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(Beam diagnostics, longitudinal beam profile, Delay Loop, OTR, ZEMAX**)**

LAYOUT OF THE LONG OPTICAL LINES IN CTF3

C.P. Welsch, E. Bravin, T. Lefèvre

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The Compact Linear Collider (CLIC) project is a multi-TeV electron-positron collider for particle physics based on an innovative two-beam acceleration concept. A high-intensity drive beam powers the main beam of a high-frequency (30 GHz) linac with a gradient of 150 MV/m, by means of transfer structure sections. The aim of the CLIC Test Facility (CTF3) is to make exhaustive tests of the main CLIC parameters and to prove the technical feasibility. One of the points of particular interest is the demonstration of bunch train compression in the Delay Loop (DL) and the combiner ring (CR).
Among others, time resolved measurements with a streak camera are planned to monitor bunch separation, to check the machine's isochronicity and to study inter-bunch behavior. This article gives an overview of the design considerations of the long optical lines and shows first results obtained during the last machine run in 2005.

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CERN, Geneva, Switzerland

Abstract

The Compact Linear Collider (CLIC) project is a multi-TeV electron-positron collider for particle physics based on an innovative two-beam acceleration concept [1]. A high-intensity drive beam powers the main beam of a high-frequency (30 GHz) linac with a gradient of 150 MV/m, by means of transfer structure sections. The aim of the CLIC Test Facility (CTF3) is to make exhaustive tests of the main CLIC parameters [2, 3] and to prove the technical feasibility. One of the points of particular interest is the demonstration of bunch train compression in the Delay Loop (DL) and the combiner ring (CR) [4,5].

Among others, time resolved measurements with a streak camera are planned to monitor bunch separation, to check the machine's isochronicity and to study inter-bunch behavior. This article gives an overview of the design considerations of the long optical lines and shows first results obtained during the last machine run in 2005.

INTRODUCTION

CTF3 is being installed at CERN in the existing buildings of the LEP pre-injector accelerators LIL and EPA. The complex starts with a 3 GHz linac that produces a pulsed electron beam with a present maximum energy of 150 MeV. The separation between the bunches at the end of the linac is 20 cm - twice the linac RF wavelength. Moreover the macrobunch is composed by alternated sequences 140 ns long of even and odd buckets, with the difference in phase between them being one RF wavelength. The linac is connected by a transfer line to the DL where a 1.5 GHz RF deflector, see Figure 1, deviates the odd bunch sequences to the left inside the DL and the even ones to the right. The DL length is 140 ns times the velocity of light c so that after this ring the odd sequence will be recombined with the incoming even sequence in such a way to fill the interleaved empty buckets. Precise adjustment of the longitudinal structure can be done with the integrated wiggler. The resulting macrobunch structure at the DL output presents 140 ns long trains of buckets separated now by 10 cm, followed by 140 ns long voids.

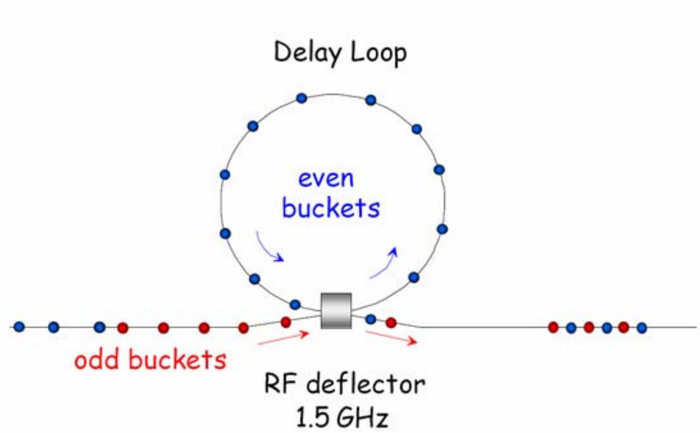

Figure 1: Schematic drawing of the injection scheme into the CTF3 Delay Loop

The timing of the bunches of subsequent batches is adjusted in such that they have a phase difference of 180 ° with respect to the 1.5 GHz RF of the deflector, Figure 2.

