

Review on RTI, RMI and TM experiments

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a discussion based on the analysis of past (5th, 6th & 7th) workshops and other meetings : 21, 22 & 23rd ISSW (International Shock Wave Symposia), 51 & 53rd APS/DFD (American Physical Society, Division of Fluid Dynamics), 43rd APS/DPP (Division of Plasma Physics), recent ECLIM & IFSA conferences.

Acknowledgements to CEA colleagues with whom some of these meetings were analysed for our official trip reports, recent IWPC TM organizers, contributors of the 23rd ISSW who let us consult their very recent work (July 2001) and colleagues who spontaneously sent their papers.

Apologies to all contributors for any omissions, distortions, low quality reproduction of their high quality work and general imperfections for this difficult exercise.

See this as a draft for our contribution to the summary experimental roundtable ?

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8th IWPC TM, Pasadena, December 10, 2001

CEA/DIF

 DAM Île-de-France

10/07/02

Outline of this review

- Introductory statistics

We cite the conclusions of roundtable for experiments at mix 99 and add comments

- Incompressible experiments
- Shock-tube for planar shock waves
- Convergent flows
- Explosively driven flows
- Laser driven flows

There is a wide spectrum of experiments but we have a clearer view of shock tubes

- Conclusions

Relative importance of experimental contributions in CTM workshop series averages 40 %

1st Princeton 1988 : ? (misplaced Proceedings)

2nd Pleasanton 1989 : ? (misplaced Proceedings)

3rd Royaumont 1991: poster 6/24, oral 12/25

summary 18 exp / 49 total = 37%

4th Cambridge 1993: RT 10/17, RM 9/14, KH 2/8, laser 4/4, converging flows 2/7 : summary 27 exp / 61 total = 44% *

5th Stony Brook 1995: 23 exp / 53 total = 43 % *

6th Marseille 1997: 44 exp / 96 total = 46% *

7th Saint Petersburg 1999: 53 exp / 126 total = 42 % *

8th Pasadena 2001: poster 25/63, oral 25/66,

summary 50 exp / 129 total = 39%

* does a proportion above 40% correlate with stronger russian attendance ?

mix 99 : summary roundtable for experiments :

incompressible domain (J. Jacobs spokesman),

Interpreted by E. Meshkov, L. Houas & JF Haas for report in the ERCOFTAC bulletin (2000) and the proceedings of the 7thIWPCTM

It had been pointed out that even if a lot of experiments, for both low Atwood numbers in the miscible and high Atwood numbers in the non-miscible ranges, have been successfully undertaken, the initial conditions generally still remain unknown.

Consequently, it was suggested for future work to carry **large Atwood number experiments for miscible liquids**, as well as to evaluate the importance of the surface tension in the RTI development.

In any case, the emphasis was made on the fact that the initial conditions must be known. From the other hand, more complex geometry experiments (multi-layer) are welcome for a better understanding of the influence on the exponent a of the mixing zone thickness evolution law.

In a near future, the influence of medium on the 2D-3D transition will also be greatly interesting.

- **Ordinary set-ups (as seen by the fluid mechanics community):**
 - Texas A & M : stationary mixing of co-flowing liquids under earth gravity @ low Atwood (small DT):
 - thermo-couples measurements for (long) time evolution of local density, statistics compared with spectral models (LANL),
 - PIV-S (for scalar) for combined instantaneous maps of velocity and density, velocity-density correlations
 - continuous mixing of co-flowing gases in curved channels (ancient CalTech work in Roshko's group)
 - Some work was in progress at Univ. of Washington (Breidenthal)
 - We need to communicate with the « non RTI-induced » mixing community (for instance, in Europe the ERCOFTAC 's Special Interest Group on variable density low speed turbulent flows).

Cold and slow, incompressible experiments (continued)

Conventional Rayleigh-Taylor set-ups

- Cambridge : great attention to the control & analysis of perturbations induced by the separating barrier removal, double interface, tilted interface, concentration measurements from fluorescent dye in arc lamp light sheet
- CalTech : RTI for miscible fluids
- Univ. of Arizona : tank accelerated downwards by weights (g above gravity)

Non-conventional (i.e. non shock-induced) Richtmyer-Meshkov set-ups

- Univ. of Arizona : falling tank bouncing on springs with long inertial flight thereafter: laser sheet visualisation of incompressible linear & non-linear RMI
- Univ. of Catalunya : similar principle reported by Redondo in 1993 : falling tank suddenly stopped on foam pad.

