Experimental testing of masonry structures subjected to extreme loads

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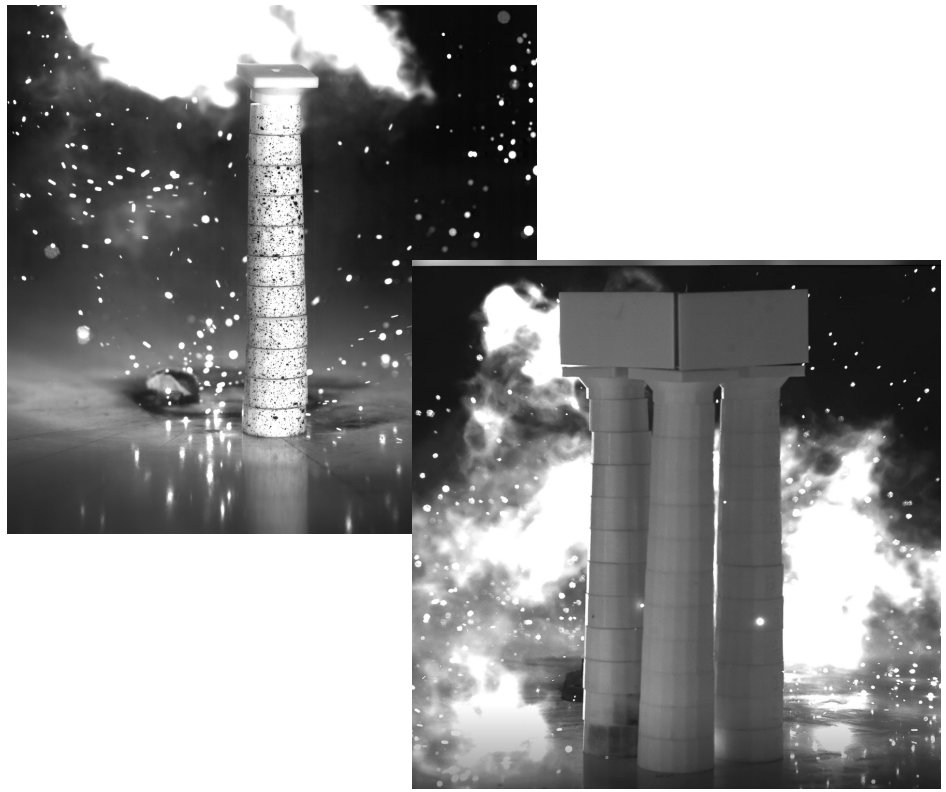
Acknowledgments: Prof. Guillaume Racineux
Eng. Emmanuel Marché



BLAST

CENTRALE NANTES

GeM Institut de Recherche en Génie Civil et Mécanique

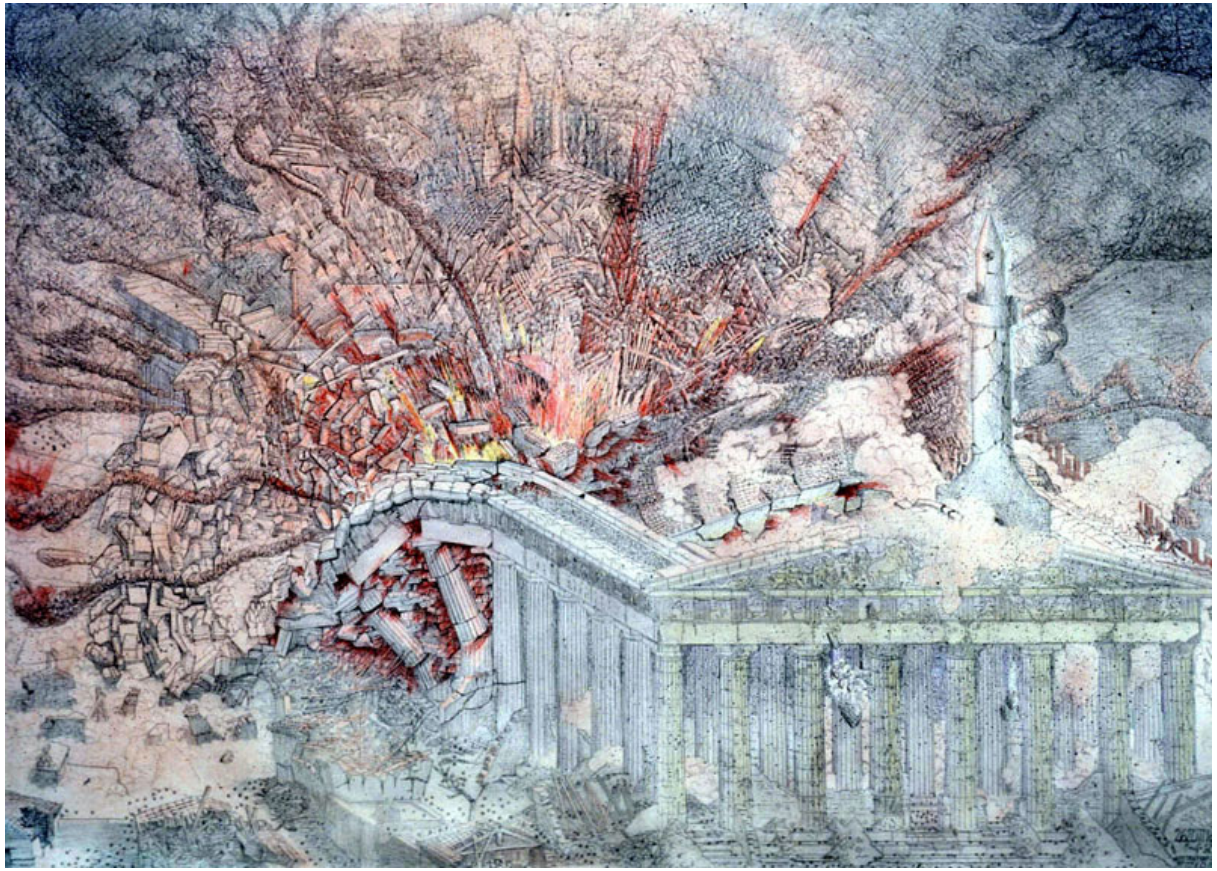
CONNECTALENT.ORG

Région PAYS DE LA LOIRE

Nantes Métropole

Historical and modern structures under explosions

Parthenon 1687



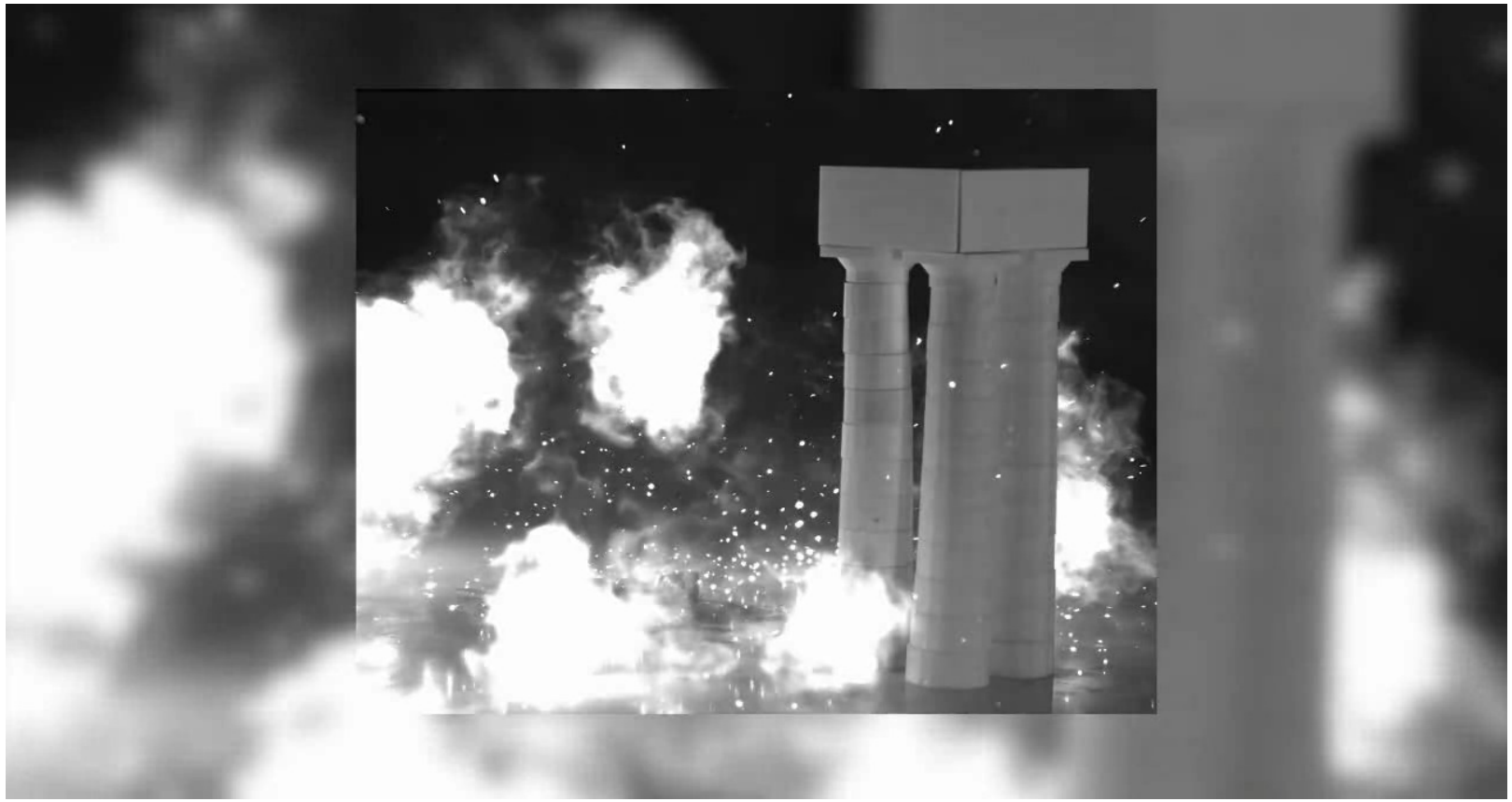
Korres et al. (1999)

Beirut 2020

https://news.sky.com/story/beirut-explosion-rescuers-search-for-survivors-after-deadly-ammonium-nitrate-blast-12042827

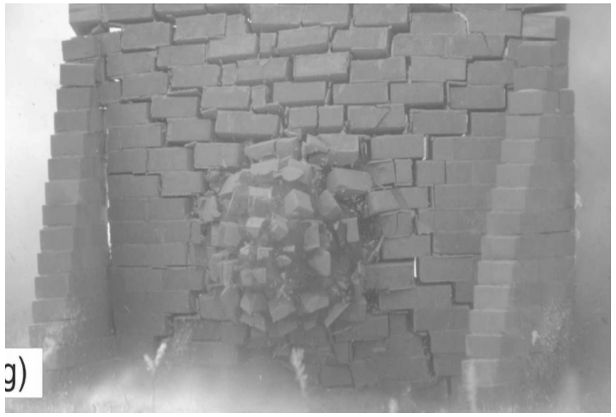
Goal

Study the fast dynamic response of structures subjected to blast scenarios experimentally.

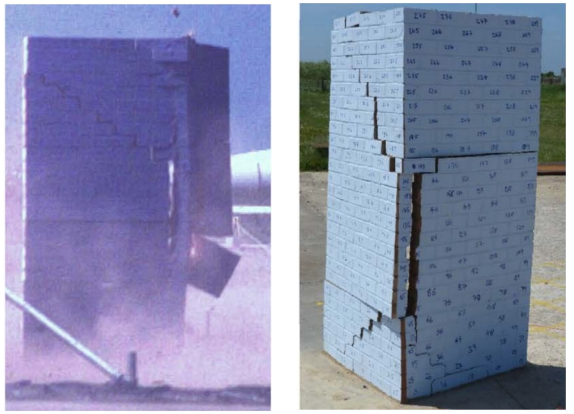


State of the art and novelty

Full scale: The experiments are not repeatable, expensive, and laborious, (Pereira et al. 2014, Ahmad et al. 2014, Li et al. 2017, Godio et al. 2021, ….).



Sielicki et al. 2019



Keys et Clubley 2017

Reduced scale: The experiments are focused on studying shock wave propagation, (Zyskowski et al. 2004, Pennetier et al. 2015, Trelat et al. 2011, Sochet,et al. 2019, ….).

Novelty: Study the structural response at a reduced scale

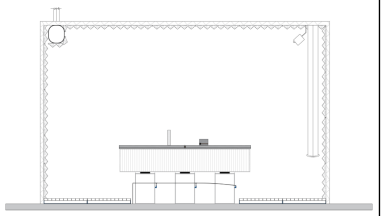
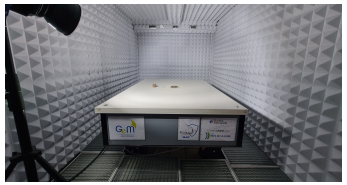
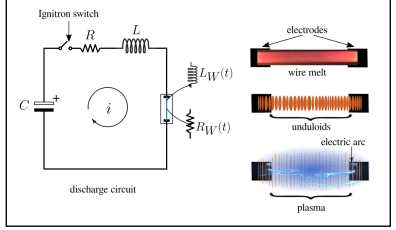
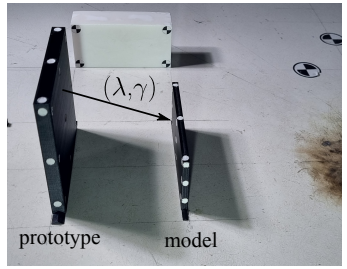
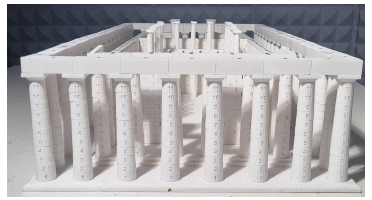
Objectives

1) Design a novel experimental setup

2) Study the explosive source

3) Validate the scaling laws

4) Proof of concept

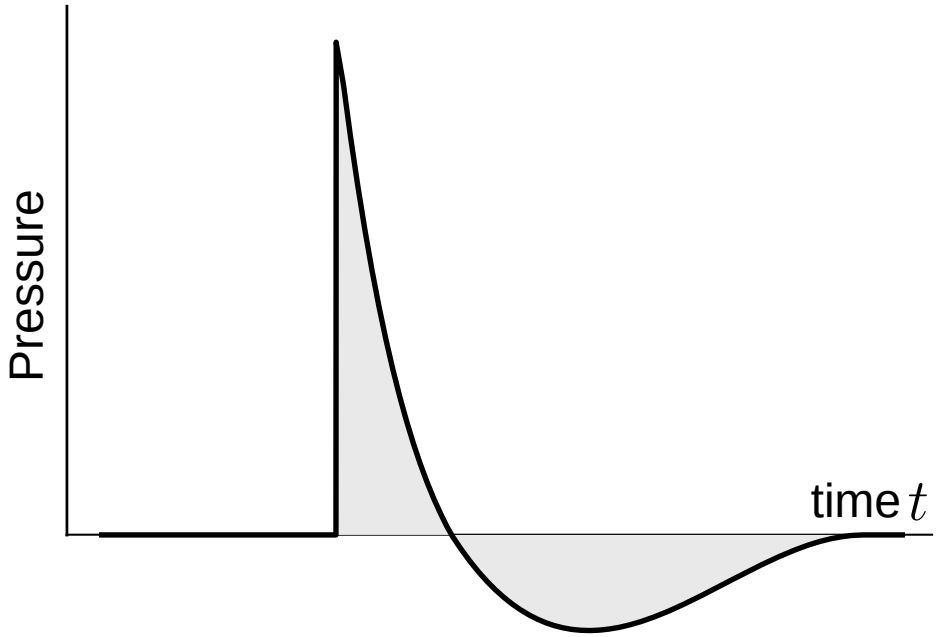
Platform (miniBLAST)		Explosive source (exploding wires)		Scaling laws	Proof of concept
Design	**Installation**	**Electric system**	**Shock wave**		
					

Explosions

Beirut explosion 2020

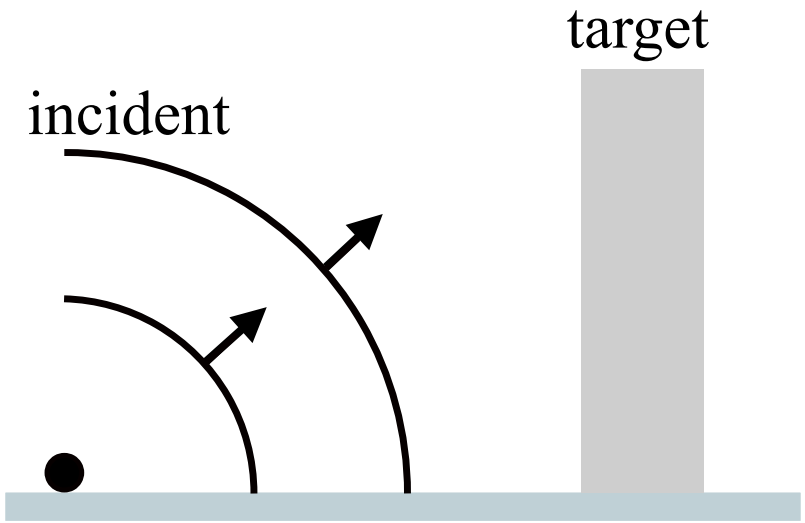
theengineer7732

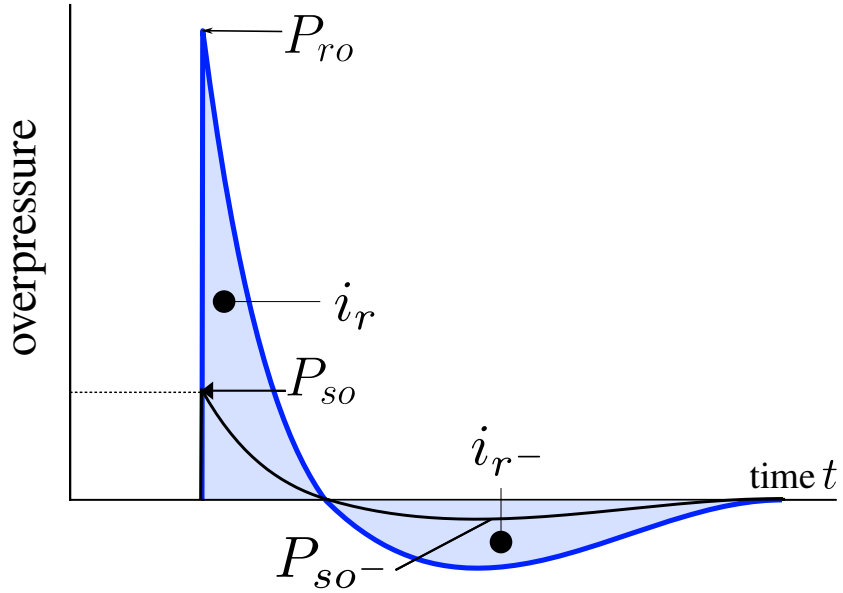
www.aljazeera.com



Blasts effects on structures

The reflected overpressure acting on a target can be far greater than the incident overpressure





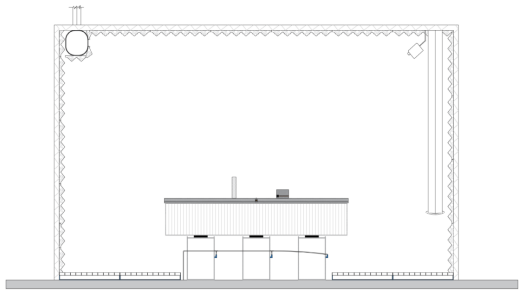
P_{so} , P_{so-} peak incident over- and underpressure

P_{ro} , P_{ro-} peak reflected over- and underpressure

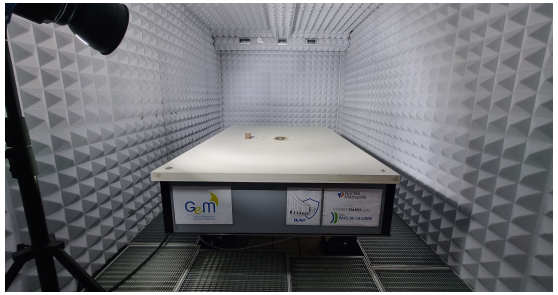
i_r , i_{r-} reflected positive and negative impulse

Platform (miniBLAST)

Design



Installation



Explosive source (exploding wires)

