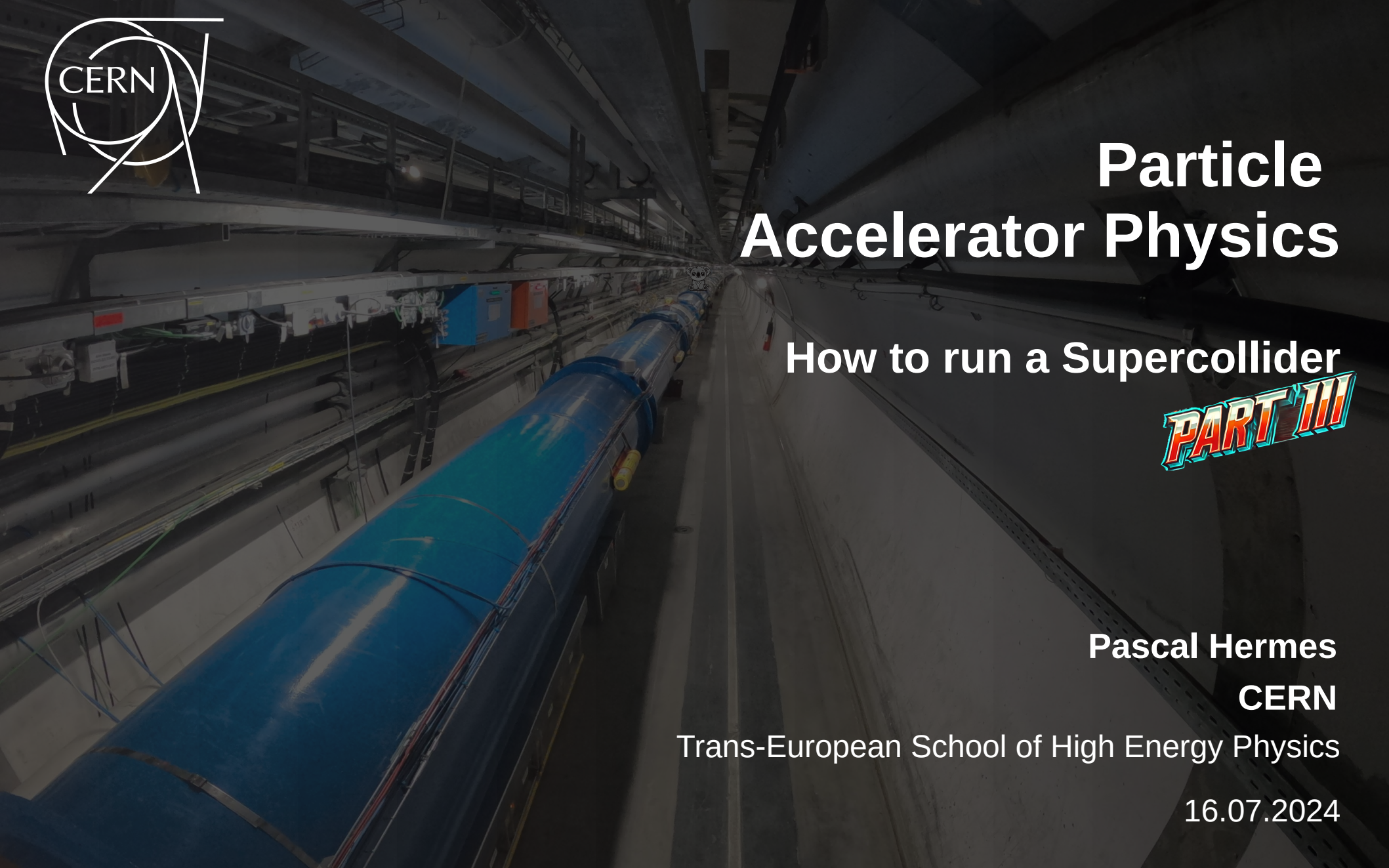


Particle Accelerator Physics

How to run a Supercollider

PART III

Pascal Hermes

CERN

Trans-European School of High Energy Physics

16.07.2024

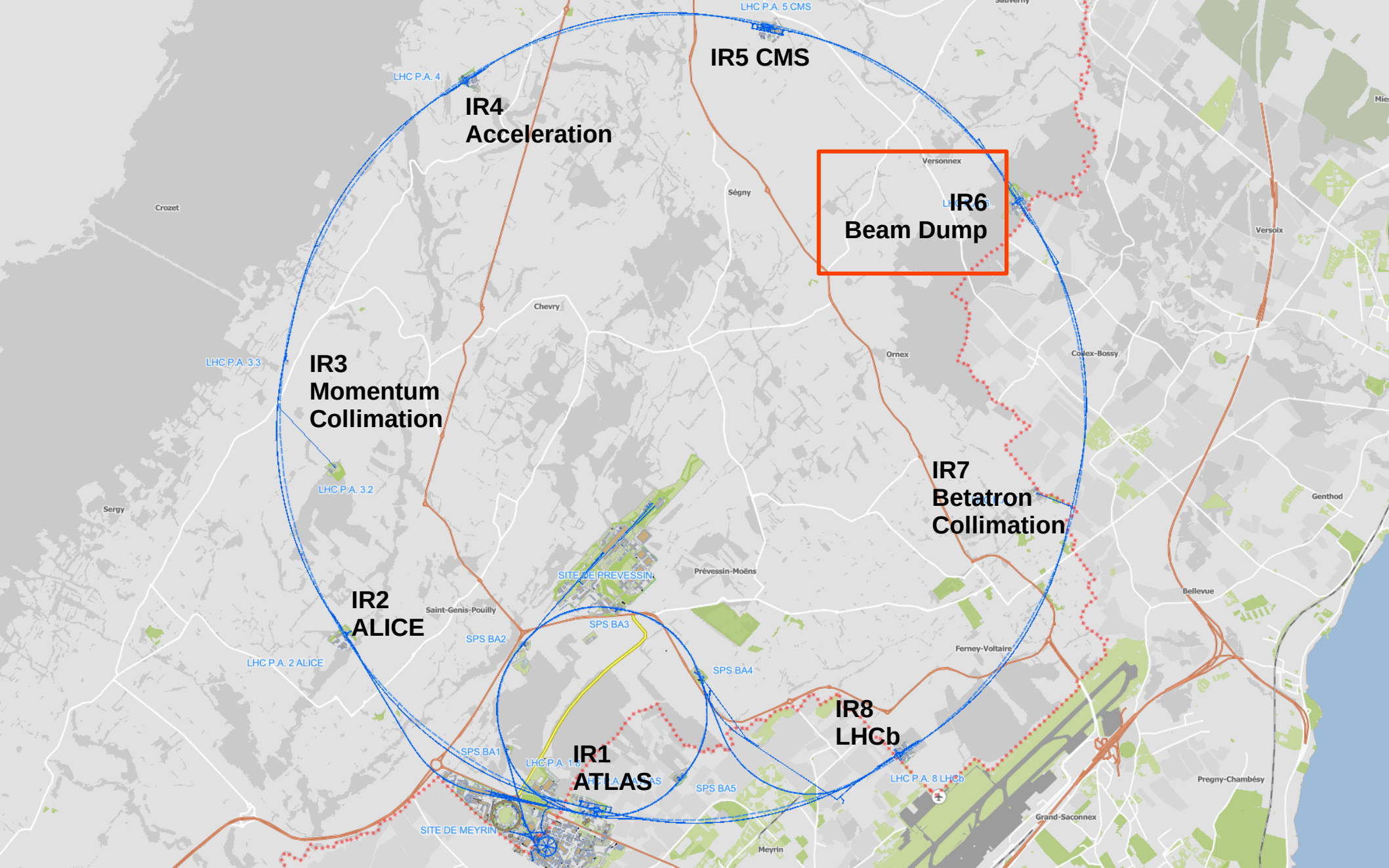
Today’s lecture

Dealing safely with high LHC beam energies

- Beam Dump
- Beam Collimation

Beam Instrumentation

Outlook to new physics at the LHC


IR5 CMS
IR4
Acceleration
IR6
Beam Dump
IR3
Momentum
Collimation
IR7
Betatron
Collimation
IR2
ALICE
IR8
LHCb
IR1
ATLAS
LHC P.A. 5 CMS
LHC P.A. 4
LHC P.A. 3.3
LHC P.A. 3.2
LHC P.A. 2 ALICE
LHC P.A. 8 LHCb
SPS BA1
SPS BA2
SPS BA3
SPS BA4
SPS BA5
SITE DE PREVESSIN
SITE DE MEYRIN
Versonnex
Ségny
Crozet
Chevry
Ornex
Cessy
Versoix
Sergy
Saint-Genis-Pouilly
Prévessin-Moëns
Ferney-Voltaire
Bellevue
Genthod
Pregny-Chambésy
Grand-Saconnex
Meyrin

LHC Stored Beam Energy

Each LHC beam carries (2023 / 2024) roughly

- 2800 bunches
- 1.6×10^{11} particles per bunch
- At 6.8 TeV energy

What is the total stored beam energy per beam?

LHC Stored Beam Energy

Each LHC beam carries (2023 / 2024) roughly 450 MJ

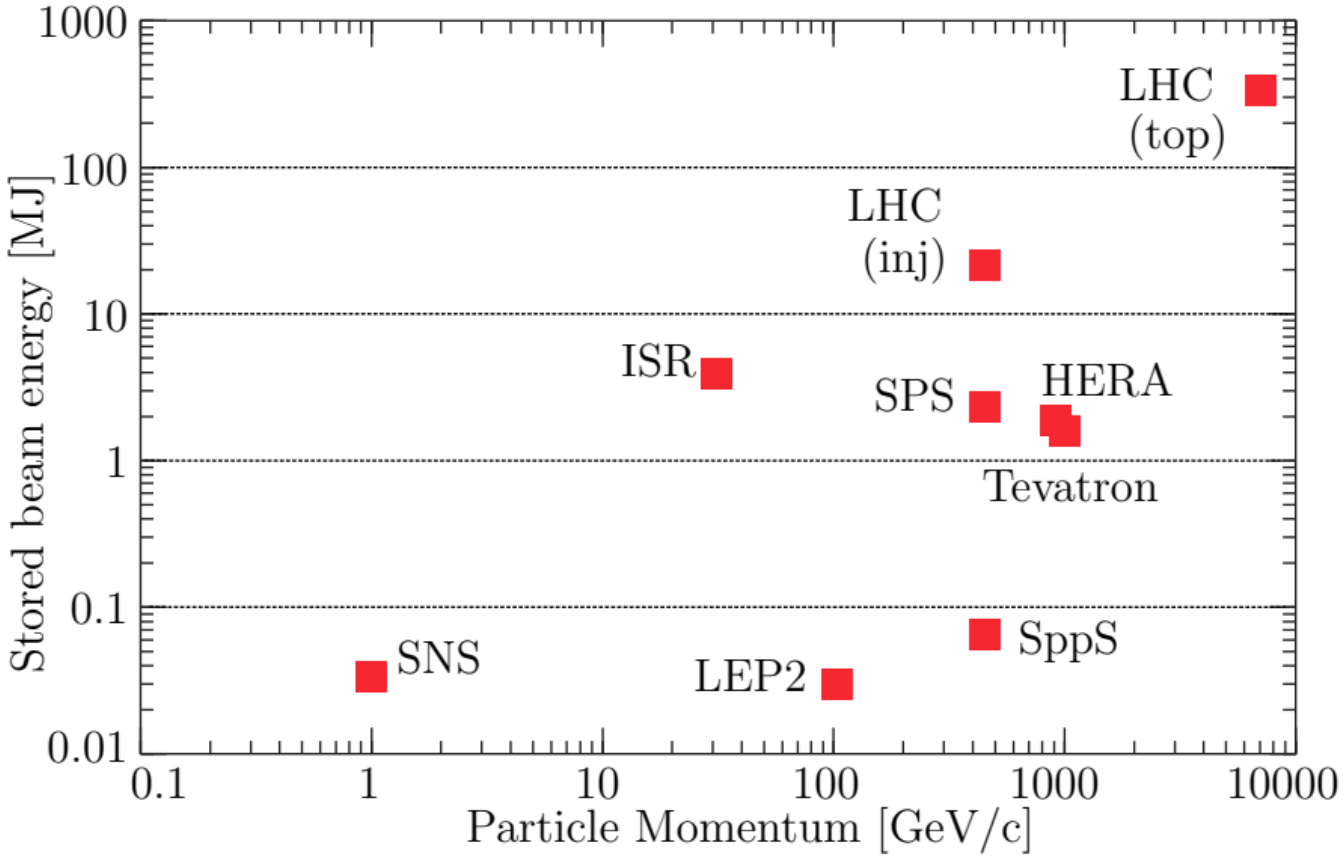
Equivalent to:

A Boeing 737 at take-off

The energy needed to jump onto the ISS

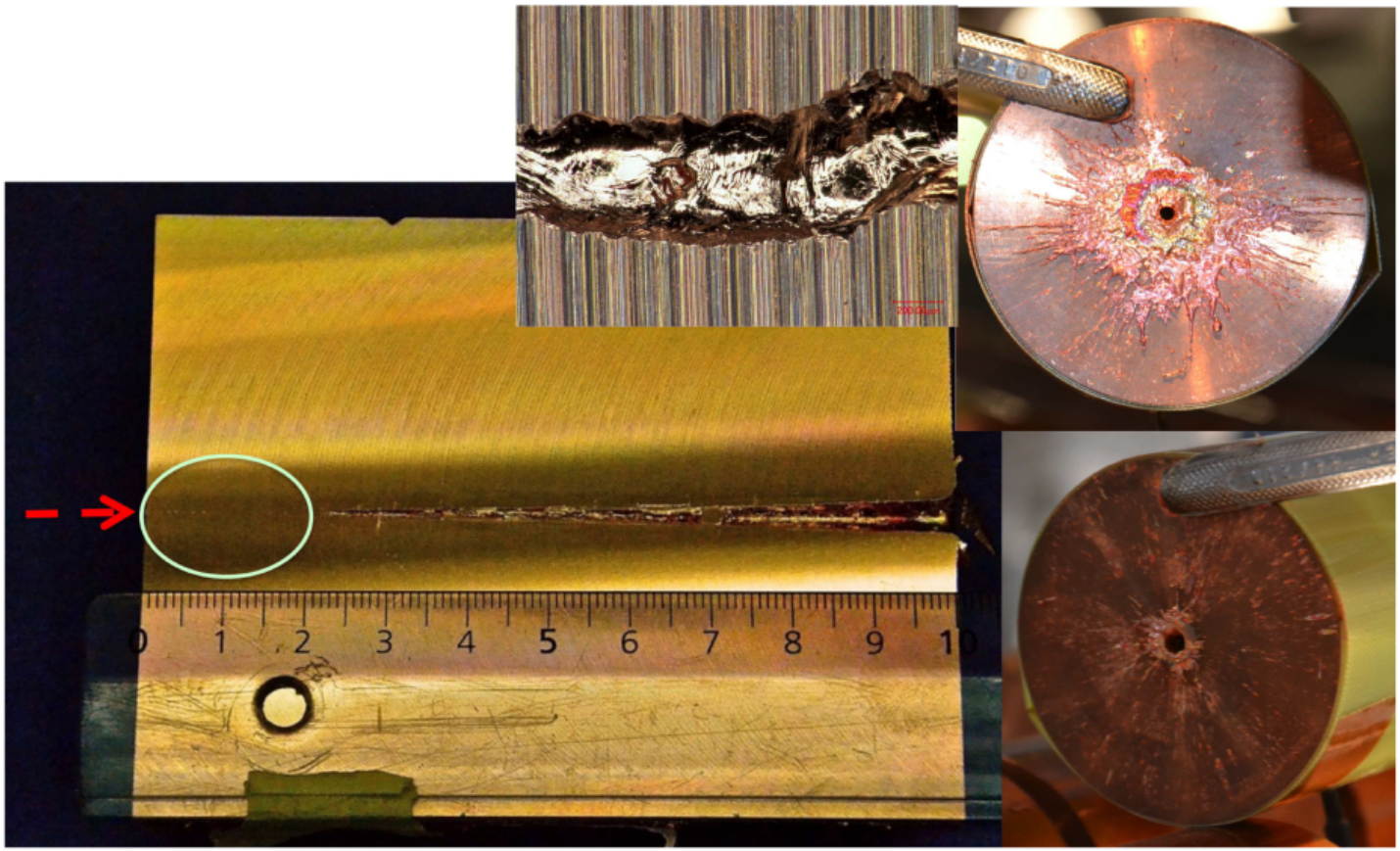
The energy released by 120kg of TNT

LHC Stored Beam Energy



R. W. Assmann et al. The final collimation system for the LHC, EPAC 2006

LHC Stored Beam Energy



F. Burkhardt, Doctoral Thesis

LHC Beam Dump

What if we want/need to get rid of the beams?

