Very High Power Density Targets

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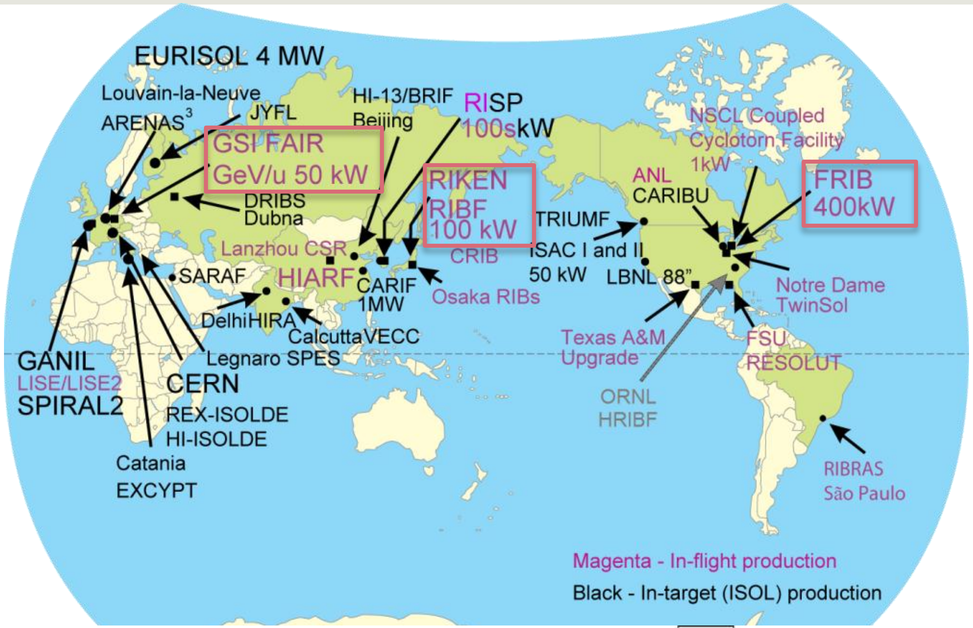
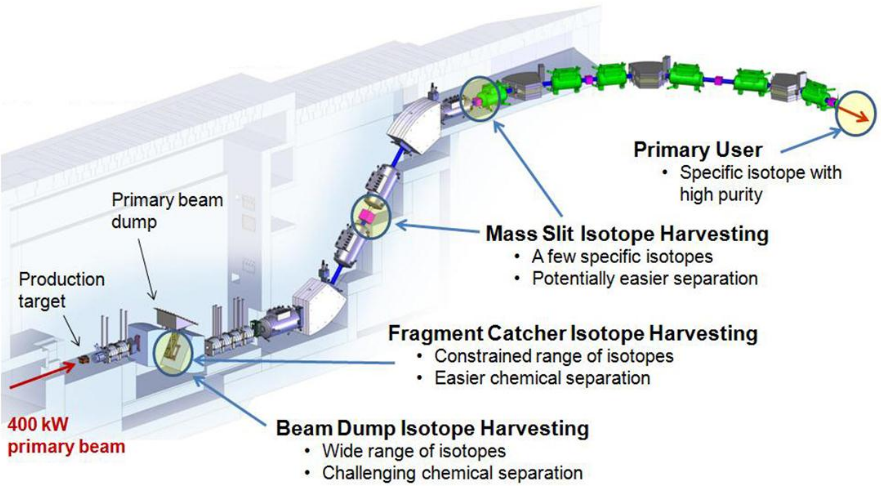
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Rare Isotope Beam Production
  - Where?
  - 3 examples : Super FRS, BigRIPS and FRIB
- Challenges for very high power density targets
- How to manage the high power density challenge
- How to manage the radiation damage challenge in the target and in sensitive components around the target
- Conclusion

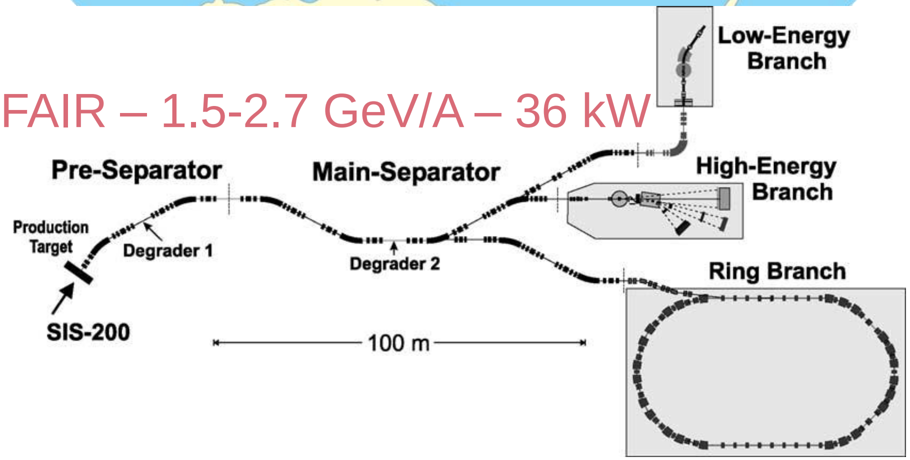
Facility for Rare Isotope Beams in the world

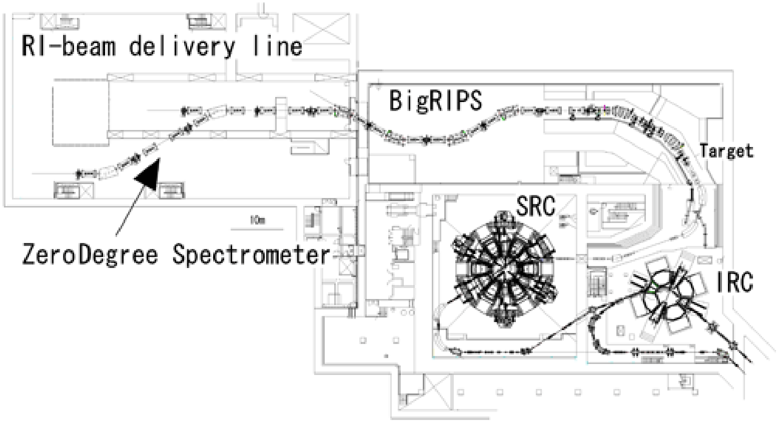




FRIB – 200 MeV/A – 400 kW

FAIR – 1.5-2.7 GeV/A – 36 kW





BigRIPS – 350 MeV/A – 100 kW

Requirements for the production target

	Super-FRS - GSI	BigRIPS - RIKEN	FRIB - NSCL
	Continuous beam / pulsed beam (τ=25-100 ns / 1Hz)	Continuous beam	Continuous beam
Primary beam Energy	1.5 to 2.7 GeV/A	350 MeV/A	200 MeV/A
Primary Beam Power	36 kW	100 kW	400 kW
Power in the target for U Beam	≈ 7 kW	22 kW	90 kW
Beam size	σ_x = 1 mm σ_y = 2 mm	σ = 0.42 mm	σ_x = 0.23 mm σ_y = 0.29 mm
Target material	Graphite SGL R 6400P	Be, C, W, …	Graphite MERSEN 2360
Target thickness depends on the primary beams	1 – 8 g/cm^2 (≈22 mm for U)	1 – 6 g/cm^2 (5.4 mm for U)	0.3 – 8 g/cm^2 (1.8 mm for U)
Lifetime	1 year	2 - 4 weeks	2 weeks
Power deposition for U Beam in static target	**≈ 0.6 MW/cm^3**	**5.7 MW / cm^3**	**60 MW/cm^3**

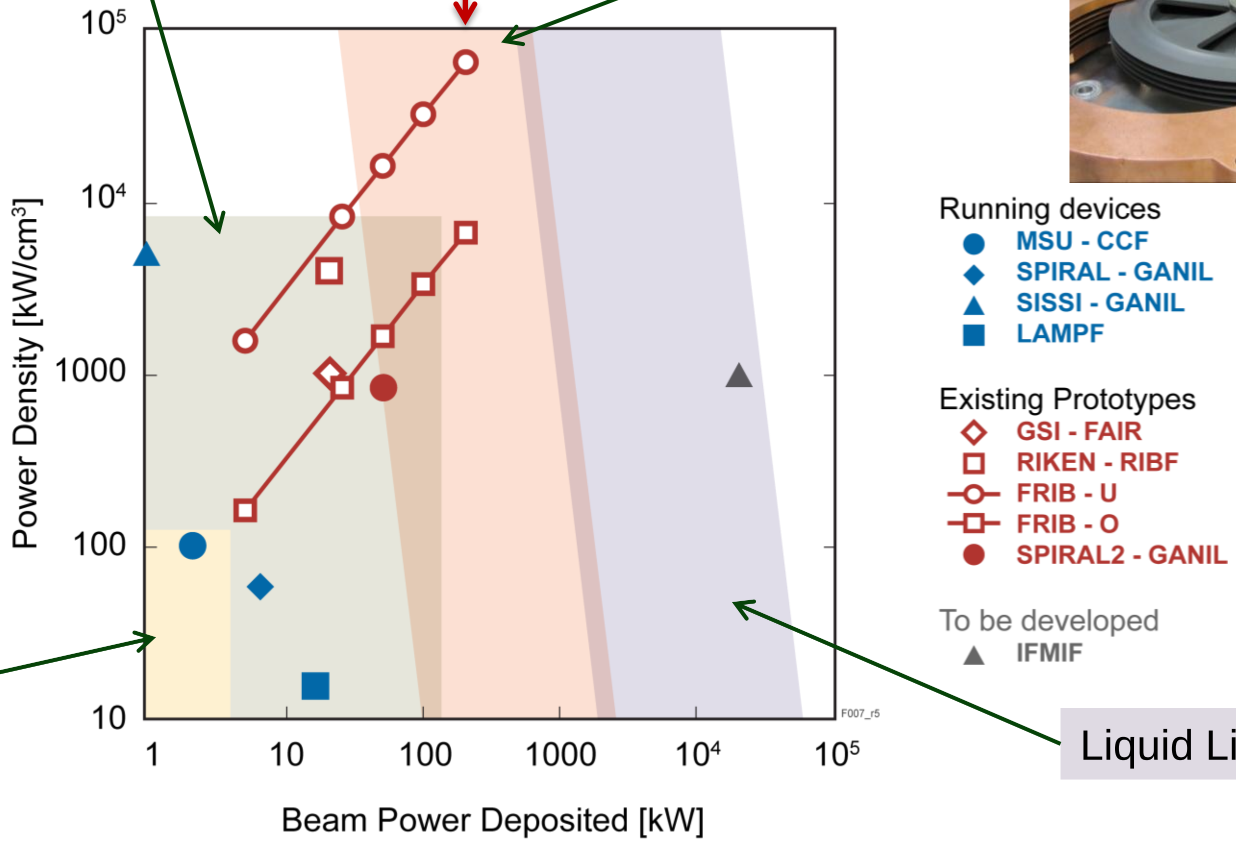
Common challenges
How to mitigate the risks?

