LOLA, the Transverse RF Deflecting Structure in TTF2

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Content:

1. Introduction

The rms bunch length of TTF 2 will be in the order of about 80 fsec or 25 μm, which is well beyond the range of streak cameras. As this parameter is of fundamental importance for a free-electron laser it needs continuous monitoring. This is possible with a Transverse RF Deflecting Structure like LOLA, which directly spreads out one bunch of the electron beam by an rf deflecting field. By measuring the resulting transverse beam width on an OTR screen it is possible to calculate and to control the absolute bunch length.

2. Description of the Bunch Length Measurement

What do we need to measure the bunch length?

We need a very high and very fast changing transverse deflecting field at the position of the bunch which is acting for a long interaction time or distance on the bunch so that the longitudinal time structure is transformed into a different enough transverse deflection at a screen.

These demands can best be fulfilled by a Transverse RF Deflecting Structure like LOLA IV, because it delivers :

a nominal deflecting peak gradient of 26 MV at 20 MW,
interaction with a travelling wave along the 3.64 m long structure,
a rapid field change with a frequency of 2.856 GHz
and no field at ± 1 μs because of a filling time of 0.645 μs.

How can one calculate the corresponding beam size ?

From the Lorentz transverse deflecting force F = e E on a particle of charge e and mass m one gets a transverse momentum on the bunch, which varies in time during the passage of the bunch. For the small kick angle $\Delta y'$ as a function of the longitudinal coordinate z along the bunch one finds

$$\Delta y'(z) = \frac{e\ V_0}{p\ c} \sin(\beta_L z + \varphi) \approx \frac{e\ V_0}{p_z\ c}\left[\beta_L z \cdot \cos\varphi + \sin\varphi\right]$$

where :

V_o	:	peak voltage
p	:	long. momentum of the beam in the structure $\approx p_z$
φ	:	rf phase compared to zero crossing of the field
β_L	:	phase constant of the structure $=2\pi/\lambda_L$
λ_L	:	wavelength in the structure
$\beta_L z$	:	$\ll 1$

For the transverse position of each ultra-relativistic electron on a screen one finds

$$\Delta y(z) \approx \frac{eV_0}{E_0} \cdot \sqrt{\beta_c \beta_p} \cdot \sin \Delta\psi_y \cdot \left(\beta_L z \cos\varphi + \sin\varphi\right)$$

where :

- β_C : beta function at the deflector
- β_P : beta function at the screen
- $\Delta\psi_y$: betatron phase advance from deflector to screen

If one takes the mean value over all particles for $\langle z \rangle = 0$ one gets the transverse centroid offset at the screen

$$\langle \Delta y \rangle = \frac{eV_0}{E_0} \cdot \sqrt{\beta_c \beta_p} \cdot \sin \Delta\psi_y \cdot \sin\varphi$$

The rms beam size on the screen due to a deflecting voltage is then

$$\sqrt{\left\langle \left(y-\langle y\rangle\right)^2 \right\rangle} \equiv \sigma_y = \sqrt{\sigma_{y0}{}^2 + \sigma_z{}^2 \cdot \beta_c\ \beta_p \left(\frac{\beta_L\, eV_0}{E_0} \cdot \sin \Delta\psi_y \cdot \cos\varphi \right)^2}$$

where

σ_{yo} : nominal beam size on screen $= \sqrt{\beta_p\, \varepsilon_{yN} / \gamma}$

σ_z : rms bunch length $= \sqrt{\langle z^2 \rangle}$

γ : Lorentz energy factor $= E_o/m_oc^2$

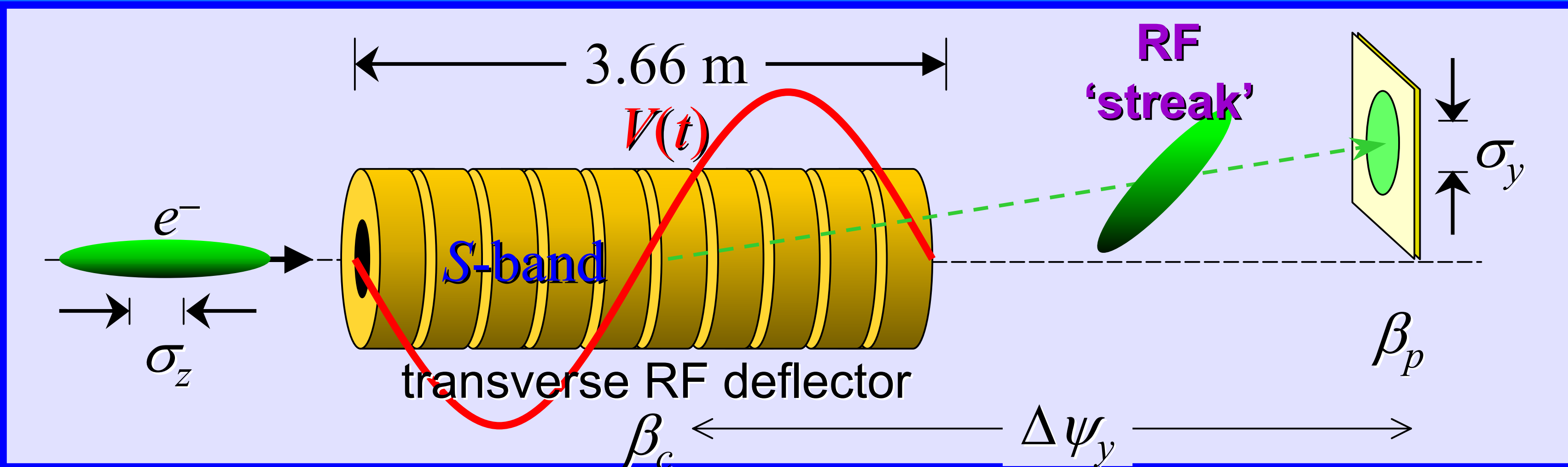
m_oc^2 : electron rest energy

ε_{yN} : normalized transverse rms emittance (in the deflection plane)

