Electrical Breakdown Involving a Gas-Solid Interface

SAND2015-4896C

Harold P. Hjalmarson, Laura B. Biedermann, Fred J. Zutavern, Chris H. Moore and Kenneth M. Williamson

Sandia National Labs

Albuquerque, NM

Jane M. Lehr

University of New Mexico

Albuquerque, NM

Pulsed Power Conference

June 1, 2015

Supported by the Advanced Strategic Computing and the Laboratory Directed Research and Development program at Sandia National Laboratories, a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy, under contract DE-AC04-94AL85000.

Sandia National Laboratories

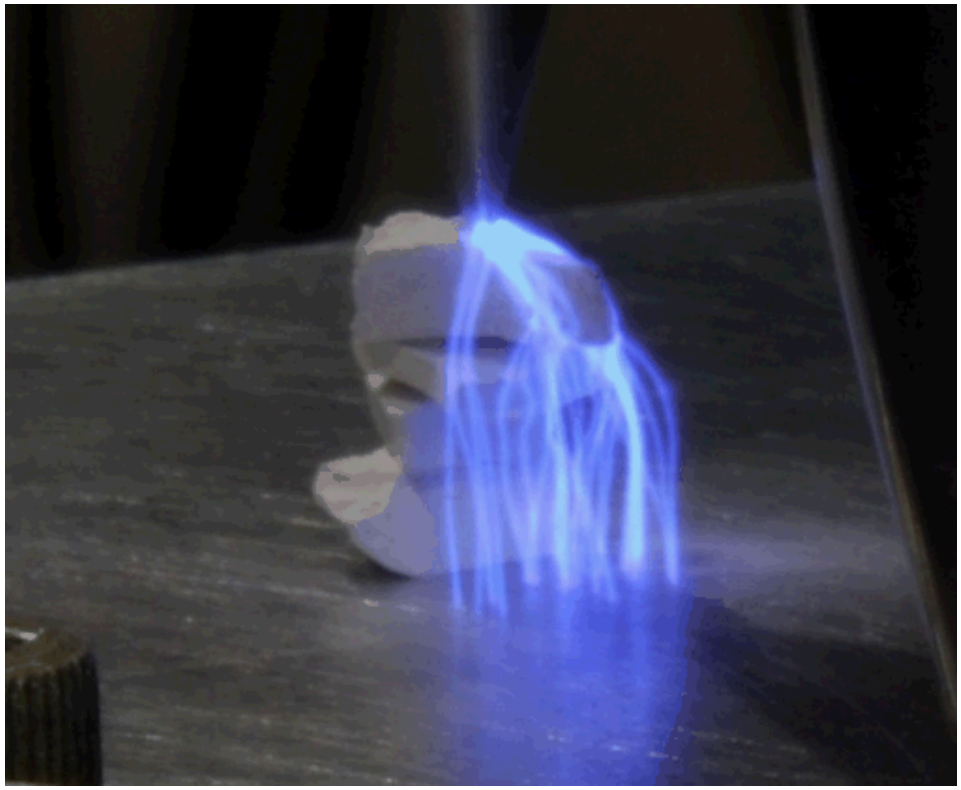
Electrical Breakdown of TiO_2 Particles

Experiments image the breakdown path across TiO_2 particles

The images reveal that breakdown occurs either across a particle surface or through pores in a particle

These experiments led to my hypothesis that thermal breakdown explains this and other data

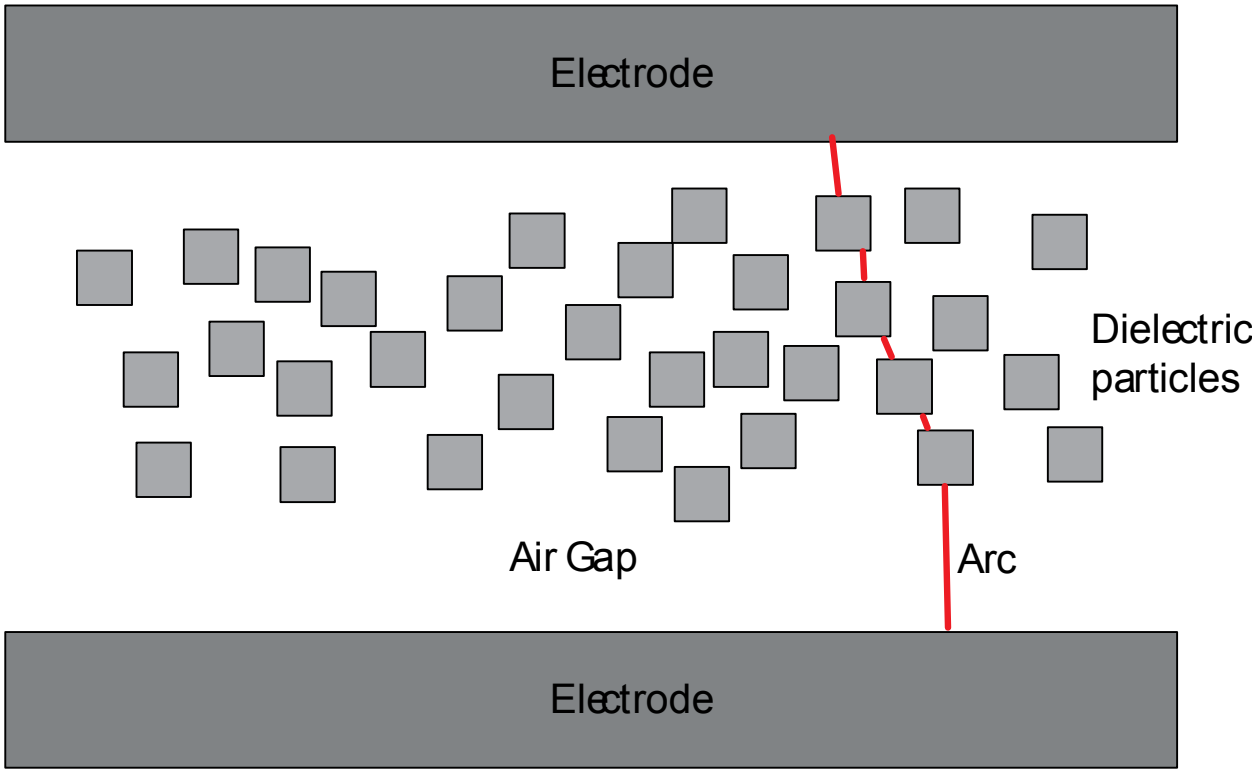
Initial experiments by Jane Lehr; more recent experiments by Ken Williamson



Electrical breakdown "hugging" the rutile surface

Lightning Arrester: Idealized Structure

Purpose: Closing switch that diverts lightning transient current to an electrical ground



Project goal: Develop a physics-based model to improve understanding and performance

Sandia National Laboratories

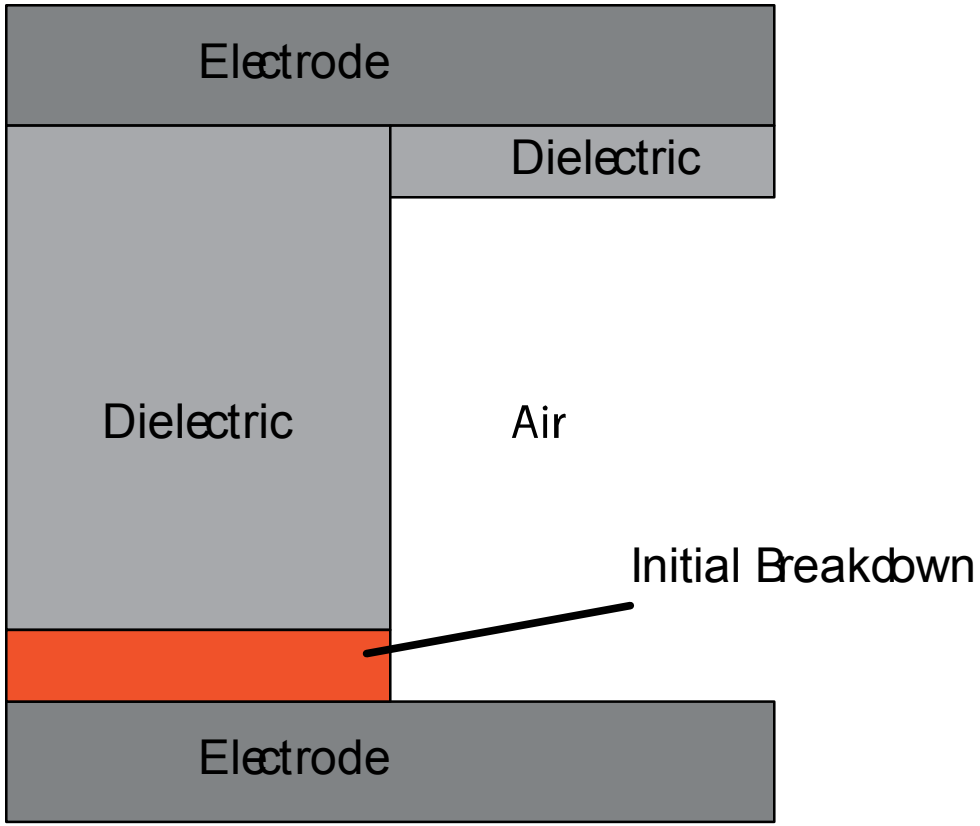
Experiments described in the talks by Laura Biedermann and Ken Williamson

Outline

- **Motivation**
  - **High permittivity dielectrics used since earliest lightning arresters in 1920's**
  - **Understand the physics effects of a high permittivity dielectric**
- **Simple Structures and Calculations**
  - **1D calculations focused on early time breakdown**
    - **Tunneling**
  - **2D calculations focused on late time effects**
    - **Electrothermal breakdown**
- **Physics**
  - **Early time: Townsend mechanism**
  - **Intermediate time: Cathode tunneling**
  - **Late time: Triggered breakdown of the entire structure**

Breakdown in Small Air Gaps

High permittivity dielectric acts like a metal at short times



The fast breakdown in the small gap triggers breakdown in the large gap

Two Types of Initial Events

- **Small gap**
  - **Tunneling produces an initial density**
  - **Avalanche growth**
- **Large gap**
  - **Background radiation produces an initial density**
  - **Avalanche growth**

