A double-crystal setup for LHC fixed-target experiments

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29 June 2023

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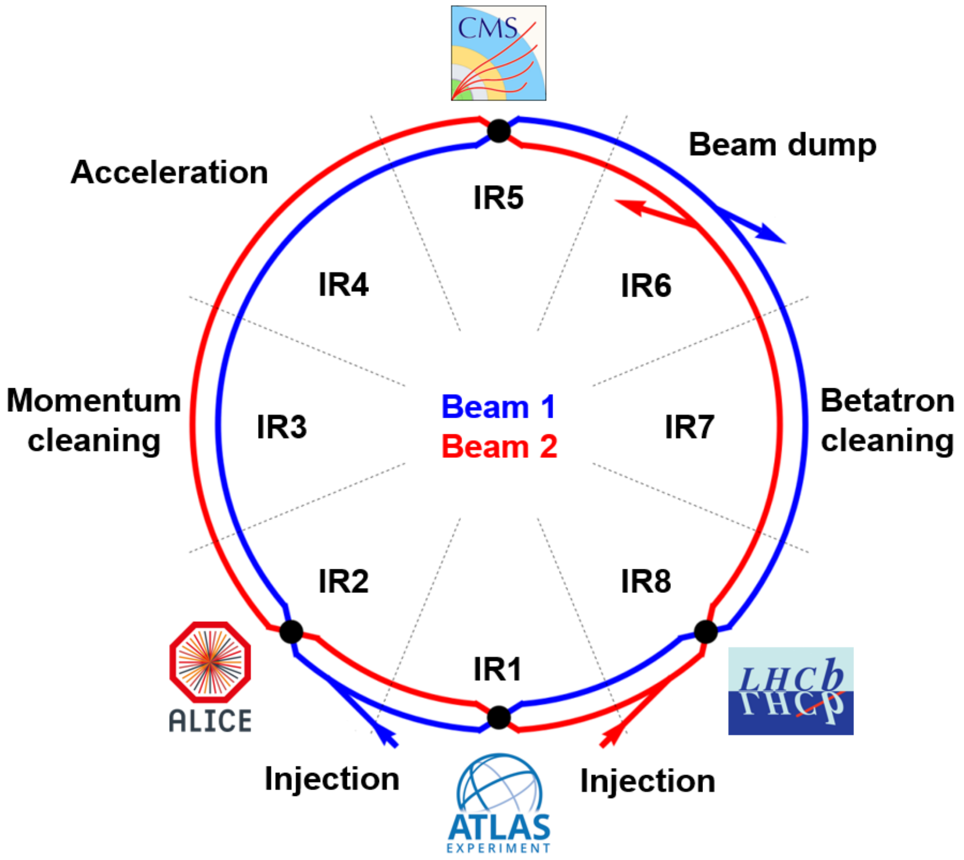
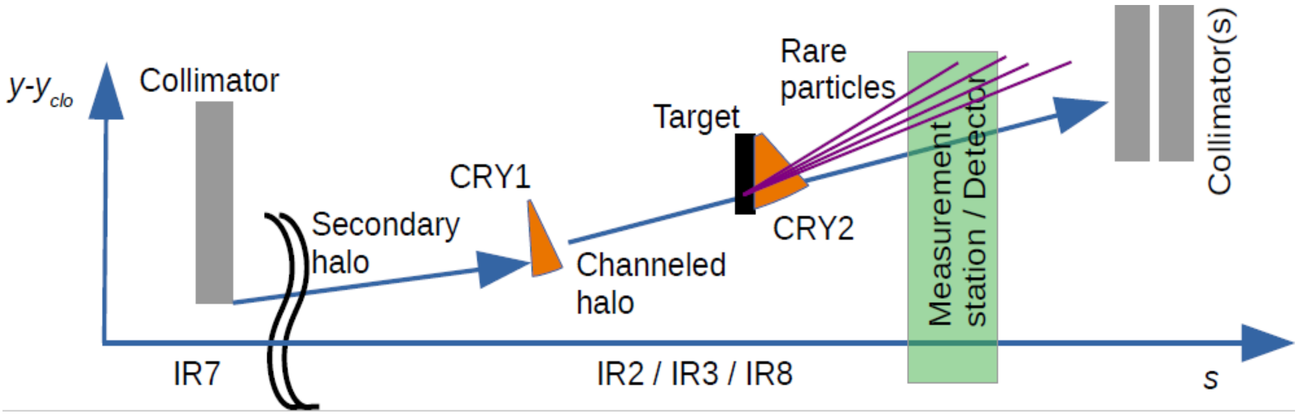
Overview of the final PBC experiment: LHC Run 4

LHC



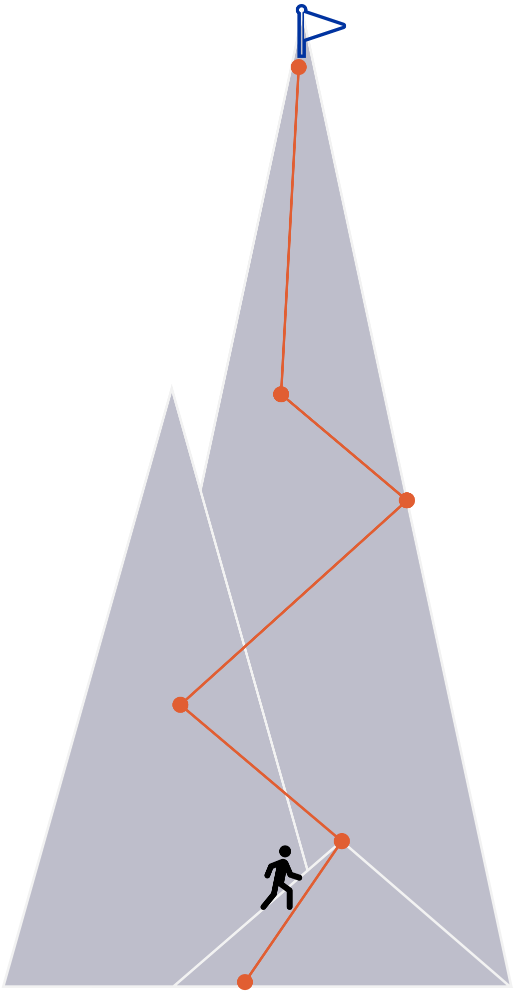
Double-crystal experiment



LHC Run 4 idea: employ unprecedented setup to measure of the electric and magnetic dipole moments (EDM and MDM) of short-lived baryons like Λ_C

First measurement of Λ_C presession!