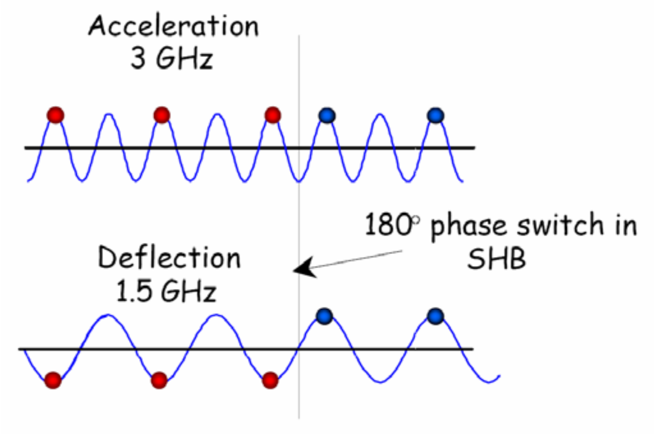

Figure 2: Illustration of required 180° phase switch between two batches of bunch trains.

An overview of the overall bunch combination process is shown in Figure 3. The necessary timing is controlled by the sub-harmonic bunchers working at 1.5 GHz in the injector region. Every 140 ns the phase of the RF is changed by 180 degrees. This requires wide band sub-harmonic buncher structures as well as an RF power source capable of switching phase over a few bunches.

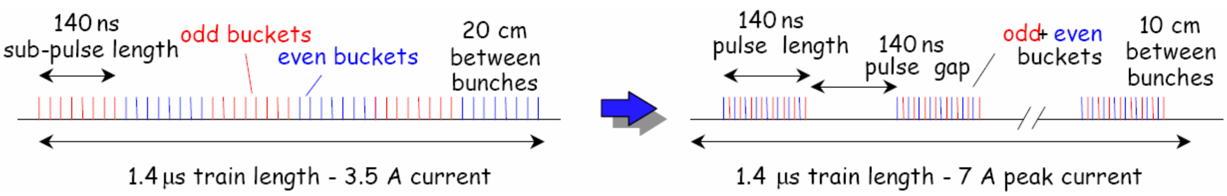

Figure 3: (x2) bunch frequency multiplication in the CTF3 Delay Loop.

One possibility to analyze in detail the longitudinal behaviour of the electron bunches in the Delay Loop as well as after the recombination process is to use a high resolution streak camera that gives access to a time resolution down to some 3 ps. In order to achieve a good time resolution, first the photons from the radiation to be analyzed are converted to electron, which are accelerated and deflected using a time-synchronized, ramped HV electric field. The signal from the electrons is then amplified with a micro channel plate (MCP), converted to γ s via a phosphor screen and finally detected using an imager like a CCD array, which converts the light into a voltage.

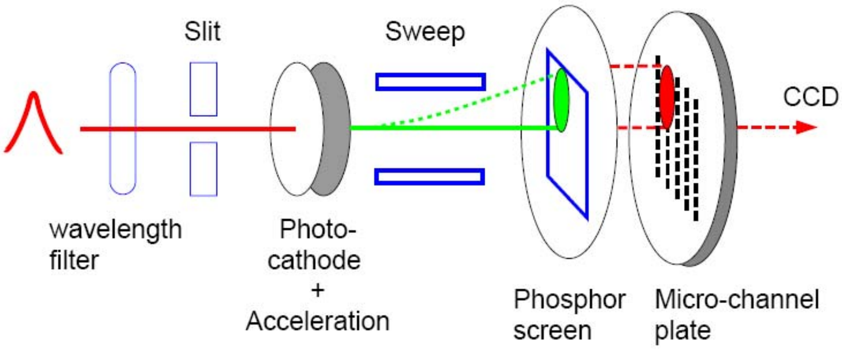

Figure 4: Principle of the streak camera [6].

DESIGN CONSIDERATIONS

It is highly desirable to have the possibility to do time resolved measurements with a good time resolution with light originating from different places in the machine. Due to the high radiation level in CTF3 and the sensitivity of the streak camera, adequate measures have to be taken in order to protect the camera. A measurement close to the accelerator clearly is not feasible.

Thus optical lines have to be designed in order to guide the light to be observed to the streak camera. It needs to be ensured that a maximum of the created light is collected and projected onto the entrance slit of the streak camera. As will be shown in the following sections, the distances that need to be covered by these optical lines reach up to 40 meters and thus require a careful layout. The design steps can be summarized as follows:

- Transmit the light over large distances using telescopic arrangements, i.e. two identical lenses placed apart two times their focal length.
- Optimize the overall system between collecting, transmitting and demagnifying optics.
- Minimize the number of optical elements in order to maximize light transmission and reduce aberrations. Each lens will absorb about ~10% of the incident light.
- Optimize the optical resolution. Even though (transverse) aberrations are not the most critical point in streak camera measurements, one would still like to have a final image where these are minimized.

