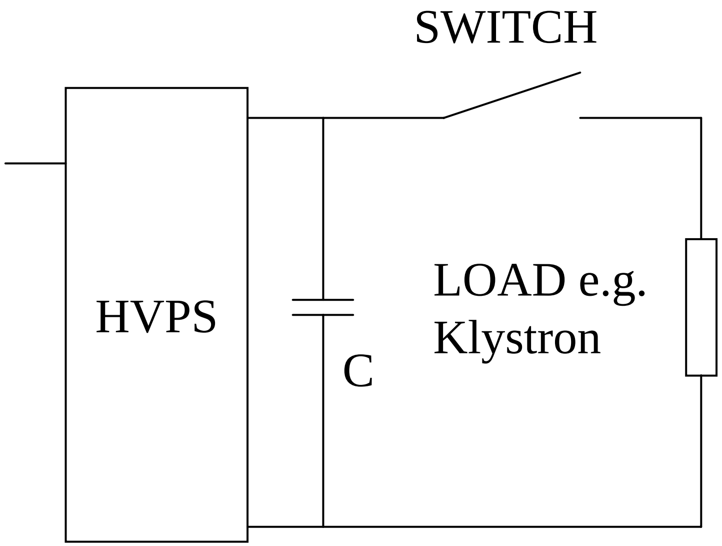
Con:

- Very high DC voltage (~100kV)
- Big capacitor bank

=> high stored energy

- Switch difficult if not impossible
  (high voltage, fast switching time,
  depends on high voltage level)

Some companies have developed
semicondictor switches for 150KV/500A



Modulator Types (1b)

Hard Tube / Series Switch Modulator

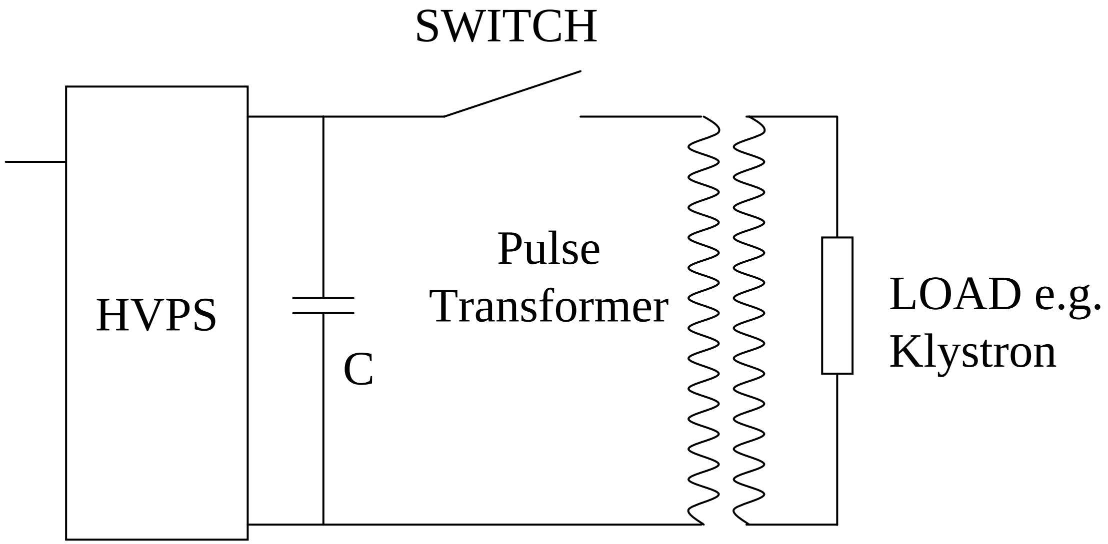
- Capacitor have to store for 1% voltage droop 50 times the pulse energy

  example: 1.5ms, 120kV, 140A, 25kJ pulse energy, stored energy 1.26MJ (C= 175mF, U =120kV)

- Switch can be vacuum tube (triode, tetrode) or stack of semiconductors (IGBT, IGCT, GTO, MOSFET)

Modulator Types (2)

Hybrid (Series Switch with Pulse Transformer)



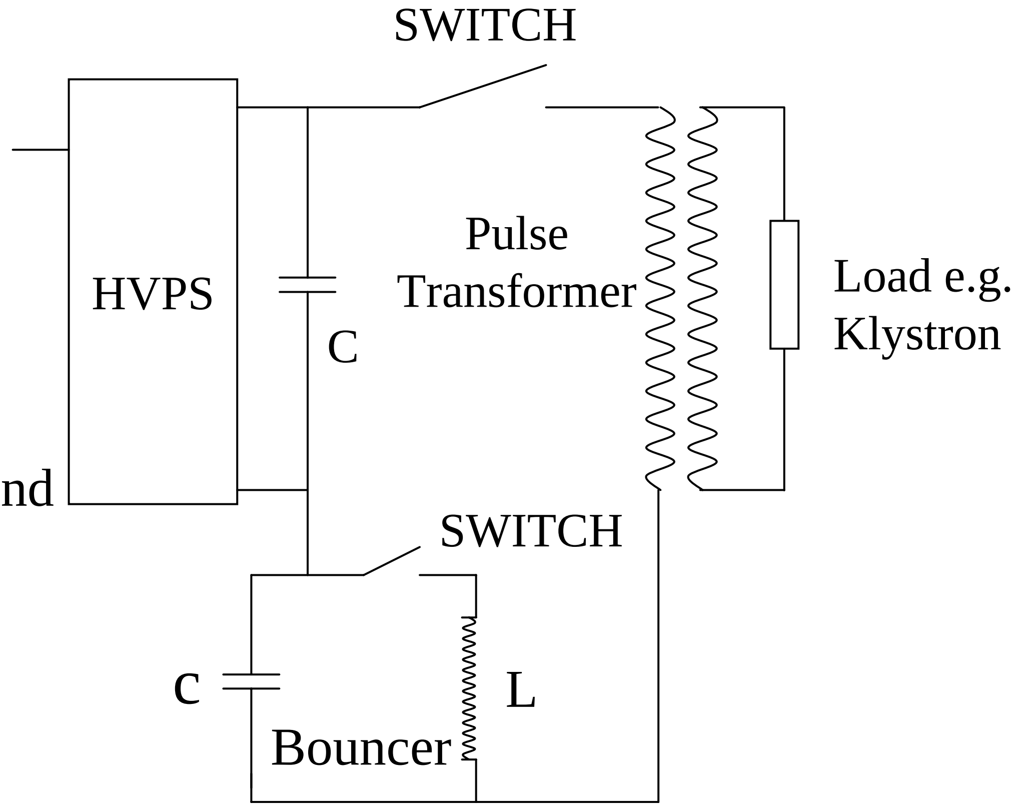
Pro:

- Lower DC Voltage
- Switch easier

Con:

- Higher current
- High stored energy
- Leakage inductance of pulse transformer limits pulse rise time

Modulator Types (3)



Bouncer Modulator

Pro:

- Lower stored energy

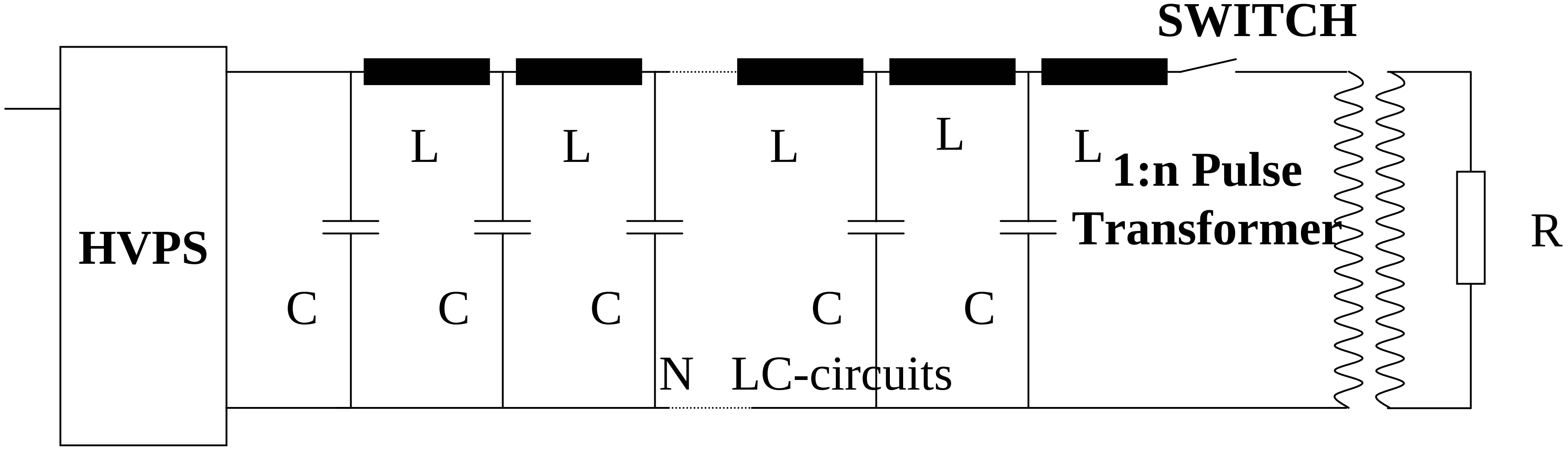
Con:

- Additional circuit with big choke and additional cap bank

Modulator Types (4)

PFN (Pulse Forming Network)

Most used for short pulse and very high voltage



Pro:

- Stored energy = Pulse energy
- Only closing switch required

Con:

- Pulse width $T = 2N \times \sqrt{L \times C}$ is not easy to adjust
- Pulse flat top must be tuned
- PFN Impedance $Z = \sqrt{L/C}$ must match load impedance $Z = R/n^2$
- Charging Voltage is 2 x Pulse Voltage

Modulator Types (5)

Series Resonant Converter

Developed at LANL (Bill Reass) for SNS

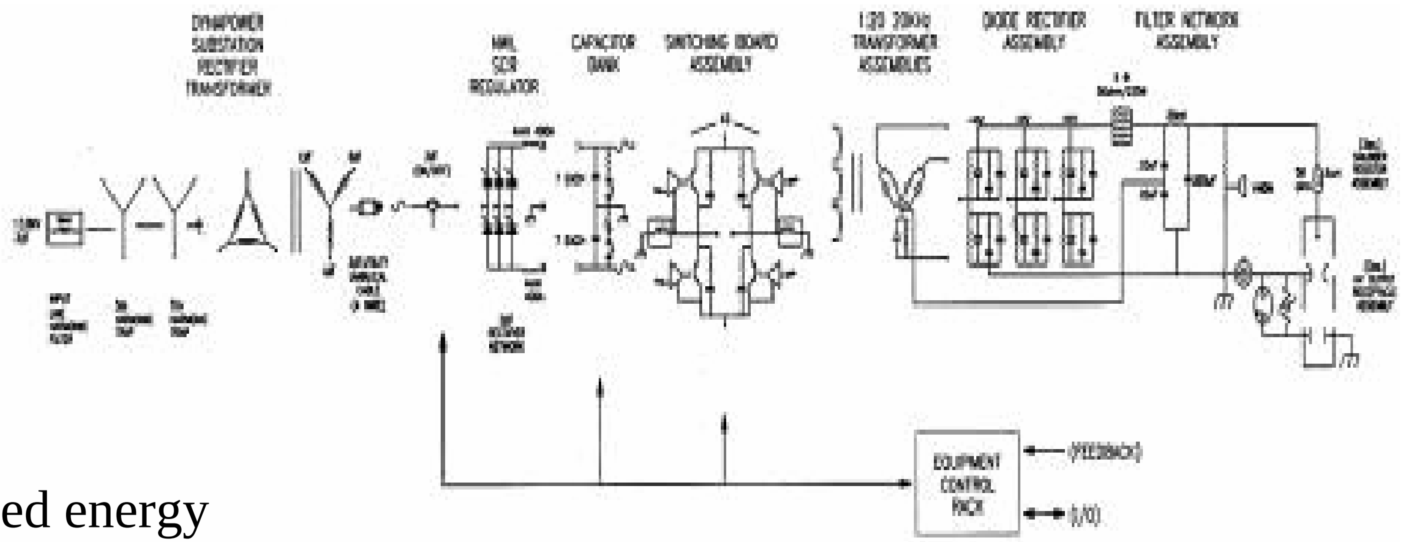


Figure 1 Simplified Block Diagram

Pro:

- Low stored energy
- Small size
- Regulation within pulse possible
- Installed at SNS

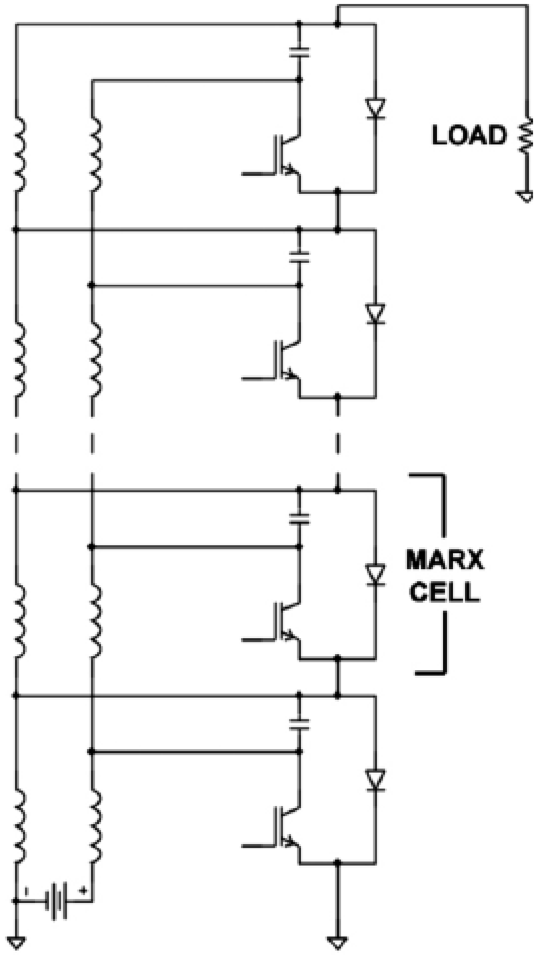
Con:

- New technology (e.g. IGBTs at high switching frequency, nanochrystalline transformer material) needs experience (but see Pro)

Modulator Types (6)

Marx Generator

Developed by Erwin Marx in the 1920s, proposed with modifications to the original design by Leyh, SLAC



Pro:

- Compact
- Potential of cost savings

Con:

- No prototype exits
- Typical use: very high voltage, short pulses, low rep. Rate (single shot), no rectangular waveform

Modulator Types (7)

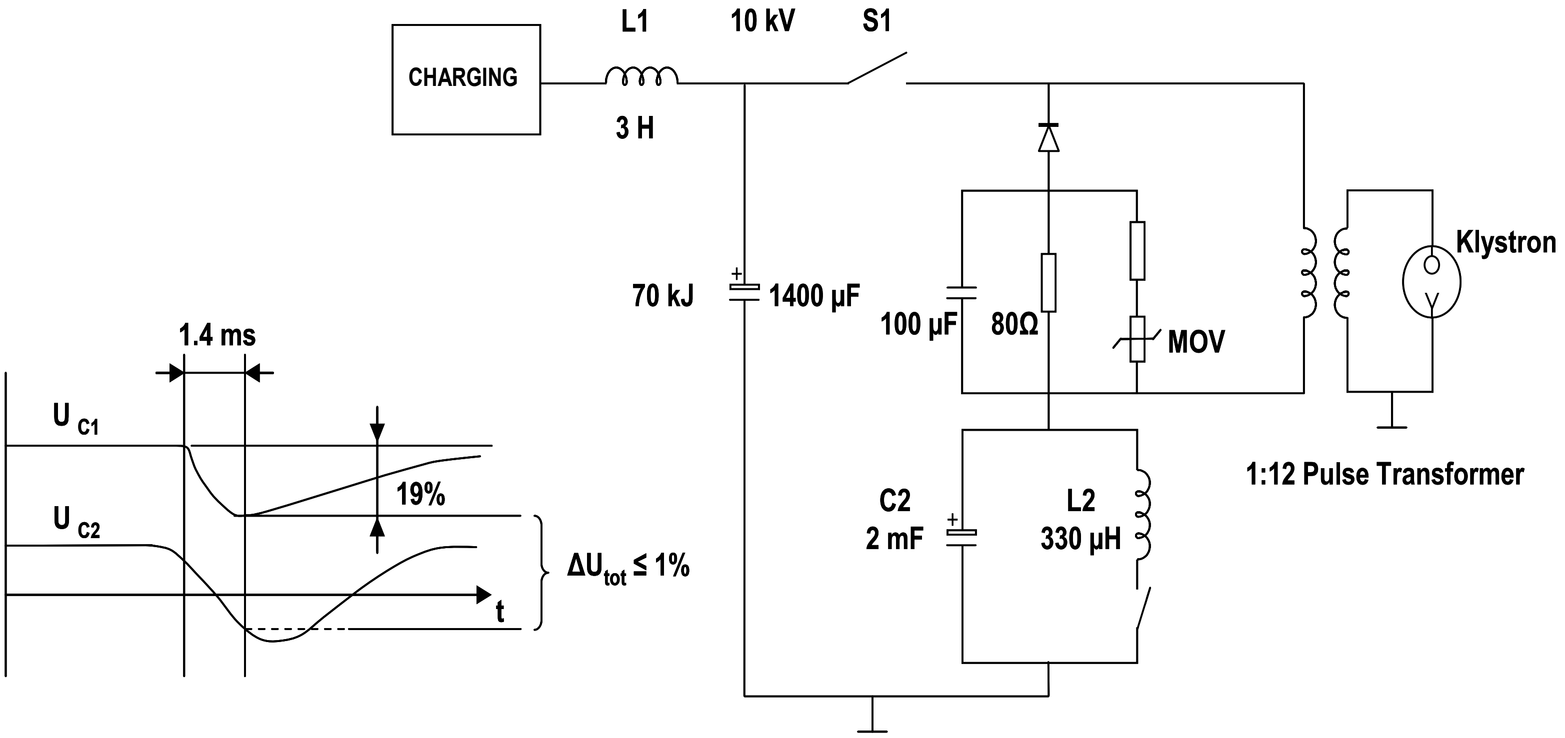
Other

- SMES superconducting magnetic energy storage (FZ Karlsruhe now installed at DESY)
- Induction type modulator
- Blumlein
- Switch mode PS
- Combinations of all already mentioned
- ……

TESLA Modulator Requirements

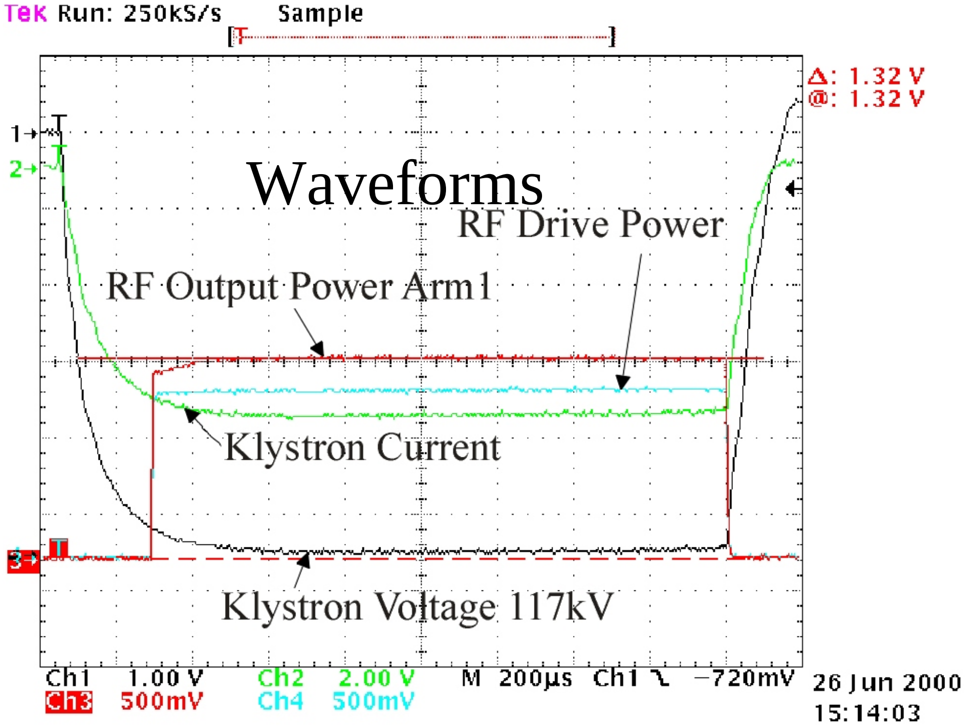
	Typical	**Maximum**
Klystron Gun Voltage:	115kV	130kV
Klystron Gun Current:	130A	150A
High Voltage Pulse Length:	<1.7ms	1.7ms
High Voltage Rise Time (0-99%):	<0.20ms	0.2ms
High Voltage Flat Top (99%-99%):	1.37ms	1.5ms
Pulse Flatness During 1.4ms Flat Top:	<±0.5%	±0.5%
Pulse-to-Pulse Voltage fluctuation:	<±0.5%	±0.5%
Energy Deposit in Klystron in Case of Gun Spark:	<20J	20J
Pulse Repetition Rate	5Hz	10Hz
Transformer-Ratio:	1:12	

Bouncer Modulator Principle



- The linear part of the oscillation of the bouncer circuit is used to compensate the voltage droop caused by the discharge of the main storage capacitor

The FNAL Modulator for TTF



FNAL Modulator at TTF

- 3 modulators have been developed, built and delivered to TTF by FNAL since 1994
- They are continuosly in operation under different operation conditions

Industry made Modulator for TTF (1)

HVPS and Pulse Forming Unit

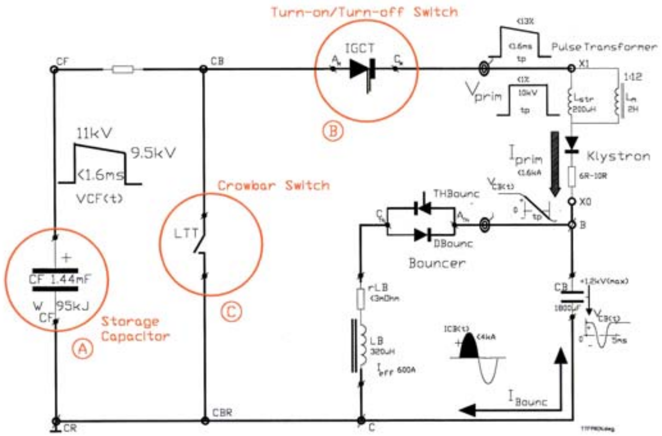
- Industry made subunits (PPT, ABB, FUG, Poynting)
- Constant power power supply for suppression of 10Hz repetition rate disturbances in the mains
- Compact storage capacitor bank with self healing capacitors
- IGCT Stack (ABB); 7 IGCTs in series, 2 are redundant

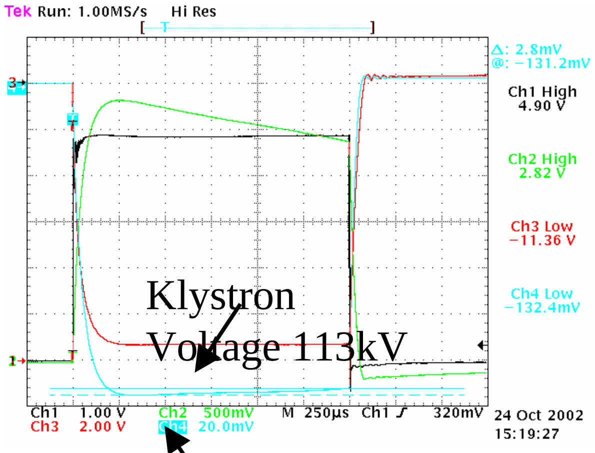
IGCT Stack

Industry made Modulator for TTF (2)

