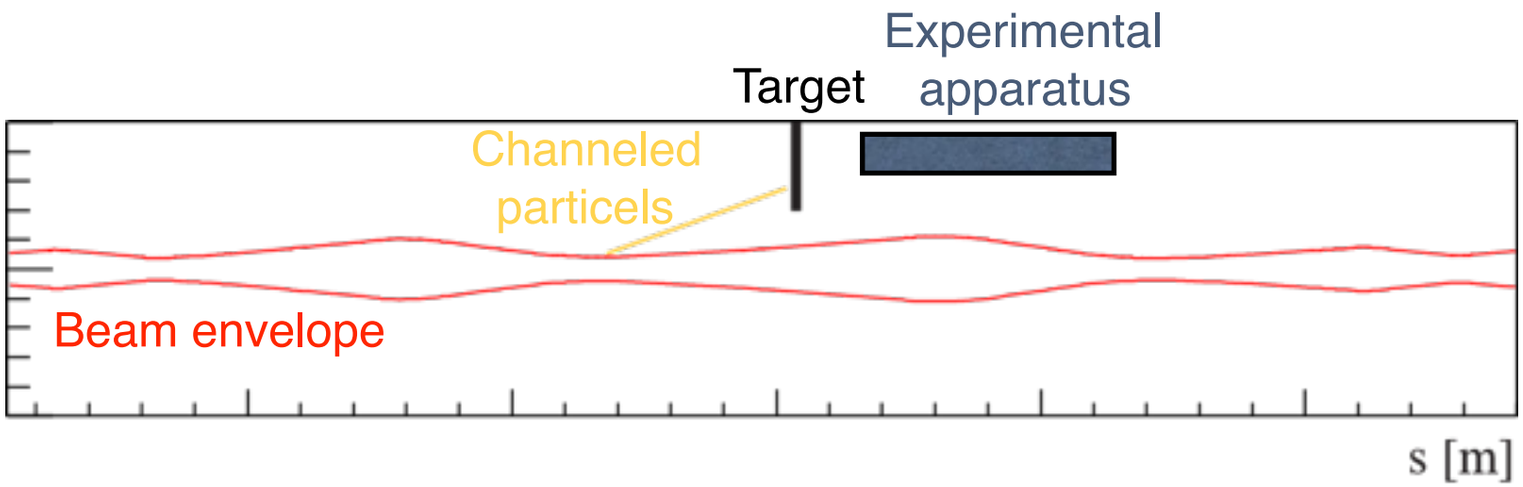
Physics Beyond Colliders — Kickoff meeting
September 6th-7th, 2016
CERN, Geneva, Switzerland

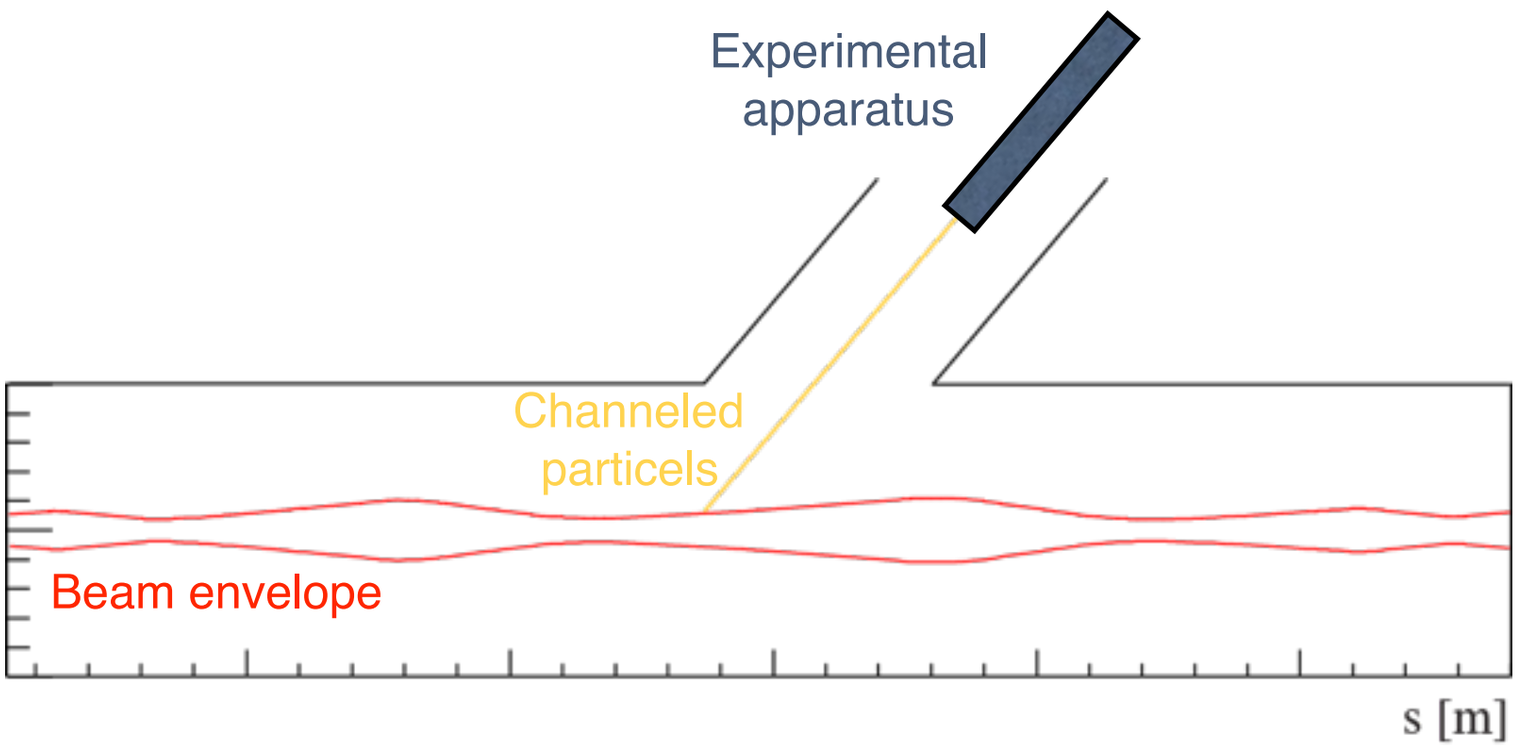
Experience with Multi-TeV Beam Channeling and Crystal Extraction at the LHC

D. Mirarchi, S. Redaelli, R. Rossi, W. Scandale

CERN, BE-ABP

LHC crystal extraction options





- In-beam targets (small angle) vs dedicated line (bigger);
- New line vs implementation in existing LHC dump line;
- Existing experiment(s) as experimental apparatus?
- Dedicated operation with crystals as primary beam restriction vs parasitic operation in shade of LHC collimation system.

No specific implementation discussed here (↦ next talk), rather illustration of how the developed know-how and experience with hardware can steer design work.

Outline

- ☑ Introduction
- ☑ UA9 results with SPS beams
- ☑ LHC collimation studies
- ☑ LHC crystal extraction
- ☑ Spill control mechanisms
- ☑ Conclusions

Acknowledgements

This talk is given on behalf of the members of the UA9 collaboration (SPS, H8 data) and LHC collimation team.

CERN groups involved in these crystal studies:
(support from many: vacuum, diagnostics, operations, services…)

BE-ABP

EN STI

Funding of LHC crystal installation:

Recent thesis works (simulations and/or measurements):

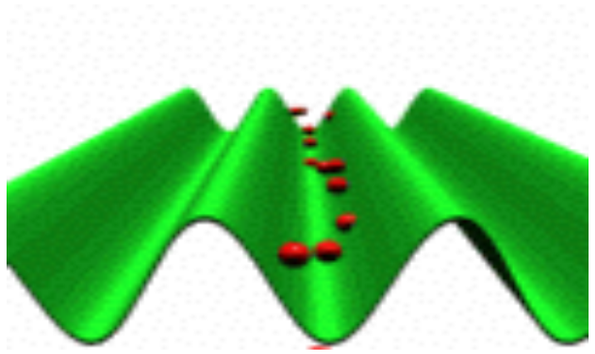
V. Previtali: CERN-THESIS-2010-133 (2010, PhD)
D. Mirarchi: CERN-THESIS-2011-136 (2011, master);
CERN-ACC-2015-0143 (2015, PhD)
R. Rossi: CERN-THESIS-2014-187 (2014, master);
PhD ongoing
P. Schoofs: CERN-THESIS-2014-131 (2014, PhD, FLUKA team)

First proposal on crystal extraction for CERN facilities — see W. Scandale, Proc. LHC Workshop, eds G. Jarlskog and D. Rein, Aachen, 1990, vol. III p. 760.

Hadron interactions with bent crystal

If the protons ***have $p_T < U_{max}$***

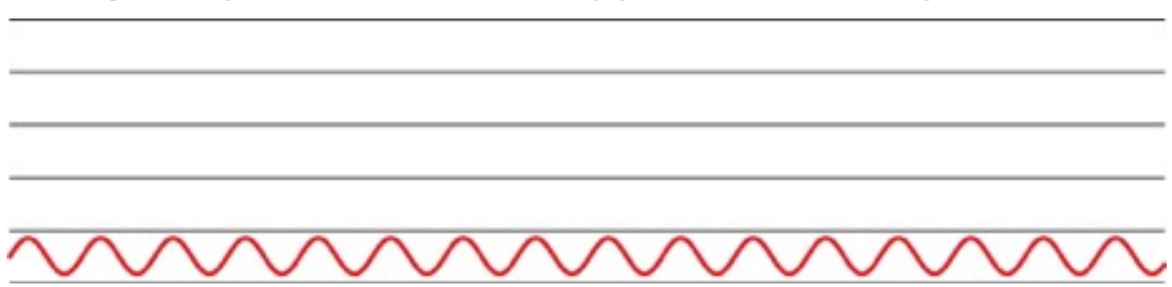
$$\theta_c = \sqrt{\frac{2U_{max}}{pv}}$$



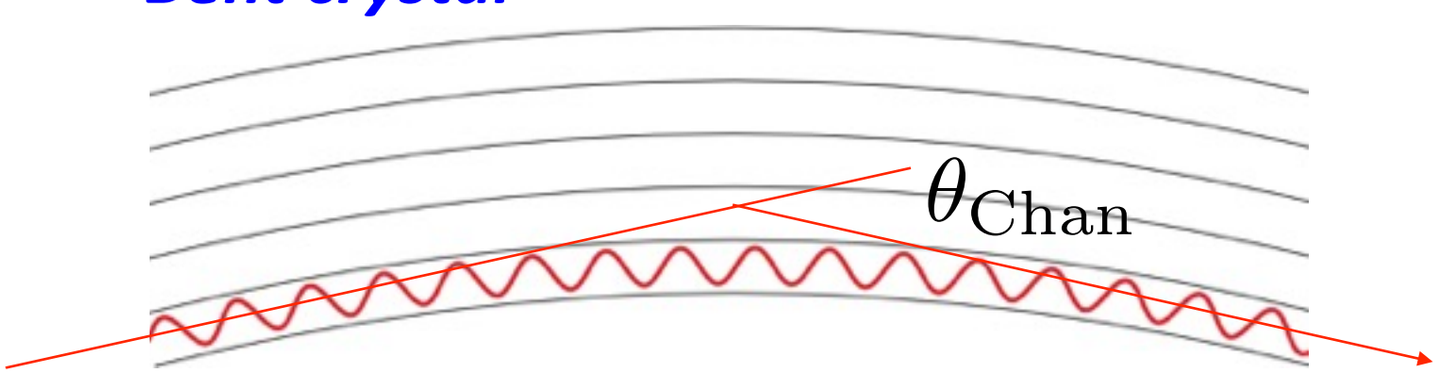
Forced to oscillate in a relatively empty space

$$x(z) = \frac{d_p}{2}\sqrt{\frac{E_t}{U_{max}}}\sin(\frac{2\pi z}{\lambda} + \phi)$$

Straight crystal: hadron "trapped" between planes



Bent crystal



Key parameters for Si crystals

Case	Energy [GeV]	θ_c [μrad]	λ [μm]
SPS coast	120	18.3	33.0
SPS coast	270	12.2	49.6
H8	400	10.0	60.3
LHC inj.	450	9.4	64.0
LHC top	6500	2.5	243.2
LHC top	7000	2.4	252.3

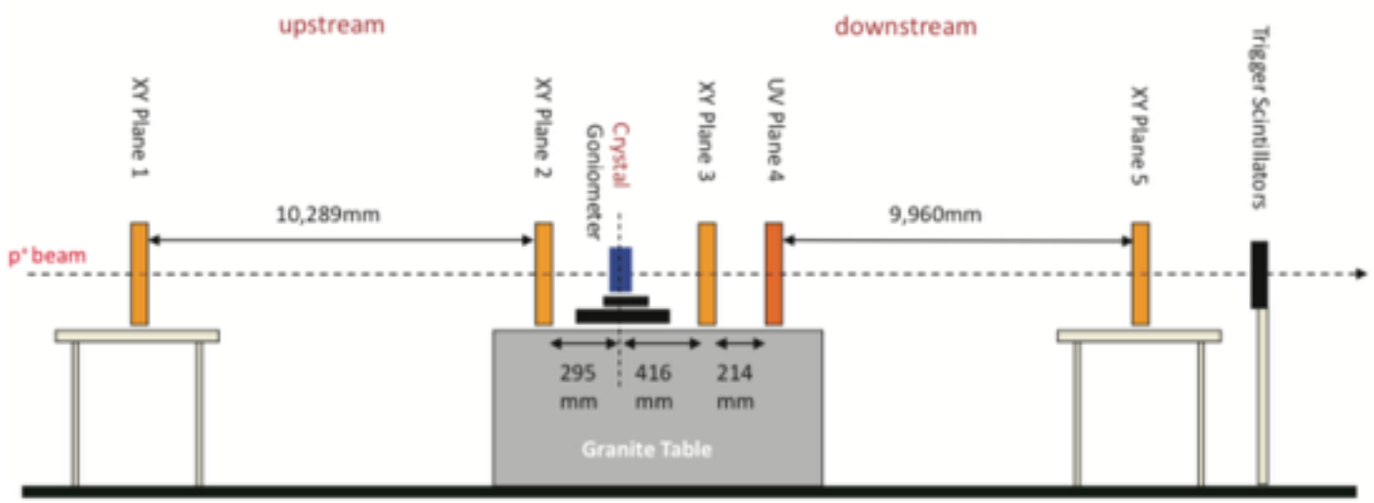
FCC (50TeV) < ***0.9 μrad***

Mechanical bending of crystal produces a net kick of trajectories of particles trapped between planes.