More vigorous incompressible RTI experiments : a VNIITF specialty
but the Linear Electric Motor facility of LLNL has become famous

At VNIITF, the setups **EKAP** and **SOM** have an high acceleration range : 100-1000 g and provide various acceleration histories (acceleration, braking, inertial)

Vertical gas guns for propelling experimental packages with various liquids :
(various Atwood, unmiscible and soon miscible, various interface geometries)

Various diagnostics : shadowgraph, X-rays, laser sheet soon ?

At LLNL, the **LEM** is characterized by controllable acceleration, state of the art diagnostics and imaginative liquids (yogurt)

Sorry, for this very uncomplete overview, the « alpha » group should take over...

mix 99 : summary roundtable for experiments (continued).

Planar shock tube experiments (JF Haas et al.)

There are 12 experimental laboratories involved with the conventional shock tube experiments :

AWE : (Aldermaston), ENIN (Moscow), CEA (France), IUSTI (Marseille), LANL, University of Arizona, University of the Negev (Beer-Sheva, Israel), University of Wisconsin (Madison), CalTech (Pasadena), SWRC (Tohoku University, Sendai), VNIIEF (Sarov) and VNIITF (Snejinsk).

Flow definition

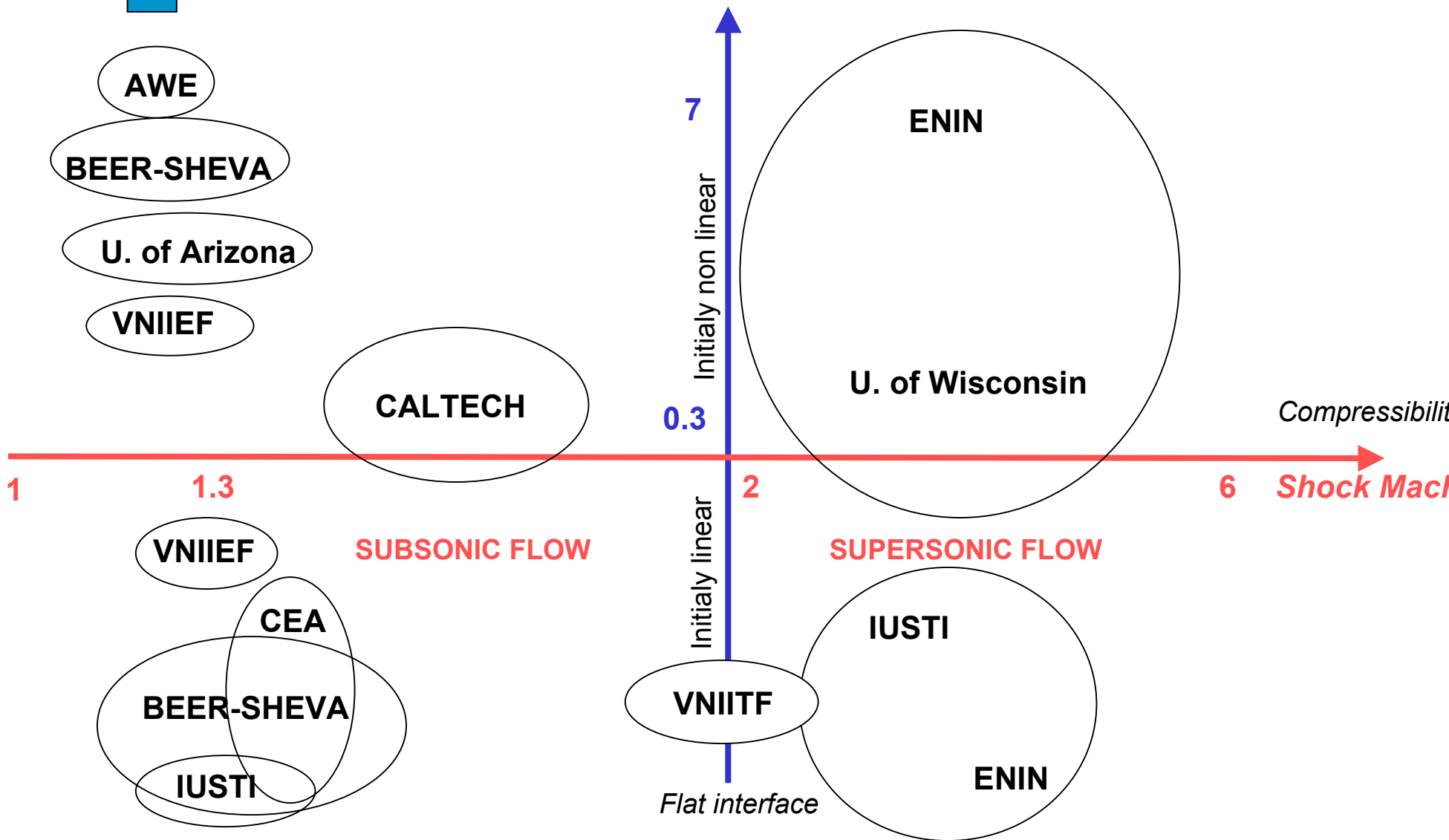
In a first plot we attempted to classify the various flows to be studied :

