Tentative Designs for X-Band and W-Band Klystrons with Corkscrew-Modulated Hollow Electron Beam

Heino Henke | Theoretische Elektrotechnik | Technische Universität Berlin |
The 6th ITG International Vacuum Electronics Workshop 2018 | Septmber 6th 2018

Technische Universität Berlin

Introduction

X-Band Klystron Design

W-Band Klystron Design

Electron Gun for Generating a Hollow Beam

Conclusions

Introduction

Why a klystron ?

- **high RF power**
- **high reliabilty**
- **various applications in the industry**

Why a klystron with <u>hollow beam</u> ?

- **higher beam power**
- **easily beam focussing strategy**
- **larger klystron structure**

[1]

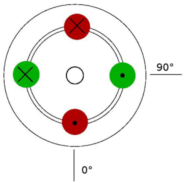
[1] A klystron as used in the storage ring at the Australian Synchrotron, Clayton, Victoria. https://commons.wikimedia.org/wiki/File:Aust.-Synchrotron,-Klystron-for-Storage-Ring,-14.06.2007.jpg

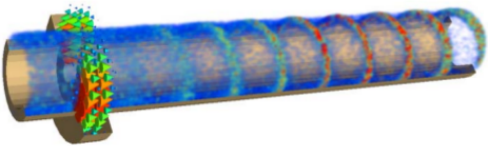
Introduction

- **X-Band Klystron with Hollow Beam for Power Amplification**
- **W-Band Klystron with Hollow Beam for Power Amplification and Frequency Tripling**

A modulated hollow beam has three components:

- hollow beam
- resonant cavity operating in rotating TM_{m10}-mode
- hollow beam modulated by rotating mode in propagation direction





X-Band Klystron Design
- TM_{110}-mode Klystron

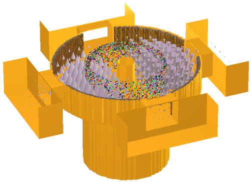
important parameters

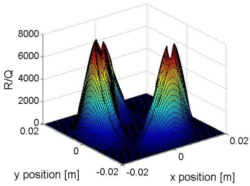
- **operating frequency:** $10\,\mathrm{GHz}$
- **mode in the cavities: TM_{110}-mode**
- **beam velocity:** $0.55 \cdot c_0$
- **beam voltage:** $100\,\mathrm{kV}$
- **beam power:** $1\,\mathrm{MW}$

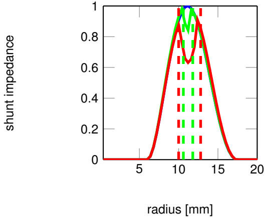
- TM_{110}-mode Klystron

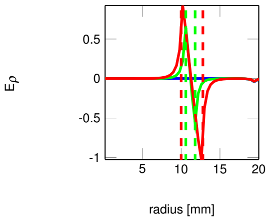
output cavity

○ one-gap cavity



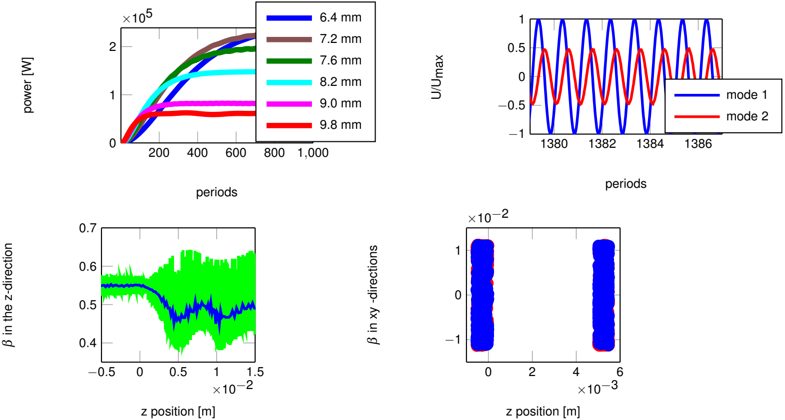






- TM_{110}-mode Klystron

output cavity

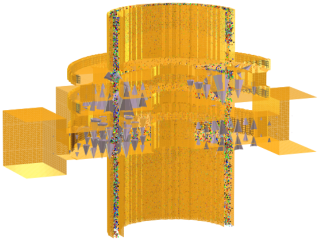


Velocity of electrons in the output cavity with an aperture width of 7.6 mm; left: β of electrons in z-direction in solid green line and average β in solid blue line; right: β of electrons in x-direction (blue dots) and in y-direction (red dots) before and after the travelling in output cavity

