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STATUS OF OSCILLATING ARM WIRE MONITOR DEVELOPMENT

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Abstract

We present the development of a high-speed oscillating-arm wire monitor (OAWM). Similar devices are in use at PSI's HIPA facility since the 1970s [1-3], however they are significantly slower. The new design maintains the compact longitudinal footprint of the original instrument; a property rarely found among fast wire monitors [4]. First performance tests demonstrated wire velocities of 4 m/s using a stepper motor and 8 m/s with a servo motor. This advancement will allow to use wire scanners to measure the beam profile in the most challenging of the HIPA beamlines, with beam current exceeding 10 mA.

MECHANICAL SETUP

The present OAWM use a 20:1 worm gear reduction and reach an on-axis wire speed of 0.75 m/s. This is not sufficient to operate at full beam current in the 0.87 MeV injection line. Lower gear reductions allow higher speeds [5]. The new prototype uses a 1:1 direct drive from the motor to the con-rod (Figs. 1-2). To allow for a smaller bellow, the bearings at the arms axis of rotation are now outside the bellow. Bearings with low play are used throughout. The inertia of the monitor arm (MA) is dominated from the material far from the axis of rotation. It consists of two half-shells, fluid formed from 0.1 mm titanium or 0.075 mm 1.4404 stainless steel sheets [6]. Gauges hold the half-shells in place while laser-welded at the outer contour and spot-welded at the elongated corrugations [7]. 6 ceramic beads are clamped in recesses; these guide the signal wire.

Tests were performed with the titanium variant of MA; either a 2-phase stepper motor PKP245D23B2 without brake [8], or a servo motor AM8113-0F01 with brake and resolver [9] were used. The stepper motor was rotated in its holder so that the starting position coincidences with a full step position. The arm position is measured with a potentiometer TEX-0025-415-002-101 [10, 4] and, only for testing in the lab, a laser triangulation sensor ILD2300-50 [11].

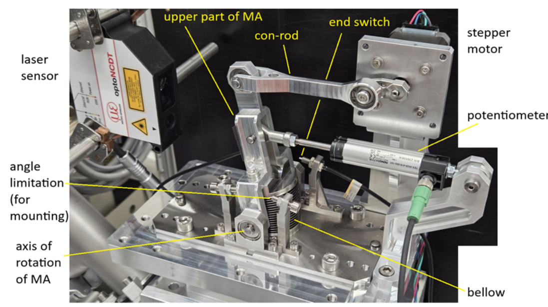

Figure 2: Setup with stepper motor in parking position.