-horizontal axis for flow compressibility, connected to the incident shock Mach #

-vertical axis for instability strength : $At kh$

An issue loosely linked to the issue of deterministic vs. random initial interface

Perturbation $A_0 k h_0$



Planar shock tube experiments (diagnostics)

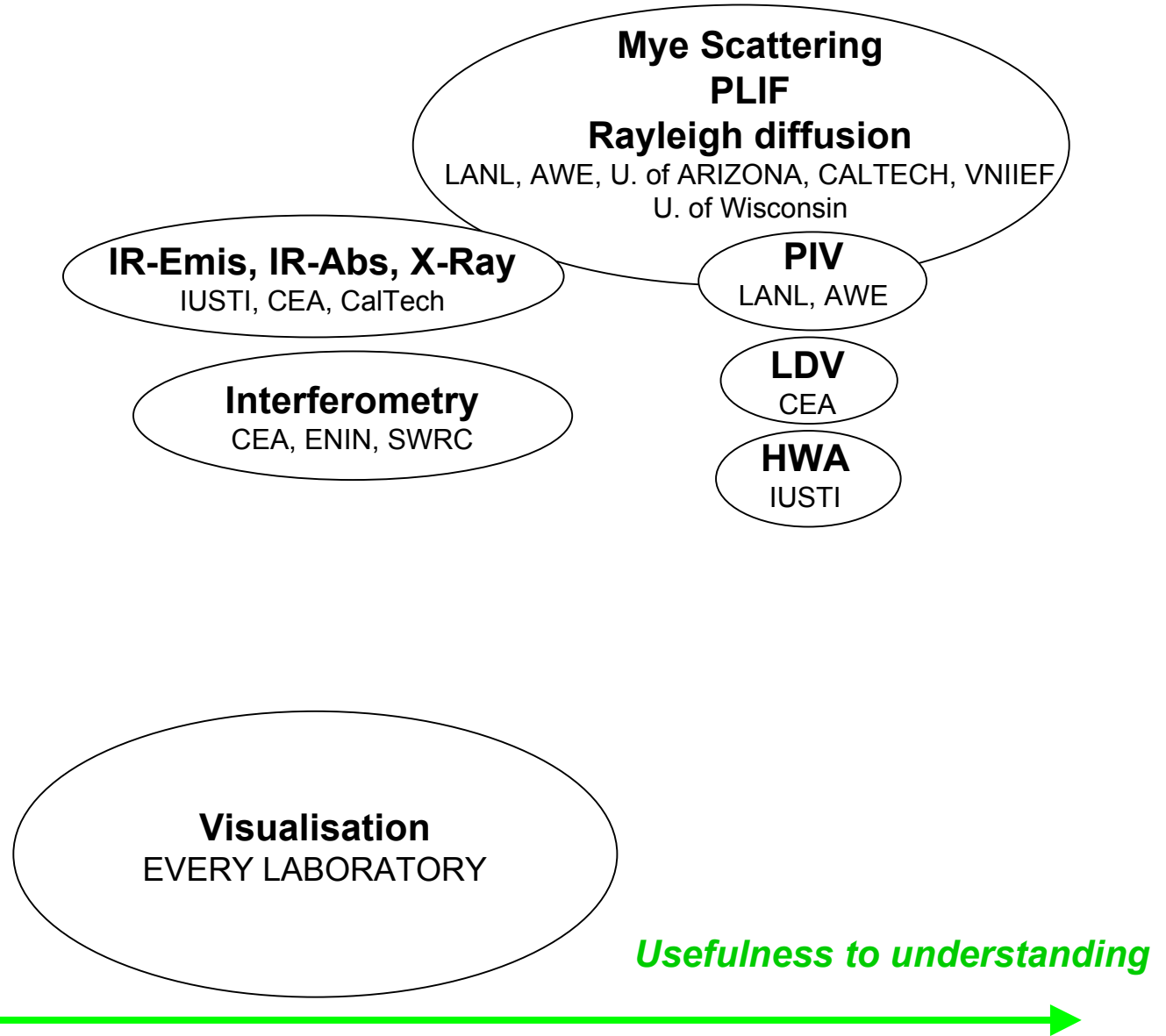
Schlieren and shadowgraph visualizations,
the laser sheet with the following principles : Mie scattering by particles
planar laser induced fluorescence (PLIF) using tracer molecules,
the Rayleigh diffusion (differential among gases)
the particle image velocimetry (PIV), the laser Doppler velocimetry (LDV),
the hot wire anemometry (HWA), the CO₂ infrared emission and absorption,
the X-ray absorption (X-Ray),
the interferometry (ENIN, SWRC), differential interferometry (CEA).

