

High Power RF

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Overview

- Remarks
- Introduction High Power RF System
- Klystron
- Modulator
- RF Waveguide Distribution
- Preamplifier, Auxiliaries, Interlocks and Controls belong to a RF system but will not be covered in this lecture due to time constraints

Remarks

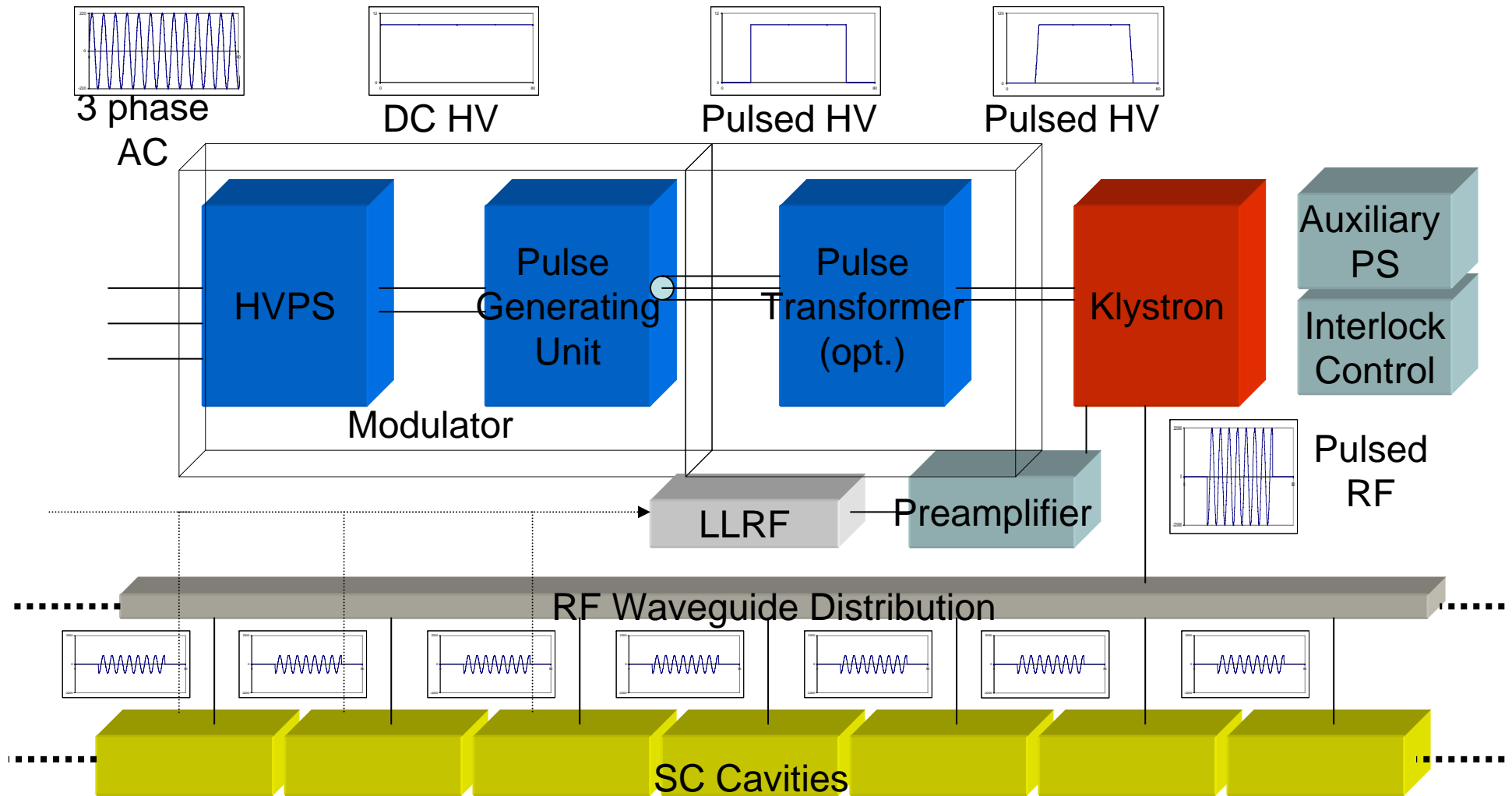
- High Power RF System is a wide area
- A basic overview on how things work can only be presented because of lack of time.
- In the appendix information on basic klystron theory is given.
- A list of references is provided.
- Examples for possible ILC components will be shown based on the TESLA Linear Collider TDR. This is reasonable since the ILC RF system baseline layout is ~90% identical to the TESLA RF system layout.

Introduction

Introduction High Power RF System (in general)

- 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 availability of components, costs etc)
- Pulse Power per Station: ~100kW to ~1-10MW (ILC) to ~100MW (norm. cond. acc.)
- Pulse Width: (~1 μ s 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 ($\sim 400\text{V AC}$) to DC HV ($\sim 1\text{-}10\text{kV}$ (100kV))
 - Pulse Generating Unit: Conversion of DC HV ($\sim 1\text{-}10\text{kV}$ (100kV)) to Pulsed HV ($\sim 1\text{-}10\text{kV}$ (100kV))
 - Pulse Transformer: Transformation of Pulsed HV (typ. $\sim 10\text{kV}$) to higher Pulsed HV ($\sim 100\text{kV}$)
- **Klystron:**
 - Conversion of Pulsed HV ($\sim 100\text{kV}$) to pulsed RF ($\sim 10\text{MW}$)
- **RF Waveguide Distribution:**
 - Distribution of RF power ($\sim 10\text{MW}$) to the cavities ($\sim 100\text{kW}$)
- **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 $\sim 1\text{mW}$ RF to $\sim 100\text{W}$ RF

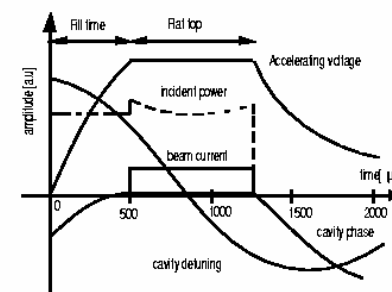
TESLA 500 RF Requirements

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:	950μs
RF pulse duration:	1.37ms
Repetition rate:	5Hz
Average RF power per station:	66.5kW

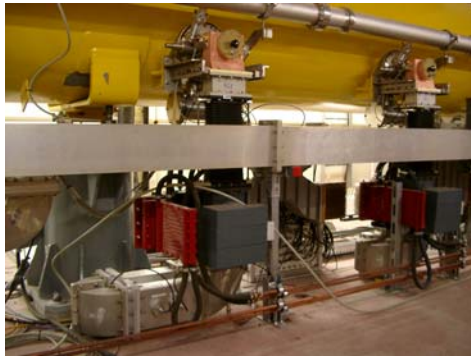


For TESLA 800 the number of stations must be doubled.
The gradient is 35MV/m.

RF System Components

developed for Tesla and installed at TTF

Klystron



RF Waveguide Distribution



Modulator

Pulse Transformer

Klystron

Possible RF Sources

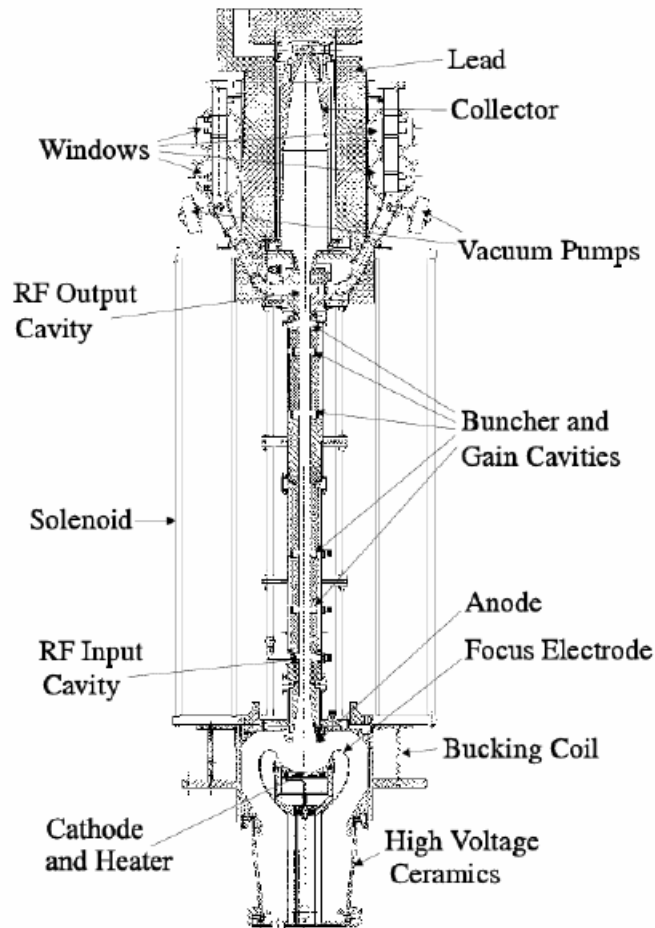
- Klystron today
 - Frequency Range: ~350MHz to ~17GHz
 - Output Power:
 - CW: up to ~1.3MW
 - Pulsed: up to ~200MW at ~1 μ s
 - up to ~10MW at ~1ms
 - Klystron Gun Voltage:
 - DC: ~100kV
 - Pulsed: ~600kV at ~1 μ s
 - ~130kV at ~1ms
- ~~Tetrode, Triode: Frequency up to ~200-300MHz, ~10kW~~
- ~~IOT: 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 $\sim 1000^{\circ}\text{C}$.
- The cathode is then charged (pulsed or DC) to several 100kV.
- Electrons are accelerated from 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
 $U=128\text{kV}$ $I=89\text{A}$ $p=1.94 \cdot 10^{-6}\text{A/V}^{3/2}$ ($\mu\text{perveance}=1.94$)



