

# SUB-fs ELECTRON BUNCH GENERATION USING MAGNETIC COMPRESSOR AT SINBAD

J. Zhu<sup>#1,2</sup>, R. Assmann<sup>1</sup>, U. Dorda<sup>1</sup>, J. Grebenyuk<sup>1</sup>, B. Marchetti<sup>1</sup>  
<sup>1</sup> DESY, Hamburg, Germany  
<sup>2</sup> University of Hamburg, Hamburg, Germany

## Abstract

In order to achieve high quality electron beams by laser-driven plasma acceleration with external injection, sub-fs bunches with a few fs arrival-time jitter are required. SINBAD (Short Innovative Bunches and Accelerators at DESY) is a proposed dedicated accelerator research and development facility at DESY. One of the baseline experiment at SINBAD is ARES (Accelerator Research Experiment at SINBAD), which will provide ultra-short electron bunches of 100 MeV to one or two connected beam lines. We present start-to-end simulation studies of sub-fs bunch generation at ARES using a magnetic compressor with a slit. In addition, the design of a dogleg with tunable  $R_{56}$  for the second beamline is also presented.

## INTRODUCTION

Plasma-Wakefield Accelerators (PWFA) can produce acceleration gradients up to 100 GV/m [1], which makes them promising candidates for compact accelerators and novel light sources. SINBAD (Short and INnovative Bunches and Accelerators at DESY) is a proposed dedicated research facility where Laser-driven Plasma Wakefield Acceleration (LWFA) with external injection will be explored by using ultra-short electron bunches generated at ARES (Accelerator Research Experiment at SINBAD) [2]. External injection allows precise manipulation of phase-spaces of electron bunches and thereby provides possibilities to optimise the subsequent acceleration and transport inside the plasma.

ARES will consist of a compact photo-injector providing ultra-short electron bunches to one of the two connected beamlines [3]. The ~5-MeV electron bunches generated by the 1-1/2 cell S-band photocathode RF-gun are accelerated by two S-band travelling-wave RF-structures (TWS) to around 100 MeV. A third S-band TWS is foreseen in the future to boost electron bunches to higher energy, which will reduce the impact of the space-charge effects on bunch compression and final focus before the plasma cell. Downstream of the photo-injector the beamline includes quadrupole magnets and a magnetic chicane bunch compressor (BC) with a slit located in the middle of it. Ultra-short bunches at ARES can be produced by both velocity bunching and magnetic compression. In order to deliver ultra-short bunches to the second beamline, a dogleg section is also foreseen.

## MAGNETIC CHICANE WITH A SLIT

Since it is difficult to directly compress the pulse duration of an electron bunch generated at a photo-injector to sub-fs in one compression stage even with a high-harmonic cavity, the slit method is employed in our design, as shown in Fig. 1 [4]. The coherence synchrotron radiation (CSR) at the chicane can be reduced by using a weak chicane and a large initial correlated energy spread. Because the slit only allows the central slice of the whole bunch to pass, the energy spread of the compressed bunch remains small enough. Likewise, the emittance of the final bunch will not be affected by the chromatic aberration from quadrupoles upstream of the chicane. More importantly, the bunch arrival-time jitter downstream of the chicane will be reduced if the chicane is weak [5], which is vitally important for plasma acceleration with external injection [6]. On the other hand, the  $R_{56}$  should be large enough in order to compress the bunch with a reasonable chirp. As a result,  $R_{56} = -10$  mm was chosen in the current design.

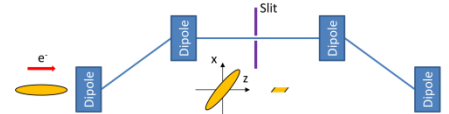


Figure 1: Schematic of the magnetic chicane with a slit.

