中国工程物理研究院
CHINA ACADEMY OF ENGINEERING PHYSICS

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The 13th International Conference **“ZABABAKHIN SCIENTIFIC TALKS”**

Experimental Study on Colliding Shock Waves and Mach Stem Formation in Metals

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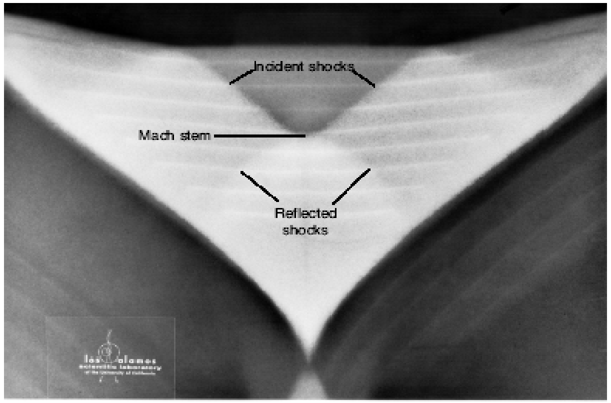
ЗАБАБАХИНСКИЕ
2017
НАУЧНЫЕ ЧТЕНИЯ

March 20-24, 2017
Snezhinsk, Chelyabinsk region, Russia

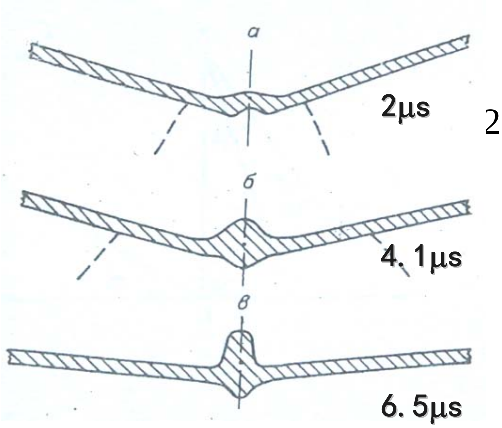
1. Motivation: To define what really happens when two shock waves meet

LANL in 1960s: **Experimental study on Mach stem formation under two shock waves collision,** LANL Sci., No,28, 2005



А.Г.Иванов
С.А.Новиков:
Столкновение
детонационных
волн на
поверхности
инертного

Трищоковая струя



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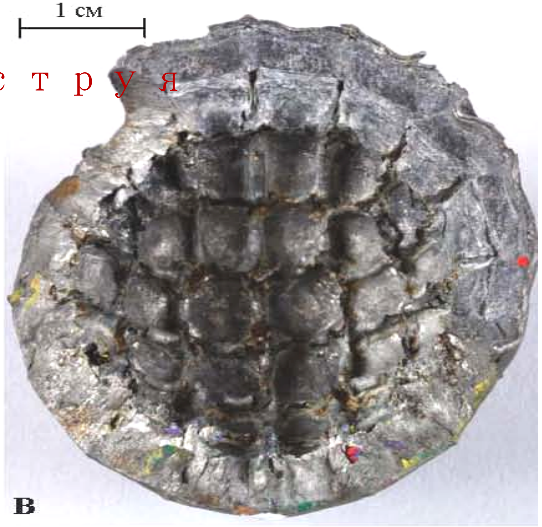
2-

2D- and 3D- experiments for verification of spall and shear strength models for some steel, E.A.Kozlov, SCCM2011



Ekaterina V. Shuvalova, VNIIEF, ZST-2012: NUMERICAL 3D SIMULATION OF SPALL AND SHEAR DAMAGE IN SHELLS OF AUSTENITIC STEEL 12KH18N10T, Fe AND STEEL 30KHGSA AT SPHERICAL AND QUASISPHERICAL EXPLOSIVE LOADING

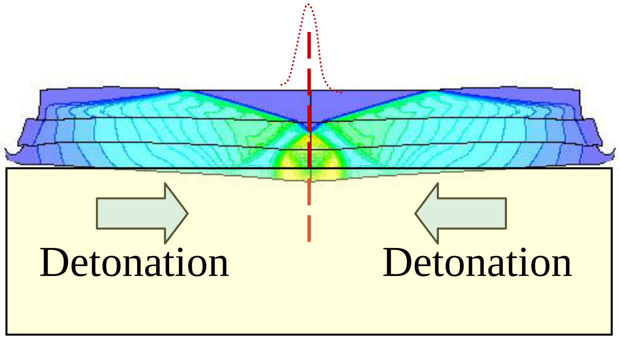
1. Motivation: Real time quantitative diagnostics by experiment

A multi-channel PDV probe was designed to quantify the dynamic response of metal flyer in the collision region of two head-on sliding detonation waves by measuring the free surface velocity profile for particles near the collision line.

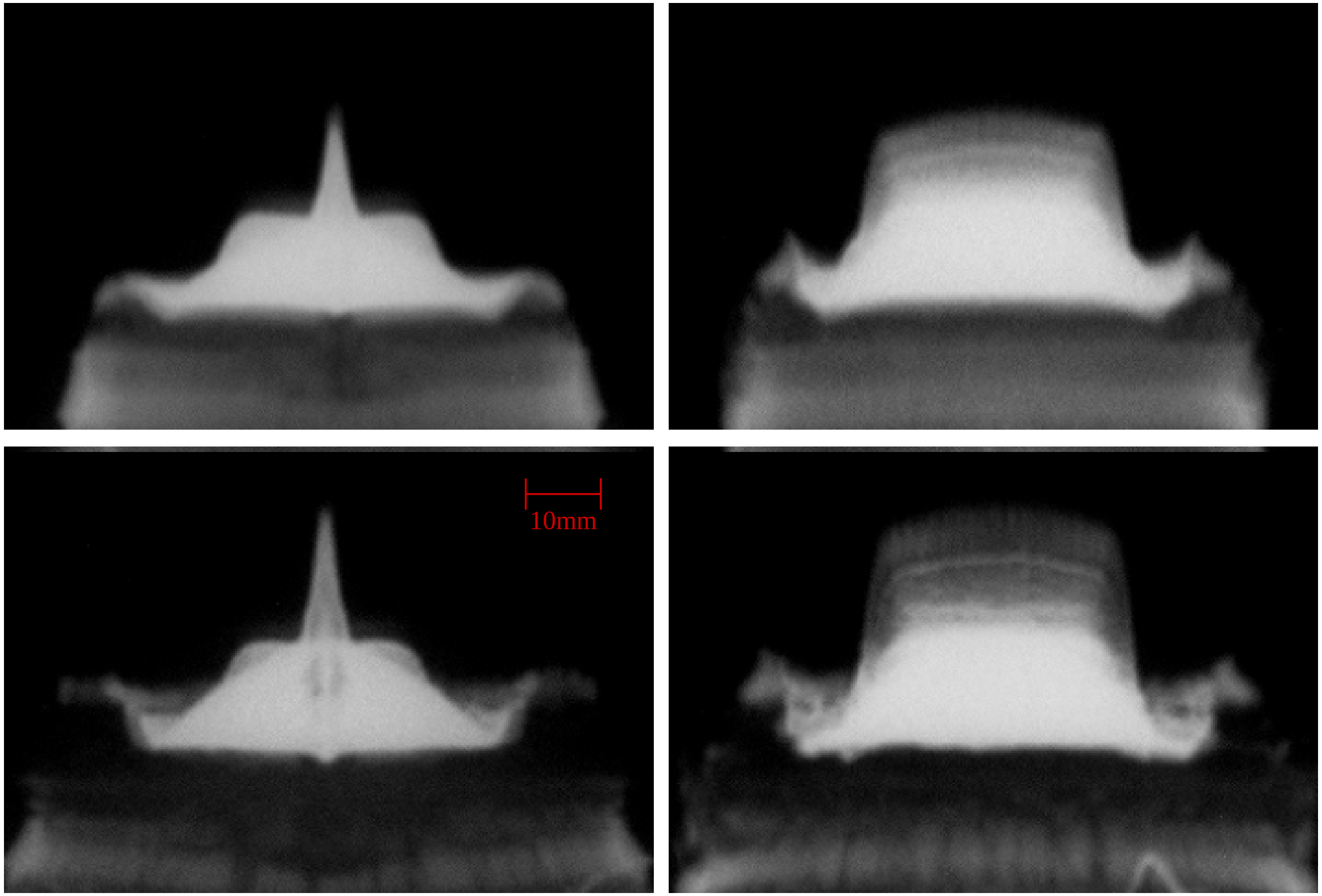
Data recorded on the free surface near the collision line show either typical regular reflection or typical Mach stem configurations as a result of two shock waves collision inside W, Sn, Pb, Ce flyer.

The distribution of particle velocity recorded on the free surface near the collision line can help to interpret the formation of jet-like spiking of flyer in the collision region and its late stage behavior, serves as a early time benchmark for hydrodynamic codes validation.