Equivalent magnetic field for **50μrad** at **7 TeV** proton beams: **310 T** (4 mm crystal)

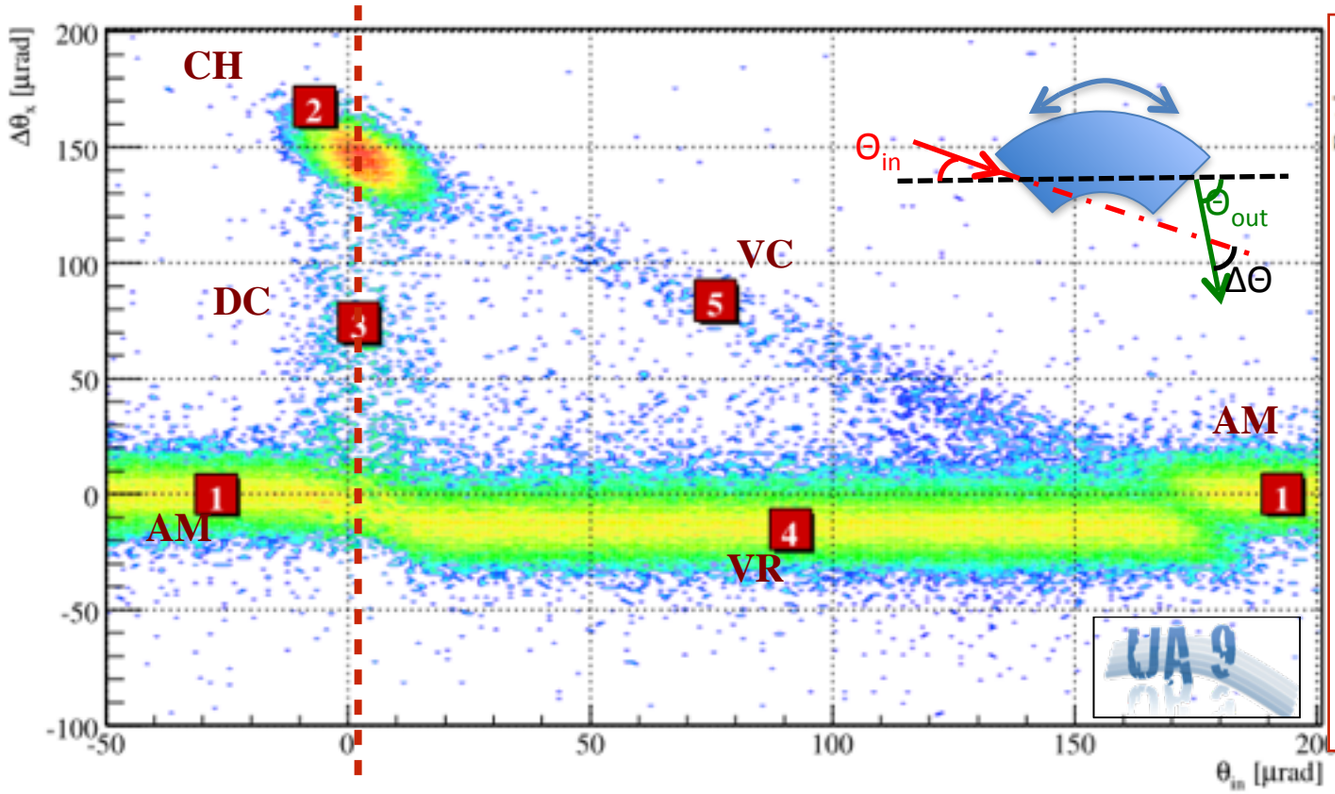
Single-pass measurements in SPS-H8

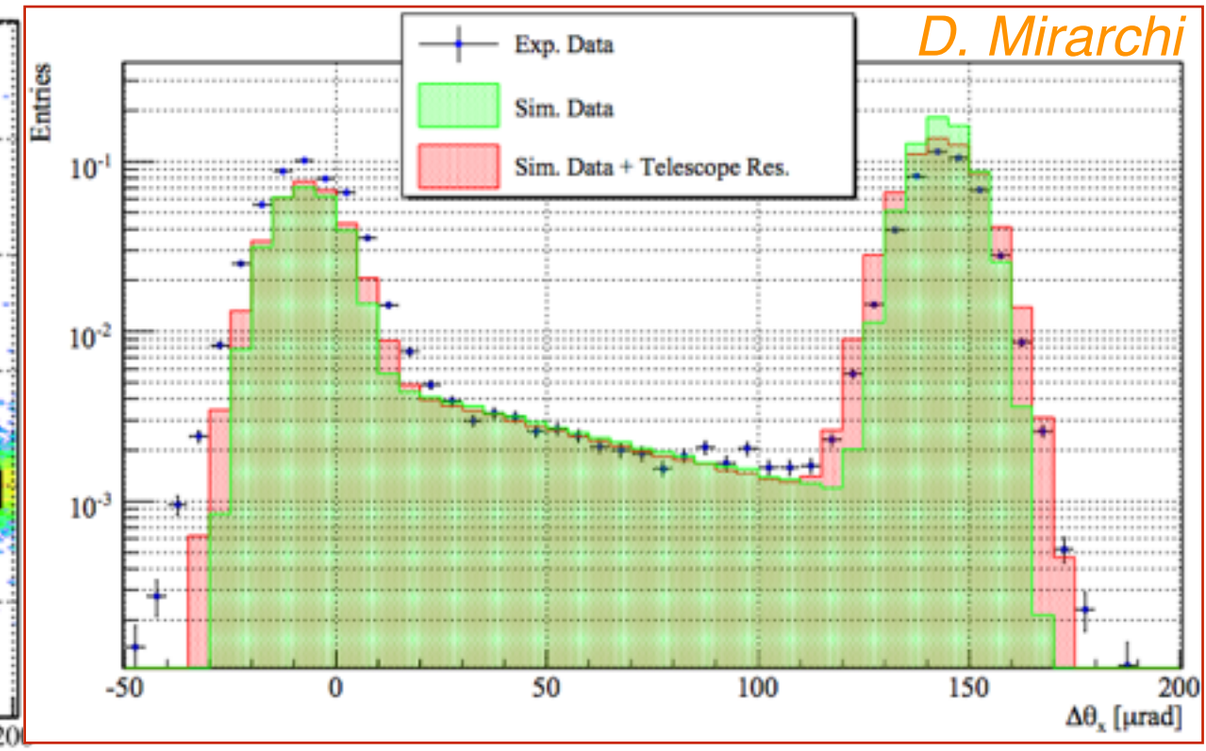
UA9 experimental setup in the SPS-H8 line (400GeV)

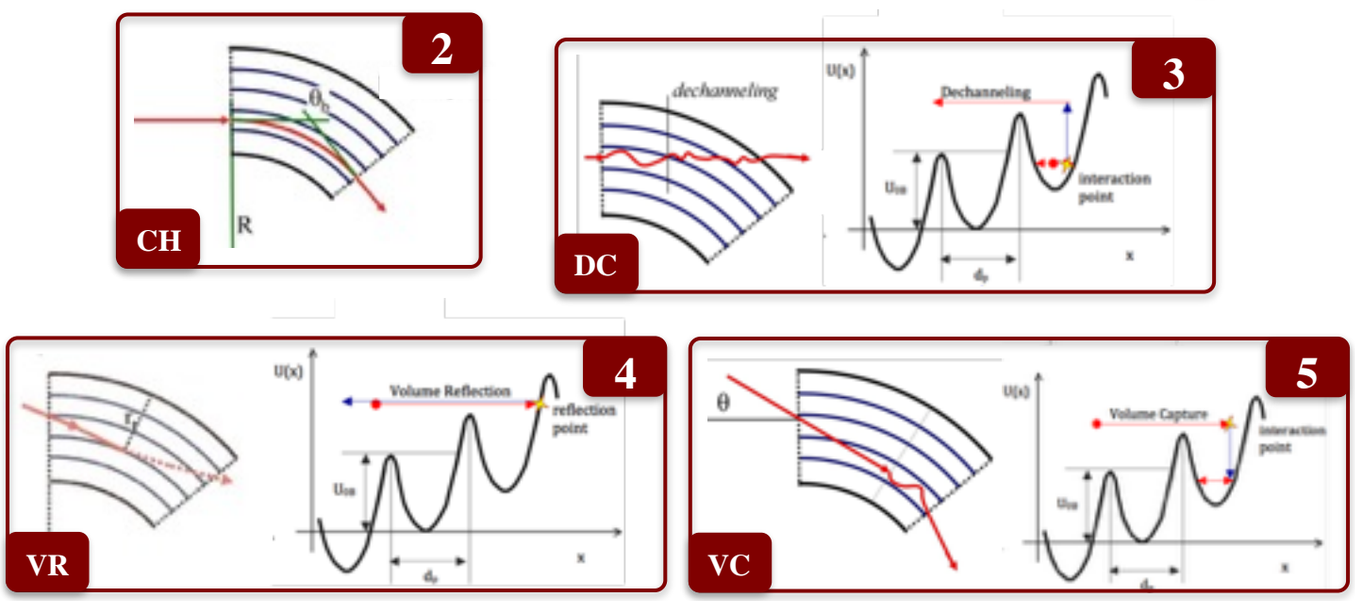


Detailed set of measurements: <u>crucial</u> for code development and characterisation of crystals; several new effects observed.

Single-pass measurements in SPS-H8



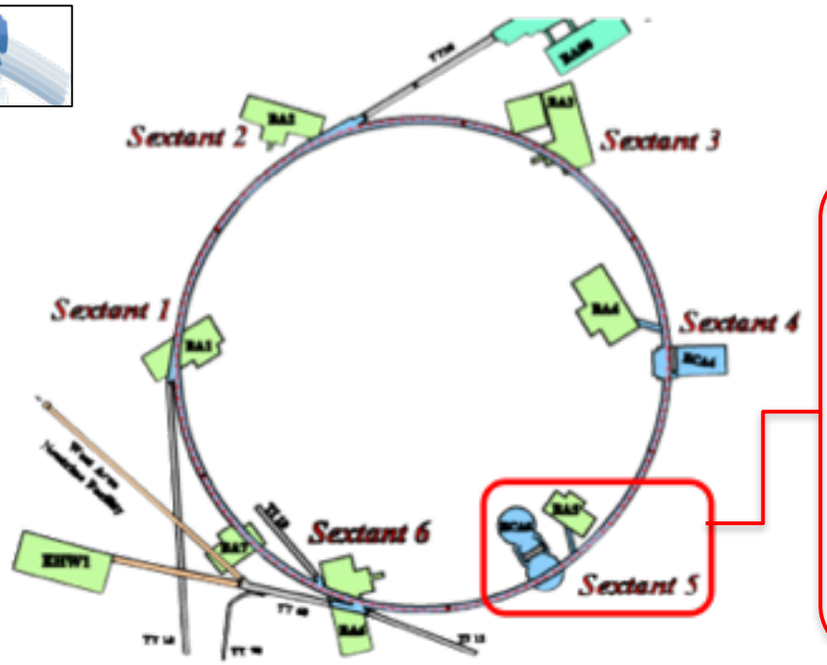




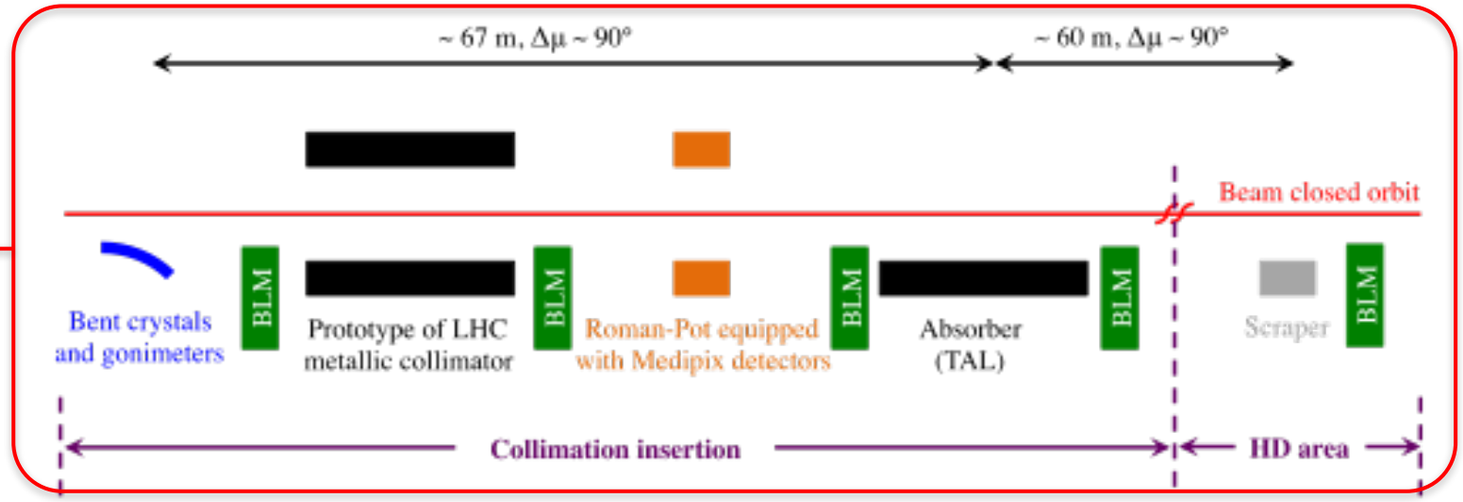
Planar channeling (simplest):
Five (5!!) different processes

Detailed set of measurements: <u>crucial</u> for code development and characterisation of crystals; several new effects observed.