Operational dump → we want fresh beam

Dump by Beam Interlock System (BIS)

Beam instabilities


High beam losses


Magnet quench / cryogenic issues

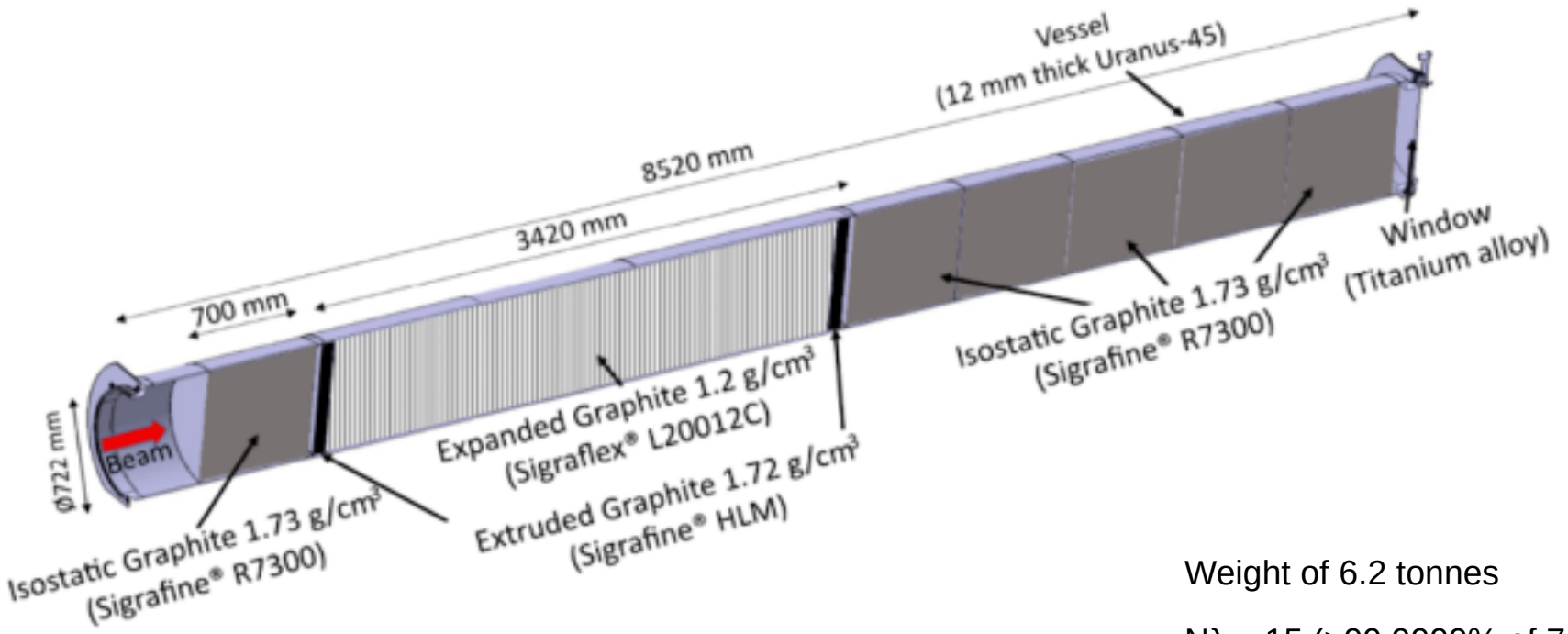

Access system

Collimator Interlocks

...

Safe and robust beam disposal needed!

LHC Beam Dump (since 2021)



Weight of 6.2 tonnes

Nλ ≈ 15 (>99.9999% of 7 TeV protons have an inelastic collision)

https://home.cern/news/news/accelerators/autopsy-lhc-beam-dump

LHC Beam Dump

Exercise:

Assume ε_N = 3.5 um rad, $\beta_{x/y}$ = 200m

Assuming 500MJ in one LHC beam

What is the energy density of an LHC beam?

1’682’495’112 J/mm^2

LHC Beam Dump

Exercise:

Assume ε_N = 3.5 um rad, $\beta_{x/y}$ = 200m

Assuming 500MJ in one LHC beam

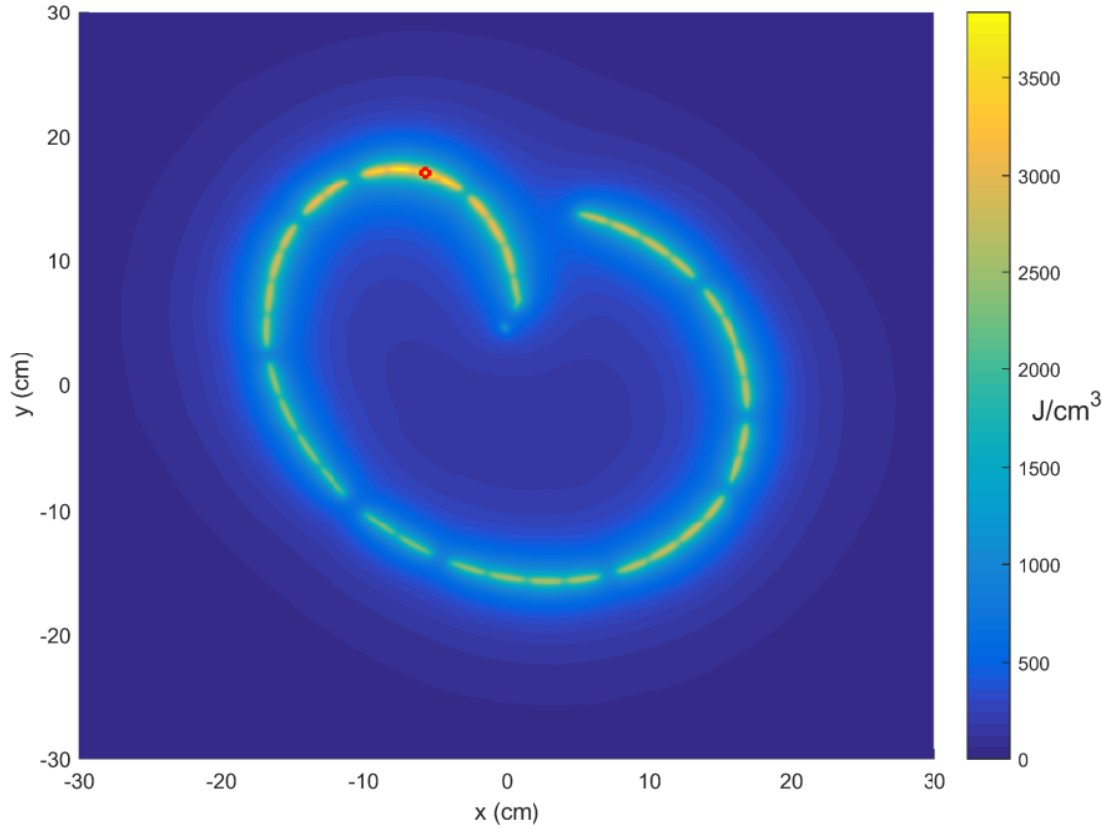
What is the energy density of an LHC beam?

1’682’495’112 J/mm^2

We must increase the surface covered by the beam!

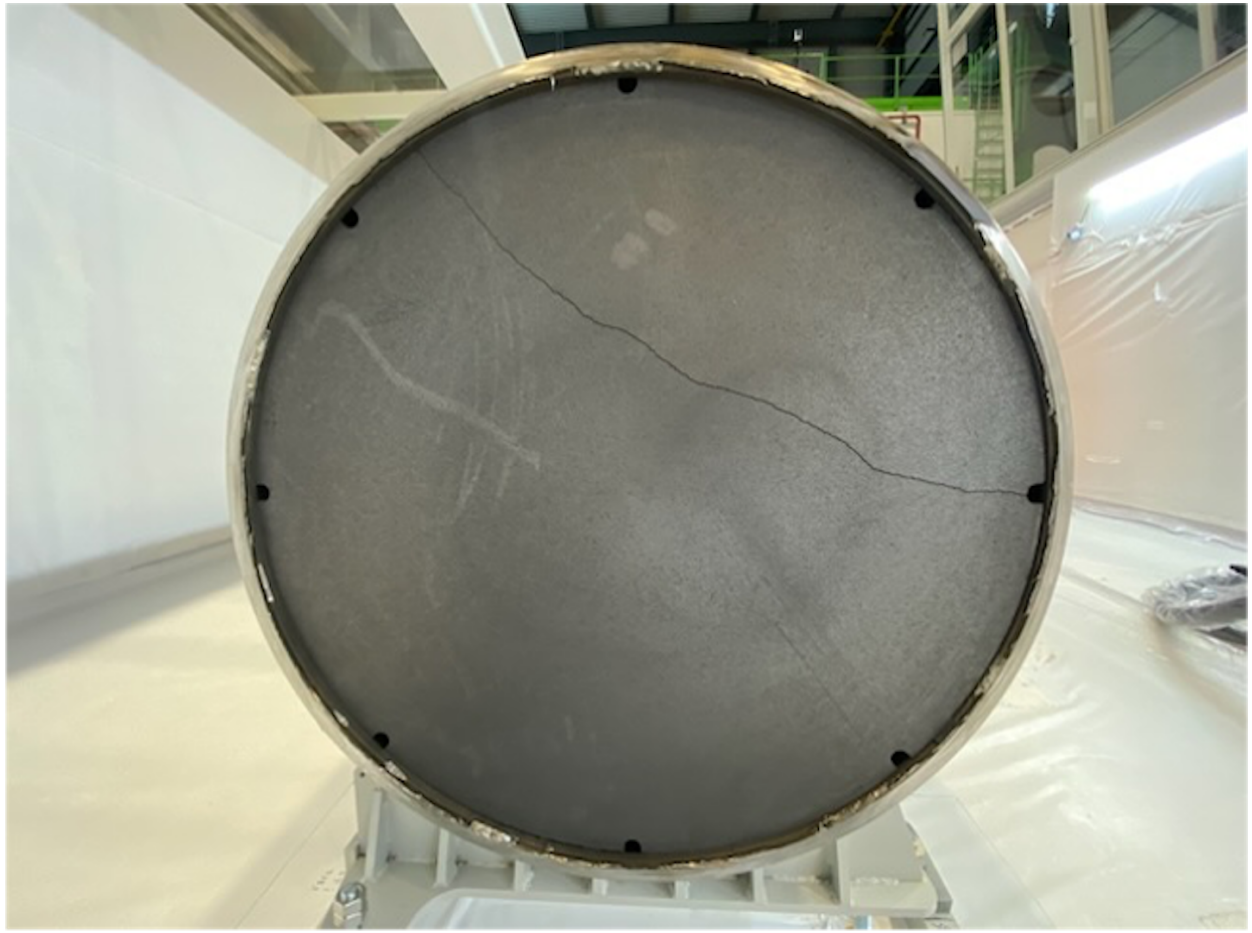
LHC Beam Dump

- Beam is swept by dilution kickers (MKB)
- 4 horizontal and 6 vertical
- 600m drift space to dump
- Figure has a circumference of about 120cm at absorber
- Beam size of 1.6mm in x and y



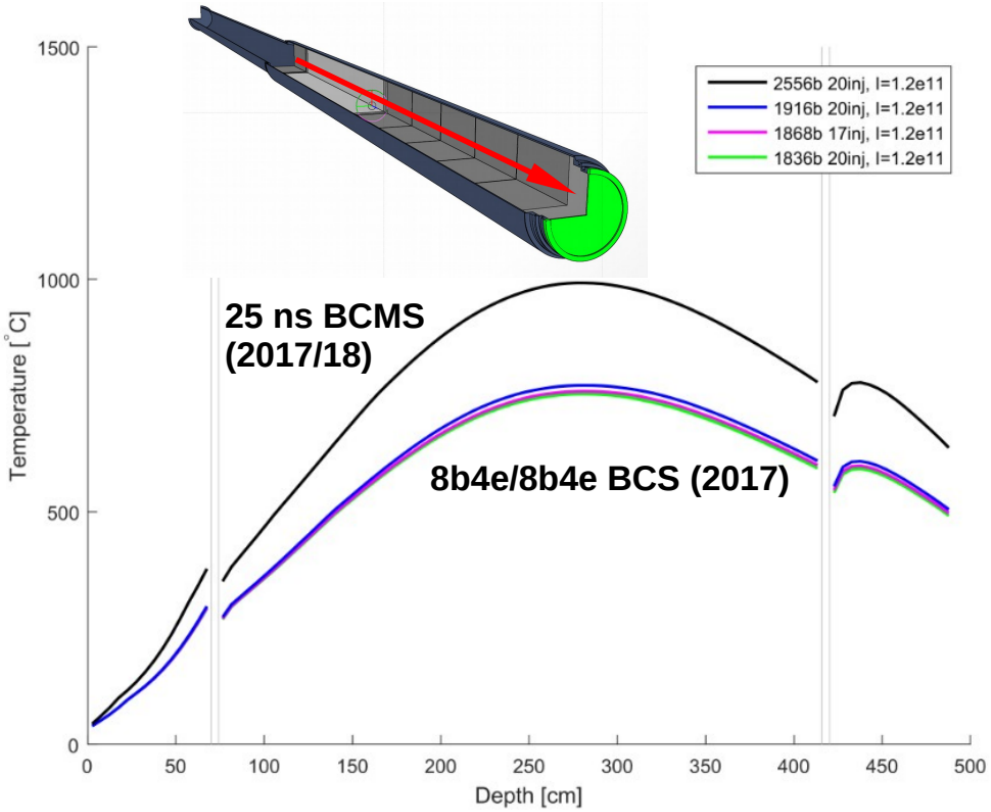
Figures courtesy of C. Wiesner and M. Frankl

LHC Beam Dump



https://home.cern/news/news/accelerators/autopsy-lhc-beam-dump

LHC Beam Dump



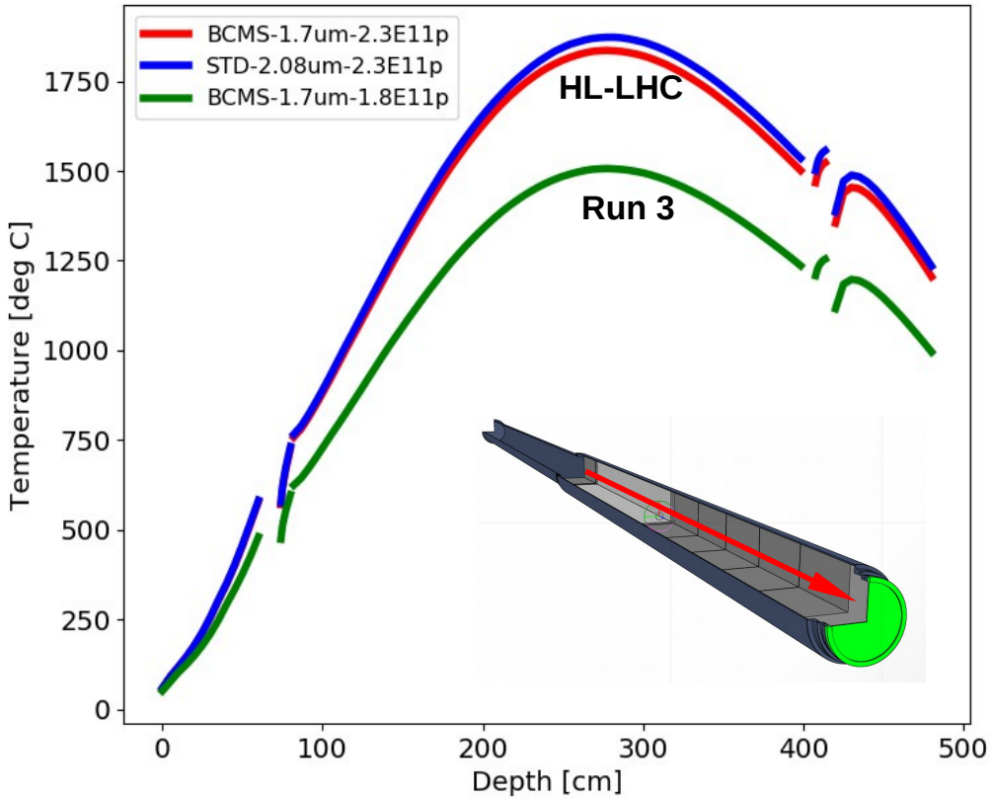


Figure by A. Lechner: https://indico.cern.ch/event/784431/contributions/3263926/attachments/1790633/2917062/2019_05_02_dumpenergydep.pdf

LHC Collimation

Collimation

- What do we do in operation to protect the machine hardware?
- **LHC Collimation System**

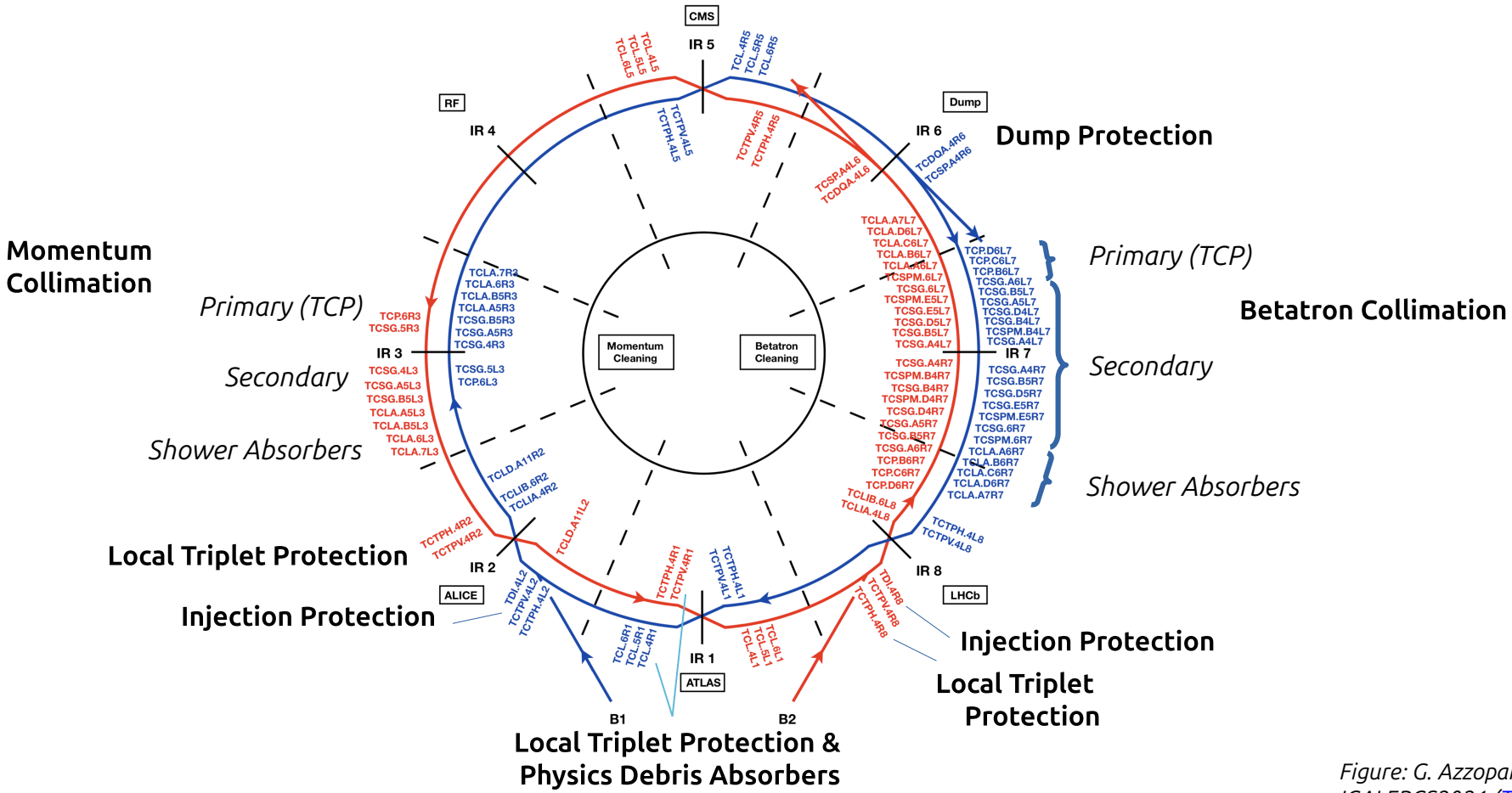
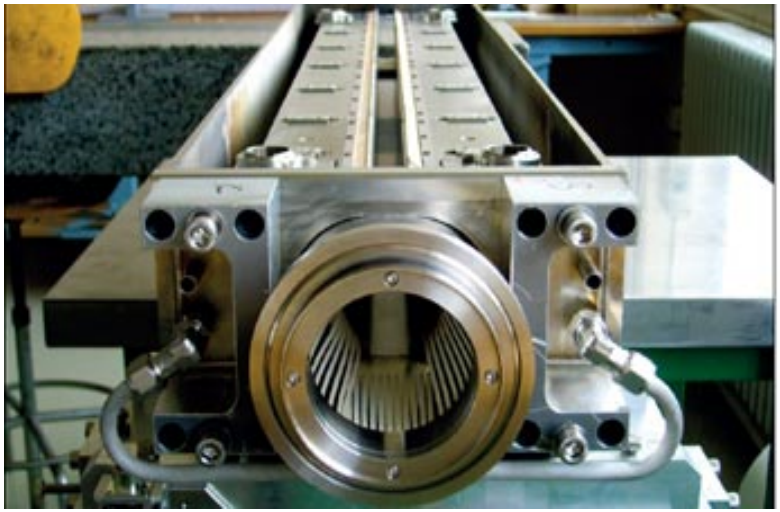
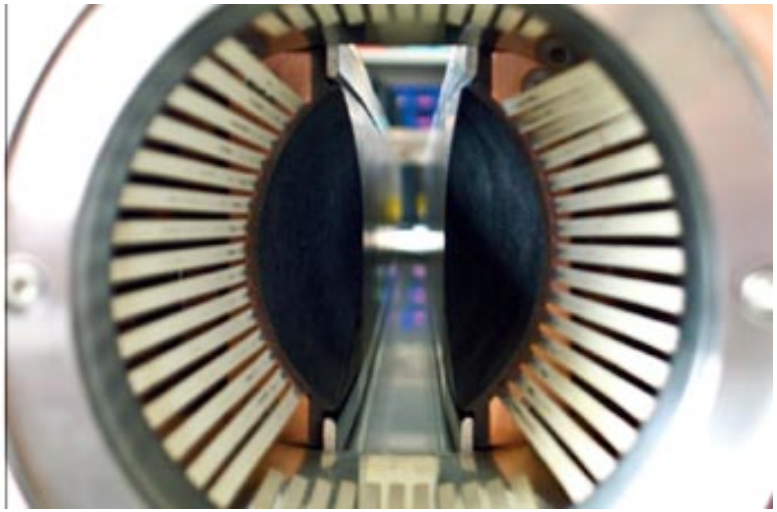


