GSI S-334 experiment

J. Lettry, F. Cerutti, A. Gerardin, S. Sgobba, R. Wilfinger

Goal of the GSI S-334 experiment:

Phase 1:

Validation of a method to produce reference samples dedicated to the validation of simulation of very fast, high energy density heat deposition as encountered in RIB, neutrino, antiproton or muon production targets or in dumps and collimators.

- GSI: Provide graphite tests samples for GSI fragmentation targets, and antiproton target.
- CERN: Provide metallic samples to benchmark high energy density short duration simulation codes (*ANSYS-AUTODYN, [4]*)
- Low activation allows post irradiation metallographic analysis
- On-line dynamic monitoring of radial velocities: Laser Doppler Vibration analysis

***Phase 2** ...stalled ?*

- Production of dedicated samples for benchmarking of the best codes in the vicinity of the expected nominal operations
- Irradiation of already aged samples (i.e. Fatigue, irradiation (dpas)

The team: R. Wilfinger, A. Kelič, B. Achenbach, K. H. Behr, A. Bruenle, F. Cerutti, H. Geissel, D.H.H. Hoffmann, A. Hug, Ch. Karagiannis, B. Kindler, K. Knie, M. Krause, M. Kulish, J. Lettry, J. Ling, B. Lommel, J. Menzel, N. Müller, H. Richter, K. Suemmerer, N.A. Tahir, M. Tomut, Ch. Trautmann, S. Udrea, D. Varentsov, H. Weick, M. Winkler, Y. Zhao

GSI S-334 experiment
at the HHT experimental area

Cylindrical target samples:

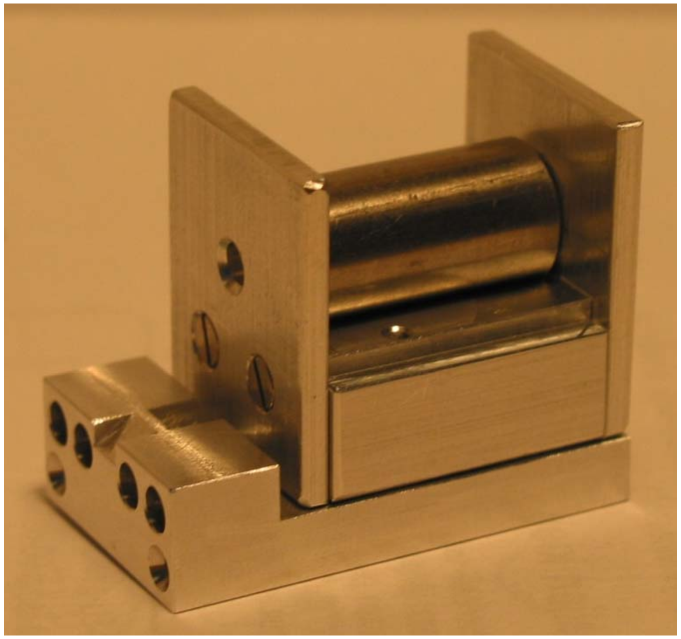
- Diameter 10 mm,
- Material, Length
  - Cu: 2, 5, 7 mm
  - Ta, W: 5 mm
  - Pb: 7 mm

Remote handled sample holder

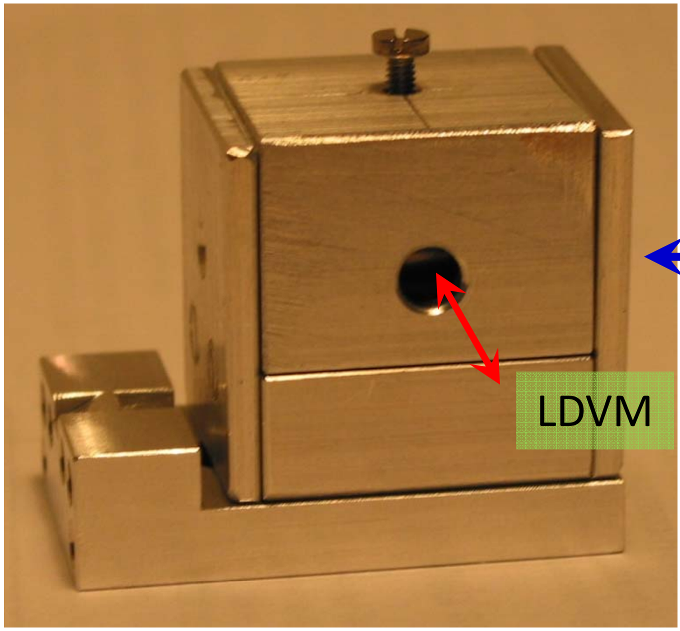
Precise positioning of:

- CERN 14 Metallic targets
- GSI Graphite targets

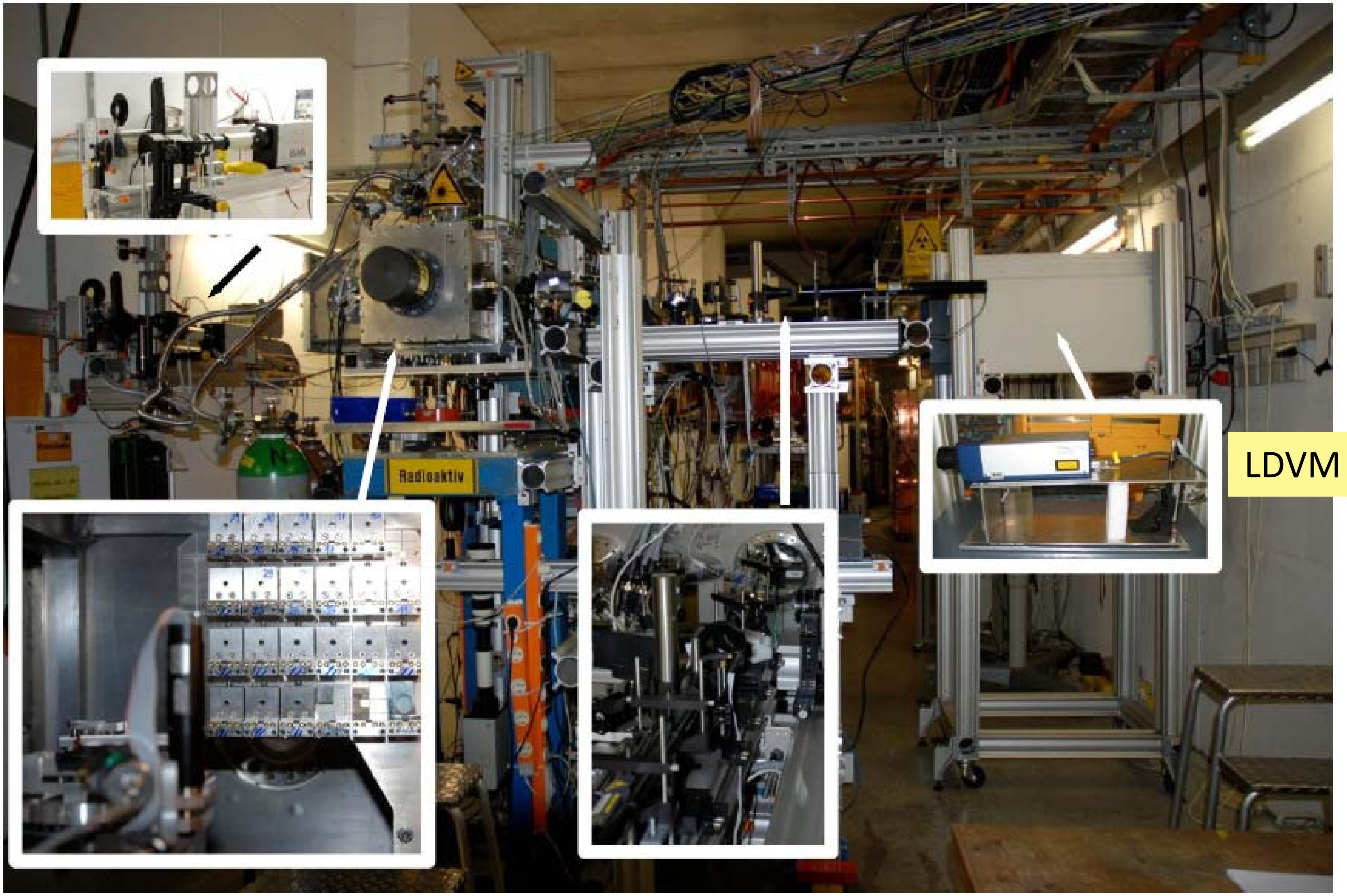
^{238}U-ion: 350 MeV/n



Confinement box



Experimental setup, from A. Hug's poster [1]



The HHT experimental area: alignment laser, intensified CCD camera, VISAR (lefttop) – target shelf and 6axis manipulator (left down) – interferometer (middle) – LDV (right)

Beam, Material properties

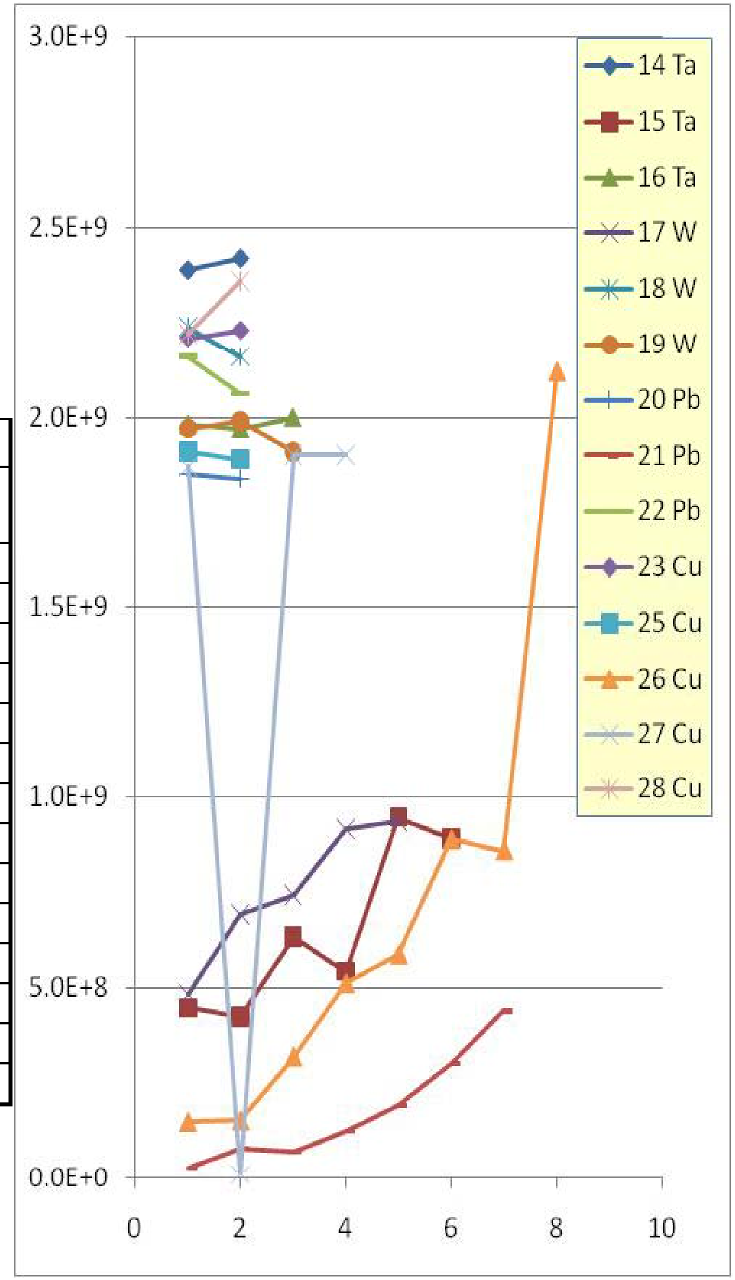
Orders of magnitude

^{238}U-ion: 350 MeV/amu *or* 83.3 GeV/U-ion
U-Pulse: 13.3 mJ / Mega-U-ion
Deposition in sample (97%): 13 J / Giga U-ion
Pulse intensity: 29 to 2,400 Mega-U-ion
Beam FWHM: 0.65, 0.85, 0.9 mm

Material		Cu	Pb	Ta	W
Z		29	82	73	74
A	amu	63.55	207.21	180.95	183.84
Density	g/cm3	8.94	10.66	16.69	19.25
Speed of sound	m/s	4650	1960	3400	5180
	mm/us	4.65	1.96	3.4	5.18
Melting point	deg.C	1084	327	3017	3422
Cp	J/g/K	0.385	0.129	0.140	0.132
Cp x (M.P. - RT)	J/g	407.7	39.0	419.3	448.4
Heat of fusion	J/g	208.7	23.0	202.1	192.0

^{238}U-ion: 350 MeV/n Irradiation parameters Ta, W, Pb & Cu samples

Probe: 10 mm cylinder			U-Pulse		Pulse Nr. Pulse intensity [M U-ion/pulse]							
#	Material	Length [mm]	sigma [mm]	[ns]	1	2	3	4	5	6	7	8
14	**Ta**	5	0.9	300	2,390	2,420						
15	**Ta**	5	0.65	300	447	423	633	543	947	890		
16	**Ta**	5	0.9	80	1,980	1,970	2,000					
17	**W**	5	0.65	300	483	693	743	916	937			
18	**W**	5	0.9	300	2,240	2,160						
19	**W**	5	0.9	80	1,970	1,990	1,910					
20	**Pb**	7	0.9	80	1,850	1,840						
21	**Pb**	7	0.65	300	29	77	68	123	193	302	438	
22	**Pb**	7	0.9	300	2,160	2,060						
23	**Cu**	2	0.9	300	2,210	2,230						
25	**Cu**	2	0.9	80	1,910	1,890						
26	**Cu**	7	0.85	300	148	152	319	511	587	889	859	2,120
27	**Cu**	7	0.9	80	1,870	9	1,900	1,900				
28	**Cu**	7	0.9	300	2,220	2,360						

