Material stress tests induced by high power electron beams

O. S. Adeyemi[2], V. Kovalenko[2], G. Moortgat-Pick[2], M Schmitz[1] ,
S. Riemann[1], F. Staufenbiel[1], A. Ushakov[2]

[1]DESY
[2]Universität Hamburg

- Motivation
- What can be measured?
  - Expected material stress
  - Experimental setup
- Safety aspects
  - Shielding against radiation
  - Activation of test material
- Summary

HELMHOLTZ GEMEINSCHAFT

DESY

Motivation

- Intense beams ⇔ high peak energy deposition density in materials
  - Targets, Collimators, spoilers, exit windows...
  - Thermal stress, high pressure (even shock waves)

  → damage or lifetime reduction of material (e.g. at ILC)

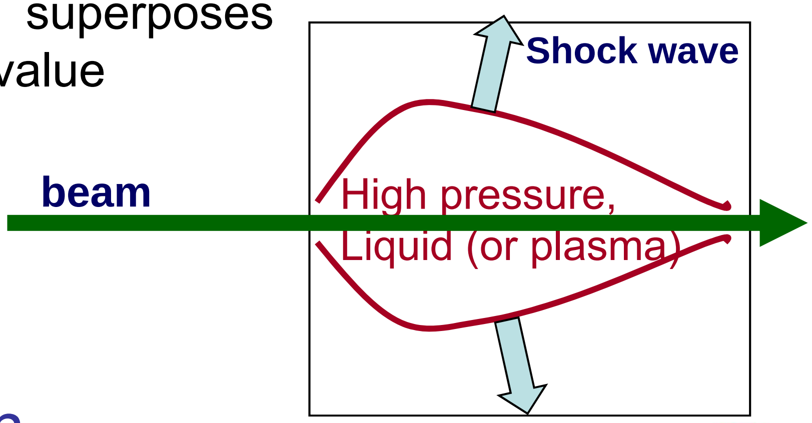
- Information exists, but:
  - **Models and codes to describe huge stress in materials have to be tested in experiments**
  - Experimental limits for e- beams:
    - SLC target (W) ⇔ benchmark: max energy deposition <35J/cm^3,
    - damage tests at KEK (W) and SLAC FFTB (Cu),
    - FLASH (Ag coated C): Schmitz et al. ⇔ 30 FLASH bunches (40x40um^2) are no problem
  - Fatigue stress which superposes material weakening by radiation

- Beam test facility:
  - Test facilities for protons and ions (HiRadMat) cannot compensate for studies with electron beams

What can be measured ?

- Energy deposition along the beam path
  - instantaneous temperature rise
  - instantaneous pressure rise
- Depending on energy deposition density, interaction duration and material: stress waves
  - Scenario 1: elastic deformation
  - Scenario 2: plastic/elastic domain
    - Permanent deformations
  - Scenario 3: shock waves:
    - Pulse length shorter than time that sound travels through target
    - Very high energy deposition from single bunches, and/or energy deposition from multiple bunch trains superposes
    - Strains and pressure exceed critical value

    ⇔ Hydrodynamical models



➔ Measurement of stress waves

➔ Optical inspection

➔ Material properties after irradiation

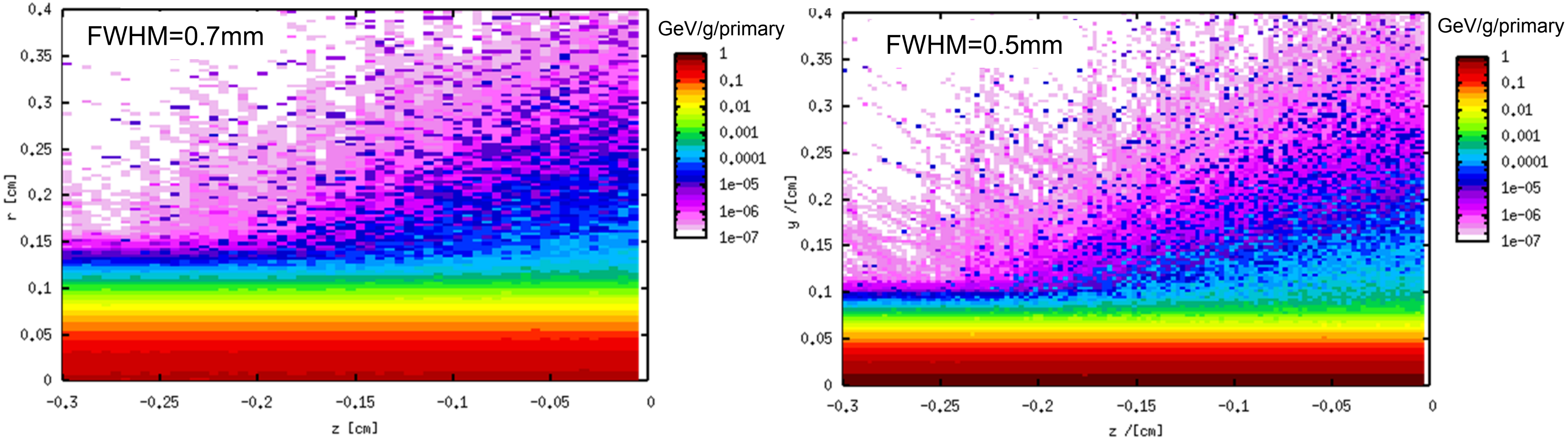
Expected material stress

Assume electron beam:

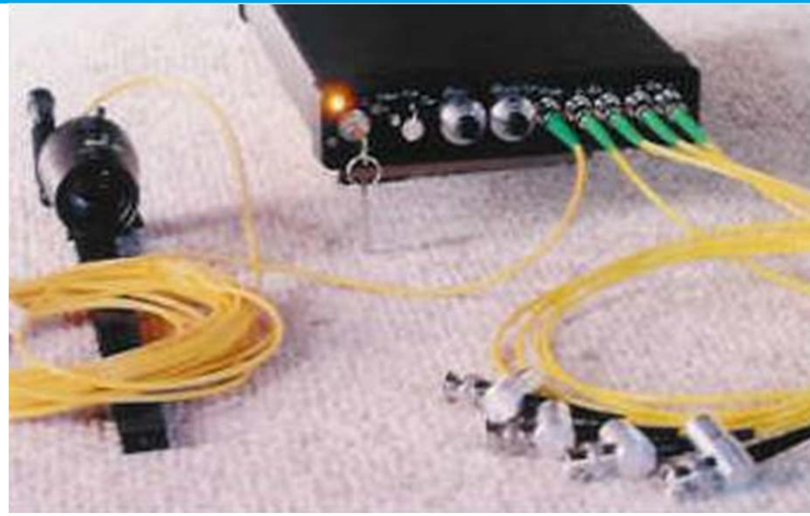
- 1 GeV, 800 bunches, 10 Hz
- Ti target: 3mm thick, r = 1cm [5mm]
- Beam size: FWHM = 700um, 500um
- Stress after 1 bunch train (0.1s)
  - Ti properties: v_{sound} = 4140m/s, T_{melt} = 1668 C, T_{vap} = 3287 C

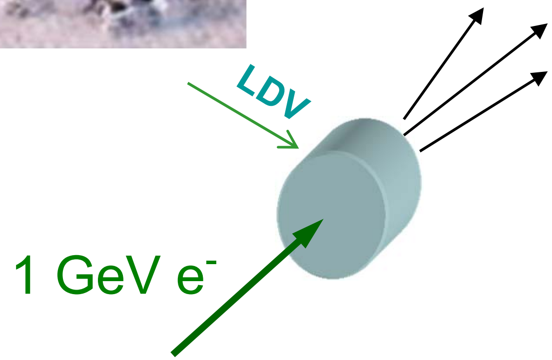
σ [μm]	ΔT_{max} [K]	ΔP [MPa]	surface velocity [m/s]
350	~300	~200	~0.01 (long), 0.001 [0.002] (radial)
250	~700	>400	~0.02 (long), 0.002 [0.004] (radial)

Energy deposition in target along beam axis



Velocity Interferometer System for Any Reflector



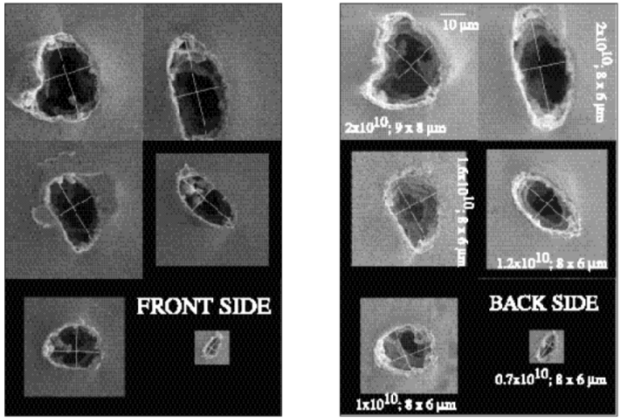


- **VISAR** (Laser Doppler Vibrometer, LDV)
  - Commercial systems available
  - Sensitivity: 0.02m/s [0.002m/s] with 50ns [500ns] resolution time (see http://www.mfaoptics.com/FiberDVI.htm)

