TARGETRY CHALLENGES & HIRADMAT

Fiona Harden, Aymeric Bouvard, Nikolaos Charitonidis, Yacine Kadi
(CERN/EN-EA)
(on behalf of the HiRadMat experiments and facility support teams)

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ARIES

HiRadMat
High-Radiation to Materials

CERN | EN ENGINEERING DEPARTMENT | EA

Points to cover

- Targetry challenges and experimental motivations
- How HiRadMat is a key player for Targetry challenges
- R&D examples with HiRadMat
- Future outlook
- Summary

Targetry challenges and experimental motivations

Targetry challenges

- To increase target power goals for accelerators continued investigation into many complex behaviours for the required facility upgrades is necessary.
- Limitations often occur due to target rather than accelerator.
- For high power target designs the following needs investigation:
  - Thermal behaviour and beam induced thermal shock/stress wave – heat dissipation and thermal-mechanical effects/deformations
  - Target designs for new physics discoveries for **Neutrino Factories, Muon Colliders, Spallation Sources**
    - e.g. particle converters for secondary/tertiary particle production and investigations
  - Cyclic fatigue
  - Radiation damage altering the material properties
  - Remote handling
  - Waste disposal
- Link between simulation and experimental concepts are vital to expand current knowledge of target properties and behaviours.

But why are controllable experimental facilities important for target investigations?

Targetry challenges

- Standard practices include:
  - High reliability on simulations with Monte-Carlo, numerical models, FLUKA, ANSYS…
  - Lack of user facilities to corroborate anticipated performances of targets and novel materials under high powered beam impacts.

- Experiments often performed in uncontrolled environments:
  - Temporary ad-hoc in-beam installations
    - ➢ Issues with logistics, safety, beam time, experimental requirements (e.g. uncontrolled beam parameters, uncontrolled beam size)

Experimental motivations

New physics opportunities arise through the study of (rare) secondary / tertiary particles;

- Muons, Neutrinos, Ions, etc.
- Produced through interaction of a primary proton beam on a target material

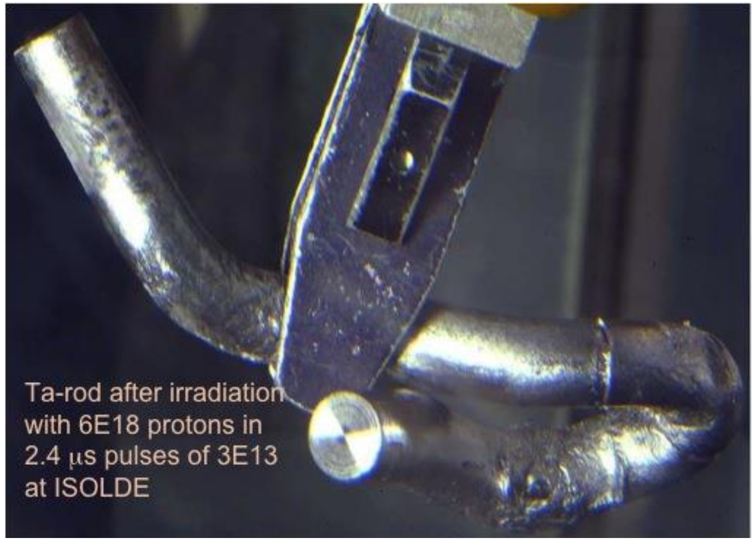
Key factor is the FLUX:

- High flux of secondary particles demands high power of the primary beam
  - Megawatt(s) of average beam power on the target
    - For example, for a proposed neutrino factory: 4 MW beam power on target

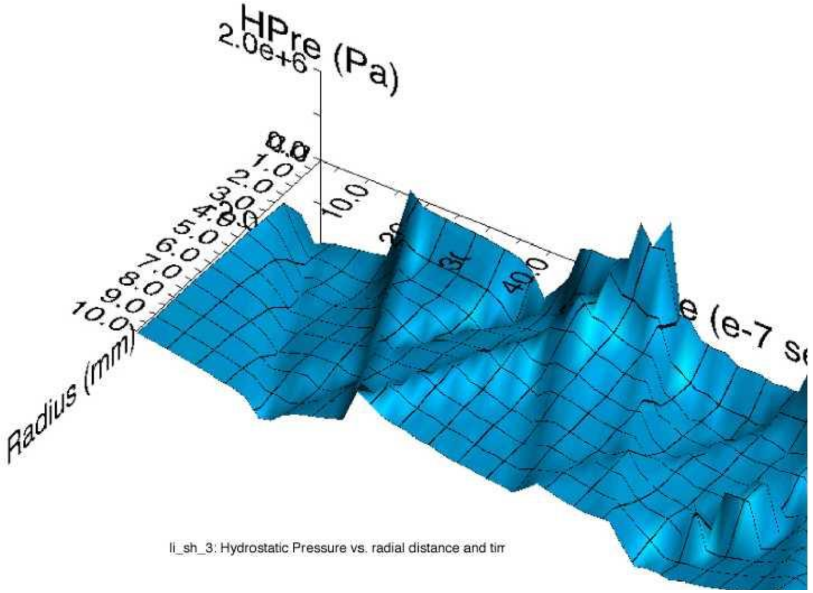
Experimental motivations

Going to the (Multi-)MW range is not trivial;

1. Rapid Temperature Increases
   - Compressive stresses occur if fast expansion of material surrounded by cooler material
   - Stress waves / thermal shocks through the target
2. Plastic deformation, cracking, fatigue potentials
3. Radiation Damage
   - Corrosion, embrittlement, swelling, etc.
4. Residual Radiation
   - Effects on materials
   - Access limitation if a problem arises.
   - Radiation Protection



Ta-rod after irradiation with 6E18 protons in 2.4 μs pulses of 3E13 at ISOLDE (photo courtesy of J. Lettry)



Simulation of stress wave propagation in Li lens (pbar source, Fermilab) [P.Hurh]

Experimental motivations

Why are controllable experimental facilities important for target investigations?

- Enables REAL BEAM experiments to be performed, which are vital:
  - To understand new materials and prototypes in these harsh environments.
  - To investigate how damage or onset damage occurs.
  - To determine the consequences which these real beam impacts may have in operation.
  - To broaden the empirical data for material models and simulations.

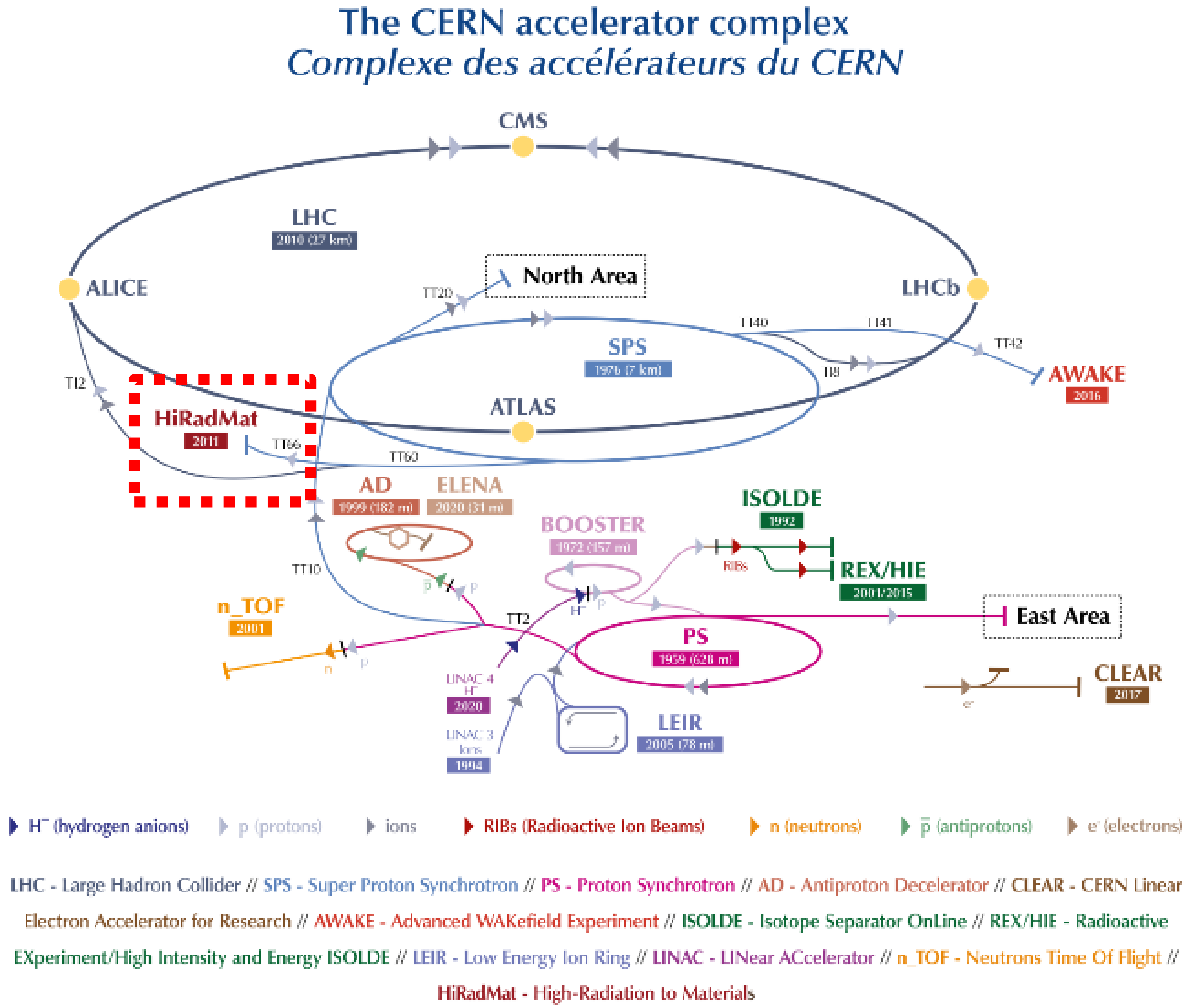
- Enables detailed investigation, specifically for the experimental needs, due to:
  - Specially designed experiments.
  - Adaptable beam pulses;
    - Beam position, beam size, pulse length, etc.
  - Beam instrumentation validated in real conditions with any limitations identified.

- It allows a true understanding to be gained of how a new material, target or prototype will behave in their intended environment.

How HiRadMat is a key player for Targetry challenges

Initial needs for the HiRadMat testing facility

- Originated from the LHC Collimation Project, due to requirements for a facility capable for "testing accelerator equipment with beam shock impacts[1] using high power LHC type beams[2]".
- Designed as an facility for R&D using pulsed high energy, high intensity proton beams (ions also possible)
- The High Radiation to Materials (HiRadMat) testing facility took its first beam in 2012[3] and has continued to deliver pulsed, high intensity, LHC-type beam to over 40 experiments.
- Developed into a facility which has, so far, completed experiments on materials testing, prototype & novel designs validation, beam monitoring devices, investigations at cryogenic temperatures and pre-irradiation materials analysis.



[1] http://lhc-collimation-project.web.cern.ch/lhc-collimation-project/HiRadMat.htm

[2] R. Assmann et al. 2009 "User Requirements for a Test Facility with High Power LHC Type Beam", EDMS No: 1130296

[3] I. Efthymiopoulos et al. 2011 "HiRadMat: A new irradiation facility for material testing at CERN", Proc. 2nd Int. Particle Accelerator Conf. (IPAC'11) paper TUPS058 1665-67.

Targetry challenges and HiRadMat

- HiRadMat is of UNIQUE importance for the investigation of the following:
  - Thermomechanical behaviours
  - Structural integrity of novel materials and prototypes
  - Pulsed beam effects
  - Material effects
- Experimental setups can vary, from simplistic designs to complex prototypes (some discussed later), allowing benchmark simulation validation, material selection and design qualification.

Beam Specifications

HiRadMat Proton Beam		Additional information
Beam Energy	440 GeV	
Energy per pulse	2.436 MJ	
Bunch Intensity	5E9 to 1.2E11 protons	
Number of Bunches	1 to 288	
Minimum Pulse Intensity	5E9 protons	(1b at 5E9 ppb)
Maximum Pulse Intensity	3.46E13 protons	(288b at 1.2E11 ppb)
Current during pulse	696.4 mA	
Power during pulse	3.1E5 MW	
Pulse Length (max)	7.95 µs	
1 σ r.m.s. beam radius	0.5 to 2.0 mm (standard)	0.25 to 4.0 mm currently upon request
Total allocated protons/year into facility	1E16 protons	equivalent to approx. 10 experiments per year at 1.0E15 protons

Super cycle options & bunch structure

- HiRadMat 'Long' Super Cycle:

  HRM_LS = 22.8 s, SFTPRO = 10.8 s, MD cycle = 7.2 s (3.6 s potentially depending on planning).

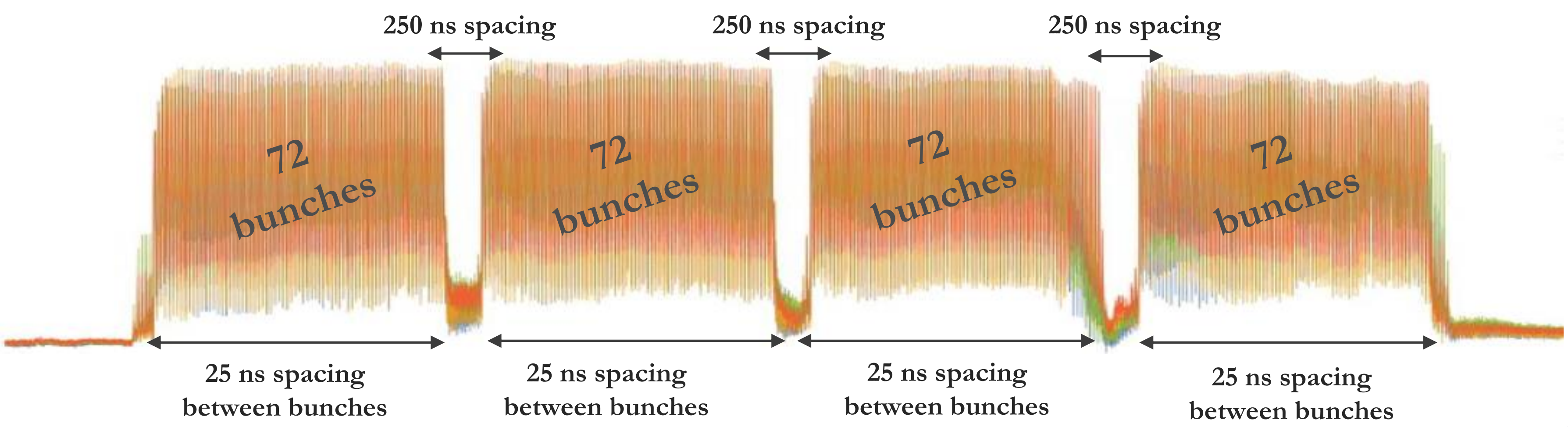
  ➢ TOTAL = 40.8 s (or 37.2 s) between pulses.