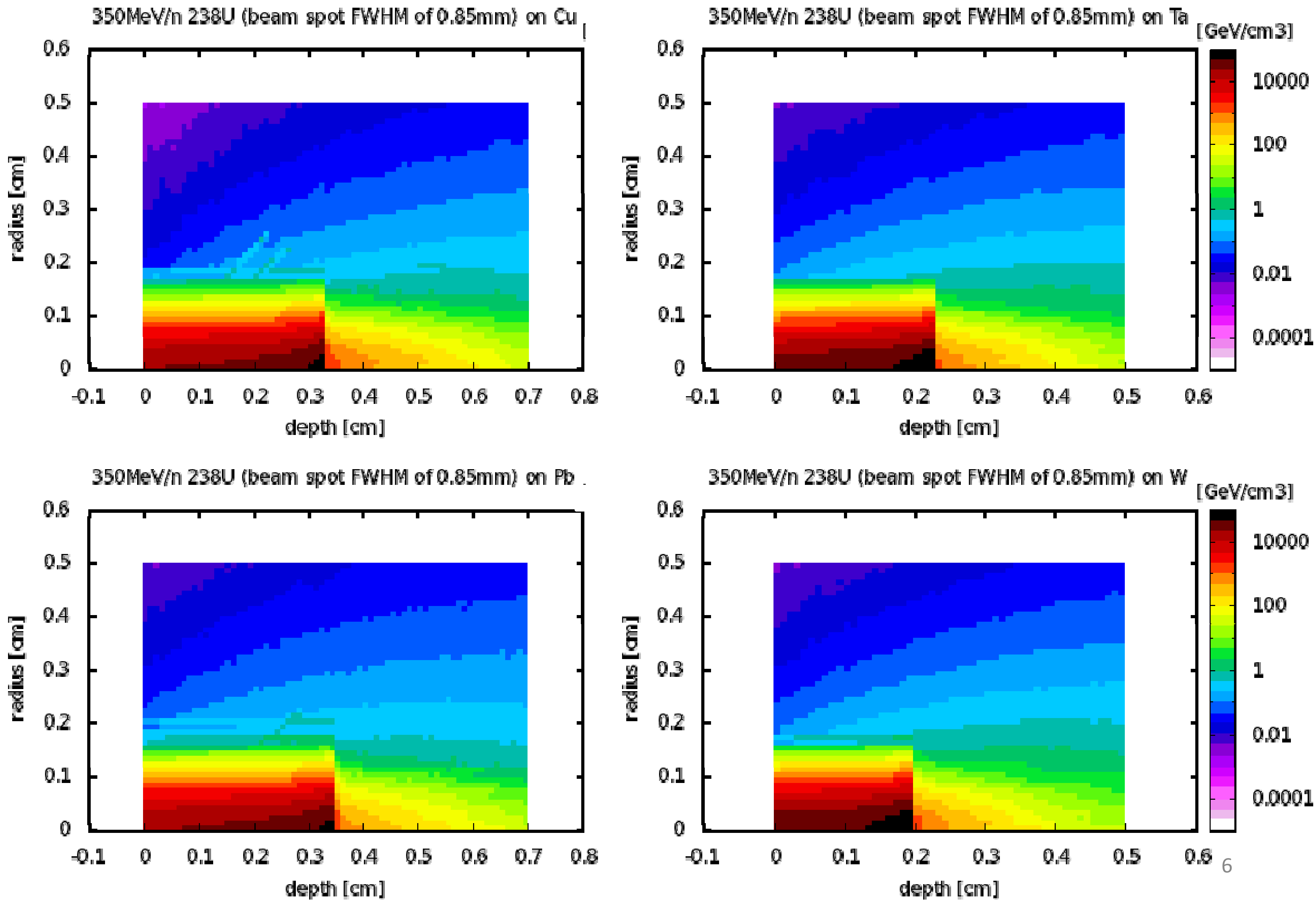


50 pulses on Metallic targets,

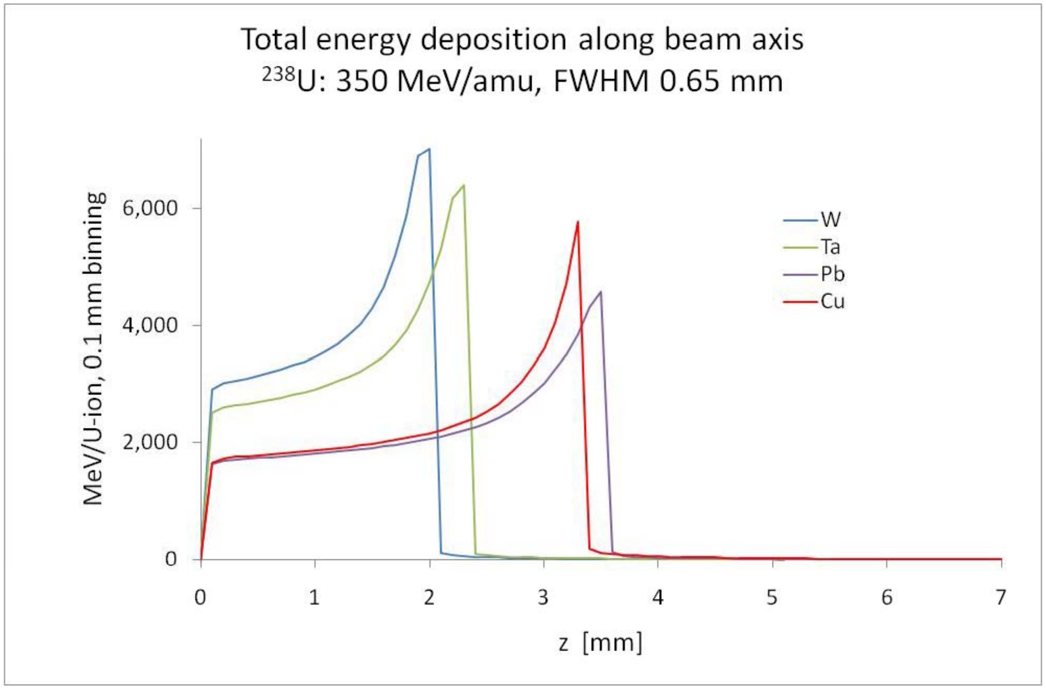
LDV-data integrated in this presentation

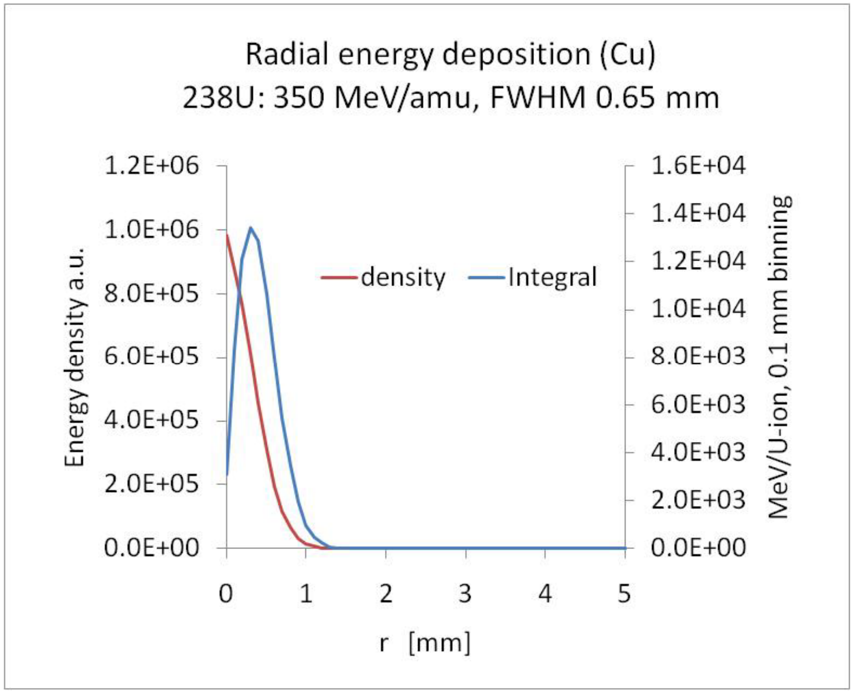
Energy deposition per U-ion 350 MeV/amu

0.65 mm FWHM, FLUKA (preliminary) courtesy of F. Cerutti



Beam profile (gaussian 0.65 mm FWHM)
Energy deposition z,r projections



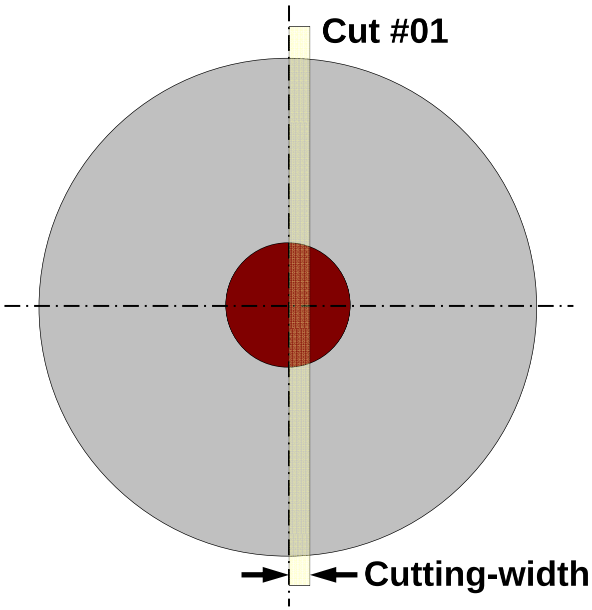


The irradiation occurs via a pencil beam on axis of the 10 mm cylindrical sample,
The beam is stopped in the middle of the 5 and 7 mm length metallic sample
The Laser Doppler Vibrometer is positioned at the height of the Bragg peak.

The pressure wave is non symmetric and builds complex interference patterns observed by only one point. 2 mm Cu samples are the closest possible to cyl. symmetric conditions.

Sample preparation & dE/dV in "*melting point*" units

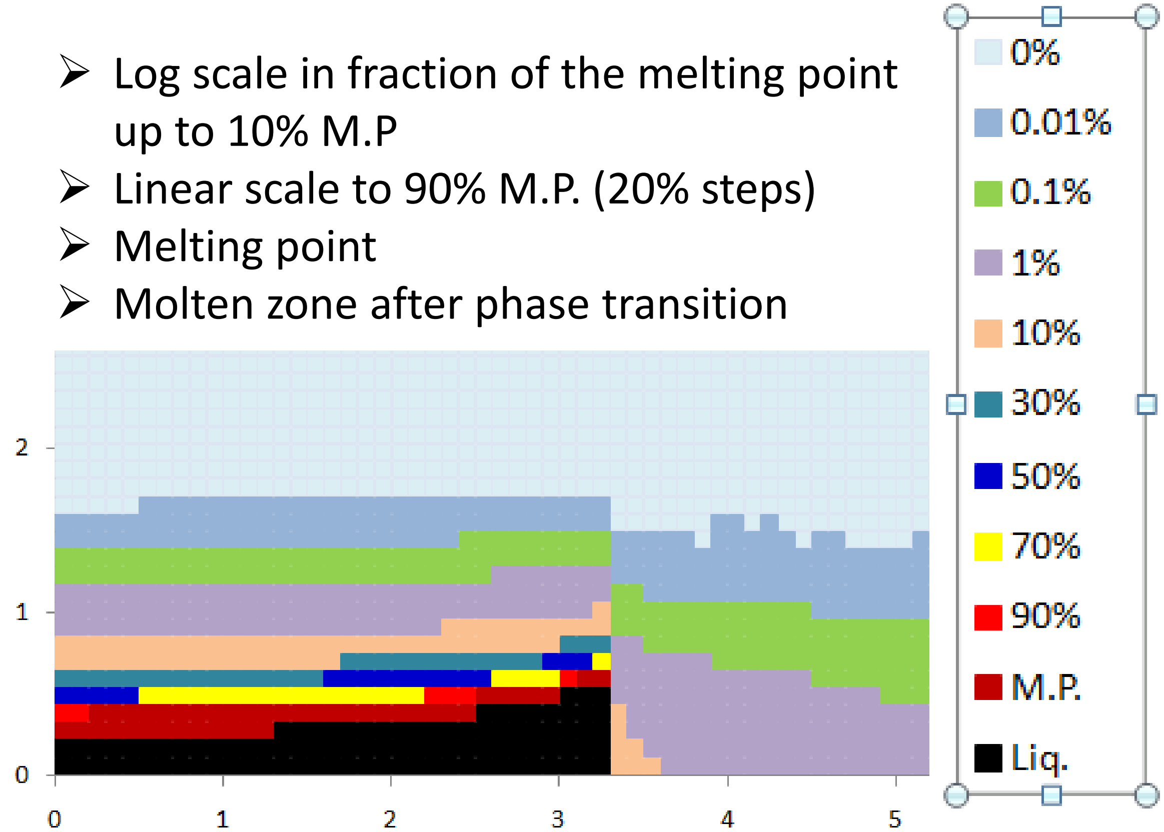
After polishing, the left side of cut#1 should be aligned on the center of the visible U-bunch impact



Material properties are strongly temperature dependant i.e. Tensile strength evolution from room temperature to the melting point.

Presentation of the energy deposition data:

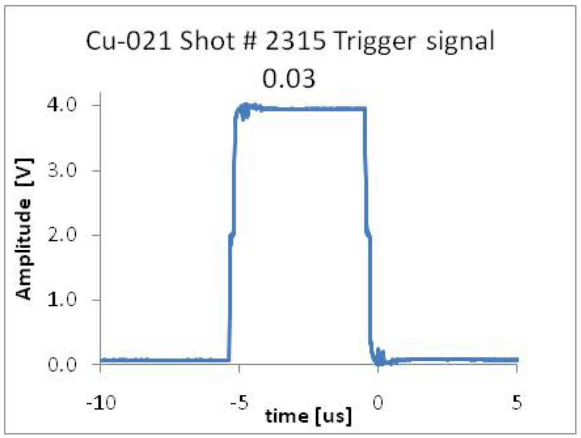
- Log scale in fraction of the melting point up to 10% M.P
- Linear scale to 90% M.P. (20% steps)
- Melting point
- Molten zone after phase transition

