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DEVELOPMENT OF BENT CRYSTAL MANIPULATION SYSTEMS FOR BEAM COLLIMATION AND EXTRACTION AT CERN

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Abstract

Manipulating high energy beams with bent crystals has applications ranging from beam collimation to slow or direct beam extraction. These systems are now integrated parts of accelerators and studied for future experimental set-ups. With growing achievements and expectations of crystal beam manipulation, requirements for the devices that operate the crystals become more stringent. They must retain the extreme angular precision required by the tight acceptance of crystal channeling. But they also must sustain longer operation, with higher beam energy, and provide additional functions. In this paper are presented crystal channeling devices in operation or development at CERN. Target Extraction Crystal devices, operated in SPS ring, reduce beam power losses during slow extraction. Target Crystal Primary Collimators are now part of LHC collimation system for ions runs. Finally, two devices are currently developed for dipole moments measurement of short-lived baryons in the LHC. This paper focuses on the relations between requirements, environment, and design of the different devices. It emphasizes how the specificity of items that share the same principle leads to unique design solutions.

INTRODUCTION

Channelling and reflection of charged particles on crystal lattices have proven to be very effective for high energy beam manipulations [1–3]. Bent crystals possess steering capabilities equivalent to very high magnetic fields, while being very compact (physical interaction length of a few mm-cm) and passive (no energy required for steering). However, they have very limited angular acceptance and require precise devices to position and orient them close to the beam. While the crystal systems remains roughly similar (a bent crystal in a metallic holder), the operating devices are heavily dependant on the crystal application (such as beam energy or particle type) and functionality.

CERN CRYSTAL MANIPULATION SYSTEMS REQUIREMENTS

Three devices are presented in this paper. The Target Extraction Crystal version A (TECA) is used in the CERN SPS Long straight section 4 (LSS4) during the slow extraction to reduces beam losses by preventing particles to impinge on the electrostatic septum wires downstream. Four Target crystal Primary Collimators TCPCs are installed in interaction region 7 of the LHC ring (IR7) and are part of the LHC collimation for betatron cleaning during ions-run, preventing quenches in the nearby superconducting magnets. The last device is the Target Crystal Collimator for Precession (TCCP); the second part of a dual crystal set-up that could be installed in the LHC interaction region 3 (IR3) at the end of 2024, as a proof of concept for measuring the dipole moment of short-lived baryons [4].

The purpose of these three devices is identical : positioning bent crystal assemblies at a given distance and orientation with respect to the circulating beam. Their differences are rooted in the specificity of their requirements, summarised in Table 1.

The TECA is operated at a lower energy, using a mix of crystal channelling (Channel.) [5] and volume reflection (VR) [6] to deflect the beam away from the Septum wires. Angular acceptance of the crystal for channeling is higher at low energy [7], which allows for a bigger tolerance in angular positioning. The full volume of the crystal is used for interaction, which means that linear position with respect to the beam is less critical.

The TCPCs are used for LHC betatron cleaning during ions runs with direct interception of the beam halo on the edge of the crystals. They require both a very high angular positioning (as the acceptance for channeling at 7 TeV/c is only around 2 µrad), but also a high linear accuracy, as the edge of the crystal must follow the drifts of the beam.

Finally, the TCCP aims to be used for high intensity proton runs, and will operate a longer crystal assembly. Two operation modes are required : direct interception of the beam halo by the crystal, or as part of a double crystal channelling experiment [4]. In this mode, a secondary particle production tungsten target must be positioned between 100 µm and 500 µm upstream of the crystal, with a 100 µm accuracy.

TECA DESIGN

Of the three devices presented, the TECA has the more permissive requirements, which allowed for a design driven by simplicity of procurement, manufacturing and commissioning. The elements of the mechanisms are presented in Figure 1. The crystal assembly (1) is attached to one of the two extremities of a lever arm, both ends being connected with a flexible hinge (3) to a linear motion system (2). Hence, linear and rotational motion are coupled by design. Linear motions are provided by stepper motors, reduced and connected to a linear platform, giving a motion resolution of

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Table 1: Devices Specifications

Spec	**TECA**	**TCPC**	**TCCP**
Particles	p^+	$^{208}_{82}$Pb	p^+
Energy	400 GeV/c	7 TeV/c*	7 TeV/c
Crystal length	2 mm	4 mm	70 mm
Crystal bending	>150 µrad	50 µrad	7 mrad
Interaction zone	Volume	Edge	Volume
Interaction type	Channel. + VR	Channel.	Channel.
Linear Res.	5 µm	5 µm	5 µm
Angular Res.	1 µrad	0.1 µrad	0.1 µrad
Angular Acc.	10 µrad	1 µrad	1 µrad
Target	No	No	Yes

* Protons equivalent

0.25 µm/step. The lever arm being 0.4 m, angular resolution achieved is 0.625 µrad/step.

