Recent PDV implementations

- Embedded fibers in D_2O
- Tilted probing
- Micro-probes
- Simulating Software

energie atomique • energies alternatives

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PDV Workshop,
LIVERMORE,
November 3rd- 4th, 2011

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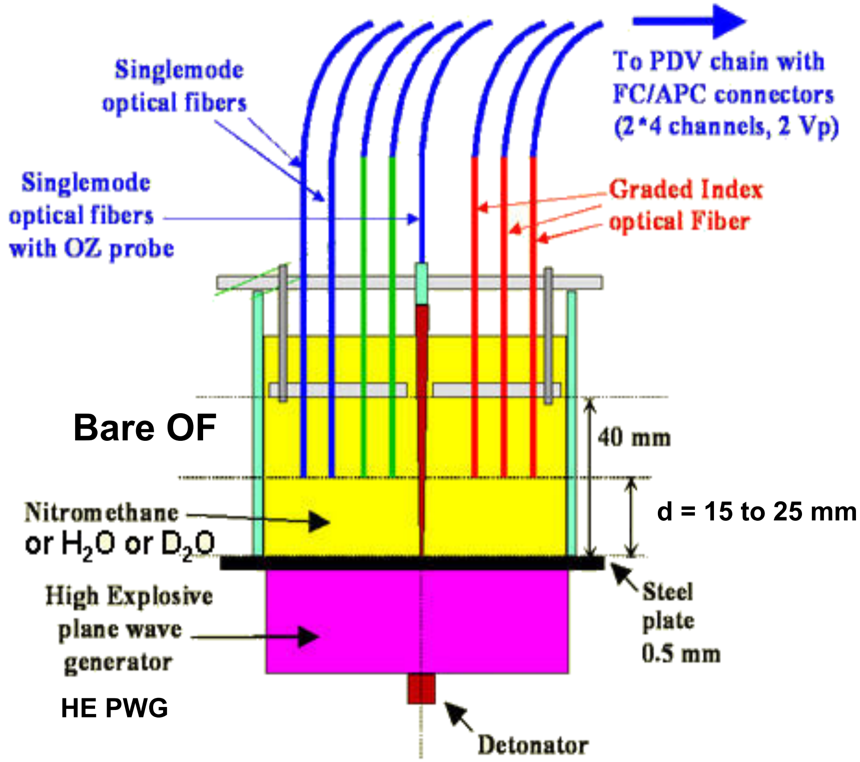
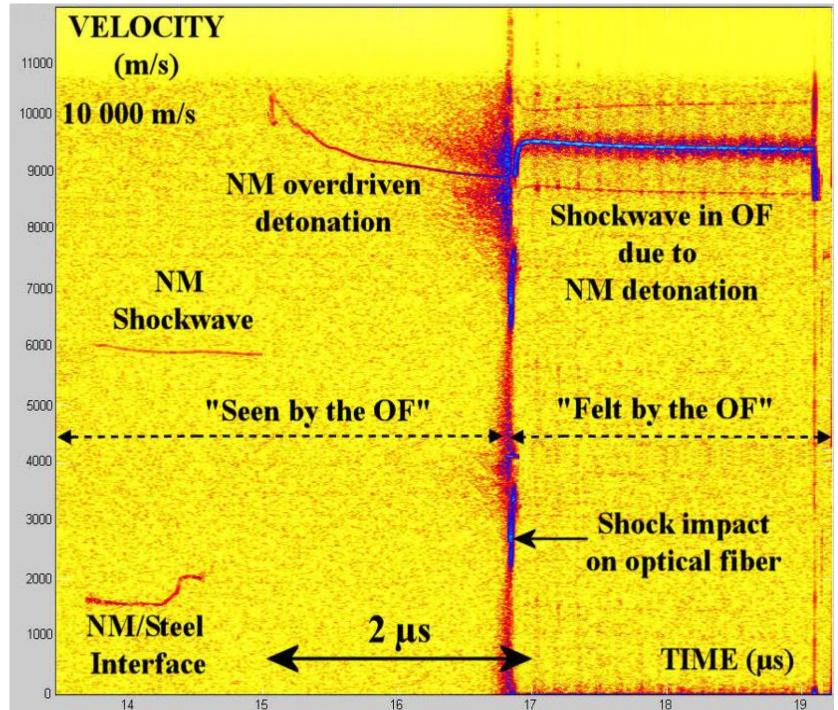
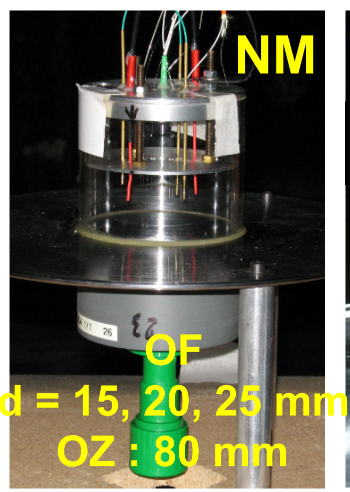
Embedded optical fibers for PDV measurements in shock-loaded, light and heavy water

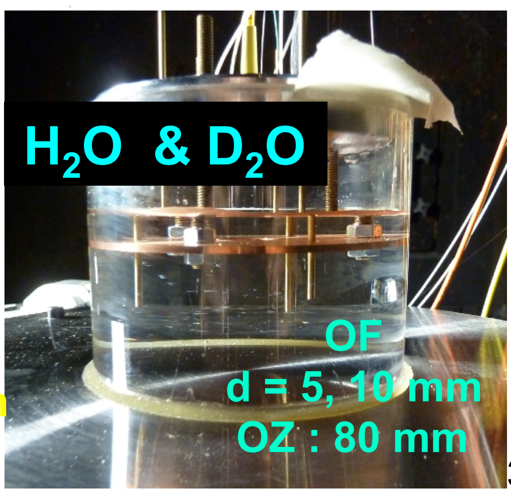
From APS-SCCM Chicago june 2011

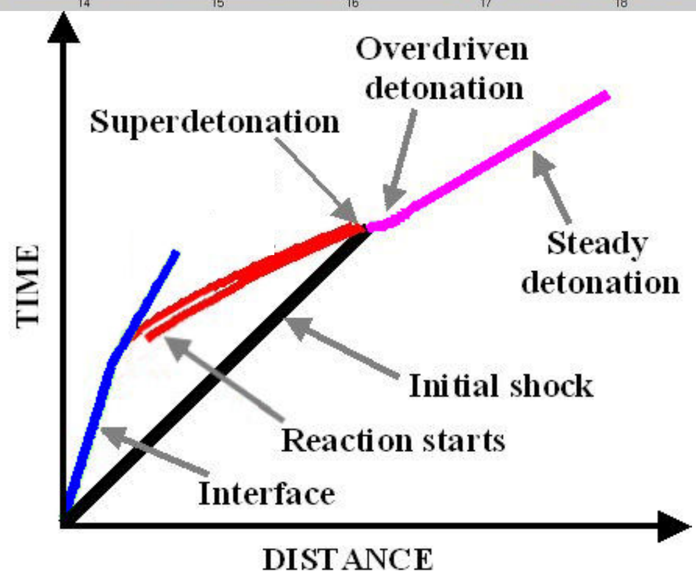
SIMPLE PDV TEST WITH BARE EMBEDDED OPTICAL FIBER IN LIQUID : NITROMETHANE







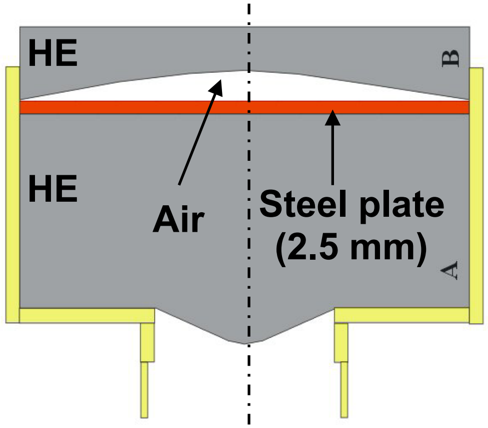




PROBLEM

- **Study started with a HE Φ 100 mm Plane Wave Generator (PWG)**
  - + easy to study nitromethane (simple setup)
  - - non sustained, but strong shock,
  - - much more complicated pressure law than the one provided by a gun shot

Octogen Plane Wave Generator



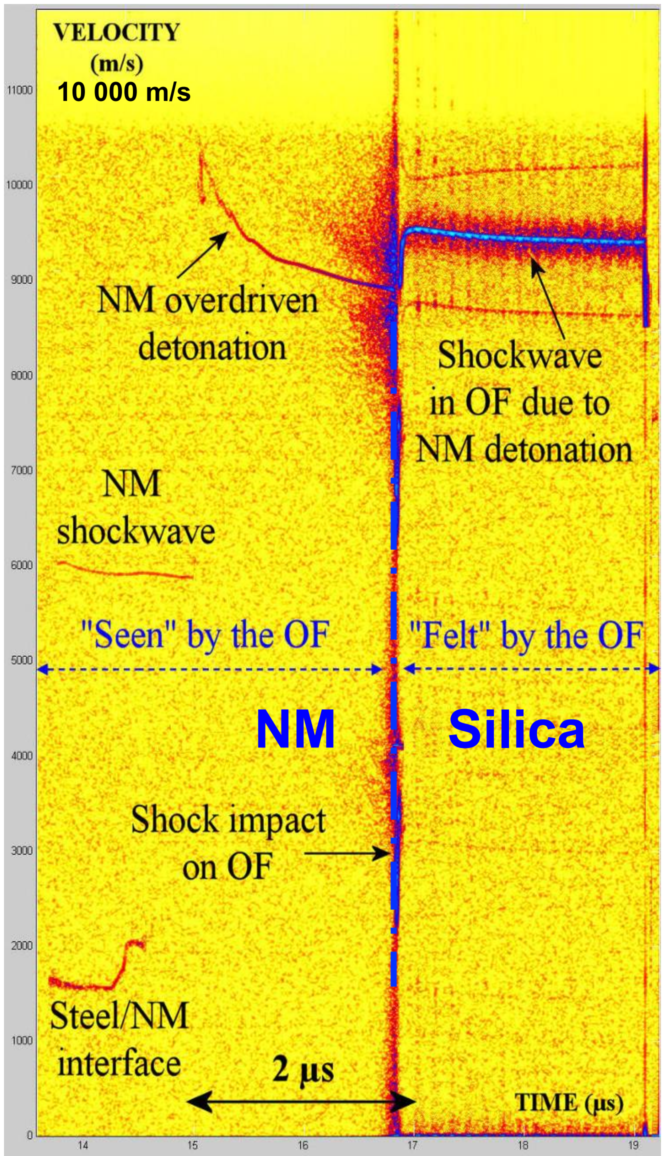
- **Since we have a shock heating in a reactive compound (nitromethane):**
  - the interface velocity law can be modified,
  - the medium optical properties can be modified,
  - after a certain time, the interface Steel/NM is no longer visible

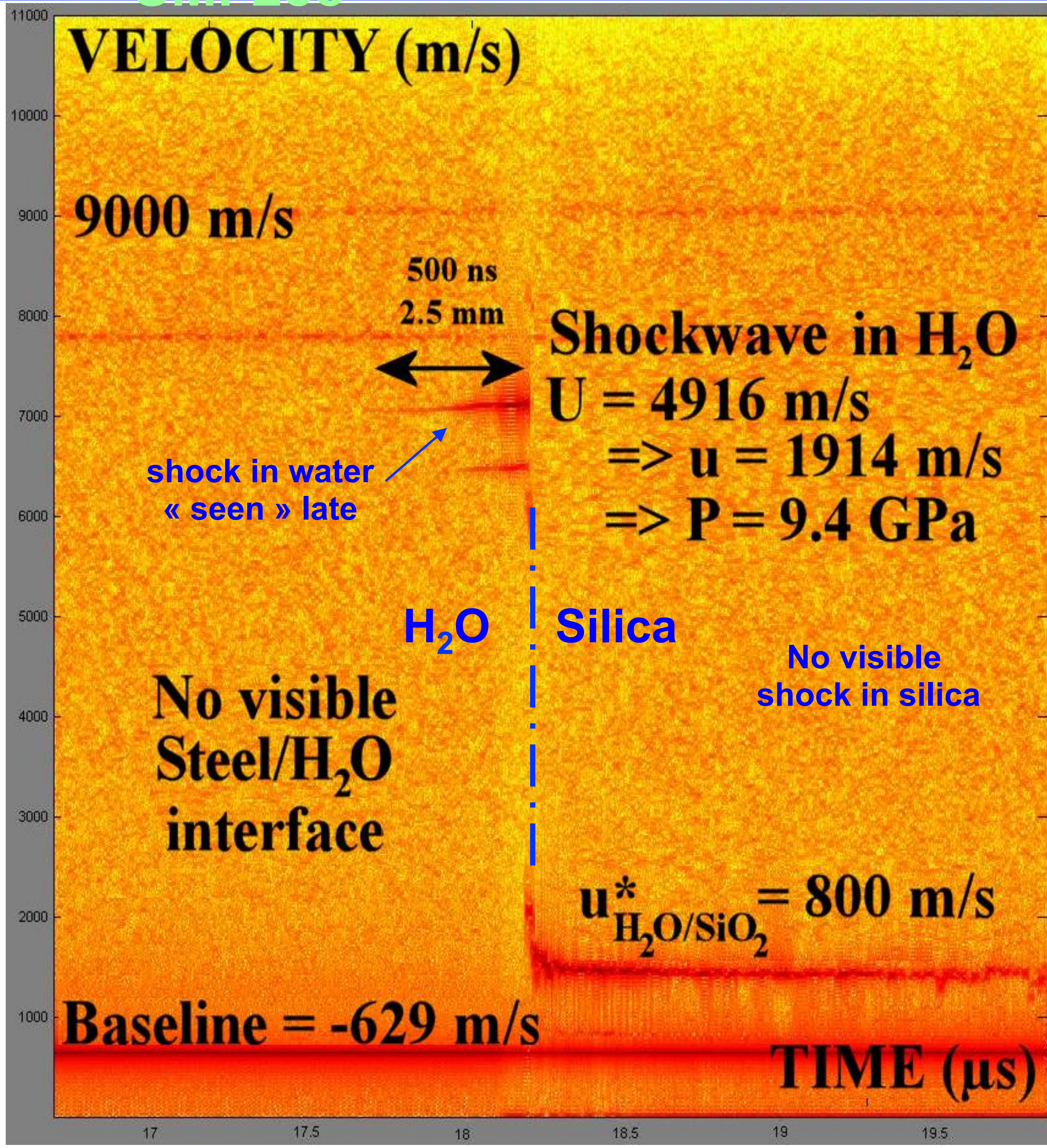
- **Thus, necessity to replace it by a well known inert liquid matter**
  - to determine the pressure loading law due to the PWG,
  - to highlight behavior differences,

- **The simplest and most common one: light water H_2O**
  - but……

SHOT 6 H_2O - Probe S1 (20 mm from the bottom) : bare SMF28e

Graded index fiber, 20 mm from the bottom

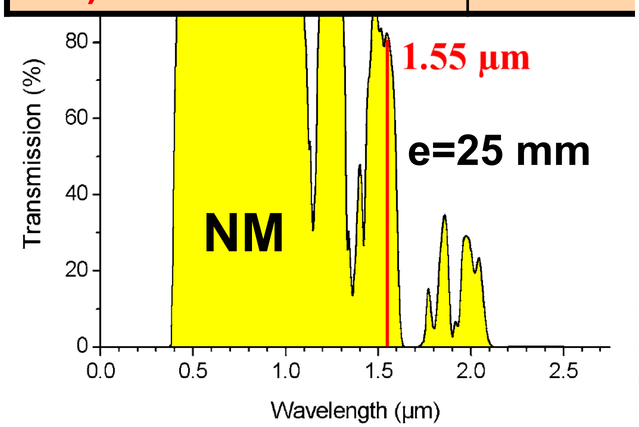


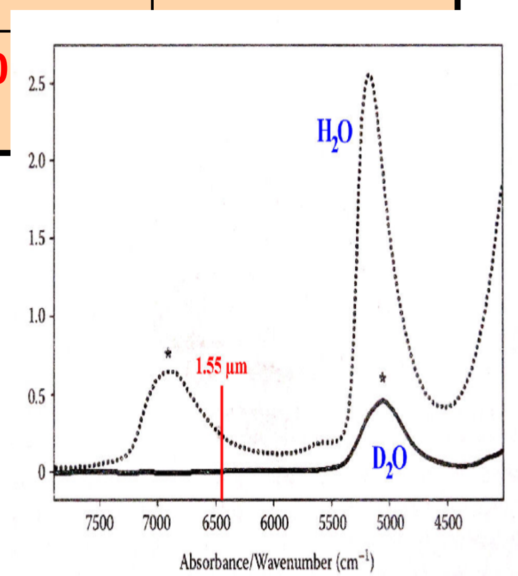


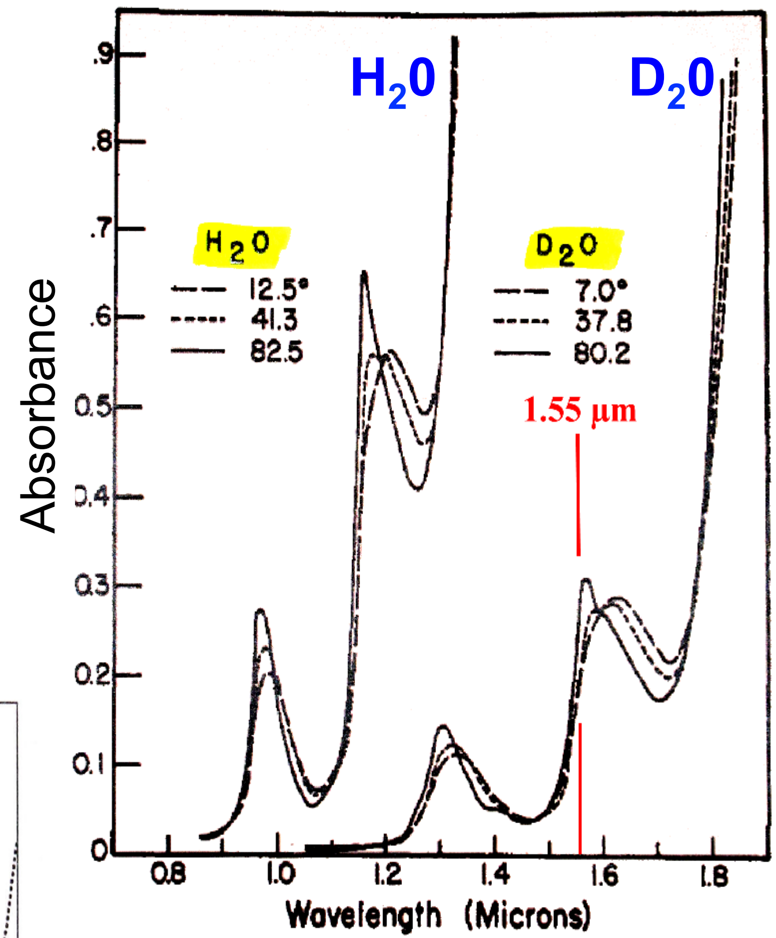
NM, H_2O & D_2O ABSORPTION COEFFICIENTS

$$T = e^{-\mu . x} = 10^{-A}$$

Absorpt. coefficients	H_20	D_2O
μ @ 500 nm	$2.33\ 10^{-4}\ cm^{-1}$	$3.10\ 10^{-4}\ cm^{-1}$
A @ 500 nm (x=1 cm)	$1.01\ 10^{-4}$	$1.35\ 10^{-4}$
T @ 500 nm (x=1 cm)	0.99978	0.99969
μ @ 1550 nm	$11.5\ cm^{-1}$	$0.5\ cm^{-1}$
A @ 1550 nm (x=1 cm)	5	0.215
T @ 1550 nm (x=1 cm)	10	



