DualSPHysics Users Workshop 2015
Welcome

Benedict D. Rogers

School of Mechanical, Aerospace & Civil Engineering (MACE)

University of Manchester

Welcome!

We warmly welcome you to the School of Mechanical, Aerospace and Civil Engineering at the University of Manchester

But first **some history**:

Manchester emerged as the **world's first industrial city**.

Manchester businessmen and industrialists established the **Mechanics' Institute** (Owen's College, UMIST, modern University of Manchester) to ensure their workers could learn the basic principles of science.

University can count **23 Nobel Prize winners** amongst its current and former staff and students

Manchester History

You are in a very historic place

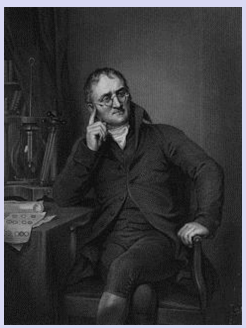
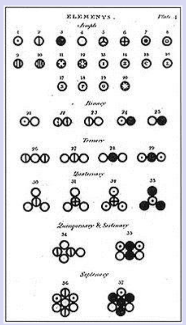
for science & engineering!

MANCHESTER 1824

Role of Manchester in Scientific & Engineering Development

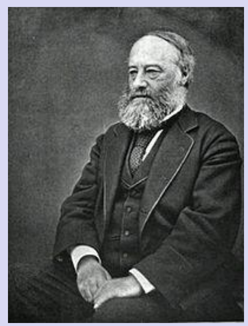
MODERN CHEMISTRY:

John Dalton (1766 – 1844) foundation of modern atomic theory

1^{st} LAW THERMODYNAMICS

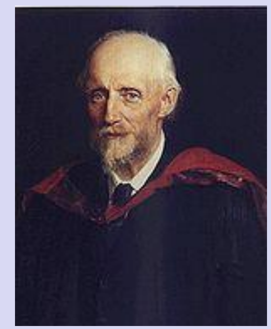
mechanical equivalence of heat postulated by **James Prescott Joule** (1819-89)



$$dU = \delta Q - \delta W$$

REYNOLDS NUMBER IN TURBULENT FLOWS:

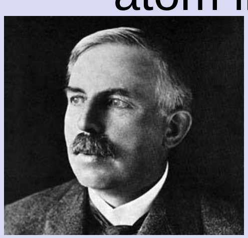
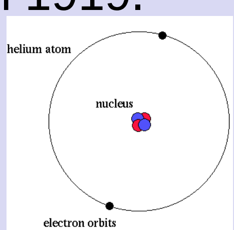
Experiments conducted by **Osborne Reynolds** the dimensionless number



$$\mathrm{Re} = \frac{\rho V L}{\mu} = \frac{V L}{\nu}$$

SPLITTING THE ATOM

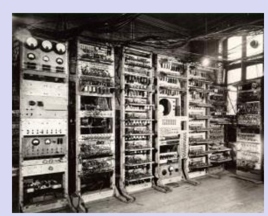
Ernest Rutherford at Manchester University discovered how to split the atom in 1919.

COMPUTERS

1^{st} memory programmable computer &

Alan Turing

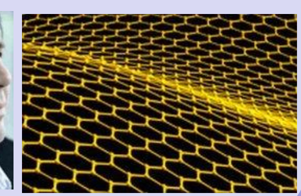



GRAPHENE:

Thinnest supermaterial in the world

Won the Nobel Prize for Physics in 2010





MANCHESTER 1824

The University of Manchester

Role of Manchester in Scientific & Engineering Development

Jodrell Bank (Cheshire) a Lovell built world's largest steerable radio telescope just after the Second World War.

Contraceptive pill (1961) and **first test tube baby** (IVF) was (1978).

World's 1st steam-powered mill, opened in 1783 by **Richard Arkwright** for cotton.

The **world's first railway station**

(Liverpool Road, 1830)

VOTES FOR WOMEN: Pankhurst founded

Women's Social & Political Union in 1903

leading to the Suffragette Movement

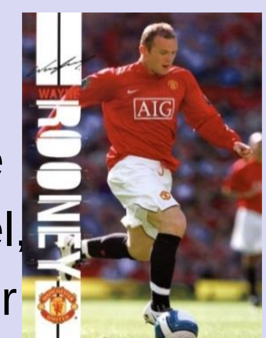
World's 1st professional football league

set up in

1888 in the

Royal Hotel,

Manchester



School of MACE

What happens in MACE?

School of Mechanical, Aerospace and Civil Engineering (MACE)

- **1000 Undergraduate students** on 3 programmes: Mech, Aero & Civil
- **500 Postgraduate Taught (PGT) Students**
- **250 Postgraduate Research (PGR) Students**
- **120 Academic Staff + 60 Postdocs**

Research in MACE:

- Aerospace engineering
- Bio-engineering
- Climate change
- Innovative manufacturing
- Management of projects
- Modelling and simulation
- Nuclear engineering
- Offshore energy and coastal engineering
- Structural and fire engineering

Laser manufacturing

http://www.mace.manchester.ac.uk

Modelling and Simulation Centre (MaSC)

What happens in MaSC?

MANCHESTER
1824

Modelling and Simulation Centre (MaSC)

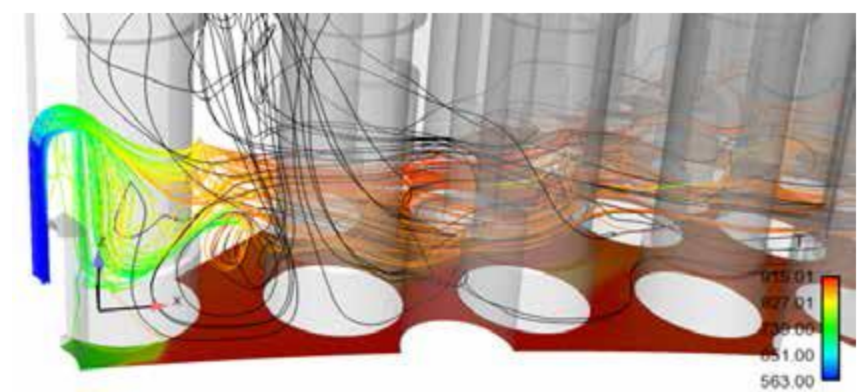
- **EDF & University of Manchester** – established in 2011 a new centre focusing on M&S

- **Initially** CFD & Computational Solid Mechanics

- **Now includes** welding technology, long-term structural graphite integrity

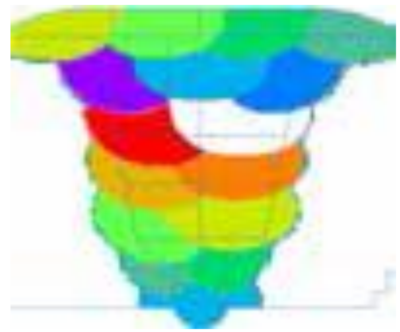
Aims of MaSC:

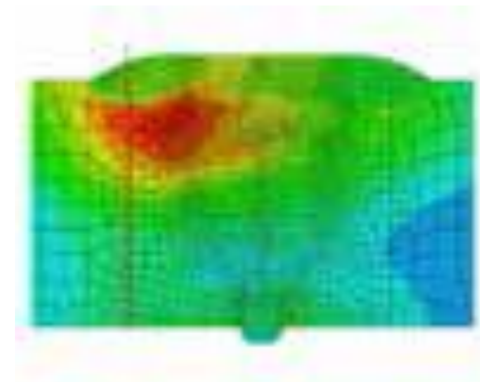
- **Scientific Excellence** – facilitating world-wide take-up of EDF open-source codes
- **Advanced Studies –** real engineering problems
- **Partnership** - stakeholders
- **Skills development** - training



Modelling and Simulation Centre (MaSC)

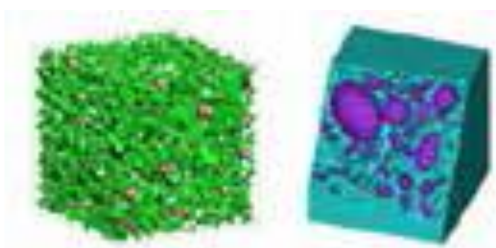
Welding Technology– experimental and numerical investigations of microstructure & weld performance





Nuclear reactor boiler support weld model

Mechanics and Physics of Solids – quasi brittle materials, metallic materials, transport through porous media



Meso-scale modelling of conrete

Moisture in cement

Cracked graphite moderator

Modelling and Simulation Centre (MaSC)

And of course SPH!!!

MANCHESTER
1824

Overview

- Motivation and why SPH
- What is Smoothed Particle Hydrodynamics (**SPH**)?
- What can SPH do? Why is it revolutionising areas of engineering simulation?

- DualSPHysics
  - Where did it come from?
  - What is a GPU?
  - What can it do?
  - Who are the DualSPHysics team?
  - What SPH activity happens in Manchester

SPHERIC - SPH European Research Interest Community

Original Motivation for SPH

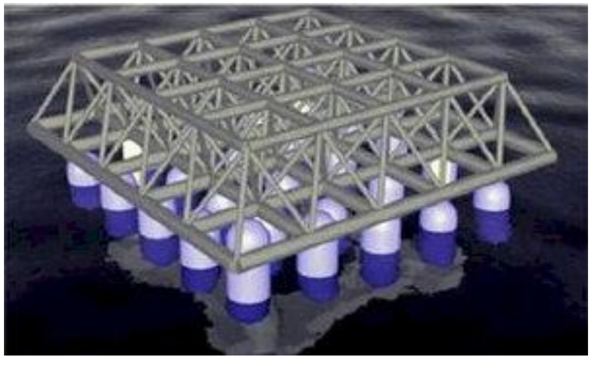
- **Free-surface flows** are rarely singly connected, e.g. beaches & wave energy devices

Breaking waves on beaches

(Photo courtesy of F. Raichlen)

Overtopping:

Wave Energy Devices: Manchester Bobber

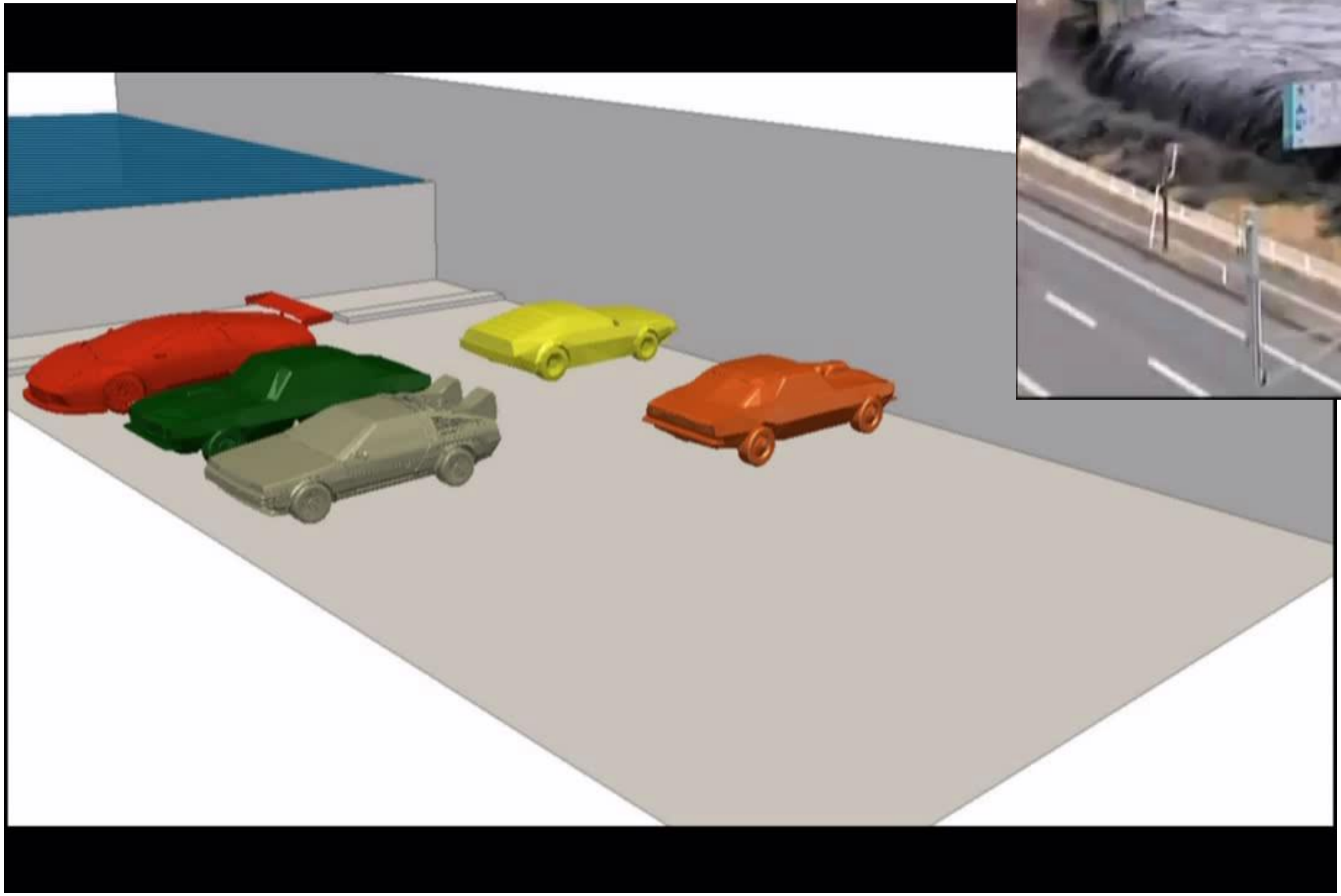


Very complex Multi-phase Multiscale problems

SPH: Has some distinct advantages in simulating these situations

Classical SPH Formulation Example

2011 Japanese Tsunami



Crespo et al. (2012)

Meshless methods: Basic Idea of SPH

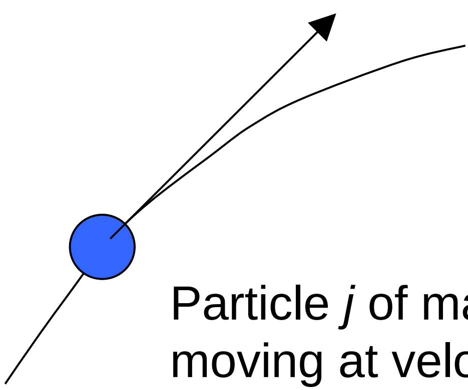
Meshless Our computation points are **particles** that now **move** according to governing dynamics , e.g. Navier-Stokes Equations

Particles move along a trajectory by **integrating** in time their velocity & acceleration

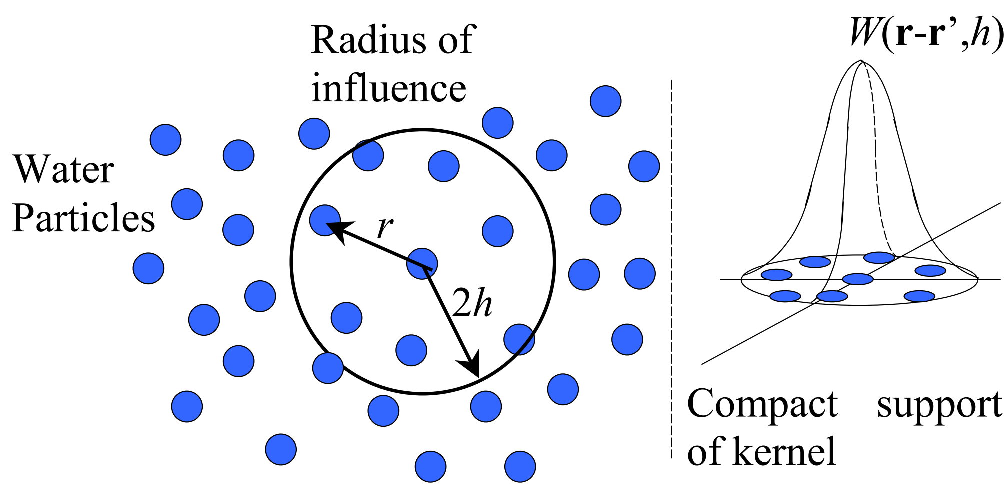
Particles possess **fluid properties** that travel with them, e.g. density, pressure; these can change with time

Local Interpolation (summation) with a **weighting function** (kernel) around each particle to obtain fluid properties

$$\langle A(\mathbf{r})\rangle \approx \sum_{j=1}^{N} A(\mathbf{r}_j)\, W(\mathbf{r}-\mathbf{r}_j, h)\frac{m_j}{\rho_j}$$



Particle j of mass m_j moving at velocity $\mathbf{v_j}$



Equations of Motion: Approximated by Summation

- Navier-Stokes equations:

$$\frac{d\rho}{dt} = -\rho \nabla . \mathbf{v}$$

$$\frac{d\mathbf{v}}{dt} = -\frac{1}{\rho}\nabla p + \upsilon_o \nabla^2 \mathbf{u} + \mathbf{F}$$

- Are recast in particle form as

(XSPH - Monaghan 1992)

$$\frac{d\mathbf{r}_i}{dt} = \mathbf{v}_i + \varepsilon \sum_j m_j \left(\frac{\mathbf{v}_{ji}}{\overline{\rho}_{ij}} \right) W_{ij}$$

$$\left(\frac{d m_i}{dt} = 0 \right)$$

$$\frac{d\rho_i}{dt} = \sum_j m_j \left(\mathbf{v}_i - \mathbf{v}_j \right) \cdot \nabla_i W_{ij}$$

$$\frac{d\mathbf{v}_i}{dt} = -\sum_j m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} \right) \nabla_i W_{ij}$$

$$+ \sum_j m_j \frac{4\upsilon_o}{\rho_i + \rho_j} \frac{\mathbf{r}_{ij} \cdot \nabla_i W_{ij}}{r_{ij}^2 + 0.01h^2} \left(\mathbf{u}_i - \mathbf{u}_j \right) + \mathbf{F}_i$$

(I use *i* and *j* to denote different particles)

This is the classical SPH form, we will change this!