- Two major technical risks
  - High power density in matter
    - High temperature
      - Evaporation
    - Thermo-mechanical constraints
      - Fatigue
      - Stress wave
    - Solution?
      - Increase the beam spot size ? Not possible due to optical requirement of high resolution separator
      - Which concept of target?
  - Radiation damage
    - Most of the studies were done with neutron and proton irradiation but not a lot of data for heavy ion beams
    - Change in physical properties
      - Impact on the target lifetime
    - Can we reduce radiation damage?

High Power Target Technology

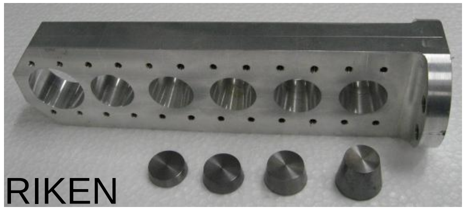
Rotating single-slice targets

FRIB - 400 kW



Rotating multi-slice targets

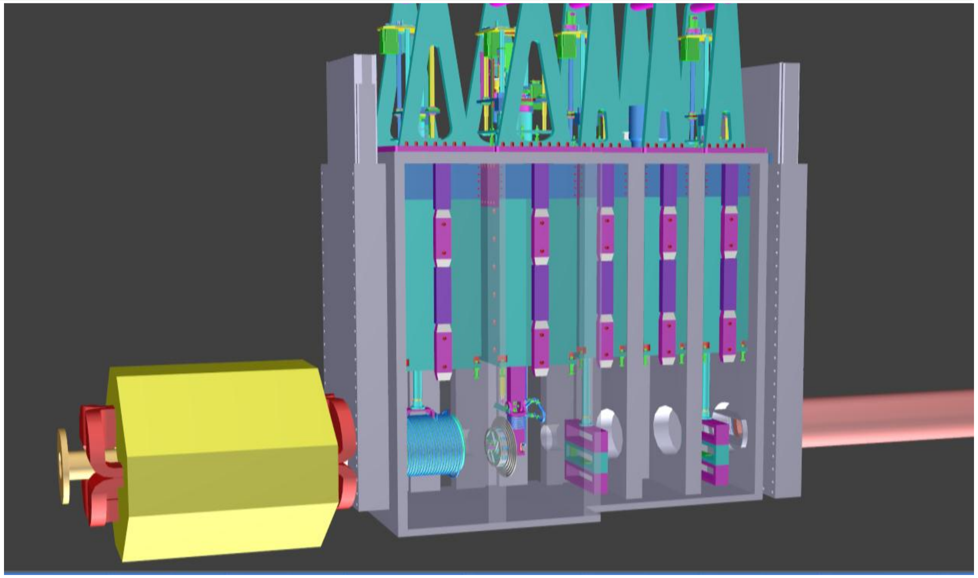
Static targets

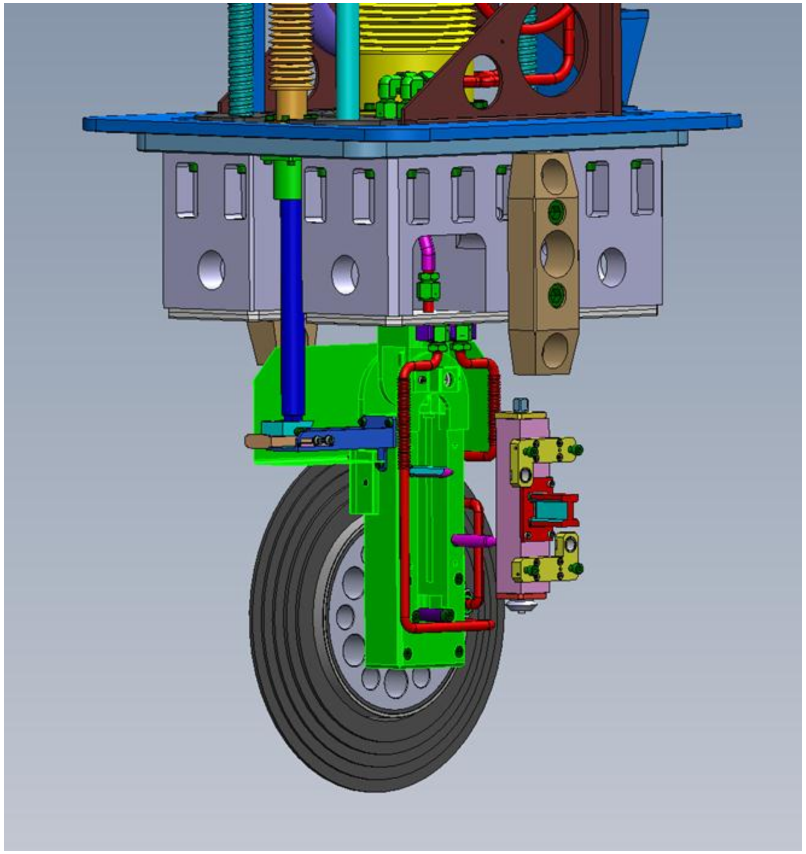


Liquid Li targets

Super FRS
single-slice Target Concept

	Super-FRS - GSI
Power deposition for U Beam	0.6 MW/cm^3
Continuous beam or **Pulsed beam (25-100 ns – 1Hz)**	
Target material	Graphite SGL R 6400P
Target thickness	1 – 8 g/cm^2 (≈ 22 mm for U)
Target diameter	45 cm
Rotation speed	60 rpm

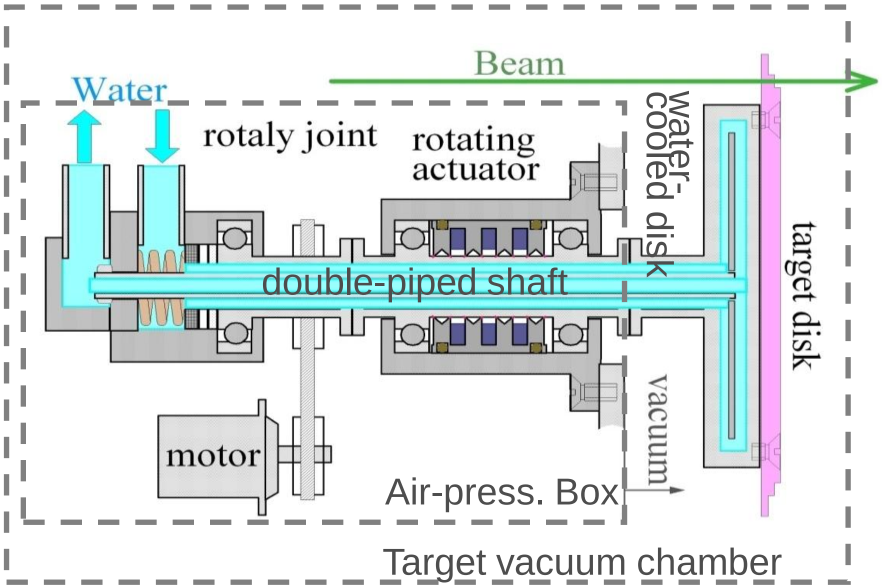




Cooled by thermal radiation

H. Weick

BigRIBS single-slice Target Concept



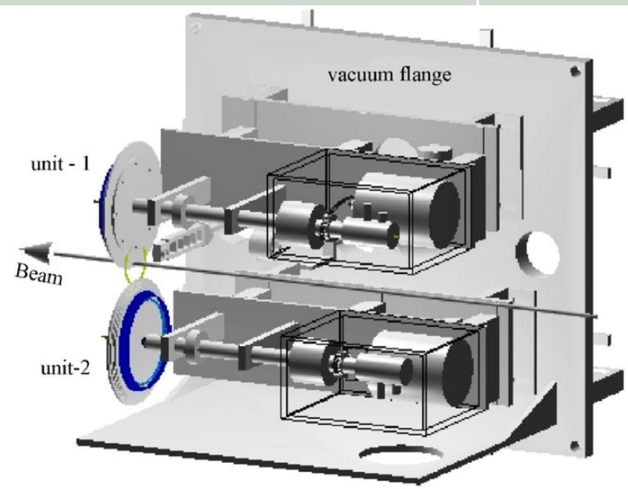
Disk target : for High-power beam

Step shaped edge
20,15,10 mm thick
for N, Ca, Ar beams
10, 7, 5 mm thick
for Kr, Xe, U beams

