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MODELING OF A STRIP LINE GENERATOR FOR ISENTROPIC COMPRESSION EXPERIMENTS*

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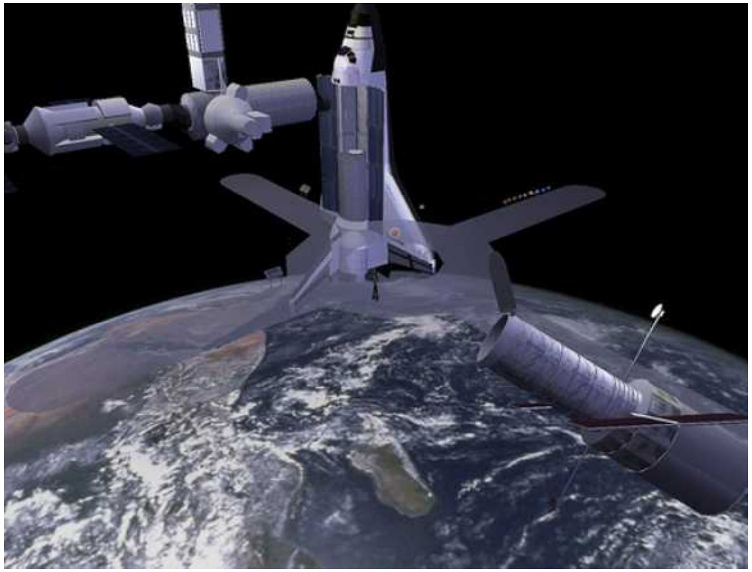
Outline

- Motivation and importance of high pressure shock compression of solids
- Description of Veloce, an electrical pulser for isentropic compression and shock physics experiments
- Description and validation of simulations
- Modeling results and future improvement
  - Current density uniformity
  - Current diffusion across the thickness of the panel
  - Effect of the peaking capacitors
- Conclusions

1) Motivation and importance of high pressure shock compression of solids

Motivation of High-Pressure Shock Compression of Solids

- High velocity impact interest is relatively new:
  - Outgrowth of World War II research
  - Critical to manned space flight
- Well-controlled impact studies to understand material response to intense dynamic loading
- Gas gun experiments:
  - Hypersonic aerodynamic phenomena associated with atmospheric reentry of space-travelling vehicles, including aero thermal phenomena
  - Armor systems for protecting space vehicles from natural meteoroid impacts and from similar encounters with man-made particles



Gun Technology & Advanced Diagnostics is Used Extensively for Weapon Science and Shock Physics

Courtesy of Bill Reinhart

Propellant Gun

~2 km/s
~1 Mbar

Single Stage Gun

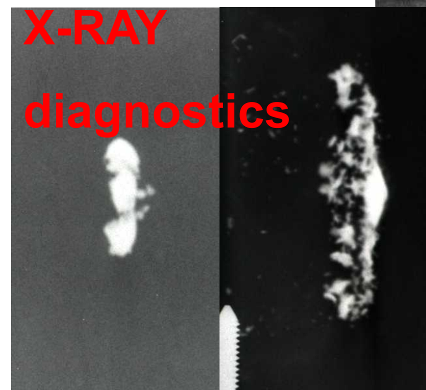
~1 km/s
~300 kbar

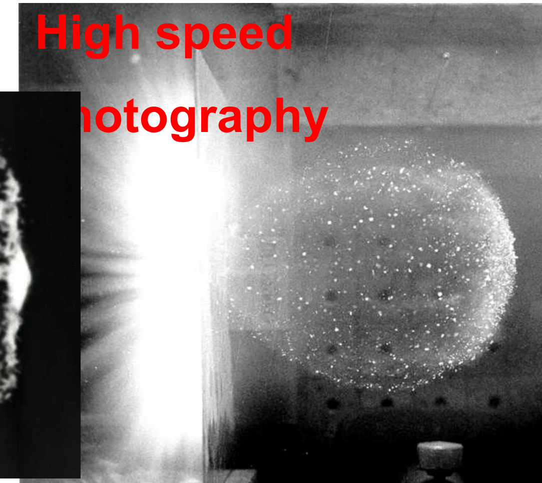
Two-Stage Gun

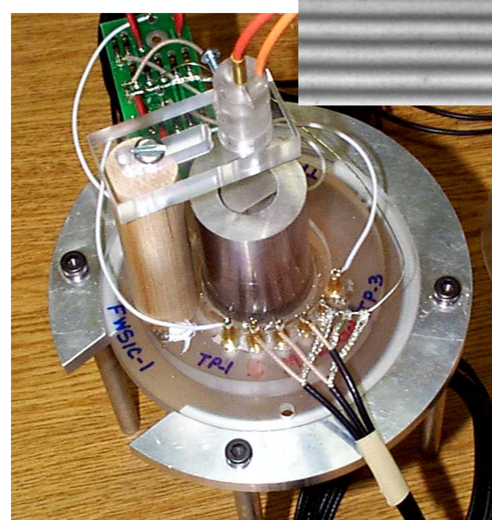
~8 km/s
~7 Mbar

Hypervelocity Launcher, HVL

~16 km/s
~20 Mbar



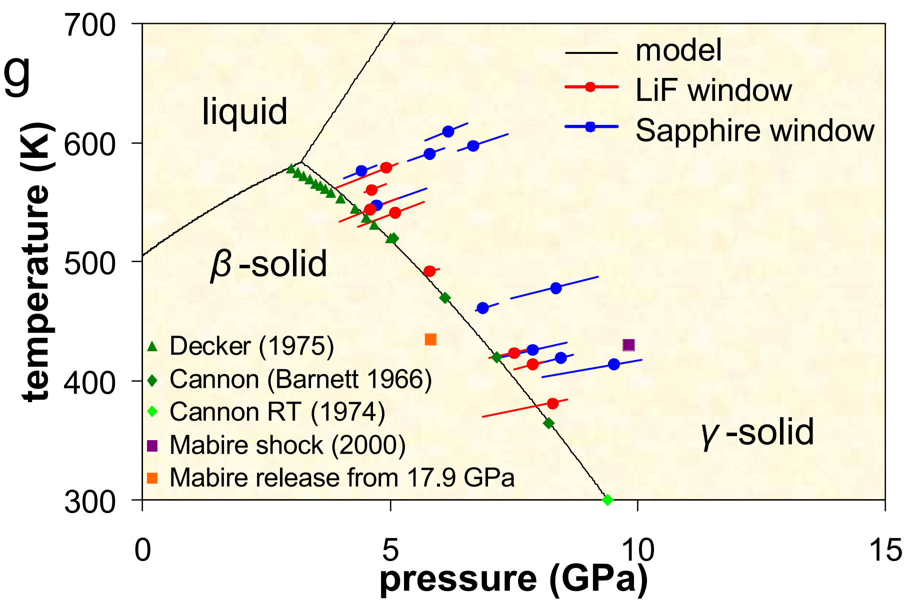




Electronic diagnostics

Motivation of High-Pressure Shock Compression of Solids

- The complete Equation of State (EOS) plays a fundamental role in these studies by specifying the thermodynamic states occurring during these events:
  - Solid
  - Liquid
  - Vapor states
  - Polymorphic phase transitions
  - Chemical reactions
- High pressure EOS of materials is usually determined by shock compression experiments:
  - Flat cylinder subjected to planar loading for time durations of a few hundred nanoseconds to several microseconds
  - Measurements of kinematics properties of the steady shock waves produced, usually shock velocity and particle velocity



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2) Description of Veloce, an electrical pulser for isentropic compression and shock physics experiments

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VELOCE – a compact electrical pulser for isentropic compression and shock physics experiments

- Strip line configuration
- Peak current: 3.5 MA
- 10 – 90% rise time: 350 ns
- Small size: 3.3 m x 2.4 m
- Kapton / Mylar insulation (no water, oil, vacuum for insulation)
- Easy to operate → fast turn around
- Low operational cost

• Veloce: a compact pulser for dynamic material characterization and hypervelocity impact of flyer plates – G. Avrillaud, Shock Compression of Condensed Matter, 2007, P. 1161

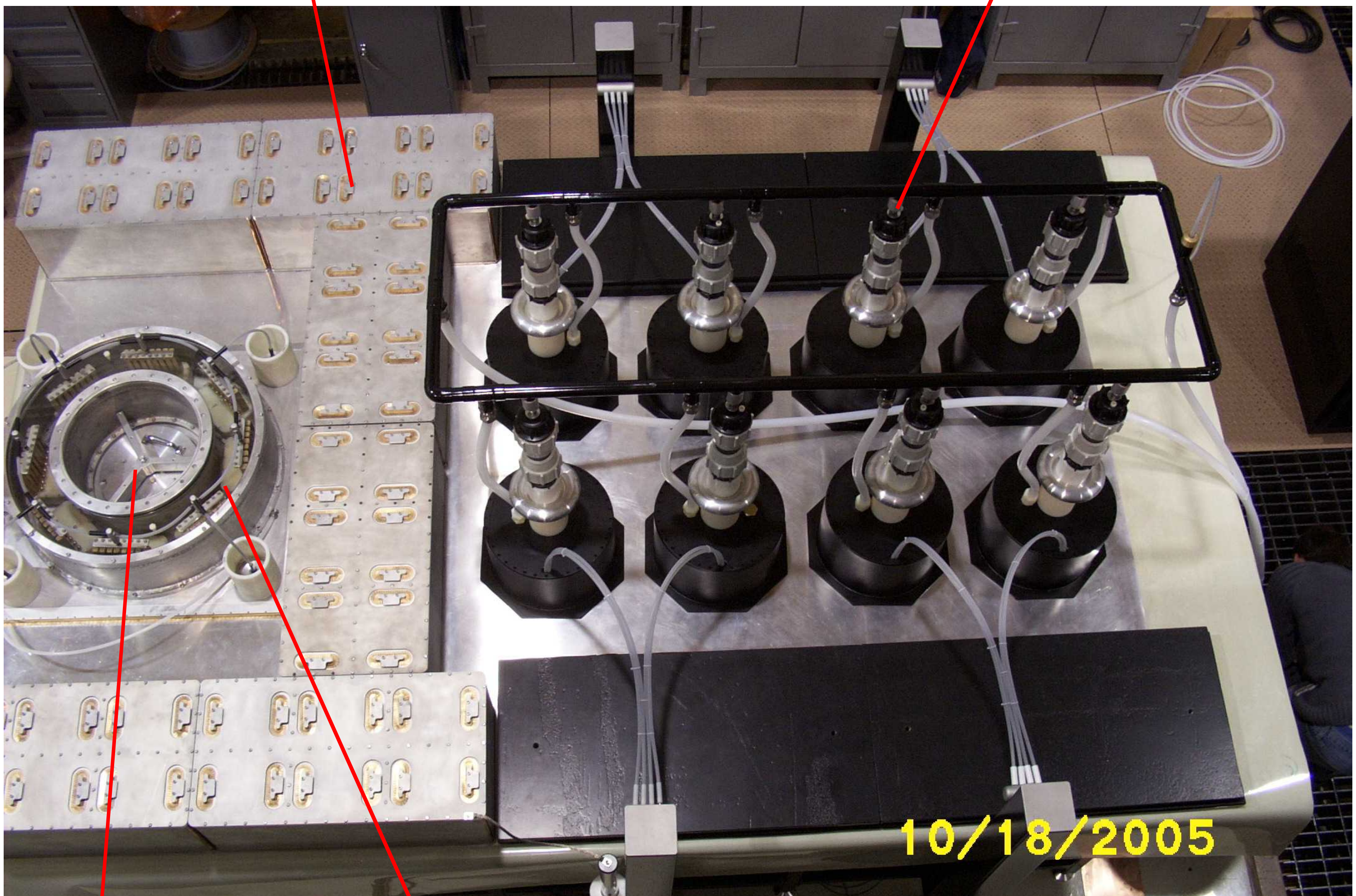
• A feasability study for a fragment-producing chemical-electrical launcher – Tom Haill, et al - Proc. of the 16th IEEE Int. Pulsed Power Conf., Albuquerque, NM, 2007

2) Description of Veloce, an electrical pulser for isentropic compression and shock physics experiments

VELOCE

48 peaking capacitors

8 main capacitors



Load chamber

Dynamic Switch

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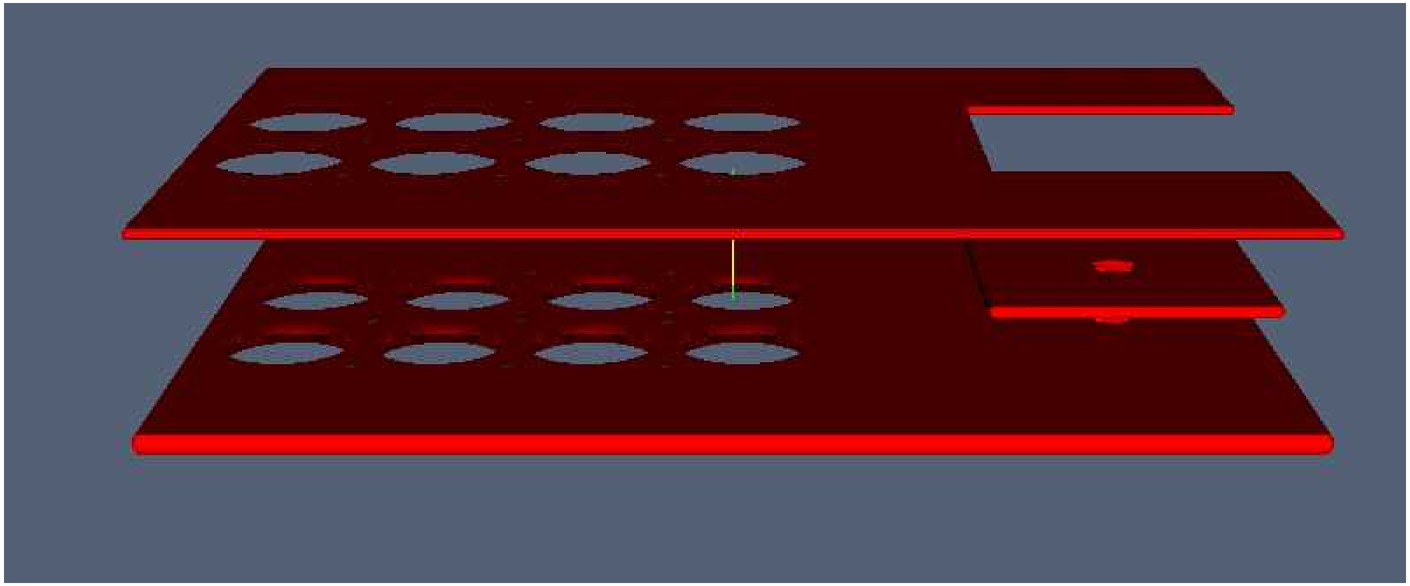
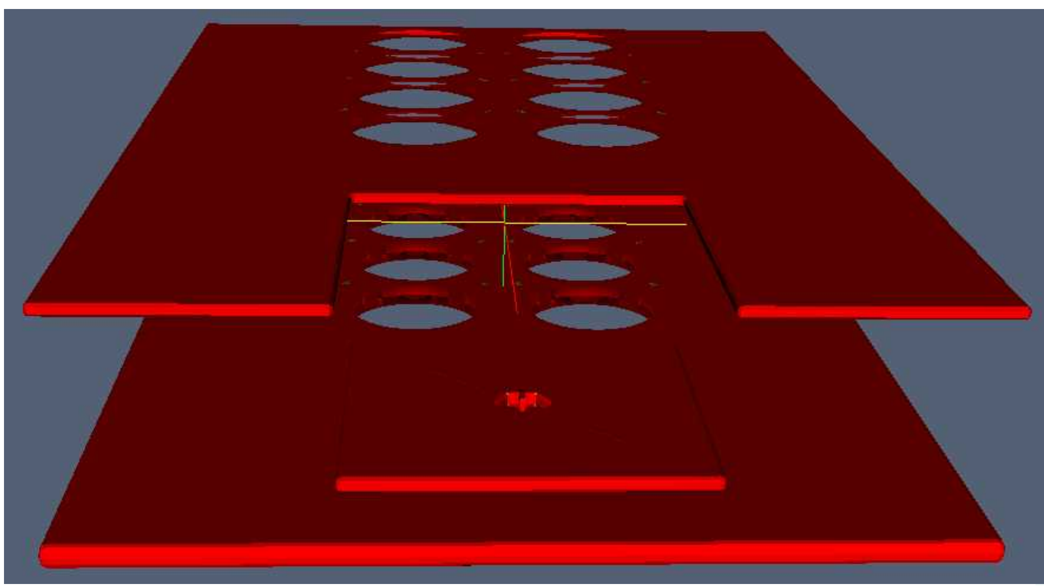
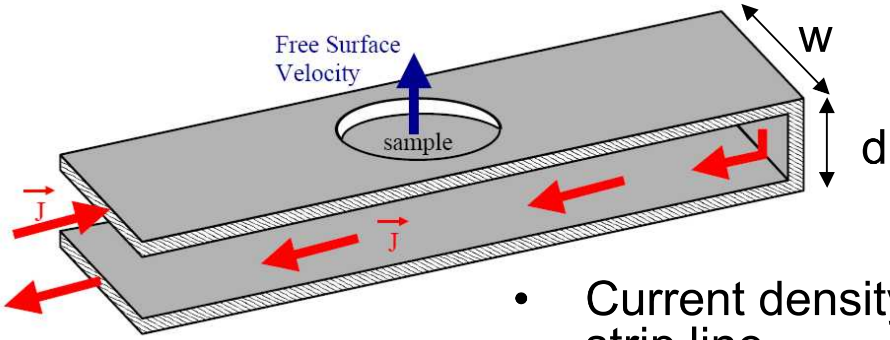
G. Avrillaud et al., “GEPI: A Compact Pulse Power Driver for Isentropic Compression Experiments and for Non-Shocked High Velocity Flyer Plates,” Proc. of the 14th IEEE Int. Pulsed Power Conf., Dallas, TX, 2003, p.913

