Collimation performance with protons and ions

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Collimation for 2023 proton run

Commissioning experience

OVERALL

- Collimation system **performed very well** at every step of the complex 2023 cycle.
- No surprises during energy ramp.
- Loss maps validation matrix expanded.
- Leveraged on 2022 experience.

COLLIMATION STRATEGY

- IR7 remain with the tight settings as in 2022.
- Changes to triplet magnet collimators (TCT) and physics debris collimators (TCL).

PROTON COLLIMATION STRATEGY

		IR 3/6/7 same as in 2022	TCT [σ]				TCL 6 [σ]	
			1	2	5	8	1	5
Injection			13	13	13	13		
Flat-top			18		18	18		
Squeeze			↓		↓			
LHCb rotation						↓		
Tune change			9.35	37	9.35			
Adjust								
Levelling	120		↓		↓	11.5	↓	↓
	60		8.5		8.5		↓	↓
	30						30	30

TCT 8 tightens from 18σ to 11σ during LHCb rotation.

Anti-telescopic (β*: 120 → 60 cm): TCT 1/5 tighten from 9.35σ to 8.5σ

Telescopic (β*: 60 → 30 cm): TCT 1/5 at constant 8.5σ

TCL6 always in at 30 σ at β* = 30 cm

F. Van der Veken, N. Triantafyllou

Commissioning experience

15-21 April 2023 — FIRST VALIDATION

- General cleaning performance similar to 2022.
- B1H cleaning worse than 2022.
- Losses on TCSPM.E5R7 were sticking out
- Losses reduced with the new 2023 settings, new procedure to validate non-linearities.

1-3 May 2023

- Dump on fill 8694 losses
- blocked the intensity ramp up.

- TCSPM.E5R7 retracted 500 µm.
- IR1 TCTs realigned (change crossing angle in ATLAS).

3-4 May 2023 — SECOND VALIDATION

- Improved B1H cleaning, back to 2022 levels.
- TCT losses lower than 2022 at small β^*.

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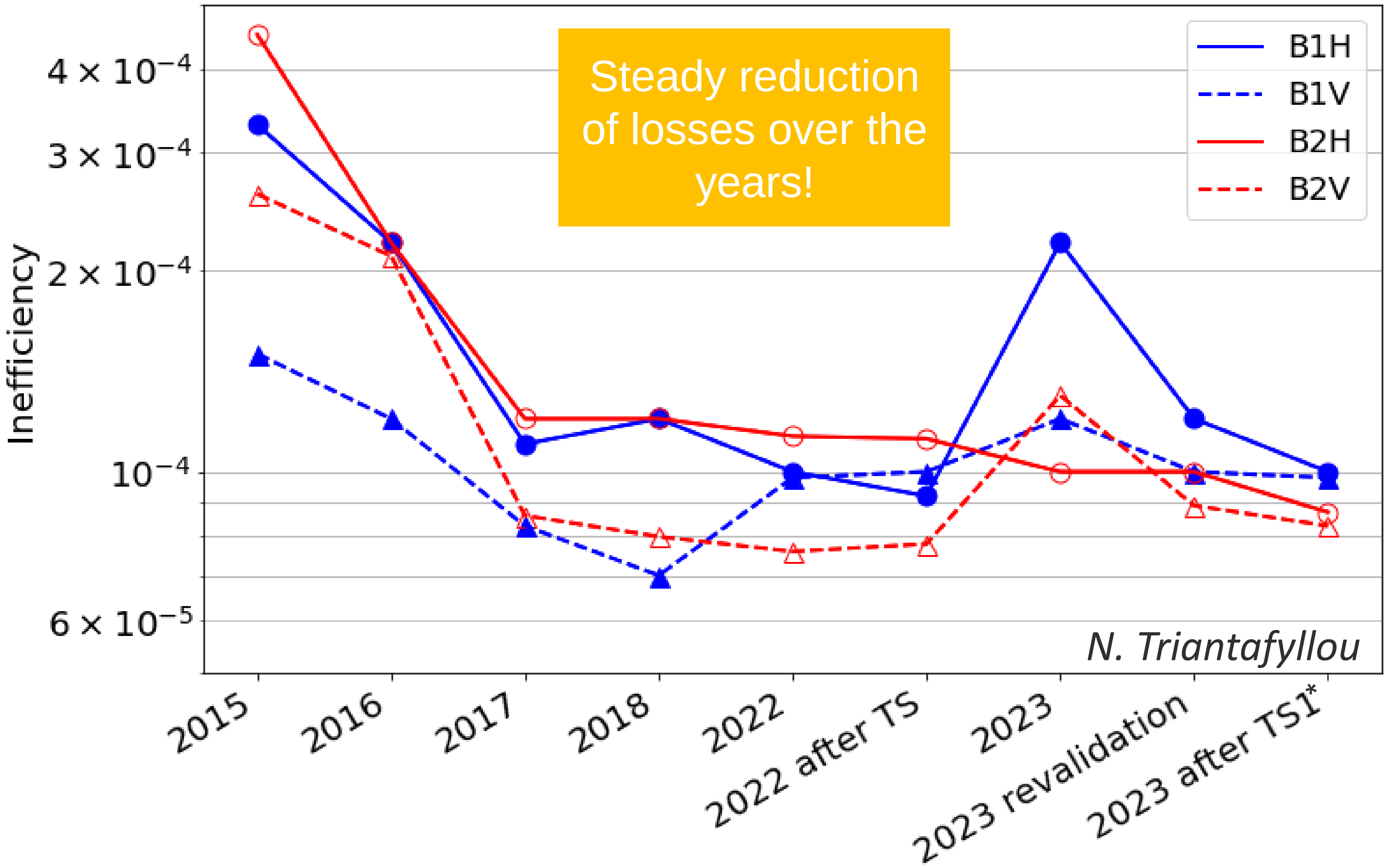
Cleaning performance



*Technical stop1 in June

Outlook for 2024

- **Baseline similar setup to 2023 + attention to TCSPM.E5R7.**
- **Studying option of tighter collimation hierarchy – would enable smaller β***
  - MD performed in 2023
- **Can tighten TCP-TCS retraction**
  - Would require more challenging collimation setup – need angular alignment.
  - More challenging to keep hierarchy over time.
  - Would give slightly higher impedance, but deemed tolerable.
  - So far no clear showstopper defined.
- **Can tighten IR6-TCT retraction**
  - Deemed possible – operated 0.8 σ tighter in 2018
- **Can tighten only at β* = 30 to limit changes**

	2023	Option a	Option b
TCP IR7	5.0	5.0	5.0
TCS IR7	6.5	6.5	6.0
TCLA IR7	10.0	10.0	9.5
TCDQ/TCSP IR6	7.3	7.3	6.8
TCT IR1/5	8.5	7.8	7.3
Protected aperture	9.5	8.8	8.3

Operations with crystal collimation in high-beta run

HIGH-BETA RUN

Special run for forwards physics experiments (TOTEM and ALPHA).