Evolution of surface shape under uneven loading

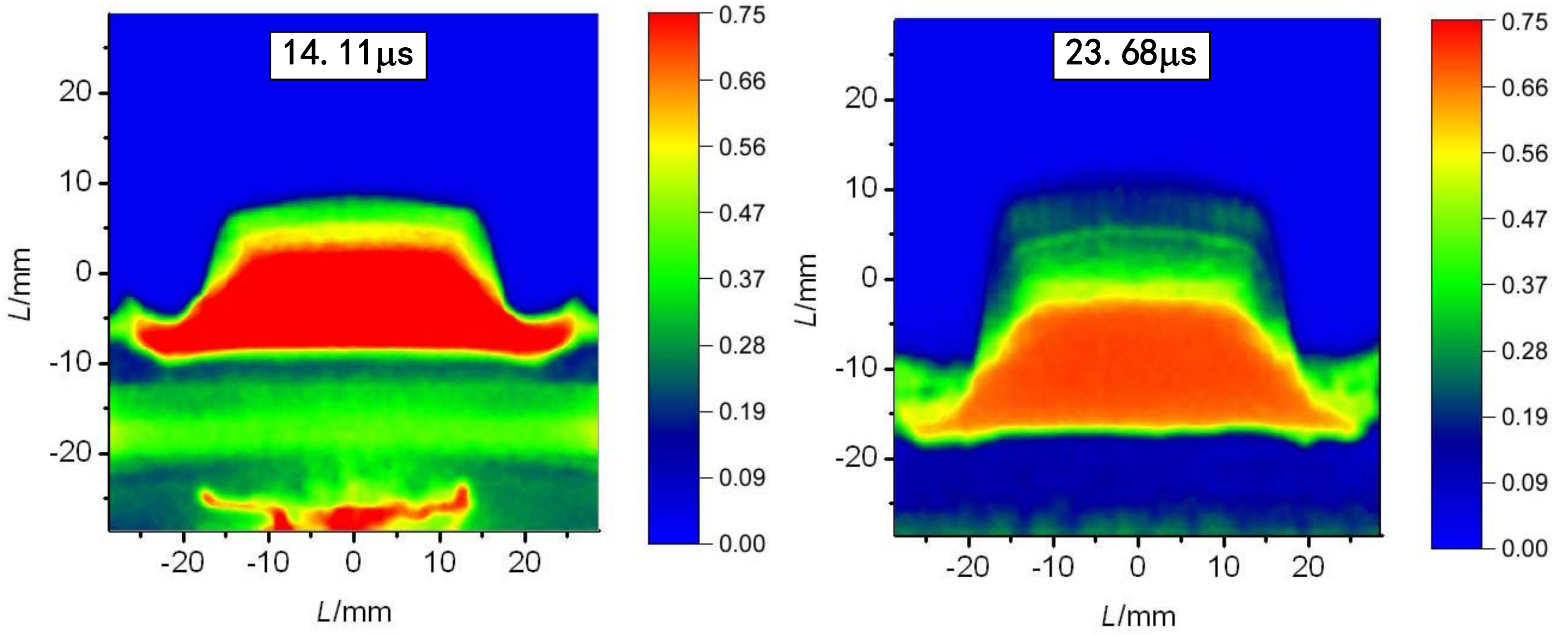


Spiking in late stage evolution: The collision spiking on Pb flyer



Density distribution in Pb spiking loaded by PETN

High gradient of particle velocity along the height of stretching spiking body.



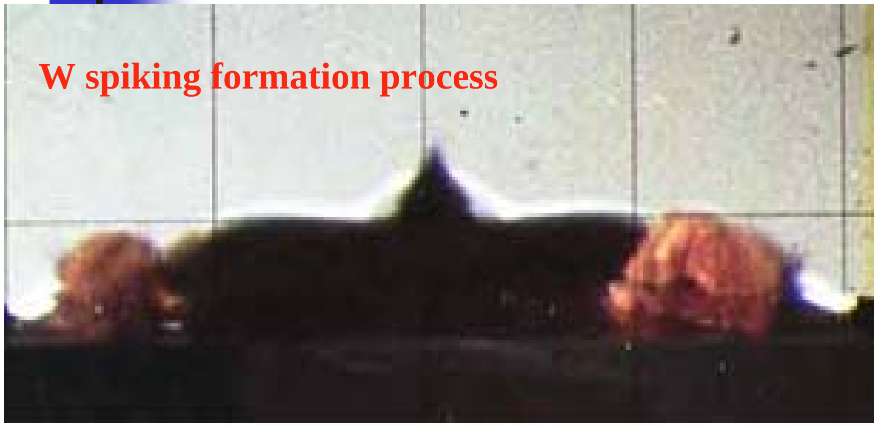
14.11μs: tip zone density **(280～560)mg/cm^2, 2.0g/cm^3 ,** **~ 0.18ρ_0**

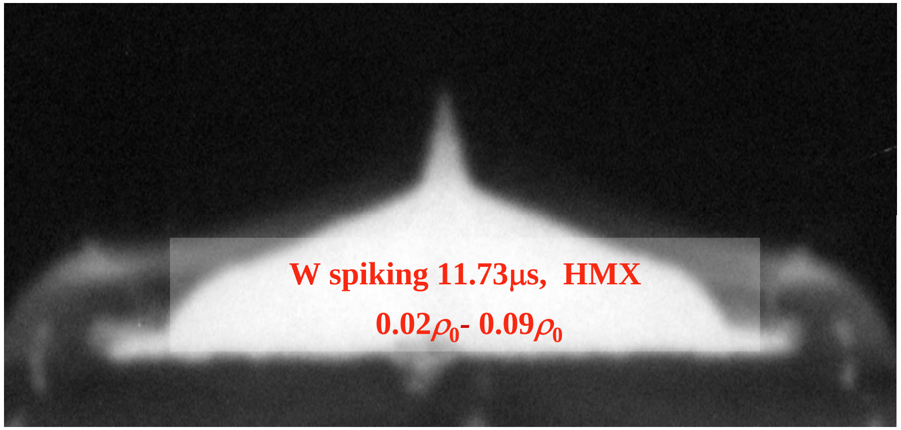
23.68μs: tip zone density **(170～250)mg/cm^2, 0.8g/cm^3 ,** **~ 0.07ρ_0**

<< **initial density of Pb ρ_0 (11.35g/cm^3),** bottom zone density (5～7)g/cm^3

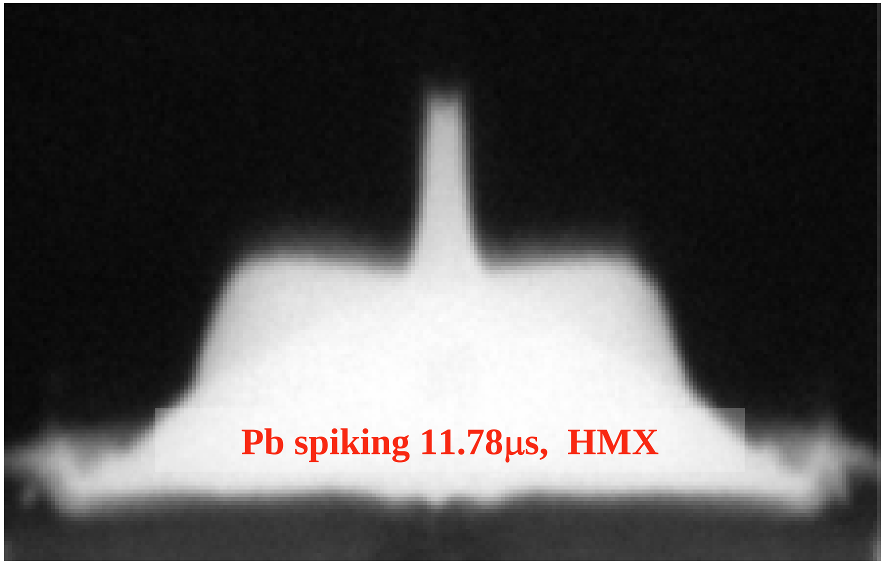
Details of spiking tip form observed in the late stage

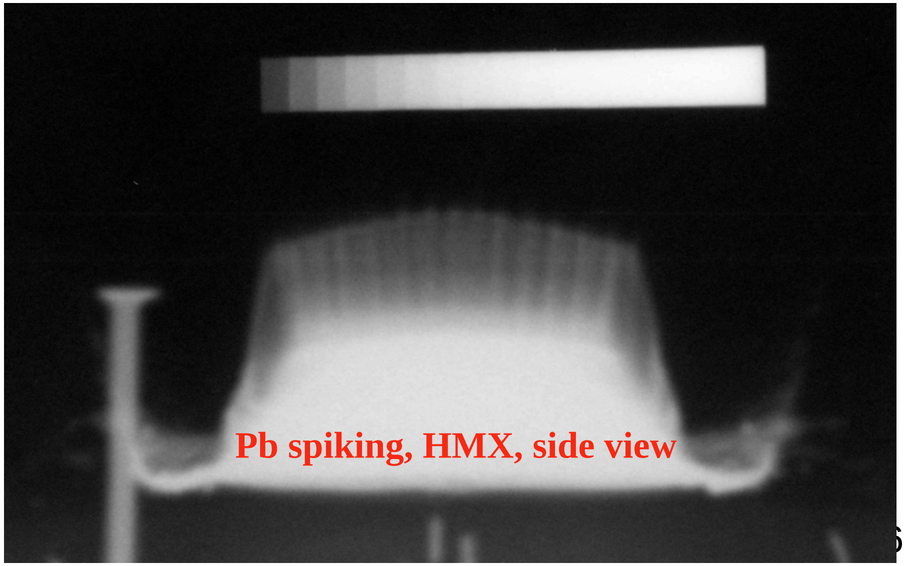
—Sharp / flat spiking tip form, pseudo-continuum jet body ~ spray ≠eject!


