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Damages and Matter ejection during HVI on brittle structures : Implications for Space Environment

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Presentation's overview

1. INTRODUCTION

2. Analysis impacted thin brittle targets : DDS & HST-CS

3. Experimental Characterisation of ejected matter

Fragments collection and high speed videos

4. Mechanical analysis of damages and SPH numerical simulations:

Simple thin SiO₂ targets vs. Multilayered HST solar cells

5. CONCLUSIONS & PROSPECTS

INTRODUCTION : Brittle materials & SD population

- **Growth suspicion of Space Debris population**

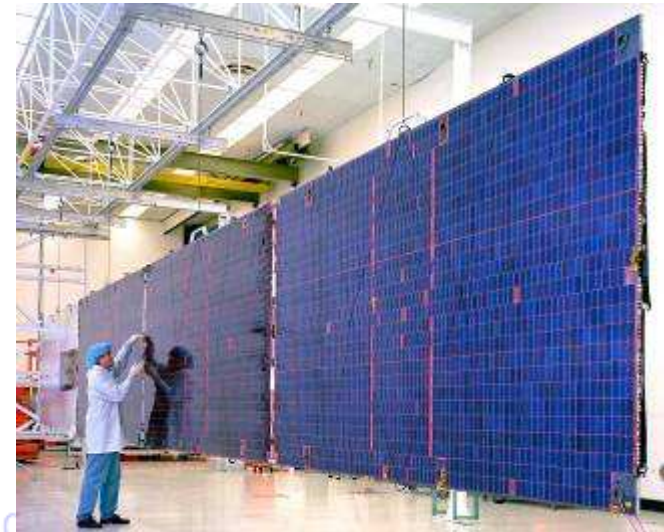
- ▶ Self generation processes (ejectas and spalls)
- ▶ Results from Hubble solar array post-flight analysis (Moussi et al, 2005) => Role of Secondary debris ?

- **Brittle materials behaviour under impact**

- ▶ Size of damages / Projectile's diameter
- ▶ Permanent densification / Spallation – big spalls
- ▶ Ejected Mass / Impacting Mass > 100

- **Use of brittle materials for Space Platforms**

- ▶ Optics
- ▶ Major constituents of **cells used for Solar arrays**
 - Protecting glass layers
 - Cell's materials
- ▶ Very Large area exposed to SD environment



⇒ Sensitivity of brittle materials to HVI added to their use for large solar panels exposed to the space environment might make them a non negligible Space Debris secondary source

Experimental facilities & Impacted targets

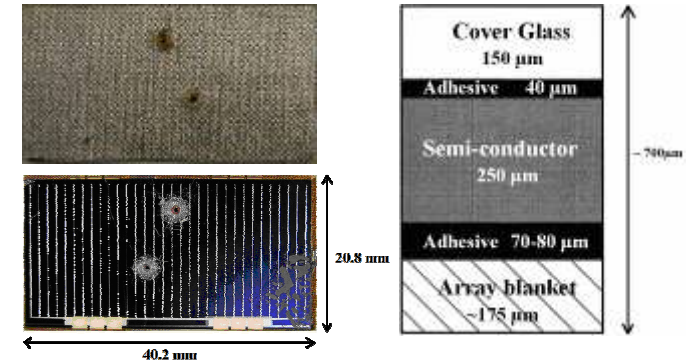
• Thin brittle Targets

▶ Disposable Debris Shield, DDS (CEA)

- 1.1 or 2mm Borofloat plates
- Role: Protection of 10mm Main Debris Shield from shrapnel resulting from Laser MegaJoule target disassembly

▶ Hubble Space Telescope Solar Cells, HST-CS (CNES/ONERA, ESA)

