Use and prospects of HiRadMat

Accelerator Material studies at HiRadMat

Adrian Fabich

HL-TCC, CERN, 2. March 2017

with input from HiRadMat user collaborations

Overview

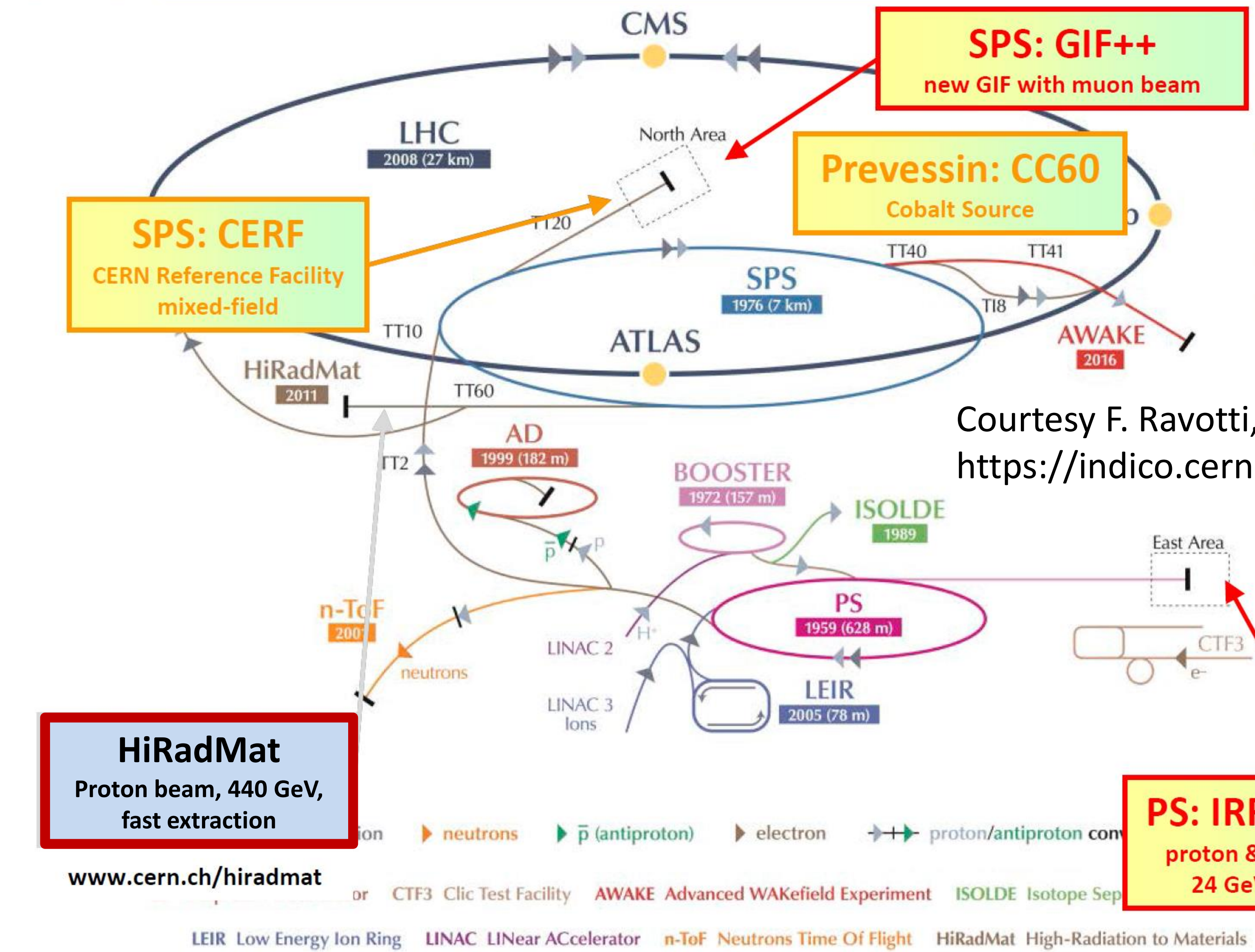
- Motivation for HiRadMat

- HiRadMat layout
- Beam parameters

- Experiments and first data views

- Long-term view
- Future extensions

CERN Irradiation Facilities from 2014



Proton Energy

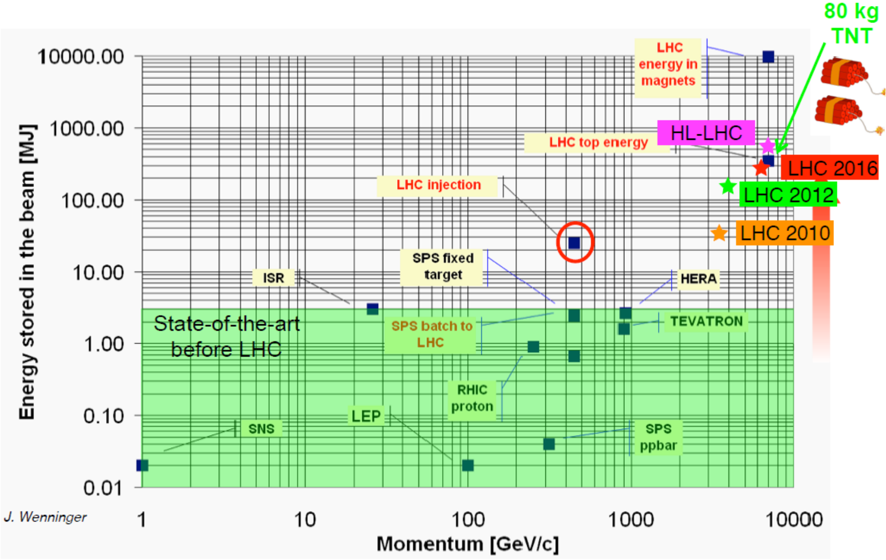
LHC	7 TeV
SPS	450 GeV
PS	23 GeV
PSB	1.4 GeV
Linac	50 MeV

Courtesy F. Ravotti, EP-DT
https://indico.cern.ch/event/303726/

From Motivation to Proposal

- 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)

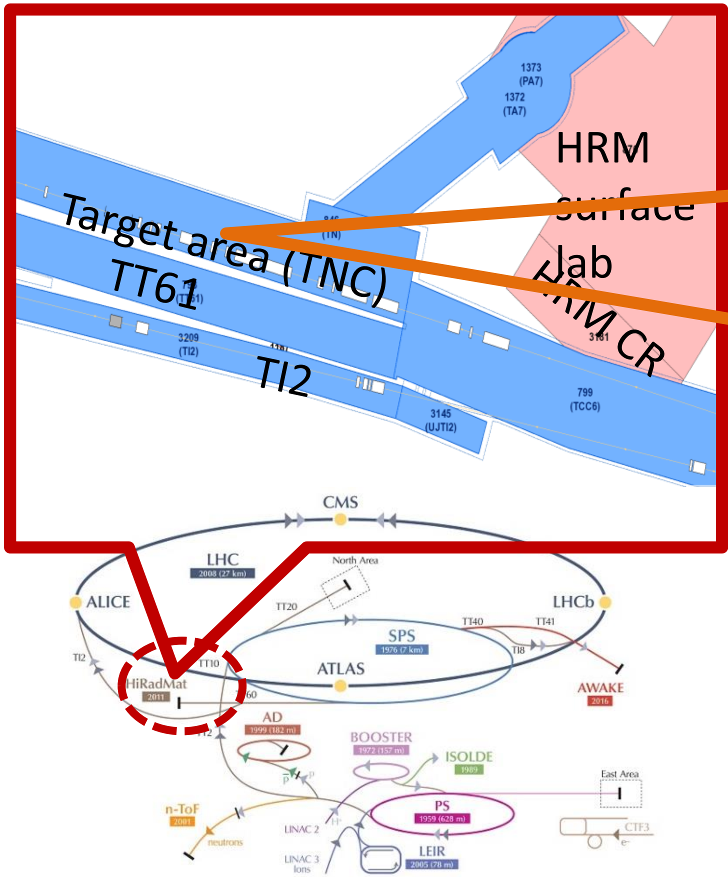
Applications:

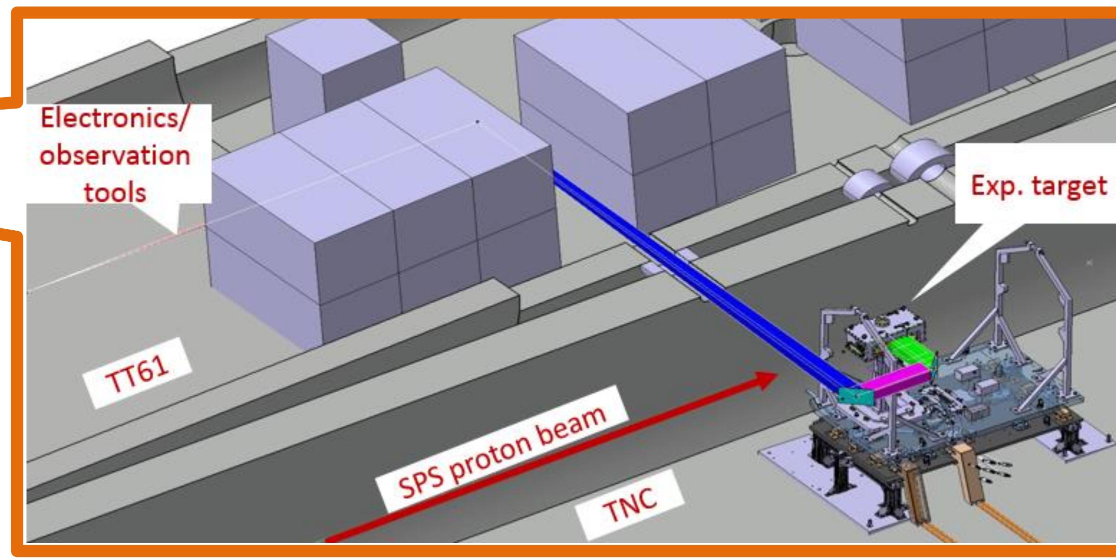
- machine components, protection devices, targets, material studies, detector testing, electronics

HiRadMat
High-Radiation to Materials

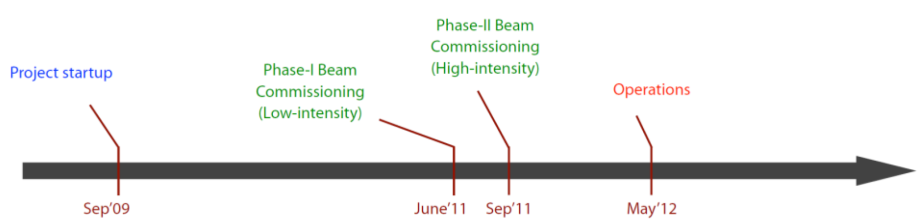
- Dedicated user facility for studying the impact of intense, pulsed beams on material

http://cern.ch/hiradmat





Operated by EN/EA supported by BE/OP, RP and EN/HE providing support to visiting user collaborations



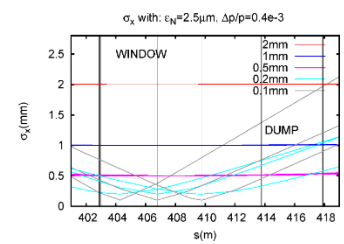
EuCARD²

Beam Parameters

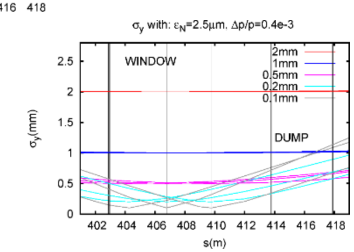
- Similar to LHC injection

	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 long-term irradiation studies: GSI, BNL-BLIP, IRRAD, CC60, GIF, GSI, AREVA …