Figure: G. Azzopardi ICALEPCS2021 (THPV012)

Collimators



Collimator Assembly

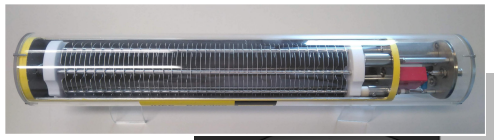


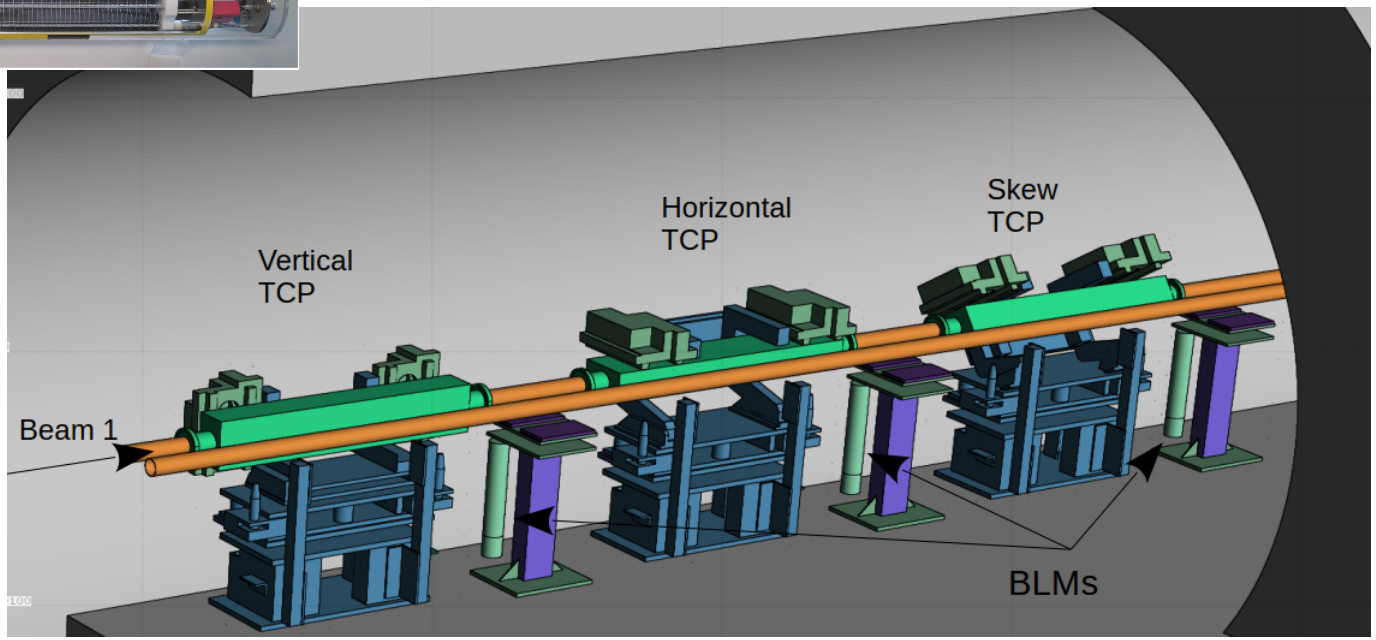
Movable collimator jaws

Figure: S. Redaelli, CERN Courier

Collimators

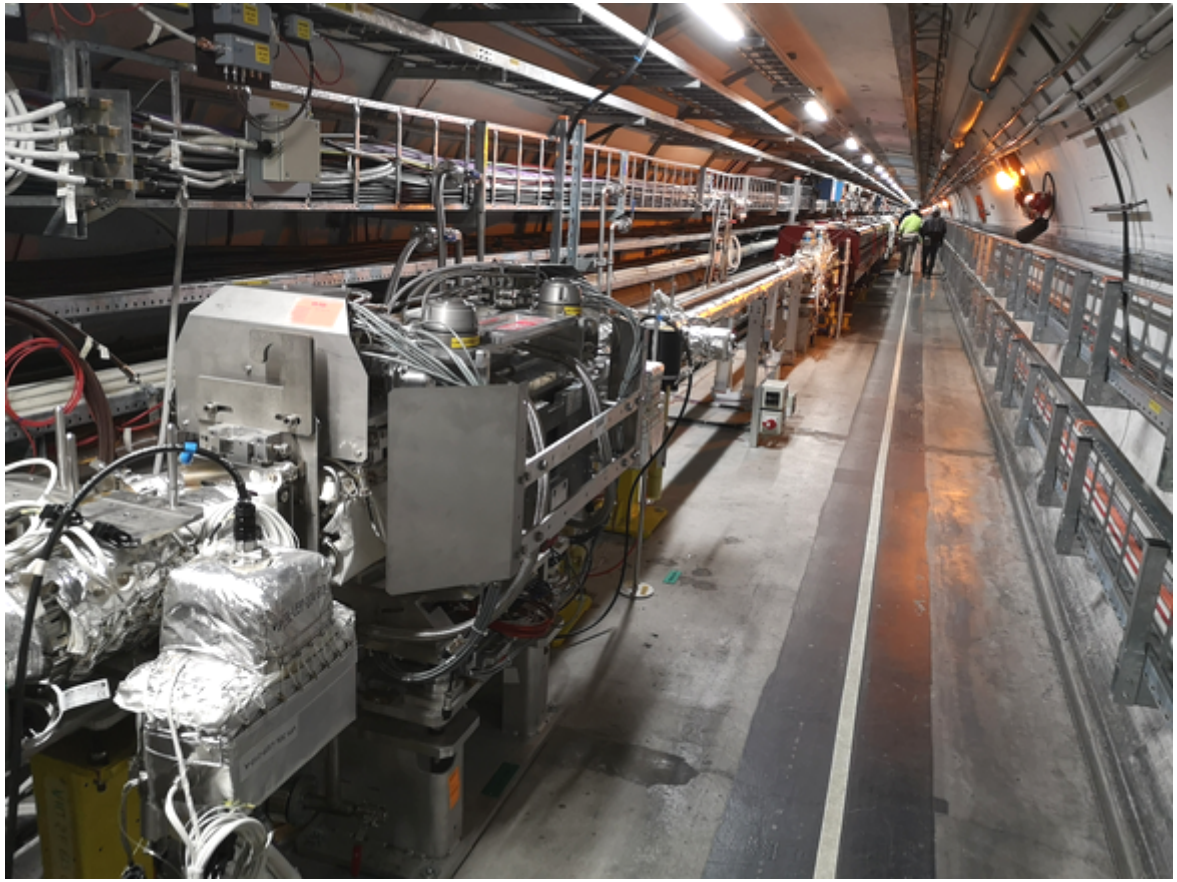
Source : S. Morales Vigo, Msc Thesis



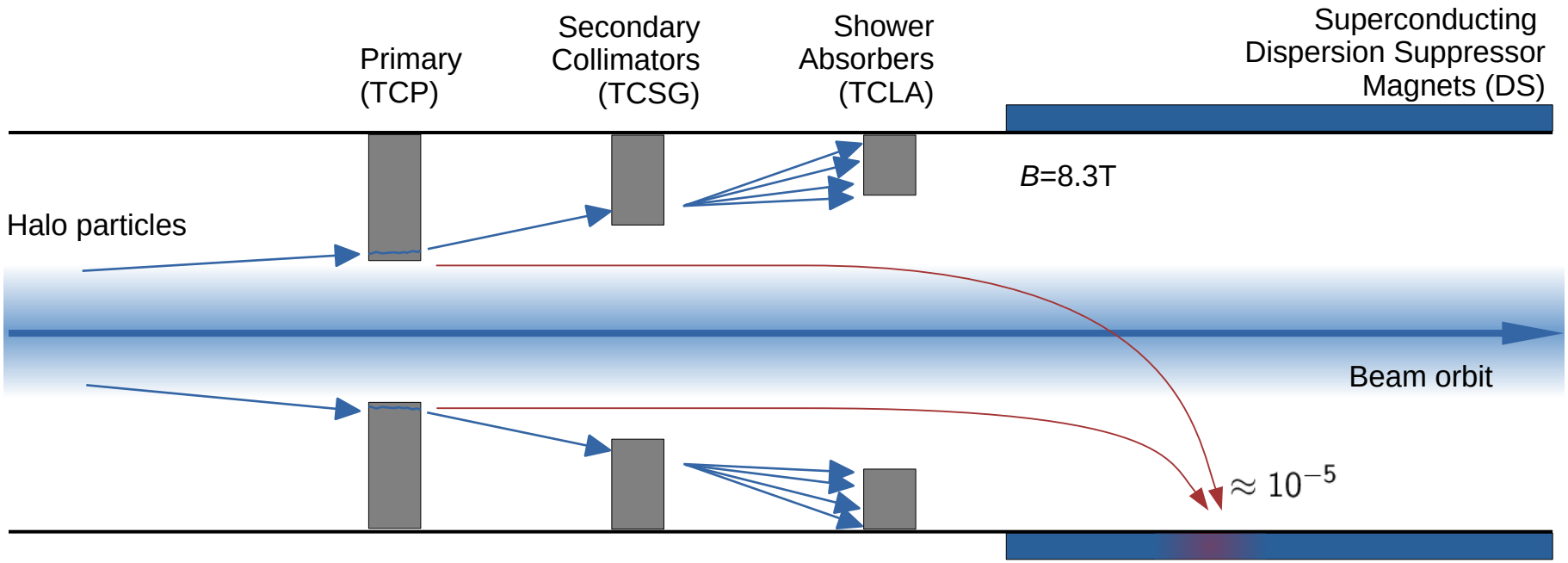


Source: E. Skordis, CollWG 181

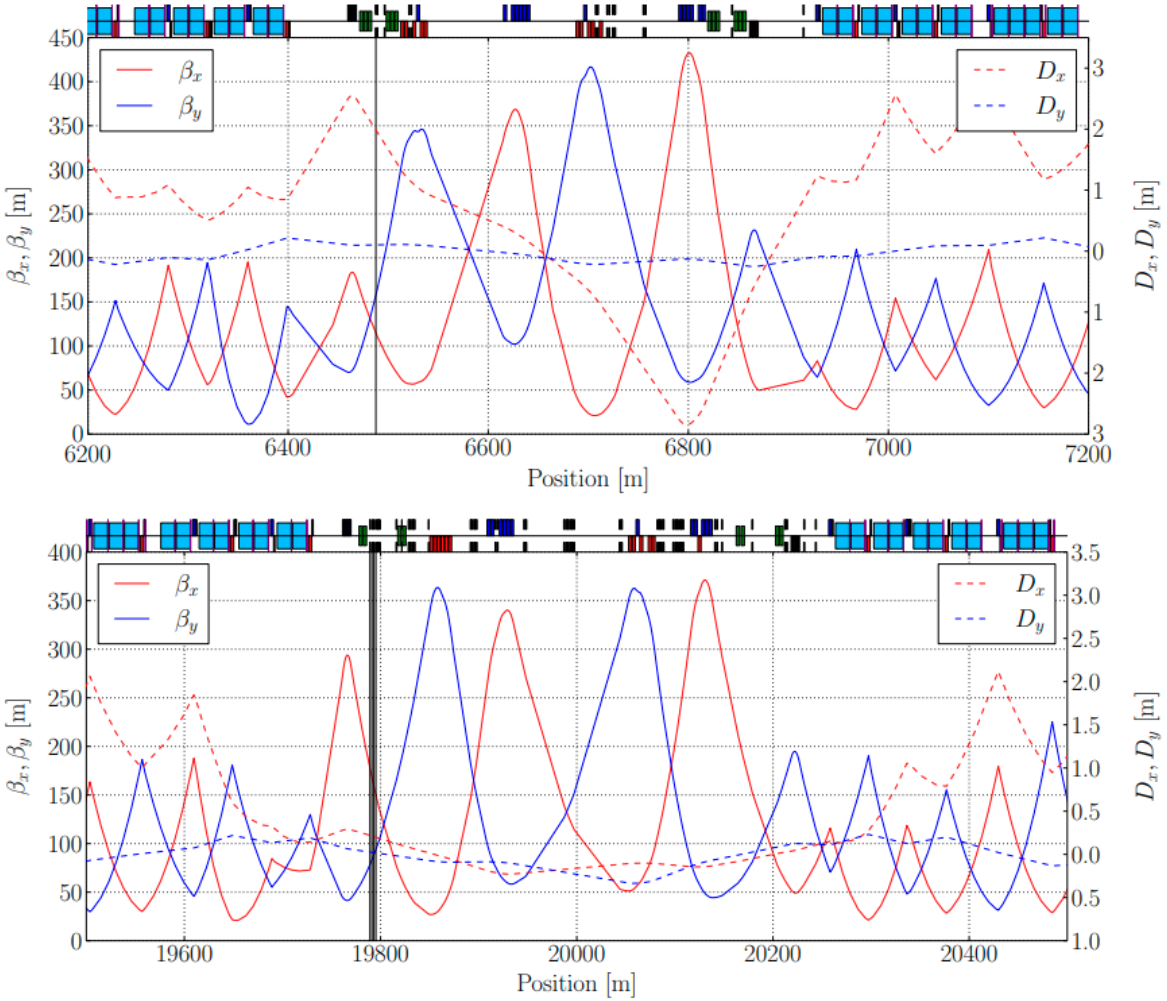
Collimators



Collimation system in IR3/IR7



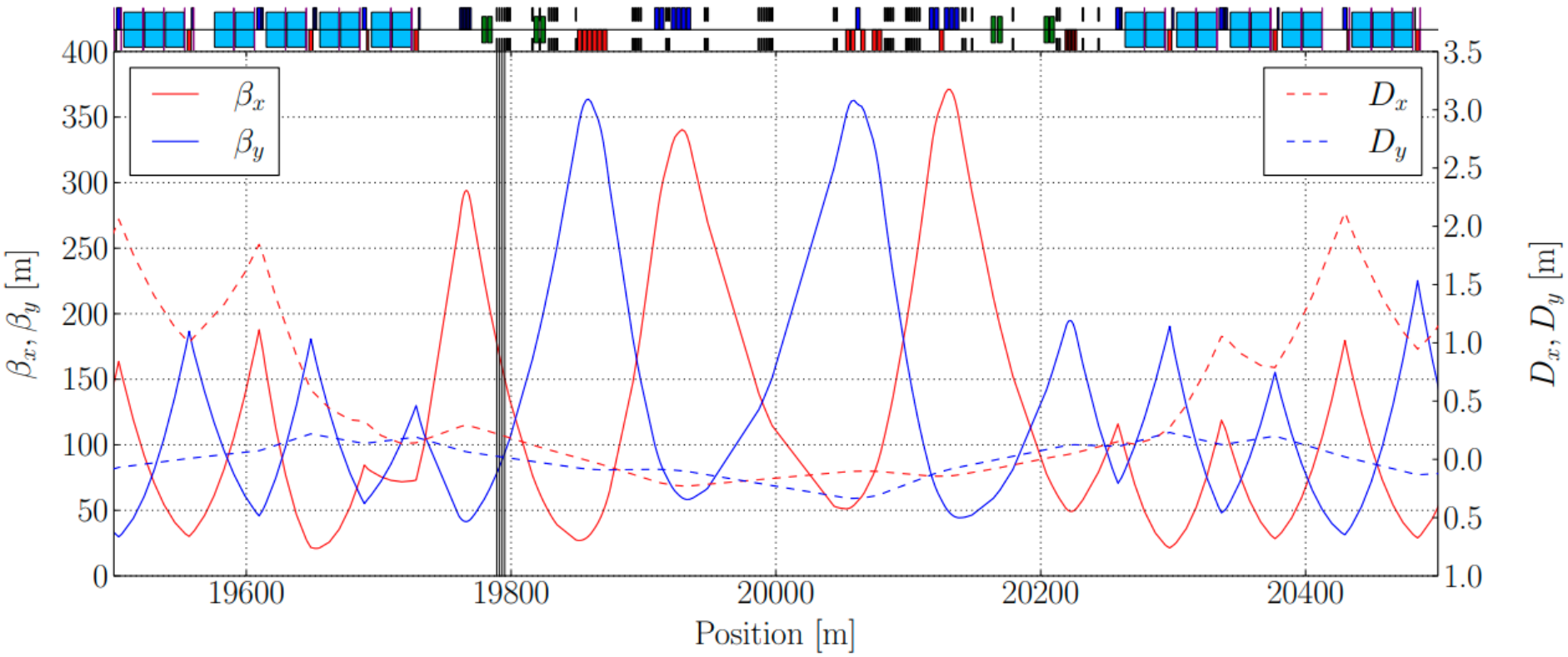
Betatron vs. Momentum Collimation



Which is betatron and which is momentum collimation?