  → measurement of shockwaves possible

Further tests

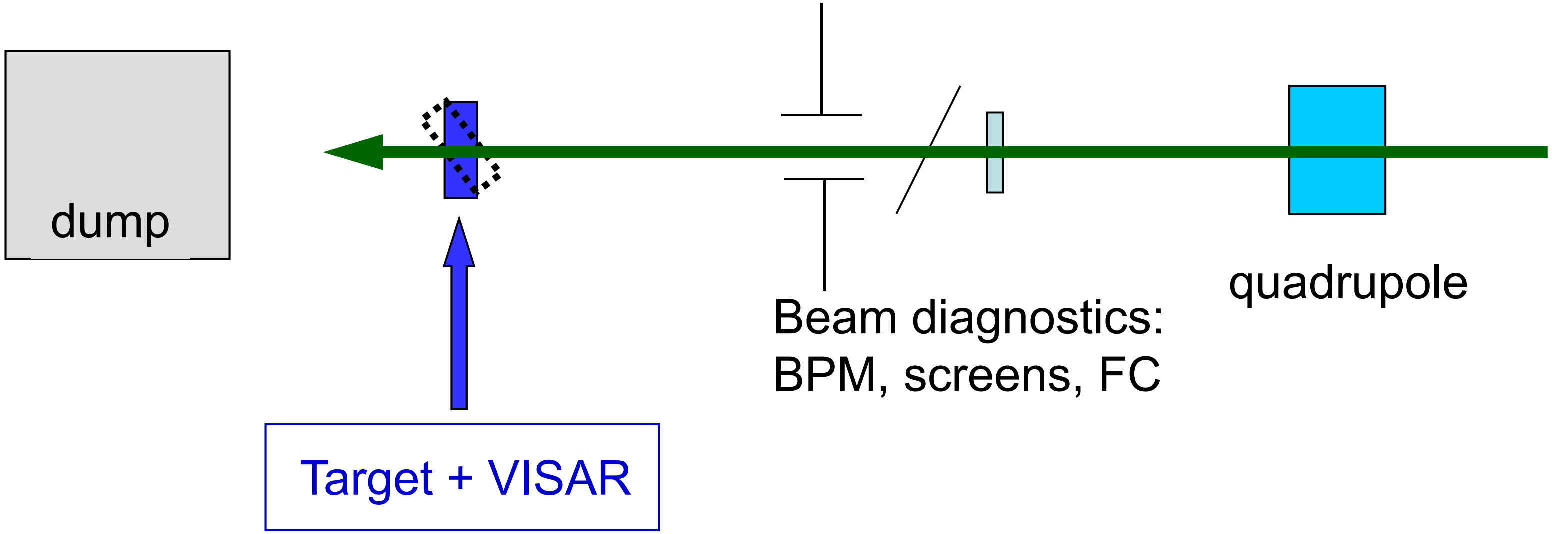
- serious damage:
  - material ejection from surface ⇔ Visual inspection after irradiation
  - Damage should be avoided. Experience from ‘damage experiments’:
    - M. Ross et al., SLAC-PUB-8605, 2000, “Single pulse damage in copper”



    - KEK: Kuriki et al., PRSTAB **9**, 071001 (2006):
      - En dep. of 0.6-4.6 J/cm^3 in W for e-beam with 3789 J/us beam ⇔ damage
      - En dep. of 0.3-1.1 J/cm^3 in W for e-beam with 33-131J/us beam ⇔ no damage

- Fatigue stress ?
  - studies necessary to understand how to evaluate
  - Long term irradiation increases safety requirements and restrictions

Experimental Setup



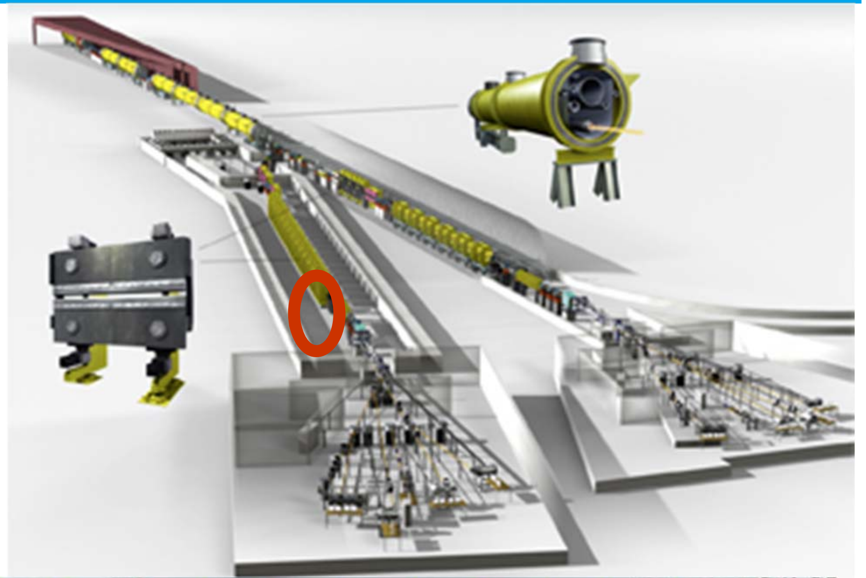
- Material stress:
  - ‘tuned’ by beam size
    → Quadrupole ⇔ focus beam to test material
    → beam diagnistics needed
- **Radiation issues: disrupted beam has to be absorbed in the dump**