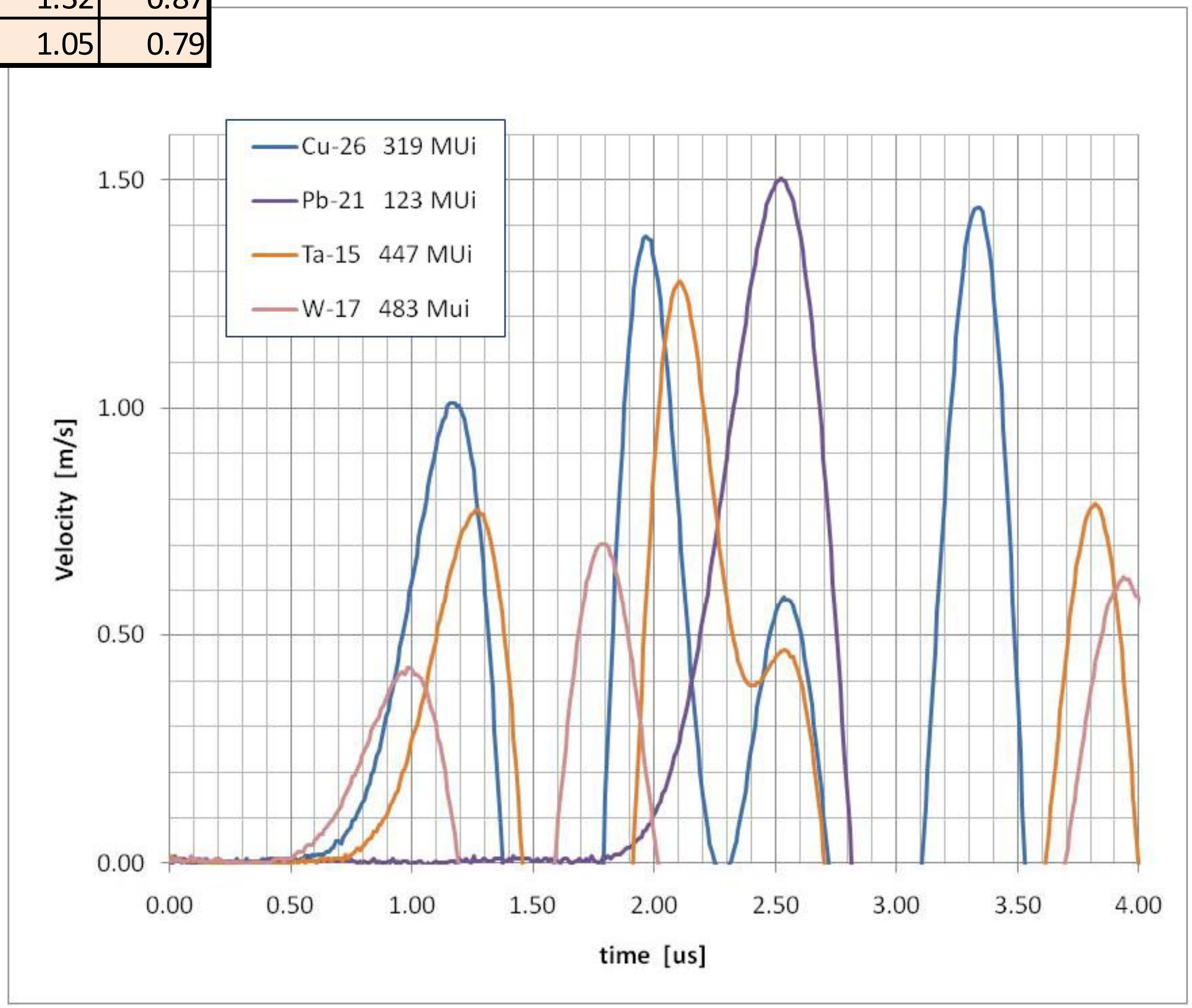


LDVM data trigger and presentation

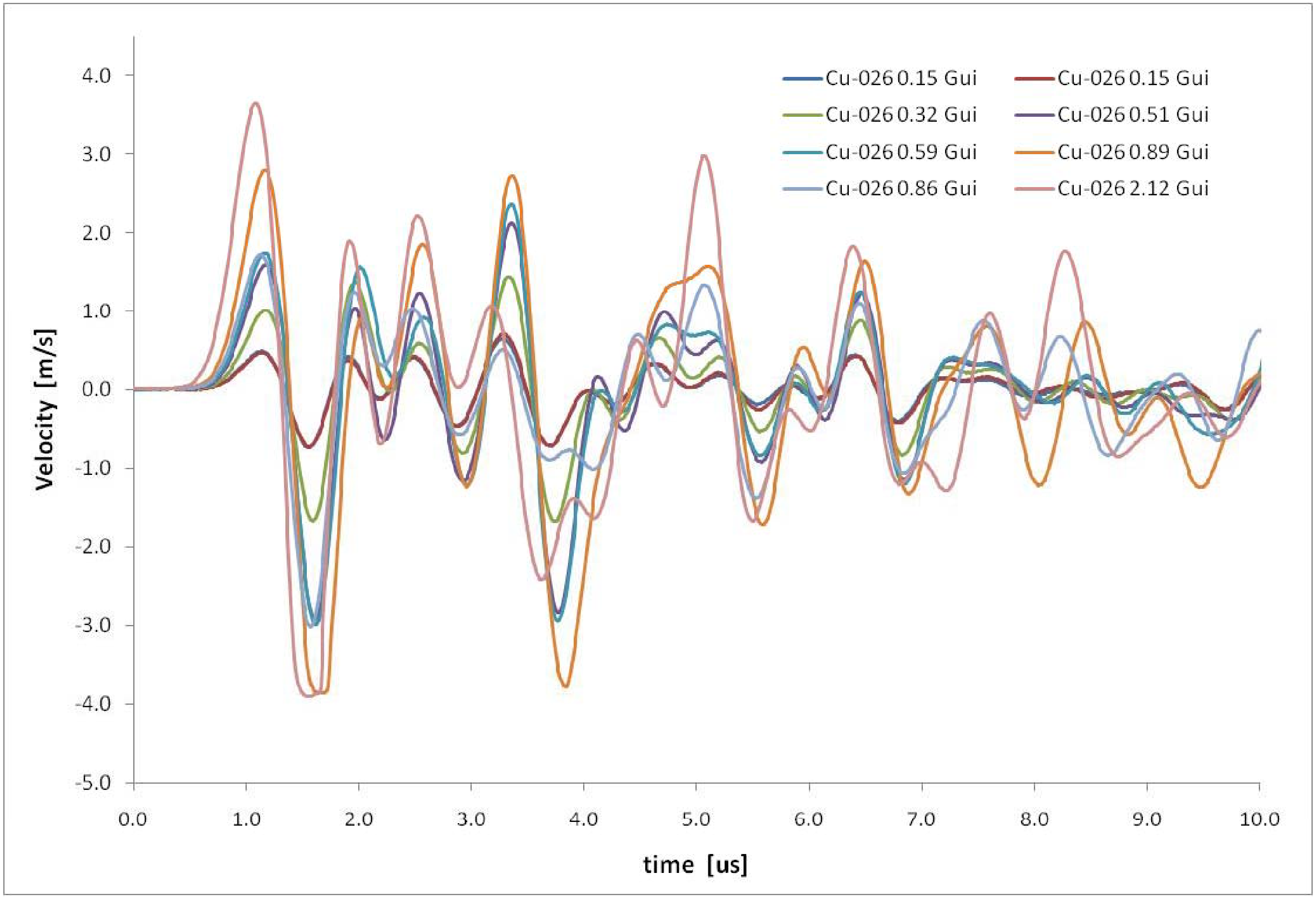
Positive velocity corresponds to increasing radius.

Travel distance 4.5	mm	Cu	Pb	Ta	W
t(d)	us	0.97	2.30	1.32	0.87
dt meas. at h/2	us	0.97	2.30	1.05	0.79

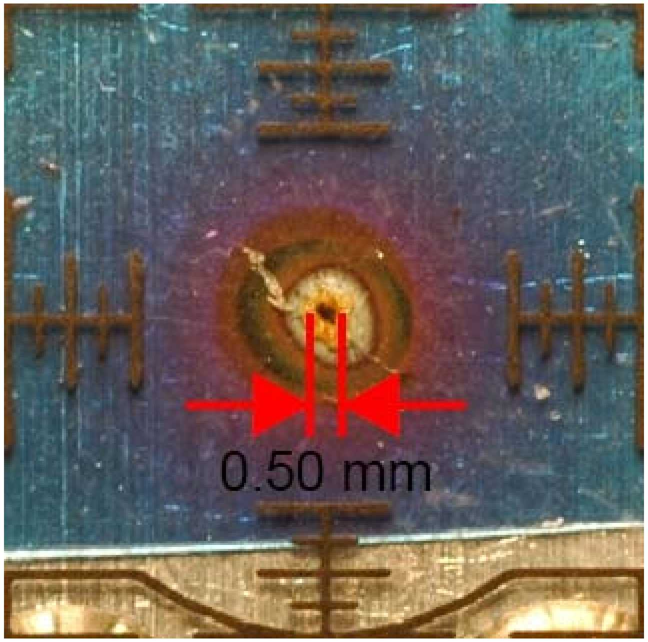


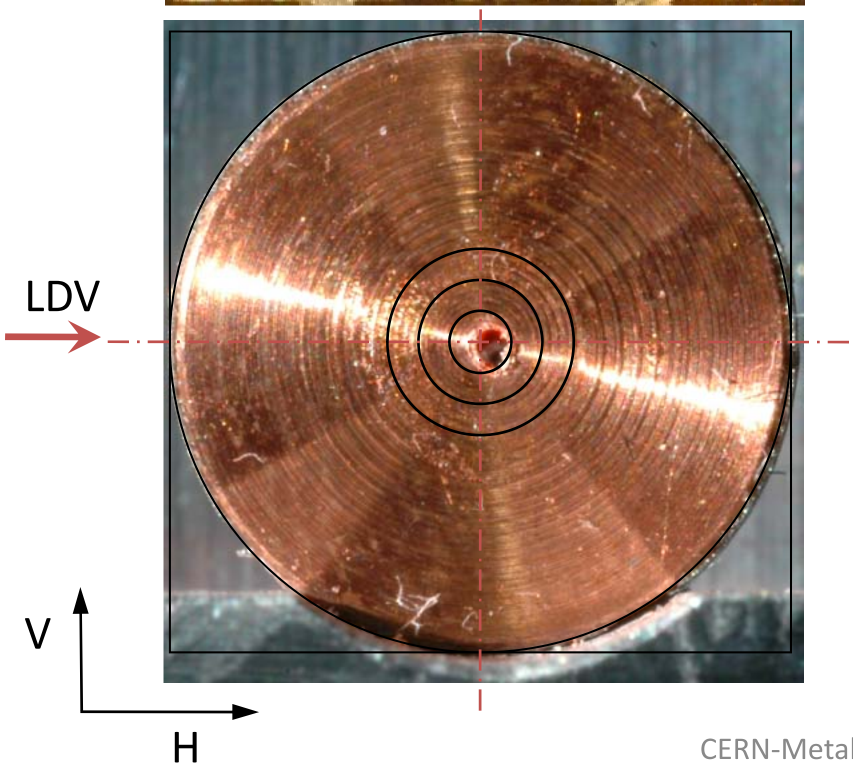


Cu-26, raw LDVM data



^{238}U-beam impact parameters: Spot size and offset from axis

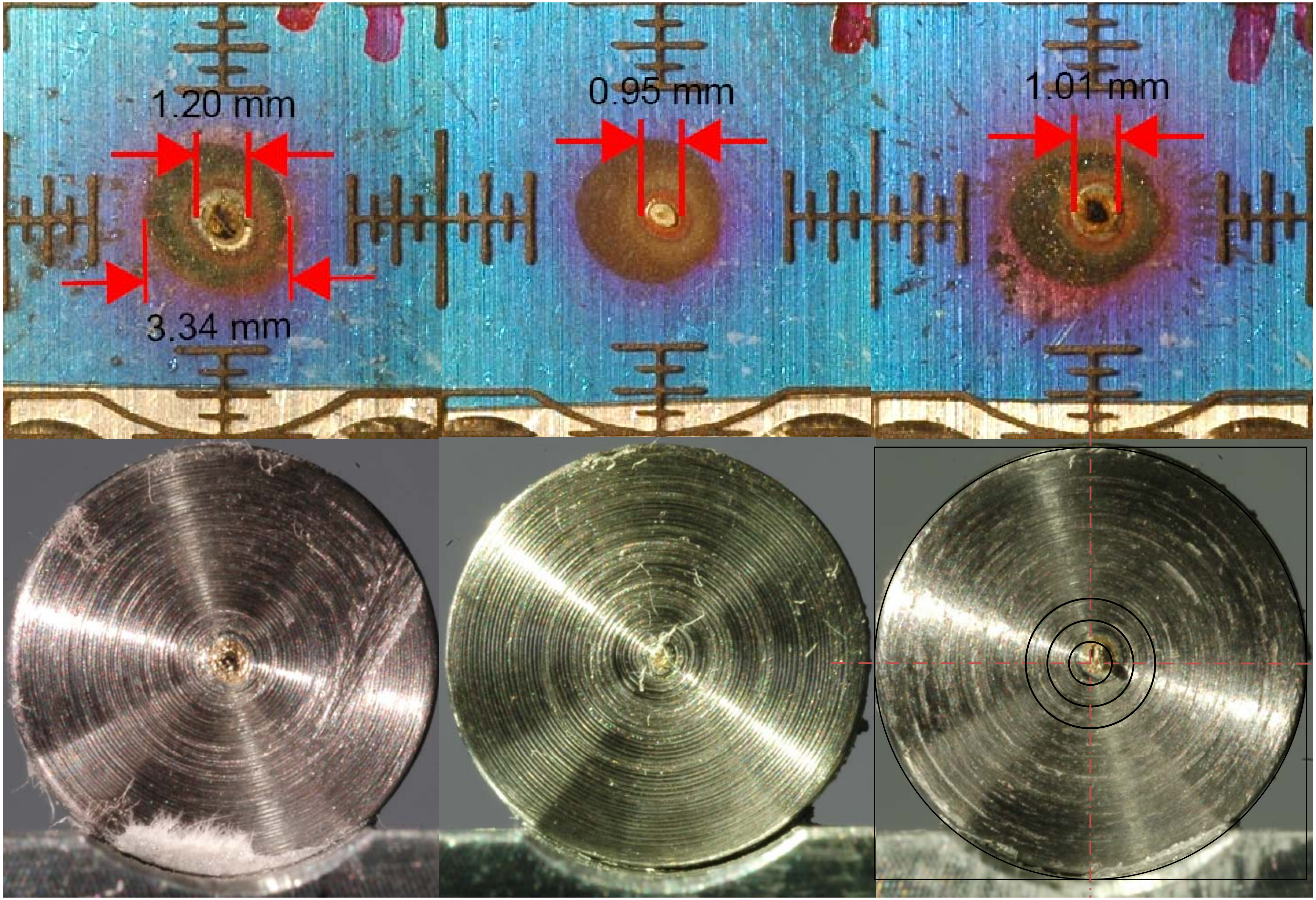




		spot size FW [mm]			beam impact [mm]		
#	Material	Hor	Vert	s [mm^2]	dH	dV	dr
14	Ta	0.4	0.5	0.63	0.20	0.10	0.22
15	**Ta**	0.3	0.3	0.28	0.10	-0.10	0.14
16	Ta	0.4	0.6	0.75	0.25	0.20	0.32
17	**W**	0.4	0.4	0.50	0.00	0.00	0.00
18	W	0.5	0.5	0.79	0.00	-0.20	0.20
19	W	0.4	0.4	0.50	0.10	0.00	0.10
20	Pb	1.3	1.2	4.90	0.20	-0.20	0.28
21	**Pb**	0.5	0.6	0.94	0.40	0.25	0.47
22	Pb	2.9	3.1	28.24	0.40	0.20	0.45
23	Cu	0.5	0.5	0.79	-0.20	-0.20	0.28
25	Cu	0.6	0.7	1.32	0.20	-0.20	0.28
26	**Cu**	0.5	0.7	1.10	0.50	-0.10	0.51
27	Cu	0.4	0.7	0.88	0.30	0.00	0.30
28	Cu	0.4	0.6	0.75	0.20	-0.05	0.21