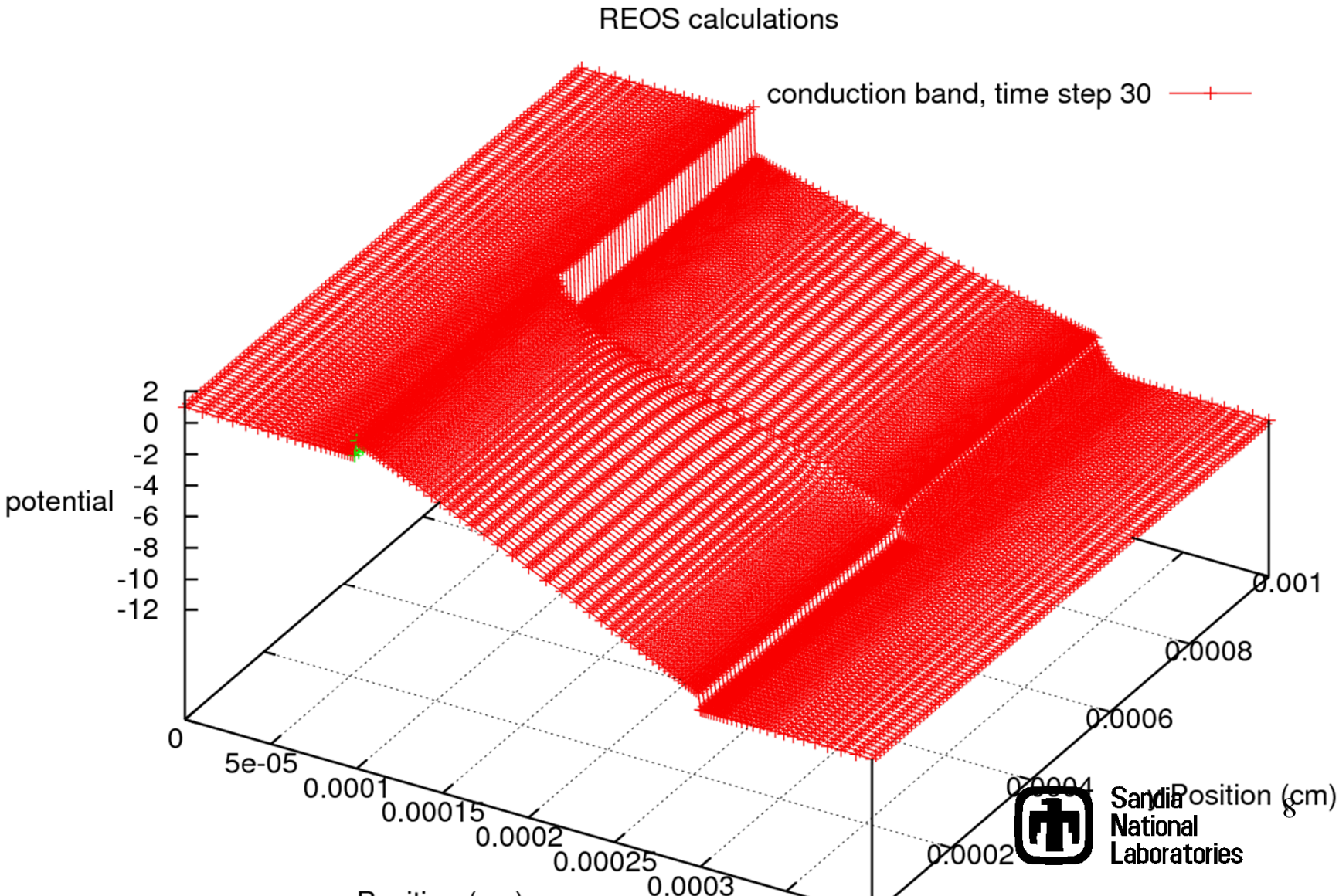
Sandia
National
Laboratories

Small Gaps

- **Very small: L = 10^{-4} cm**
- **The large electric field causes tunneling**

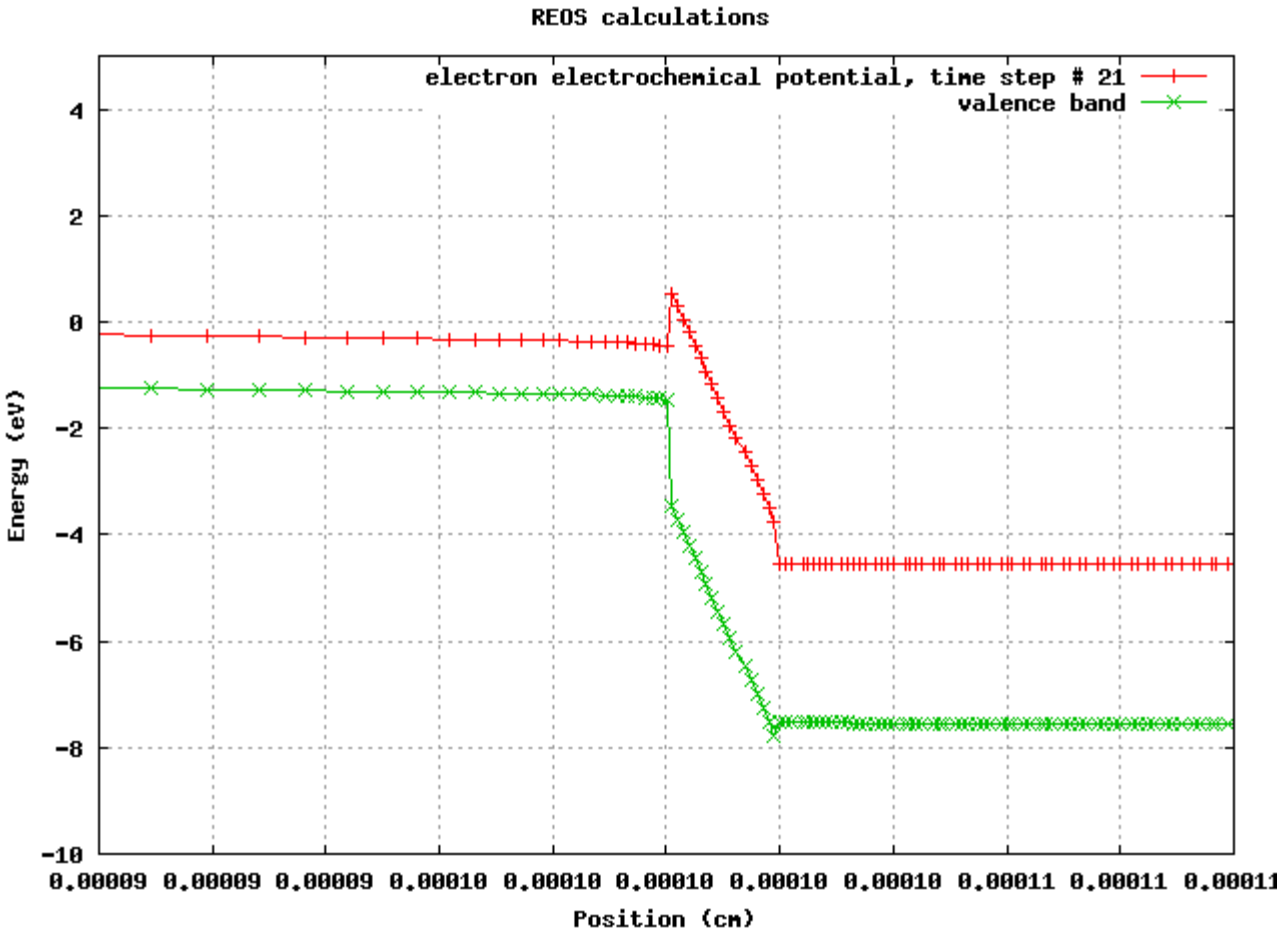
Sandia
National
Laboratories

Large Electric Field in the Air Gap



Sandia National Laboratories

Tunneling in the High Field Region



Sandia National Laboratories

Large Gaps

A crude rate equation

$$\frac{\partial n}{\partial t} = R - Tn + Sn + An$$

$R =$ Ionizing radiation rate

$T =$ Transport removal of electrons

$S =$ Secondary injection of electrons: photoemission (PE) and secondary electron emission (SEE)

$A =$ Avalanche creation of electron-ion pairs

Sandia National Laboratories

Time Evolution: Initial Density

An initial density is set by the applied field

$$\frac{\partial n}{\partial t} = R - Tn$$

Steady state: $\frac{\partial n}{\partial t} = 0$

$n_0 = R / T$

$R = 0.01$ Rad/s, assume Rad $= 10^{13}$ e-ion cm^{-3} sec^{-1}

$T = V / L = 10^7$ sec^{-1}

Using $V = 10^6$ cm/sec and $L = 10^{-1}$ cm

$T = V / L = 10^7$ sec^{-1}

Assembling

$n_0 = R / T = 10^4$ cm^{-3}

Sandia National Laboratories

Time Evolution: Growth

Now focus on the avalanche term

$$\frac{\partial n}{\partial t} = R - Tn + Sn + An$$

Assume large voltage; then the avalanche term dominates

$$\frac{\partial n}{\partial t} = An$$

$$n(t) = n_0 \, \mathrm{e}^{At} \text{ with}$$

$$\mathrm{n}_0 = 10^4 \text{ cm}^{-3}$$

Very rapid growth if the field is very large

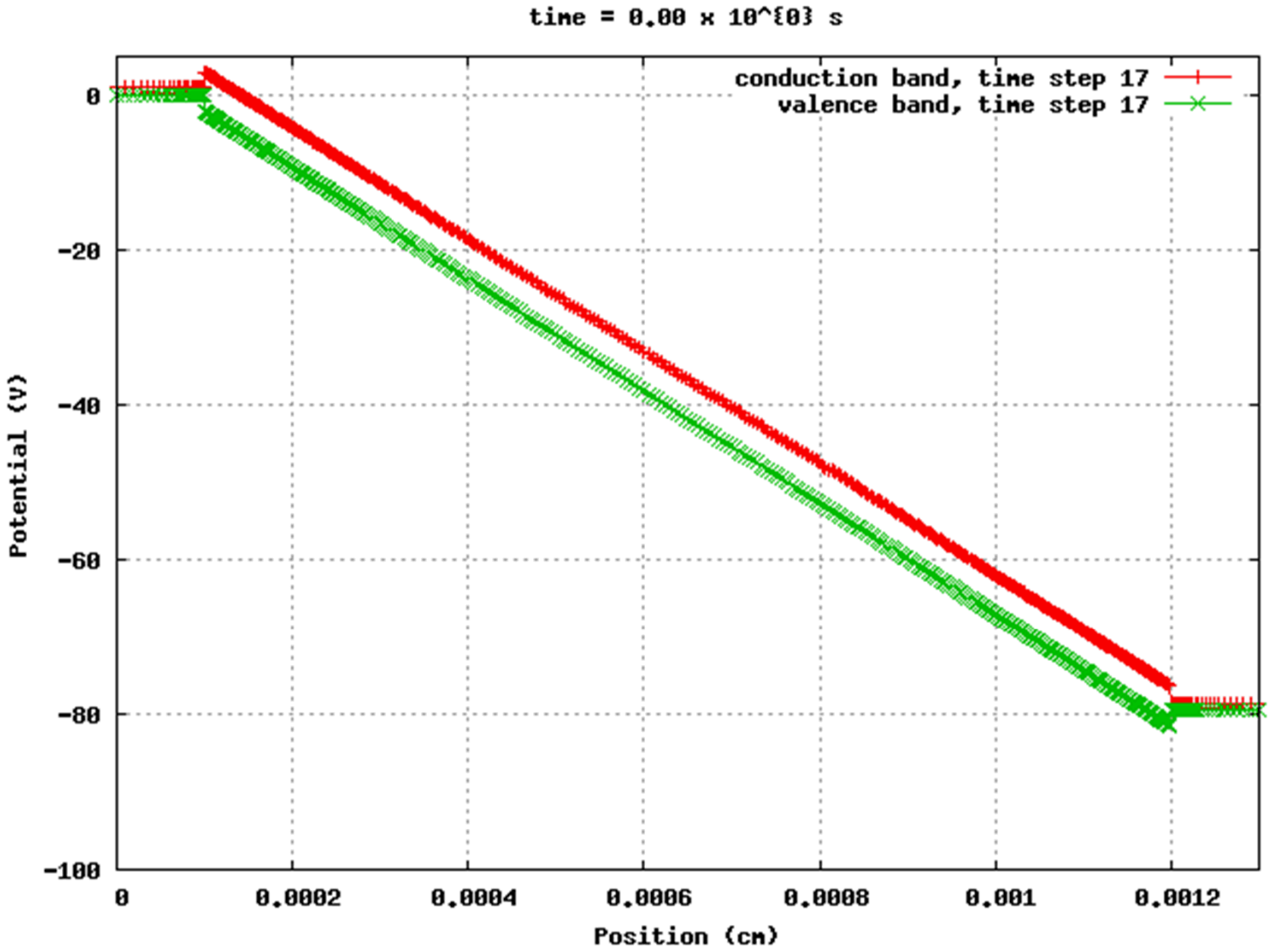
Sandia National Laboratories

Calculations

- **Composite dielectric**
  - **Air**
  - **Rutile**
- **Townsend mechanism**
- **Results**
  - **Breakdown occurs from numerical noise**
  - **Current flows through the electron-blocking contact**

Sandia
National
Laboratories

Air Gap Breakdown: Townsend Mechanism



Breakdown: Temporal Sequence

Physics

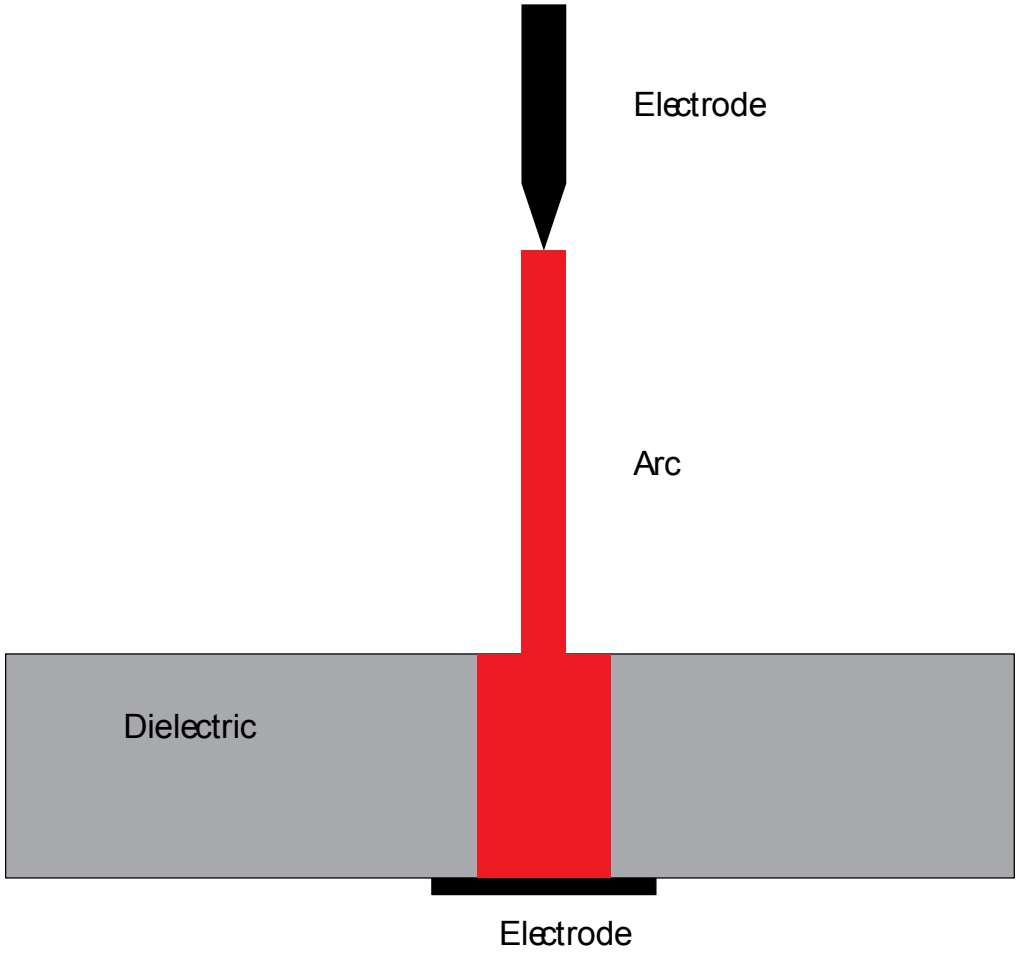
- **Initial breakdown**
  - **Tunneling if the air gap is very small**
  - **Townsend mechanism in the air gap**
  - **Rapid growth of electrons and ions**
- **Intermediate breakdown**
  - **Electron flow increases the electric field (spatial separation of electrons and ions)**
  - **Tunneling injection of electrons from the cathode**
- **Final breakdown**
  - **Electrons and photons from the small gap initiate breakdown in the large gap**

Idealized Structure and Experiment: Vertical

Short times: The insulating dielectric acts like an electrode to cause air breakdown

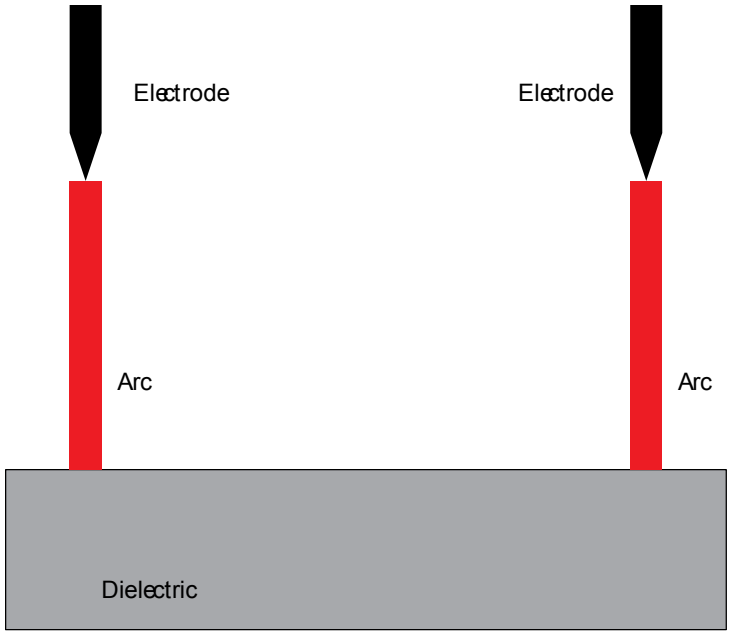
Intermediate times: Space charge limited current flows in the solid dielectric

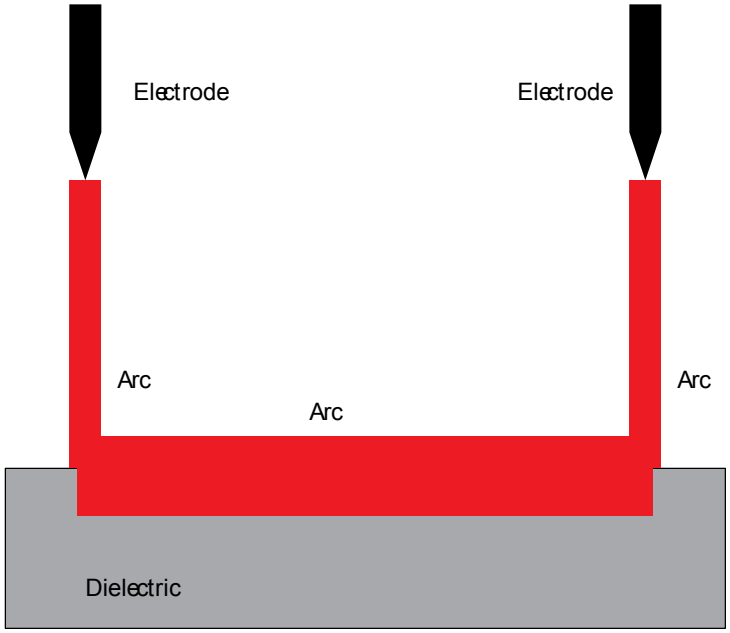
Long times: Either electrothermal breakdown from Joule heating or quenching of the air arc by deposited charge



Qualitative discussion of REOS results

Idealized Structure and Experiment





Early times: Air breakdown with the dielectric acting like a metal

Late times: Very conductive air breakdown causes breakdown of the solid dielectric

