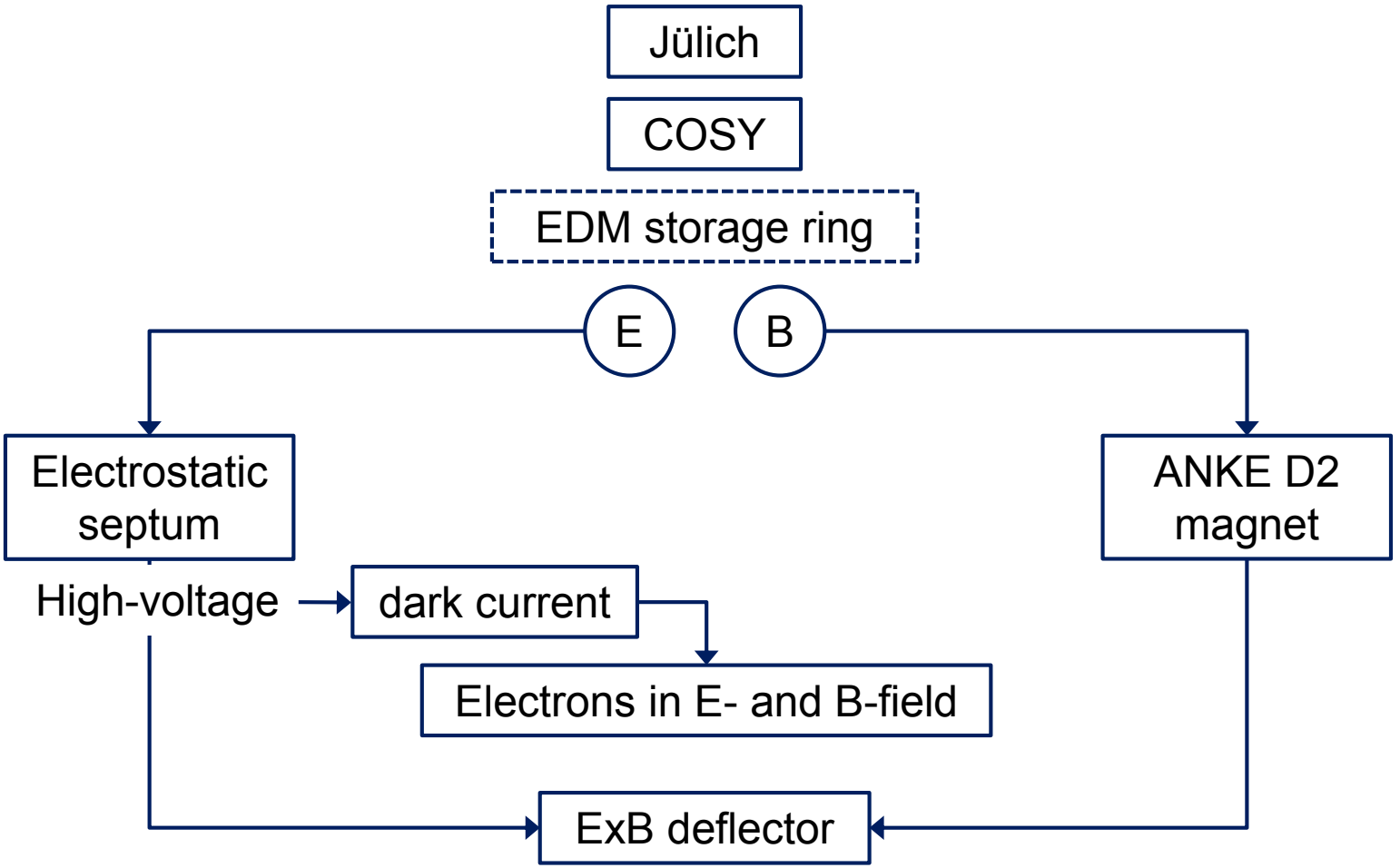
JÜLICH
FORSCHUNGSZENTRUM

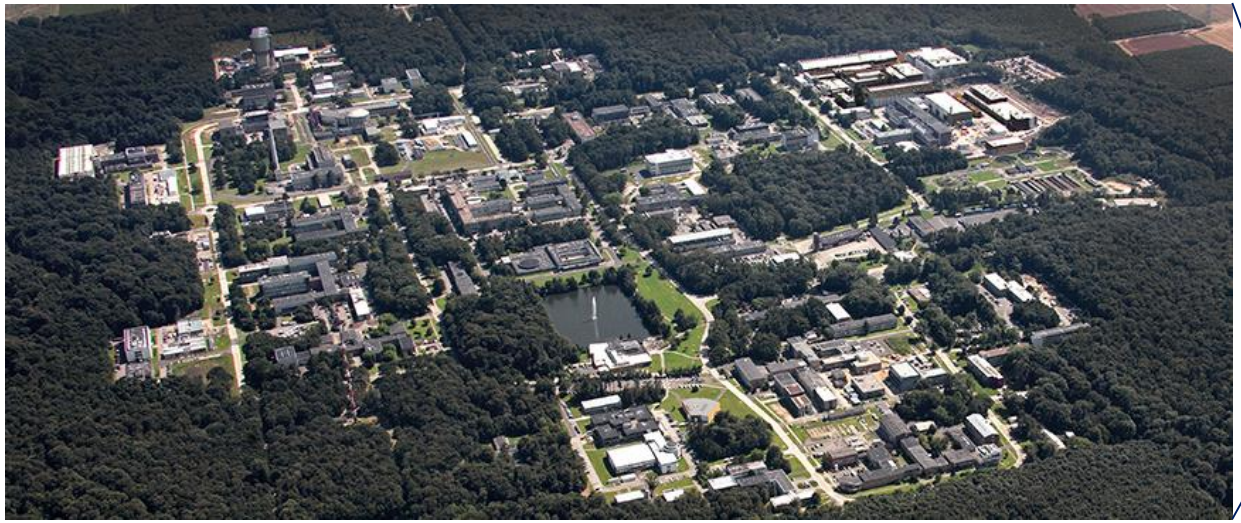
ExB Deflector Development

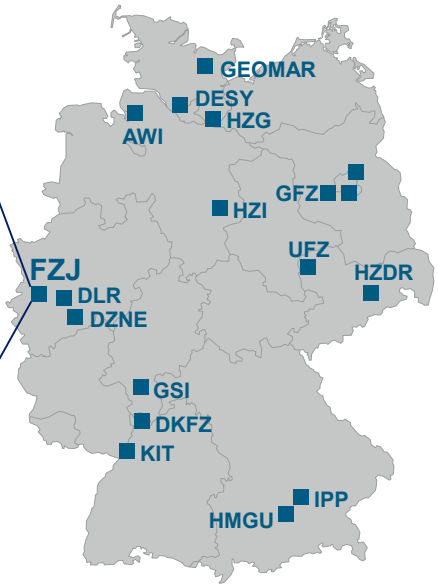
2016-09-12 | Jürgen Böker
Institute for Nuclear Physics

Outline



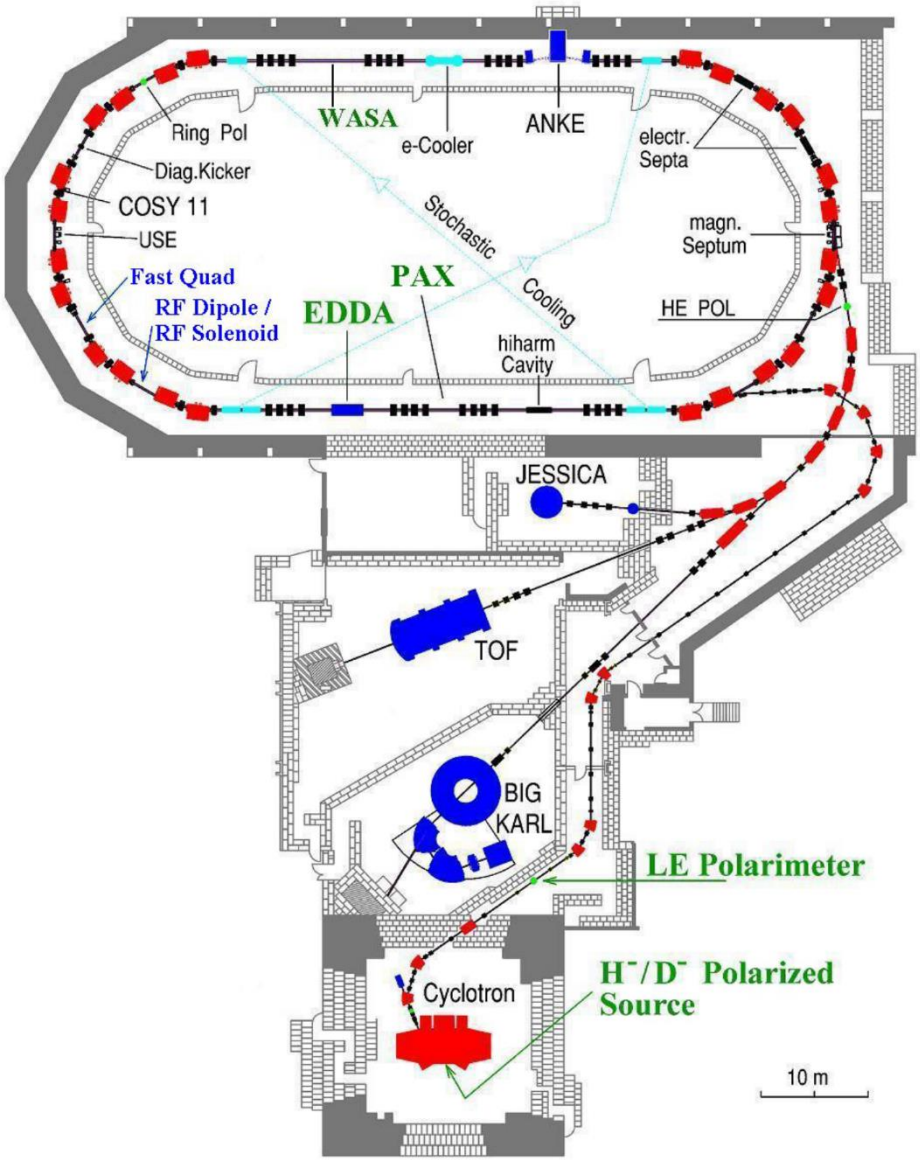
Forschungszentrum Jülich





- Founded 11 December 1956
- Partners Federal Republic of Germany (90%)
  North-Rhine-Westphalia (10%)
- Revenue € 525.4 million 2014
- Structure 9 institutes
  2 project management organizations
  (project volume: € 1.8 billion)
- Employees 5,768 (total)

COSY – COoler SYnchrotron



- 184 m circumference
- Proton momentum 0.3 - 3.3 GeV/c
- Species: protons, deuterons incl. polarized beams
- Stochastic + electron cooling

JULIC

- In operation since 1968
- H.-P. May‘s Poster THP04
- O. Felden‘s Poster MOP18

Why are we here?

- Dominance of matter over anti-matter in the universe

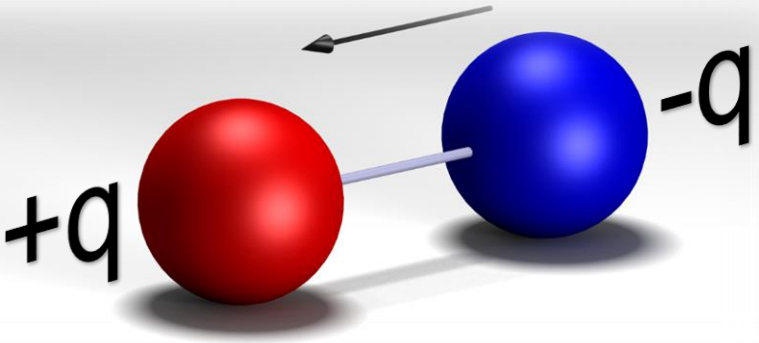
	$(n_B - n_{\bar{B}})/n_\gamma$
Observed	$(6.11 \pm 0.19) \times 10^{-10}$
SM exp.	$\sim 10^{-18}$

WMAP+COBE (2003)

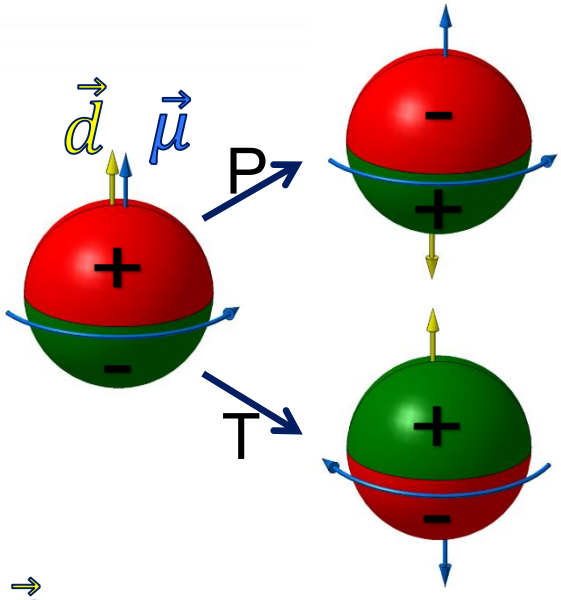
- Sakharov conditions
  - → Baryon number violation
  - → CP violation
  - → Non-equilibrium

Electric dipole moment (EDM)

- Charge separation in particles
  classic definition: $\vec{d} = \sum_i q_i \vec{r}_i$
  water molecule $\left|\vec{d}\right| \approx 10^{-8}\,\mathrm{e\,cm}$



- Permanent EDMs violate
  $\boldsymbol{P}$ and $\boldsymbol{T}$ symmetry $\left(\overset{\boldsymbol{CPT}}{\Longrightarrow} \boldsymbol{CP}\right)$



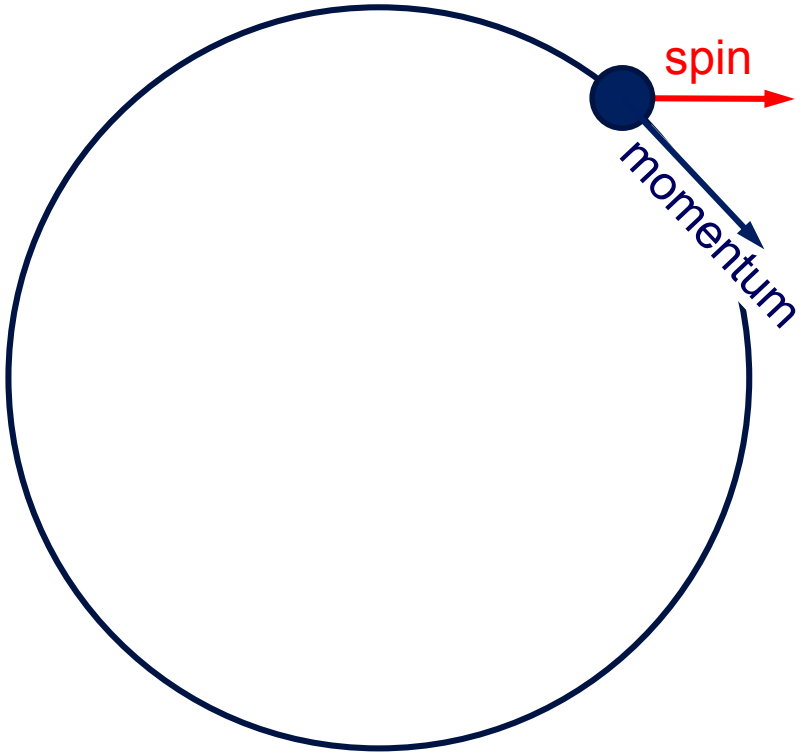
$\vec{d}$ Electric dipole moment

$\vec{\mu}$ Magnetic dipole moment

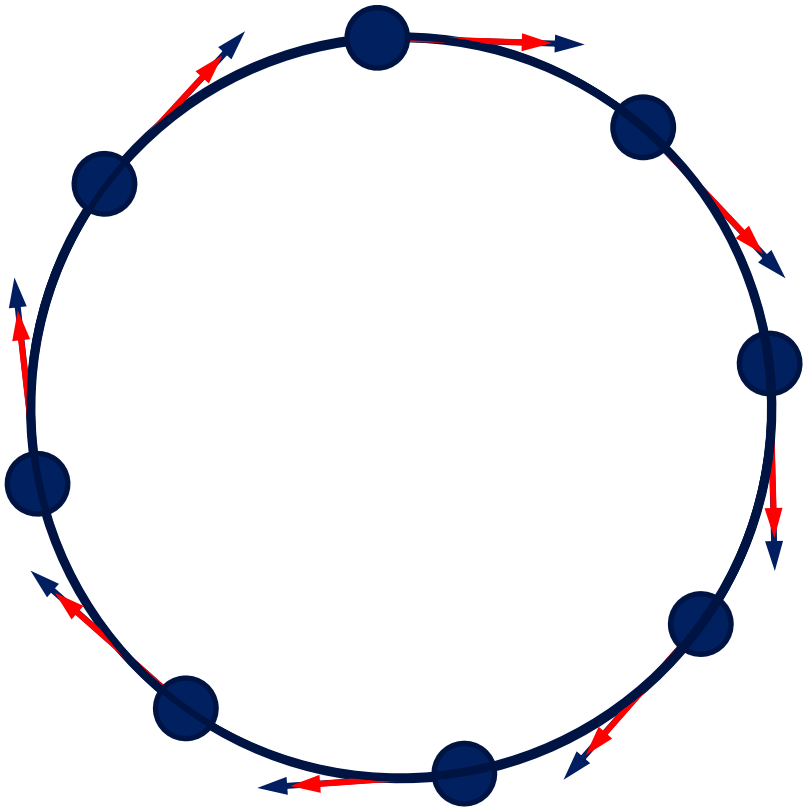
Image: adopted from https://en.wikipedia.org/wiki/Neutron_electric_dipole_moment

Ingredients

1. Polarized, charged particle beam

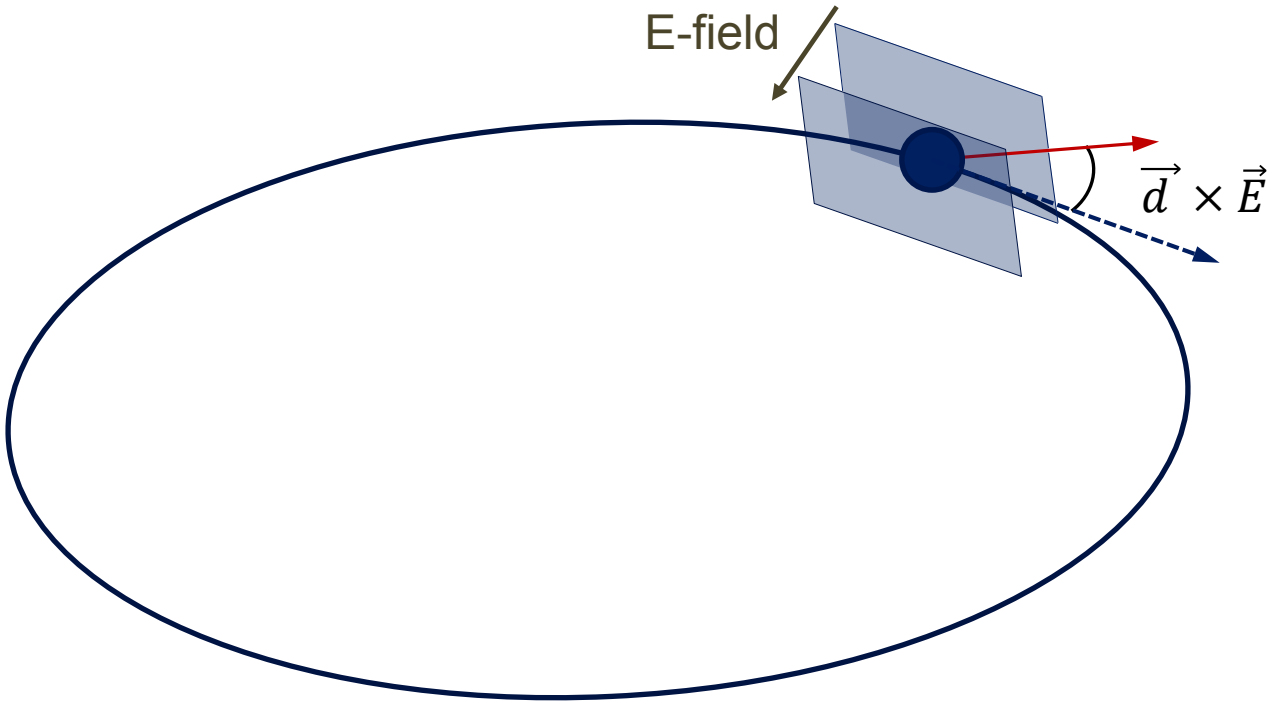


2. Align spin with momentum



Ingredients

3. Apply a radial electric field



EDM causes a vertical polarization!

Thomas BMT Equation

$$\vec{\Omega}_{\mathrm{MDM}} = \frac{q}{m}\left(G \cdot \vec{B} - \frac{\gamma G}{\gamma + 1}\vec{\beta}\left(\vec{\beta} \cdot \vec{E}\right) - \left[G - \frac{1}{\gamma^2 - 1}\right]\frac{\vec{\beta} \times \vec{E}}{c}\right)$$

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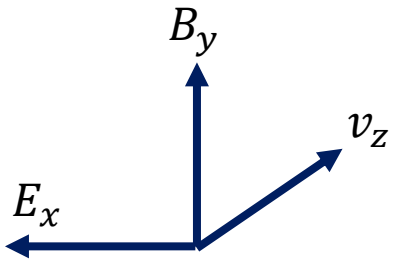
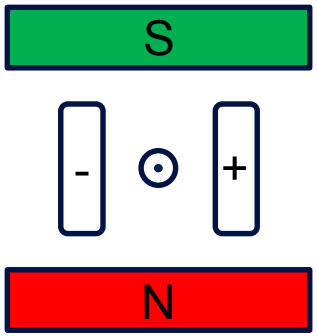


$$E_x \neq 0$$
$$B_y \neq 0$$
$$\beta_z \neq 0$$

$\Rightarrow$



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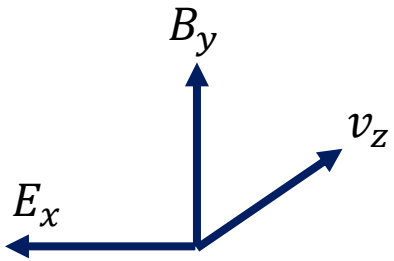

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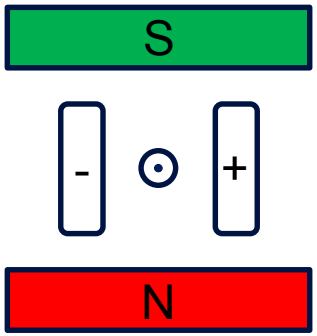
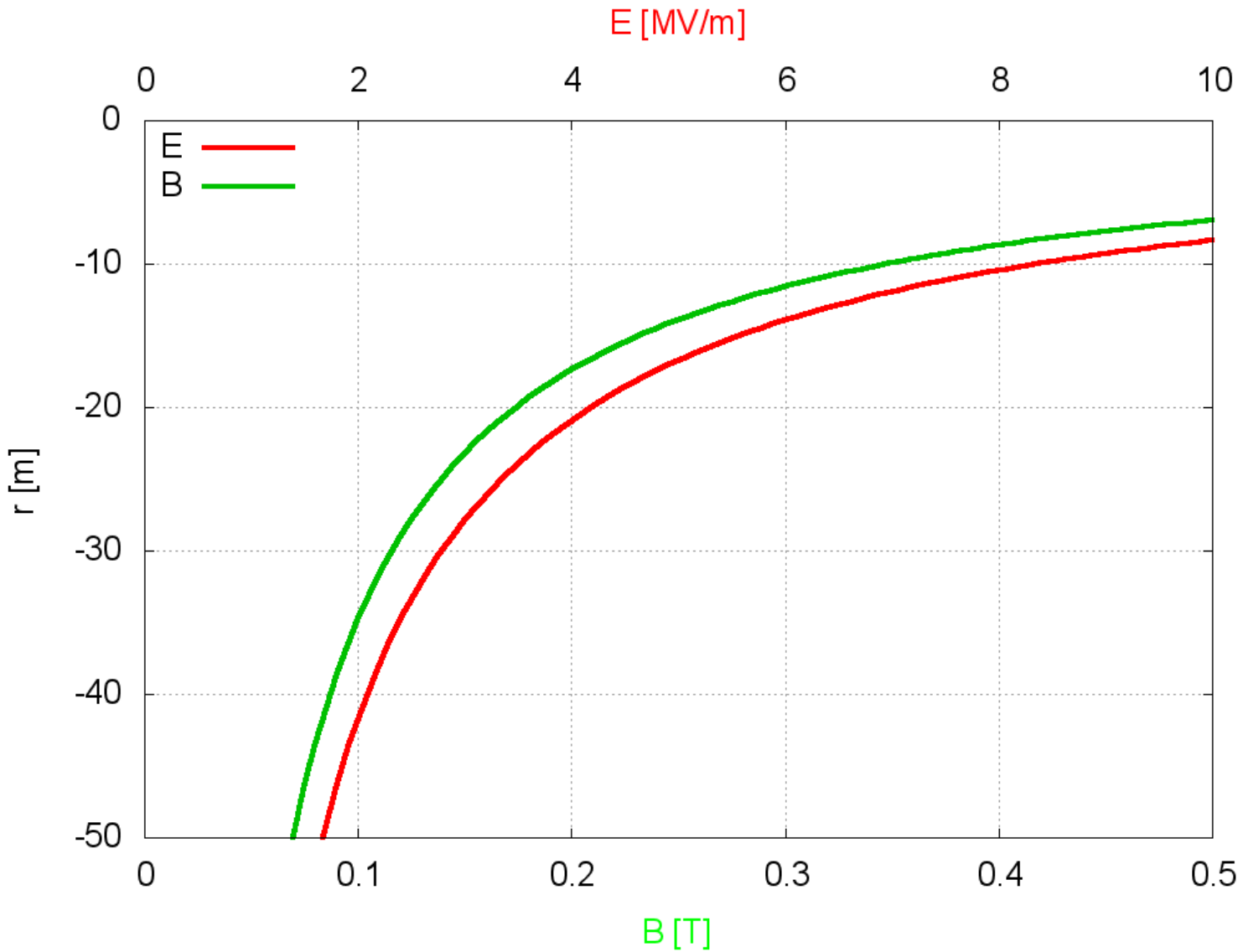


$\Rightarrow$

$$\boxed{\frac{cB_y}{E_x} = \frac{\beta_z}{G}\left[G - \frac{1}{\gamma^2 - 1} \right]}$$

$$p_d = 970\ \mathrm{MeV/c} \quad \Rightarrow \quad \frac{cB_y}{E_x} = 12.47$$

ExB Fields for 970 MeV/c Deuterons

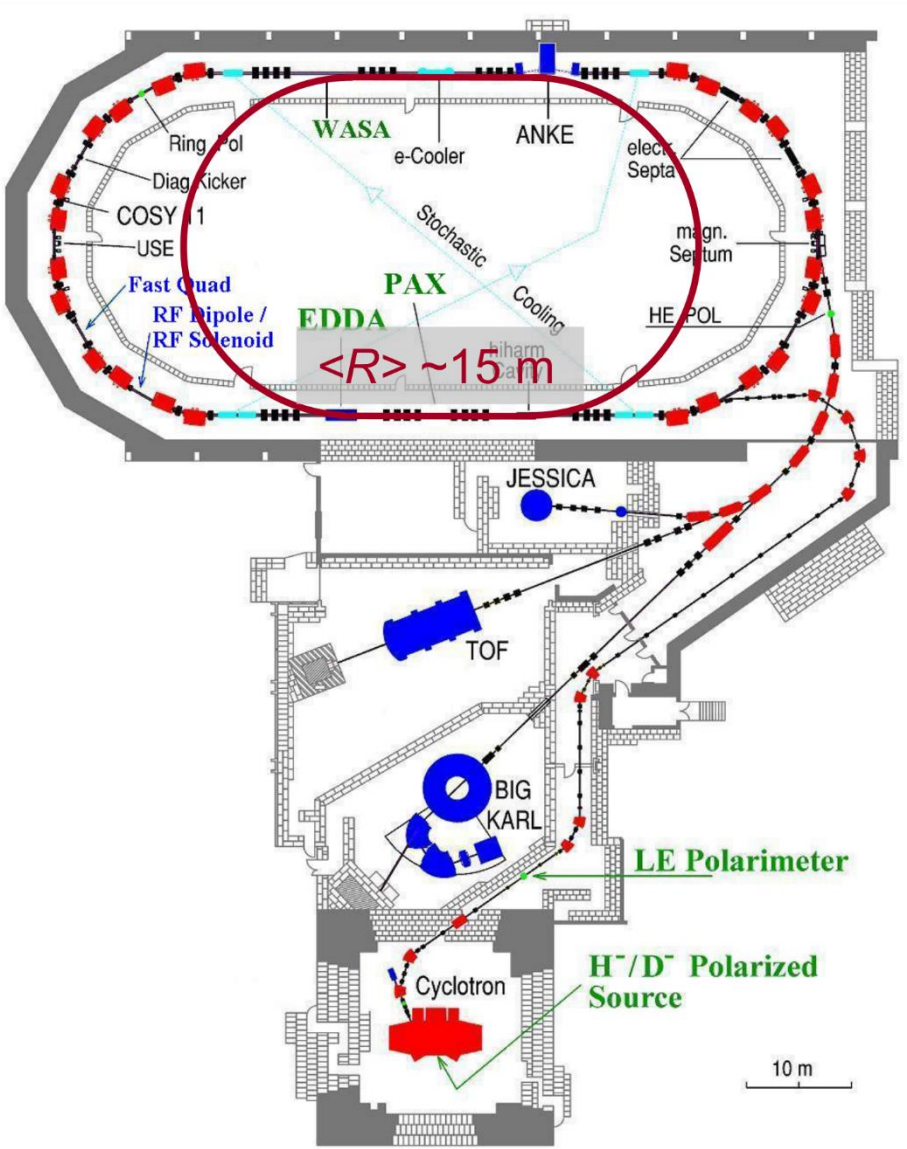


r = 15 m

E = 6 MV/m

B = 0.25 T

COSY → EDM-Ring



CERN Courier Sep.‘16

Storage ring steps up search for electric dipole moments

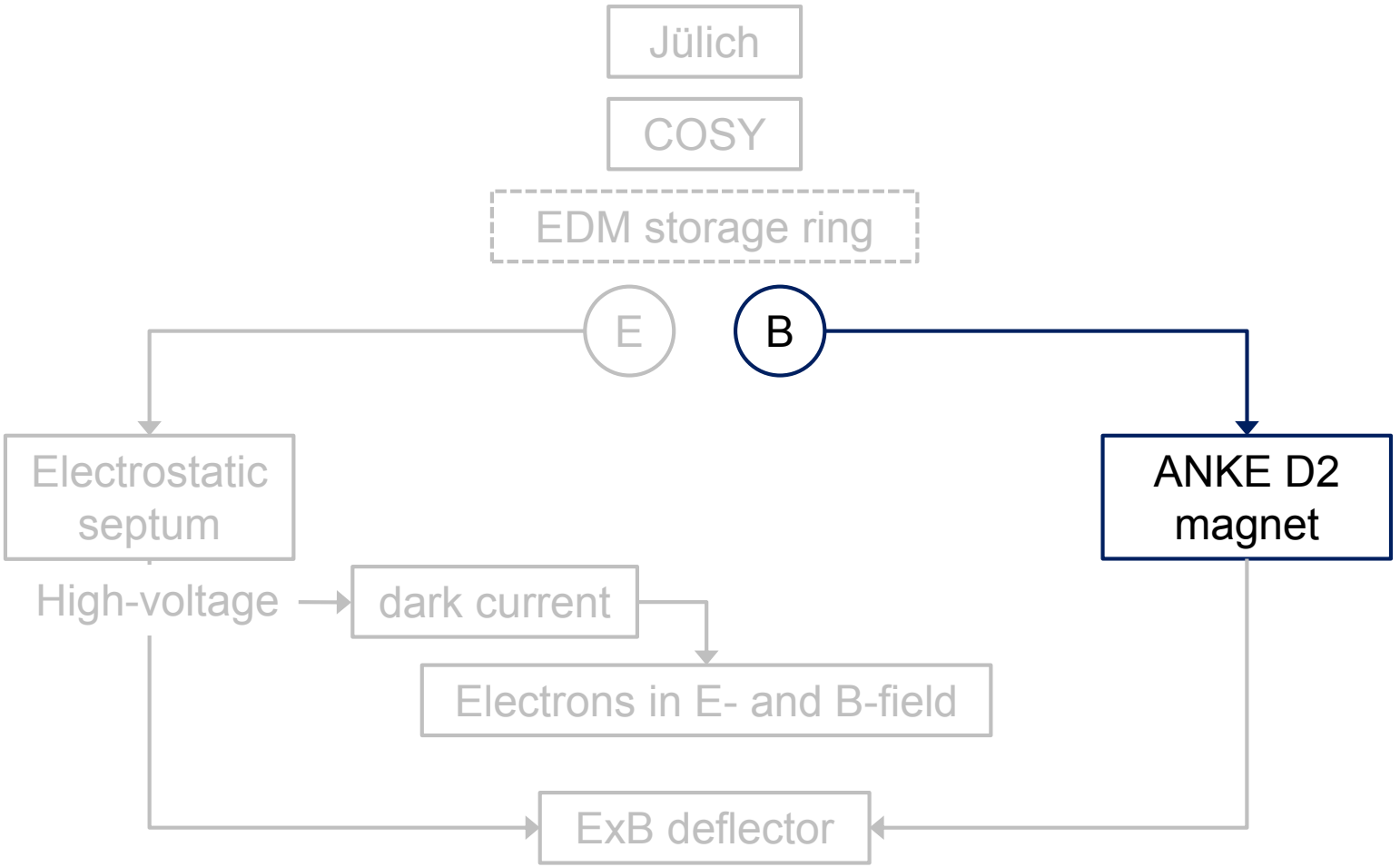
The JEDI collaboration aims to use a storage ring to set the most stringent limits to date on the electric dipole moments of hadrons, describe **Paolo Lenisa**, **Jörg Pretz** and **Hans Ströher**.

The fact that we and the world around us are made of matter and only minimal amounts of antimatter is one of the fundamental puzzles in modern physics, motivating a variety of theoretical speculations and experimental investigations. The combined standard models of cosmology and particle physics suggest that at the end of the inflation epoch immediately following the Big Bang, the number of particles and antiparticles were almost in precise balance. Yet the laws of physics contrived to act differently on matter and antimatter to generate the apparently large imbalance that we observe today.

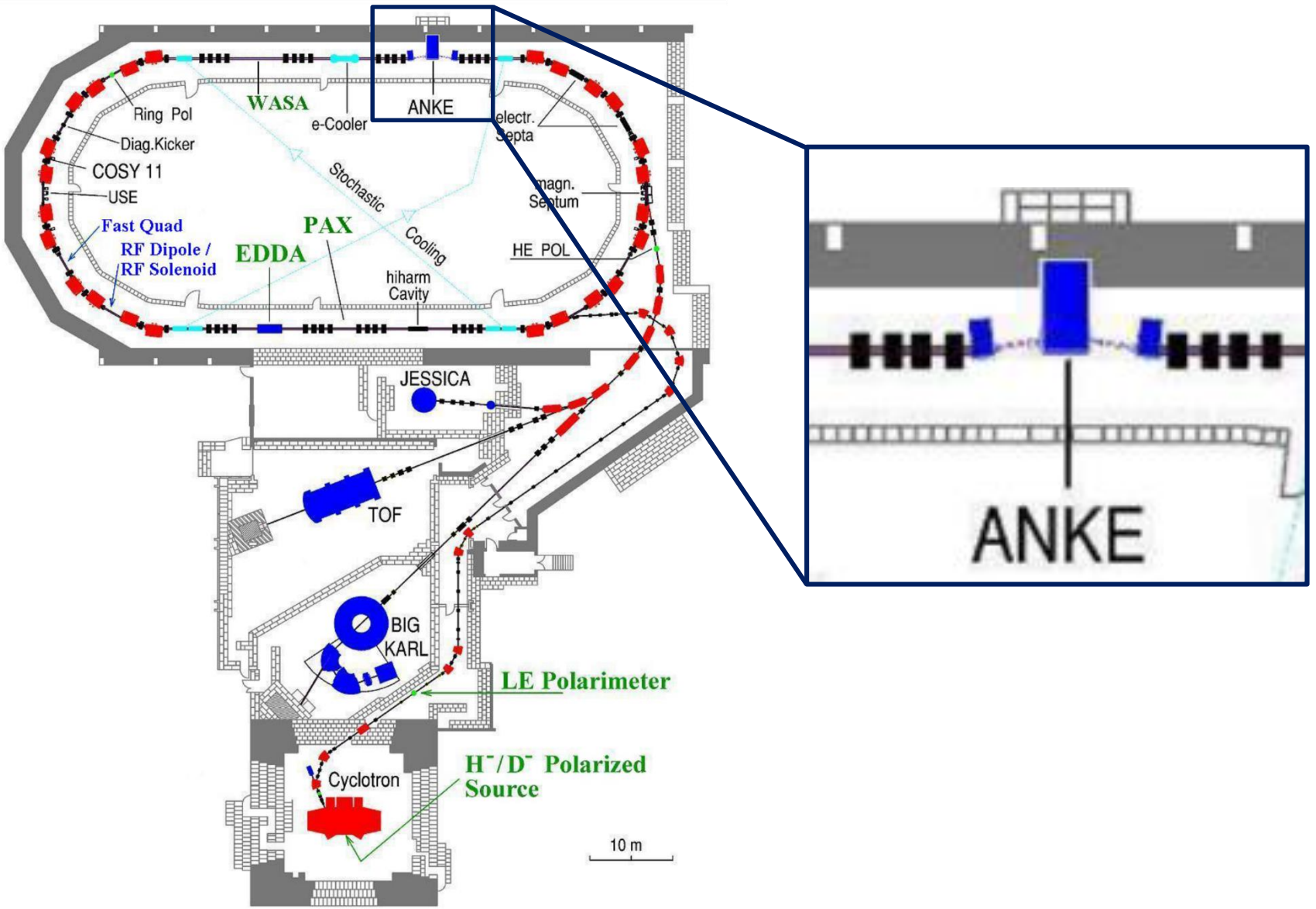
One of the necessary mechanisms required for this to happen – namely CP violation – is very small in the Standard Model of par-

Forschungszentrum Jülich

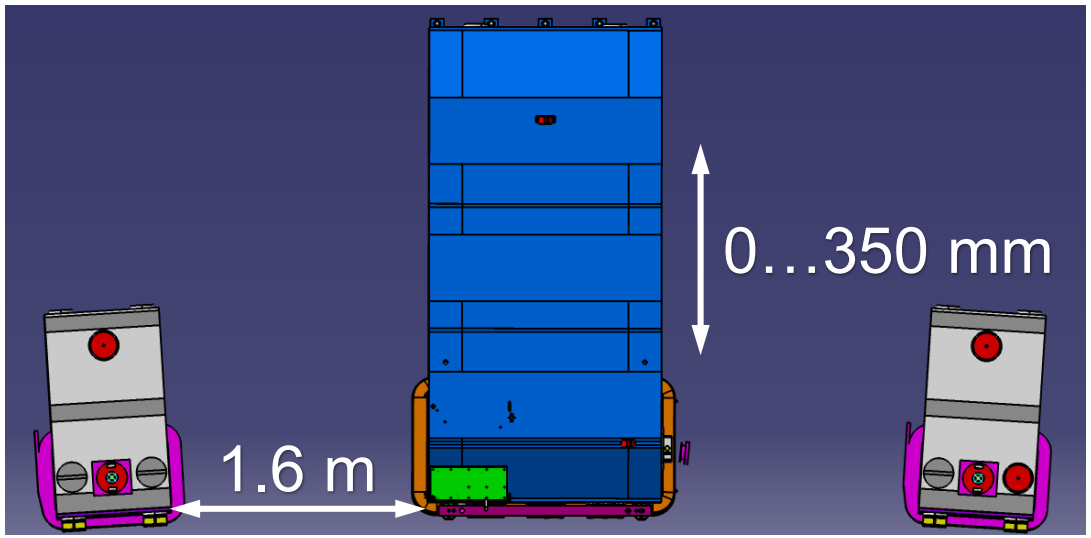
The COSY storage ring at the Forschungszentrum Jülich in Germany is being modified to search for very small electric dipole moments.

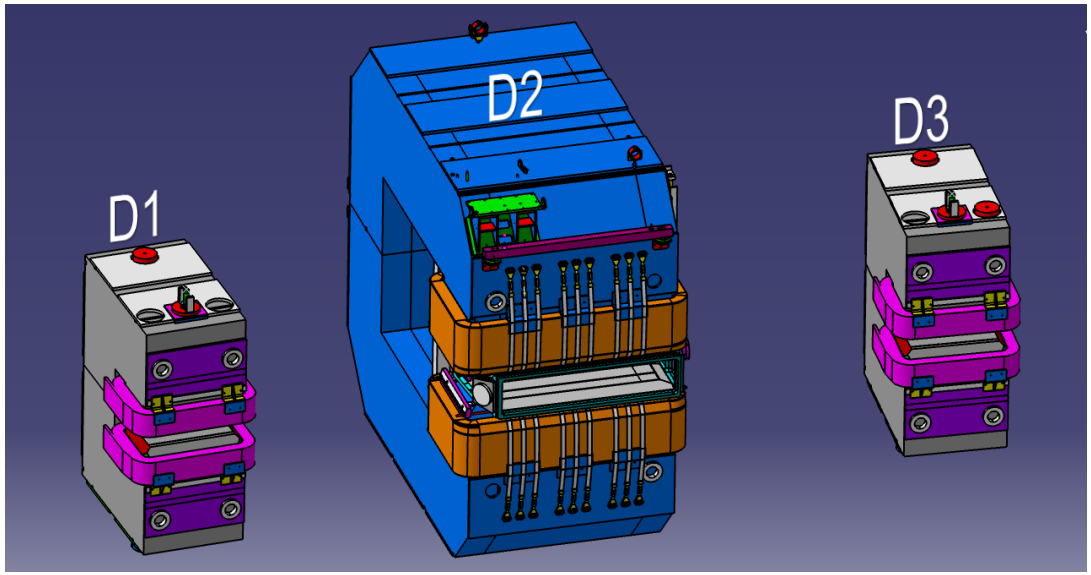


COSY - ANKE

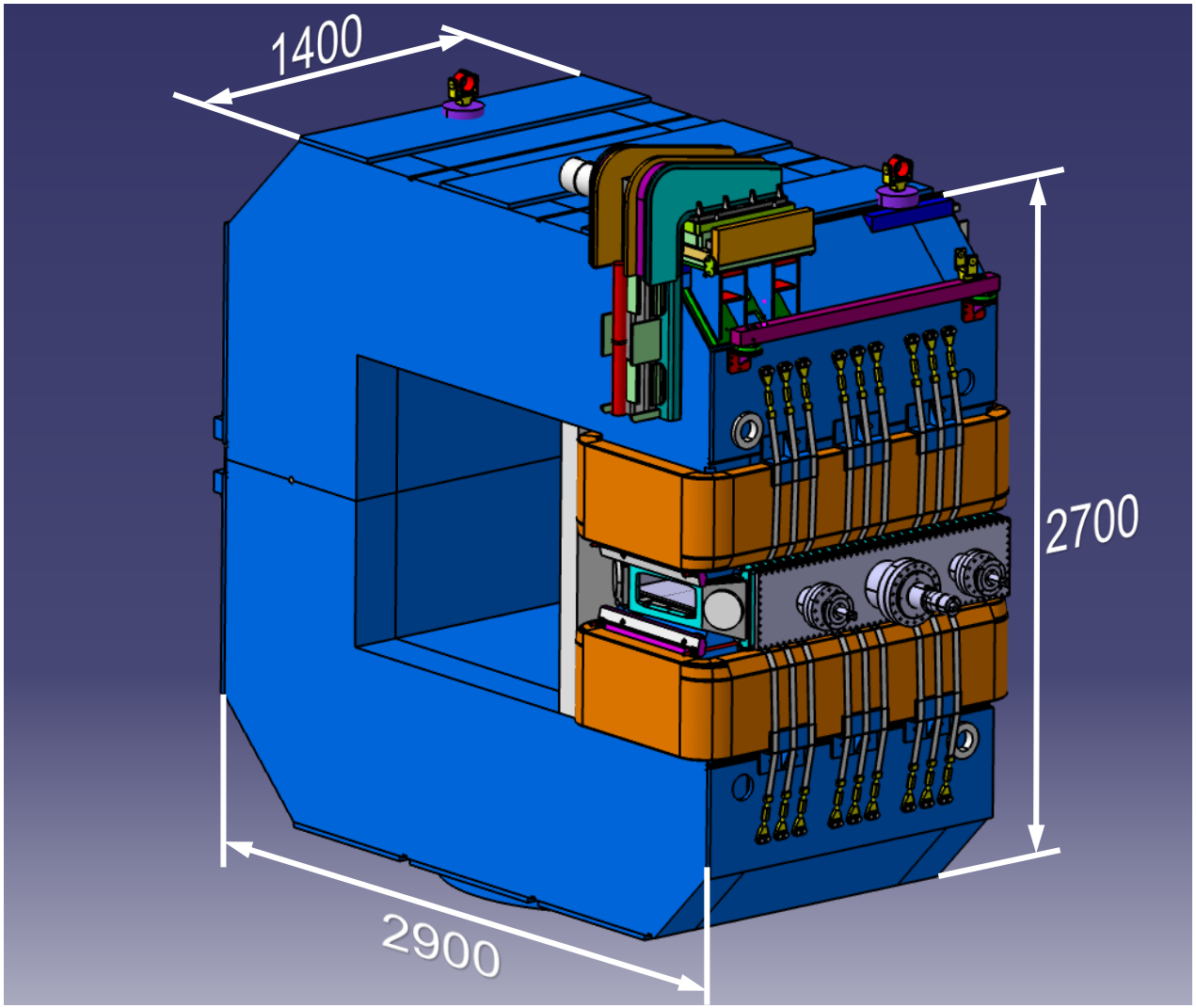


ANKE Chicane

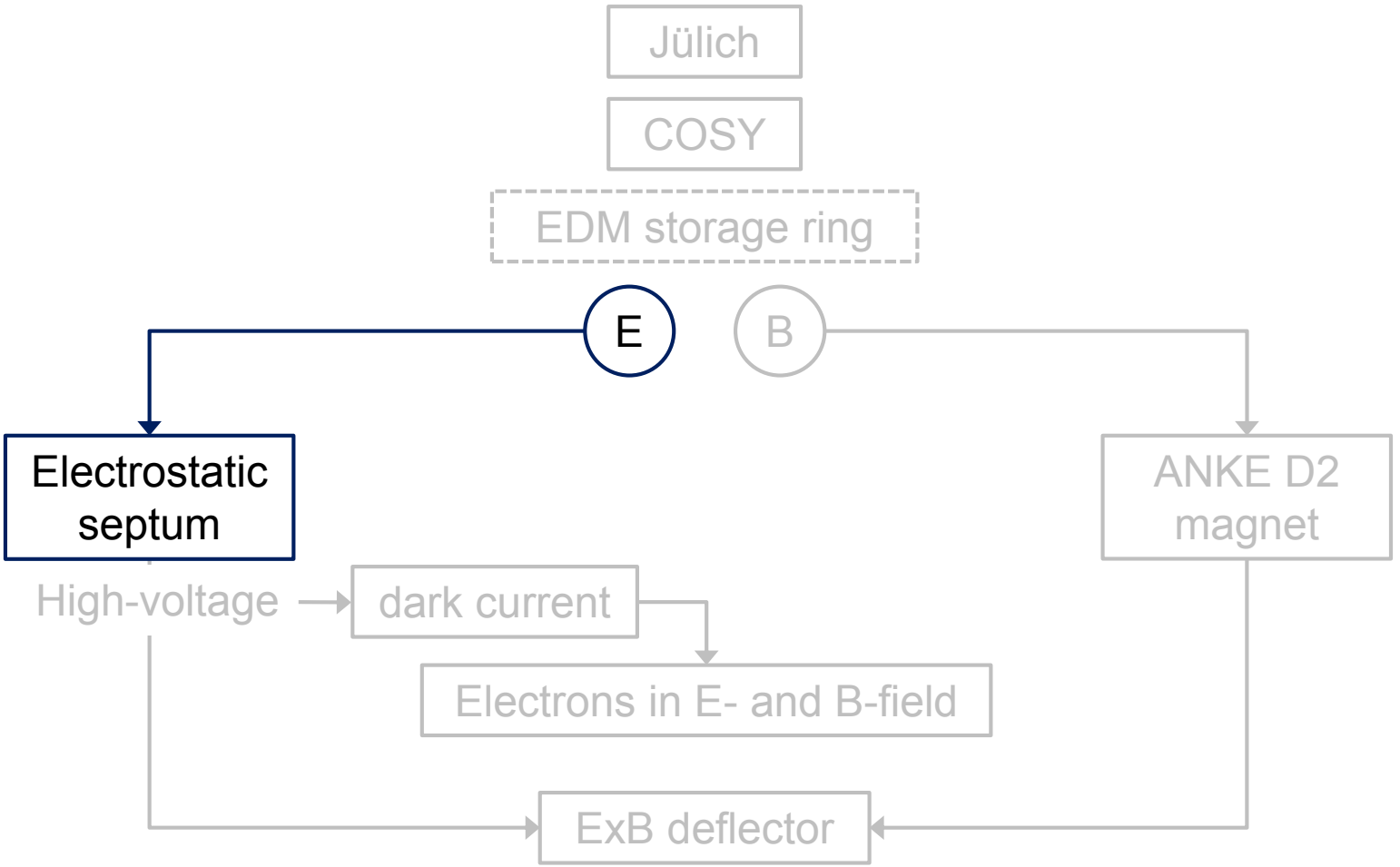




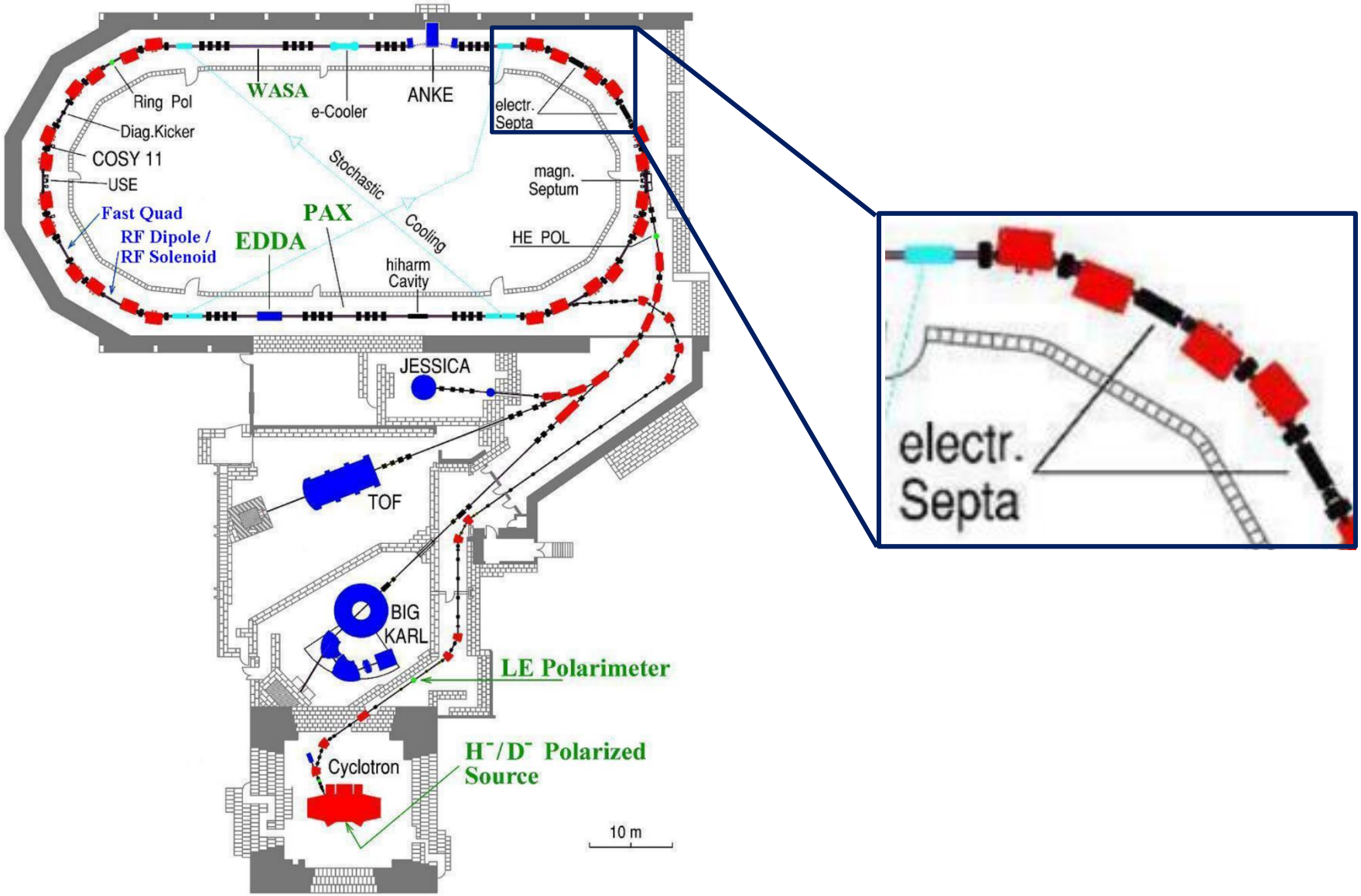
ANKE D2



- B_{max} = 1.6 T
- m = 64 t
- Gap height 200 mm

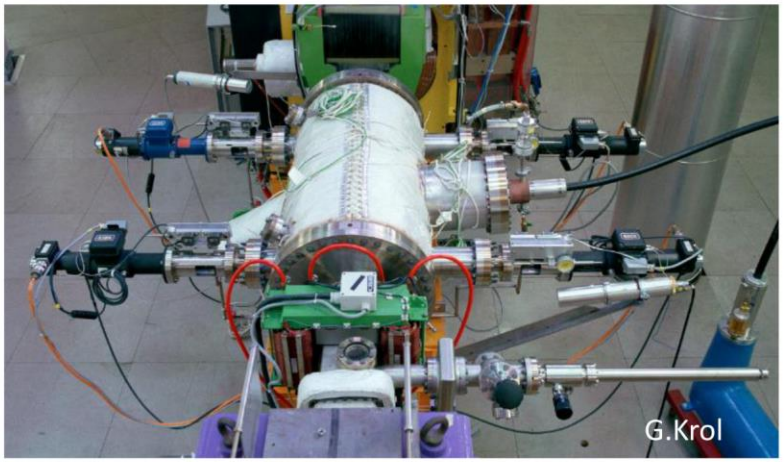


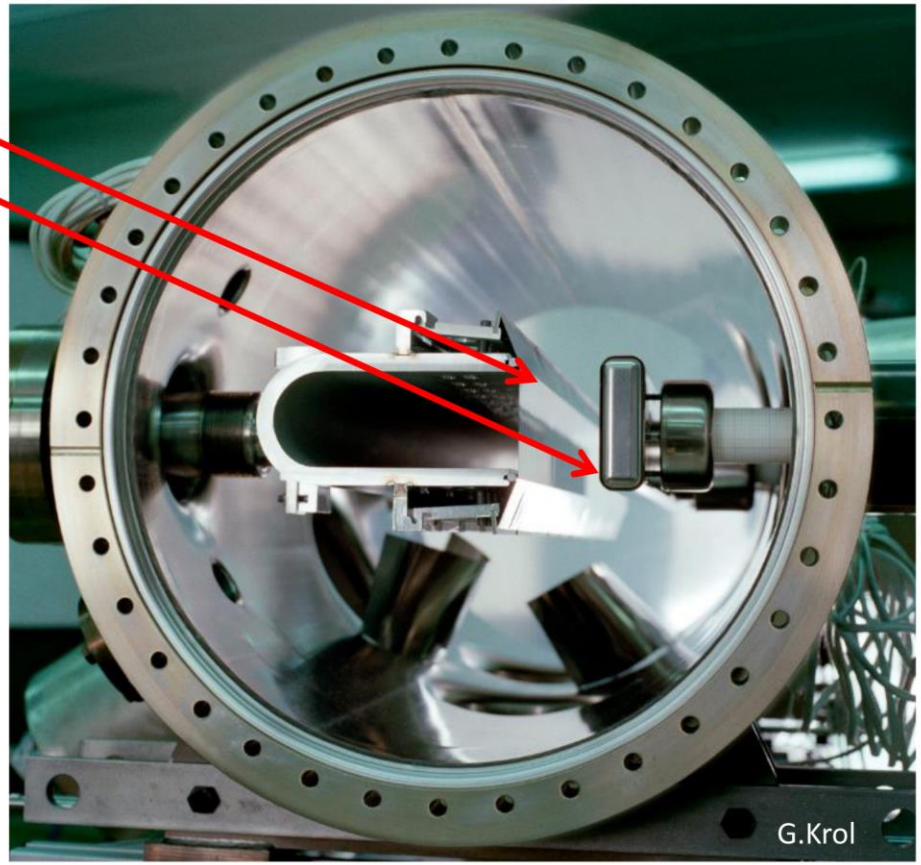
COSY – Electrostatic Septum



COSY Extraction Septum

- Grounded septum foil (0.1 mm Mo)
- Max. 200 kV on cathode (coated Al)
- Max. 120 kV/cm (3.3 GeV/c)
- In situ bakeable to 300°C
- Moveable electrodes (r, r')

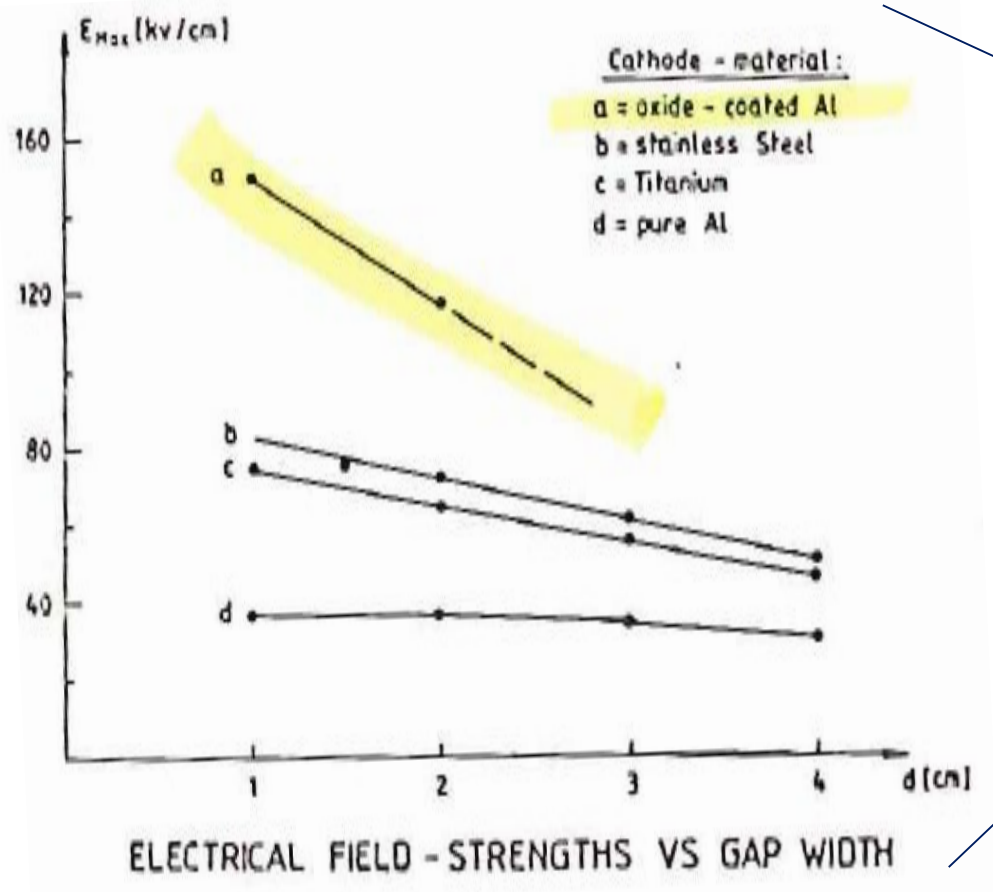




500 mm

Courtesy: Ralf Gebel | IKP-4

COSY Electrostatic Septum



1) High voltage- and vacuum tests

High voltage tests have been done with different cathode materials. All pure metal cathodes (Al, Ti, stainl. steel) were not able to sustain the required field strength of 80 kV/cm at a gap distance of 2 cm (compare Fig. 1).

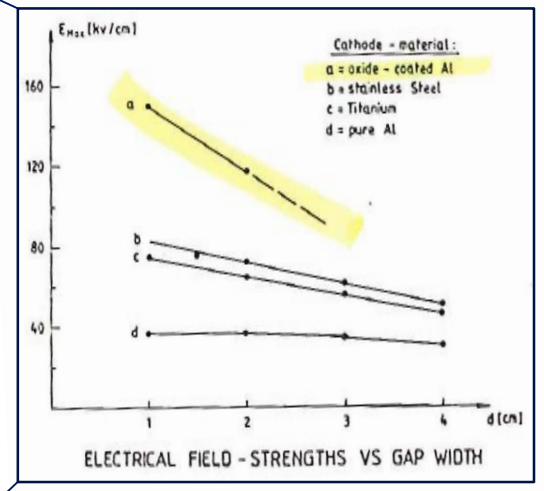
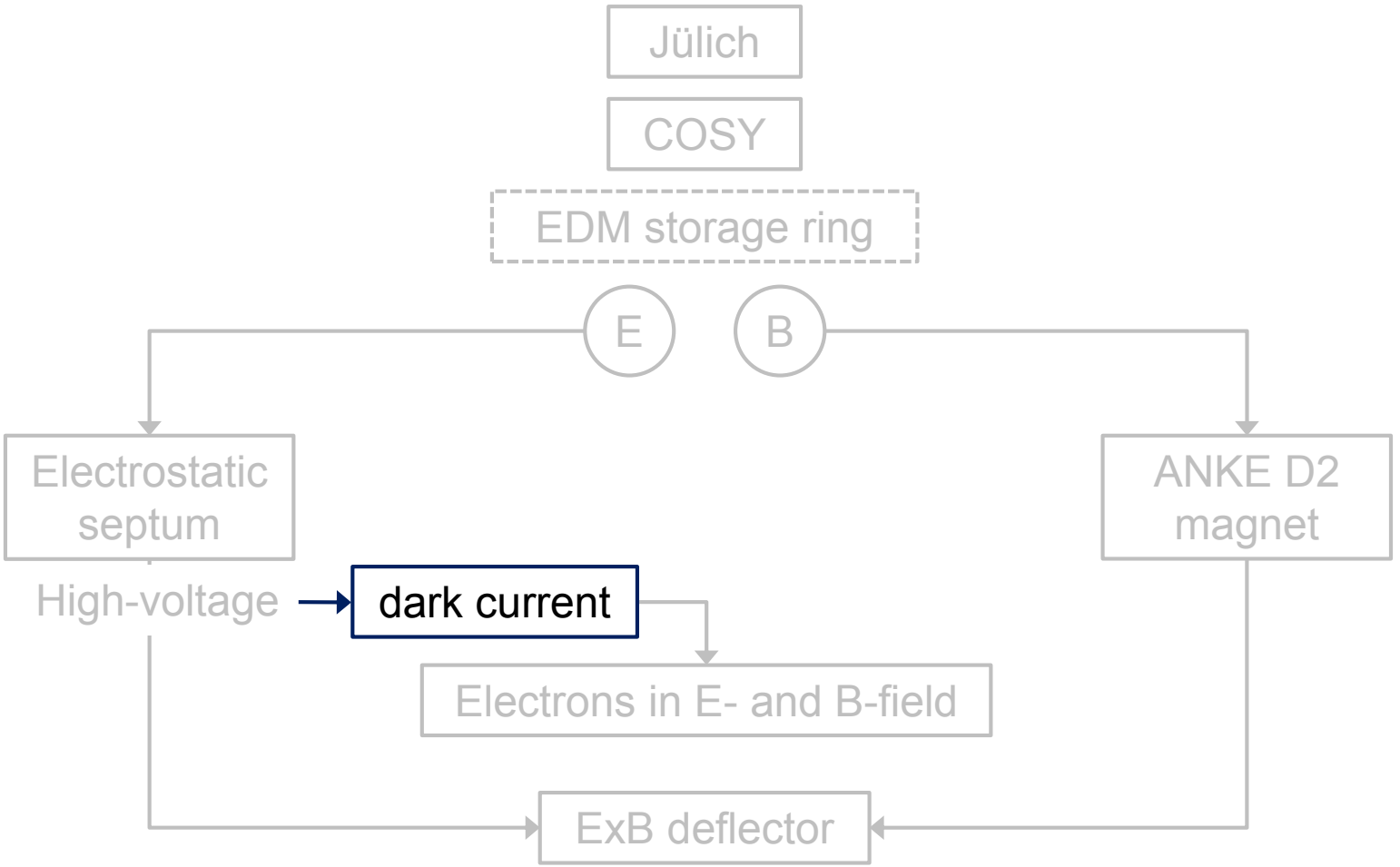


Fig. 1

The maximum field strength for this electrode distance could not be increased above 65 kV/cm, even by enhancing the curvature radii at the edges of the cathode, which improved the high voltage behaviour slightly. Excellent results were achieved with an anodic oxided Al-cathode. By using this material the maximum field strengths for short gap distances could be raised by nearly a factor of 2.

Eickhoff et al.: Design and operation test of the SIS Electrostatic septa (GSI report 1987)



Dark Current

- Fowler-Nordheim theory
  - Tunneling of electrons
  - Field enhancement factor

$$J = \mathrm{a}E^2 \exp\left(-\frac{b}{E}\right)$$

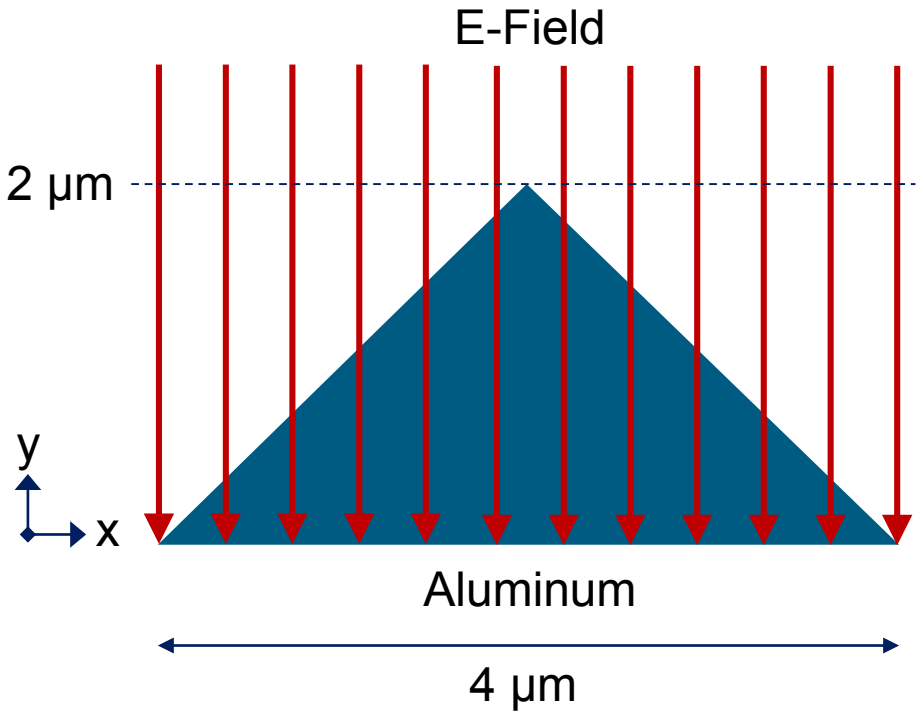
$$E = \gamma E_M$$

Material	Work function Φ [eV]
Aluminum	4.06 – 4.26
Titanium	4.33
Titanium Nitride	4.7 – 5.3
Tungsten	4.23 – 5.22

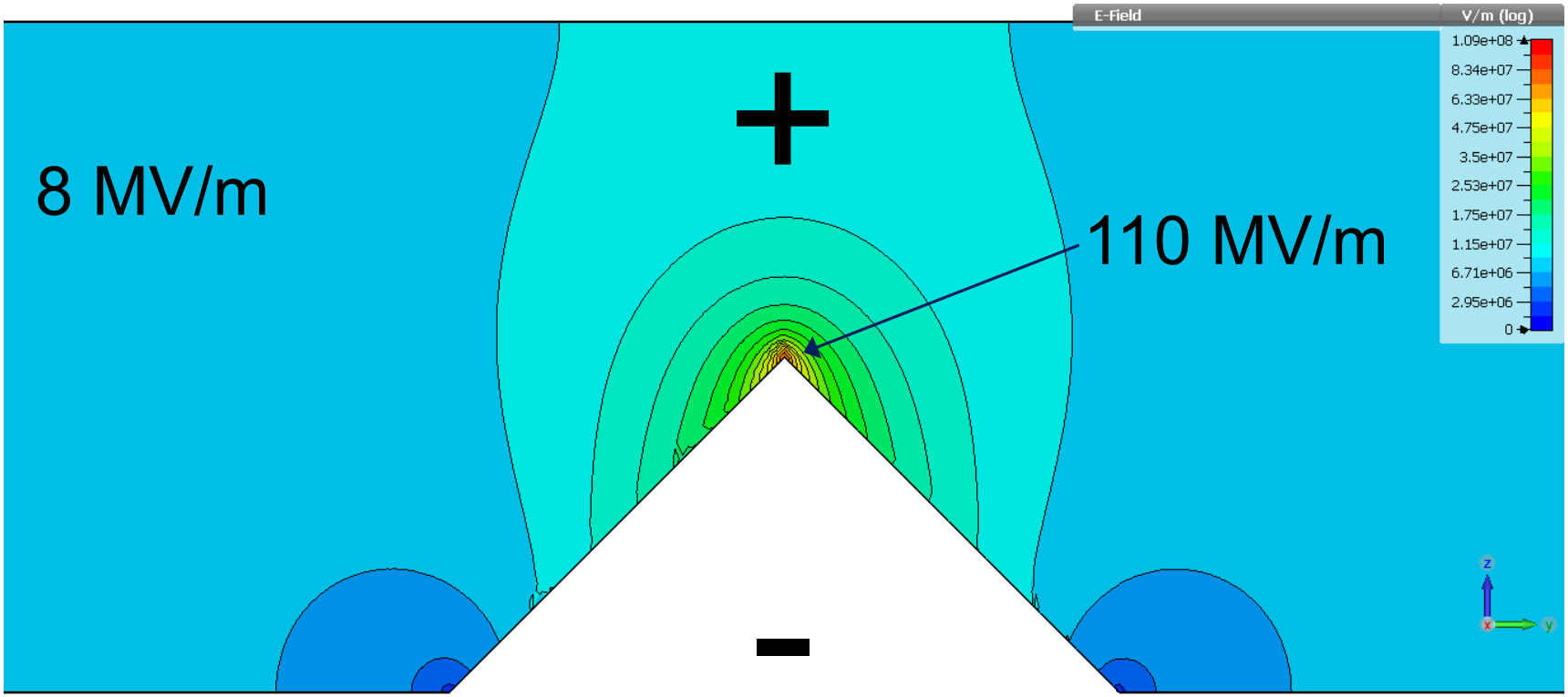
$$E_{BSI} \cong 1.73 \times 10^8 \left(\frac{\Phi}{\mathrm{eV}}\right)^2 \qquad E_{BSI}(4\mathrm{eV}) \cong 2.8\ \mathrm{GV/m}$$

Dark Current

Field enhancement factor	Tunnel ionisation
⇓	⇓
CST field simulation	PIC simulation (EPOCH)
	• Collisional ionisation • Single atoms are ionized!



CST - E-Field Simulation of a Tip



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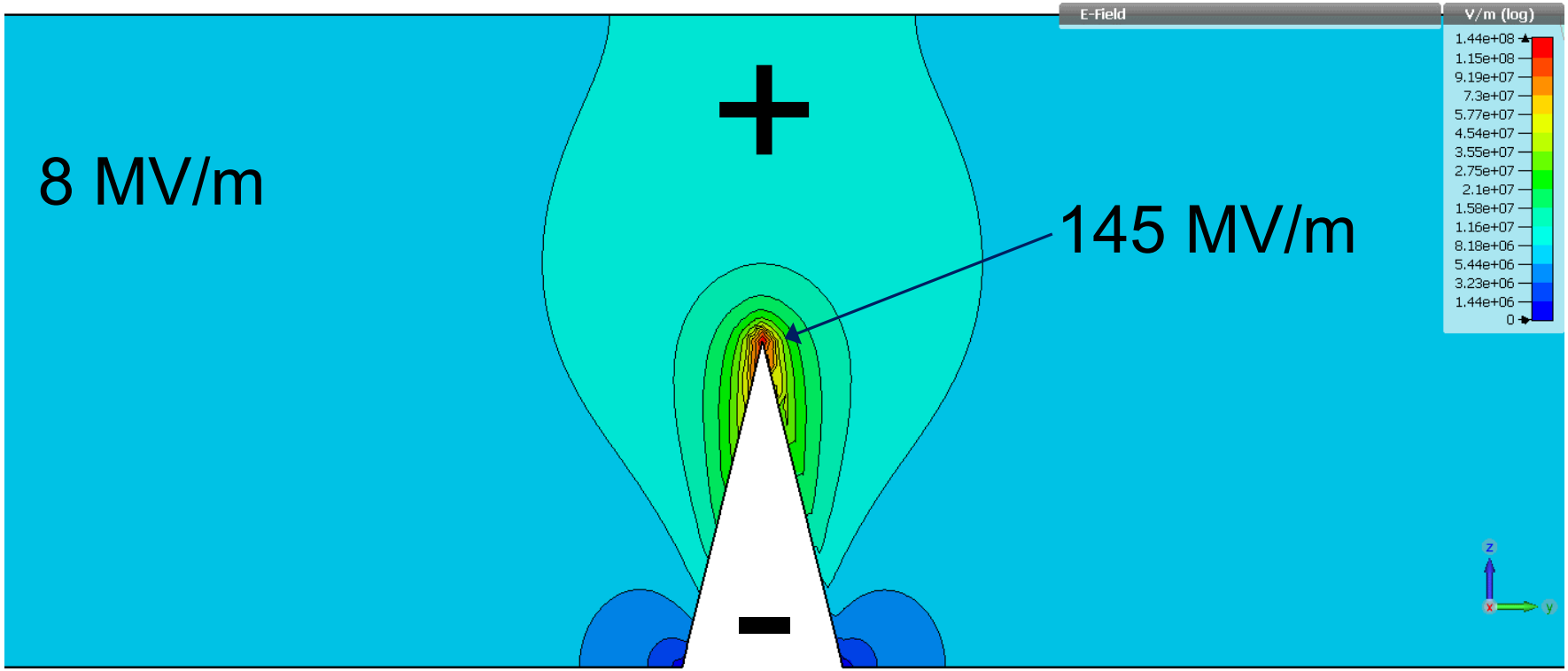
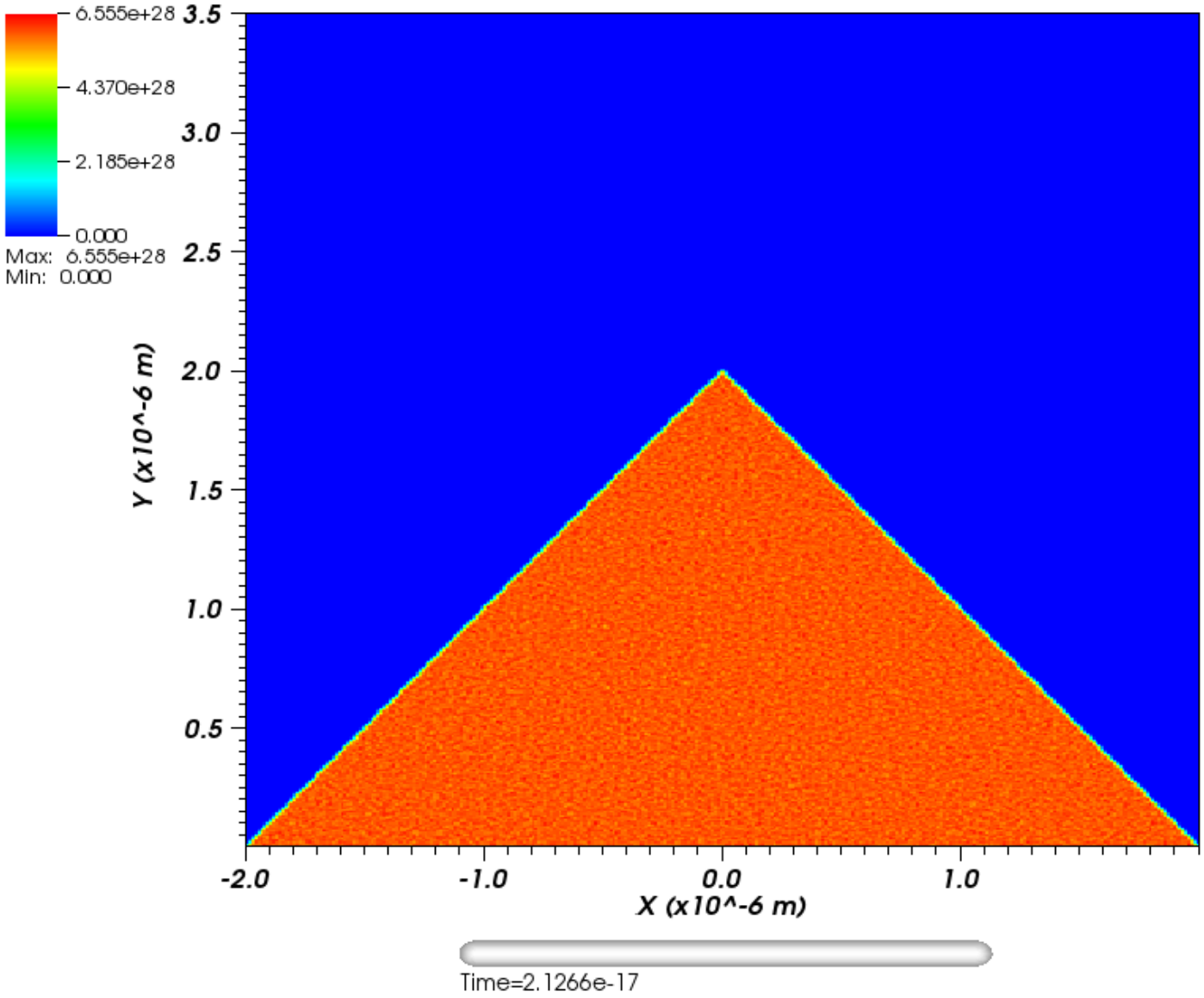
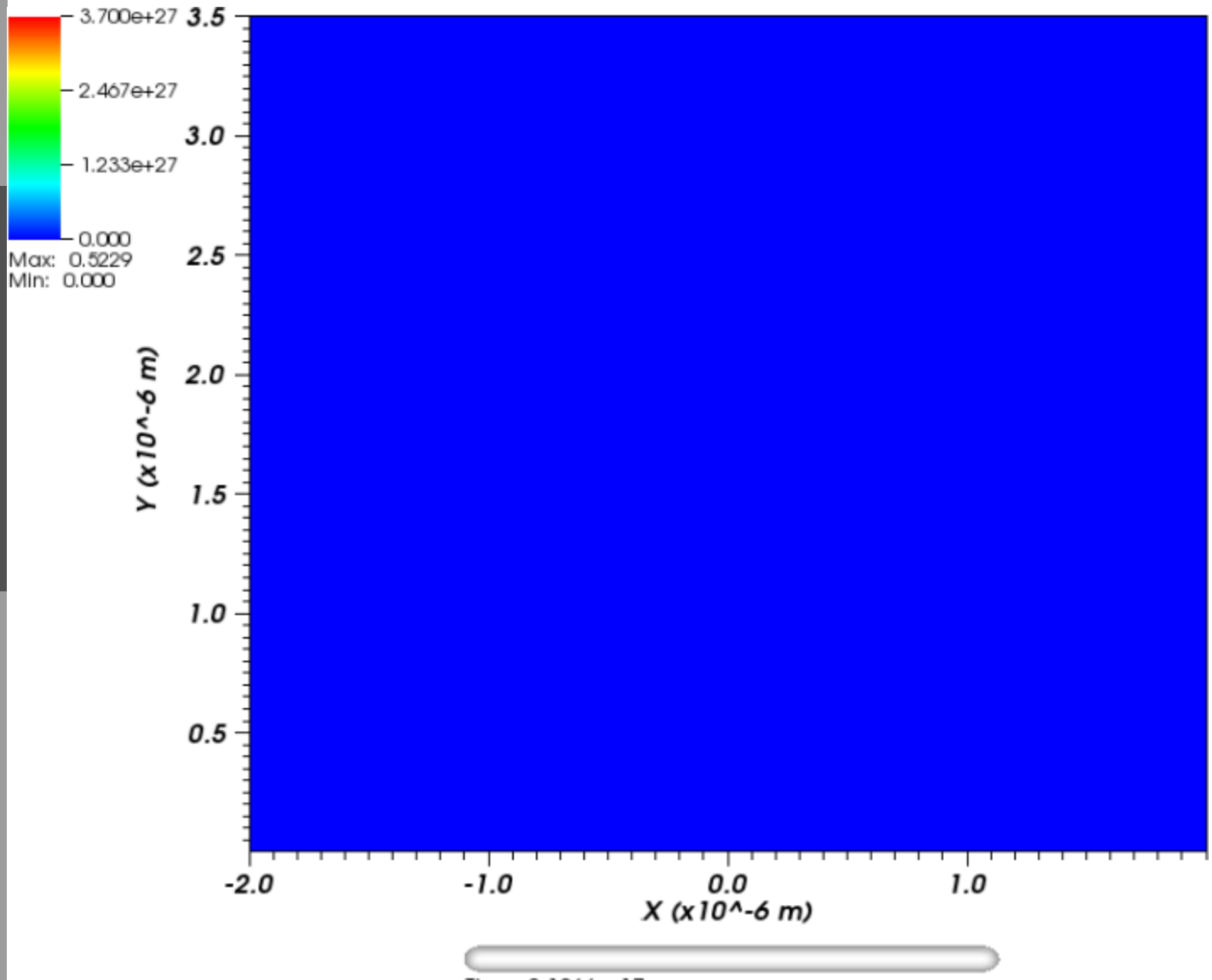


PIC - Aluminum Density



- E_y = -2 GV/m
- Φ = 4 eV
- t_{tot} = 2.3 ps

PIC - Electron Density



- E_y = -2 GV/m
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- t_{tot} = 2.3 ps
- t_{comp} = 2 d

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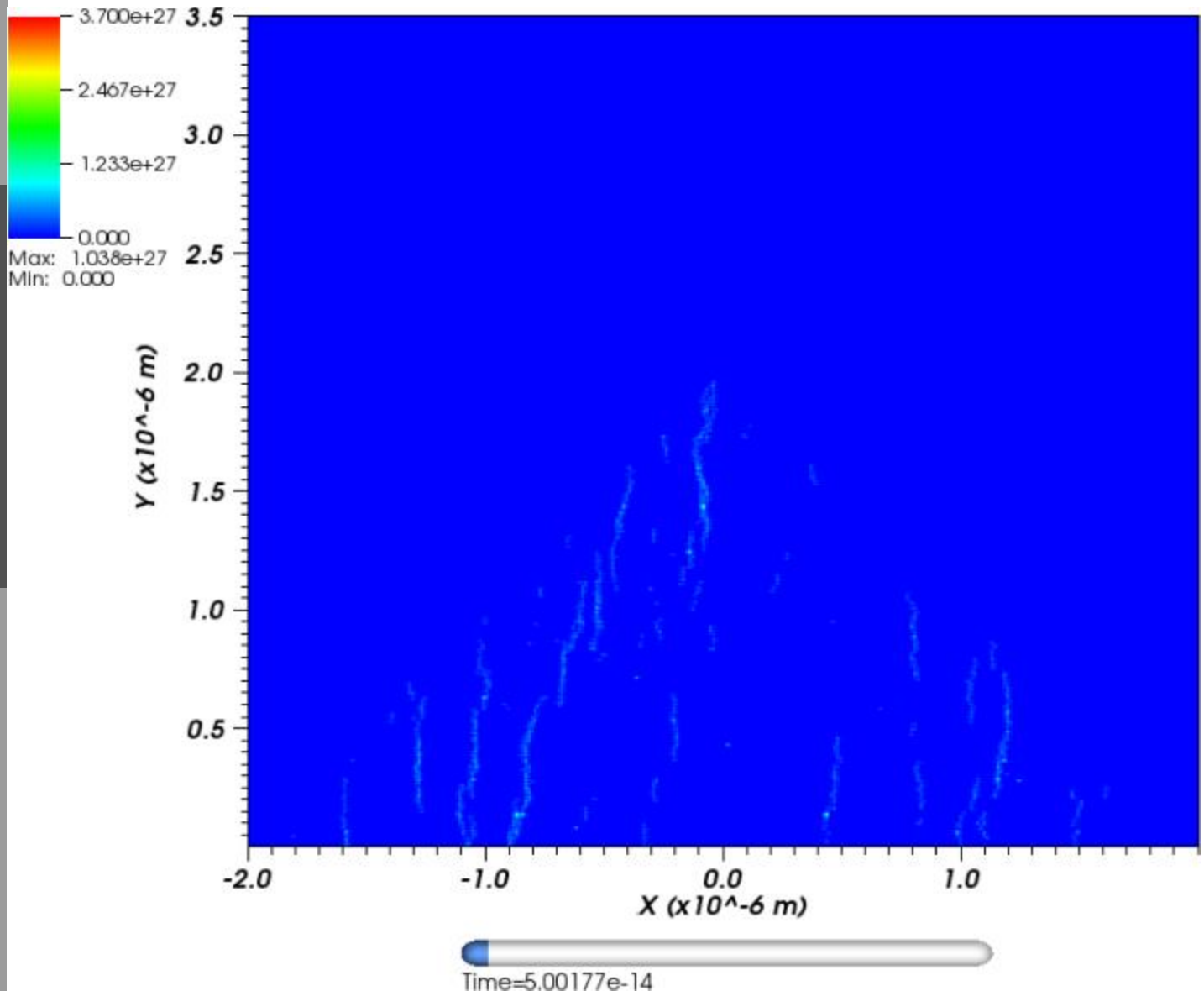