Modeling of Veloce pulser



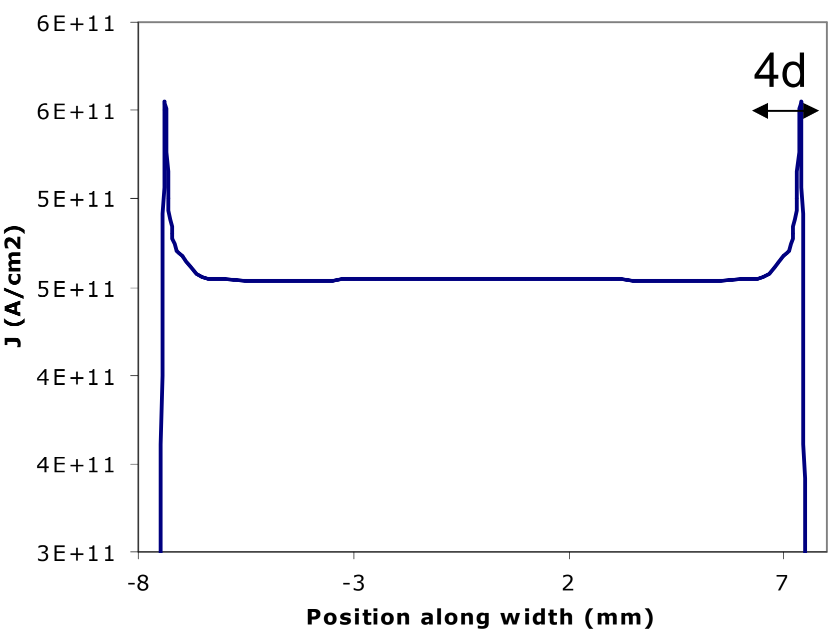


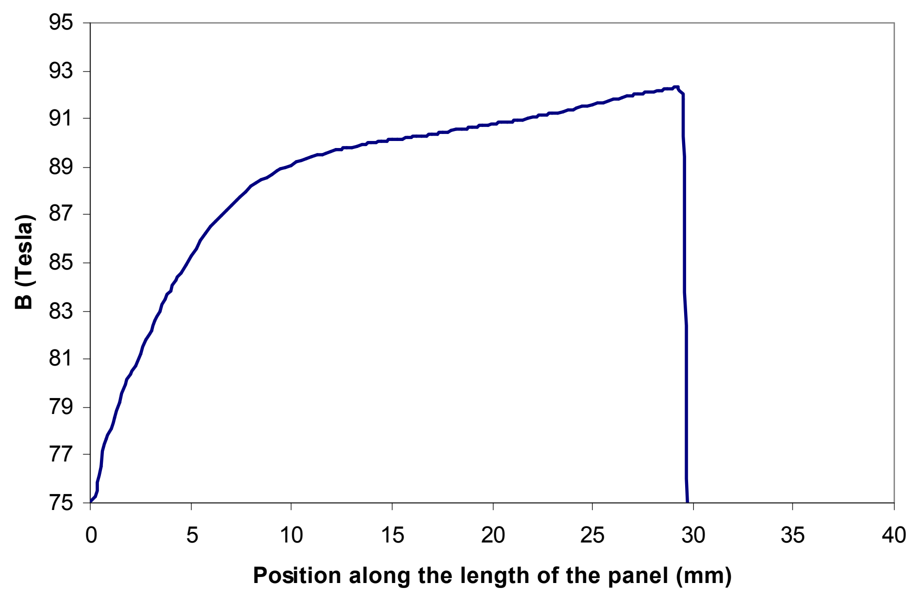
Pressure uniformity issues in magnetically driven strip line configuration experiments



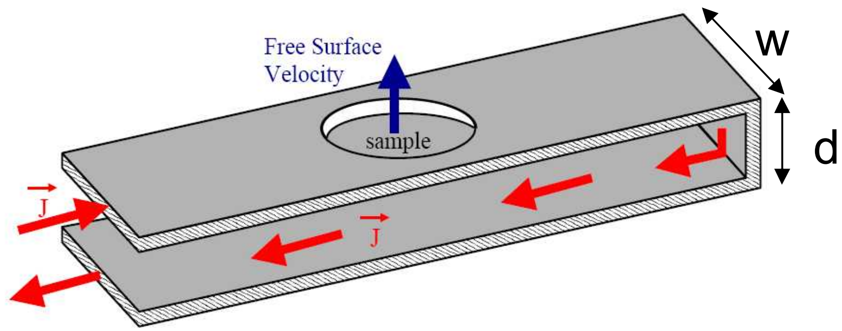
$$P_{mag} = K_I \cdot \frac{\mu_0}{2} \left(\frac{I}{w}\right)^2$$

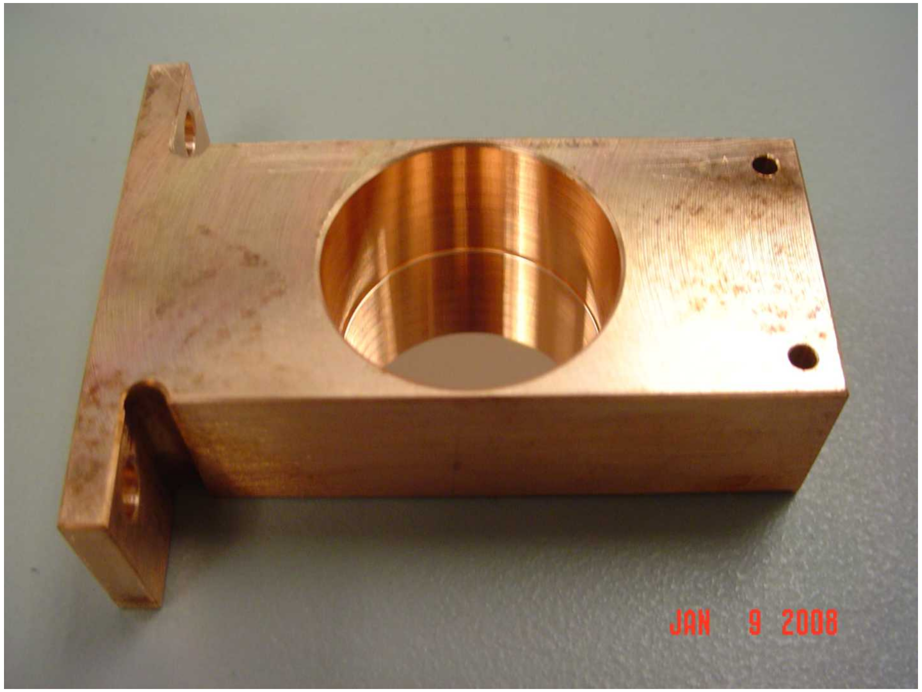
- Current density non-uniformity at the entrance of the strip line
- Current density rises along the length of strip line
- Pressure uniformity across sample: ~3% - <1% needed

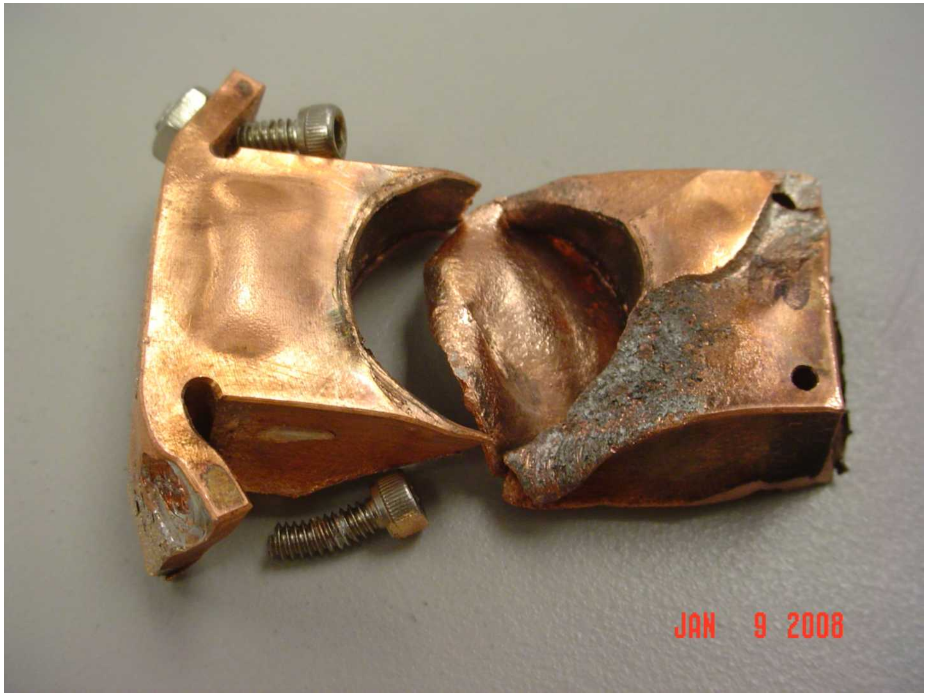




Panel before and after shot







3) Description and validation of simulations

ALEGRA: a Magneto Hydrodynamic Code

- Arbitrary Lagrangian-Eulerian finite element 2-D and 3-D code
- Includes:
  - Magneto hydrodynamics (MHD)
  - Thermal conduction
  - Radiation transport
  - Material models
- Coupled with large number of material data (equation of states, opacity tables…)
  - Equation of State, Yield models, plasticity models, fracture models, burn models
  - Electrical and thermal conductivity, ionization models
  - Linear diffusion, Implicit Monte Carlo, Collisional radiation transport

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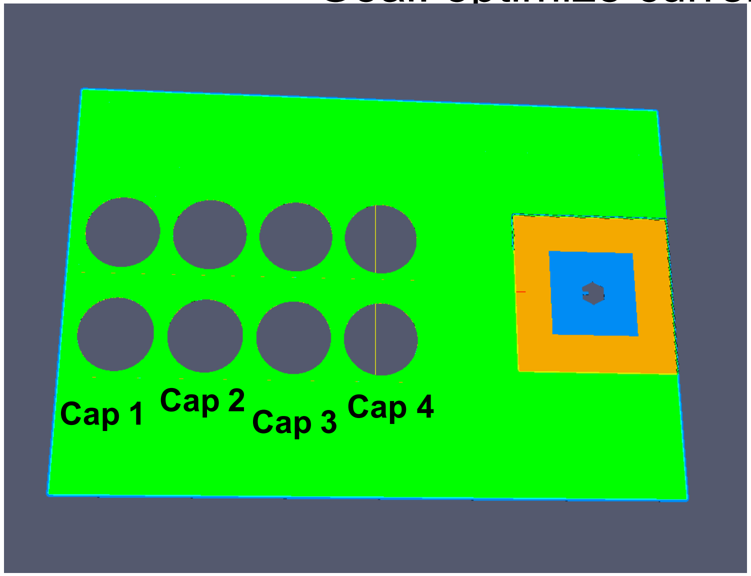
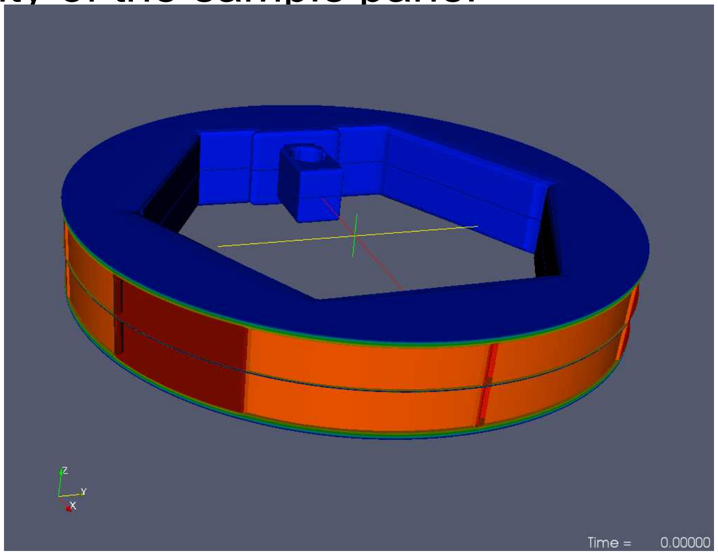
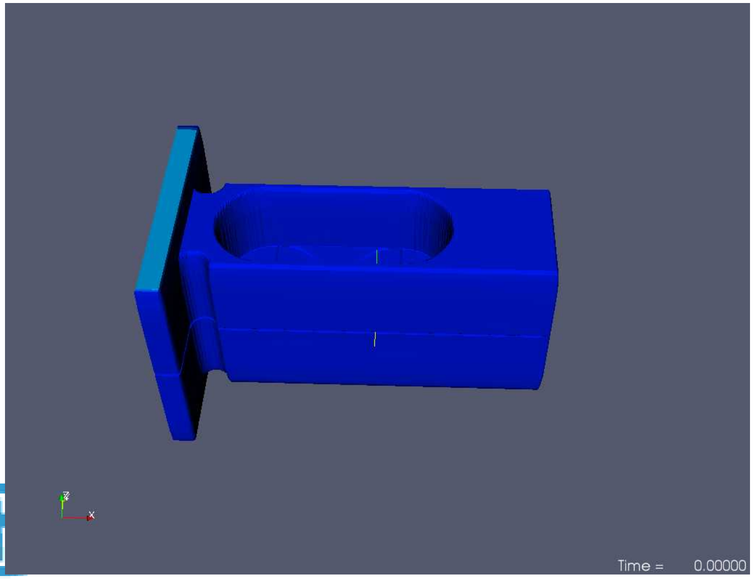
VELOCE MHD Simulations

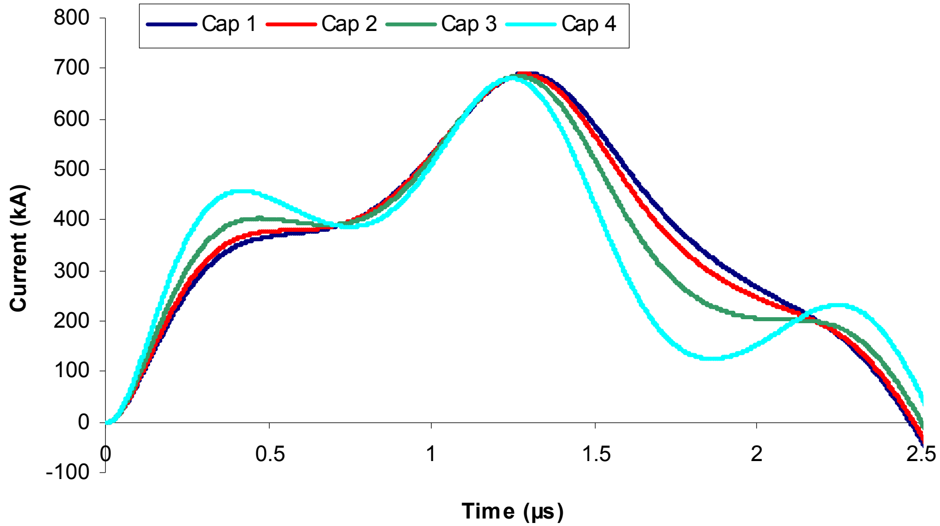
Goal: optimize current uniformity of the sample panel



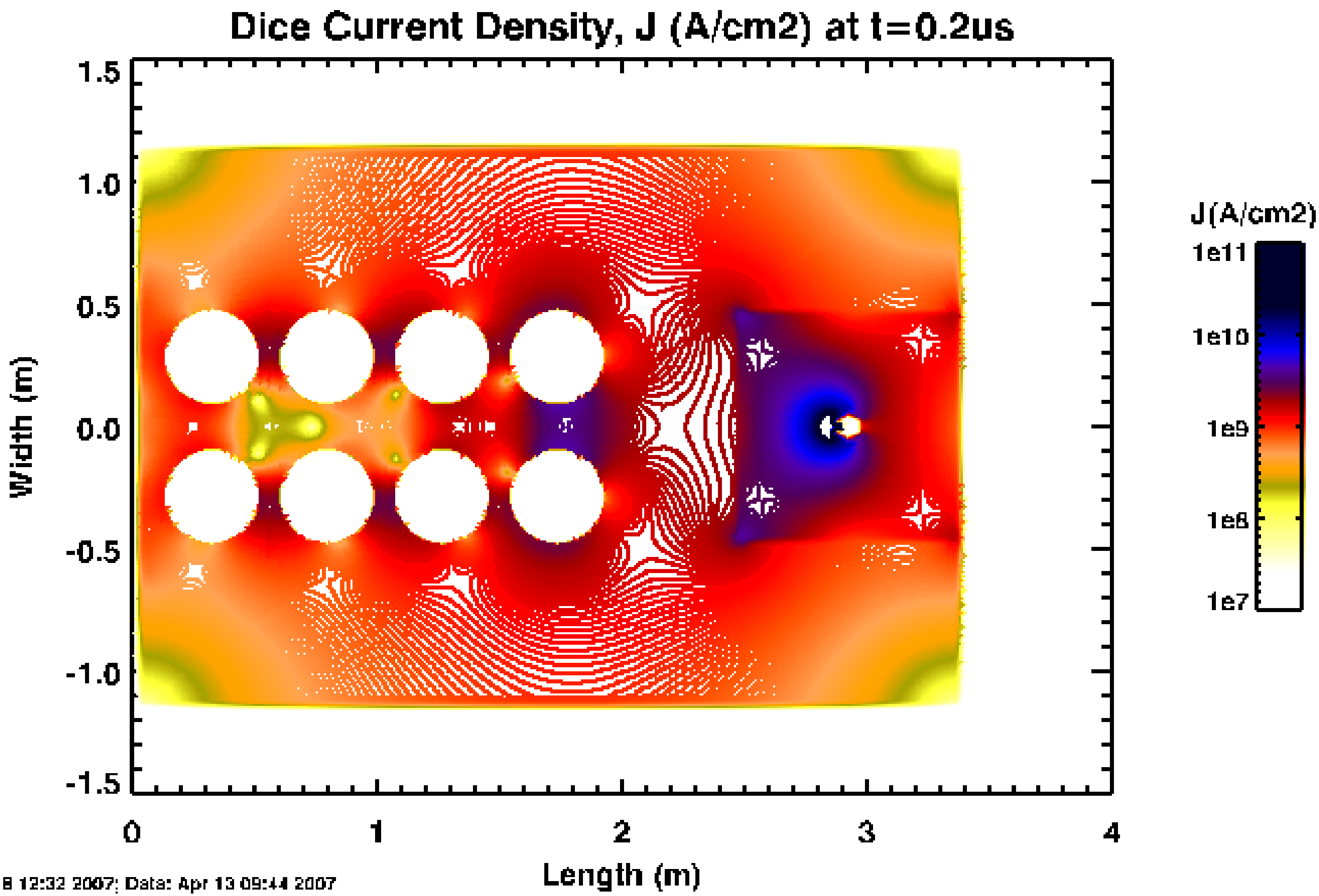




Current waveforms from 2D circuit simulations by G. Avrillaud ITHPP, Thegra, France