In a second plot, we sought to relate the performance of diagnostics to its usefulness for physical understanding, hence modelling and simulation : not so simple !

It should be obvious that an experiment has to be imaginatively designed before spending time and money on sophisticated diagnostics

Complexity of diagnostic

Danger Zone



mix 99 : summary roundtable for experiments.

Shock tube experiments (continued)

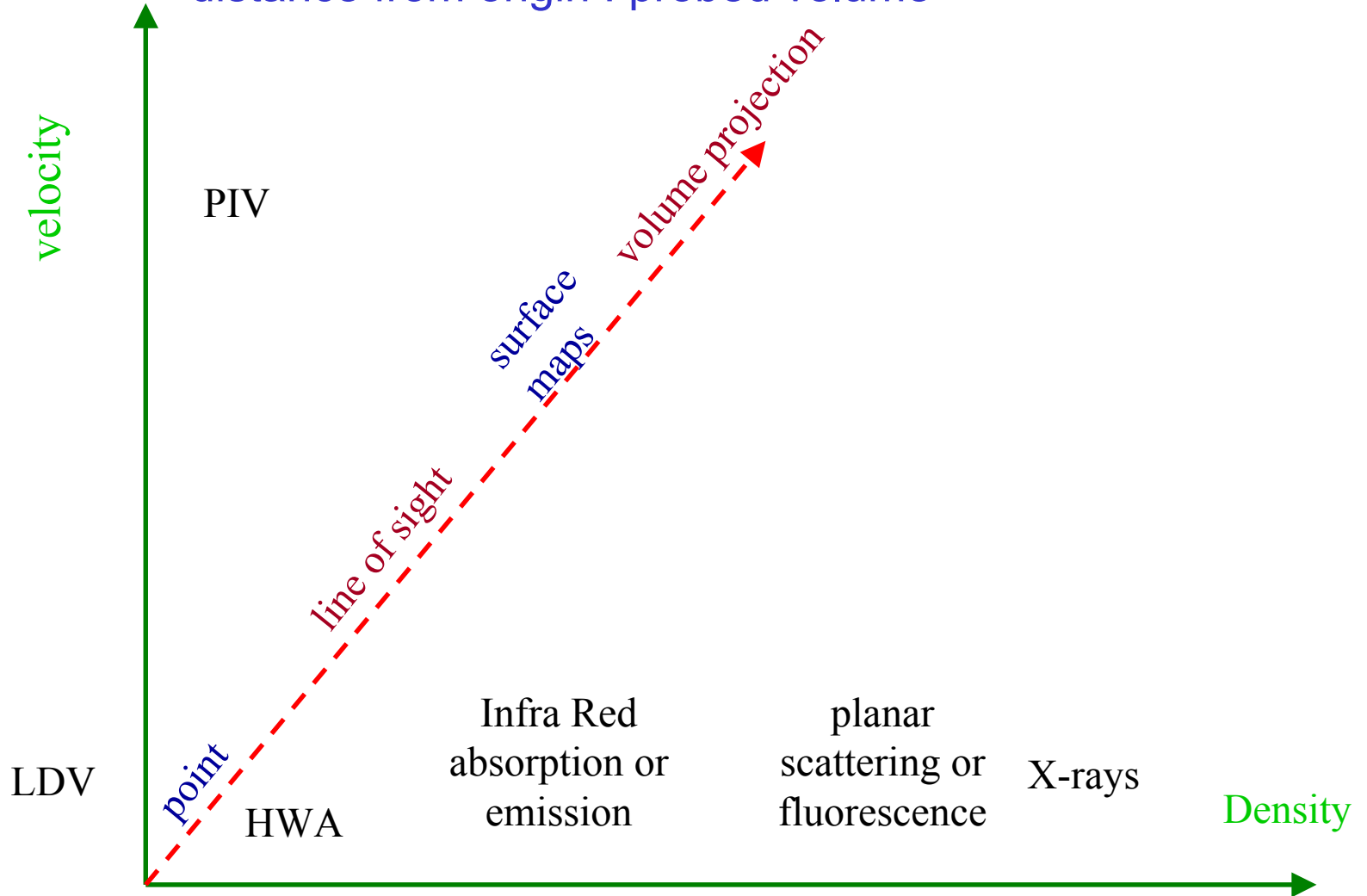
The choice of the "usefulness to understanding" axis on the second graph was problematic as no laboratory would like to be positioned on the left side !