- Low leakage inductance pulse transformer (ABB) L<200mH resulting in shorter HV pulse rise time of <200ms
- Light Triggered Thyristor crowbar avoiding mercury of ignitrons

Pulse Transformer





Klystron Voltage 113kV

Klystron Current 132A

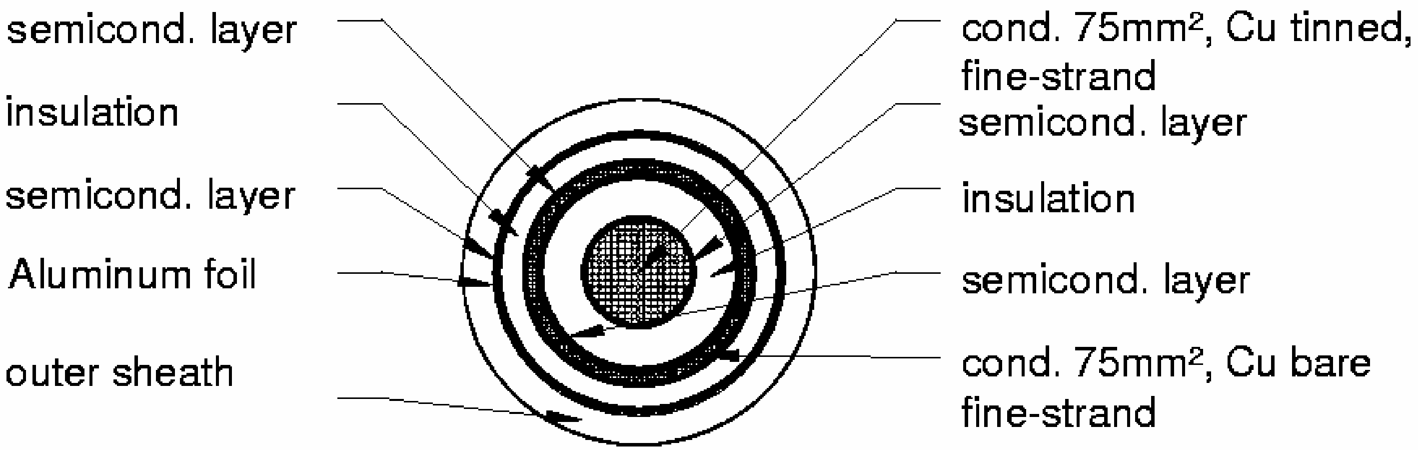
Bouncer Modulator Status

- 10 Modulators have been built, 3 by FNAL and 7 together with industry
- 9 modulators are in operation
- 10 years operation experience exists
- Many vendors for modulator components are available

HV Pulse Cable (1)

- Transmission of HV pulses (10kV, 1.6kA, 1.57ms, 10Hz from the pulse generating unit (modulator hall) to the pulse transformer (accelerator tunnel) if PGU and PT are separated
- Length ~3km (depends on site and tunnel layout)
- Impedance of 25 Ohms (4 cable in parallel will give 6.25 Ohms in total) to match the klystron impedance
- Triaxial construction (inner conductor at 10kV, middle conductor at 1kV, outer conductor at ground)

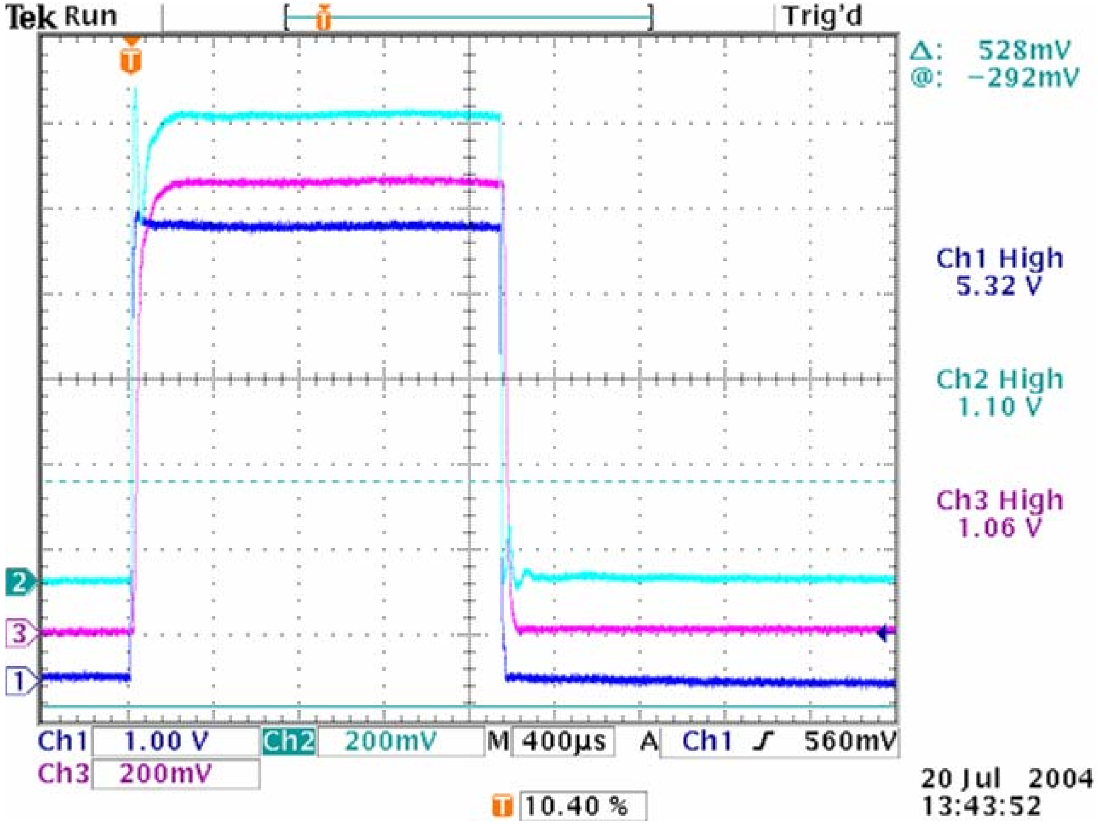
HV Pulse Cable (2)



Diameter 30mm

Dielectric material: XLPE

HV Pulse Cable (3)



Primary Current 1.1kA

Klystron Voltage 128kV

Primary Voltage 10.6kV

- Test with 1.5km long cables and a 5MW klystron show the feasibility of pulse transmission
- Remaining problem: EMI needs investigation

RF Waveguide Distribution

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)

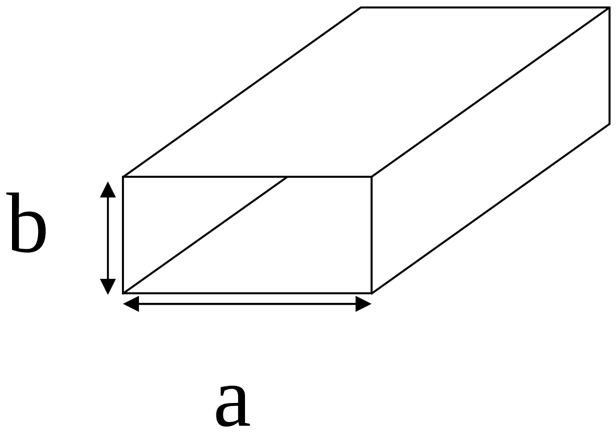
Distribution of RF power is done by:

- 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

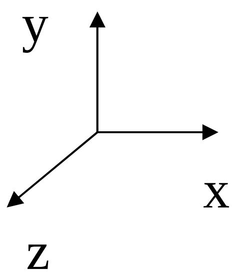
Rectangular Waveguide



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

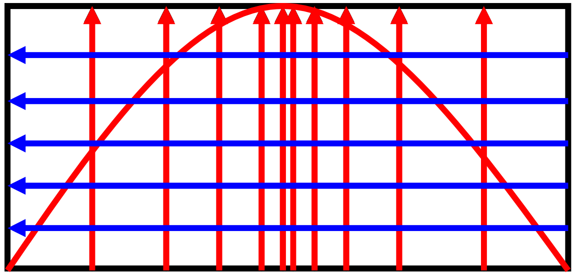
- In a rectangular waveguide only nm- modes below (above) a certain wavelength l_{cnm} (frequency n_{cnm}) can propagate.

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

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

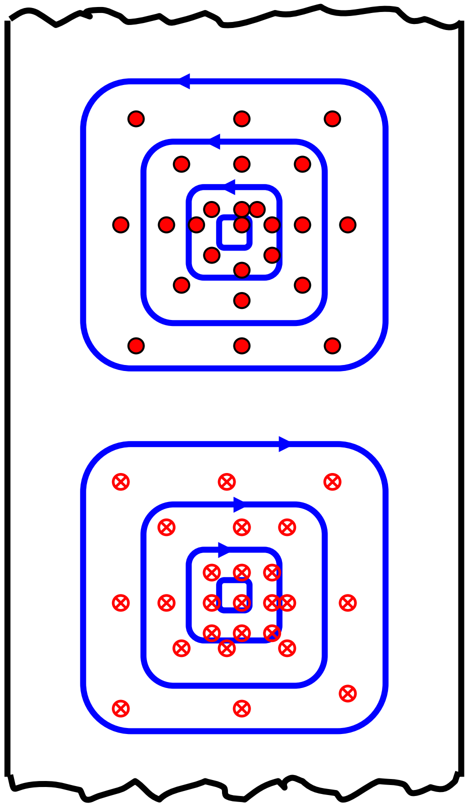
Rectangular Waveguides

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



Cutoff Frequency:
n_{c10}=c/2a

E-Field
H-Field



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:

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

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}

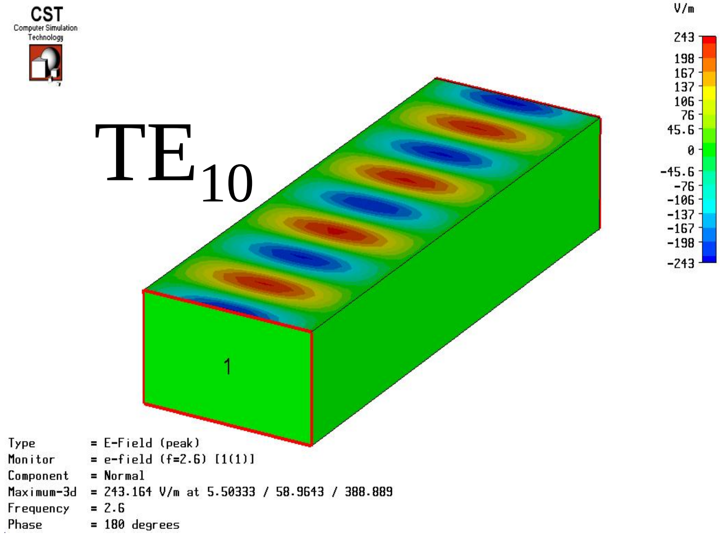
$$P_{RF} = 6.63 \times 10^{-4} a[cm] b[cm] \left[\lambda / \lambda_g \right] E[V/cm]^2$$

- 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}.

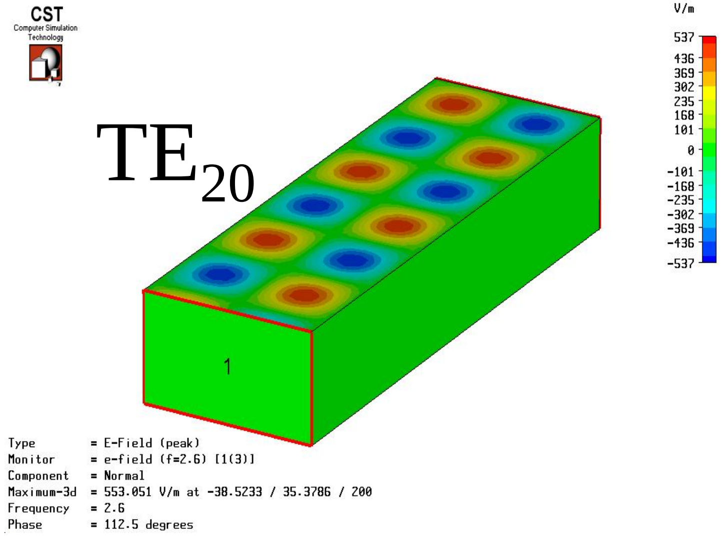
- In air it is E_{max}=32kV/cm and in SF6 it is E_{max}=89kV/cm (1bar, 20°C). Problem with SF6 is that although it is chemically very stable (1) it is a green house gas and (2) if cracked in sparcs products can form HF which is a very aggressive acid.