Physics Beyond Colliders: IR3 experiment



Final PBC double-crystal experiment
Aim: To measure the magnetic and electric dipole moments of rare baryons (Λ_c).

Run 4
HL-LHC
2029 +

Proof-of-principle (PoP) test stand
Aims: To gain operational and technical experience.
To characterise the IR3 crystals.
To measure crystal channelling efficiency at TeV energies.

Run 3
LHC
2025 +

Crystals in the LHC
Collimation crystals are already installed in IR7.
Crystal prototypes for IR3 are being manufactured and tested.

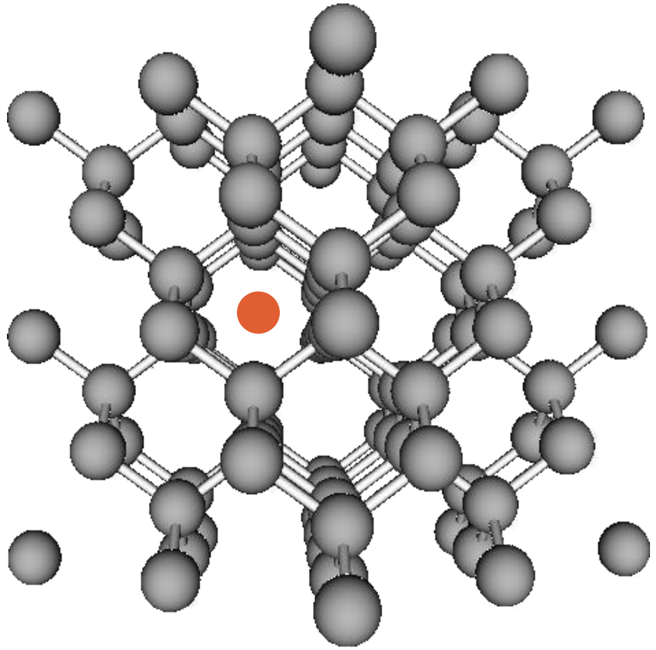
Run 3
LHC
2023 (today)

Contents

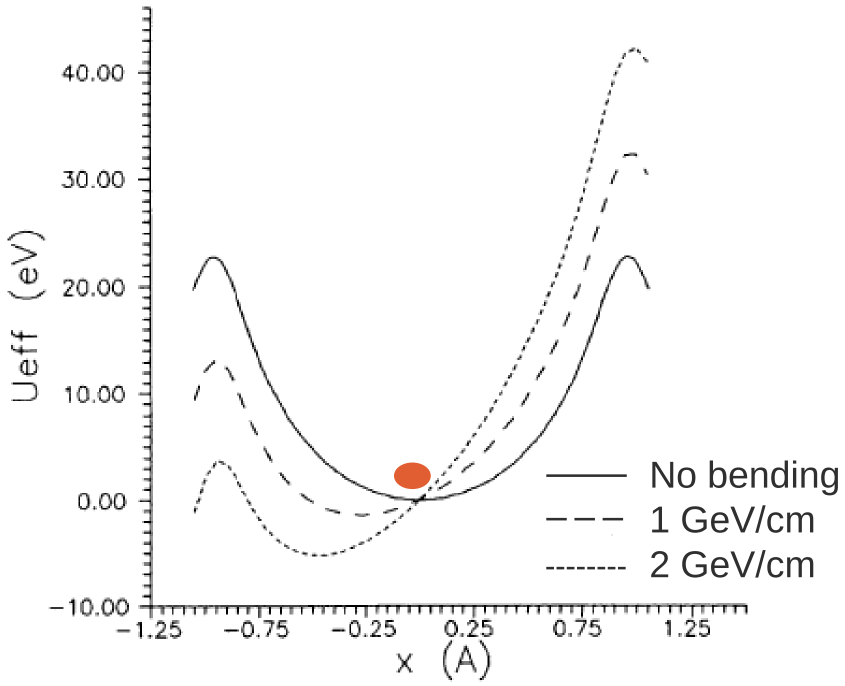
Why use crystals?

Charged particles follow the lattice structure of the silicon crystal. Holders clamp the silicon crystal sheet into a bent position. Proton trajectories are bent by the crystal in a short distance.