← Be : 20,15,10 mm thick

K. Yoshida San's talk

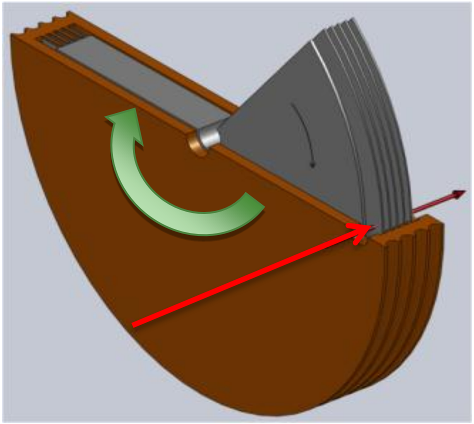
	BigRIPS - RIKEN
Power deposition for U Beam	5.1 MW / cm^3
Target material	Be, C, W…
Target thickness	1 – 6 g/cm^2 (5.4 mm for U)
Target diameter	30 cm
Rotation speed	100-300 RPM



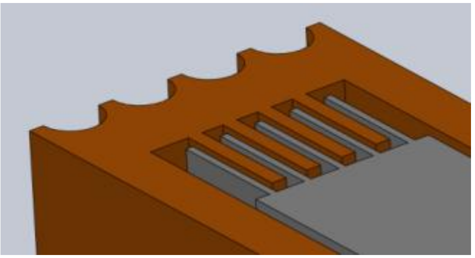
Cooled by water loop

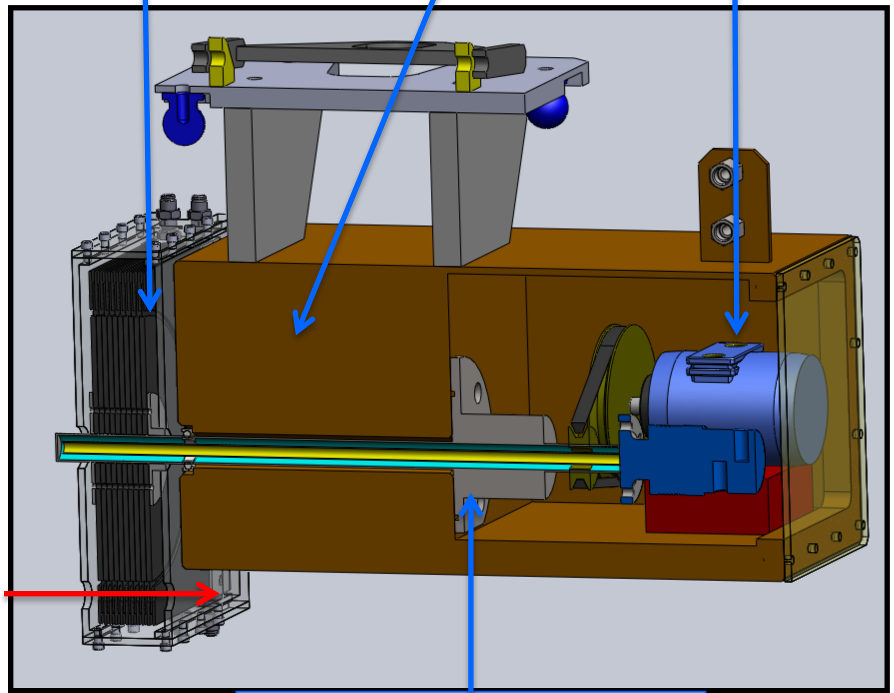
FRIB
Multi-slice Target Concept

	FRIB - NSCL
Power deposition for U Beam	60 MW/cm³
Target material	Graphite MERSEN 2360
Target thickness	0.3 – 8 g/cm² (1.8 mm for U)
Slice thickness	0.1 to 10 mm
Target diameter	30 cm
Rotation speed	5000 rpm


Static heat sink
(only lower half shown)

Rotating wheel



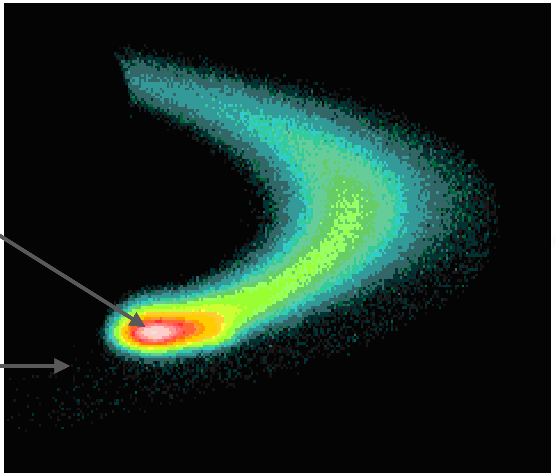


Cooled by thermal radiation

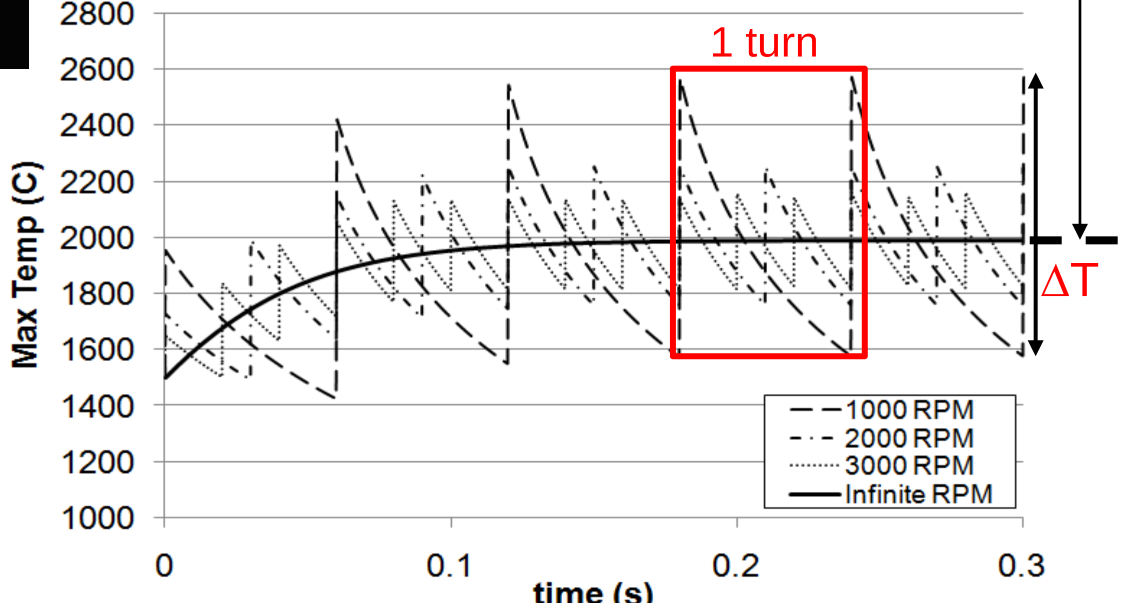
Thermo-mechanical challenge for
Pulsed beams / rotating targets / rotating beams

Tmax

Tmin



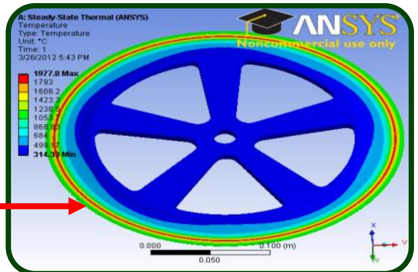
Average temperature



Calculated temperature changes

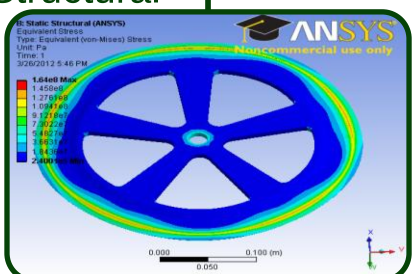
Thermo-mechanical simulations to guide the design