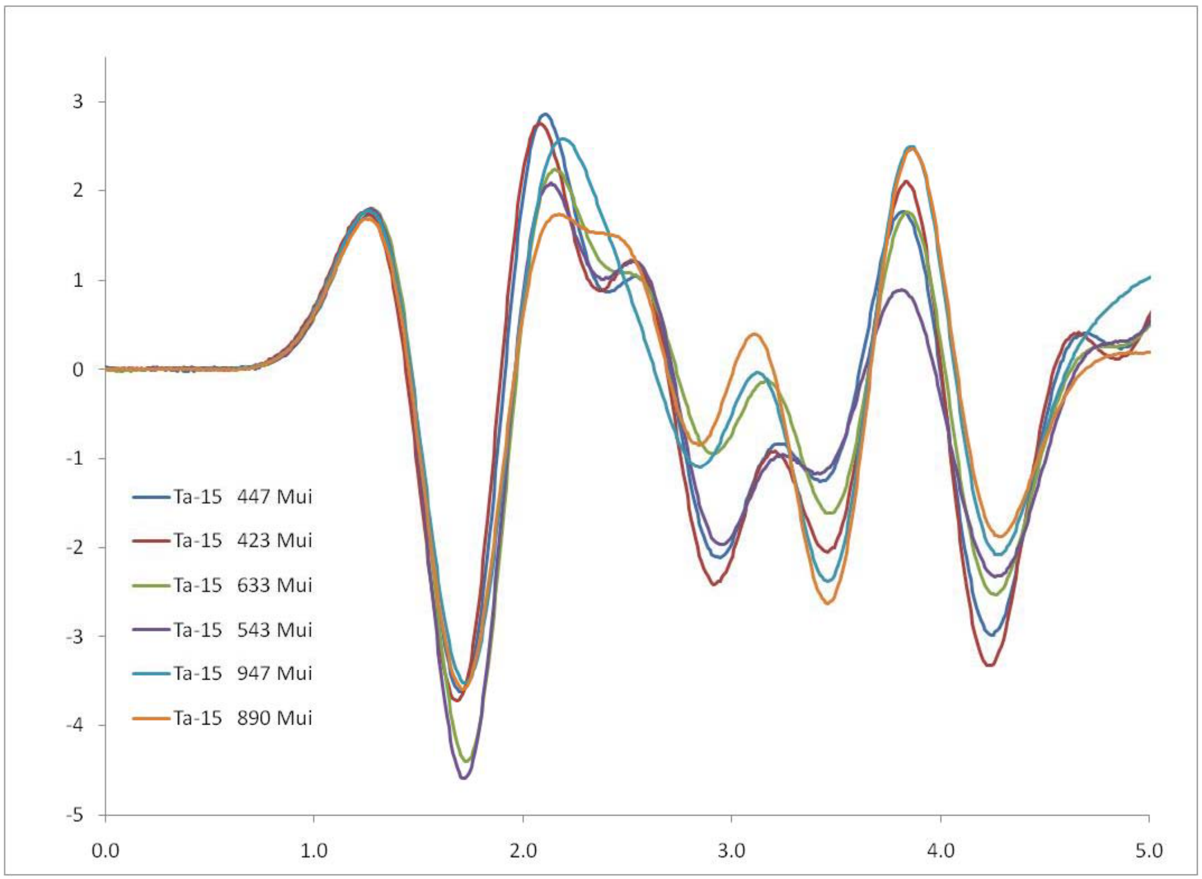
- Beam spot size is measured on a film located on the sample
- Beam impact is measured on the sample between 0.1 and 0.5 mm radius

Ta - 14, 15, 16



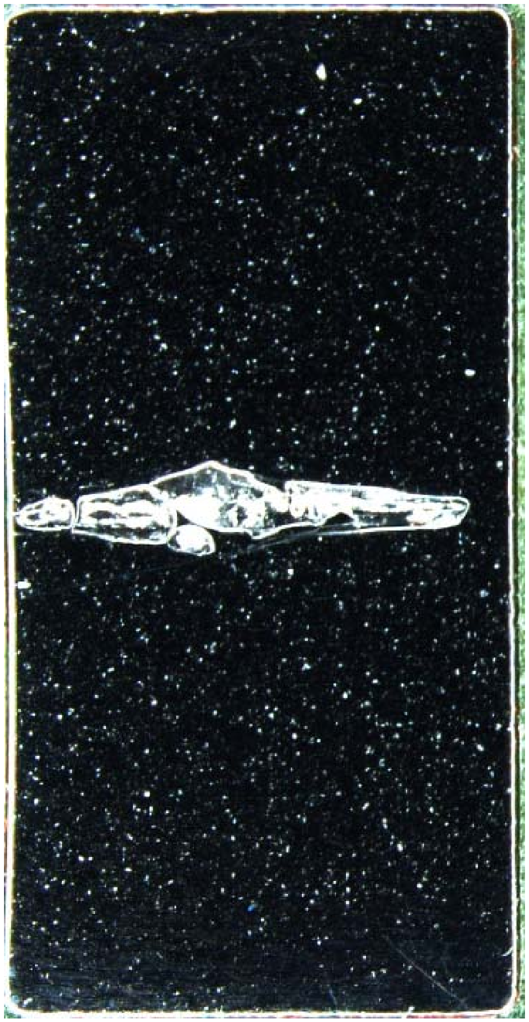
Scaling with beam intensity Ta-15

All curves scaled by to 1 G U-ions.
Perfect scaling of the first wave at intensity up to 890 Mui !
The variation of the second wave peak are likely related to the different initial energy deposition and distribution of stress.
From these data, the sample may be only weakly damaged if at all ! Interesting cross check with metallurgical observations.



Ta-14, Ta-15, Ta-16

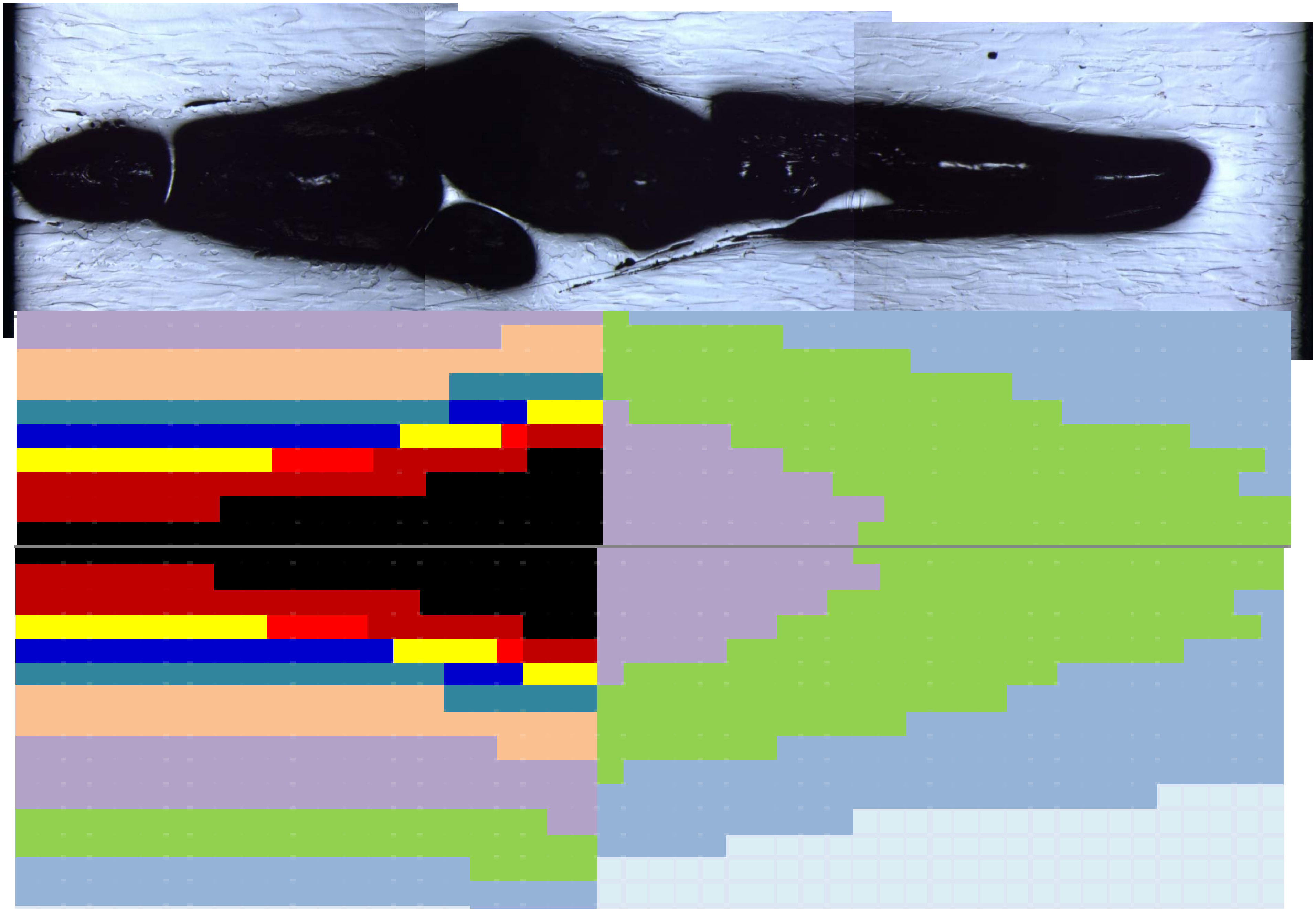
2x 2.4 Gui



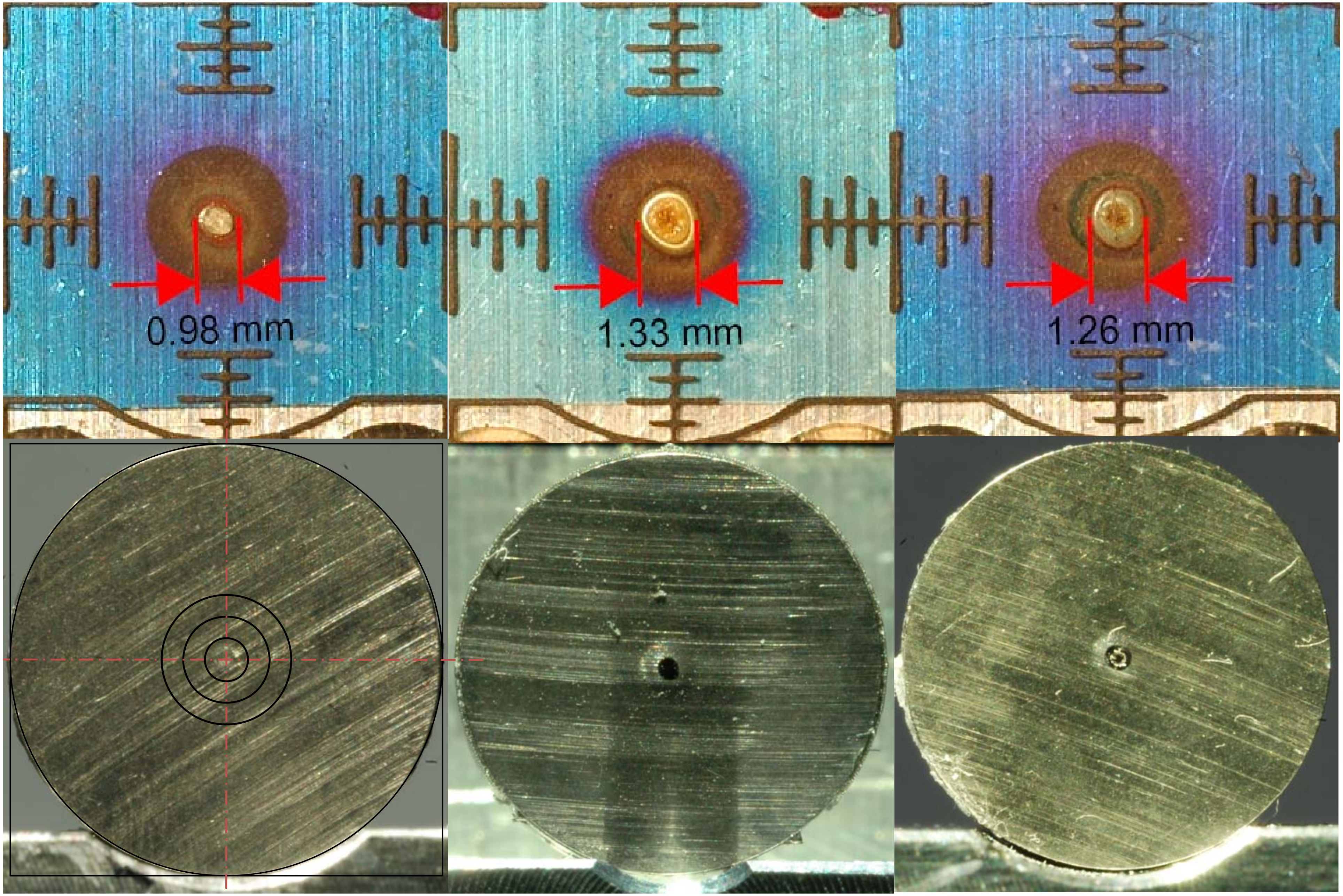
6x 450-890 Mui

3x2 GUi

Ta-14, 2 x 2.4 GUi

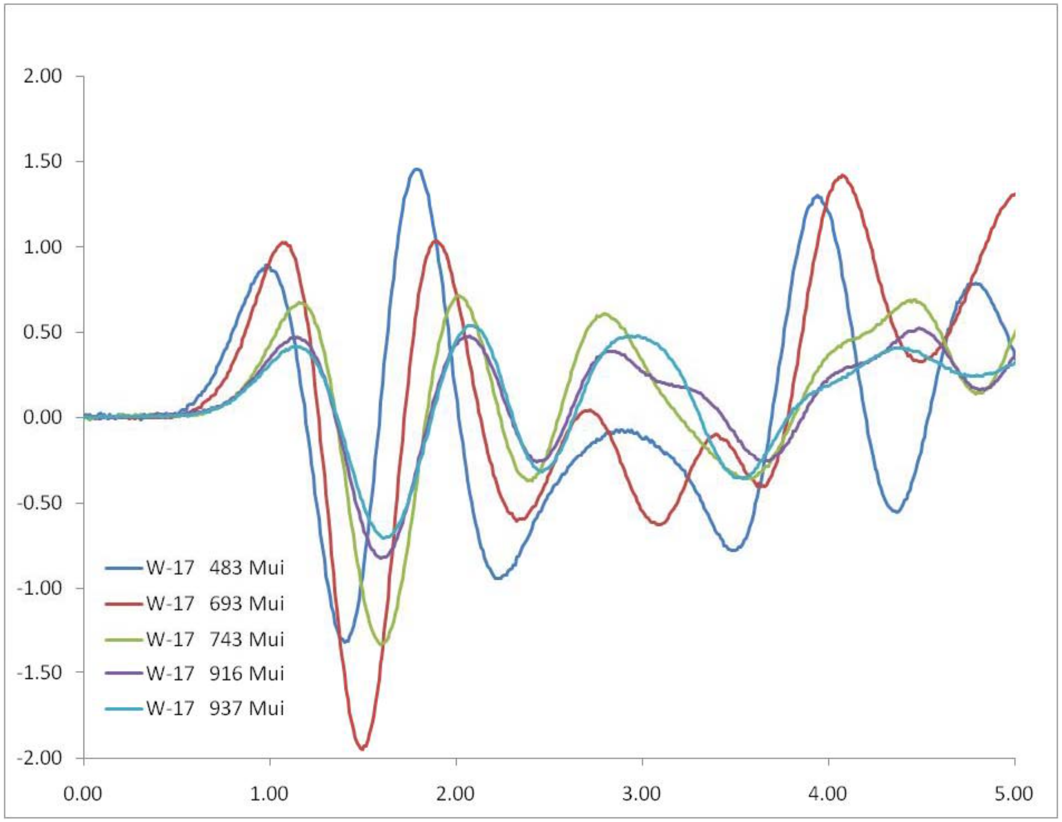


W – 17, 18, 19

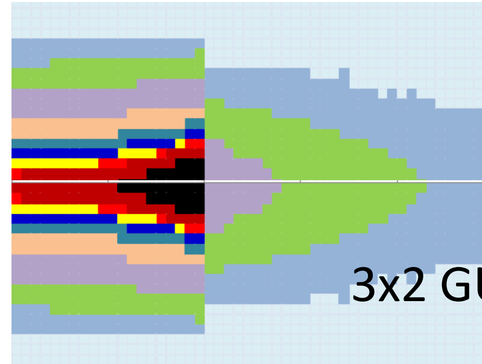


Scaling with beam intensity W-017

All curves scaled by to 1 G U-ions.
No scaling of the first wave at all. The W-sample is expected to be the most resilient and U-pulse intensities are between 0.5 and 1 GUi. The sample is possible damaged or may also have slightly moved.
A delay is observed in the three last measurements (0.25 us)
Very low intensity shots are missing and would be help understanding this response.