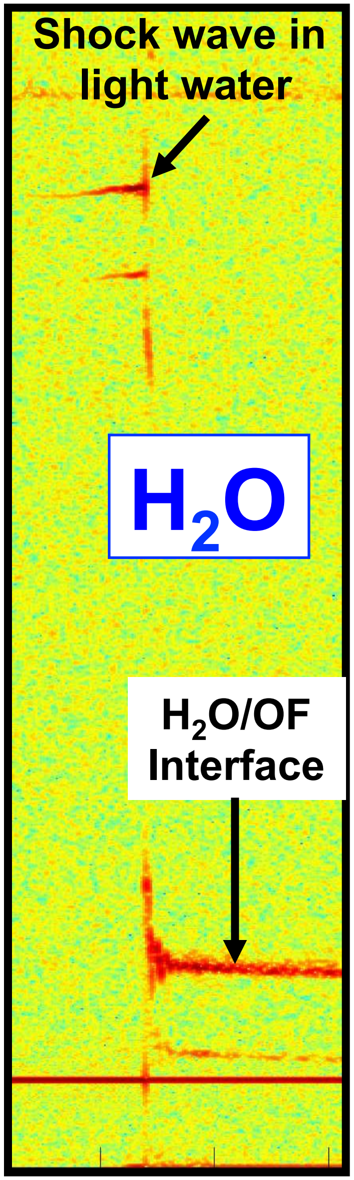


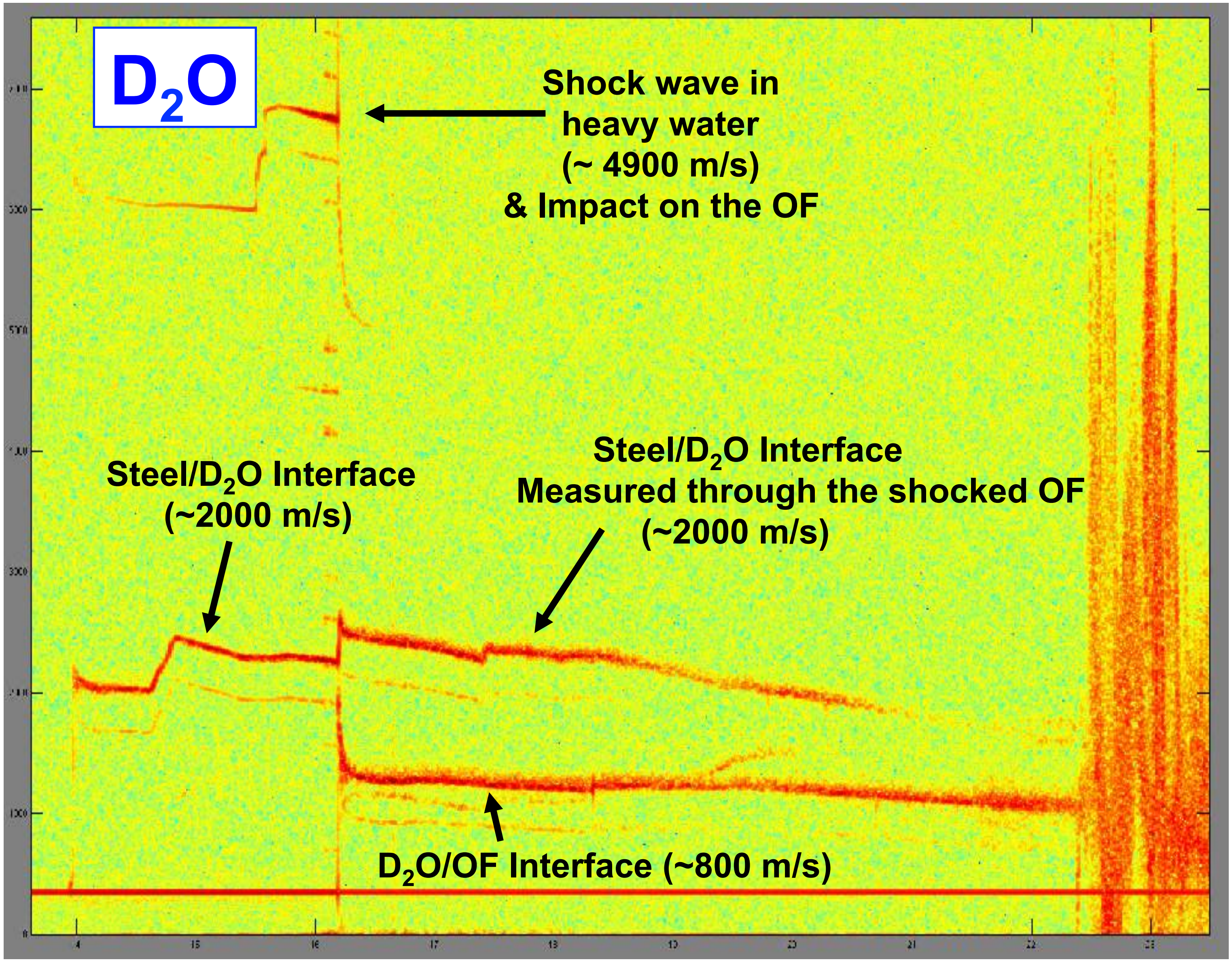


Near-infrared spectra of liquid H_2O and of liquid D_2O at various temperatures.

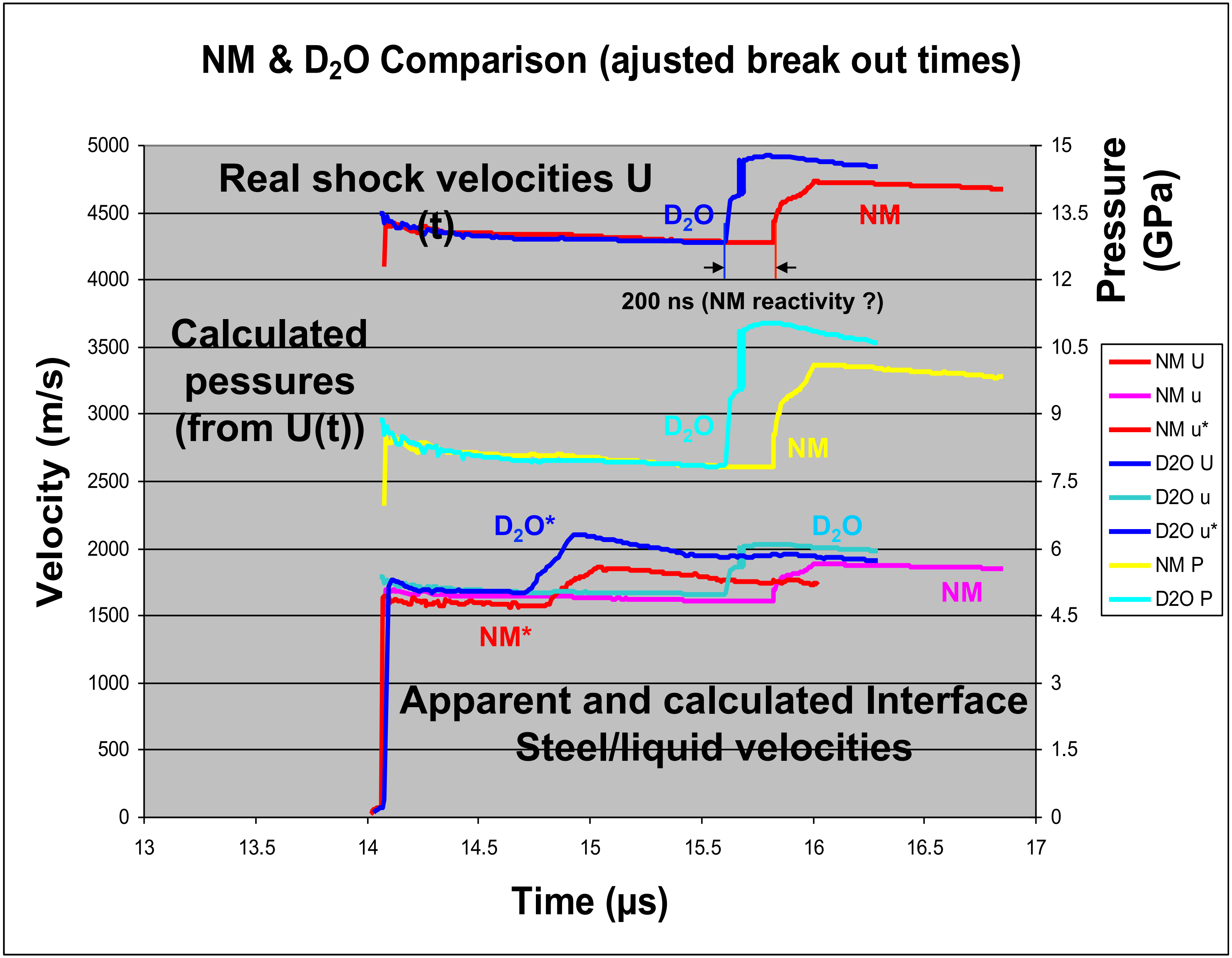
M. Thomas et al
A Near-Infrared Study of Hydrogen Bonding in Water and Deuterium Oxyde
The Journal of Physical Chemistry 69 (1965) 3722- 3726

SHOT 6 H_2O & SHOT 7 D_2O (Cell bottom - OF = 10 mm)

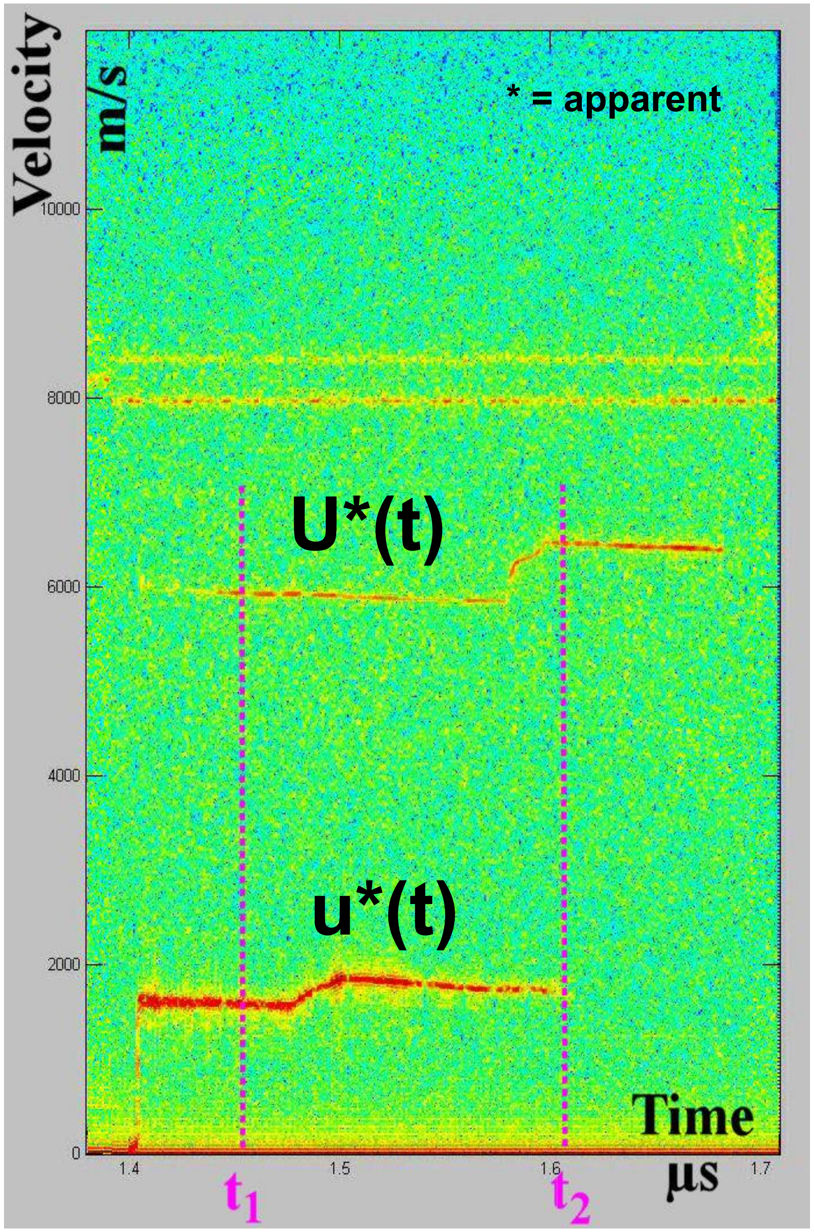


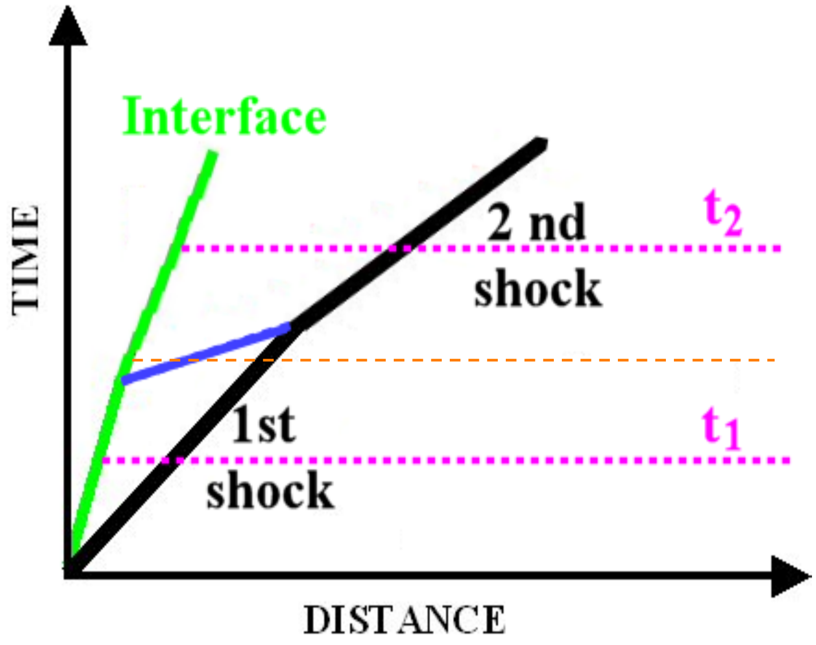


NM & D_2O Comparison



U(t) CONTINUOUSLY MEASURED & REFRACTIVE INDEX DETERMINATION





*** = apparent velocity**

$$U = \frac{U^*}{n_0}$$

$$u = \frac{U - C_0}{s}$$

$$n = \frac{U^* - u^*}{U - u}$$

Refractive index in the shocked medium

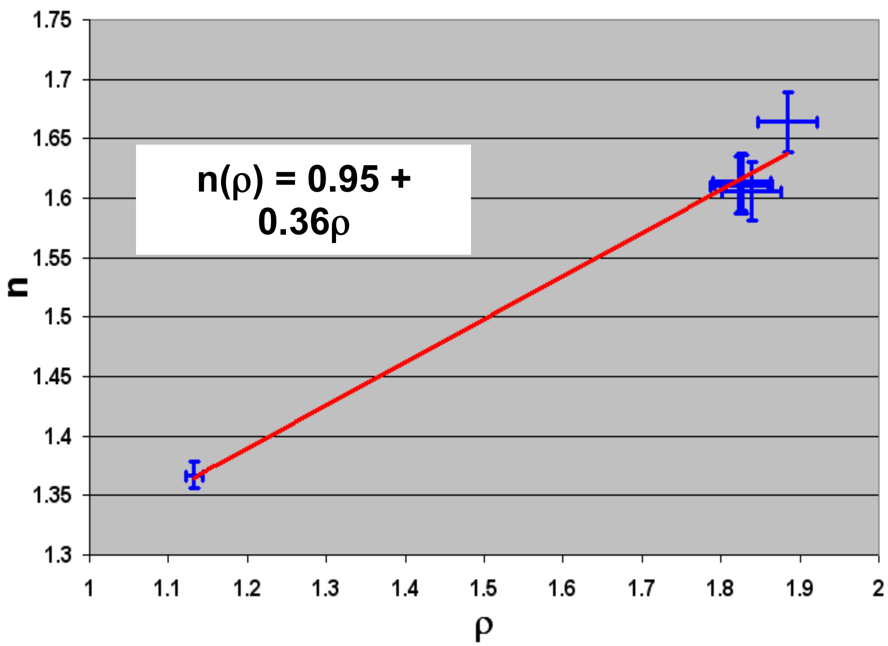
n(ρ) @ 1.55 μm for NM & D_2O (Gladstone-Dale approximation)

NM

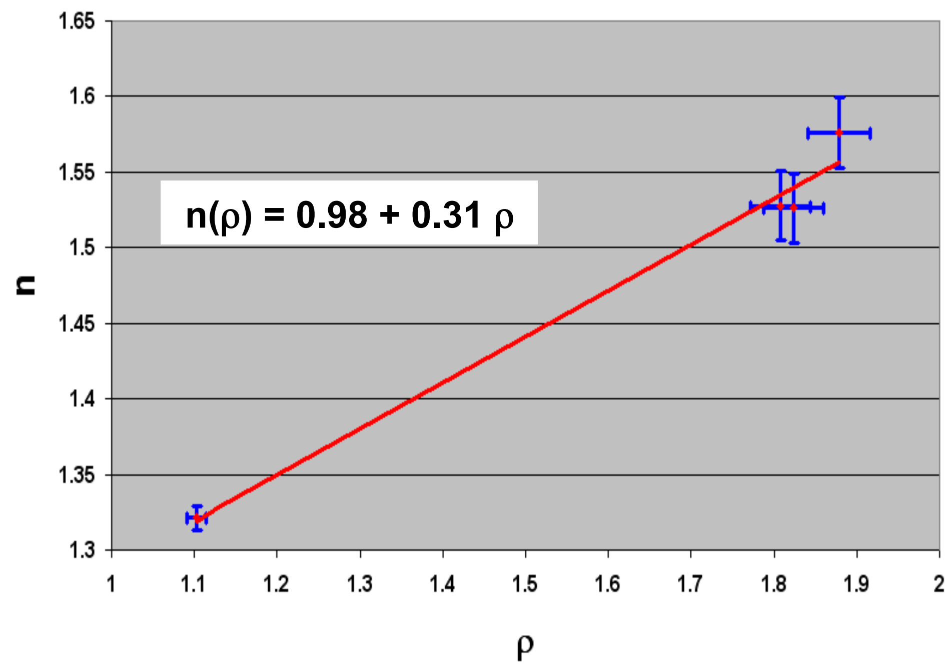
	t μs	U	u	u*	P	ρ	n
						1.134	1.3679
Shot 1	13.74	4421	1694.5	1669	8.49	1.8388	1.6059
Shot 1	14.23	4321	1633.3	1581.7	8.00	1.8231	1.6107
Shot 5	14.45	4349	1651	1601	8.14	1.828	1.6116
Shot 5	14.82	4338	1644	1587	8.09	1.826	1.6136
Shot 5	16.04	4729	1883	1733	10.10	1.884	1.664

NM	Fresnel reflectivity coefficient R
1st shock 8 GPa	0.67%
2nd shock 10 GPa	0.95%

NM n(ρ)



D_2O n(ρ)



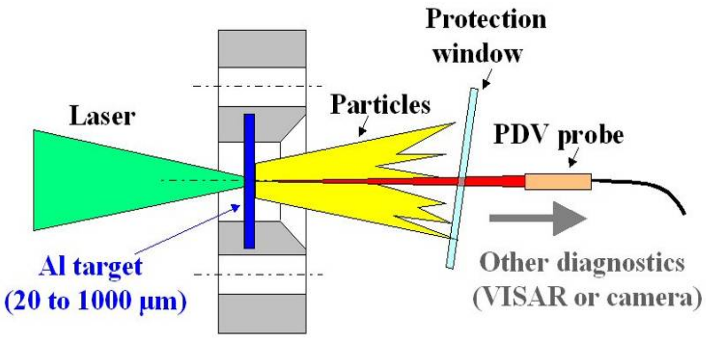
D_2O

	t μs	U	u	u*	P	ρ	n
						1.1040	1.3220
Shot 7	14.01	4436	1751	1766	8.58	1.8240	1.5264
Shot 7	14.61	4305	1676	1675	7.97	1.8078	1.5277
Shot 7	15.62	4906	2022	1940	10.95	1.8780	1.5762

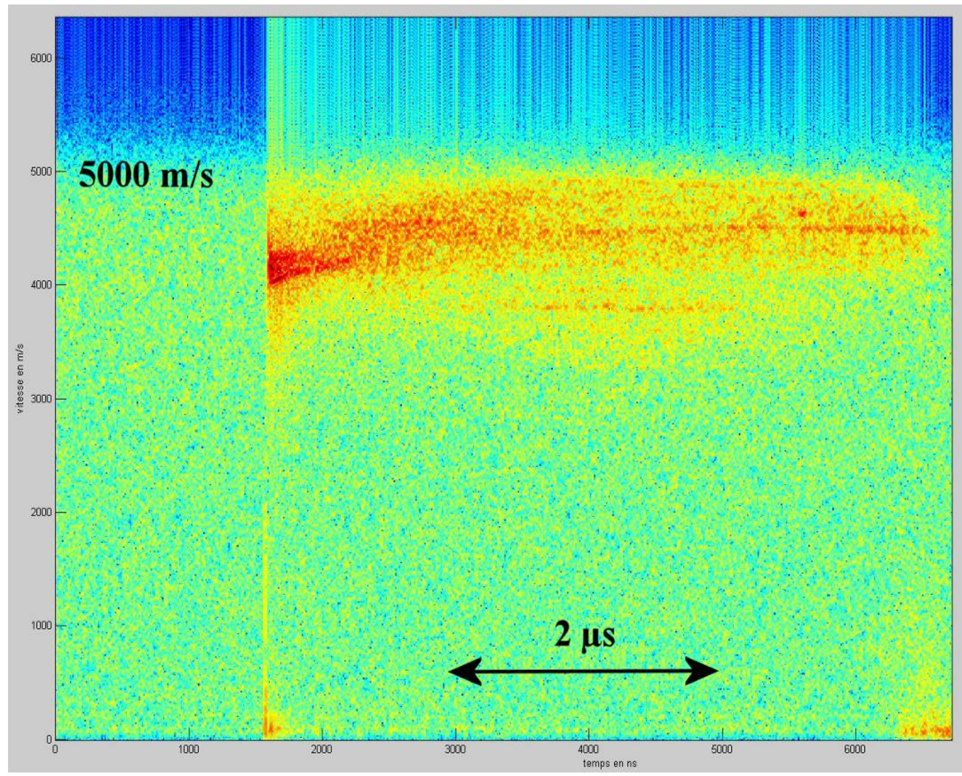
D_2O	Fresnel reflectivity coefficient R
1st shock 8 GPa	0.51%
2nd shock 10.6 GPa	0.77%