- HiRadMat 'Short' Super Cycle:

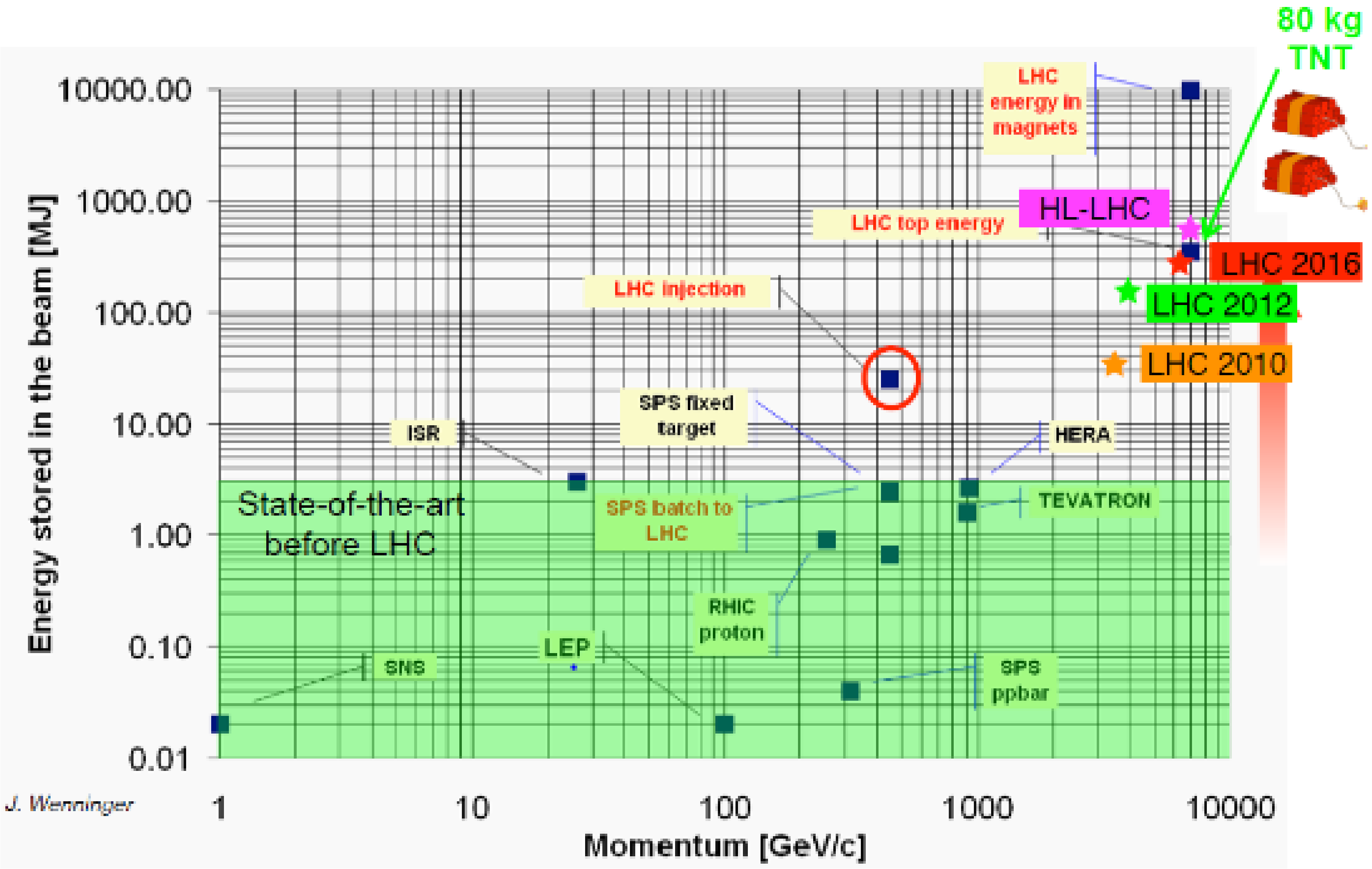
  HRM_SS = 8.4 s, SFTPRO = 10.8 s, MD cycle = 7.2 s (3.6 s potentially depending on planning).

  ➢ TOTAL = 26.4 s (or 22.8 s) between pulses.

HiRadMat pulse structure for maximum (288 bunches) [7.95 μs pulse]



MW range of materials slide



HiRadMat flexibility can be exploited to reach conditions exceeding those imposed by the SPS by, for example:

- Reducing beam transverse size (σ) to increase peak energy density U_{max} which governs local damage (e.g. spallation, fragmentation, localised melting).

R&D examples with HiRadMat

Pulsed beam effects

Courtesy of N. Charitonidis, et al.

HRMT10 Motivations & Findings

Goal:

Investigate an alternative for liquid mercury (a proposed solution for Neutrino Factory); granular (powdered) targets – to study the response of static tungsten powder impinged with a high energy, high power proton beam pulse.

Tungsten powder chosen due to:

- High Z
- High melting point
- Good Flowability (proved by RAL)

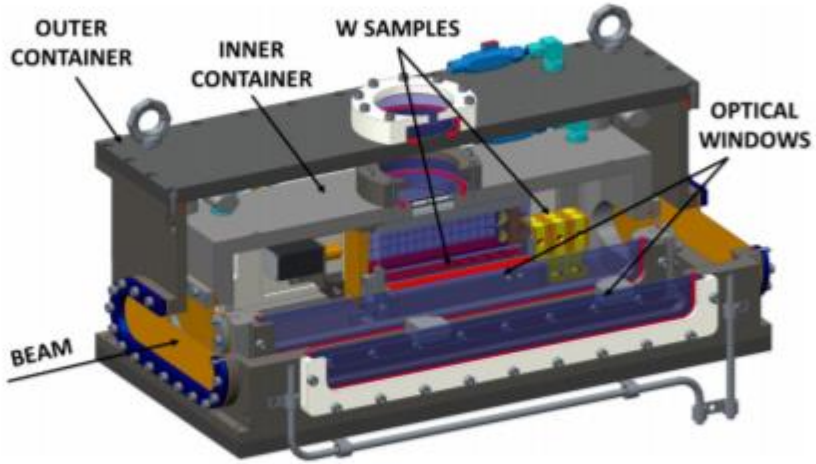


FIG. 2. Section drawing of the tungsten powder rig.

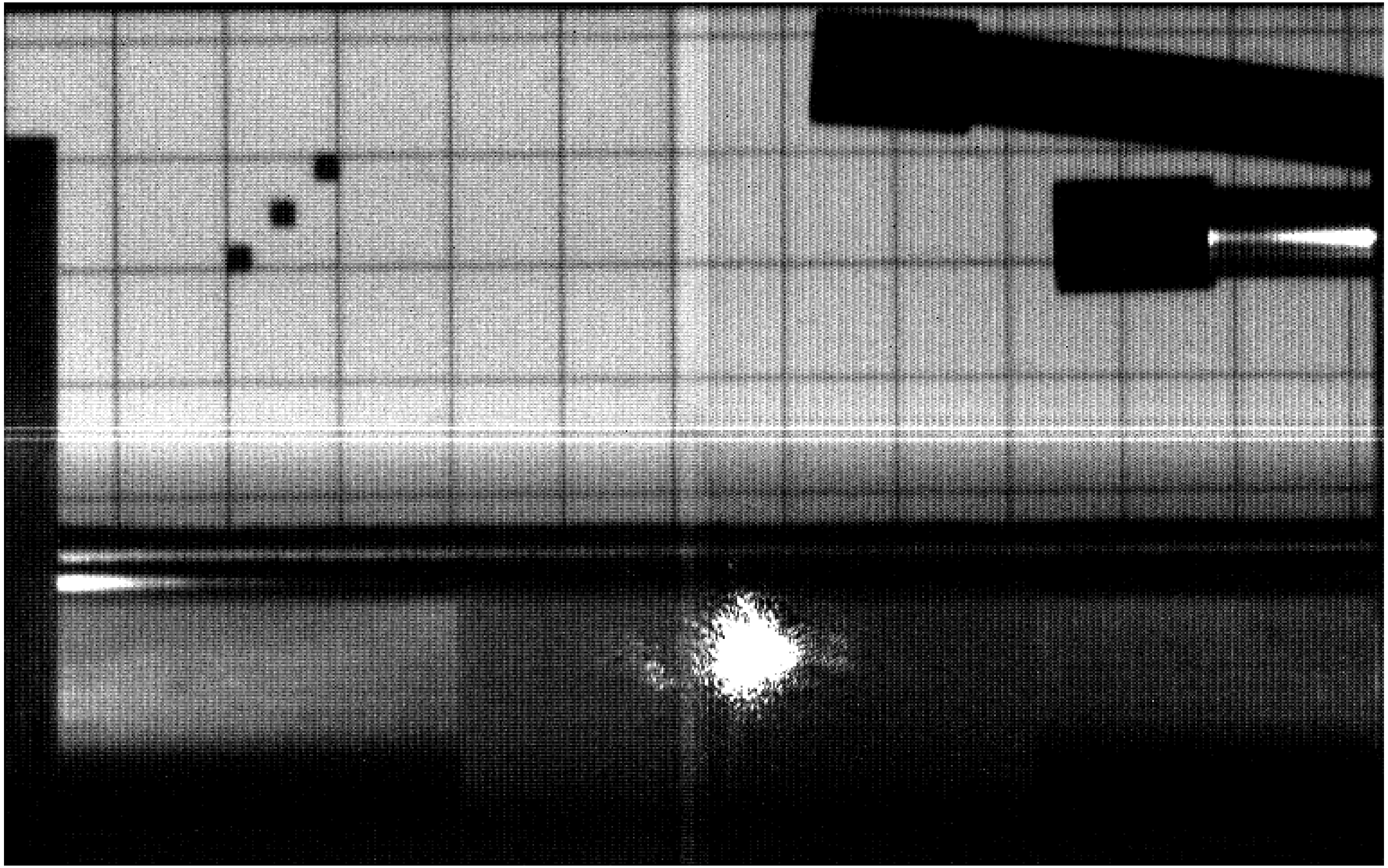
HiRadMat beam adaptability

- Neutrino Factory single pulse
  - 6.25E13 protons at 8 GeV at 50 Hz
- Maximum energy deposition per NF pulse at **Hg**: **approx. 200 J/g (FLUKA)**
- Maximum energy deposition per NF pulse at **W-powder**: **approx. 200 J/g (FLUKA)**

Tune the beam parameters of HiRadMat (440 GeV) in order to match this maximum energy deposition

- 6.25E13 protons at 8 GeV at 1.5 mm sigma
  - Equivalent to 3.7E12 protons at 440 GeV at 1.5 mm sigma

Single pulse comparisons provided same energy deposition maximum obtained (200 J/g)



Effect of a high-power incident proton beam on a tungsten powder target.
In this video, 1.7E11 protons at 440 GeV are impinging on the target.
https://videos.cern.ch/record/1975404

Tungsten powder immersed in helium atmosphere perturbed when impinged by 440 GeV proton beam[1].

Experiment led to further investigation with **HRMT22**, investigating the effect of granular tungsten powder in both helium and vacuum atmospheres[2].

[1] O. Caretta et al. 2014 "Response of a tungsten powder target to an incident high energy proton beam" Phys. Rev. ST Accel. Beams, 17, 101005

[2] O. Caretta et al. 2018 "Protons beam induced dynamics of tungsten granules" Phys. Rev. Accel. Beams, 21, 033401

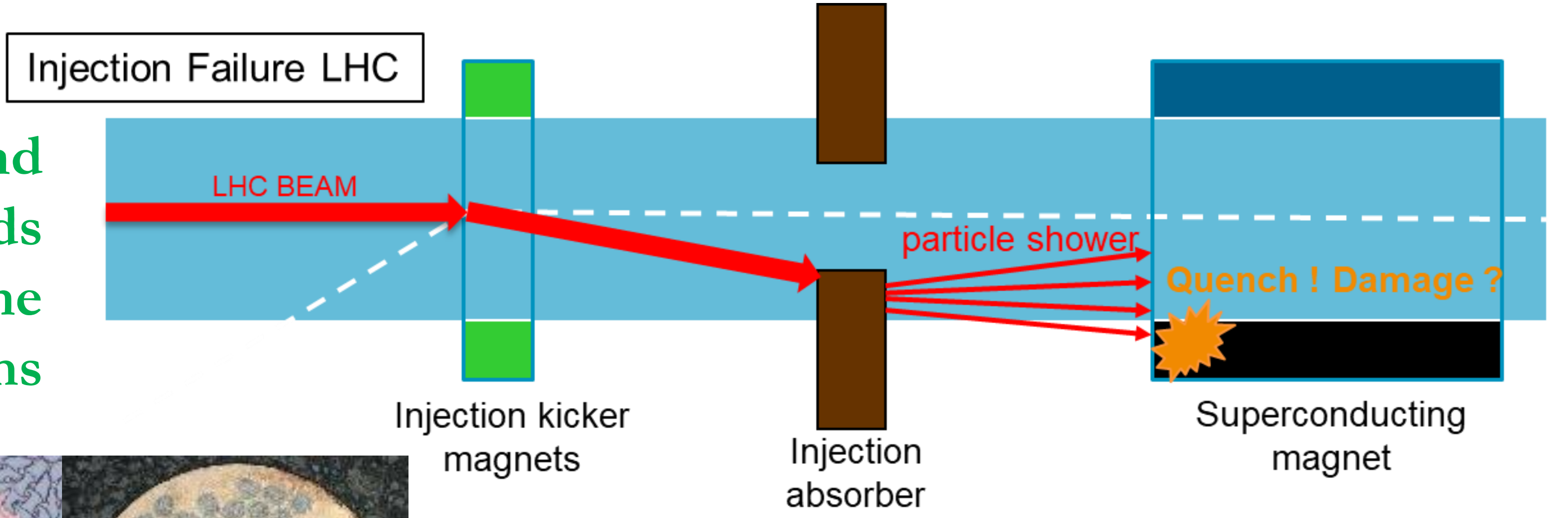
Damage limitations

Courtesy of V. Raginel, A. Will, D. Wollmann et al.

