HSE

Occupational Health & Safety and Environmental Protection unit

Radiation Protection aspects of the BDF/SHiP prototypes tests in 2018

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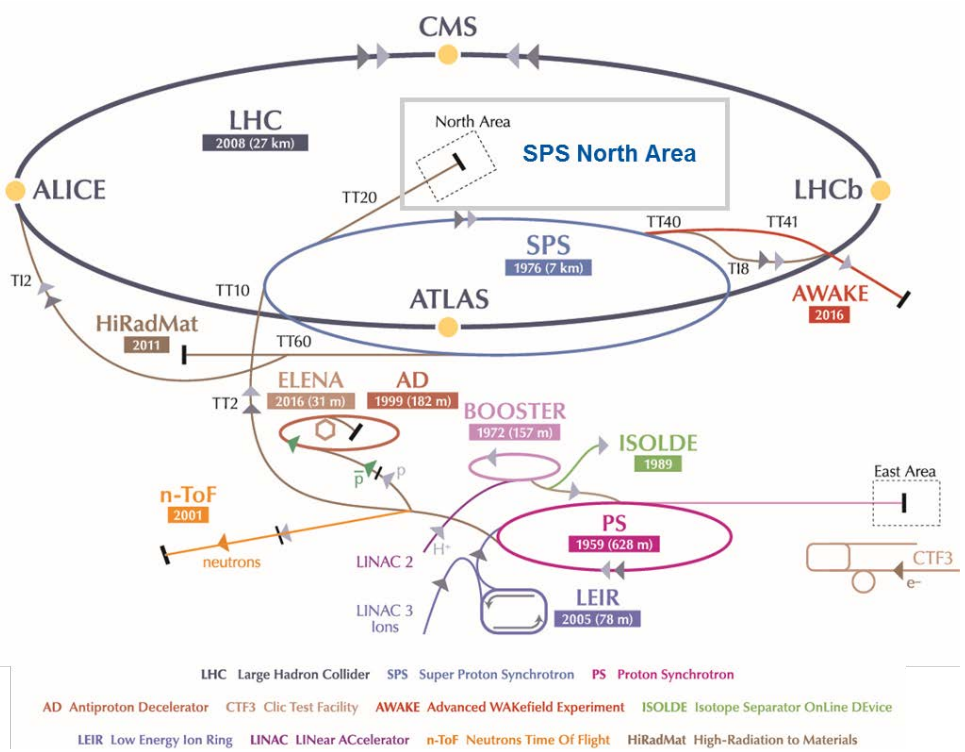
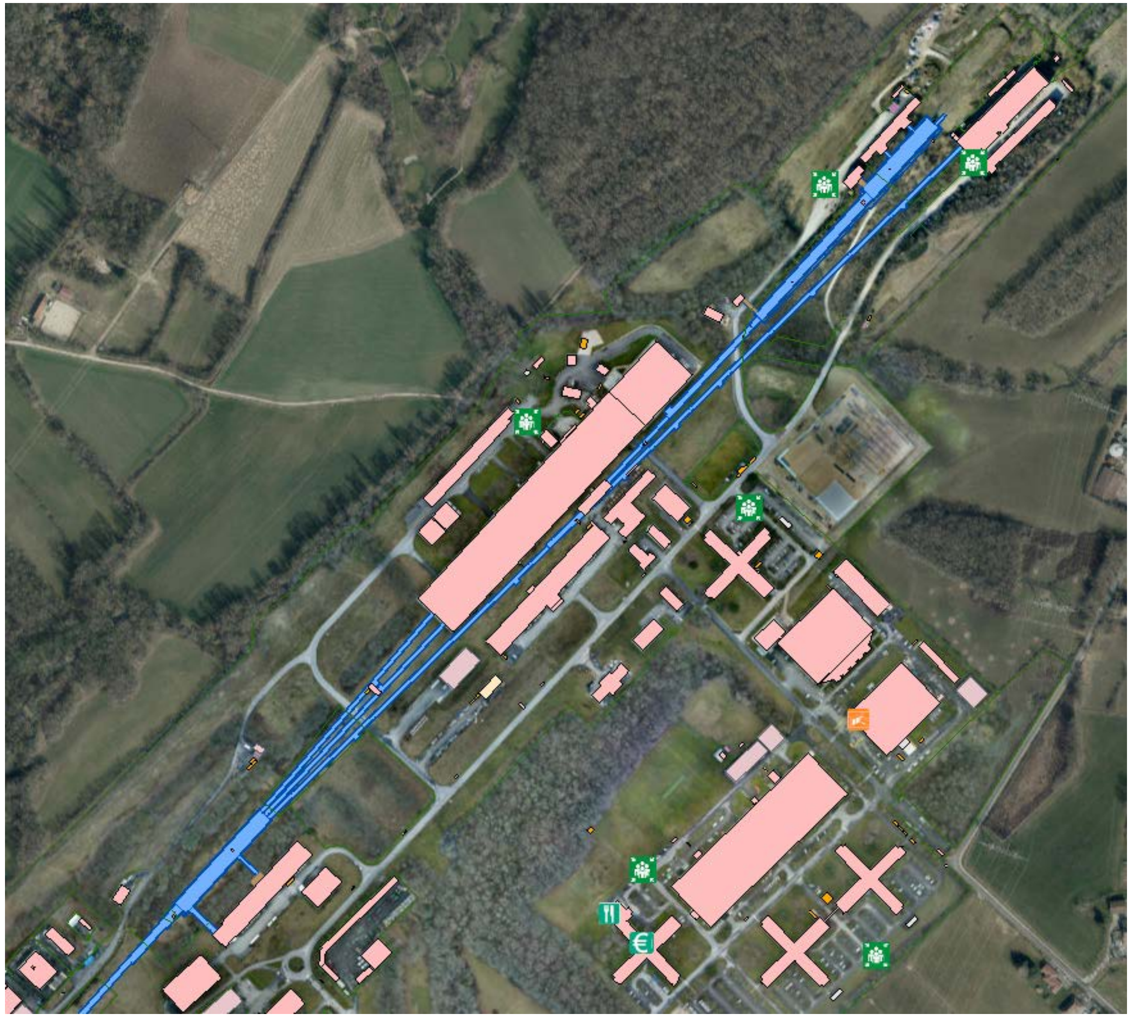
Outlook

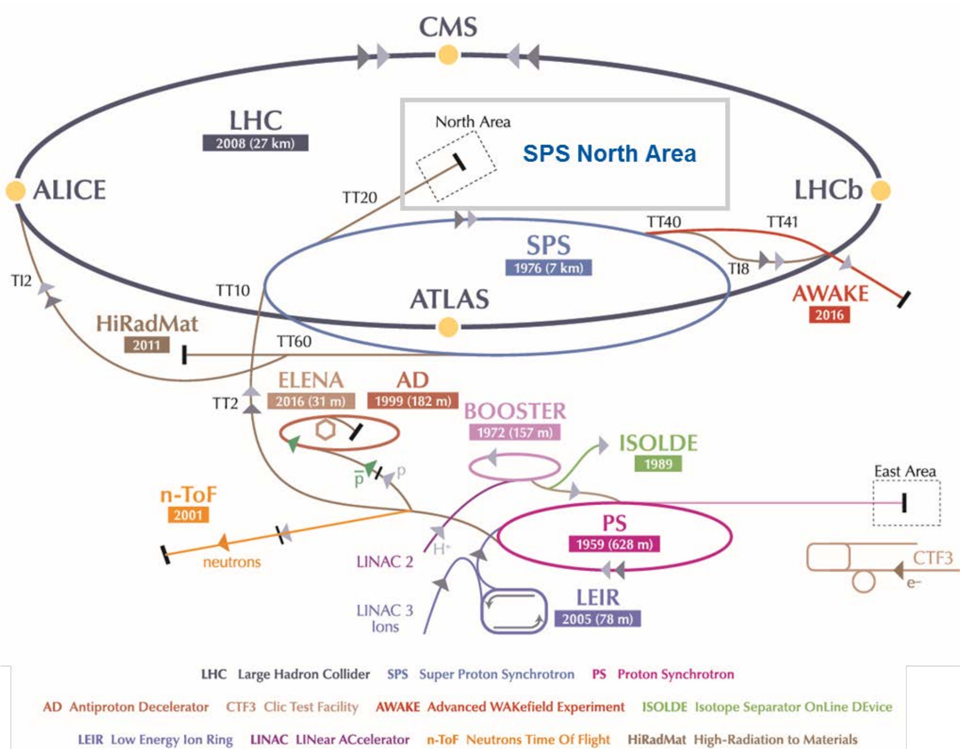
- BDF/SHiP concept
- SHiP test beams
  - Muon flux measurement
  - Charm production cross section measurement
- BDF prototype target test beam
  - Radiological aspects during the test
  - Benchmark of samples activation and tritium out-diffusion
- Summary and conclusions