Maximum beam intensity/density

Eagerly waiting for nominal LIU intensities

- Increasing from 1.3e11 to 2e11 protons/bunch
- Required for full testing in the regime of HL-LHC and beyond
- Only available after LS2 (beyond LS2)

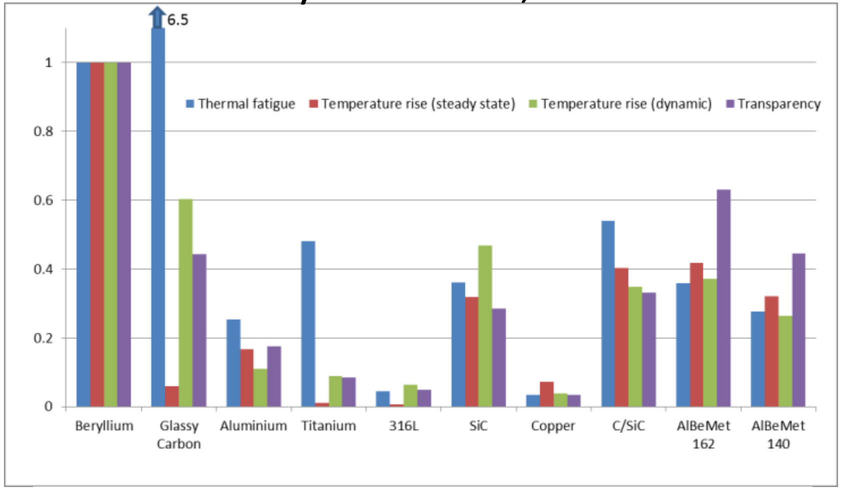
Already today, HiRadMat achieves future energy densities in targets

- focussing beam spot down to sub-millimeter range

HiRadMat experiment

GlassyC experiment

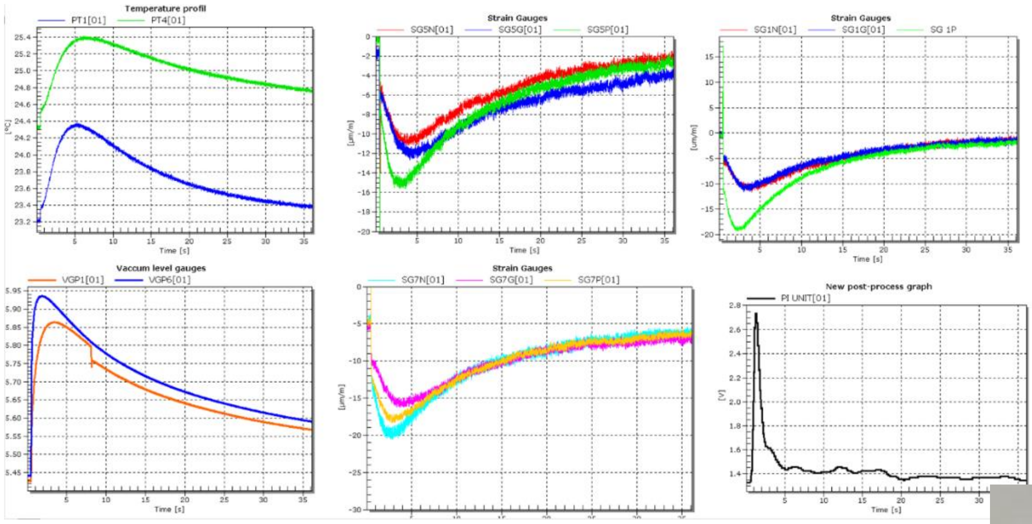
Courtesy: C. Garion, L. Baudin et al.

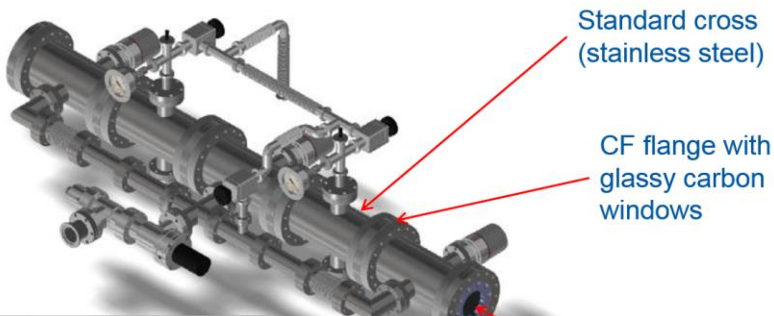


New material for vacuum windows

- Glassy Carbon obtained by the pyrolysis at high temperature of a highly reticulated resin
- 98 % (weight) of carbon and 2% of oxygen.

- Option for HiRadMat itself?

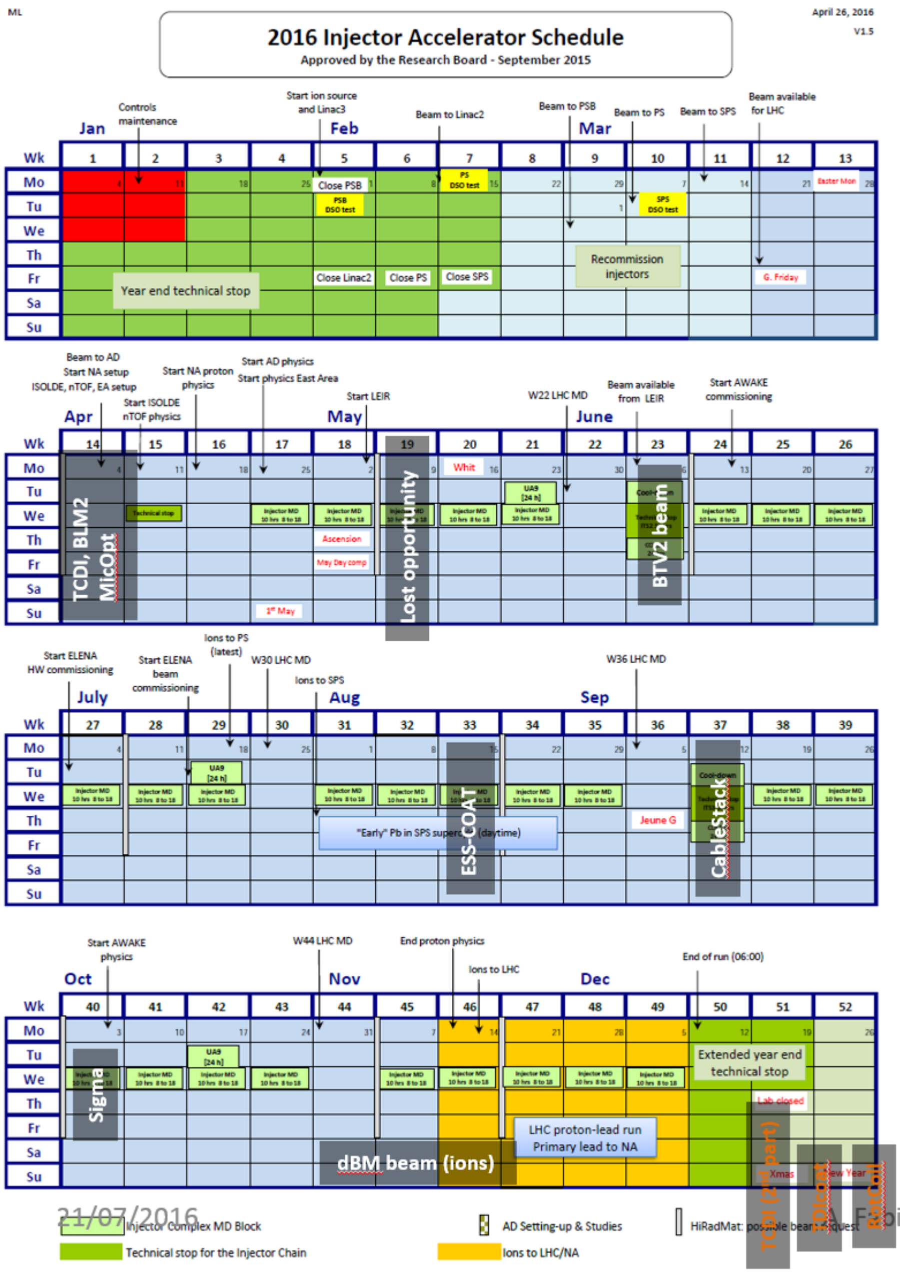


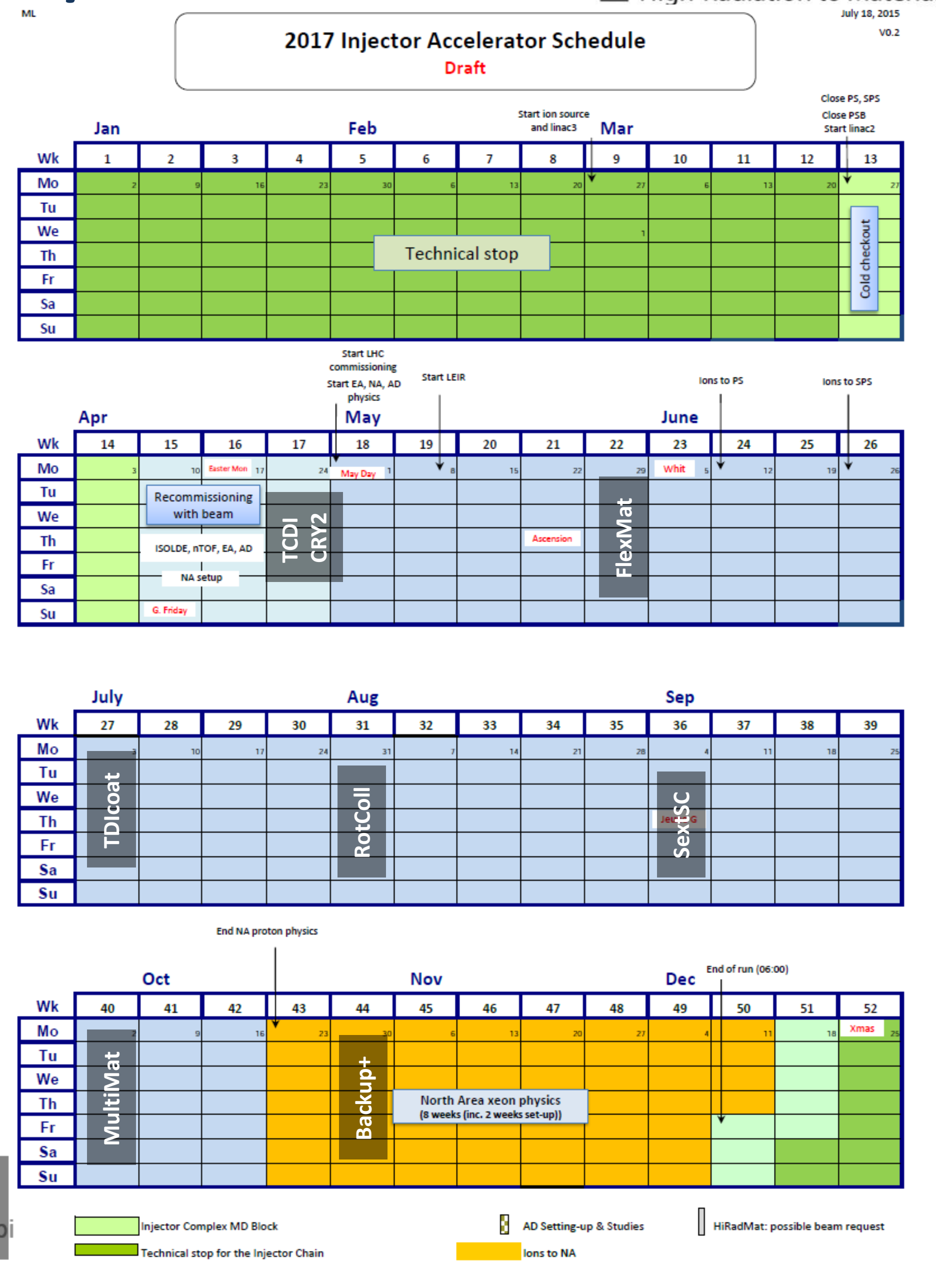


- Online monitoring using strain gauges and temperature sensors
- Post-irradiation evaluation (PIE) ongoing: microscopy