Equations of Motion: Approximated by Summation

- Navier-Stokes equations:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\rho\nabla.\mathbf{v}$$

- Are recast in

(XSPH - Mo

$$\frac{\mathrm{d}\mathbf{r}_i}{\mathrm{d}t} = \mathbf{v}_i + \varepsilon\sum_j$$

$$\left(\frac{\mathrm{d}m_i}{\mathrm{d}t} = 0\right)$$

$$\mathbf{u}_j\big) + \mathbf{F}_i$$

(I use *i* and *j* to den

Main points are that:

(i) we do not need to treat the **free surface**

(ii) No expensive meshing

(iii) SPH is Meshless & can therefore capture nonlinearity

This is the classical SPH form, we will change this!

SPH for fluid flows

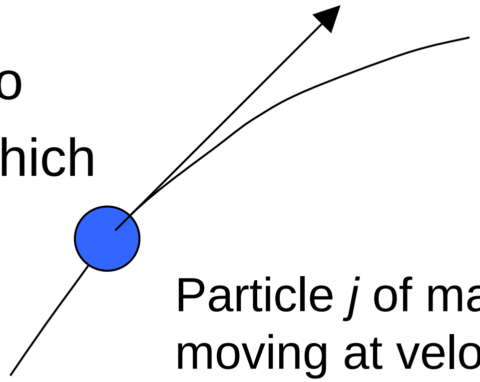
What can SPH offer?

What can SPH do that other models cannot?

What can SPH offer the simulation of nonlinear flows?

SPH is a Lagrangian method

(a) Our computation point are the particles so we can track what happens to the particles which represent the water, the sediment, etc.



Particle *j* of mass m_j moving at velocity $\mathbf{v_j}$

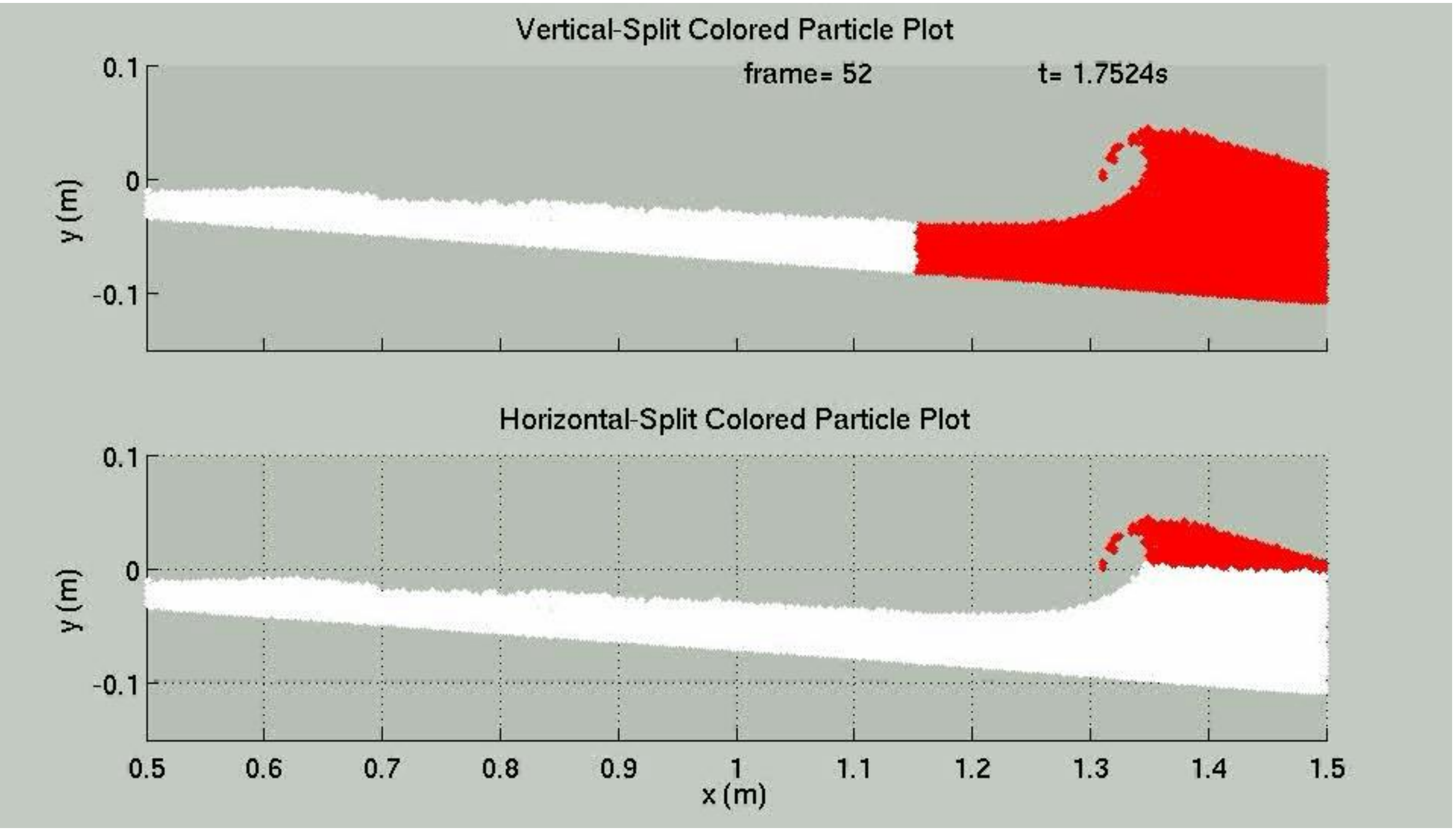
(b) This means we **avoid** the computation of the **nonlinear advection terms** within SPH

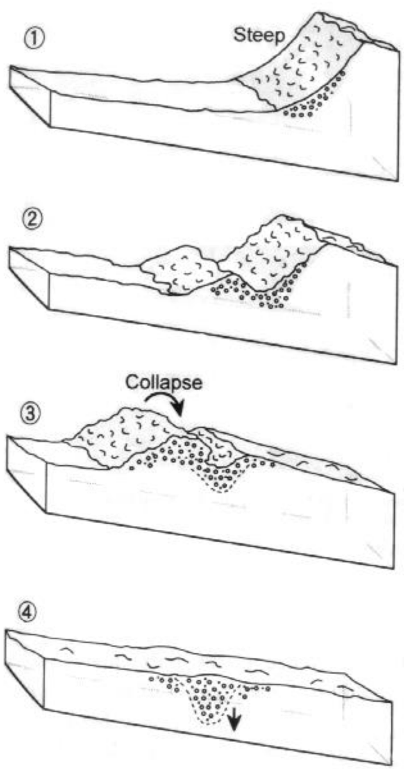
$$\frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z} = \quad \frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla \quad \Rightarrow \frac{D}{Dt}$$

Only the RHS of our equations need SPH treatment

This makes nonlinear phenomena very easy to examine, in particular **FORMATION mechanisms**, eg. mixing …

ICCE 2004: Captured downbursting-like phenomenon in 2-D





Kubo & Sunamura (2001) hypothesis

- Rogers & Dalrymple (2004)

DualSPHysics - what is it?

Where did DualSPHysics come from?

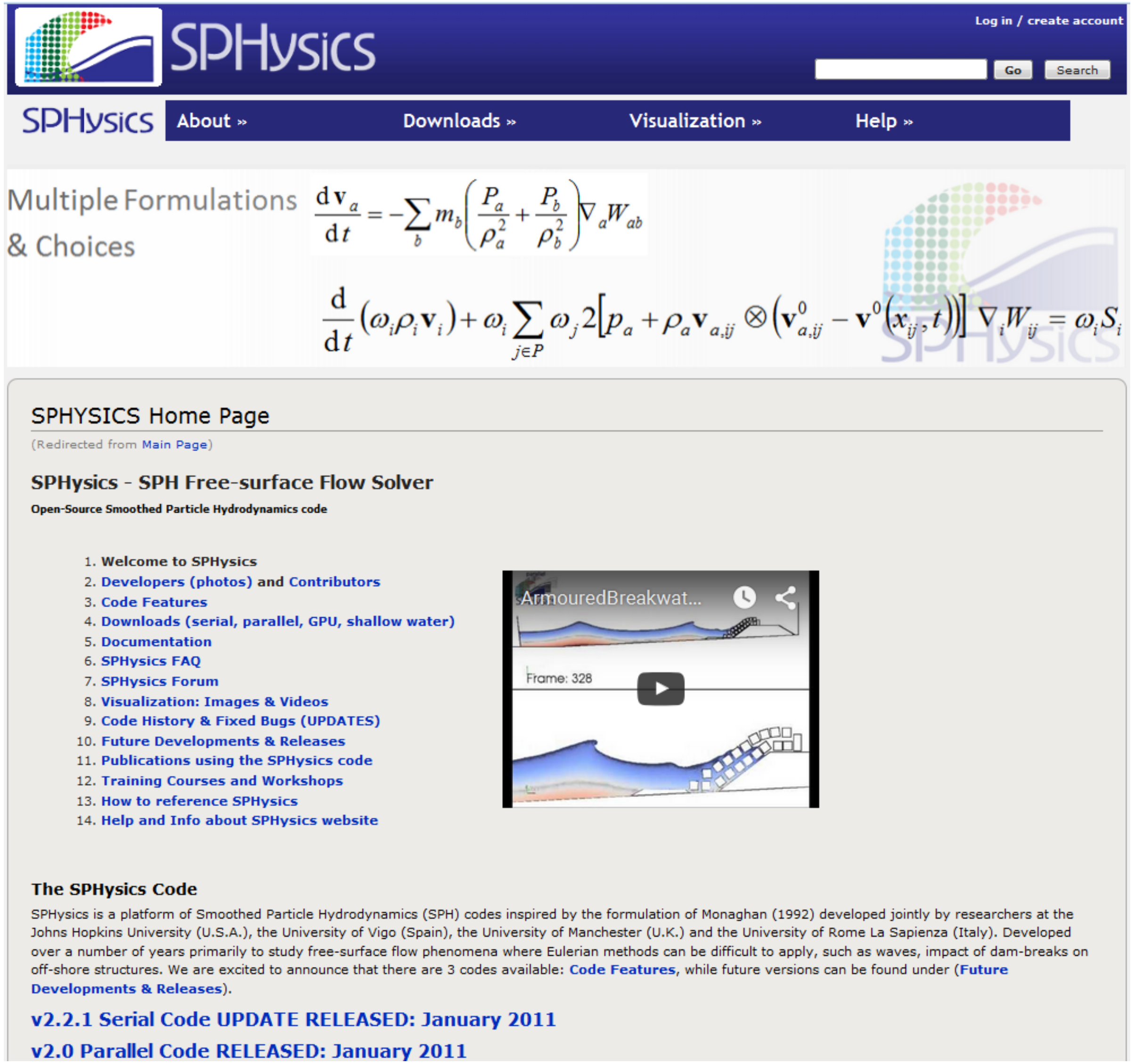
What can DualSPHysics offer?

MANCHESTER
1824

DualSPHysics History - SPHysics

FORTRAN → **CUDA/C++**

SPHysics – 1st open-source code for free-surface flow (FORTRAN)



Result of 8 years of work

Released in 2007

Collaboration between 4 institutions

- University of Manchester
- Universidade de Vigo
- Johns Hopkins University
- University of Rome La Sapienze

SPHysics – 1st open-source code for free-surface flow (FORTRAN)

- Code had 5 test cases

- 2-D & 3-D

- Choice of options beyond anything else available: kernels, timestepping, formulations & completely open source (mistakes, coding tricks, …)

- Importantly it was VALIDATED against simple cases

BUT

- It was very slow
- Restricted to 100,000 particles (simulations took 2-3 weeks)
- Had primitive pre- and post-processing

DualSPHysics History - GPUs

SPH *was* prohibitively expensive computationally

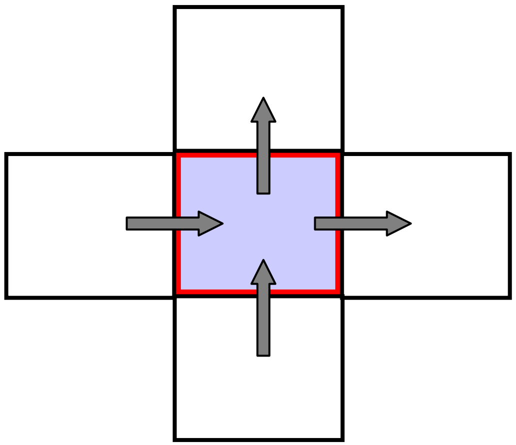
MANCHESTER
1824

SPH is costly computationally, Why?

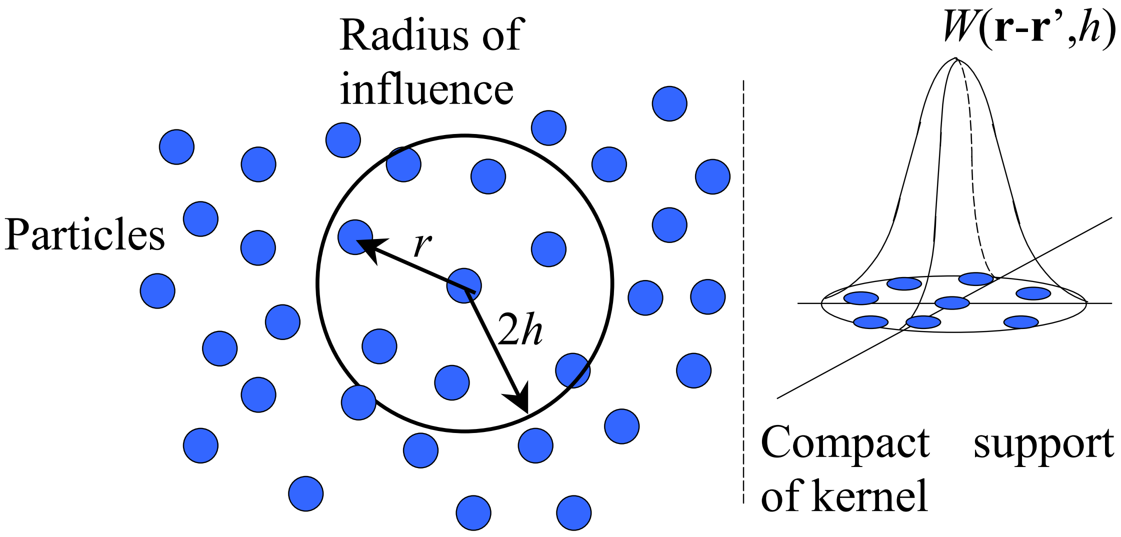
- The main problem is due to the interpolation procedure itself

- In Finite Volume, Finite Element & Finite Difference Schemes, the stencil around any cell usually contains only a small number of neighbouring cellsl e.g. **In 2-D FVM only 4 neighbouring cells**

Finite Volume (FVM) Stencil



SPH Stencil



- In **2-D**, each particle typically interacts with **20-50 particles**
- In **3-D**, each particle typically interacts with **100-400 particles**

Hardware Acceleration: the options

(i) Using parallel (**supercomputer**) machines with lots of cores (individual CPUs) and divide the work over them

Qu: What's the difference between a parallel machine and a supercomputer?

(ii) **FPGAs** – Field Programmable Gate Arrays: well used in astrophysics simulations, but expensive and not portable

(iii) **GPUs** – Graphics Processing Units: the **hot topic** of scientific computing

TOP SUPERCOMPUTERS IN THE WORLD June 2015

http://www.top500.org

R_{max} and R_{peak} values are in TFlops. For more details about other fields, check the TOP500 description.