The rf deflecting voltage should be large enough, that the calculated beam size on the screen dominates the nominal beam size. For a voltage of 25 MV and the following TTF 2 parameters

$\sigma_z \approx 25\mu m$ $(\beta_c\beta_p)^{1/2} \approx 51m$ $\gamma\varepsilon_{yN} \approx 5\mu m$ $\Delta\psi_y \approx 15.8°$
$\varphi \approx 0°$ $\lambda_L = \lambda_o \approx 105mm$ $\sigma_{yo} \approx 317\mu m$ $P_o \approx 18MW$

shows a calculation at 600 MeV a beam size of $\sigma_y \approx 925\ \mu m$. This is about a factor of 3 compared to the nominal beam size of 317 µm !



$$\sigma_y = \sqrt{\sigma_{y0}^2 + \sigma_z^2 \beta_c \beta_p \left(\frac{2\pi e V_0}{\lambda E_0} \sin \Delta\psi_y \cos\varphi \right)^2}$$

$$\langle \Delta y \rangle = \frac{eV_0}{E_0} \sqrt{\beta_c \beta_p} \sin \Delta\psi_y \sin\varphi \,, \qquad V_0 \approx \left(1.6 \text{ MV/m/MW}^{1/2}\right) L \sqrt{P_0}$$

$\sigma_z \approx 25\ \mu\text{m}$
$E_0 \approx 0.6$ GeV
$(\beta_c \beta_p)^{1/2} \approx 51$ m
$\gamma\varepsilon_y \approx 5\ \mu\text{m}$

$\Delta\psi_y \approx 15.8°$
$\varphi \approx 0°$
$\lambda \approx 105$ mm
$\sigma_{y0} \approx 317\ \mu\text{m}$

$L \approx 3.66$ m, $V_0 \approx 25$ MV,
$P_0 \approx 18$ MW
$\sigma_y \approx$ **925** μ**m**

3. Description of LOLA IV

LOLA was called after its designers at SLAC :

Greg **LO**ew
Rudy **L**arsen
Otto **A**ltenmueller

What is the aim of LOLA ?

Originally several LOLA structures were designed and fabricated in the mid sixties at SLAC as RF separators for secondary particles with the same momentum, but different mass.

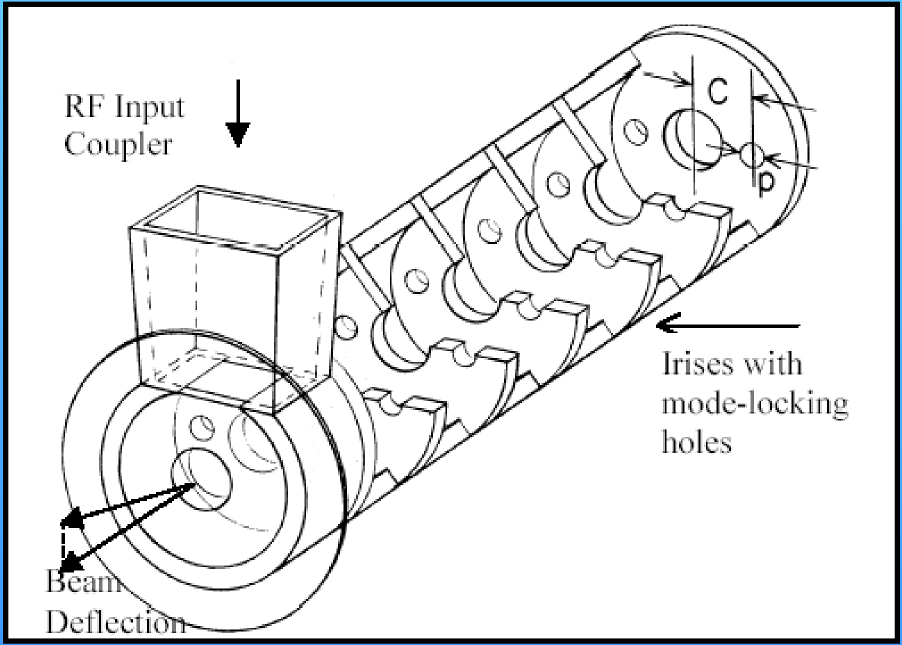
LOLA IV, which was built at SLAC in 1968, is now intended to use as beam phase monitor for bunch length measurements in TTF 2.

What kind of structure is LOLA IV?

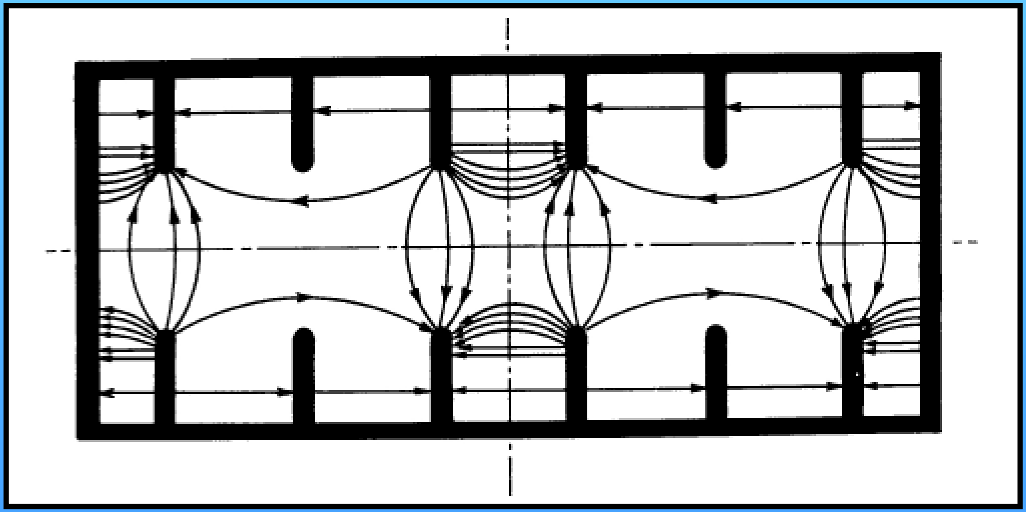
LOLA IV is a 12 feet long disk-loaded waveguide structure of the constant impedance type, this means, that the inner diameter of the structure and the diameter of the iris apertures are constant along the structure. Because of the constant impedance characteristics the transverse deflecting electric field is reduced with attenuation and therefore not constant along the structure.