Exp. Schedule 2016/2017

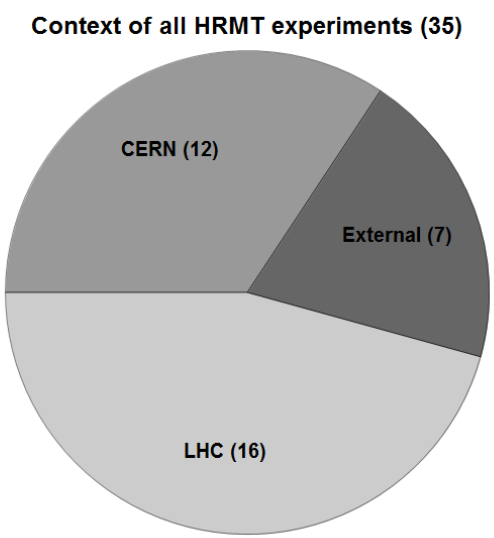
HiRadMat
High-Radiation to Materials





Context of HiRadMat Experiments

Status January 2017



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	

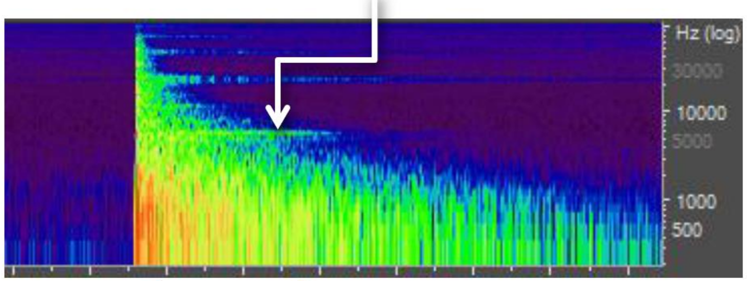
- User collaborations from CERN, BNL, FNAL, GSI, ESS and universities Europe-wide
- HiRadMat is **participant to FP7-TransNationalAccess (EuCARD2 & Aries) providing travel funds** to visiting scientists.

Testing an Optical Microphone

Courtesy:
Balthasar Fischer, Xarion (AT)
Daniel Deboy, KUG

Spectrogram (20Hz - 100 kHz)

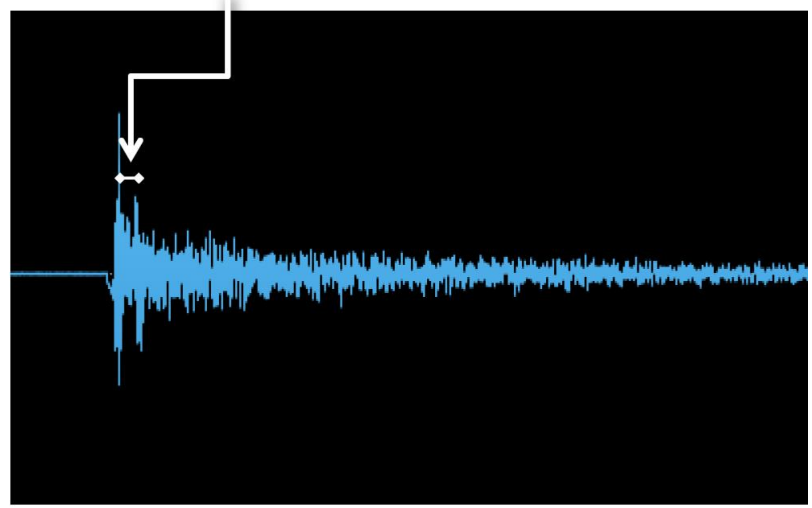
material resonance



0.5 s

Time signal

6ms reflection delay
(target is placed 1.05m away from tunnel wall)

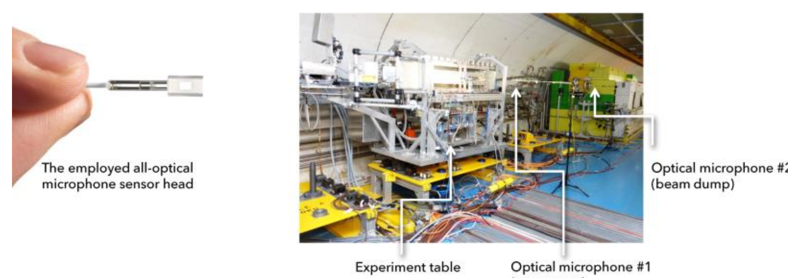


0.1 s

- Impacts are clearly detected by Optical Microphone
- Peak sound pressure: 166 Pa; 138 dB SPL (tentative!)

- Thorough analysis:
  - radiation effects
  - correlation between intensity and sound pressure level
  - sound time-of-arrival for location detection

Experimental setup

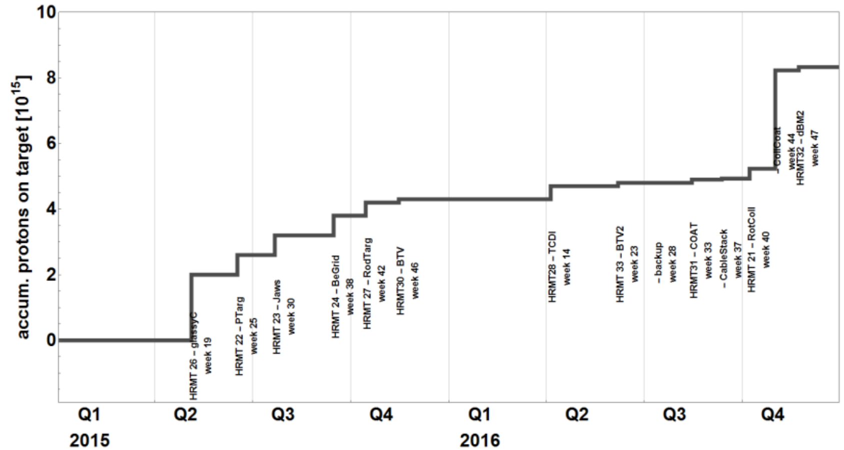


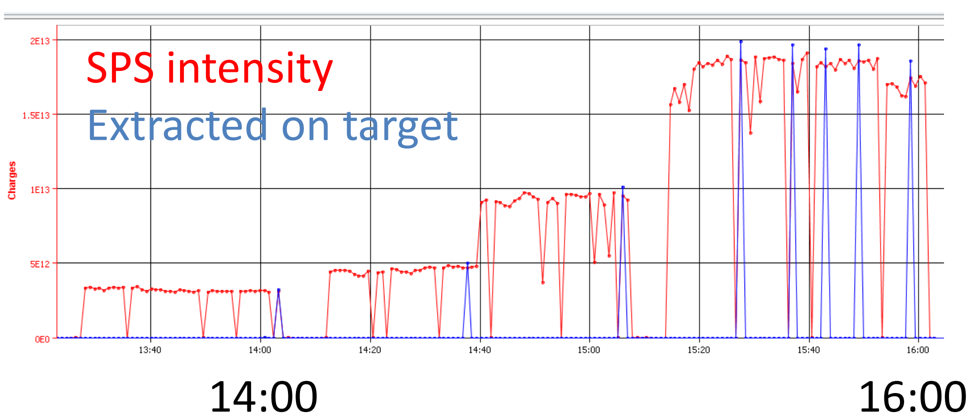
An experimental beam program

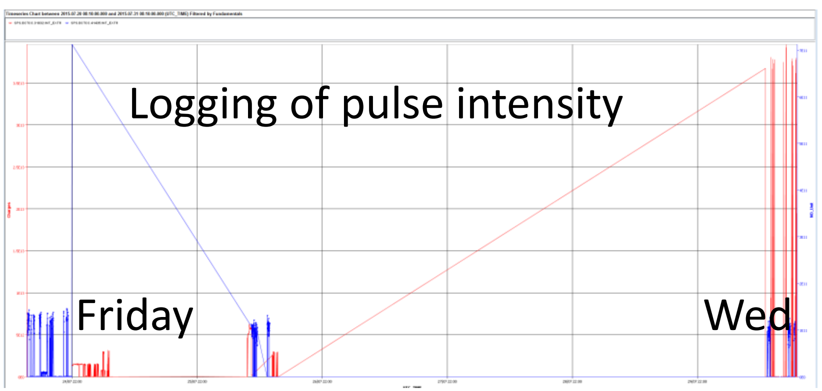
Single pulse experiments

- Typically 100-500 pulses per experiment (10 exp./year)
  - Lasting a few shifts per experiment

- Limitation on air activation
- Allowing easier personnel access to irradiation area







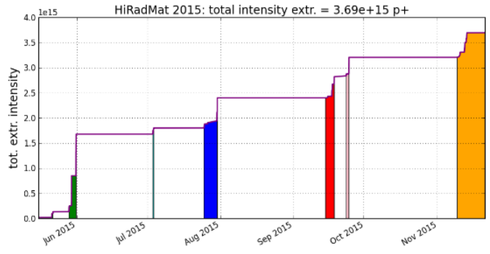
Injectors to HiRadMat in 2015

- Accumulated SPS cycle time: 4.0 days

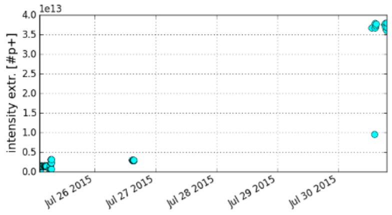
Variable Statistics between 2015-02-16 16:13:00.000 and 2015-12-01 16:13:00.000 (UTC_TIME)

Includes : MIN Value, MAX Value, AVG Value, Standard Deviation, Frequency | Selection Modes : Rows

Variable Name	# Values	MIN Timestamp	MAX Timestamp
SPS::FEI_HIRADMAT	0		
SPS::HIRADMAT1	0		
SPS::HIRADMAT2	0		
SPS:FEI_HIRADMAT:FEI_HIRADMAT	0		
SPS:HIRADMAT_4INJ_FB11100_FT500_Q20_2014_V1:HIRA...	0		
SPS:HIRADMAT_4INJ_FB11100_FT500_Q20_2014_V1:HIRA...	13531	2015-05-10 12:13:56.535	2015-09-28 19:24:24.135
SPS:HIRADMAT_HIGH_INTENSITY_2011_V1:HIRADMT1	0		
SPS:HIRADMAT_HIGH_INTENSITY_2011_V1:HIRADMT2	0		
SPS:HIRADMAT_L7200_2010_V1:HIRADMT1	0		
SPS:HIRADMAT_L7200_2011_V1:HIRADMT1	0		
SPS:HIRADMAT_L7200_2012_V1:HIRADMT1	0		
SPS:HIRADMAT_L7200_NORTHBUMP_2012_V1:HIRADMT1	0		
SPS:HIRADMAT_PILOT_Q20_2014_V1:HIRADMT1	11339	2015-04-04 16:55:49.335	2015-11-21 12:39:50.535
SPS:HIRADMAT_TEST_V1:HIRADMT1	0		



Courtesy V. Kain



- Total intensity extracted: 3.7e15 pot
- Excellent performance of the injectors providing beams with large flexibility, in the largest intensity range for multi-bunch pulses. All planned beams provided.

