Experiment specific configuration in TCC8/ECN3 – Status & outlook: BDF/SHiP

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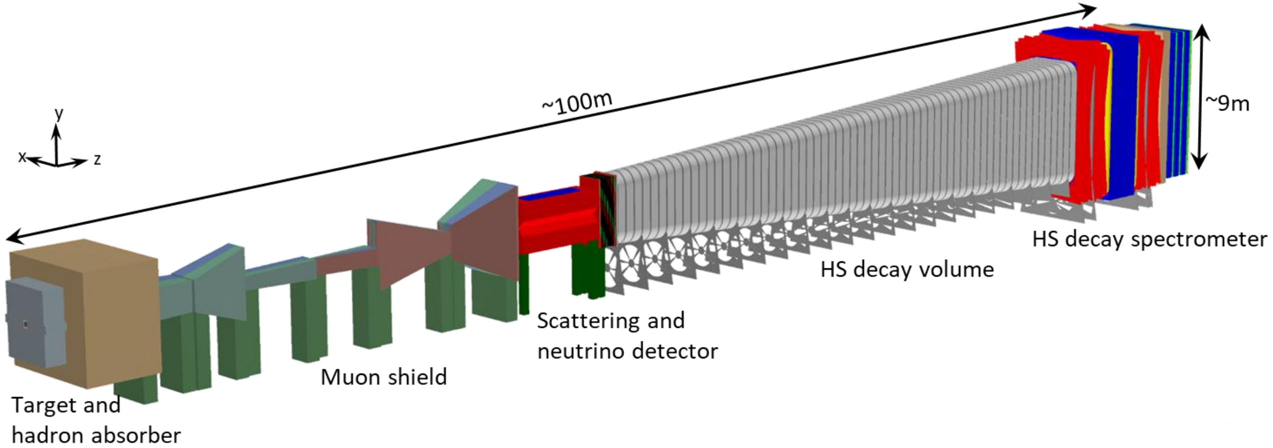
On behalf of the BDF Working Group supported by the SHiP collaboration, SPS Crystal Assisted Slow Extraction WG, SPS Loss and Activation WG, and UA9 collaboration

PBC Annual Workshop, 7-9 November 2022

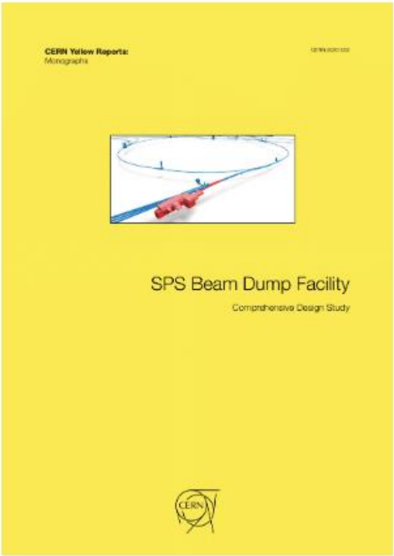
Introduction to BDF/SHiP

- The proposed Beam Dump Facility (BDF) is foreseen to be located at the SPS
- It allows to make use of the currently **unused** 4×10^{19} protons per year of the SPS and SPS' possibility of slow extraction with this very high energy and intensity
- The SPS and the new facility would offer unique possibilities to enter a **new era** of **exploration** at the **intensity frontier**
- BDF is designed and optimized for beam-dump physics to make major impact in the field
- BDF will be dedicated to the **Search for Hidden Particles** (SHiP) experiment
- The BDF study team submitted a CDS report in 2019 with an in-depth feasibility study



Key BDF beam parameters	
Momentum [GeV/c]	400
SPS beam Intensity per cycle	4×10^{13}
Cycle length [s]	7.2
Spill duration [s]	1
Avg. beam power on target [kW]	355
Protons on target (POT)/year	4×10^{19}
Total POT in 5 years data taking	2×10^{20}

CDS includes studies on beam delivery, target complex, experimental area, prototyping of key subsystems, radiological aspects, safety, integration and CE



Location and layout optimization study

ESPP 2020

Strong support for physics case, suitability of CERN injector complex, and community interest in medium term/size complementary scientific programme

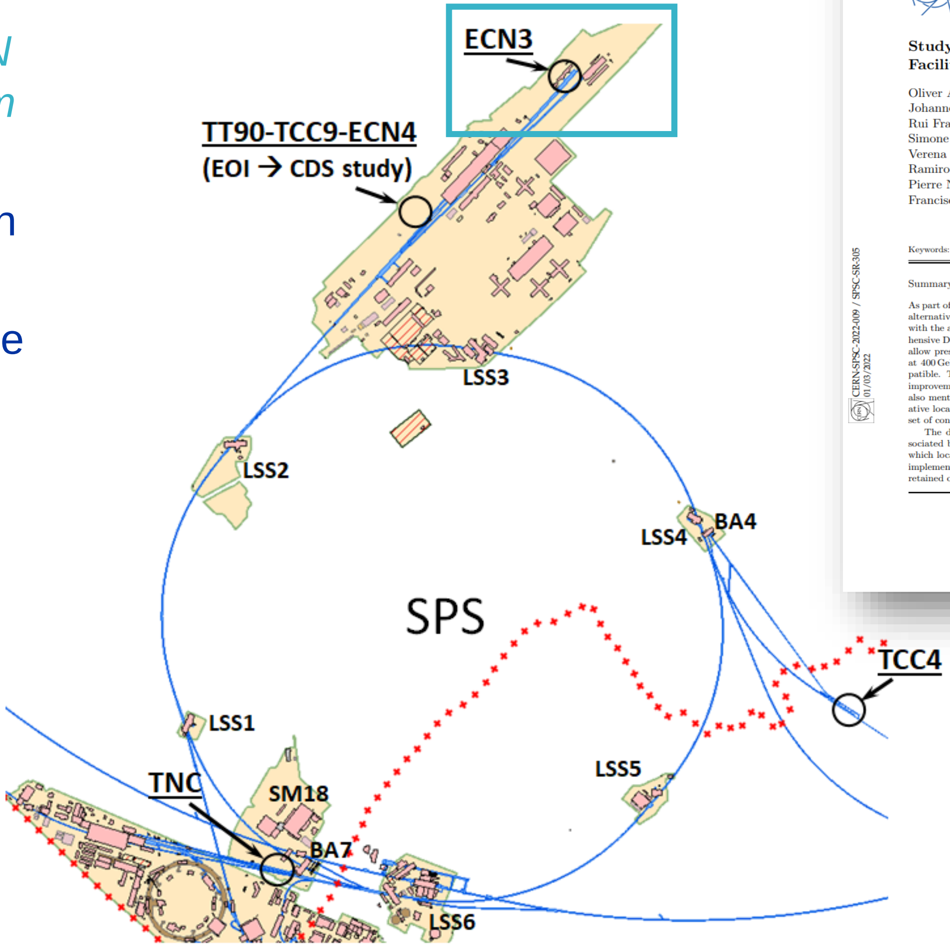
- Main point: CERN budget overstrained with main ESPPU commitments
- 2020 September: CERN launch of study for more cost-effective implementation

Optimization study

CERN management/PBC encourages focus on ECN3 for BDF/SHiP

Decision process over 2022-23 for future physics programme in ECN3 defined (see slide in backup)

- Two principal candidate experiments for ECN3: HIKE (K^+/K_L) / SHADOWS (see talk by J. Bernhard) and BDF/SHIP



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CERN-PBC-Notes-2022-002

1 March 2022

Study of alternative locations for the SPS Beam Dump Facility

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Keywords:

Summary

As part of the main focus of the BDF Working Group in 2021, this document reports on the study of alternative locations and possible optimisation that may accompany the reuse of existing facilities with the aim of significantly reducing the costs of the facility. Building on the BDF/SHiP Comprehensive Design Study (CDS), the assessment rests on the generic requirements and constraints that allow preserving the physics reach of the facility by making use of the 4×10^{19} protons per year at 400 GeV that are currently not exploited at the SPS and for which no existing facility is compatible. The options considered involve the underground areas TCC4, TNC, and ECN3. Recent improvements of the BDF design at the current location (referred to as 'TT90-TCC9-ECN4') are also mentioned together with ideas for yet further improvements. The assessments of the alternative locations compiled the large amount of information that is already available together with a set of conceptual studies that were performed during 2021.

The document concludes with a qualitative comparison of the options, summarising the associated benefits and challenges of each option, such that a recommendation can be made about which location is to be pursued. The most critical location-specific studies required to specify the implementation and cost for each option are identified so that the detailed investigation of the retained option can be completed before the end of 2022.

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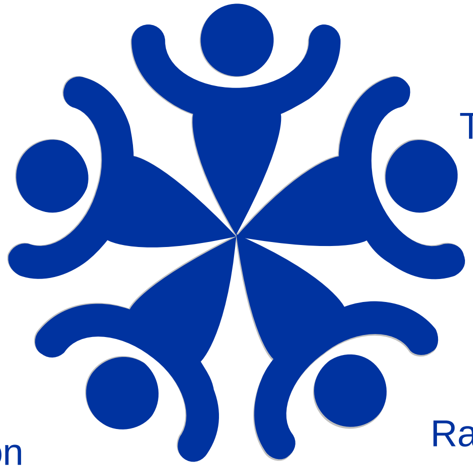
Objective: Preserve SHiP's original physics reach and scope (see talk by H. Lacker)

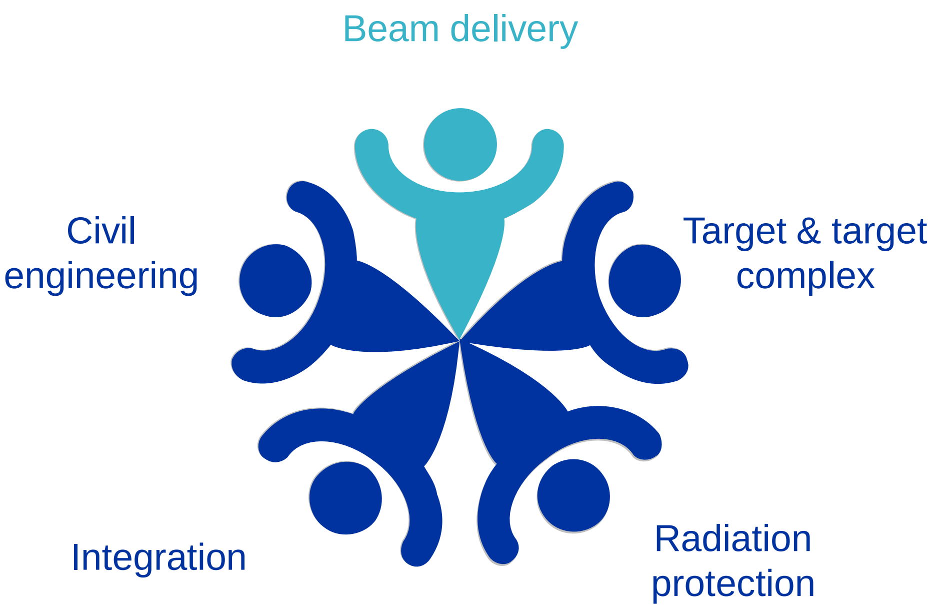
CDS design and prototyping studies largely generic