In addition, constraints from the available space in the machine, type of lenses on hand and installations of other diagnostic equipment, using part of the optical lines in parallel, influence the final layout of the optics to a high degree. A bird's eye view of the DL with the two optical lines that were installed in 2005/2006 is shown in Figure 5.

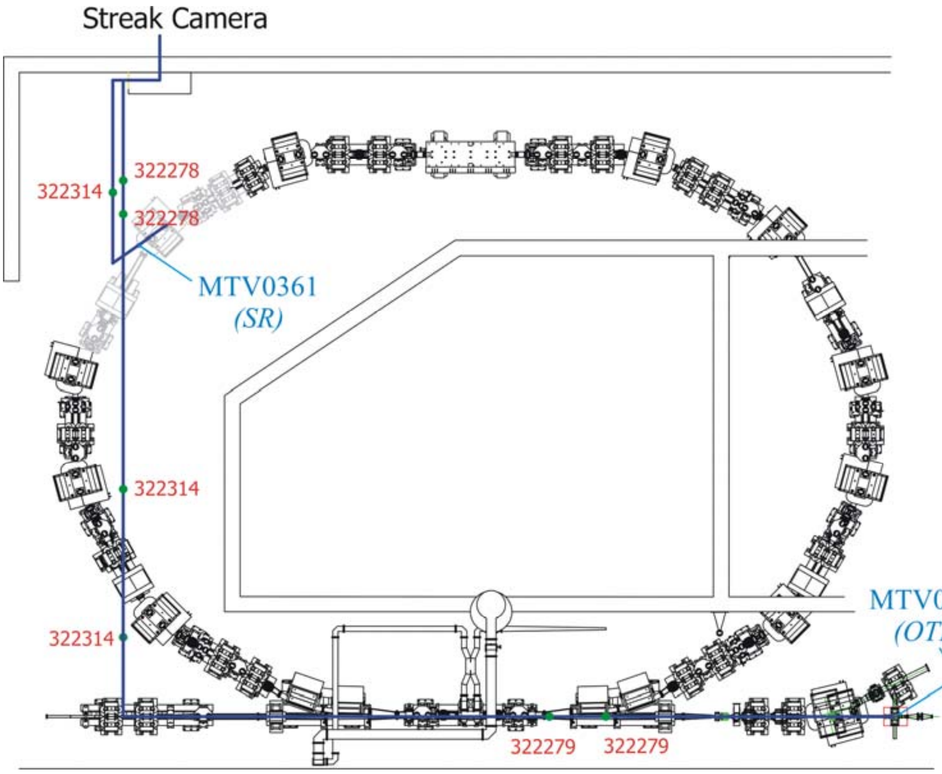

Figure 5: DL with the two optical lines installed in 2005/2006. Numbers correspond to achromatic lenses. Details are given later in the text.

LIGHT CHARACTERISTICS FROM MTV0361 AND MTV0550

In order to find the optimum layout of the optical lines, one needs to know the characteristic parameters of the initial light distribution in detail. Profile measurements based on synchrotron radiation [see e.g. 7, 8] are today well established and used in most high energy storage rings. In the DL, synchrotron light is exploited for measurements at the bending magnets CD.BHE0240, CD.BHF0330 and CD.BHE0360 [9]. While a local CCD camera is installed in the machine in the first two cases, an optical line to the synchrotron light laboratory in building 2002 is used to project light on a CCD camera, a gated intensified camera, the streak camera and eventually a CID camera system [10]. The parameters necessary for the calculation of the SR emission characteristics are summarized in the Table 1.

Table 1: Overview of the DL parameters

Parameter	Value
Energy	150 MeV
Relativistic γ	292.5
Current	5.4 A
Bending Radius	1.078 m
Bending Angle	30°

The half opening angle θ of the light cone emitted at the centre of the bending magnet is given by the relation between the transverse and longitudinal momentum of the circulating electrons [11]

$$\tan\theta = \frac{p_y}{p_z} = \frac{p_0^{'}}{\beta\gamma\, p_0^{'}} \approx \frac{1}{\gamma} \qquad (1)$$

Since $\gamma >> 1$, $\tan\theta \approx \theta$ and thus in this particular case θ *=0.2°*. This value is then used in the numerical simulation of the optical line.

A second point of interest when it comes to synchrotron radiation is the emitted power, which can reach enormous values in high energy machines.