Steady State Thermal

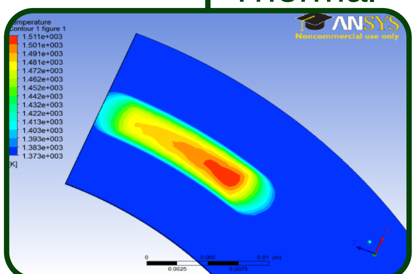


1900 ºC ± 200 ºC

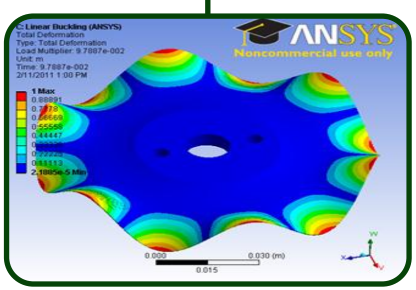
Steady State Structural



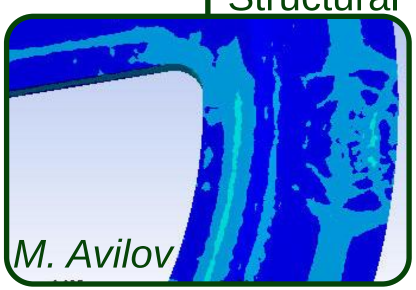
Transient Thermal



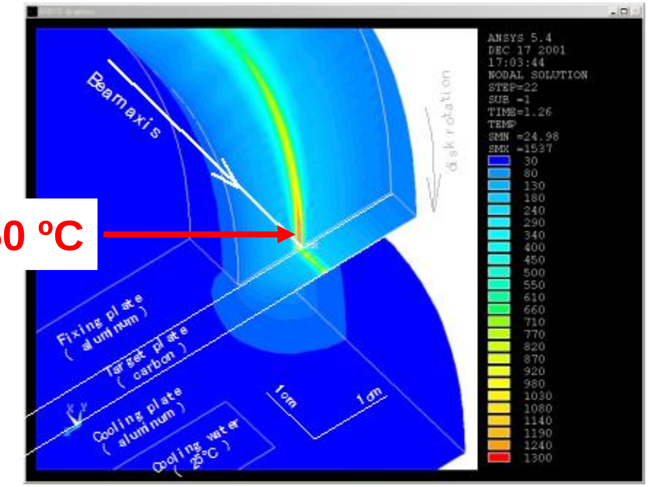
Buckling



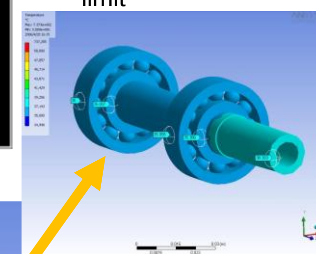
Transient Structural

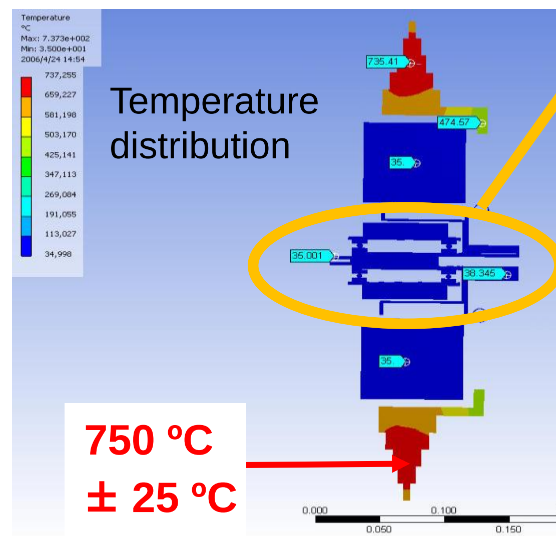


Tmax = 1550 ºC



Hub:
T_{Max} = 35 ºC
T_{limit}: = 150 ºC

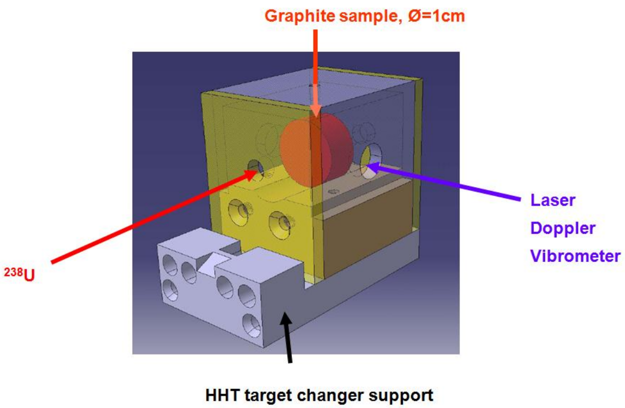




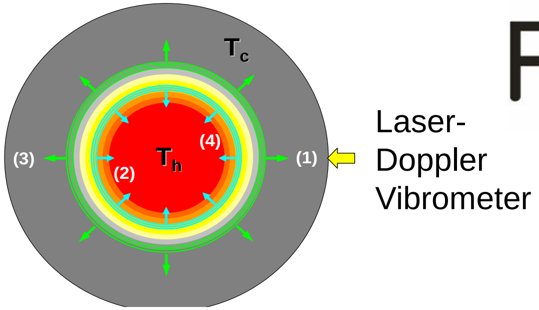
750 ºC ± 25 ºC

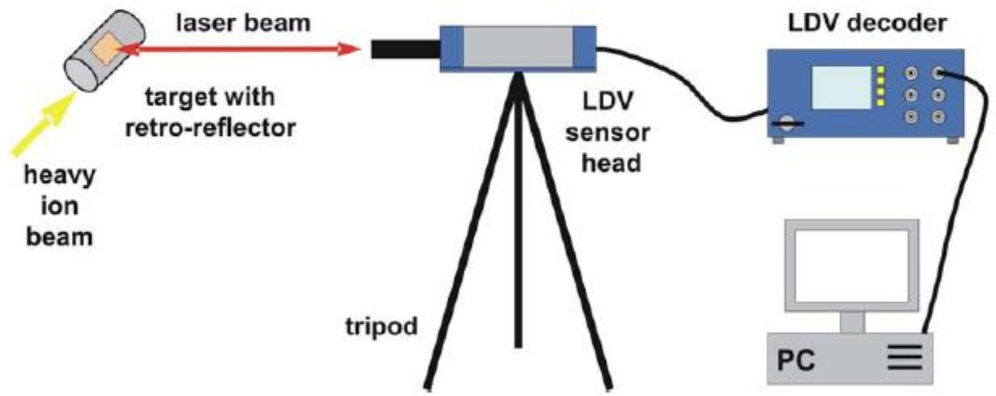
- ^{238}U
- N = 10^{12} ions/s
- σ_x = 1 mm
- σ_y = 2 mm
- ω = 1 Hz
- d = 4 g/cm^2
- P = 12 kW

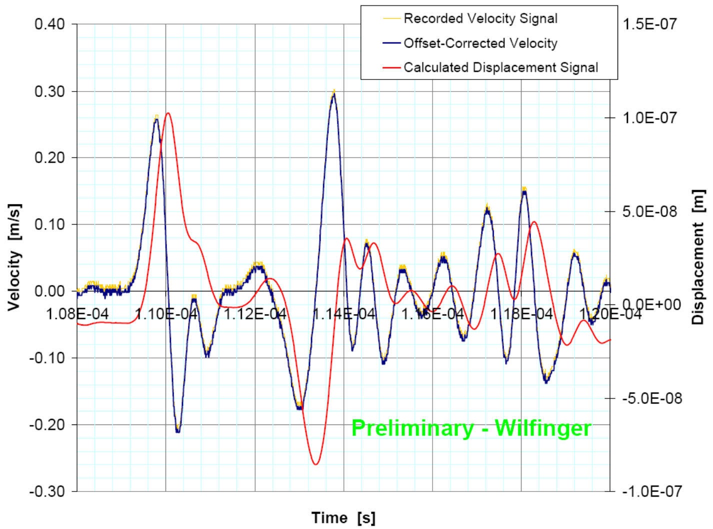
Pulsed beam is a challenge
Experimental investigations of shock waves in graphite



Measure surface vibrations of graphite target with Laser Doppler Vibrometer (LDV)





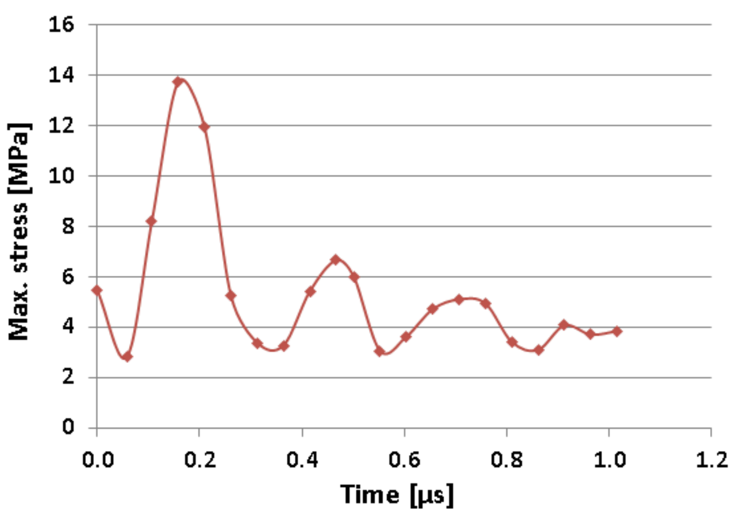


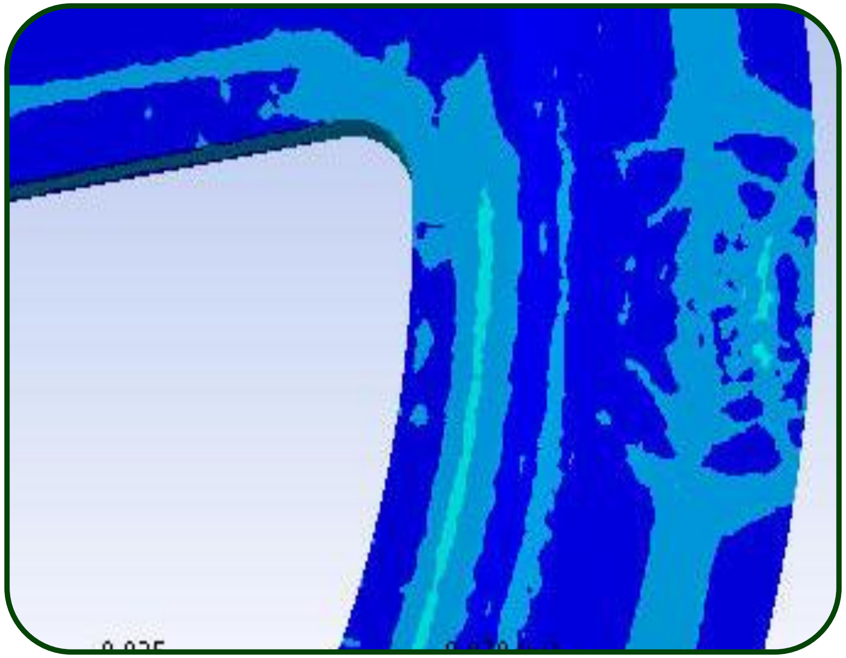
R. Wilfinger, A. Kleic, D. Varentsov et al.