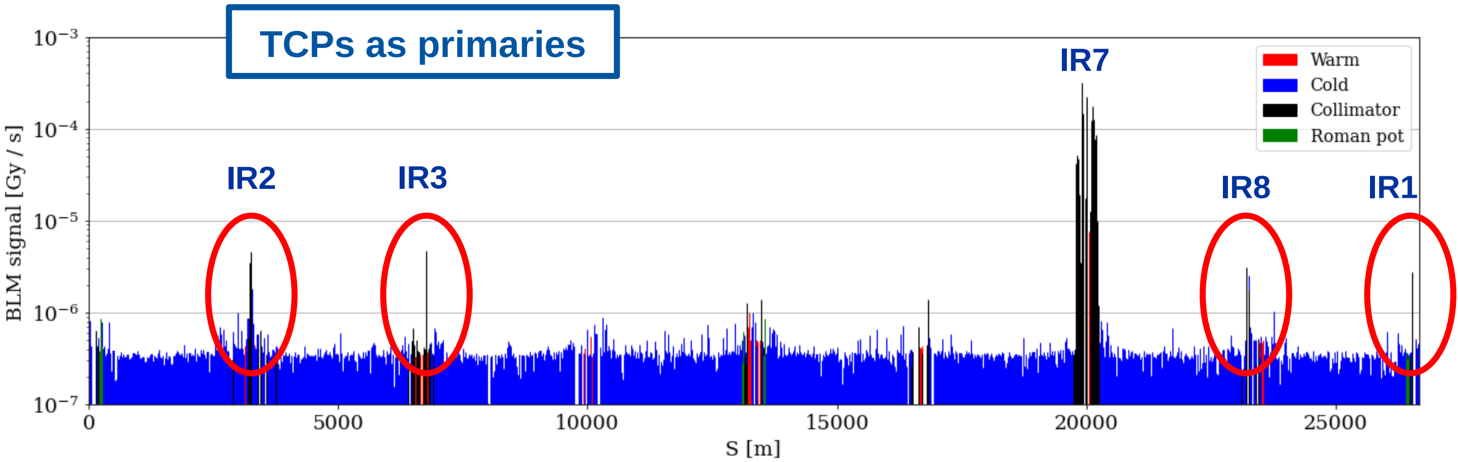
REQUIREMENTS + CHALLENGES

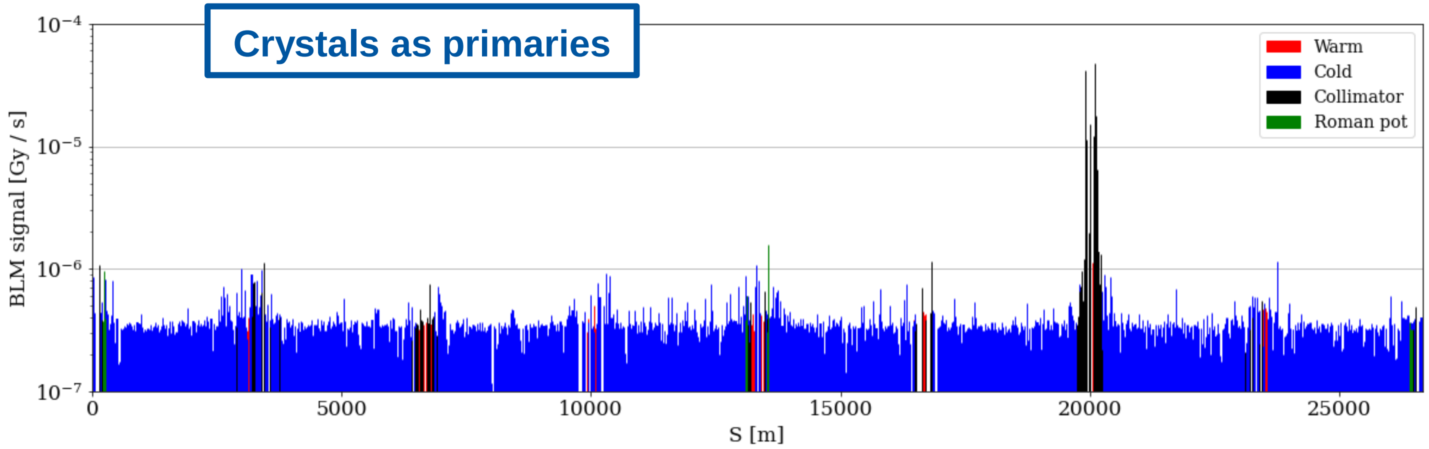
- Roman pots very close to the beam - around 3 σ half gap.
- Large β* at the collision point.
- Experiments very sensitive to background.
- Super tight multi-stage collimation hierarchy margin (~10 µm) - very sensitive to orbit drifts.
- Challenging beam scraping when moving collimators.

→ Crystal collimation necessary.

OUTCOME

- Crystal collimation was an essential contributor.
- First time with automatic beam scraping.
- Very successful run!





M. D'Andrea, R. Bruce

Collimation for 2023 ion run

Main updates

Main updates – crystal collimation

NEW CHALLENGES

- Increased beam energy: 6.8 → 6.37 Z TeV.
- Increased stored energy: 13 → 17.5 MJ.
- Increase in number of bunches: 100ns spacing → 50ns spacing.
- Full squeeze in all IPs in the ramp.
- Dispersion suppressor collimation in ALICE for significant peak luminosity increase with new hardware.

MAIN COLLIMATION UPDATES

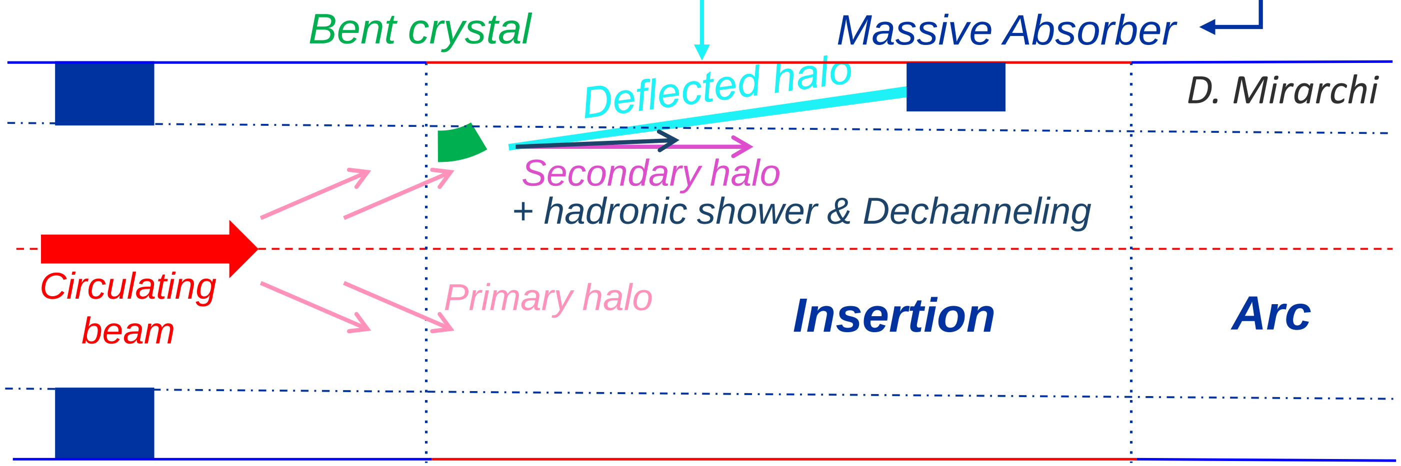
- First deployment of crystal collimation.
- New BFPP bumps + TCLD.

PRINCIPLES OF CRYSTAL COLLIMATION

1
- Bent crystal is the primary collimator.
- Crystalline planes can "channel" the incoming halo particles.
- Significant reduction in inelastic interactions.

2
The bend provides a significant angular kick.

3
The channeled halo is intercepted by a downstream absorber.



Main updates – collisional losses

PROBLEM

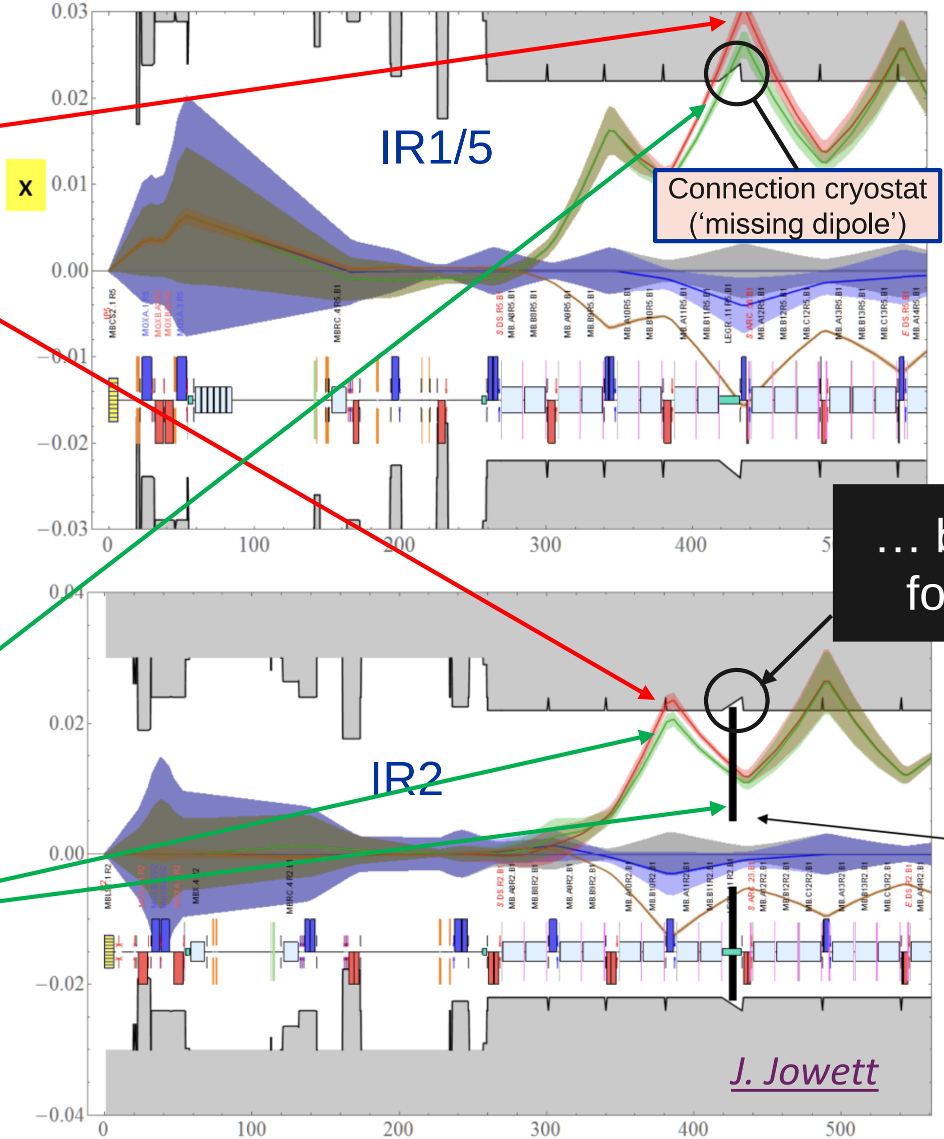
Bound free pair production (BFPP) from collisions produce beamlet that hits the dispersion suppressor regions.

SOLUTION

Orbit bumps could deviate beamlet to empty connection cryostat for IR1/5 in Run 2

SOLUTION

New orbit bumps + new collimator (TCLD) solve the problem for IR2 in Run 3!



SOLUTION

IR8 also used orbit bumps to direct losses to a cell with higher BLM threshold.

RESULT

- ALICE **peak luminosity**, $\mathcal{L}_{peak}$, is a **factor 6** higher w.r.t. Run 2.
- Quench test without alleviation found a $\mathcal{L}_{peak}$ 3 times smaller than the one achieved.
- → Confirmation that the **TCLDs** were **essential** to raise ALICE **luminosity**.

