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DEVELOPMENT OF A FAST EXTRACTION METHOD FOR SHORT HIGH INTENSITY PULSES AT ELSA

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Abstract

Studies concerning the FLASH effect for radiation therapy are currently performed at ELSA. The booster synchrotron is used in a preliminary mode of operation to deliver electron beam pulses of 1.2 GeV energy with fixed length of 250 ns to irradiate cell samples. To enable different spill durations ranging from nanoseconds up to several ms in an energy range of 0.8 GeV to 3.2 GeV a fast extraction from the stretcher ring is developed. Therefore a repurposing of the existing injection kickers for extraction is under study to achieve single turn extraction, up to extraction within a few turns. While the effect on the beam dynamics is observed with a streak camera, the measurement of the extracted beam is performed via current and chromox monitors. For longer spill durations, reaching up to ms, the feasibility of multiple concepts for a quicker resonant extraction at ELSA is investigated.

FLASH@ELSA

The electron accelerator facility ELSA at the University of Bonn is a three stage accelerator. First a linear accelerator (linac) accelerates electrons up to 26 MeV, provided by either a thermal or a polarized source. Afterwards the electrons are injected into the booster synchrotron and accelerated up to 1.2 GeV. The electrons are then injected with a rate of up to 50 Hz into the stretcher ring, where they can be further accelerated up to 3.2 GeV.

Current FLASH Operation Mode

For current irradiation studies [1] a direct extraction of electron pulses with a pulse length of 250 ns and charges of up to 2.5 nC from the booster synchrotron to an experimental area is used. The extracted electrons are therefore guided via the stretcher ring used as transfer beam line towards the extraction site.

Extraction Site

Before irradiating a target placed inside a water phantom, the electron pulses pass several detectors (Fig. 1). First traversing an integrating current transformer (ICT) right after the beamline exit, for a measurement of the pulse charge. The transverse beam profile and position is measured with a luminescence screen (chromox) camera setup. It is analyzed by an in-house developed image analysis software package [2]. This setup provides precise information on the beam profile, position and spill charge.

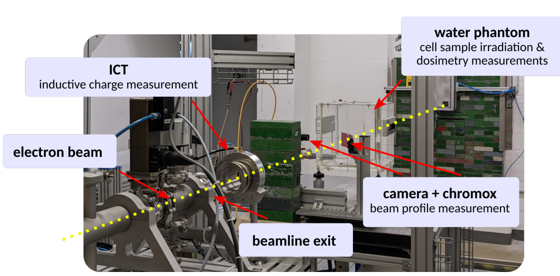

Figure 1: Experimental setup for cell sample irradiation and dosimetry measurements.

SINGLE TURN EXTRACTION

Three fast kicker magnets dedicated for the injection process are located in the stretcher ring. Their location is marked in Fig. 2. The usage of those kickers for single turn extraction is investigated.

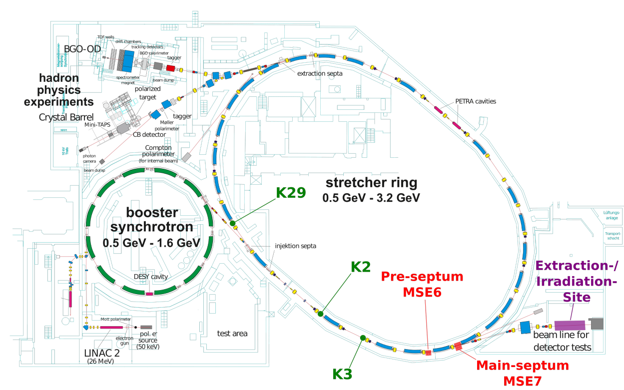

Figure 2: Accelerator facility ELSA with the marked location of the injection kickers in green, pre- and main-septum in red and the extraction site in purple.

Investigation of the beam optics for single turn extractions shows that a combination of kicks must be used. Thus producing a large offset from the design orbit at the position of the pre-septum to cross the septum blade for extraction. To achieve this offset, large beta functions at the location of the injection kickers and the pre-septum as well as a suitable phase advance between kicker and septum are essential. Following [3] one obtains for the displacement at the pre-septum:

$$\Delta x_{\mathrm{sep.}} = \Delta x'_{\mathrm{kicker}} \sqrt{\beta_{\mathrm{kicker}} \beta_{\mathrm{sep.}}} \sin\left(\mu_{\mathrm{kicker}\to\mathrm{sep.}}\right), \qquad (1)$$

where the influence of a kick $\Delta x'_{\mathrm{kicker}}$ to the beam displacement $\Delta x_{\mathrm{sep.}}$ at the septum is described, with the beta functions β_i and the phase advance $\mu_{\mathrm{kicker}\to\mathrm{sep.}}$. Those quantities are simulated with the simulation toolkit ELEGANT [4] and given in Table 1, stating the usability of the kickers for single turn extraction. Since linear beam optics are assumed for Eq. (1), further simulations including sextupole field contributions from dipoles and chromaticity correcting sextupoles were conducted. These simulations lead to a suitable kicker setting for single turn extraction with extraction efficiencies

