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IMPLEMENTATION OF A TUNE SWEEP SLOW EXTRACTION WITH CONSTANT OPTICS AT MedAustron

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Abstract

Conventional slow extraction driven by a tune sweep perturbs the optics and changes the presentation of the beam separatrix to the extraction septum during the spill. The constant optics slow extraction (COSE) technique, recently developed and deployed operationally at the CERN Super Proton Synchrotron to reduce beam loss on the extraction septum, was implemented at MedAustron to facilitate extraction with a tune sweep of operational beam quality. COSE fixes the optics of the extracted beam by scaling all machine settings with the beam rigidity following the extracted beam's momentum. In this contribution the implementation of the COSE extraction technique is described before it is compared to the conventional tune sweep and operational betatron core driven cases using both simulations and recent measurements.

INTRODUCTION

The MedAustron synchrotron employs a betatron core driven slow extraction to perform nominal operation. Another common slow extraction technique relies on ramping up (or down) some or all quadrupoles in the machine to vary betatron tune of the circulating beam towards the resonance. Implementing a tune sweep based method in MedAustron is interesting academically [1], as the machine was not designed to operate in such a way. Furthermore, MedAustron has contemplated performing bunched multi-energy extraction in order to speed up operation, which cannot be performed with the betatron core.

CONSTANT OPTICS SLOW EXTRACTION

There are certain issues with conventional tune sweep. As the tune is swept the radial position of the on-resonance separatrix moves along the dispersion vector due to the changing extracted momentum, rendering ineffective the superposition of separatrices achieved via the Hardt condition. Moreover, particles with different momenta 'see' different optics at extraction, due to the fact that they have different magnetic rigidities. These effects can be partially compensated with a dynamic extraction bump, but it complicates operation.

A solution to this can be achieved with COSE [2], where the whole machine's beam rigidity $B\rho$ (or reference momentum $p_{\text{ref}} = q \cdot B\rho$, where q is the particle's electric charge) is scaled synchronously with the tune sweep. All magnets in the lattice must follow the same ramp from their respective $B_{n,\text{start}}$ to $B_{n,\text{end}}$ for COSE to be performed successfully, where B_n represents the n-th order multipole of the magnetic field. In order to determine magnet field strength sweep, it is sufficient to enforce a constant optics as follows,

$$k_{n,\text{start}} = q\frac{B_{n,\text{start}}}{p_{\text{start}}} = q\frac{B_{n,\text{end}}}{p_{\text{end}}} = k_{n,\text{end}}. \tag{1}$$

Since $p_{\text{end}} = (1 + \Delta p/p)p_{\text{start}}$, one can write,

$$\frac{B_{n,\text{end}}}{B_{n,\text{start}}} = (1 + \Delta p/p), \tag{2}$$

illustrating that the magnetic strengths must be scaled by the same relative change in momentum.

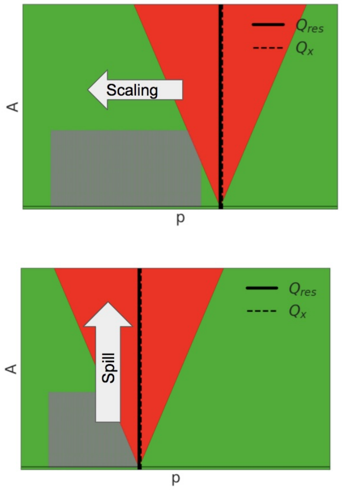

Figure 1: Steinbach diagram illustration of COSE.