- 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.

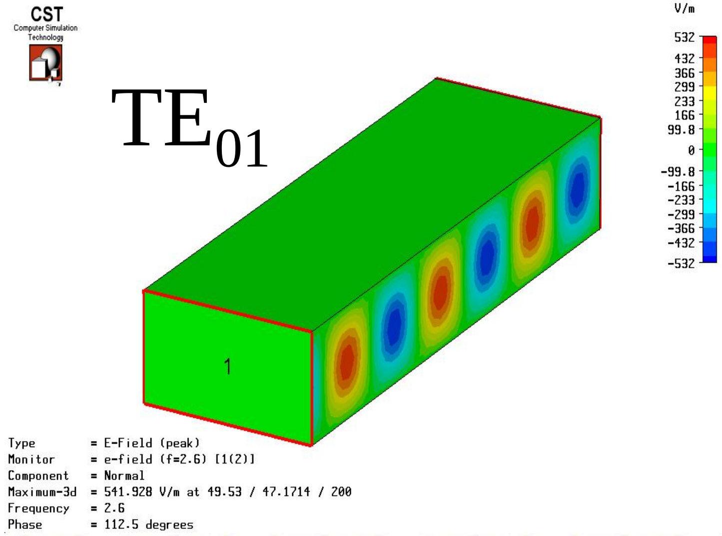
Straight Waveguide (1)



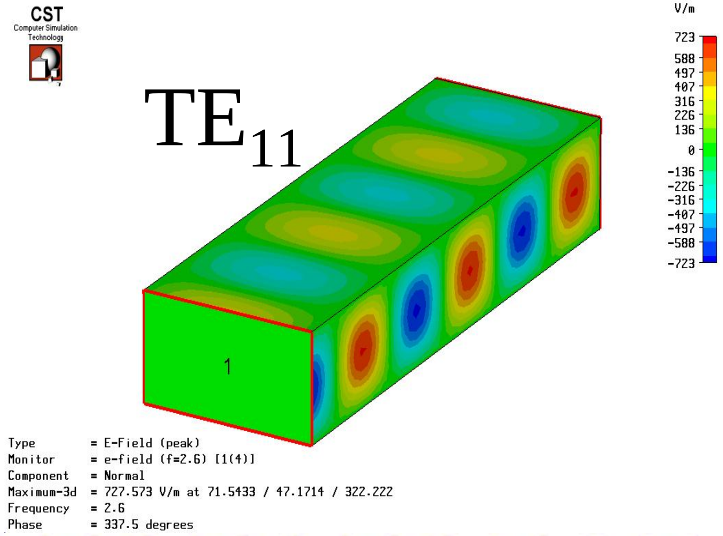
```
Type         = E-Field (peak)
Monitor      = e-field (f=2.6) [1(1)]
Component    = Normal
Maximum-3d   = 243.164 V/m at 5.50333 / 58.9643 / 388.889
Frequency    = 2.6
Phase        = 180 degrees
```



```
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
```

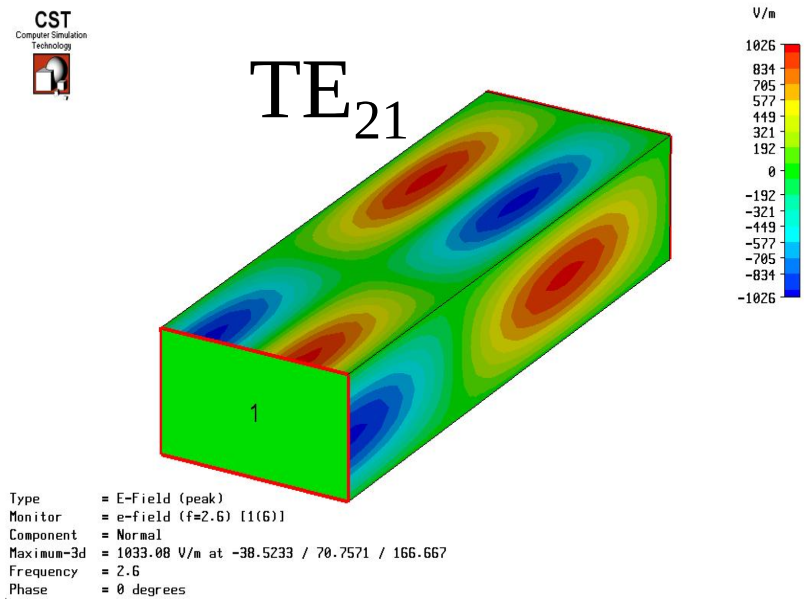


```
Type         = E-Field (peak)
Monitor      = e-field (f=2.6) [1(2)]
Component    = Normal
Maximum-3d   = 541.928 V/m at 49.53 / 47.1714 / 200
Frequency    = 2.6
Phase        = 112.5 degrees
```

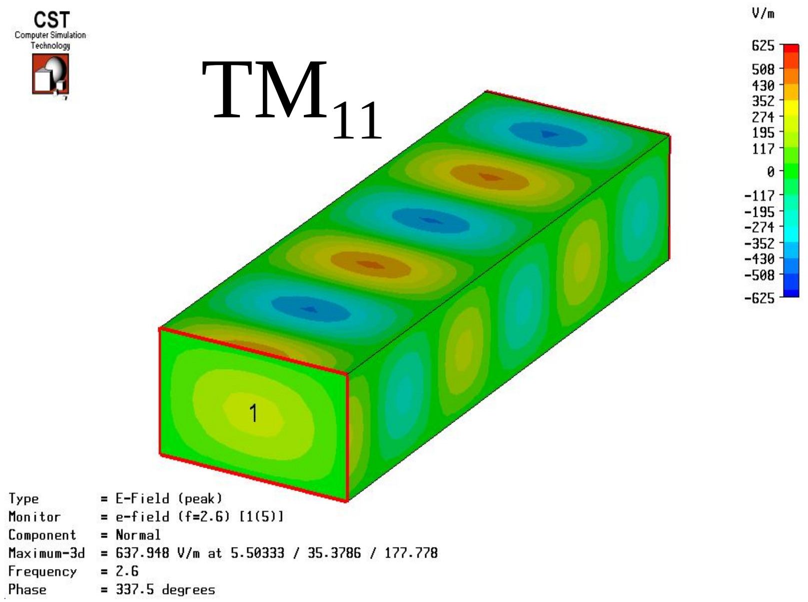


```
Type         = E-Field (peak)
Monitor      = e-field (f=2.6) [1(4)]
Component    = Normal
Maximum-3d   = 727.573 V/m at 71.5433 / 47.1714 / 322.222
Frequency    = 2.6
Phase        = 337.5 degrees
```

Straight Waveguide (2)


TE_{21}

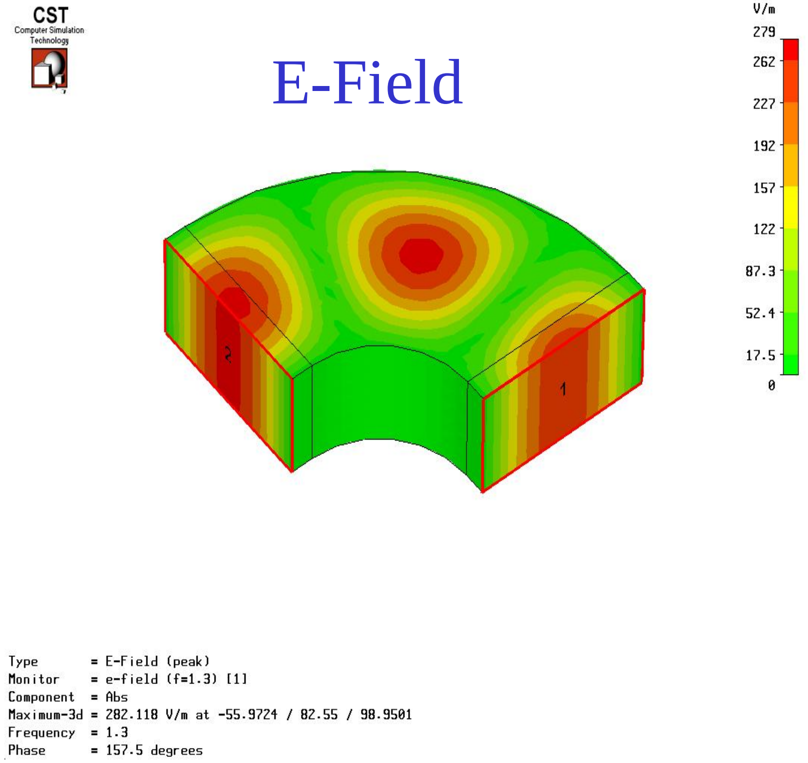
```
Type         = E-Field (peak)
Monitor      = e-field (f=2.6) [1(6)]
Component    = Normal
Maximum-3d   = 1033.08 V/m at -38.5233 / 70.7571 / 166.667
Frequency    = 2.6
Phase        = 0 degrees
```