- 0.7mm multilayered structure
- Front-back & Front-top impacts



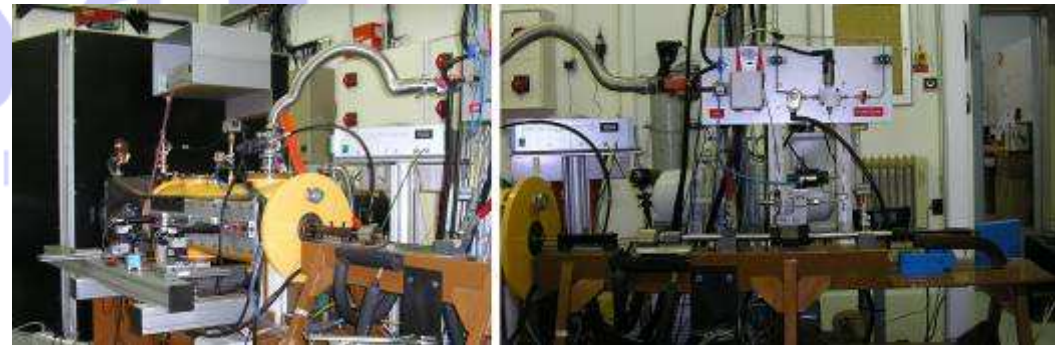
• Experimental facilities and Analysis procedure

▶ MICA double stage light gas gun (CEA)

- Projectiles : $\Phi < 2\text{mm}$
- Velocities : 800 – 4500 m/s
- This study: D=500μm Steel Spheres

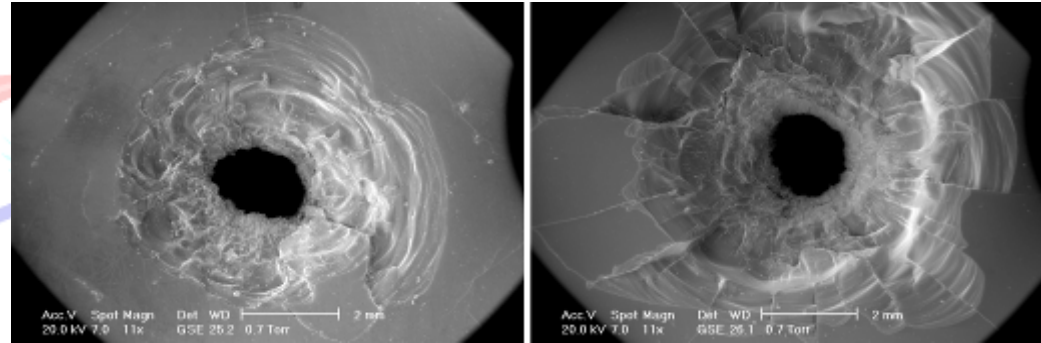
▶ Analysis procedure

- *Confocal & SEM microscopy*
- *Perthometer to compute ejected volume*
- *Coating and cutting*



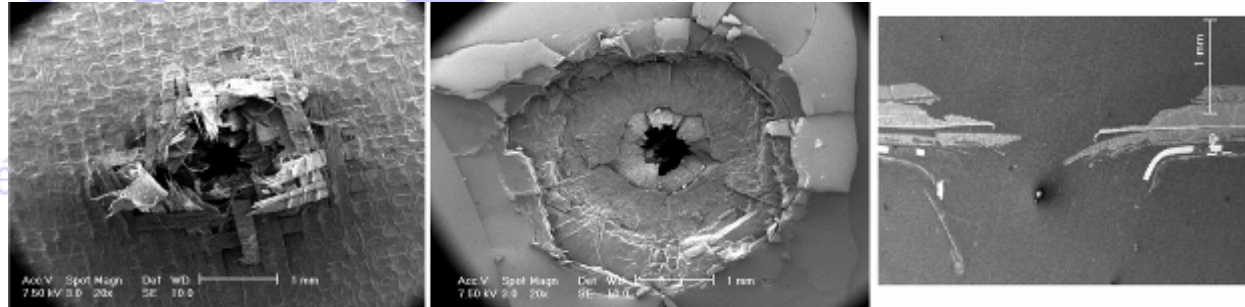
- **2mm Disposable Debris Shield, DDS (CEA)**

- ▶ Similar Damages for both faces:
 - Perforation hole or central pit
 - Shattered zone / fractured zone
 - Wide spallation zone / Radial cracks
- ▶ Shielding performances:
 - Ballistic Limit: $V \sim 1500$ m/s
 - Spallation Limit: $V \sim 1250$ m/s



