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Warsaw University of Technology

Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

LHC Collimation Project
CERN

Crystal implementation in IR2 and studies for a test-stand in IR3

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Acknowledgments:

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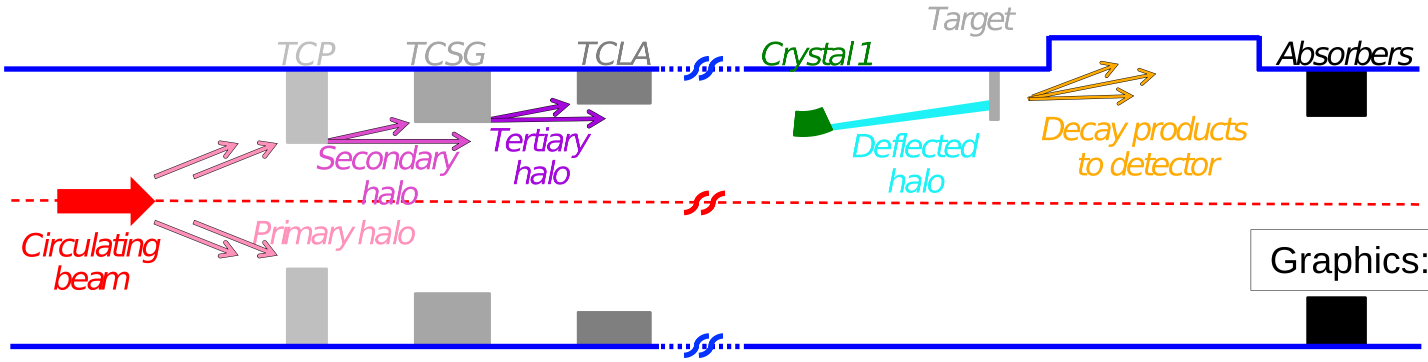
Fixed Target experiments at LHC - Strong2020 Workshop

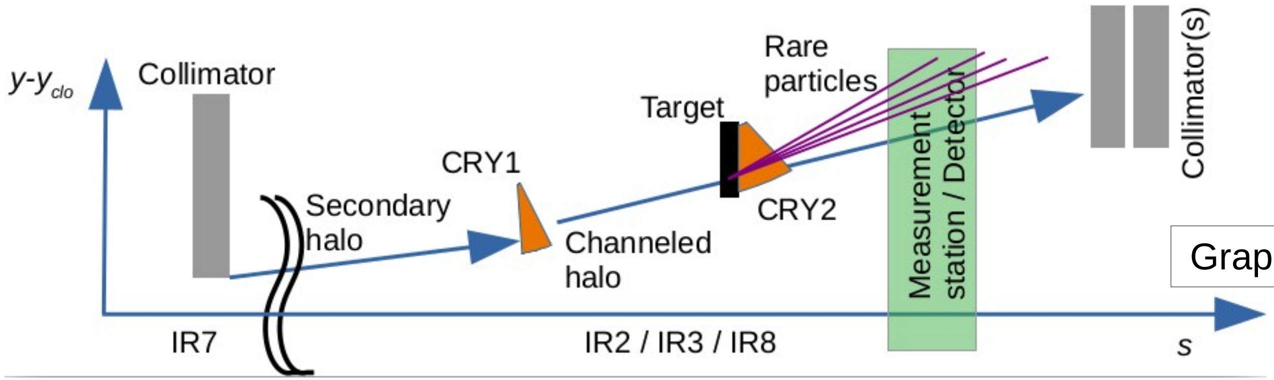
Layout for crystal based fixed-target experiment in IR2



Graphics: D. Mirarchi

- Halo particles are intercepted and disposed by the collimation system.
- Part of the **secondary halo** is **intercepted by the crystal** and **deflected towards the target.**
- Local absorbers capture additional losses coming from the crystal+target assembly.
- **Parasitic operation** means that **fixed-target collisions** occur in **parallel to beam-beam collisions.**
- Parasitic operation is possible only if **new loss spikes stay within acceptable limits** (e.g. not larger than usual losses).
- For the ALICE case, the setup is optimized to provide a maximum **flux of protons on target** (PoT) that can be handled by the detector acquisition system. This is in the order of **10^7 p/s.**

Double-crystal layout for fixed-target experiment in IR3/IR8



Graphics: P. Hermes

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- Parasitic operation is possible only if **new loss spikes stay within acceptable limits** (e.g. not larger than usual losses).

- **Double-crystal layou**t, with a **second crystal directly after the target**, allows to study **electric and magnetic dipole moments of short-lived baryons**. It's technical feasibility is more challenging.

Outline

- Crystal implementation in IR2
- Studies on experimental test-stand with crystals in IR3

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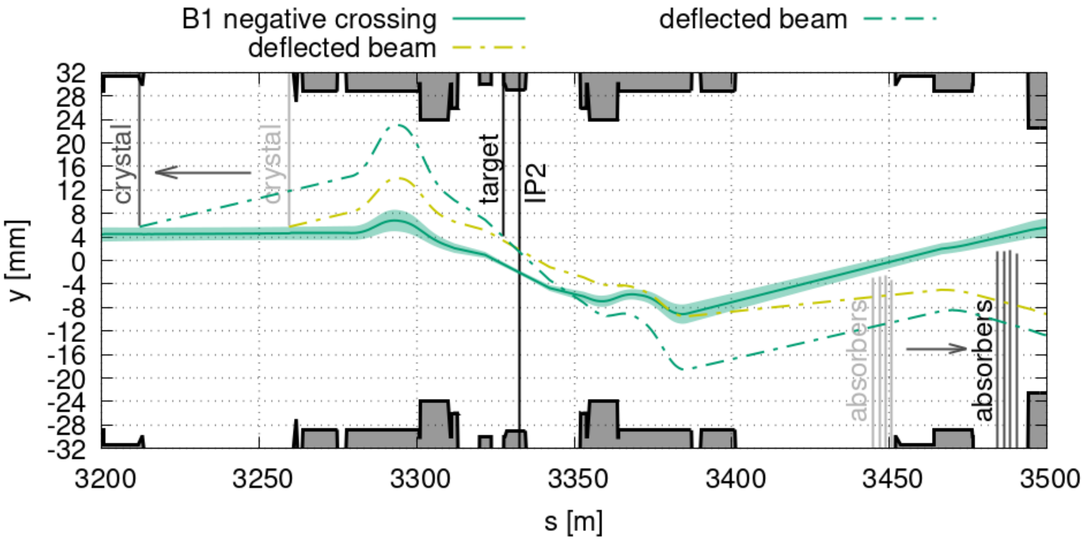
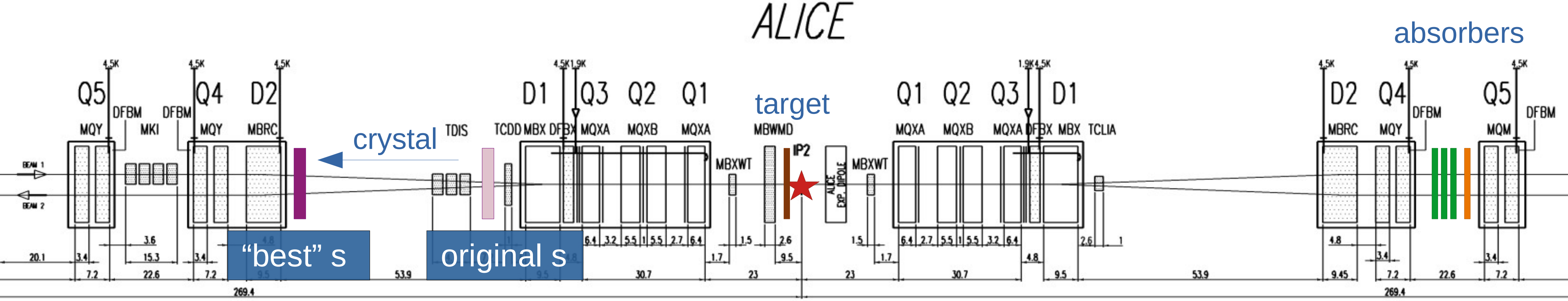
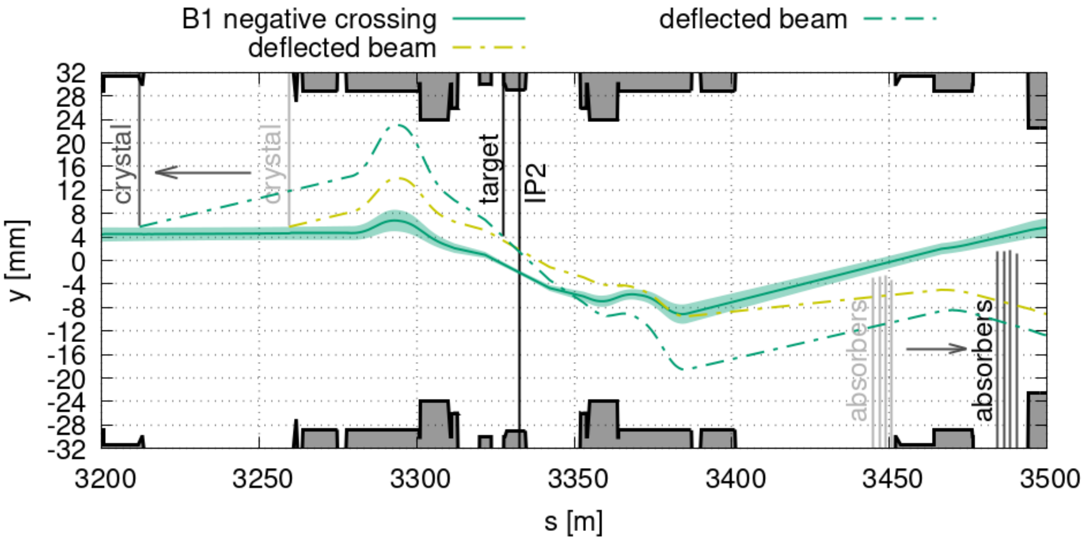
IR2 layouts being considered