Tilted probing

AXIAL PROBING: CONSTANT VELOCITY VS TIME

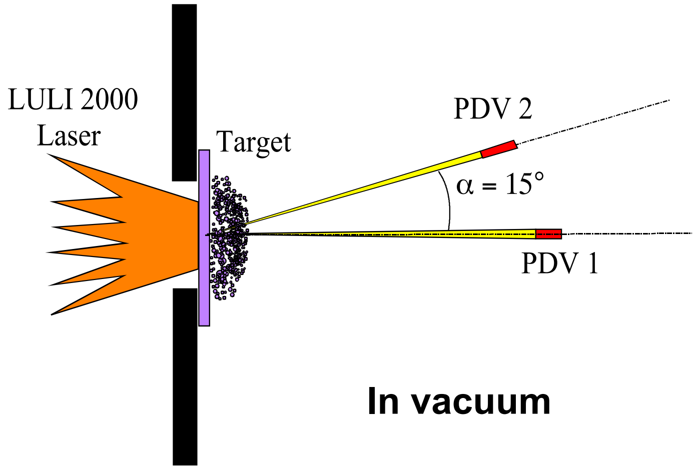


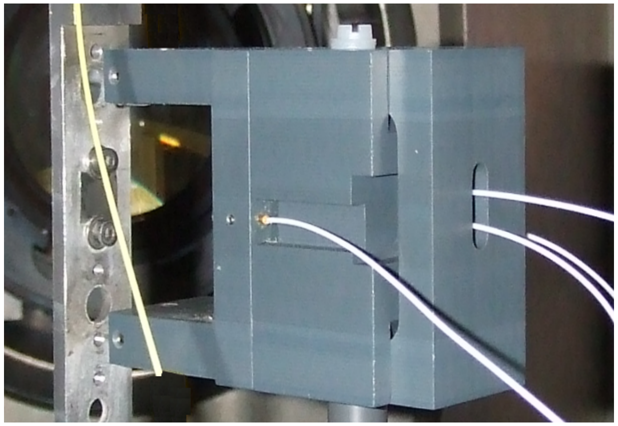
In vacuum

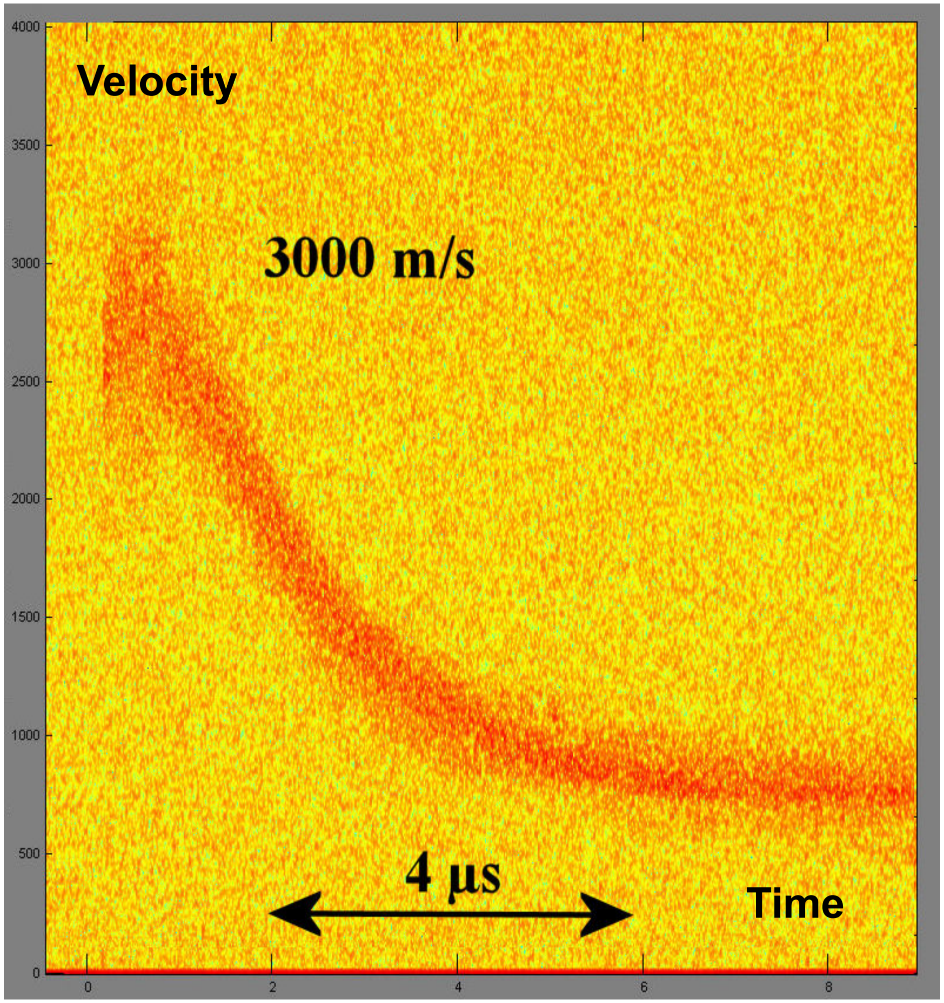


LULI Al 200 µm

TILTED PROBING: APPARENT DECELERATION

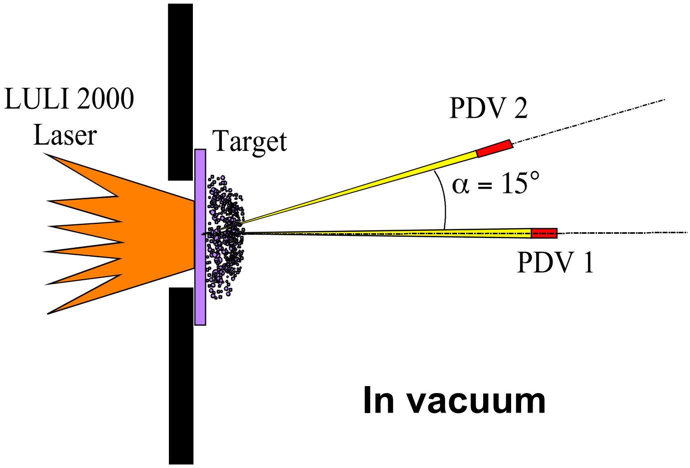




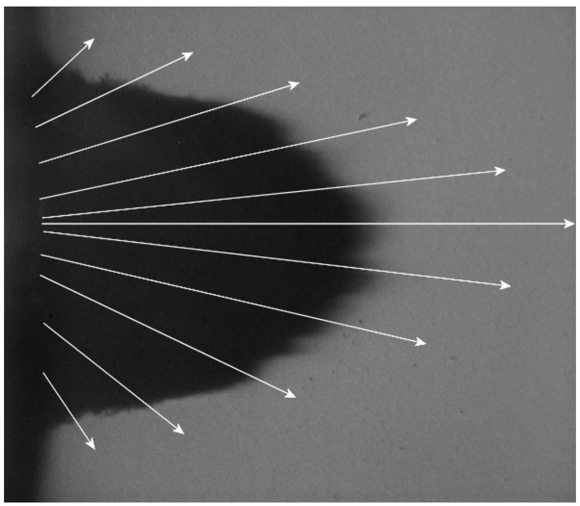


LULI Sn 100 µm

TILTED PROBING : EXPLANATION FROM SHADOWGRAPHY

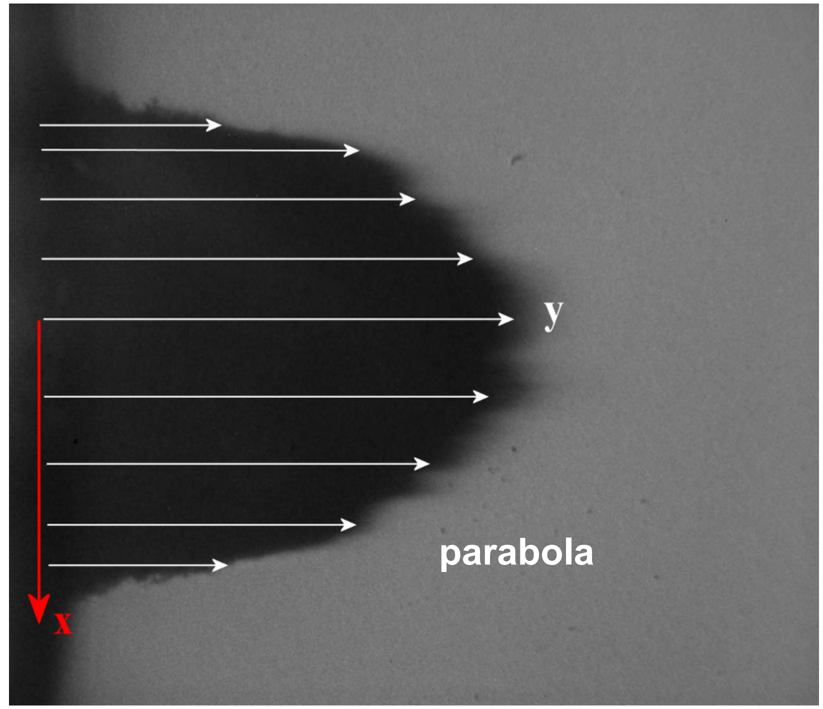


In vacuum



Complex velocity field (2D)
Difficult to describe it except with many pictures

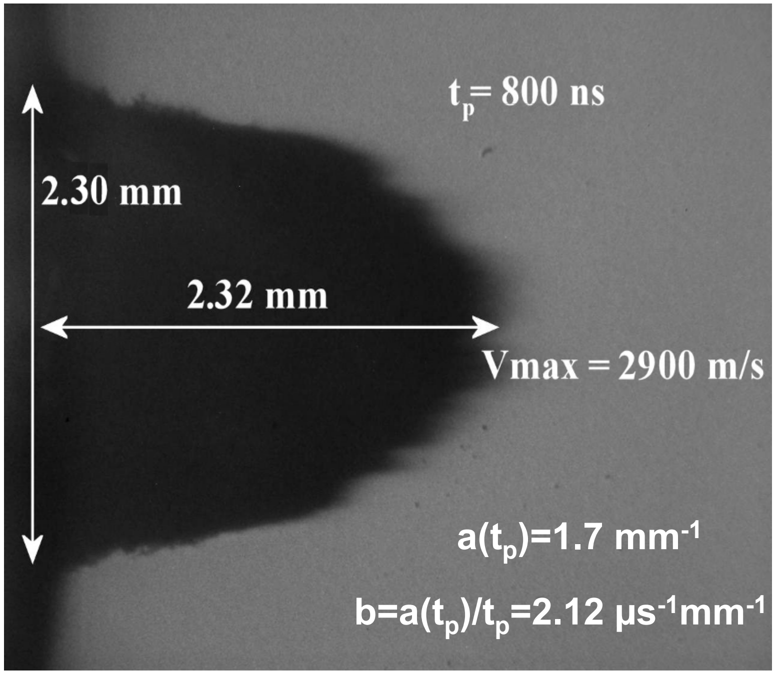
Shadowgraphy
t_p= 800 ns

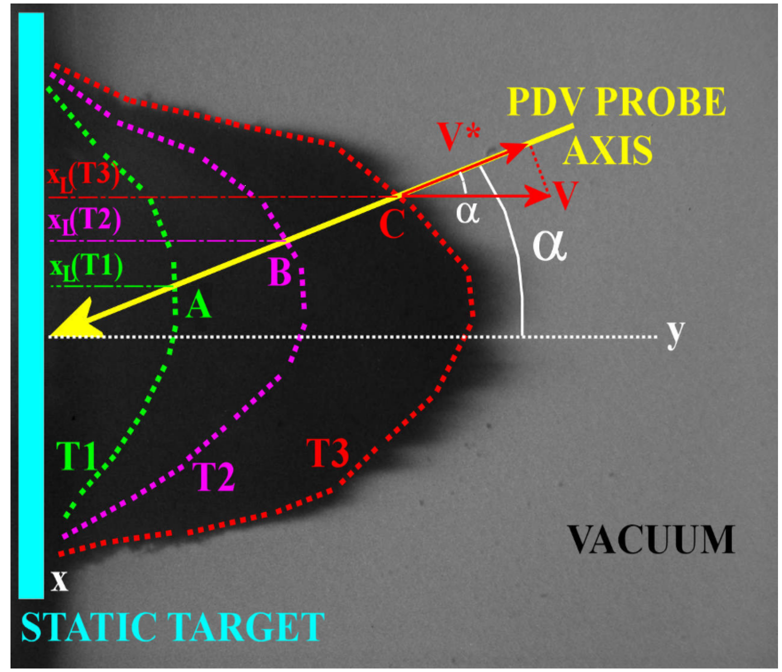


Simple model : Hypothesis

- **parallel velocities // oy**
- **all edge particles start at the same time (t=0 ns)**
- **y(x,t) is a considered as a parabola**
- **vacuum, no particle decelaration**

TILTED PROBING





Cloud parabola

$$b = \frac{a(t_p)}{t_p}$$

$$y(x,t_p) = V_{max}.t_p - a(t_p).x^2$$

$$V(x) = \frac{y(x,t) - y(x,t_p)}{t - t_p} = \frac{y(x,t_p)}{t_p}$$

$$y(x,t) = (V_{max} - b.x^2).t$$

PDV axis

$$y(x) = \frac{x}{\tan(\alpha)}$$

$$b.t.x^2 + \frac{x}{\tan(\alpha)} - V_{max}.t = 0$$

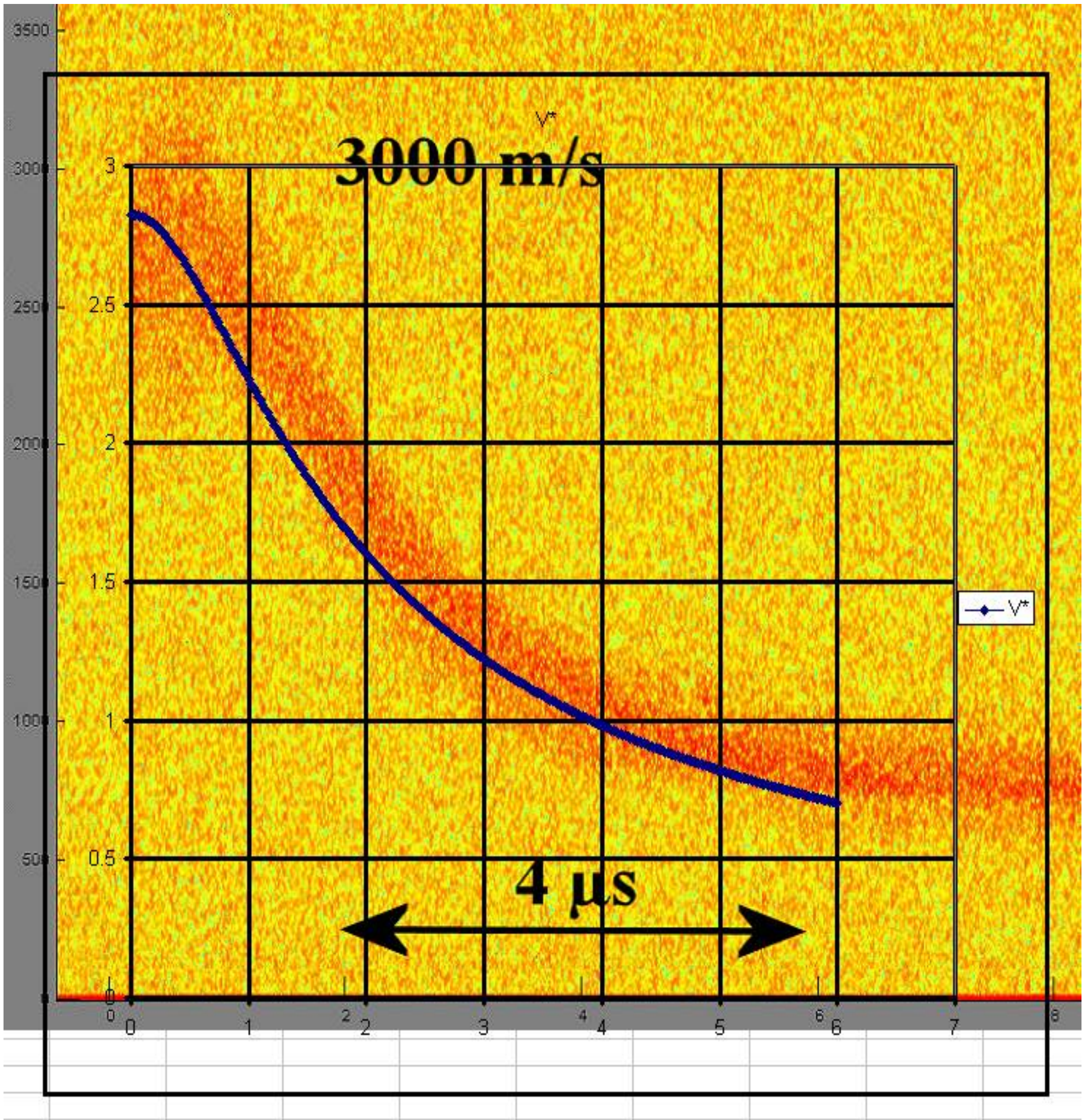
$$x_L(t) = \frac{\sqrt{1 + 4.b.V_{max}.t^2.\tan^2(\alpha)} - 1}{2.b.t.\tan(\alpha)}$$

$$V(x_L(t)) = V_{max} - b.x_L^2.t_2$$

$$V^*(x_L(t)) = (V_{max} - b.x_L^2.t_2).\cos(\alpha)$$

Measured apparent velocity

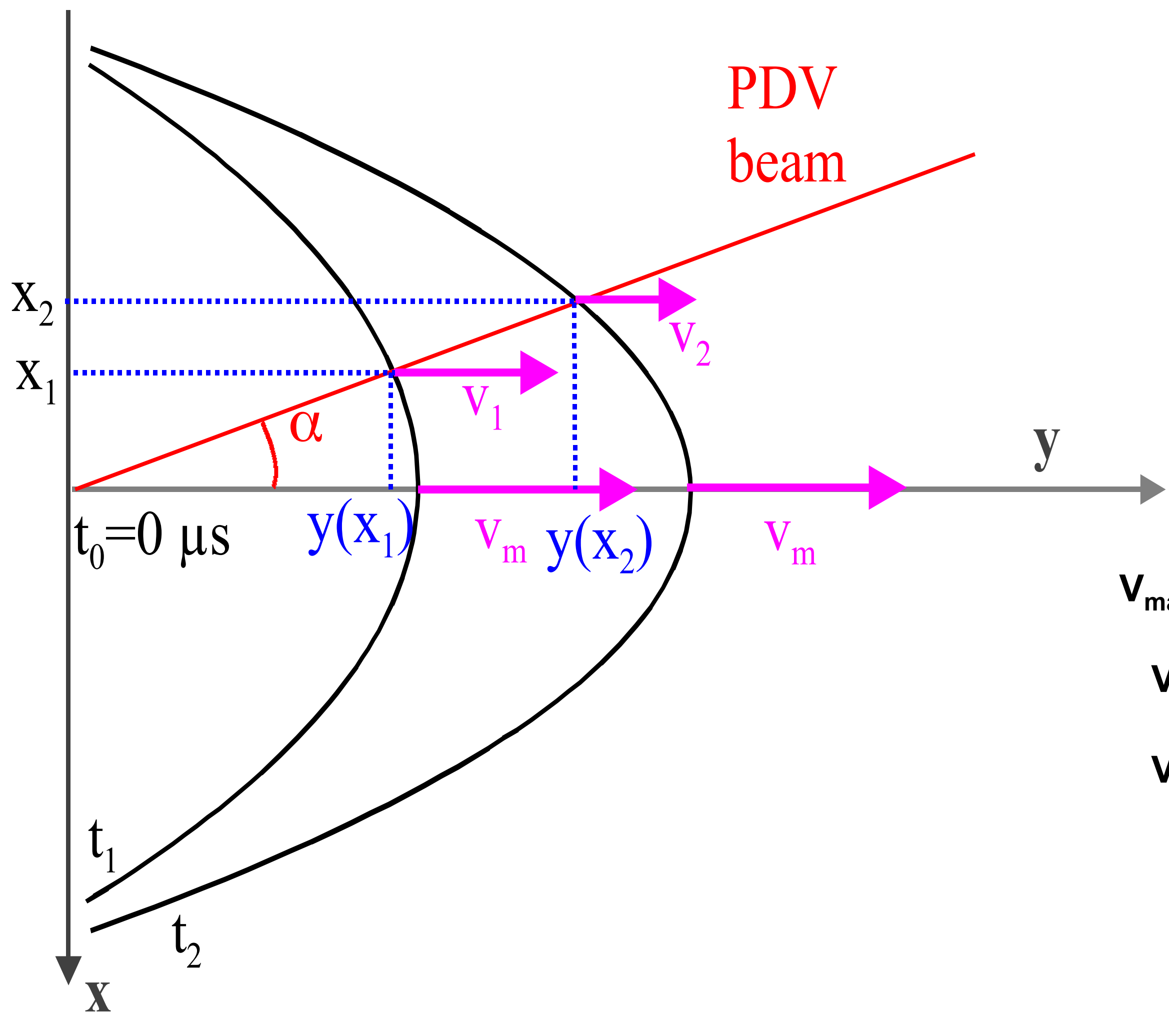
TILTED PROBING : MODEL–PDV COMPARISON



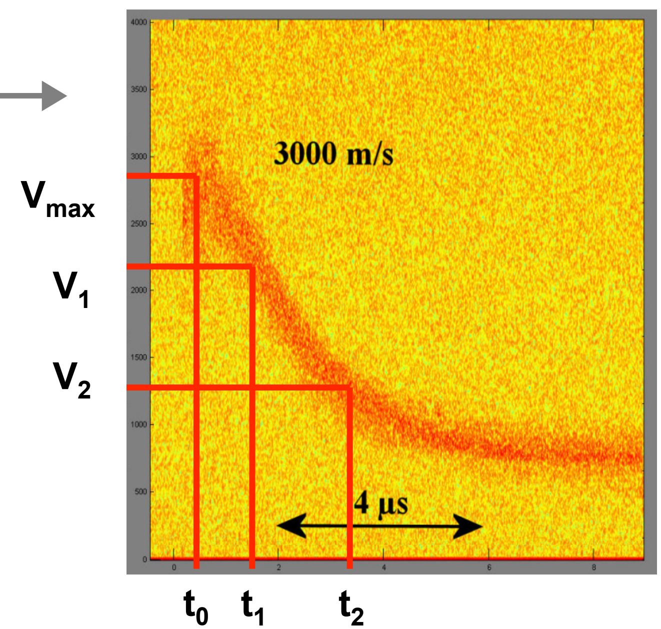
α	15 °
V_{max}	2900 m/s
t_P	800 ns
a	1.7 mm^{-1}
b	2.1 mm^{-1} μs^{-1}

LULI 2000
Target: Sn
Thickness: 100 µm

TILTED PROBING : CLOUD SHAPE FROM PDV



$$y(x_2) = V_m.t_2 - b.x_2^2.t_2 = V_2.t_2$$
$$y(x_1) = V_m.t_1 - b.x_1^2.t_1 = V_1.t_1$$
$$V_2 = V_m - b.x_2^2$$
$$V_1 = V_m - b.x_1^2$$
$$x_2 - x_1 = (V_2.t_2 - V_1.t_1).\tan(\alpha)$$



$$b = \frac{V_2 - V_1}{(V_1^2.t_1^2 - V_2^2.t_2^2).\tan^2(\alpha)} = \frac{V_m - V_1}{V_1^2.t_1^2.\tan^2(\alpha)}$$

CONCLUSION

- **Optical Fibers in H_2O: 2 signals observed (very low transparency @ 1.55 µm)**
  - Bad transparency à 1.55 µm: no visible signals in the medium,
  - Visible H_2O/OF Interface (800 m/s*),
  - No visible shock in the silica

- **Optical Fibers in D_2O: : 3 signals observed (good transparency @ 1.55 µm)**
  - Good transparency à 1.55 µm: Visible signals
    steel/D_2O interface & shockwave in D_2O
  - Visible D_2O/OF Interface (800 m/s*),
  - No visible shock in the silica, but still visible steel/D_2O interface after OF impact

- **Shock wave velocity U(t) continuously measured in: NM & D_2O**
  - n(ρ) determination,

- **Tilted probing**
  - Different investigation of the 2D particle cloud,
  - Good comparison : shadowgraphy and PDV (simple model),
  - Possibility to re-build the cloud shape from PDV signal.