Optimization study of BDF/SHiP at ECN3



Synergies with NA-CONS

- The current optimization study of BDF/SHiP at ECN3 is aimed to address
  - ➢ Principal technical feasibility issues
  - ➢ Implementation in terms of integration and civil engineering
  - ➢ Estimates of the material cost and CERN personnel needs, together with a detailed road map
- It builds on the **comprehensive studies** and **accomplish-ments** of the **BDF Comprehensive Design Study**
- Beam delivery is covered by dedicated **ECN3 Beam Delivery Task Force** (see talk by M. Fraser), but major work for high intensity beam delivery to North Area done in the context of previous BDF studies
- Synergies with the North Area Consolidation (NA-CONS) programme are being investigated together with NA-CONS


Beam delivery
Civil engineering
Target & target complex
Integration
Radiation protection

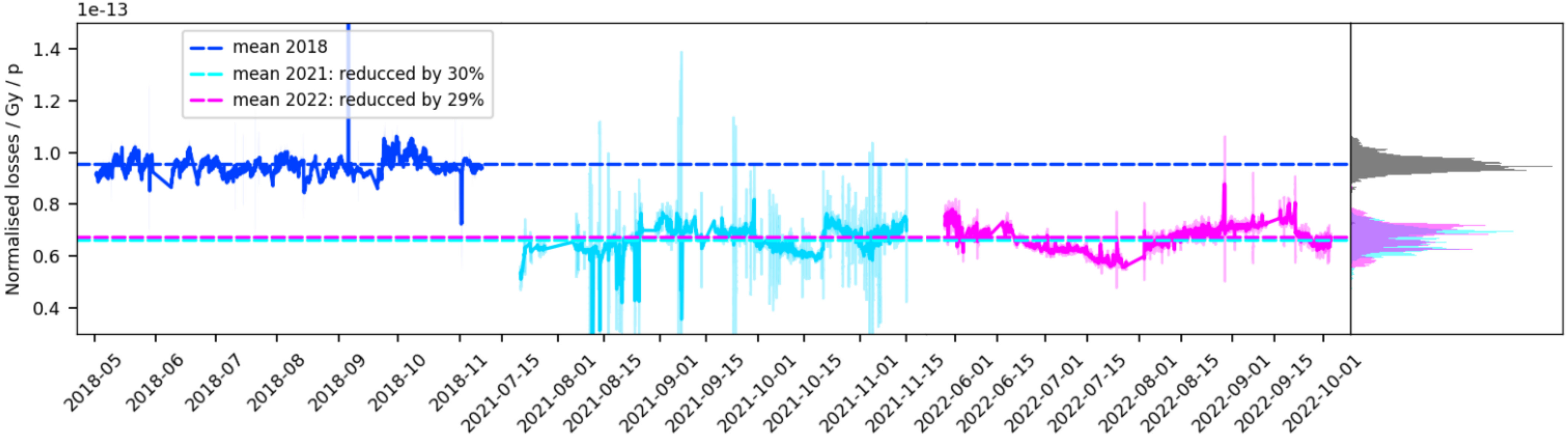
Slow extraction – LSS2 crystal shadowing system

- BDF/SHiP assumes SPS, slowly extracted 1 s spills with $4x10^{13}$ p / 7.2 s
- Slow extraction of (4 + 1) x 10^{19} p/year to the North Area requires reduction of losses by factor 4
- Pioneering developments made in the field of slow extraction beam loss reduction (see references)

➢ Shadowing from LSS2 using a thin bent crystal has been demonstrated

➢ In operation since 2021, reducing beam loss by about 30% (thanks also to installation of new electrostatic septa, ZS)

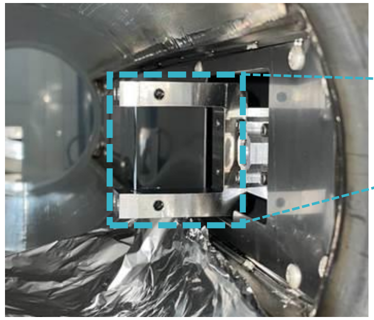
LSS2 loss reduction

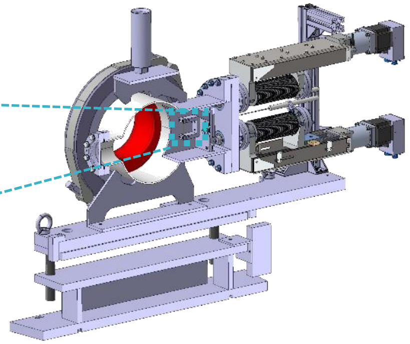


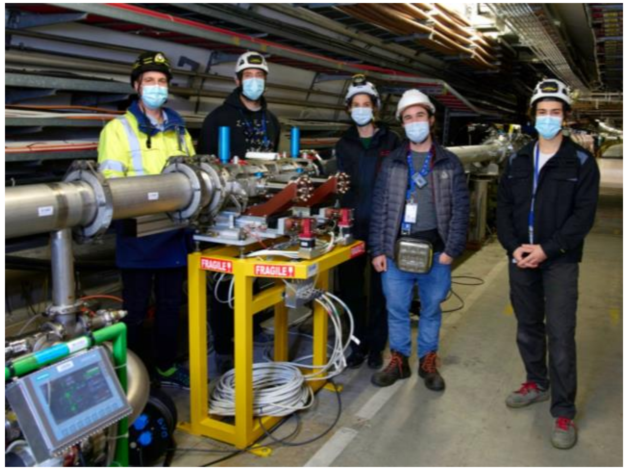
Courtesy of F. Velotti (SY-ABT-BTP)

Slow extraction – LSS4 crystal shadowing system

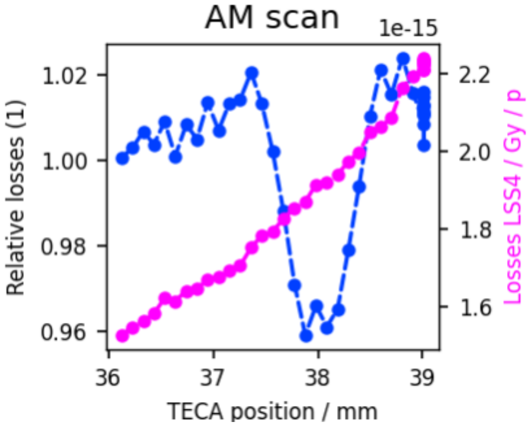
- Active R&D on-going with a new, optimized crystal shadowing system installed in SPS LSS4 during YETS 21/22
- New system has achieved a loss reduction of 45% loss reduction
- Investigating the possibility to make the LSS4 system operational in 2023
- Further optimisation is planned with the development of new crystals: aiming at 75% to 90% loss reduction in the future



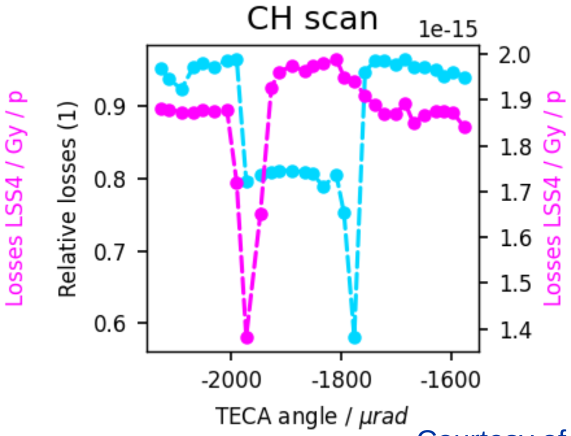




Linear scan to position crystal



Angular scan to align crystal



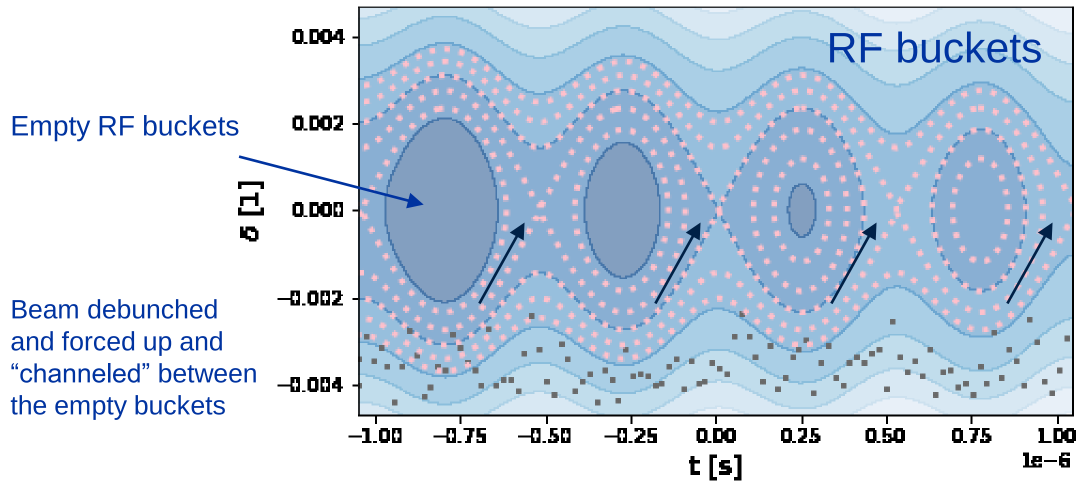
Courtesy of F. Velotti (SY-ABT-BTP)

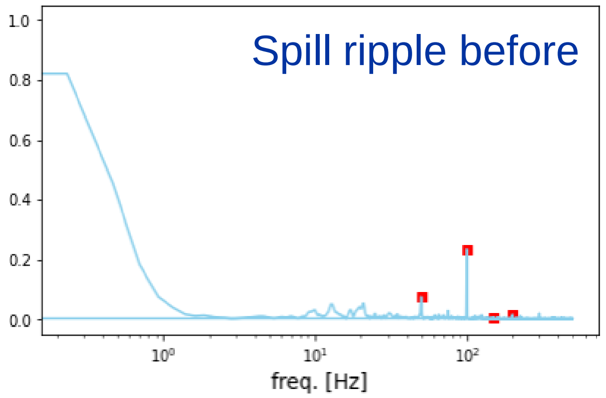
Spill quality

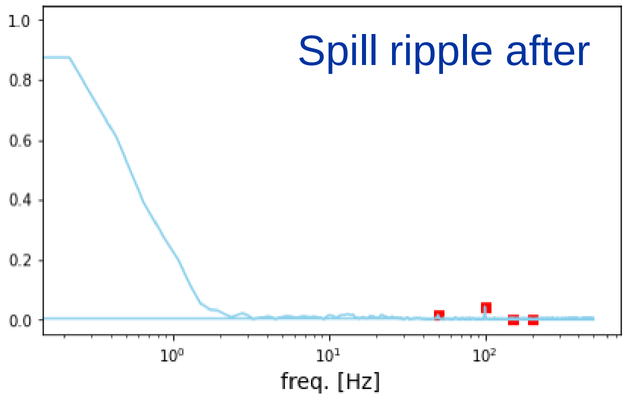
Beam dynamics simulations of machine imperfections (power converter ripple etc.)