Compared to accelerating structures, which are normally of the constant gradient type and where both diameters are reduced along the structure to stabilize the field gradient, LOLA has constant iris apertures of about the double diameter !

This gives for the used TM_{11} hybrid mode a strong inductive coupling from cell to cell, which leads to a negative dispersion or a reduction of the wave number with frequency in the dispersion diagram, that means, that unlike to a normal waveguide the wavelength in the waveguide and also the phase velocity of this structure is growing with rising frequency. This in turn is followed by a negative phase velocity.

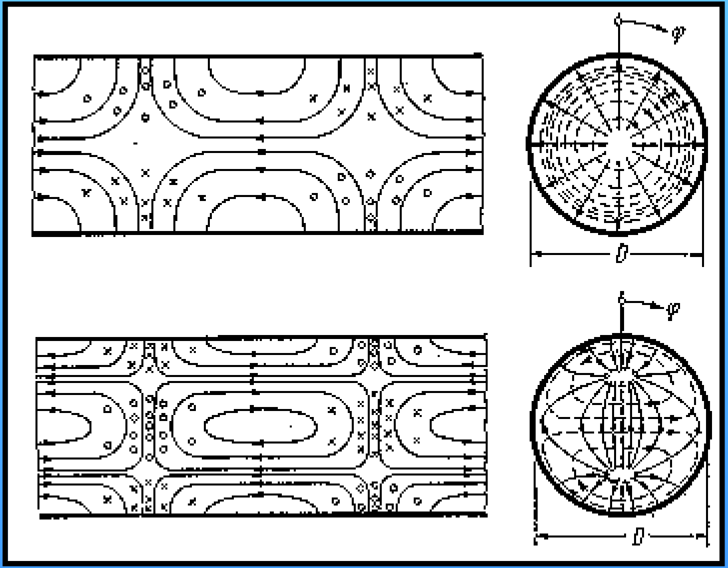


This drawing shows the structure in a cut away view and the indicated beam direction against the power flow in the structure. Also shown is the vertical kick of the beam deflection, which is determined by the rf input coupler, and symmetrical to the iris apertures are shown mode-locking holes, which prevent the TM_{11} hybrid mode from a other-wise possible rotation.



This drawing shows the momentary field distribution of the TM_{11} hybrid mode for the phase shift of $2\pi/3$ per cell when the transversal electric field is zero in the longitudinal symmetry plane of the shown part of the structure. The longitudinal field is always zero everywhere on the axis of the structure, but has a growing amplitude off axis with a different sign above and below the axis.

It can easily be seen that the field distribution repeats its shape after 3 cells. A wavelength is thus 3 cells long and one has a phase shift per cell of 360° / 3 = 120° or $2\pi/3$ as expected. The shown transverse fields on both sides of the longitudinal symmetry plane do not have the maximum values, because the phase shift between both irises is as mentioned only 120°.



For comparison are shown in this figure the field distributions of the TM_{01} and the TM_{11} modes in empty waveguides. The left cut away view of the TM_{11} mode looks like two anti parallel TM_{01} modes above each other. The electrical field lines at the centre of the structure are closed solid lines and they have to be closed lines. Along these closed lines there is no reversal of the field direction allowed.

The right cut away view (transverse to the waveguide) shows the transverse electric field (as solid lines) and the transverse magnetic field (as broken lines) of the TM_{11} mode where they have their maximal amplitudes.

If there would be an iris aperture, the coupling through this iris would come only from the magnetic field and not from the electric field, because the electric field doesn't point through the opening of the iris, but a magnetic field across an opening means strong coupling. This strong coupling leads to the negative dispersion and the backward wave characteristic which was already mentioned.

The transverse electric field looks rather homogeneous and this is indeed the case, as will be shown now, because **this homogeneous electric field is an important feature of the transverse deflecting structure !**

Calculation of the transverse deflecting field

The principle on which the transverse deflecting structure functions is the production of a deflecting force resulting from the field components of the TM_{11} hybrid mode travelling synchronously with the particles of a bunch.

To find the field components we first have to keep in mind that the particles are travelling on the axis of a periodically disc loaded circular waveguide. Due to the periodicity of the structure, which perturbs the fields distribution, we have also a periodicity of the field with the cell length or period L. Instead of writing

$$\underline{E}_{(z)} = \underline{E}_{(z=o)}\, e^{-j\beta z}$$

for the field along an unloaded structure, we have now to write

$$\underline{E}_{(z)} = \underline{E}_{p(z)}\, e^{-j\beta_o z}$$

where $\underline{E}_{p(z)}$ is a periodic function with the period L. Here is used the Floquet theorem

$$\underline{E}_{(z+L)} = E_{(z)}\, e^{-j\Psi_o}$$

with

$$\Psi_o = \beta_o L$$

the phase shift per cell.