W spiking formation process

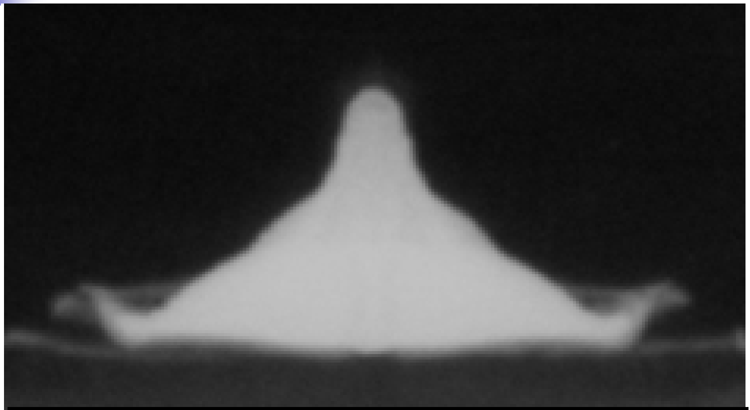

W spiking 11.73μs, HMX

$0.02\rho_0$- $0.09\rho_0$

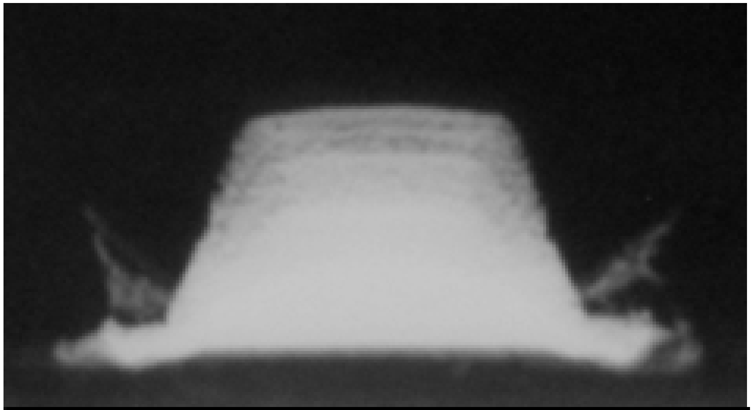

Pb spiking 11.78μs, HMX


Pb spiking, HMX, side view

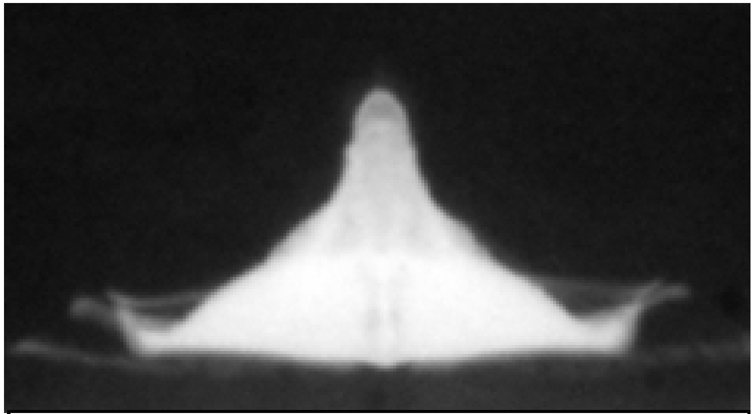
Not so slim spiking with blunt tip on Cerium flyer?



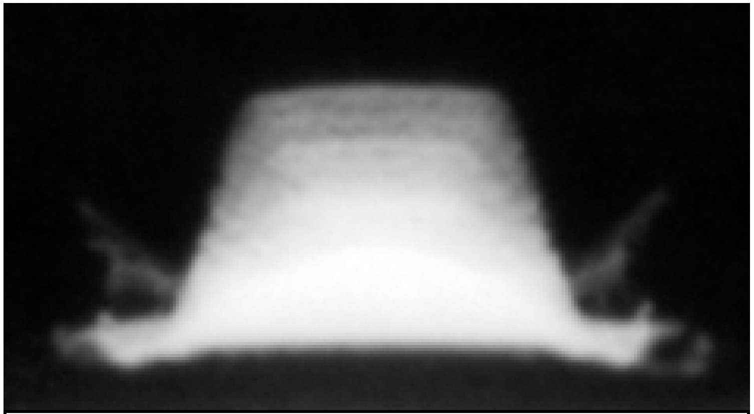
Ce, 18.57μs, PETN



Ce, 18.40μs, PETN

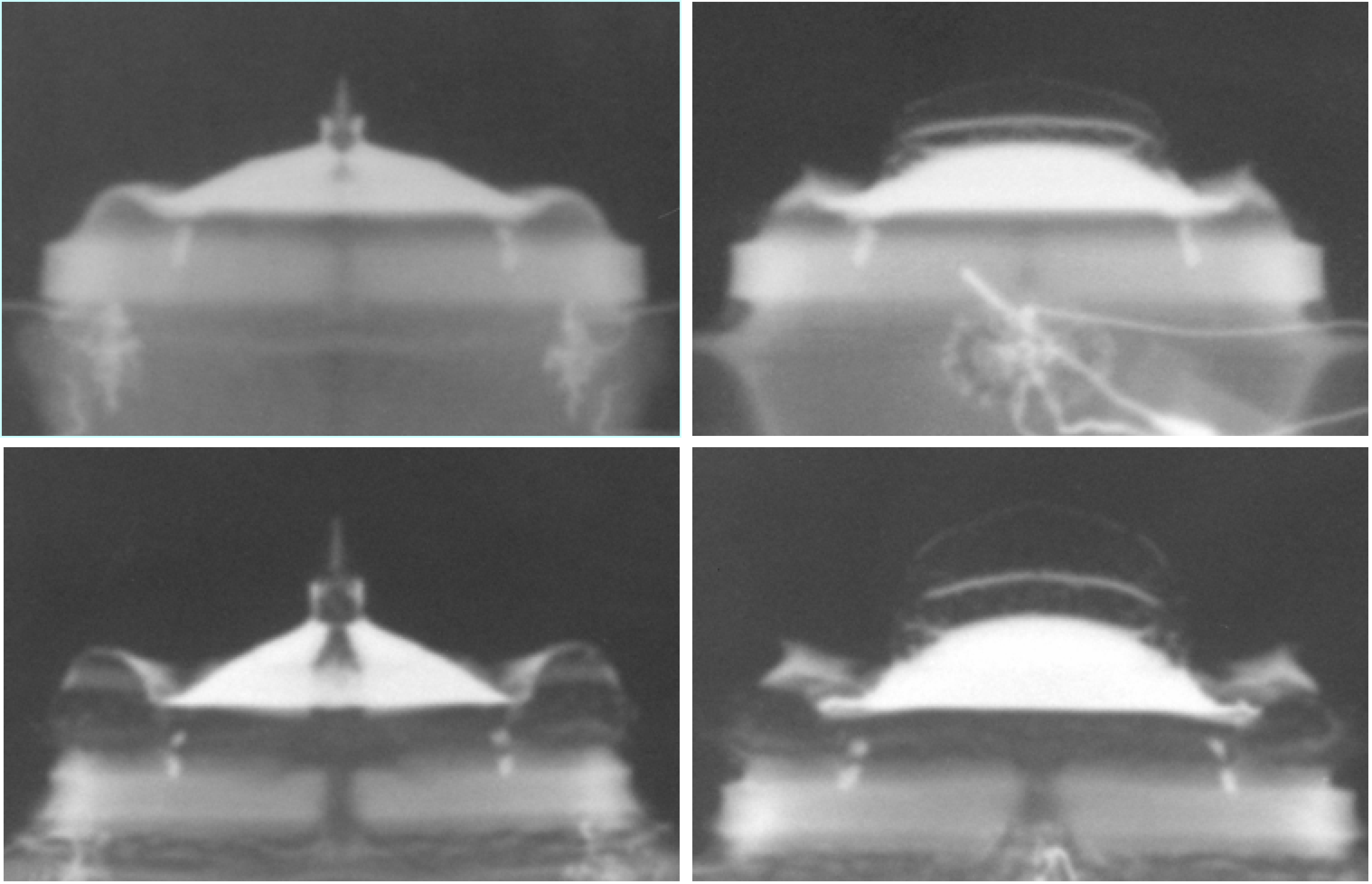


Ce, 21.44μs, PETN



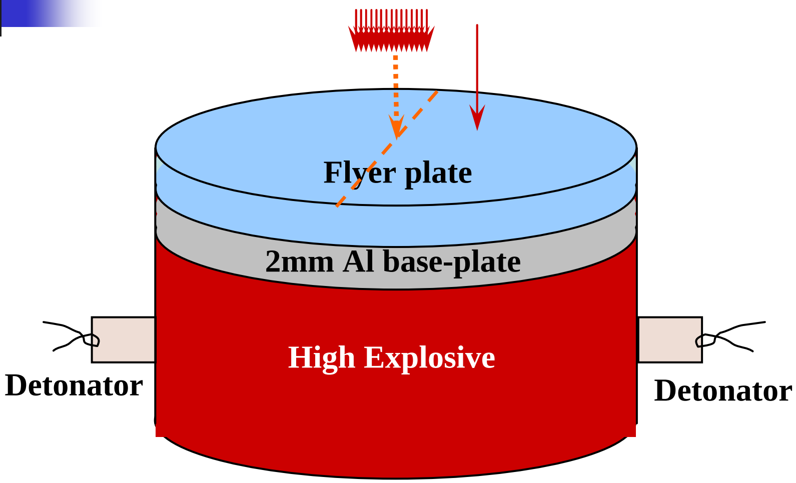
Ce, 21.16μs, PETN

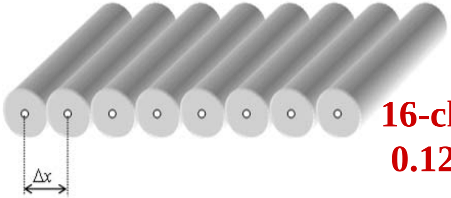
Spiking in the form of solid spall / fracture for Cu



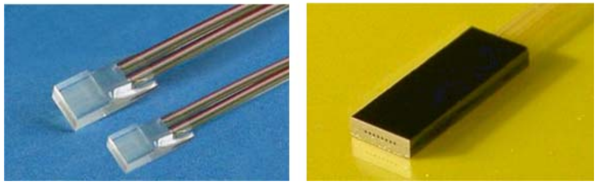
Spiking with complicated structures inside caused by EOS…Strength…Spall?