- **Hubble Space Telescope Solar Cells, HST-CS (CNES/ONERA, ESA)**

- ▶ Impacts generating damages on the cover glass side of the solar cell
- ▶ **Front-Top morphologies**
 - Central pit with compacted cover glass
 - Wide spallation zone
- ▶ **Front-back morphologies**
 - No damages in the substrate
 - Wide spallation zone in the cover glass and/or the silicon layer

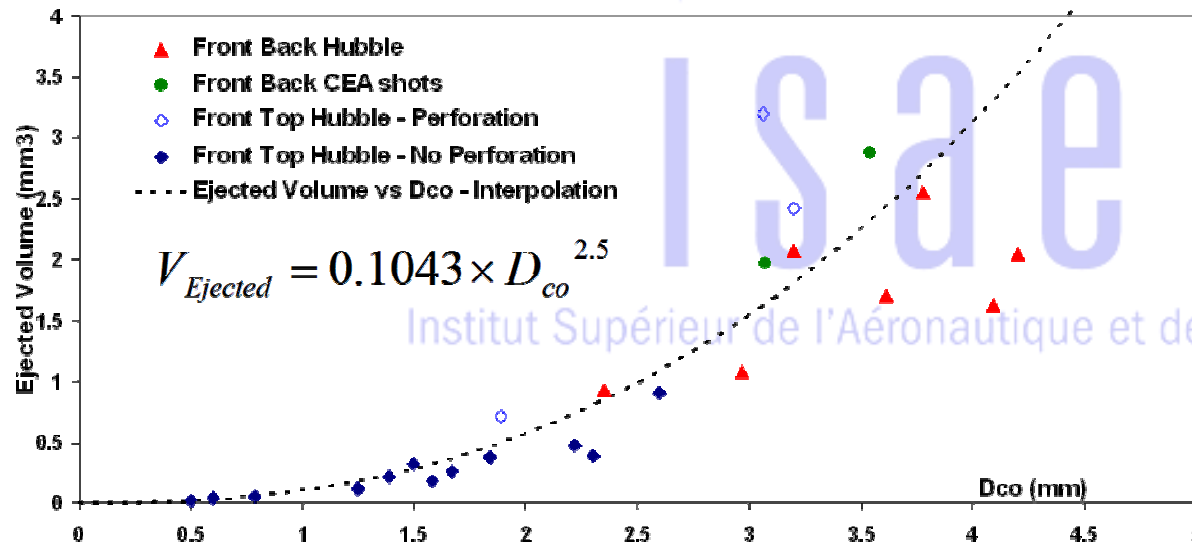


Ejected Volumes measurements

• 2mm Disposable Debris Shield : Importance of rear spallation

Impact velocity	1350 m/s	1900 m/s	2200 m/s	3010 m/s
Total ejected mass	48.8 mg (No-Perf)	73.1 mg (Perf)	95.3 mg (Perf)	122 mg (Perf)
% ejected mass due to rear spallation	68 %	59%	72 %	82 %
Mass Ratio	95.6	143.3	186.8	239.1
Volume ratio	338	507	660	845

• HST-CS Front-Top & Front-Back craters



Total number of major craters on Hubble solar arrays :

⇒ 494 FT / 508 FB

⇒ $V_{Ejected} \sim 0.1043 \times D_{co}^{2.5}$

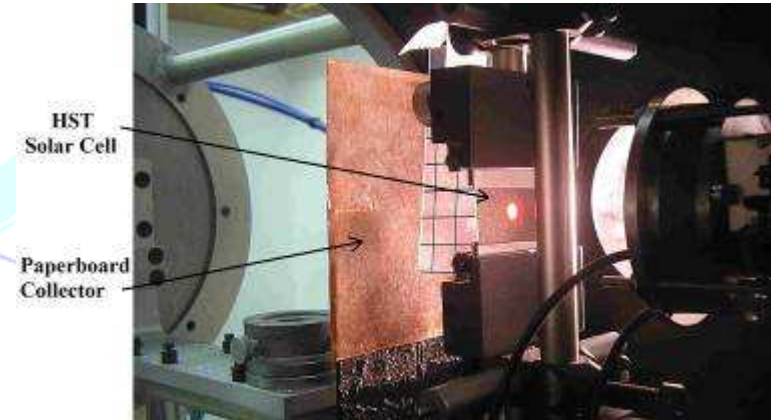
Total ejected volume for 5 year Exposure = ~ 1530 mm³

89% due to Front-back impacts

Corresponding number of $D=50\mu\text{m}$ Spheres = 20.000.000 objects !!!

