NOVEL SCHEMES FOR THE NARROW BAND SPARC THZ SOURCE USING A COMB LIKE E-BEAM

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Abstract

The development of radiation sources in the THz spectral region has become more and more interesting because of the peculiar characteristics of this radiation: it is non ionizing, it penetrates dielectrics, it is highly absorbed by polar liquids, highly reflected by metals and reveals specific "fingerprint" absorption spectra arising from fundamentals physical processes.

The THz source at SPARC is an accelerator based source for research investigations (e.g. material science, biology fields).

By means of e-beam manipulation technique, a longitudinal modulated beam, the so-called comb beam, can be produced at SPARC. In terms of THz sources, such e-beam distribution allows to produce high intensitiy narrow band THz radiation, whose spectrum strongly depends on the charge distribution inside the e-beam.

In this paper different linac schemes are compared. In particular, spectra obtained using the comb beam compression through velocity bunching including a IV harmonic RF section is showed.

COMB COMPRESSION AT SPARC

The goal of the THz experiment at SPARC is the realization and characterization of a THz source collecting Coherent Transition Radiation. Electron bunches accelerated and compressed in the SPARC linac [1] are bended by a dipole on the second beamline (Fig. 1 A). The radiation is generated by making the bunches hit a metallic target (350 μm Silicon Dioxide wafer covered by 80 nm Aluminum layer). The reflected Transition Radiation generated at the target is collected and characterized.

Depending on the longitudinal distribution of electrons inside the bunch, coherence in the emission of radiation can be obtained at different wavelengths.

Two main schemes to transport the beam are under optimization: single bunch and laser comb.

The classical longitudinal charge distribution inside an electron bunch is gaussian. Ignoring charge density instabilities inside the electron bunch, in order to obtain coherent radiation at the frequency of 1 THz (~ 0.3 mm) a bunch length smaller than 1 ps is requested.

Through the velocity bunching technique [2] is possible to compress the bunch while it is traveling in the RF accelerating structure. In this way, sub-ps bunch length can be reached.

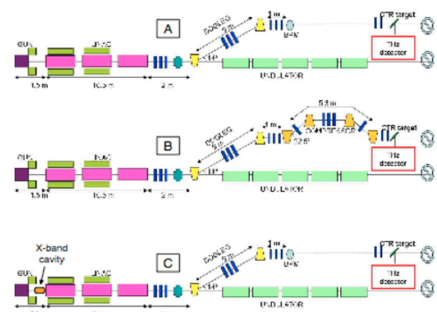

Figure 1: *A)* present layout of the SPARC accelerator; *B)* layout of SPARC with the addition of a magnetic compressor; *C)* layout of SPARC with the addition of an X-band cavity after the gun .

The radiation produced in such a way is broadband and in the range 0.15 - 5 THz. A peak power with an order of magnitude of 10^8 W has already been observed in this regime [3].

If the Laser Comb technique is used, a laser pulse with a sawtooth shape illuminates the cathode. The technique used for the generation of this laser shape relies on a birefringent crystal, where the input pulse is decomposed in two orthogonally polarized pulses with a time separation proportional to the crystal length. Different crystal thickness are available (10.353 mm in the SPARC case). Putting two crystals, is possible to generate a 4 pulses comb (since each one of the two sub-pulses going out the first crystal is split in two pulses in the second one) [4].

The electron bunch produced via photo-emission maintains the shape of the laser until the space charge force mixes the longitudinal micro-bunches providing the tuning of density modulation into energy modulation. The previous electron distribution can be recovered by the compression of the bunch inside a dispersive system (magnetic compressor or RF cavity) [5]. When a comb electron structure impinges the metallic target, an almost monochromatic pulse of radiation at the wavelength of the spacing between the micro-pulses is produced [6]. The Form Factors correspondent to such kind of electrons distributions show indeed peaks at the repetition frequency of the comb structure and its higher harmonics. The amplitude of the peaks depends on the length of each sub-bunch and its bandwidth becomes smaller increasing the number of sub-bunches.