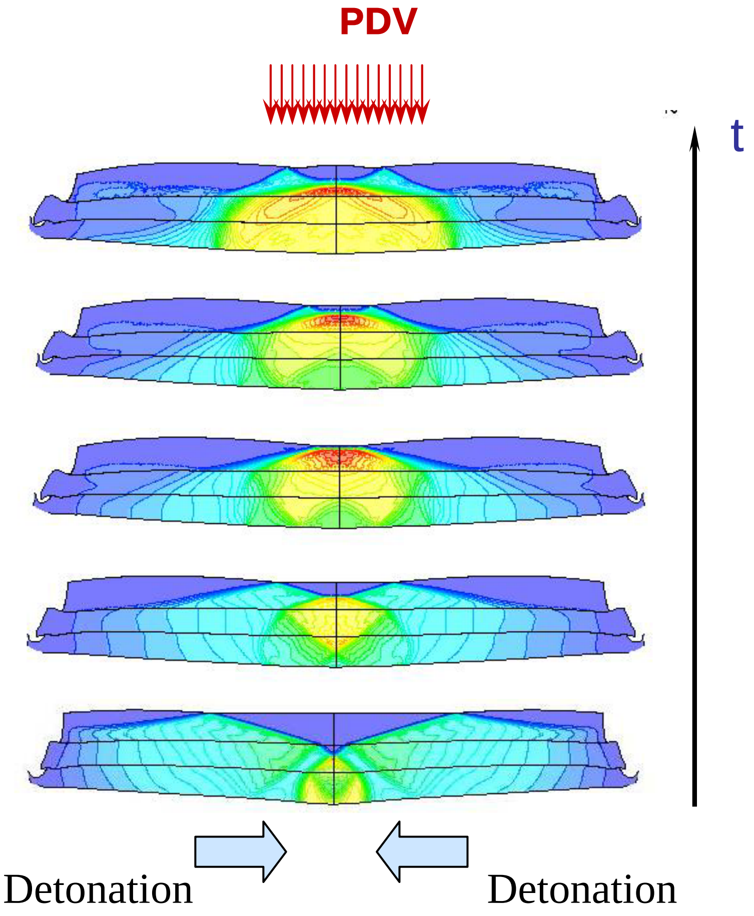
2. Experimental Set-up and Diagnostics



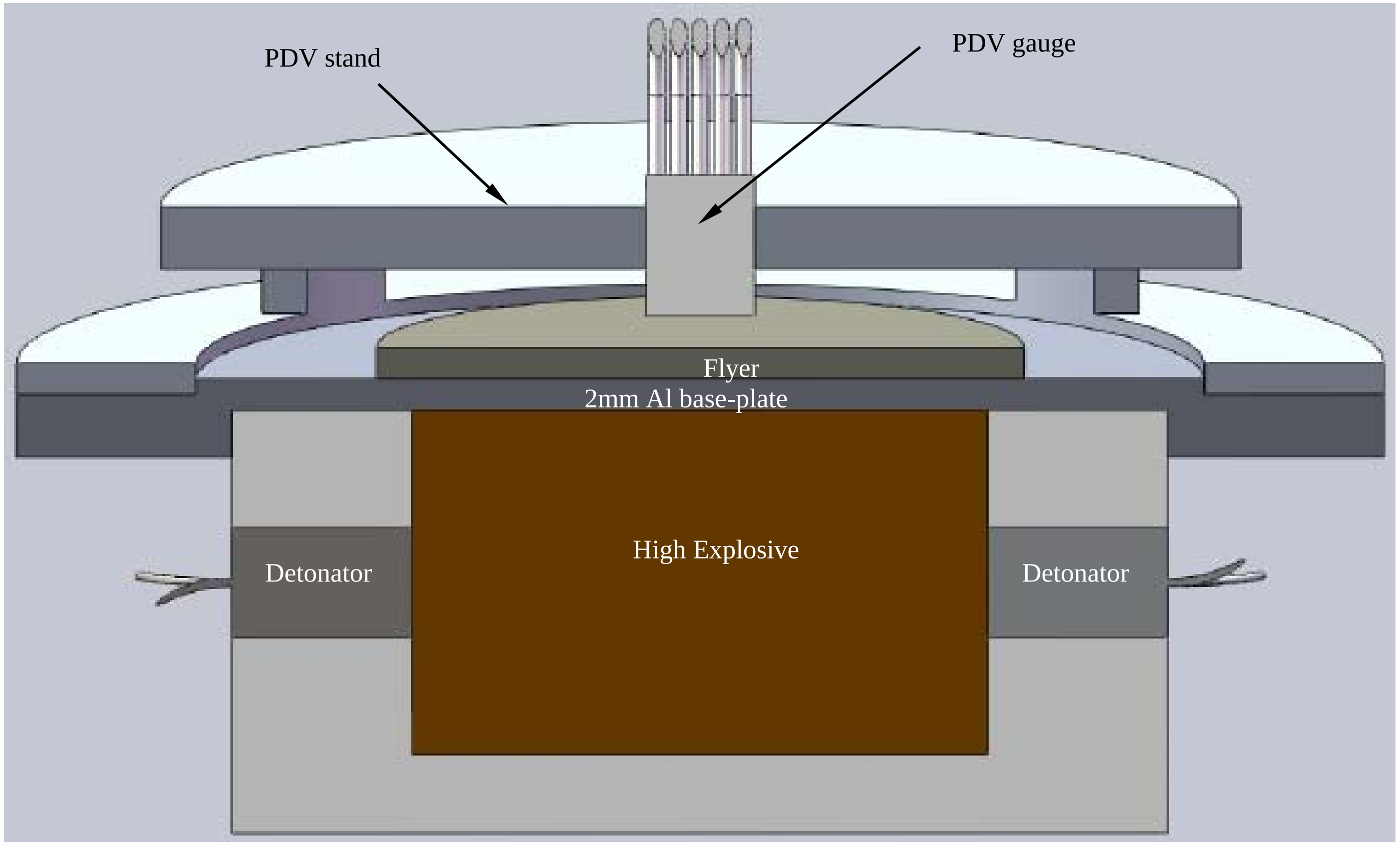


16-channel PDV probe with 0.127mm, 0.25mm spacing





Experimental assemble and flyer parameters

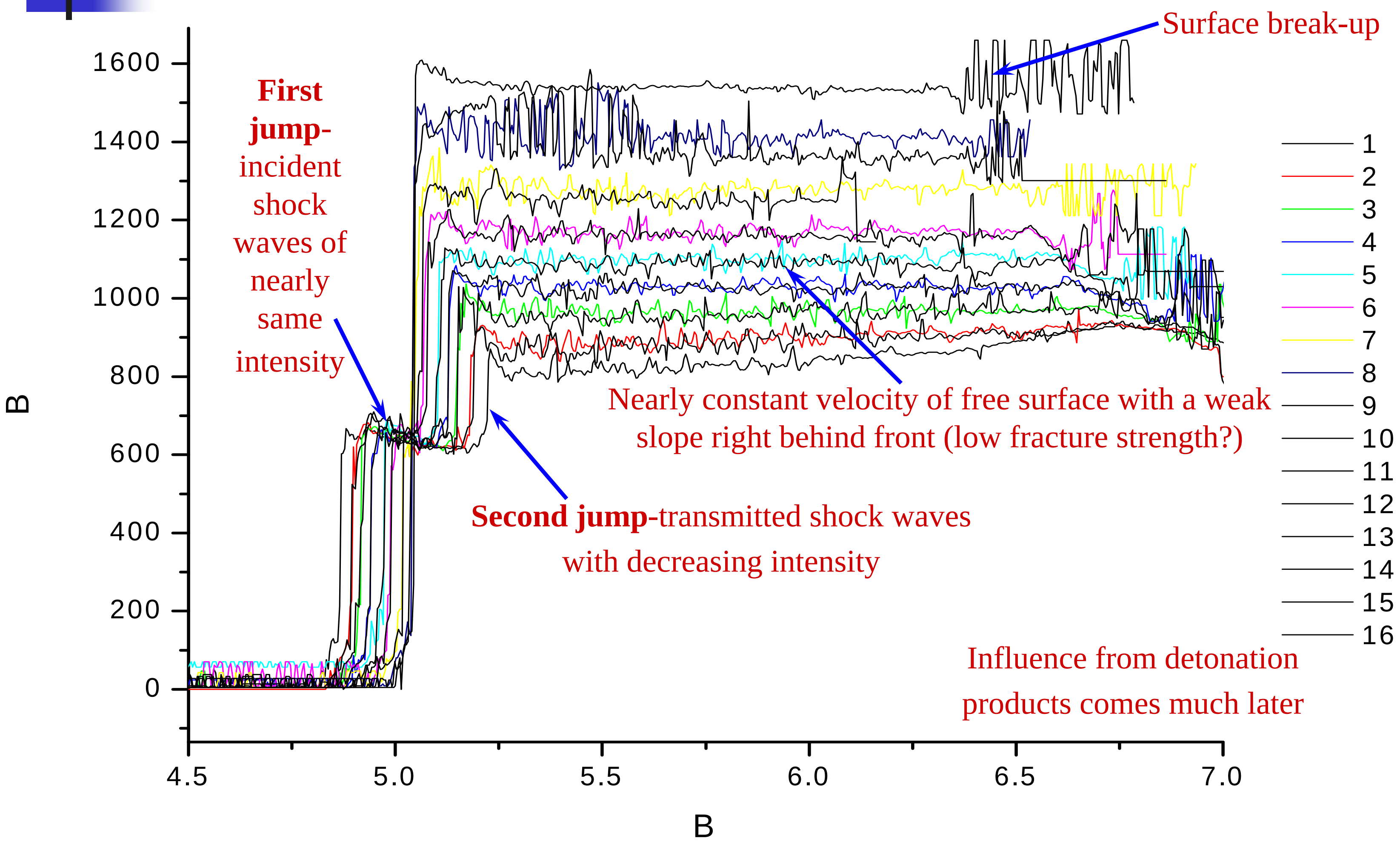


Φ32 mm×22 mm 96.5% RDX based PBX , 2 mm Al alloy base plate,

1.5mm W, 2mm Pb, 2.5mm Cu, 3.1mm Sn, 3.3 mm Ce flyer

3. Experimental results: regular reflection of two shock waves

－ 16-channel velocity profiles by center of W flyer with 0.25mm spacing



Surface break-up

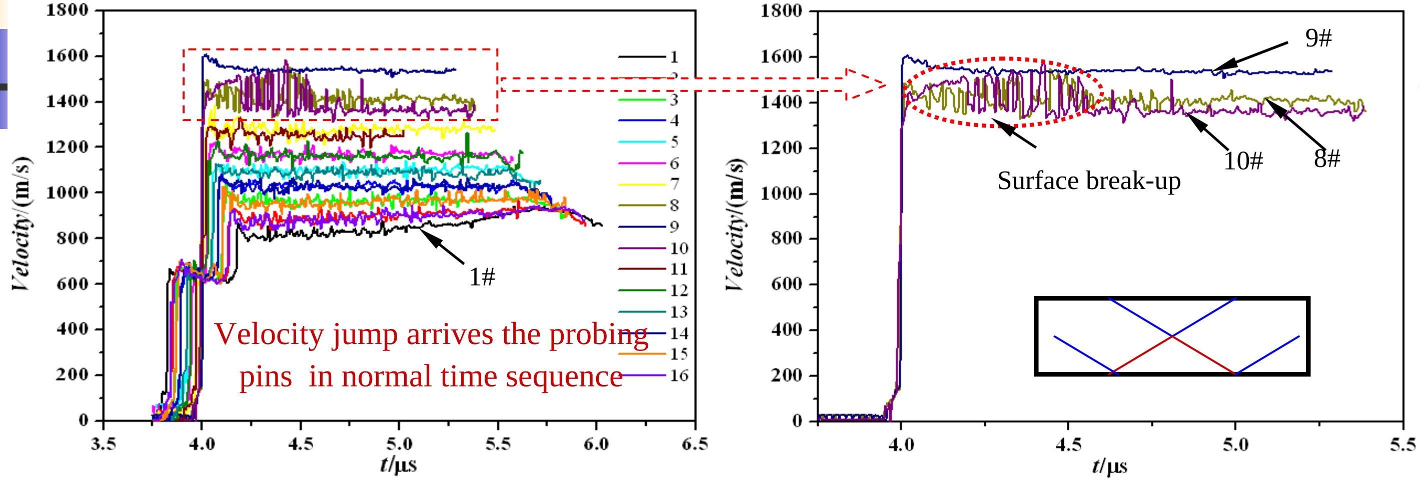
First jump- incident shock waves of nearly same intensity

Nearly constant velocity of free surface with a weak slope right behind front (low fracture strength?)

Second jump-transmitted shock waves with decreasing intensity