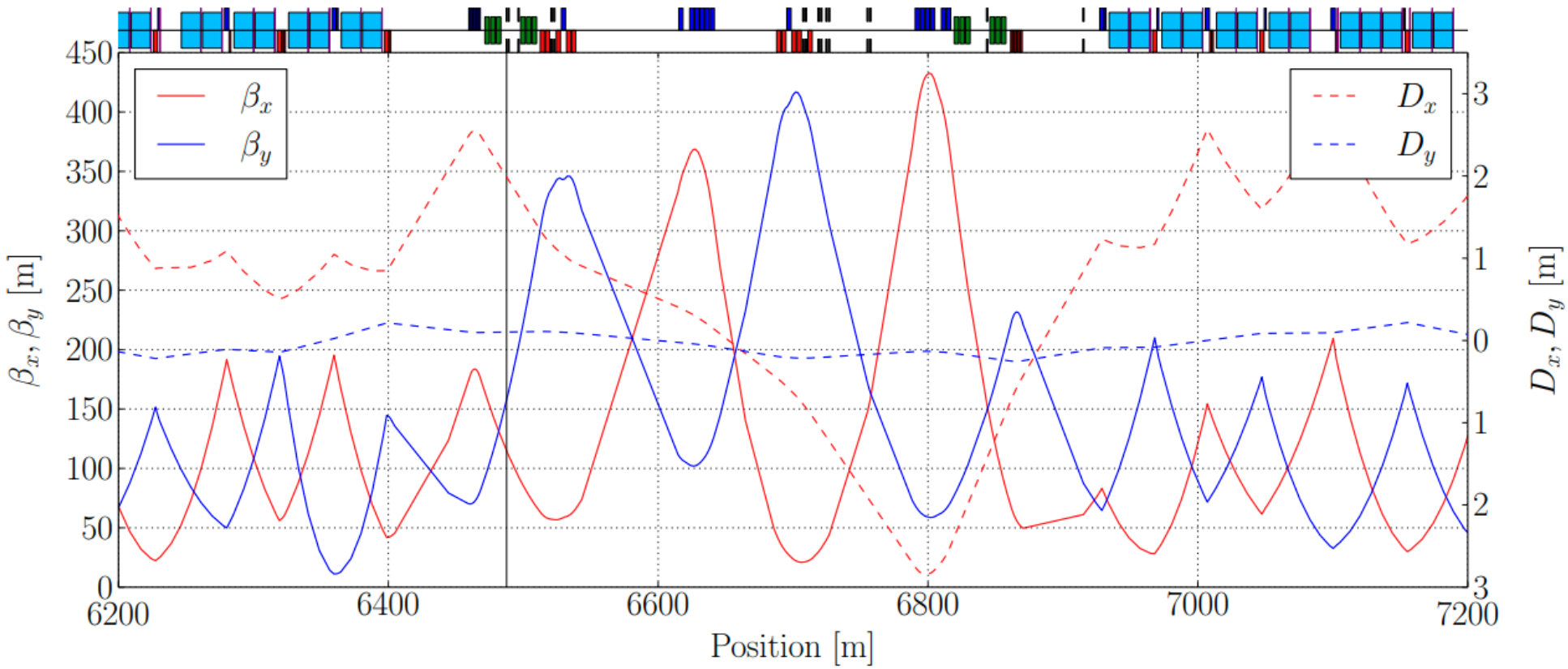
Betatron vs. Momentum Collimation

$$x(s) = \sqrt{2\,J\,\beta(s)}\,\cos(\phi(s) + \phi_0) + D_x(s)\,\frac{\Delta p}{p}$$

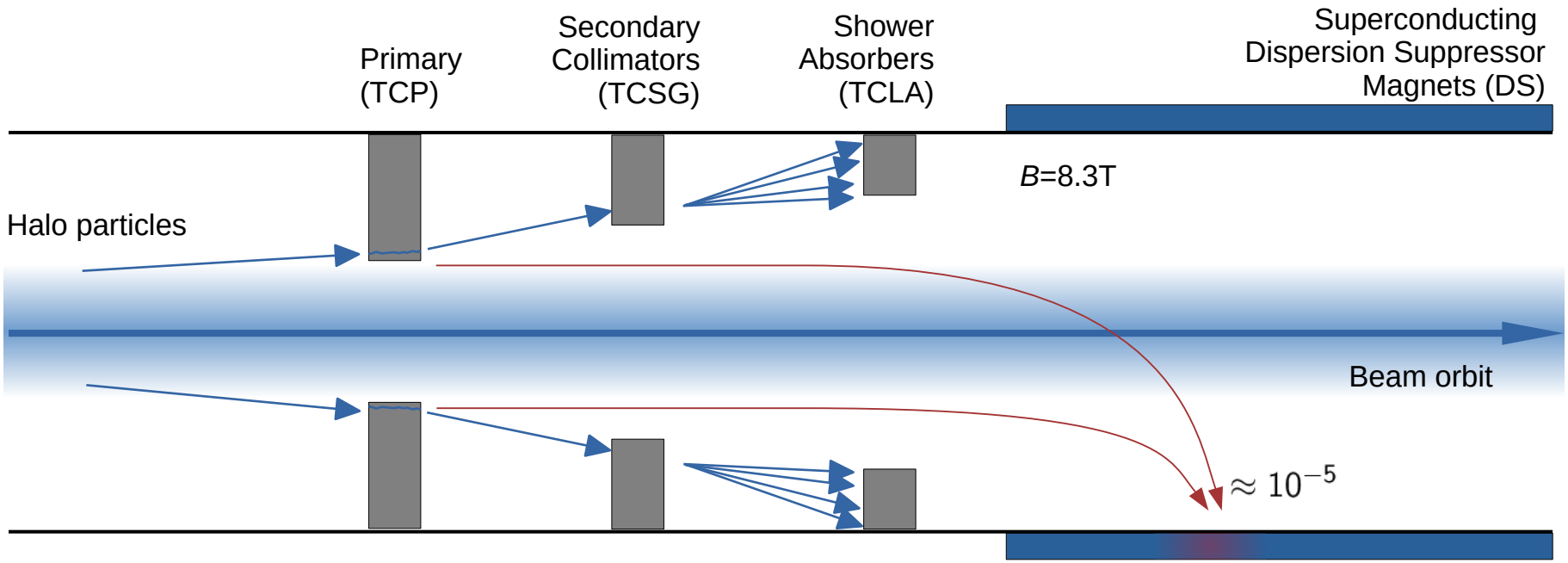


Betatron vs. Momentum Collimation

$$x(s) = \sqrt{2\,J\,\beta(s)}\,\cos(\phi(s) + \phi_0) + D_x(s)\,\frac{\Delta p}{p}$$



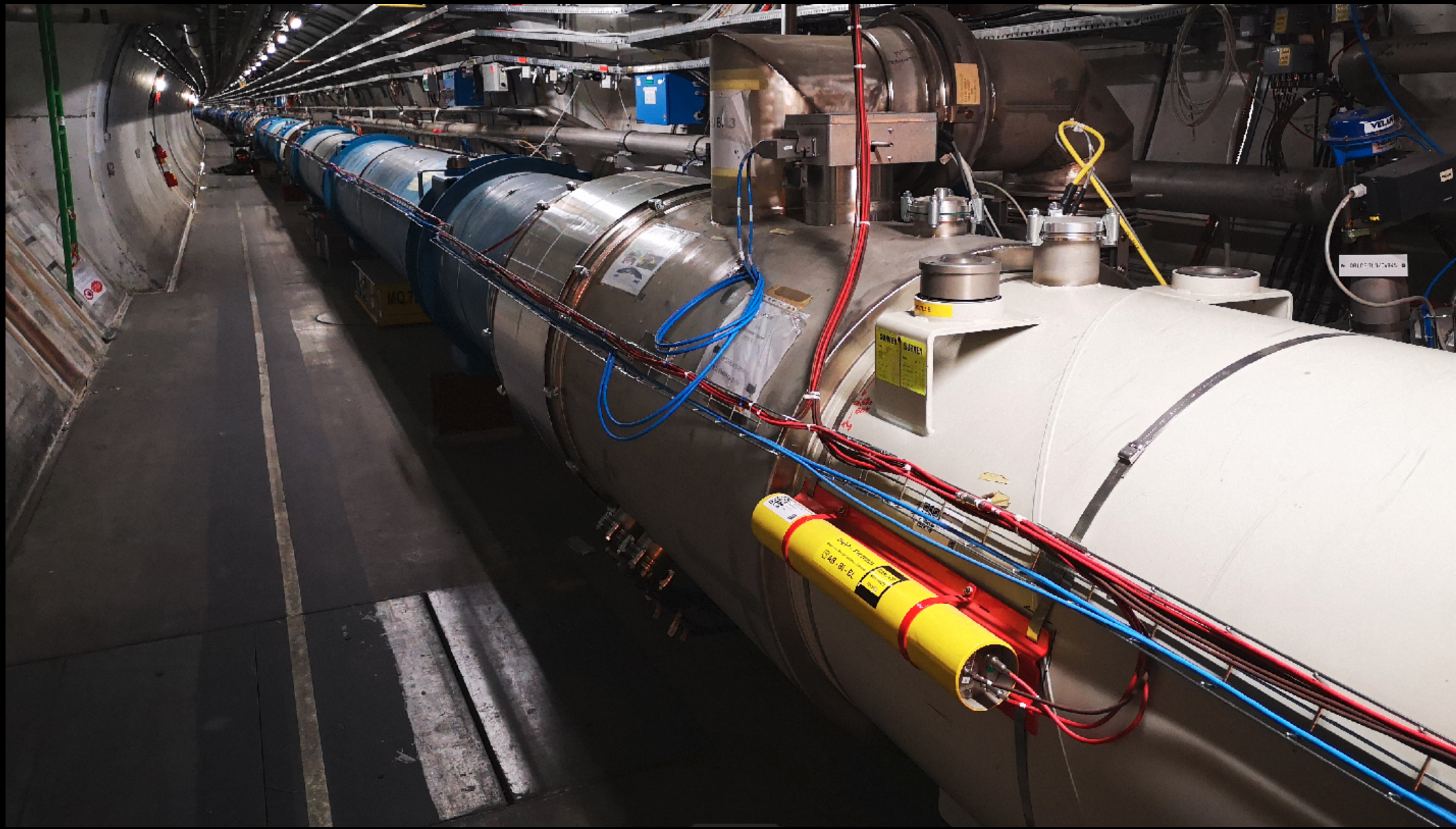
Collimation system in IR3/IR7



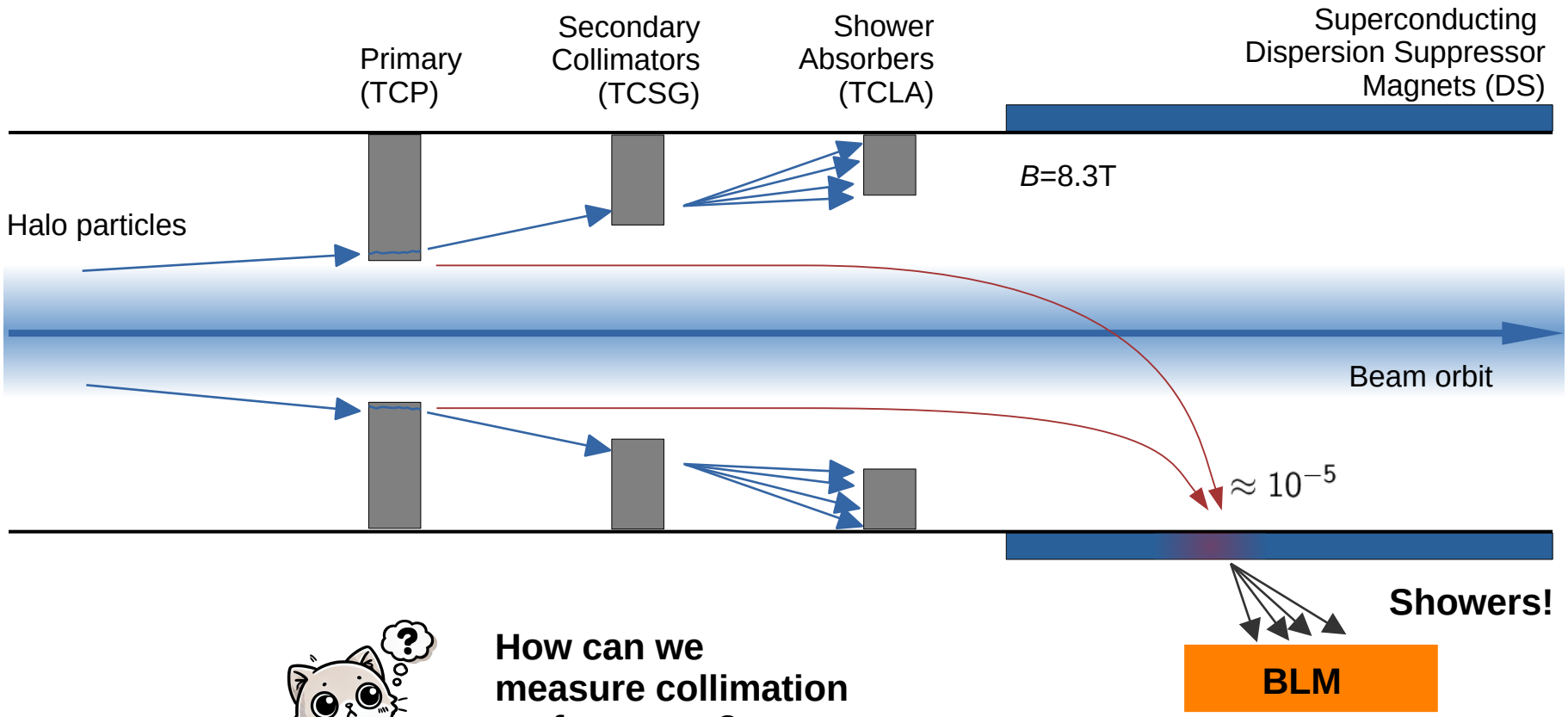
How can we measure collimation performance?

Beam Loss Monitors


G-1x2000mm² Cu-Max W.P. 16 bar - Isolation Level 3kV - EPDM
H-FLOHE/EB024325-06/13

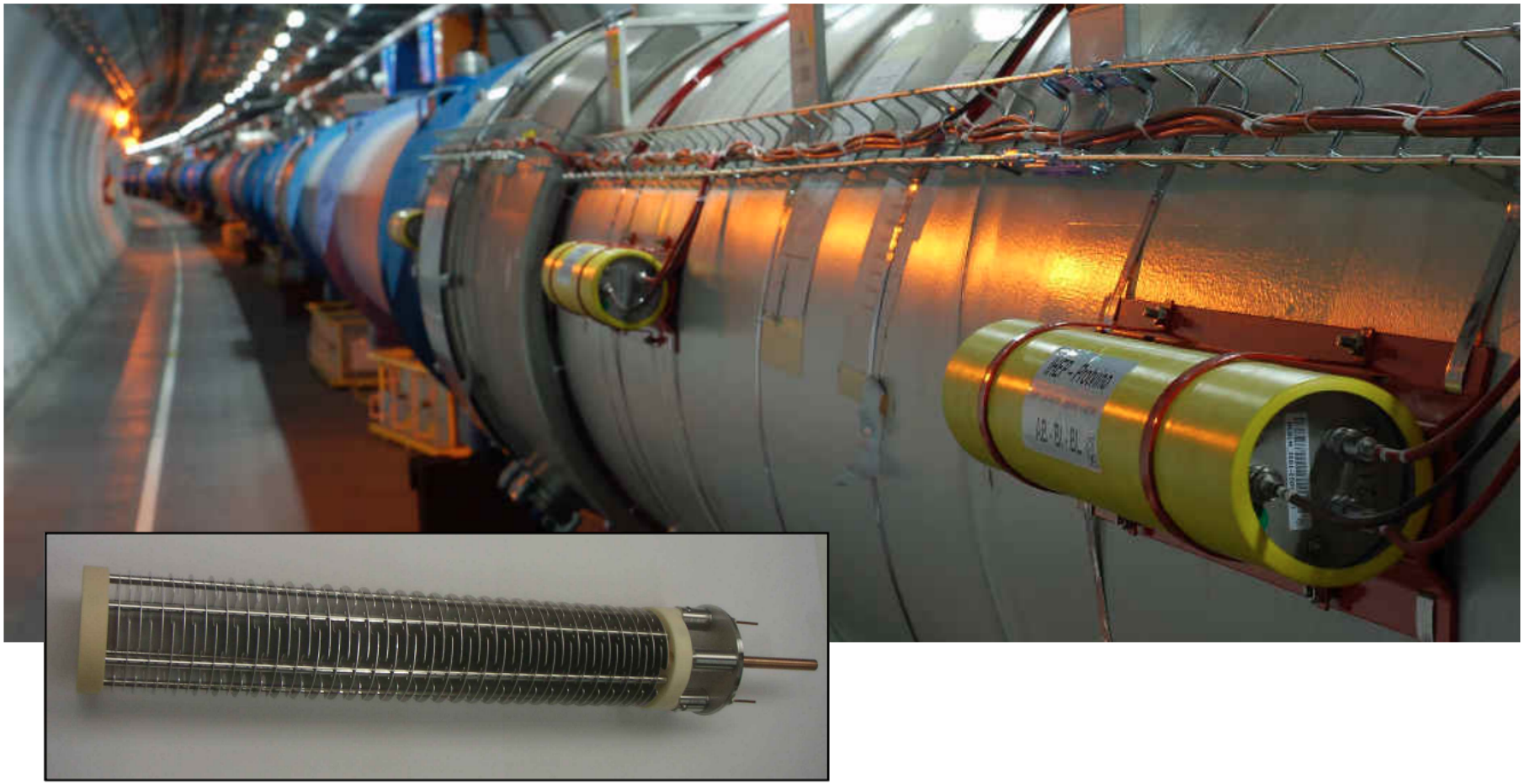


Collimation system in IR3/IR7

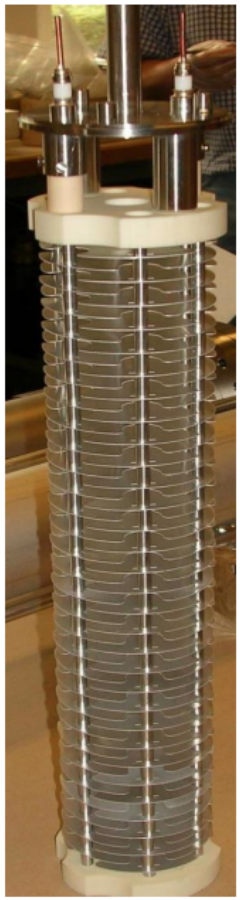


How can we measure collimation performance?