Electric system

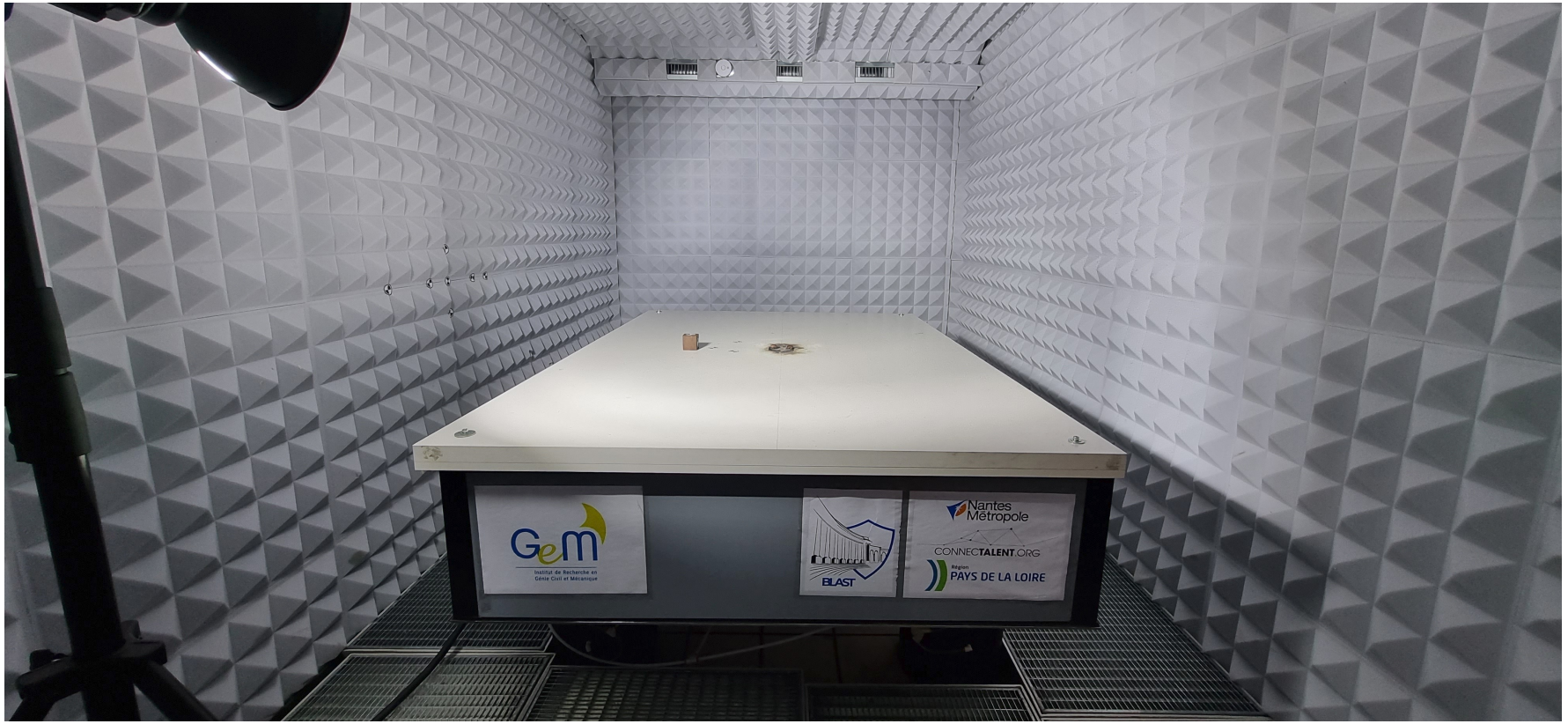
Shock wave

Scaling laws

Proof of concept

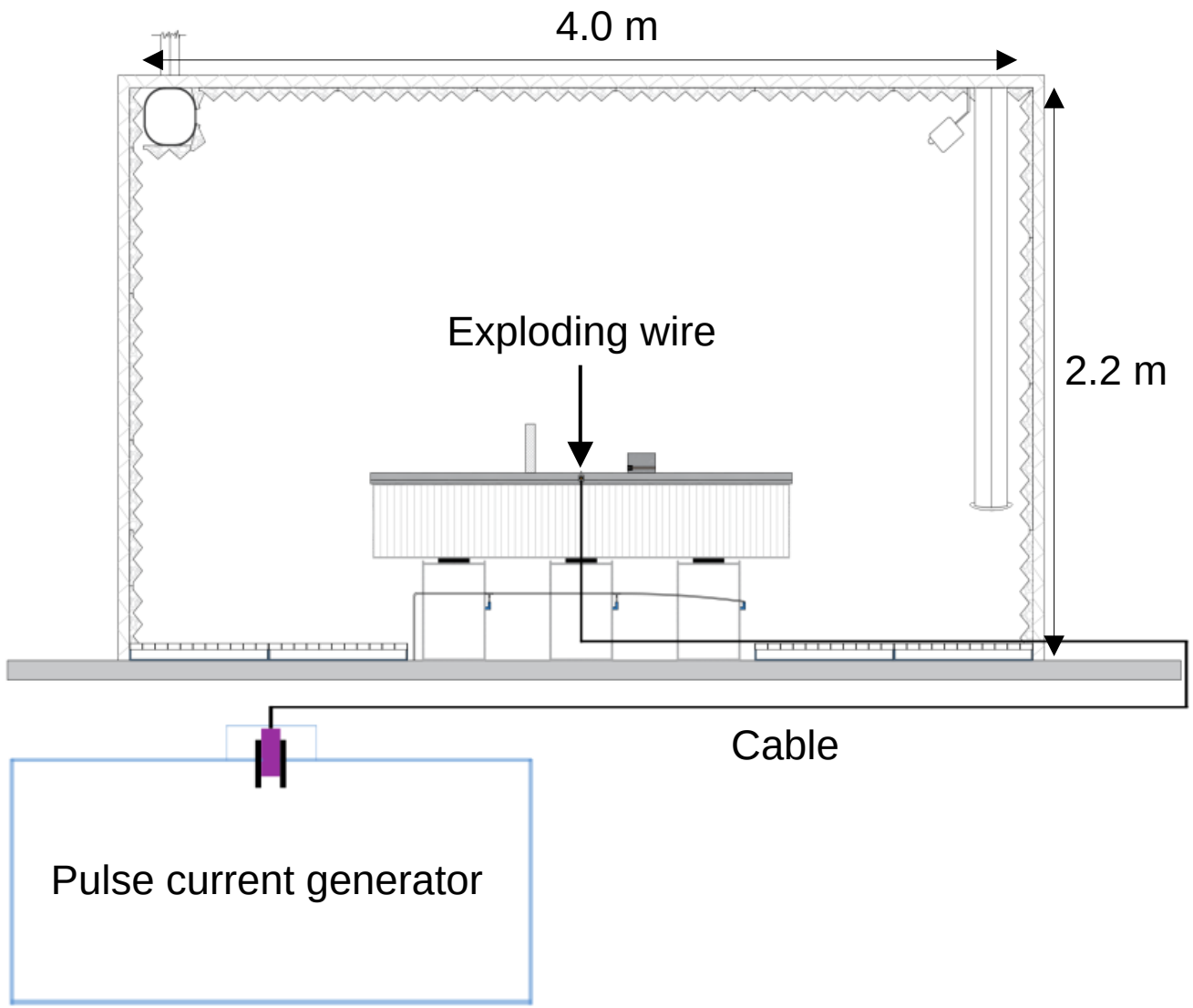
miniBLAST and design steps

- Explosive source and its components
- Metrology
- Structure prototyping and optical table
- Environmental safety



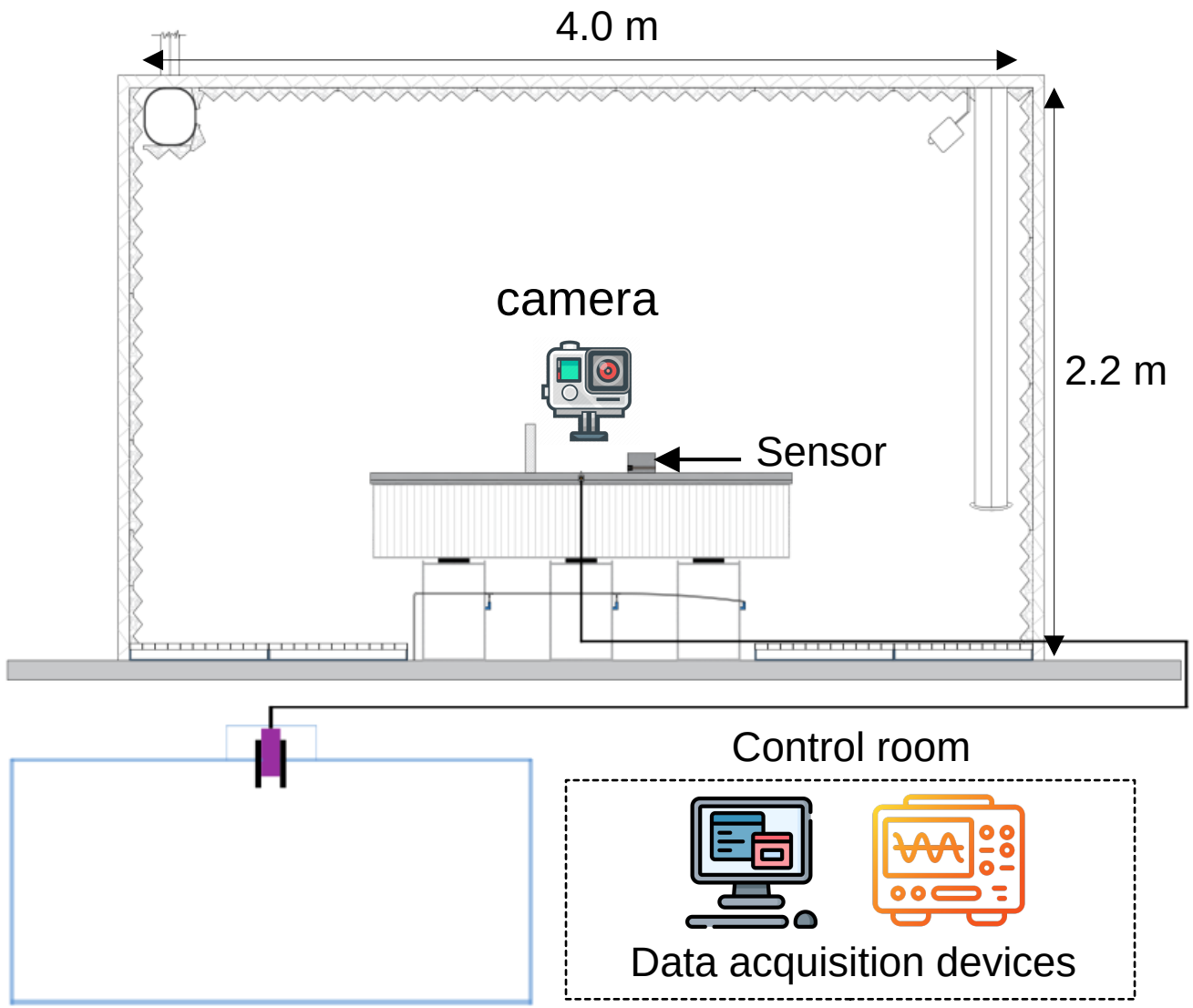
miniBLAST and design steps

- Explosive source and its components



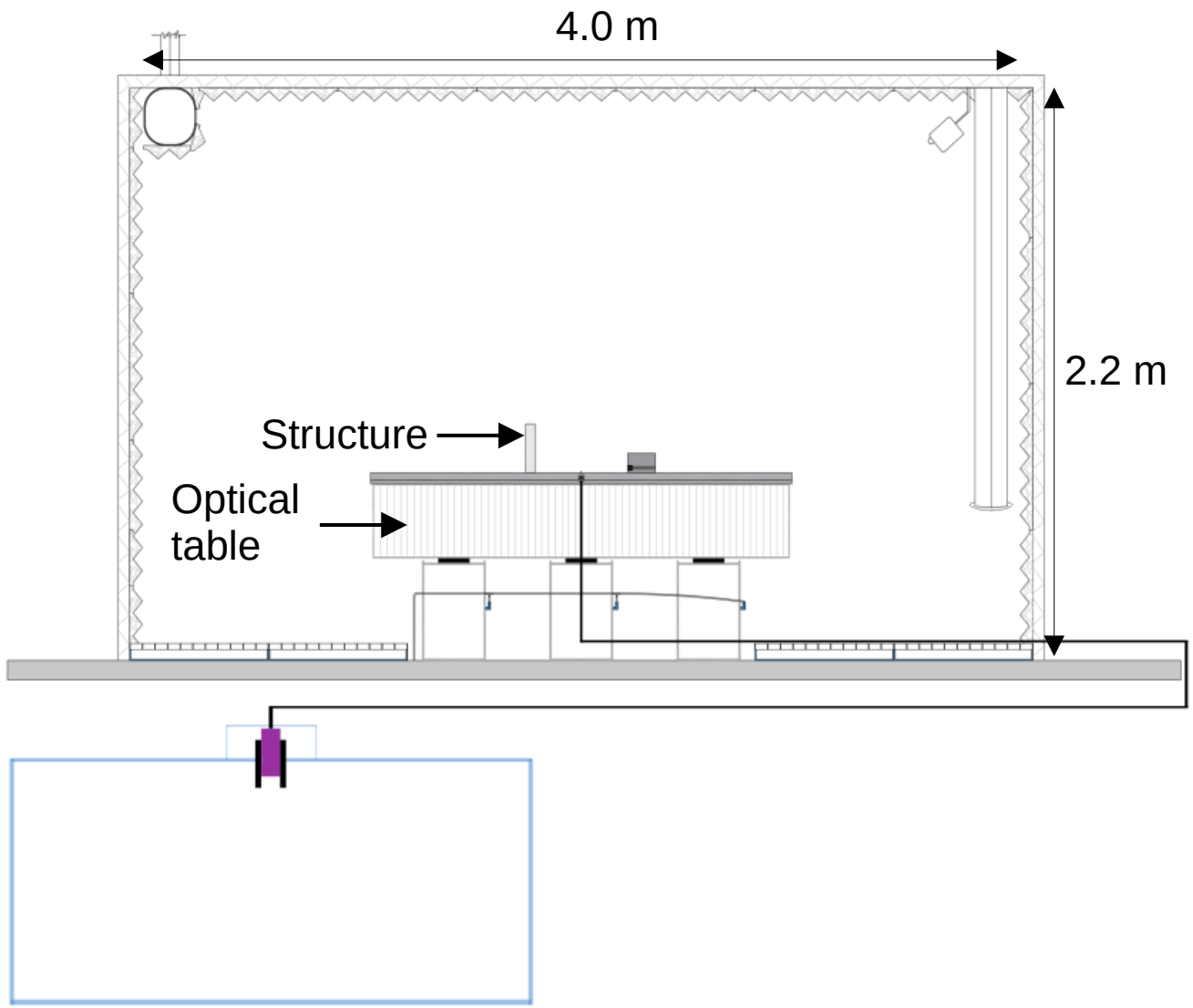
miniBLAST and design steps

- Explosive source and its components
- Metrology
  - Sensors
  - Data acquisition devices
  - Cameras



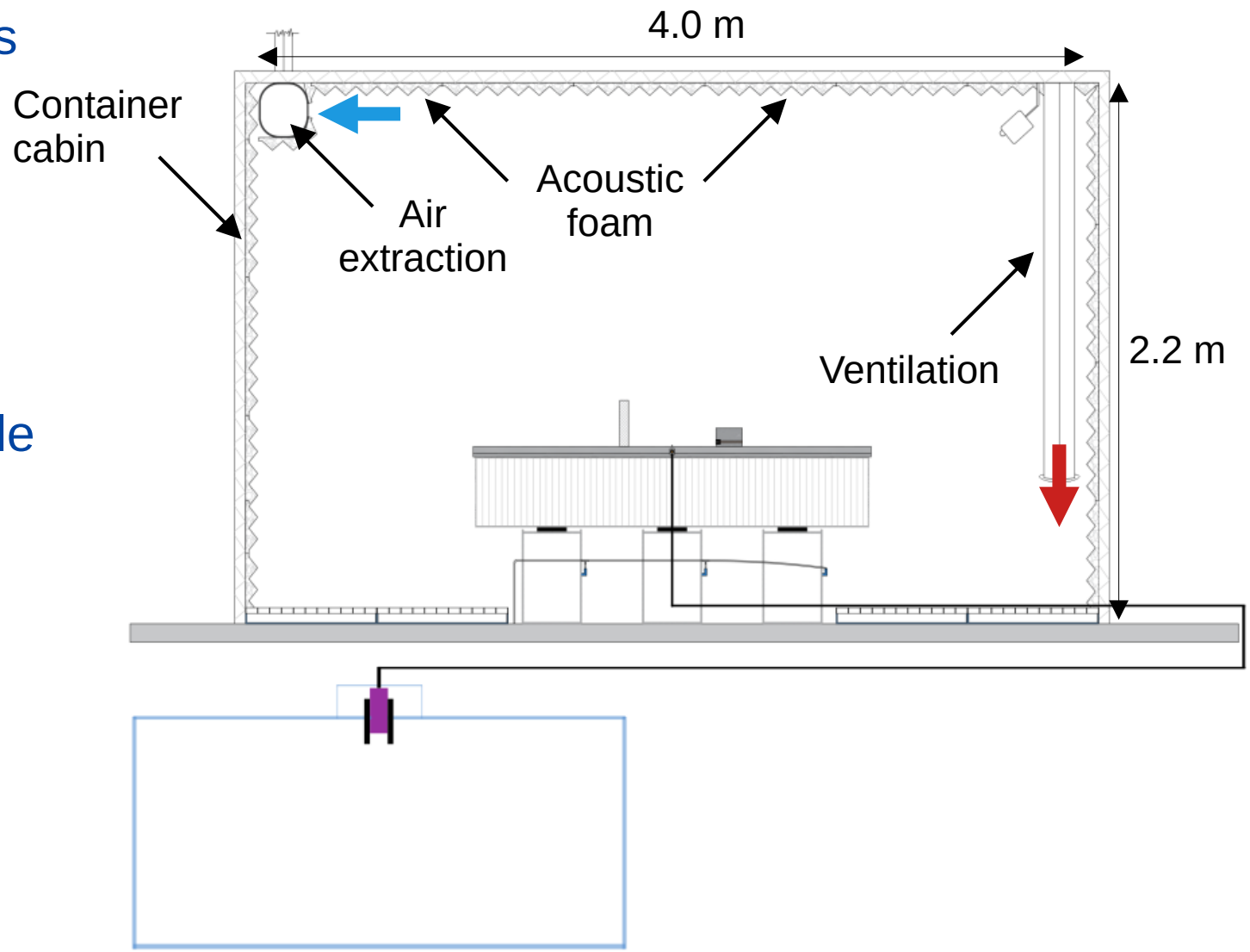
miniBLAST and design steps

- Explosive source and its components
- Metrology
  - Sensors
  - Data acquisition devices
  - Cameras
- Structure prototyping and optical table
  - Optical table
  - Structure prototyping (FDM, SLA)



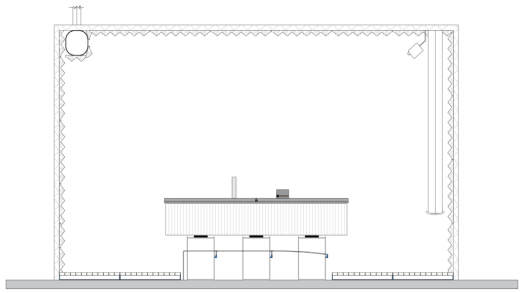
miniBLAST and design steps

- Explosive source and its components
- Metrology
  - Sensors
  - Data acquisition devices
  - Cameras
- Structure prototyping and optical table
  - Optical table
  - Structure prototyping (FDM, SLA)
- Environmental safety
  - Container cabin
  - Acoustic foam
  - Ventilation system

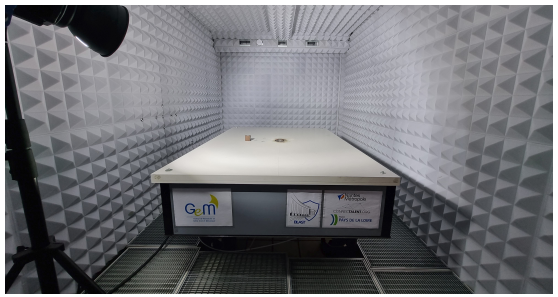


Platform (miniBLAST)

Design



Installation



Explosive source (exploding wires)