R. Bruce

Collimation for 2023 ion run

Commissioning experience and performance improvement

Commissioning experience

MAIN ACHIEVEMENTS

First time crystal collimation during physics operations with high beam intensity.

- Standard commissioning procedures.
- Setup and maintain crystal channeling (added new tools).
- Creation and deployment of a crystal ramp function.
- Finalize collimation settings.

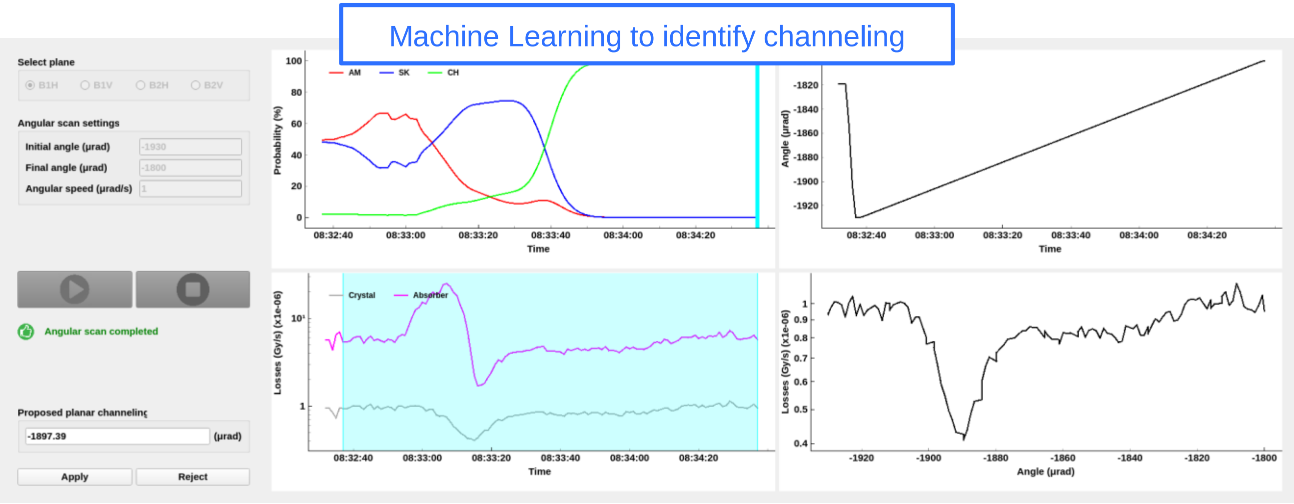
DELAYS AND ISSUES

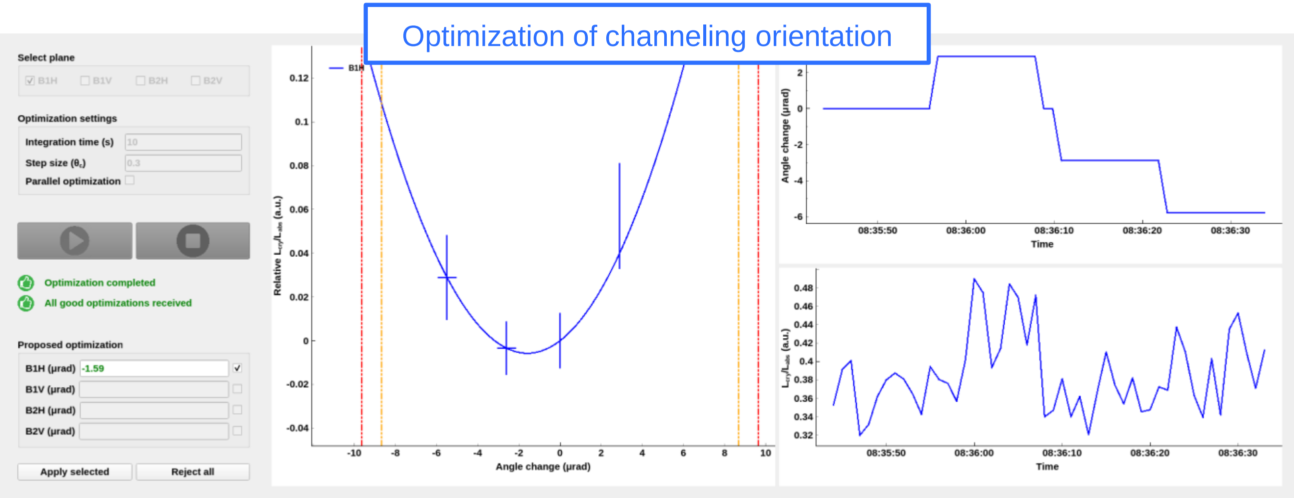
Many new and complex challenges:

- Energy ramp losses.
- Channeling reproducibility.
- 10 Hz events.
- ALICE background issue.
- …

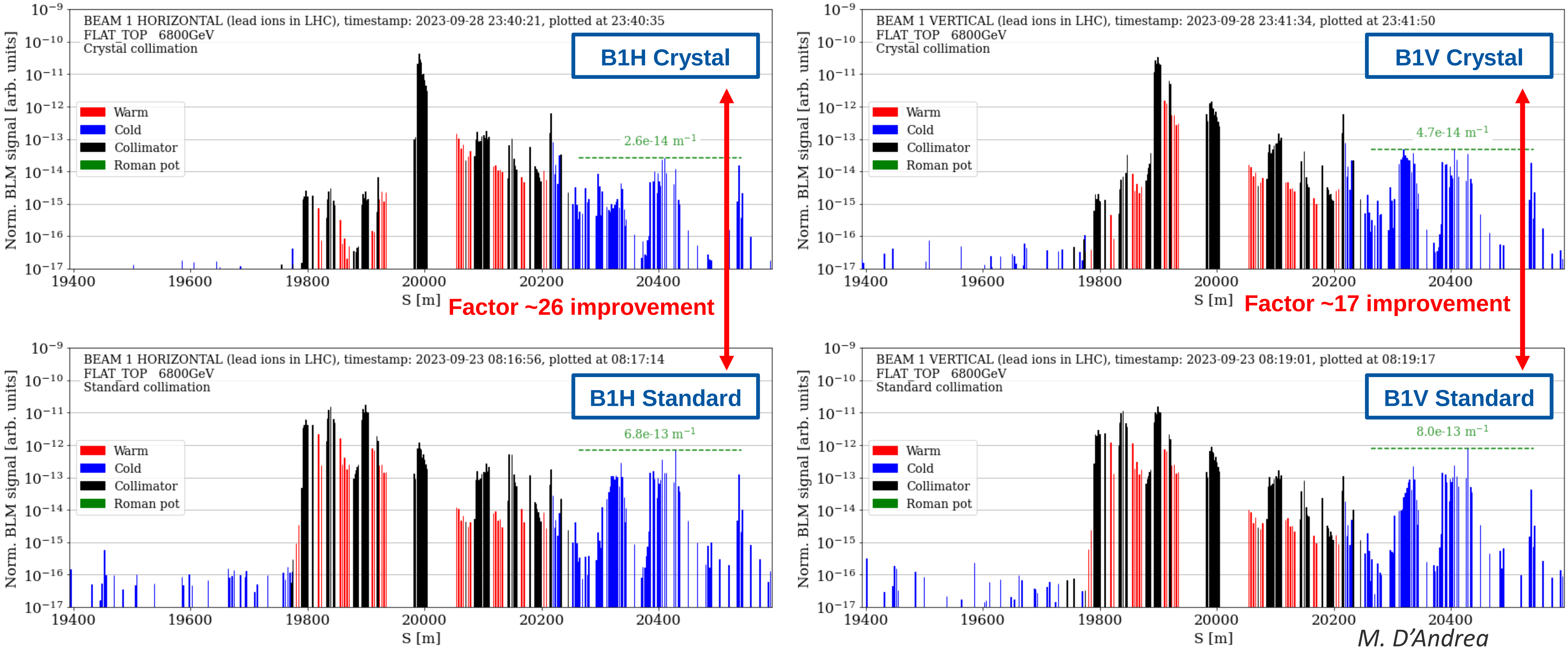
OVERALL

- Successful experience of first operational crystal collimation.
- Had to modify settings on the fly as done in 2018.
- Tight initial plan of 4 days.