TiO_2 (rutile) has a large dielectric constant, approximately 86

Sandia National Laboratories

Summary

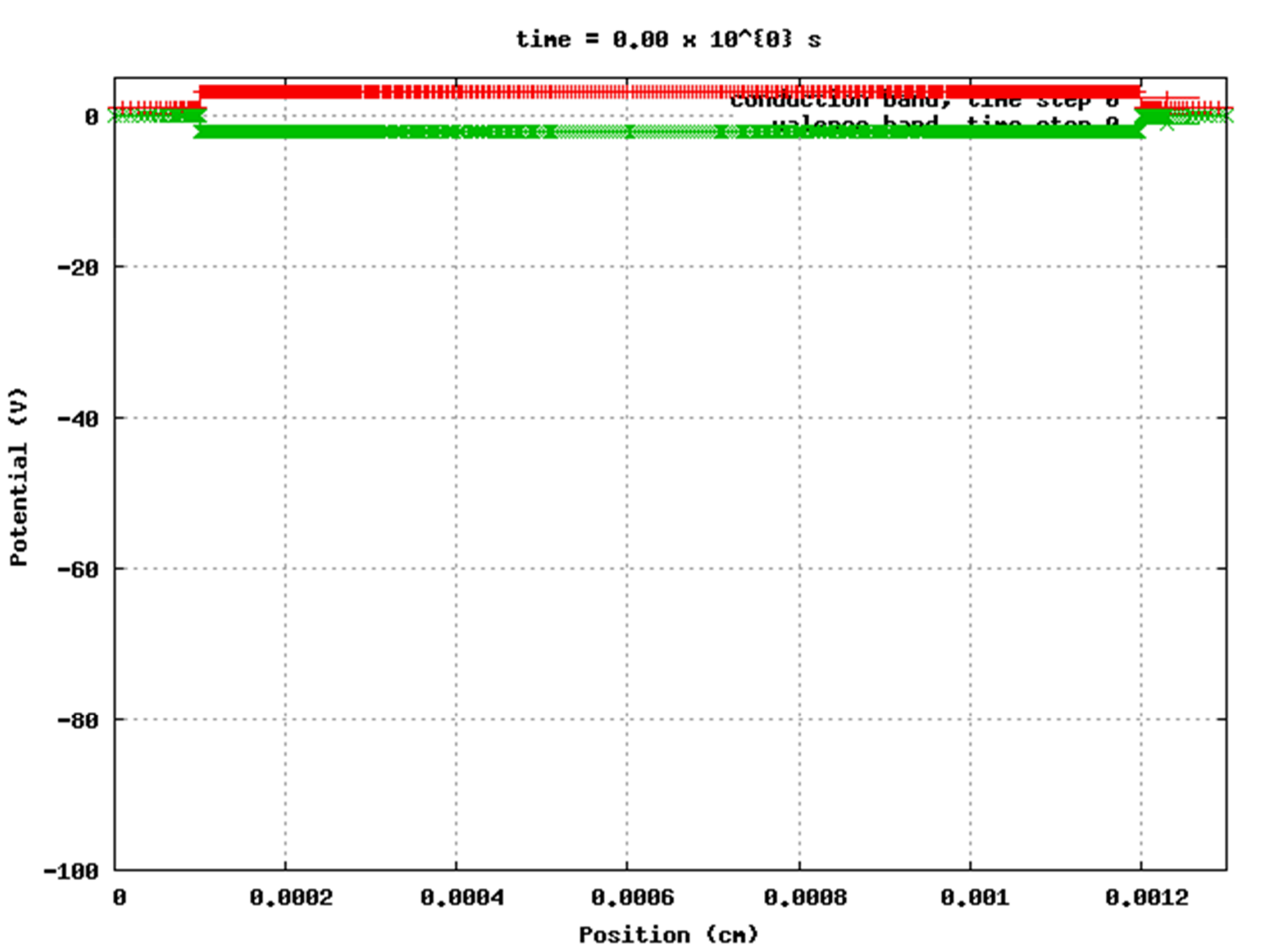
- **Small air gap**
  - **Tunneling causes breakdown**
- **Large air gap**
  - **Air breakdown at short times**
  - **Tunneling**