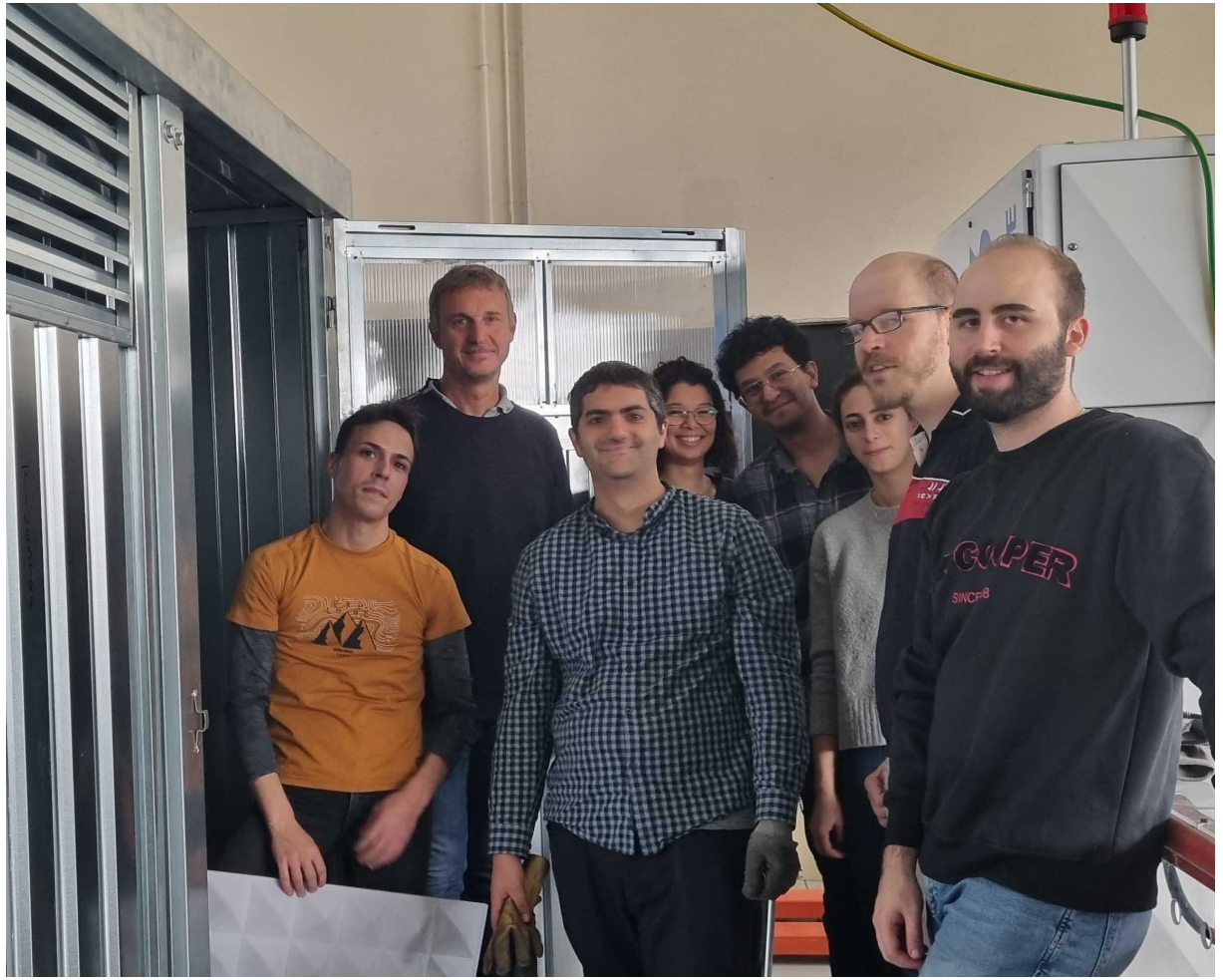
Electric system

Shock wave

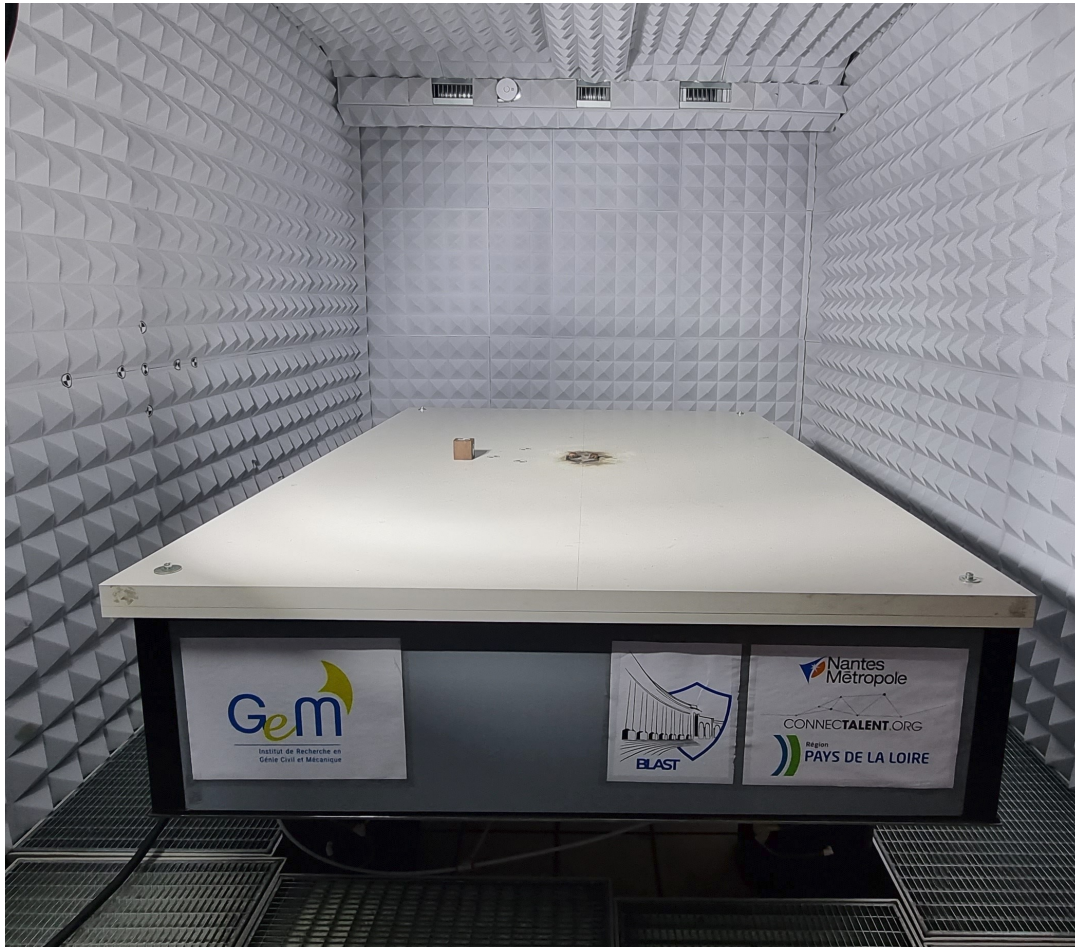
Scaling laws

Proof of concept

Novel experimental setup



Novel experimental setup



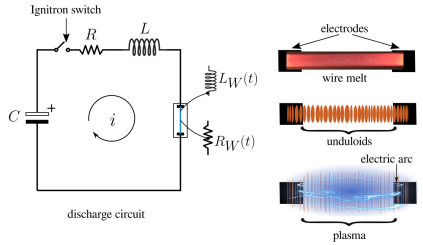
Platform (miniBLAST)

Design

Installation

Explosive source (exploding wires)

Electric system



Shock wave

Scaling laws

Proof of concept

Explosive source mechanism

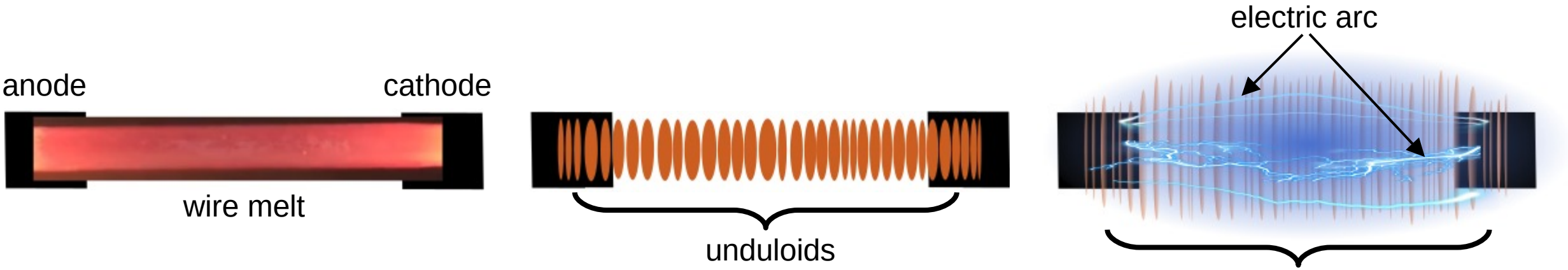
The following stages take place in the exploding wire

S1. current discharge and wire's melt

S2. formation of unduloids

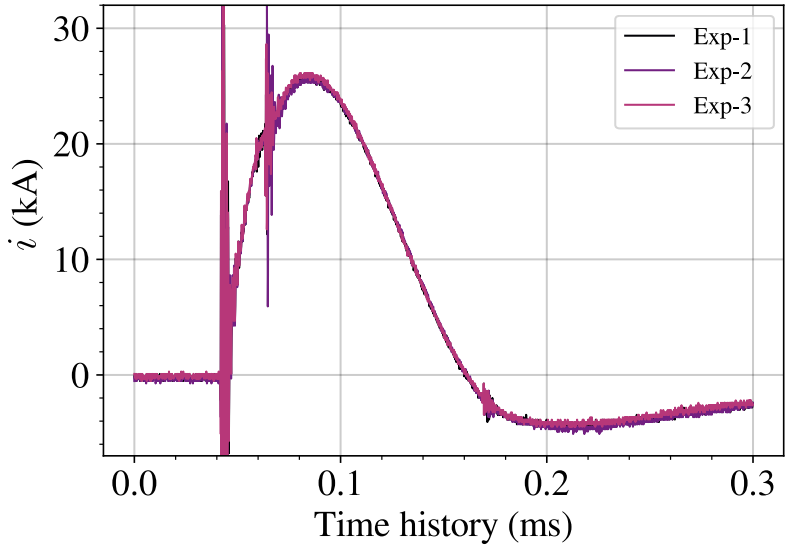
S3. electrical breakdown and appearance of electric arcs

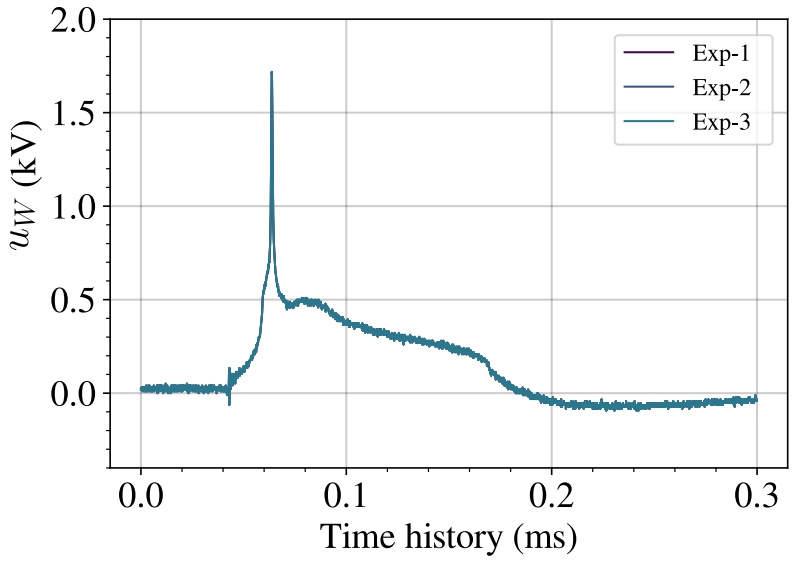
S4. formation of pressure shock waves

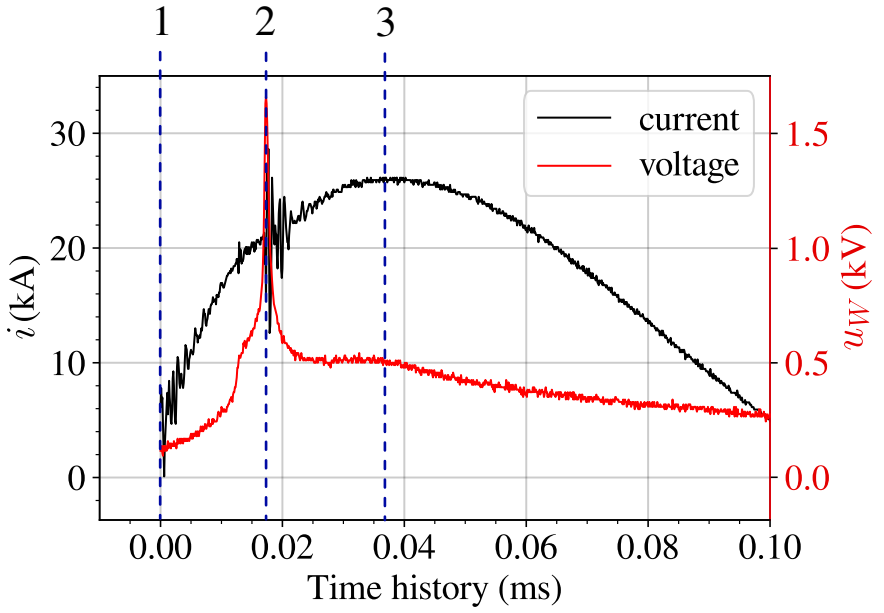


Liu et al. (2019)

Current and voltage evolution

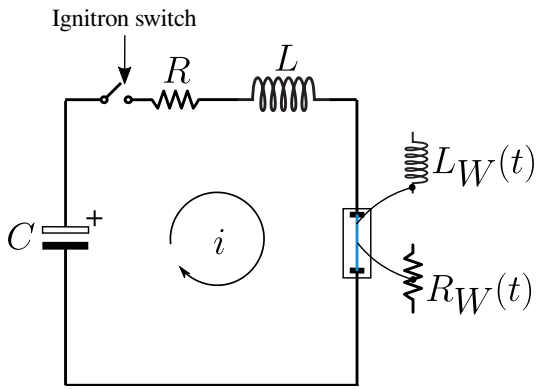






$i(t)$ discharge current

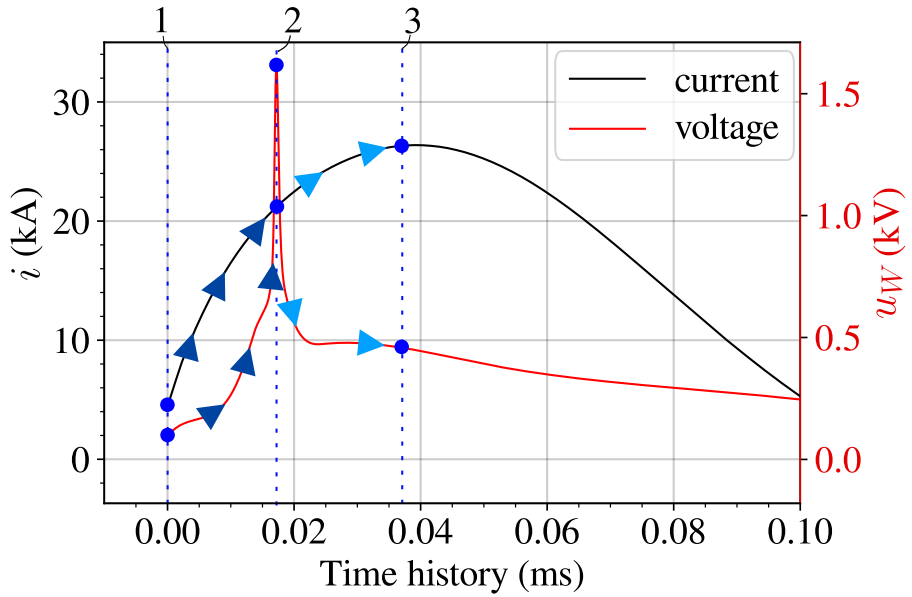
$u_W(t)$ potential difference of the wires extremities (voltage)

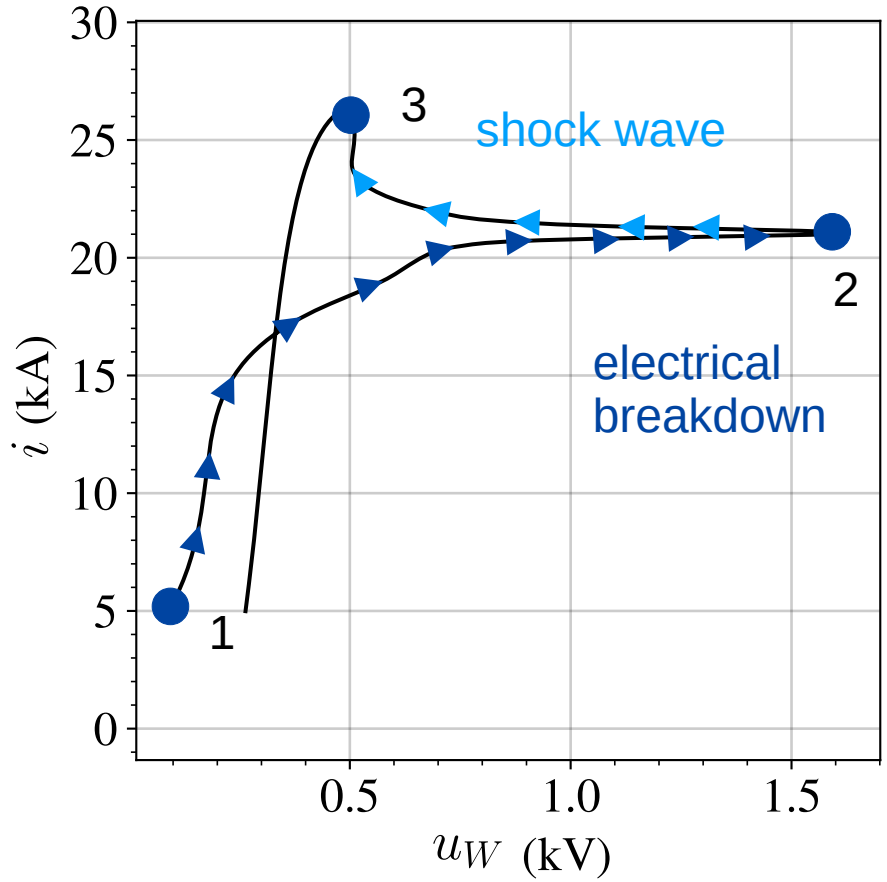


Current and voltage evolution

Explosion stages

- 1-2: formation of unduloids and electrical breakdown (s1 and s2)
- 2-3: electric arcs (s3) and pressure shock wave (s4)





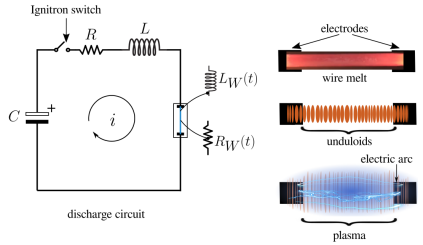
Platform (miniBLAST)

Design

Installation

Explosive source (exploding wires)

Electric system



Shock wave

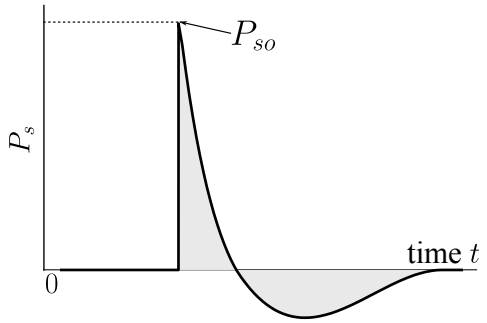
Scaling laws

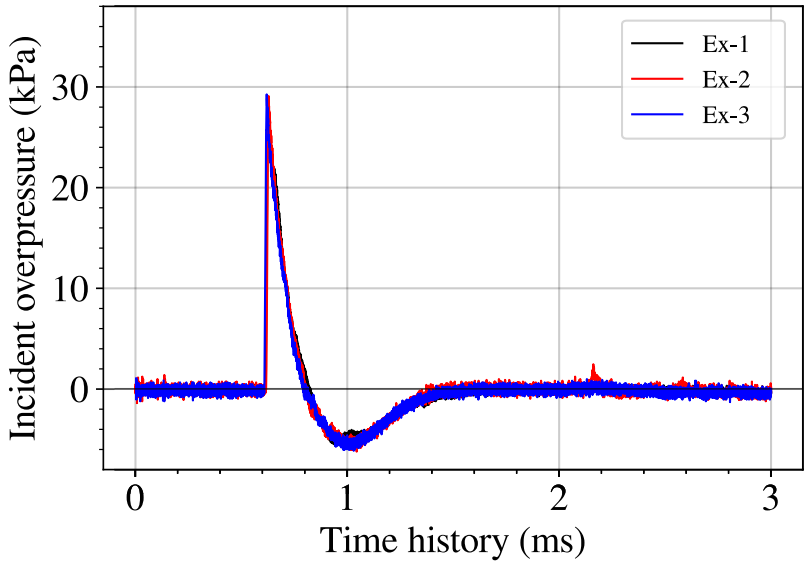
Proof of concept

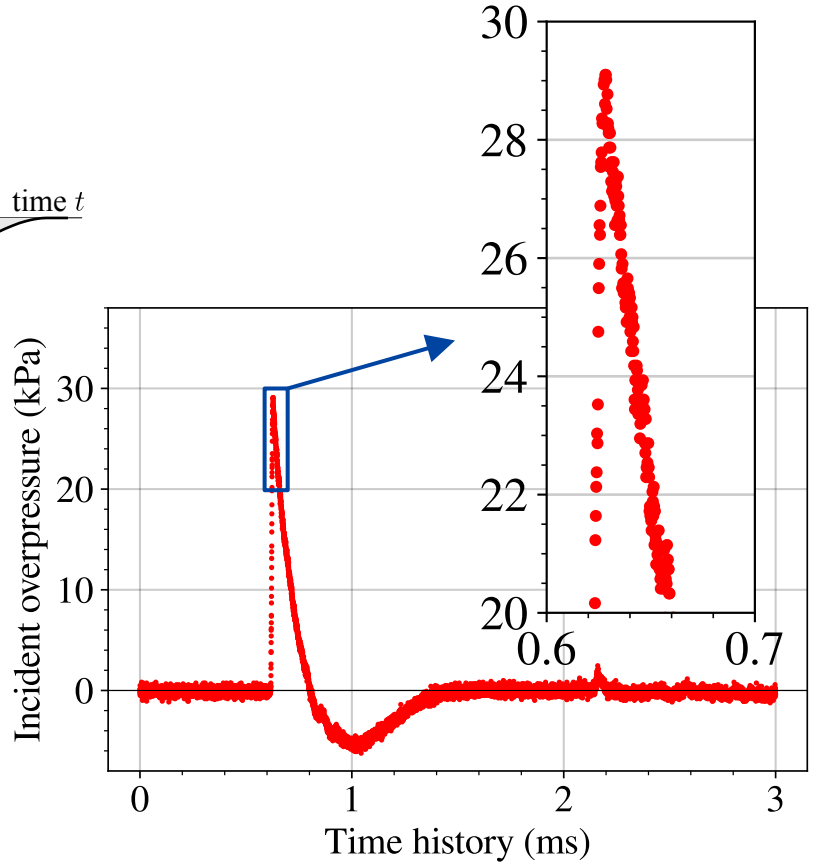
Shock wave measurements

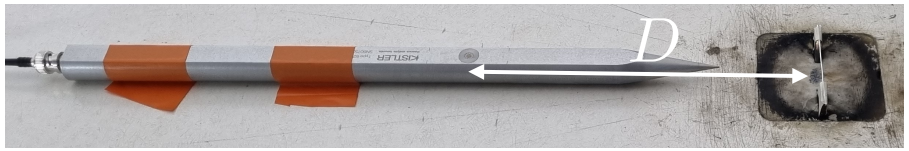
Analysis of the pressure signal

- signals are highly repeatable
- sampling frequency (5 MS/s)
- pressure signature







