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ENHANCING BEAM TIME AVAILABILITY BY A FACTOR OF TWO: SIMULTANEOUS OPERATION OF HADRON PHYSICS AND DETECTOR TEST BEAM LINES AT ELSA

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Abstract

The electron accelerator facility ELSA houses two external high-energy beam lines. These deliver primary electron beams with energies between 0.8 and 3.2 GeV, extracted via slow resonant extraction from a synchrotron to a total of three different experimental sites. One beam line hosts two hadron physics experiments, while the second, located on the opposite side of the synchrotron, is used for detector tests and medical physics experiments.

Recently a new operation mode has been developed to serve both external beam lines with an extracted electron beam simultaneously. This enables running detector test experiments at low rates (tens of kHz) alongside high-rate hadron-physics experiments at GHz extraction rates, significantly increasing beam time availability.

We present properties and underlying beam dynamics of this operation mode, with particular emphasis on advanced methods for rate control at the second beam line.

ELECTRON STRETCHER FACILITY

At the Electron Stretcher Facility ELSA (see Fig. 1) polarized or unpolarized electrons are accelerated to energies of up to 3.2 GeV within a three-staged accelerator scheme including a Linac, the Booster Synchrotron and the ELSA stretcher ring [1]. A source for polarized electrons or a thermionic gun, operated at 50 kV and a traveling wave Linac are available as pre-injector. The following Booster Synchrotron further accelerates the electrons and transfers them to the main storage ring at an energy of typically 1.2 GeV.

After accumulating typically 30 mA in the stretcher ring, the electrons are accelerated up to 3.2 GeV and are then slowly extracted to one of the experimental sites. The first external beamline splits up and serves two hadron physics experimental sites E1 and E2. The second beamline delivers electrons to the third experimental site E3 utilized for detector testing [2], irradiation experiments and medical physics [3].

Resonant Extraction

The electron beam is extracted from the main storage ring and delivered to the experiments. This is realized via resonant extraction at a third integer betatron resonance in the horizontal plane. This resonance is driven by dedicated sextupole magnets in the dispersion free straights of the storage ring.

During the extraction, the betatron tune in the horizontal plane is shifted towards $Q_x = 4\frac{2}{3}$ by four dedicated fast

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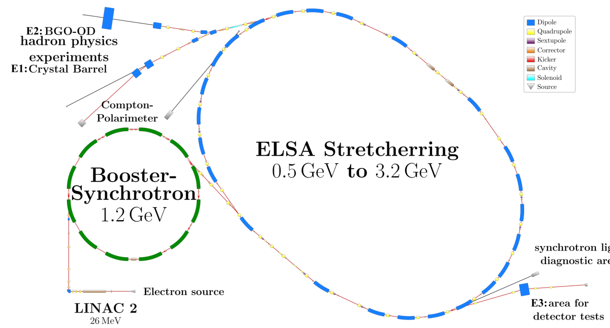

Figure 1: Electron Stretcher Facility ELSA.

ramping air core quadrupole magnets. For each external beamline separate pre- and main septum magnets are installed, guiding a portion of the beam to the external beam lines. Due to a superperiodicity of 2, the Twiss parameters at both extractions points are identical.

In vicinity of the resonance, a separatrix is formed in phase space, indicating the stable region inside (compare simulation in Fig. 2). By the introduced tune shift towards the resonance, the separatrix shrinks in size and more particles become unstable. The rate of unstable particles, and thus, the rate of extracted electrons is then stabilized and controlled by a software PID controller with the air core quadrupole current as control value.

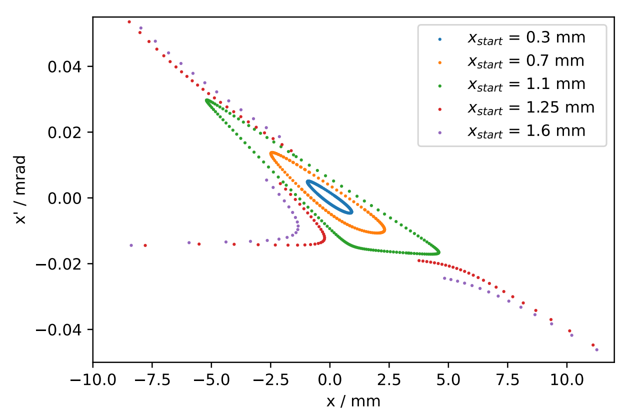

Figure 2: Xsuite [4] simulation of 5 electrons with different start amplitudes for 150 revolutions indicating stable and unstable phase space regions. Extraction sextupole strength was set to $m_{\text{ex}} = 1.2\,\text{m}^{-3}$. Simulated in vicinity of third integer betatron resonance.

Simultaneous Resonant Extraction Due to the aforementioned superperiodicity of $P = 2$, simultaneous extraction at the first and second beamline is, in principle, naturally possible. The betatron phase advance between the two locations is $\Delta\Psi = 4\frac{2}{3}\pi$. Consequently, an identical separatrix

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structure is formed in phase space at both pre-septum magnets. Owing to the phase advance, however, the separatrix at the second extraction point is rotated in the clockwise direction by two branches relative to the first.