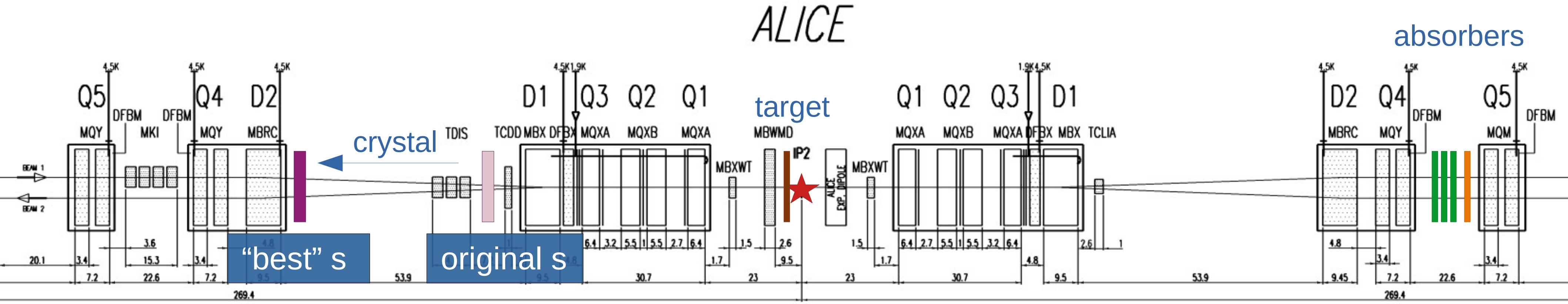


IR2 layouts being considered

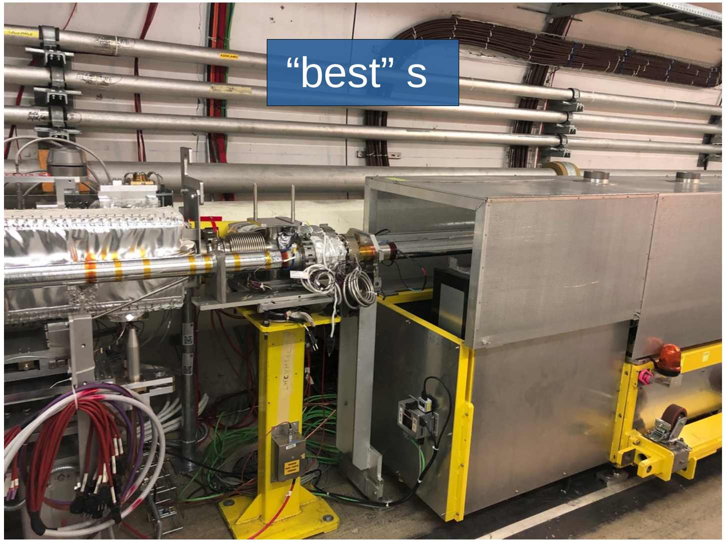


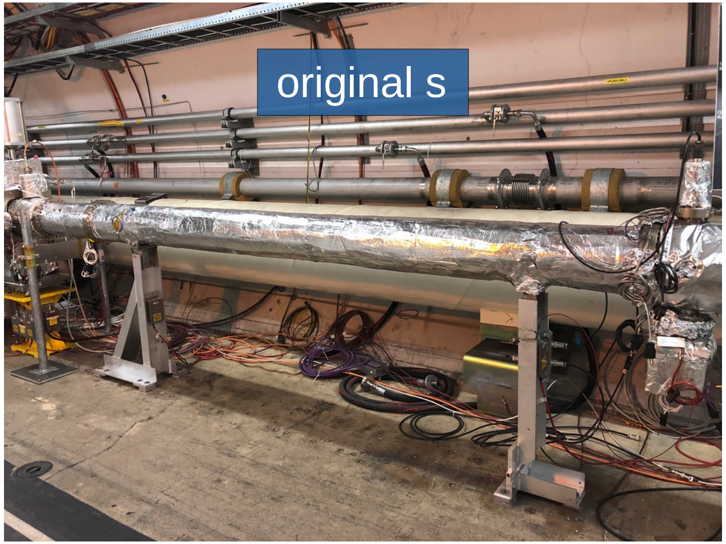
s [m]	3217m “best”	3259m “original”
Δμ (TCP.D) [deg]	144	168
PoC [1e-3]	2.5	0.6

More than a factor of 4 of difference!



Space constraints





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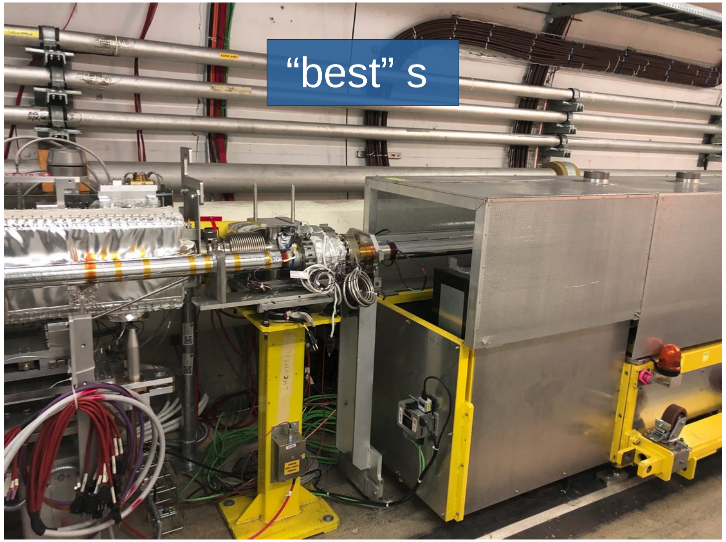
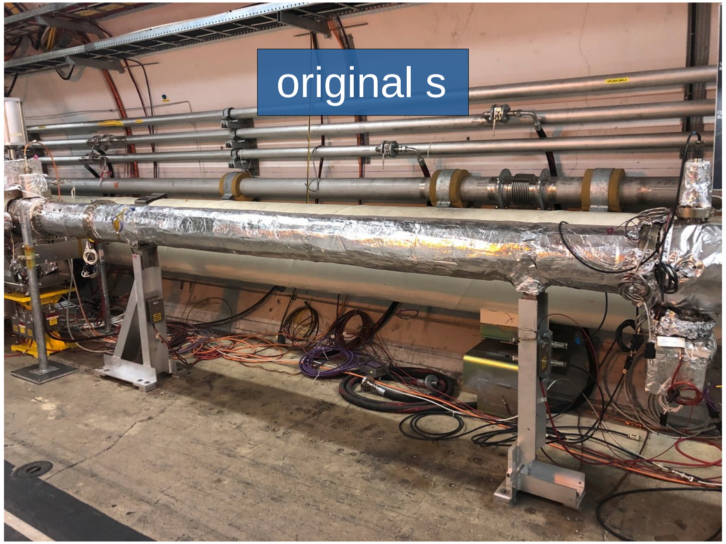
More than a factor of 4 of difference!
But difficult for crystal installation.

Space constraints





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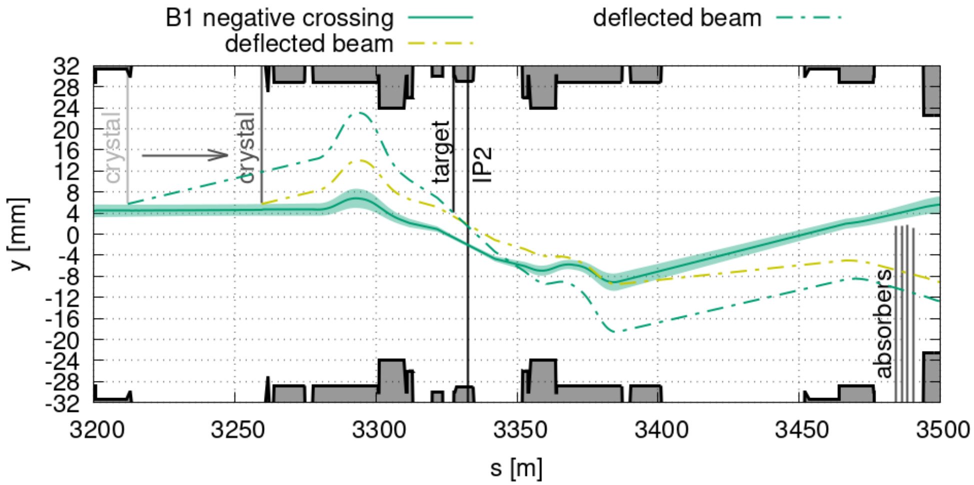
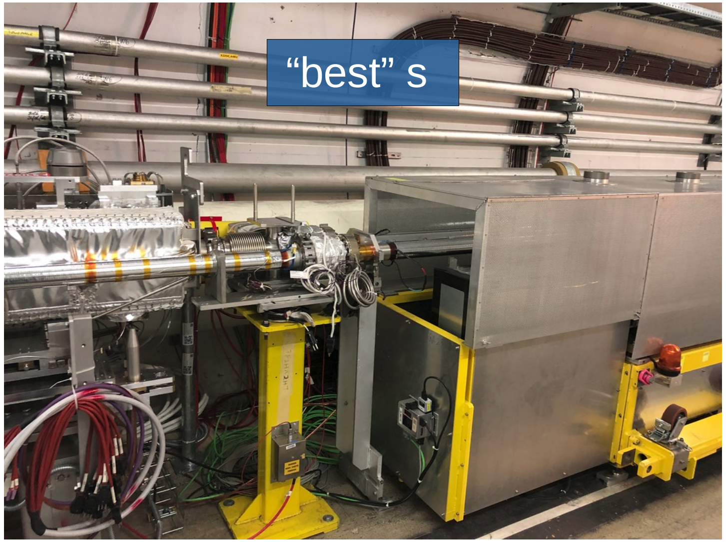
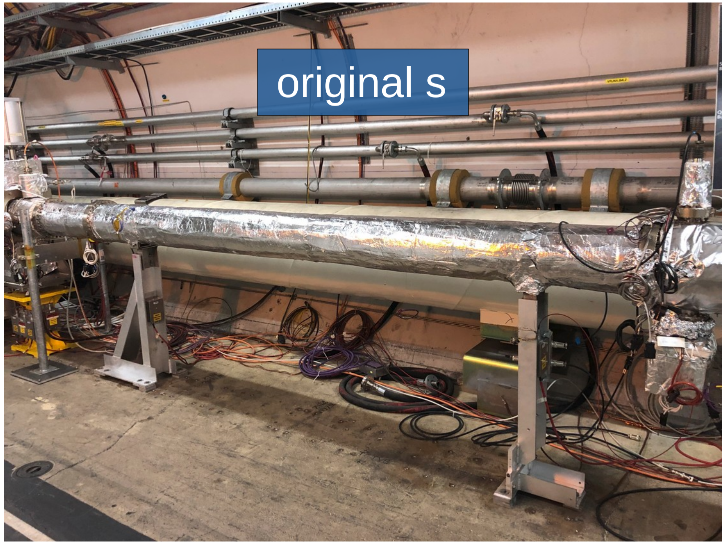


Can we move back to the original location and recover the performance?

Space constraints





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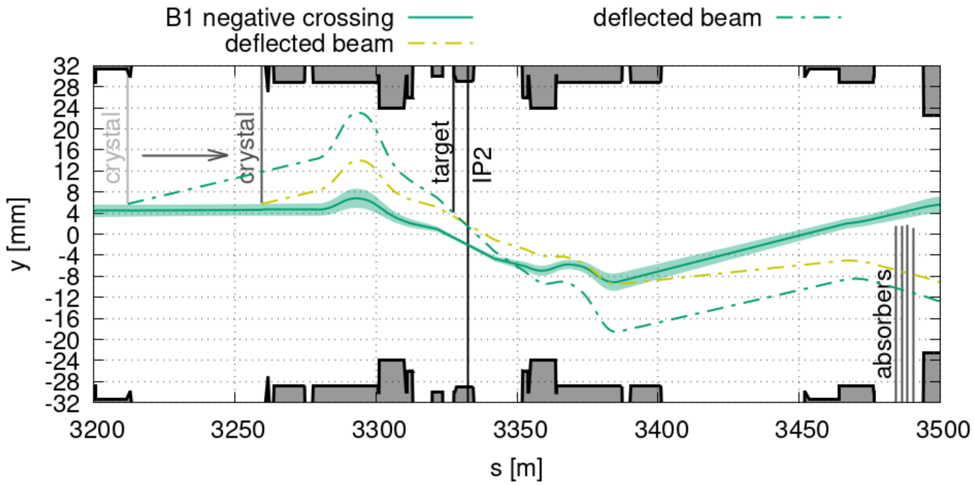
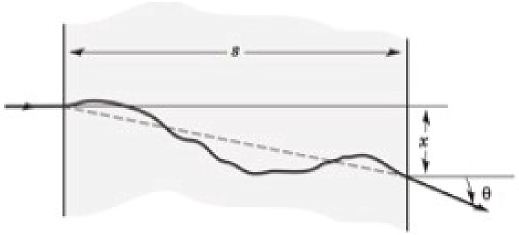


Can we move back to the original location and recover the performance?

