HiRadMat Facility

Overview of the Physics Programme 2012-2018

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Collider-Accelerator Department

BROOKHAVEN
NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

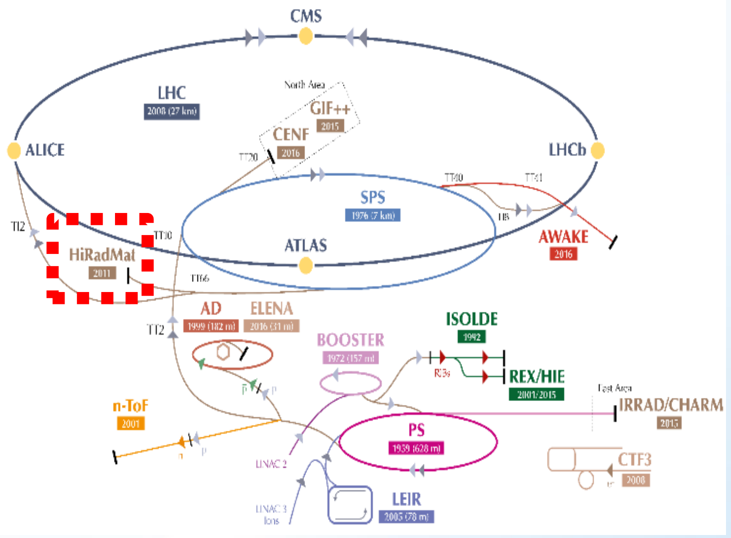
HiRadMat core aim

A test facility for Accelerator Components with High Power Beams

- Intense, high energy beam beam interaction with matter
- fast strain rate
- thermo-mechanical shock (and possibly shock) generation and response of materials

Focussing (to-date) primarily on:

- LHC and HL-LHC collimators
- High power accelerator targets
- Beam windows
- Magnets
- Special instrumentation components (detectors, radiation monitors, etc.



All these applications though are inherently linked with the material structure (microstructure) and its physical properties and can potentially have other applications

Why are we all here?

Why now?

HiRadMat at the crossroad

HRM To-date: From its inception to a rich contribution

What has started as the means to assess LHC collimating element resilience to beam impact

- Provided the means and served HL-LHC in further understanding novel materials and other critical systems (i.e. beam monitoring devices)
- Enabled the testing of prototypes and novel designs
- Provided the means to understand accident scenarios on complete systems

- Enabled studies of novel materials, detectors for both LHC and a broader base

- Enabled the study of exotic new target concepts

- Has pushed the envelope and enabled the ex-situ of long-term irradiation damage in materials with fast processes and high strain rates induced by intense pulses (pre-irradiated materials)

- Has expanded the experimental/user base to include international collaborations and other important large accelerator projects

To-date: HRM saw first beam in 2012 and has since delivered pulsed, high intensity, beams to over 40 experiments

Parameters

Beam Energy	440 GeV
Pulse Energy (max)	2.4 MJ
Bunch Intensity	5 10^{9} to 1.2$10^{11}$ protons
Number of Bunches	1 to 288
Minimum Pulse Intensity	5 10^{9} protons
Maximum Pulse Intensity	**3.5 10^{13}** protons
Pulse Length (max)	7.95 µs
1 σ r.m.s. beam radius	can achieve optics to as low as **σ = 0.25 mm**

Objective as we move forward:

With its unique parameters,

- 440 GeV proton beams of pulse length 7.95μs and max energy of 2.4 MJ
- Ion beams of energy 173.5 GeV/nucleon and pulse energy of 21kJ

Assess as what is the role HRM can play in

- Condensed matter physics
- Material science that serves next generation accelerators
- Materials science that (perhaps) serves next generation reactors
- Fusion materials (?)
- Materials engineering
- Means to study extremely fast processes
- Theoretical modelling and simulation
- In looking deep into the structure of matter, SYNERGY with other means of probing (i.e. synchrotrons)?

Thus the guiding questions of our workshop are:

Do we see a role of HRM in

- modeling and simulation of radiation effects and what possible experiments are there to facilitate it
- Material studies for next generation nuclear (and possibly fusion)
- Capturing dynamics of radiation effects (particularly due the availability of ion beams at HRM)
- Modeling and simulation of high strain rate effects due to the intense, short pulsed beams and of the extreme states and phase changes produced?

What type of experiments could be envisioned/facilitated that may help answer these questions

or, better yet

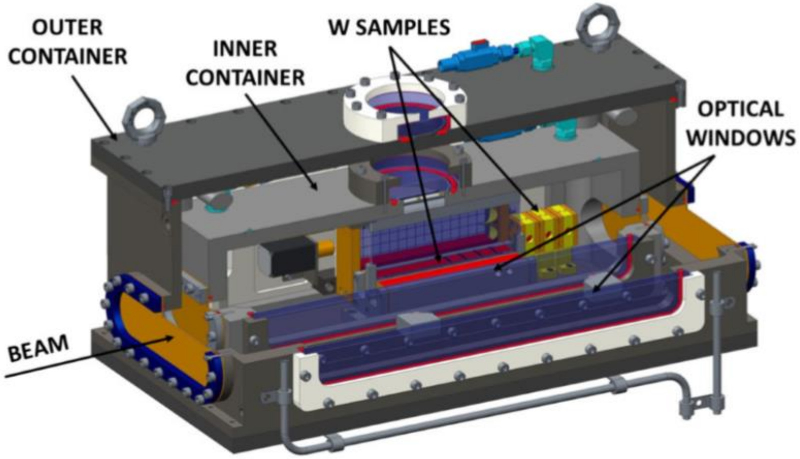
What are the interested parties out there that, if they became aware of the available capabilities at HRM, could undertake these experiments?

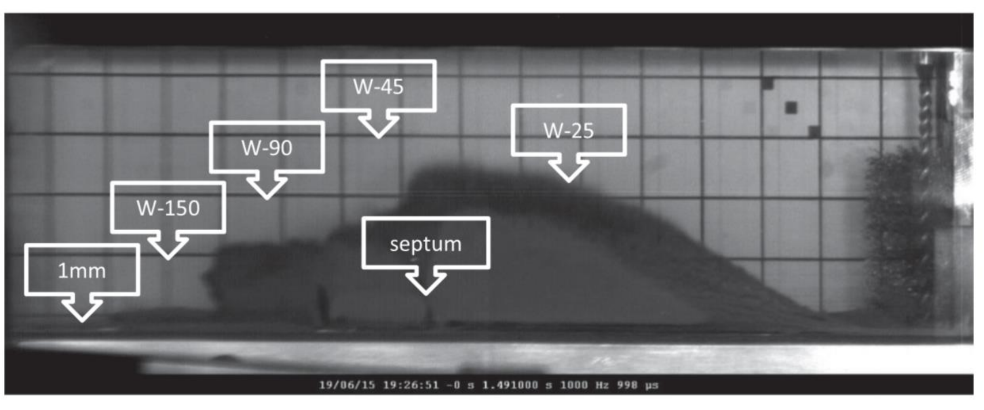
A track record of successfully completed important experiments thus far.