1º	Tianhe-2 (China)	33.0 petaflops/s	(consumption: 17808 KW)	(CPUs)	
2º	Titan (USA)	17.5 petaflops/s	(**consumption: 8209 KW**)	(**with GPUs**)	

Rank	Site	System	Cores	Rmax	Rpeak	Power
2	DOE/SC/Oak Ridge National	Titan - Cray XK7 , Opteron 6274 16C 2.200GHz,	560,640	17,590.0	27,112.5	8,209
10	Government United States	Cray XC30, Intel Xeon E5-2697v2 12C 2.7GHz, Aries interconnect Cray Inc.	225,984	3,143.5	4,881.3	

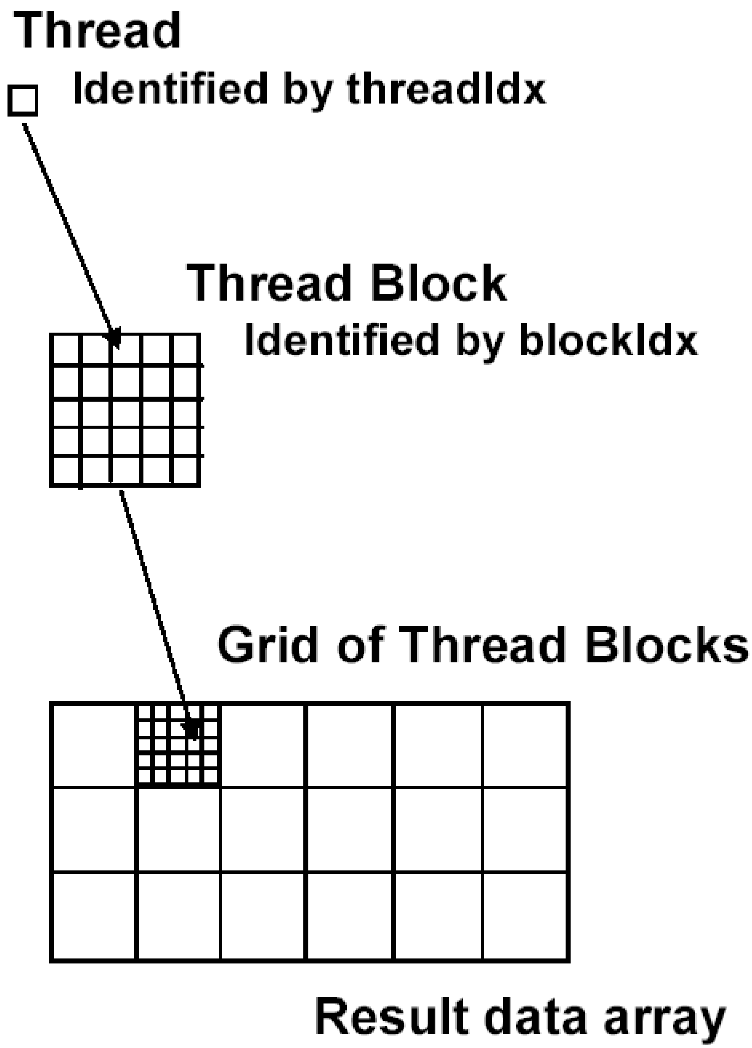
Energy Efficient GPU co-processors are now a key component in HPC

Part of computing Emerging Technology 2015 Conference:

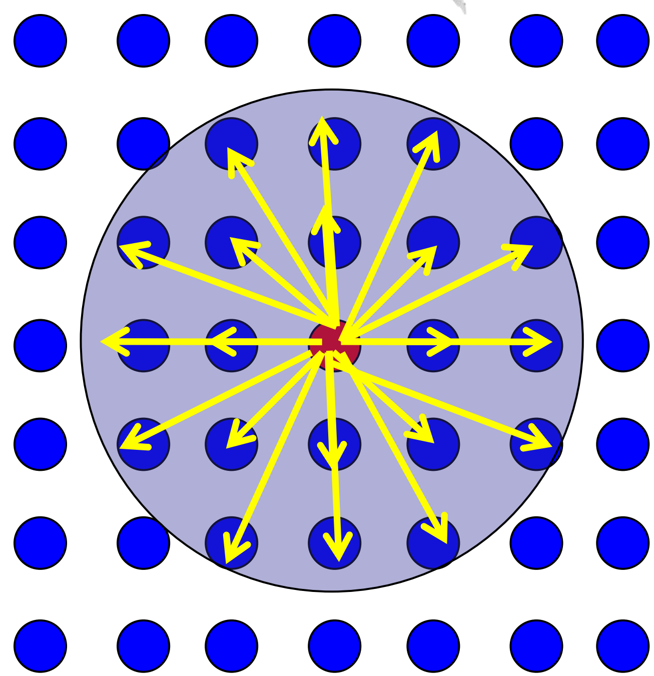
http://emit.manchester.ac.uk

There are now several GPU codes …

SUMMATION SOLUTION



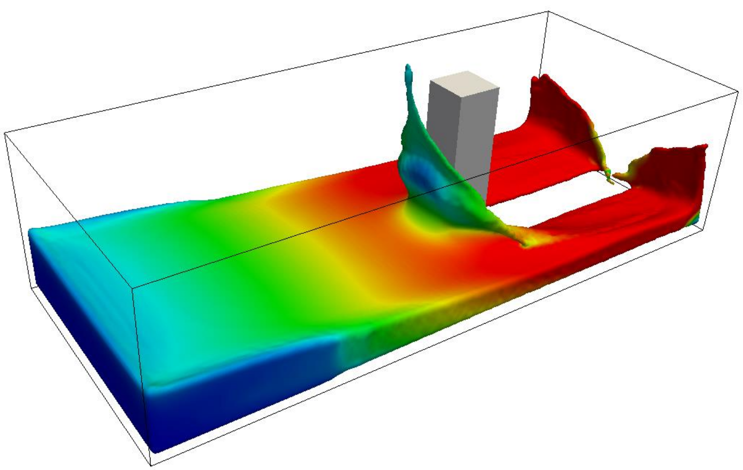
GPU / CUDA

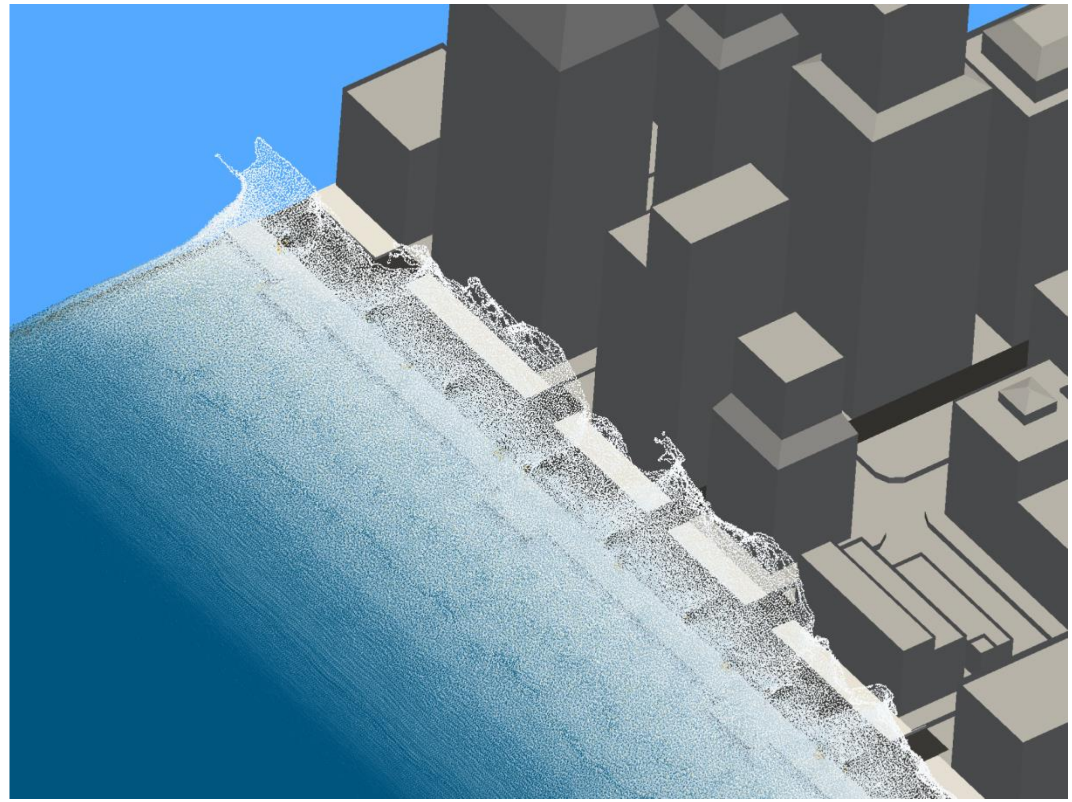


$$\left(\frac{d\mathbf{u}}{dt}\right)_i = -\sum_j m_j\left(\frac{p_j}{\rho_j^2}+\frac{p_i}{\rho_i^2}\right)\nabla_i W_{ij} + \mathbf{g}$$

$i \rightarrow j$

DualSPHysics, new GPU computing on SPH models





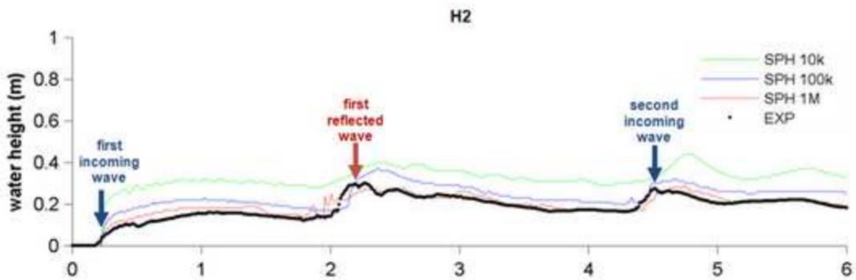
A.J.C. Crespo, J.M. Dominguez, A. Barreiro and M. Gómez-Gesteira
EPHYSLAB, Universidade de Vigo, SPAIN

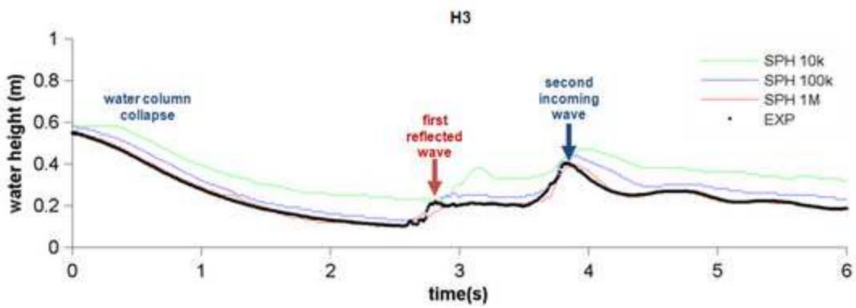
B. D. Rogers and D. Valdez-Balderas
MACE, The University of Manchester, U.K.

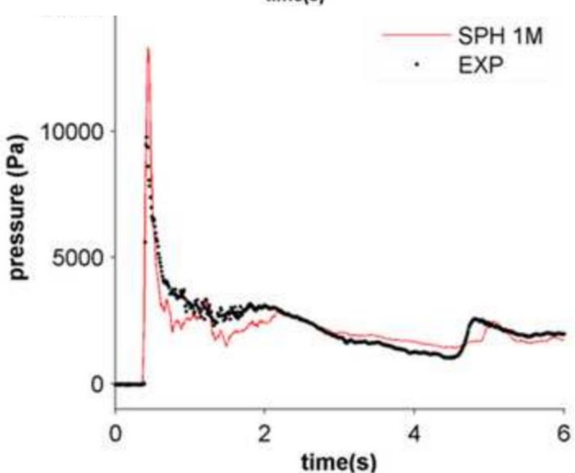
GPU validation for a dam break flow impacting on an obstacle

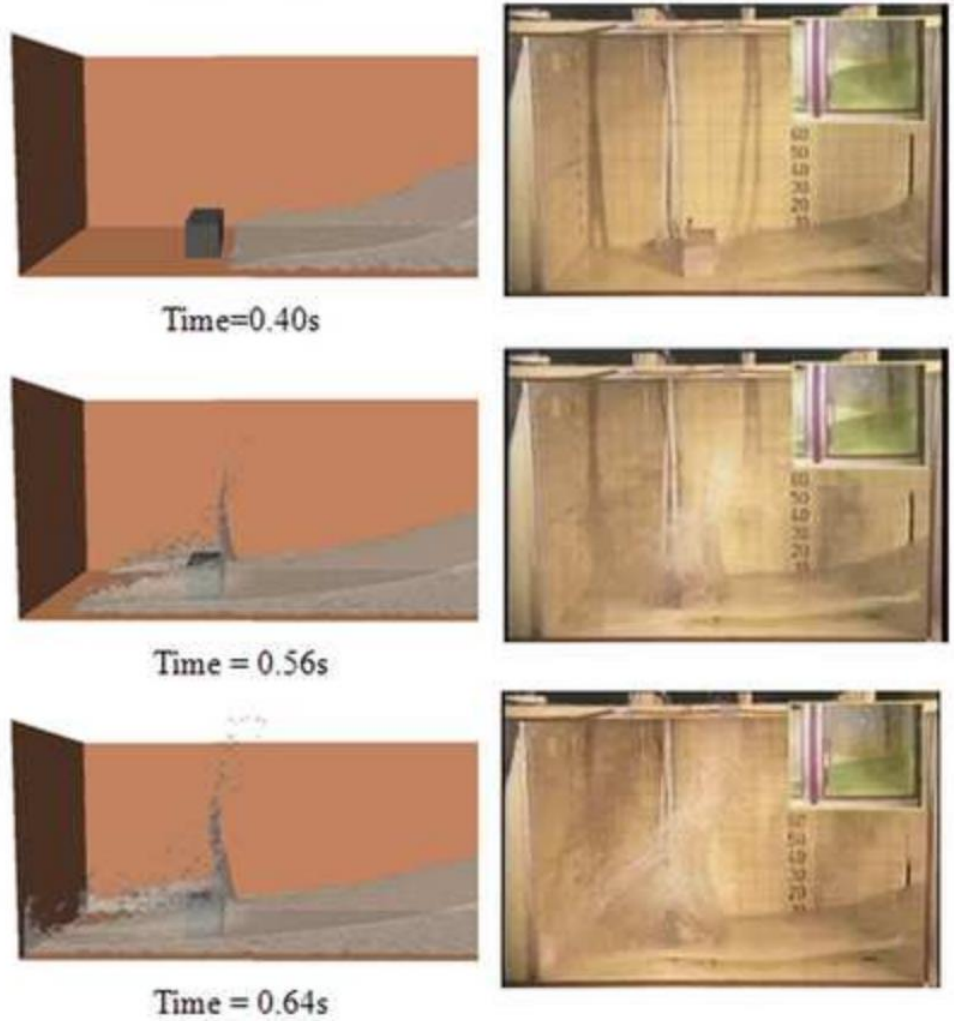
SPHERIC BENCHMARK TEST CASE 2

Crespo AJC, Dominguez JM, Barreiro A, Gómez-Gesteira M and Rogers BD. 2011. *GPUs, a new tool of acceleration in CFD: Efficiency and reliability on Smoothed Particle Hydrodynamics methods.* PLoS ONE. doi:10.1371/journal.pone.0020685







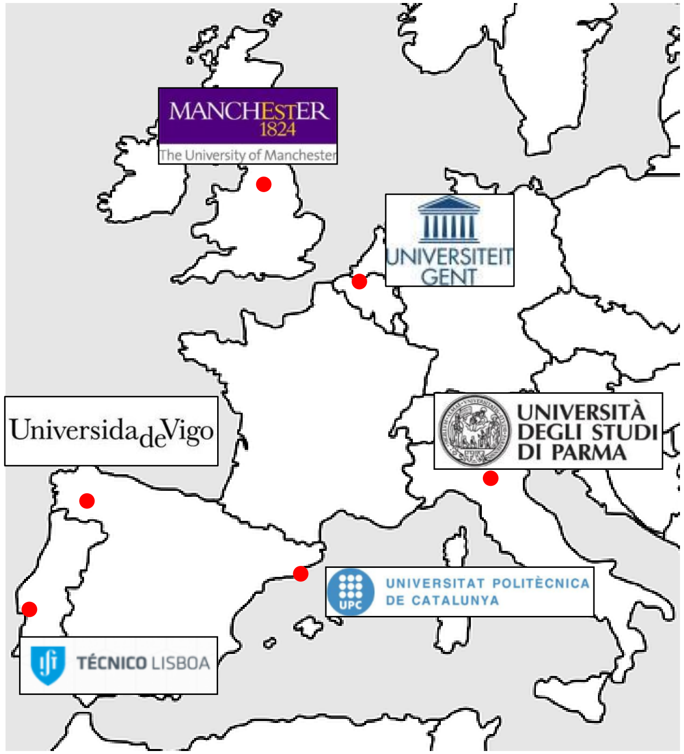


The DualSPHysics project team

Who are we?

