Nuclear Inst. and Methods in Physics Research, A 924 (2019) 394–399

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

A high angular resolution silicon microstrip telescope for crystal channeling studies

G. Hall [*], G. Auzinger, J. Borg, T. James, M. Pesaresi, M. Raymond

Blackett Laboratory, Imperial College, London SW7 2AZ, UK

ARTICLE INFO

Keywords:
ASIC electronics
Tracking detectors
Silicon microstrips
Crystal channeling

ABSTRACT

A charged particle telescope has been deployed for data taking at high rates in a CERN beam line using protons and other particles. The apparatus has a baseline of approximately 10 m in each arm, and achieves an angular resolution of 5.4 μrad using 400 GeV/c protons. The electronic readout and data acquisition system is based on that developed for the CMS Tracker, and provides almost deadtime-free operation at trigger rates of up to about 10 kHz.

The telescope was developed to characterize crystals used in channeling experiments with a primary objective to validate them for use in a future LHC beam collimation system. The telescope has also been used for other studies of fundamental phenomena associated with the channeling process.

The telescope is described, and its measured performance, referring to results from channeling studies, including recent measurements in heavy ion beams.

1. Introduction

A charged particle telescope has been developed for data taking by the UA9 collaboration [1,2] at high rates in the CERN H8 beam line using protons and other particles. It has been previously described [3] so only a brief summary of the system is given here, with further details of its operation which have not previously been reported. It normally uses ten planes of silicon microstrip sensors, arranged as five pairs, each measuring two coordinates, with an active area of 3.8 × 3.8 cm^2. The apparatus has a baseline of approximately 10 m in each arm. The sensors are instrumented by a system based on the electronic readout chain developed for the CMS Tracker [4] and a simplified version of the data acquisition software, to provide almost deadtime-free operation at trigger rates of up to 9 kHz.

The telescope was developed to characterize crystals, most commonly made of silicon, used in channeling experiments with a primary objective to validate them for use in a future LHC beam collimation system. Channeling is a well-established phenomenon whereby a charged particle is confined by the strong electrostatic potential well between crystalline planes [5]; by bending the crystal a parallel particle beam, or its halo, can be steered in a selected direction and hence used for efficiently reducing the LHC beam halo. A series of measurements of such crystals have been carried out over several years, and a prototype beam collimation system was installed in the LHC in 2016. Meanwhile, this telescope has also been used for other studies of fundamental phenomena associated with the channeling process.

2. Layout

The telescope layout is shown in Fig. 1. The upstream section for measurement of incoming tracks is formed by planes 1 and 2 while outgoing tracks are measured using planes 3, 4 and 5; both sections have lever arms of ~10 m. A precise goniometer is provided at the center of the apparatus between planes 2 and 3 to perform angular scans of a crystal mounted on the goniometer, to orientate it for channeling.

A narrow, low divergence 400 GeV/c proton beam is available in the external H8 beamline of the CERN SPS; other types of particle and energy can also be provided. The beam is ejected with a time structure consisting of a flat top when particles are present, lasting about 10 s, followed by about 35 s of no beam. Events are triggered on the coincidence of signals from a pair of plastic scintillators placed downstream of the telescope. The goniometer angle is adjusted in steps in the intervals when no particles are present. The data capture rate must be high enough to capture typically a few thousand events at each angular position to provide adequate statistics.

In this configuration, the dominant contribution to the angular resolution is from multiple scattering due to the sensors while the position resolution of the microstrips closest to the crystal determines the impact parameter resolution at the crystal. The sensor thickness was measured to be 320 μm, so each station of two planes contributes ~2.4 μrad for minimum ionizing hadrons.