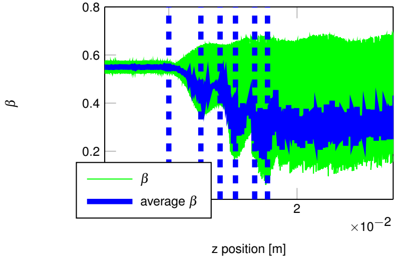
- TM_{110}-mode Klystron

output cavity

○ three-gap cavity



Three-gap structure excited in π mode, gap lengths are tapered

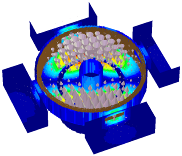


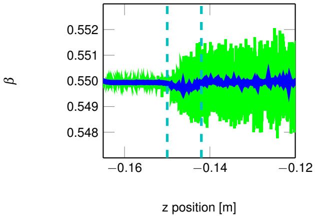
cavity	$\overline{P}_{out}$	β	$\overline{P}_{out}/\overline{P}_{int}$
one-gap	210 kW	0.35	5.3
two-gaps	310 kW	0.20	4.9
three-gap	460 kW	0.13	5.0

- TM_{110}-mode Klystron

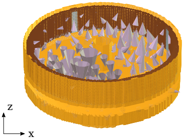
input and idler cavities

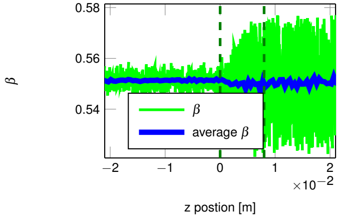
○ input cavity





○ idler cavity





- TM$_{110}$-mode Klystron

isolation strategy

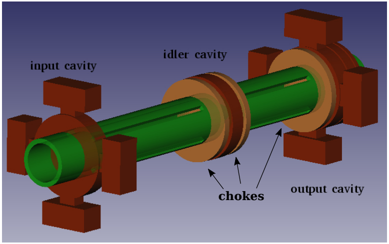
Technische Universität Berlin

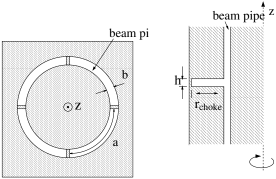
- **choke**

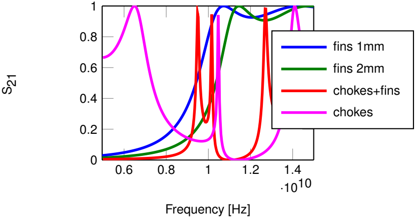
bandstop filter

- **fins**

high-pass filter



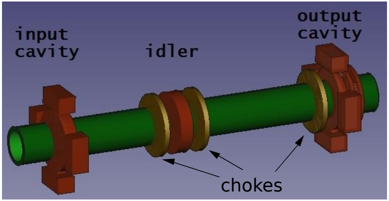


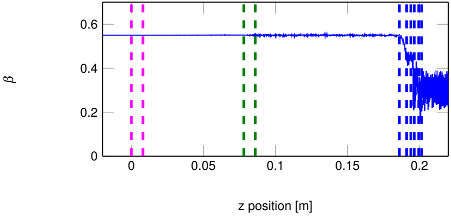


Top view of four fins which connect inner and outer conductors (left); side view of a radial transmission line as choke (right)

- TM_{110}-mode Klystron

whole klystron

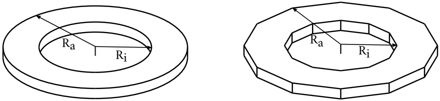




$$\overline{P}_{out} = 500\,\mathrm{kW}$$

Normalized velocity β of electrons in TM_{110} X-band klystron with chokes

X-Band Klystron Design
- TM_{310}-Mode Klystron



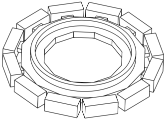
important parameters

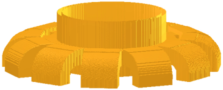
- **operating frequency:** $10\,\mathrm{GHz}$
- **mode in the cavities: TM_{310}-mode**
- **beam velocity:** $0.55 \cdot c_0$
- **beam voltage:** $100\,\mathrm{kV}$
- **beam power:** $5\,\mathrm{MW}$