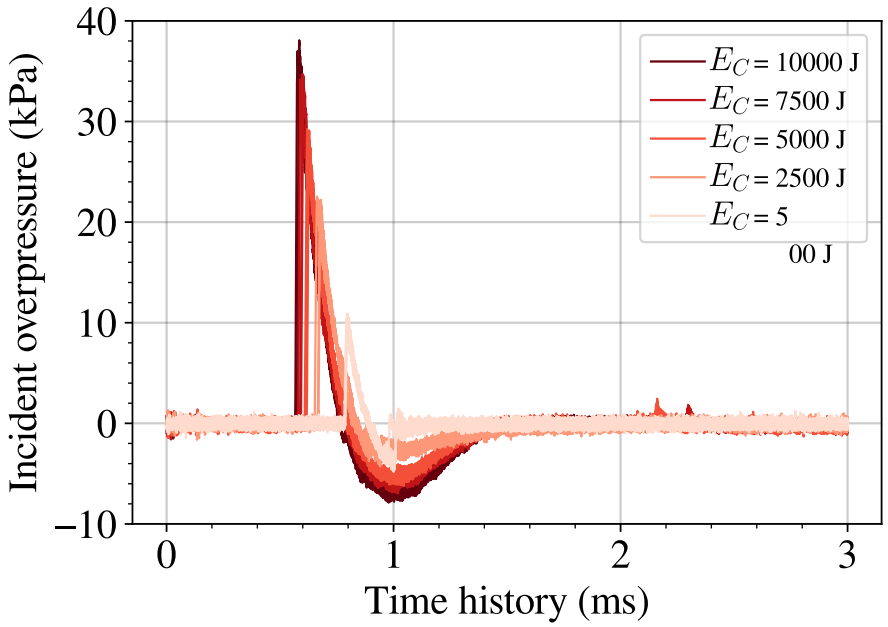


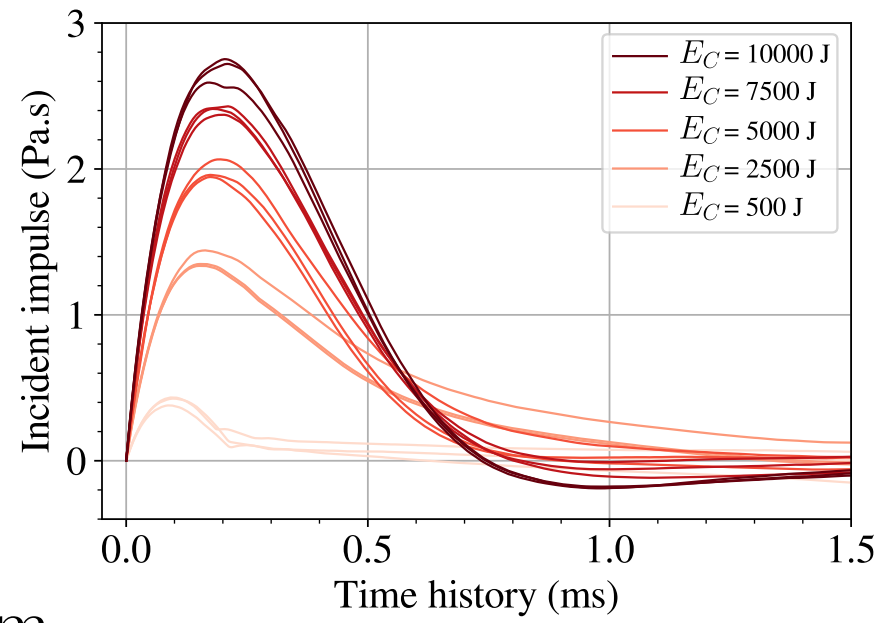
Shock wave measurements

We characterize the explosive source by measuring the incident overpressure for:

$$D \in [20, 70]\,\mathrm{cm} \quad E_C \in [500, 10000]\,\mathrm{J}$$

- incident impulse is calculated as: $i_s = \int_{t_A}^{t} P_s(t)\,dt$
- as the energy increases, pressure and impulse increase

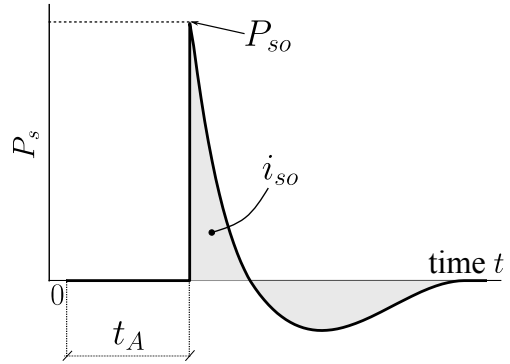




$D = 30$ cm

Blast parameters

We define the scaled distance in terms of the internal energy of the explosive source:



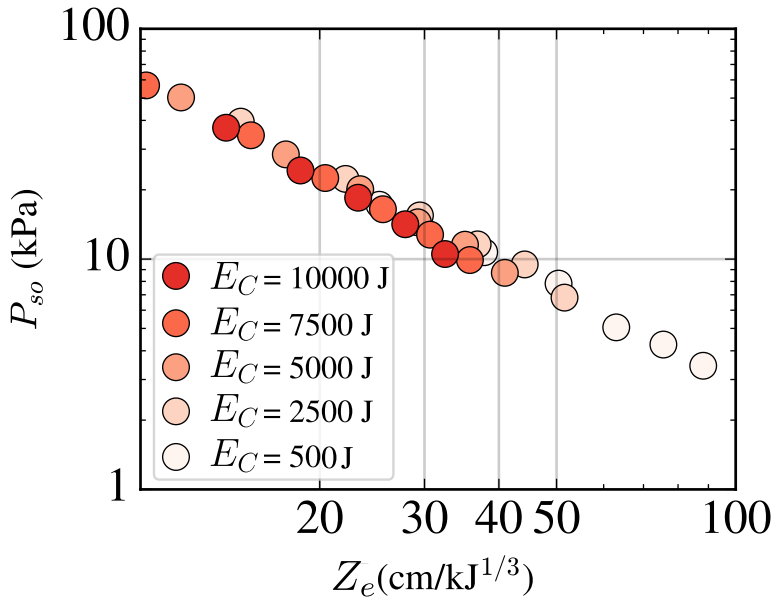
$$Z_e \equiv \frac{D}{E^{1/3}}$$

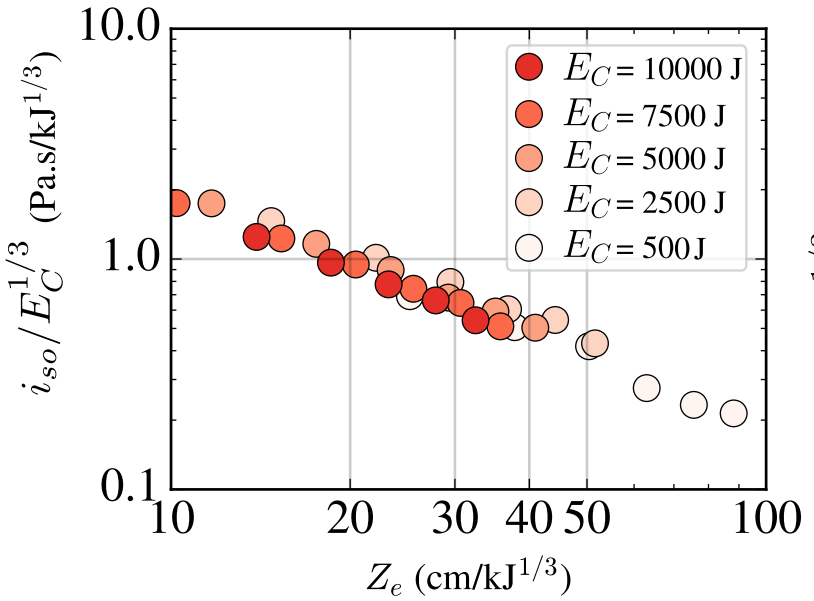
Hopkinson (1915); Cranz (1925)