BLM Functionality



LHC BLM System



- Stainless steal cylinder
- Parallel Al electrodes distance 0.5 cm
- Diameter 8.9 cm, Length 60 cm
- Sensitive volume 1.5 l
- Voltage 1.5 kV
- Low pass filter at the HV input
- Ion collection time 85 us
- N2 gas filling at 1.1 bar

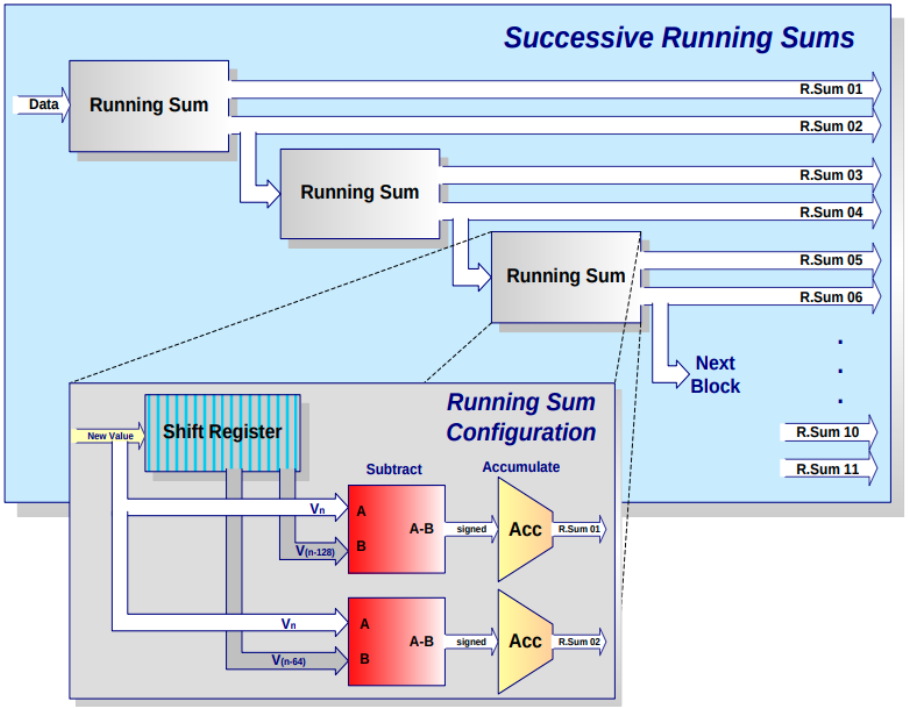
Courtesy of C. Zamantzas

LHC BLM System

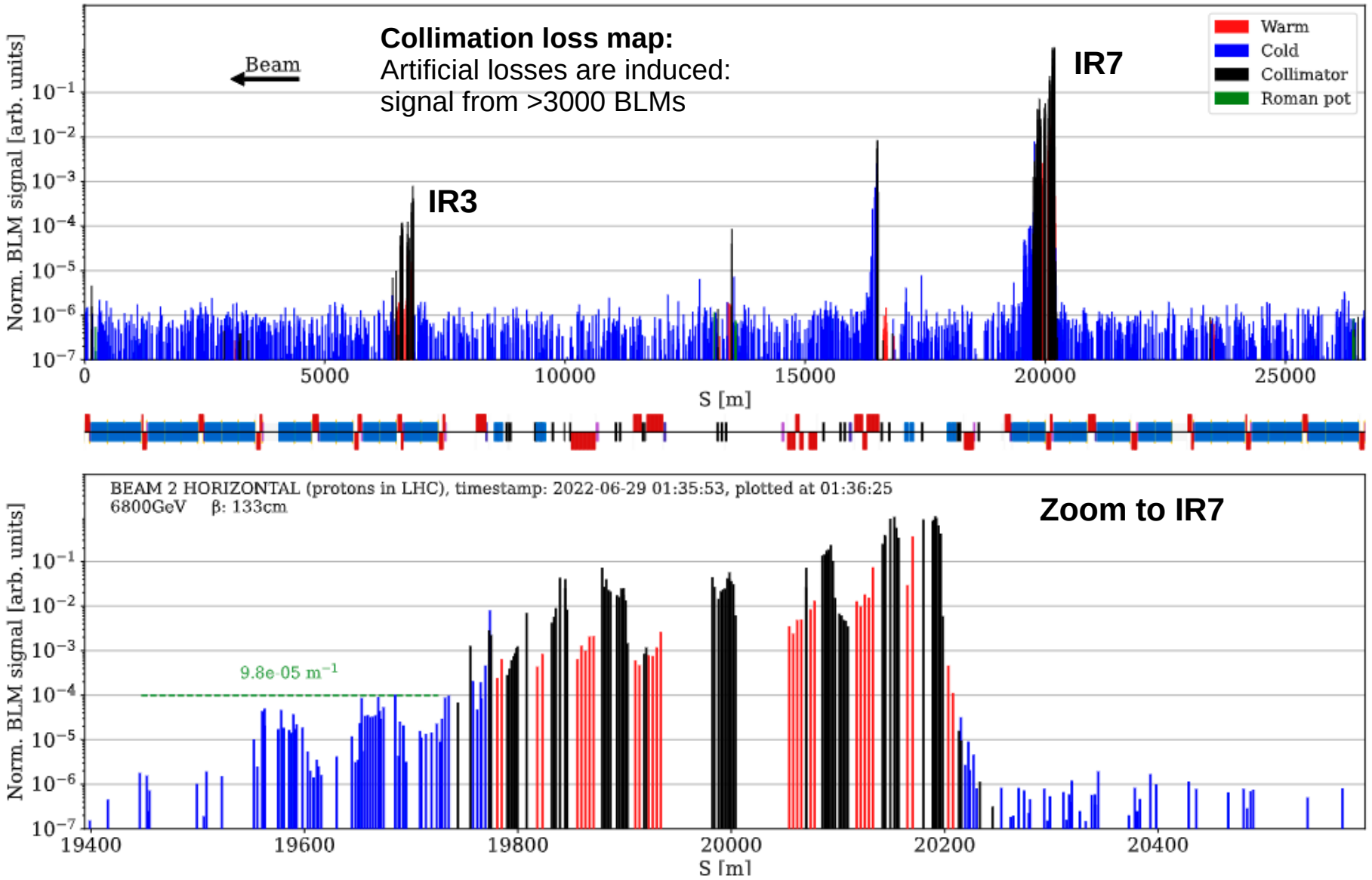
Constantly compared to pre-defined thresholds → beam dump if too high!

Successive Running Sums configuration

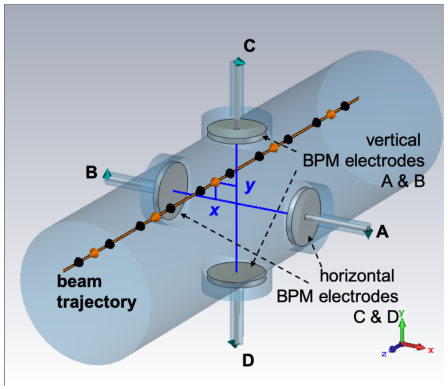
Running Sums		Refreshing		Shift Register Name	Signal Name	bits used
40 µs steps	ms	40 µs steps	ms			
1	0.04	1	0.04	SR0	RS 01	20
2	0.08	1	0.04		RS 02	22
8	0.32	1	0.04	SR1	RS 03	22
16	0.64	1	0.04		RS 04	22
64	2.56	2	0.08	SR2	RS 05	26
256	10.24	2	0.08		RS 06	26
2048	81.92	64	2.56	SR3	RS 07	32
16384	655.36	64	2.56		RS 08	32
32768	1310.72	2048	81.92	SR4	RS 09	36
131072	5242.88	2048	81.92		RS 10	36
524288	20971.5	16384	655.36	SR5	RS 11	40
2097152	83886.1	16384	655.36		RS 12	40



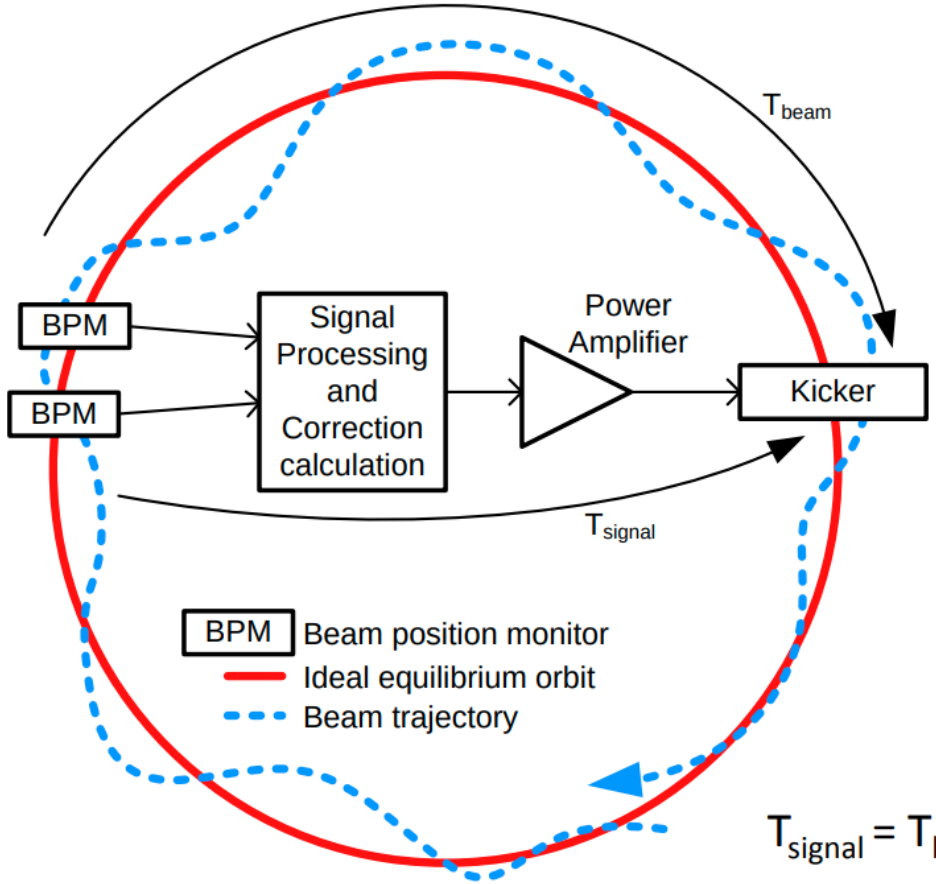
Courtesy of C. Zamantzas


Collimation loss map:
Artificial losses are induced:
signal from >3000 BLMs
Beam
IR3
IR7
Warm
Cold
Collimator
Roman pot
Norm. BLM signal [arb. units]
S [m]
BEAM 2 HORIZONTAL (protons in LHC), timestamp: 2022-06-29 01:35:53, plotted at 01:36:25
6800GeV β: 133cm
Zoom to IR7
9.8e-05 m⁻¹

Transverse damper (ADT)



Beam Position Monitor (BPM)



$$T_{signal} = T_{beam} + n\,T_{rev}$$

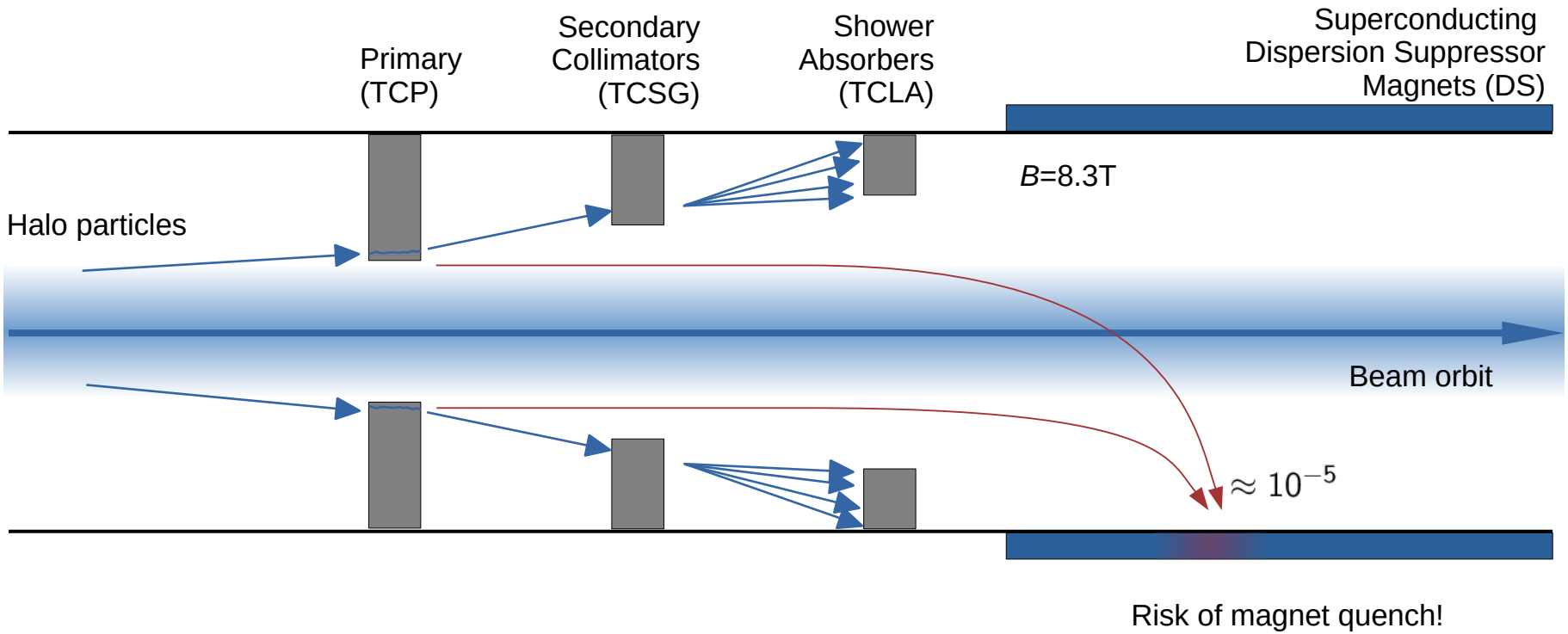
ADT:

- Electric kicker
- Normally used for orbit stability
- Can be used to induce random noise
- Induce artificial losses

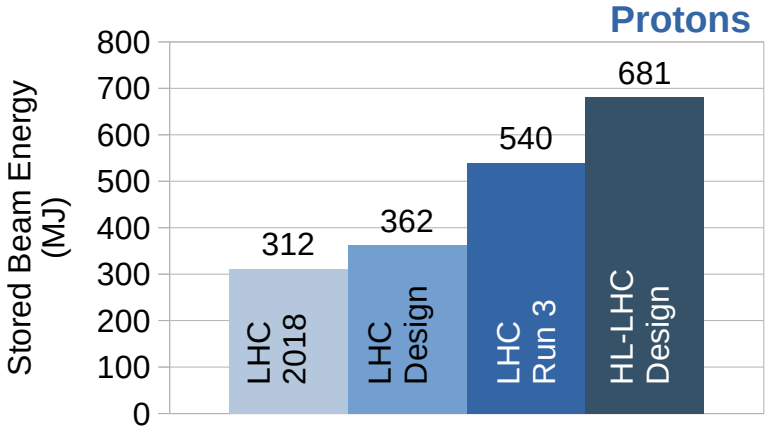
W. Hofle, Transverse Feedback in the HL -LHC Era

Wendt, BPM Systems: A brief Introduction to Beam Position Monitoring, CAS, (2020)

Beam Position Monitors



Beam losses in LHC and HL-LHC



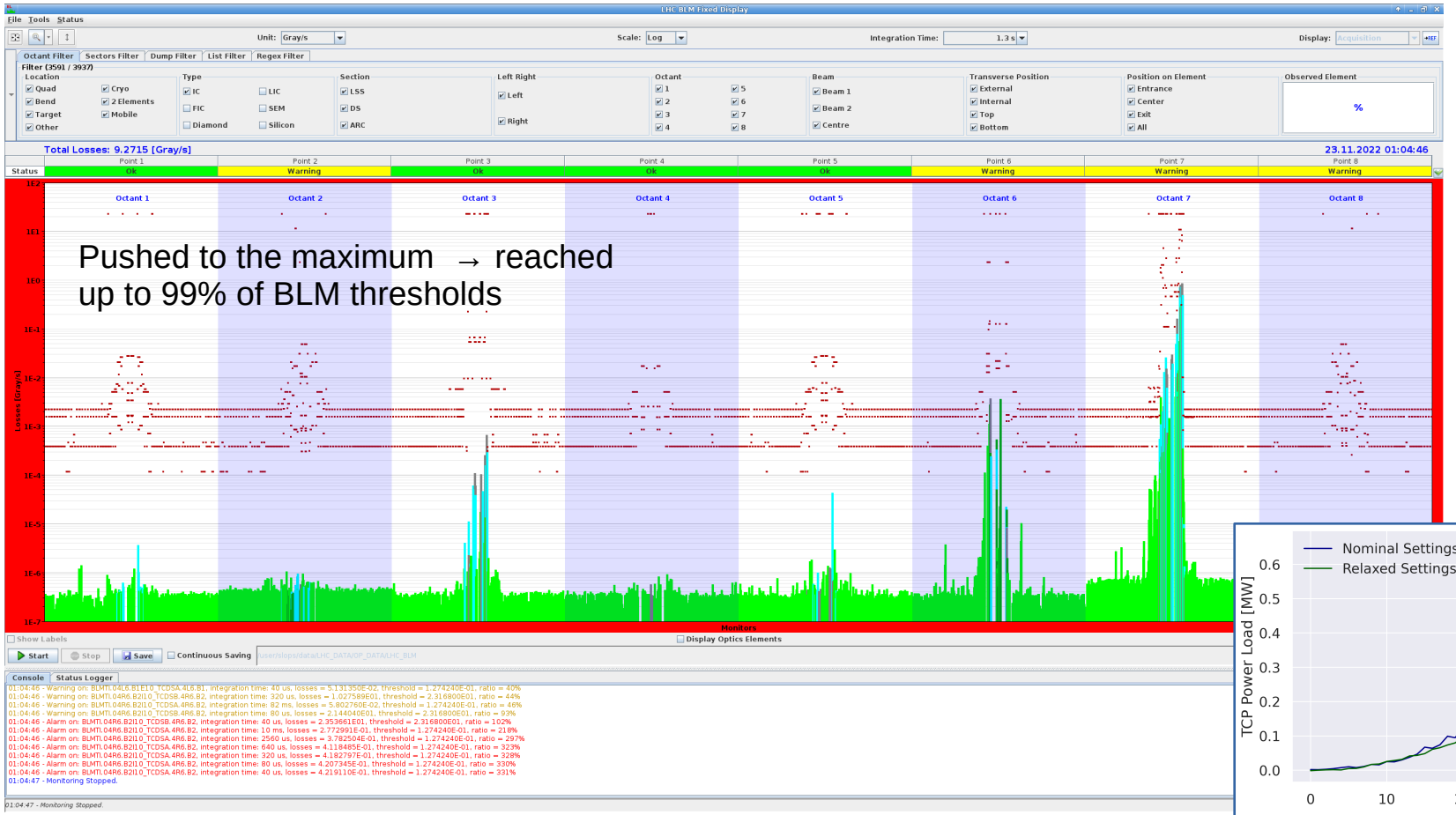
Can we reach such high loss rates without inducing a magnet quench?