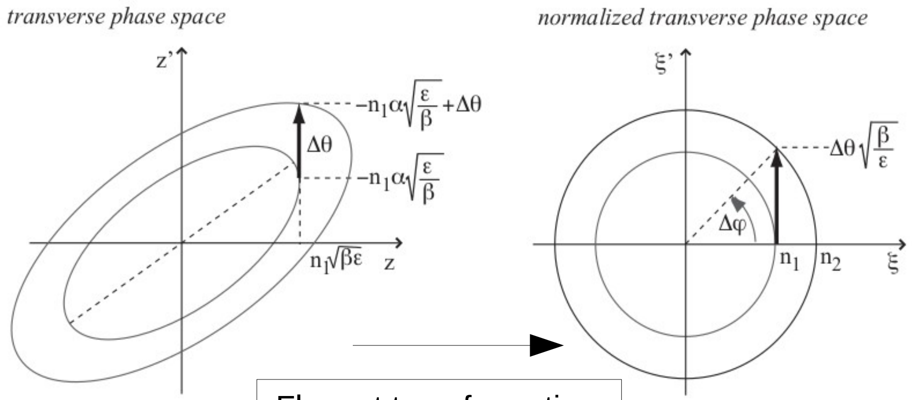
Interaction with a primary collimator



$$\sqrt{\langle\theta_p^2\rangle} = \frac{13.6}{cp[\mathrm{MeV}]}\sqrt{\frac{s}{\chi_0}}\left(1+0.038\cdot\left(\frac{s}{\chi_0}\right)\right)$$

χ_0 : radiation length

Molière's multiple-scattering theory: scattered particles gain a **transverse RMS kick**.



Flouqet transformation

$$z_\beta = n_1\sqrt{\varepsilon\beta}\,\sin(\phi_z)$$
$$z'_\beta = n_1\sqrt{\frac{\varepsilon}{\beta}}\,(\cos(\phi_z)-\alpha\sin(\phi_z))$$

$$z \rightarrow \xi = \frac{z}{\sqrt{\beta\cdot\varepsilon}}$$
$$z' \rightarrow \xi' = \frac{z\cdot\alpha + z'\cdot\beta}{\sqrt{\beta\cdot\varepsilon}}$$

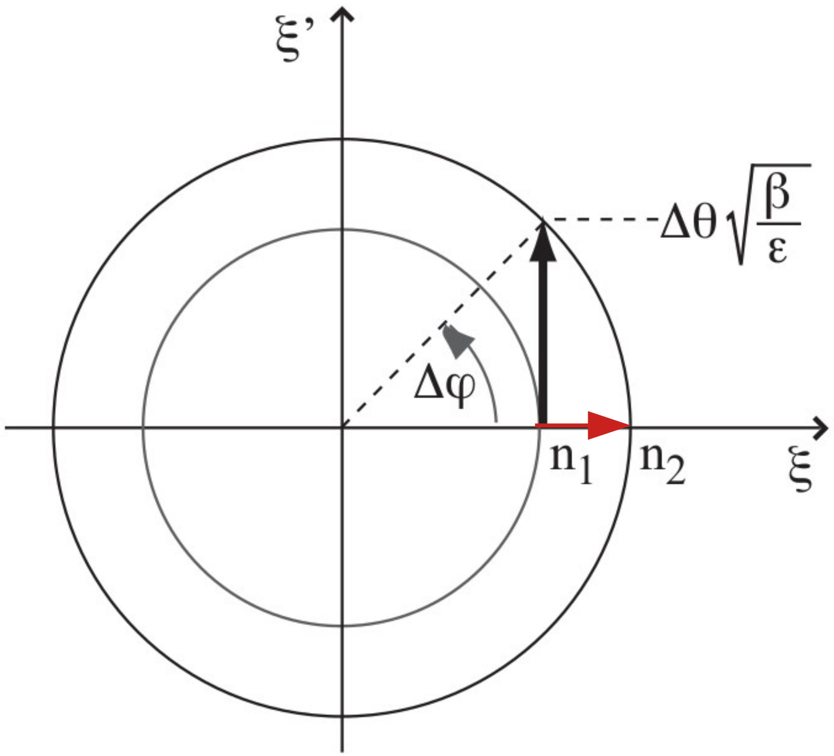
Circle of radius n1:

$$\xi_\beta = n_1\,\sin(\phi_z)$$
$$\xi'_\beta = n_1\,\cos(\phi_z)$$

Change of amplitude and phase:

$$n_k = \sqrt{n_1^2+\Delta\theta^2\cdot\frac{\beta}{\varepsilon}}$$
$$\Delta\phi = -\mathrm{sgn}(\Delta\theta)\cdot\arccos\left(\frac{n_k}{n_1}\right)$$

Effect of scattering



- Scattering angle transforms into the maximum amplitude growth at the location where the phase advance is 90º ± Δφ.
- Such a phase advance is desired between the primary vertical collimator (TCP.D) and the crystal.
- Phase advance close to 0º or 180º is not favorable.
- Phase advance can be modified by changing the β function.

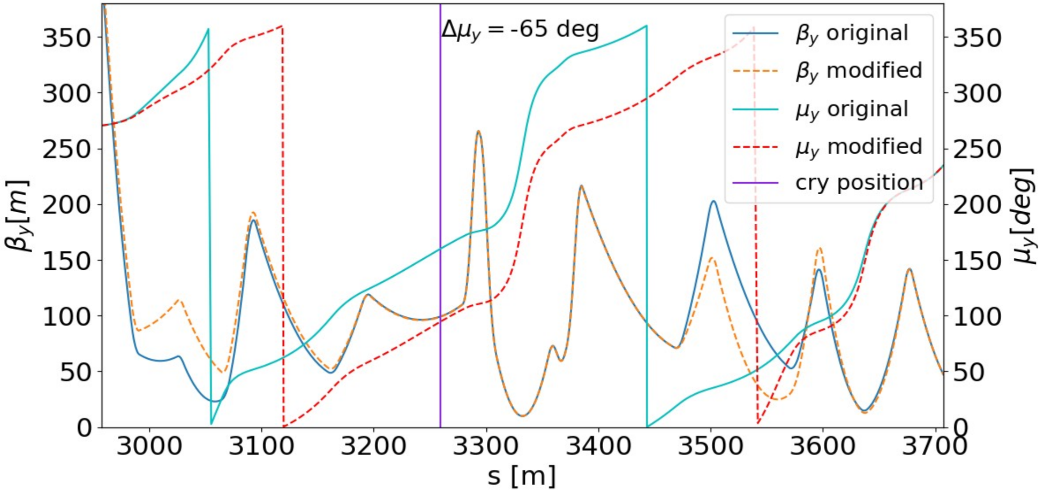
$$\psi(s) = \int_0^s \frac{ds}{\beta(s)}$$

Shift of phase at the crystal

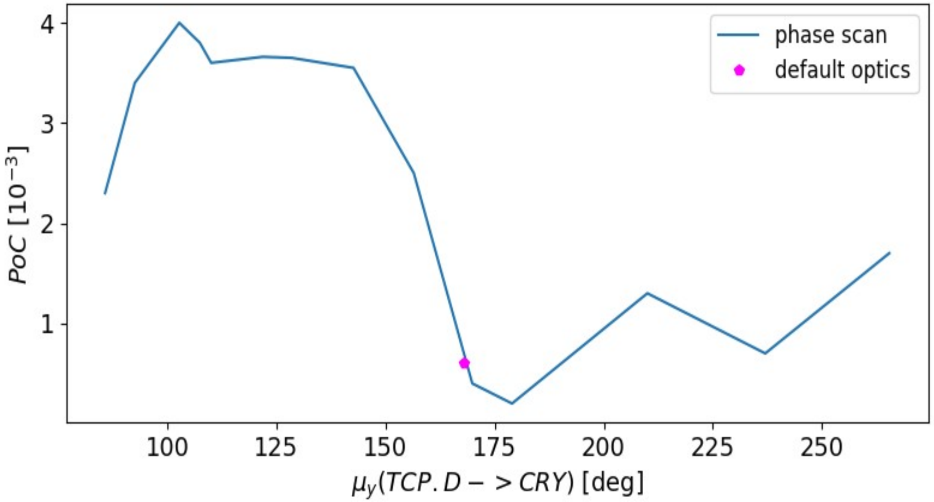
```
extract, sequence=lhcb1, from=start_subseq, to=IP2, newname=subseq;
save, sequence=subseq, file=subseq.madx, beam=true;

extract, sequence=lhcb1, from=start_subseq, to=end_subseq, newname=subseq_full;
save, sequence=subseq_full, file=subseq_full.madx, beam=true;

!___________Match half IR_______________
call, file="subseq_full.madx";

use, sequence=subseq_full;
select, flag=twiss, clear;
select, flag=twiss, column=KEYWORD,NAME,S,L,X,Y,PX,PY,BETX,BETY,ALFX,ALFY,MUX,MUY,DX,DY,DPX,DPY;
twiss, beta0=subseq_twiss, file="twiss_subseq.txt", save;

!****matching IP with MQ quads****
match, sequence=subseq_full, beta0=subseq_twiss;
  constraint range=IP2, betx=10.0, bety=10.0, alfx=0.0, alfy=0.0, dx=0, dpx=0;
  constraint range=CRY.FIR.B1, muy=7.262;
  vary, name=kq10.l2b1;
  vary, name=kq9.l2b1;
  vary, name=kq8.l2b1;
  vary, name=kq7.l2b1;
  vary, name=kq6.l2b1;
  vary, name=kq5.l2b1;
  vary, name=kq4.l2b1;
  lmdif, calls=500, tolerance=1e-8;
endmatch;
twiss, beta0=subseq_twiss, file="twiss_subseq_aftermatch.txt", save;

!___________Match full IR_______________
select, flag=twiss, clear;
select, flag=twiss, column=KEYWORD,NAME,S,L,X,Y,PX,PY,BETX,BETY,ALFX,ALFY,MUX,MUY,DX,DY,DPX,DPY;
twiss, beta0=subseqfull_twiss, file="twiss_subseqfull.txt", save;

!****matching IP with MQ quads****
match, sequence=subseq_full, beta0=subseq_twiss;
  constraint range=end_subseq,
        betx=subseqfull_twiss->betx, bety=subseqfull_twiss->bety,
        alfx=subseqfull_twiss->alfx, alfy=subseqfull_twiss->alfy,
        dx=subseqfull_twiss->dx, dpx=subseqfull_twiss->dpx,
        muy=subseqfull_twiss->muy;
  vary, name=kq10.r2b1;
  vary, name=kq9.r2b1;
  vary, name=kq8.r2b1;
  vary, name=kq7.r2b1;
  vary, name=kq6.r2b1;
  vary, name=kq5.r2b1;
  vary, name=kq4.r2b1;
  lmdif, calls=500, tolerance=1e-8;
endmatch;
twiss, beta0=subseq_twiss, file="twiss_subseqfull_aftermatch.txt", save;

!Back to the whole ring
use,sequence=lhcb1;
select, flag=twiss, clear;
select, flag=twiss, column=KEYWORD,NAME,S,L,X,Y,PX,PY,BETX,BETY,ALFX,ALFY,MUX,MUY,DX,DY,DPX,DPY;
twiss,    sequence=lhcb1, centre=true,     file=twiss_thinb1_aftermatch.txt; save;

!Rematch tune & chroma
call, file="slhc/toolkit/rematch_tune.madx";
call, file="slhc/toolkit/rematch_chroma.madx";
```

Optics change in MAD-X

- Strength of quads 10-4.L2B1 (upstream from IP2) is modified to set the desired phase at the crystal.
- IP2 parameters stay unchanged.
- Strength of quads 10-4.R2B1 (downstream from IP2) is modified to recover the nominal phase.