As the function $\underline{E}_{p(z)}$ is periodic with period L, it is possible to expand it in a Fourier series, but here we have a space- and not a time-periodicity. For this reason the harmonics are named **space harmonics**. We get:

$$\underline{E}_{p(z)} = \sum_{n=-\infty}^{\infty} \underline{E}_n \cdot e^{-j(2\pi n z/L)}$$

and with the following complex amplitudes of the space harmonics

$$\underline{E}_n = \frac{1}{L} \cdot \int_{z_o}^{z_o+L} \underline{E}_{p(z)} \cdot e^{j(2\pi n z/L)}\, dz$$

one obtains:

$$\underline{E}_{(z)} = \sum_n \underline{E}_n \cdot e^{-j\left(\beta_o + \frac{2\pi n}{L}\right) z} = \sum_n \underline{E}_n \cdot e^{-j\beta_n z}$$

and

$$\underline{E}_n = \frac{1}{L} \cdot \int_{z_o}^{z_o+L} \underline{E}_{(z)} \cdot e^{j\beta_n z}\, dz$$

where $\beta_n = \beta_o + \frac{2\pi n}{L}$ or $\Psi_n = \Psi_o + 2\pi n$

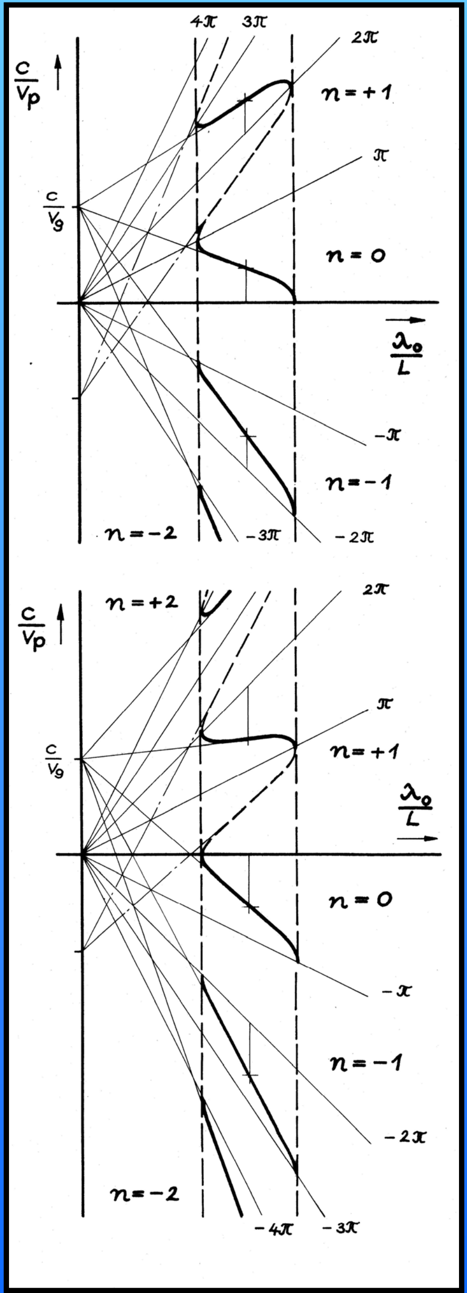
and $n = 0, \pm 1, \pm 2, \ldots.$

Now we have for the phase velocities :

$$v_{p,n} = \frac{\omega}{\beta_n} = \frac{\omega}{\frac{\psi_o}{L} + \frac{2\pi\, n}{L}}$$

or

$$\frac{c}{v_{p,n}} = \frac{c}{v_{p,o}} + n \cdot \frac{\lambda_o}{L}$$



Dispersion diagram for forward fundamental space harmonic

This result is shown in 2 dispersion diagrams, the upper diagram for positive dispersion and a forward fundamental space harmonic (n = 0) and the lower diagram for negative dispersion and a backward fundamental space harmonic (n = 0) as it is the case for LOLA.

Dispersion diagram for backward fundamental space harmonic

For negative n are also negative phase velocities possible, but for all space harmonics we get the **same group velocity** :

$$\frac{1}{v_g} = \frac{d}{d\omega} \cdot \beta_n = \frac{d}{d\omega}\left(\beta_o + \frac{2\pi n}{L}\right) = \frac{d\beta_o}{d\omega}$$

or

$$\frac{c}{v_g} = \frac{c}{v_{p,n}} - \frac{\lambda_o}{L} \frac{d\left(c / v_{p,n}\right)}{d\left(\lambda_o / L\right)}$$

The Fourier-analyzed field components of the **fundamental space harmonic** in the aperture of the irises (r < a) of LOLA at the velocity of light are

$$\underline{E}_r = \underline{E}_o \left[\left(\frac{kr}{2}\right)^2 + \left(\frac{ka}{2}\right)^2\right] \cos\theta$$

$$E_\theta = \underline{E}_o \left[\left(\frac{kr}{2}\right)^2 - \left(\frac{ka}{2}\right)^2\right] \sin\theta$$

$$\underline{E}_z = j\, \underline{E}_o\, k\, r \cos\theta$$

$$Z_o H_r = -\underline{E}_o \left[\left(\frac{kr}{2}\right)^2 - \left(\frac{ka}{2}\right)^2 + 1\right] \sin\theta$$

$$Z_o H_\theta = \underline{E}_o \left[\left(\frac{kr}{2}\right)^2 + \left(\frac{ka}{2}\right)^2 + 1\right] \cos\theta$$

$$Z_o H_z = -j\, \underline{E}_o\, k\, r \sin\theta$$

With : $k = 2\pi/\lambda_o$: free-space wave number

Z_o : free-space impedance

The equations of motion in cylindrical coordinates for a charged particle interacting with a electromagnetic field are

$$\frac{d}{dt}\left(\gamma \dot{r}\right) - \gamma r \dot{\theta}^2 = \frac{e}{m_o}\left(E_r + r\dot{\theta} B_z - \dot{z} B_\theta\right)$$

$$\frac{1}{r}\cdot\frac{d}{dt}\left(\gamma r^2 \dot{\theta}\right) = \frac{e}{m_o}\left(E_\theta + \dot{z} B_r - \dot{r} B_z\right)$$

$$\frac{d}{dt}\left(\gamma \dot{z}\right) = \frac{e}{m_o}\left(E_z + \dot{r} B_\theta - r\dot{\theta} B_r\right)$$