Sensor signals are read out by APV25 chips [6,7]; the APV25 is a 128 channel 0.25 μm CMOS ASIC designed for CMS silicon microstrips with

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[*] Corresponding author.
E-mail address: g.hall@imperial.ac.uk (G. Hall).

https://doi.org/10.1016/j.nima.2018.08.060
Received 7 February 2018; Accepted 19 August 2018

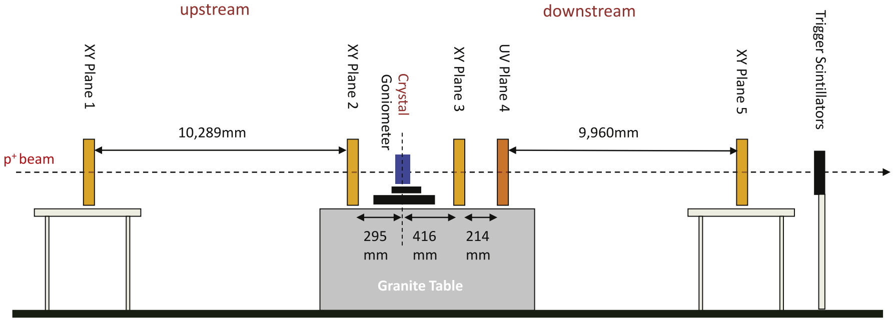

Fig. 1. Experimental layout in the H8 beam line, showing typical locations of the sensor planes and goniometer.

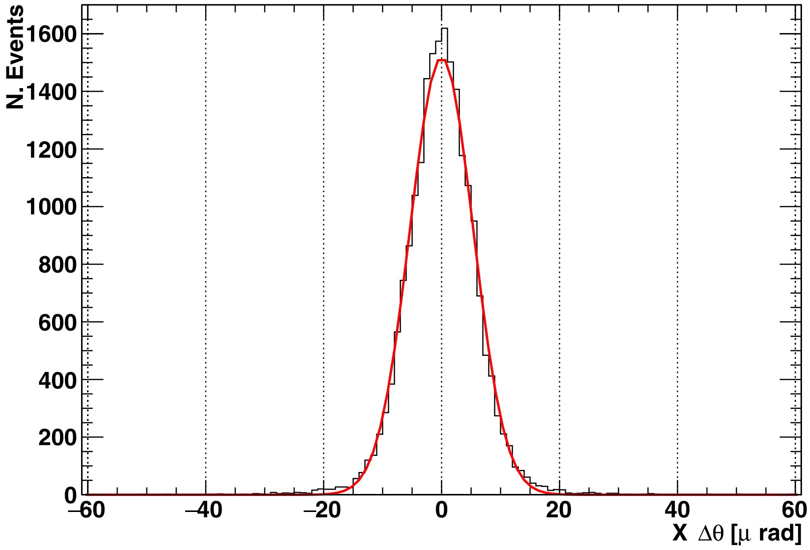

Fig. 2. The distribution of the measured difference between incident and outgoing angles in the horizontal plane for 400 GeV/c protons, with a Gaussian fit to the data. As there is no crystal in place for this alignment measurement, the data are centered on zero. Virtually identical behavior is observed in the vertical plane.

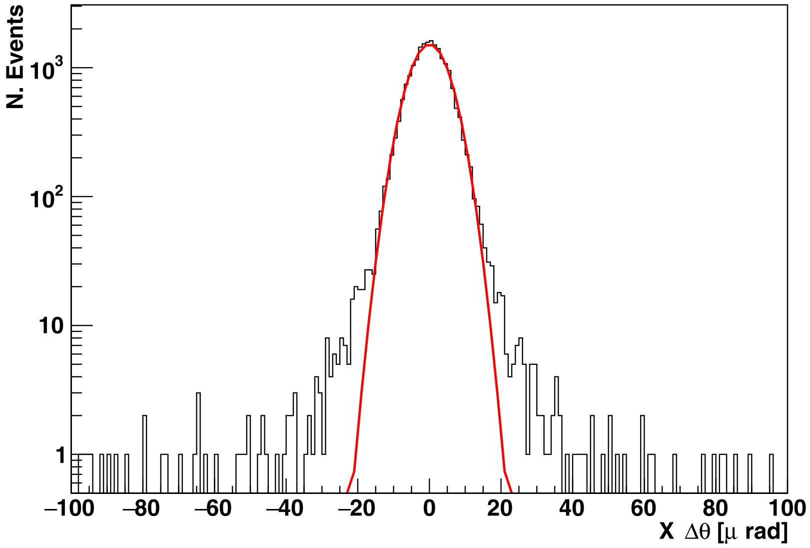

Fig. 3. The data of Fig. 2 plotted on a log scale.