Protons on crystal (PoC) vs phase shift



- Original location is nearly at the worst phase (180deg) for the default optics.
- Phase shift by ~65deg allows to increase the system performance significantly.
- The required optics change is minor and easy to be implemented.

Protons on crystal (PoC) vs phase shift

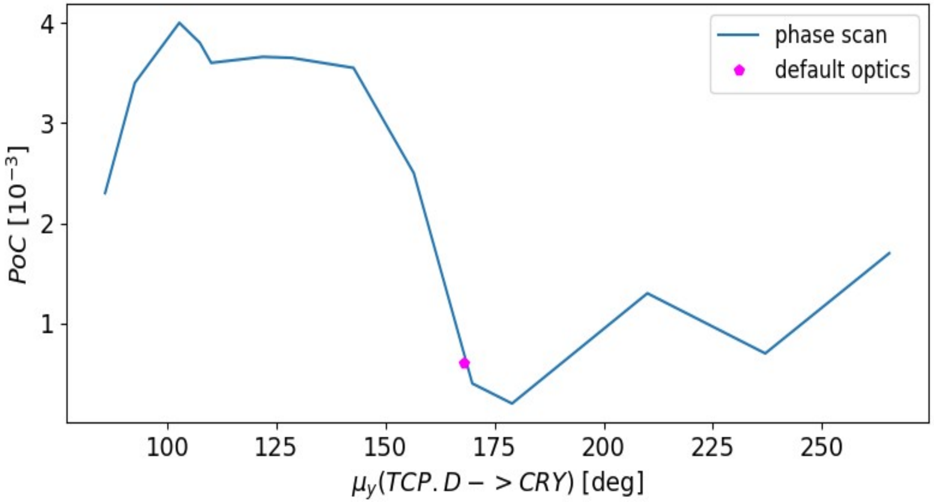


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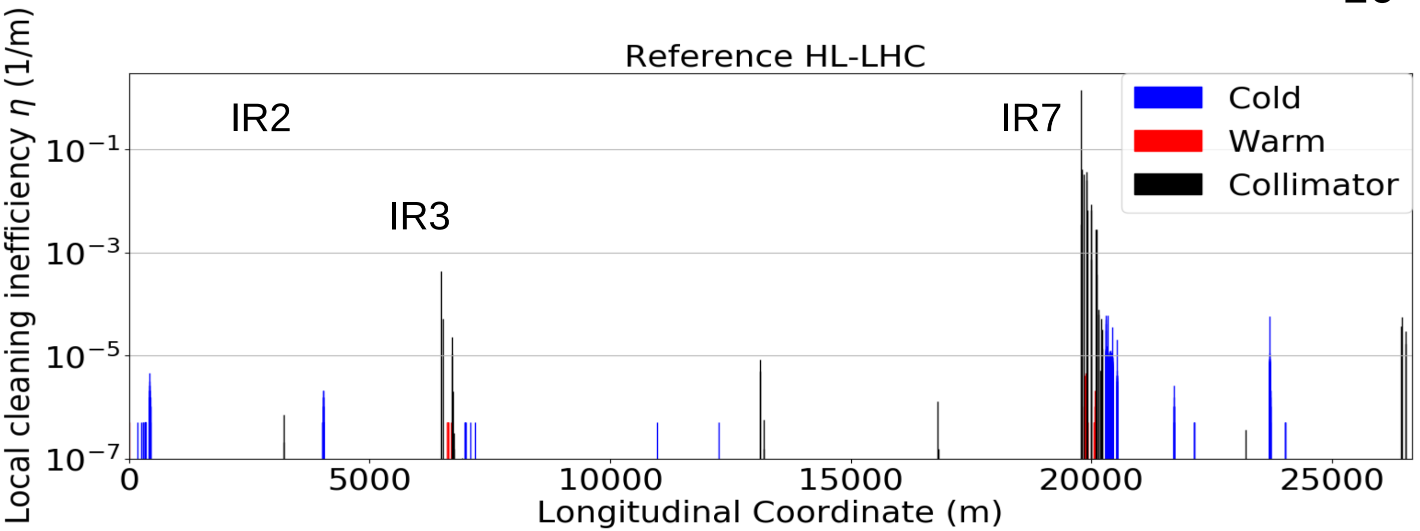
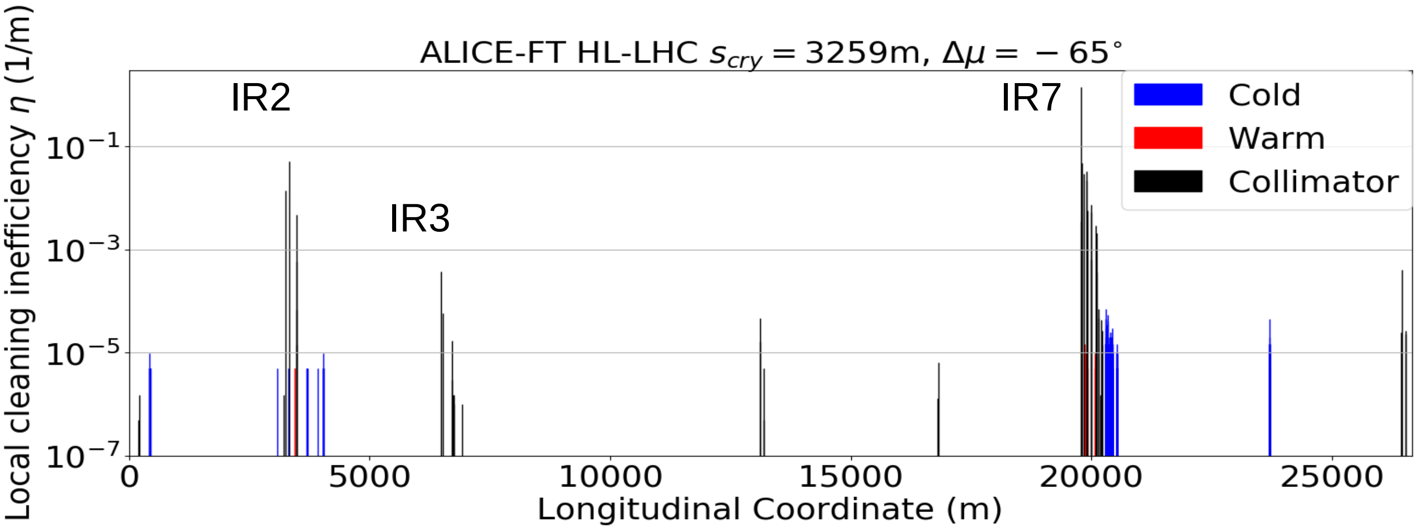
Table 3: Normalised strengths of quadrupoles for nominal and modified optics. IR2 left and IR2 right stand for regions upstream and downstream from the IP2, respectively.

	Quadrupole strength k_1 [10^{-3} m^{-2}]			
Quadrupole	IR2 left		IR2 right	
number	nominal	modified	nominal	modified
10	-6.39	-6.15	7.30	7.30
9	7.01	6.89	-6.60	-6.82
8	-5.41	-3.59	6.71	6.30
7	7.60	7.42	-6.36	-7.47
6	-4.91	-4.17	4.33	4.20
5	2.99	2.88	-3.63	-4.09
4	-2.80	-2.67	3.74	2.60

Loss map comparison

- HL-LHC v1.5 optics, $\beta^* = 10$m
- Coll settings:
  - $n_\sigma(TCP_{IR7})=6.7$,
  - $n_\sigma(CRY_{IR2})=[$**7.3,** $7.5, 7.9]$,
  - $n_\sigma(TCS_{IR7})=9.1$,
  - $n_\sigma(TCLA_{IR7})=12.7$
- Sixtrack5
- Annular beam halo at 6.7σ
- 2.1M particles, 300 turns
- **No extra losses.**
-





