13th International Workshop on Spallation Materials Technology
30 October – 4 November 2016, Chattanooga, US

Spallation materials R&D and application for Beam Intercepting Devices (BID) at CERN and the HiRadMat facility

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EN Department, STI Group
Targets, Collimators and Dumps section

CERN | EN ENGINEERING DEPARTMENT

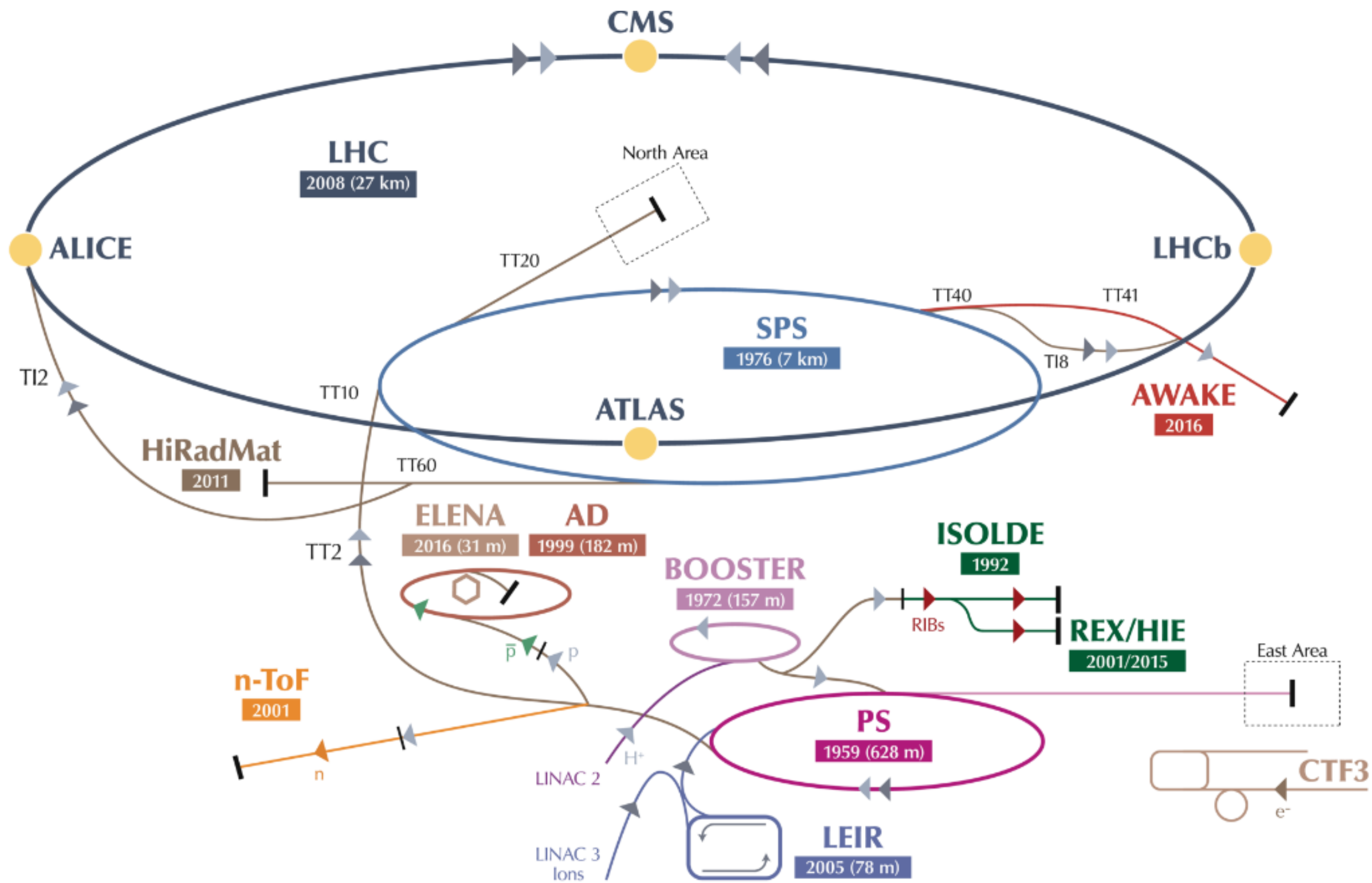
Outlook

- Introduction to CERN accelerator complex
- n_TOF spallation target
- The HiRadMat facility
- AD-Target and HiRadMat 27 experiment
- The proposed Beam Dump Facility
- Long-term irradiation BLIP for high-Z material

Review of CERN’s spallation targets

- CERN has a long and varied history of fixed target experiments, contributing to a diverse program of research
  - Essential part of the lab’s scientific program
- Hadron physics (COMPASS, NA61...)
- Nuclear physics (ISOLDE)
- Neutron physics (n_TOF)
- Antimatter physics (AD)
- *Proposed “Hidden particle” searches (BDF/SHiP)*

CERN's accelerator complex



~10^{15} proton/year to LHC

>10^{20} protons/year to fixed targets

Ongoing projects on spallation target

1. **New spallation target for n_TOF**
2. **Antiproton production target** & related R&D

- For both, beam validation in 2018, installation in 2020, operation in 2021

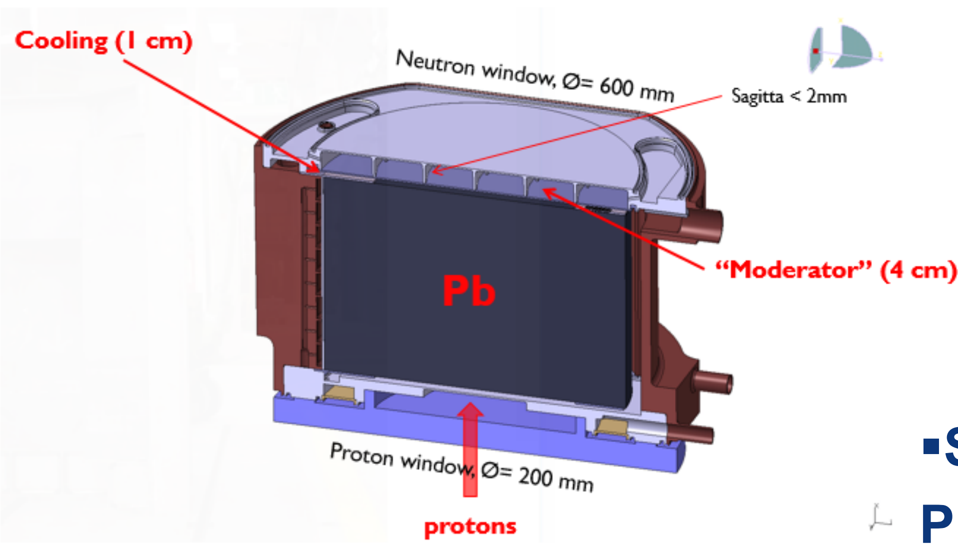
3. **Beam Dump facility**
   - R&D project to be developed 2017-2019

- Materials of interest
  - Ti6Al4V, iridium, TZM, Pb + pure Si

n_TOF spallation target

n_TOF spallation target #2

- n_TOF facility, currently running a lead-based (bare core) spallation target for neutron production
- Wide neutron spectrum from 25 meV to 20 GeV (11 orders of magnitude)



- 7 years operation:
  - Average conductivity **<0.15 μS/cm**
  - Oxygen content below **80 ppb**
  - Full continuous purification via redundant ion exchangers
  - Purified N_2 flush via a Liqui-Cel® membrane
- **Significant water contamination with Pb spallation products**

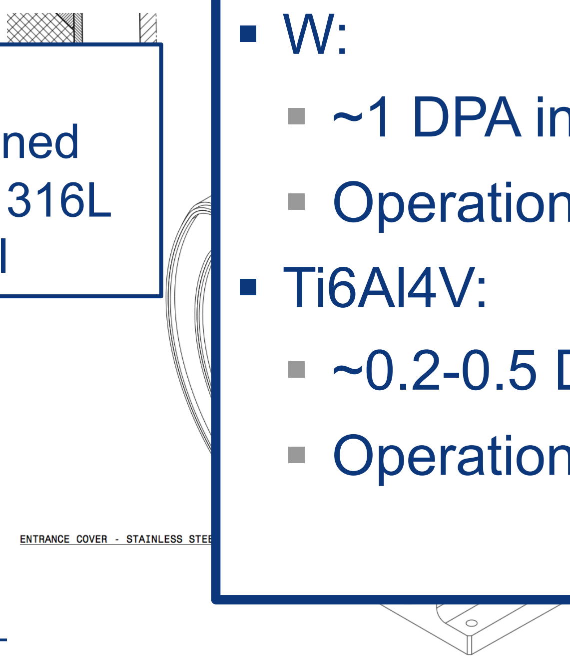
n_TOF spallation target #3

- Two solutions being investigated
  - **Ti6Al4V-contained pure Pb core (shrink fit + cast)**
  - **Ta-cladded W core (HIPping) + Pb multiplier**
- Critical objective is to guarantee thermal contact between the core material a

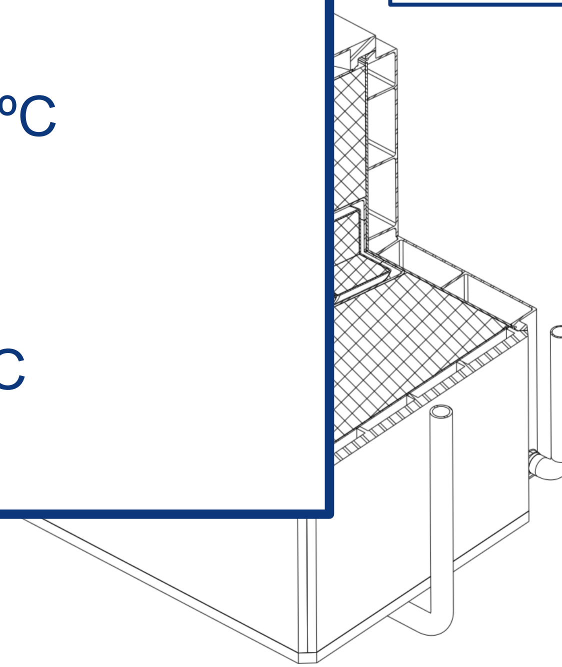
For POT of 2e20 (10 years of operation):

- W:
  - ~1 DPA in the core
  - Operational T ~100-200 ºC
- Ti6Al4V:
  - ~0.2-0.5 DPA
  - Operational T <90-100 ºC

Ti6A-contained Pb w/ 316L vessel

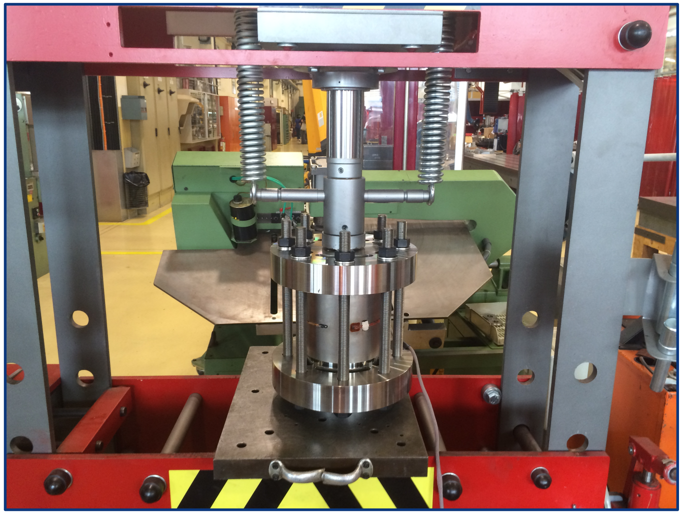


Ta-cladded W



n_TOF material prototyping (I/II)

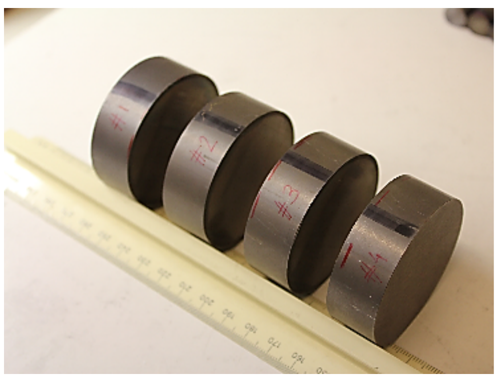
- Ti6Al4V-contained Pb prototypes (1:4)
  - Pb cryogenic shrink fitting into Ti6Al cylinder

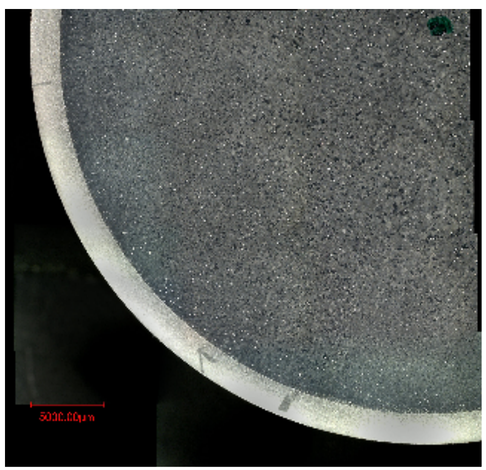


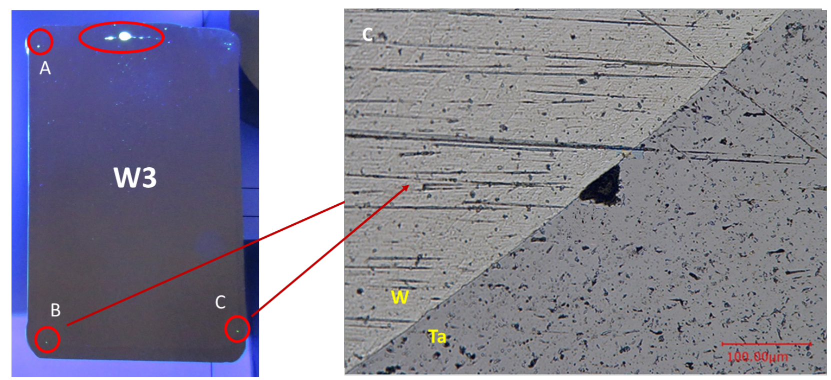
- First results encouraging, prototyping finalization by April 2017
- Possibility to add a beryllium stiffener to contain Pb plasticization is under study

n_TOF material prototyping (II/II)

- Ongoing orders with external companies to validate quality of the surface bonding
  - Non destructive + destructive tests
  - Synchrotron x-ray tomography (ESRF)
- Possible development in-house at CERN at a later stage
- Results are positive and convincing that the “recipe” is correctly executed





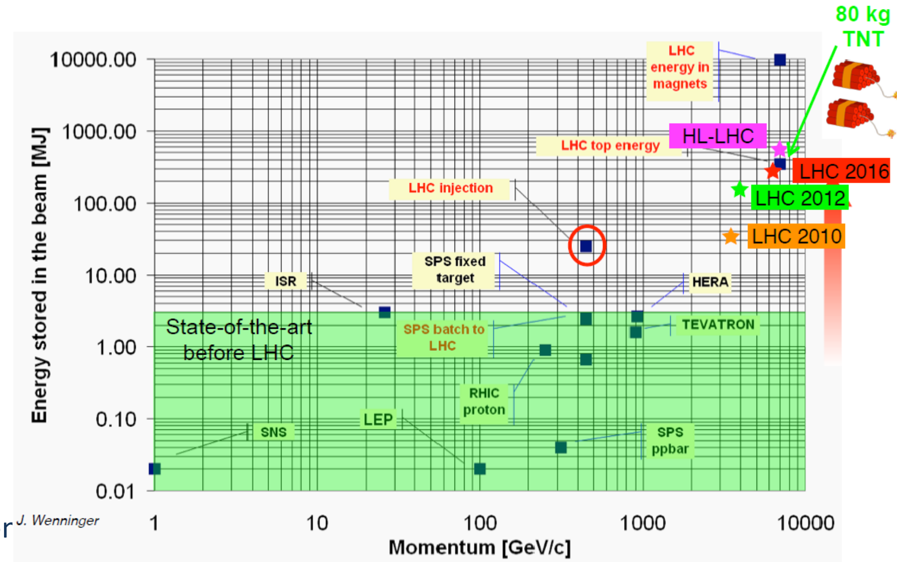


Intermezzo
HiRadMat facility

HiRadMat

- Beam intensity increases in particle accelerators
  → materials of near-beam equipment must be able to withstand the higher energy deposition/radiation

- Testing in an existing facility is difficult/inconvenient
  Typically an accelerator is already used for physics
  - Limited in access for installation works
  - Limited in space along the beam line
  - Missing infrastructure
  - Limited in beam time



Request for a dedicated test facility:

- **HighRadMat - High Rad**iation to **Mat**erials
  Initiated and executed by R. Assmann and I. Efthymiopoulos

Facility target:
  - provide irradiation area with beams similar to LHC injection
  - with scanning possibilities in intensity and spot size
  - Designed for single-pulse experiments (long-term irradiation is excluded for operational aspects)

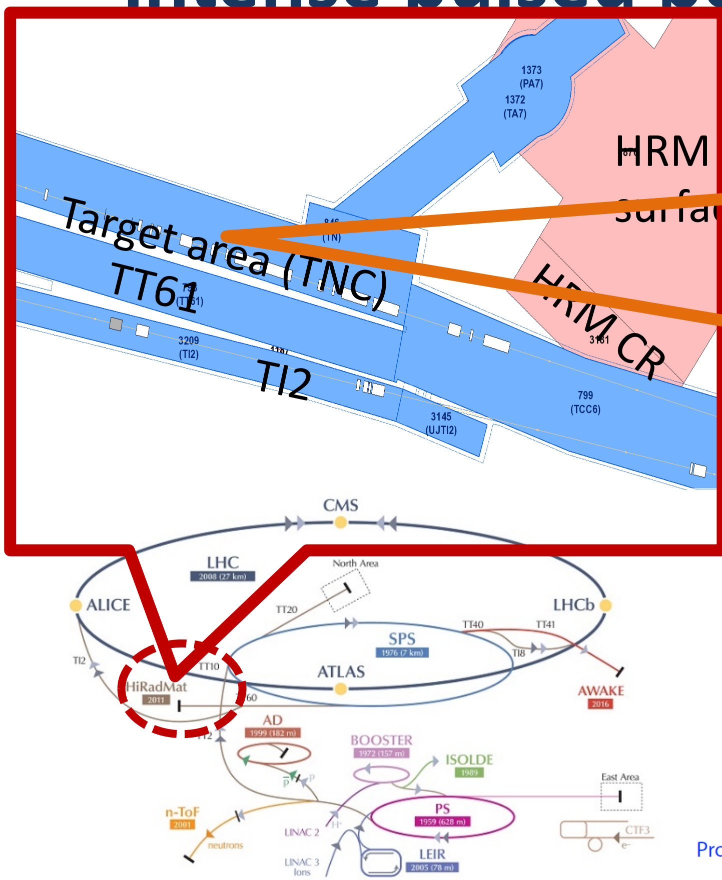
Applications:
- machine components, protection devices, targets, material studies, detector testing, electronics

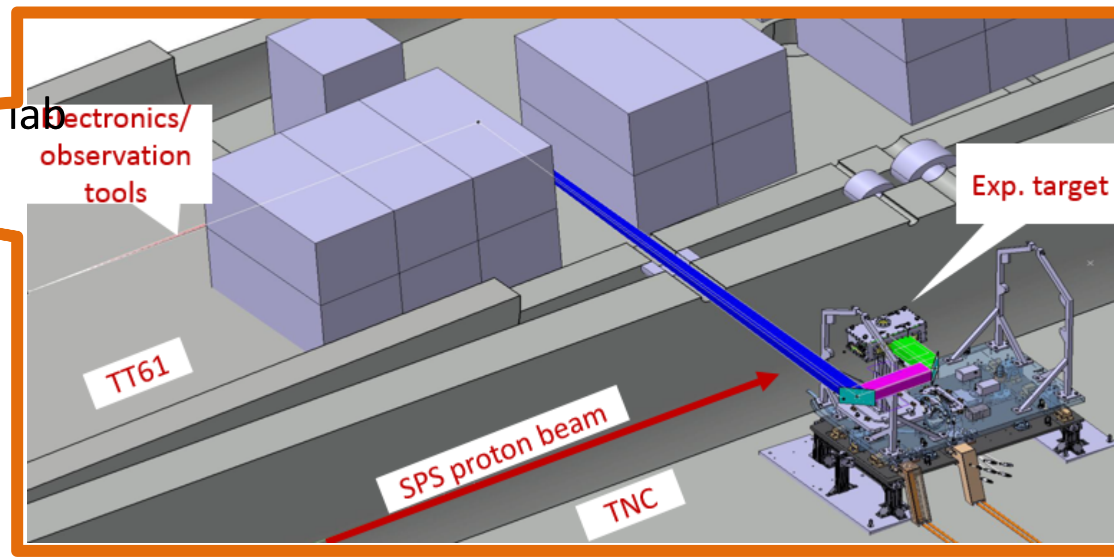
Courtesy: A. Fabich (CERN EN/EA)

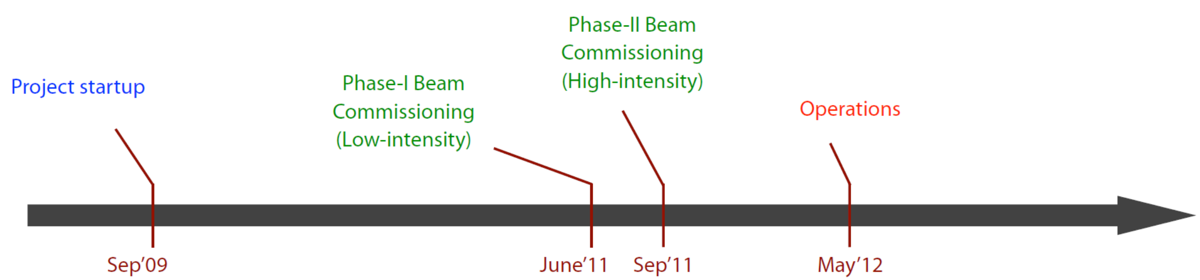
HiRadMat
High-Radiation to Materials

- **Dedicated facility for studying the impact of intense pulsed beams on material**

http://cern.ch/hiradmat







EuCARD²

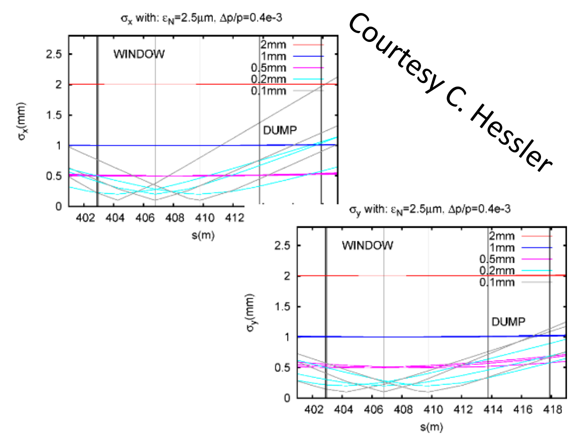
HiRadMat
High-Radiation to Materials

Beam Parameters

- Similar to LHC injection

	Protons	Heavy ions (Pb^{82+})
Beam energy	440 GeV	173 GeV/u
Bunches/pulse (max)	288	52
Pulse intensity (max)	$3\ 10^{13}$	$4\ 10^{9}$
Bunch spacing	25, 50, 75 or 150 ns	100 ns
Pulse length (max)	7.2 µs	5.2 µs
Beam spot	variable around 1 mm^2	
Pulse energy (max)	3.4 MJ	21 kJ

- Variable pulse intensity
- Variable bunch sequence
- Variable beam focus



Courtesy C. Hessler

- Single pulses
  - Typically 100 pulses per experiment (10/year)
  - Limitation on air activation
  - Allow personnel access to irradiation area

For classical irradiation: GSI, BNL-BLIP, IRRAD, CC60, GIF, AREVA …

Courtesy: A. Fabich (CERN EN/EA)

Maximum beam intensities

Eagerly waiting for nominal LIU intensities

- From 1.3e11 to 2e11 protons/bunch
- Required for testing in the regime of HL-LHC and beyond

- Only available after LS2 (beyond LS2)
- Required RF upgrade during LS2

HiRadMat allows focussing beam spots down to sub-millimetre range

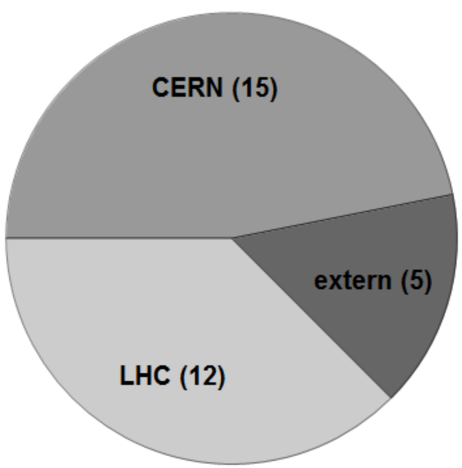
- Primary beam windows and beam dump need to be verified for withstanding peak densities at smallest focussing (with smaller emittance)

List of experiments

Status of experiments (Sept. 2016)

- 19 completed
- 5 approved
- 8 submitted

Context of HRMT



Target R&D
Granular target technology
RIB target
RodTarg - AD target
Collimation (LHC and injectors)
Crystal collimation
tunneling experiment
Rotating collimator
Transfer lines collimators (3x)
SPS ejection septum protection
material studies
Prototyping (LHC and injector types)
Detectors
BLM - beam loss monitors
Optical microphone
Rpinst - RP Instrumentation R&D
diamond detectors
BTV beam monitors
More ...
GlassyC
Beryllium specimen
Cryogenic elements

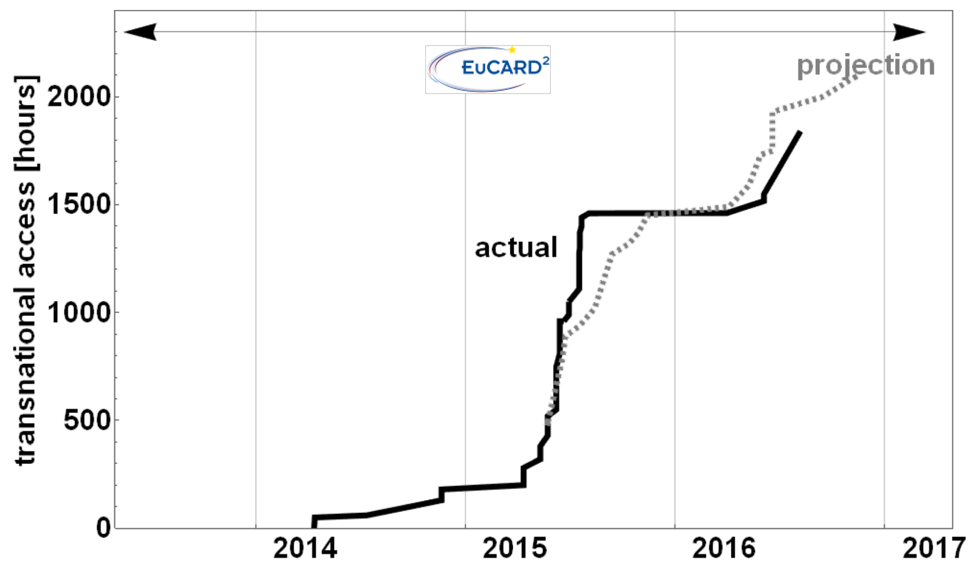
year	Acronym	Leading inst. (nat.)	HRMT index	Approval status	TNA status
2015	BLM2	CERN	19	Data taking	
2015	TPSG4-2	CERN	25	Cancelled	
2015	GlassyC	CERN	26	Completed	
2014	dBM	CZ	17	Completed	Granted
2015	BeGrid	UK	24	Completed	Granted
2017	SextSC	CERN		Approved SB	
2015	Jaws	CERN	23	Completed	Granted
2017	RotColl	CERN	21	Approved	
2015	RodTarg	CERN	27	Completed	
2017	CRY2	CERN	18	Approved SB	
2015	MicOpt	AT	20	Completed	Granted
2015	PTarg	UK	22	Completed	Granted
2015	FiberBLM	CERN		Submitted	
2016	TCDI	CERN	28	Data taking	
2017	MultiMat	CERN		Approved SB	Applied
2017	BTV	CERN	30	Completed	
2016	dBM2	CZ	33	Approved	Applied
2016	ESScoat	NO	34	Completed	Granted
2016	BTV2	CERN	32	Completed	Granted
2017	TDIcoat	CERN		Approved SB	
2016	CableStack	CERN	31	Approved	
2017	FlexMat	GSI		Submitted	Applied
2017	GlassyC2	CERN		Submitted	
2012	TISD	CERN	01	Completed	
2012	RADTOL	CERN	02	Cancelled	
2012	SLACRC1	CERN	03	Cancelled	
2012	BLM	CERN	04	Completed	
2012	VDWBR	CERN	05	Cancelled	
2012	TPSG4	CERN	06	Completed	
2012	TCDQ	CERN	07	Cancelled	
2012	TCDS	CERN	08	Cancelled	
2012	LCOL	CERN	09	Completed	
2012	WTHIMBLE	UK	10	Completed	
2012	DYNVAC	CERN	11	Cancelled	
2012	LPROT	CERN	12	Completed	
2012	LCMAT	CERN	14	Completed	
2012	RPINST	CERN	15	Completed	
2012	UA9CRY	CERN	16	Completed	

Courtesy: A. Fabich (CERN EN/EA)

HiRadMat
High-Radiation to Materials

Transnational Access

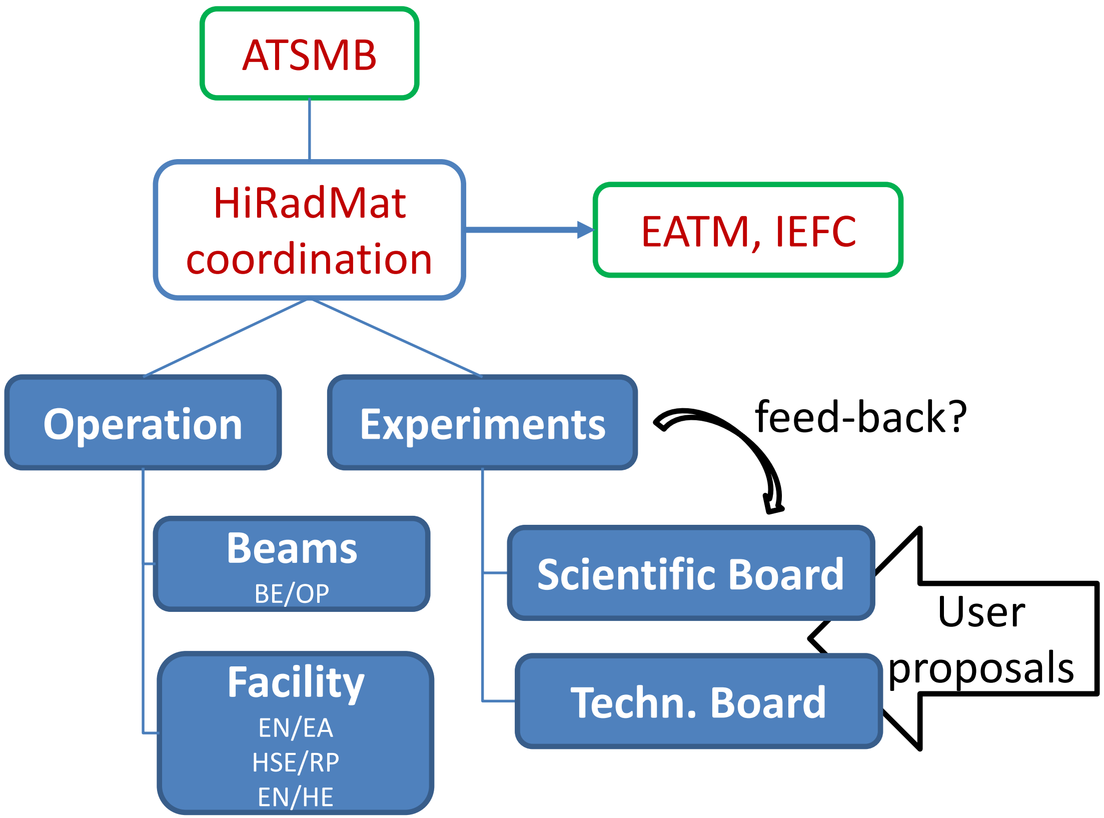
- EU funded support for external users on travel/subsistence



EuCARD-2 is co-funded by the partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453.

- More than 200 user*days at CERN enabled
- HiRadMat is work package in the recently approved FP7-Aries (2017-2021).

Applying for beam time



Regular meetings for daily operation:

- Experimental Area management with CERN groups
- Users meeting (with video conferencing)

Beam time application

Proposal submission to HiRadMat management

- Experiments are reviewed by the HiRadMat Scientific Board
  - Scientific interest of the experiment, feasibility and post-irradiation analysis
  - Expected results and publications to the interest of the scientific community
- Approval validated by the HiRadMat Technical Board
  - Integration, operational and safety aspects, radiation protection and waste management

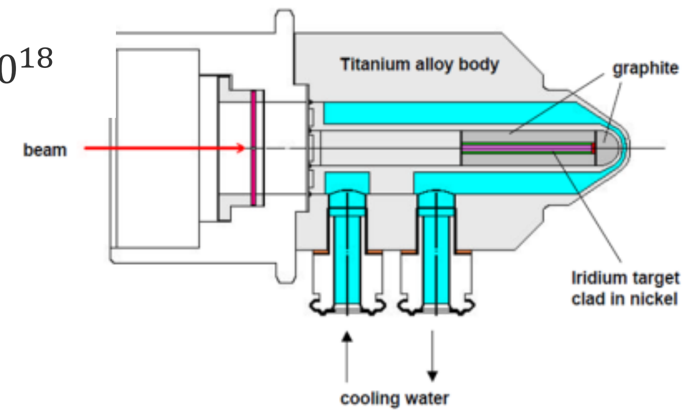
Accessible to the world-wide science community

AD-target and HiRadMat 27

AD-target

PS Proton Beam

- 26 GeV/c
- **POTs/year =** $2.1 \cdot 10^{18}$



- Current design (from 1989)
- Target core:

⌀ 3 mm x 55 mm length rod of **Iridium**

- Core material is subjected to extreme thermo-mechanical loads
  - ΔT > 2000 °C, Tss = 150 °C
  - ~ 1 DPA/year in the core