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
```

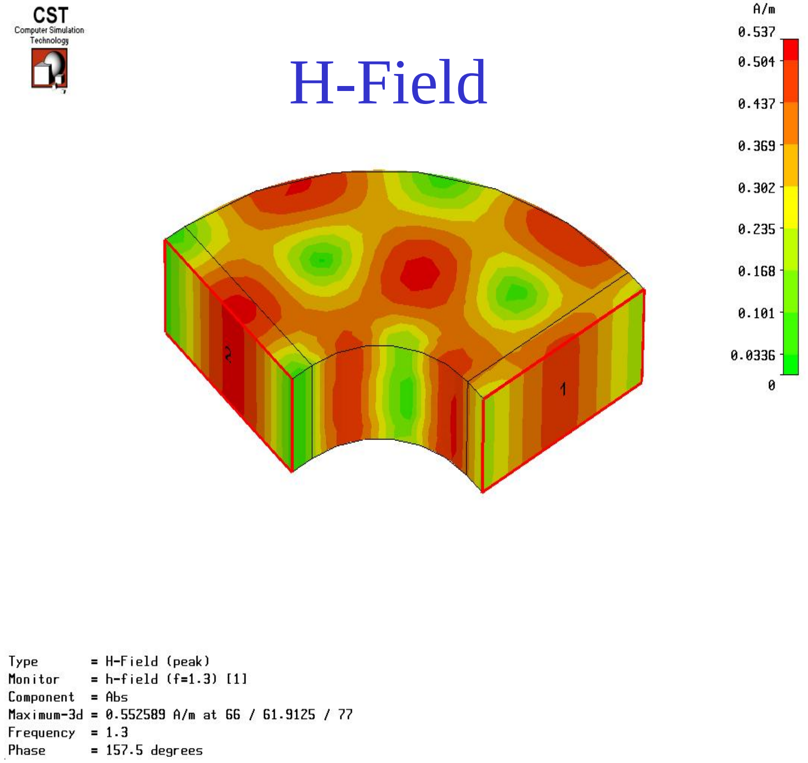
H-Bends

E-Field



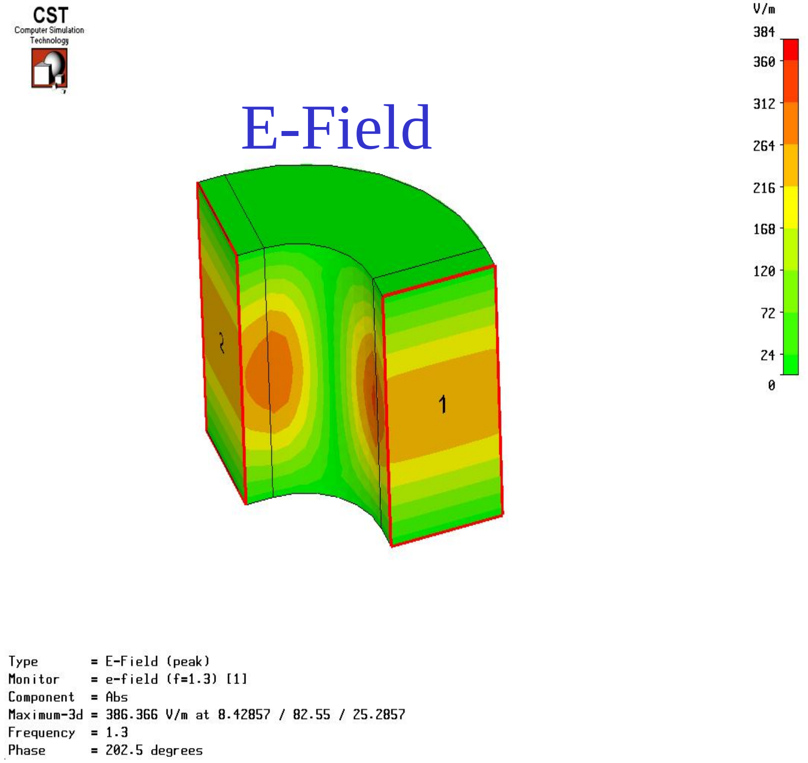
```
Type       = E-Field (peak)
Monitor    = e-field (f=1.3) [1]
Component  = Abs
Maximum-3d = 282.118 V/m at -55.9724 / 82.55 / 98.9501
Frequency  = 1.3
Phase      = 157.5 degrees
```

H-Field



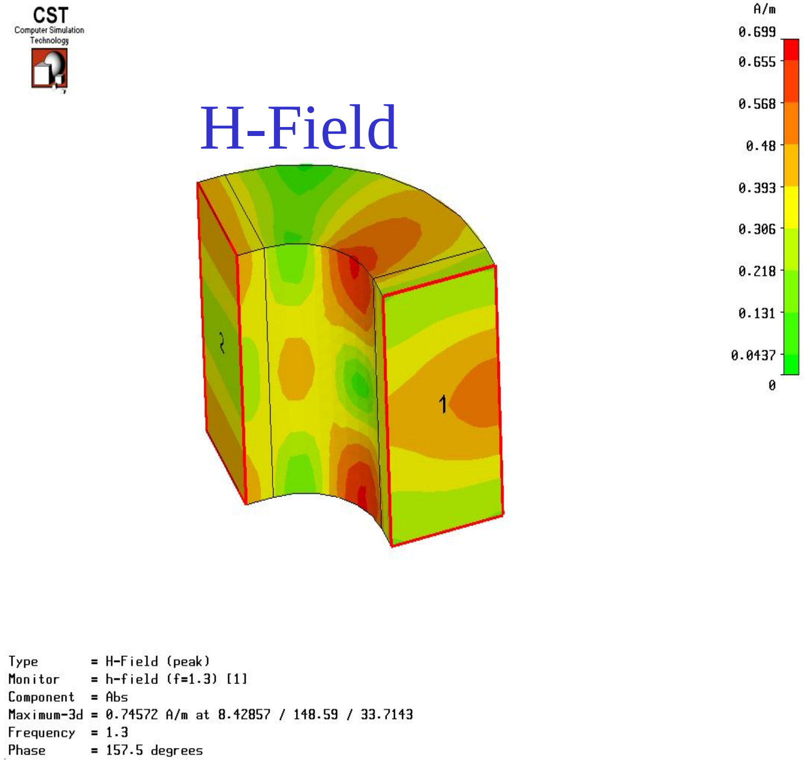
```
Type       = H-Field (peak)
Monitor    = h-field (f=1.3) [1]
Component  = Abs
Maximum-3d = 0.552589 A/m at 66 / 61.9125 / 77
Frequency  = 1.3
Phase      = 157.5 degrees
```

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
```

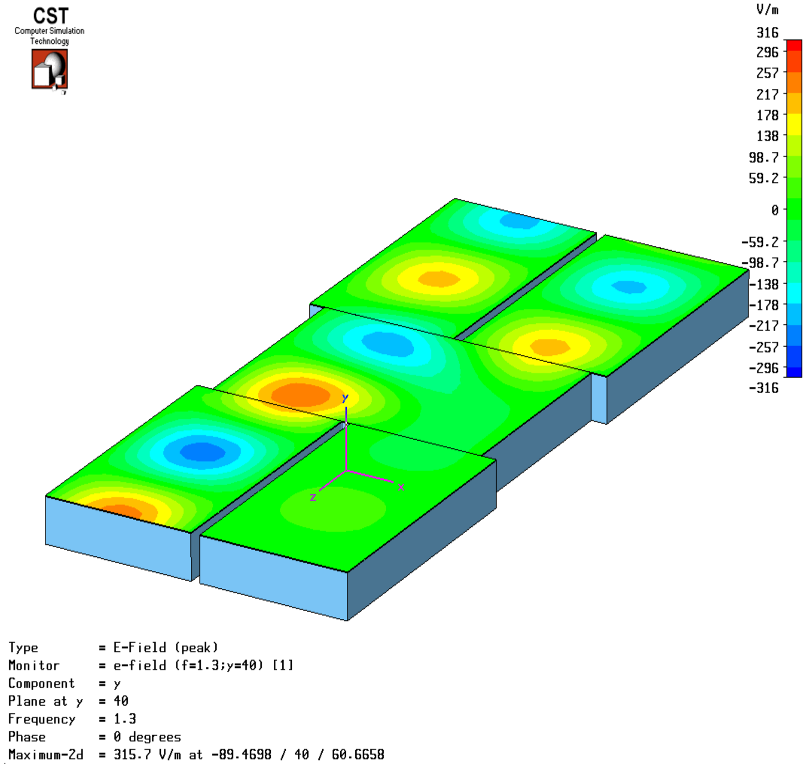


H-Field

```
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.

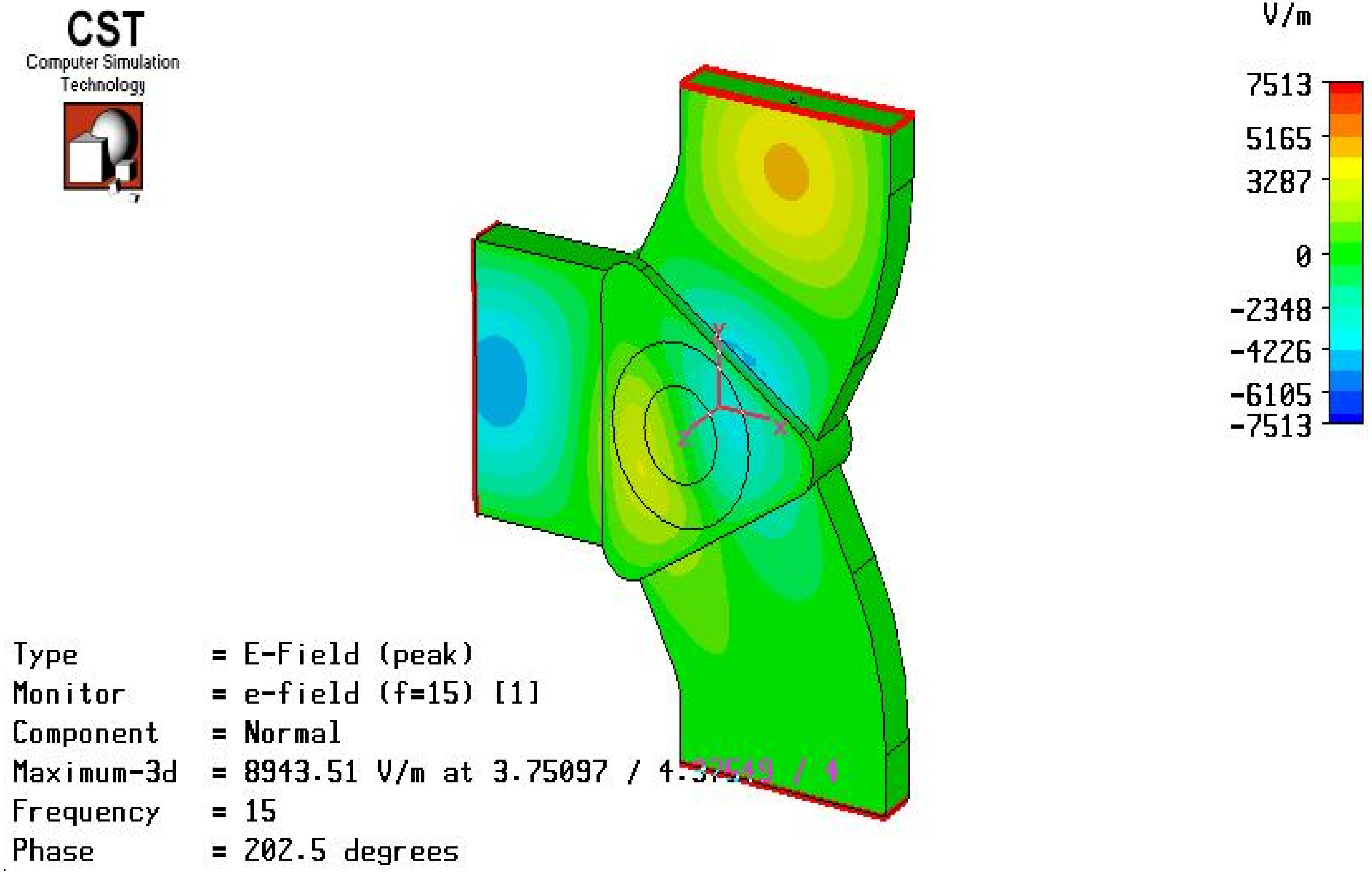
- The ciculator protects the RF source from reflected power.

- 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

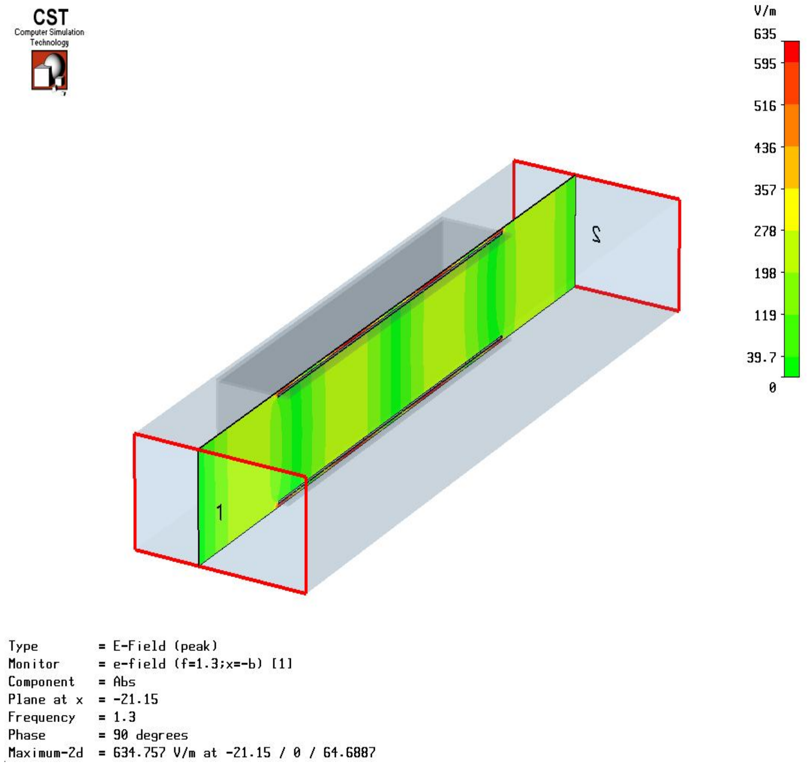
$$\rho = \frac{Z_L - Z}{Z_L + Z}$$

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.

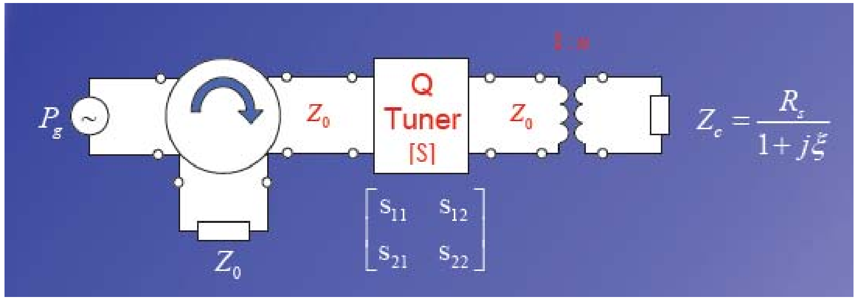
$$\beta_g = \sqrt{k^2 - (\pi / a)^2}$$