From the more than 40 experiments conducted, a flavor indicative of the wide applicability is presented

The Development of Fluidized Powder Target Technology for a Neutrino Factory or Muon Collider

Proton beam induced dynamics of tungsten granules



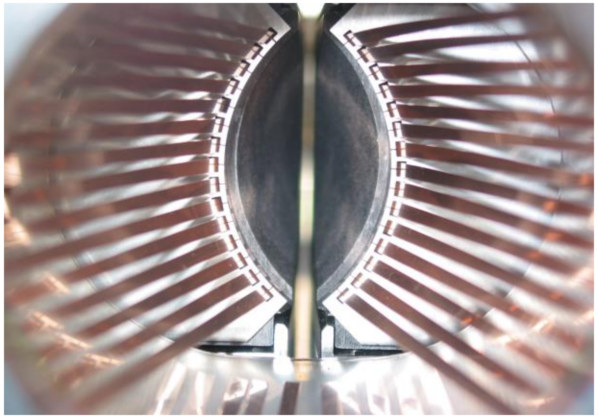


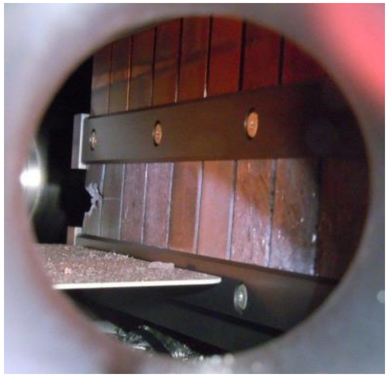
Interesting behavior was observed: non-aerodynamic lift mechanism

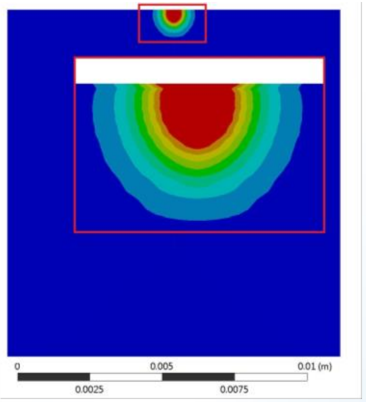
Question is whether there is relevance to nano-structure response

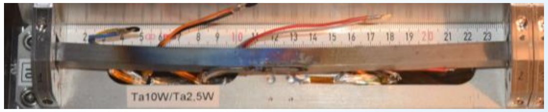
LHC Collimation materials studies

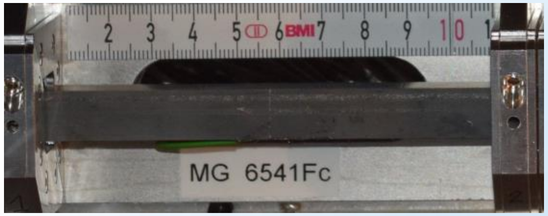
A wide array of well-known, as well as novel materials have been explored and under different beam impact scenarios











A great deal has been learned regarding material/composite/compound behavior under shock. New compounds developed in the process.

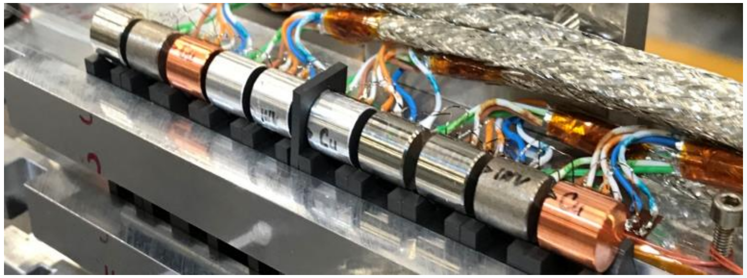
POTENTIAL applicability in non-LHC applications and fields

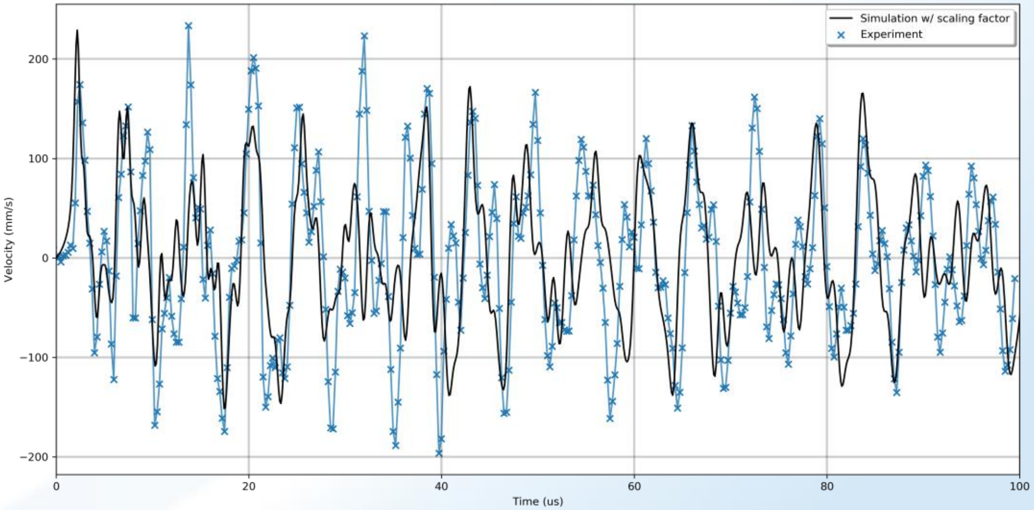
Desired response, but what about long-term resilience ➔ Radiation damage experiments

FlexMat experiment

An excellent example of broad applicability and interface with other research

- Test dynamic response of advanced carbon materials for:
  - Targets
  - Beam dumps & catchers
  - Collimators
  - Cladding for production targets
- Collaboration with p-bar target
  - Test of candidate materials (Inconel, Invar, Cu)
  - Mock-up FAIR p-bar target
- Influence of structure and density on dynamic response to direct beam impact
- Provide benchmark for numerical simulations





Beryllium Grid and Irradiated material Experiments

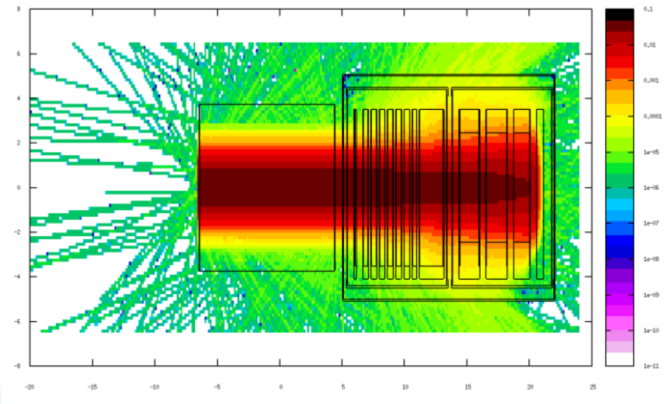
GOALS

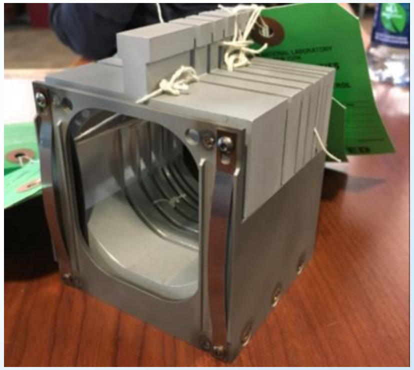
Expose Beryllium to even higher beam intensities than what was achieved in HRMT24

Identify thermal shock response differences between non-irradiated and previously irradiated material specimens (Be, C, Ti, Si)

Explore new and novel materials to evaluate their resistance to thermal shock and suitability as target materials

Real-time measurement of the dynamic thermomechanical response of graphite to benchmark numerical simulations