- 2012: 2 days, 1.4e16 pot

Variable Statistics between 2012-02-16 16:13:00.000 and 2012-12-15 16:13:00.000 (UTC_TIME)

Includes : MIN Value, MAX Value, AVG Value, Standard Deviation, Frequency | Selection Modes : Rows

Variable Name	# Values	MIN Timestamp	MAX Timestamp	MIN Value	MAX Value	AVG Value	Standard Deviation	Frequency
SPS::FEI_HIRADMAT	0							NaN/year
SPS::HIRADMAT1	0							NaN/year
SPS::HIRADMAT2	0							NaN/year
SPS:FEI_HIRADMAT:FEI_HIRADMAT	0							NaN/year
SPS:HIRADMAT_4INJ_FB11100_FT500_Q20_2014_V1:HIRA...	0							NaN/year
SPS:HIRADMAT_4INJ_FB11100_FT500_Q20_2014_V1:HIRA...	0							NaN/year
SPS:HIRADMAT_HIGH_INTENSITY_2011_V1:HIRADMT1	0							NaN/year
SPS:HIRADMAT_HIGH_INTENSITY_2011_V1:HIRADMT2	3734	2012-06-13 05:58:07.335	2012-11-30 09:42:34.935					22/day
SPS:HIRADMAT_L7200_2010_V1:HIRADMT1	0							NaN/year
SPS:HIRADMAT_L7200_2011_V1:HIRADMT1	8801	2012-05-09 06:40:19.335	2012-10-10 08:27:07.335					2/hour
SPS:HIRADMAT_L7200_2012_V1:HIRADMT1	3072	2012-10-11 09:36:02.535	2012-11-03 22:57:57.735					5/hour
SPS:HIRADMAT_L7200_NORTHBUMP_2012_V1:HIRADMT1	2197	2012-10-11 10:00:13.335	2012-10-22 15:09:31.335					8/hour
SPS:HIRADMAT_PILOT_Q20_2014_V1:HIRADMT1	0							NaN/year
SPS:HIRADMAT_TEST_V1:HIRADMT1	0							NaN/year

HiRadMat experiment

BPM diamond detectors

Development of

- Online monitoring of **beam position at experiment**
- Measuring of beam halo on four quadrants

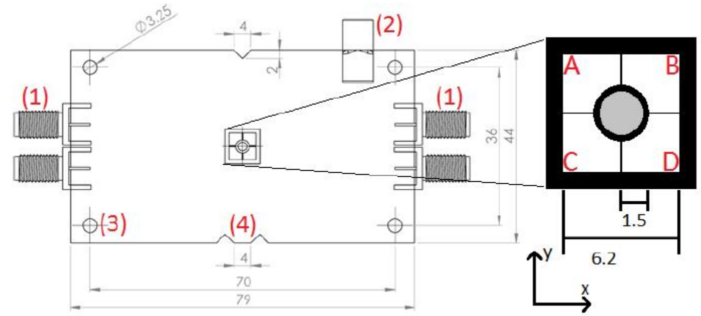


FIGURE 3.2: A schematical view of a detector module, with units in *mm*. Each gold pad has a side length of 3 *mm* and a separation to one another of 0.2 *mm*. The hole of the gold plating has a radius of 1.5 *mm*.

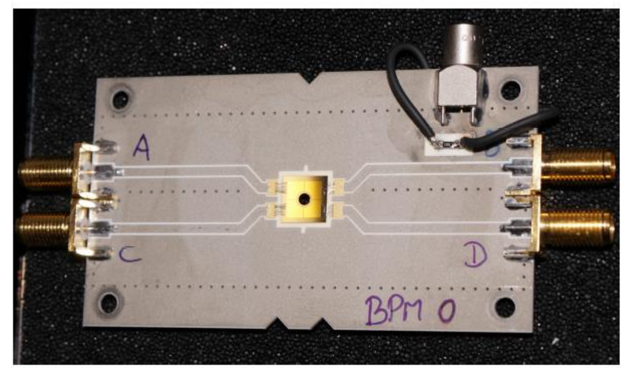
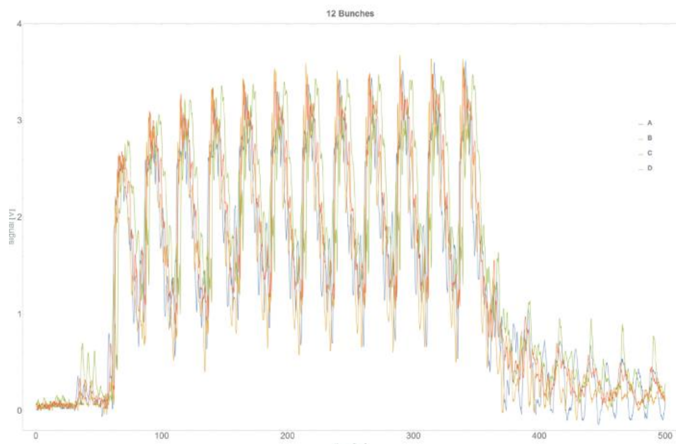
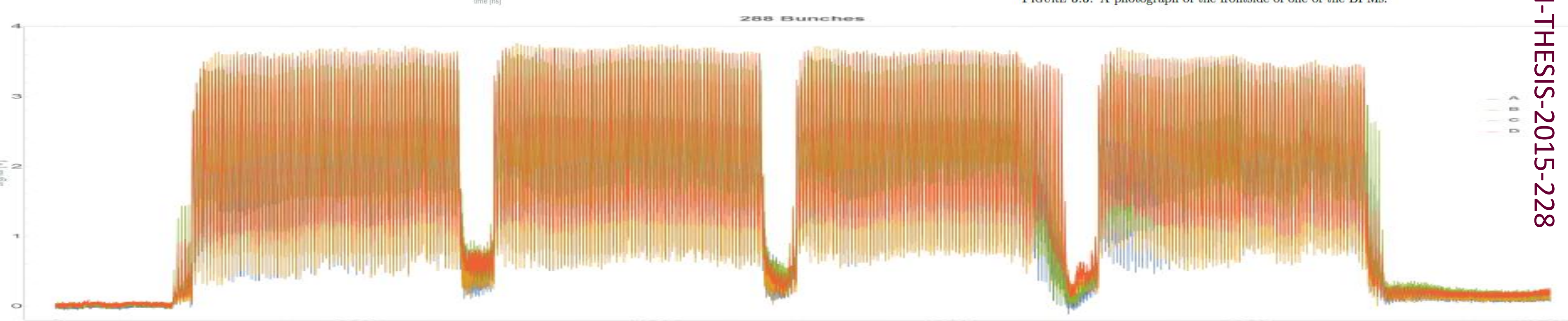


FIGURE 3.3: A photograph of the frontside of one of the BPMs.





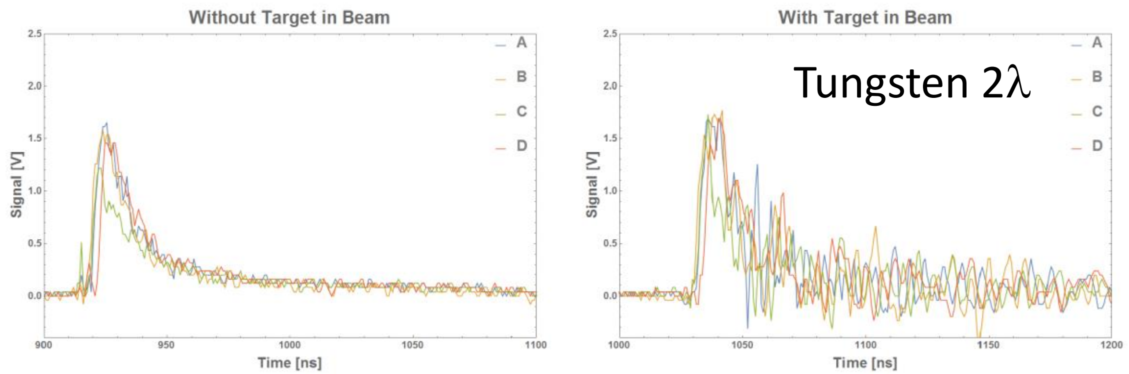
Courtesy B. Lindstrom, CERN-THESIS-2015-228

I. Efthymiopoulos et al.

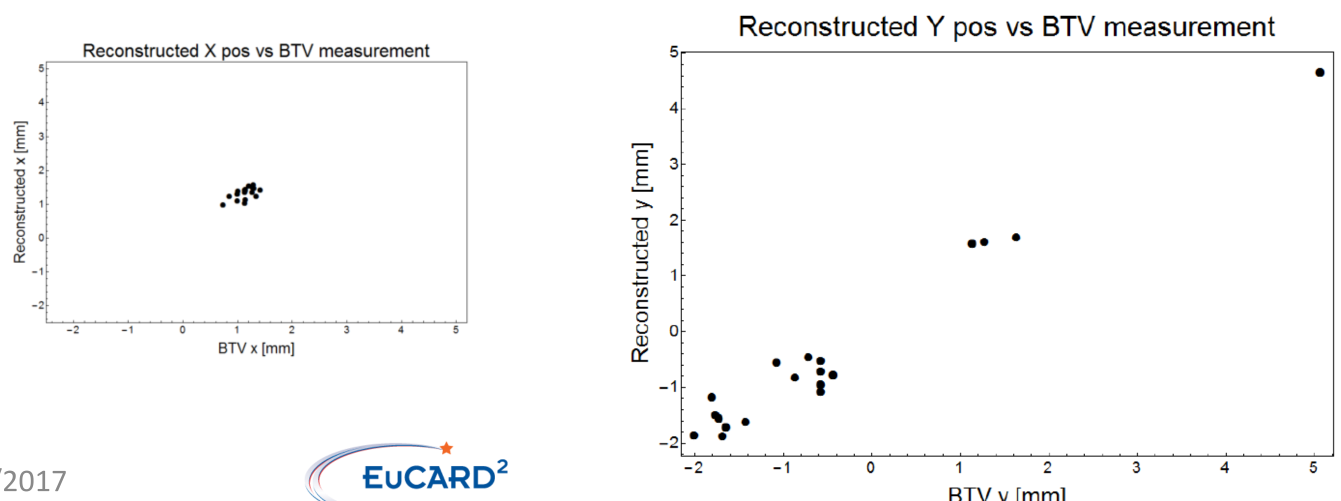
Beam position with TARGET downstream

Courtesy B. Lindstrom, CERN-THESIS-2015-228

- Noise induced from backscattered particles



- Beam position still deducible



ATLAS pixel/strip modules

New user in 2017

- Testing ATLAS inner detector and electronics
  - Present models and prototypes of future models
- Estimate the damage threshold of the under fast extracted, intense proton beam irradiation
- As basis for the evaluation of the damage risk in case of fast HL-LHC beam losses.

Candidate for permanent reference measurements in HiRadMat?

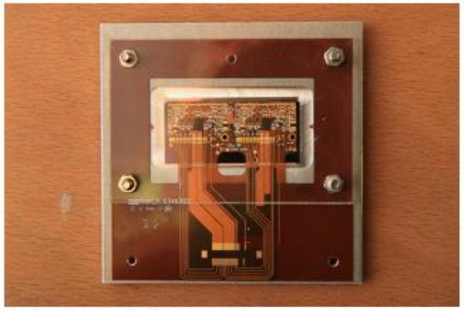


Fig.1: Pixel Module.