```
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)

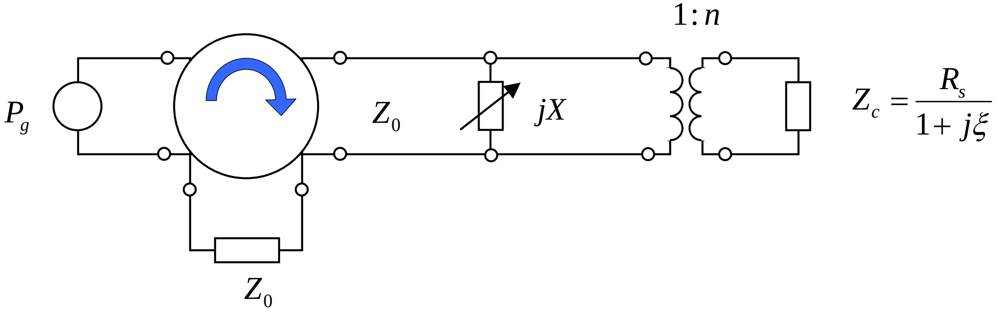


Figure 1: *Equivalent circuit of cavity powered through a circulator with the variable obstacle (no moving along waveguide)*

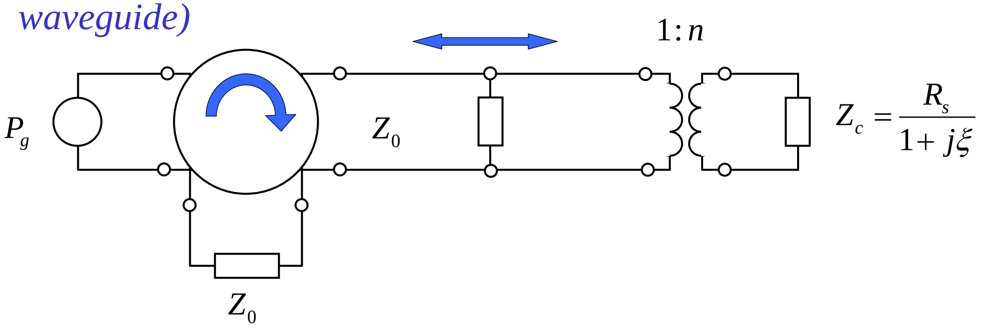
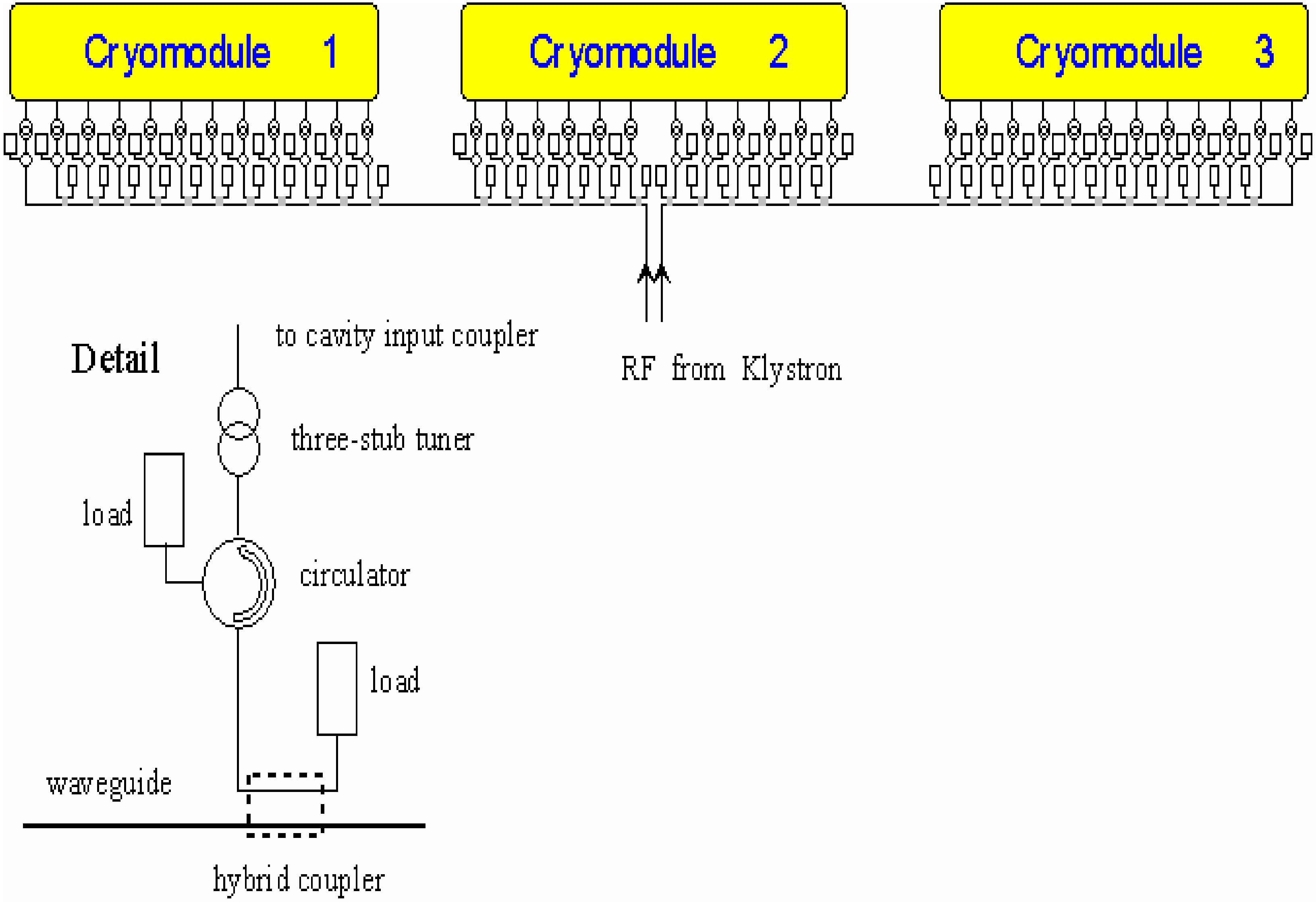


Figure 2: *Equivalent circuit of cavity powered through a circulator with the fixed obstacle moving along waveguide*

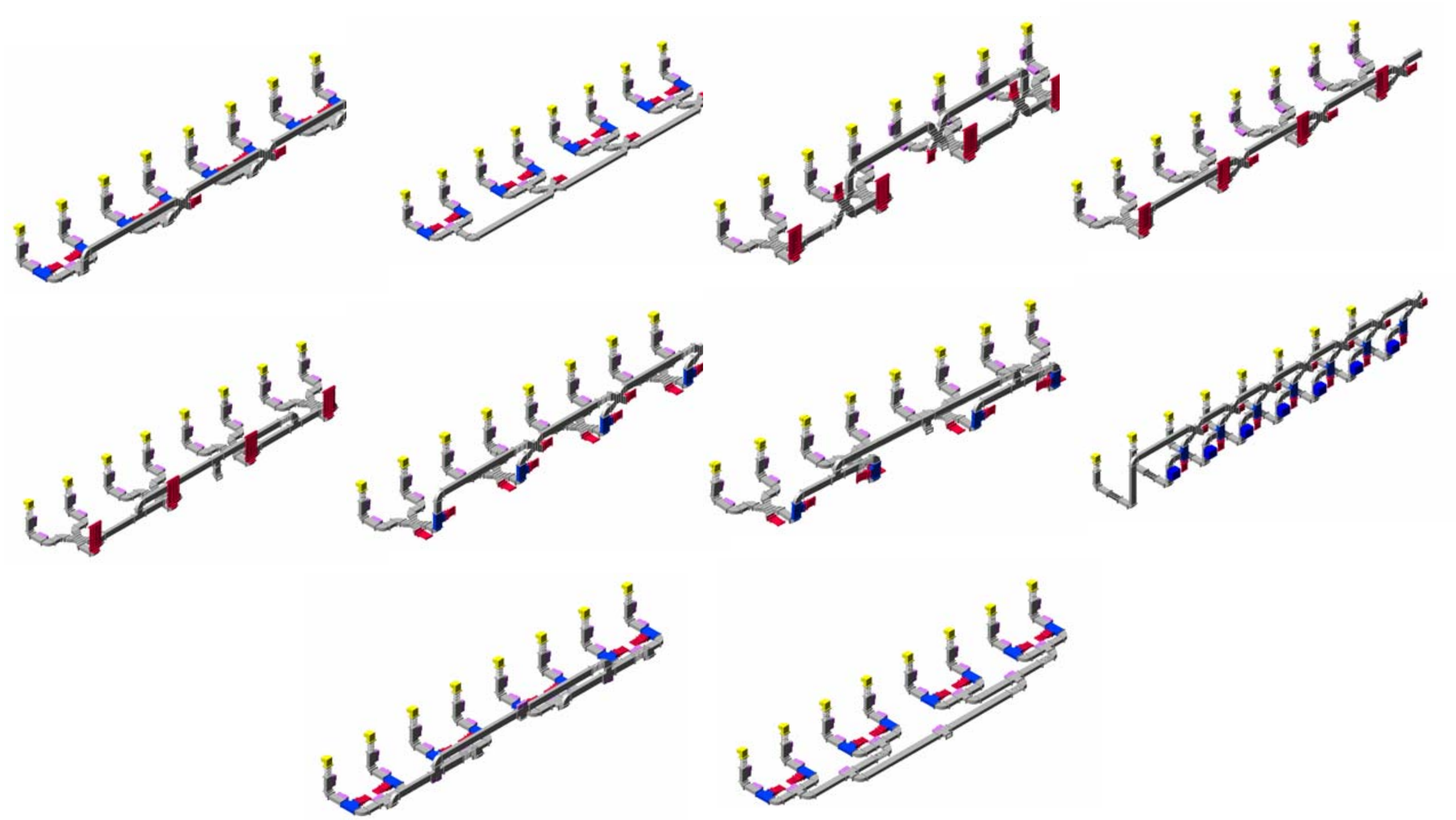
Linear Distribution System (1)

- 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

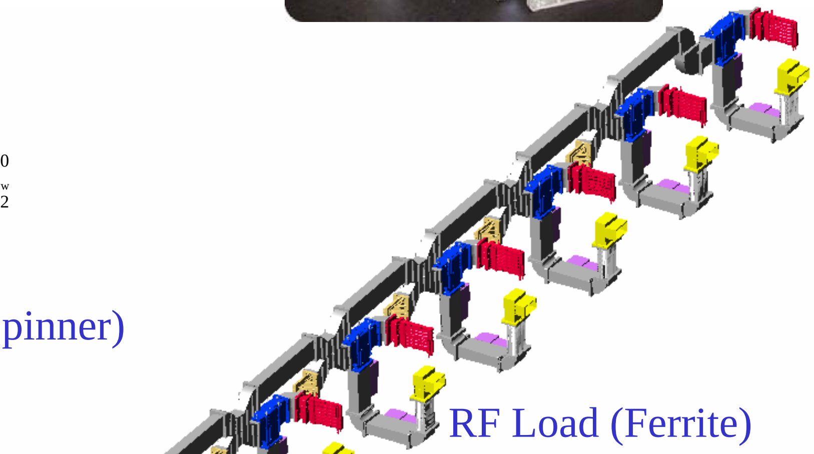
E and H Bends (Spinner)