Crystal lattice

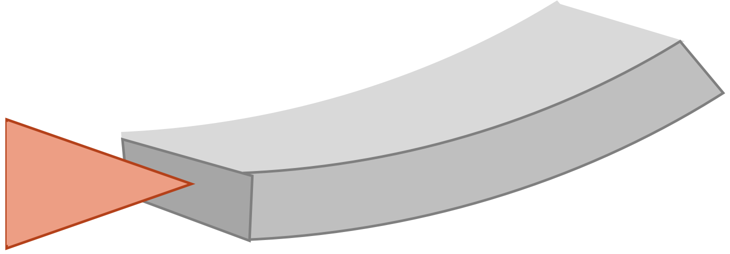


Channel particles



V. M. Biryukov et al., 1997
doi: 10.1007/978-3-662-03407-1.

Bend trajectory



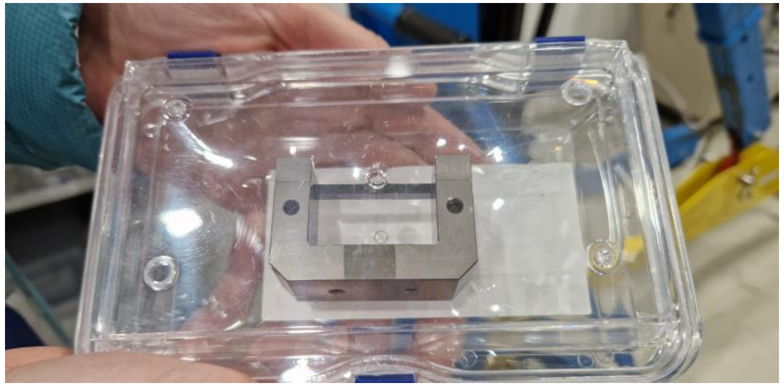
Critical angle

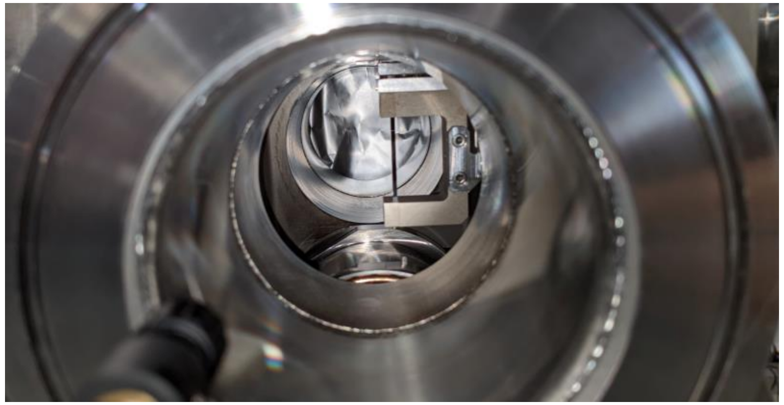
Λ_C will decay before it reaches the end of a magnet. Bend them more quickly with crystals!

The LHC crystals: TCCS and TCCP

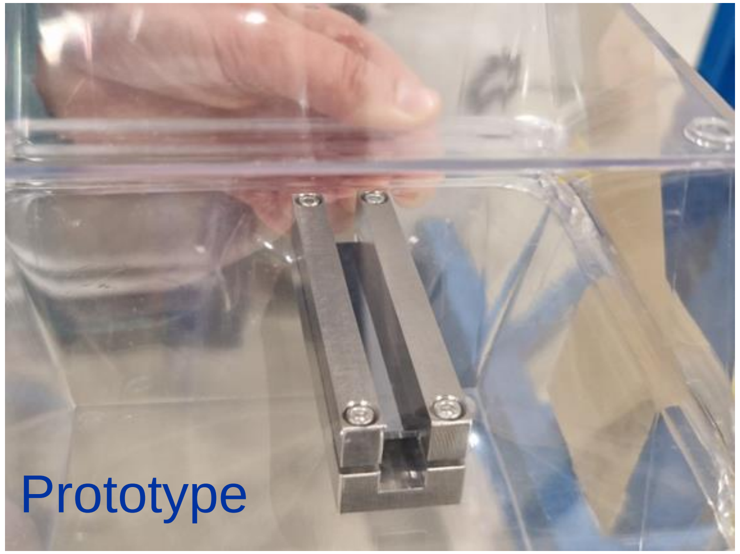
Charged particles follow the lattice structure of the silicon crystal. Holders clamp the silicon crystal sheet into a bent position. Proton trajectories will be bent by the crystal.

TCCS (crystal 1)

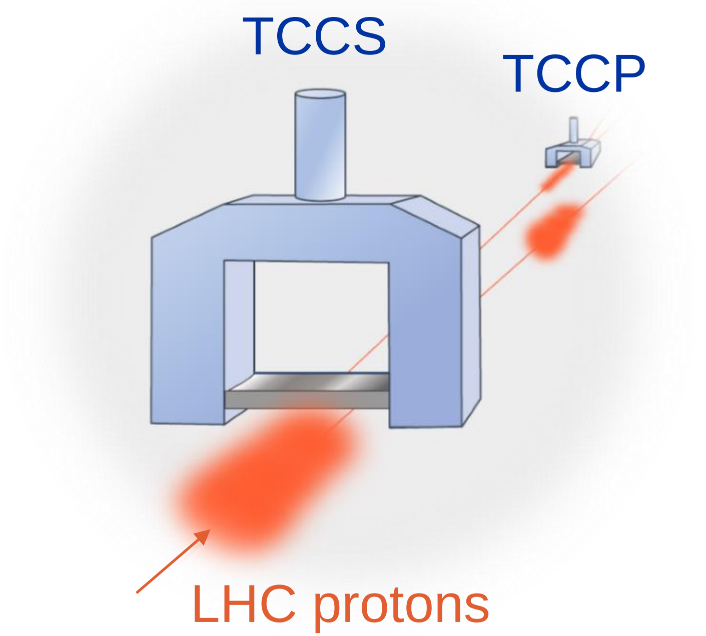




TCCP (crystal 2)



Arrangement



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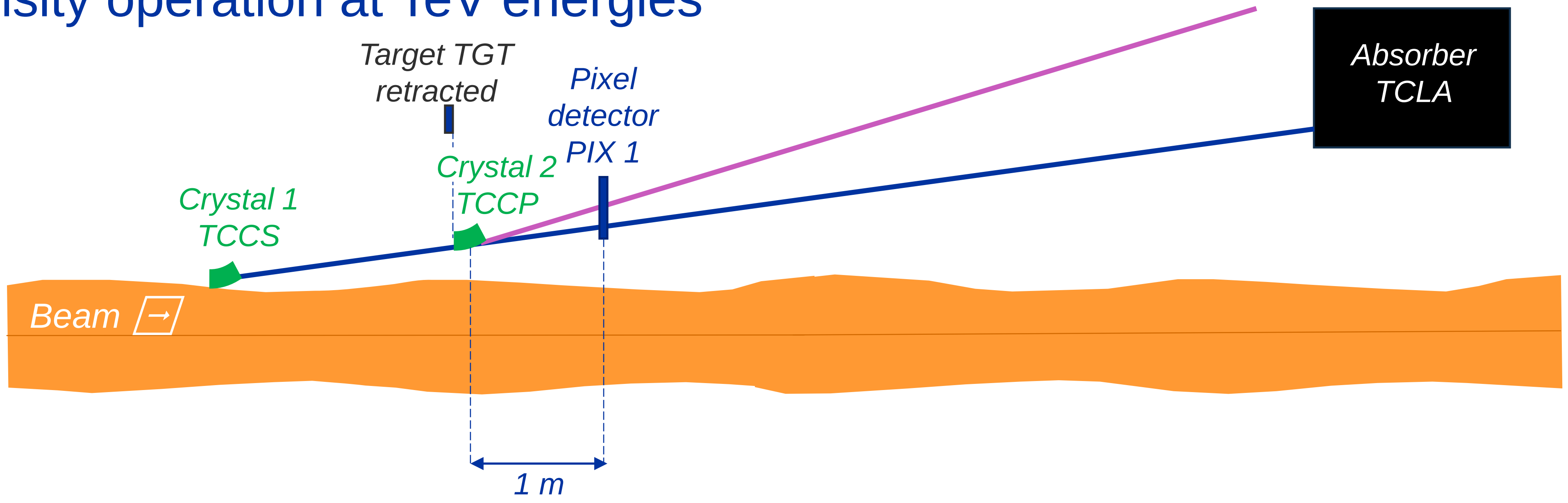
A Proof of Principle experiment
low intensity operation at TeV energies