Tensile strength of graphite under shock-loading conditions ~ 65 MPa

⇒ As long as ΔT is below 650 K induced stress stays below the critical one.

Rotating target is a challenge
Stress wave calculation in graphite



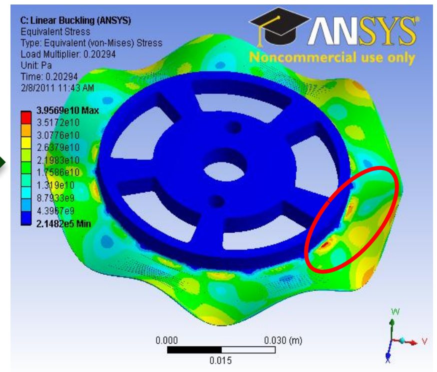


M. Avilov

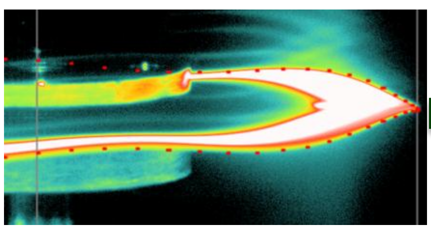
- To mimic rotating target, we used pulsed beam

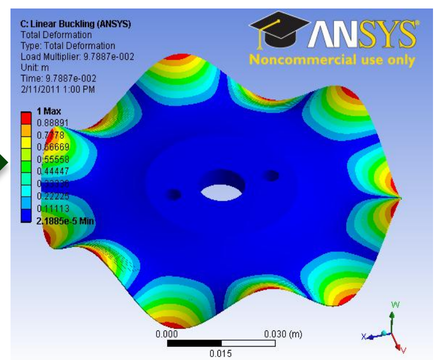
  ⇨ **Overall stress due to dynamical stress < 10 % of the total stress**

Target shapes optimization

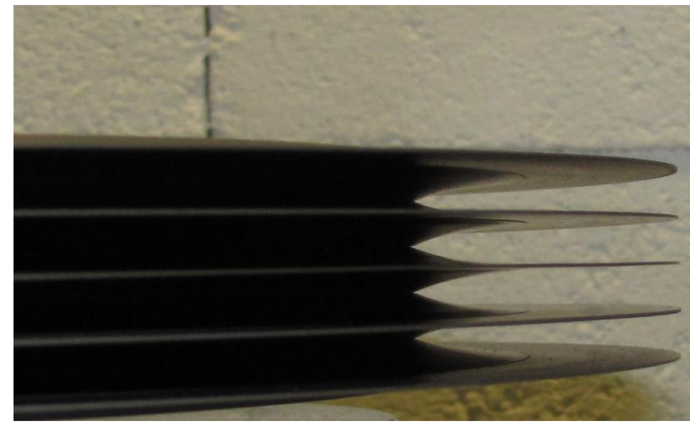


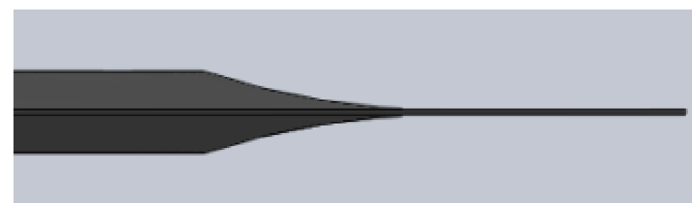
Sandia National Laboratories





M. Avilov, F. Pellemoine, W. Mittig and Sandia Team



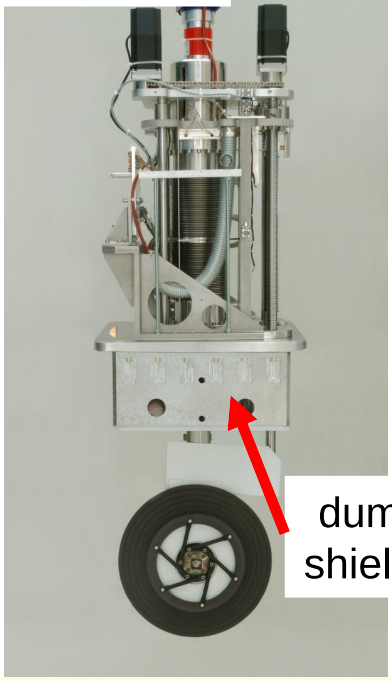


Diameter 30 cm
Target thickness
0.3 mm/slice

Prototype Target
to be used at FRS with SIS18 beams

FAIR

C. Karagiannis et al.

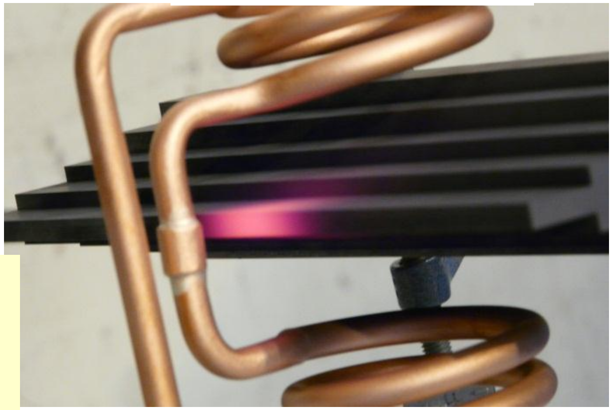


dummy shielding

drive test at company

Torsion proof Shaft Coupling

Induction heating



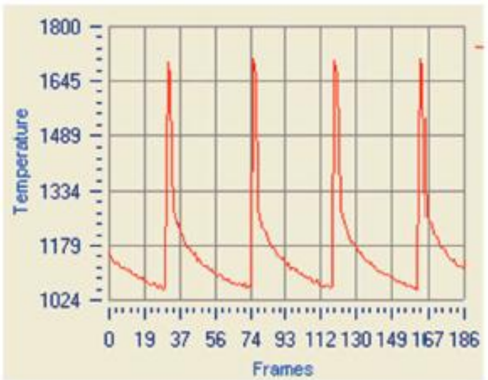
- Prototype target ready
- Off-line tests started
- Induction heating (≈ 10 kW transferred) to target
- Challenge with bearing (now running during ≈ ½ year)

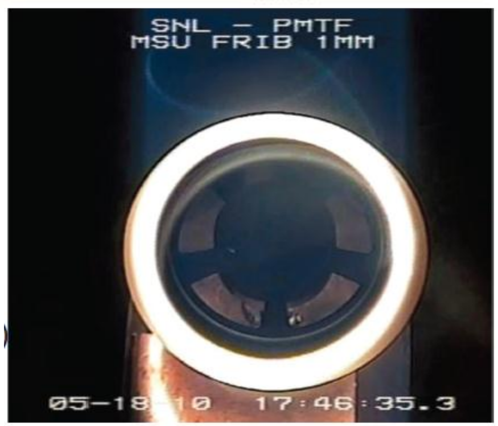
K.-H. Behr
M. Gleim

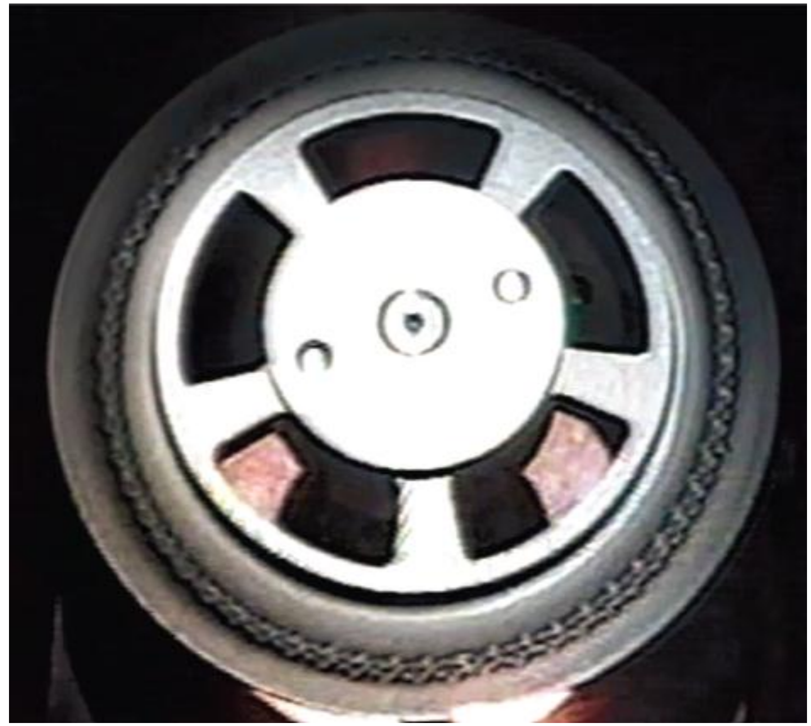
Prototype Target
Single-slice 20 kW Target Prototype

- Destructive tests with 20 keV electron beam at Sandia Laboratories (NM, USA)
  - Extreme conditions at 1 Hz (target 10 cm, 1 mm)
  - P = 1.65 kW , ΔT = 640 ºC
  - P = 3.3 kW, ΔT = 1800 ºC ⇨ plasma effect