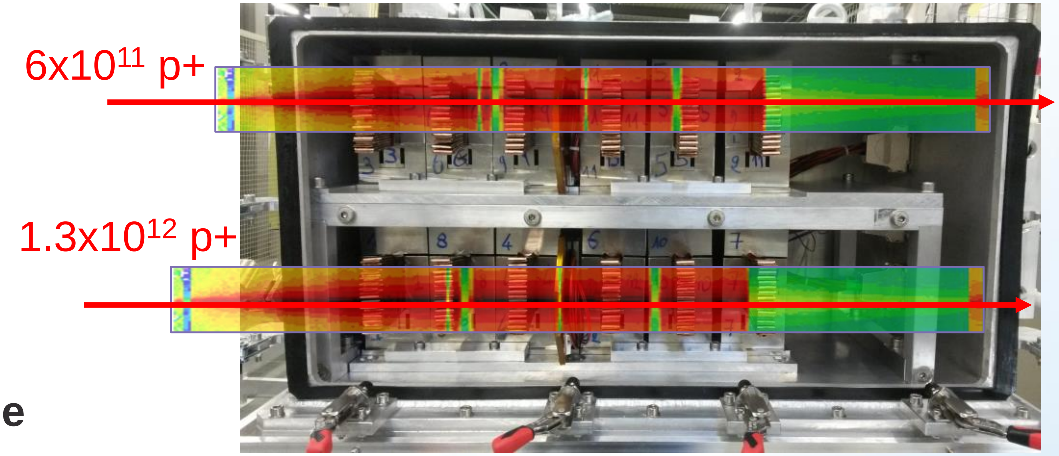


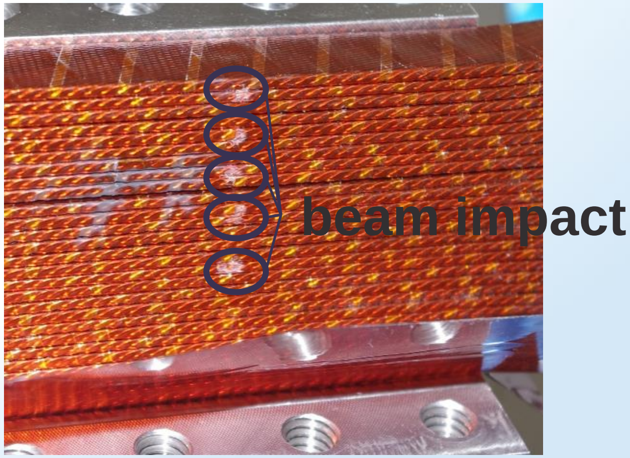


Superconducting Magnet Components Damage Tests at room temperature

Study **damage mechanisms** and limits of **superconducting magnets components** due to instantaneous beam impact

- **LHC Nb-Ti and HL-LHC Nb_3Sn magnet.**
- Instantaneous beam impact = **Ultra-fast beam losses <270 μs**
- Beam impact leads to **temperature rise** causing **thermo-mechanical stresses** that can lead to magnet performance degradation





Side view of a Nb-Ti cable stack after beam impact

ATLAS PixRad experiment

Goal Study effects of accidental beam-loss scenarios for ATLAS tracking detector (Pixel and Strips) at HL-LHC

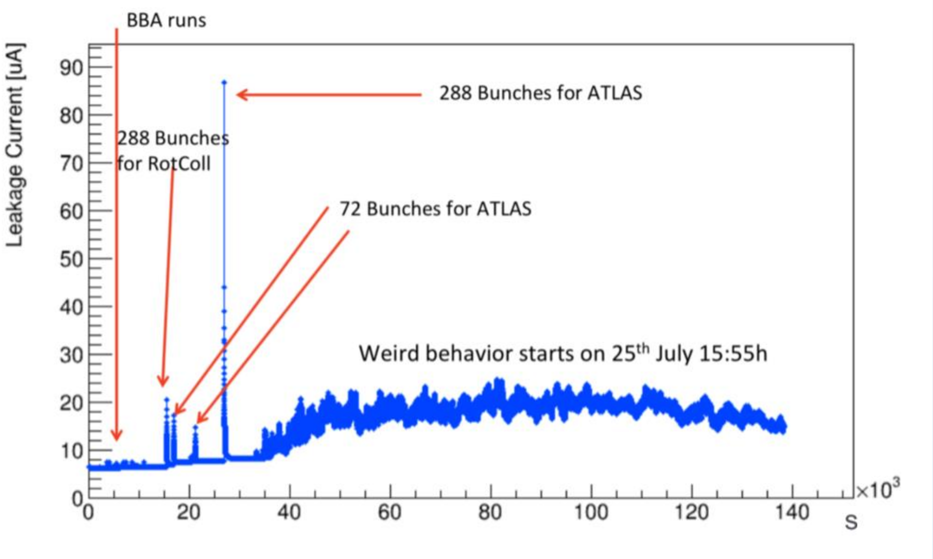
Provide realistic estimate of the damage threshold for sensors and electronics

Evaluate the performance degradation due to the radiation damage

HL-LHC failure scenarios: asynchronous beam dump or wrong injection settings

- unlikely that off-orbit protons hit directly
- Possible scenario: protons hit the TCT4 collimators (120m away from the IP) and shower experiments

Measure damage threshold beyond which detector performance begins to degrade



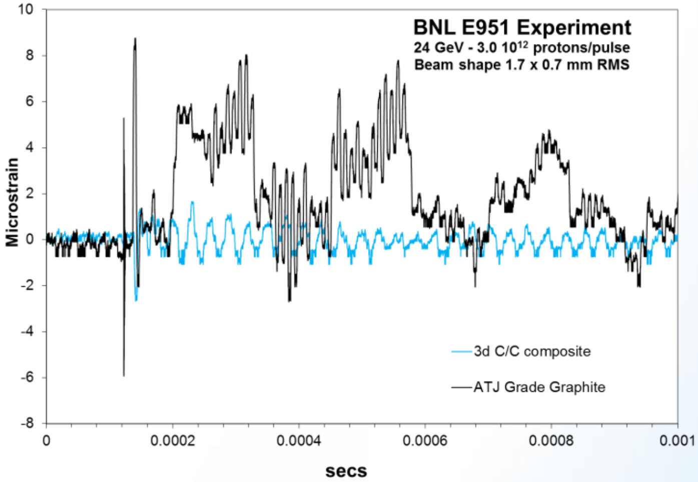
However

The interest or need to understand intense beams
&
accelerator material interaction for new initiatives pushing power to MW levels

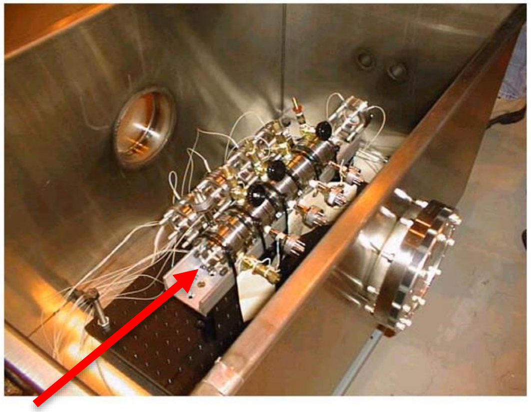
not new and has led to dedicated beam experiments for SNS and Neutrino Factory
BNL, E951 (2000-2001) experiments

Needed to understand how composites respond as compared to conventional graphite, for example