Klystron Output Power

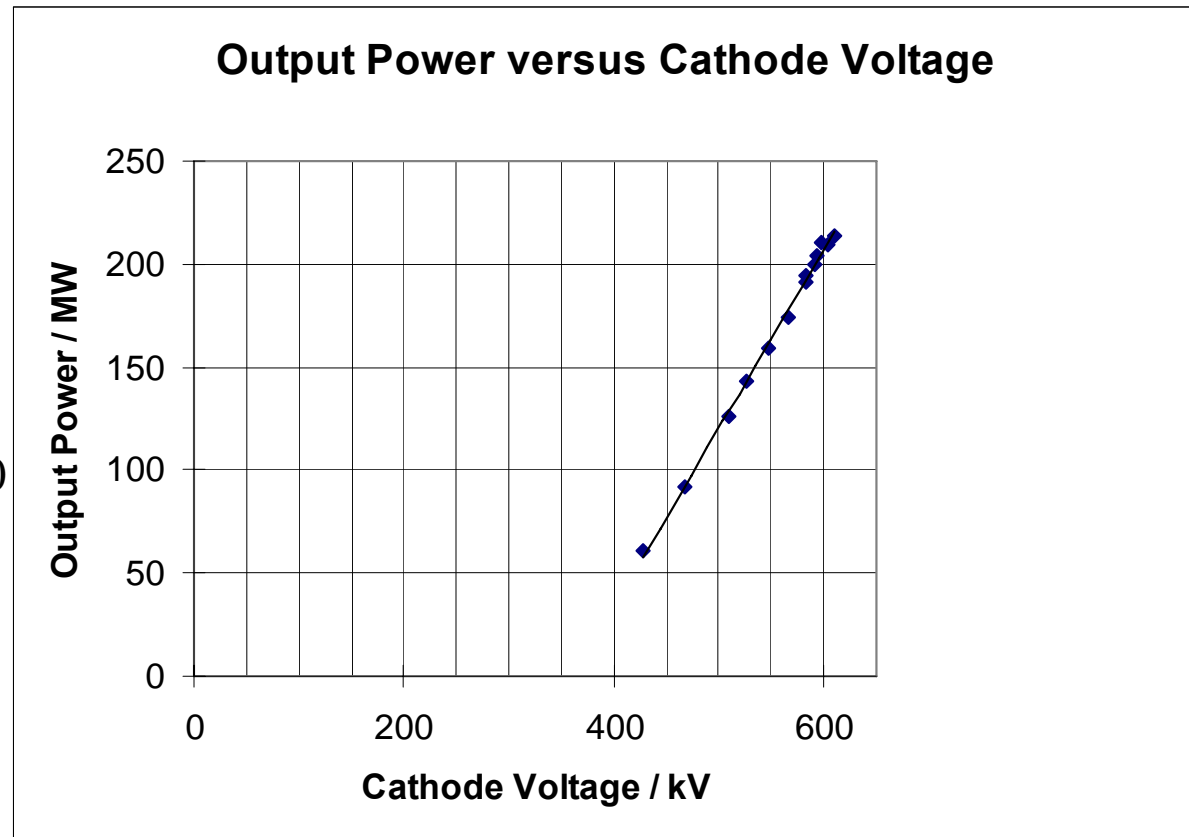
$$P_{RF} = \eta P_{Beam}$$

$$P_{Beam} = UI$$

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

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

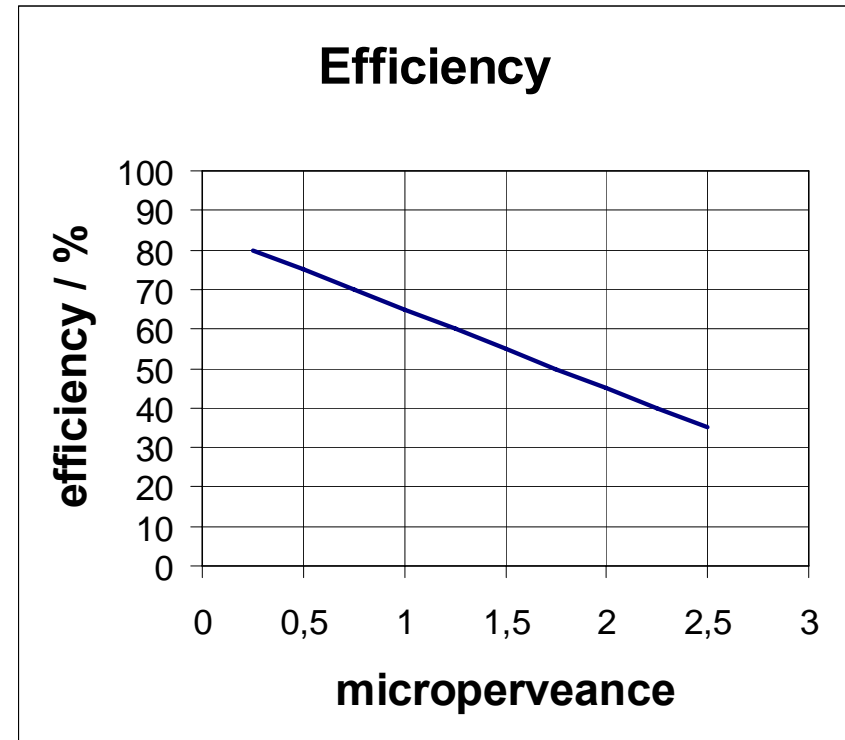
$$P_{RF} \propto U^{>5/2}$$



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

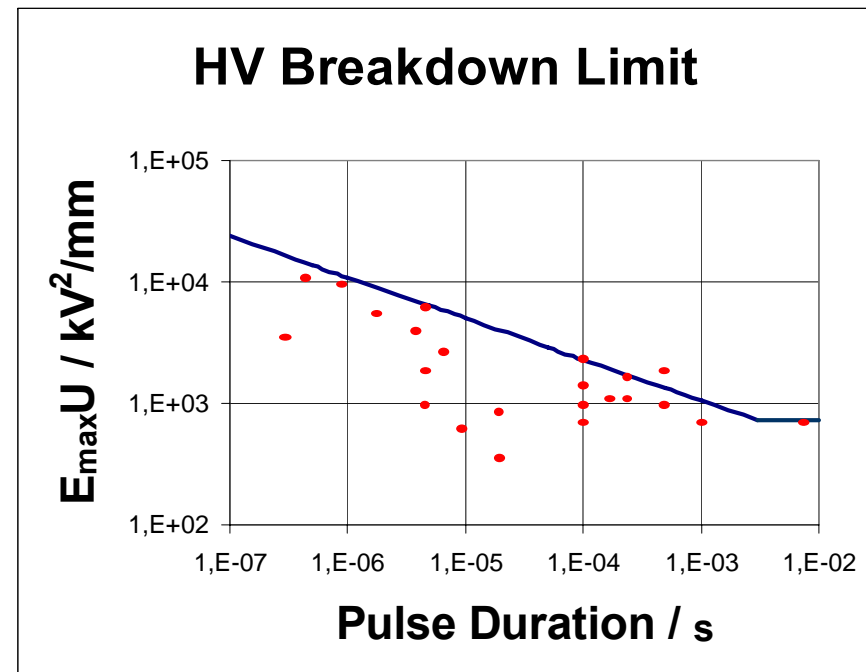


Rule of thumb formula from fit to experimental data

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

Klystron Gun Breakdown Limit

- Disadvantage: higher voltage increase the probability of breakdown
- The breakdown limit EU depend on the pulse duration



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

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:

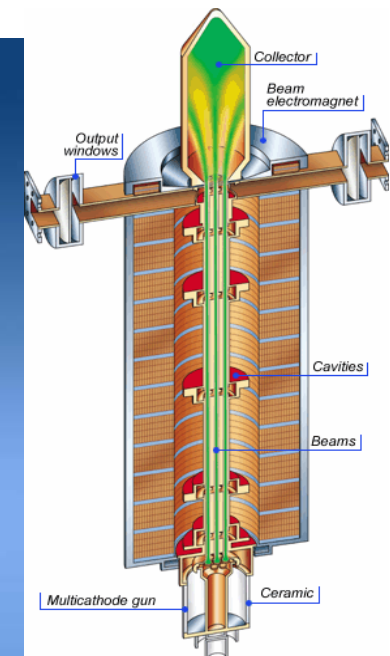
=> low perveance per beam thus high efficiency

low voltage compared to klystron with single low perveance beam

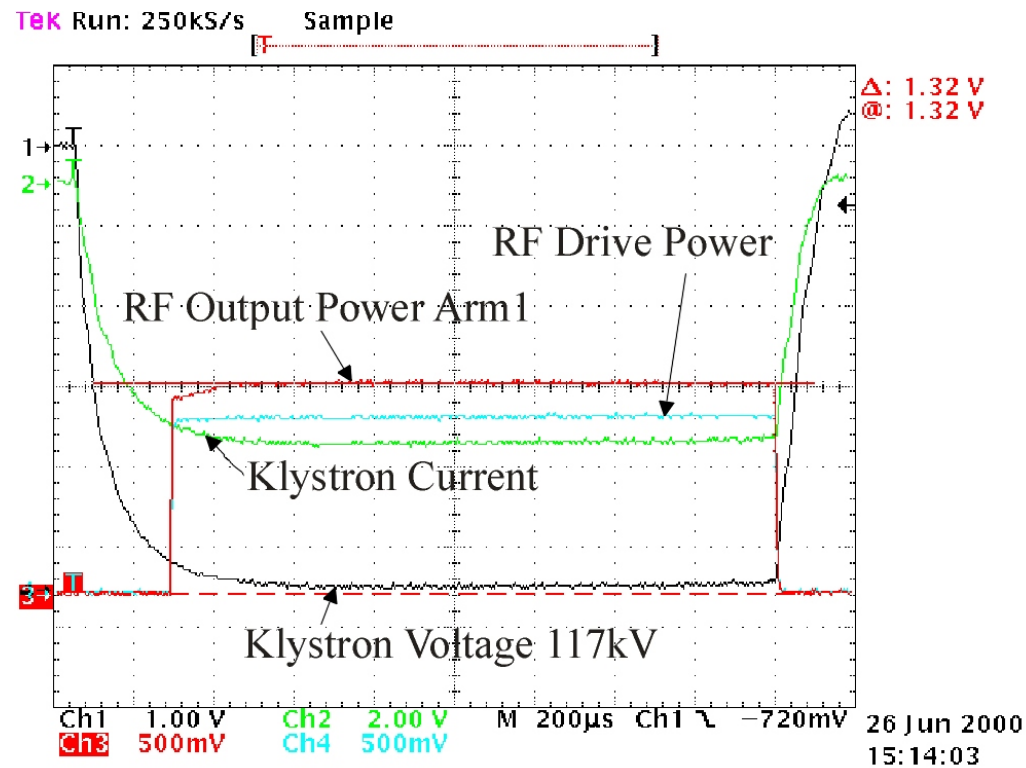
Multi Beam Klystron THALES TH1801 (1)

Measured performance

Operation Frequency:	1.3GHz
Cathode Voltage:	117kV
Beam Current:	131A
μ perveance:	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

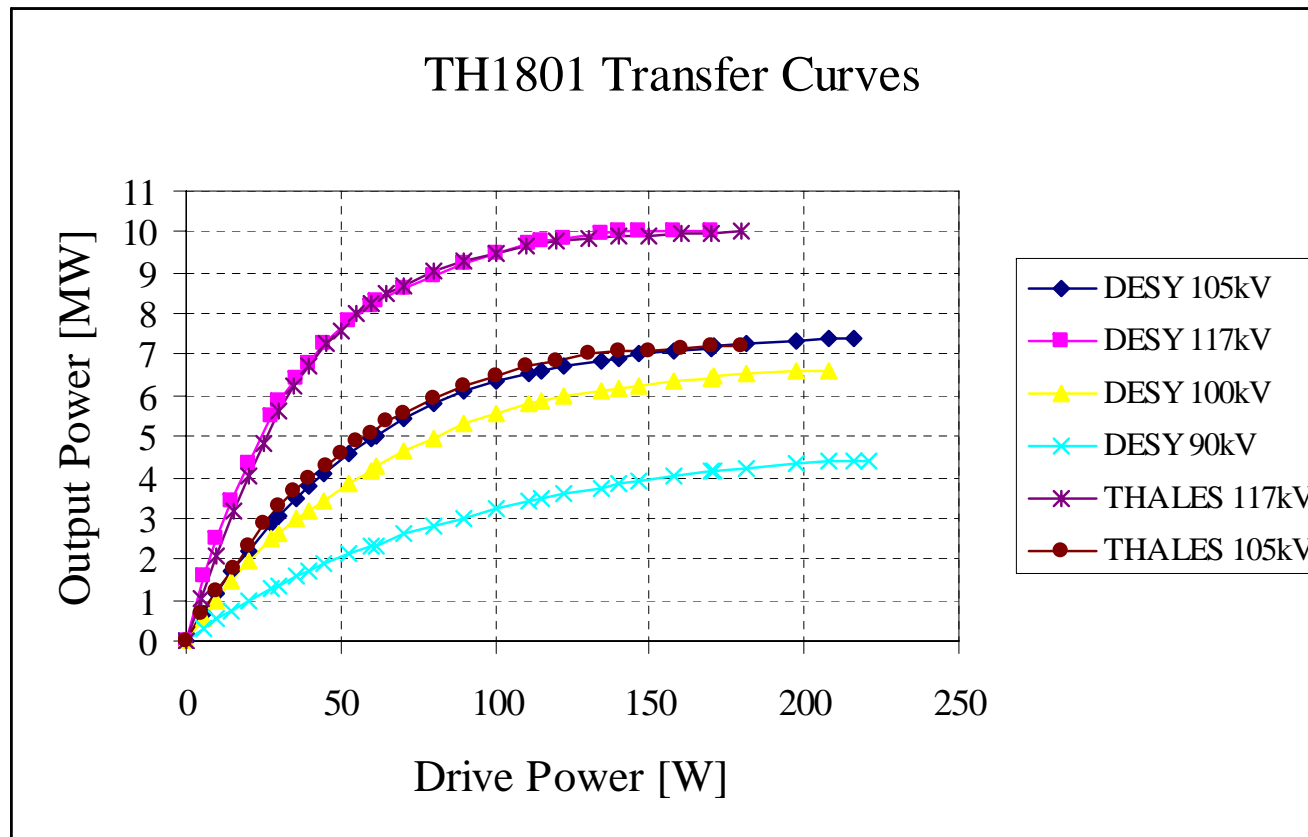


Multi Beam Klystron THALES TH1801 (2)



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

Multi Beam Klystron THALES TH1801 (3)

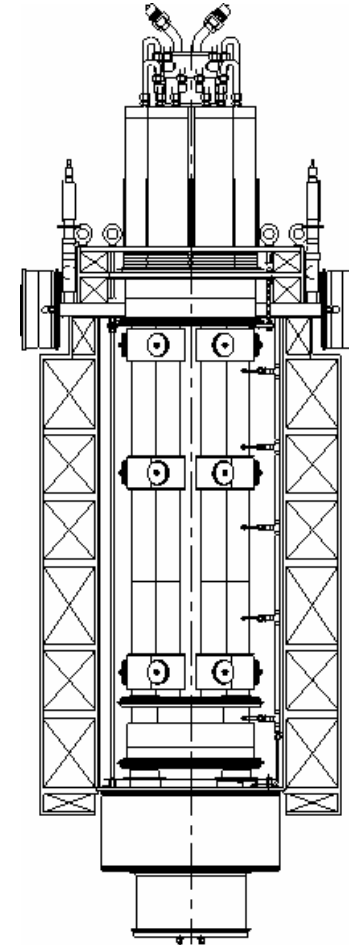


Transfer Curves: RF output as function of RF drive power with klystron voltage as parameter

Multi Beam Klystron CPI VKL-8301(1)

Design Features:

- 6 beams
- HOM input and output cavity
- Individual intermediate FM cavities
- Cathode loading:
$2.5\text{A}/\text{cm}^2$ 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)
μperveance	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)

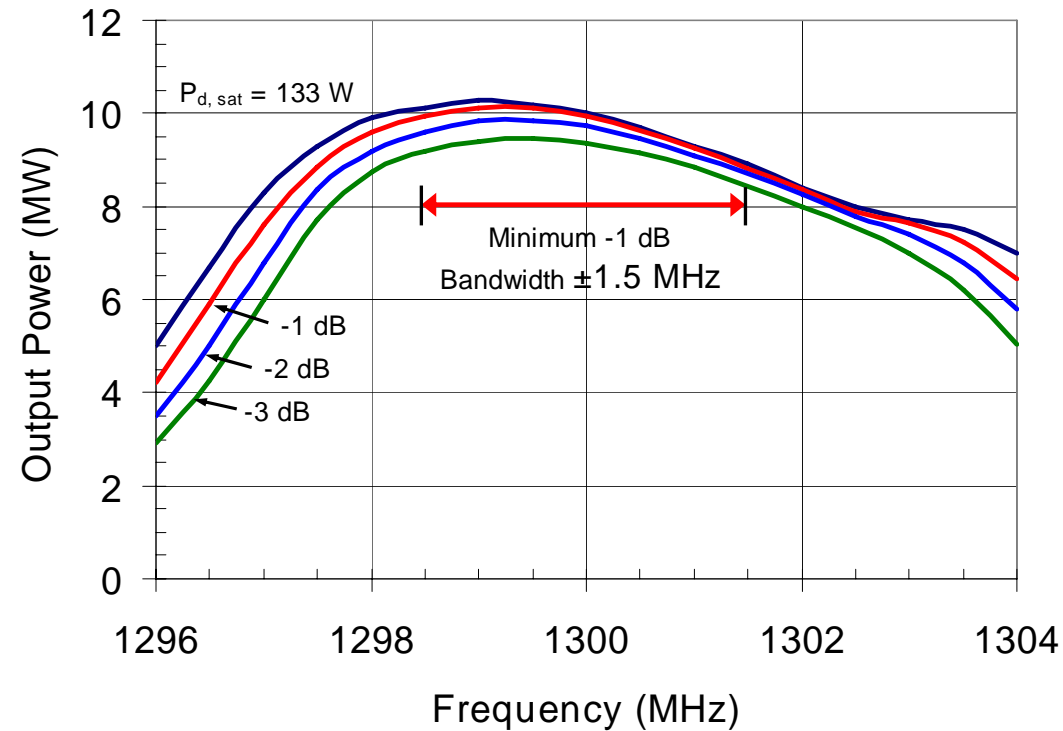
Measured Operating Parameters at
CPI at 500 μ s pulsewidth