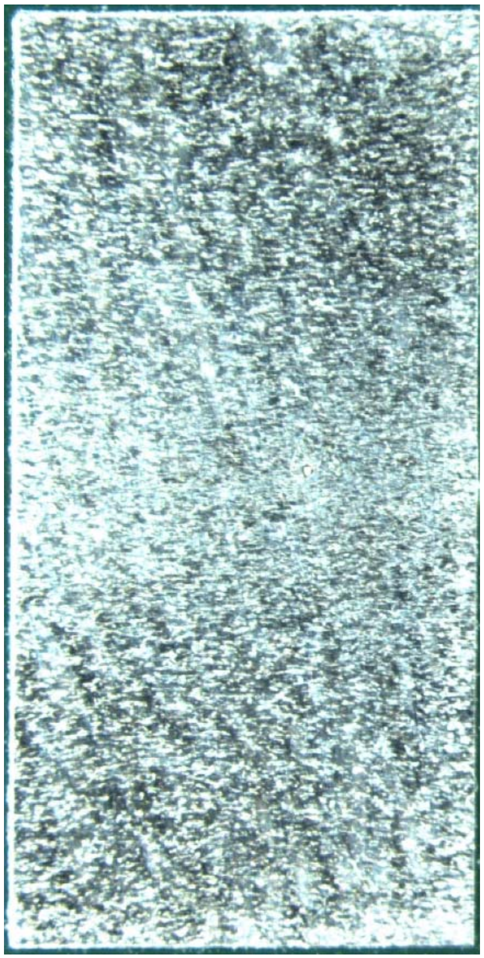
W-17, W-18, W-19

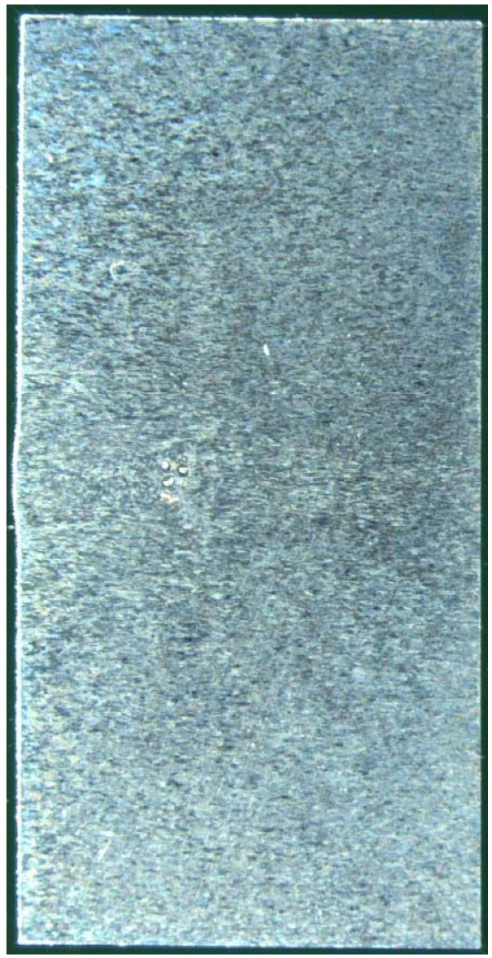


5x 480-930 Mui

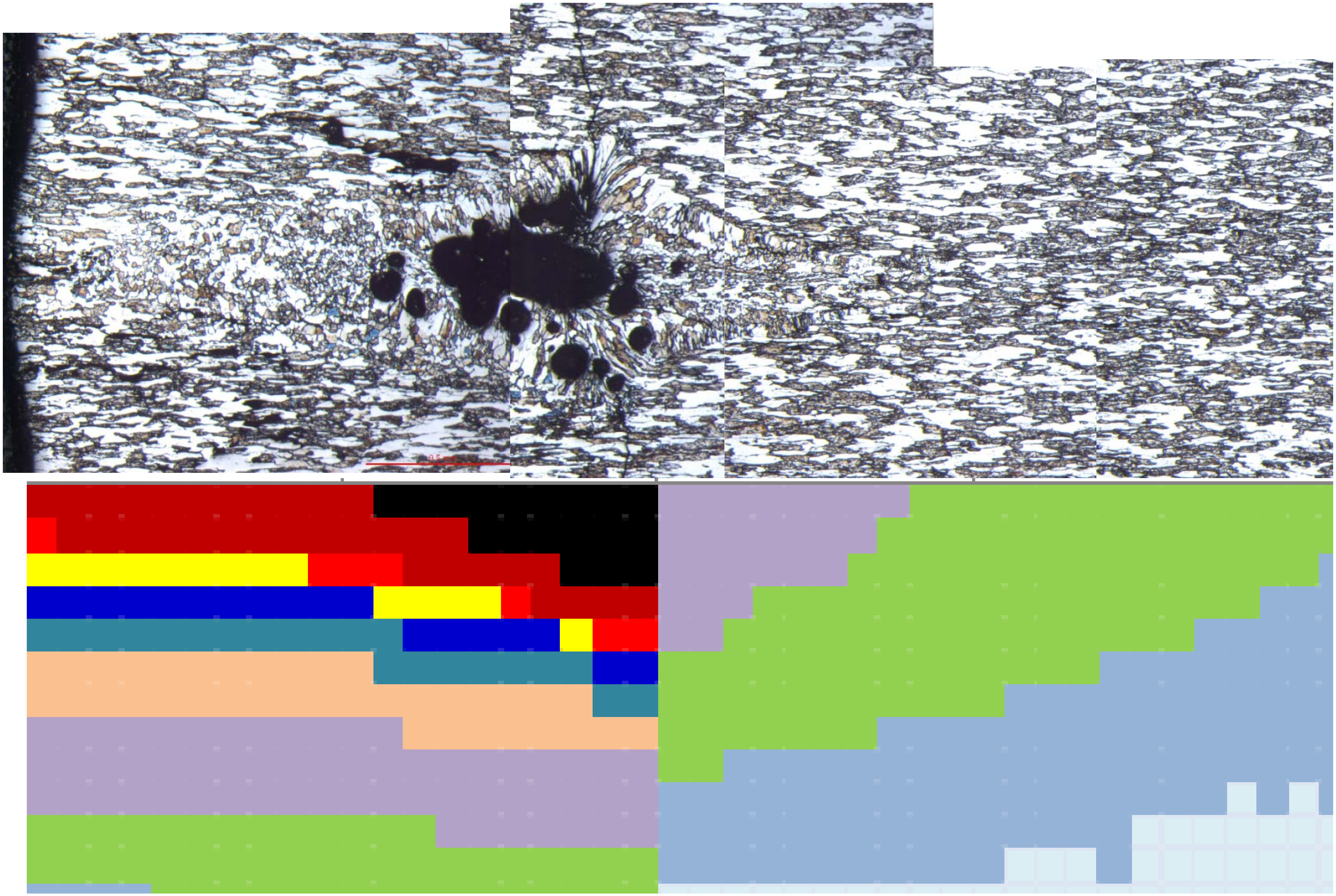
2x 2.2 Gui

3x2 GUi

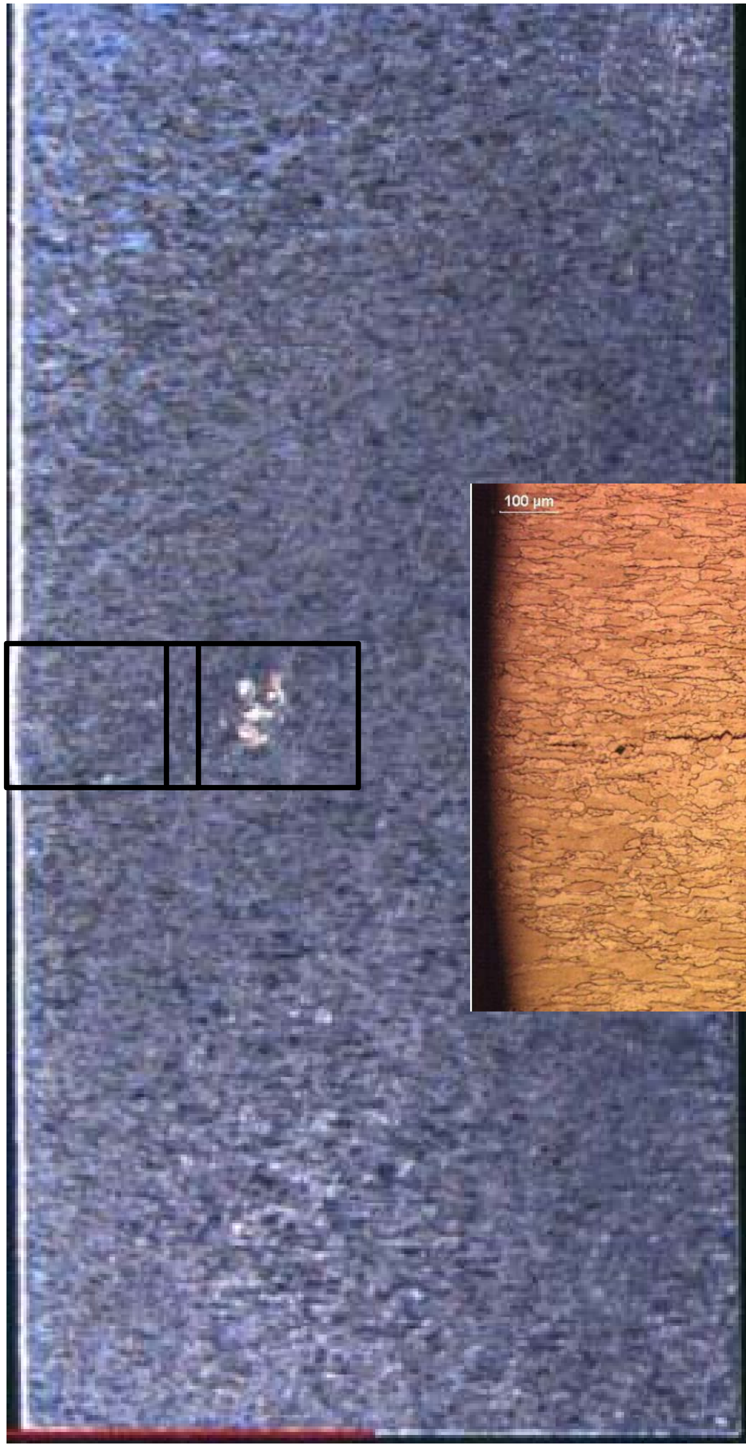




W-19 3x 1.95 GUi

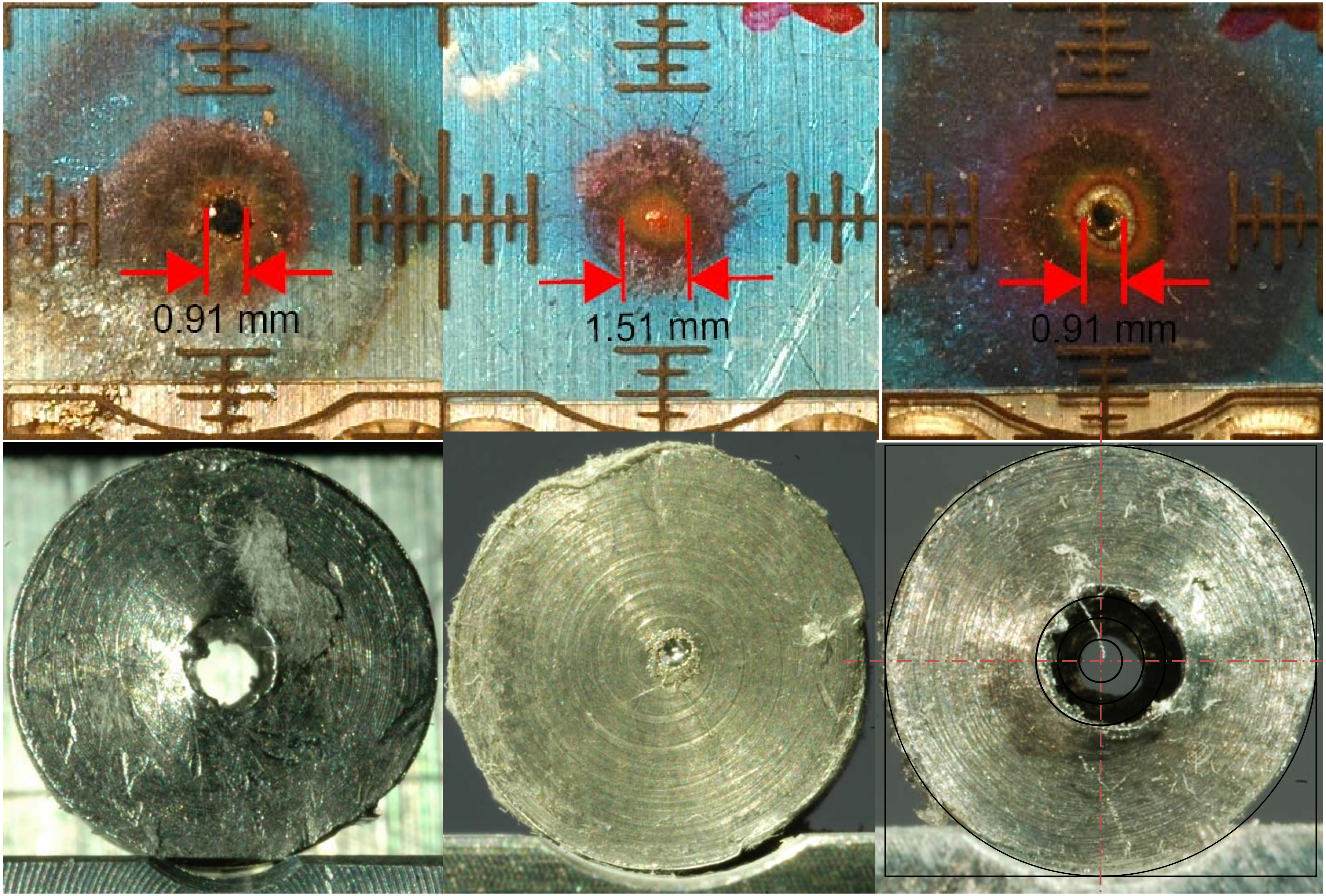


W-18, 2x2.2 GUi



Deformation of the beam entrance surface,
Re- crystallisation (different grain orientation)
Grain boundary cracks and 0.05-0.2 mm holes