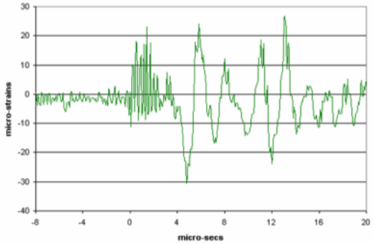
24 GeV 3 10^{12} p/pulse

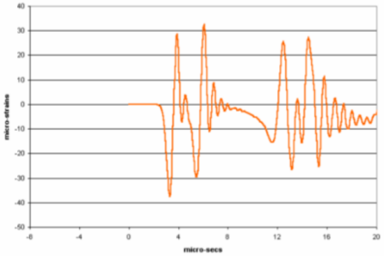


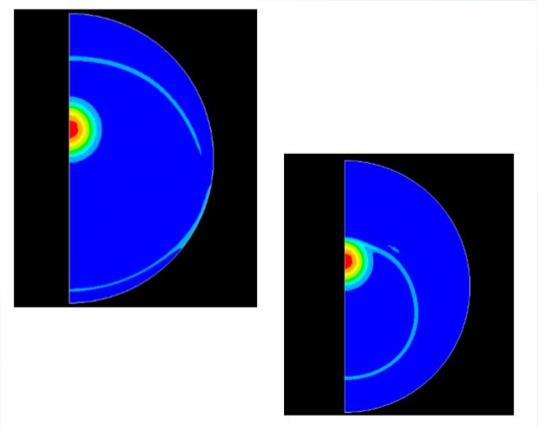
Or, how novel materials can serve as beam windows while enclosing a Hg jet target



Or, how well can we predict the response due a beam pulse





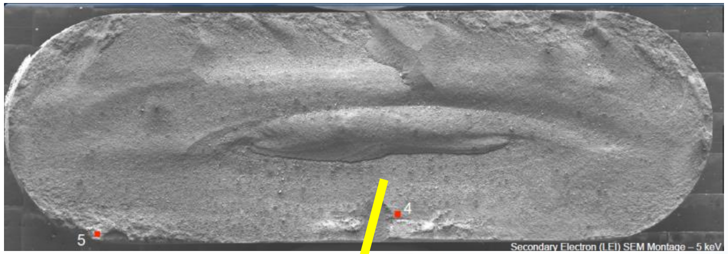


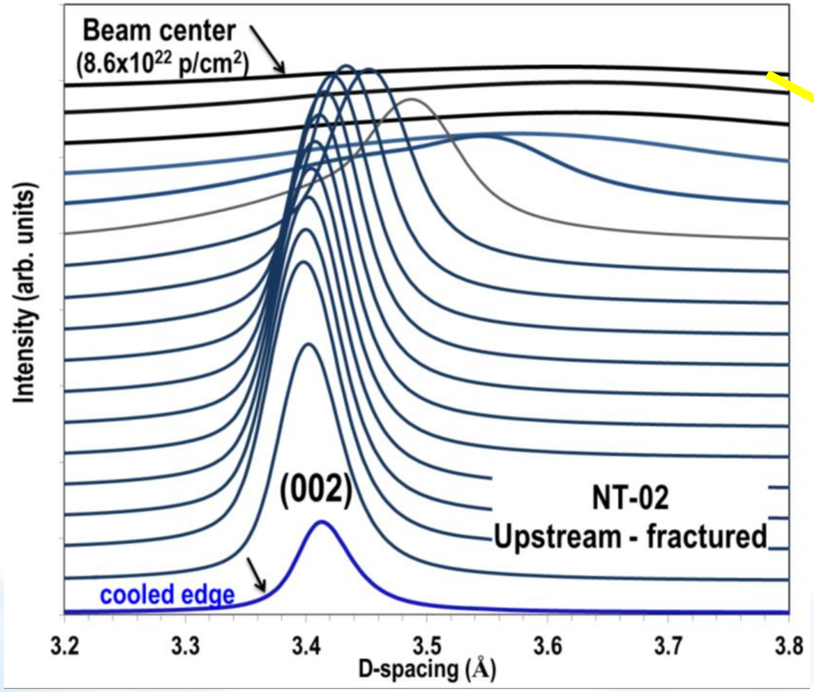
Intense beams, long-term damage and microstructure

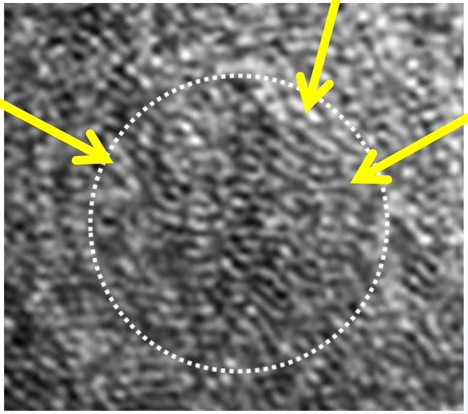
Case study where intense, tight beams are accompanied by long term irradiation damage

6.1 x10^{20} protons were delivered on NT-02 target resulting in a peak fluence **8.6x10^{21}** protons/cm^2