## Start-to-end Simulation

The start-to-end (S2E) simulation of the beam dynamics at ARES were performed with ASTRA [7] and IMPACT-T [8]. The electron bunch was first transported to the end of the linac by using ASTRA with 2D cylindrical-symmetric space-charge effects, and then the rest part was simulated by using IMPACT-T with 3D space-charge effects and 1D CSR effect. The photocathode laser is assumed to follow a Gaussian longitudinal distribution with rms duration of 3 ps, and a uniform transverse laser intensity distribution was taken at the photocathode. The two TWSs are operated at the same gradient and phase in order to minimize the bunch arrival-time jitter [5]. The chirp of the bunch at the linac exit is approximately  $-1/R_{56}$  in order to fully compress the bunch. The final longitudinal phase-spaces (LPS) and the current profiles 0.4 m downstream of the last dipole magnet with two different initial bunch charges are shown in Fig. 2, and the parameters of the final bunches are summarized in table 1. The results indicate that sub-fs electron bunch with charge of several pC is achievable at ARES. However, it is found that the bunch starts to

#jun.zhu@desy.de

elongate soon after compression, as shown in Fig. 3, which implies that the ultra-short bunch should be matched into the plasma in a short distance.

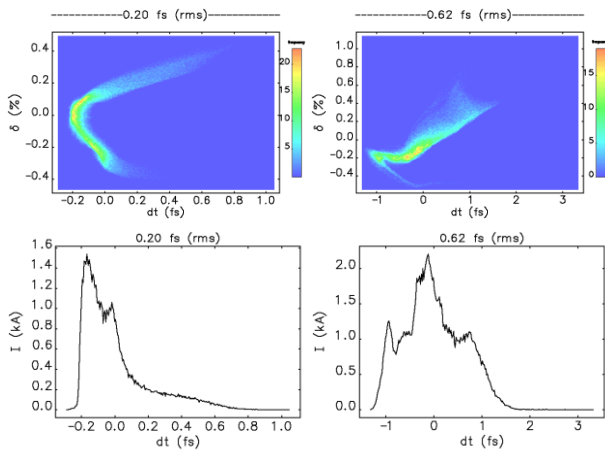


Figure 2: LPSs (up) and current profiles (down) 0.4 m downstream of the last dipole for initial bunch charges of 10 pC (left) and 100 pC (right). The full-width of the slit in both cases is 0.4 mm.

Table 1: Summary of Final Bunch Parameters

Initial bunch charge (pC)	10	100
Final bunch charge (pC)	0.38	2.77
$\varepsilon_x$ ( $\mu\text{m}$ )	0.05	0.24
$\varepsilon_y$ ( $\mu\text{m}$ )	0.05	0.18
Energy spread (%)	0.19	0.22
Final bunch length (fs)	0.20	0.62

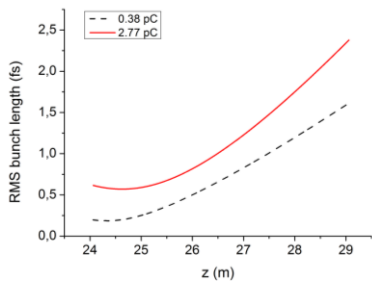


Figure 3: Bunch length evolution in a drift space with initial phase-spaces shown in Fig. 2.

### Transverse Wake Field at the Slit

The impact of the transverse wakefield at the slit to the beam emittance was studied analytically. Following [9], the emittance growth was found to be negligible for the typical slit and beam parameters at ARES. In addition, the experiments at FERMI@Elettra FEL also demonstrated that the slit had little impact on the quality of the low-charge beam [10].

### Final Bunch Charge

Although the final bunch charge can be adjusted by changing the initial bunch charge  $Q_0$  extracted from the cathode, the timing jitter studies show that the contribution of the gun charge jitter to the bunch arrival-time jitter is given by  $\Delta t = -C \Delta Q_0 / Q_0$ , where  $C$  is a constant. The coefficient  $C$  as a function of the initial bunch charge is shown in Fig. 4. Unfortunately, the bunch arrival-time jitter increases dramatically as the initial bunch charge increases. The reason is that the charge jitter will introduce energy jitter due to the space charge effects in the linac, which increases as the initial bunch charge increases. Finally, the energy jitter will be converted into the arrival-time jitter in the chicane.