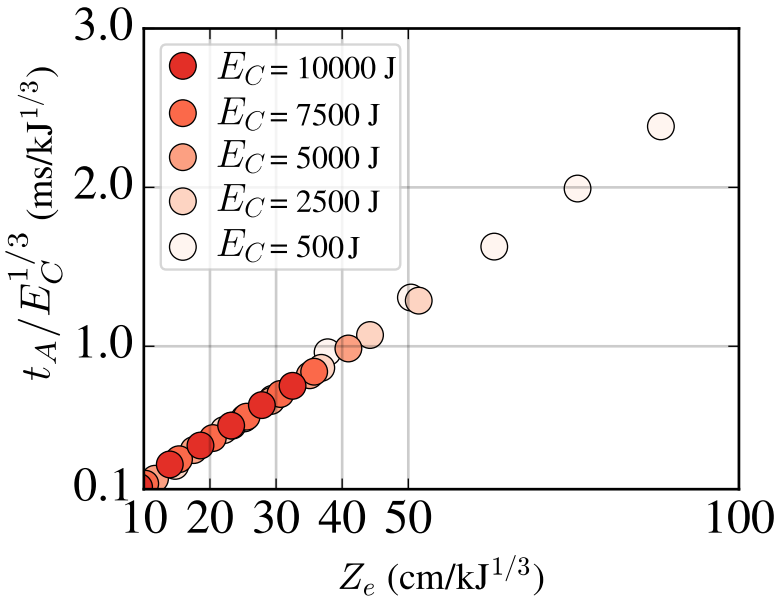
assumption: $E = E_C$

E internal energy

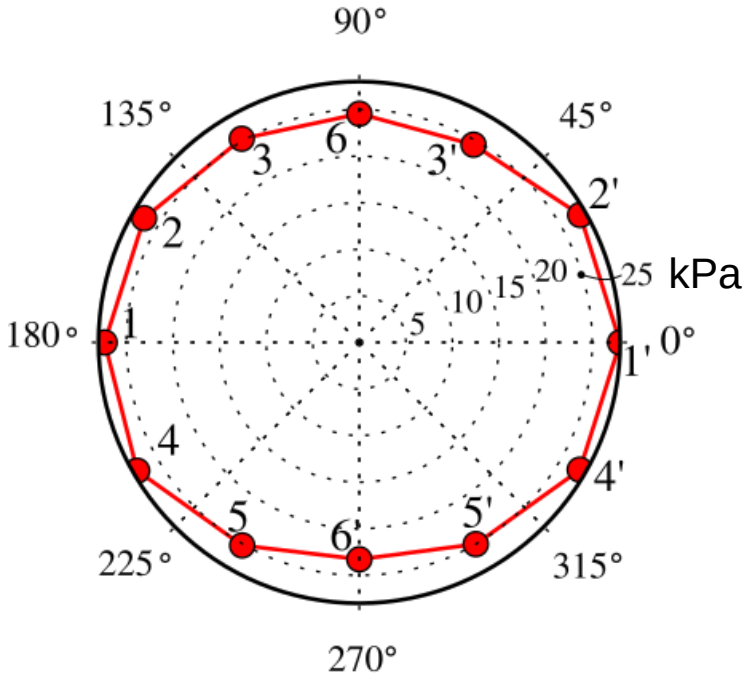
Z_e scaled distance



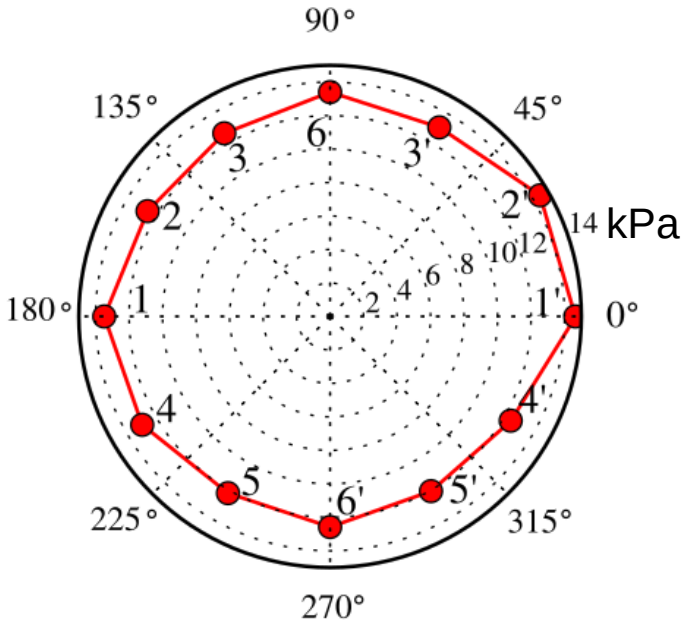




Shock wave sphericity

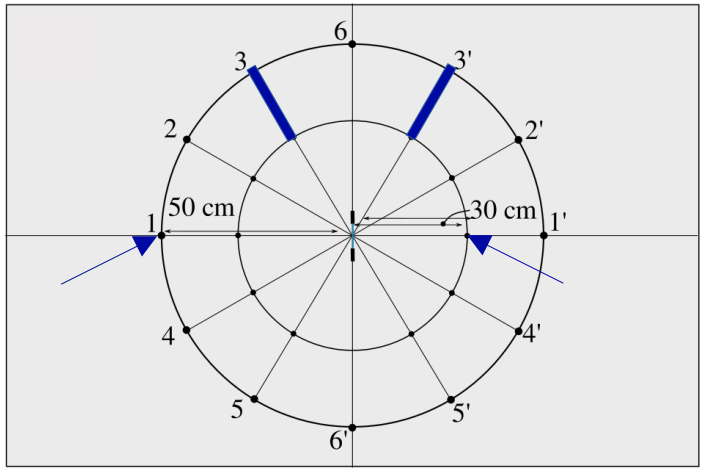


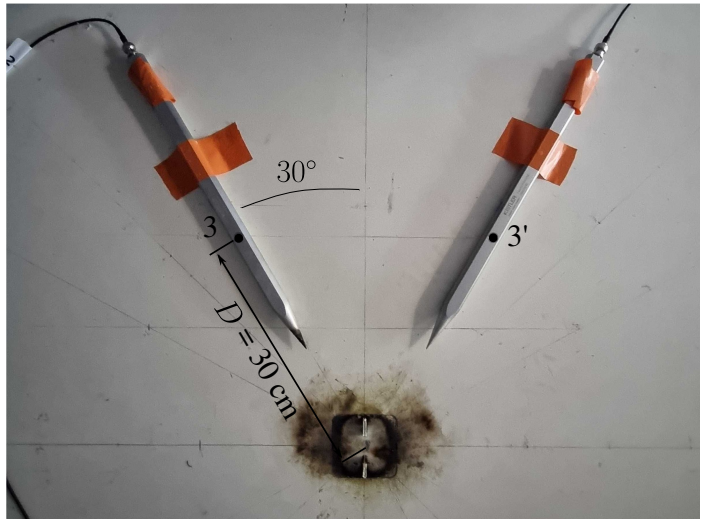
$D = 30$ cm



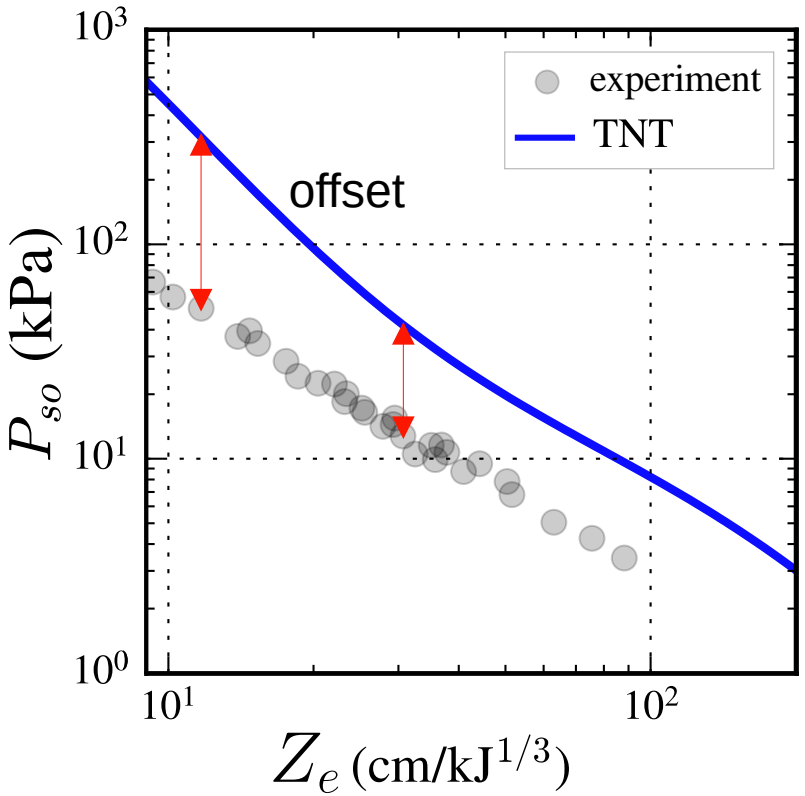
$D = 50$ cm

sensors

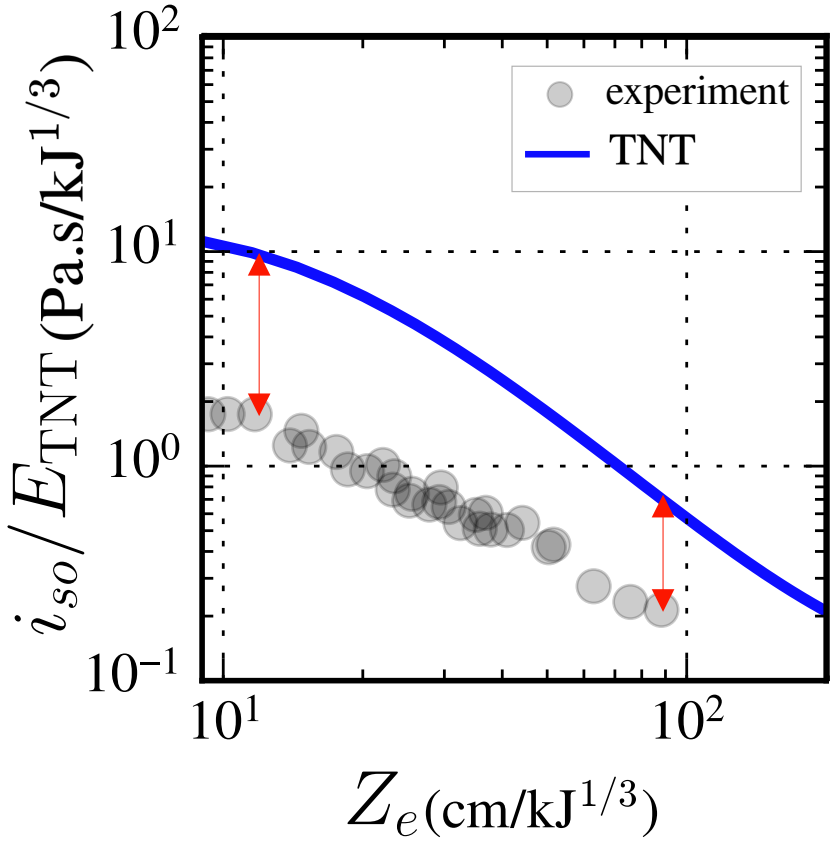




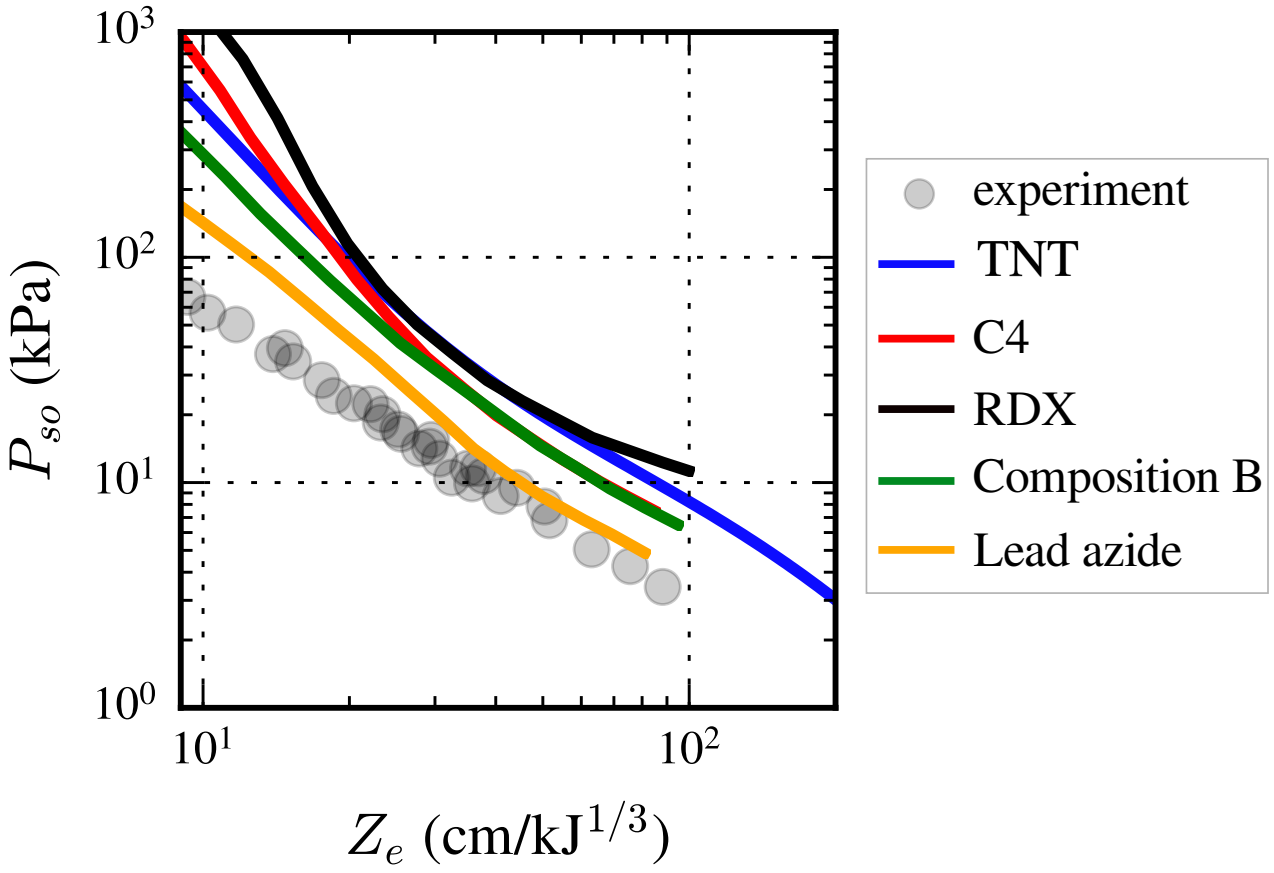
Equivalency with TNT?

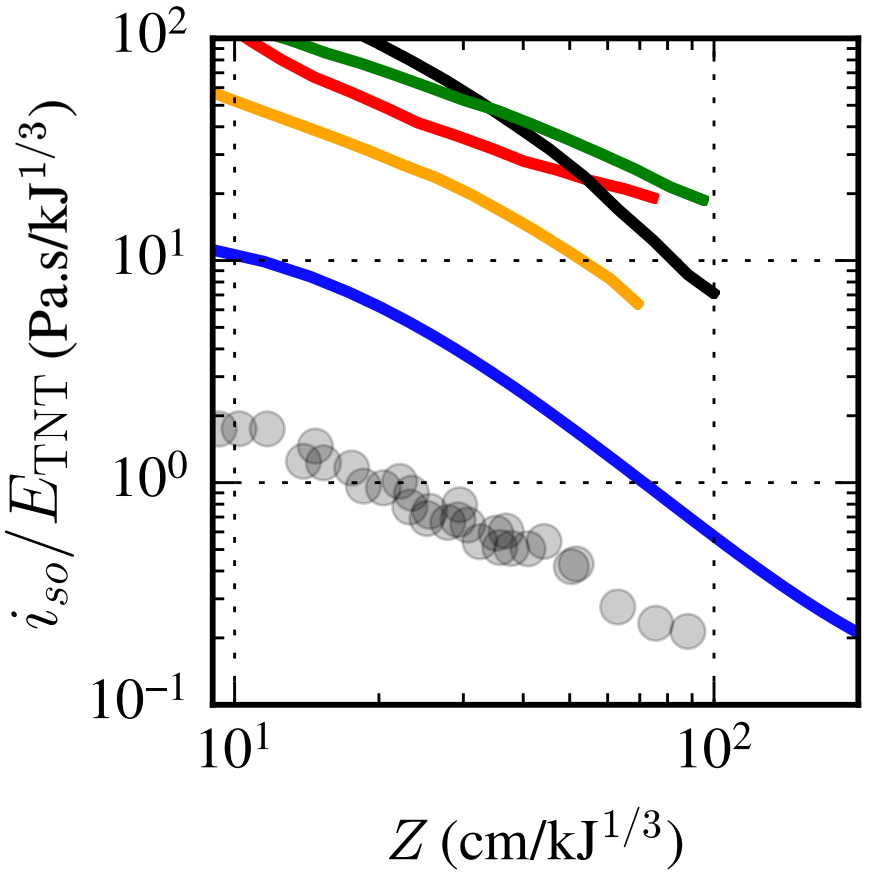


Kingery & Bulmash 1984



Equivalency with other explosives?



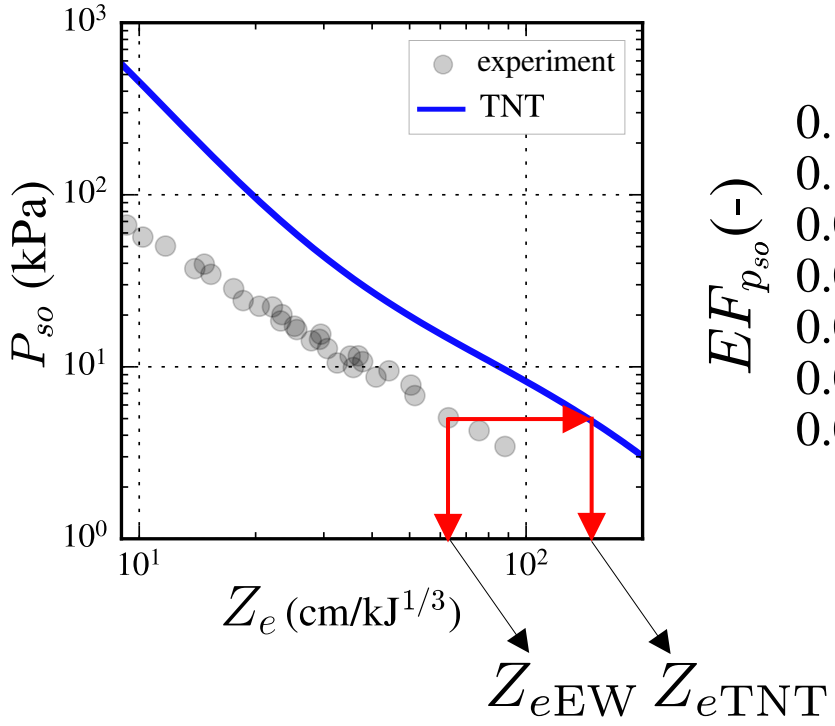


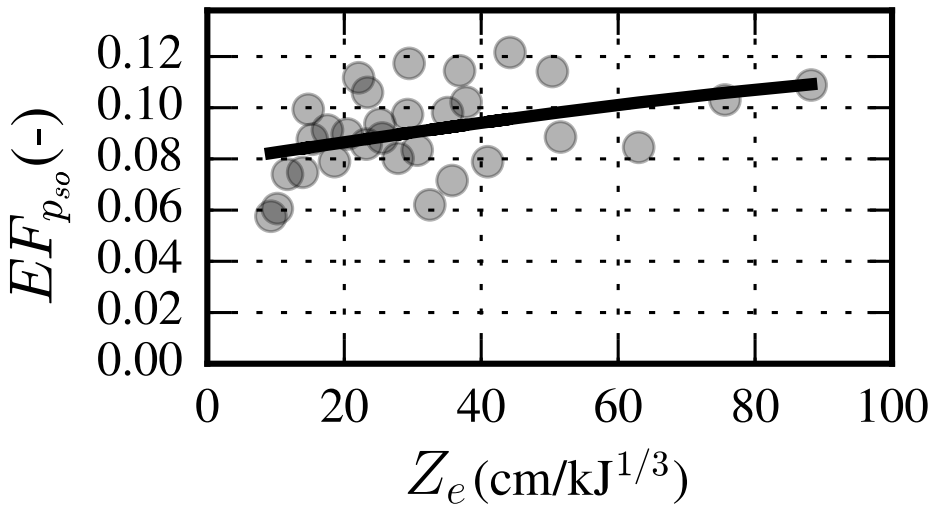
TNT Equivalence mass

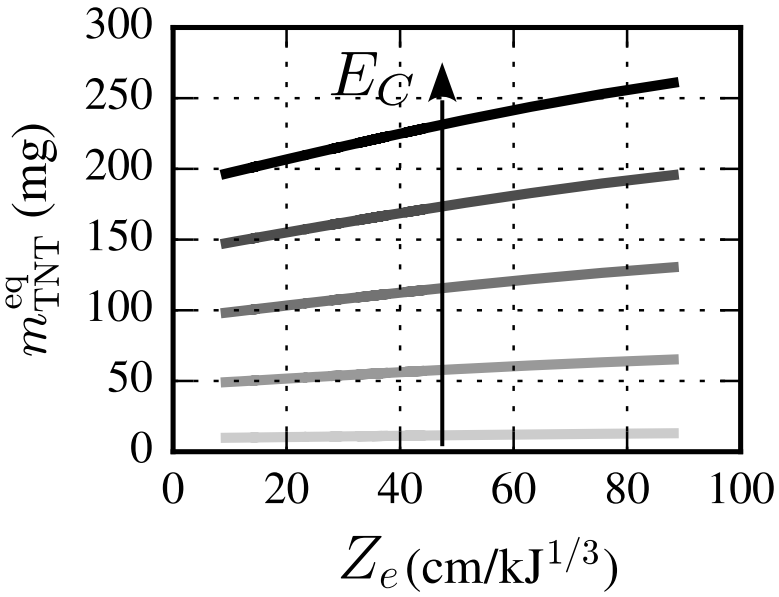
TNT equivalency factor based on the incident overpressure (according to Xiao et al. 2020)

$$EF_{p_{so}} = \left(\frac{Z_{e\mathrm{EW}}}{Z_{e\mathrm{TNT}}} \right)^3_{p_{so}^{\mathrm{EW}} = P_{so}^{\mathrm{TNT}}}$$

equivalent TNT mass is calculated as: $m_{\mathrm{TNT}}^{\mathrm{eq}} = EF \frac{E_{\mathrm{EW}}}{e_{\mathrm{TNT}}}$







e_{TNT} specific (per unit mass) internal energy of TNT equal to 4.184 MJ/kg

Platform (miniBLAST)

Design

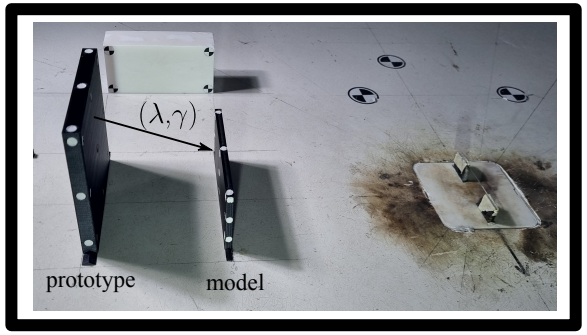
Installation

Explosive source (exploding wires)

Electric system

Shock wave

Scaling laws



Proof of concept

Scaling laws for reduced-scale testing

Methodology

- Similitude theory
- Assumptions (Masi et al. 2021):

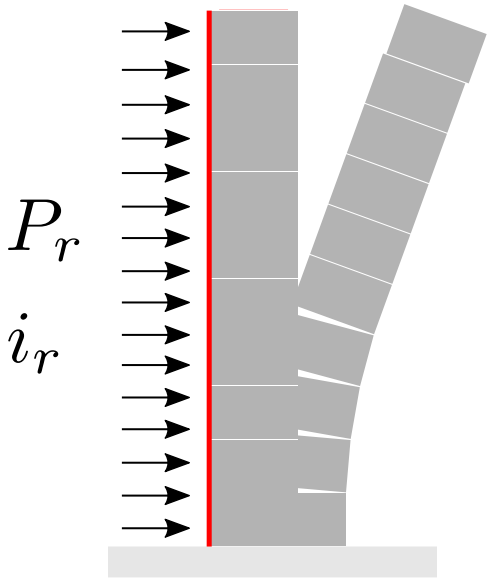
  1) Rigid-body response

  2) Blast loads

     - acts uniformly and simultaneously

     - impulsive load

  3) Friction and gravity



Scaling laws for reduced-scale testing

Scaling laws

- scaling ratios:

geometric scale factor: $\lambda = \frac{\tilde{l}}{l}$

density scale factor: $\gamma = \frac{\tilde{\rho}}{\rho}$

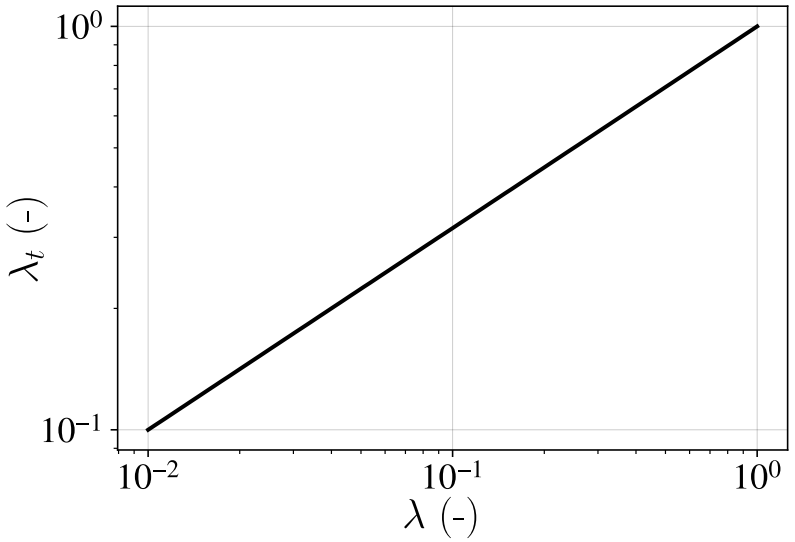
$\tilde{f}$ model

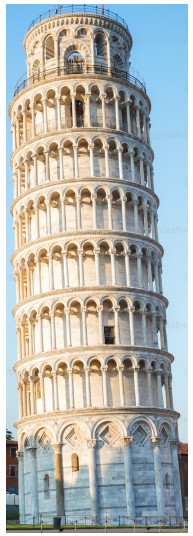
f prototype

l , ρ Length and density

- scaling factors for the rigid-body response

$$\lambda_t = \lambda^{1/2}$$



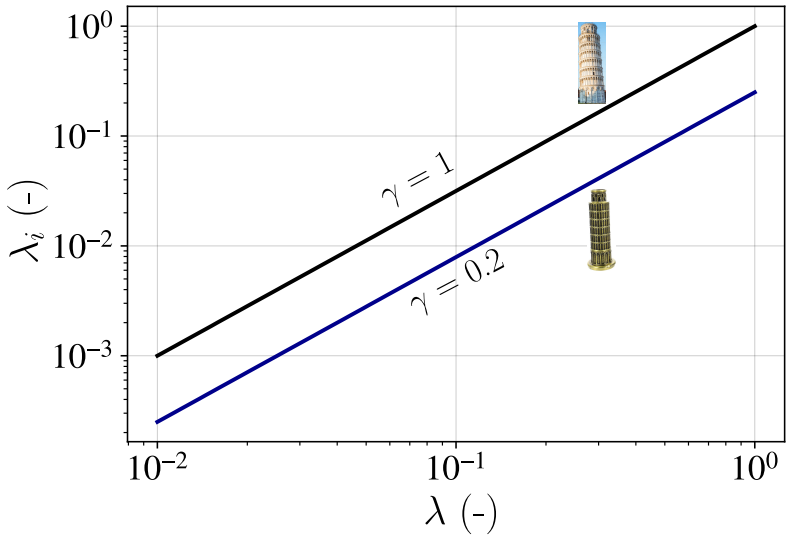


prototype

$\lambda = \frac{1}{100}$

model

$$\lambda_i = \gamma\lambda^{3/2}$$



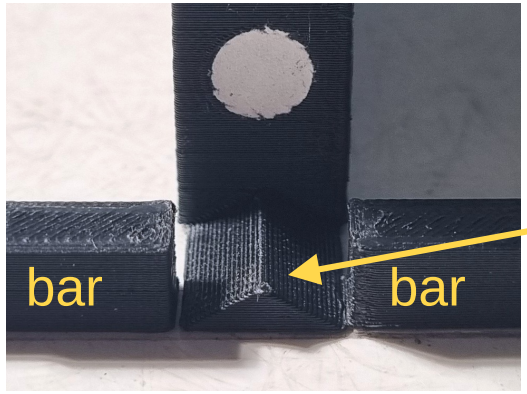
Validation of the scaling laws

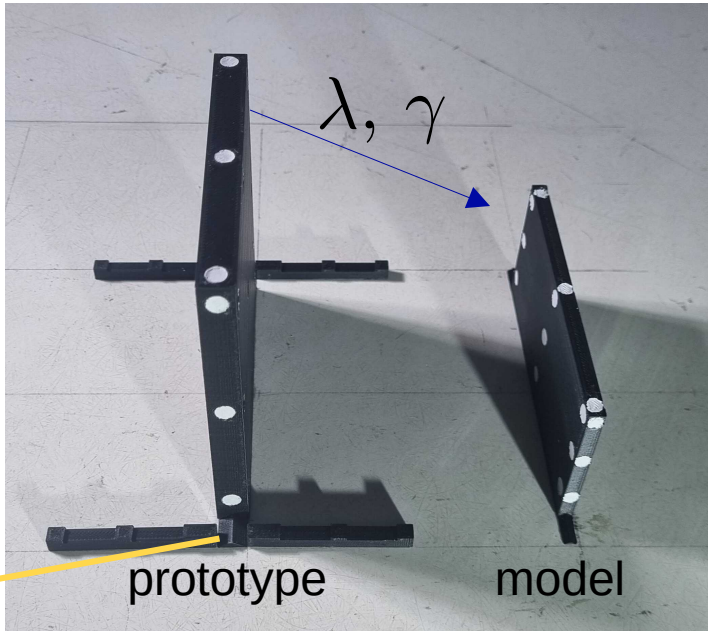
Prototype and model response to be validated through: rocking

	$2b$ (mm)	$2h$ (mm)	$2w$ (mm)	ρ (kg/m^3)	$\mu(\varphi)$ (°)
Prototype	10	100	100	411	19.92 ±0.121
Model	5	50	100	411	20.10 ±0.129

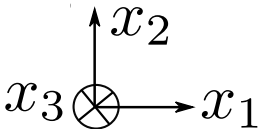
friction

- 2D out-of-plane response
- minimize sliding and uplifting





$$\lambda = 0.5,\ \gamma = 1$$



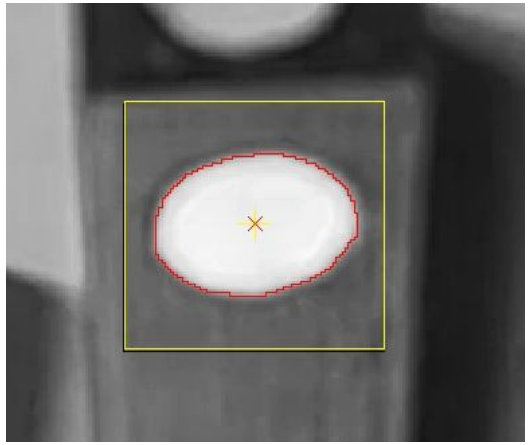
Stereometry with GoPro cameras

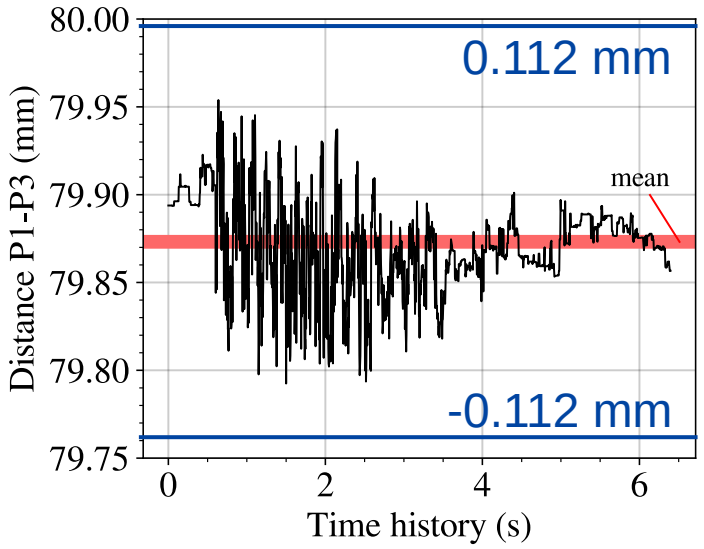
- Particle Tracking Velocimetry (PTV)
- Camera: 240 fps
- Cheap, robust and we can use multiple cameras
- Calibration

