Material Testing Demands by Heavy-Ion Pulsed Beams – by FAIR

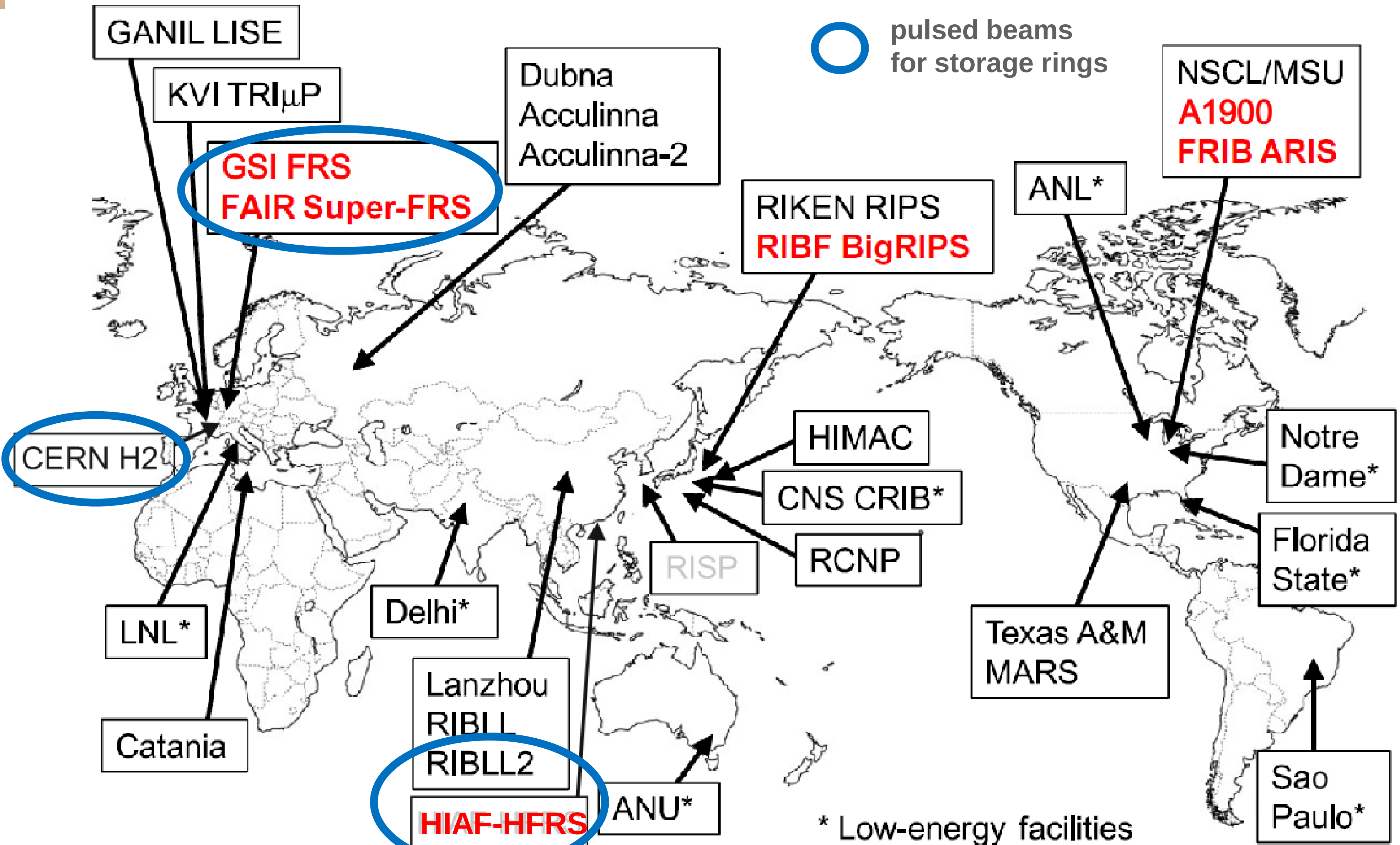
Helmut Weick, GSI Helmholtzzentrum

HiRadMat workshop, 11.07.2019

- In-Flight Rare Ion Production
- FAIR / Super-FRS
- Beam Power Comparison
- Targets and Beam Catchers
- Material Tests at GSI

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

Production of RIBs In-Flight

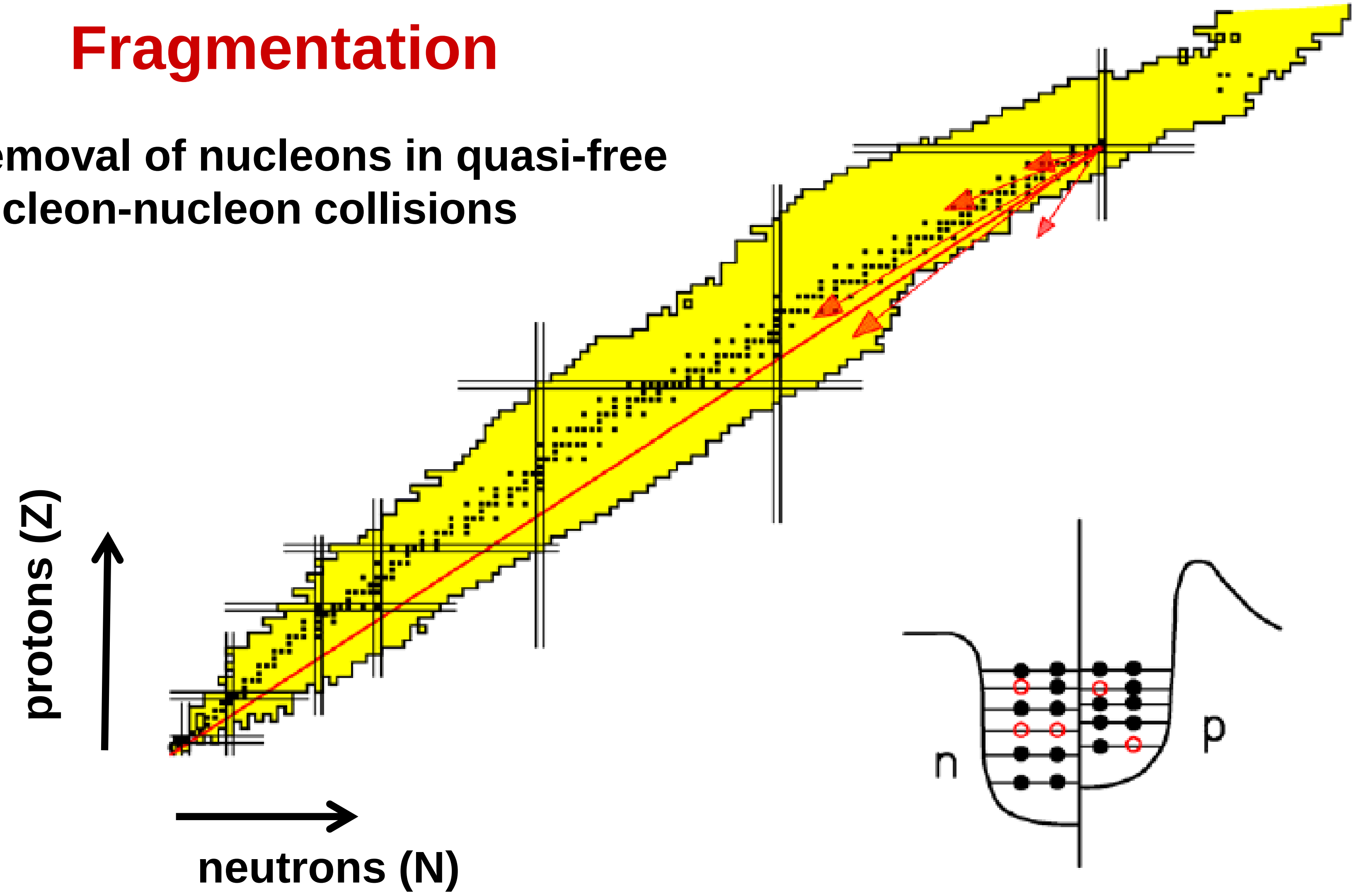


adapted from T. Kubo, NIM B 376,102 (2016)

How to produce Rare Isotopes ?

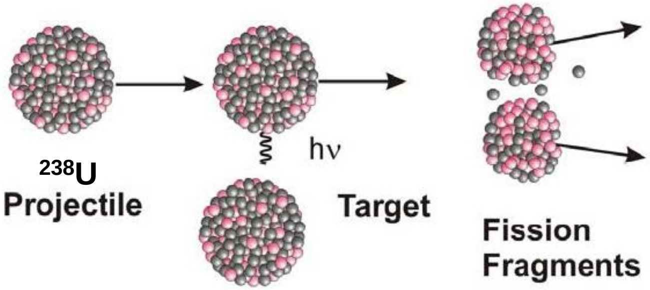
Fragmentation

Removal of nucleons in quasi-free nucleon-nucleon collisions

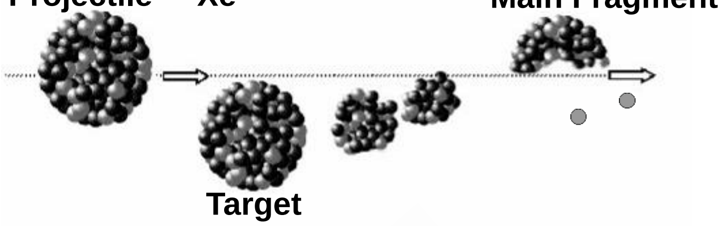


Production Cross sections

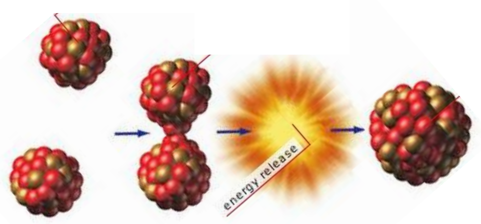
Projectile fission



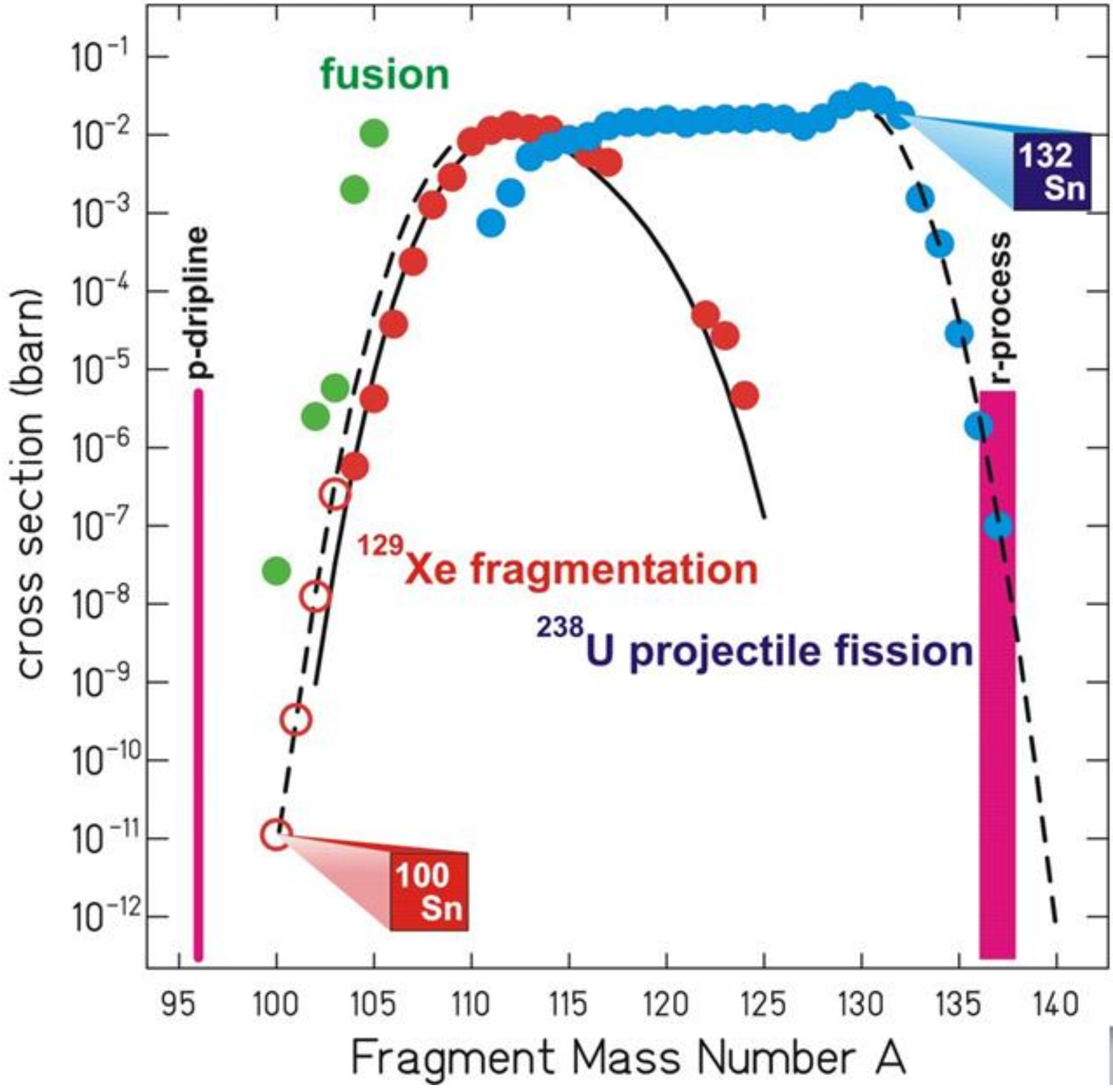
Projectile fragmentation



Fusion (only at lower velocity)