Micro probing

MICRO PROBING : AN OTHER WAY OF SENSING VELOCITIES

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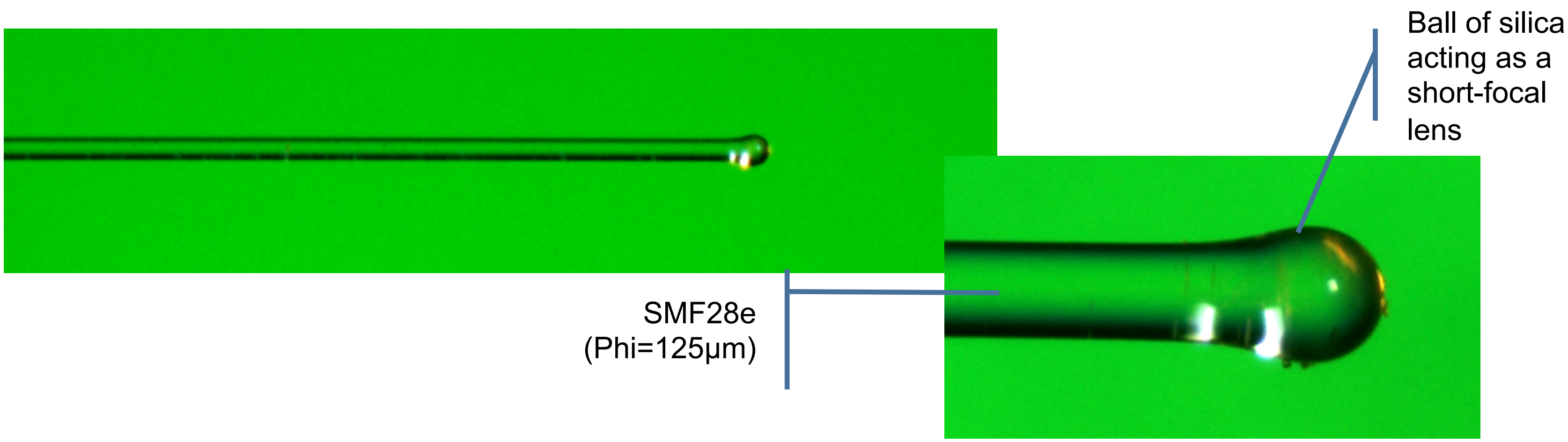
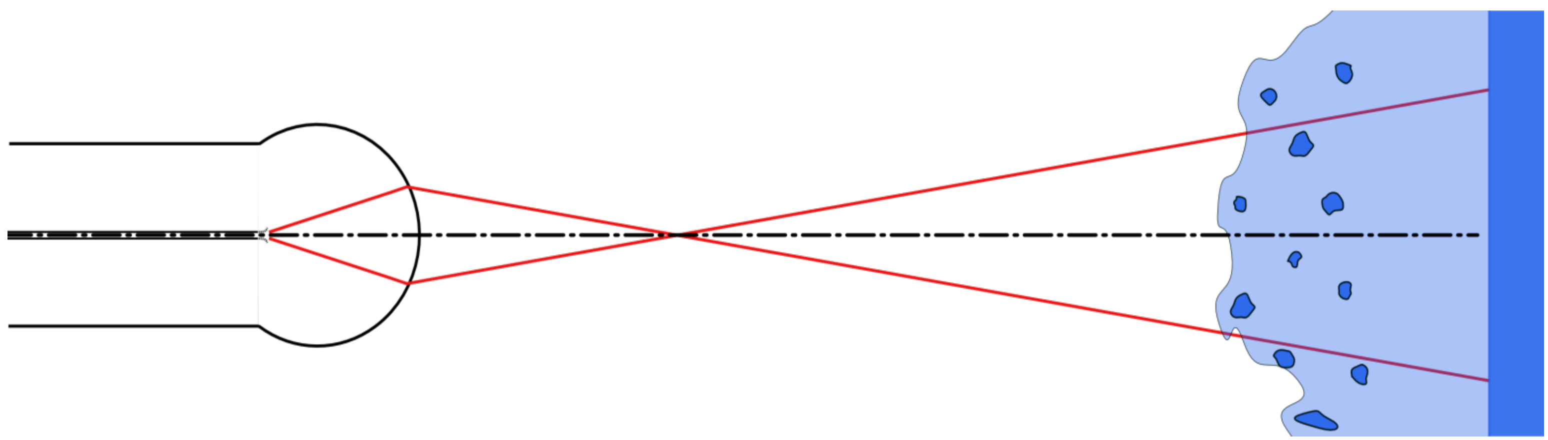
- **PDV is a very powerful means to observe complex phenomena involving multiple velocities**
  - Sometimes, this wealth is overwhelming, and it might be useful to limit the field of measurement.
  - This is typically true when measuring clouds of particles which, during the whole experiment exhibit a continuous evolution of a number of velocities over both time and space.
  - Microprobes were first designed in order to supplement the PDV signal obtained with collimated probes, by probing a very limited volume at a well known position
- **Tested on a tin cloud generated by a gun, probably more complex than expected…**

MICRO PROBING : AN OTHER WAY OF SENSING VELOCITIES

- **Structure of a microprobe**
  - Made from a bare fiber

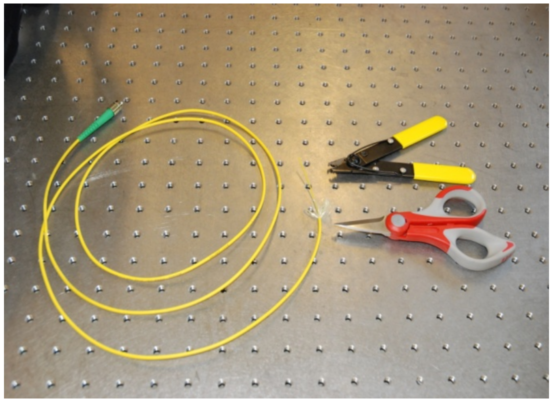


- **Idea: very localized sensing in all 3 dimensions**

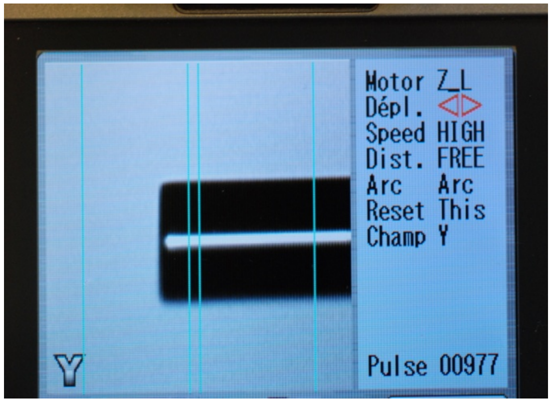


MICRO PROBING : AN OTHER WAY OF SENSING VELOCITIES

- **Manufacturing tutorial:**

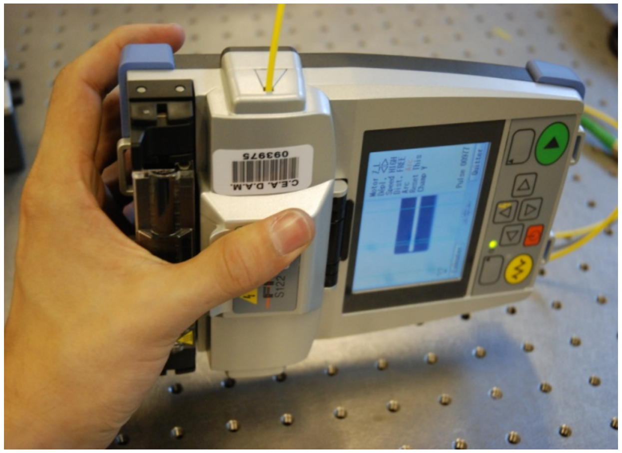


Step 1: Bare SMF28e, cleaved



Step 2: Manual positioning in the welder

Step 3: Choose manual program and set apporx. 10s cooking time

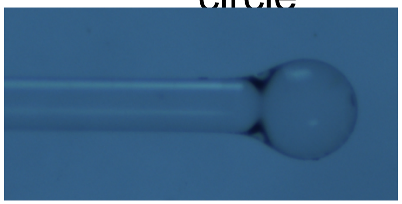


Step 4: Whille arking, hold the welder at 90° to end up with a symetrical bubble

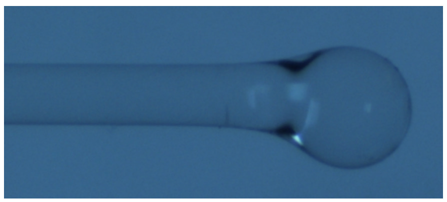
MICRO PROBING : AN OTHER WAY OF SENSING VELOCITIES

- **Manufacturing repatability:** based on geometry

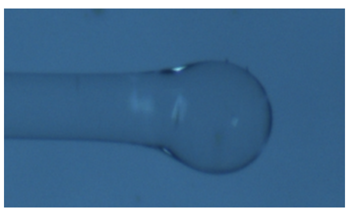
Characteristics of the probes used on the shot: profile very well approximated by a circle



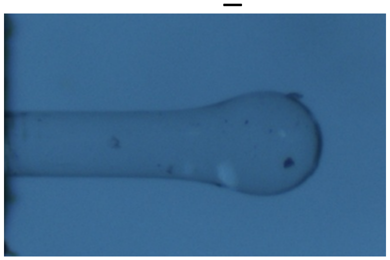
Probe_1



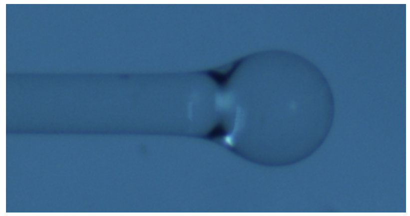
Probe_2



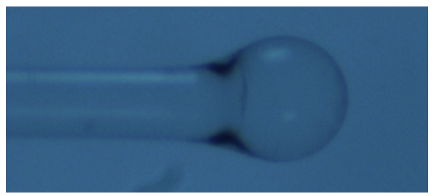
Probe_3



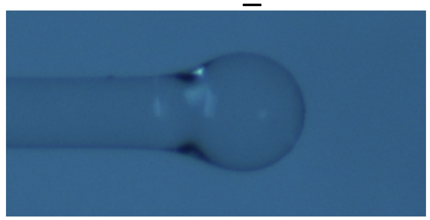
Probe_4



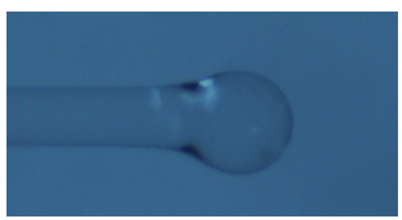
Probe_5



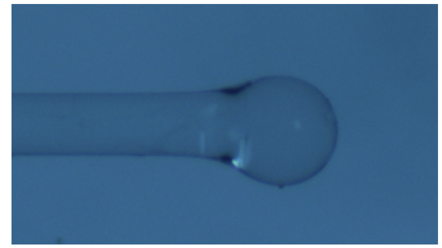
Probe_6



Probe_7



Probe_8



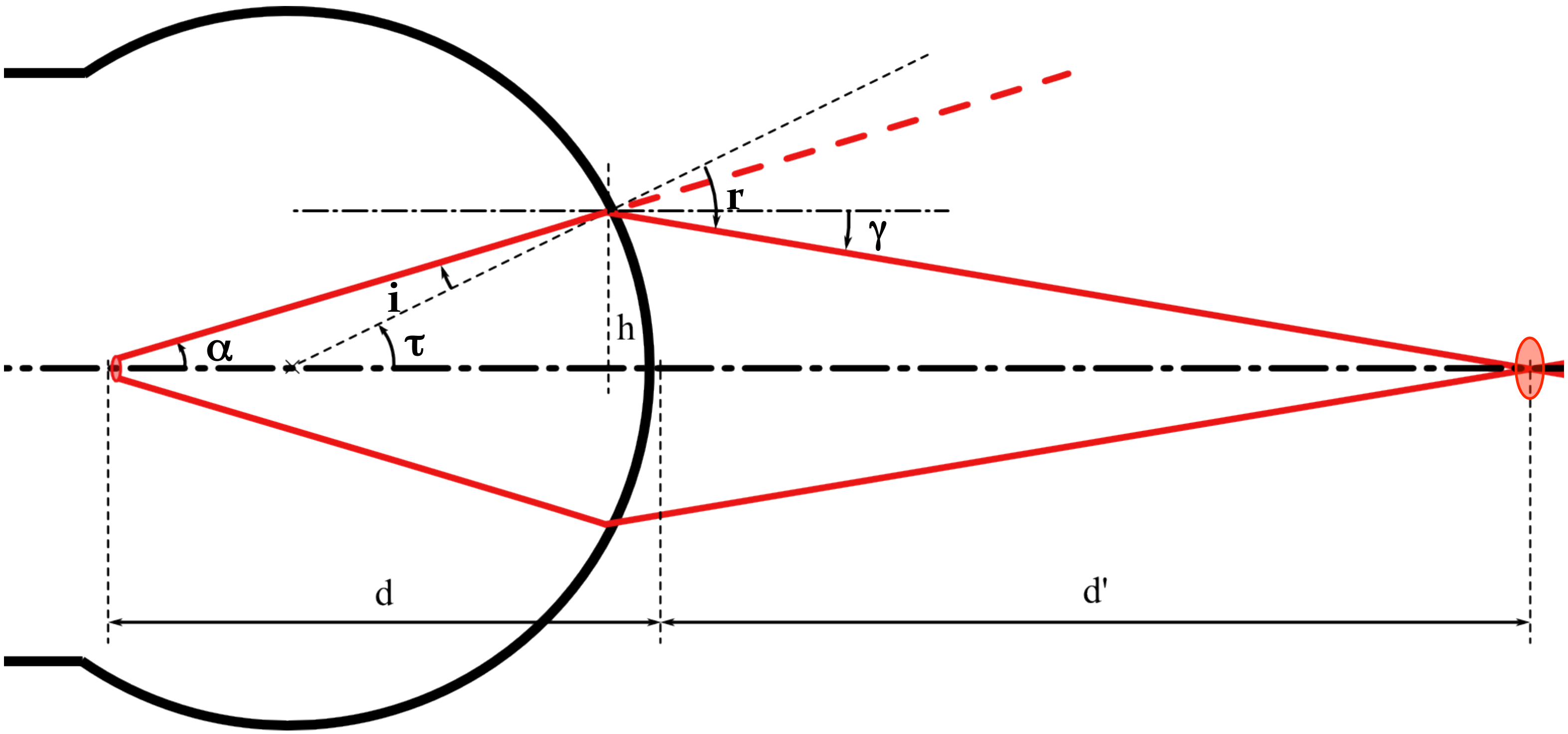
Probe_9

Probe #	Distance to Free Surface (mm)	Cladding diameter (pix)	Phi (pix)	R (µm)	Cladding (µm)
1	**10**	**200**	**380**	238	**125**
2	**15.2**	**96**	**200**	260	
3	**20.1**	**100**	**175**	219	
4	**Broken**	**97**	**160**	206	
5	**10.4**	**98**	**190**	242	
6	**15**	**100**	**186**	233	
7	**20**	**100**	**167**	209	
8	**25.6**	**100**	**180**	225	
9	**20**	**98**	**180**	230	

Global radius	**229µm**
STD	**7%**

MICRO PROBING : AN OTHER WAY OF SENSING VELOCITIES

- **Probe optical characteristics :** first estimate through Gauss approx.



$$
\begin{cases}
\gamma = r + \tau \approx -\dfrac{h}{d'} \\
\tau = \alpha - i \approx \dfrac{h}{R} \\
r \approx n \cdot i \\
\alpha \approx -\dfrac{h}{d}
\end{cases}
\Rightarrow
\begin{cases}
\gamma = \left[n + (n-1) \cdot \dfrac{d}{R} \right] \cdot \alpha \\
d' = \dfrac{d \cdot R}{n \cdot R + (n-1) \cdot d}
\end{cases}
$$

$(d \leq 0)$

$(R \geq 0)$

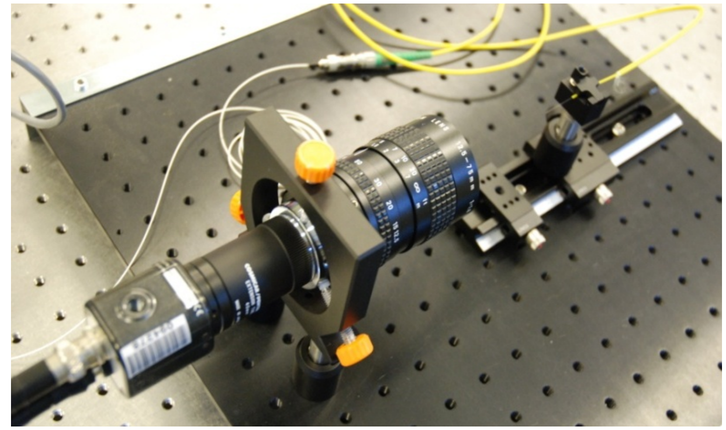
Assuming d=-2R, α=ON/n=0.14/1.46

we get:

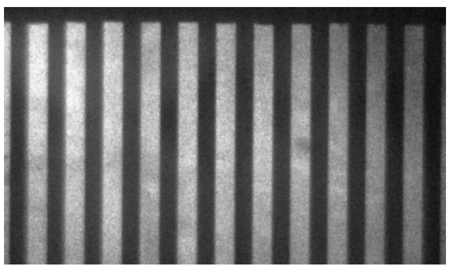
$$
\begin{cases}
d' = \dfrac{2R}{2-n} \approx 850 \mu m \\
g_y = \dfrac{n}{n - 2 \cdot (n-1)} \approx 2.74 \\
\gamma \approx 0.051
\end{cases}
$$

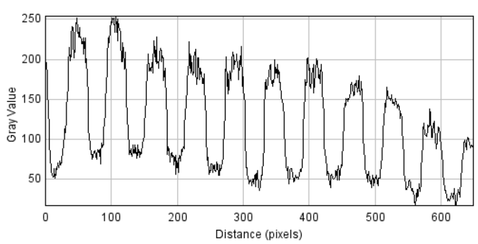
MICRO PROBING : AN OTHER WAY OF SENSING VELOCITIES