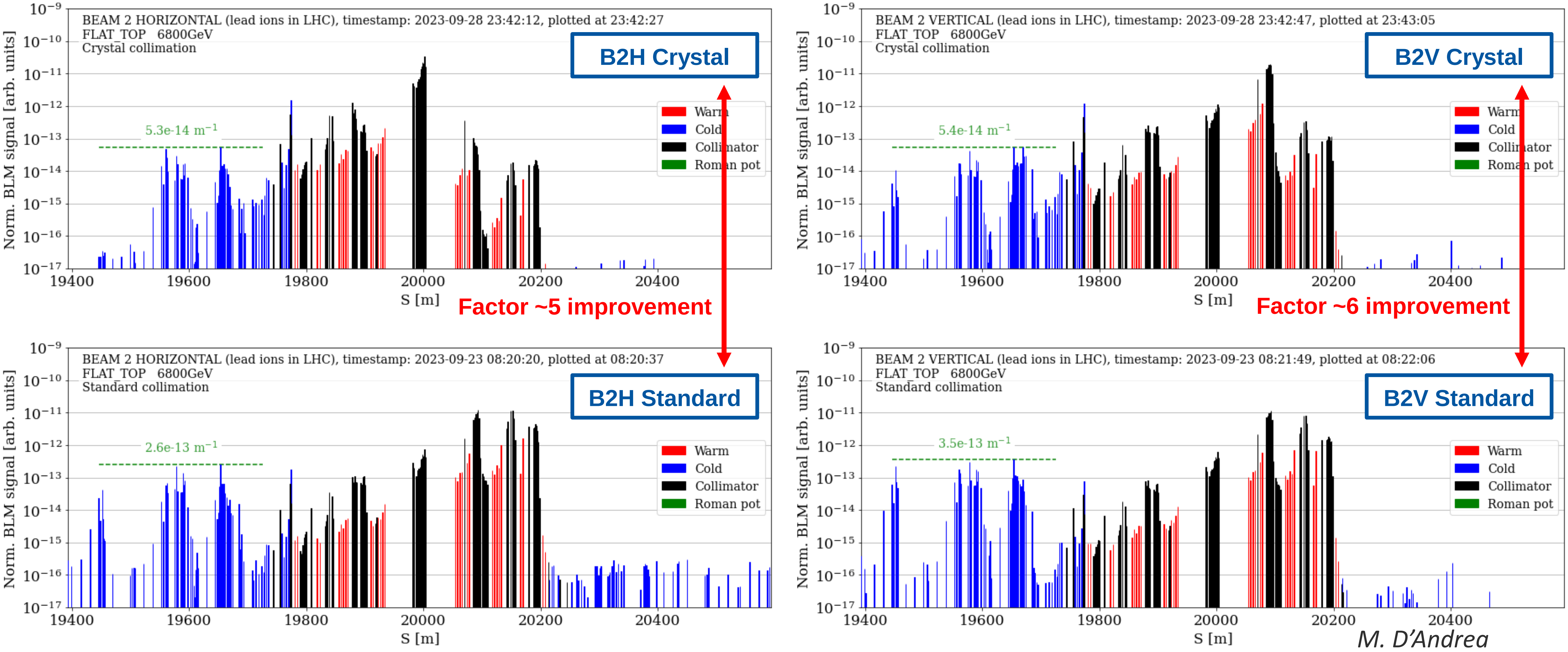




Performance improvement with crystal collimation – B1



Performance improvement with crystal collimation – B2



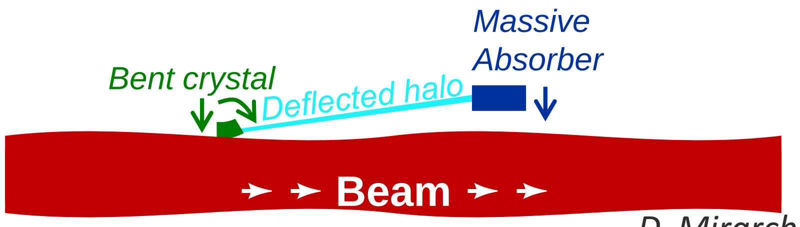
Collimation for 2023 ion run

Challenges

Collimation during energy ramp

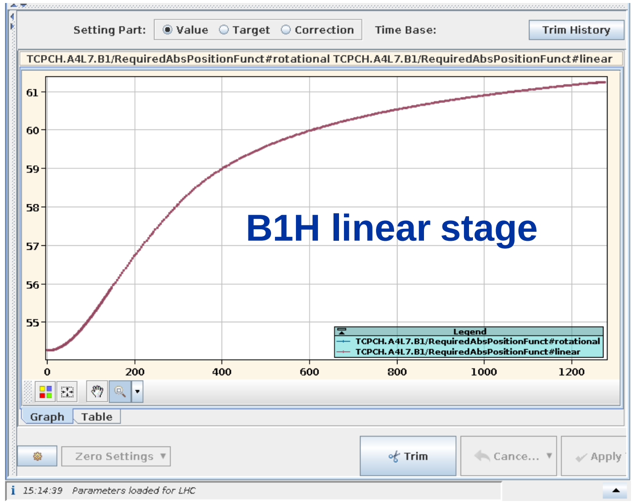
CHALLENGE

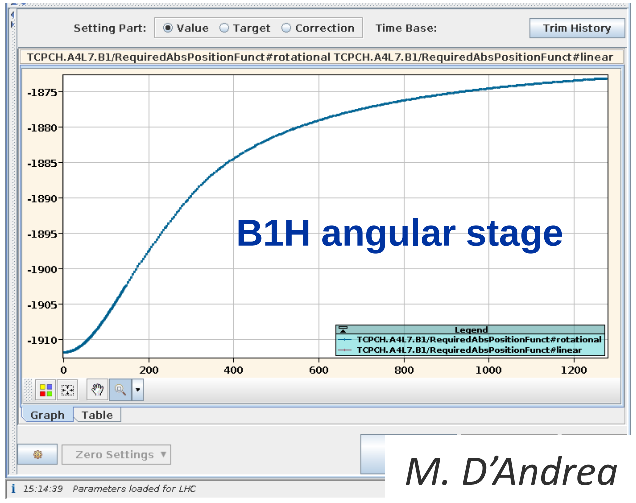
- Combined squeeze + ramp
- Change of beam size and divergence during ramp.
- The crystal must follow the beam envelop in transverse and angular position.
- Channeling acceptance reduces from ~10 to ~2 μrad.



SOLUTION

- Reference settings at injection and flat-top used to generate ramp function in control system.
- **Successful functioning achieved during machine development.**





M. D'Andrea

LOSSES DURING ENERGY RAMP

- Important losses observed during operational energy ramp – significant slowdown.
- Crystals not in perfect channeling orientation may have worsened the situation.
- Many mitigations applied…
- Not well understood – investigation in progress.
- More from the collimation side in next slides…

R. Bruce

Reproducibility of optimal channeling

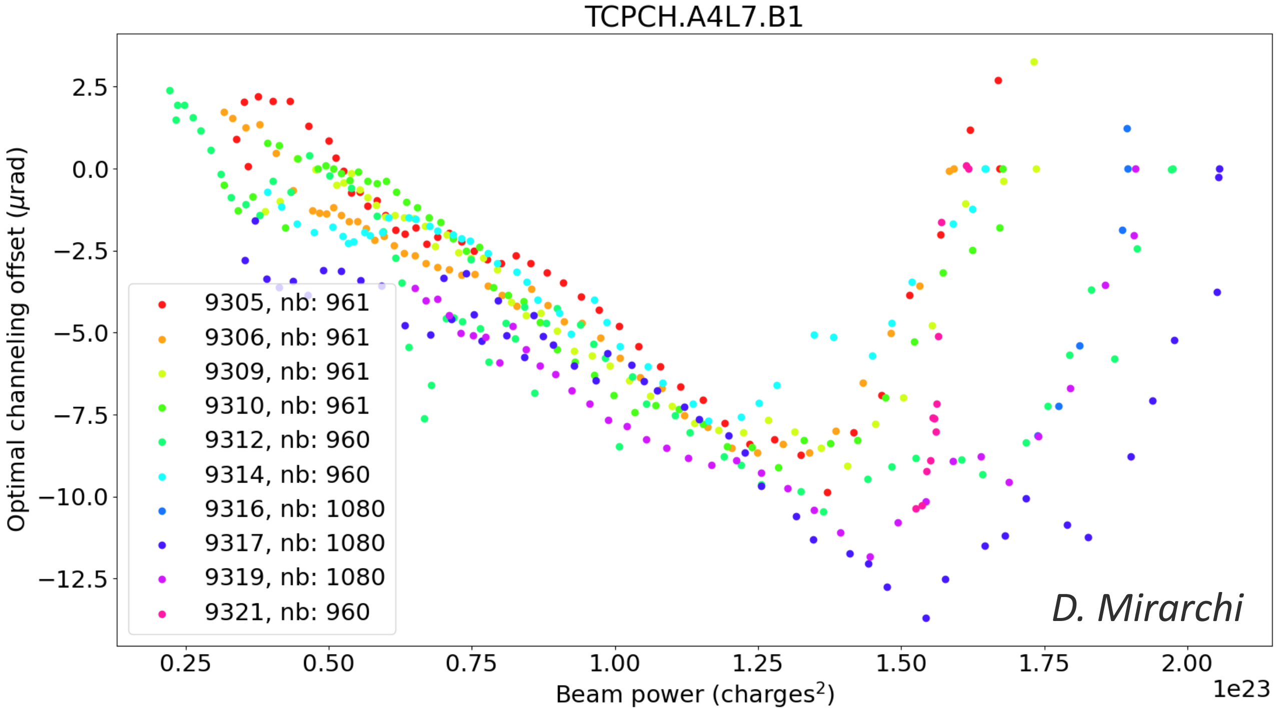
Drifting crystal angle during
- Flat-top
- Ramp (likely, but no monitoring)
- 10 Hz events

Degraded cleaning

Not well understood

Possible dependence on temperature

Mitigations deployed:
- Automatic crystal realignment at top energy
- Ramp function update
- Increase in bunch length



Investigations in progress:
- Detailed analysis
- Simulation and measurement of impedance on spare crystals.
- Component deformation exploration.
- …

Improvement challenges:
- Better real-time control.
- Implementation during energy ramp up.
- …

Collimation for 10Hz events

SITUATION

- 10 Hz orbit oscillations are back for B1H as in 2017-8
- 8 dumps + some "near misses".
- Not fully understood.

WHAT IT MEANS FOR CRYSTAL COLLIMATION

Orbit oscillations means potential impact angle out of crystal acceptance, $\theta_c \sim 2.1$ µrad.