SPS channeling of circulating beams

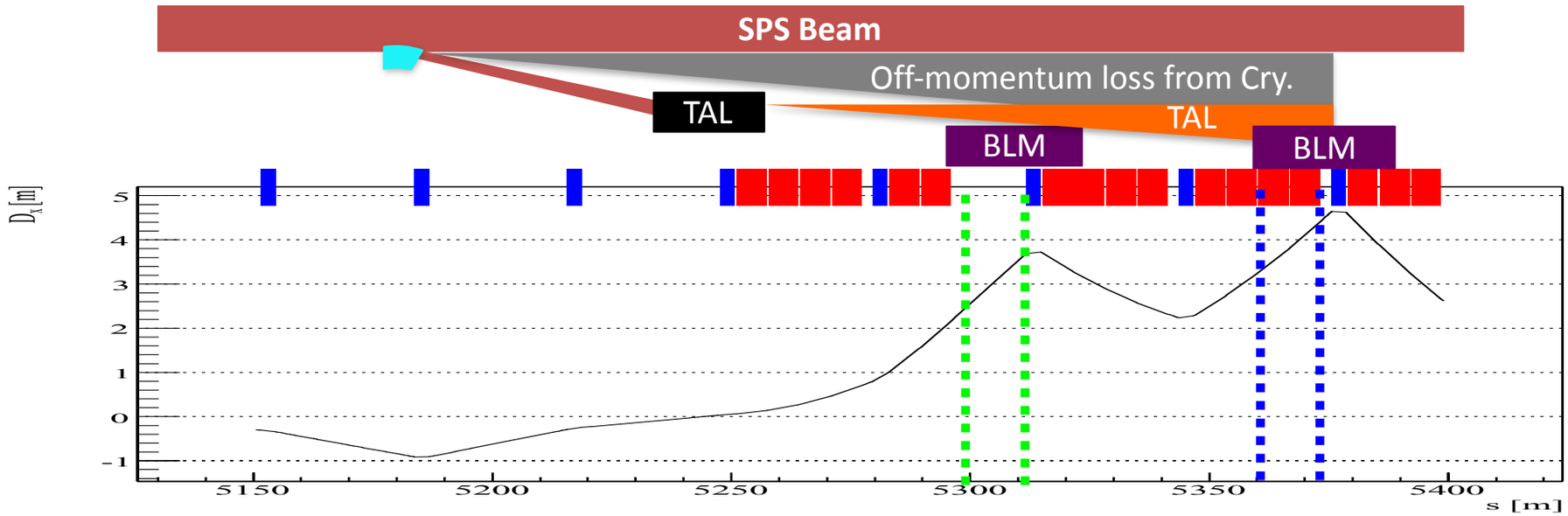


UA9 experiment setup installed in the SPS-LSS5: hardware from UA9 and collimation project

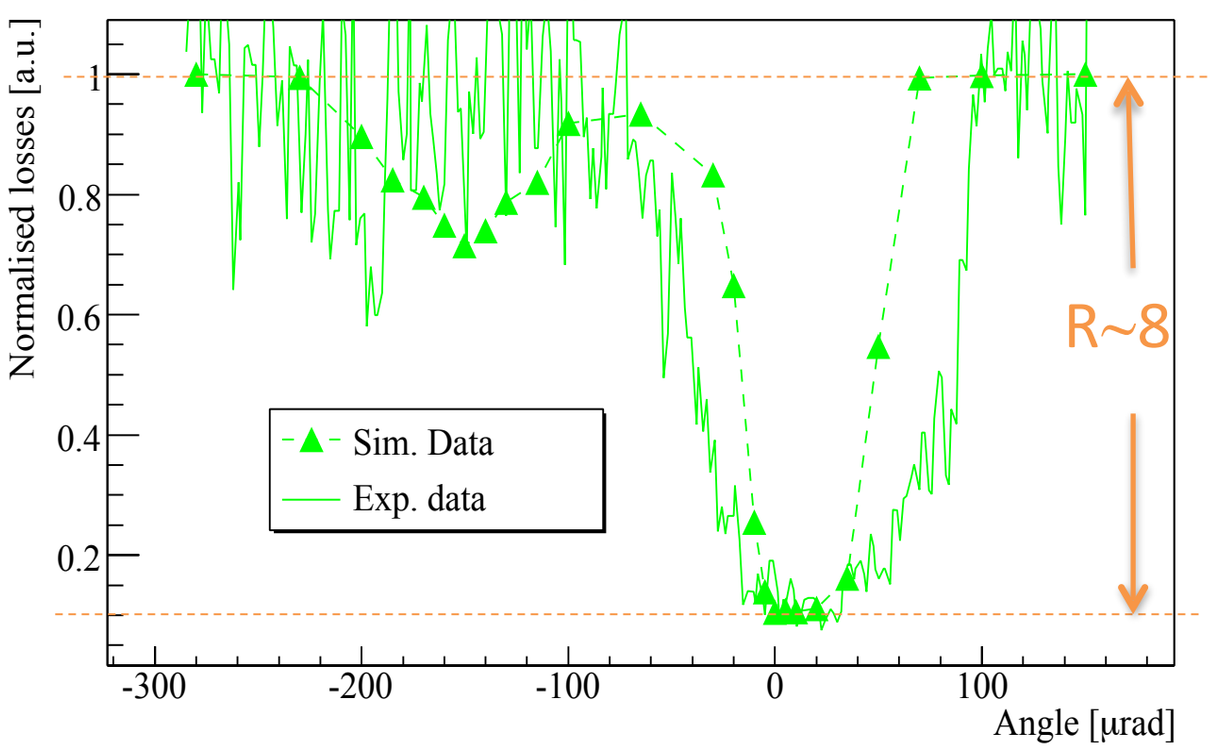


Additional complexity:
Edge effects on crystal surface;
Beam dynamics of particles with larger amplitudes/energy errors;
Scattering on other collimators;
Details of aperture models.

Simulations versus measurements



First high-dispersion area area



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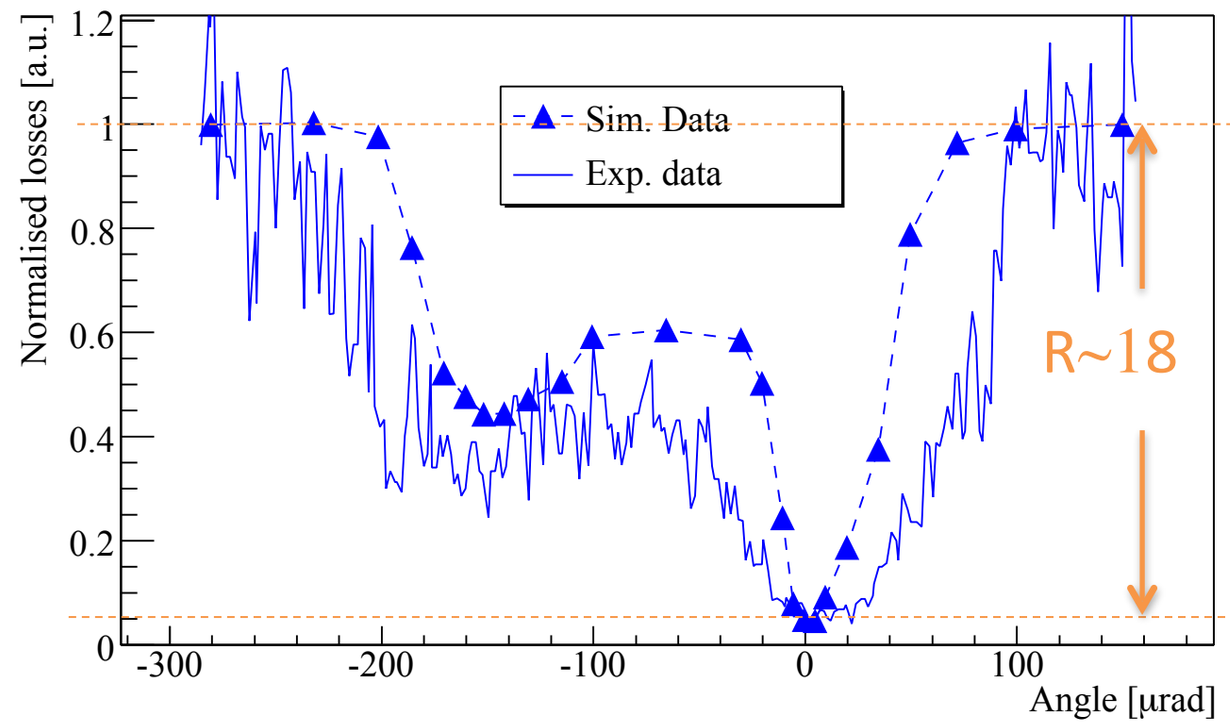

Phys.Lett. B748 (2015) 451-454

PhD work by D. Mirarchi

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- ☑ Introduction
- ☑ UA9 results with SPS beams
- ☑ **LHC collimation studies**
- ☑ LHC crystal extraction
- ☑ Spill control mechanisms
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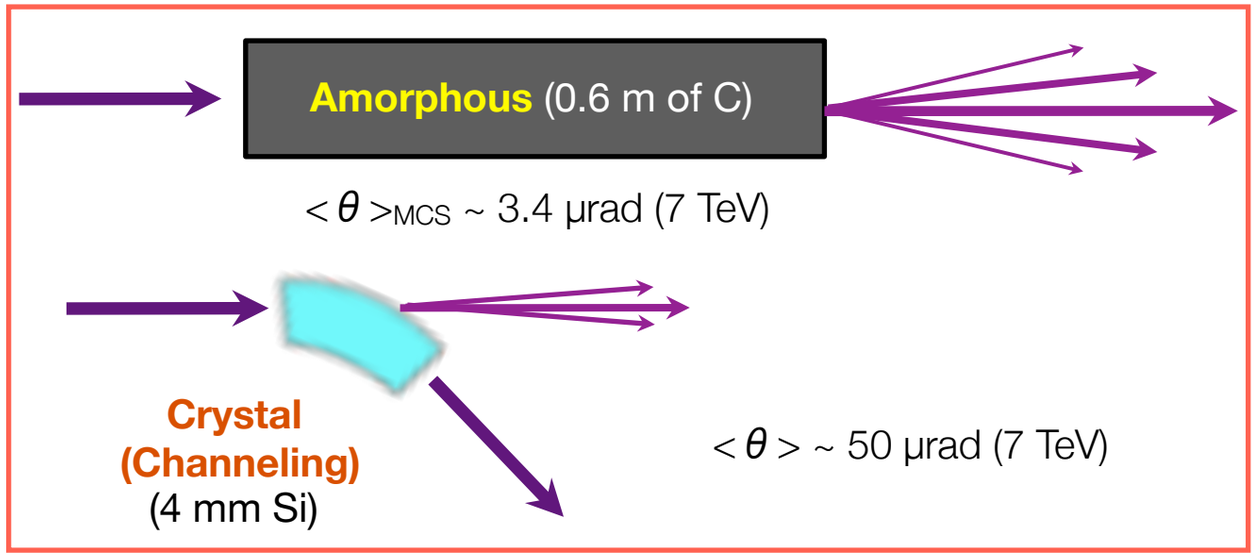
Concept of crystal collimation

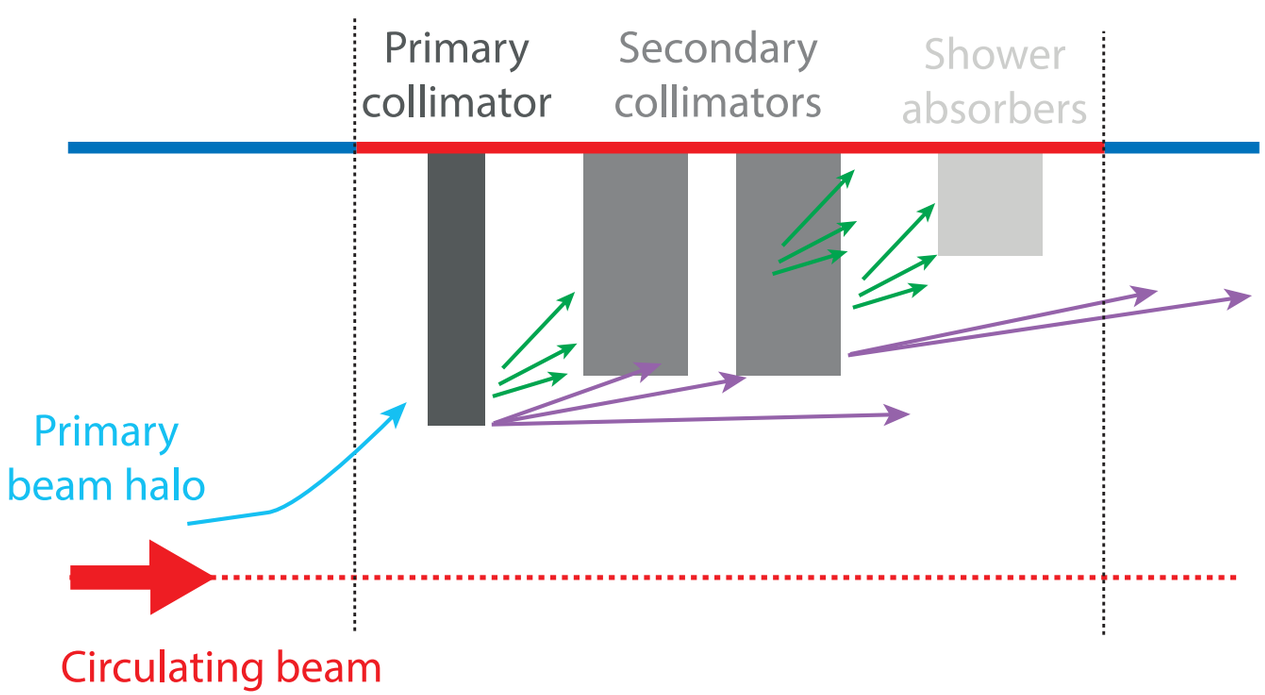


Crystals as primary collimators: **large angles** and **reduced change of rigidity** (diffractive losses and ion fragmentation).