Fracture surface



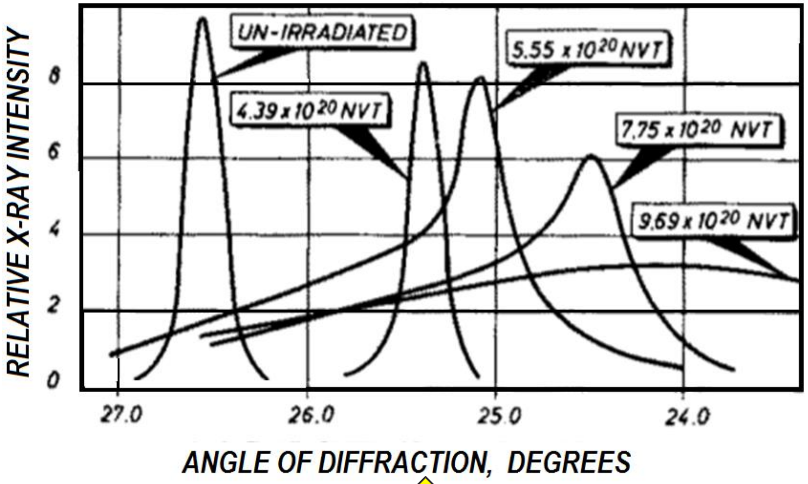


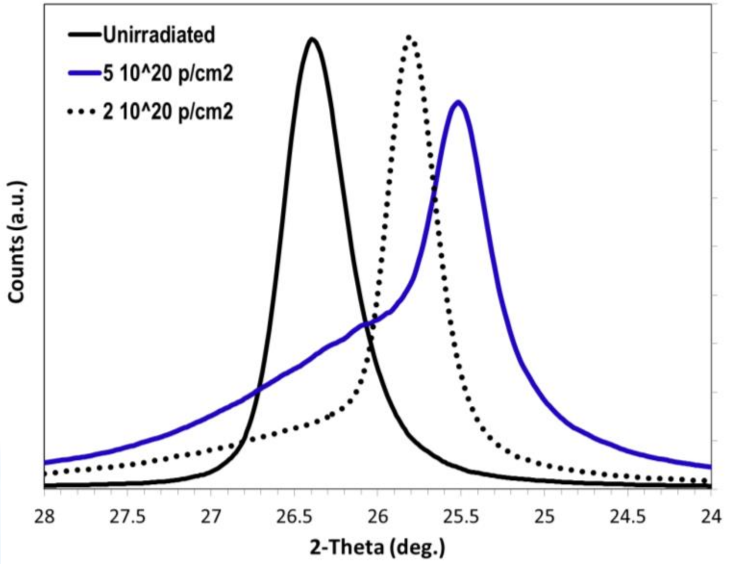


Graphite fragmentation into nano-crystallites

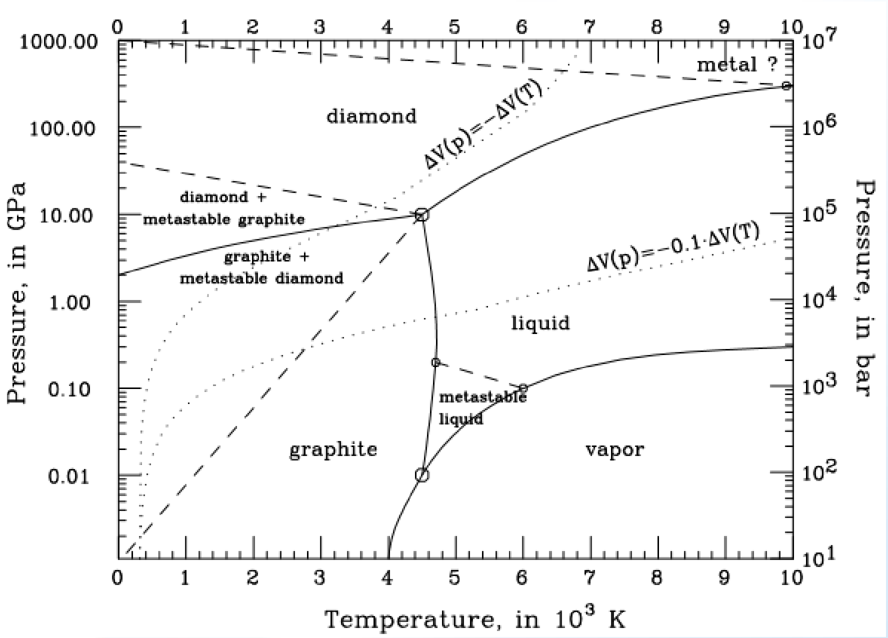
Correlation of X-ray and electron microscopy
in IDENTIFYING the state of NuMI target at FAILURE

Lattice Damage in graphite:





What is the disturbance to the lattice structure as intense beams induce phase transitions in carbon?



On Graphite Transformations at High Temperature and Pressure Induced by Absorption of the LHC Beam (after Zazula, CERN)

Therefore

The strength of HRM in placing materials into extreme states and answering fundamental questions about the survivability of both known and novel materials is only one part of the story

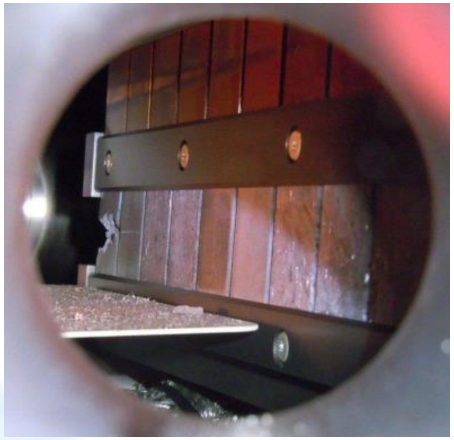
What makes it more useful is its interface with other parallel activities that cover different aspects of the fundamental question

Couple of things:
How materials respond in accumulated damage?
How do we probe for both (fast and slow damage)?

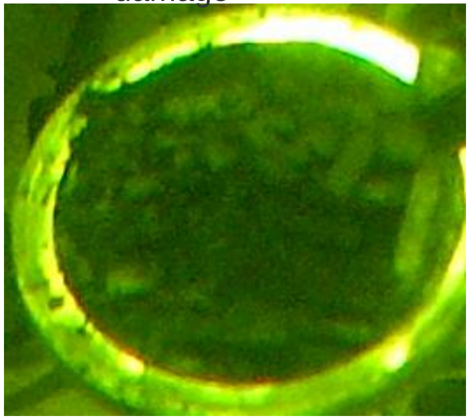
Following is a clear example of this synergy: HRM and Long-term damage

Mo Carbide-Graphite compounds for HL-LHC - Evolution

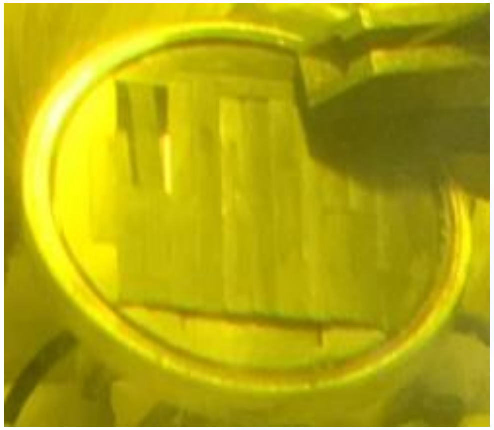
HRM testing



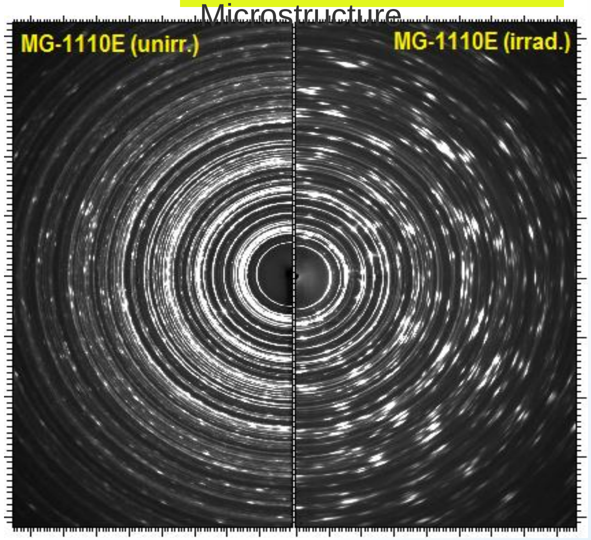
Long-term damage

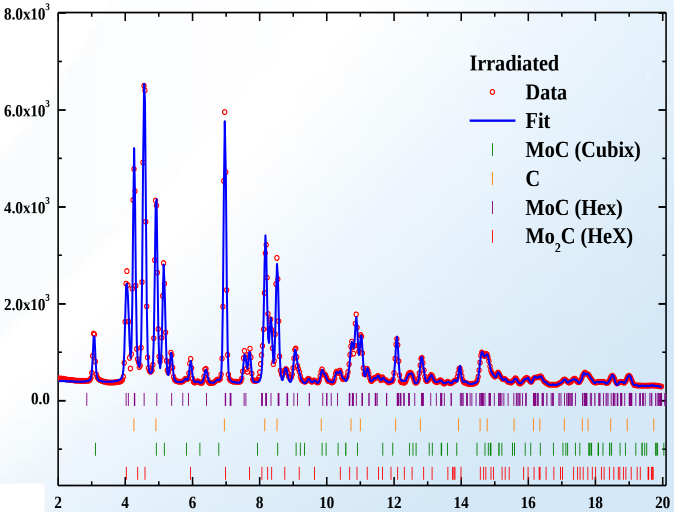


Development



Probing of Microstructure





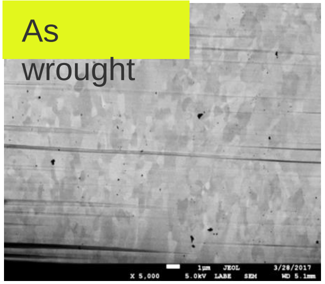
Other interests and applications of such compounds??