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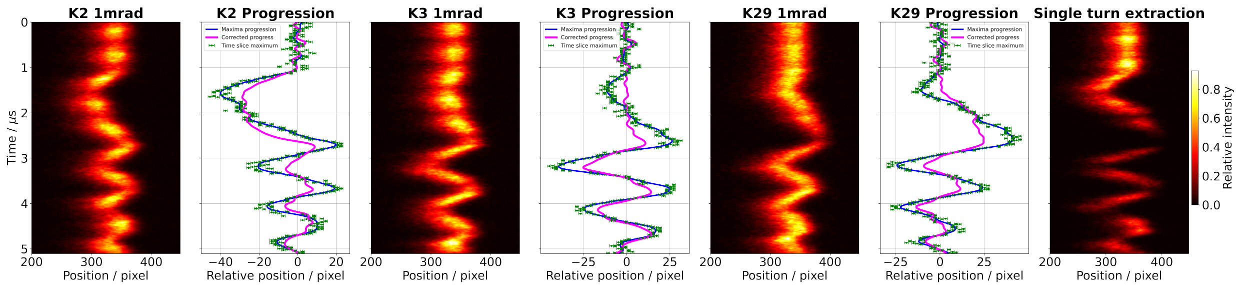

Figure 3: Horizontal response measurement via streak camera for 1 mrad single kicks with a corrected progression in magenta, where kick contribution of the other kickers are corrected for. A response from the single turn extraction is shown on the right.

up to 90 %. The setting combines a kick of the kicker K2 with a kick from K29 delayed by one turn. Due to the long pulse length of over 1 µs kicker K2 is also active a turn later when K29 fires. The extraction method was tested successfully at energies from 1.28 GeV to 3.2 GeV. In the following, additional measurement are carried out at 2.5 GeV investigating properties of the extracted beam.

Table 1: Simulated beta functions, phase advance $\mu_{i\rightarrow \text{sep.}}$ to the pre-septum and the displacement at the pre-septum by a kick of 1 mrad, for a horizontal tune of $Q_x = 4.39$ with the use of ELEGANT [4].

Element i	β_i	$\mu_{i\rightarrow \text{sep.}}$	$\Delta x_{\text{sep.}}(\Delta x'_{\text{kicker}} = 1\,\text{mrad})$
Pre-sep.	15.99 m	–	–
K2	14.12 m	207°	−6.71 mm
K3	14.12 m	108.7°	14.23 mm
K29	14.09 m	422.4°	13.30 mm

Beam Dynamic Measurement

The effect of the kicker setting on the dynamics of the beam is studied via measuring the horizontal and vertical behavior of the beam by the emitted synchrotron radiation (SR) with a streak camera. The SR beam line is located at the bending magnet behind the main-septum. Looking at the recorded horizontal beam responses depicted in Fig. 3, a clear displacement in the position of the 548 ns bunch train starting at around 1 µs is visible. As minor contributions from remaining kickers are expected when a single kicker is triggered, individual responses were analyzed and a correction function was worked out to estimate the isolated response of the kicker in use. The qualitative behavior of the corrected responses is matching with observations from simulations. Further studies checking a quantitative correlation of measurements and simulations are in progress. An observable decrease of intensity for the single turn extraction points out the loss of beam current in the process of extraction.

Spill Duration Measurement

A correlation between the pulse length of a pulse that traverses the ICT sensor and the rise time t_{rise} of the sensor signal was found in a measurement (see Fig. 4). For the calibration measurement a rectangular sample pulse is sent through a wire placed in the middle of the sensor, while the rise time of the ICT signal is measured simultaneously. For the single turn extraction we measure signal rise times of 445(6) ns , averaged over 6 single turn extractions, yielding spill durations of 331(15) ns. We assume that the spill duration length is limited by the finite kicker pulse rise times in the range of around 100 ns, resulting in a deviation of the spill duration regarding the revolution time of 548 ns. Further studies investigating the shortened spill duration are ongoing.

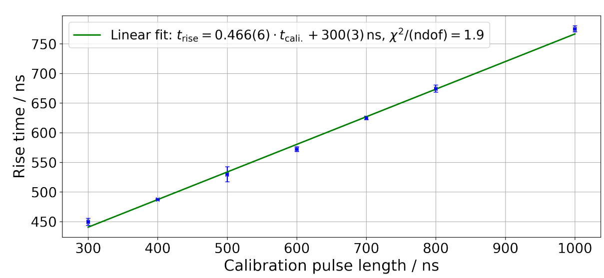

Figure 4: Correlation between the calibration pulse length and the rise time (10 - 90 %) of the ICT sensor signal.