Investigation of radiofrequency (RF) techniques to improve spill quality duty factor:

- **Empty Bucket Channeling** employed with 800 MHz cavities at low voltage to suppress low frequency spill ripple carried out with NA62 collaboration:







- Improved spill quality by reduction of slow intensity variations of the beam

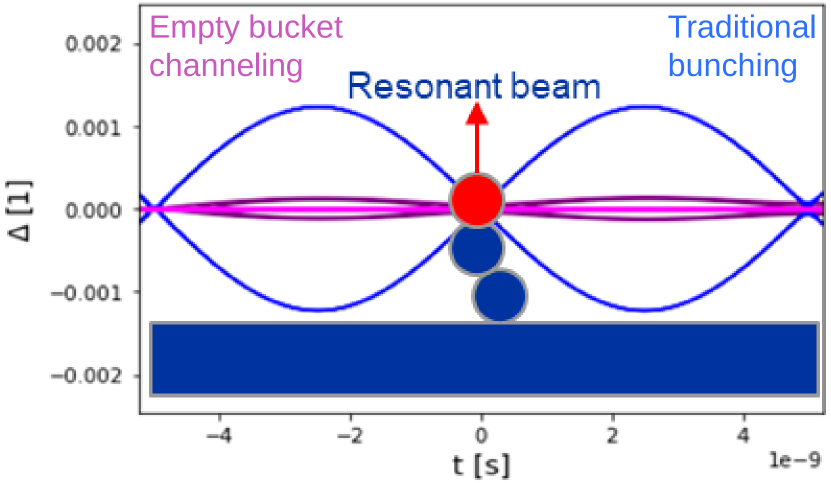
Courtesy of P. Arrutia (SY-ABT-BTP)

Alternative bunched mode operation

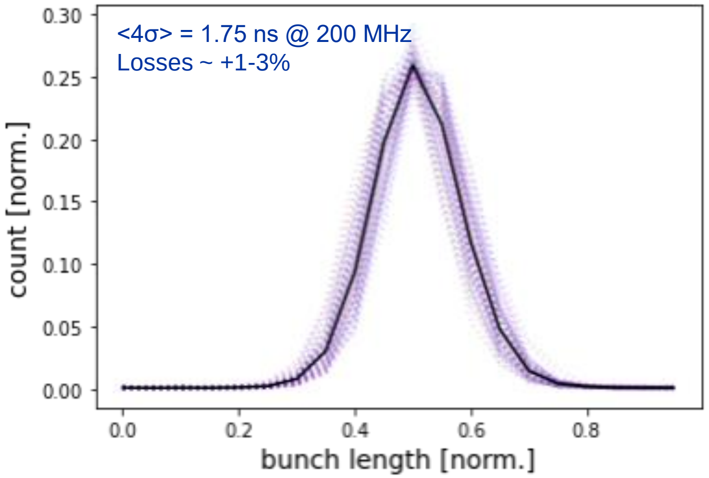
- Empty bucket channeling can also be used for bunching the beam
- In machine tests this year the SPS 200 MHz system was used to bunch the beam

➢ Bunch length compared to simulation with good agreement and low increase in beam loss at extraction

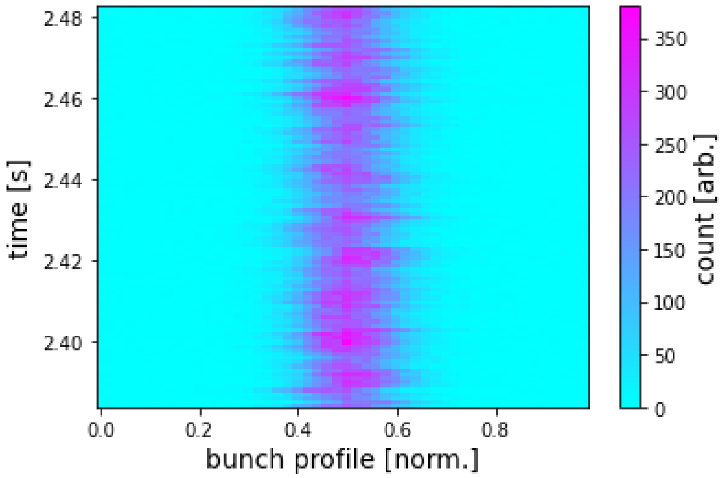
Schematic of empty bucket channeling for bunching



Bunch profile



0.1 MV ~ 1% of voltage



➢ Possible technique to provide slow-extracted bunched beams for time-of-flight discrimination against neutrino background in search for LDM at BDF/SHiP

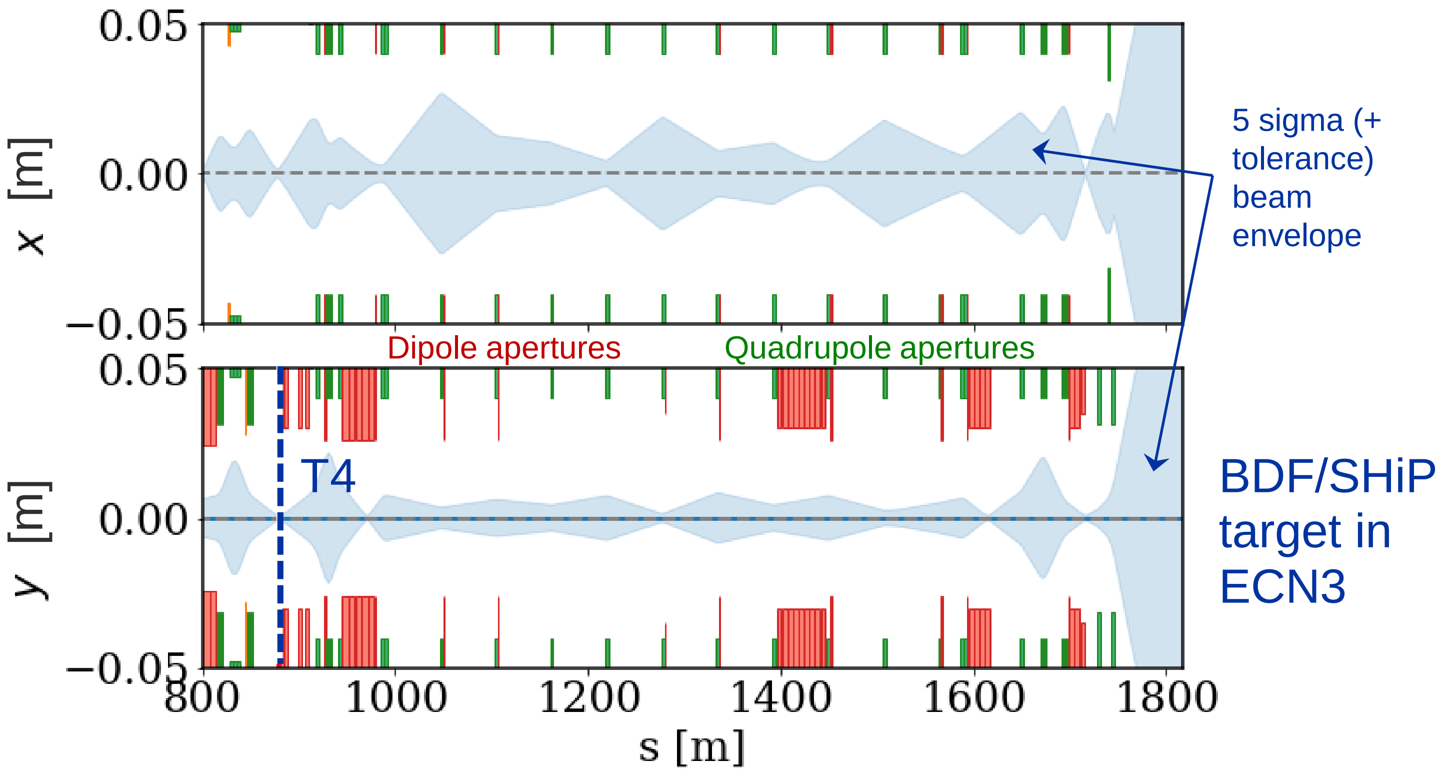
Courtesy of P. Arrutia (SY-ABT-BTP)

BDF/SHiP beamline in TCC8

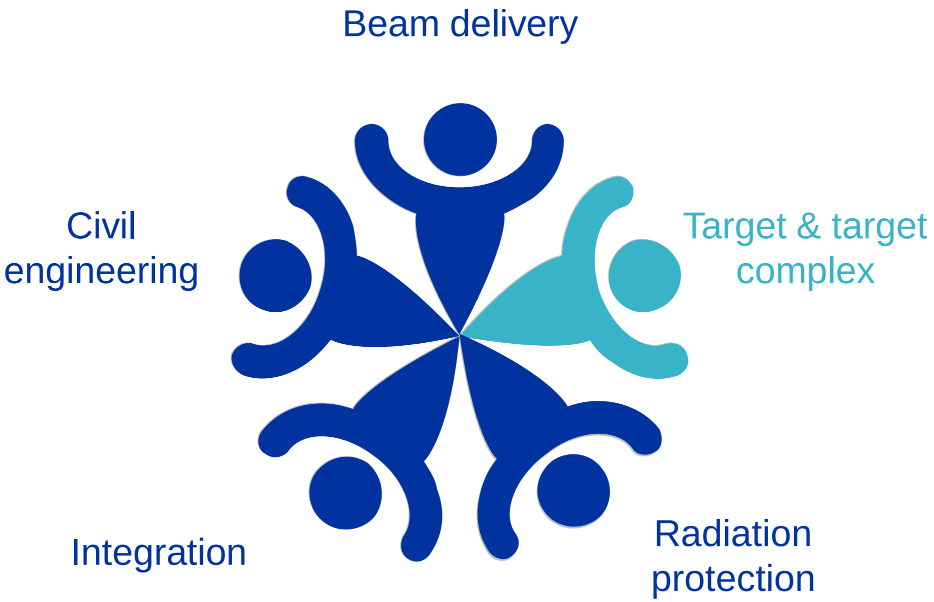
- The baseline BDF/SHiP scenario involves diluting the slow extracted spill over the BDF target's front-face to reduce the energy density in the target core
- The beamline in TCC8 will mainly consist of drift space and the beam dilution system
- As an alternative, the dilution system could possibly be removed by instead sufficiently increasing the beam size at the target

➢ Preliminary studies show that the beam size could possibly be sufficiently increased (beam size of $1\sigma = 35\ \text{mm}$)

BDF/SHiP in ECN3 scenario without dilution system using a quadrupole triplet:



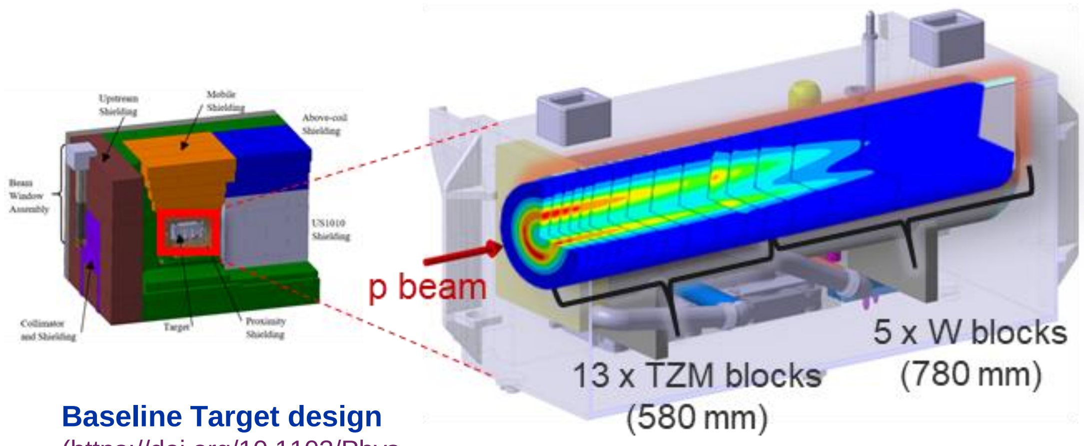
Courtesy of R. Ramjiawan (SY-ABT-BTP)