VELOCE Simulations: full machine



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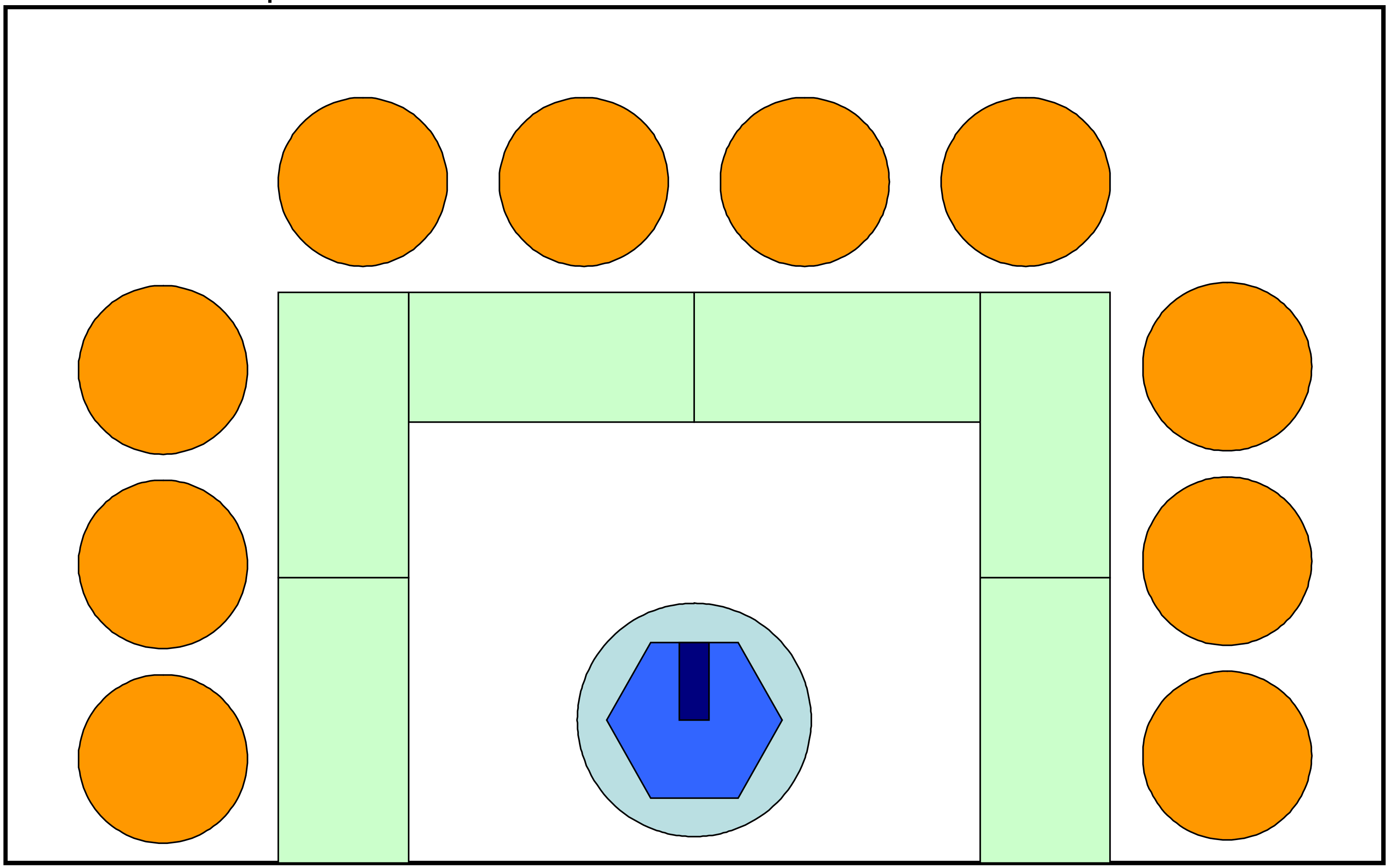
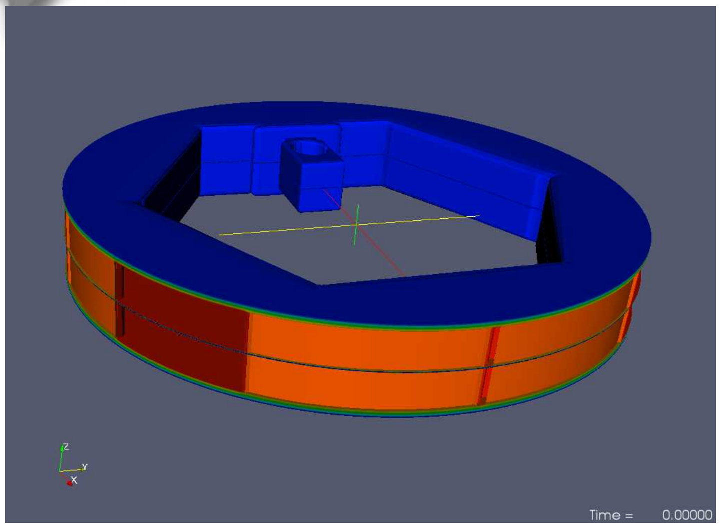
VELOCE Upgrade: Proposed Design

- Redistribute main capacitors around peaking capacitors
- Add 2 or 4 main capacitors

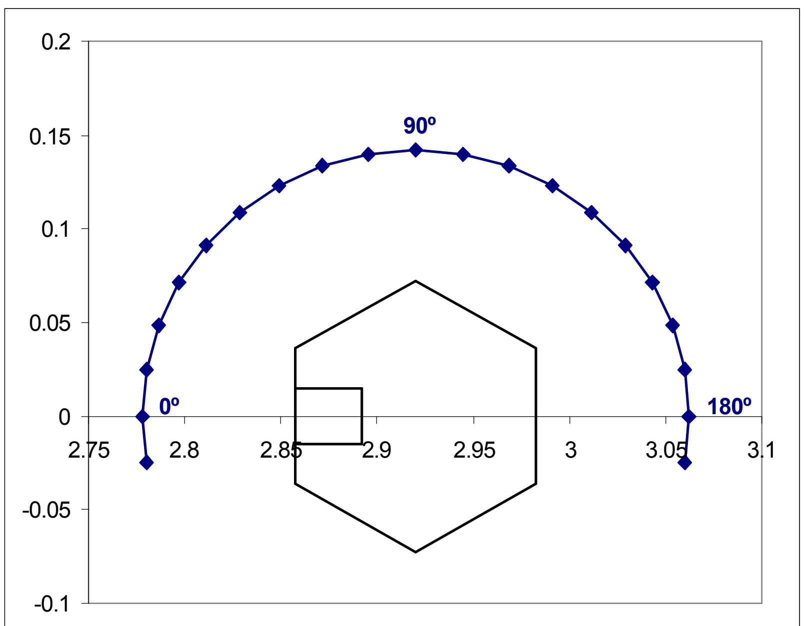
→ Increase the current by ~20 %

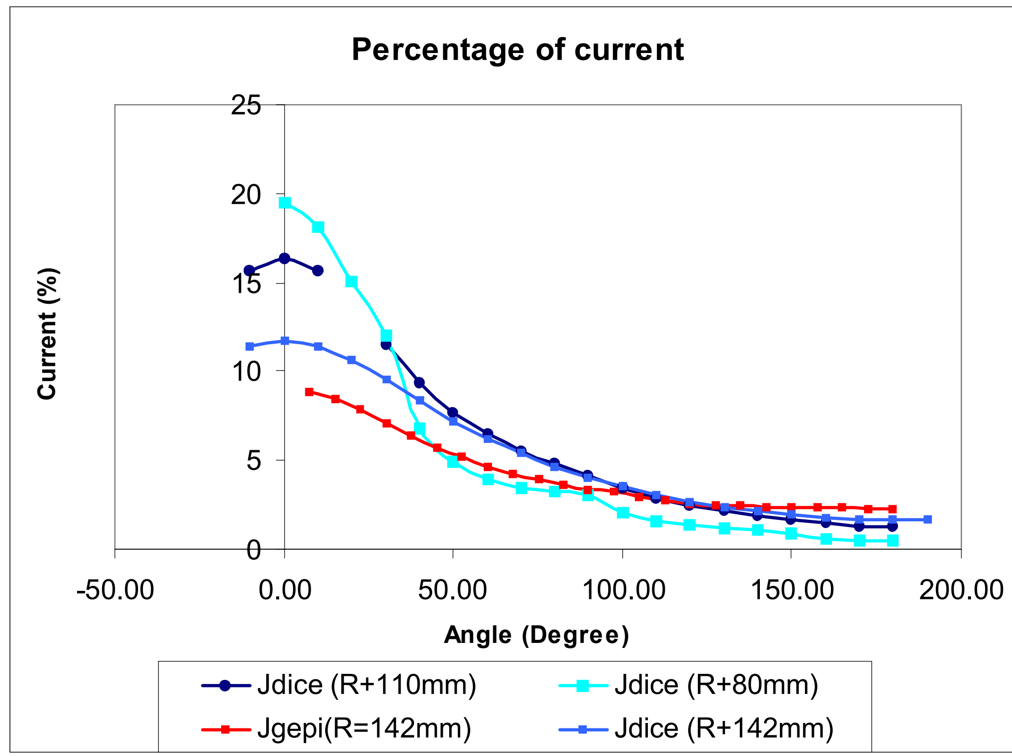


VELOCE Simulations: Load Area



<u>Circular boundary</u>: input current distribution from whole Veloce simulation - Current distribution more favorable than for the French machine GEPI





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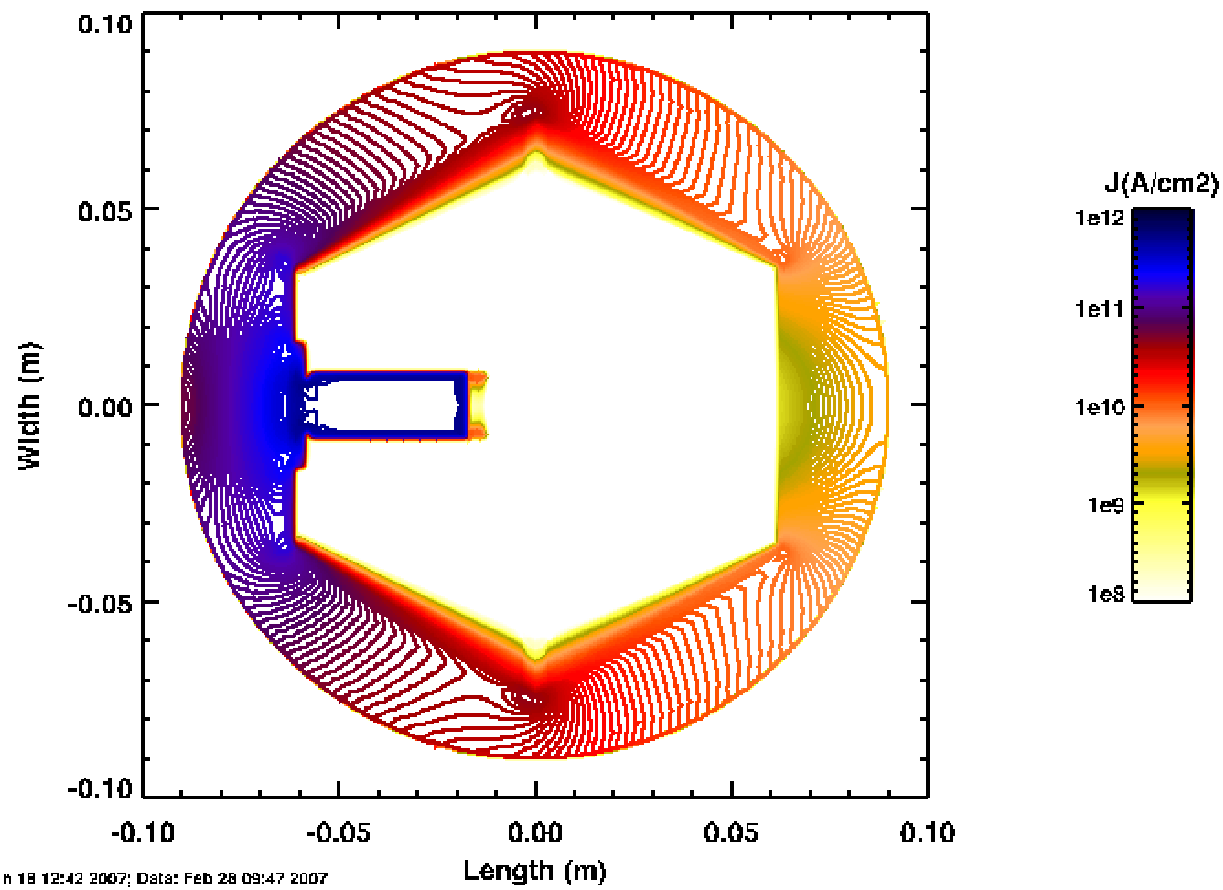
VELOCE Simulations: Load Area

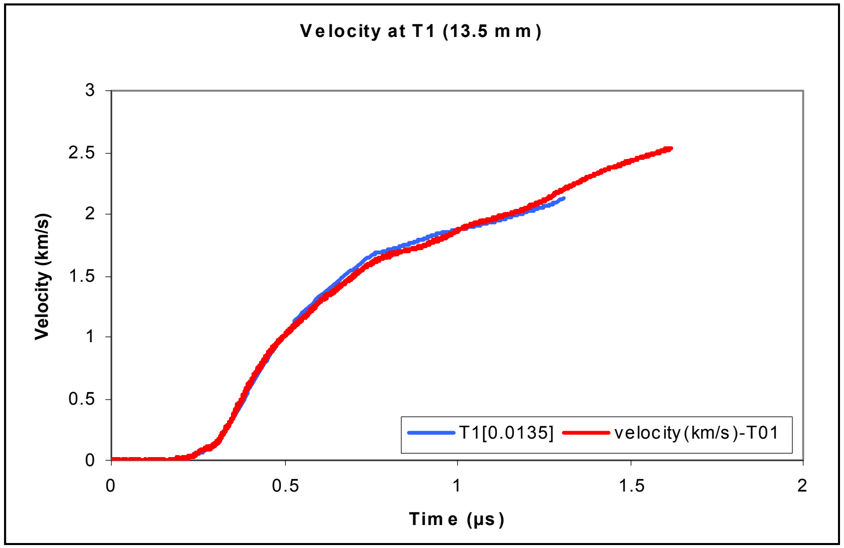
Most of the current distributed on panel side

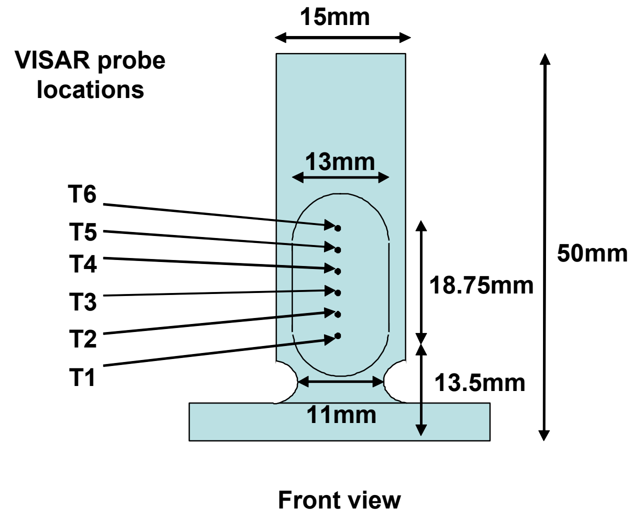


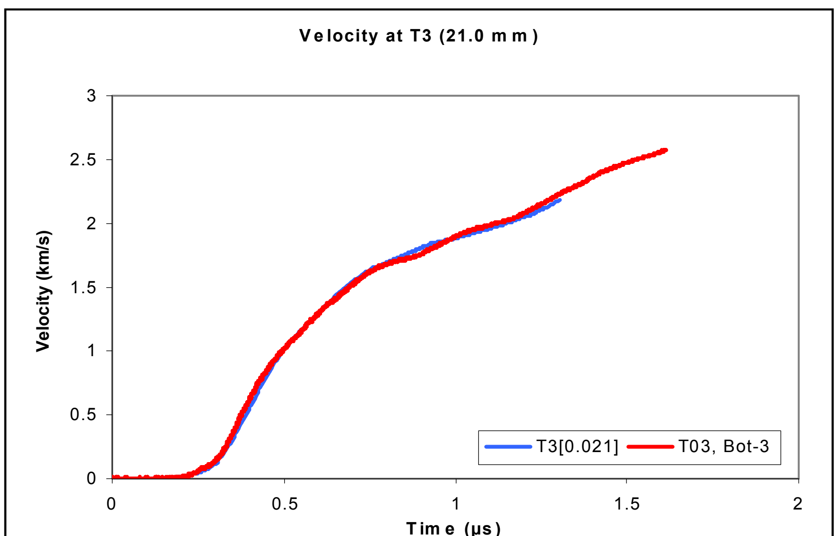
- Resolution limited because of size of simulation → Simulation of panel

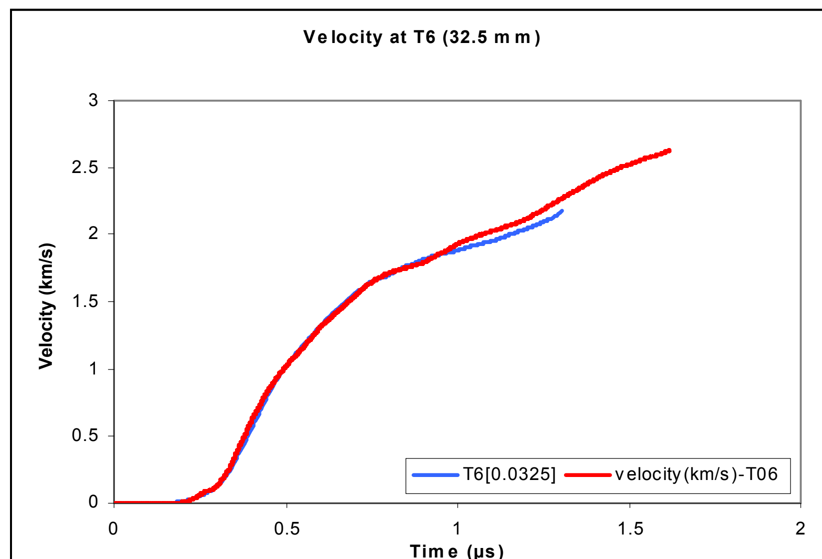
DICE Simulations: Load Area

Comparison of measured and calculated free surface velocity at different probe positions (– model – experiment)