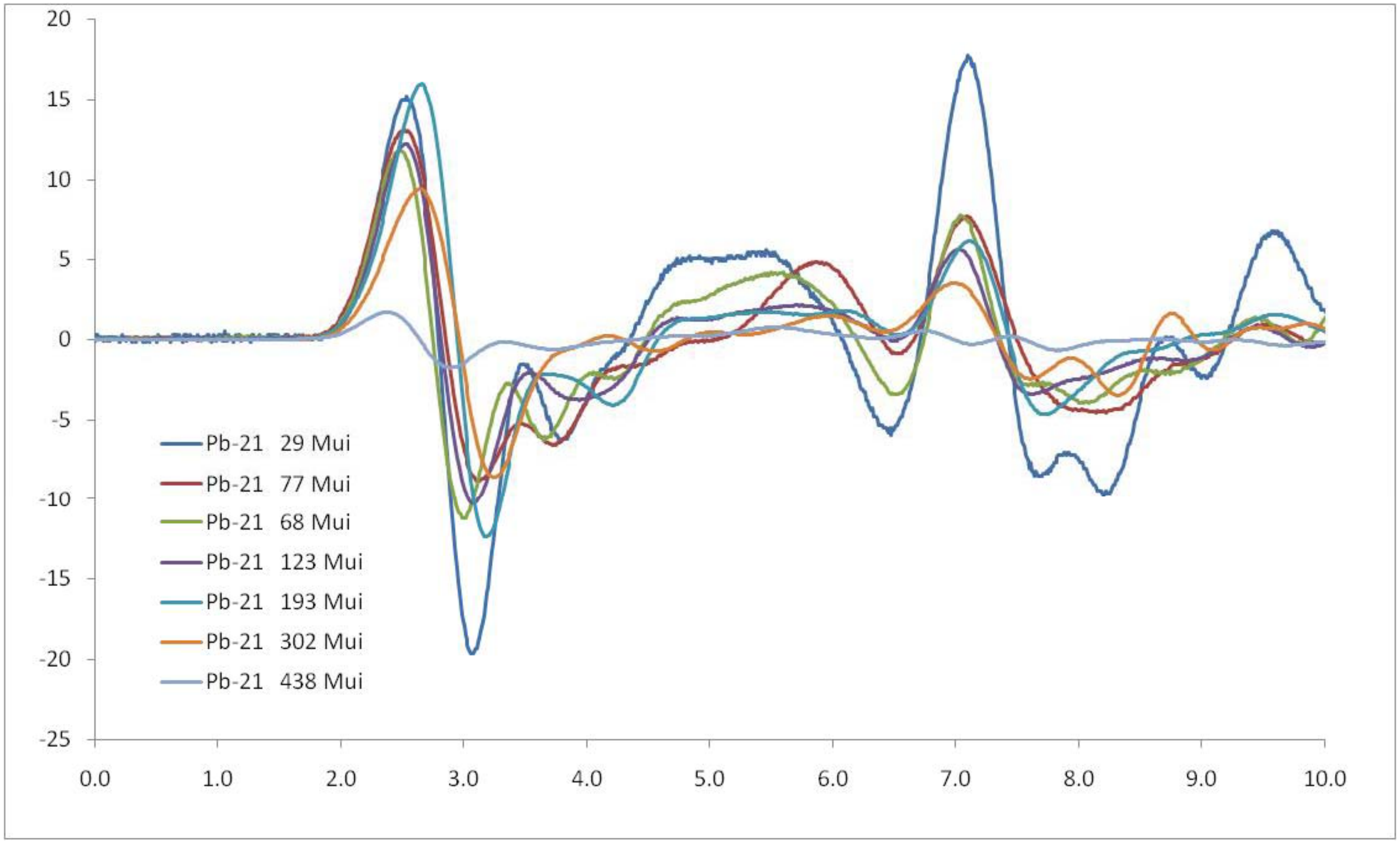
Pb – 20, 21, 22



Scaling with beam intensity Pb-21

All curves scaled by to 1 G U-ions.

The scaling of the first wave at intensity below 70 Mui ends after the first 120 Mui pulse, the 400 MUi brings only 10% of the expected velocity; the sample is likely to be severely damaged or even hollow !

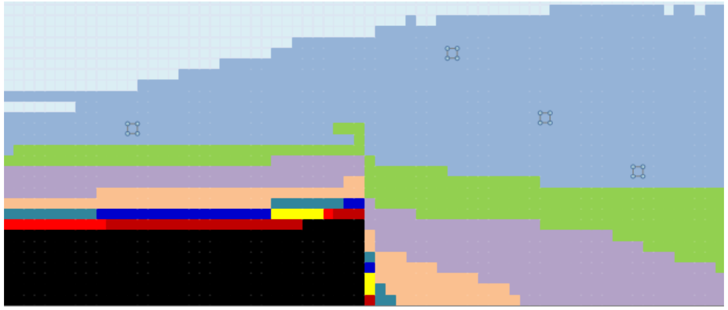


Pb-21, Pb-22

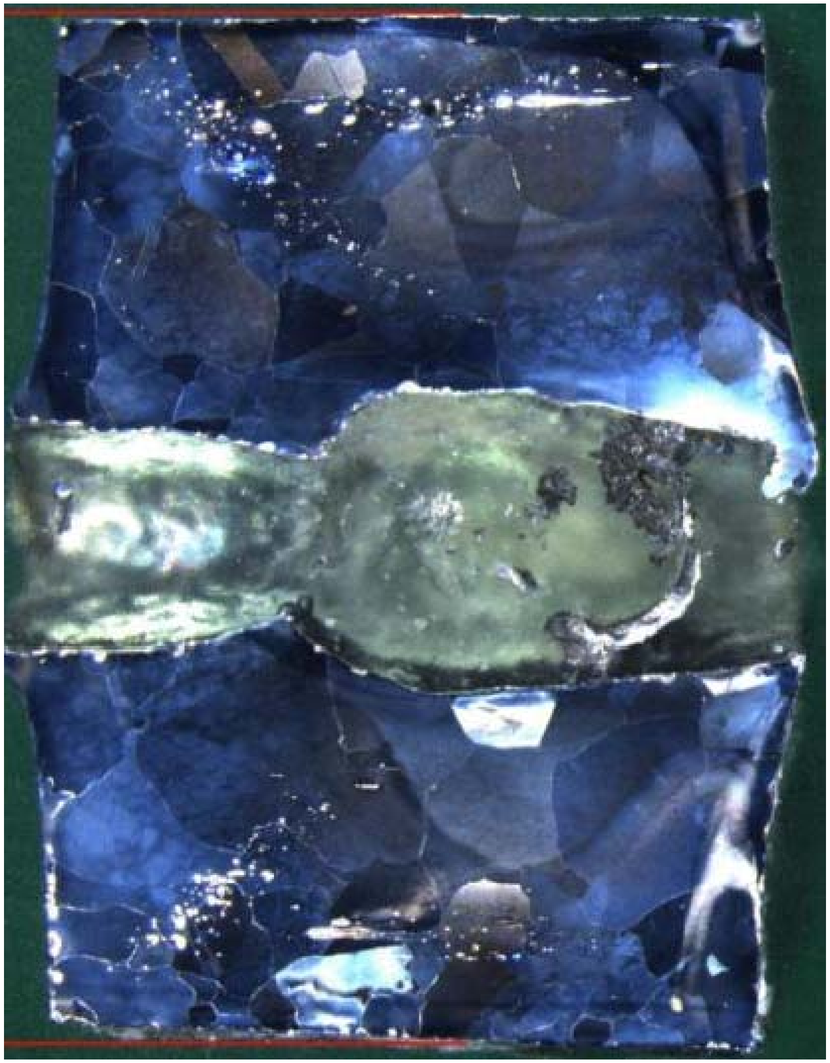
7x 29-438 Mui

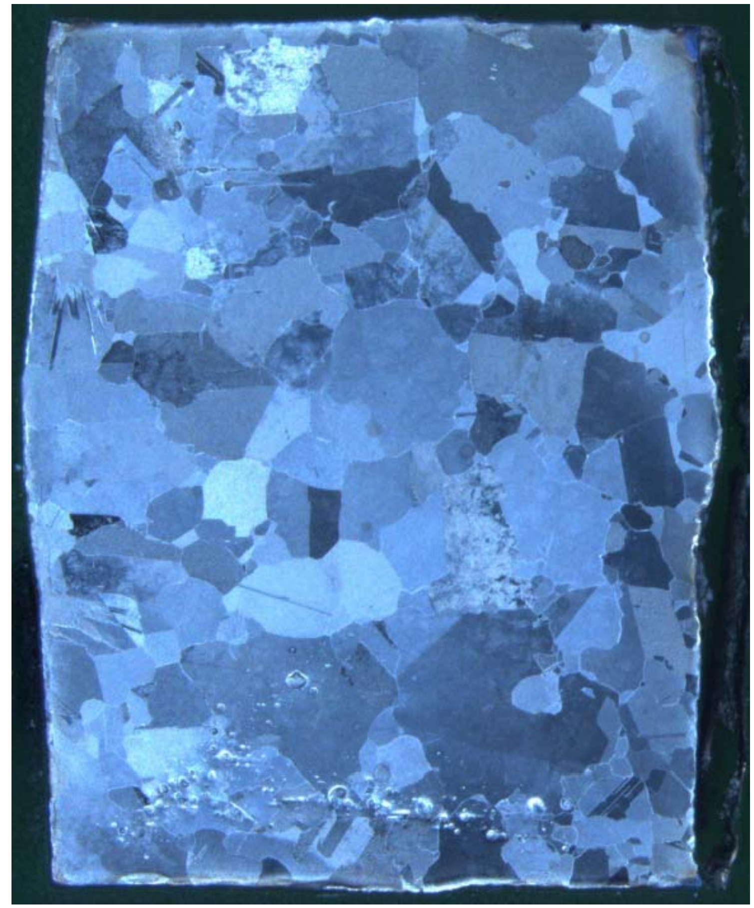
2x2.1 GUi

Pb-20, 2x 2.2 GUi

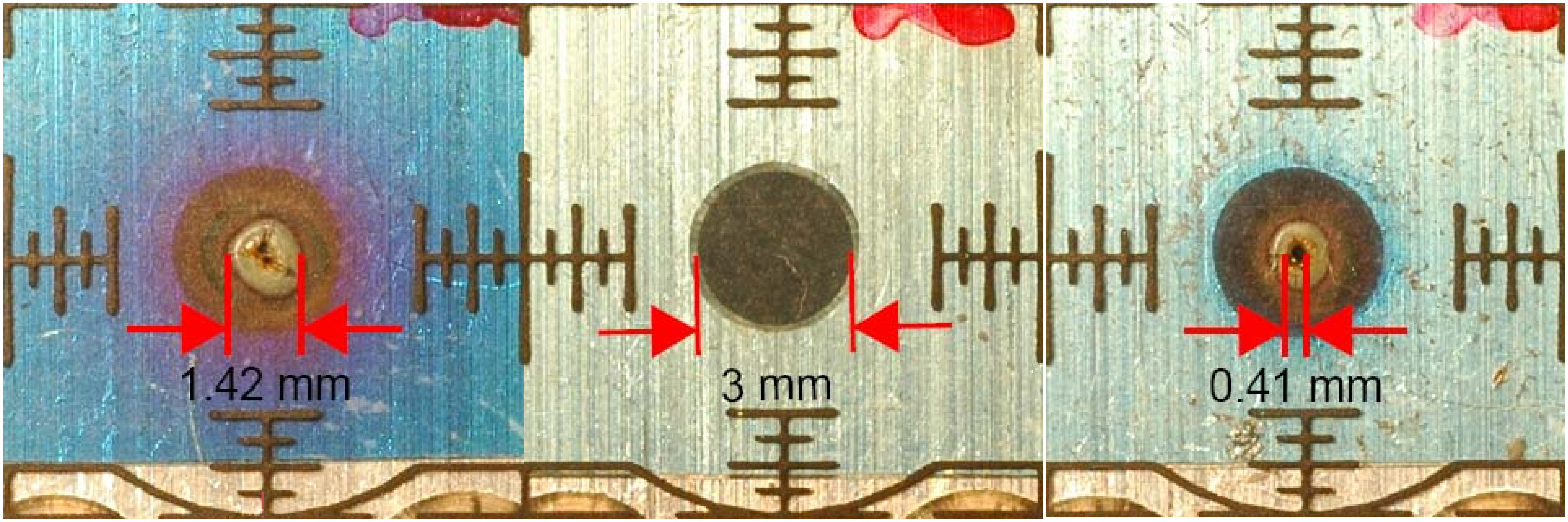


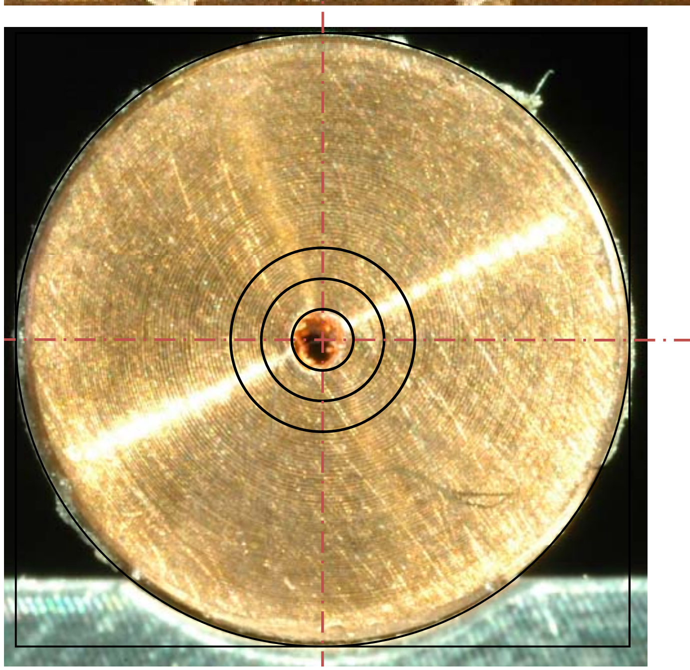
Dynamic pressure wave interference induced
Holes in the Pb matrix where initial heating was
Below 0.1% of the melting point.
On a cylinder at 4 mm from the center and
on a 45 deg line … which of the two pulses …