Beam delivery
Target & target complex
Radiation protection
Integration
Civil engineering

BDF target studies

+info on the BDF Comprehensive Design Study: https://doi.org/10.23731/CYRM-2020-002

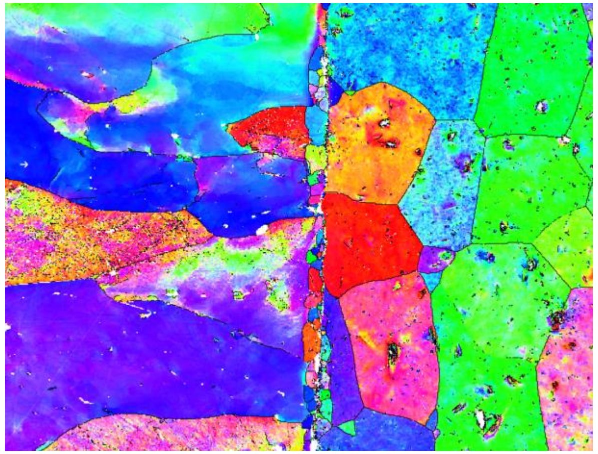
- **BDF Prototype Target**
  - Manufacturing validation of the Ta & Ta-alloy cladded pure W and TZM blocks (https://doi.org/10.1002/mdp2.101)
  - BDF-like beam tests (identical stress/temperatures) (*https://doi.org/10.1103/PhysRevAccelBeams.22.123001*)
- **PIE of the prototype target**
  - Understand survivability of the target materials & cladding-core bonding (https://doi.org/10.18429/JACoW-IPAC2021-WEPAB365)
  - Preliminary results indicate good adherence confirming viability of the target design



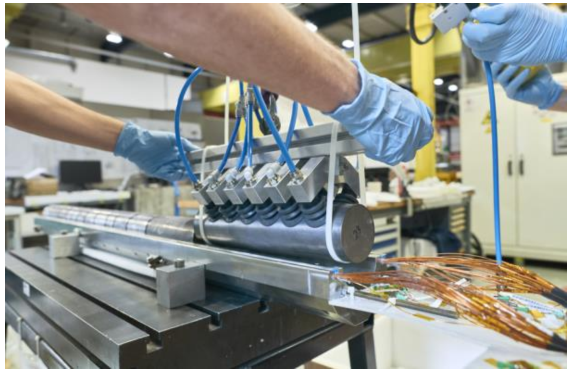
Baseline Target design
(https://doi.org/10.1103/PhysRevAccelBeams.22.113001)

TZM: 0.08% Ti – 0.05% Zr – Mo alloy
Protective cladding: Ta alloy

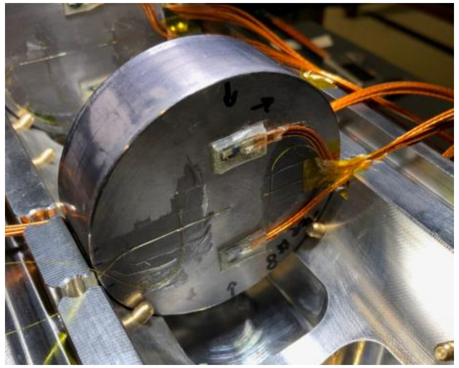
EBSD at interface of un-irradiated block



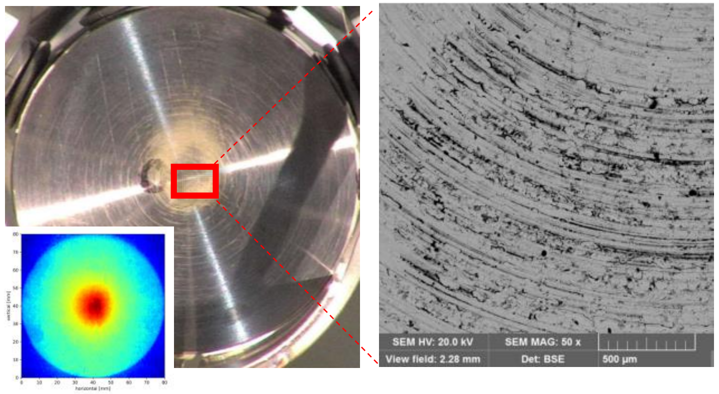
BDF prototype target



Prototype instrumentation



PIE visual + optical microscopy inspections



Courtesy of R. Ximenes (SY-STI-TCD)

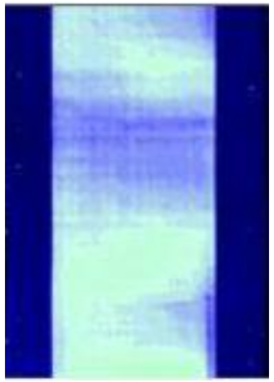
BDF target studies (cont.)

- **BDF Cladding R&D with Nb-alloys**
  - Assess viability of alternative claddings (Nb, Nb1Zr & Nb10Hf1Ti) → Advantages of Nb: lower decay heat, cheaper, very good thermal/mechanical properties
  - Manufacturing validation w/ first capsules HIPed successfully
  - Next: Cutting + optical microscopy to inspect interfaces
  - 2nd HIP and samples extraction for mechanical and thermal characterization of bonded interfaces in Nov 2022
- **Material characterization of Nb alloys**
- **Loss-Of-Cooling Accident studies** (see references)
- **Cladding residual stress measurements**
- **Oxidation test campaign**
- **Non-diluted 35 mm (1σ) beam under investigation**
- **Heavy liquid metal target feasibility**
  - Exploratory study. Collaboration with ENEA
  - Preliminary FLUKA + CFD calculations to define required Pb flow
  - Sketch of PID of the installation done and currently assessing integration in ECN3

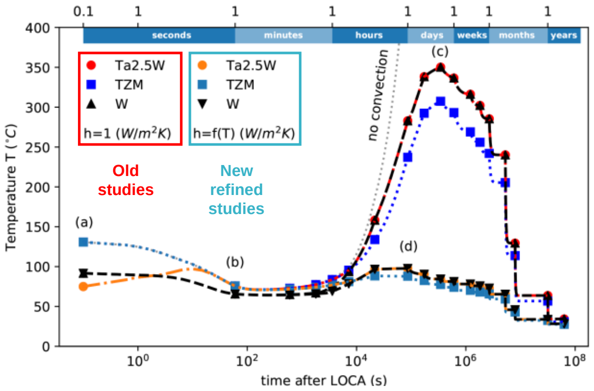
Ta2.5W degradation at different temperatures under oxidizing atmosphere

Successfully bonded Nb-alloy cladded block

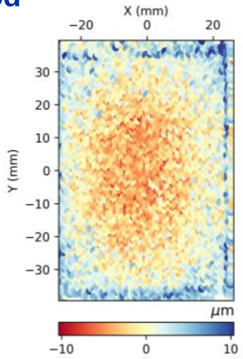
UT imaging



Thermal evolution during LOCA



Residual stress measurements via the Counter method



Courtesy of R. Ximenes (SY-STI-TCD)

BDF/SHiP Target complex

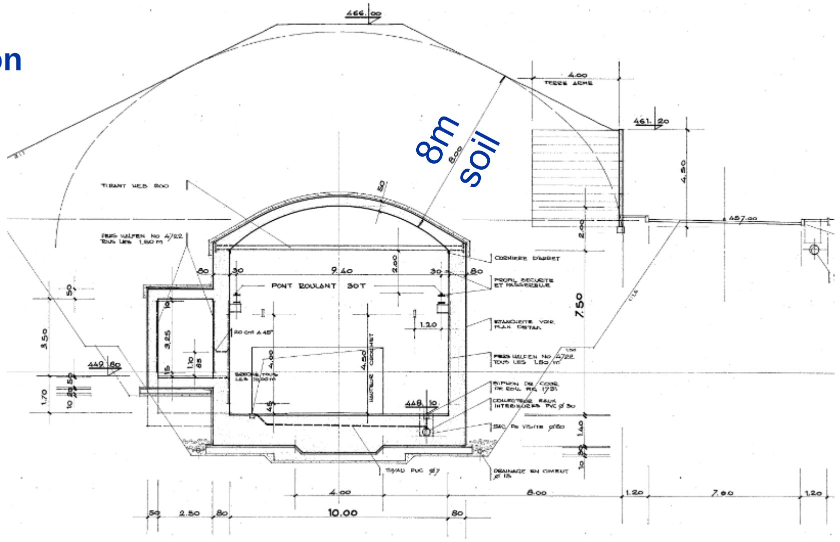
Optimisation for implementation in TCC8 target area

- Advanced design study performed for TCC8
  - Benefit of reusing an existing cavern of more comfortable size including its infrastructure (e.g overhead crane, services)
  - Use advantage of the shielding created by the soil above the cavern (~8 m)

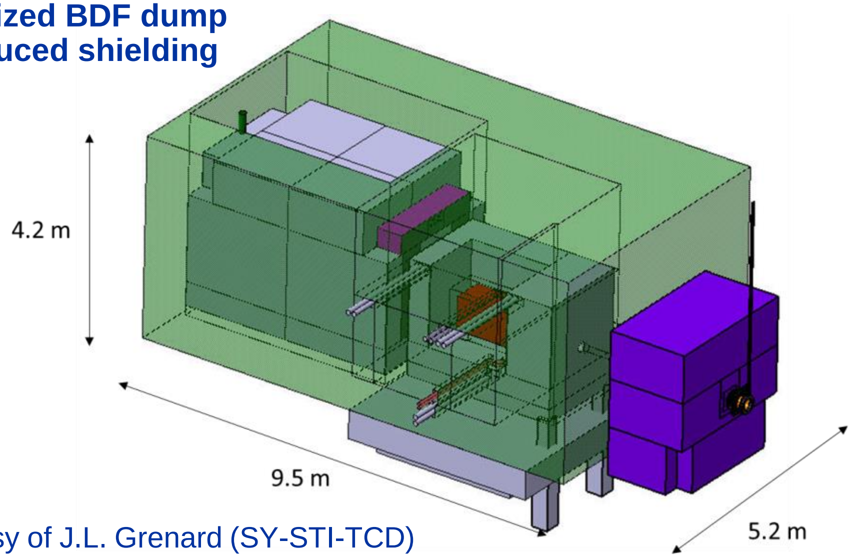
Shielding optimization

- Driving parameters of the cost
  - ECN3 configuration optimization of cast iron volume in order to optimize costs
  - Optimization of raw material usage (cast iron vs. concrete) for shielding
  - Re-use of existing, already activated TCC8 shielding blocks
  - Shielding embedded in an optimized N_2 confinement

TCC8 cross-section



Optimized BDF dump w/ reduced shielding



Iron (+ stainless steel for proximity shielding + US1010 for muon shield): 182 m^3 (1310 t)

Surrounding concrete shielding is not shown (reuse existing, already activated TCC8 shielding)

Courtesy of J.L. Grenard (SY-STI-TCD)

BDF/SHiP Target complex (cont.)