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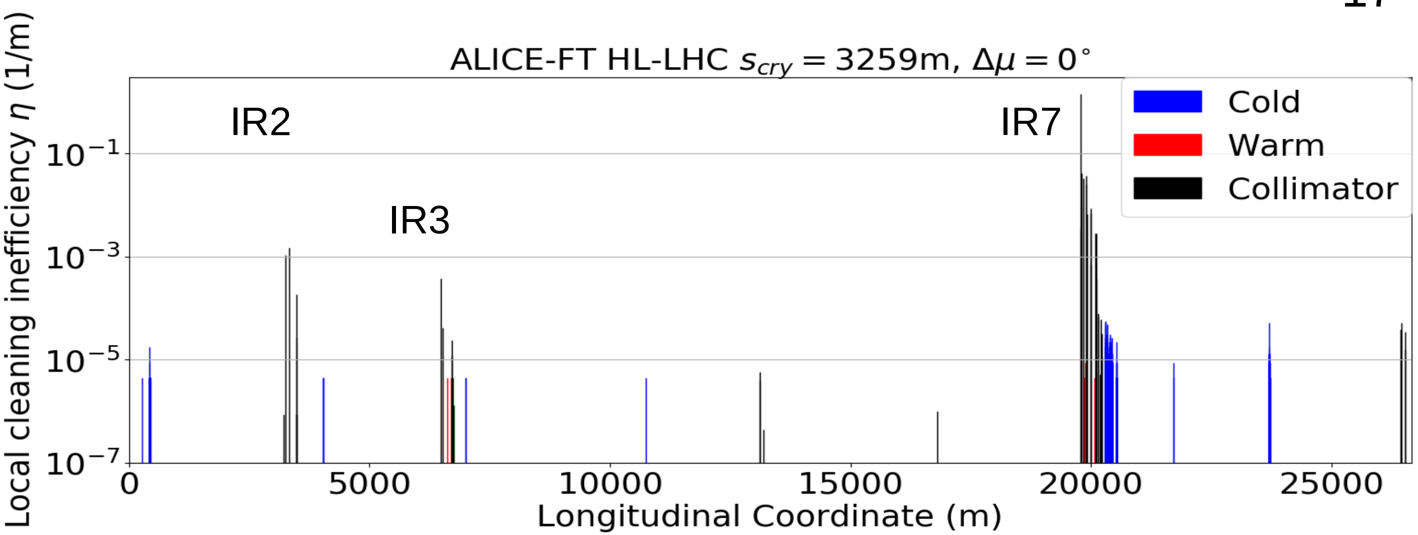
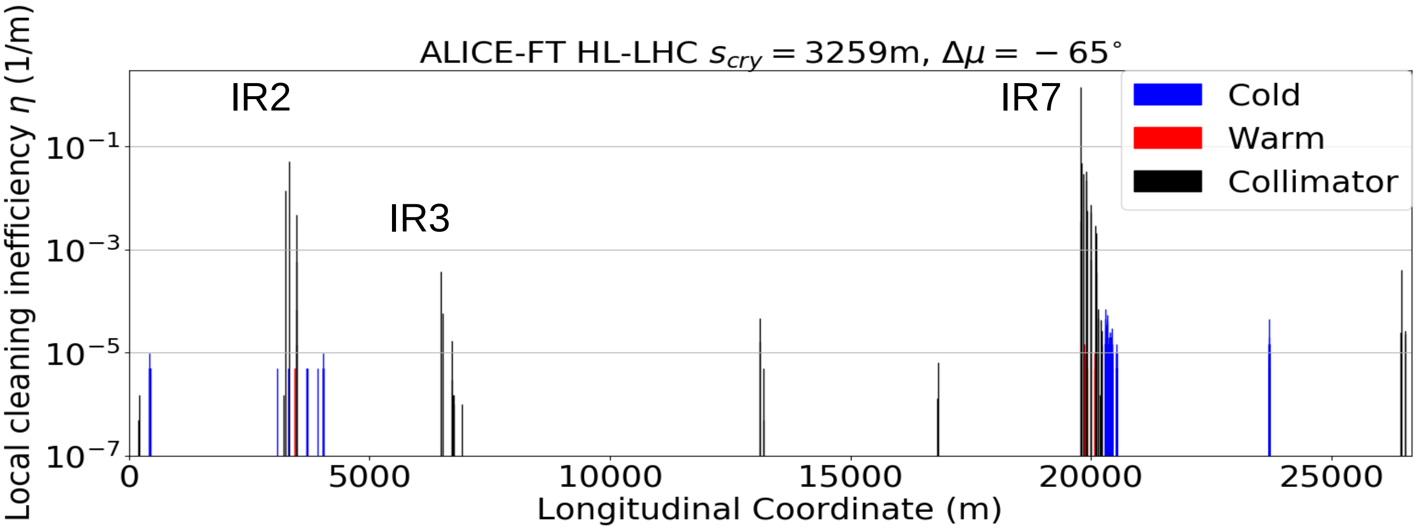
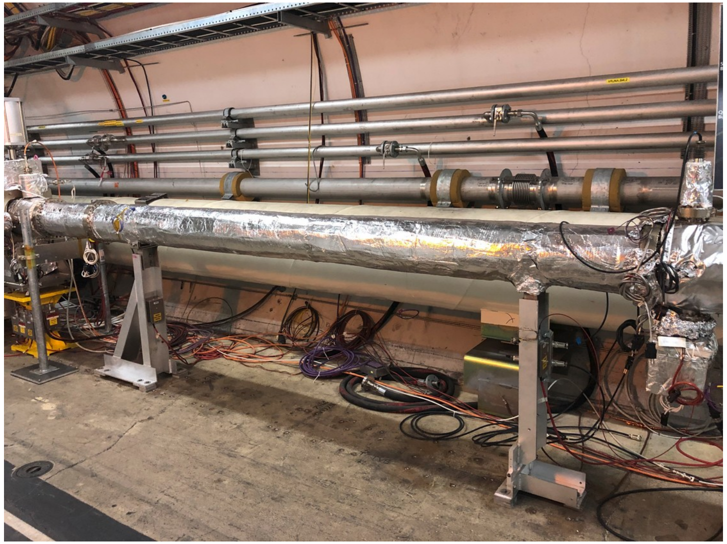
- Sixtrack5
- Annular beam halo at 6.7σ
- 2.1M particles, 300 turns
- **No extra losses.**
- **Significantly more protons on the crystal and target.**





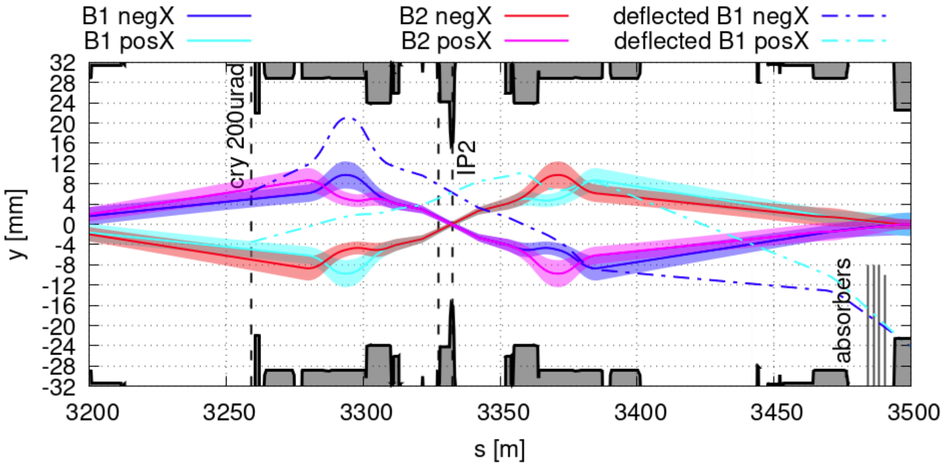
Assets of having the crystal at s=3259m

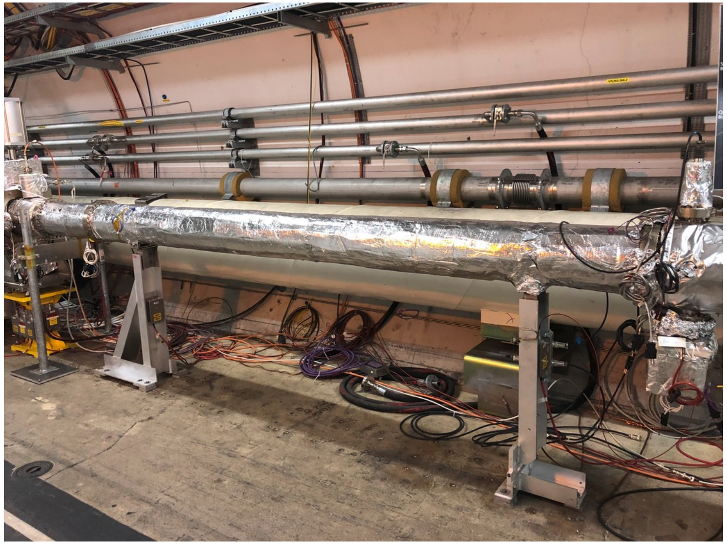
- Good space availability for the crystal installation.
-
-



Assets of having the crystal at s=3259m

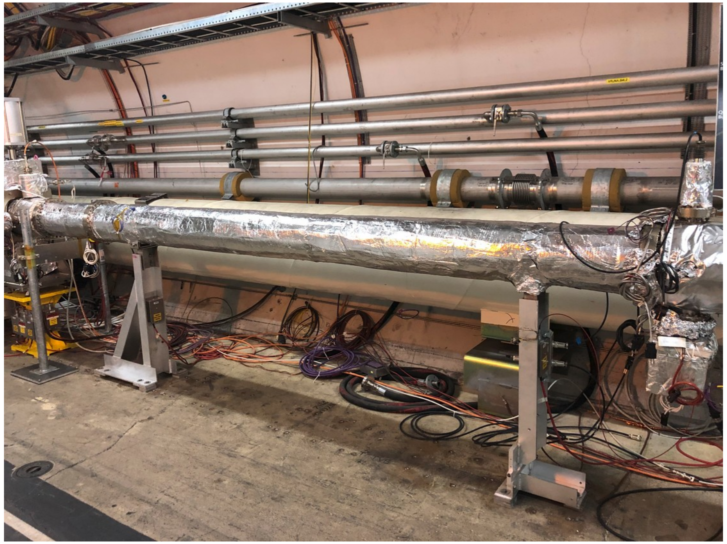
- Good space availability for the crystal installation.
- A single crystal (200μrad) can cover both ALICE polarities. A movable target is then needed.
-

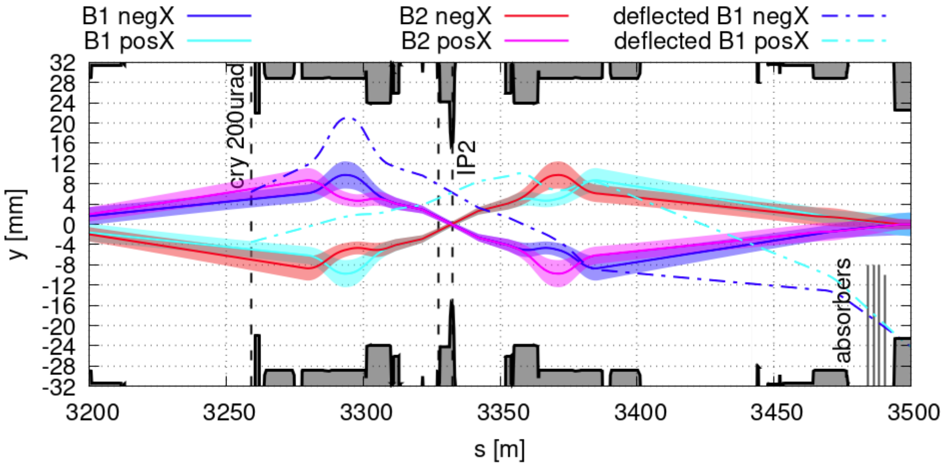


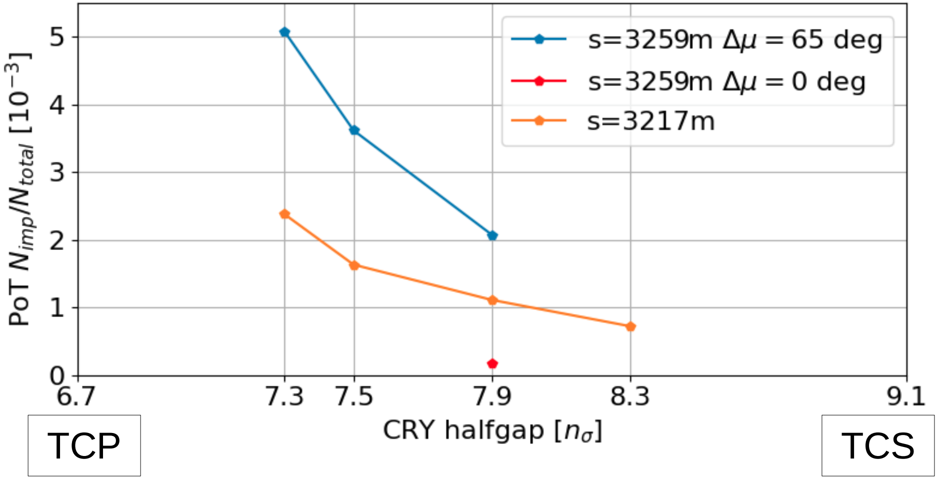


Assets of having the crystal at s=3259m

- Good space availability for the crystal installation.
- A single crystal (200µrad) can cover both ALICE polarities. A movable target is then needed.
- About a factor of 2 increase of protons on target (PoT) when the crystal is at the optimal phase – comparing to crystal at s=3217m at default optics.