Peak Power Output	10	MW
Ave. Power Output	150	kW
Beam Voltage	120	kV
Beam Current	139	A
μ perveance	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

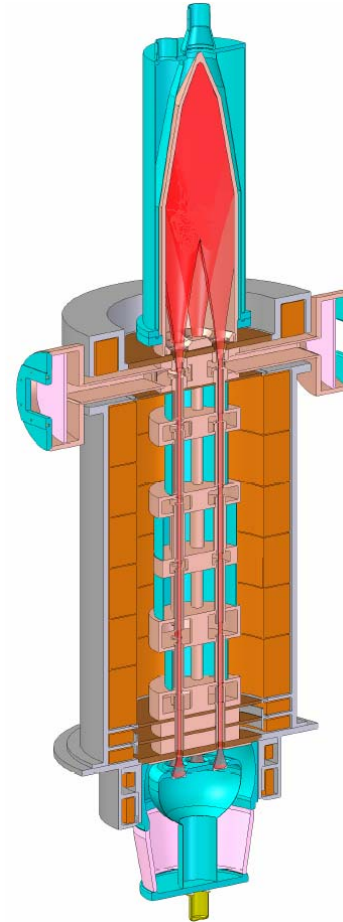


Output power as function of frequency

The TOSHIBA E3736 MBK (1)

Design Features:

- 6 beams
- Ring shaped cavities
- Cathode loading: <2.1 A/cm²



Design Layout

The TOSHIBA E3736 MBK (2)

Measured performance

Voltage: 115kV

Current: 135A

μ perveance: 3.46

Output Power: 10.4MW

Efficiency: 67%

Pulse duration: 1.5ms

Rep. Rate: 10Hz



Klystron ready for shipment

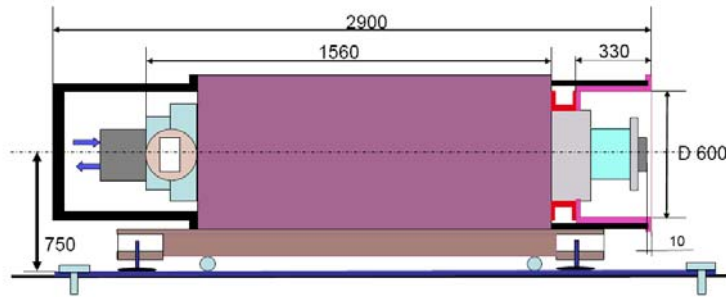
Horizontal Klystron

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

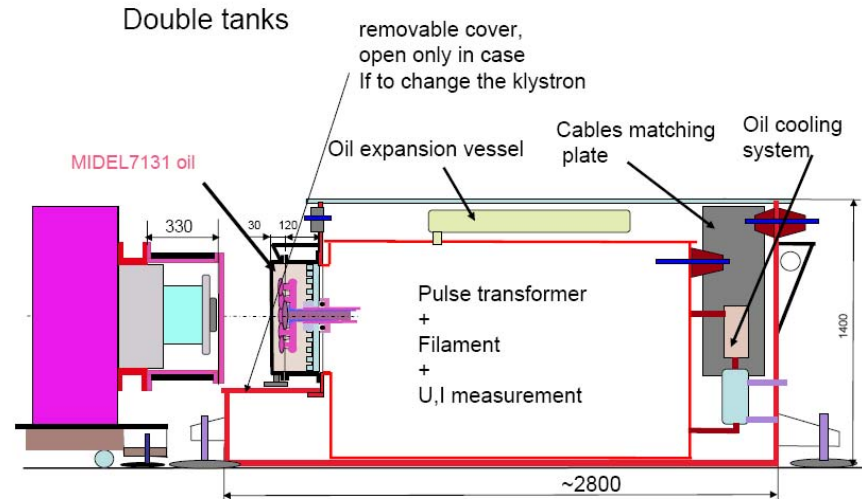
Aspects

- 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

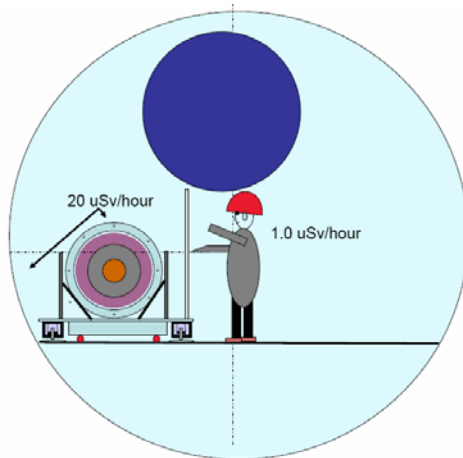
Horizontal MBK



Horizontal MBK



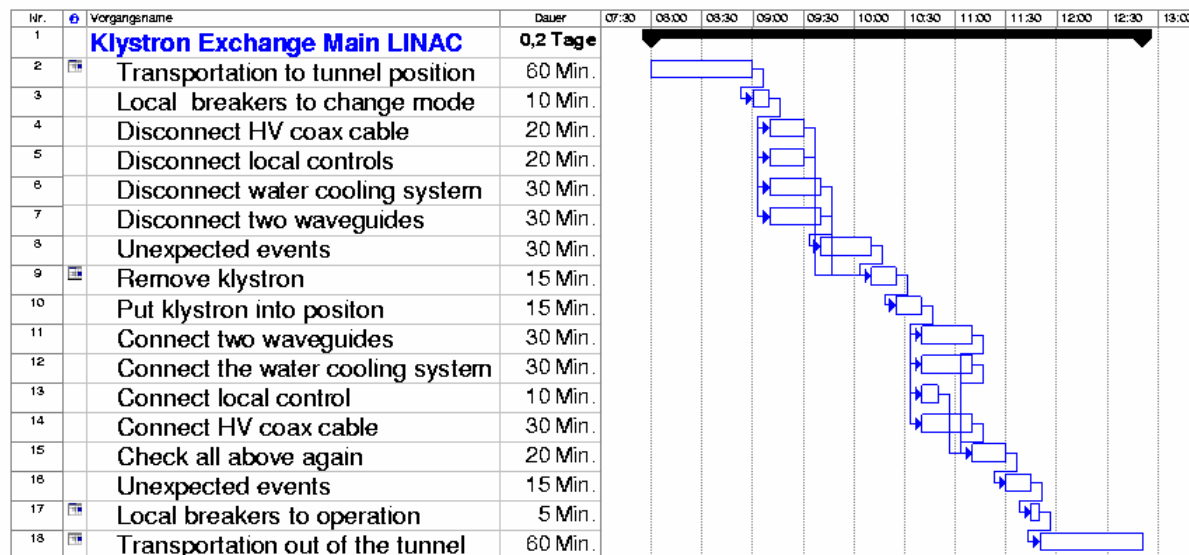
MBK gun and pulse transformer



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



Modulator

Modulator Types (1)

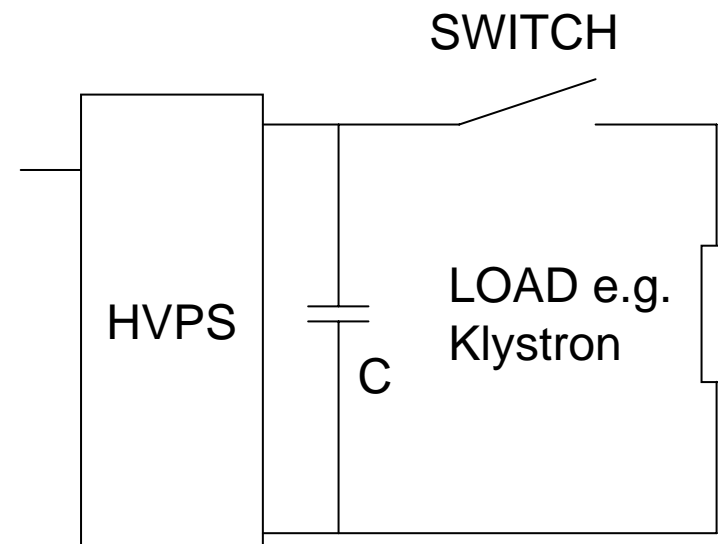
Hard Tube / Series Switch Modulator

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
semiconductor 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= 175 μ F, U =120kV)

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

Modulator Types (2)

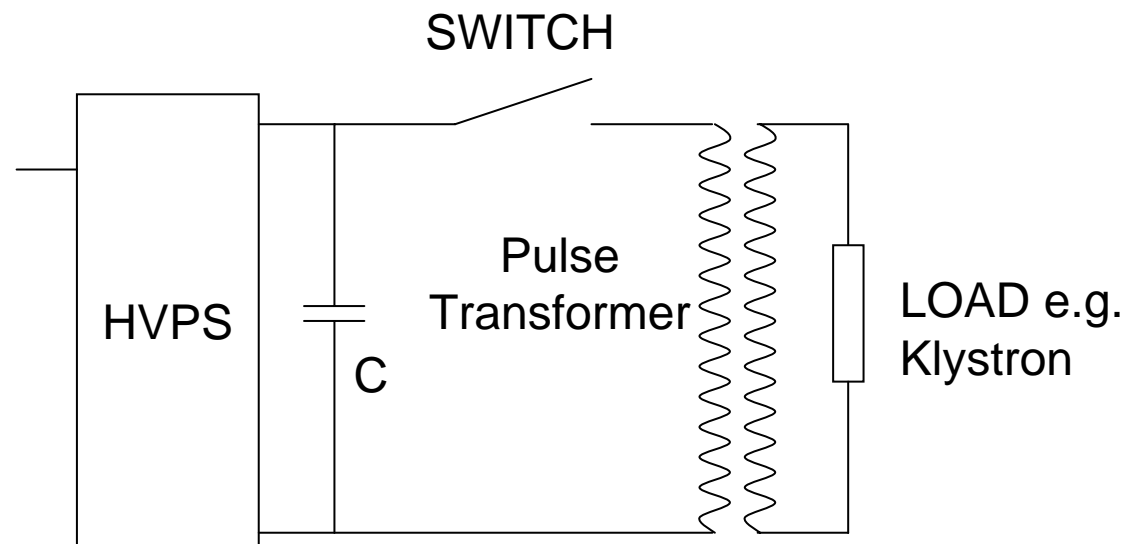
Hybrid (Series Switch with Pulse Transformer)

Pro:

- Lower DC Voltage
- Switch easier

Con:

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



Modulator Types (3)

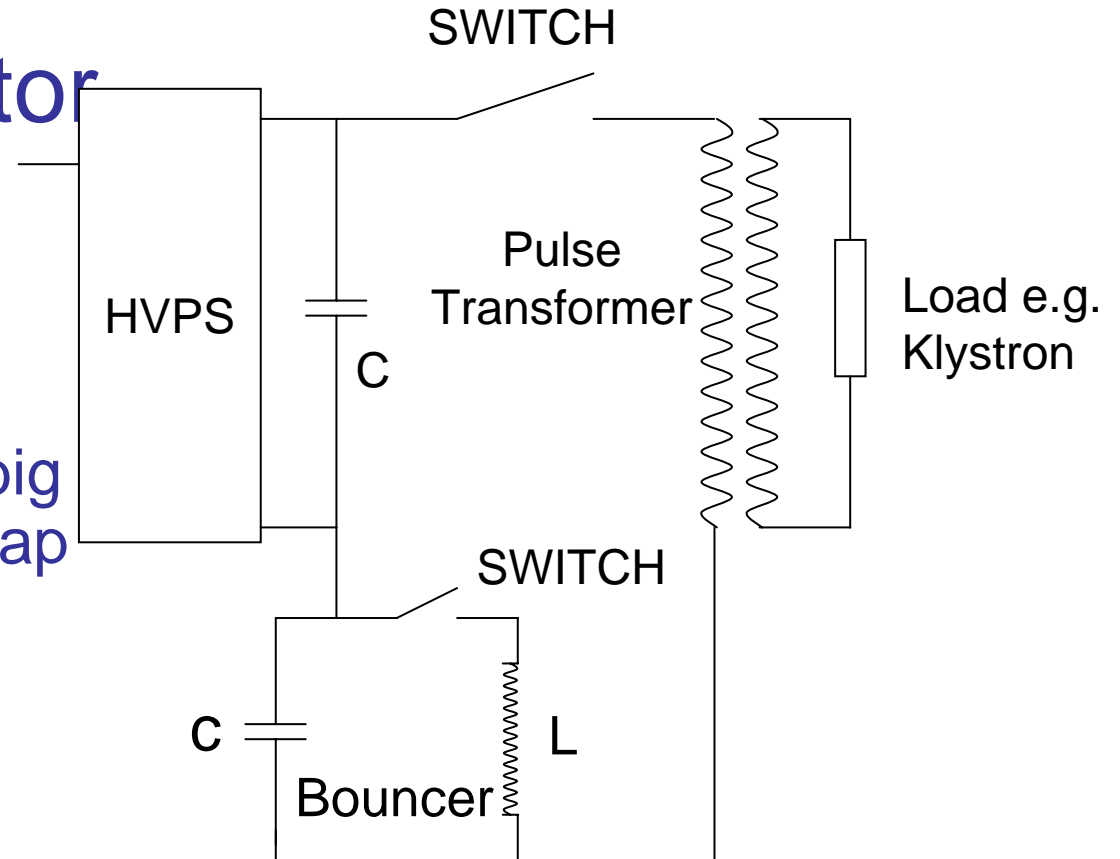
Bouncer Modulator

Pro:

- Lower stored energy

Con:

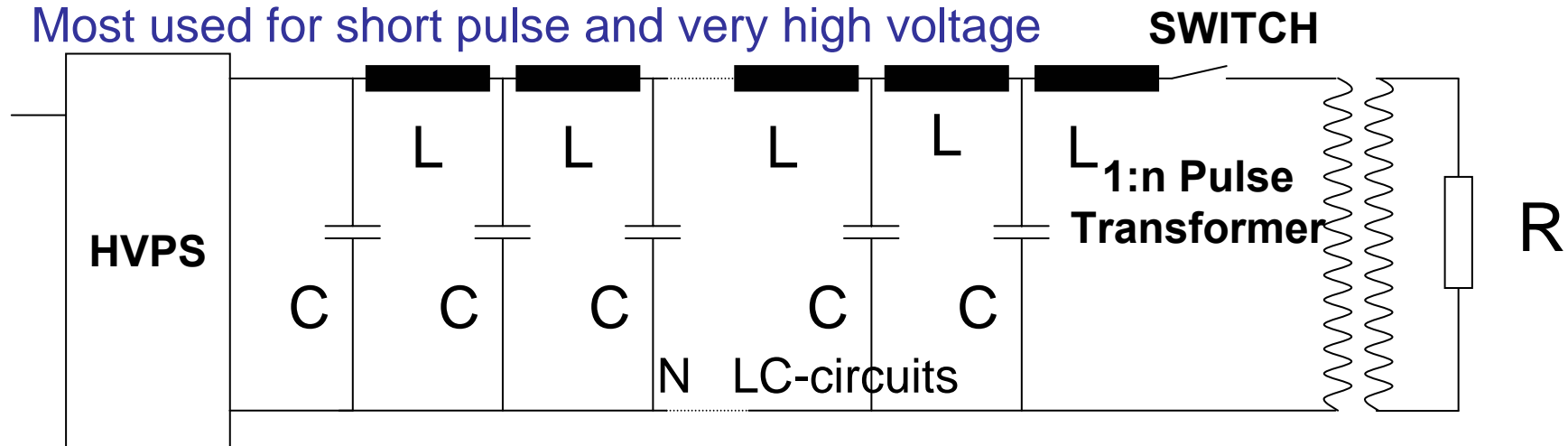
- Additional circuit with big choke and additional cap bank



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

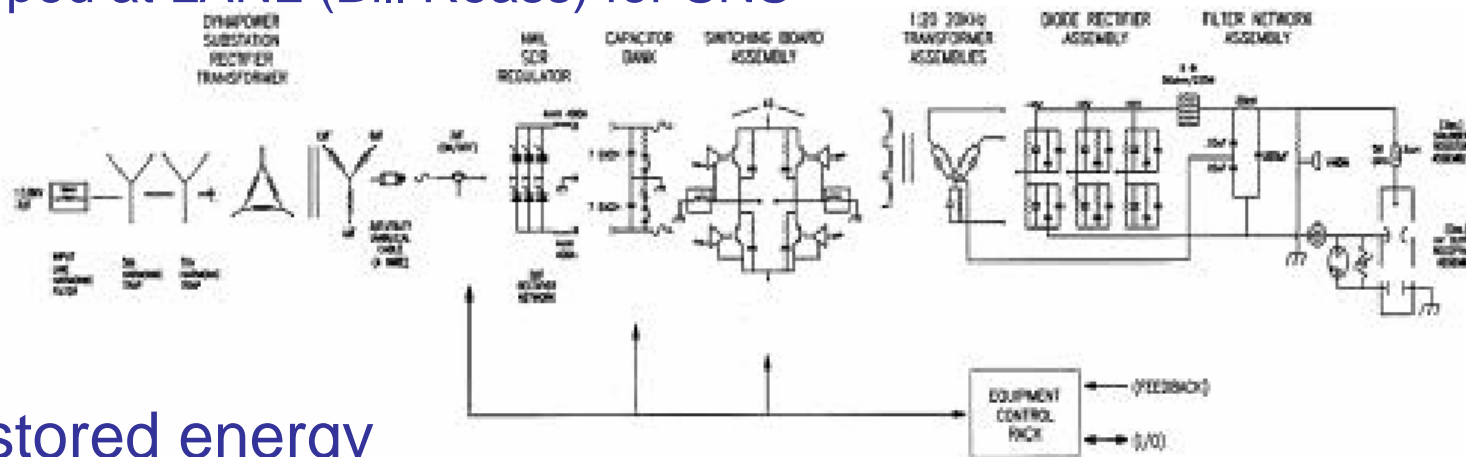


Figure 1 Simplified Block Diagram

Pro:

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

Con:

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

Modulator Types (6)

Marx Generator

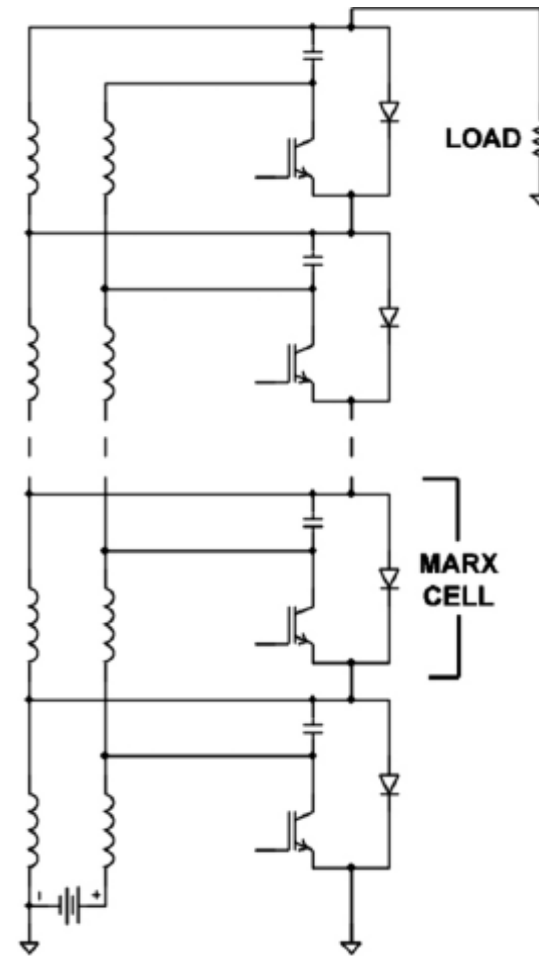
Developed by Erwin Marx in the 1920s,
proposed with modifications to the
original design by Leyh, SLAC

Pro:

- Compact
- Potential of cost savings

Con:

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



Modulator Types (7)

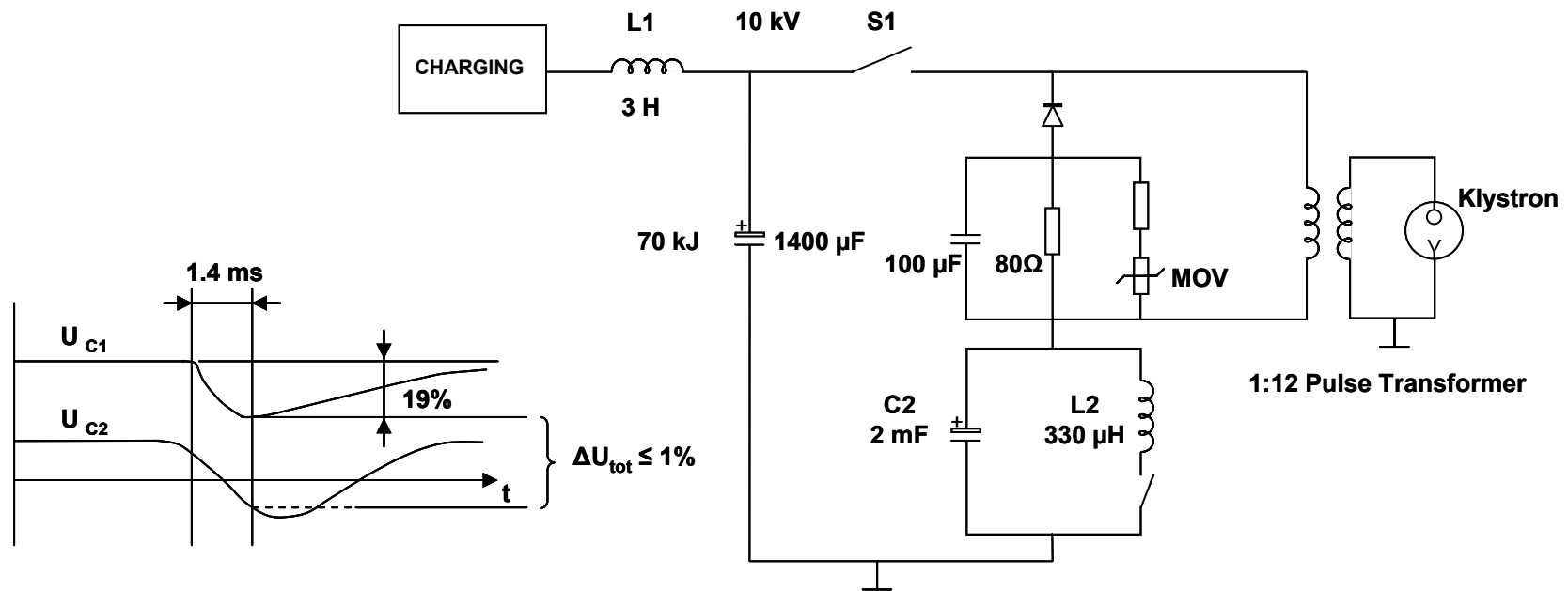
Other

- 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

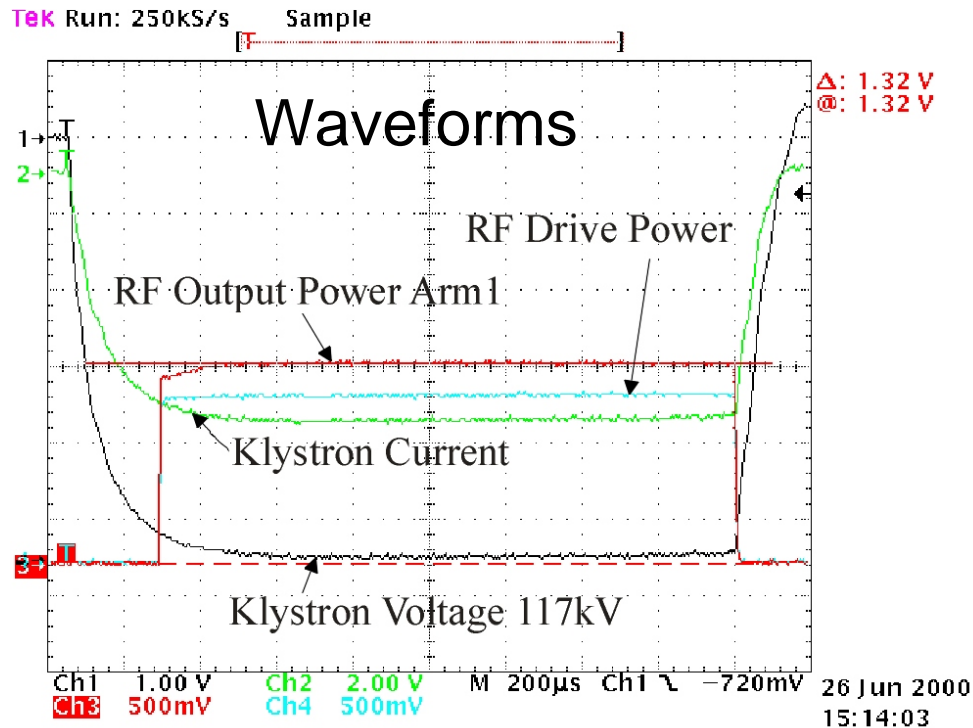
	Typical	Maximum
Klystron Gun Voltage:	115kV	130kV
Klystron Gun Current:	130A	150A
High Voltage Pulse Length:	<1.7ms	1.7ms
High Voltage Rise Time (0-99%):	<0.20ms	0.2ms
High Voltage Flat Top (99%-99%):	1.37ms	1.5ms
Pulse Flatness During 1.4ms Flat Top:	< $\pm 0.5\%$	$\pm 0.5\%$
Pulse-to-Pulse Voltage fluctuation:	< $\pm 0.5\%$	$\pm 0.5\%$
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 continuously in operation under different operation conditions

Industry made Modulator for TTF (1)