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)

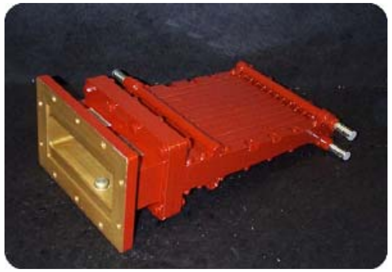
Directivity, dB	⌑30
Return loss, dB	⌑35
Coupling factor, dB (due to tolerance overlapping only 13 different coupling factors instead 18 are nessesary)	12.5; 12.0; 11.4; 10.7; 10.1; 9.6; 9.1; 8.5; 7.8; 7.0; 6.0; 4.8; 3.0
Accuracy of coupling factor, dB	⌖0.2



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, 🖓T ⌖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

Literature: Textbooks and School Proceedings

- M.J. Smith, G. Phillips, Power Klystrons Today, Research Studies Press 1994
- G.N. Glasoe, J.V. Lebacqs, Pulse Generators, MIT Radiation Laboratory Series, McGraw-Hill, New York 1948
- R. E. Collin, Foundations For Microwave Engineering, McGraw Hill 1992
- D. M. Pozar, Microwave Engineering, Wiley 2004
- CERN Accelerator School: Radio Frequency Engineering, 8-16 May 2000, Seeheim, Germany
- CERN Accelerator School: RF Engineering for Particle Accelerators, 3-10 April 1991, Oxford, UK

Literature: References (1)

1. C. Bearzatto, M. Bres, G. Faillon, Advantages of Multiple Beam Klystrons, ITG Garmisch-Partenkirchen, May 4 to 5, 1992.
2. R. Palmer, Introduction to Cluster Klystrons, Proceedings of the International Workshop on Pulsed RF Power Sources For Linear Colliders, RF93, Dubna, Protvino, Russia, July 5-9,1993, p 28.
3. A. Beunas, G. Faillon, 10 MW/1.5 ms, L-band multi-beam klystron, Proc. Conf. Displays and Vacuum Electronics, Garmisch-Partenkirchen, Germany, April 29-30 1998.
4. A. Beunas, G. Faillon, S. Choroba, A. Gamp, A High Efficiency Long Pulse Multi Beam Klystron for the TESLA Linear Collider, TESLA Report 2001-01.
5. H. Bohlen, A Balkcum, M. Cattelino, L. Cox, M. Cusick, S. Forrest, F. Friedlander, A. Staprans, E. Wright, L. Zitelli, K. Eppley, Operation of a 1.3GHz, 10MW Multiple Beam Klystron, Proceedings of the XXII International Linear Accelerator Conference. Linac 2004, Lübeck, Germany, August 16-20, 2004, p 693
6. A Balkcum, E. Wright, H. Bohlen, M. Cattelino, L. Cox, M. Cusick, S. Forrest, F. Friedlander, A. Staprans, L. Zitelli, Continued Operation of a 1.3GHz Multiple Beam Klystron for TESLA, Proceedings of the Sixth International Vacuum Electronis Conference, IVEC 2005, Noordwijk, The Netherlands, April 20-22, 2005, p 505.

6\. A. Yano, S. Miyake, S. Kazakov, A. Larionov, V. Teriaev, Y.H.Chin, The Toshiba E3736 Multi-Beam Klystron, Proccedings of the XXII International Linear Accelerator Conference. Linac 2004, Lübeck, Germany, August 16-20, 2004, p 706

7\. Y.H.Chin, A. Yano, S. Miyake, S. Choroba, Development of Toshiba L-Band Multi-Beam Klystron for European XFEL Project, Proceedings of the 2005 Particle Accelerator Conference, PAC05, Knoxville, USA, May 16-20, 2005, p 3153

8\. W. Bothe, Pulse Generation for TESLA, a Comparison of Various Methods, TESLA Report 94-21, July 1994.

9\. H. Pfeffer, C.Jensen, S. Hays, L.Bartelson, The TESLA Modulator, TESLA Report 93-30.

10\. The TESLA TEST FACILITY LINAC-Design Report, Ed. D.A. Edwards, Tesla Report 95-01.

Literature: References (2)

11. H. Pfeffer, L. Bartelson, K. Bourkland, C. Jensen, Q. Kerns, P. Prieto, G. Saewert. D. Wolff, A Long Pulse Modulator for Reduced Size and Cost, Fourth European Particle Accelerator Conference, London 1994.
12. H. Pfeffer, L. Bartelson, K. Bourkland, C. Jensen, P. Prieto, G. Saewert. D. Wolff, A Second Long Pulse Modulator For TESLA Using IGBTs, Proceedings of the Fifth European Particle Accelerator Conference, EPAC96, Sitges (Barcelona), 10-14 June 1996, p. 2585.
13. W. Kaesler, A Long-Pulse Modulator for the TESLA Test Facility (TTF), Proccedings of the XXII International Linear Accelerator Conference. Linac 2004, Lübeck, Germany, August 16-20, 2004, p 459
14. H.-J. Eckoldt, N. Heidbrook, Constant Power Power Supllies for the TELSA Modulator, TESLA Report 2000-36.
15. H.-J. Eckoldt, Pulse Cables for TESLA, TESLA Report 2000-35.
16. T. Grevsmühl, S. Choroba, P. Duval, O. Hensler, J. Kahl, F.-R. Kaiser, A. Kretzschmann, H. Leich, K. Rehlich, U. Schwendicke, S. Simrock, S. Weisse, R. Wenndorff, The RF-Station Interlock for the European X-Ray Laser, Proccedings of the XXII International Linear Accelerator Conference. Linac 2004, Lübeck, Germany, August 16-20, 2004, p 718
17. H. Leich, S. Choroba, P. Duval, T. Grevsmühl, V. Petrosyan, S. Weisse, R. Wenndorff, An Advanced Interlock Solution for TTF2/XFEL RF Stations, Proceedings of the 14th IEEE_NPSS Real Time Conference, Stockholm, Sweden, June 4-10, 2005, p. 36
18. H. Leich, S. Choroba, P. Duval, T. Grevsmühl, A. Kretzschmann, U. Schwendicke, R. Wenndorff, The Design of a Technical Interlock for TTF2/XFEL RF Stations, NEC 2005, XX International Symposium on Nuclear Electronics & Computing., (to be published)
19. V. Katalev, S. Choroba, RF Power Distributing Waveguide System for TESLA, Proceedings of the Russian Particle Accelerator Conference, Rupac 2002, Obninsk, Russia, October 1-4, 2002, p. 79
20. V. Katalev, S. Choroba, Tuning of External Q and Phase for the Cavities of a Superconducting Linear Accelerator, Proccedings of the XXII International Linear Accelerator Conference. Linac 2004, Lübeck, Germany, August 16-20, 2004, p 724

Appendix

Klystron: Gun (1)

- Cathode typical:

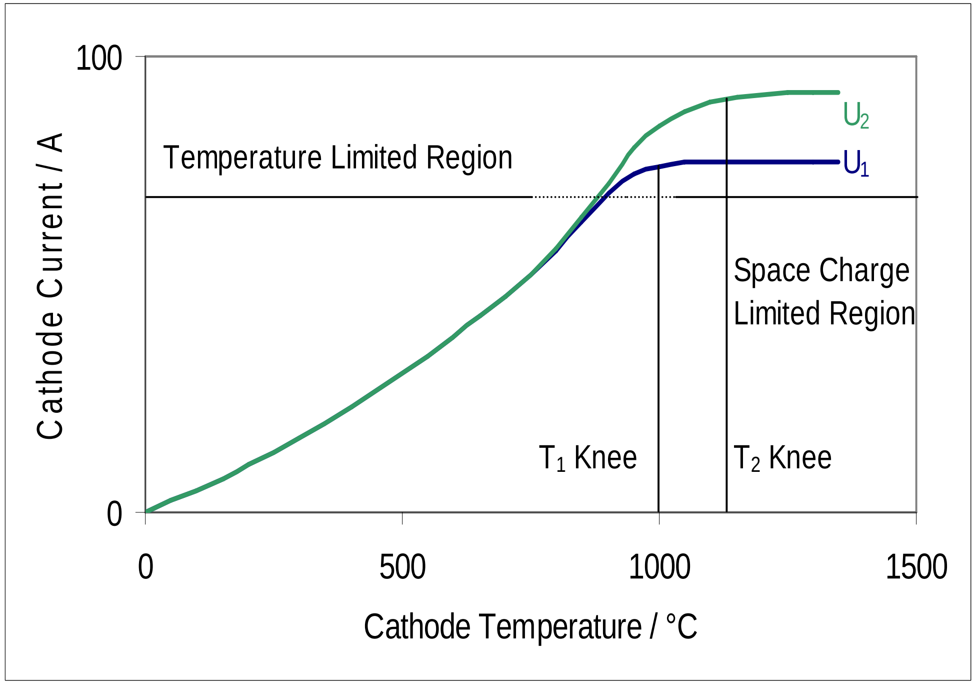
  A) M-Type: Tungsten-Matrix impregnated with Ba and coated with Os/Ru

  B) Oxide (BaO, CaO or SO)

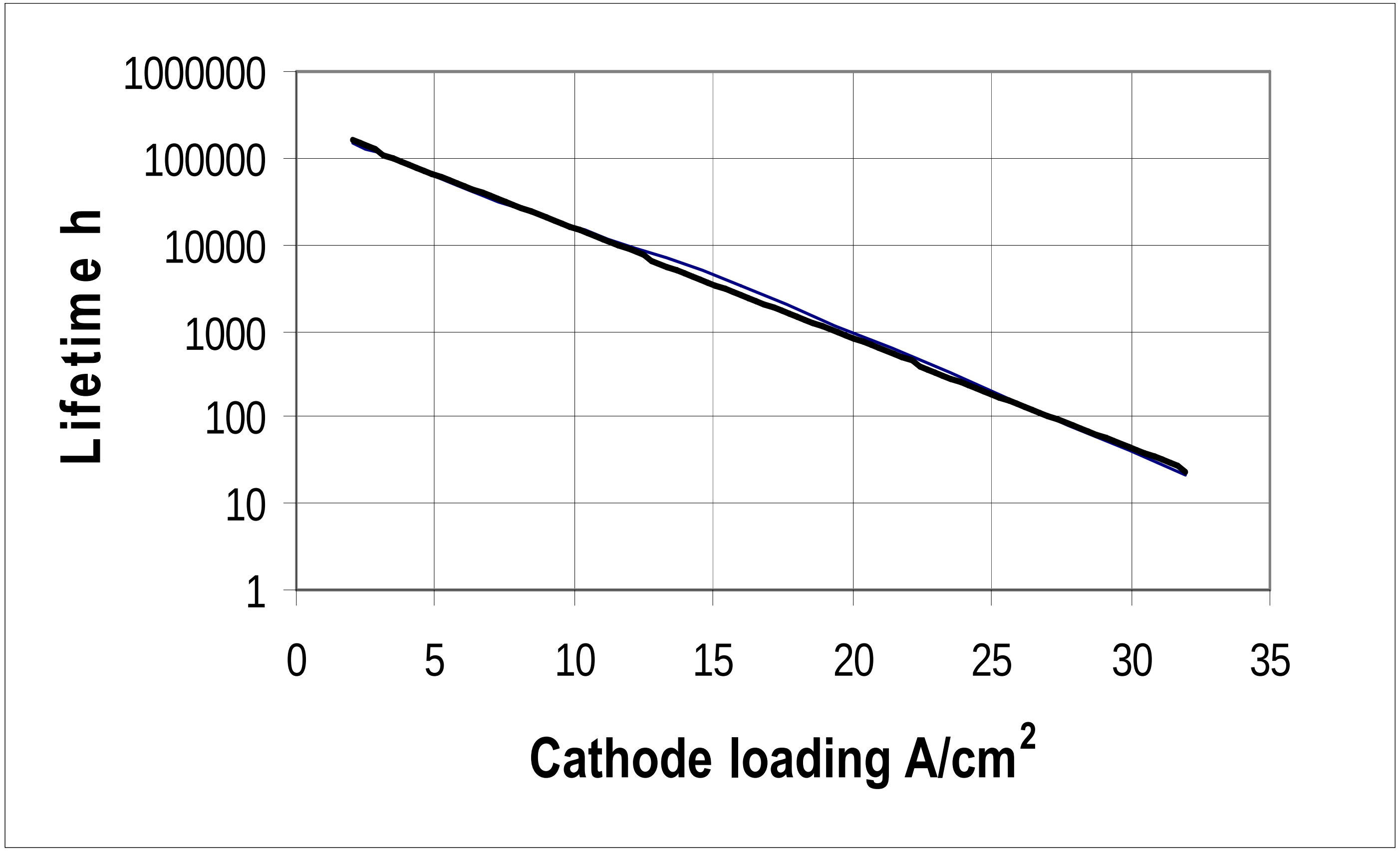
- Cathode is operated in the space charge limited region (Child-Langmuir Theory)

  $j=(4/9)\mathbf{e}_0[(2e)/m]^{1/2}U^{3/2}/d$

- Integration gives: $I=pU^{3/2}$



Klystron: Gun (2)



For higher cathode loading it is required to operate at higher cathode temperature => the cathode lifetime decreases.