Protons on target

- Protons on Target (PoT) is a fraction of beam halo that received a correct deflection from the crystal (channelling) and hit the target.

- Number of protons on target per fill can be estimated as:

$$N_{PoT}=\frac{1}{2}PoT\int_0^{T_{fill}}\frac{1}{\tau_{coll}}I_0\exp\left(\frac{-t}{\tau_{BO}}\right)\exp\left(\frac{-t}{\tau_{coll}}\right)dt$$

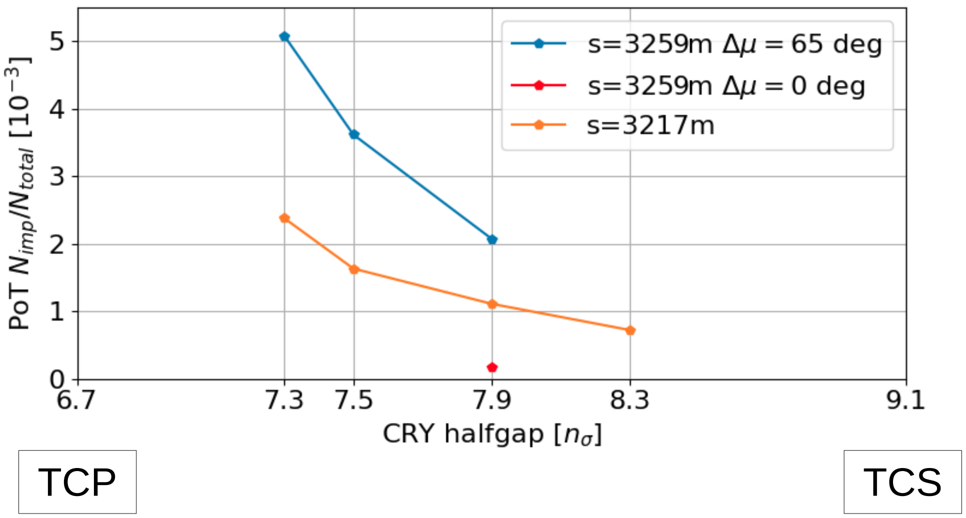
which for 2018 operation would result in about:

$2.7\cdot10^{10}$ protons per fill --> $7.6\cdot10^{6}$ protons per second

assuming [Eur. Phys. J. C (2020) 80:929]:

$$I_0=2556\cdot1.1\cdot10^{11}\,p,\ \tau_{BO}=20\,h,\ \tau_{coll}=200\,h,\ T_{fill}=10\,h$$

- HL-LHC beam intensity will be about x2 larger.
- **ALICE can handle about 10^7 protons on target per second.**



Crystal layout at IR2

Crystal:

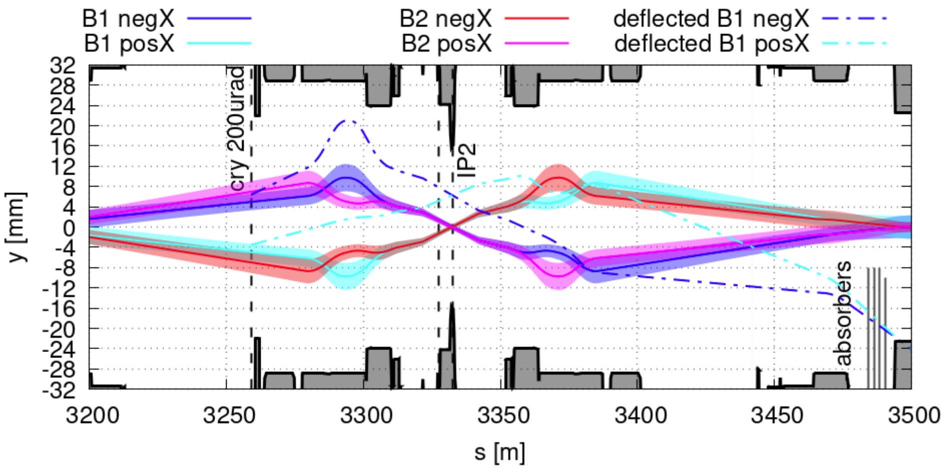
- bending radius: 80 m
- bending angle: 200 μrad
- length: 16 mm
- material: Si (110)
- s-position: 3259m (0m at IP1)

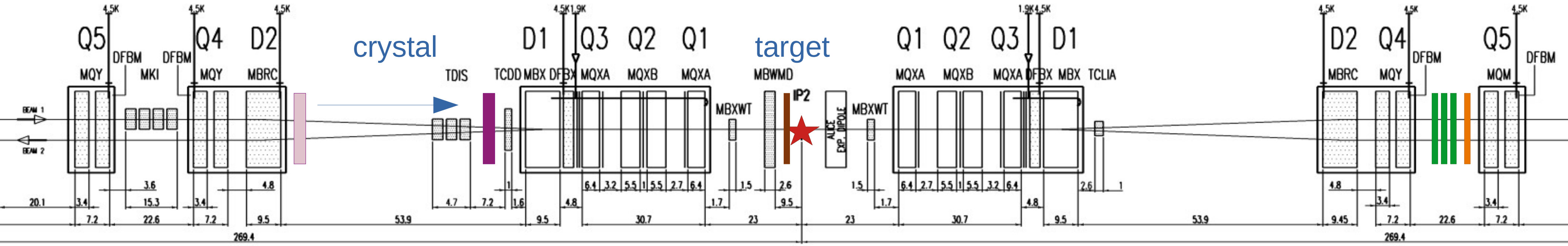
Target:

- length 5mm
- material tungsten
- s-position: 4.8m upstream from the IP2

Absorbers:

- 3 TCSGs: graphite, 1m long, at 10σ
- 1 TCLA: tungsten, 1m long, at 13σ
- the numer of absorbers may decrease – this will be studied with FLUKA E deposition simulations.





Summary on IR2 crystal implementation studies

- A **correct phase advance** between the **primary collimator and the crystal** is **crucial** for reaching a **high performance** of the system.
- Phase advance can be adjusted using a **minor, local modification of optics**. Such optimization is needed **every time optics changes**.
- S-location 3259m is the **only location** where **one crystal** can serve **both crossing scenarios**. It is also **good in terms of space availability** for the crystal **installation**.
- The **expected proton flux on target** for the crystal at 3259m, after phase advance optimization, is **$7.6 \cdot 10^6$ p/s** (assuming 2018 beam conditions).
- ALICE can handle about **10^7 p/s** on target.
- All the **estimations rely on** complex multi-turn tracking **simulations**. An **experimental verification** of the system’s performance and **identification of operational challenges** is needed in a **dedicated test-stand**, possibly to be deployed at **IR3**.

References

- Publications:

  - A Local Modification of HL-LHC Optics for Improved Performance of the Alice Fixed-Target Layout, IPAC’22 MOPOST024, waiting for publication.
  - Status of layout studies for fixed-target experiments in ALICE based on crystal-assisted halo splitting, https://accelconf.web.cern.ch/hb2021/papers/mop26.pdf
  - A fixed-target programme at the LHC: Physics case and projected performances for heavy-ion, hadron, spin and astroparticle studies https://doi.org/10.1016/j.physrep.2021.01.002
  - LHC fixed target experiments: Report from the LHC Fixed Target Working Group of the CERN Physics Beyond Colliders Forum https://doi.org/10.23731/CYRM-2020-004
  - Physics opportunities for a fixed-target programme in the ALICE experiment https://cds.cern.ch/record/2671944
  - Layouts for fixed-target experiments and dipole moment measurements of short-lived baryons using bent crystals at the LHC https://doi.org/10.1140/epjc/s10052-020-08466-x

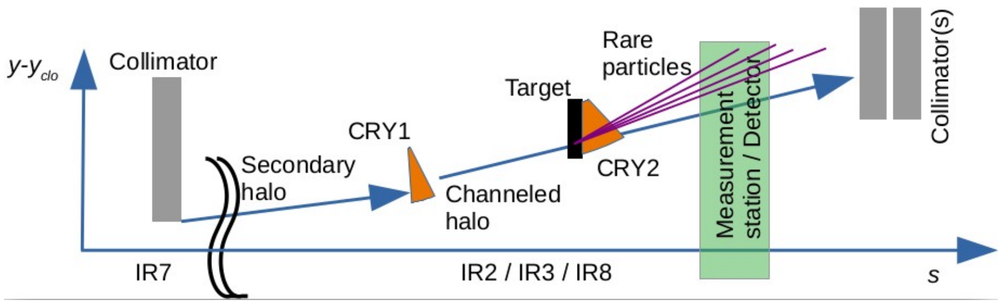
- Presentations:

  - F. Galluccio, W. Scandale Proposal for beam splitting in LHC IR2 https://indico.cern.ch/event/853688/contributions/3620725/
  - A. Fomin, Updates on IP2 FT layouts https://indico.cern.ch/event/981210/contributions/4132813
  - D. Kikoła, A fixed-target program in the ALICE experiment https://indico.cern.ch/event/1002356/contributions/4229546/
  - M. Patecki, Status of the crystal based ALICE fixed target layout, https://indico.ijclab.in2p3.fr/event/7201/contributions/22532/

Outline

- Crystal implementation in IR2
- Studies on experimental test-stand with crystals in IR3
  - This part is presented on behalf of the CERN Collimation Team
  - Materials come from P. Hermes et al.

IR3 test stand for crystal-based fixed target experiments



Challenges for FT experiments

- Crystals must respect the collimation system hierarchy.
- Particle losses coming from the layout of crystals+target must be safely disposed.
- Crystals alignment and angular orientation must be well controlled due to limited angular acceptance at 7TeV.
- A large bending angle (some mrad) and a significant length (some cm) of CRY2 is needed.
- An optimized phase-advance between the IR7 primary collimator and CRY1 is needed.