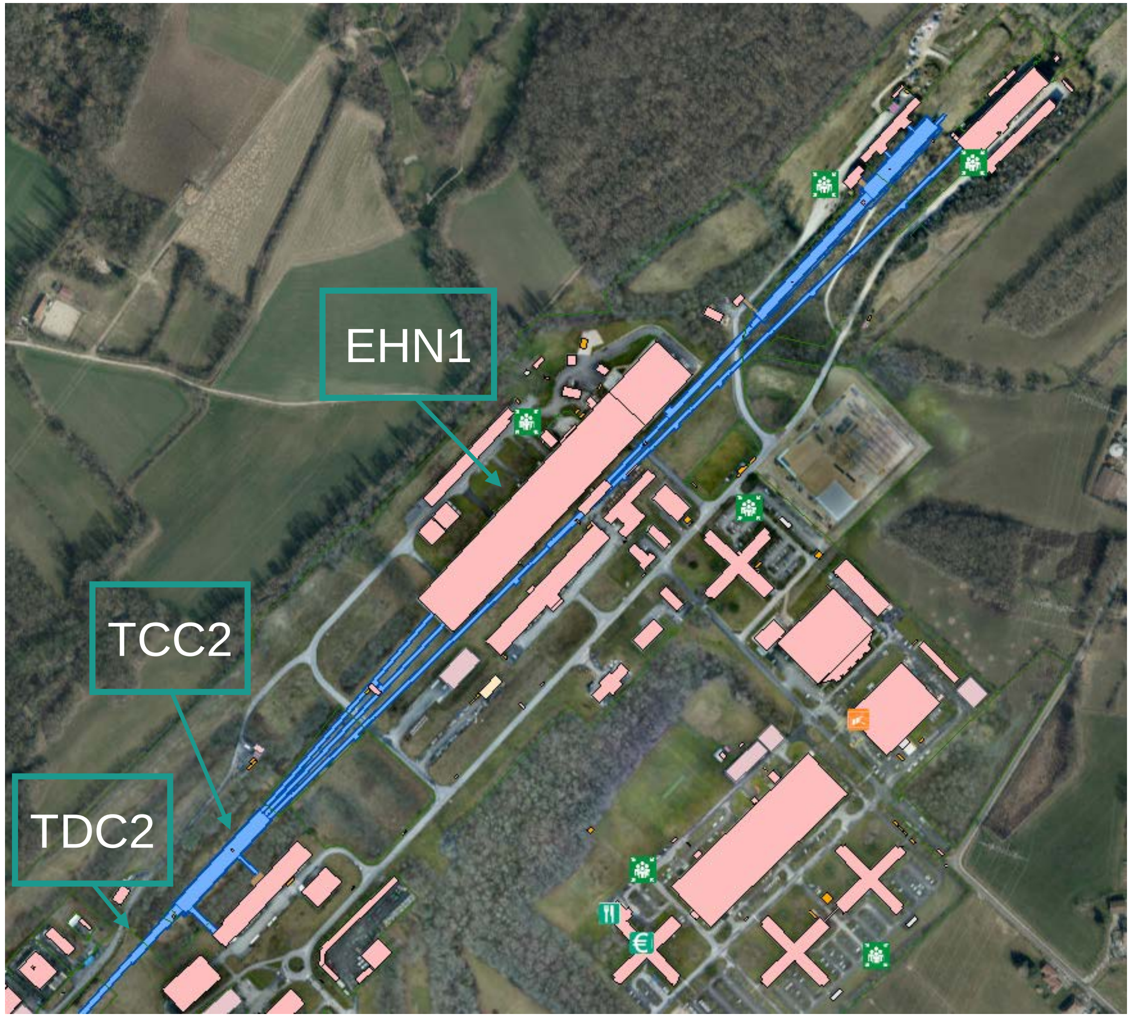
The SPS North Area



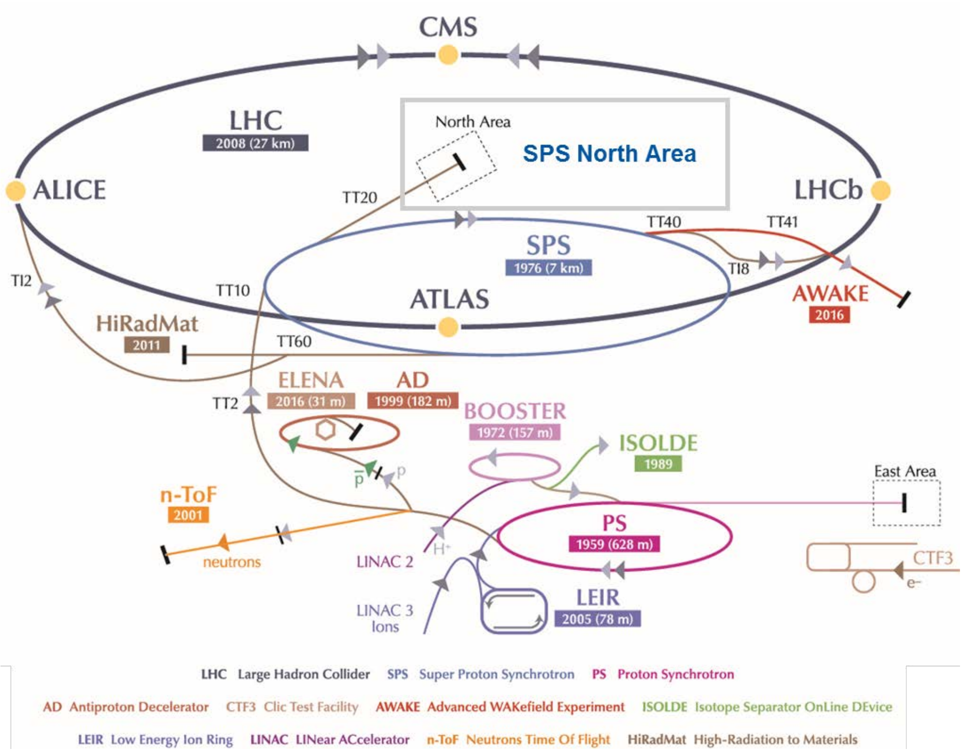


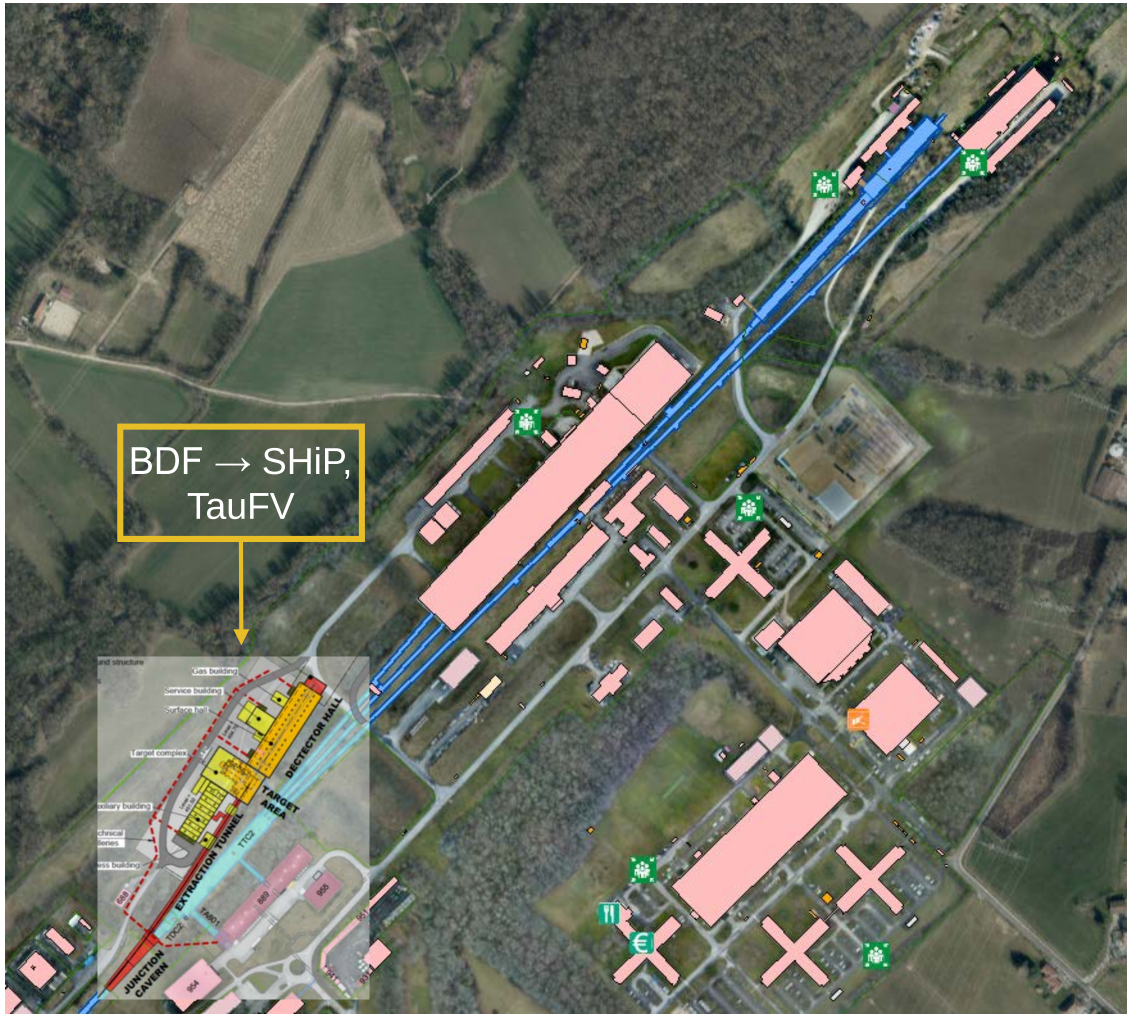
The SPS North Area



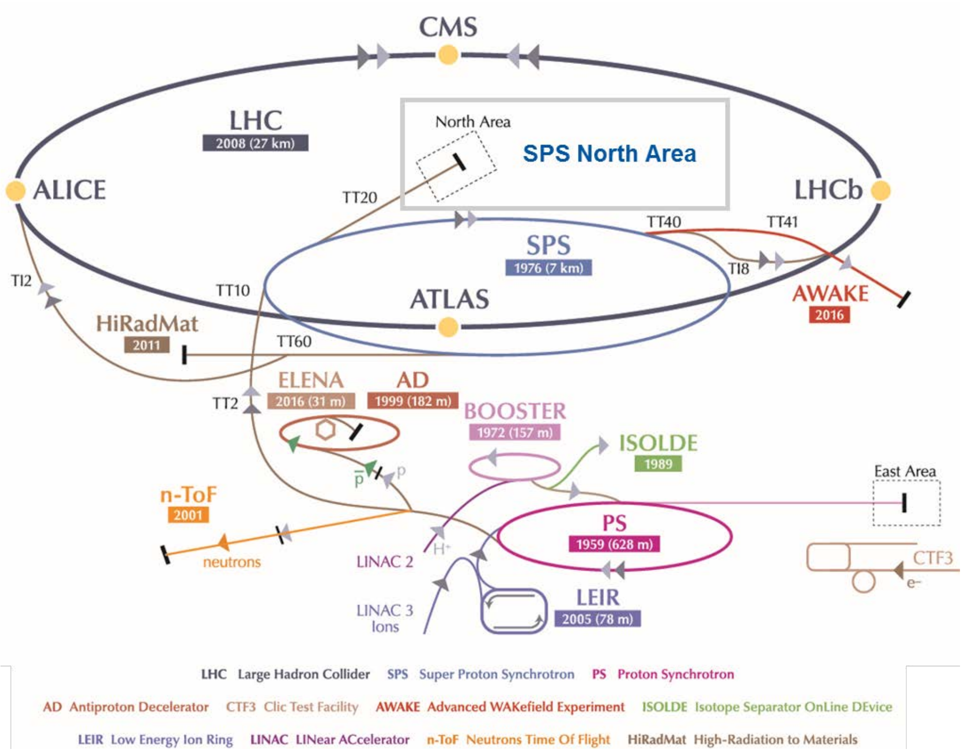


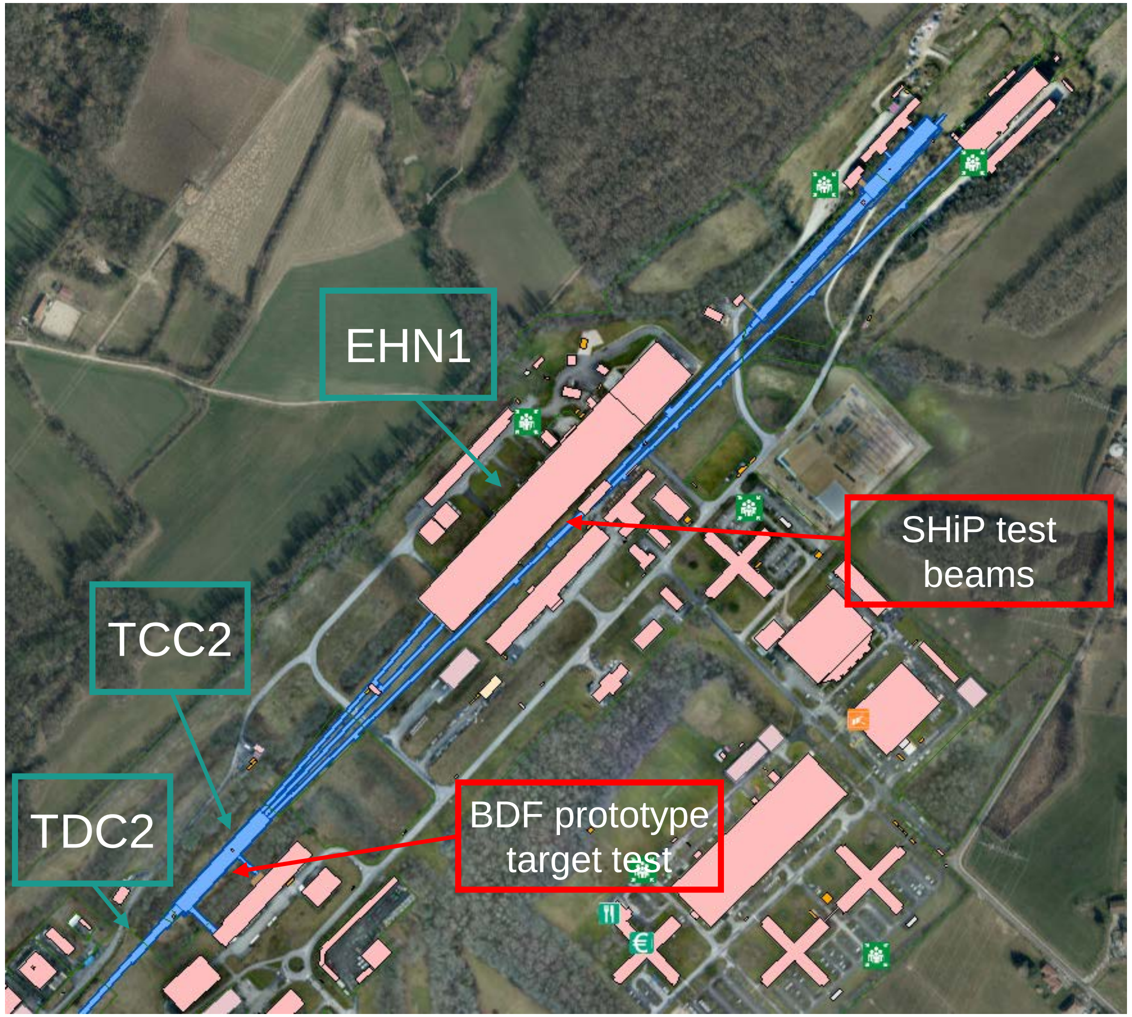
The SPS North Area





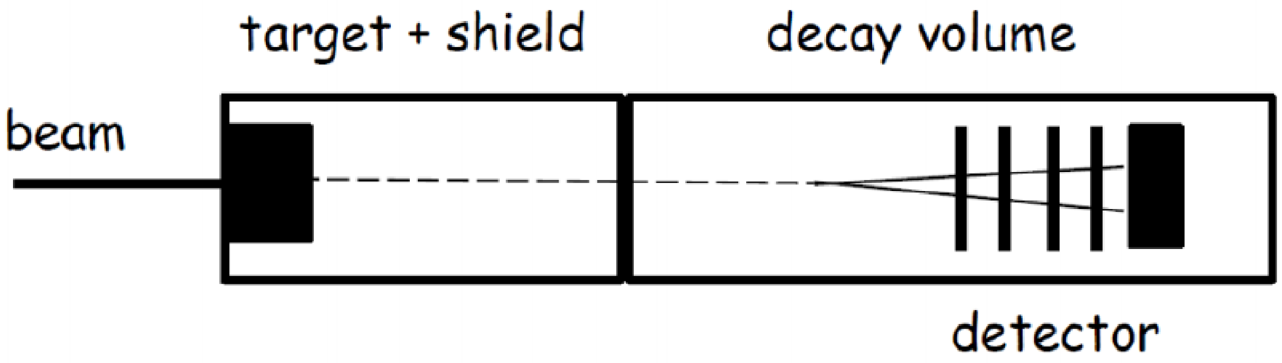
The SPS North Area





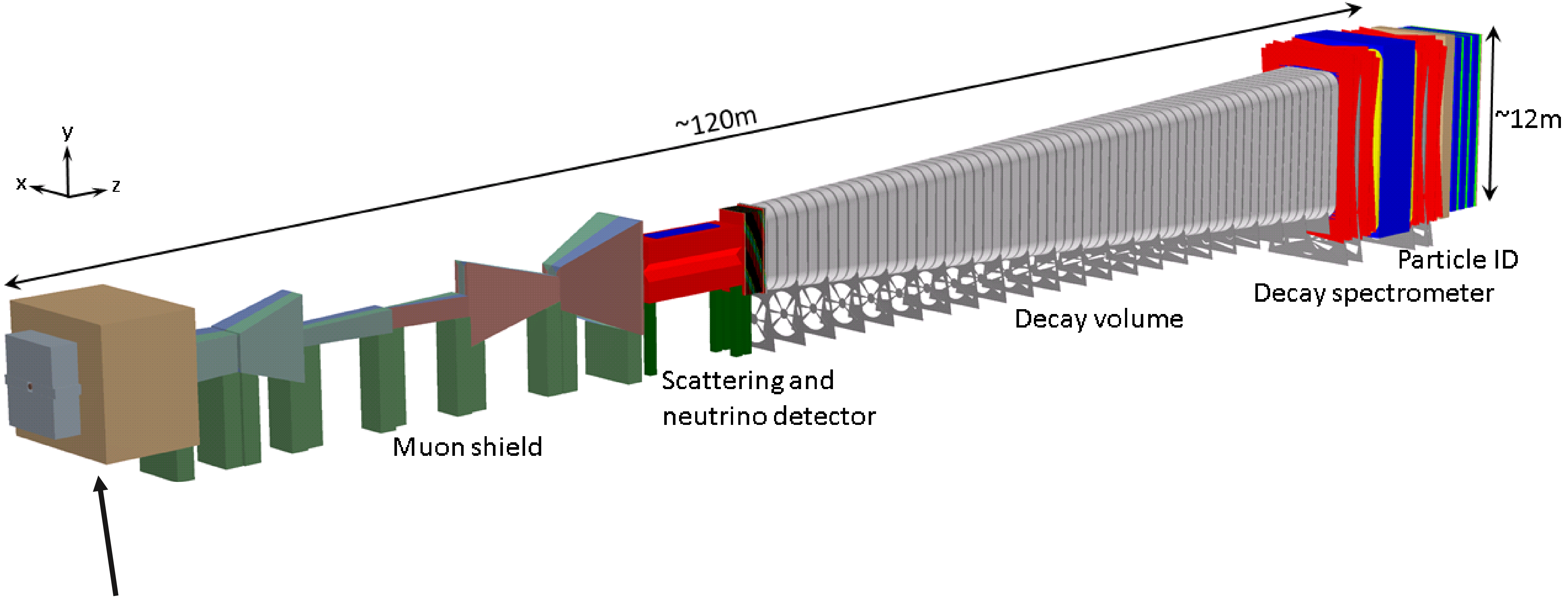
The SHiP experiment

Experimental concept [1]



- **High Intensity** beam into an heavy target ($12\lambda_{int}$):
  - Maximize New Physics particles production
    - either coming from heavy (charmed) meson decays or from proton-nucleus interactions
  - Suppress pion and kaon decays which is source of background
- Minimize the flux of SM particles in the detector
- Define a (large) fiducial volume where the background level is approximately zero
- Detection by decay or by interaction with matter