capacitances of 10–20 pF. The front-end amplifier produces a CR-RC shaped pulse with a peaking time of 50 ns, and consecutive samples of the pulse shape are continuously stored in an analog pipeline memory every 25 ns using a 40 MHz clock. The operational mode of the APV25 chip, and bias settings, are programmable via an I^2C interface; more details can be found in [6]. For this application the chip was configured to operate in peak mode, where a single sample (for every channel) is retrieved from the pipeline following an external trigger, and an output data frame is produced containing the analog samples from all 128 channels. Accessing the analog memory is achieved by write

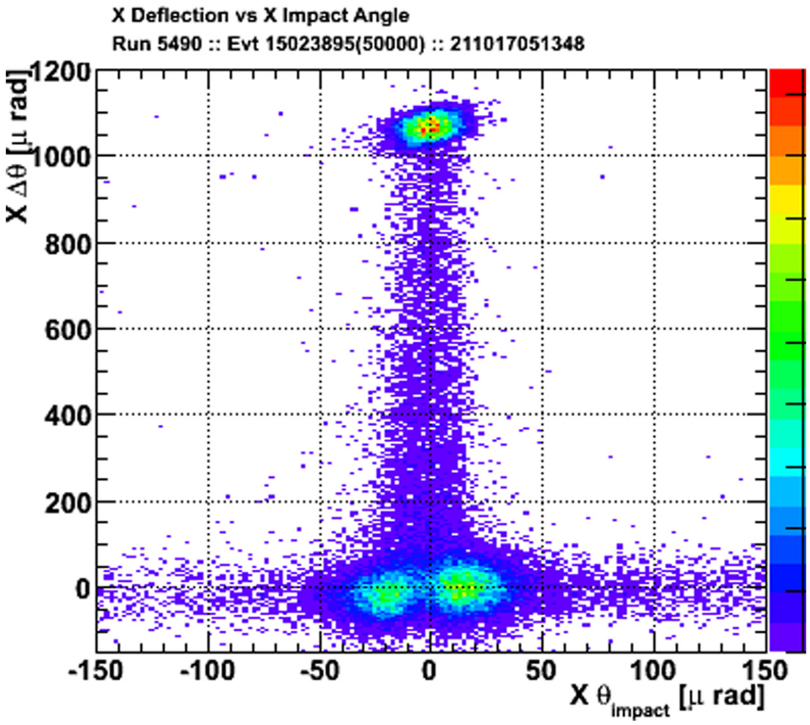

Fig. 4. Horizontal (x) angular deviation vs. impact angle on the crystal for incident pions of 180 GeV/c. The double peak structure around $\Delta\theta = 0$ is due to depopulation of that region by particles captured due to channeling.

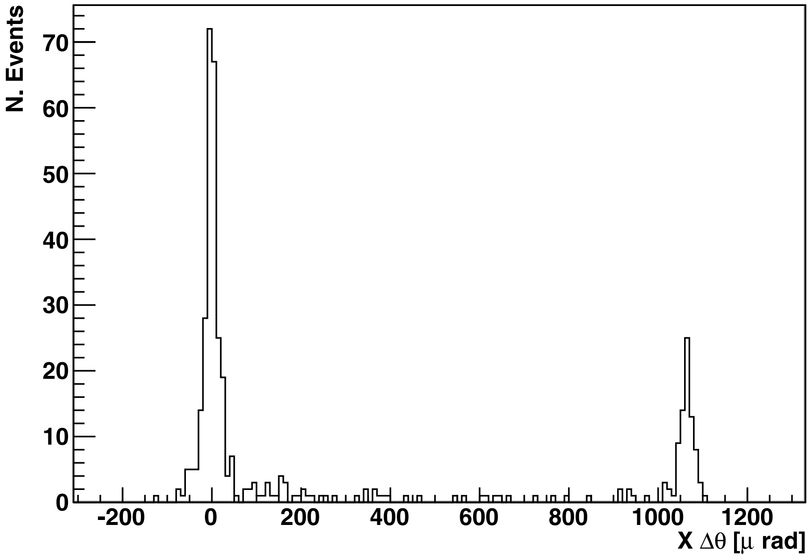

Fig. 5. Deflection angle of incident pions of 180 GeV/c by a 56.8 mm long silicon crystal showing the undeflected beam with the channeled particle peak on the right.

and trigger pointers, with a programmable delay (latency) between them, such that when a trigger is applied the corresponding data sample which is retrieved was stored a latency period previously. The latency accommodates all delays (signal propagation, decision taking) associated with generating the trigger.