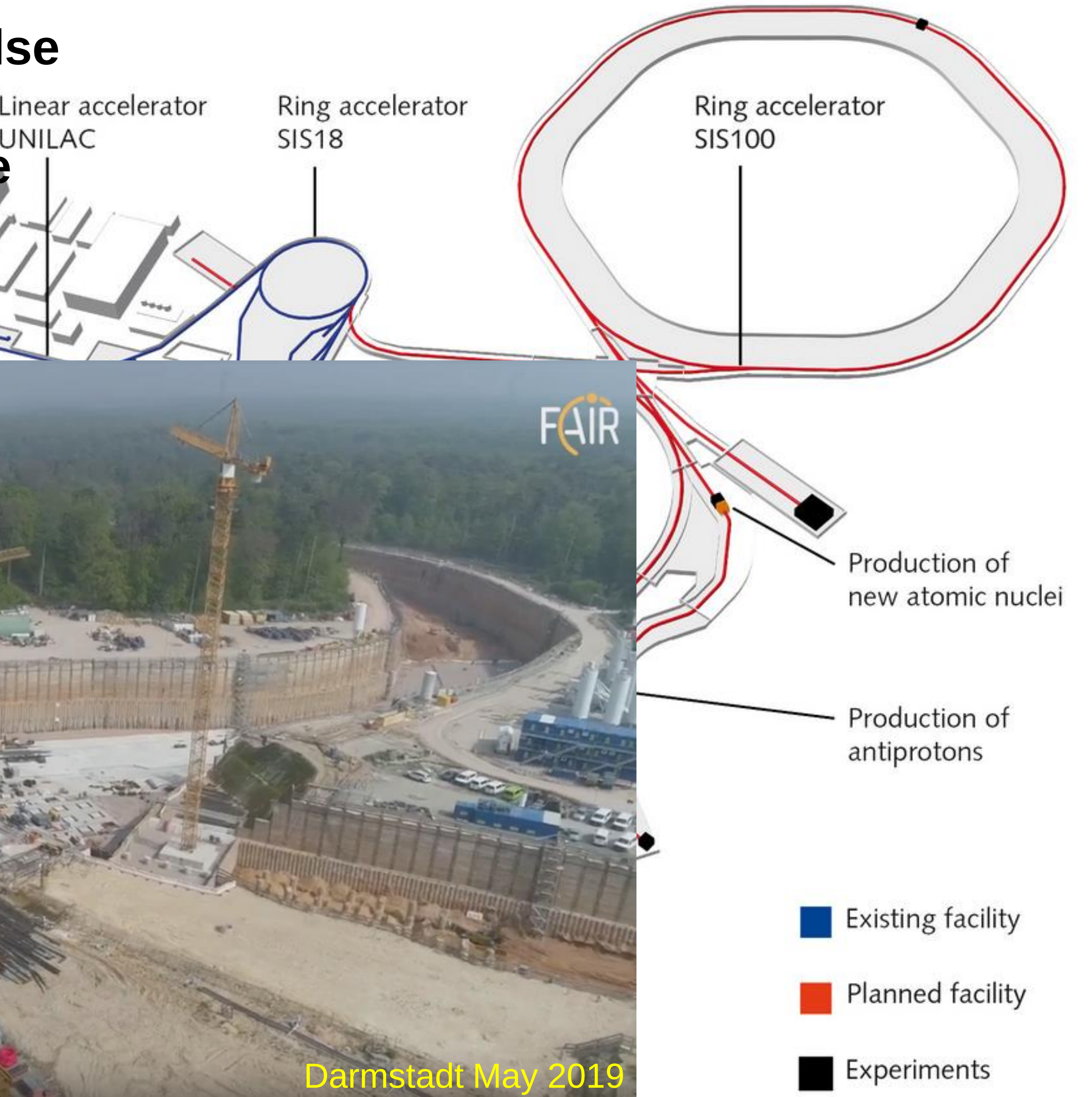
Tin isotopes by different methods



FAIR
Facility for Antiproton and Ion Research

0.4-2.7 GeV/u U^{28+}, $5x10^{11}$/pulse
11 GeV/u Au^{79+}, 10^{10}/pulse
28 GeV protons, $2x10^{13}$/pulse

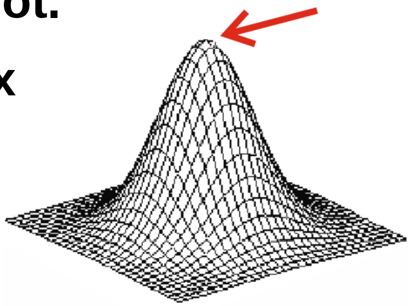
fast or slow extraction



Beam Comparison

Energy deposition in copper for $\sigma_x = \sigma_y = 0.5$ mm beam spot.

In peak of 2-dim Gaussian: $dE/dm_{ion} = 1 / (2\pi\ \sigma^2)\ \ * dE/d\rho x$

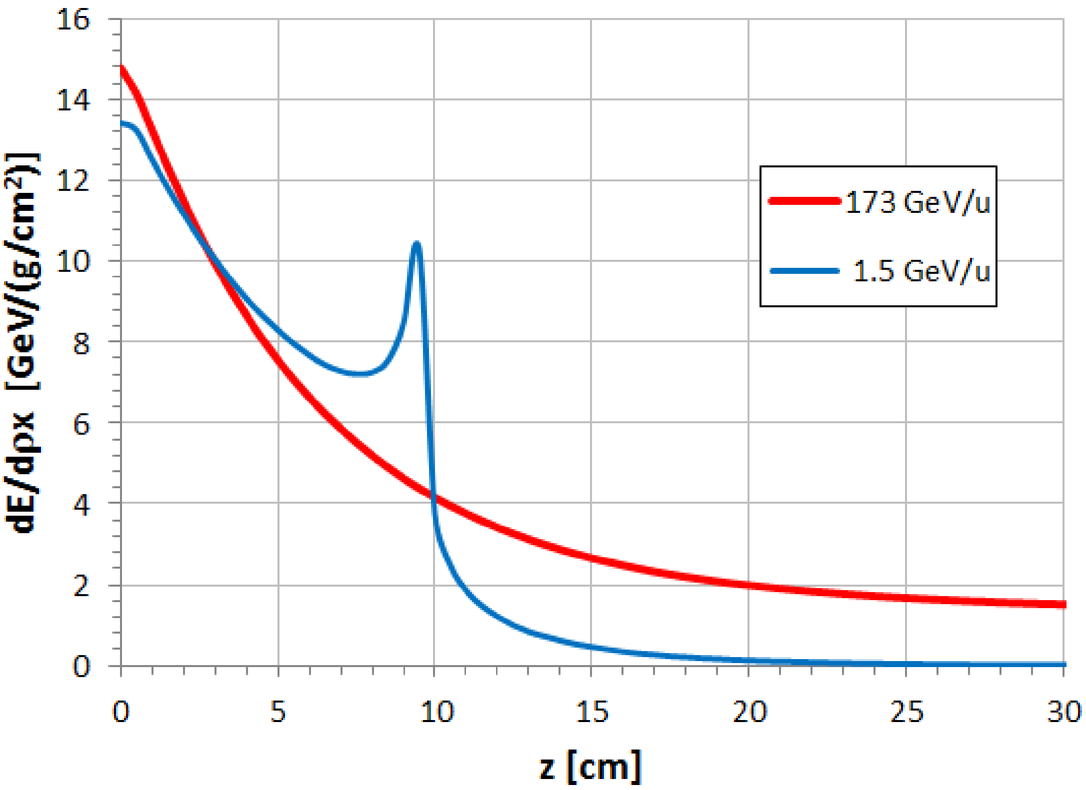


GSI / FAIR beams only one bunch per pulse.

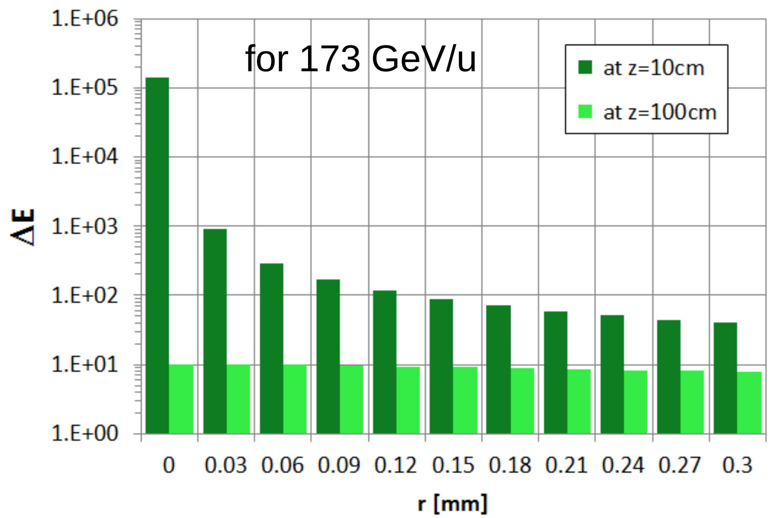
	HiRadMat protons	HiRadMat Pb	FAIR U^{28+}	GSI U^{28+}	GSI U^{73+}	
E / m =	437	173.5	1.5	0.125	1.0	GeV/u
$dE/d\rho x$ =	0.00211	12.8	13.8	~35	14.5	$GeV/(g/cm^2)$
dE/dm_{ion} =	~0.94*	817	878	2228	922	GeV/g
N / bunch =	1.5e11	5e7	5e11	2e10	2.5e9	
bunches =	288	52	1	1	1	
dE/dm =	~26.0*	0.34	70.3	7.1	0.37	kJ/g
pulse length Δt =	7.2	5.2	0.09	0.4	0.1	μs
$\Delta s = c\ \Delta t$ =	27.4	19.8	0.34	1.52	0.38	mm

*** incl. build-up**

ΔE for Pb-ions



Radial distribution of point-like beam

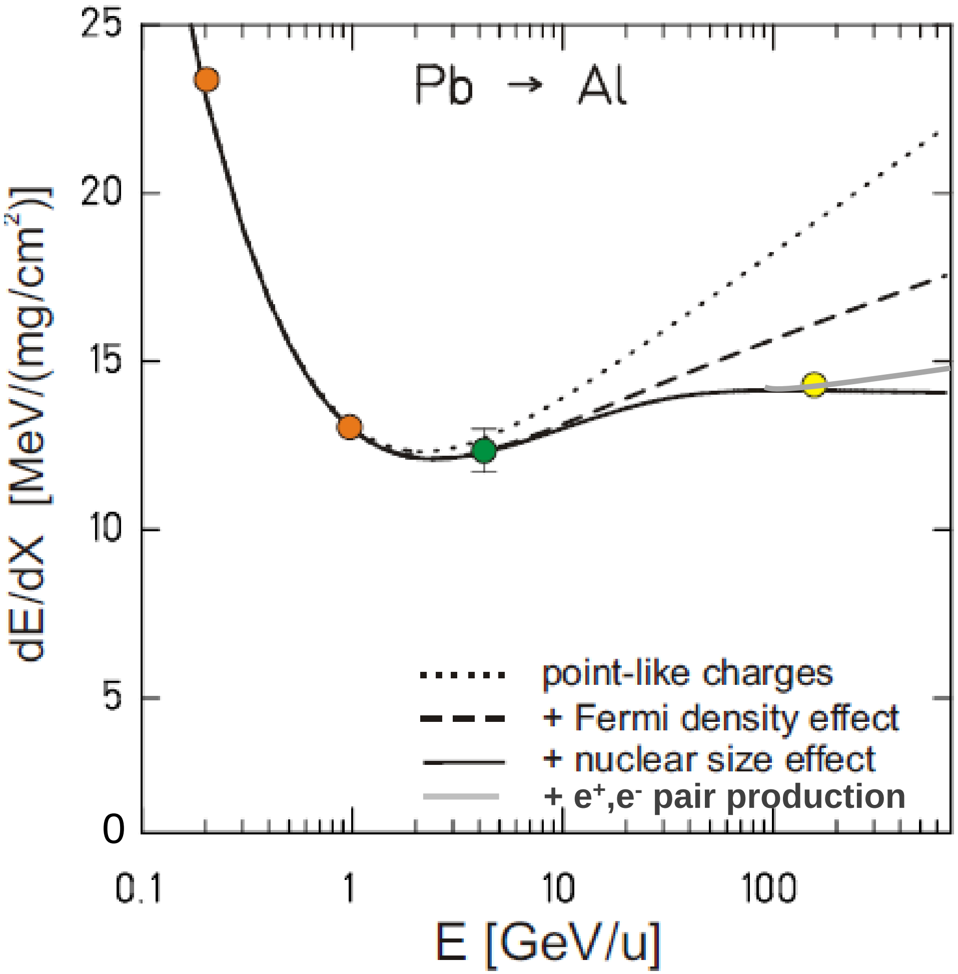


⇒ high ΔE region dominated by beam spot size

FLUKA, Ekaterina Kozlova

FLUKA in mode DEFAULT does not give a good dE/dx description,
→ rescaled according to ATIMA predictions

dE/dx for Relativistic Heavy Ions



SIS/FRS, Scheidenberger, Weick et al.