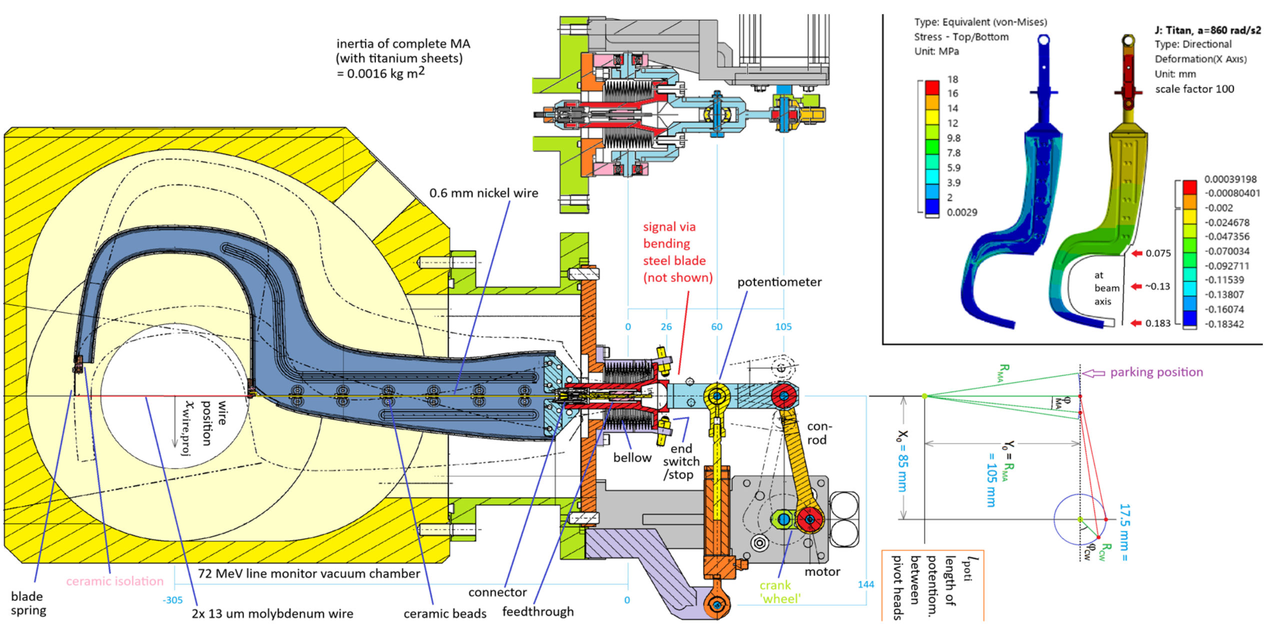

Figure 1: Setup of prototype (horizontal MA). Insert: ANSYS calculation [12] of deformation and stress of MA at constant angular acceleration equal to the maximum acceleration of the below discussed preset trajectory at an on-axis wire speed of 3.9 m/s. Maximum load on the relevant load-bearing areas of the shells is ~10 MPa, much less than the yield strength of 203 MPa for titanium grade 1 (which corresponds to ~17.4 m/s). With the stainless-steel variant, the numbers are ~15 MPa, 596 MPa, ~24.7 m/s at similar deformation and 15 % increased inertia of the MA.

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ELECTRONICS SETUP

PSI standard motion control software, ECMC [13], was used for controlling and acquiring data. The servo motor is fed by an EL7211 driver with brake chopper EL9576 and brake resistor ZB8110, controlled by a C6025-0000 industrial PC [9]. A 'learning' algorithm is implemented, modifying the motor current trajectory to minimize differences of the resolver trajectory to the pre-defined motor angle trajectory ('adaptive feed forward'). The trajectory is updated every millisecond. Several runs are needed to converge.

The 2-phase stepper motor is fed in open-loop by an EL7062 driver [9] controlled by the PC. Driver parameters are updated every millisecond to follow the same pre-defined motor angle trajectory as the servo motor.

The potentiometer is read out every millisecond by an analog input card EL3255 [9] controlled by the PC, while the laser sensor is connected directly via EtherCAT.

SIMULATIONS

Assuming the setup shown in Fig. 1 as rigid bodies coupled with no play, analytic formulae were derived to describe precisely the relations of φ_{CW}, φ_{MA}, $x_{\mathrm{wire,proj}}$, l_{poti} (Fig. 1). (In [5] this was done approximately.) Assuming a preset trajectory of motor angle φ_{CW} over time, the trajectories of the other parameters and their time derivatives can be calculated. With the inertias and masses of the parts, the torques and forces can be determined. Figure 3 (black lines) shows this for wire trajectories (f-h) moving the wire 'forward' (1-way) through the beam (φ_{CW} = 180° to 360° in Fig. 1). The motor trajectories (a-d) are chosen to reduce acceleration (h) and jerk of the wire movement and to be limited to linear angular acceleration variations (c) to ease the realization with stepper drivers.

From the geometry, the dependency of the potentiometer signal on wire position can be predicted (f vs. i, black line). In turn, the wire position (f, red line) can be inferred from a measured potentiometer signal (i, red line). The difference of measured to preset wire position trajectories (j, red and green line) is similar to the prediction of the simulation for the shift between rotor and stator field of the stepper motor resulting from the actual torque (j, blue, e, orange line). It can be largely corrected (e, grey line) [5].

Similarly, the wire position can be derived from the motor angle, either by a resolver - in case of the servo motor, or by the step count - in case of the stepper motor.

Figure 3 (k) depicts the difference of the wire position corresponding to a full step (1.8°) of the 2-phase stepper motor. A loss of 4 full steps corresponding to a motor tooth would clearly be visible in the potentiometer signal.

FIRST DRIVE TESTS

We tested the monitor with a pre-vacuum in the chamber at several velocities of 1-way moves. No ringing of the bellow was visible when observed with a 125 Hz camera. Some transversal oscillations of the MA were observed with amplitudes up to ~±2 mm at 4 m/s, increasing at higher speeds; this seems to be not critical.