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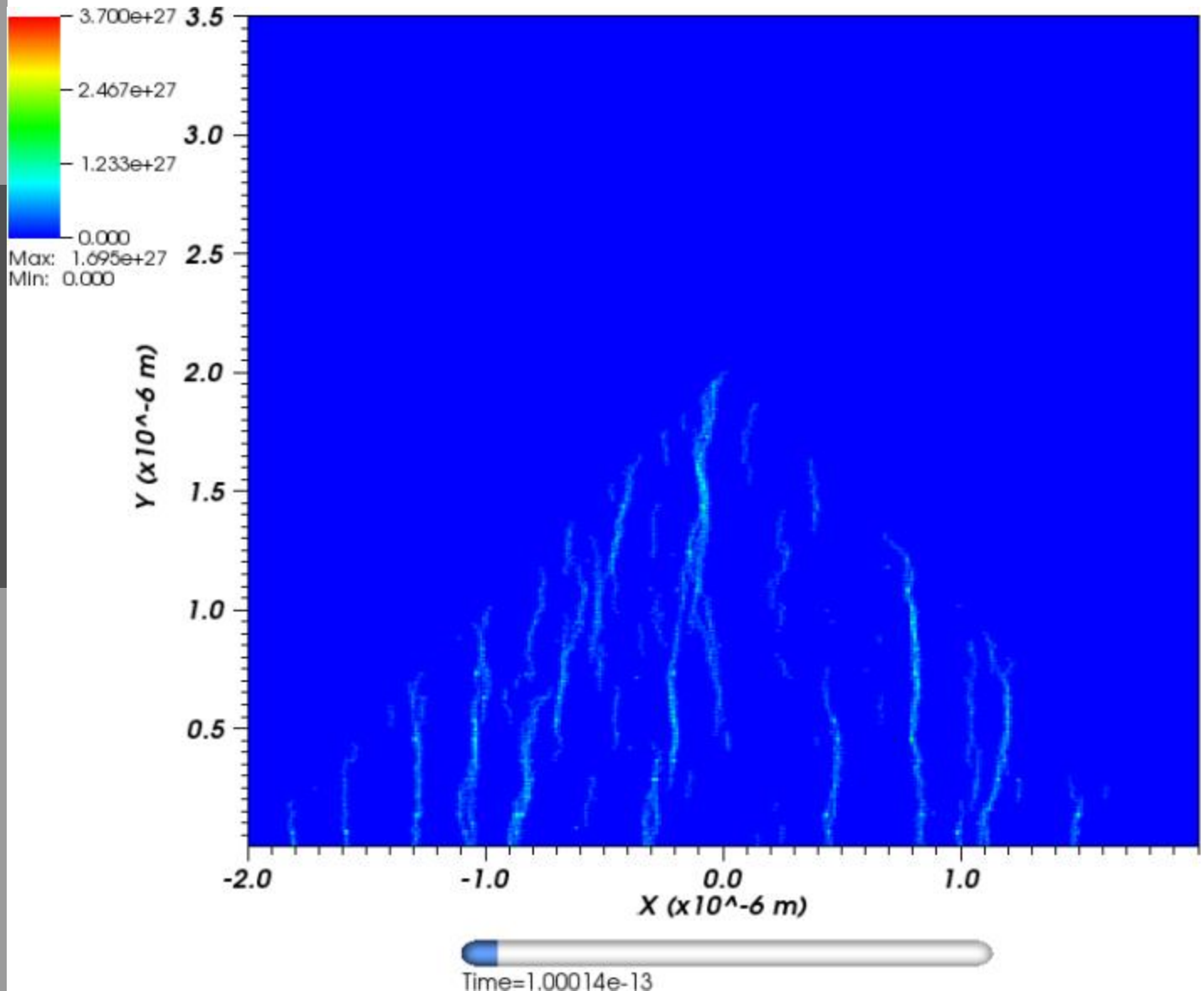

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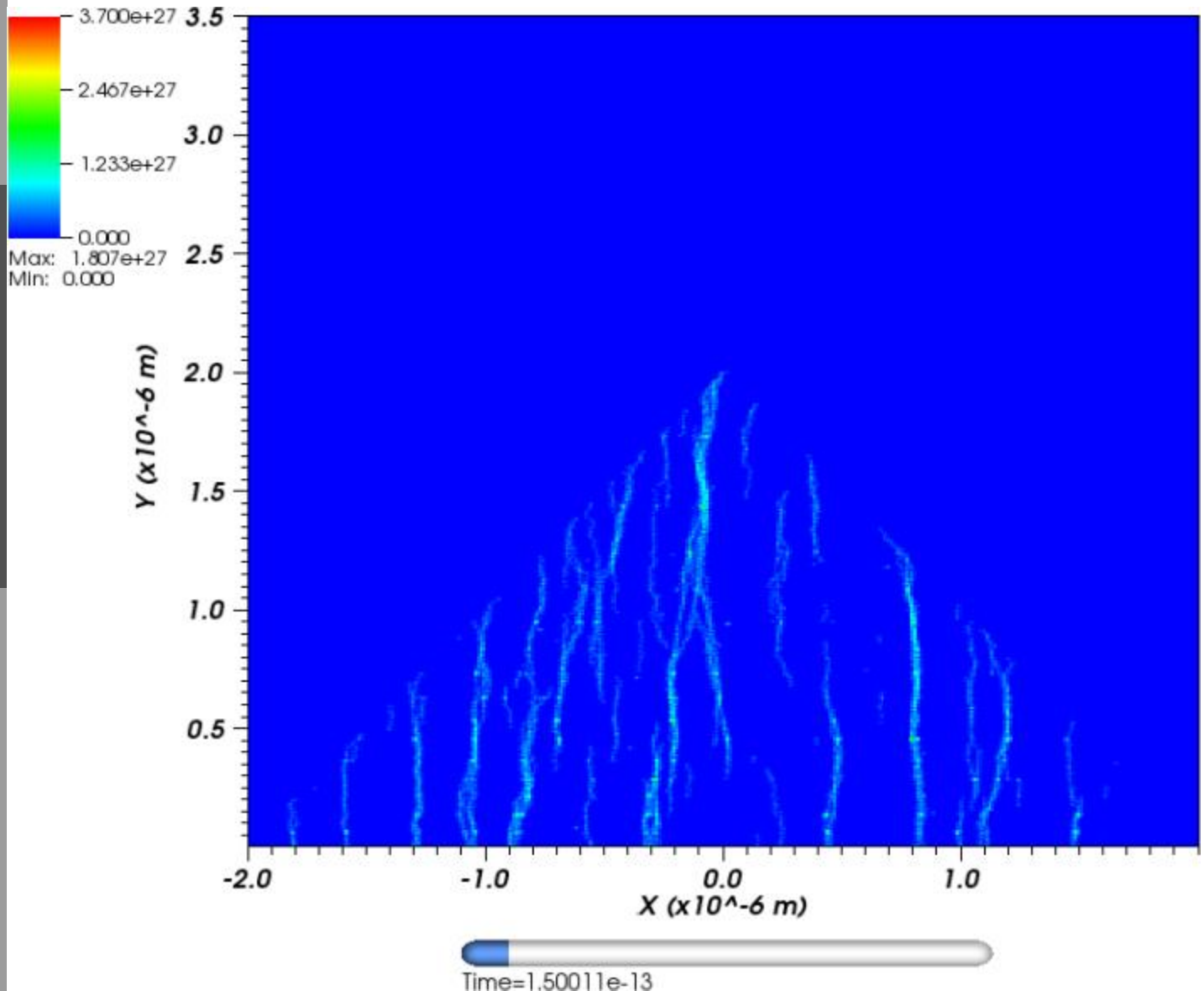

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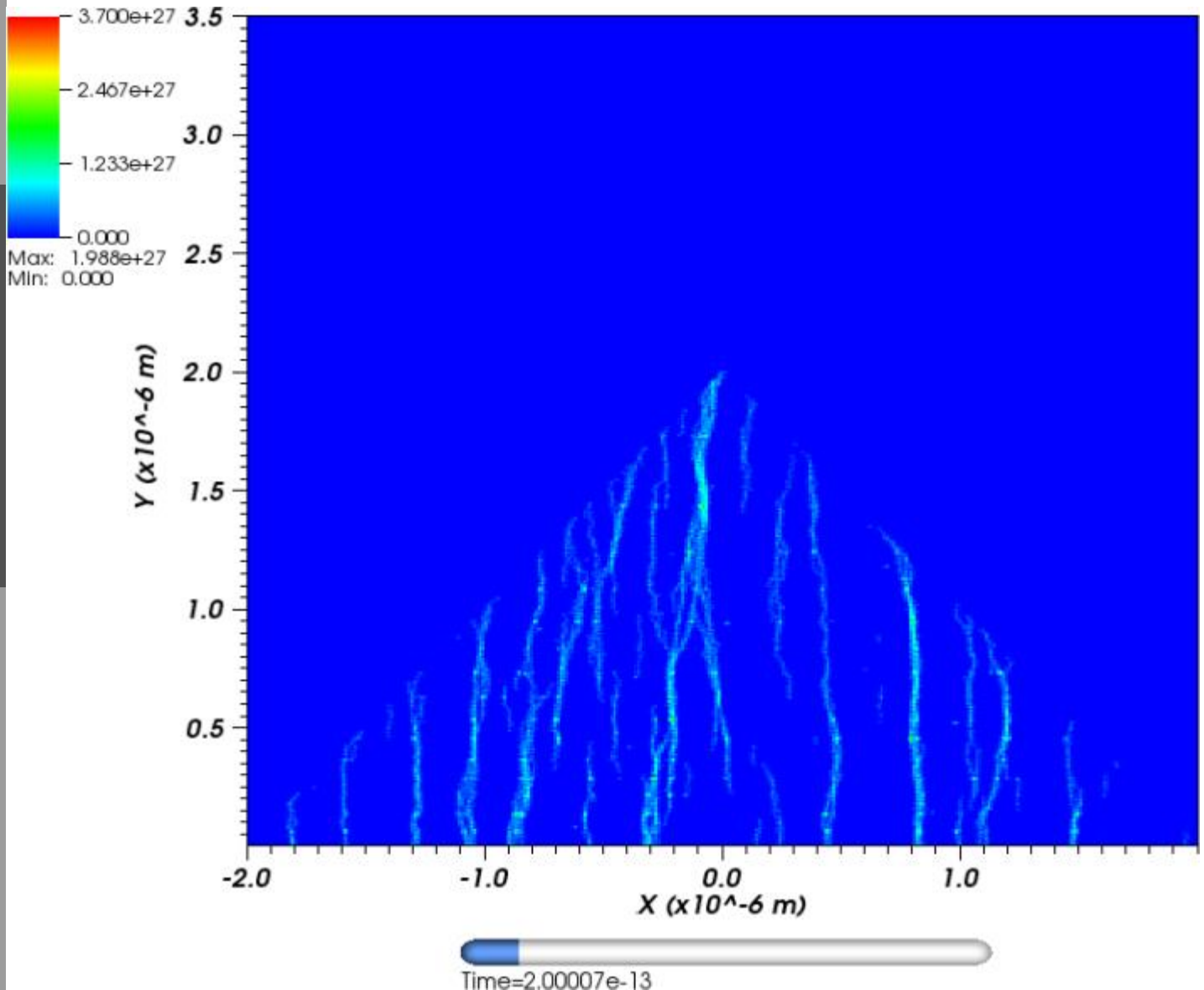

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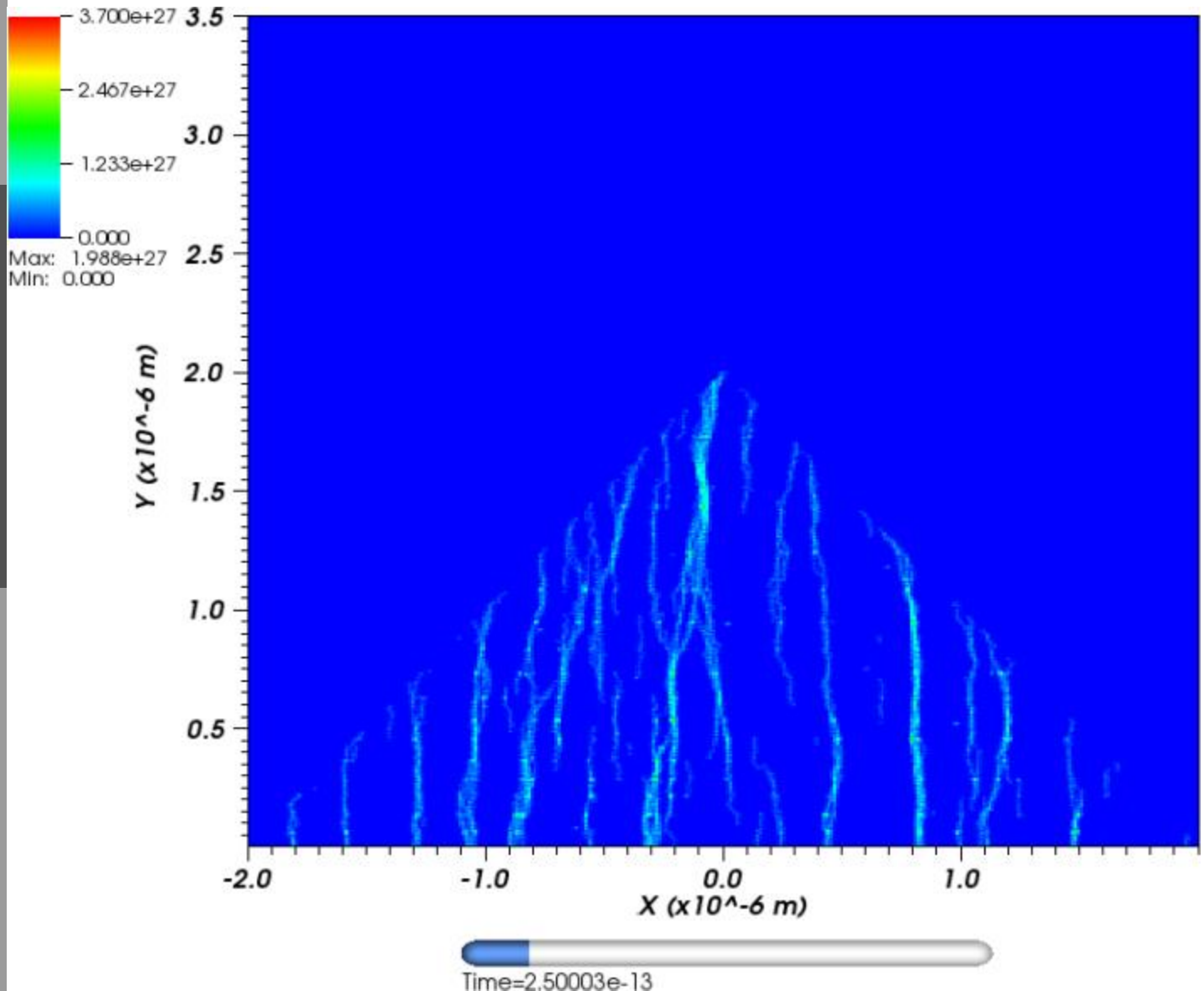

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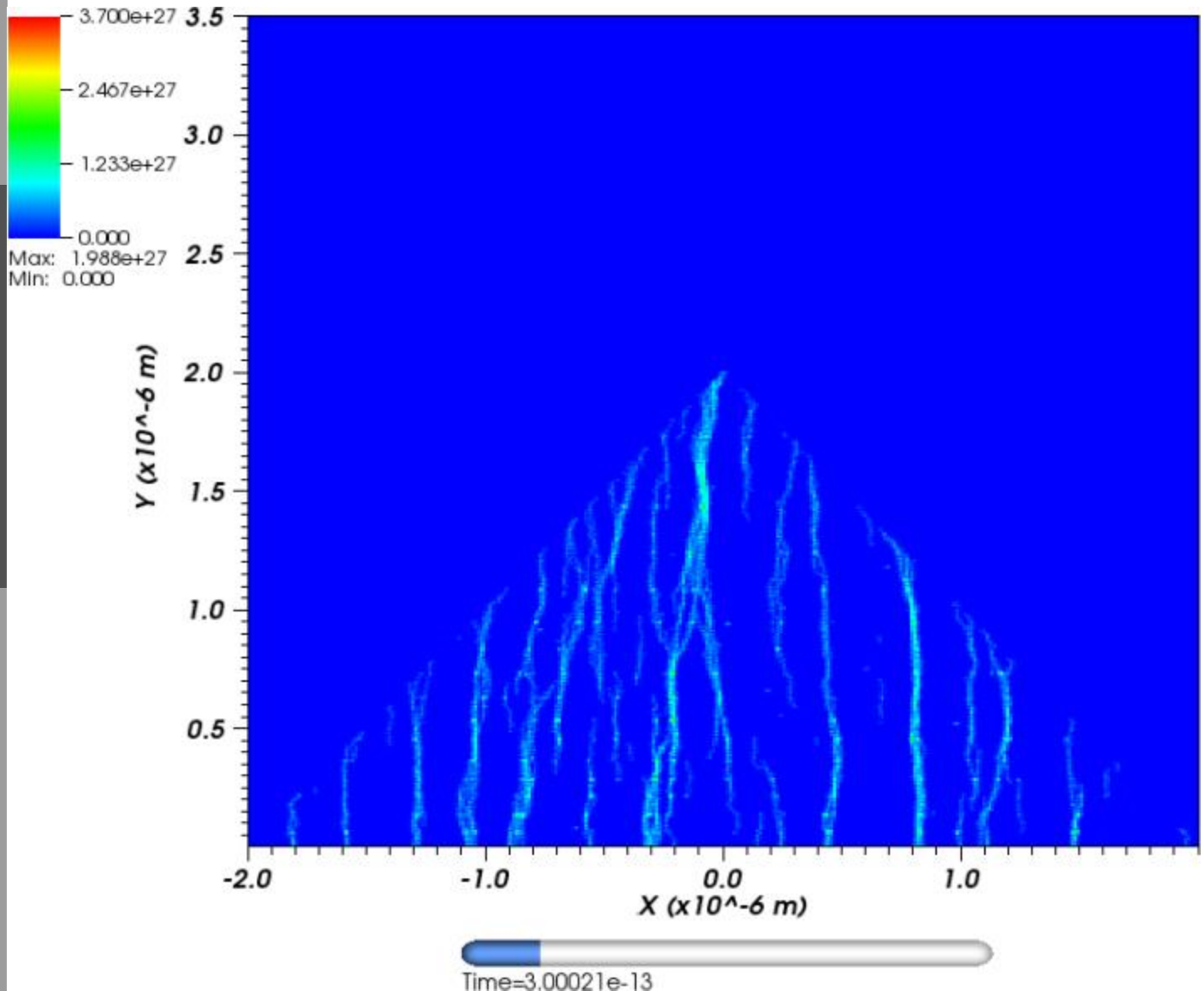

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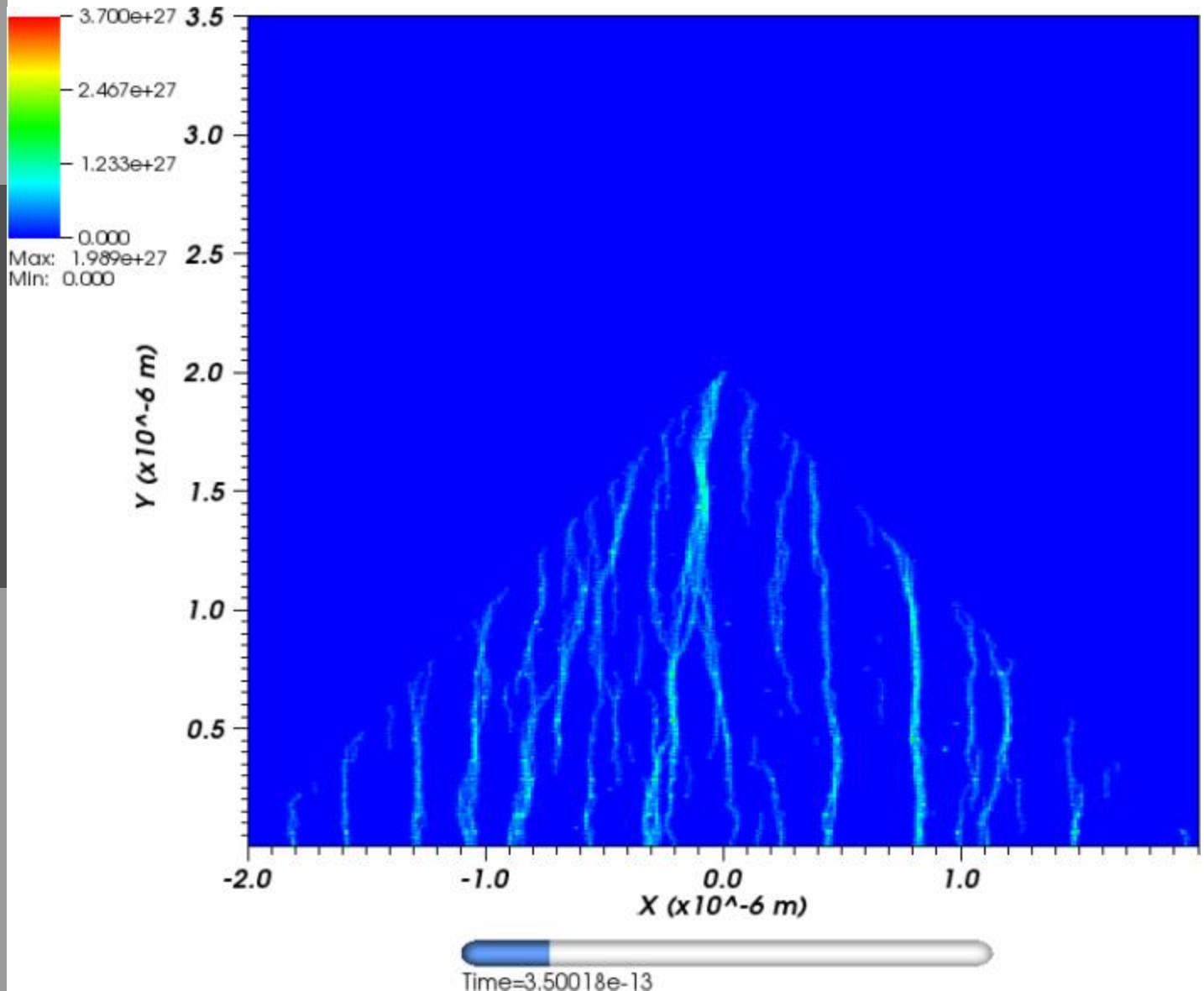

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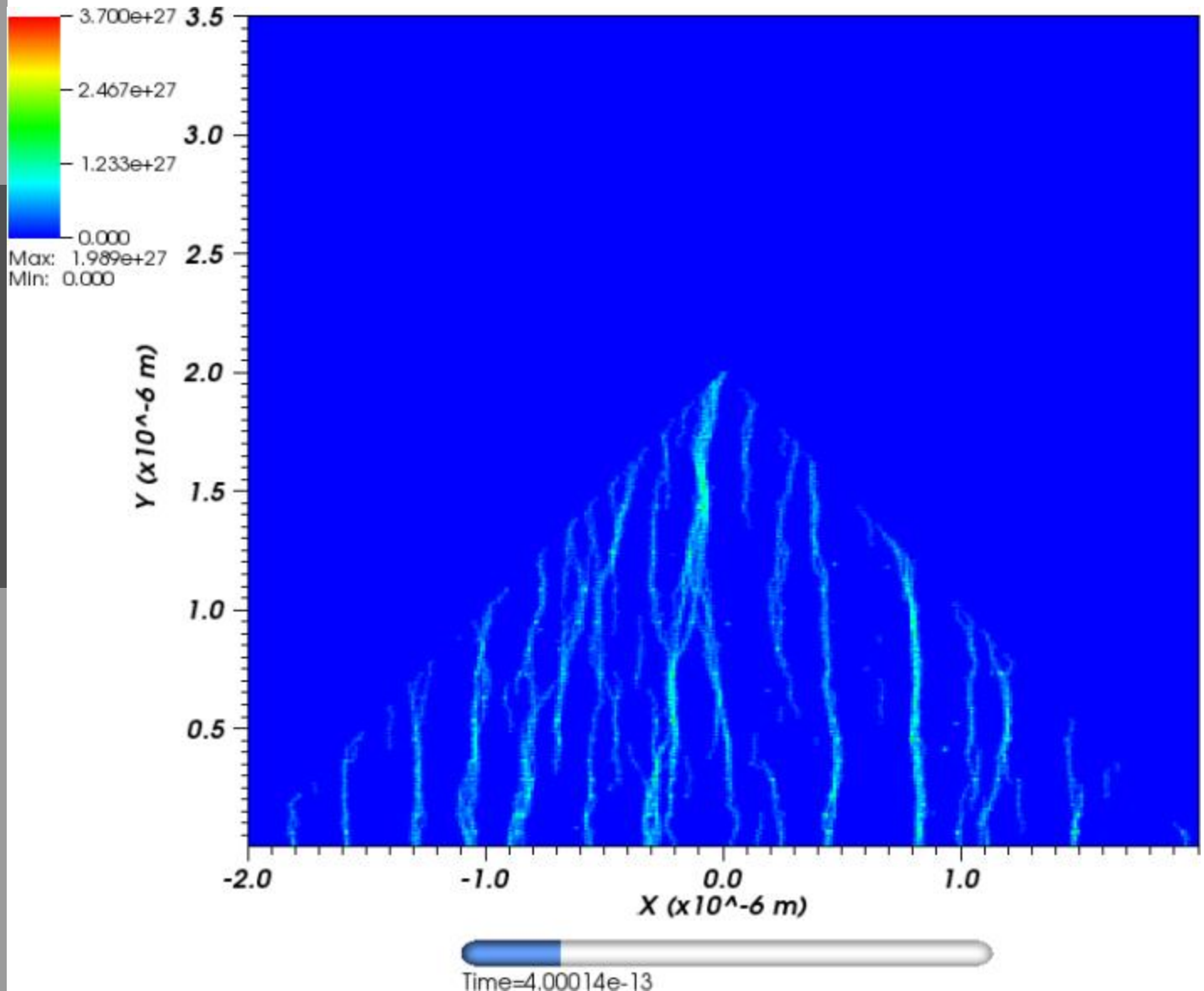

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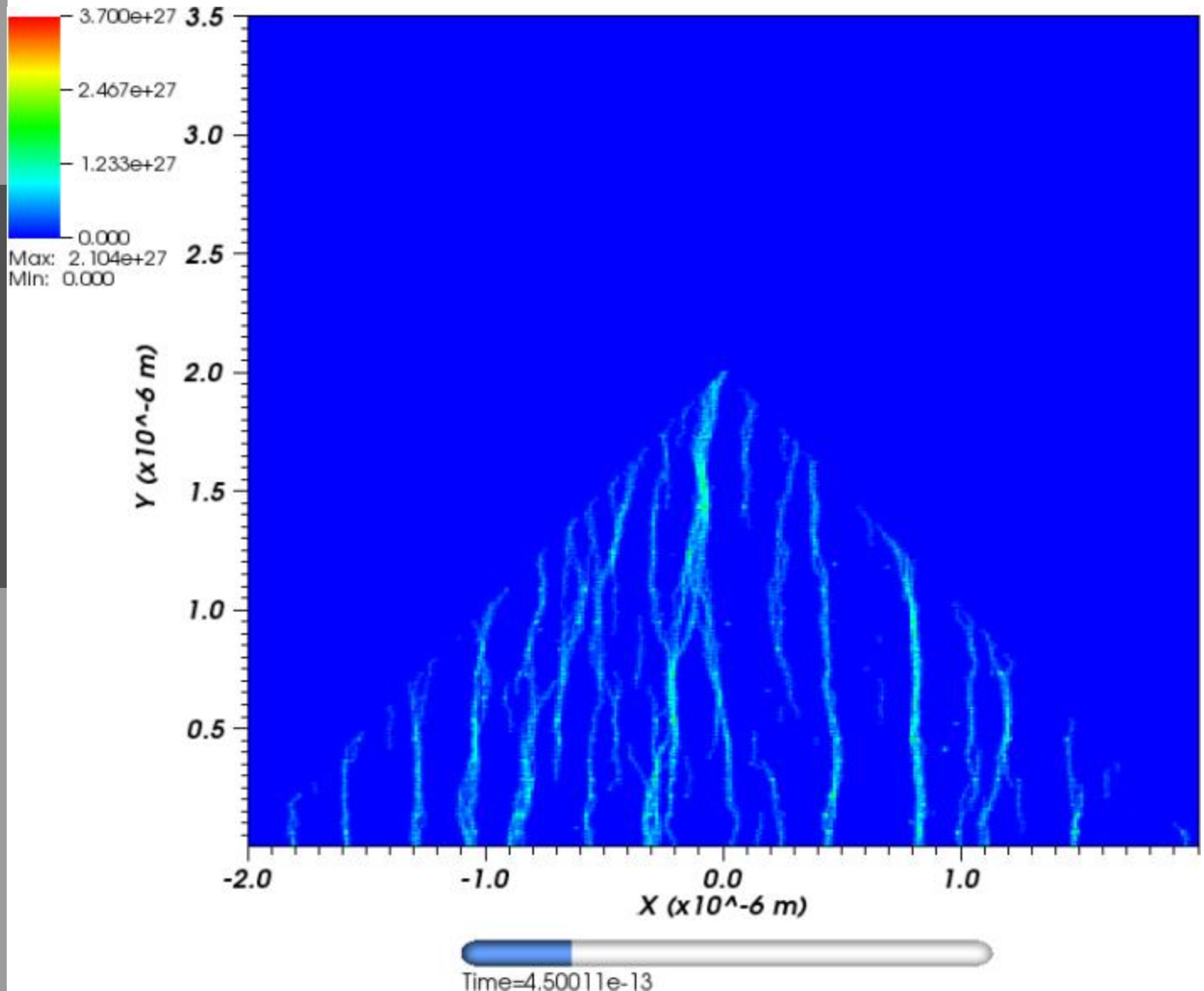

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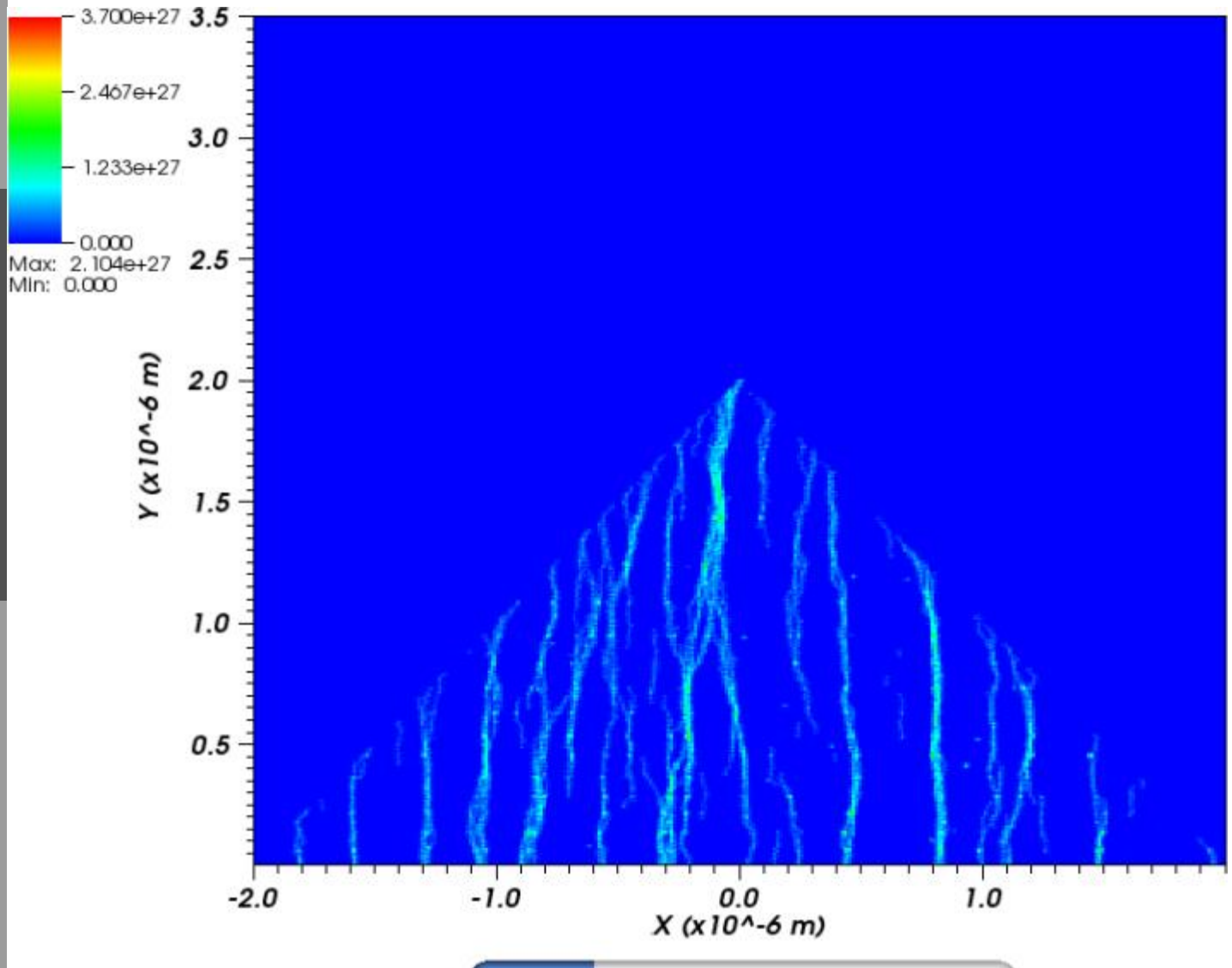

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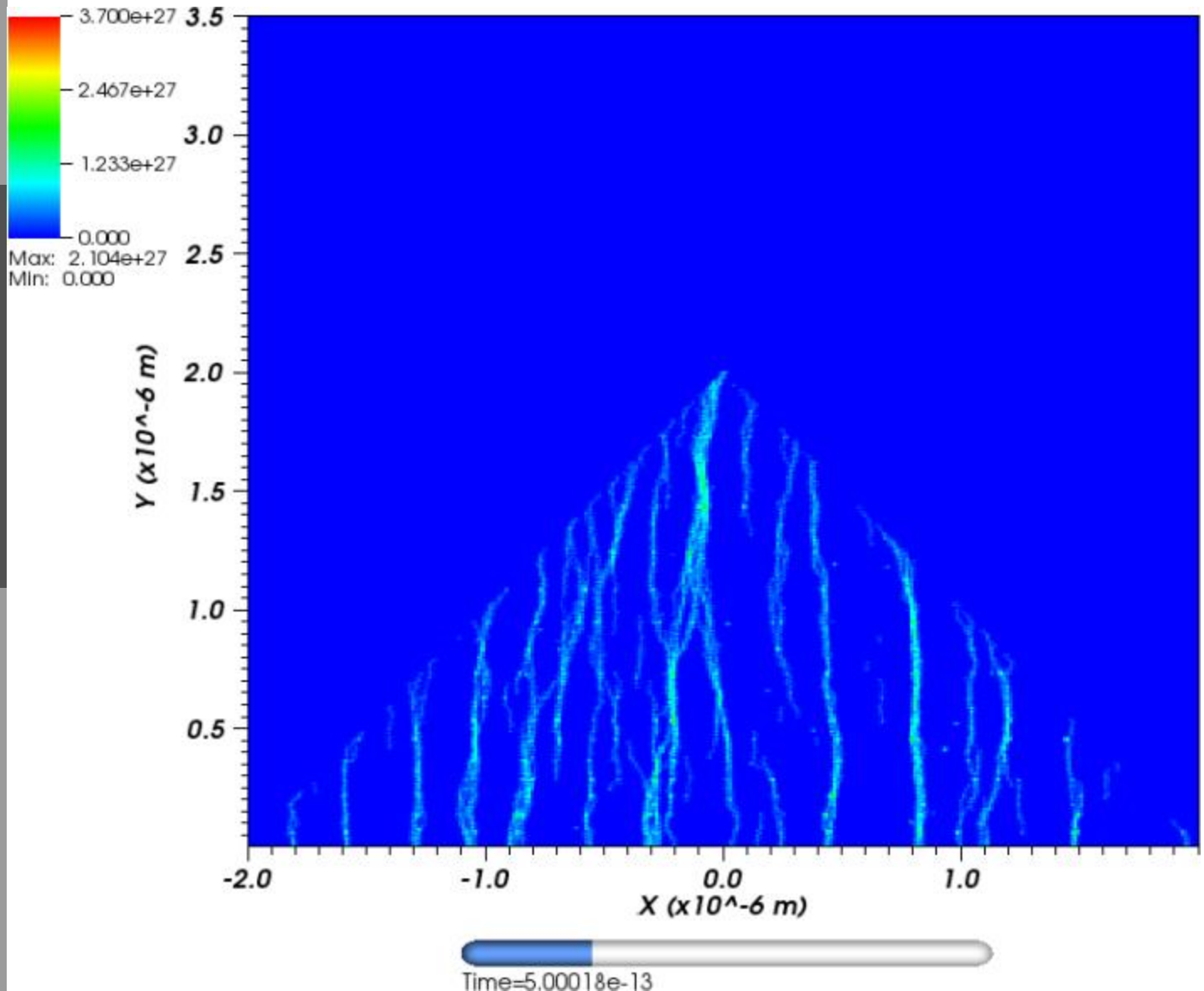

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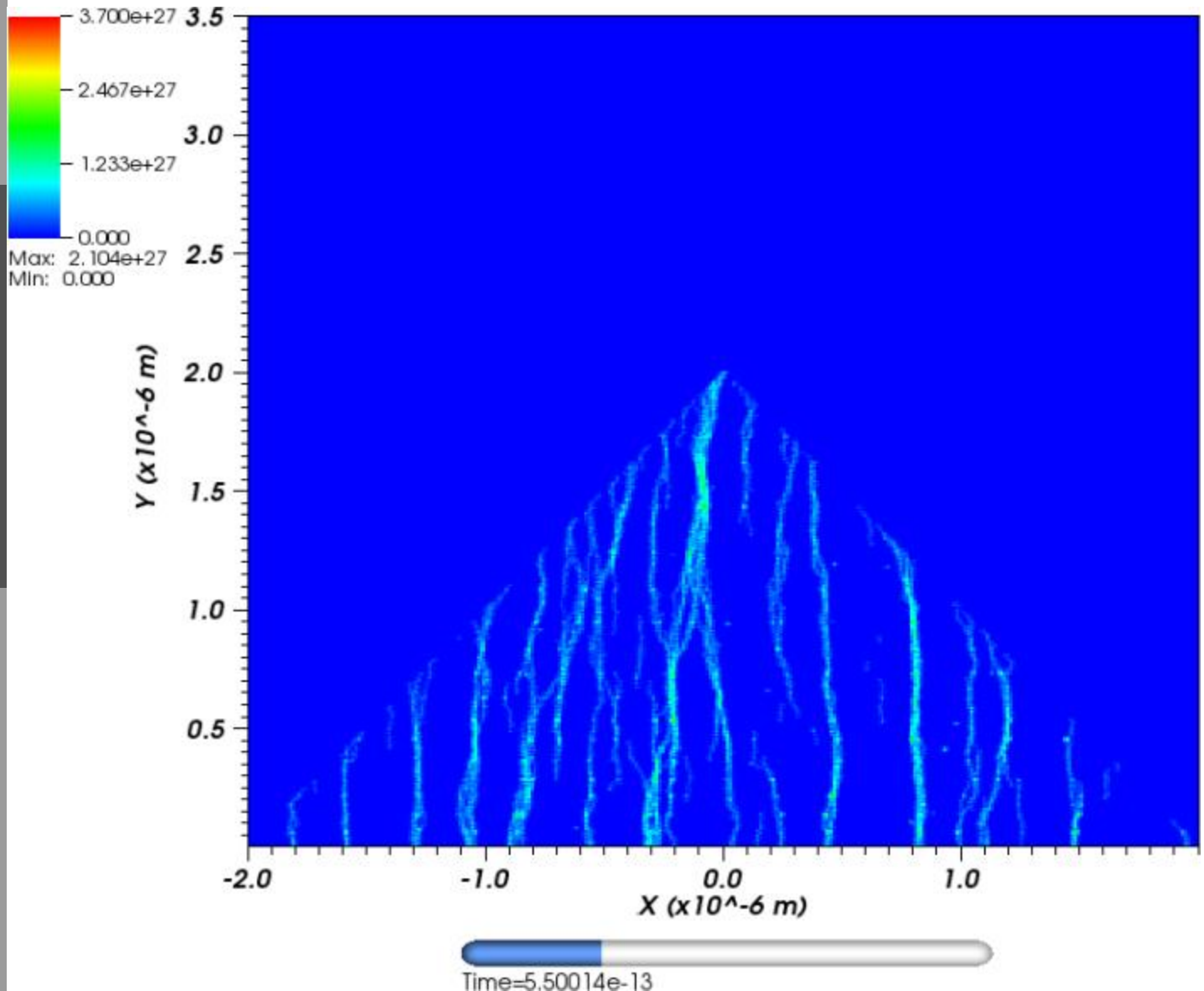

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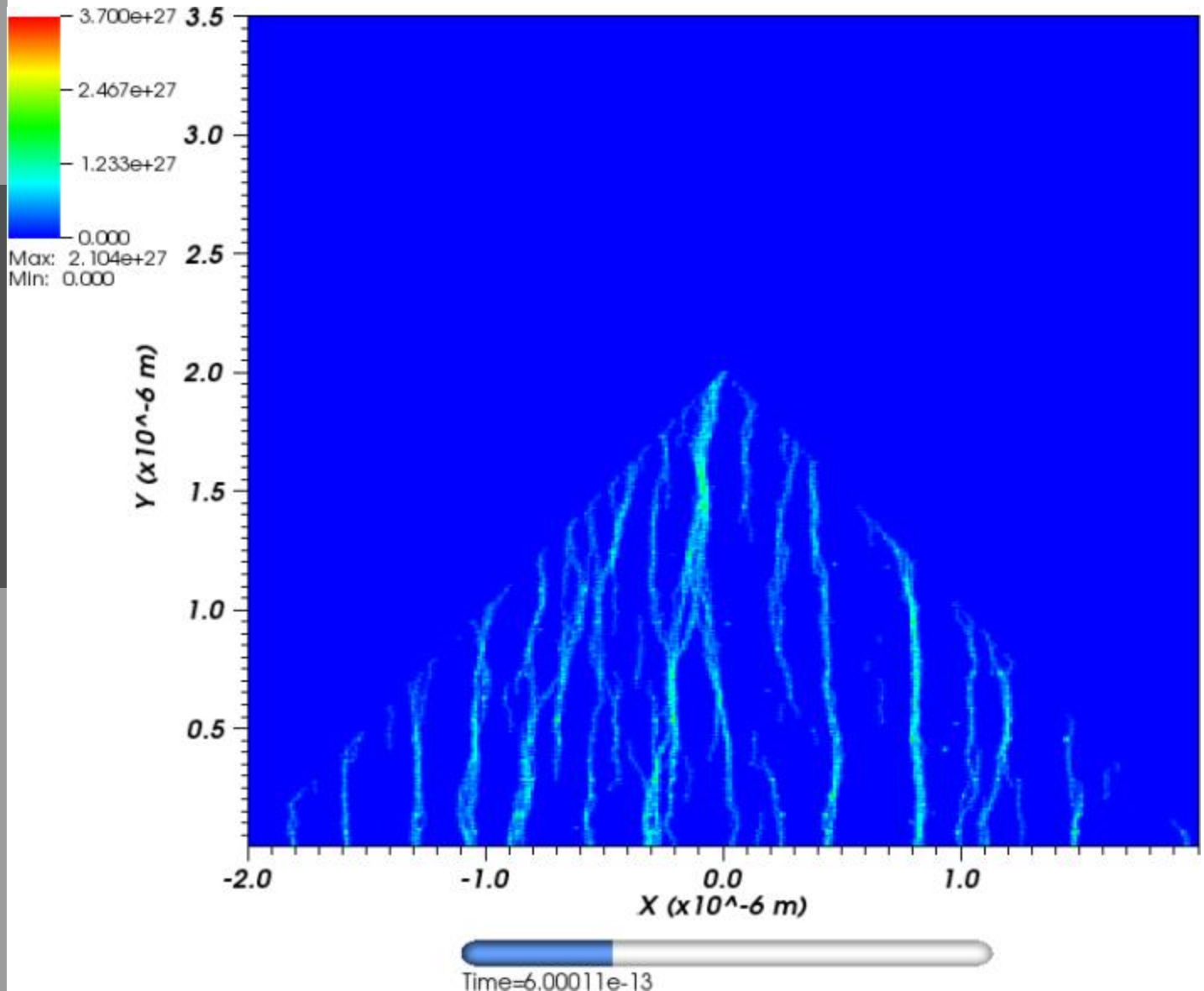
PIC - Electron Density



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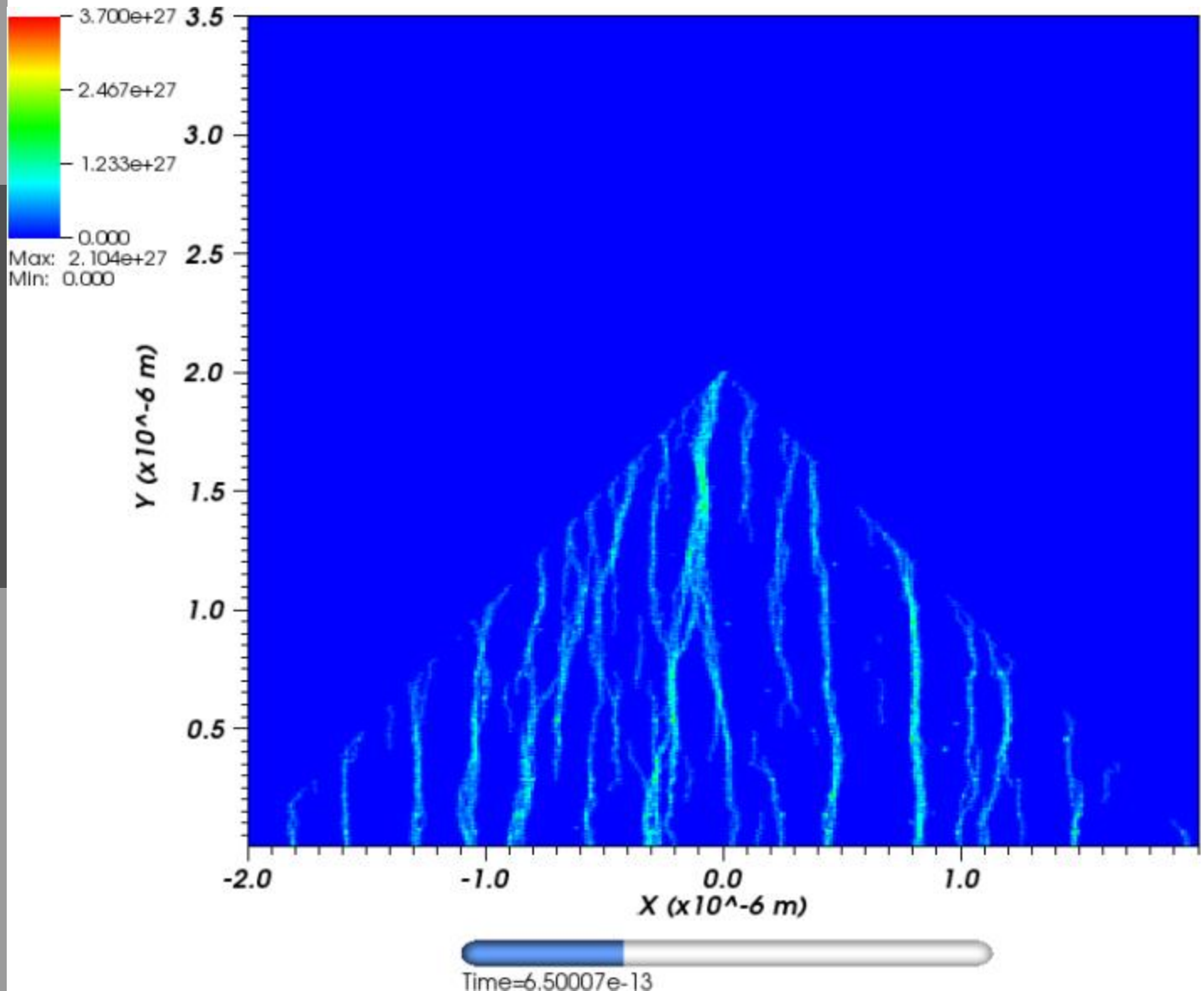

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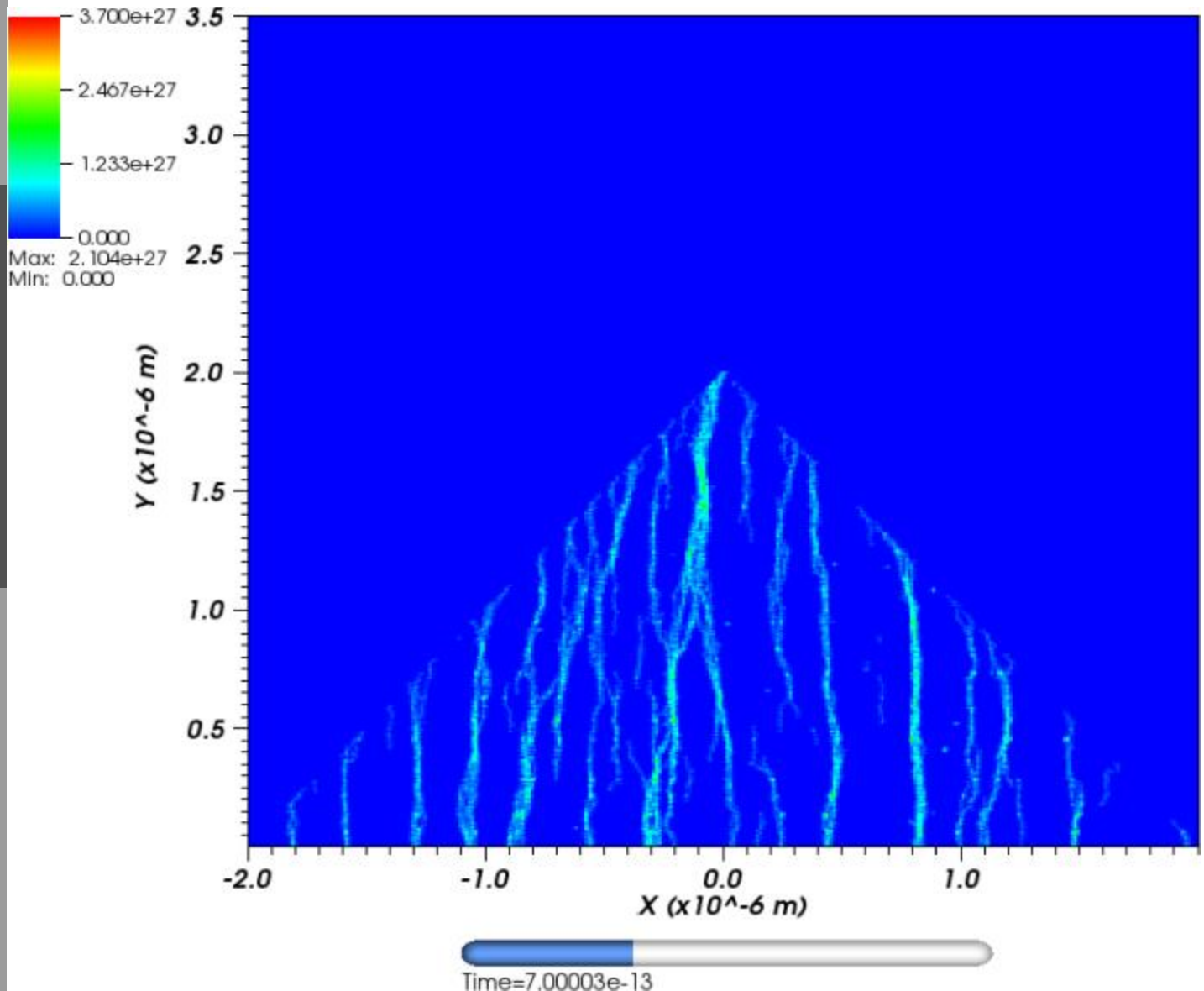

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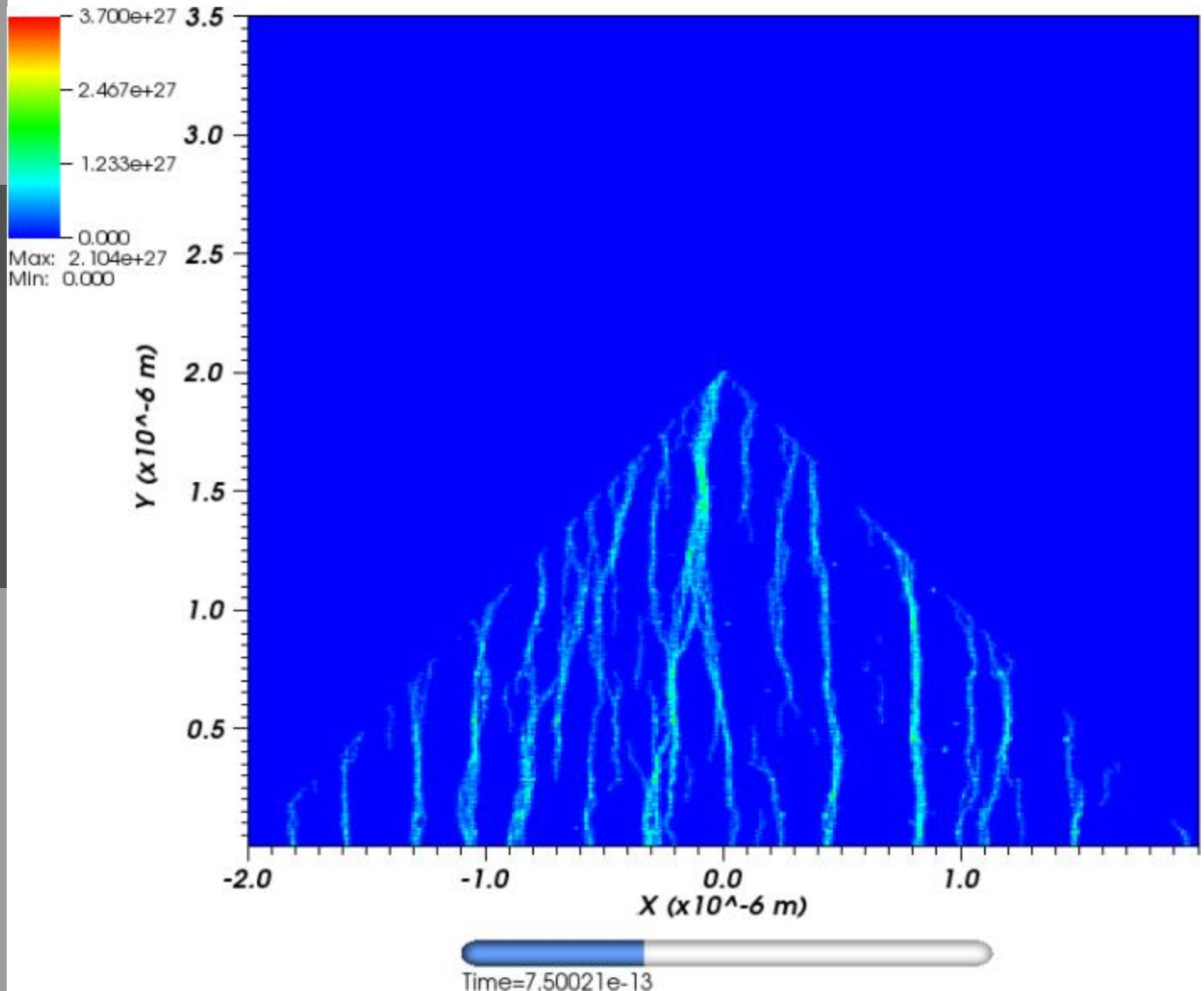

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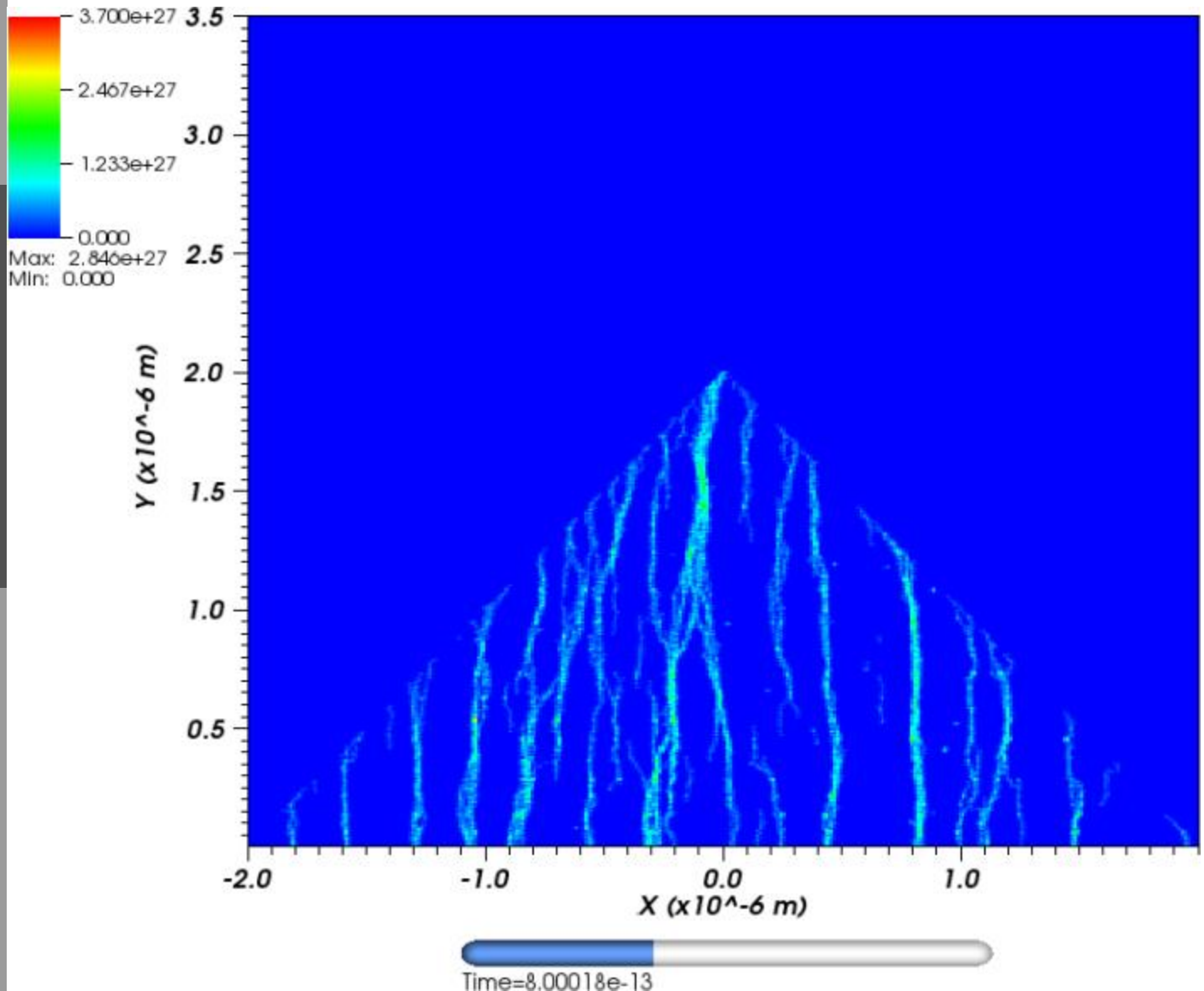

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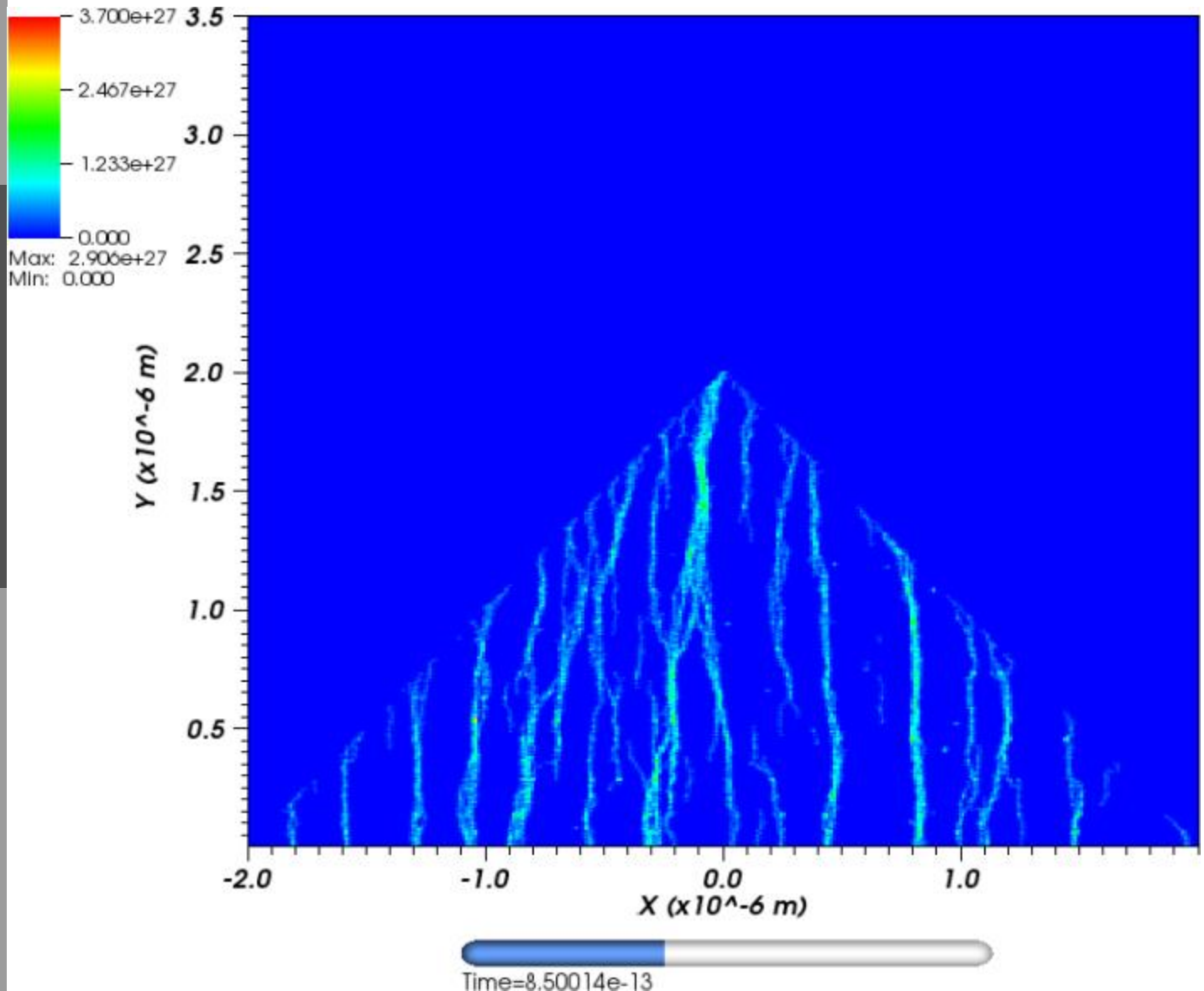

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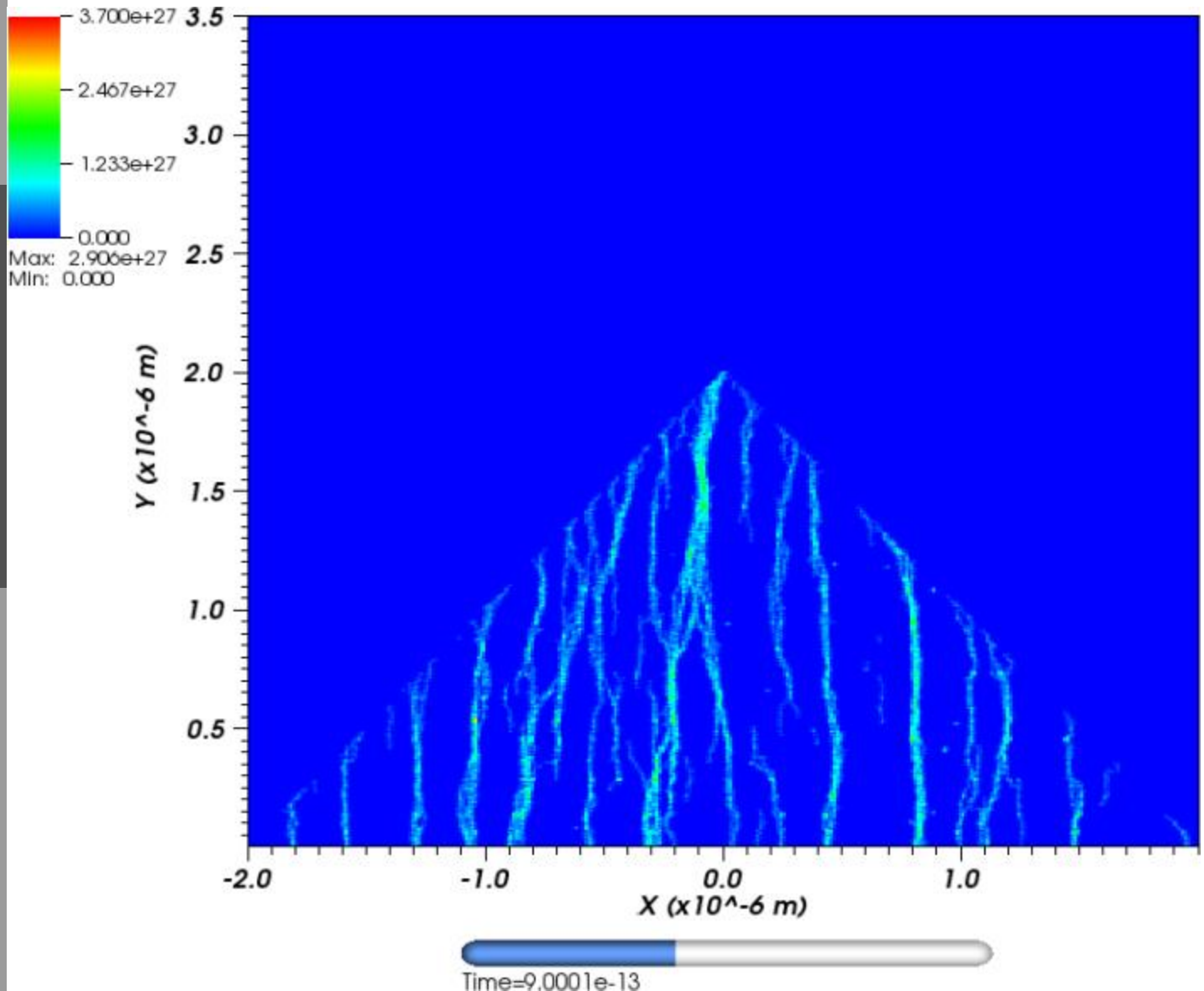

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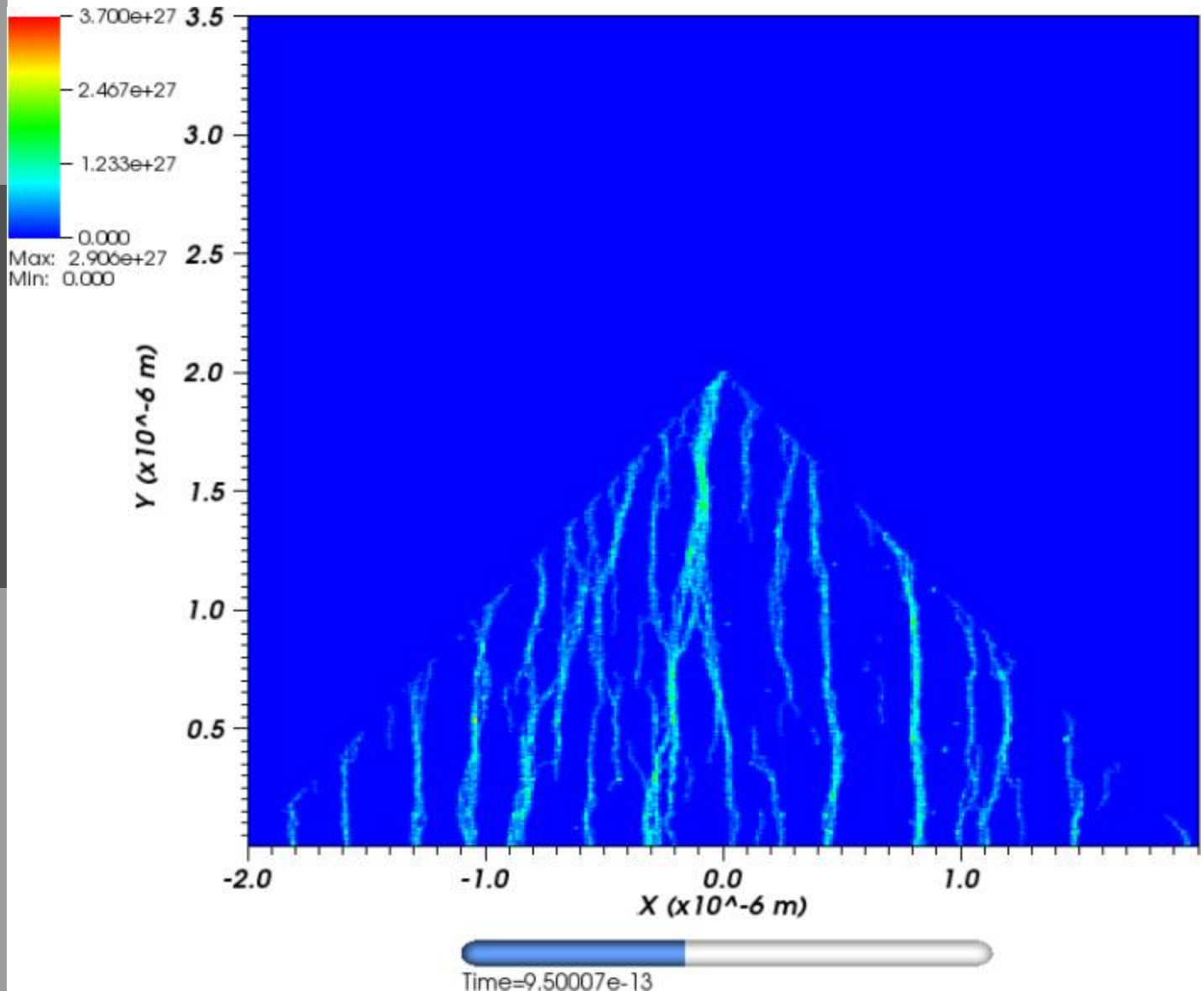

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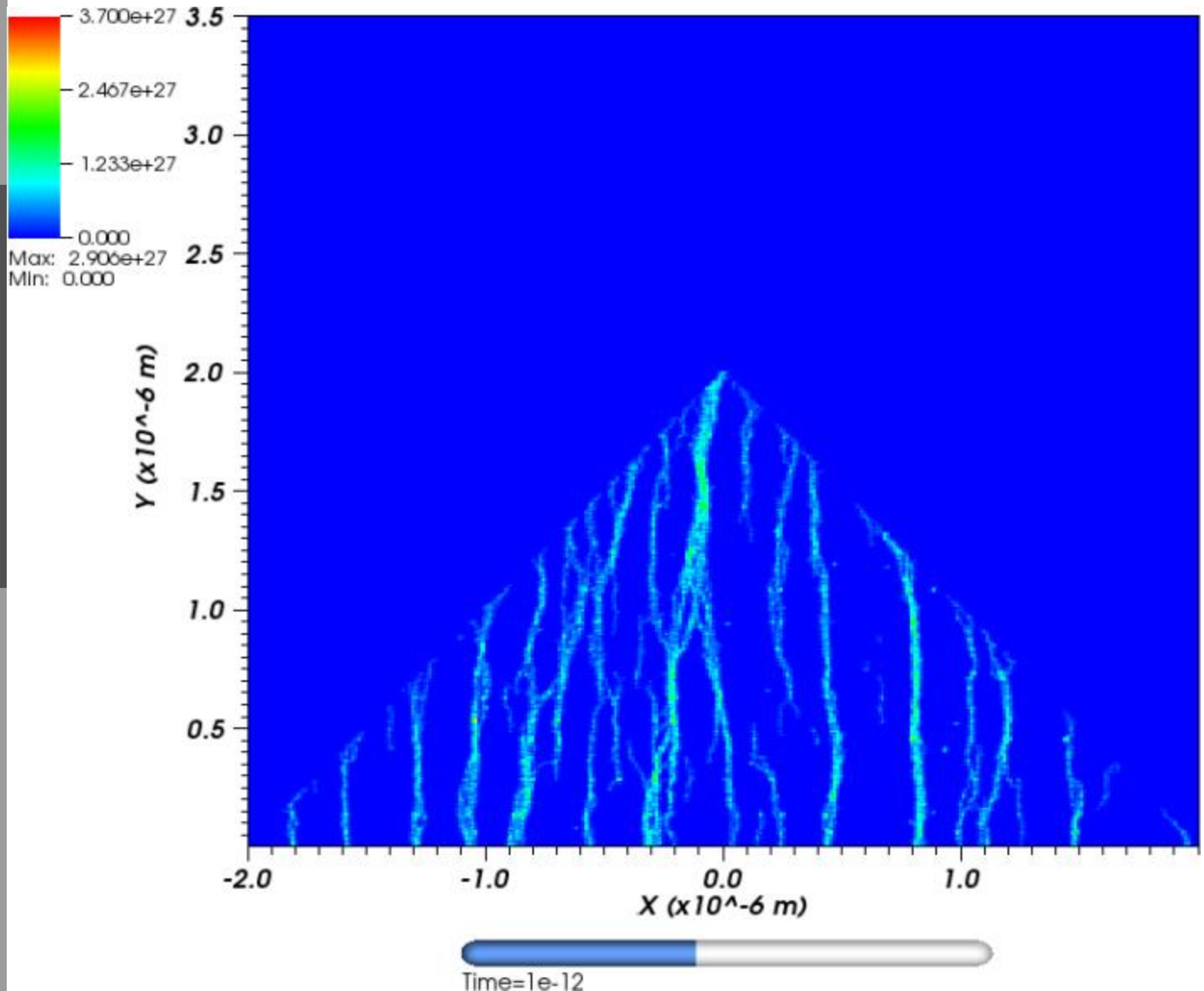

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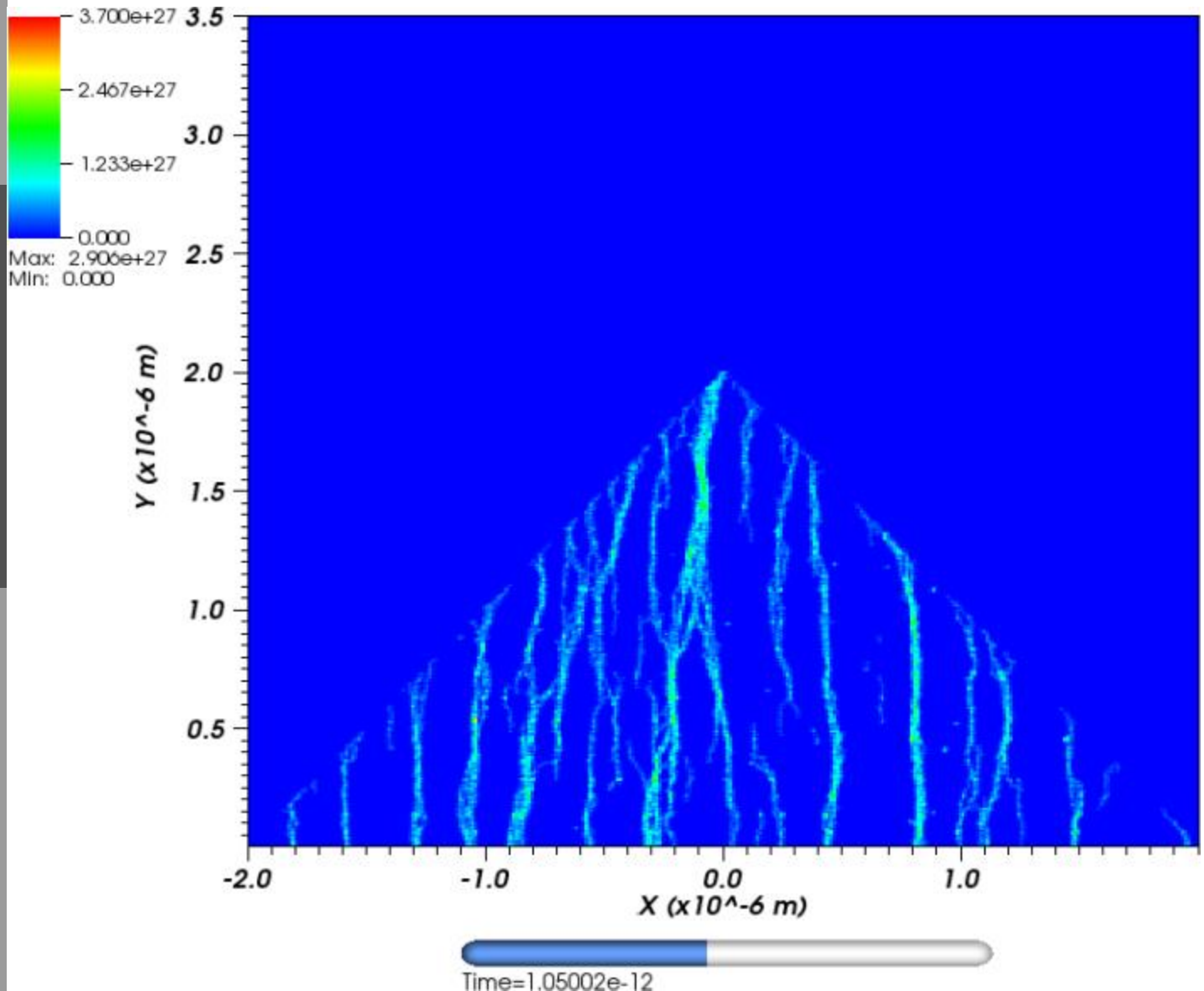

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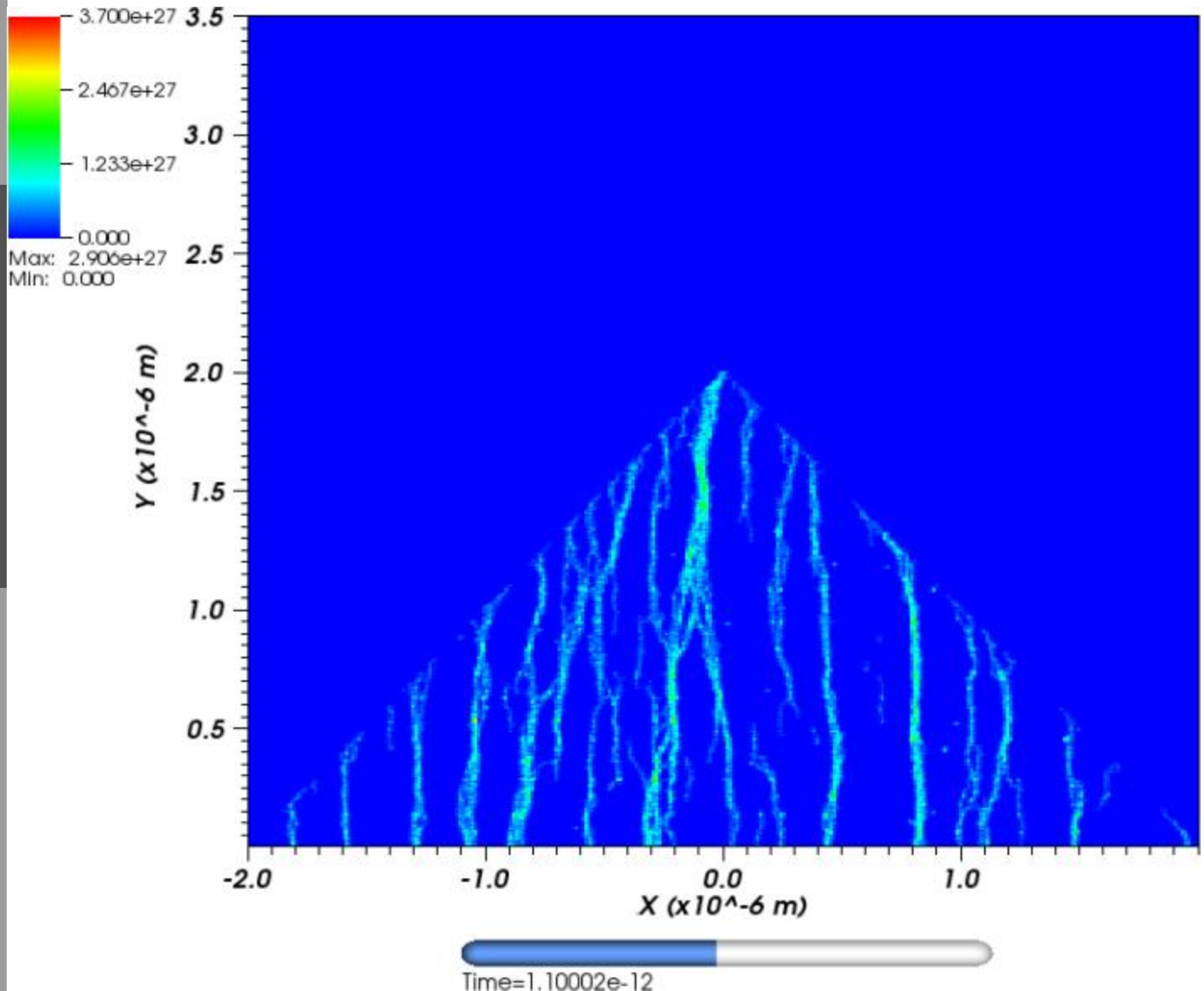

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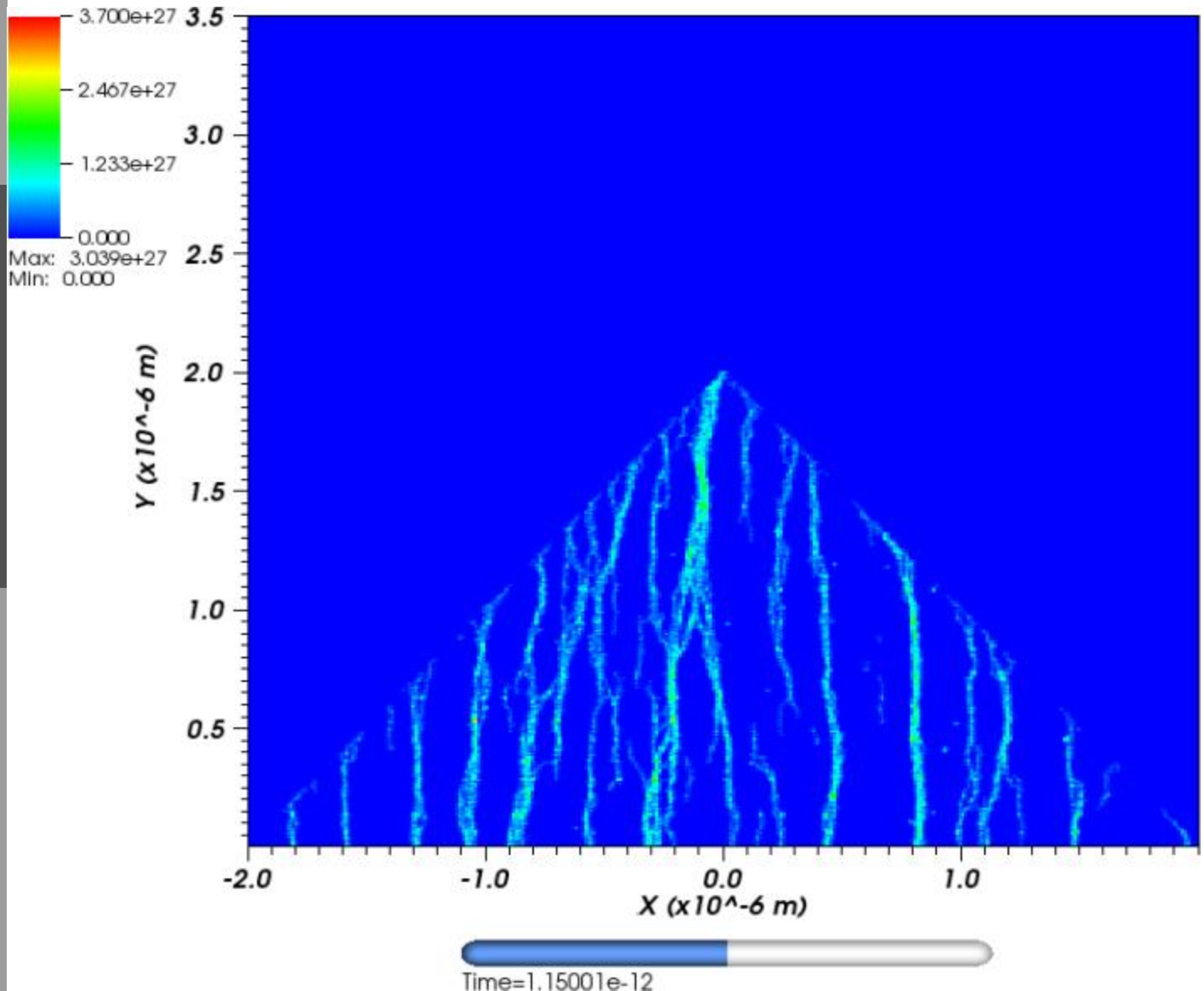