As an afterthought, we could have drawn instead a map with two axis, one dedicated to the measurement of the **density field**, the other for the **velocity field**.

The distance from the origin could be proportional to the **probed volume** (local vs. global).

Most of the presently used diagnostics would then be positioned on the density axis, LDV and PIV on the velocity axis and the HWA somewhere in between (probably closer to the density as explained on the poster E37).

Density versus velocity diagnostics,
distance from origin : probed volume





mix 99 : summary roundtable for experiments.

Shock tube experiments (continued)

The discussion pointed out the parameters such as interface geometry, the shock tube dimension and the initial interface control.

Again, it appears that the initial conditions, both wavelengths and amplitudes of the perturbations and the mechanical properties of the membrane, must be known.

An effort has to be undertaken on this fundamental point of interest for the next conference.

Richtmyer-Meshkov shock tube experiments : some issues on flow definition

single mode interface (Arizona, Wisconsin, Caltech)
deterministic multiple mode (ENIN, Beer-Sheva)
simple geometries : transverse curtain, round jet, tilted
plane, step, bubbles (LANL, AWE, VNIIEF)
undetermined, multimode planar interface (CEA, IUSTI,
VNIIEF, VNIITF, ENIN)

continuous or discontinuous interfaces : the killing of
small scale turbulence or the membrane problem ?

low / high Mach # : incompressible / compressible flow

the Reynolds # : transition to turbulence, boundary
layers

shock and reshock (of variable strength, ENIN)



Review on RT, RM & TM experiments

The issues on shock tube diagnostics

Shadowgraph & Schlieren (AWE, Beer Sheva, Marseille)

Interferometry (Sendai, Moscow, CEA)

Flash X-rays (CalTech, CEA-Vaujours)

Laser sheet visualization

 Mie scattering (VNIIEF, AWE)

 Rayleigh scattering (CalTech & Los Alamos, Madison)

 Planar laser induced fluorescence

Velocity measurements : PIV (Los-Alamos), LDV (CEA)

Combined velocity & concentration : HWA (Marseille)

Cleanest looking results for membrane-less experiments and macroscopic perturbations with laser sheet diagnostics

- Excellent measurement of RMI growth rate @ Mach 1.1-1.2 for single mode linear & non-linear regimes (U. of Arizona) : comparison with analytical models.

- Turbulent mixing soon arising from RMI @ Mach 3 (U of Wisconsin) :

after schlieren observations of discontinuous interfaces (with code comparisons), the initial interface is now controlled by gravity-induced RTI after sinusoidal plate removal and observed using planar Mye scattering.

Precise comparison of experiments of [shocked SF6 curtain](#) or [cylindrical SF6 jet](#) @ Mach 1.2 with simulations (Los Alamos) :

[good agreement for concentration field, but low experimental velocities as compared to code](#), very detailed discussions about codes : first order « better » than second order, use of turbulence models.

- Archetypal (late 80's) shocked SF6 or Helium gas cylindrical jet at Caltech using PLIF (Jacobs) and Rayleigh scattering (Budzinski) in large shock tube @ Mach 1.1 - 2.0

- Wish from a simulation specialist: good measures of mixed mass of accelerated heavy gas jets ?



But membrane based interfaces still have a future :
they can enhance TM at small scale and can be destroyed

VNIIEF relies on irregular membranes or on burning by combustible gas mixture prior shock

VNIITF has invented the MIRAGE membrane with controlled burning

ENIN lets the hot shocked gases burn the membrane

CEA and IUSTI slice the membrane with a very fine wire mesh

An important effort on the analysis of laser sheet based diagnostics :

AWE experiments on shocked SF6 layers with discrete downstream defects and membrane :

good agreement with 2D or 3D code using postprocessor for multiple scattering

(now 10th order, see Holder et al.).