DualSPHysics Project:

- University of Manchester
- University of Vigo (Spain)
- University of Parma (Italy)
- University of Lisbon (Portugal)
- University of Ghent (Belgium)



Websites

- Free open-source **SPHysics** code:
  http://www.dual.sphysics.org

Downloaded 1000s of times: The world's 1st open-source plug & play SPH code

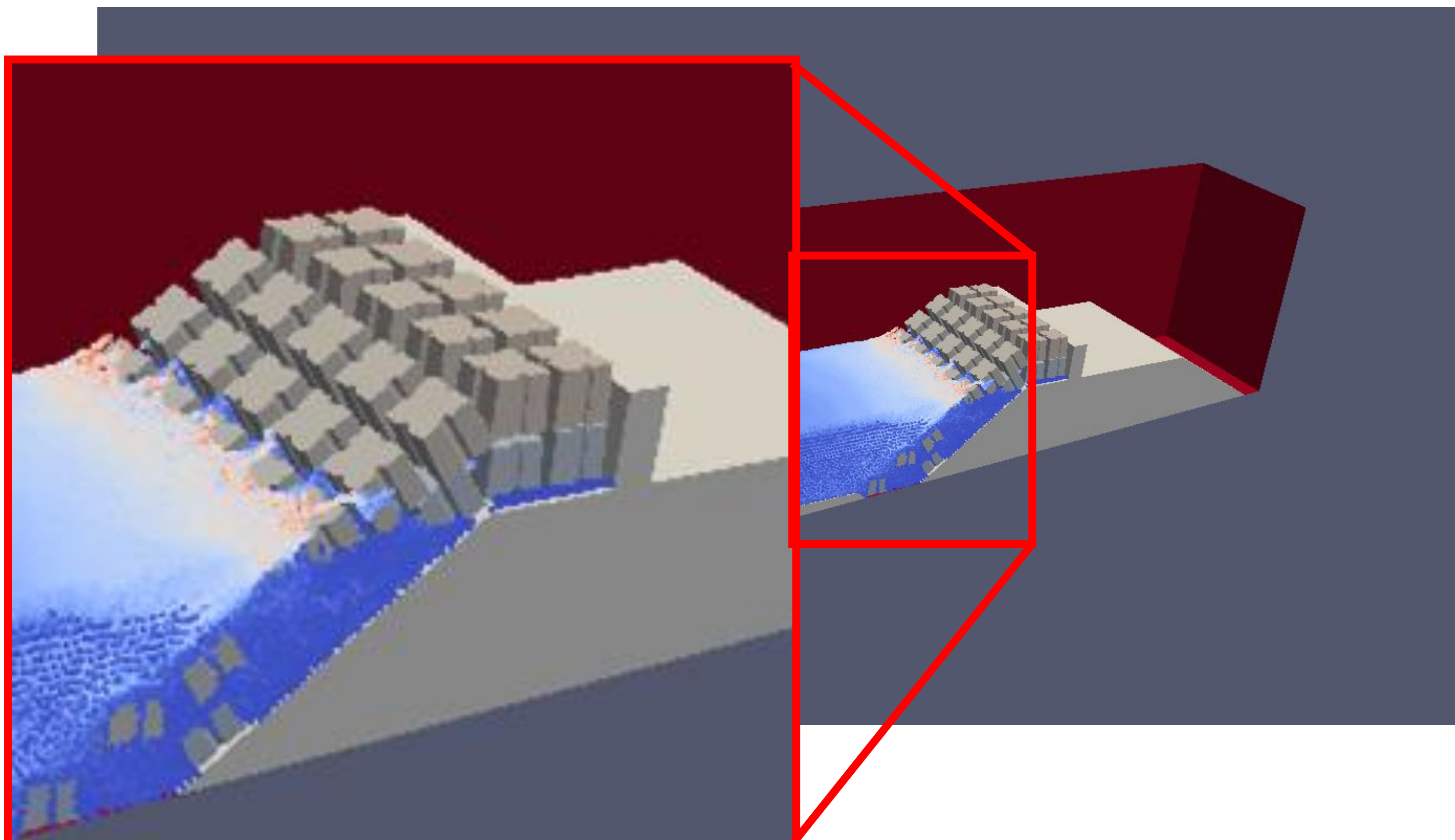
The DualSPHysics Areas of Activity

What do we do?

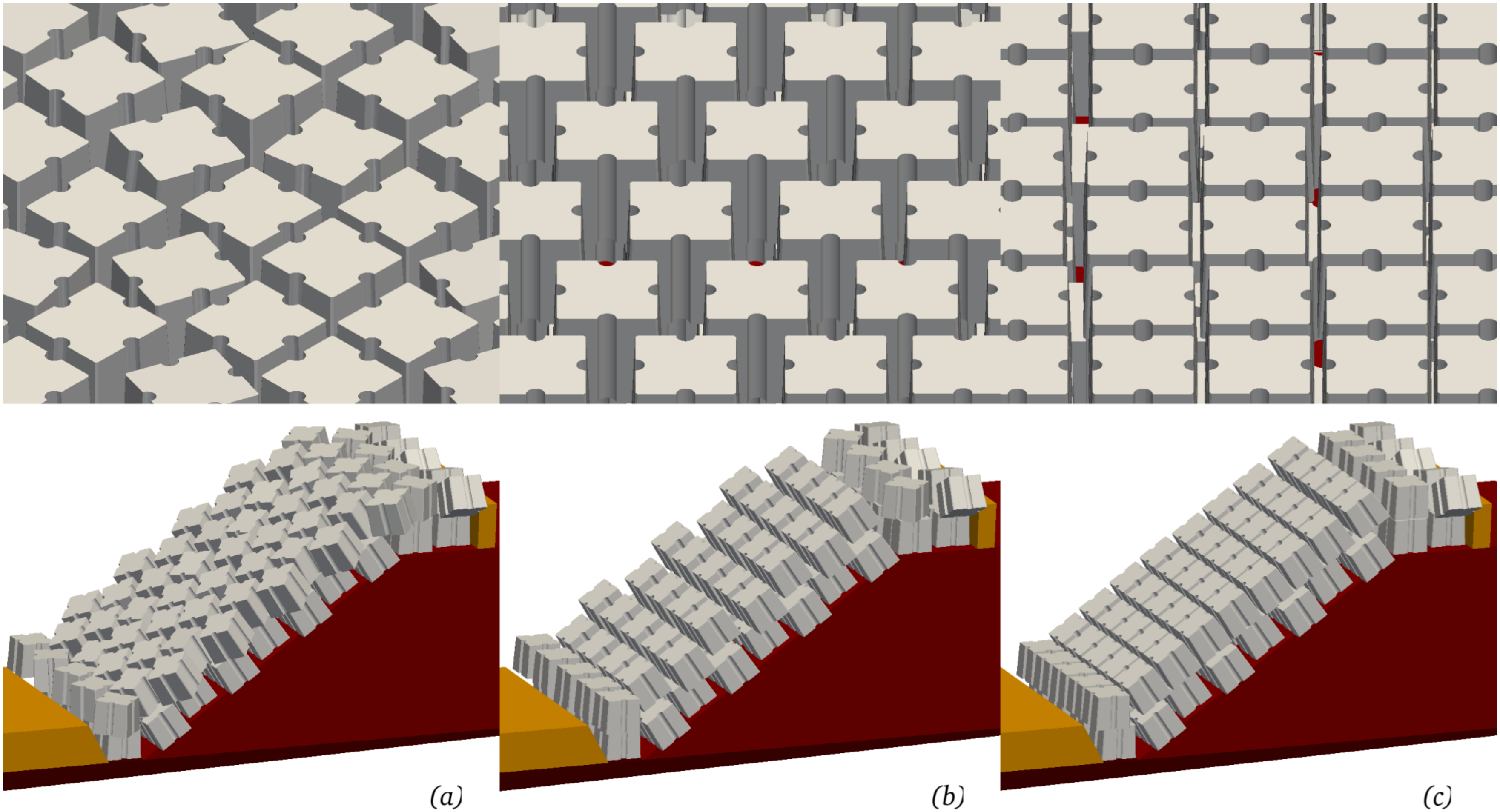
What can SPH offer the simulation of breaking waves?

SPH does not require a computational mesh

- Don't have to mesh the entire domain
- Running simulations in complex geometries is theoretically not an issue.



The Zeebrugge Breakwater in 3-D (Altomare *et al.* 2014)

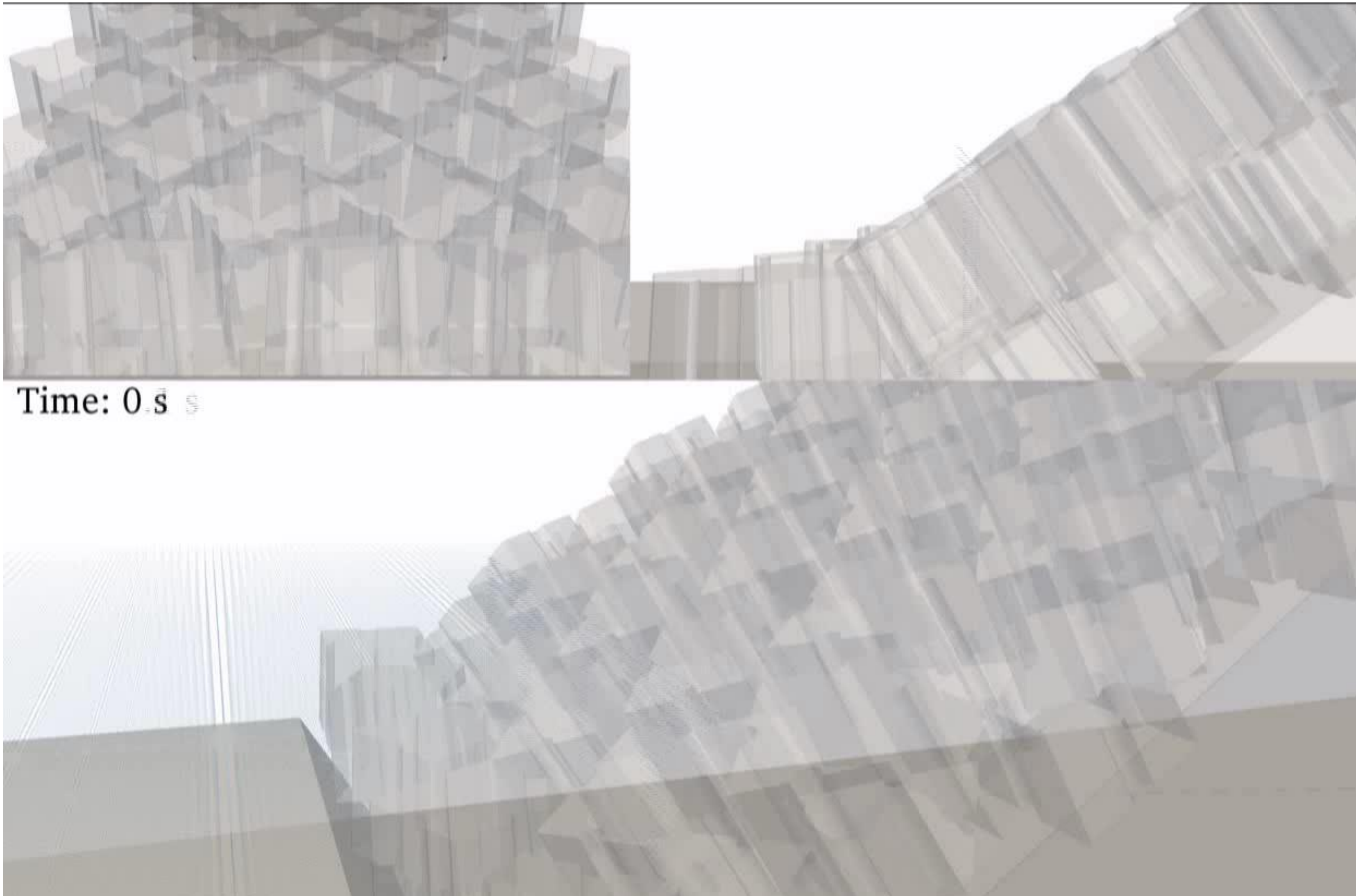


With **GENCASE** & **POST-PROCESSING** we can look at the different effect of layout very easily without needing the expensive experiments.

MANCHESTER 1824

The University of Manchester

We can now examine the Zeebrugge Breakwater in 3-D (Altomare et al. 2014)



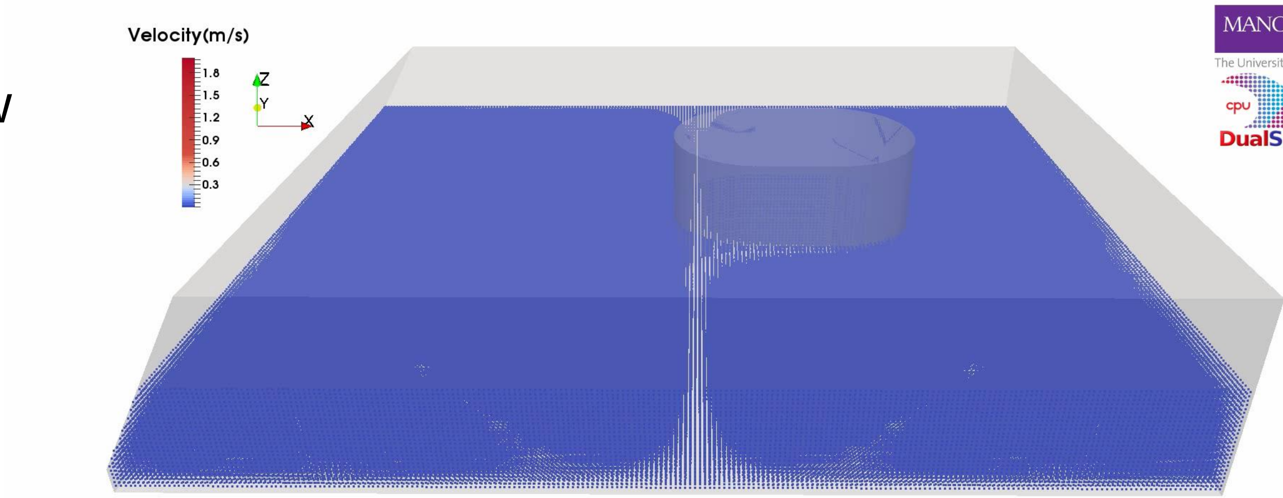
Fuel-tank sloshing with Leading Motorsport Company (F1)

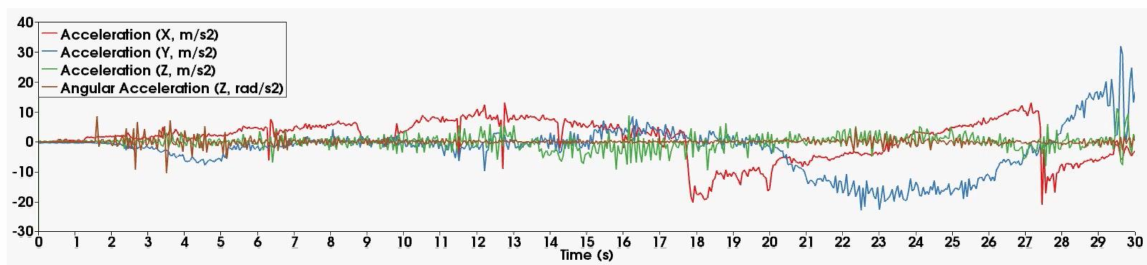
Real engineering problems are now accessible

Only allowed to show highly simplified geometry

Accelerations are up to 5*g*

Comparisons with in-tank footage were close.