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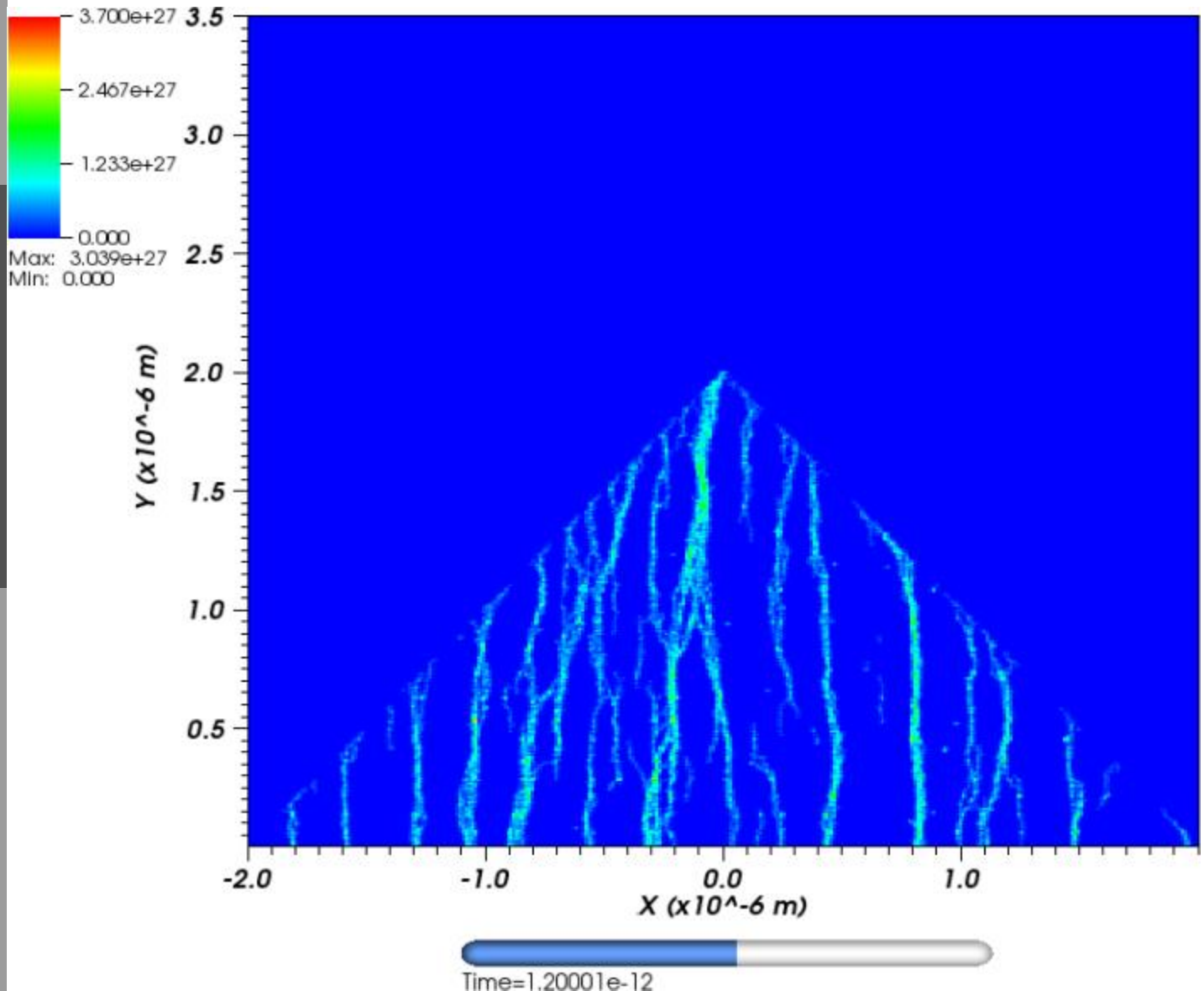

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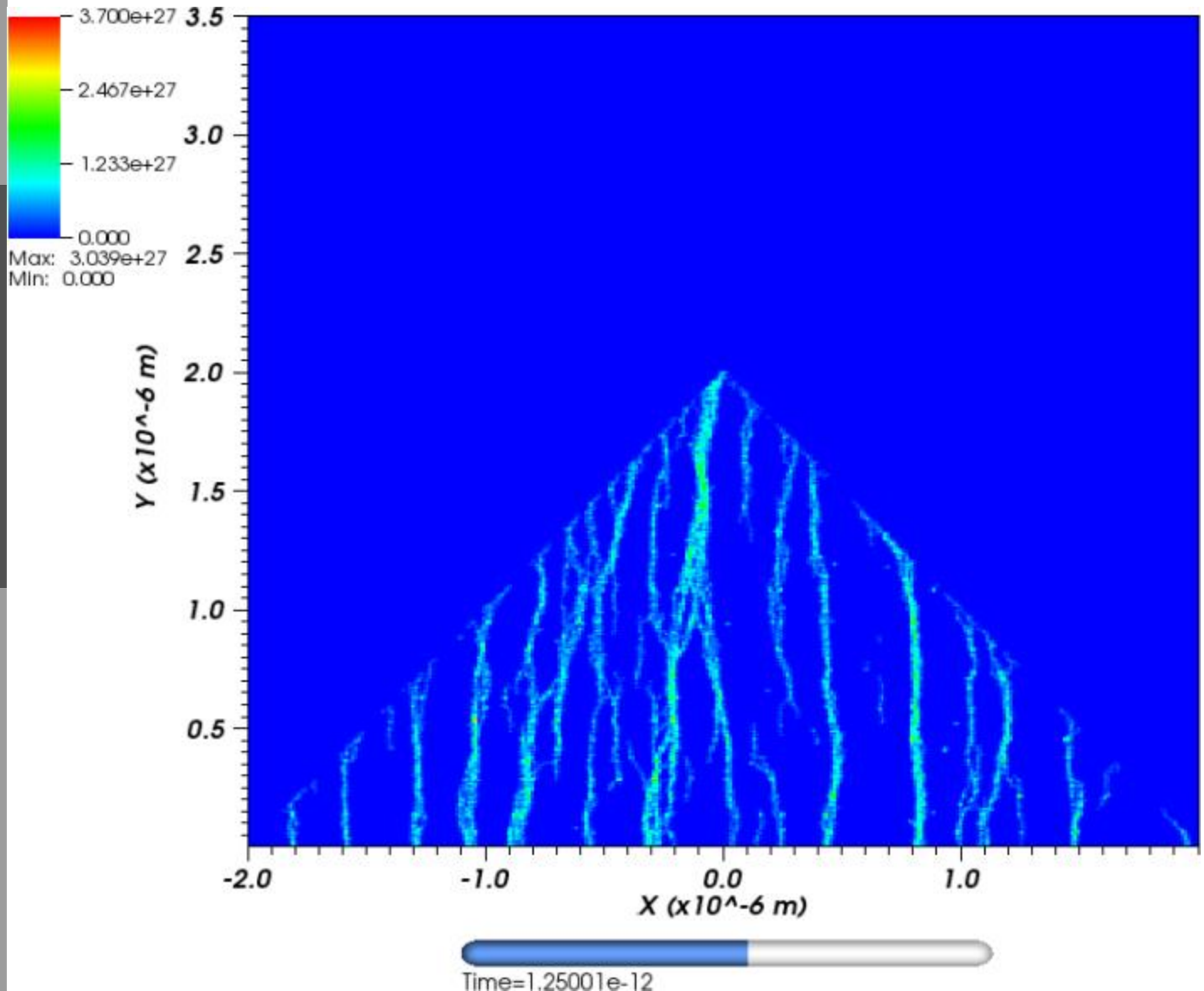

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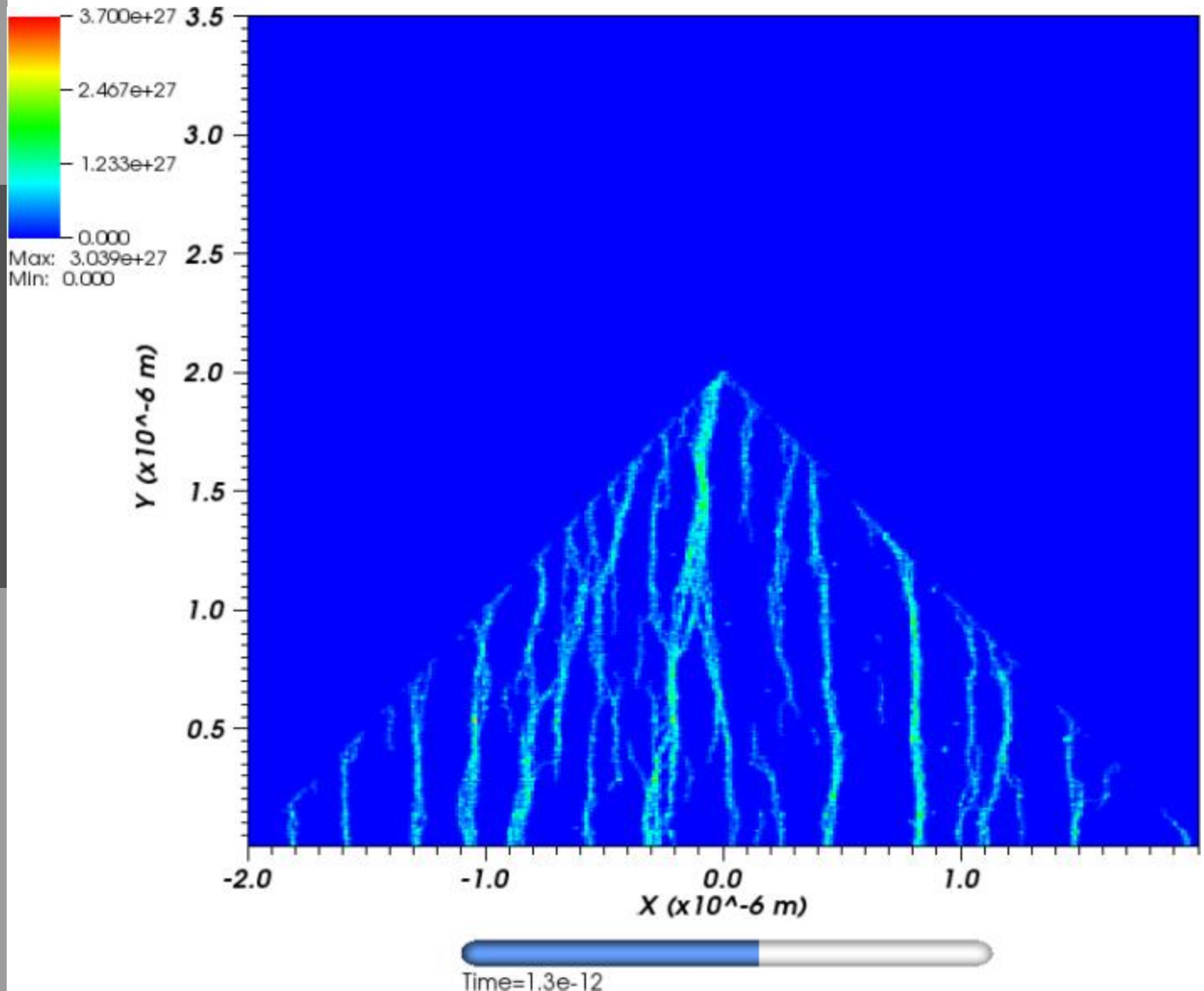

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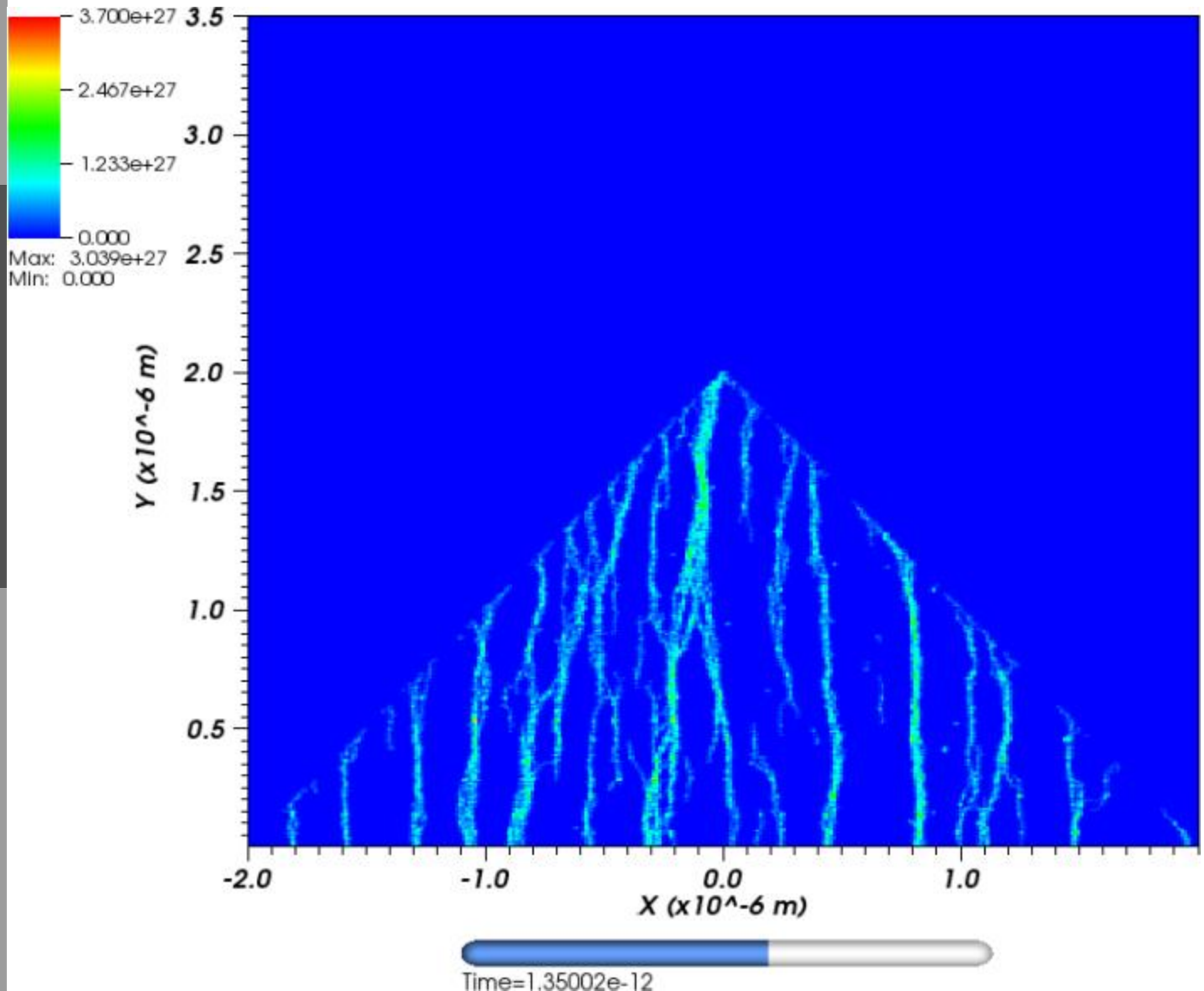

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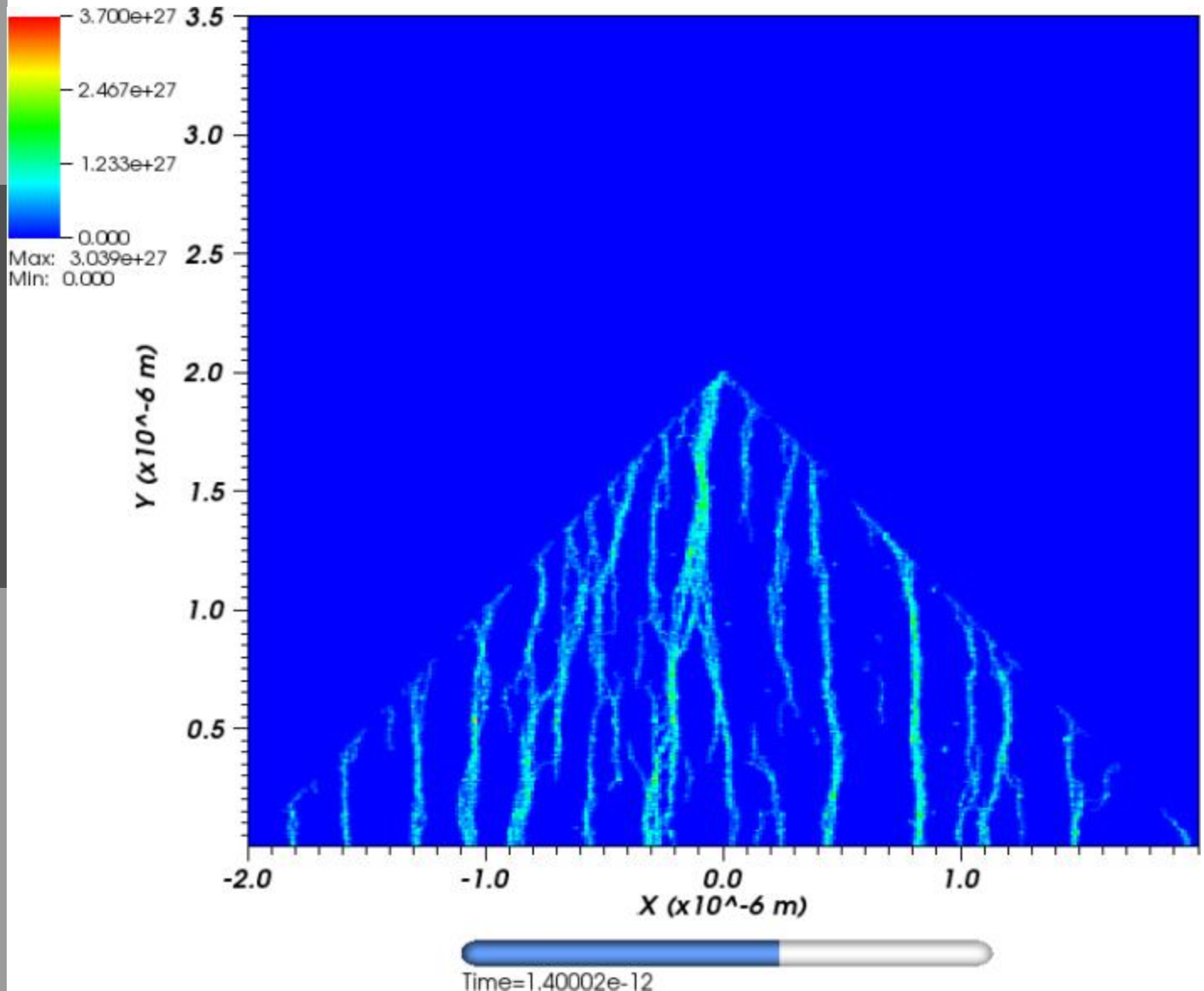

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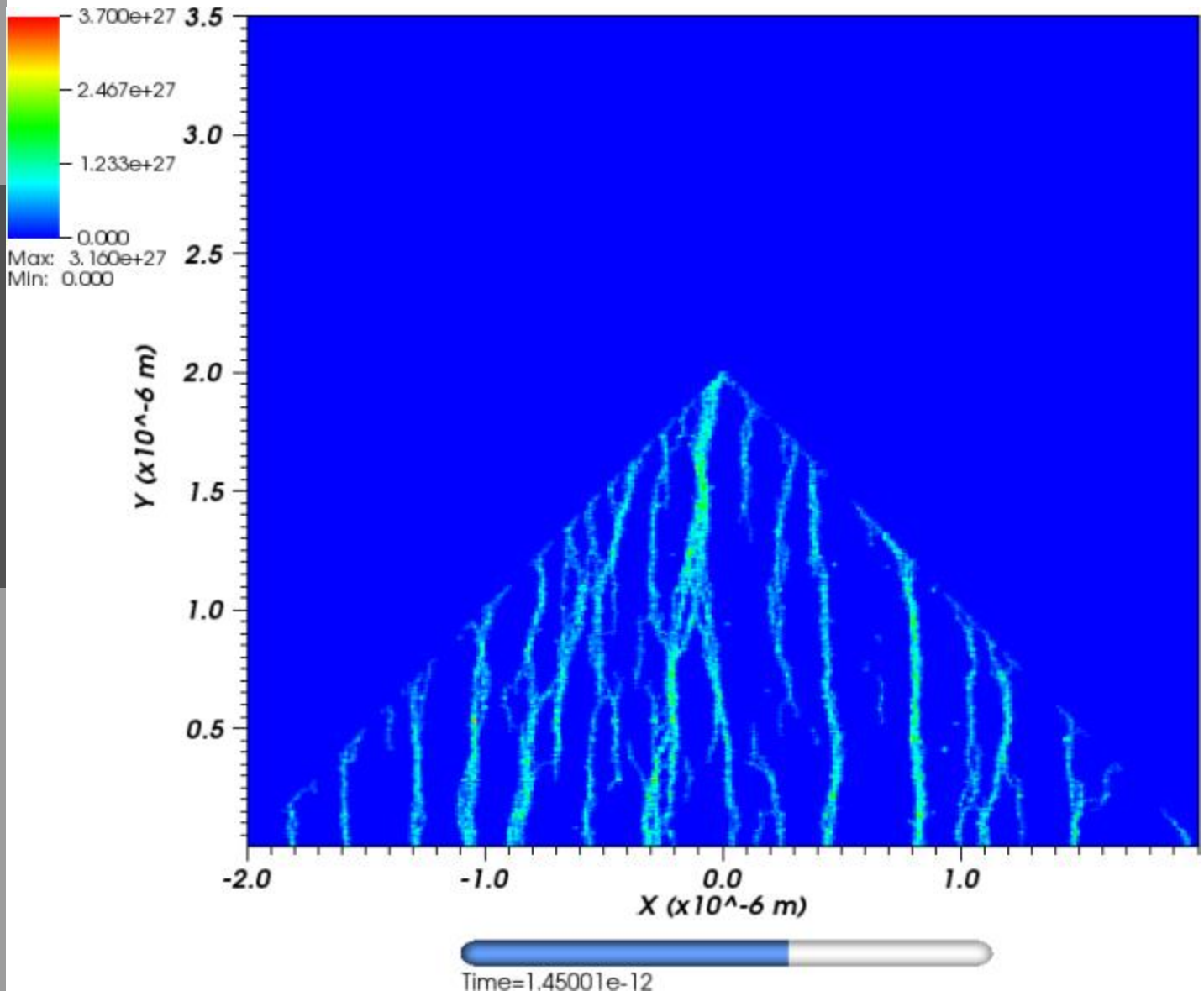

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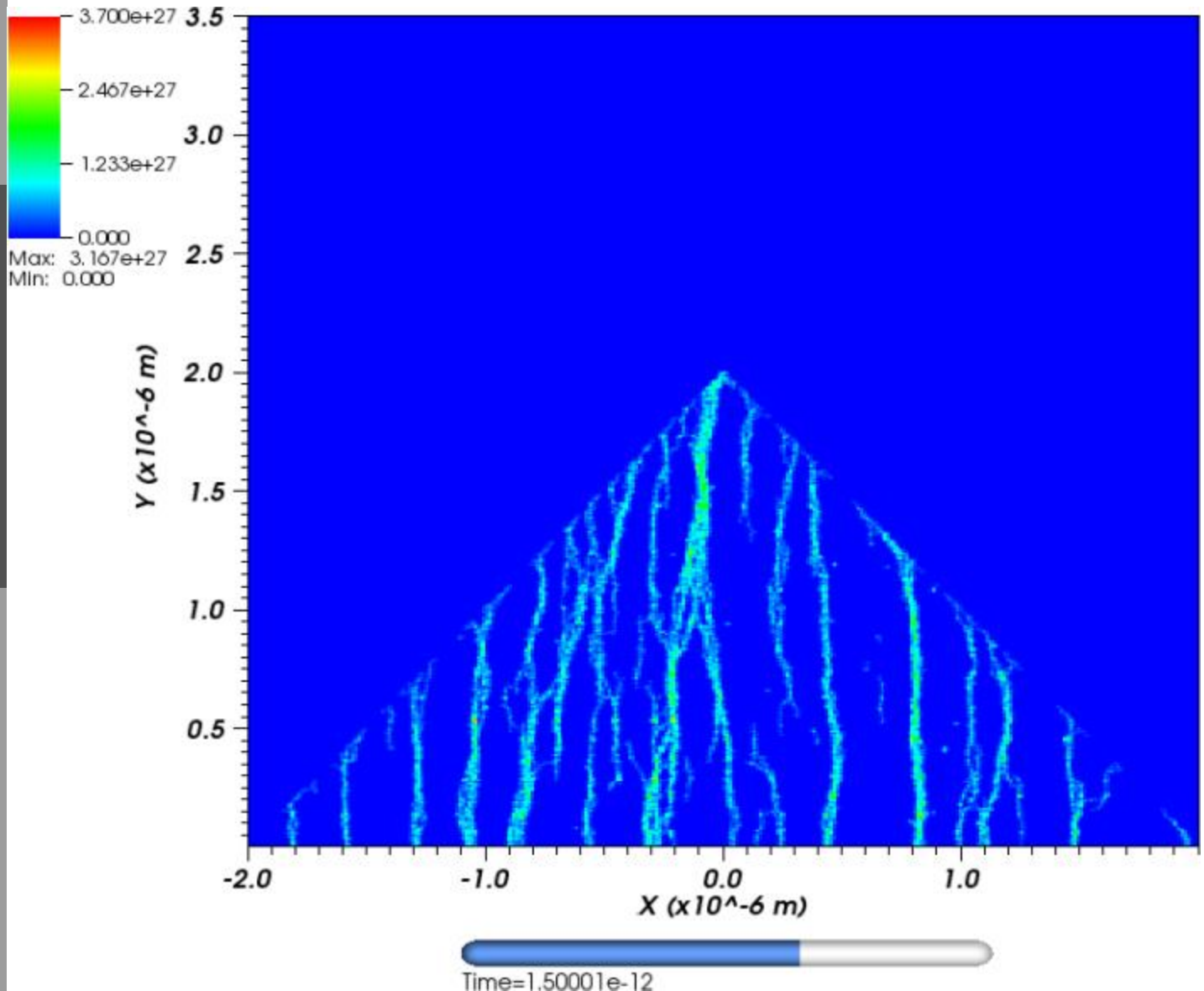

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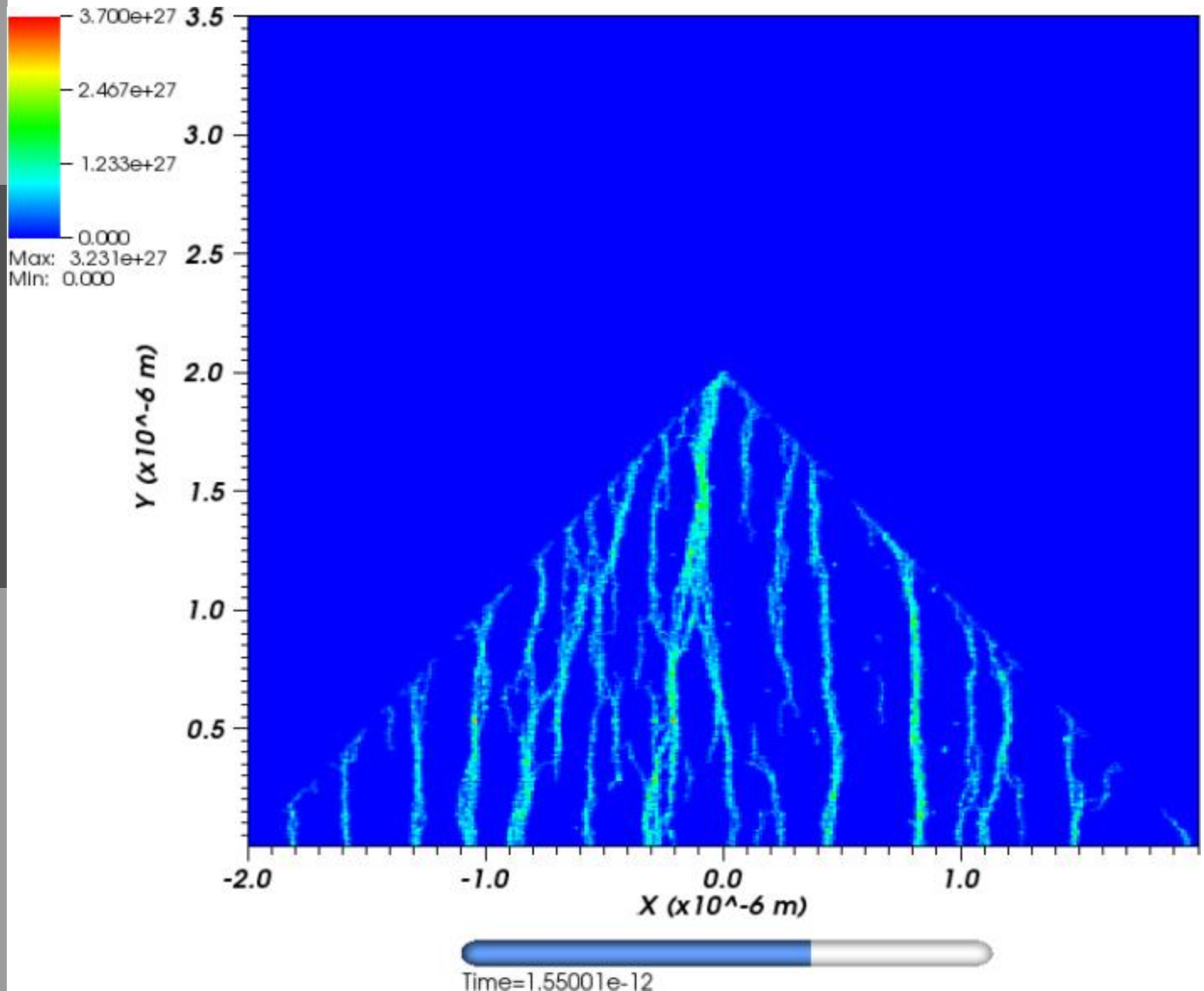

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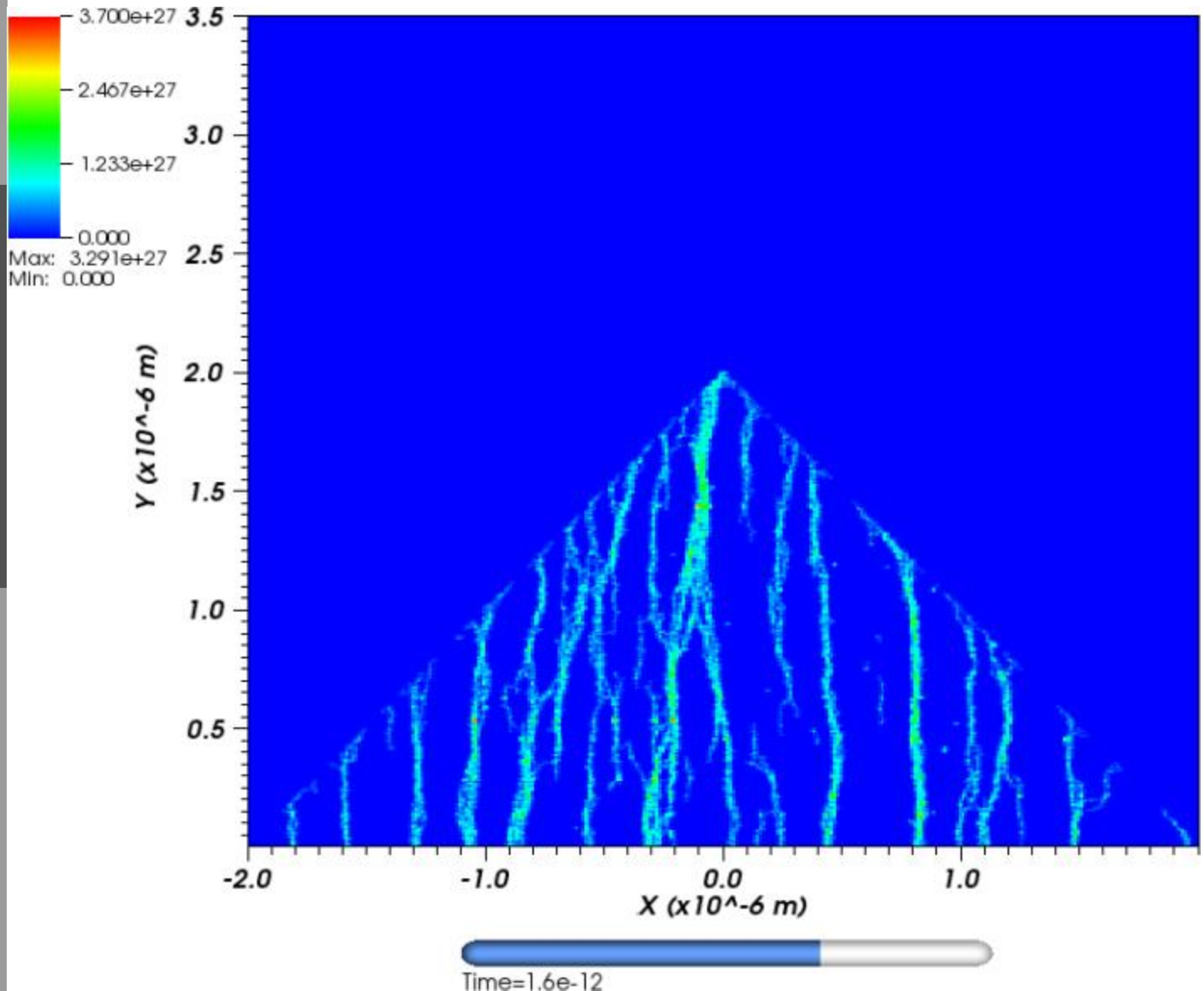

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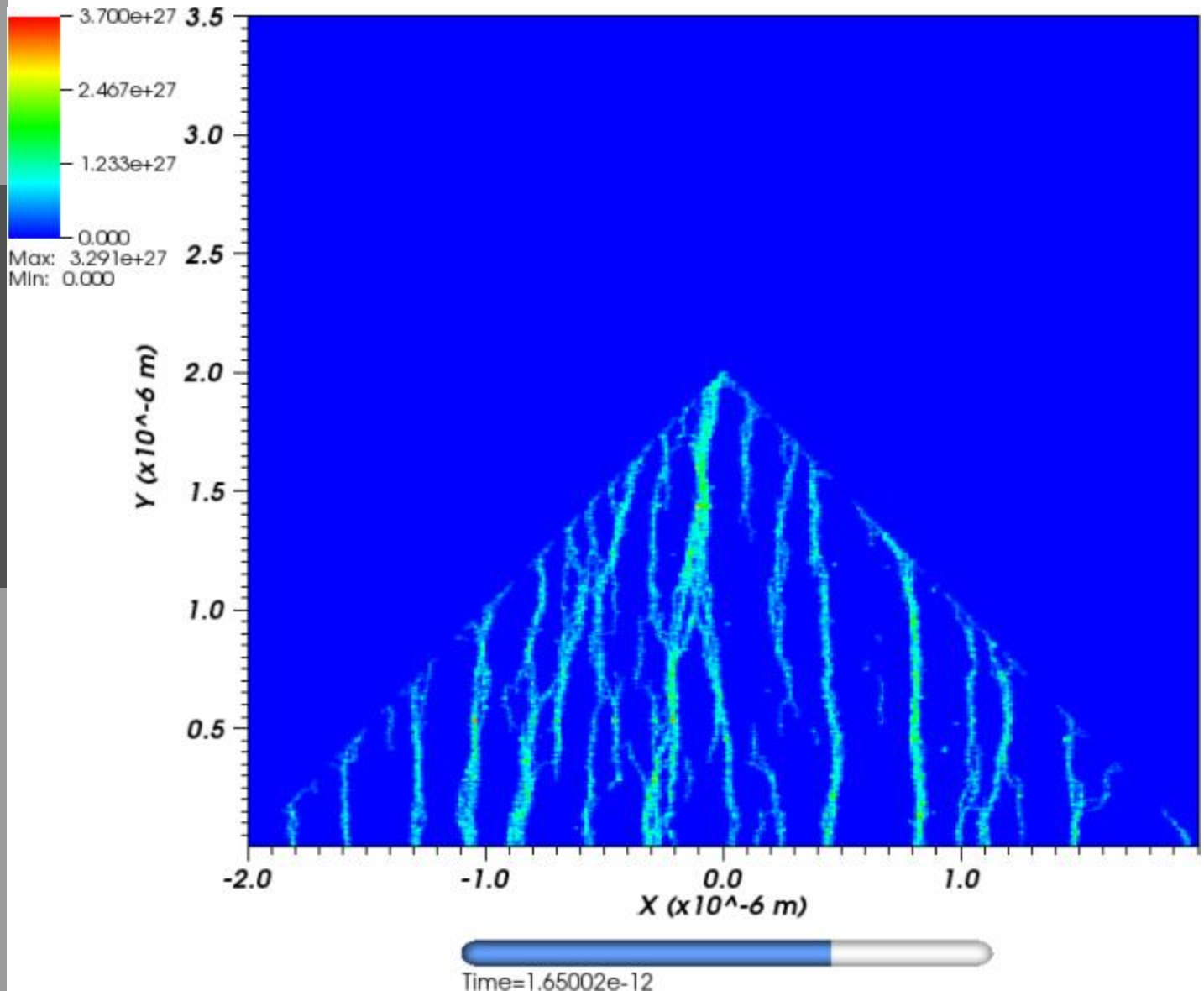

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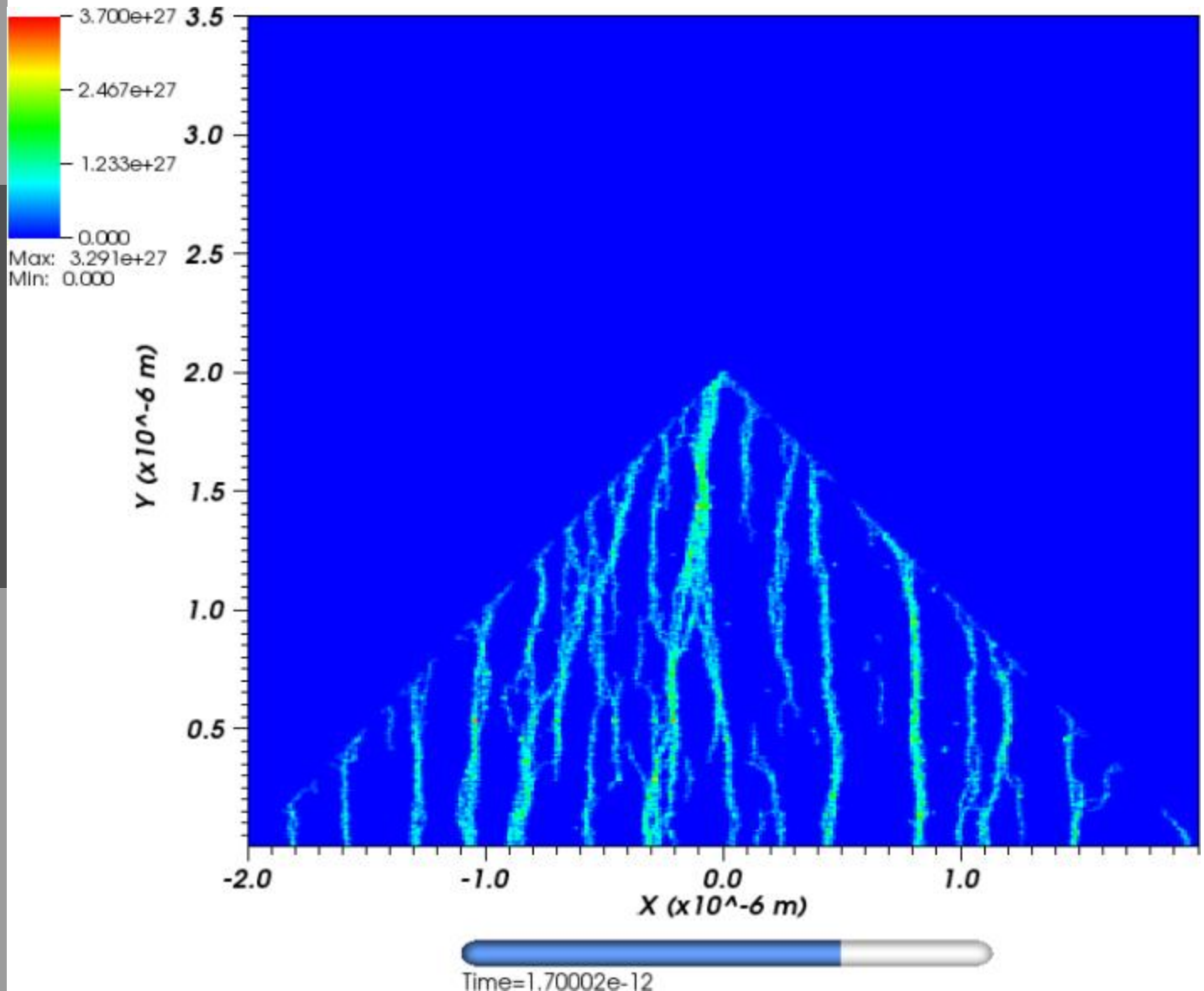

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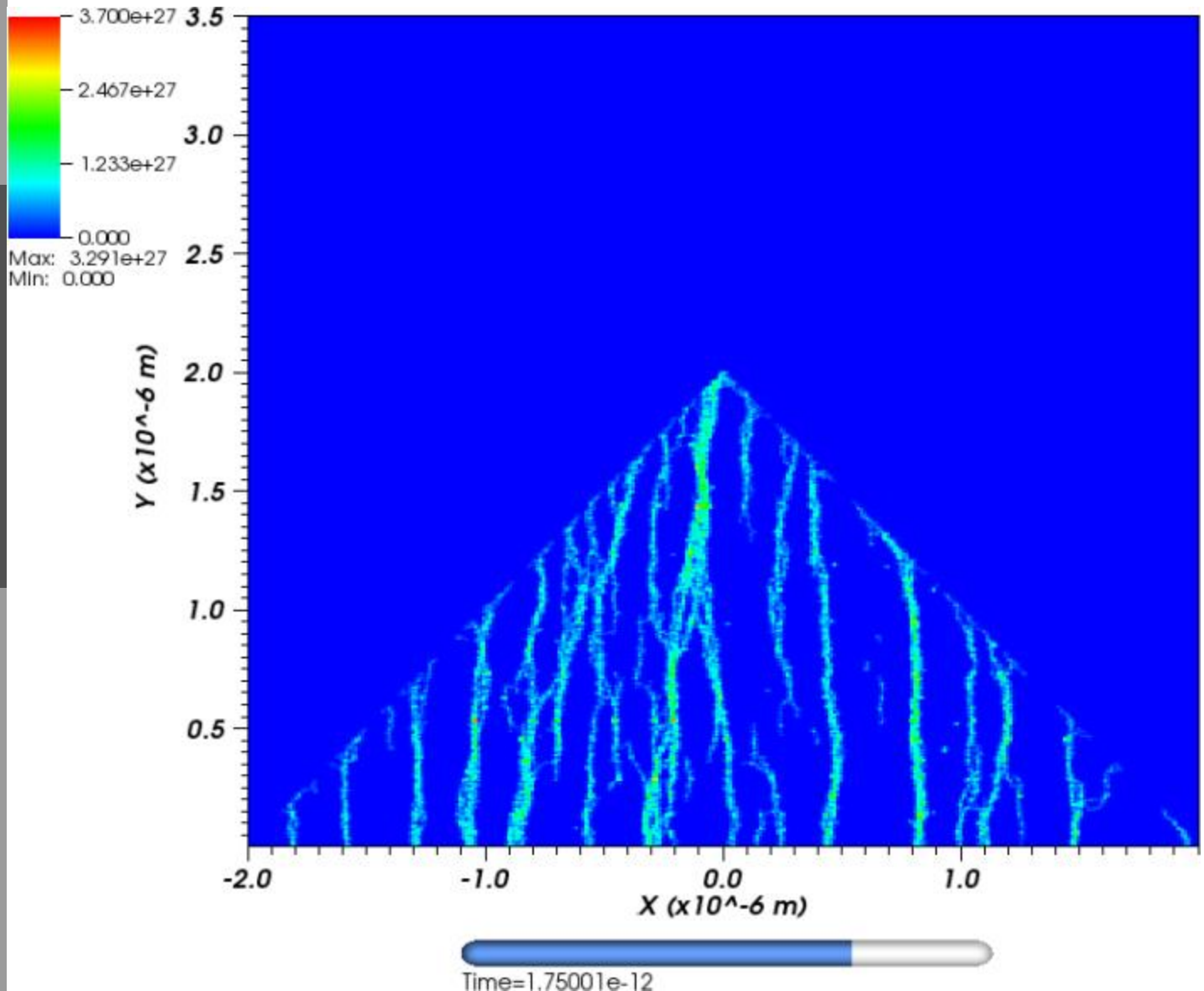

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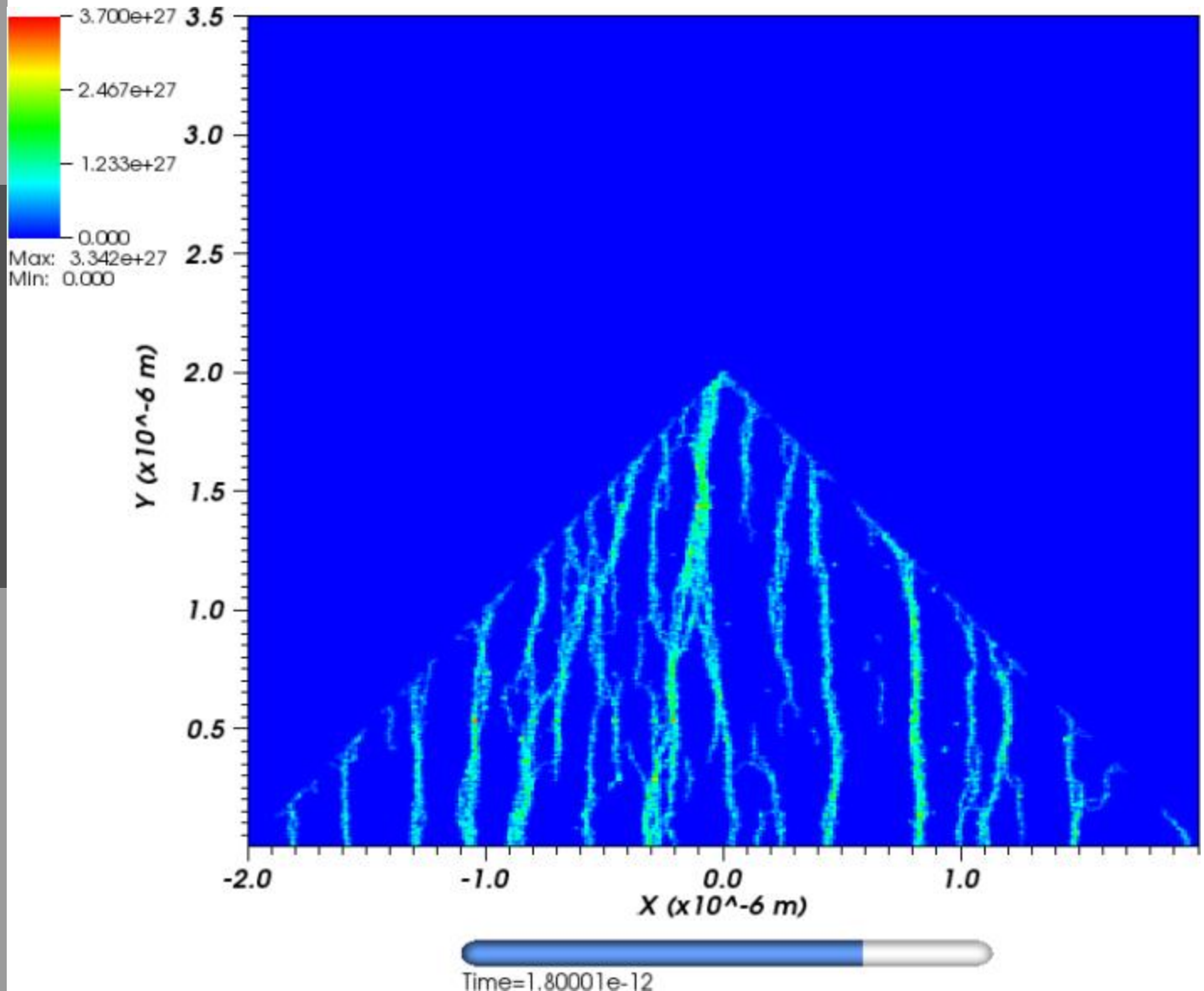

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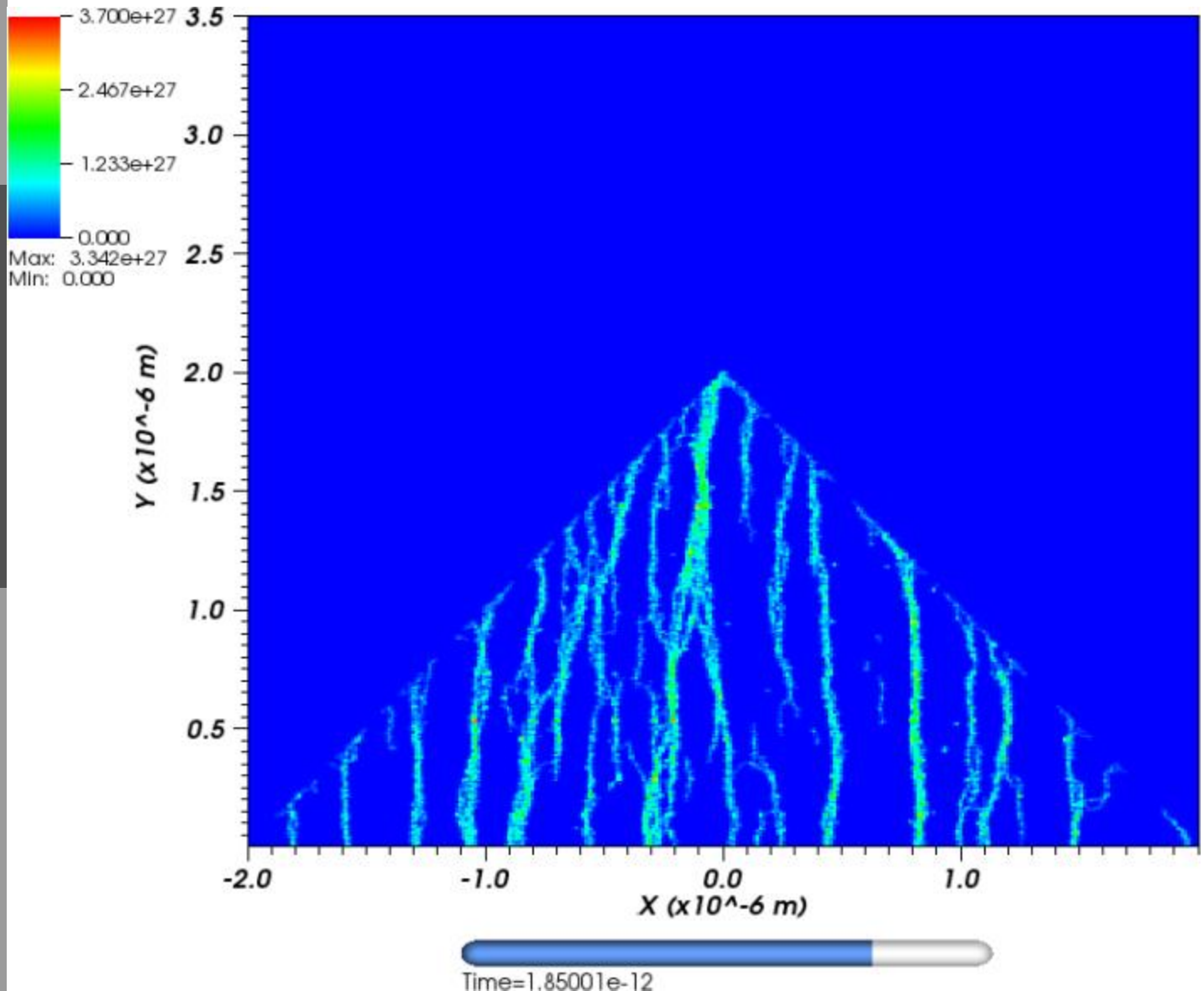

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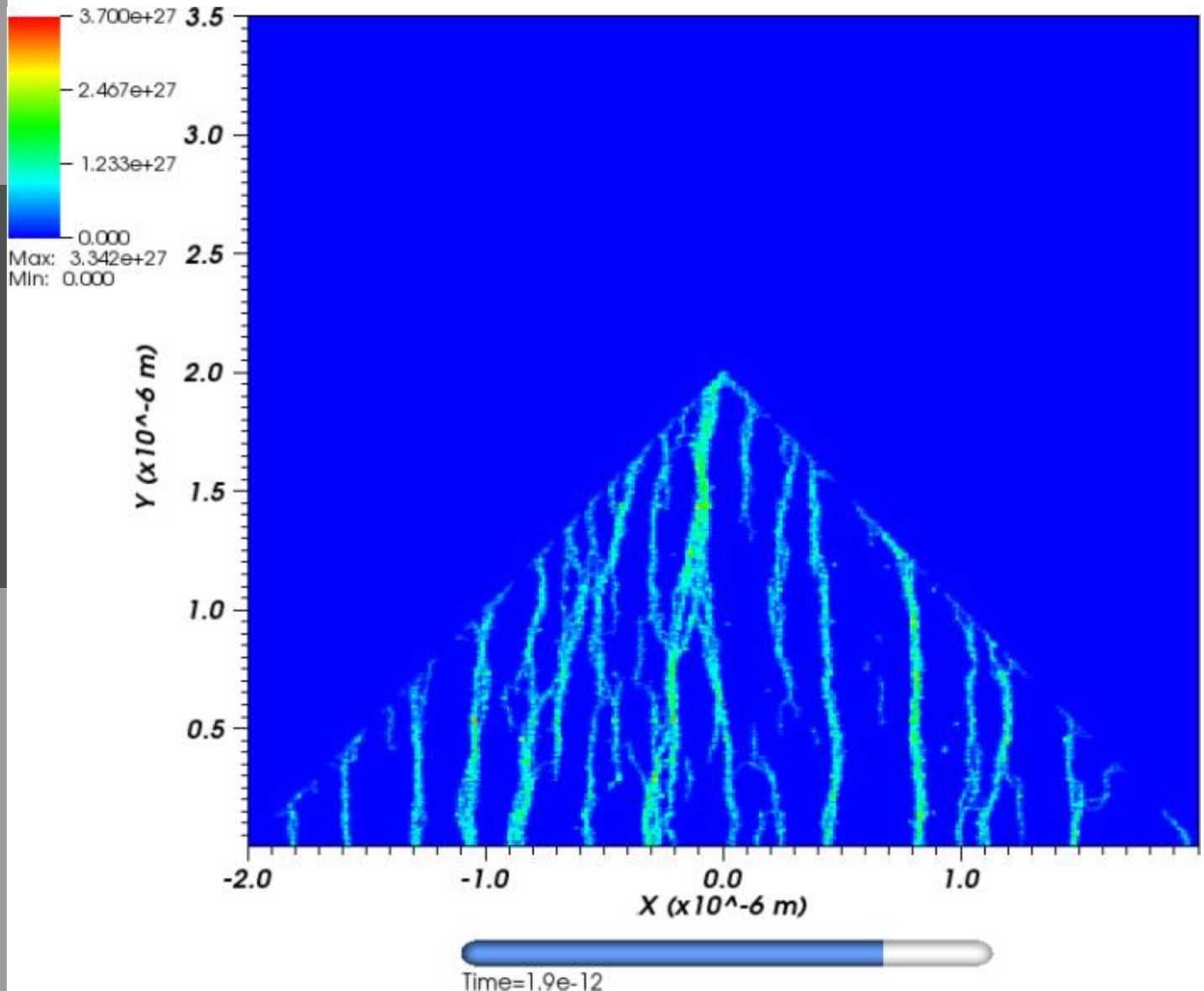

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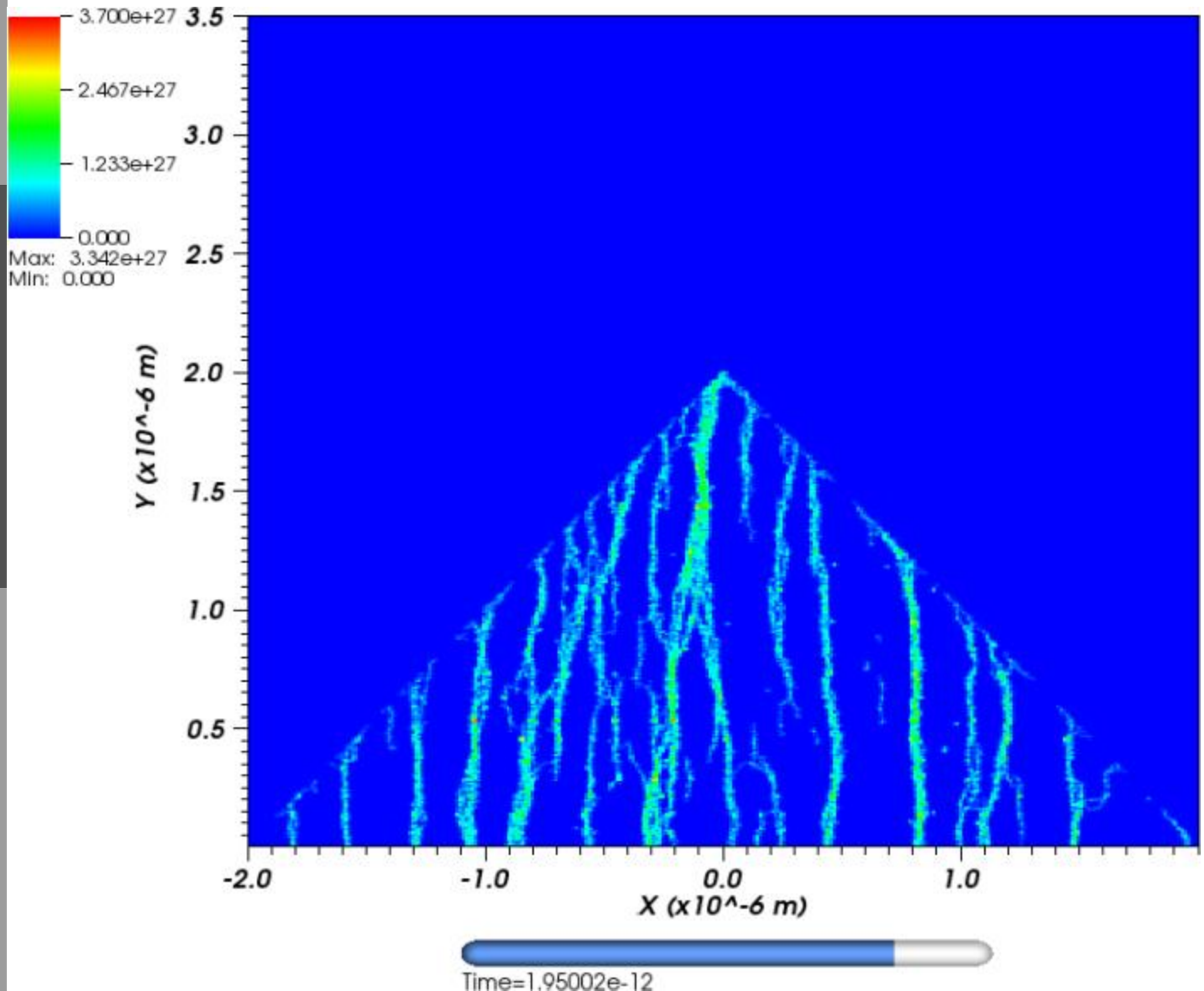

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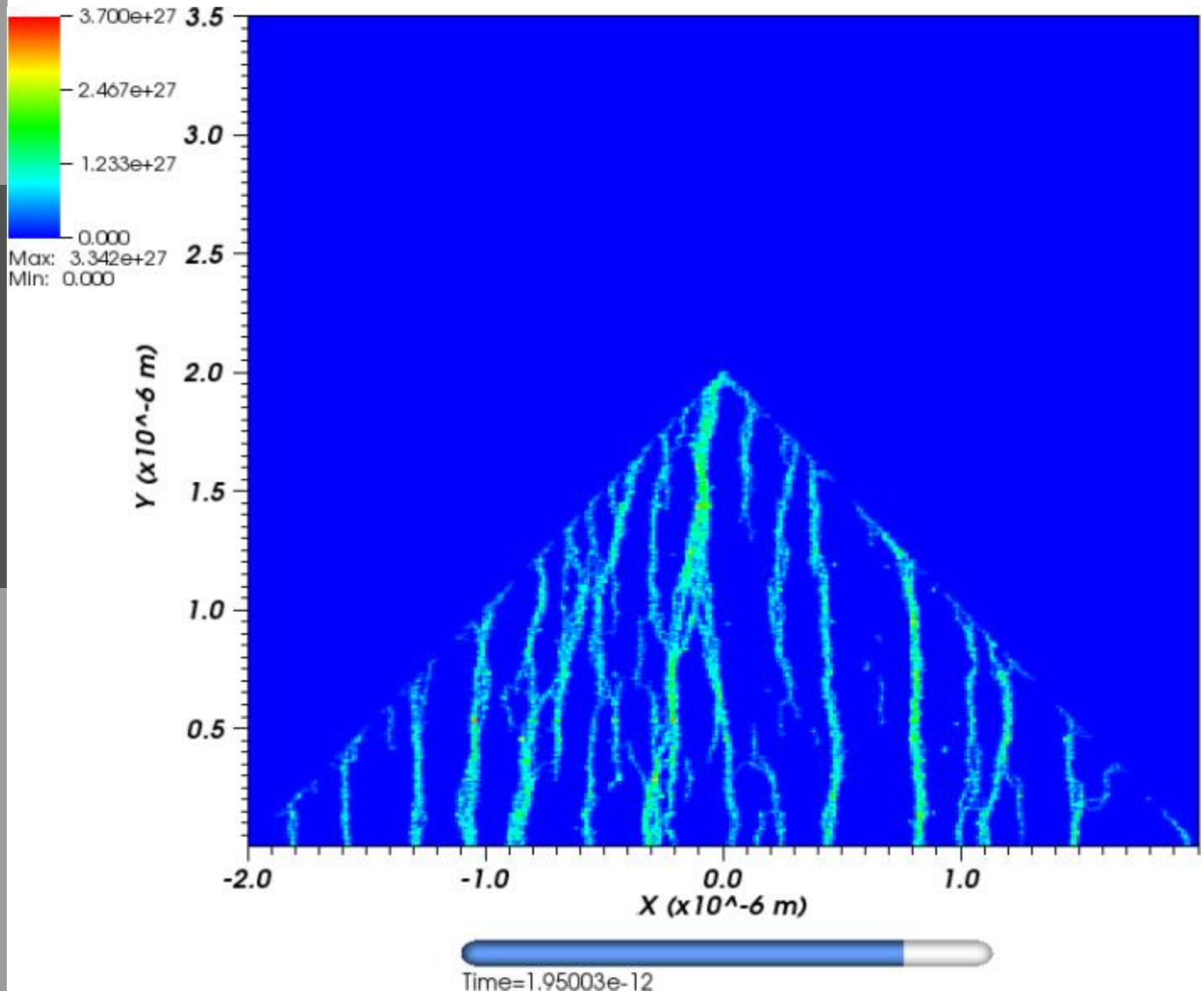

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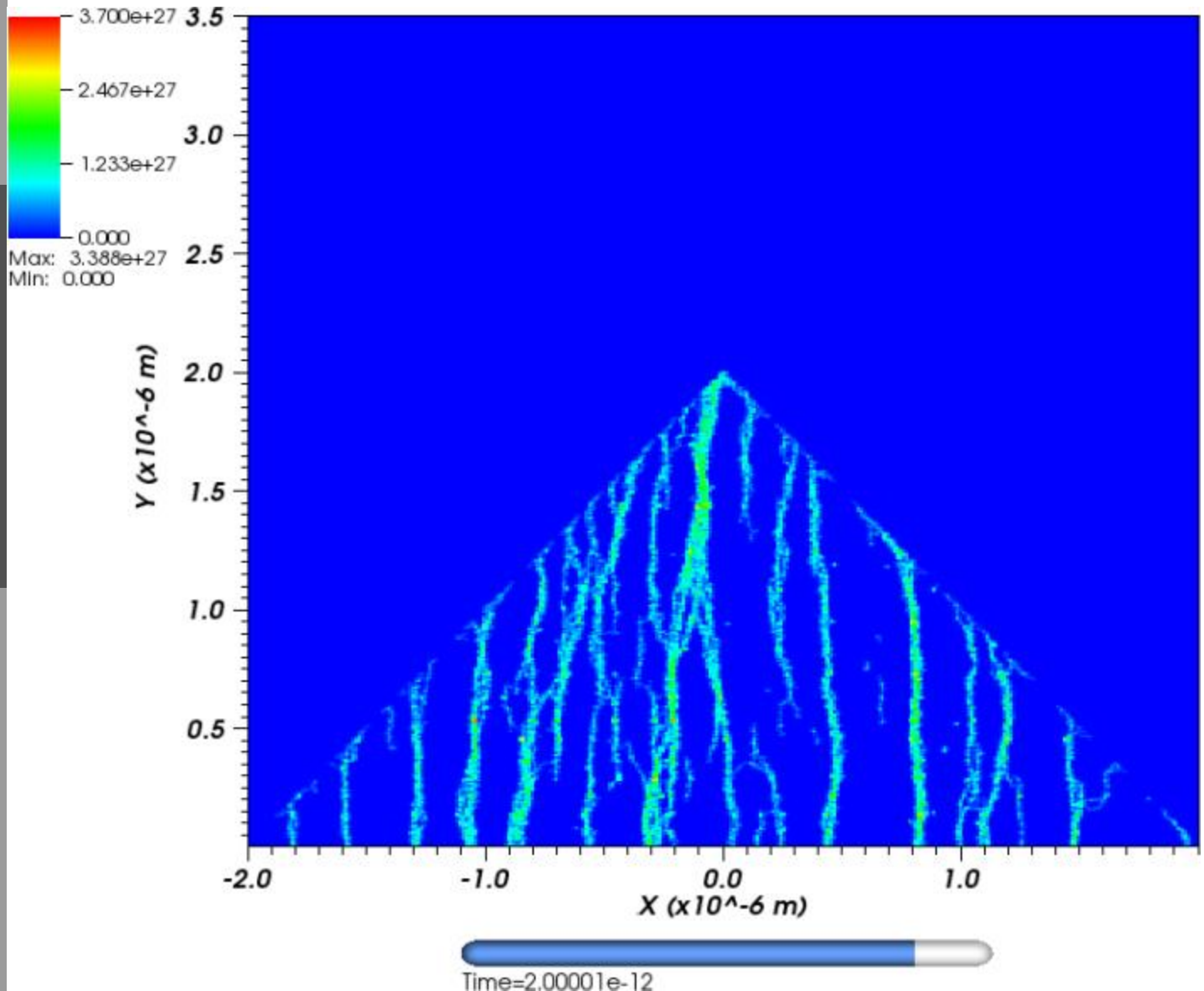

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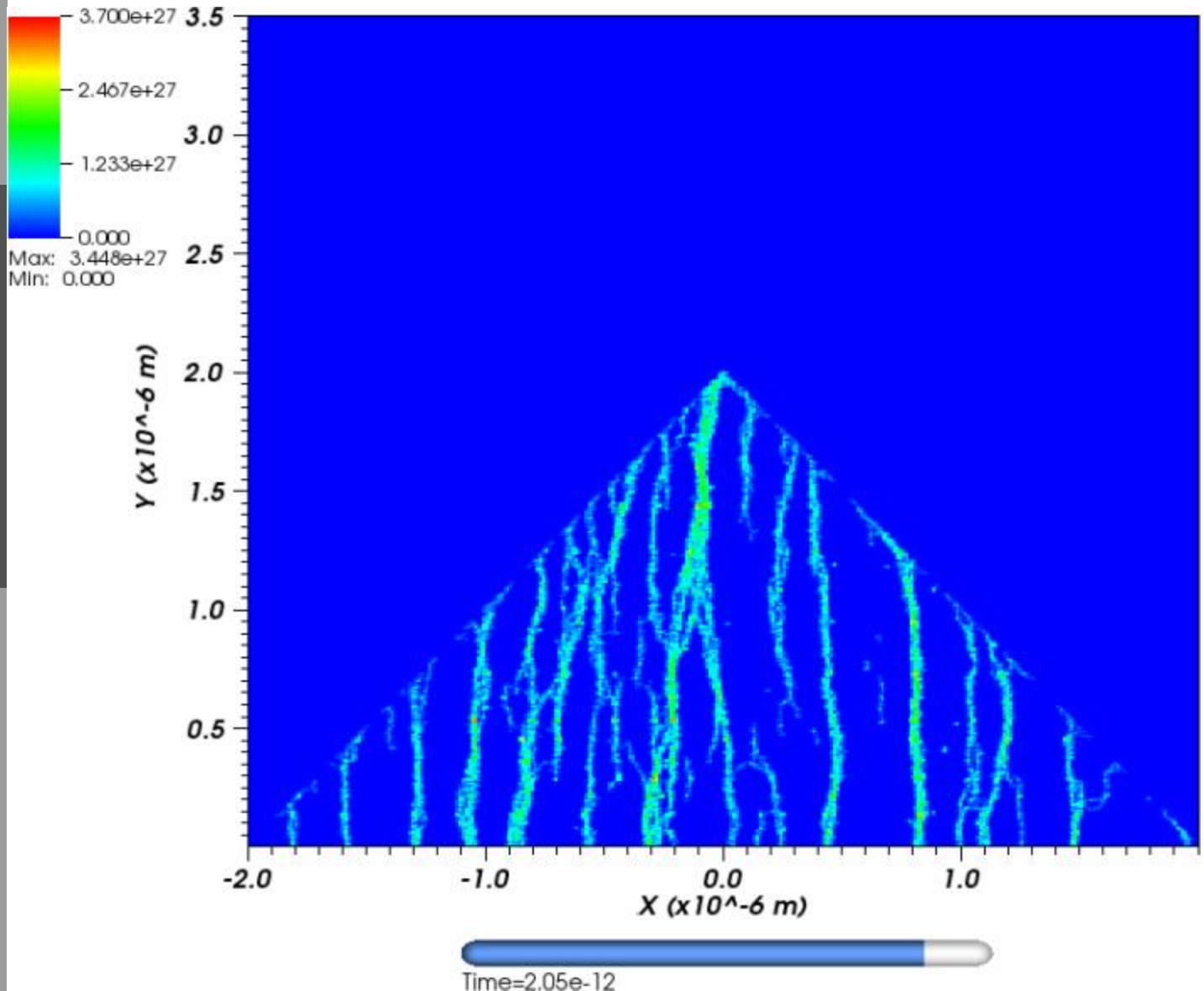

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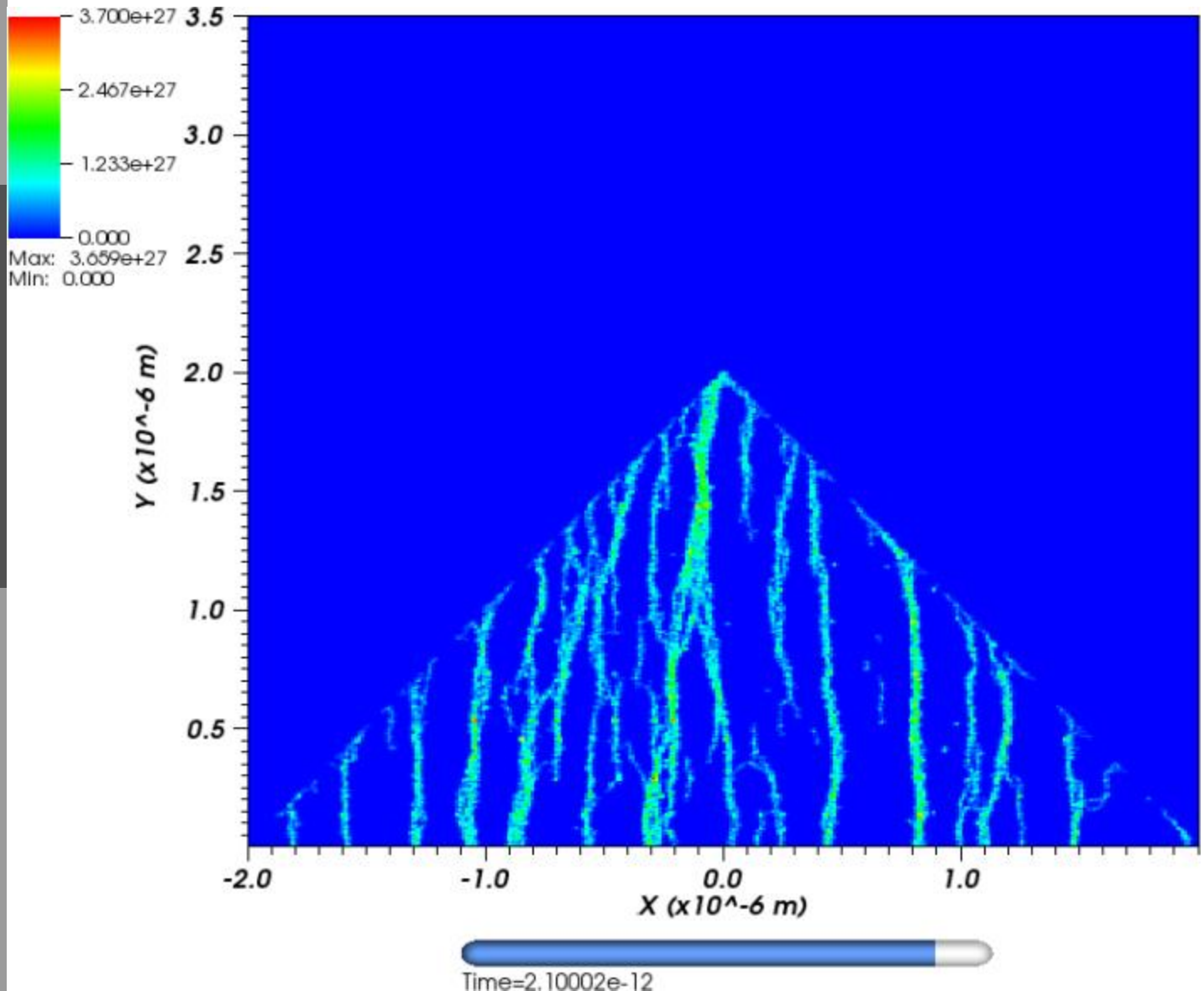

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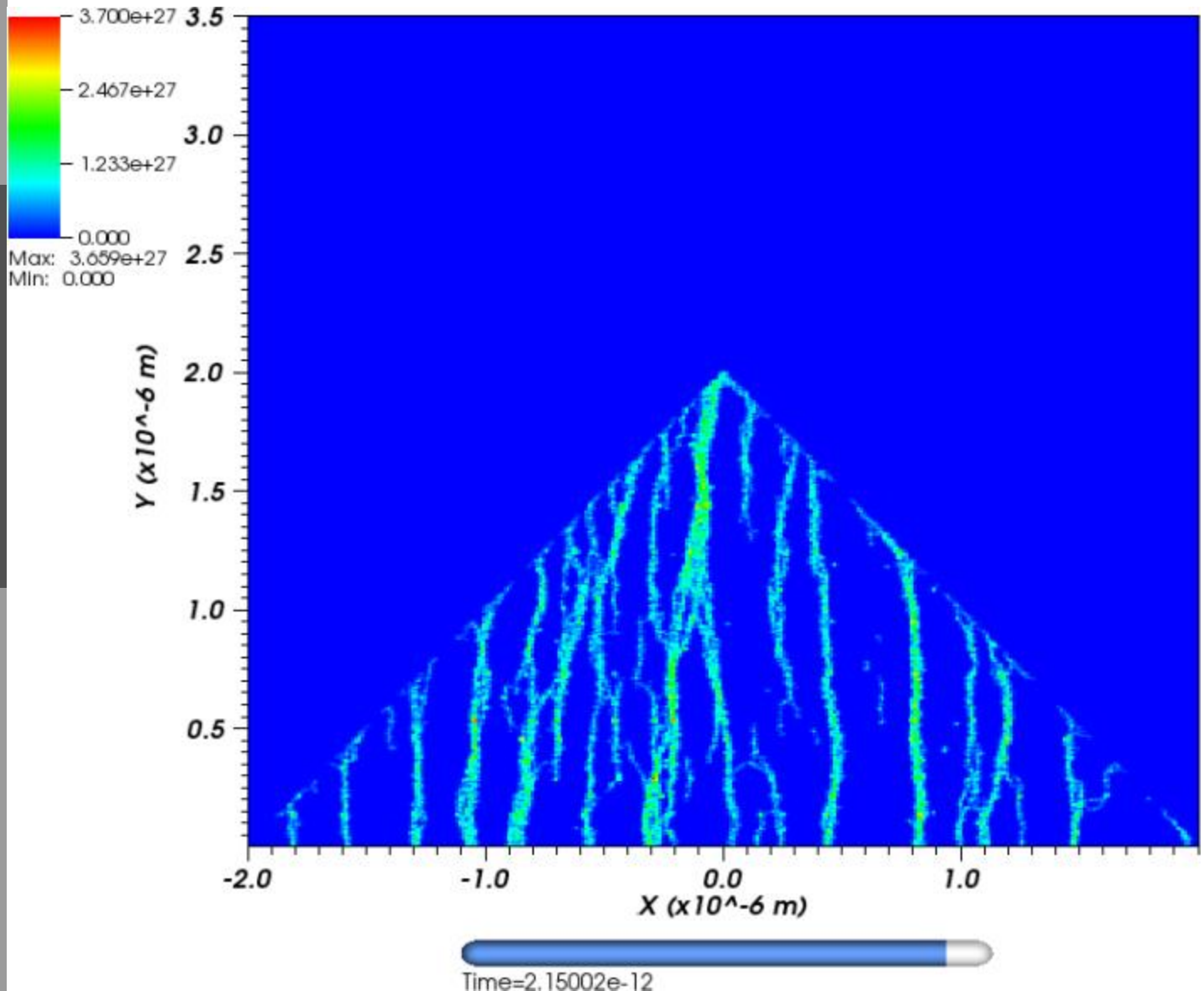

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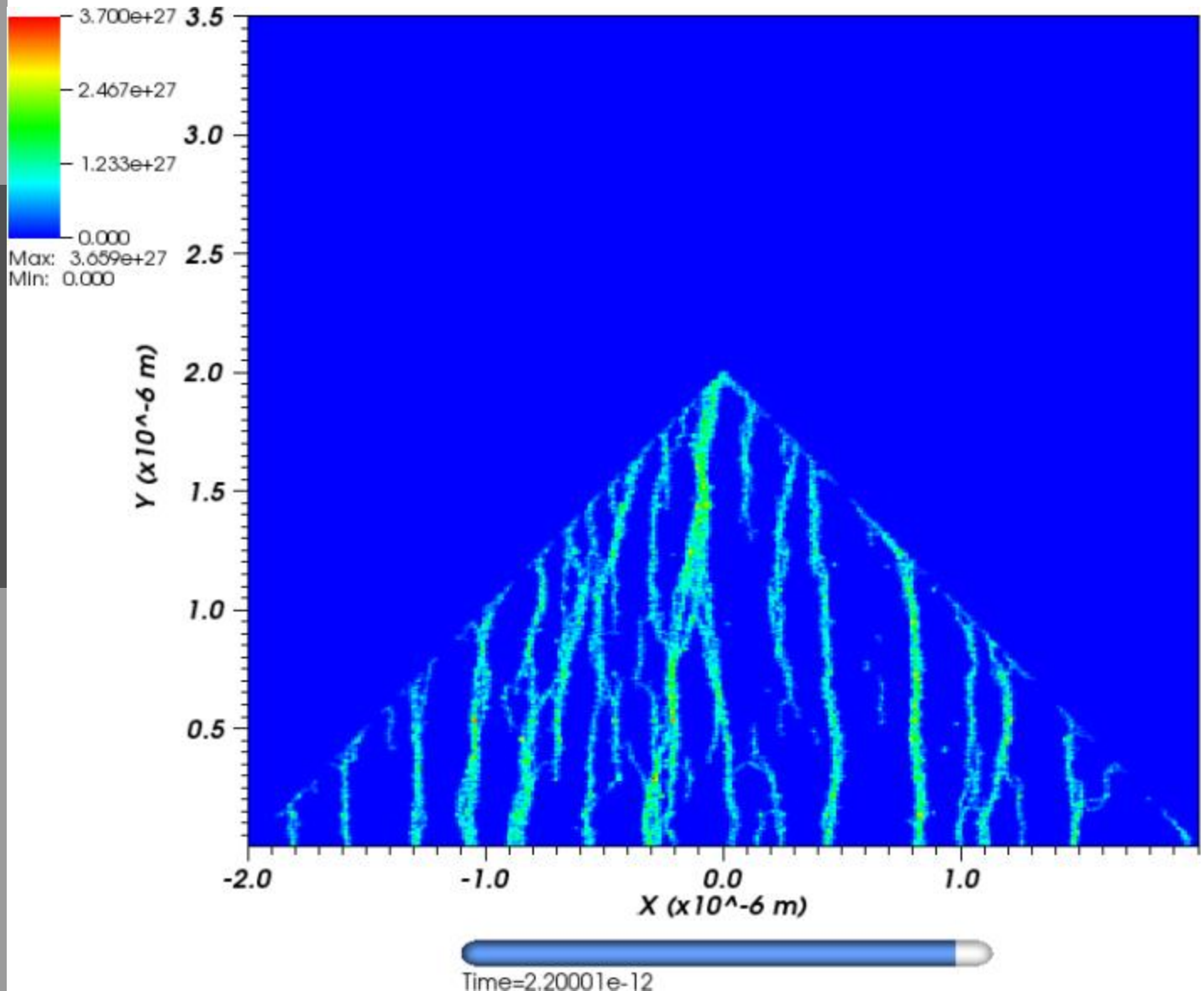

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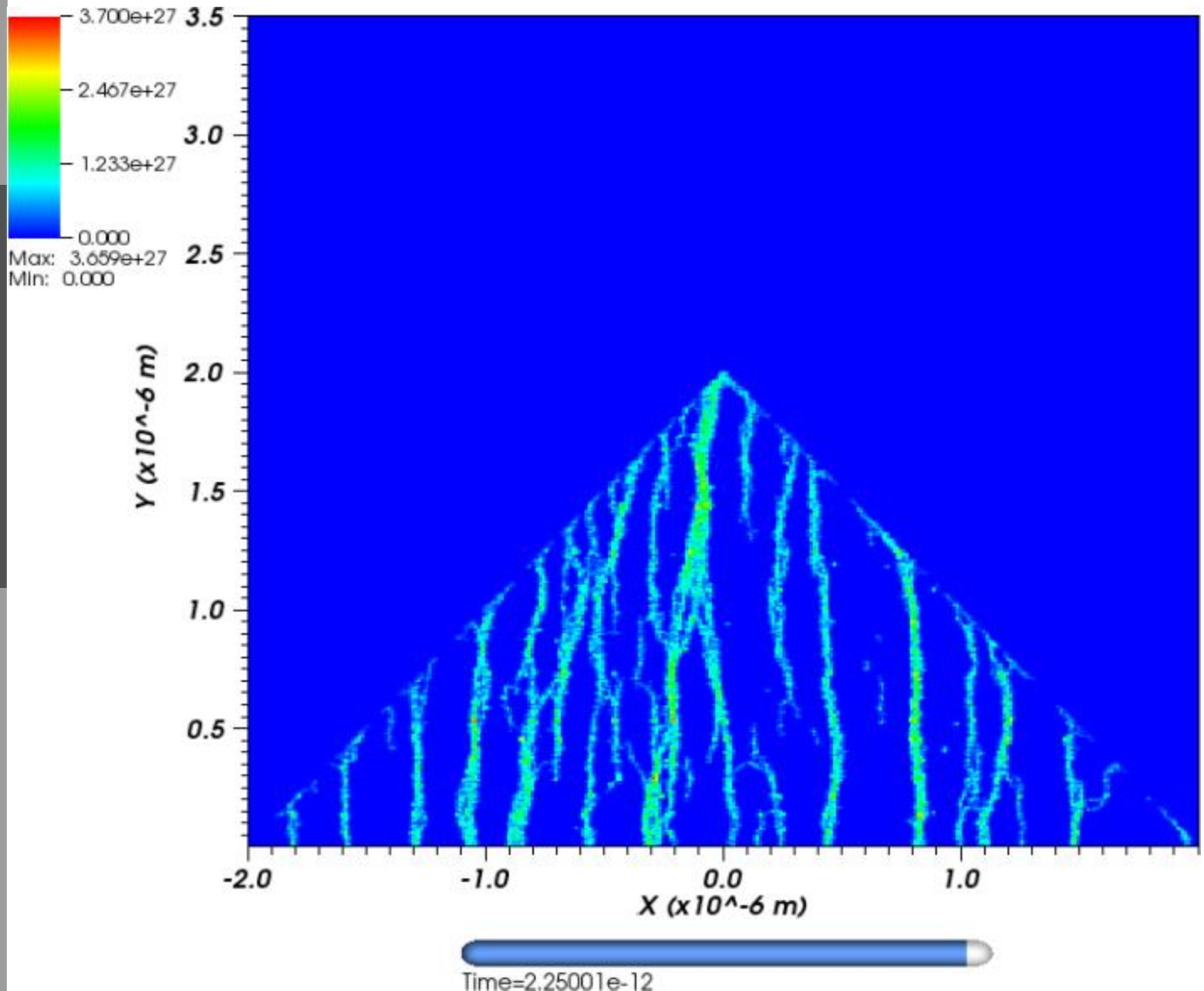

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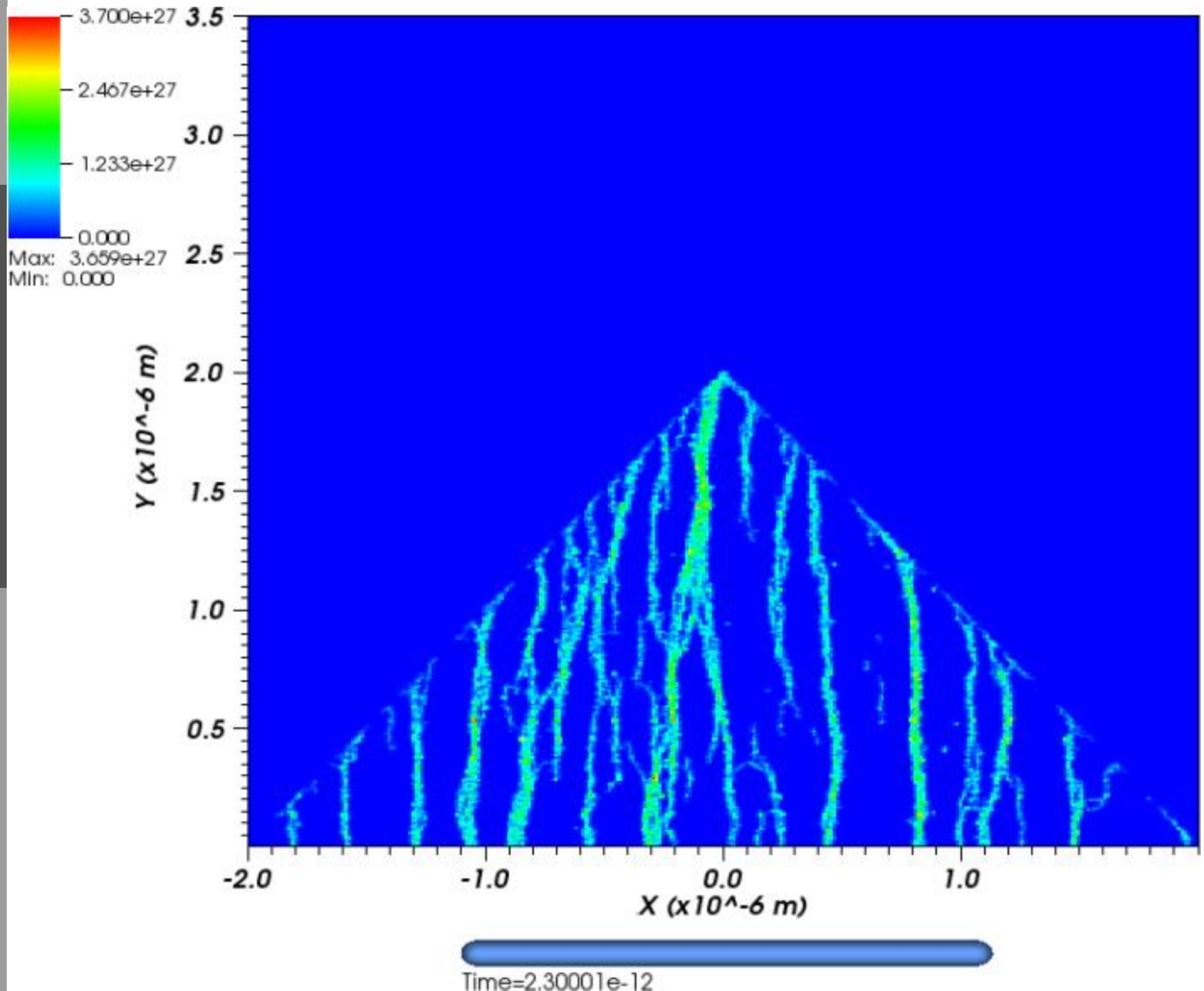