AGS, G. Arduini et al.

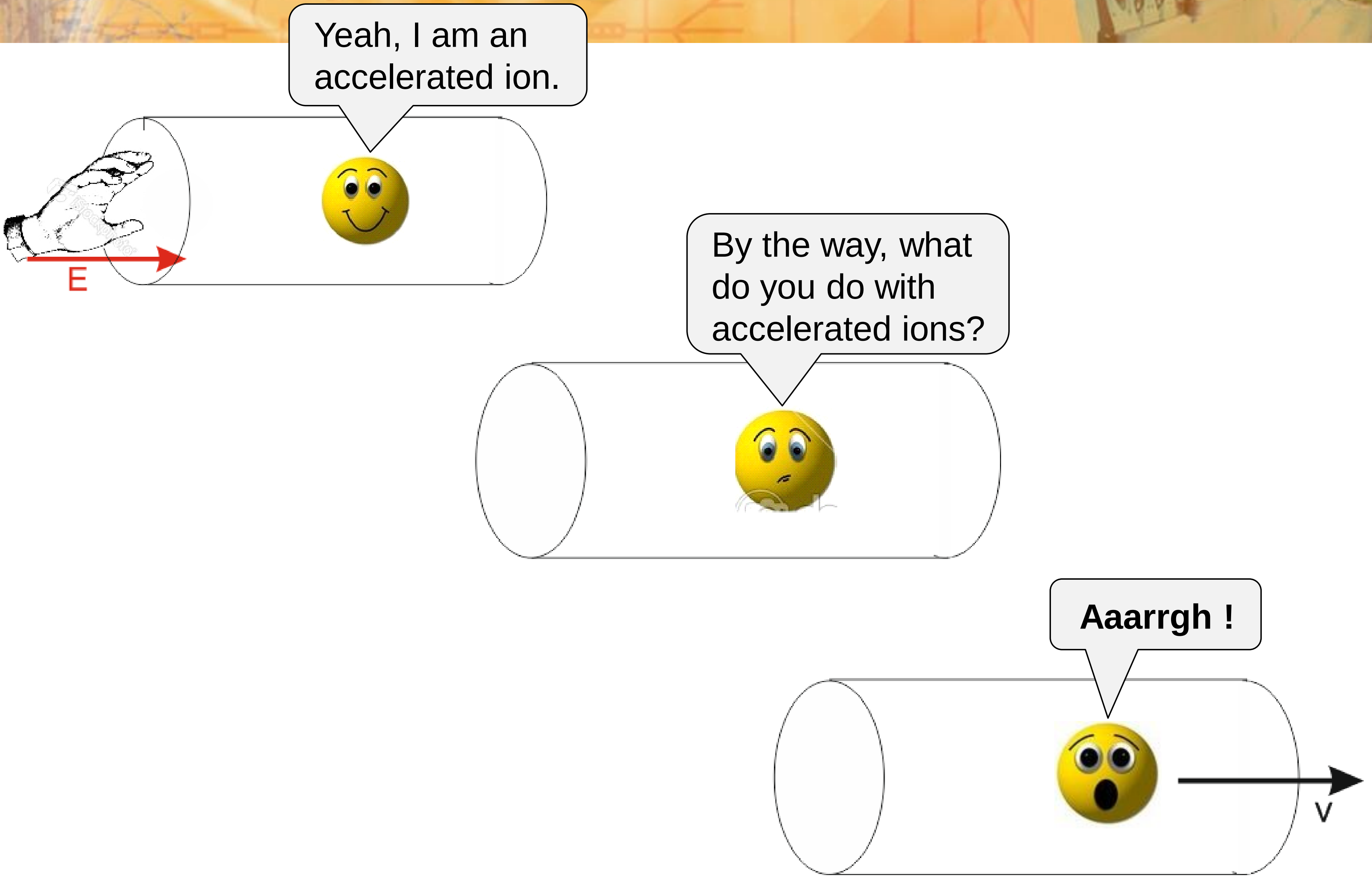
CERN-SPS, S. Datz et al.

$\Delta L_{LS}(Z_1,v)$
Lindhard-Sørensen extension, includes nuclear size effect for $\gamma \gg 1$.

Fermi density effect for relativistic velocities

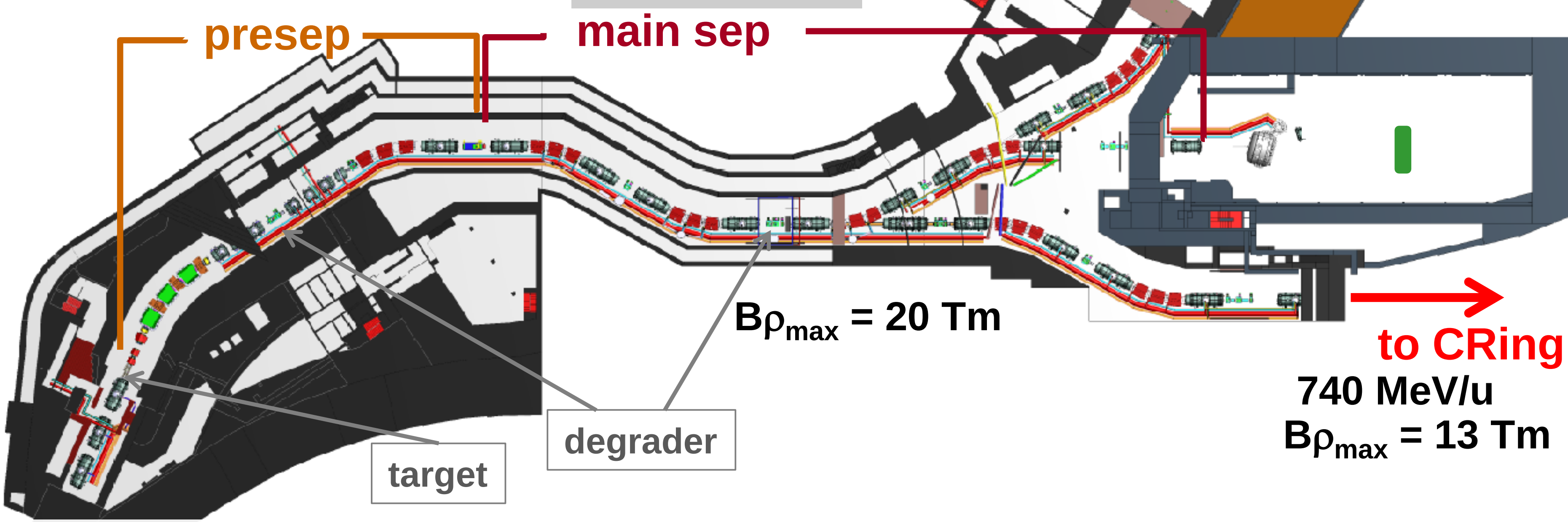
$$\frac{dE}{dx} = \frac{4\pi Z_1^2 e^4}{m v^2} N Z_2 \left[\ln\left(\frac{2m\gamma^2 v^2}{I}\right) - \beta^2 + \Delta L_{LS} - \delta/2 + \Delta L_{e+,e-} \right]$$

The fate of accelerated ions



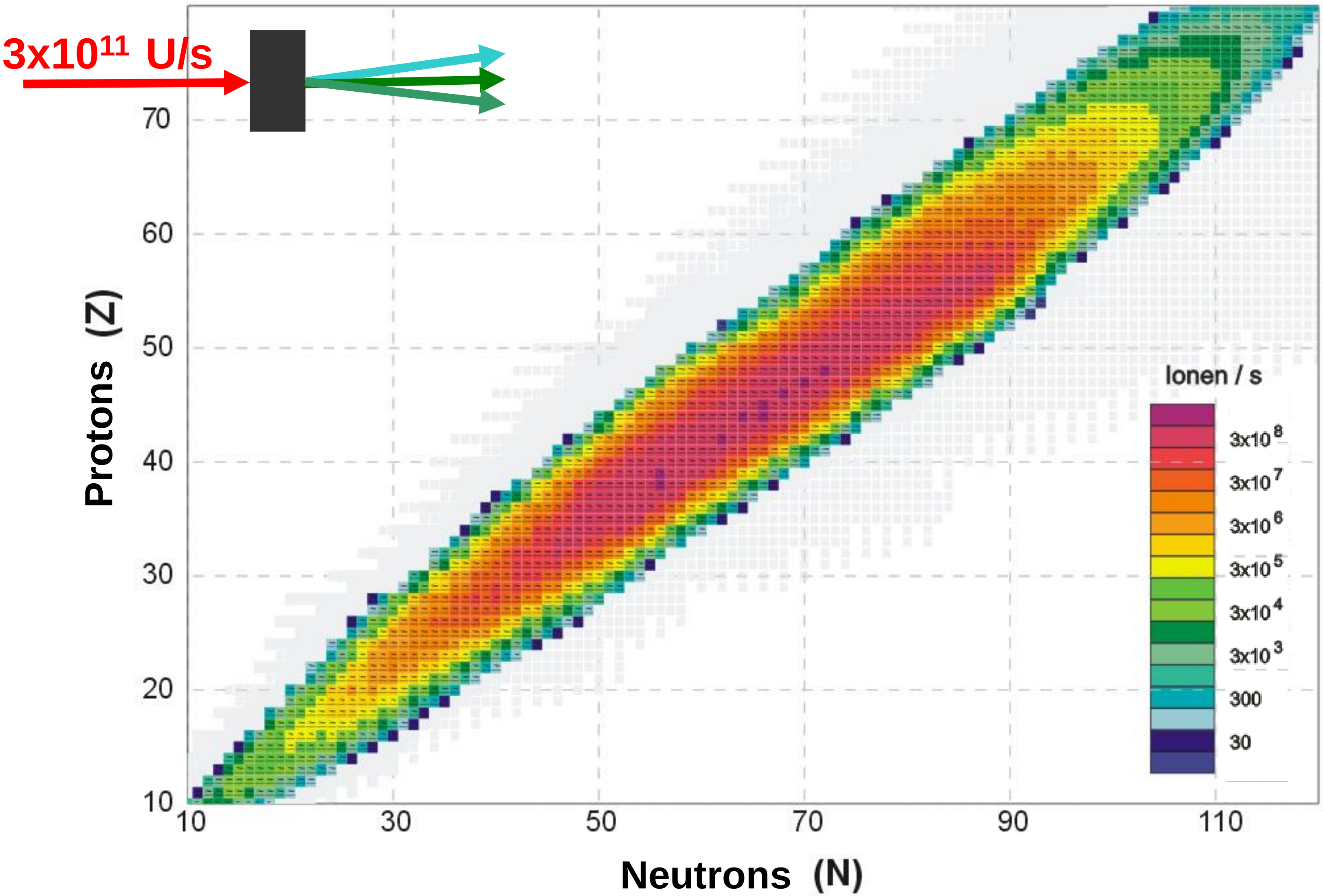
Super-FRS

(Super-Conducting Fragment Separator)