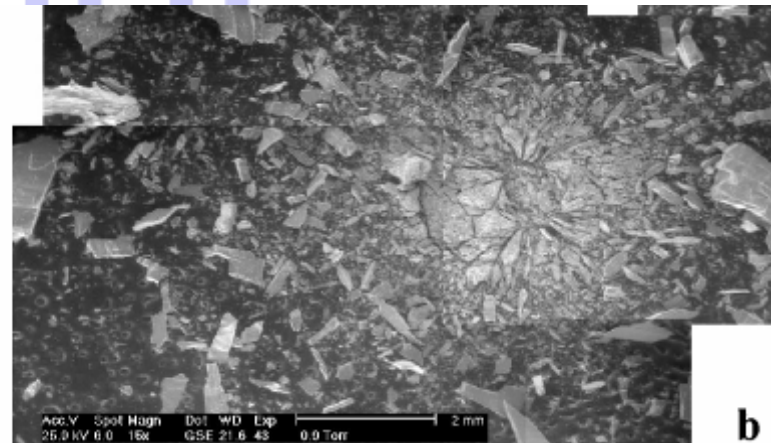
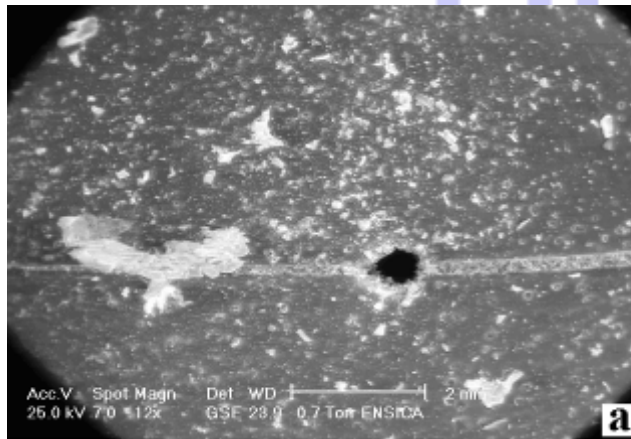
- Experimental setups

- ▶ Paperboards coated with adhesives
- ▶ Aerogel collectors
- ▶ Location: ~ 10cm behind an impacted target

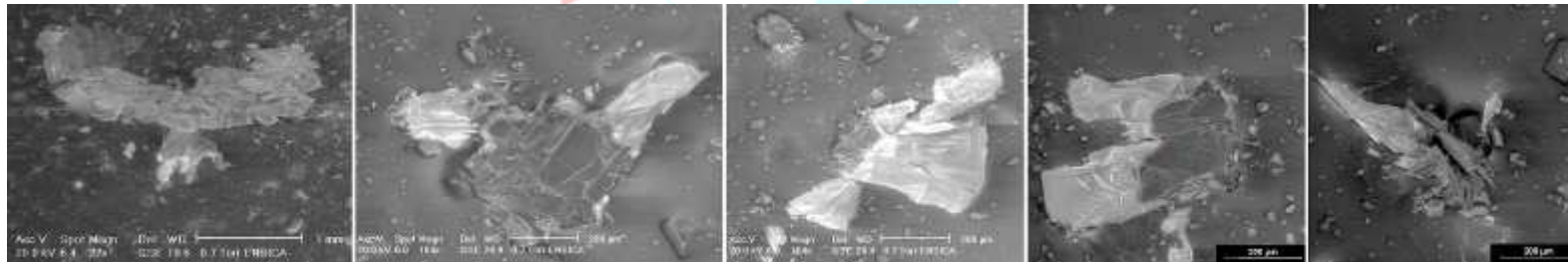


- Collected fragments clouds

- ▶ HST solar cell impacted at $V = 2.89$ km/s (a)
- ▶ 2mm DDS impacted at 3 km/s (b)