HRMT37 (SextSc) Motivations

Goal:

Measure the damage mechanisms and limits of superconducting strands under cryogenic conditions due to the impact of high intensity proton beams and the degradation



Nb-Ti strand (LHC)

Nb_3Sn strand (HL-LHC)

HTS tapes (future acc. magnets..?)

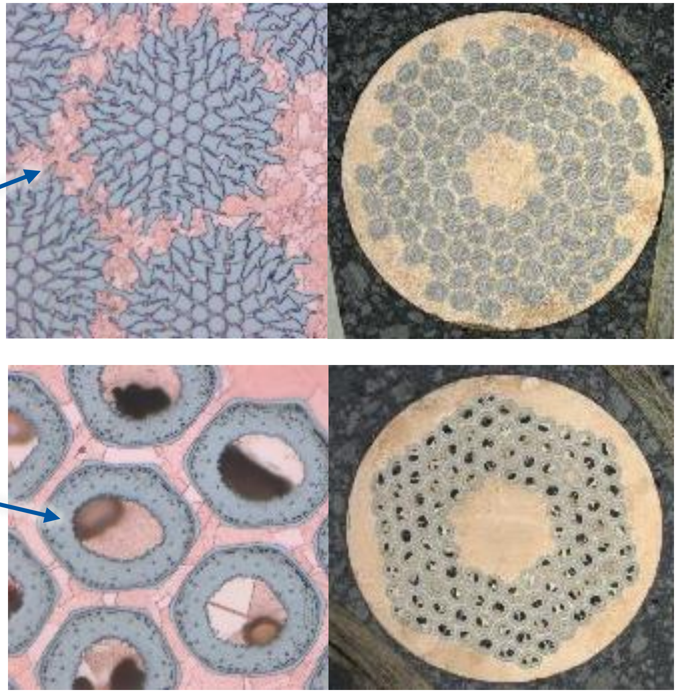


Image courtesy M. Meyer, CERN

One such event per year in today's LHC was possible. No damage observed so far.

In HL-LHC:

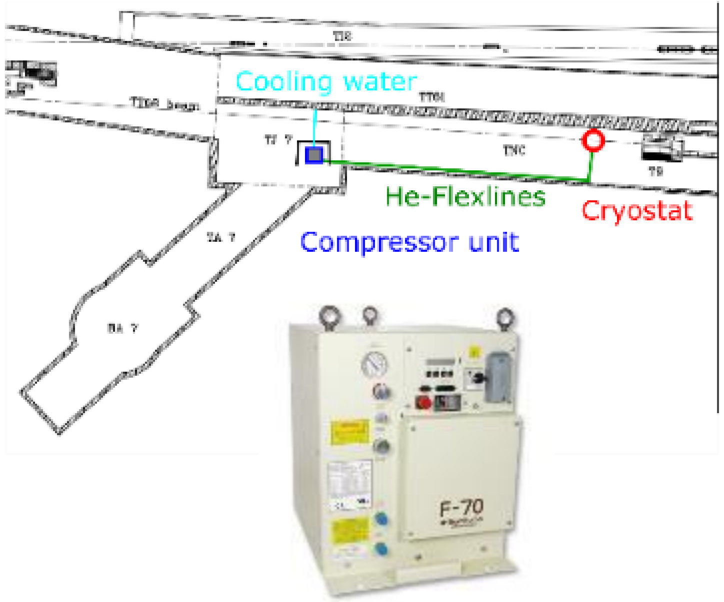
- **increase of beam intensity**
- **new inner triplet magnets using Nb_3Sn**

⇒ investigate the damage limits of superconducting magnets !

Image from [redacted]ore, CAS Zuerich 2018

Courtesy of A. Will, D. Wollmann et al.

HRMT37 Experiment



horizontal stage Δx = 330mm
Accuracy +/- 300µm

vertical stage Δy = 200mm
Accuracy +/- 50µm

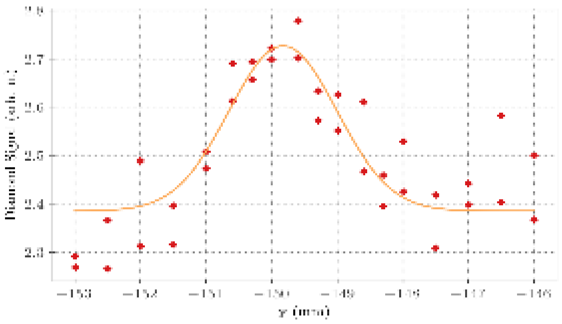
Beam axis is fixed, relative to HiRadMat experimental table

- Metrology of sample holders performed beforehand; Survey after installation

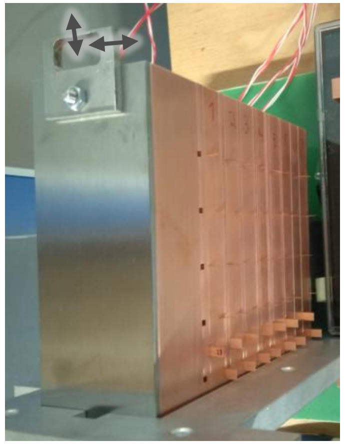
Beam based alignment

- drive the sample holder step-wise into beam, measure losses as function of sample holder position (via Diamond detectors)
  - loss-pattern expected to be symmetric around the 'wire' centre if beam shape is symmetric

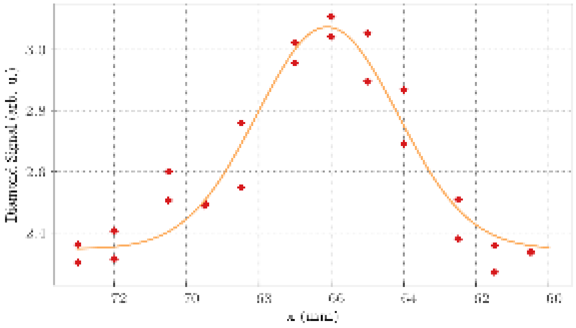
vertical



Fit: y_0 = -149.7 mm (nominal -150.5 mm)



horizontal



Fit: x_0 = -66.1 mm (nominal -65mm)

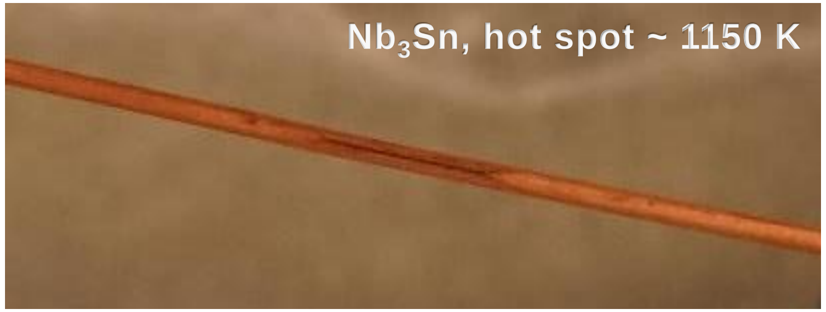
Courtesy of A. Will, D. Wollmann et al.

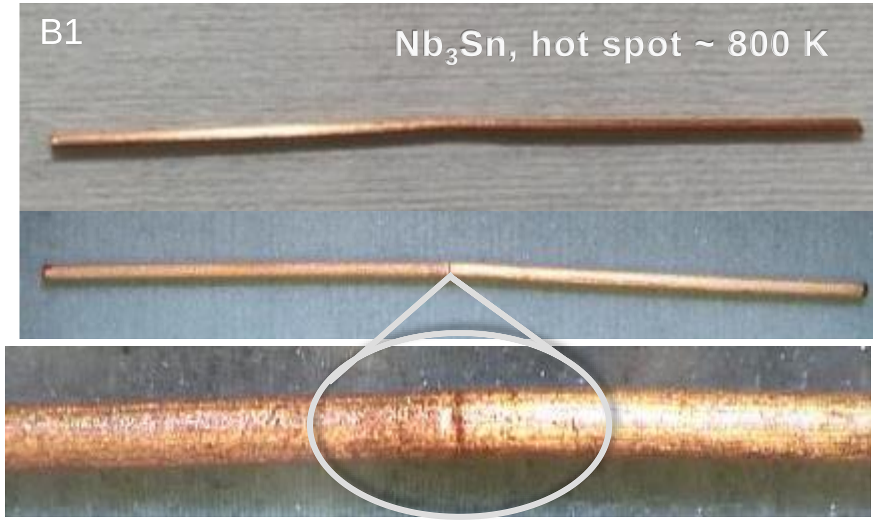
HRMT37 Results

LTS sample extraction

First visual inspection

- Bending of strands visible after beam impact starting from ~800K



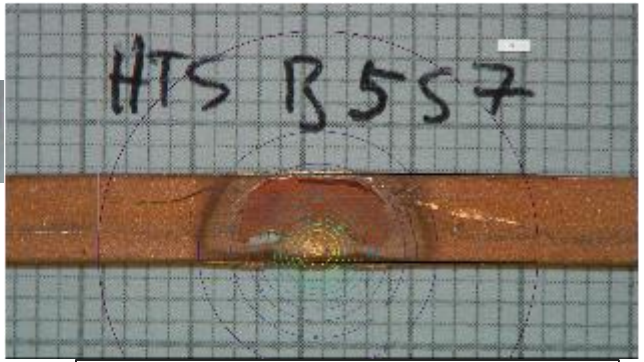


HTS sample extraction

Up to 700K-800K samples very little to no visible damage

Publication anticipated; initial results presented at; https://indico.cern.ch/event/796548/contributions/3532103/attachments/1895990/3128025/SM_Submission_Jonathan.ppx

YBCO tape, hot spot ~ 1030 K



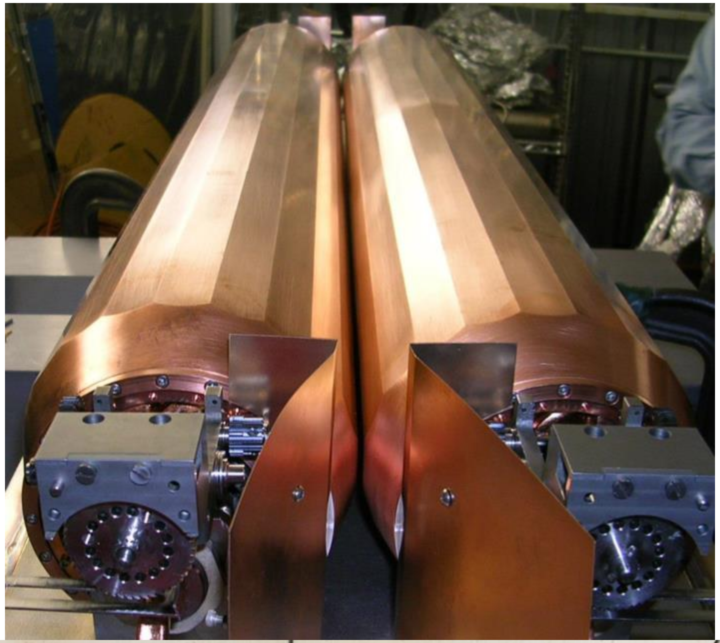
YBCO tape, hot spot ~ 1100 K

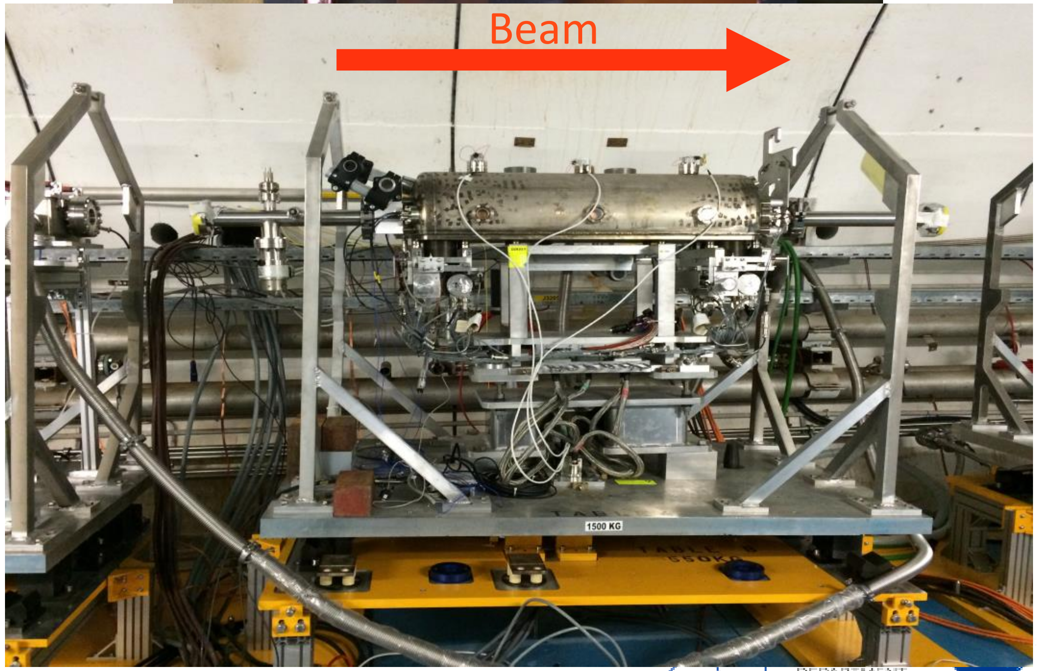
Materials investigation & prototypes validation

Courtesy of A. Bertarelli, F. Carra et al.