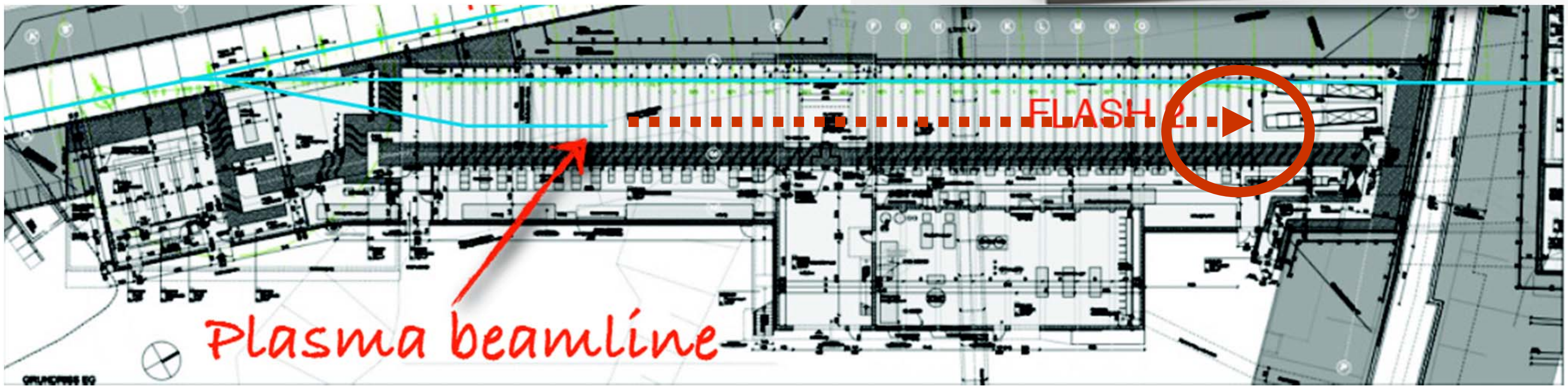
HELMHOLTZ GEMEINSCHAFT

DESY

Implementation into FLASH

For **safety reasons**, the experiment must be located near the beam dump

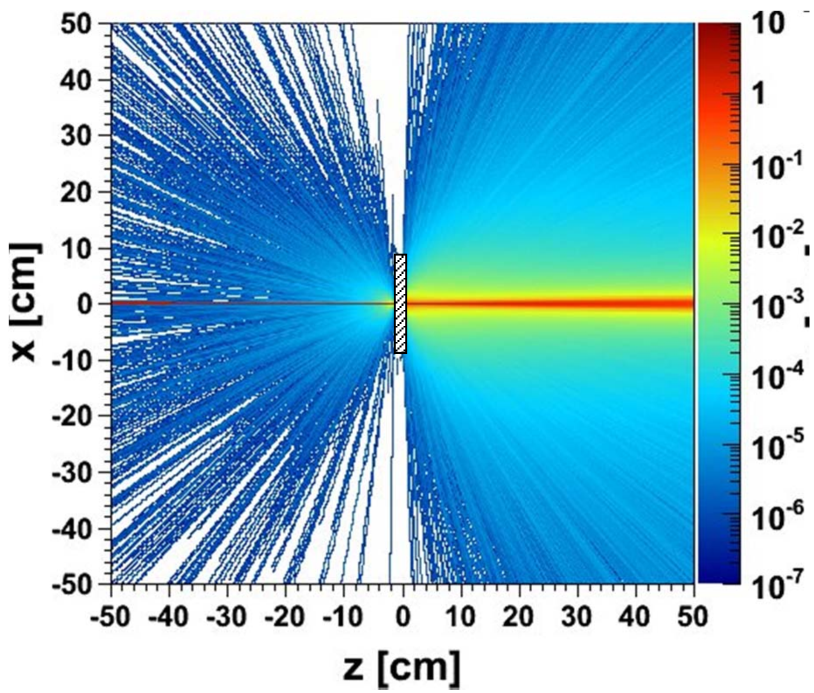




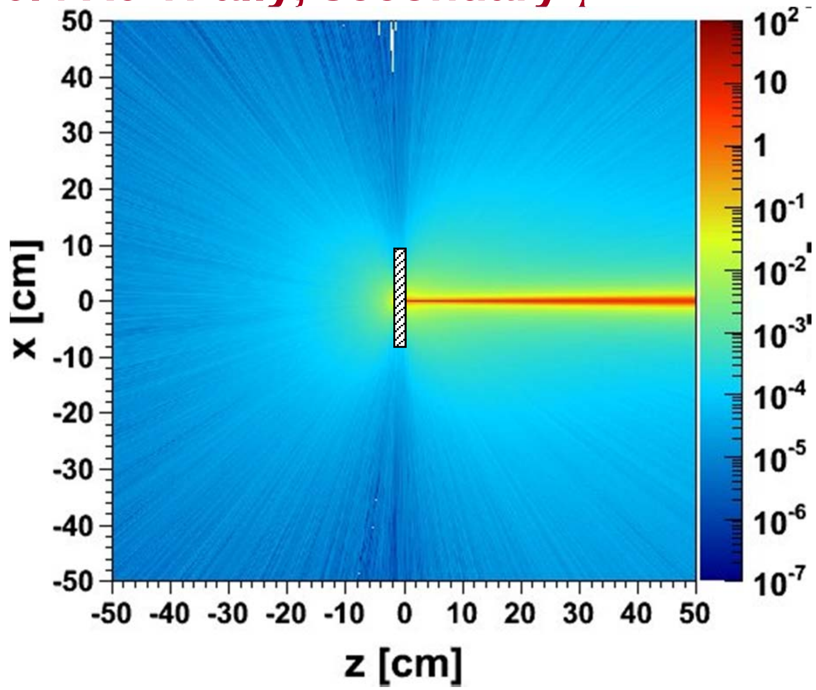