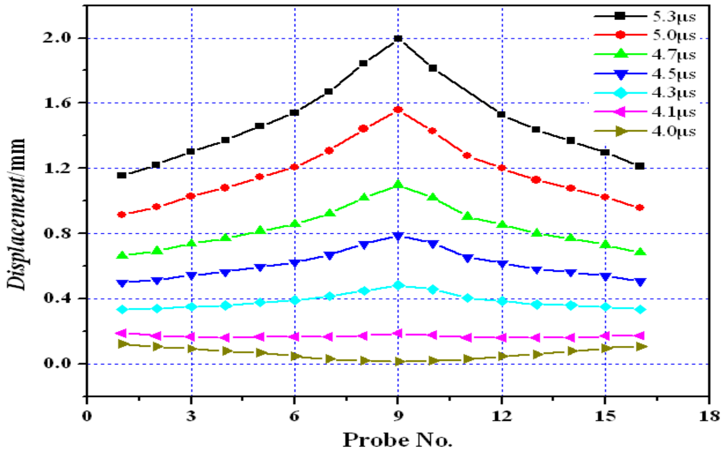
Influence from detonation products comes much later

Interpretation of the data for regular reflection

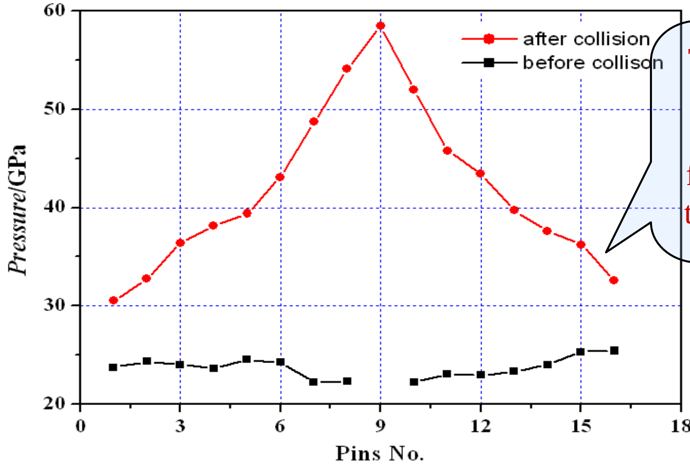


Velocity jump arrives the probing pins in normal time sequence

The intensity of reflection shock wave decreases with further distance to the collision line



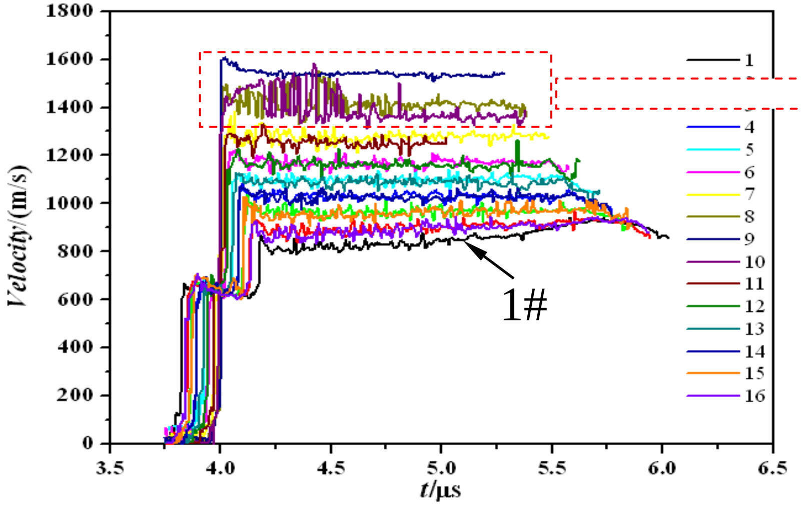
Displacement of surface in time sequence

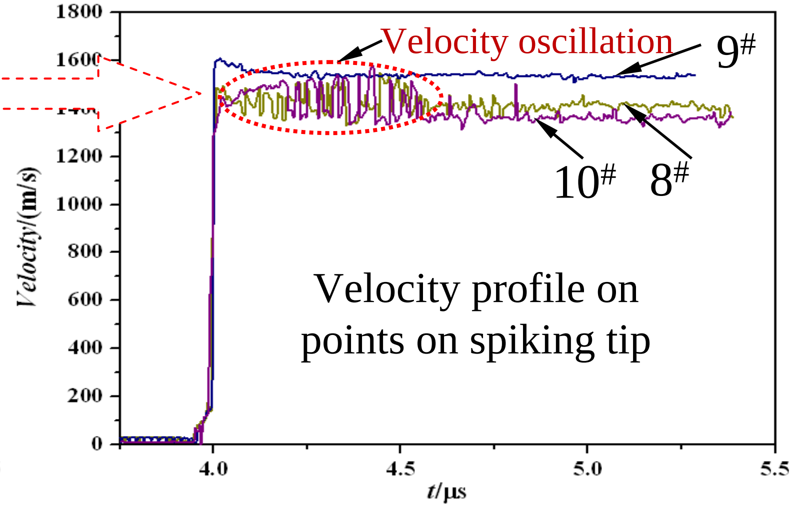


The slope shows the side release effect from the free surface after the incident front

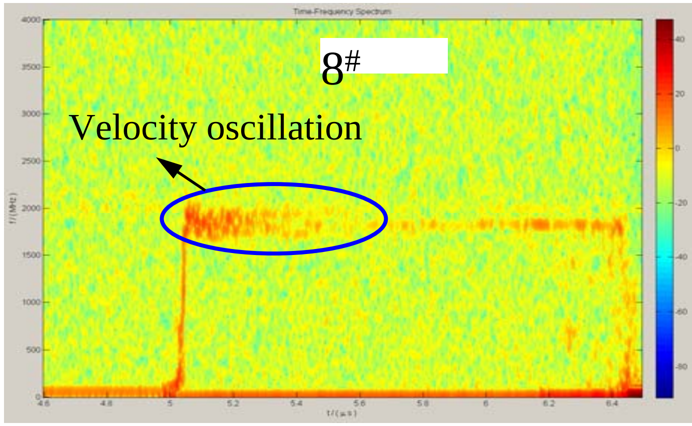
Pressure on the incident and reflection wave

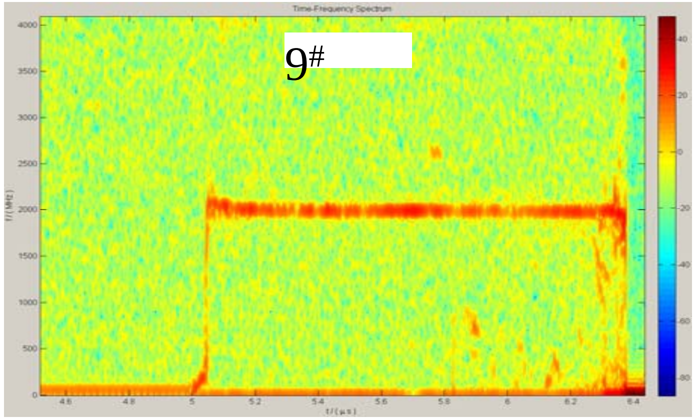
Interpretation of the data for regular reflection loading in W