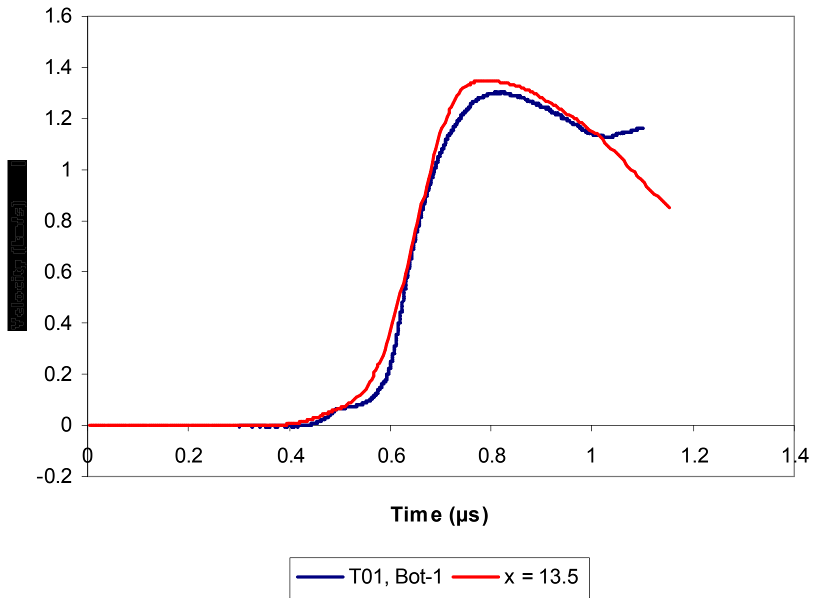


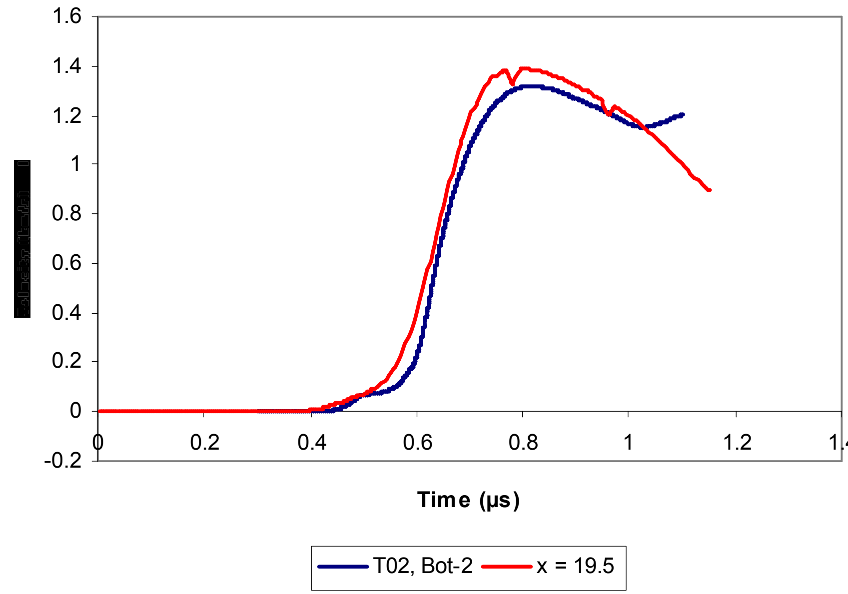


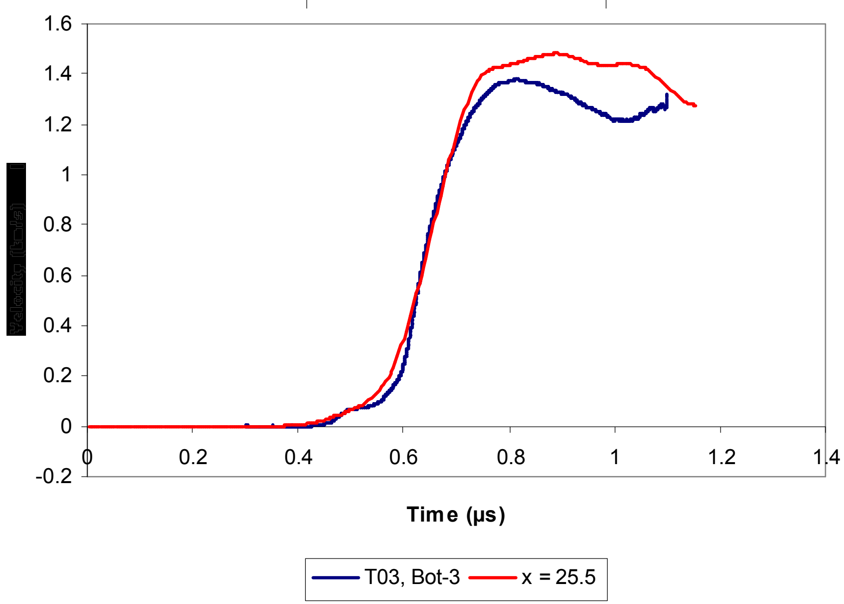




Reference Panel: free-surface velocity curves







Simulation and experimental free-surface velocity as a function of time at three positions along the length of the panel : 13.5mm, 19.5mm and 25.5mm.
Reference panel: 15mm x 35mm x 2.5mm

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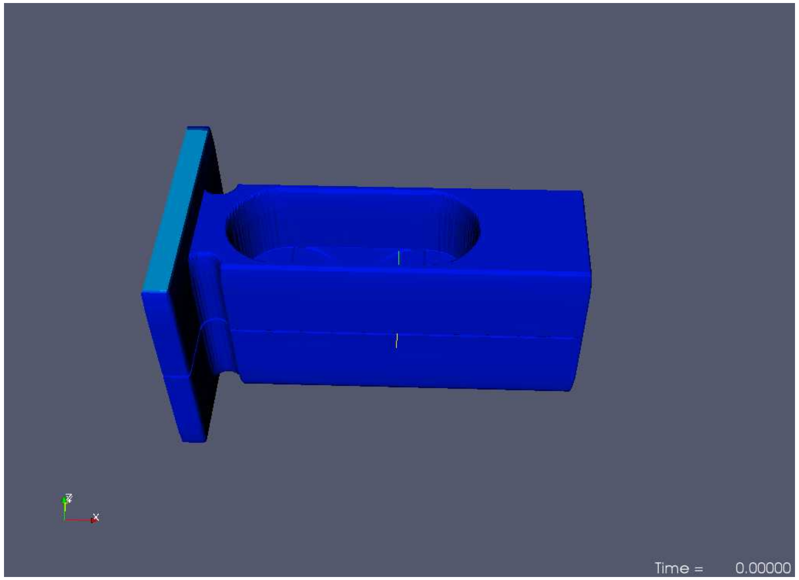
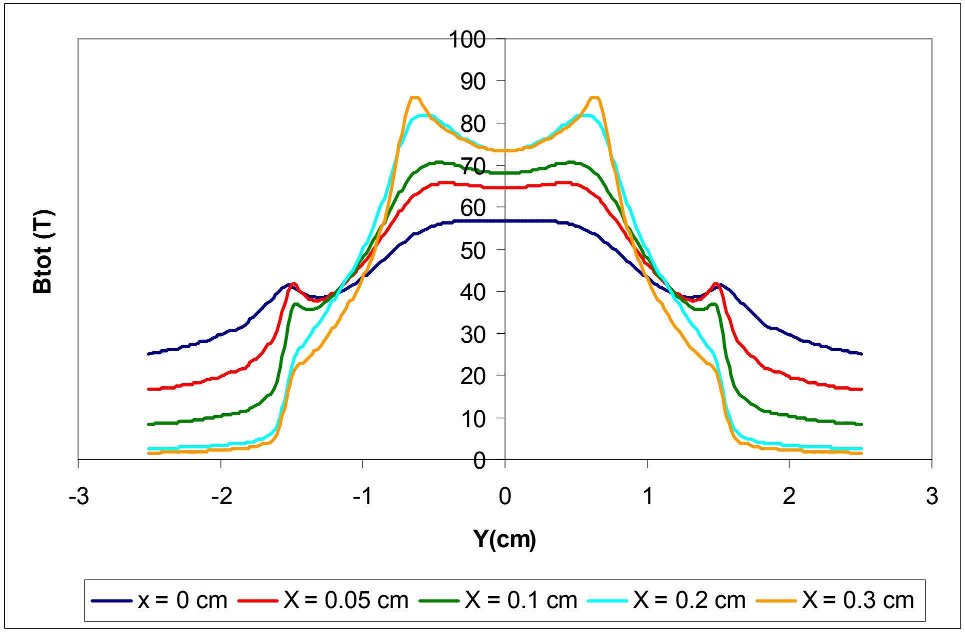
VELOCE Simulations: Panel Area



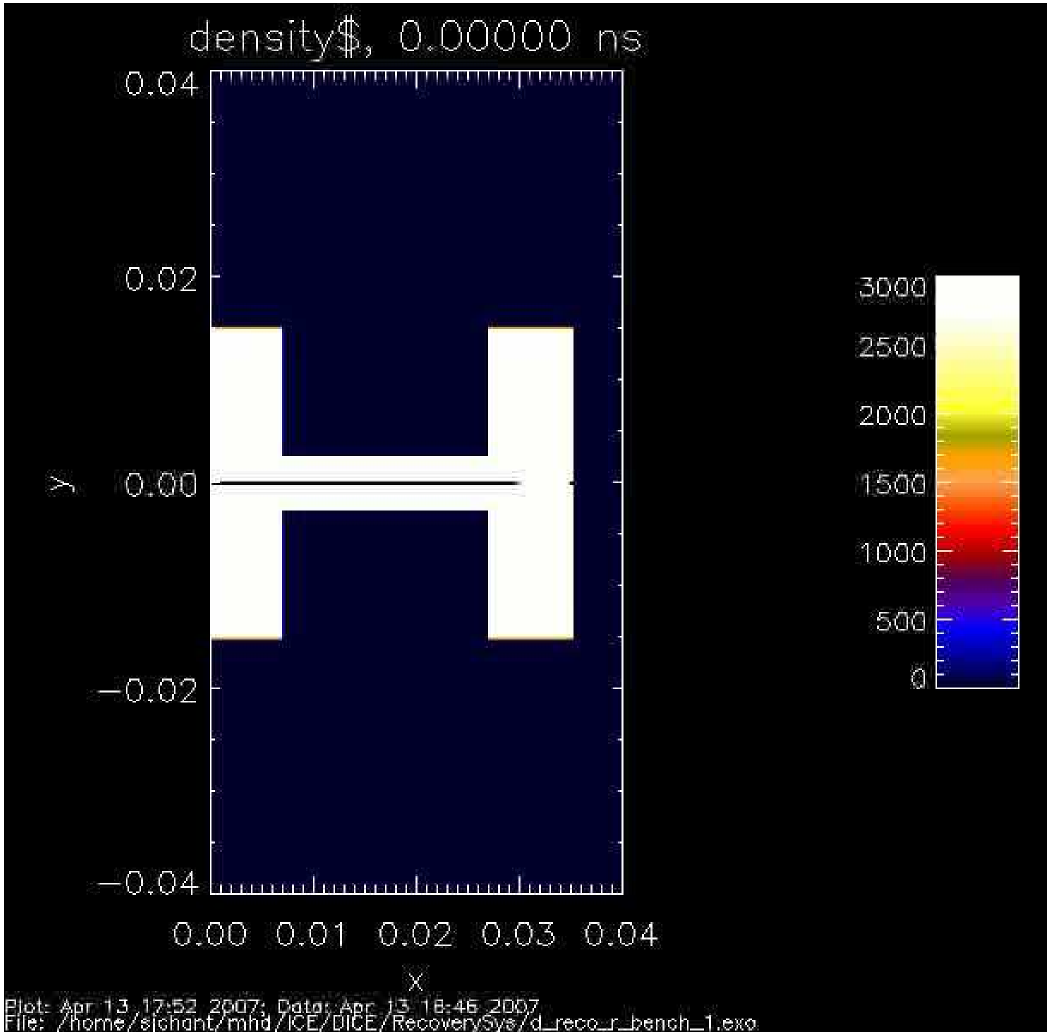
Input current distribution for panel simulation



Resolution :
- 0.25 mm in X and Y direction (panel plane)
- 0.0425 mm graded to 0.25 in z direction

DICE Simulations: Panel Area

Density profile as a function of time



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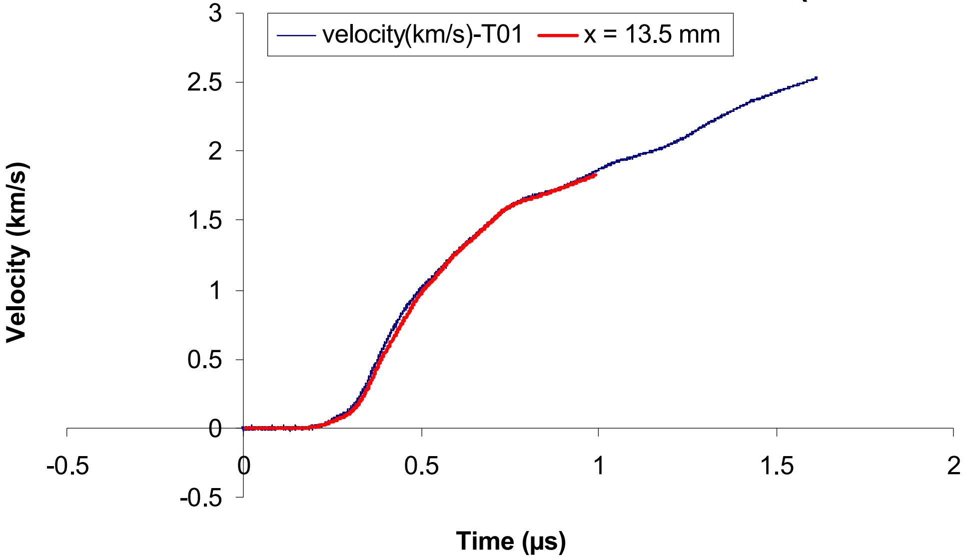
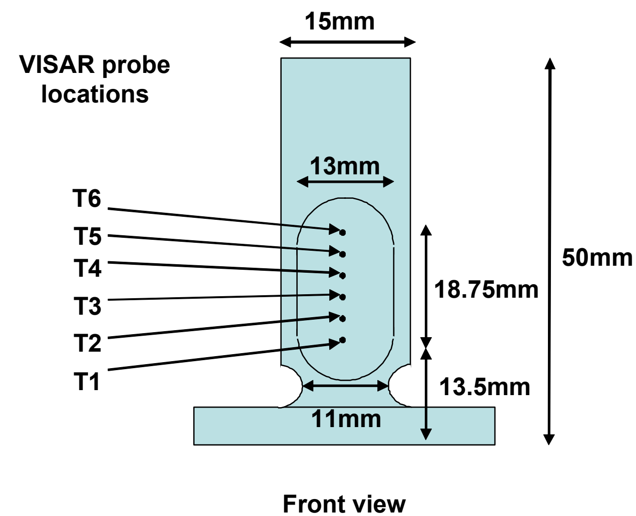
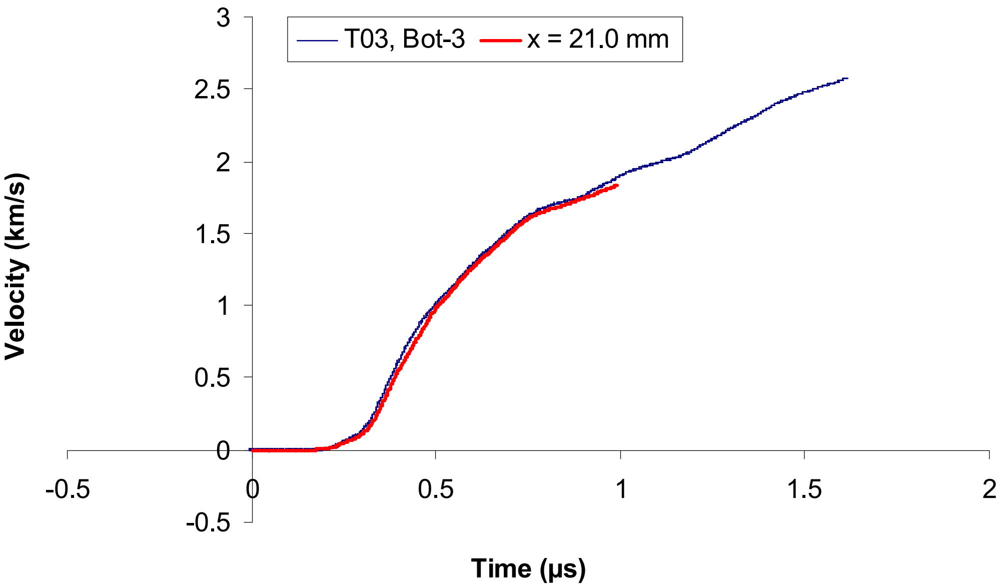
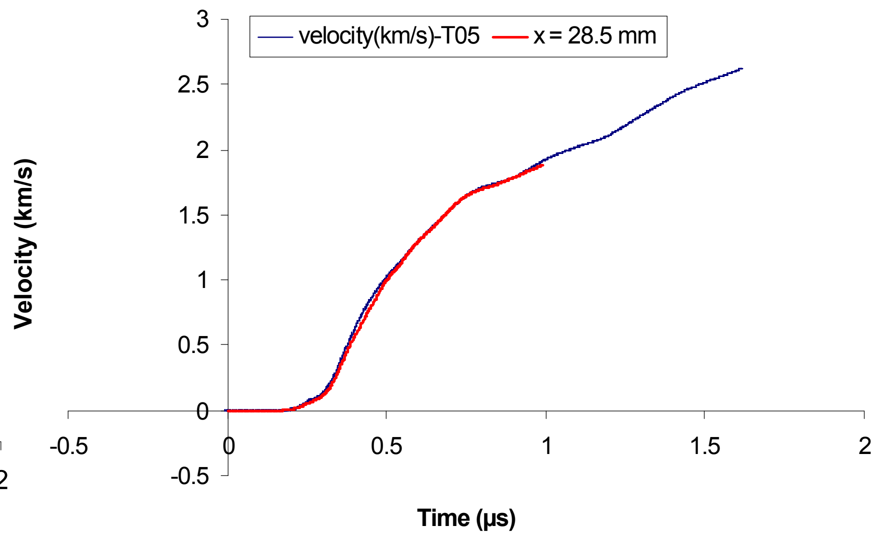
VELOCE Simulations Benchmarking

Comparison of measured and calculated free surface velocity at different probe positions (– model – experiment)



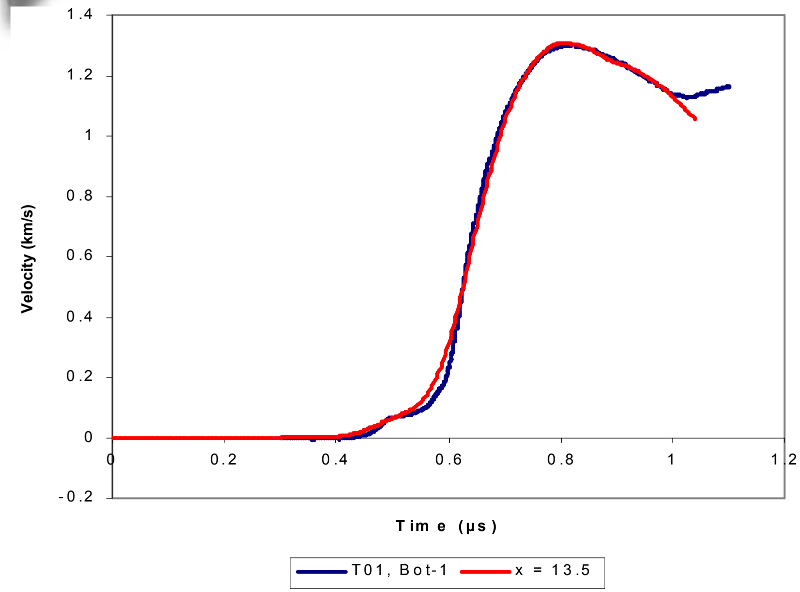


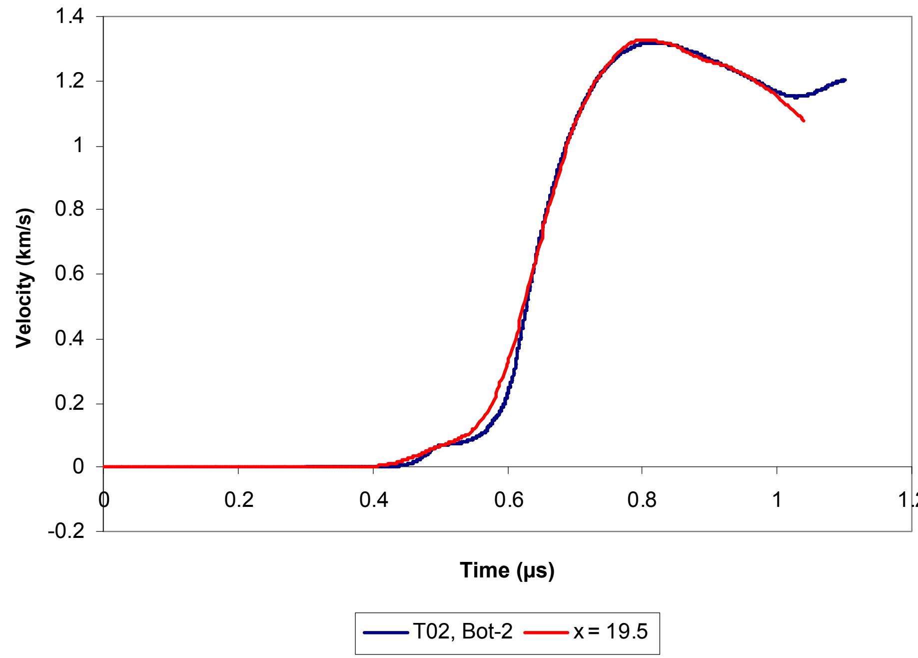


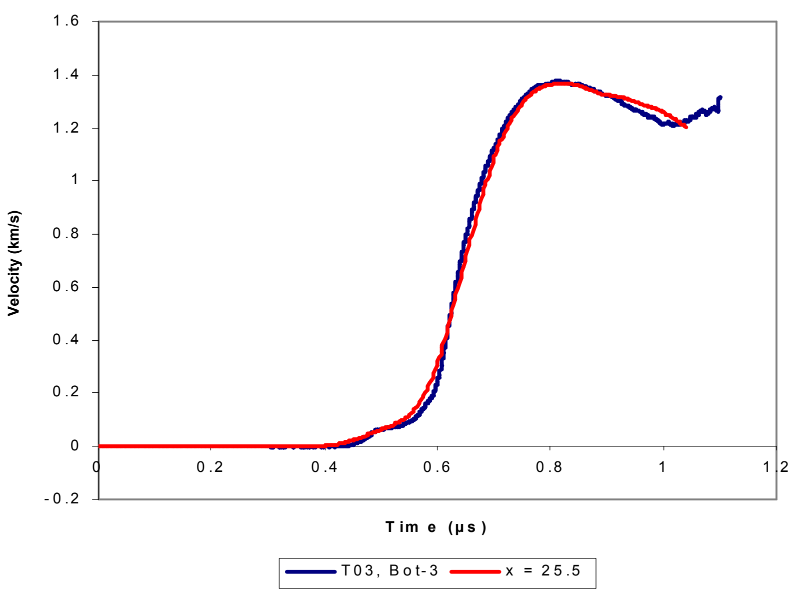


VELOCE Simulations: Panel Area

Reference Panel: free-surface velocity curves







Simulation and experimental free-surface velocity as a function of time at three positions along the length of the panel : 13.5 mm, 19.5 mm and 25.5 mm.

Reference panel: 15 mm x 35 mm x 2.5 mm

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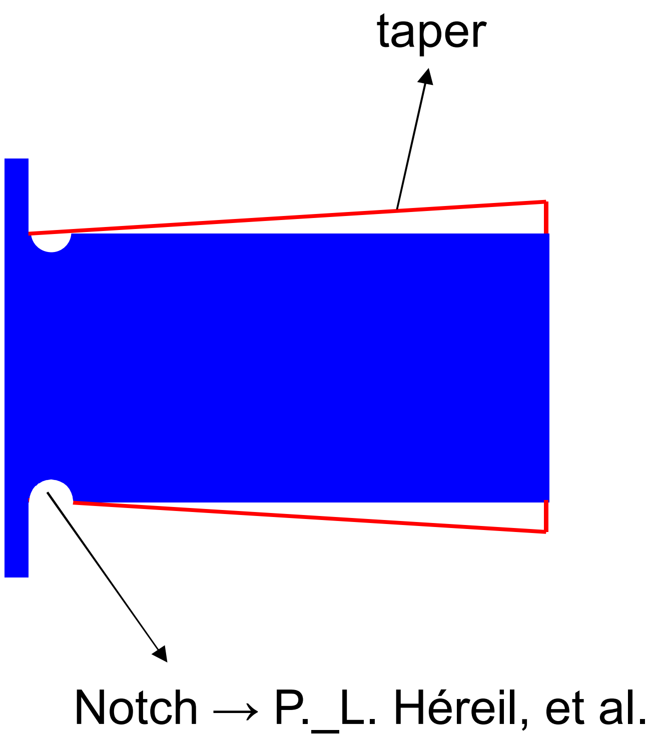
4) Modeling results and future improvement

DICE Simulations: Panel Area

- Reference panel: 15mm x 35mm x 2.5mm
  - Different notch size
  - Different taper
- Long panel: 15mm x 50mm x 1mm
  - Different notch size
  - Different taper
- Reference panel: 20mm x 45mm x 1mm
  - Different notch size
  - Different taper
- Tilted panel



Reference: T. Ao, J.R. Asay, S. Chantrenne, M.R. Baer, and C.A. Hall, 'A compact strip-line pulse power generator for isentropic compression experiments'

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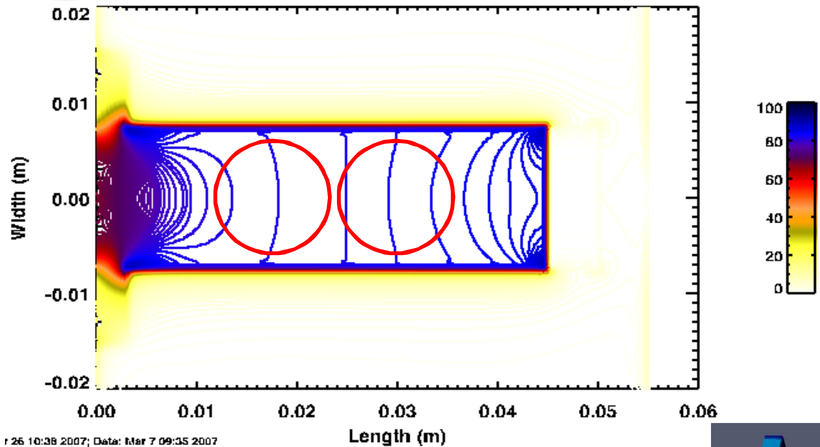
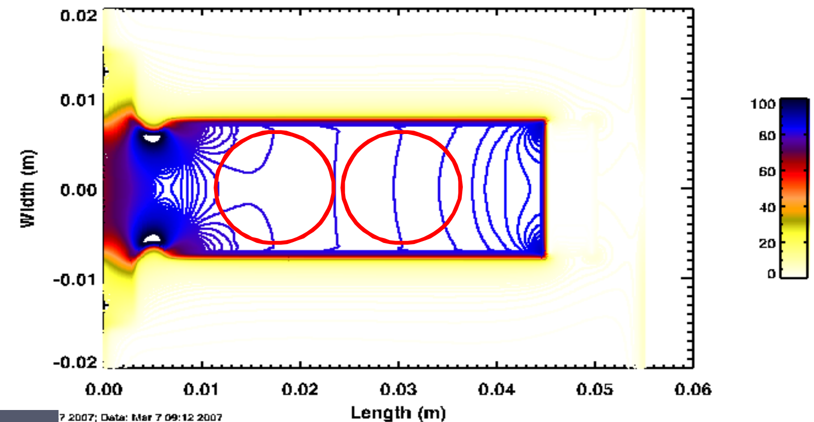
Simulation Results – Long Panel

notch size variation - R = 1.5mm, 1.0mm, 0.5mm and no notches

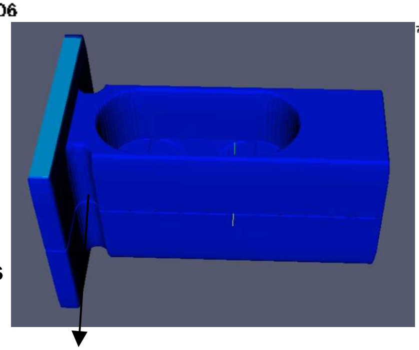
15mmx50mm panel, no notches, B at t=0.2μs



15mmx50mm panel, notches r=1.0mm, B at t=0.2μs

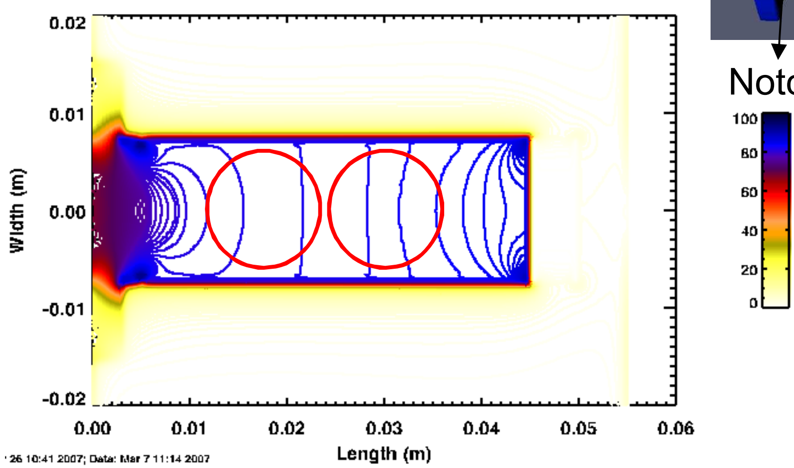


Resolution: ~0.5 % between levels

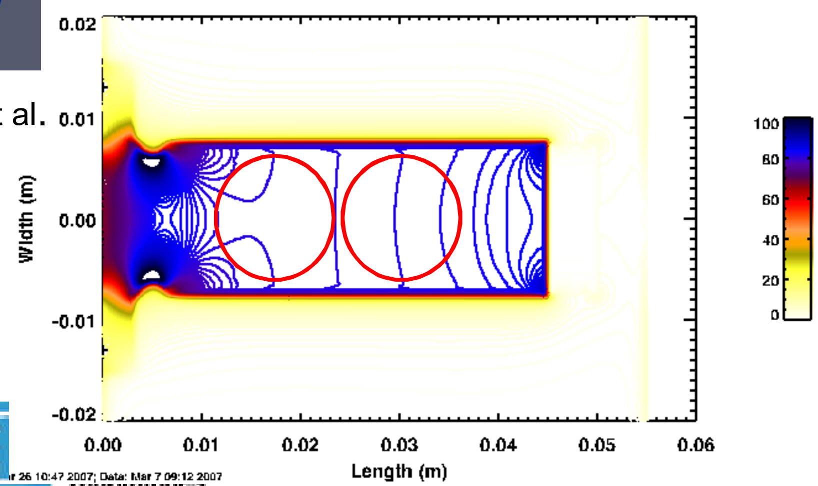


Notch → P.-L. Héreil, et al.

15mmx50mm panel, notches r=0.5mm, B at t=0.2μs

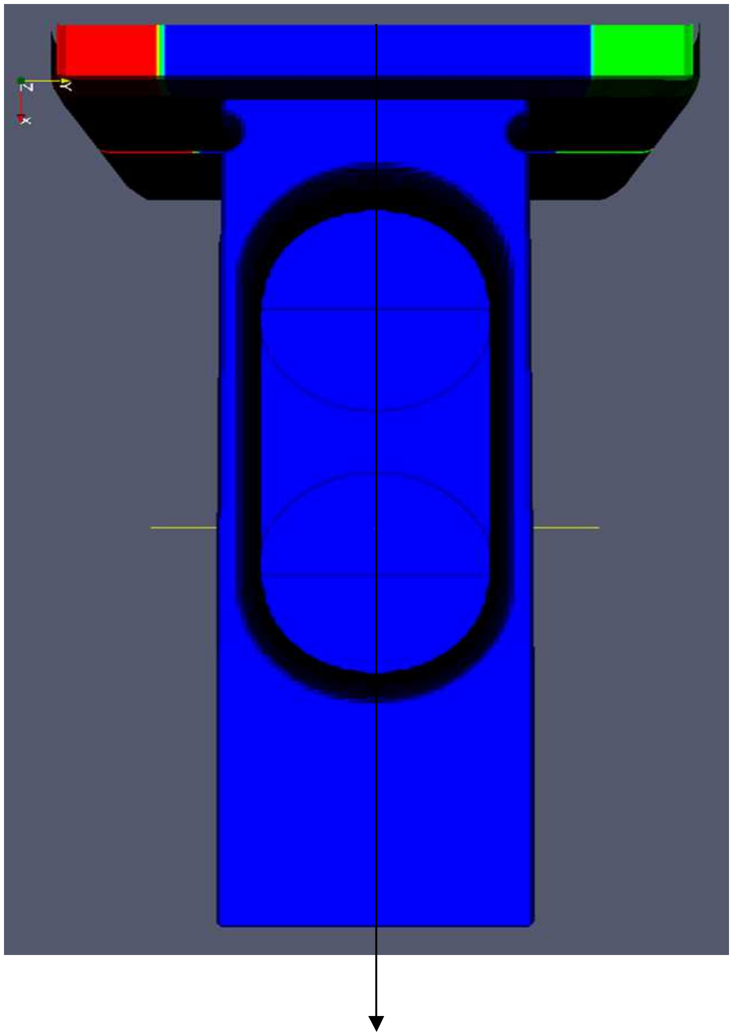


15mmx50mm panel, notches r=1.5mm, B at t=0.2μs

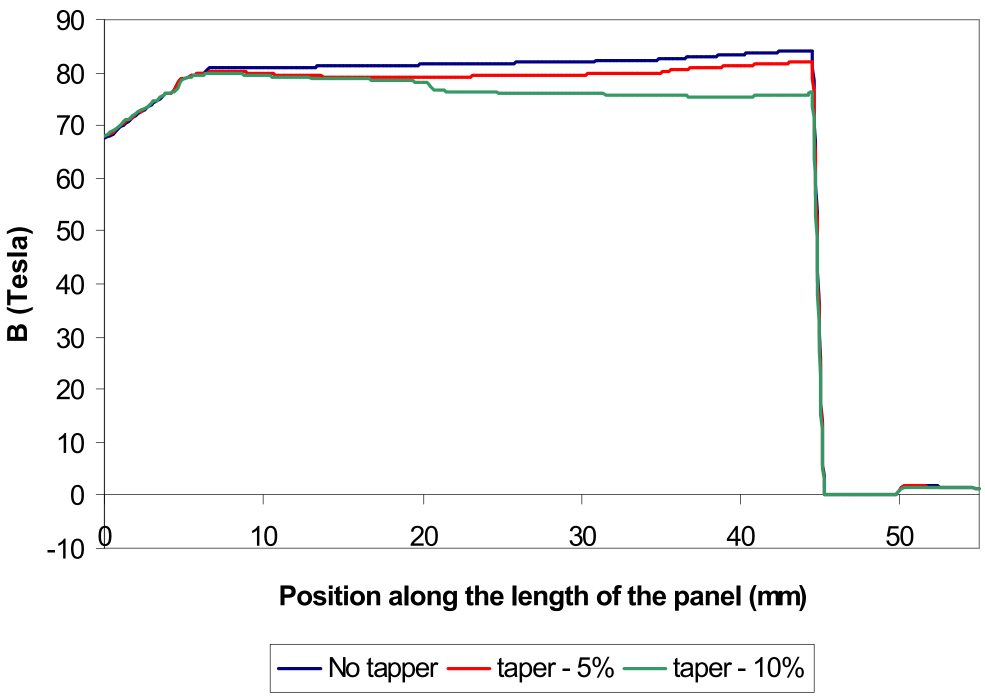


Tapered Long Panel: 0% - 5% - 10%

Taper = 5%



B (T) at the edge of the panel between the two panels. B is directly proportional to Jtot.