SHiP overview



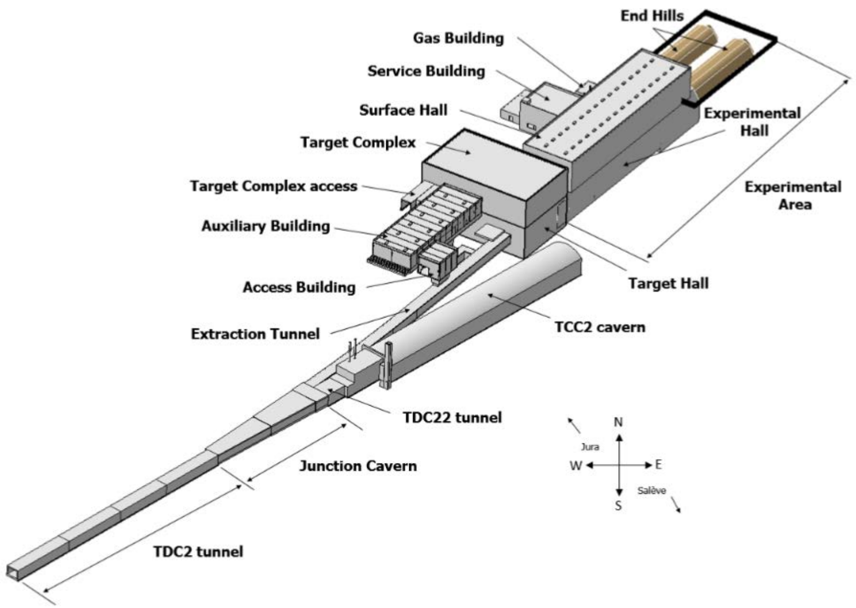
BDF target and target complex

The Beam Dump Facility at SPS

BDF [2] is a proposed permanent facility in the North Area at CERN

- High intensity proton beam slow extraction → Design of the facility not only driven by radiological constraints
- Proximity to experimental and public areas
  → **Minimize impact on other facilities and environment**
- Dense target located at the core of the facility
  - Absorb majority of the SPS beam
  - **High activation expected**
- Keep **flexibility for future installations**

Civil engineering layout and surrounding facilities



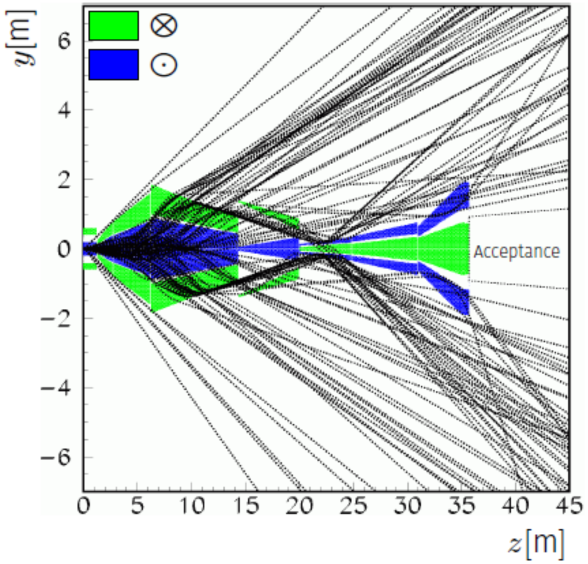
Key beam parameters for SHiP

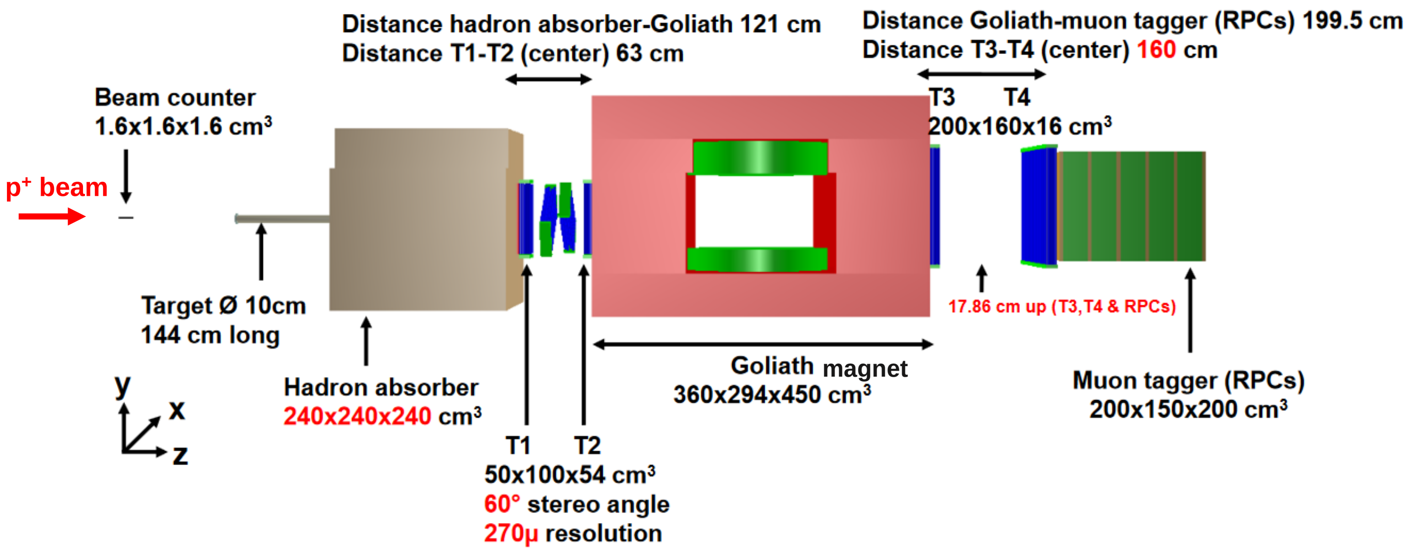
Momentum	400 GeV/c
Beam intensity on target	4×10^{13}
Cycle length	7.2 s
Spill duration	1 s
Avg. beam power on target	355 kW
Protons on target (PoT)/year	4×10^{19}
Total PoT in 5 years data taking	2×10^{20}

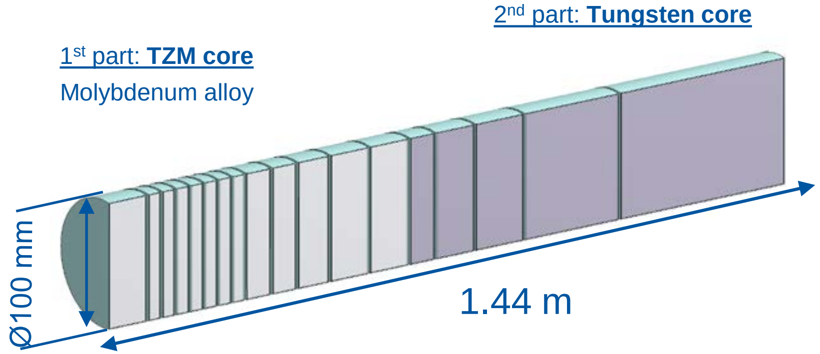
SHiP test beams in H4

SHiP muon flux measurement

- SHiP uses a series of shielding magnets to reduce the muon-flux inside the experiment's acceptance by several orders of magnitude
- The design of this shield [3] relies on the phase space of the muons
- Measure the flux and phase space [4] before the construction of the shield







Shielding requirements

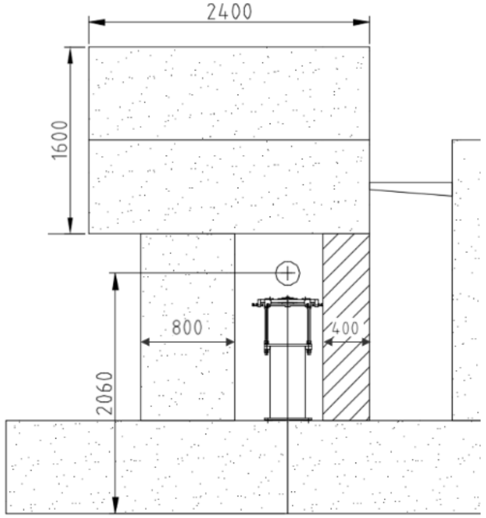
- Proposal to accumulate $6*10^{11}$ 400 GeV/c PoT over a month
  - Need of beam intensity of 10^7 p/spill (maximum in normal configuration in this zone is 10^6 p/spill)

- Dedicated shielding designed (using FLUKA simulations) to respect ambient dose equivalent rate limits
  - Areas accessible during beam operation classified as Supervised Radiation Area with no permanent workplaces (<15 μSv/h) - This includes the crane driver cabin.

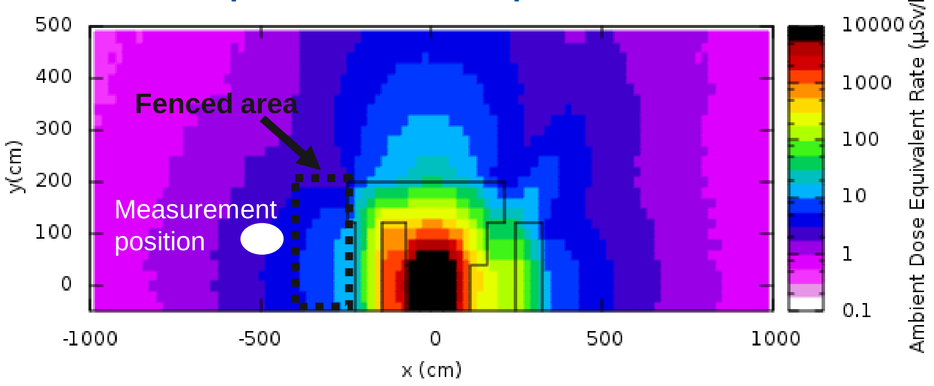
Beam parameters for muon flux measurement

Momentum	400 GeV/c
Beam intensity on target per spill	1×10^7
Cycle length	14-24 s
Spill duration	4.8 s
Max protons on target (PoT)/week	2.5×10^{11}
Total PoT	6×10^{11}