A simultaneous extraction allows concurrent delivery of electrons to both external beamlines and operation of two experiments at the same time, effectively doubling the net available beam time. Despite this potential advantage, differing requirements with respect to extractions rates (i.e., beam current), beam spot size and stability, as well as accessibility of the experimental areas for setup modification impose important operational constraints discussed in the following.

Hadron Physics Experiments

At the first external beamline (see Fig. 1, upper left area) the two hadron physics experiments CB-ELSA/TAPS and BGOOD are hosted. For both, either the unpolarized or the spin polarized electron beam is converted to a linearly or circularly polarized photon beam via bremsstrahlung on copper or diamond targets. The photon beam is utilized for photoproduction experiments off nucleons.

Especially for the linearly polarized beam, a stable electron beam divergence and precise alignment of the orientation of the electron beam and the diamond crystal are essential [5]. Therefore a high pointing stability of the beam on a short and long term basis is to be ensured. The data processing capabilities of the upstream detector components further limit the electron beam current to typically 1 nA, corresponding to an extraction rate of $\approx 10\,\mathrm{GHz}$.

Typical beam times for the hadron physics experiments last from 2 up to 5 weeks with almost no interruptions for accessing the experimental area.

Detector Tests

At the second external beamline on the opposite side of the stretcher ring, the E3 area is located (cf. Fig. 1, bottom right). Here, up to four experiments on movable table-top sites can be set up. Typical use cases are detector tests using the primary extracted electron beam. Each electron path is detected using a beam telescope and the corresponding tracks are reconstructed. Typically, the electron rate is adapted to the detector's readout capability to allow for efficient track reconstruction and optimized beam time usage.

The rate is directly user controllable and can be regulated within six orders of magnitude, i.e. from 100 Hz up to 625 MHz with typical rates in the range of a few 100 kHz [6]. The corresponding beam current is limited to 100 pA with typical currents of a few fA.

In contrast to the hadron physics experiments, the typical beam times at the E3 beamline last between a few hours up to days, with interruptions on a regular basis to improve and change the detector setup on-site.

Medical Physics

Beside detector testing setups, the E3 area is equipped with one experiment designated to medical physics research. Goal of the experiment is the investigation of the so called FLASH effect in radiation therapy. Here the ultra high energy electrons (UHEE, GeV range), are used to irradiate cancer cells with highly intense and short pulses to reach the FLASH regime with dose rates above $40\,\mathrm{Gy\,s^{-1}}$.

To reach these high dose rates, corresponding high extraction rates and short pulses need to be achieved. For this purpose, a dedicated single turn extraction mode was developed recently [3].

SIMULTANEOUS EXTRACTION

Since beam stability requirements are particularly strict for the hadron physics experiments conducted in areas E1 and E2, these experiments are designated as the *primary* experiments in the proposed *simultaneous extraction* mode. The detector tests as *secondary* experiments in area E3 were found to be well suited for concurrent operation. Due to the comparatively low extraction rates required for detector tests, their simultaneous operation does not significantly reduce the overall extraction efficiency.

With its specialty of required short pulses to reach high dose rates, the FLASH studies require exclusive beam times and are incompatible with the simultaneous extraction mode.

To improve the understanding of the extraction mechanism and to optimize the accelerator settings for simultaneous extraction, comprehensive simulations in ELEGANT [7] and Xsuite [4] including synchrotron radiation effects were performed.

Although the simulations could confirm the feasibility of the simultaneous extraction, it was not possible to transfer the results into settings on the real machine. Due to multipole components and misalignment of the accelerators' main magnets, parameters as the tune, tune shift span and especially the extraction sextupole strength could only be elaborated experimentally.

Rate Control

As discussed above, rate control at the primary experiment can be achieved using the PID controller driven by the experiments' rate measurement. The extraction rate can be adjusted via the PID setpoint. However, the rates at both extraction points remain coupled proportionally. Consequently an *additional* method for independent rate control at the secondary experiment was required.

Therefore, two different techniques were investigated:

Closed Orbit Displacement It was initially observed that the extraction rate at the second extraction site can be controlled directly by introducing a closed orbit (CO) bump at the position of the pre-septum (see Fig. 3, left). This moves the beam towards the septum blade and thereby increases the extraction rate. This method exhibits a clear linear dependence on the magnitude of the applied CO bump, as shown in Fig. 4. However, stray magnetic fields generated at the septum blade itself affect the CO correction and render the calculation of a perfectly closed bump susceptible to errors. The resulting, unintended displacement at the first extraction causes a shift of the beam position on target at the hadron

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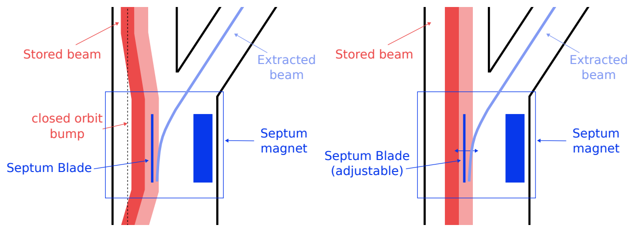

Figure 3: Schematic view of extraction process at the pre-septum with different methods for rate control at the secondary experiment: a) using a closed orbit bump, b) moving of the septum blade.