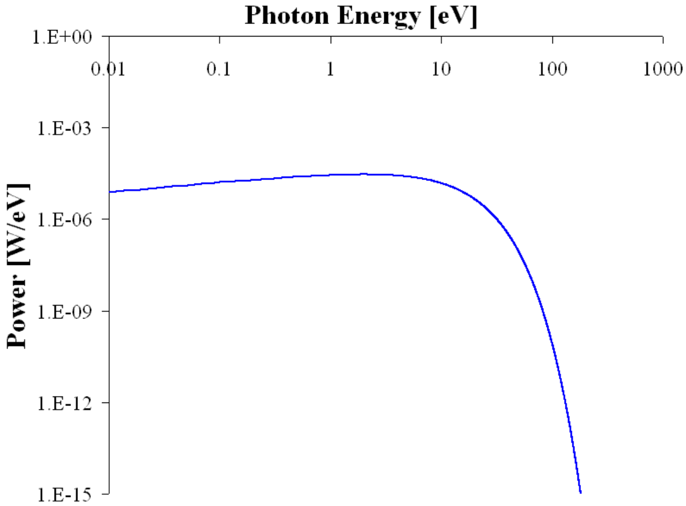

Figure 6: Emitted synchrotron light power as a function of photon energy in the bending magnets of the CTF3 Delay Loop. Beam current: 5.4 A, Energy: 150 MeV

It is important to know the emitted total power to be able to decide e.g. about whether or not cooling of the mirrors is required. As can be seen from Figure 6, the emitted total power does not exceed some *mW* and thus is not a critical point in the case of the DL.

Optical transition radiation (OTR) [12,13,14] is today established as a reliable and precise technique. It provides a signal in the visible range linear to the bunch charge and also offers a spatial resolution down to the μm range and thus covers the requirements at CTF3 [15, 16, 17]. The number of OTR photons N_{OTR} that are created within a specific wavelength interval between λ_a and λ_b at a beam energy γ is given by [12]

$$N_{OTR} = \frac{2\alpha}{\pi}\ln\left(\frac{\lambda_b}{\lambda_a}\right)\left[\ln(2\gamma) - \tfrac{1}{2}\right] \qquad (2)$$

where the fine structure constant $\alpha = e^2/(\hbar c) \approx 1/137$ was used.

The relative OTR emission intensity as a function of the emission angle from MTV0550 behind the DL with nominal beam current and at an energy of *E=150 MeV* is shown in the following Figure 7.

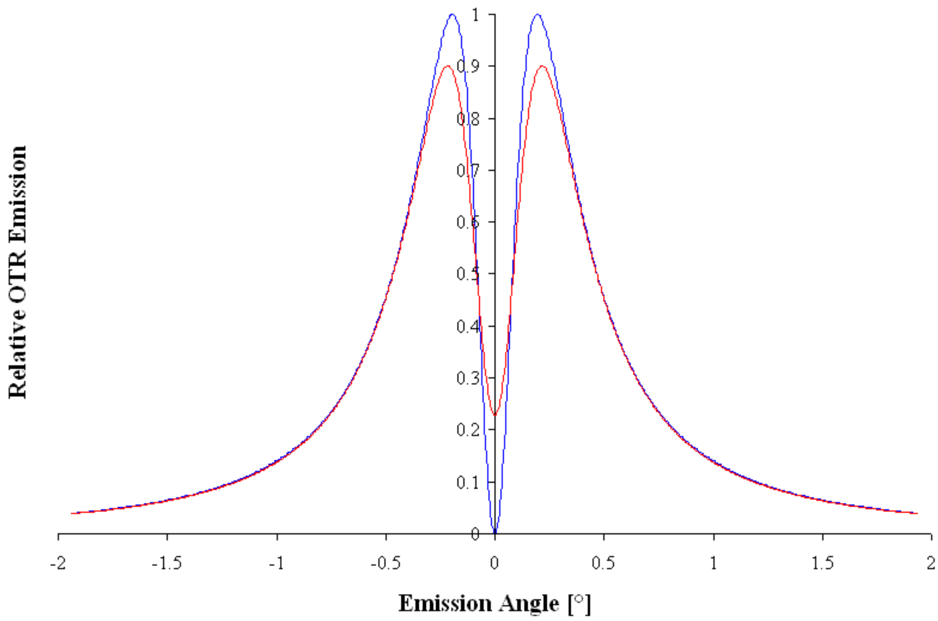

Figure 7: Angular distribution of transition radiation as a function of θ for a 150 MeV electron beam without (—) and with (—) a beam divergence of 1 mrad.