Klystron: Beam Focussing

- Confined flow: The cathode is in the magnetic field of a solenoid (common in travelling wave tubes).

- Brillouin focussing: No magnetic field lines are threading through the cathode. The beam is entering the magnetic field of a (electromagnetic) solenoid around the drift tube section.

  B is B=1.2 - 2 x B_B (typ ~1000G)

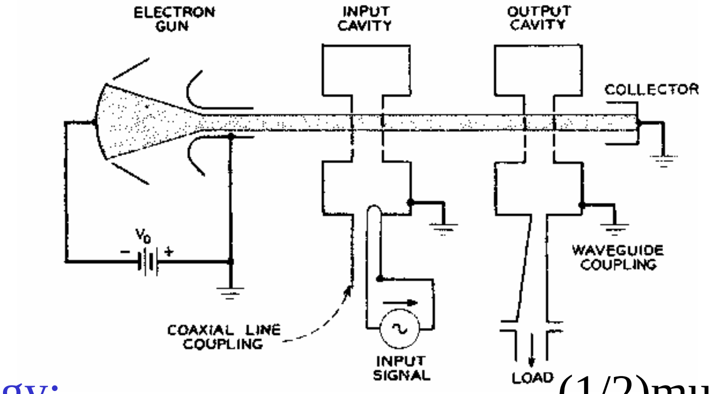
  with B_B Brillouinfield

  with b beam radius, u_e beam velocity, I beam current

- Focussing can also be done with permanet magnets: Periodic Permanent Magnet focussing (PPM) e.g. pulsed high power X-Band klystrons (SLAC, KEK).

$$B_B = \sqrt{(2I\, m_0)/(\varepsilon_0 \pi b^2 u_e e)}$$

Klystron: Ballistic Theory (1)
Treatment of individual electrons without interaction



Inititial electron energy: $(1/2)mu_0^2=eV_0$

Electron Energy gain in the input cavity: $(1/2)mu^2-(1/2)\ mu_0^2=eV_1\sin wt$

$u=u_0(1+(mV_1/V_0)\sin wt)^{1/2}$

Assume $V_1<<V_0$: $u=u_0(1+(mV_1/2V_0)\sin wt)$

The arrival time t_2 in the second cavity depends on the departure time t_1 in the first cavity with the assumption of an infinite thin gap:

$t_2=t_1+l/u=t_1+l/u_0(1+(mV_1/2V_0)\sin wt_1)=t_1+l/u_0-(lmV_1/2u_0V_0)\sin wt_1)$

or $wt_2=wt_1+q_0-X\sin wt_1$ with $q_0=l/u_0$ and $X=q_0mV_1/2V_0$ called bunching parameter

Klystron: Ballistic Theory (2)

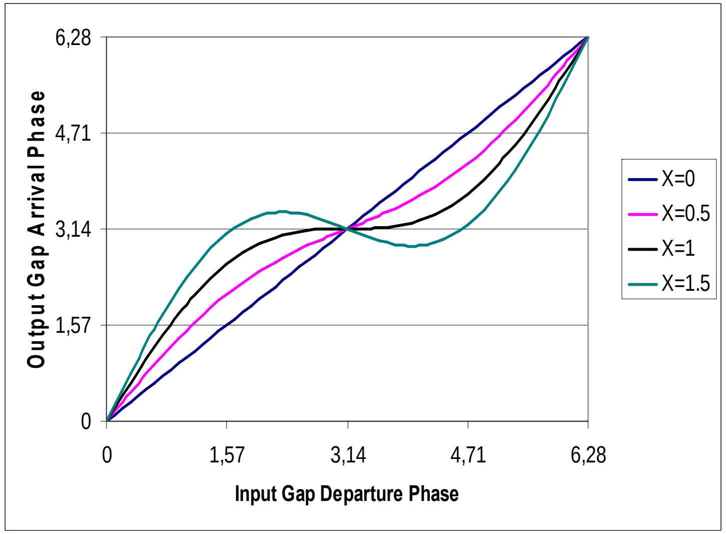
Because of charge conservation: Charge in the input cavity between time t_1 and t_1+dt_1 equals the charge in the output cavity between time t_2 and t_2+dt_2

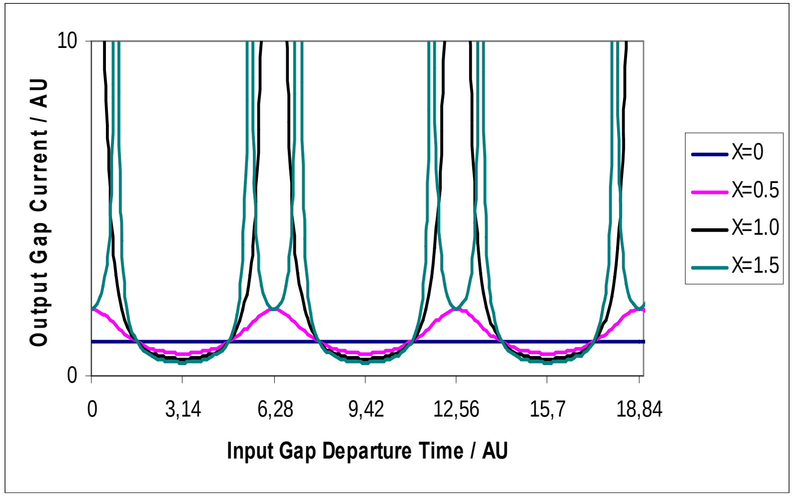
$I_1dt_1=I_2dt_2$

With $dt_2/dt_1=1-X\cos wt_1$ and $I_2= I_1/(dt_2/dt_1)$ one gets

$I_2= I_1 1 /(1-X\cos wt_1)$

$I_2= I_1 ABS(1 /(1-X\cos wt_1))$





Klystron: Ballistic Theory (3)

Fourier transformation of the current in the output gap I_2

$$I_2 = I_0 + \sum_{n=1}^{\infty} [\, a_n \cos n(\omega t_2 - \theta_0) + b_n \sin(\omega t_2 - \theta_0)]$$

$$a_n = (1/\pi) \int_{\theta 0-\pi}^{\theta 0+\pi} I_2 \cos n(\omega t_2 - \theta_0) d(\omega t_2) \qquad b_n = (1/\pi) \int_{\theta 0-\pi}^{\theta 0+\pi} I_2 \sin n(\omega t_2 - \theta_0) d(\omega t_2)$$

$$a_n = (I_0/\pi) \int_{-\pi}^{\pi} \cos n(\omega t_1 - X \sin \omega t_1) d(\omega t_1)$$

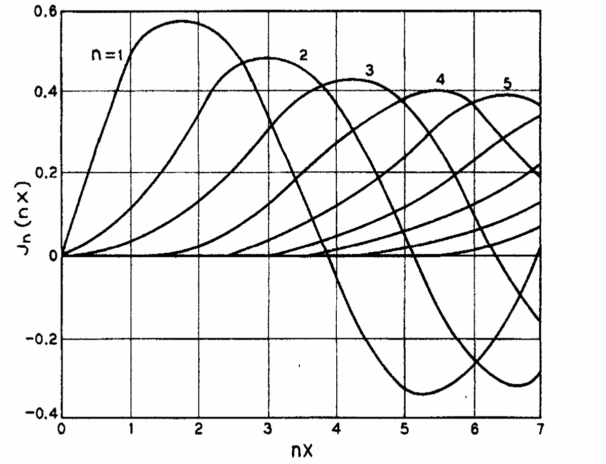
$$b_n = (I_0/\pi) \int_{-\pi}^{\pi} \sin n(\omega t_1 - X \sin \omega t_1) d(\omega t_1) = 0$$

$a_n = 2 I_0 J_n(nX)$ with J_n Besselfunction of the n- th order

Klystron: Ballistic Theory (4)

$$I_2 = I_0 + 2 I_0 \sum_1^\infty J_n(nX)\cos n(\omega t_1 - \theta_0)$$

$$I_\omega = 2 I_0 J_1(X)\cos(\omega t - \theta_0)$$



Bessel functions of various orders. The maximum value of J_1 occurs at $X = 1.84$ and is equal to 0.582.

Maximum Output Power:

$$P_\omega = \overline{I_\omega V_\omega} = 2\times 0.58\,(I_0/\sqrt{2})(V_0/\sqrt{2}) = 0.58\,P_{Beam}$$

Klystron: Space Charge Waves

- Space charge forces counteract the bunching
- Any perturbation in an electron beam excites an oscillation with the plasma frequency
- Therefore we have 2 waves with the Phase constants
- And therefore
- The group velocity is
- The density modulations appear at a distance of

$$\Omega = \sqrt{\left((e/m_0)(\rho_0/\varepsilon_0)\right)}$$

$$\beta_{e1} = \beta_e(1+\Omega/\omega)$$

$$\beta_{e2} = \beta_e(1-\Omega/\omega)$$

$$\beta_e = \omega/u_e \qquad u_{e2} = u_e/(1-\Omega/\omega)$$

$$u_{e1} = u_e/(1+\Omega/\omega)$$

$$u_g = d\omega/d\beta_e = u_e$$

$$\lambda_p = 2\pi u_e/\Omega$$

This means that the driftspace or the distance between cavities is determined by the plasma frequency (klystron current) and the electron velocity (klystron voltage) and is given by $\lambda_p/4$

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Klystron: Coupling (1)

- Up to now we have neglected the transit time t in the cavity gap
- The transit angle is: f=wt
- The coupling factor is: K_1=(sin(f/2))/(f/2)
  e.g. K_1=1 max if f=0 (infinite thin gap)
- In addition there is the transversal coupling factor
  $K_t=J_0(b_e r)/J_0(b_e b)$ with b=beam radius and r=tunnel radius and J_0 modified Besselfunction
- The total coupling factor is $K=K_1K_t$ and determines the RF voltage in the cavity gap generated by the RF current
- A typical number is K ~0.85 at ~1GHz

Klystron: Coupling (2)

- The RF current in the output cavity is given by K and the beam RF current I_2
- $I_{2C}=I_2K\cos(f_{2C}/2+p/2)$ with f_{2C} transit angle of the output cavity
- I_{2C} generates an RF voltage in the output cavity of $V_{2C}=I_{2C}/G_2$ with $G_2=G_{2C}+G_{Load}$
- The coupling to the load must be adjusted so that no electrons are reflected that means that $V_{2C}<V_{0}$. Otherwise oscillations would be caused.