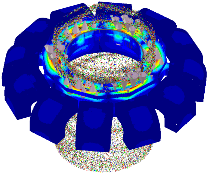
- TM_{310}-mode Klystron

output cavity

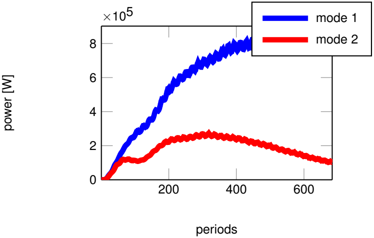
○ output cavity with 12 couplers







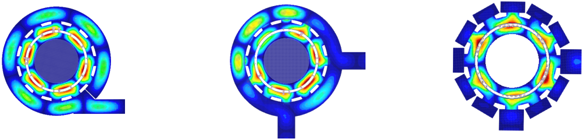
cavity	$\overline{P}_{out}$	η	$\overline{P}_{out}/\overline{P}_{int}$
one gap	1.20 MW	24%	9
two gaps	1.80 MW	36%	9



- TM_{310}-mode Klystron

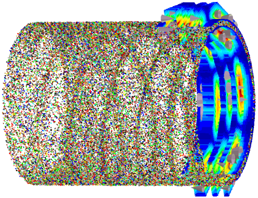
output cavity

◦ output cavity with fewer than 12 couplers



only the third configuration works

◦ output cavity without couplers

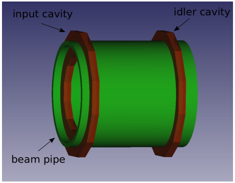


cavity	average β	$\overline{P}_{out}$
three-gap	0.40	2.29 MW
four-gap	0.38	2.51 MW

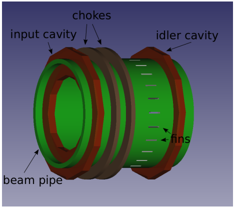
- TM_{310}-mode Klystron

input and idler cavities

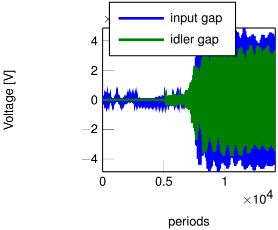
Coaxial beam pipe connects the input cavity and the idler cavity



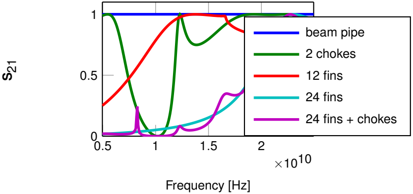
2 chokes and 24 fins placed between input cavity and idler cavity



Normalized voltages across the input gap and the idler gap by unsuccessful charging

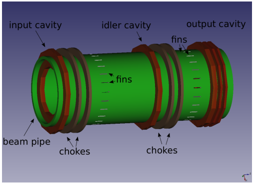


S_{21} of beam pipe with different filters

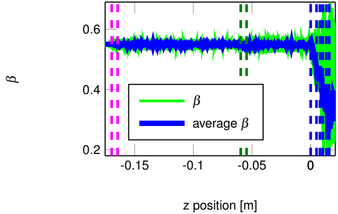


- TM_{310}-mode Klystron

whole klystron



Configuration of the whole klystron with the isolation variant of 24 fins and 2 chokes



Normalized velocity β of electrons while the beam is moving through the klystron operating in the TM_{310}-mode

$$U_{new} = \frac{m_e c^2}{e} \sqrt{\frac{1}{1 - \left(\frac{\beta_{new} \cdot c_0}{c_0}\right)^2} - 1} \qquad (1)$$

$$\overline{P}_{out} = (U - U_{new}) I \cdot \frac{\beta_\kappa}{1 + \beta_\kappa} \qquad (2)$$

$\overline{P}_{out}$ here is $2.75\,\mathrm{MW}$, while β_{new} is 0.33.

Technische Universität Berlin

W-Band Klystron Design

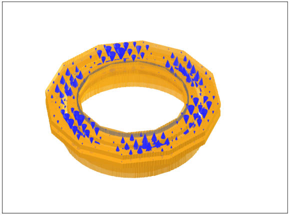
important parameters

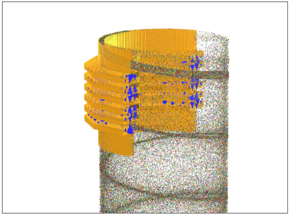
- **resonant frequency of the input and idler cavities:**$30\,\mathrm{GHz}$
- **resonant frequency of the output cavity:**$90\,\mathrm{GHz}$
- **mode in the input and idler cavity: $\mathbf{TM_{110}}$-mode**
- **mode in the output cavity: $\mathbf{TM_{310}}$-mode**
- **beam velocity:** $0.412 \cdot c_0$
- **beam voltage:** $50\,\mathrm{kV}$
- **beam power:** $50\,\mathrm{kW}$