With the field components of the fundamental space harmonic from above one obtains for the motion of a highly relativistic particle at dz/dt? c and synchronisation with the maximal transverse electric field at $E_z = H_z = 0$ of the fundamental space harmonic

$$\frac{d}{dt}\left(\gamma \dot{r}\right) - \gamma r \dot{\theta}^2 = \frac{eE_o}{m_o}\cdot\cos\theta$$

$$\frac{1}{r}\cdot\frac{d}{dt}\left(\gamma r^2 \dot{\theta}\right) = -\frac{eE_o}{m_o}\cdot\sin\theta$$

$$\frac{d}{dt}\left(\gamma \dot{z}\right) = 0$$

In rectangular coordinates one can write for $\theta = 0$

$$F_y = e\,E_o$$
$$F_x = 0$$
$$F_z = 0$$

These equations of motion show that the transverse force and also **the transverse deflecting field is constant over the aperture of the iris** and in the direction of the axis of symmetry of the radial component of the field ($\theta = 0$) and according to the assumed approximation there is **no longitudinal energy gain** and **therefore the deflector is free of aberrations over the aperture !**

With the above field components it is also possible to calculate the power flow through the iris aperture by integrating the **Poynting vector** over the aperture S

$$P_z = \frac{1}{2}\,\mathrm{Re}\left\{\oint_S (\vec{E}\,x\,\vec{H}^*)\,d\vec{S}\right\}$$

One obtains for the power in z direction

$$P_z = \frac{\pi a^2}{2}\cdot\frac{\left|E_o\right|^2}{Z_o}\cdot\left(\frac{k\,a}{2}\right)^2\cdot\left[\frac{4}{3}\cdot\left(\frac{k\,a}{2}\right)^2 - 1\right]$$

This is also a very interesting result, because one observes that **the power can be positive or negative** or in other words the **deflecting mode can be a forward or a backward wave mode** depending on whether ka > $\sqrt{3}$ or ka < $\sqrt{3}$. For 2856 MHz, the cross-over value of a is 2.9 cm and one has no net power flow along the structure and the group velocity is zero.

The iris aperture of LOLA is 44.88 mm. With a = 2.244 cm the term in the bracket is negative and this indicates **that the transverse deflecting mode in LOLA is a backward wave mode as already mentioned.**

For the transverse deflecting voltage one calculates with the exact formula:

$$V_o = \sqrt{r_{sh} \cdot L \cdot P_o \cdot \left(1 - e^{-2\tau}\right)} = 26.70 MV$$

where

Shunt impedance	r_{sh}	= 16 MΩ / m
Structure length	L	= 3.64 m
Input power	P_o	= 20 MW
Attenuation	τ	= 0.477 N

Also used is

$$V_o = 1.6 MV \cdot \frac{L}{m} \cdot \sqrt{P_o / MW} = 26\ MV$$

Parameters of LOLA IV

Type of structure	Constant impedance structure
Mode type	TM 11 (Hybrid Mode)
Phase shift / cell	120° (2 Pi / 3)
Cell length	35 mm
Design wavelength	105 mm
Nominal operating frequency	2856 MHz
Nominal operating temperature	45 °C
Quality factor	12100
Relative group velocity	**-** 0.0189 **!!**
Filling time	0.645 µs
Attenuation	0.477 N = 4.14 dB
Transverse shunt impedance	16 MOhm / m
Deflecting voltage	$V_o = 1.6\ MV \cdot L/m \cdot (P_o/MW)^{1/2}$
Nominal deflecting voltage	26 MV at 20 MW
Maximum operating power	25 MW
Length of structure	3640 mm (about 12 feet)
Disk thickness	5.84 mm
Iris aperture	44.88 mm
Cavity inner diameter	116.34 mm
Cavity outer diameter	137.59 mm

Consequences of the Parameters of LOLA IV :

Due to the high Q value the temperature of LOLA has to be stabilized at 45°C ± 0.1 °C

LOLA has no integrated load and needs therefore a dry external load (no water in the waveguide!). Two SiC loads for 40 MW / 2µs and 10 Hz were ordered at Nihon Koshuha in Japan.

The resonant frequency of LOLA is not harmonic to 1.3 GHz :

2856 MHz : 1300 MHz = 2.196 923076 923076 923076 …

Synchronisation is possible only for 1 bunch per pulse train !

Due to the necessary input power of up to 22 MW a powerful klystron was needed, because as there was no chance to install the klystron nearby the final position of the klystron was 75 m away. The attenuation of the waveguide system was already theoretically 1.6 dB (factor 1.45), but could be up to 3 dB (factor 2) due to additional attenuation from bends, flanges and surface roughness, so that a klystron with a output power of 44 MW was needed.

The phase velocity is negative and the power flow has to be therefore against the direction of the beam and the power is thus fed in at the downstream end of LOLA !