Some throttling of the trigger is required, to avoid extreme Poisson fluctuations in the rate which might cause pipeline overflow. Because the APV25s are configured with different latencies to accommodate particle time of flight differences over the 20 m of the apparatus, which is not the case in CMS, a conservative limit which vetoes triggers within 1024 40 MHz clock cycles of the previous trigger was adopted. The resulting dead time is small.

3. Track reconstruction

The method used is as described in [3]. Briefly, a single 2D hit is required in each plane for the event to be included, and two straight line fits with three parameters $\theta_{in}, \theta_{out}, d_0$ (representing incident and outgoing angle and transverse impact parameter at the target) are applied to each projection (x, horizontal, or y, vertical), with z the direction along the beam. Multiple scattering error correlations are included in the fit covariance matrix, and a χ^2 cut is applied to the fitted tracks.

Normally the lateral dimensions of the H8 beam are such that it is well contained within the silicon telescope; the channeling angle, which

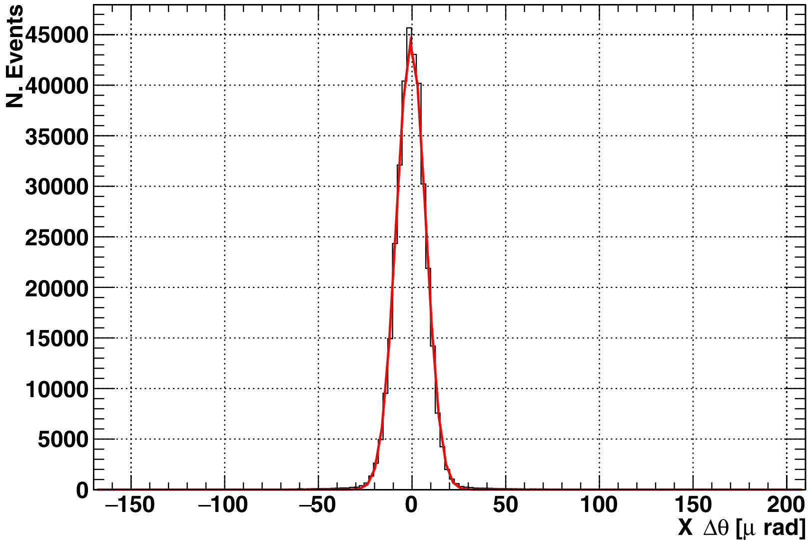

Fig. 6. The distribution of the measured difference between incident and outgoing angles in the horizontal plane for 150A GeV/c xenon ions, with a Gaussian fit to the data.

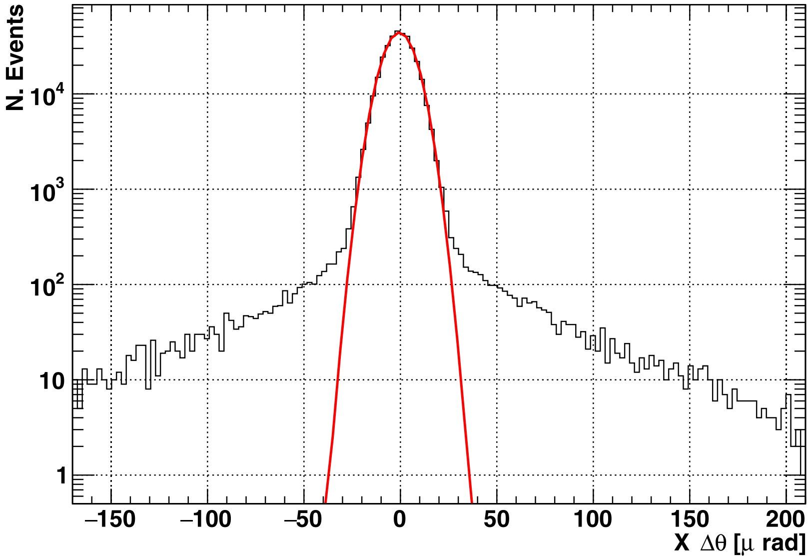

Fig. 7. The data of Fig. 6 plotted on a log scale, to display the non-Gaussian tails of the distribution.