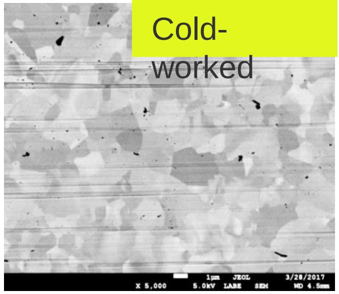
GlidCop: An LHC collimator material (explored) BUT also a fusion reactor material

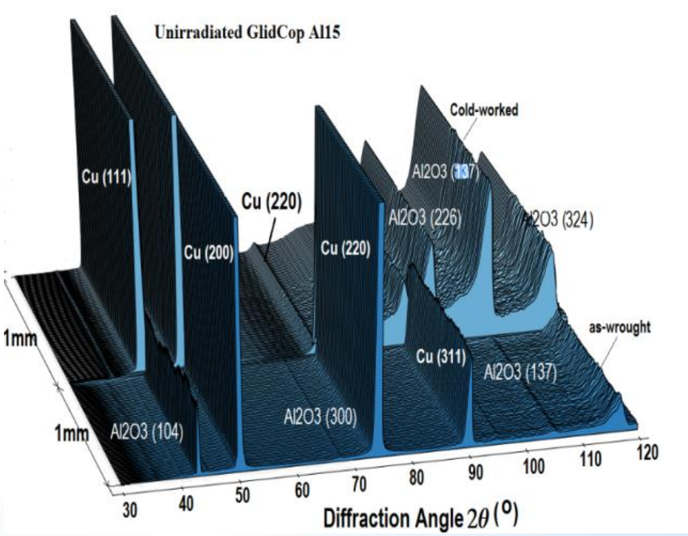

HRM testing

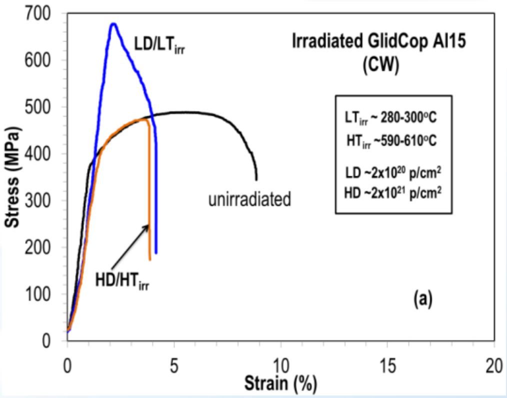
Radiation damage lowers the melting point of W, an effect that could contribute to material failure in nuclear fusion reactors and other applications where materials are exposed to particle radiation from extremely hot fusion plasma.

Microstructure matters?


As wrought


Cold-worked





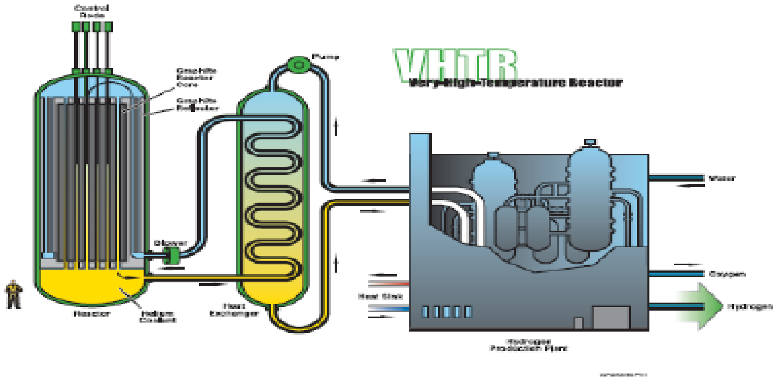
But we believe that HRM has more to offer ….

- Beam intensity
- Time structure and delivery
- Offer a path to study
    - Extreme conditions in matter ➔ phase evolution
    - Dynamic aspects of damage
    - Extreme strain rates

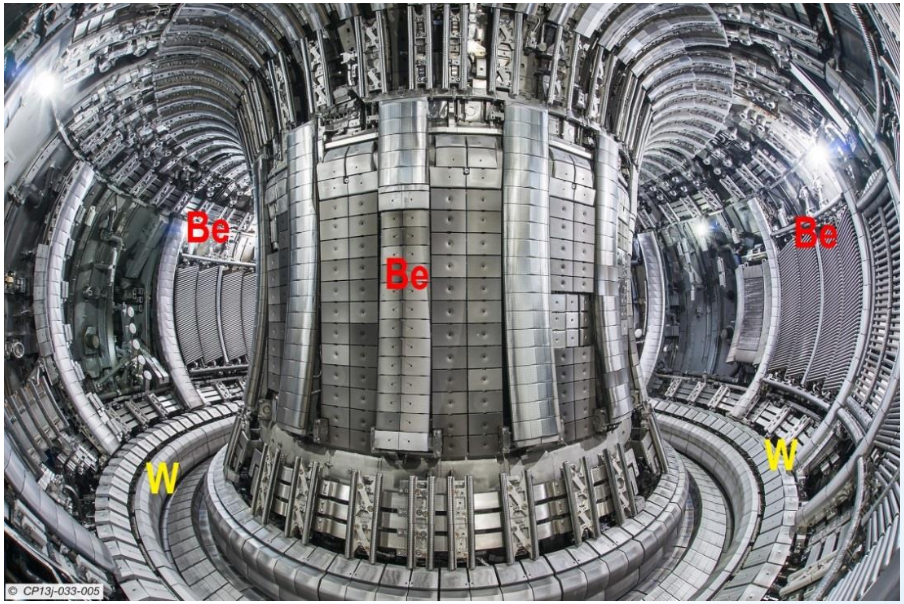
So, where else can we connect?