Nitrogen vessel

- Nitrogen as alternative to helium for inert gas embedding
  - ➢ Benefit of target installation in an underground cavern
  - ➢ N_2 tightness easier to achieve (and less cost for raw material)
- Also, the option of a vacuum vessel is being investigated

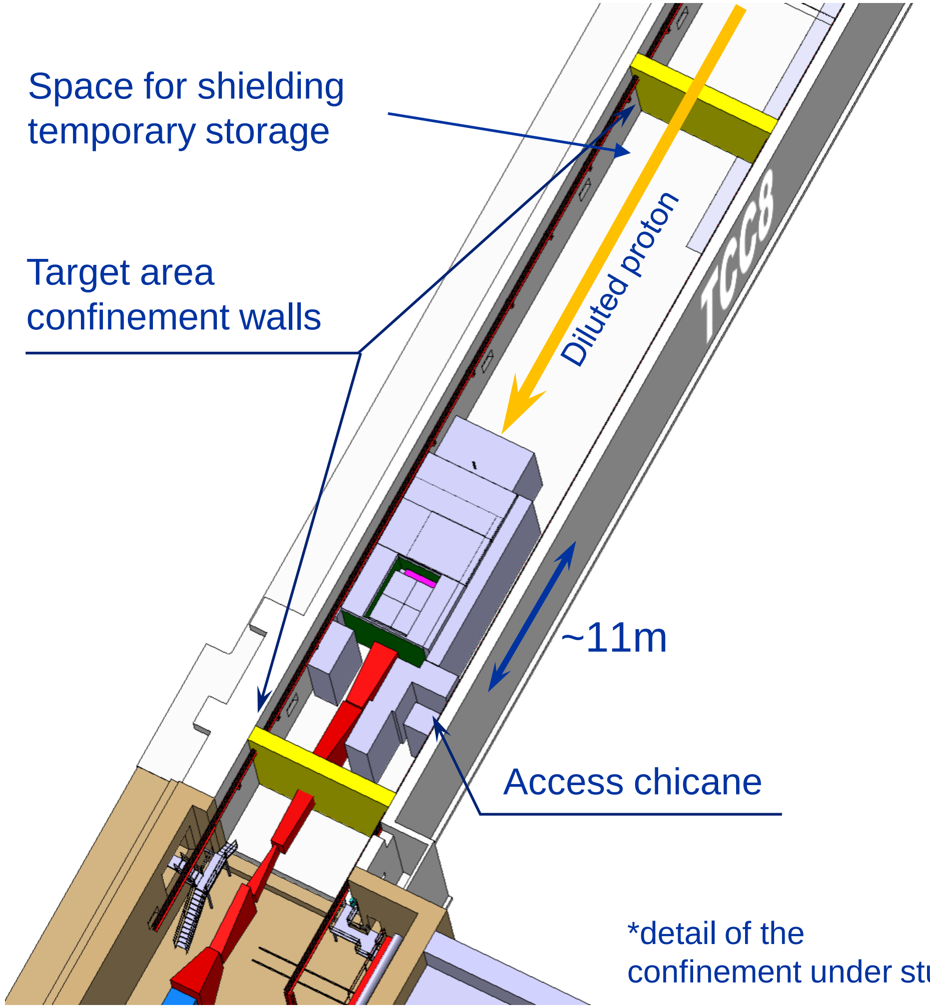
Handling

- Existing overhead travelling crane 30 t capacity upgrade
- Revised handling concept for target and associated shielding blocks
- Identification of steps to perform a target exchange

Optimization of overall infrastructure

- Beam line raised by 0.5 m (1.2 m → 1.7 m; potentially more in further studies) to reduce CE works
- Optimisation of walled confinement of complex with dedicated ventilation
- Preliminary routing of cooling circuit on the side of the target

Iteration with NA-CONS to identify synergies to reuse already foreseen consolidated infrastructure



*detail of the confinement under study

Courtesy of J.L. Grenard (SY-STI-TCD)


Beam delivery
Civil engineering
Target & target complex
Integration
Radiation protection

RP studies for a design optimization of BDF@ECN3

BDF target complex shielding is optimized according to the ALARA approach

Optimization required to ensure that exposure of personnel to radiation and radiological impact on environment are As Low As Reasonably Achievable

PROMPT RADIATION

RESIDUAL RADIATION

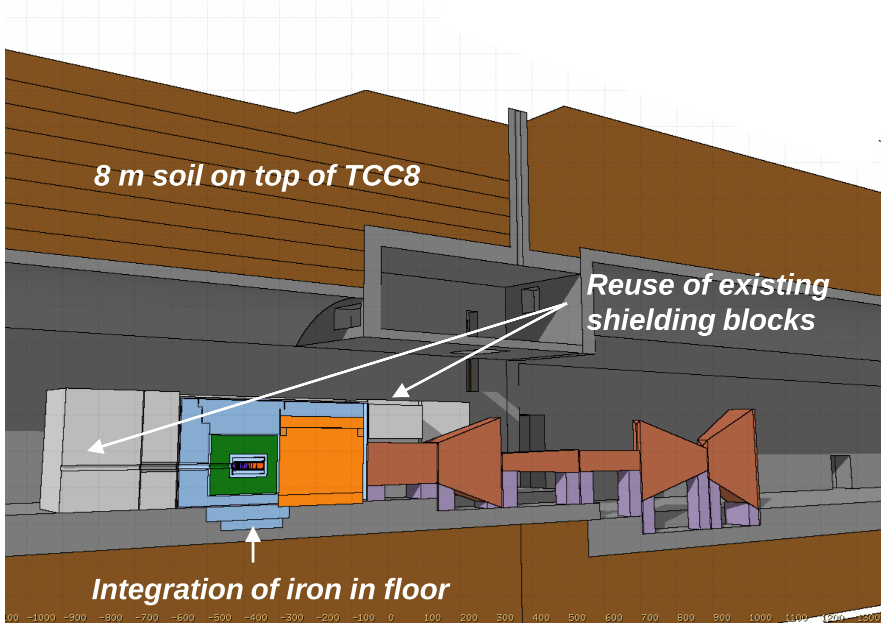
AIR & GROUND WATER ACTIVATION

ENVIRONMENTAL IMPACT

Optimization performed with FLUKA Monte Carlo studies

FLUKA hosted by CERN (FLUKA v4-2.2), [1-3]

FLUKA geometry
Created using FLAIR [4]



- Detailed TCC8/ECN3 FLUKA geometry (Thanks to BE-EA!) was extended and refined
- General updates included amongst others ground profiles, TCC8 floor, transfer tunnels, PP851 access chicane and material compositions
- The BDF CDS design was used as basis and further optimized wrt. area-specific advantages and constraints

Courtesy of G. Mazzola (SY-STI-BMI / HSE-RP-AS)

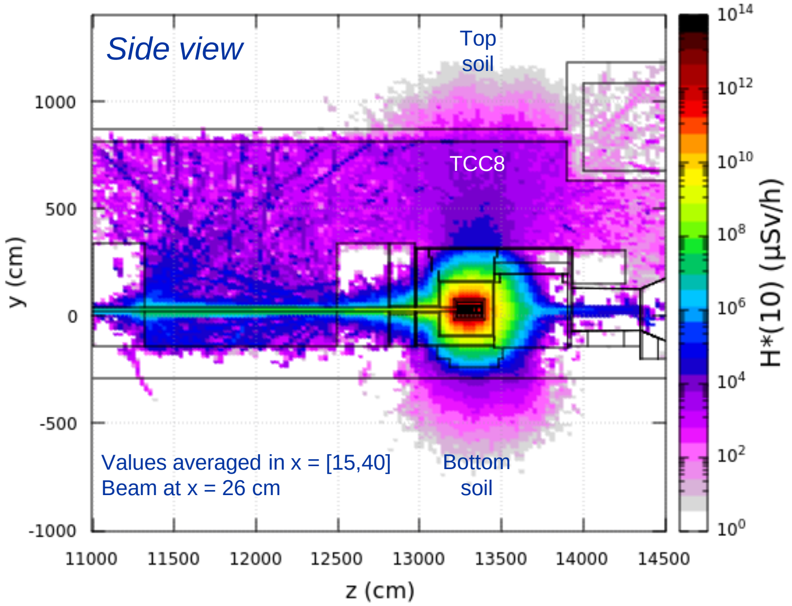
Prompt radiation

PROMPT RADIATION

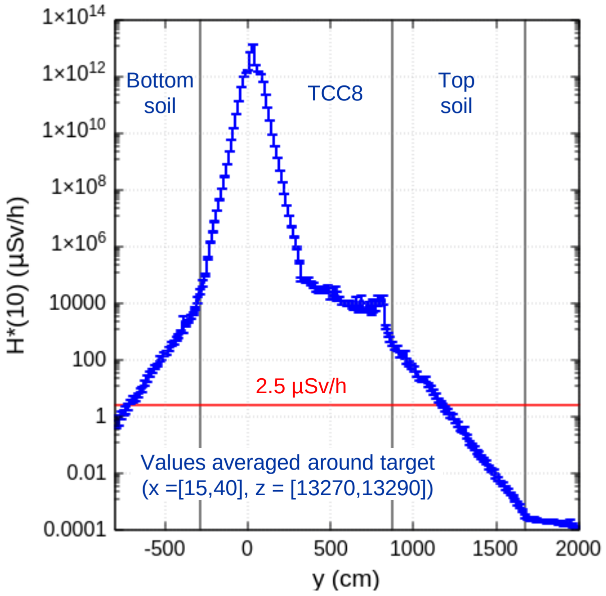
Goal is to reduce above-ground prompt radiation to comply with the given RP limits. Additional soil on top of TCC8/ECN3 as well as reuse of existing shielding blocks allow for a shielding reduction wrt. CDS design

Preliminary results normalized to the maximum beam intensity of $4 * 10^{13}$ p/spill every 7.2 s

Prompt ambient dose equivalent in TCC8



Prompt ambient dose equivalent along y



- Prompt dose rates are well contained in the BDF target/dump area
- Prompt dose rates above-ground are well below the limit of a Non-designated Area (2.5 µSv/h)
- Floor iron shielding reduces prompt dose rates inside the soil allowing soil activation (H-3, Na-22) to be below given design limits

Courtesy of G. Mazzola (SY-STI-BMI / HSE-RP-AS)

Activation

RESIDUAL RADIATION

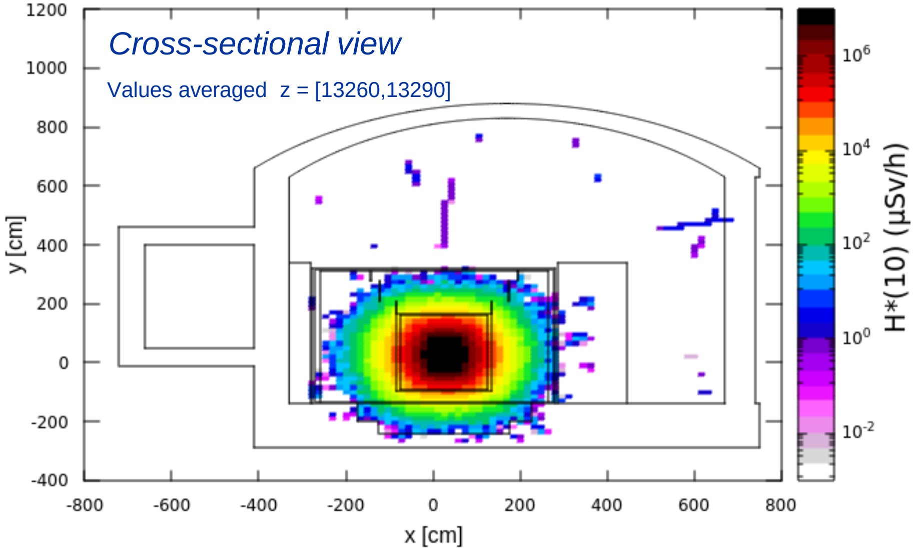
Shielding design also takes into account limitation of activation in the target and experimental areas