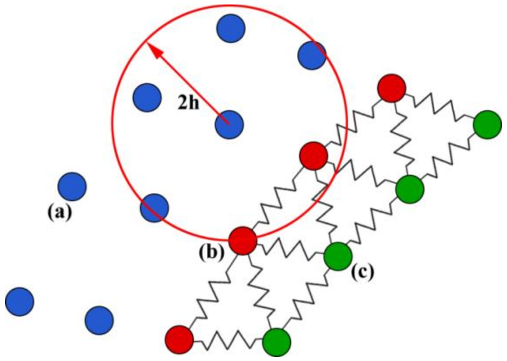


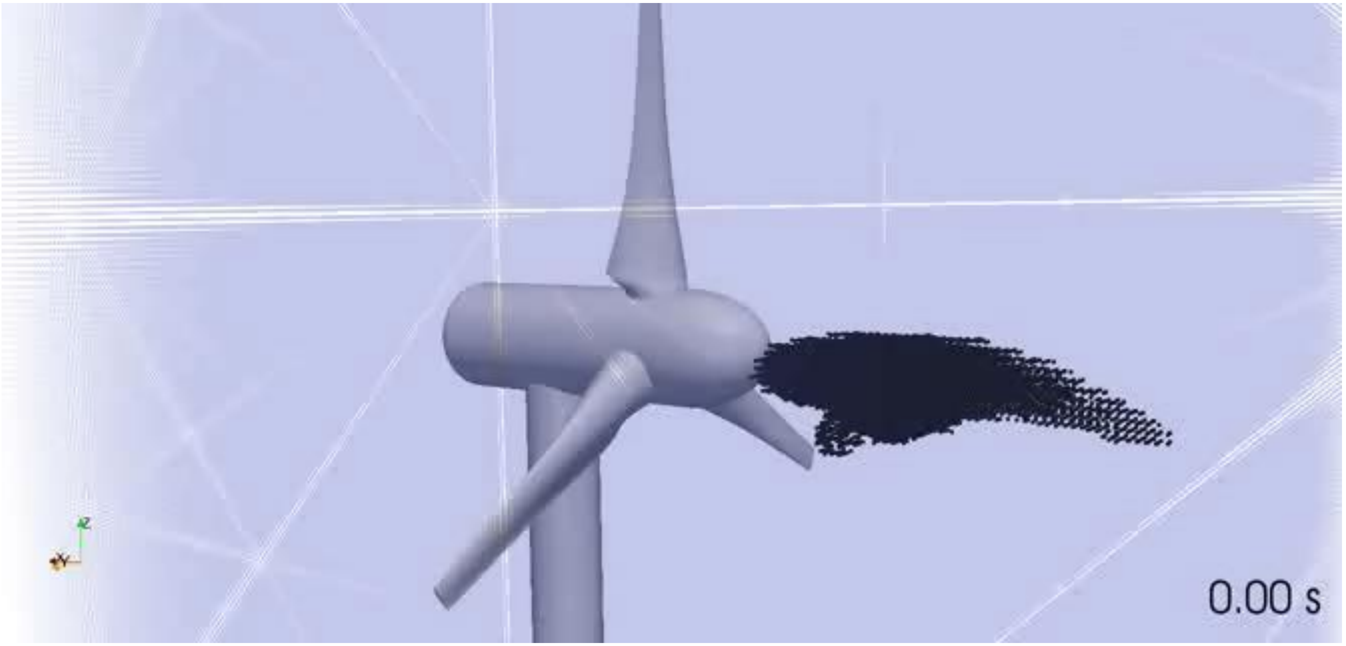
Longshaw & Rogers (2015), Advances Engineering Software

Funded by Knowledge Transfer Account (KTA), *now the IAA*

Combined SPH-MSD Simulation

After many validation cases:





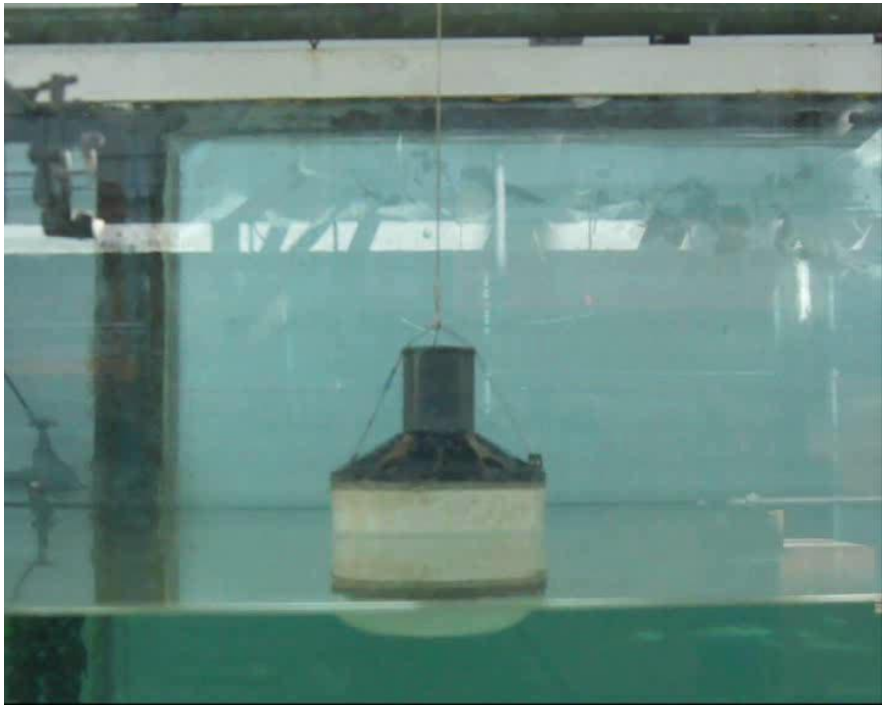
Involves different Young's moduli of elasticity for different elements of whale

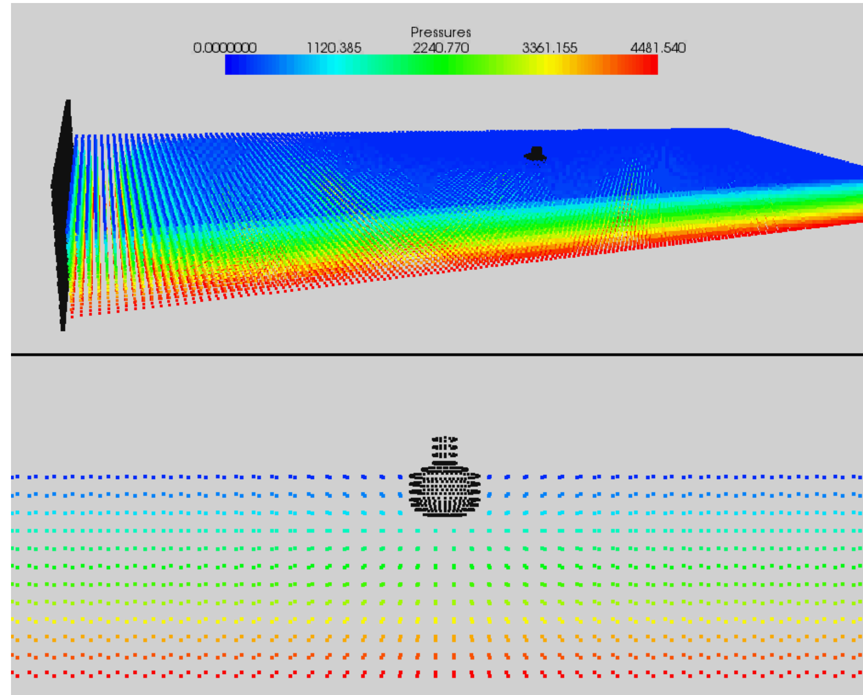
Manchester SPH Activity

What work do we do at Manchester?

Example 2-D & 3-D validation & applications

Heaving Wave Energy Device Experiments





Weller *et al*. (2013)

Focussed wave groups impacting

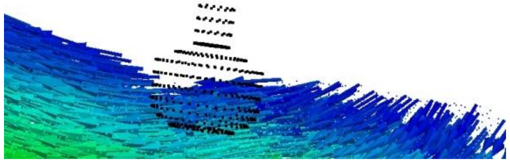
Omidvar *et al*. (2013)

SPH-ALE simulation

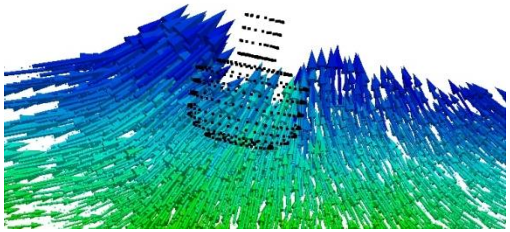
Resolution issue (see later …)

3-D Wave Energy Device Simulation

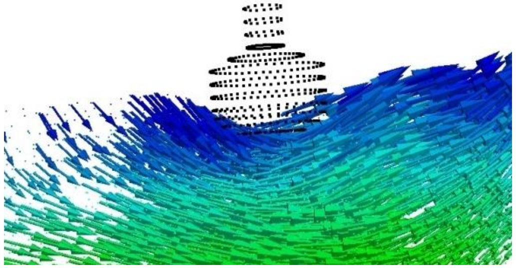
t = 3.8 s



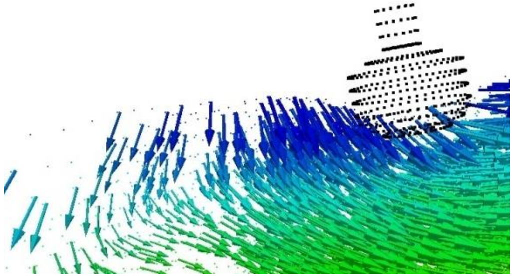
t = 4.2 s



t = 4.4 s



t = 4.6 s



Better SPH: The options

1. Density filtering

$$\rho_a^{new} = \sum_b \rho_b \tilde{W}_{ab} \frac{m_b}{\rho_b} = \sum_b m_b W_{ab} \Big/ \sum_b W_{ab} \frac{m_b}{\rho_b}$$

Dissipative

2. Volume diffusion methods:

$$\frac{\mathrm{d}\rho_i}{\mathrm{d}t} = \sum_j m_j \left(\mathbf{v}_i - \mathbf{v}_j\right) \cdot \nabla_i W_{ij}$$

$$\frac{\mathrm{d}\rho_i}{\mathrm{d}t} = \sum_j m_j \left(\mathbf{u}_i - \mathbf{u}_j\right) \cdot \nabla_i W_{ij} - \frac{\mathbf{r}_{ij}}{r_{ij}} \cdot \nabla_i W_{ij} \left(\frac{c_{ij}}{\rho_j} \left(\rho_j - \rho_i\right) \right)$$

3. Introducing ALE formulations & Riemann solvers

$$\frac{\mathrm{d}\mathbf{v}_i}{\mathrm{d}t} = -\sum_j m_j \left(\frac{P_i}{\rho_i^2} + \frac{P_j}{\rho_j^2} \right) \nabla_i W_{ij}$$

$$\frac{\mathrm{d}\mathbf{v}_i}{\mathrm{d}t} = -\sum_j m_j 2P_{ij}^* \left(\frac{1}{\rho_i^2} + \frac{1}{\rho_j^2} \right) \nabla_i W_{ij}$$

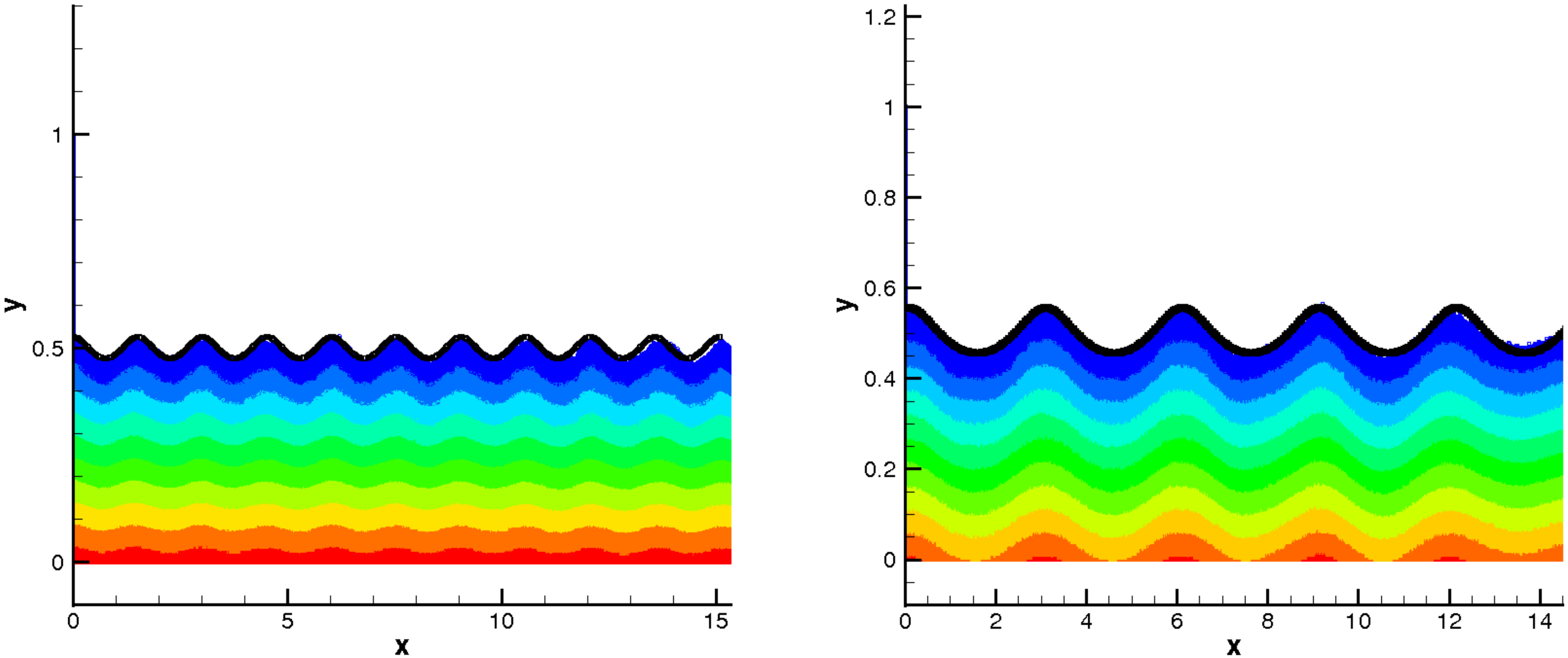
4. Incompressible SPH (ISPH) **+ shifting (unique Manchester project)**

$$\nabla \cdot \left(\frac{1}{\rho} \nabla p^{n+1} \right)_i = \frac{1}{\delta t} \nabla \cdot \mathbf{u}_i^*$$

$$\delta \mathbf{r}_s = -\mathcal{D} \left(\frac{\partial C}{\partial s} \mathbf{s} + \alpha \left(\frac{\partial C}{\partial n} - \beta \right) \mathbf{n} \right)$$

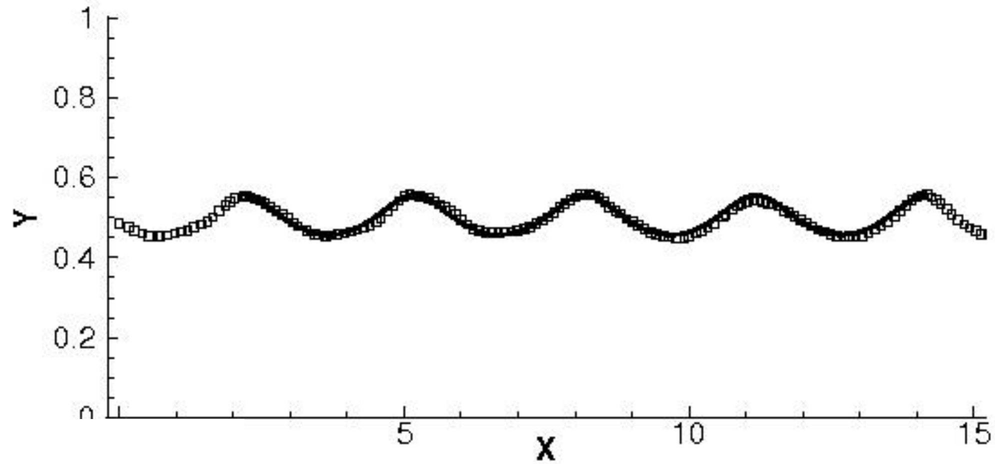
Shift particles to maintain stability.