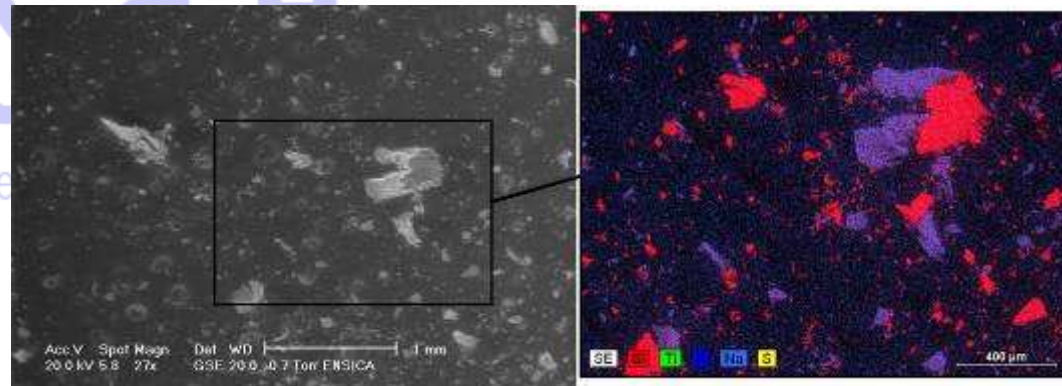


- Fragments generated behind an HST-CS (100mm^2 collector)
 - Collector perforated by Projectile (fragmentation?)
 - **6 major spalls** (Typical size $> 300\mu\text{m}$) & **70 spalls** (Typical size $> 150\mu\text{m}$)



‣ Fragments origin – Spectrometer analysis (Mapping mode)

- **Silicon fragments**
 - Numerous
 - Small fragments ($< 70\mu\text{m}$)
- **Glass spalls**
 - Big spalls ($> 100\mu\text{m}$)
 - 1 huge spall ($3 \times 1.5 \times 0.15\text{mm}$)
 - Remnant layer of silicon on many glass spalls



- Shot 52-05 and 55-05 – MICA Launcher – Video $\sim 12\mu\text{s} / \text{frame}$

- ▶ Target: 1.1mm Disposable Debris Shield (Borofloat glass)
- ▶ Projectile: Steel Sphere, $\Phi = 500\mu\text{m}$
- ▶ **Ejection phenomenology** :
 - Impact $\rightarrow 30\mu\text{s}$: High velocity jets – $V \sim 1000 \text{ m/s}$
 - $50\mu\text{s} \rightarrow 1\text{ms}$: Spalls clouds expansion – $V \sim 40 - 150 \text{ m/s}$
 - Incident impacts: Same ejection processes with \neq ejection angles



Shot 52-05 – $V \sim 3000\text{m/s}$ – $\alpha = 0^\circ$



Shot 55-05 – $V = 3140\text{m/s}$ – $\alpha = 15^\circ$

- Shot 56-05 – MICA Launcher – Video ($0 \rightarrow 1\text{ms}$; $\sim 12\mu\text{s} / \text{frame}$)