AIR & GROUND WATER ACTIVATION

Air activation is reduced w/ N_2 vessel and shielding. Activation and contamination of ground water and soil is prevented with additional shielding in the cavern floor

Preliminary results normalized to $4 * 10^{13}$ p/spill with 6000 spills/day and $4 * 10^{19}$ p/year for 5 years operation

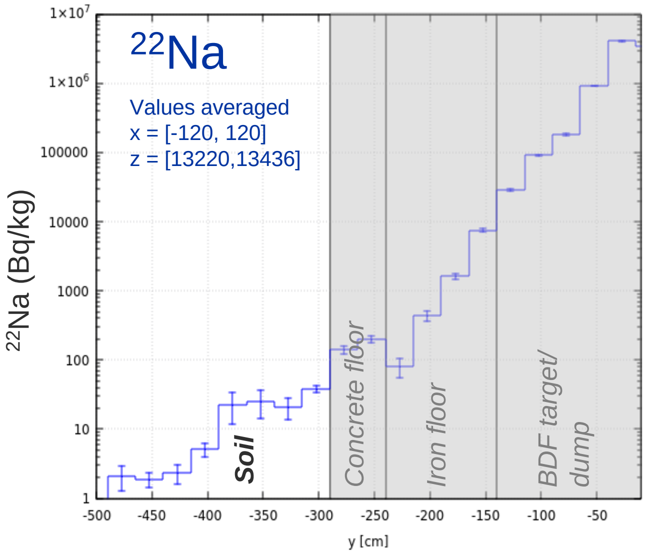
Residual H*(10) for 1 day cooling at target



Computed for different cooling times

- Residual dose rates are well contained in the BDF target/ dump area
- Reached values of few tens μSv/h on top and on Jura side of vessel

Soil activation below TCC8 (most critical)



Also computed for ^{3}H

- Soluble radionuclides ^{3}H and ^{22}Na are critical for groundwater protection
- Thanks to floor Fe shielding specific activities of ^{3}H and ^{22}Na are below respective limits (1 kBq/kg, 50 Bq/kg)
- Shielding could possibly be further reduced w/ a future hydrogeological study

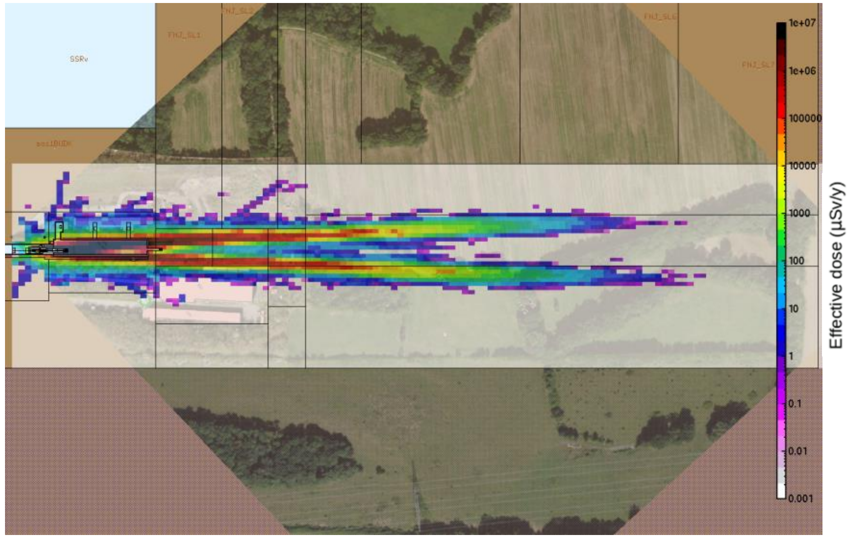
Courtesy of G. Mazzola (SY-STI-BMI / HSE-RP-AS)

Environmental impact

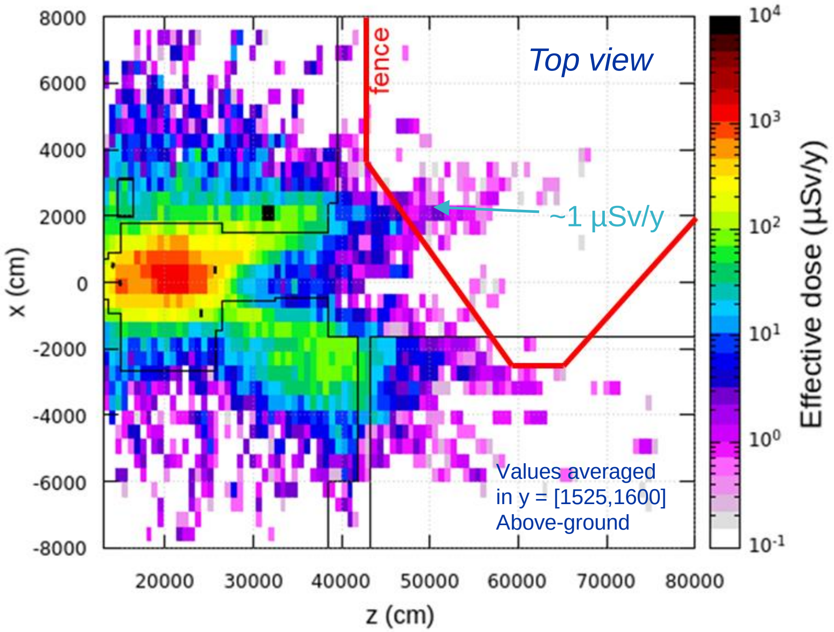
ENVIRONMENTAL IMPACT
Reduce environmental impact from prompt radiation and releases of activated air to fulfill CERN's **dose objective** for the **public** of <**10 uSv/year**

Preliminary results normalized to $4 * 10^{19}$ p/year and a safety factor 3

Underground effective dose

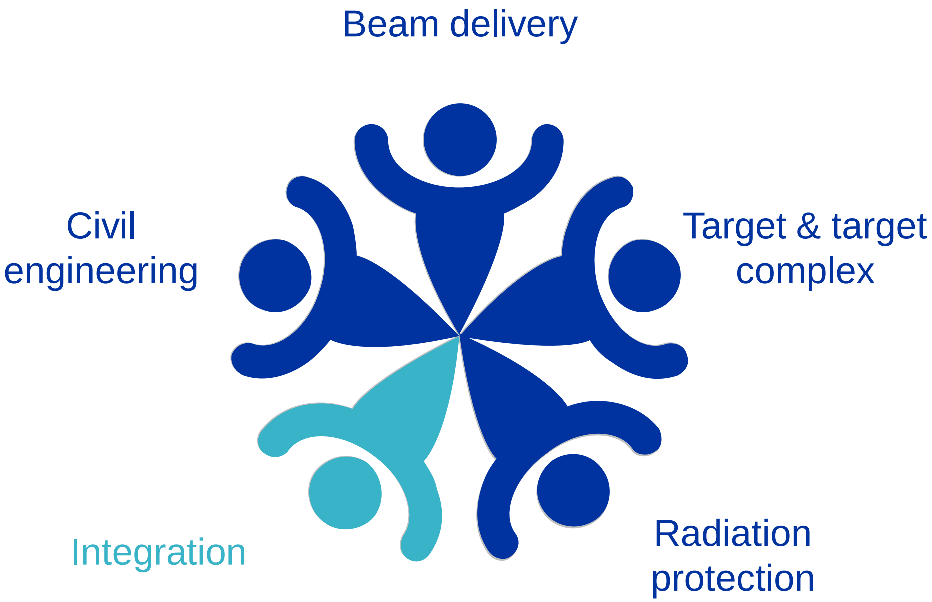


Aboveground effective dose at CERN fence and beyond

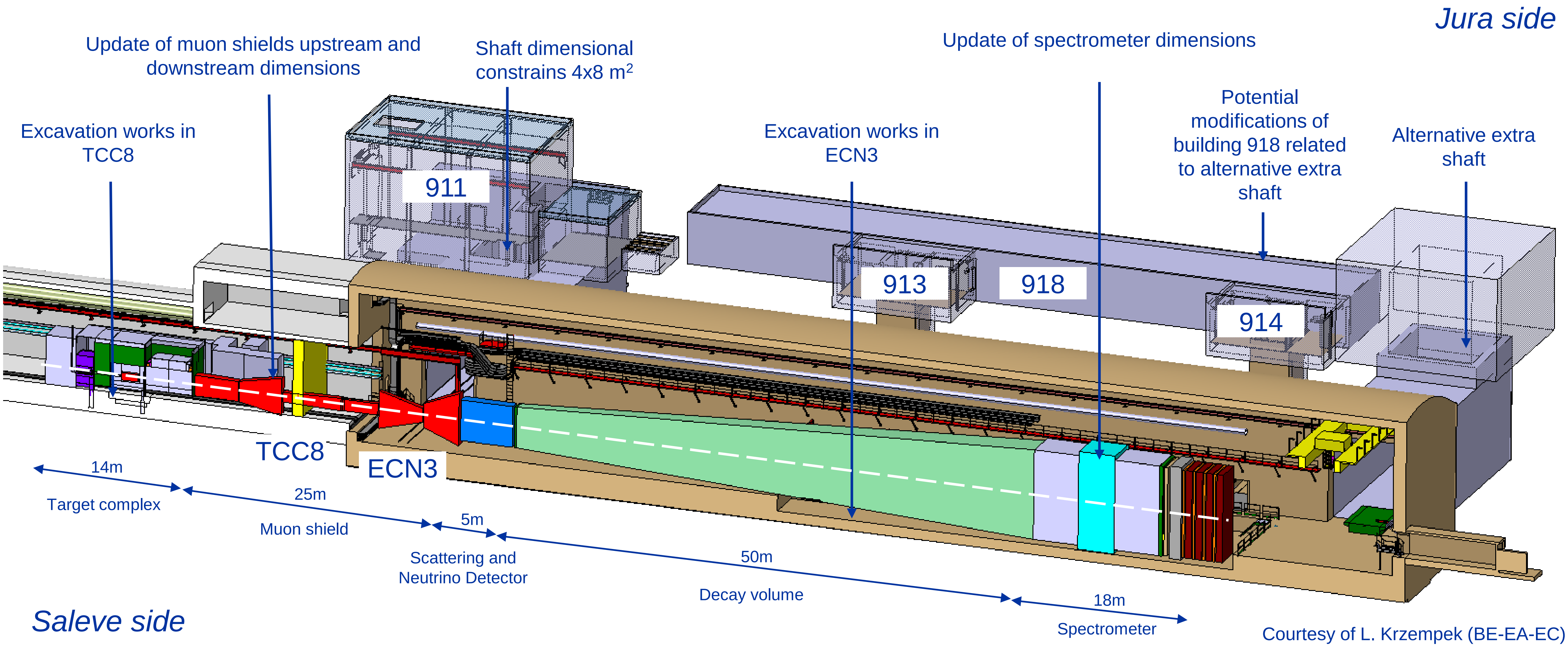


- High energy muons are mainly deflected horizontally remaining well below the ground level
- Annual dose at CERN fence far below the 1 mSv/y limit
- Annual dose beyond CERN fence also well below dose objective for members of the public
- Study of air releases ongoing, but thanks to N_2 vessel and shielding and based on CDS studies expected to have a negligible radiological impact on the public
- Design of ventilation system also allows to guarantee that air releases have a negligible radiological impact