4. Modulator and Klystron 5045 commissioning

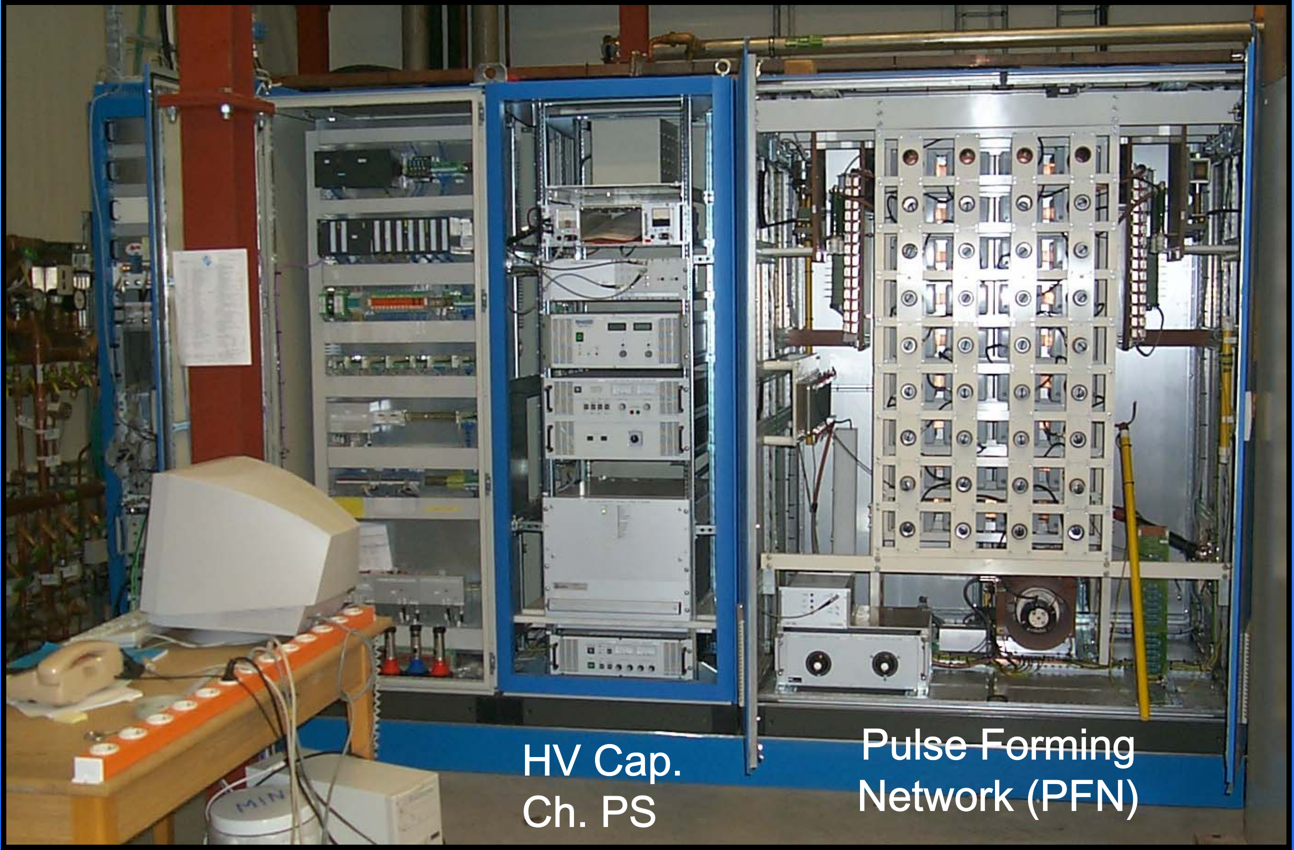
The Klystron 5045 with tank and cable:

The Klystron and the cable were provided by SLAC.
They arrived together with LOLA at DESY in April 2003.
The assembly and commissioning took place in September with the help of T. Smith, M. Ross and D. McCormick from SLAC.

- **Some Basic Datas**
  - The operating frequency is 2856 MHz.
  - Beam voltage : 350 kV, Beam current : 397 A
  - Peak RF output power: 61.5 MW, RF pulse width: 3.5 µs.
  - Gain: 51.6 dB, Drive Power: 422 W
  - Efficiency: 44 %, Microperveance: 1.92
- **Needed parameters for the use in TTF2**
  - The klystron will operate at 1 Hz, for conditioning at 10 Hz.
  - Output RF power up to 45 MW with a pulse length of 1µs.
- **During the conditioning (December 2003) achieved parameters**
  - LOLA input power 23MW with a pulse length of 0.5 µs.
  - LOLA input power 18MW with a pulse length of 1µs.

The Modulator and its components:

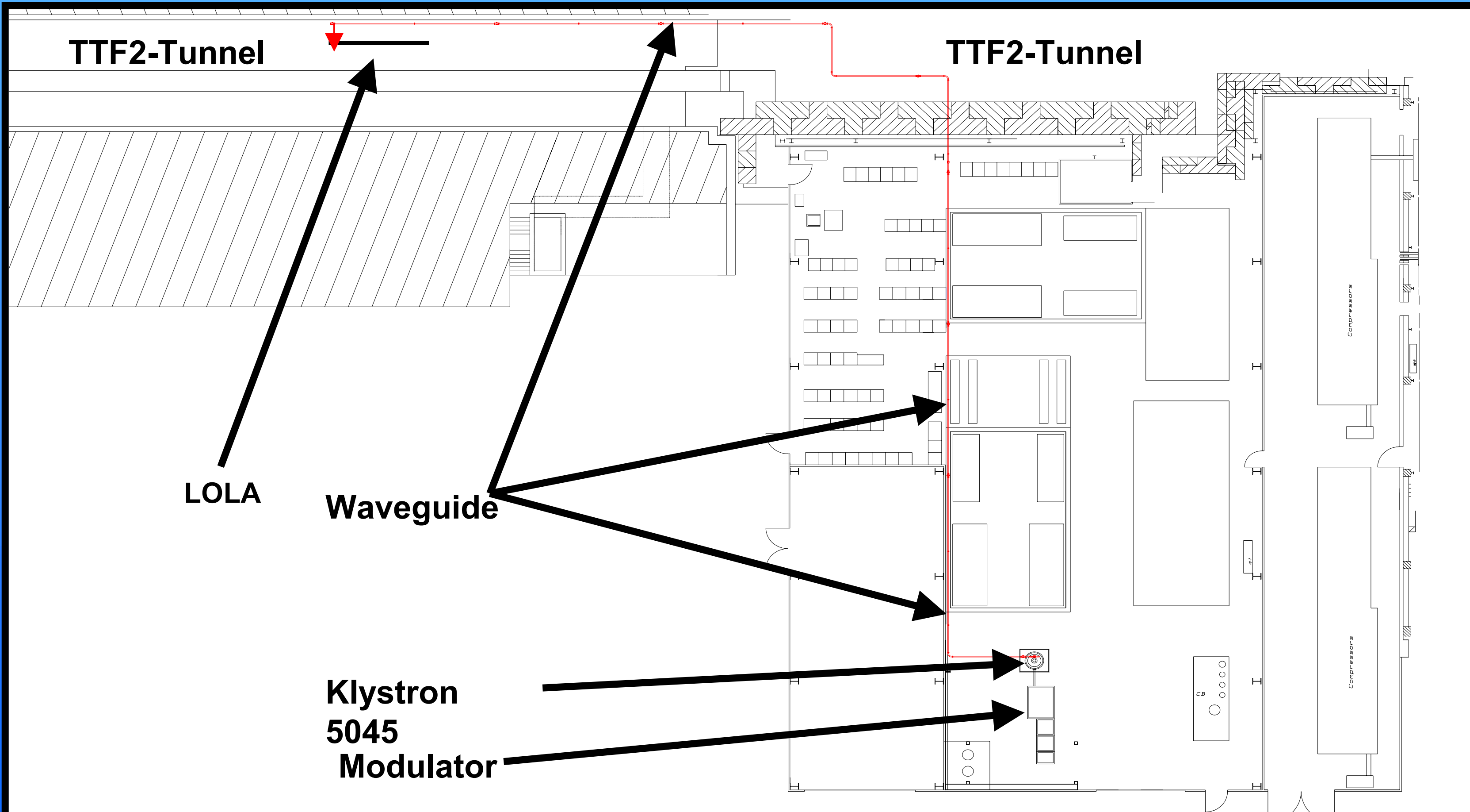
- The 150 MW modulator with a pulse width of 5µs and a repetition frequency of 10 Hz was ordered at PPT by DESY.
- It is a line-type pulser with a 50 kV capacitor charging power supply and a SPS control system incl. Ethernet interface.



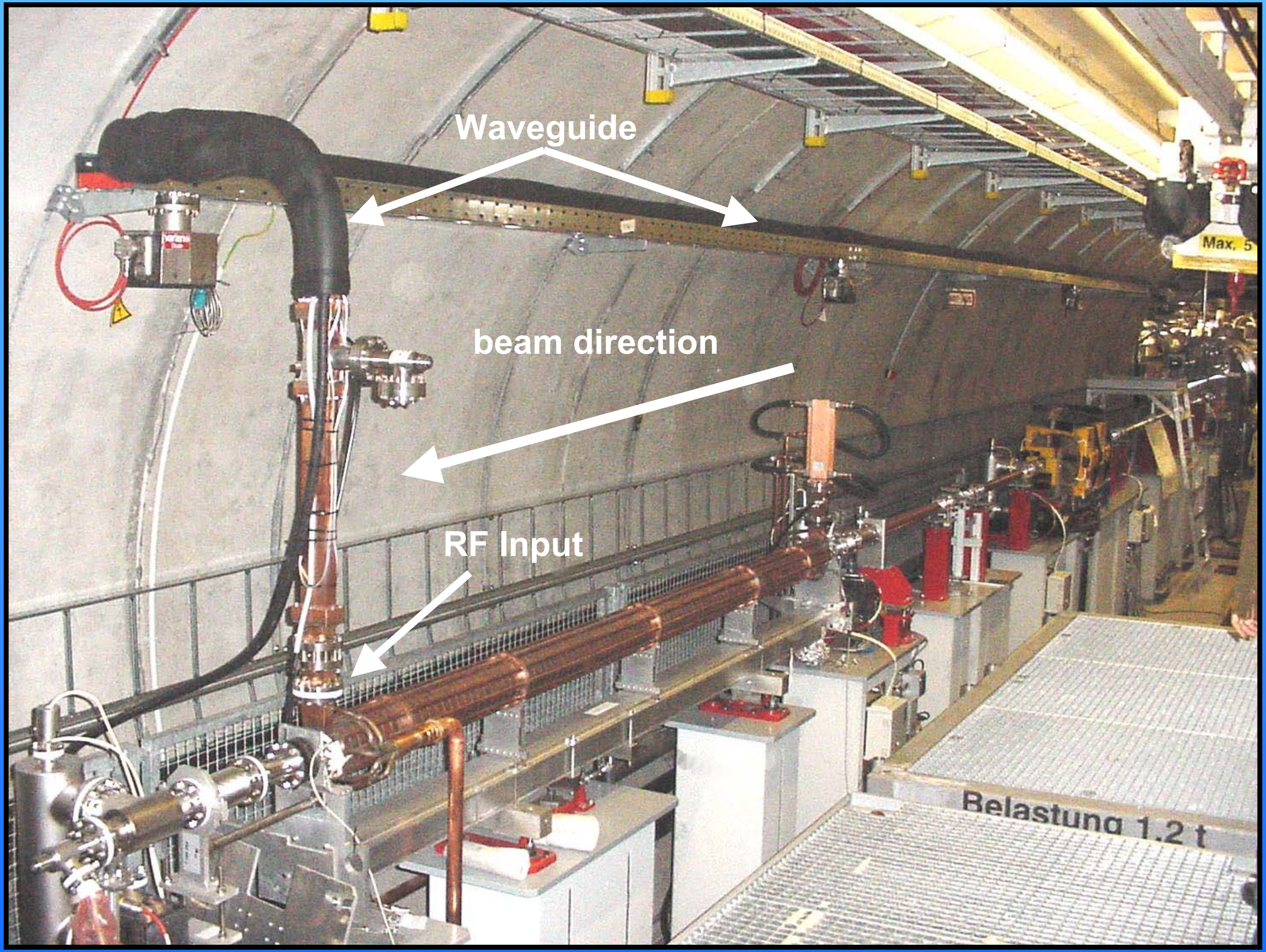
5. Waveguide and LOLA Commissioning

The Waveguide:

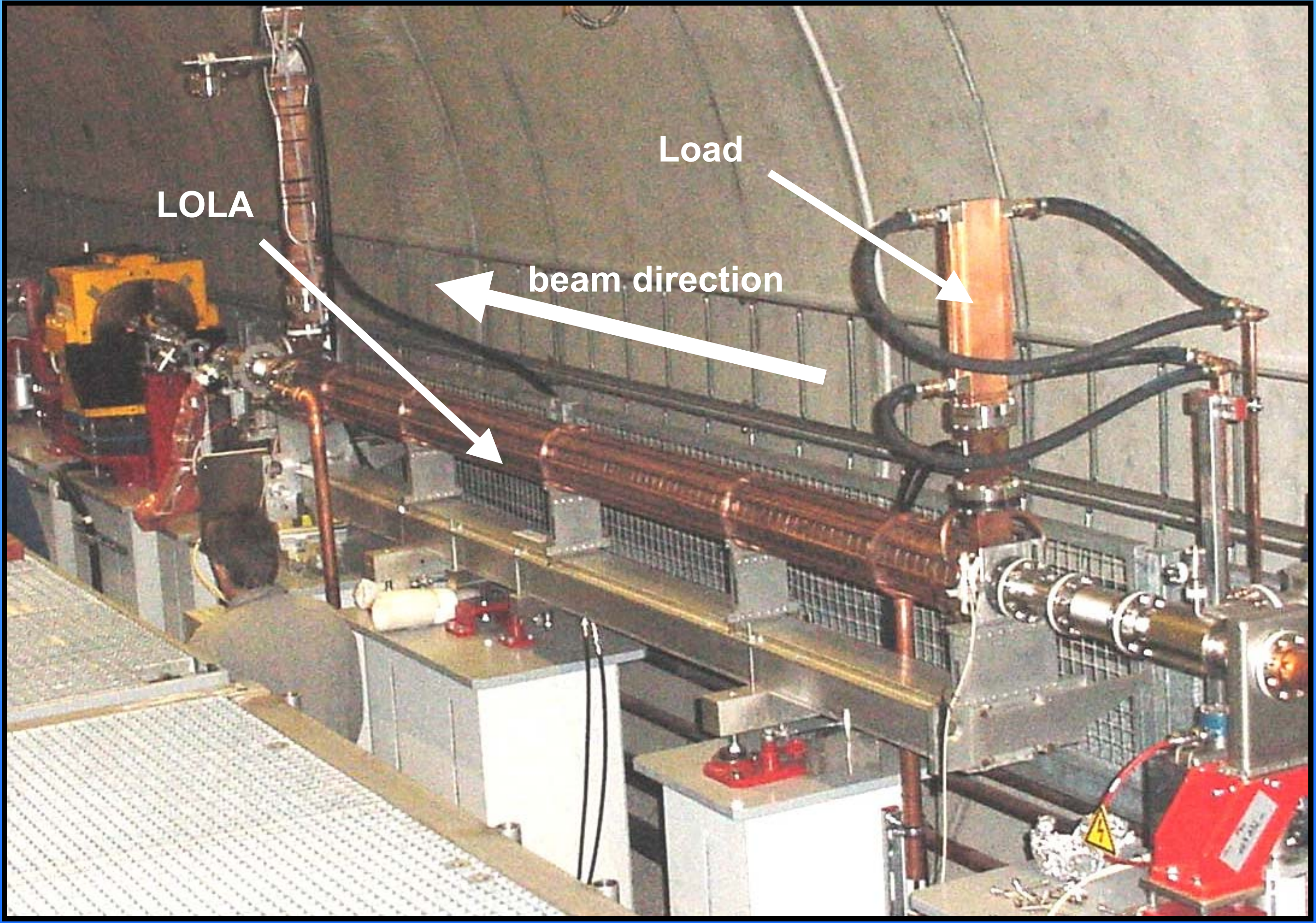
The waveguide length between klystron and LOLA is 75 m. The theoretical attenuation is 1.6 dB, measured was 2.6 dB. The maximal power on the waveguide is 45 MW and at the LOLA input 25 MW. The waveguide material was contributed by SLAC. Brazing and machining was done at DESY. As the phase shift is 2.8°/K the waveguide is heater stabilized at 35°C.



LOLA in the TTF2 Tunnel



LOLA in the TTF2 Tunnel



6. List of Contributors

Field of activity	Group	Contact
Coordination at SLAC		M. Ross D. McCormick T. Smith
Coordination at DESY	MIN	H. Weise M. Nagl K. Klose
Installation of LOLA and the vacuum components in the TTF2 Beamline.	MVP MPL	K. Zapfe H. Remde G. Weichert
Wave guide	MVA MVP MIN	D. Jagnow H. Remde J. Rothenburg
Modulator, Klystron 5045, RF Compone nts	MIN	M. Rakutt J. Herrmann R. Jonas
Water -cooling Klystron + Cavity	MKK	F.-R. Ullrich O. Krebs
Synchronisation	MHF -P	S. Simrock M. Ross
BIS + Interlock	MVP	M. S taack
DOOCS	MVP	K. Rehlich
Trigger	MVP	K. Rehlich
Diagnostic Screens	MPY	K. Honkavaara D. Noelle