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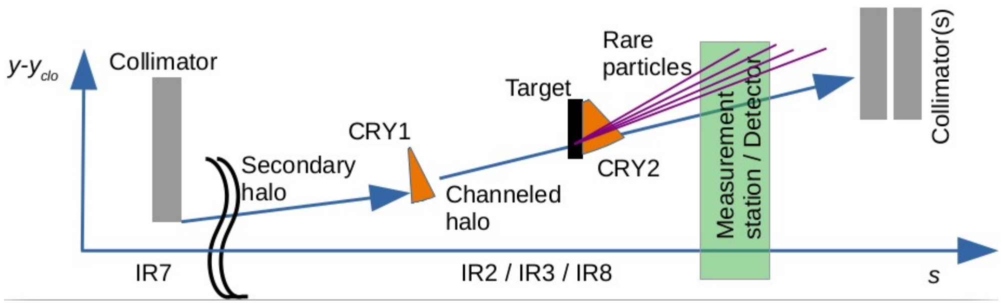

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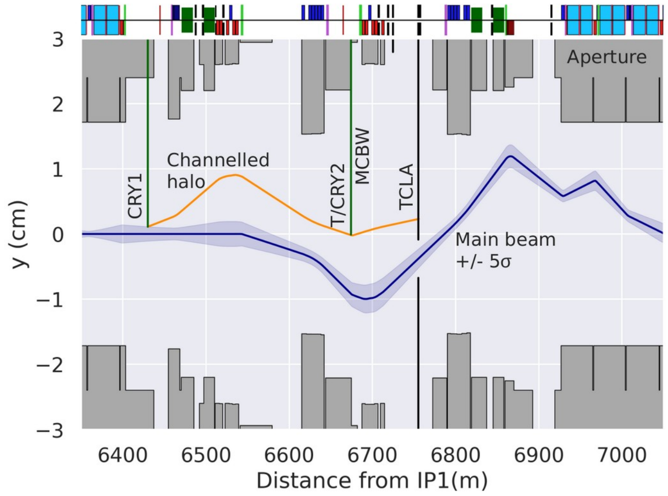
Experimental verification

- System performance is evaluated based on complex multi-turn tracking simulations which must be verified experimentally.
- Methods of adapting the crystal to the dynamic conditions of the machine must be developed.
- Methods of controlling the optimal crystal position/orientation in the presence of usual machine imperfections must be developed.
- Experimental characterization of a long, large-bending angle crystal (CRY2) at high energy (~TeV) is needed.

Layout for the IR3 test stand

- IR3 provides good space availability to host such a test stand.
- Design based on studies described in [Eur. Phys. J. C (2020) 80:929]
- System to be installed in the vertical plane.
- One of the existing dipole corrector magnets can be used as a spectrometer.
- This requires moving such a magnet by about 10m upstream to create a space for the CRY2 installation. This would cause about 15% reduction of efficiency for local orbit correction.
- Orbit bump created by the spectrometer can be well compensated by other orbit correctors nearby.
- Installation of the target next to the CRY2 is under investigation.
- An existing vertical absorber will be used to intercept losses emerging from CRY2(+Target).

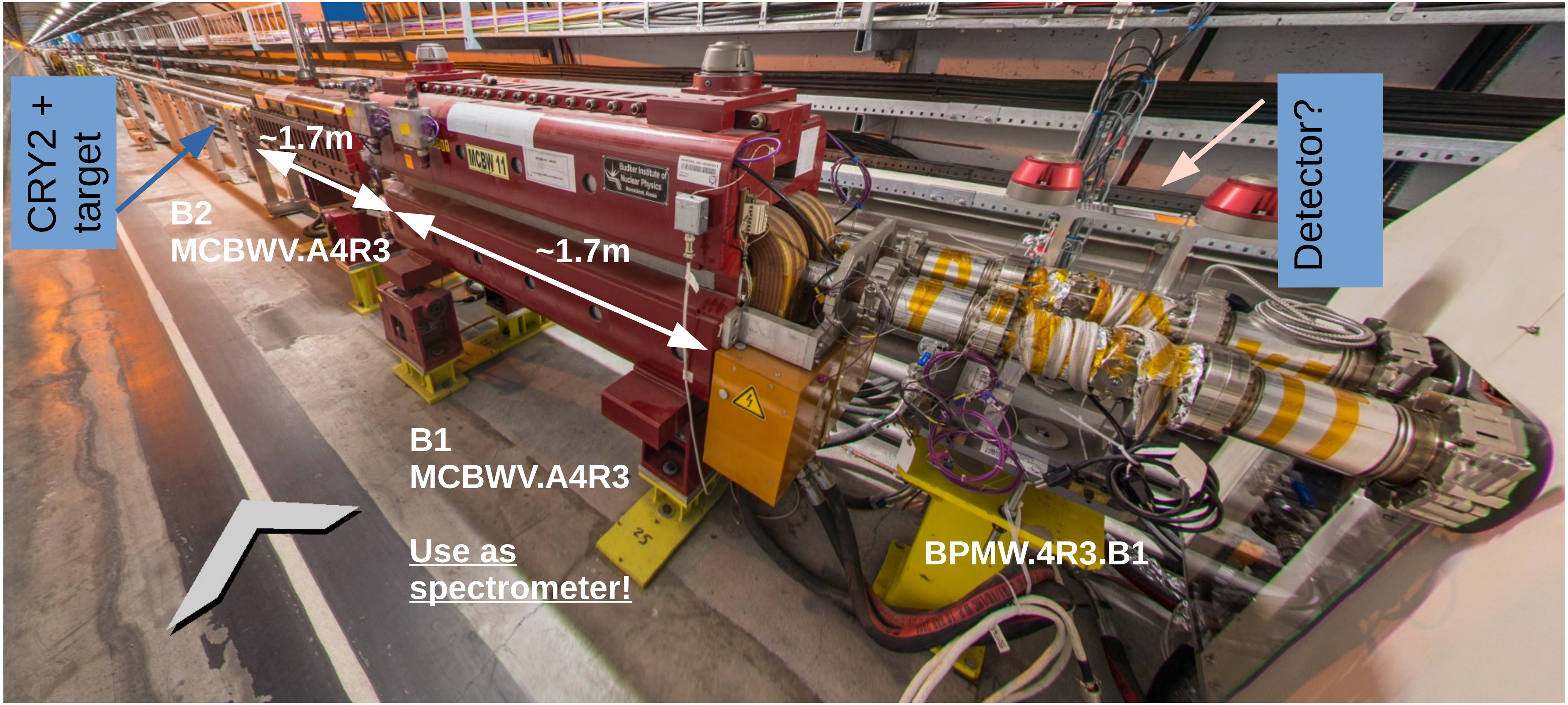


Device	Position (m)	Angle (μrad)	Length (m)	Integrated mag. f. (Tm)	Material
CRY1	6431.0	50	0.004	-	Si
Target	6674.5	-	0.005	-	W
CRY2	6674.5	7000	0.075	-	Si
MCBWV.4R3.B1	**6674.9***	-	1.7	1.87	-
TCLA.A5R3.B1	6755	-	100	-	W

Devices already in place

*) Moved upstream by ~ 10m

MCBWV.A4R3 as a spectrometer



https://edms.cern.ch/panoramas/viewer?fov=90.00&id=36409858&lat=-27.06&lon=241.01

- To be checked: available space at BPM position → enough for detector?

Summary on IR3 test stand studies

- Experimental verification of crystal based fixed target experiments is crucial for their successful implementation.
- A design of a dedicated test stand to be installed in IR3 is under development.
- It could be operated already in Run3.
- Already performed studies indicate that the proposed layout meets the design requirements. Further studies are in progress.

Thank you for your attention!

Extra slides

Comparison with ion optics
simulation settings

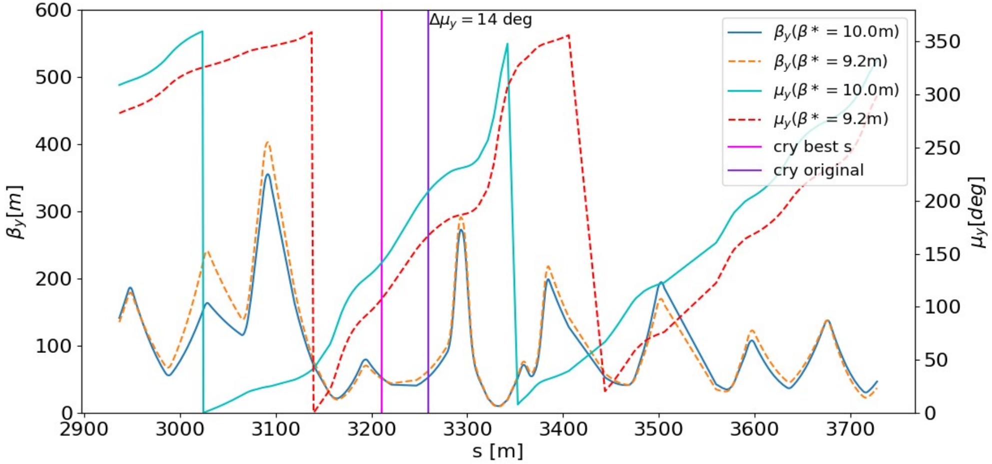
- Only one IR2 optics scenario available for HL-LHC v1.5

- RunII ion optics scenarios used for comparison with my modifications
- /afs/cern.ch/eng/lhc/optics/runII/2018/ION
- Only optics, no SixTrack studies.

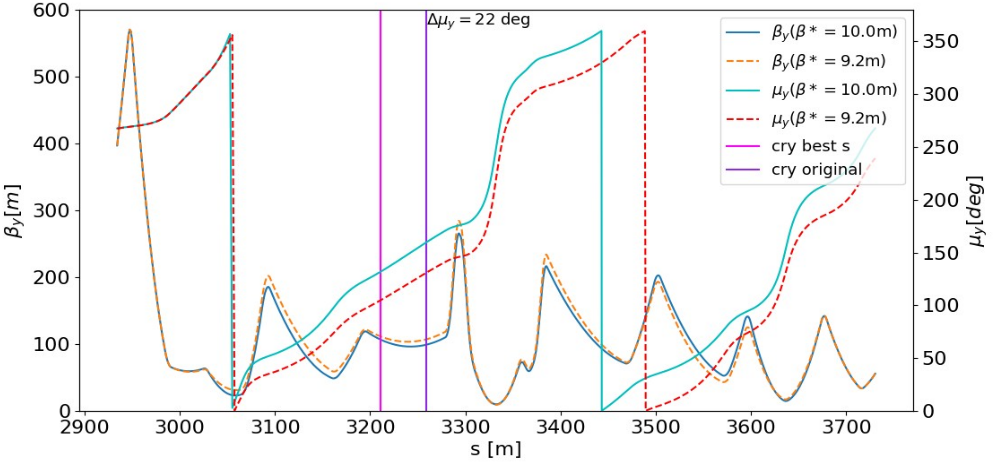
- Ion optics changes globally (all IRs)
- My changes concern IR2 only.