Courtesy of G. Mazzola (SY-STI-BMI / HSE-RP-AS)


Beam delivery
Civil engineering
Target & target complex
Integration
Radiation protection

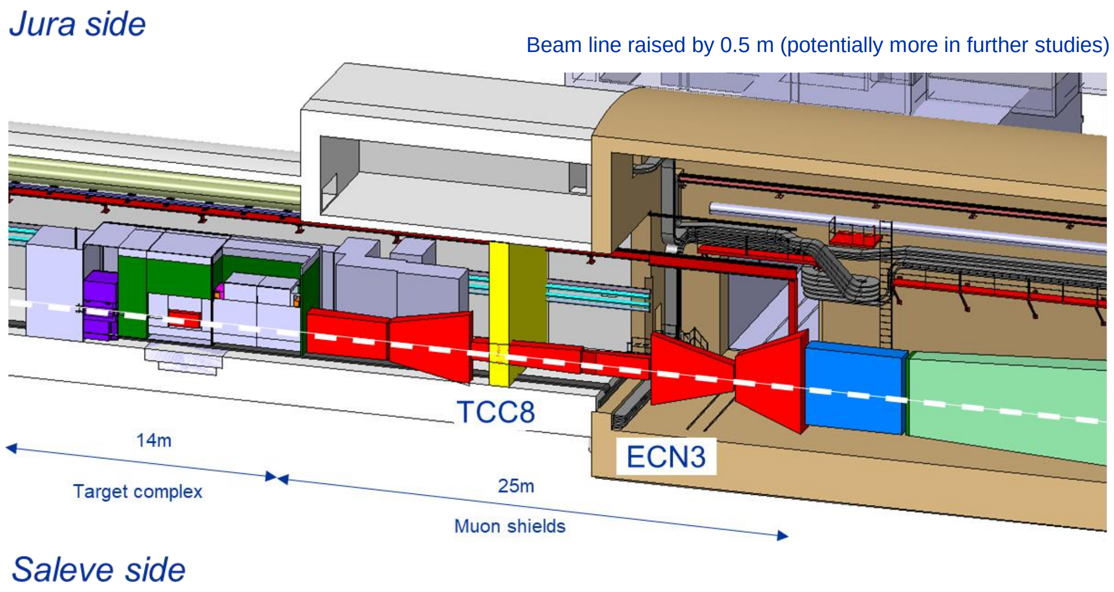
BDF/SHiP integration in TCC8/ECN3



Courtesy of L. Krzempek (BE-EA-EC)

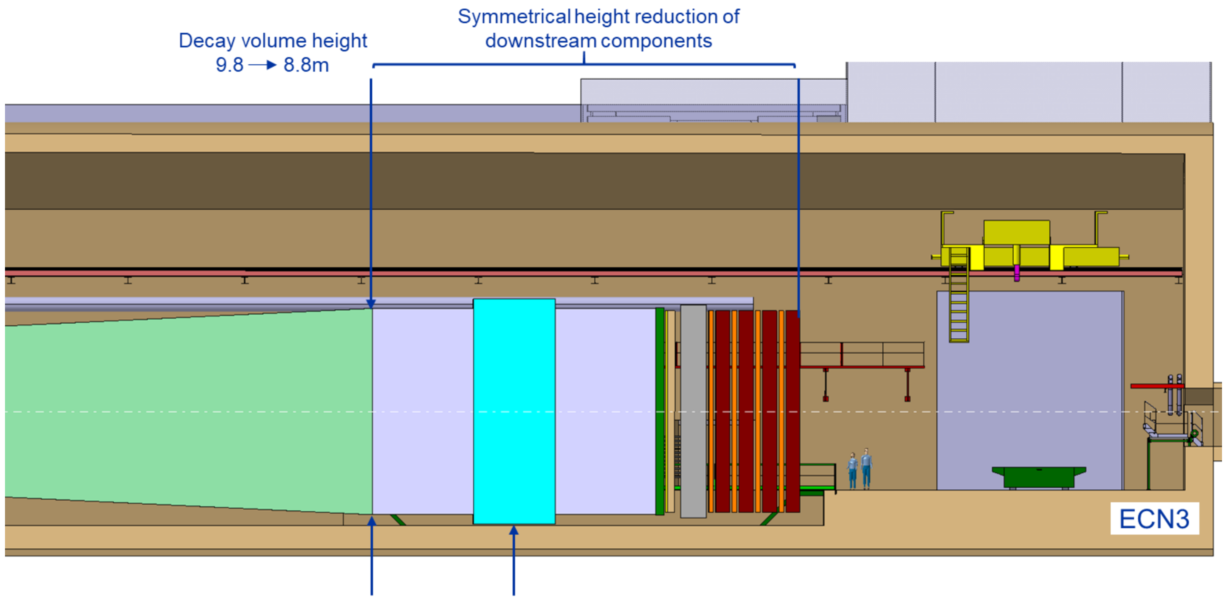
Optimization

Muon shield optimization



- Optimization of BDF/SHiP vertical/longitudinal position and muon shield result in no interference with TCC8/ECN3 floor
- No extra excavation works are required

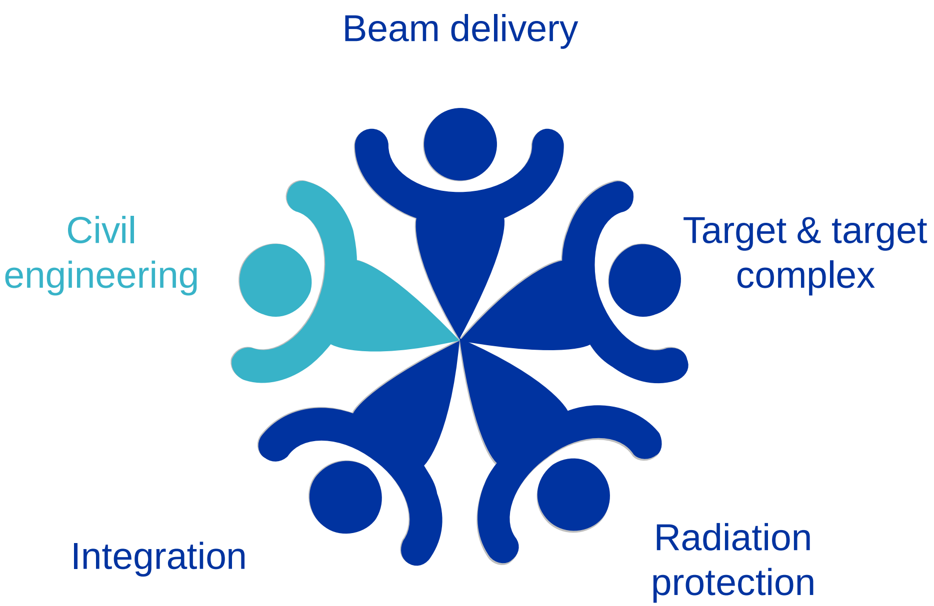
Reduction of excavation works



- Optimization of BDF/SHiP position and SHiP decay volume and downstream components reduces excavation works in ECN3
- Impact on other services were studied and no showstoppers were identified

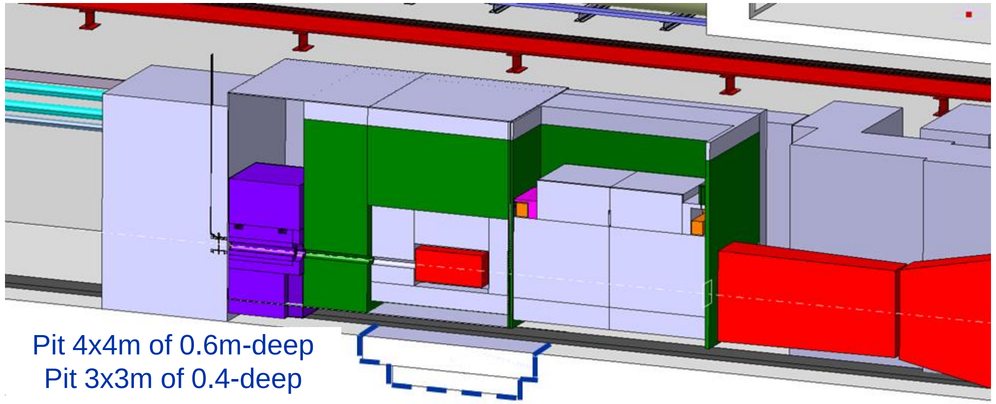
- **Minor civil engineering to adapt BDF/SHiP to ECN3**

Courtesy of L. Krzempek (BE-EA-EC)

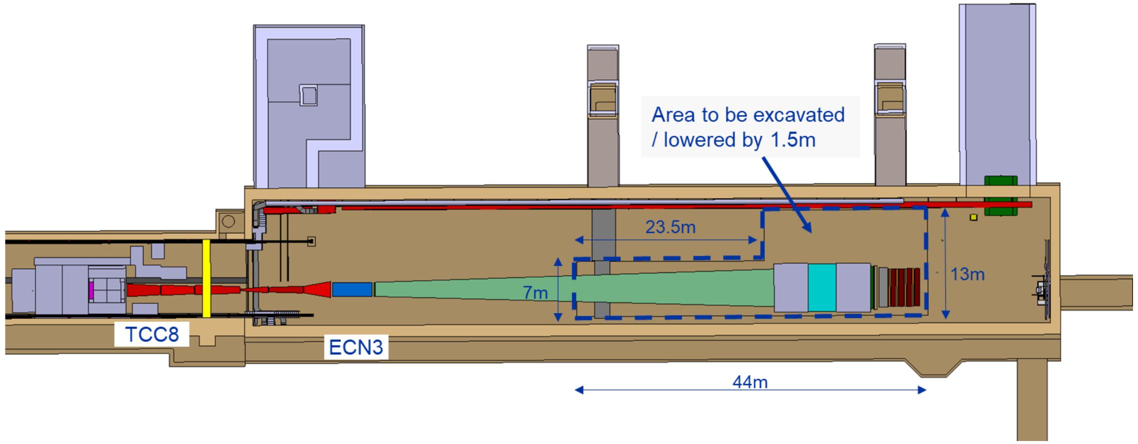

Beam delivery
Civil engineering
Target & target complex
Integration
Radiation protection

Trenches

Trench in target area



Trench in experimental area



Target complex

- Creating of pit in the floor of the TCC8 to embed part of the shielding and services of the target complex