- 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

HVPS and Pulse Forming Unit



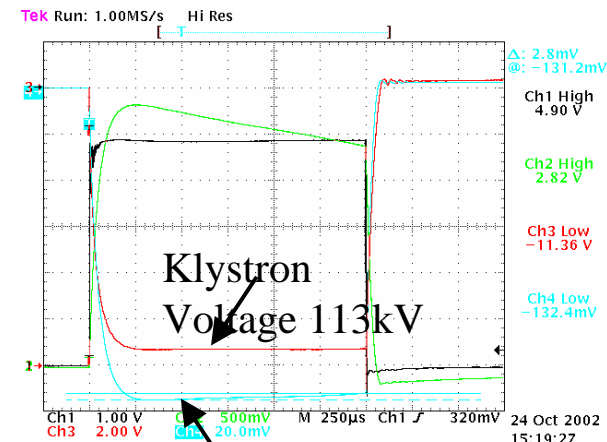
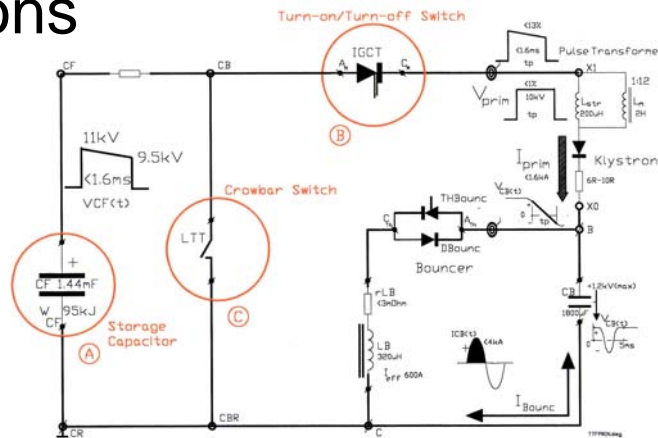
IGCT Stack

Industry made Modulator for TTF (2)

- Low leakage inductance pulse transformer (ABB) $L < 200 \mu\text{H}$ resulting in shorter HV pulse rise time of $< 200 \mu\text{s}$
- Light Triggered Thyristor crowbar avoiding mercury of ignitrons



Pulse Transformer



Klystron Current 132A

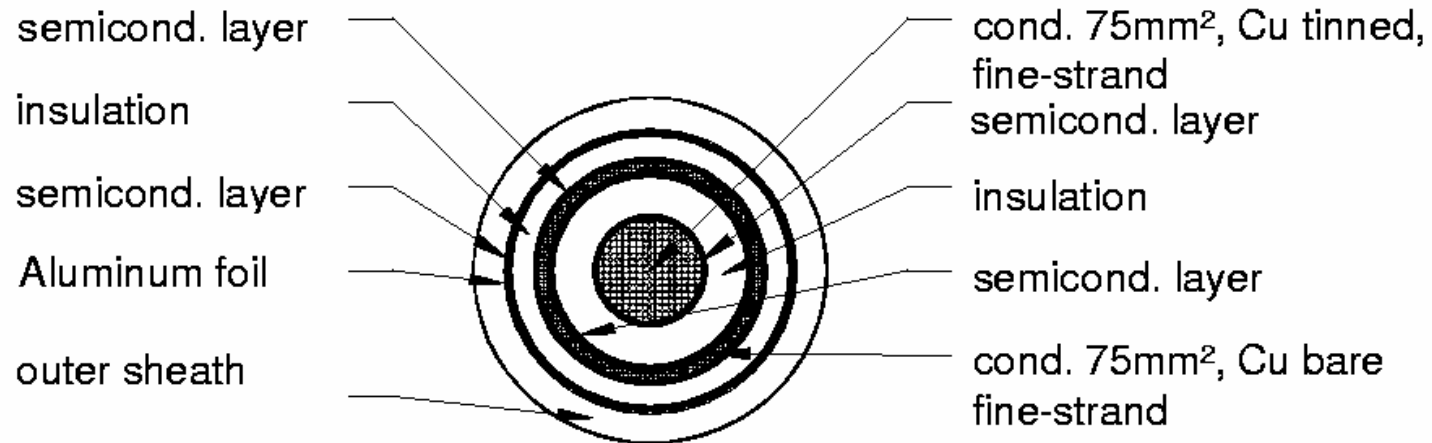
Bouncer Modulator Status

- 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)

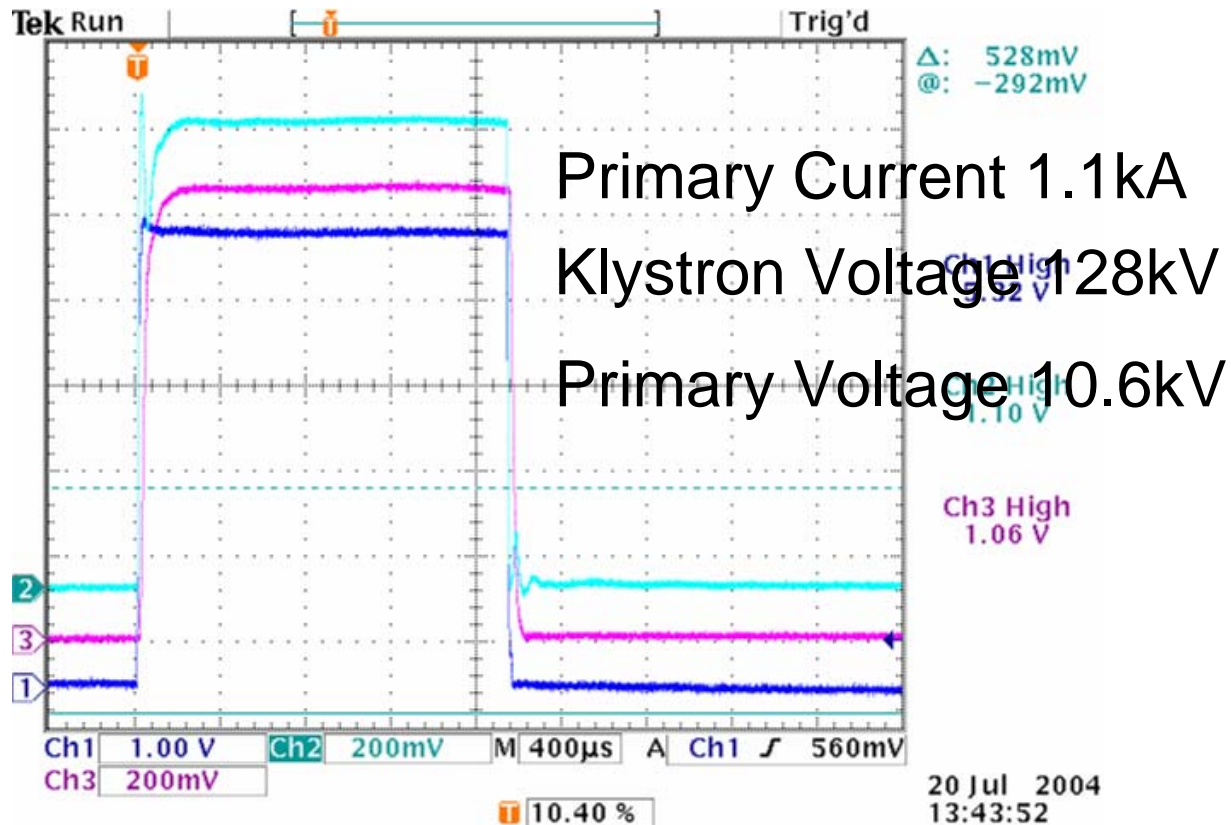
HV Pulse Cable (2)



diameter 30mm

dielectric material: XLPE

HV Pulse Cable (3)



- 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)

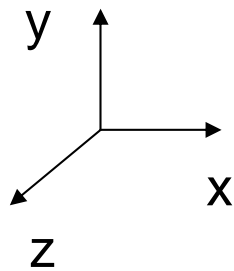
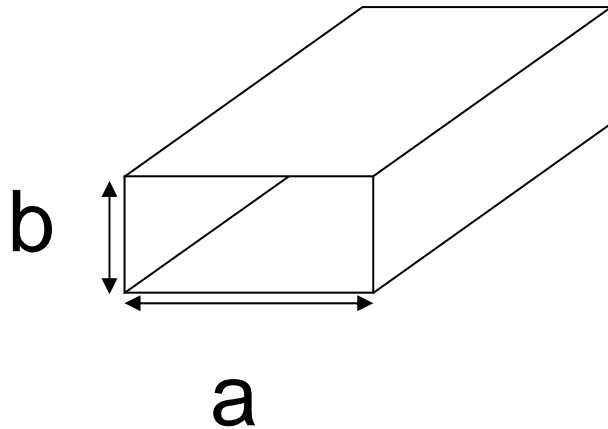
Distribution of RF power is done by:

- 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})

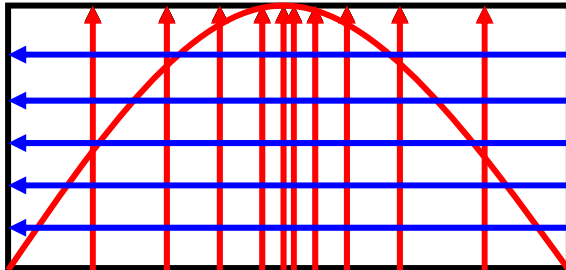
Cut off wavelength

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

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

Rectangular Waveguides

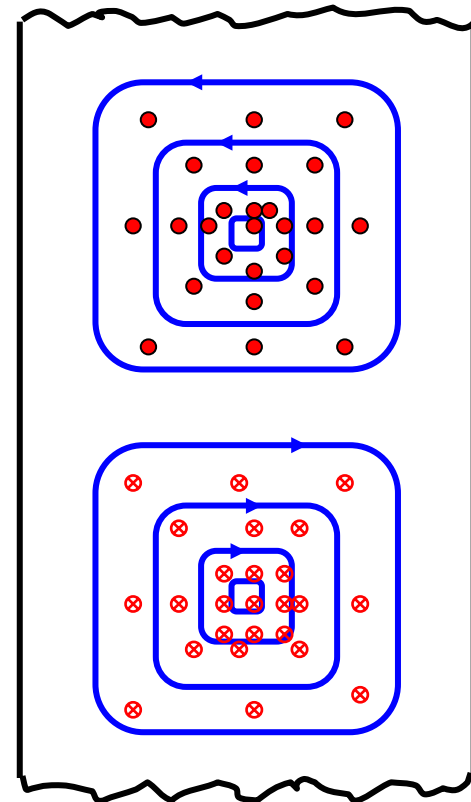
- The mode with lowest frequency propagating in the waveguide is the TE_{10} (H_{10}) mode.



E-Field
H-Field

Cutoff Frequency:

$$\nu_{c10} = c/2a$$



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) $a=6.5\text{inch}$
 $b=3.25\text{inch}$ $\nu_{c10}=908\text{MHz}$
- WR770 $a=7.7\text{inch}$ $b=3.85\text{inch}$
 $\nu_{c10}=767\text{MHz}$

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 TE₁₀

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

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

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

- λ_g is the distance between two equal phase planes along the waveguide and is longer than λ
- The impedance Z of the waveguide is

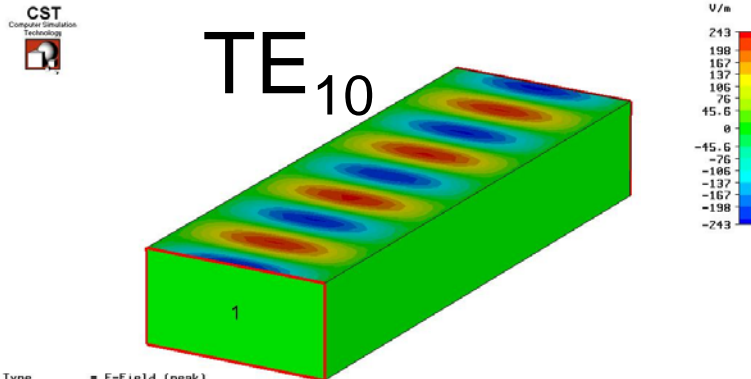
$$Z = \frac{377\Omega}{\sqrt{1 - \left(\frac{\lambda}{\lambda_{c10}}\right)^2}}$$

Power in TE₁₀

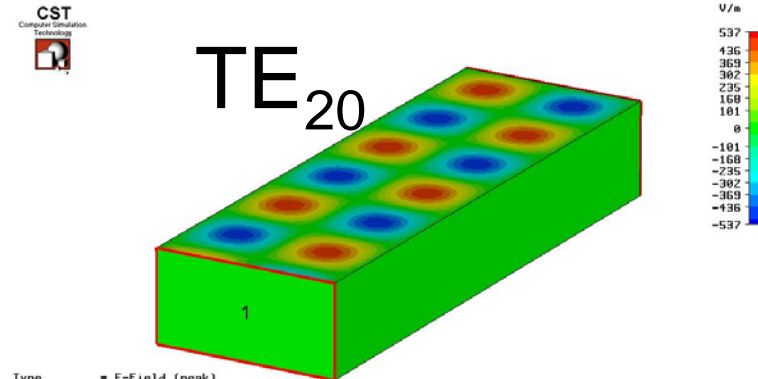
$$P_{RF} = 6.63 \times 10^{-4} a[cm]b[cm] \left[\frac{\lambda}{\lambda_g} \right] E[V/cm]^2$$

- The maximum power which can be transmitted theoretically in a waveguide of certain size a, b and wavelength λ is determined by the breakdown limit E_{\max} .
- In air it is $E_{\max} = 32 \text{ kV/cm}$ and in SF₆ it is $E_{\max} = 89 \text{ kV/cm}$ (1 bar, 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 sparks 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, humidity, 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.