Cross sectional view of target shielding



Prompt ambient dose equivalent rate



CERN Area Classification

	Area	Dose limit [year]	Ambient dose equivalent rate: permanent	Ambient dose equivalent rate: low occupancy	Sign	
	Non-designated	1 mSv	0.5 μSv/h	2.5 μSv/h		
Radiation Area	Supervised	6 mSv	3 μSv/h	15 μSv/h	Dosimeter obligatory / Dosimètre obligatoire	
Radiation Area	Simple	20 mSv	10 μSv/h	50 μSv/h	Dosimeter obligatory / Dosimètre obligatoire	Controlled Area
Radiation Area	Limited Stay	20 mSv		2 mSv/h	LIMITED STAY / SÉJOUR LIMITÉ / Dosimeters obligatory / Dosimètres obligatoires	Controlled Area
Radiation Area	High Radiation	20 mSv		100 mSv/h	HIGH RADIATION / HAUTE RADIATION / Dosimeters obligatory / Dosimètres obligatoires	Controlled Area
Radiation Area	Prohibited	20 mSv		> 100 mSv/h	PROHIBITED AREA / ZONE INTERDITE / No Entry / Défense d'entrer	Controlled Area

Radiation measurements and residual activation

- At the beginning of the test beam ambient dose rate were measured
  - Using REM counter (WENDI)

Intensity	Measured prompt dose rate (uSv/h)	Simulated prompt dose rate (uSv/h)	Ratio Measured/Simulated
10^7 p every 14s	4±1	4.4±0.1	0.9±0.2

- After 1 week got a request from the experiment to raise intensity to $2*10^7$ p/spill
  - Second measurement was performed to authorized it

Radiation measurements and residual activation

- At the beginning of the test beam ambient dose rate were measured
  - Using REM counter (WENDI)

Intensity	Measured prompt dose rate (uSv/h)	Simulated prompt dose rate (uSv/h)	Ratio Measured/Simulated
10^7 p every 14s	4±1	4.4±0.1	0.9±0.2
$2*10^7$ p every 19s	7±1	6.5±0.1	1.1±0.1

- After 1 week got a request from the experiment to raise intensity to $2*10^7$ p/spill
  - Second measurement was performed to authorized it

- After 15 days of cooling residual ambient dose rate from the target were measured

Position	Measured residual dose rate (uSv/h)	Simulated residual dose rate (uSv/h)	Ratio Measured/Simulated
Contact	11±1	13.0±0.1	0.85±0.8
At 10 cm	4.7±0.1	5.40±0.02	0.87±0.02
At 40 cm	1.0±0.1	1.40±0.02	0.71±0.07

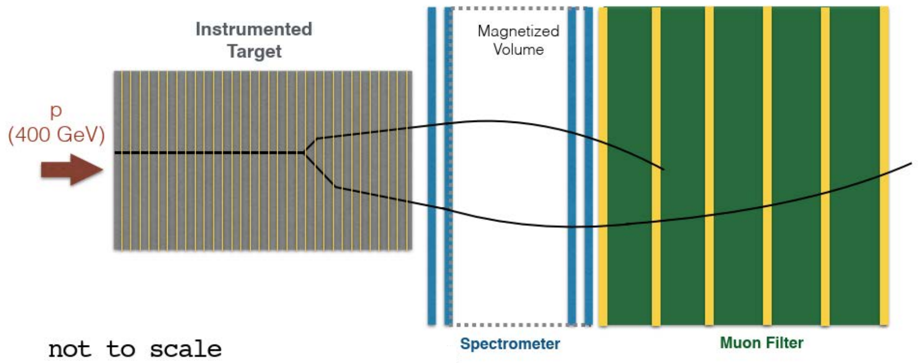
Good agreement found with simulations within 30%

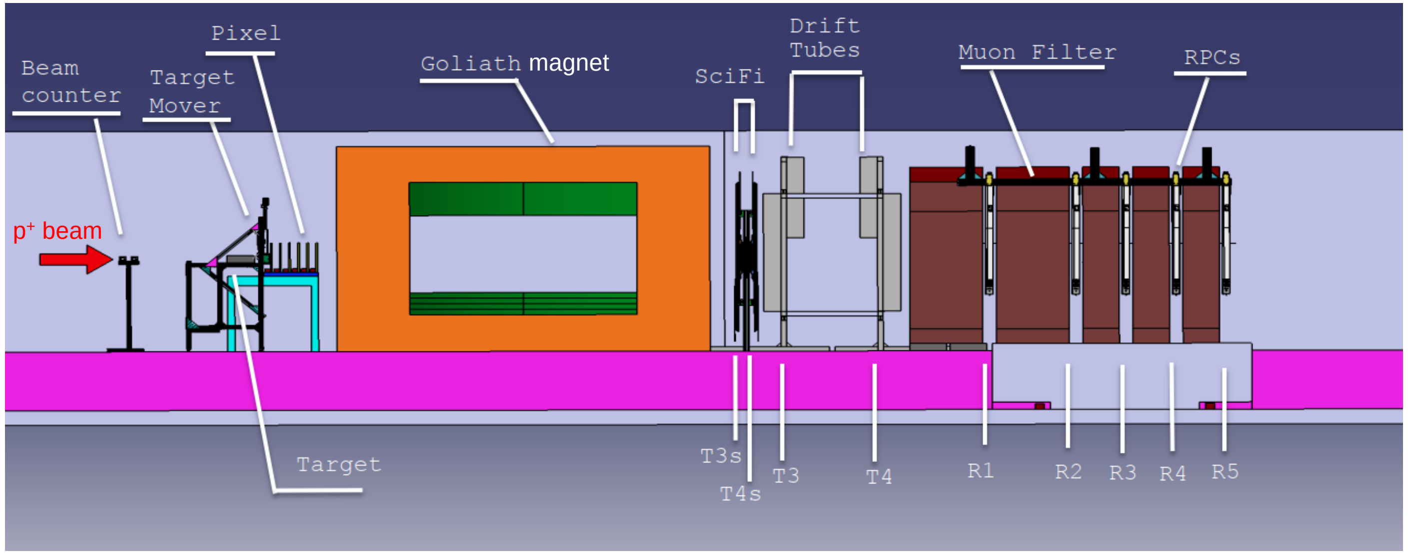
SHiP charm production cross section measurement

- Motivation:
  - Study charm production
  - Measure for first time charm production in hadronic cascades [4]

- Flux of hidden particles and expected tau neutrinos depend on charmed hadron production

- Similar setup as the muon flux measurement





- The target for the muon flux measurement has not been used in this configuration

- Use of dedicated lead target instrumented with nuclear emulsions as tracking detector

Activation of the target

- No need of additional shielding for the test due to low beam intensity required (10^5 p/spill)

- Particular care of the target:
  - Use of ultra-pure lead slices (up to 3.5λ)
  - Keep the activation below Swiss clearance limits (LL)
    - Limit number of pulses on different lead layers

Radionuclide	Half-life	Activity (Bq)	Multiple of LL (Bq/kg)
Pb-202M	3.57h	1.90e+01	0.002
Tl-195	1.16h	1.40e+01	0.001
Pb-199	1.5h	1.00e+01	0.001

Activities of the most activated lead slice after irradiation with 50 spills

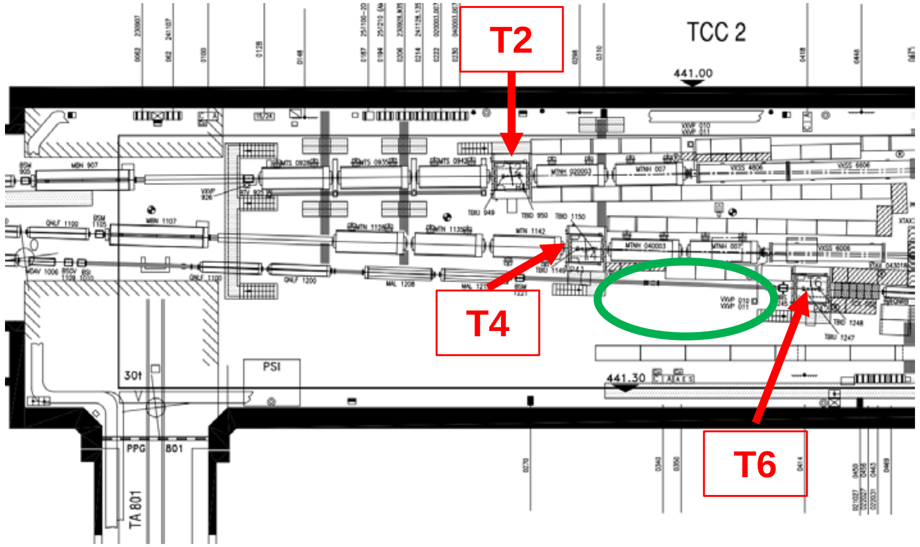
- Simulations predicted slices to be well below clearance limits

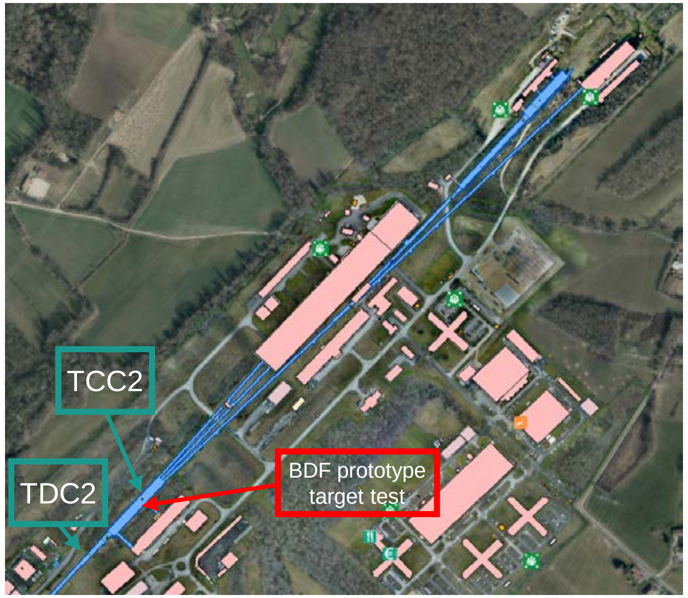
- Radiation measurements after the test beam confirmed that compliance with the clearance limits for the lead slices and they were therefore treated as non radioactive material

