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BUNCH LENGTH MEASUREMENTS USING TRANSVERSE DEFLECTING SYSTEMS

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Abstract

Shorter and shorter bunch lengths (some 10 fs) require sophisticated bunch length measurement devices. Free electron lasers - but not only - use transverse deflecting systems. Employing suitable diagnostic tools measurements are not limited to bunch lengths but can be extended to longitudinal profiles and phase-space distributions, and slice emittances. Not only do successfully operated systems aid the commissioning and operation of FELs but they allow control over more sophisticated phase-space manipulations. The design and construction of such systems, actually operated at different RF frequencies, includes cavity design and fabrication, powerful RF systems, low level RF control, beam lines, diagnostics, and data analysis.

INTRODUCTION

Many applications for electron beams require very short bunchlengths in the order of a few 10 fs and below. These applications range from FEL and electron diffraction to experiments towards novel accelerator schemes. Often the electron bunches are created with a considerably longer pulse length and only later they are compressed to their ultimate length. During the acceleration and compression process several non-linear effects can occur. Also coherent effects excited by the short intense bunches may occur. For a well-controlled operation of such accelerators longitudinal beam diagnostics with sufficiently low time resolution is required. Streak cameras which are used for diagnosing bunch lengths in the picosecond range are limited at resolutions of approximately 100 fs [1, 2]. Other diagnostic methods have been developed like spectroscopy of coherent radiation from the beam [3, 4, 5] or electro-optic sampling of the self-field of the beam [6]. Often these measurement techniques suffer from frequency cut-off, resonances or loss of phase information. Furthermore they are limited to diagnosing the current profile only. Another possibility is longitudinal phase space tomography by energy-modulating the bunches, which suffers from an uncomplete rotation in phase-space [7].

A much more straightforward method for measuring the longitudinal phase space is by streaking the original bunches with a transverse deflecting structure [8].

LAYOUT OF TDS BEAM DIAGNOSTICS

The most basic layout of a TDS beam diagnostics system is the combination of a high frequency deflector with a viewscreen after a short drift. By injecting the beam into the deflector at the zerocrossing of the RF the electrons in receive a transverse kick depending on their relative position within the bunch. The beam size on the viewscreen is given by the square sum of the streaked and un-streaked beam size [9]:

$$\sigma_y = \sqrt{\sigma_{y0}^2 + \sigma_{ys}^2},$$

with

$$\sigma_{ys} = \omega \sigma_t \frac{eV_0}{E} \cos\varphi \sqrt{\beta_d \beta_s} \sin\Delta\psi, \quad (1)$$

with ω the angular frequency and V_0 the effective deflecting voltage of the RF and E the beam energy, β_d, β_s the beta function at the deflector and screen, respectively, and $\Delta\psi$ the betatron phase advance between deflector and screen. The RF phase φ is zero at the zerocrossing of the field. The lower limit for the resolution may be defined as the point when the streak equals the natural beam size on the screen. This condition results in the following expression for the minimum achievable resolution [10]

$$\frac{1}{\sigma_{t0}} = \omega \frac{eV_0}{E} \cos\varphi \sqrt{\beta_d / \varepsilon} \sin\Delta\psi. \quad (2)$$

It is interesting to note that the resolution does not depend on the beta function at the location of the screen.

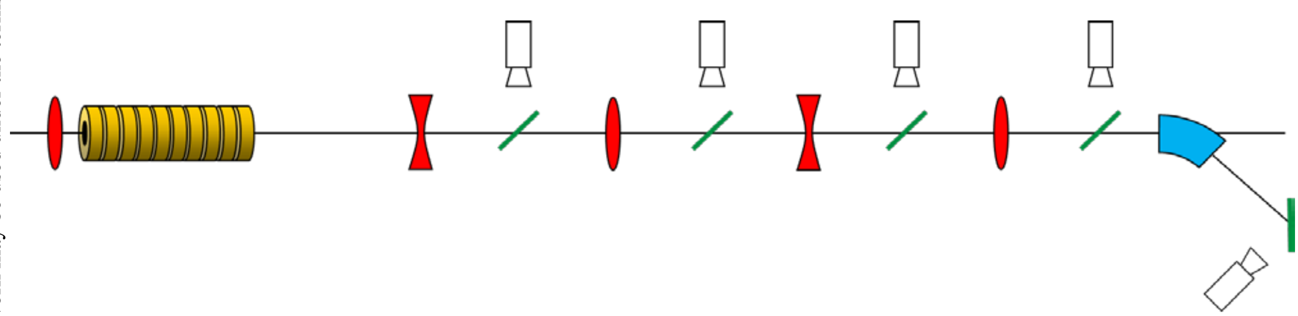

Figure 1: Typical setup of a TDS beam diagnostic system. The minimal system consists of a structure and a viewscreen. A spectrometer magnet allows to image the longitudinal phase-space. A series of screens along a FODO structure serves to measure slice emittances easily.