The production of a train of bunches with time separation less than 1 ps suitable for producing THz radiation is challenging. Most of techniques developed and tested have severe limitation [7] [8]. In particular is difficult to obtain a very well defined and periodic comb structure with high charge electron bunches. In this scientific environment, the SPARC experiment is the only one that applies RF-compression to the electron beam produced by the comb shaped laser. The main limitation of this scheme is in the non-linearities arising from the RF-compression.

The same limitation is present even considering the insertion of a magnetic compressor after the dogleg (see Fig. 1B) [9] [10].

In this paper a possible improvement of the SPARC layout including an X-band structure placed at the exit of the gun is considered (Fig. 1C). The results of the optimized transport for a 2 and 4 bunches comb train with the three layouts in Fig.1 are compared.

Fourth Harmonic Cavity: Principle of Operation

The use of a higher harmonic cavity in order to linearize the longitudinal phase space is based on the following simple analytical considerations: due to the sinusoidal nature of RF voltage

$$V = V_0 sin(\phi_0) + \Delta\phi V_0 cos(\phi_0) - \frac{1}{2}\Delta\phi^2 V_0 sin(\phi_0) + ...$$

the second order term in V can be cancelled by using a cavity with frequency $h \cdot f_{rf}$ so that:

$$V_h = V_h sin(\phi_h) + h\Delta\phi V_h cos(\phi_h) - \frac{1}{2}(h\Delta\phi)^2 V_h sin(\phi_h) + ...$$

where φ_h is a decelerating phase.

The hypothesis of the insertion of an X-band structure immediately after the gun in the SPARC linac has already been investigate in the past for the single bunch compression; for this reason, a compact standing wave accelerating structure operating at a frequency f =11.424 GHz, with 5 MeV energy gain, has already been designed [11], [12], [13]. Moreover in ref. [14] the optimization of the RF-compression for the SPARC nominal bunch has been handled. In the following the same setup considered in this reference has been applied in order to optimize the compression of the 4 pulses comb.

Bunches Train Optimization

The compression of a bunches train is much more complicate than for the single bunch. In order to obtain a clear modulation in the form factor, the longitudinal charge profiles of the sub-bunches have to be as much similar as possible one to each other. In addition to that, their length has to be much shorter than 1 ps and their relative distance has to be properly matched to the desired emission frequency. Figure 2 show the comb compression respectively by RF-wave and magnetic chicane of a 2 bunches comb with a total charge of 180 pC, a rms length at the cathode of 100 fs and relative distance of 4.27 ps.

The amplitude and the central frequency of the peaks can be varied changing the compression parameters. On top of the picture different RF-compression settings, using the layout A in Fig.1, are compared.

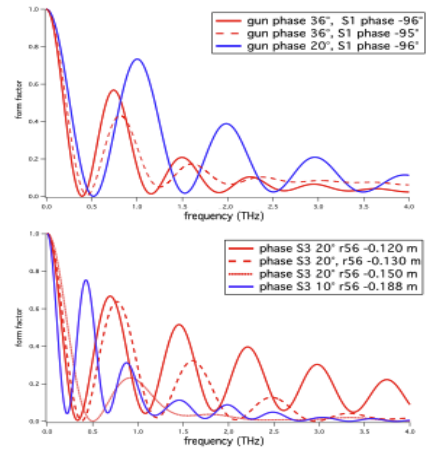

Figure 2: Form Factors correspondent to the 2 pulses comb distribution at the THz station.

The distance between the two pulses can be varied both slightly changing the gun RF phase and the phase of the compressing accelerating section (named S1 in the legend, 0° is the on crest phase). Since the length of the pulses changes, the curves have different amplitudes too. On bottom of Fig. 2 different magnetic compression settings are compared.

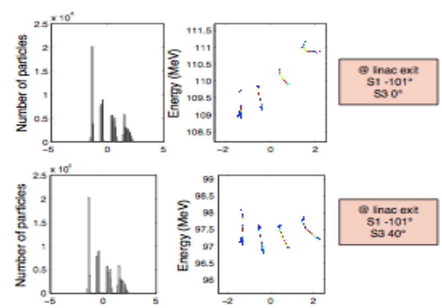

Figure 3: Longitudinal charge profile and phase space of the 4 pulses comb with 360 pC total charge. The bunch has been deeply over-compressed using S1 section. On top: comb at the exit of the linac if it travels on crest in the second and third accelerating sections. On bottom: comb at the exit of the linac if the S3's phase is used to compensate the energy difference between the four bunches.