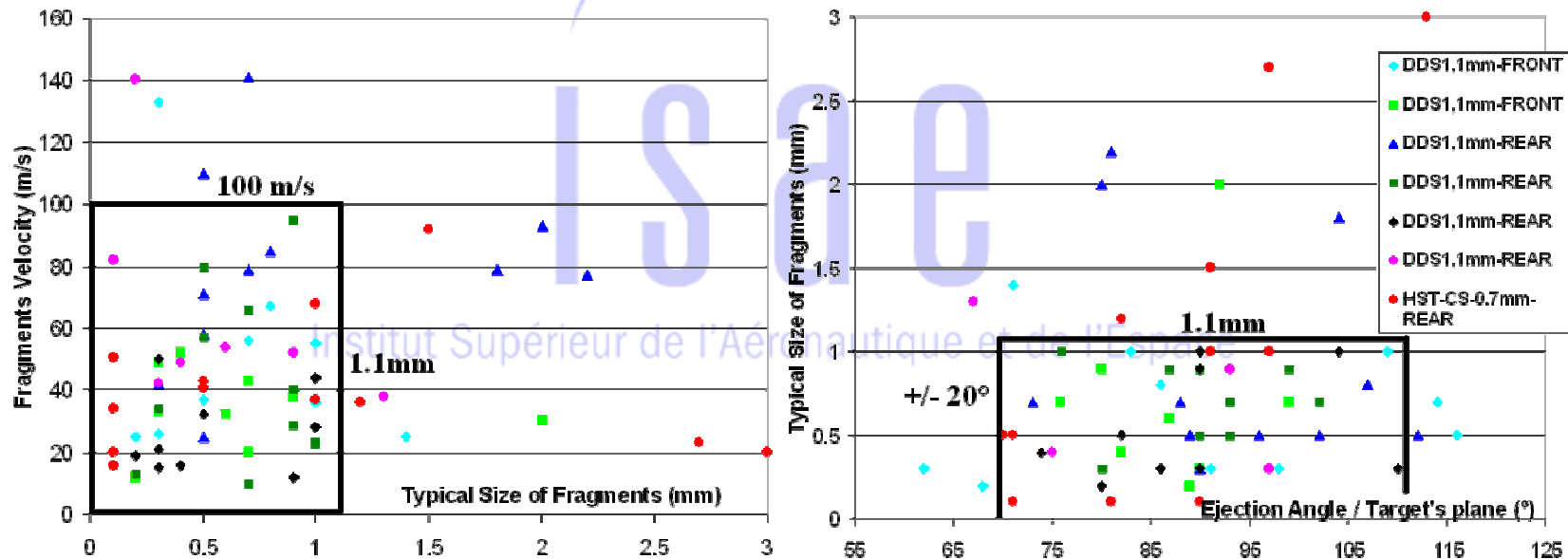
- ▶ Target: **0.7mm Hubble's solar cell – Front-back impact**
- ▶ Projectile: Steel Sphere, $\Phi = 500\mu\text{m}$ - Velocity = **2890 m/s**
- ▶ **Ejection phenomenology :**
 - Impact $\rightarrow 30\mu\text{s}$: High velocity jets – $V \sim 900\text{m/s}$
 - $30\mu\text{s} \rightarrow 1\text{ms}$: Spalls clouds expansion – $V \sim 100\text{m/s}$



- ⇒ **Similar ejection velocities / DDS**
- ⇒ **Less spalls (thinner target)**
- ⇒ **Unorganised spalls clouds**

• Spalls clouds analysis

- ▶ Size, velocity and ejection angle measurement of representative spalls
- ▶ No considerations on spalls number
- ▶ **Principal characteristics of ejected spalls**
 - Size : 100µm to 1.1mm (maximal dimension)
 - Velocity: 0 – 100m/s
 - Ejection angle / impact axis: +/- 20°
 - DDS / HST-CS: unorganised spalls clouds for HST-CS, no clear size's distribution)



Shock Response of brittle structures

- **Dynamic behaviour of glasses under intense shock loadings & Material Modelling**
 - ▶ **Compressive behaviour – Modified JH-2 material model**
 - Elastic behaviour under HEL (Hugoniot Elastic Limit)
 - Fragmentation and densification above HEL
 - Isotropic damage above HEL for compressive fragmentation
 - Polynomial EOS with permanent densification effects for compression and releases
 - ▶ **Tensile behaviour – Tensile failure criterion**
 - Principal stress criteria with tensile deactivation of SPH particles
 - ▶ **Material model Validation**
 - Compressive behaviour validated for Explosives testing & flyer plates impacts $P \rightarrow 35\text{GPa}$ (CEA-CESTA)
 - Ability to model 1D spallation
 - Validation for Fused Silica and Pyrex Glass
- **Shock propagation in a multilayered structure: application to solar cells**
 - ▶ Role of involved material
 - ▶ 3 layers simplification: *Substrate (composite + adhesive) / Semi conductor (Silicon) / CMX cover glass*
 - ⇒ **Tensile loadings due to rarefaction waves propagating into HST-CS coming from:**
 - CMX coverglass free surface
 - Si/CMX interface
 - ⇒ **High pressure levels reached into Silicon layer due to its high shock impedance**
 - ▶ Role of adhesives layers ?