The maximum of the OTR light distribution is found at an emission angle of $\theta = 0.2°$, which will be the base for the ZEMAX simulations described in the following section. Furthermore it can be seen from the plot that a measurement of the OTR intensity distribution as a function of the emission angle gives direct access to a measurements of the beam divergence, which can even be extended to a single shot emittance measurement [18]. This interesting option might be a choice for CTF3 in the near future.

ZEMAX RESULTS

In order to optimize the overall layout of the optical lines, the computer code ZEMAX [19] was used. It is a comprehensive software tool for optical design and integrates all the features required to conceptualize, design, optimize, analyze, tolerance, and document virtually any optical system. It contains a huge library of lenses from a variety of manufacturers and allows the computation of the quality of the final image.

With a total track length of 11.25 m between the center of the dipole CD.BHE0360 and the entrance slit of the streak camera, a beam transport by means of only two achromatic lenses and a final focusing lens right in front of the camera is feasible. It should be pointed out that all optical manipulations need to be done before the light enters into the final ~4 m long passage between the buildings 2002 (streak camera lab) and 2003 (DL).

Table 2: List of the elements of the optical line from MTV0361 to the SC lab.

Object	**Distance [mm]**
Light Source *(SR)*	
Mirror	890

Lens *(f=310 mm, #322278)*	290
Mirror	560
Lens *(f=1500 mm, #322314)*	1155
Mirror	2153
Optical Chicane	

The position of the mirrors is fixed by the constraints in the machine while the initial light distribution results from the calculation of the OTR emission as present in the last section. The program then computes the quality of the final image and gives various tools to optimize the overall setup. The result of the process is shown in Figure 8, where the ray aberrations and spot diagram of the final image, i.e. at the position of the CCD or streak camera is shown. Since this line will also be used for transverse profile measurements, it is important to reduce the errors as much as possible in order to achieve a good image quality. The maximum values of the aberrations are around 20 μm at a distance of ± 15 mm, which corresponds to the size of the entire OTR screen.

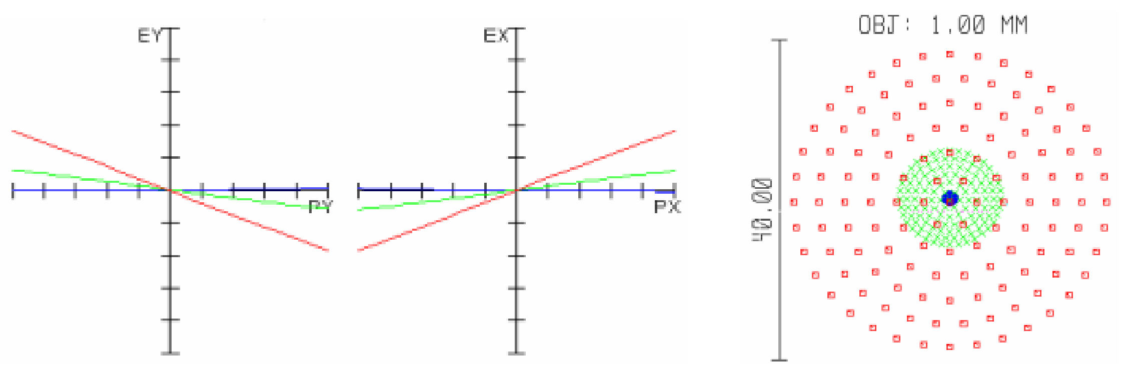

Figure 8: Ray aberrations and spot diagram of the optical line from MTV0361.

As demonstrated before, the initial opening angle of the OTR at MTV0550 is $\alpha = 0.2$. In contrast to the above described optical line from the DL bending magnet, the distance that needs to be covered stretches out to roughly 40 meters. Thus telescopic arrangements, where two achromatic lenses with identical focal lengths f are placed at a distance $d \approx 2 \cdot f$, have to be used. This configuration guarantees proper light transport even over large distances and allows verifying the correct positioning with the help of intermediate image planes.

Table 3: List of the elements of the optical line from MTV0550 to the SC lab.