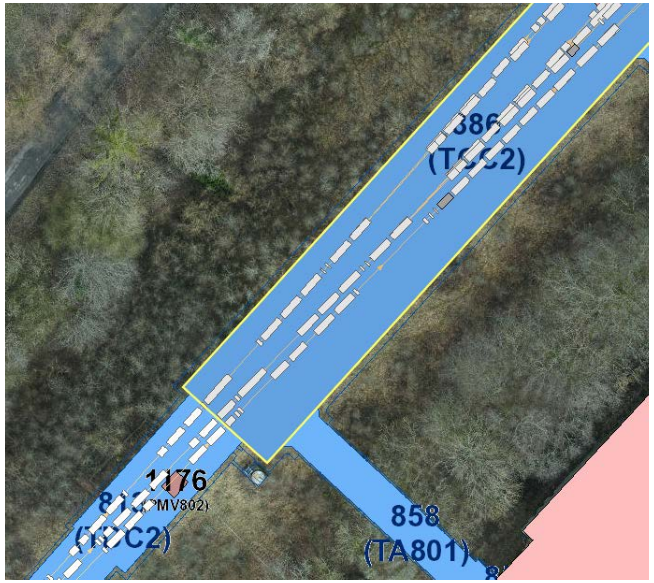
BDF/SHiP target prototype test

- Target prototype test to evaluate material response and instrumentation in an unprecedented regime of temperature and stresses

- BDF conditions require slow extraction
  - Available in the North Area target zone (TCC2)







- 3 targets in the North Area target zone (T2,T4,T6)
- Intensities up to 10^{13} protons per pulse

Available space for the test beam upstream of T6 thanks to lack of wobbling magnets and absence of vacuum pipe

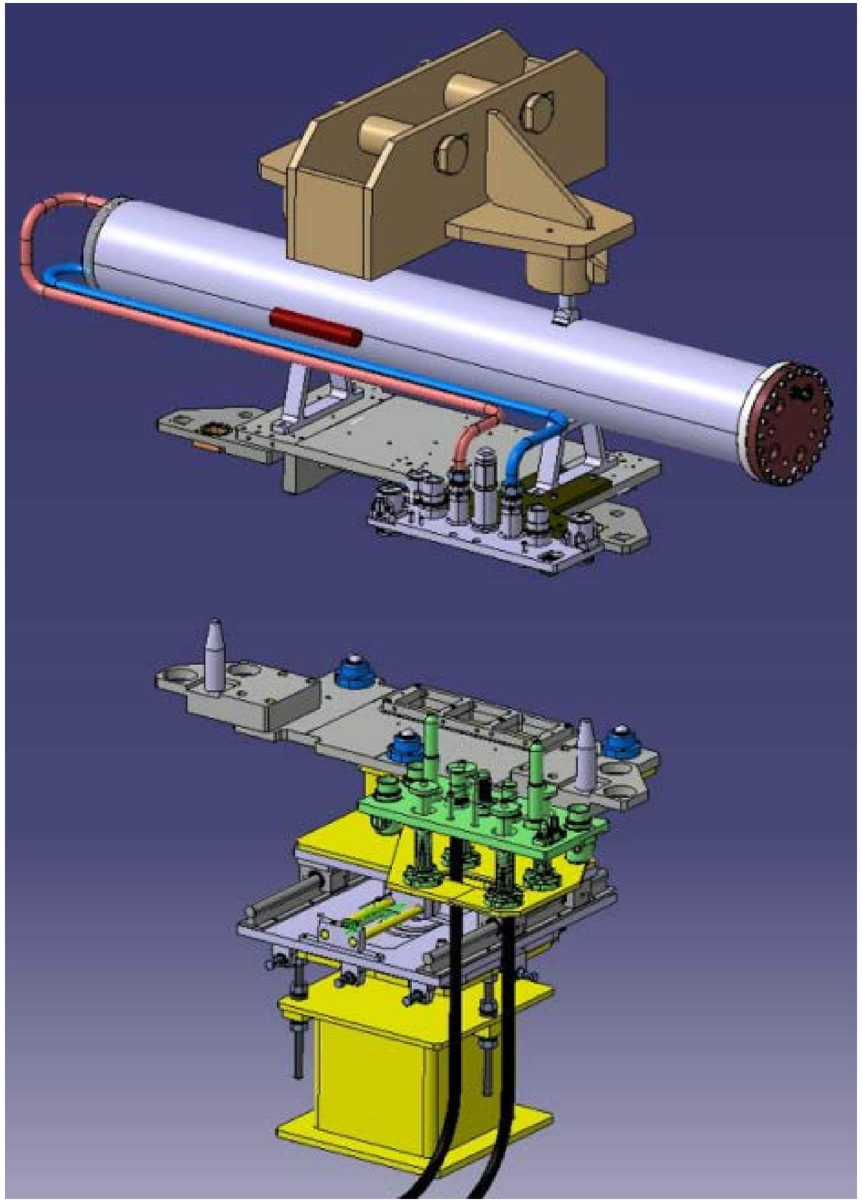
BDF/SHiP target prototype test

- The target replica consists in a reduced scale prototype of the BDF final target [5][6]:
  - cylinders have a diameter of 80 mm (instead of 250 mm)
  - same length distribution
  - same core and cladding materials

- High beam load and high density / Z composition of target → high material activation:
  - Target installation and dismantling remote handling friendly
  - Particular care to radiation protection aspects

Beam parameters for BDF prototype test

Momentum	400 GeV/c
Beam intensity on target	5×10^{12}
Cycle length	7.2 s
Spill duration	1 s
Objective protons on target (PoT)	3×10^{16}
Power deposited on target each cycle (kW)	23

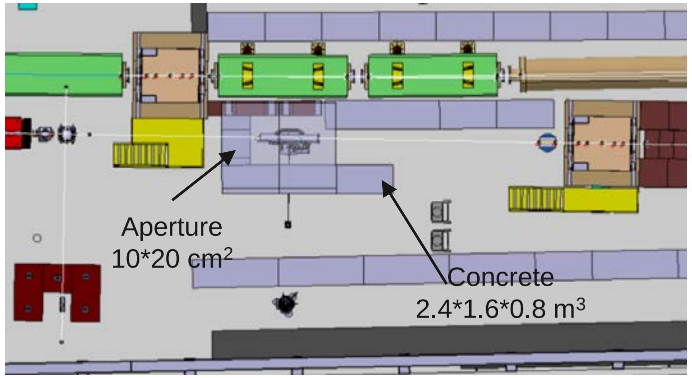


Shielding and residual dose rate

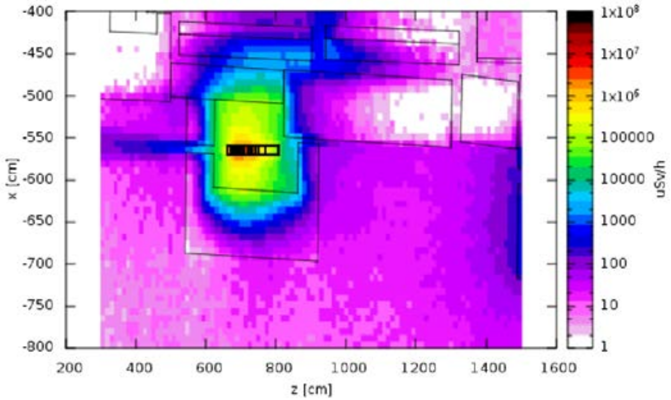
- Shielding and residual dose studied with the maximum foreseen intensity and objective PoT ($3*10^{16}$ PoT)
- During the test collected $2.4*10^{16}$ PoT
- Target residual dose rate measured after 11 months and 20 days

Position	Measured dose rate (mSv/h)	Simulated dose rate (mSv/h)
Contact to target	26±1	25.15±0.01
40 cm from target	5±1	4.42±0.01

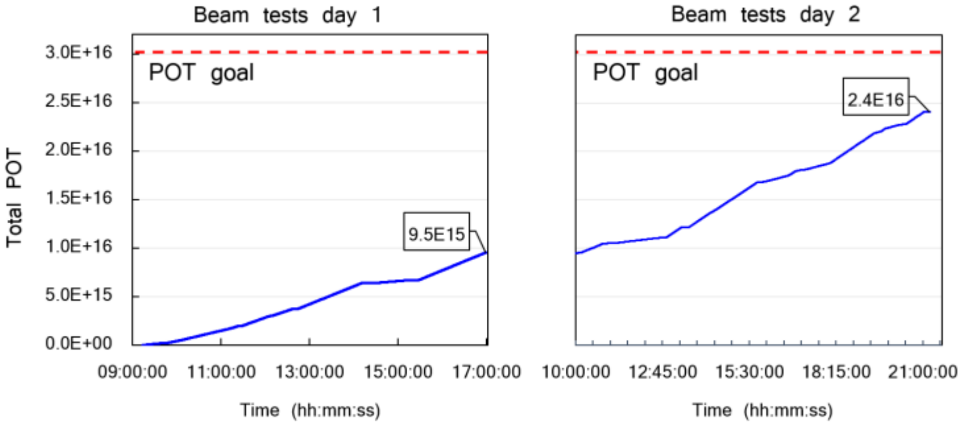
Shielding configuration



Residual dose rate for $3*10^{16}$ PoT
(1 week cooling)



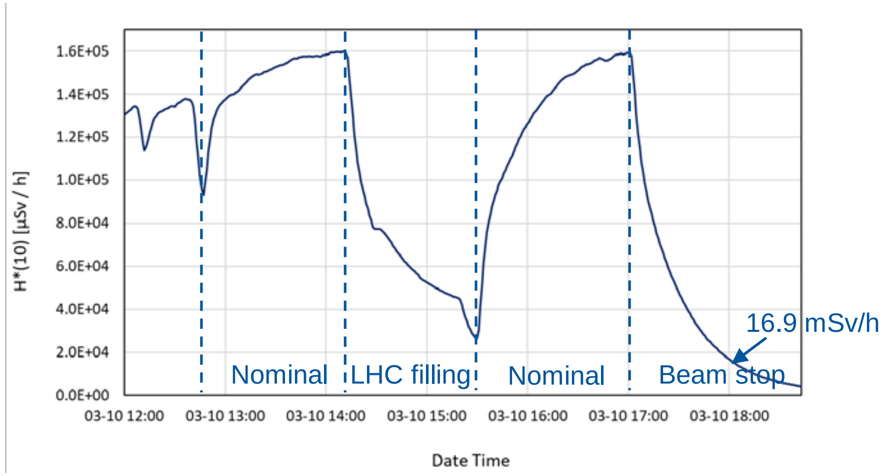
1st beam on 03/10/2018 and 2nd on 24/10/2018