Machine	Duration (s)	Min. beam lifetime (s)	Stored beam energy (MJ)	Beam loss power (kW)
LHC	10	720	362	**503**
HL-LHC	10	720	681	**946**

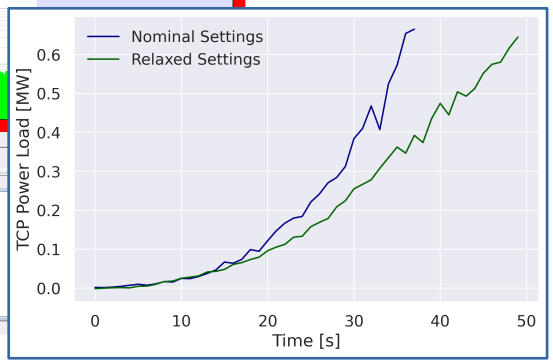
$$N(t) = N_0 \exp\left(-\frac{t}{\tau}\right)$$

Beam intensity evolution

Quench Test 2022



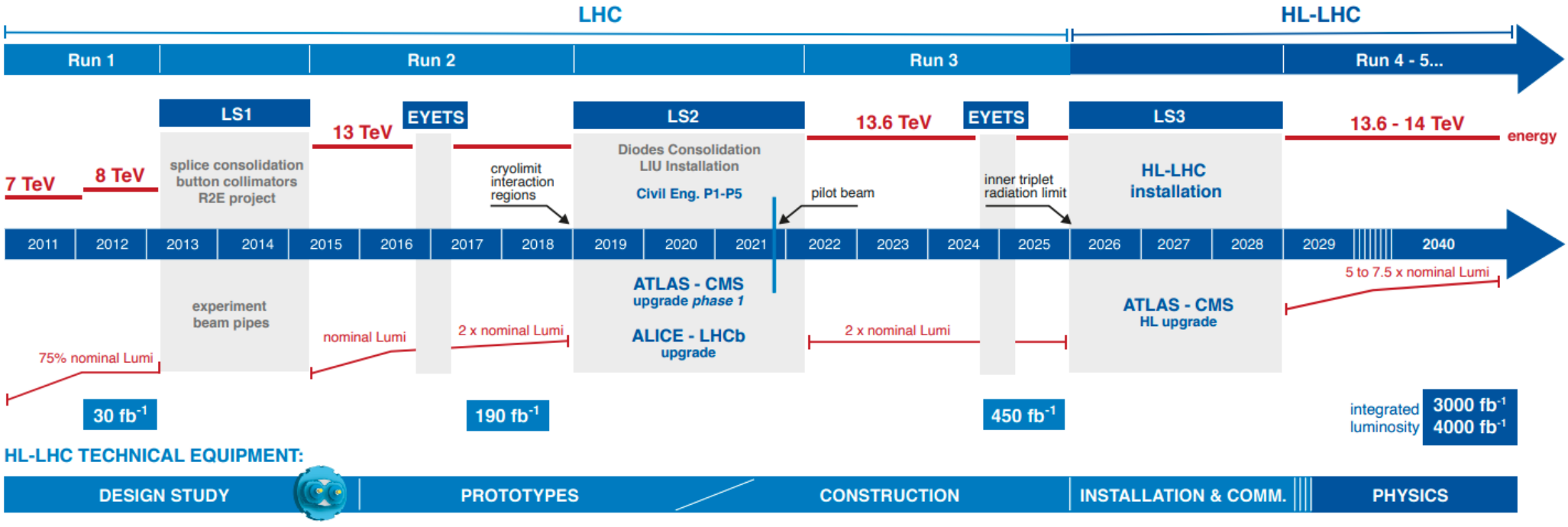
No quench!



Quench Test 2022

What’s next for the LHC?

LHC / HL-LHC Plan



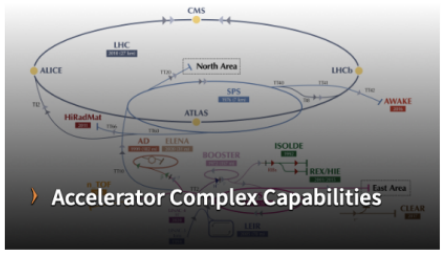
Goal: increase instantaneous luminosities a factor of 5 to 7.5

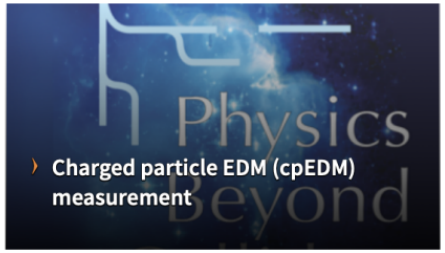
Physics Beyond Colliders (PBC)

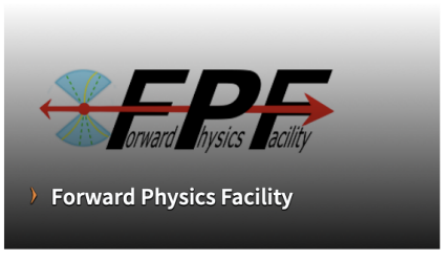
Accelerators & Technology Domain

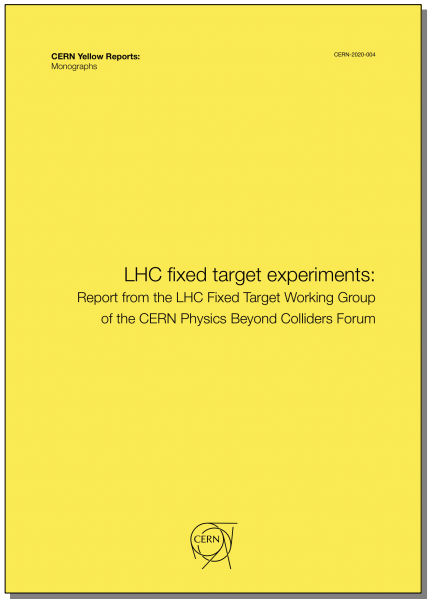
The Working Groups in the Accelerators & Technology Domain are coordinated through the PBC Accelerators & Technology Committee, a steering committee which meets around once per month. The steering committee includes the CERN conveners of the various Working Group in the Accelerators & Technology Domain. The Working Group's core members include accelerator experts and representatives of the projects. Requests from the Working Groups (tests, prototypes, manpower) are discussed by the steering committee.

ACCELERATORS & TECHNOLOGY WORKING GROUPS







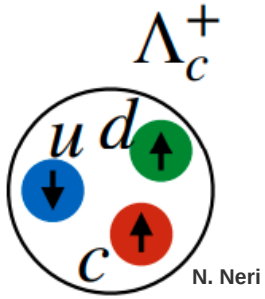


CERN Yellow Report
CERN-2020-004

LHC FT WG Updated Mandate (2021)

"the [FT] WG will continue investigating FT proposals and conduct the relevant R&D to provide, as much as possible, the necessary support towards the evaluation of their technical feasibility."

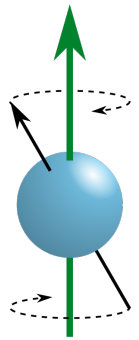
Charmed Baryon EDM/MDM



$\tau \sim 10^{-13}$s

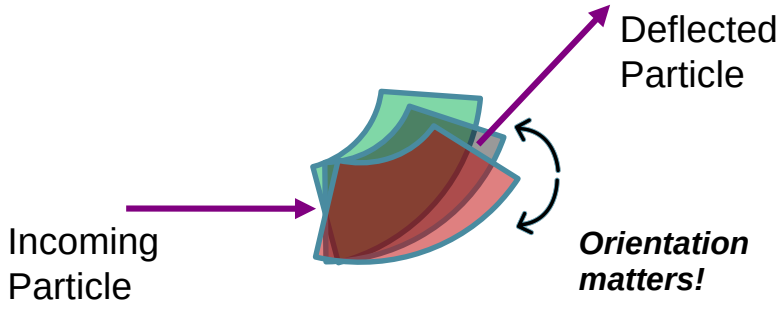
Electric and Magnetic Dipole Moments (EDM/MDM) of interest for particle physics!

But **how can we measure spin precession** with such short lifetimes?

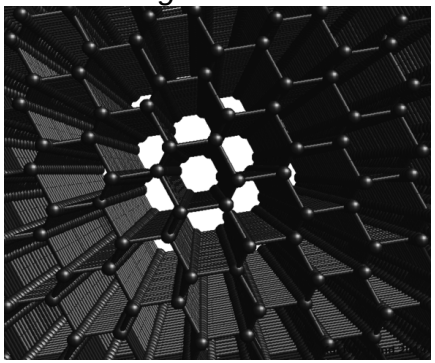


Deflection in bent crystals

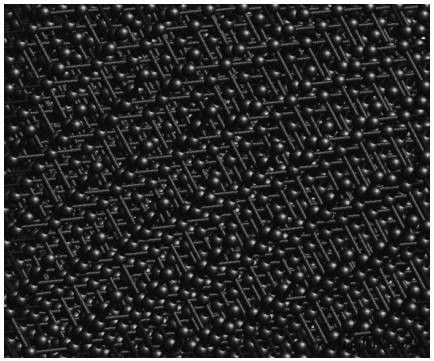
Particle channelling induces deflection



Channelling orientation

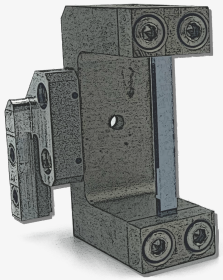


Random orientation



Knordlun, CC BY-SA 3.0 via Wikimedia Commons

Bent Silicon crystal for LHC Collimation

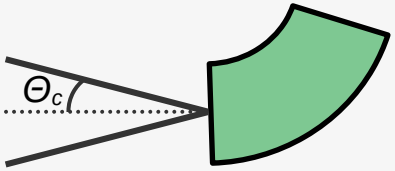


50µrad / 4mm

Equivalent deflection to ~300Tm magnet!

A. Mazzolari

Critical angle Θ_c

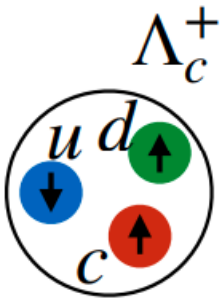


Angular Acceptance

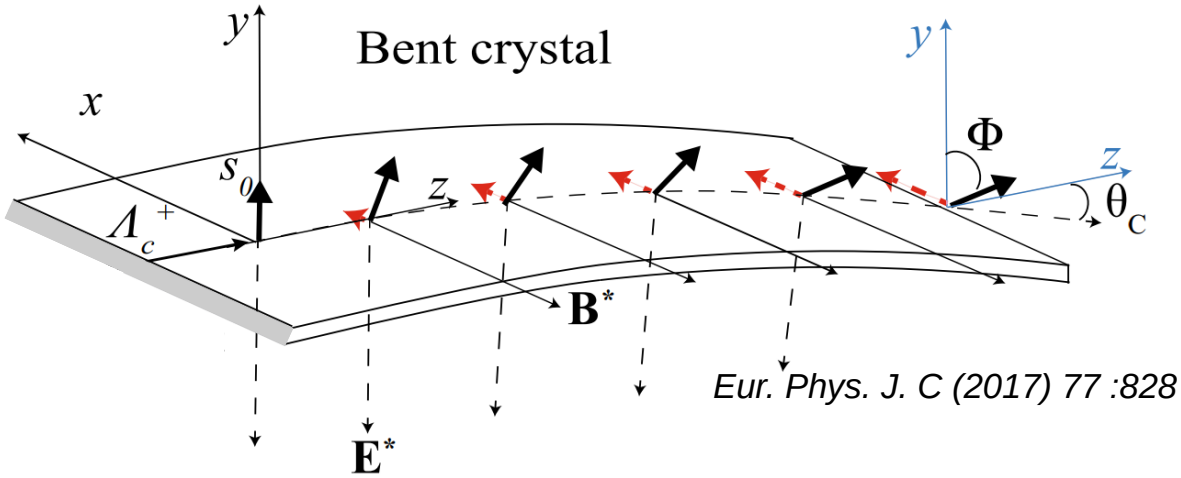
Energy [GeV]	Crit. Angle [µrad]
180	18
450	9.4
7000	2.4

Silicon

Charmed Baryon EDM/MDM



$\tau \sim 10^{-13}$s



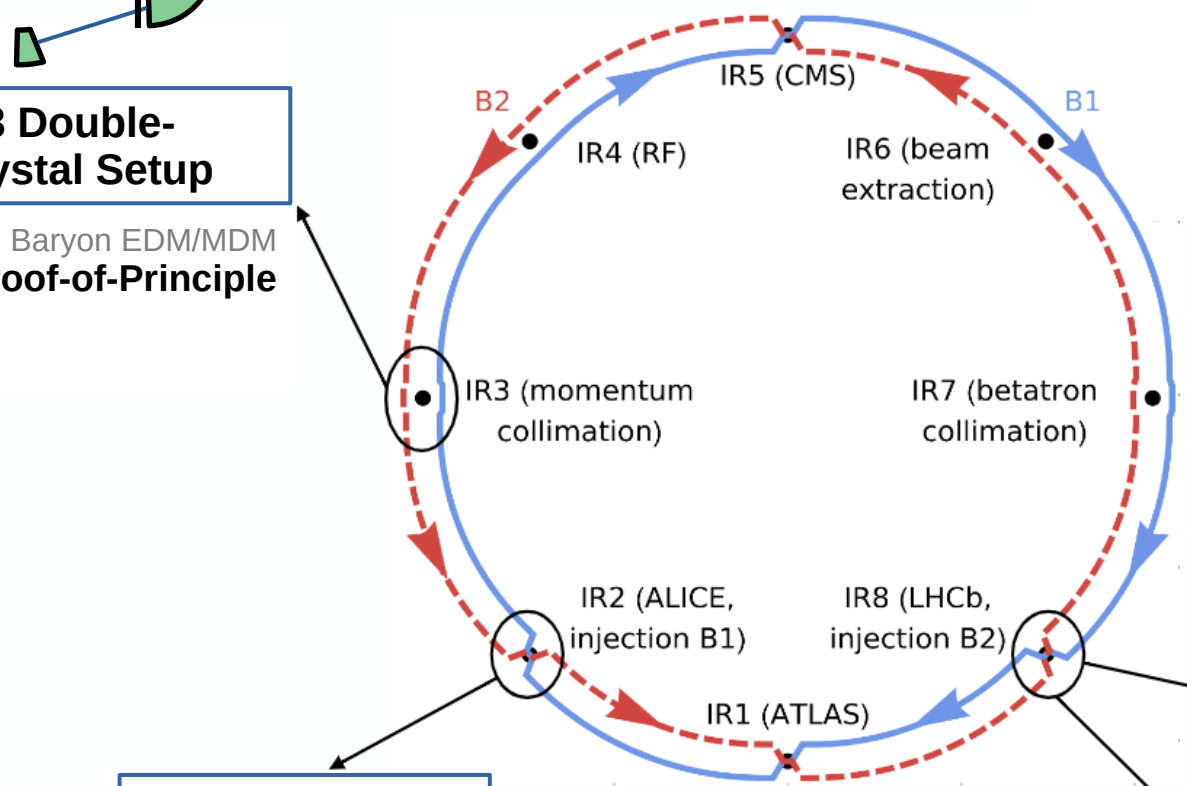
Eur. Phys. J. C (2017) 77 :828

Crystals can deflect & induce spin precession

E-field between atomic planes ~1GV/cm , effective magnetic field ~500T

Λ_c^+ EDM and MDM becomes visible!