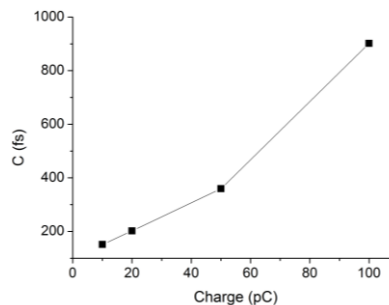


Figure 4: Coefficient  $C$  as a function of bunch charge.

Other methods which can change the final bunch charge include increasing the slit width and reducing the initial bunch length. As seen from the simulation result with low charge in Fig. 2, because of the nonlinearity of the LPS, the longitudinal profile of the bunch consists of a high charge concentration in the bunch head with a long trailing tail. As a result, the final bunch length increases quickly as the slit becomes wider, while the peak current of bunch remains almost the same. A possible solution is to employ a high-harmonic cavity to linearize the LPS of the bunch.

The initial bunch length can be reduced by using a cathode laser with tens of fs duration or compressing the bunch earlier with velocity bunching. However, the influences on the bunch arrival-time jitter with both schemes need to be further studied.

### DOGLEG

The dogleg will deliver ultra-short bunches to a medical-imaging beamline. The horizontal displacement between the two beamlines is required to be at least 1 m. The dogleg and the chicane also share the first two dipoles while the second dipole bends beams to opposite directions for each configuration, as shown in Fig. 5. The dogleg should be able to either transport ultra-short bunches produced by velocity bunching or compress bunches from ps to sub-fs. In order to transport the ultra-short bunch without elongating it too much, positive  $R_{56}$  in the order of sub-mm is required. Furthermore, the  $R_{56}$  is supposed to be tweaked continuously around the working point. On the other hand, in order to compress the ps

bunch with a reasonable chirp, the  $R_{56}$  of the dogleg should become comparable to the  $R_{56}$  of the chicane.

In the current design, there are six quadrupole magnets ( $Q_i$ ,  $i=1-6$  from upstream to downstream) inside the dogleg, where the quadrupole strengths of Q1 and Q6, Q2 and Q5, Q3 and Q4 are the same respectively. The  $R_{56}$  of the dogleg can be changed mainly by adjusting the strength of Q1 and Q6, while the strengths of the other quadrupoles need to be tweaked slightly in order to completely suppress the dispersion at the dogleg exit. The design optics and the evolution of  $R_{56}$  for the case with overall  $R_{56}$  of approximate 0.2 mm are shown in Fig. 6. Note that the  $R_{56}$  in the drift space ( $\sim -0.026$  mm/m for 100 MeV beam) is not included in the plot. The beam dynamic simulation of ultra-short bunches inside the dogleg can be found in [11].

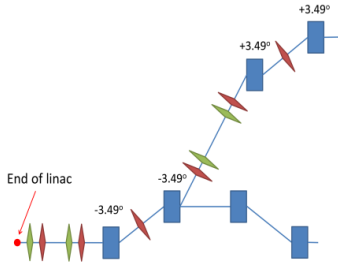


Figure 5: Configuration of the dogleg at ARES.