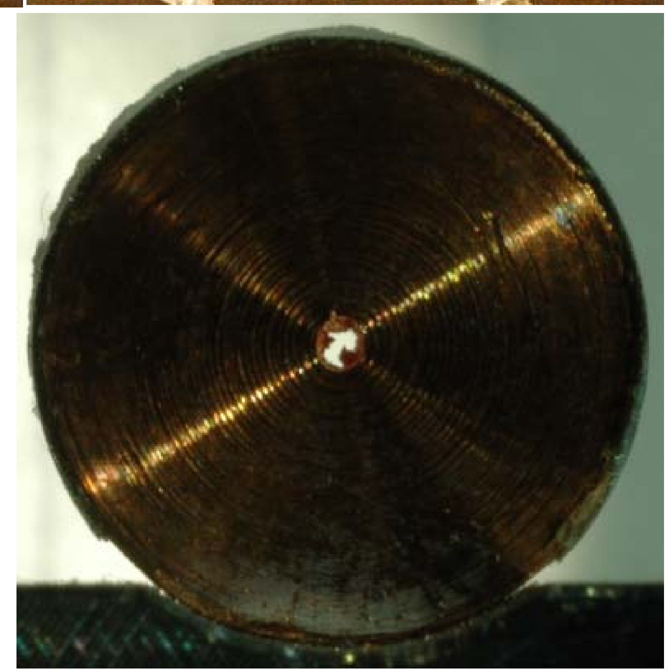




Cu – 23, 24, 25

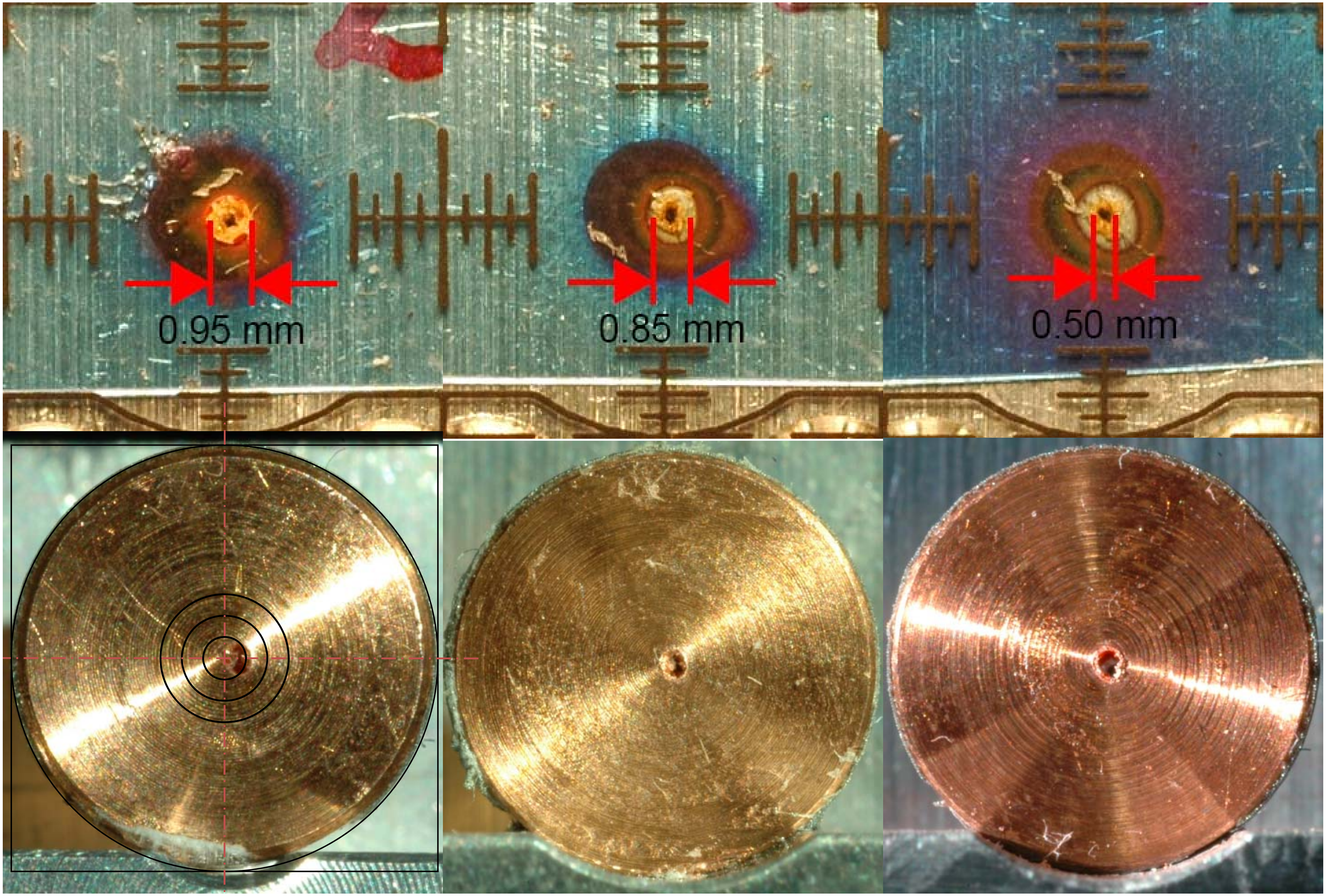






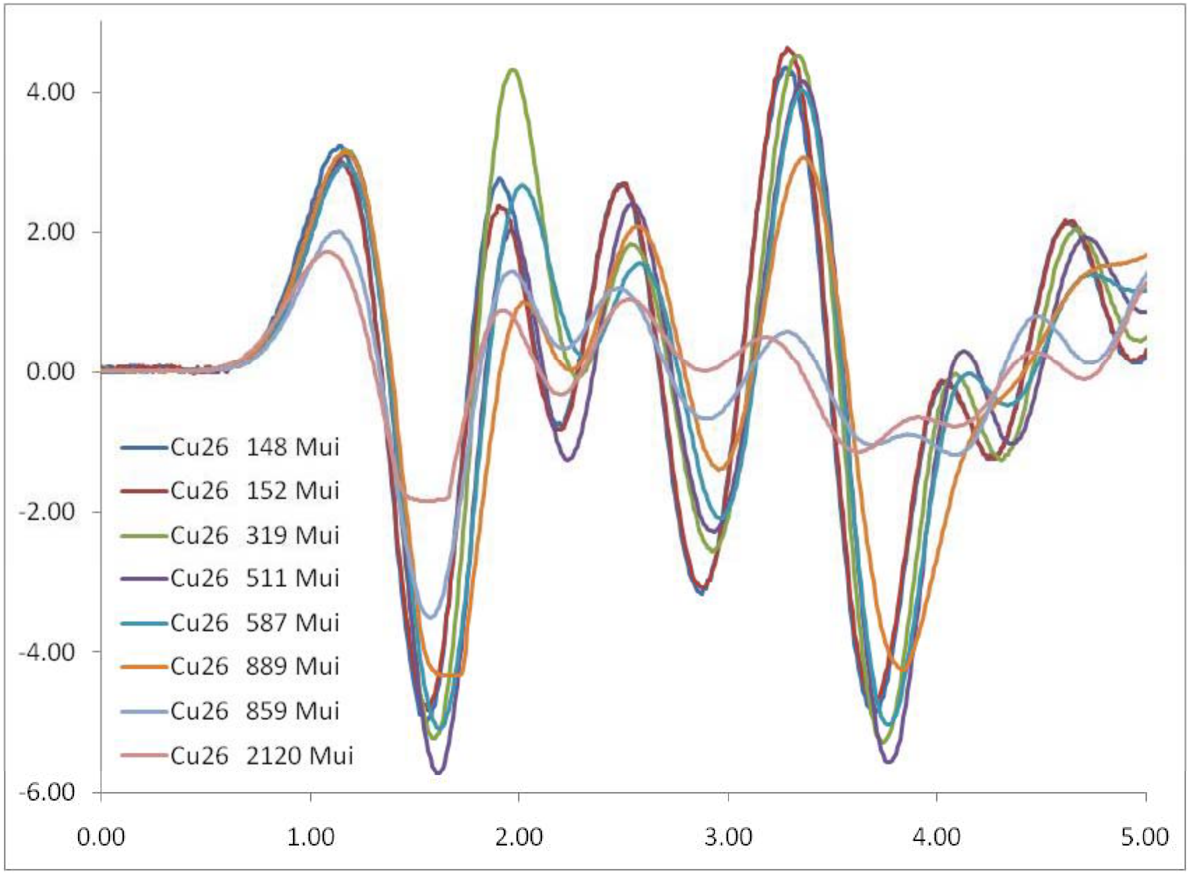
CERN-Metallic targets GSI ^{238}U beam

Cu – 26, 27, 28



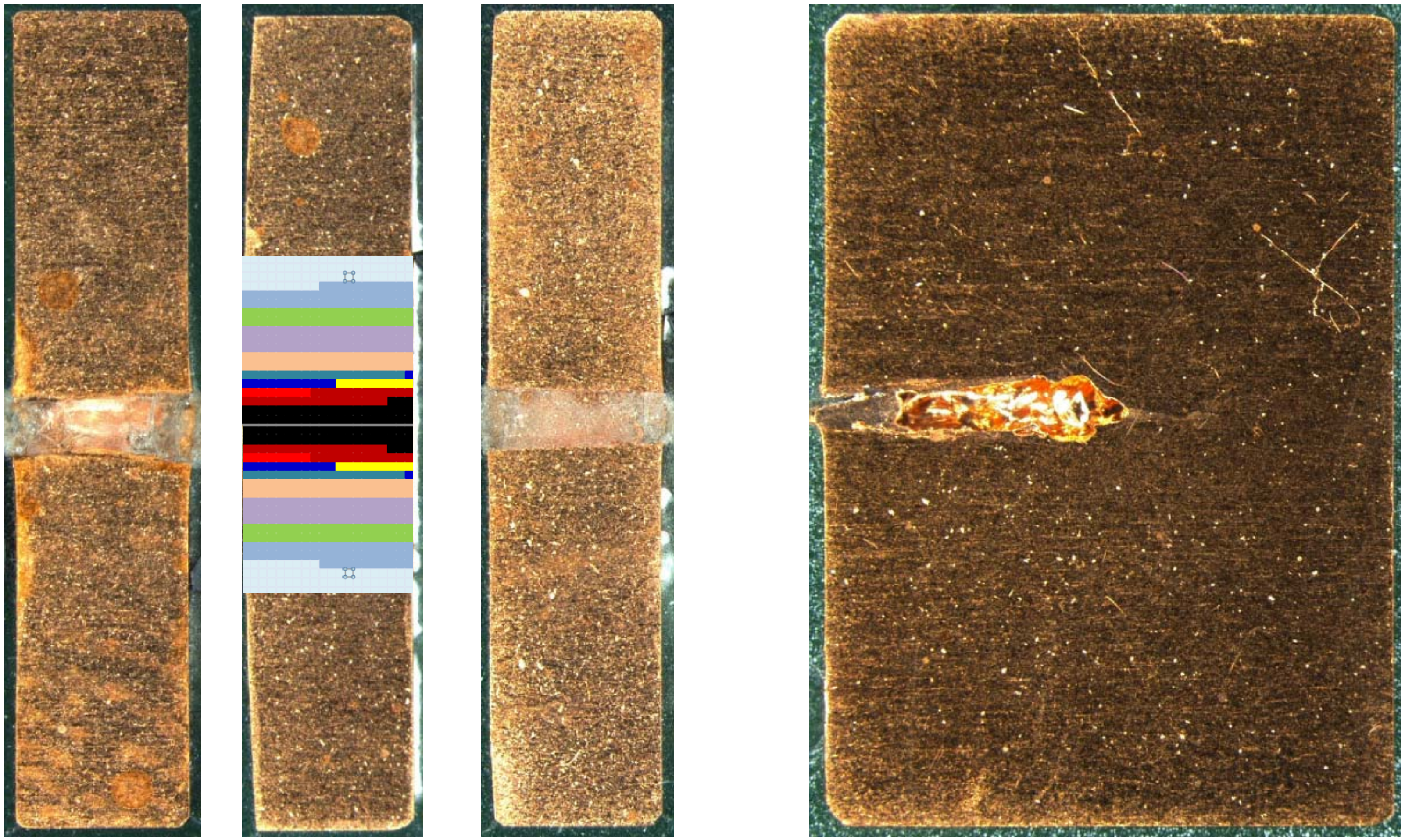
Scaling with beam intensity Cu-026

All curves scaled by to 1 G U-ions.
The obvious scaling of the first wave at intensity below 600 Mui ends after the first 900 Mui pulse, at this energy density, the sample is likely to be damaged !



Cu-23, *Cu-24*, Cu-25, Cu-26

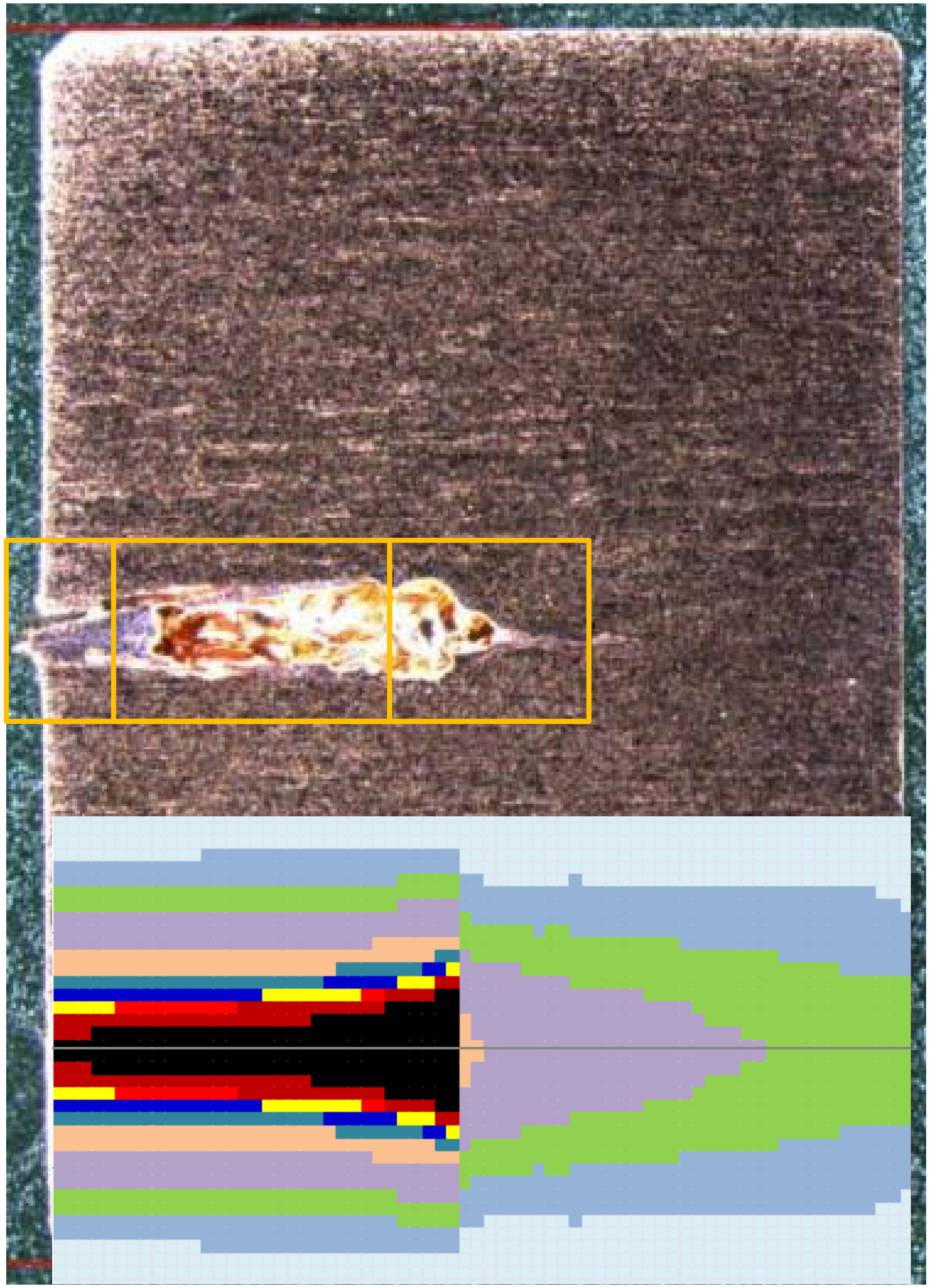
2x 2.2 Gui | 0 | 2x 2.2 Gui | 8x 148-2120 Mui