WHAT WE FOUND

- Impact angle changed by:

Orbit angle from oscillations ~ θ_c

+

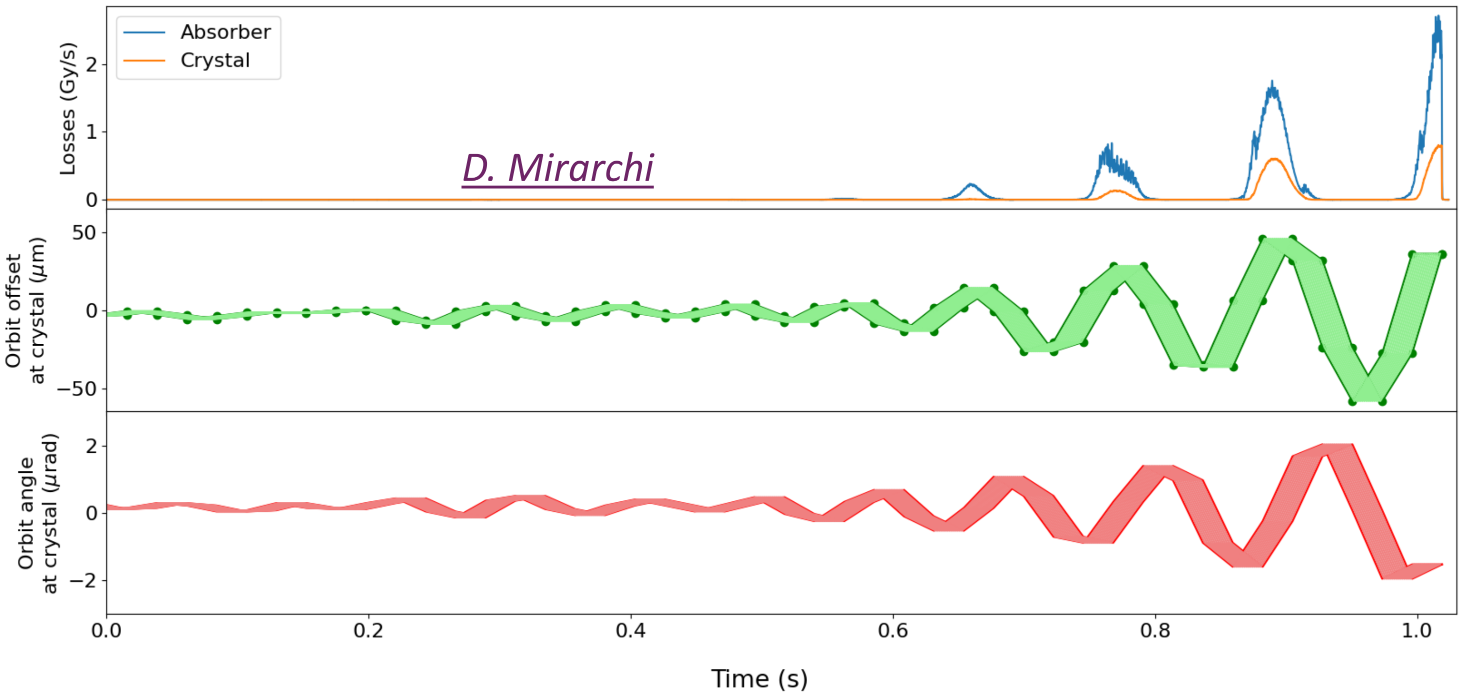
Orientation change from orbit offset ~ 0.2-0.4 µrad

→ Oscillations brings artificially crystal out of optimal channelling.

- Crystals are at the limit or out of channeling at moment of dump.

OVERALL

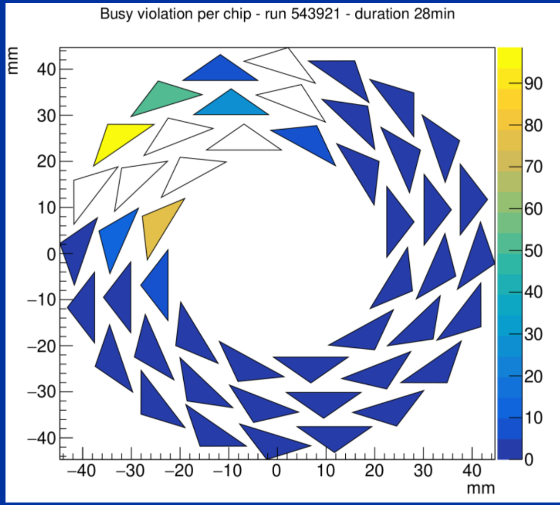
- With crystal collimation could tolerate higher oscillations (40-85 µm) than with standard system.
- Issue not solved yet.
- Possible idea: change collimation hierarchy…



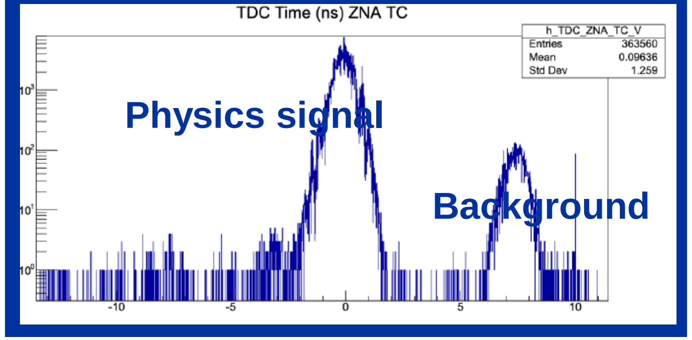
Mitigation for ALICE background

PROBLEM

Strong background observed in ALICE

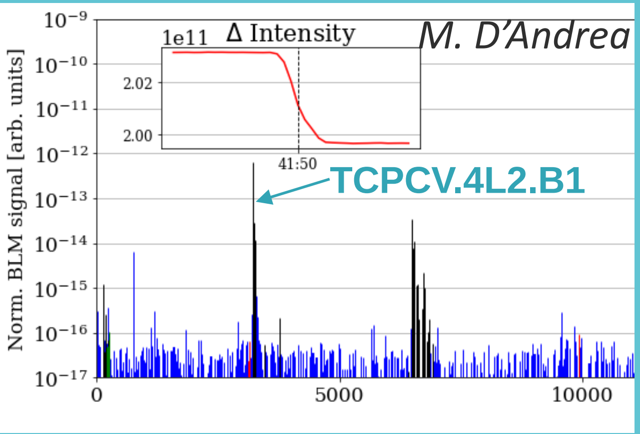


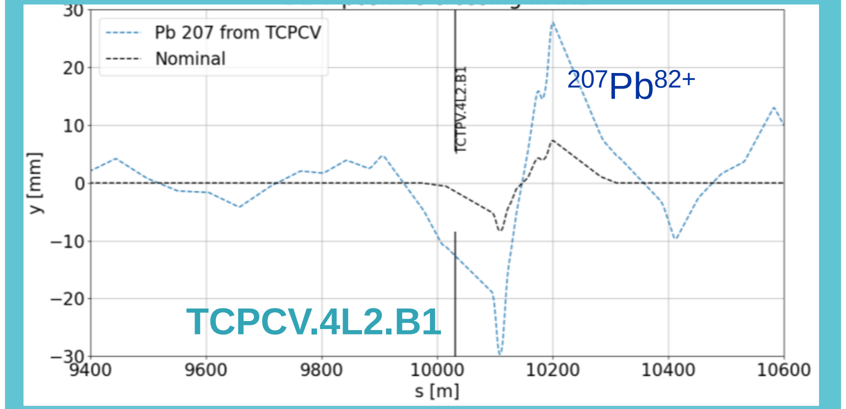
Chips of inner tracking system
Fully saturated chips in white



INVESTIGATION

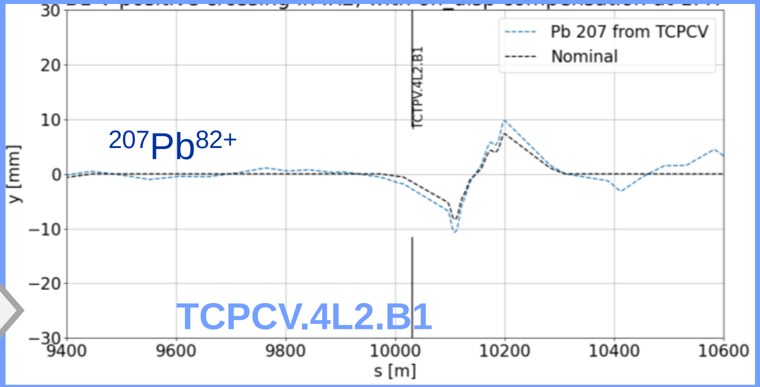
- Many different collimator settings checked.
- Main source: $^{207}Pb^{82+}$ from primary stage (right side), crystal or TCP.

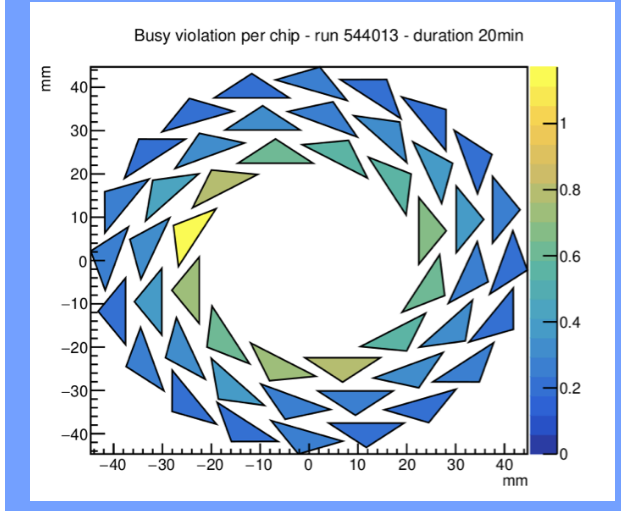




SOLUTION

Mitigation:
Dispersion correction + Retract right TCLD
→ Successful mitigation!