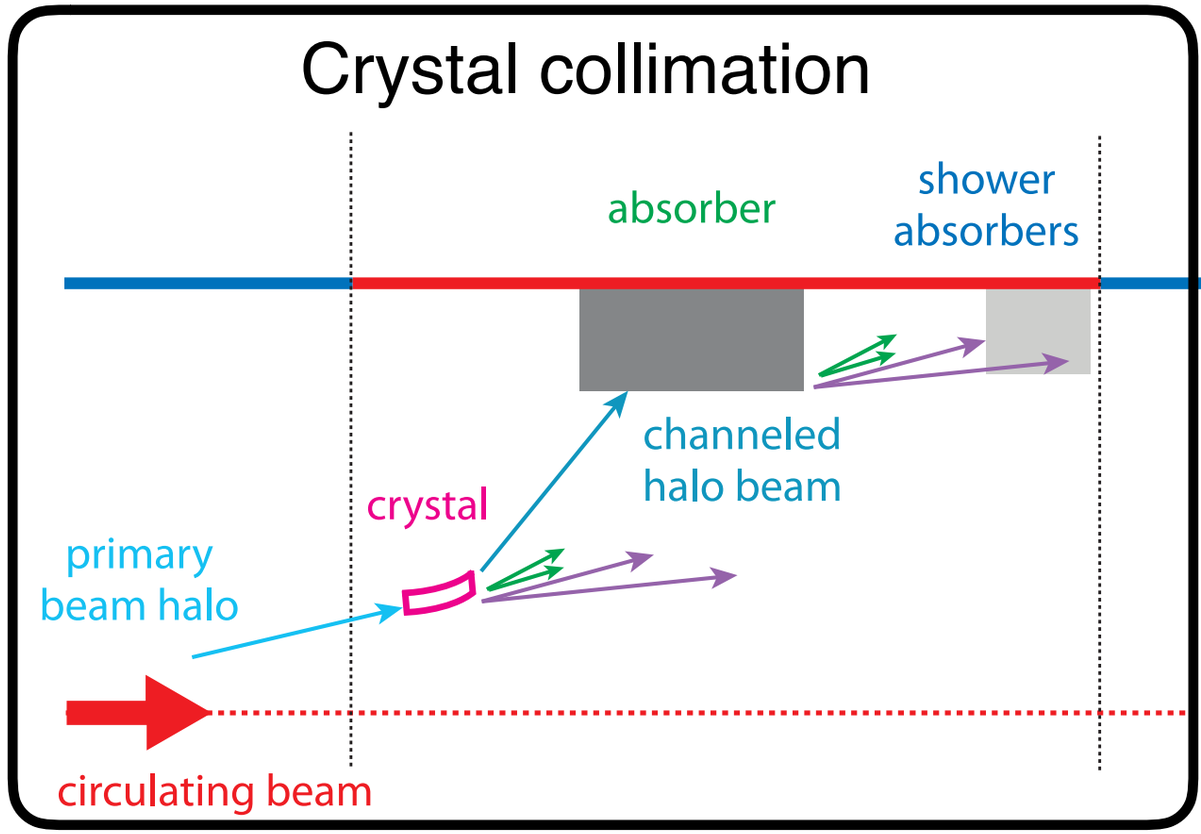
Challenges for the LHC:

- small angular acceptance **~2 μrad**;
- localization of losses up to **1.0 MJ** in one single collimator absorber.

Present multi-stage collimation



Crystal collimation



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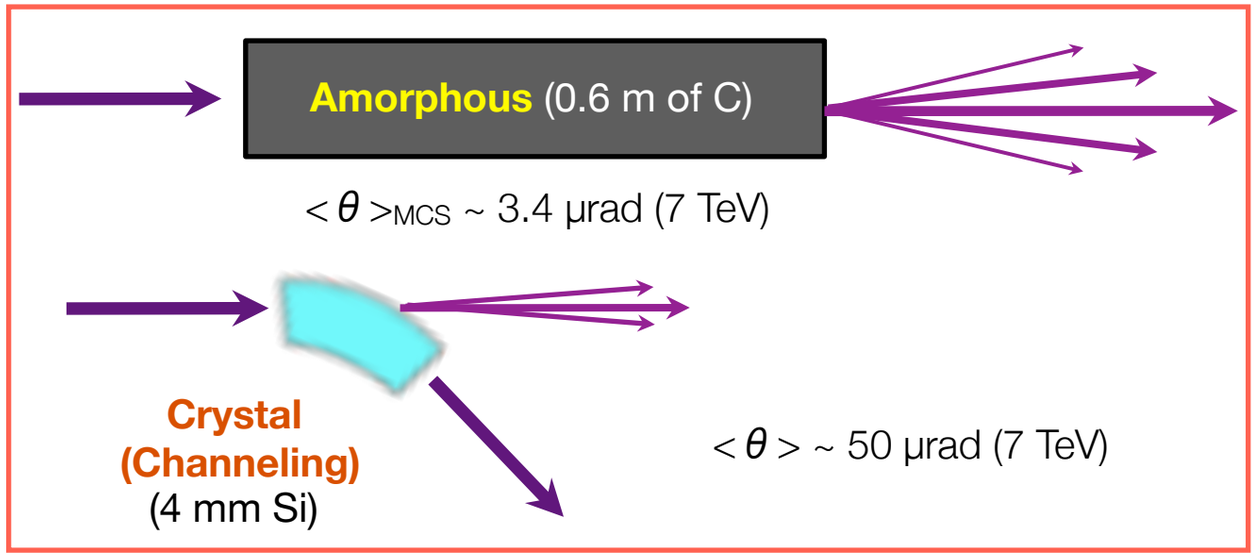

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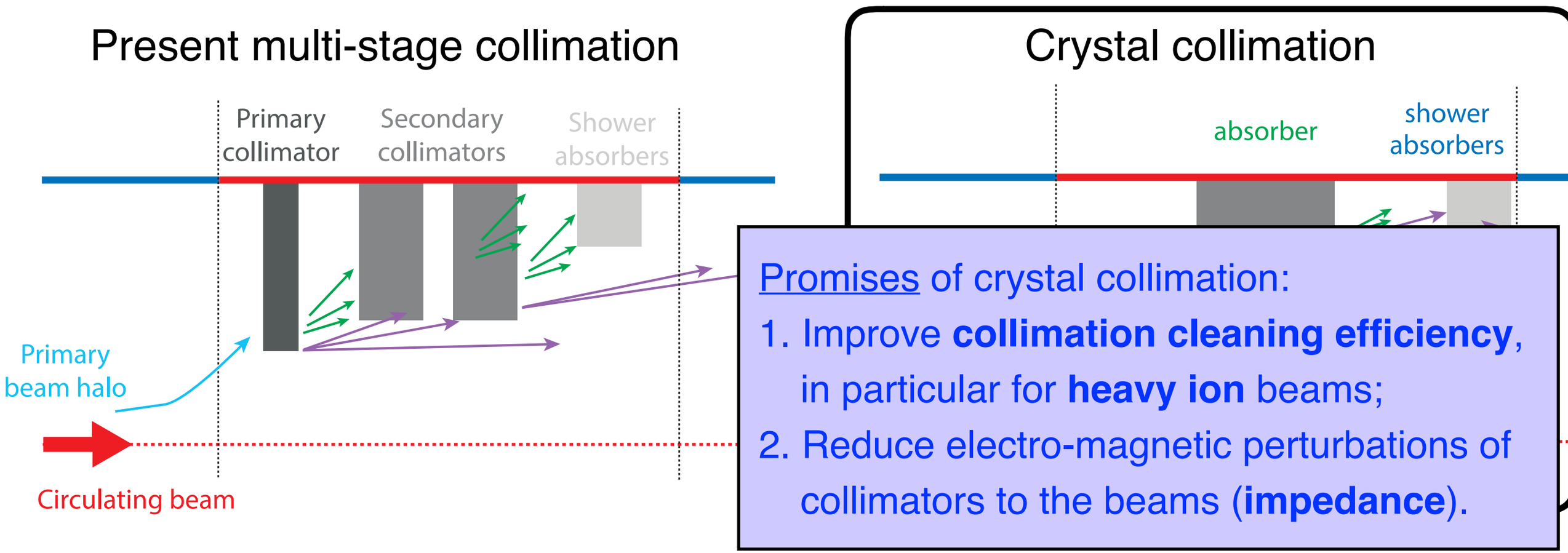
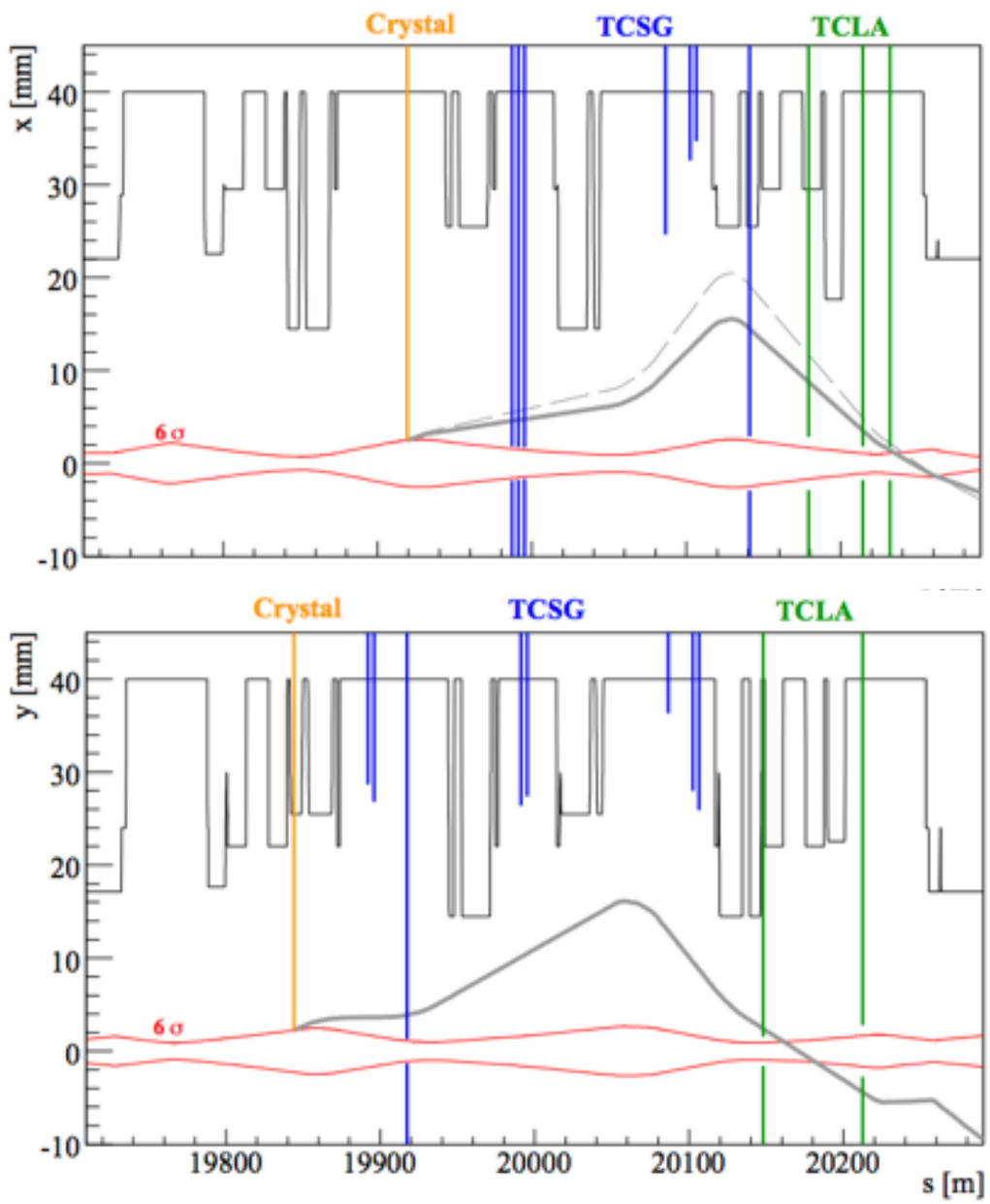


Promises of crystal collimation:

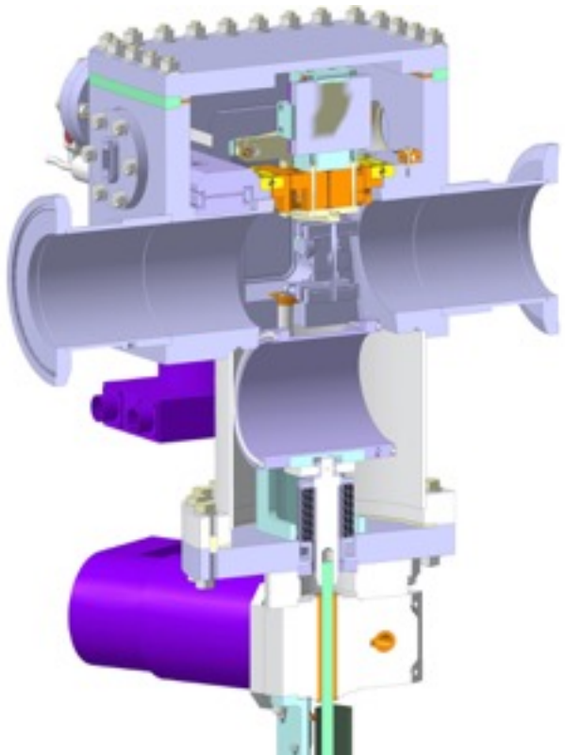
1. Improve **collimation cleaning efficiency**, in particular for **heavy ion** beams;
2. Reduce electro-magnetic perturbations of collimators to the beams (**impedance**).

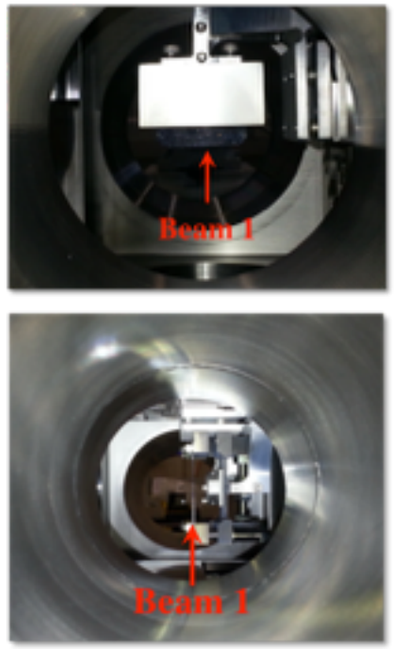
Layout of LHC crystal collimation setup



- Two crystal technologies (strip and quasi-mosaic);
- Optimized for collimation studies for ions and protons, all energies;
- Feasibility tests, compatible with low-intensity beams.