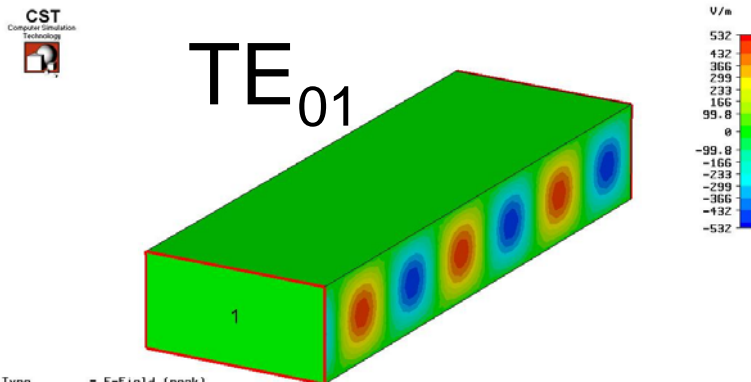
Straight Waveguide (1)



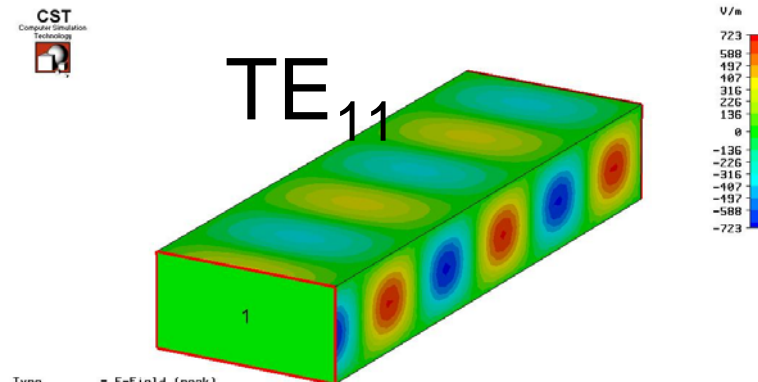
Type = E-Field (peak)
 Monitor = e-field (f=2.6) [1(1)]
 Component = Normal
 Maximum=3d = 243.164 V/m at 5.58933 / 58.9643 / 388.889
 Frequency = 2.6
 Phase = 180 degrees



Type = E-Field (peak)
 Monitor = e-field (f=2.6) [1(3)]
 Component = Normal
 Maximum=3d = 553.951 V/m at -38.5233 / 35.3786 / 200
 Frequency = 2.6
 Phase = 112.5 degrees

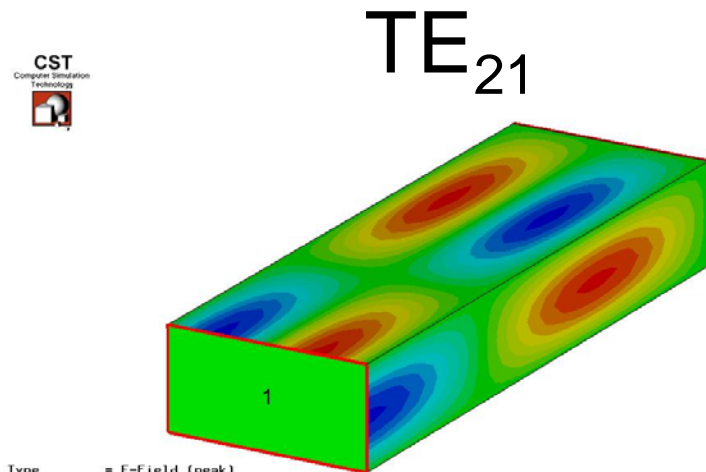


Type = E-Field (peak)
 Monitor = e-field (f=2.6) [1(2)]
 Component = Normal
 Maximum=3d = 541.928 V/m at 49.53 / 47.1714 / 200
 Frequency = 2.6
 Phase = 112.5 degrees

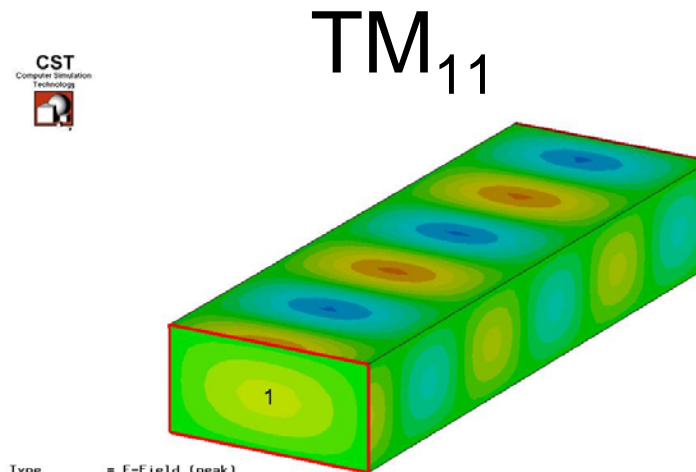
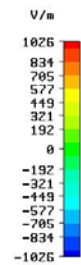


Type = E-Field (peak)
 Monitor = e-field (f=2.6) [1(4)]
 Component = Normal
 Maximum=3d = 727.573 V/m at 71.5433 / 47.1714 / 322.222
 Frequency = 2.6
 Phase = 337.5 degrees

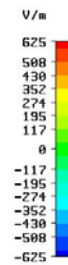
Straight Waveguide (2)



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

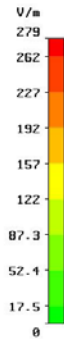
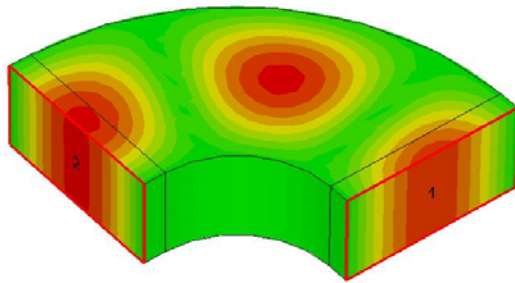


Type = E-Field (peak)
 Monitor = e-field (f=2.6) [1(5)]
 Component = Normal
 Maximum-3d = 637.948 V/m at 5.50333 / 35.3786 / 177.778
 Frequency = 2.6
 Phase = 337.5 degrees

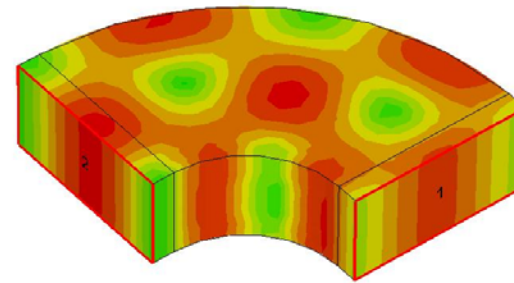
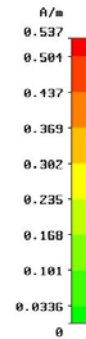


H-Bends

E-Field



H-Field



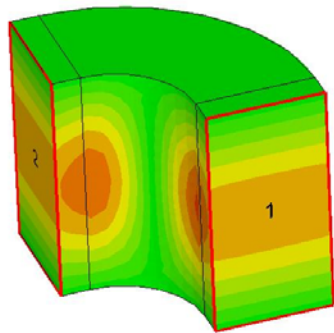
Type = E-Field (peak)
Monitor = e-field (f=1.3) [1]
Component = Abs
Maximum-3d = 282.118 V/m at -55.9724 / 82.55 / 98.9501
Frequency = 1.3
Phase = 157.5 degrees

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

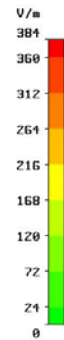
E-Bends



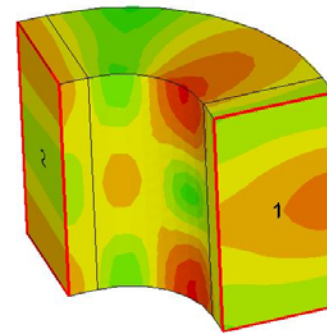
E-Field



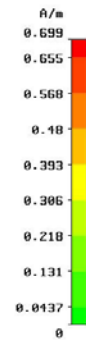
Type = E-Field (peak)
Monitor = e-field (f=1.3) [1]
Component = Abs
Maximum-3d = 386.366 V/m at 8.42857 / 82.55 / 25.2857
Frequency = 1.3
Phase = 202.5 degrees



H-Field

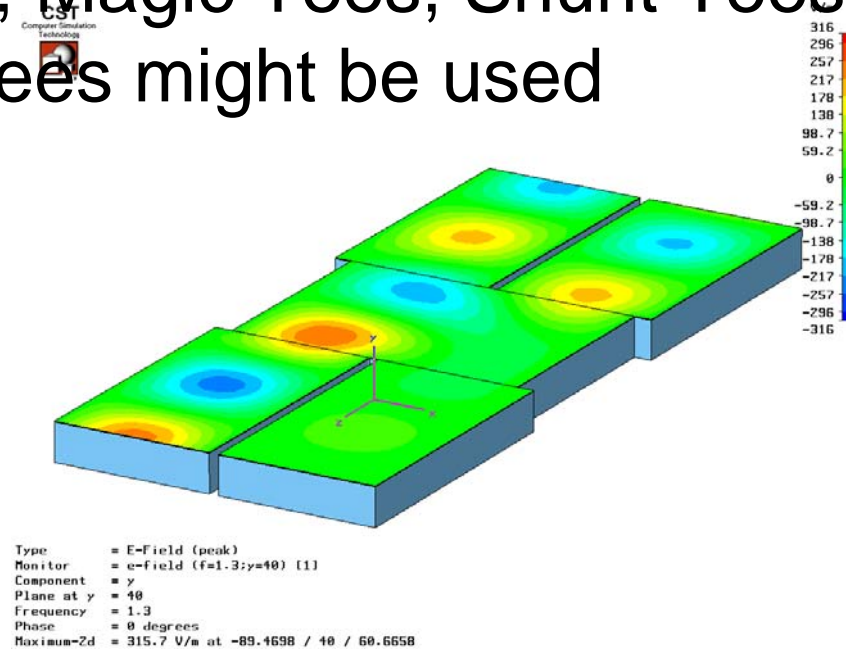


Type = H-Field (peak)
Monitor = h-field (f=1.3) [1]
Component = Abs
Maximum-3d = 0.74572 A/m at 8.42857 / 148.59 / 33.7143
Frequency = 1.3
Phase = 157.5 degrees



Power Coupler

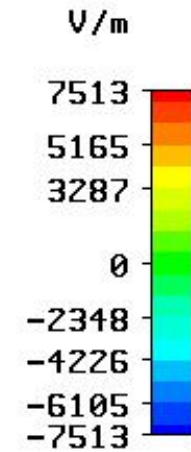
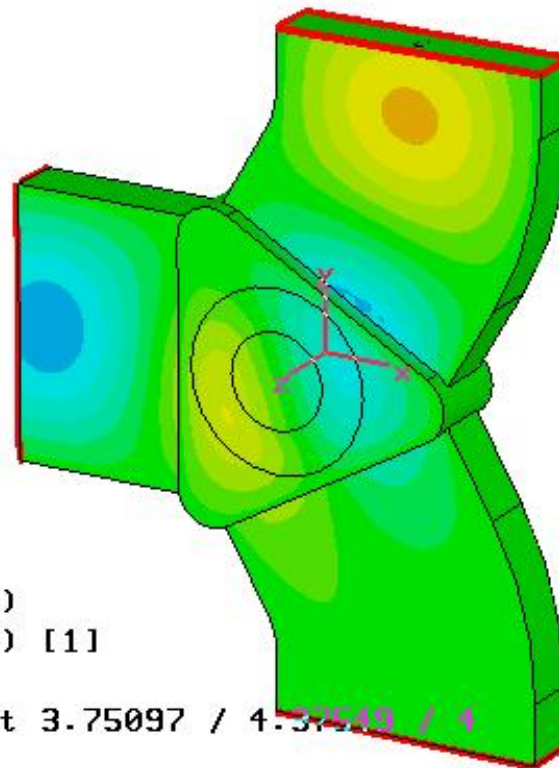
- Power Couplers are used to couple out a certain amount of power from a main waveguide arm
- Hybrids, Magic Tees, Shunt Tees, Series Tees might be used



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 transferred to port (2), but if power is entering (2) it is transferred to (3) and then absorbed in a load.
- The circulator 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 circulator.
- 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 / 4.37519 / 1
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

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

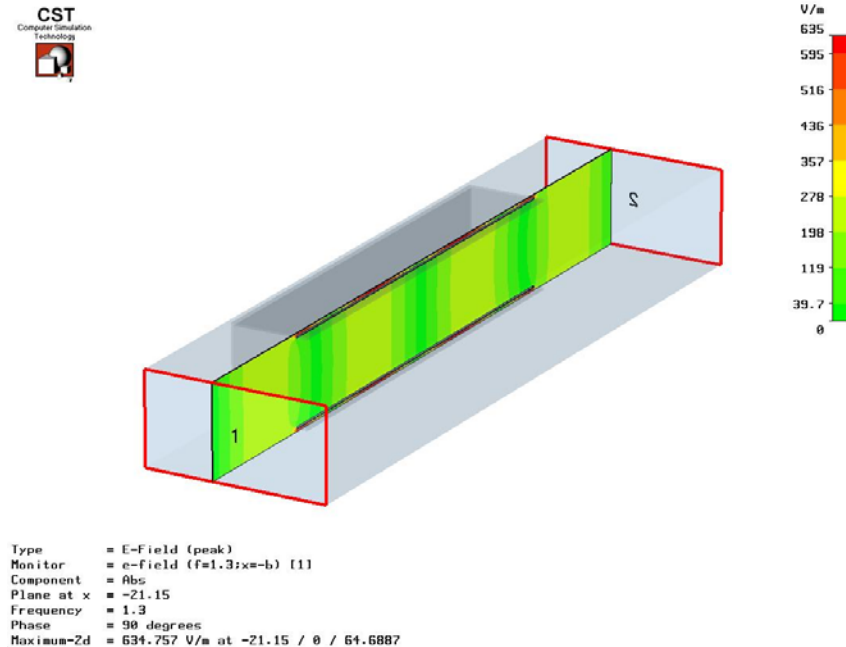
$$\rho = \frac{Z_L - Z}{Z_L + Z}$$

With Z waveguide impedance of the waveguide and Z_L load impedance

Phase Shifter

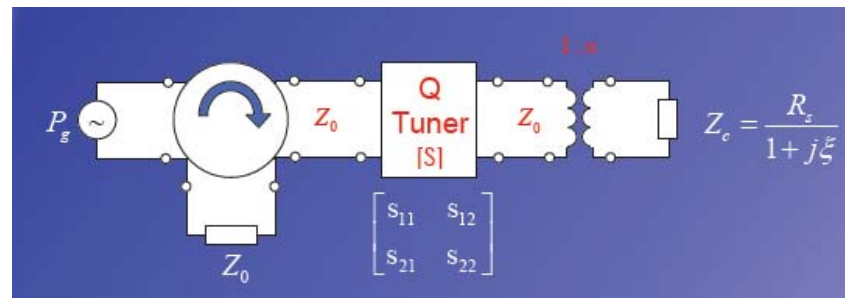
- By adjusting the dimensions of the waveguide e.g. the width a changes and therefore the phase constant changes.