HRMT21 (RotCol) Motivations

- SLAC rotatable collimator designed (Glidcop) as part of the US-LARP collaboration.
- Low impedance secondary collimator capable of withstanding 7 TeV failures (to be installed as part of the LHC Phase II collimation).
- 20 collimating surfaces in case of beam damage.





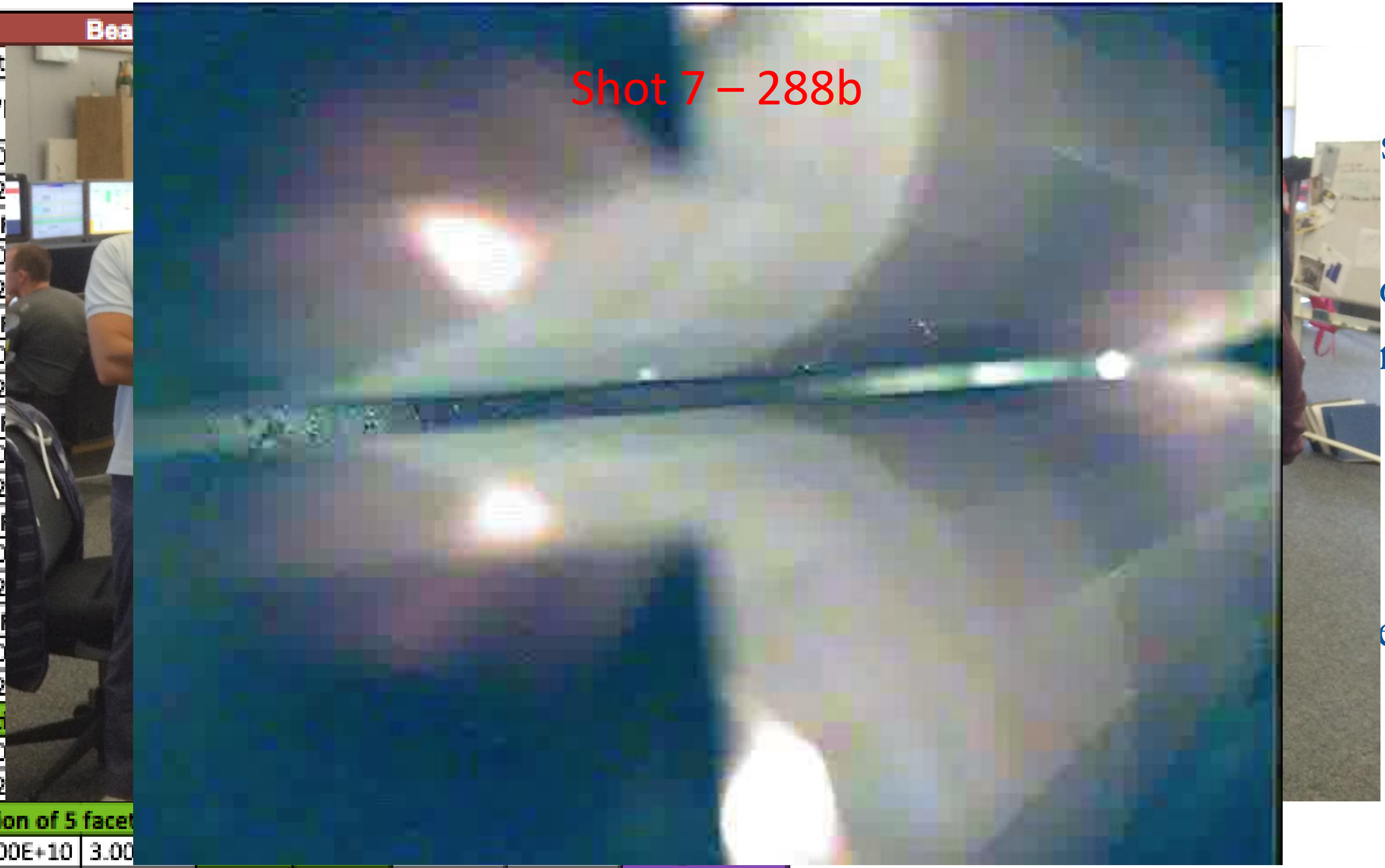
Goals:

- ❖ **demonstrate that the rotation functionality works for the design failure at top energy (asynchronous beam dump 8 bunches at 7 TeV).**
- ❖ **Investigate onset damage for cases of LHC injection error (288 bunches at 450 GeV).**
- ❖ **Integrity of cooling pipes of jaws.**
- ❖ **Material ejecta debris impacts.**

Courtesy of A. Bertarelli, F. Carra et al.

HRMT21 Findings

Bea								
No	Int							
	# bunches	p/						
1-25	1	6.0						
26	6	1.2						
27-51	1	6.0						
52	12	1.2						
53-77	1	6.0						
78	24	1.2						
79-103	1	6.0						
104	36	1.2						
105-129	1	6.0						
130	48	1.2						
131-155	1	6.0						
156	72	1.2						
Rotati								
157-181	1	6.0						
182	144	1.2						
Rotation of 5 facet								
183-207	1	6.00E+10	3.00					
208	288	1.20E+11	3.46E+13	0.35	0.35	25	7.2	Shot #8
Total			9.96E+13			Total	~31.5 hours	



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Courtesy of C. Torregrosa et al.

HRMT48 (PROTAD) Motivations

Goal:

To impact with high energy, high intensity proton beam, several real scale prototypes for the future AD production target to assess the validity of the current designs under equivalent operational conditions.

Ta-Degraders manufacturing

- Ø28 mm Ta cylinder press fitted and EBW sealed in Ti-Grade 5 cladding
- Inserted in SS + Ti-Grade 5 windows air cooled capsule

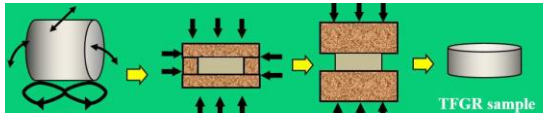
PROTAD Targets manufacturing

1) Ti-grade 5 external envelopes manufactured at CERN
- **x6 two/parts machined and EBW**

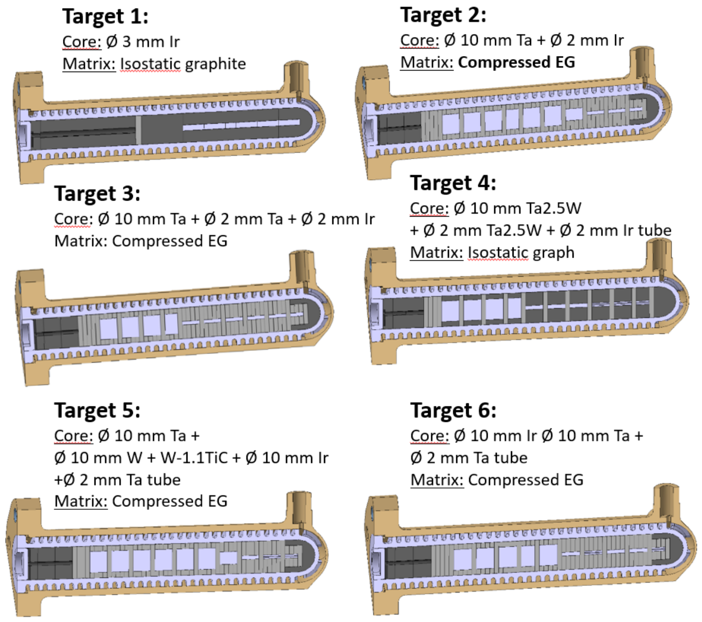
- x2 3D-Printed

2) Filled with the **high-Z cores** and **isostatic graphite or pre-compressed EG matrices** respectively

Core & Matrices sealed by EBW



Inclusion of novel materials (W-TiC) manufactured by out colleagues from KEK and JPARC (Japan)

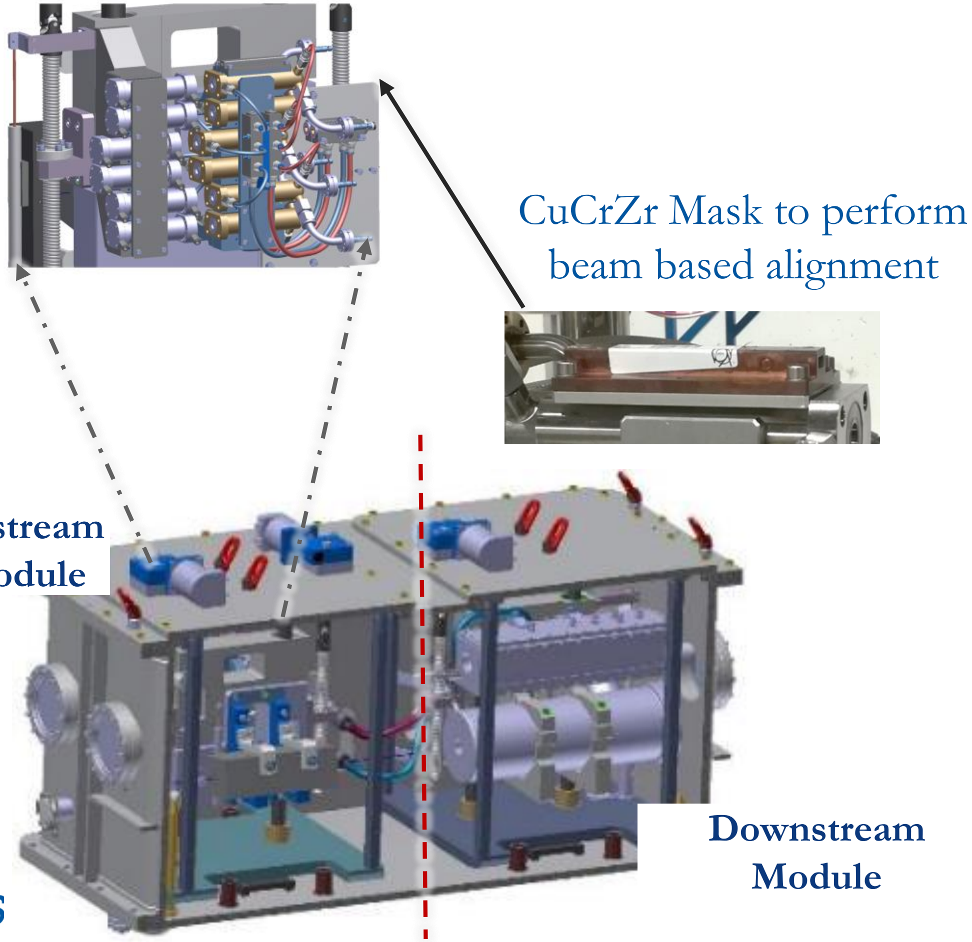


- **Target 1:**
  Same as the old design
- **Target 2:**
  Investigate Ta response (larger diameter) & Ir at the downstream
- **Target 3:**
  Ta response (annealed + 2 mm diameter) & Ir at the downstream
- **Target 4:**
  Ta2.5W + Ir tube at the downstream
- **Target 5:**
  W and W-1.1TiC (KEK) + Ta tube
- **Target 6:**
  Ir response (larger diameter)

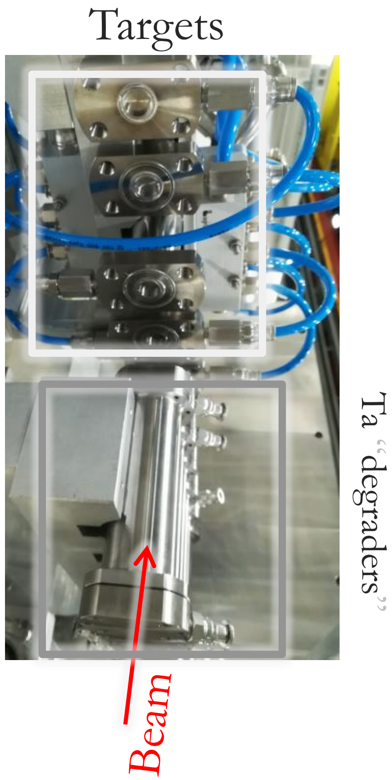
Courtesy of C. Torregrosa et al.