- **Lab characterisation:** uneasy due to small size

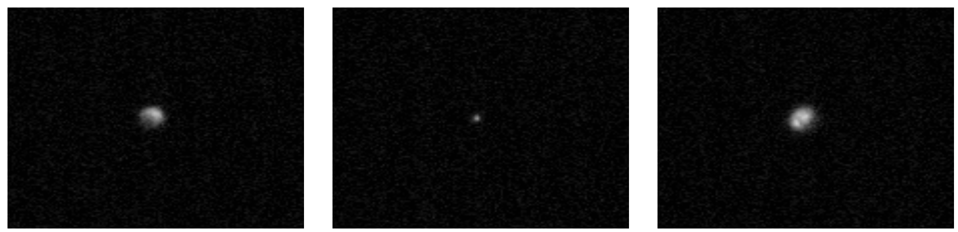


- **Setup:** IR camera, Pentax lens in macro mode (long back focal distance)

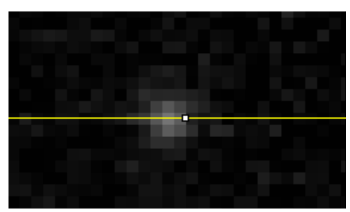


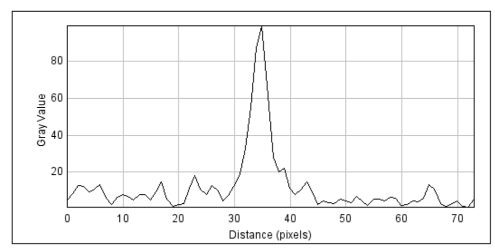


System calibration
1 pixel = 14.6 µm



Measured NA = 0.034



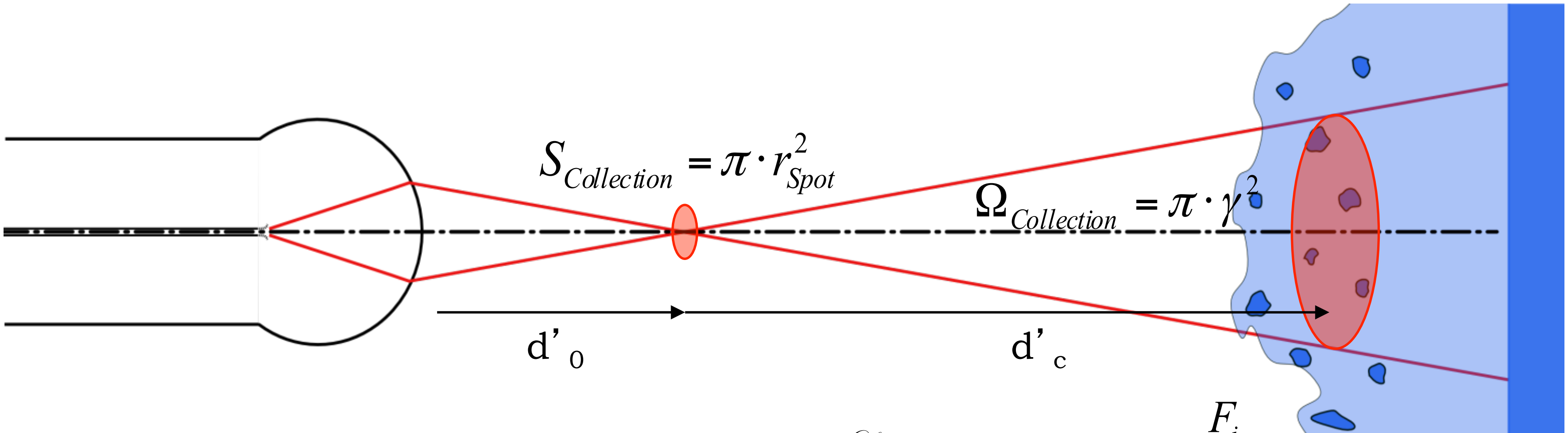


Focal point diameter measured 60 µm

(Measurement accuracy not considered high due to low detector dynamic and inadequate system resolution)

MICRO PROBING : AN OTHER WAY OF SENSING VELOCITIES

- **Probe efficiency:** based on previous model
  - The cloud considered perfectly lambertian, Gauss approximation still applied



$$\mathcal{L}_{Cloud} = \frac{F_i}{2\pi \cdot \left[\pi \cdot \left(\gamma \cdot (d'_c - d')^2\right) + \pi \cdot r_{Spot}^2\right]}$$

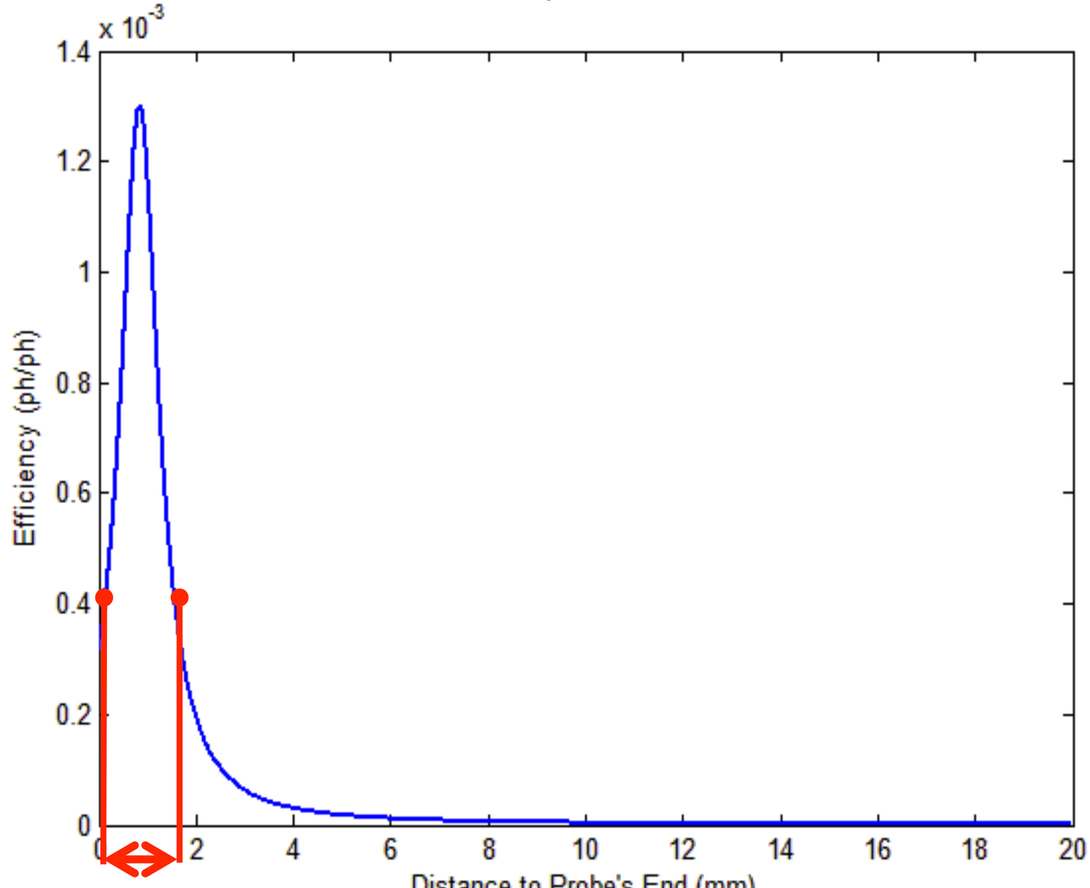
- Finally,

$$\eta(d') = \frac{\gamma^2 \cdot r_{Spot}^2}{2 \cdot \left[\gamma^2 \cdot (d'_c - d'_0)^2 + r_{Spot}^2\right]}$$

$$r_{spot} \approx 24.7\,\mu m$$

MICRO PROBING : AN OTHER WAY OF SENSING VELOCITIES

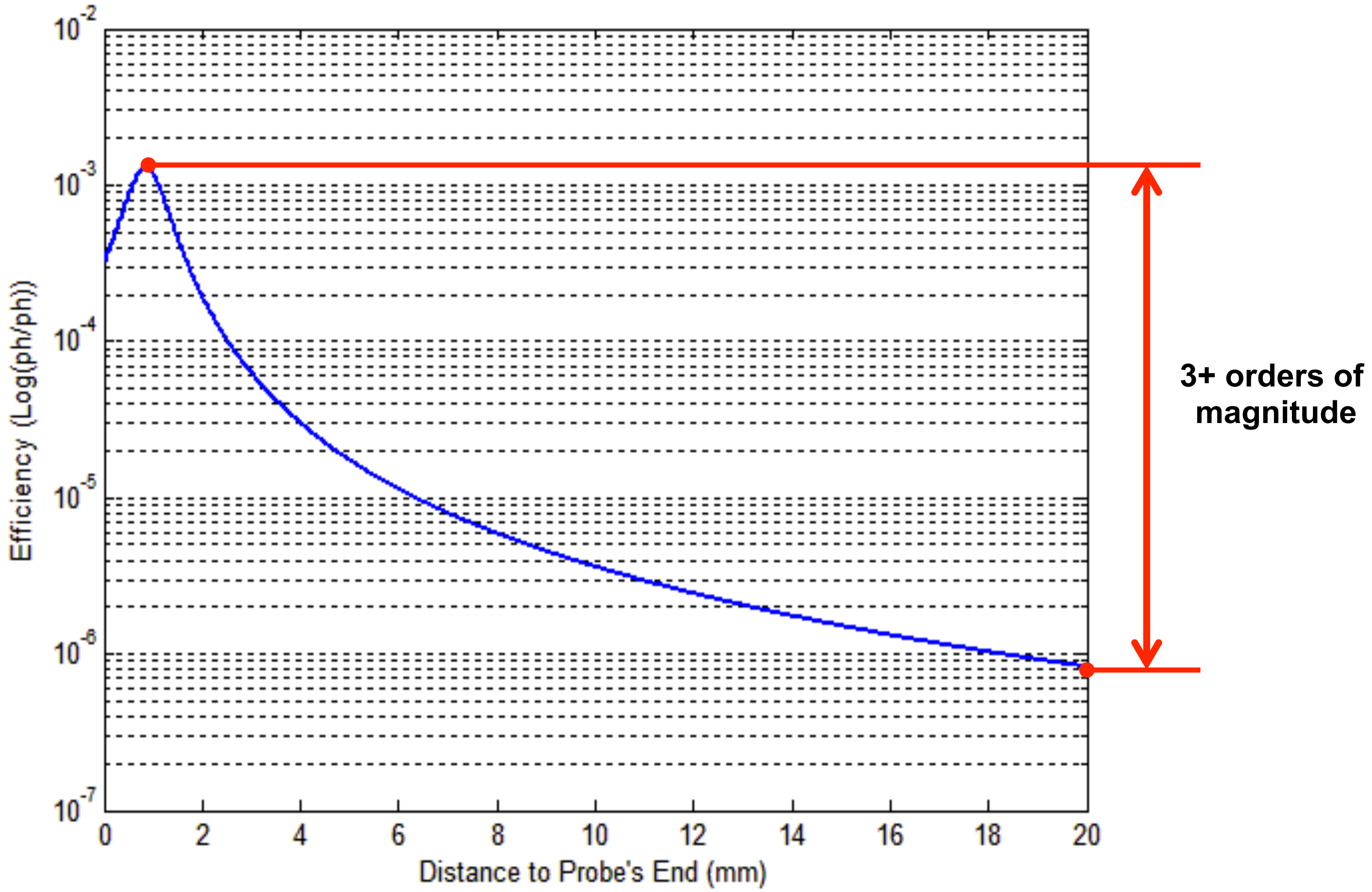
- **Probe awaited efficiency vs distance to probe's end:** based on previous model
  - Highly peaked efficiency curve along the probe axis. Considering the very small transverse spot size (< 100 µm)
  - The expected depth-wise selectivity is:



Almost 1 order magnitude swept within less than 2 mm

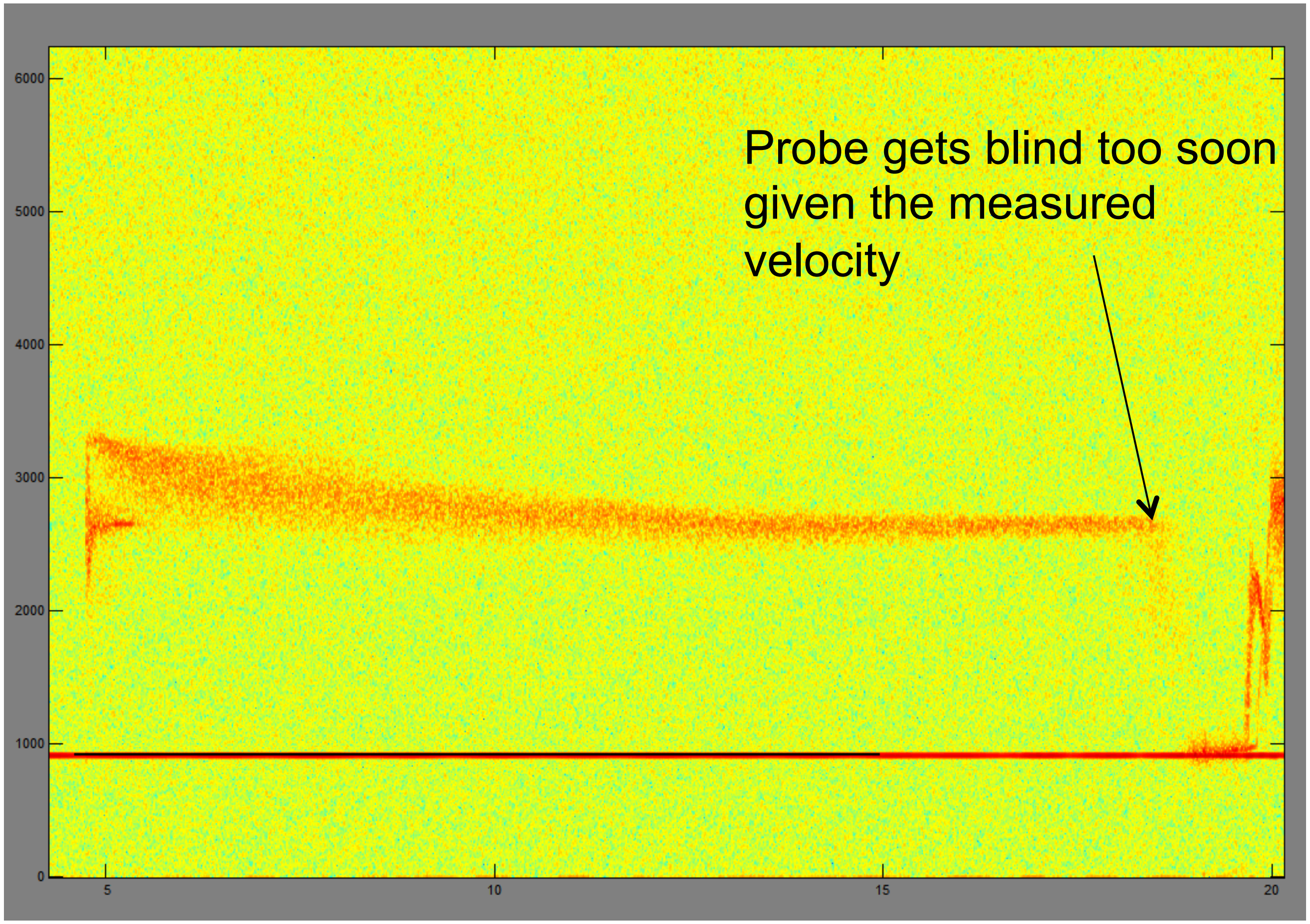
MICRO PROBING : AN OTHER WAY OF SENSING VELOCITIES

- **Probe awaited efficiency (log scale) vs distance to probe's end:**



MICRO PROBING : AN OTHER WAY OF SENSING VELOCITIES

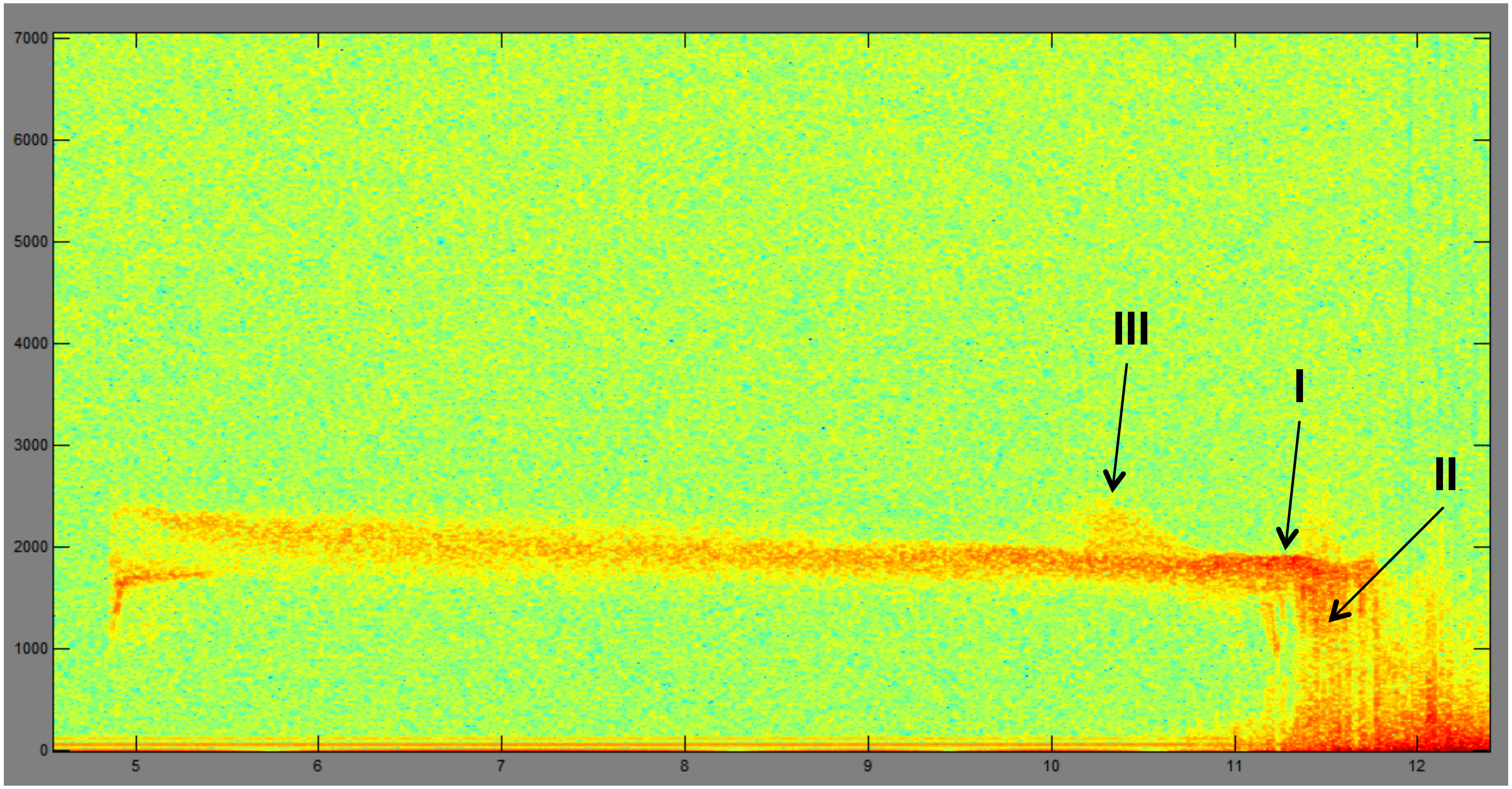
- **Results on a shot:**
  Gun shot on machined tin target under atmospheric pressure.
  - 3 Collimated probes at 28 mm from the free surface
  - 9 micro-probes set at 10, 15, 20 and 25 mm
  - Dense cloud : free surface quickly disappears, probes get blind very quickly
- **Spectrogram from a collimated probe:**