Object	**Distance [mm]**
Light Source *(OTR)*	
Lens *(f=500 mm, #322279)*	6430
Lens *(f=500 mm)*	1060
Mirror	8130
Lens *(f=1500 mm)*	1550
Lens *(f=1500 mm)*	2560
Lens *(f=310 mm)*	2860

Lens *(f=310 mm)*	650
Mirror	3310
Optical Chicane	

Again, the calculations started using the light distribution calculated with the methods presented in the last section and the input of the required mirror positions. Due to the existing wave guides, vacuum chambers and ventilation tubes around the DL, only a limited number of positions for the lenses were possible and a number of different constraints had to be taken into account during the optimization process. In addition, the height of the ceiling in building 2003 changes from 2.50 m around the rf deflector to 3.0 m towards the linac and thus a compact optical chicane consisting of two *d=100 mm* mirrors had to be integrated into the system.

Since the aim of this long line is the analysis of longitudinal beam profiles, transverse aberrations in the final image are not as important as in the case of MTV0361. However, one always tries to onptimize the image quality as much as possible in order to have the possibility to check the correct alignment with the help of intermediate images. It should be pointed out that the relatively large deviations that can be seen in the spot diagram in Figure 9 can be suppressed by introducing a wavelength filter right in front of the streak camera.

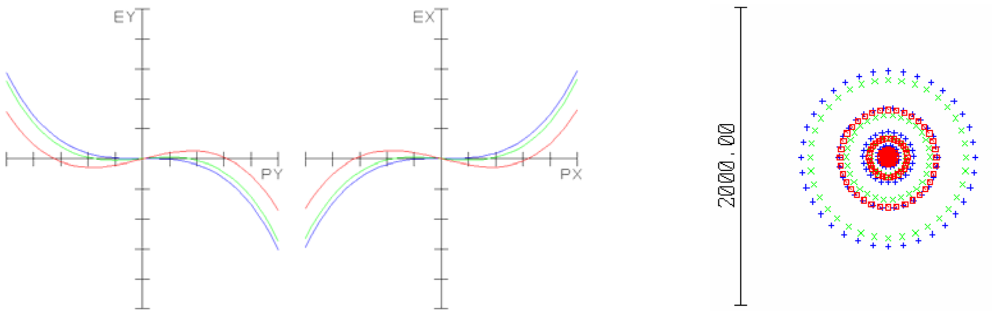

Figure 9: Ray aberrations and spot diagram of the optical line from MTV0550.

With an overall path length of 33,777.91 meters at a wavelength of 450 nm, the time required for the light to travel the distance from MTV0550 to the streak camera lab is around 113 ns. As the index of refraction of the lenses is a function of the wavelength, the total path lengths is too. The following Table 4 shows the resulting spatial and temporal differences. The results clearly indicate that for shortest possible time resolutions, wavelength filter will have to be used in order to minimize longitudinal aberrations.

Table 4: Longitudinal aberrations as a function of the light wavelength

Wavelength [nm]	**Δs [mm]**	**Δt [ps]**
450	reference	0
550	-4.48	-14.9
650	-2.85	-9.5

PRESENT STATUS AND FIRST RESULTS

The two lines that were described in the previous sections were successfully installed during the last two shut-downs in 2005/2006. First results from MTV0361 were already obtained at the end of the last year.

To ensure the flexibility of the overall system, optical "x-shaped" rails with a length of typically ~ 1m were installed in the DL, with their positions centered around the positions calculated by ZEMAX. They are hold in place by "U" shaped supports that were available from earlier installations in EPA, Figure 10.

The different height of the DL ceiling was compensated by newly manufactured tubes placed between the "U" supports and the ceiling. Final adjustment in all three dimensions is realized by different types of translations stages.

Achromatic lenses were used for both the lenses in the telescopic configurations and for an intermediate and final focusing. Lens diameters of 80 mm and 100 mm ensure capturing of most of the emitted light.

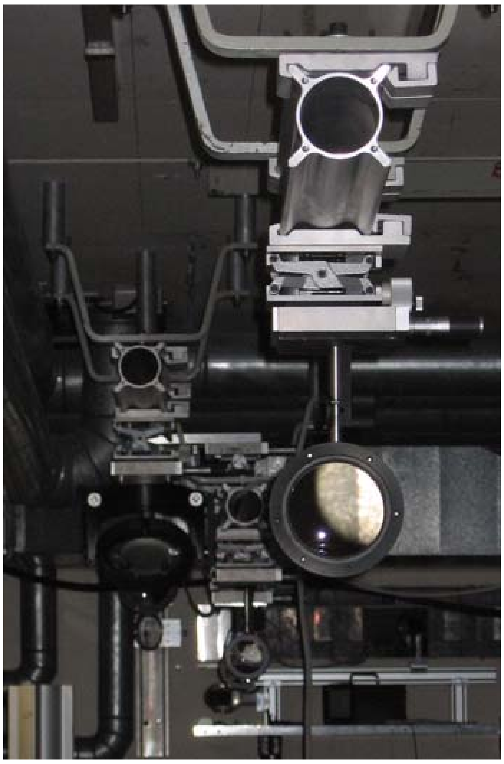

Figure 10: Photograph of part of the optical lines.