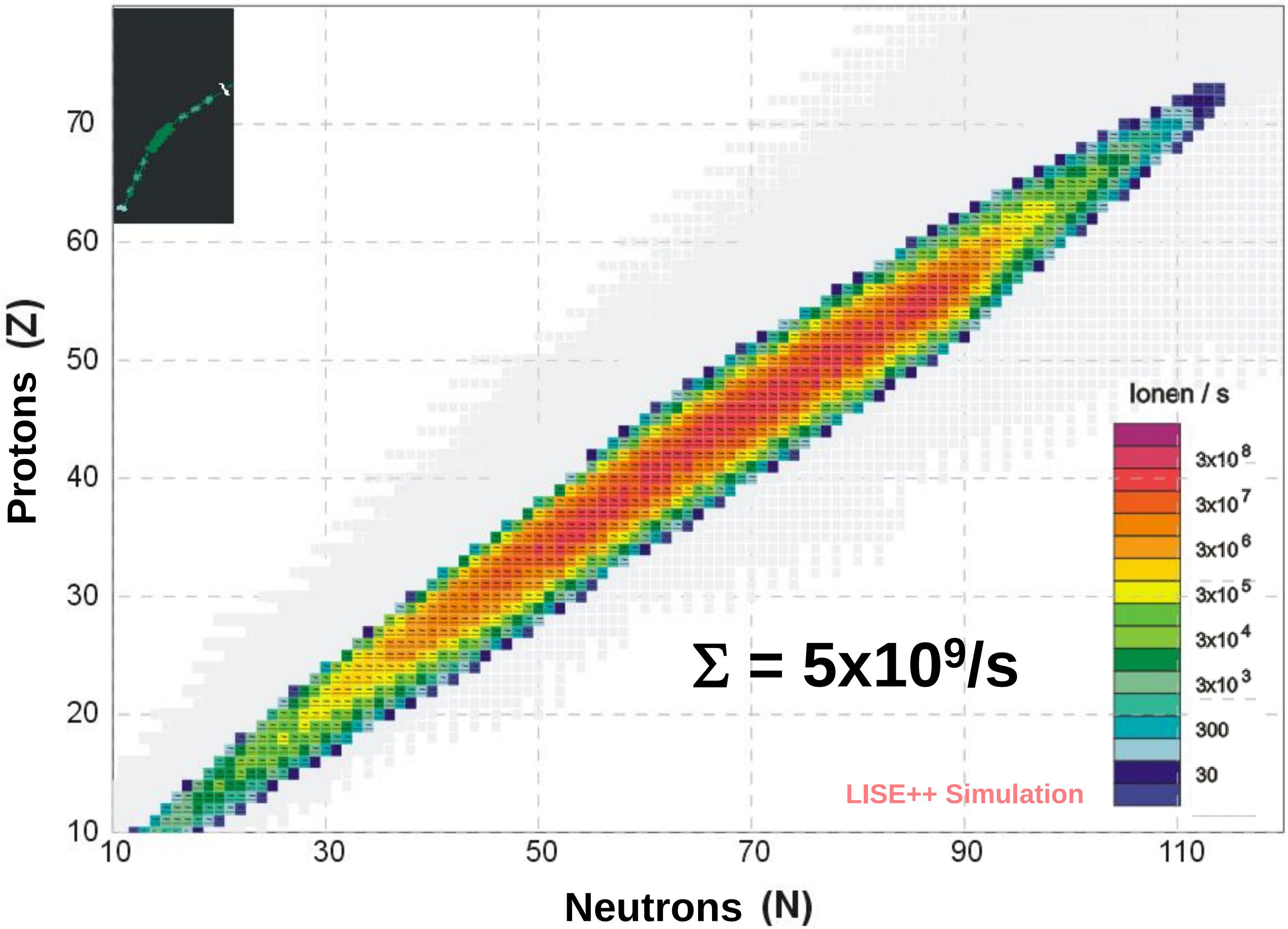
Separation

All fission fragments after target, 1.5 GeV/u ^{238}U --> 4 g/cm^2 ^{12}C



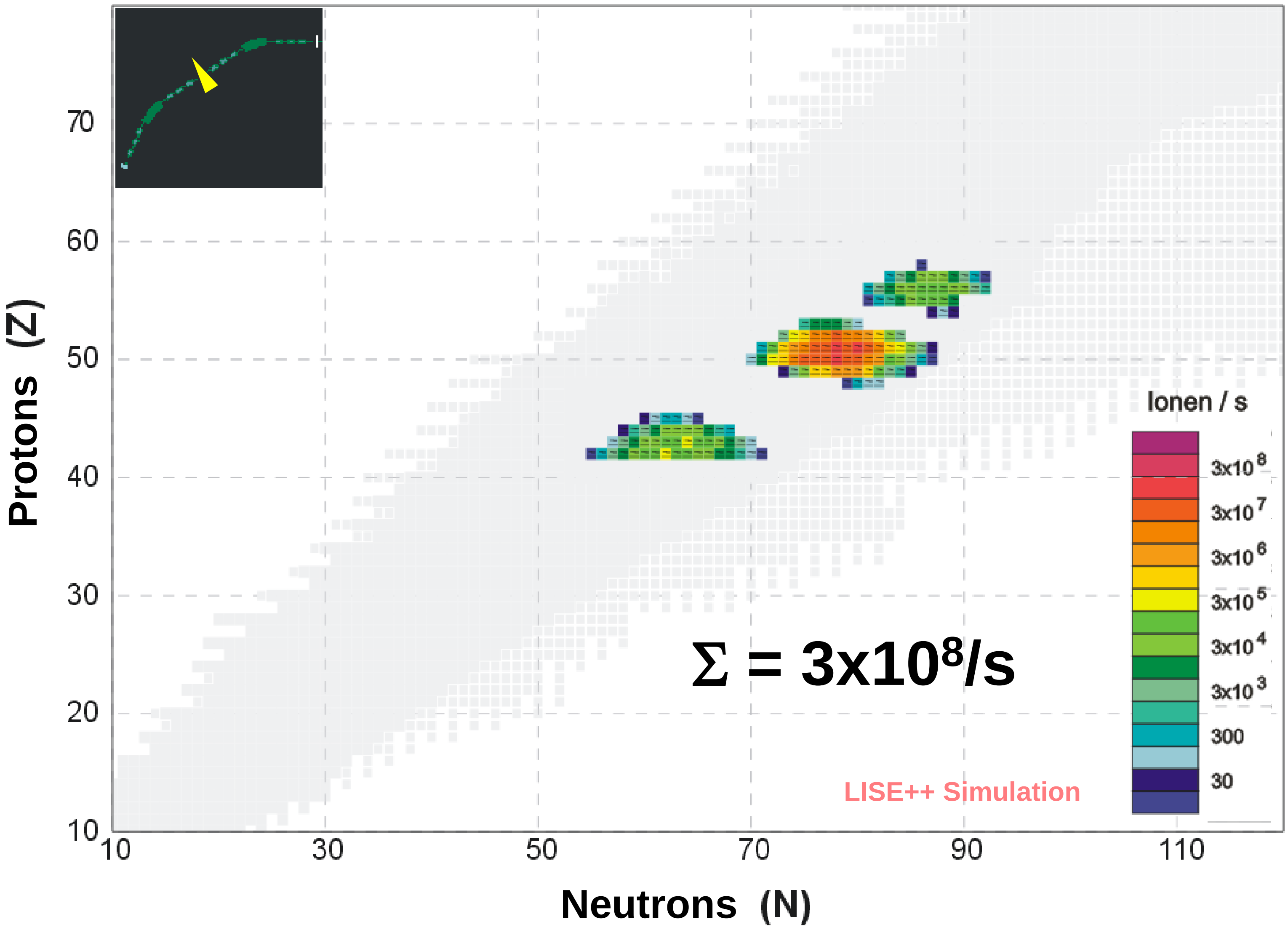
Separation

Separation only by Bρ



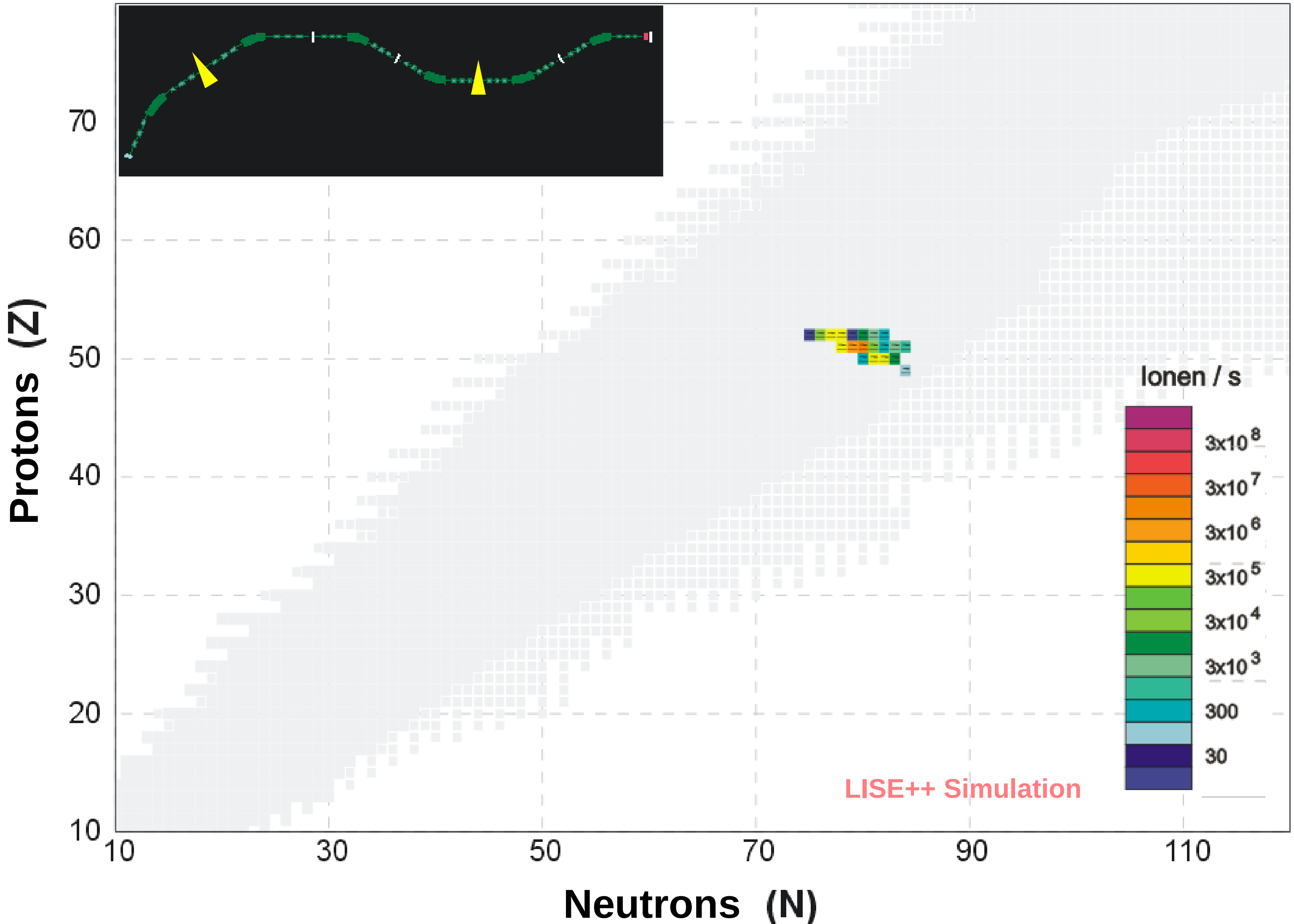
Separation

Separation after pre-separator (Bρ-ΔE-Bρ)

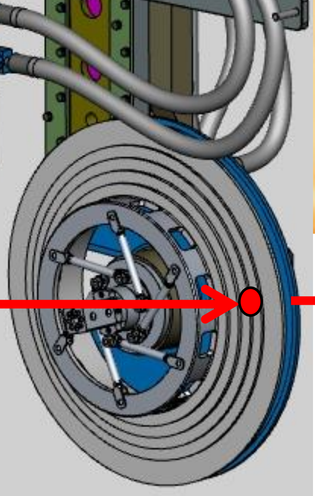


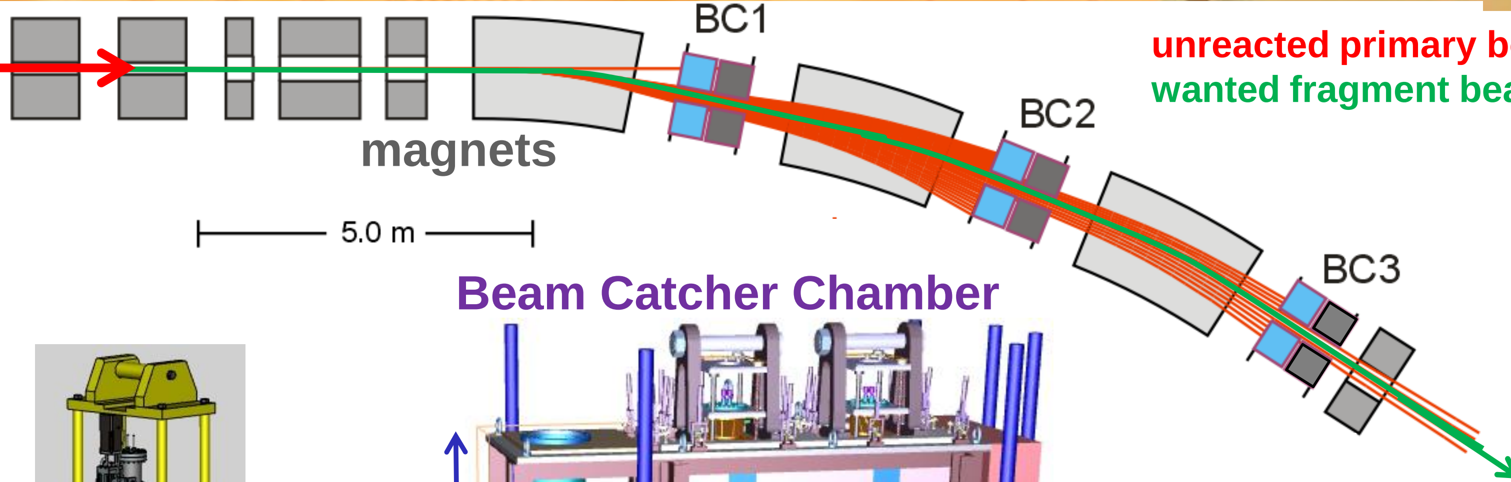
Separation

Separation after main separator (Bρ-ΔE-Bρ) x (Bρ-ΔE-Bρ)