HRM & Nuclear Materials

Advanced Reactor Concepts

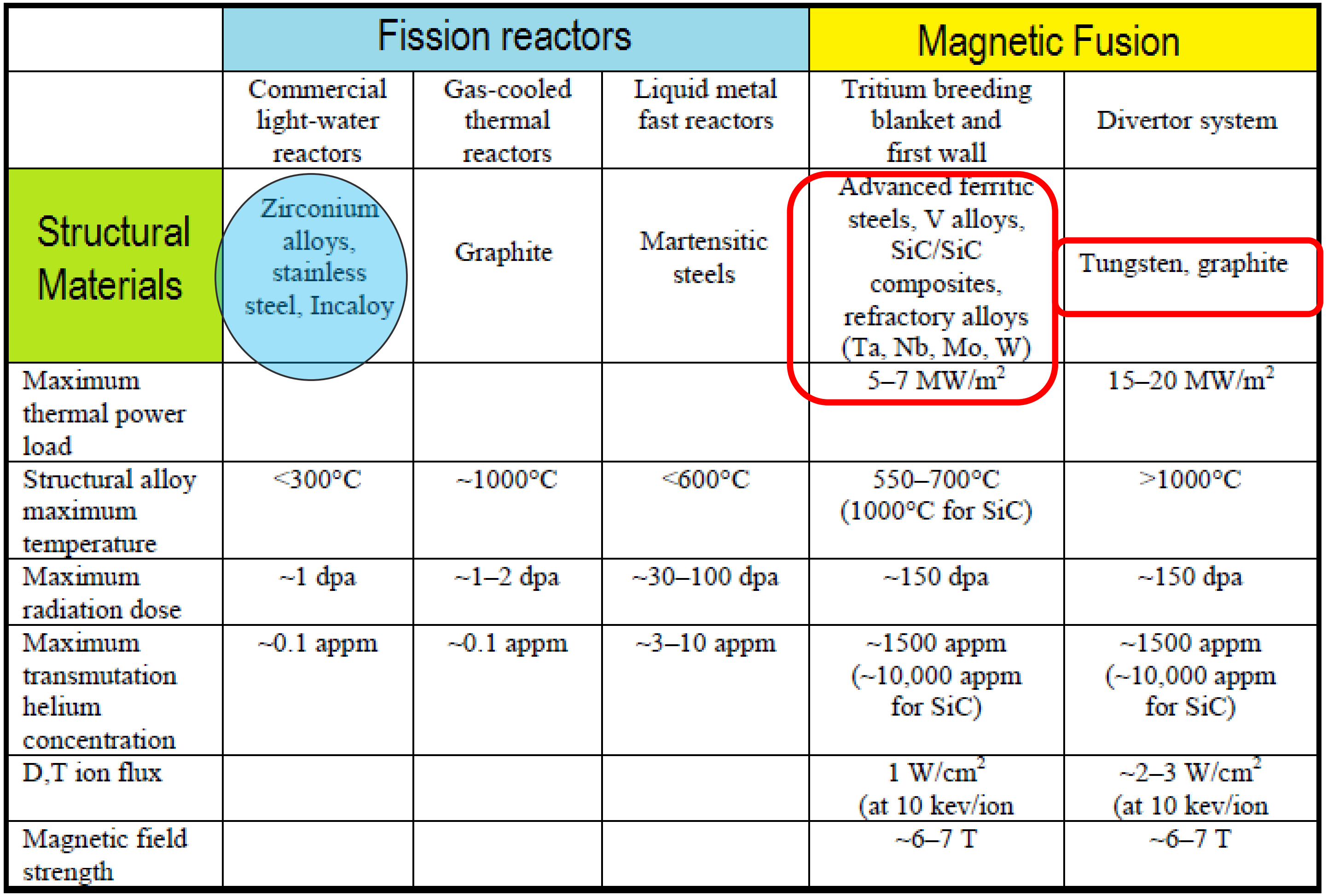


Very high temperature reactor



Graphite, Be, W, etc.

Extreme environments for structural materials fission reactors and magnetic fusion systems



	Fission reactors			Magnetic Fusion	
	Commercial light-water reactors	Gas-cooled thermal reactors	Liquid metal fast reactors	Tritium breeding blanket and first wall	Divertor system
Structural Materials	Zirconium alloys, stainless steel, Incaloy	Graphite	Martensitic steels	Advanced ferritic steels, V alloys, SiC/SiC composites, refractory alloys (Ta, Nb, Mo, W)	Tungsten, graphite
Maximum thermal power load				5–7 MW/m^2	15–20 MW/m^2
Structural alloy maximum temperature	<300°C	~1000°C	<600°C	550–700°C (1000°C for SiC)	>1000°C
Maximum radiation dose	~1 dpa	~1–2 dpa	~30–100 dpa	~150 dpa	~150 dpa
Maximum transmutation helium concentration	~0.1 appm	~0.1 appm	~3–10 appm	~1500 appm (~10,000 appm for SiC)	~1500 appm (~10,000 appm for SiC)
D,T ion flux				1 W/cm^2 (at 10 kev/ion	~2–3 W/cm^2 (at 10 kev/ion
Magnetic field strength				~6–7 T	~6–7 T

HRM has a role to play in:

Experiments in several areas where its **proton and ion beams** can bring about extreme states

- Accelerator materials and systems
- Next generation fission materials
- Fusion-relevant materials (possibly)

Broaden role in next generation, high intensity accelerators

Radiation effects on electronics

Potentially capturing the dynamics of these radiation effects

Connecting experimental and theory/simulation studies of radiation effects in materials

Potential role of HRM to synergistically with probes such as synchrotrons help understand damage evolution to the microstructure of materials

Defect dynamics with ion beam pulses combined with ex situ probing

Nucleation and growth of phases, voids, cracks

Nucleation and mobility of defects, nucleation of phases and growth under highly dynamic stress state is poorly understood

Validation of Codes and Simulation for materials in extremes

Equations of State (EOS)

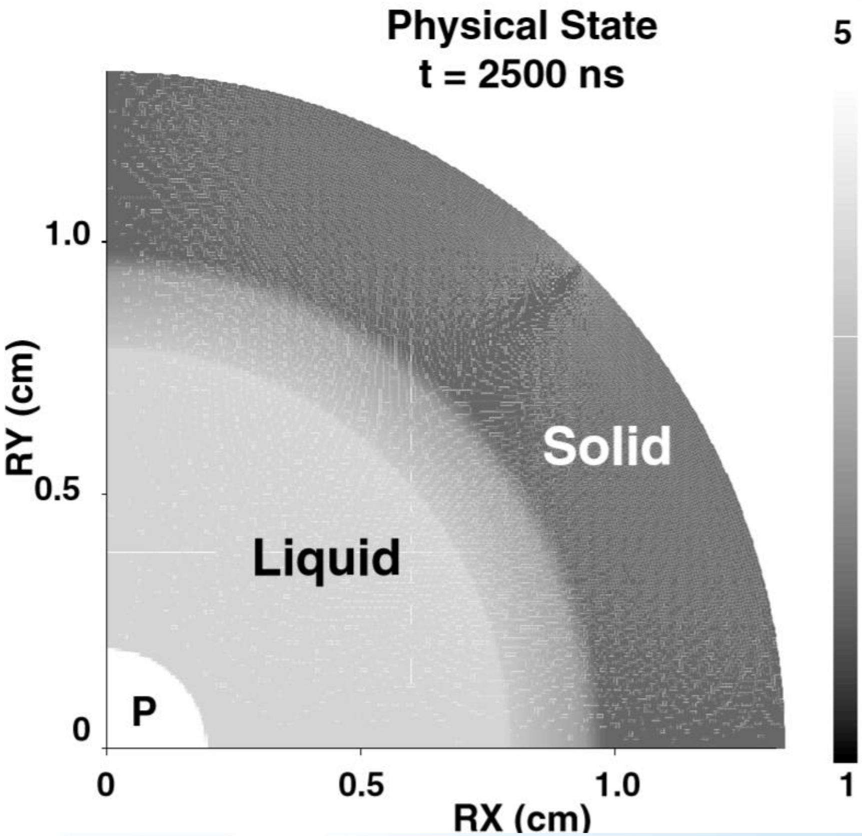
LHC-like beams were considered in past for this possibility …

Equations of State (EOS)

HRM proton bunches deposit high specific energies potentially inducing exotic states of high energy density in matter

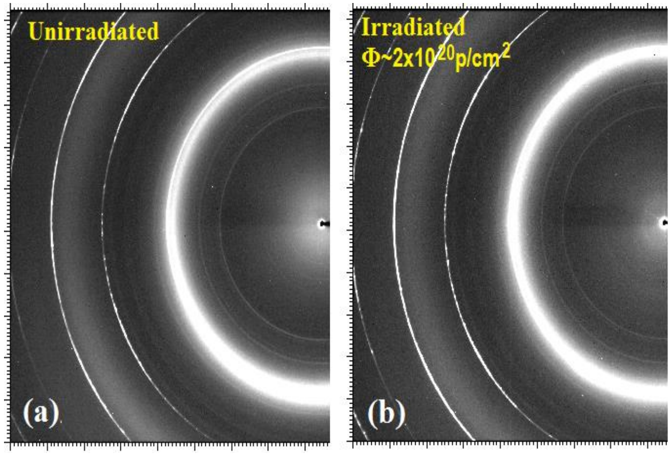
Therefore studies of high-energy density (HED) states can be envisioned. These may include hot liquid states, exotic phase transitions etc.

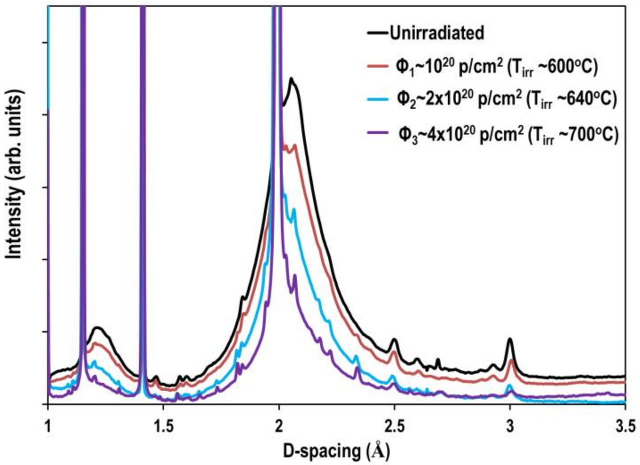
Equation of state (EOS) properties of interest to many branches of basic and applied physics.