Physics Beyond Colliders – LHC Fixed Target Studies



IR3 Double-Crystal Setup

Charmed Baryon EDM/MDM
Pending Proof-of-Principle

*After **2016***
PBC kick-off

SMOG2

Gas Target

For high-x & intermediate Q^2 QCD exploration
Installed in LS2

Single Crystal Setup

Halted

IR8 Double-Crystal Setup

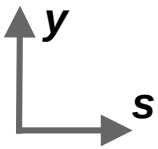
Charmed Baryon EDM/MDM
Pending Proof-of-Principle

S. Redaelli, PBC General WG, 02/12/2021

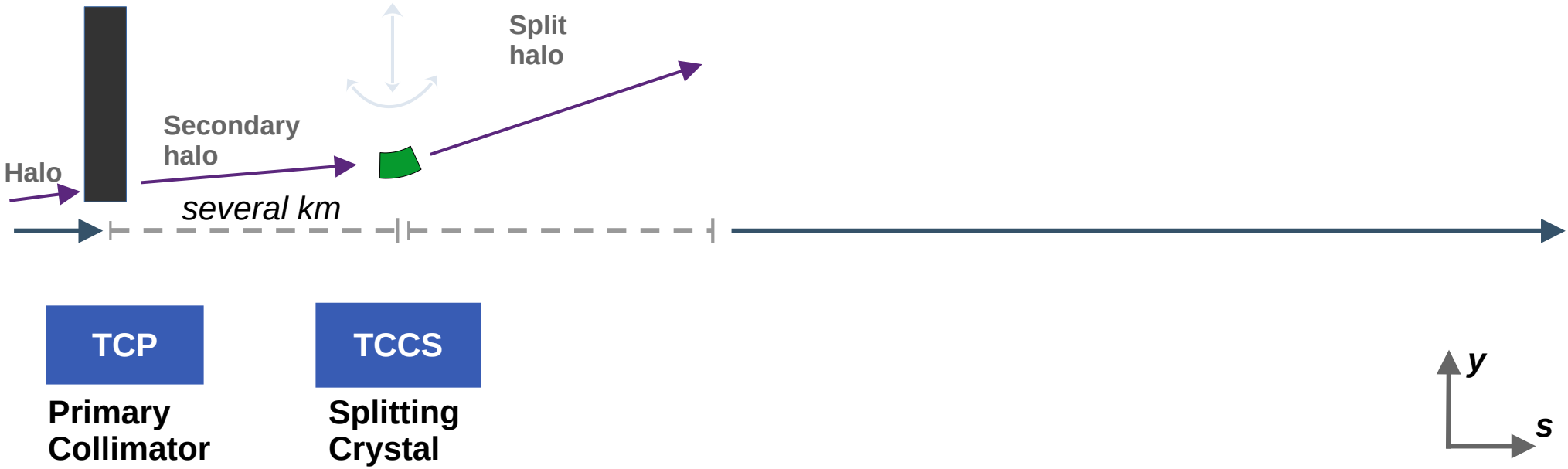
Double Crystal FT Experiment

TCP

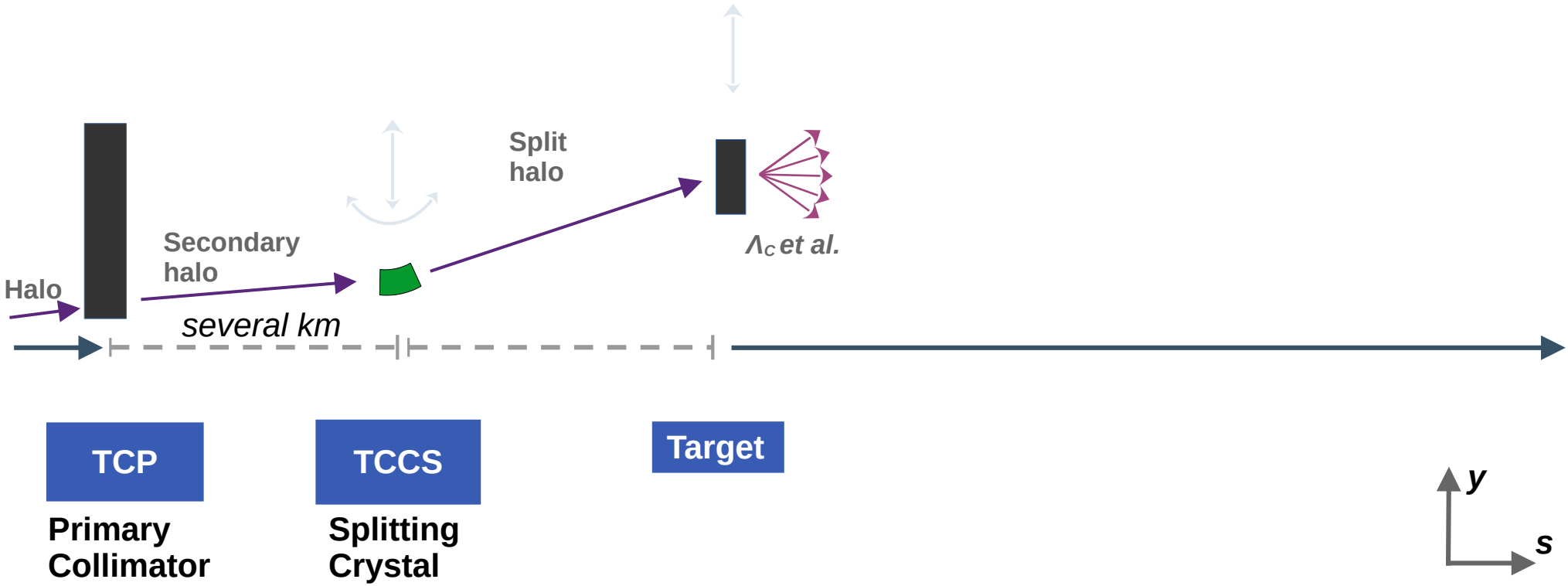
Primary Collimator



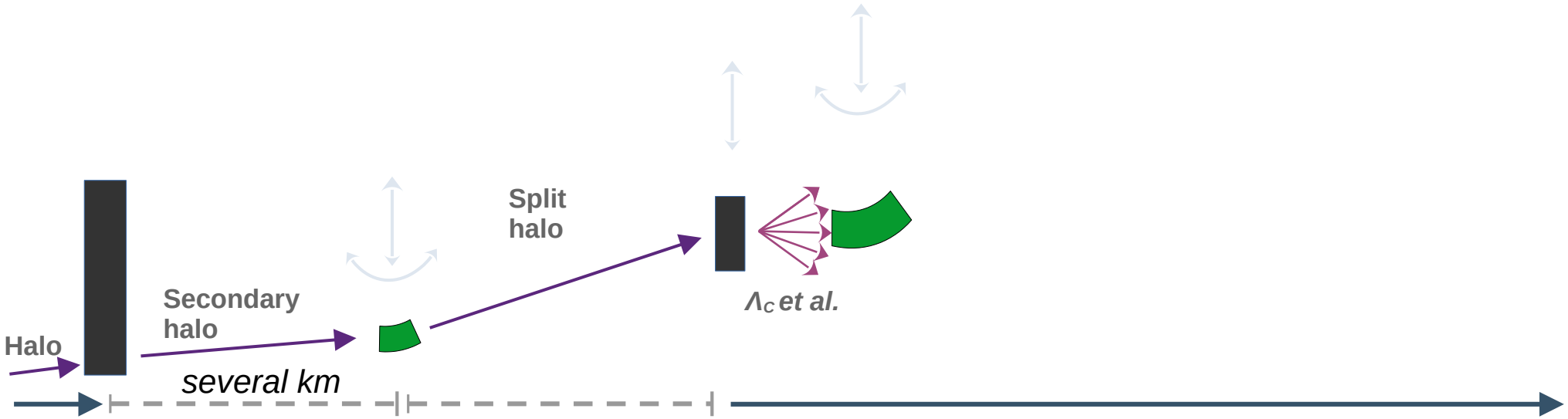
Double Crystal FT Experiment



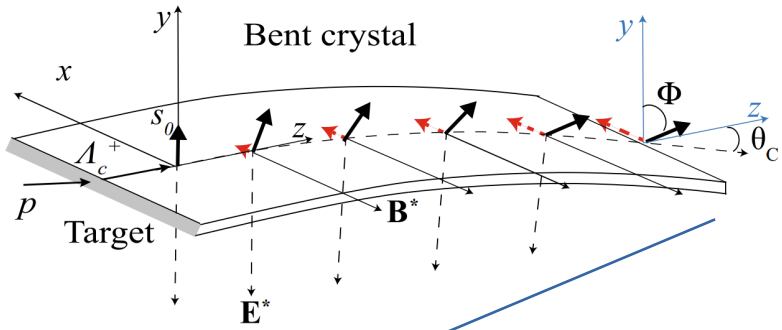
Double Crystal FT Experiment

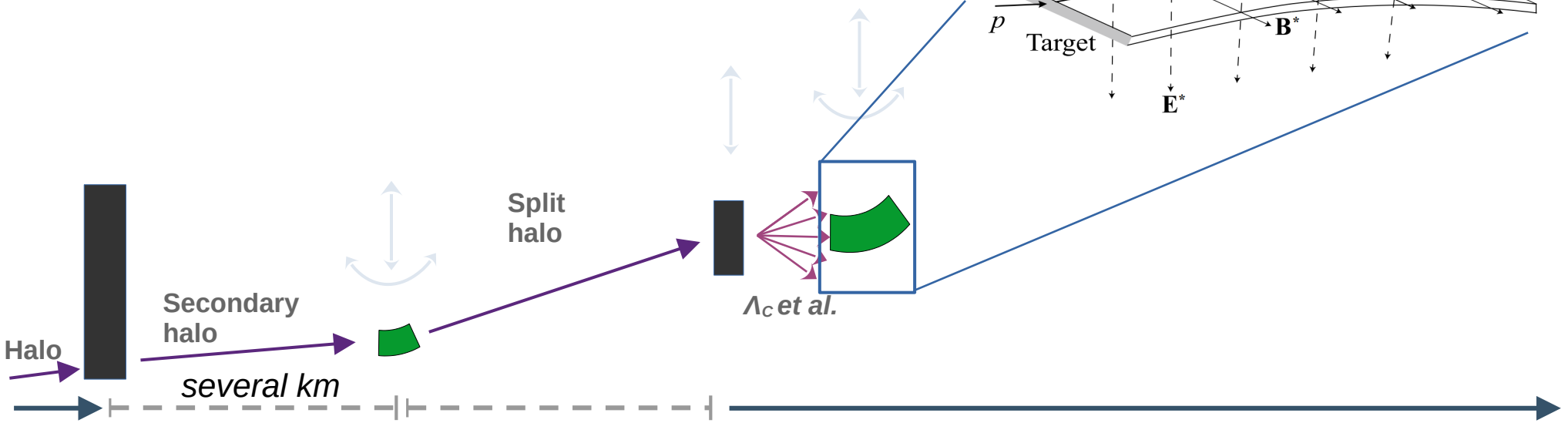


Double Crystal FT Experiment



Double Crystal FT Experiment



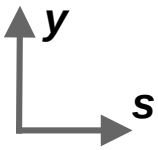


TCP — **Primary Collimator**

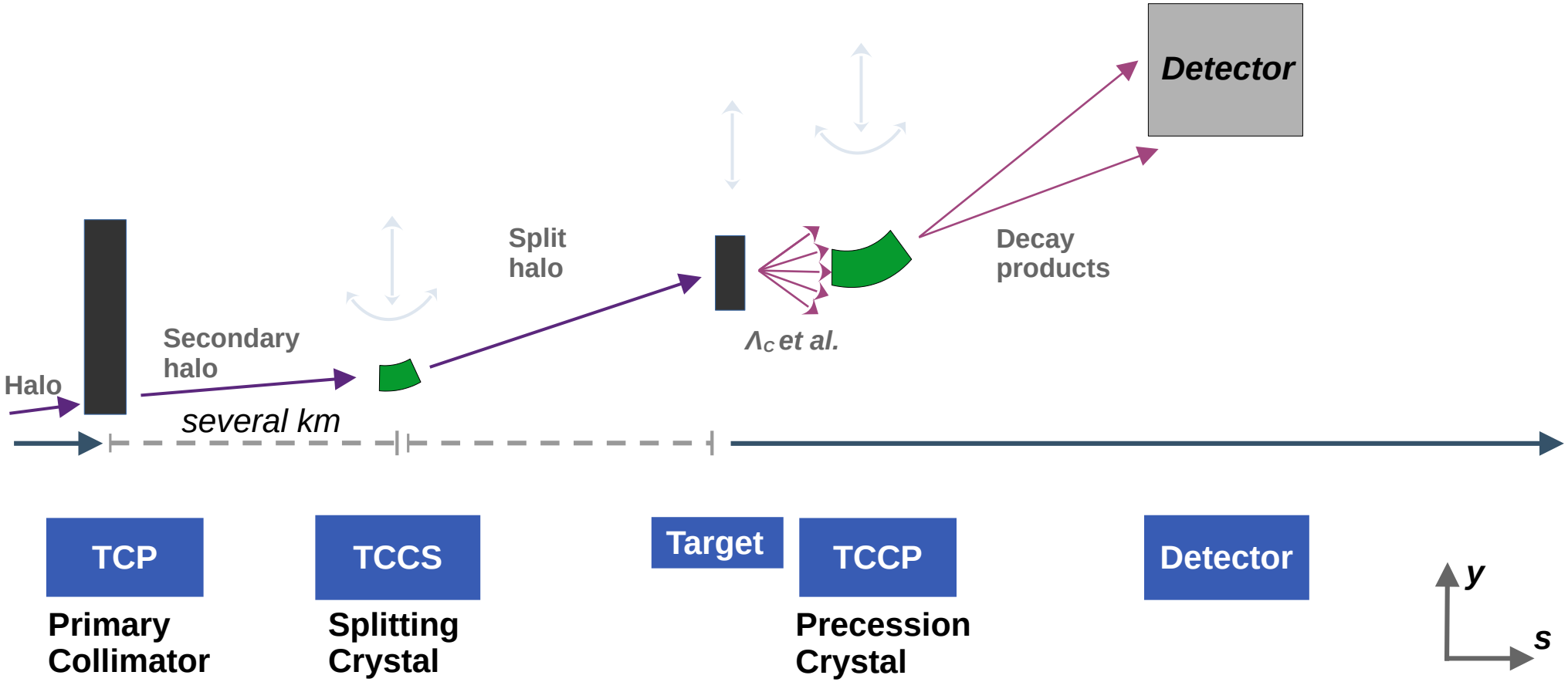
TCCS — **Splitting Crystal**

Target

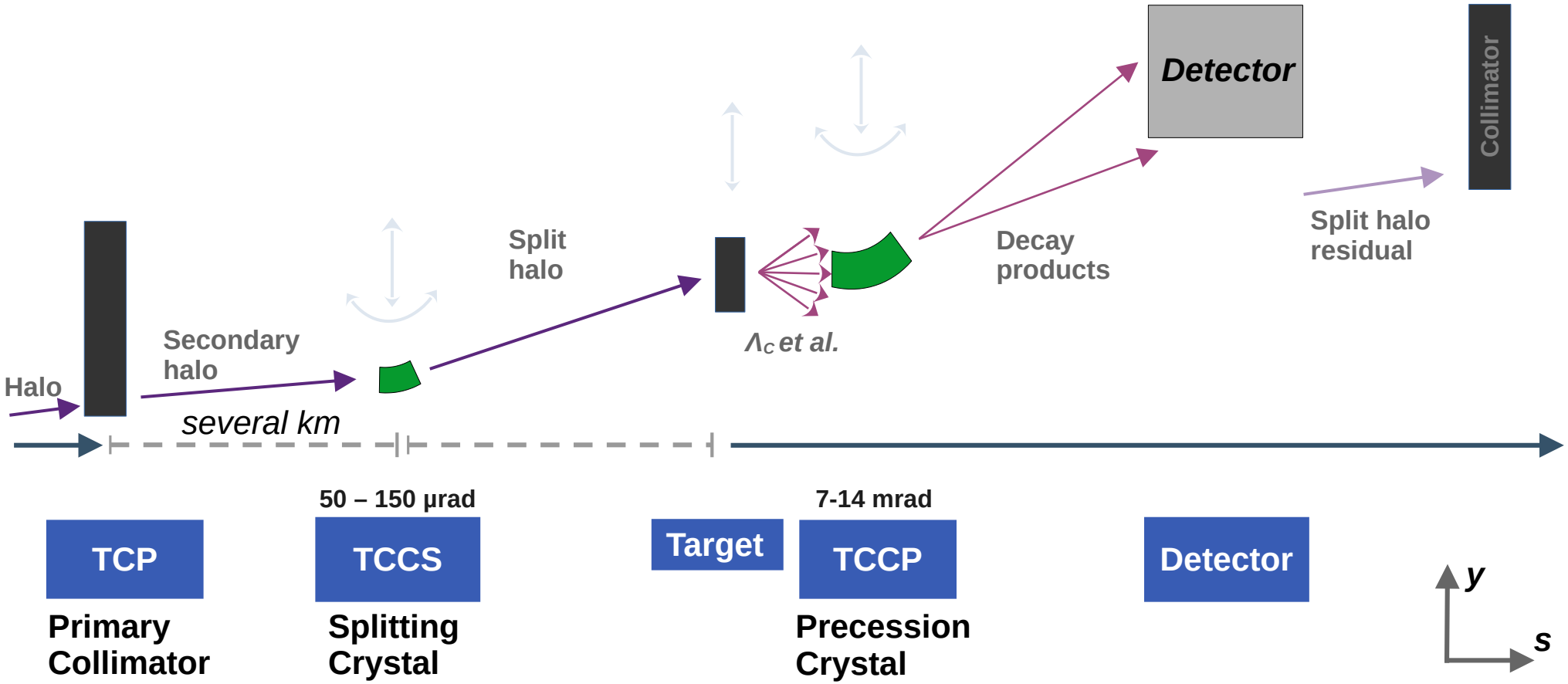
TCCP — **Precession Crystal**



Double Crystal FT Experiment



Double Crystal FT Experiment



2025 Proof of Principle - TWOCRYST

Validate crystal properties

Operational feasibility

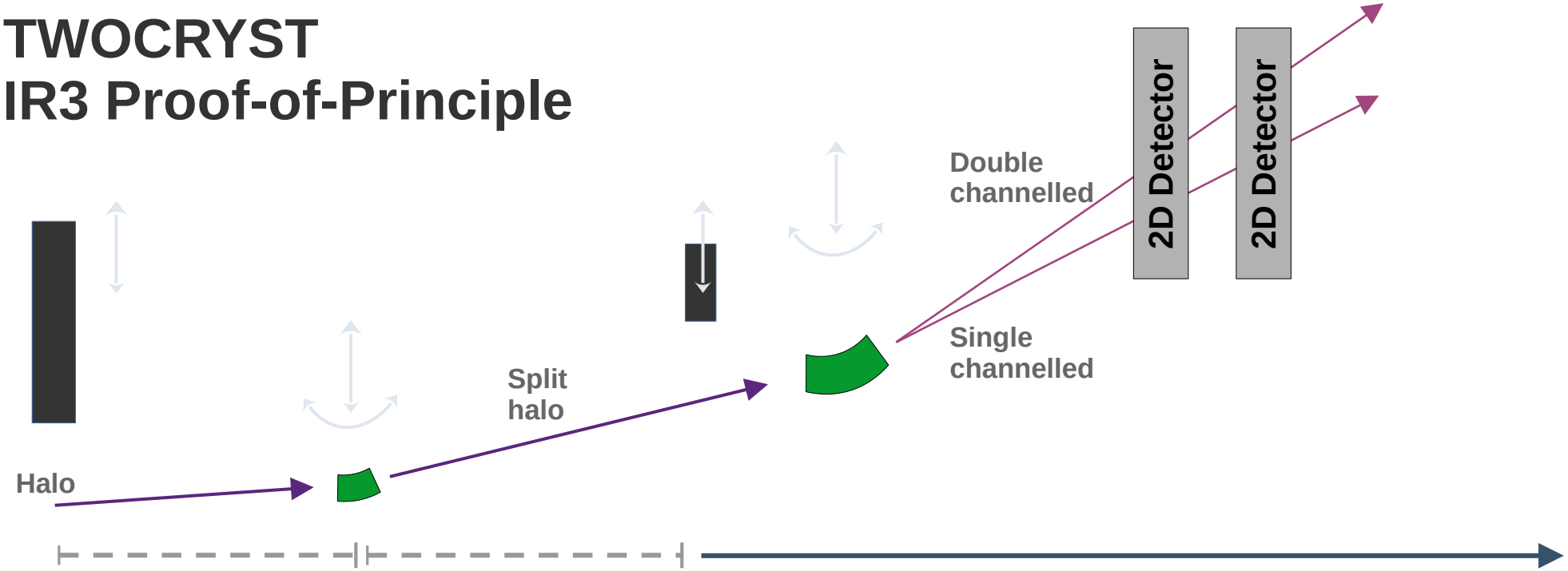
Performance estimates

Proof-of-principle test stand:
TWOCRYST

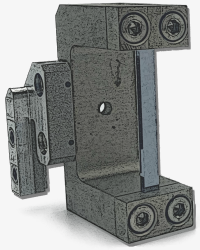
TWOCRYST input crucial for experiment proto-collaboration (LoI in preparation)