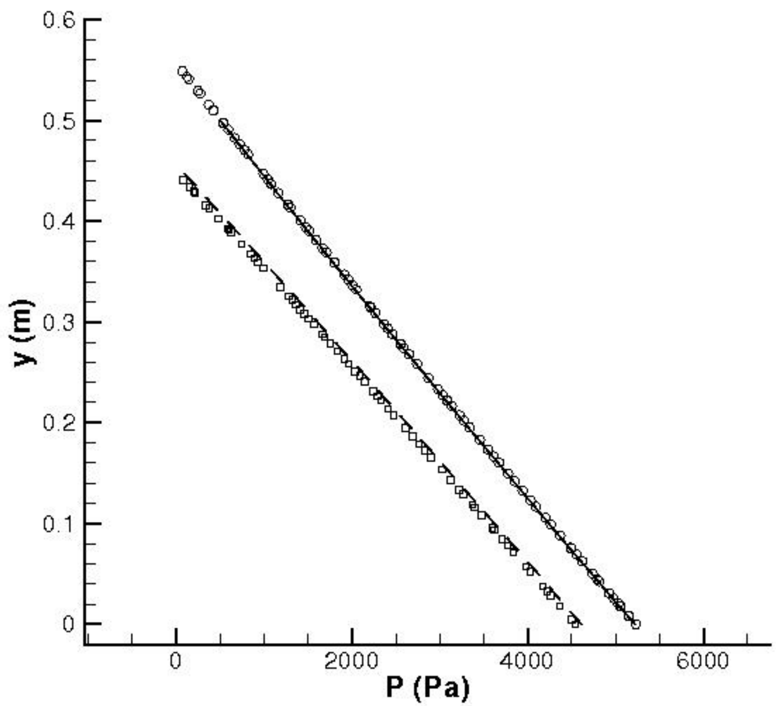
Improvement in wave propagation using Incompressible SPH

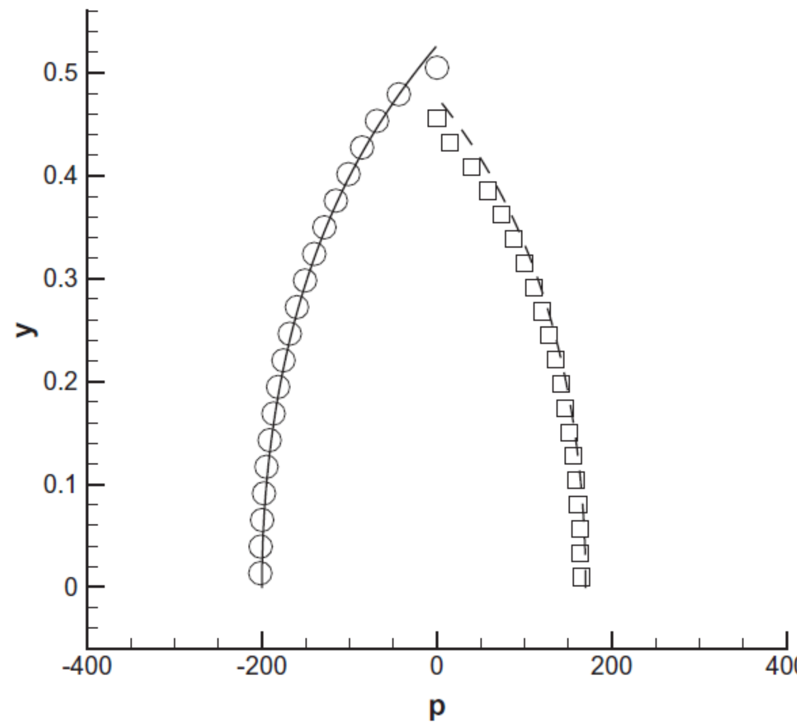


Comparison of wave propagation along a channel (including pressure contours) with free-surface predictions of SAWW (bold black line).
(a) Wave height *H = 0.05m at t = 19.5s. (b) Wave height H = 0.1m at t = 9.75s.*

Free surface in the regular wave case. Square symbols = ISPH; solid line = code SAWW Squares = ISPH; solid lines = code SAWW. Time = 12.53s, wave height H = 0.1m, wave length = 3.0m.







Full & Dynamic Pressure along the vertical line at cross sections, wave crest & trough. Solid lines = wave crest, code SAWW; dashed lines = wave crest, code SAWW; circles = wave crest, ISPH; diamonds = wave crest, ISPH.

SPH free-surface Applications

Application: Fluid-Structure Impact Modelling

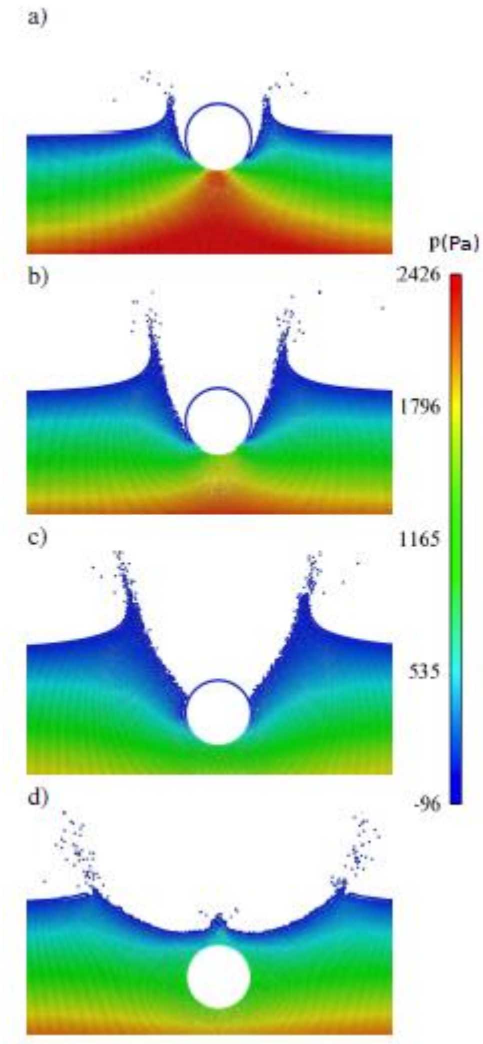
Skillen *et al*. (2013), CMAME

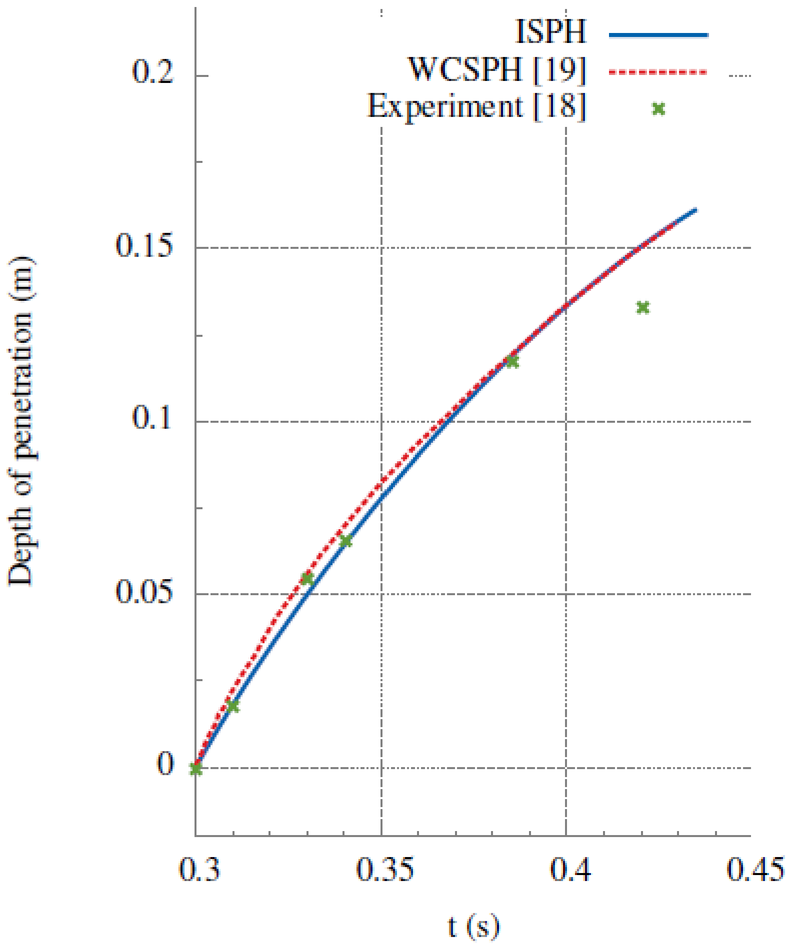
MANCHESTER 1824

ISPH for Impact

VALIDATION:

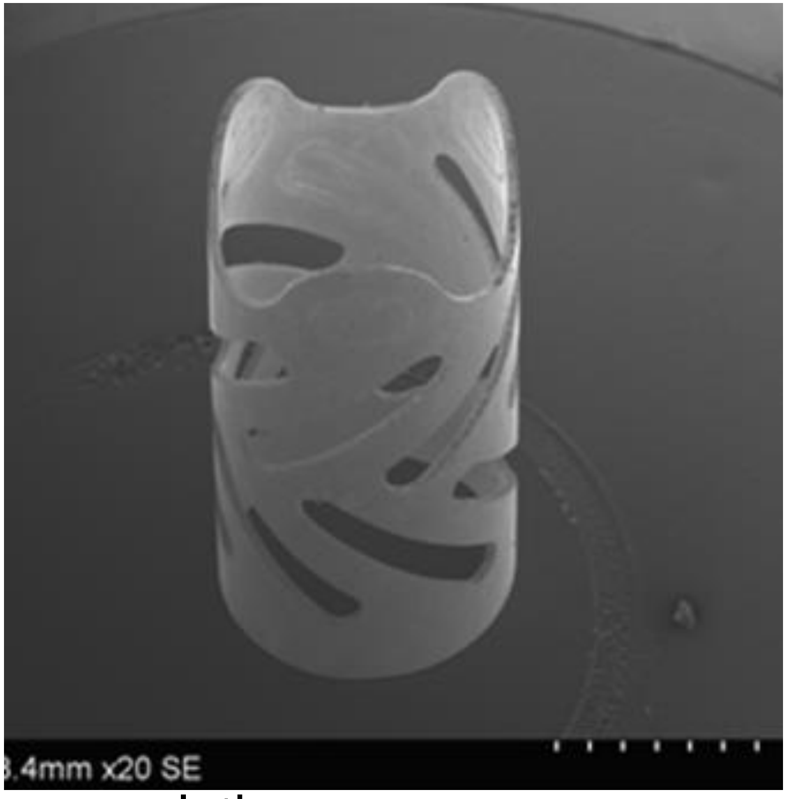
Cylinder dropping onto a surface (comparison with Greenhow & Lin experiments) – Depth of penetration





Now ***multi-phase ….***

Laser Cutting Applications



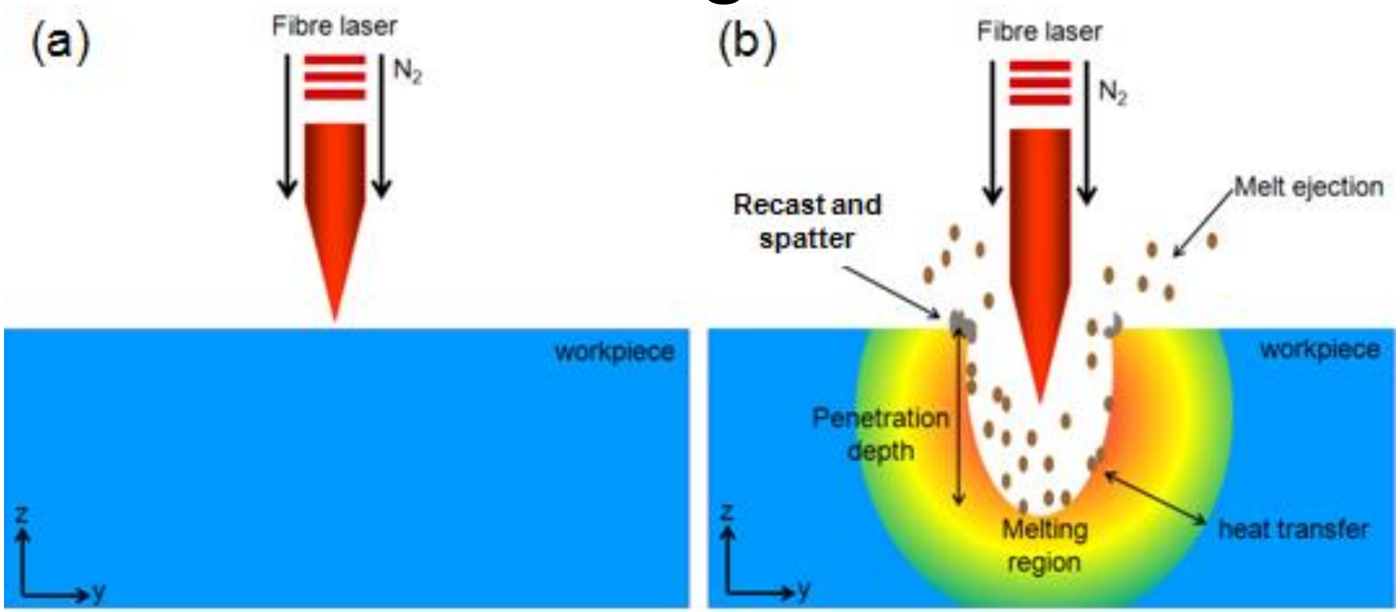
platinum

SEM images of laser cut samples:

MANCHESTER 1824

- Laser beam heats the surface of the object in **very short pulses** (typically ms to ps)
- For ms heating, the surface particles increase in Temperature, melt & leave the surface – ideal for SPH
- Backwall damage and debris result
- Assist gas helps the removal of particles within the cut
- Water removes particles under the cut

Laser Cutting Process 1



Heat Transfer

$$c_p \frac{dT}{dt} = \frac{1}{\rho}\nabla(k\nabla T) + Q - Q_v$$

SPH

$$c_{p,i}\frac{dT_i}{dt} = \sum_j \frac{m_j}{\rho_i \rho_j}(k_i + k_j)\left(\frac{T_i - T_j}{\mathbf{r}_{ij}^2}\right)\mathbf{r}_{ij}.\nabla_i W_{ij} + Q - (Q_v)$$

Laser Beam

$$\rho_m = \rho(T)$$

Laser changes Temperature & density

⇨

$$P_{vap} = P_0 \exp\left[\frac{L_v}{R}\left(\frac{1}{T_b} - \frac{1}{T_s}\right)\right]$$

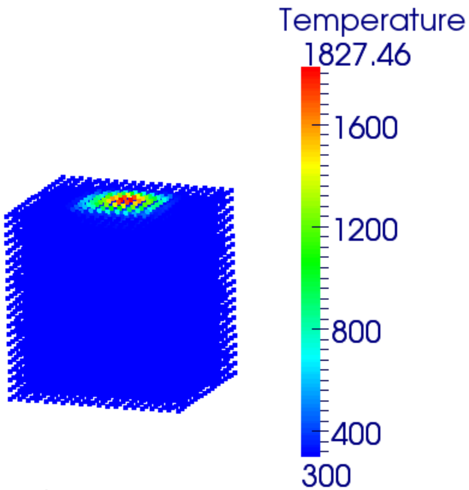
Changes in surface temperature & pressure

⇨

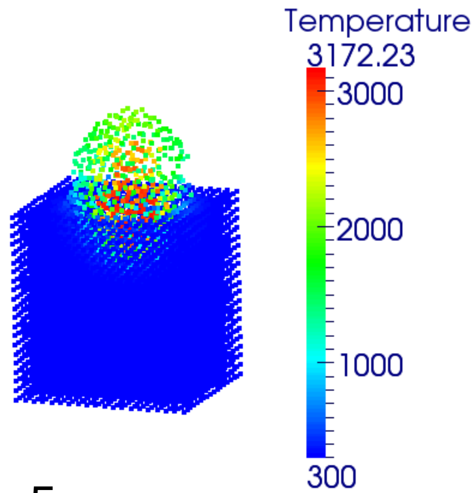
$$V_m = \sqrt{\frac{2(P_{vap} + P_{eff})}{\rho_m}}$$