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1D PIC Simulations

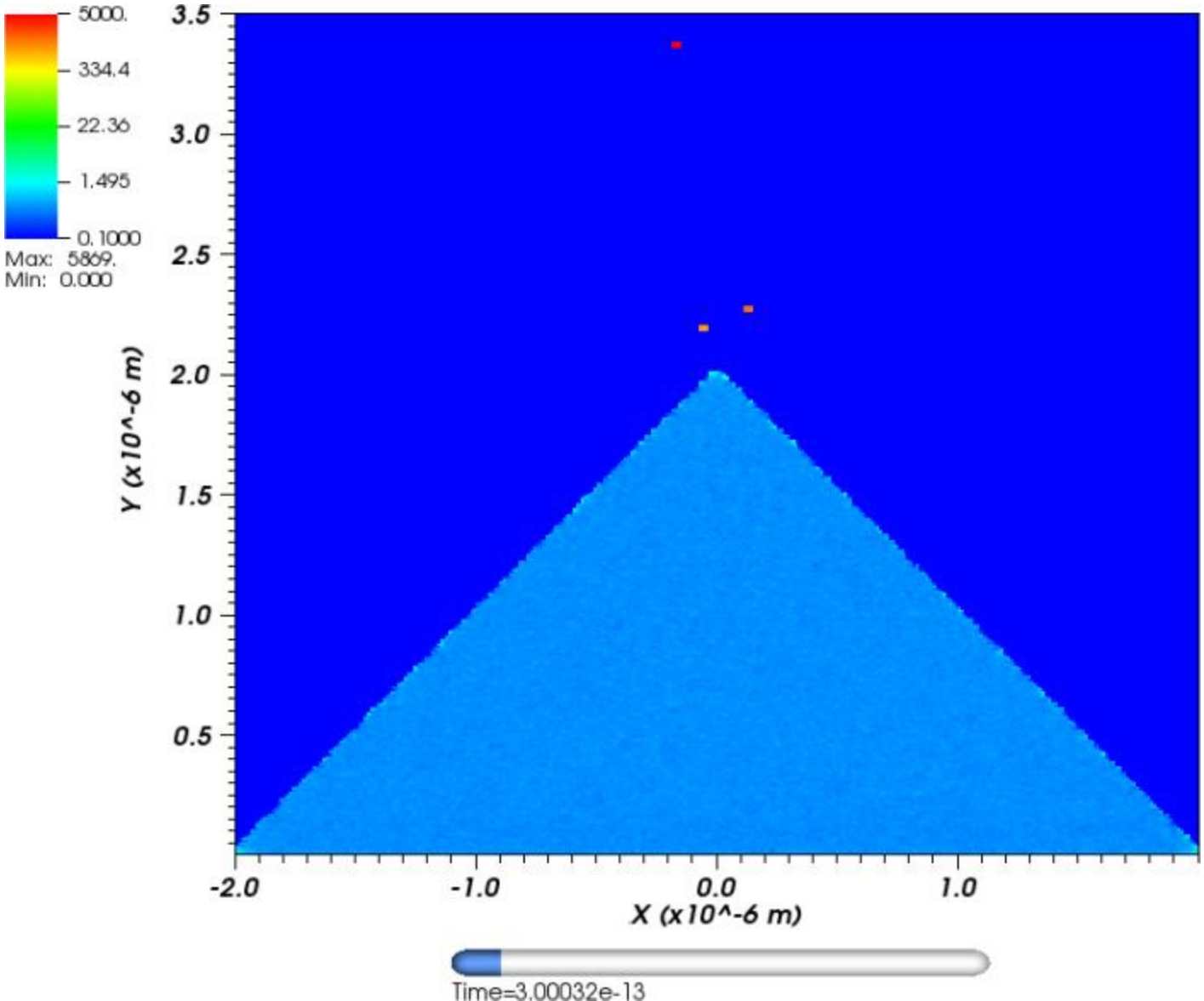
Dark current requires a certain electron density

Occurs after 500 ps
(not feasible for a 2D simulation)

2nd 2D simulation with:

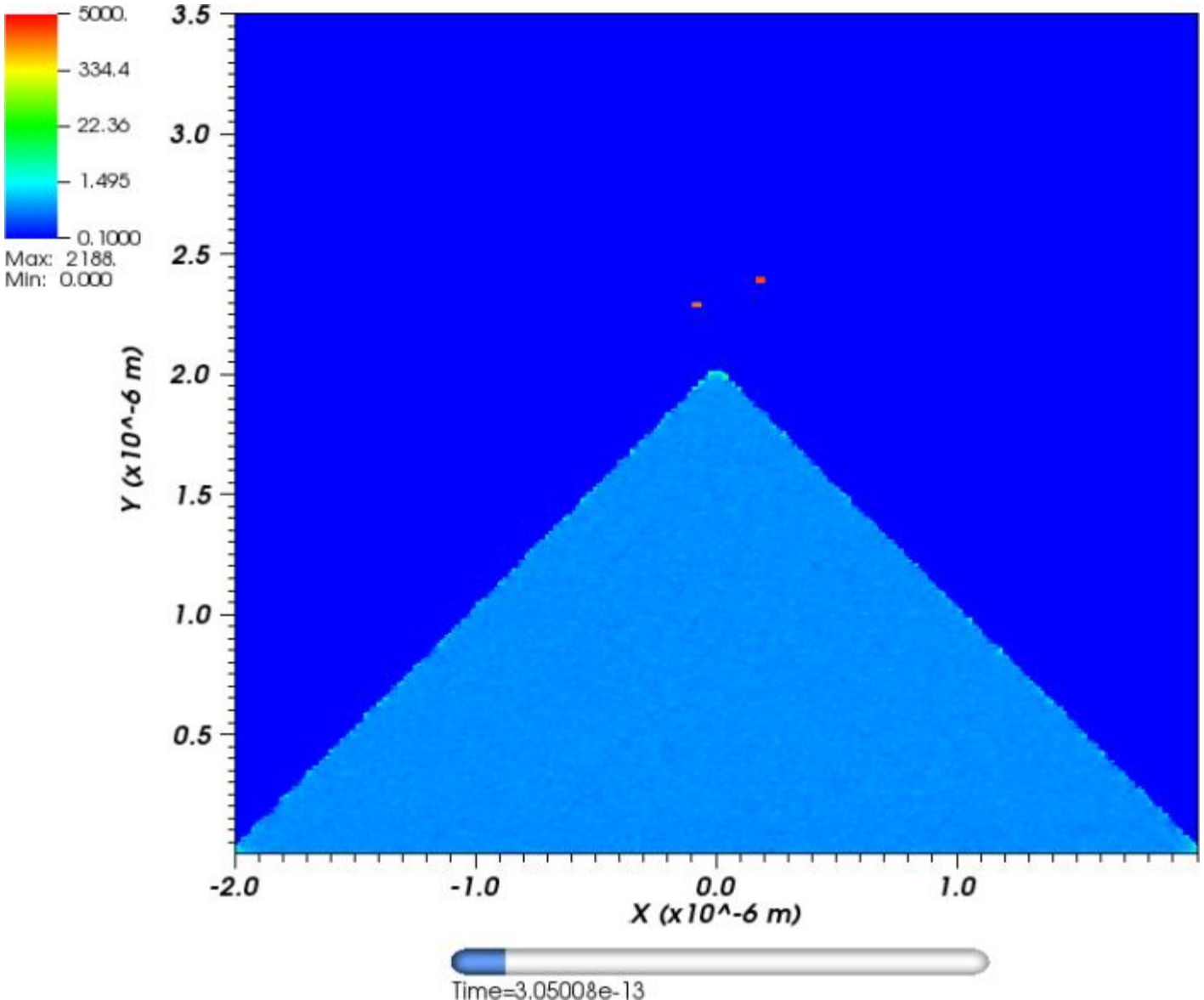
- Given electron density
- No ionization

PIC - Electron Energy Pt.II



- E_y = -2 GV/m
- No ionization
- t_{tot} = 0.8 ps

PIC - Electron Energy Pt.II



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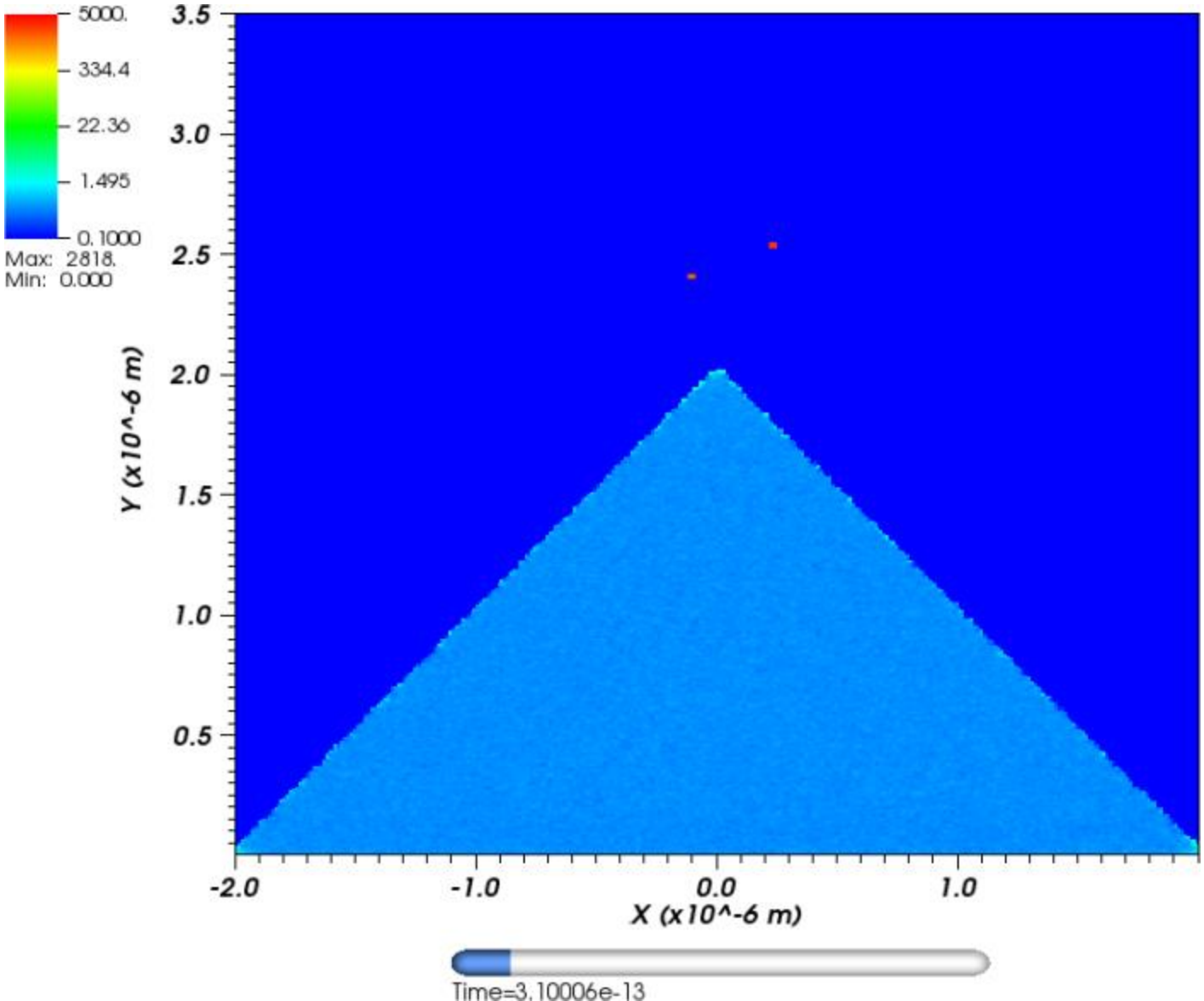

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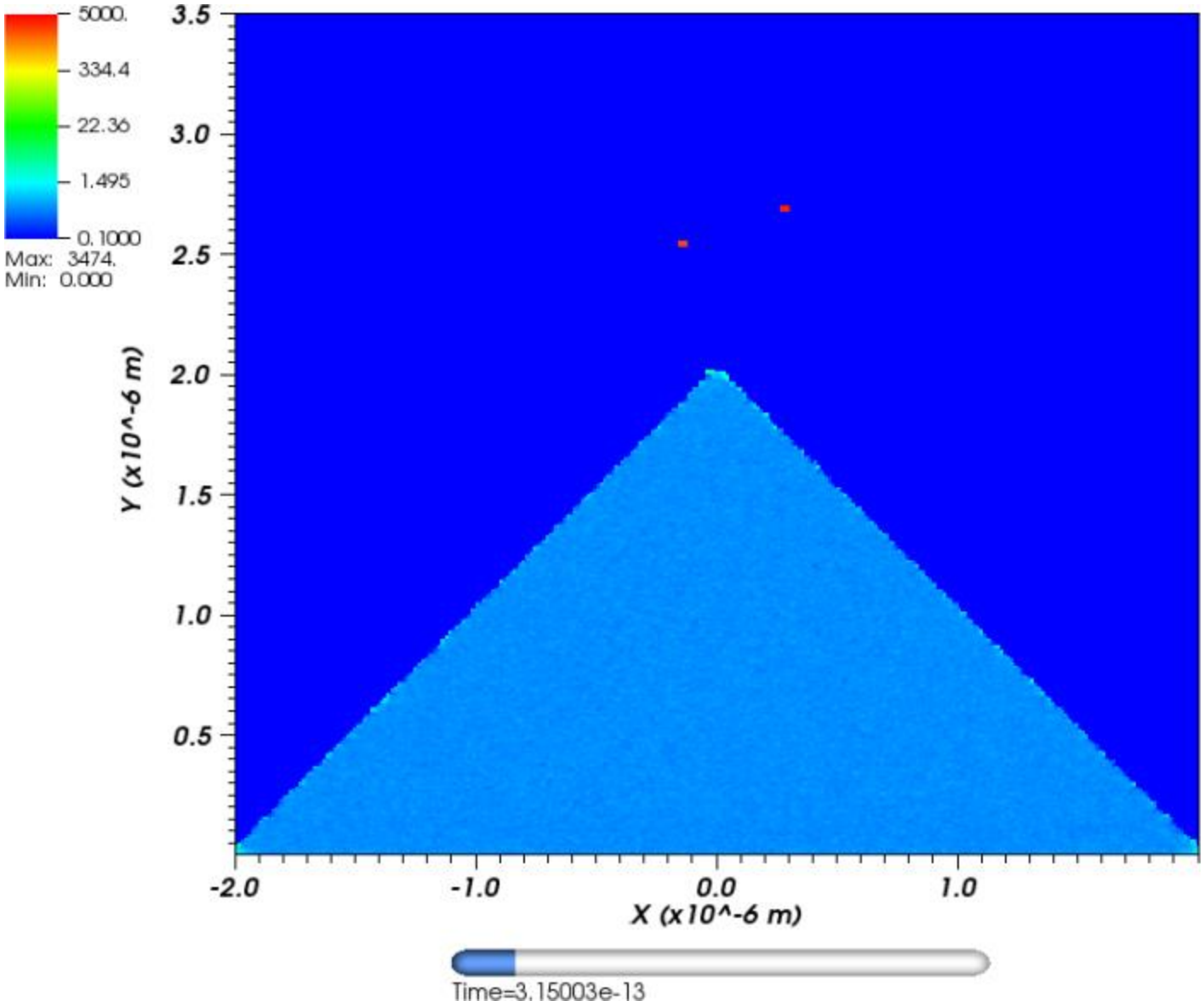

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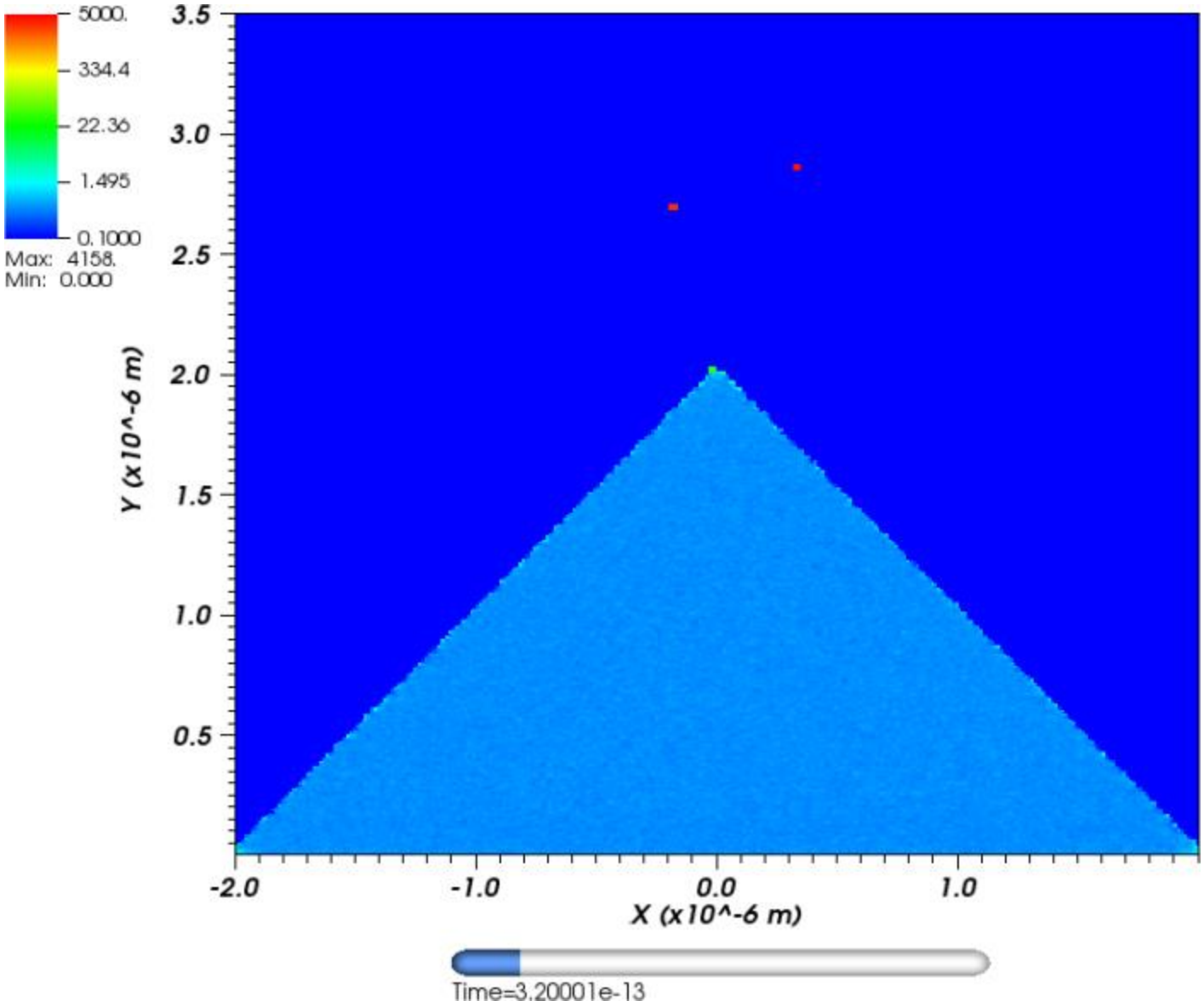

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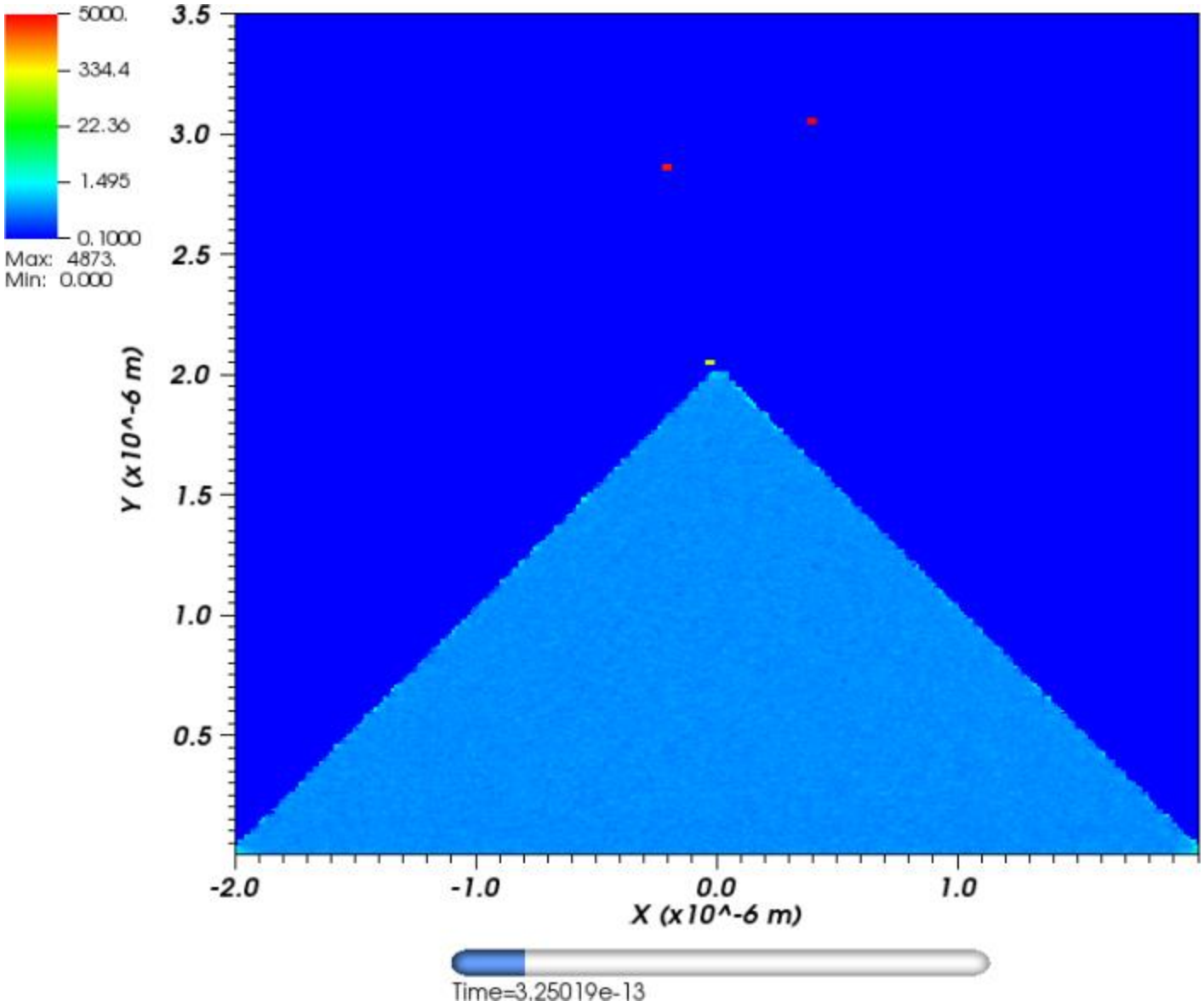

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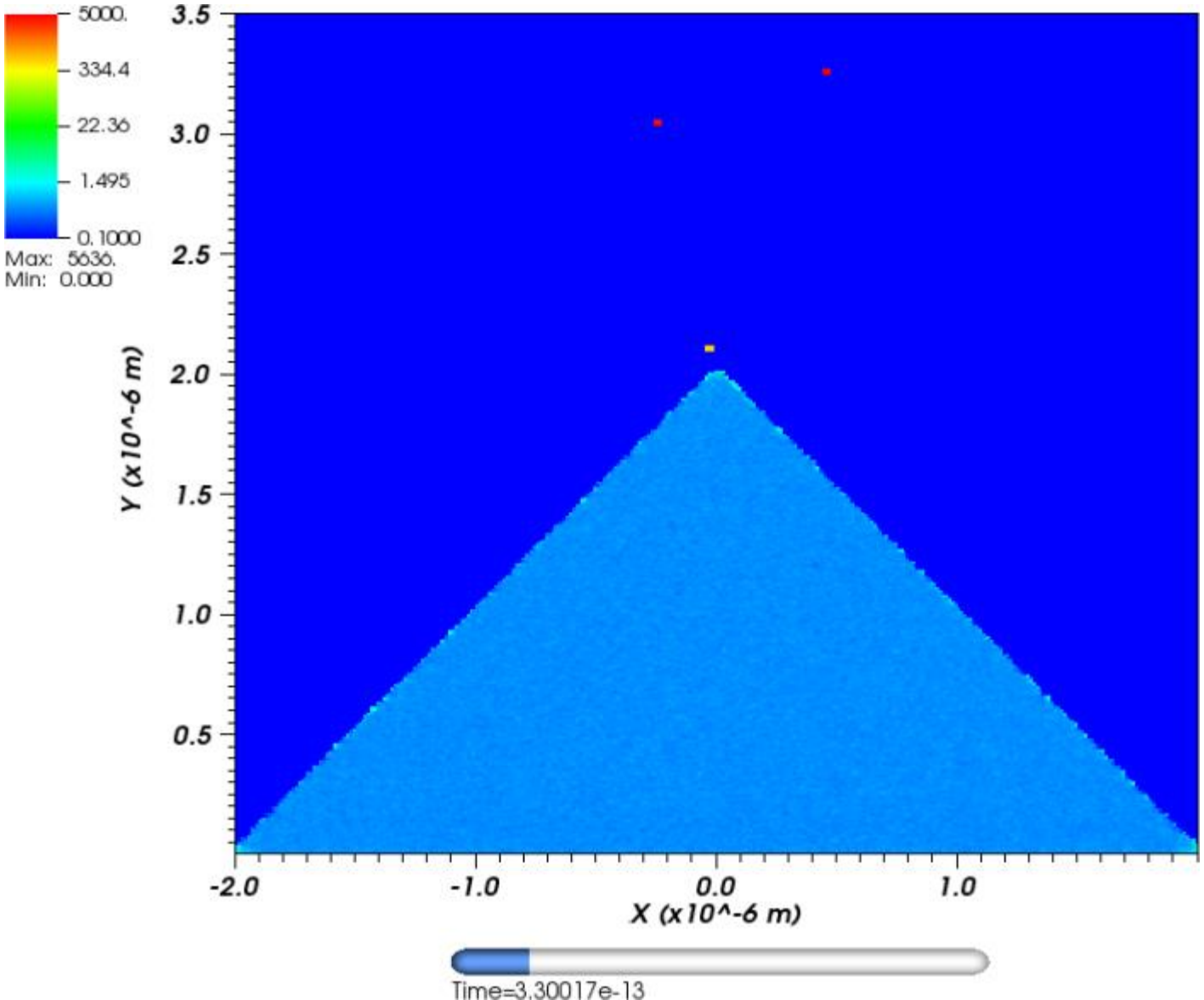

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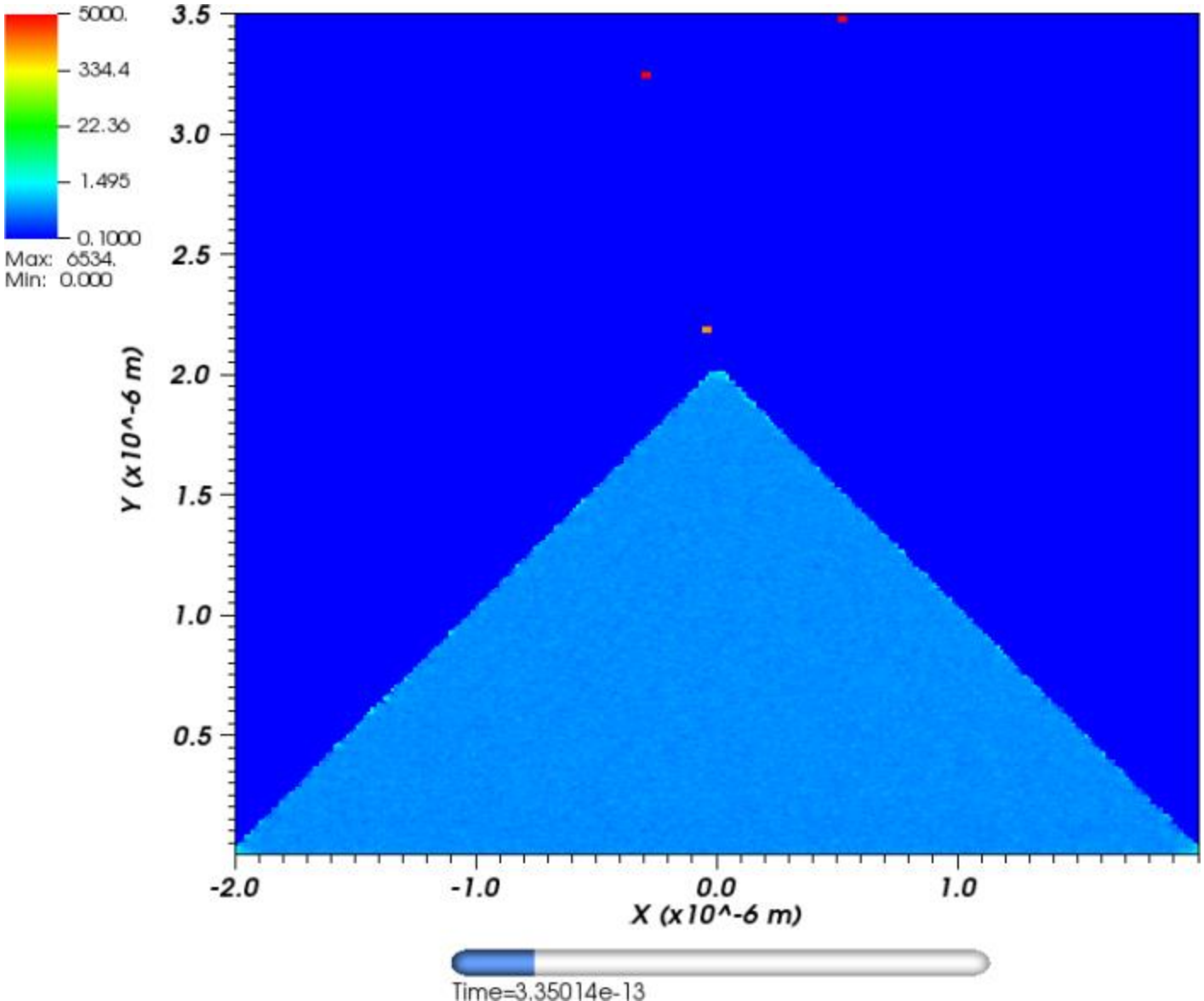

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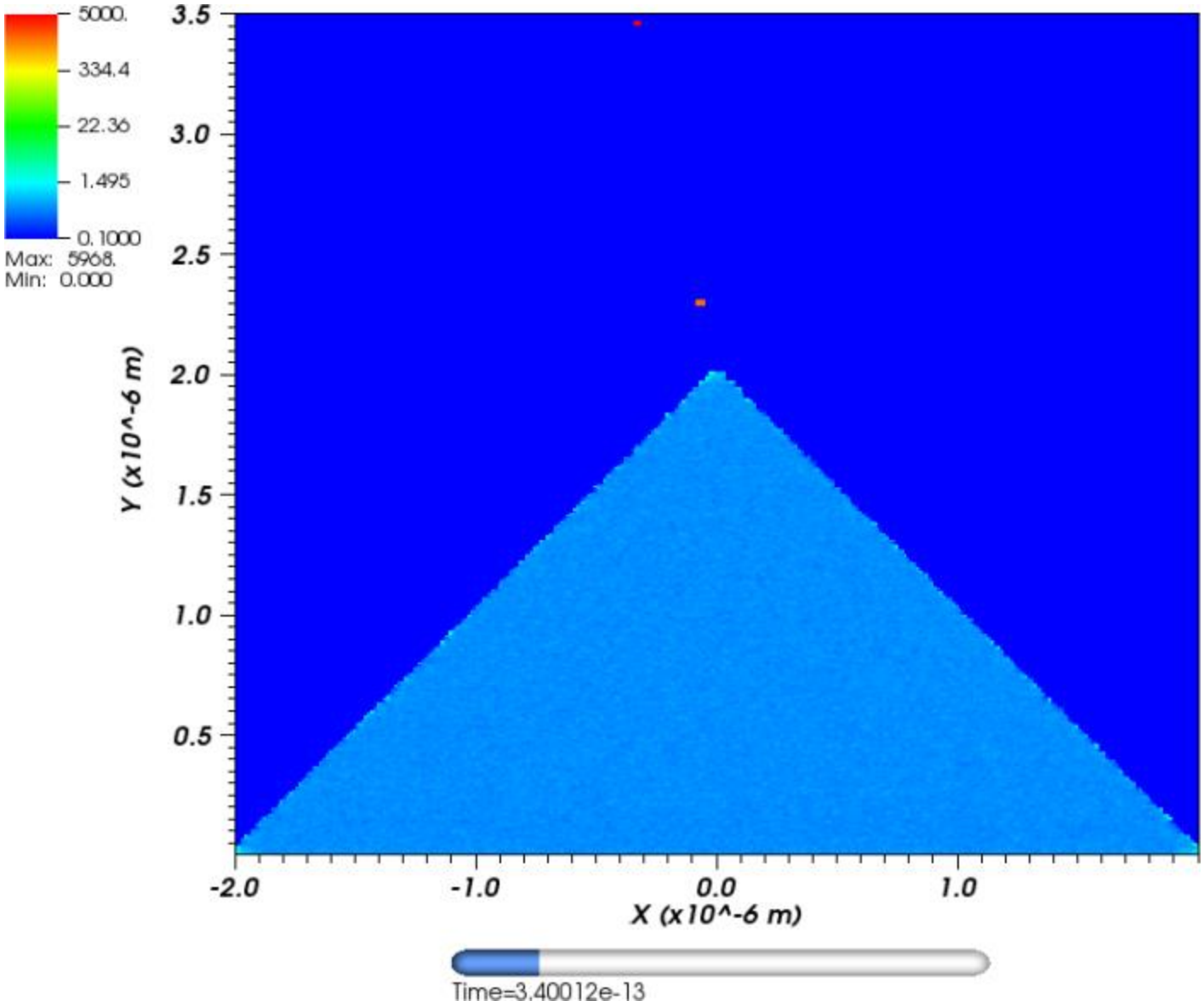

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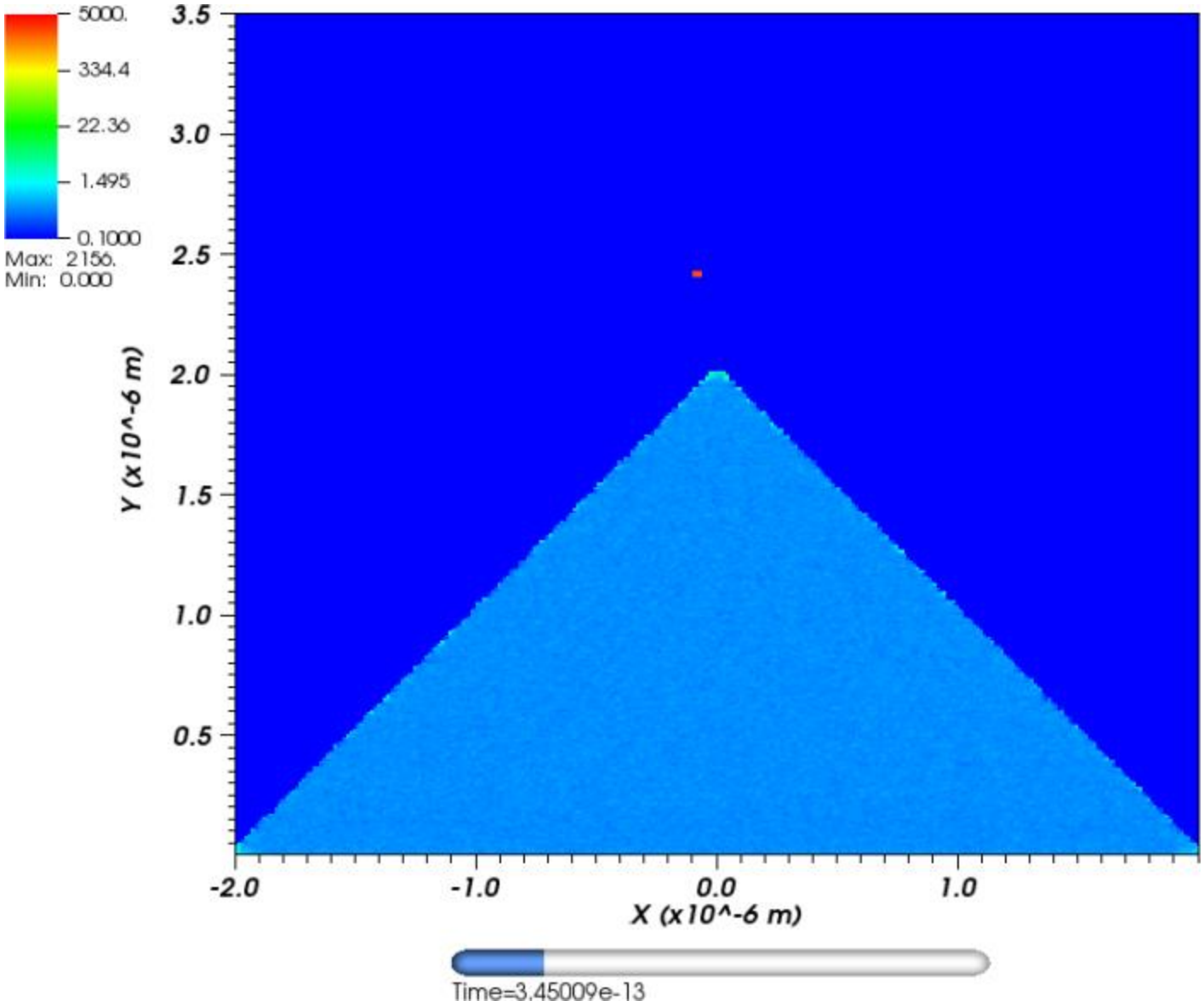

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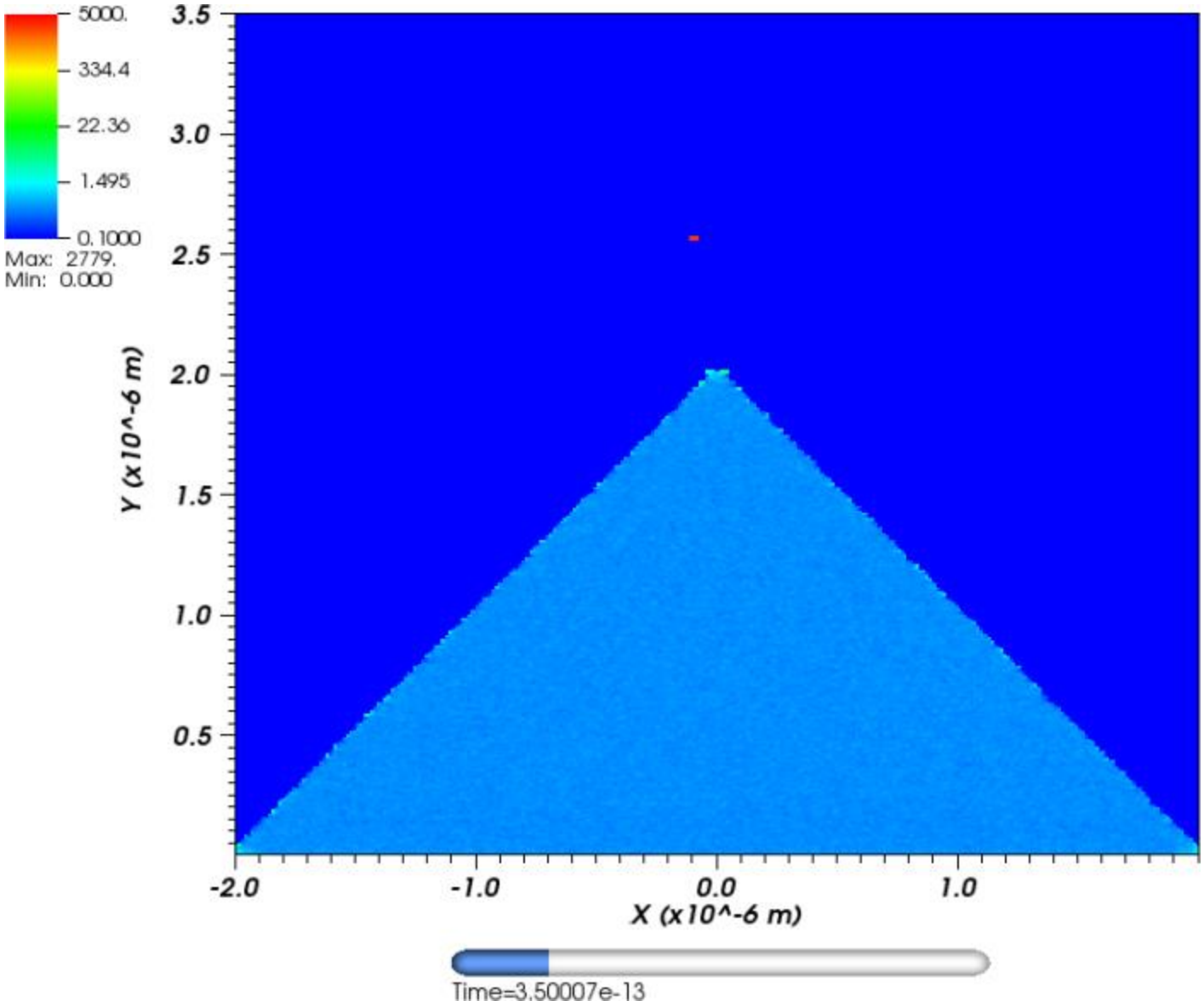
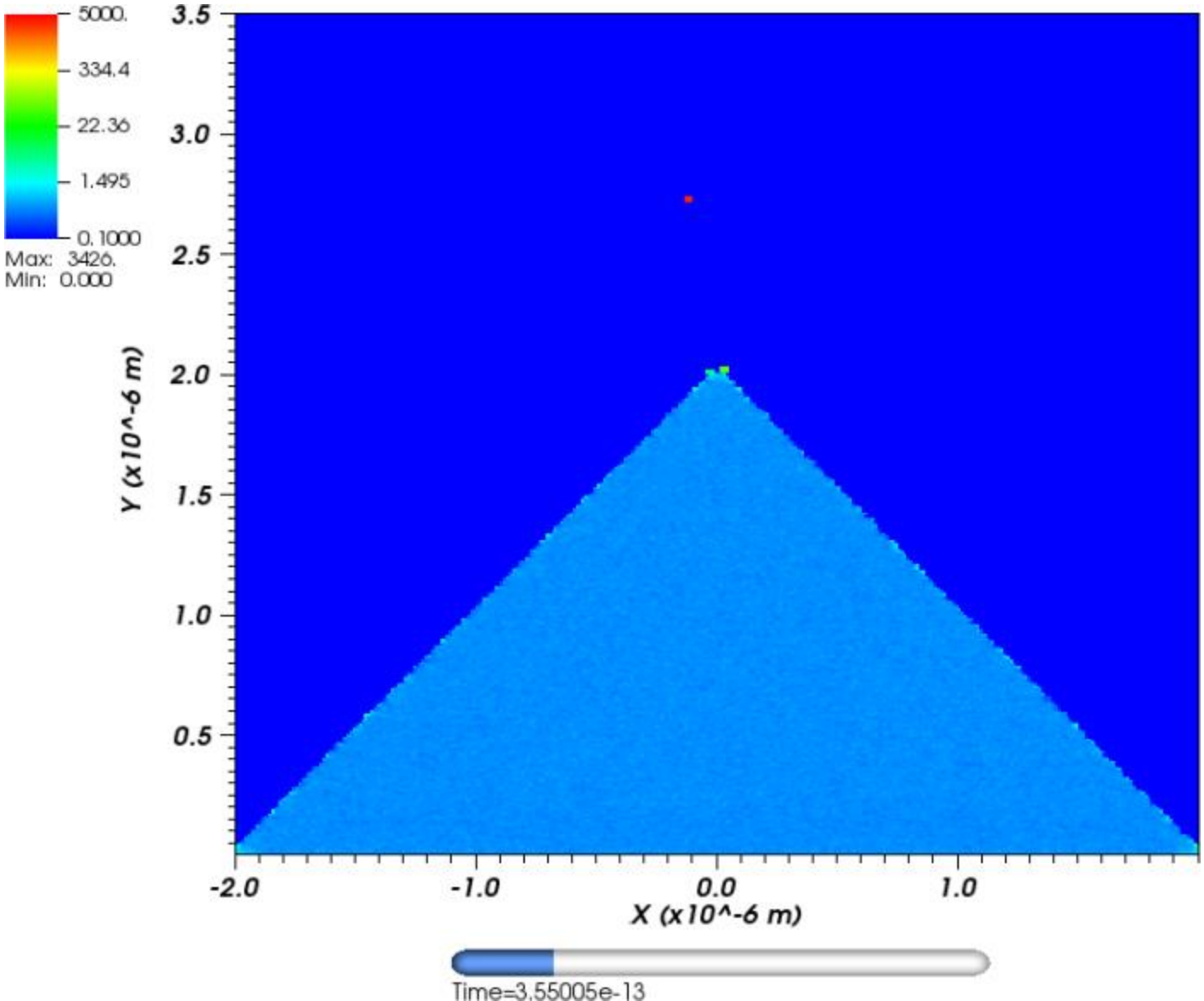
PIC - Electron Energy Pt.II



- E_y = -2 GV/m
- No ionization
- t_{tot} = 0.8 ps

PIC - Electron Energy Pt.II



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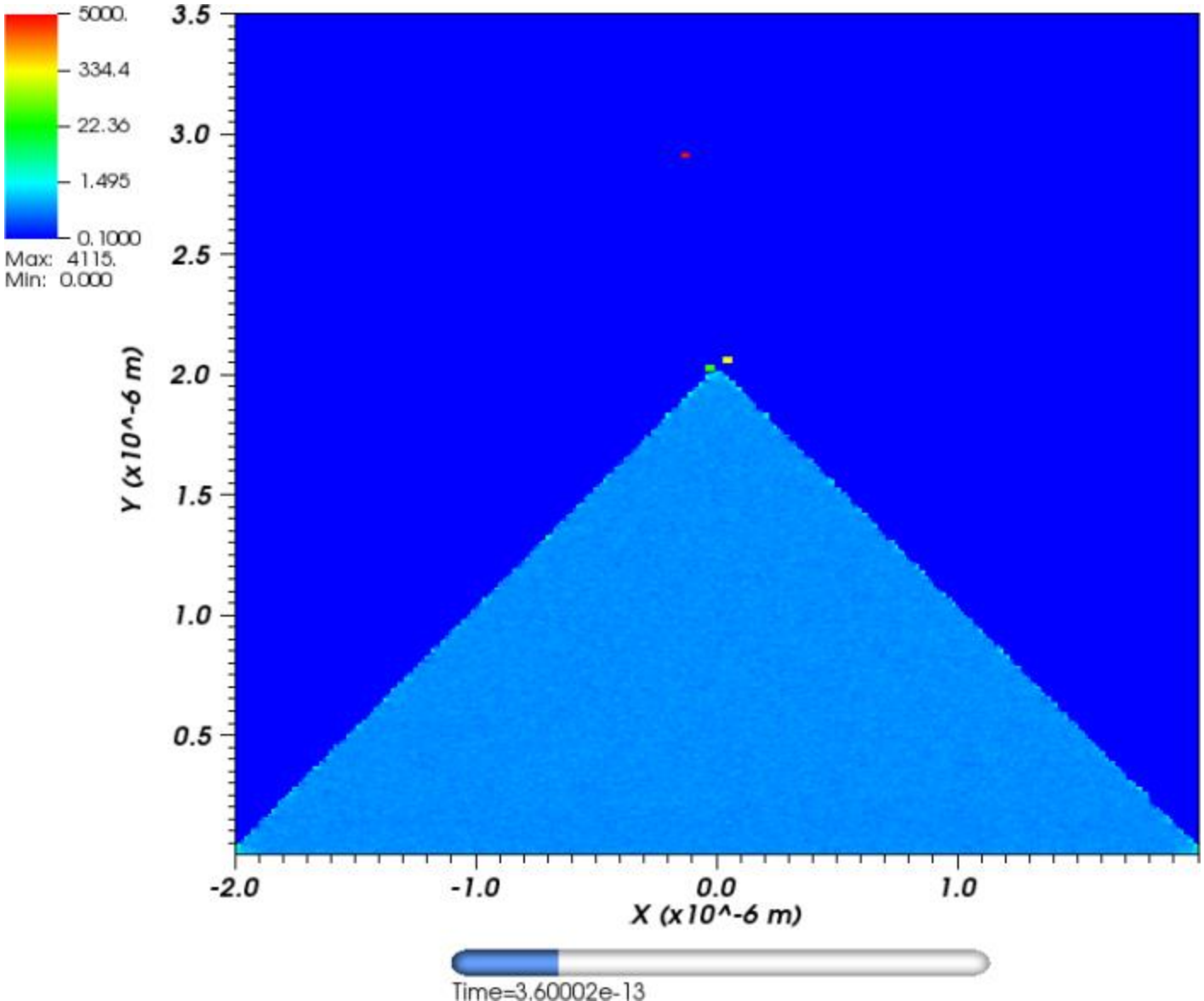
PIC - Electron Energy Pt.II



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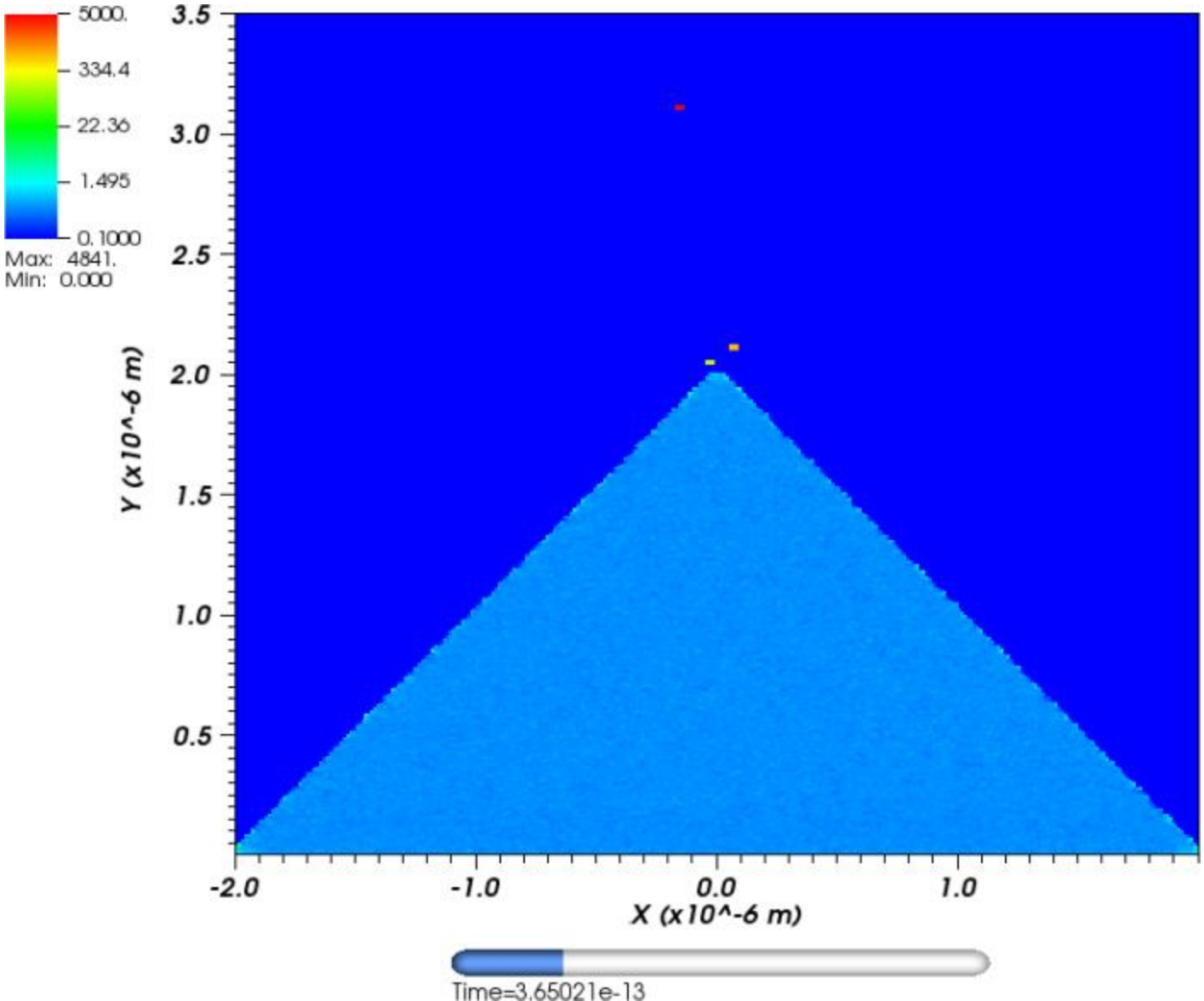
PIC - Electron Energy Pt.II



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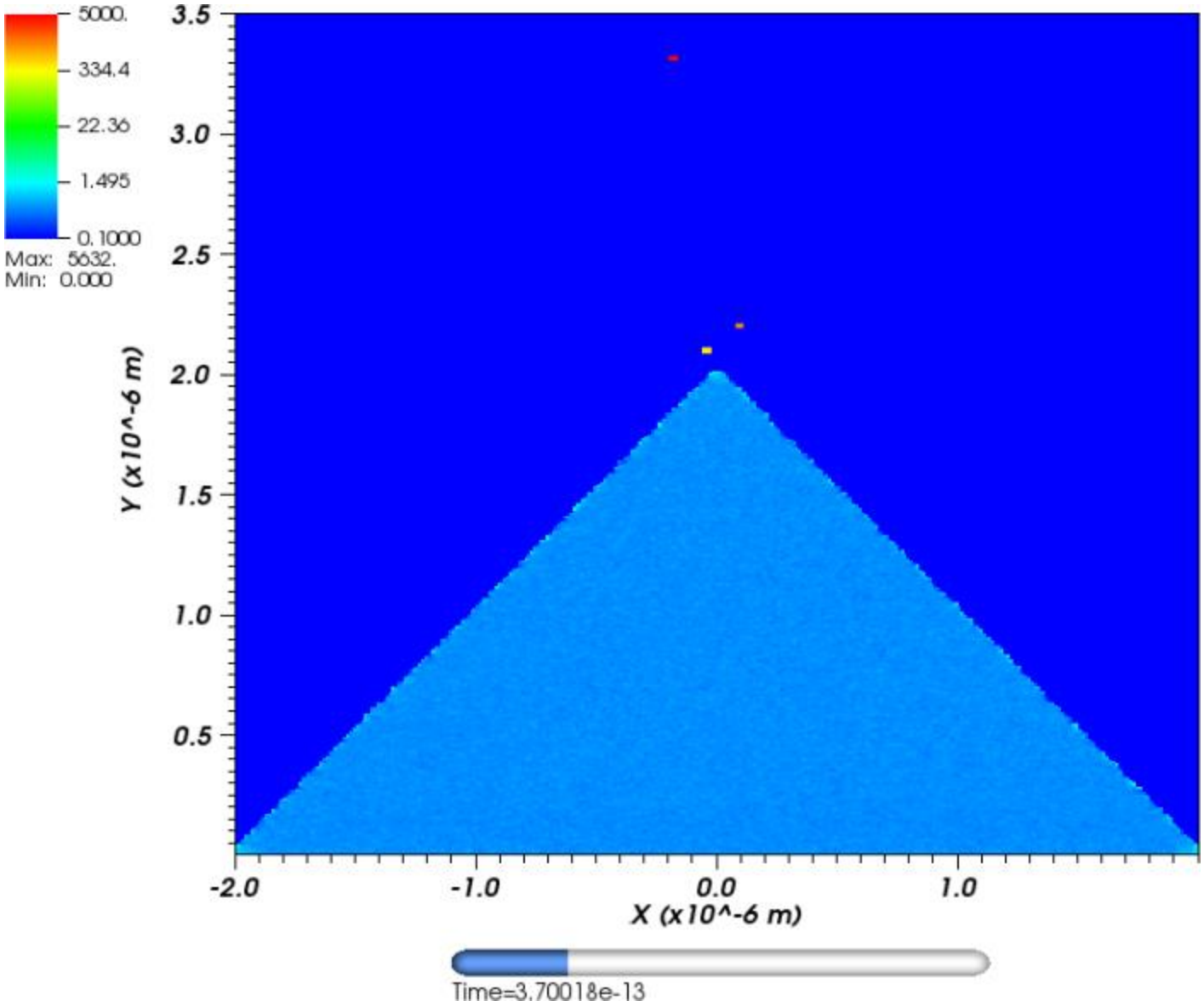

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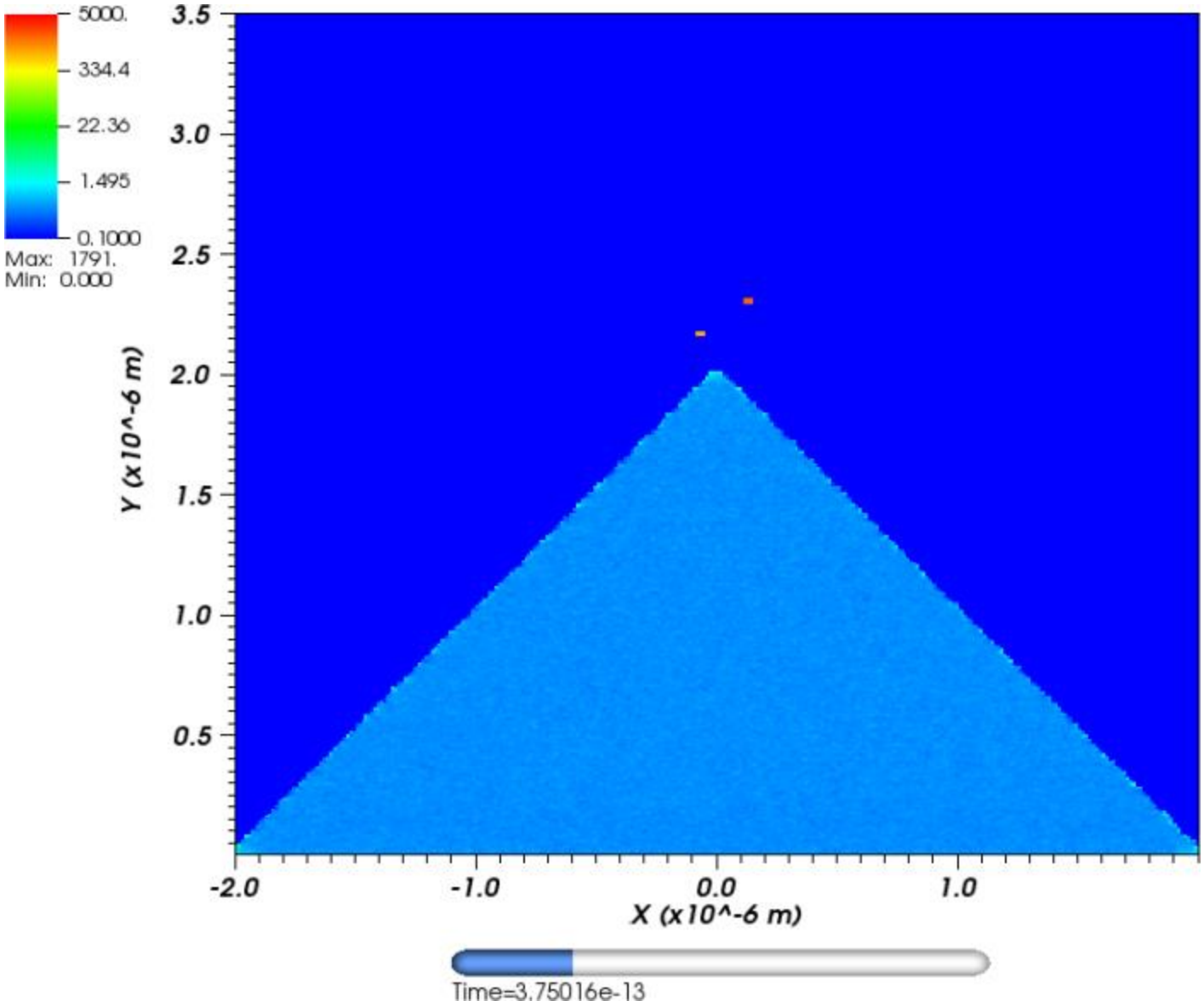

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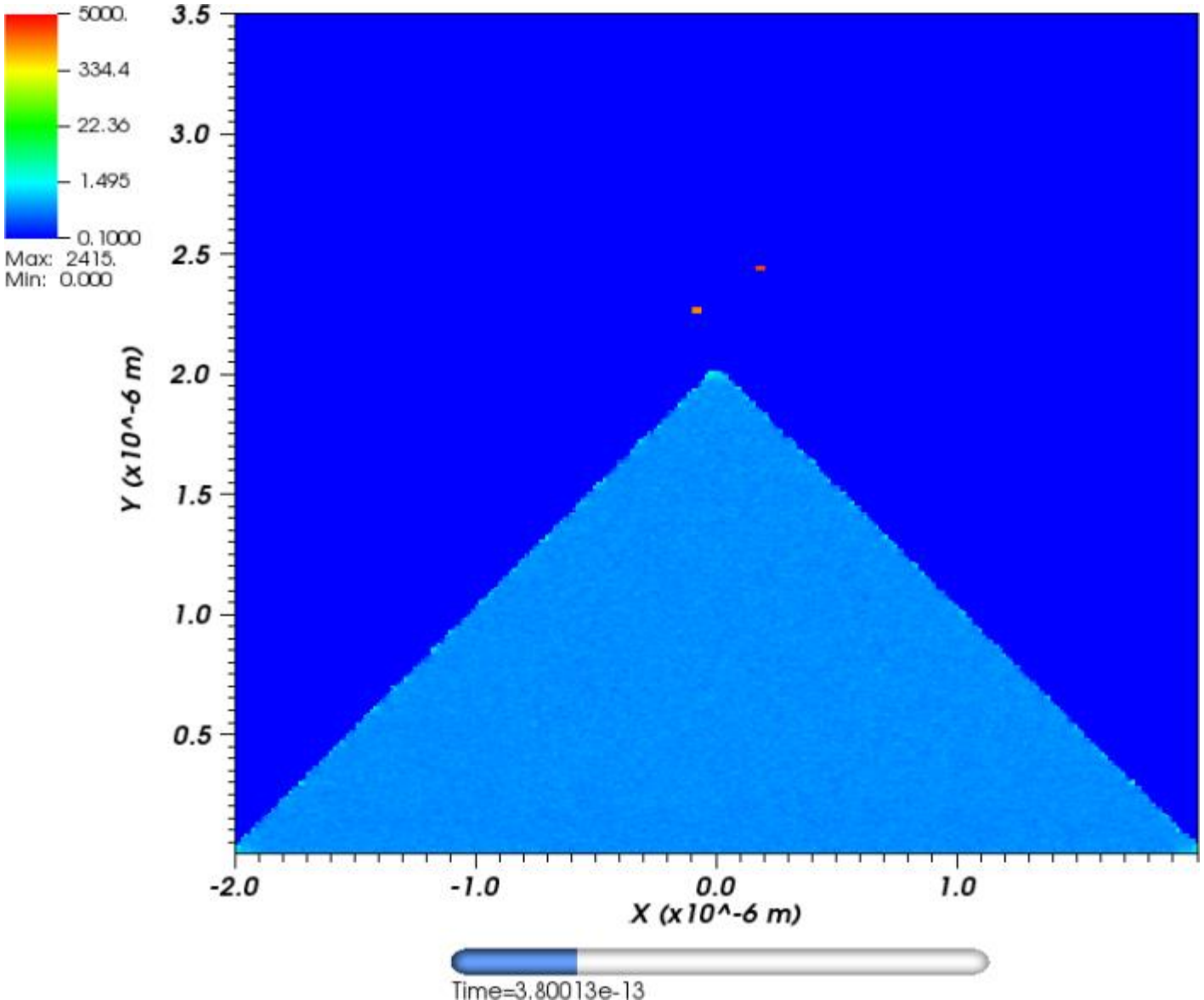

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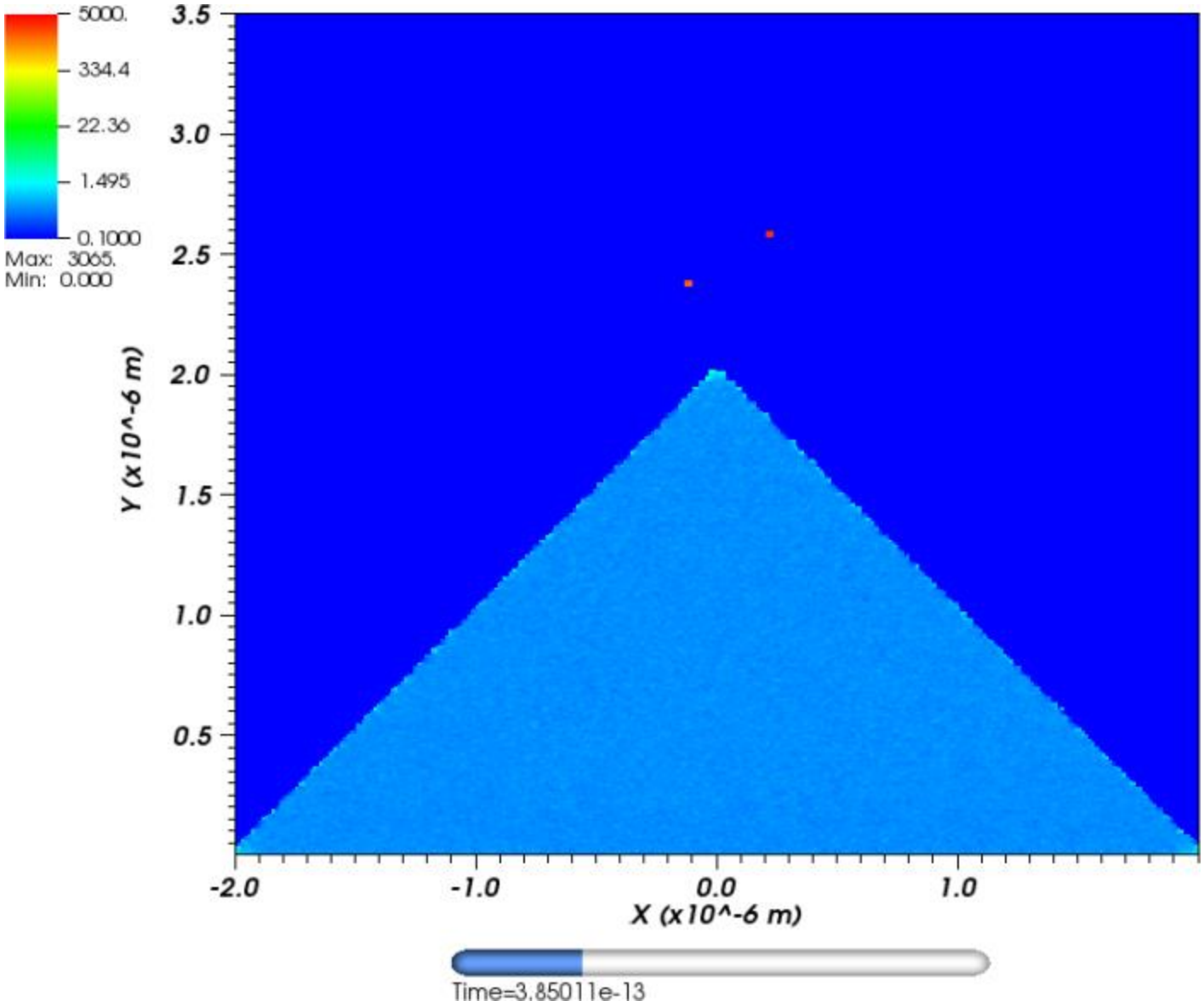

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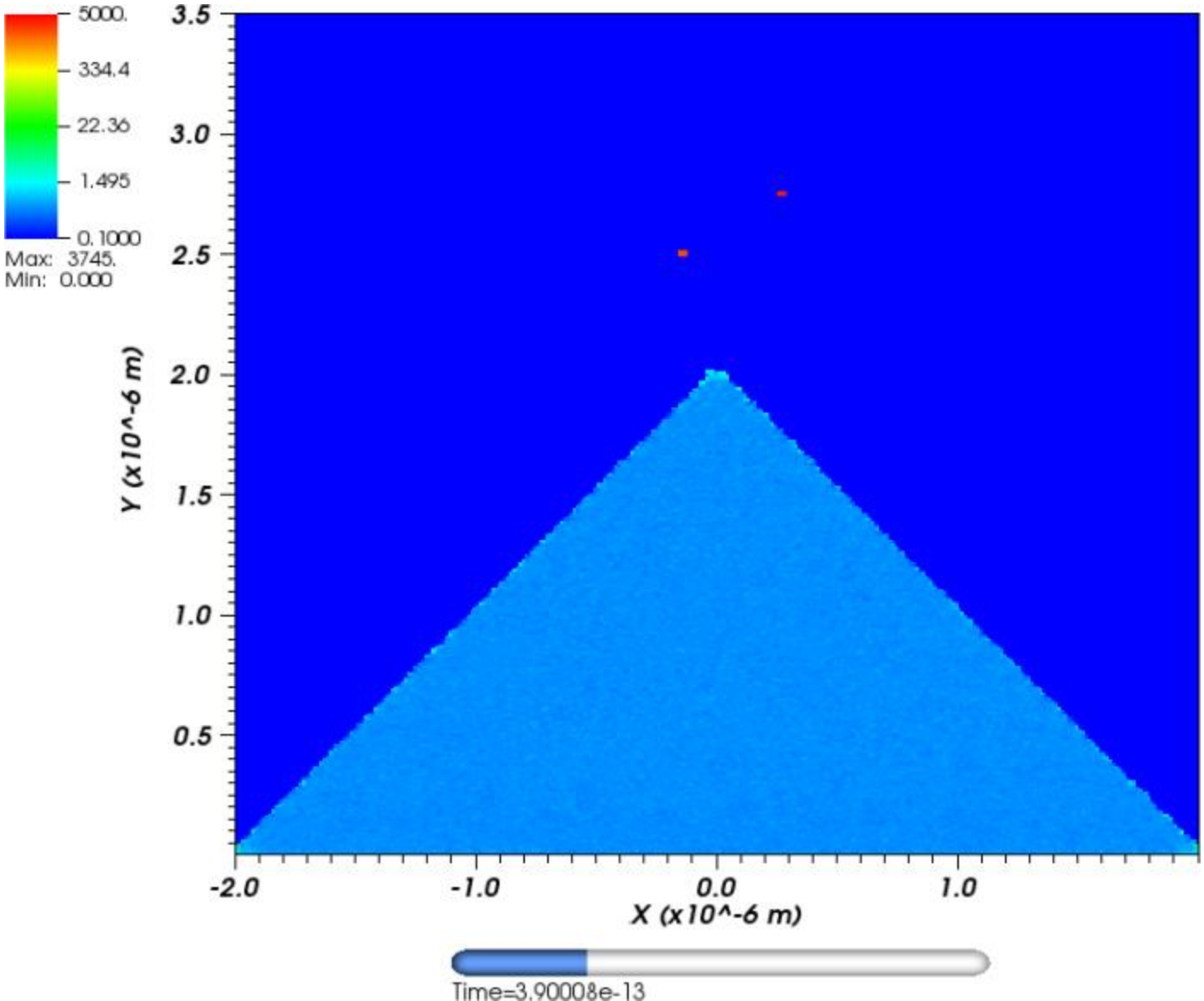

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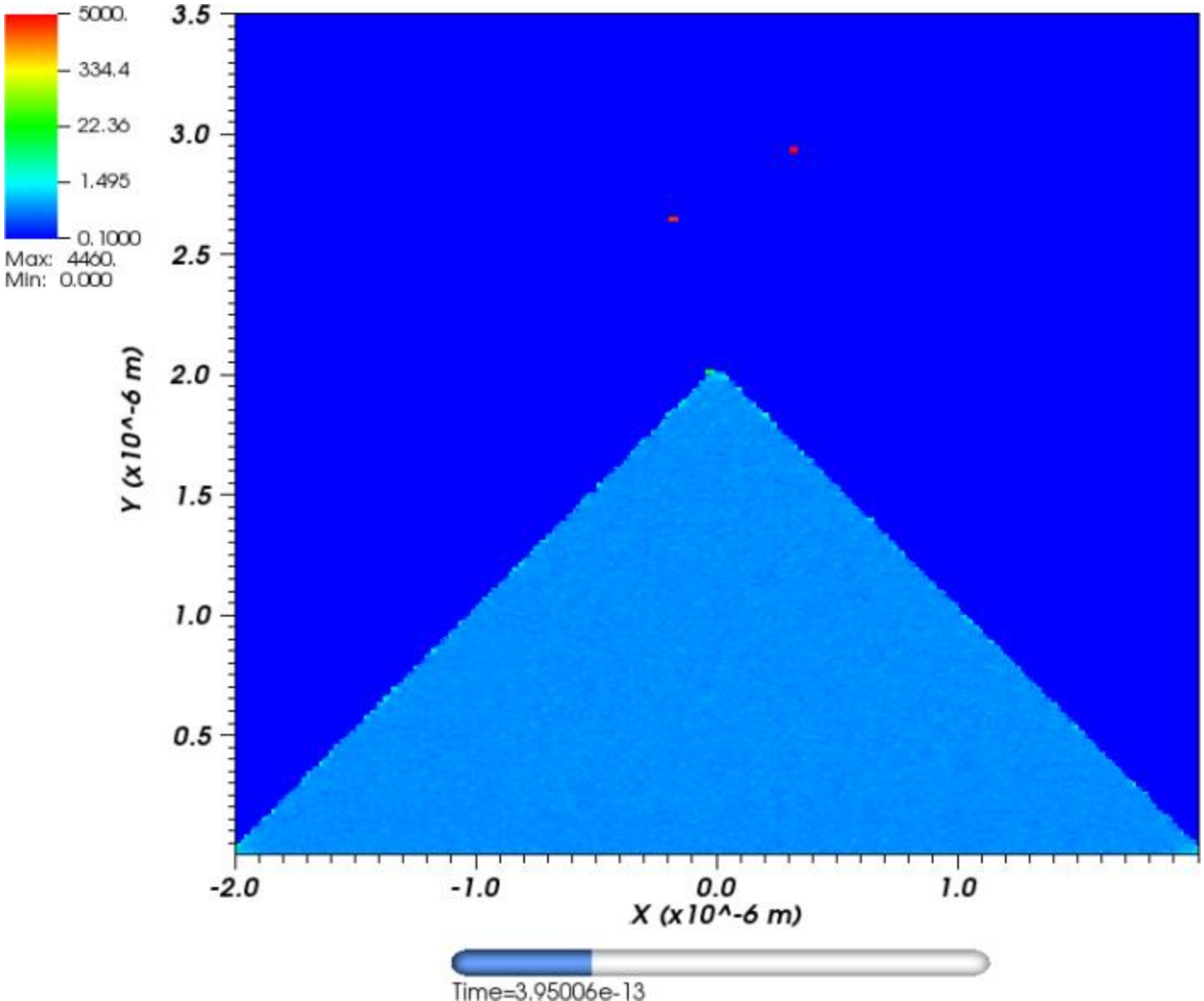

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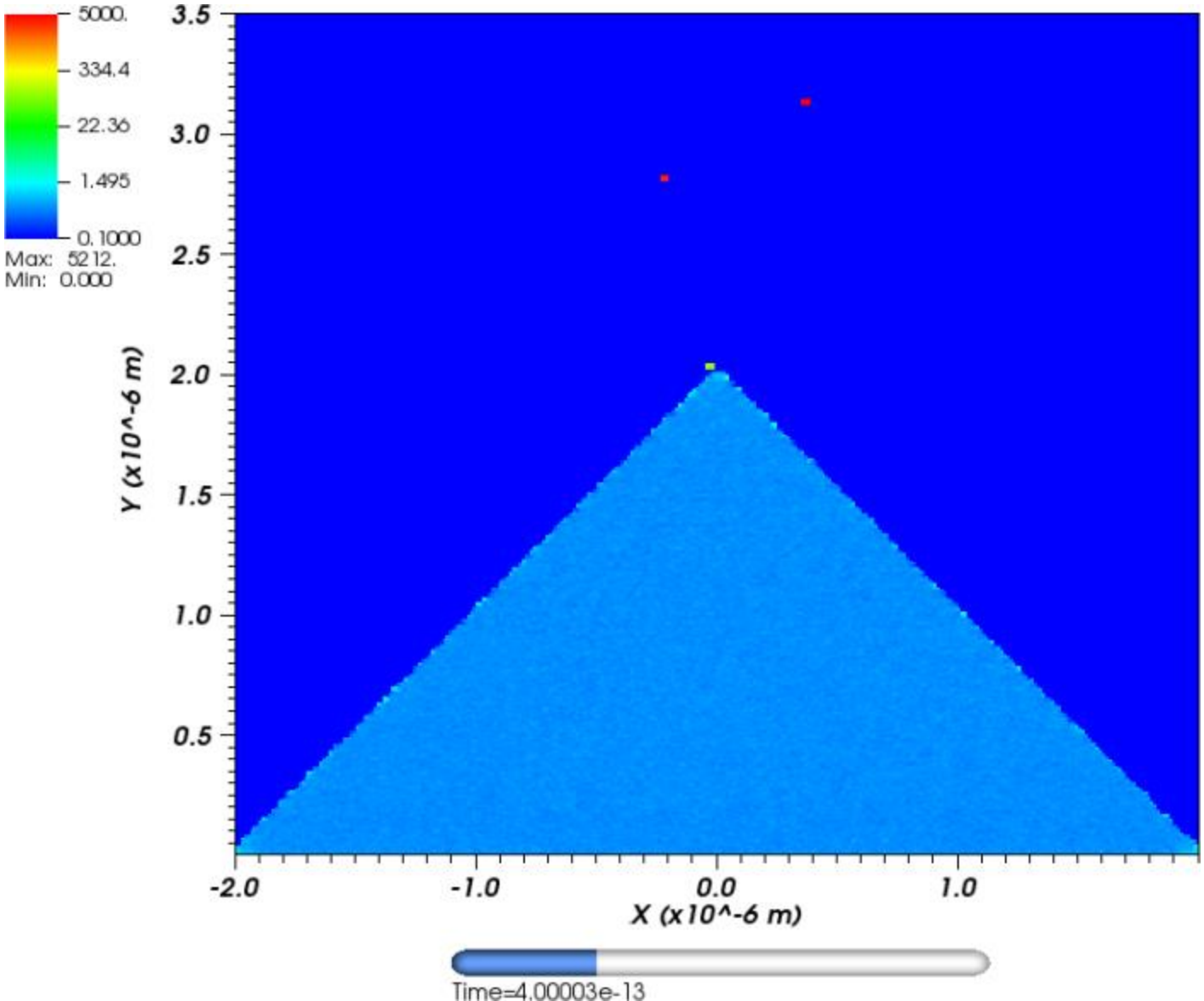

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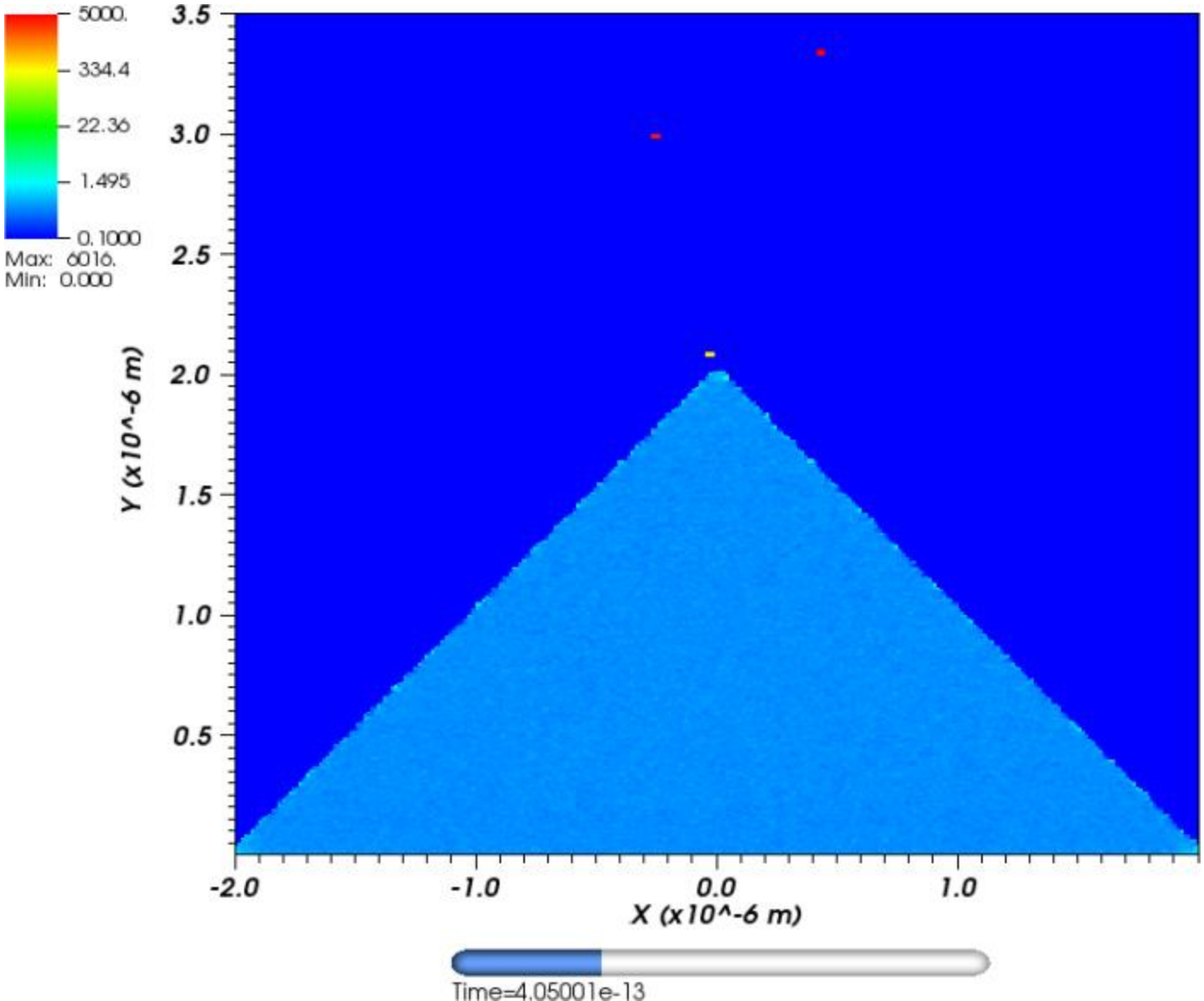

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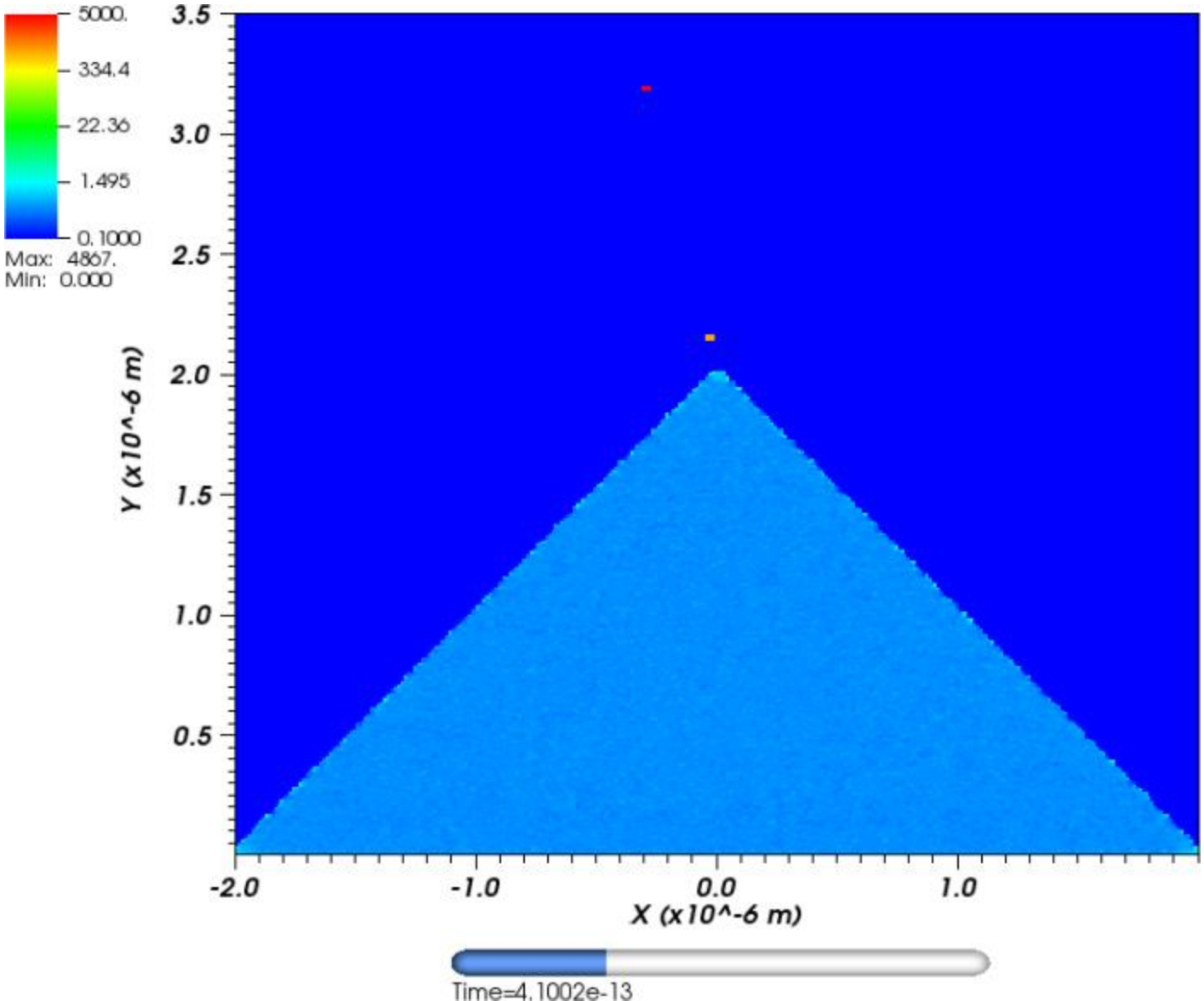