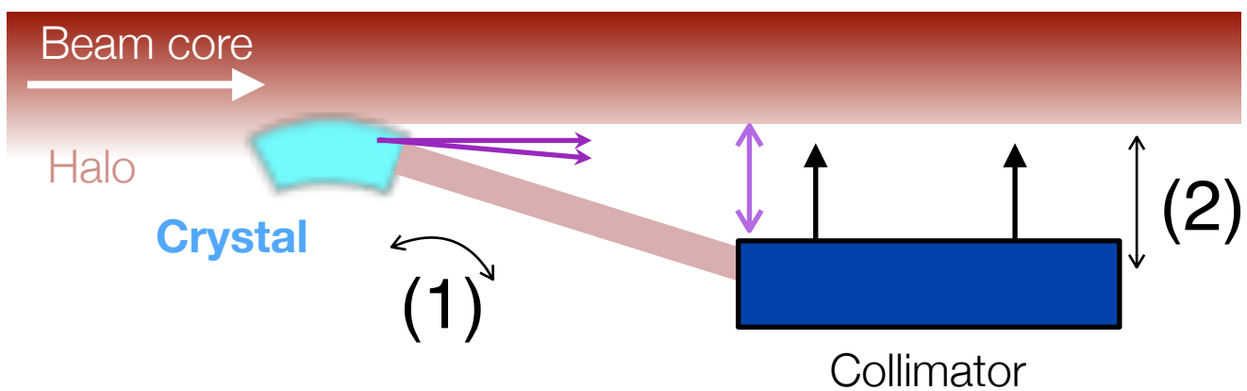
Name	s [m]	Collimation plane	Bending [μrad]	Length [mm]	Mat.
TCPC.4L7.B1	19919.24	Hor.	50	4	Si
TCPC.6L7.B1	19843.82	Ver.	50	4	Si

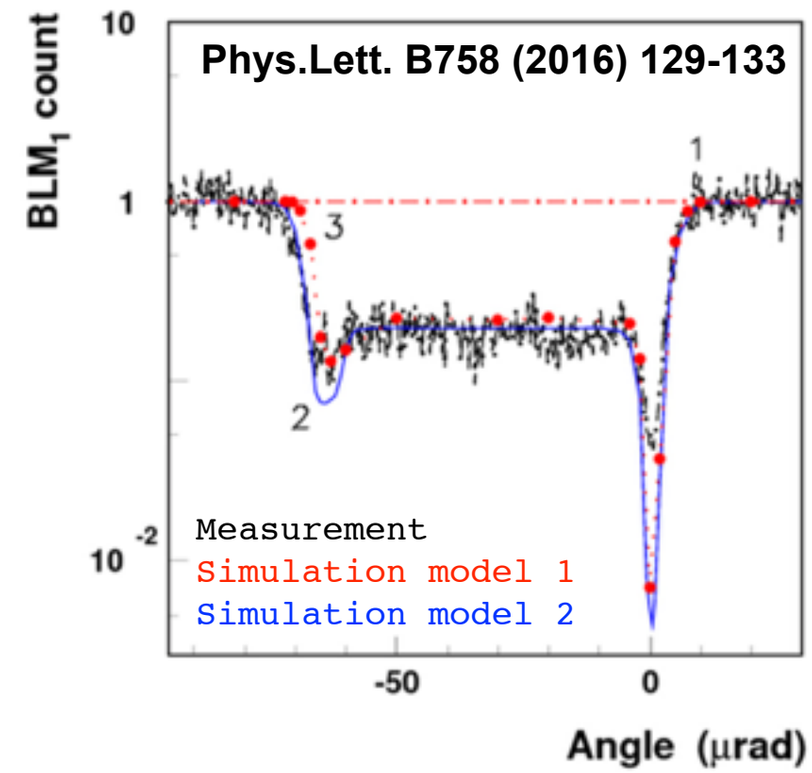




Hardware developed by EN/STI with industry (goniometer sub-microrad resolution)

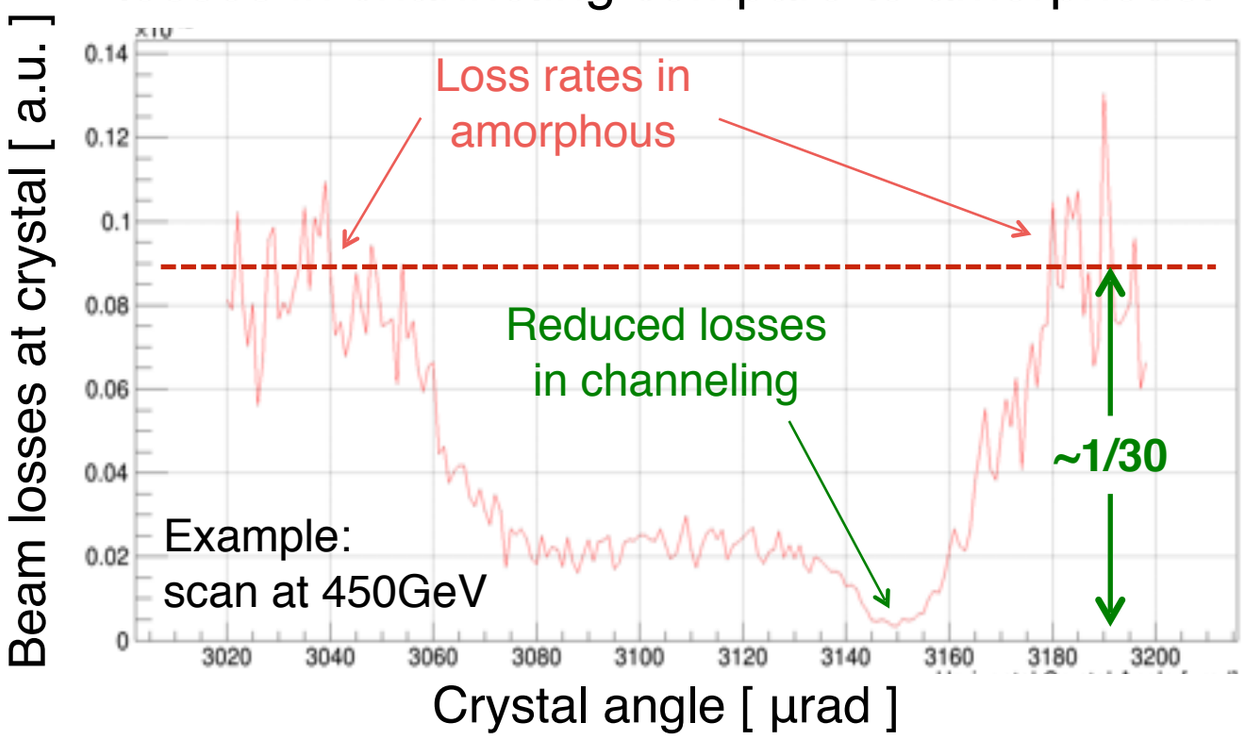
First proton channeling at 6.5 TeV



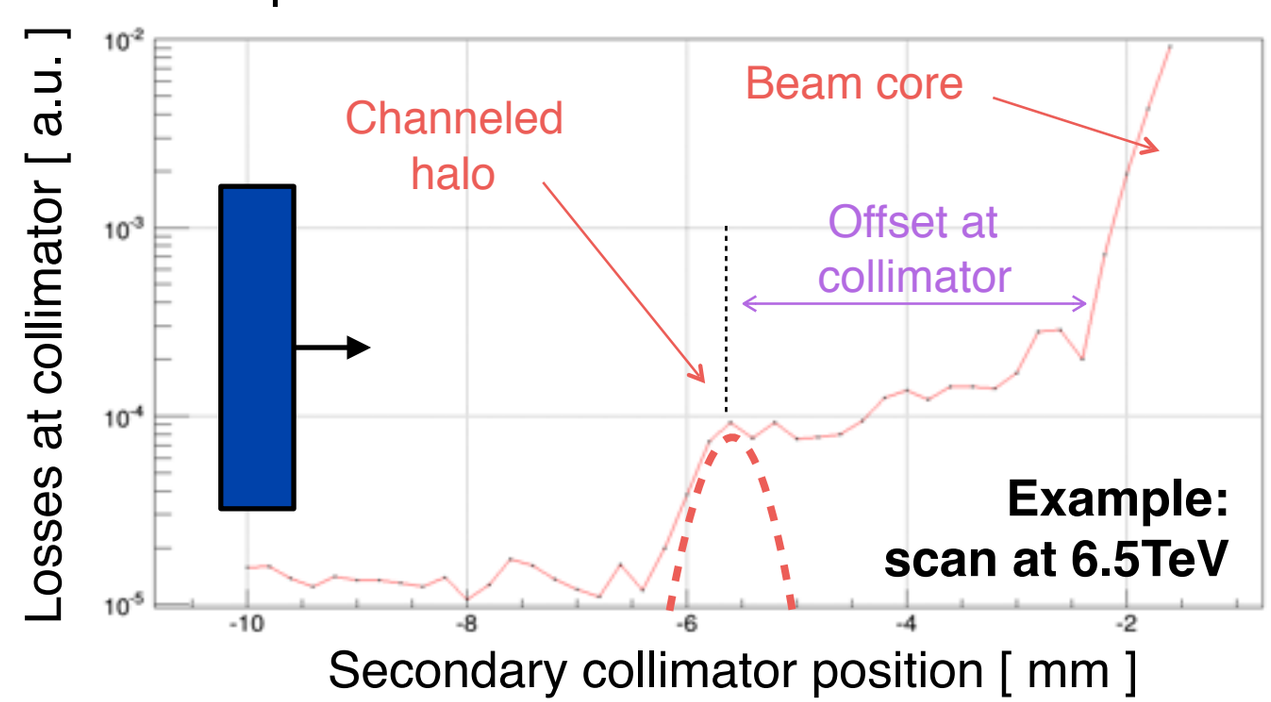


Critical: Achieved the required angular control of better than ~1 μrad (A. Masi *et al.*)

(1) **Angular scan**: strong reduction of local losses in channeling compare to amorphous.



(2) **Linear collimator scan**: measures the profile of the channeled halo.



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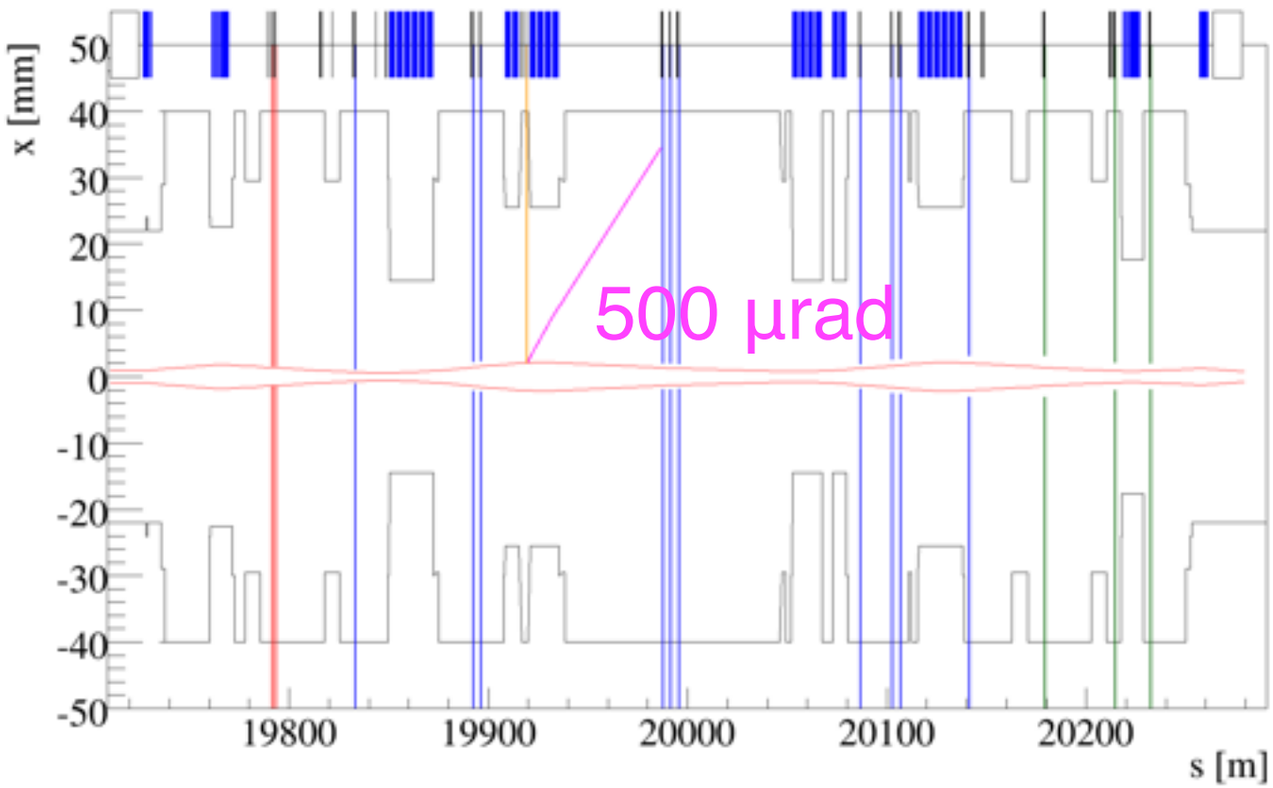
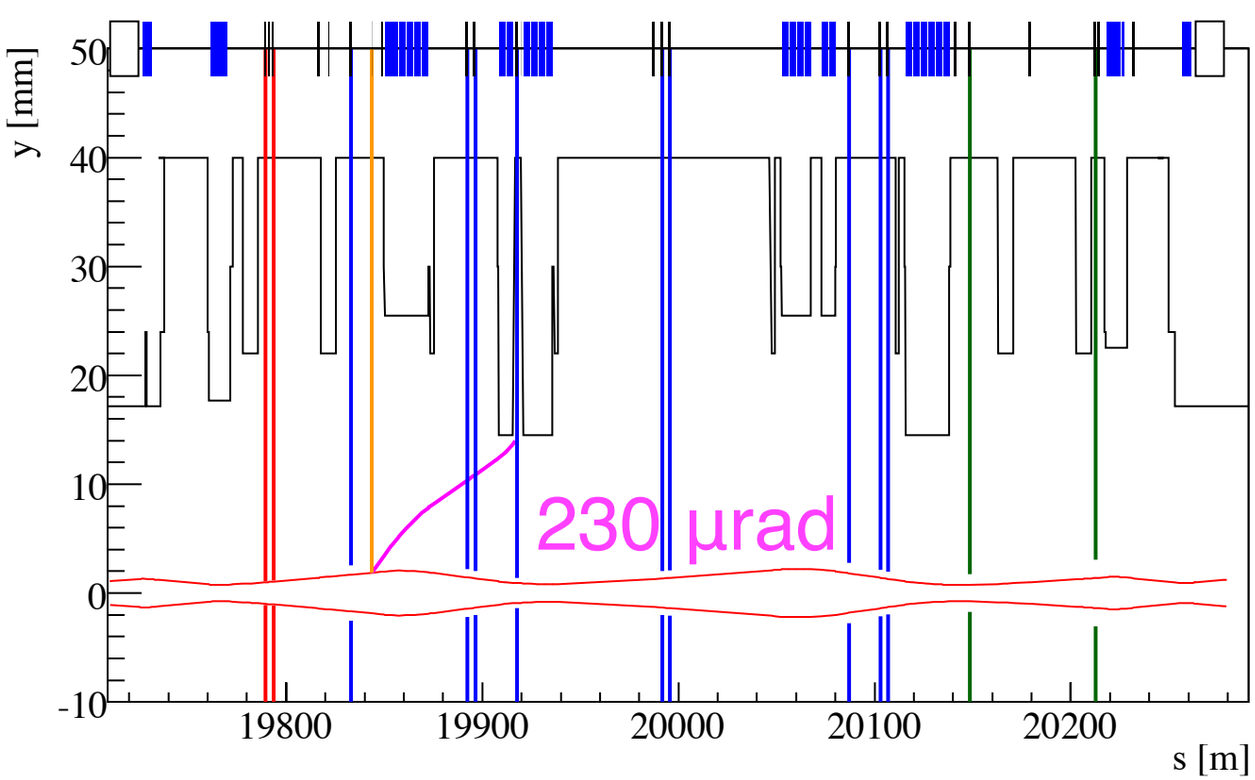
IR7 layouts and beam tests