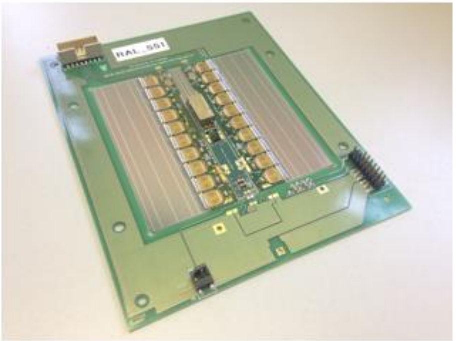


Fig.2: Strip module.

Online monitoring

Provided by the HiRadMat facility

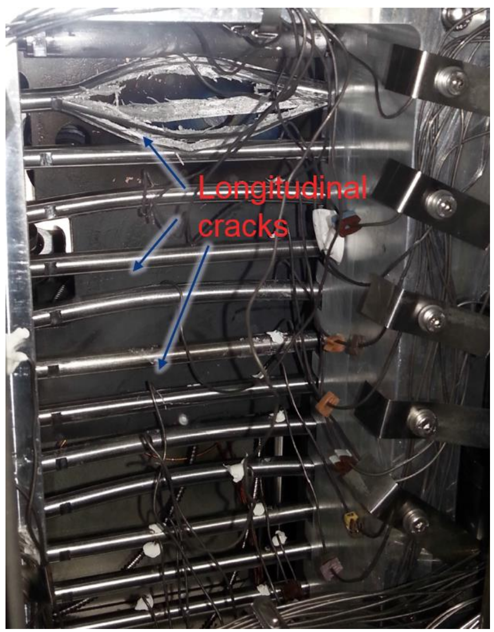
- **Beam performance**
  - Intensity: BCT transformers in SPS/transfer line
  - Beam position/profile
    - BPM in transfer line
    - Air core current transformer, BTV at experiment

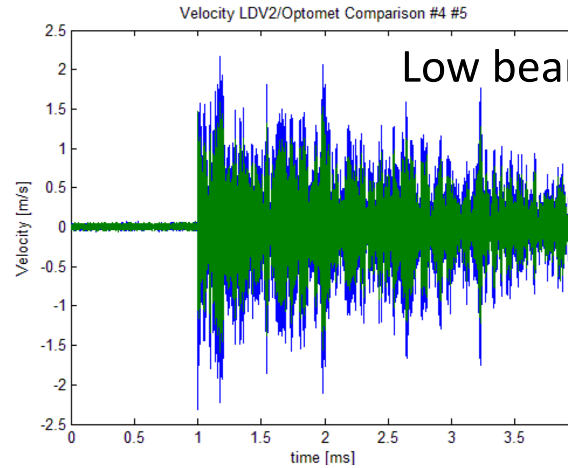
- **Radiation monitoring**
  - RadMons in TNC and TT61
  - BLMs along the transfer line and experimental setup

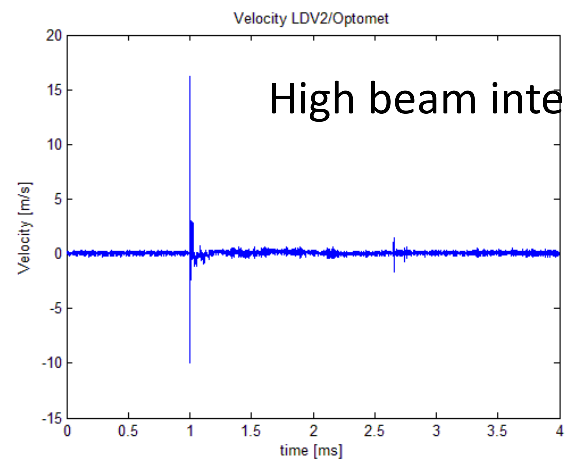
Production targets

M. Calviani et al.

- **Motivation:**
  - Reduce the uncertainties existing in the core material response of the AD-Target
  - Assess the material selection for a new AD-Target for LS2
- **Goals:**
  - Recreate the same extreme conditions as reached in the AD-target in a controlled environment (validation of hydrocodes calculations)
  - **Identify mechanism of failure and limits** of the materials of interest impacted by proton beams





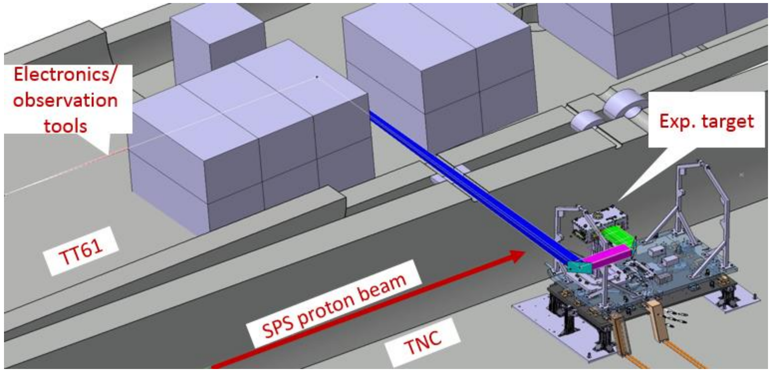


Electronics/DAQ in TT61

with feed-through to TNC for direct cabling

Specifications

- Maximum cable length/optical path: 15 m
  - From electronics to target center
- Similar prompt radiation levels as in TJ7 bunker
  - Thick target, 3e12 ppp
  - 10e6 hadrons/cm2 for full intensity pulse



Additional shielding implemented (September 2015):

Optional counter measures: Increase distance (additional optical path/cable length)

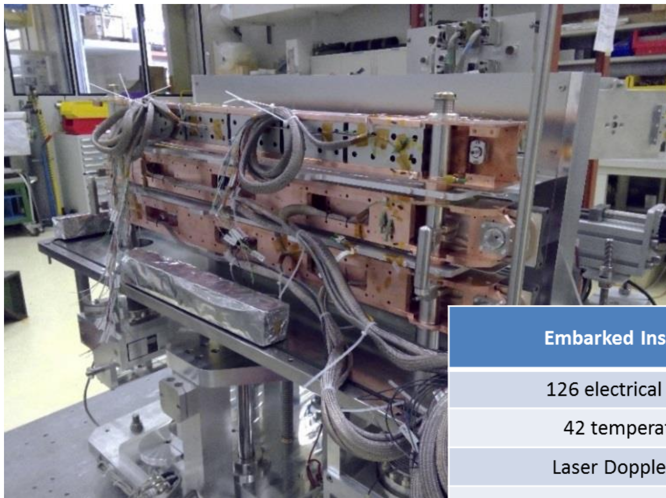
CERN

HiRadMat
High-Radiation to Materials

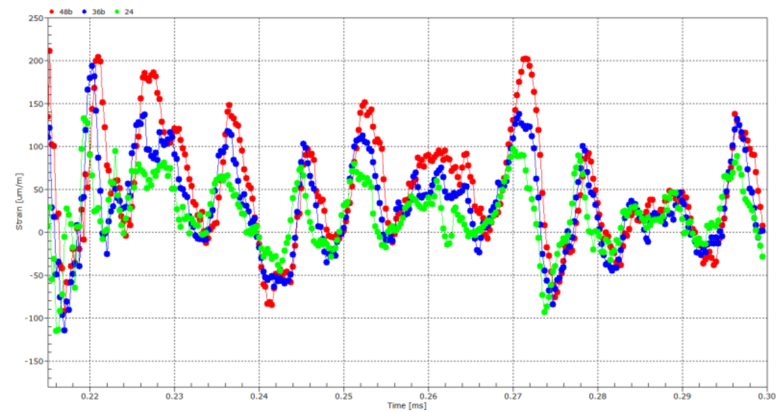
HRMT-23 JAWS

- designed to test and qualify against LHC and HL-LHC accident scenarios **three collimator jaws** (HL-LHC with MoGr, HL-LHC with CuCD, LHC with CFC)

Courtesy: M. Guinchard et al.



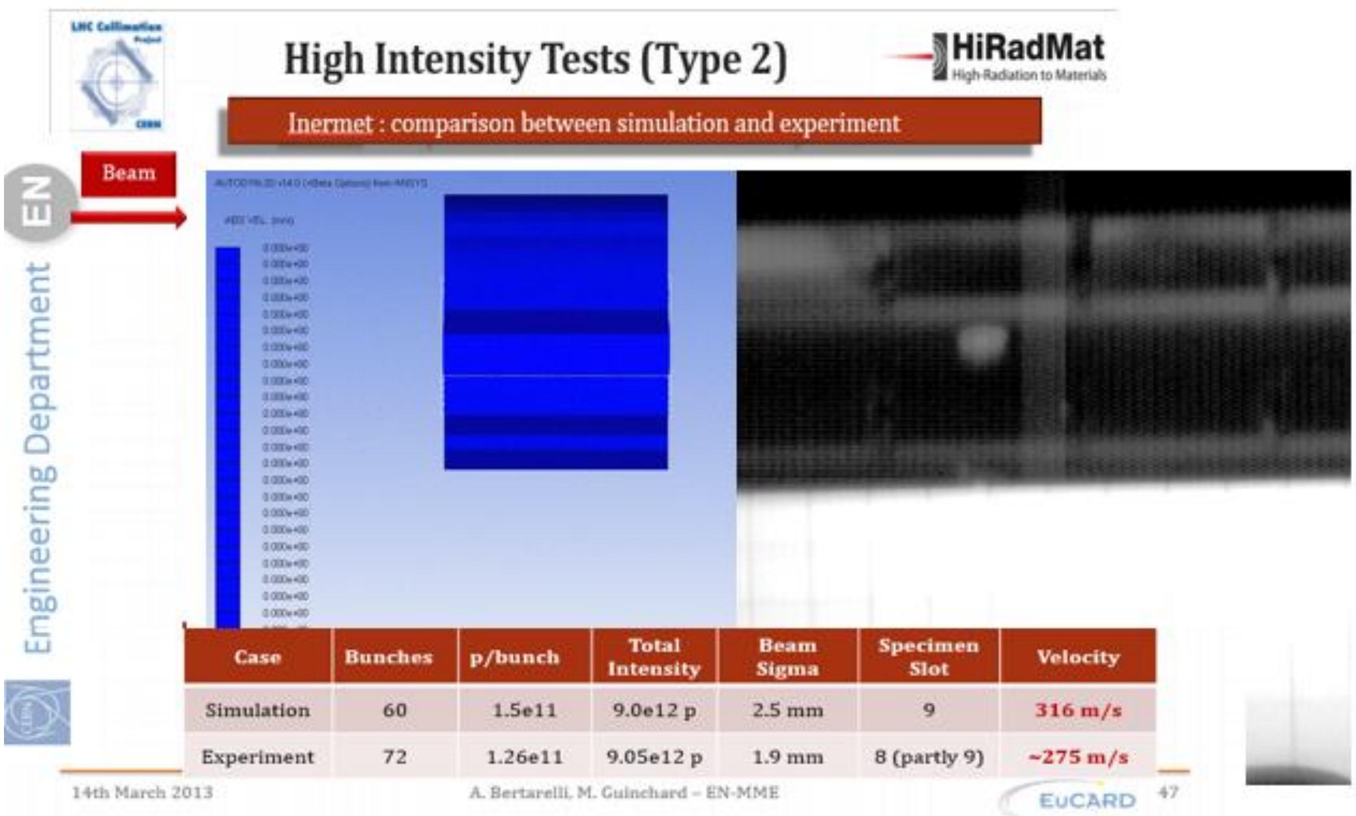
Embarked Instrumentation	Sampling frequency
126 electrical strain gauges	4 MHz
42 temperature probes	200 Hz
Laser Doppler Vibrometer	4 MHz
Water pressure sensor	100 kHz
60 strain Fibre Bragg Gratings	500 Hz
HD Camera inspection	*" 4K "*
Fast Speed Camera + LED lighting system	20 000 fps



