Simulation of fs bunch length determination with the 3-phase method and THz dielectric-loaded waveguides

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1. Introduction

* The measurement of electron bunch lengths below 100 fs rms, required in many applications (free electron laser, ultrafast imaging, etc.), is very challenging and involves technically complicated devices and methods like the transverse deflecting cavities and the electro-optical sampling.

* The 3-phase method is a conceptually simple indirect diagnostics which allows determining the bunch length through the measurement of the variation of the energy spread with the injection phase in an accelerating structure (linac) [1].

* The purpose of our study is first to demonstrate the impossibility to use conventional RF accelerating structures to obtain a fs resolution with the 3-phase method, and then to provide a first evaluation of the achievable resolution when using THz-driven dielectric-loaded waveguides as accelerating structure.

2. 3-phase method and assumptions of the study

* The 3-phase method consists in the inversion, with a least-square algorithm, of the following equation (travelling wave) [1]:

$$\sigma_f^2 = \frac{4\sigma_t^2 \sigma_E^2}{\sin^2 \phi} + \frac{4\sigma_t^2 \sigma_E^2}{\sin^2 \phi} + \sigma_t^2 + \sigma_E^2$$

$$f$$ and $$E$$ = accelerating field frequency and amplitude; $$L$$ = accelerating structure length, $$\phi$$ = bunch injection phase; $$e$$ = elementary charge, $$\sigma_t$$ and $$\sigma_E$$ = rms bunch length, chirp and energy spread at the accelerating structure entrance. At least 3 measurements of $$\sigma_E$$ (rms energy spread at the accelerating structure exit) for 3 different $$\phi$$ are required.

* We assume in our study a resolution of $$10^{-4}$$ for the spectrometer measuring the energy spread (10 keV at 100 MeV).

3. Conventional RF accelerating structures VS THz dielectric-loaded waveguides at the fs level

* A conventional 3 GHz accelerating structure cannot be used for fs bunch length determination with the 3-phase method. For long structures, the energy spread pattern as a function of the injection phase is completely dominated by the space-charge forces which leads to unphysical results (imaginary value of $$\sigma_t$$). For short structures, the impact of space-charge forces is greatly reduced but the maximum energy spread variation with the injection phase becomes well below the spectrometer resolution and is therefore non-measurable experimentally, simply preventing to apply at all the 3-phase method.

* The use of short (a few cm long) dielectric-loaded waveguides driven by high frequencies (> 100 GHz) and amplitudes (> 100 MV/m) accelerating fields [3] would allow overcoming these two limitations and reach the fs level with the 3-phase method.

4. Influence of field amplitude

* Relatively low field amplitudes in THz dielectric-loaded waveguides (50 MV/m at 300 GHz) will induce sufficiently high energy spread variations to allow resolving more than 3 points and obtaining a good bunch length reconstruction with the 3-phase method (< 0.5% discrepancy).

5. Influence of drift space

* The spectrometer can be placed at a realistic distance from the dielectric-loaded waveguide exit with only a small degradation of the 3-phase method accuracy due to space-charge forces (4.3% discrepancy with the expected value for $$D = 2 \text{ m}$$).

6. Influence of bunch charge

* The accuracy of the 3-phase method with dielectric-loaded waveguides is rapidly deteriorated by the space-charge forces when the bunch charge increases (discrepancy with the expected value becomes higher than 20% above 10 pC charge).

7. Conclusions & Prospects

* Our simulations show that the two limitations to the 3-phase method to reach fs resolution with conventional RF accelerating structures (space-charge forces and too small variations of the bunch energy spread with the injection phase) could be overcome by using dielectric-loaded waveguides driven by THz pulses thanks to their shorter length, higher frequency and field amplitude. An ultimate resolution better than 5% (300 as) for the determination of a 6.25 fs rms bunch length at 100 MeV and 1 pC charge has been simulated.

* This ultimate resolution can be degraded by several effects which have to be carefully studied in future simulations and experiments: Uncertainty on and jitter of the field amplitude and injection phase into the linac; Perturbation of the energy spread measurement due to coherent synchrotron radiation in the spectrometer; Increase of the effect of space-charge forces due to transverse focusing of the bunch between the linac exit and the spectrometer.

*References: