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

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Presentation's overview

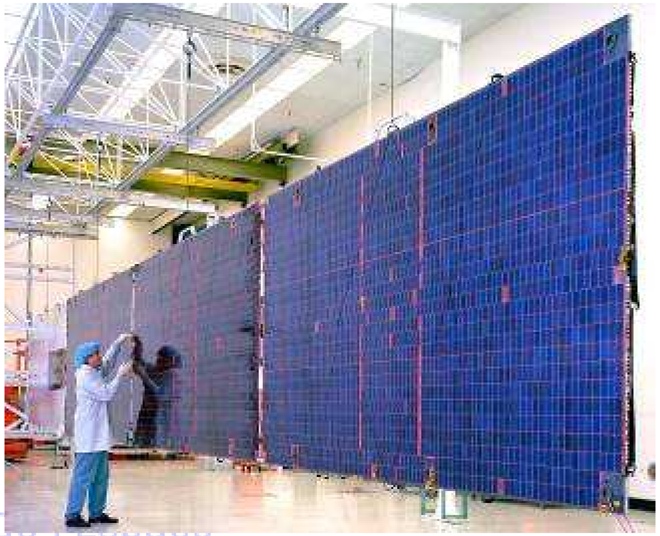
1. **INTRODUCTION**
2. **Analysis impacted thin brittle targets : DDS & HST-CS**
3. **Experimental Characterisation of ejected matter**
   Fragments collection and high speed videos
4. **Mechanical analysis of damages and SPH numerical simulations:**
   Simple thin SiO2 targets vs. Multilayered HST solar 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**

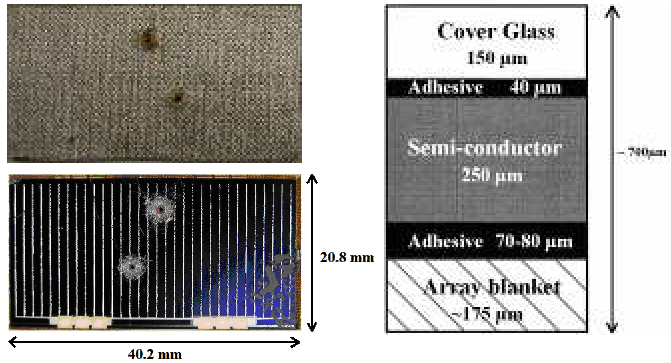
- ***Use of brittle materials for Space Platforms***
  - Optics
  - Major constituents of **cells used for Solar arrays**
    - Protecting glass layers
    - Cell's materials
  - Very Large area exposed to SD environment



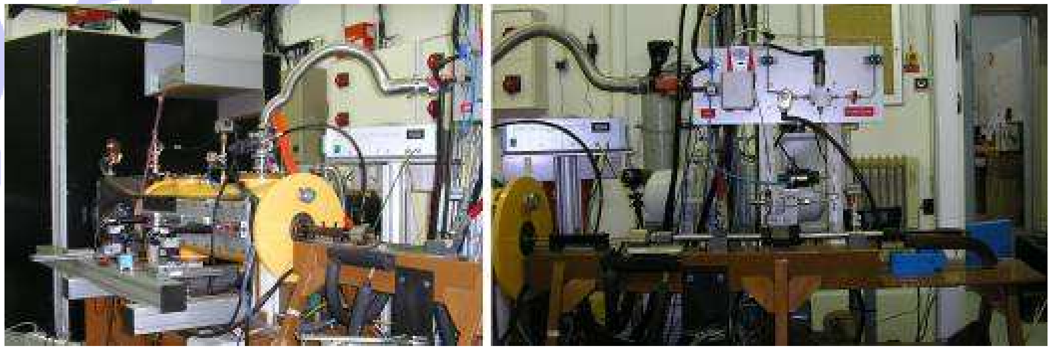
⇒ Sensitivity of brittle materials to HVI added to their use for large solar panels exposed to the space environment might make them a non negligible Space Debris secondary source

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 shrapnels 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

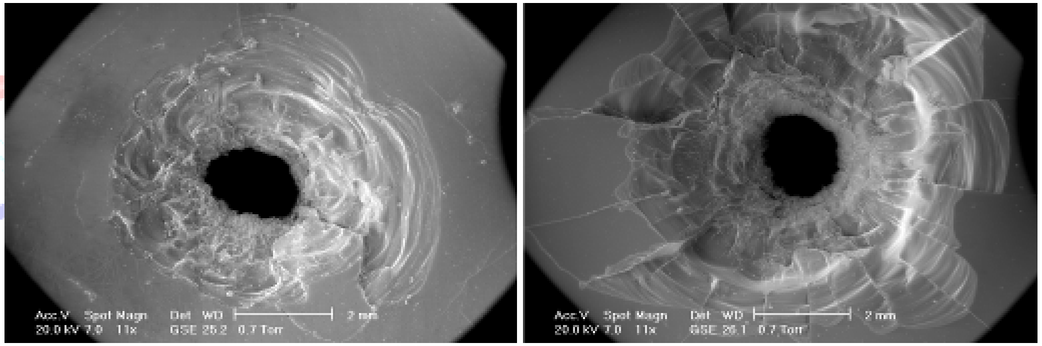


- **Experimental facilities and Analysis procedure**
  - MICA double stage light gas gun (CEA)
    - Projectiles : Φ < 2mm
    - Velocities : 800 – 4500 m/s
    - *This study:* D=500µm Steel Spheres
  - Analysis procedure
    - *Confocal & SEM microscopy*
    - *Perthometer to compute ejected volume*
    - *Coating and cutting*

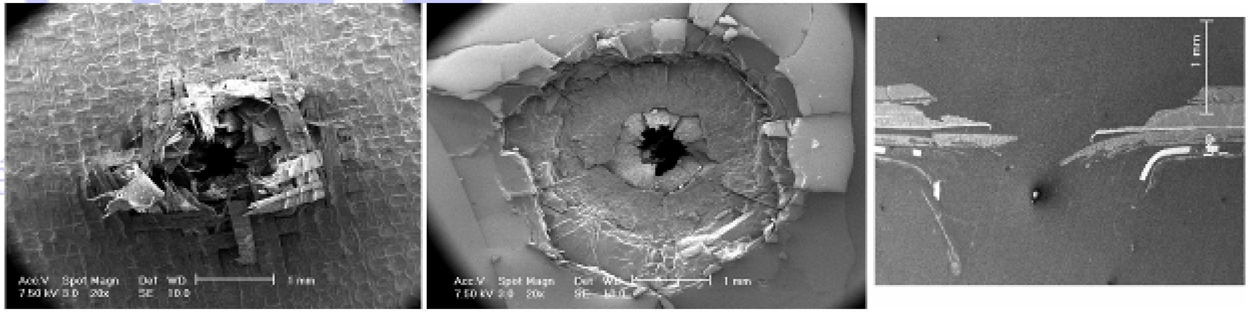


Craters analysis : 2mm DDS & 0.7mm HST-CS

- **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 ~ 1500 m/s
    - Spallation Limit: V ~ 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



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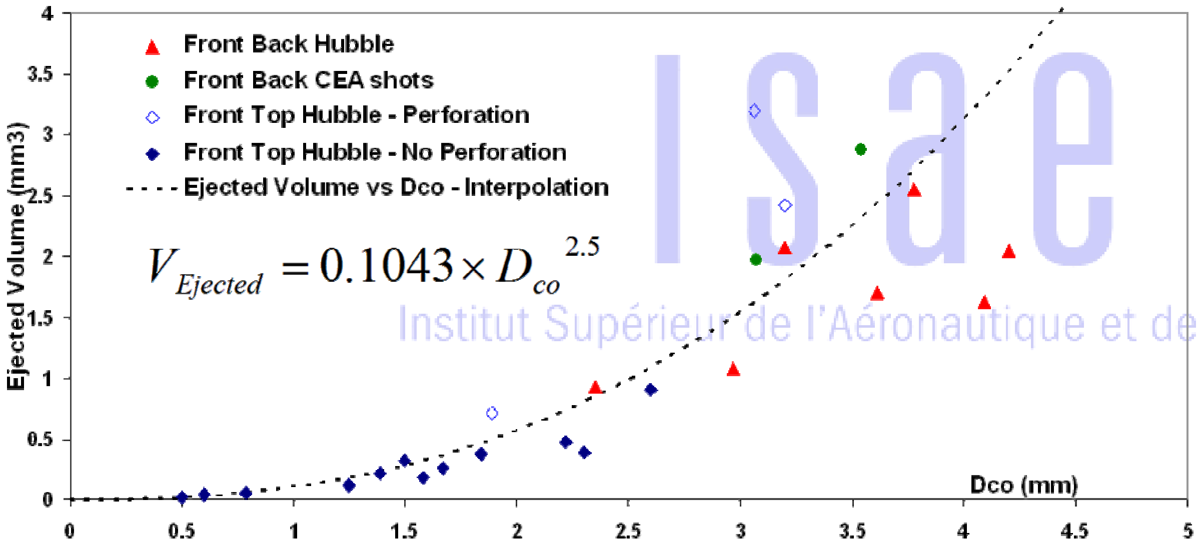
Ejected Volumes measurements

- **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*
- ⇒ *VEjected ~ 0.1043 x Dco* $^{2.5}$

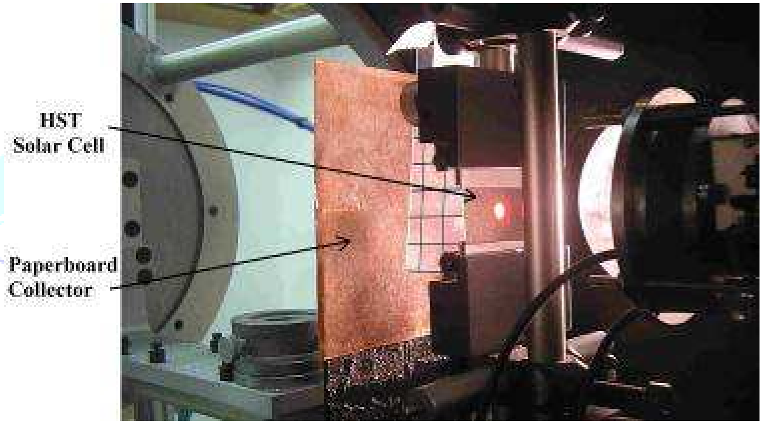
Total ejected volume for 5 year Exposure = ~ 1530 mm³

89% due to Front-back impacts

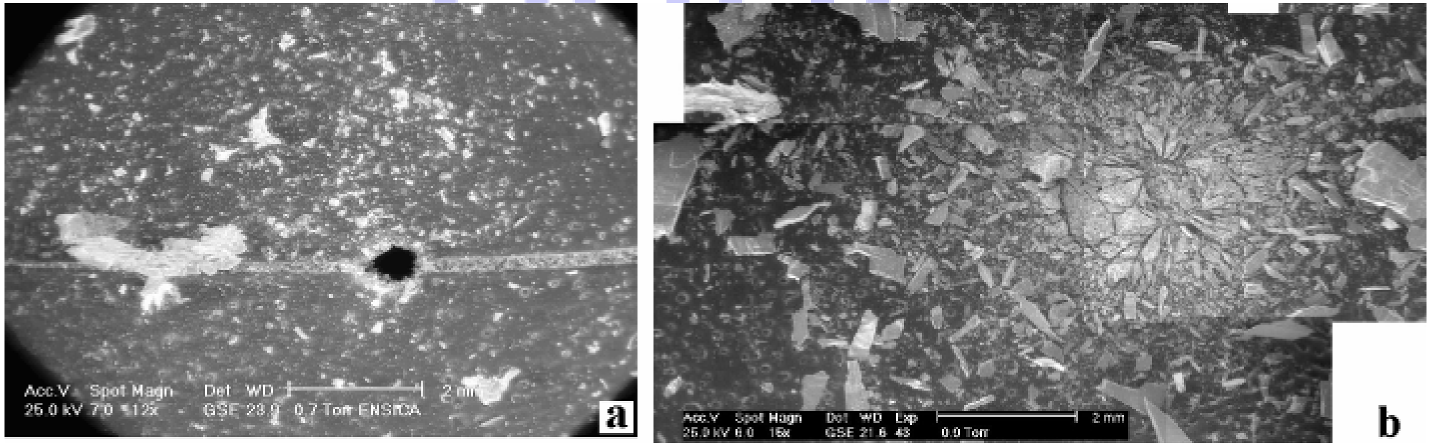
Corresponding number of D=50µm Spheres = 20.000.000 objects !!!

Passive collection of ejected fragments

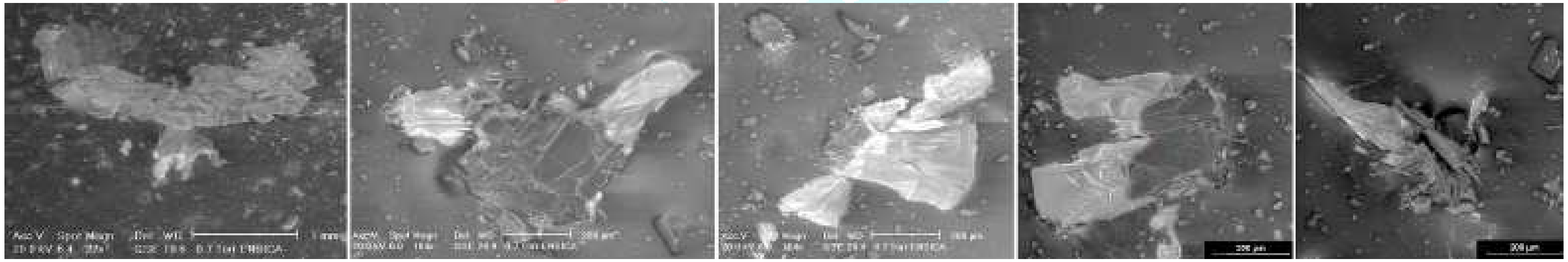
- Experimental setups
  - Paperboards coated with adhesives
  - Aerogel collectors
  - Location: ~ 10cm behind an impacted target



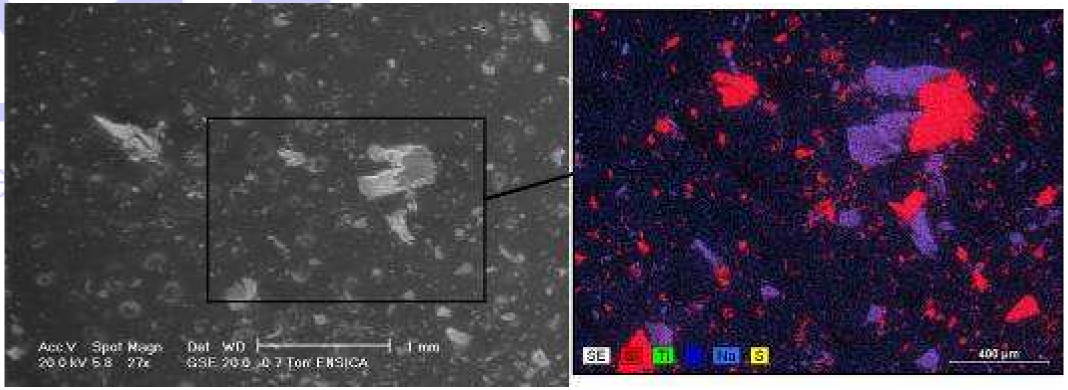
- Collected fragments clouds
  - HST solar cell impacted at V = 2.89 km/s (a)
  - 2mm DDS impacted at 3 km/s (b)



- Fragments generated behind an HST-CS *(100mm² collector)*
  - Collector perforated by Projectile (fragmentation?)
  - **6 major spalls** (Typical size > 300µm) & **70 spalls** (Typical size > 150µm)



  - **Fragments origin – Spectrometer analysis (Mapping mode)**
    - **Silicon fragments**
      - Numerous
      - Small fragments (<70µm)
    - **Glass spalls**
      - Big spalls (>100µm)
      - 1 huge spall (3 x 1.5 x 0.15mm)
      - Remnant layer of silicon on many glass spalls



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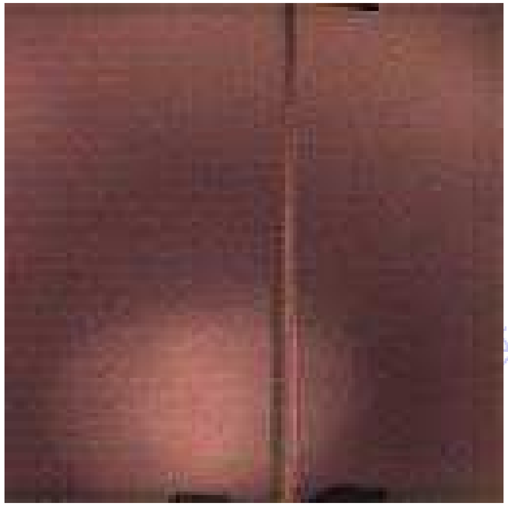
- Shot 52-05 and 55-05 – MICA Launcher – Video *~12µs / frame*
  - Target: **1.1mm Disposable Debris Shield (Borofloat glass)**
  - *Projectile:* Steel Sphere, Φ = 500µm
  - ***Ejection phenomenology :***
    - *Impact → 30µs: High velocity jets – V ~ 1000 m/s*
    - *50µs → 1ms: Spalls clouds expansion – V ~ 40 - 150 m/s*
    - *Incident impacts: Same ejection processes with ≠ ejection angles*

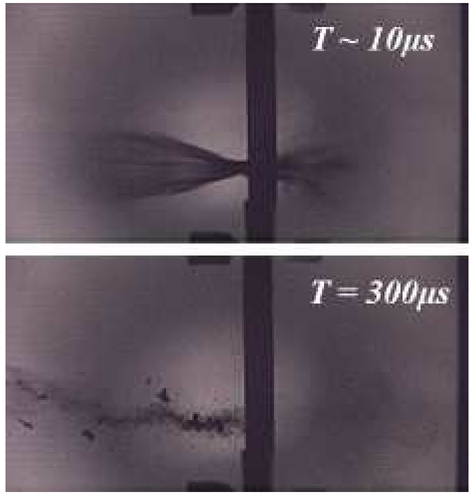


Shot 52-05 – V ~ 3000m/s – α = 0°

Shot 55-05 – V = 3140m/s – α = 15°

High Speed Videos 2/3

- Shot 56-05 – MICA Launcher – Video (*0→1ms; ~12µs / frame)*
  - Target: **0.7mm Hubble's solar cell – Front-back impact**
  - *Projectile:* Steel Sphere, Φ = 500µm - Velocity = **2890 m/s**
  - ***Ejection phenomenology :***
    - *Impact → 30µs:* *High velocity jets – V~900m/s*
    - *30µs → 1ms:* *Spalls clouds expansion – V~100m/s*



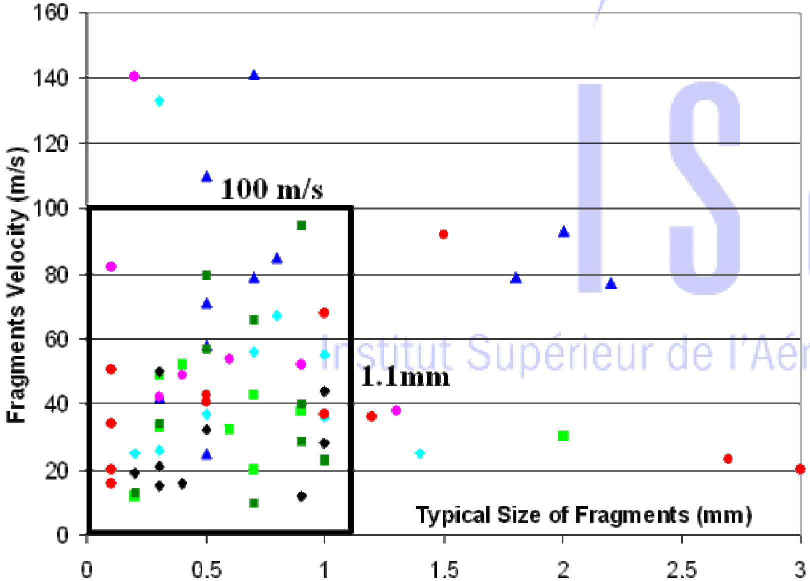
⇒ ***Similar ejection velocities / DDS***

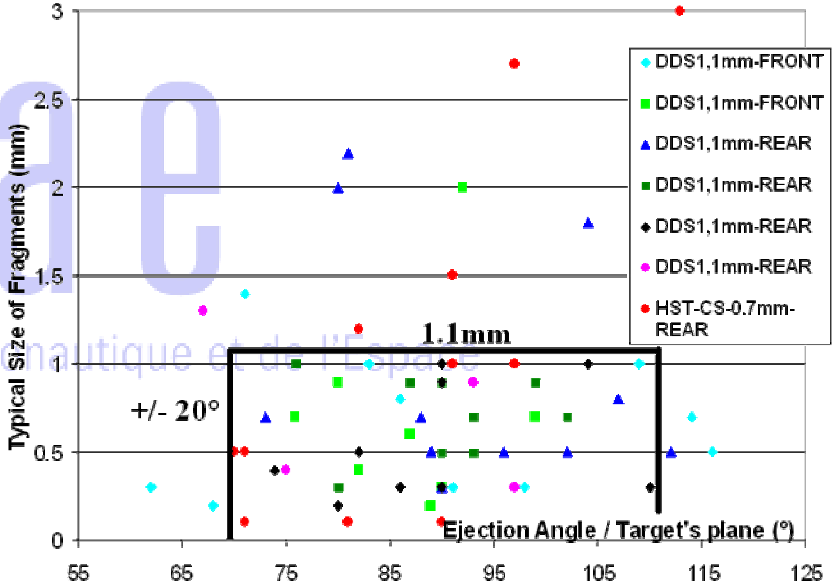
⇒ ***Less spalls (thinner target)***

⇒ ***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)





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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 → 35GPa (CEA-CESTA)
    - Ability to model 1D spallation
    - Validation for Fused Silica and Pyrex Glass

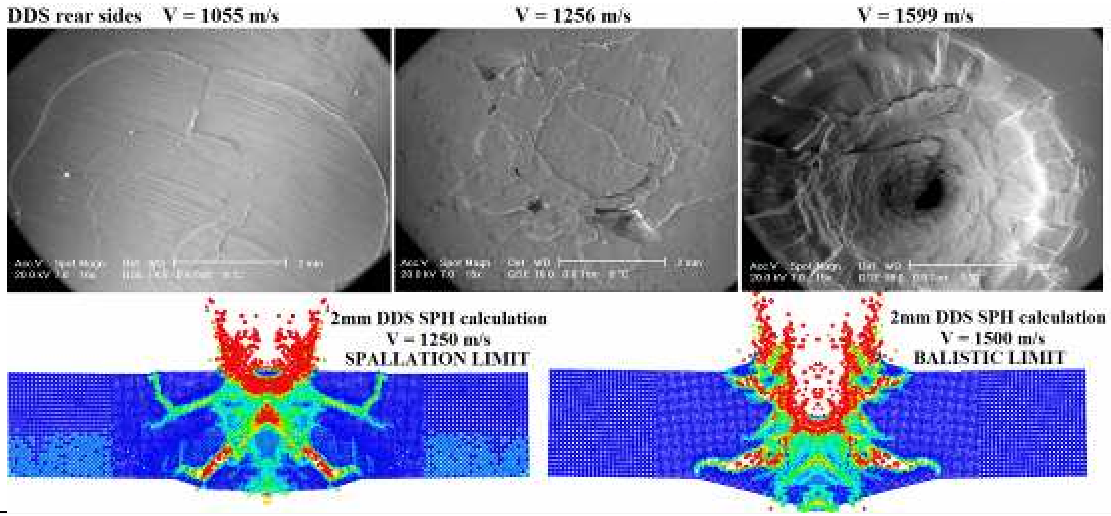
- **Shock propagation in a multilayered structure: application to solar cells**
  - Role of involved material
  - 3 layers simplification: *Substrate (composite + adhesive) / Semi conductor (Silicon) / CMX cover glass*

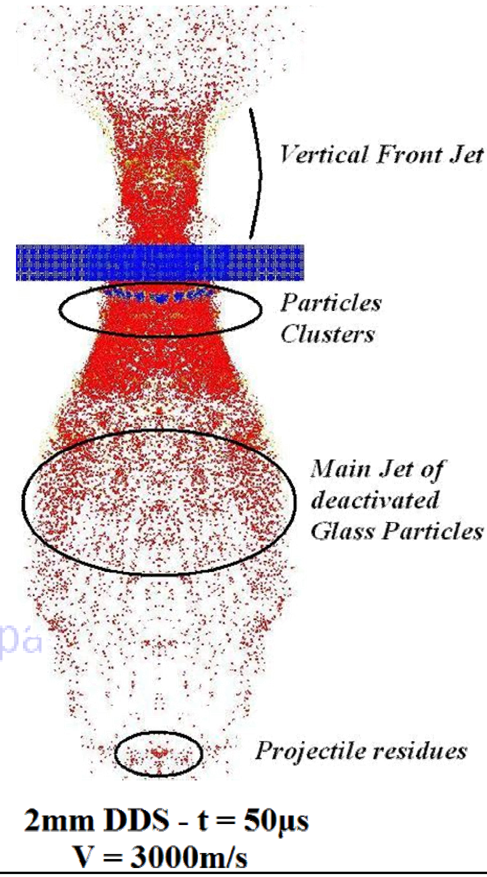
    ⇒ **Tensile loadings due to rarefaction waves propagating into HST-CS coming from:**
    - CMX coverglass free surface
    - Si/CMX interface

    ⇒ **High pressure levels reached into Silicon layer due to its high shock impedance**
  - Role of adhesives layers ?

3D SPH Numerical Simulations – 2mm DDS

- **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





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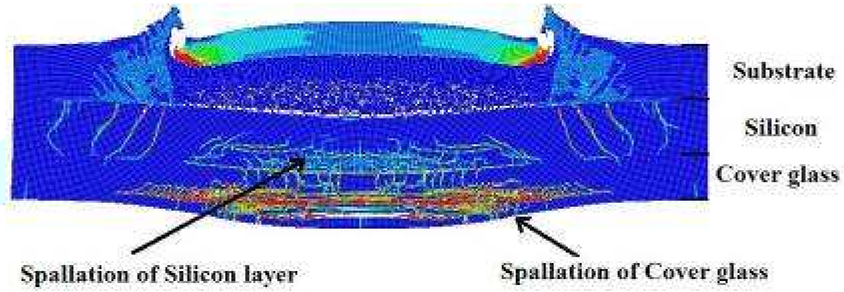
- 2D SPH calculations
  - Analysis of stacking effects on potential spallation effects
  - 150µm Al projectile, V = 1000m/s, HST 3 layers (Si & CMX modelled with JH-2-HVI)

⇒ **Silicon & cover glass layers are submitted to intense tensile loadings**

⇒ **Bigger spalls in the cover glass**

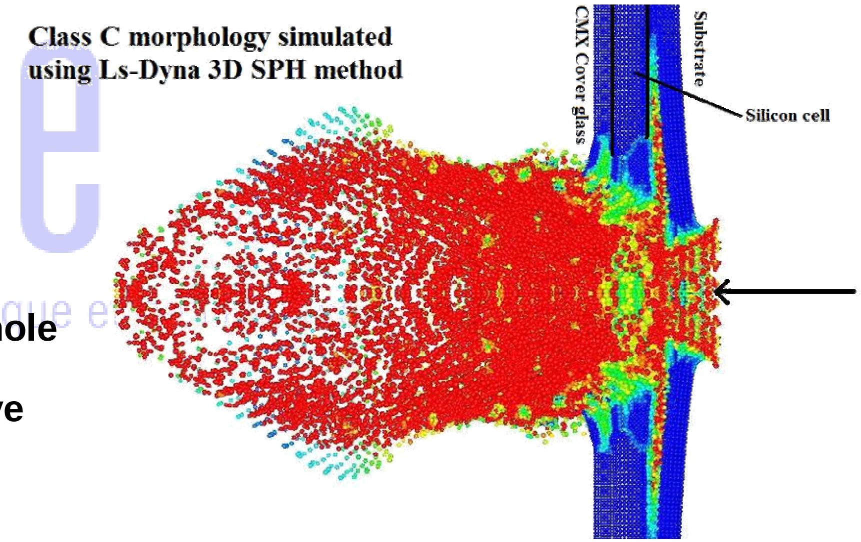
Note: Necessity to identify the behaviour of Silicon under shock intense shock loadings…



- Preliminary 3D SPH calculations
  - 700µm 3 layers solar cell (Al / Si / SiO2)
  - Model: 185.000 particles
  - D=300µm Spherical Aluminium Projectile
  - Velocity range: 500 to 4000m/s

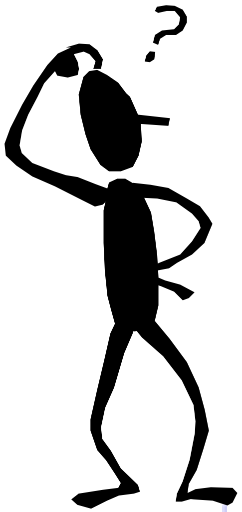
⇒ **Ability to reproduce class C morphologies with hole in substrate and spallation of Si and CMX layers**

⇒ **As for DDS, both high velocity jets and spalls have been reproduced**



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***



Any Questions ?

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