Other important issues were presented by the AWE team in Marseille :

characterisation of photographic film and laser sheet intensity, removal of membrane fragments :

a good example for the recently started effort at IUSTI and the one just starting one at CEA.

Other shock-tube experiments with laser sheet diagnostics have been long around or are just starting.

VNIIEF(Sarov) : tilted and step interface with cigarette smoke, comparison with 2D or 3D code

IUSTI (Marseille) : multimode air/helium and air/krypton interface using Mye scattering in new large shock tube with pulsed copper vapor laser (as in AWE, see poster E17 by Houas et al.)

CEA (Bruyères) : preliminary shots on planar interfaces using Mye scattering from prehistorical single pulse 2 Joule ruby laser (see abstract E21 by Lassis et al., but poster is not available).

Other visualization and densitometry methods

Classical refractive visualisation (shadowgraph, schlieren) still in use : Beer Sheva, IUSTI, ENIN (Moscow), VNIITF, VNIIEF, CEA

Interferometry at ENIN and SWRC (Sendai, Japan)

Differential interferometry, useless in turbulence, just as qualitative as color schlieren (CEA, reported in mix 95, to be revived?)

Flash X-ray densitometry (Caltech, mix 89, CEA, mix 93&95, to be revived), needs xenon as absorber of low energy X-rays but provides an excellent averaged concentration in turbulence

Laser interferometric tomography (Bashurin et al., Sarov) : the principle of LIT was described in Stony Brook and its application to a propane jet in air and to wire explosion in air was shown in Marseille : application to RT&RM induced mixing ?

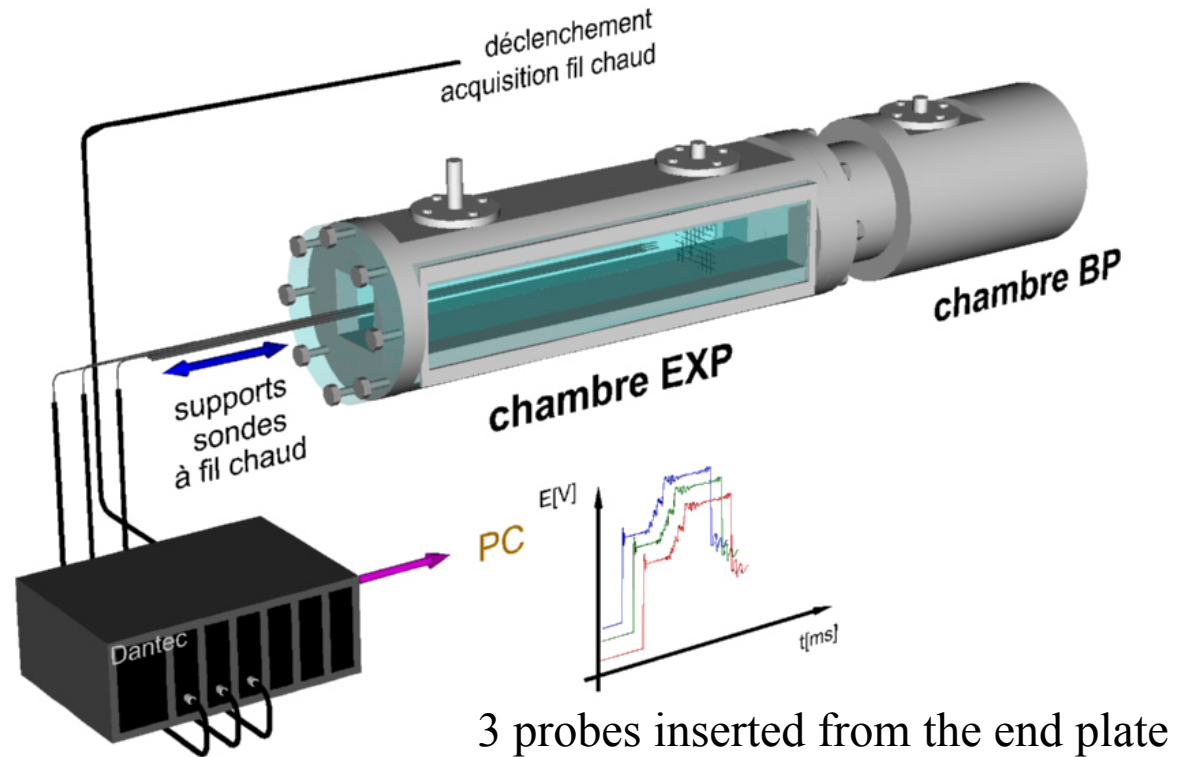
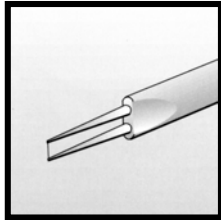
Infrared emission and absorption was explored at IUSTI from 1985 to 1995.