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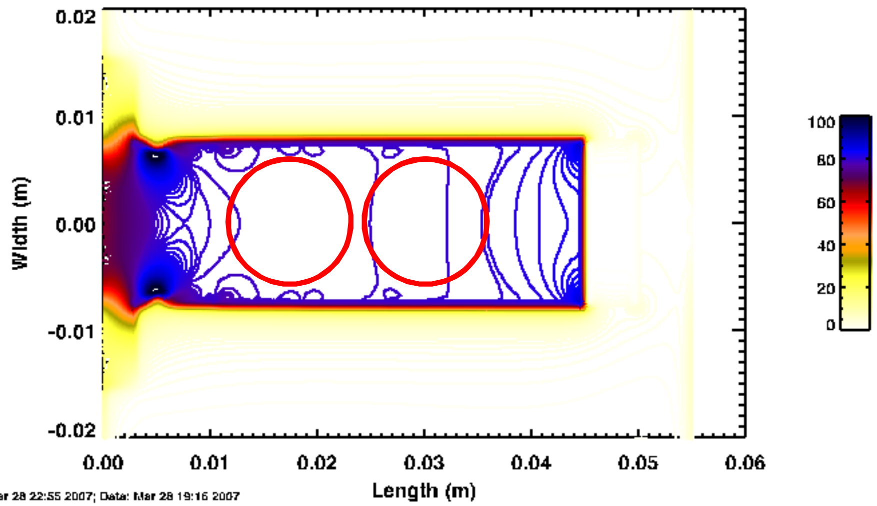
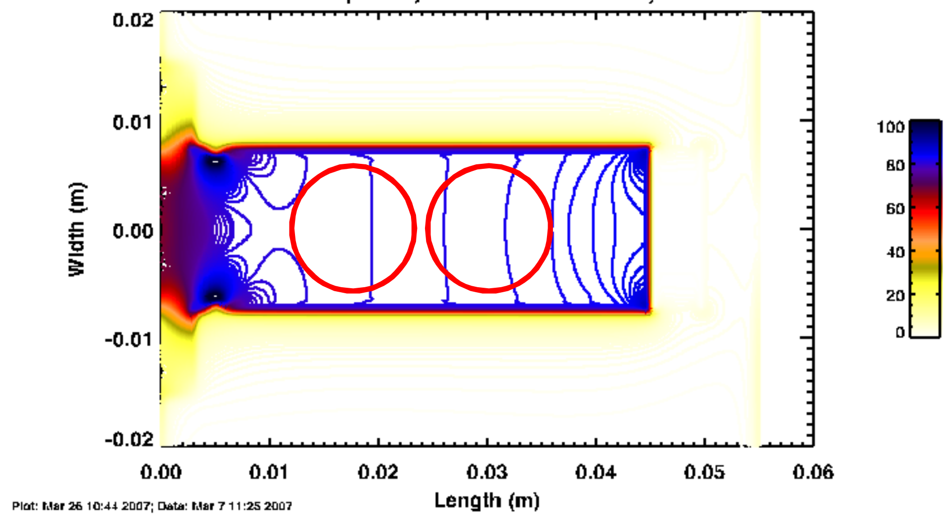
Tapered Long Panel: 0% - 5% - 10%

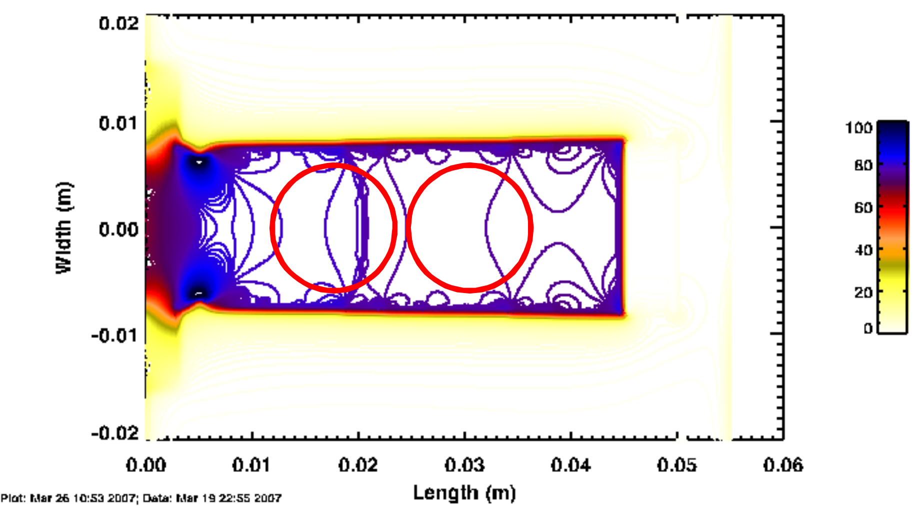
15mmx50mm tapered panel (5%), notch r=1.0mm, B at t=0.2μs



15mm x 50mm panel, notches r=1.0mm, B at t=0.2us



15mmx50mm tapered panel (10%), notch r=1.0mm, B at t=0.2μs



Resolution: 0.5 % between levels
The contour irregularities at the edges are due to the mesh that is not parallel to the edge

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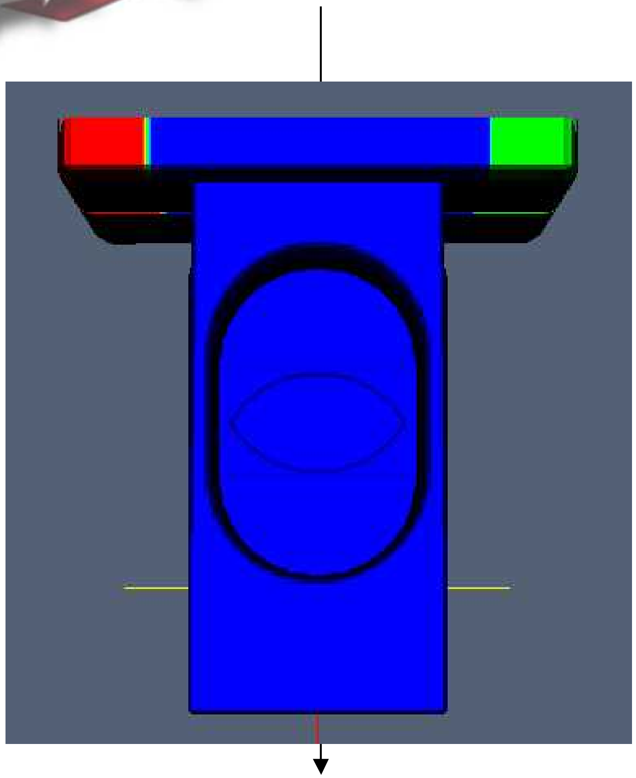
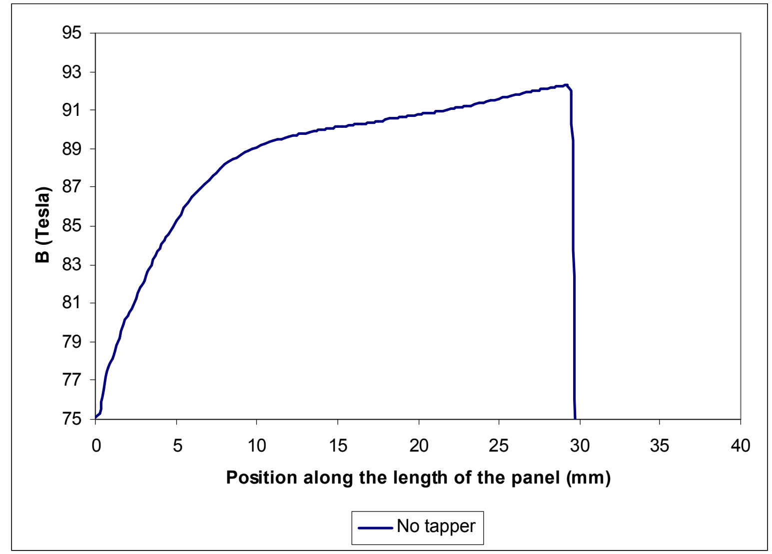
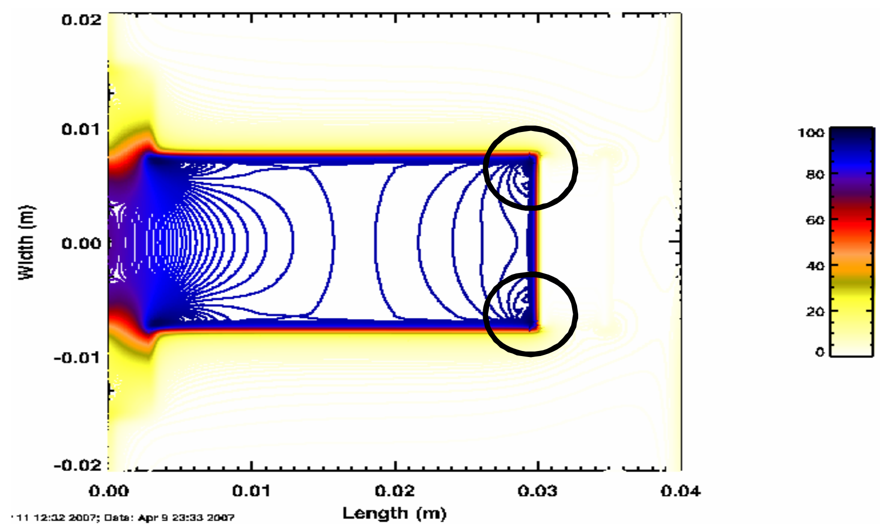
Current density non uniformity at the end of the panel





Problem: B at the edge of the contact is about 15% higher than in the center, causing B to increase by about 3% along the usable part of the panel → need to reduce/eliminate the hot spot at the end of the contact by modifying the contact area of the panel



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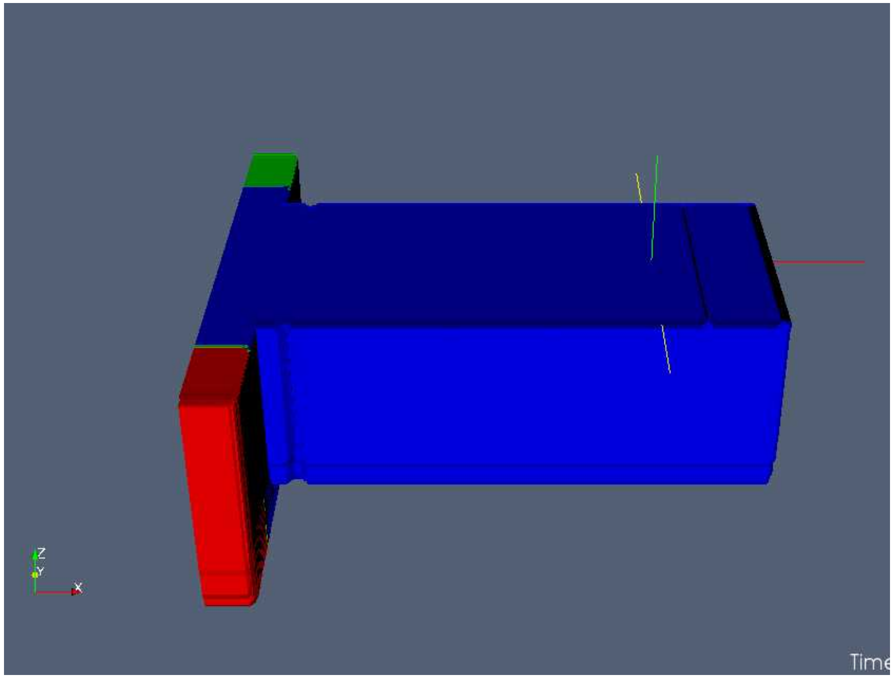
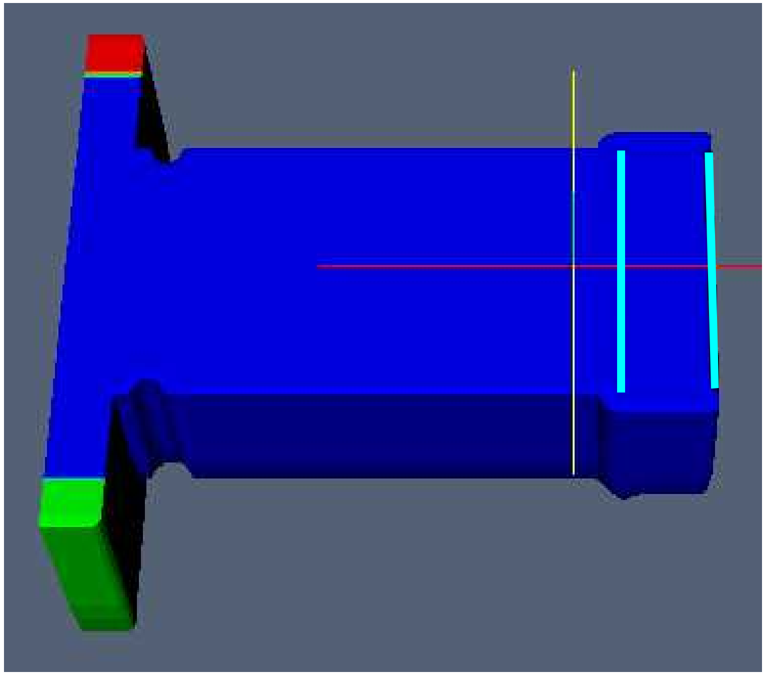
B (T) at the edge of the panel between the two panels. B is directly proportional to Jtot.

Proposed modification

Original panel



Modified panel

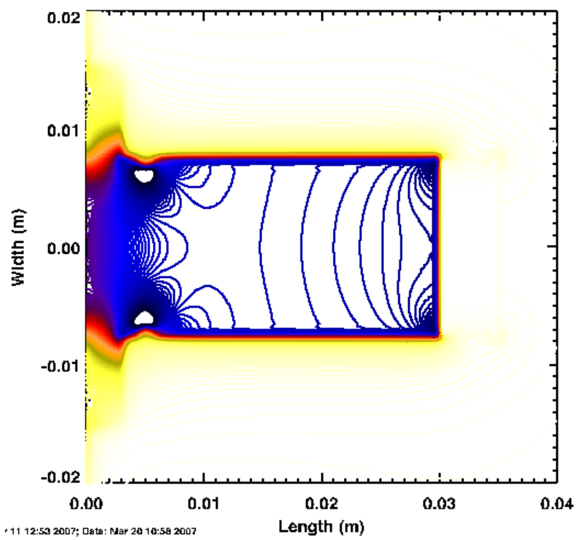


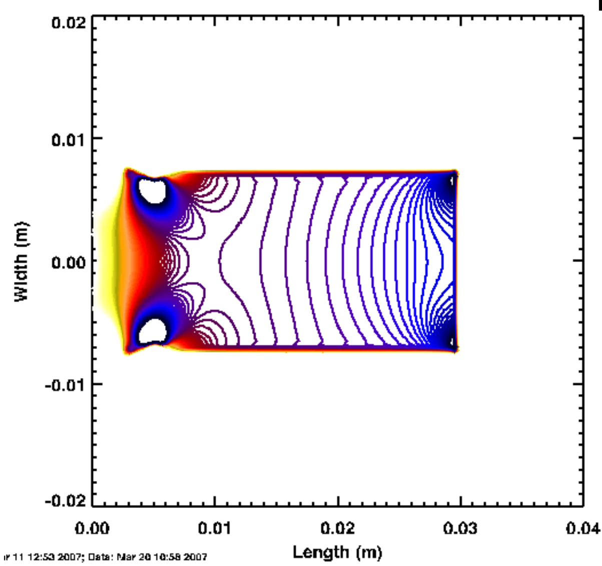
Bottom panel with contact. Contact does not show well because we are limited by the resolution of the simulation.

Preliminary Results

Original panel

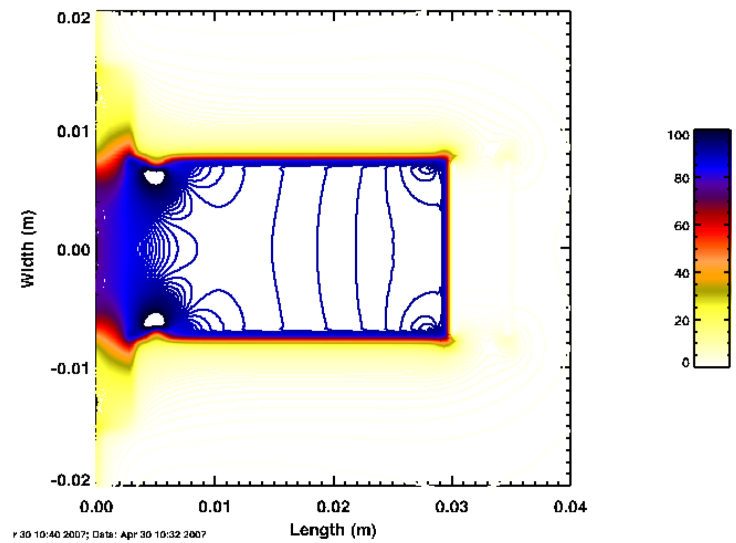
15 mm x 35 mm, 1 mm notch original panel, B at 0.2 μs

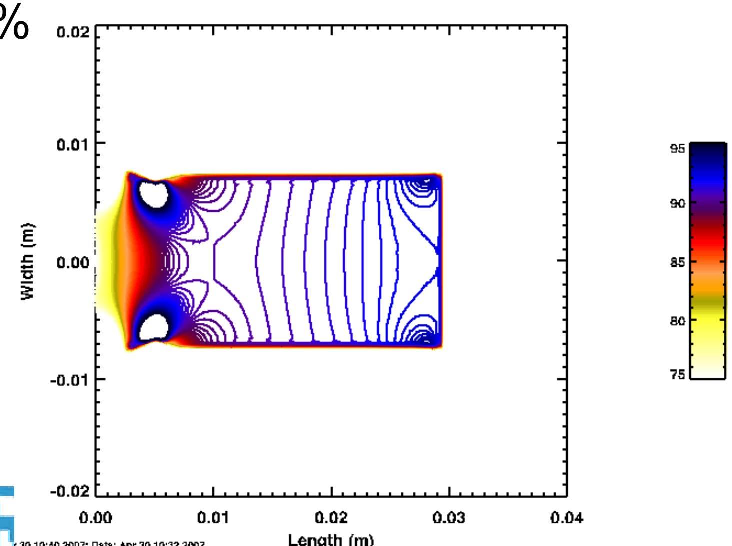




Modified panel

15 mm x 35 mm, 1 mm notch extended panel in contact area, B at 0.2 μs





Resolution:
Top plots: 0.45 %
Bottom plots: 0.25%

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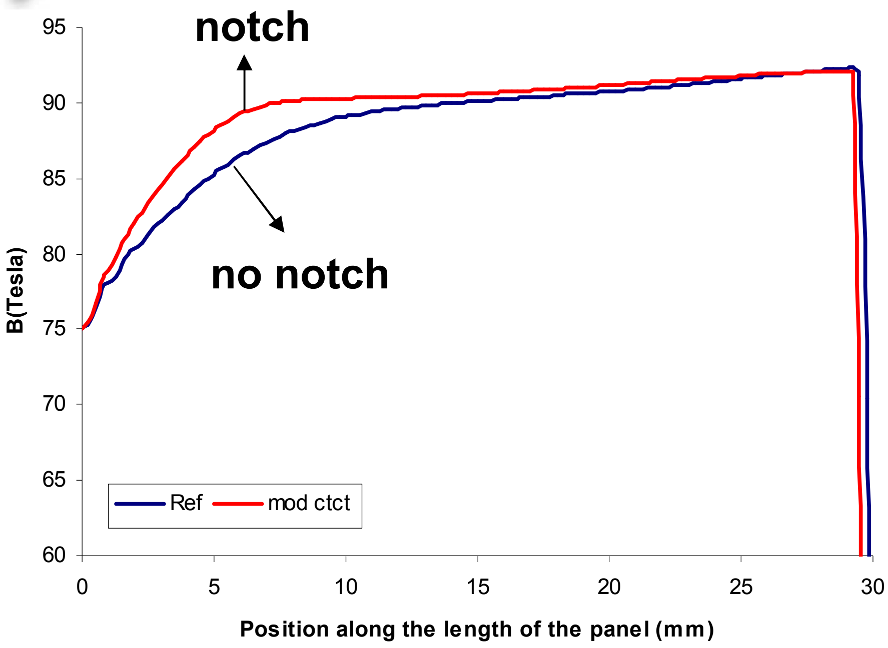
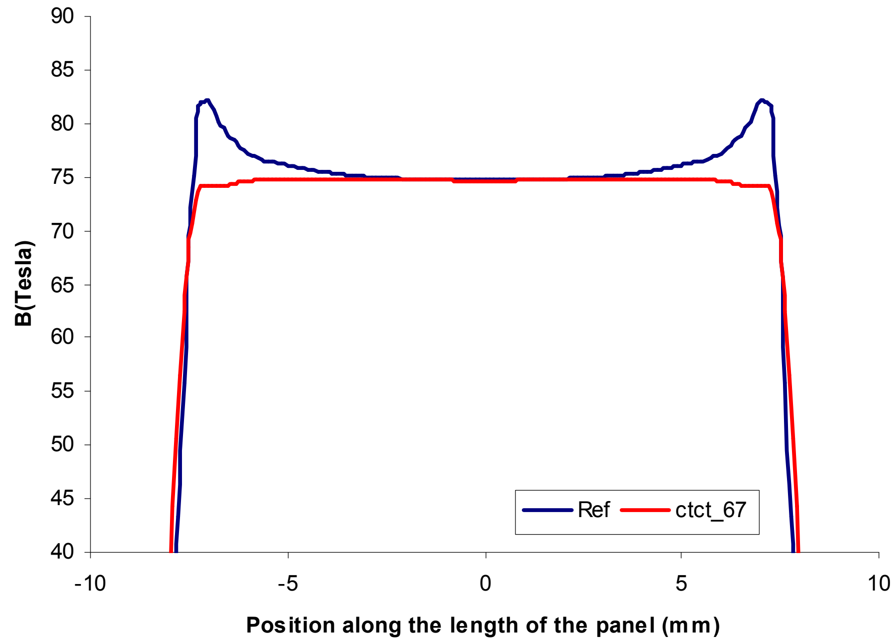
Present Results



B at the edge of the panel between the two panels.



B along the width of the panel at the edge of the contact between the two panels.

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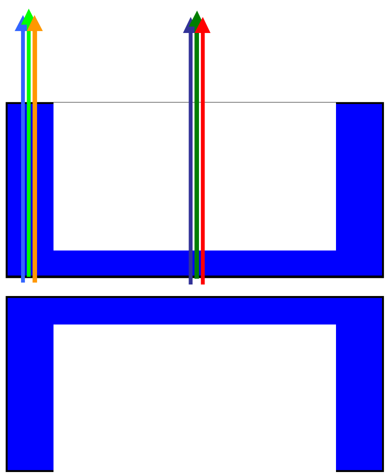
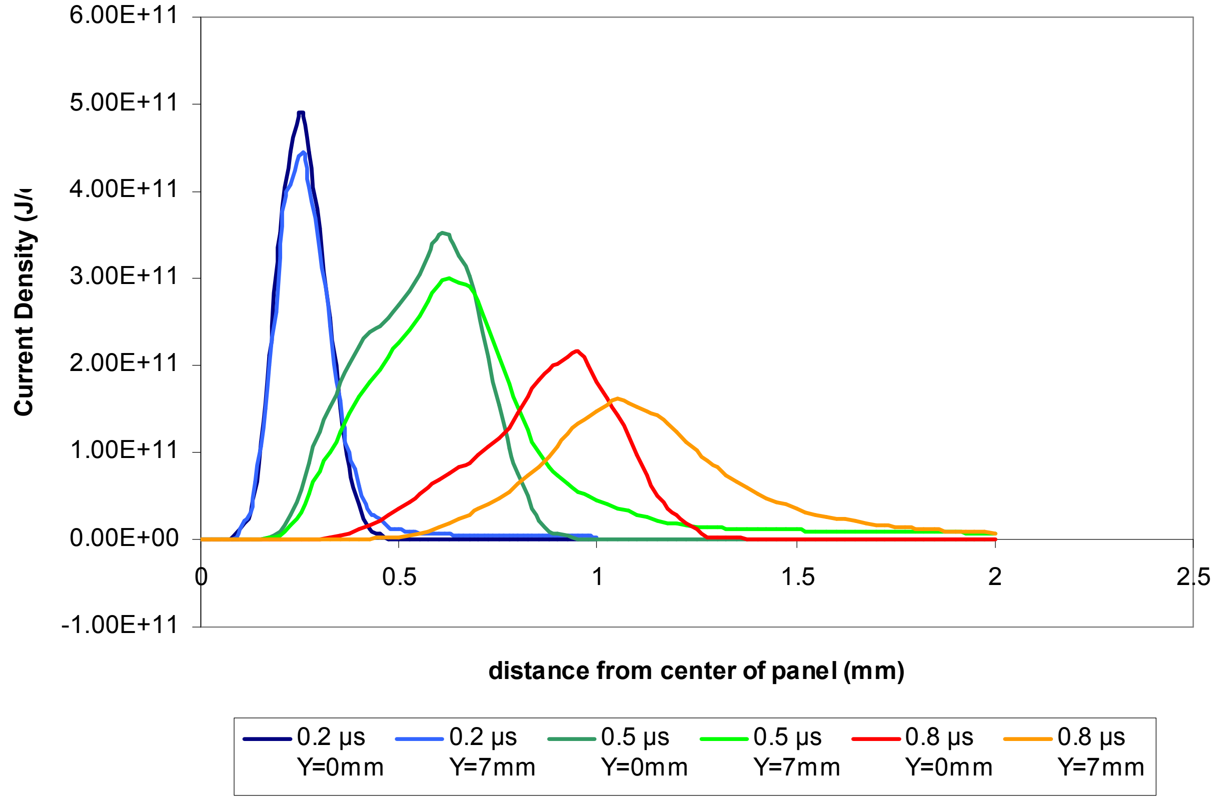
VELOCE Simulations: Load Area
Current Diffusion in the Panel





Total current density across the thickness of the panel at 2 cm from the bottom of the panel at three different times: 0.2 µs (blue curves), 0.5µs (green curves) and 0.8 µs (red-orange curves). The current density is estimated in the center of the panel width (Y=0 mm) and at the edge of the panel width (Y=7mm).

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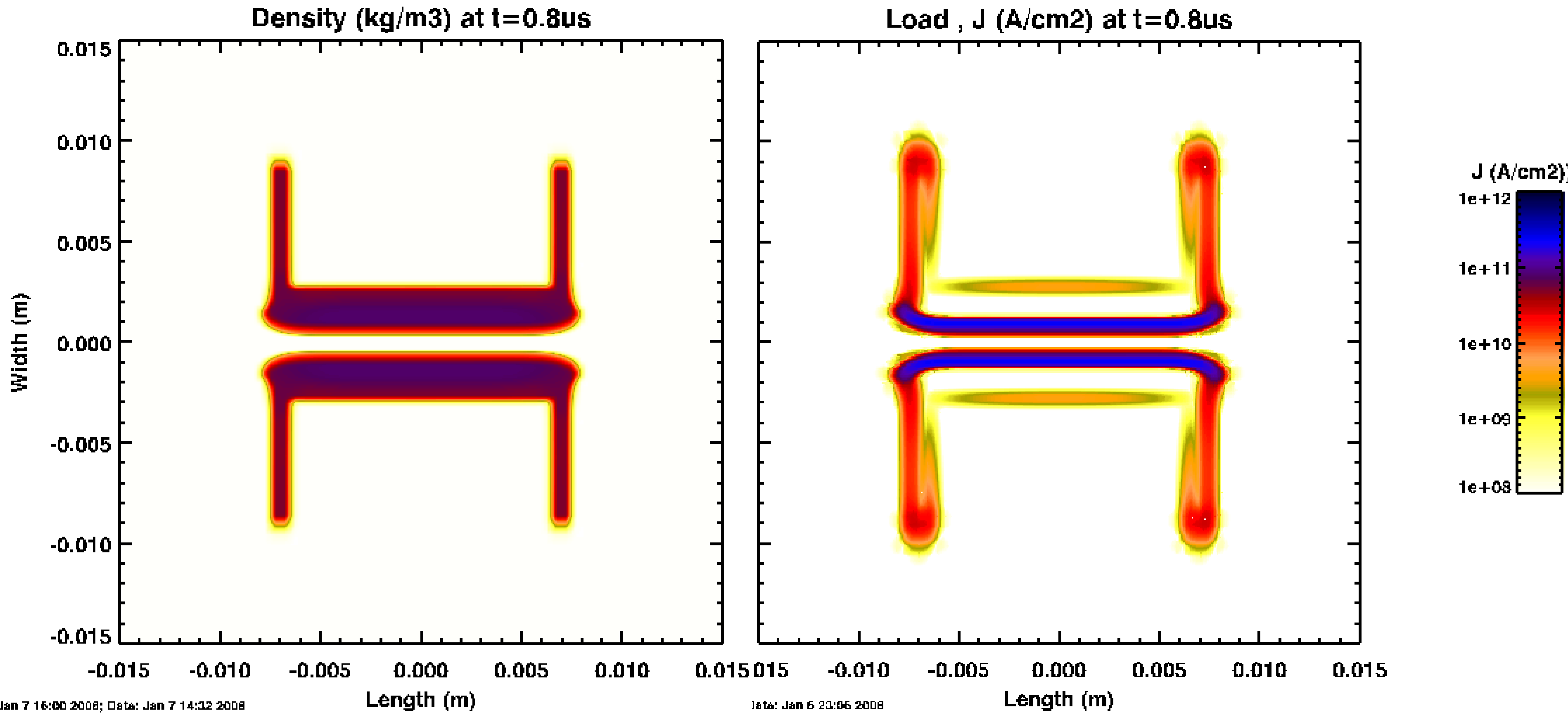
VELOCE Simulations: Load Area

Increased current in edges of the panel



Current density across the width of the panel at the location of the center of the sample along the length of the 35 mm panel at 800ns

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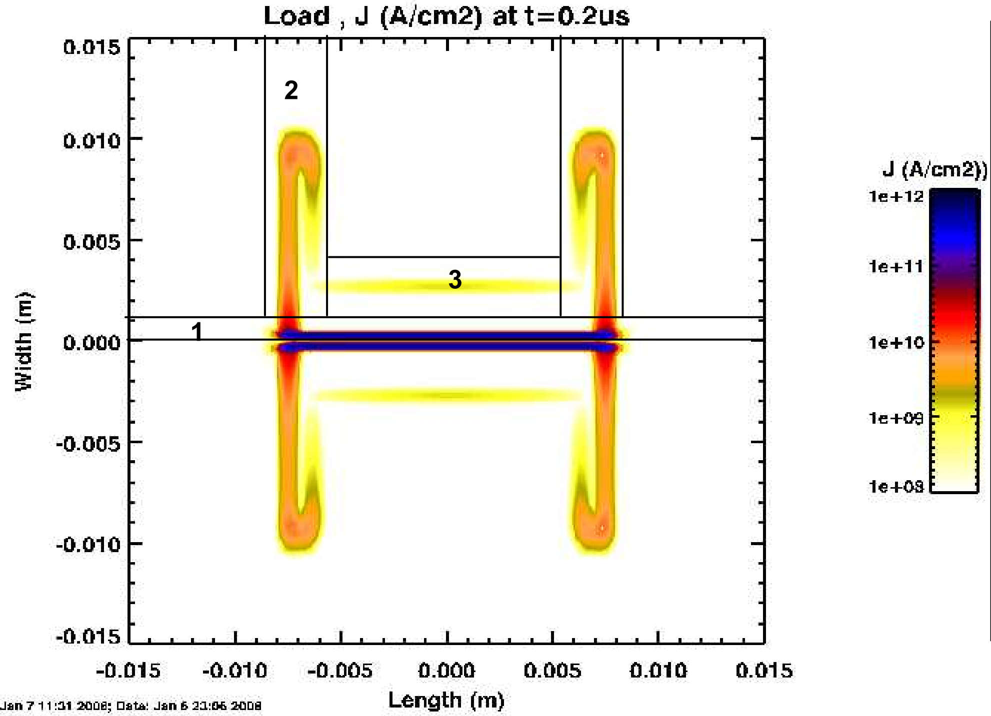
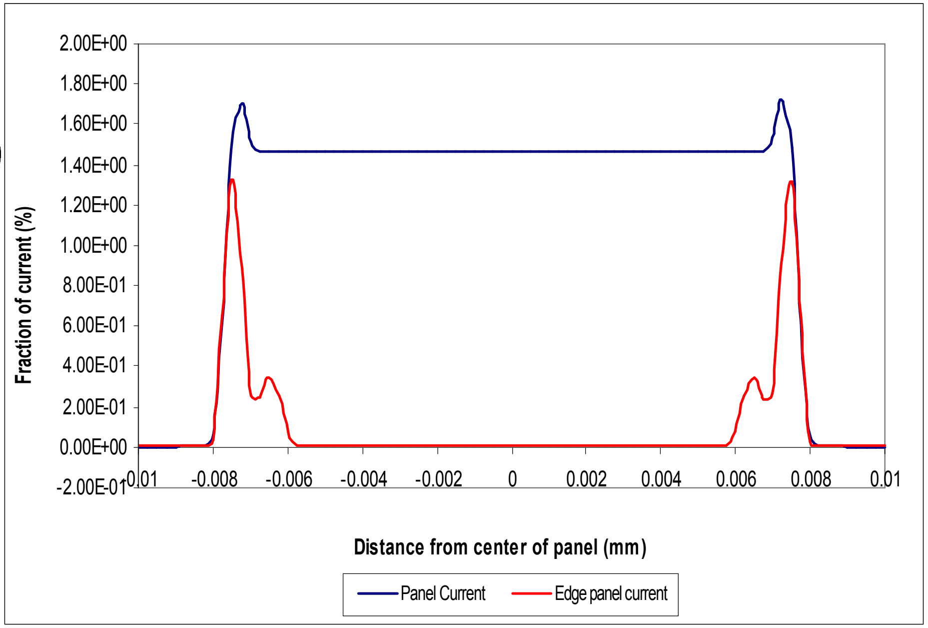
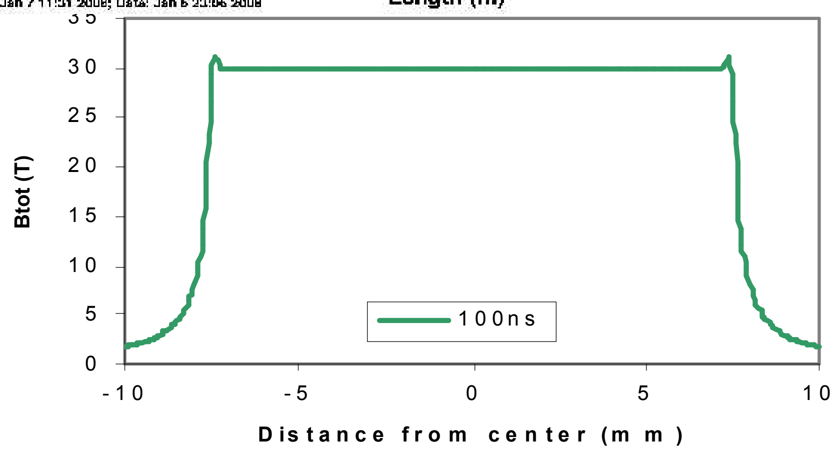
VELOCE Simulations: Load Area

Increased current in edges of the panel







Current at the edge of the panel at 200 ns:

- Area 1: 91.29%
- Area 2: 8.29%
- Area 3 : 0.42%

Using the magnetic field at the edge of the panel to evaluate the current uniformity across the panel is inaccurate at the edge of the panel.

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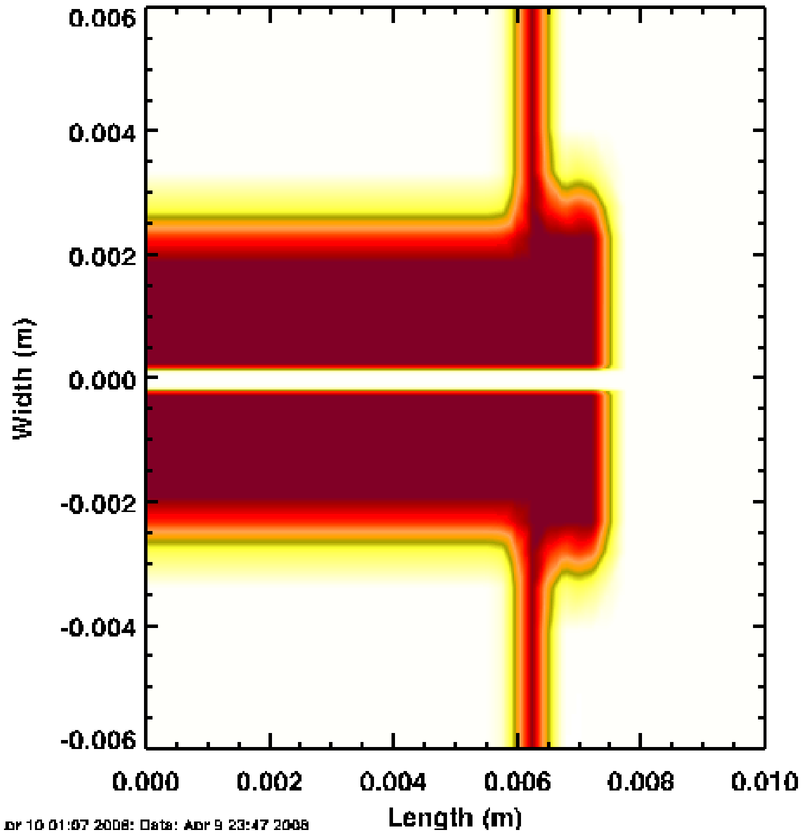
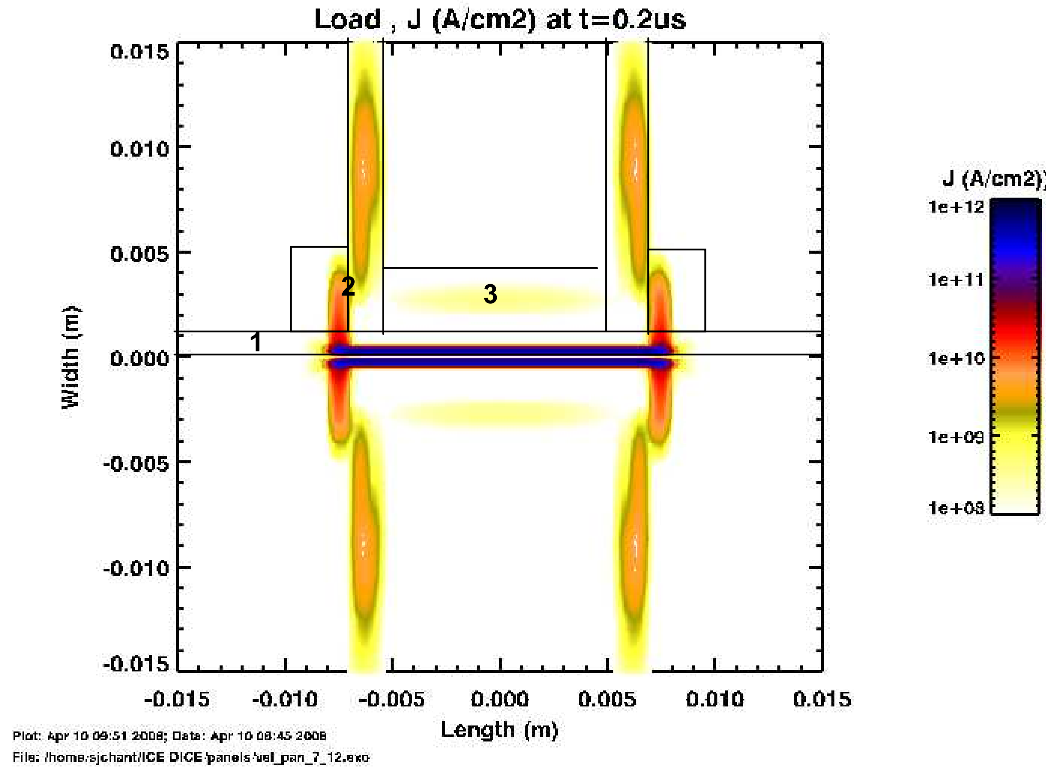
VELOCE Simulations: Preliminary design to reduce fraction of current in panel sides





Current at the edge of the panel at 200 ns:

	standard pane	preliminary design
• Area 1:	91.29%	95.15%
• Area 2:	8.29%	4.74%
• Area 3 :	0.42%	0.11%

Current in the panel sides cannot be eliminated but can be greatly reduced.