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The physics of the deflecting mode in first order result in the following relation between transverse kick and off-axis acceleration (Panofsky-Wenzel [11])

$$V_z(y) = kyV_0. \tag{3}$$

The above basic setup was used in the first applications of this measurement scheme [9, 12]. The full potential of a TDS system is achieved with an extended setup. For this a spectrometer dipole and an additional screen is required. This allows for direct imaging of the longitudinal phase space [13]. The above relations (2) and (3) however imply a conflict between the achievable longitudinal $\sigma_z = c\sigma_t$ and relative energy resolution $\delta_E = \sigma_E/E$

$$\delta_E \sigma_z = \varepsilon. \tag{4}$$

Figure 1 shows one further extension of the setup. Here 4 screens positioned with suitable phase advance within a FODO lattice are used to quickly measure the transverse emittance of slices of the bunch [14]. Due to the need to space the screens appropriately for the emittance measurement one has to find a compromise between this and the optimal phase advance for the TDS streak [15]. Unimpeded measurement of the slice emittance is only possible in the plane perpendicular to the deflection of the TDS. In the direction of the streak the longitudinal and transverse distribution are intermixed. One might attempt to de-convolute the two with tomographic methods. However, even when an algorithm suitable for the limited rotation data [16] is applied, the resolution of the beam size measurement will suffer [7].

In the case of the superconducting linacs FLASH and the European XFEL the evolution was advanced another step by placing the viewscreens away from the beam axis. The bunches to be measured are deflected onto the screens by fast kicker magnets [17]. That way it is possible to perform the diagnostics for selected bunches within the bunch train only.

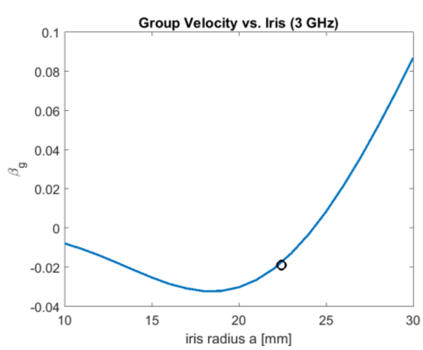

Figure 2: Group velocity of the deflecting mode versus radius of the iris at 3 GHz.

BASIC PROPERTIES OF THE DEFLECTING MODE

In the literature the deflecting mode is referred to as hybrid EM mode HEM_{11} [17]. It shows a strong resemblance of the TM_{11} mode but latter waveguide mode does not provide any deflection at a phase velocity equal *c*. In a cylindrically symmetric structure the two polarizations of the mode are degenerate and can mix. To prevent this, the symmetry of the structure is broken on purpose. Usually holes are placed into the iris walls for this.

For analysis of the deflecting mode numerical studies with CST MICROWAVE STUDIO [18] have been performed and some general scaling behaviour studied.

Figure 2 shows the group velocity as a function of iris radius for a mode frequency of 2.856 GHz and a phase shift of 120° per cell. At small iris sizes the coupling between the cells is dominantly magnetic and hence the group velocity negative. The circle indicates properties of LOLA IV [19]. The slight deviation from the curve is caused by the simplified model. The corresponding effective average deflecting field is shown in Fig. 3. At the crossover point of the group velocity the calculation diverges and becomes unreliable. Apparently the deflection becomes very strong for small apertures.

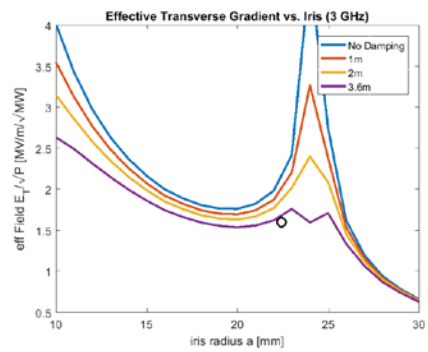

Figure 3: Effective average deflecting field.

When the iris radius is kept constant to a certain degree this counteracts the increase of field with frequency that normally would be expected (see Fig. 4). This is due to the fact that the group velocity increases at the same time. Note however that according to Eq. (2) the higher frequency is still advantageous for time resolution. But for other applications this might be interesting.