Point velocity and density measurements are motivated by modelling needs in 1D code, 2D exp. maps are better suited to comparison to 2D & 3D simulation ?

- Laser Doppler Velocimetry (LDV): was used on planar air/SF6 interfaces in CEA-Vaujours (Poggi et al., mix 97) : direct measurement of velocity, no detection of mixing zone passage by itself. To be used again in CEA-Bruyères in a larger shock tube (abstract E21). Non intrusive but seeding required, OK for reshock.
- Constant temperature hot wire anemometry (CTA) explored in IUSTI since 1997 : the signal is a fonction of concentration and velocity. Recent analysis (poster E37) shows that the density is better resolved than velocity. Intrusive method, problematic for reshock.
- Simultaneous measurements of LDV and CTA in CEA in 2002 ?
- Small scale resolution : LDV OK, CTA and PIV problematic ?
- PIV seems ideal for large structures, long time development of instability.

85 mm × 85 mm test section of IUSTI 's shock tube for hot wire measurement of RMI-induced Mixing Zones

The wire is 1.25 mm long
has a diameter of 5 μm
and breaks too often !

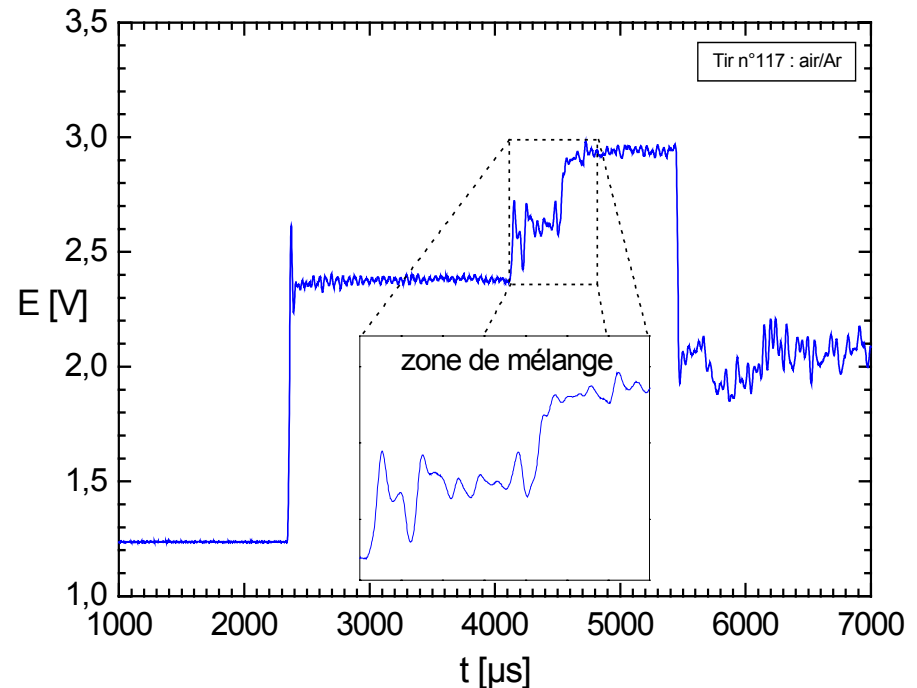


Borrowed from Laurent Schwaederlé 's presentation for his succesful thesis defense on December 7th 2001

The signal clearly shows the mixing zone passage and yields the local density time evolution



But the probes are intrusive and will disturb the reshock phase



Meet Dr Schwaederlé in front of his poster E37 to learn about the first application of this ancient technique to our difficult flows !



Gas detonation driven experiments on jelly layers or gas interfaces : a VNIIEF tradition followed at LLNL

Easiest method to study material with strength and with well defined defects:

- in mix 99 : accelerated layer in square box at VNIIEF (Zhidov)
- applications to security against accidental explosions : protective liquid layers
- subject left to be commented by the specialists !