- **Mesh, boundary conditions and material model**

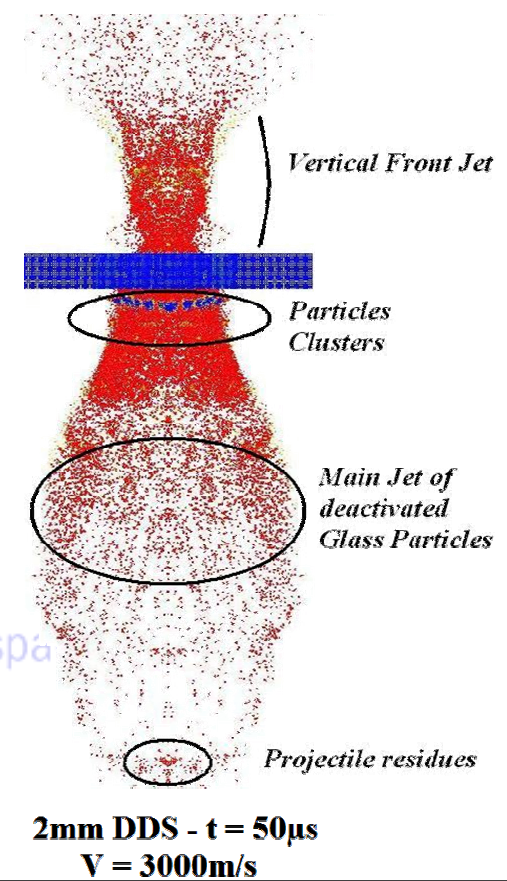
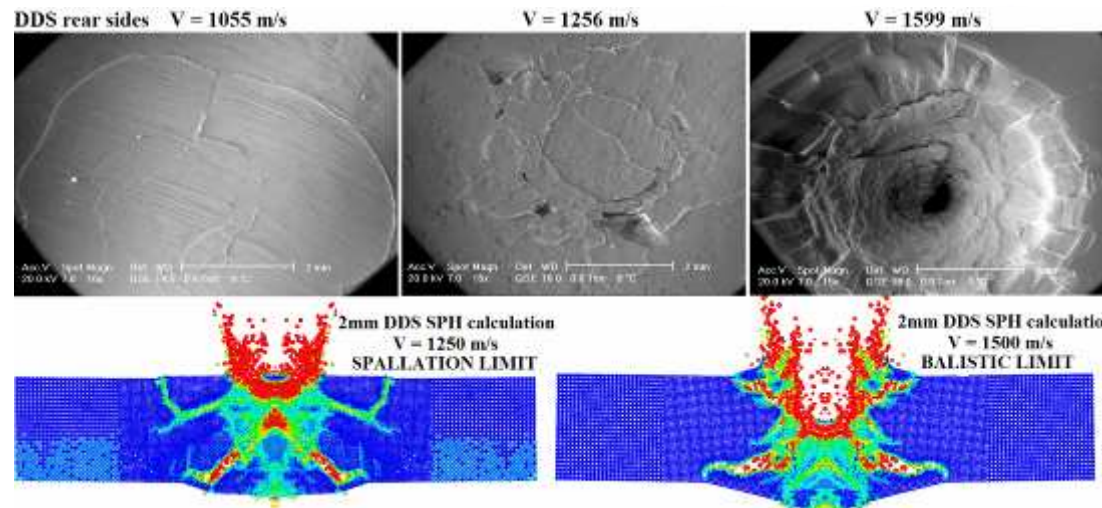
- ▶ 2 mm DDS (210.000 particles) – Modified JH-2 material model (Fused silica data set)
- ▶ Steel Spherical projectile (544 particles) – Steinberg-Guinan material model + Mie-Gruneisen EOS
- ▶ Normal impacts with 2 symmetry planes
- ▶ Velocity range: 800 to 4000m/s

- **Damages & Shielding performances**

- ▶ Ballistic limit (1500m/s) & spallation limit (1250m/s)
- ▶ Spalled diameters (err% < 12% until ballistic limit)

- **Prediction capabilities for matter ejection**

- ▶ High velocity clouds of deactivated particles
- ▶ Clusters of active particles