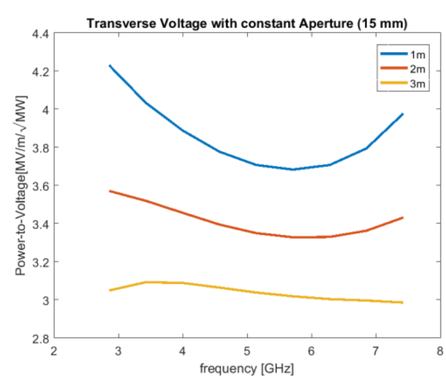

Figure 4: Deflecting field versus frequency while keeping the aperture constant.

Figure 5 shows the expected behaviour of increasing voltage when the cell is scaled as a whole. For longer structures this effect is limited by the increase of damping with frequency. Here the usual optimizations of structure length apply. For comparison the plot also shows the total voltage with the power split into two shorter structures.

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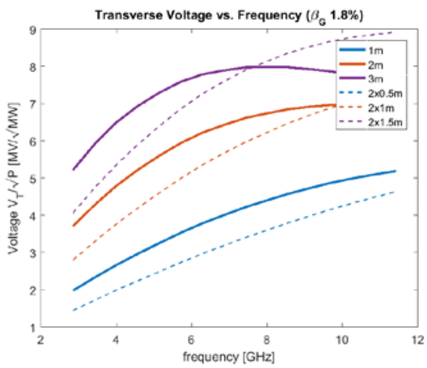

Figure 5: Deflecting field versus frequency with constant group velocity. The dashed curves are calculated for two structures with the input power split between the two.

EXAMPLE TDS SYSTEMS

Depending on the intended application there is a wide range of design parameters to choose from. Table 1 gives a summary of a few examples of transverse deflecting structures for beam diagnostics. The most important boundary conditions are of course the intended streak, the beam energy and the available space. Given the considerable cost involved with building and maintaining a high power RF station the availability of a suitable RF source plays an important role, too.

Consequently the first implementations [9, 11] relied on the structure LOLA IV that was available in storage at SLAC and klystrons from the SLAC linac. The systems allowed for time resolution in the order of 10 fs. Currently they are used in the bunch compressor of the LCLS [20] and in the first undulator beamline of FLASH [11].

At the Shanghai DUV-FEL facility a TDS was installed directly at the RF gun [21, 22]. Because of the low beam energy and availability of excess RF power from the gun klystron a shortened version of LOLA IV was the most straightforward solution.

At the SPARC facility a standing wave TDS was developed [23] to be used at beam energy of 150 MeV. The design results in a very high power to voltage ratio. For mode stabilization longitudinal rods are placed into the cells. The design was so successful that it was adopted for FERMI@Elettra [24, 25] and the SwissFEL injector test facility [26].

At the high energy end of the FERMI@Elettra facility a system of two TDS is installed [25, 27]. One of the two deflects horizontally the other vertically. The nominal input power of 15 MW is provided by one output arm of a high power klystron that can be switched between the two deflectors. The other arm of the klystron serves to power an accelerating structure [28].

For the European XFEL a deflector with an active length of 1.5 m was developed [29]. A shortened version of 0.5 m is used in the injector at 150 MeV, a single TDS is foreseen for the first bunch compressor at 700 MeV and a combination of two structures is installed in the second bunch compressor at 2.4 GeV. The latter two are connected in series to effectively form a 3 m structure. The fill-time of the structure was chosen such, that it can be filled and emptied between two consecutive bunches in 4.5 MHz operation of the FEL.

The drive linac for the FEL facility SACLA operates in C-Band. It was therefore logical to also design a C-Band TDS [30]. The change in frequency not only boosts power to voltage ration but also with the factor ω in Eq. (2) increases the speed of the streak. The overall improvement in temporal resolution over an otherwise comparable S-Band deflector is approximately a factor of 3.

Table 1: Specifications of Selected TDS Structures

	LOLA IV	Shanghai DUV-FEL IHEP	SPARC FERMI SwissFEL	FERMI	European XFEL INR	RAIDEN SACLA SwissFEL	LCLS	PolariX
Active length [m]	3.64	0.35	0.25	2.466	2×1.5	2×1.7	2×1	1
Frequency [GHz]	2.856	2.856	2.998	2.998	2.998	5.712	11.424	11.995
Fill-Time [ns]	645	62	800	500	2×333	2×269	2×106	130
Group Velocity/c	-0.0189	-0.0189	SW	-0.0157	-0.0152	-0.0214	-0.0315	-0.0266
Iris Diameter [mm]	44.88	44.88	36	25	43.4	12×20	10	8
typ. Vltg, Pwr [MV, MW]	26, 20	0.56, 1	4.9, 5	23, 15	25.9, 20	60, 40	85, 160	12.8, 6
Pwr-to-Vltg [MV/m/√MW]	1.6	1.6	8.8	2.4	1.9	4	5.46	6.12
Beam Energy [MeV]	1100	5	150	1200	1500	1450	15000	1100

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Another noteworthy design feature is the phase advance per cell of 5π/6 in contrast to 2π/3 used elsewhere. This reduces the number of irises per length and hence the manufacturing cost [31]. The iris has a racetrack shape for mode stabilization. To highlight this, the inventors dubbed the structure RAIDEN.