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Veloce Simulation: Taking into account of peaking capacitors

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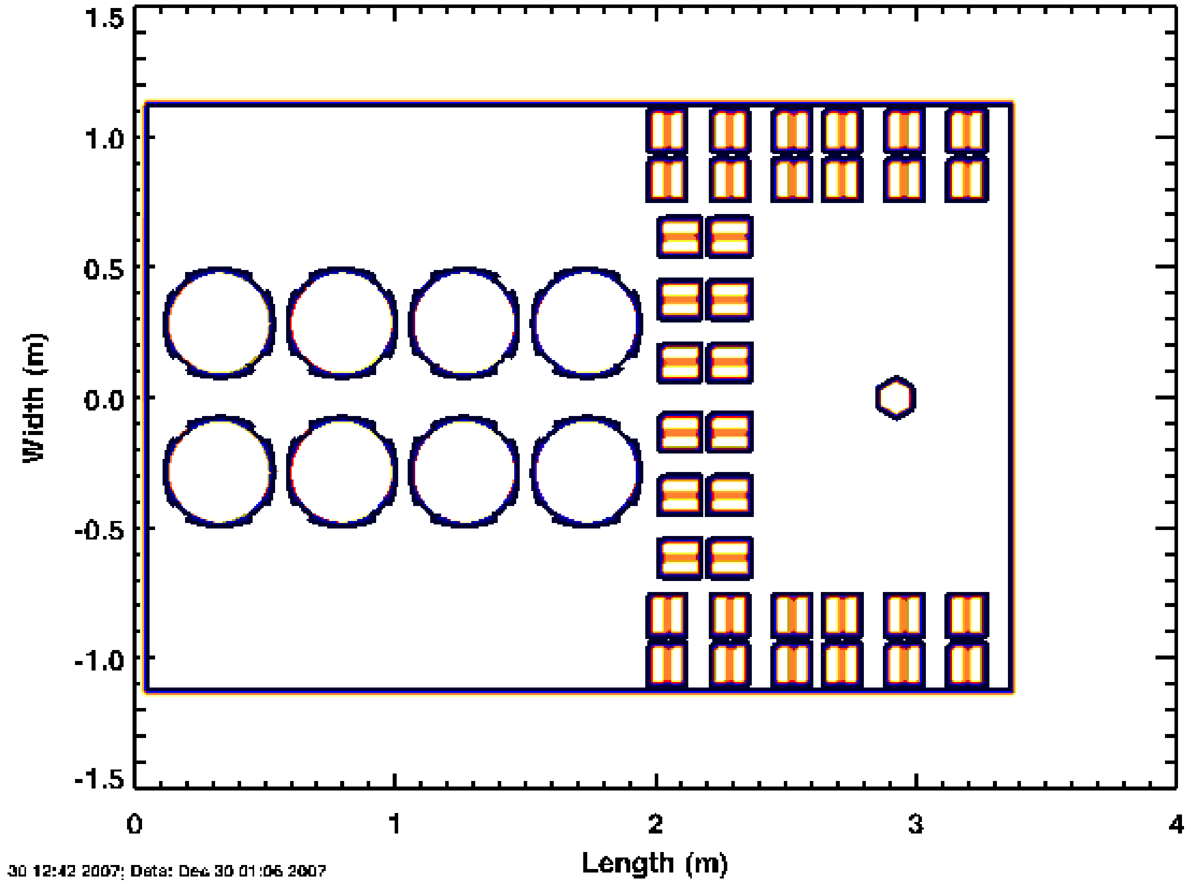
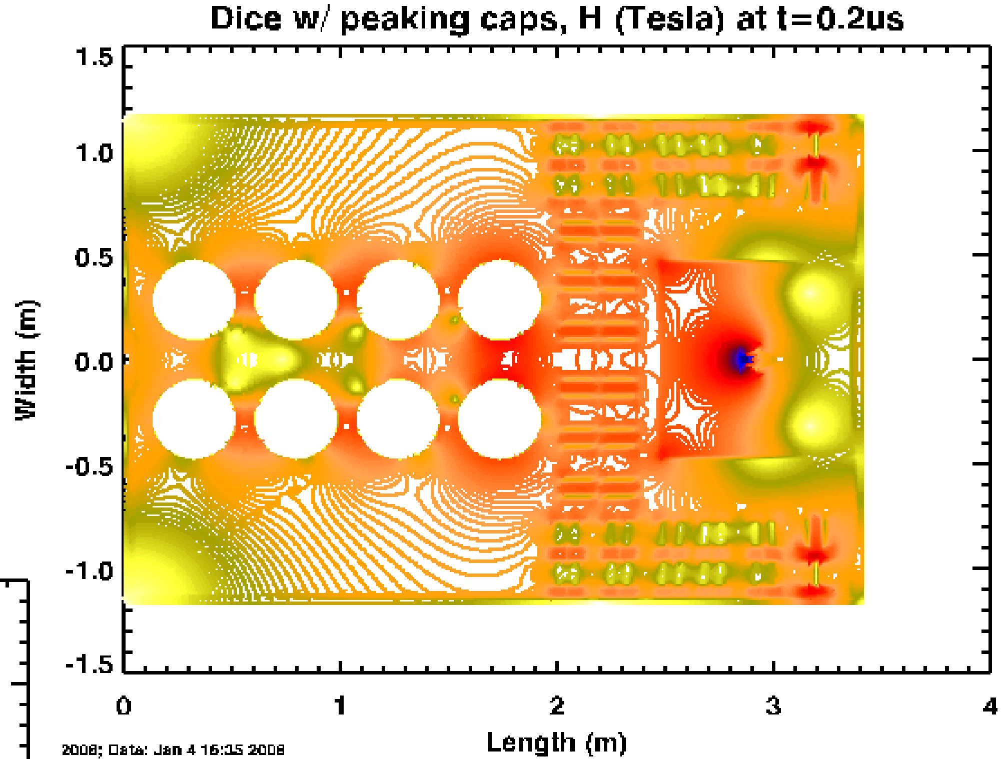
Veloce Simulation: Taking into account of peaking capacitors

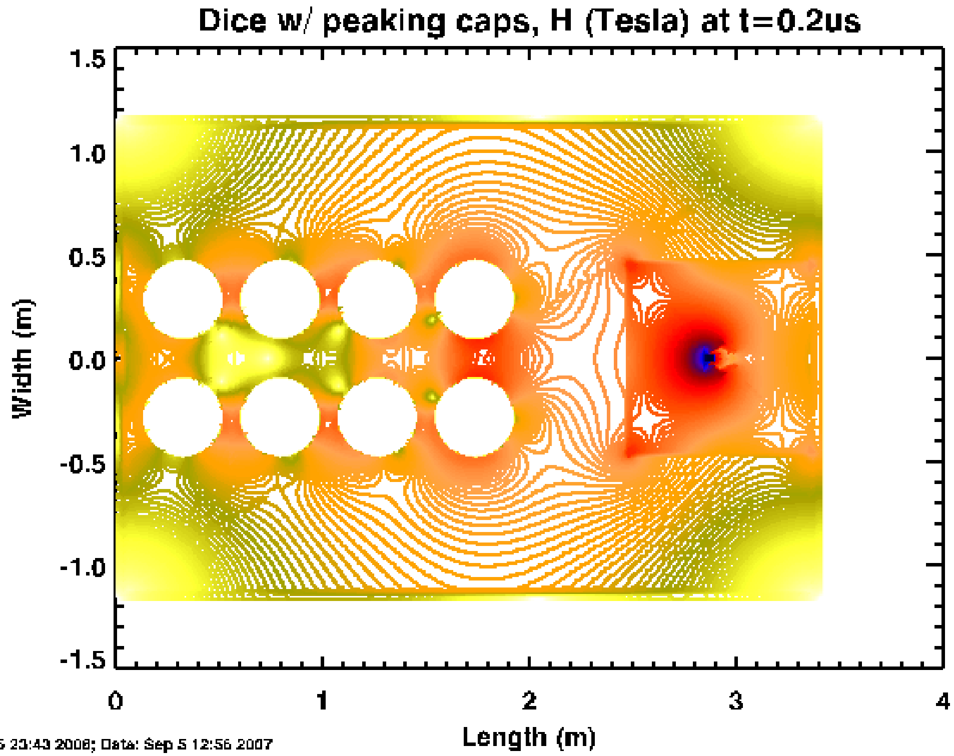


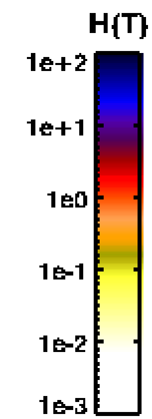
Peaking capacitors simulation attempt by introducing equivalent inductance, capacitance, and resistance in the original mesh

Taking into account of peaking capacitors

Simulation Results







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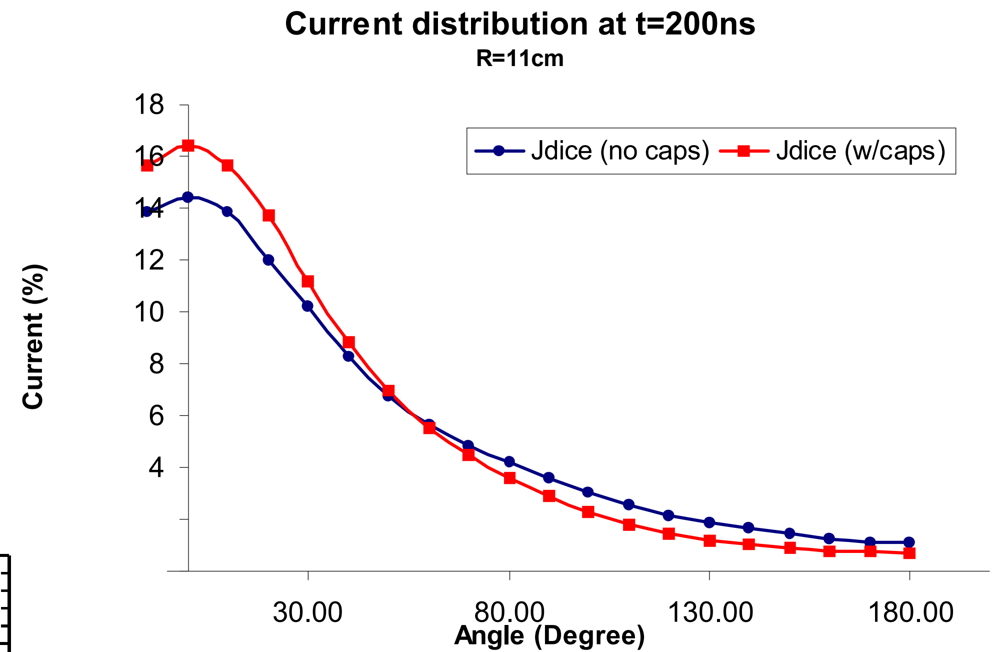
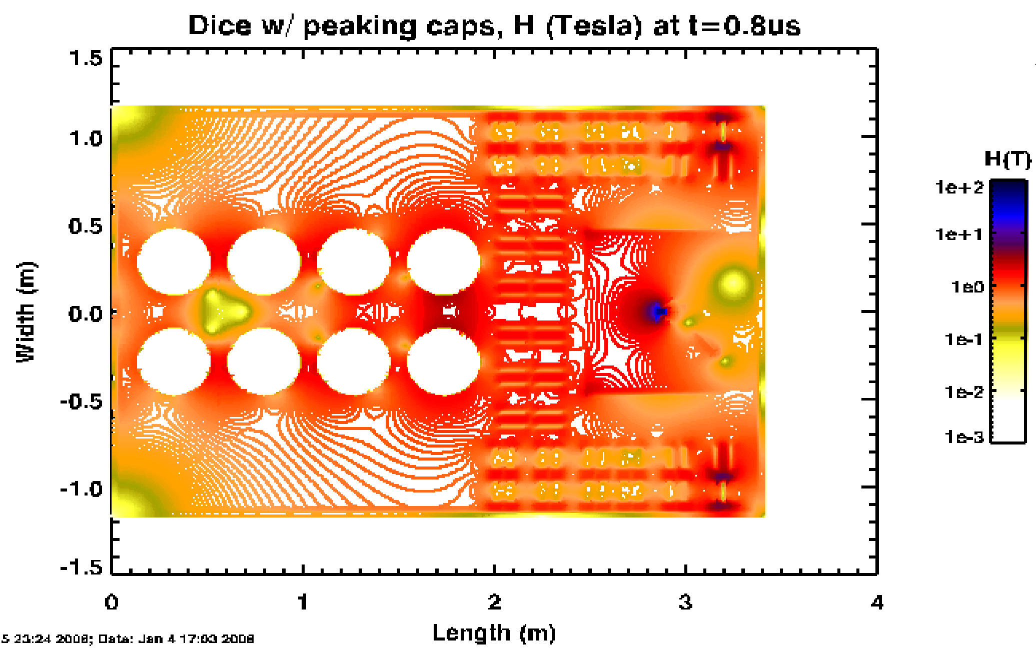
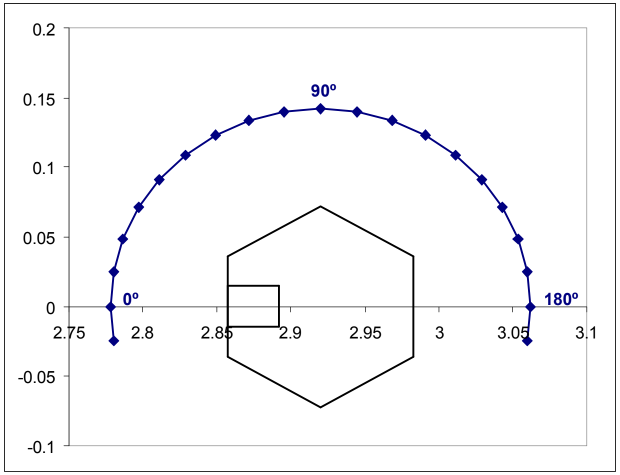
Taking into account of peaking capacitors

Simulation Results

Current angular distribution modified by change of inductance when peaking capacitors are included







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Conclusions

- 3D simulations of VELOCE allow us to:
  - understand the current density distribution across the sample panel for a wide variety of panels thereby increasing the uniformity of the current and improving measurement accuracy
  - design the optimum panel for a specific sample minimizing the number of shots required for a given sample
- The simulations reproduced experimental free-surface velocities very well; resolution is the only limitation in 3D
- To obtain accurate results, spatial resolution is critical
- Dielectric constant should be added as input parameter in Alegra (maybe need to add more physics?)
- "Accomplishing the impossible means only that Jim Asay will add it to your regular duties" – Doug Larson

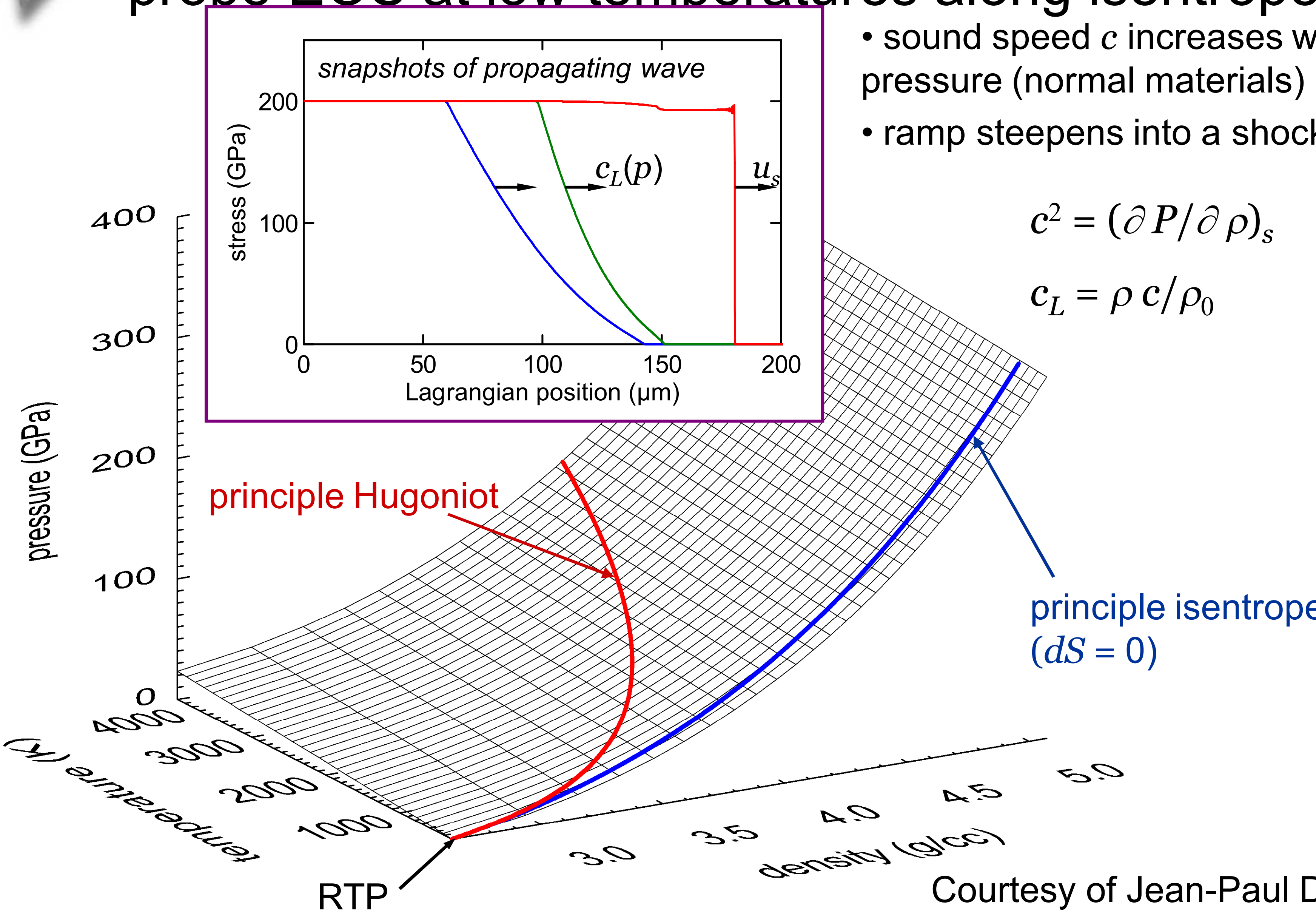
5) Backup Slides

Unsteady (ramped) compression waves probe EOS at low temperatures along isentrope

- sound speed c increases with pressure (normal materials)
- ramp steepens into a shock

$$c^2 = (\partial P/\partial \rho)_s$$

$$c_L = \rho\, c/\rho_0$$



Courtesy of Jean-Paul Davis