HRMT48 Experiment

PROTAD targets tested within the STI-Multipurpose Experiment.
Example of experiment optimisation (3 different experiments in one experimental tank

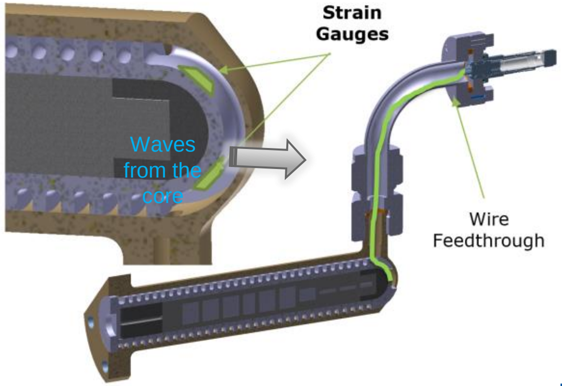


Relative movement between the "Ta-Degraders" and PROTAD targets (to compensate internal damage in the first)



Instrumentation:

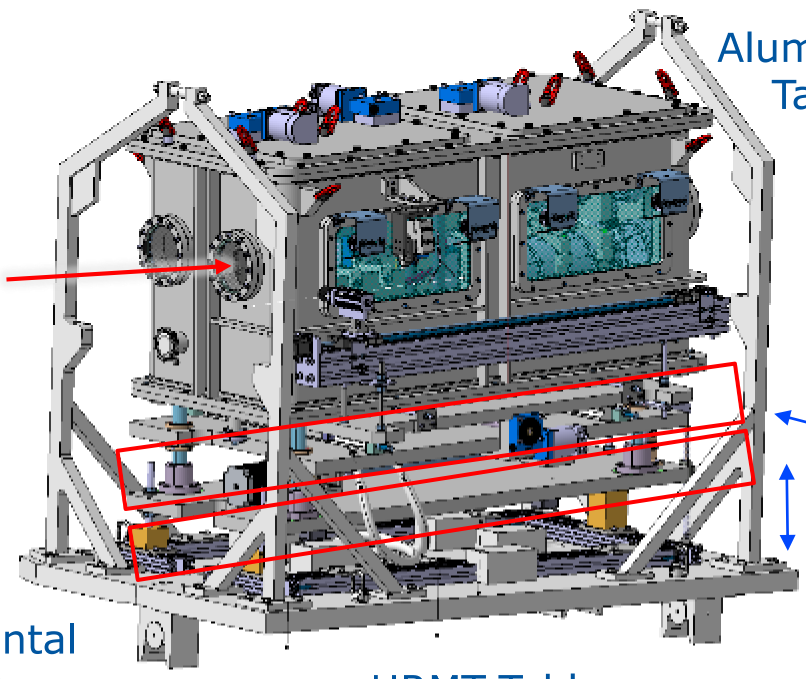
- Fast acquisition rate strain gauges (4 MHz) attached to the internal downstream Ti-Grade 5 window.
  (Inside the cooling channel)
- The goal is to measure the potential dynamic stresses in the window due to wave propagations from the core

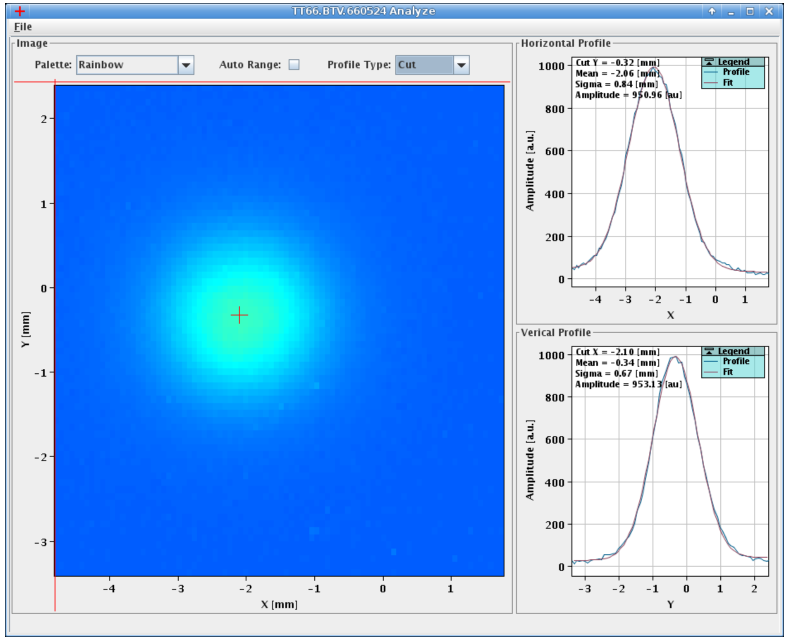


Courtesy of C. Torregrosa et al.

HRMT48 Beam time (analysis ongoing)

Beam Pulse List							
No	Intensity			Beam spot *[mm]*		Bunch spacing *[ns]*	Pulse length *[us]*
	# bunches	p/bunch	Total	Sigma_x	Sigma_y		
1 to 100	1	1.20E+11	1.20E+11	0.7	0.7	25	2.50E-02
100 to 150	16	5.30E+10	8.40E+11	0.7	0.7	25	0.4
150 to 400	16	5.30E+10	8.40E+11	1	1	25	0.4





BTV reading on pulse on Target 6 (degrader at 8 mm)

Materials (non-irradiated and irradiated) investigations

HRMT24 (BeGrid)

HRMT24 Goals

- Investigate specimen arrays containing thin Beryllium discs and slugs (various commercial grades and thicknesses)
- Points to cover, temperature, strain and displacement measurements.

"Thermal shock experiment of beryllium … pulses", K. Ammigan, et al., Phys. Rev. Accel. Beams 22, 044501, 4 April 2019

Courtesy of P. Hurh, K. Ammigan et al.

HRMT43 (BeGrid2) Motivations & Experiment

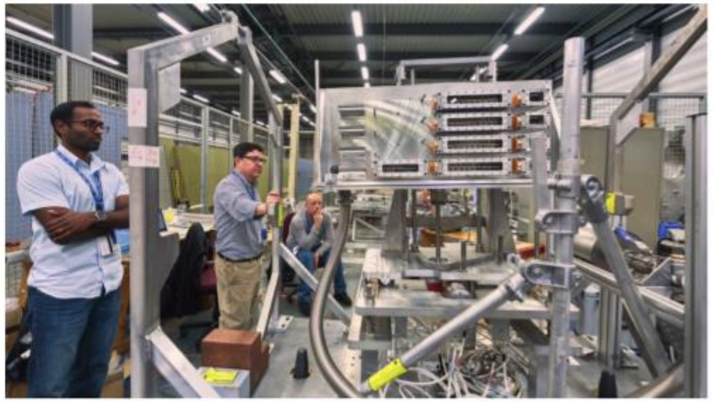
HRMT43 Goals

- Compare **thermal shock response between non-irradiated and previously proton irradiated material** specimens from BNL BLIP (Be, C, Ti, Si, Si-coated graphite)
  - ➢ **First test with activated materials at HiRadMat**
- Explore **novel materials** such as metal foams (C, SiC) and electrospun fiber mats (Al_2O_3, ZrO_2) to evaluate their resistance to thermal shock and suitability as target materials
- Real-time measurement of dynamic thermo-mechanical response of graphite slugs to help benchmark numerical simulations
- PIE of specimens (Profilometry, Optical & SEM)

Great logistical effort (transport, containment, handling, installation) from all teams to install pre-irradiated samples into HiRadMat.

Pulse	Array	No. of bunches	Bunch intensity	Pulse intensity	σ_x (mm)	σ_y (mm)
1	3	144	8.40E+10	1.21E+13	0.26	0.26
2	4.1	144	8.47E+10	1.22E+13	0.26	0.25
3	4.2	144	8.54E+10	1.23E+13	0.26	0.26
4	4.3	144	8.33E+10	1.20E+13	0.26	0.26
5	4.4	144	8.26E+10	1.19E+13	0.26	0.25
6	4.5	144	8.30E+10	1.21E+13	0.26	0.25
7	2	216	1.17E+10	2.53E+13	0.30	0.28
8	1	288	1.22E+10	3.51E+13	-	-

Total protons on target: 1.33e14

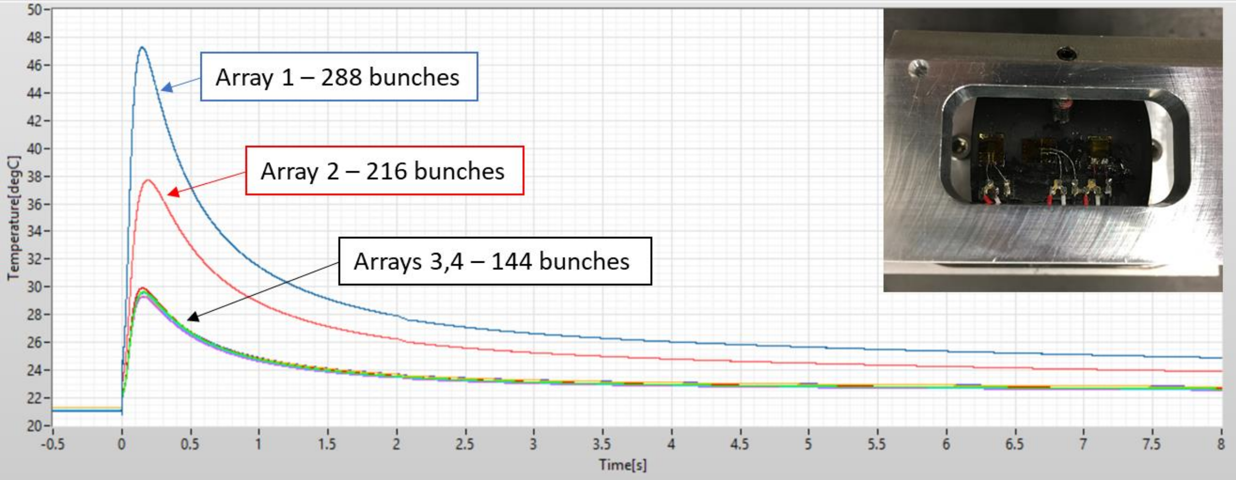


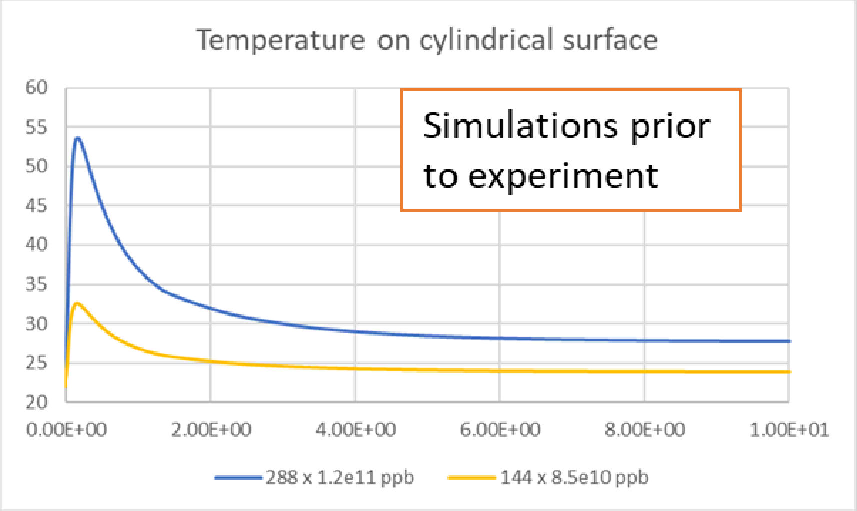
October 1 – 2, 2018 4:00am
BeGrid2 Exposure completed

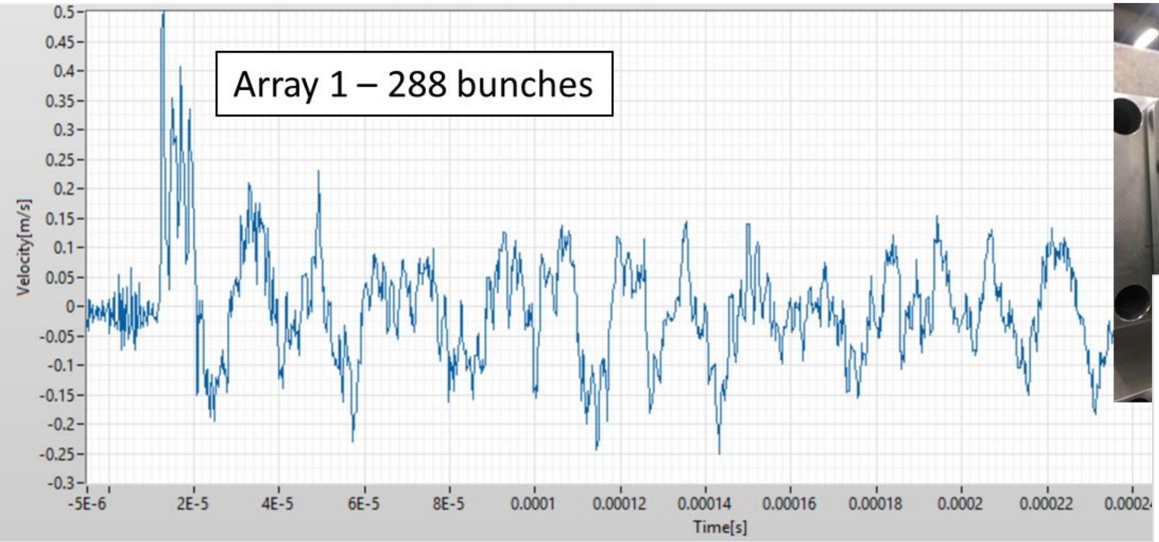
Courtesy of P. Hurh, K. Ammigan et al.