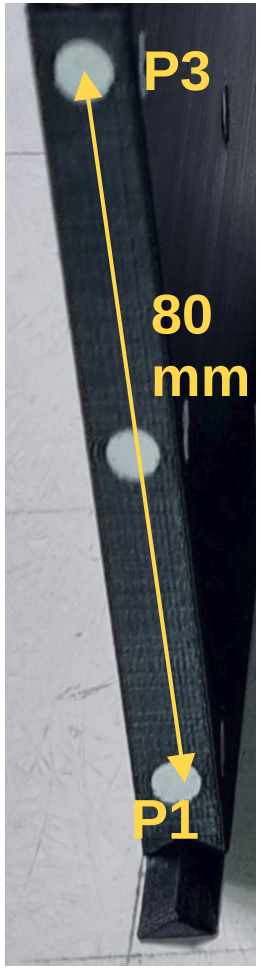
3D Particle Tracking Velocimetry (PTV)

PTV analysis through TEMA Classic software

- block motion (centroid)
- resolution: ± 0.112 mm/pixel (windows size: 2704 × 1520 pixels)







Block response

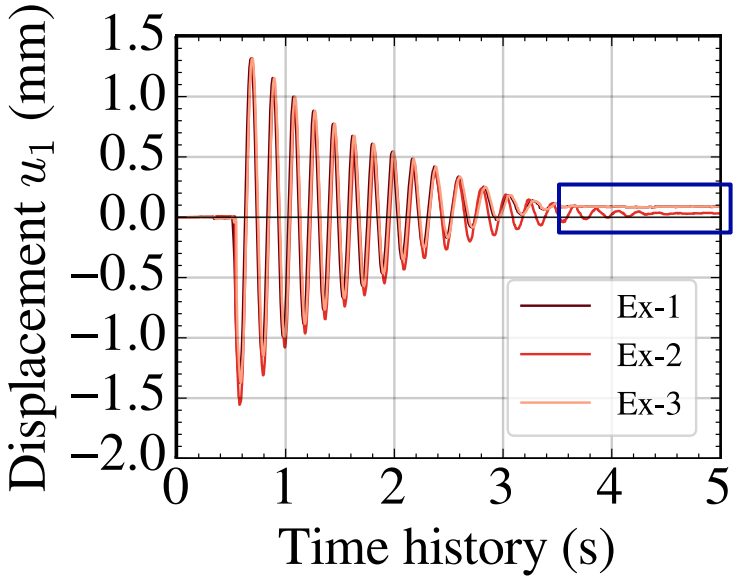
Prototype

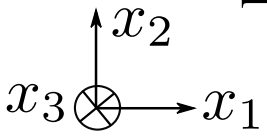
Model

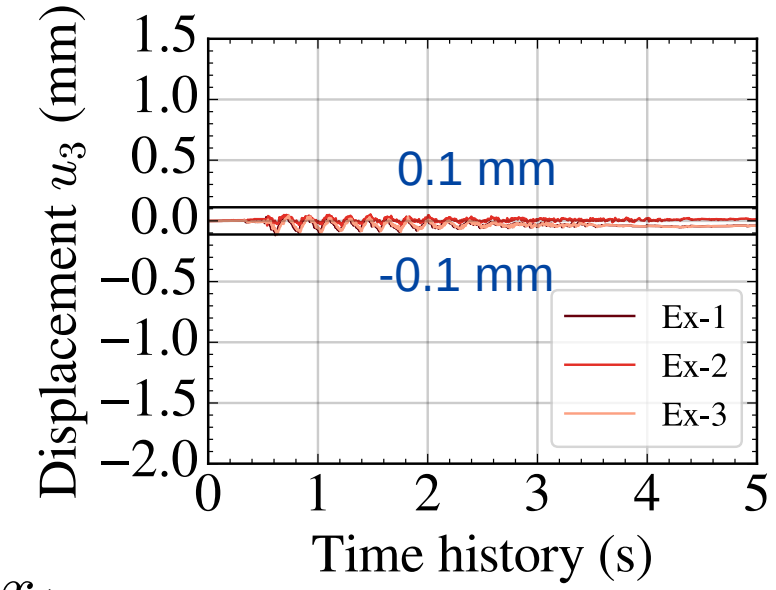
Results

Prototype

1. structural response is highly repeatable
2. negligible sliding
3. 2D motion in x_1 - x_2 (u_3 negligible)



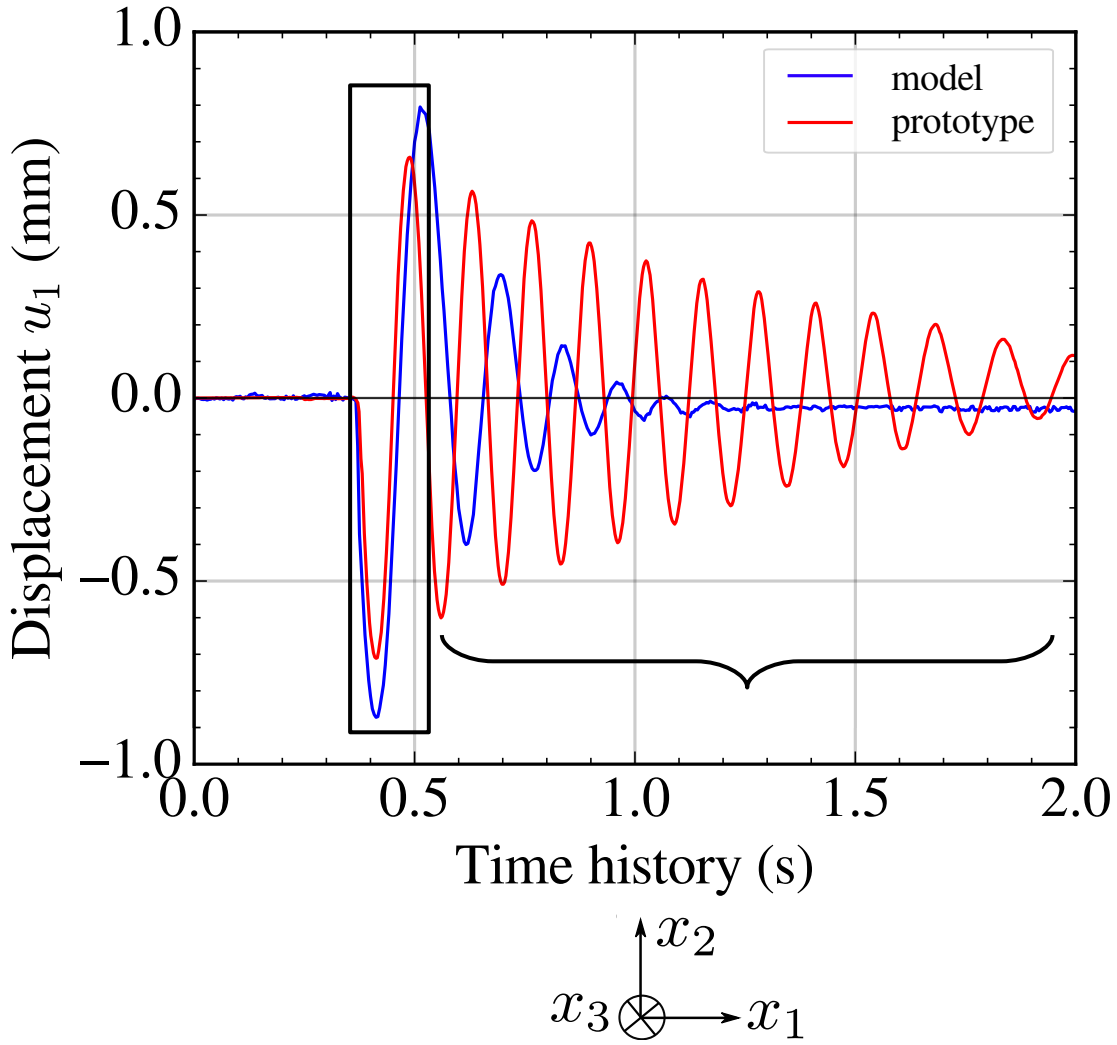




Comparison: model and prototype (down-scaled)

1. similar initial amplitude

2. different damping and oscillation period

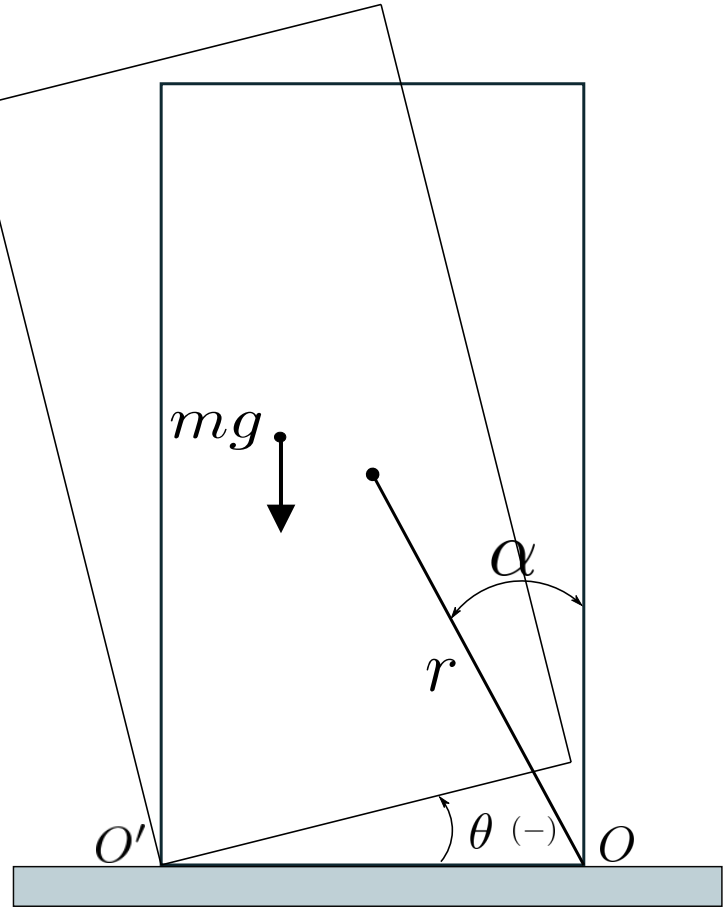


Restitution coefficient and damping

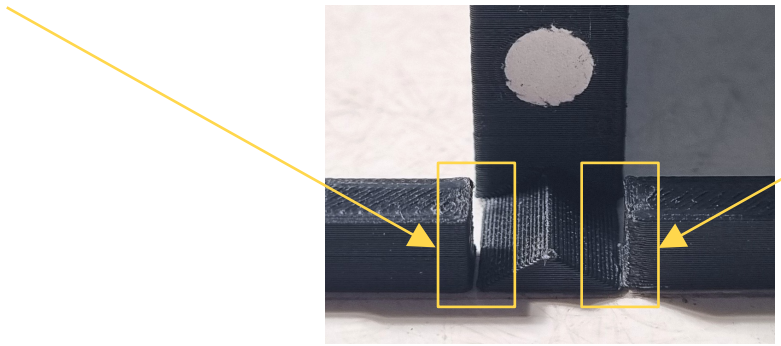
The restitution coefficient (Housner 1963)

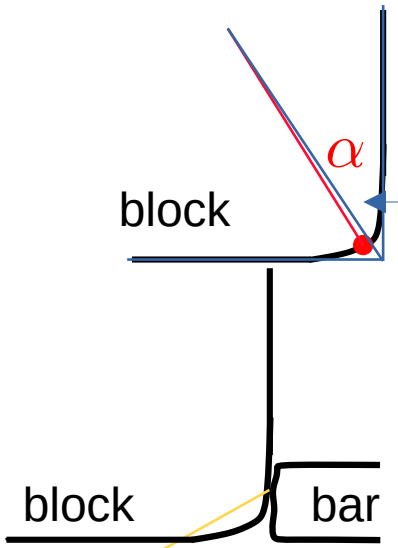
$$\mathcal{I}\dot{\theta}_1 - 2mrb\dot{\theta}_1 \sin\alpha = \mathcal{I}\dot{\theta}_2$$

$$r_s = 1 - \tfrac{3}{4}\left(1 - \cos(2\alpha)\right)$$



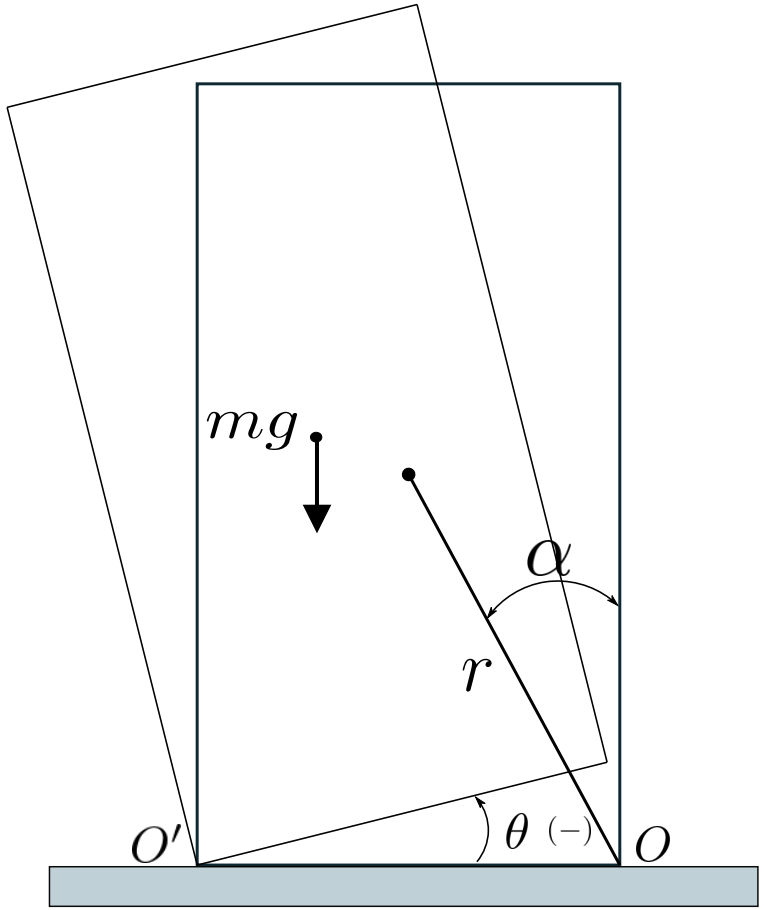
- block edges are not perfect
- friction with the support
- sliding at the base



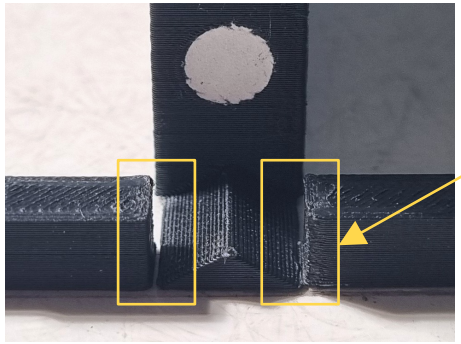


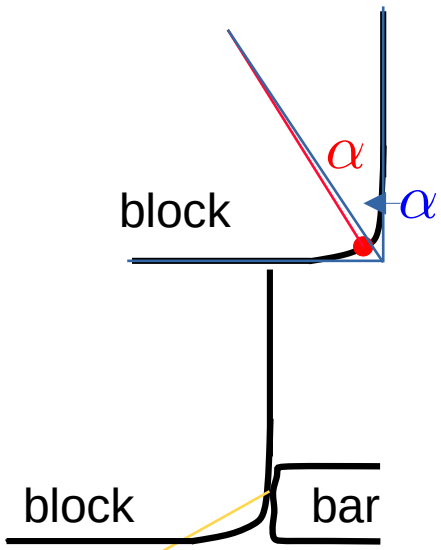
Rocking period

Solving the equation of motion, the period of free vibration (Hounser 1963)

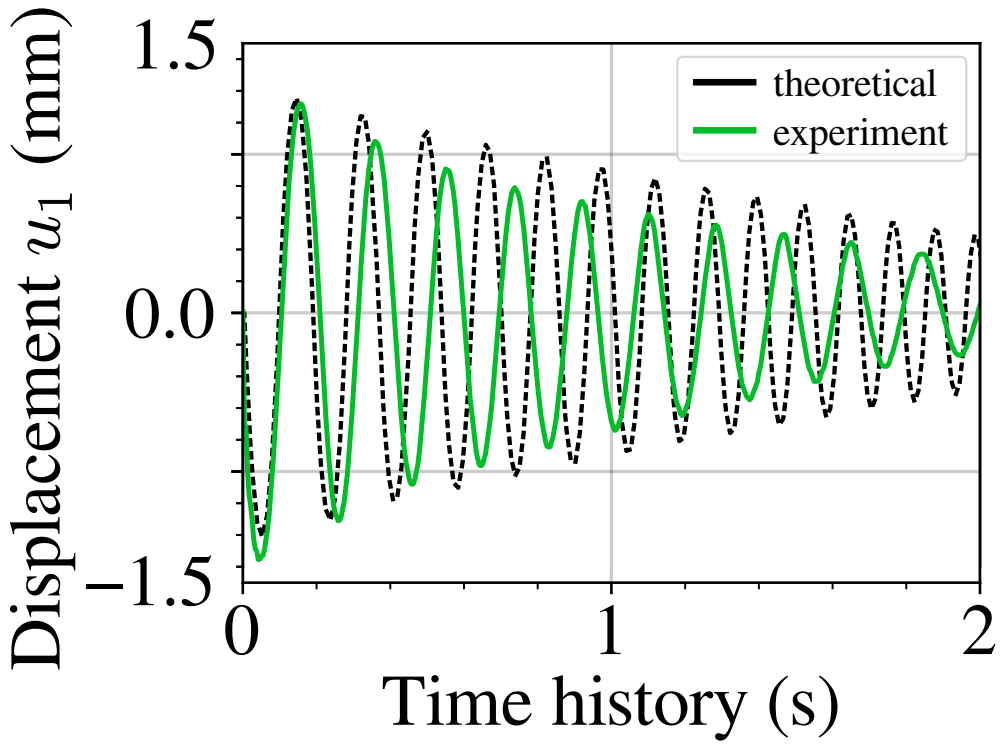


$$T = \frac{8}{\sqrt{\frac{3g}{r}}} ln \left[\frac{1}{1-\theta_0/\alpha} + \sqrt{\left(\frac{1}{1-\theta_0/\alpha} \right)^2 - 1} \right]$$

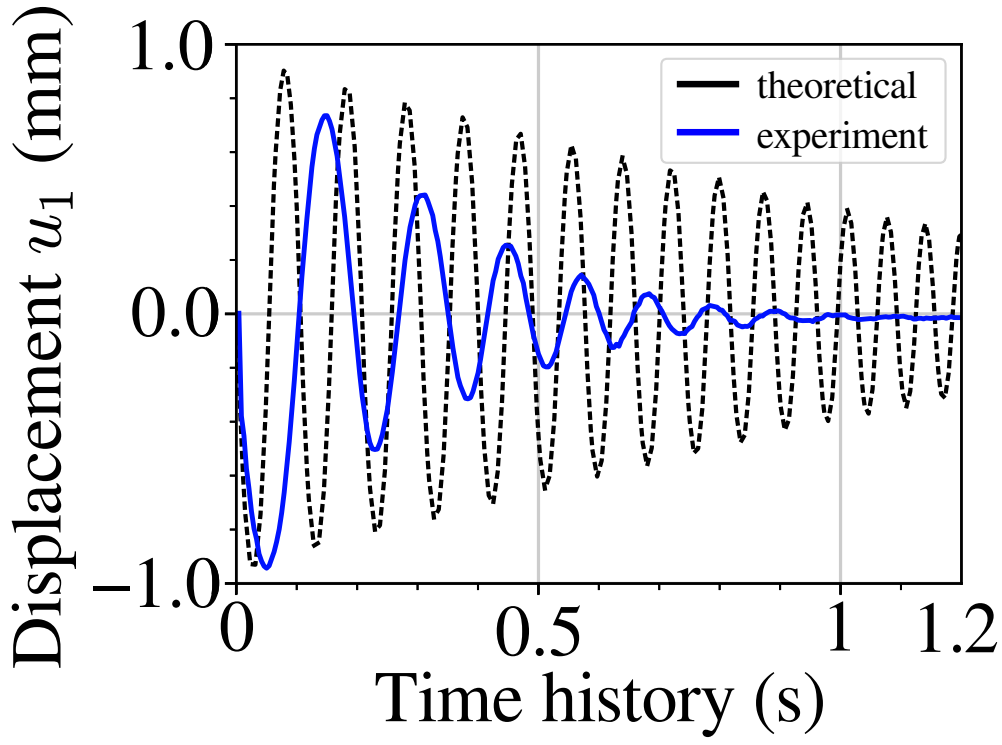




Comparison between the experimental and the analytical



prototype



model

Platform (miniBLAST)