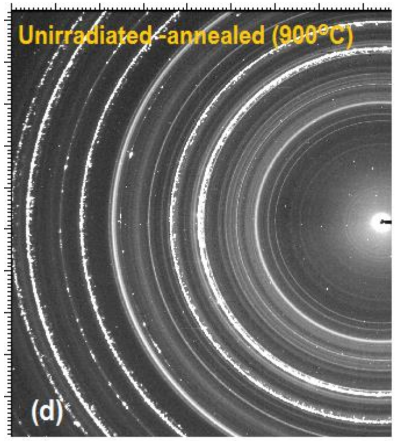


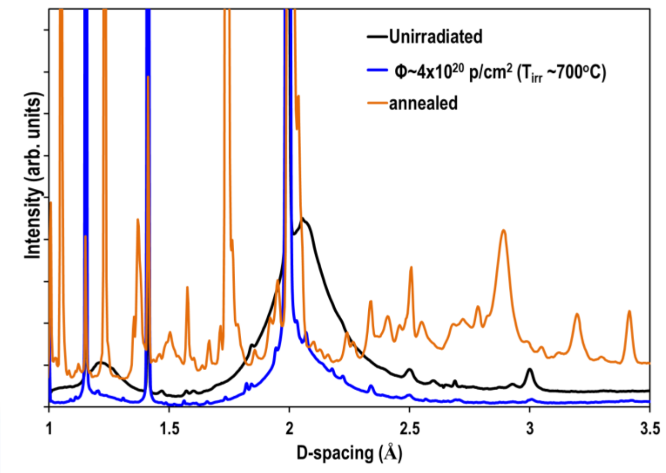
Numerical simulations of the thermodynamic and hydrodynamic response of a solid copper target that irradiated with an LHC-type beam (Tahir et al.)

What happens to nano-structures under HRM beams? Different behavior than less-intense, prolonged irradiation?





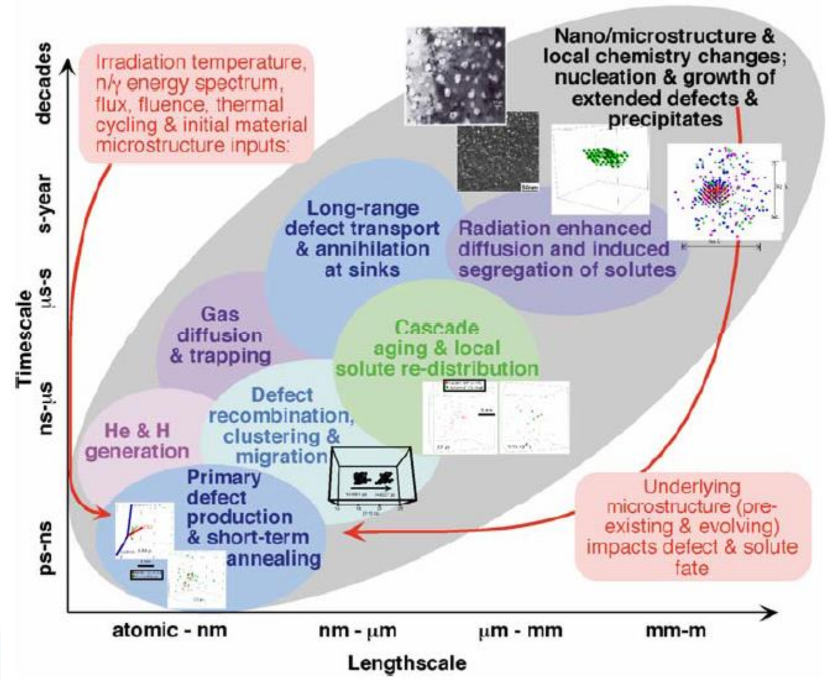


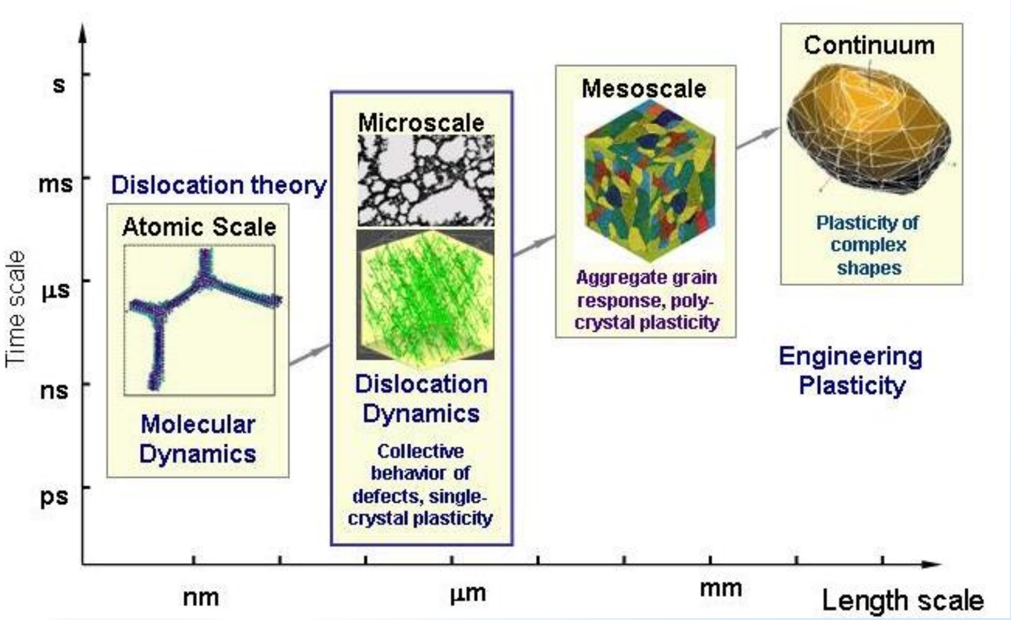


Challenges of connecting scales - materials under extremes

Unique position of HiRadMat to help advance the field

Understanding the multi-scale time evolution of radiation damage is of fundamental importance for our understanding of radiation effects





So one can think of HRM as a place to do unique experiments that cannot be realized elsewhere

How does the NEAR future look at HR

LoIs :

1. FNAL
2. ESS
3. J-PARC (3)
4. UA9 Collaboration CERN/EN-STI
5. CERN/TE-MPE (2)
6. CERN/TE-ABT
7. CERN/TE-MPE (2)
8. RAL
9. CERN/EN-MME
10. AGH, ESSnuSB project

Anticipated

1. CERN/EP-UAT
2. GSI

Message here:

HiRadMat from just LHC collimators that it begun now has drawn interest from international collaborations and large accelerator facilities

In summary ….

- HRM, based on what it has achieved in a few short years serving larger initiatives, is (should) here to stay. It has been a great asset to the accelerator community

- However, not always a direct correlation between a facility's contribution and its **secure** future

- The more particle accelerators move towards the MW levels the more vital the availability and capability of HRM become

But its future need not solely depend on providing the means and ways systems respond to ever increasing intensity beams BUT on tapping into the broader science field of matter in extreme conditions

- HRM's unique beam parameters that can truly bring about EXTREME states provide a strong base on which the studies/experiments can broaden into exciting new areas of engineering materials (nuclear and otherwise)

- Synergistically with other exciting probing techniques HRM can play a large role in the validation and benchmarking of numerical simulations, thus expanding its experimental reach into this large domain

- So, its true potential is not just the ability to deliver intense beams, but in that it can synergistically, with other experimental facilities can lead to a complete package