W-Band Klystron Design

output cavity

- output cavity in prism form with 12 edges
- tuning ring instead of output waveguides
- modulation depth of beam is 5%
- coupled gap cavity in π-mode





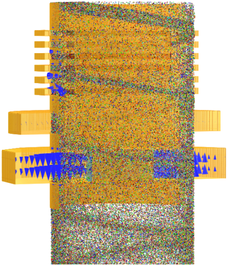
cavity	$\overline{P}_{out}/\overline{P}_{in}$ [%]
two gaps	0.8%
four gaps	1.32%
six gaps	1.986%

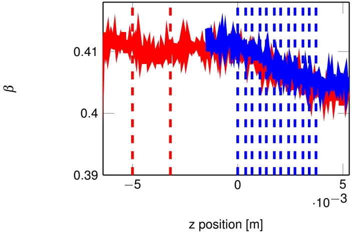
W-Band Klystron Design

output cavity

- Output cavity with "penultimate"cavity

the "next to the last"cavity, operates in TM_{110}-mode, inductively excited, improves the bunch quality





output efficiency of six gap cavity with penultimate: 2.36%

W-Band Klystron Design

Idler Cavity

- improve the gain of the klystron
- inductively excited for modulation enhancement

$$\Phi = \tan^{-1}\left(\frac{\omega_0^2 - \omega^2}{\omega_0 \omega / Q}\right) \tag{3}$$

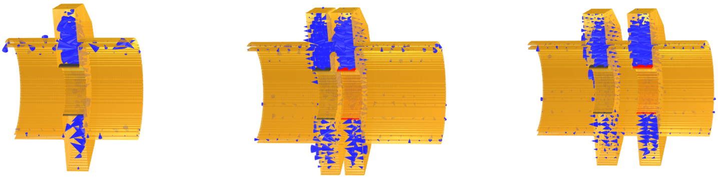
Beam under Investigation with initial modulation depth of 1%

Φ	modulation depth [%]	power loss [%]
65°	2.3543	0.025
70°	2.1359	0.016
75°	1.8689	0.009
80°	1.6504	0.006
85°	1.3592	0.002

W-Band Klystron Design

Idler Cavity

- Three Idler Types:
  Single Idler , Coupled Idler and Clustered (but not Coupled) Idler



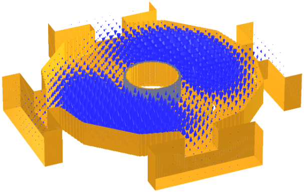
$\Phi = 80^\circ, Q = 1000$, modulation depth=1%

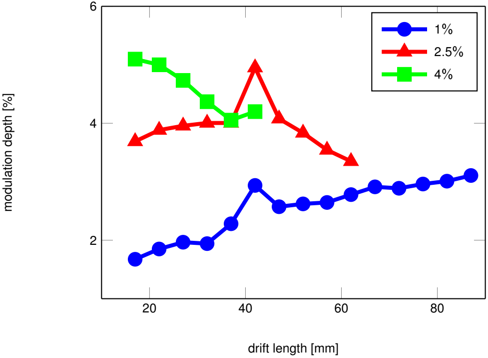
idler type	modulation depth in %
one single cavity with Q	1.65
coupled cavities with half Q	1.38
clustered cavities with half Q	1.58
clustered cavities with Q	2.67

W-Band Klystron Design

Input Cavity and Drift Length of Electron Beam

- input cavity in TM_{110}-mode with four power feeding waveguides
- after different drift lengths electron beam with initial modulation depth of 1%,2.5% and 4% achieve different new depths in clustered idler