- With high intensity beam pulses on thick target - electronics in TT61 failed

	GlassyC	PTarg	Jaws	BeGrid	BLM2	RodTarg
Target	Thin 0.1 λ	Thick 2 λ	Thick >2λ	Thin 0.25 λ	Thin 0 λ	Thick 2 λ
p.o.t. (1e15)	1.2	0.03	1.1	0.3	0.3	0.2
Max. pulse intensity (1e13)	3.5	0.2	3.8	3.8	3.8	0.2
BLM411 response	0.016	0.0001	0.003	0.0004	0.0004	0.0003
BLM518 response	0.1	0.01	0.14	0.02	0.02	0.01
BLM526 response (just after nominal target position)	0.23	0.2	0.27 (sat.?)	0.22	0.15	0.2

Validation of collimator materials



LHC Collimation Project

High Intensity Tests (Type 2)

HiRadMat
High-Radiation to Materials

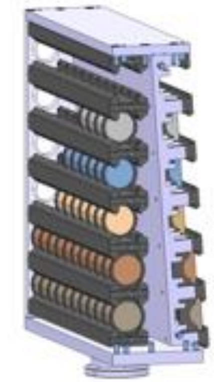
Inermet : comparison between simulation and experiment

Beam

EN Engineering Department

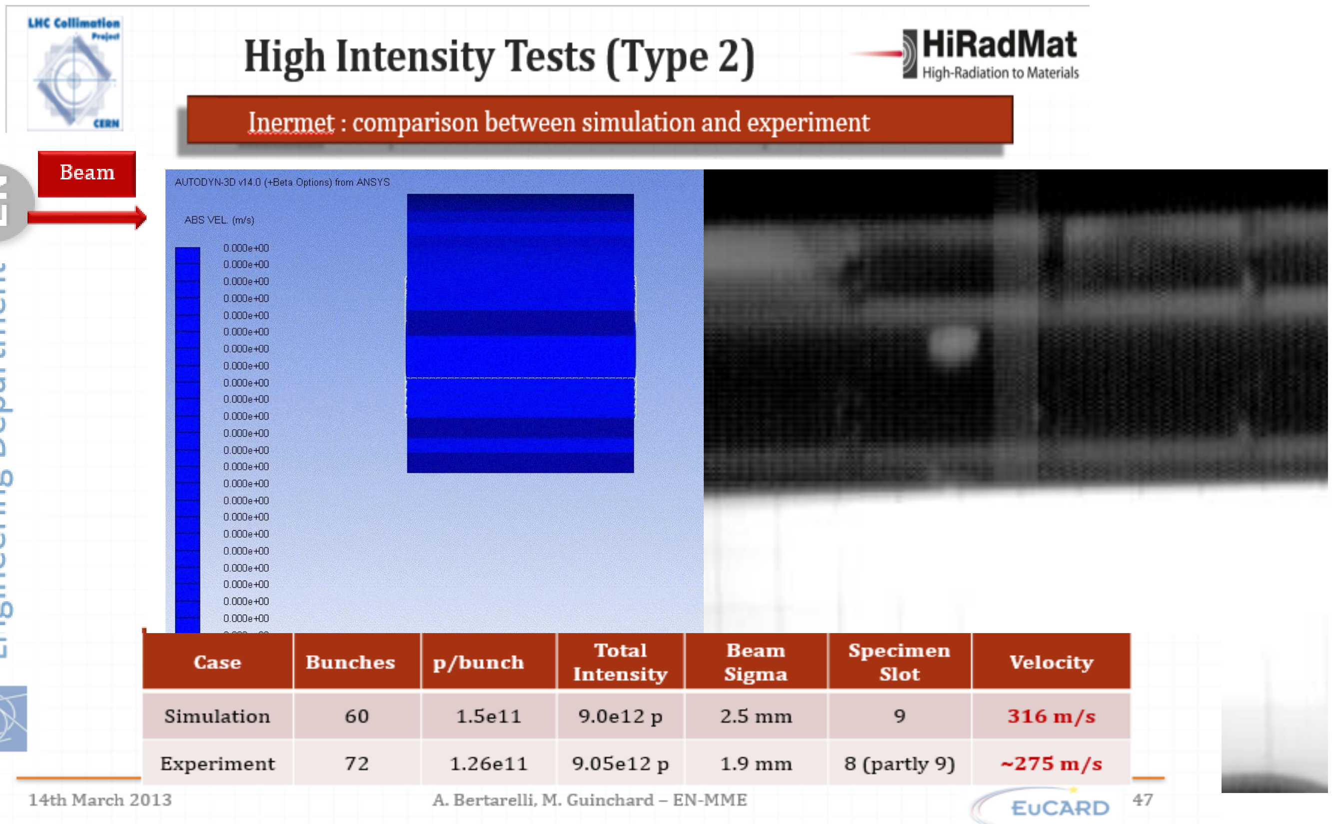
Case	Bunches	p/bunch	Total Intensity	Beam Sigma	Specimen Slot	Velocity
Simulation	60	1.5e11	9.0e12 p	2.5 mm	9	316 m/s
Experiment	72	1.26e11	9.05e12 p	1.9 mm	8 (partly 9)	~275 m/s

14th March 2013 A. Bertarelli, M. Guinchard – EN-MME EuCARD 47



Courtesy: A. Bertarelli, M. Guinchard

Validation of collimator materials

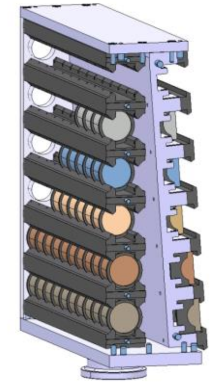


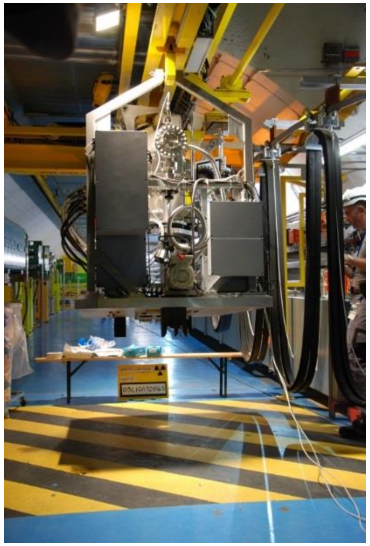
High Intensity Tests (Type 2)

Inermet : comparison between simulation and experiment

Case	Bunches	p/bunch	Total Intensity	Beam Sigma	Specimen Slot	Velocity
Simulation	60	1.5e11	9.0e12 p	2.5 mm	9	316 m/s
Experiment	72	1.26e11	9.05e12 p	1.9 mm	8 (partly 9)	~275 m/s

14th March 2013 A. Bertarelli, M. Guinchard – EN-MME EuCARD 47





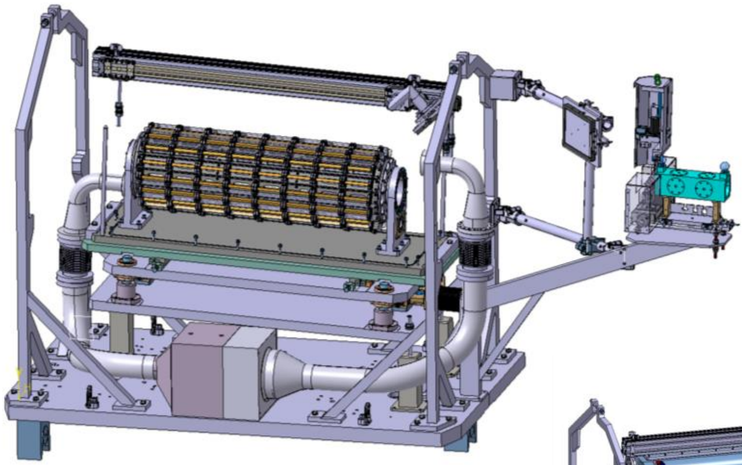
Courtesy: A. Bertarelli, M. Guinchard

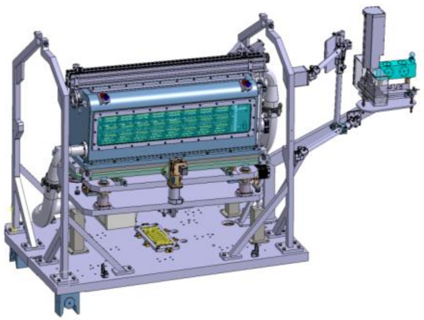
HRMT36 - MultiMat experiment in 2017

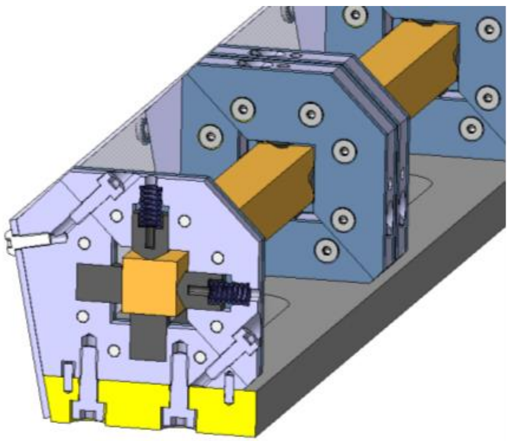
HiRadMat
High-Radiation to Materials

- **Rotatable Barrel** with up to **16 independent target stations** (1 m long) easy to mount and dismount, hosting several specimens and/or small devices.
- **Comprehensive Acquisition system** based on Strain Gauges, Fiber Bragg Grating (FBG), Temperature probes, LDV, Rad-hard Camera, Accelerometers
- Bench-marking simulation codes with material properties/response
- Non-destructive testing

Additional design criteria: containment and target holder **re-usable** for further material tests







Courtesy: A. Bertrarelli

Experiment proposals 2017 and beyond

First ideas/proposals in preparation:

- FCC collimation/absorbers/dumps
  - Reasonable testing for present material choices
- Vacuum windows for high power beams
- Studies for production targets
  - "physics beyond colliders"
- High power proton targetry
- Beam monitoring for LHC/FCC
  - "permanent" test bench for BE/BI
- BLMs
- Material research with pre-irradiated materials

Material Testing and Research

Explore the potential for conducting unique experiments that cannot be realized elsewhere

- Exposing materials with accumulated irradiation damage to intense particle beams
  - E.g. HRMT38 by GSI, **dynamic response of pre-irradiated** targets of high-damping materials
  - **Testing of a several Beryllium grades** (intended for targets and vacuum windows) that can have wider impact (fusion reactors, moderators, etc.) (HRMT24-BeGrid)
  - **Novel carbon structures** (i.e. Glassy Carbon) while searching for vacuum window materials with potential applications outside the original aim (HRMT26-GlassyC)