is chosen for practical reasons and set by bending the crystal, can then be as large as the dimensions of the sensors permit. The angle at which the beam is incident on the crystal is important for channeling studies, since only particles within a certain critical angle can be captured by the crystal planes [5]. This angle can be written for silicon crystals as $\theta_{crit} \approx 6.3$ μrad/$\sqrt{p}$ where p is the particle momentum in TeV; this corresponds to 10 μrad for 400 GeV/c protons. The divergence of the beam is therefore relevant for channeling studies, since it will determine the overall channeling efficiency for the beam provided, but the incoming arm of the telescope allows the selection of trajectories which fall within the critical angle.

The H8 beam divergence varies with the particle type and energy; for 400 GeV/c protons typical measured values were $\sigma(\theta_y) = 7.45$ μrad and $\sigma(\theta_x) = 10.24$ μrad.

For the angular reconstruction the difference $\Delta(\theta) = \theta_{in} - \theta_{out}$ is the quantity of most interest. Alignment runs are carried out with no crystal in place on the goniometer, from which fits to the distribution of angular deviations give $\sigma(\Delta\theta) = 5.38 \pm 0.03$ μrad for the overall angular resolution of the full telescope in both x and y (Fig. 2). The ultimate resolution is predicted to be 4.4 μrad, assuming the system to be in vacuum with perfect alignment, a hit resolution of 7 μm, and using the Moliere description of multiple scattering [8]. The difference is attributed to imperfect knowledge of the material in the system, including multiple scattering contributions from air in regions where the vacuum pipe could not be extended, and non-Gaussian tails, which are visible in the data (Fig. 3). A simulation modified to include some of these effects estimates an angular resolution of ~5.0 μrad.

Data have been taken with range of beam particles, including 400 GeV/c protons, 180 GeV/c π, light (e.g. Ar) and heavy (e.g. Pb, Xe) ions, and a large number of different crystals and types of crystal have been characterized. Typical data taking runs acquire ~10 million triggered events. An example of data taken with 180 GeV/c pions is shown in Fig. 4 where the angular deviation vs incident impact angle on the crystal is plotted. The channeled particle peak is clearly visible at $\Delta\theta \sim 1050$ μrad, as well as fewer particles with smaller angular deviation, which have been dechanneled [5] during the traversal of the crystal. This can be seen in Fig. 5 which plots the angular deviation for pions within an angular range of ±10 μrad, which is less than the critical value of ±15 μrad.

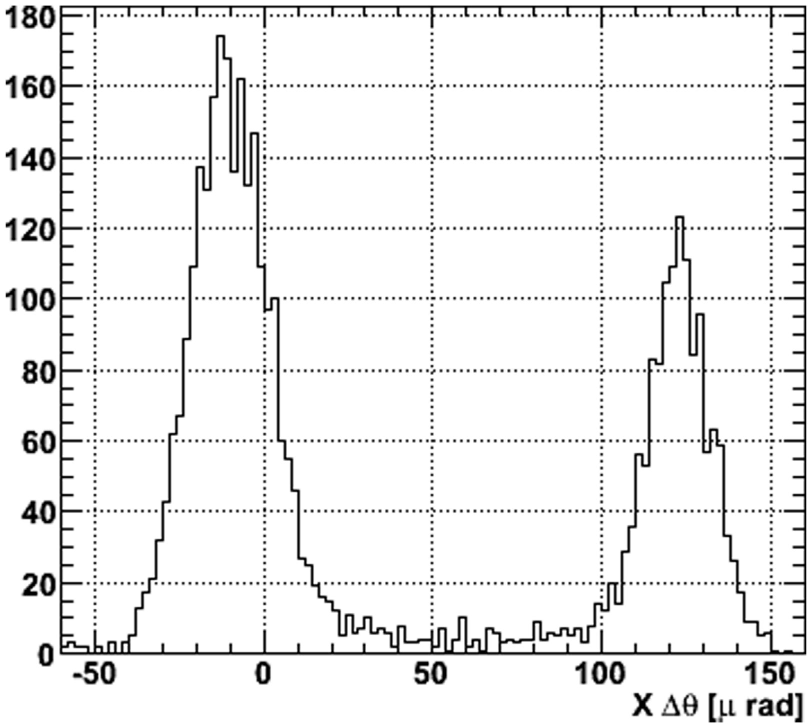

Fig. 8. Horizontal deflection angle of 150A GeV/c xenon ions using a 2.5 mm long silicon crystal showing the undeflected and channeled particle peaks. Note the negative shift in the non-channeled particles, caused by volume reflection.