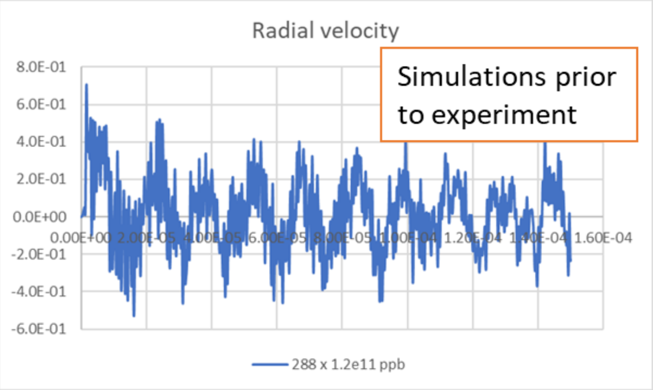
HRMT43 (BeGrid2) Findings

Temperature on cylindrical surface of slugs







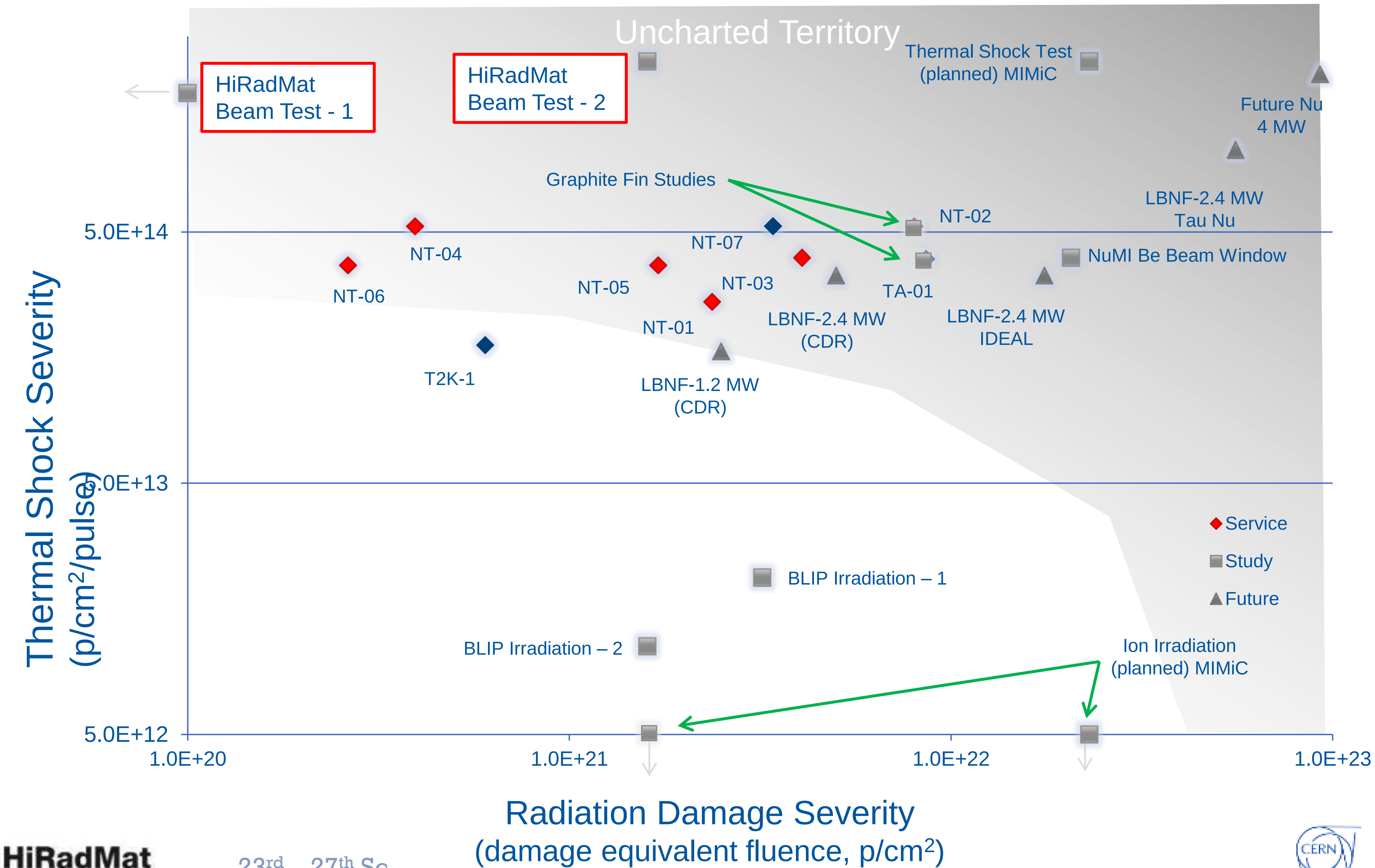


Numerical simulations currently being updated with experimental beam parameters to benchmark results

PIE to be performed at CCFE in September – results to follow

Nu HPT R&D Materials Exploratory Map

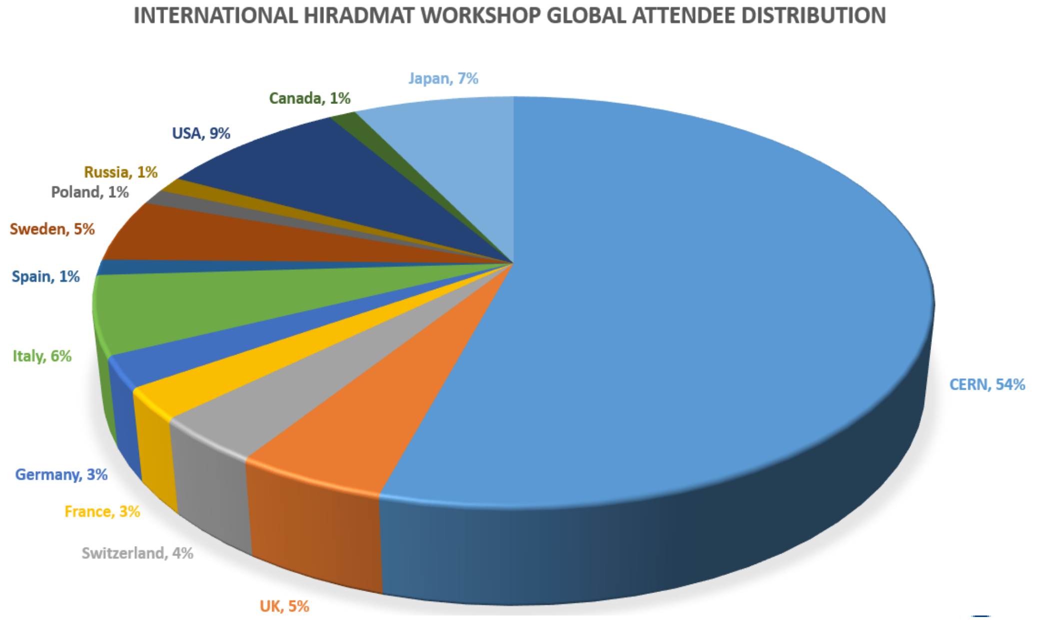
Courtesy of P. Hurh (FNAL)
https://indico.cern.ch/event/767689/sessions/311785/#20190711



Future outlook

International HiRadMat Workshop

- 3 day workshop held from 10th to 12th July 2019 (https://indico.cern.ch/event/767689/overview)
- Total of 81 participants from (54% CERN, 46% non-CERN)
- 37 presentations from 12 different topic areas (i.e. HiRadMat Facility; Remote Sensing & Beam Instrumentation; Materials Science & Beam Induced Damage Research; Future Accelerator Projects; Rare Isotope Beams; Fusion Materials R&D; Advanced Light Sources (seminar); Spallation Neutron Sources; Neutrino & Muon Facilities; Theoretical Modelling; Laser Driven Shock Waves (seminar); Letters of Interest for future operation).
- 12 LoIs currently submitted for future interest in the facility. More anticipated
- Workshop summary report and executive report currently being prepared.

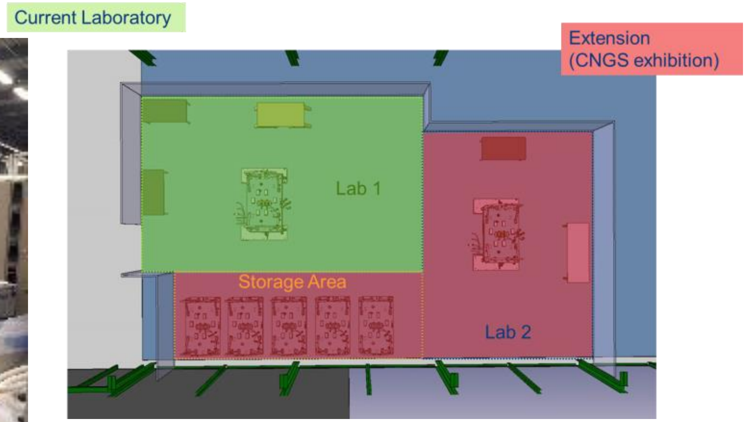


HiRadMat Operation Strategy

Strategy 1 (low-level)

Upgrade current surface lab proposal:

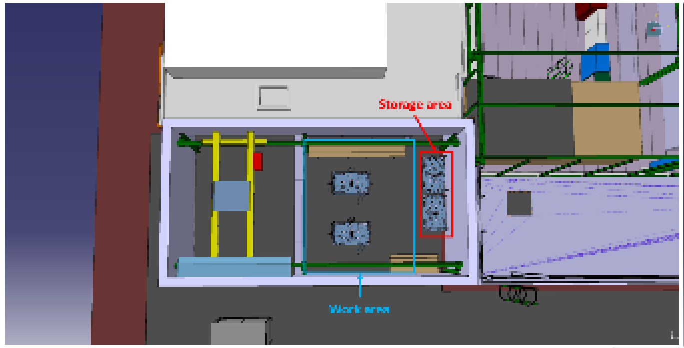
- ❖ Increase size of lab area to accommodate increased number of users.
- ❖ Increase surface space meaning 2 experiments can be fully accommodated at one time.
- ❖ More storage, tools, working areas for users
- ❖ Improve survey conditions
- ❖ Improve space for transport logistics.

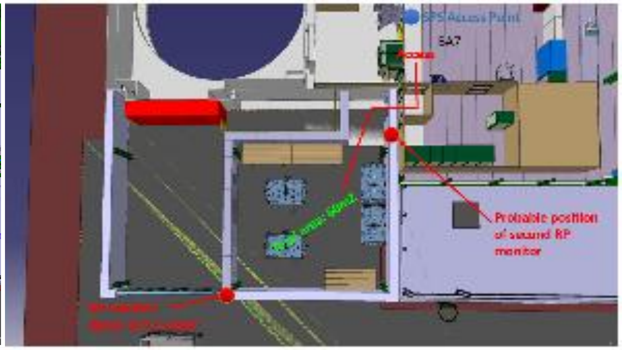


Strategy 2 (mid-level)

New surface lab proposal

- ❖ Better accommodate array of different experiments entering HiRadMat.
- ❖ Possibility to temporally increase radiation protection classification to accommodate pre-irradiated experiments.
- ❖ Lab design relevant for current (and anticipated future) needs – size, storage, table integrations, electronics, survey etc.)
- ❖ Improved transport logistics (entering surface lab, installing in experimental area and exiting experimental area post-irradiation).





Strategy 3 (high-level)

Upgrade experimental area to enable HL-LHC type beams

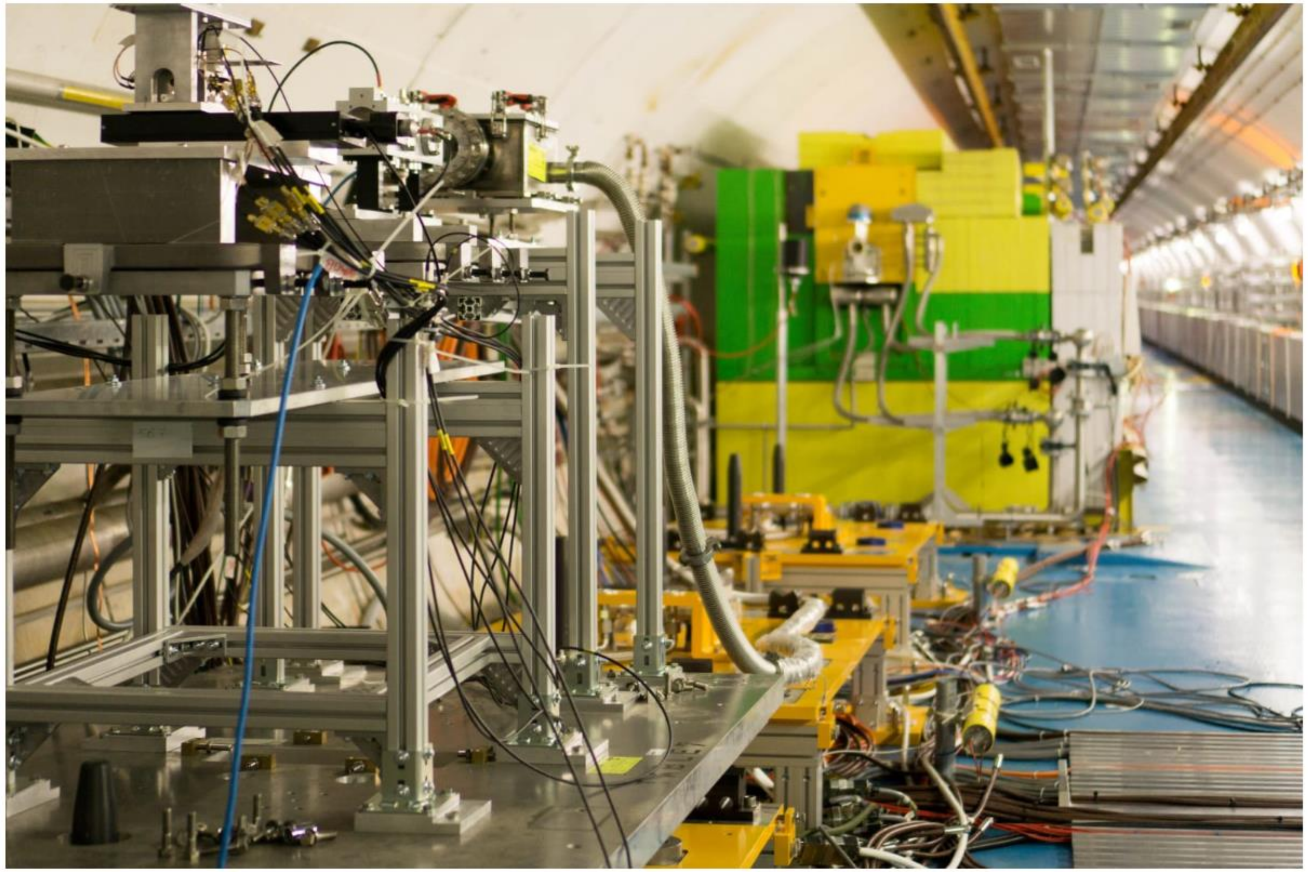
- ❖ Beam windows & dump studies required.

Summary

Conclusions

HiRadMat described as a strategic asset for the investigation of novel materials, prototypes and thermo-mechanical principles for Targetry challenges.

- Thermomechanical behaviours
  (e.g. thermal shock / resistance)
- Structural integrity of novel materials and prototypes
  (e.g. cases for accidental beam strike, proof of concept, design verification)
- Pulsed beam effects
  (e.g. theoretical model validations, material impacts, damage thresholds)
- Material effects
  (e.g. non-irradiated and irradiated materials)



Interested in future experiments, contact hiradmat@sps.cern.ch

Thank you to all teams & groups involved with the HiRadMat operation:
BE/BI, BE/OP, EN/CV, EN/EA, EN/HE,
EN/MME, EN/SMM, EN/STI, HSE/RP, TE/MPE

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For presentation material, special thanks to:
M. Calviani, C. Torregrosa et al. (CERN/EN-STI)
A. Bertarelli, F. Carra et al. (CERN/EN-MME)
A. Will, D. Wollmann et al. (CERN/TE-MPE)
P. Hurh, K. Ammigan et al. (Fermilab)
T. Ishida et al. (J-PARC)

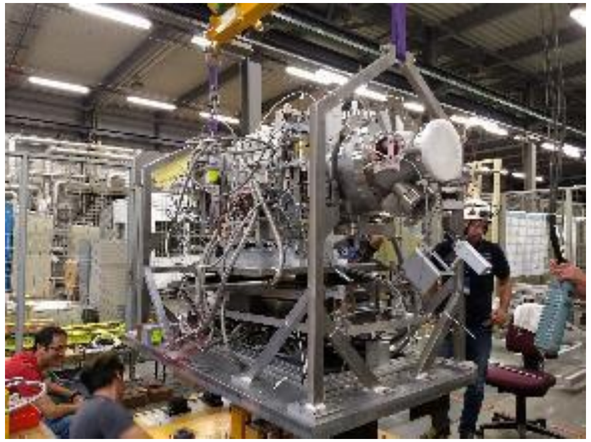
CERN

Back-Up Slides

Surface Infrastructure

HiRadMat Surface Lab

- Located in bldg. 876/R-017.
- Supervised Radiation Area.
- Contains laboratory fixed tables enabling pre-commissioning tests on experiments before final installation in experimental area.