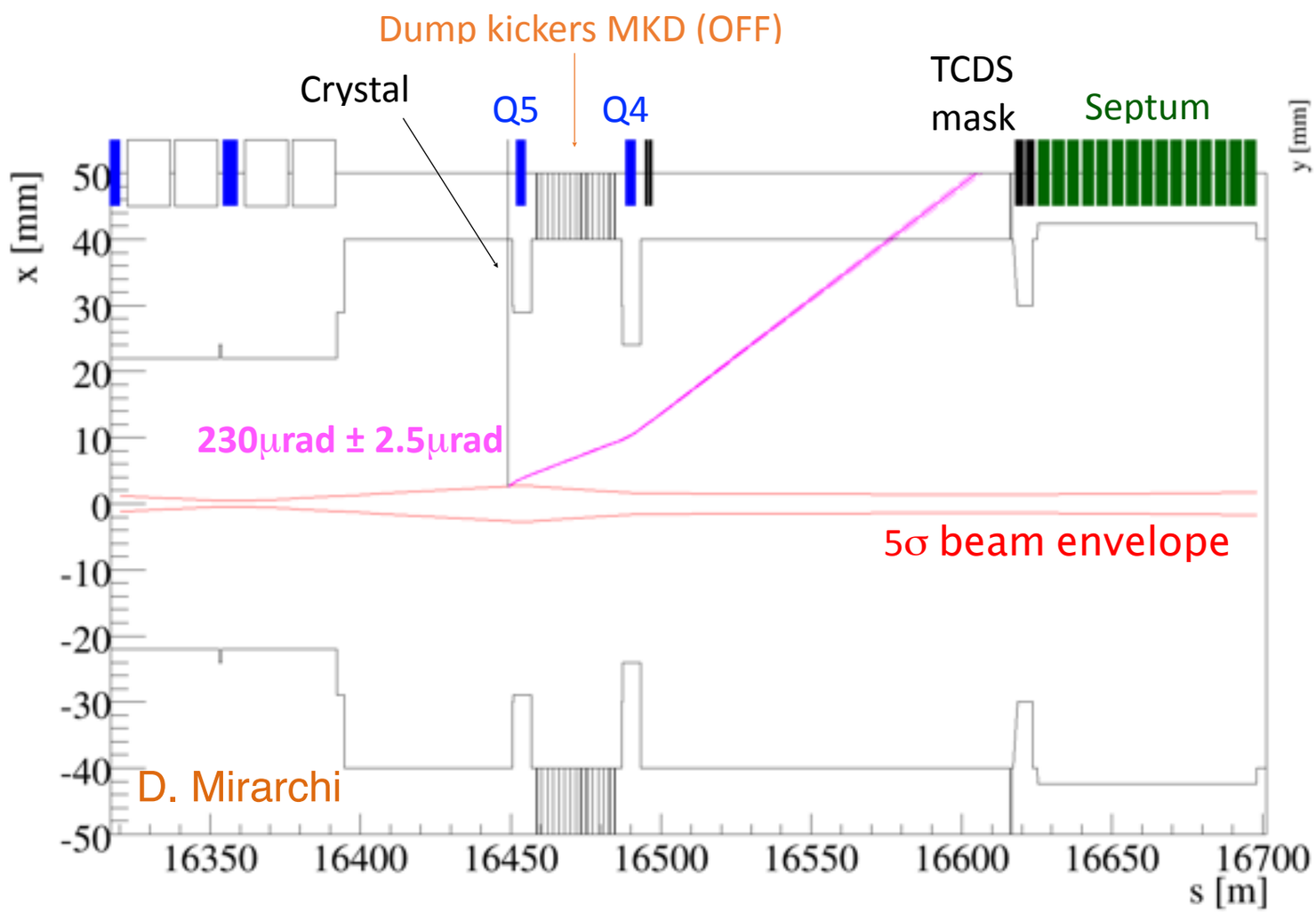


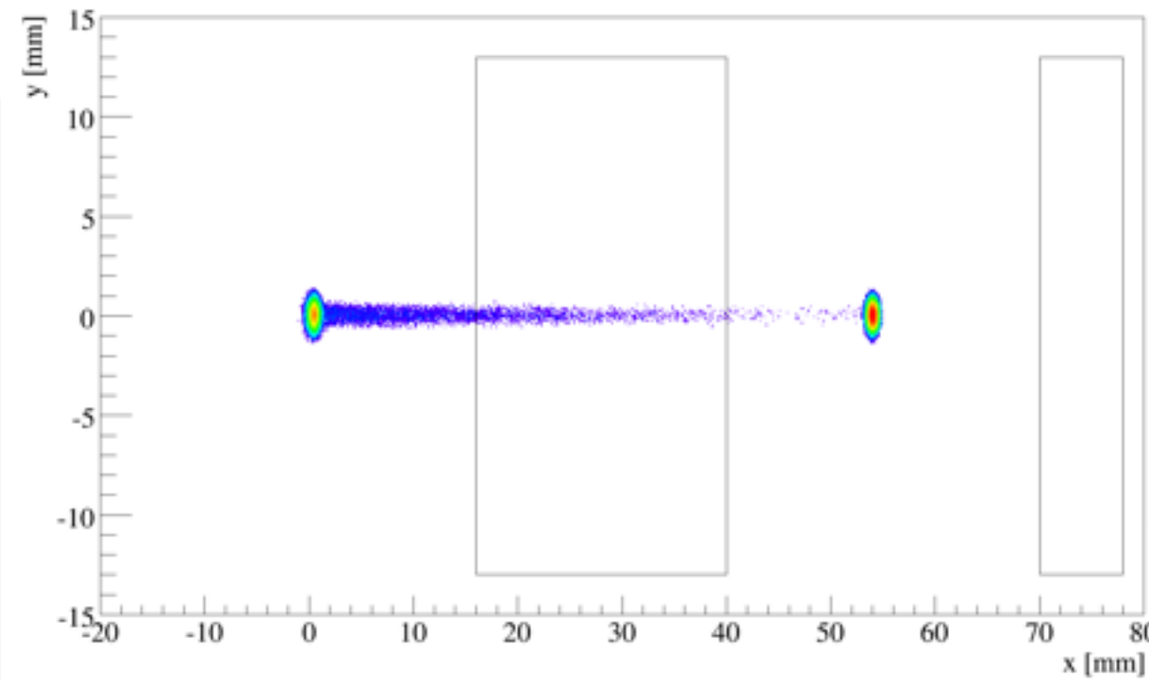


- *Present setup: 2 crystals with design angles of 50 µrad (measured: ~40 µrad in V and ~65 µrad in H);*
- Aperture compatible with angles of ~ 200 µrad (V) and 500 µrad (H);
- A well instrumented setup that **can be used** for new crystal's characterisation after completion of collimation studies (earliest: 2018).

Any ideas for a detector that can be installed into a 1.48m slot available for collimation upgrades?

Implementation in dump insertion





Bending of 230 μrad could extract beams into the present dump line, in analogy with kicker magnets (relies on kicks from Q5/Q4).

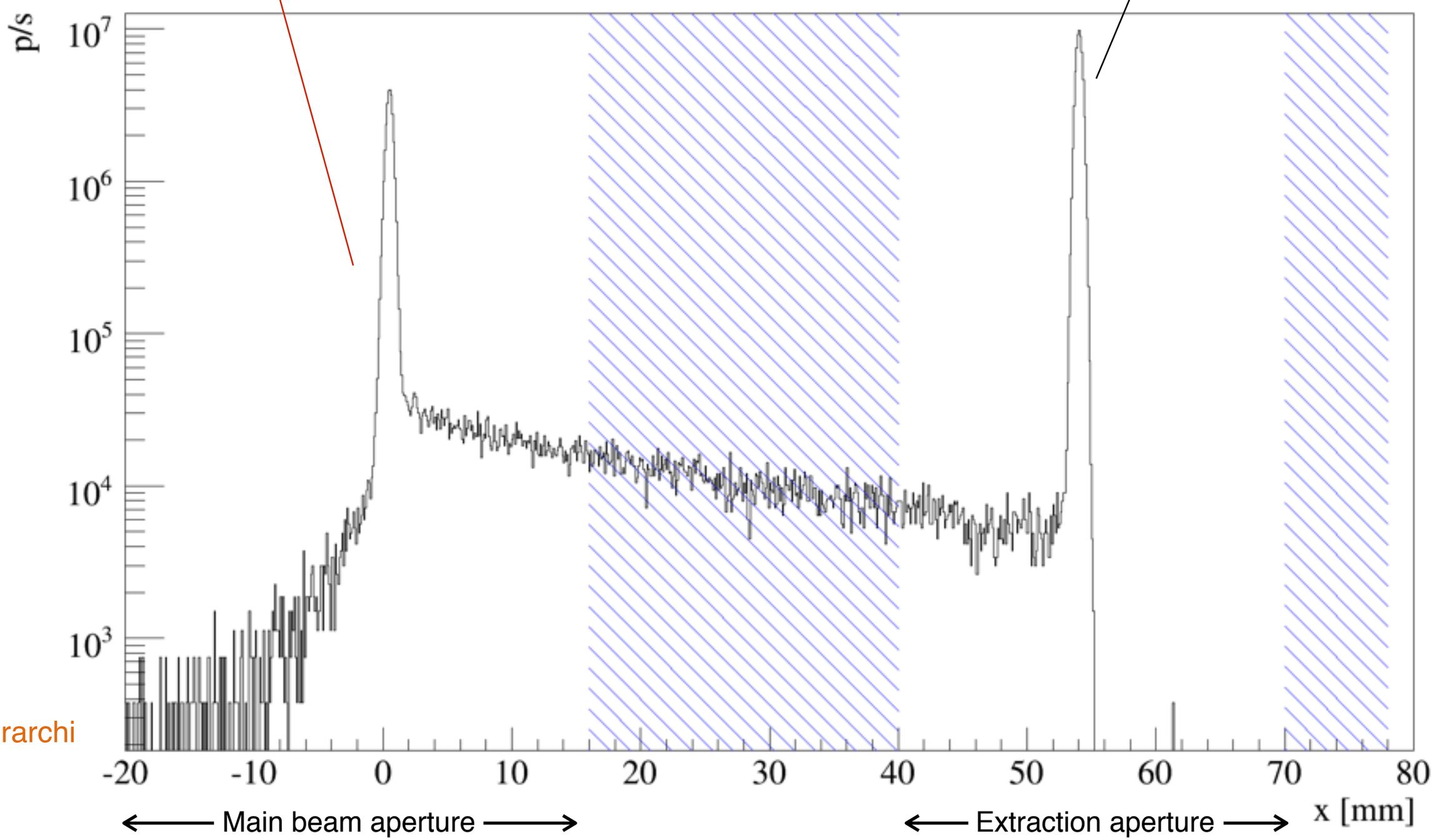
Probably need a different angle to separate channeled beam from standard dump — integration in dump line would have to be studies.

First look at crystal as primary restriction (low-intensities scenario).

Beams downstream of crystal

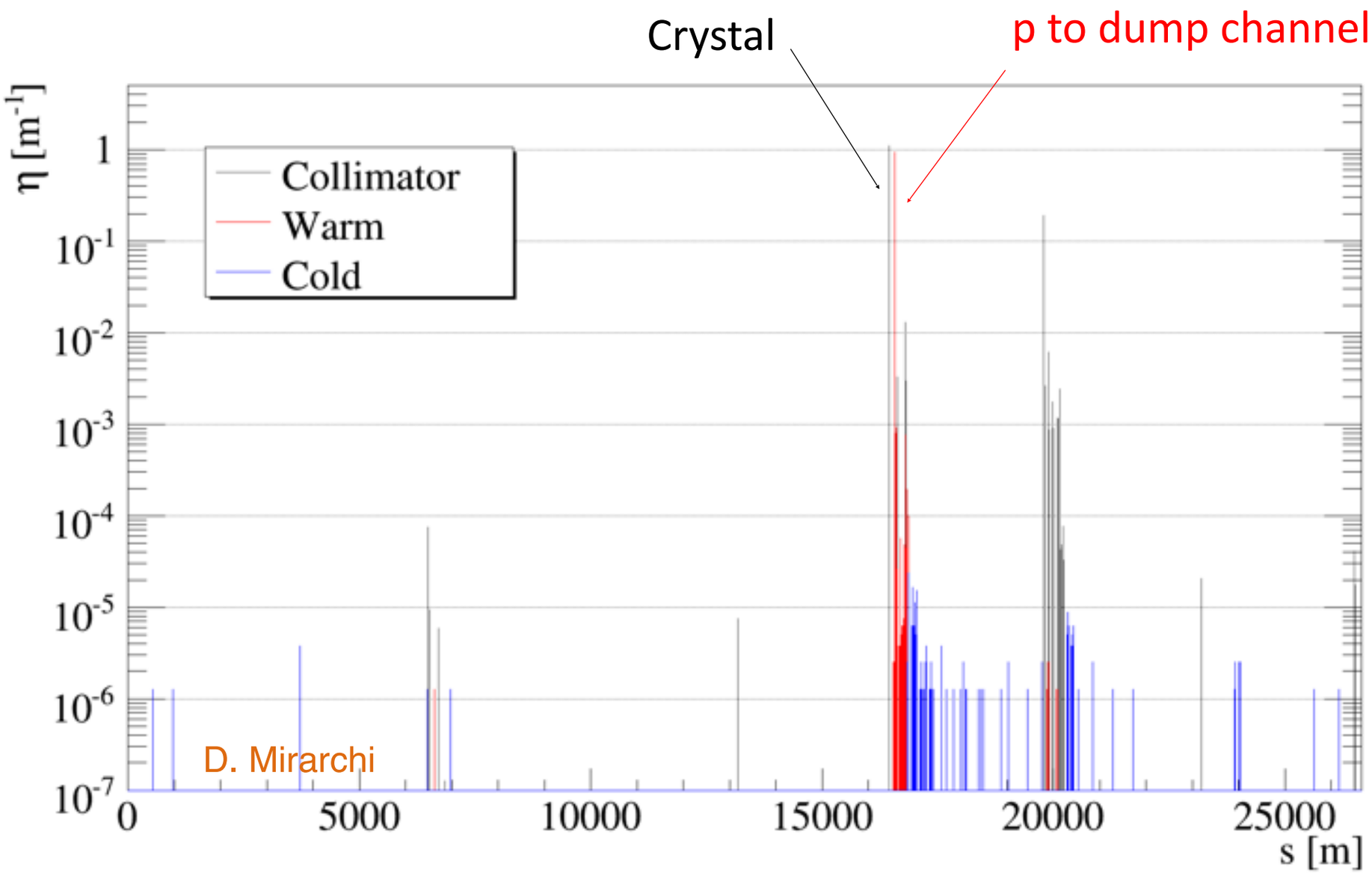
These particles must be safely disposed of!