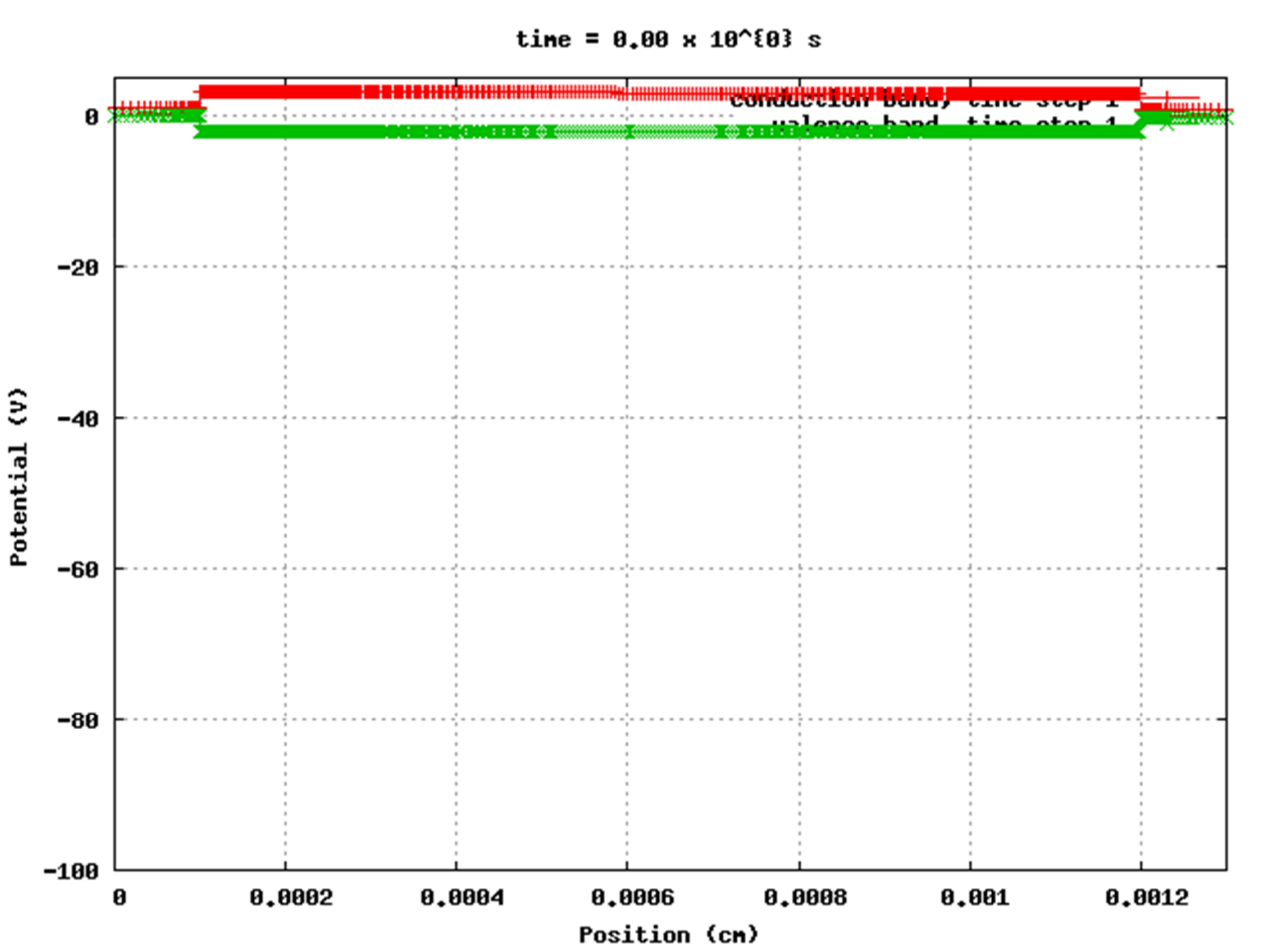
Breakdown: Temporal Sequence

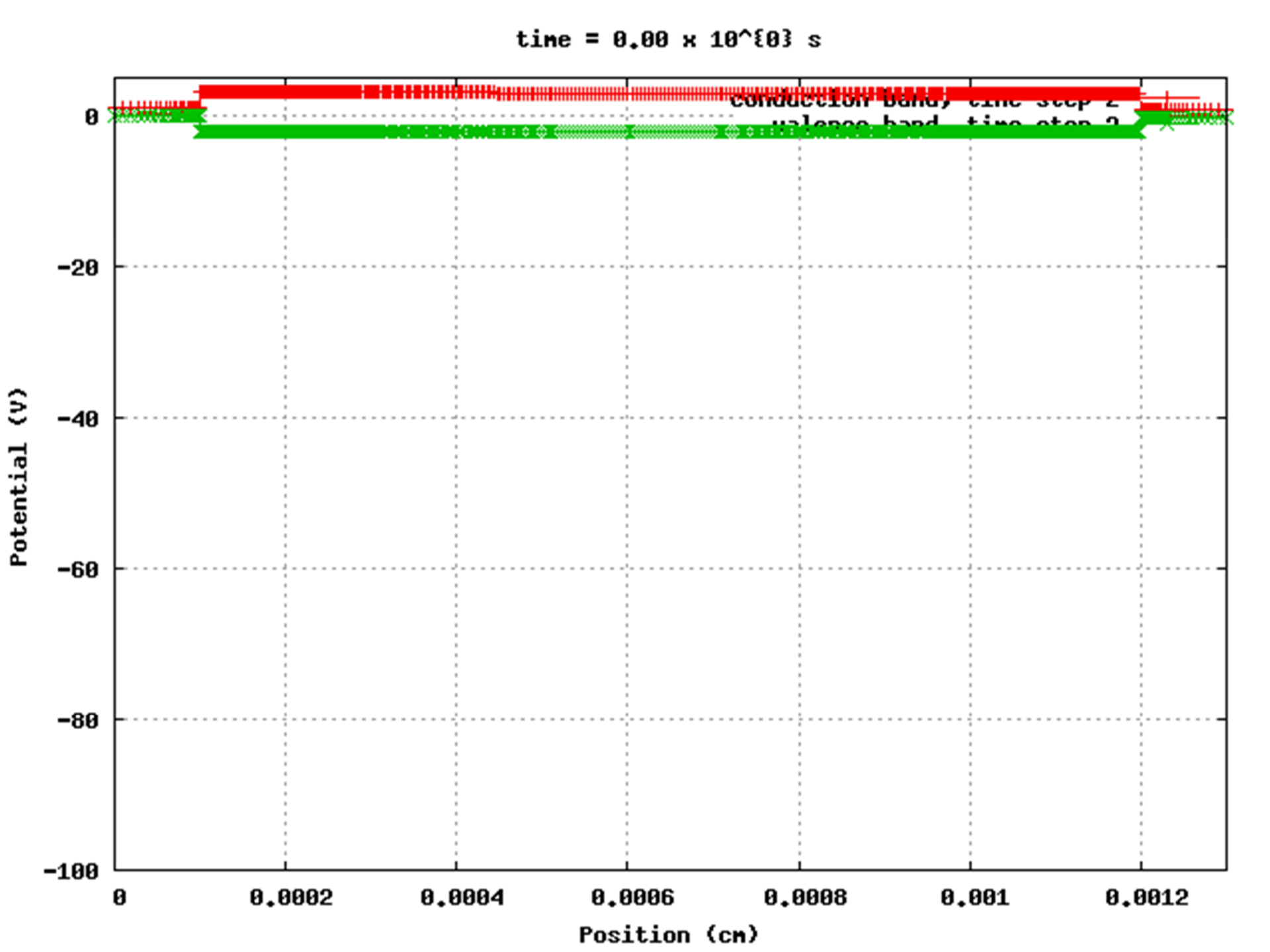
Photo Album

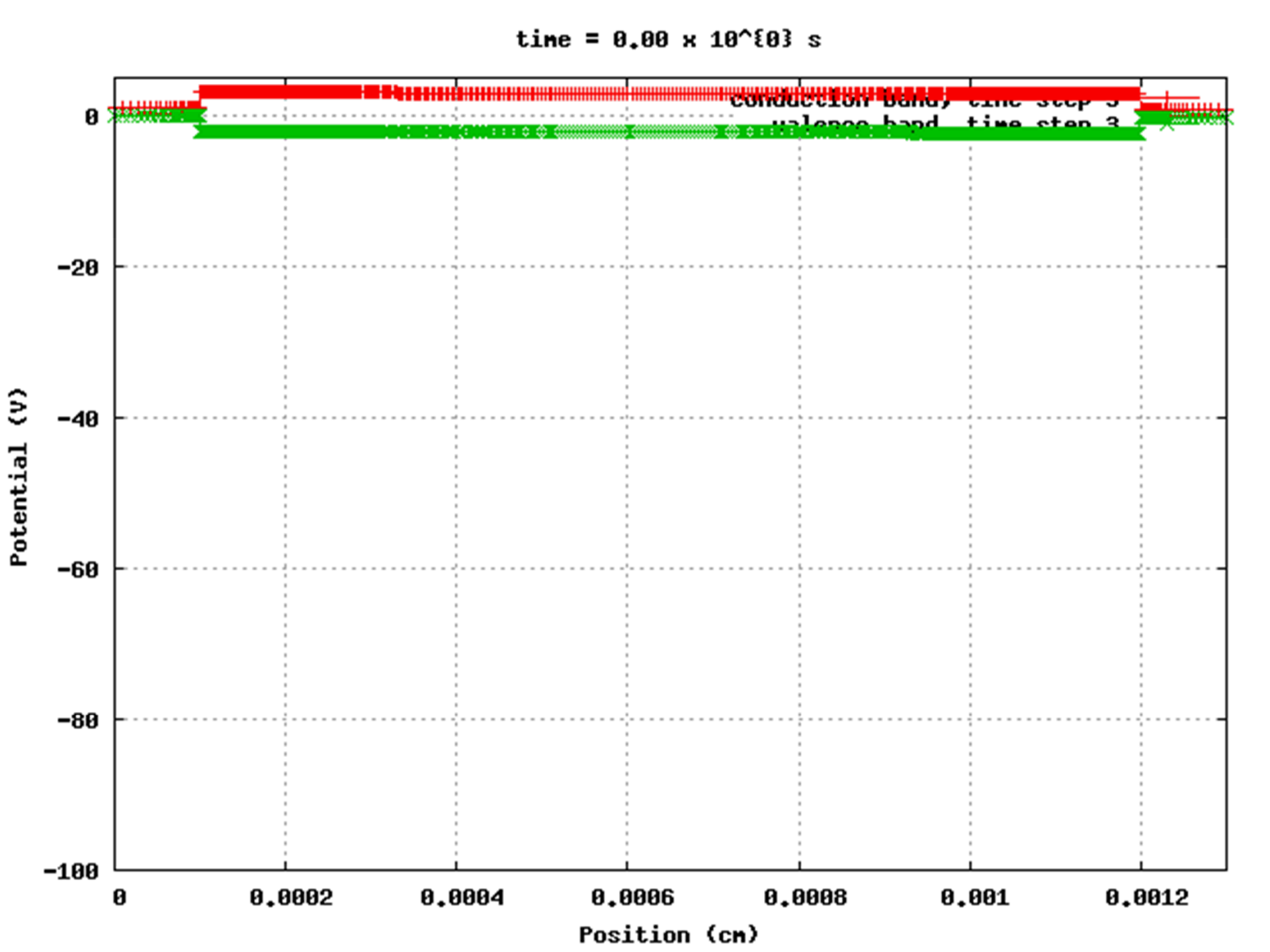
by Hjalmarson, Harold P

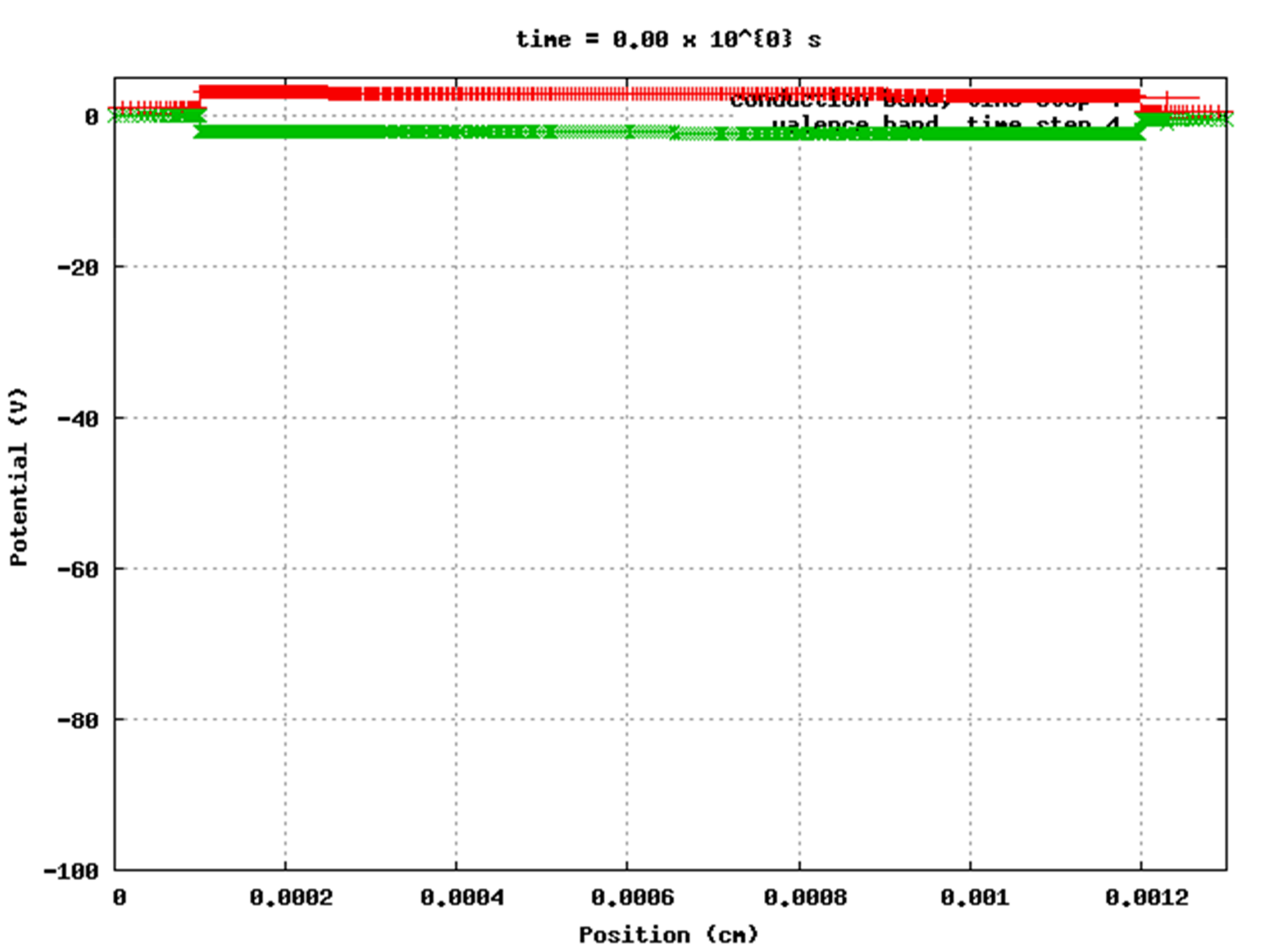
Sandia
National
Laboratories

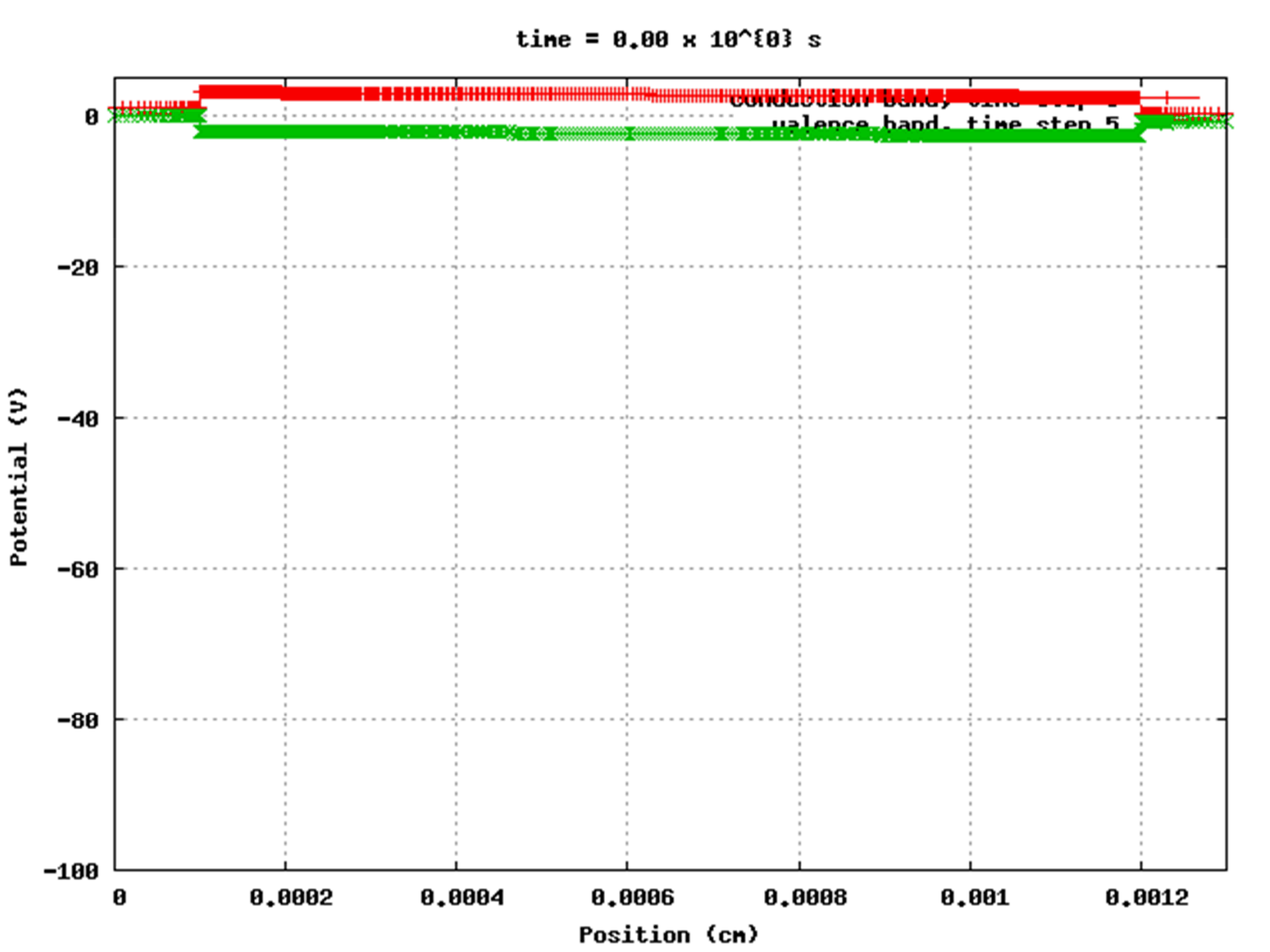

time = 0.00 x 10^{0} s
conduction band, time step 0
valence band, time step 0
0
-20
-40
-60
-80
-100
Potential (V)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)

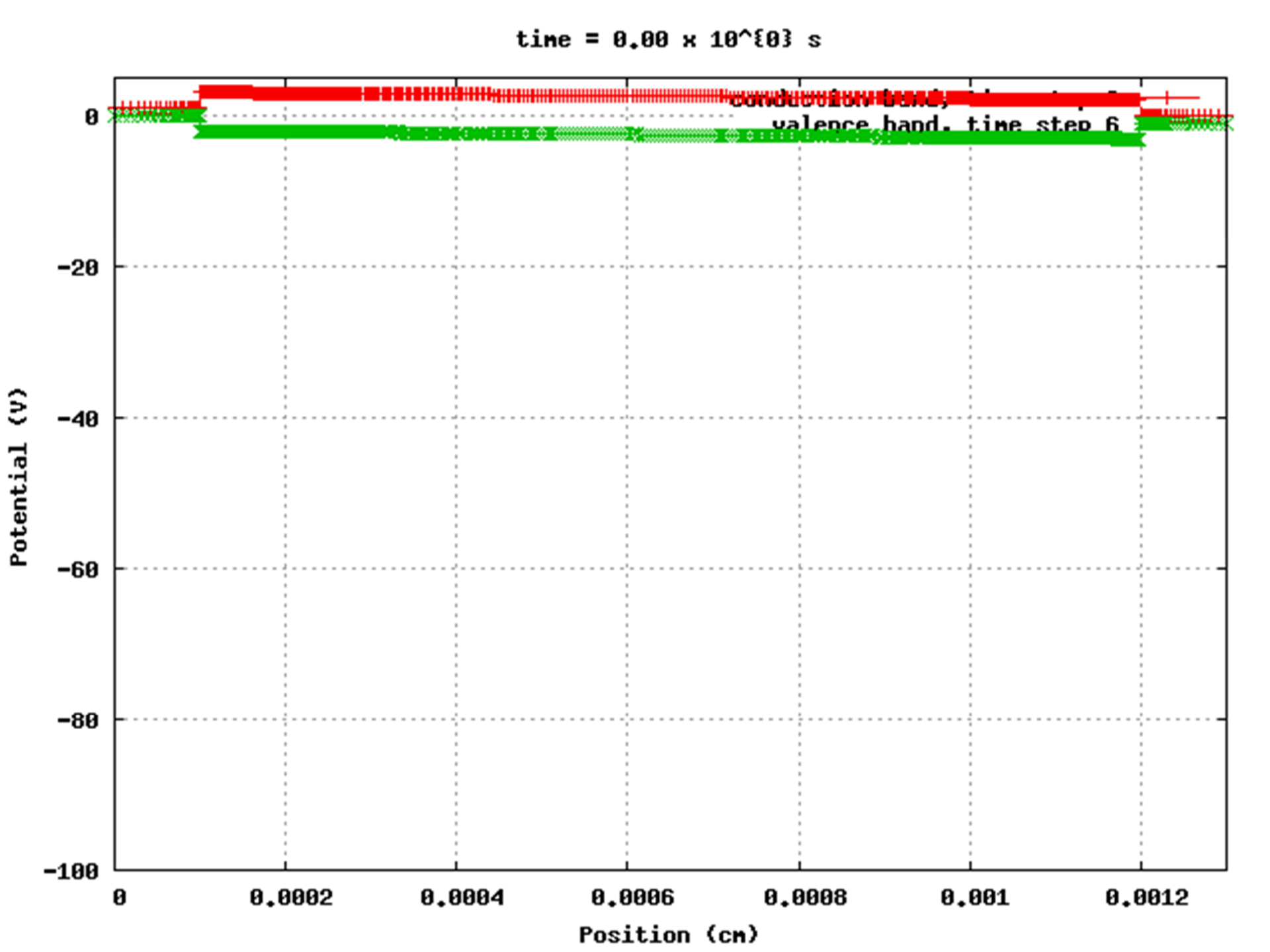

time = 0.00 x 10^{0} s
conduction band, time step 1
valence band, time step 1
0
-20
-40
-60
-80
-100
Potential (V)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)

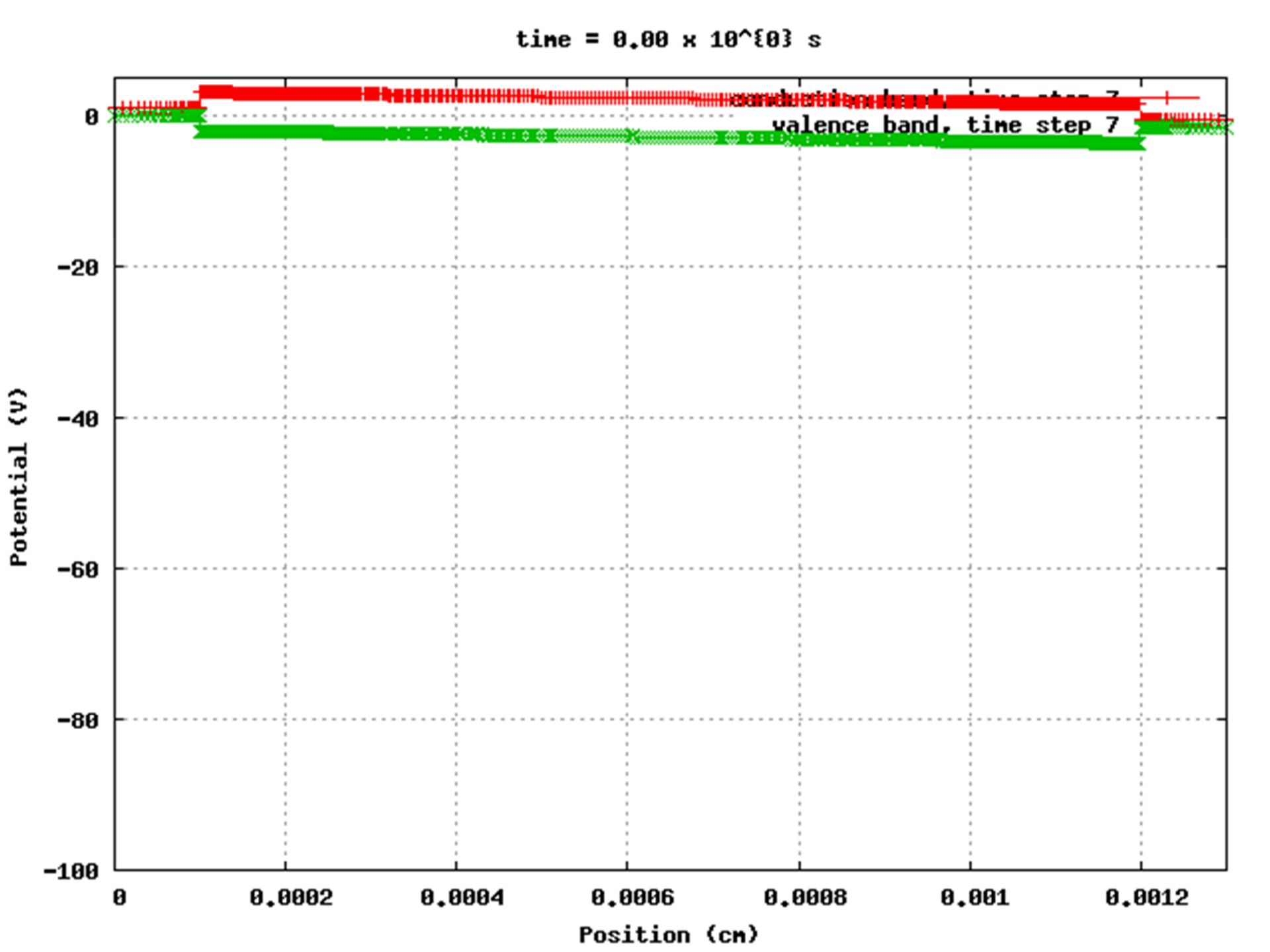

time = 0.00 x 10^{0} s
conduction band, time step 2
valence band, time step 2
0
-20
-40
-60
-80
-100
Potential (V)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)