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



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)

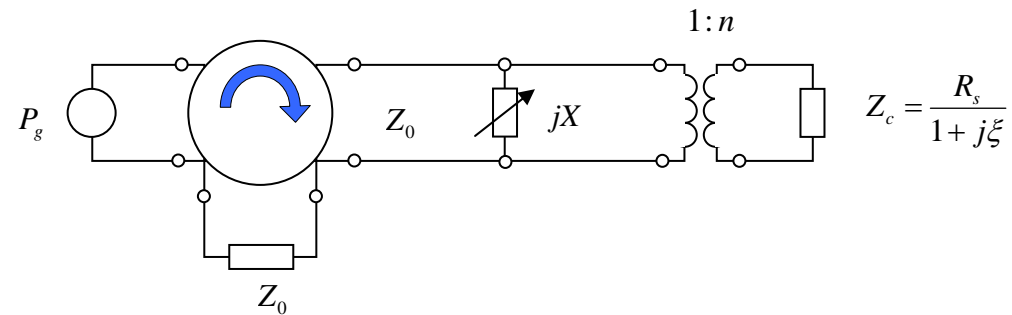


Figure 1: Equivalent circuit of cavity powered through a circulator with the variable obstacle (no moving along waveguide)

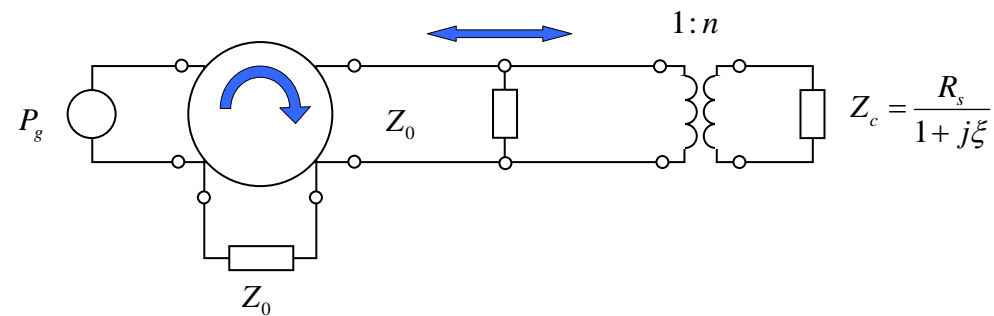
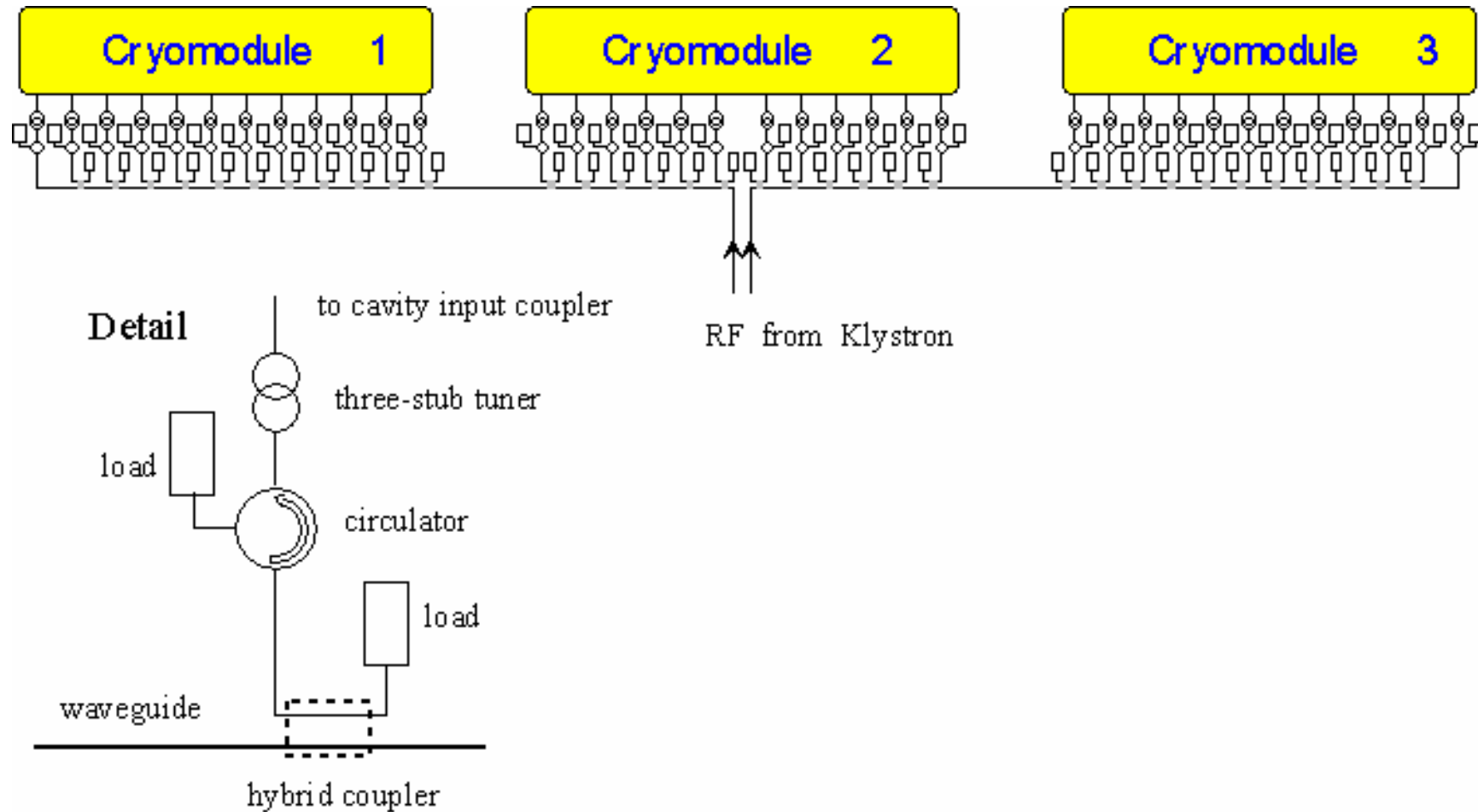


Figure 2: Equivalent circuit of cavity powered through a circulator with the fixed obstacle moving along waveguide

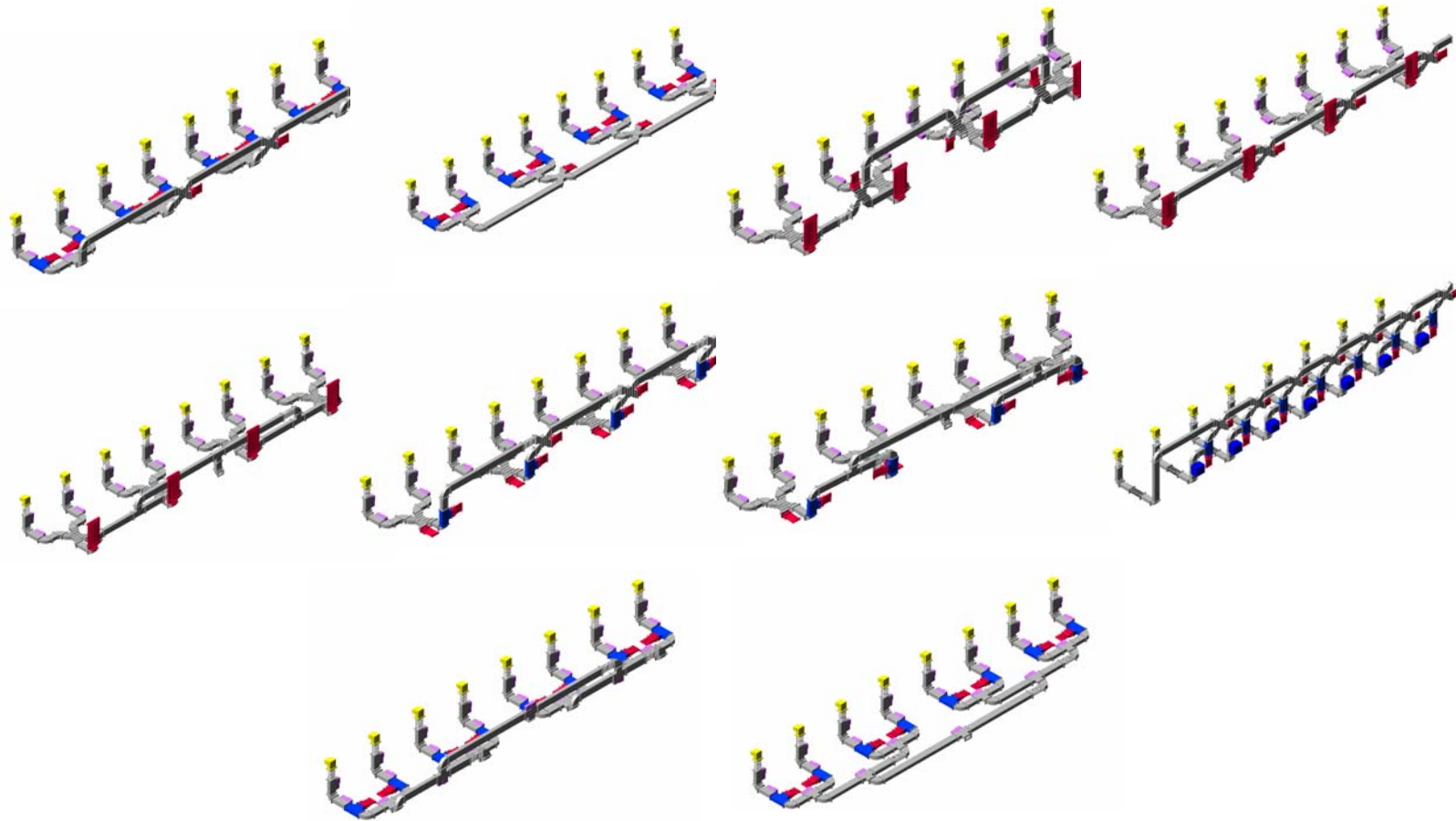
Linear Distribution System (1)

- 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, Beijing, China)



Changing phase, degree
Impedance matching range
Max power, MW

± 60
 $1/3Z_w \text{ to } 3Z_w$
2

* Z_w – waveguide impedance

E and H Bends (Spinner)



Circulator (Ferrite)



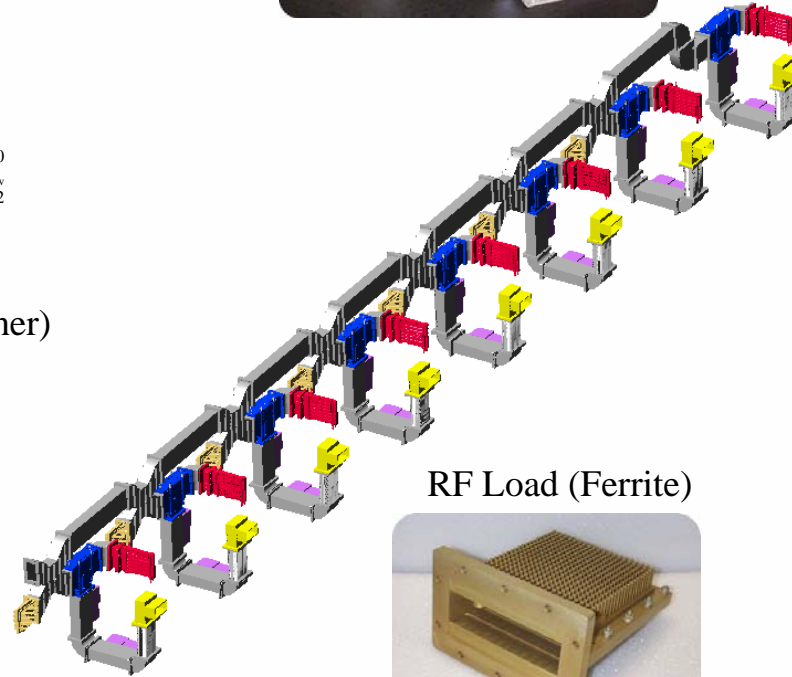
Type	WFHI 3-4
Peak input power, MW	0.4
Average power, kW	8
Min isolation at 1.3 GHz, dB	>30
Max insertion loss at 1.3 GHz, dB	≤0.08
Input SWR at 1.3 GHz (for full reflection)	1.1