⇔ Experiment and dump aboveground

Particle distribution after target

0.4 X0 Ti alloy, secondary e-



0.4 X0 Ti-ally, secondary γ

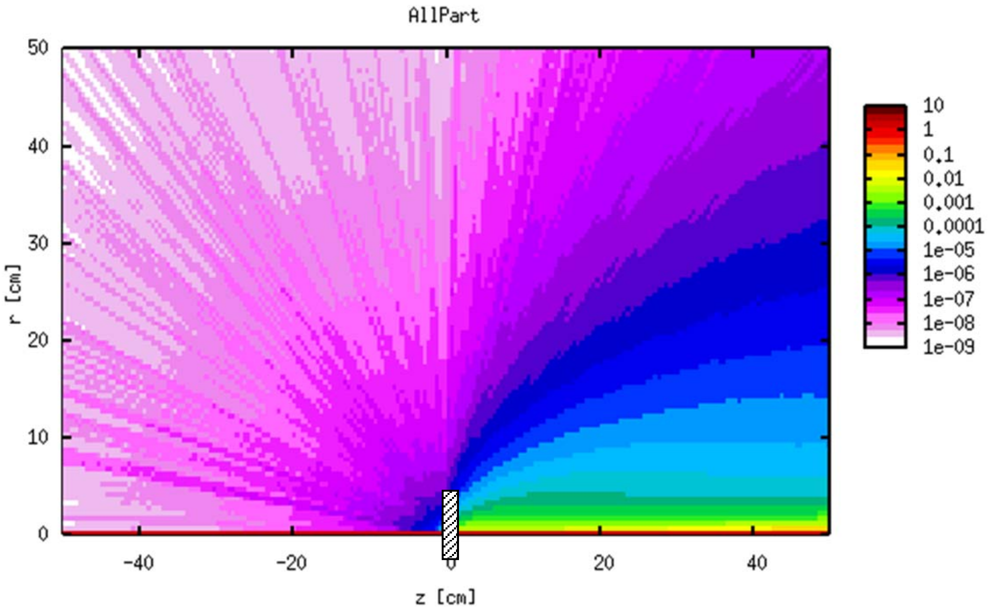


Particles carrying ≈99% of incoming power hit dump at distance 50cm within Ø 20 cm if target thickness = $0.4X_0$