Ejection velocity with assist gas N_2

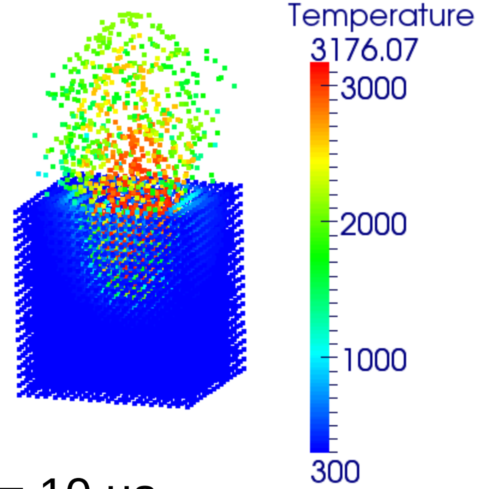
Dry Laser Cutting



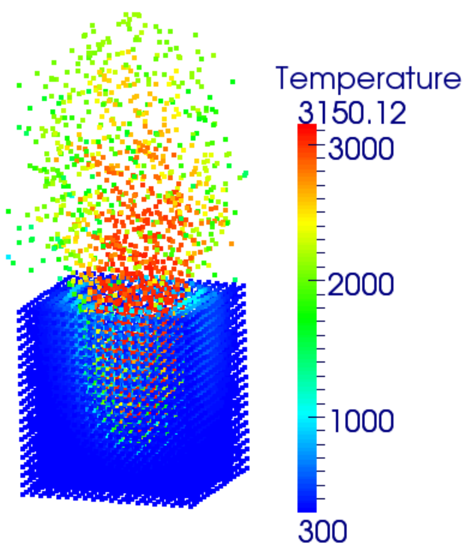
t = 0.5 µs



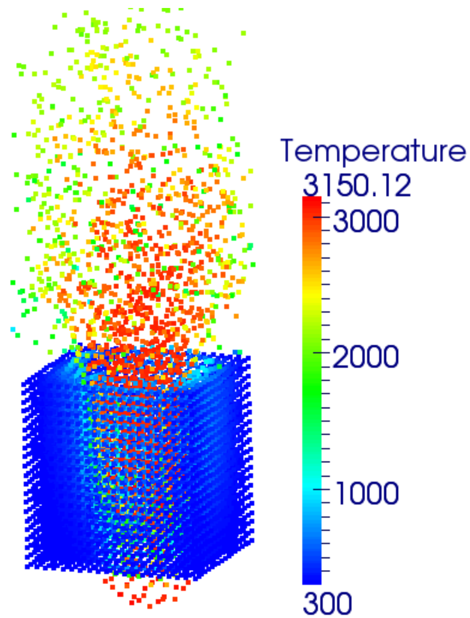
t = 5 µs



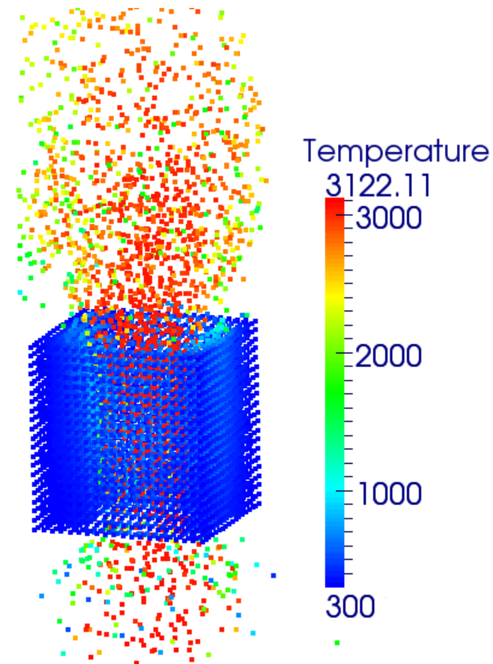
t = 10 µs



t = 15 µs



t = 20 µs



t = 25 µs

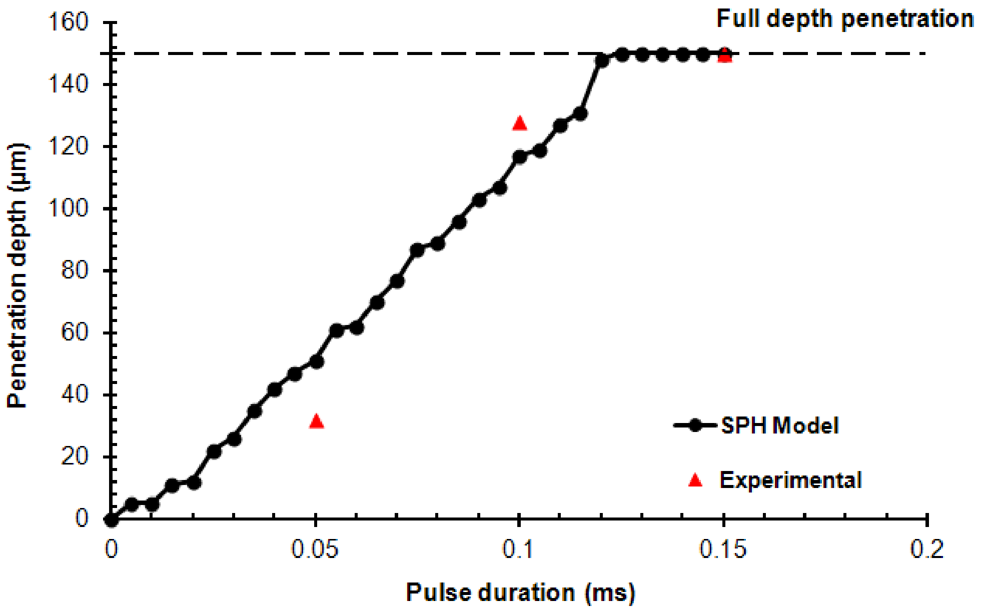
Dry Laser Cutting: Penetration Depth

Experiment

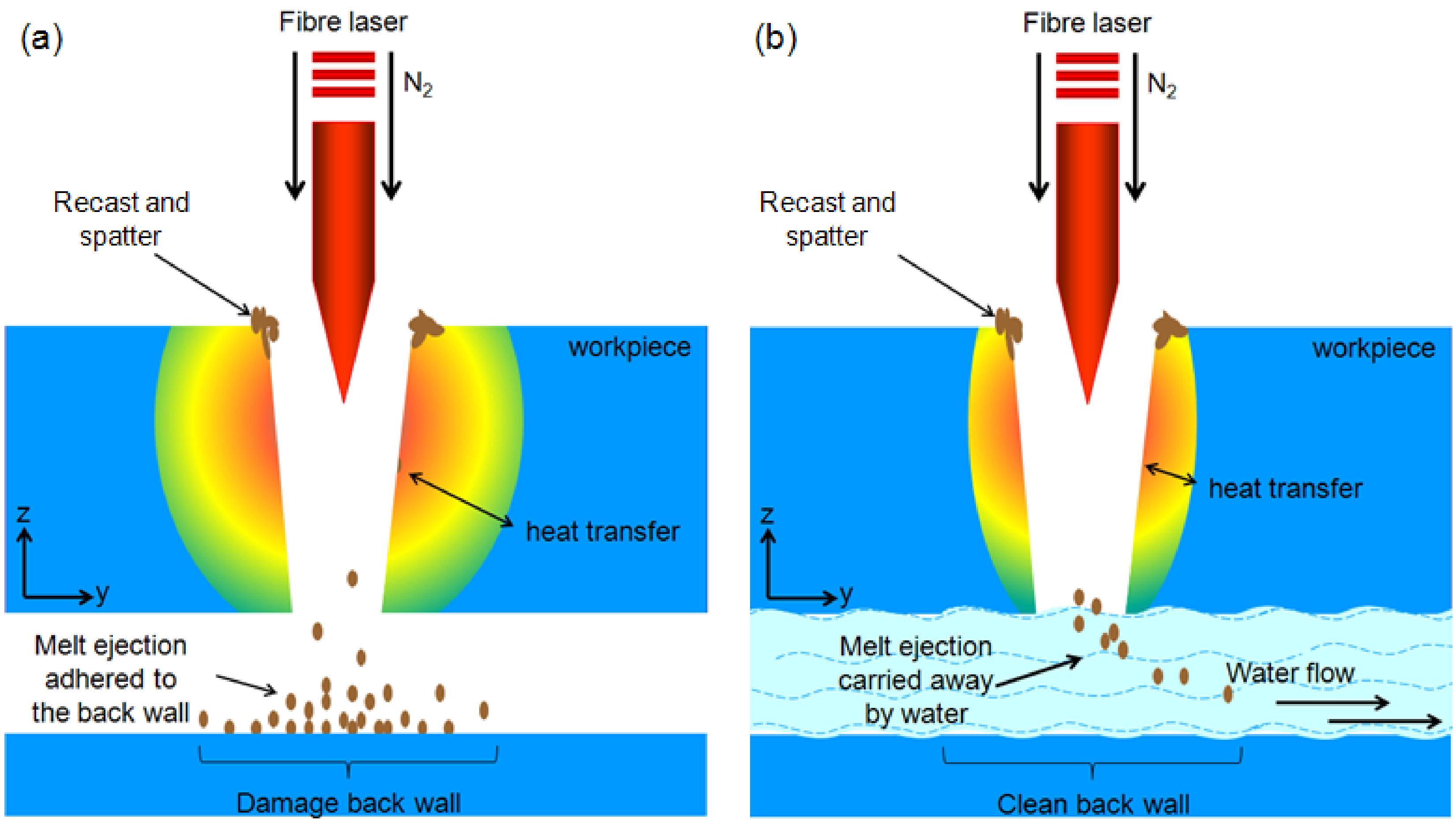
Penetration depth obtained experimentally at different pulse duration with 100 W peak power at single pulse (a) τ = 0.05 ms, (b) τ = 0.1 ms and (c) τ = 0.15 ms.

SPH

Penetration Depth



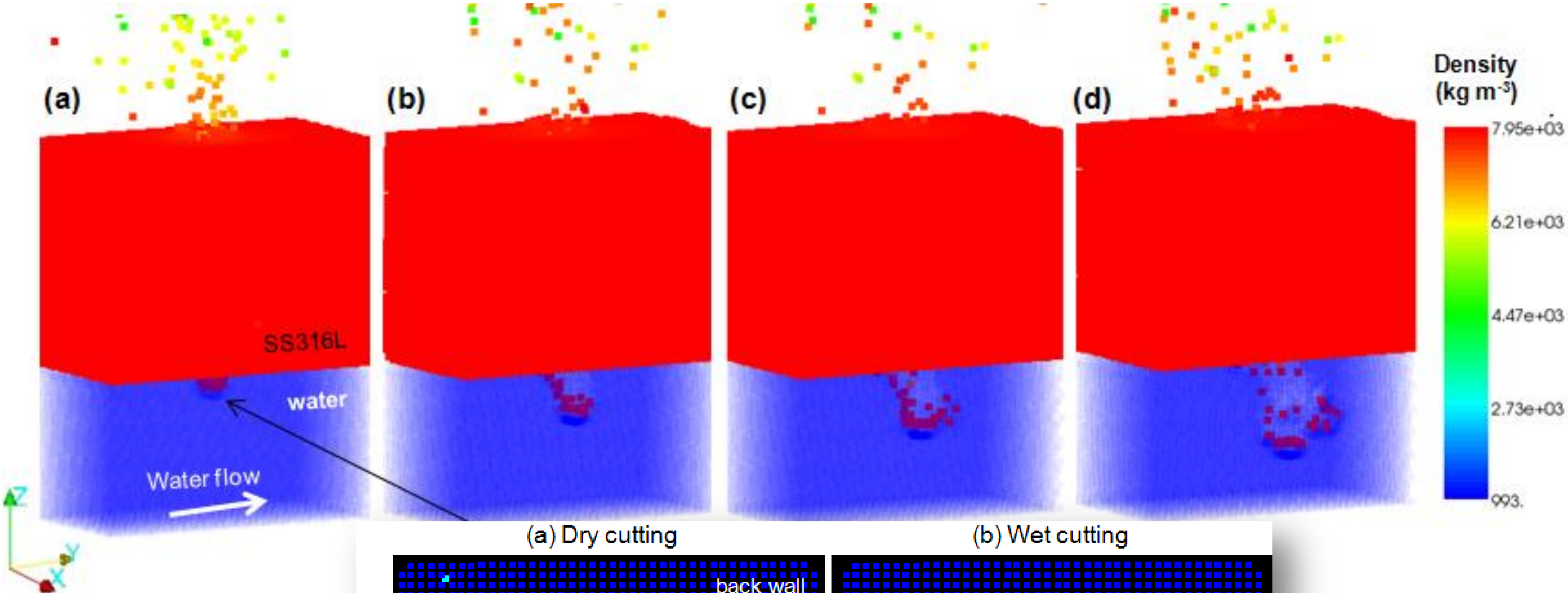
Dry & Wet Laser Cutting



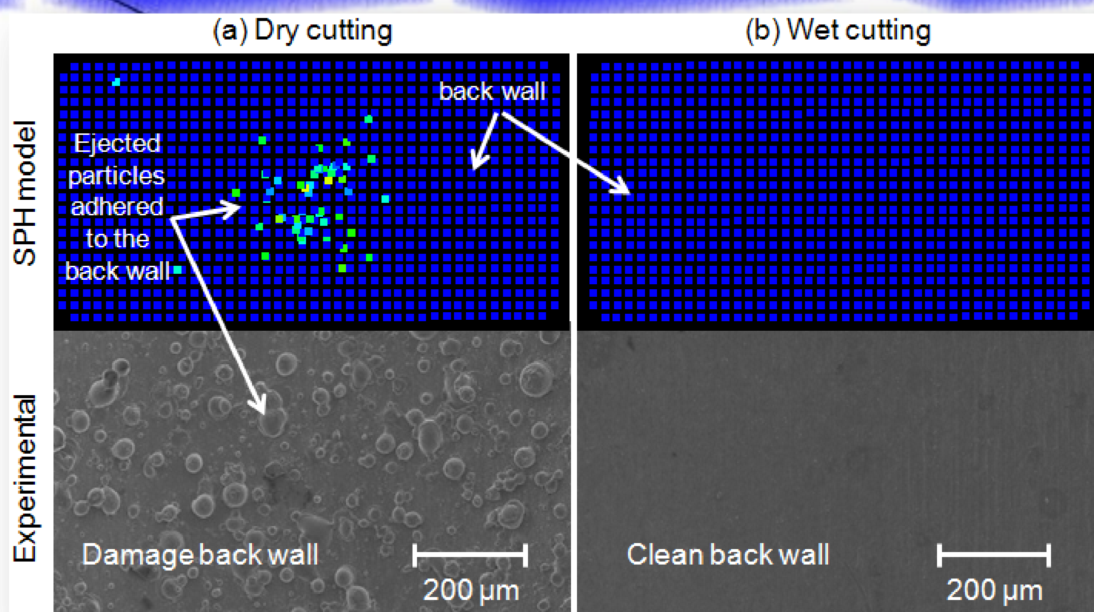
In both cases, the solid phase changes directly into the gaseous phase

We are not modelling Molecular Dynamics, but use continuum description & SPH to represent the physics.

Wet Laser Cutting



t = 0.150 ms



SPH

Experiment

Backwall Damage Comparison

SPH free-surface applications

Turbulence Modelling

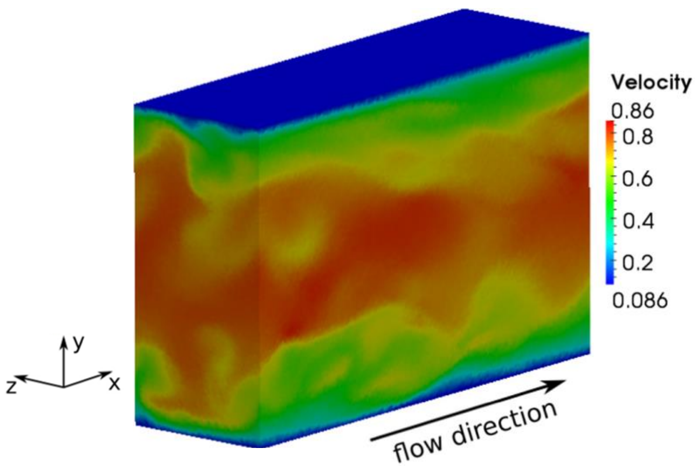
Mayrhofer et al. (2013, 2015)

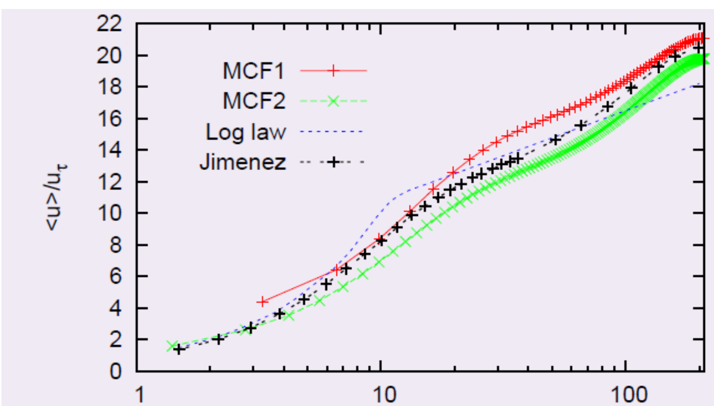
Even though we introduced compressible LES into SPH a decade ago, the random thermal motion is awkward and the wall boundary conditions are still proving difficult.