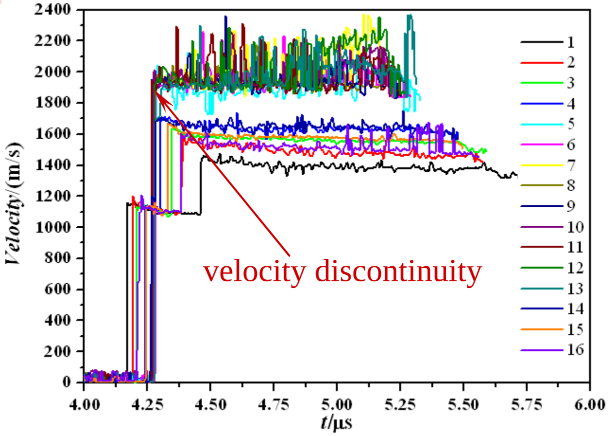


Velocity profile on points on spiking tip

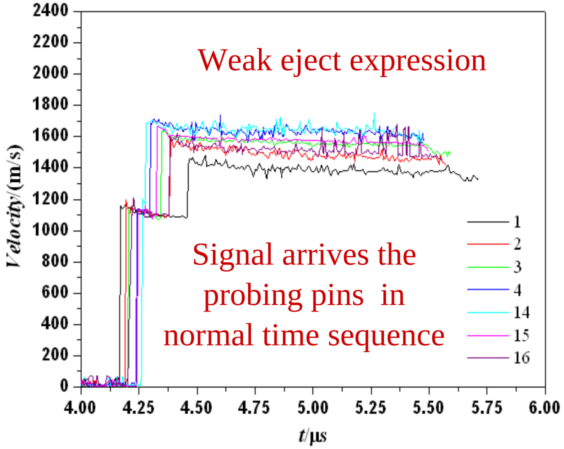




Interpretation of the data for Mach reflection

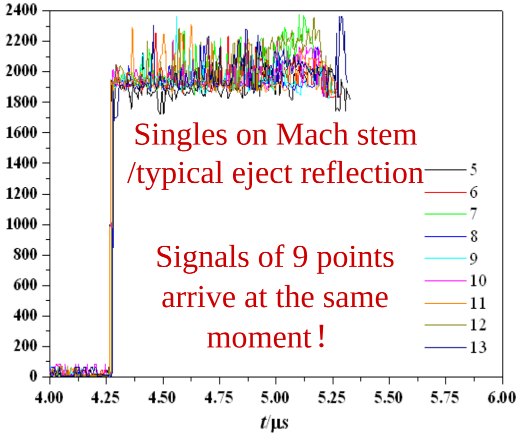


velocity discontinuity



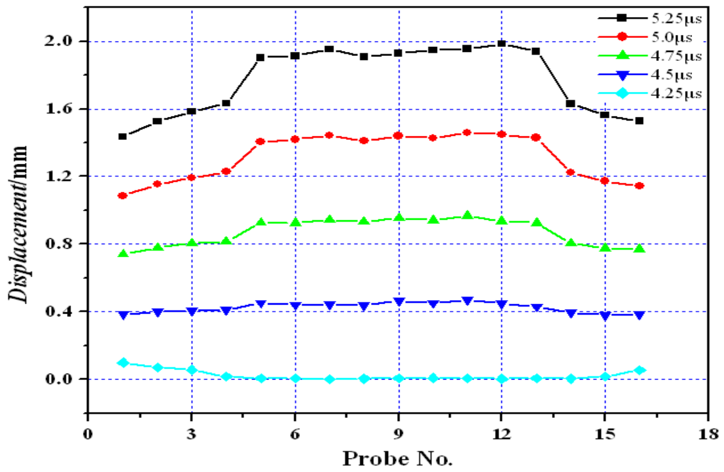
Weak eject expression

Signal arrives the probing pins in normal time sequence

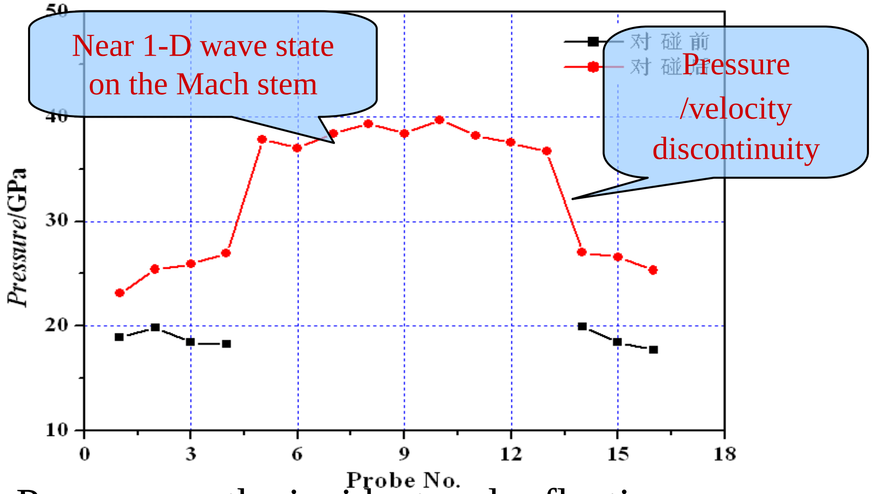


Singles on Mach stem /typical eject reflection

Signals of 9 points arrive at the same moment!



Displacement of surface in time sequence

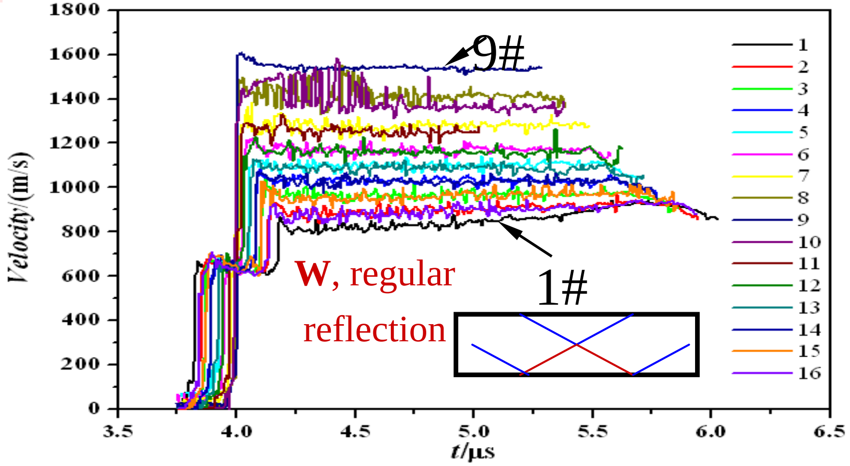


Near 1-D wave state on the Mach stem

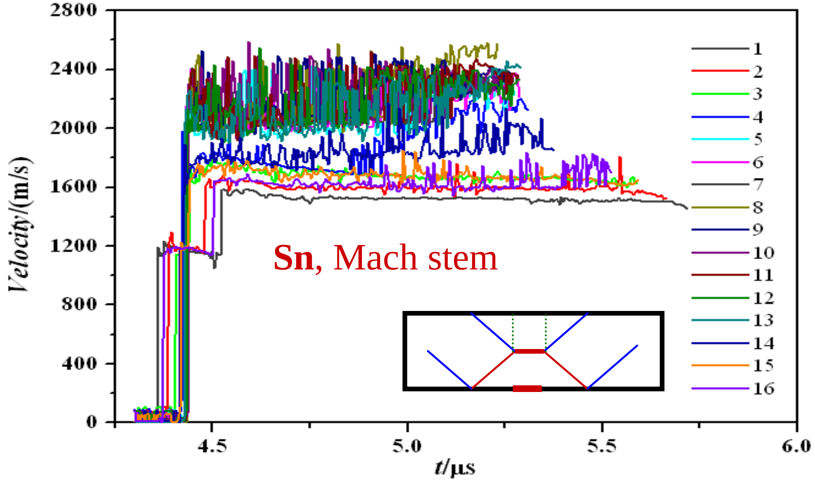
Pressure /velocity discontinuity

Pressure on the incident and reflection wave

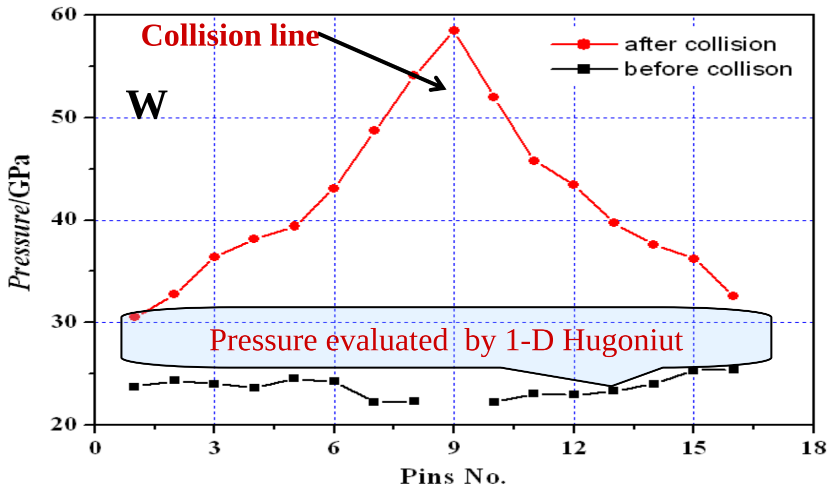
Comparison of regular and Mach reflection characteristics