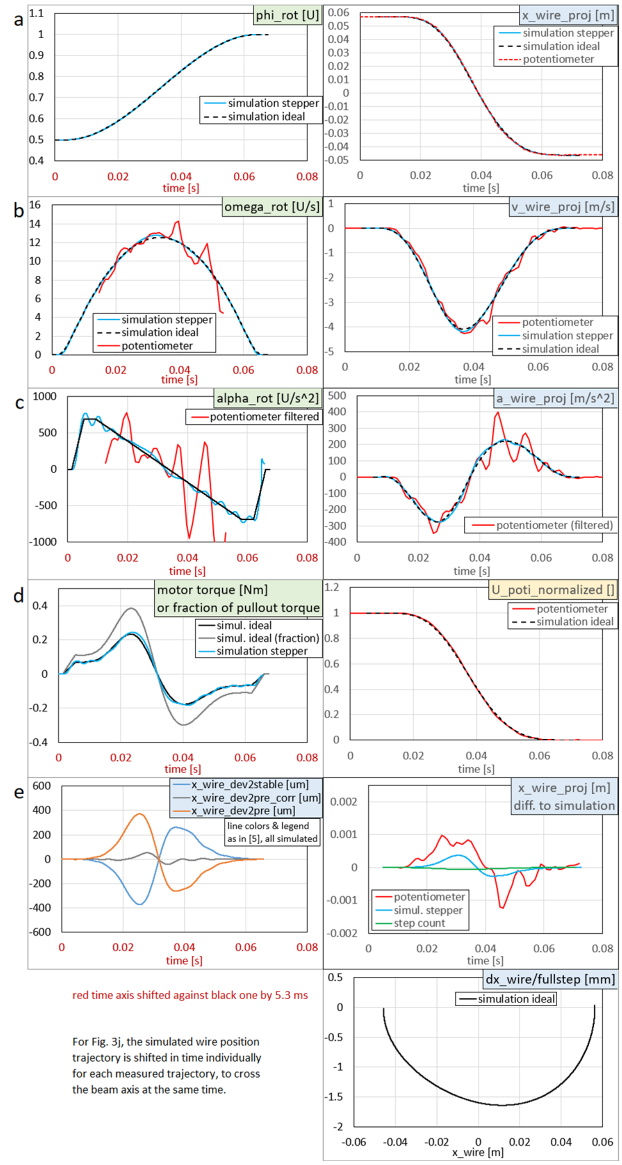

Figure 3: Simulation and measurement of 1-way forward move. 2-phase stepper motor, titanium arm, 4 m/s on-axis wire speed.

With the stepper motor, 4 m/s (Fig. 3) is a suitable speed. The MA movement is very reproducible (Fig. 4). Measured oscillations around the preset trajectories are larger than predicted by simulation, but still moderate. This still holds if imperfections of the motor [5] (not shown) are included in the simulation. Closer to the limit of losing steps, measured and predicted oscillations increase, while the readback of the step-count (Fig. 5 (b), green line) still suggests a perfect approximation of the preset trajectory; this is unlikely. We were unable to determine if the oscillations are due to the motor, the mechanics, or a sub-optimal reproduction of the step trajectory by the controller. For future testing, we intend to use a step-direction driver to observe better the generated step sequence. We observed the stepper motor losing steps above 5.1 m/s, the simulations predicted 5.5 m/s.

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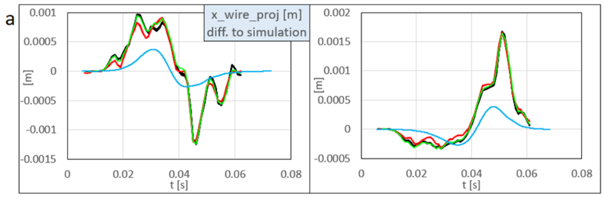

Figure 4: Deviation of wire position from prescribed trajectory over time. 1-way run, 4 m/s on-axis wire speed. (a) forward, (b) backward. Blue: due to phase shift between angular position of rotor and stator field of ideal stepper motor (simulation). Other lines: measured by potentiometer. Black: 8 subsequent runs (MA hanging down). Green: ditto, 1 run 3 days later. Red: 2 subsequent runs with MA horizontal. The shift of the wire position due to gravity acting on the MA is about 0.1 mm.