Sandia National Laboratories





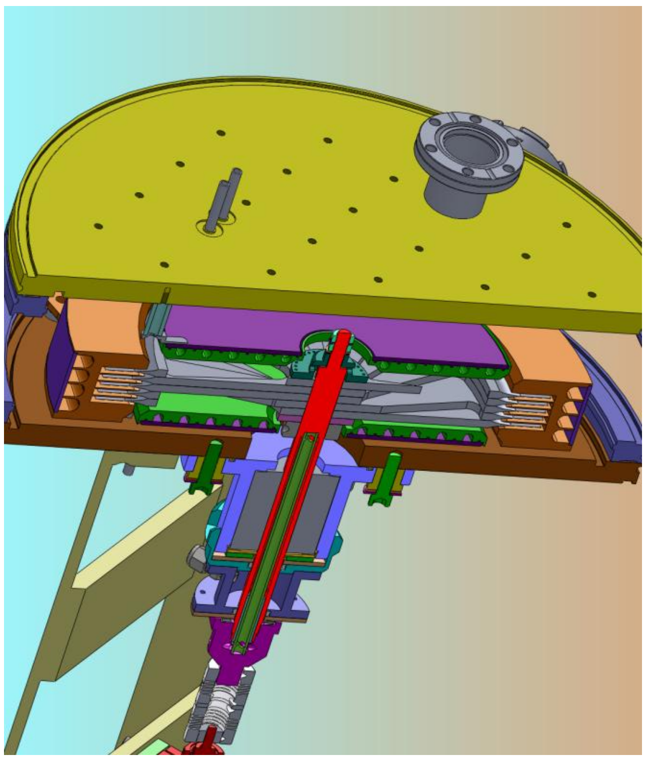


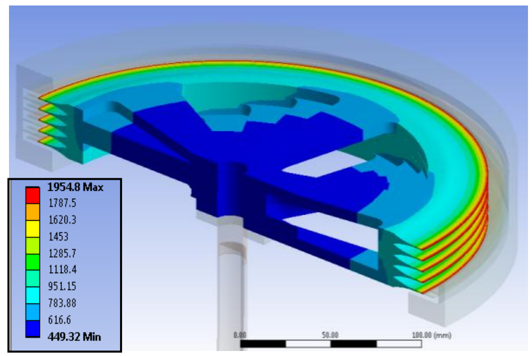
W. Mittig, F. Pellemoine and Sandia Team

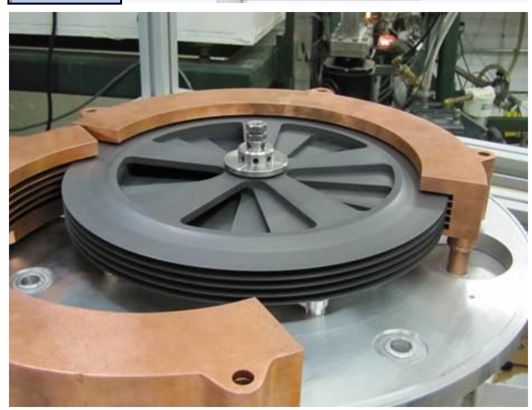
Prototype Target
Multi-slice 50 kW Target Prototype

Budker Institute of Nuclear Physics

- Prototype for FRIB production target
  - 5 slices - 5000 rpm - 30 cm diameter
  - Cooling system designed for 70 kW dissipated power capability



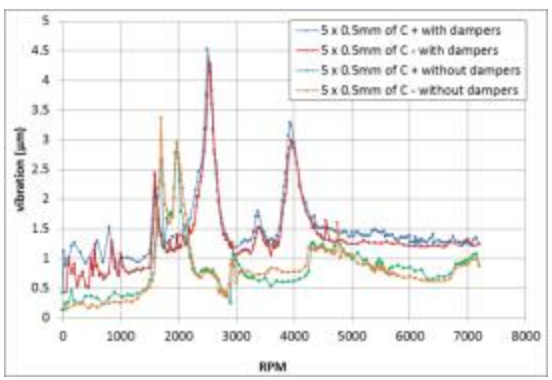




M. Avilov, S. Fernandes, W. Mittig, F. Pellemoine and BINP team

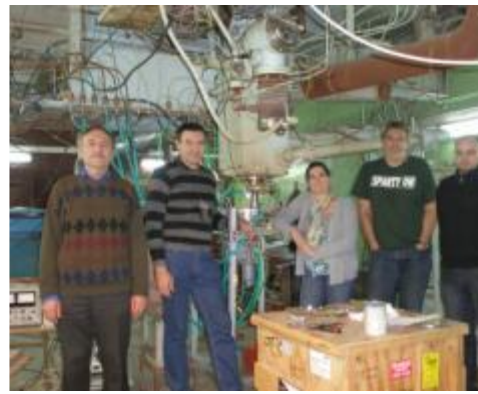
Prototype Target
Extensive tests

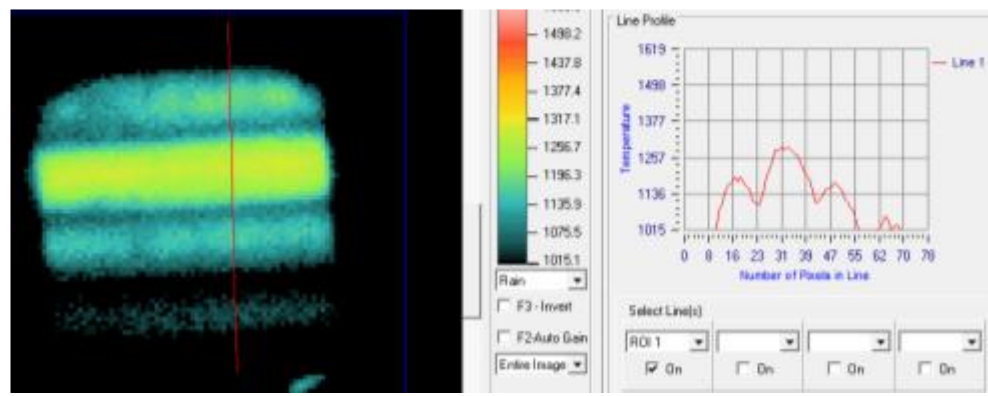
- Mechanical tests
  - Test complete at 5000 RPM
  - Drive tests during one week



- Electron beam tests (1MeV)
  - P max = 40kW
    - (P max/slice ≈ 10 kW) T max ≈ 1600 °C

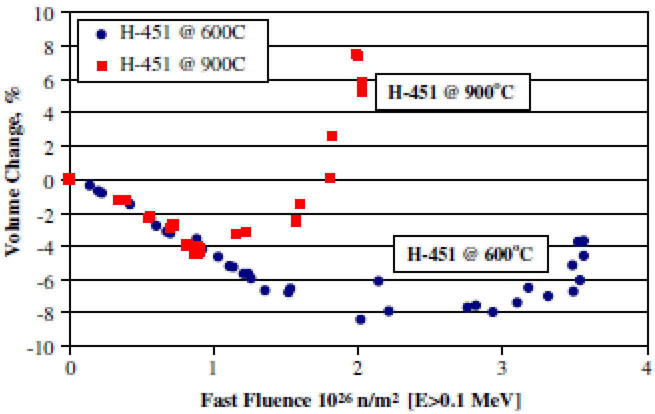
Budker Institute of Nuclear Physics



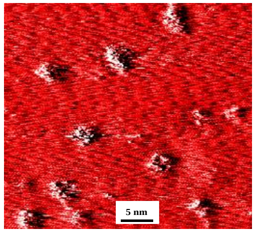


Other challenge for high power targets
Irradiation damage in graphite

- Simulation and tests off line or with electrons help to mitigate thermo-mechanical constraints
- But irradiations by charged heavy ion induce changes of physical properties ⇨ decrease target performance
  - Thermo-mechanical properties
    - thermal conductivity, tensile and flexural strength
  - Electronic properties
    - Resistivity
  - Structural properties
    - microstructure and dimensional changes
  - Swelling
  - Irradiation creep
  - …
- Most of the studies were done with neutron and proton irradiation but not a lot of data for heavy ion beams



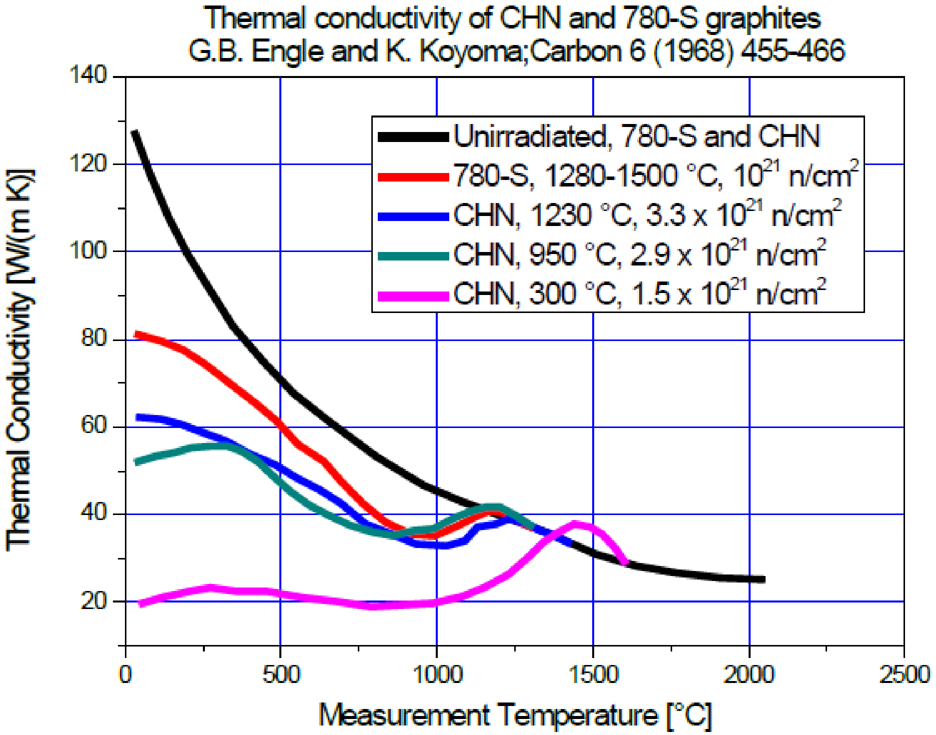
T. Burchell, L. Snead, JNM 371 (2007) 18-27



J. Liu et al./ NIM B 245 (2006) 126.

Annealing of irradiation damage at high temperature

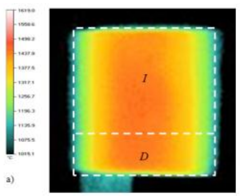
- Annealing observed at high temperature with neutron irradiations
  - How much will annealing help with heavy ions?