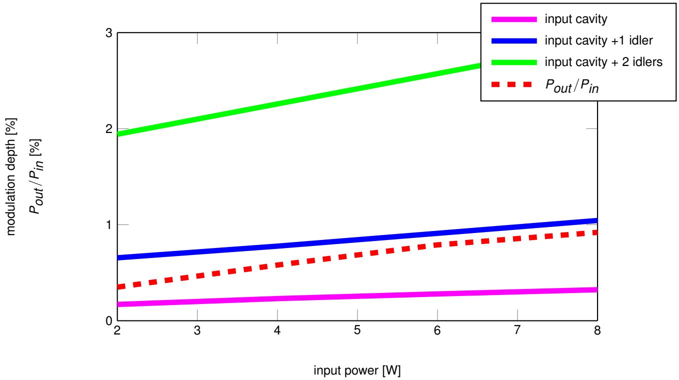




W-Band Klystron Design

Linearity of Klystron

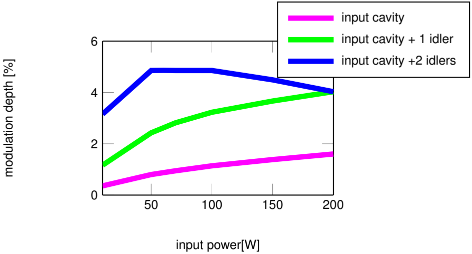
– linear area



W-Band Klystron Design

Linearity of Klystron

– non-linear / saturation area



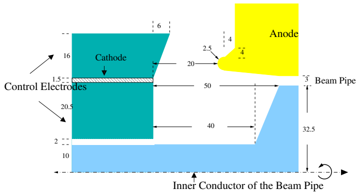
Power Recovery

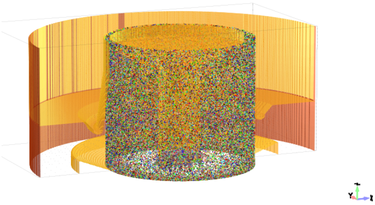
overall efficiency of this klystron

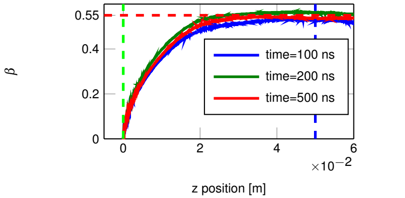
$$\eta_{ov} = \frac{\overline{P}_{out}}{\overline{P}_{in} - \overline{P}_{rec}} = 10.4\% \quad (4)$$

Electron Gun for Generating a Hollow Beam

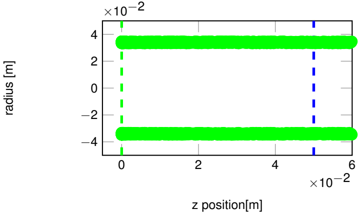
Electron Gun for Non-compressed Beam







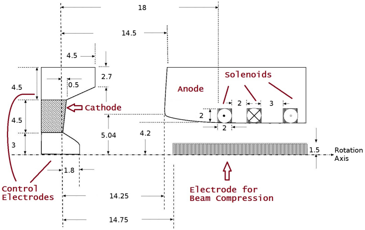
Normalized electron velocity as a function of longitudinal distance z for different calculation times

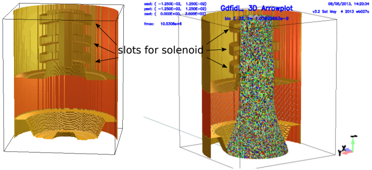


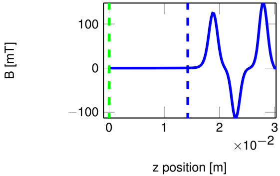
Electron distribution in the electron gun

Electron Gun for Generating a Hollow Beam

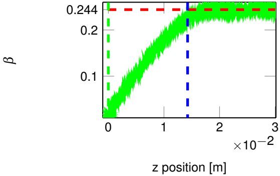
Electron Gun for Compressed Beam







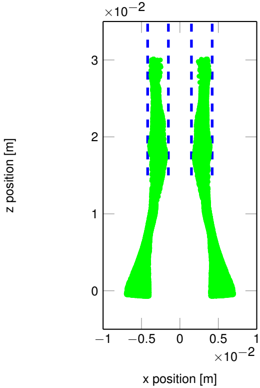
Magnetic flux in z direction at radius of 2.85 mm



Velocity of electrons in longitudinal direction continuously increases in the electron gun

Electron Gun for Generating a Hollow Beam

Electron Gun for Compressed Beam



Cross-section of electron beam in the electron gun with convergent trajectory; the beam pipe is marked with dashed blue lines

Conclusions

– **Chances**
  great potential of power amplification up to MW
  linearity in known area
  easy to manufacture

– **Challenges**
  realisation of electron gun for compressed beam
  stability under high power

○ This project is founded by Deutsche Forschungsgesellschaft.