Ex.: 3 nominal bunches (3e11p)
↦ **spill of ~10^7p/s** (1h lifetime)



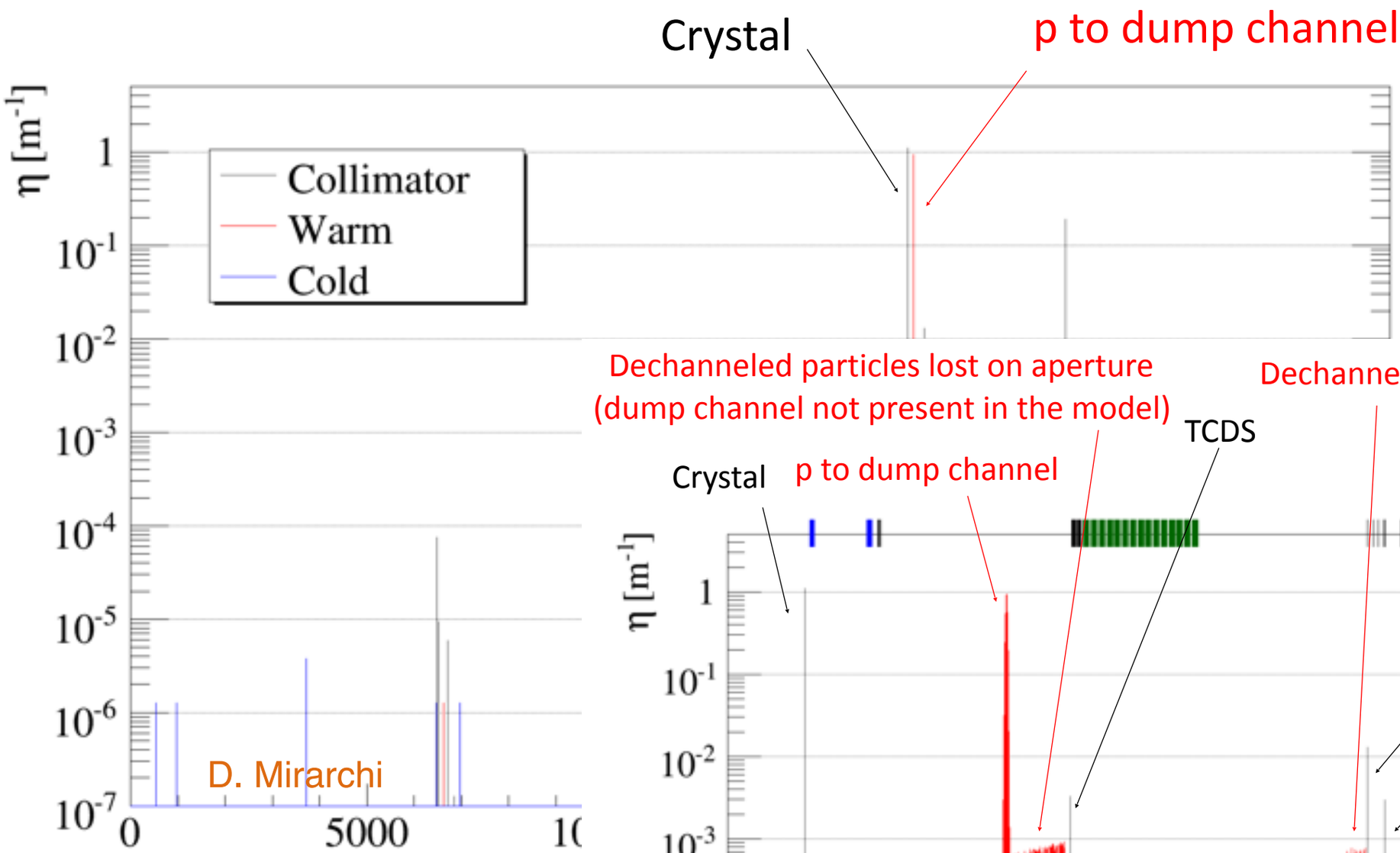
D. Mirarchi

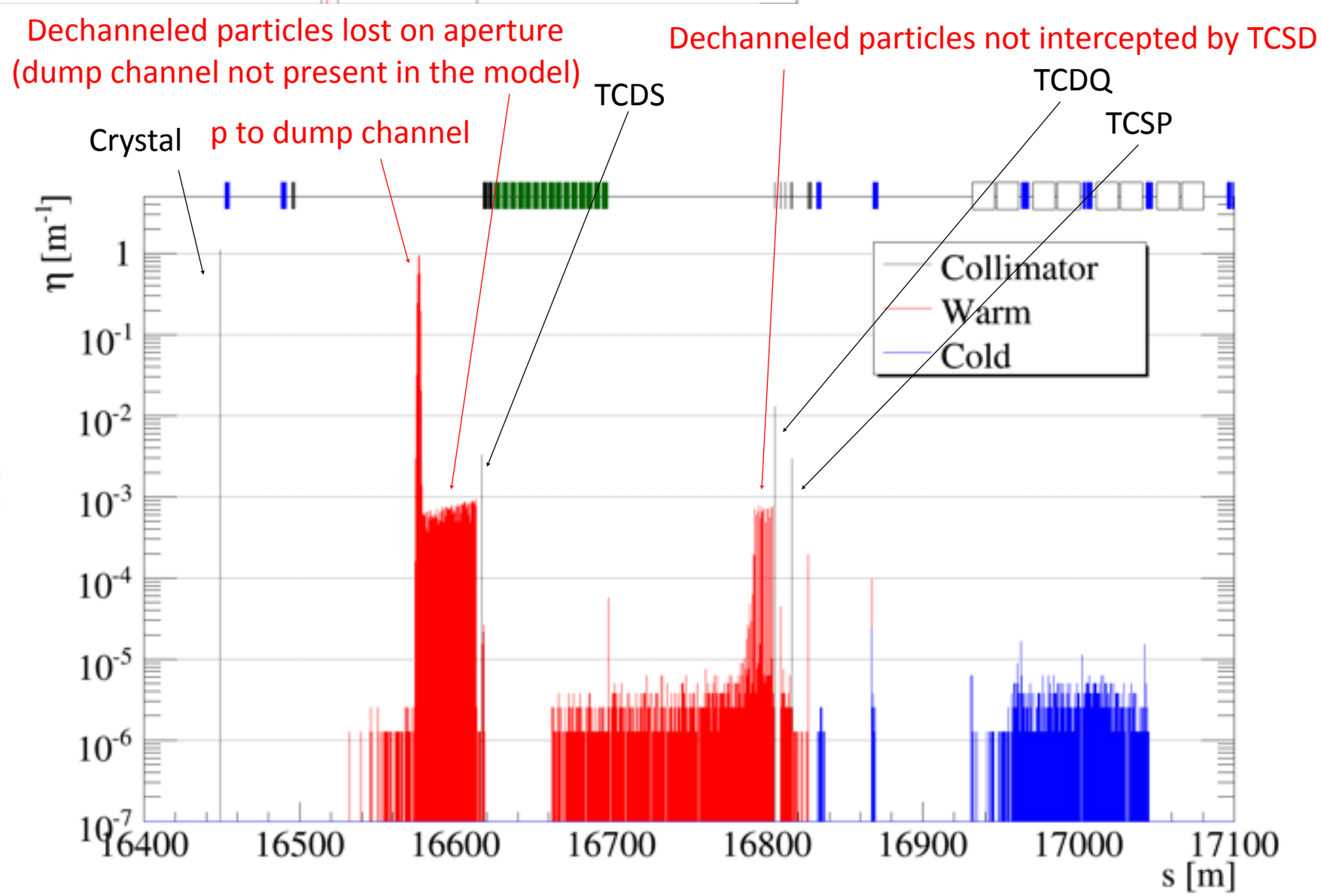
Loss distributions (crystal as primary)



Only compatible with low intensities!

Loss distributions (crystal as primary)

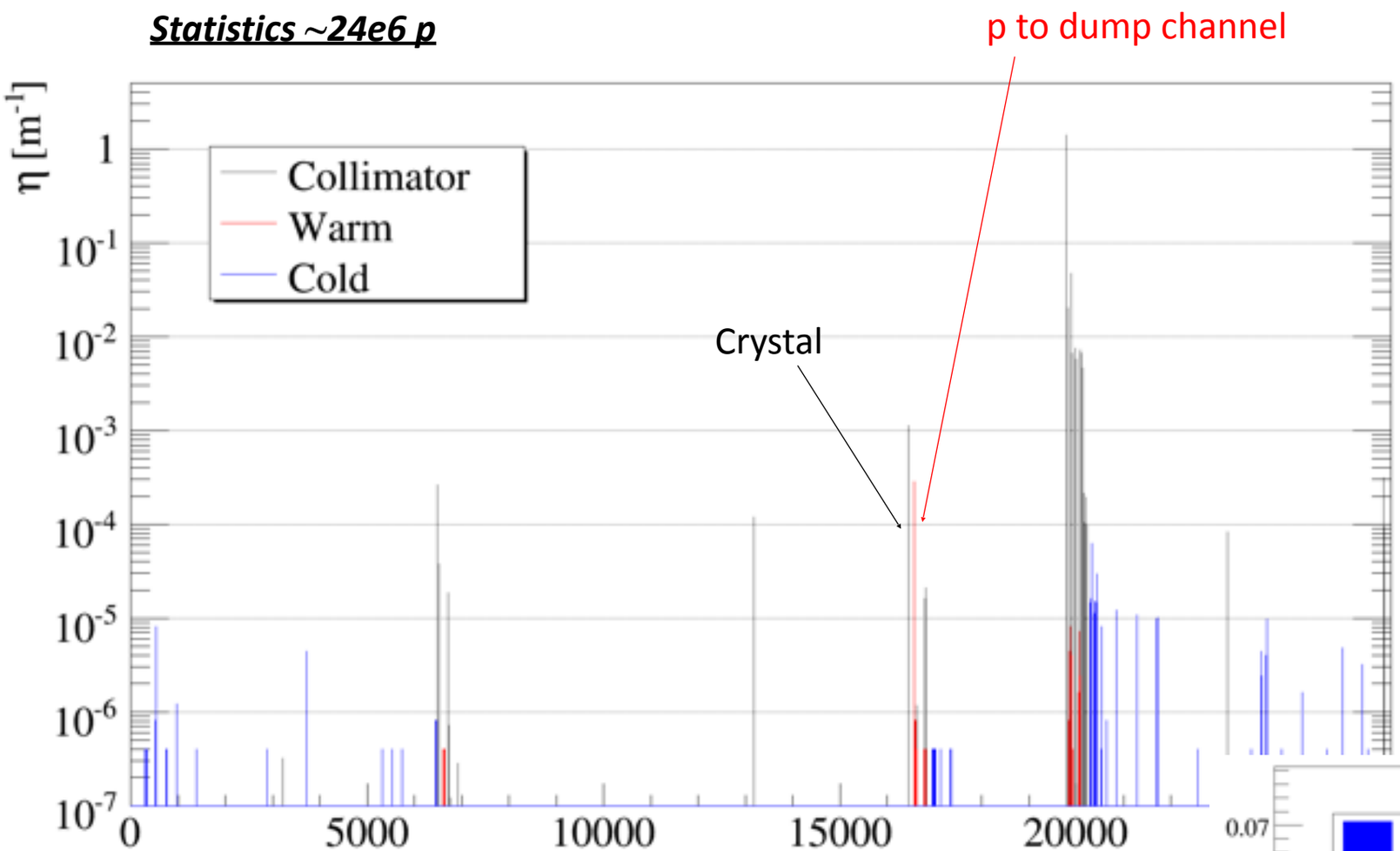




Only compatible with low intensities!