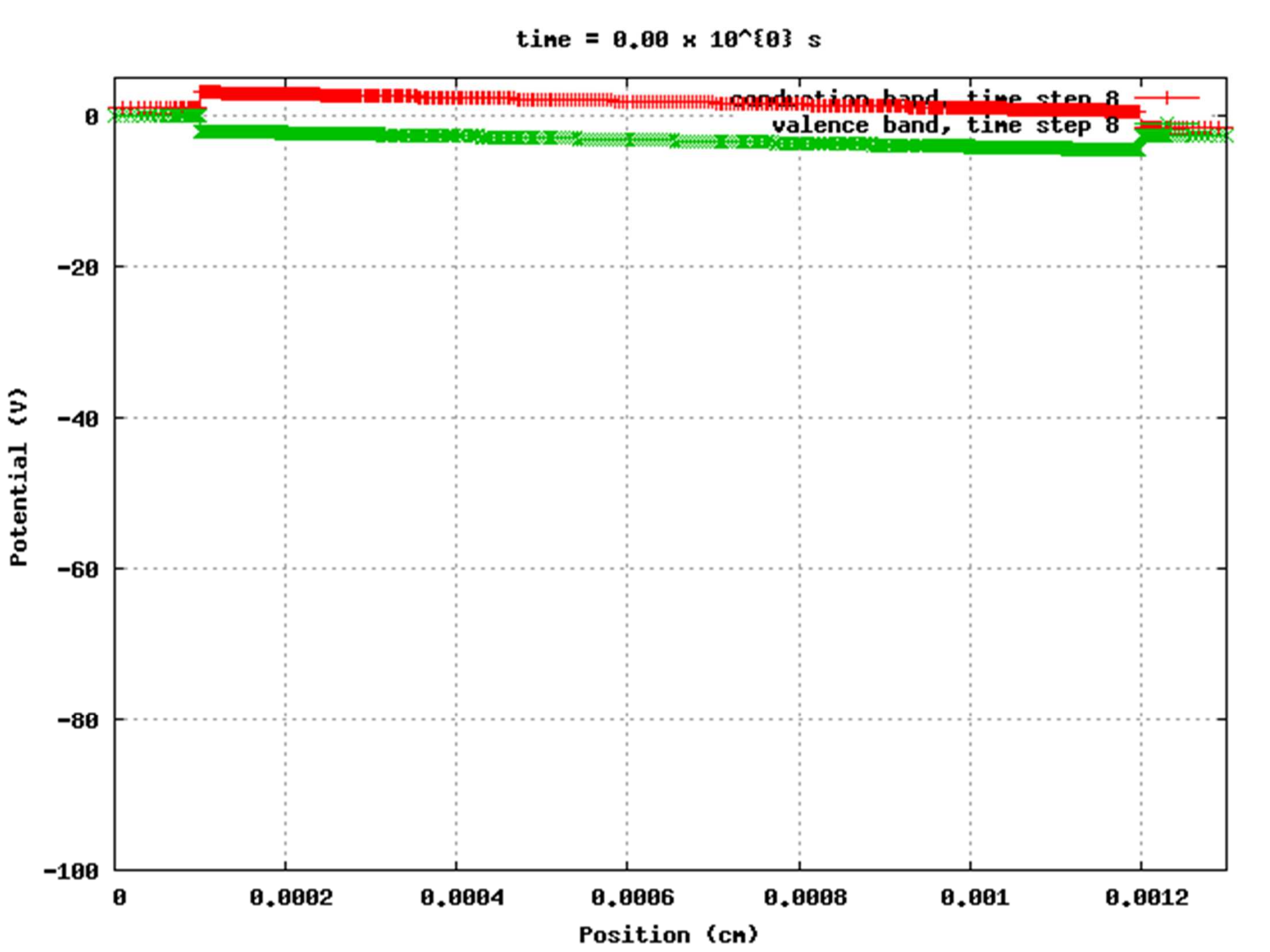

time = 0.00 x 10^{0} s
conduction band, time step 3
valence band, time step 3
0
-20
-40
-60
-80
-100
Potential (V)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)

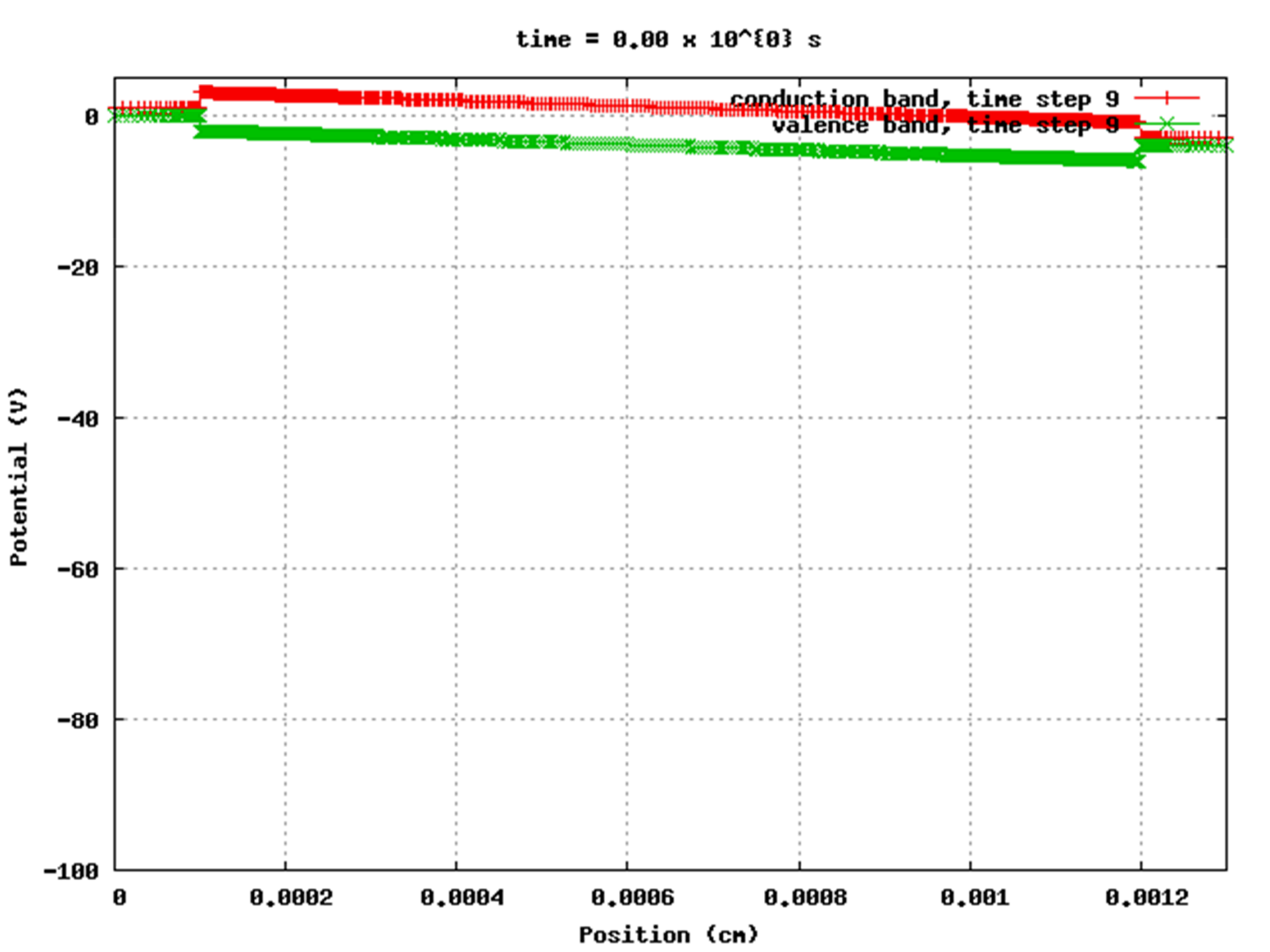

time = 0.00 x 10^{0} s
conduction band, time step 4
valence band, time step 4
0
-20
-40
-60
-80
-100
Potential (V)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)

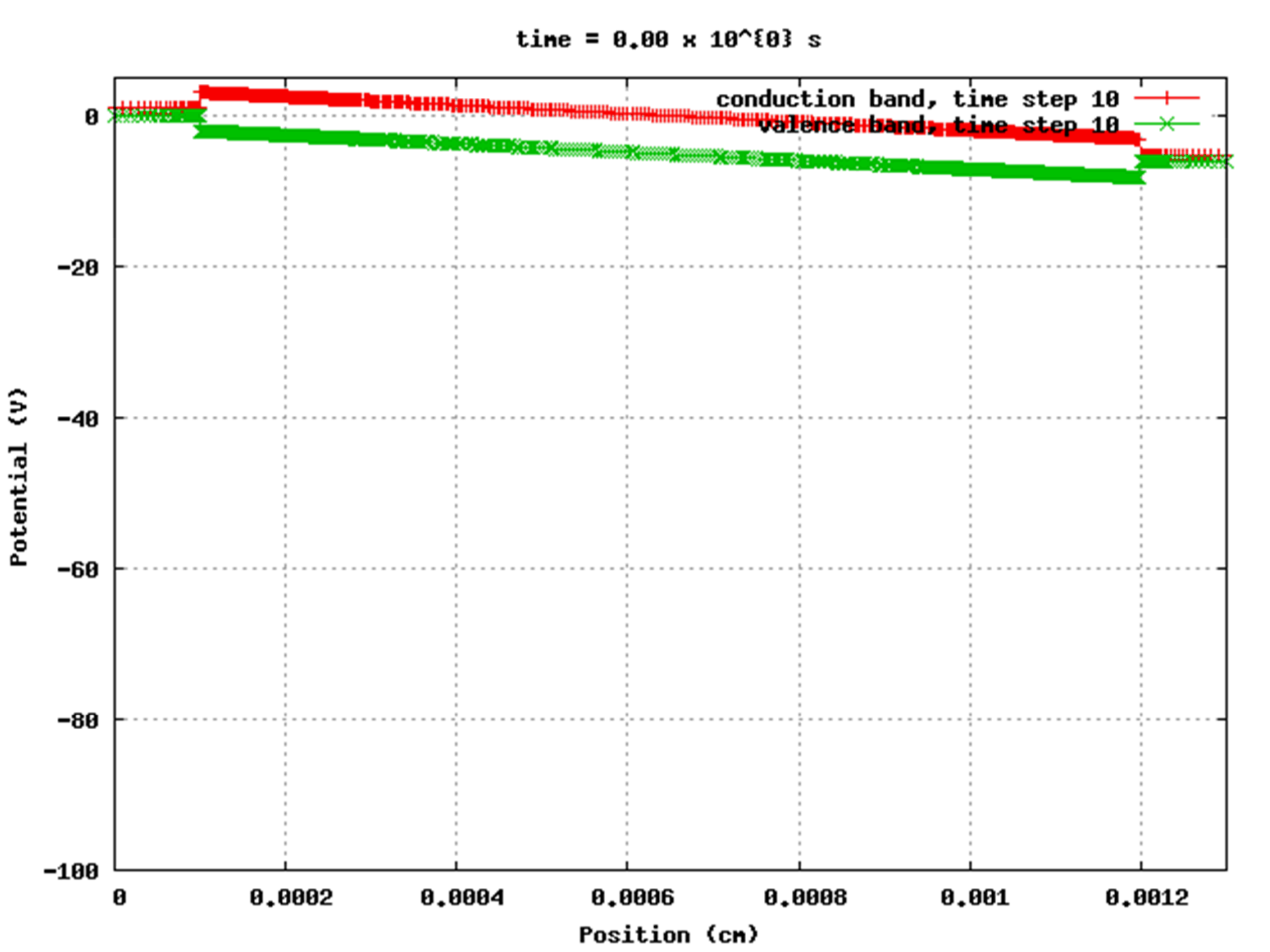

time = 0.00 x 10^{0} s
valence band, time step 5
0
-20
-40
-60
-80
-100
Potential (V)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)

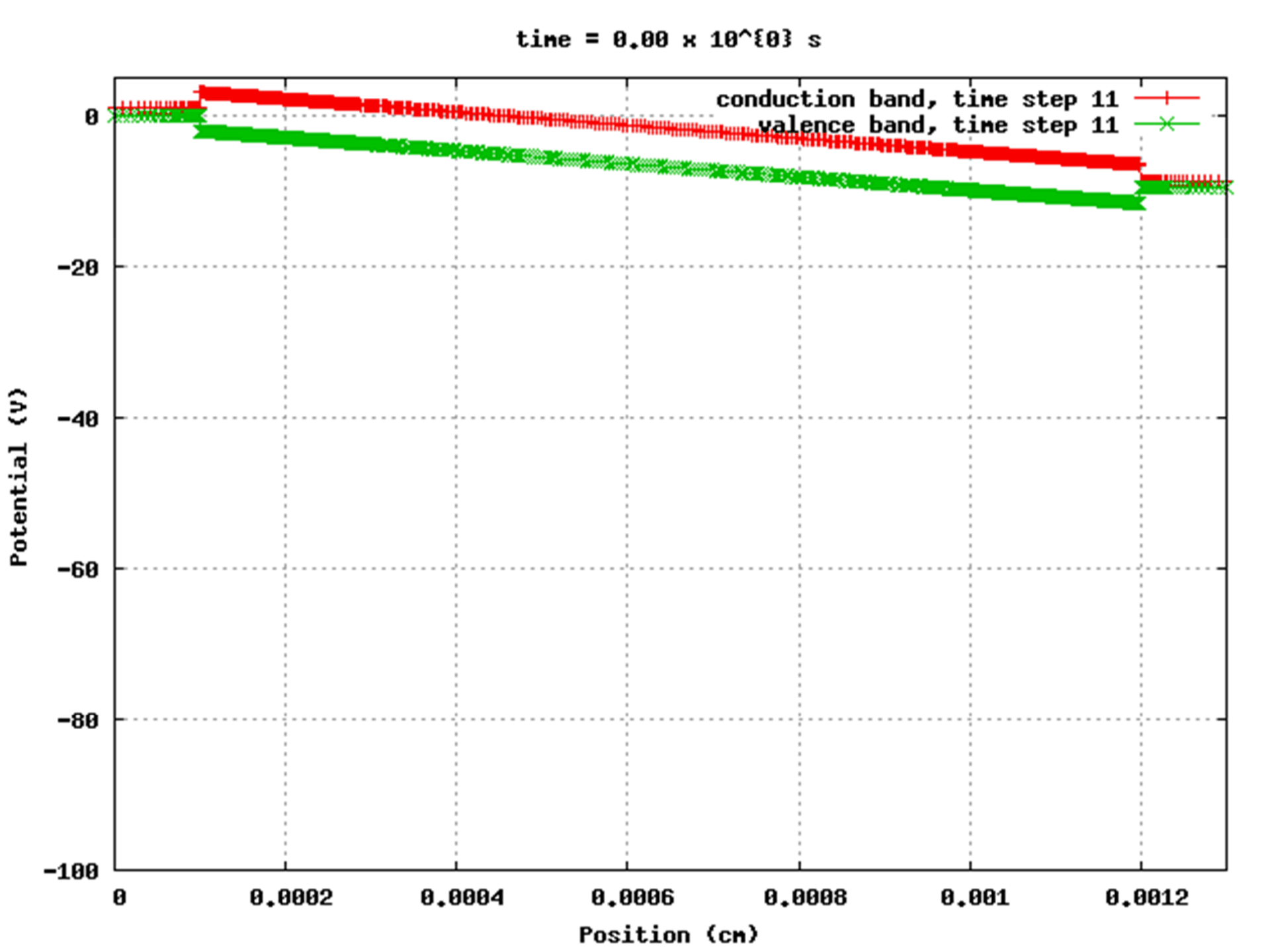

time = 0.00 x 10^{0} s
valence band, time step 6
0
-20
-40
-60
-80
-100
Potential (V)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)