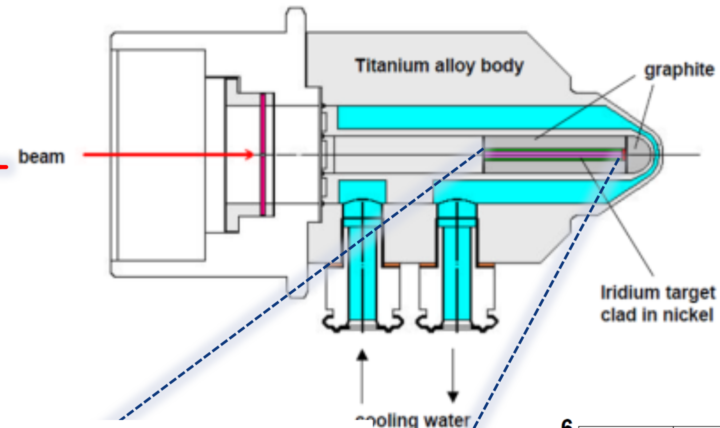
RaDIATE- activities of irradiation of Ir in the context of this project already started

- New design for the next 20 years of operation is on-going
  - **Ta is considered as a strong core-material candidate**

AD-target

PS Proton Beam

- 26 GeV/c
- Primary beam
  0.5 mm x 1 mm
- 1.45e13 ppp
- **430 ns pulse length**

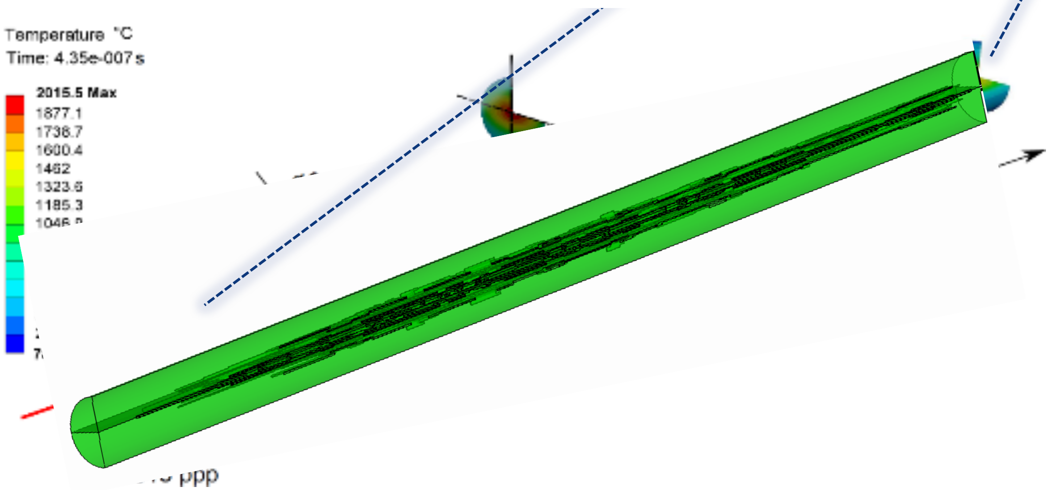


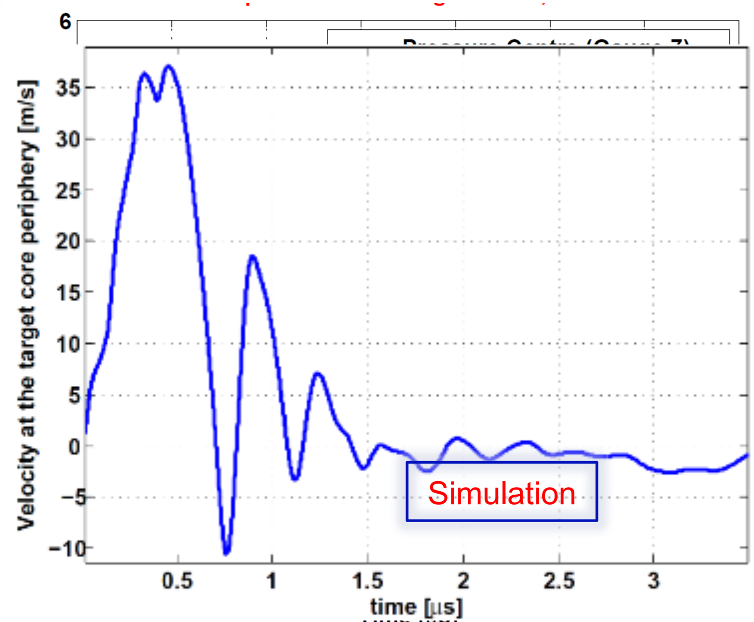
Target core made of ⌀ 3 mm x 55 mm length

rod of **Iridium**

$\rho = 23\ g/cm^3$

Adiabatic T rise at target core: ΔT > 2000 °C





Surface velocity including a failure model

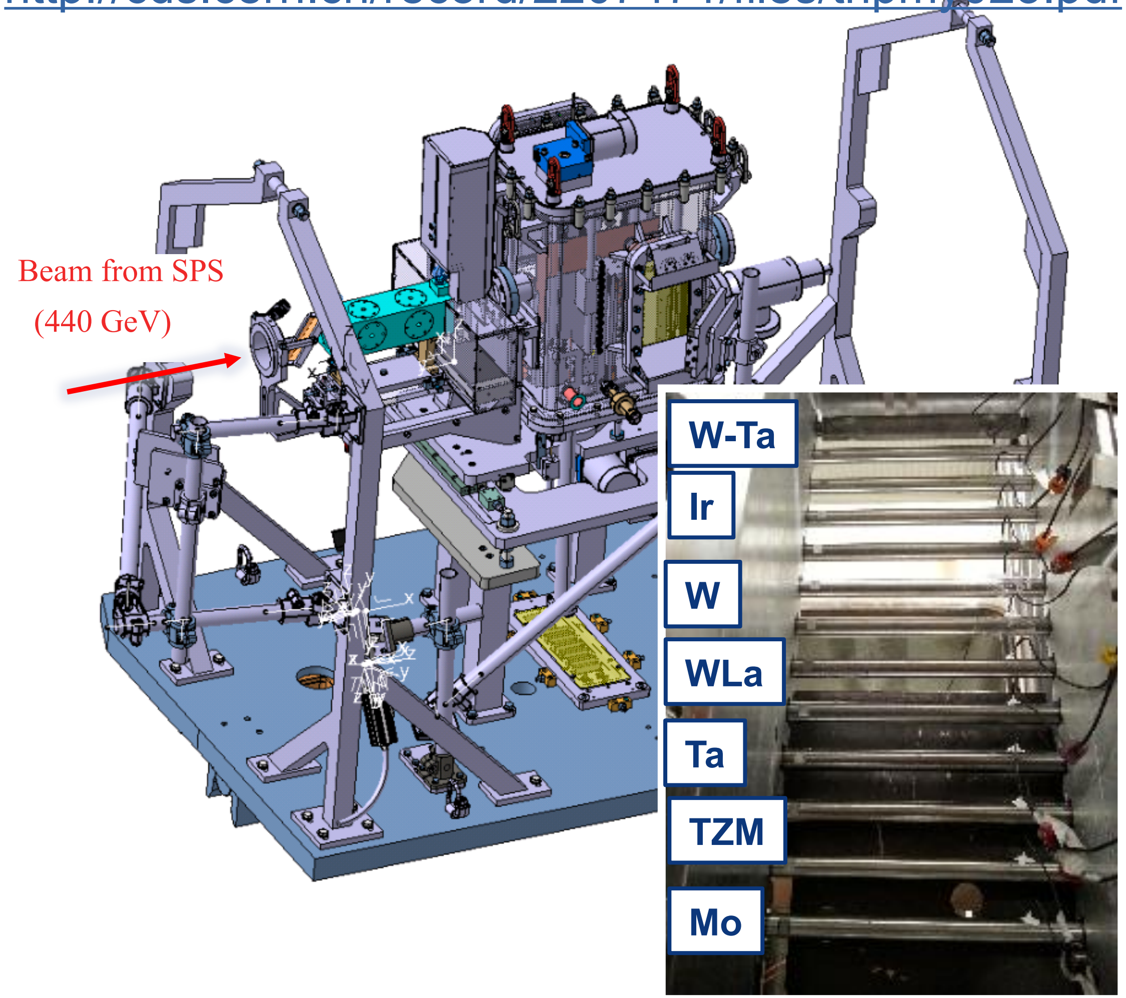
Compressive-to-tensile radial pressure wave

High Density Materials of Interest

1) **Iridium:**
   - Current target material and the highest density ($23\ \mathrm{g}/cm^3$)
2) **Pure Tungsten:**
   - High density ($19.2\ \mathrm{g}/cm^3$) and strength. **R&D applicable to n_TOF, collimators, SHiP**
3) **W-L:** Tungsten doped with 1-2% of lanthanum oxide (La_2O_3)
   - Improved mechanical properties at high temperatures, increase of recrystallization temperature.
4) **Molybdenum:**
   - Lower density ($10.3\ \mathrm{g}/cm^3$) but high strength, less demanding conditions.
5) **TZM:** Molybdenum Alloy: Titanium-Zirconium-Molybdenum:
   - Stronger than pure molybdenum, higher recrystallization temperature and properties at high temperature. **R&D applicable to SHIP target**.
6) **Tantalum**
   - High density ($16.7\ \mathrm{g}/cm^3$), **very ductile compare to the rest of tested materials**.
7) **Cladded Target: W cladded in Ta**
   - Investigation of cladded solution to reduce pressure wave. **R&D in cladding interface behavior of HIPing**. **Applicable to spallation targets**

Experiment using the HiRadMat Facility

http://cds.cern.ch/record/2207471/files/thpmy023.pdf

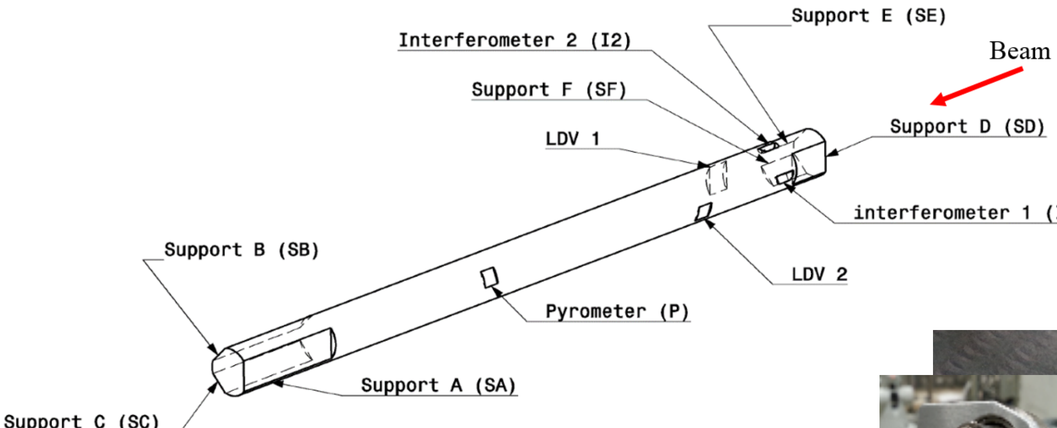


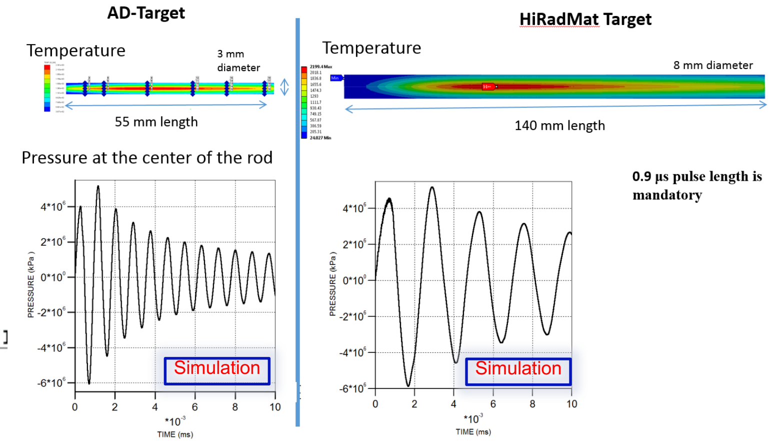
- 13 rods of high-Z materials impacted by 440 GeV/c beam
- Irradiation performed in a **ramped** way to obtain material response at intermediate state before reaching AD-Target conditions
- Experiment carried out in November 2015