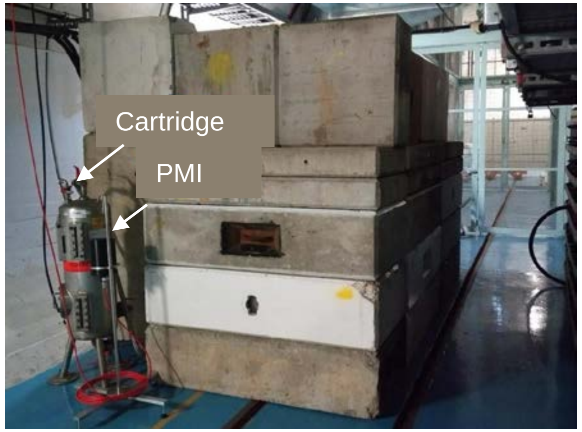
Water activation

- Dedicated cooling station for target cooling with demineralized water
  - Risk of target damage due to high mechanical stresses
  - Mechanical filters and ion exchanger to catch impurities and activated ions
- Water activation estimated using Actiwiz3 Creator → 18.7 mSv/h at 40 cm after 1h of beam stop
- PMI at cartridge at 40 cm distance in agreement with simulations

PMI dose rate



Shielded cooling station



Water activation

- Sampling valve for indication about target integrity → samples included spallation products
  - Debris present in the first 2 samples
  - Fit to simulation indicates bronze as the parent material (target wheels or pins to stop blocks)
  - Chemical analysis scheduled in October 2019 to confirm
  - Quantity estimated 0.03 g/l

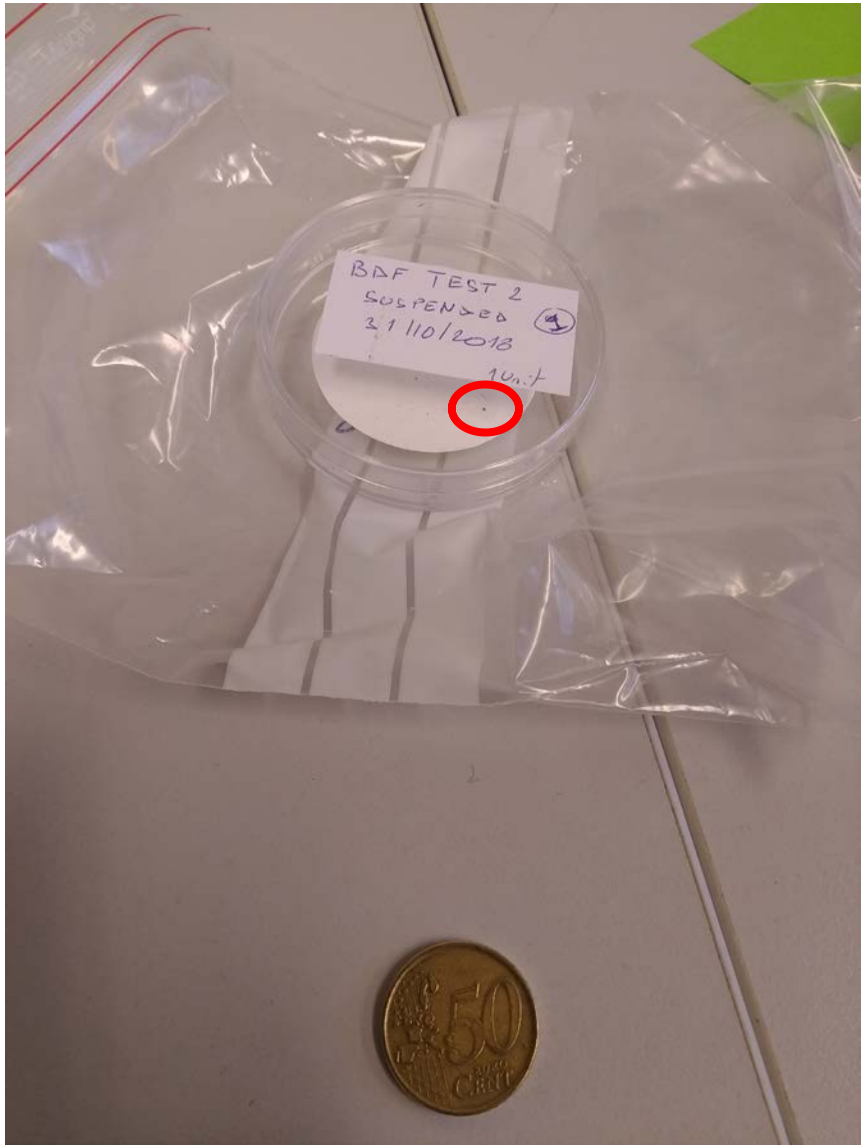
After 1st beam session

Nuclide	Activity (Bq/l)	Error 1 sigma
Be-7	7.70E+03	6.6%
Sc<Sc44m	2.49E+01	6.9%
Sc-46	1.51E+01	7.8%
Y-87	1.45E+01	8.4%
Ag-106m	1.41E+01	9.6%

After 2nd beam session

Nuclide	Activity (Bq/l)	Error 1 sigma
Sc<Sc44m	8.69E+01	5.7%
Y-87	4.85E+01	6.2%
Be-7	2.37E+03	6.8%
Sc-46	6.88E+01	6.8%
Lu-171	8.51E+01	6.8%
Tb-155	4.57E+01	7.0%
Tm-166	7.05E+00	7.7%
Yb-169	3.13E+01	7.8%
Gd-149	3.79E+01	8.1%
Eu<Gd146	1.19E+01	8.3%
In-111	1.13E+01	8.5%
Tm-167	7.14E+01	8.9%
Sc-47	1.17E+02	9.2%
Ru-97	1.27E+01	9.3%

NB: Only nuclides with error < 10% are shown



Tritium out-diffusion

Tritium has a very low radio-toxicity but it can be a radiation hazard when:

- inhaled
- ingested via food or water
- absorbed through the skin

- Tritium is relatively volatile and can diffuse through materials
- 95% of BDF tritium is produced in the target, **out-diffusion** important for the environmental impact of the facility
  - It can be absorbed by the water (HTO form) and circulated in the water cooling system.
- For the iron and concrete shielding tritium outgassing contributes to contamination of air as well during no beam periods.
- Assumption of an immediate **release of 100%** can be **over-conservative**
- In literature **diffusion coefficients** for tritium [7] are **available only for few materials** and not in the full temperature range
  - Arrhenius equation used to extrapolate to operational temperatures

Tritium out-diffusion from BDF prototype target

Analysis of tritium concentration in the cooling circuit of the BDF

- Several samples (1 every two months) analysed through liquid scintillation
- Measurements showed higher concentration than simulated

PoT collected	Simulated H-3 concentration (Bq/l)	Measured H-3 concentration (Bq/l)
2.5e16	$(2.7\pm0.3)*10^5$	$(4.8\pm0.5)*10^5$ (11/2018) $(5.1\pm0.5)*10^5$ (1/2019) $(5.1\pm0.5)*10^5$ (3/2019) $(5.1\pm0.5)*10^5$ (5/2019)

No significant out-diffusion seen during no beam period

Two possible explanation of the higher tritium concentration:

- Release of tritium from the bronze debris
- Tritium out-diffusion during beam period → to be estimated

Material	Max temperature during beam (ºC)	Temperature no beam (ºC)	Ratio between diffusion constants
TZM	280	20	$5*10^7$
W	160	20	150
Ta	195	20	10

Tritium out-diffusion from BDF samples

- Profit from the BDF prototype test to measure H-3 out-diffusion from different samples
  - Possibility to measure tritium diffusion rates
- Samples include most critical materials for BDF: Tungsten, Tantalum, TZM, Cast Iron and Concrete
- Support for samples on outer target tank and remote handling procedure for sample removal
  - Removed with robot after first irradiation in October 2018 with $0.9*10^{16}$ PoT
- Measure of tritium outgassing in air with a bubbler and outgassing in water by immerging the samples
  - Temperature during the measurement between 12-18 ºC

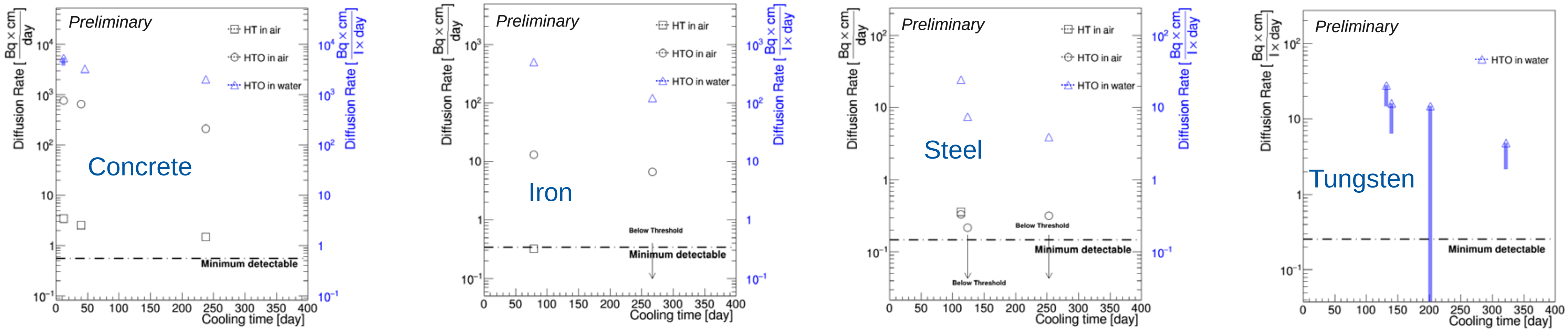
Material sample support

Measurement setup

Tritium out-diffusion from BDF samples

Material	Simulated H-3 Activity (Bq)
Concrete	1.6×10^5
Iron	2.2×10^5
Steel	8.3×10^4
Tungsten	8.7×10^4