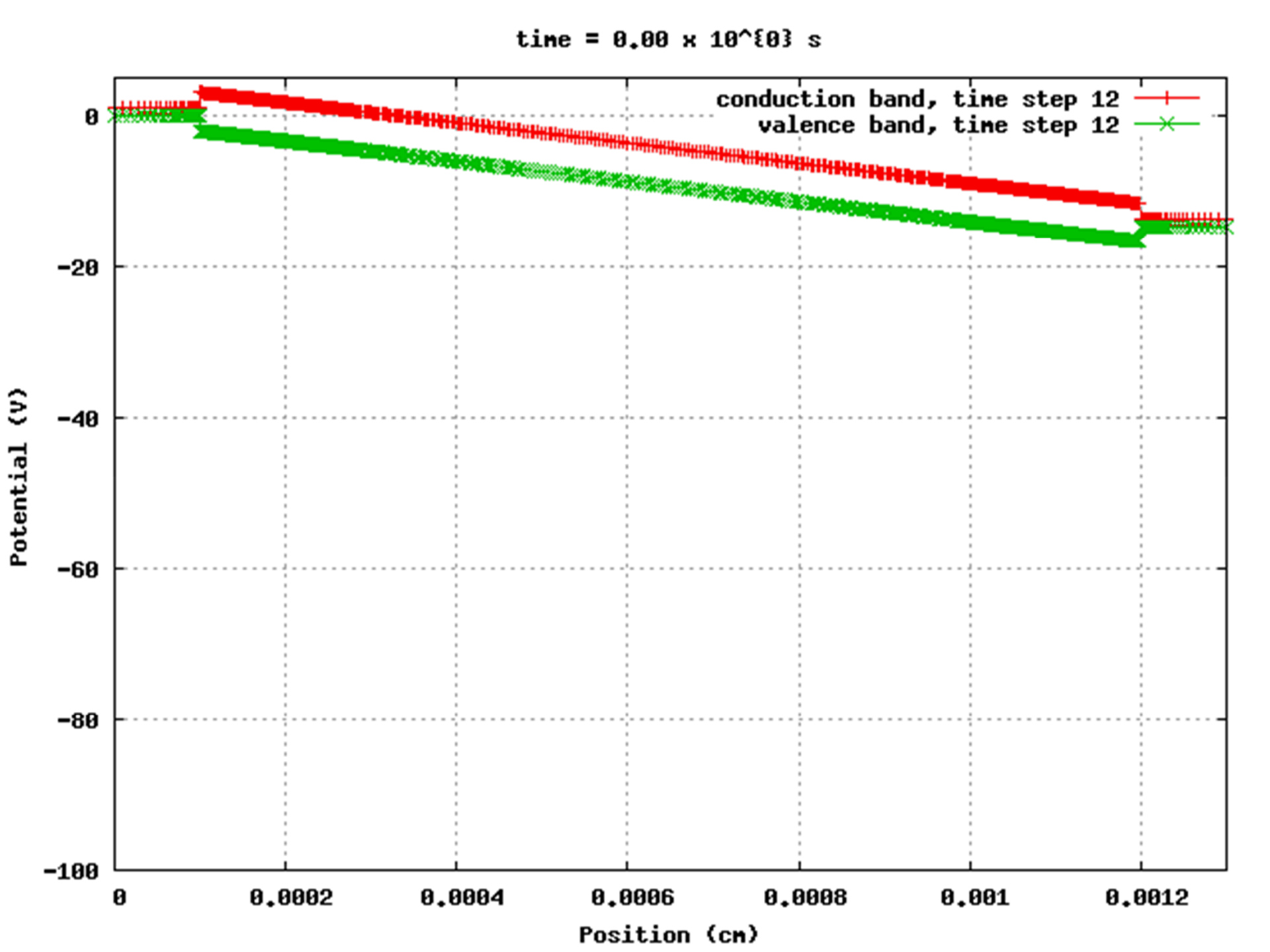

time = 0.00 x 10^{0} s
conduction band, time step 7
valence band, time step 7
0
-20
-40
-60
-80
-100
Potential (V)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)

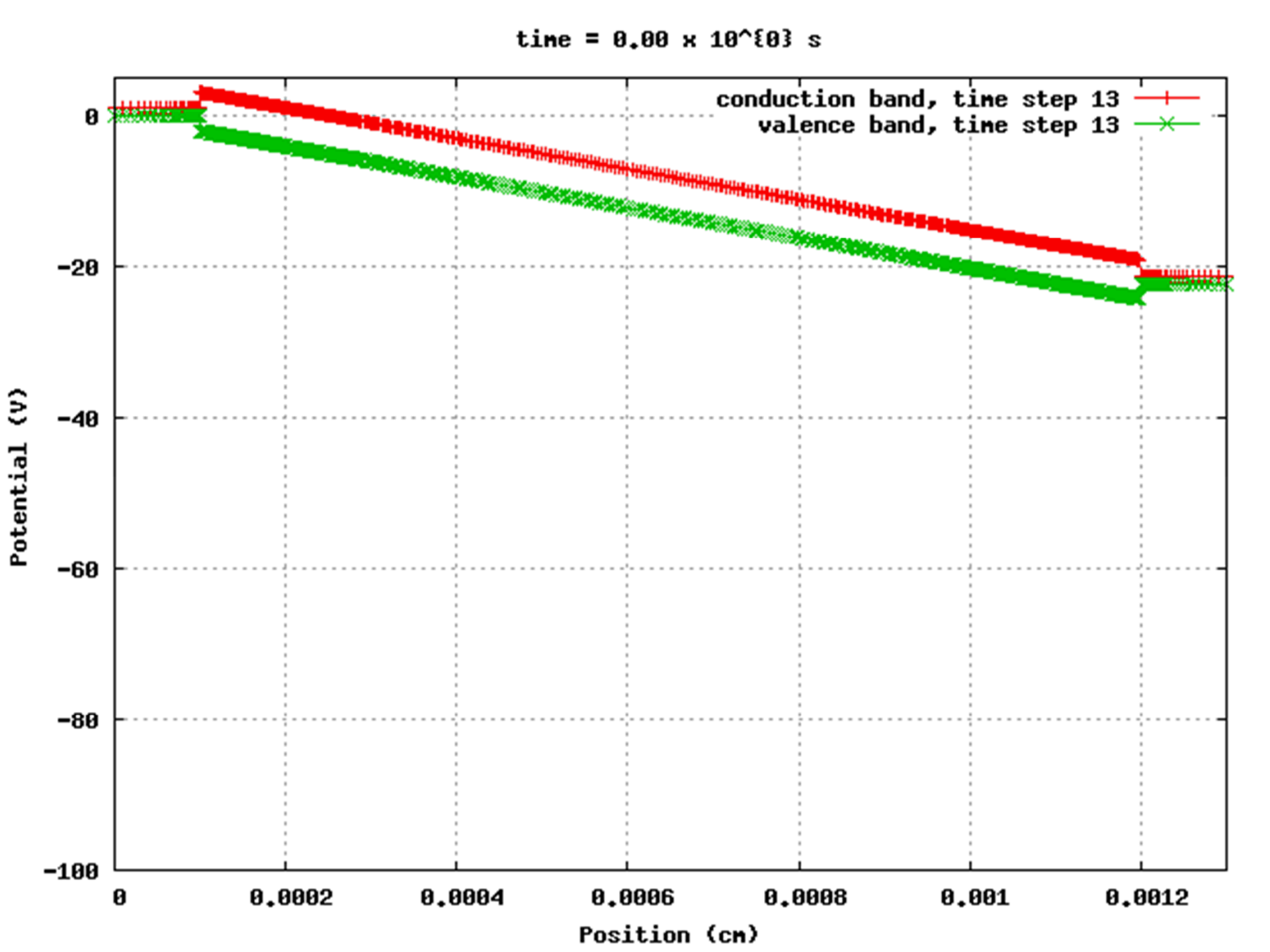

time = 0.00 x 10^{0} s
conduction band, time step 8
valence band, time step 8
0
-20
-40
-60
-80
-100
Potential (V)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)

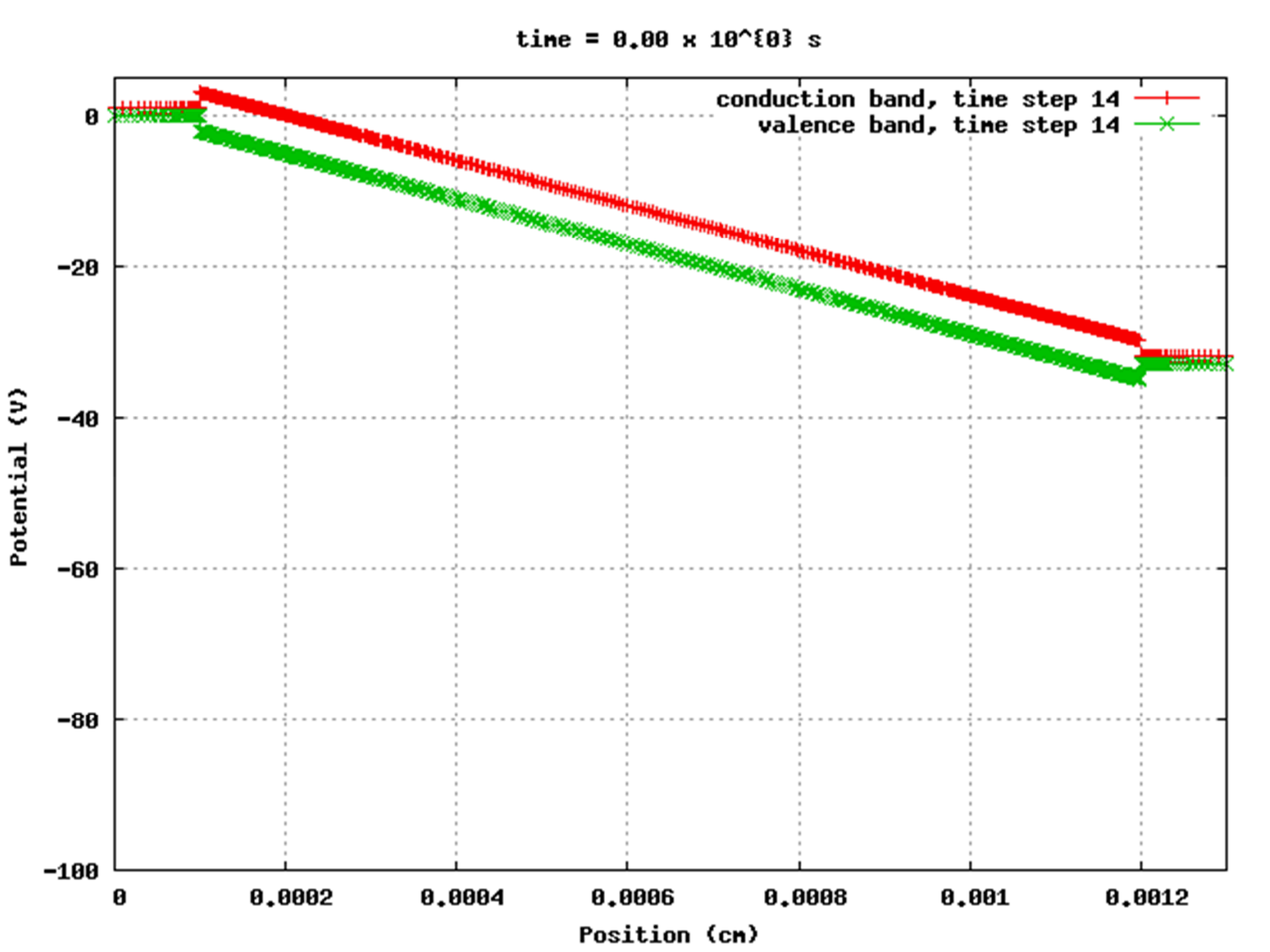

time = 0.00 x 10^{0} s
conduction band, time step 9
valence band, time step 9
0
-20
-40
-60
-80
-100
Potential (V)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)

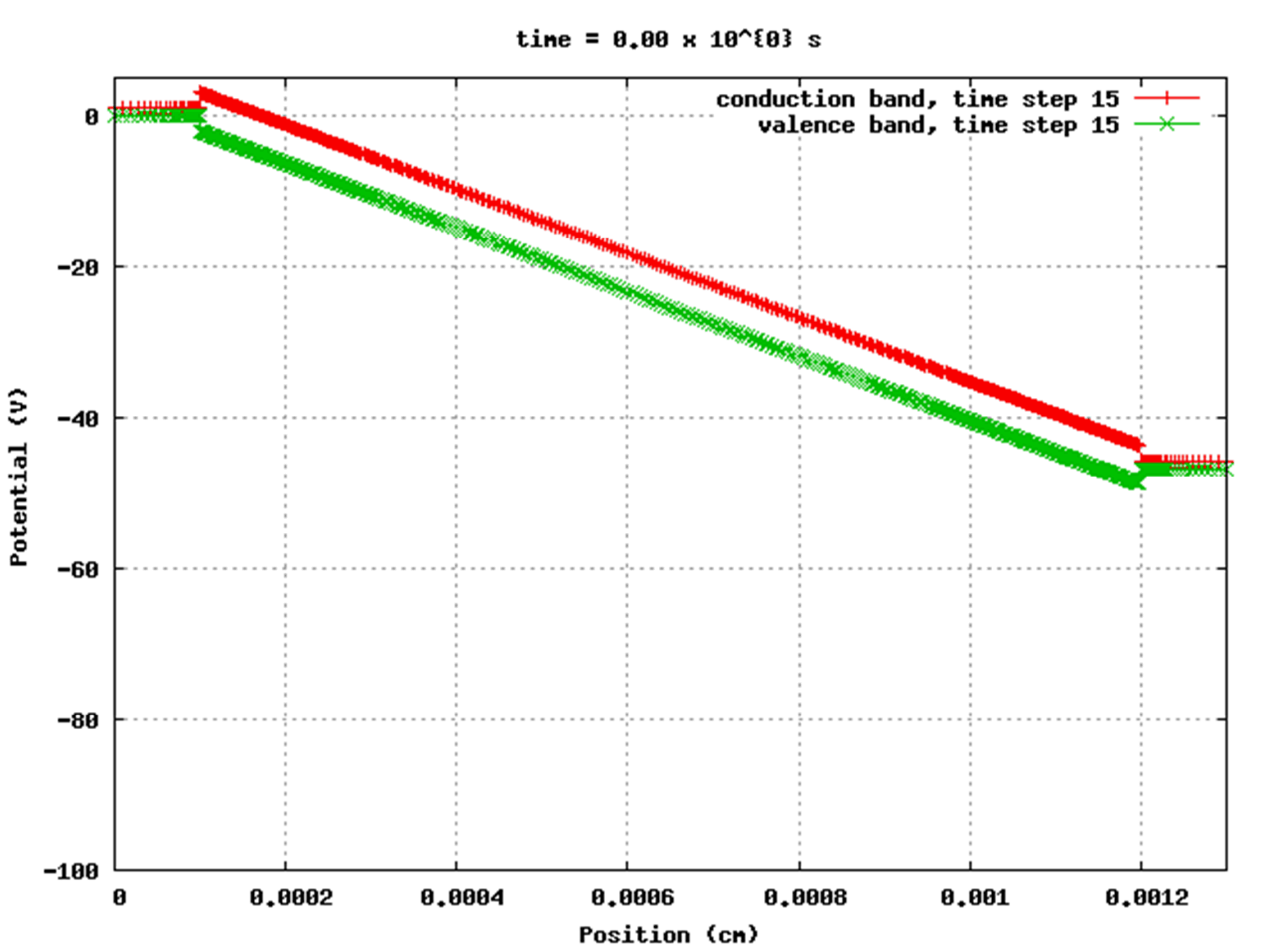

time = 0.00 x 10^{0} s
conduction band, time step 10
valence band, time step 10
0
-20
-40
-60
-80
-100
Potential (V)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)