Design

Installation

Explosive source (exploding wires)

Electric system

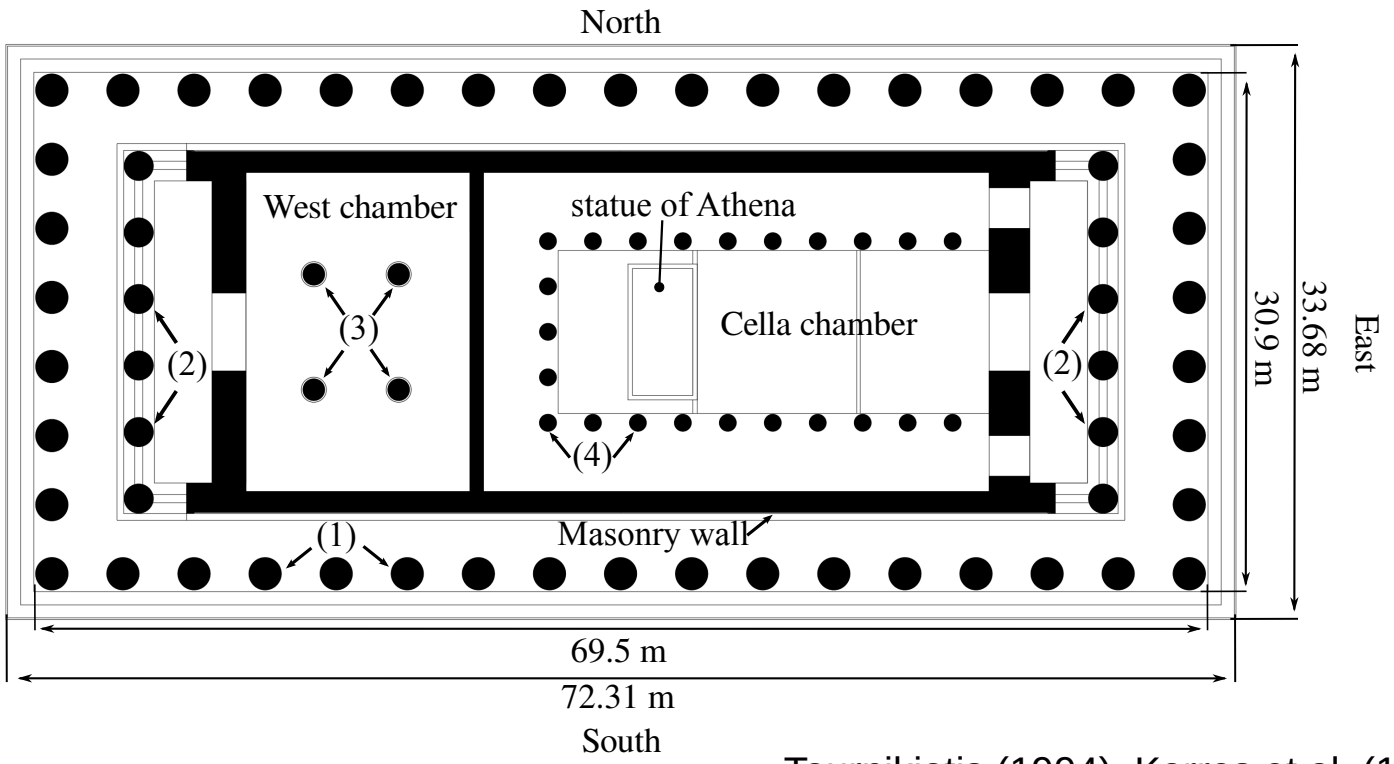
Shock wave

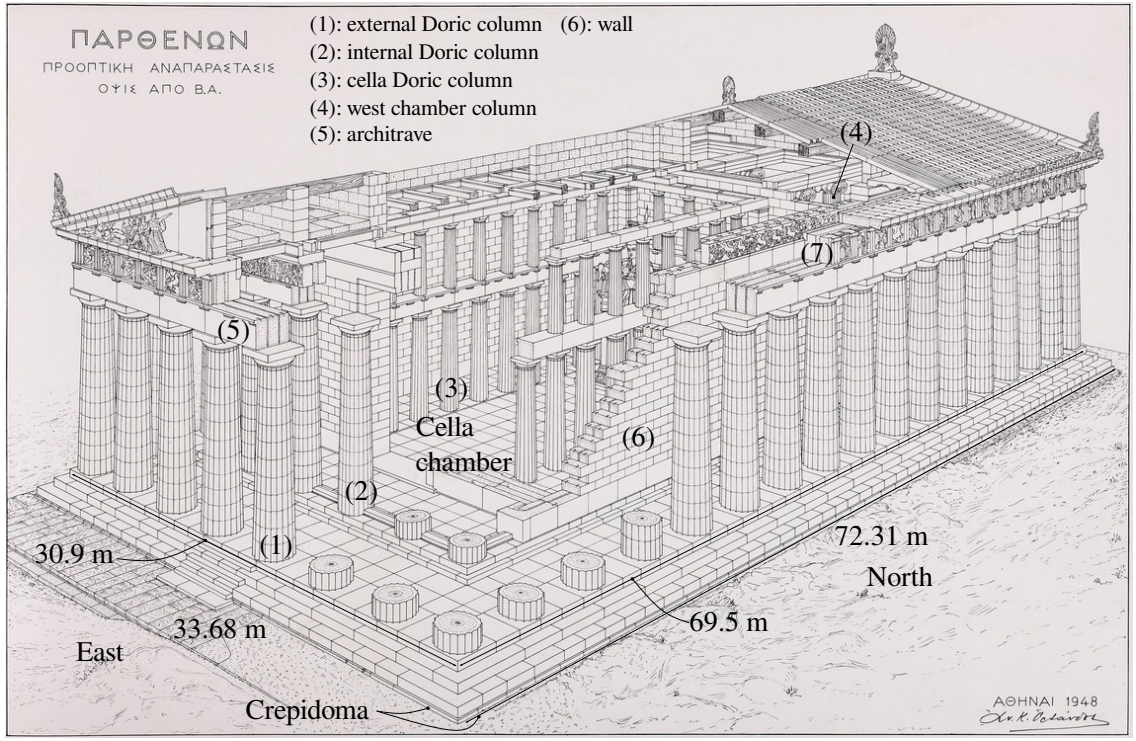
Scaling laws

Proof of concept

Parthenon of Athens

We aim here to model the Parthenon at a reduced scale in the laboratory.

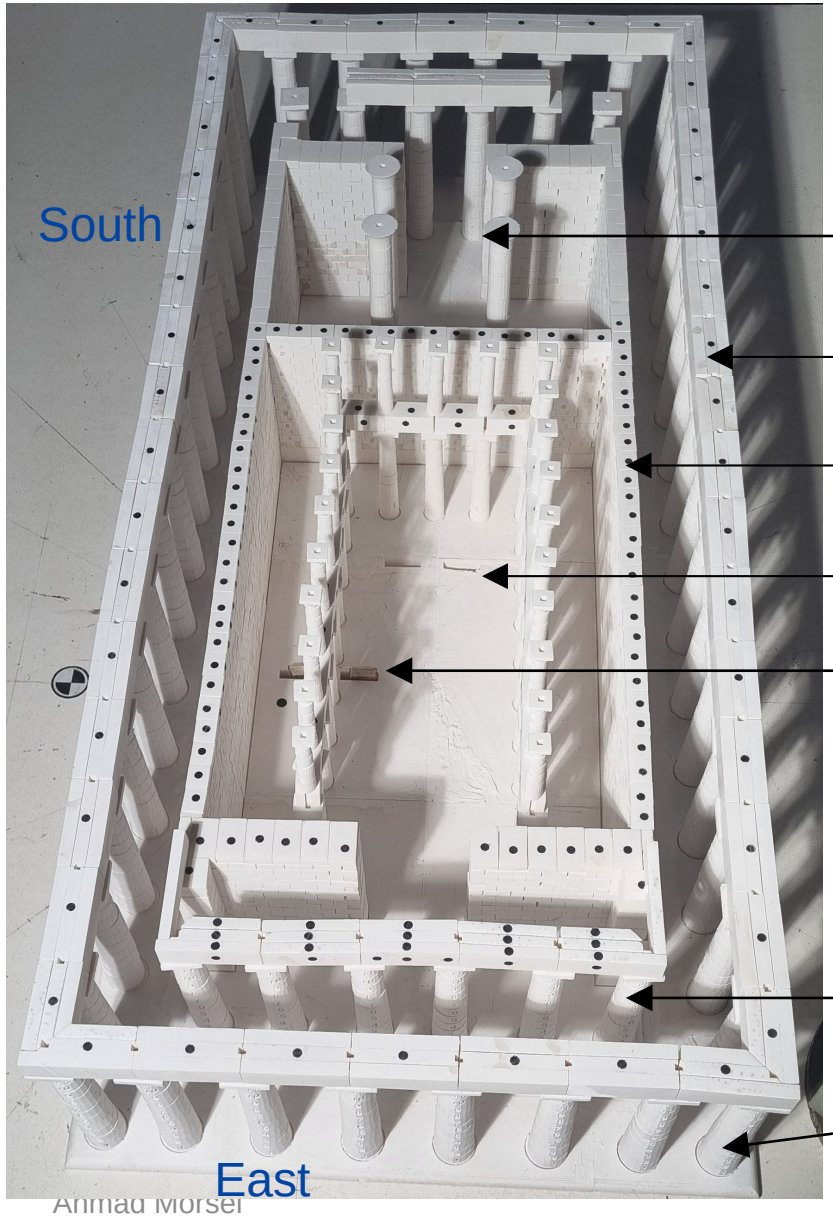




Tournikiotis (1994), Korres et al. (1999), Zambas (1994)