- Collaborations from FNAL, BNL, GSI, CERN, PSI

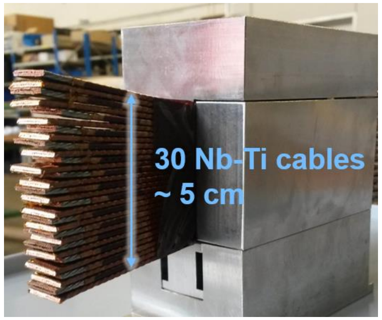
Cryogenic experiments

V. Raginel, D. Wollmann

See also MPP 11/11/16
https://indico.cern.ch/event/587075/

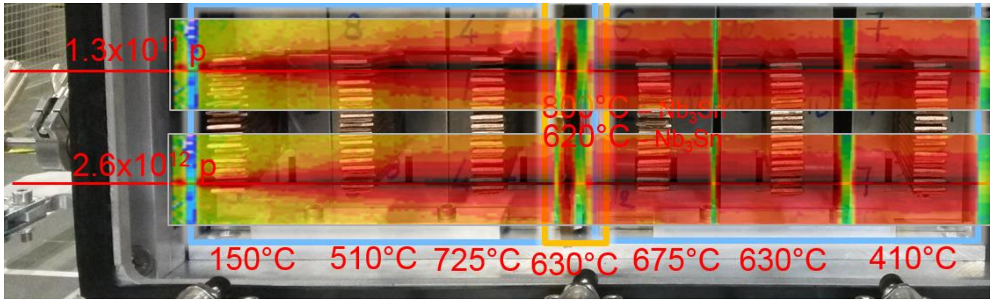
- HiRadMat experiments on cable strands suggested in 2015

- Motivated by HL-LHC failure cases (injection, extraction)
- Several experiments planned without beam and with beam:
  1. Heat stacks of cables in an oven to different peak temperatures and measure dielectric strength of the insulation
  2. Heat insulation by a short current pulse and measure dielectric strength
  3. Heat a single strand by a current pulse and measure critical current
  4. Expose stacks of cables to radiation in **HiRadMat** at RT and measure dielectric strength and critical current
  5. Expose stacks of cables to radiation in **HiRadMat** at cryogenic temperatures and measure dielectric strength and critical current



- Experimental campaign from 2016-2018
  - Measure the degradation of the insulation
  - Measure the degradation of critical current of Nb-Ti

Currently preparing the cryogenic infrastructure and operational procedures



Summary

- HiRadMat is a user facility
  - dedicated for in-beam testing
  - with fast extracted beams (LHC injection like)

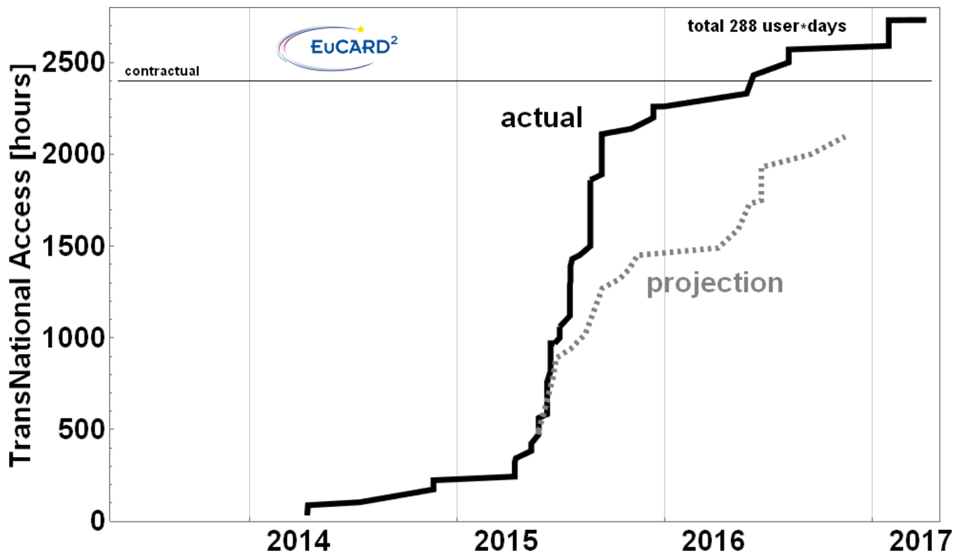
- Proposals are made extending the variety of research topics – also in view of HiLumi.

- Continuously investigating further needs taking advantage of HiRadMat

Annex

Transnational Access

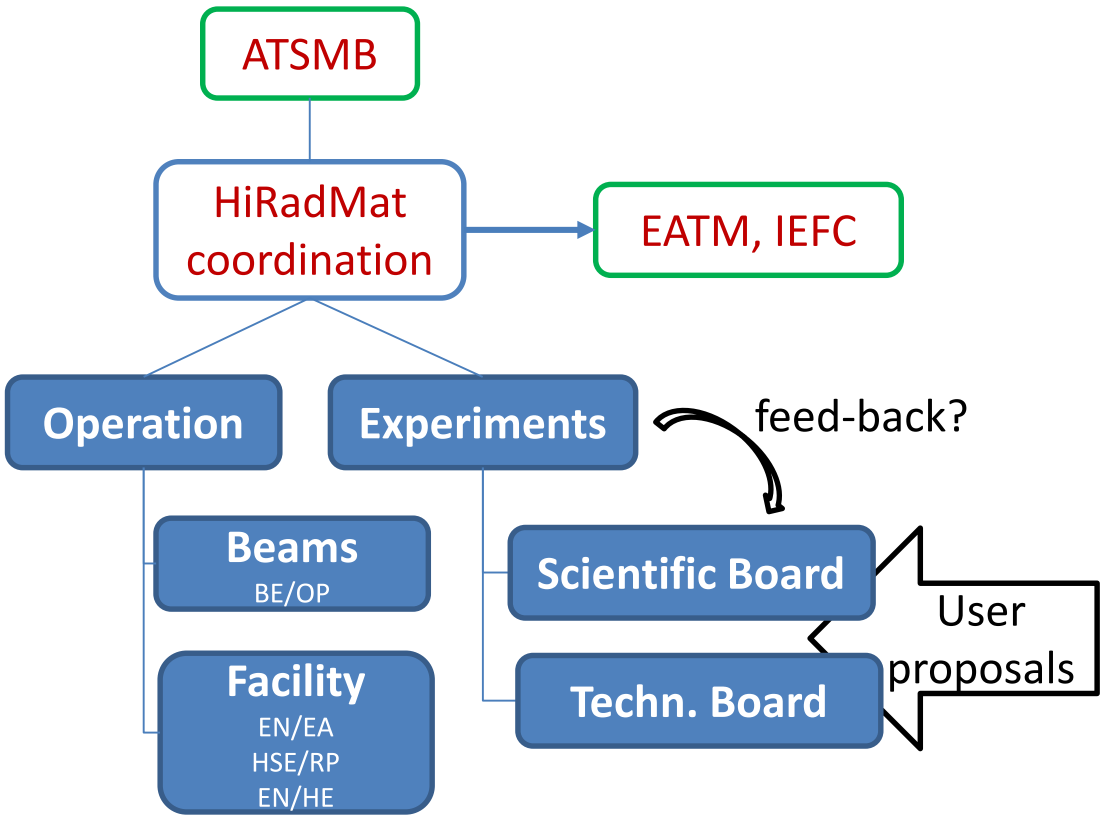
- EU funded support for external users on travel/subsistence



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

- More than 280 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

HiRadMat Scientific Board

HiRadMat
High-Radiation to Materials

- Is the executive body that manages the facility.
- Evaluates the scientific merit of the proposed experiments, their feasibility, the proposed online information during beam time, the post-irradiation analysis plans and the expected results and publications to the interest of the scientific community.
- Distributes the EUCARD Transnational Access funds - contractual obligation from EC
- **Members:**

Bernie RIEMER, MSc
Senior Research Engineer
ORNL/SNS
Target development team leader

Nick SIMOS, Ph.D, P.E (chair)
Senior Scientist
Nuclear Science Department & Photon Sciences Directorate BNL
Project leader of BNL Linac Isotope Producer (BLIP)

Michael WOHLMUTHER, PhD
Senior Scientist
Paul Sherrer Institute - PSI
Radiation transport & Multiphysics Group
Head of Target Development Group

Adrian FABICH (scientific secretary)
Beam physicist – EN/EA group

Stefano SGOBBA
Materials Engineer – EN/MME group

Sebastien EVRARD
Mechanical Engineer – EN/EA group

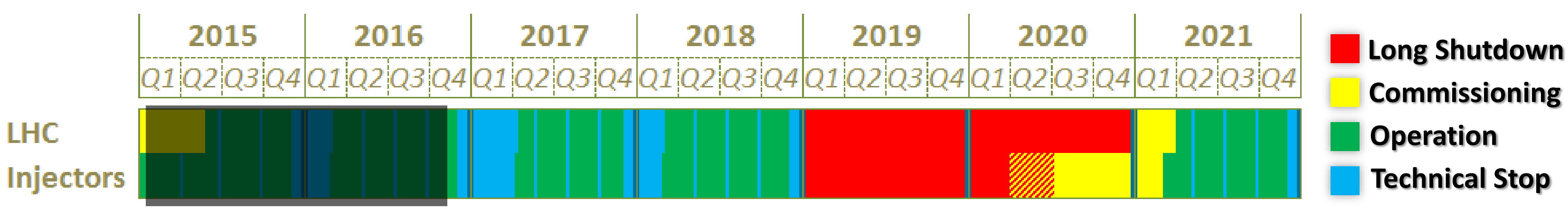
Stefano Redaelli
Mechanical Engineer - BE/ABP group

Alfredo Ferrari
Senior physicist - EN/STI group

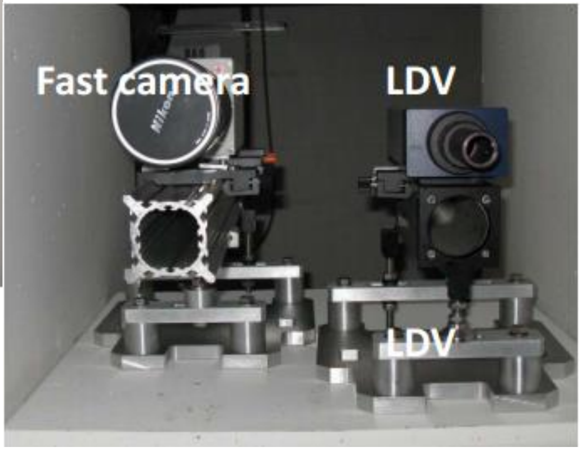
EN Engineering Department

Beam availability until LS2

- Two years left until LS2
  - 2016: 34 weeks
  - 2017: “shorter” beam year (26 weeks)
  - 3 experiments shifted from 2016, total 6 dedicated experiments already in the pipeline



With CERN support to visiting teams

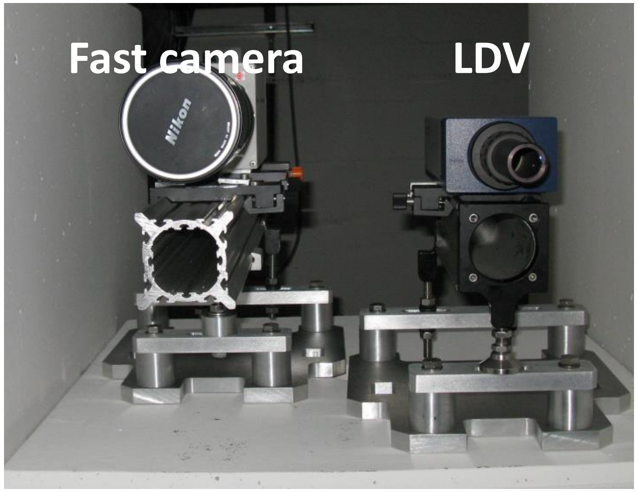


- Assisting during preparation, installation, operation and follow-up
- Advising in safety matters and radiation-protection

Measurement tools

Provided with the expertise of various groups at CERN

- Laser-Doppler vibrometer
  - Measuring surface velocities of several m/s
  - tens of MHz sampling
- Optical high-speed recording
  - High-speed camera with several kHz frame rate