Cu-27, Cu-28

3x 1.9 GUi

2x 2.2 GUi

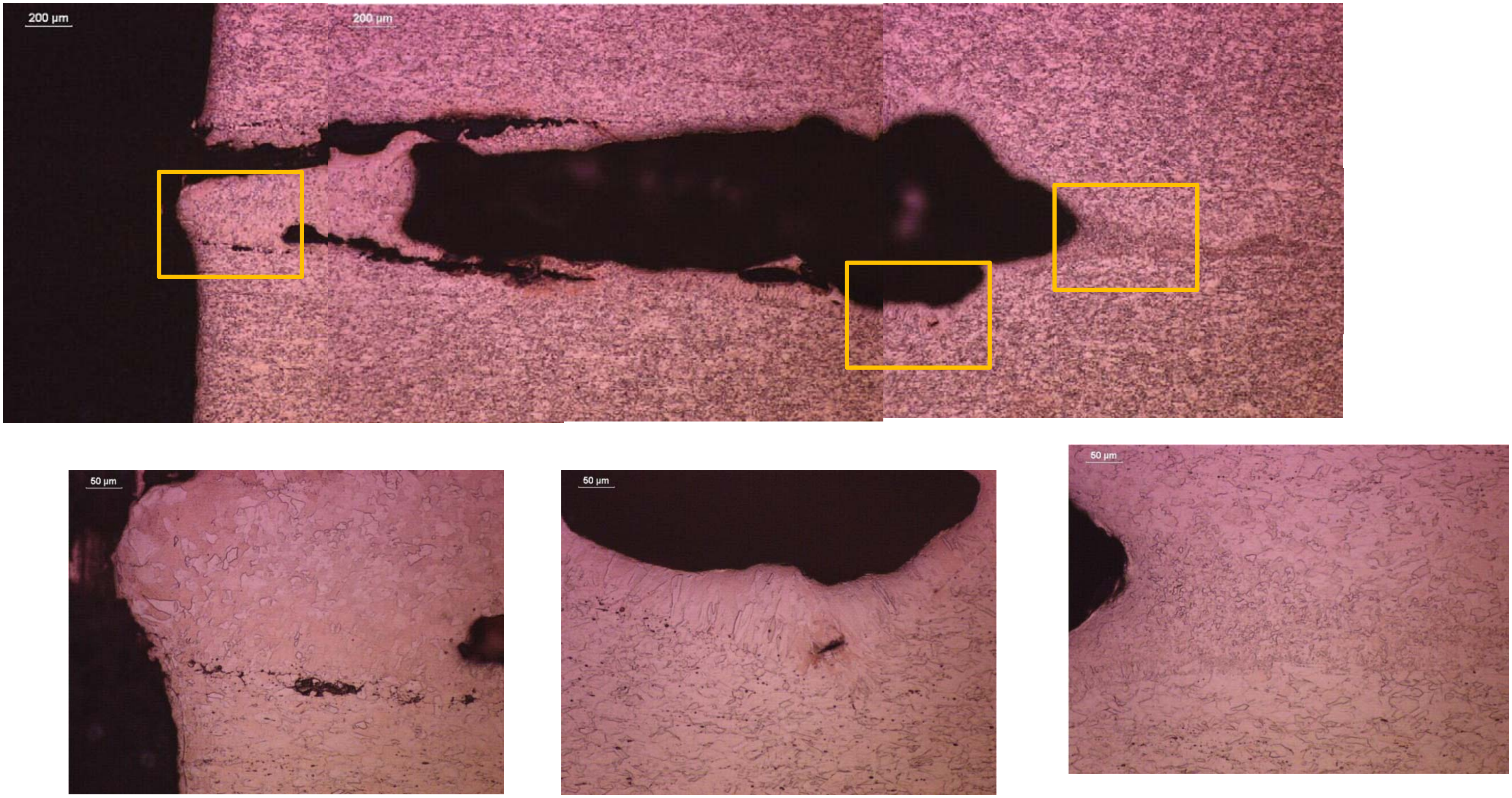


Cu-26

8x 148-2120 Mui

2.1 GUi M.P. zoning

Cu-26-b,c



Re- crystallization zones visible all around the molten-removed zone.
A very fine meshing of the modeling software would be required to track 50 microns regions

As a conclusion /outlook

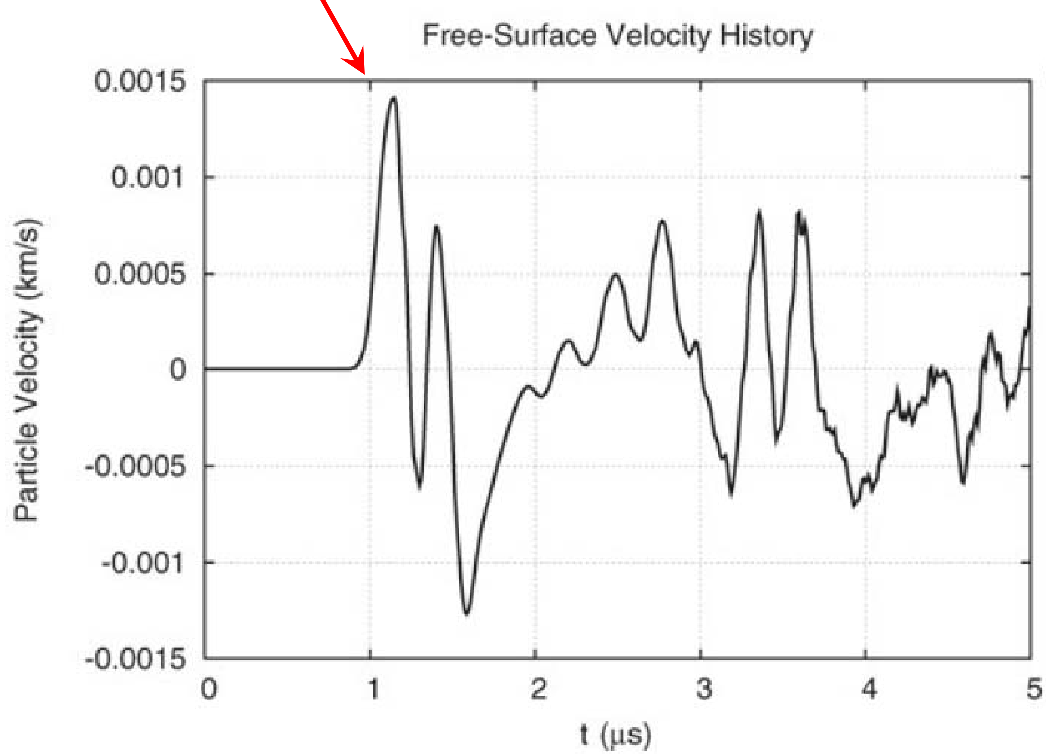
- The LDVM was operated at distances of up to 30 m from high radiation areas and through vacuum sealing windows. It is a unique tool to gather real time data in high dose rate areas.
- The GSI samples were all multi shots irradiated, the understanding of the metallurgical observations becomes very complex and single shot probes would have been necessary.
- The sensitivity of the LDVM to investigate "small effects" via vibration eigenmodes damping time constant was demonstrated, however the sample holder at GSI would have an unknown contribution, It is not applied here but remains a potential interesting approach.
- Damaged samples were identified. (as a matter of fact all samples were submitted to high intensities and damaged ...). Precise zoning of the molten zones with a quite simple energy deposition (FLUKA). Refrain from shooting as hard as possible in the phase 2 ☺
- Intensive work mandatory to validate the models' equation of state, dedicated experimental validation unavoidable, i.e AUTODYNE simulation presented in ref. 4.

References, related publications :

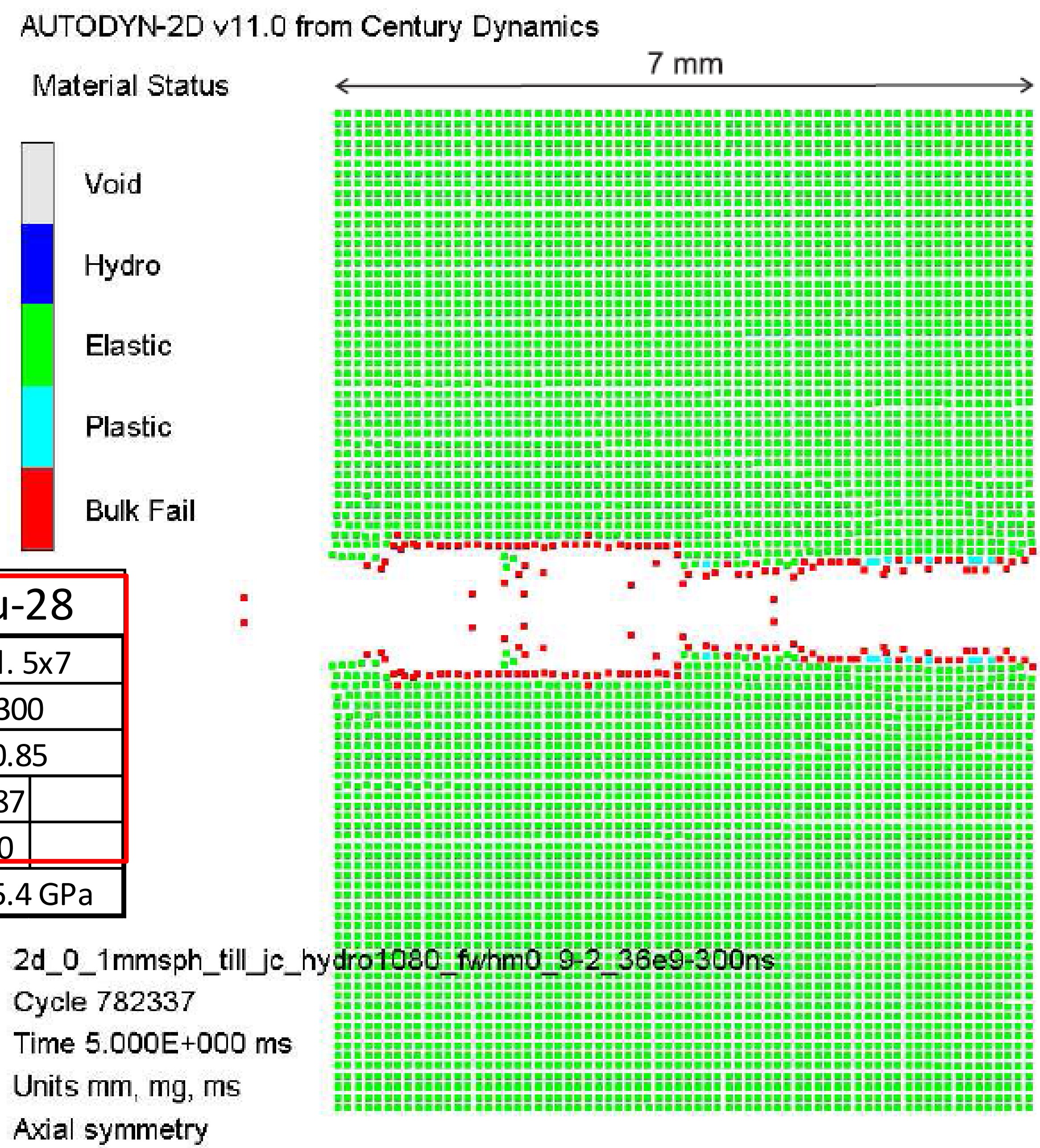
1) *Gasdynamic issues in transverse beam size measurements.* A. Hug, D. Varentsov, V. Turtikov, D.H.H. Hoffmann, A. Fertman, M. Kulish, J. Menzel, V. Mintsev, N. Muller, D. Nikolaev, B. Sharkov, N. Shilkin, V. Ternovoi, and S. Udrea,
2) *Study of thermal stress waves induced by heavy ion beams,* A. Hug, R. Wilfinger, A. Kelič, B. Achenbach, K. H. Behr, A. Bruenle, R. Catherall, F. Cerutti, H. Geissel, D.H.H. Hoffmann, Ch. Karagiannis, B. Kindler, K. Knie, M. Krause, M. Kulish, J. Lettry, J. Ling, B. Lommel, J. Menzel, N. Müller, H. Richter, K. Suemmerer, N.A. Tahir, M. Tomut, Ch. Trautmann, S. Udrea, D. Varentsov, H. Weick, M. Winkler, Y. Zhao. GSI-poster 2008.
3) R. Wilfinger, et al., "*Proton induced thermal stresswave Measurements using a Laser Doppler Vibrometer*", RNB7 Proceedings, EPJ—Special Topics, Vol. 150, 2007, p. 379–382.
4) H. Richter, et.al, *Simulation of target response due to uranium ion beam impact*, E. Eur. Phys. J. A 42, 301–306 (2009)
5) N. Tahir *et al., Numerical modeling of heavy ion induced stress waves in solid targets, Laser Part. Beams 25, 523 (2007)* 523–540.

N. Tahir et.al. [5]

Ref.5 N. Tahir		Cu		Pb		Ta		W				C	
diameter x Length	[mm]	cyl. 5x7		cyl. 5x7		cyl. 5x5		cyl. 5x5				cyl. 5x15	
duration	[ns]	500		500		500		250		500			
beam size FWHM	[mm]	0.5		1.0		0.5		0.5		1.0		0.5	2.0
Elastic	Gui, m/s	50	1.4	25	1.2	50	0.35	50	0.7	150	2.1	2000	1.6
Plastic		150	2.3	55	2.5	150	1.2	125	3.3	500	3.3	4000	2
Rupture						4000	24						



H. Richter et.al. [4]



Ref.4 H. Richter		Cu-26		Cu-28	
diameter x Length	[mm]	cyl. 5x7		cyl. 5x7	
duration	[ns]	300		300	
beam size FWHM	[mm]	0.85		0.85	
Plastic	Gui,	587	4.65	587	
Rupture	m/s	2120		2x2120	
(*) tuning of rupture pressure: -2.16, -1.8, -5.4 GPa					