An interesting way of conceptualising COSE is as the betatron core extraction in a different frame of reference. A particle with longitudinal momentum p has a tune distance

$$\delta Q = Q'_x\frac{\Delta p}{p} = Q'_x\frac{p - p_{\text{ref}}}{p_{\text{ref}}}. \tag{3}$$

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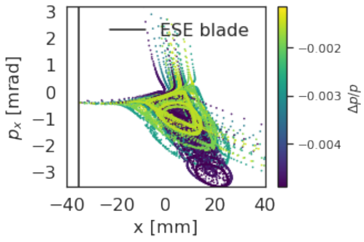
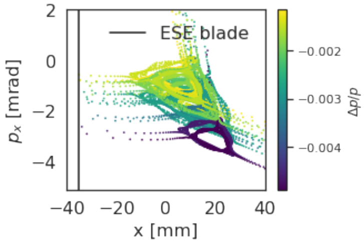
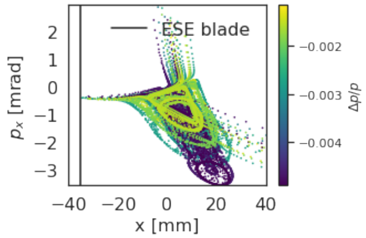
The betatron core brings this quantity towards zero (towards the unstable region) by varying p, while COSE does so by varying p_{ref}. The main difference between the two methods is that for COSE the extracted beam's longitudinal momentum changes over time. Figure 1 shows the COSE extraction in a Steinbach diagram. Notice how the resonant tune Q_{res} and the reference tune Q_x move together through the different momenta of the stack. Ideally, one would also scale the extraction septa and all the transfer line magnets downstream in a synchronous manner to compensate for the changing extracted momentum. We did not perform this scaling for these studies due to the added technical complications of such an operation at MedAustron.



(a) Betatron core.



(b) Q-sweep.



(c) COSE.

Figure 2: Horizontal phase space trajectories at ESE during extraction for each scheme in simulation. Each color represents a different initial $\Delta p/p$.

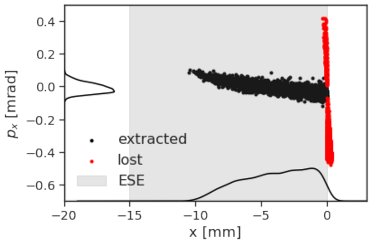
MEASUREMENTS AND SIMULATION RESULTS

In this section, MedAustron's nominal extraction scheme (betatron core driven) is compared to traditional Q-sweep and COSE. Both particle tracking simulations and measurements are presented and discussed. The main simulation parameters are shown in Table 1.

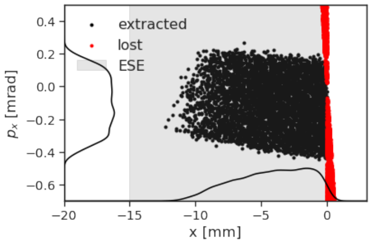
Figure 2 shows the simulated phase space trajectories of particles with different initial $\Delta p/p$ at the location of the electrostatic extraction septum (ESE). It can be seen that the nominal and COSE schemes produce identical portraits with all separatrices aligned at the blade of the ESE, as expected. Nevertheless, it is important to reiterate that the extracted momentum will vary over time for COSE. On the other hand, in Q-sweep a large angular variation of separatrices with different $\Delta p/p$ can be observed. This is because of the non-zero dispersion vector at the ESE. The simulated extracted horizontal phase spaces for each scheme are shown in Fig. 3. The variation observed during the Q-sweep results in a large horizontal emittance blowup, in addition to an increase in beam loss on the ESE's blade for the Q-sweep technique.

Table 1: Extraction Simulation Parameters

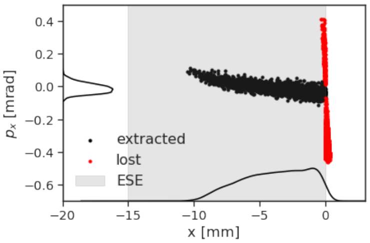
Parameter	**Value**
# of particles	10^5
Kinetic Energy [MeV]	250
$\Delta p/p$	0.004 (uniform)
$\epsilon^N_{x,RMs}$ [mm.mrad]	0.519
$\epsilon^N_{y,RMs}$ [mm.mrad]	0.519



(a) Betatron core.



(b) Q-sweep.



