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ARC COMPRESSOR TEST IN A SYNCHROTRON - THE ACTIS PROJECT

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Abstract

ACTIS (Arc Compressor Test In a Synchrotron) is an experiment aimed to demonstrate the reliability of arc compressors as lattices capable to increase peak current and brightness of an electron beam as it is bent at large angles. This kind of devices has been proposed at theoretical level in several works over the past decades and could be the key to achieve compact and sustainable Free Electron Lasers in the near future. The experiment has been developed since 2019 in the joint effort between INFN, Solaris National Synchrotron Radiation Center and Elettra - S.T. S.C.p.A. The experiment will take place at Solaris (Krakow). Solaris is a synchrotron whose ring is injected by a 550 MeV linac that will be used to prepare the beam with a proper chirp. ACTIS involves also the commissioning of two beam length detectors to be installed downstream of the linac and of the first ring lap. In addition, the low energy model of the machine was built to identify the optimal working point for the experiment and to foresee the longitudinal profile of the beam that will be measured. In this work we present the experiment and report first results obtained in the study phase.

INTRODUCTION

Studies on the beam dynamics of arc compressors (AC) have been performed in the last two decades mainly in the context of designs of Free Electron Lasers (FELs) based on energy-recovery linacs (ERLs) [1–4] and, more recently, on a Two-Pass Two-Way linac (TPTW) [5–8].

The lattice of these arc compressors is based on a serie of achromatic cells, typically Double Bend Achromats (DBAs) or Triple Bend Achromats (TBAs), where optical functions have to be precisely tuned. The use of arcs as compressors allows to correct chromatic aberrations, cell by cell considering Coherent Synchrotron Radiation (CSR) emission betatron kicks arising in the bending magnets [9, 10]. A review article published in 2015 [11] contains very important studies in the frame of this activity. In these studies it is shown the use of arcs to perform a longitudinal compression of the bunches (up to a compression factor of 30) in the 0.2-7 GeV energy range keeping the growth of the normalized emittance under 0.1 mm-mrad, considering bunches with total charge up to 150 pC.

A new type of arc compressor was presented in 2019 in the context of the Conceptual Design Report (CDR) of the MariX FEL [12, 13] co-funded by the INFN and University of Milan. The CDR of this innovative machine presents a bubble shaped arc compressor (BAC) used to increase the beam peak current, up to 100 multiplication factor, while the beam is u-turned and re-injected in the cryogenic booster operated in continuous wave in the way to double the energy gain from the same booster. The scheme based on the double acceleration stage in the booster plus the compression and u-turn stage in the BAC is the so called two-pass two-way (TPTW) scheme.

Up to now, the possibility of compressing bunches into magnetic arcs has been predicted only theoretically also because of costs of a dedicated machine, therefore no demonstrators were built.

ACTIS would be the first experimental proof of the proper functioning of these promising devices. In addition, the results obtained would be the cornerstone for the realization of future highly sustainable machines based on the TPTW scheme, such as BriXSinO [14–16].

THE EXPERIMENT

The ACTIS experiment can count on the support of four different institutions interested in the project:

The **INFN - Milan** that is the proposing institution and is strongly interested in the demonstration of the principle behind the TPTW scheme developed in recent years.

The **Solaris National Synchrotron Radiation Centre** that hosts the experiment, provides the machine, local expertise and experience in synchrotron radiation detection.

The **Elettra - Sincrotrone Trieste S.C.p.a.** that has great experience in arc compressor beam dynamics and synchrotron machines. It is interested in experimental demonstration of the operation of these devices as a natural continuation of theoretical studies done previously.

The **INFN - Frascati Lab.** that offer a collaboration with SPARC_LAB dedicated to the detection of THz and sub-THz coherent radiation produced in bending magnets by compressed bunches.

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The Solaris synchrotron, at the National Synchrotron Radiation Centre in Kraków, Poland, is an ideal machine to carry out this test [17]. Here a ring composed by 12 DBAs is injected by a long electron linac at 550 MeV, many synchrotrons are injected at low energy and accelerate bunches purely in the storage ring (energy ramp-up). The linac will be used to generate a linear chirp in the beam (i.e., introduce longitudinal energy correlation) and then inject it into the ring. The buches will then be compressed into the DBAs by exploiting their R_{56} factor during one revolution of the same ring, each DBA will introduce a change of the rms length (σ_s) equal to $\Delta\sigma_s = \sigma_{\delta_E} R_{56}$, where σ_{δ_E} is the bunch rms energy spread.

One of the key points to the success of the experiment is to be able to measure the length of electron bunches before and after the compression in the storage ring. Beam length measurements will be performed with two separate detectors that have been studied in the context of this experiment, one at the end of the linac and a second one after the the 12th DBA.