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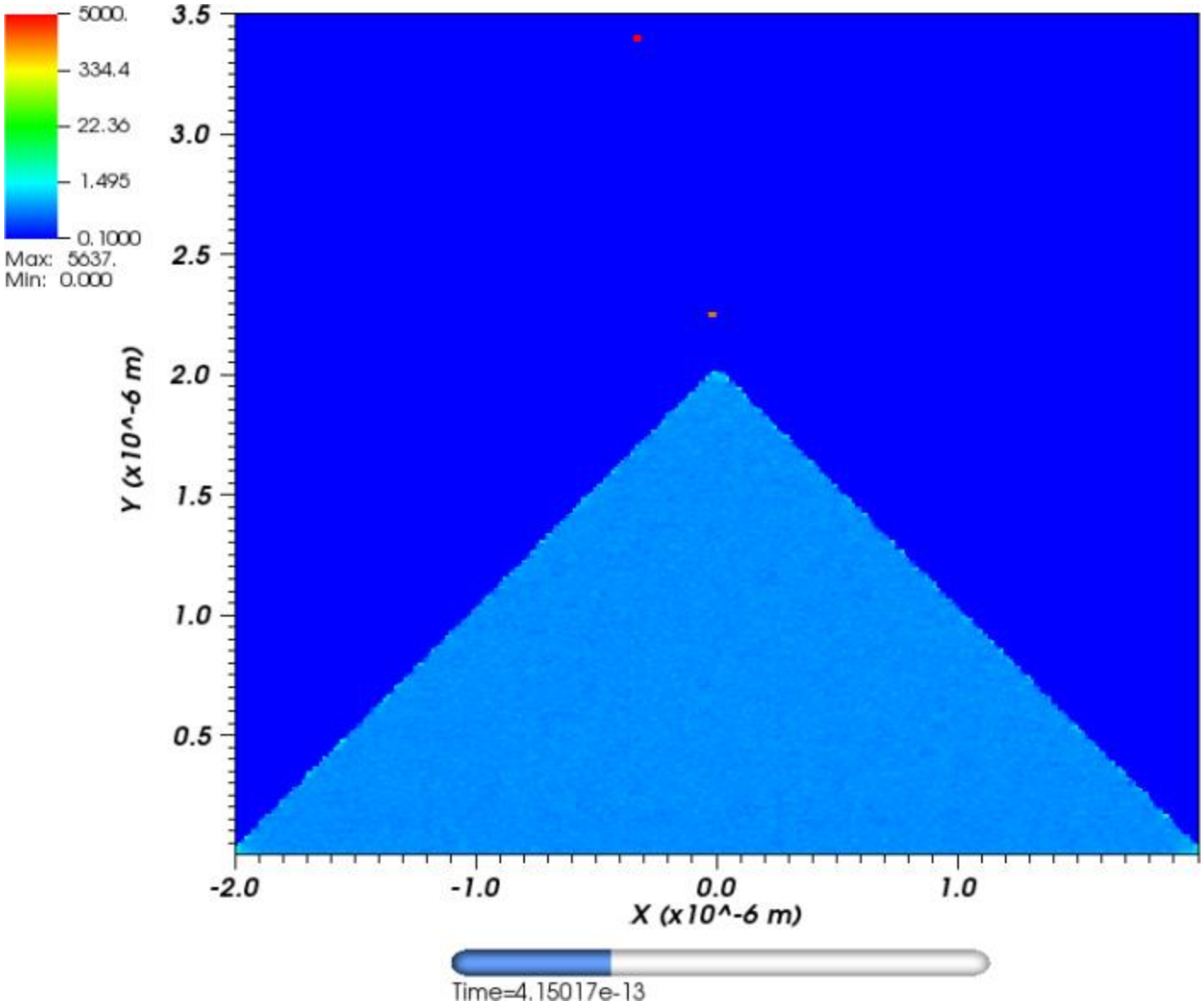

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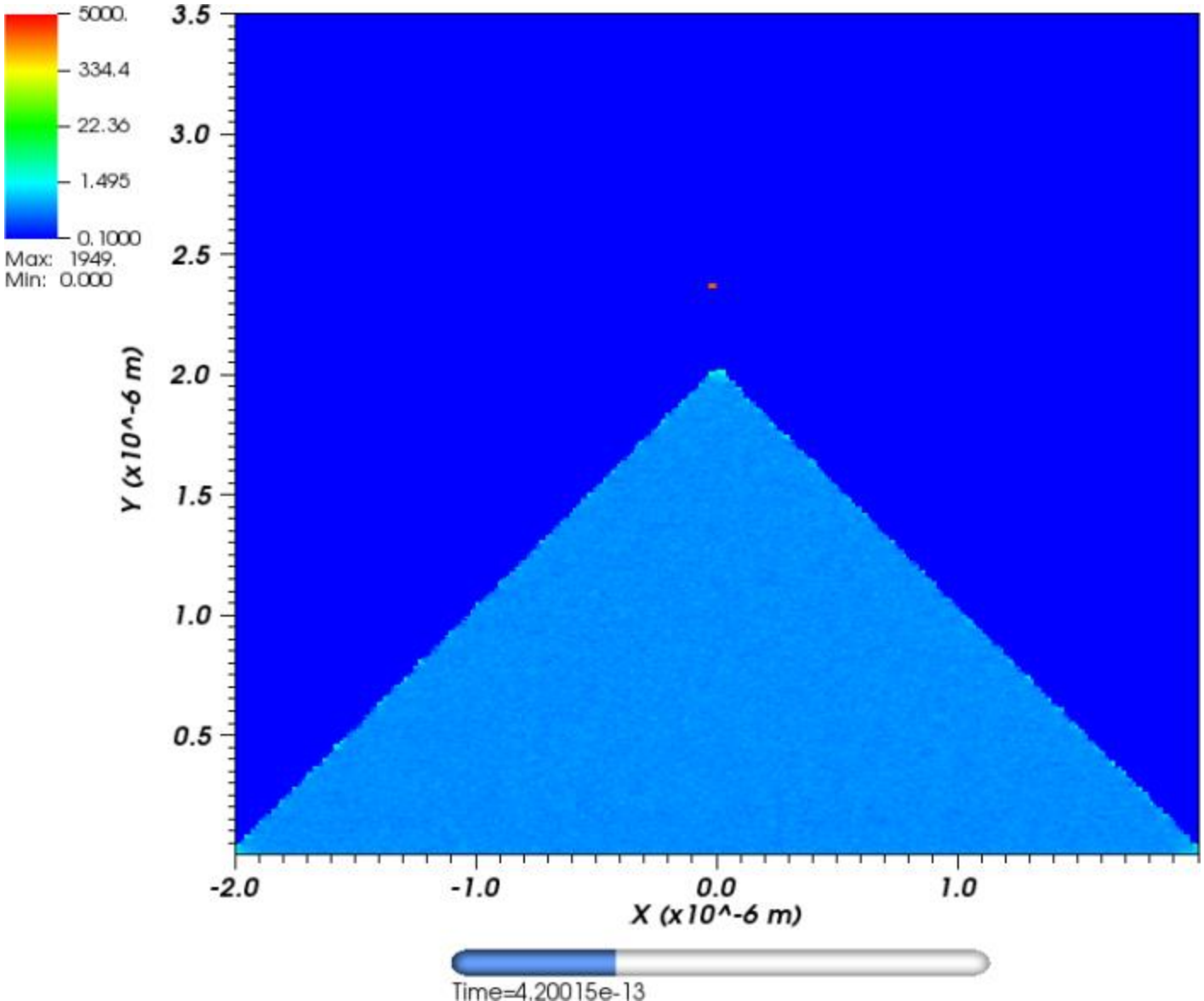

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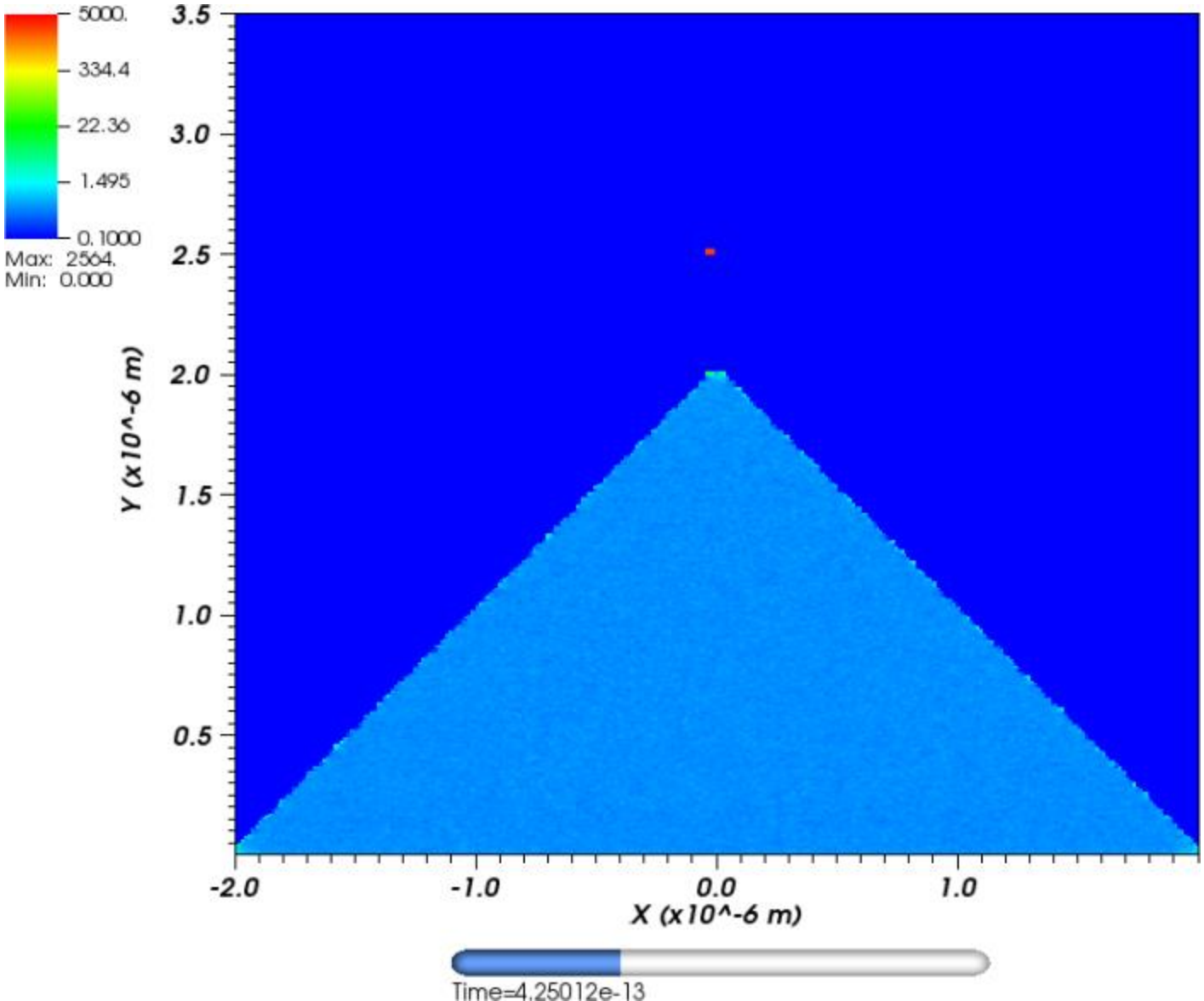

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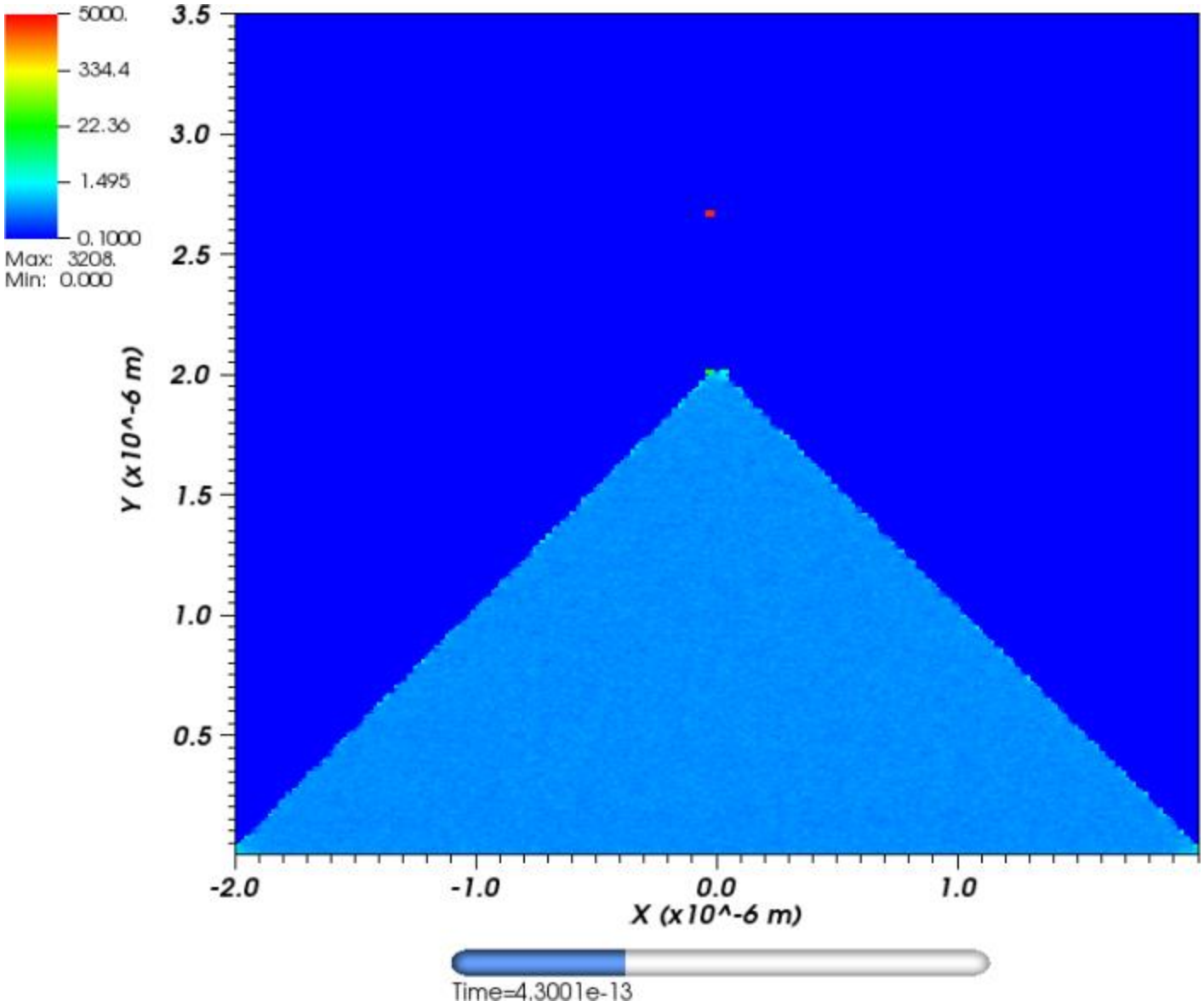

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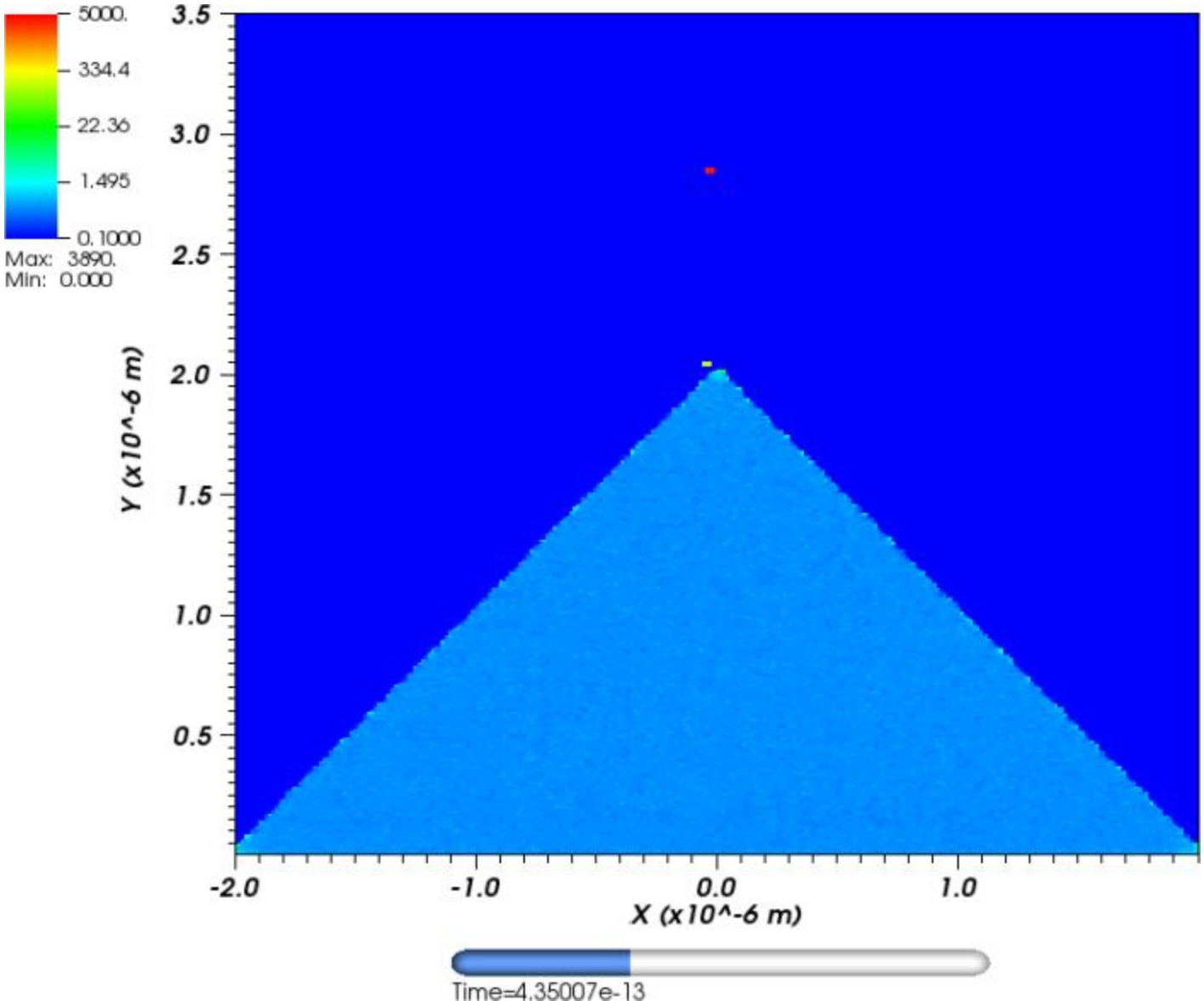

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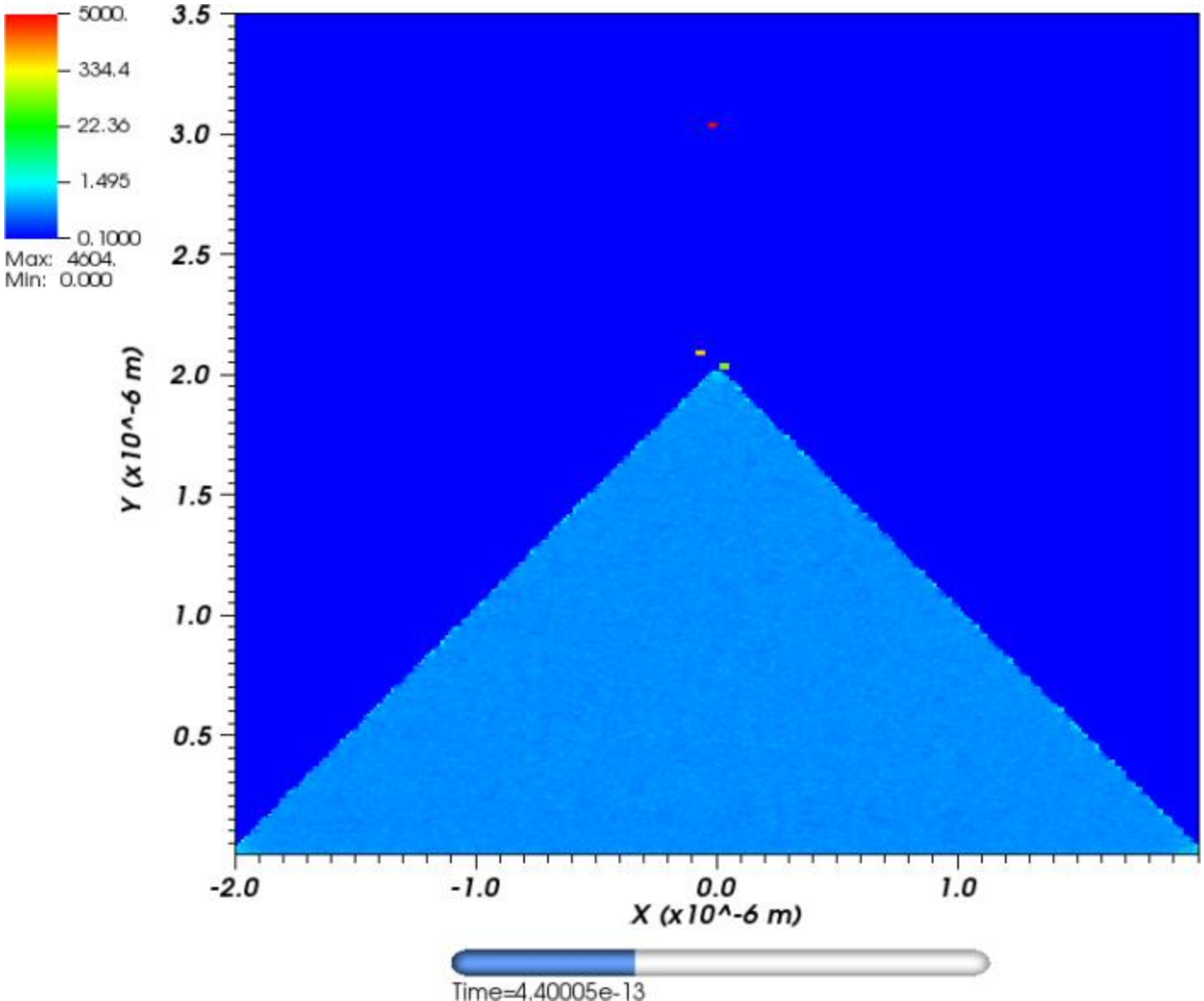

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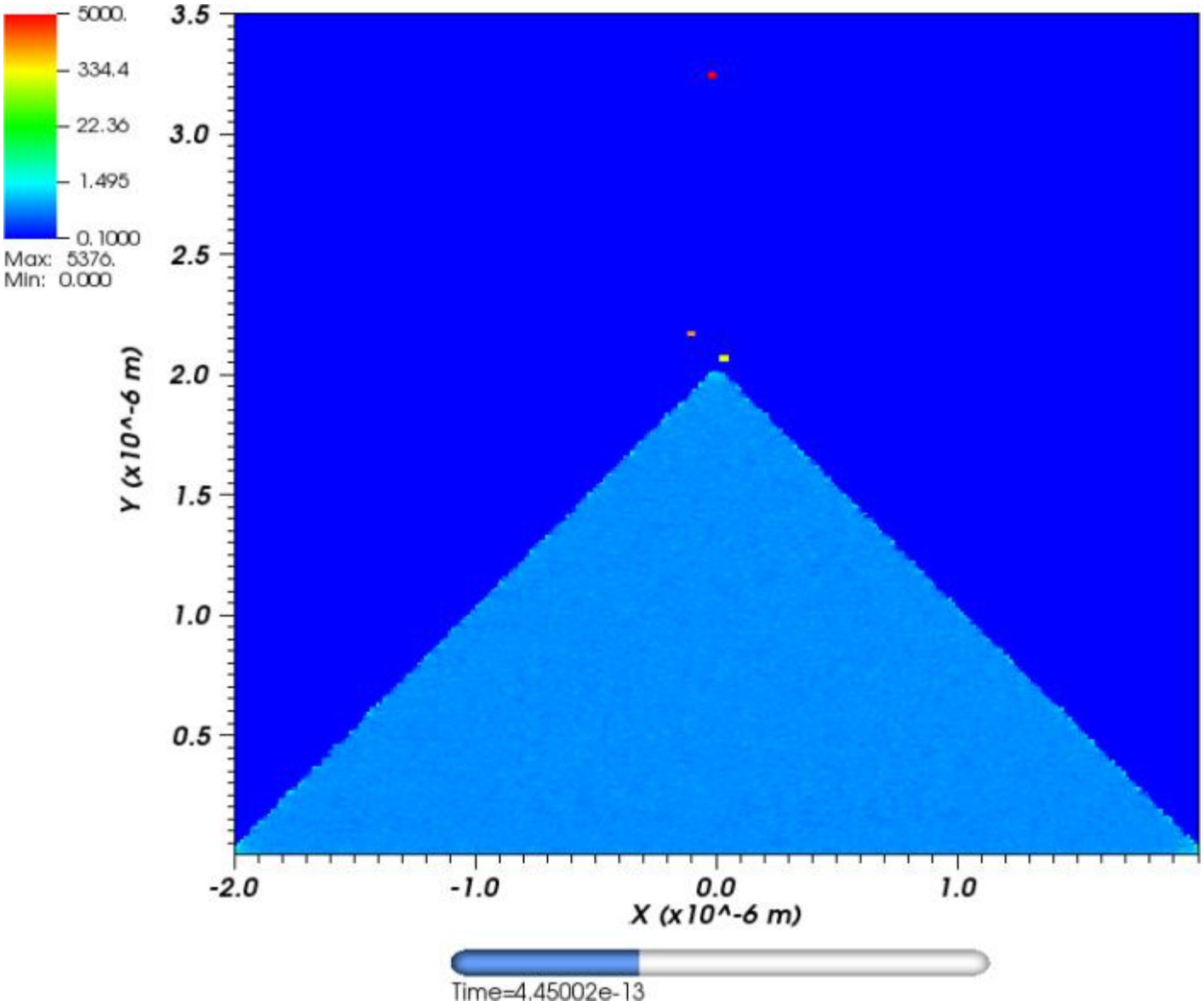

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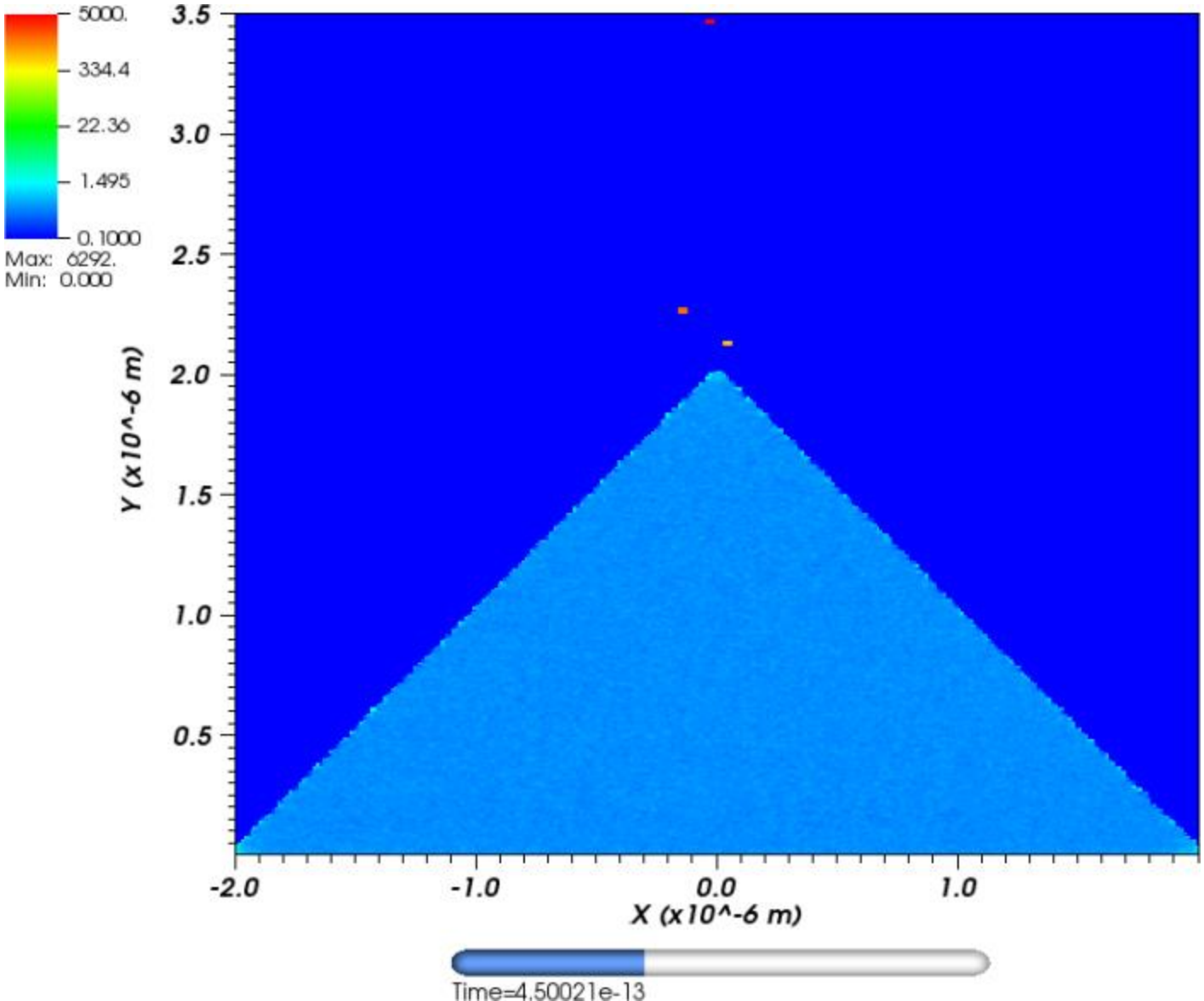

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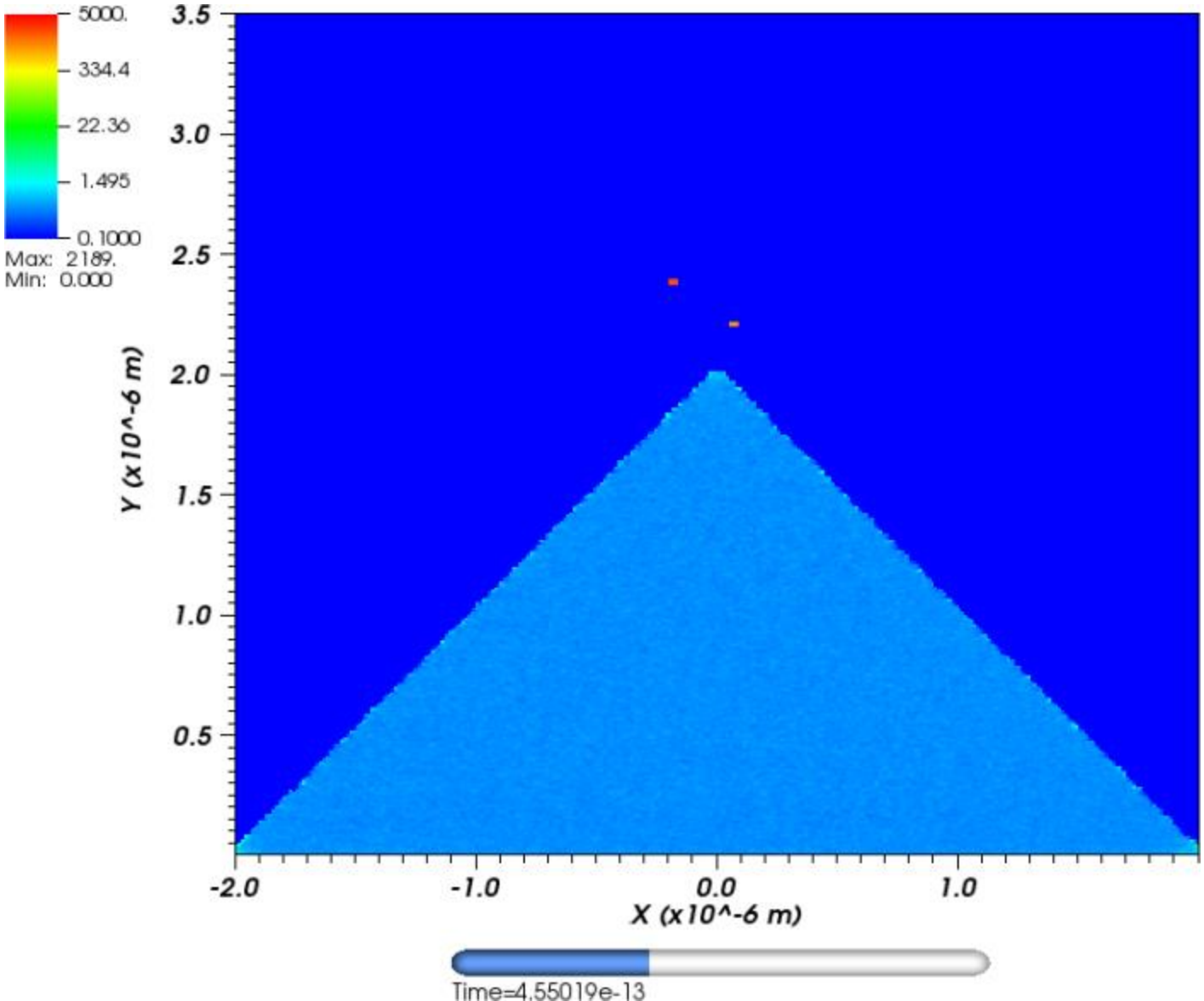

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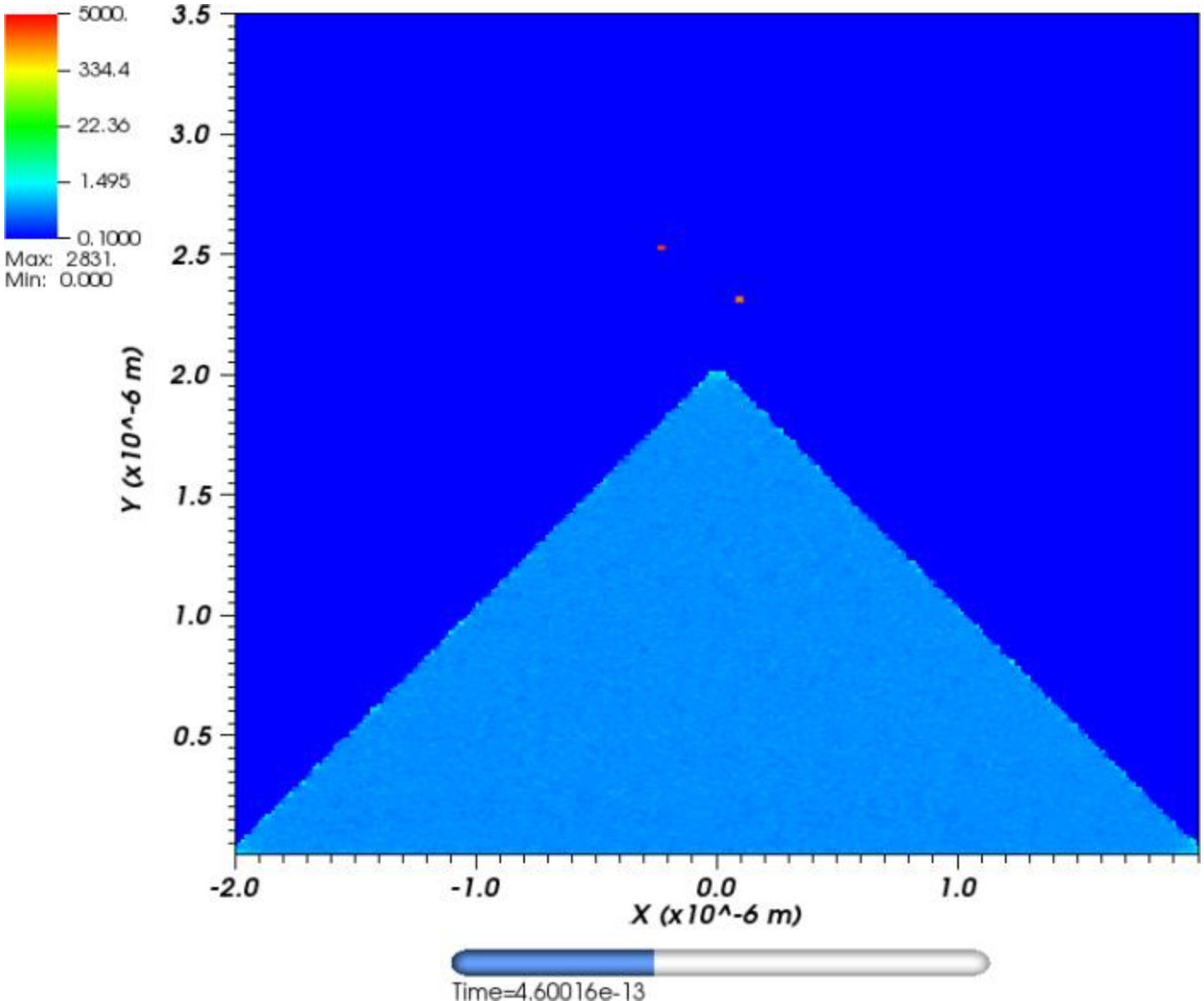

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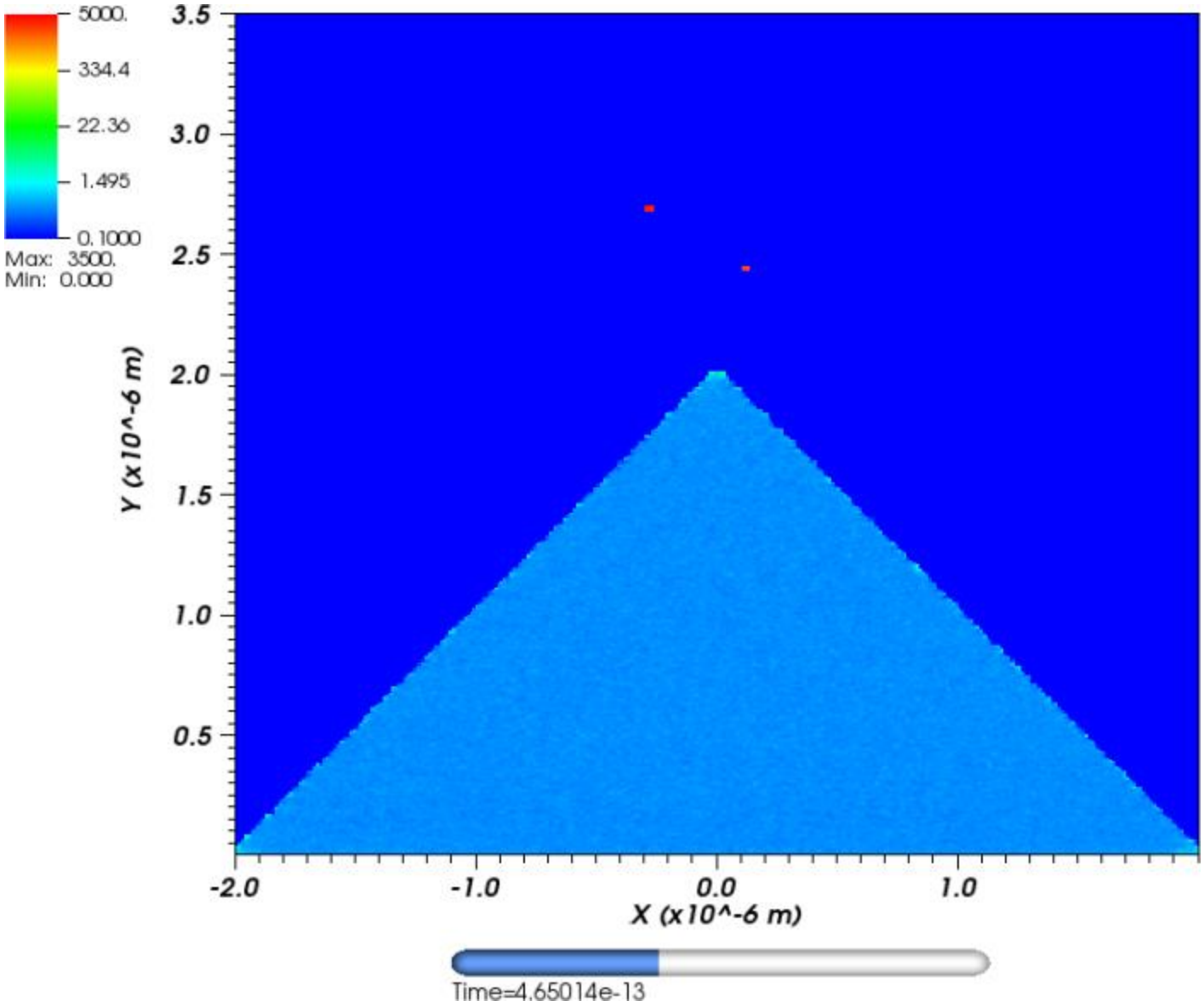

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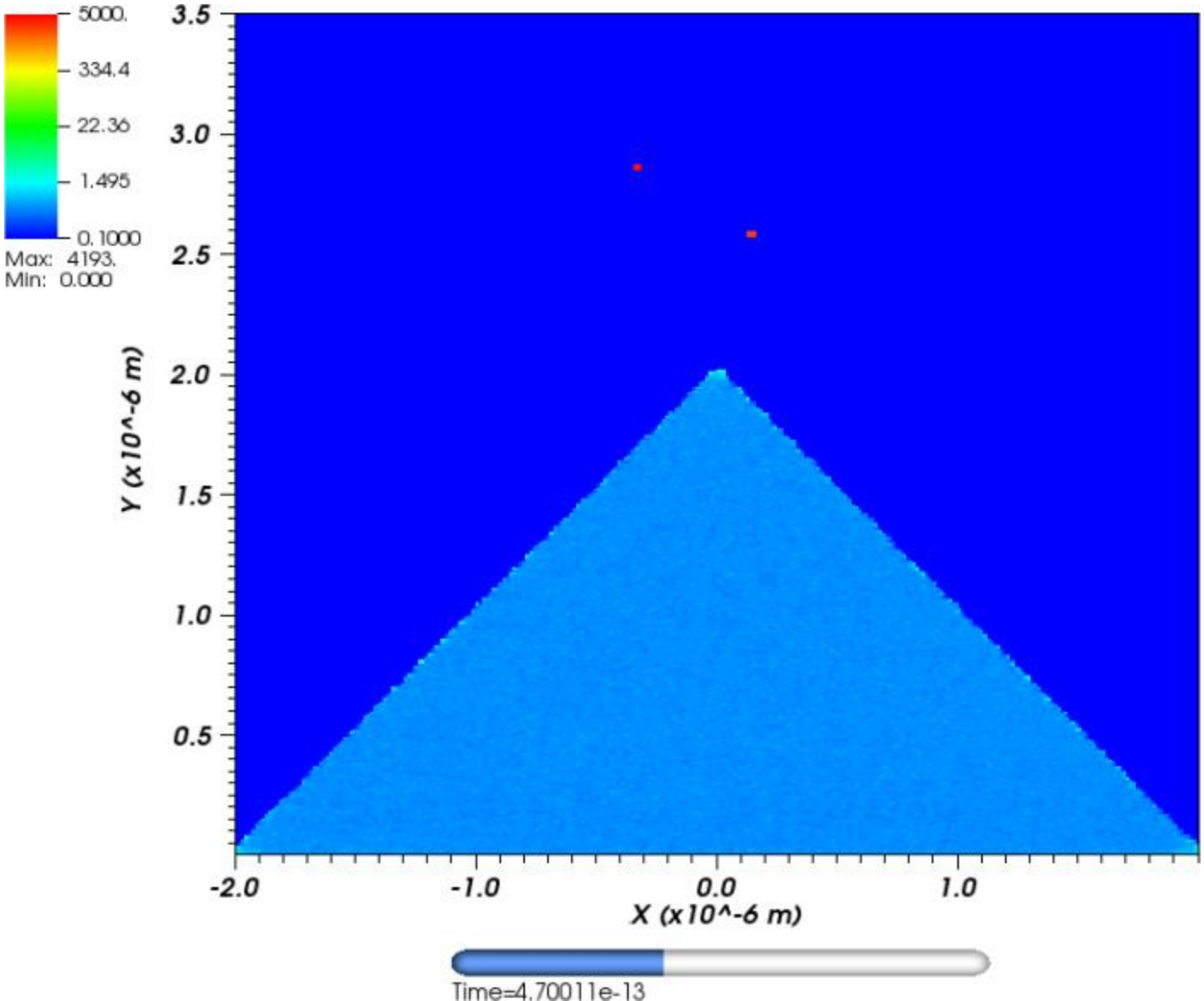

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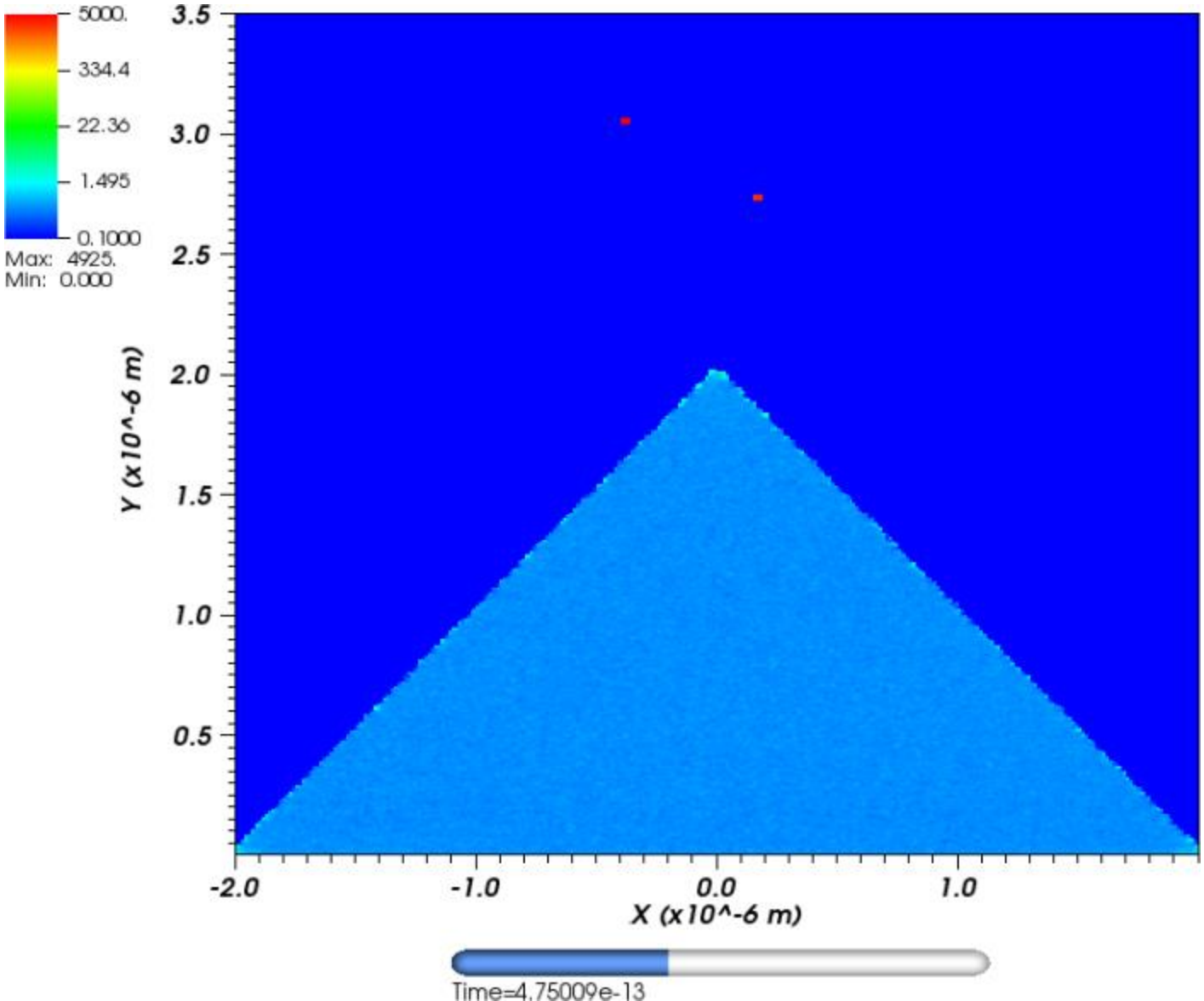

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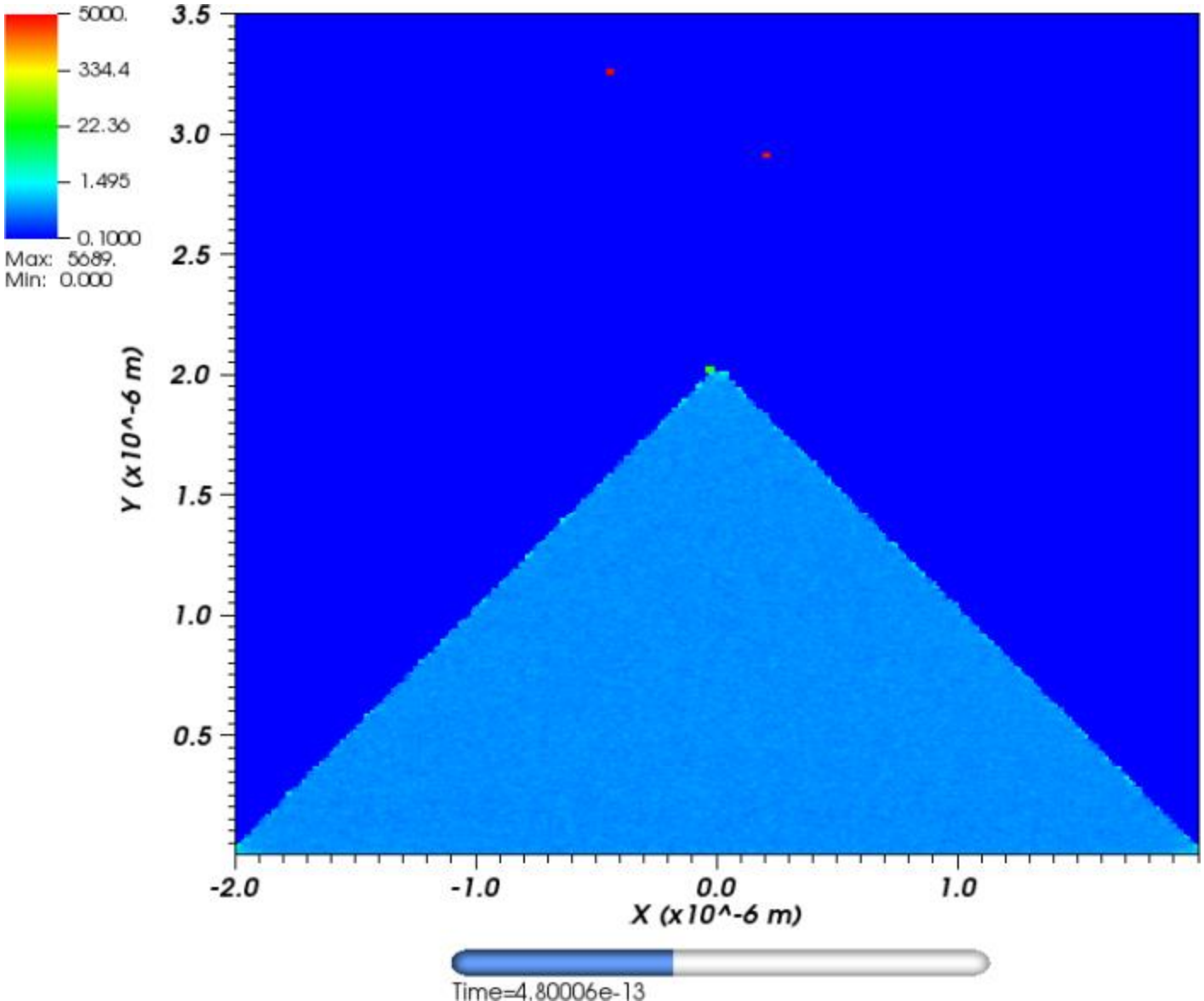

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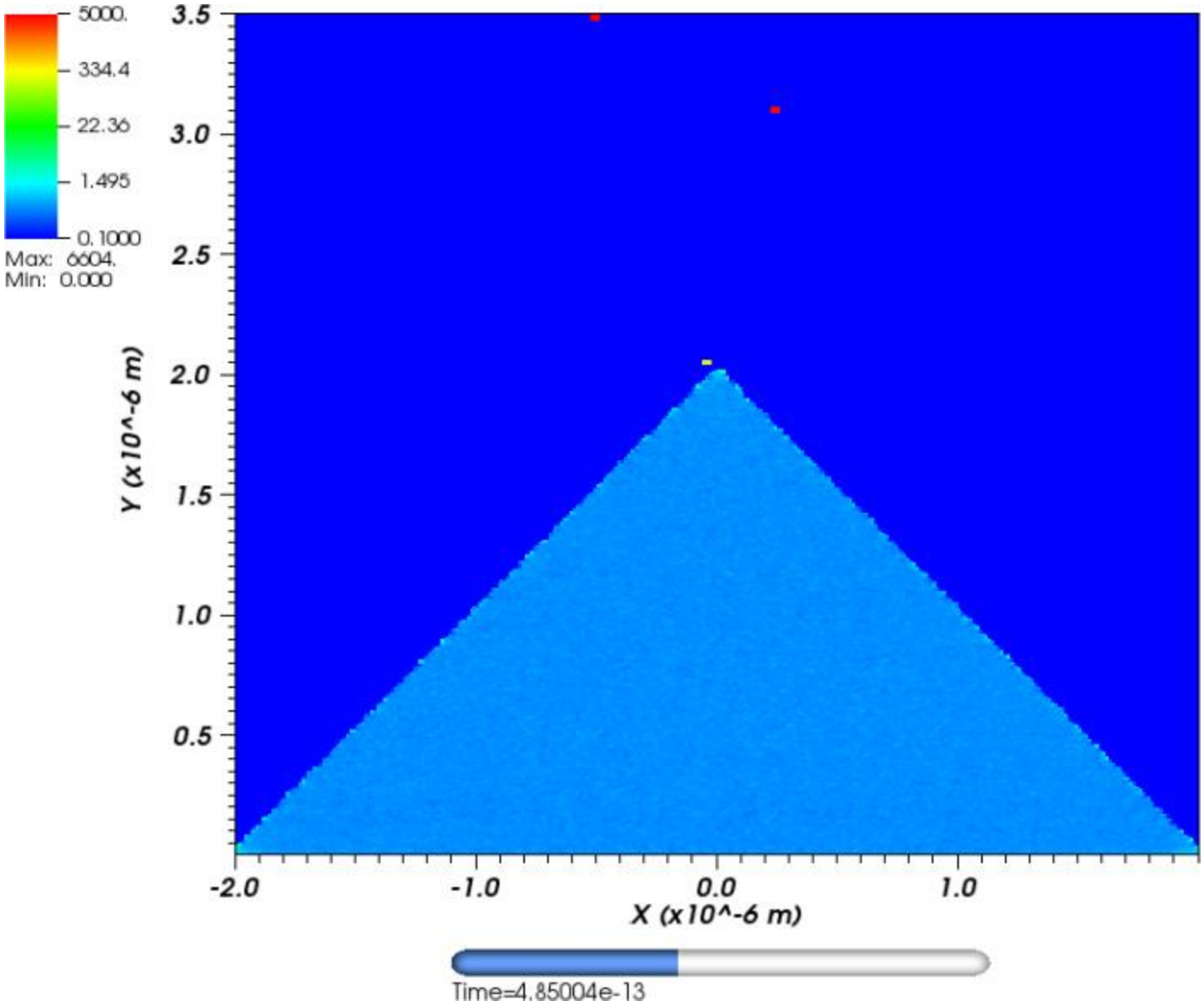

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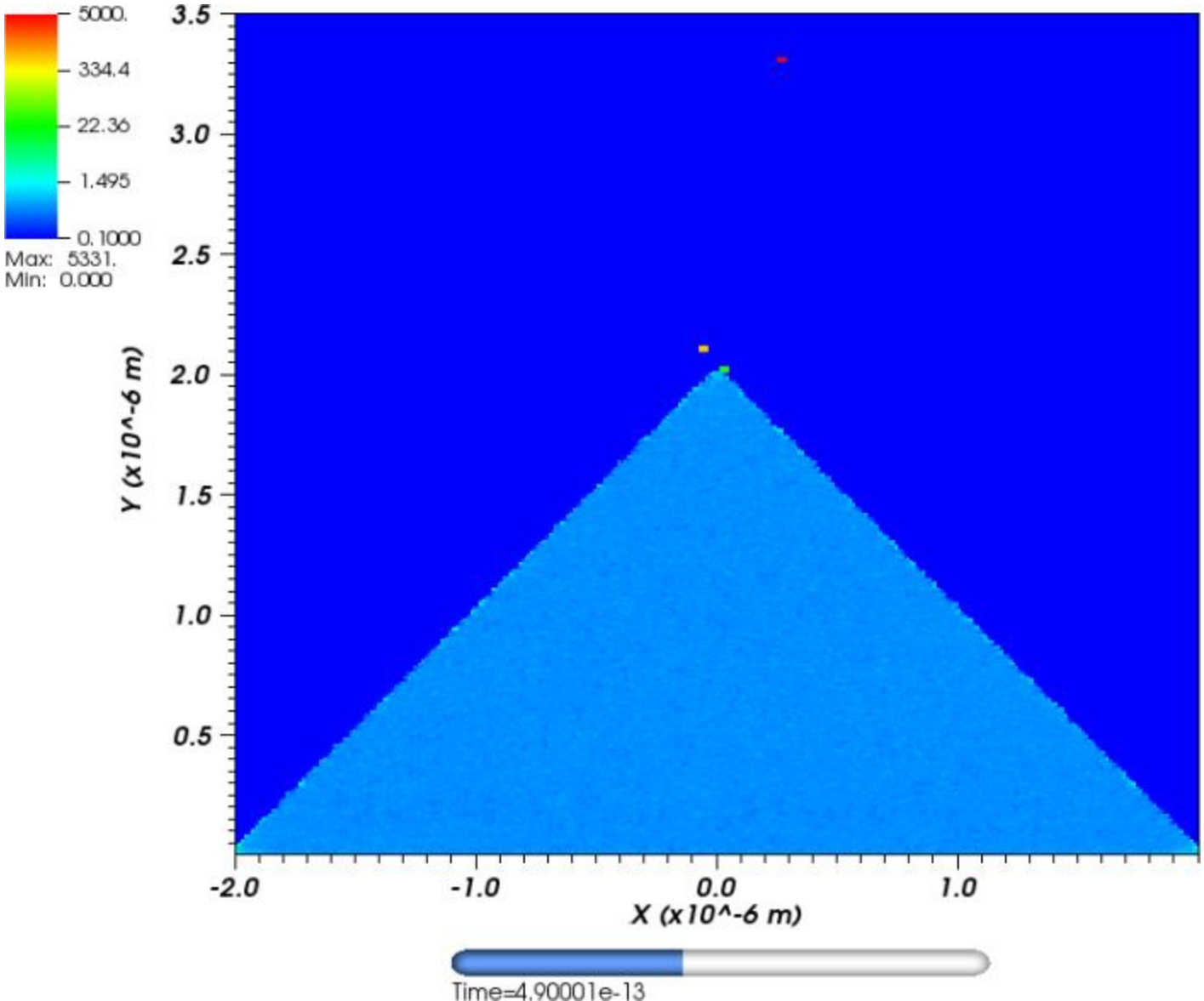

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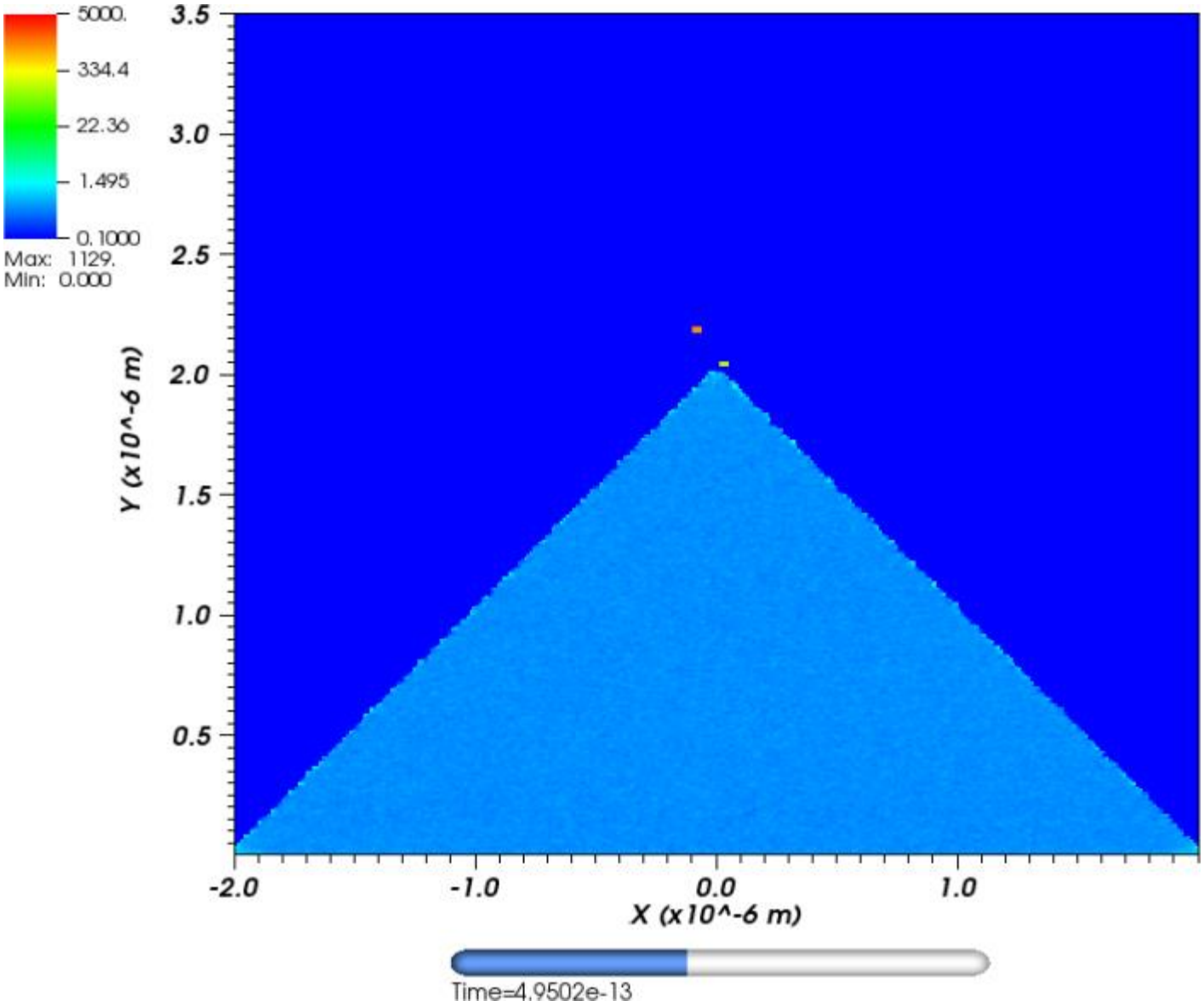

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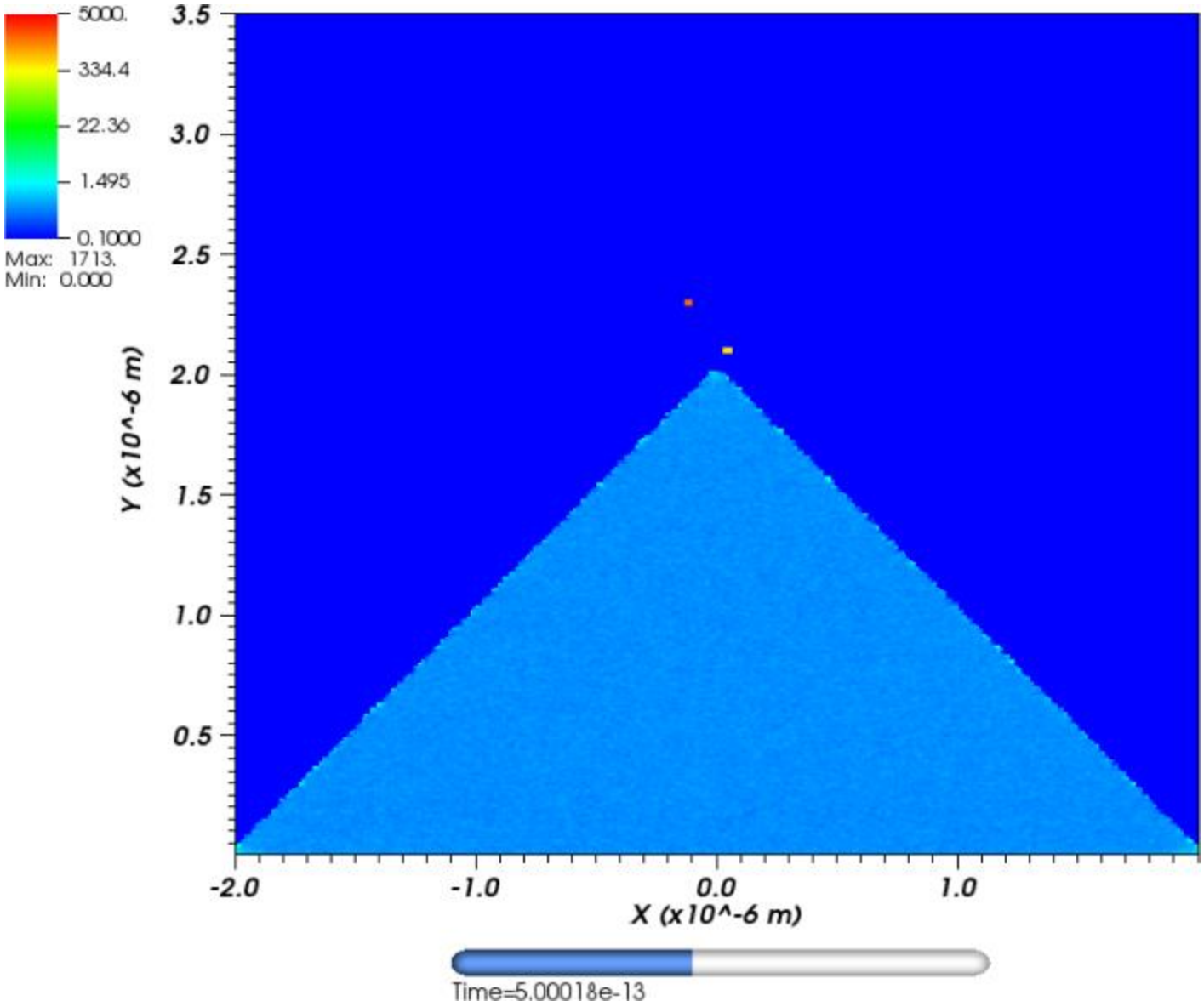

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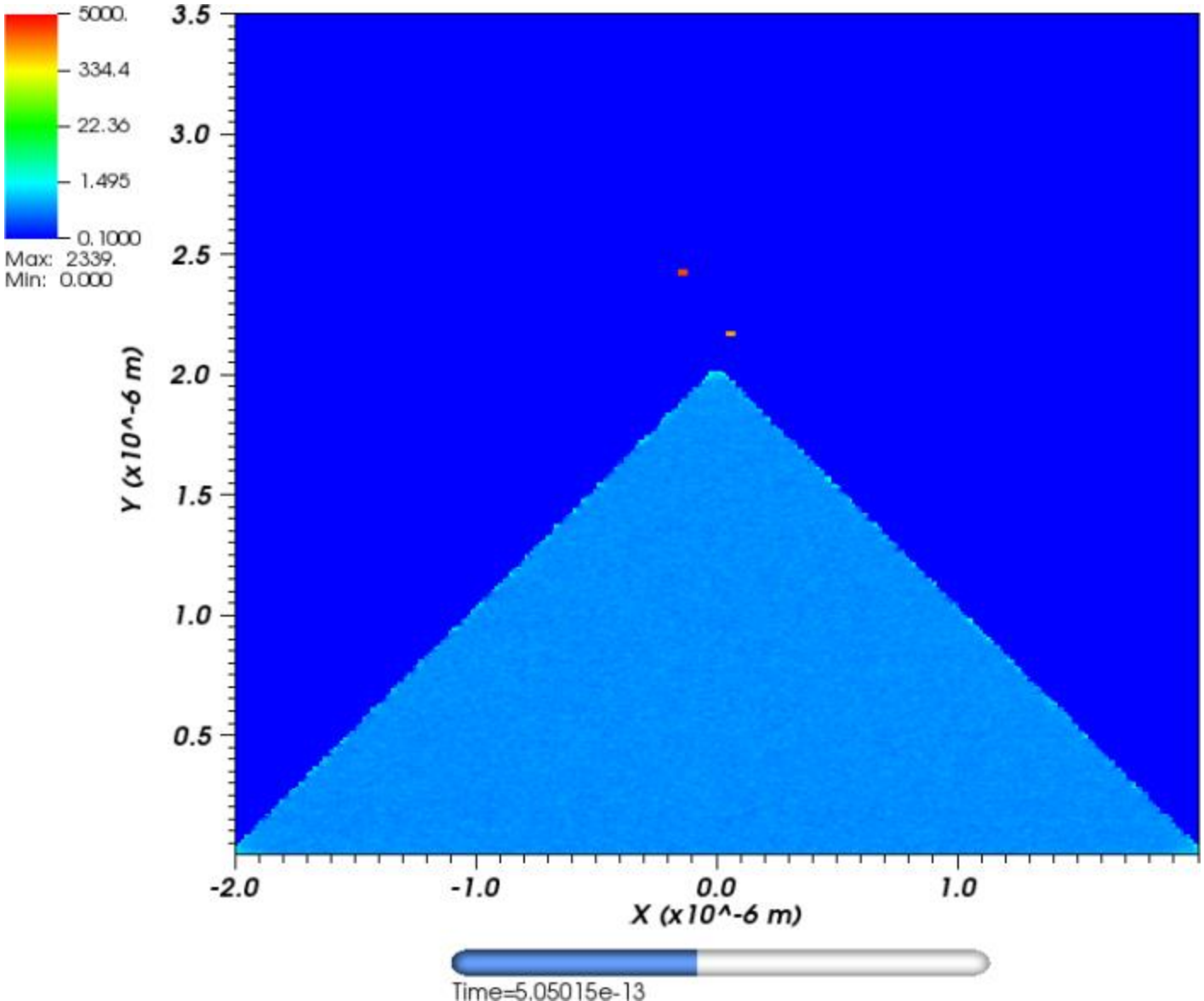

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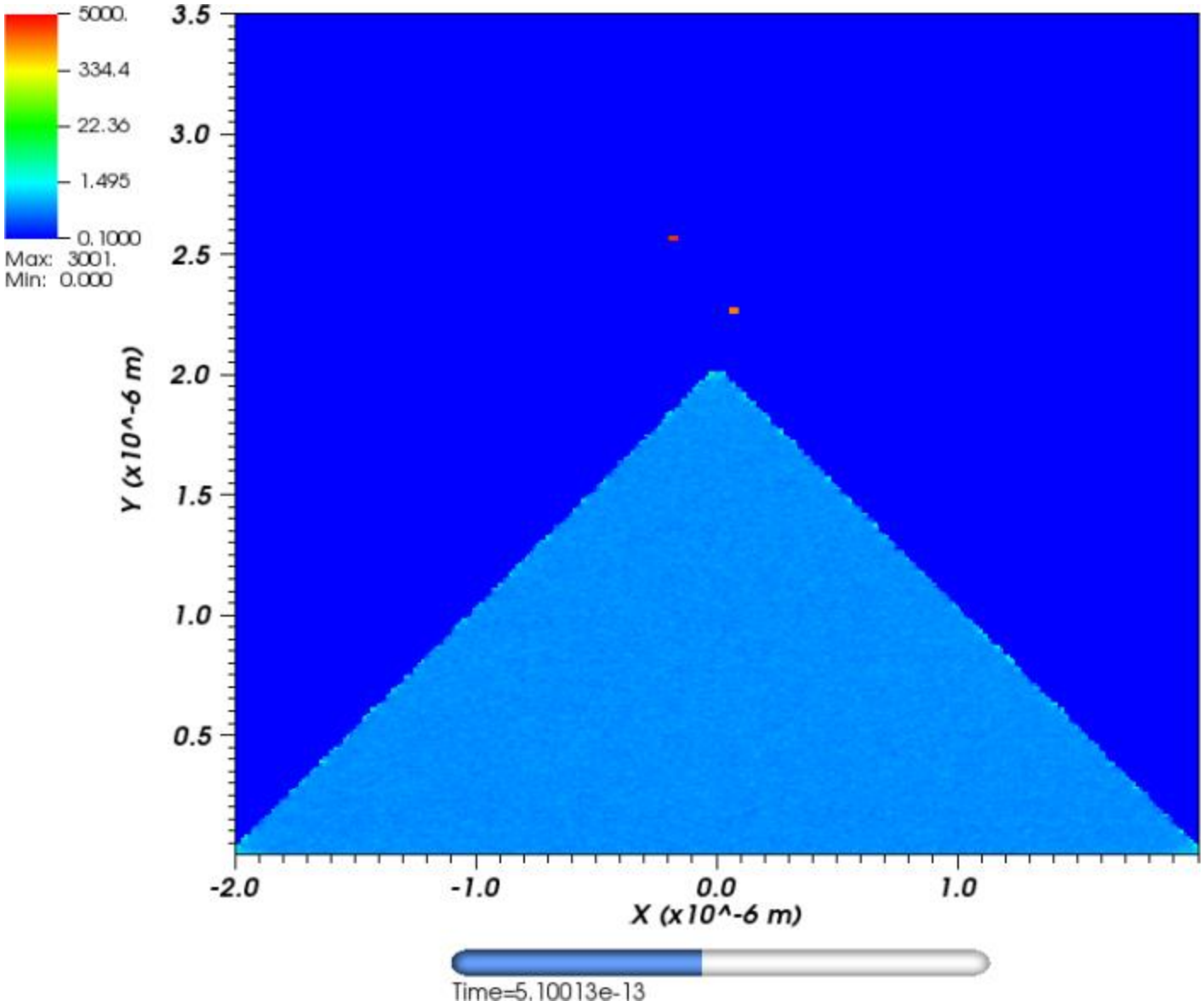

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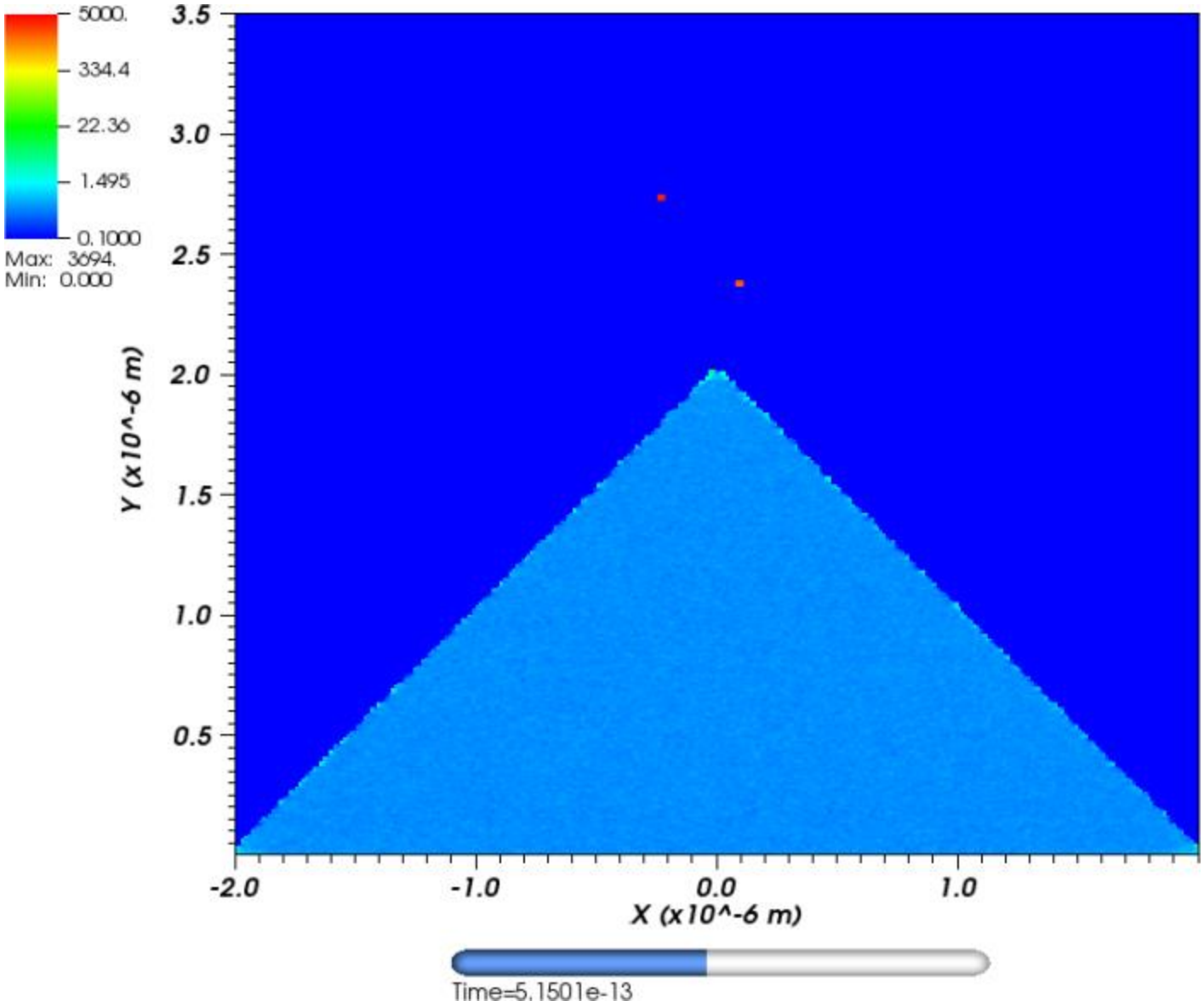

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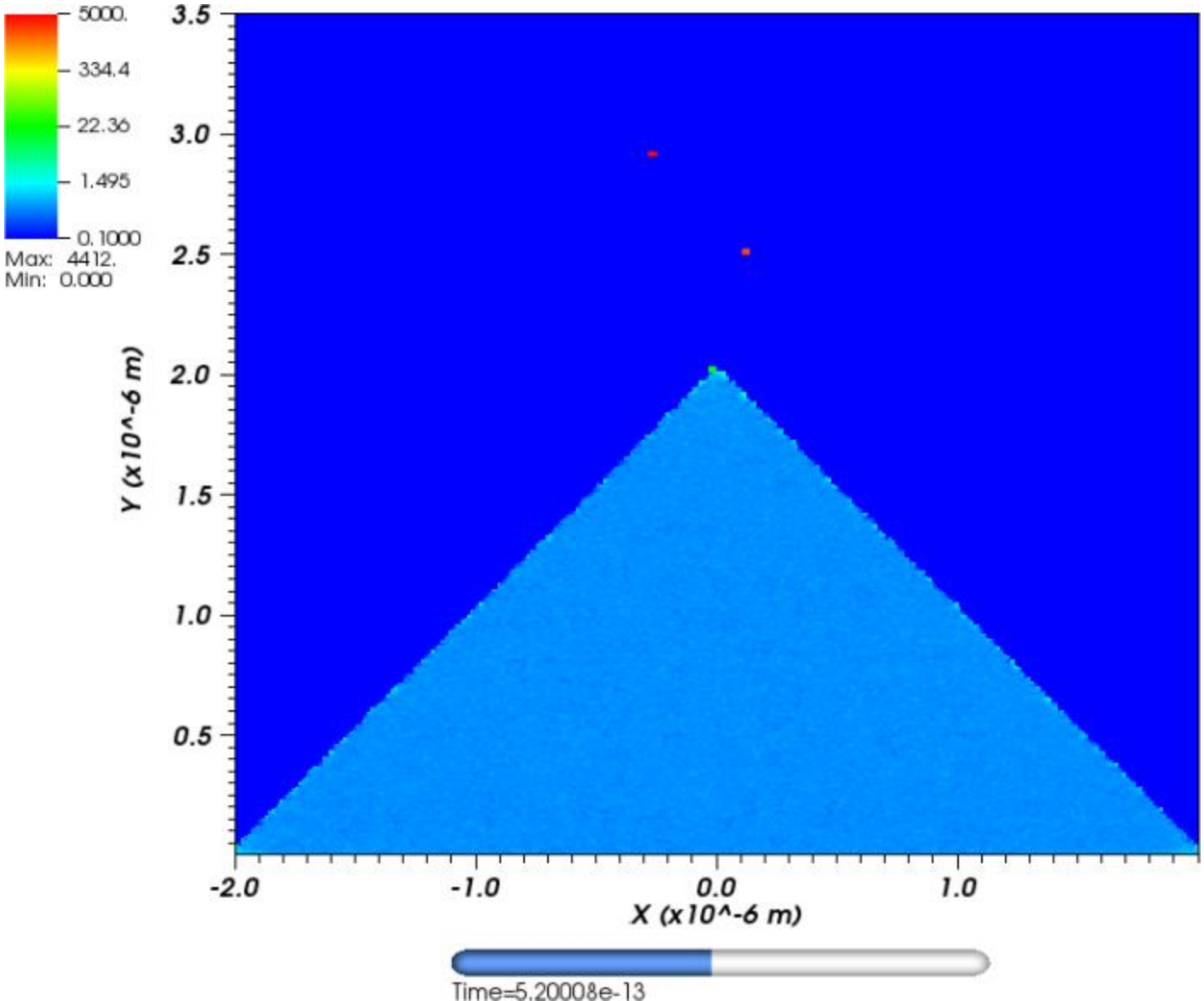

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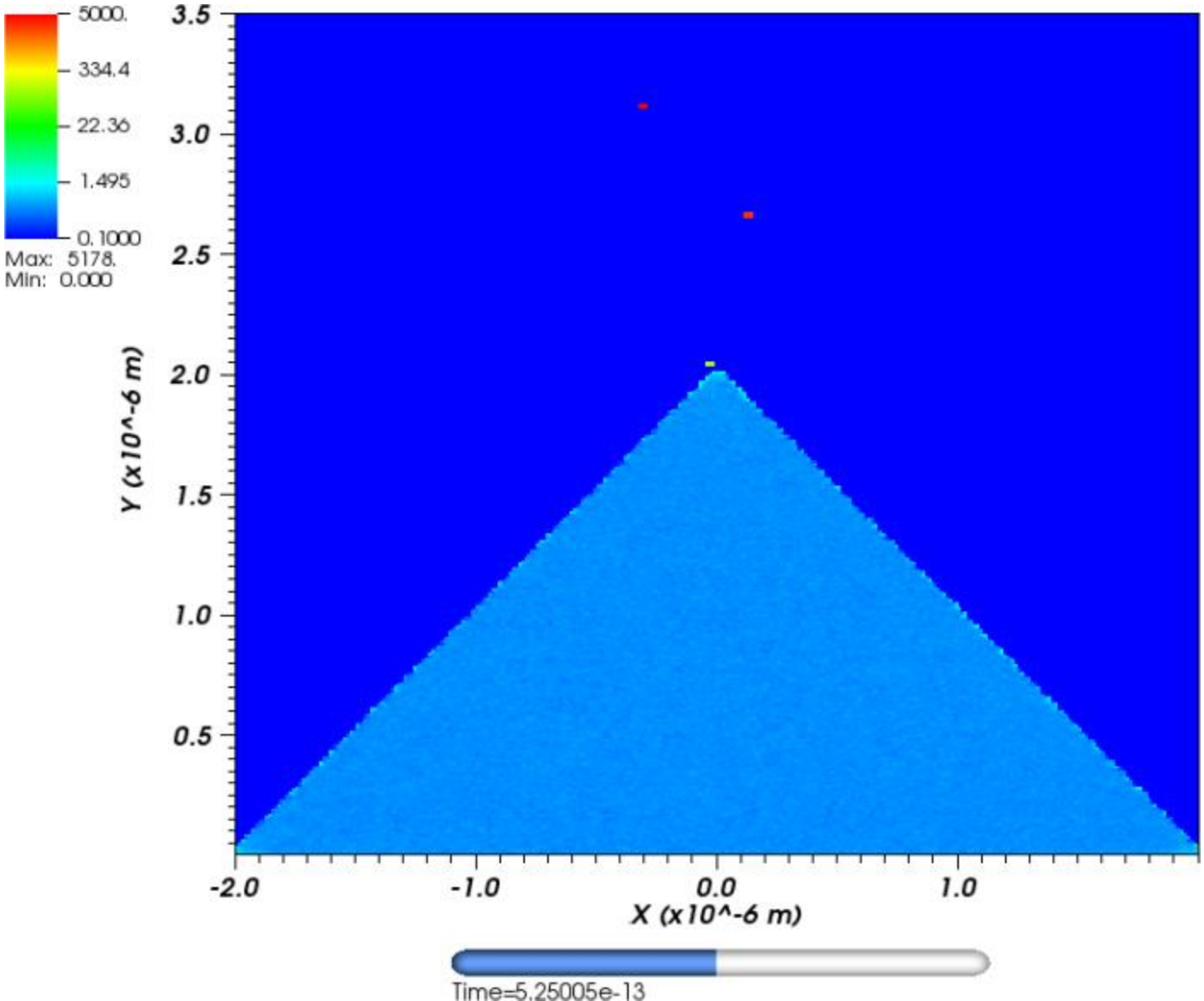