- Diamond detectors, strain gauges, temperature sensors …
- Beam monitoring
  - High precision (< 0.1 mm) alignment/survey to experimental tables/beam
    Based on BTV/air core current transformer
  - Intensity monitoring
- Radiation monitoring with RadMons and beam loss monitoring

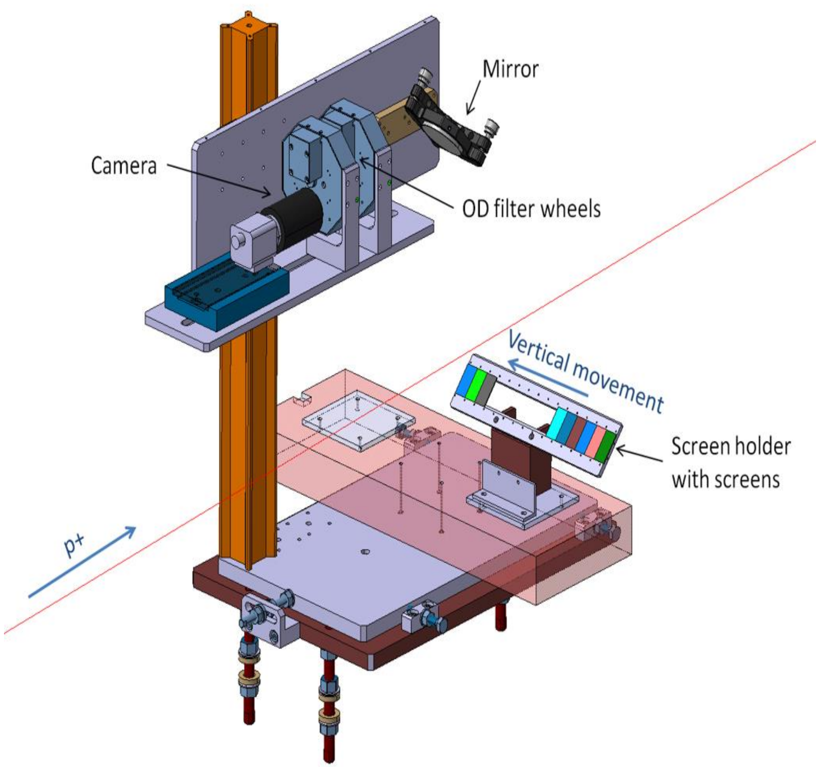
Facility extensions and improvements

- Hot cell for HRM users
  - Potentially in collaboration with PSI
- Surface lab: full mock-up scenario of TNC/TT61+feed-throughs
  - Also reduces working hours in tunnel
- Infrastructure for cryogenic experiments
- Develop/identify common instrumentation
  - Preclude redundant developments of identical systems
  - Develop instrumentation and read-out as a facility service
- Beam monitoring
  - Units of BPKG/BTV available to experiments
  - Beam sigma measurement in the full range
    - BTV, diamond detectors
  - Performance to be established/documented

Beam sigma to be measured in the full intensity range

Courtesy: T. Lefevre

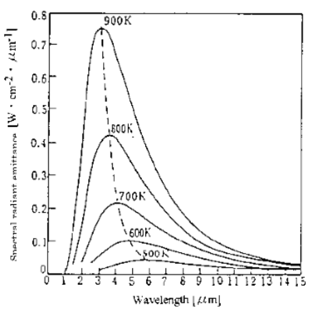
BTV screen with variable screen materials

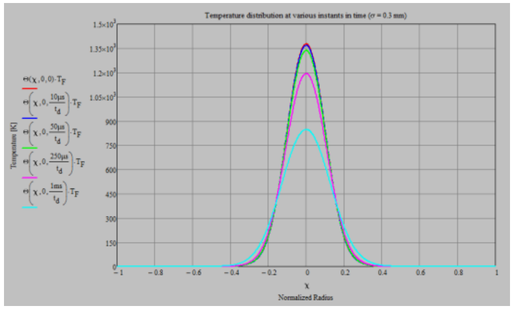


Camera to be located outside target area

ALTERNATIVE:

- Investigating the possibility to perform Beam size measurement on the experimental tank entrance window observing Black-body radiation



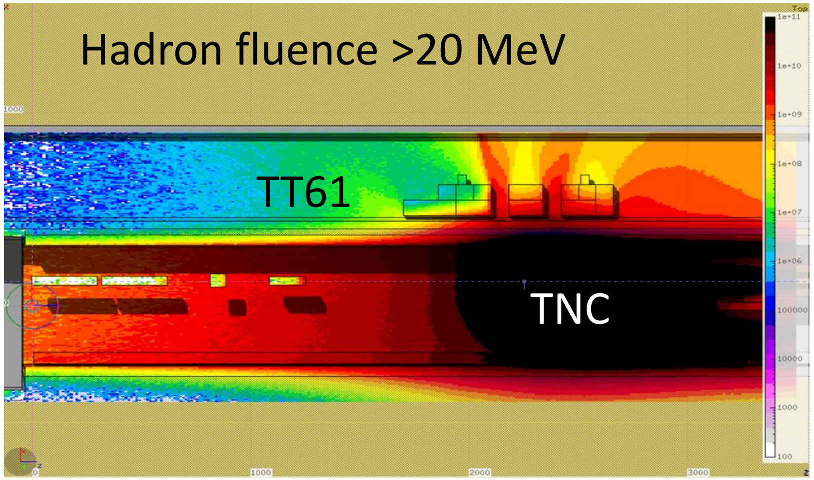


* To get the best profile of the beam, we should use longer wavelentgh (8-14um)

* IR camera from BI can be tested at some point.
  * Less photons at longer λ – is the camera sensitive enough
  * Still some distortion of the image. Thermal image profile will be smaller than the real beam profile
  * Would require an optical line since the camera are not rad-hard digital camera

Radiation levels in TT61

- 1e15 protons on target (1 experiment)
- Thick target – 2 nuclear interaction lengths



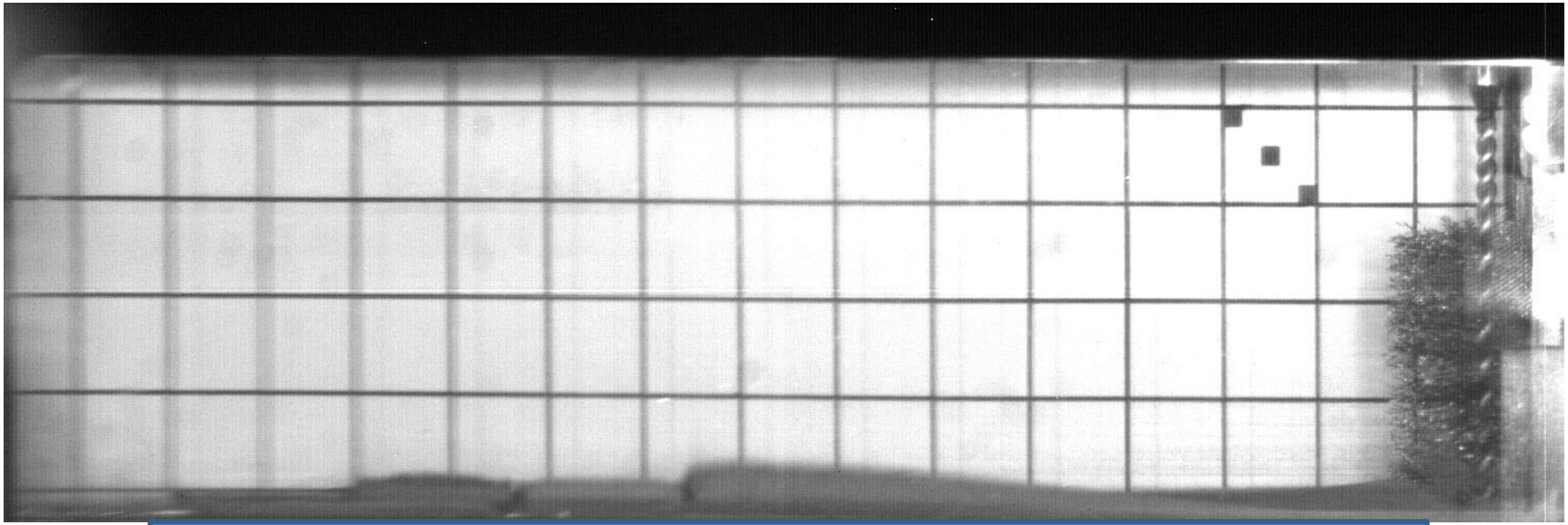
Courtesy: N. Charitonidis

- Maximum radiation levels: 1e6 to 1e7 heh/cm2 at electronics in TT61
- Further improvements only by increasing distance

TNC annual dose (for 1e16 pot): 1-5 kGy

Tungsten powder target

- Collaboration RAL-CERN

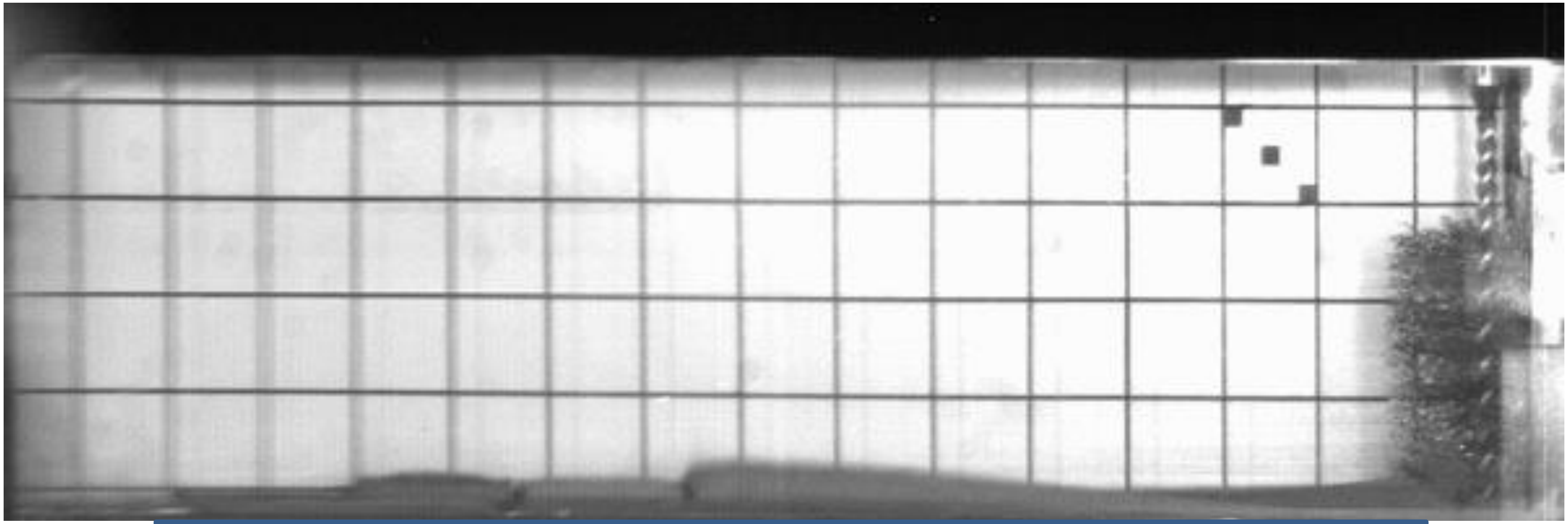


Trough with tungsten grains

proton beam

Tungsten powder target

High speed imaging provided by EN/EA



Different grain sizes along beam direction

proton beam