(c) COSE.

Figure 3: Horizontal phase space distributions at ESE for each scheme in simulation. Extracted particles are shown in black and lost ones in red.

Beam Size Comparison

We first focus our attention on the extracted distributions obtained from simulation. Table 2 lists the fitted root-mean-square (RMS) emittances from the extracted distributions shown in Fig. 3 (and the respective vertical profiles, not shown). COSE produces a similar transverse beam profile as the betatron core extraction, while Q-sweep results in a much larger beam with a factor 10 increase in the horizontal emittance. Vertical emittances remain identical, as expected.

Table 2: Extracted Emittances for Each Scheme from Simulation

Scheme	$\epsilon_{\mathbf{x,RMS}}$ [mm.mrad]	$\epsilon_{\mathbf{y,RMS}}$ [mm.mrad]
Betatron core	0.04	1.8
Q-sweep	0.4	1.8
COSE	0.04	1.8

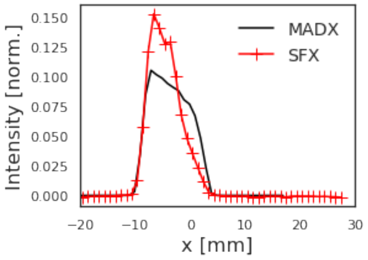
The simulation results can be compared to the measurements by using a Scintillating Fibre Hodoscope (SFX) located in the High Energy Beam Transfer line (HEBT), which transports the beam from the ring to the irradiation rooms. One can compare the simulated transported distribution to the integrated intensity measured by the SFX throughout the spill. Figure 4 shows this comparison for each scheme in the horizontal plane. Measurements and simulation agree qualitatively, showing that COSE produces very similar results to the nominal scheme, while Q-sweep results in a larger beam. All schemes were practically indistinguishable from each other in the y-plane, both in measurements and simulation.

Beam Loss Comparison

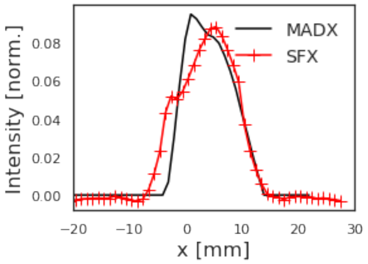
In order to study losses in simulation, the whole ESE is considered as a black body object (including its thin blade), i.e. all particles that impact the equipment are immediately absorbed and lost. For our studies, the most relevant features of the ESE are that the blade has an effective thickness of 0.1 mm and that the gap between the anode and cathode is 15 mm in width and large enough in height not to play a role in the losses. COSE and the nominal scheme produce similar losses (9.5% and 9.4%, respectively) while traditional Q-sweep causes losses to increase by 30 % (12.3% losses). Regarding measurements, no beam loss monitors were available near the ESE nor the magnetic septa. However, prompt beam loss monitoring improvements are planned in the future in order to expand on these results.

CONCLUSION

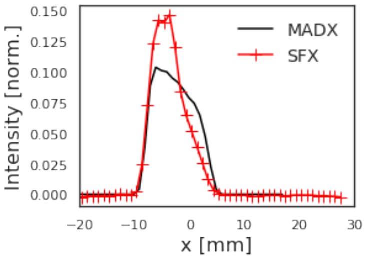
Traditional Q-sweep and COSE were implemented at the MedAustron synchrotron. Both schemes were compared to the nominal (betatron core driven) slow extraction procedure through simulation and measurements. While Q-sweep results in a large horizontal emittance blowup (factor 10) and an increase in losses by 30%, COSE manages to produce beam of operational quality. Beam size measurements agree with simulation, but losses could not be compared due to the lack of beam loss monitors near the ESE. These studies serve as a proof of concept of the COSE extraction method in medical synchrotrons that rely on the Hardt condition.



(a) Betatron core.



(b) Q-sweep.



(c) COSE.

Figure 4: SFX horizontal integrated intensity, both simulated and measured.

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