http://cds.cern.ch/record/2064079?ln=en

Design of the HRMT27 Targets

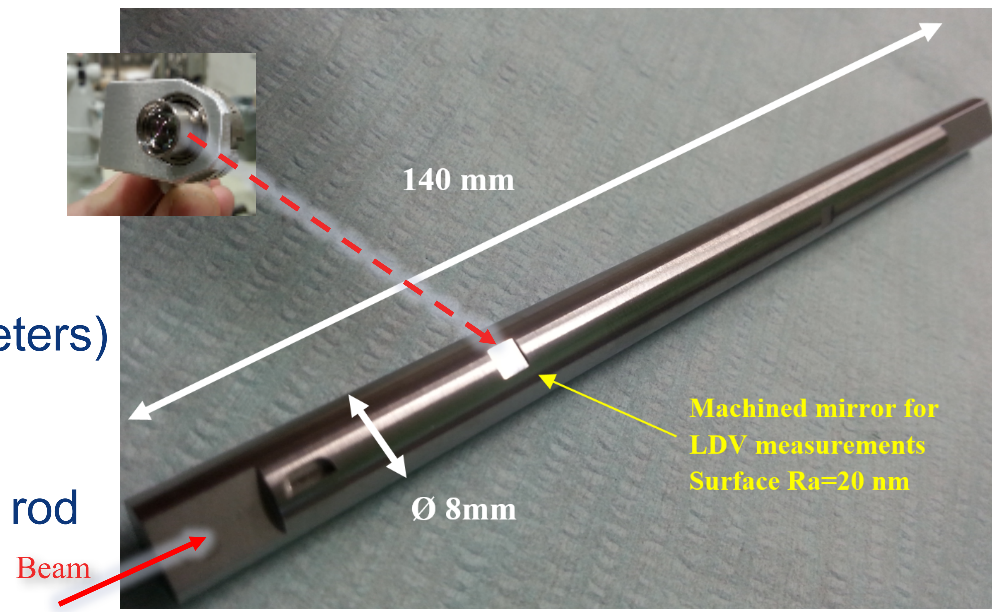
8 mm diameter rods





Measuring Optically
- Velocity (LDVs)
- Displacement (LDVs + interferometers)
- Temperatures (Pyrometer)

+2 Thermocouples attached on each rod surface

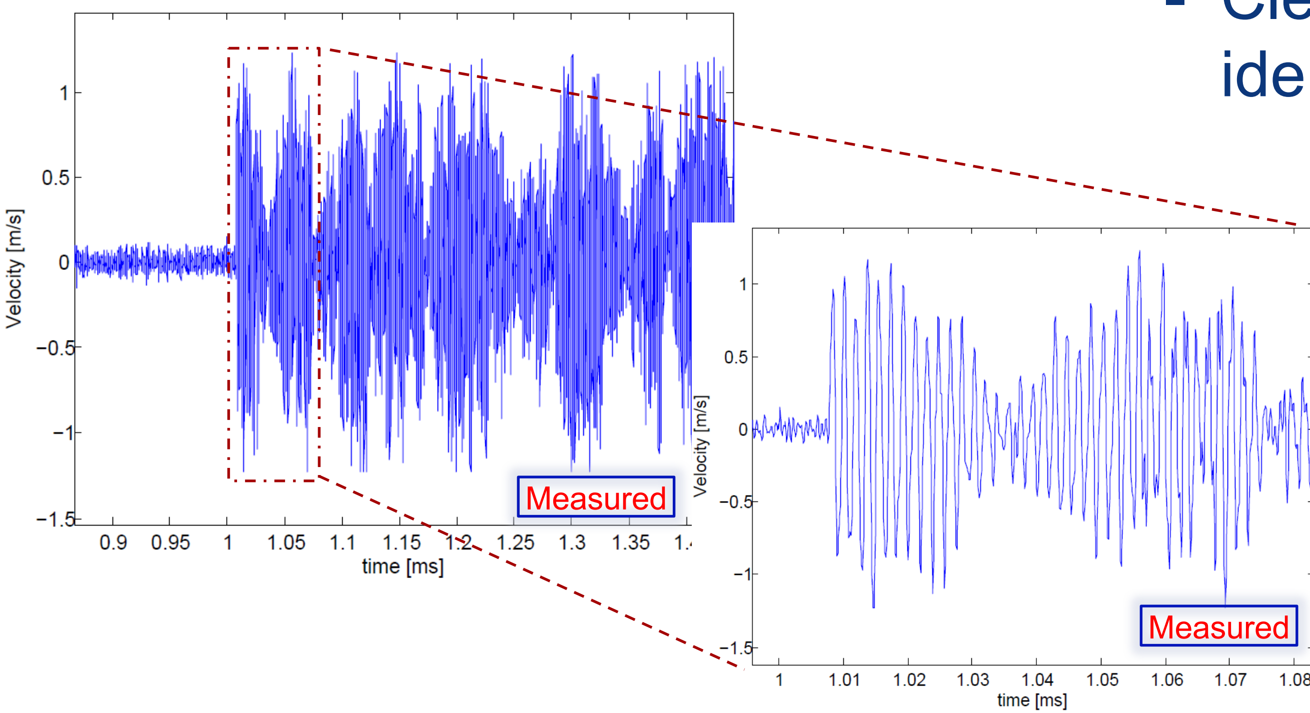


Dynamic Response at Low Intensity (1)

1.15*10^{11} ppp impacted in **TZM** target

- Elastic response
- Clear radial wave identified

Target Surface Velocity

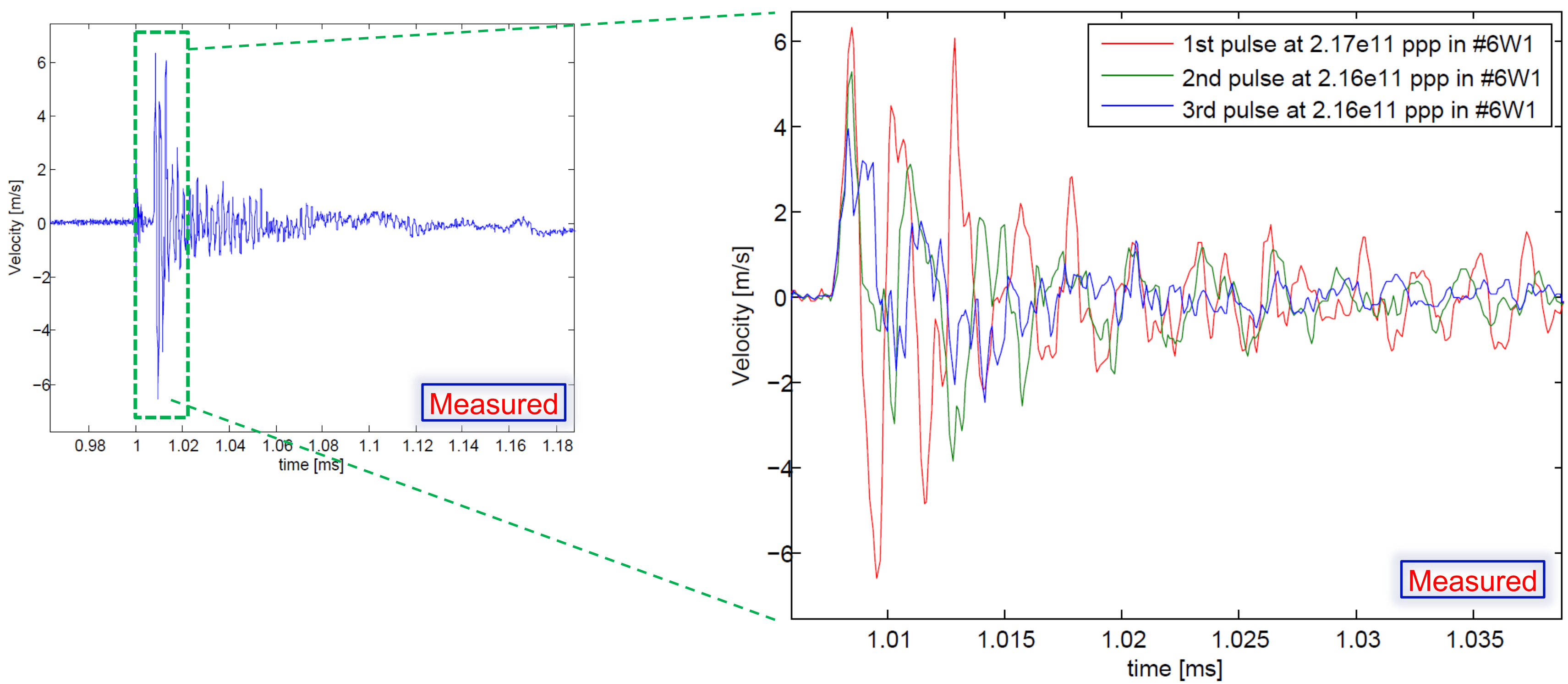


Material	Measured Radial Wave period
Mo/TZM	1.8 μs
W/W-La	2.3 μs
Ir	2.2 μs
Ta	2.75 μs
W-Ta	3.35 μs

Change of Dynamic Response when Increasing Intensity

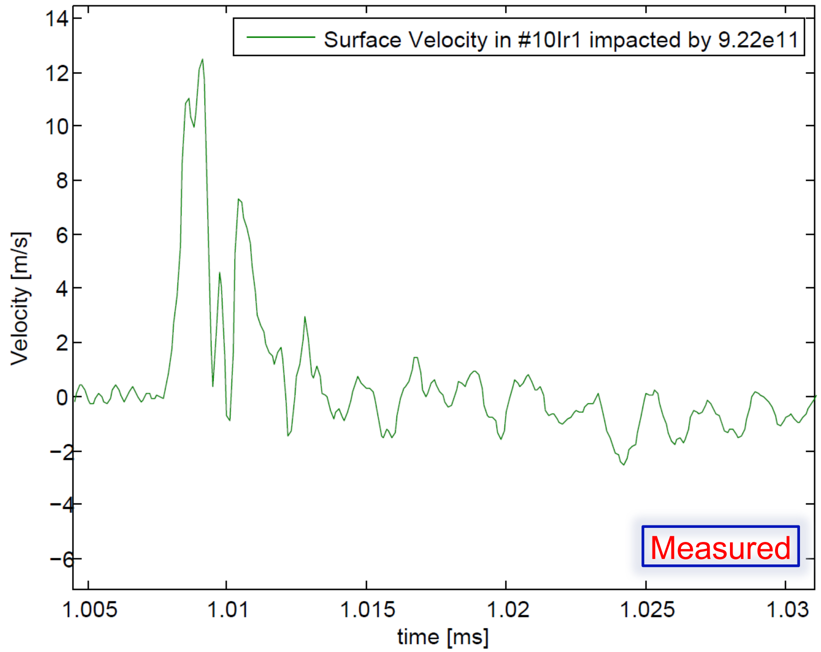
Three consecutive pulses of $2.15 \cdot 10^{11}$ ppp
(~7 times less than the conditions reached in the AD-Target)