The control system for the device operates in closed loop on the stepper motor resolver signals, but open loop on the crystal angular position. Even though the crystal can be observed through the viewports (4) for initial alignment, no direct measurement of the crystal angular position is possible in operation, but rather it is indirectly measured based on a relationship known a priori of the linear axes positions and corresponding crystal angle. The crystal is ultimately finely positioned using the measured beam losses as a reference. Moreover, only one of the two linear actuators is used for angular correction, which implies that small parasitic linear motions occurs. Theses motions remains acceptable as the beam interacts with the full volume of the crystal.

When the crystal is not used, it is hidden away from the beam by retracting the holder behind a plate with cutouts that closes the lever arm chamber, to reduce the coupling impedance of the device.

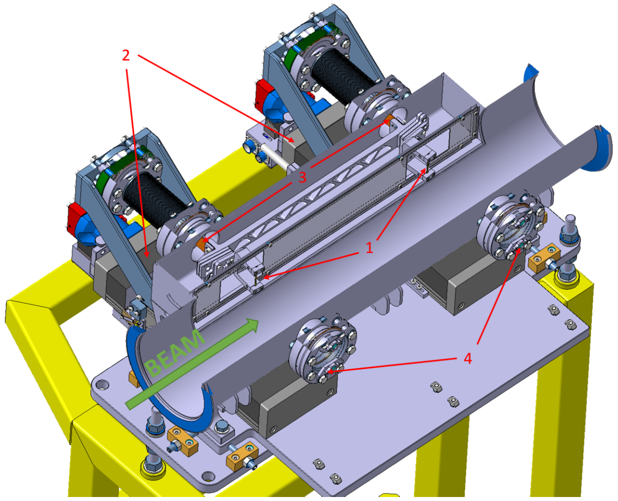

Figure 1: Cutview of the TECA | 1-Bent Crystal Assemblies | 2-Linear motion stages | 3-Flexible hinges | 4-Viewports and alignment mirrors.

TCPC DESIGN

Compared to the TECA, TCPCs are operated with beams of much higher energy and lower crystal acceptance. The accuracy of angular positioning has to be one tenth of the TECA's . To achieve 1 µrad accuracy, the design strategy adopted differed from the TECA.

Core design elements are presented in Figure 2. Linear and angular motions were separated, to minimize parasitic mechanical couplings. While linear motion is still driven by a reduced stepper motor, the rotational motion is now performed by a dedicated rotational stage, displayed in Figure 3. The actuator of the rotational stage is a piezo-eletric piston, with a spring acting as preload to avoid backlash. The pivot function is achieved by the flexion of flexible thin blades within a single part, to avoid any contact friction between the elements.

The electronic control of the crystal angular position is now in closed loop control with direct feedback of the crystal angle provided by an interferometry system. Three optical heads measure an accurate distance to matching retroreflectors rigidly linked to the crystal assembly, providing a measurement feedback with less than 0.1 µrad resolution.

Finally, the TCPC use is limited to ion beams, as the beam coupling impedance would be very high for nominal intensity proton beams (see Table 2) [8]. A replacement chamber was designed that can be inserted to cloak the crystal cavity when the crystal is in the parking position, offering the proton passage a continuous vacuum chamber.

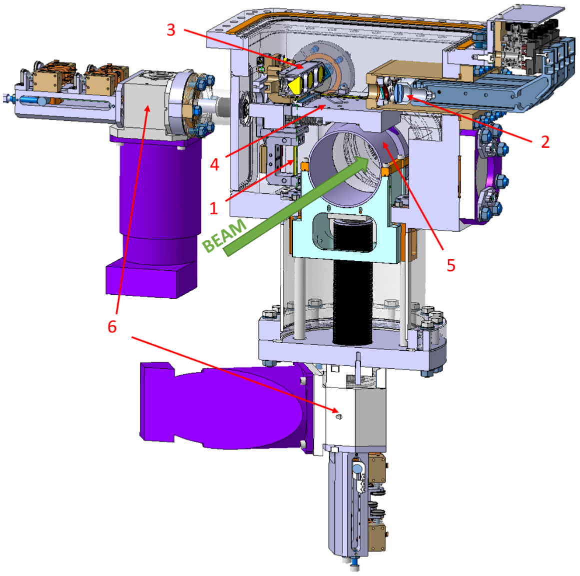

Figure 2: Cutview of the TCPC core assembly | 1-Bent Crystal Assembly | 2-Interferometer optical heads | 3-Retroreflectors | 4-Rotational stage | 5-Replacement chamber | 6-Linear actuators.