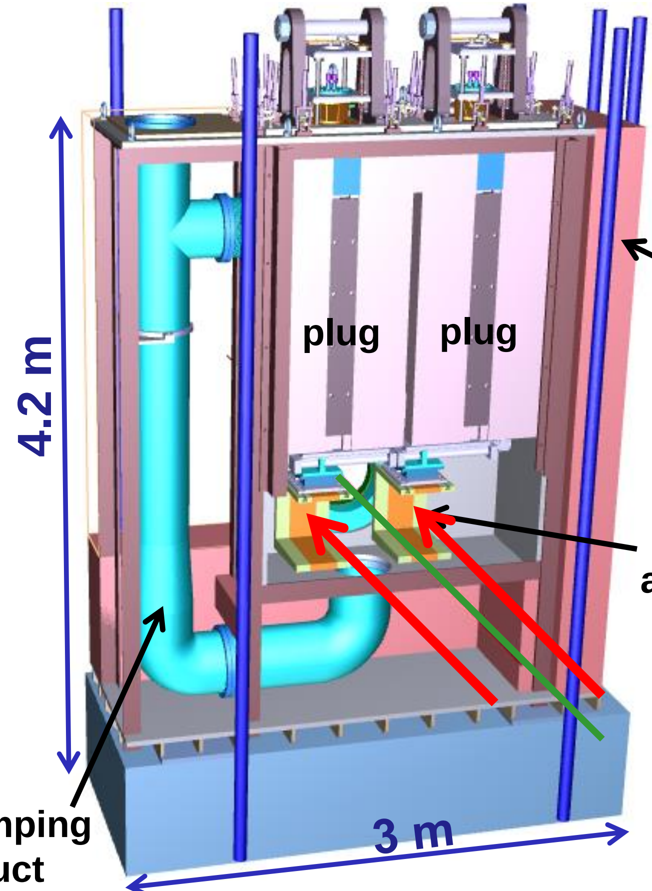


Beam Interaction Points

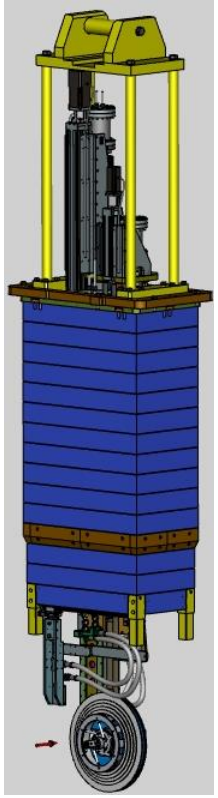




Beam Catcher Chamber



Target plug, Graphite wheel



university of groningen

KVI-CART
Michel Lindemulder

CSIR-CMERI Durgapur
Avik Chatterjee,
Abhijit Mahapatra

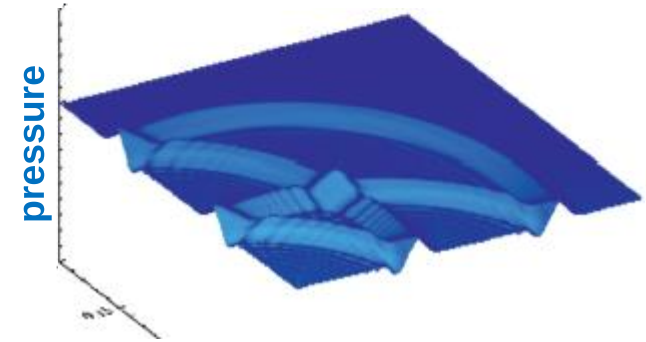
Material Choice

a simple temperature and stress calculation

Instantaneous energy deposition

$$\frac{dQ}{dm} = \frac{dE}{\rho dx} \frac{n}{\Delta x \, \Delta y}$$

stopping power
number of ions
spot size



$$\Delta T = \frac{dQ}{dm} \frac{A}{c_{mol}}$$

molar mass
heat capacity

at high T

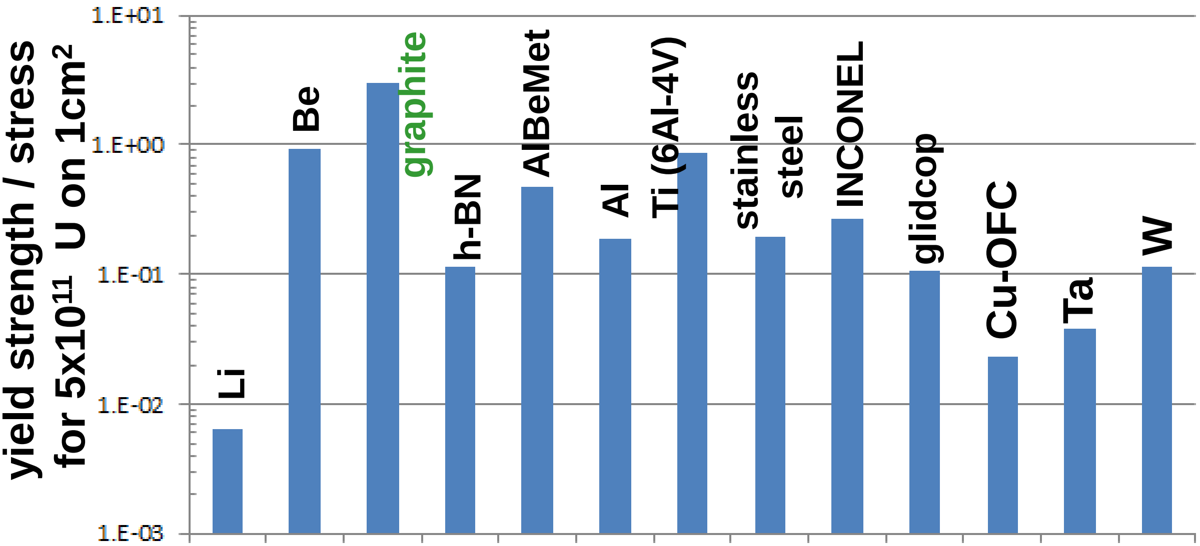
$$c_{mol} \sim 25 \frac{J}{mol\,K}$$

low A → low ΔT

$$P = K \, \alpha \, \Delta T$$

bulk modulus
thermal expansion coeff.

polycrystalline graphite, more nuclear x-section less slowing-down by electrons.



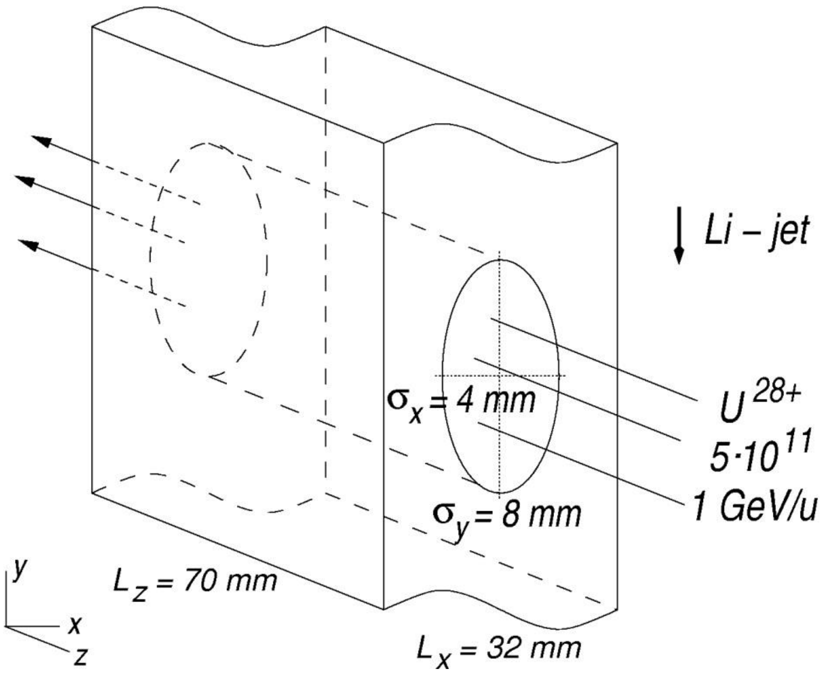
Initial compressive pressure, wave propagates to boundary → tensile stress.

plastic deformation
not exactly elastic,
cyclic stress, cracks?

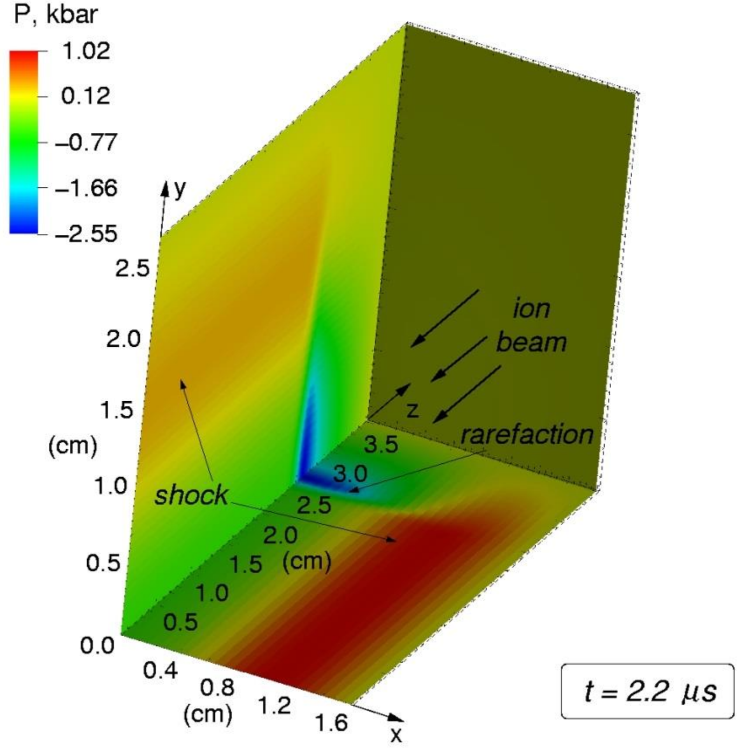
Liquid Lithium Jet - Spall Strength

Hydro-dynamical calculation:

Anna Tauschwitz et al., NIM A 591 (2008) 447



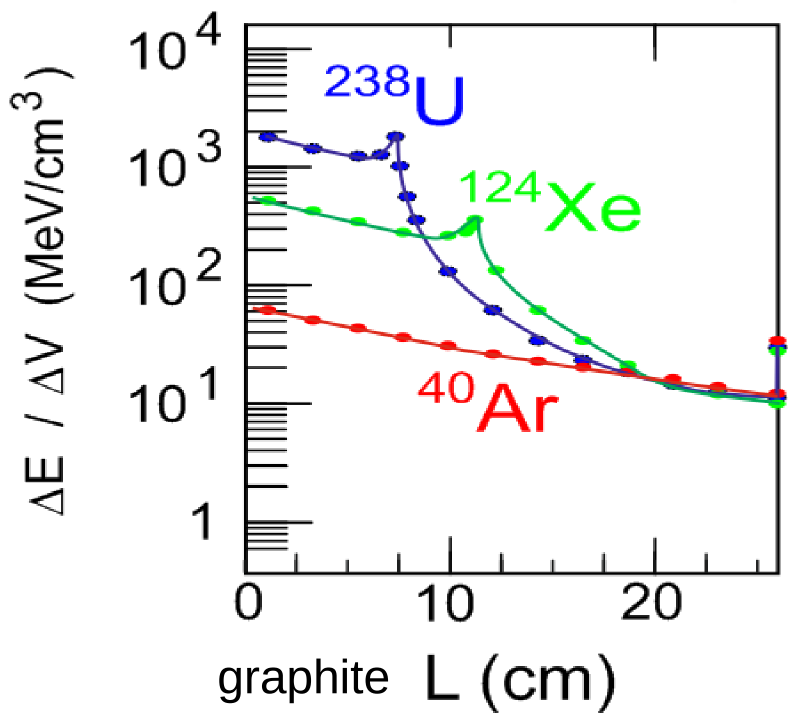
Negative pressure!