β* = 10m and 9.2m

Ion optics 2018



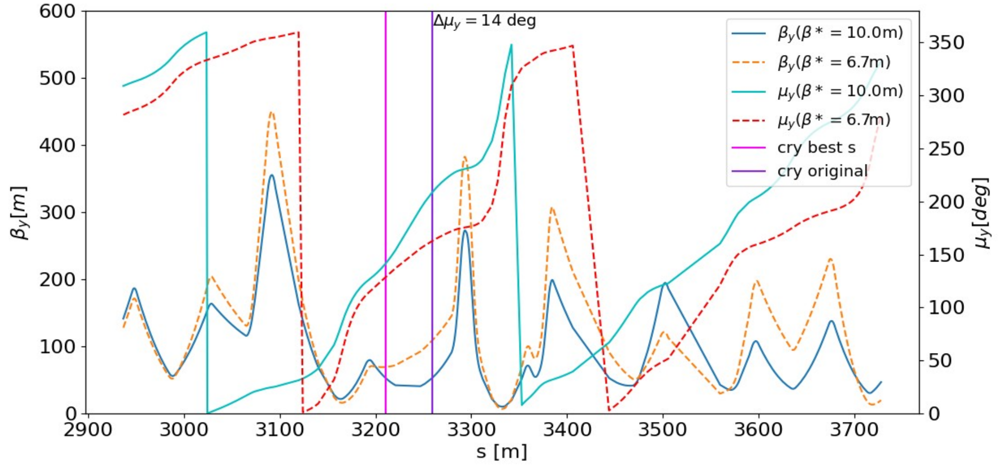
HL-LHC v1.5 with my changes



Qualitatively very similar effect

β* = 10m and 6.7m

Ion optics 2018



HL-LHC v1.5
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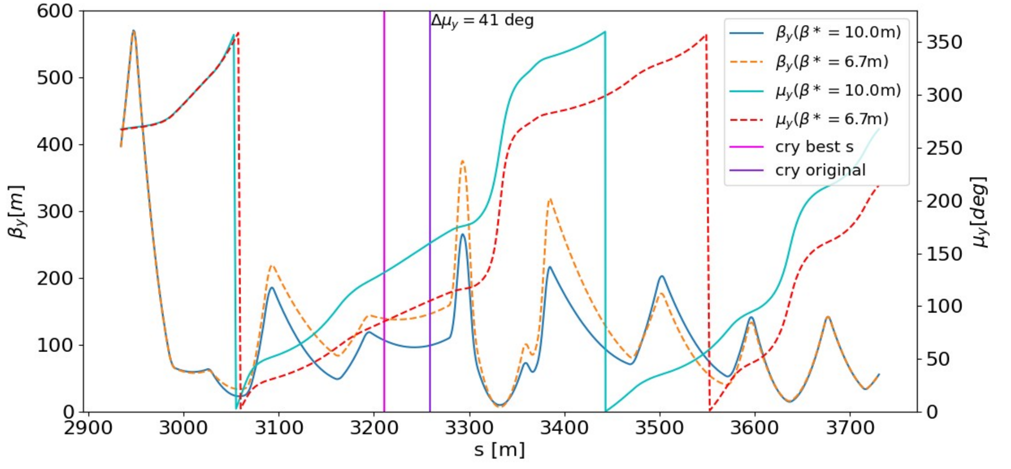
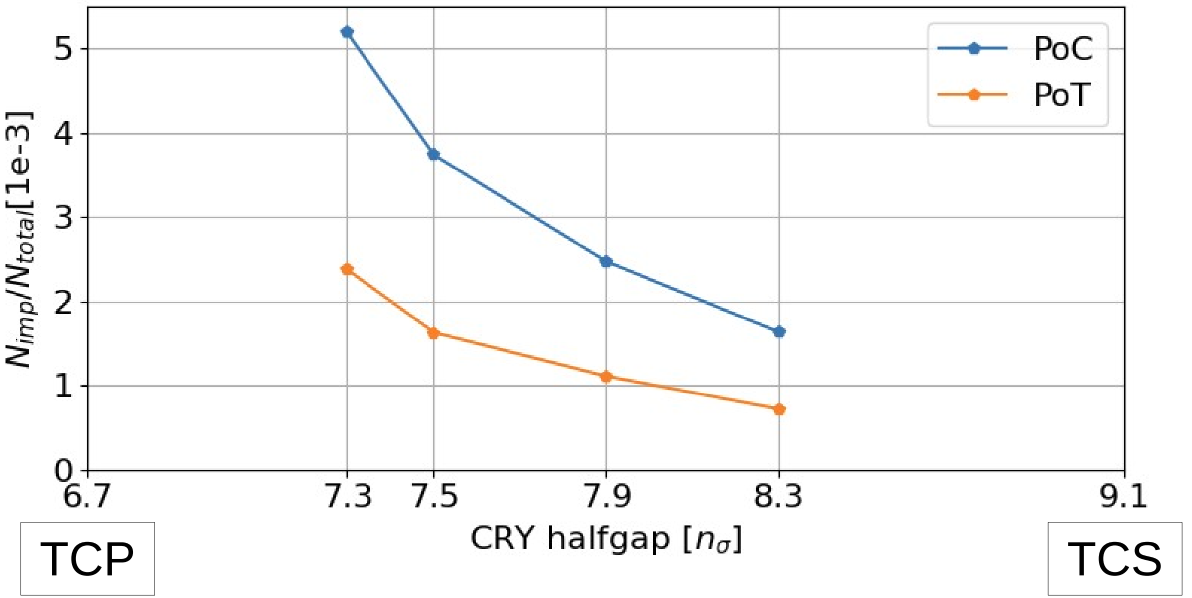


Qualitatively very
similar effect

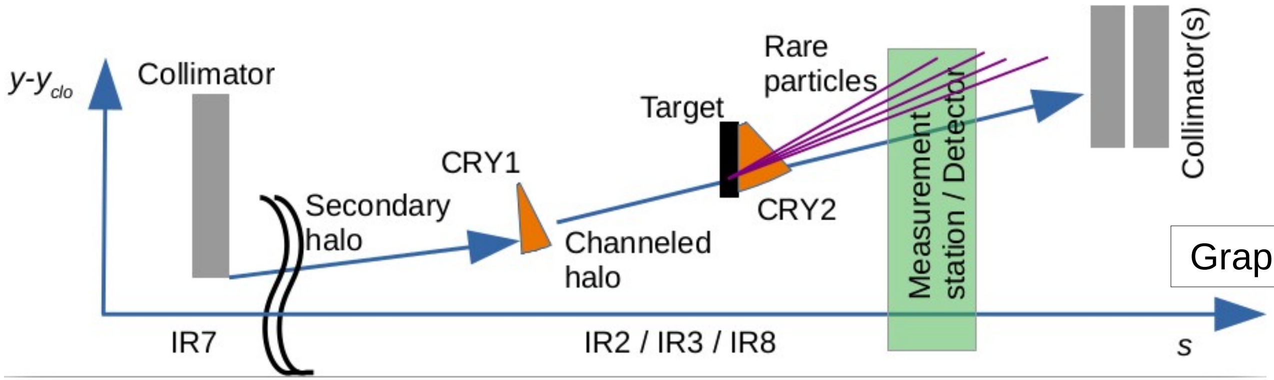
Summary of ion optics review

- 2018 ion optics was analyzed for several IP2 β* values.
- A very similar effect is observed as for manual changes of HL-LHC optics.
- Lower β* values cause a change of phase advance in a favorable way.
- Optics at the region of concern is rather flexible and required modifications should be easy to be implemented.
- This is only a verification of concept. Final optics matching requires a support from optics experts.

PoC (s=3217)


PoC
PoT
5
4
3
2
1
0
N_{imp}/N_{total}[1e-3]
6.7
7.3
7.5
7.9
8.3
9.1
CRY halfgap [n_σ]
TCP
TCS

Challenges of crystal-based fixed target experiments



Graphics: P. Hermes

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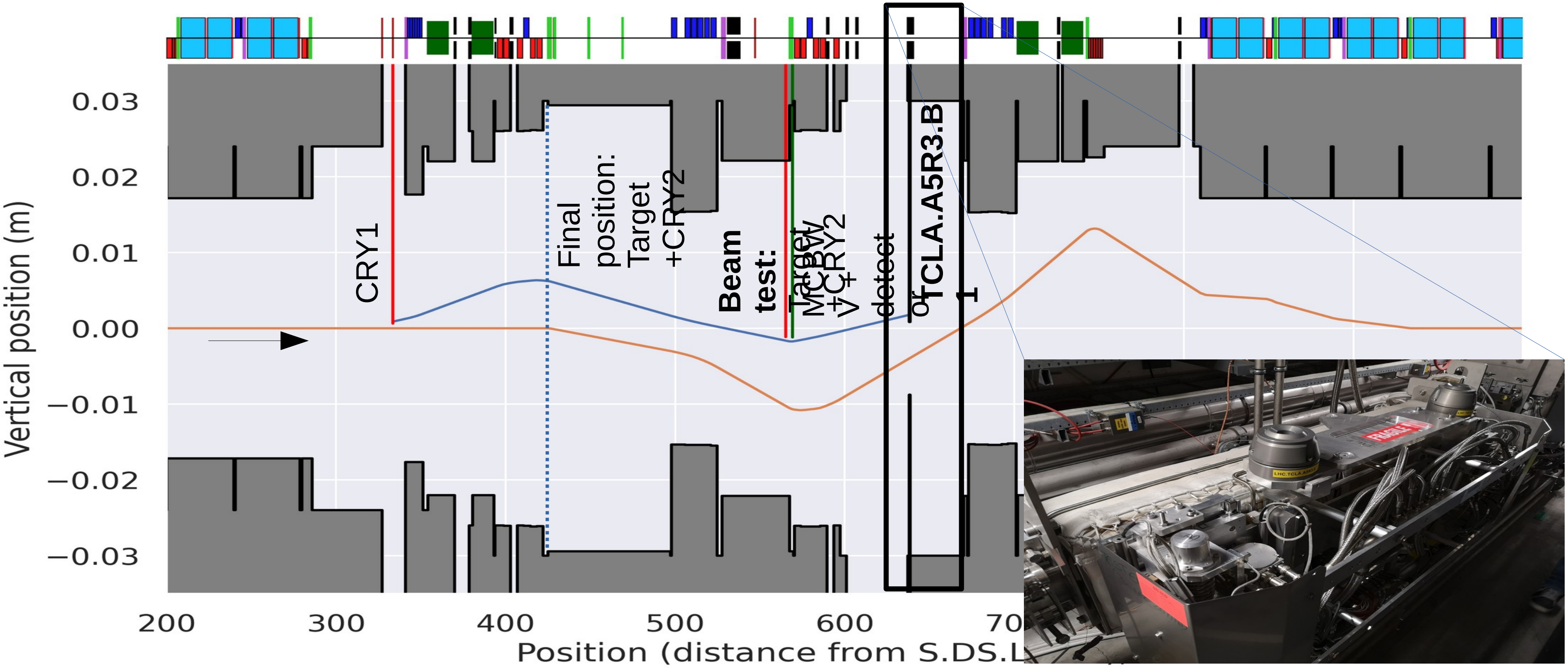
- An optimized phase-advance between the IR7 primary collimator and CRY1 is needed;

An experimental test stand is planned to be deployed in IR3 to experimentally verify above listed challenges.

Possible tests in Run 3



Backup