Another main point is to build a reliable beam dynamics simulation of the machine. To build this model of the machine and align it with the beam parameters being measured, we decided to exploit an AI-based tool that we develop in Milan. The tool is called GIOTTO [18] and is an optimizer based on a Genetic Algorithm capable of driving beam dynamics simulation codes that consider space charge non linear effects.

Intensive development of several new features in GIOTTO has been done, which has allowed us to constitute the first model of the Solaris low-energy line.

BUNCH LENGTH DETECTORS

The compression capability of DBAs will be verified by measuring the length of the electron bunches just before they are injected into the ring and after they have traveled a complete turn of its lattice.

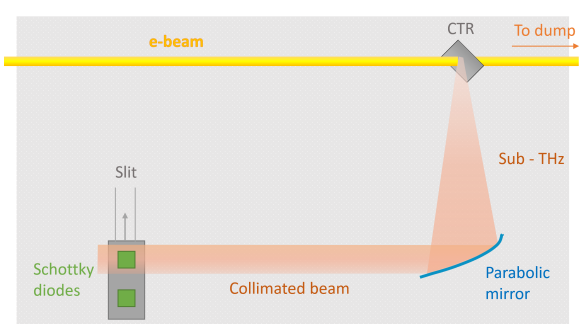

Figure 1: Sub-THz detector to be installed in at linac end.

The rms length of electron bunches is estimated to be on the order of tens of ps before the compression and down to below one ps at maximum compression. For this reason, it was necessary to devise two detectors of different nature to be installed on two separate breadboards at two different points in the machine. The first detector setup, to be mounted at the end of the LINAC, will consist of two Schottky diodes working in the (sub-)THz region, as shown in Fig. 1. The second detector setup shown in Fig. 2 will be used to measure the compressed bunch length in the ring and it will follow the same operational principles of the one considered for the bunch length measurement in the linac. However, it

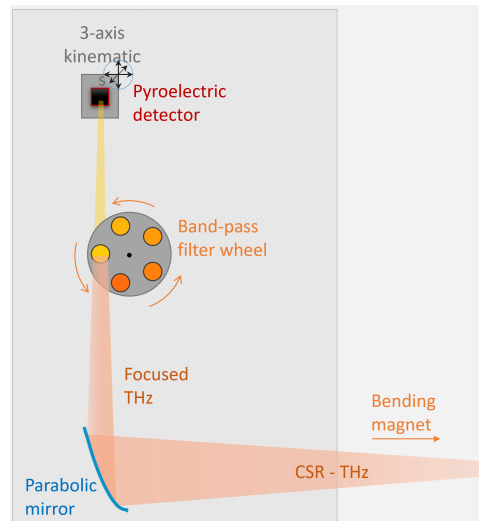

Figure 2: THz class detector to be installed in the ring.

will exploit a different detector, i.e. a pyroelectric detector, sensitive from 0.1 to 30 THz. In both setups the detectors will be coupled to band-pass filters in order to increase the resolution of the measurement by a narrow selection of the spectral powers. For the first setup, wave-guide band-pass filters will be adopted, while for the second wire-grid filters. The idea for the measurement of the bunch length is based on the power balance of coherent radiation (Coherent Transition Radiation, CTR, for the linac and Coherent Synchrotron Radiation for the ring) collected by the detectors in different ranges of frequency, which is uniquely related to the bunch length if the temporal profile is known/assumed. For gaussian bunches the method has been demonstrated in Refs. [19, 20].

SIMULATIONS

The lattice of the machine can conceptually be divided into two main blocks and simulated with different codes. The first block is an area characterized by the need to take space-charge effects into account so as to adequately reconstruct realistic beam dynamics. This portion of the line includes a radio frequency thermionic gun (Fig. 3 shows the bunches at gun exit), a solenoid for transverse beam control, a chopper section (electrostatic stripline) that manipulates the temporal structure of the beam in macro-bunches (triplets of bunches) of 200 pC at a frequency of 100 MHz [21]. Immediately after the chopper there is a second solenoid and an energy filter (a DBA with a scraper in the center) to longitudinally compress the bunches and filter the tail particles. Downstream of the filter there is a booster (about 40 m long) made up of 6 S-band cavities (2998.5 MHz, 5.2 m long)