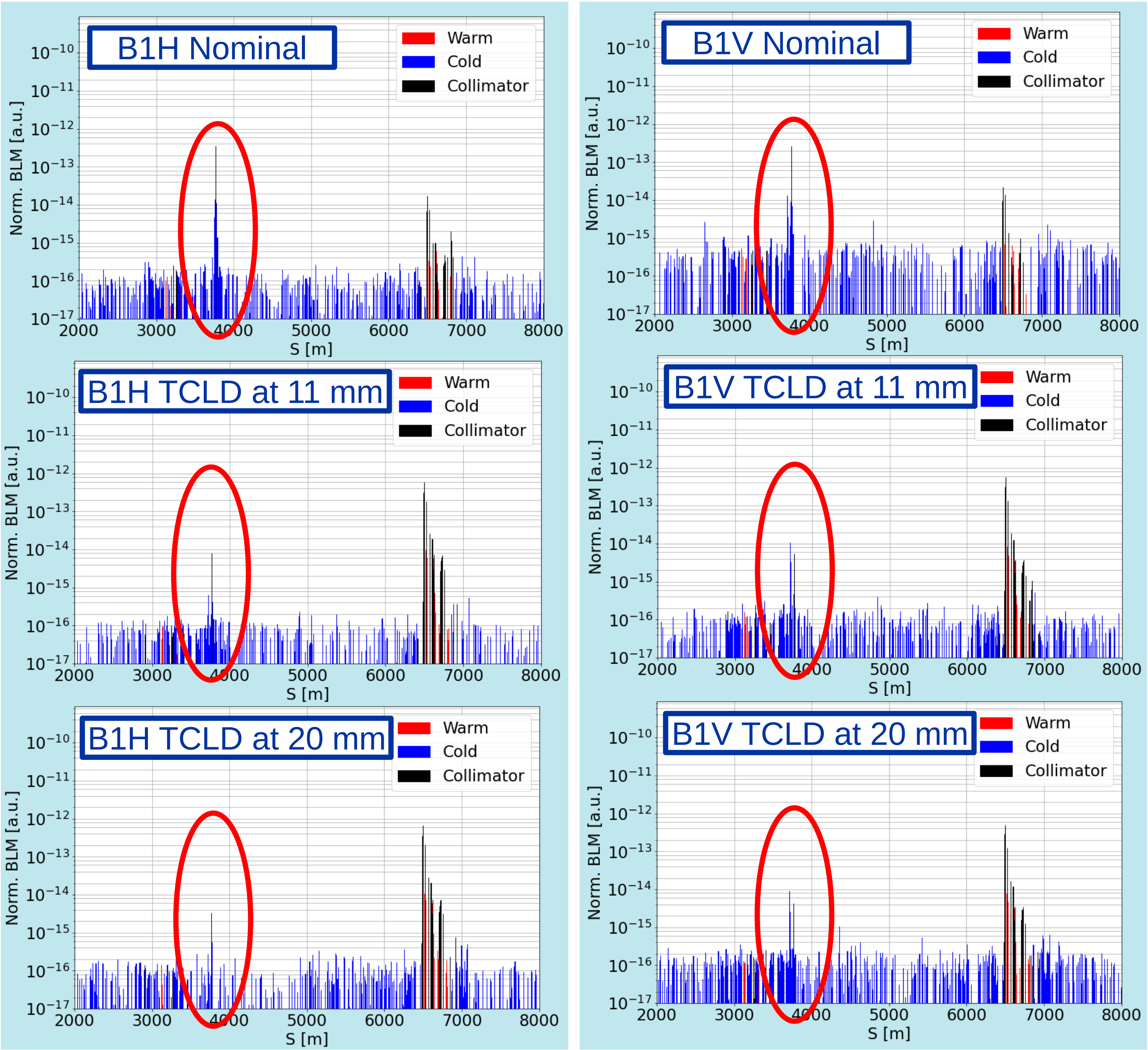


R. Bruce
S. Porteboeuf

Crystal MD highlight

- 18th Oct 2023 for ~5h.
- Dedicated to crystal collimation improvement.
- Reduced losses with retracted right TCLD jaw (BFPP losses on left jaw).
- Studied losses at Q6 and IR7 DS with different TCLA settings.
- Updates on collimation settings during negative polarity validation.

Right TCLD jaw retraction



Lessons learnt for 2024

- **Crystal collimation is essential for the reduction of losses in the DS.**
- **TCLD + orbit bump successfully tackle collisional losses for ALICE.**
- **It is needed to find a way to keep crystal in channeling especially during ramp (automatic optimization not possible).**
- **10 Hz events were still present and were cause of many beam dumps.**
  - Investigate crystal channeling and collimation performance during 10Hz.
- **Need to study Pb207 in advance to minimize issues (e.g. experimental background).**

Summary

Proton collimation

- Very good cleaning performance.
- Complex validation matrix.
- Similar setup as baseline for 2024 – studying tighter options.
- Successful high-beta run with crystal collimation.

Heavy-ion collimation

- Many challenges.
- First time deploying crystal collimation.
- Cleaning improvement thanks to crystal collimation.
- Difficult to maintain channeling reproducibility.
- Challenging events: losses during ramp + 10Hz events.
- Improvements and understanding needed for crystal stability and 10Hz events for 2024.
- Improved collisional loss reduction, crucial for peak luminosity improvement in ALICE.
- Successful real-time mitigation of high background signals in ALICE.

We would like to acknowledge essential contributions from other colleagues from ABP, OP, STI, MME, CEM

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LHC cycle

	E [GeV]	Optics	ß* 1/5 [m]	ß* 2 [m]	ß* 8 [m]	X 1 [µrad] V	X 5 [µrad] H	X 2 [µrad] V	X 8 [µrad] H →V
Injection	450	1	11	10	10	-170	170	170	-170
Ramp	450-6800	1-20	11 → 2	10	10 → 2	-170 → -135	170 → 135	170 → 200	-170 → -200
Flat Top	6800	20	2	10	2	-135	135	200	-200
Squeeze	6800	20-22	2 → 1.2	10	2	-135	135	200	-200
LHCb Rotation	6800	22	1.2	10	2	-135	135	200	H: -200 → 0 V: 0 → 200
Tune Change	6800	22	1.2	10	2	-135	135	200	200
Adjust	6800	22	1.2	10	2	-135	135	200	200
Large Levelling	6800	23-34	1.2 → 0.6	10	2	-135 → -145	135 → 145	200	200
Levelling	6800	34-43	0.6 → 0.3	10	2	-145 → -160	145 → 160	200	200