HRMT45 Transport

HiRadMat Control Room

- Located in bldg. 876/R-003.
- DAQ and offline monitoring systems can be set-up for each experiment.

Experimental Area

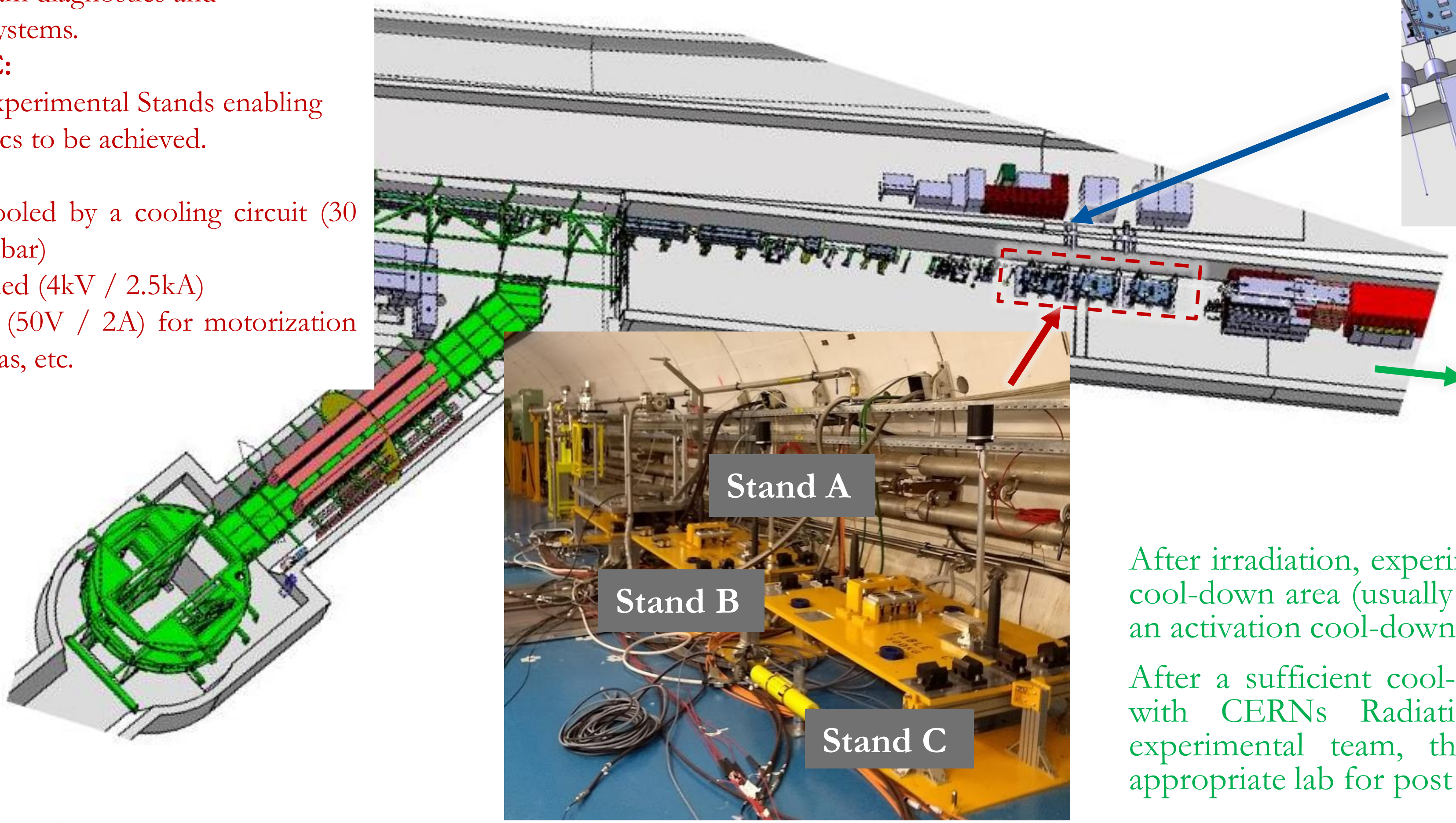
HiRadMat has dedicated feed-throughs into an adjacent tunnel (TT61) where additional electronic and measurement systems can be added (e.g. equipment for cameras, radiation sensitive cameras and LDVs).

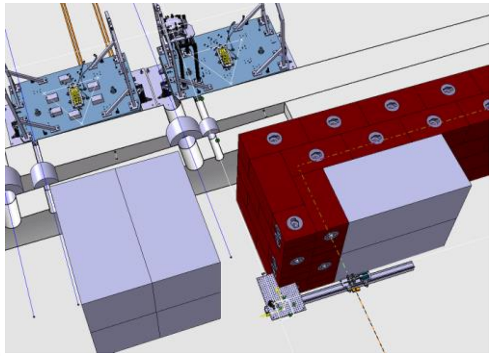
Shielding optimised in order to protect sensitive equipment from prompt radiation.

HiRadMat Experimental Test Area

- **Stand A:**
  Dedicated Beam Instrumentation Stand providing beam diagnostics and monitoring systems.
- **Stand B & C:**
  Dedicated Experimental Stands enabling different optics to be achieved.

- Tables are cooled by a cooling circuit (30 kW, $3m^3/h$, 9bar)
- Power provided (4kV / 2.5kA)
- Signal cables (50V / 2A) for motorization stages, cameras, etc.





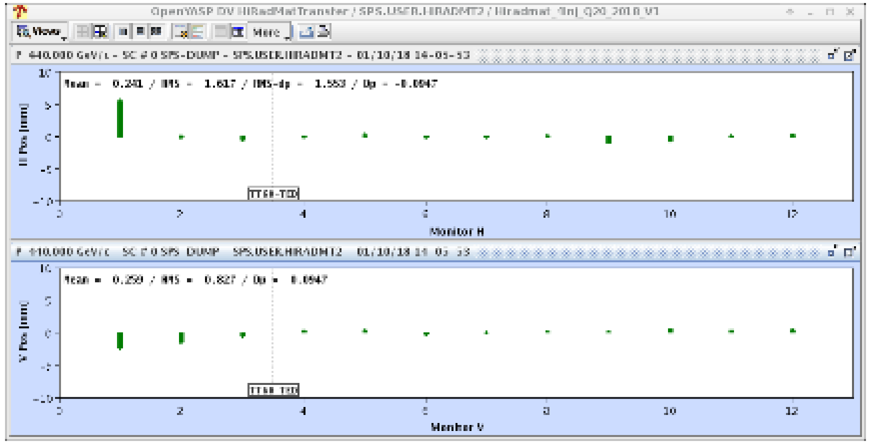
After irradiation, experiments are moved to the HiRadMat cool-down area (usually 1-2 weeks after beam) to allow for an activation cool-down of the irradiated samples.

After a sufficient cool-down period, and in coordination with CERNs Radiation Protection group and the experimental team, the experiments is moved to an appropriate lab for post irradiation examination.

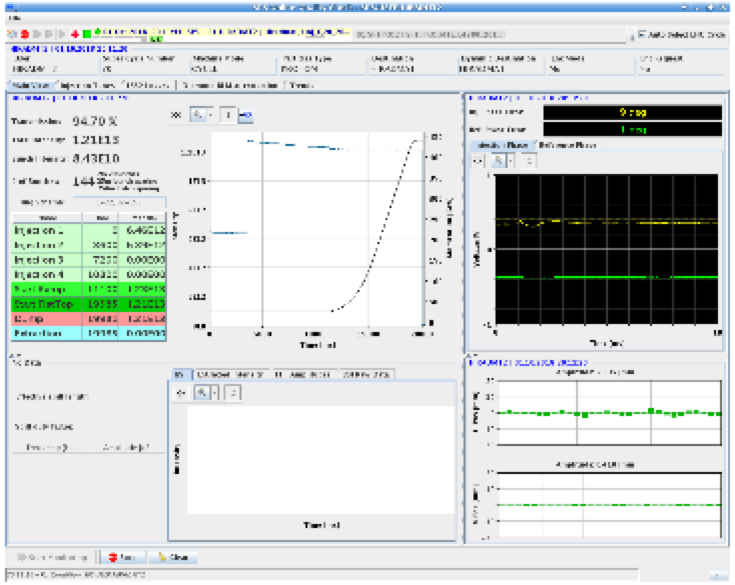
Support for users

SPS Operation

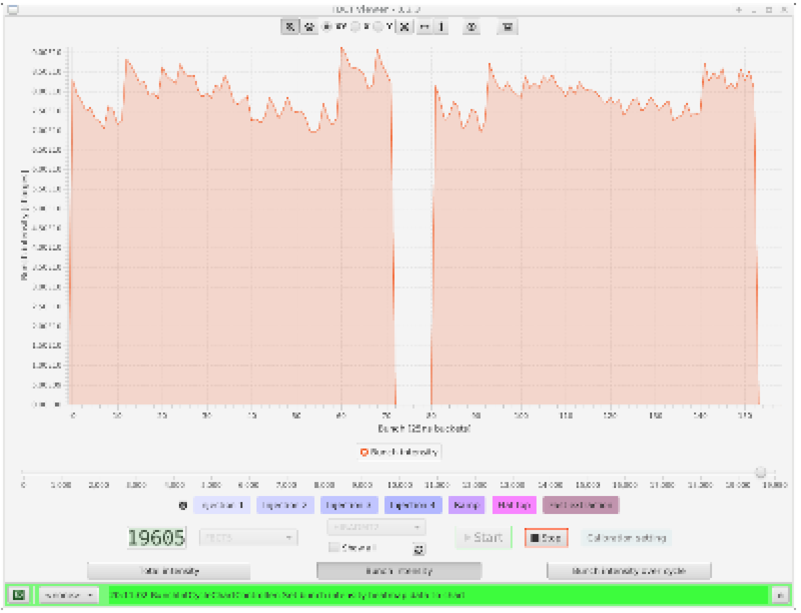
Colleagues from SPS Operations provides high quality proton (or ion) beam to the HiRadMat experiment. Standard procedures relating to beam trajectory, beam emittance, beam spot size, proton bunch sets, etc. are all completed by the experts during the dedicated HiRadMat beam time.



Example of the HiRadMat proton beam trajectory for 12 bunches delivered to experiment.



Example of the extracted intensity for delivered 144 protons.

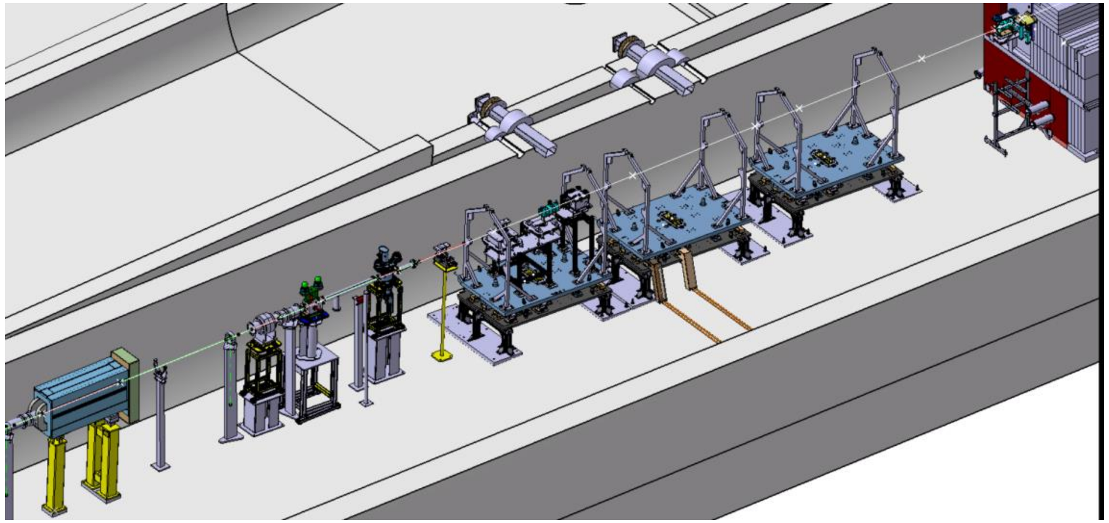


Example of quality of bunch-bunch intensity for 144 bunches (2×72 bunches)

Support for users

HiRadMat Operation

- CERN colleagues available to assist with in situ measurements and monitoring, e.g. LDV, strain gauges, radiation hard camera, experiment motorisation.
- Beam diagnostic systems provided through collaboration with HiRadMat and Beam Instrumentation Group.
- Data stored and available for analysis after beam time.