The alignment was done using a laser that simulates the light path from the optical lab to the OTR screen. An accurate initial positioning of the laser is required and it needs to be ensured that all mirrors and lenses are hit through their center. Intermediate images can be used for control and optimization purposes. The whole process needs to be done with the ambient light switched off and thus other machine access was not possible during this time.

Measurements with the streak camera shall be feasible under all operating conditions of the DL, why an additional lead shielding in between the building 2002 and 2003 needed to be installed. A metallic plate in a height of 2 meters was installed to support a wall of lead bricks with a thickness of 100 mm, guaranteeing stopping of all shower particles. In addition, a radiation detector was installed in the passage between the two zones to monitor the overall radiation level.

The chicane shown in Figure 11 consists of a several optical rails, type X48 [20], that allow a flexible positioning of all elements. In total, the setup houses three fixed mirrors and a flip mirror that is controlled manually from the streak camera lab and allows the selection of either of the two long lines. The overall weight of the structure with the installed lead shielding is around 1 ton. The mechanical stability was studied in detail [21].

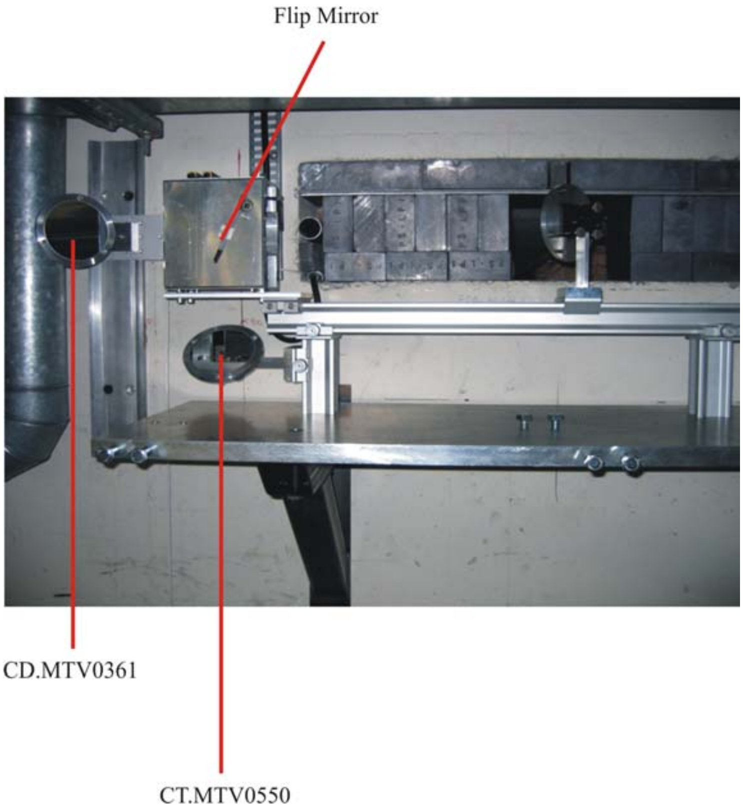

Figure 11: Photograph of the optical chicane (without lead shielding). The manually controlled flip mirror allows choosing between the light from MTV0361 and MTV0550.

Even though not foreseen to be already installed and used during the last CTF3 run 2005, the line from MTV0361 was successfully mounted and operated. The results from measurements using either magnetic or rf inflection of the bunches are shown in Figure 12.