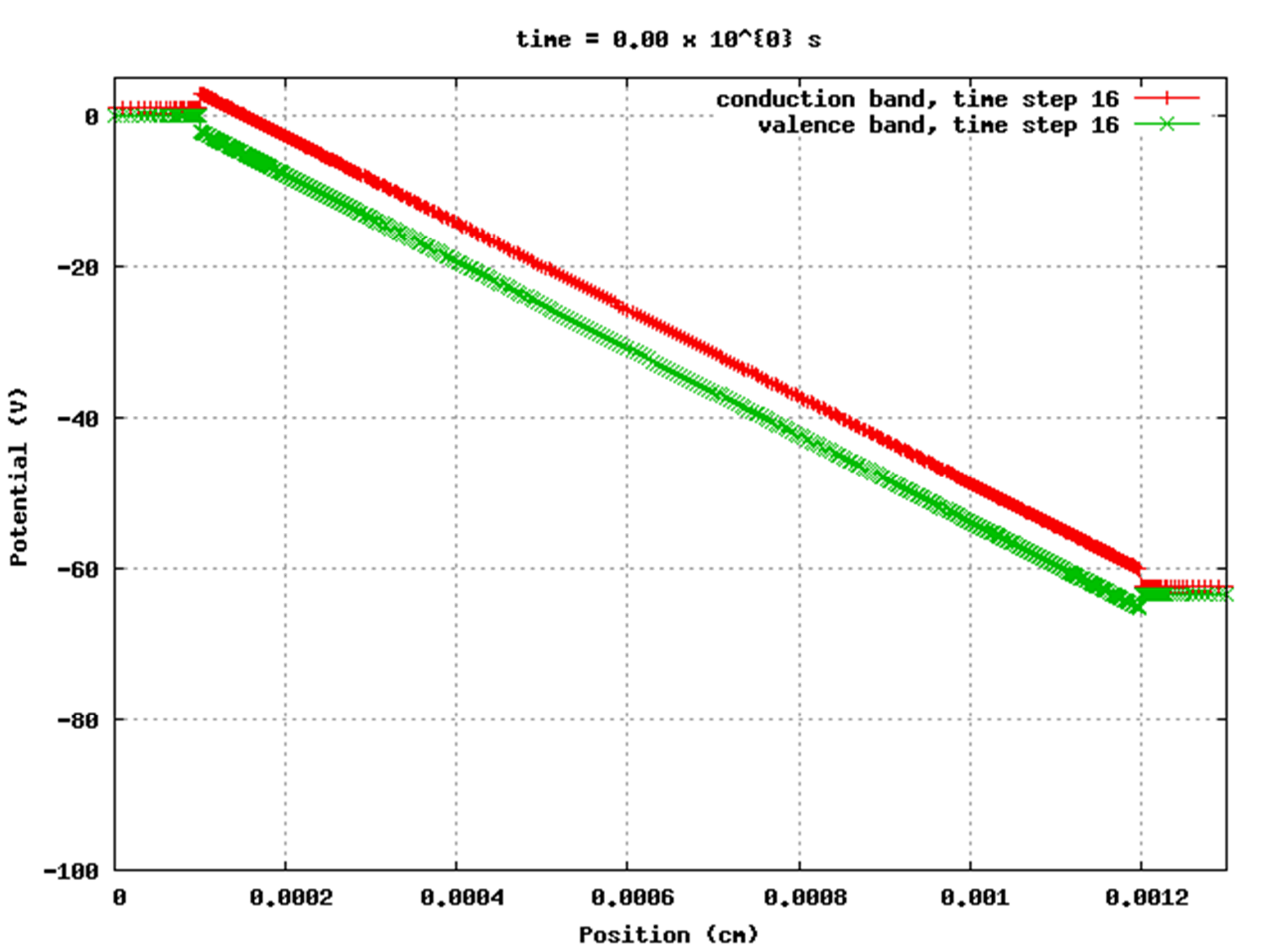

time = 0.00 x 10^{0} s
conduction band, time step 11
valence band, time step 11
0
-20
-40
-60
-80
-100
Potential (V)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)

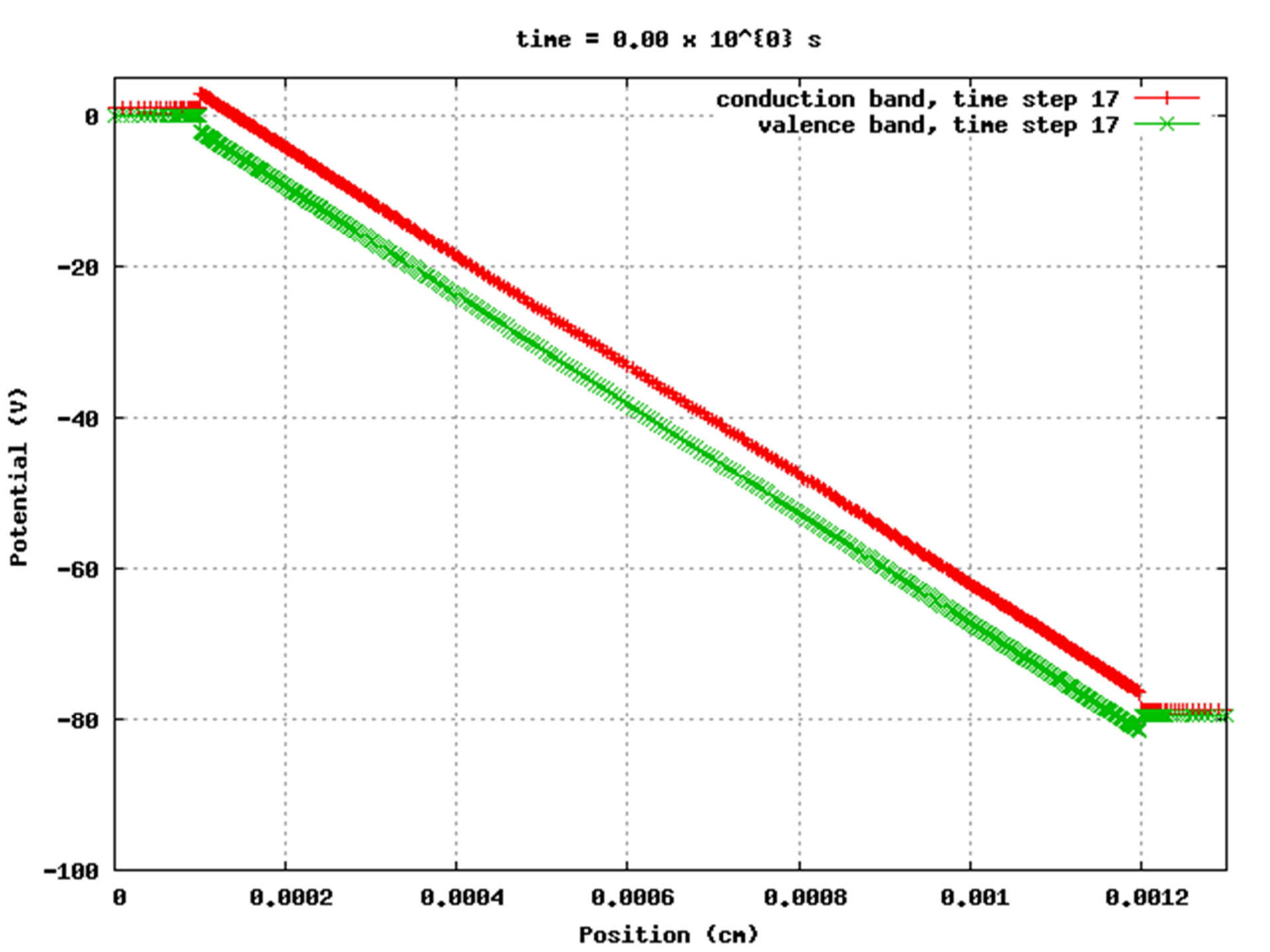

time = 0.00 x 10^{0} s
conduction band, time step 12
valence band, time step 12
0
-20
-40
-60
-80
-100
Potential (V)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)

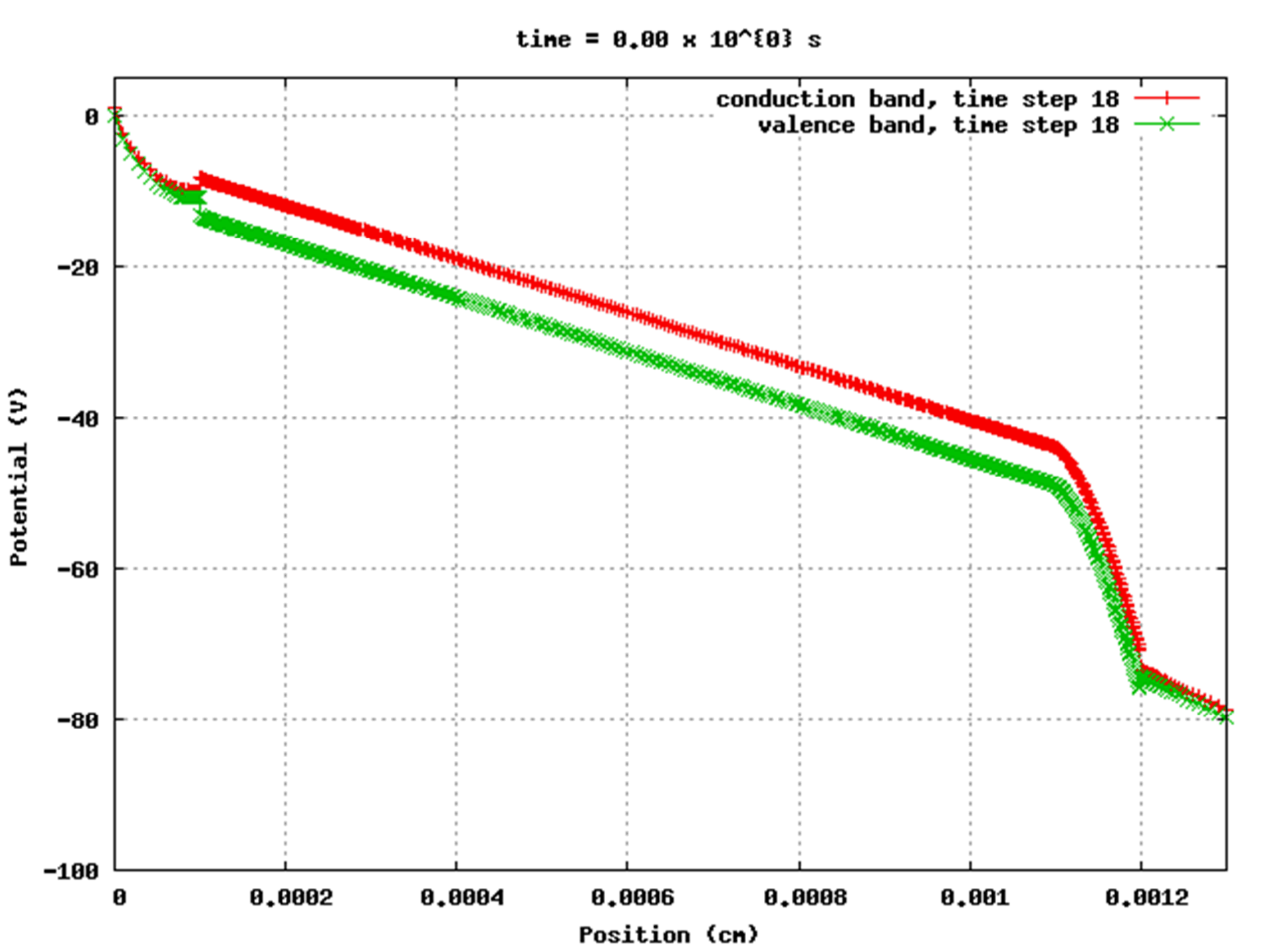

time = 0.00 x 10^{0} s
conduction band, time step 13
valence band, time step 13
0
-20
-40
-60
-80
-100
Potential (V)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)

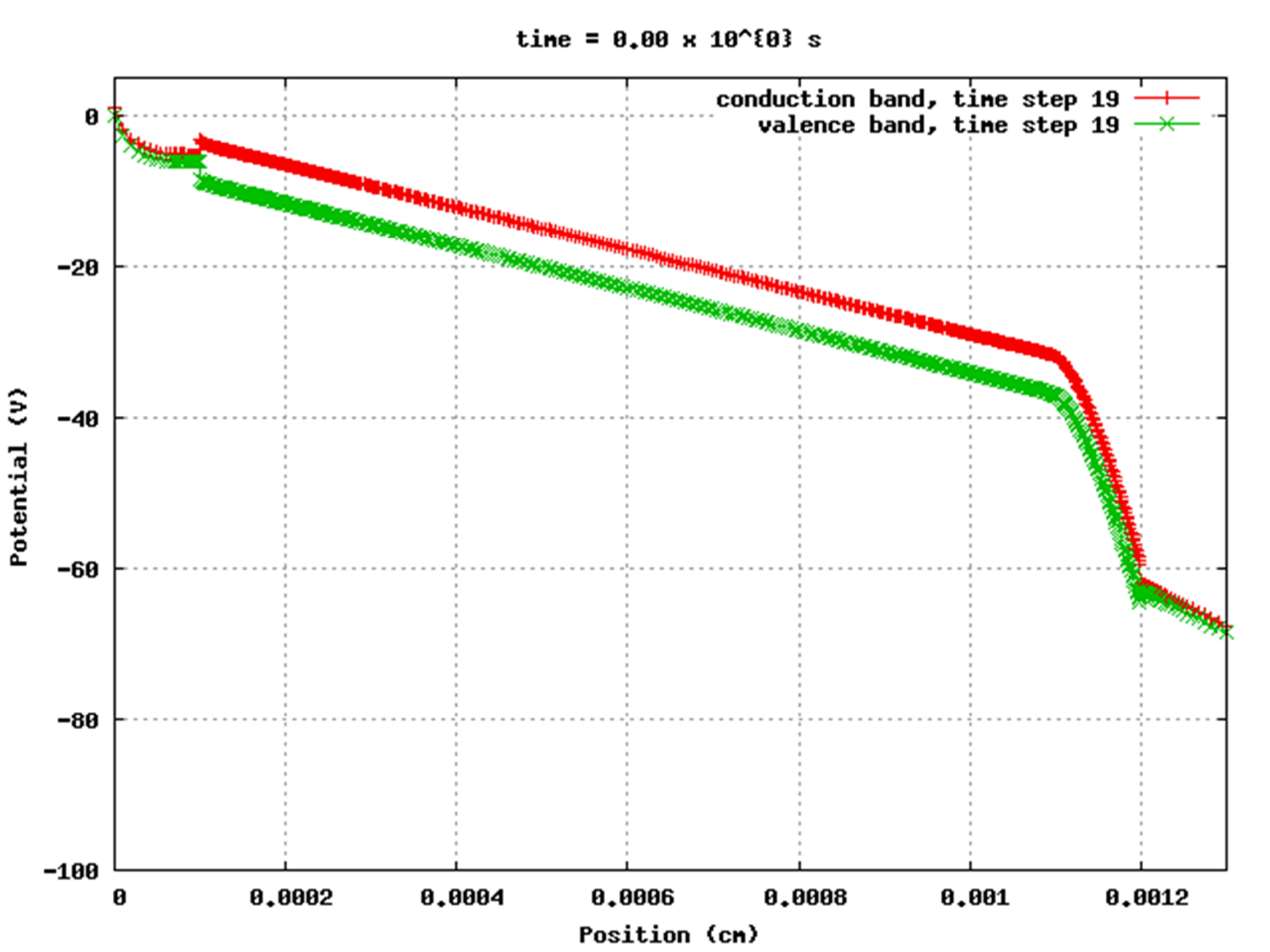

time = 0.00 x 10^{0} s
conduction band, time step 14
valence band, time step 14
0
-20
-40
-60
-80
-100
Potential (V)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)