Fixed Beam Instrumentation Table, currently includes a Diamond Detector, BPKG and BTV

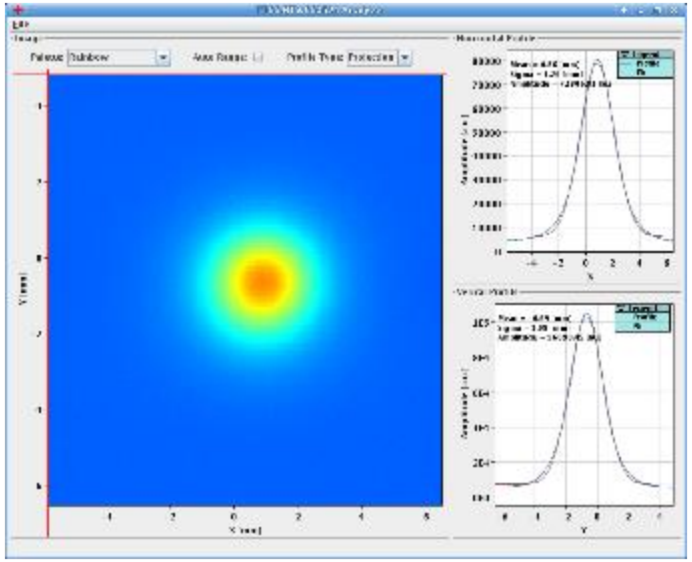
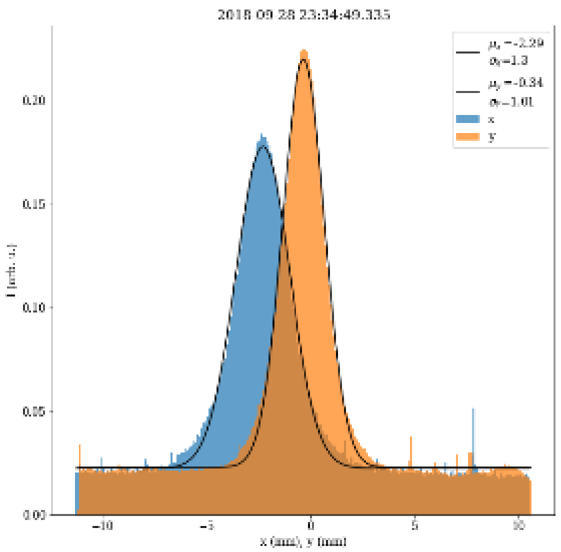


Image obtained from HRM-BTV

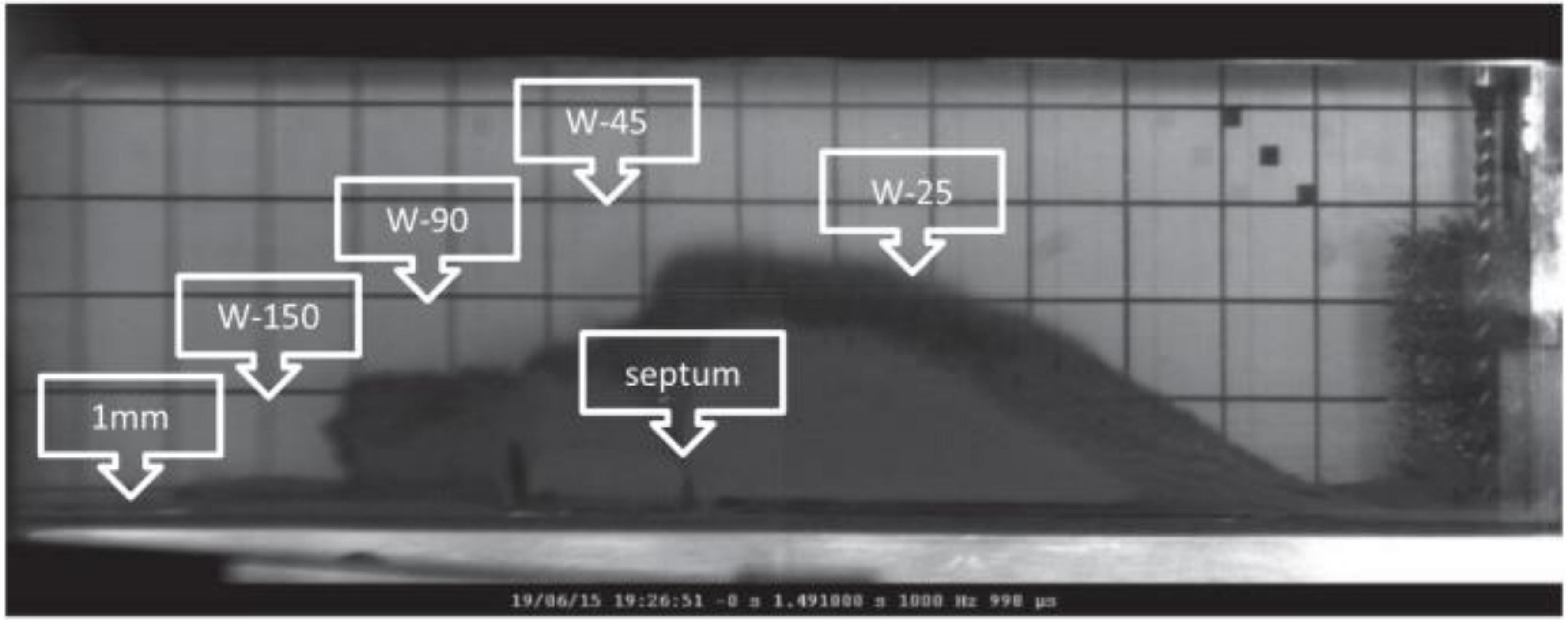


Ions

HiRadMat Ion Beam (data from 2015)	
Beam Energy	173.5 GeV/nucleon (36.1 TeV per ion)
Pulse Energy (max)	21 kJ
Bunch Intensity	3.0×10^{7} to 7.0×10^{7} ions
Number of Bunches	52
Minimum Pulse Intensity	3.0×10^{7} ions (1b at 3.0×10^{7} ions)
Maximum Pulse Intensity	3.64×10^{9} ions (52b at 7.0×10^{7} ions)
Pulse Length (max)	5.2 μs
Beam size at target	Variable around 1 mm^2

HRMT22 Results

HRMT22 Results



The Development of Fluidized Powder Target Technology for a Neutrino Factory or Muon Collider, where HiRadMat proton beam induced dynamics of the tungsten granules.

Interesting behavior was observed: non-aerodynamic lift mechanism, slower in helium atmosphere.
Behaviour is systematic and can be explained only by the fact that different physics dominate the first milliseconds of the movement.

Courtesy of A. Will, D. Wollmann et al.

HRMT37 Cryostat design

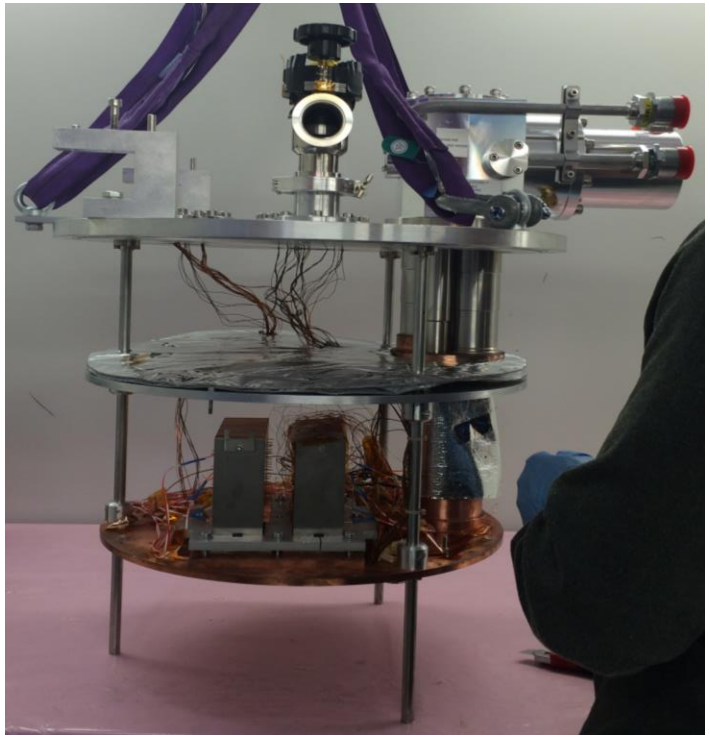
Pulse-Tube Crycooler based

- Ø 525 mm, height 860 mm
- cooling power of 1W at 4K
- 40m He-gas supply lines
- 100 signal wire feed throughs
- 8 temperature sensors

Two stages

- 1st stage ~30K, cools thermal shield
- **2nd stage ~4K**
  - Cu interface plate
  - Two sample holders

Designed and built with an industry partner



Courtesy of P. Hurh, K. Ammigan et al.

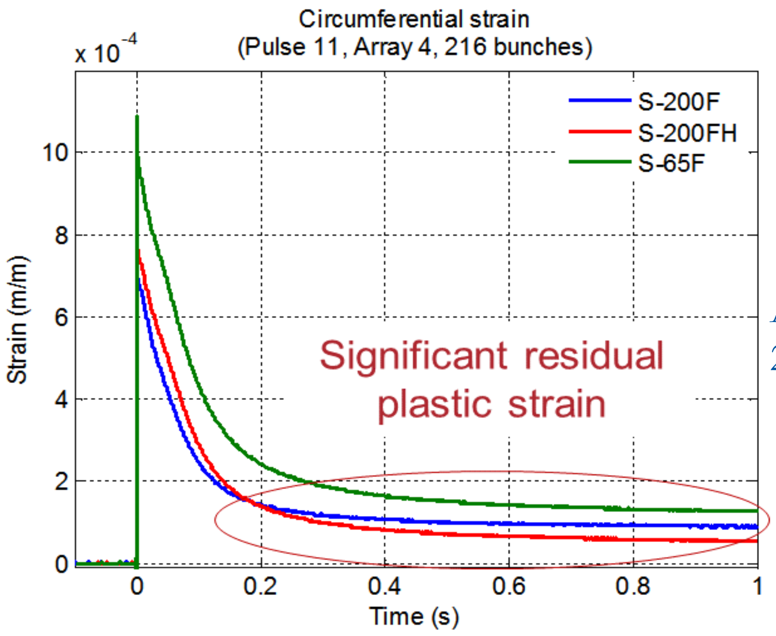
HRMT24 (BeGrid) Motivations & Findings

HRMT24 Goals

- **Investigate specimen arrays containing thin Beryllium discs and slugs (various commercial grades and thicknesses)**
- **Points to cover, temperature, strain and displacement measurements.**

Real-time thermomechanical measurements

- Instrumented Be slugs in downstream containment boxes
- LDV for radial displacement measurements



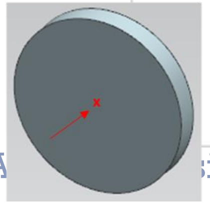
Array 4 – 216 bunches, 2.8e13 POT

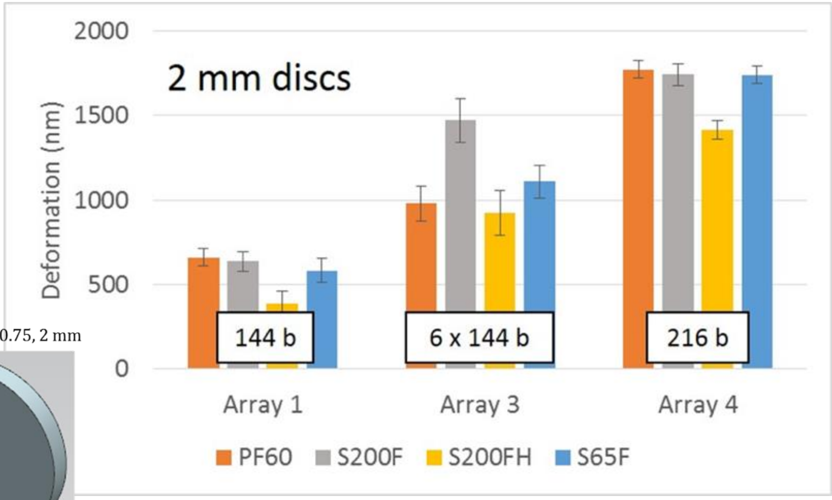
HRMT24 results:

PIE performed at University of Oxford (**Optical microscopy and profilometry to measure out-of-plane plastic deformations**)

- Distinctive strain response for the three different Be grades
- Residual plastic strain observed upon cool-down
- All Be grades showed less plastic deformation than predicted by available literature strength models
- S200FH showed least plastic deformation, in agreement with empirical strength model
- Observed plastic strain ratcheting in Array 3
- Glassy carbon windows survived without signs of degradation

Ø 15 mm, t: 0.25, 0.75, 2 mm





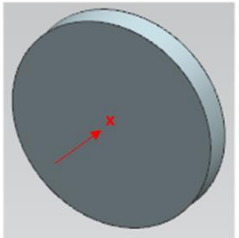
"Thermal shock experiment of beryllium … pulses", K. Ammigan, et al., Phys. Rev. Accel. Beams 22, 044501, 4 April 2019

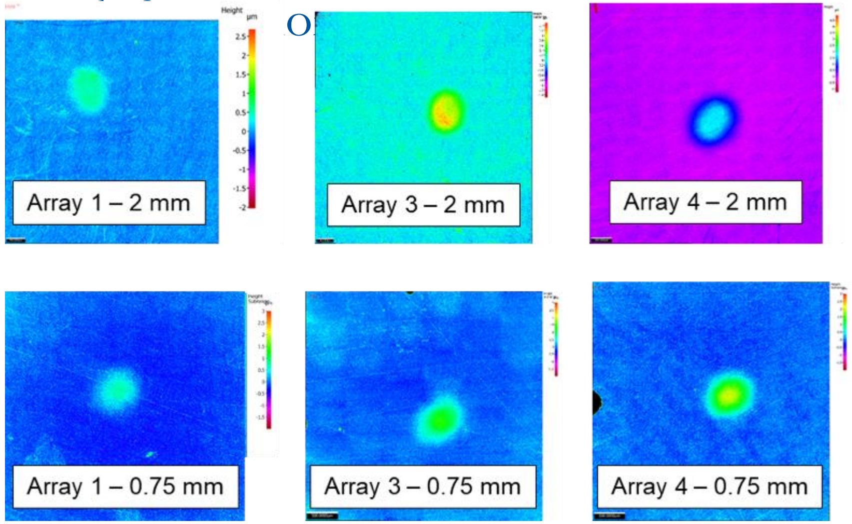
Courtesy of P. Hurh, K. Ammigan et al.

HRMT24 Results - PIE

- Thin disc specimen PIE performed at University of Oxford
- Optical microscopy and profilometry to measure out-of-plane plastic

Ø 15 mm, t: 0.25, 0.75, 2 mm





S-65F grade specimens

- ➢ All Be grades showed less plastic deformation than predicted by available literature strength models
- ➢ S200FH showed least plastic deformation, in agreement with empirical strength model
- ➢ Observed plastic strain ratcheting in Array 3
- ➢ Glassy carbon windows survived without signs of degradation