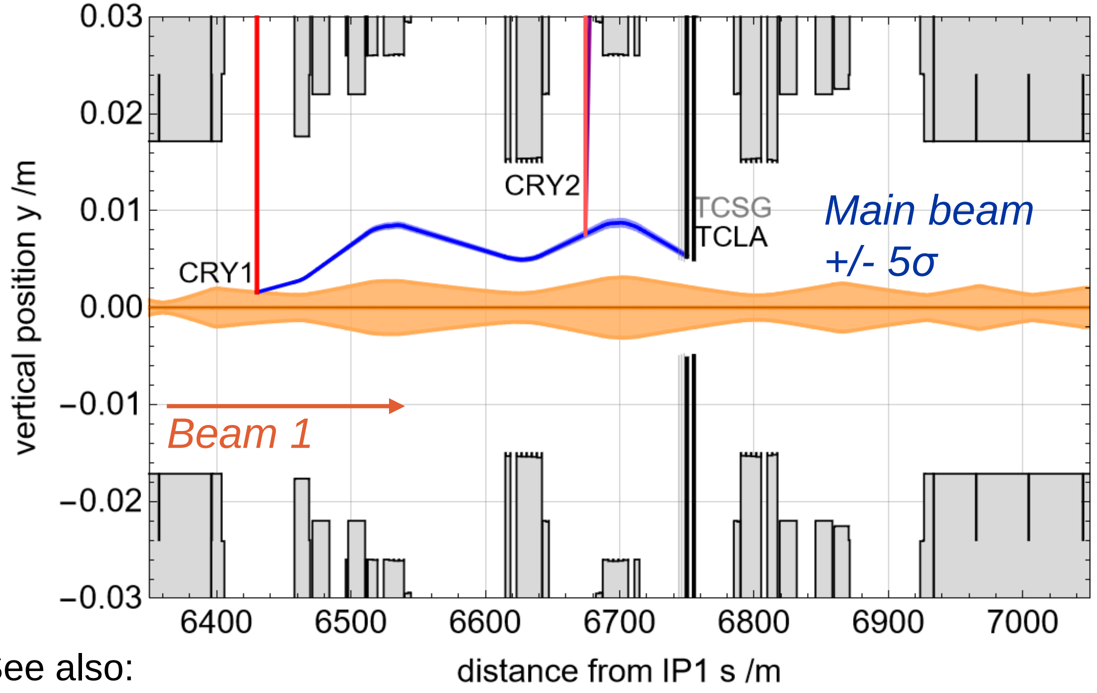
A goal on the journey: find the channelling efficiency of crystal 2 (TCCP)

Align CRY1 with the edge of the main beam (~5σ) to produce channeling – one spot on pixel detector
Align CRY2 (linear and angular position) to produce double-channelling – second spot on pixel detector
Measure intensity of double-channelled halo spot on the detector, to **find the channelling efficiency** of CRY2

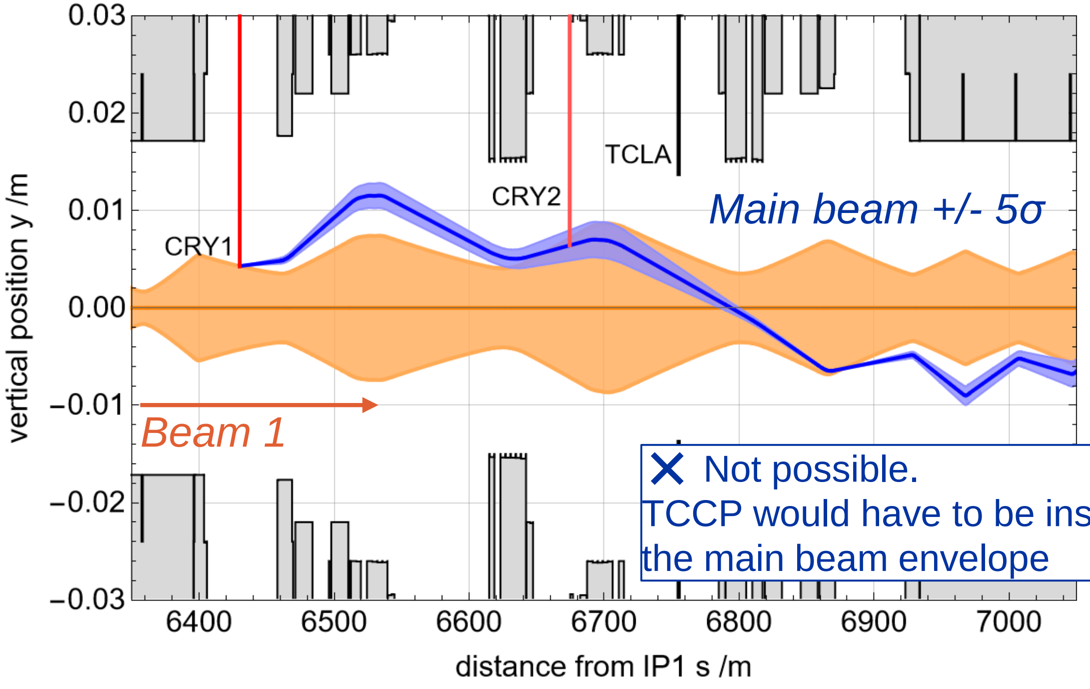
Layouts and energy

A layout was initially designed for 6.8 TeV. Crystal alignment to be done at different energies ~1-3 TeV. A natural starting point is injection energy (450 GeV). Is it possible…?