- Preliminary results shown for a subset of the materials
  - Measurement still ongoing
- Results normalized by the ratio $\frac{\text{surface}}{\text{volume}}$
- Other beta emitters contamination for the measurement in water shown as shaded area → Tungsten shows the highest contamination
- Higher diffusion from concrete at ambient temperature
  - Good choice to reduce concrete inside BDF He vessel

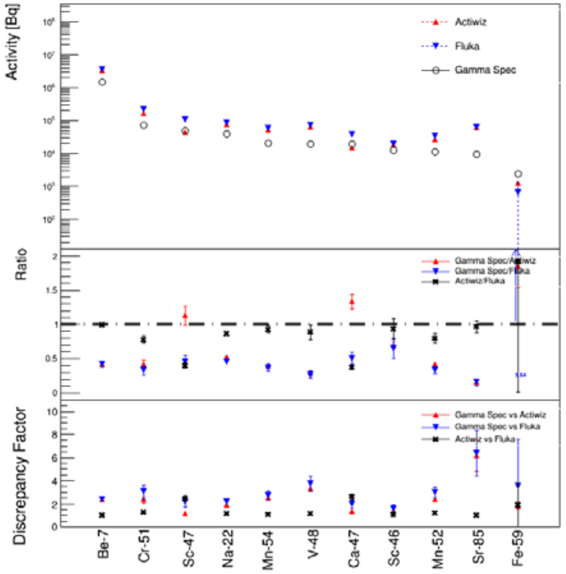


Activation of BDF samples to benchmark FLUKA/Actiwiz simulations

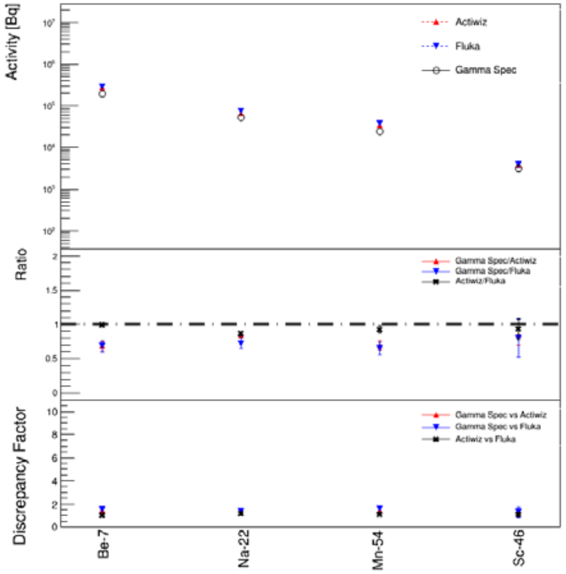
- Profit from the activation of BDF samples to benchmark simulations
- Good agreement between simulation and gamma spectroscopy data
  - From relatively short (few days/weeks after beam stop) to long (few months) cooling times

Concrete

3 weeks of cooling

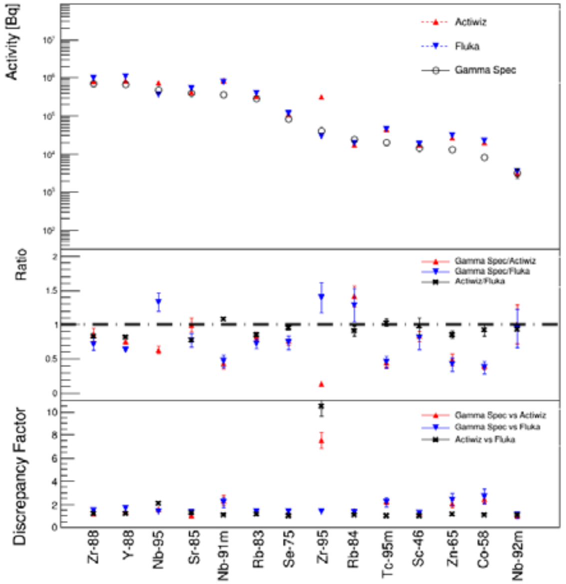


7 months of cooling

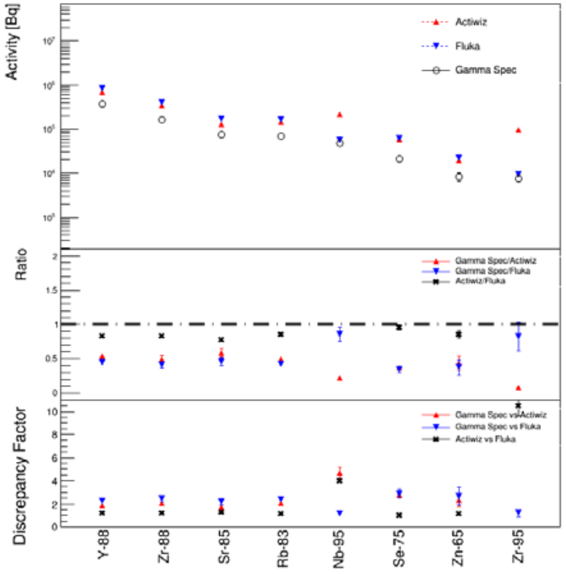


TZM

3 months of cooling

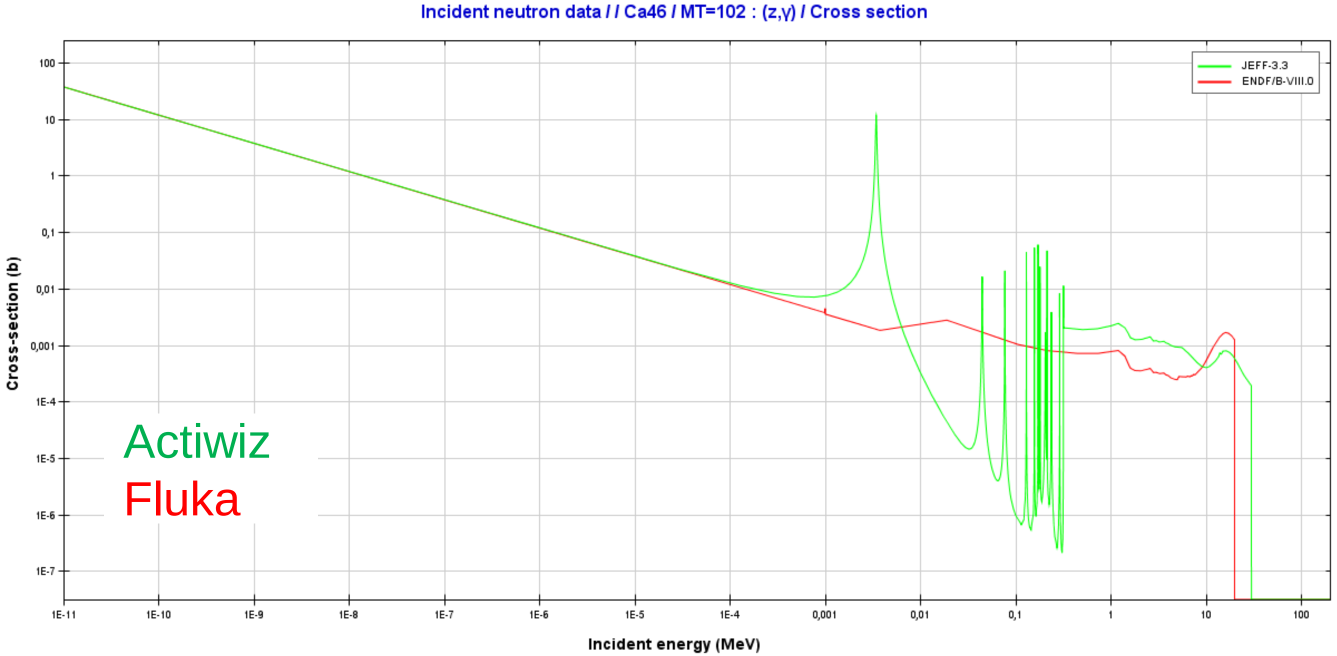


7 months of cooling



Activation of BDF samples to benchmark FLUKA/Actiwiz simulations

- Profit from the activation of BDF samples to benchmark simulations
- Good agreement between simulation and gamma spectroscopy data
  - From relatively short (few days/weeks after beam stop) to long (few months) cooling times
- Differences between FLUKA and Actiwiz traced down to different low energy neutron cross sections:
  - For example Ca-47 from Ca-46



Summary and conclusions

- The proposed BDF would be a **new facility** with unprecedented beam intensity deposited on target
  - SHiP will be the first experiment on this facility

- Three test beams have been successfully conduced at CERN during 2018
  - Radiological studies and optimization measures were critical for the success of these test beams
  - Studies of water activation gave insight on the target integrity
  - Profit from the test beams to better understand **tritium out-diffusion**, which it is important for the BDF environmental impact
    - Tritium diffusion measurements on samples **performed at CERN for the first time**
    - **Concrete shows higher diffusion** than other materials
    - Tungsten diffuses out other beta emitters as well

- Part of these studies are included in the BDF comprehensive design study:

  C. Ahdida et al., SPS Beam Dump Facility: Comprehensive Design Study, CERN-PBC-REPORT-2018-001

Thank you for your attention!

References

[1] **SHiP Collaboration**, *A facility to Search for Hidden Particles (SHiP) at the CERN SPS,* arXiv:1504.04956, 2015
[2] **K. Kershaw et al.,** *Design Development for the Beam Dump Facility Target Complex at CERN,* JINST 13 P10011, 2018
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