Tungsten



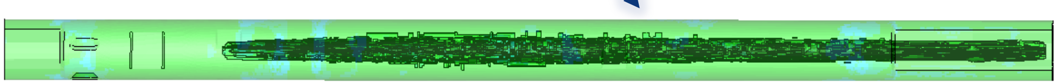
- Clear change fast damp of the radial wave
- Max reached velocity in W is reduced down a 30% in the consecutive pulses in W
- **Distorted** radial wave could indicate that internal damage is already taking place

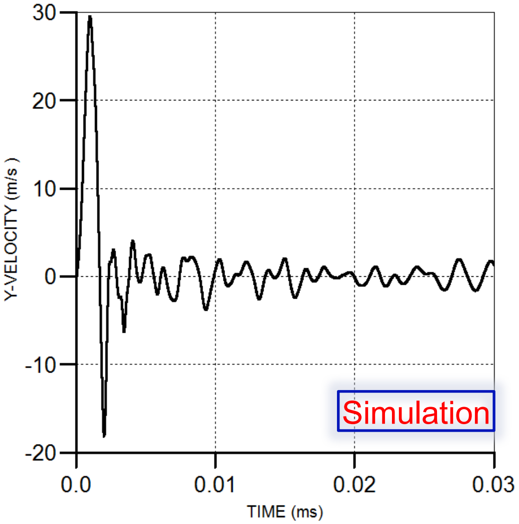
Material Responses at Higher Intensity



Most of the targets present a **damped** and completely **distorted radial wave** when increasing intensity above 7.5*10^{11} ppp (~half of AD-target conditions)

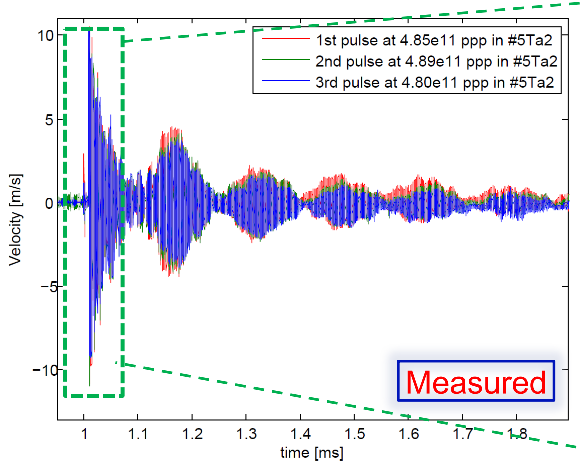
Example of <u>simulation</u> considering internal damage

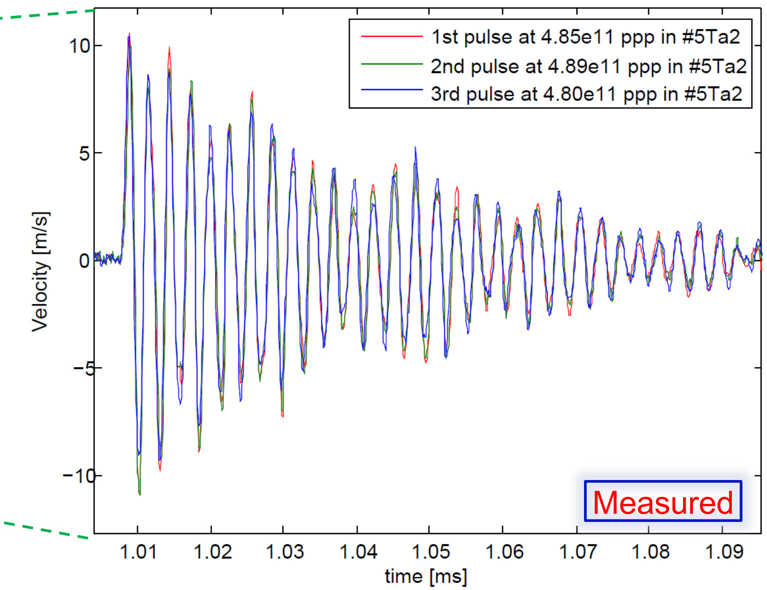




Tantalum Targets: A Different Response

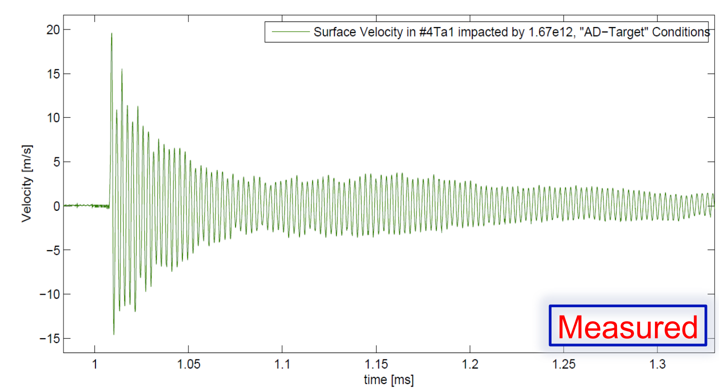
Three consecutive pulses of $4.95 \cdot 10^{11}$ ppp in Ta target



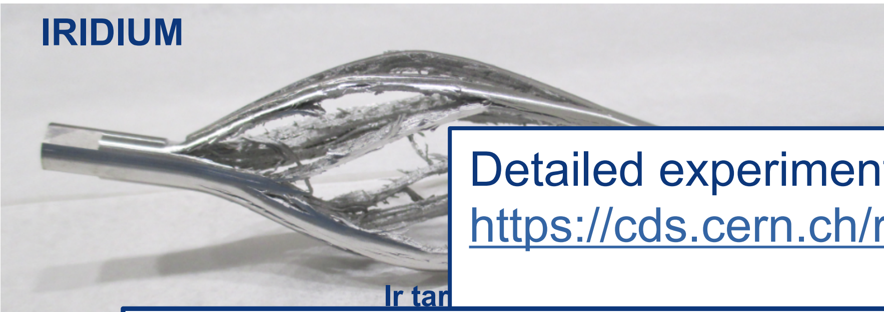


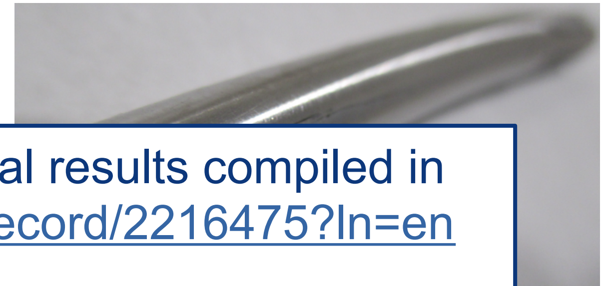
- Even at this intensity the velocity is much less damped.
- **Nicely propagated radial wave** (absence of internal cracks).

- Tantalum target still presents a clear response with no change in the radial frequency.
- Maximum reached **velocity up to 20 m/s**



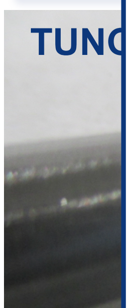
Targets after the experiment





Longitudinal cracks in **Iridium** at intermediate intensities.

Detailed experimental results compiled in
https://cds.cern.ch/record/2216475?ln=en



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CERN-EN-2016-004

2016-07-04

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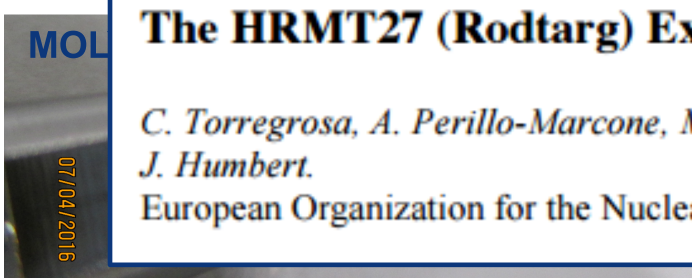
The HRMT27 (Rodtarg) Experiment: Design, Operation and First Results

C. Torregrosa, A. Perillo-Marcone, M. Calviani, M. Butcher, D. Horvath, E. Fornasiere, L. Gentini, J. Humbert.
European Organization for the Nuclear Research, Geneva, Switzerland