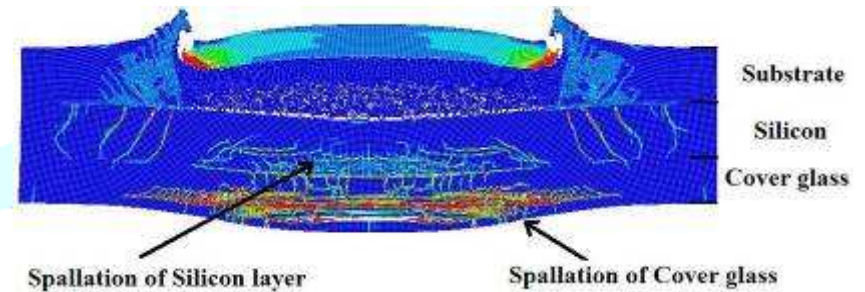


- 2D SPH calculations

- ▶ Analysis of stacking effects on potential spallation effects
- ▶ 150µm Al projectile, $V = 1000\text{m/s}$, HST 3 layers (Si & CMX modelled with JH-2-HVI)

- ⇒ **Silicon & cover glass layers are submitted to intense tensile loadings**
- ⇒ **Bigger spalls in the cover glass**

Note: Necessity to identify the behaviour of Silicon under shock intense shock loadings...

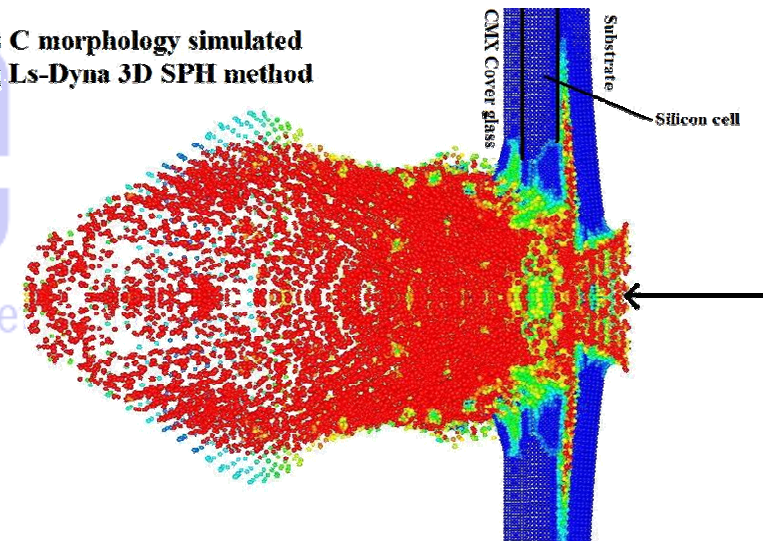


- Preliminary 3D SPH calculations

- ▶ 700µm 3 layers solar cell (Al / Si / SiO2)
- ▶ Model: 185.000 particles
- ▶ $D=300\mu\text{m}$ Spherical Aluminium Projectile
- ▶ Velocity range: 500 to 4000m/s

- ⇒ **Ability to reproduce class C morphologies with hole in substrate and spallation of Si and CMX layers**
- ⇒ **As for DDS, both high velocity jets and spalls have been reproduced**

Class C morphology simulated using Ls-Dyna 3D SPH method



Conclusions & Prospects

• CONCLUSIONS

- ▶ **Front-Back impacts** causing **spallation** of cell's **brittle layers** are the most damaging for the space environment: 90% of total ejected mass from HST arrays due to FB impacts
- ▶ **Characterisation of ejected matter**
 - Small Silicon fragments due to cell's confinement
 - Bigger glass spalls due to spallation phenomenon of the protecting glass
- ▶ **Meshless numerical methods** coupled to adapted material models provide interesting results for simple brittle targets
 - Damages and Shielding performances of DDS + Ejection tendencies conform with experiment
 - Encouraging preliminary results for damages on 3 layers simplified Silicon cell

• FUTURE WORK

- ▶ **Experimental study of solar cells new generation**
 - Germanium vs silicon cells
 - Substrate (carbon/Honeycomb) and potential channelling of projectile residues
 - Sticking conditions
- ▶ **Numerical simulations**
 - 2D analysis of stacking and sticking effects on loading conditions seen by the target
 - Improvements of 3D SPH simulations of HVI on simplified solar cells structures
- ▶ ***Post collection analysis of aerogel collectors using 3D X-rays tomography***

HVI on Brittle Structures : Implications for Space Environment



Any Questions ?

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