MICRO PROBING : AN OTHER WAY OF SENSING VELOCITIES

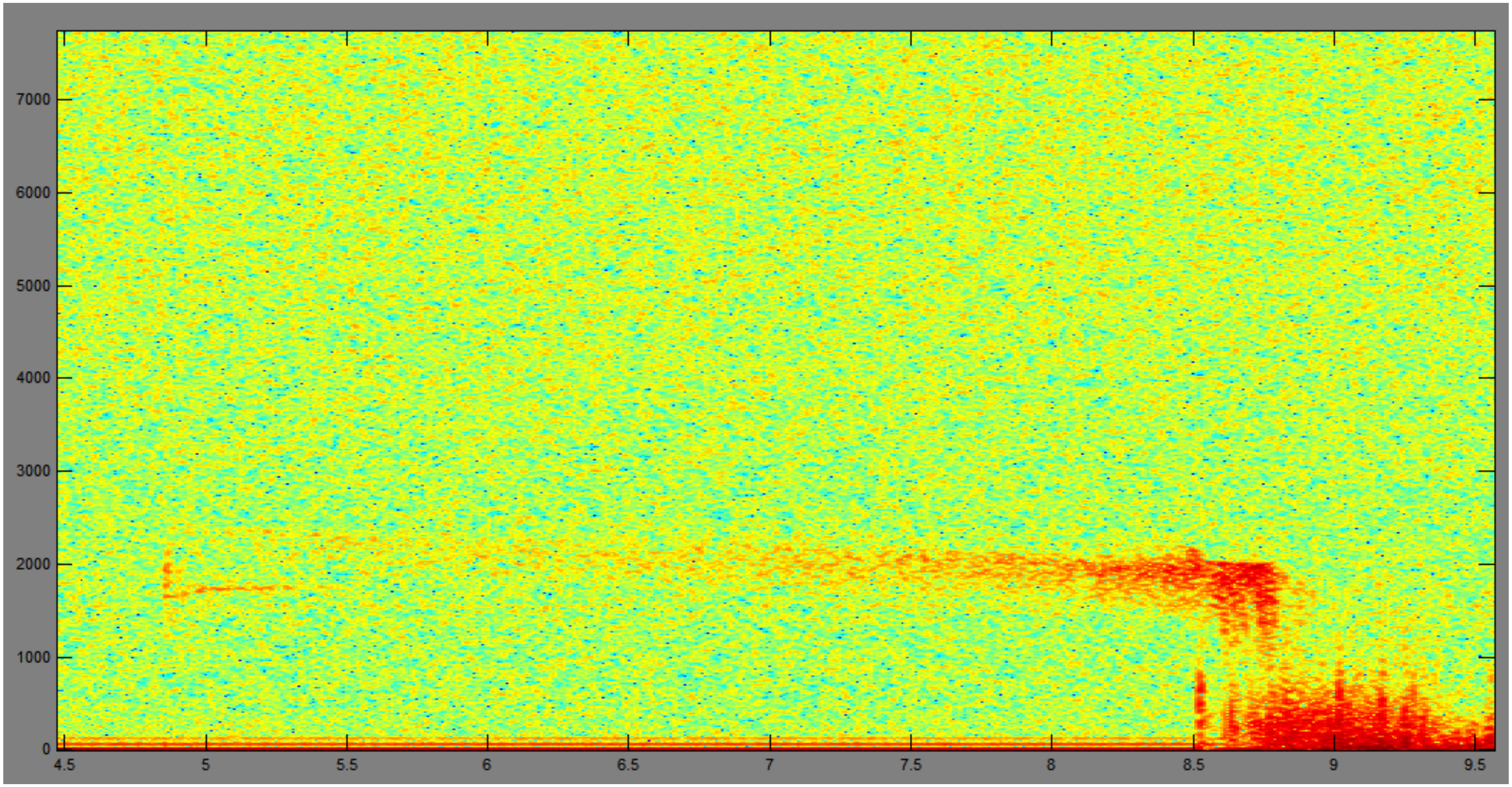
- **Micro probes spectrograms features:**
  Appears on every spectrograms
  - **I** - Strong signal velocity on few pixels (timewise and spectralwise)
  - **II** - Then, 'velocitie falls-off'

  On some (3 out of 9-1 broken=8) spectrograms
  - **III** - Sudden appearance of a cloud/tracks at higher velocities
  - **IV –** The whole experiment is caught, from break-out to impact



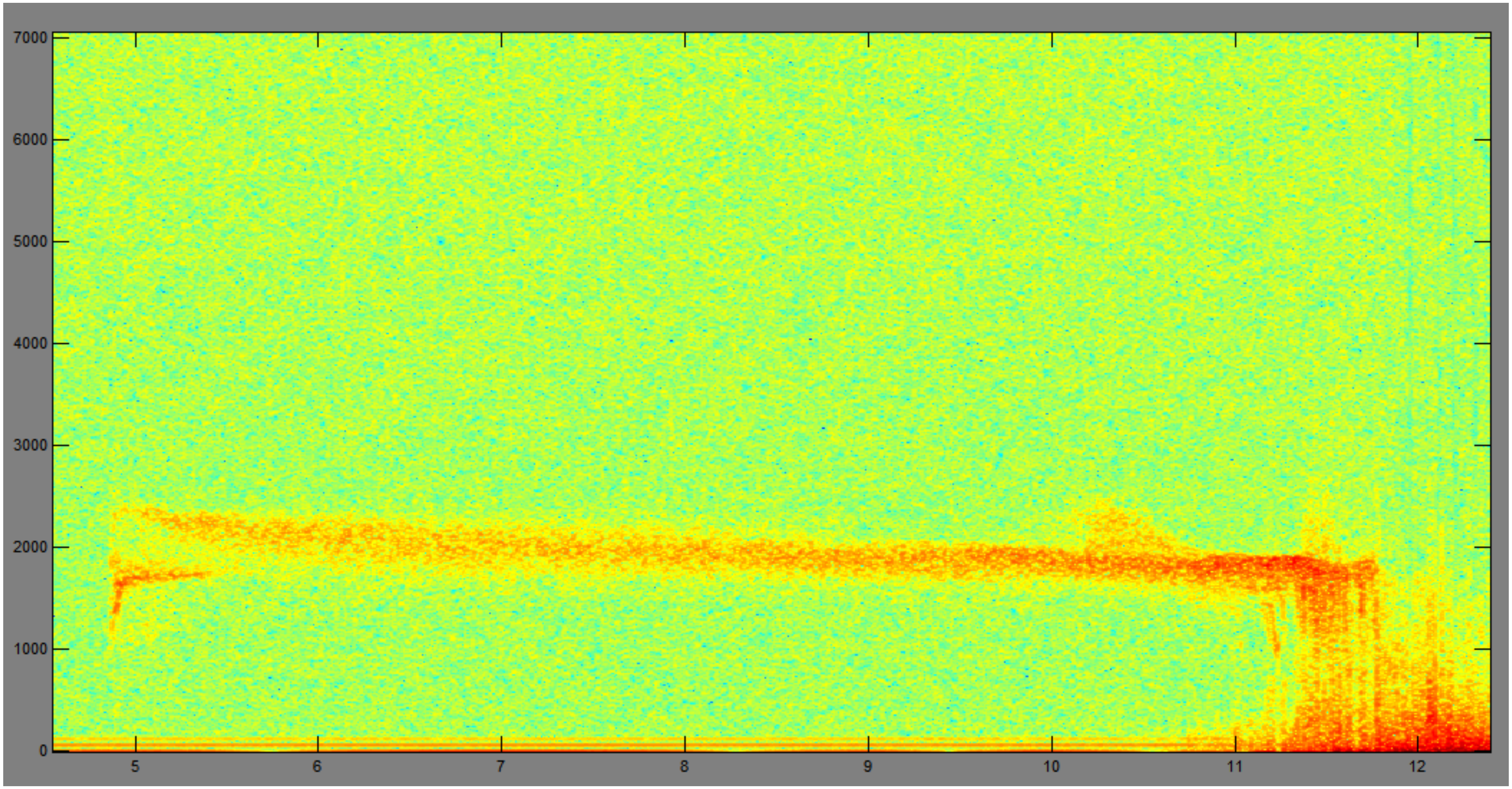
MICRO PROBING : AN OTHER WAY OF SENSING VELOCITIES

- **Spectrogram from a micro probe:** at 10 mm from FS



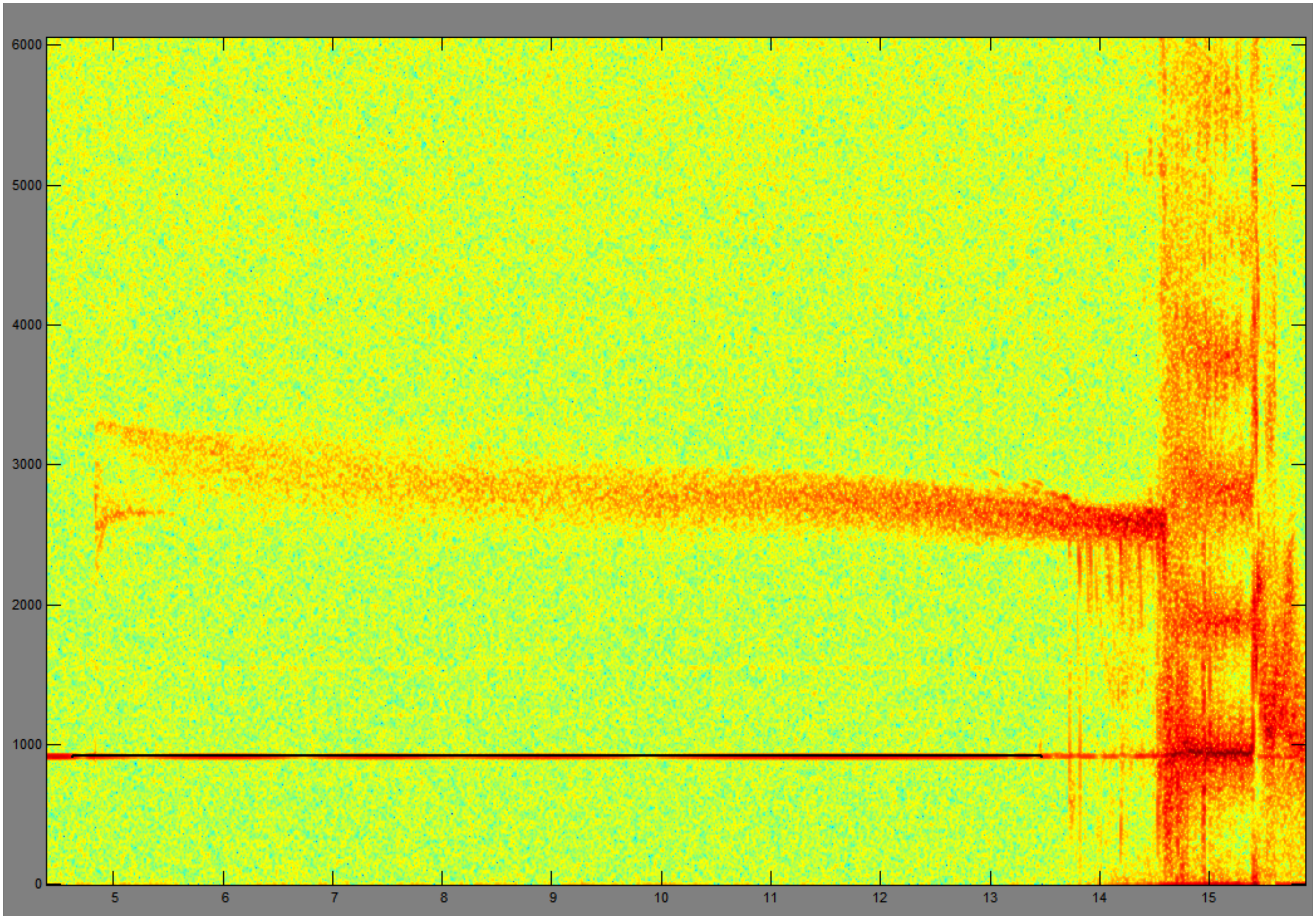
MICRO PROBING : AN OTHER WAY OF SENSING VELOCITIES

- **Spectrogram from a micro probe:** at 15 mm from FS



MICRO PROBING : AN OTHER WAY OF SENSING VELOCITIES

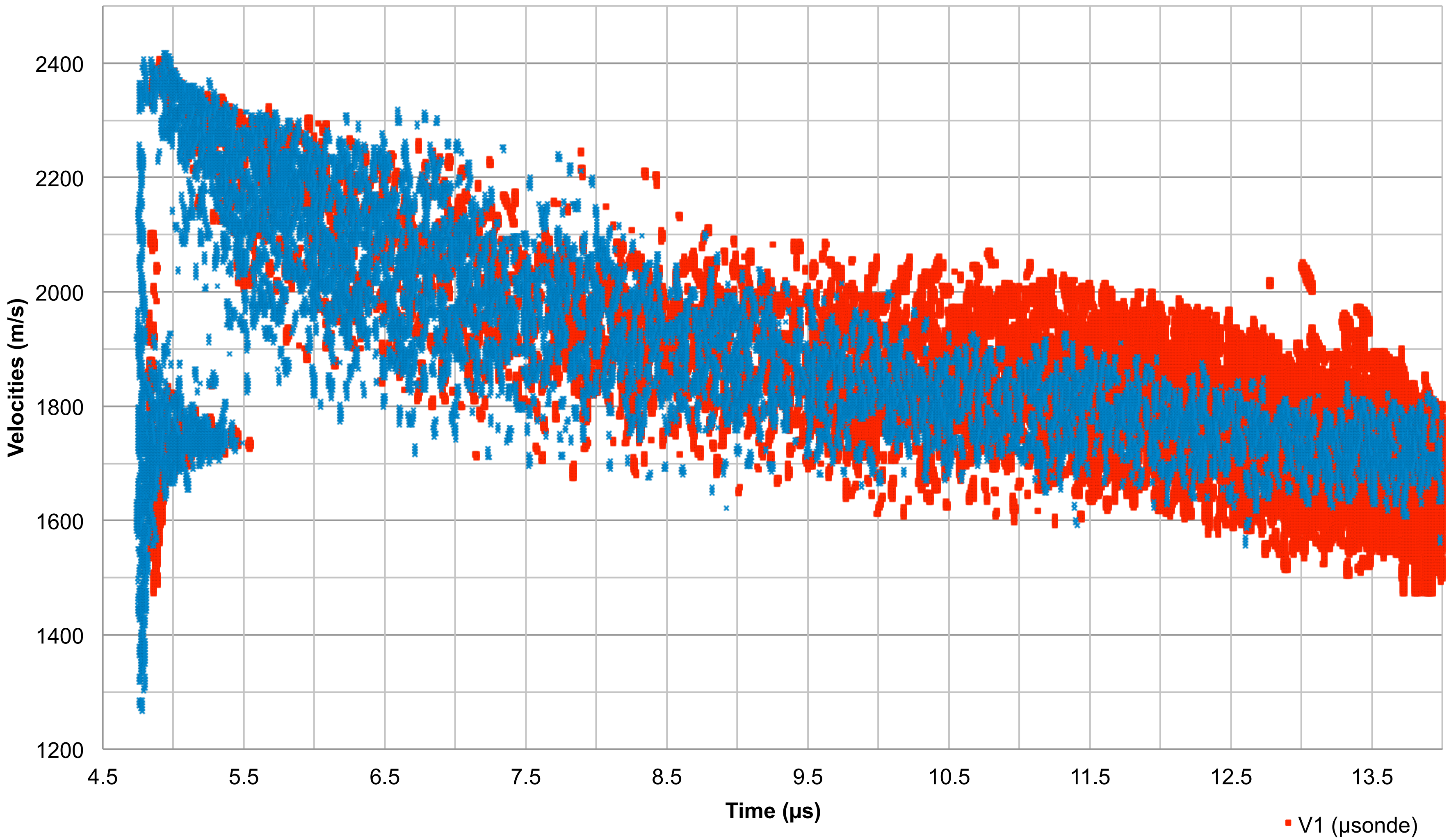
- **Spectrogram from a micro probe:** at 25 mm from FS



MICRO PROBING : AN OTHER WAY OF SENSING VELOCITIES

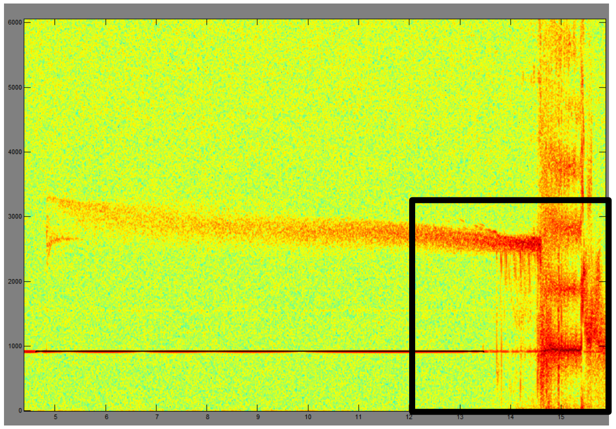
- **Collimated VS micro probe:** different measurements (blue=collimated, red=micro probe)…

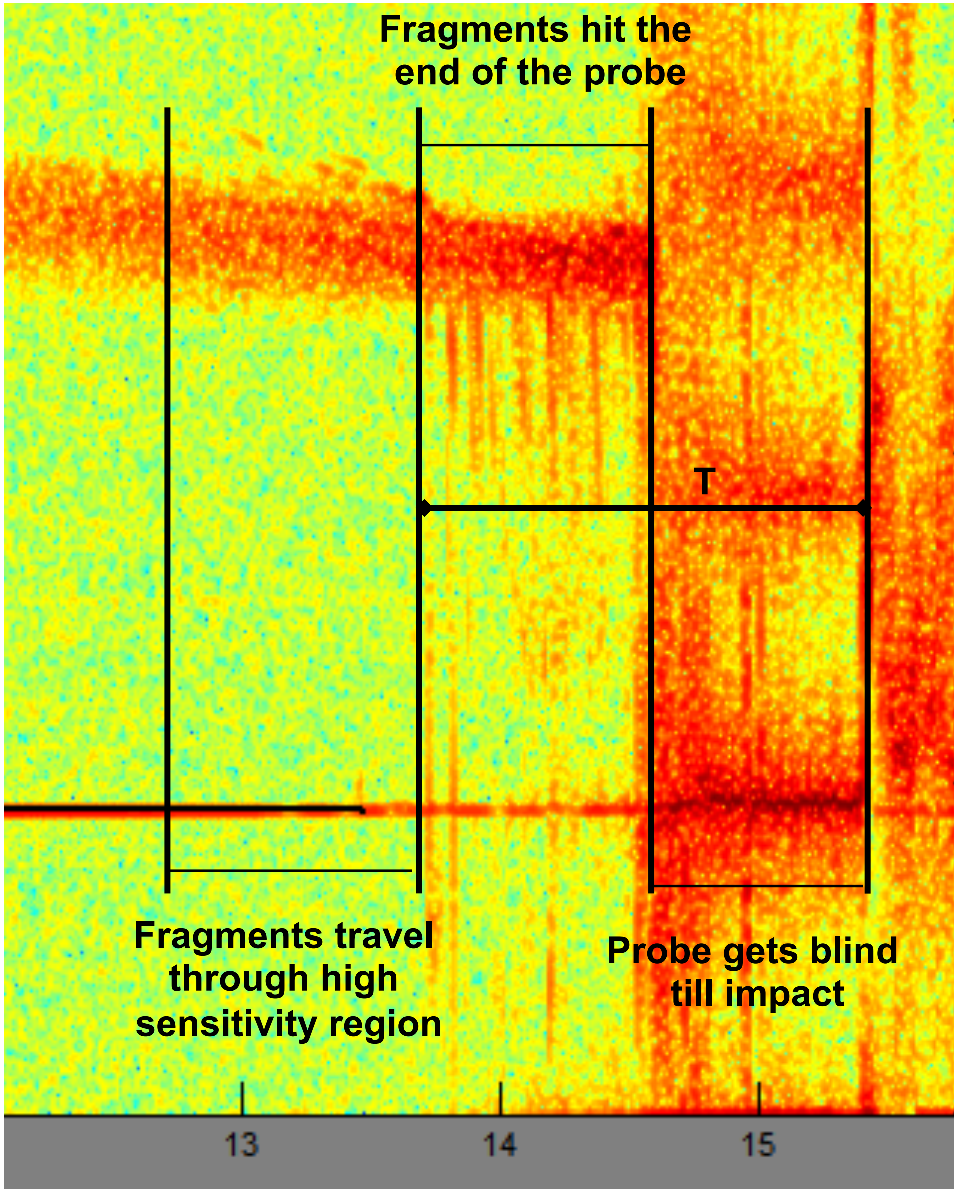
  …not only due to different NA (velocities would be lower on the red cloud)



MICRO PROBING : AN OTHER WAY OF SENSING VELOCITIES

- **Spectrogram from a micro probes (#9):** possible explanation





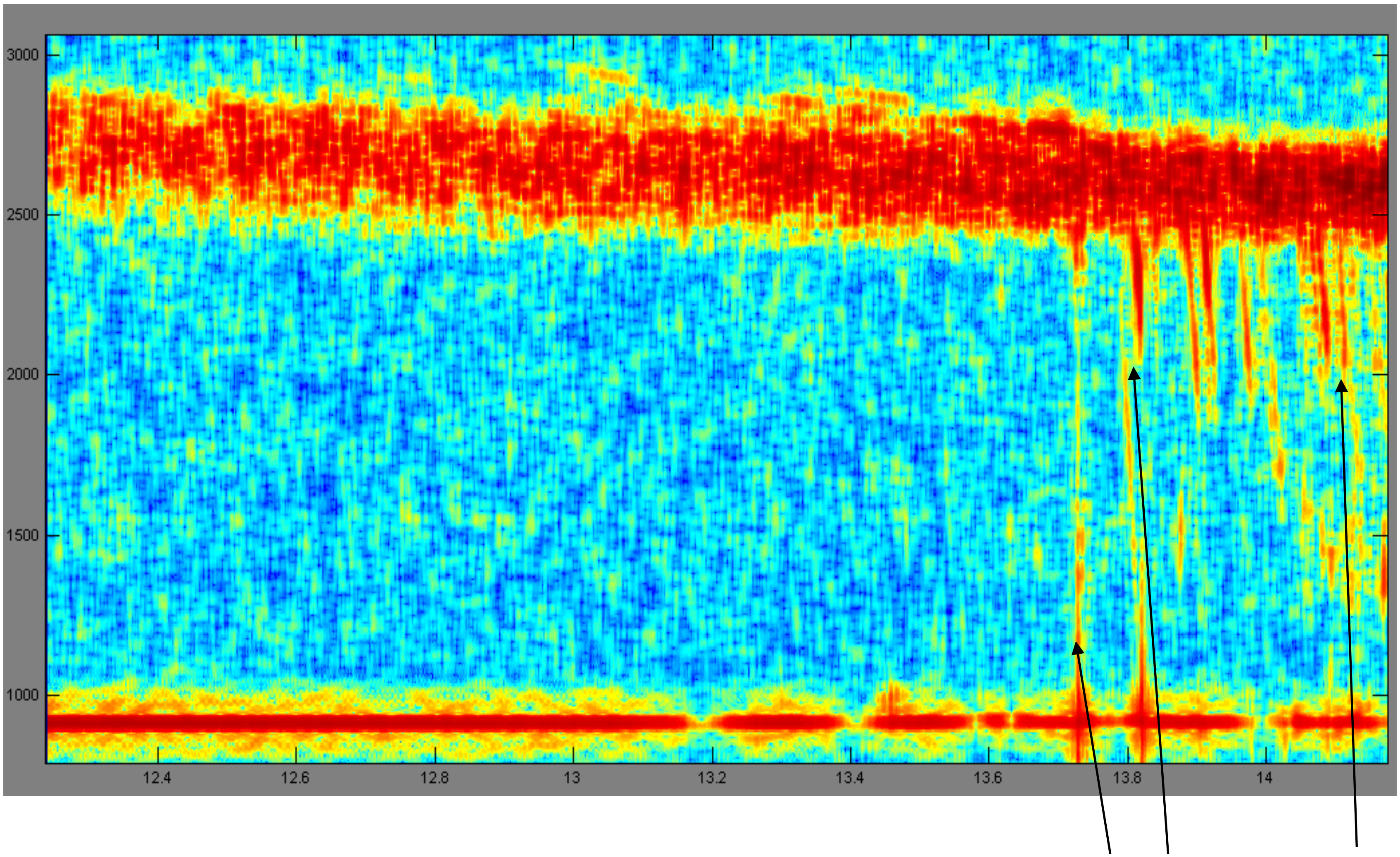
<u>To be consolidated/confirmed by future shots</u>