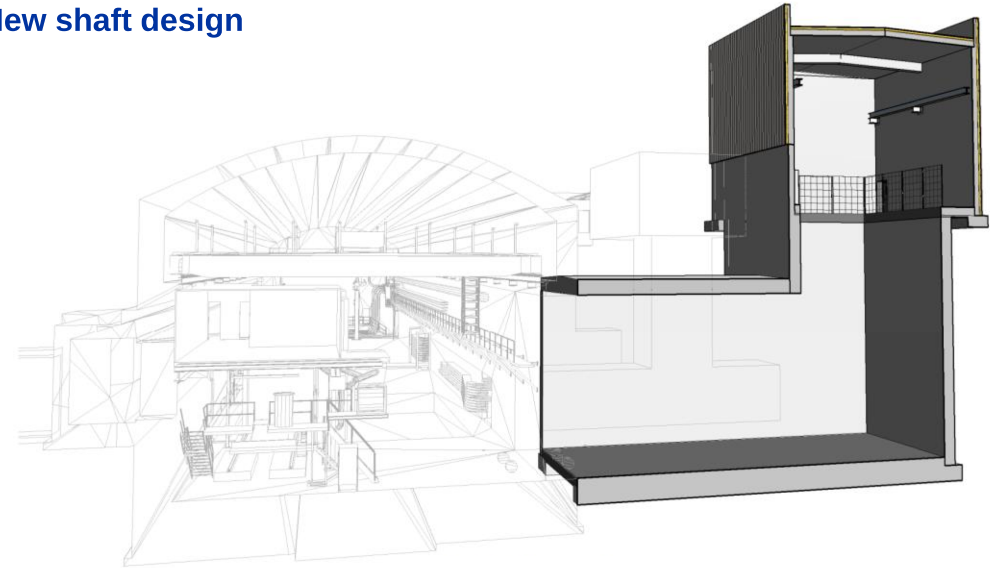
Experimental area

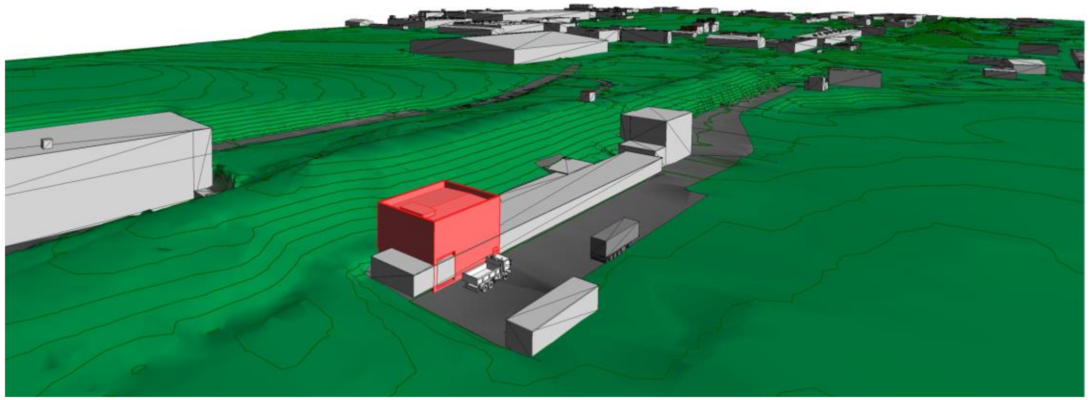
- Modifications required to the ECN3 floor
  - Creating a 7 m wide, 23.5 m long and 1.5 m deep trench under a part of the decay volume of the detector
  - Lowering the floor by approx. 1.5 m under the spectrometer section leaving 1.5 m on the each side of the tunnel for passage

Courtesy of L. Krzempek (BE-EA-EC) and K. Balaszs (SCE-DOD-FS)

Equipment shaft

New shaft design





- Personnel access via the two existing personnel access shafts (PT 853, PT 854)
- New equipment shaft is proposed for the CE works and to allow installation/access to the experimental area
- Proposed location at the end of the B918
- Required CE works were identified
  - Demolishment of the B918 over an approx. 20m length
  - Demolishment of the retaining wall
  - Shaft excavation
  - Tunnel excavation
  - Connection to ECN3 – cutting out the sidewall of cavern
  - Relocation of the existing drain system and other networks

➢ **Implementing BDF at the ECN3 looks a feasible option**

➢ Engagement of an external consultant for a detailed CE study on the impact of the proposed works on the existing facility (ongoing) → revised offer for CE feasibility study and preliminary cost estimate for BDF/SHiP + HIKE/KLEVER

➢ Detailed study needed on the relocation of the existing networks

Courtesy of K. Balaszs (SCE-DOD-FS)

Conclusion and outlook

- **BDF/SHiP is a mature general-purpose platform for exploration of feebly interacting particles**
- **Advanced status of the studies for an implementation and optimization of BDF/SHiP in TCC8/ECN3**
- **While maintaining the same functionality as of the CDS version, the optimization led to a significant cost reduction** (e.g. shielding volume, civil engineering, existing infrastructure and services)

Possible timeline

- ECN3 decision process 2022-2023
- ~2-3 years for TDR, followed by preparation for construction, component production
- Decommissiong/consolidation/modification/installation of beamline & BDF/SHiP ~5 years starting from beginning of LS3
- Commissioning / operation from 2030

Backup Slides

Decision process on ECN3 future programme

Decision Timeline for the Facility - SPSC

- **Produce list of candidate experiments for ECN3 (November 2022).**
  - By then **the experiments have submitted Letters of Intent.**
  - First discussion of these Letters of Intent in the November 2022 SPSC meeting.
  - Prepare first input on different experiment options to the December 2022 Research Board meeting.
- **First report by ECN3 Beam Delivery Taskforce (December 2022).**
  - To deliver document to IEFC on physics 'agnostic' feasibility for high-intensity facility in ECN3.
- **Final SPSC statement on meaningful physics justification for a high-intensity ECN3 facility (February 2023).**
  - Necessary input for next MTP, defined in March 2023 RB (including or not the high-intensity facility).
- **Research Board decision on go-ahead for launching preparatory work for high intensity beam to ECN3.**
  - Based on SPSC and IEFC inputs.
  - The accelerator sector must provide the upgrade plan for high-intensity beam delivery to ECN3.
- **Need more detailed information from the experiments (mid-late 2023).**
  - Full proposals (or at least provide sufficient details for a correct SPSC judgement).
- **Final SPSC conclusions on the experiments (November 2023).**
  - Recommendation on the future ECN3 physics program to the Research Board for final decision.

CERN management/SPSC/PBC

BDF/SHiP main documentation

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- **Reconstruction of 400 GeV/c proton interactions with the SHiP-charm project, under internal review, to be submitted to EPJC**
- **BDF/SHiP Location and Layout Study, SPSC-2022-009**

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- *V. Kain et al., Resonant slow extraction with constant optics for improved separatrix control at the extraction septum, Phys. Rev. Accel. Beams 22, 101001 (2019)*
- *F.M. Velotti et al., Septum shadowing by means of a bent crystal to reduce slow extraction beam loss, Phys. Rev. Accel. Beams 22, 093502 (2019)*

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- *M. Pari et al., Characterization of the slow extraction frequency response, Phys. Rev. Accel. Beams* ***24****, 083501 (2021)*
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Radiation protection

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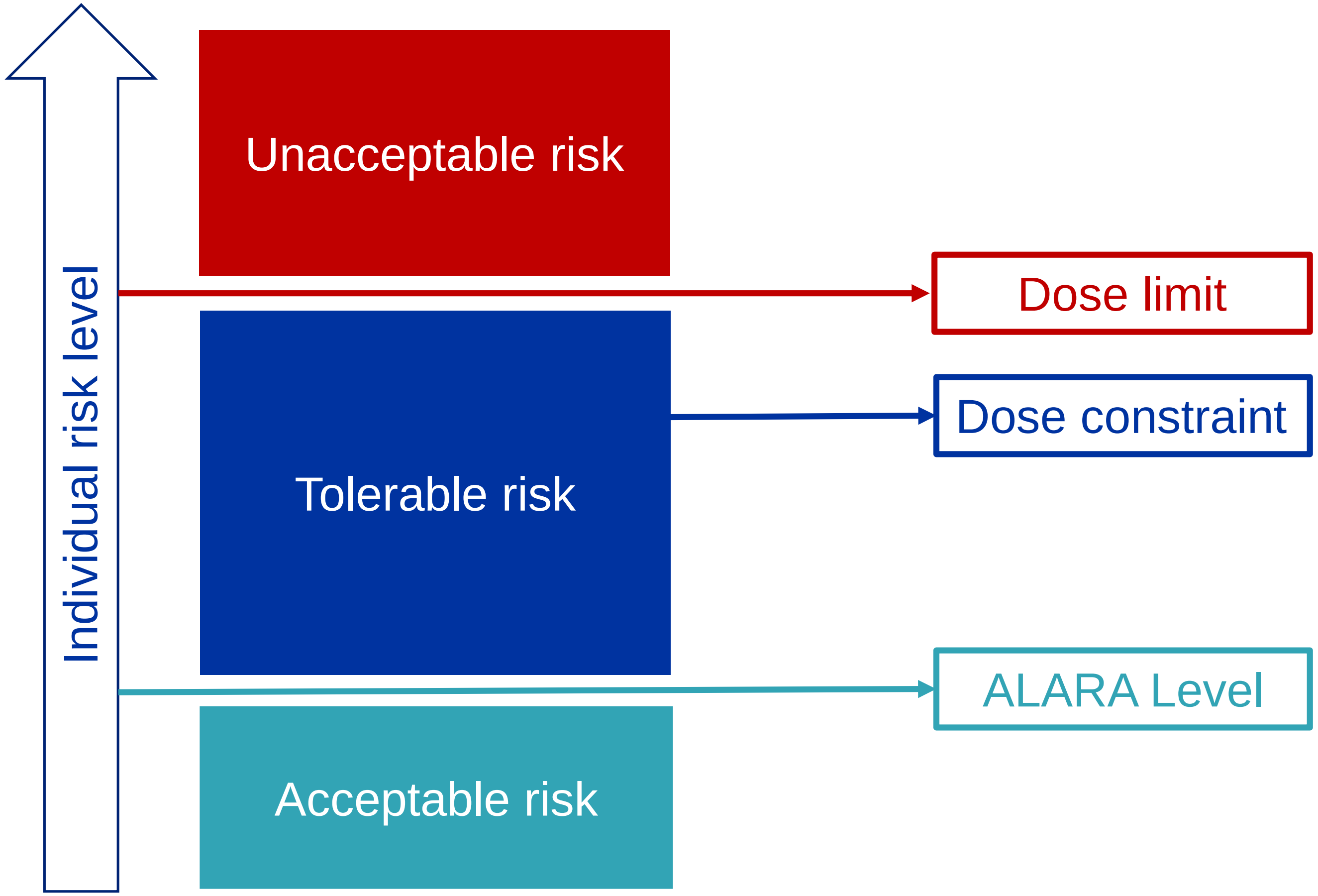
Dose Optimization at CERN



	CERN workers		Population
	Radiation Workers	Other Workers	
Dose limit	20 mSv/yr*	1 mSv/yr	300 µSv/yr
Dose constraint	3 mSv/yr	100 µSv/yr	10 µSv/yr
ALARA Level	100 µSv/yr	10 µSv/yr	10 µSv/yr

Optimization process

* Apprentices and students (age 16-18): 6 mSv/yr
  Pregnant women: 1mSv/yr

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