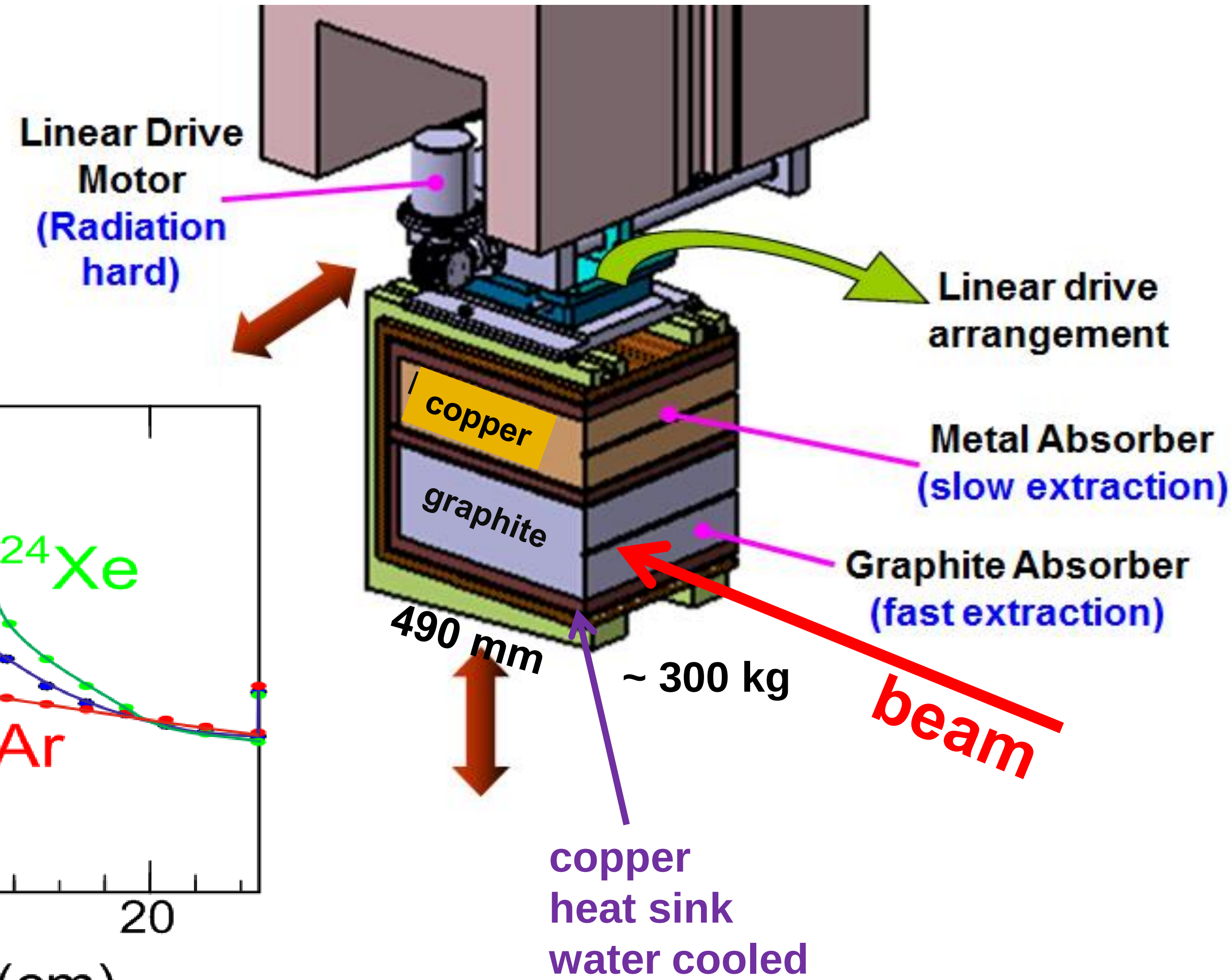


Calculated spall strength P_s of liq. Li is only -0.09 kbar = **-9 MPa**

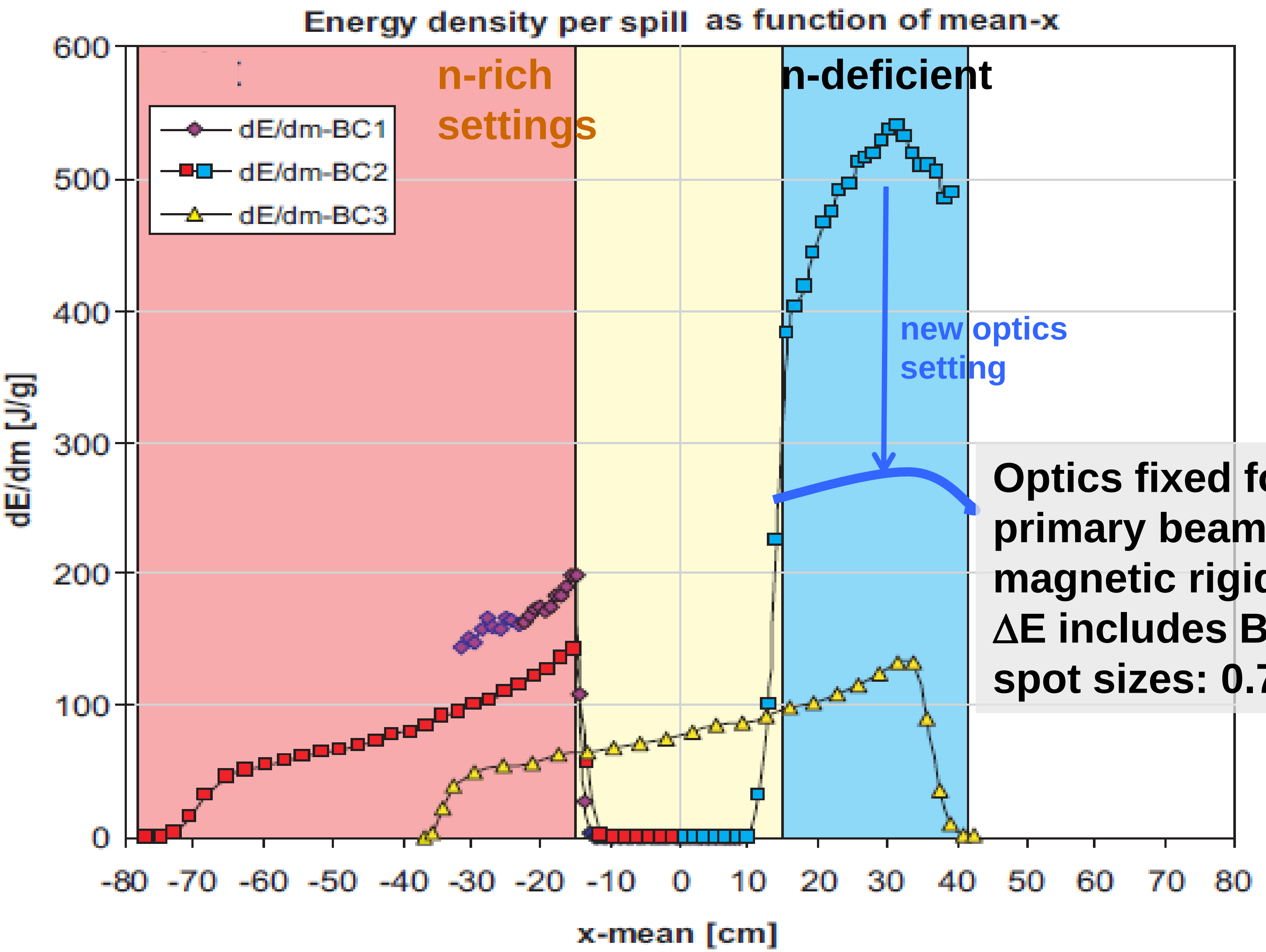
➔ Li jet will break after 210 ns, many droplets with v > 100 m/s

Energy Deposition and Absorber Design





Beam Spot on Absorber



Optics fixed for fragment beam, primary beam of different magnetic rigidity, $\Delta B\rho/B\rho \leq 30\%$
ΔE includes Bragg peak.
spot sizes: 0.7 cm^2 - 3 cm^2

Beam Absorber Simulation

Use Gaussian beam spot and 17.2 kW (1500 MeV/u ^{238}U)
beam comes in 50ns pulses with 28.6kJ every 1.67s.

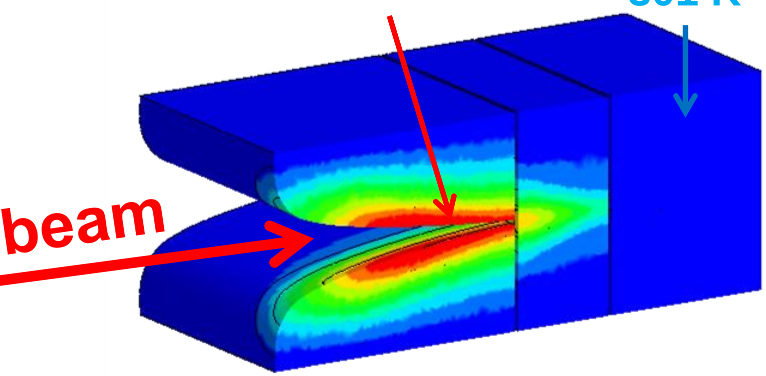
graphite SGL 6650

CSIR-CMERI Durgapur
Amit Kumar with
ANSYS + LS-Dyna

after reaching
thermal equilibrium

$T_{max} \rightarrow$ 1504 K

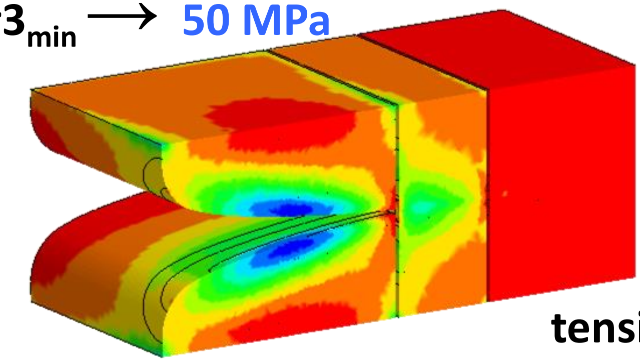
301 K



Apply radiation damage only
in inner region of beam spot
λ =15 W/m-K in radiation damaged areas

compression in
hot spot on inside

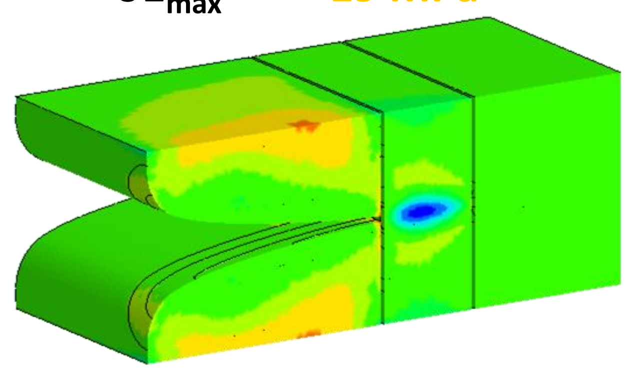
$\sigma3_{min} \longrightarrow$ 50 MPa



absorber
divided into
6 segments

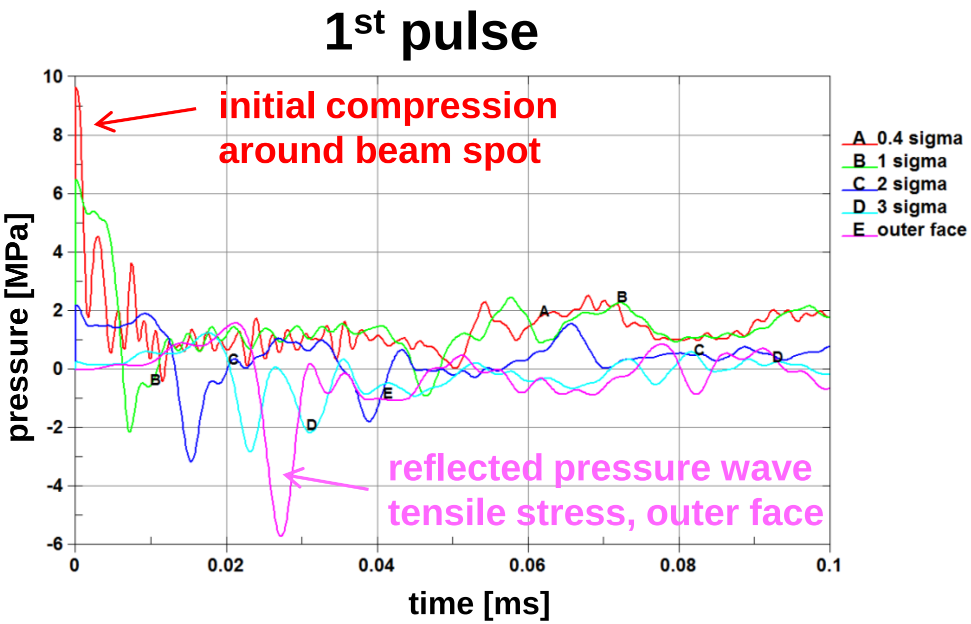
tensile stress by reflected
pressure wave on outside

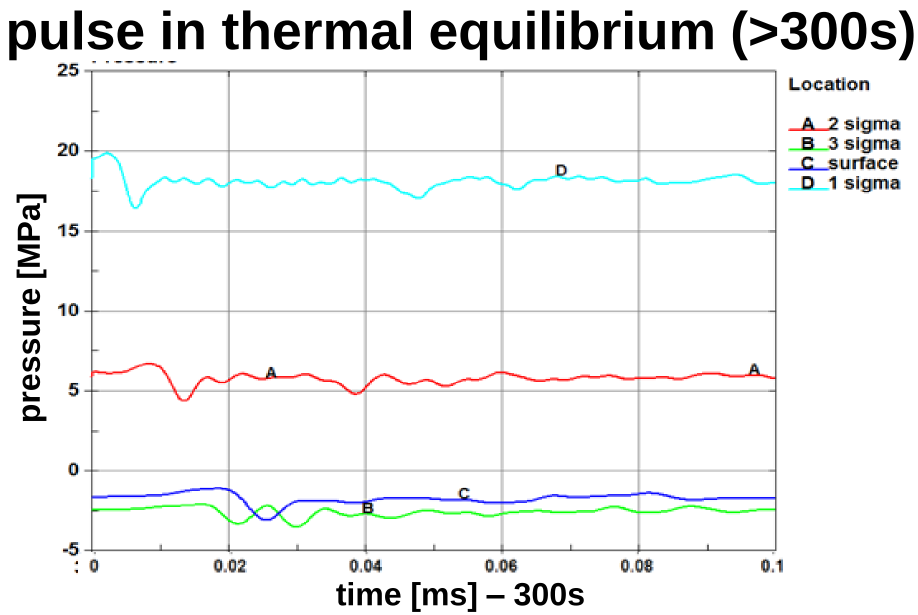
$\sigma1_{max} \longrightarrow$ -19 MPa

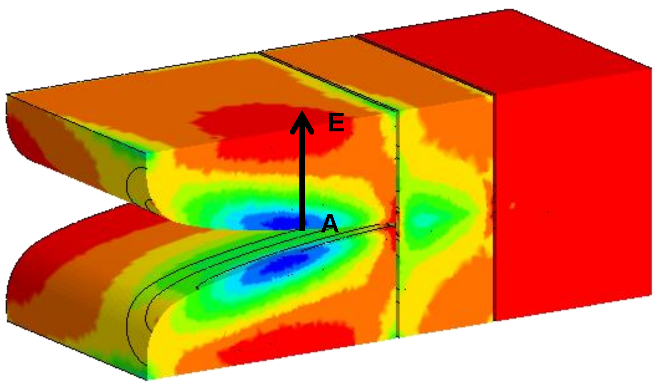


Beam Catcher Stress

Amit Kumar with LS-Dyna







initial energy =	1500 MeV/u,	740 MeV/u
T_max =	1504 K,	720 K
ΔT_max =	134 K,	310 K
max. pressure =	11 MPa,	23 MPa
min. pressure =	-6.0 MPa,	-8.4 MPa

⇒ ok, according to Coulomb-Mohr criterion for brittle materials with factor > 1.5

Tests at FRS Target Stations, GSI 2014

$1x10^{10}$ U^{29+}/pulse at 125 MeV/u,
long pulse FWHM ~ 500ns

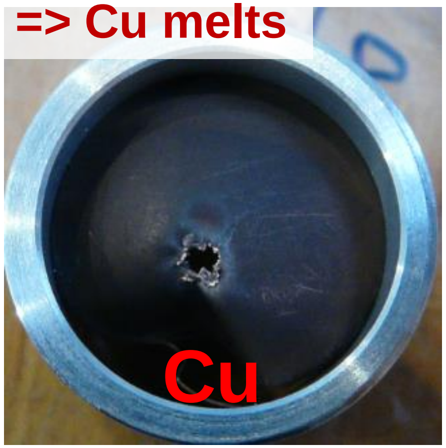
on target 1: σ_x = 0.4 mm, σ_y= 1.0 mm
on target M: σ_x= 1.2 mm, σ_y= 1.4 mm

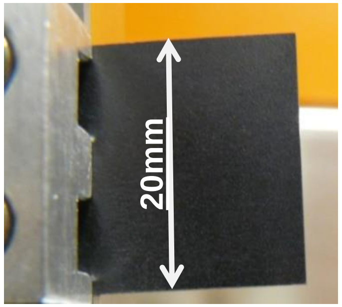
Tantalum melts in beam spot, but cannot drill through cm thick target in 100 pulses (range = 0.55 mm).