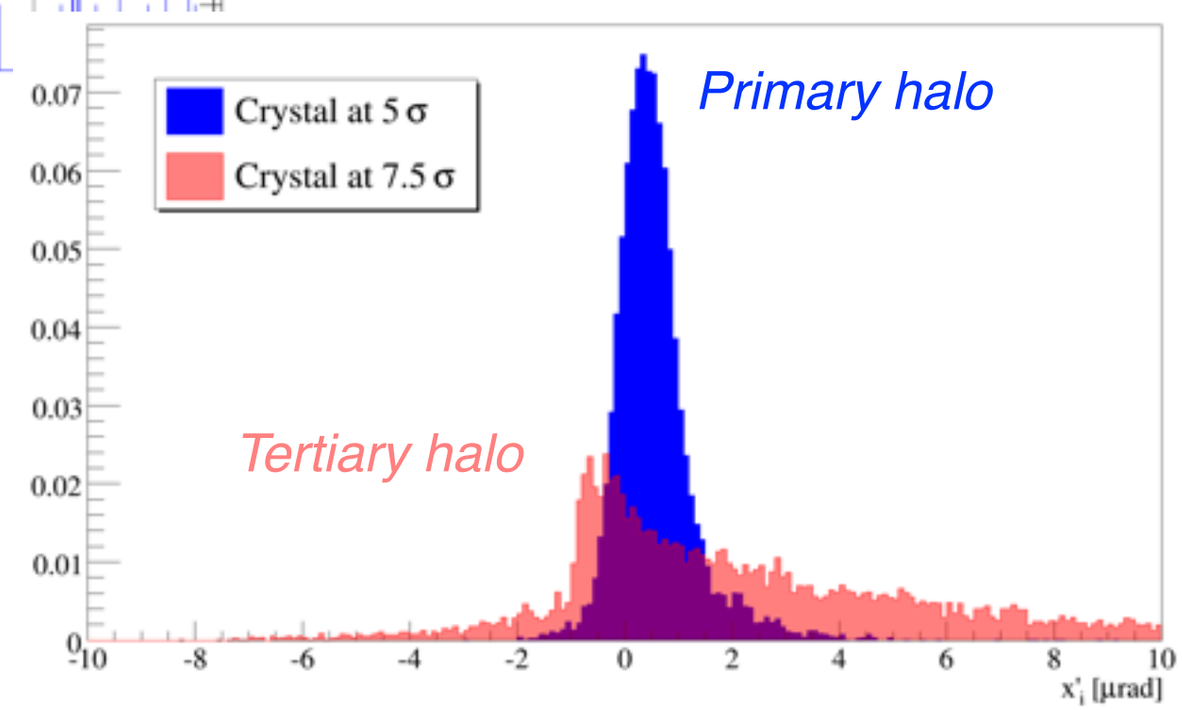
Operation with crystal as secondary

Statistics ~24e6 p



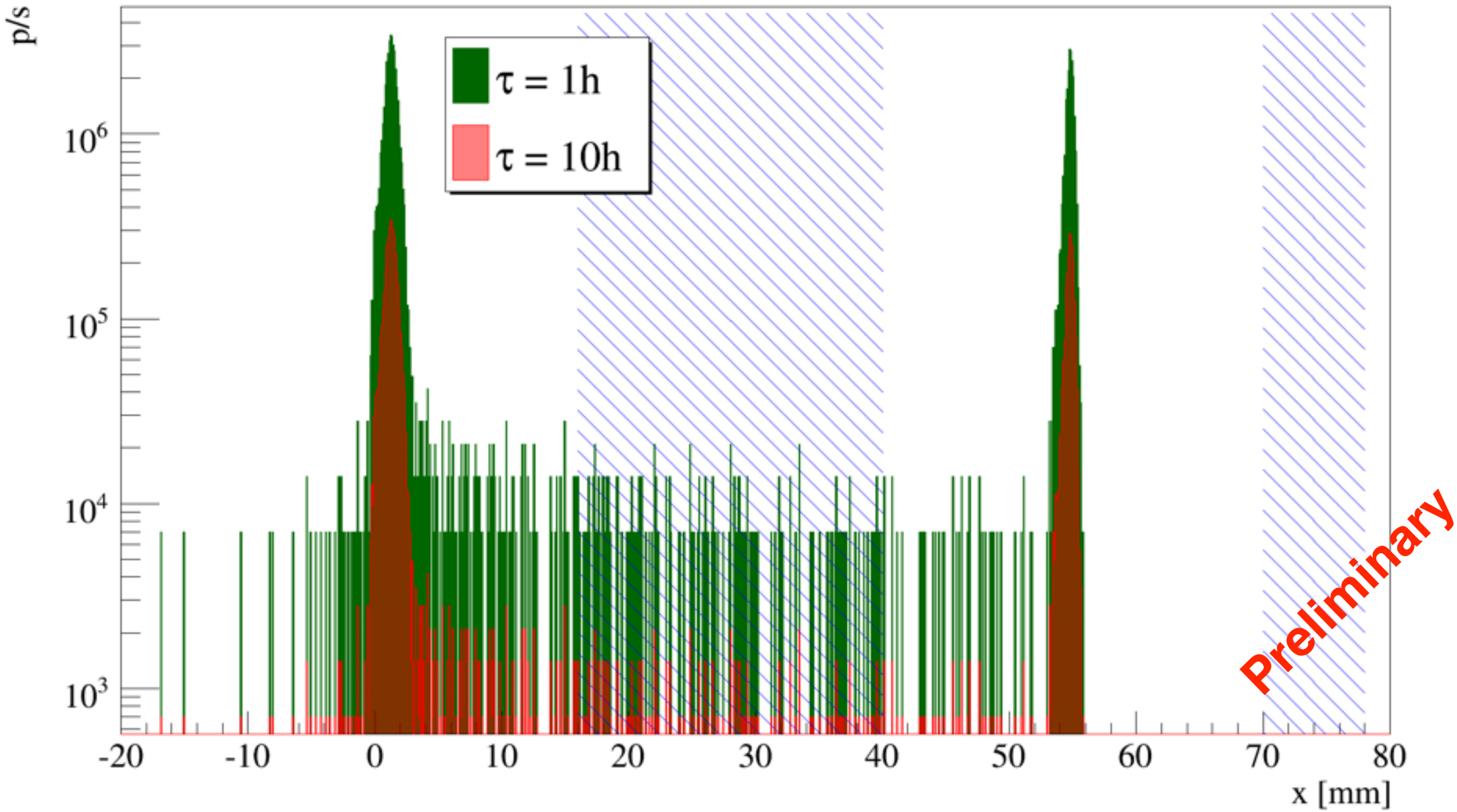
This scheme would not perturb the standard cleaning mechanisms in the collimation insertion. Implication for dump insertion clearly to be assessed.

Crystals at the transverse amplitude of secondary collimators would intercepts a (broader) distribution of tertiary halo particles.
Might work with higher intensities!



Achievable spill rates with full LHC

Nominal LHC: 3.2e14p, 1h and 10h lifetime,
with a crystal in IP6 at 7.5 sigmas.



Controlled beam depletion

(studied as active halo control for beam collimation)

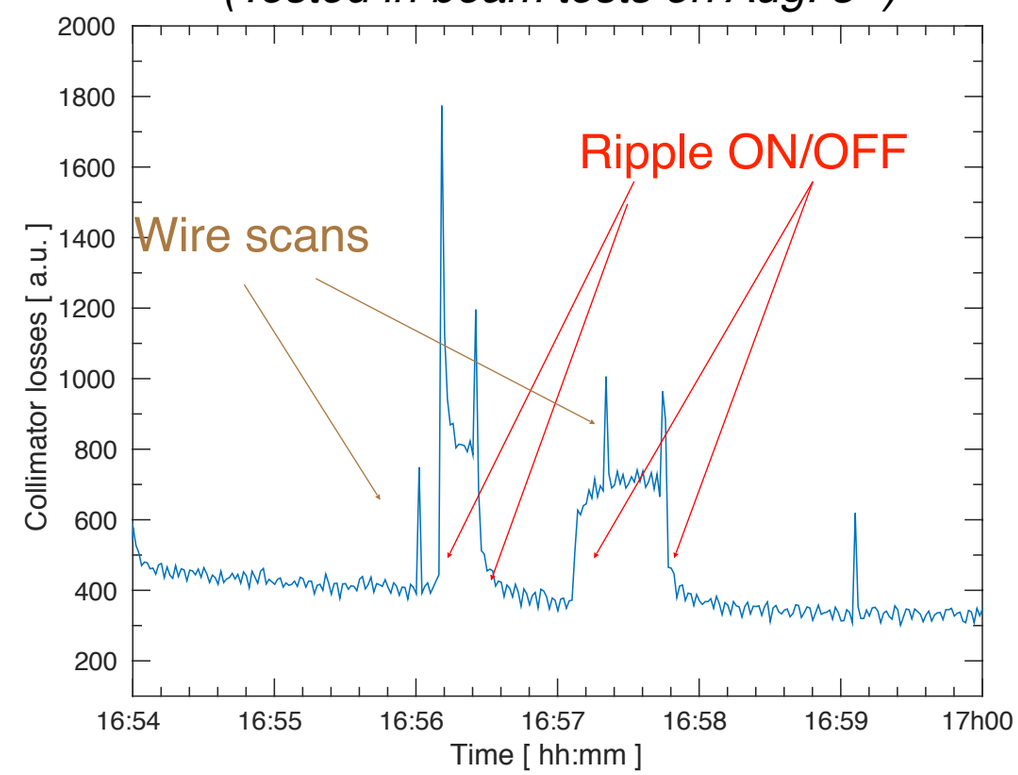
- Tune noise through ripple of quadrupole power supplies.

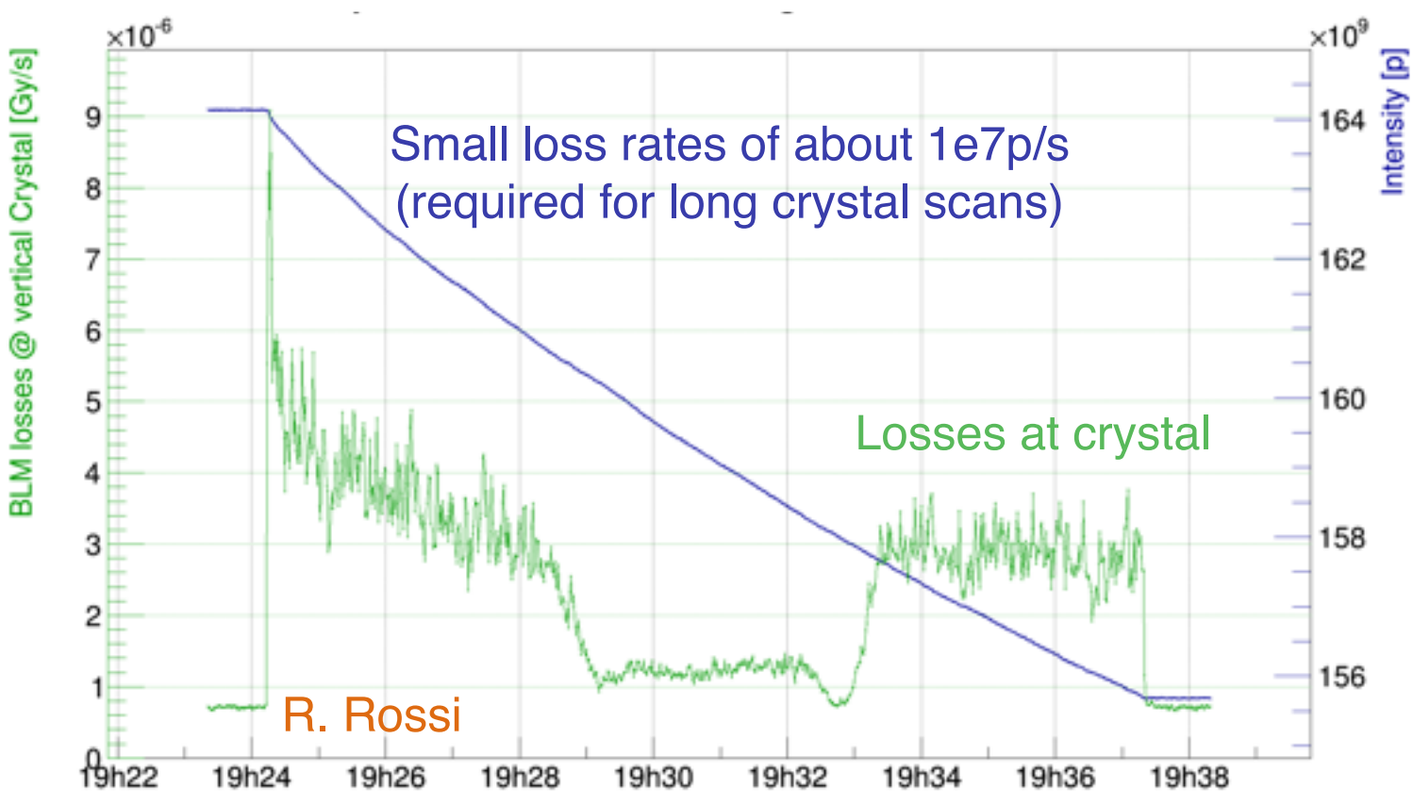
  Ongoing beam tests: LHC + SPS

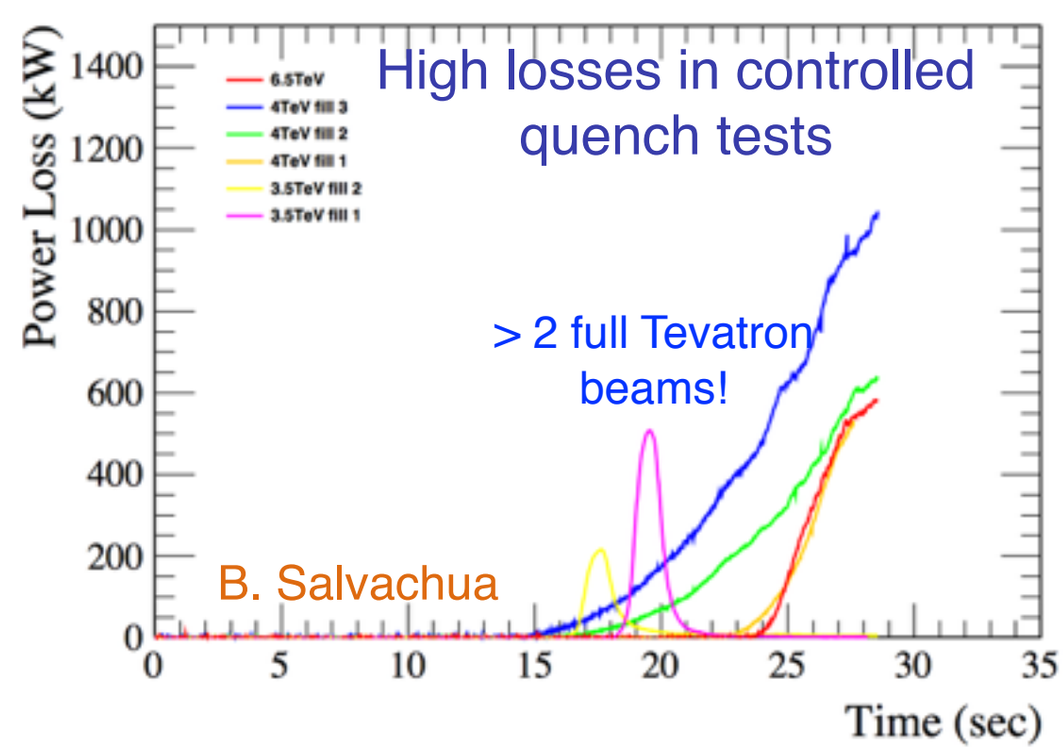
- LHC transverse dumper (ADT): bunch-by-bunch noise and various resonant excitation methods. *Thanks: D. Valuch.*
- Hollow electron lenses for halo control.

  Upcoming HL-LHC project review: Oct. 6th.

SPS tune ripple: 0.5 A at 1kHz
(Tested in beam tests on Aug. 3rd)







Conclusions

- Reviewed where we are with channeling of multi-TeV hadron beams

  Very promising recent results at the LHC, profiting from several years of studies by UA9.

- We have operational experience and simulation tools, and the hardware for angular control — validations at SPS and LHC, broad energy range.

  "So simple that it cannot be true", but the devil is in details!

  Present understanding relies on several years of studies and measurements.

  Very fertile field for students and post-docs — see list of PhD thesis of recent years!

- We are confident that we can master this technology up to 7 TeV.

  Still: outstanding test program at the LHC to be completed, but results are encouraging.

- Outlined some possible applications to LHC extracted beam experiments.

  First look indicates promising possibilities, clearly more studies would be needed.

  Extension to other machines — lower or higher energies — is possible.

- Proposed methods to control **spill rates**: strong synergy with ongoing studies of **active loss controls** for LHC collimation upgrades.

  Tune resonances from quadrupole ripple, transverse damper, hollow e-lenses.

- Contact us to discuss if you have ideas on how to use crystals!

  *Present installation in collimation insertion: **unique setup** to test new crystal ideas.*