Hybrid Coupler (RFT, Spinner)



Directivity, dB	±30
Return loss, dB	±35
Coupling factor, dB	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

(due to tolerance overlapping only 13 different coupling factors instead 18 are necessary)

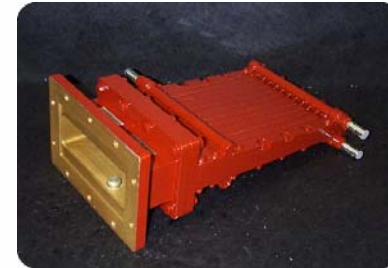


RF Load (Ferrite)



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

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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.
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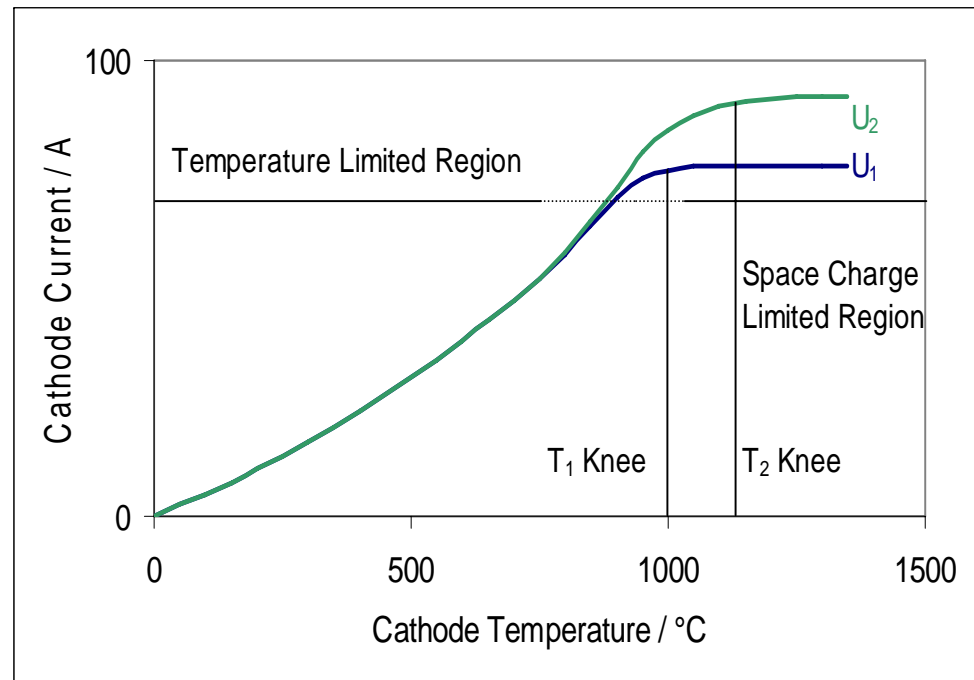
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18. H. Leich, S. Choroba, P. Duval, T. Grevsmühl, A. Kretzschmann, U. Schwendicke, R. Wenndorff, The Design of a Technical Interlock for TTF2/XFEL RF Stations, NEC 2005, XX International Symposium on Nuclear Electronics & Computing., (to be published)
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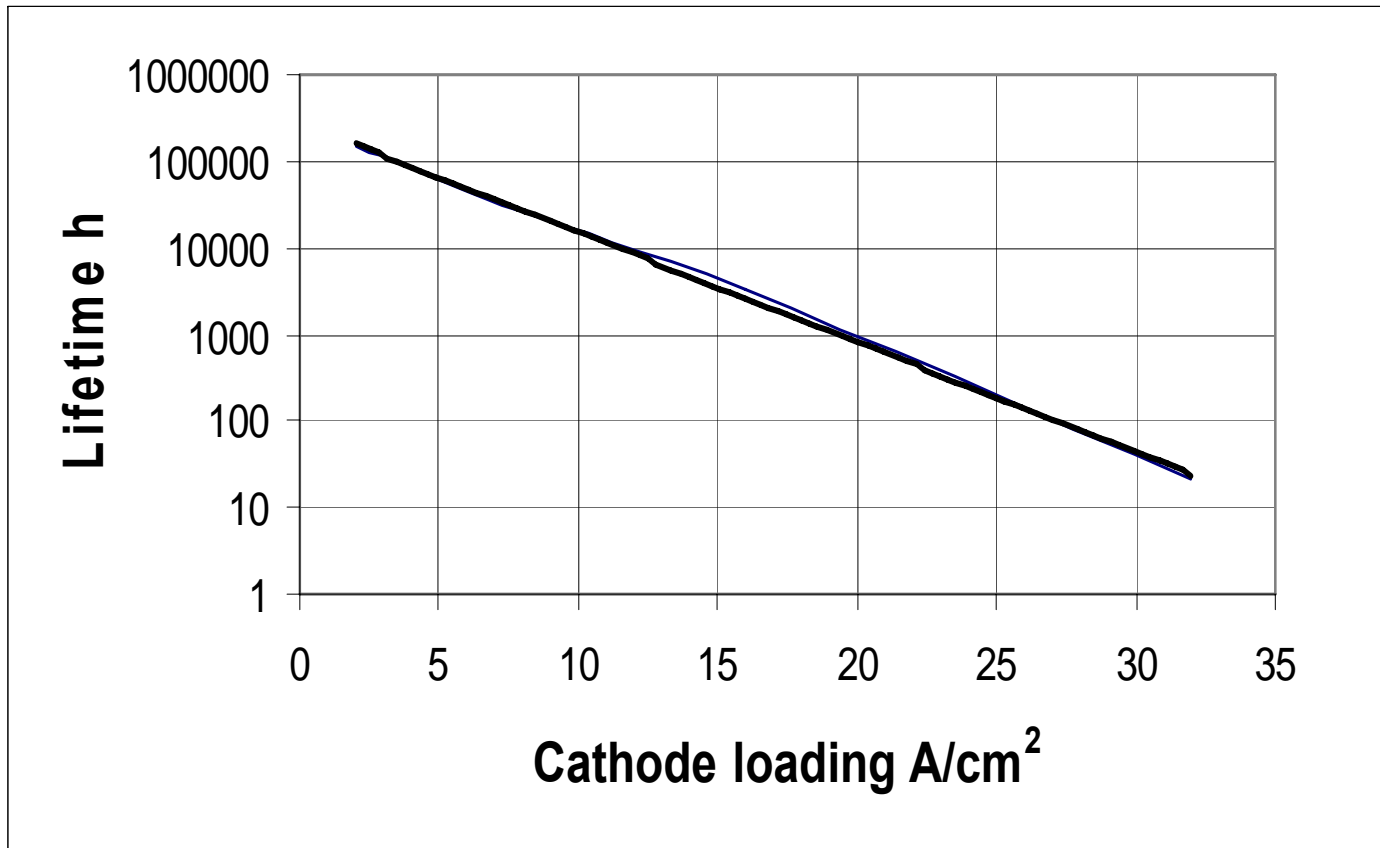
Appendix

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)
$$j = \frac{4}{9} \epsilon_0 \left[\frac{2e}{m} \right]^{1/2} U^{3/2} / d$$
- 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 $B = 1.2 - 2 \times B_B$ (typ $\sim 1000\text{G}$)

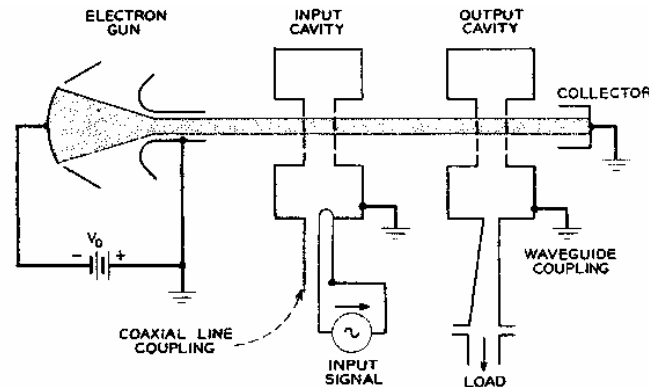
with B_B Brillouinfield $B_B = \sqrt{(2I m_0) / (\epsilon_0 \pi b^2 u_e e)}$

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

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

Klystron: Ballistic Theory (1)

Treatment of individual electrons without interaction



Initial electron energy:

$$(1/2)mu_0^2=eV_0$$

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

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

Assume $V_1 \ll V_0$:

$$u=u_0(1+(mV_1/2V_0)\sin\omega t)$$

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:

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

or $\omega t_2=\omega t_1+\theta_0-X\sin\omega t_1$ with $\theta_0=l/u_0$ and $X=\theta_0 mV_1/2V_0$ called **bunching parameter**

Klystron: Ballistic Theory (2)

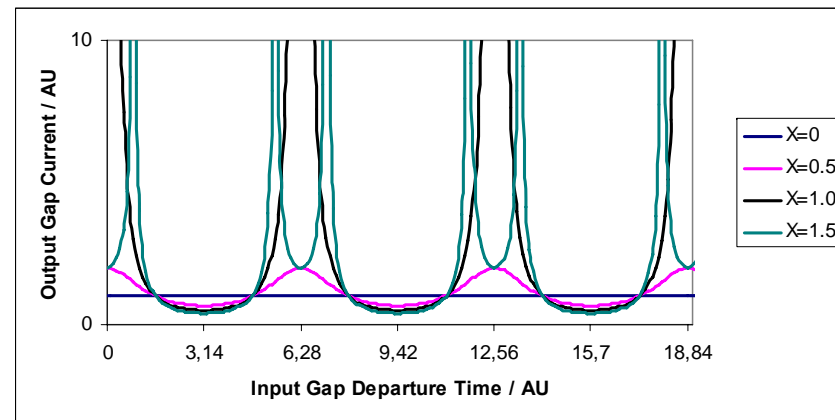
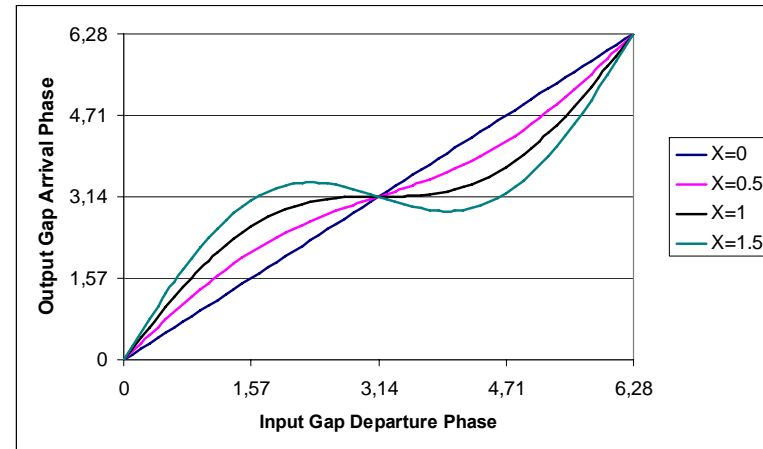
Because of charge conservation:
 Charge in the input cavity between time t_1
 and t_1+dt_1 equals the charge in the output
 cavity between time t_2 and t_2+dt_2

$$I_1 dt_1 = I_2 dt_2$$

With $dt_2/dt_1 = 1 - X \cos \omega t_1$ and $I_2 =$
 $I_1 / (dt_2/dt_1)$ one gets

$$I_2 = I_1 / (1 - X \cos \omega t_1)$$

$$I_2 = I_1 \text{ABS}(1 / (1 - X \cos \omega t_1))$$



Klystron: Ballistic Theory (3)

Fourier transformation of the current in the output gap I_2

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

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

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

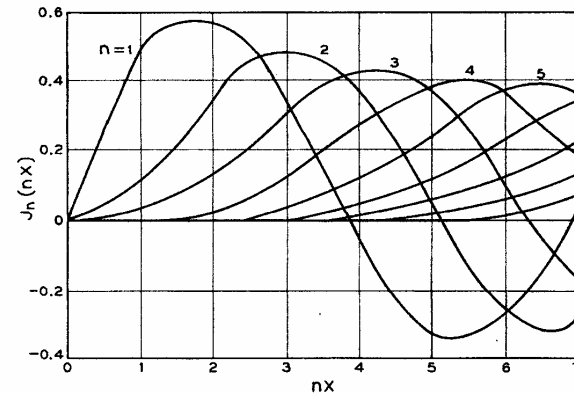
$$b_n = (I_0/\pi) \int_{-\pi}^{\pi} \sin n(\omega t_1 - X \sin \omega t_1) d(\omega t_1) = 0$$

$$a_n = 2 I_0 J_n(nX) \quad \text{with } J_n \text{ Besselfunction of the } n\text{-th order}$$

Klystron: Ballistic Theory (4)

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

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



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

$$\Omega = \sqrt{\left(\frac{e}{m_0}\right)\left(\frac{\rho_0}{\epsilon_0}\right)}$$

- Therefore we have 2 waves with the Phase constants

$$\beta_{e1} = \beta_e (1 + \Omega / \omega) \quad \beta_{e2} = \beta_e (1 - \Omega / \omega) \quad \beta_e = \omega / u_e$$

- And therefore

$$u_{e1} = u_e / (1 + \Omega / \omega) \quad u_{e2} = u_e / (1 - \Omega / \omega)$$

- The group velocity is

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

- The density modulations appear at a distance of

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

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

$$\lambda_p / 4$$

Klystron: Coupling (1)

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

Klystron: Coupling (2)

- The RF current in the output cavity is given by K and the beam RF current I_2
- $I_{2C} = I_2 K \cos(\phi_{2C}/2 + \pi/2)$ with ϕ_{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 $G_2 = G_{2C} + G_{\text{Load}}$
- 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.