4. Data taking with heavy ions

Since significant data taking at the LHC uses ion beams of different types, and these present particular challenges for the beam collimation process, it is essential to characterize channeling crystals with ion beams as well as protons and pions. However, ion beams also present challenges for the telescope operation. The APV25 was designed with hadrons such as pions in mind and the signals expected are those typical of singly charged minimum ionizing particles (MIPs) incident on sensors of up to 500 μm thickness. In contrast, a fully stripped ion will generate a charged signal in the silicon Z^2 times larger than a singly charged hadron, where Z is the atomic number of the ion. For example, xenon ions ($Z = 54$) will generate signals of almost 3000 MIPs, which is well beyond the ∼7 MIP linear dynamic range of the APV25.

The two principal concerns about such large signals were that capacitive coupling between the microstrips might spread the signal across many channels and considerably worsen the spatial resolution, or that significant exposure to such large signals might damage the sensors. Both of them could only be established by experimental tests. In addition, a feature of the APV25 discovered during CMS commissioning [9], where rare recoiling silicon ions generate extremely large ionization deposits in the sensors, can cause a voltage baseline shift in the amplifier and give rise to some dead time during operation. However, even at the data taking rates in H8 this does not have a very significant impact on data, in view of the veto on close consecutive triggers already mentioned.

There is no possibility to adjust the amplifier gain in the APV25. Hence it was decided to operate the sensors only partially depleted to reduce the ionization signal sizes; thus the normal sensor operating voltage of 150 V was reduced to 3.6 V. In the data analysis, a threshold of approximately 5 MIPs was applied to each strip to be included in a cluster, which is very different from the criteria used to identify clusters in MIP data taking [3]. Clusters of up to 20 strips were allowed, compared to 8 normally. Under these conditions, most clusters were small, with the peak cluster size in a xenon beam of 150A GeV/c (A is the ion atomic number) found to be ∼3 strips compared to 1–2 normally. Under these conditions, the angular resolution for the complete telescope was found to be $\sigma(\Delta\theta)$ = 7.8 μrad, to be compared to 5.4 μrad with 400 GeV/c protons. For lead ions of 30A GeV/c $\sigma(\Delta\theta)$ = 29.6 μrad was measured.

Fig. 6 shows alignment data for a xenon beam of 150A GeV/c, and Fig. 7 shows the same data plotted on a log scale, where the non-Gaussian tails are very visible. Data taken with a 2.5 mm long silicon crystal to channel xenon ions is shown in Fig. 8; in this case the channeling deflection angle is $\Delta\theta \sim 120$ μrad. In this mode, the incident beam appears to be deflected in the opposite direction. This is caused by a phenomenon known as volume reflection [5] whereby beam particles can be reflected by the potential due to the crystal planes. In a bent crystal, this occurs in the opposite direction to capture by channeling.

In addition to measurements to characterize crystals for collimation of LHC beams, other studies using channeling have been carried out in the H8 beam using this telescope. They include observations of parametric X-ray radiation [10], beam focusing and defocusing using bent crystals which were specially cut for the purpose [11], and measurements to demonstrate the reduction in nuclear scattering events when particles are channeled [12].

5. Conclusions

A silicon microstrip tracking telescope has been used for several years for high rate data taking in the CERN H8 beam line with several types of incident particle. Measurements have been taken with xenon and lead ions, which generate very large ionization signals. With adjustment of the sensor operating voltage and thresholds to select hits used to construct clusters, the angular resolution of a xenon ion beam of 150A GeV/c traversing the full telescope was measured to be 7.8 μrad, to be compared to the 5.4 μrad with 400 GeV/c protons. The sensors and telescope were found to be reliable for periods of operation lasting several weeks, with no evidence of damage.

Acknowledgments

We gratefully acknowledge financial support from the UK Science and Technology Facilities Council, United Kingdom. We thank our collaborators in the UA9 experiment, and CERN, Switzerland for support with test beams.

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