TCCP DESIGN STRATEGIES

Compared to a TCPC, the TCCP present additional design challenges. The angular accuracy and resolution require-

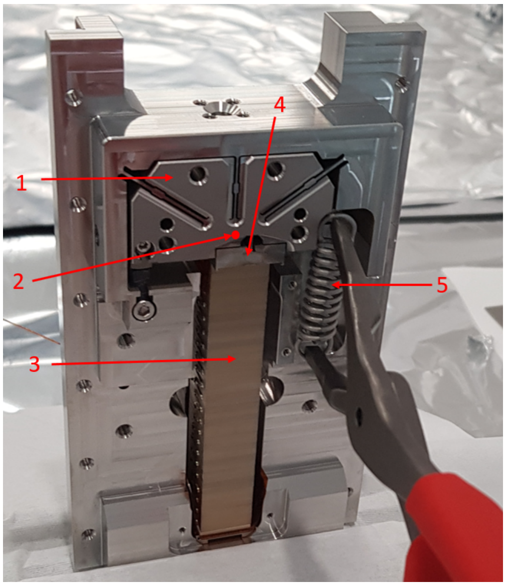

Figure 3: Picture of TCPC rotational stage during assembly |1-Crystal fixation block | 2-Flexural pivot axis | 3-Piezoelectric stack | 4-Piston | 5-Tensioning spring.

ments remain identical, and hence the design of TCCP will have a similar construction to that of the TCPC, with independent linear and angular motions, a dedicated rotational stage, and an interferometer to measure the angular position of the crystal.

The target used for production of secondary particles will be designed with an independent linear motion. As it has to move within 500 µm the crystal, the motion will be guided by precision linear rails, and will feature an adjustment mechanism.

Unlike the TCPCs, the TCCP aims to be designed for use with proton beams of high intensity. The strategy to mitigate the device impedance is to avoid the presence of low frequency resonant modes due to the geometry and materials in vicinity of the beam. Preliminary impedance studies were conducted to evaluate the effects of various cavities designs on the induced electromagnetic power losses, as more than a few watts of heating would require a complex cooling system. The model used a simple beam tube with a cut out on one side to accommodate for the passage of the crystal holder. Results of theses studies, summarized in Table 1, showed that this cavity design is a significant improvement compared to the TCPC cavity studied in [8]. In identical conditions (crystal in parking position), the losses are 100 times lower. The most critical design element for the equipment is to maintain electrical continuity between the beam tube and the crystal holder. Electromagnetic losses in operational position remain important, primarily because of the shape of the crystal holder itself. Further improvement could be achieved by changing the design and materials of the crystal holder.

The schematic design of the equipment is presented in Figure 4. A rotational stage similar to the one of the TCPC (3) is linked to a crystal assembly (1) relocated to be inserted through the side of the beam tube. The tungsten target (2) and rotational stage are moved by linear motion systems with stepper motors located out of the vacuum tank (5). Electric contacts (8) between the tube, crystal holder support and target support ensure that most of the vacuum tank is invisible to the beam for loss minimisation.

Table 2: Power losses scenarios for several design configurations. Reference beam is LHC-HL proton beam with 2760 bunches, 2.2e11 proton per bunch, bunch spacing of 25 ns.

Config.	RF Contacts	Cry. Pos.	Losses
TCPC w. chamber retracted [8]		Parking	595 W
TCCP	No	Parking	5 W
TCCP	Yes	Parking	2 W
TCCP	Yes	Operation	570 W

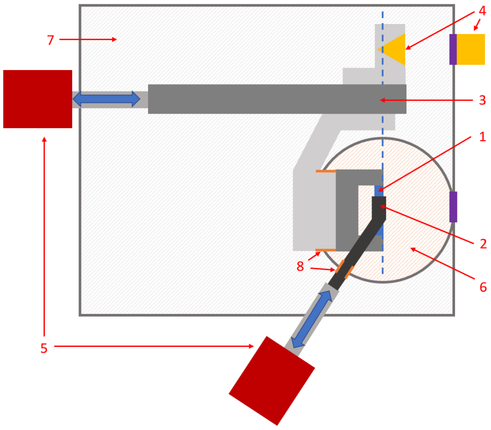

Figure 4: TCCP core schematics, cutview perpendicular to beam axis | 1-Crystal | 2-W Target | 3-Rotational stage | 4-Interferometry system | 5-Linear motion systems | 6-Electromagnetic cavity | 7-Vacuum tank | 8-Electric contacts.

CONCLUSION

Three devices operating bent crystal for beam manipulation were presented in this paper. The TECA uses a simple design to provide a passive loss reduction up to 40 % during slow extraction from the SPS to the CERN North Area [9]. Its effectiveness has already been demonstrated and short term improvements will focus on the characteristics of the crystal assembly rather than the device itself. The four TCPCs operating for betatron cleaning during ions runs at IR7 of the LHC constitutes a reference for high precision goniometers, as they are able to reliably maintain the crystals in the very narrow acceptance range of crystal chanelling at high energy. Finally, the TCCP aims to capitalize on the know-how acquired with TCPC design to accommodate a longer crystal, an independent tungsten target, and operation for proton beams up to HL-LHC nominal intensities.

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