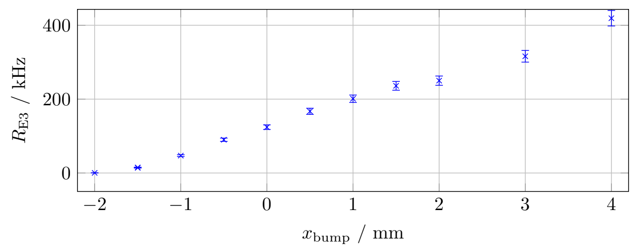

Figure 4: Rate R_{E3} of extracted electrons at E3 beamline in dependence of the magnitude of the closed orbit bump x_{bump}.

physics experiments. This displacement scales with the magnitude of the CO bump and prohibits stable operation of the experiment. Consequently this method does not achieve the required specificationsis for rate control.

Septum Blade Position A similar approach exploits the possibility of moving the blade integrated into the pre-septum towards the beam in order to increase the extraction rate (see Fig. 3, right). As the impact on the circulating beam is negligible, this method provides excellent control on the electron rate in the second external beamline. The corresponding linear relationship between the extraction rate and septum blade position is shown in Fig. 5. It should be noted, that the septum blade position is given relative to an arbitrary reference point with larger values indicate positions closer to the beam.

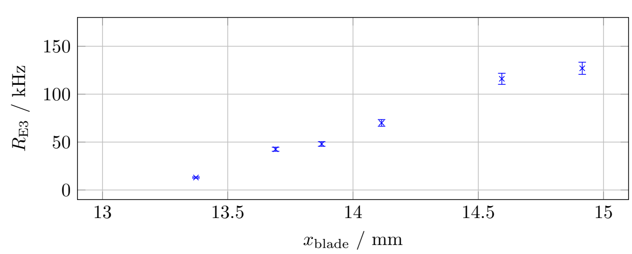

Figure 5: Rate R_{E3} of extracted electrons at E3 beamline in dependence of the septum blade position x_{blade}.

Rate Stability To verify the rate stability during an extraction cycle, the individual extraction rates were measured. At the primary experiment the so called *tagger rate*[1] was measured by the CB-ELSA/TAPS experiment. At the E3 area, the direct electron rate was measured by a 3 cm × 3 cm scintillator placed between the beamline exit and the detector setup.

[1] The *tagger rate* refers to a rate proportional to the conversion rate of electrons to photons via bremsstrahlung. The conversion efficiency is approximately 1:1000.

In Fig. 6 the exemplary extraction rates are shown during a typical extraction cycle with a spill duration of 9 s for the primary (blue) and secondary (red) experiment.

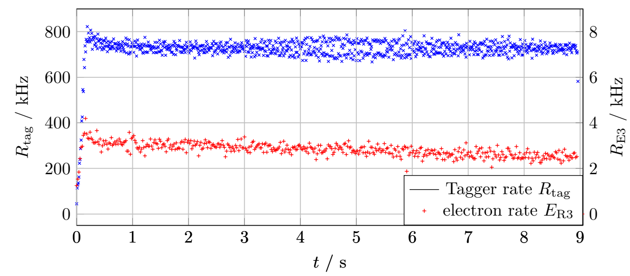

Figure 6: Event rate of tagged electrons at CB-ELSA/TAPS experiment (R_{tag}) and simultaneous electron rate at the detector test beamline (R_{E3}).

CONCLUSION

Here we have presented the development and optimization of a new operational mode enabling the concurrent operation of two experiments via simultaneous extraction using resonant extraction techniques at two extraction points in an electron synchrotron. This mode has been in routine operation at ELSA since the beginning of 2025.

Beam Time Overview 2025

In total, an additional 1654 hours, corresponding to 55 % of beam time, were made available, of which 606 hours were effectively utilized (i.e., with open beam shutter) for detector tests and related experiments running in parallel to the primary hadron physics program (see Fig. 7).

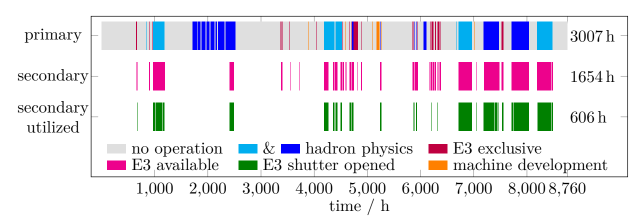

Figure 7: Beam times in 2025. Shown are time slots of primary experiment, of secondary experiment availability and of requested beam at secondary experiment.

The introduction of the simultaneous extraction mode has been met with very positive feedback from the user community, as it provides substantially increased operational flexibility and significantly more beam time compared to conventional single-experiment operation.

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