Beam Stability Measurement

For future irradiation studies with cell samples of sizes in the order of mm a beam stability in the sub mm range is required. A measurement of over 350 extraction cycles is used to measure the beam stability of position and width via the beam profile monitor placed in the extraction site (see Fig. 1). The fluctuation for the horizontal (x) and vertical (y) orientation are shown in Fig. 5. The distributions root mean squares (RMS) characterize those fluctuations and are given in Table 2. In comparison with the booster extraction method the stability has improved over all parameters, especially in the horizontal plane, improving by one order of magnitude.

Spill Charge Fluctuation

A study on the stability of the spill charge via the ICT shows a large fluctuation of the extracted charge, as shown in Fig. 6. This observed large variations of the spill charge might arise from a combination of inhomogeneous filling patterns (seen in the bunch train structure of the synchrotron

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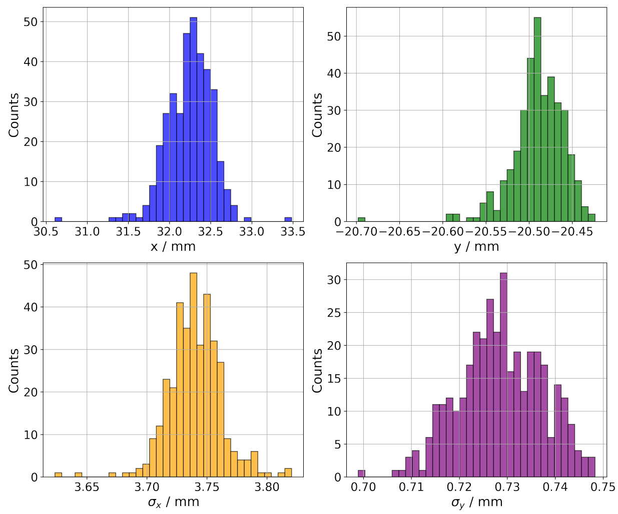

Figure 5: Fluctuation on the beam position and width in horizontal and vertical direction.

Table 2: Statistical fluctuation as RMS of the beam position and width for both orientations, for the ELSA single turn extraction mode at 2.5 GeV (**E**) and former extraction from the booster at 1.2 GeV (**B**).

	RMS(x)	**RMS(y)**	**RMS(σ_x)**	**RMS(σ_y)**
E:	0.277 mm	0.030 mm	0.022 mm	0.009 mm
B:	2.44 mm	0.053 mm	0.51 mm	0.075 mm

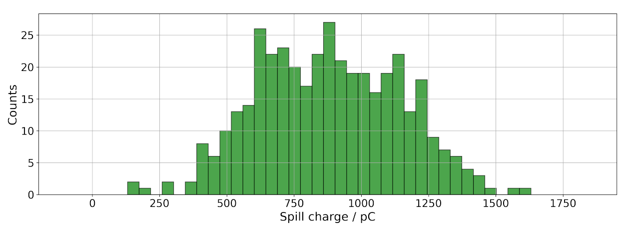

Figure 6: Fluctuation of a mean spill charge of $\bar{Q}$ = 879 pC with RMS(Q) = 267 pC.

light in Fig. 3) and a shortened spill duration of less than a revolution period. During this measurement extraction efficiencies up to 35 % could be reached. Assuming a stored beam current of 50 mA at 2.5 GeV, a reachable spill charge maximum of 9.59 nC is extrapolated. Additional measurements are planed to verify and test spill charge limits.

OUTLOOK

Beside the single turn extraction the feasibility of extraction with spill durations reaching up to milliseconds using resonant extraction at ELSA is under investigation. The method for $1/3^{\text{rd}}$ integer resonant extraction allows for much longer spill durations compared to single/multi turn extraction (a general description is given in Ref. [5]). Two techniques, a fast tune shift with fast ramping air quadrupoles and a driven coherent excitation of the betatron oscillation via a strip line kicker are under study. In first tests at an energy 1.28 GeV spill duration of under 10 ms were achieved for both methods. Time resolution from the beam current monitor of the stretcher ring with 10 ms is limiting this measurement. Therefore additional equipment, for measuring the spill duration such as a fast beam intensity monitor is required to visualize and characterize the resonant extraction.

CONCLUSION

A new extraction method repurposing the injection kickers for single turn extraction is developed. Measurements on the spill duration and beam stability prove the sufficiency for irradiation studies concerning the FLASH effect. A new single turn extraction enables irradiation with a spill duration of 331(15) ns for energies up to 3.2 GeV. Considering reached extraction efficiencies of up to 35 % at 2.5 GeV spill charges up to 9.59 nC seem achievable. First tests on resonant extraction with spill durations under 10 ms seem possible. However, additional measurements are to be performed to facilitate the resonant extraction method for future irradiation studies.

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