At the SwissFEL it was decided to obtain structures of this kind at their first undulator (Aramis) [32]. Two commercially available structures were installed and are routinely operated at 80 MV deflecting voltage [33].

The availability of equipment and yearlong experience in X-Band enabled SLAC to develop and install an X-Band TDS for LCLS [34]. The large deflecting voltage and high frequency allow for time resolution of a few femtoseconds at the full beam energy of 15 GeV [35]. The structure is located behind the undulator and allows to indirectly measure the length of the X-ray pulse [36].

NEW DEVELOPMENTS

As mentioned above slice emittance measurements are only possible perpendicular to the streaking direction. Therefore it is desirable that the streaking direction may be changed. This is of course possible with a second deflector but a deflector with adjustable polarization would be superior.

A design has been proposed at CERN for X-Band TDS with variable polarization. A collaboration has been formed between CERN, PSI and DESY to design, build and test such structures [38]. The input coupler with two arms is built such that the phase relation between the two arms determines the orientation of the mode that is fed into the structure. The structure itself is strictly axially symmetric to avoid any cause for deterioration of the mode polarization. There is no cell tuning or RF pickup. Meanwhile the design is well advanced and the prototype underway [39]. High power RF tests are foreseen for early 2019 and first beam tests in the following summer. Referring to the main features of the structure it is called PolariX.

At INR an RF deflector has been proposed [40] with a field configuration that more closely resembles a TE_{11} mode. It promises better RF efficiency than the conventional structures and the design was optimized to reduce higher order aberrations of the field. This will be advantageous for high precision measurements or in cases where the TDS is used for beam manipulations. A prototype has been built and soon will be tested with beam in the REGAE facility [41] at DESY.

RF CONTROL

The streak applied in the most powerful TDS systems is so fast that the requirements for RF phase stability are governed by limits to beam position jitter. These limits are either given by the size of the beam image on the screen or even by particle loss. In the case of LCLS the limit was derived to be smaller than 0.1° at X-Band [35]. This corresponds to 20 fs and is 10 times the resolution of the measurement. For the PolariX TDS in FLASH the requirement for phase stability was determined to be 0.25°. This corresponds to a temperature stability of 35 mK in the structure and 10 mK in the pulse compressor.

RF feedback loops acting from pulse to pulse can relax the temperature requirements assuming that temperature changes develop over the time span of several RF pulses. Given the short duration of the RF pulses a fast feedback within the pulse is often next to impossible. This means that fast jitters are often passed on undamped.

The biggest source for fast phase jitter is the klystron modulator. For a 6 MW X-Band klystron as it is used at FLASH the translation is 3 fs phase jitter per 10 ppm voltage jitter. This stability can indeed be achieved with the most modern semiconductor switched modulators. The voltage stability of more conventional modulators however lies in the range of several 100 ppm, which can pose a limit to the maximum available streak [37].

APPLICATIONS

The first and most obvious application of TDS was for pure bunch length and longitudinal bunch profile measurements [9, 11]. A whole new domain is the extension to measuring the longitudinal phase space. This allows for example to adjust RF phases and bunch compression in real-time [13]. Measurements of the slice emittance and matching [14, 42] offer a much better handle on adjusting the beam optics than measuring the pure projected emittance ever could. For the commissioning and operation of two color [43] or seeding schemes [44] TDS are practically indispensable.

Moving the TDS behind the undulator opened up more diagnostics possibilities and enables continuous monitoring [35]. This way it is possible to not only measure the longitudinal profile of the electron bunch but indirectly also the length of the X-ray pulse [36]. This is very useful when the beam is manipulated to achieve X-ray pulses even shorter than the electron bunches [45].

CONCLUSION

Transverse deflecting structures provide very powerful means for time resolved beam diagnostics in the femtosecond range. Their full potential is still being explored and expanded. The only limit to their widespread application seems to be the cost involved for building and maintaining such systems.

The overview presented here is by nature subjective and limited. By no means are topics or devices not mentioned here considered unimportant.

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