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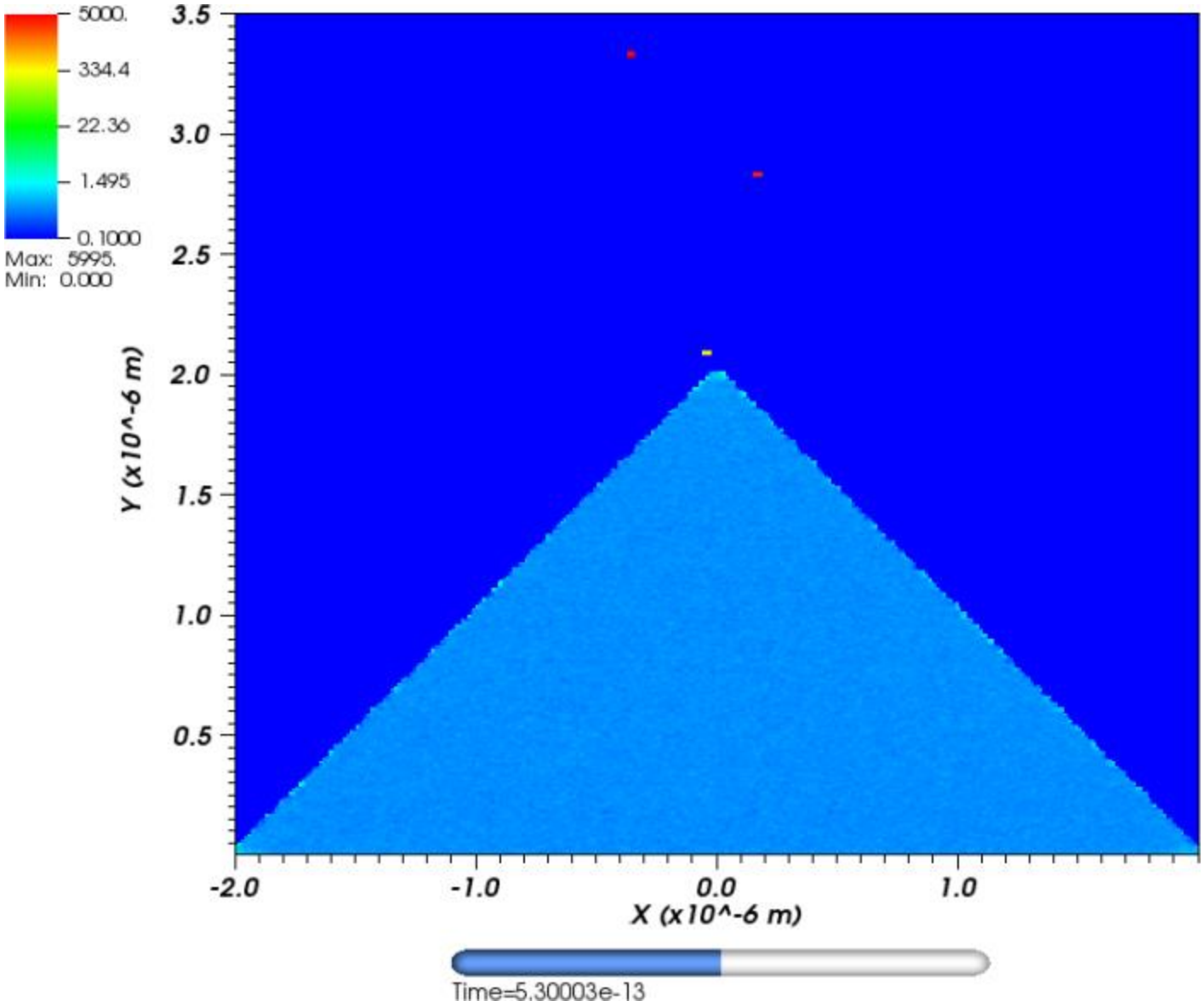

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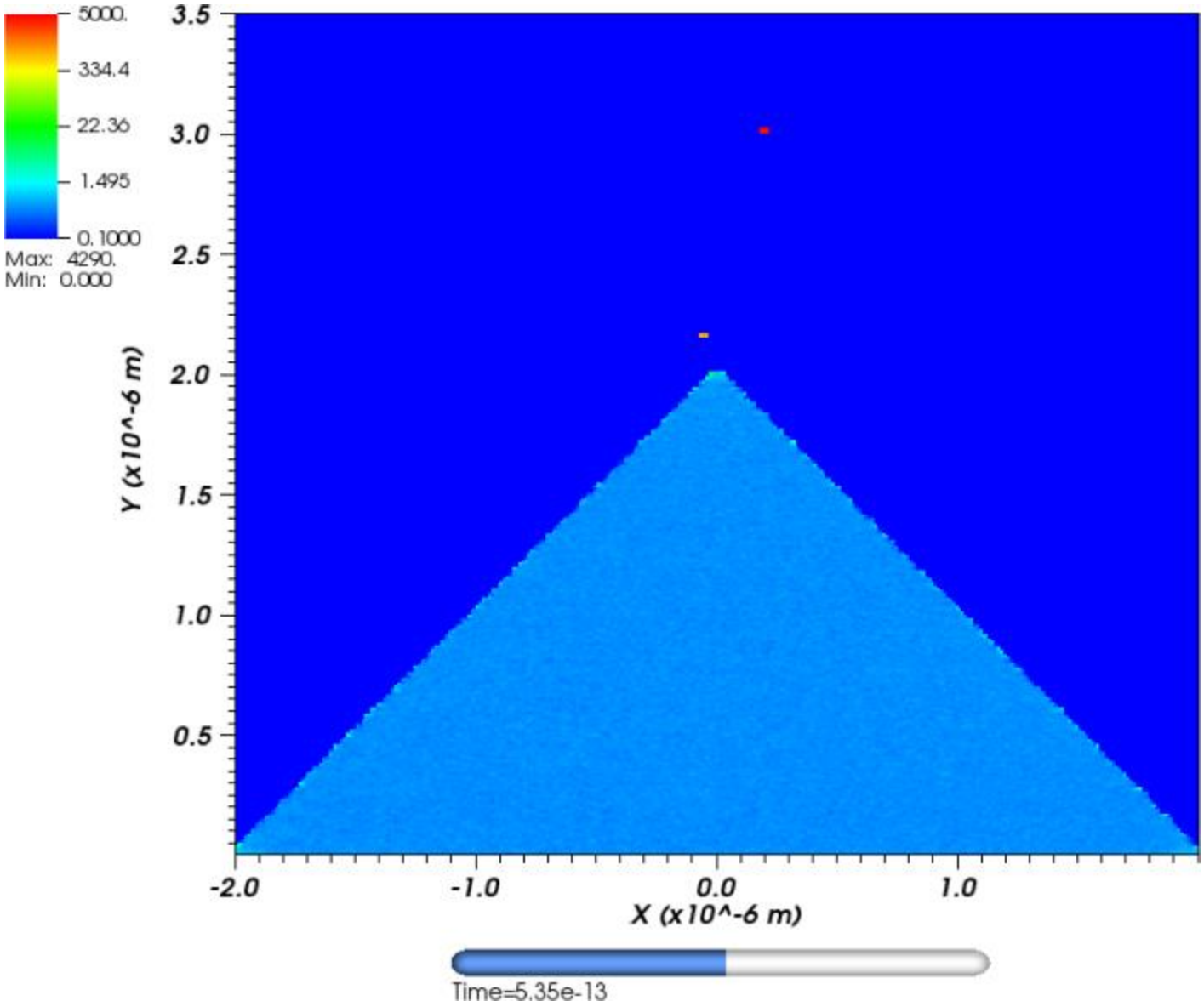

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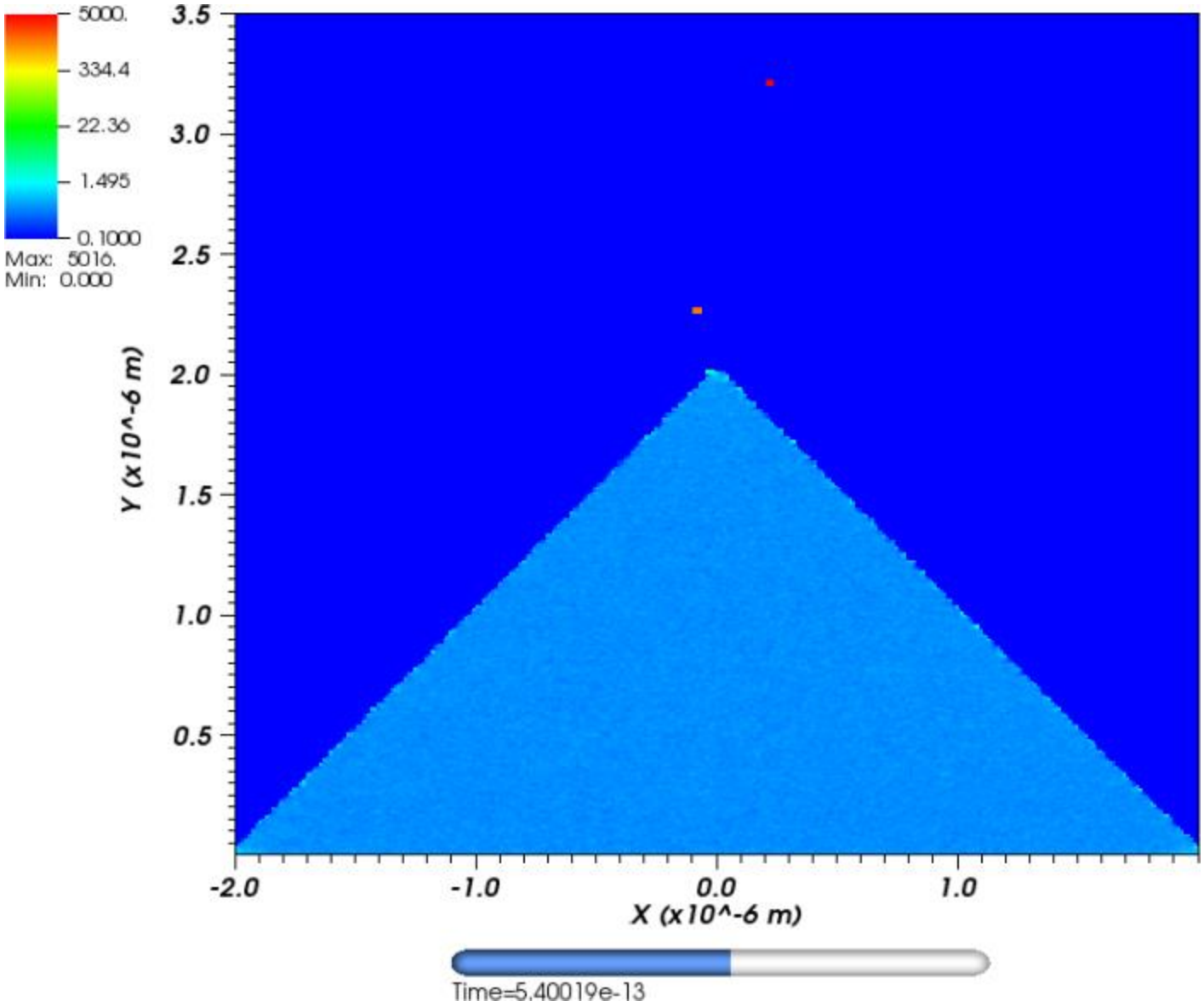

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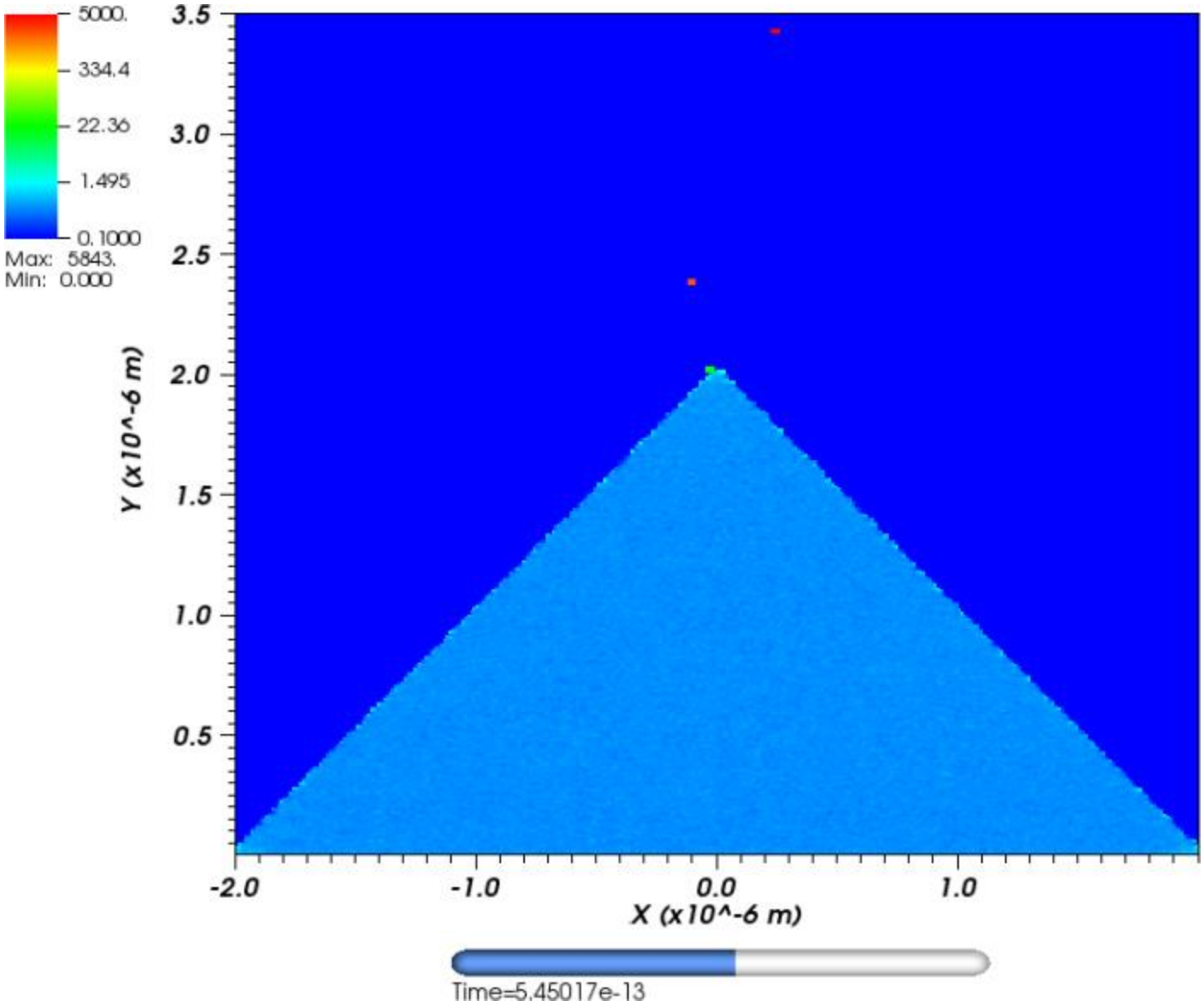

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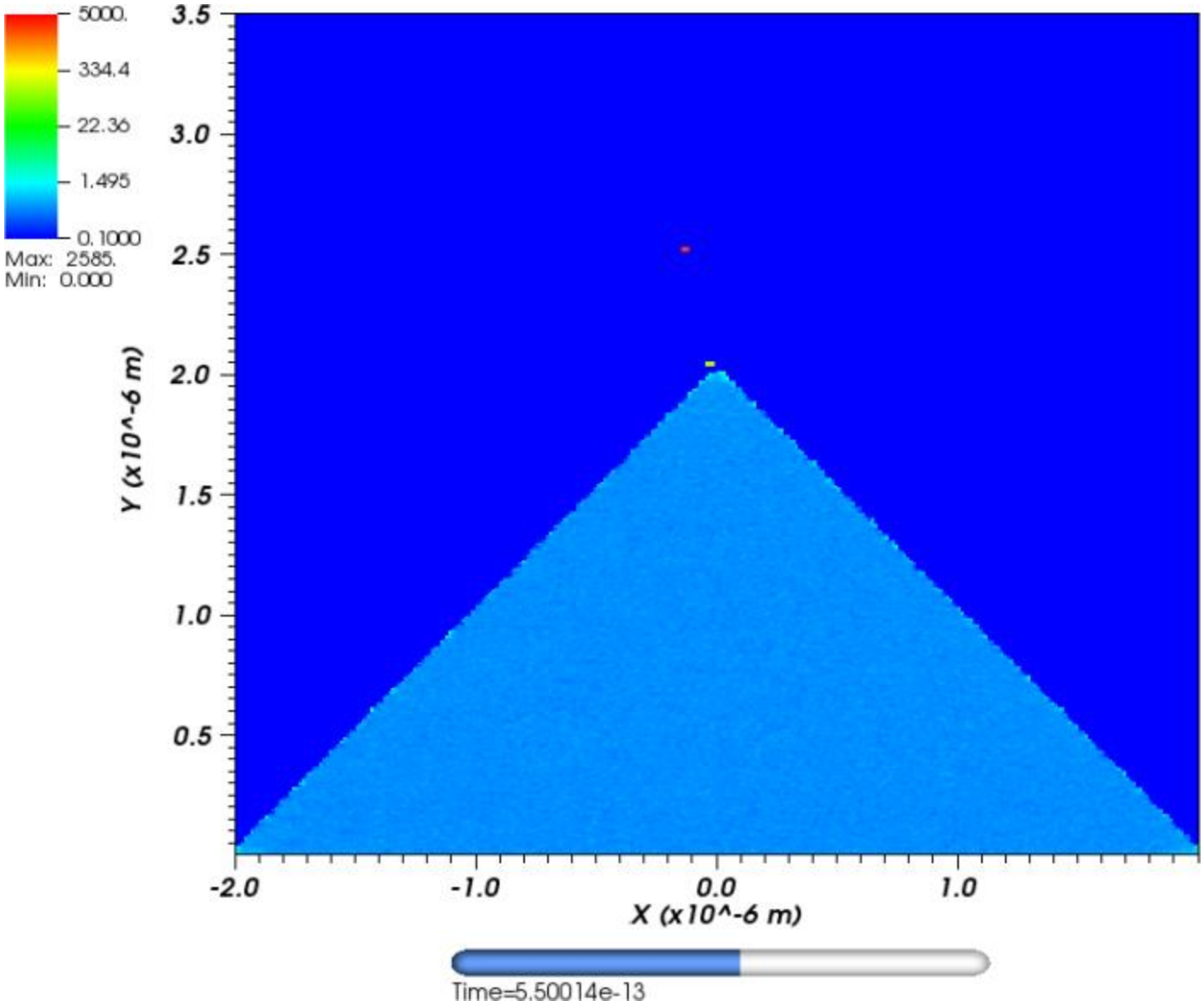

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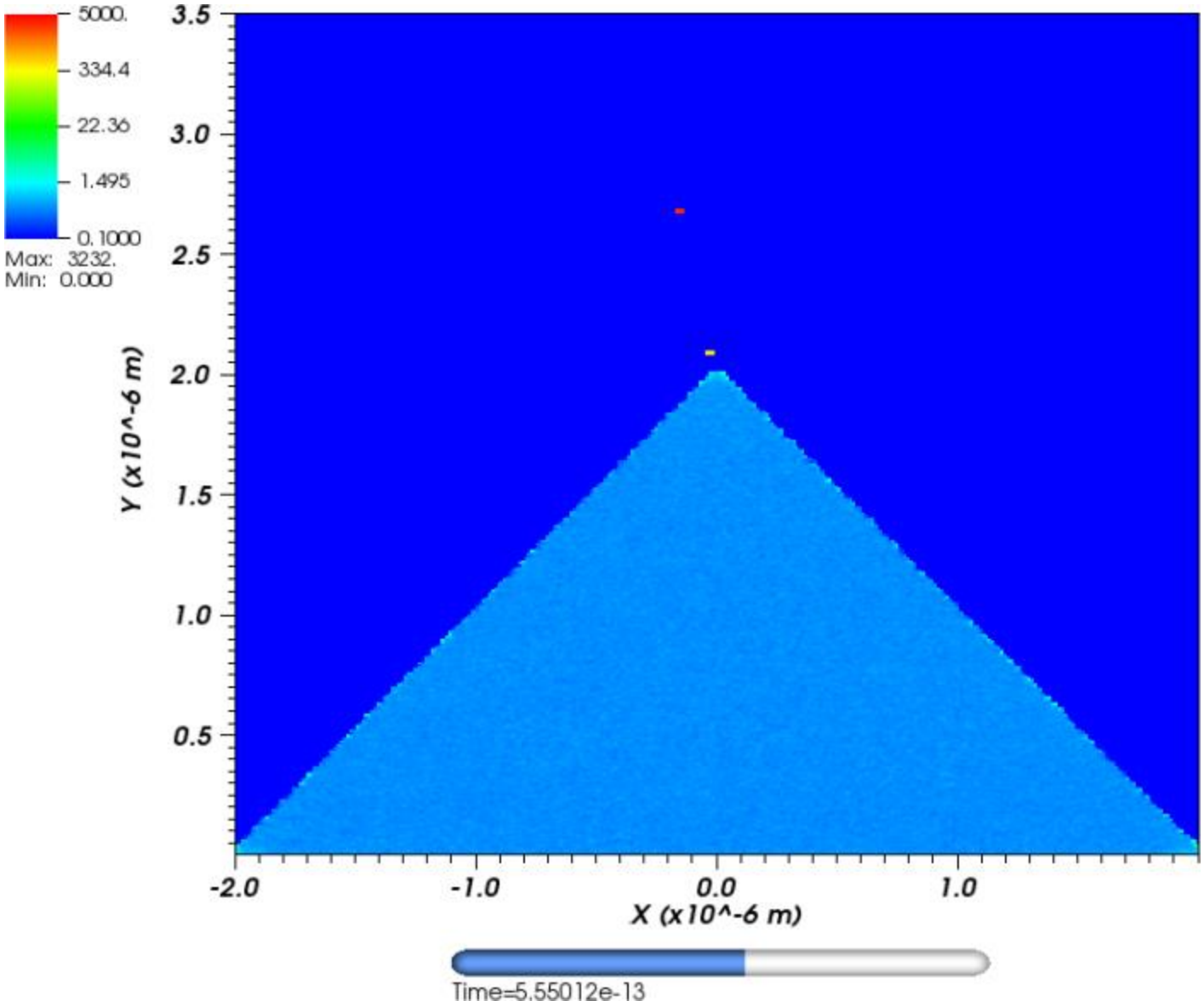

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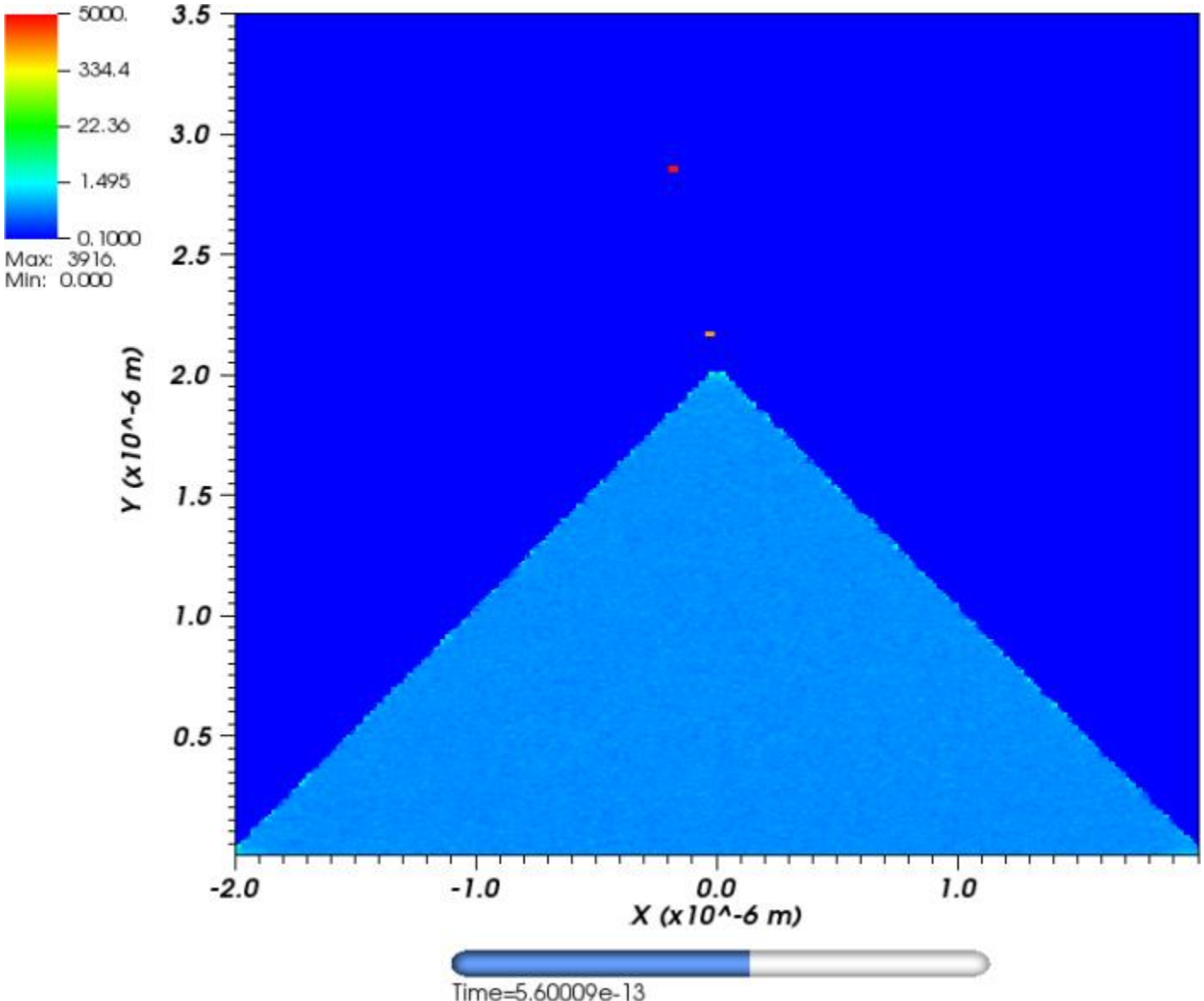

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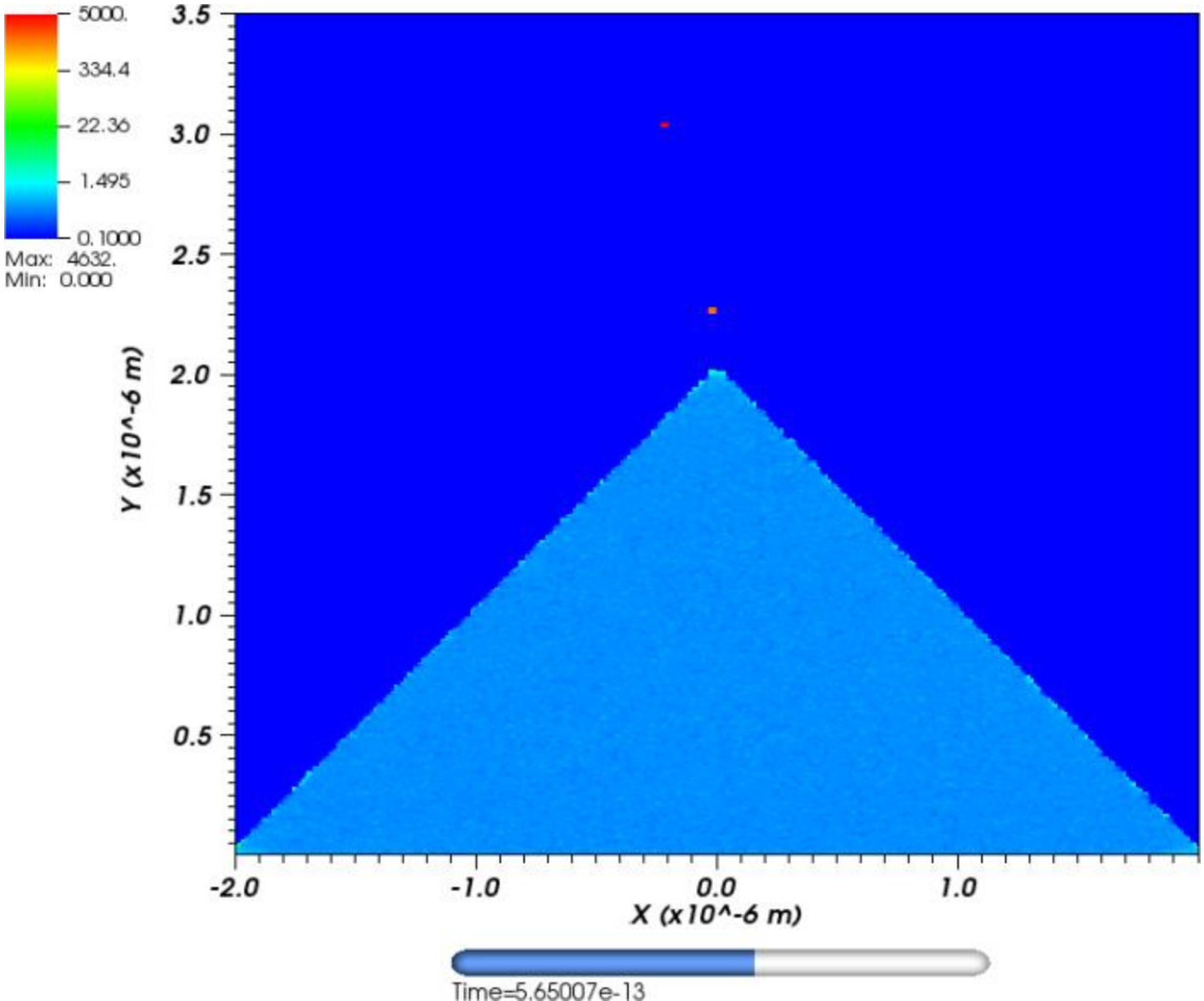

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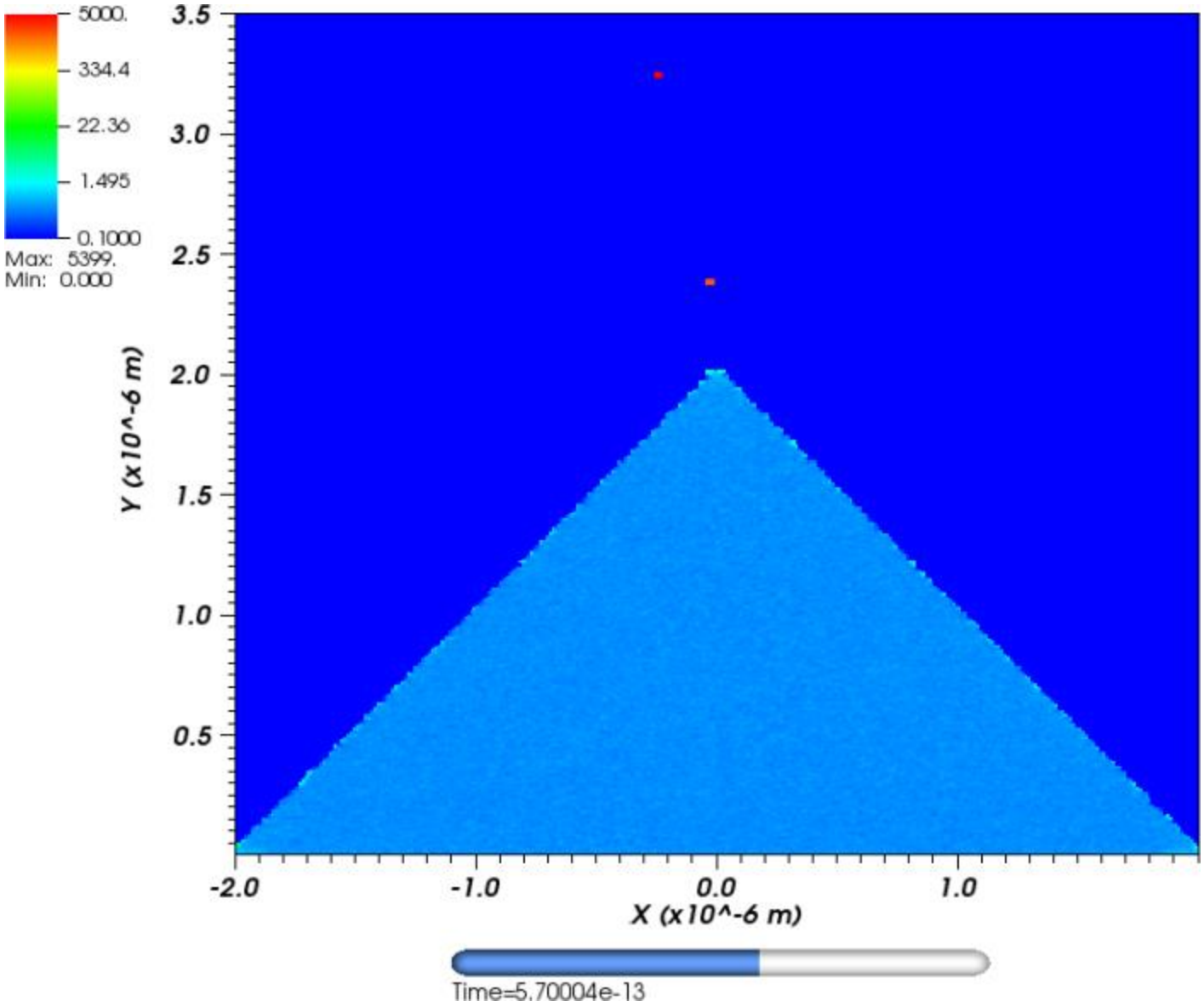

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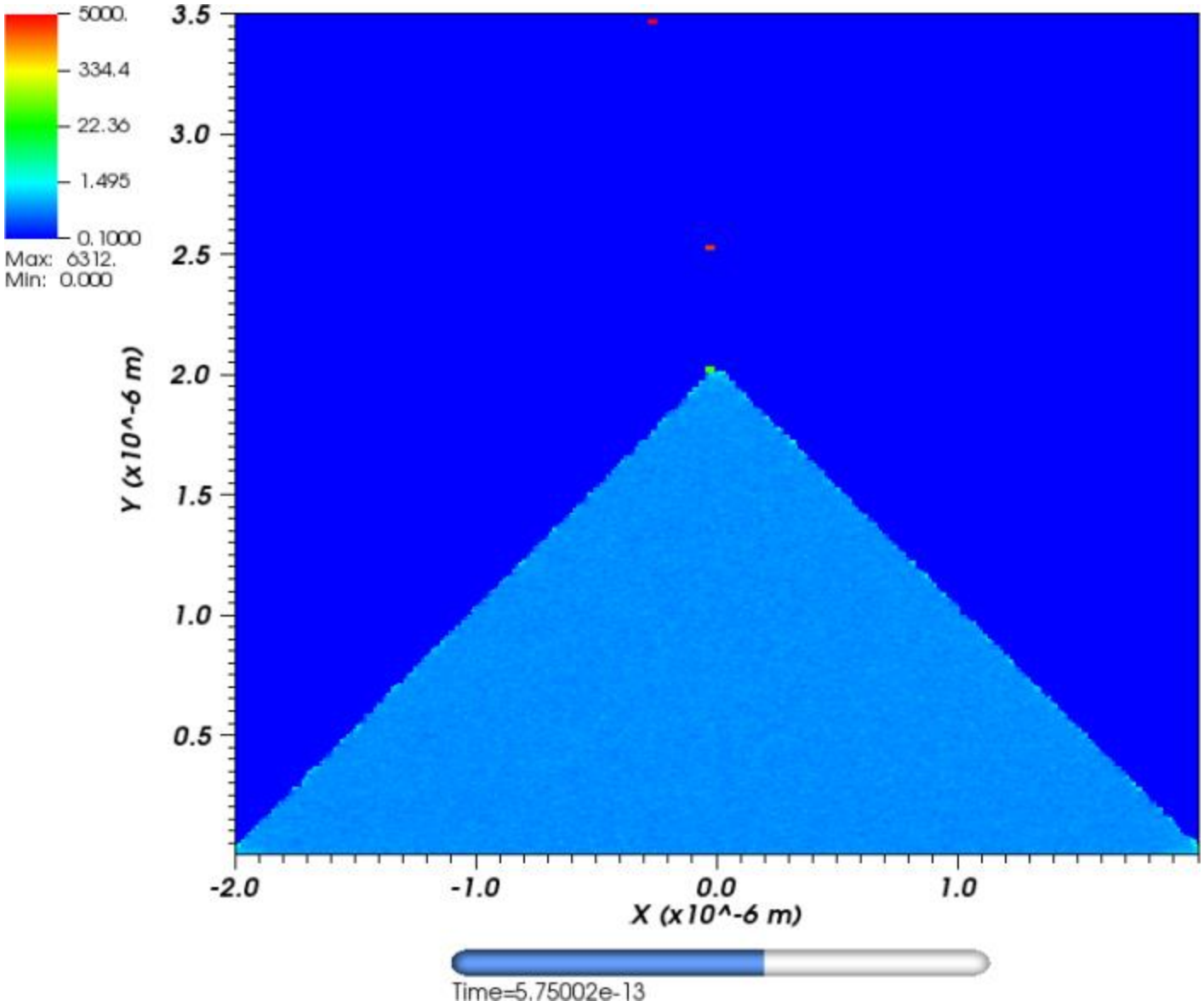

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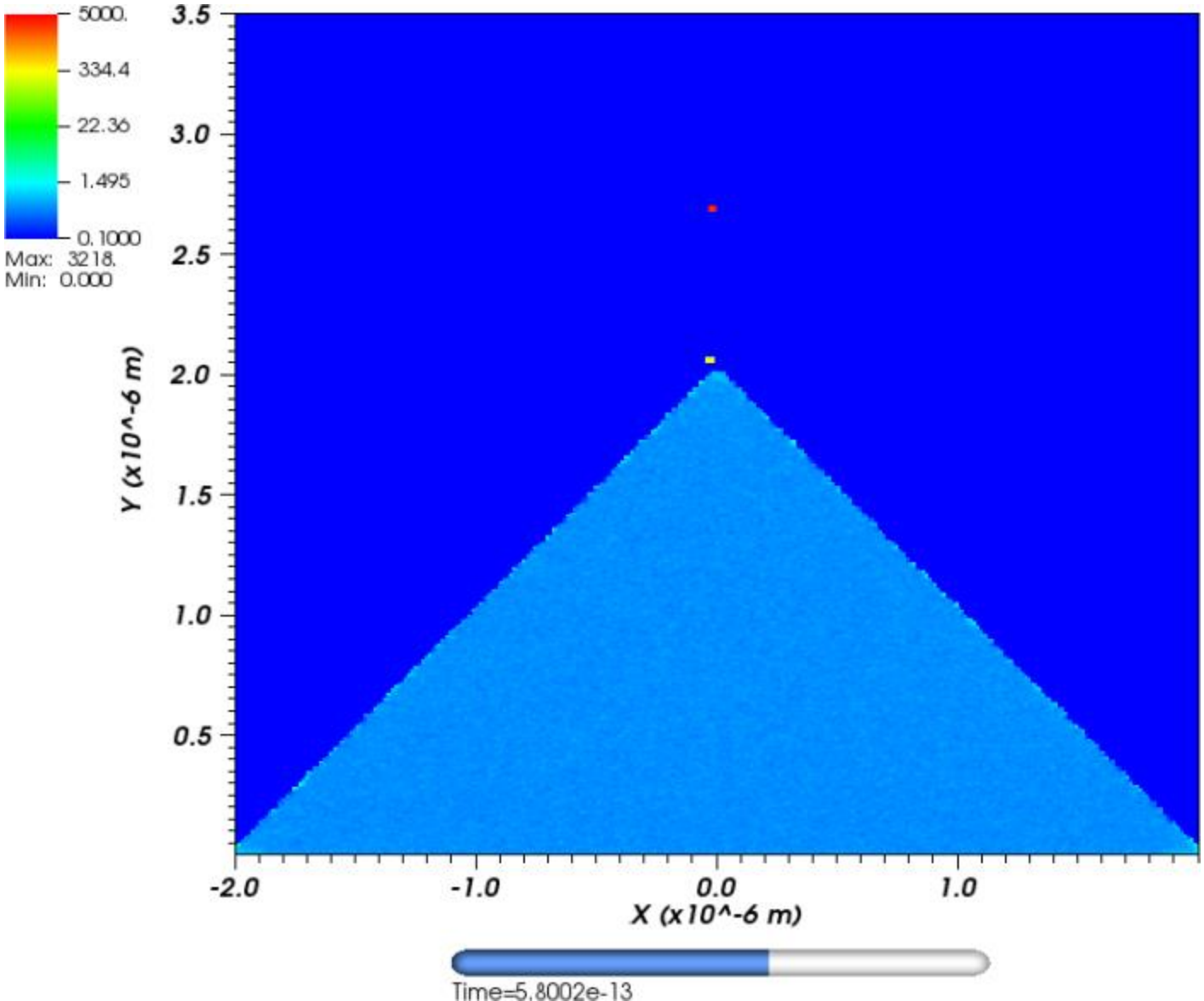

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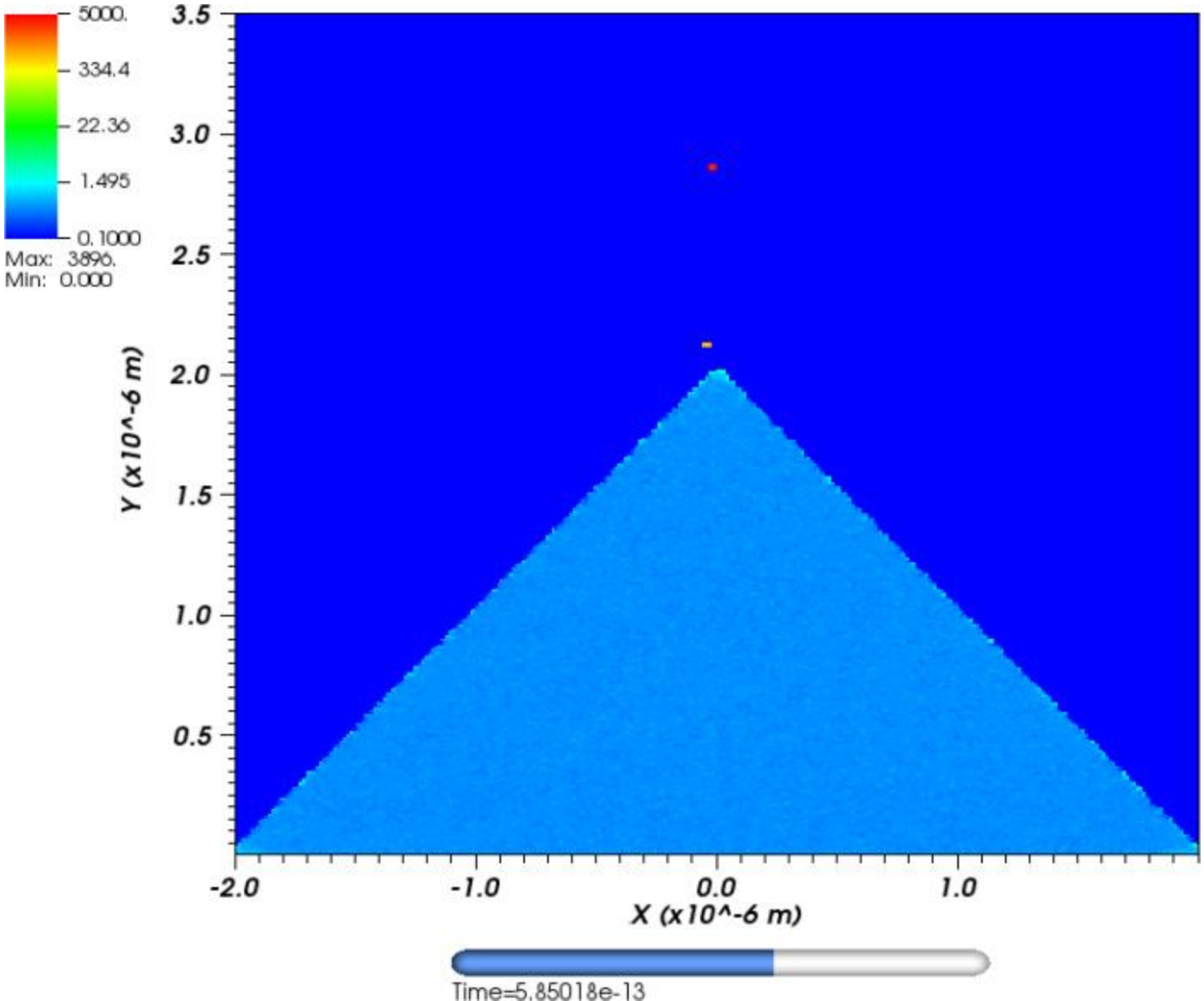

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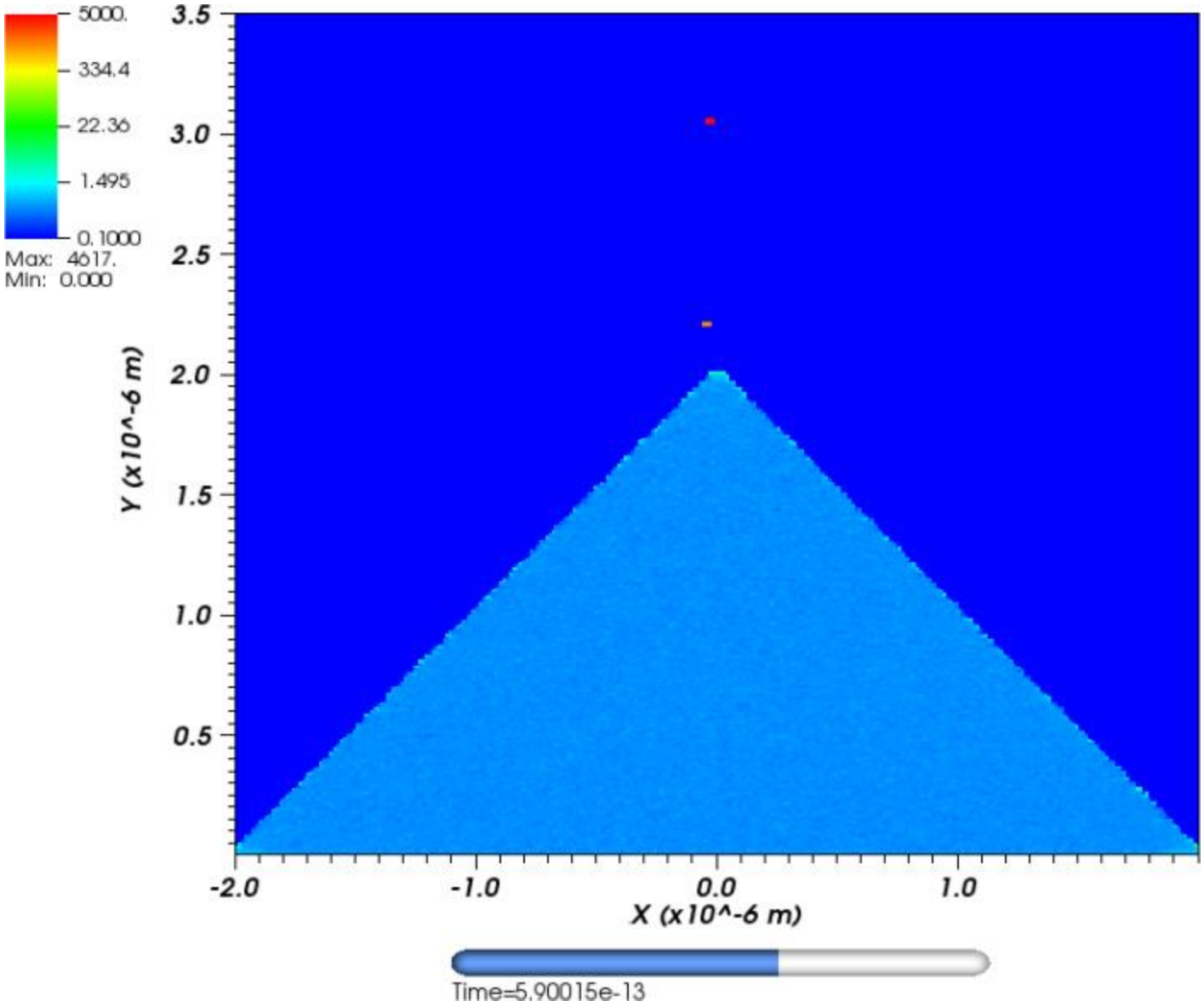

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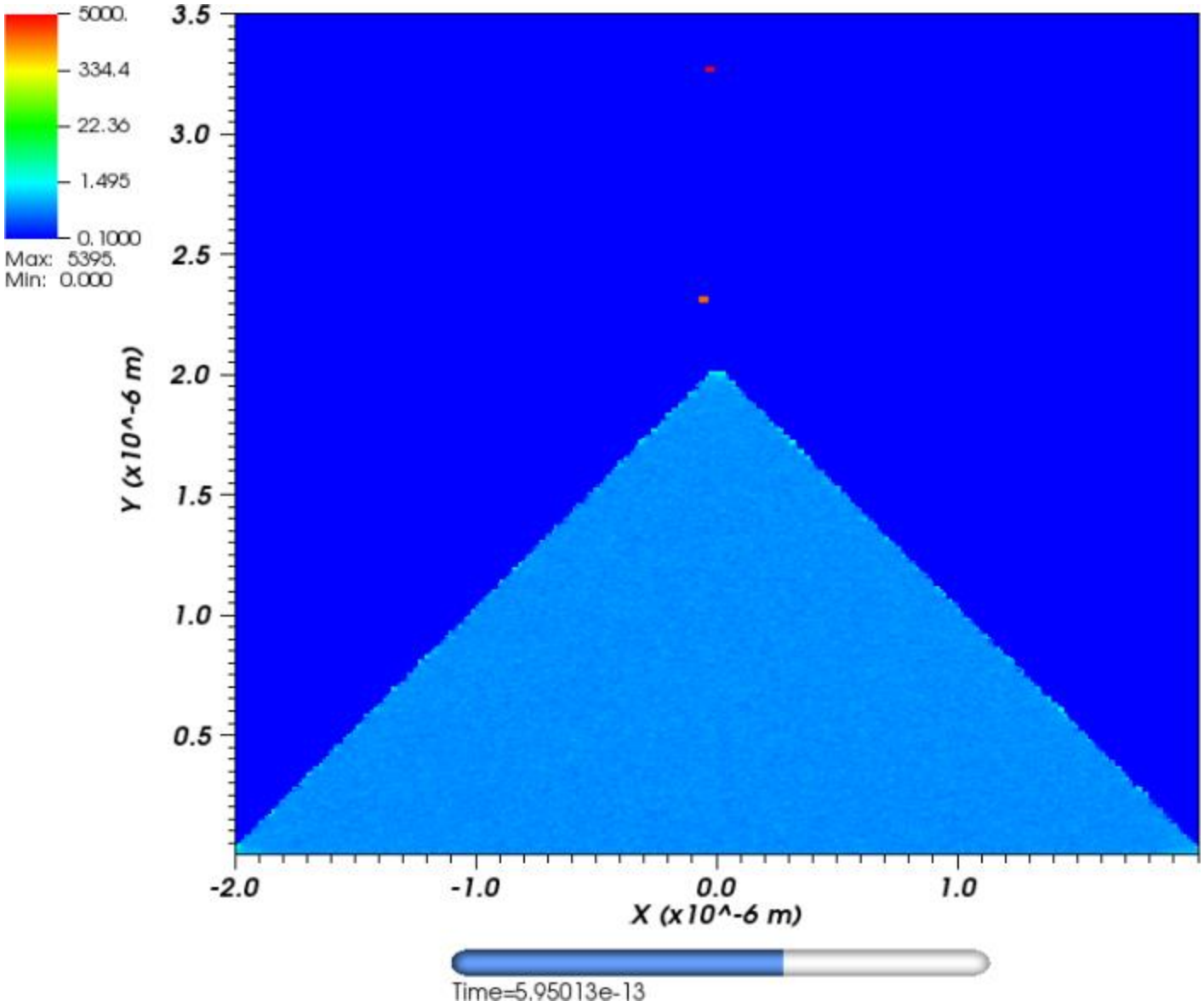
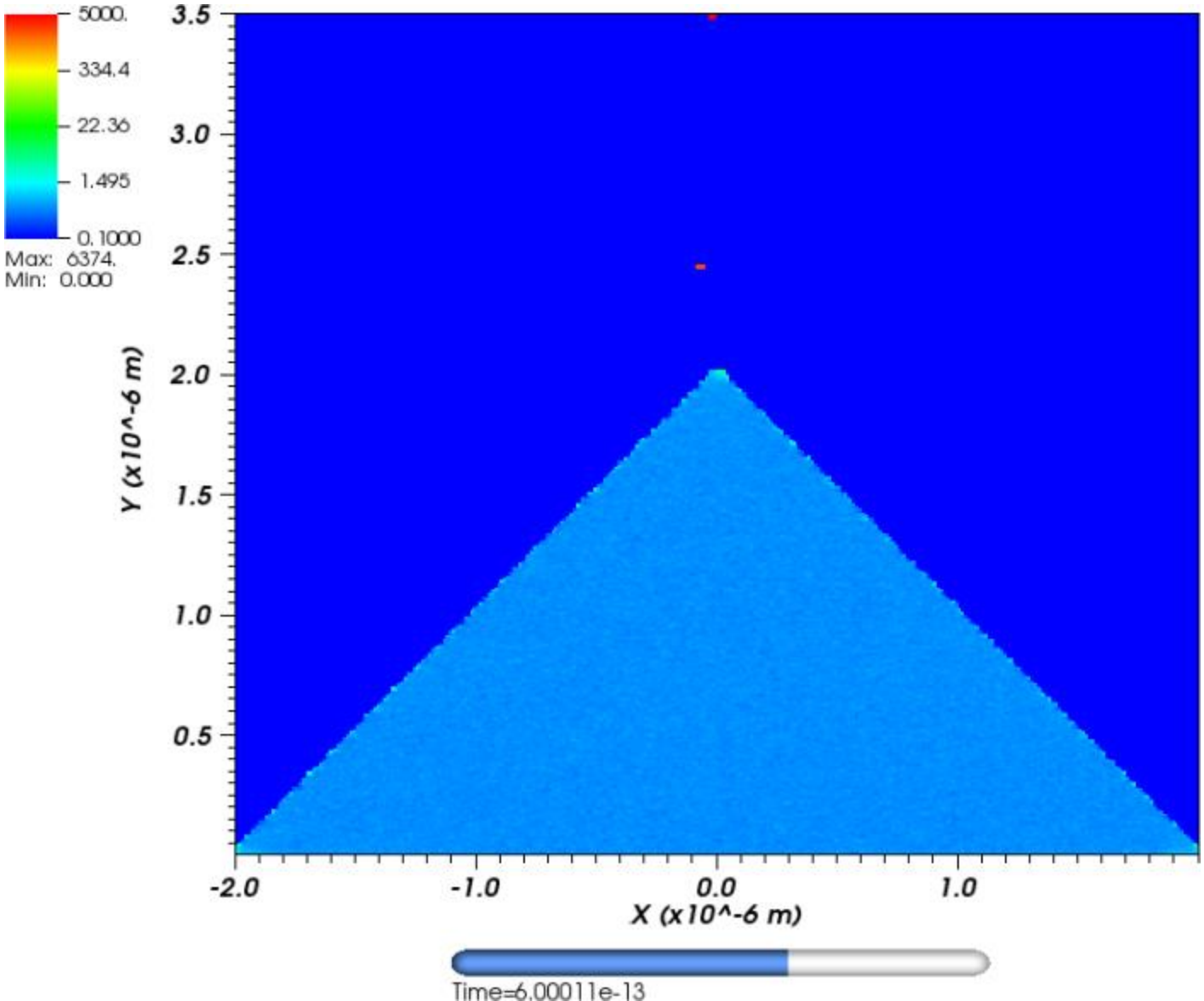
PIC - Electron Energy Pt.II



- E_y = -2 GV/m
- No ionization
- t_{tot} = 0.8 ps

PIC - Electron Energy Pt.II



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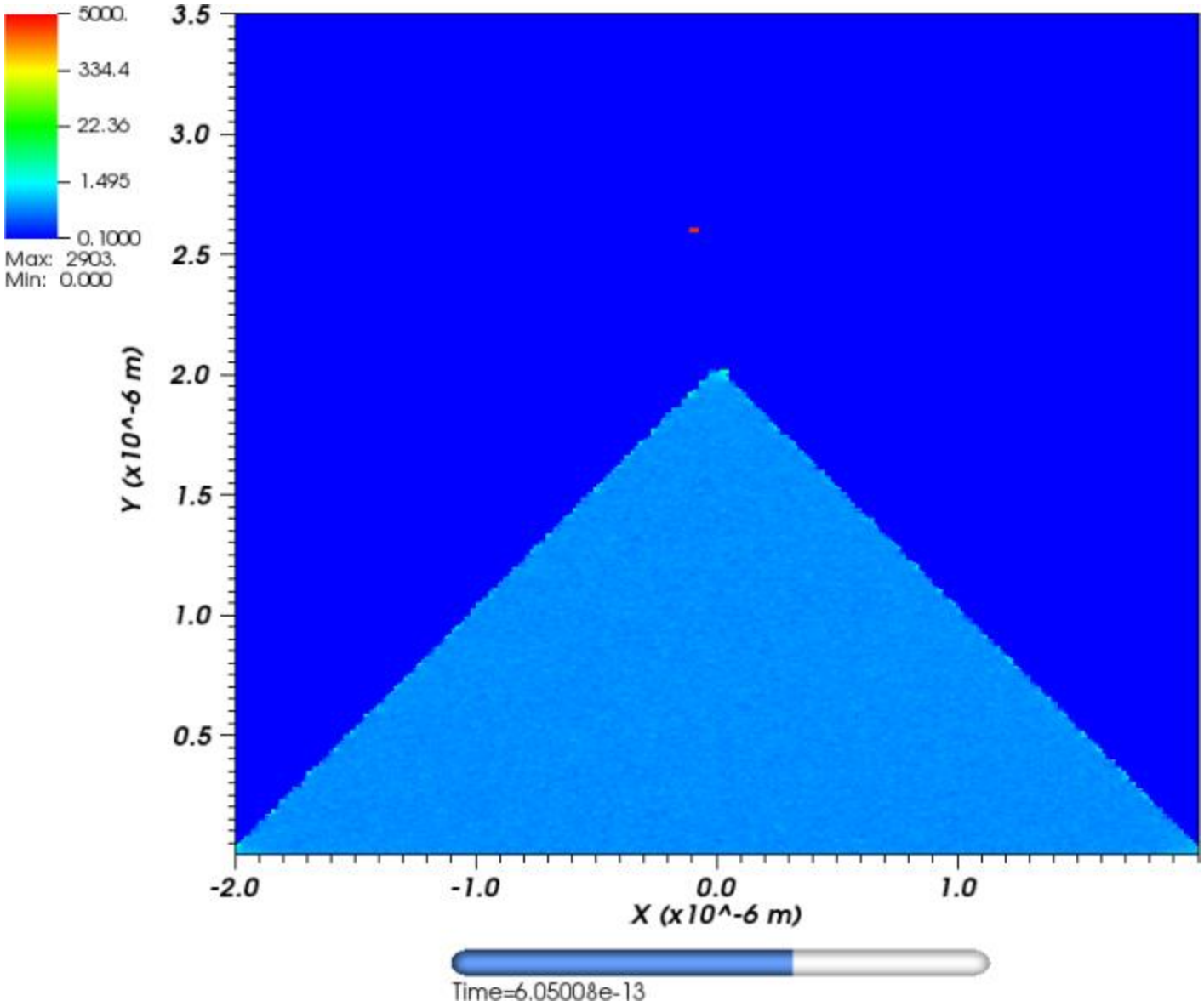
PIC - Electron Energy Pt.II



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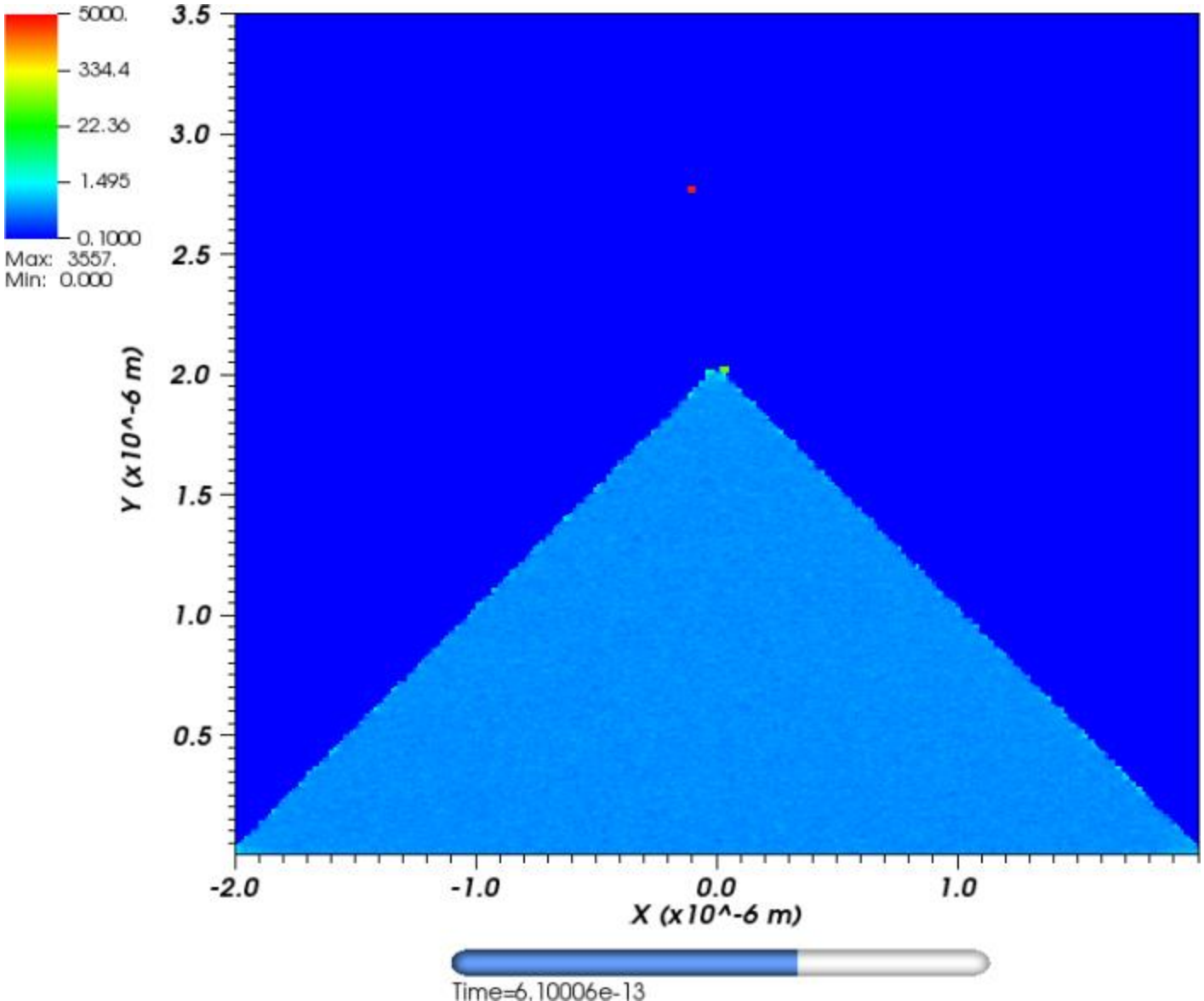
PIC - Electron Energy Pt.II



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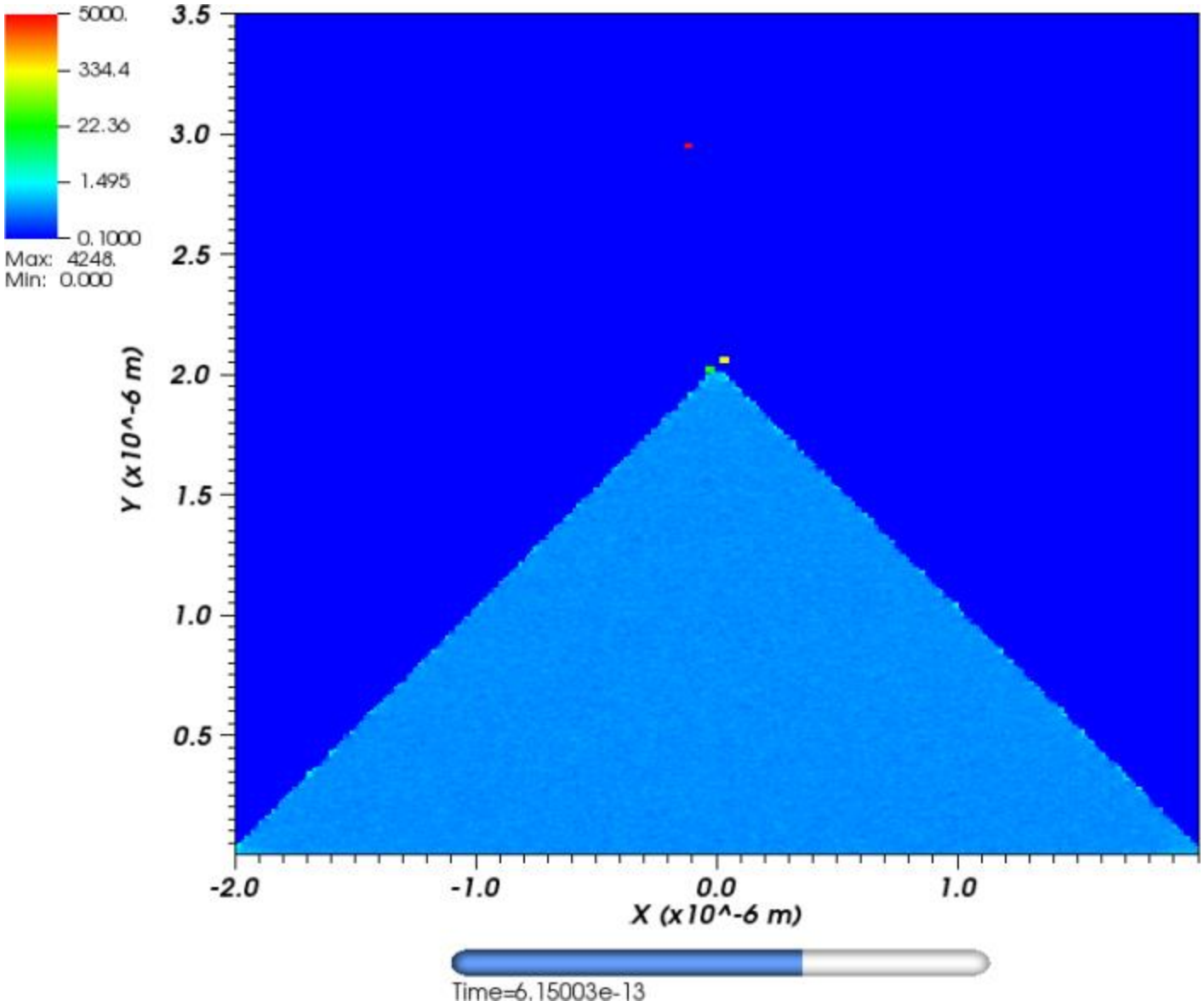
PIC - Electron Energy Pt.II



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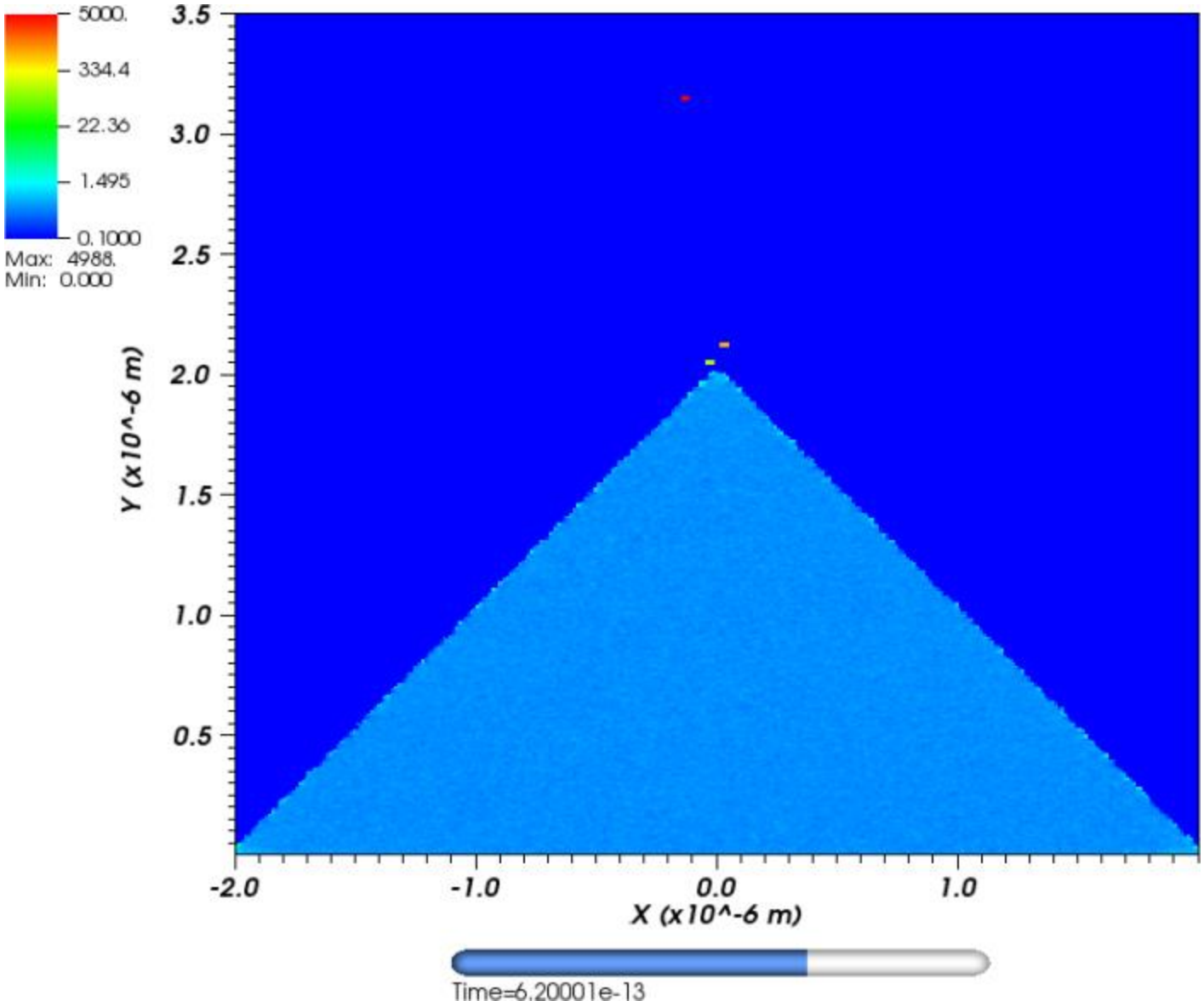
PIC - Electron Energy Pt.II



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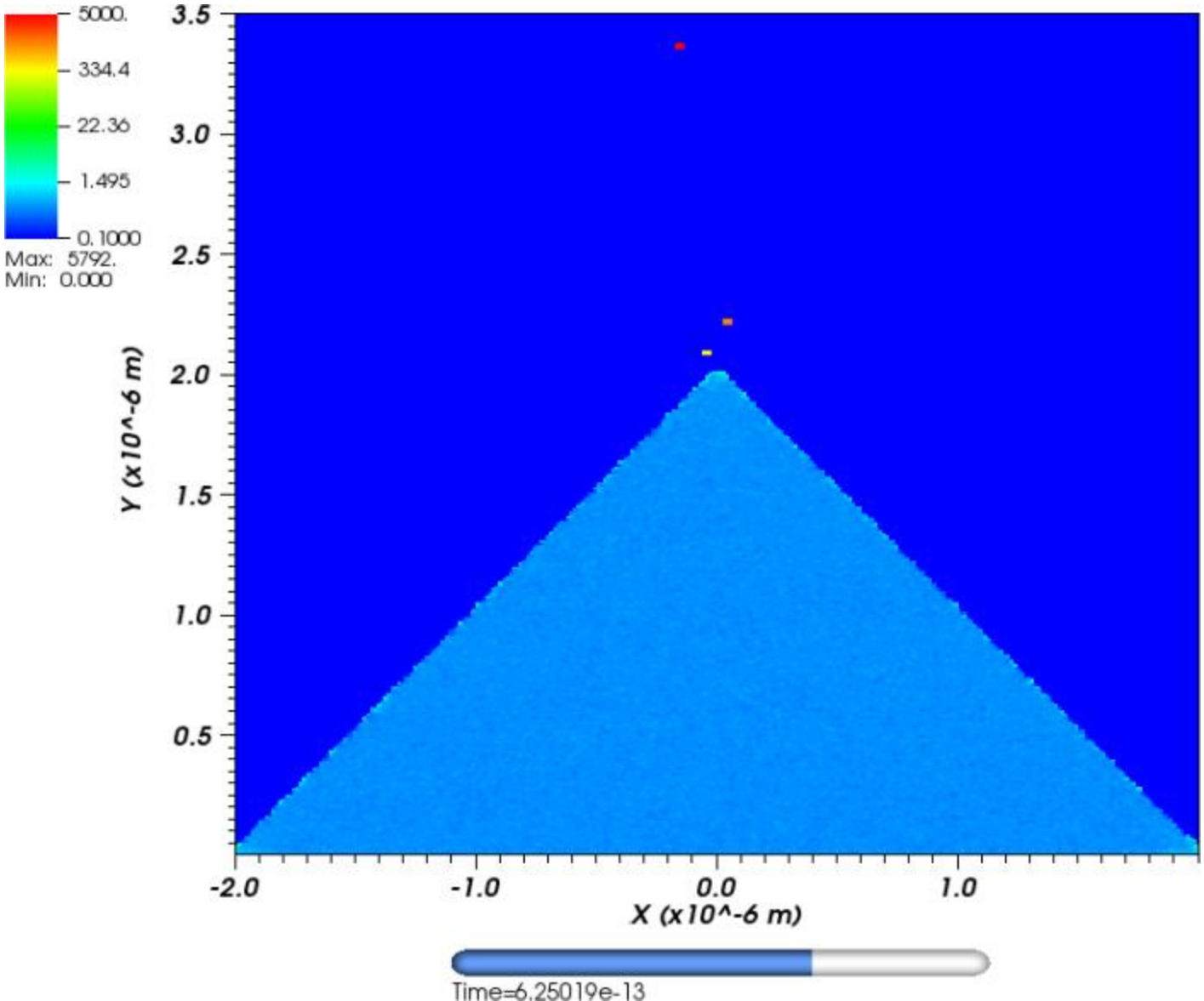

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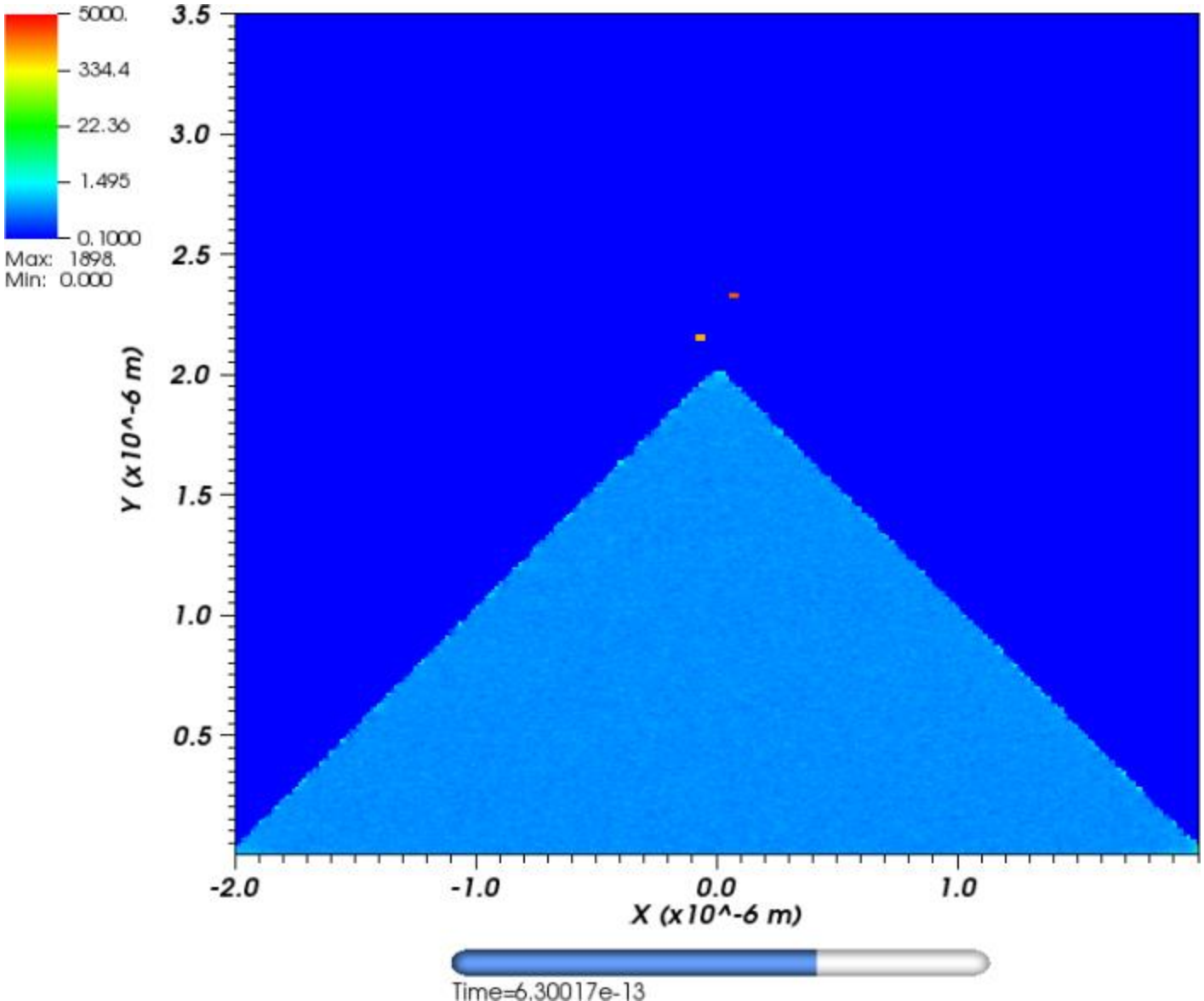

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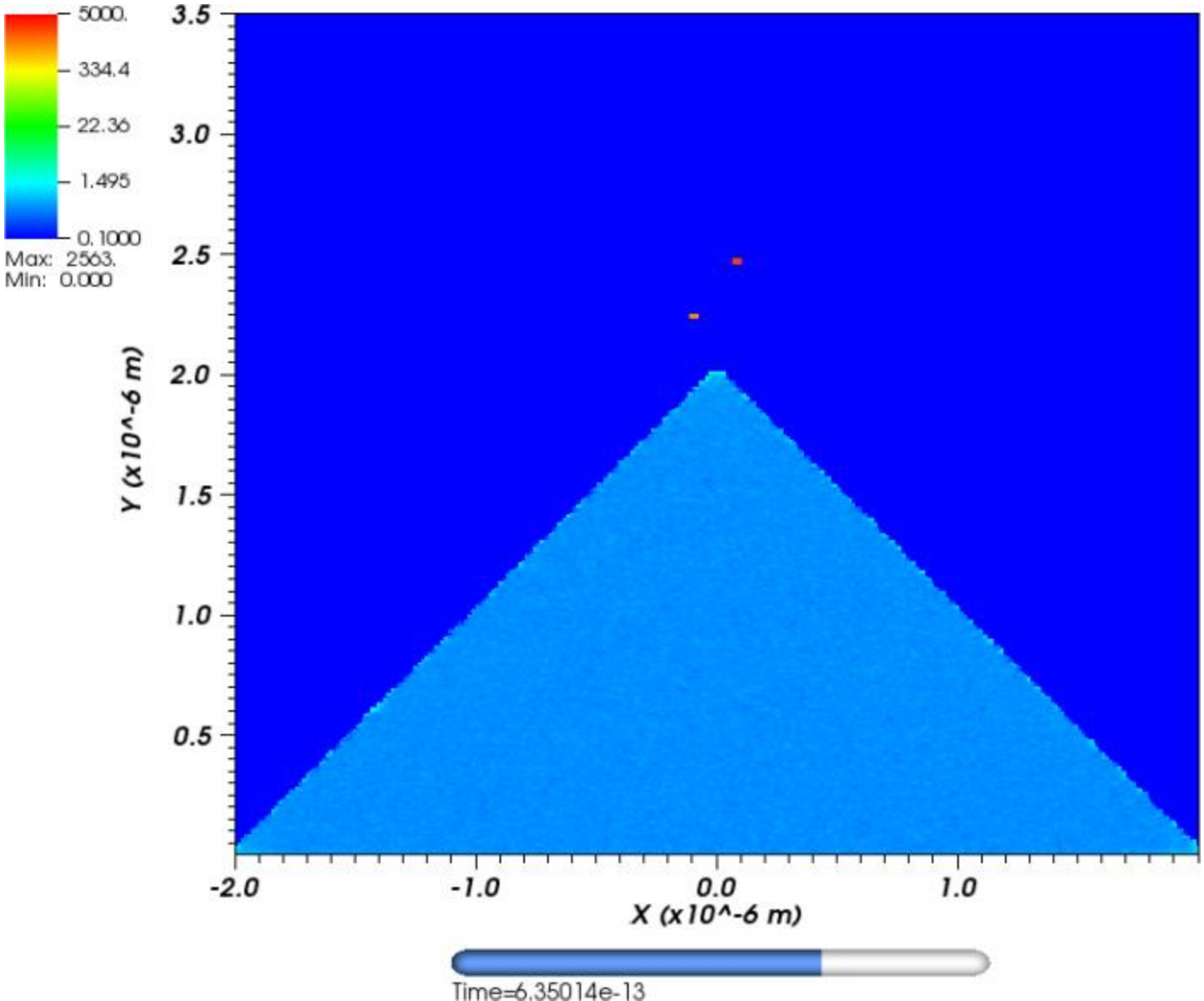
PIC - Electron Energy Pt.II



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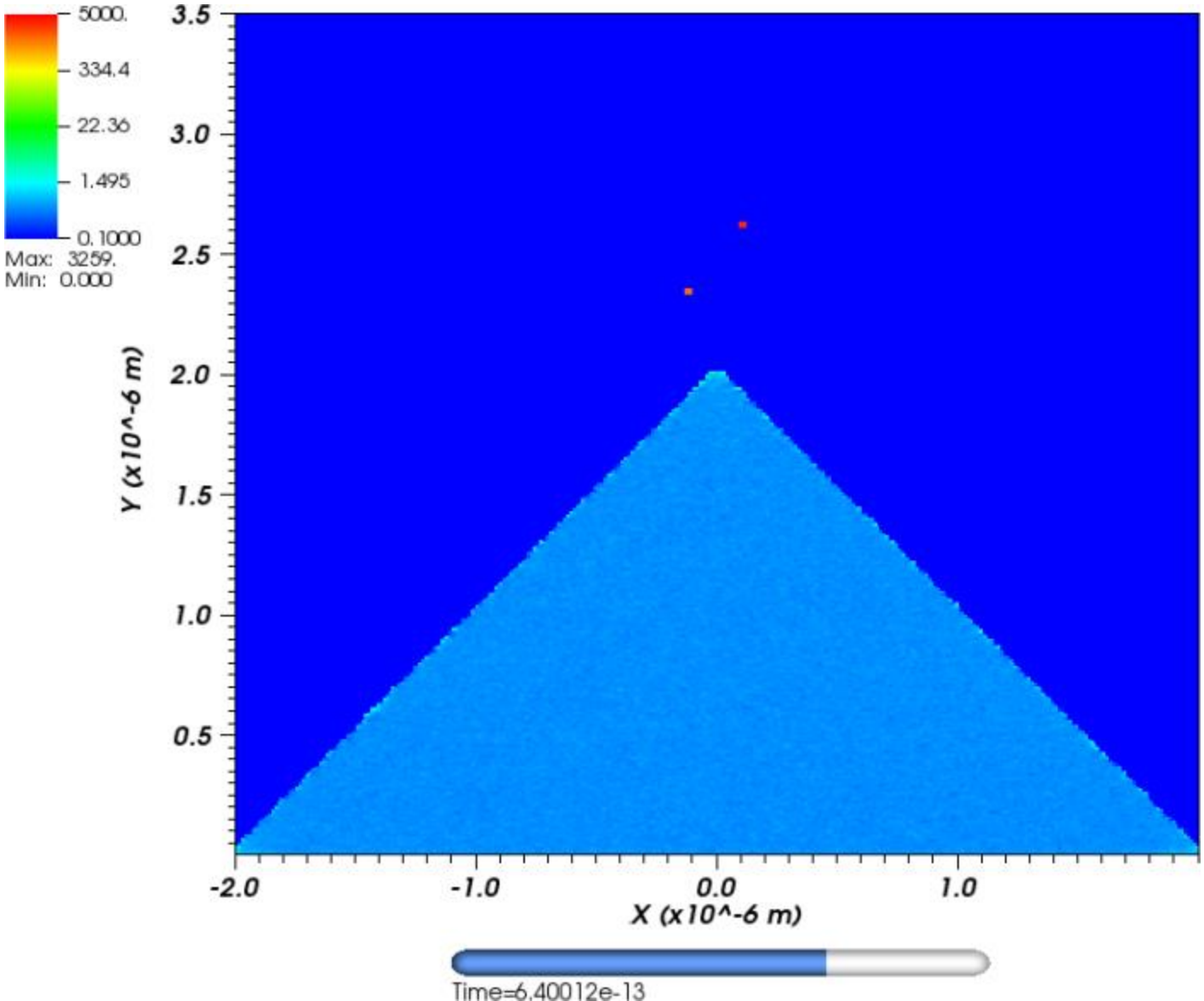
PIC - Electron Energy Pt.II