3D printed with: $\lambda = 1/70$ and $\gamma = 0.667$

Parthenon at reduced scale



West chamber

architrave

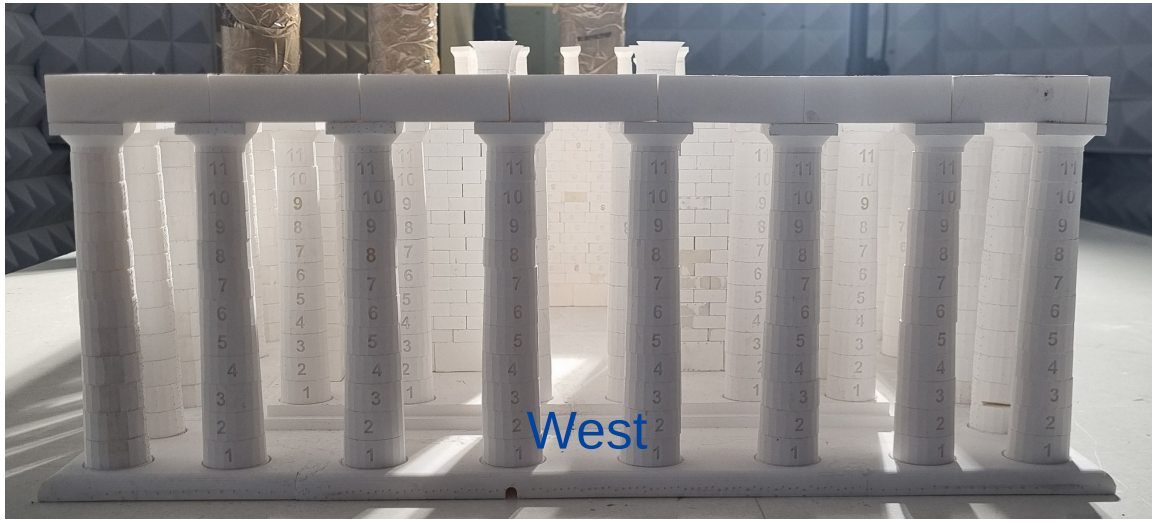
wall

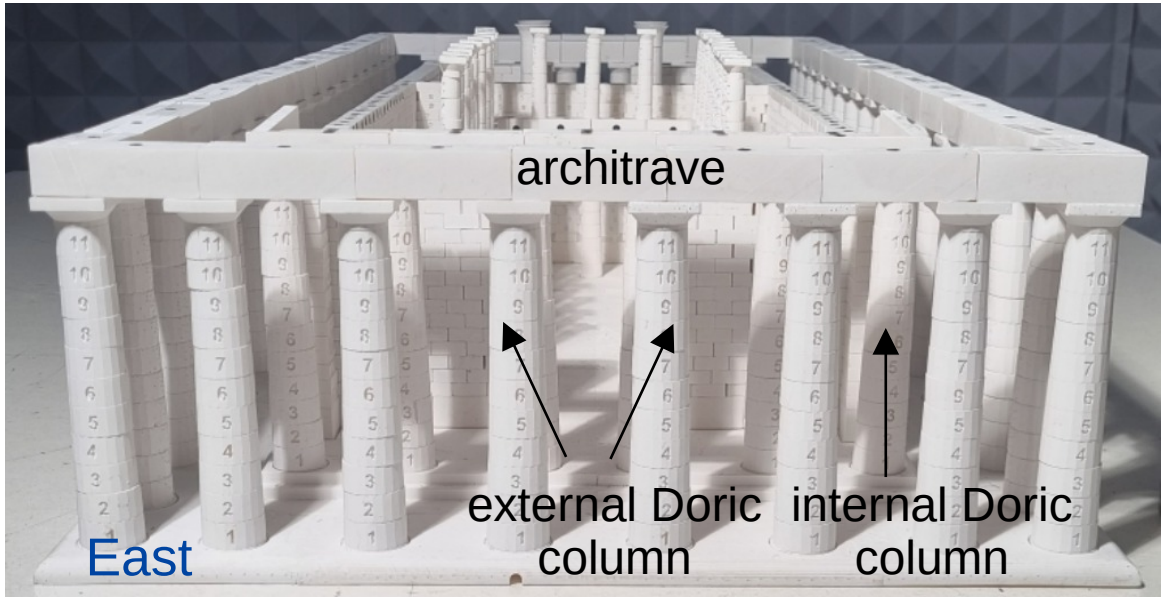
Cella chamber

explosion location

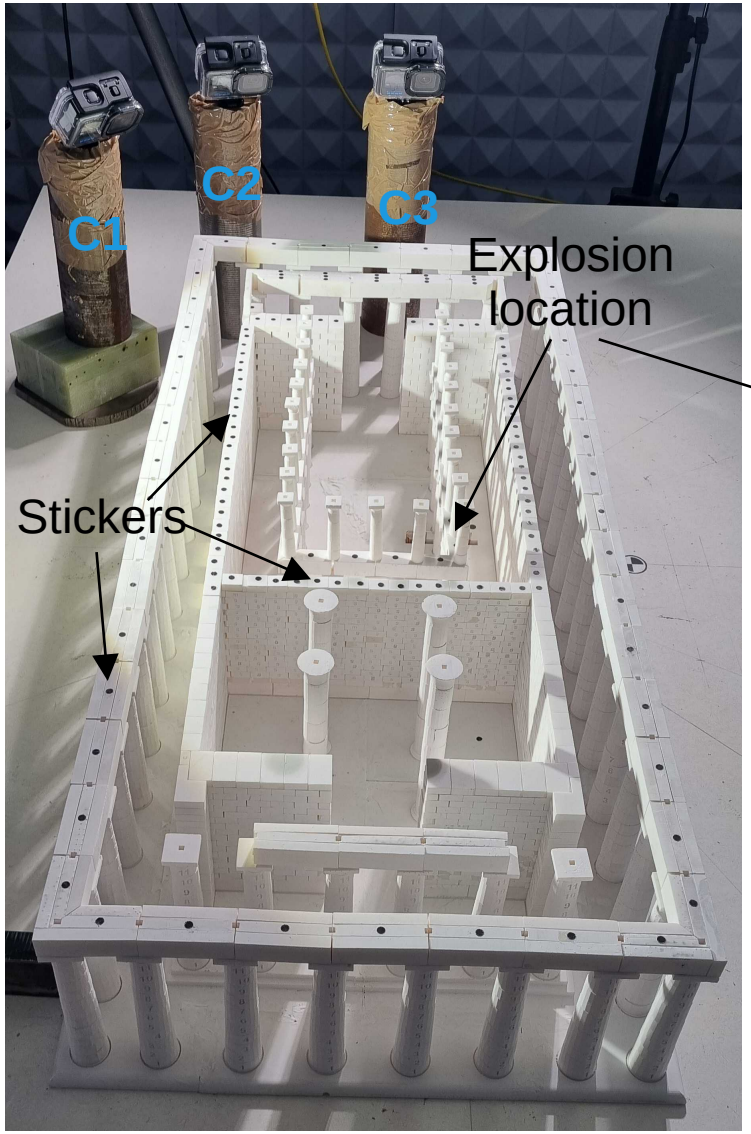
internal Doric column

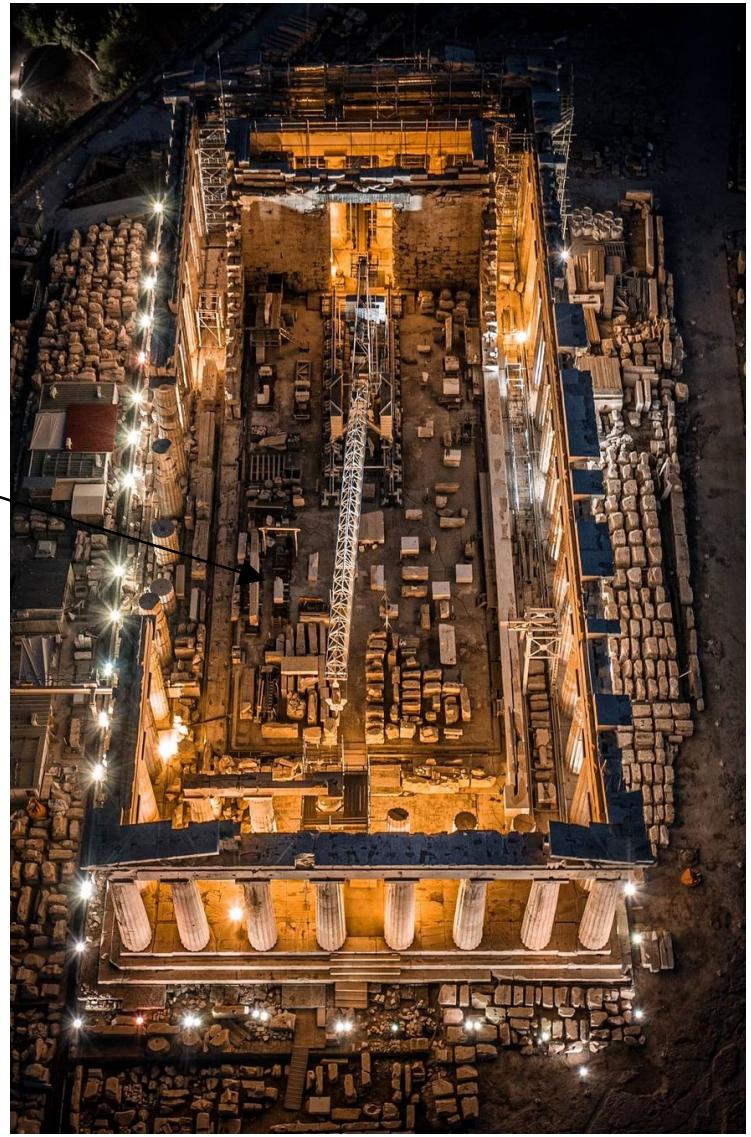
external Doric column





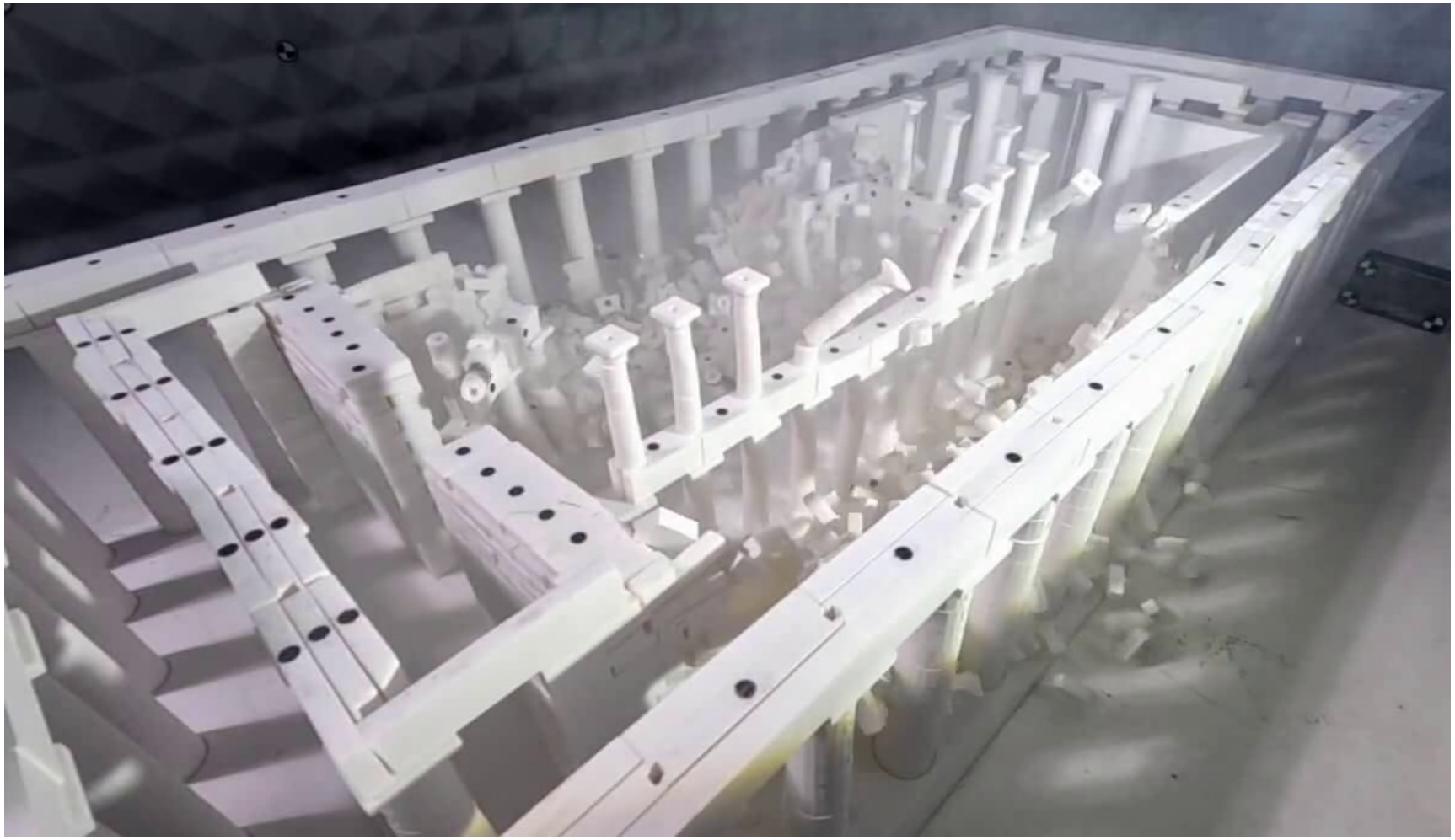
Experimental setup





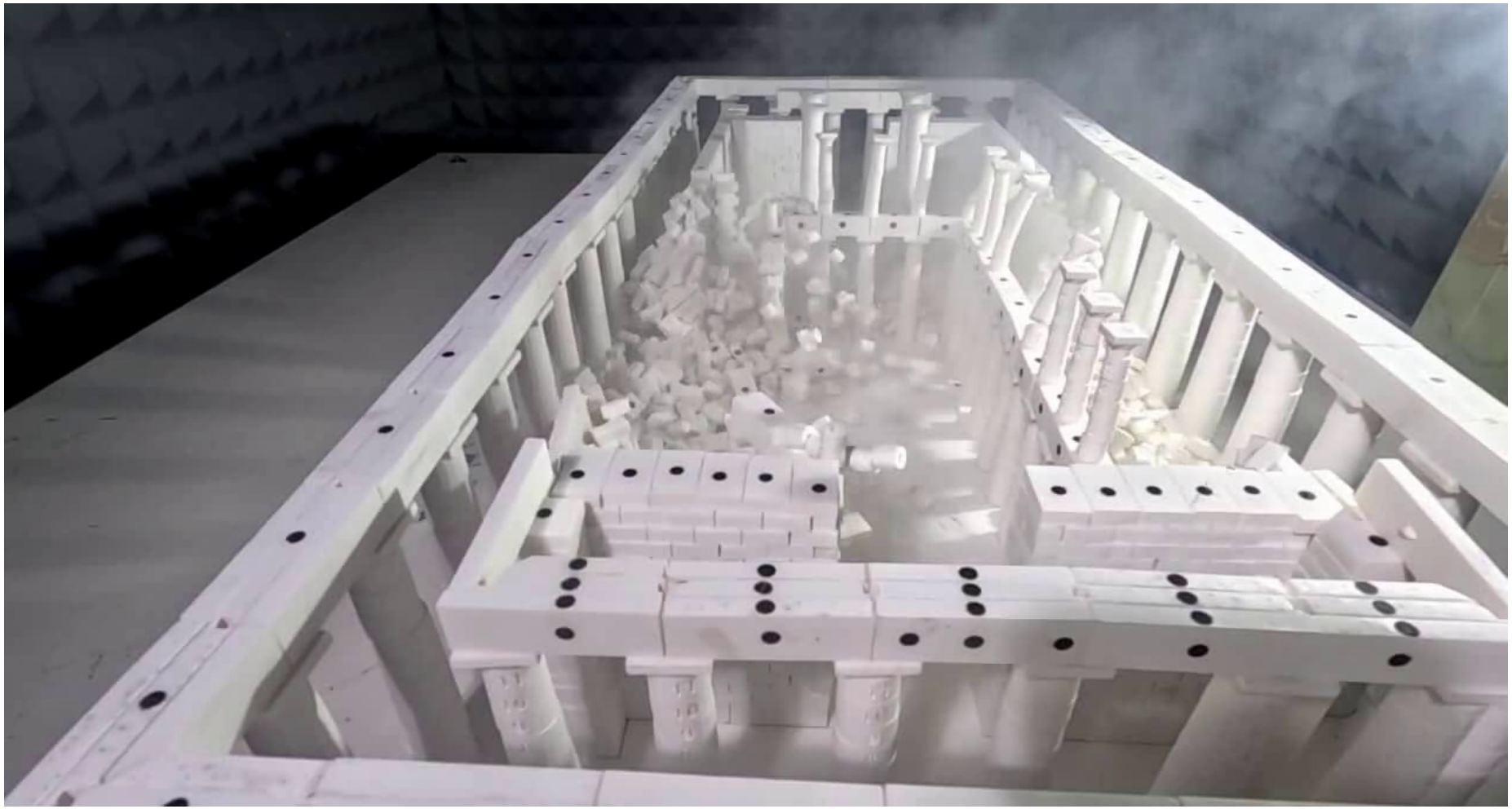
https://www.reddit.com/r/interestingasfuck/comments/jeh8iy/aerial_view_of_the_parthenon_in_athens_greece/

Parthenon explosion



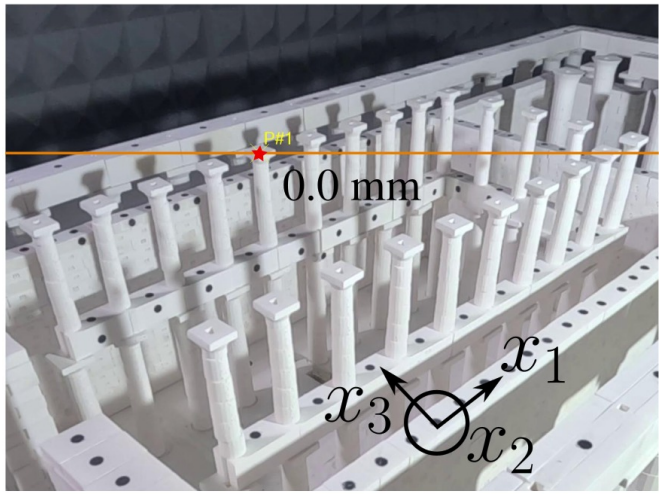
C1 (speed 1/8 normal)

Parthenon explosion

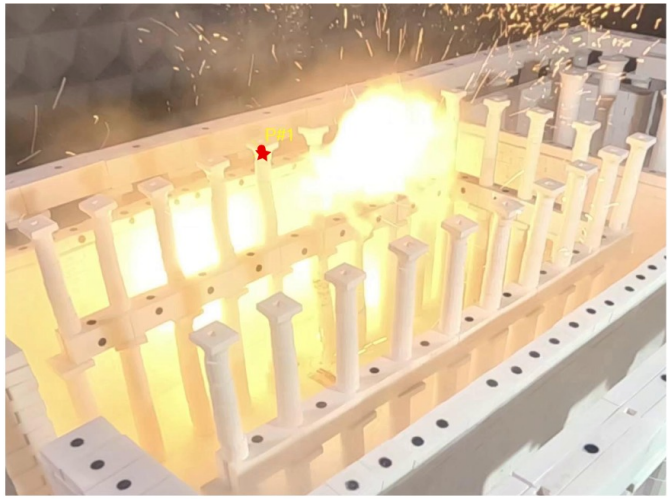


C3 (speed 1/8 normal)

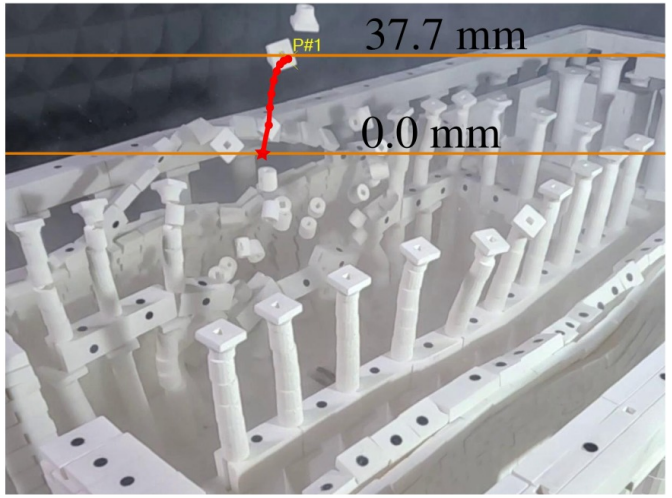
Block tracking



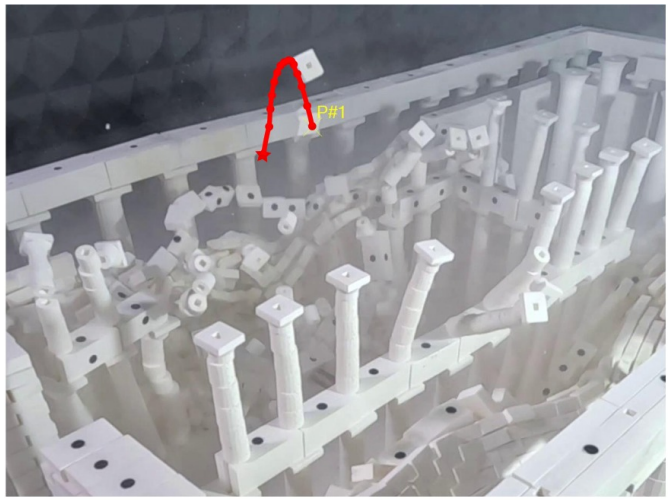
$t = 0.0$ s



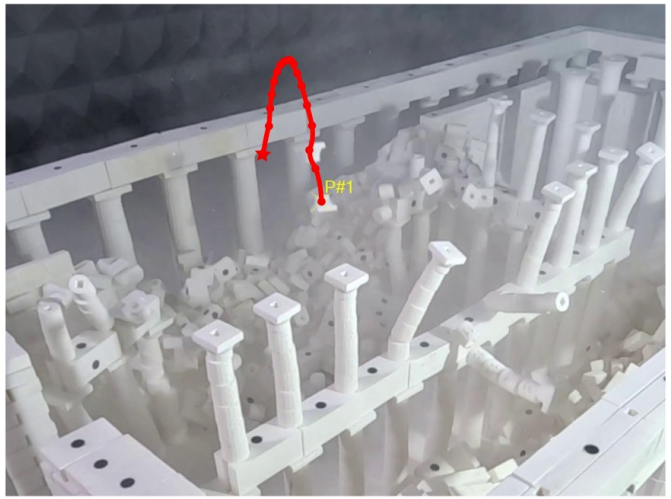
$t = 12.5$ ms



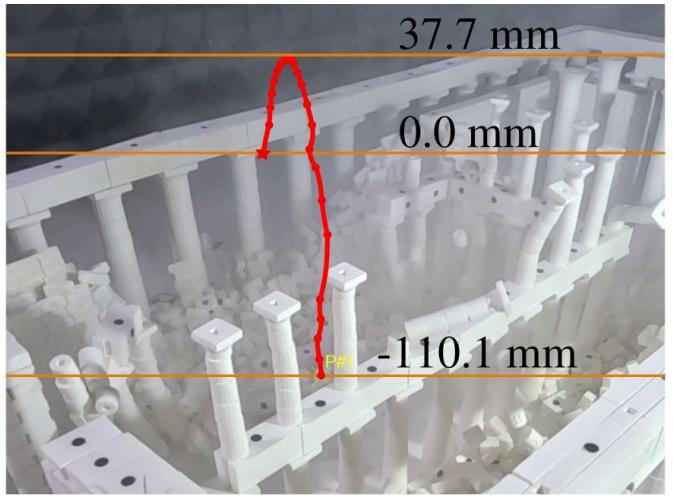
$t = 116.6$ ms



$t = 200.0$ ms

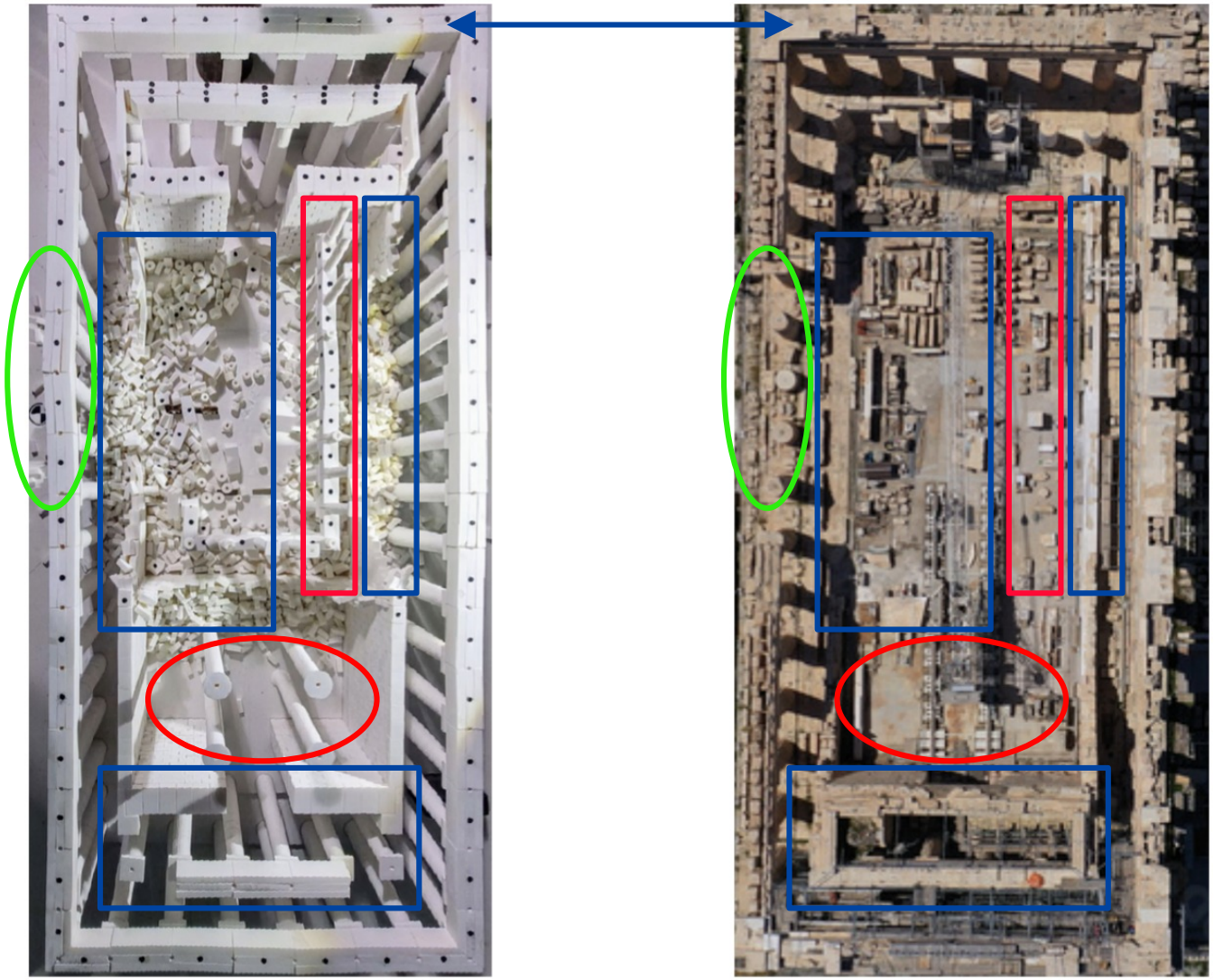


$t = 250.0$ ms



$t = 350.0$ ms

Comparison between model and prototype



model

prototype

Conclusions

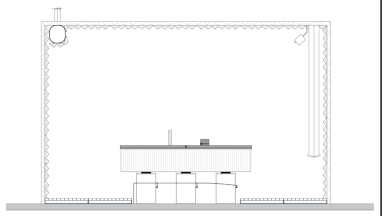
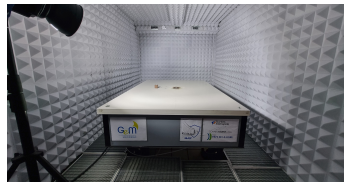
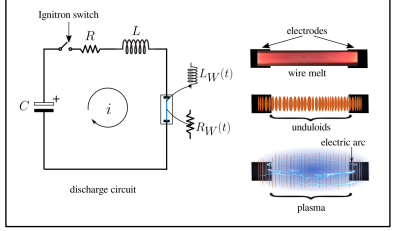
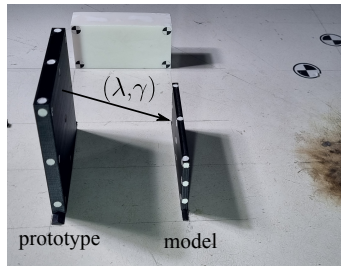
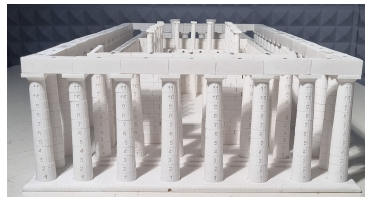
Main objectives were

1) Design a novel experimental setup

2) Study the explosive source

3) Validate the scaling laws

4) Proof of concept

Platform (miniBLAST)		Explosive source (exploding wires)		Scaling laws	Proof of concept
Design	Installation	Electric system	Shock wave		
					

Conclusions

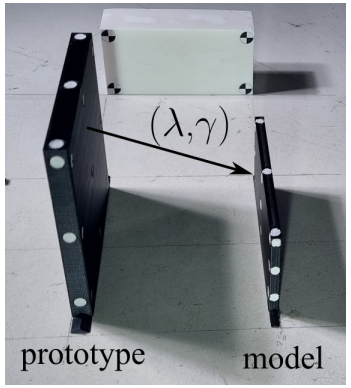
Main findings were

1. Novel experimental platform (miniBLAST) designed and installed
   - methodology adopted and reasoning behind the design and installation
   - safety and metrology
2. Explosive source analysis
   - exploding wire mechanism and study of the current and voltage evolution
   - pressure distribution measurements and shock wave sphericity
   - TNT equivalency
3. Study the dynamic response of structures
   - first experimental test of the scaling laws
   - study the Parthenon of Athens at reduced scale

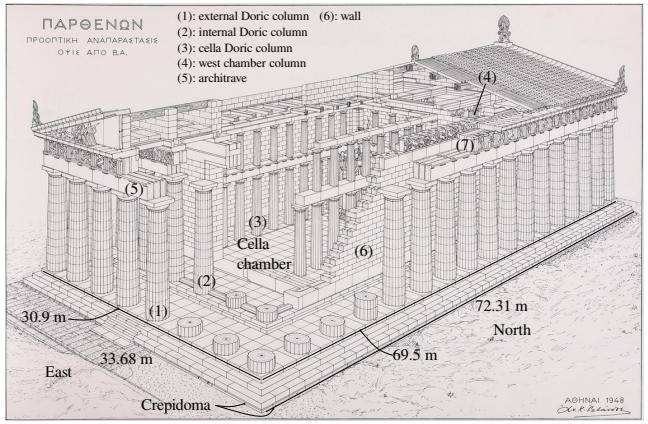
Perspectives

1. Parametric study of the explosive source
   - exploding wire parameters (length, diameter,….)

2. Complete the validation of the scaling laws
   - improve printing of the blocks
   - improve supports



3. Continue the study of the explosion of Parthenon
   - improve the model
   - answer to open questions of what happened in 1687….



Thank you for your attention