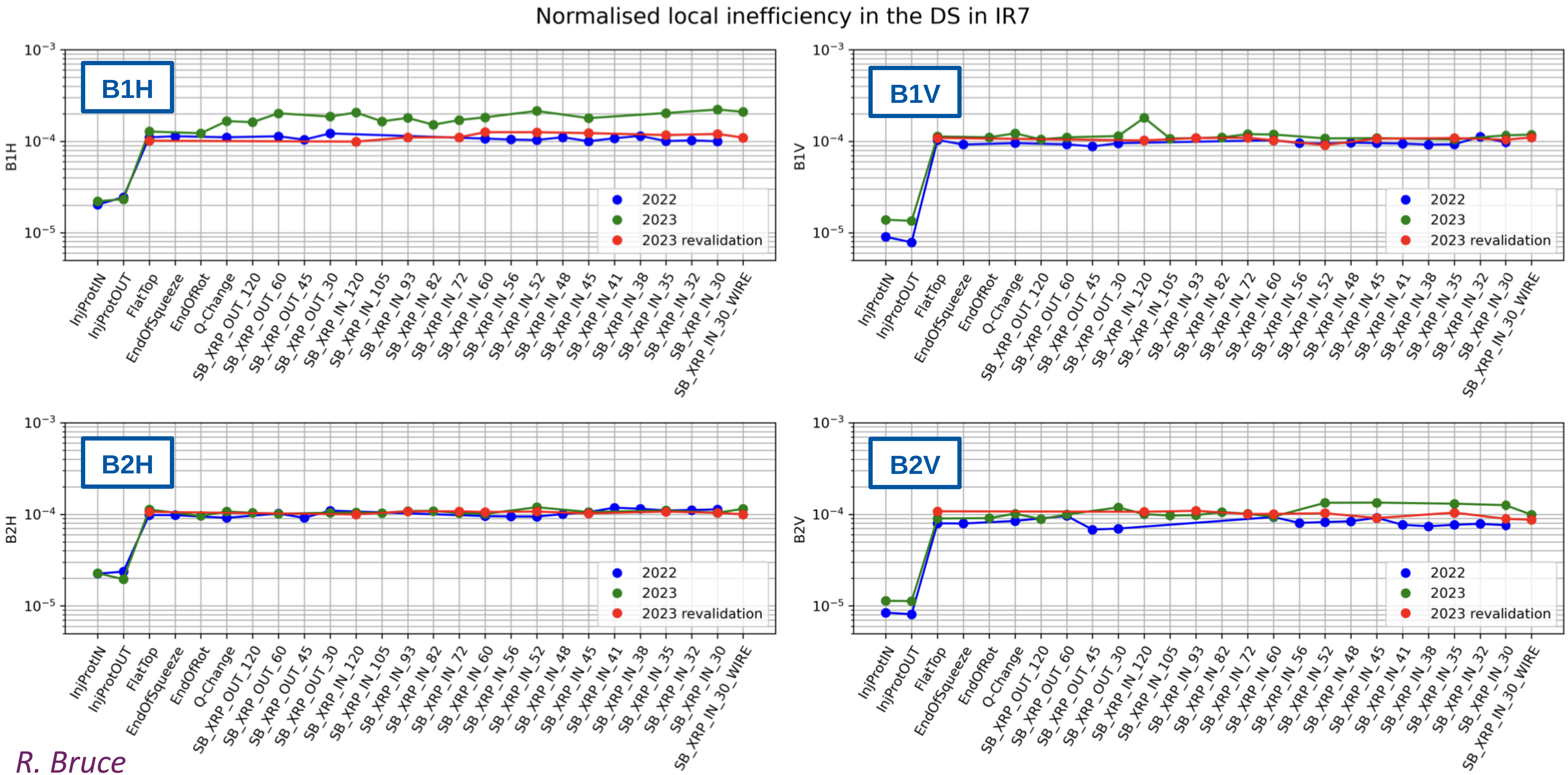
F. Van der Veken

Collimator Settings

		IR7 [σ]			IR3 [σ]			Dump [σ]		TCT [σ]				TCL [σ]		
		TCP	TCSG	TCLA	TCP	TCSG	TCLA	TCDQ	TCSP	1	2	5	8	4	5	6
Injection		5.7	6.7	10	8	9.3	12	8	7.5	13	13	13	13	-	-	-
Ramp		↓	↓	10	↓	↓	↓	↓	↓	↓	↓	↓	↓	-	-	-
Flat Top		5	6.5	10	15	18	20	7.3	7.3	18	37	18	18	-	-	-
Squeeze		5	6.5	10	15	18	20	7.3	7.3	↓	37	↓	18	-	-	-
LHCb Rotation		5	6.5	10	15	18	20	7.3	7.3	9.35	37	9.35	↓	-	-	-
Tune Change		5	6.5	10	15	18	20	7.3	7.3	9.35	37	9.35	11.5	-	-	-
Adjust		5	6.5	10	15	18	20	7.3	7.3	9.35	37	9.35	11.5	-	-	-
Levelling	**120**	5	6.5	10	15	18	20	7.3	7.3	↓	37	↓	11.5	↓	↓	↓
	60	5	6.5	10	15	18	20	7.3	7.3	8.5	37	8.5	11.5	↓	↓	↓
	30	5	6.5	10	15	18	20	7.3	7.3	8.5	37	8.5	11.5	17	42	30
XRP OUT															17	

F. Van der Veken

Proton cleaning performance



R. Bruce

Detailed Ion Collimation setup

	IR7 [σ]					IR3 [σ]			DUMP [σ]			TCT [σ]				TCL
	TCPCH	TCPCV	TCP	TCS	TCLA	TCP	TCG	TCLA	TCDQ	TCSP	TCLD	1	2	5	8	all
Injection	5.7	5.7	6.7	6.7*	10	8	9.3	12	7.5	7.5	out	13	13	13	13	
Flat-top											out					
Adjust/ Physics (negative polarity)	4.75	5	6	6.5**	8	15	18	20	7.3	10.3	30	10.5	B1: 13, B2: 10.5	10.5	15	25 mm
Adjust/ Physics (positive polarity)					10						L: 30, R: 11 mm					

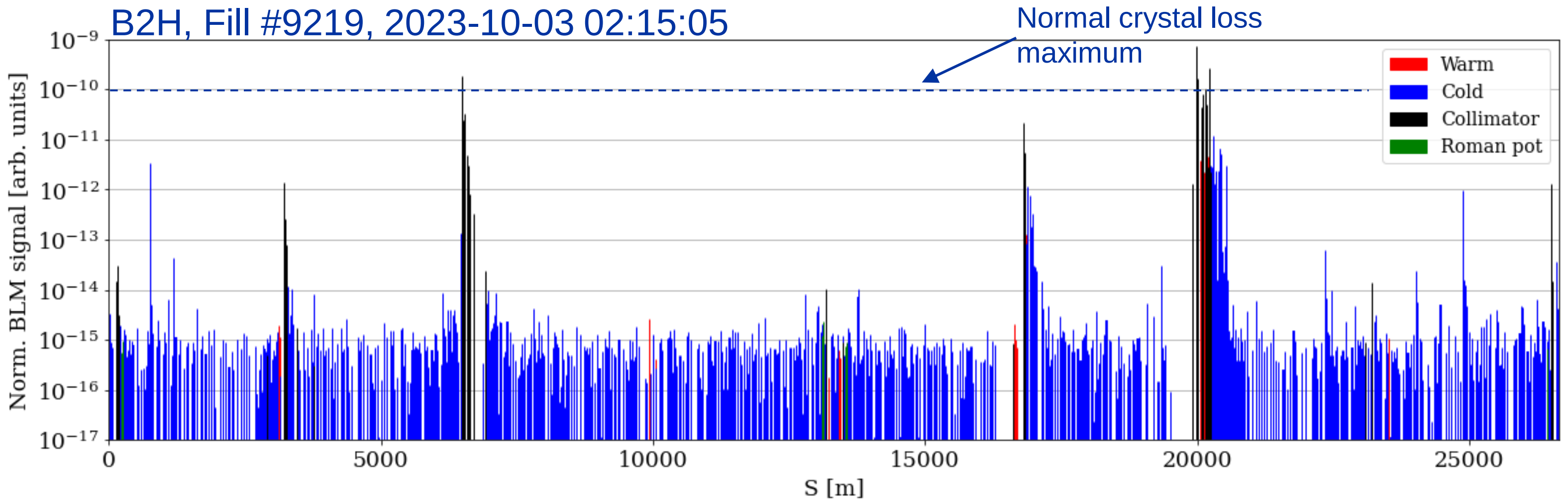
*TCSG.D4L/R7 and TCSPMs at 7.2 σ
** TCSPM.B4L/R7 at 8 σ; TCSG.E5R7 and TCSG.6R7 at 23 mm,

Losses during the energy ramp

- Important losses observed during energy ramp
- Transverse losses around 6.1 - 6.7 Z TeV are the strongest limitation, mainly in fast running sums.
- Significant slowdown of intensity ramp up.
- Various possible causes.
- Crystals not in perfect channeling orientation may have worsened the situation.
- Many mitigations applied…

R. Bruce

- Not well understood.
- Investigation in progress.



Crystal setup and automatic alignment

INITIAL SETUP

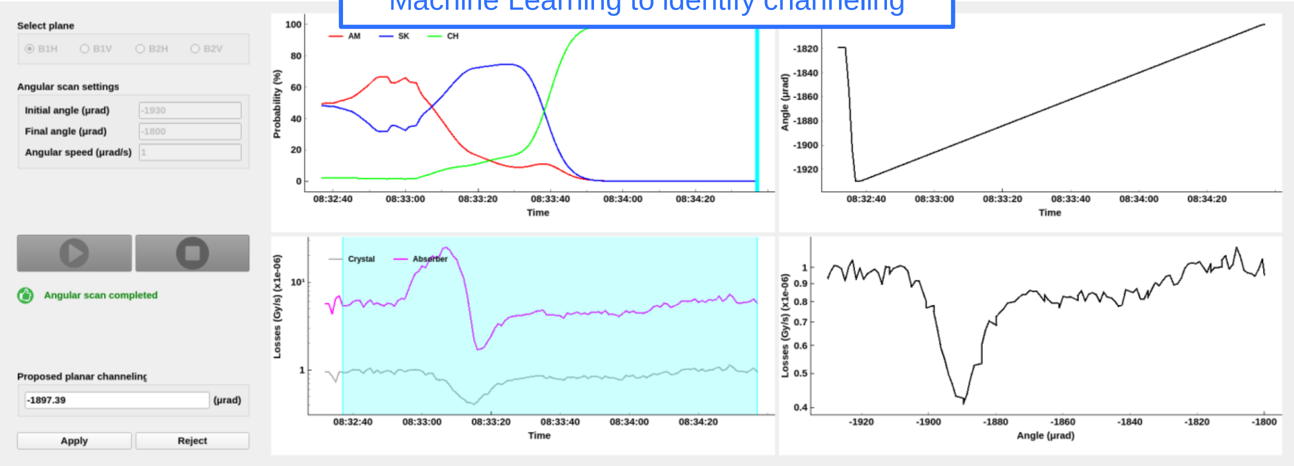
Crystal should be set in channeling orientation. There are two components:

- **Transverse alignment to beam envelop:** done manually with aid of TCP.
- **Angular alignment to divergence:** ML tool.