Beam 1 – trajectory at 6.8 TeV (Flat Top)



Beam 1 – trajectory at 450 GeV (Injection)

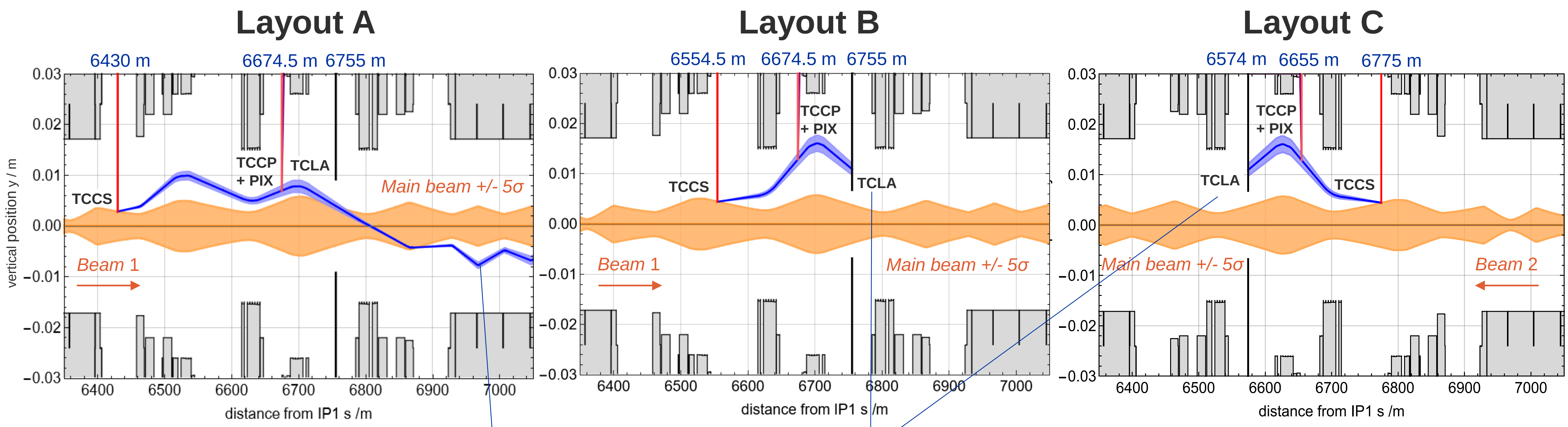


✕ Not possible.
TCCP would have to be inside the main beam envelope

See also:
P. Hermes, IPAC 2022

Need to consider other layouts

PoP: Considering 3 layouts at 1 TeV



Channelled halo from CRY1 can be absorbed at downstream TCT collimator (IR5).

Channelled halo from CRY1 absorbed at local vertical TCLA

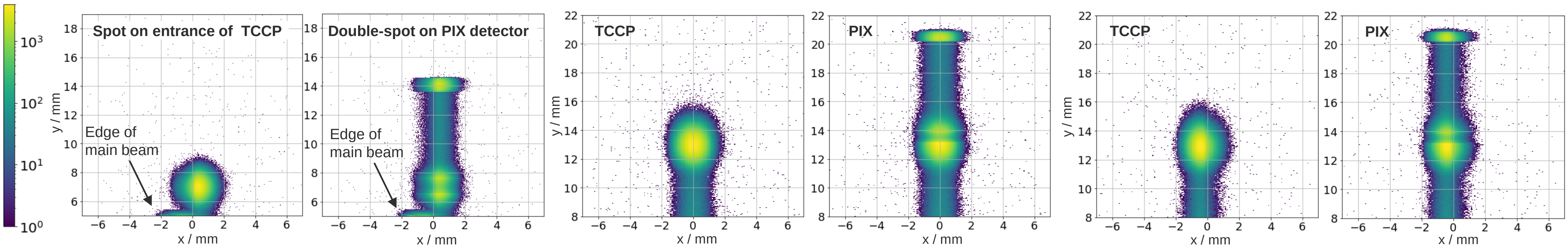
Conclusions
All 3 layouts feasible.
CRY2 and PIX1 are close to the main beam in layout A.
Local TCLA can be used as an absorber in layouts B and C.

PoP: Considering 3 layouts at 1 TeV

SixTrack simulations with 4 000 000 particles give the expected distribution at the entrance of TCCP and at the PIX for the PoP experiment.

Layout A | **Layout B** | **Layout C**

protons

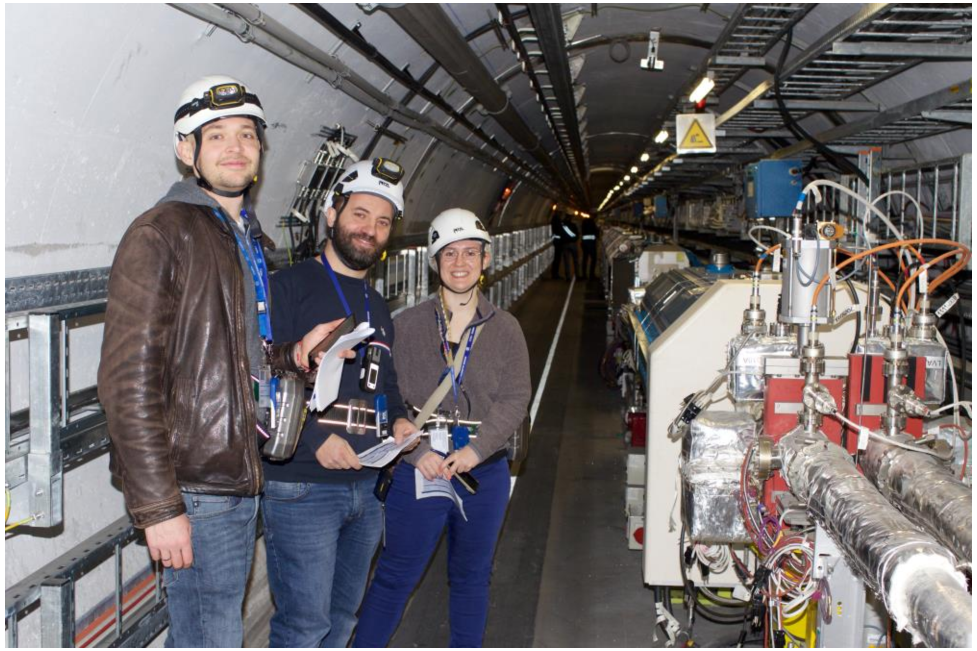


PIX needs to be located close to the edge of the main beam for layout A

Conclusions
All 3 layouts feasible.
Layout A less advantageous;
- Injection energy alignment
- PIX proximity to main beam
- Local TCLA

New layouts: is there space in the tunnel?