W, regular reflection

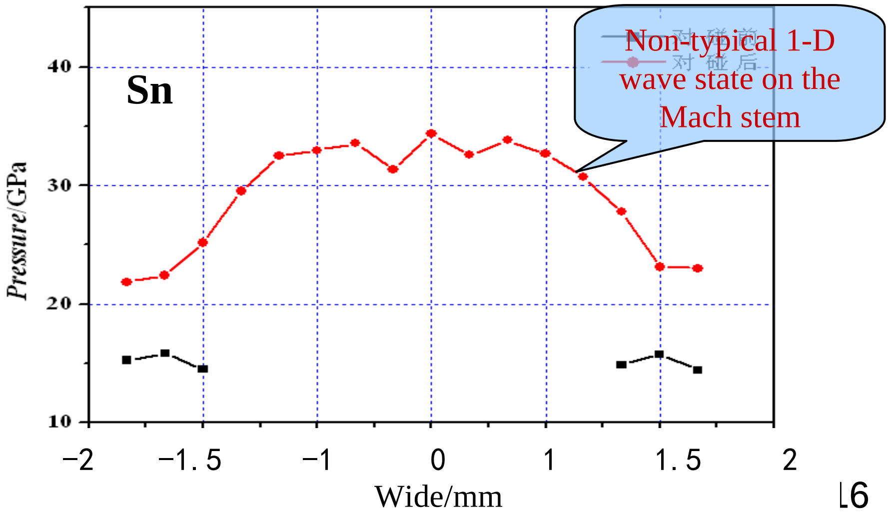


Sn, Mach stem



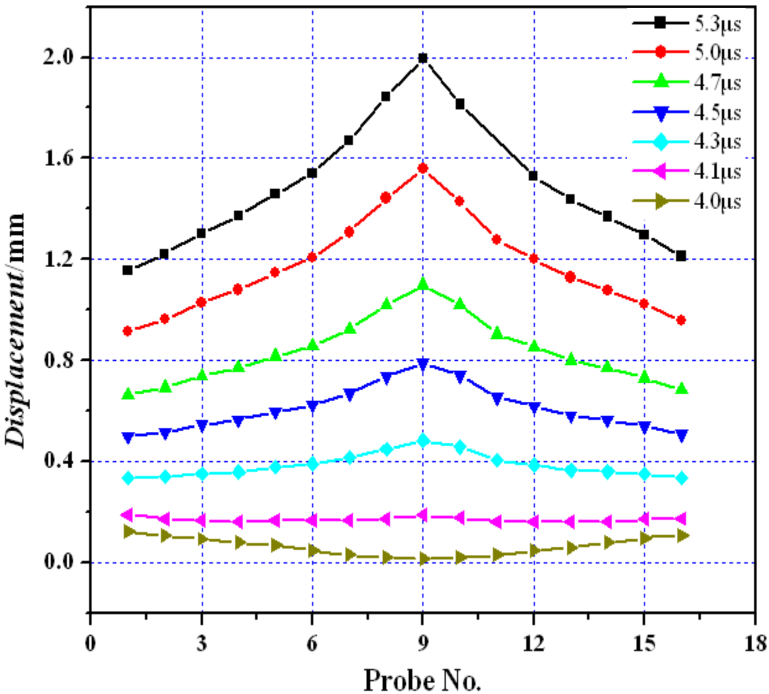
Collision line

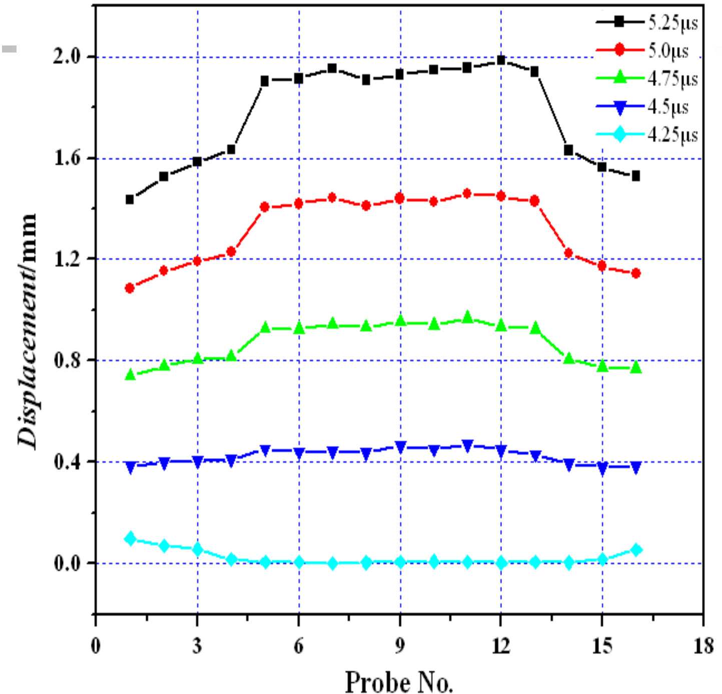
Pressure evaluated by 1-D Hugoniut

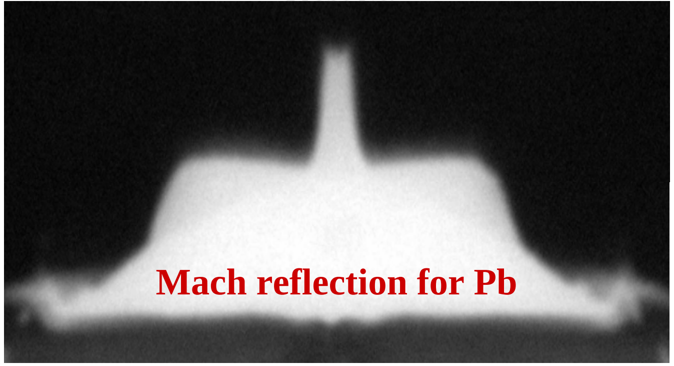


Non-typical 1-D wave state on the Mach stem

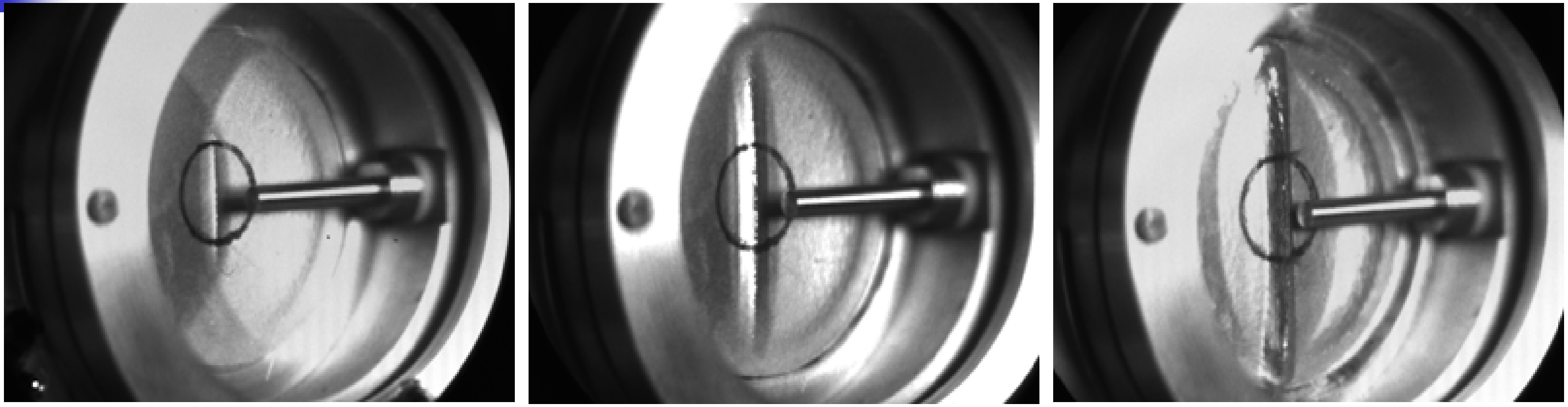
Comparison of surface displacement for two wave configuration