Collimated probes may be blind to certain optical density/velocities that focussed microprobe get thanks to inhomogeneous efficiency

Under this plausible scenario, total depth T of the cloud would be about 3.5 mm

MICRO PROBING : AN OTHER WAY OF SENSING VELOCITIES

- **Spectrogram from probe #9:** interesting area w dual pass 50-10 ns window



Very steep fall-off

MICRO PROBING : AN OTHER WAY OF SENSING VELOCITIES

- **Conclusion:**
  - Micro probes are easy to make and they bring another look to rich PDV measurement without being intrusive
  - Focussed probe's spectrograms are the result of a **competition** between **scatering efficiencies of the samples depth-wise and the efficiency of the probe, which also varies in distance**.
  - This localised jump of sensitivity **may** reveal phenomena that would remain undetected otherwise.
  - Data and explanations **still have to be consolidated** (only 1 shot with few probes)
  - Future shots should be made on less dense clouds

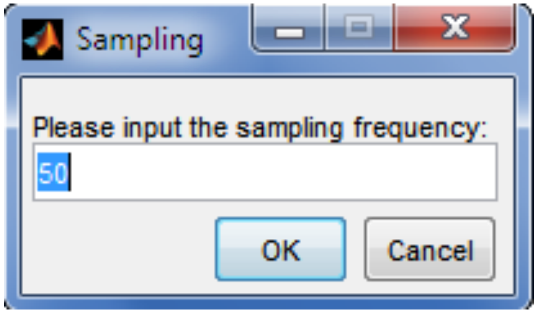
PDV signal generator

PDV SIGNAL GENERATION

- **Is a try to answer to different needs:**
  - Predicting spectrograms in situations where we may find a combination of undersampling, multiplexing, signal clipping…
  - Assisting the understanding of complex spectrograms (typ. Velocity measurements with transparent windows)
  - Benchmarking algorithms (PDV WS, Austin, 2009)
- **Provided as Windows-compiled package and Matlab source cod**
- **Here is a tutorial on what it does, and how to use it.**

PDV SIGNAL GENERATION

Launching the software brings the following dialog box:



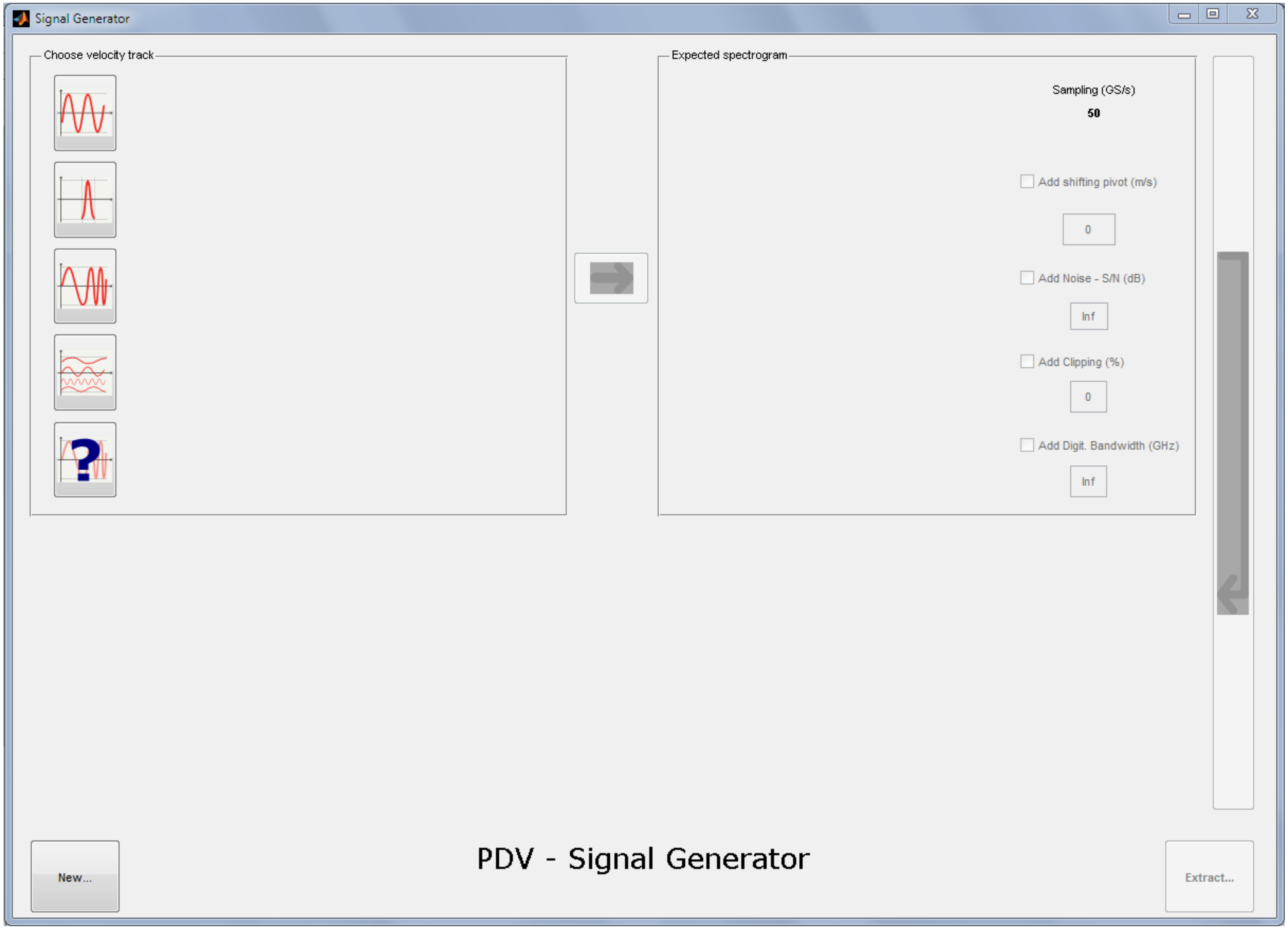
It will define, in GS/s, the rate of the digitization.

There is no limitation on this frequency. Be carefull when using high frequencies (> 100 GS/s), creating short signals (a few tens of µs).
This is particularly true when the desired export file format is *.csv*.

The principle is to create all sorts of PDV signals by combining elementary velocity tracks. This is done in the main interface.

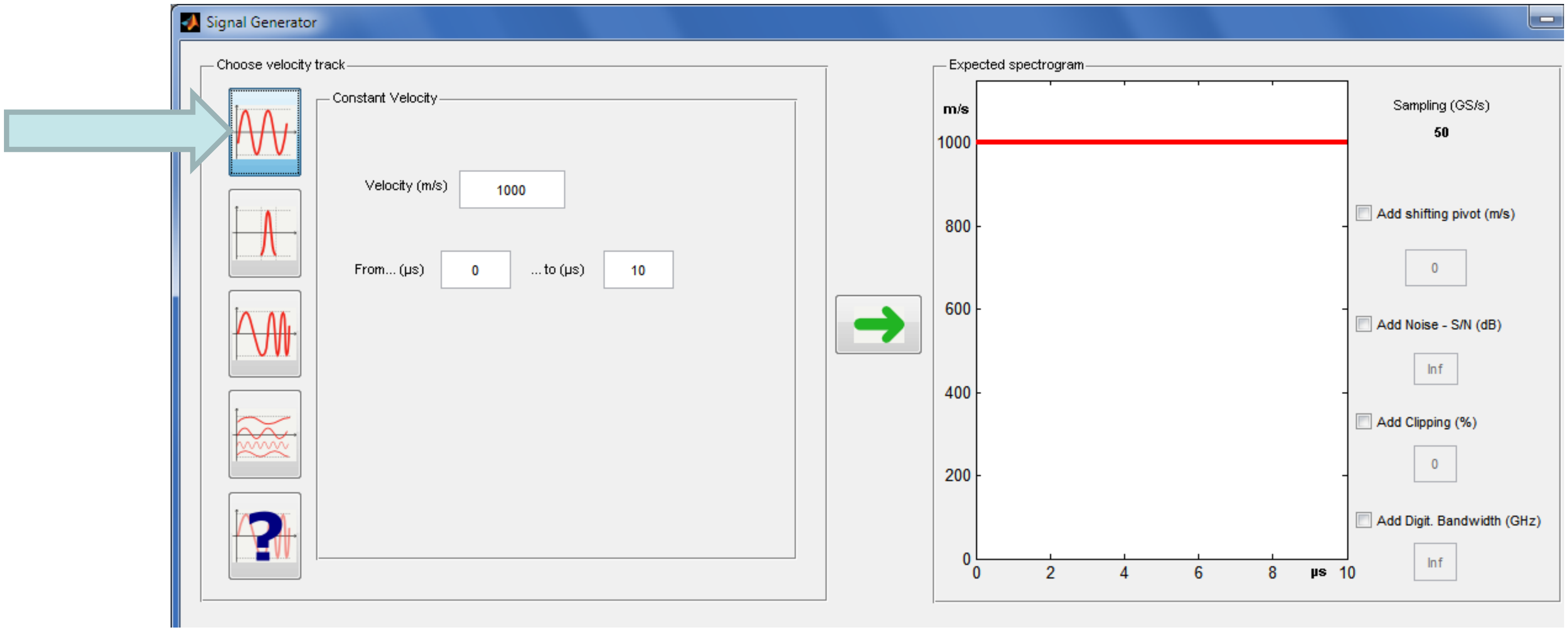
PDV SIGNAL GENERATION

Main interface comes up then:



PDV Signal Generator

Adding a constant velocity to the signal:



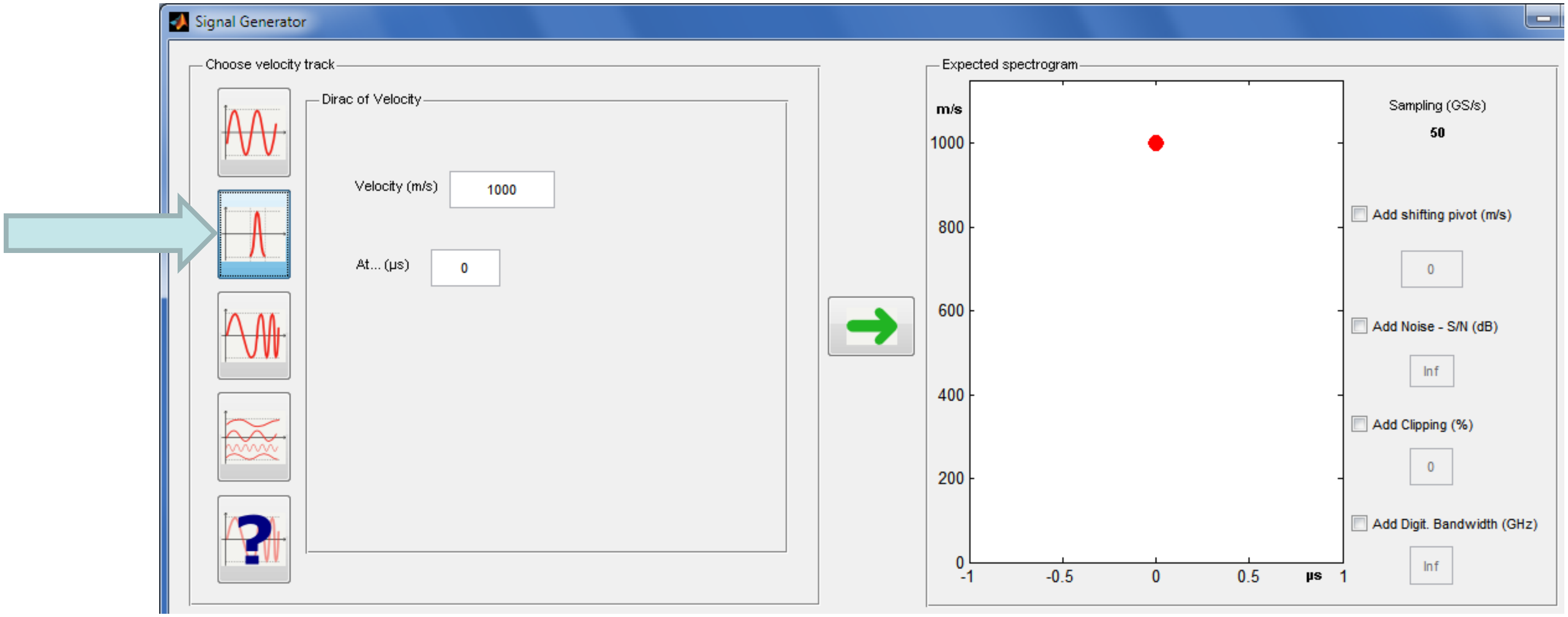
Input:

- desired velocity in m/s (`v`)
- start time and end time in µs (`Config.T0` and `Config.Tend`)

Defined:

```
case 1 %Constant velocity
    v=Config.V;
    v=abs(v-features.Pivot);
    s=single(sin(2*pi*2*v/(lambda)*t));
    signal(:,i)=s.*(t>=Config.T0*1e-6).*(t<=Config.Tend*1e-6);
```

Adding a dirac of velocity to the signal (i.e.: a single period of signal at a given velocity) :



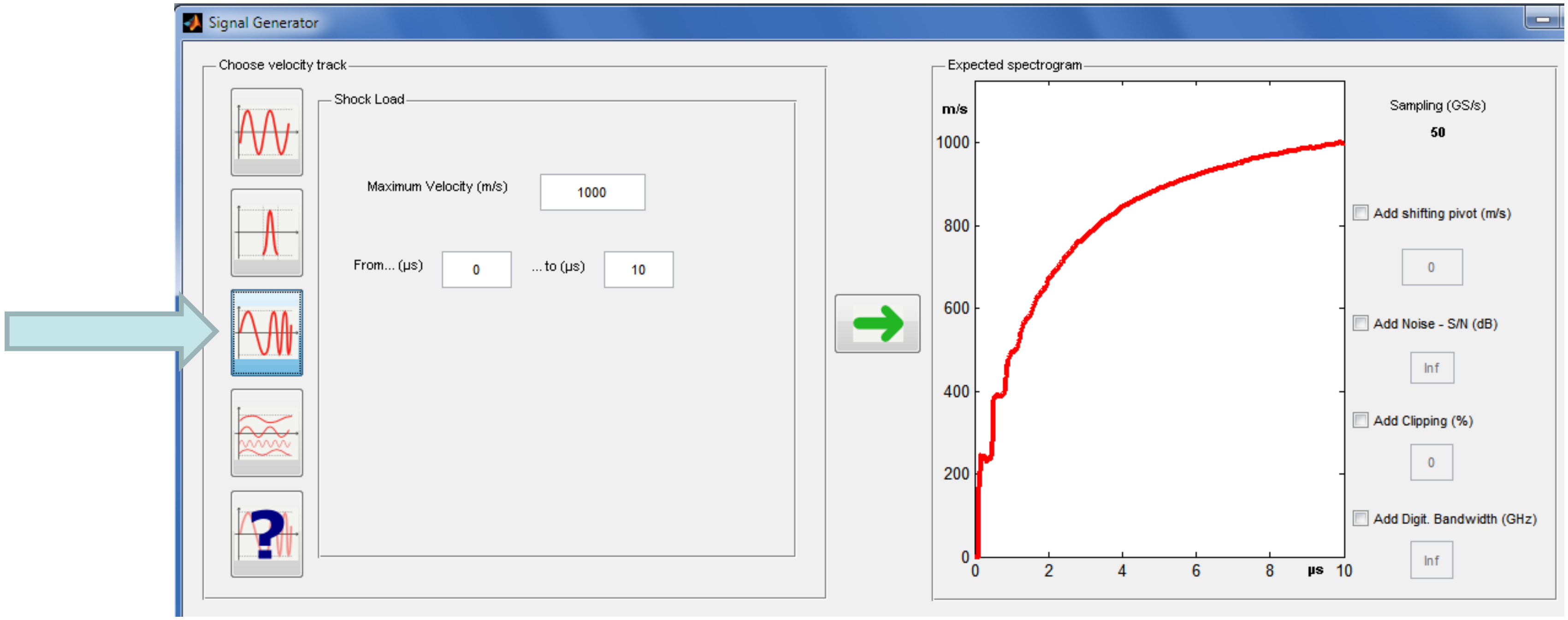
Input:

- desired velocity in m/s (`v`)
- position in time of the dirac in µs (`Config.Tdirac`)

Defined:

```
case 2 %Dirac
    v=Config.VDirac;
    s=single(sin(2*pi*2*v/(lambda)*t));
    dir_dur=lambda/2*v;
    signal(:,i)=s.*(t>=(Config.TDirac-dir_dur/2)*1e-6).*(t<=(Config.TDirac+dir_dur/2)*1e-6);
```

Adding a shock-load type velocity to the signal:



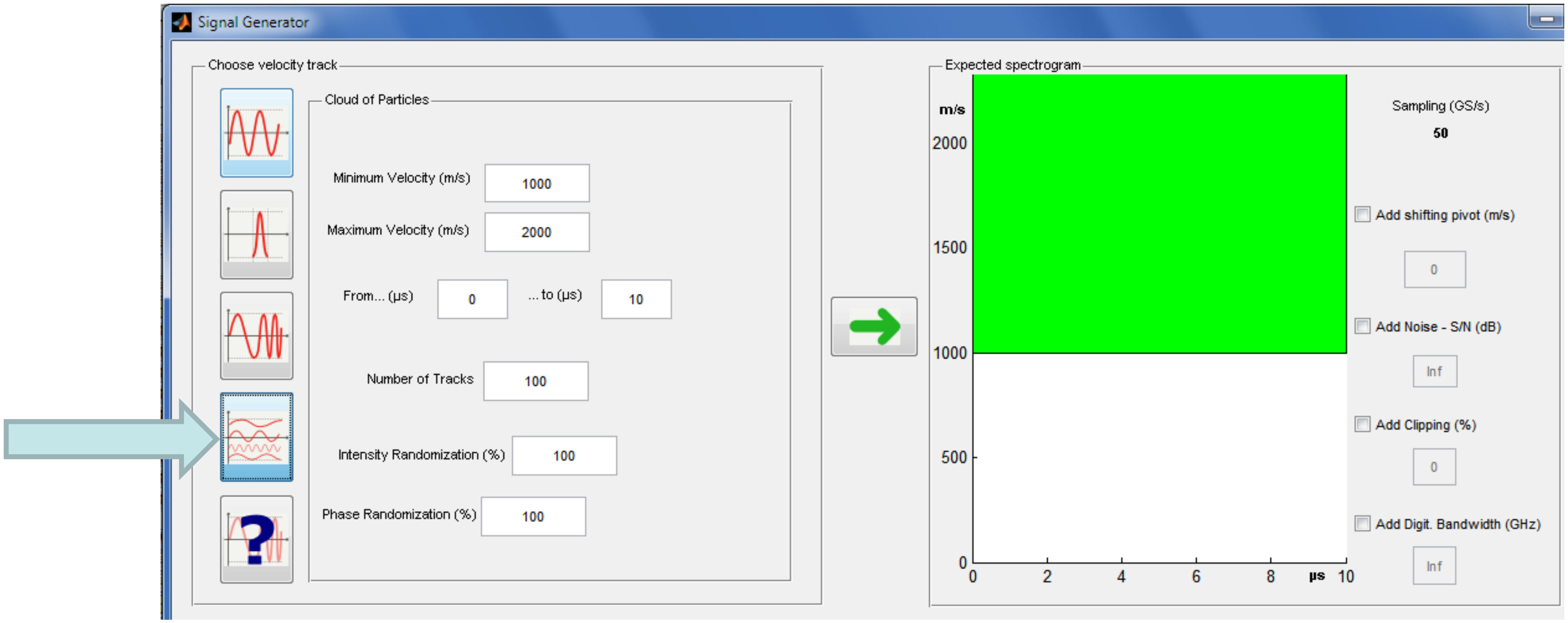
Input:

- desired reached velocity in m/s (`v`)
- start time and end time in µs (`Config.ShockLoadT0` and `Config. ShockLoadTend`)