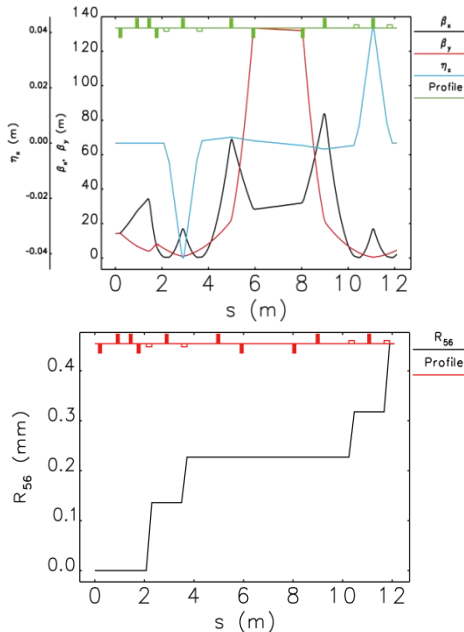


Figure 6: Design optics (up) and evolution of  $R_{56}$  (down) along the dogleg beamline. Simulation was performed with ELEGANT [12].

The nominal optics for the case with overall  $R_{56}$  of about 10 mm is shown in Fig. 7. With a slit located at the place where the dispersion is very large, e.g. at the entrance of Q1, the bunch length can also be compressed from  $\sim$ ps to sub-fs. However, ELEGANT simulation shows that there is significant emittance growth after

compression because of the optics. Moreover, the final bunch length is much longer than the chicane case because the  $T_{566}$  of the dogleg is almost ten times the  $T_{566}$  of the chicane.

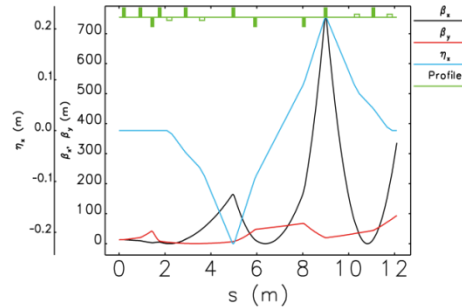


Figure 7: Design optics for  $R_{56}=10$  mm.

## CONCLUSION

By using the magnetic chicane with a slit, generation of sub-fs electron bunch with charge of several pC at ARES was demonstrated by S2E simulation. However, further studies are needed to reduce the bunch arrival-time jitter with high bunch charge.

We also presented a design of the dogleg with tunable  $R_{56}$ . The nearly isochronous configuration makes it possible to deliver the ultra-short bunch produced by velocity bunching to the second beam while preserving the quality of the bunch as much as possible. However, when the  $R_{56}$  of the dogleg became comparable to the  $R_{56}$  of the chicane, significant bunch quality deterioration was observed.

## REFERENCES

- [1] V. Malka et al., 2002, Science 298, 1596 (2002).
- [2] R. Assmann, "SINBAD – A Proposal for a Dedicated Accelerator Research Facility at DESY", TUPME047, Proc. IPAC2014, <http://jacow.org/>.
- [3] B. Machetti et al., TUPWA029, Proc. IPAC2015, <http://jacow.org/>.
- [4] P. Emma et al., "Attosecond X-ray Pulses in the LCLS Using the Slotted Foil Method", TUBIS01, Proc. FEL2004, <http://jacow.org/>.
- [5] J. Zhu et al., WEPMA031, Proc. IPAC2015, <http://jacow.org/>.
- [6] J. Grebenyuk et al., "Laser-driven Acceleration with External Injection at SINBAD", TUPME064, Proc. IPAC2014, <http://jacow.org/>.
- [7] K. Flöttmann, ASTRA particle tracking code <http://tesla.desy.de/~meykopff/>.
- [8] J. Qiang, S. Lidia, R. D. Ryne et al., Phys. Rev. ST Accel. Beams 9, 044204 (2006).
- [9] P. Tenenbaum, K. L. F. Bane, L. Eriksson et al., Phys. Rev. ST Accel. Beams 10, 034401 (2007).
- [10] S. Di Mitri, D. Castronovo, I. Cudin et al., Phys. Rev. ST Accel. Beams 16, 042801 (2013).
- [11] B. Machetti et al., TUPWA030, Proc. IPAC2015, <http://jacow.org/>.
- [12] M. Borland, "elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation," Advanced Photon Source LS-287, September 2000.