Visit to IR3 in February 2023 to check component positions and space requirements



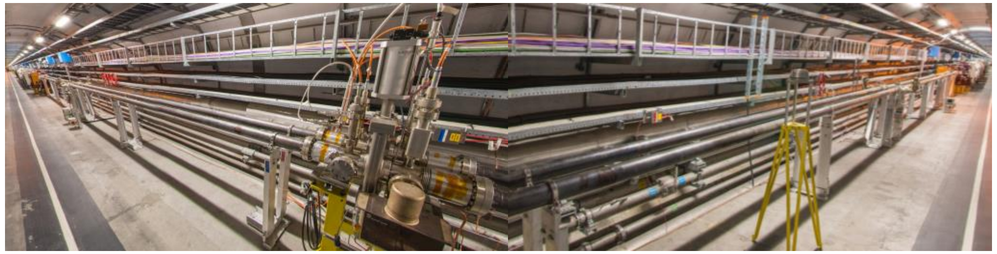
Old layout; cry1 at 6451 m
Floor not suitable (see: 31st PBC-FT WG)

Layout B; cry1 at 6554.5 m
Plenty of space available

Layout A; cry1 at 6430 m
Some space available

Layout C; cry1 at 6775 m
Space available

Conclusion
Enough space is available for all 3 layouts!



Layouts A,B,C;
cry2 at 6655 - 6675 m
Plenty of space available

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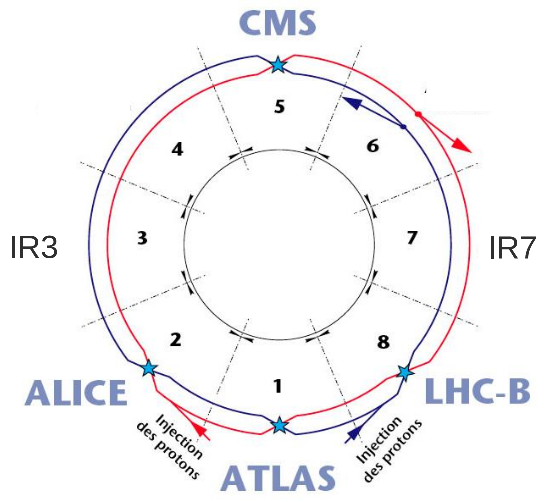
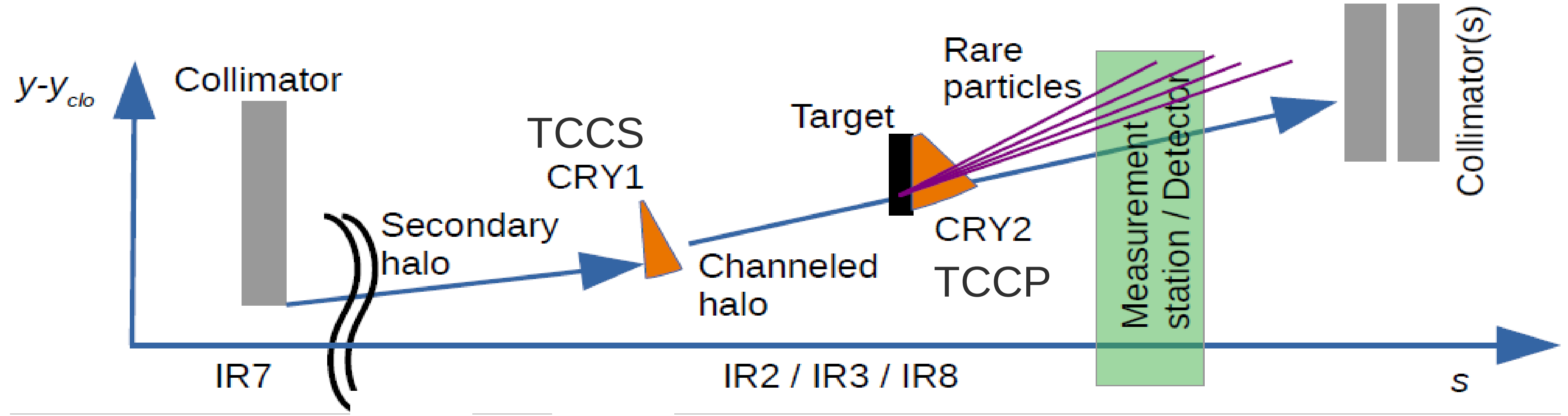
Reminder: the final PBC experiment

double-crystal setup – high intensity operation





Protons impact the TCP in IR7 – **some particles form a secondary halo**

Intercept halo particles with a first **bent crystal** (CRY1) directing them **towards a fixed target**

Fixed target at safe distance from beam Proton interactions produce rare baryons

A second **bent crystal enforces precession** of the rare baryons

Detector including spectrometer: measure precession + decay products

Collimators: safely absorb residuals of the channelled halo

See also:
S. Redaelli, PBC Kick-off workshop 2016
W. Scandale, PBC Kick-off workshop 2016

Physics Beyond Colliders (PBC) at HL-LHC

- Uses halo protons at **7 TeV**
- Orbit corrector scheme compensating for spectrometer kick (part of detector station)
- **Only** the **rare baryons (few TeV) can be channeled by TCCP** (7 TeV protons are too energetic to be channelled)

HL-LHC collimation options include:

Relaxed settings:

TCP (IR7) at 8.5 σ
TCSG (IR7) 10.1 σ
TCLA (IR3) 23.7 σ

TCCS (IR3) 9.0 σ

Tight settings:

TCP (IR7) at 6.7 σ
TCSG (IR7) 9.1 σ
TCLA (IR3) 23 σ

TCCS (IR3) 7.2 σ

6 cases

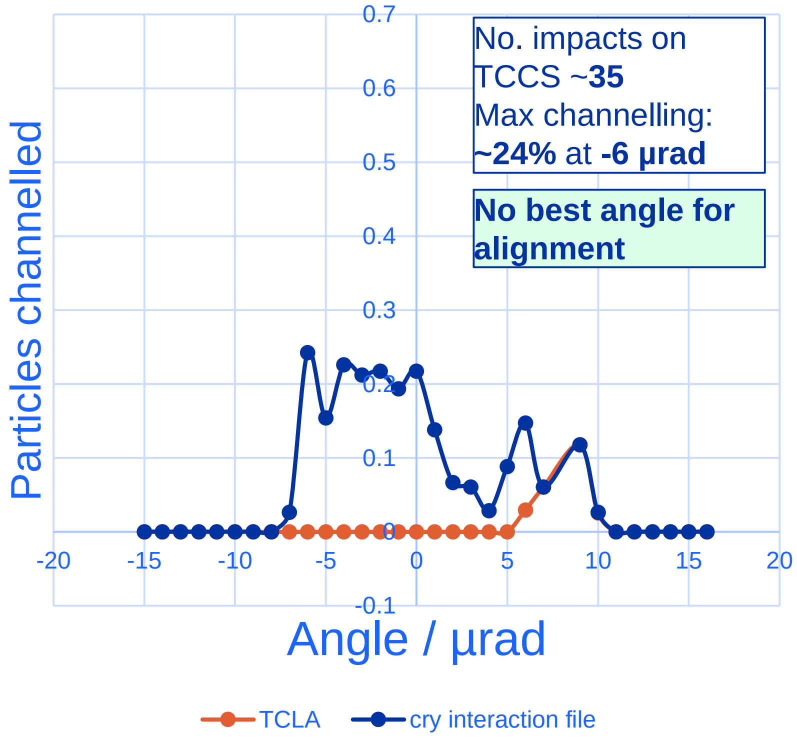
I compare the setups by considering the number of **protons-on-target** (PoT)

Alignment of crystal 1 (TCCS) at relaxed settings

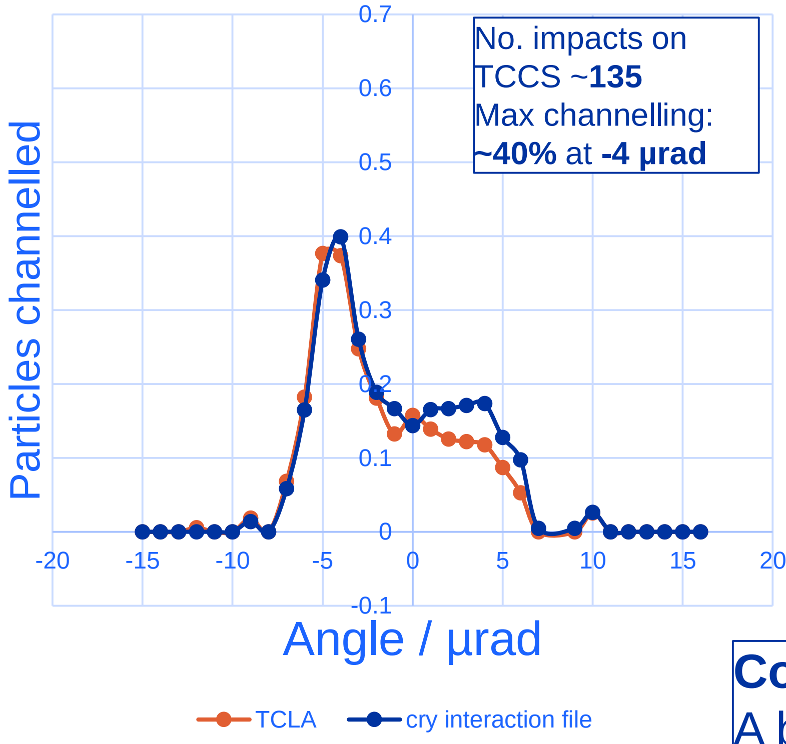
SixTrack simulation

In the HL-LHC setup we align the first crystal to a secondary halo. Challenge: for layout A, there was not a good angle for alignment.