Defined:

```
case 3 %Shockload
    load(strcat(cd,'/ShockLoad.mat')); %Shockload velocity curve is perfectible : it exhibits
    % velocity jumps in the slowly varying region
    t_v=linspace(Config.ShockLoad_T0*1e-6,Config.ShockLoad_Tend*1e-6,length(velocity(:,1)))';
    v=Config.ShockLoad_V/max(velocity(:,2))*velocity(:,2);
    v=abs(v-features.Pivot);
    v=interp1(t_v,v,t,'linear');
    %get rid of nans
    v(isnan(v(:)))=0;
    s=single(sin(2*pi*(2/lambda)*cumtrapz(t,v)));
    signal(:,i)=s.*(t>=(min(t_v))).*(t<=(max(t_v)));
```

Adding a cloud-of-paticles type velocity to the signal:



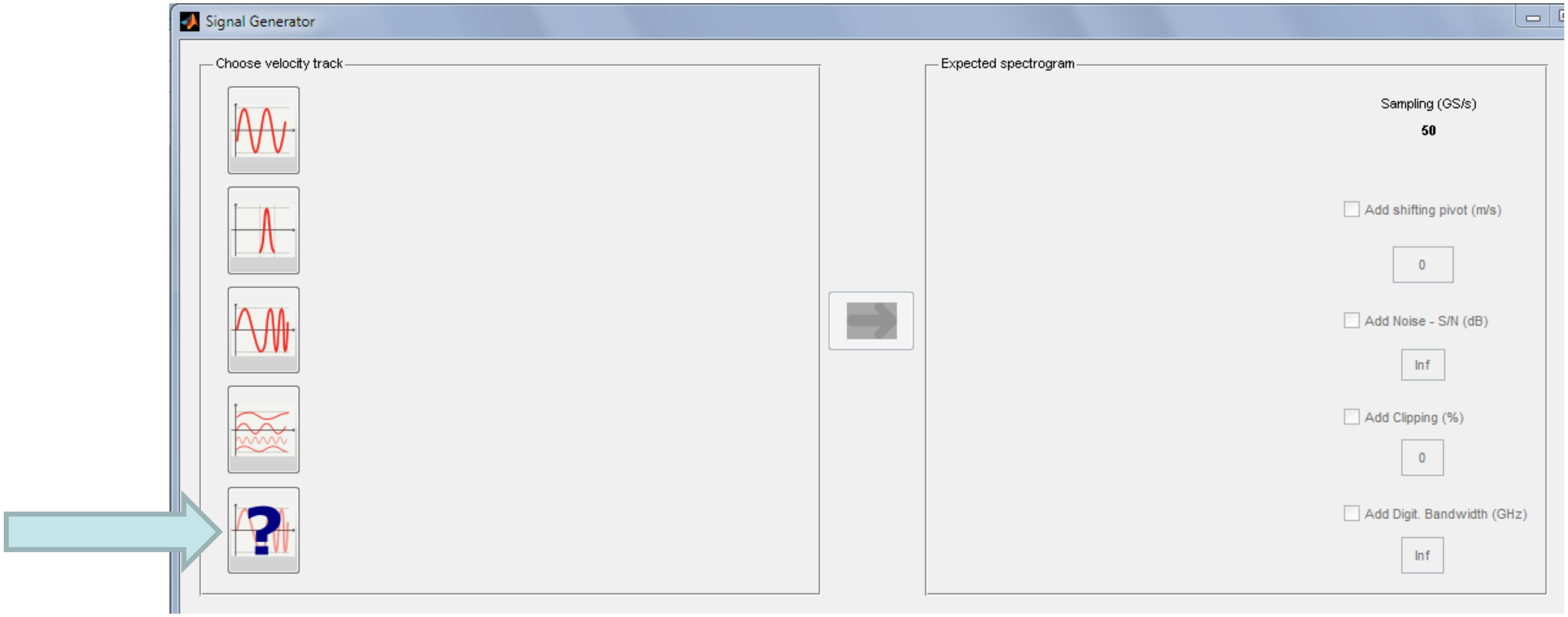
Input:

- desired top velocity in m/s (`Config.Cloud.MaxVel`)
- desired minimum velocity in m/s (`Config.Cloud.MinVel`)
- start time and end time in µs (`Config.CloudT0` and `Config. CloudTend`)
- number of sub-waves composing the cloud (`Config.Cloud_Nsig`)
- Intensity and Phase randomization in % (`Config.Cloud_Irand` and `Config.Cloud_PhiRand`) ; 100 % means intensity or phase of the wavelets are set randomly

Defined:

```
case 4 %Particles
    v=ones(Config.Cloud_NSig,1);
    v_rand=rand(Config.Cloud_NSig,1);
    %create random amplitudes
    Av=((1-Config.Cloud_IRand/100).*v+Config.Cloud_IRand/100.*v_rand);
    Av=Av/(Config.Cloud_NSig*mean(Av));
    v=linspace(max(Config.Cloud_MinVel-features.Pivot,0),abs(Config.Cloud_MaxVel-features.Pivot)
    %create random phase changes
    phi=2*pi.*ones(Config.Cloud_NSig,1);
    phi_rand=2*pi*rand(Config.Cloud_NSig,1);
    phi=((1-Config.Cloud_PhiRand/100).*2*pi+Config.Cloud_IRand/100.*phi_rand);
    for k=1:length(v)
        s=single(Av(k).*sin(2*pi*2*v(k)/(lambda)*t+phi(k)));
        signal_cloud(:,k)=s.*(t>=Config.Cloud_T0*1e-6).*(t<=Config.Cloud_Tend*1e-6);
        signal_cloud(isnan(signal_cloud(:,k)),k)=0;
    end
    signal(:,i)=sum(signal_cloud,2);
```

Adding a user-created signal:



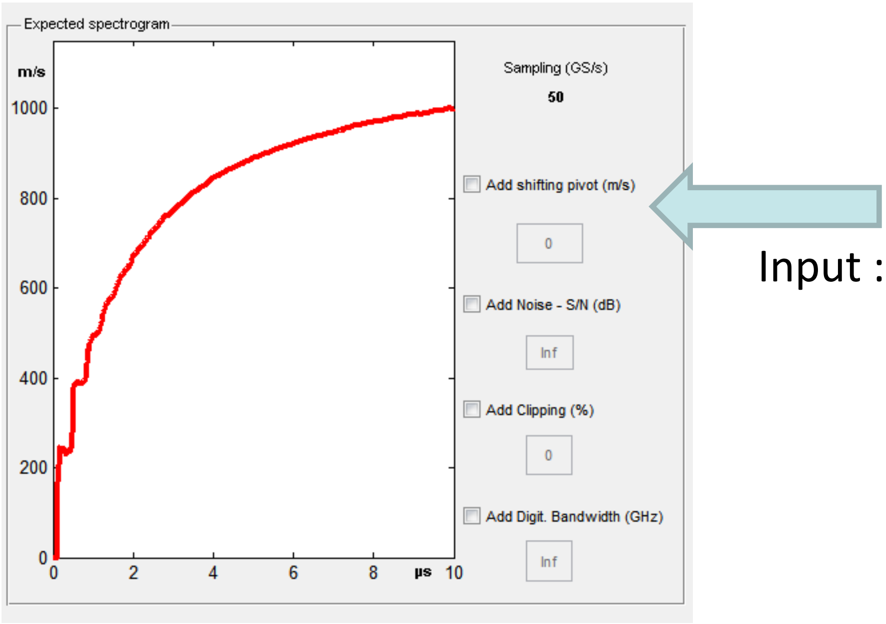
In this case, user inputs a *.csv* or *.mat* file formatted as a single vector of the form: (`time`, `velocity`). `time` shall be in µs, `velocity` in m/s.

- Matlab file is a single [n,2] variable containing the expected signal.
- A working *.csv* file would look like:

```
0.01;10
0.02;20
0.03;30
0.04;40
0.05;50
0.06;60
0.07;70
0.08;80
0.09;90
0.1;100
0.11;110
0.12;120
0.13;130
0.14:140
```

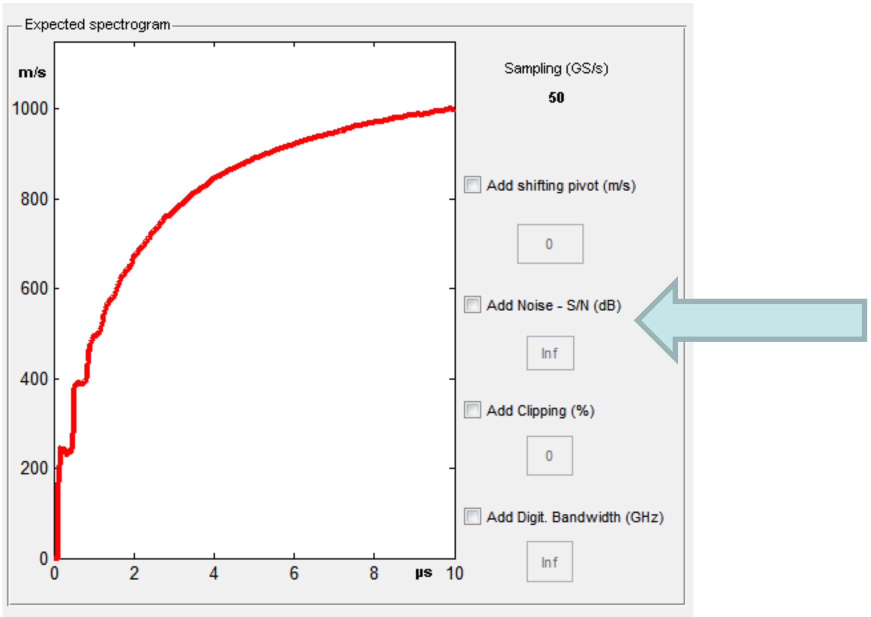
PDV Signal Generator

On top of generating any combination of elementary tracks, it is possible to synthesize common phenomena found in PDV systems:

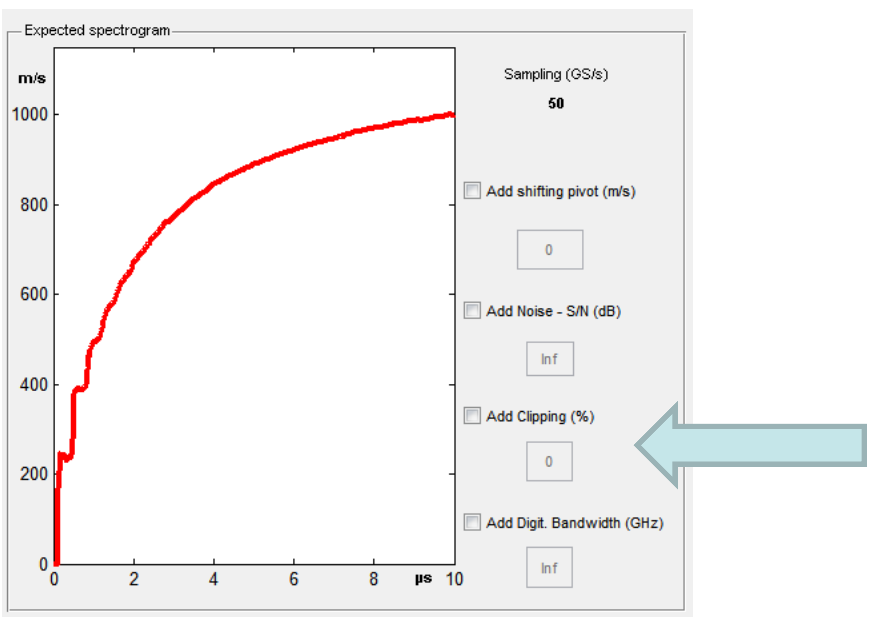


Up or Down Shifting Frequencies
Input : equivalent shift (named pivot) in m/s
(can be positive or negative)

PDV Signal Generator

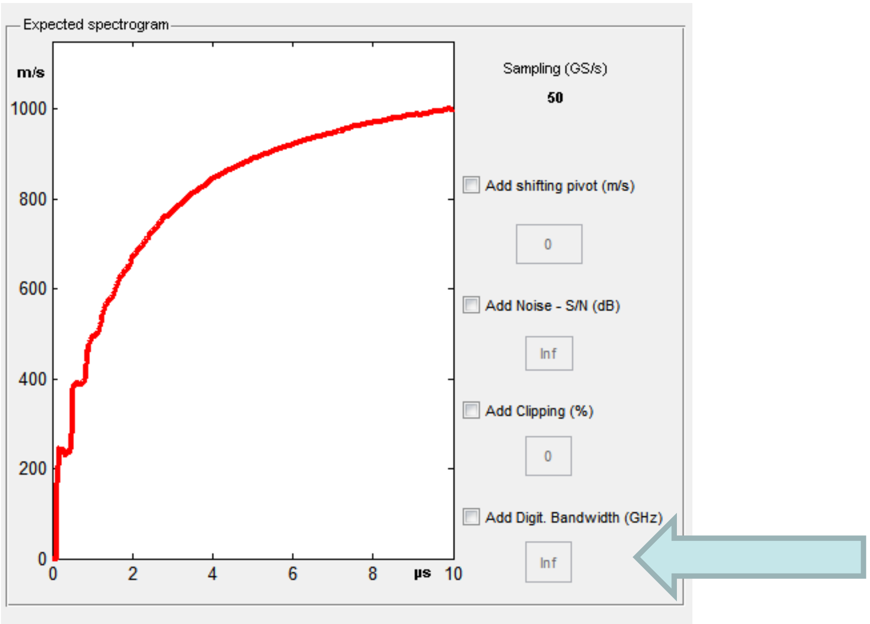


Adding noise
Input : SNR in dB



Adding digitizer saturation
(clipping on the signal)
Input : percentage of the amplitude
30 % clipping on a sine means
its amplitude will be 0.7

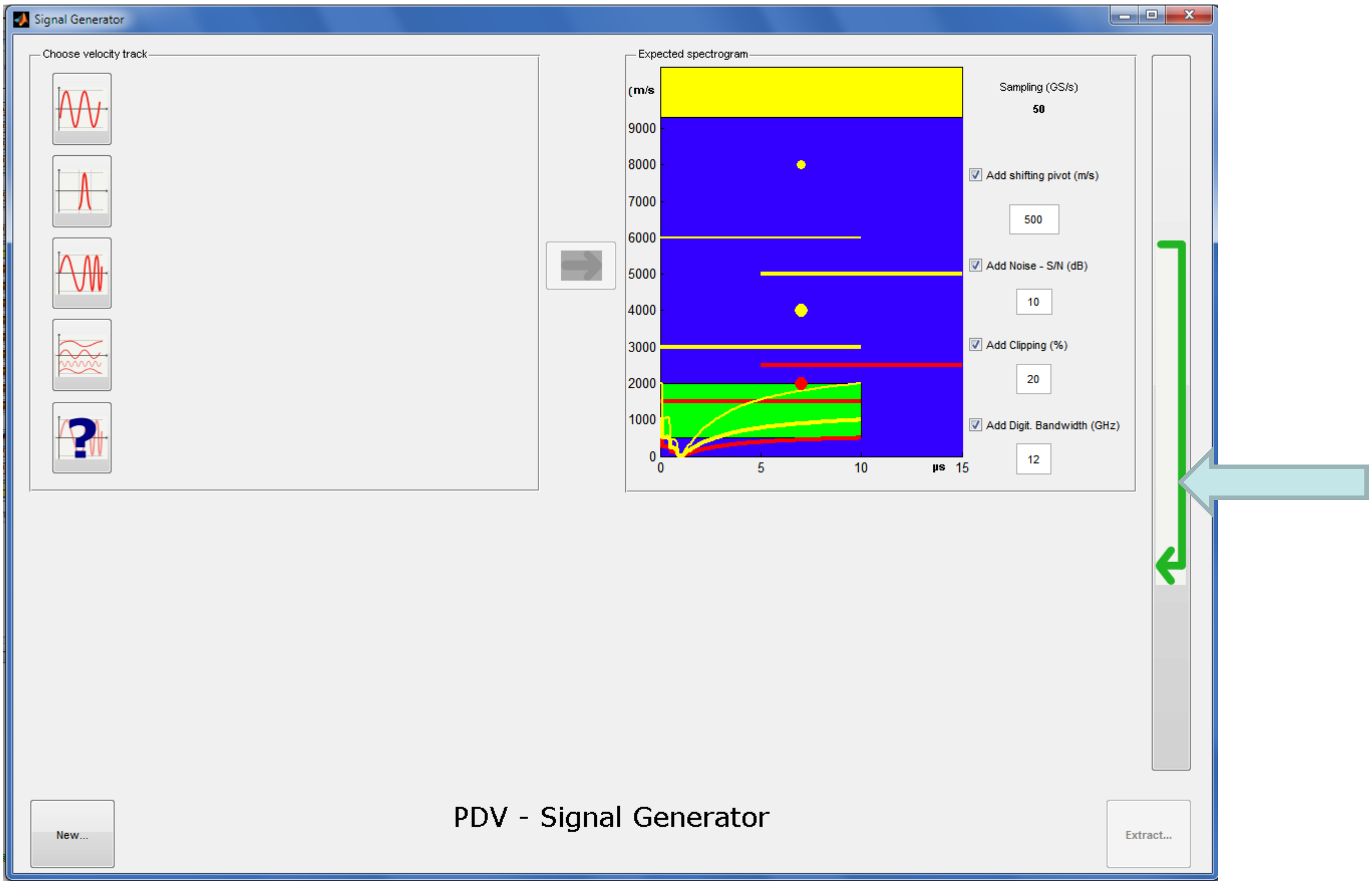
PDV Signal Generator



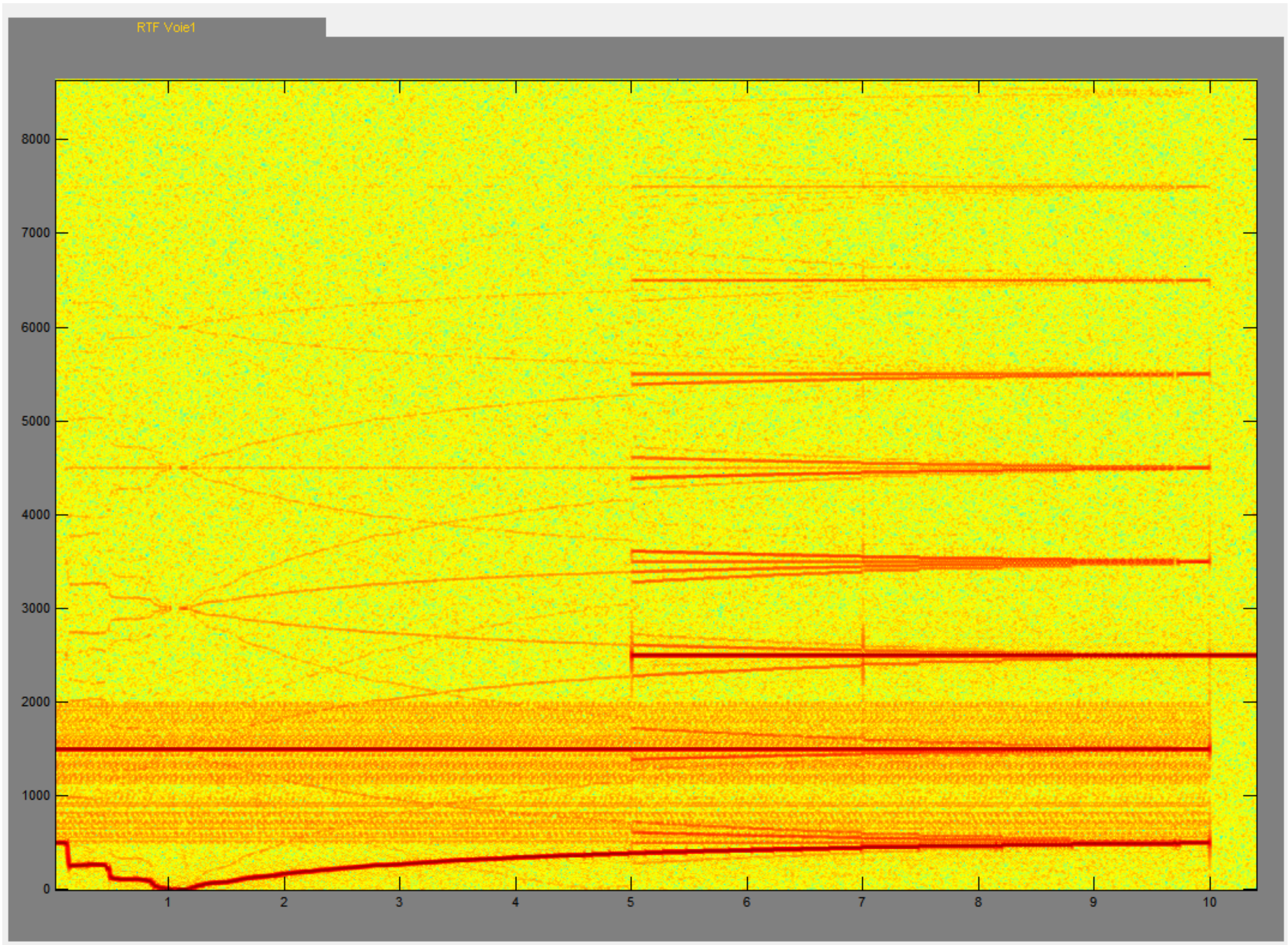
Account for limited
digitizer capability (low pass filter)
Input : Bandwidth (in GHz)

PDV Signal Generator

Signal is created when clicking on the 'Generate' button:



Preceding signal, as processed through Sliding FFT algorithm:



The End