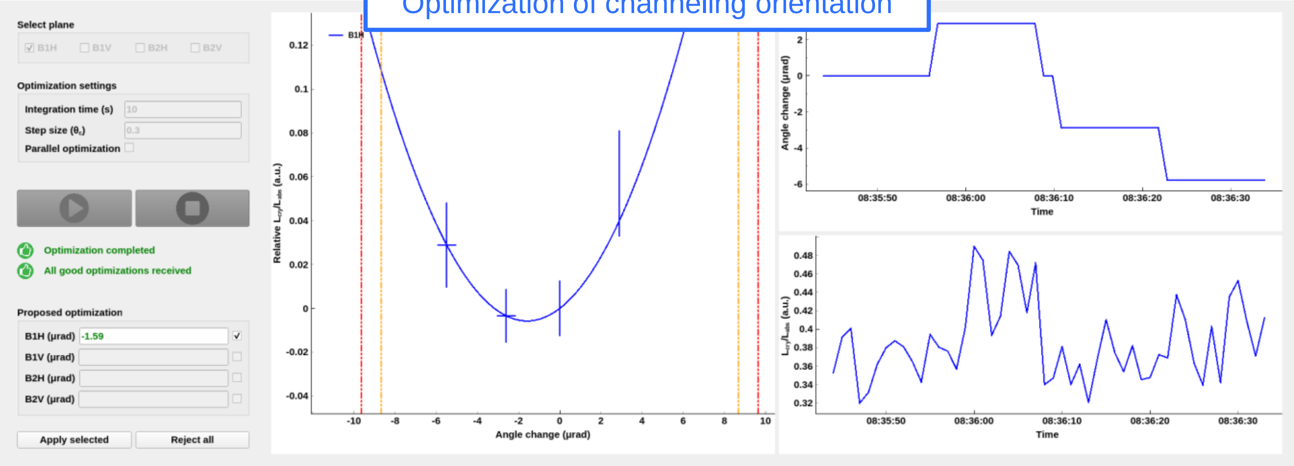
CONTINUOUS ALIGNMENT

- Channeling optimization tool.
- Drift detection.

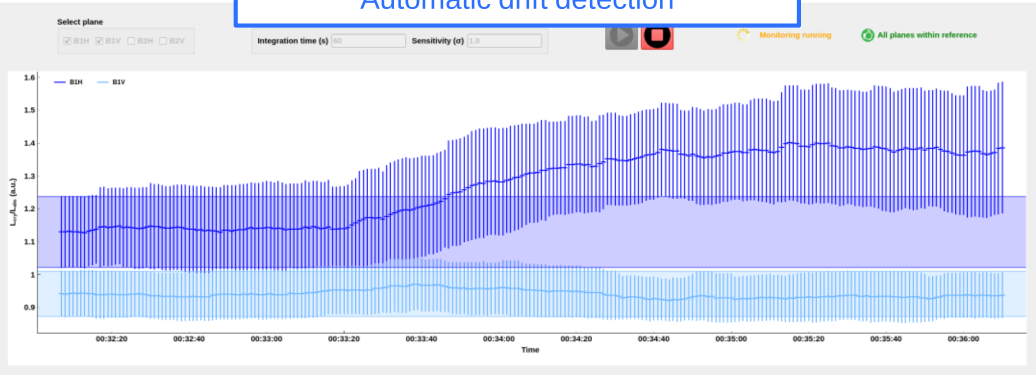
Machine Learning to identify channeling



Optimization of channeling orientation

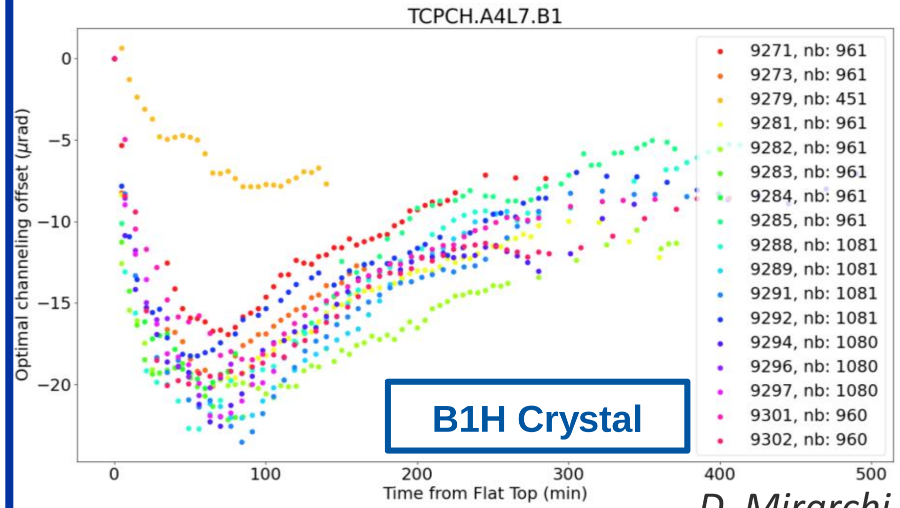


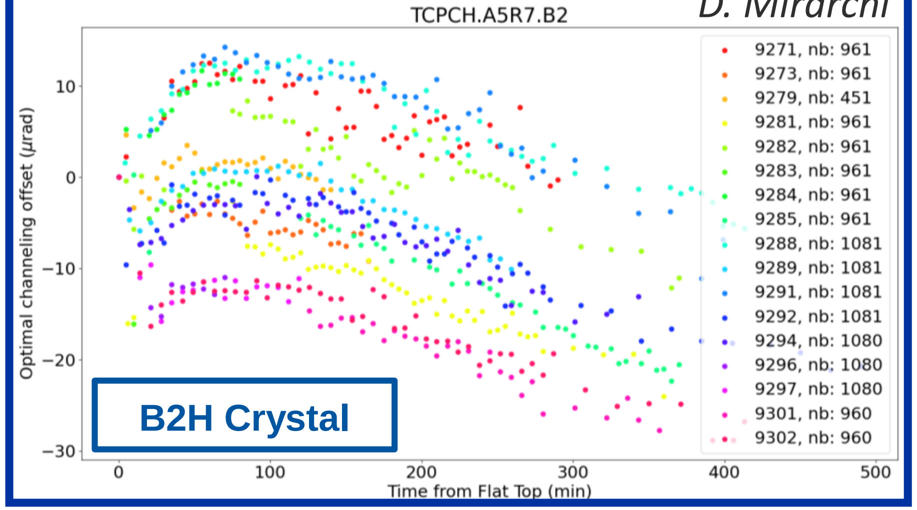
Automatic drift detection



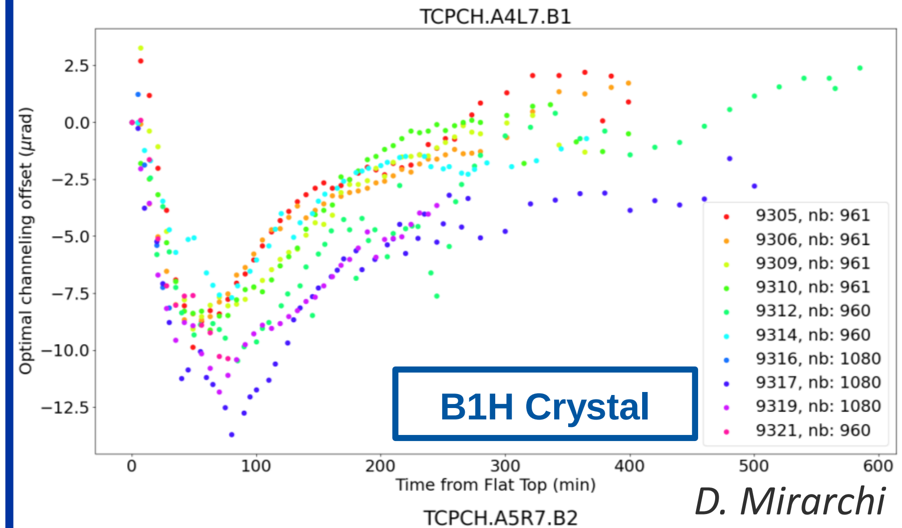
Reproducibility of optimal channeling

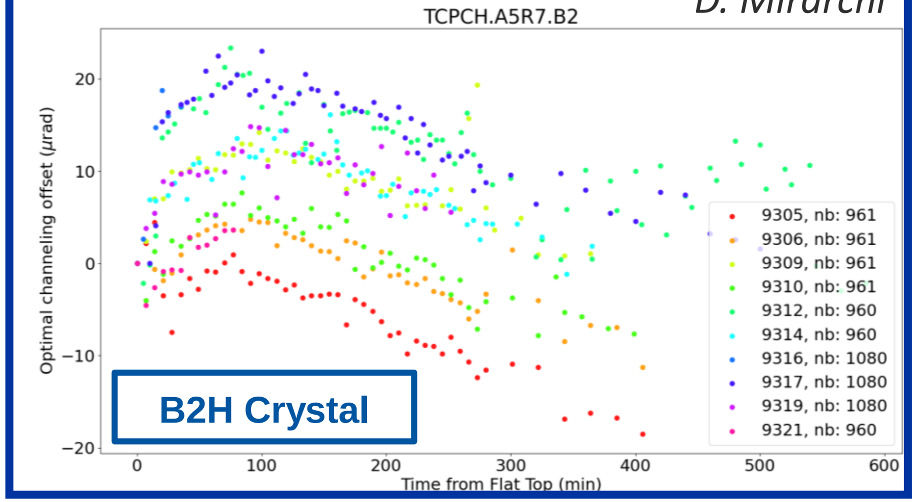
Before automatic optimization





After automatic optimization





In channeling most of the time after ramp function update.

Work in progress for crystal orientation stability

Works ongoing and planned:

- **Revised of impedance simulations.**
- **New measurements on the prototypes: nothing dramatic observed.**
- **Refined estimated power deposition values.**
- **Attempt to identify correlation between measurements, in particular in the ramp.**
- **Planned hardware tests on crystal holder and goniometer.**

Hardware update likely only in LS3.

Present focus for collimation is on software.