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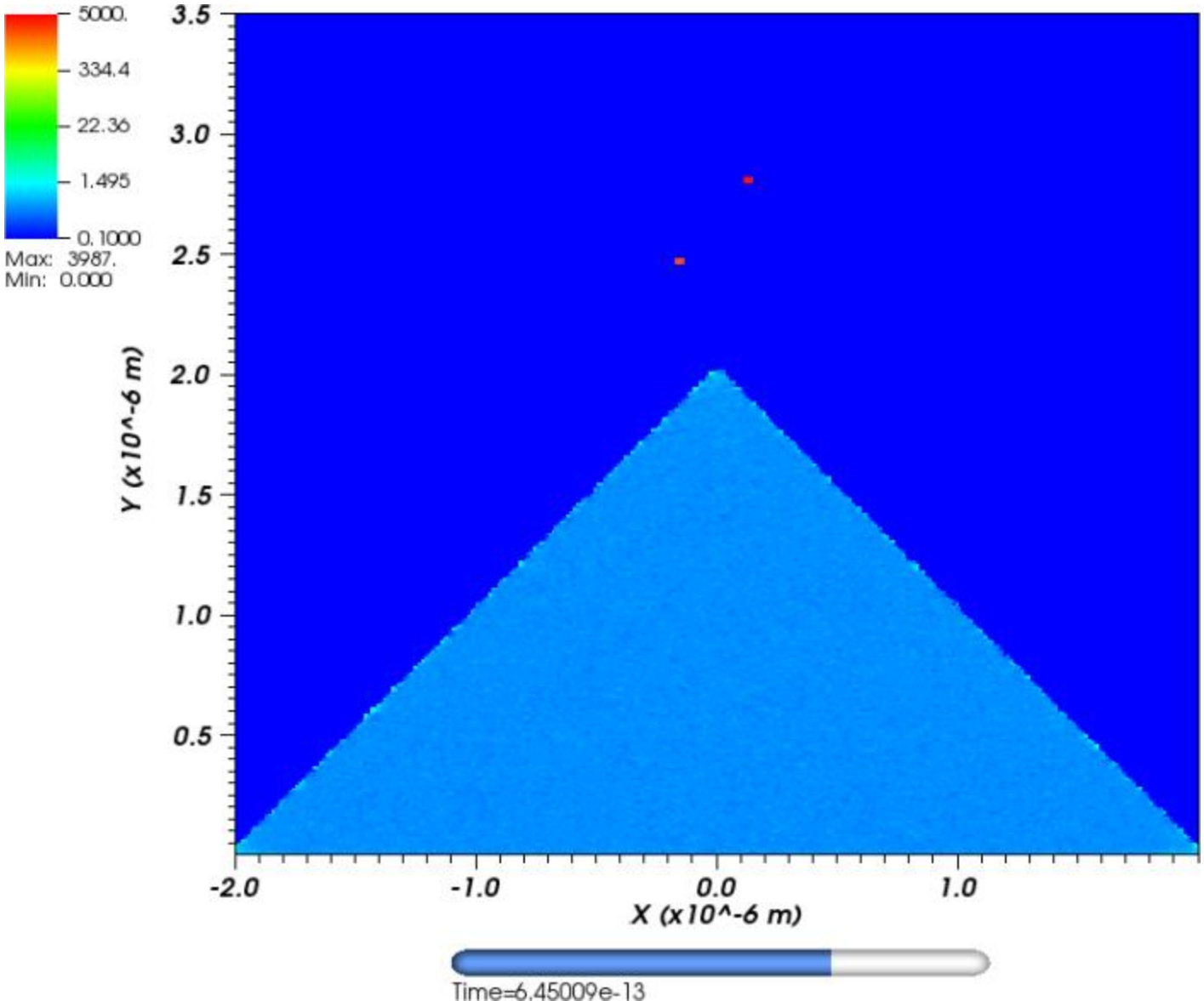
PIC - Electron Energy Pt.II



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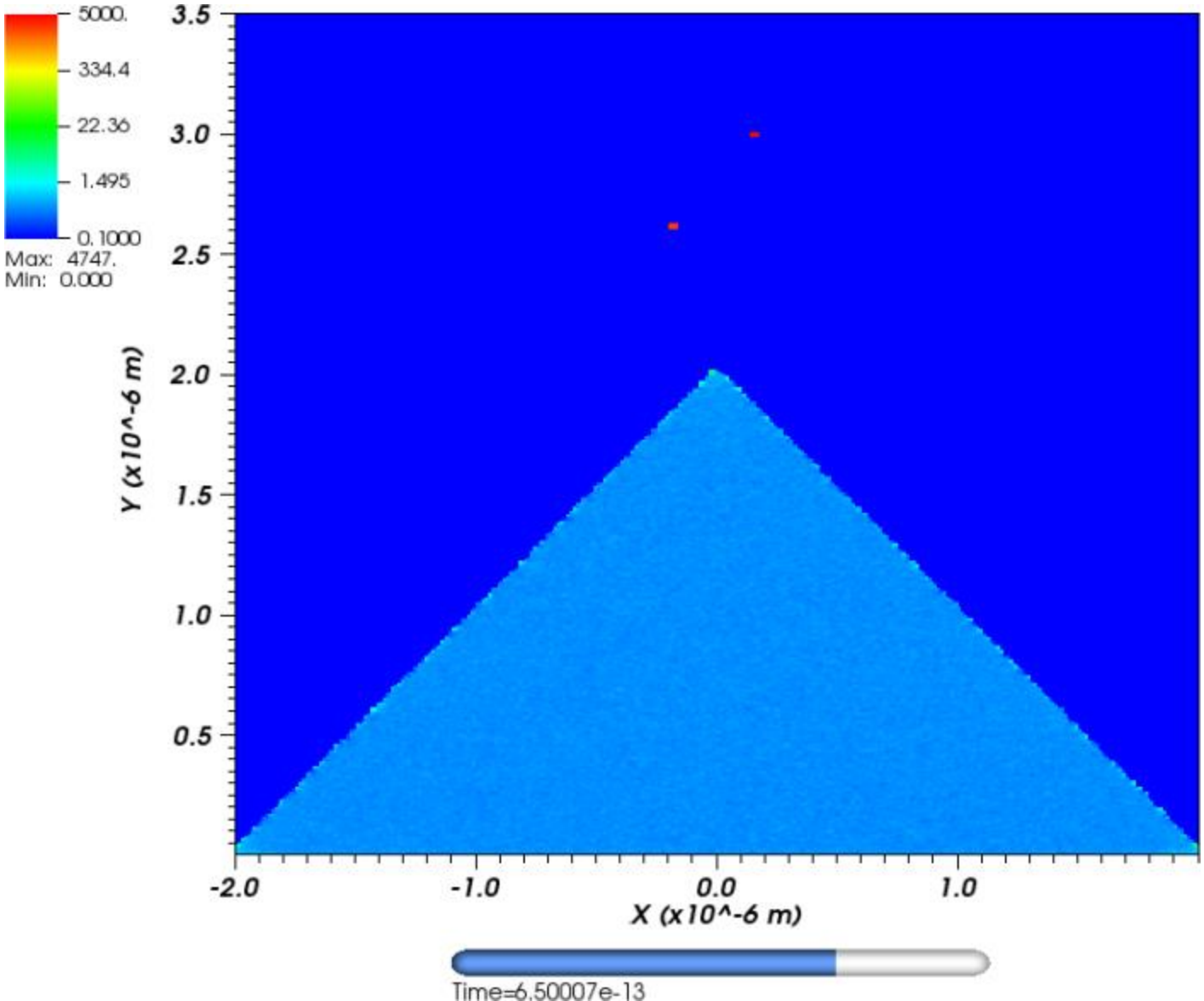
PIC - Electron Energy Pt.II



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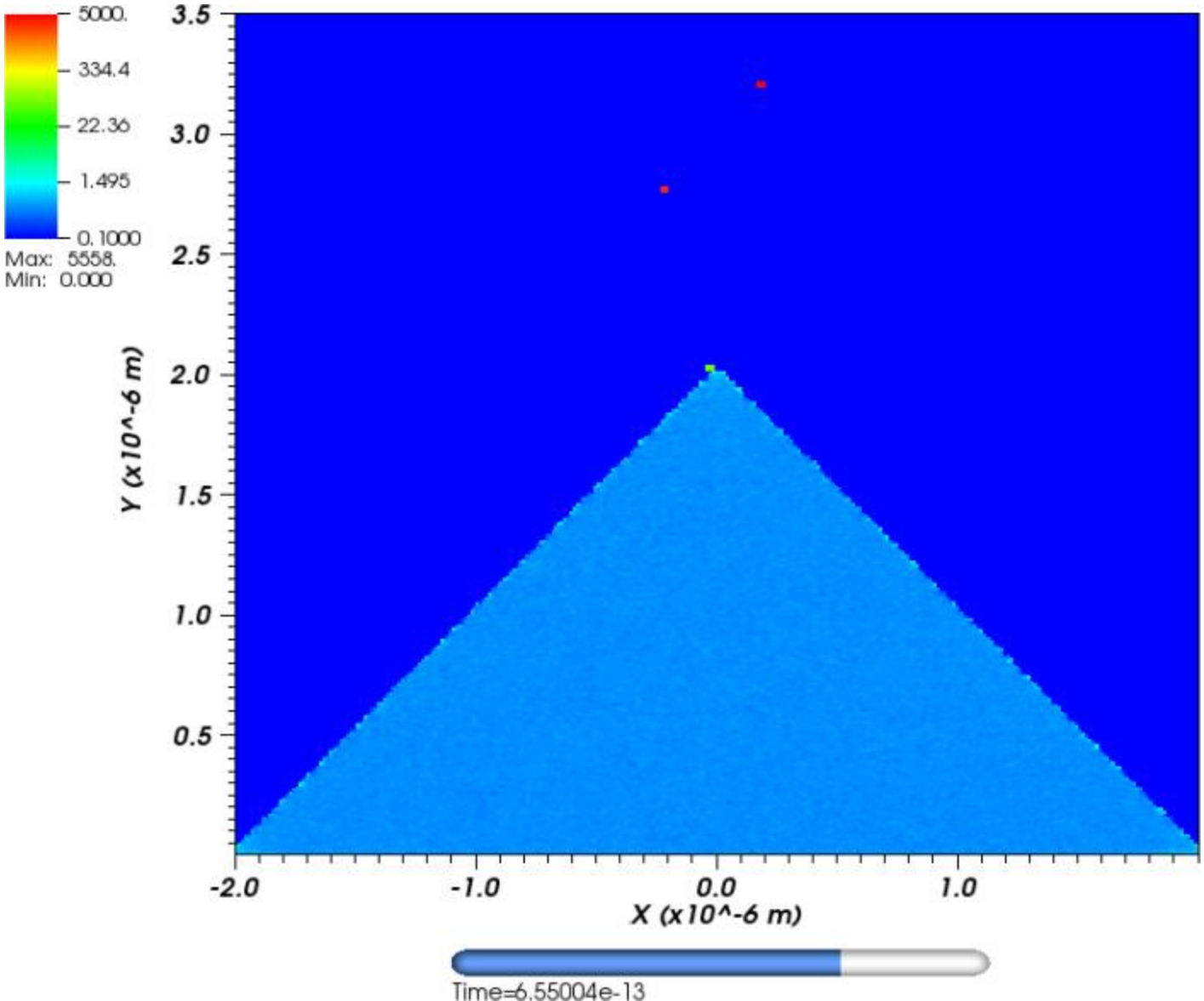
PIC - Electron Energy Pt.II



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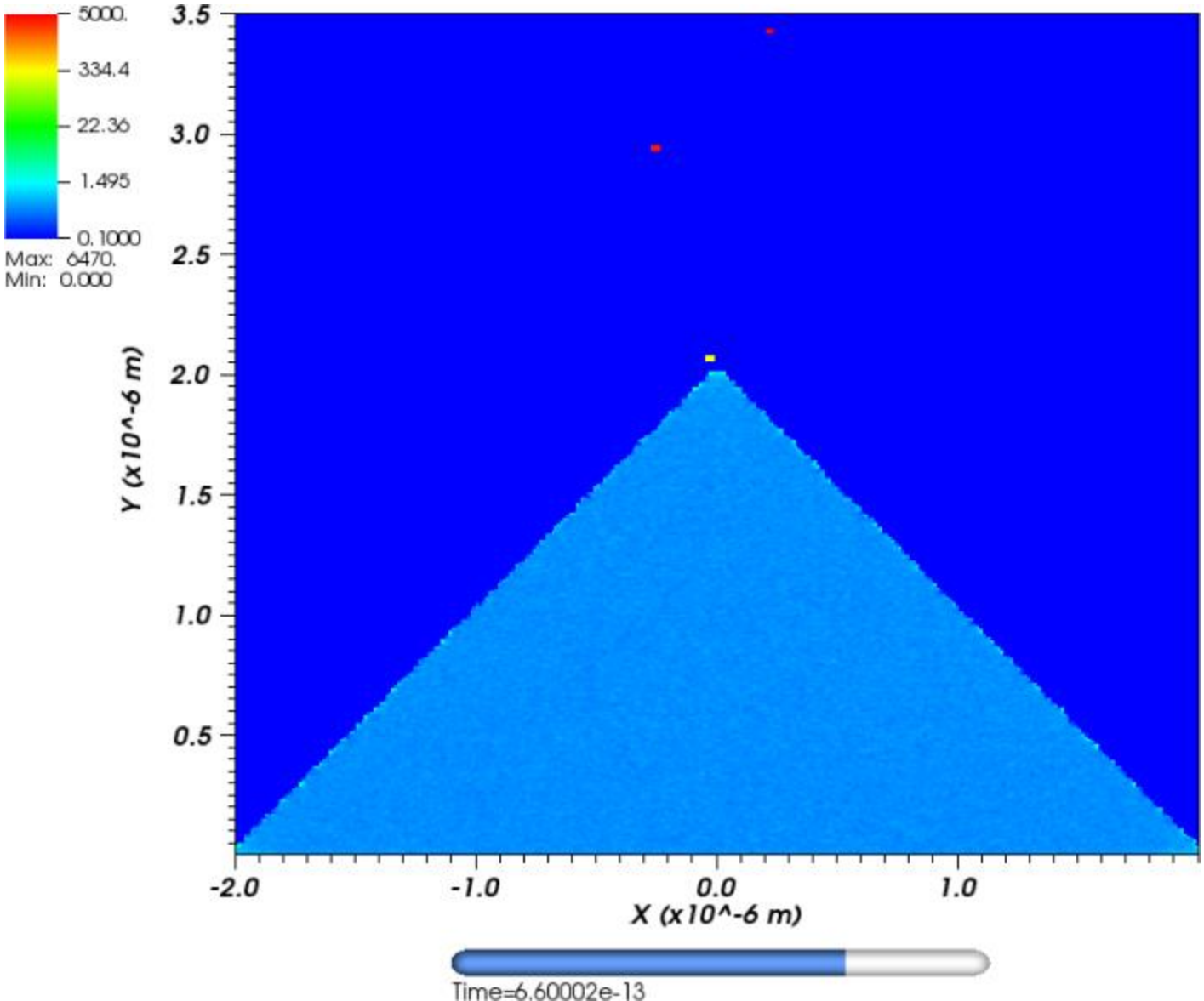
PIC - Electron Energy Pt.II



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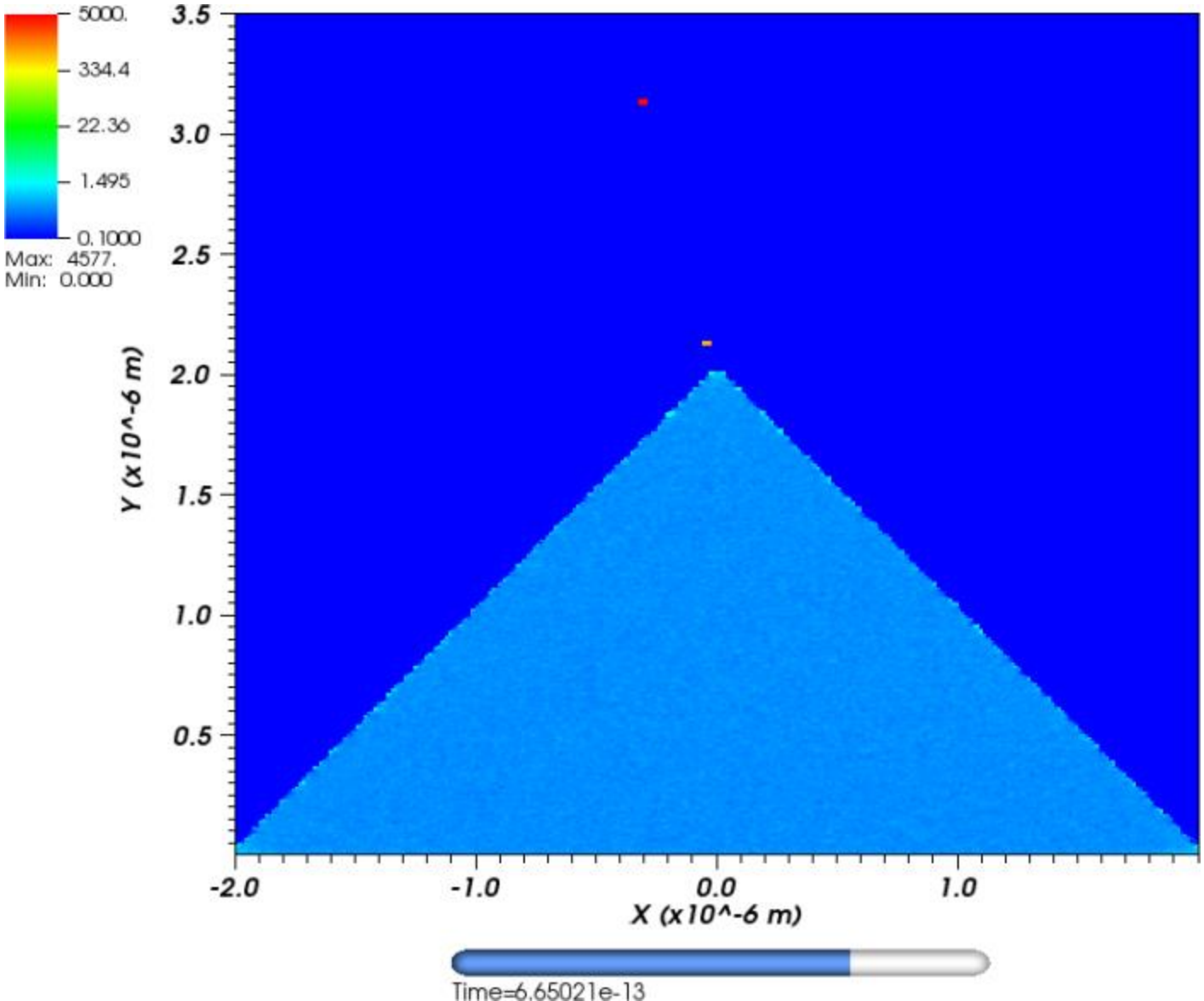
PIC - Electron Energy Pt.II



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- No ionization
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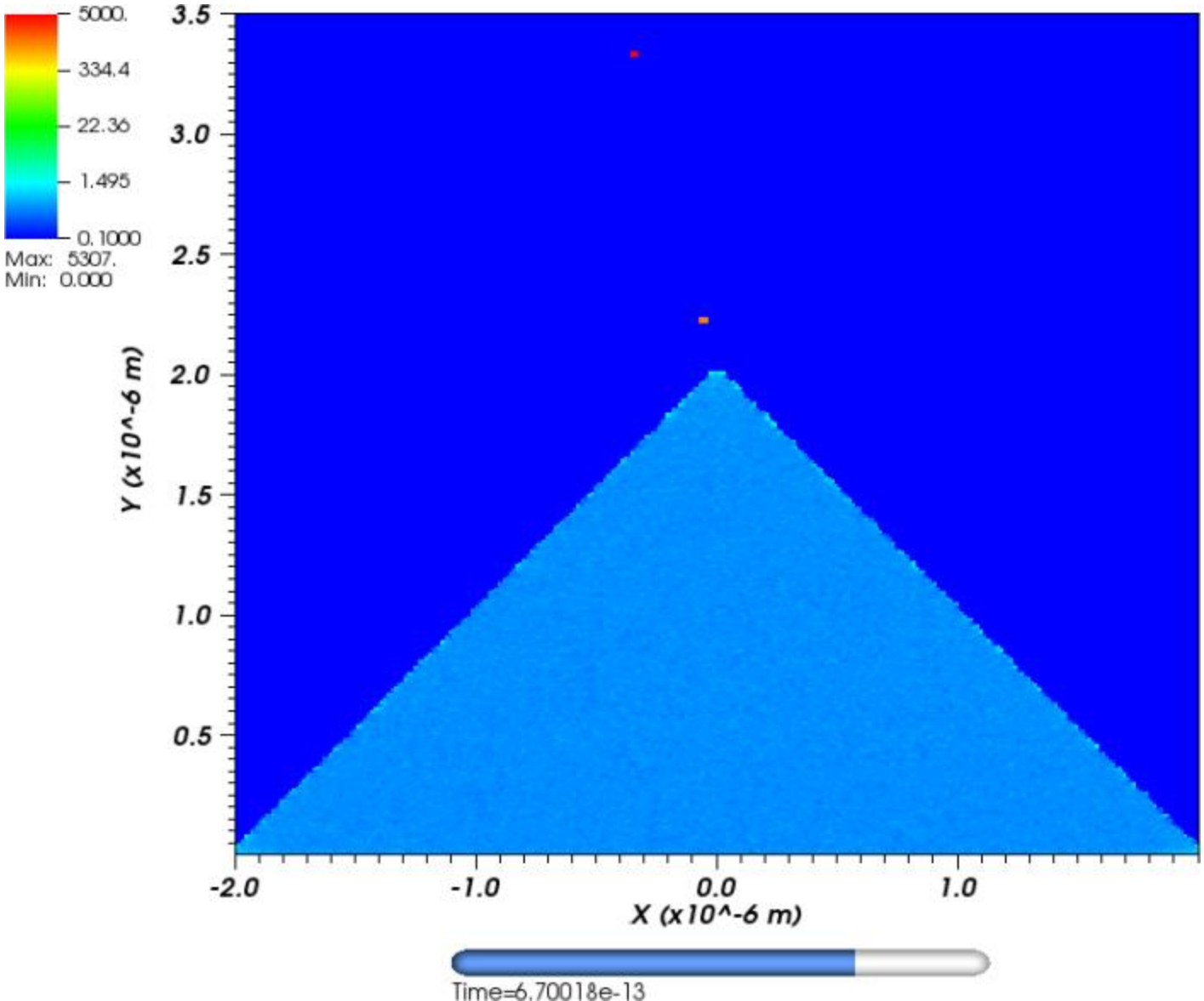
PIC - Electron Energy Pt.II



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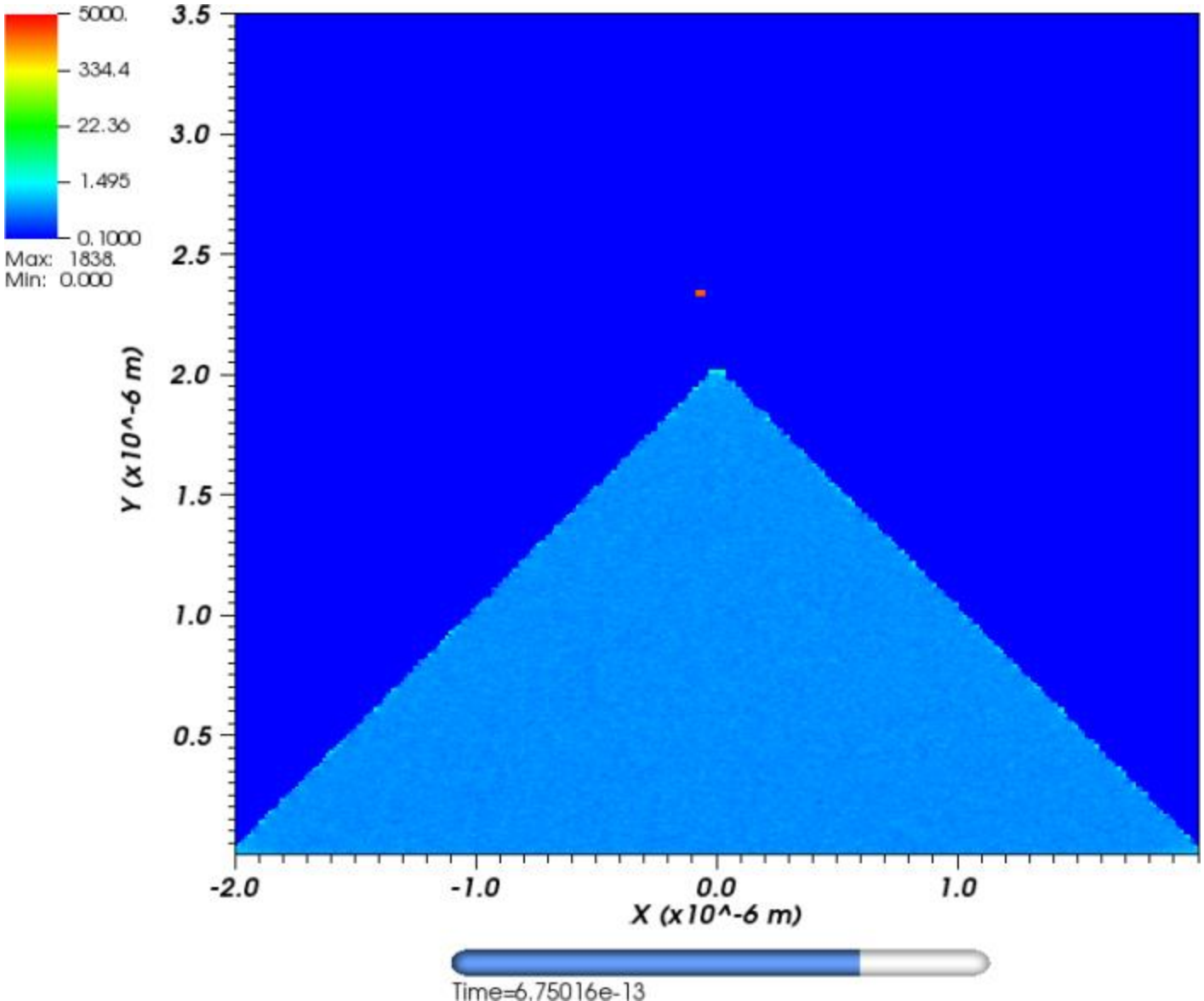
PIC - Electron Energy Pt.II



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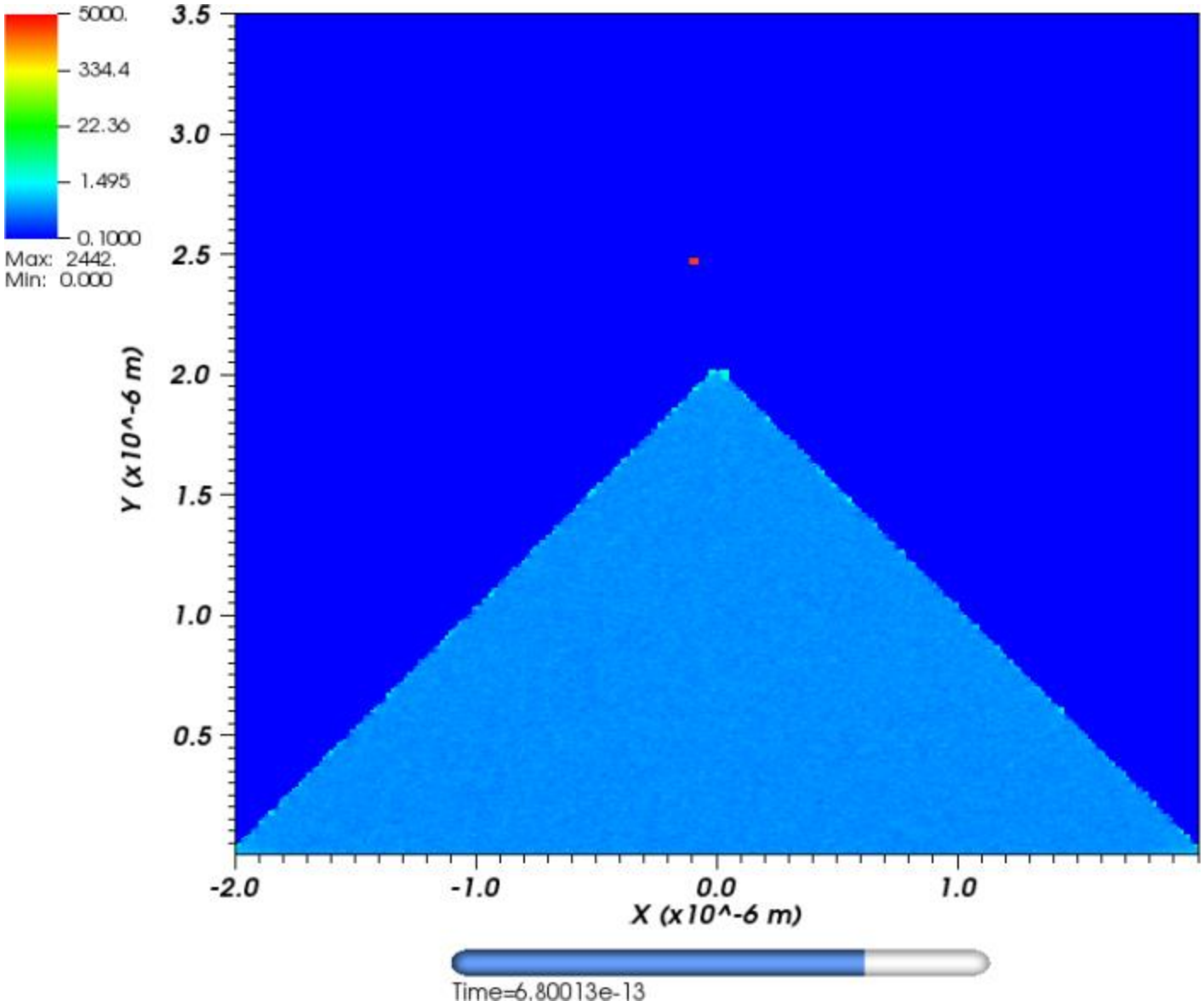

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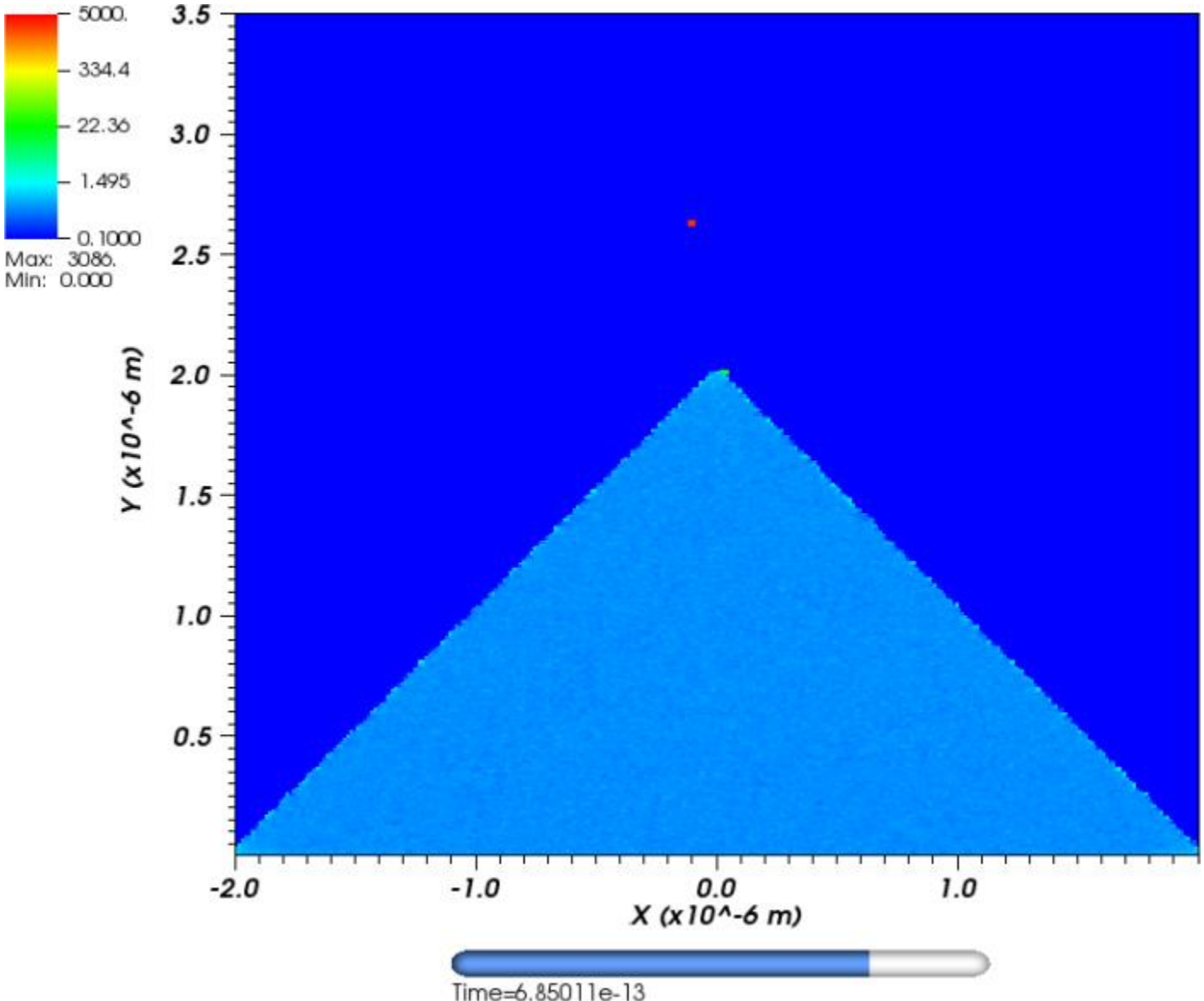

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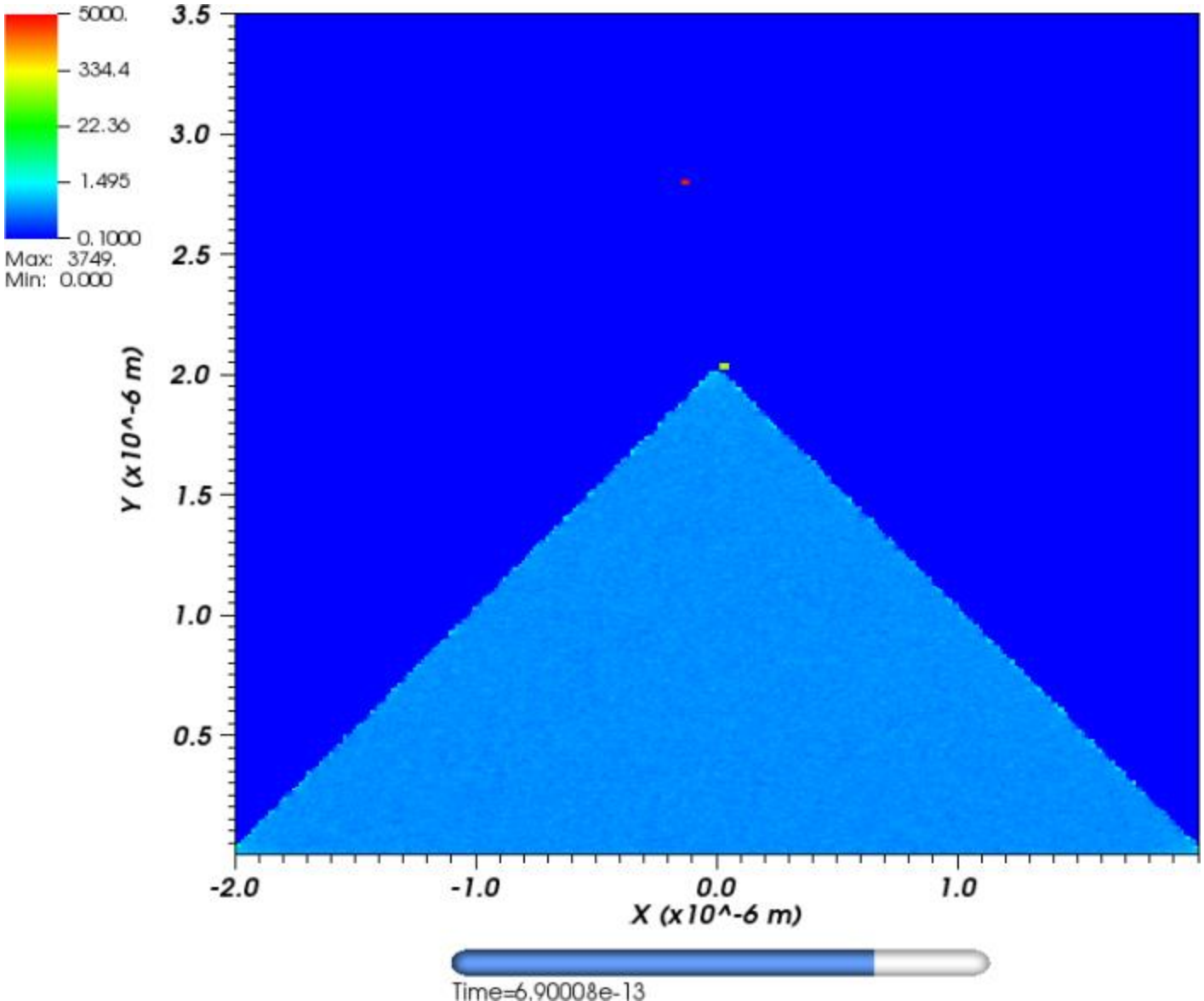
PIC - Electron Energy Pt.II



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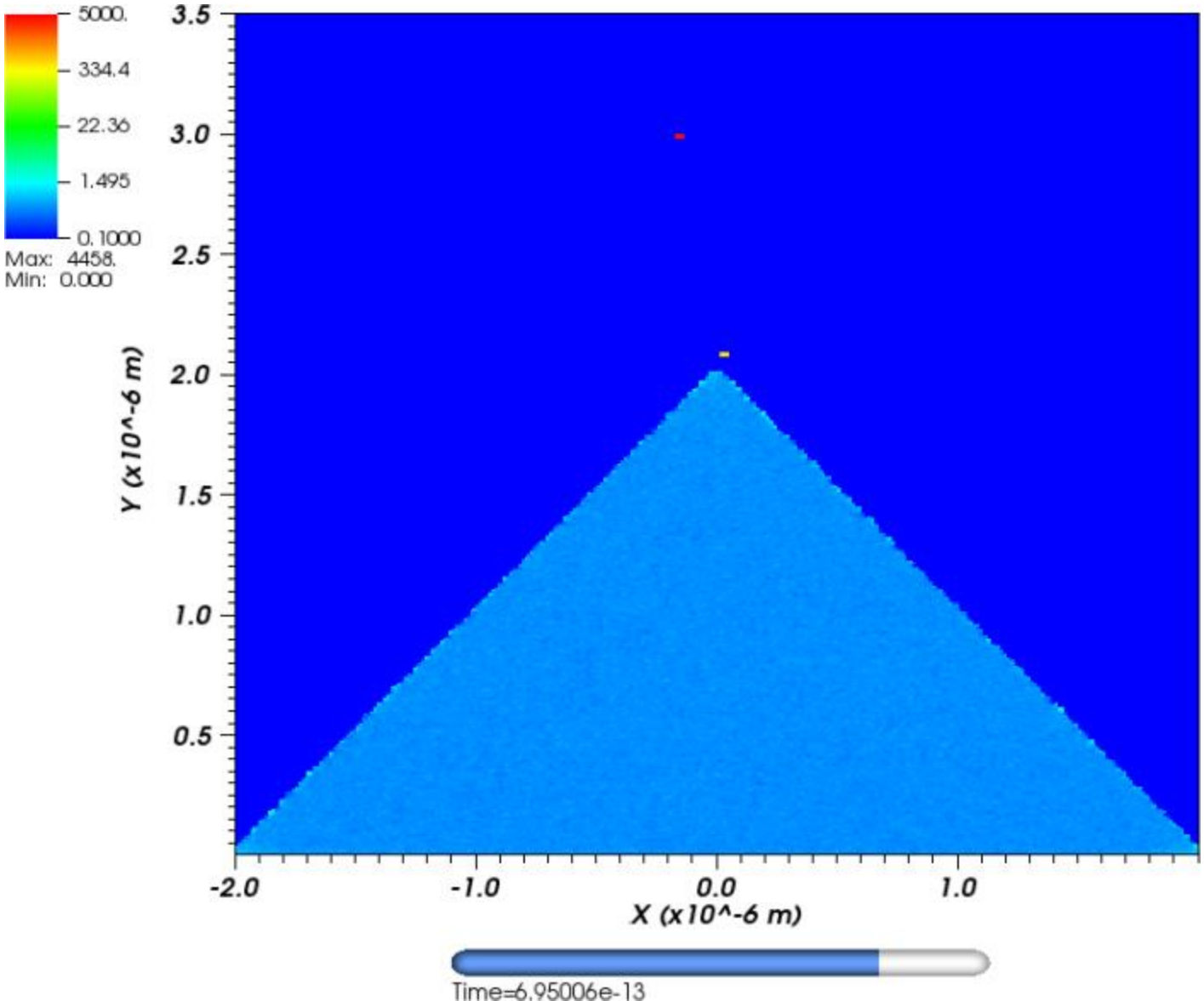

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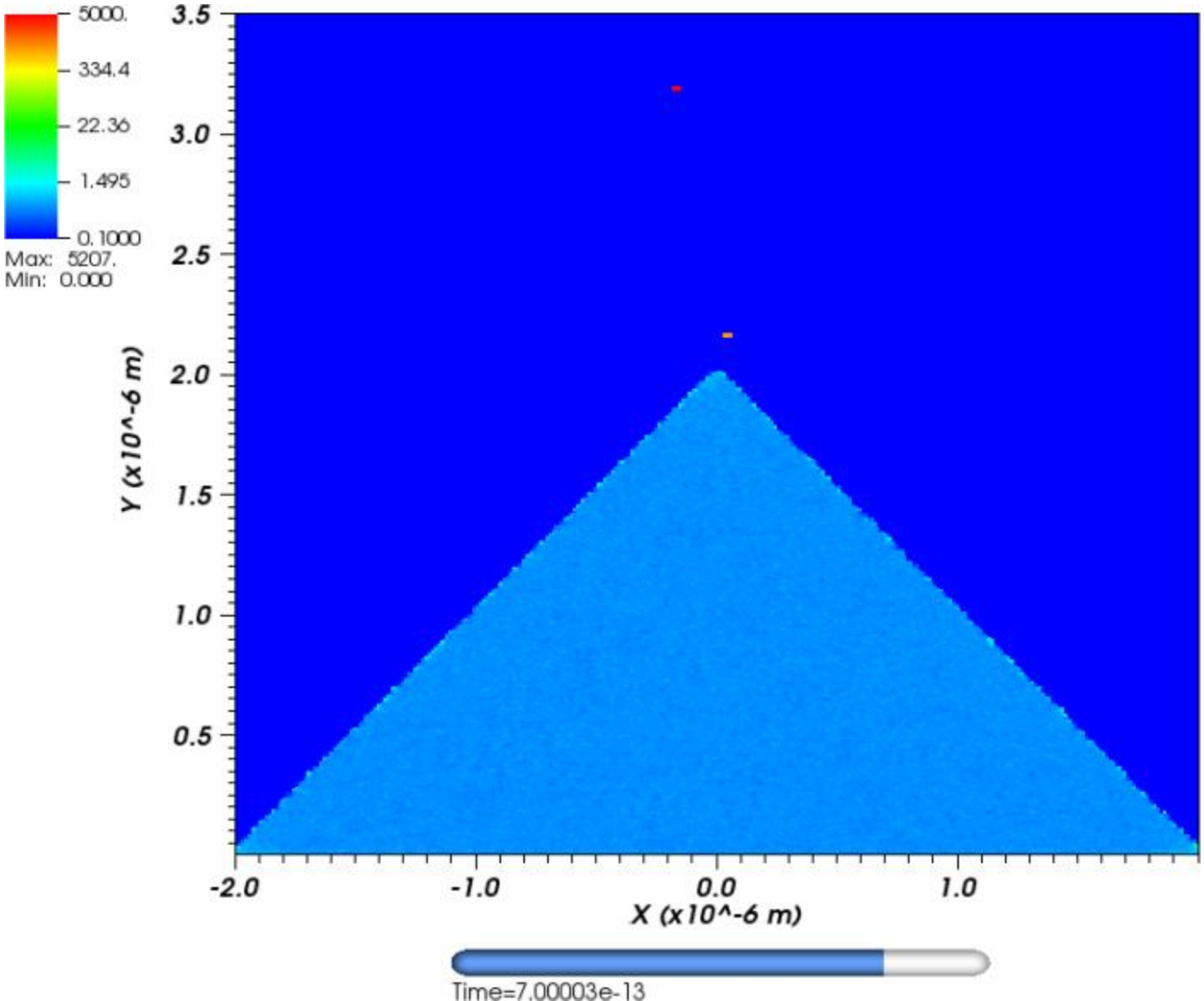
PIC - Electron Energy Pt.II



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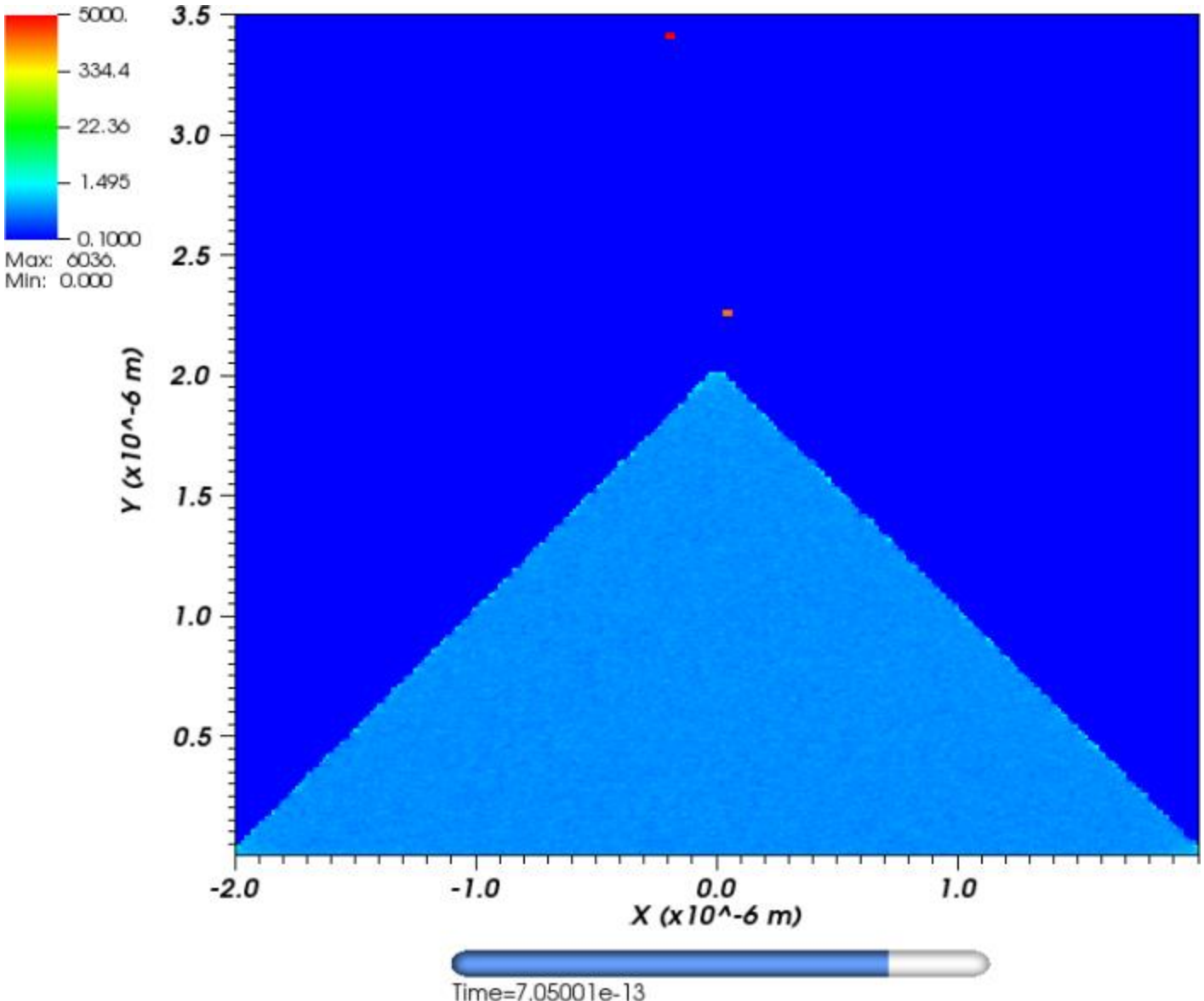

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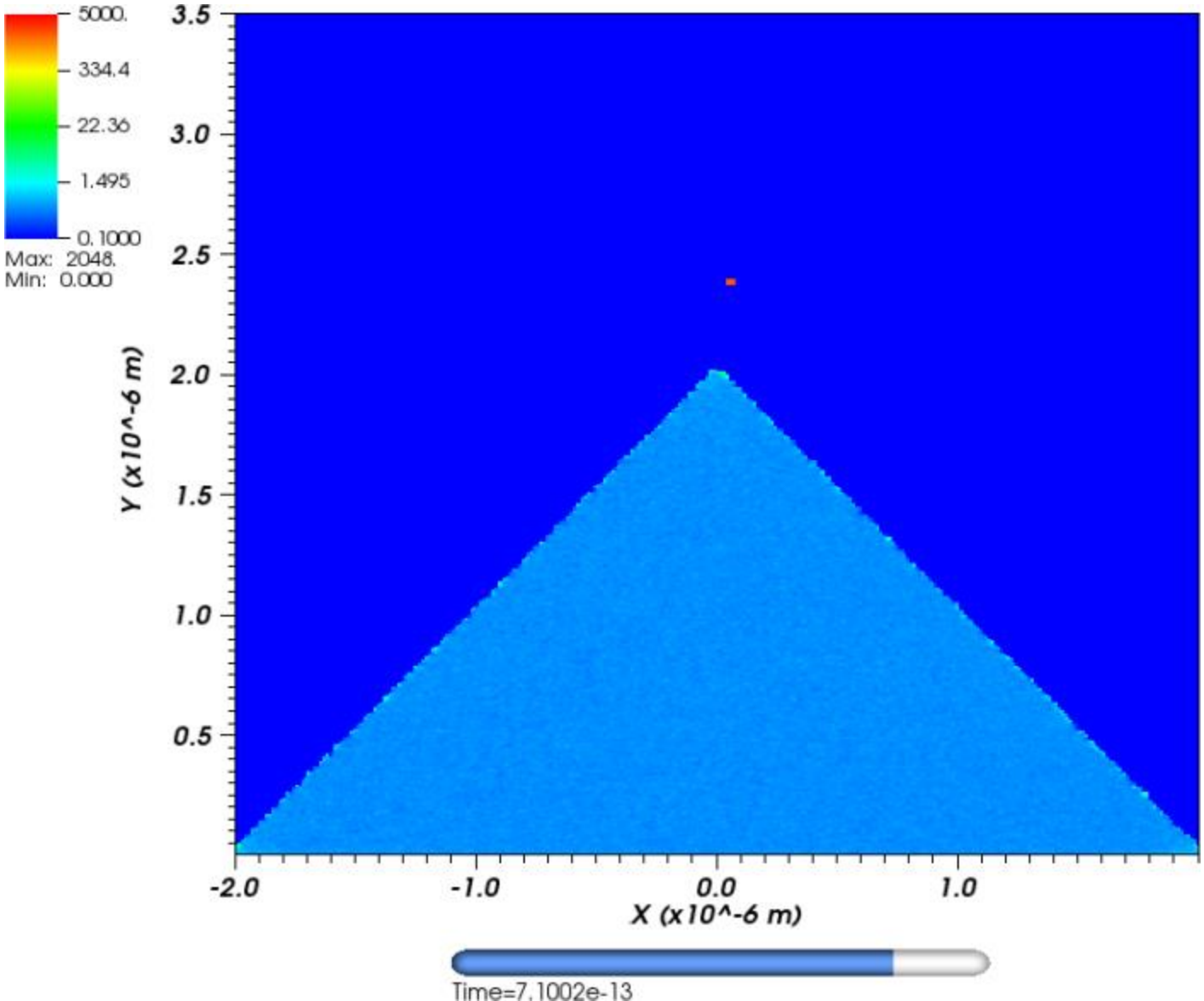

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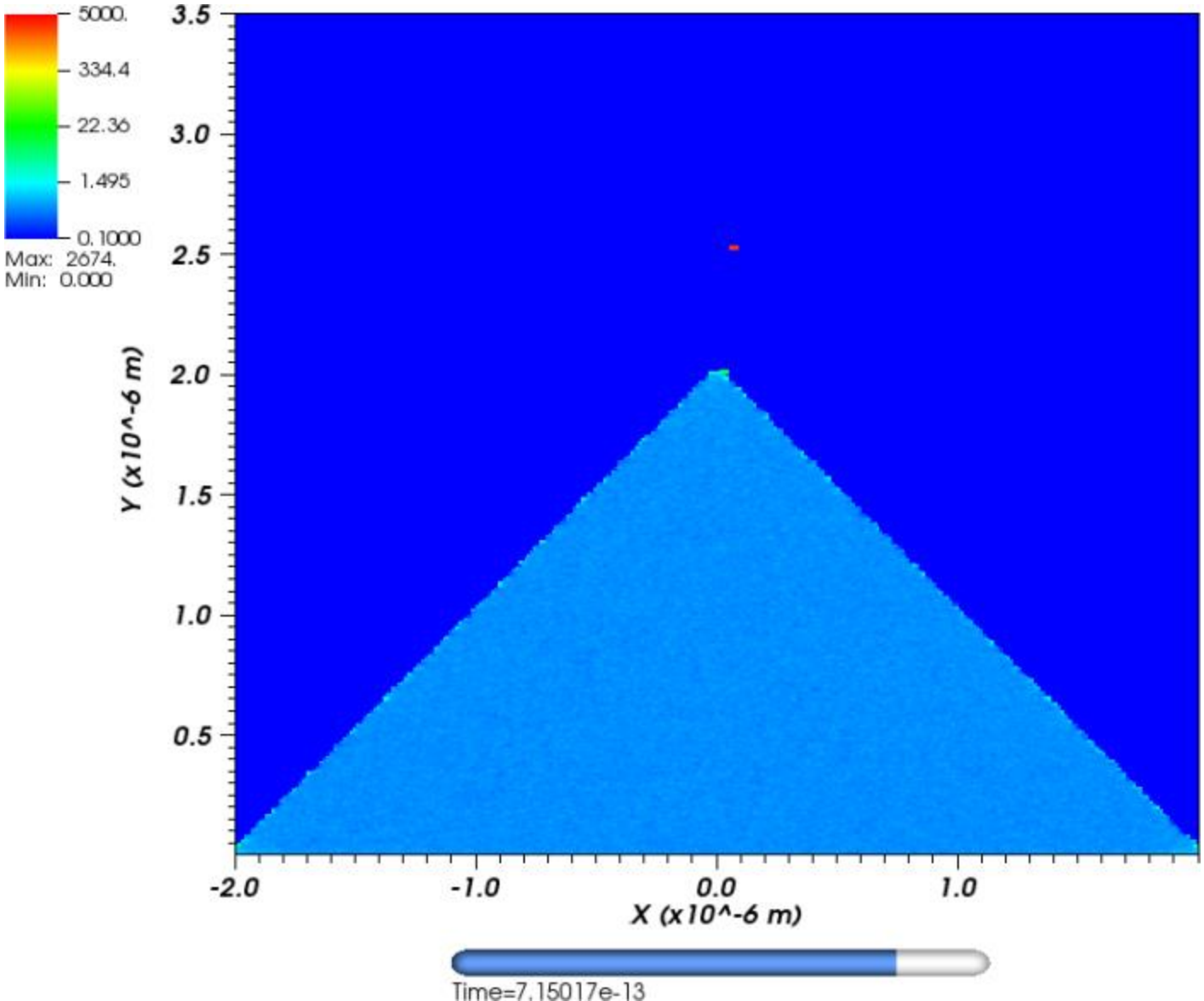

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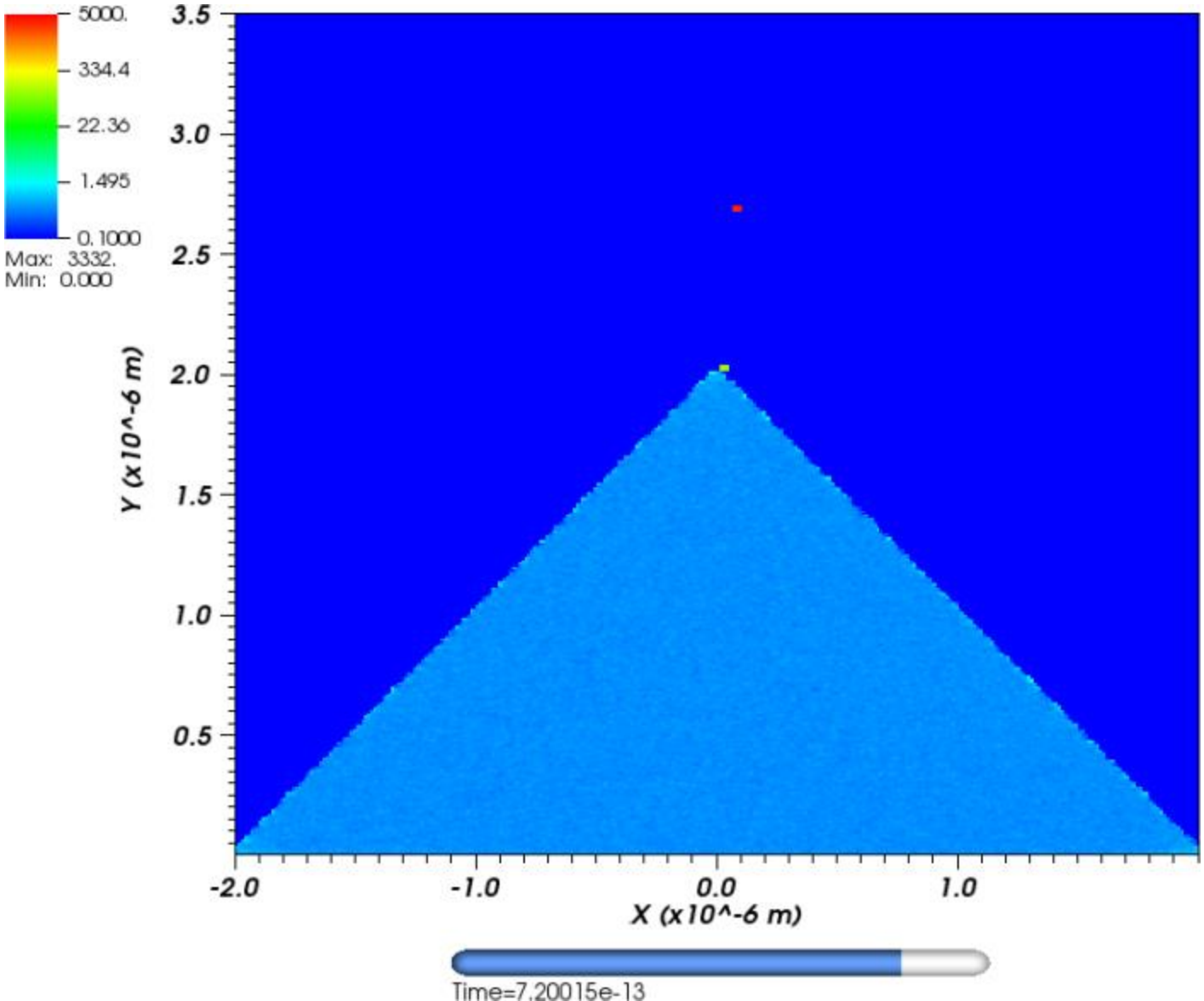

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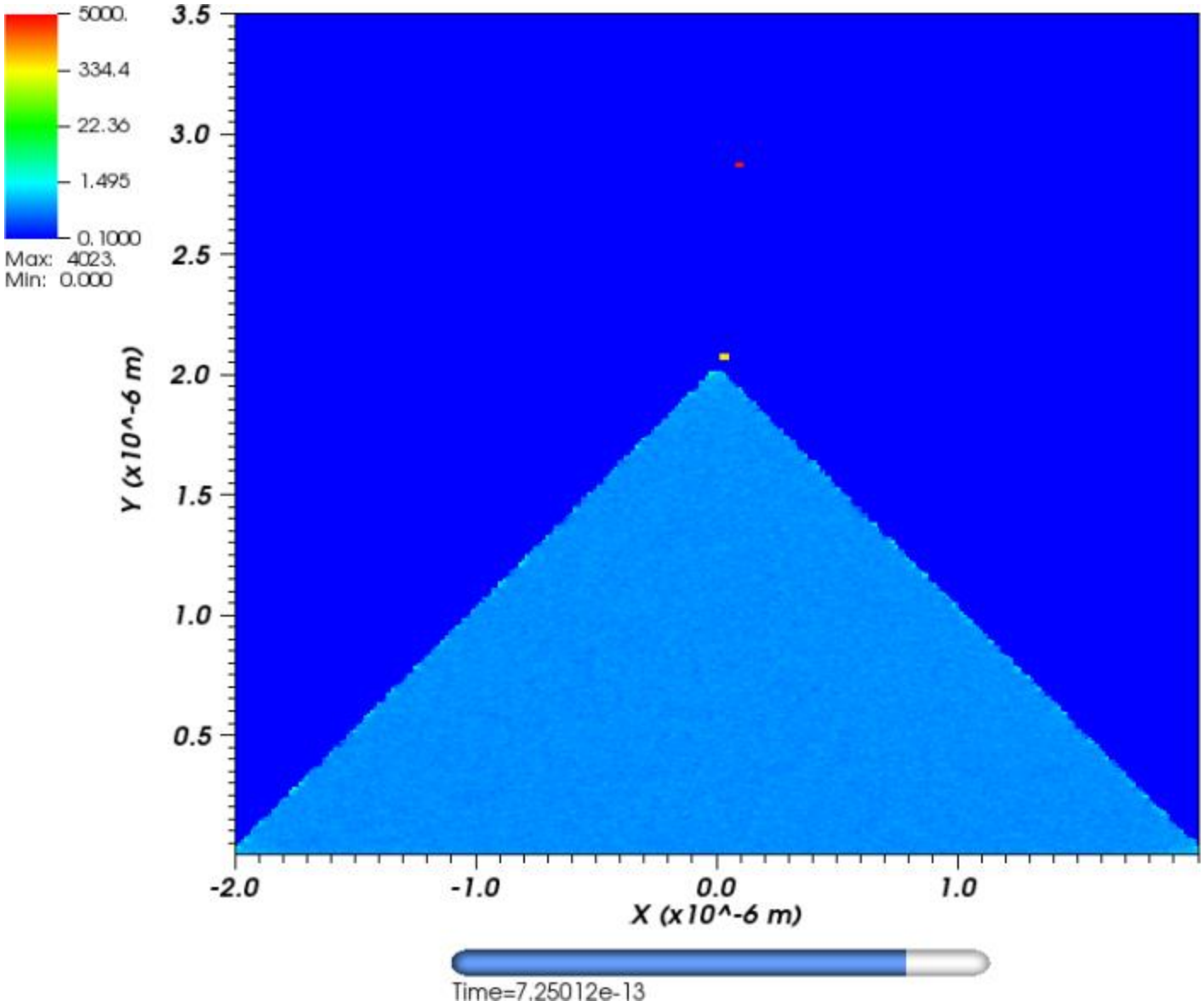

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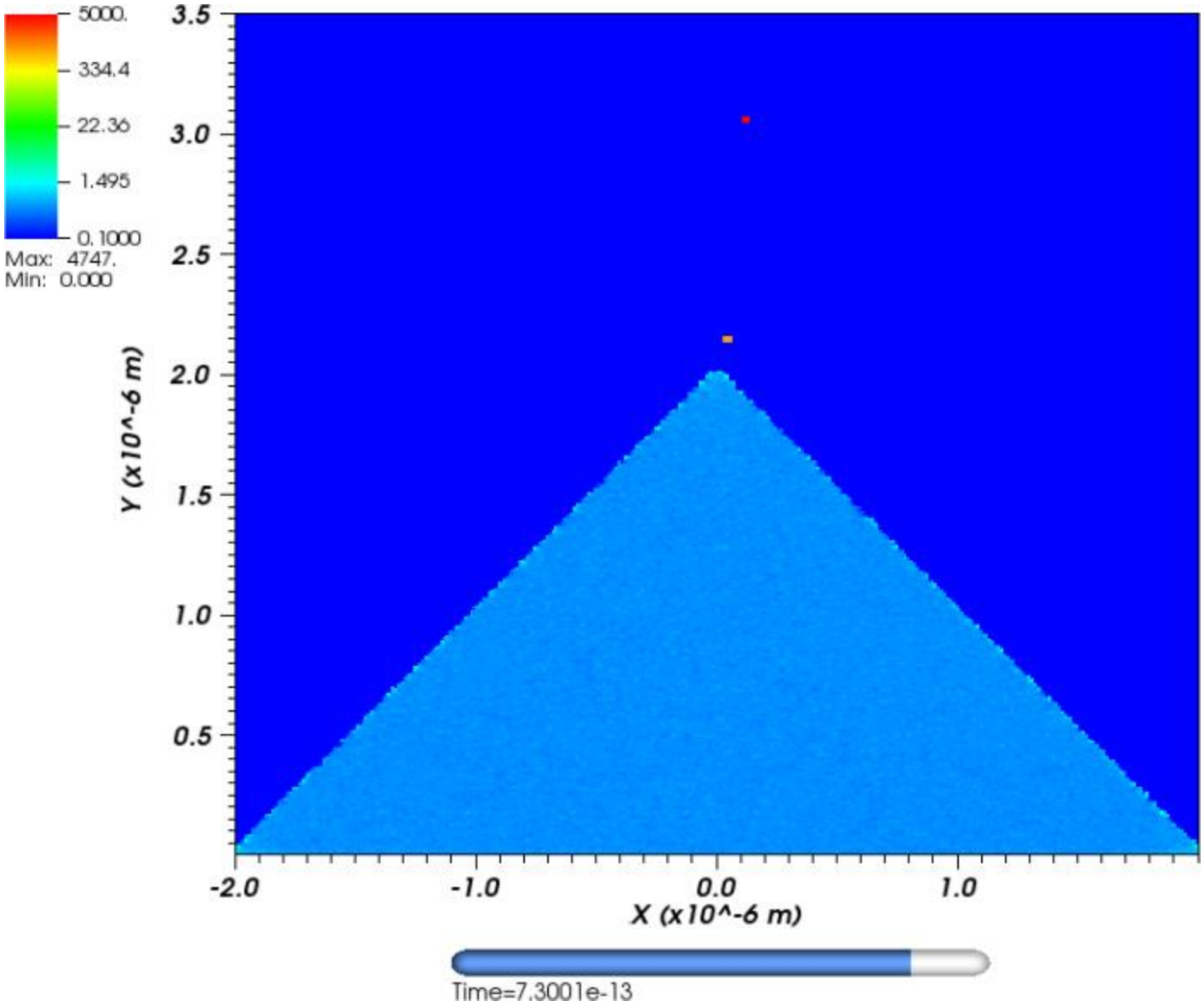

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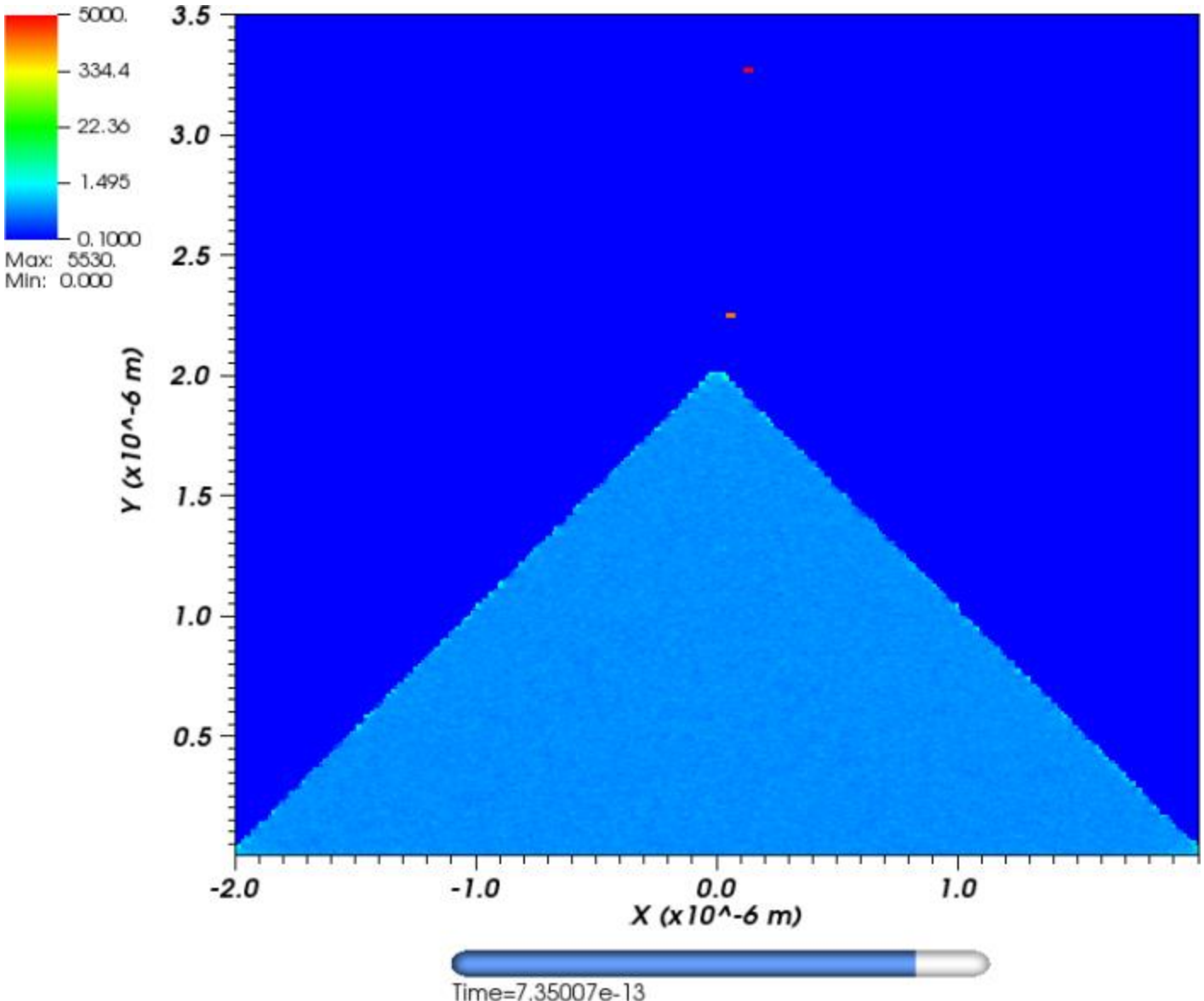

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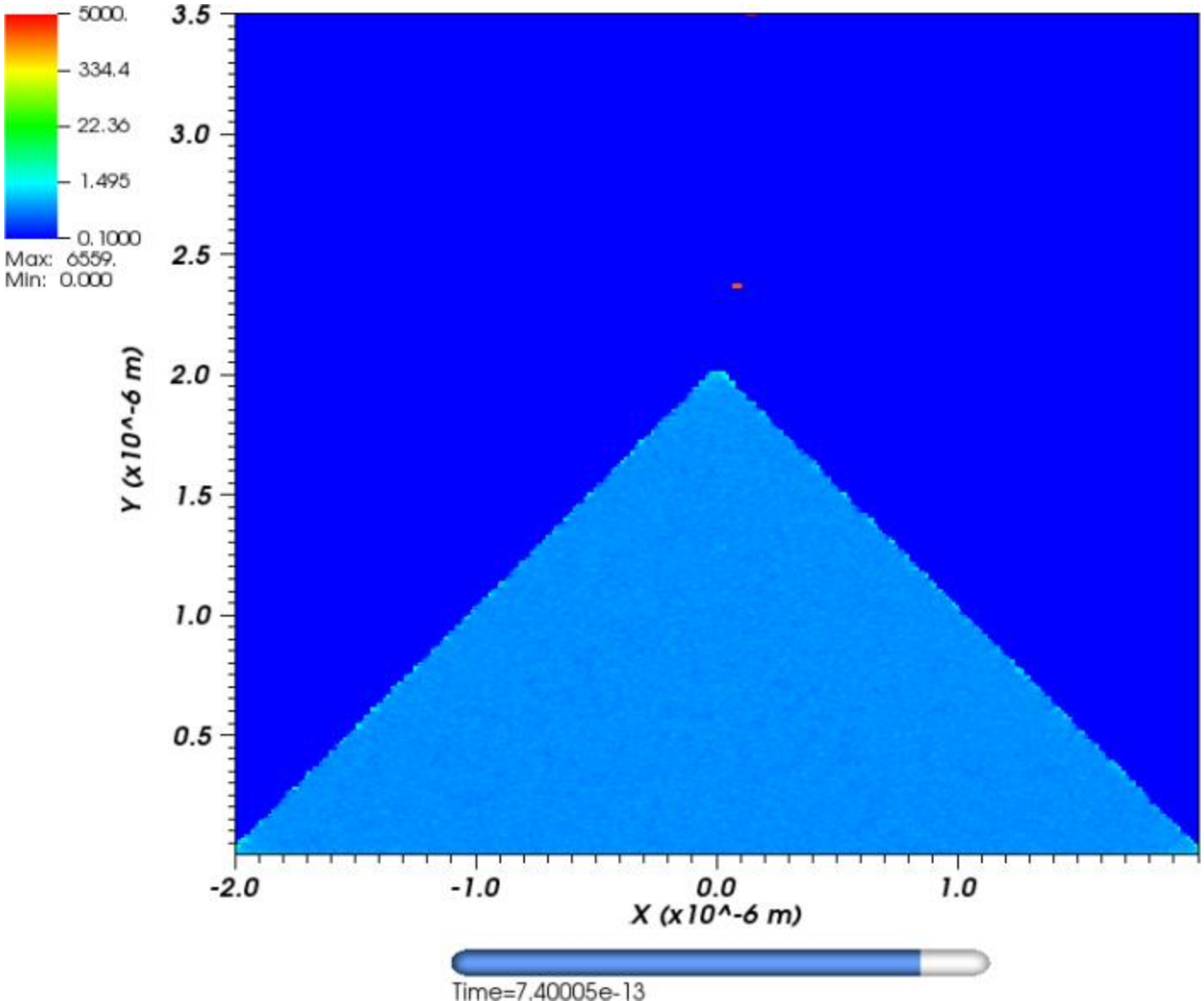

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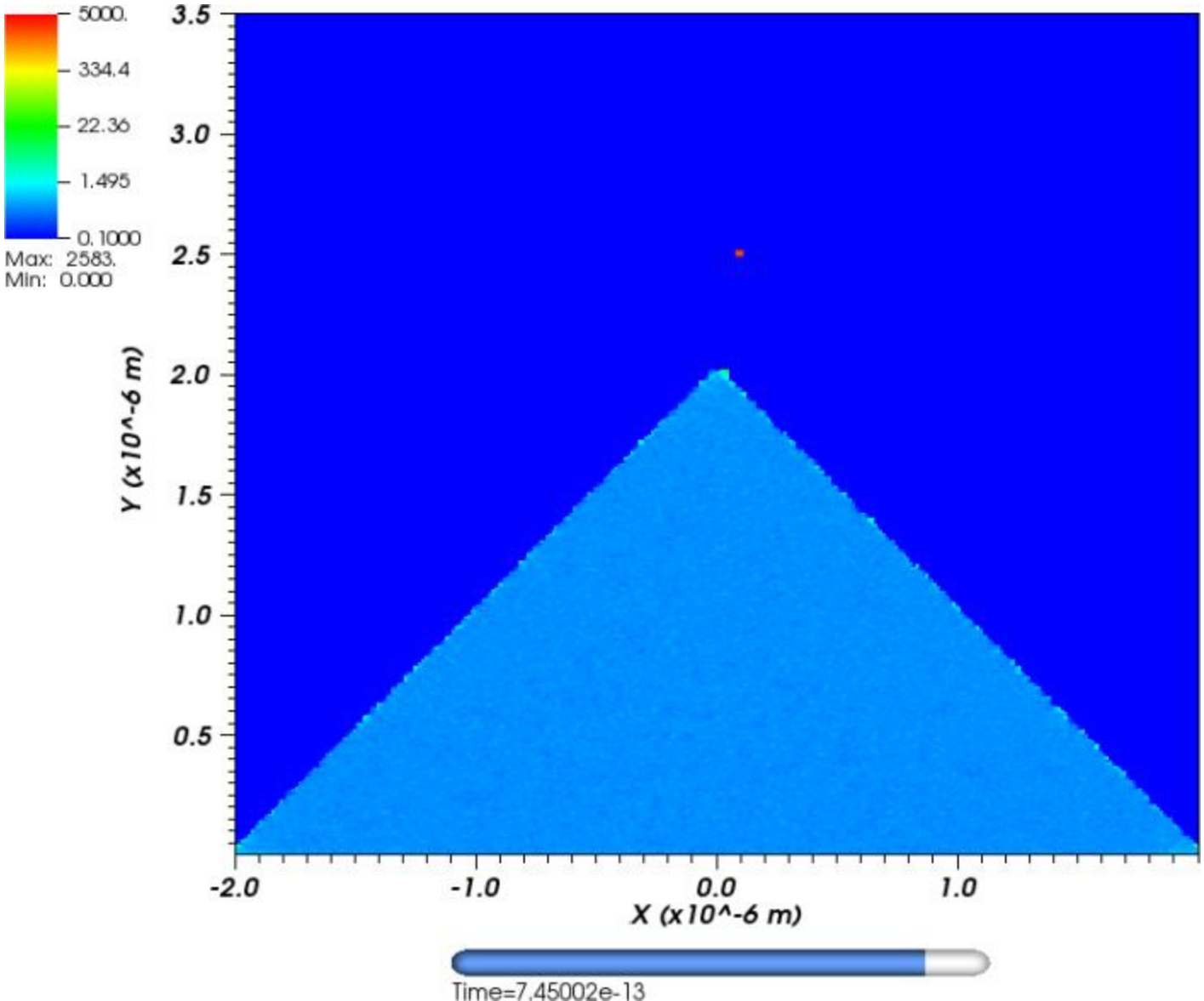

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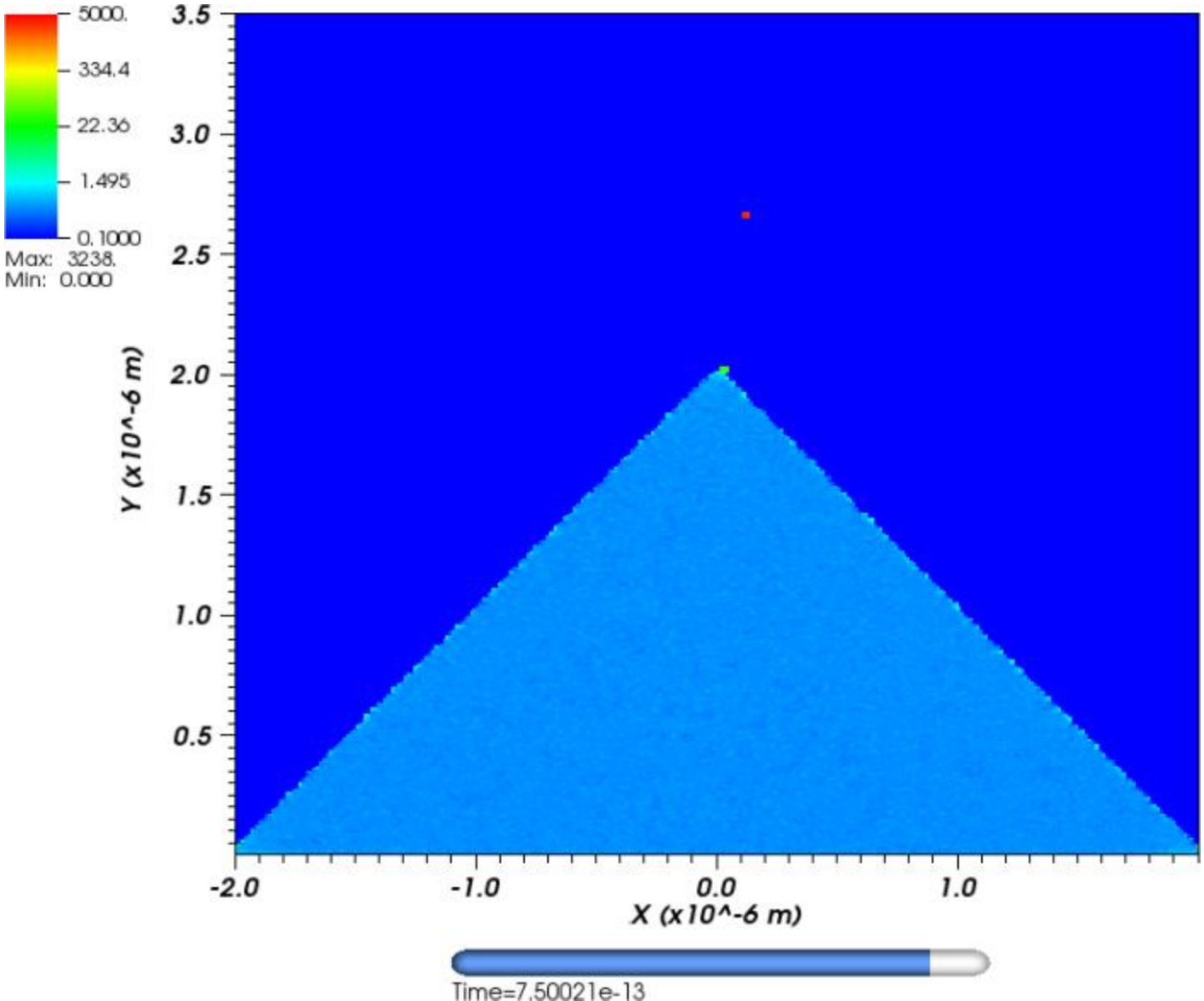

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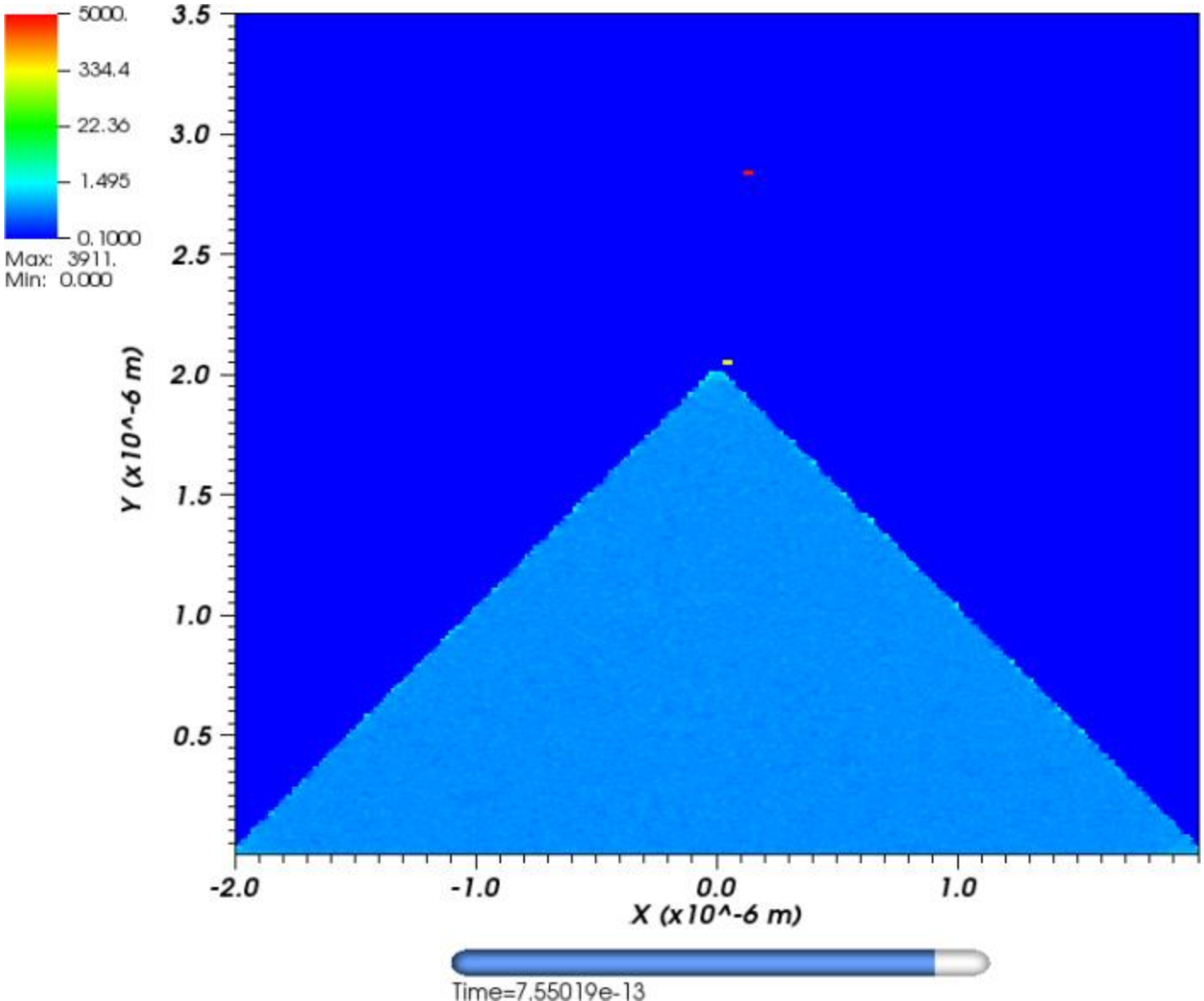