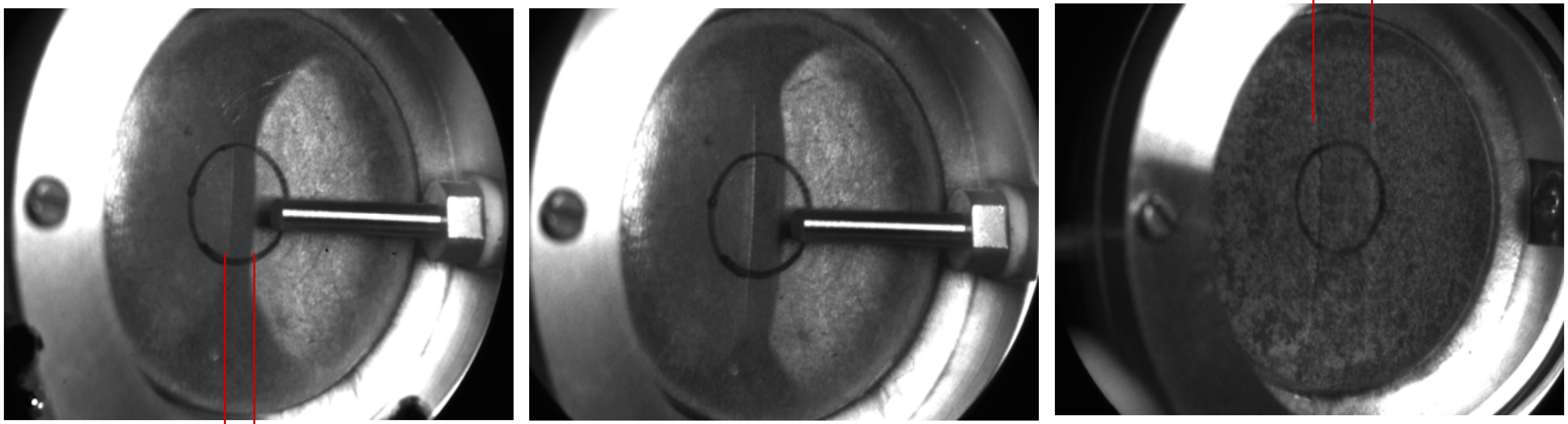




Optical observation of regular and Mach reflection on free surface

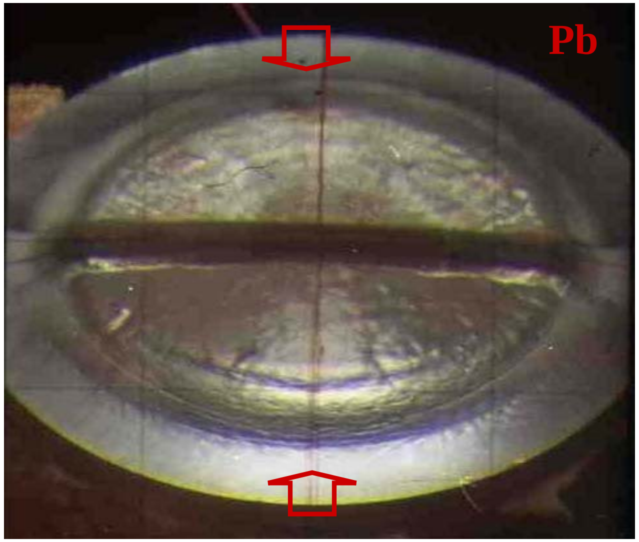


Surface movement on **W flyer**: regular reflection configuration

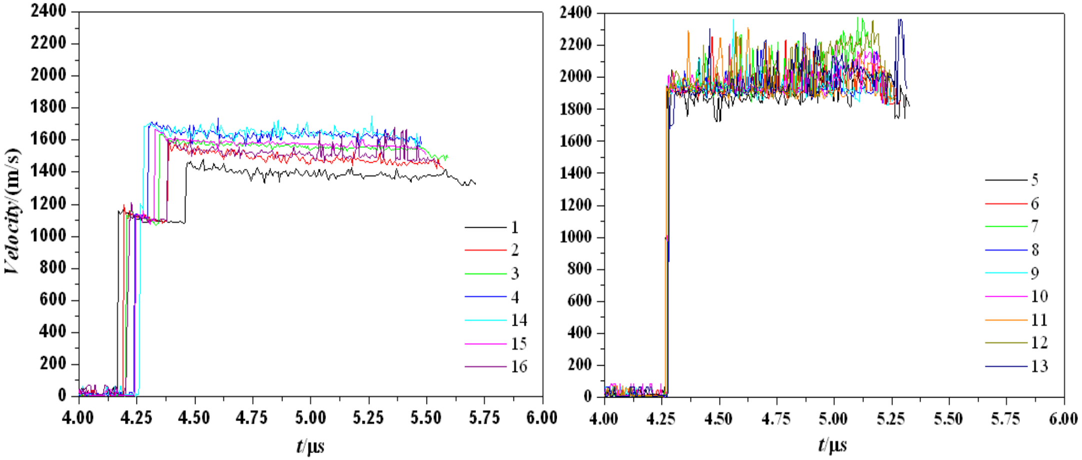


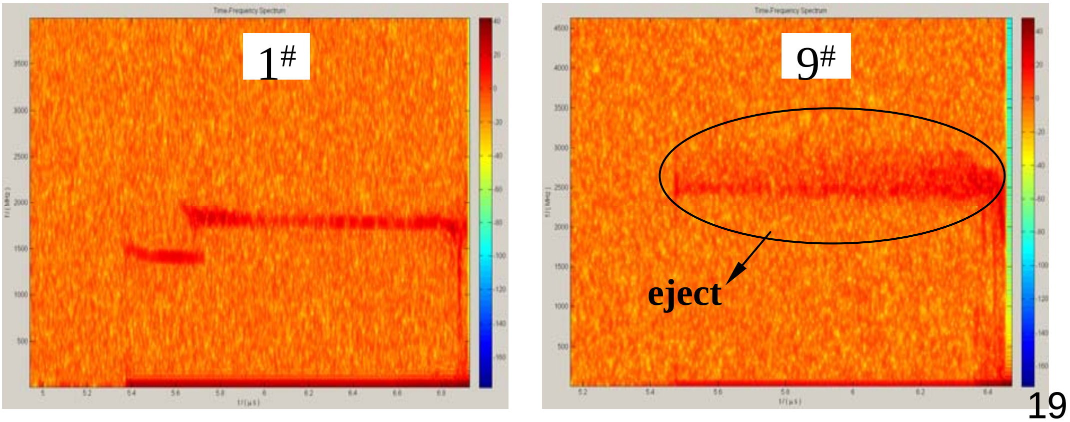
Surface states on **Pb** and **Ce flyer**: Mach reflection configuration

The eject on surface of Lead on Mach stem and outside (regular reflection)



Velocity profile on different points (9-13 on Mach stem)





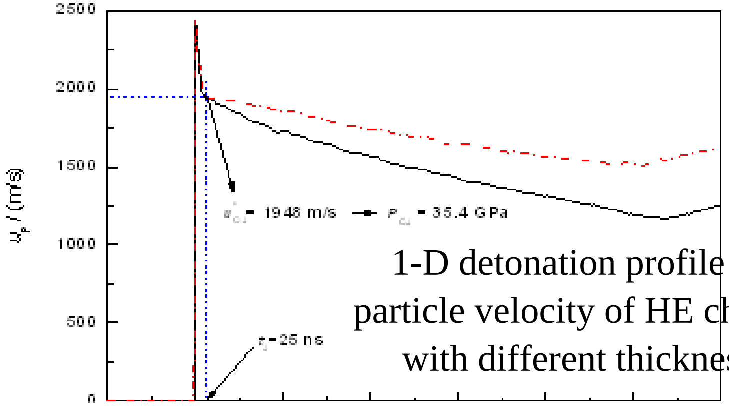
Discussion / Conclusion

- Exp. data about early stage state evolution behind free surface – **none**.
- The diagnostics of multi-channel PDV probe of small spot size can be used to trace the shock wave collision event with high spatial resolution. Velocity profiles recorded immediately after the incident and reflected shock waves are directly related to material properties and could be used **to validate hydrodynamic codes and <u>material models as continuum</u>**.
- The late stage evolution of the jet-like spiking is not the expression of traditional cumulative jet as a result of mass flow being squeezed to the symmetric collision plane, but the inertial expanding of the debris of the bumping event of two head-on shock waves which lasted only ~100ns, during which grand velocity gradient is created inside the bulk. The late stage spiking configuration evolution and mass distribution are useful for **the validation of <u>fracture models</u> in hydrodynamic codes**.

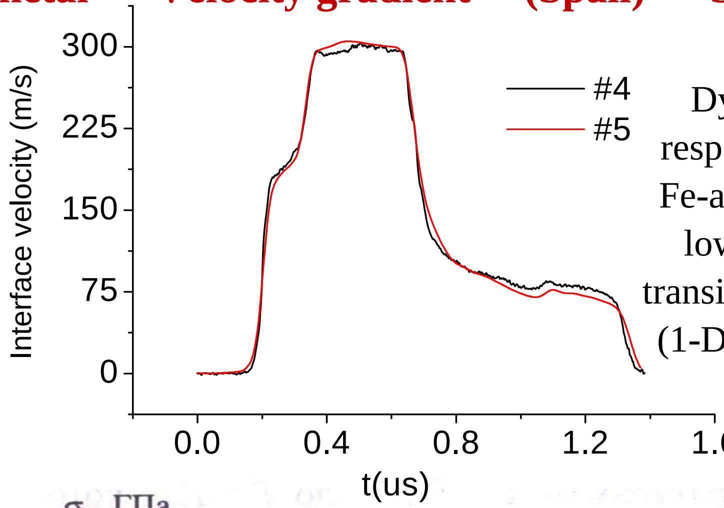
Challenge in modeling material dynamic behaviors from the experimental view …

Perspective to predict the complexity of dynamic response of materials by codes?

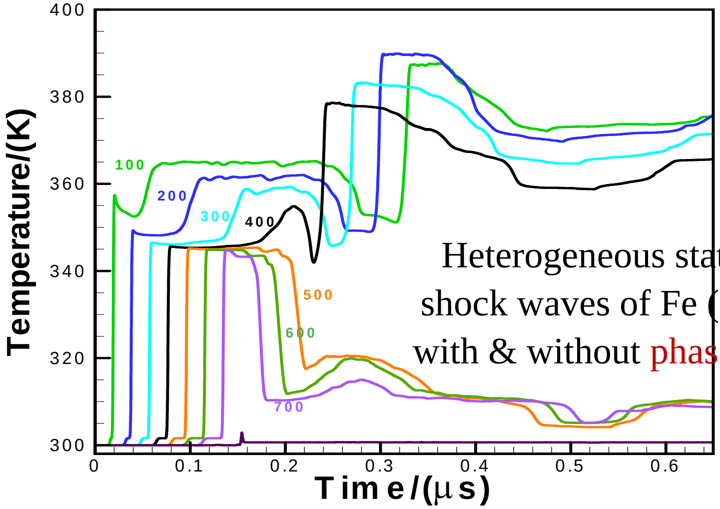
Detonation wave in HE → Shock wave in metal → Velocity gradient →(Spall) → Spiking



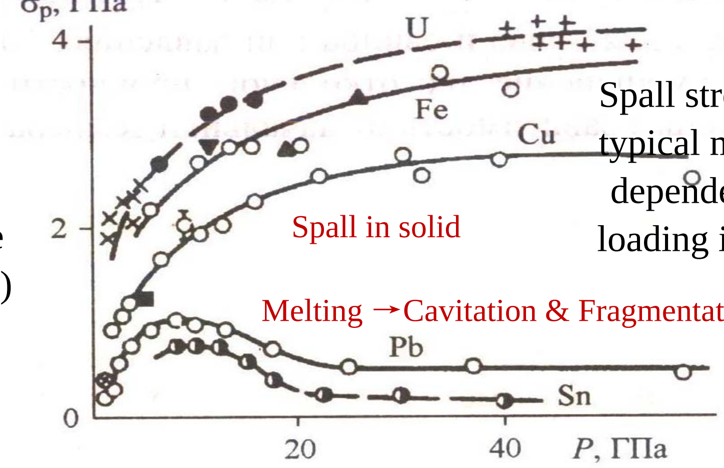
1-D detonation profile of particle velocity of HE charge with different thickness



Dynamic response of a Fe-alloy with low phase transition stress (1-D loading)



Heterogeneous states behind shock waves of Fe (in 1-D case with & without phase transition)



Spall in solid

Melting →Cavitation & Fragmentation

Spall strength of typical metals in dependence on loading intensity

Thanks for attentions！

ЗАБАБАХИНСКИЕ
2017
НАУЧНЫЕ ЧТЕНИЯ

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