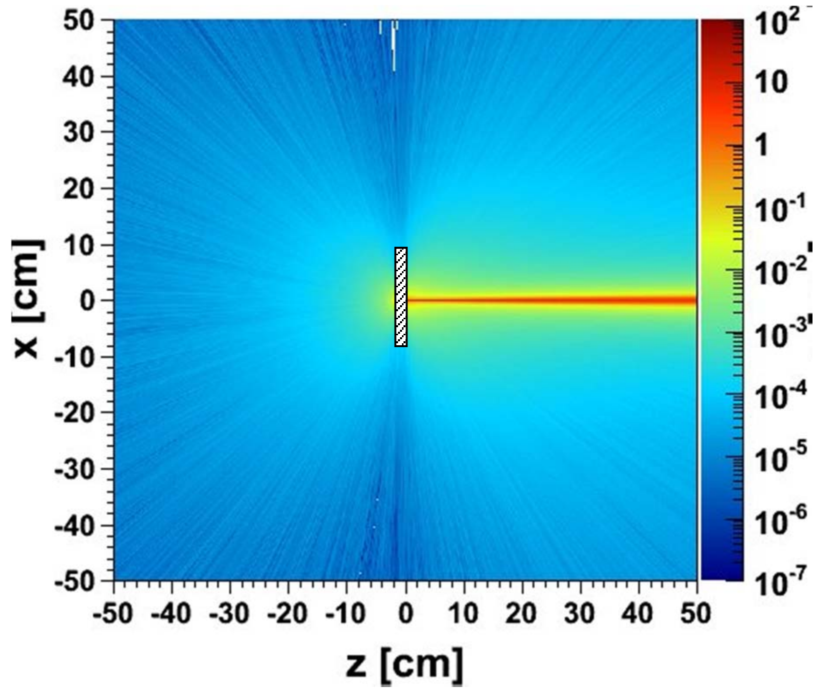
➔ **thin targets are recommended**

Particle distribution after target

0.08 X0 Ti alloy, secondary particles

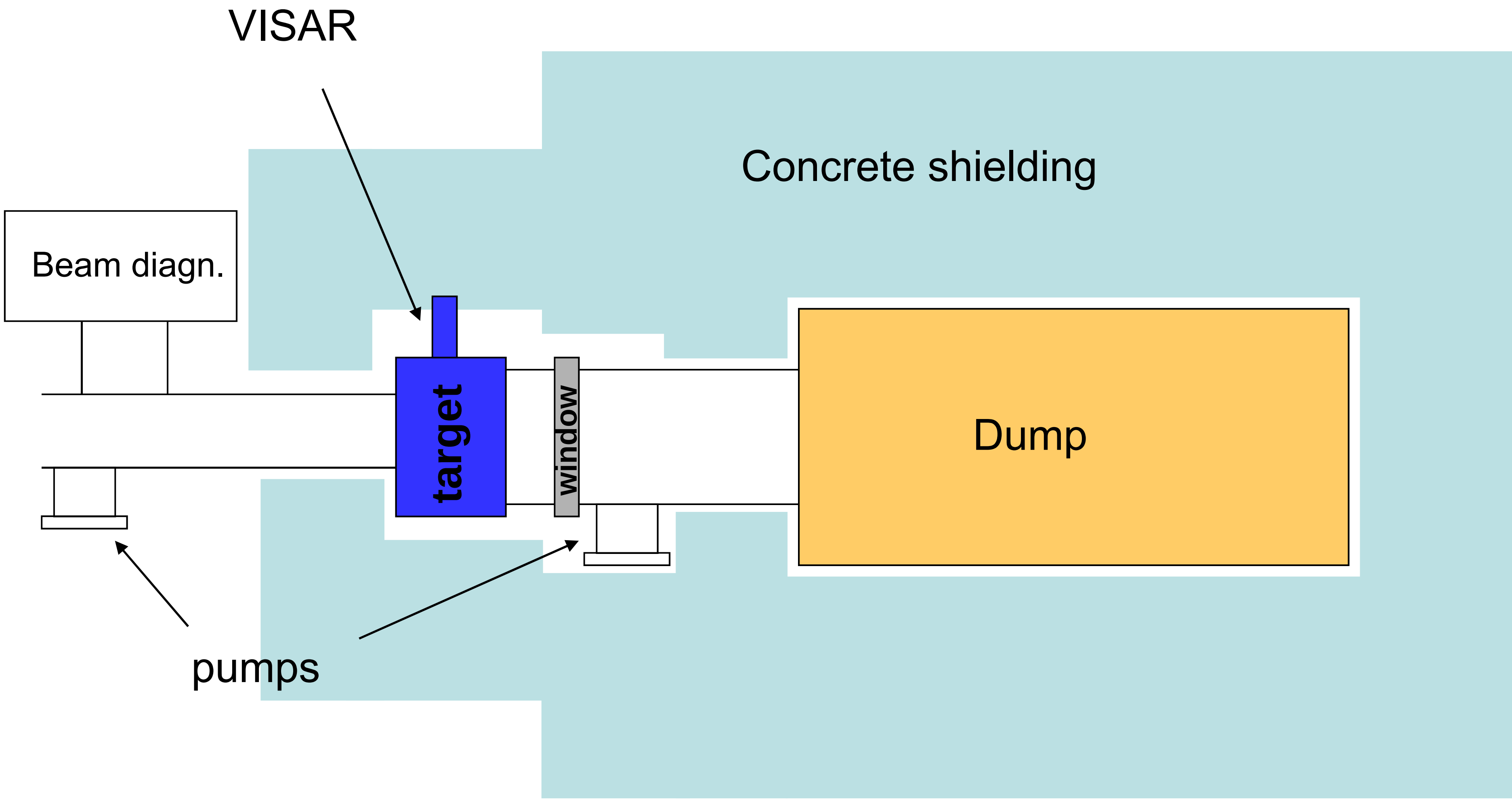


0.4 X0 Ti-alloy, secondary γ



Radiation safety requirements can be fulfilled using thin targets

Beam Dump (not to scale)



Neutron production in target and shielding

electron beam assumption:

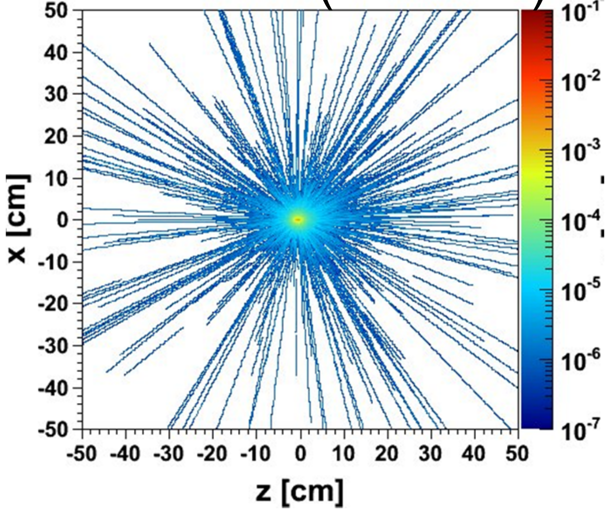
1 GeV, 1nC, 800 b/train, 10Hz

- Thin target ($0.4X_0$), low Z (Ti)
  → $2x10^{-3}$ neutrons per incoming e-
    → **~1.9 m concrete (normal)** ⇔ 2mSv/a

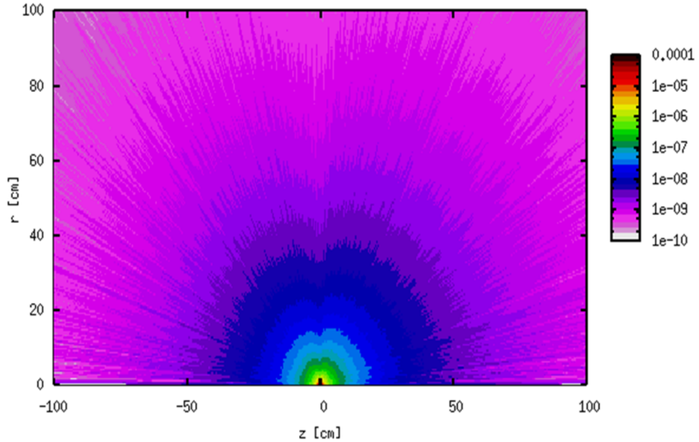
- Thin target ($0.08X_0$), low Z (Ti)
  → $2x10^{-5}$ neutrons per incoming e-
    → **~1.9 m concrete (normal)** ⇔ 2mSv/a

- Thick targets not recommended
- Dump also needs neutron shielding

Neutrons (0.4X0 Ti)

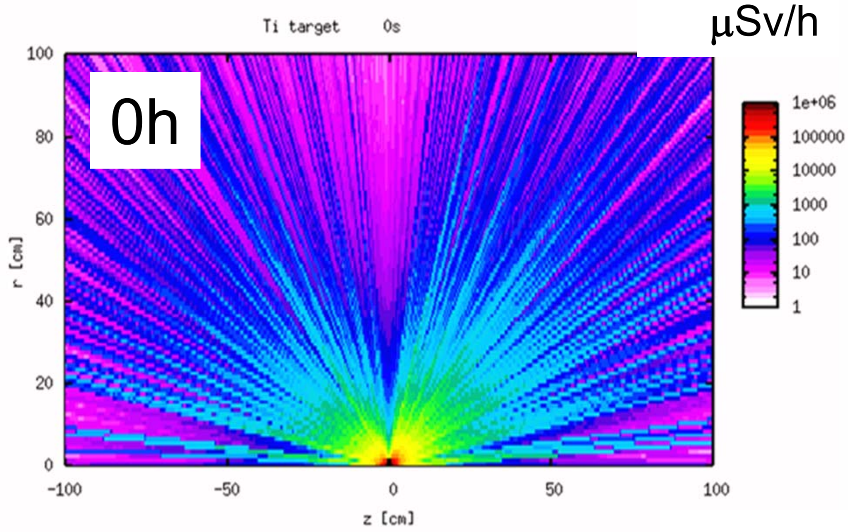


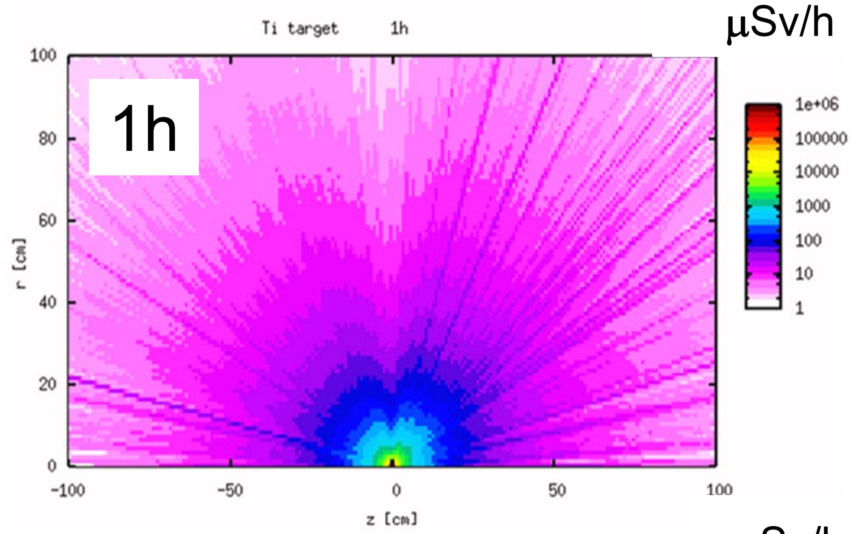
Neutrons (0.08X0 Ti)