Irradiation Test at UNILAC at GSI/Darmstadt

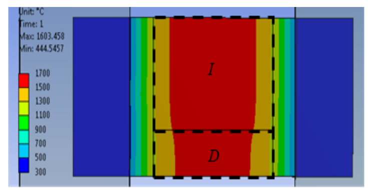
- Au-beam 8.6 MeV/u
  - Up to 5.6 10^{10} $cm^{-2}.s^{-1}$
  - Fluence up to 10^{15} cm^{-2}
  - Samples heated to different Temperature

I = 35 A

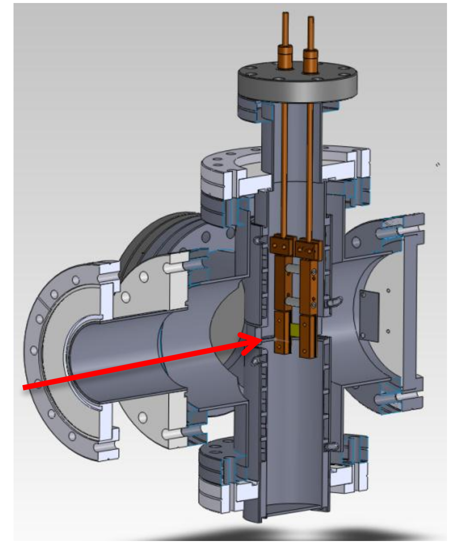


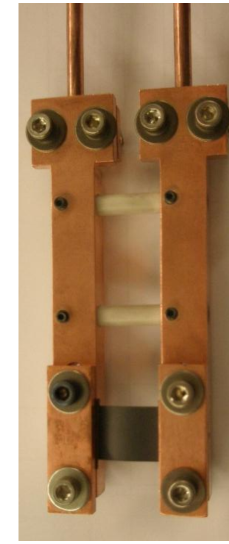
T_{max} = 1480 (± 30 ºC)

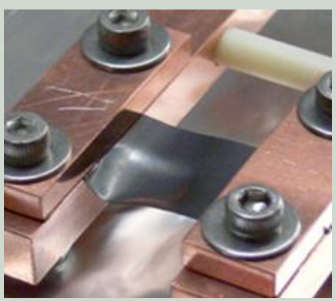
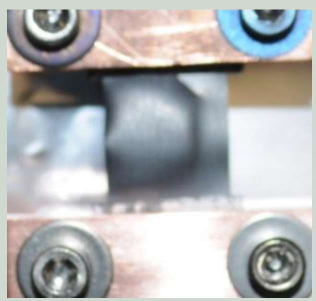
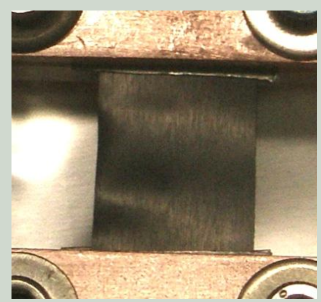
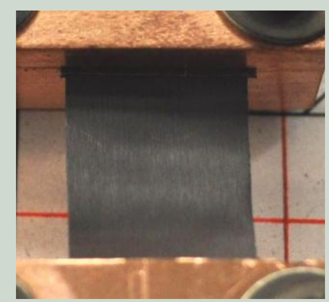
I = 35 A + beam



T_{max} = 1600 ºC



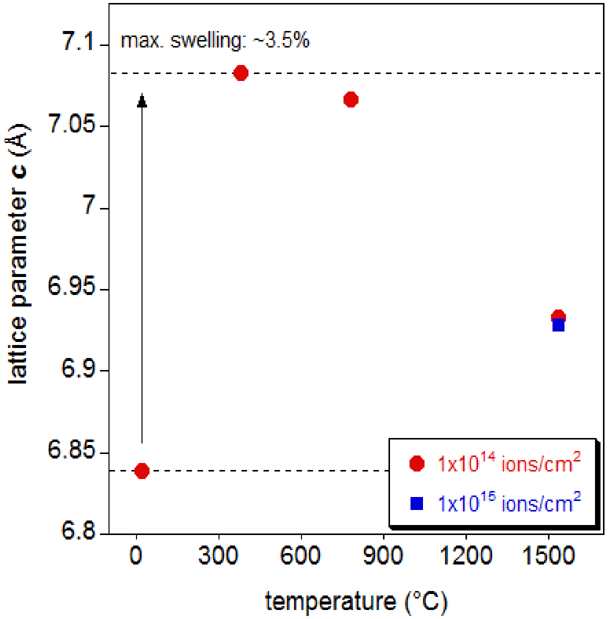


2360 – 1 A 345°C – 10^{14} cm^{-2}	2360 - 11 A 630°C – 10^{14} cm^{-2}	2360 - 25 A 1170°C – 10^{14} cm^{-2}	2360 - 35 A 1525°C – 10^{15} cm^{-2}
			

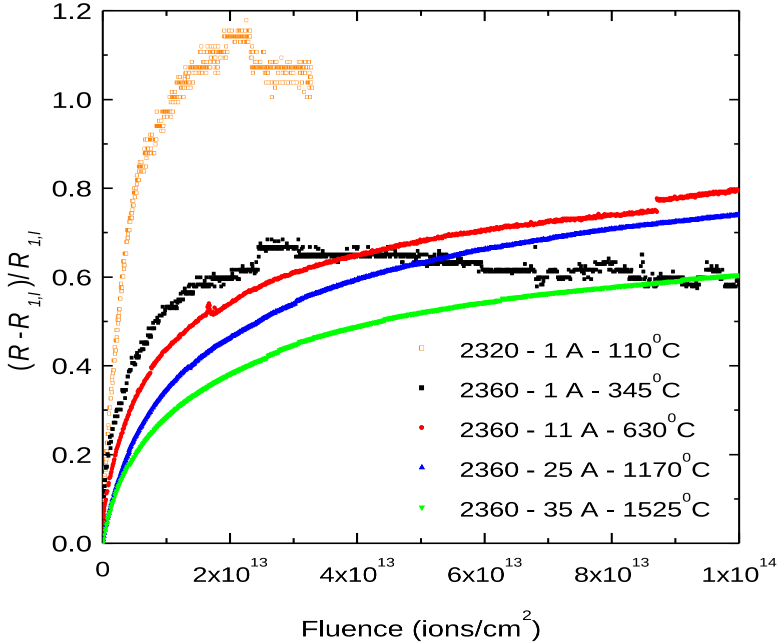
M. Avilov, S. Fernandes, W. Mittig, and GSI team

Annealing of Damage at High Temperature (> 1300°C)

XRD Preliminary results – M. Lang



S. Fernandes



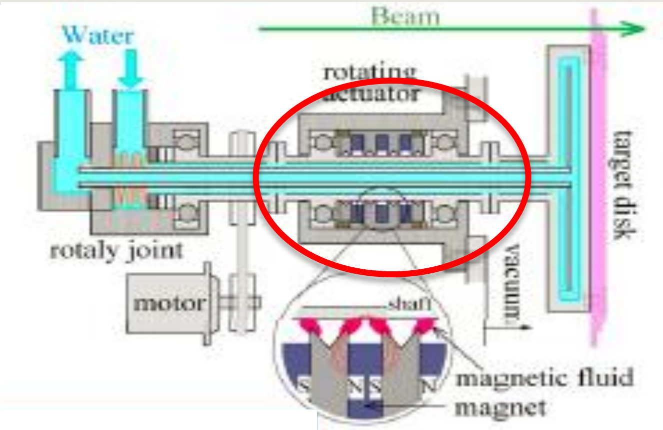
Annealing effect also confirmed with:

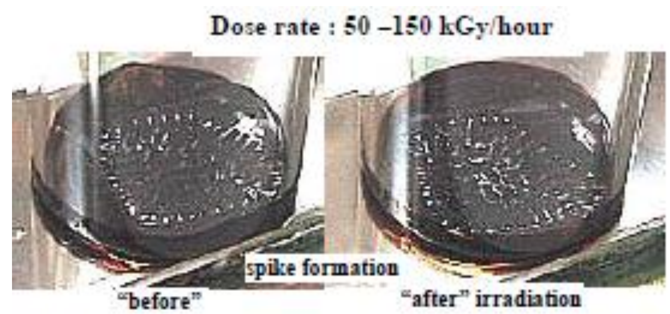
- Young's Modulus
- Thermal diffusivity

} Scientific Report 2011 GSI + collaborators

Radiation damage to sensitive components: Ferro fluidic feedthrough

RIKEN

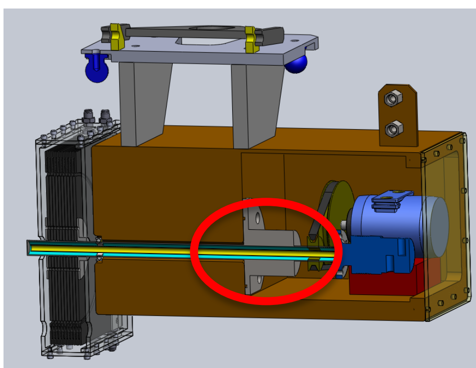


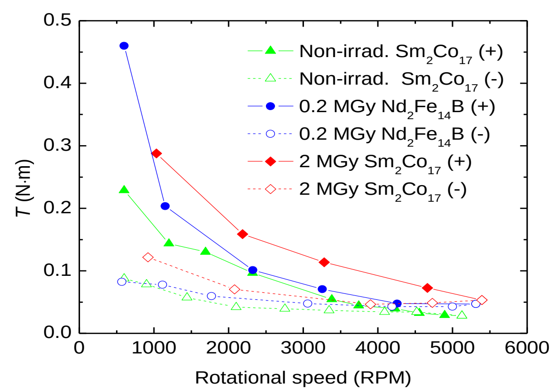


- γ irradiation converted from 50 MeV e-beam at LNS, Tohoku Univ., Japan
  - No significant change on the viscosity was observed up to the total dose of 0.7-1.8 MGy

FRIB

BROOKHAVEN NATIONAL LABORATORY



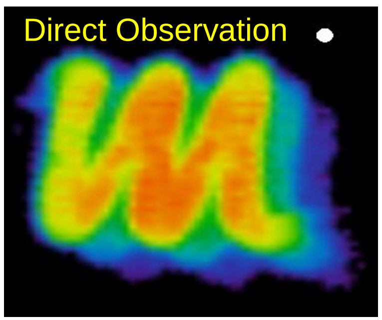


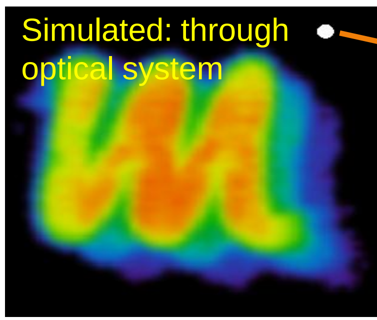
S. Fernandes, W. Mittig, and BNL team

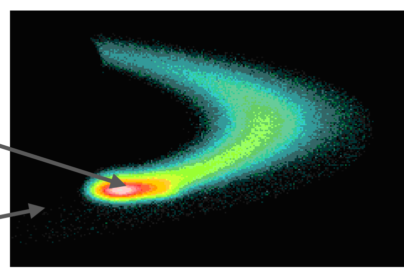
- 0.2, 2, 20 MGy mixed p, n and γ irradiation converted from proton beam at BNL (112 MeV)
  - No significant change in FF performance was observed up to the total dose of 2 MGy

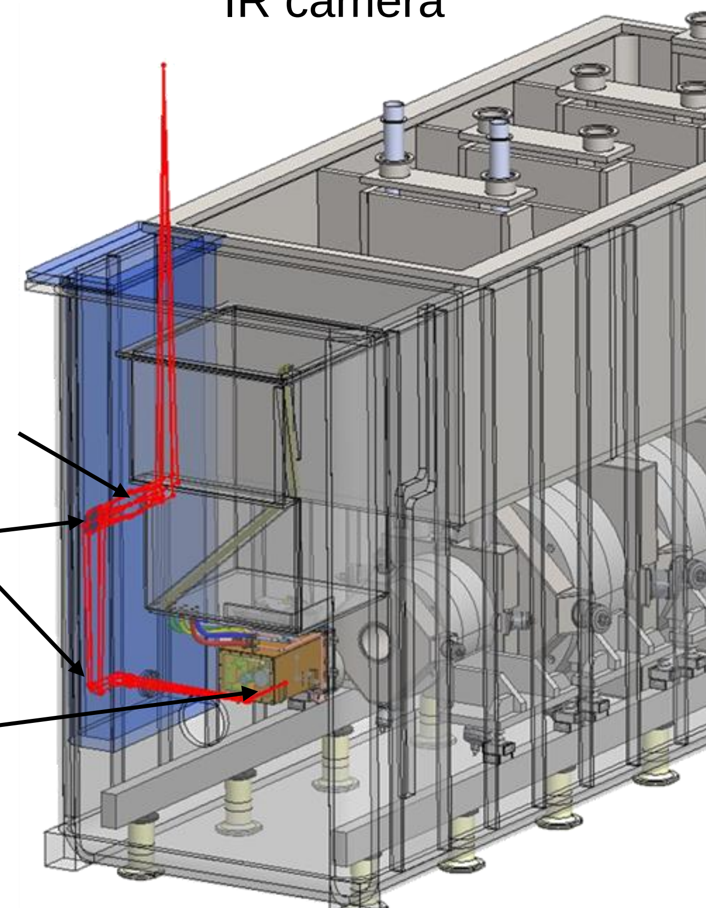
Beam-spot monitoring and radiation shielding

- Primary beam diagnostics
  - Monitor primary beam position on the target
  - Required for rare isotope beam tuning and for machine protection





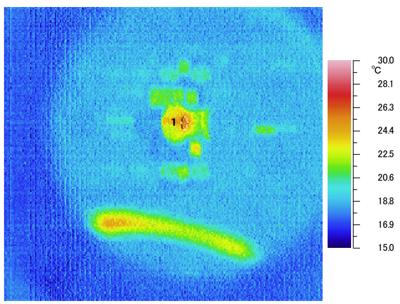


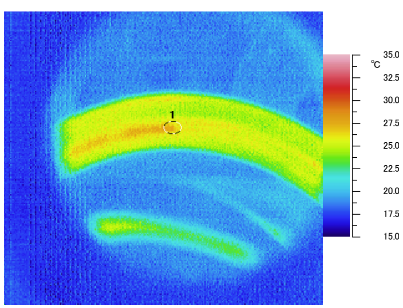


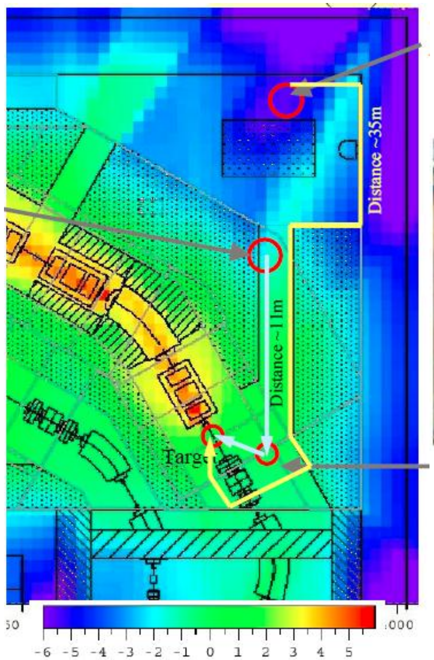
M. Hausmann

Beam-spot monitoring and radiation shielding

Infrared camera surrounded by lead shields.





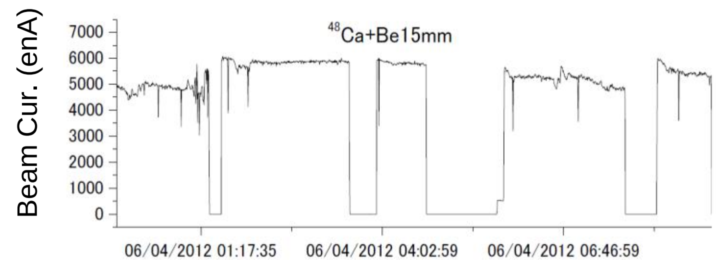


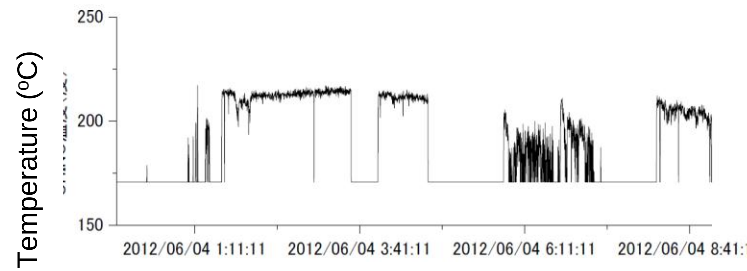
Mirror

Fiber scope Temperature monitor

Infrared Fiber Scope

Continuous monitor, T>200^{o}C





K. Yoshida San's talk

Summary

- The three main projects, using In-flight production targets, have similar challenges
  - High power density
  - Heavy ion irradiation damages
- Extensive simulations and tests during R&D phase are necessary to optimize high power target design and help to mitigate thermo-mechanical stress
- Electron beam tests are very useful in order to study thermo-mechanical answer of a system without activation and radiation damage due to ion beams
- Heavy-ion irradiation tests show annealing of radiation damage at high temperature
- Most of the time, the 2 main risks were tested separately
- No facility exists now to provide such heavy ion beams to study combined effects of the 2 main risks
  - R&D will continue …

Thank you for your attention