These simulations were made using the layout in Fig. 1B. The distance between the two pulses can be varied changing the phase of the third accelerating section S3, responsible for the energy chirp of the bunches, and the R_{56} of the magnetic chicane. Also in this case, the length of each sub-pulse varies together with their distance producing a change in the amplitude of the Form Factor's modulation.

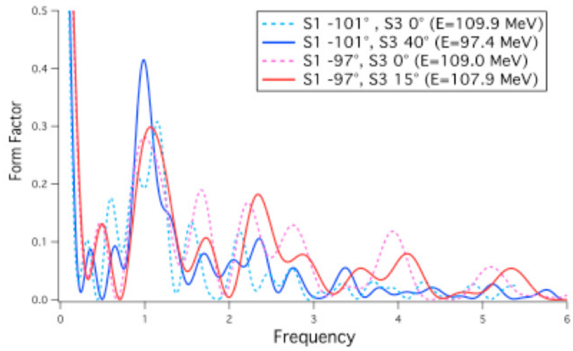

Figure 4: Form Factors at the THz station correspondent to different RF-compressor phase (S1 in the legend) and third accelerating section phase (S3 in the legend).

Working with a 4-pulses comb the non-linearities of the compression are critical. Figure 3 show the longitudinal phase space at the end of the linac for a compression phase of −101°(deeply over-compressed bunch, i.e. all the sub-bunces are de-bunching at the exit of the linac). The curvature in the longitudinal phase space is responsible for the non perfect periodicity of the train longitudinal charge distribution at the exit of the linac (top of Fig. 3). The energy spread between the bunches can be compensate moving off crest the third accelerating section of the linac (bottom of Fig. 3) but both the projection of the single sub-bunches and their relative distances remain different. This produce an increment of noise in the form factor modulation (see Fig. 4).

When the X-band structure is included in the layout the non-linearities coming from the RF compression are removed (see Figure 5), thus all the sub-bunches have almost the same length and equal relative distance.

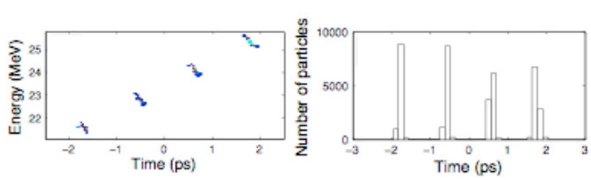

Figure 5: Longitudinal phase space and charge profile at the exit of the linac if the fourth harmonic cavity is switched on.

The correspondent form factor at the linac exit show a very regular modulation (see Figure 6A), including narrow band peaks also for the higher harmonics. If the comb is properly matched, its longitudinal shape is not much degraded by the transport along the dogleg till the THz station.

CONCLUSIONS

Very promising simulations have shown the possibility of performing linear RF-compression of high charge comb beams by using a fourth harmonic RF cavity at SPARC.

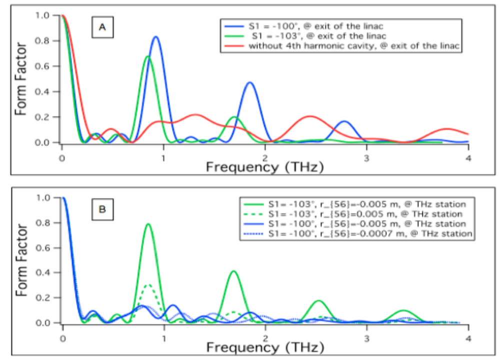

Figure 6: Form Factors of the 4 sub-pulses comb for different over-compression phases and correction of non-linearities by the fourth harmonic cavity. A: Form Factors at the exit of the linac compared with the one obtained without the 4th harmonic cavity for S1= -97° (this case has been chosen since it presents the highest peak of modulation at the exit of the linac); B: Form Factors at the THz station for different R_{56} values on the dogleg with fourth harmonic cavity switched on.

In particular the transport of a 4 bunches train with 360 pC total charge showed an amplitude of the peaks for the form factor modulation 4 times greater than the case without the correction of non-linearities. Moreover the band of the peaks is reduced and higher order harmonics are visible.

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