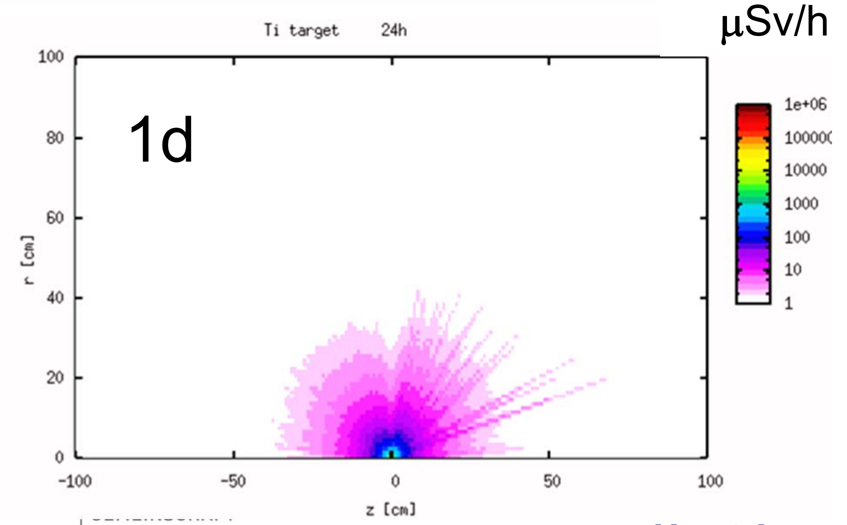


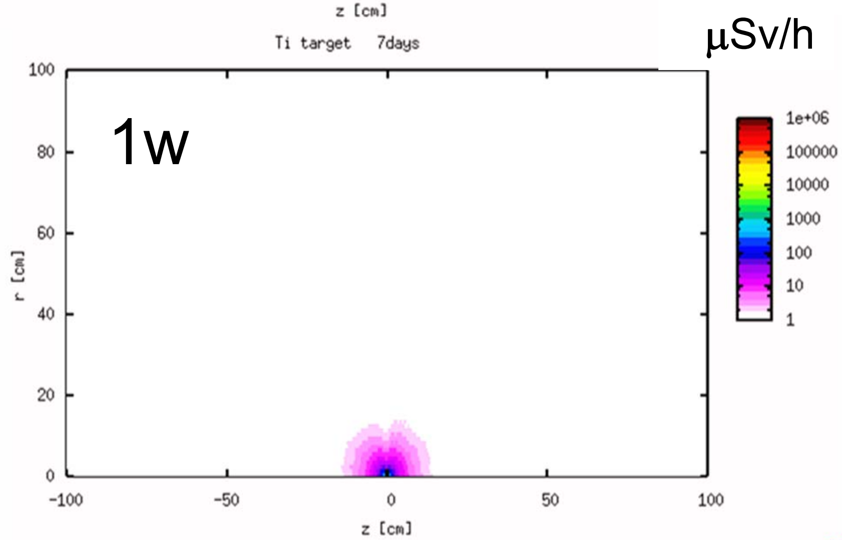
Target activation

- Assumption: 1 hour exposure
  - 1GeV e-, 1nC/bunch, 800 bunches/train, 10 Hz
  - Cylindrical Ti target: 3mm length, 1cm diameter









Target activation

- Assumption: 1 hour exposure
  - 1 GeV e-, 1nC/bunch, 800 bunches/train, 10 Hz
  - Cylindrical Ti target: 3mm length, 1cm diameter
- Dose rates (ambient dose equivalent rate) at z=0, r=100cm:

Cooling Time	Dose rate [mSv/h]
0 second	~0.05
1 hour	~0.01
1 day	<0.001
1 week	<0.001

Summary

- Electron beam at FLASH offers great opportunity for accelerator material tests
  - material stress and shock wave models and the corresponding codes can be tested
  - Results are important for linear e+e- collider communities
- Material tests require
  - Space in beam line near the dump, test chamber
  - Quadrupole to focus the beam, flexible choice of beam intensity
  - Beam diagnostics
  - Instrumentation to measure surface vibration and temperature
  - safety measures, in particular radiation aspects, determine final layout
- Ongoing work, plans:
  - detailed simulations specified to the experimental conditions at FLASH
  - Optimization of test target dimensions and specifications
  - Pay attention to HiRadMat experiences

But we do not have the resources to built and maintain a separate beamline