All goals must be achieved in 2025

TWOCRYST
IR3 Proof-of-Principle

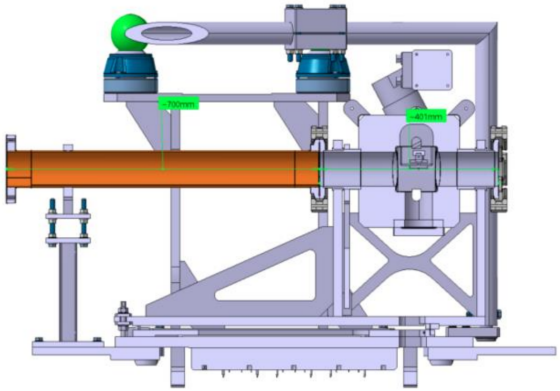


TCCS



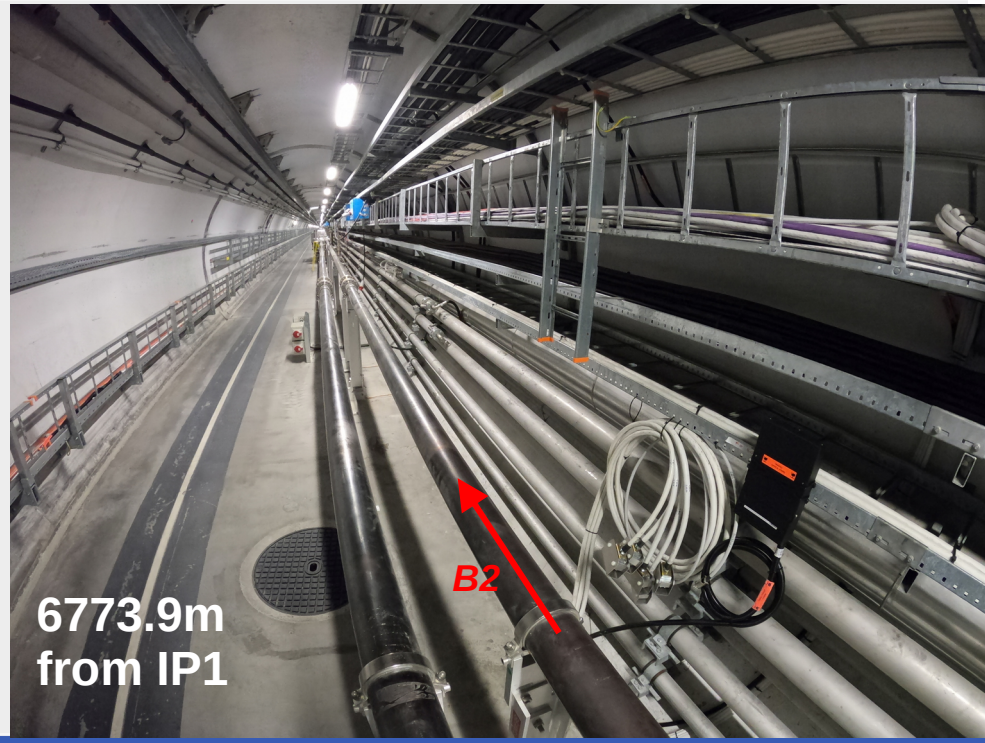
50µrad / 4mm

TCCS crystal for splitting of beam particles



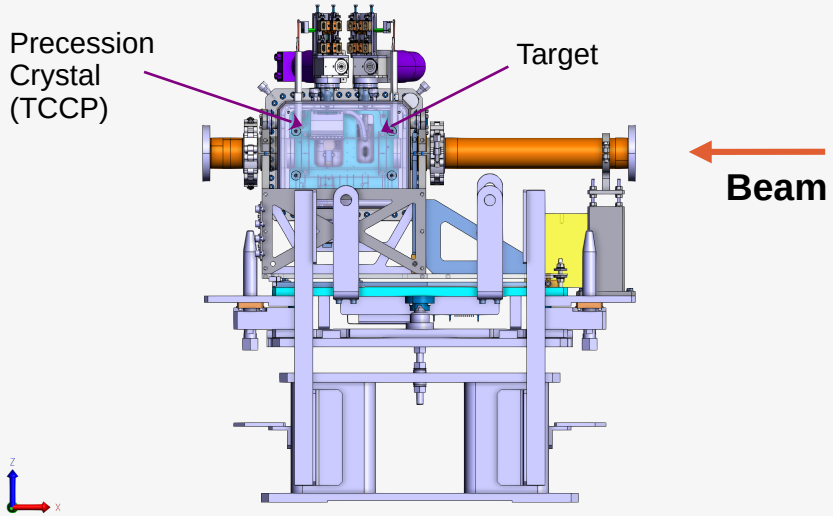
TCCS goniometer: recovered from LHC IR7

TCCS installation slot in IR3



TCPC - STI device in collaboration with CEM

Target - TCCP Assembly

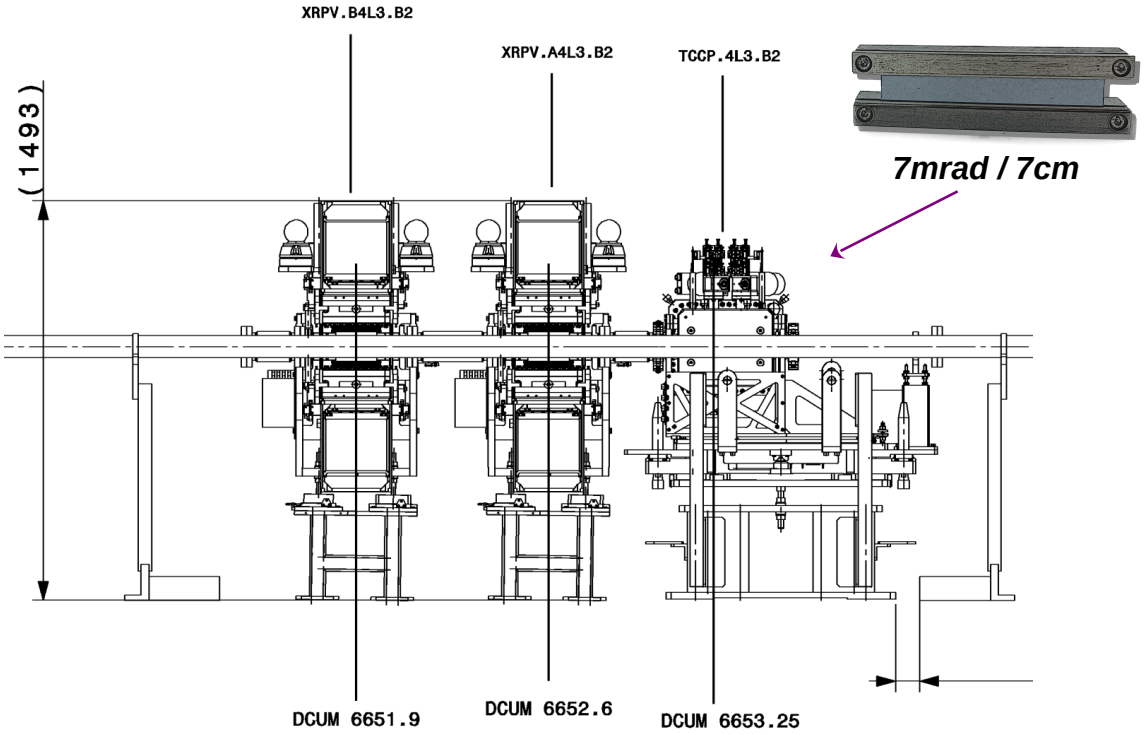


R. Seidenbinder

Assembly designed for TWOCRYST

Independent motion of target and TCCP crystal

Construction and validation within 2024



Roman Pot Stations

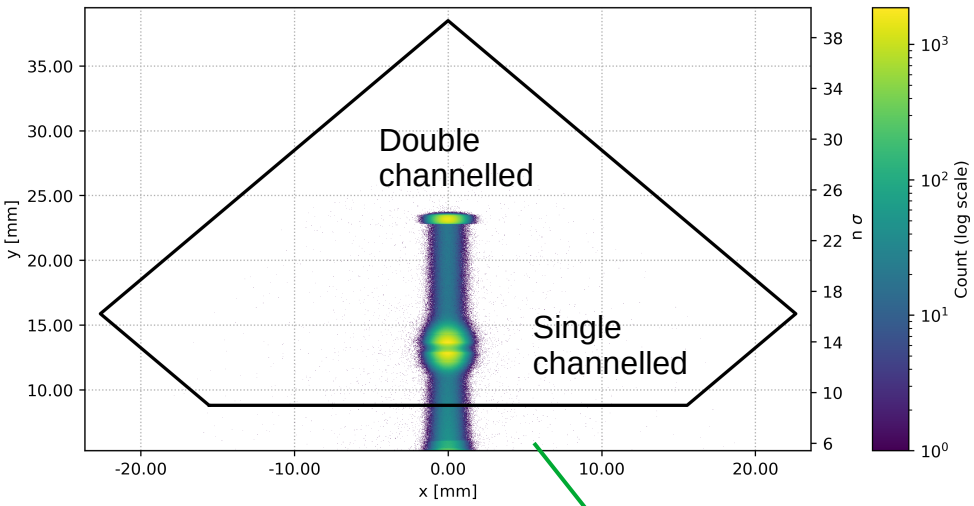
Removal of two ATLAS-ALFA stations after high-β run 2023

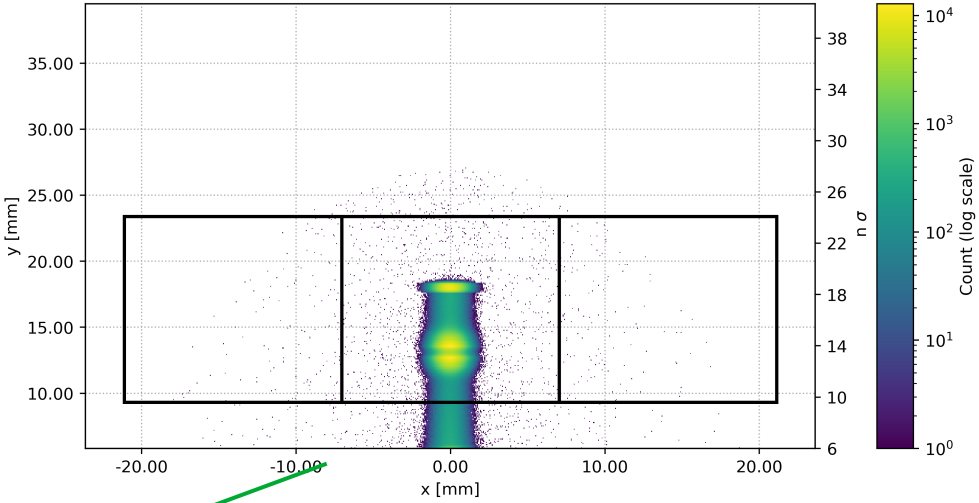
ALFA detectors removed

Station refurbishment ongoing

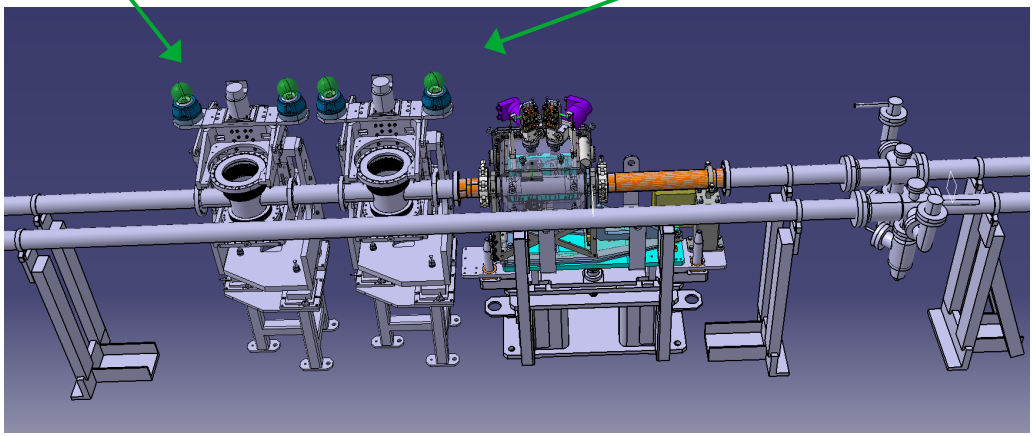
Photographs: Courtesy of S. Jakobsen

Measurement





TWOCRYST
fiber tracker



TWOCRYST
silicon pixel
detector

Summary

Summary

Betatron motion and function $u(z) = \sqrt{2\,J\,\beta(z)}\,\cos(\psi(z) + \psi_0)$

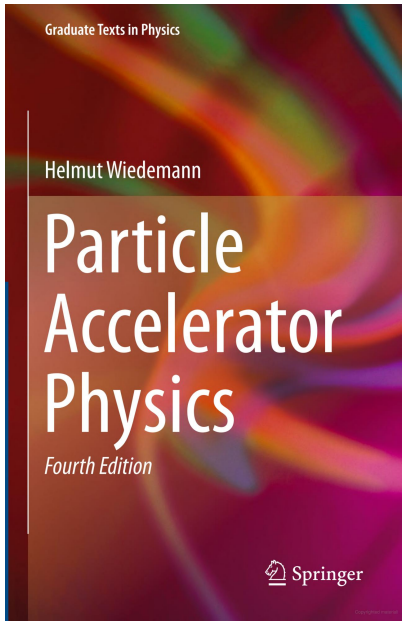
Emittance $\epsilon = \langle J \rangle$

Beam Size $\sigma = \sqrt{\epsilon\,\beta(z)}$

Normalized Emittance $\epsilon_N = \beta\,\gamma\,\epsilon$

Luminosity $\mathcal{L}_0 = f\,k_b\,\frac{N_1\,N_2}{4\,\pi\,\epsilon\,\beta^*}$

Literature



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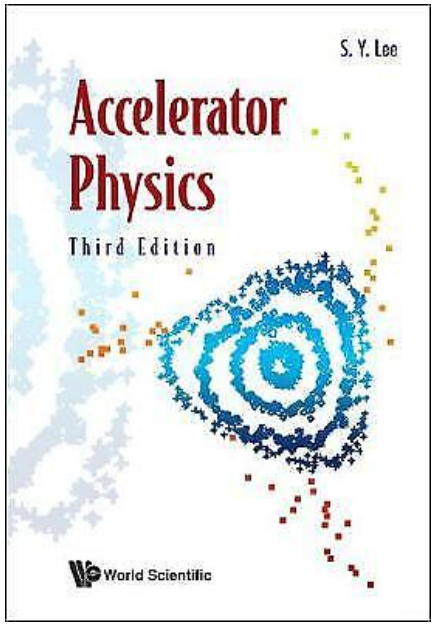
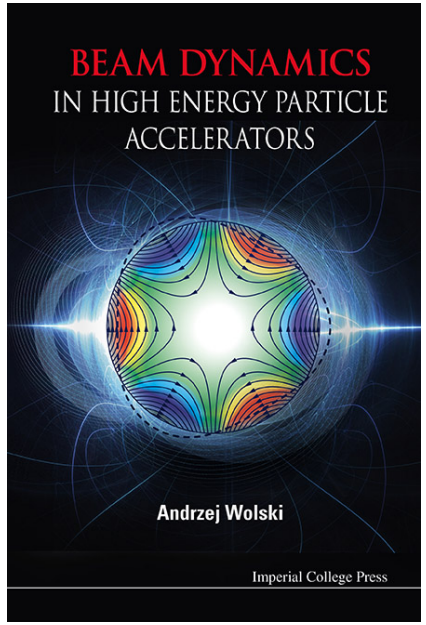
Free lecture material online





Acknowledgments

A big ❤️ to Joschua Dilly for the help in the preparation of these slides

Thanks to all the colleagues and LHC teams that prepared material shown here!

Feedback / questions:
pascal.hermes@cern.ch