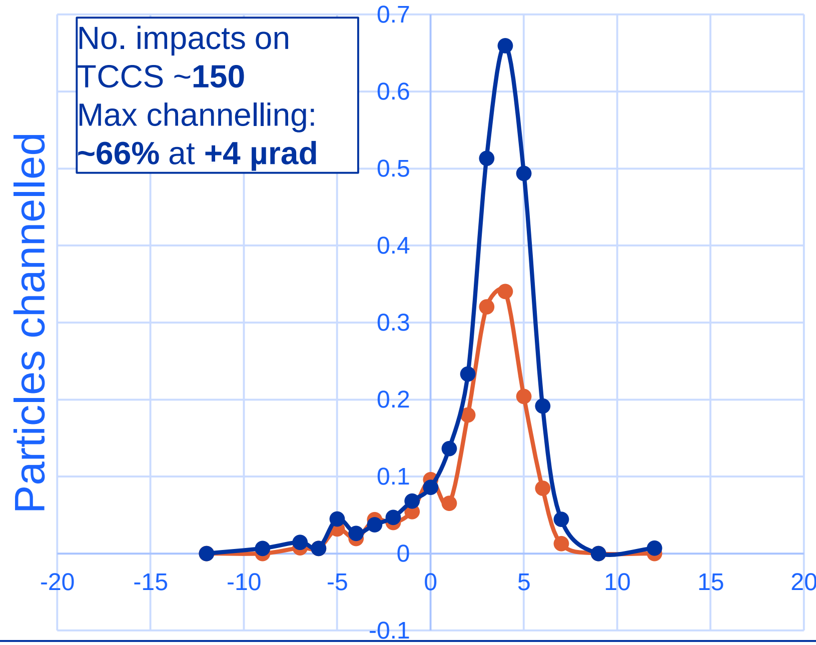
Layout A



Layout B



Layout C

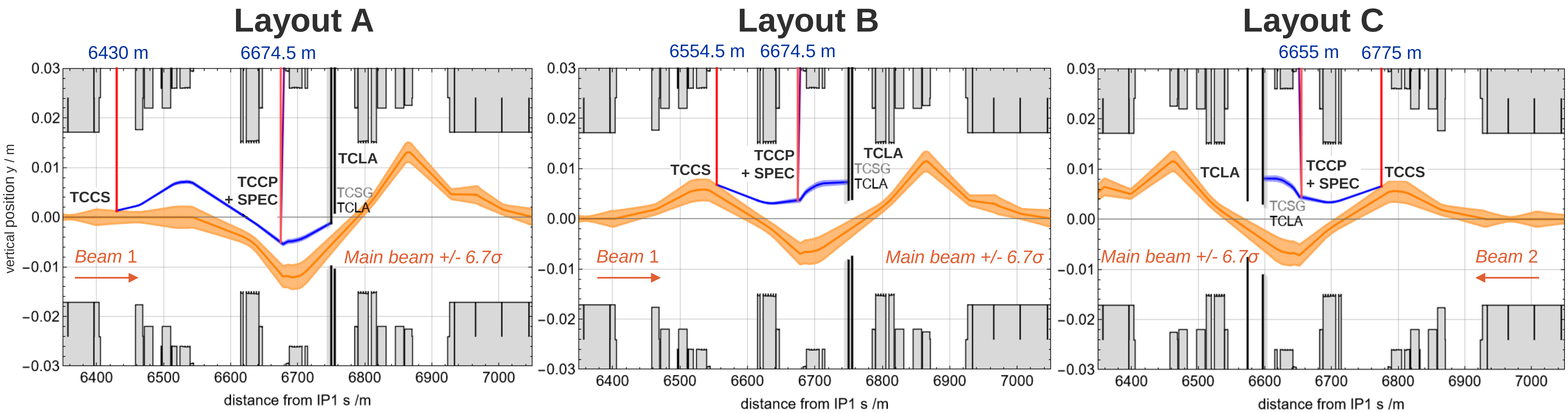


Conclusion

A best angle for channeling is not clear for layout A at relaxed collimation settings.

PBC: Considering 3 layouts at 7 TeV

Inclusion of a spectrometer magnet with field of 4 Tm. The orbit bump caused by this magnet was matched back to the nominal closed orbit by local vertical corrector magnets using MADX.



Aperture limit for each layout;
A: aperture limit at 6858 m, N1: 12.3 σ
B: aperture limit at 6858 m, N1: 17.6 σ
C: aperture limit at 6471 m, N1: 18.2 σ

Conclusions
In all 3 cases the bump can be corrected.
Layout C is least-close to the aperture.

PBC: Comparing protons-on-target for the 3 layouts

$$PoT(t) = \frac{1}{2}\frac{I(t)}{\tau}\exp\left(-\frac{t}{\tau}\right)\frac{N_{\mathrm{imp}}^{\mathrm{Cry}_1}}{N_{\mathrm{sim}}}\varepsilon_{CH}^{\mathrm{Cry}_1}$$

Assume $I(t)$ decays from $2.8\text{x}10^{14}$ protons with 20h burn off time τ_{BO}.
Beam lifetime τ of 200h.
Fill time t_{max} of 10h.

Layout (Beam)	TCP y[σ]	TCCS s[m]	TCCP s[m]	Proportion Channelled	$\int^{10}$ PoT dt [×10^{10}]
A (1)	8.5	6430	6674.5	0.17	0.11
B (1)	8.5	6554.5	6674.5	0.35	1.40
C (2)	8.5	6755	6655	0.58	1.19
A (1)	6.7	6430	6674.5	0.39	0.52
B (1)	6.7	6554.5	6674.5	0.30	1.55
C (2)	6.7	6755	6655	0.57	1.26

Conclusions
In line with previous calculations
More PoT for tighter collimation settings
Greatest PoT for Layout B!

Eur. Phys. J. C (2020) 80:929
https://doi.org/10.1140/epjc/s10052-020-08466-x
THE EUROPEAN PHYSICAL JOURNAL C
Check for updates
Regular Article - Experimental Physics

Layouts for fixed-target experiments and dipole moment measurements of short-lived baryons using bent crystals at the LHC

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https://doi.org/10.1140/epjc/s10052-020-08466-x

Cry_1 aperture (σ)	IR3 $\frac{N_{\mathrm{imp}}^{\mathrm{Cry}_1}}{N_{\mathrm{sim}}}$	$\varepsilon_{CH}^{\mathrm{Cry}_1}$	$\int_{10h} PoT(t)dt$ (p)
5	0.78	0.66	2.8×10^{12}
6	2.4×10^{-3}	0.40	5.2×10^{9}
7	2.7×10^{-4}	0.26	3.8×10^{8}
8	1.3×10^{-4}	0.12	8.4×10^{7}

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1. Introduction to the PBC double-crystal experiment in IR3
2. Why use crystals?
3. Layout considerations for
   a) Proof of Principle (PoP) for Run 3 LHC
   b) Physics Beyond Colliders (PBC) for Run 4 HL-LHC
4. **Summary**

Overall Summary

Layout B is the most advantageous. We propose to move forward with Layout B.

Phase	Advantage	A	B	C
PoP	**Can** be aligned at injection (5σ & 450 GeV). Saves operational time.		★	★
PoP	At 1 TeV, CRY 2 and pixel detector are located **far from the edge** of the main beam.		☆	☆
PoP	**Existing local TCLA can absorb** the channeled beam from CRY 1.		☆	☆
Final	With **relaxed collimation settings**: The crystal 1 can be aligned to the secondary halo		★	★
Final	With **tight collimation settings**: The crystal 1 can be aligned to the secondary halo	★	★	★
Final	**More Protons-on-Target**		★	☆
		1	5	4.5

We have a winner! Layout B

Thank you.
Read the IPAC 2023 paper:
https://doi.org/10.18429/JACoW-IPAC2023-MOPL048