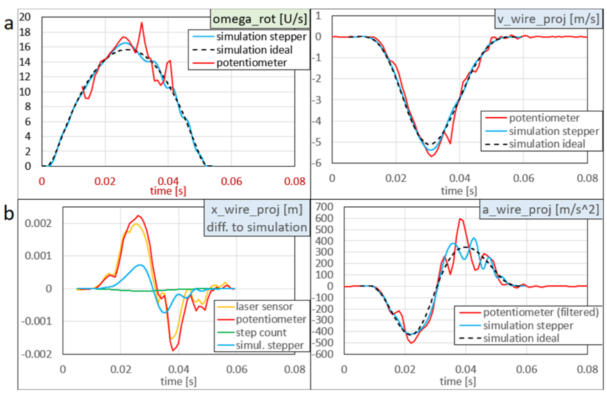

Figure 5: As Fig. 3 but at 5 m/s.

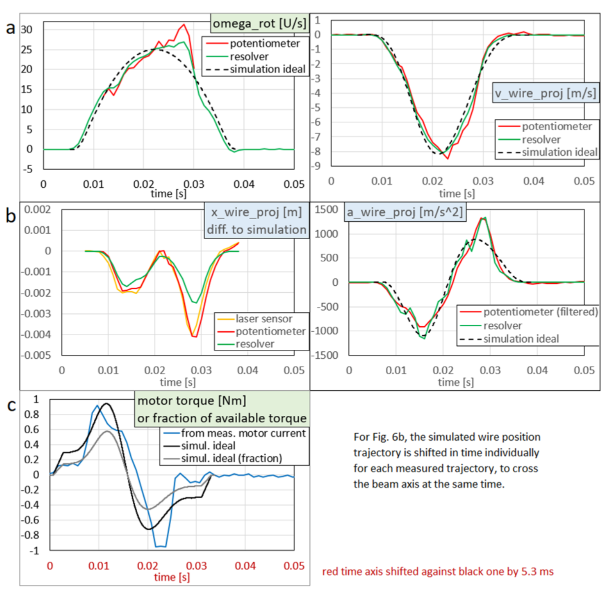

Figure 6: Simulation and measurement with servo motor. Titanium arm, 1-way forward, 8 m/s on-axis wire speed. The adaptive feed forward had not converged here.

In first tests, we reached 8 m/s with the servo motor (Fig. 6), but still with large deviations from the preset trajectory. We have not yet determined the maximum speed the motor can provide. According to the simulation, with the preset trajectory, it should be ~9.1 m/s at a maximum of 80 % use of available torque.

With a strong motor, irregular trajectories can lead to forces acting on the MA, which surpass the limit given by the yield strength of the thin shell (see Fig. 1) and damage it. The risk is increased by repetitive movements which may excite transversal oscillations of the MA. It is useful to limit speed and path length of the motor trajectory and to enforce waiting times between runs.

OUTLOOK

We foresee lab tests of the lifetime of the MA, drive, bellow, potentiometer, and the end switches, and of the accuracy of wire position determination. In addition, we are preparing a vacuum chamber for testing a prototype on the 0.87 MeV line with different configurations of motors, position sensors, and cables. We also will check which wire (or foil) speed is sufficient to operate the monitors at full beam current without onset of thermionic emission.

The fully developed device should serve in the new proton beam lines of the IMPACT project [14], as spares, as replacement for the wire monitors in the 0.87 MeV line, and later in the other beam lines of HIPA. At low beam energies it will allow to measure at full beam current, at higher energies it will reduce the beam losses during the wire passing as well as the resulting need to temporarily increase the interlock levels of the beam loss monitors.

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AUTHOR CONTRIBUTIONS

RD provided drive simulations, preset trajectories and measurement evaluation, specified drive mechanics, motors, potentiometer, end switches, supported the mechanical design and initiated and guided the project. AS configured the controller software, performed the drive tests, specified the driver electronics and provided it partly. SW performed pre-tests with 2-phase and 5-phase stepper motors and electronics. RN, SL, RB, MS, RD supported the measurements. MR designed and organized the drive mechanics, SL mounted it. The light-weight arm was designed by SJ, its manufacturing was developed, organized or performed by DB, SB, MM, RN. XW provided the ANSYS calculations.

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