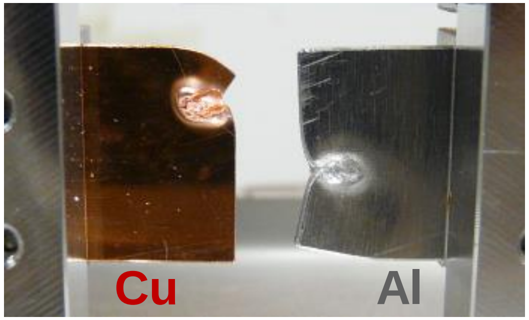
No effect after 100-1000 pulses on:
graphite, Mo-graphite, beryllium,
flexible graphite (SIGRADUR),
glassy carbon

in graphite:
E/m_{max} = 2.9 kJ/g => ΔT ~1400 K (target 1)
E/m_{max} = 0.75 kJ/g => ΔT ~ 360 K (target M)
but no clear shock wave front, too long pulses.

Ø=20mm targets, t <1mm
in peak ~2 kJ/g => Cu melts







Ronja Knöbel, HW
Marilena Tomut

from
GSI-UNILAC

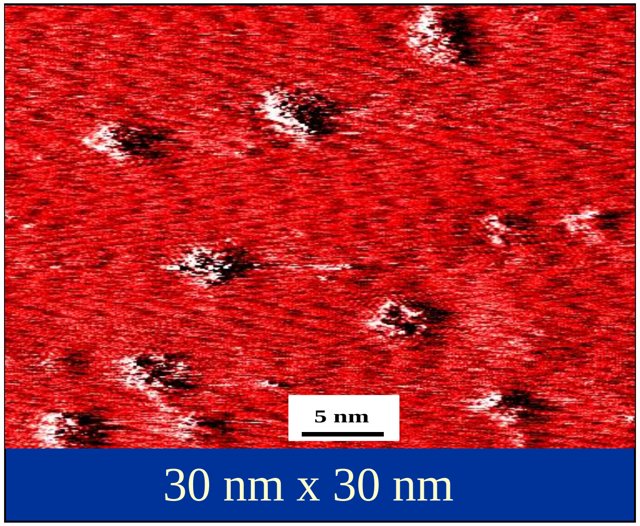
Radiation Damage by Heavy Ions

Track formation at high dE/dx (high Z ions Uranium, Pb, Au)
track diameter few nm, at fluence $10^{14}/cm^2$ track next to track

With $3x10^{11}$ U/s max. fluence ~ 10^{17} /cm^2
on same spot of target wheel or catcher.

At 0.4 - 1.5 GeV/u lower dE/dx
damage reduced by factor ~1000
→ ok for target wheel
- but beam stops in beam catcher

Big effect at low velocity (Bragg peak)
Use UNILAC at GSI (8.6 MeV/u),
for sample preparation,
Low activation for maximum damage.
Limited area max. 1cm^2, range = 0.1 mm.



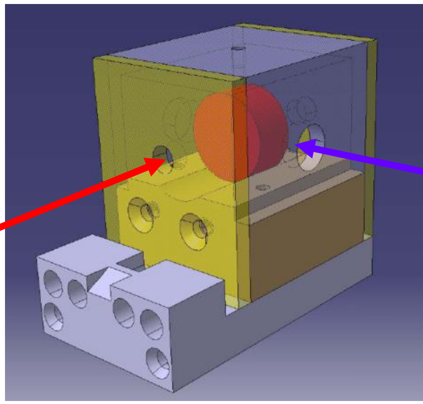
surface of HOPG graphite hit by U ions

Efficiency of track formation at higher velocity?
Recrystallization into what structure? (glass-like)

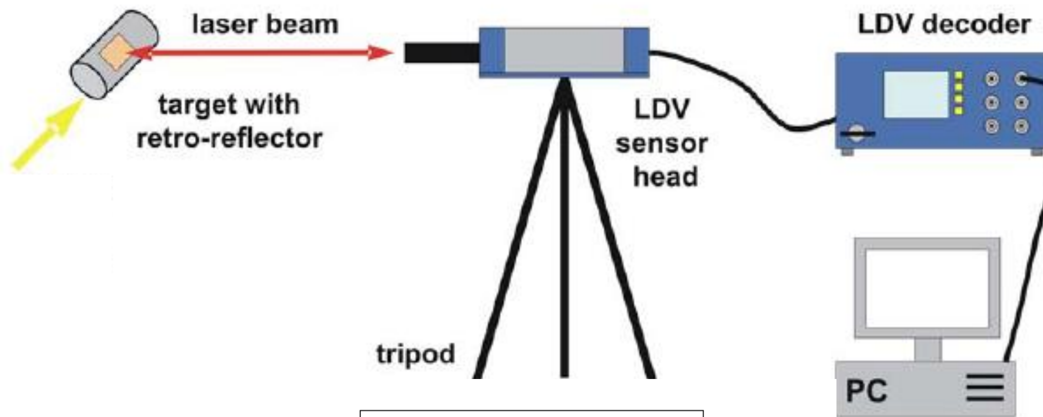
S334, Experimental Setup

GSI plasma physics cave (HHT) 2007, together with CERN

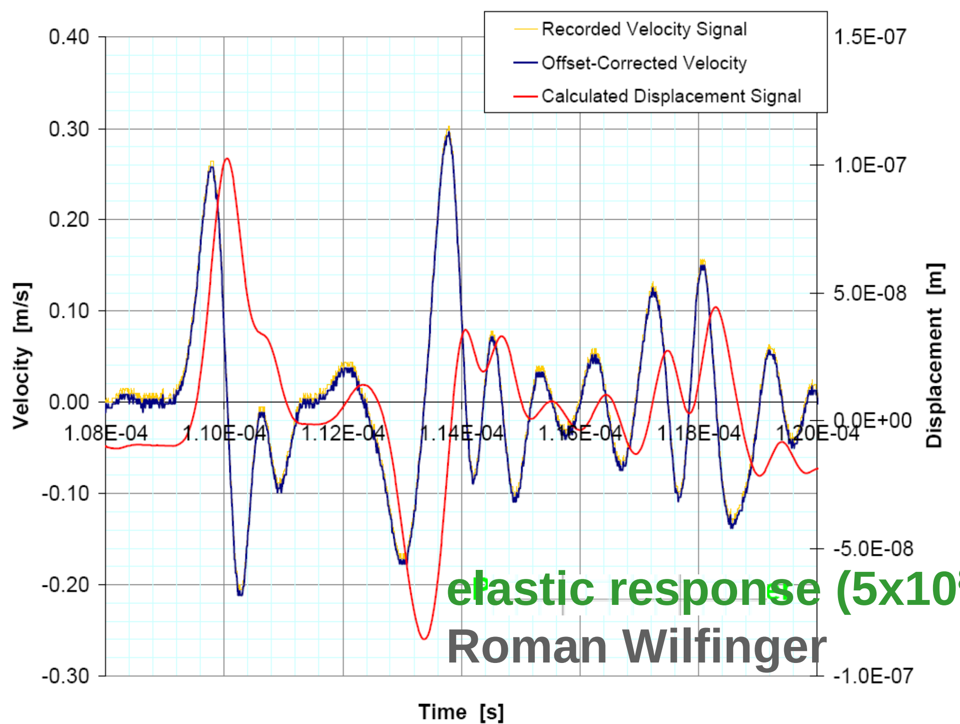
^{238}U



Laser Doppler Vibrometer



- ^{238}U beam at 350 MeV/u
- $\leq 2.5 \cdot 10^9$ ^{238}U/pulse
- 300ns (FWHM) pulse
- $\sigma_x = \sigma_y \approx 0.365$ mm
- cylinder targets, d=10 mm, L=10mm (graphite, Cu, W, Pb)



elastic response (5×10^8/pulse)

Roman Wilfinger

Roman Wilfinger, Jacques Lettry, Dmitry Varentsov, Serban Udrea, Aleksandra Kelic, et al.

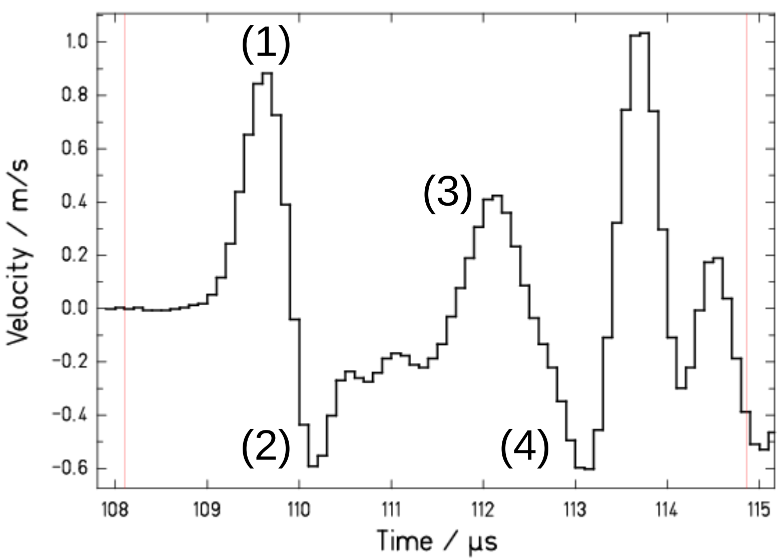
Elastic Radial Stress Wave

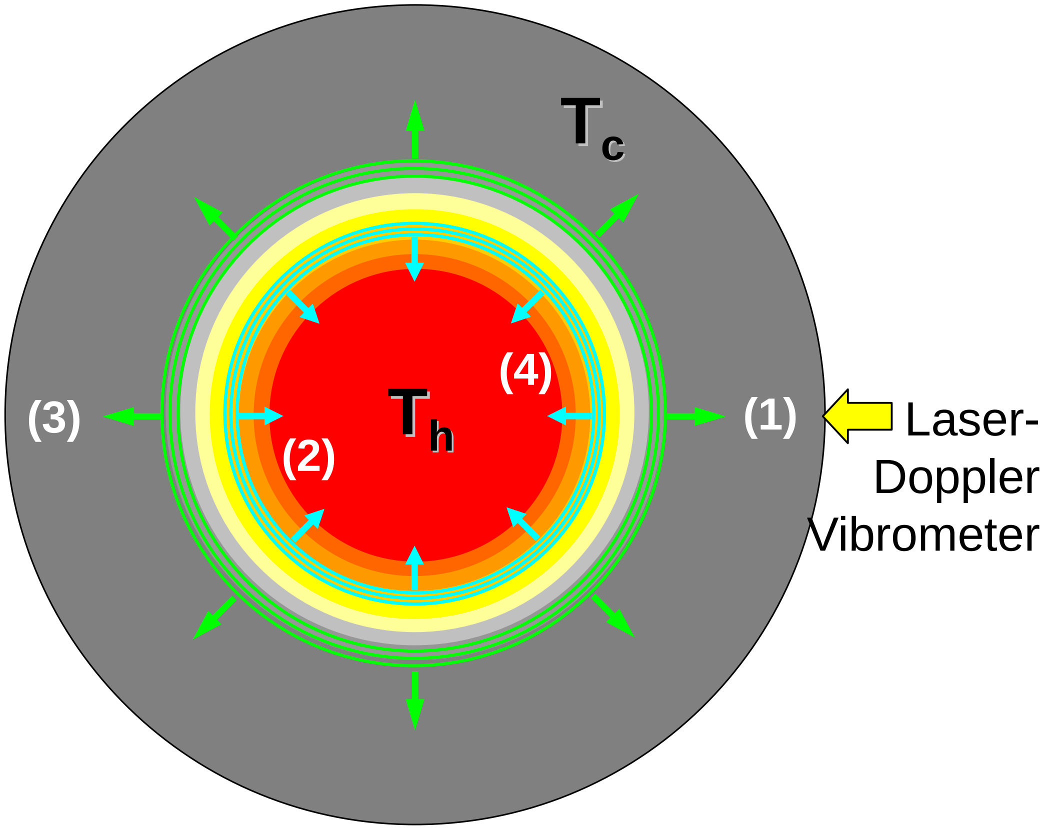
<u>Pulse 2486:</u>

- Intensity: 2.5×10^9 ^{238}U part/spill
- Beam-spot size: σ = 0.365 mm
- Graphite sample d=10 mm, L=10 mm
- $\Delta E/\Delta m$ = 1.3 – 1.7 kJ/g in max. of peak

– ΔT (from deposited energy) ~ 700 K

- calc. pressure +42 .. -25 MPa

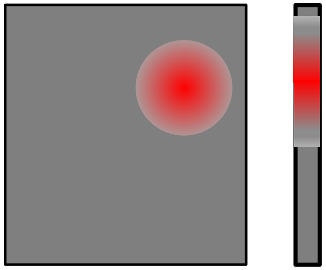




(1) . . . Compression wave,
(2) . . . Tension wave,
(3) . . . Compression → reflection → tension front,
(4) . . . Tension → reflection → compression front.