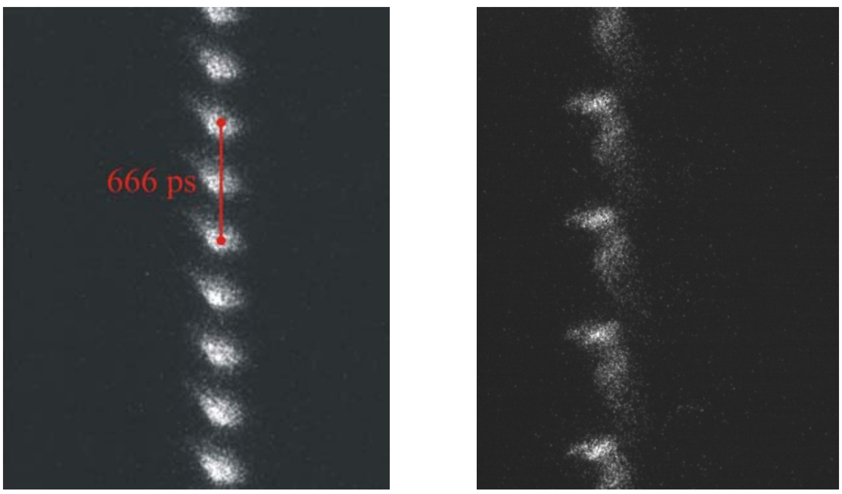

Figure 12: Measurements of the longitudinal bunch distribution with magnetic (left) and rf deflection into the DL, corresponding to 3 GHz and 1.5 GHz bunch frequency respectively.

OUTLOOK

With the newly installed long optical line from MTV0550 it will be possible to study in detail the bunch recombination after the delay loop. The streak camera provides the ideal tool for measurements on shortest time scales.

In addition to the existing diagnostics, two more lines will be added to the existing ones, allowing measurements from light coming from the bending magnets BHF0795 and BHF0750 of the combiner ring, see [22]. The even longer optical paths in these cases put high demands on the layout of the optical system in particular since part of the existing lines will have to be reused and thus a proper matching between the sections needs to be ensured..

Studies with ZEMAX are presently being done and it is foreseen to realize the new installations during 2006.

REFERENCES

[1] R.W.Assmann, et. al., “A 3 TeV e+e- Linear Collider Based on CLIC Technology”, CERN 2000–008

[2] G. Geschonke, A. Ghigo (ed.) et al.: “CTF3 Design Report”, CERN/PS 2002-008 (RF)

[3] CLIC Study Team, "Proposal for Future CLIC Studies and a New CLIC Test Facility (CTF3)", CERN/PS 99-047 (LP) and CLIC Note 402 (1999).

[4] F. Sannibale, "Driving Beam Delay Loop Design for CTF3", CTF3 Note 023 (2001)

[5] C. Biscari et al, "CTF3: Design of Driving Beam Combiner Ring", Proc. 7th European Part. Acc. Conf., Vienna, Austria (2000)

[6] M. Geitz, “Bunch Length Measurements” Proc. DIPAC 1999, Chester, UK

[7] C. Bovet et al, "The LEP Synchrotron Light Monitors", Proc. IEEE Part. Accel. Conf., San Francisco, USA, pp 1160 - 1162 (1991)

[8] A. Hofmann and F. Meot, "Optical Resolution of BeamCross-Section Measurements by means of SynchrotronRadiation", Nucl. Inst. Meth. A **203**, pp 483 - 493 (1982)

[9] https://edms.cern.ch/file/706436/1/Delay_Loop_2006.ppt

[10] C.P. Welsch et al, "High Dynamic Range Beam Profile Measurements", to be published (2006)

[11] K. Wille, "Physik der Teilchenbeschleuniger und Synchrotronstrahlungsquellen", Teubner (1996)

[12] L. Wartski et al, J. Appl. Phys. **46**, pp 3644 (1975)

[13] L. Wartski, "Etude du rayonnement de transition optique produit par des électrons d'énergie 30 à 70 MeV. Application aux diagnostics de faisceaux de particules chargées.", Thesis at the Université de Paris-Sud (1976)

[14] D.W. Rule and R.B. Fiorito, “Imaging Micron Sized Beams with OTR”, AIP Conf. Proc. **229** (1991)

[15] M. Castellano and V. A. Verzilov, “Spatial resolution in optical transition radiation beam diagnostics”, PRST-AB **1** 062801 (1998)

[16] V.A. Lebedev, “Diffraction-limited resolution of the optical transition radiation monitor”, Nucl. Instr. Meth. A **372** pp 344 (1996)

[17] X. Artru et al, "Resolution power of optical transition radiation: Theoretical considerations", Nucl. Instr. Meth. B **145** pp 160 (1998)

[18] R.B. Fiorito, D.W. Rule, "Optical Transition Radiation Beam Emittance Diagnostics", AIP Conf. Proc. **319** (1994)
[19] http://www.zemax.com
[20] http://www.newport.com
[21] https://edms.cern.ch/file/624728/1/ssr.pdf
[22] https://edms.cern.ch/file/700154/3/CR_layout.ppt