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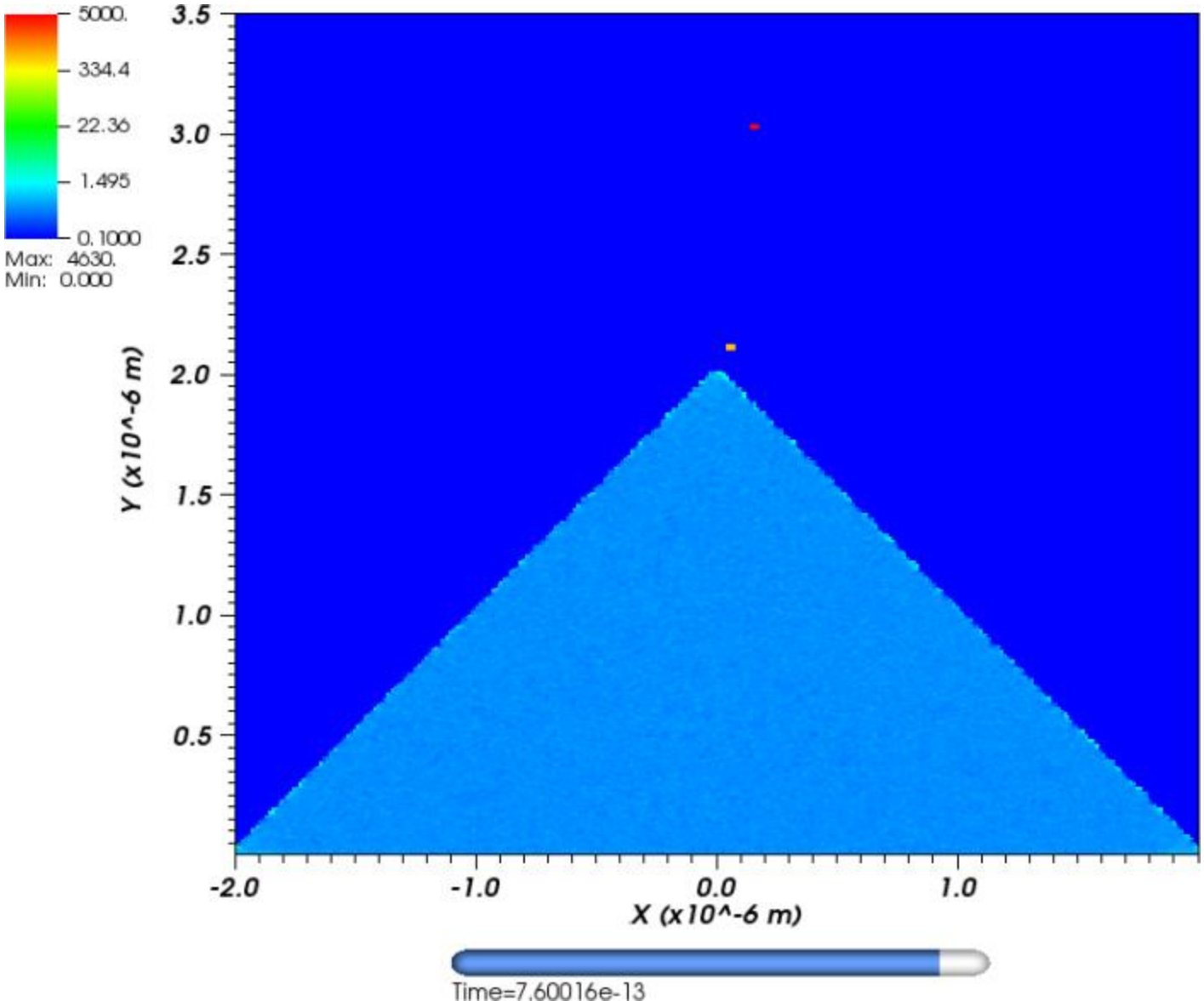

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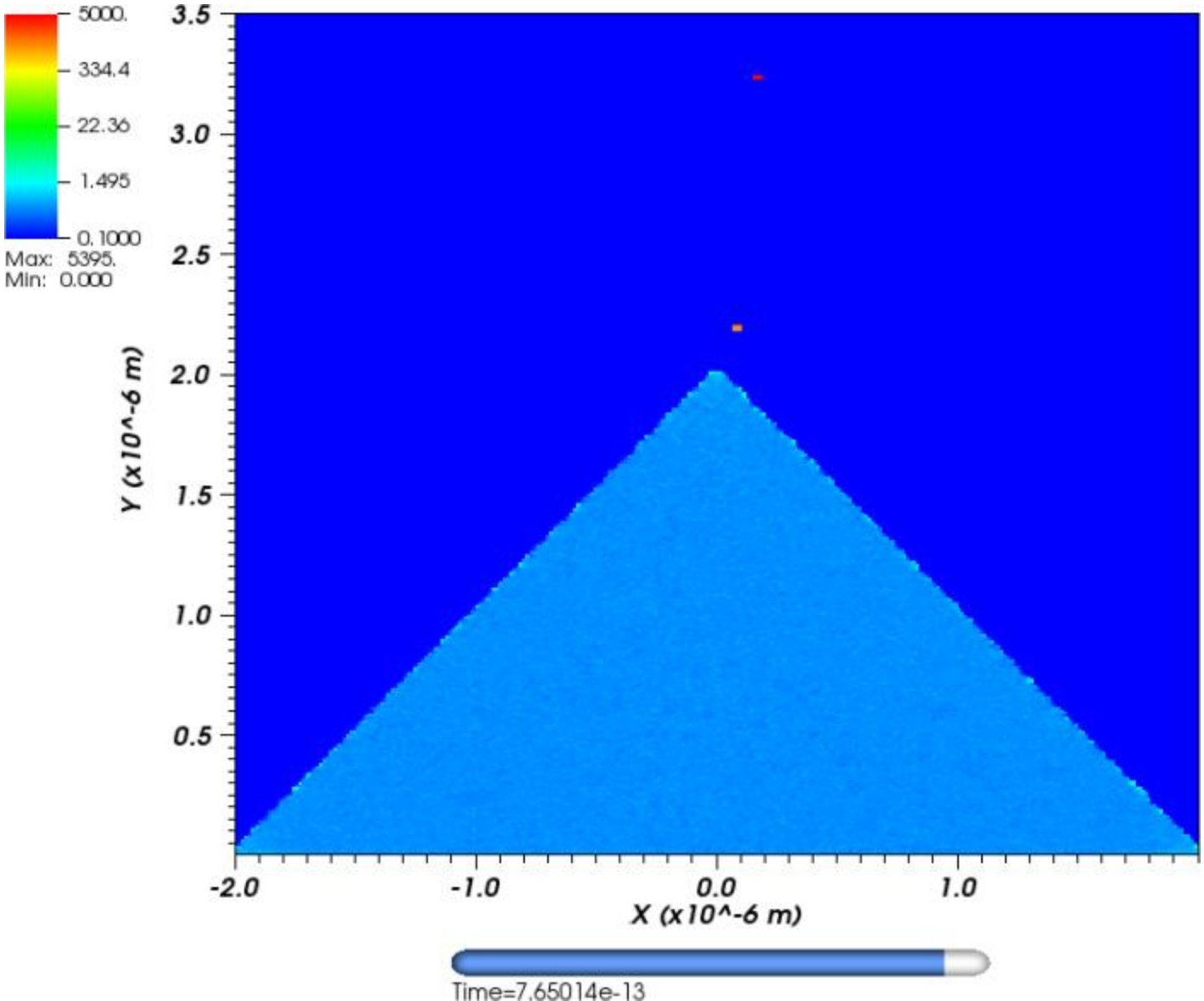

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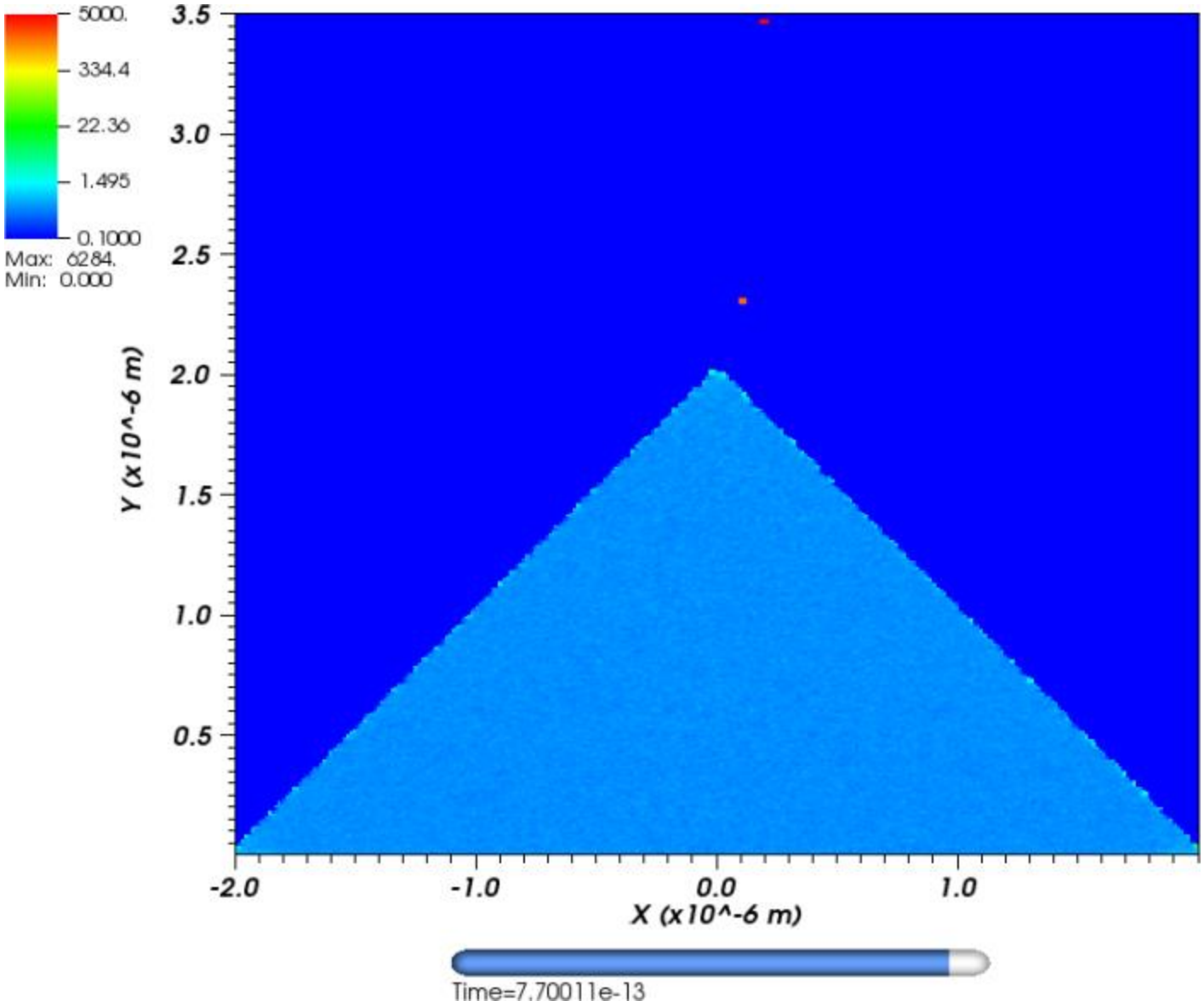

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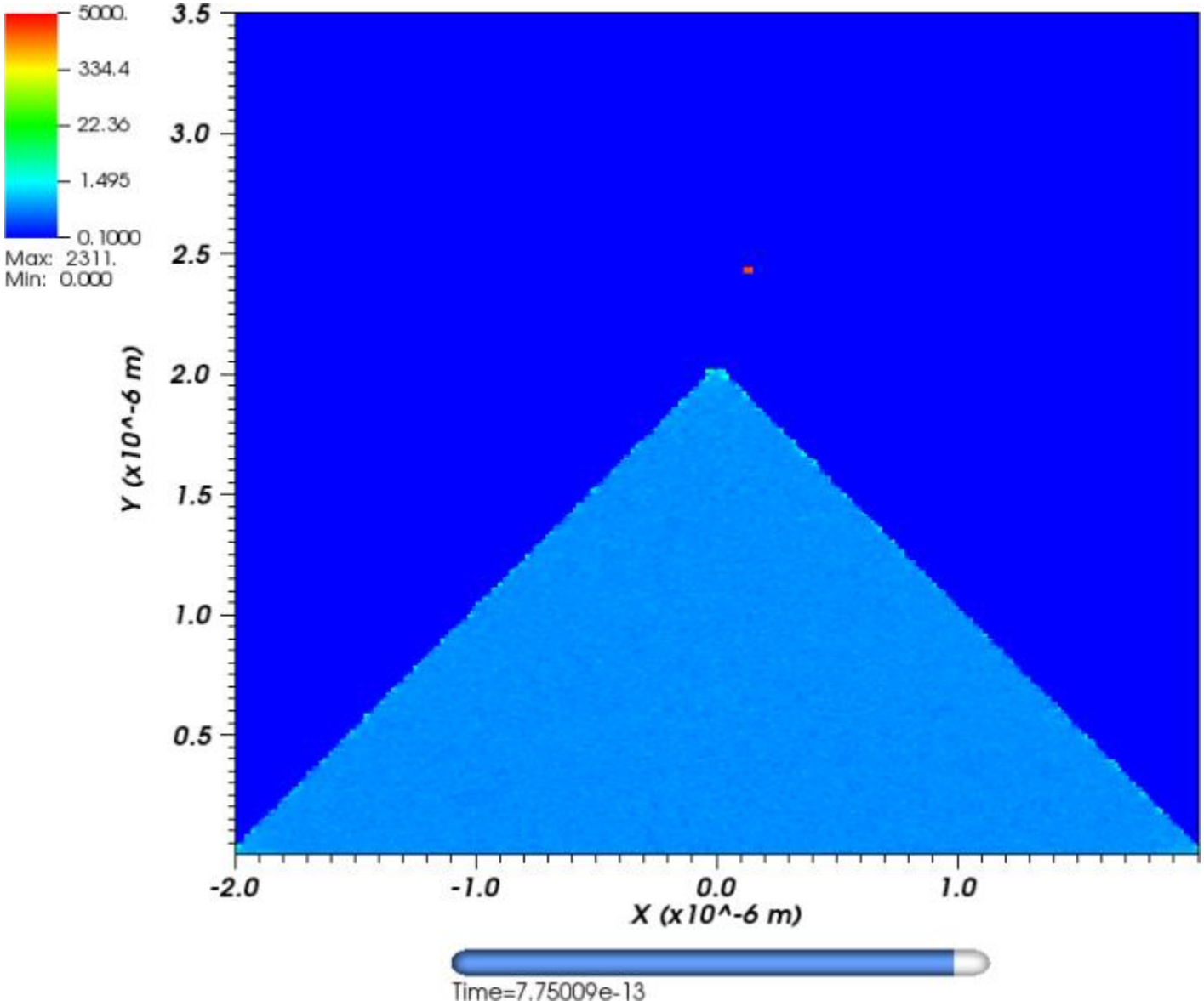

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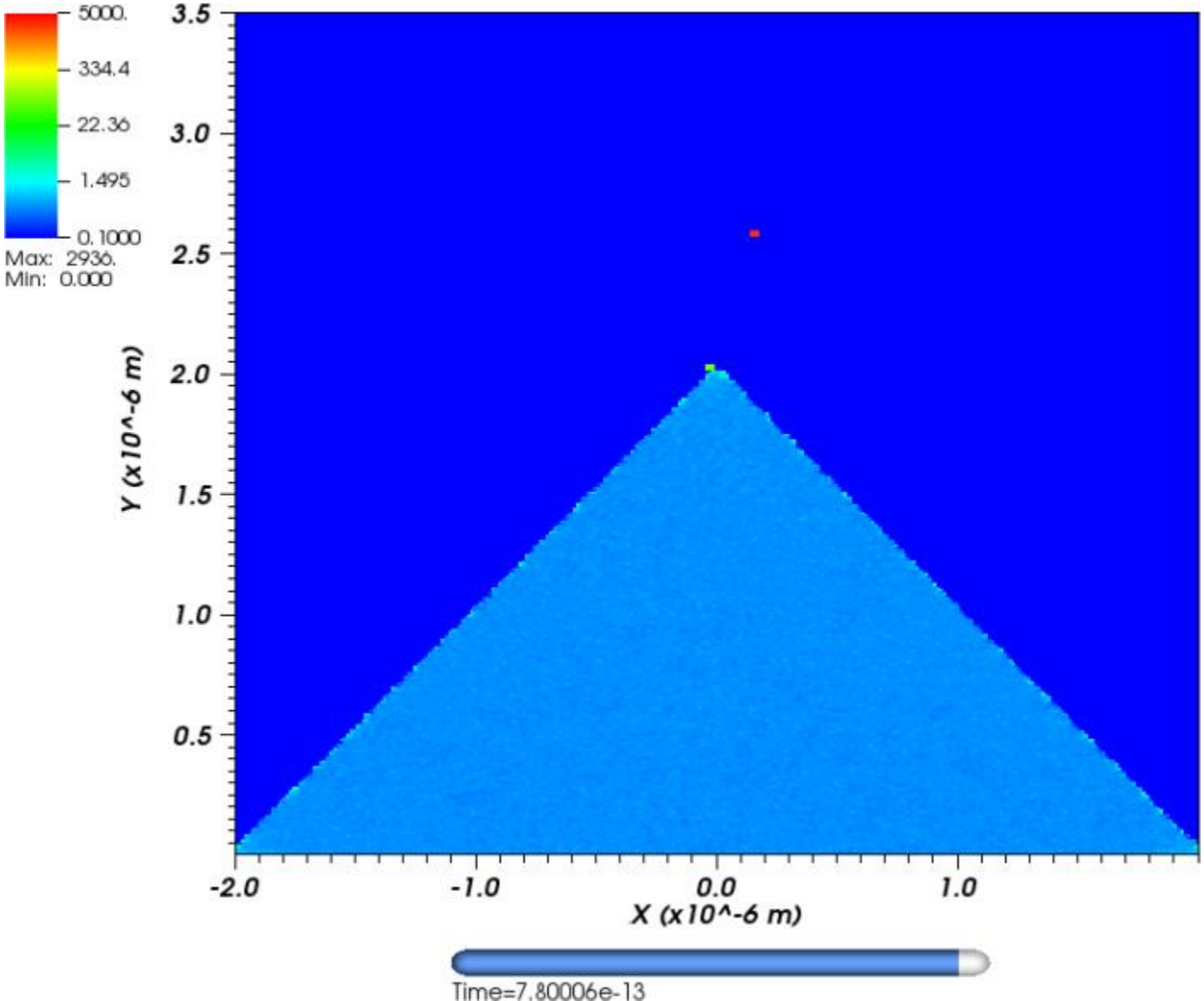

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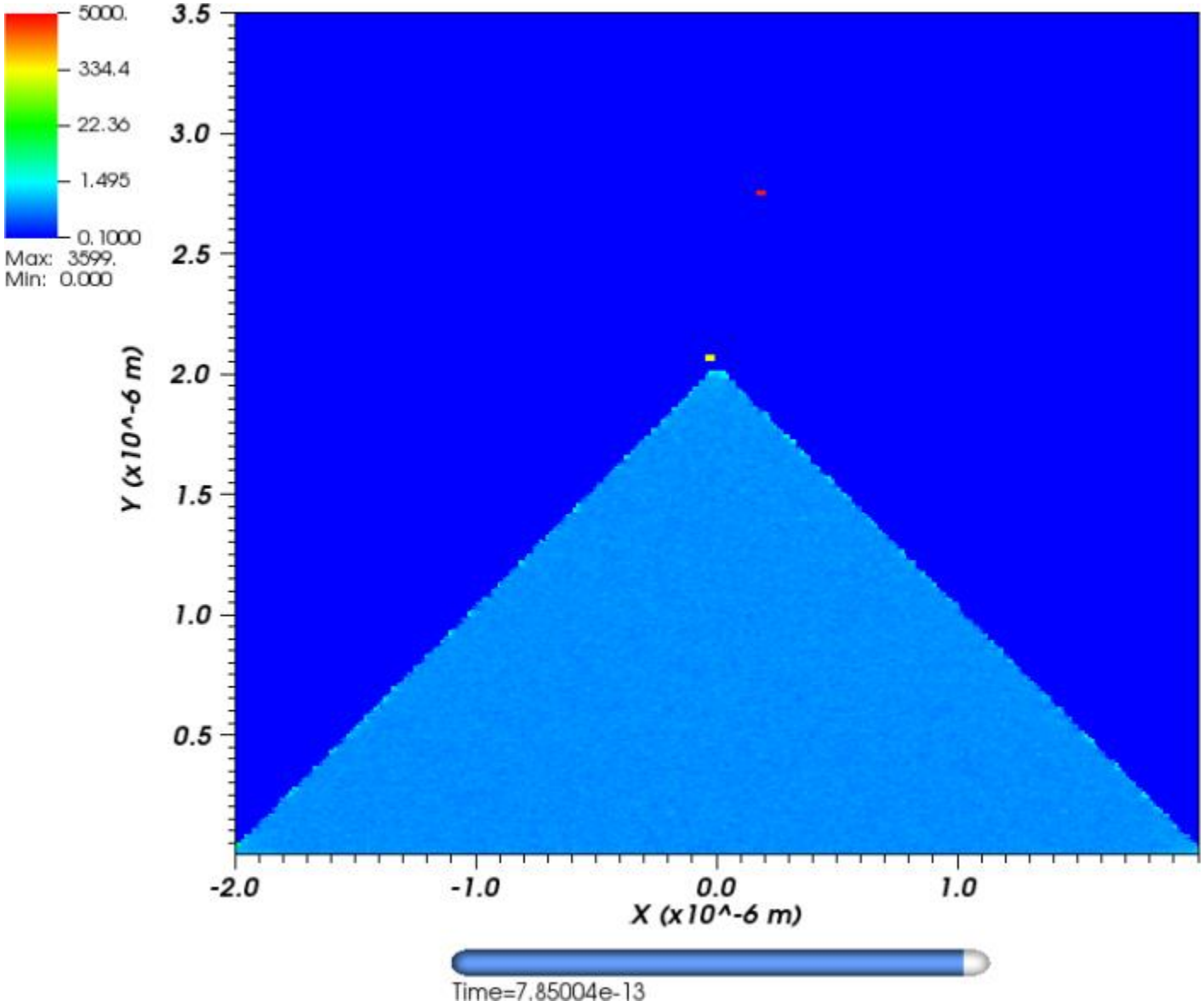

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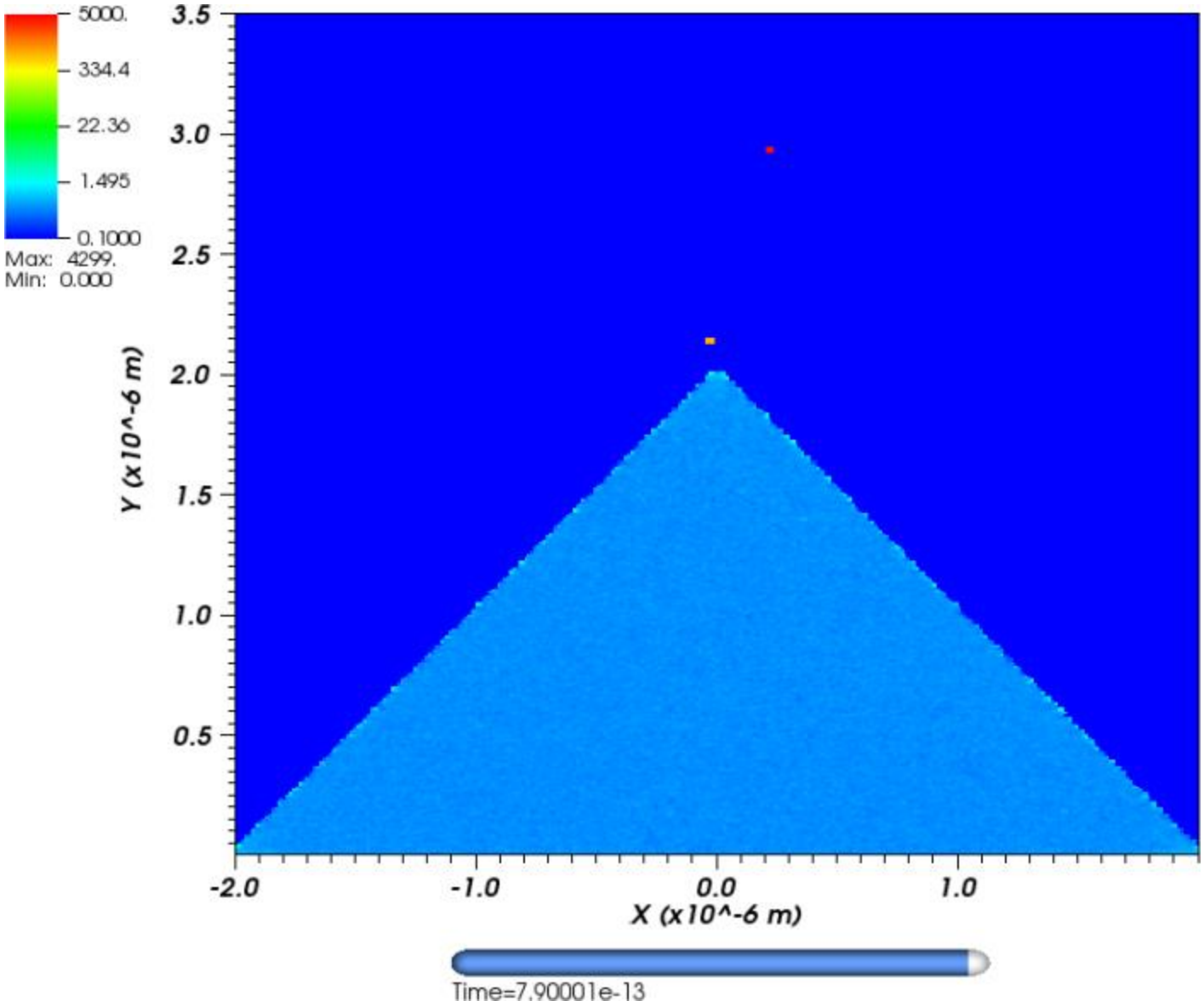

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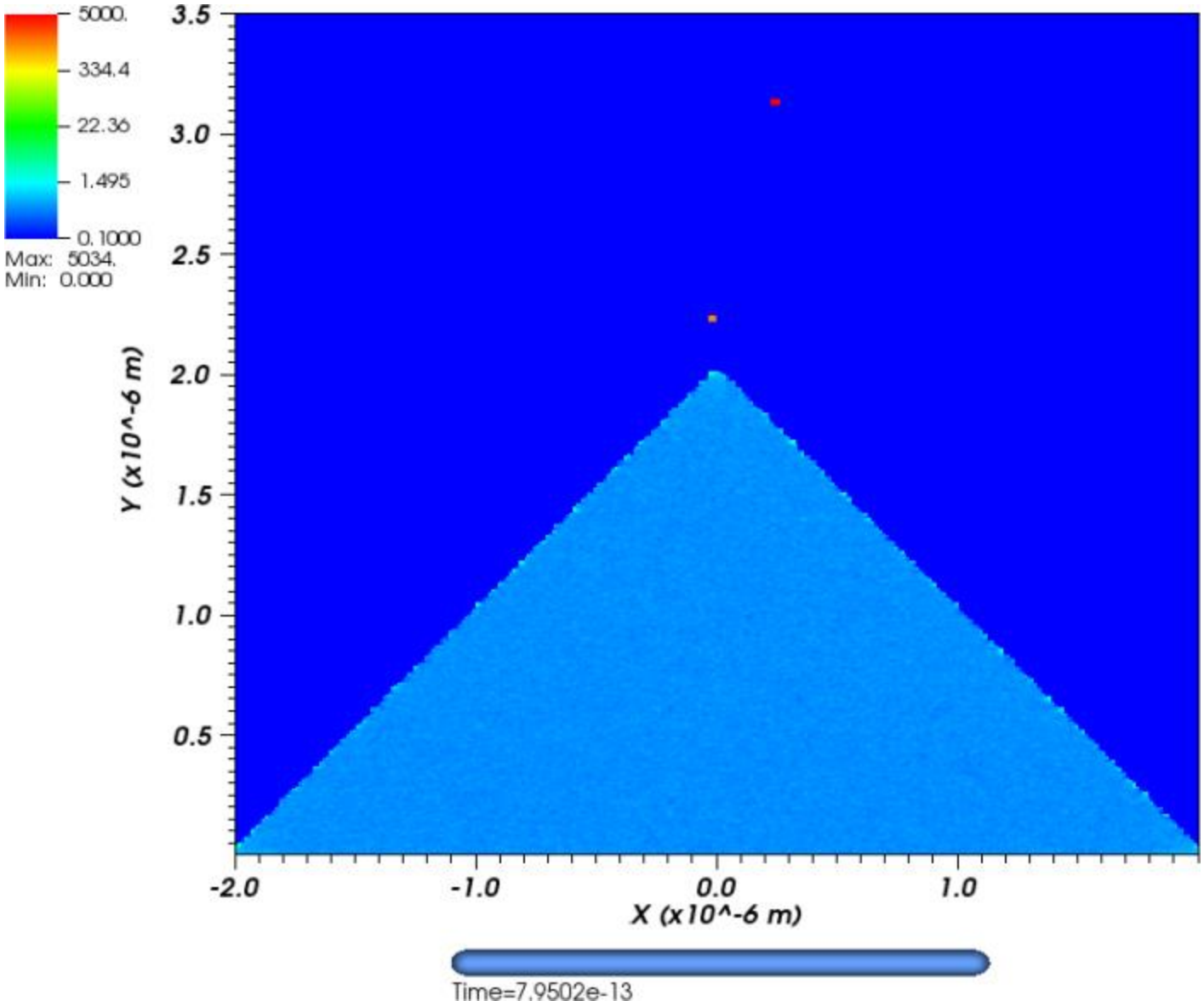

- E_y = -2 GV/m
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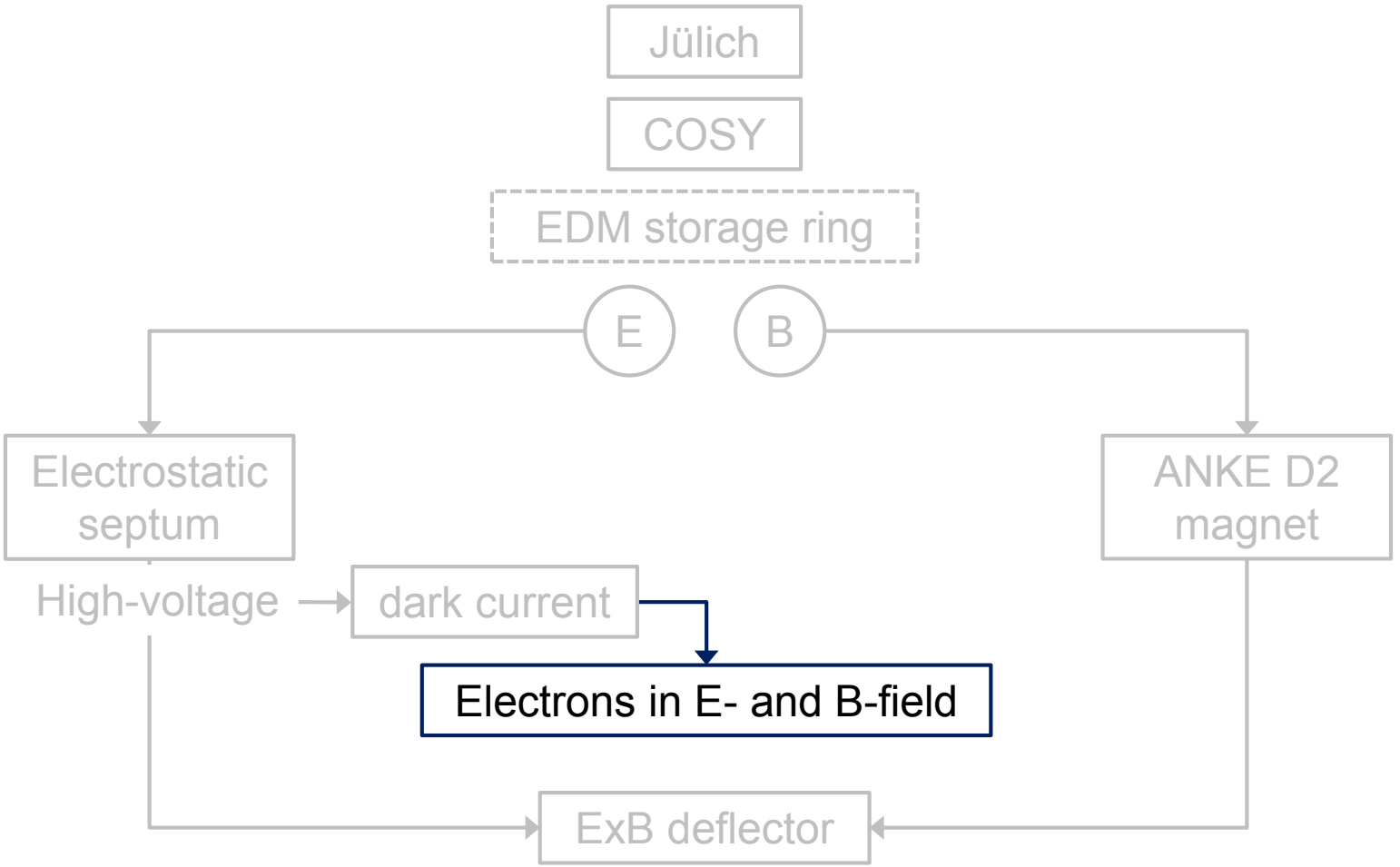
- t_{tot} = 0.8 ps

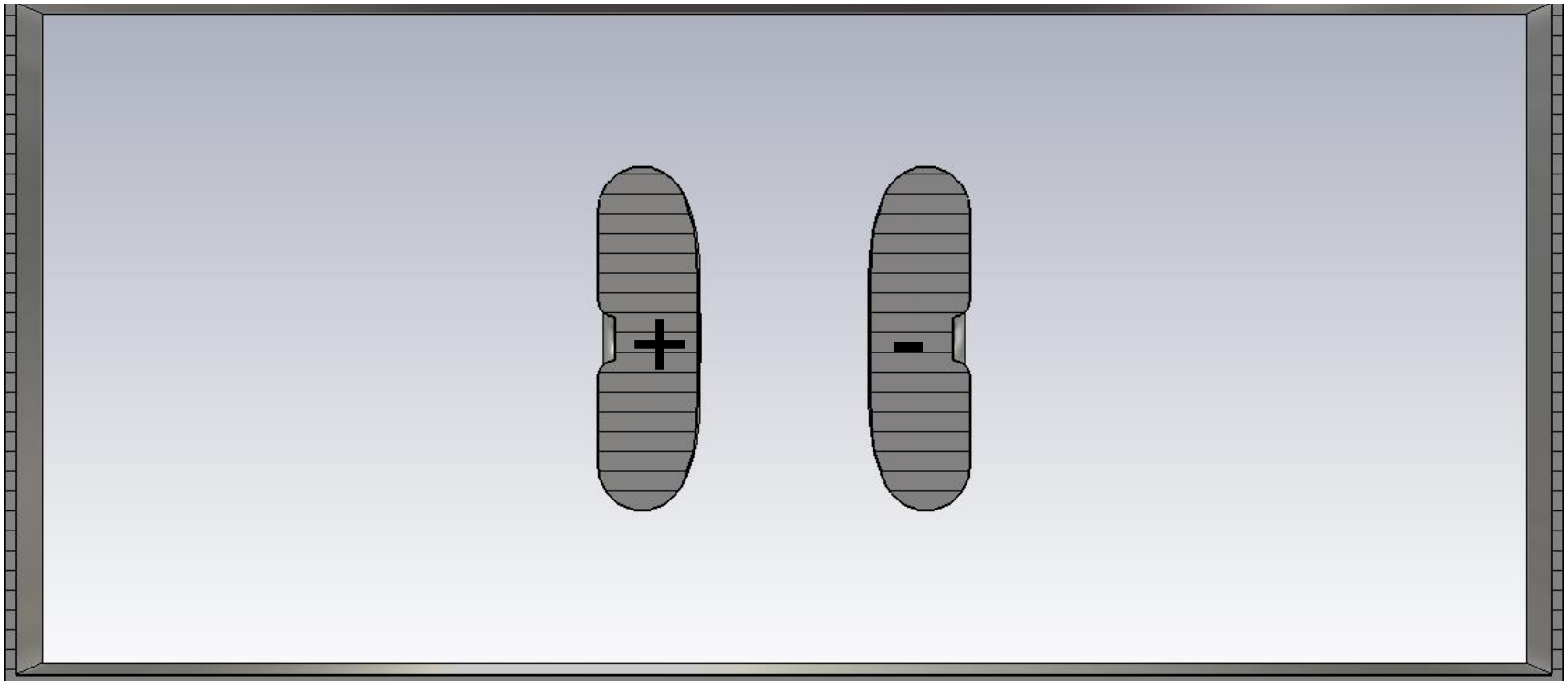
Conclusion Dark Current

- CST
  - Geometric shape can cause a 50x higher field
    → smooth surfaces
- PIC
  - Limits: amount of material + timespan
    → E-field increased to increase probability for tunneling
  - Reality: a lot of time and material, but low(er) E-field
    → limit amount of material + drainage of electrons
  - High work function



Electron Trajectories for E-field only

- Electrons‘ initial energy: 50 eV
- Voltage: ±100 kV → 4MV/m



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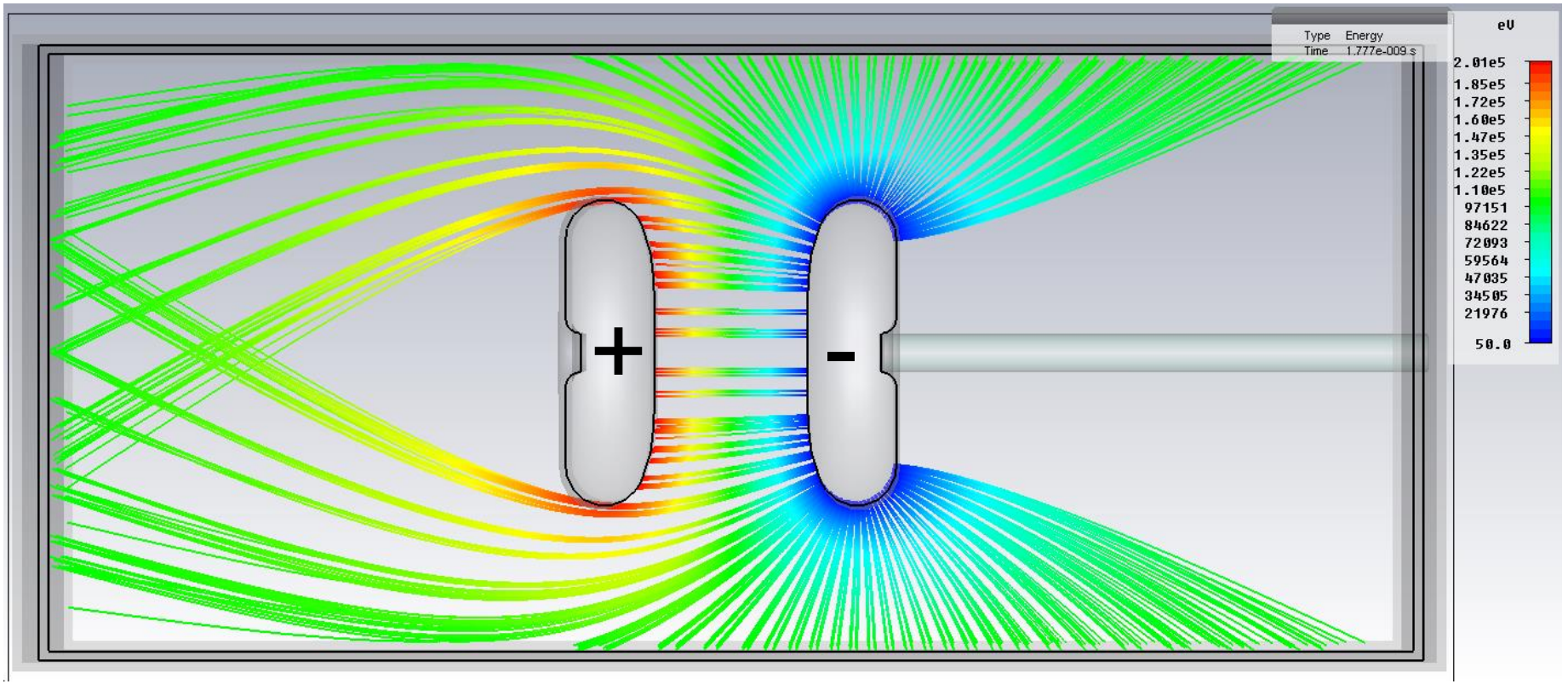
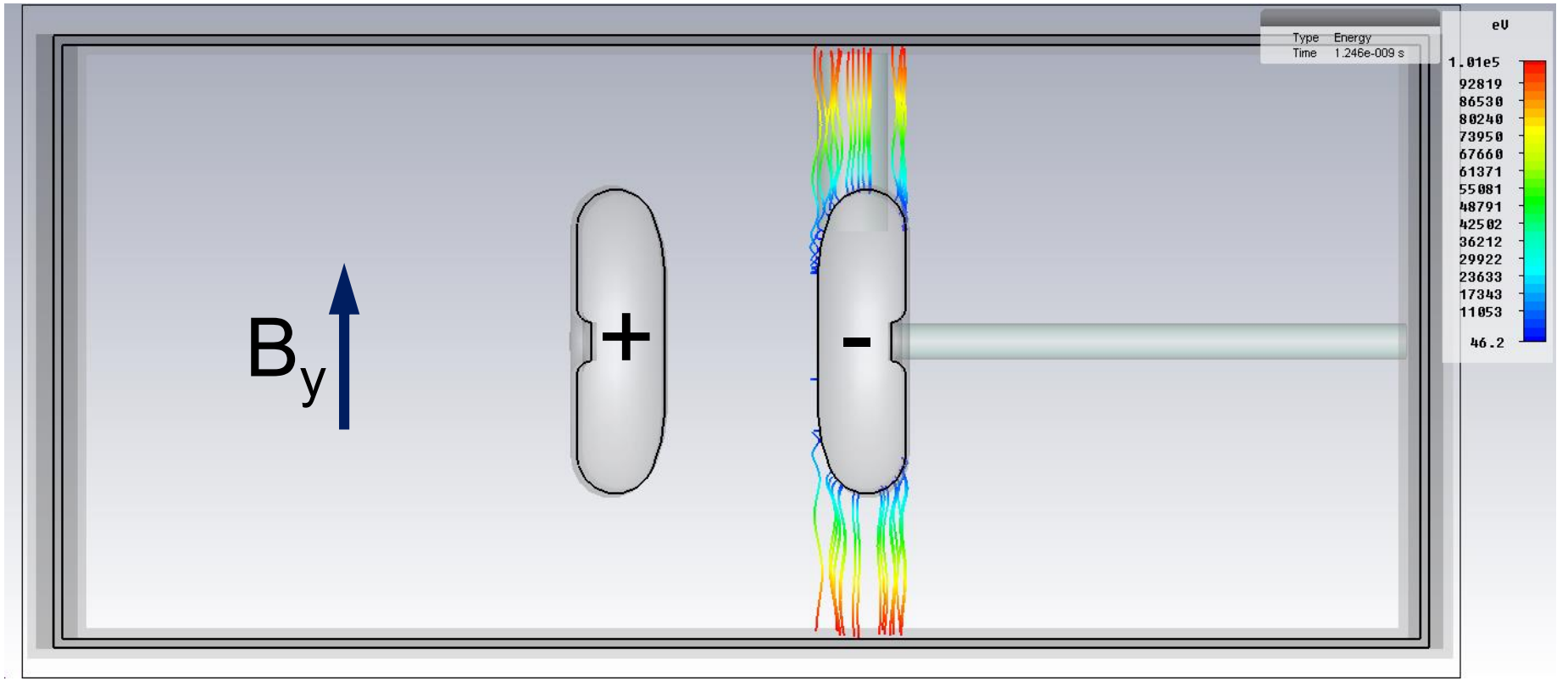
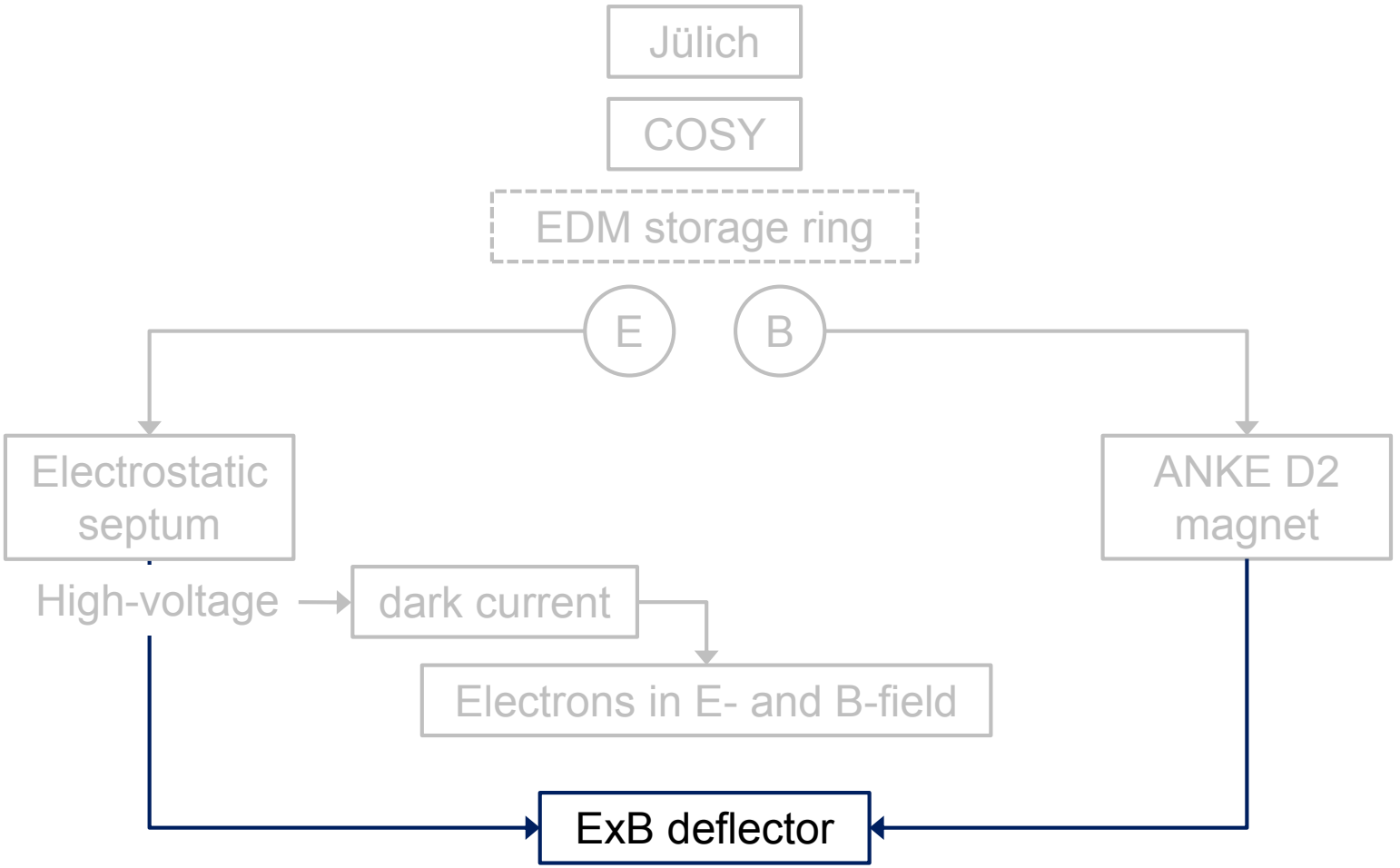


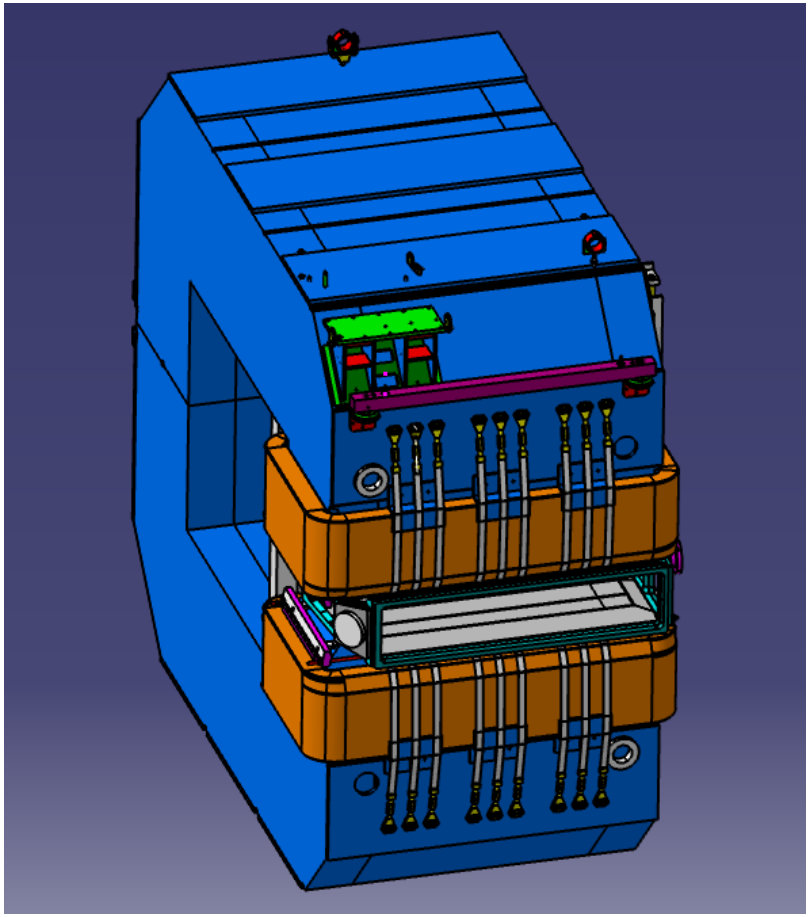
Electron Trajectories for E- and B-field

- Electrons‘ initial energy: 50 eV
- Voltage: ±100 kV → 4MV/m
- B-field: 0.15 T

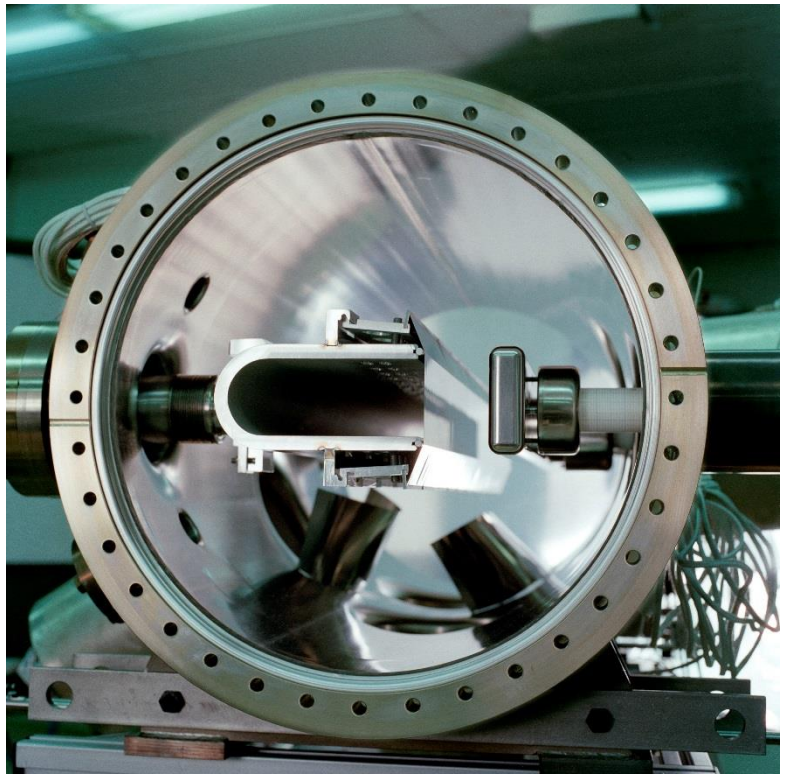




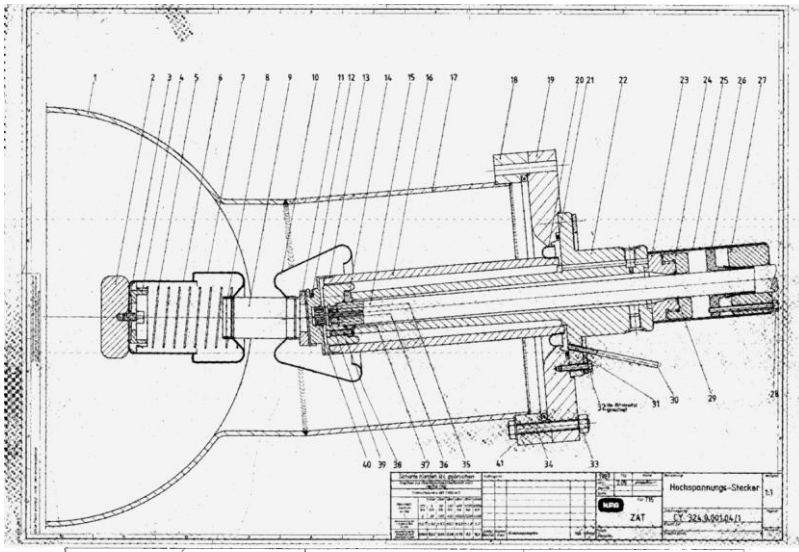
Combine E and B

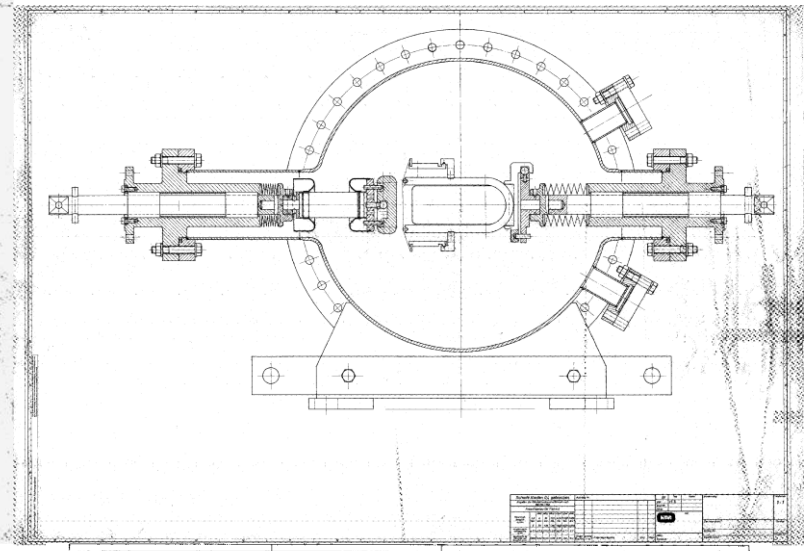


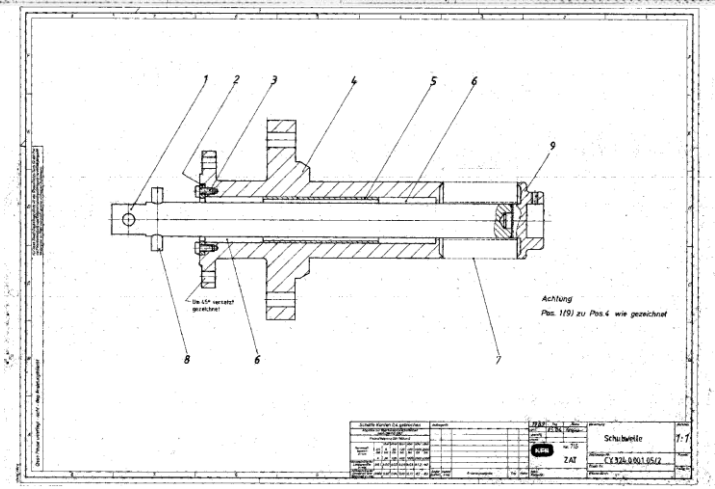
+

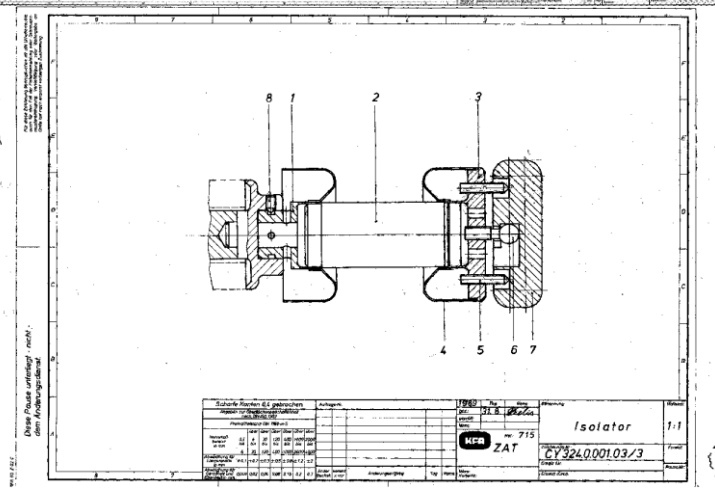


Technical Drawings – Electrostatic Septum



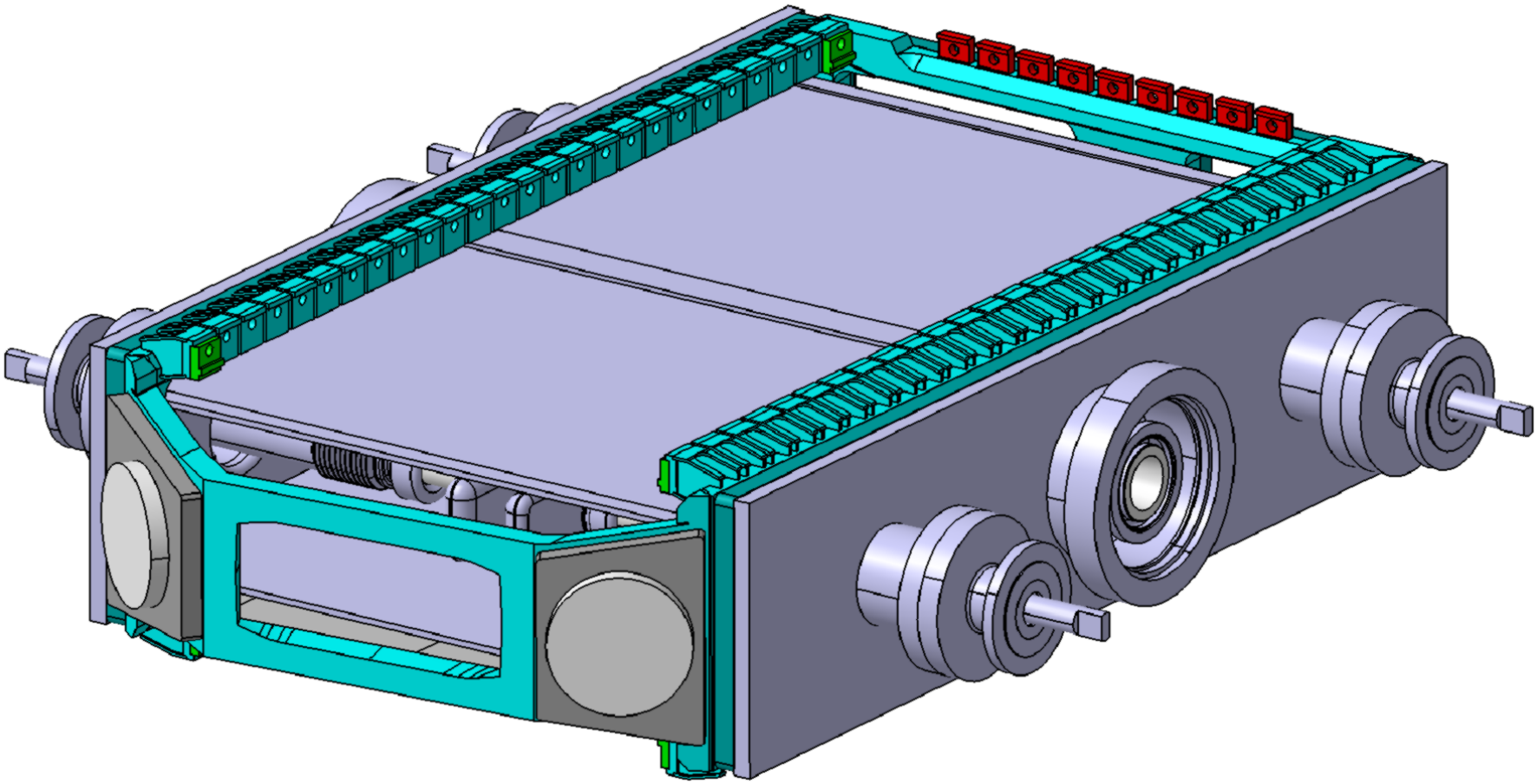




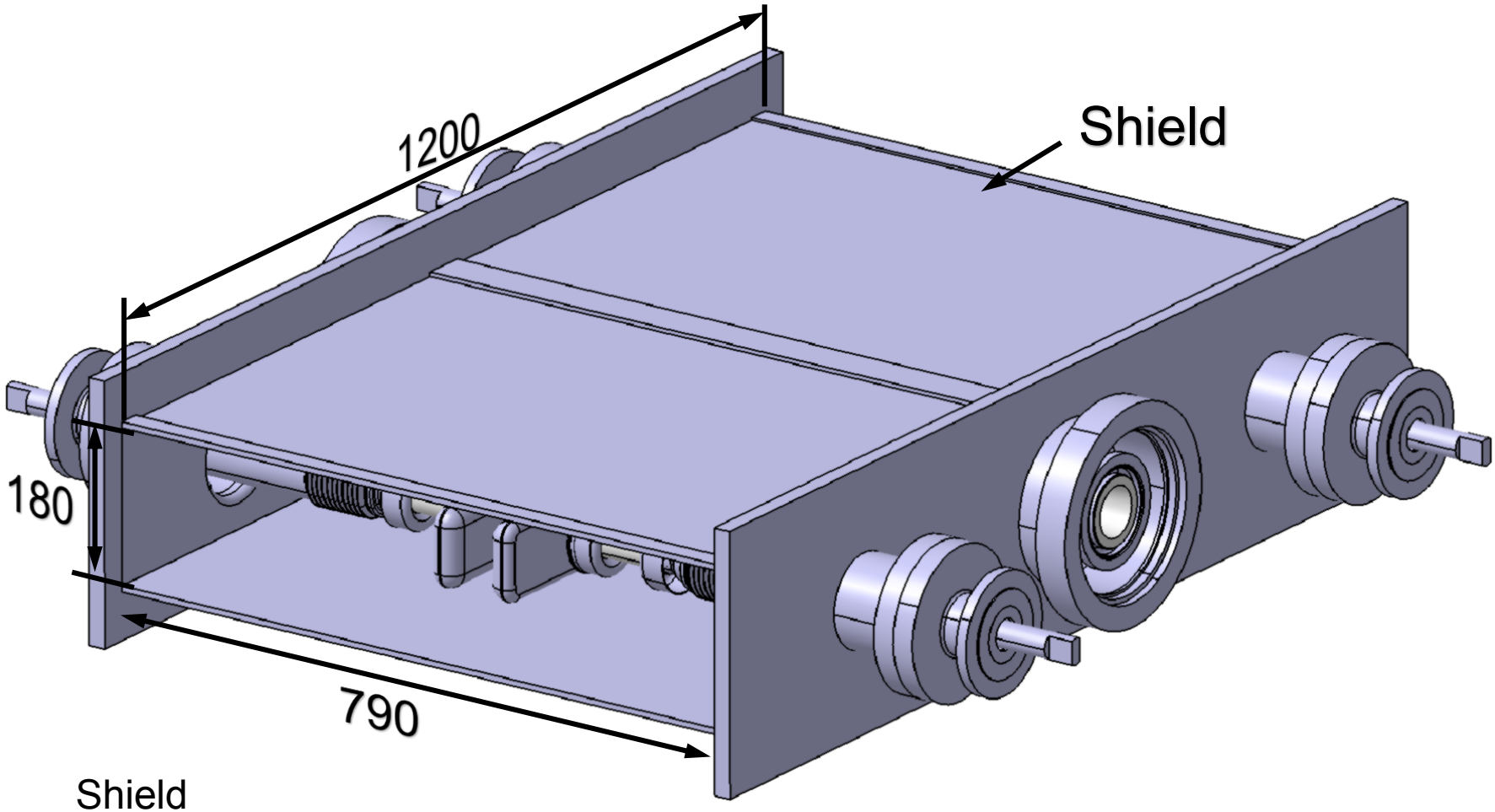


JÜLICH
FORSCHUNGSZENTRUM

Deflector w/ Vacuum Chamber



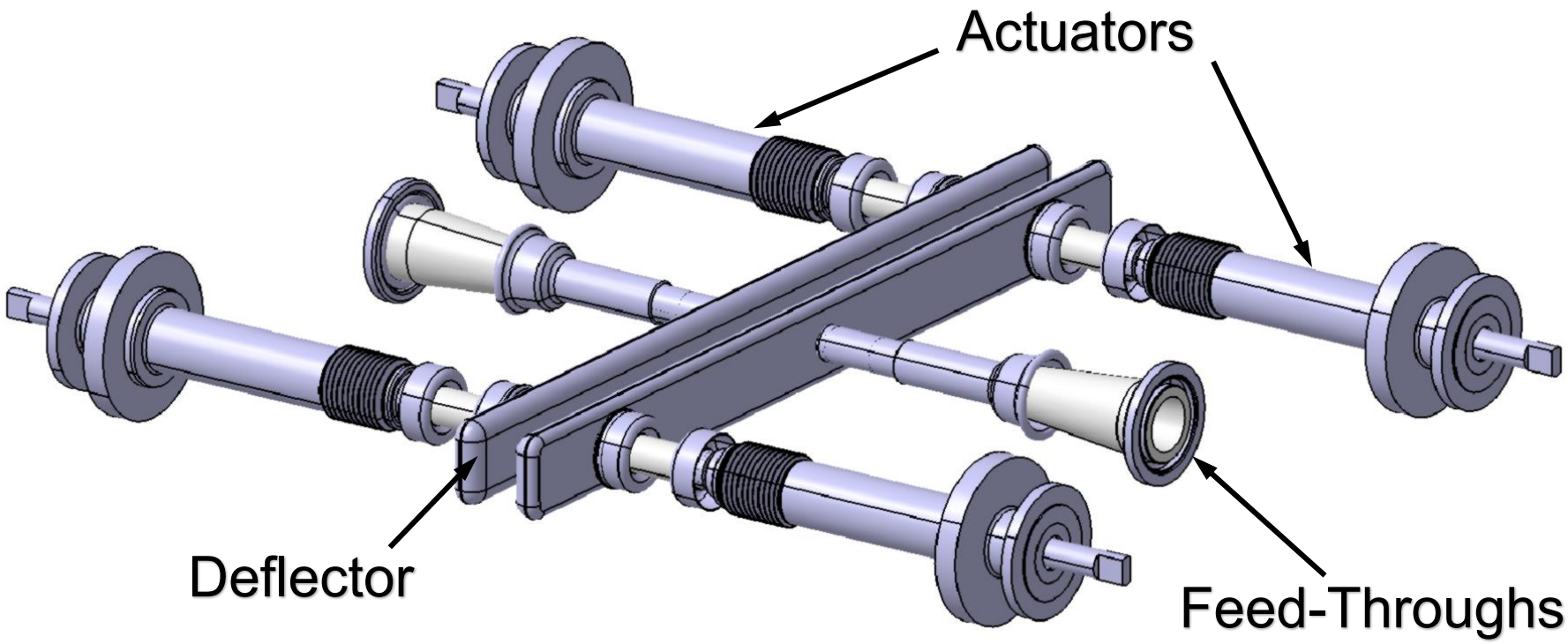
Deflector



Shield

- Inserted between chamber wall and deflector
- Shield is on ground potential
- Deflector „sees“ only the shield

Deflector w/o Shields

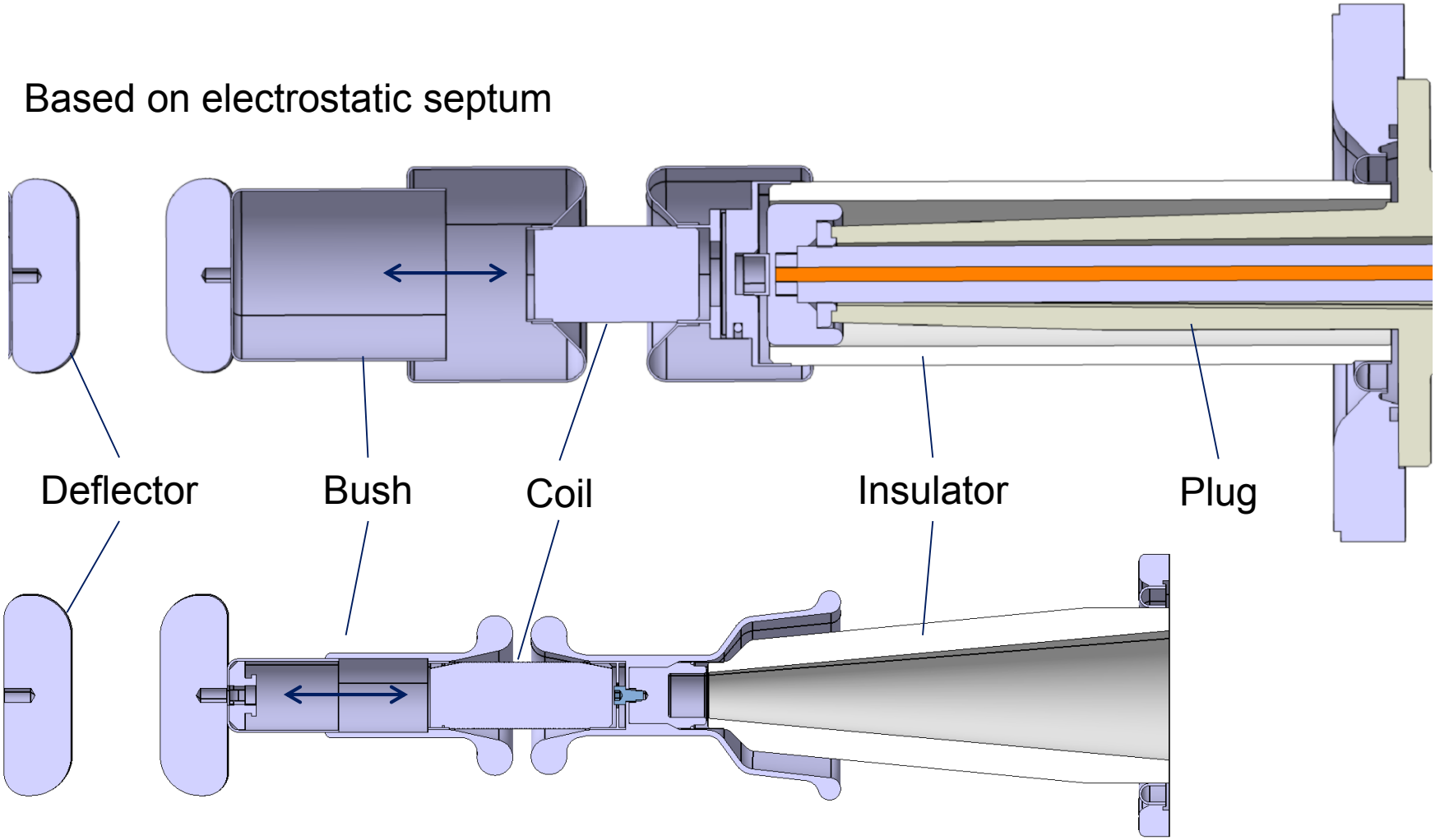


Deflector:

- Length 1020 mm
- Height 90 mm
- Gap 40 - 80 mm

HV-Feed-through Designs

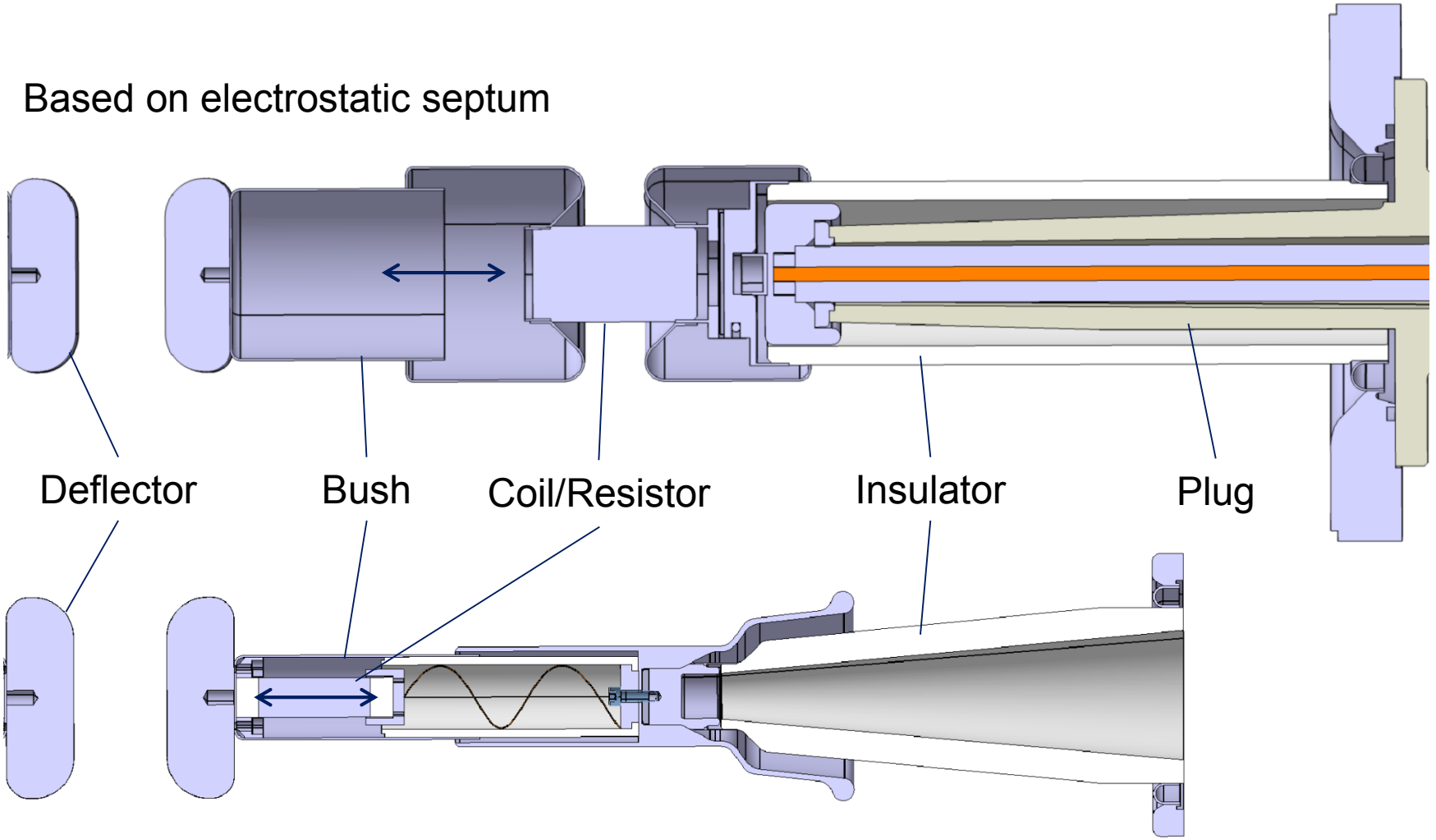
Based on electrostatic septum



Influenced by inverted insulator design (JLab)

HV-Feed-through Designs

Based on electrostatic septum



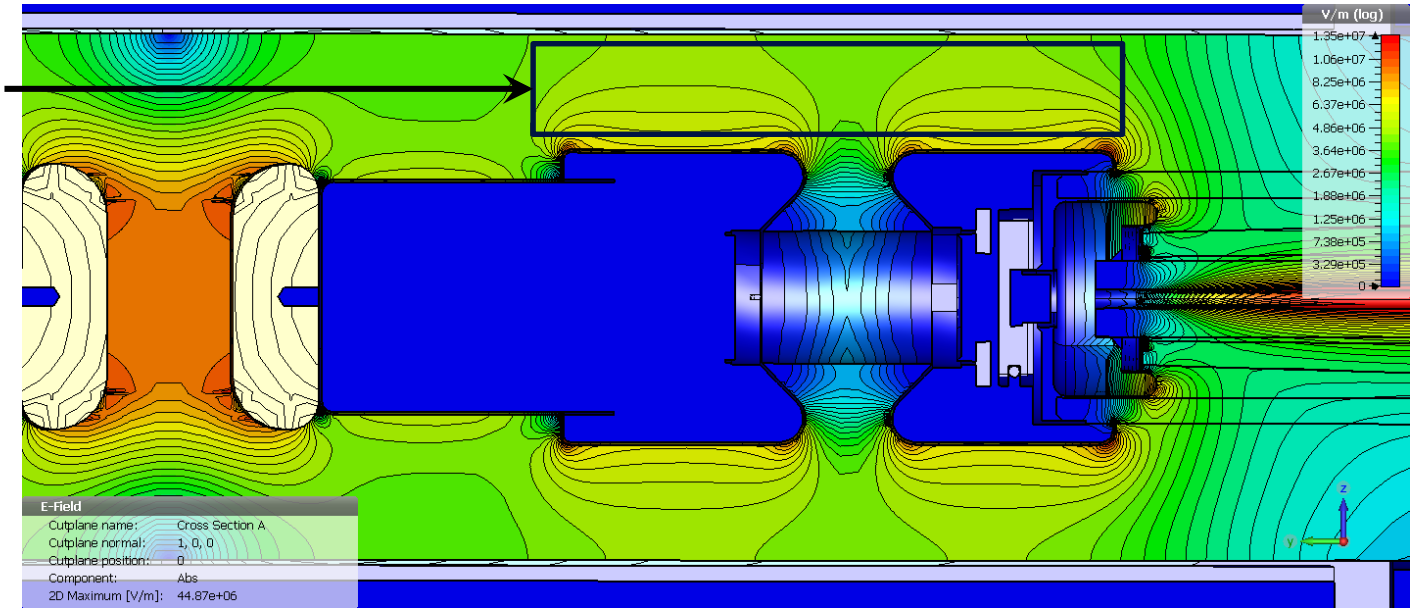
Influenced by inverted insulator design (JLab) w/ CERN recommendations

E-Field Maps

JÜLICH FORSCHUNGSZENTRUM

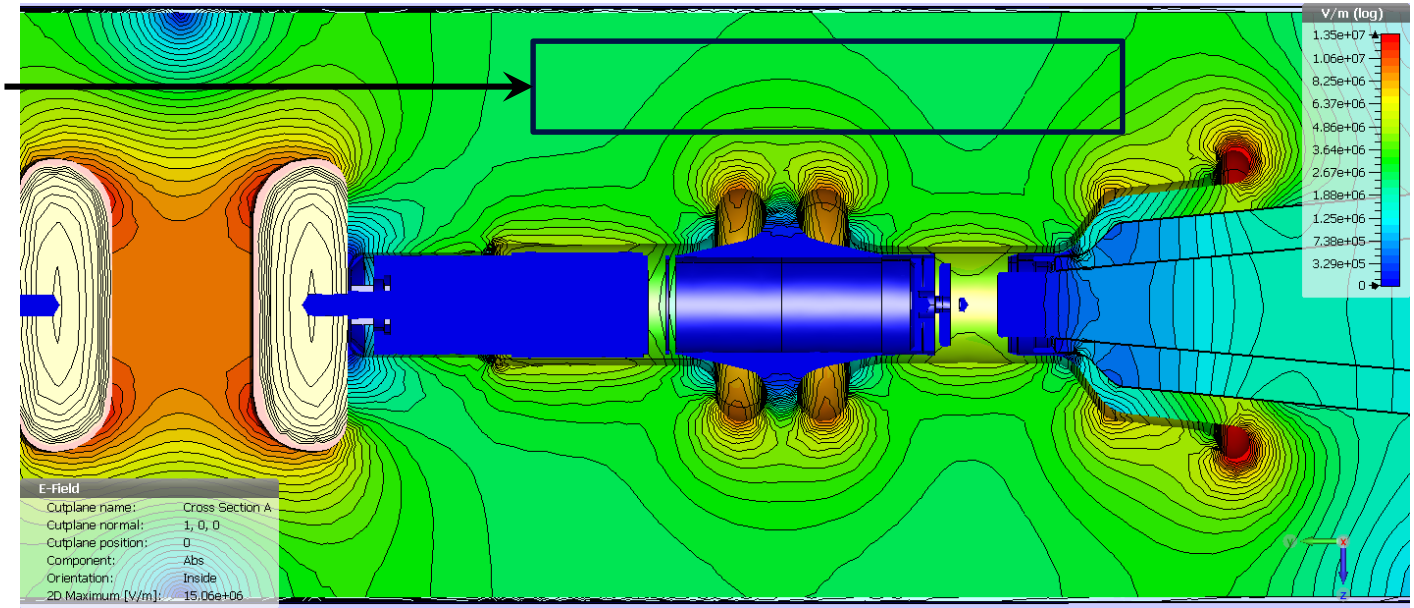
6 MV/m

Septum Design



3 MV/m

Inverted Insulator (JLab)

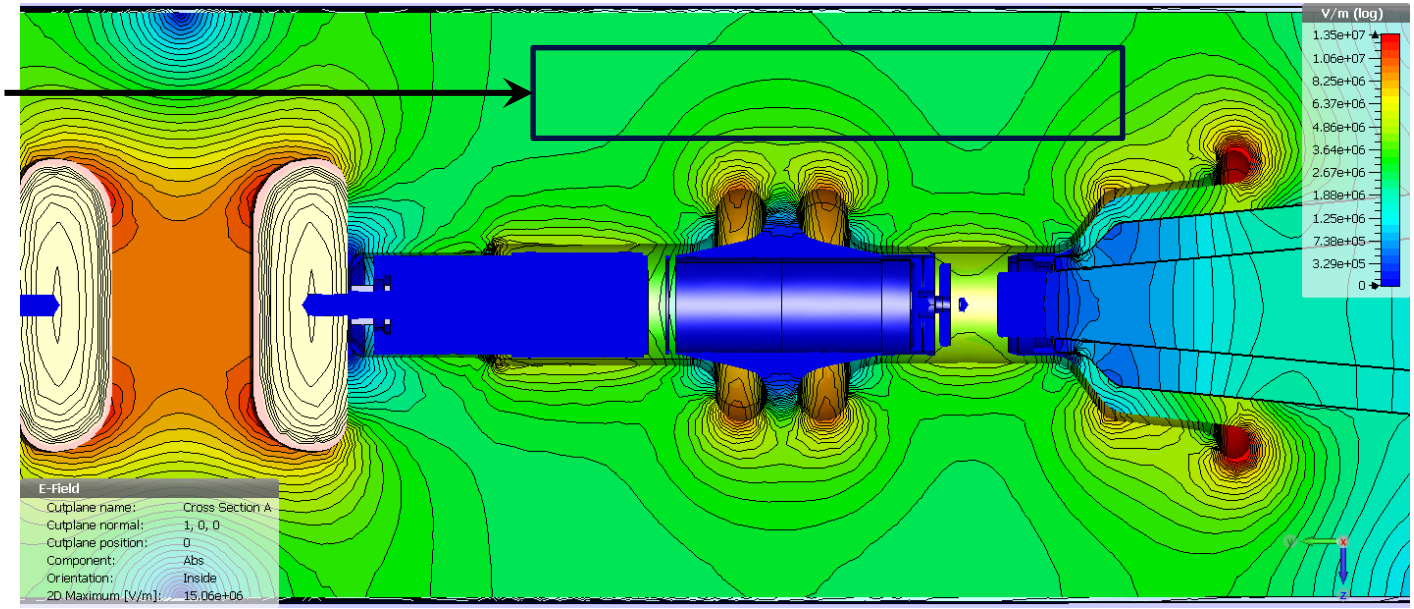


E-Field Maps

JÜLICH FORSCHUNGSZENTRUM

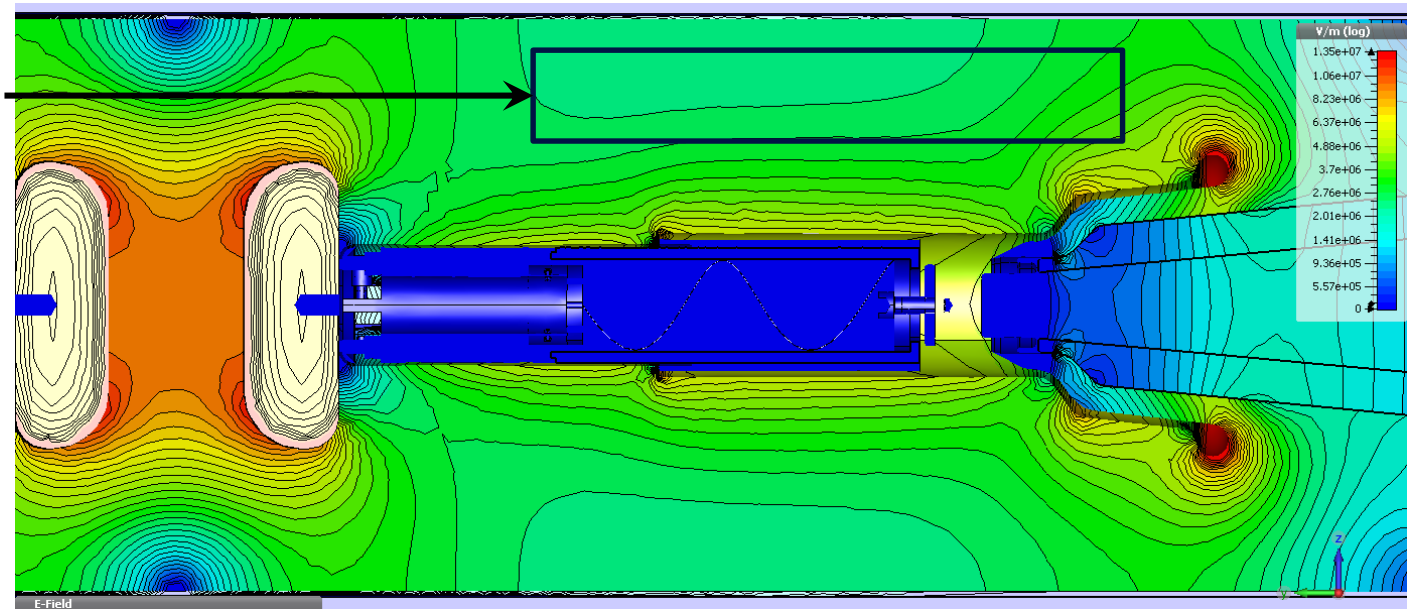
3 MV/m

Inverted Insulator (Jlab)



2.5 MV/m

Inverted Insulator (Jlab) w/ CERN ideas



Summary

- Electric dipole moment (EDM)
- Basic ingredients for ExB deflector
  - Moderate/low B-fields
  - Strong E-fields
- E-fields

  → Dark current
    - » Smooth surfaces / geometries
    - » Drainage of electrons
    - » Limit amount of material
    - » High work function

  → Field grading