Vertical combustion tube for nonstationary compressible RTI flows

listen to review presentation by Zaytsev tomorrow, see poster E43

Ectromagnetic shock tube for Rayleigh-Taylor mixing at high gas speeds
in VNIIEF , also multipurpose OSA facility: initial RMI phase due to
strong shock, then constant acceleration for stable or unstable RTI
phase.

The measurement of the behavior of converging shock waves is useful for the study of the evolution of the interface perturbation from the linear to the non-linear (still deterministic) regime. In the last few years, novel converging shock experiments have appeared.

The cylindrical implosion can be obtained from the coalescence into a detonation wave of spherical explosions from a large number of point sources. *At AWE : the large chamber (30° sector, 1 m radius) is a difficult undertaking but with promising laser sheet diagnostics.*

From VNIIEF, we have seen results obtained with smaller, fully circular detonation chamber, with traditional visualisation.

It can also be generated using a diaphragmless vertical shock tube (SWRC, Sendai).

At VNIIEF, spherical chambers have been used with diagnostics from wall mounted pressure transducers (timing and intensity of reflected waves with or without TMZ inside.

A pertinent suggestion was made about the visualization of a spherically converging flow inside a cone by the holographic interferometry technique (SWRC, Sendai). We certainly hope to be able to discuss such experiments during the next workshop.

Unfinished business

High explosive experiments

a russian domain of excellence

Z-pinch experiments

a competitor to laser experiments ?

Laser driven experiments

At mix 99 : Bruce Remington, the spokesman for the laser experiments subgroup brilliantly summarized the goals of laser (and all) experiments:

We must demonstrate that we can access to interesting scientific domains: i.e. the linear and non-linear regimes (ICF) of the RT/RM-I as well as to turbulent mixing (supernovae), but also the behavior of liquids (or solids) at high pressure (planetary interior) and the coupled radiation hydrodynamics (photo evaporation front).

But experiments have to be improved to facilitate independence of their results from the facility (an issue of science versus "facility calibration"). For this, we need to derive scaling laws in each domain (test of "scalability") and to develop the required numerous diagnostics. We are not there yet.

The action items for future laser facilities (LIL, NIF, LMJ) are: progress towards longer steady drive, large enough ground facilities allowing turbulent regimes, bright source of hard X-rays combined to spectroscopy, codes to grasp all domains, use of the spallation experiments for demonstrating facility independence, specific diagnostics for astrophysics motivated experiments, spherical effects in explosions, convergence effects in spherical implosions. In any case, we have a long and interesting way to do in this domain which is still full of promises.

We like laser experiments which mimic shock tubes or supernovae !

T. Peyser wrote in 1995: « Nova, the world's largest laser, was used to drive one of the world's smallest shock tube » and obtain various exciting flows :

- non linear RMI growth from sawtooth initial perturbations @ Mach 20 (1995)
- hypervelocity jet from hemispheric defect (1995)
- developed mixing from broad spectrum multimode perturbations (1997)
- reshock @ Mach 15 of a primary shock induced mixing zone (1999)

We will see some careful checks of theories for RMI in the compressible , non-linear regime from experimental results obtained on Omega @ Mach 10 with comparisons with shock tube results from ENIN (@ Mach 3).

Note that mixing experiments in large size and at large Reynolds for Mach 10 to 20 shocks could be obtained in the (intermediate) shock tube section of free piston facilities such as T5 here at CalTech (1998 proposal by Bradford Sturtevant).



At mix 99 , Evgenij Meshkov insisted on practical and peaceful applications of RT&RMI & TM experiments.

Finally, it is about time for our scientific community to harness turbulent mixing in nature and ordinary technology and try to bring some (more?) contribution to humanity.

Some Sarov colleagues have already pointed out some interesting ways such as the fighting of forest fires by explosive methods (joint project VNIIEF-IUSTI), the conception of new explosive light sources and of protective liquid wall against explosions (VNIIEF, after an idea from the czar Peter the Great ?).

The common point of these three methods is the development of turbulent mixing arising from the evolution of hydrodynamic interface instability.



Preliminary conclusions....

Experimental investigators should collaborate with theory and simulation specialists :

by proposing and carrying out imaginative experiments with reasonable diagnostics

but the diagnostics can also be simulated in code postprocessors

The experiments should be fun (because these flows are exciting)

to be continued in the experimental discussion, tuesday 11, 16:15-16:45