n Ta

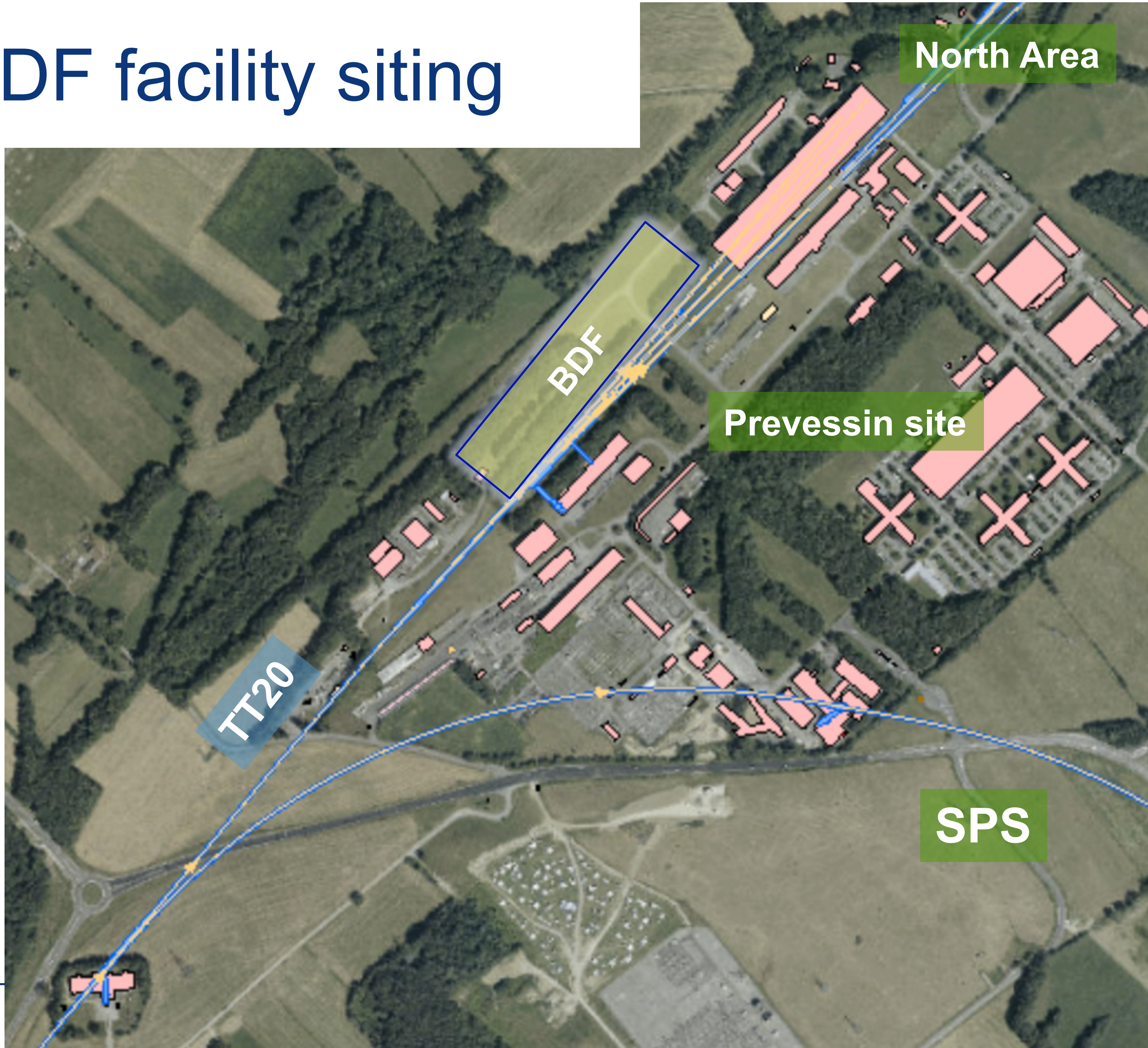


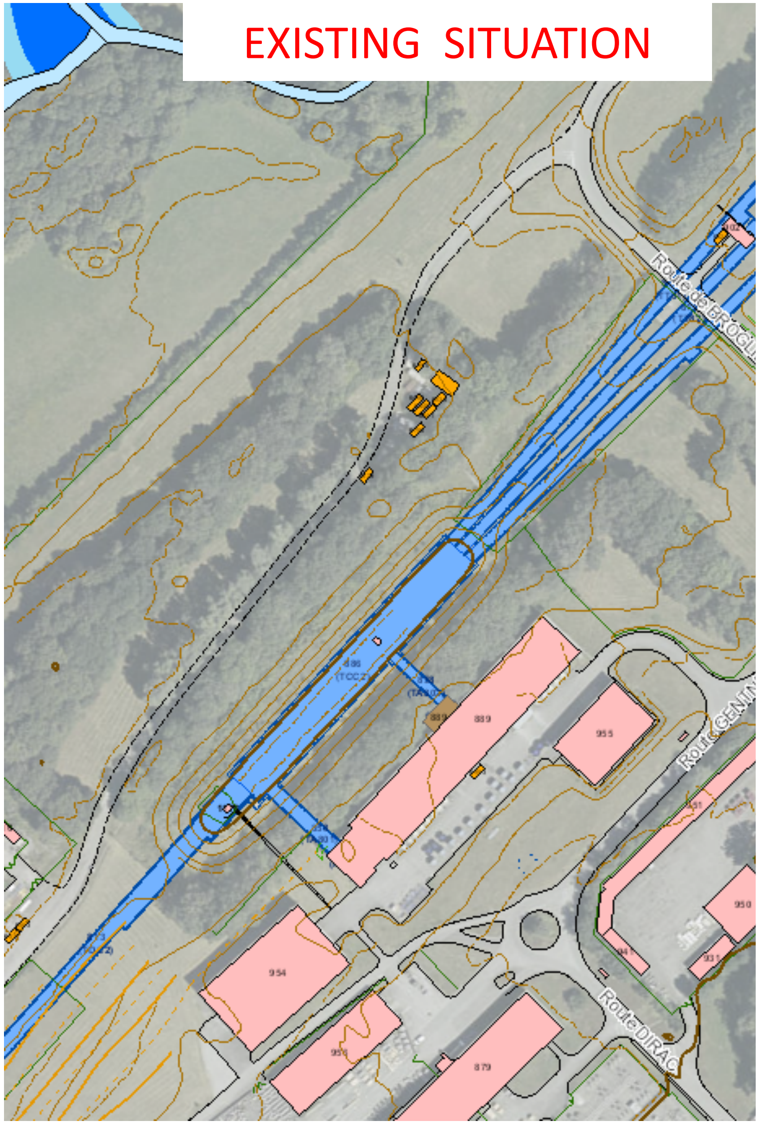
Long-term: Beam Dump Facility

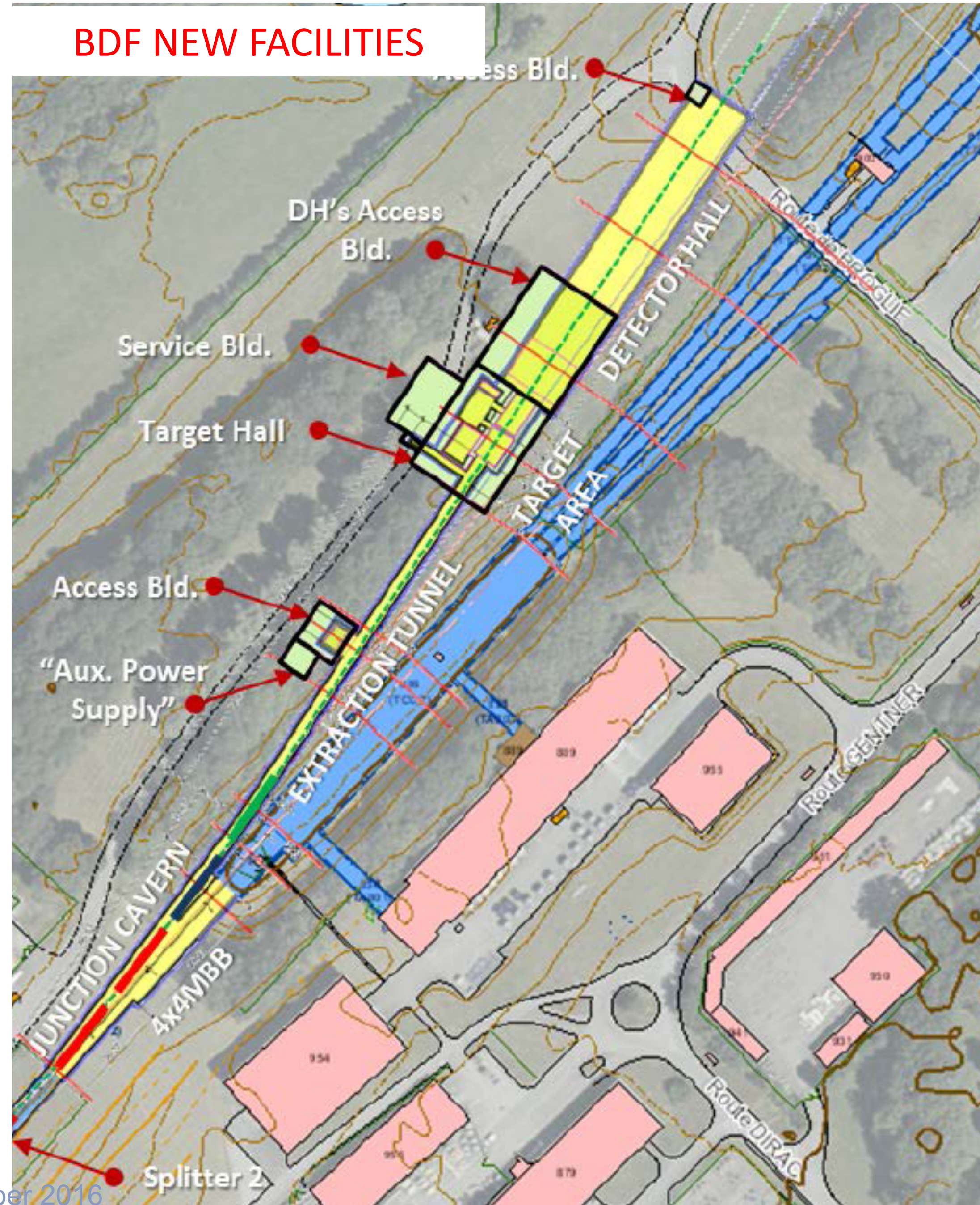
Beam Dump Facility (BDF)

- CERN is launching the study of a general purpose Beam Dump Facility on the CERN site (Prevessin)
- The experiment requires the realization of a high intensity target complex to house a heavy target capable of receiving up to 400 kW beam power (pulsed)
- See SPS Beam Dump Facility at the recent Physics Beyond Colliders workshop at CERN

BDF facility siting




EXISTING SITUATION
Route de BROGLIE
Route DIRAC


BDF NEW FACILITIES
DH's Access Bld.
Service Bld.
Target Hall
Access Bld.
"Aux. Power Supply"
Splitter 2
DETECTOR HALL
TARGET AREA
EXTRACTION TUNNEL
JUNCTION CAVERN
4x4MBB
Route de BROGLIE
Route GENTNER
Route DIRAC

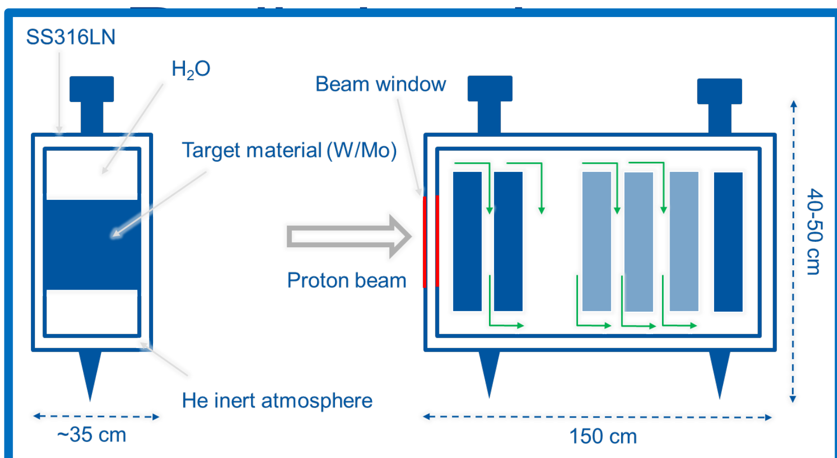
BDF Target/Dump and Facility

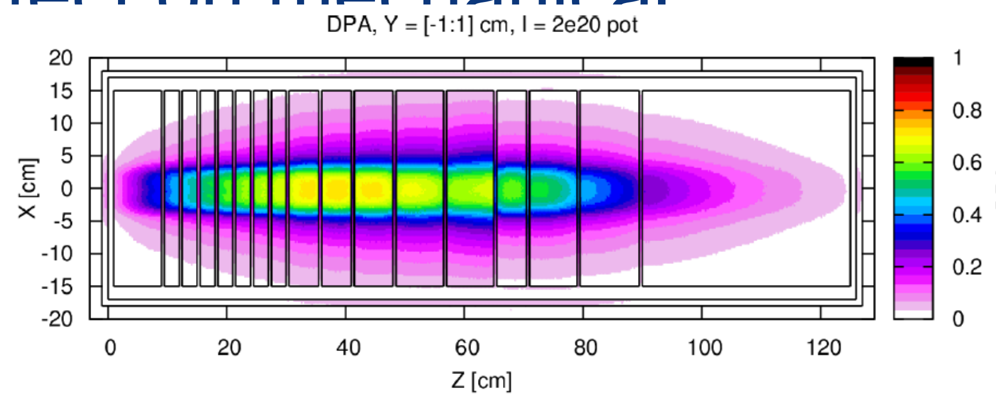
- **Beam power 355 kW, 1 s spill up to 2.56 MW**
- Target must be as dense as possible to maximize production and reduce backgrounds
- High energy deposition per unit volume → significant **heating due to beam (320 kW)**
- Need of a challenging water cooling system
  - ~200 m^3/h, 20 bar
- Material damage due to cumulated radiation

The proposed BDF target

- 120 cm long, hybrid configuration
- 60 cm TZM (4λ) + 60 cm W (6λ), Ta cladded
- 40 x 40 cm^2 transversal size
- Target core in a double walled SS container