MANCHESTER 1824

Turbulence within SPH:

Quasi DNS, velocity average in streamwise direction: Re = 10,000



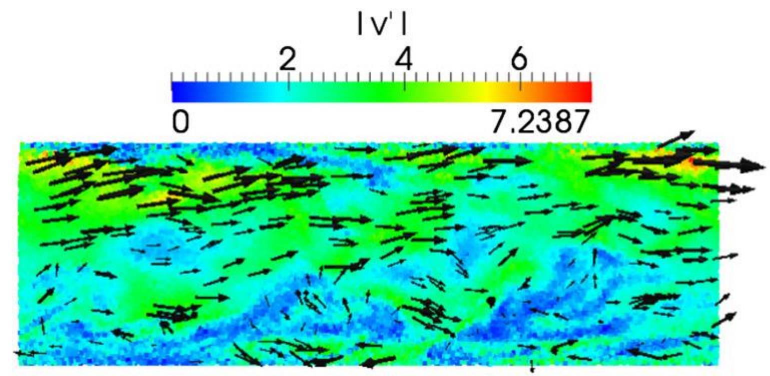


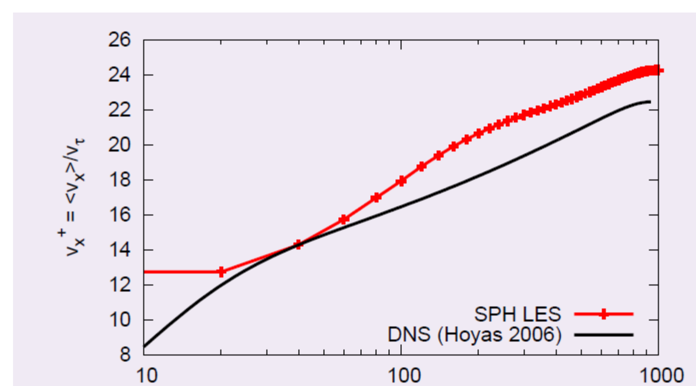
$y^+ = y\, u_\tau / \nu$

x component of velocity average $< u >$ (binning)

MCF = minimal channel flow

LES, velocity average in streamwise direction: $\mathrm{Re}_\tau = 1000$





$y^+ = y\, v_\tau / \nu$

x component of velocity average $\langle \underline{v} \rangle$

LES of channel flow at $Re_\tau = 1000$

SPH free-surface Applications

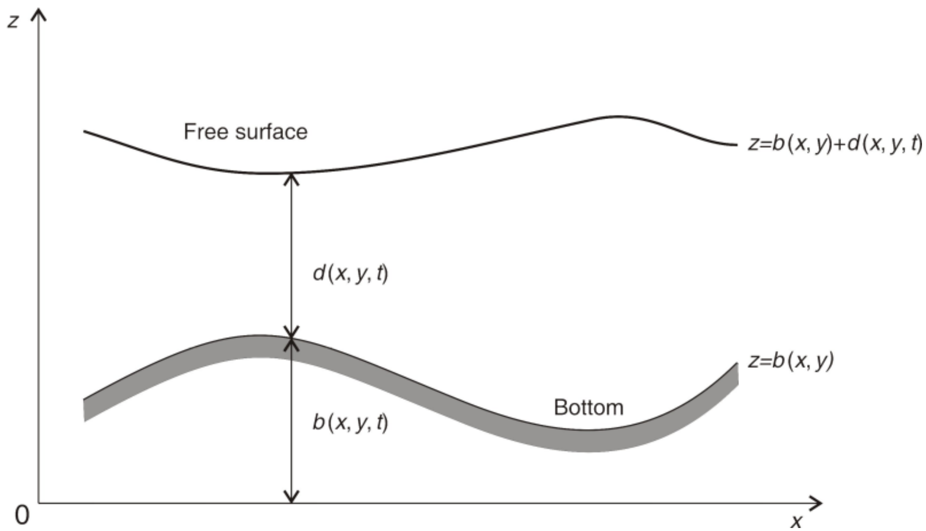
Application 7: Large-scale Flooding

Vacondio, Rogers & Stansby

(IJNMF 2010, 2011, 2013, JHE 2012, AWR 2014)

Larger-scale inundation Modelling with SPH

For modelling inundation, 3-D SPH is clearly too localised, but the shallow water equations allow us to model large areas



Shallow Water Equations

Non-conservative formulation of SWEs:

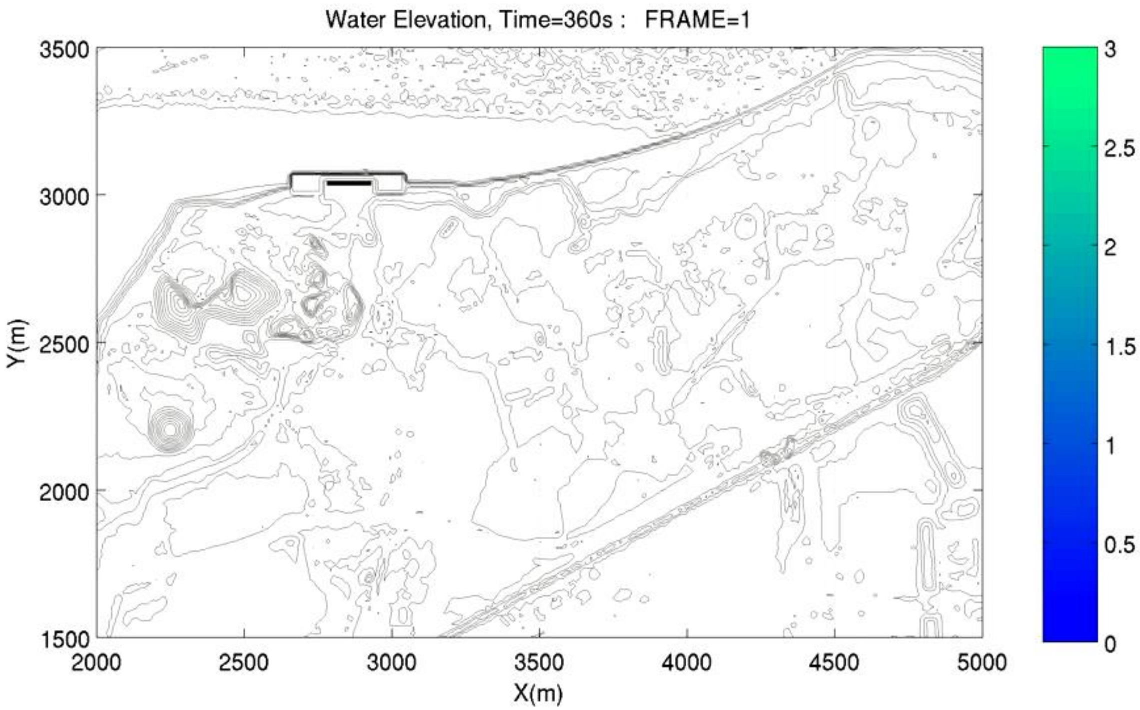
$$\frac{Dd}{Dt} = -d\nabla\cdot\mathbf{v}$$

$$\frac{D\mathbf{v}}{Dt} = -g\nabla d + g\left(\nabla b + S_f\right)$$

Different set of equations!

SPH is a methodology for solving any set of equations!!

Thamesmeade: Example Simulation



Improved Boundary Conditions (inlet/outlet)

Solid walls,

Particle refinement:

splitting & coalescing

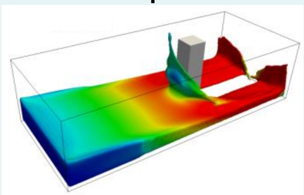
SWE-SPHysics

Flooding of Thamesmeade in the 1950s: Vacondio et al. (2012, JHE)

Click here for Movie

MaSC Highlights: Smoothed Particle Hydrodynamics (SPH)

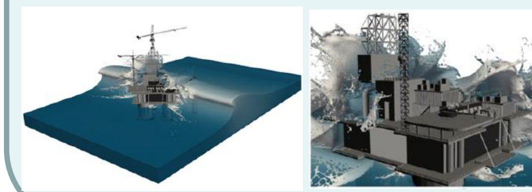
Development of SPH on GPUs with U-Vigo: DualSPHysics open source, **100x speedup** (millions of particles on your laptop!)



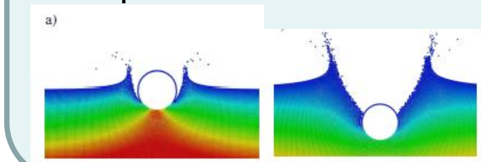
DualSPHysics

Development of Multi-GPU DualSPHysics with U-Vigo

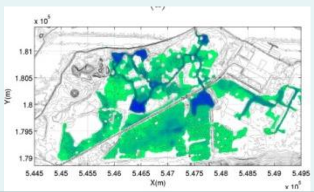
World's 1st 1-billion particle simulation on 64 GPUs



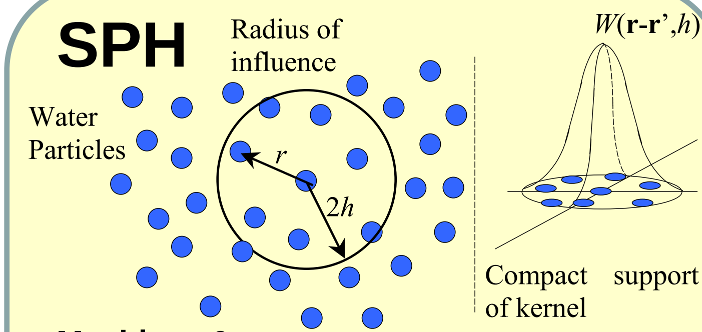
Development of World's 1st stabilised free-surface strictly incompressible SPH



Development with U-Parma of **World's 1st** open-source solver of Shallow Water equations with variable resolution SPH



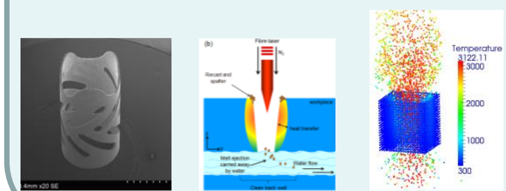
SPH



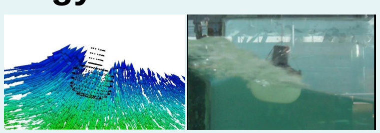
Meshless & nonlinear simulation technique

$$\langle A(\mathbf{r})\rangle \approx \sum_{j=1}^{N} A_j\, W(\mathbf{r}-\mathbf{r}_j, h)\frac{m_j}{\rho_j}$$

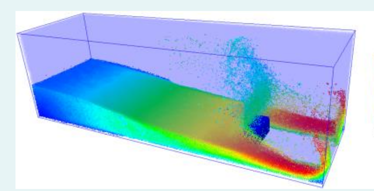
Development of World's 1st 3-phase laser cutting SPH model



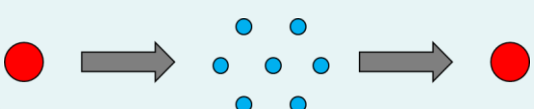
Application of SPH to **wave energy conversion**



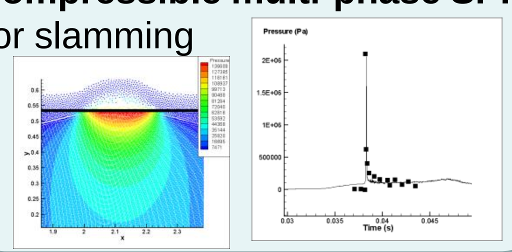
Development of **multi-phase air-water SPH on GPUs**



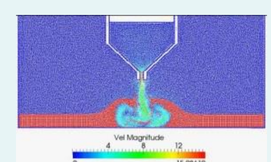
Development with U-Parma & BAE Systems of **rigorous** variable SPH resolution with splitting & merging



Development of **incompressible compressible multi-phase SPH** for slamming

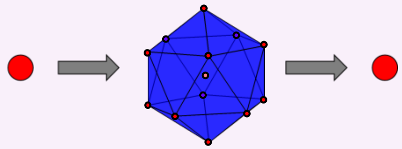


Development of **multi-phase soil-water SPH on GPUs**



Manchester SPH: New Developments & Possibilities

Development of 3-D dynamic particle refinement SPH on GPUs with U-Vigo & U-Parma using DualSPHysics



cpu gpu DualSPHysics

Development of SPH for **THERMAL HYDRAULIC FLOWS**

Development of SPH for **Non-Newtonian flows**

Development of higher-order convergence SPH

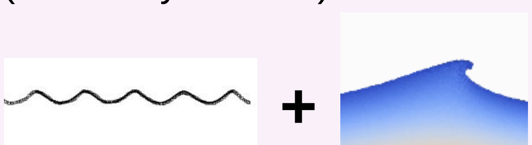
Development of SPH for **Bubbly flows**: intumescent paints & steel production

Development of SPH **Fluid-Structure Interaction (FSI)**

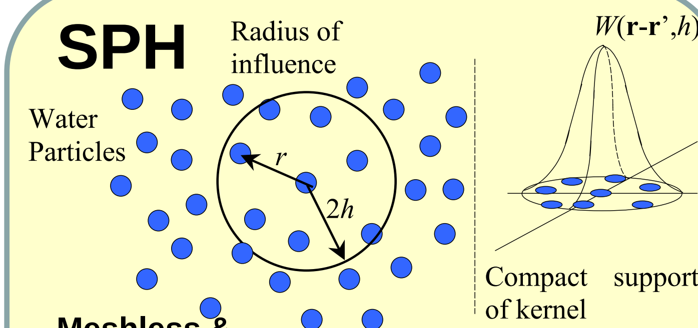
Froude Krylov forces; membranes

Development **COUPLING SPH with a far-field model** with City University

(funded by EPSRC)



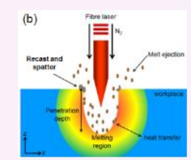
SPH



Meshless & nonlinear simulation technique

$$\langle A(\mathbf{r})\rangle \approx \sum_{j=1}^{N} A_j\, W\left(\mathbf{r}-\mathbf{r}_j, h\right)\frac{m_j}{\rho_j}$$

Development of 3-phase laser cleaning & keyhole processing SPH model



Application to Soil Erosion with University of Brasil for agriculture

(funded by EPSRC)

Development for granular flows and Hot Isostatic Pressing (HIP)

(funded by EPSRC NNUMAN)

Development of **multi-phase SPH for WELDING on GPUs**

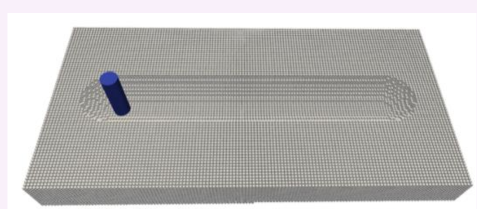
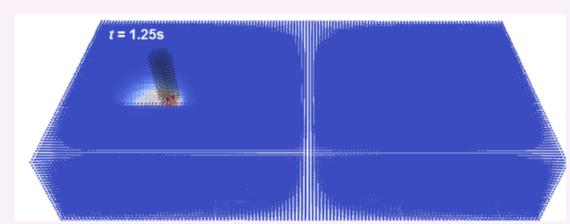


Figure 11: Initial particle layout to represent TG4 specimen.



Manchester MaSC SPH Group 2015

Lead Academic Staff

Dr Benedict Rogers

Prof. Peter Stansby

Dr Steve Lind

Collaborating Academic Staff

Prof. Dominique Laurence

Prof. Yong Wang

Dr Lee Cunningham

Dr Alistair Revell

Research Assistants

Dr Athanasios Mokos

Dr Georgios Fourtakas

Permanent Visitors

Dr Alex Crespo

Dr Jose Dominguez

Dr Renato Vacondio

Dr Xiaohu Guo (STFC)

Research Students

Burak Cirpici – just obtained PhD

Gede Pringgana

Abouzied Nasar

Antonios Xenakis

Ahmad Wael al-Shaer

Alex Chow

Sam Hunter

Annelie Baines

eDF

NATIONAL NUCLEAR LABORATORY

SPHERIC

International Research Initiative: http://wiki.manchester.ac.uk/spheric

- Founding member
- Steering Committee
- Webmaster (2005-2015)

-Chair (2015 -)

-10 International Workshops

-2016 in Munich

-Training Day

- 70 Institutions are members: universities, government research labs & industrial companies

DualSPHysics Users Workshop

Workshop origins

Workshop structure

MANCHESTER
1824

DualSPHysics Users Workshop

Origins:

- Since release, DualSPHysics has been downloaded 1000s times
- DualSPHysics website has a **users' forum** where a lot of questions get asked about how to use the code.
- We often get approached by both industrial companies & academic organisations who ask us one question repeatedly:

"Can SPH do this?"

Hmmm, we need a workshop!

Aims of Workshop:

- Hear how other users of DualSPHysics are using the code
- Hear the latest developments from the DualSPHysics team
- Give you an opportunity to make suggestions to help guide the future development of the DualSPHysics project.

Thank you

Acknowledgments

- U-Man: Abouzied Nasar, Alex Chow, George Fourtakas, A Mokos
- U-Vigo: Alex Crespo, Jose Dominguez, Moncho Gomez-Gesteira, Anxo Barreiro, Orlando Feal
- Flanders Hydraulics: Corrado Altomare
- U-Parma: Renato Vacondio
- U-Lisbon: Ricardo Canelas

Websites

- Free open-source Dual**SPHysics** code:
  http://www.dual.sphysics.org
- **SPHERIC** = SPH European Research Interest Community:
  http://wiki.manchester.ac.uk/spheric