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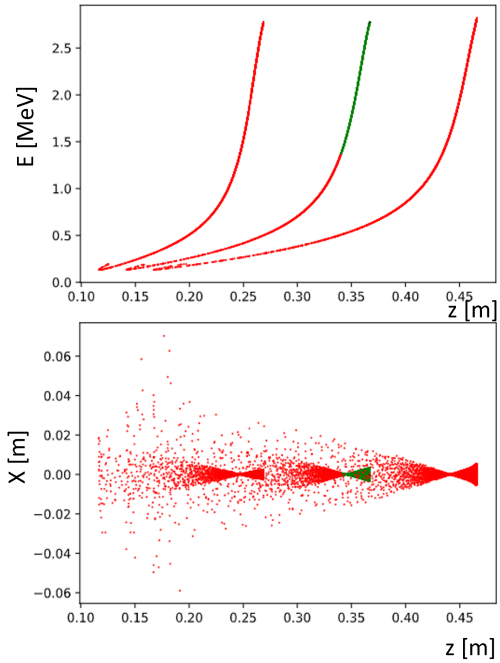

Figure 3: Three bunches at gun exit, green portion have been selected for further single-bunch simulations downstream.

which accelerates the beam from 2 MeV to over than 500 MeV.

From the gun to this point we simulate the effects of space charge (with particular attention to the area before the booster) using a full-3D particle-in-cell code: ASTRA [22].

The second block of the machine is simulated using `Elegant` (ELEctron Generation ANd Tracking) [23], a code suitable for the simulation of dispersive lines taking into consideration possible CSR emission effects thanks to a fast 1-D model [24]. This second part of the machine is composed of a linear section, the vertical dog-leg transport line that carries the beam 1.4 m higher respect the linac level and a circular lattice made up of 12 identical DBAs (each 4.5 m long and 3.5 m spaced) assembled in concrete blocks. Each DBA consists of two bending magnets flanked with strong focusing quadrupoles and sextupoles.

Simulating a machine model in the presence of space-charge is notoriously a challenging problem. Under these conditions the beam dynamics is greatly complicated because of the way the Coulomb repulsion between particles correlates strongly and nonlinearly the effects of the various machine elements. The use of AI-based optimizers such as GIOTTO turns out to be a very suitable choice under these conditions. GIOTTO is natively capable of driving ASTRA in multiobjective genetic optimizations and has been employed in numerous tasks such as design of matching-capture line from scratch in plasma acceleration-based FELs and injectors design [5, 25–27].

The capabilities of GIOTTO were greatly improved during this activity to reconstruct beam dynamics from data measured on the machine. In particular, it was necessary to add the ability to perform optimizations on multi-position beam parameters at measurement stations to simultaneously target all measured parameters.

We also developed an ad hoc post-processor to allow rotated bunch-frames handling and evaluation of dispersion parameters from the particle distributions (key features when optimizing the energy filter). This post-processor, called RotnSlice actually allows the capabilities of ASTRA to be extended by providing very useful support in the case of rotated reference frames as shown in Fig. 4.

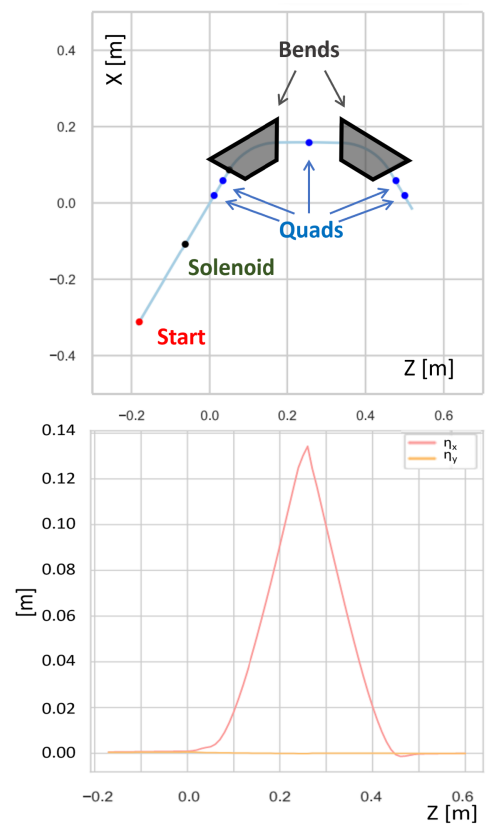

Figure 4: **Top:** aerial view of the energy filter. **Bottom:** dispersion function optimized with GIOTTO and ASTRA.

CONCLUSION

ACTIS aims to demonstrate the feasibility of arc compressors and to be a milestone in the study for new acceleration schemes such as TPTW double acceleration. Two equipment to measure the length of electron bunches have been designed taking into account different radiation types emitted before and after the bunch compression. The devices will be assembled in next months at INFN's Frascati National Laboratories (LNF). The low-energy simulation model of the Solaris machine was built taking advantage of newly developed features of an AI-based beam dynamics optimizer (GIOTTO) coupled with ASTRA.

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