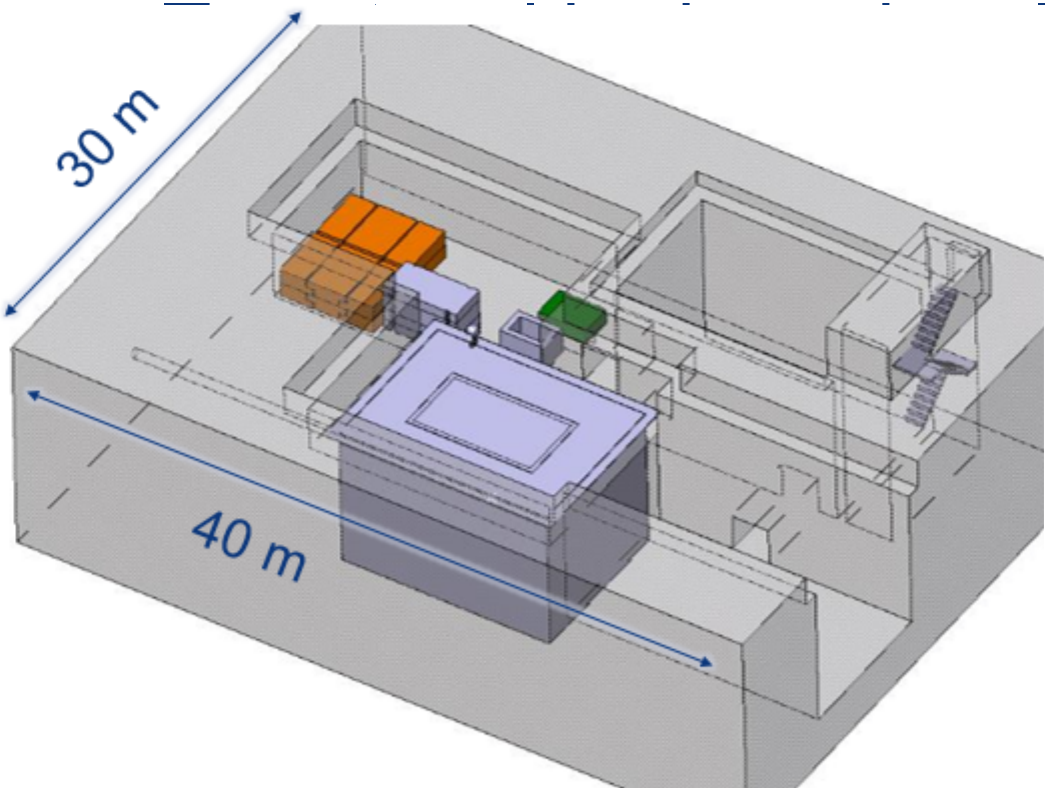
ffect on mechanical

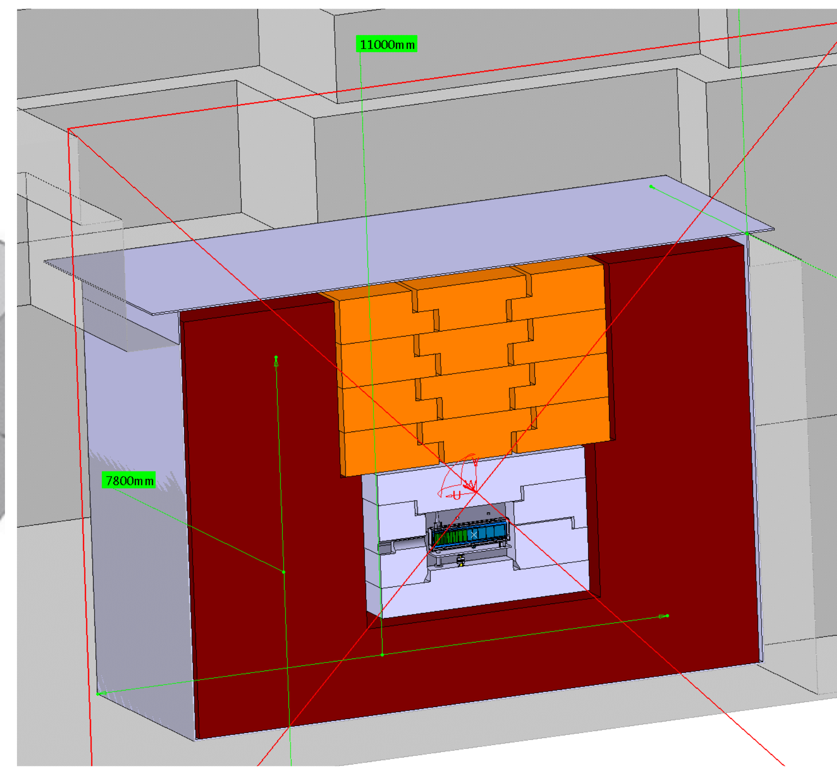




BDF Target Complex

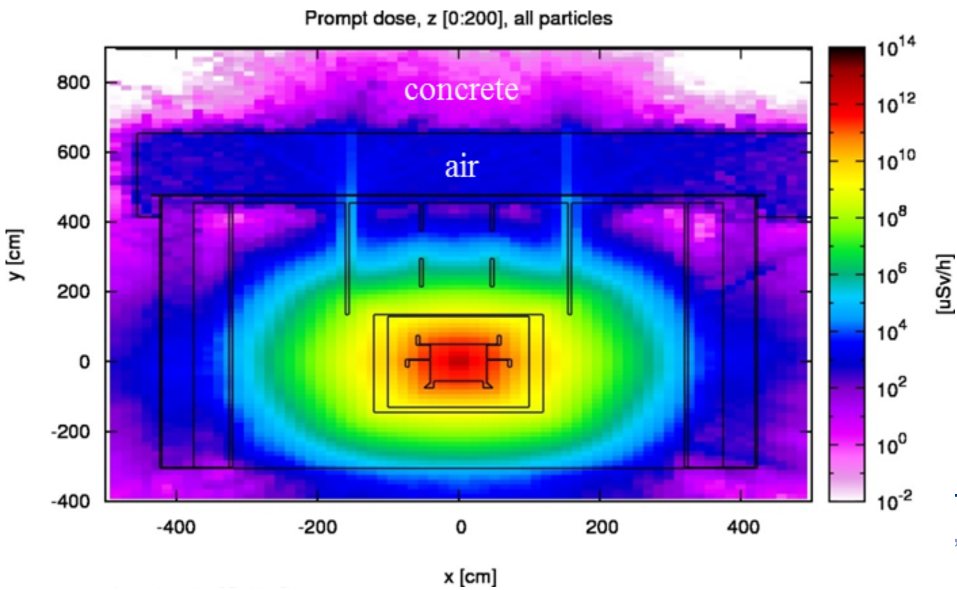
- Target is located 15 meters underground
- Cast-iron hadron absorber encloses production target (460 m^3)

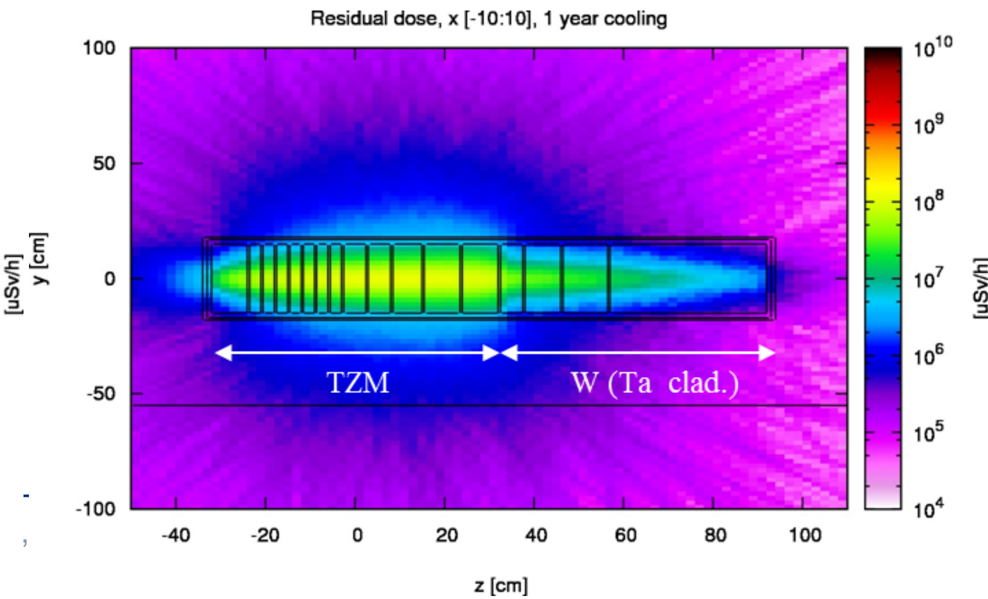




BDF Radiation protection

- Prompt dose rate under control in accessible areas
- Dump **residual dose rate ~10 Sv/h** after 1 week
  - Handling of the target an outstanding item
- Target station design adapted to configure the bunker for a **different dump design**





BDF prospects

- Comprehensive Design Report requested by CERN management by end **2019**
- Focus on:
  - Target/dump design and reliability (including prototype beam test in 2018), including radiation long-term testing
  - Optimisation of target complex design
  - Prototyping of He-vessel purification system design

BLIP long-term tests within RaDIATE

- Radiation tests foreseen at BLIP (0.5-1 DPA cumulative)
  - TZM samples → BDF target & AD-target
  - Iridium → AD-target
  - CuCrZr → Internal SPS high intensity dump (TIDVG)
  - Silicon → intermediate density absorber material (LHC absorbers)
  - Flexible graphite → present material for LHC main dump plus shock damper for AD-target
- *See P. Hurh presentation on RaDIATE*

Conclusions

- Significant activity on development of high-Z spallation targets/dump active at CERN since around 2 years
- R&D on high-Z material include mechanical tests, dynamical test with proton beams and long-term radiation damage tests
- Projects on the short and medium terms will be challenging

CERN | EN ENGINEERING DEPARTMENT

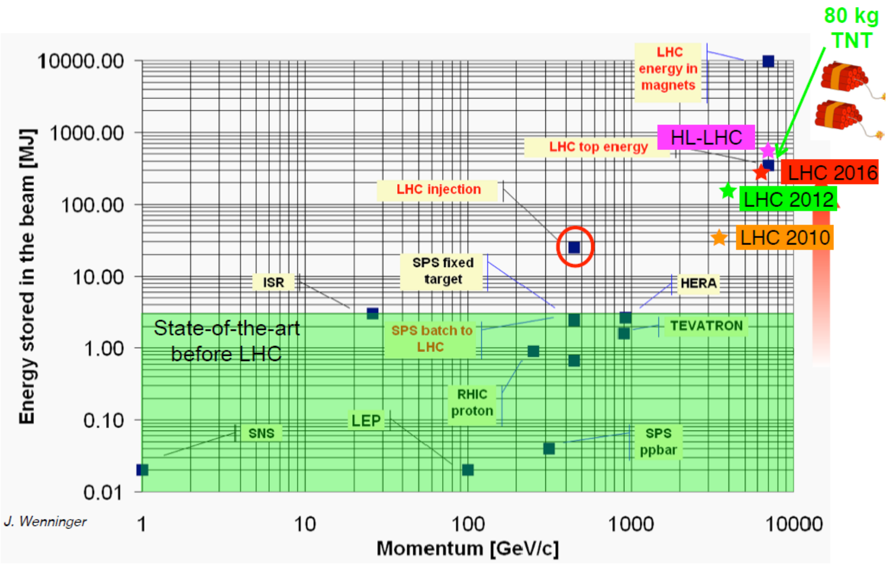
Thanks

Courtesy: A. Fabich (CERN EN/EA)

HiRadMat

- Beam intensity increases in particle accelerators
  → materials of near-beam equipment must be able to withstand the higher energy deposition/radiation

- Testing in an existing facility is difficult/inconvenient
  Typically an accelerator is already used for physics
  - Limited in access for installation works
  - Limited in space along the beam line
  - Missing infrastructure
  - Limited in beam time



Request for a **dedicated** test facility:

- **HighRadMat - High Radiation to Materials**
  Initiated and executed by R. Assmann and I. Efthymiopoulos

Facility target:

- provide irradiation area with beams similar to LHC injection regime
- with scanning possibilities in intensity and spot size
- Designed for single-pulse experiments (long-term irradiation is excluded for operational aspects)

Applications:

- machine components, protection devices, targets, material studies, detector testing, electronics