Downscale for Testing ?

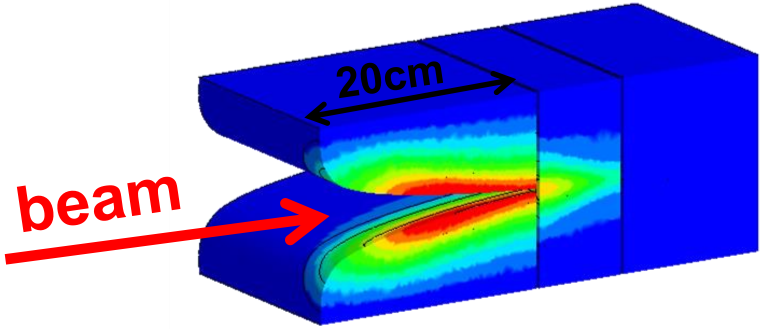
Future: enlarged beam spots to make target survive.
Today: test with small beam spot on downscaled prototype.
Peak energy can be reached, but stress at critical surfaces?
Also time structure needs to be scaled down.

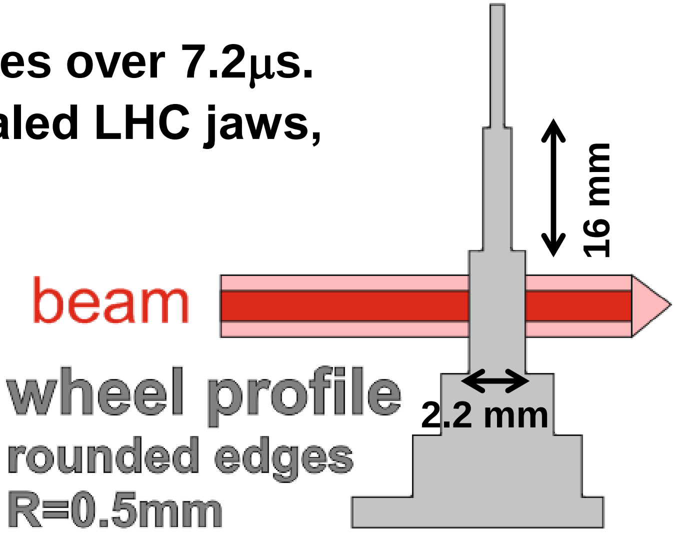


Problem in 2014 test, bunch compression cavity was broken.
→ Δt (FWHM) ~ 0.5 μs, v=2.2 mm/μs, sample 1mm thick, spot~1mm

Now new 2nd cavity in SIS-18 => Δt (FWHM) = 100 ns possible.
SIS-100: 9 cavities to merge four SIS-18 pulses to one 90ns pulse, by barrier bucket and bunch compression cavities.

HiRadMat is good, but more difficult with 288 bunches over 7.2μs.
However, A. Bertarelli's talk yesterday, 1/10 downscaled LHC jaws, a reasonable "shock" front can be formed.





Summary - Conclusion

- HiRadMat with Pb beam no gain compared to proton beam.
  Lower energy density and Pb projectile fragments very fast.
  Heavy-Ion Testing should be done at lower energy facility.

- Proton beam reaches values for FAIR testing.
  Superposition of many bunches requires improved simulation.

Key questions for FAIR: What is the best carbon material?
No damage outside beam spot -> properties preserved
in spot dramatic changes (see talk M. Tomut).

High dose heavy-ion irradiation at low E → **Pulsed beam testing with real shapes with in beam diagnostics**

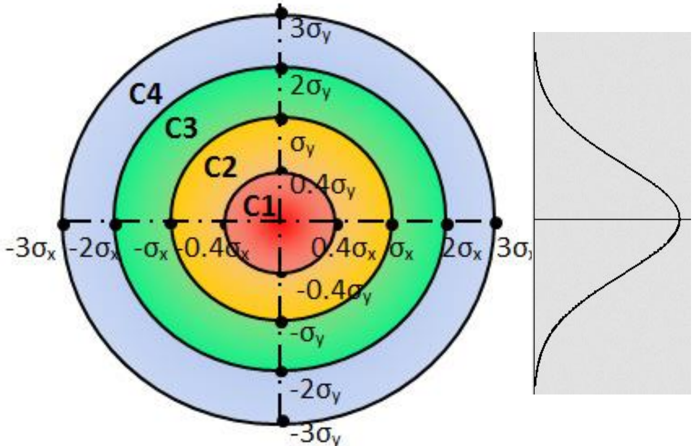
empty

Thermal Simulations by CMERI

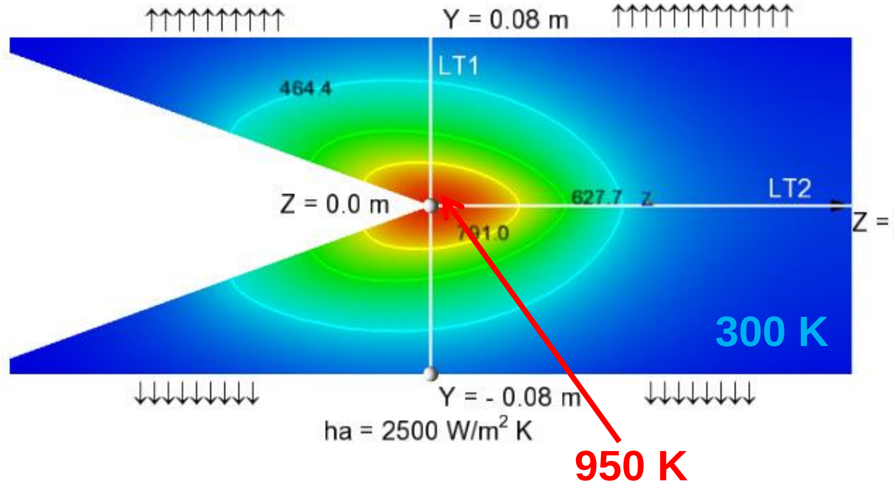
- consider radiation damage -

Use Gaussian beam spot and 17 kW (1500 MeV/u ^{238}U)

Amit Kumar with ANSYS

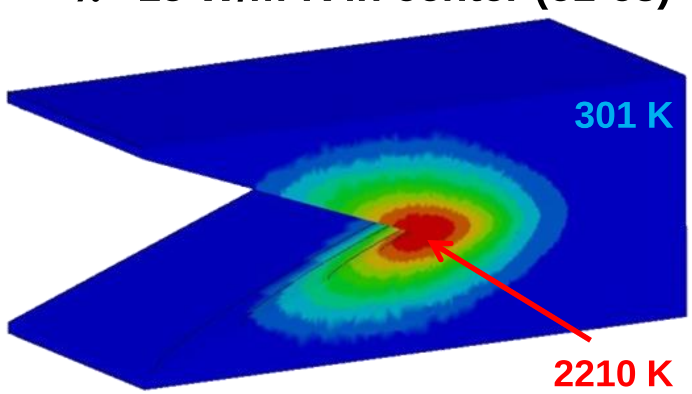


fresh SGL 6650

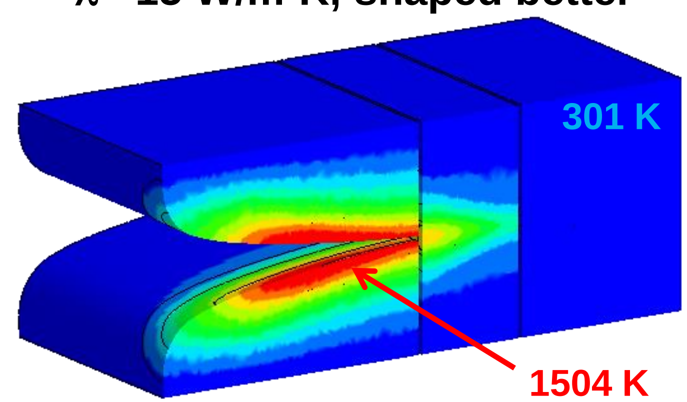


Apply radiation damage only in inner regions of spot (c1..c3)

modified material
λ =15 W/m-K in center (c1-c3)

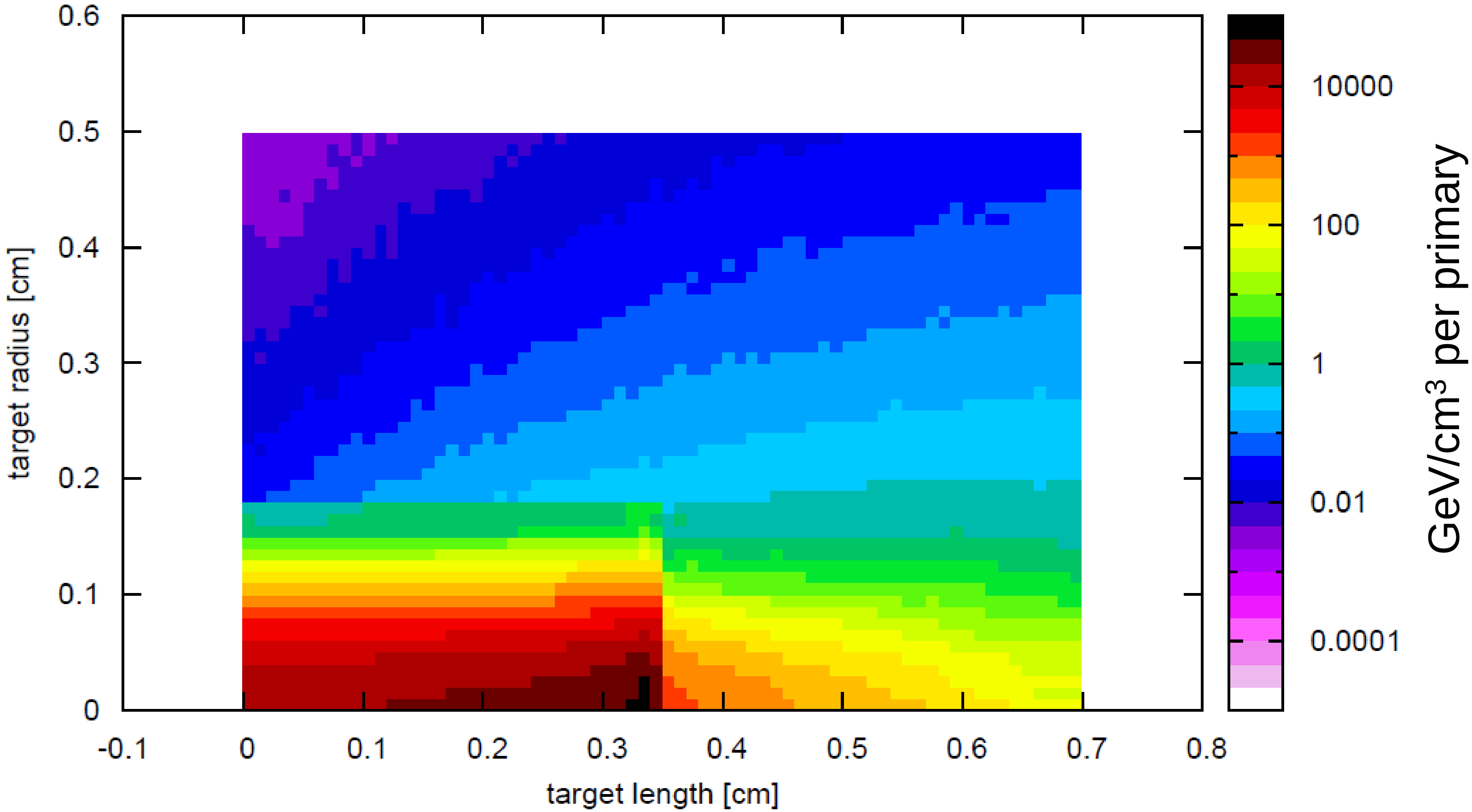


λ =15 W/m-K, shaped better



Energy Deposition in Copper Cylinder

FLUKA simulation of ΔE by 350 MeV/u ^{238}U beam on copper cylinder



thesis Herta Richter, TU Vienna 2011
Eur. Phys. J. A 42, 301–306 (2009)

Target Ladder Scan