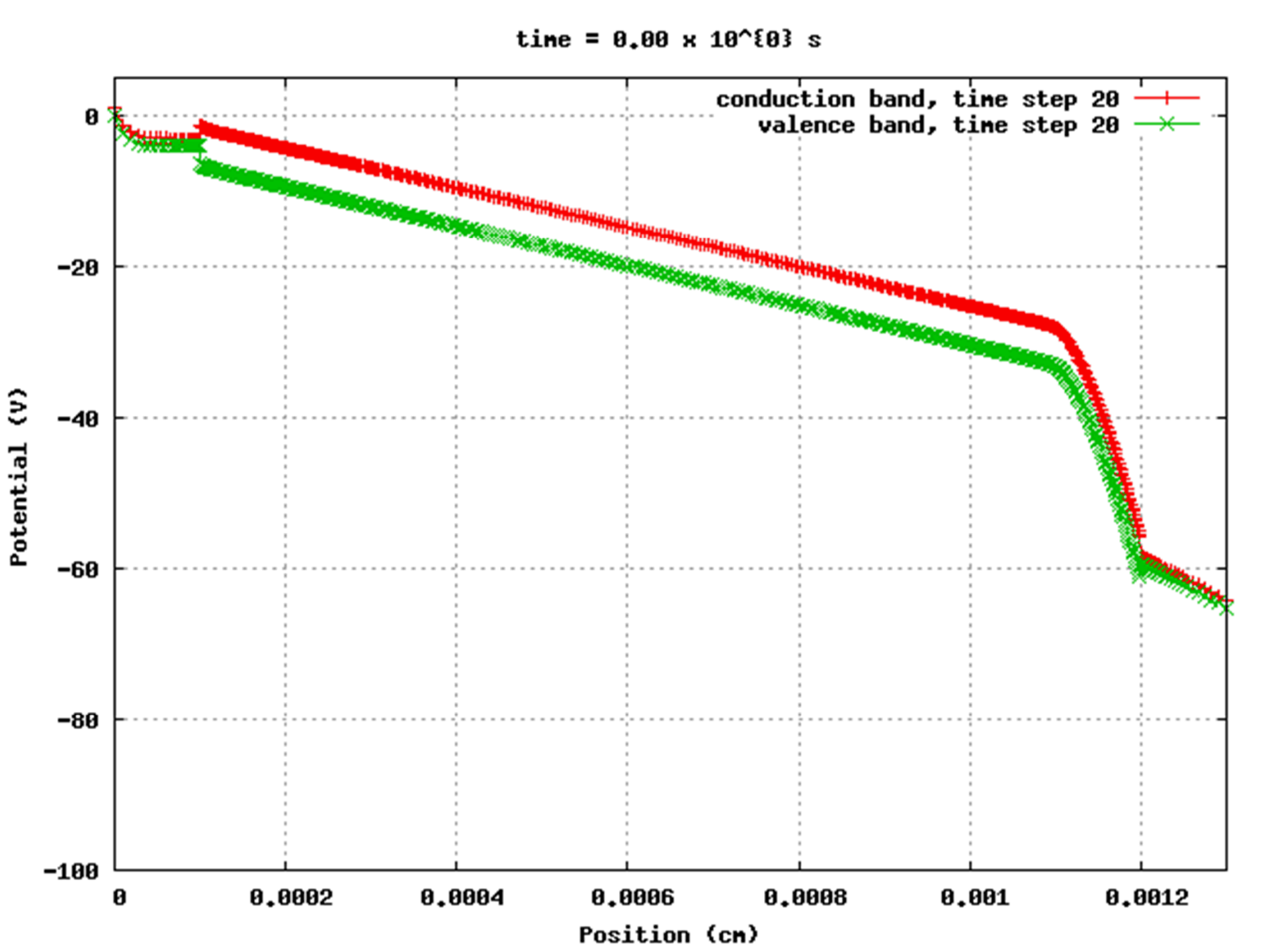

time = 0.00 x 10^{0} s
conduction band, time step 15
valence band, time step 15
0
-20
-40
-60
-80
-100
Potential (V)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)

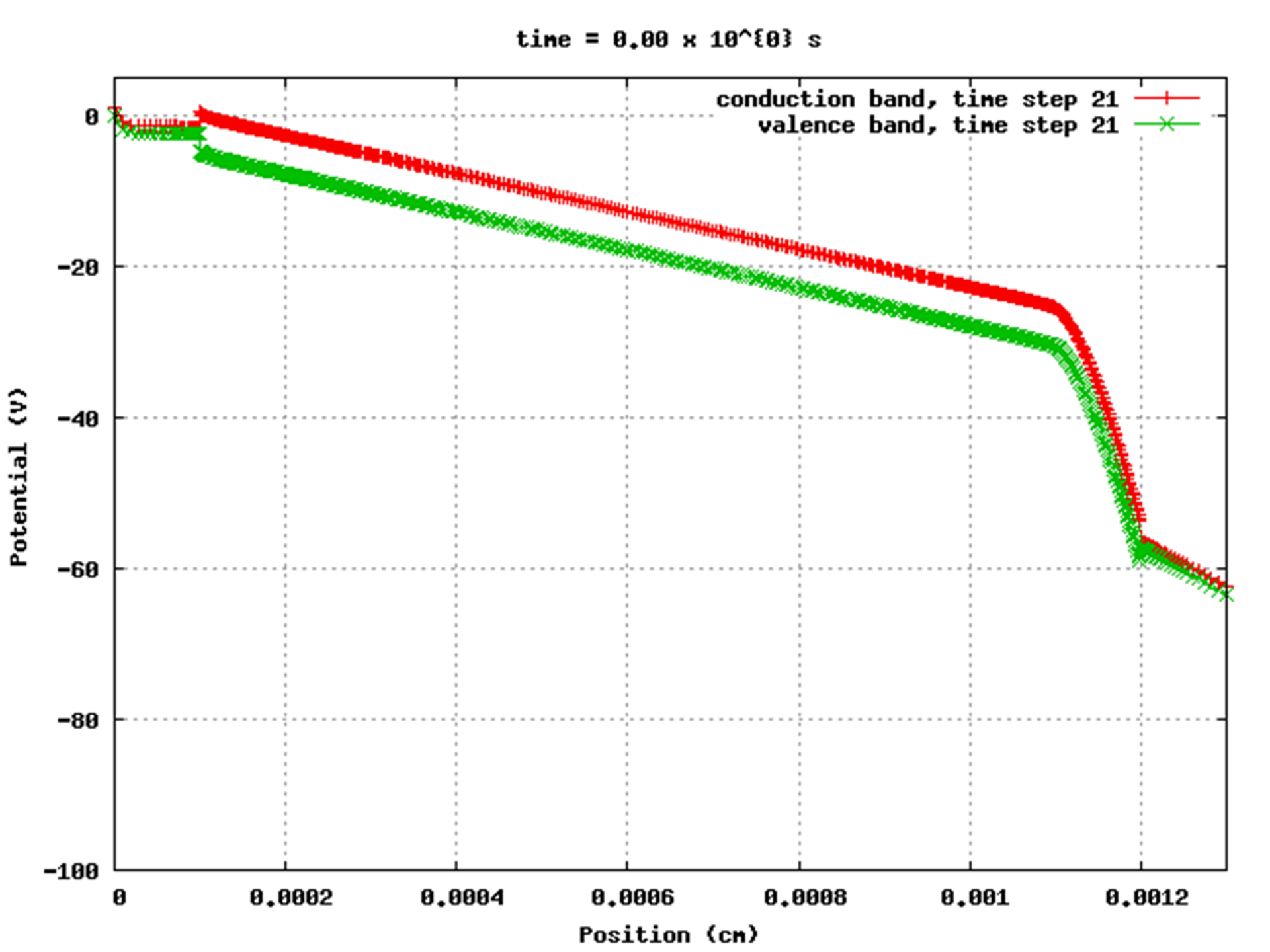

time = 0.00 x 10^{0} s
conduction band, time step 16
valence band, time step 16
0
-20
-40
-60
-80
-100
Potential (V)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)

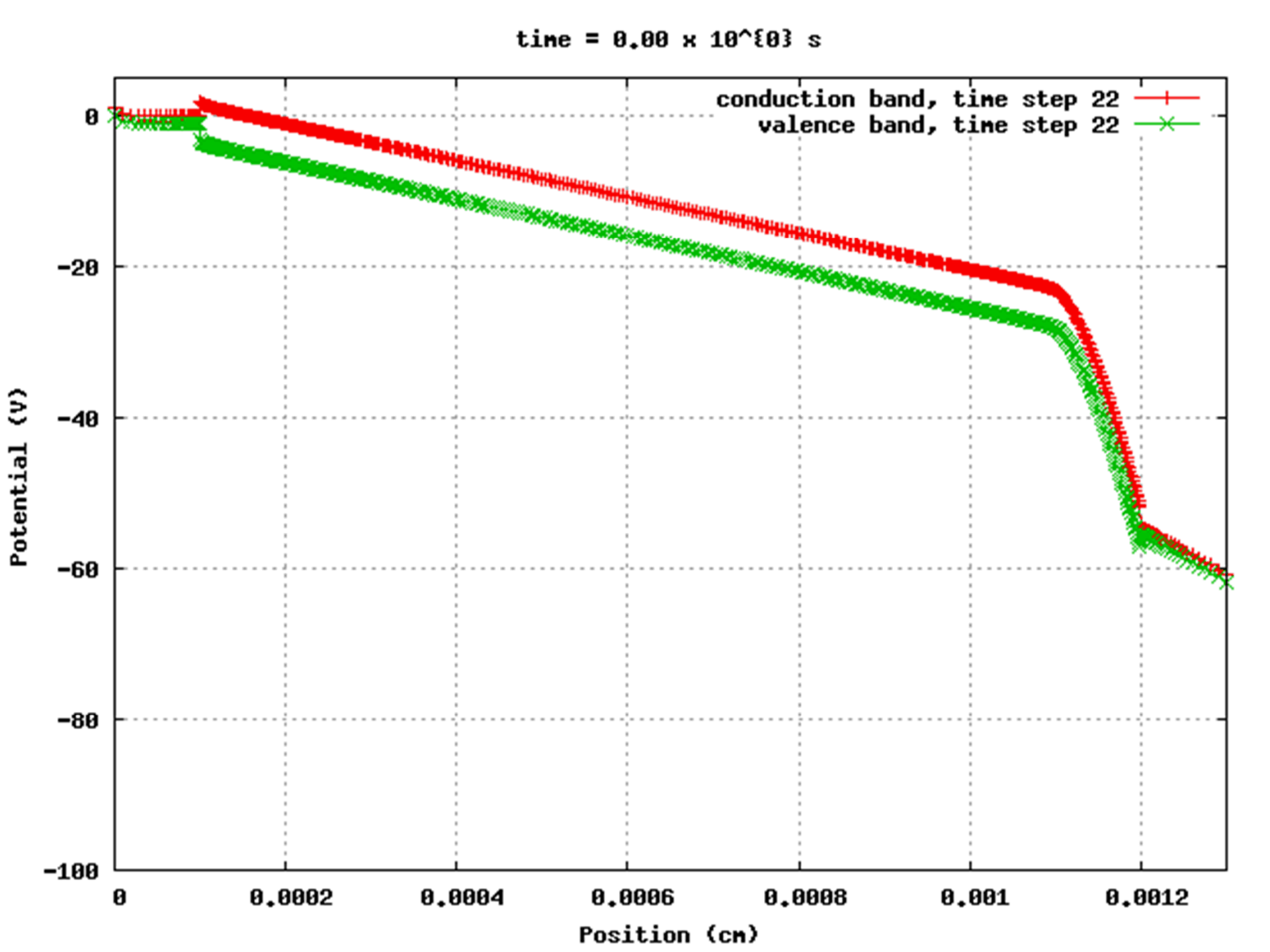

time = 0.00 x 10^{0} s
conduction band, time step 17
valence band, time step 17
0
-20
-40
-60
-80
-100
Potential (V)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)

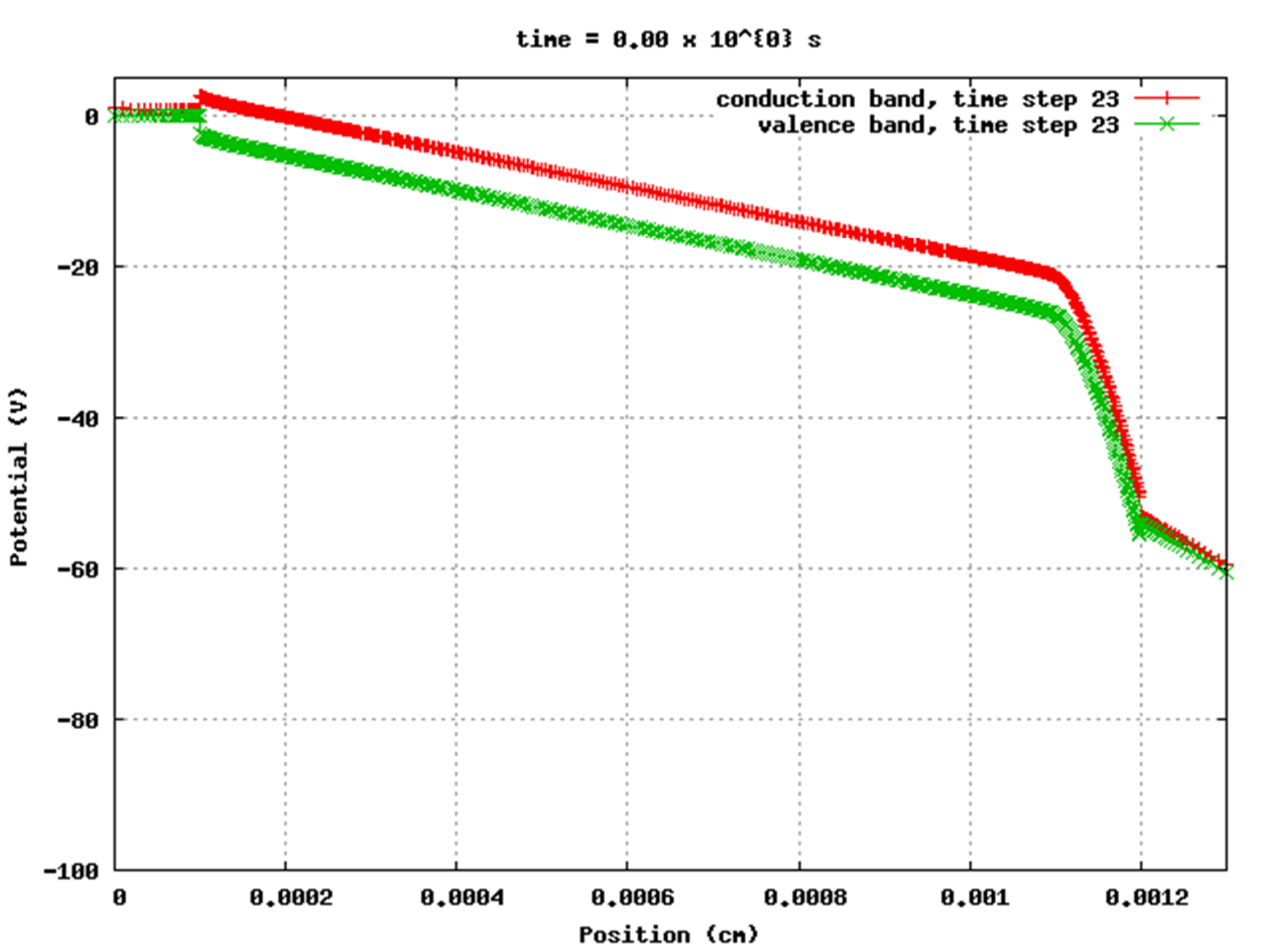

time = 0.00 x 10^{0} s
conduction band, time step 18
valence band, time step 18
0
-20
-40
-60
-80
-100
Potential (V)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)

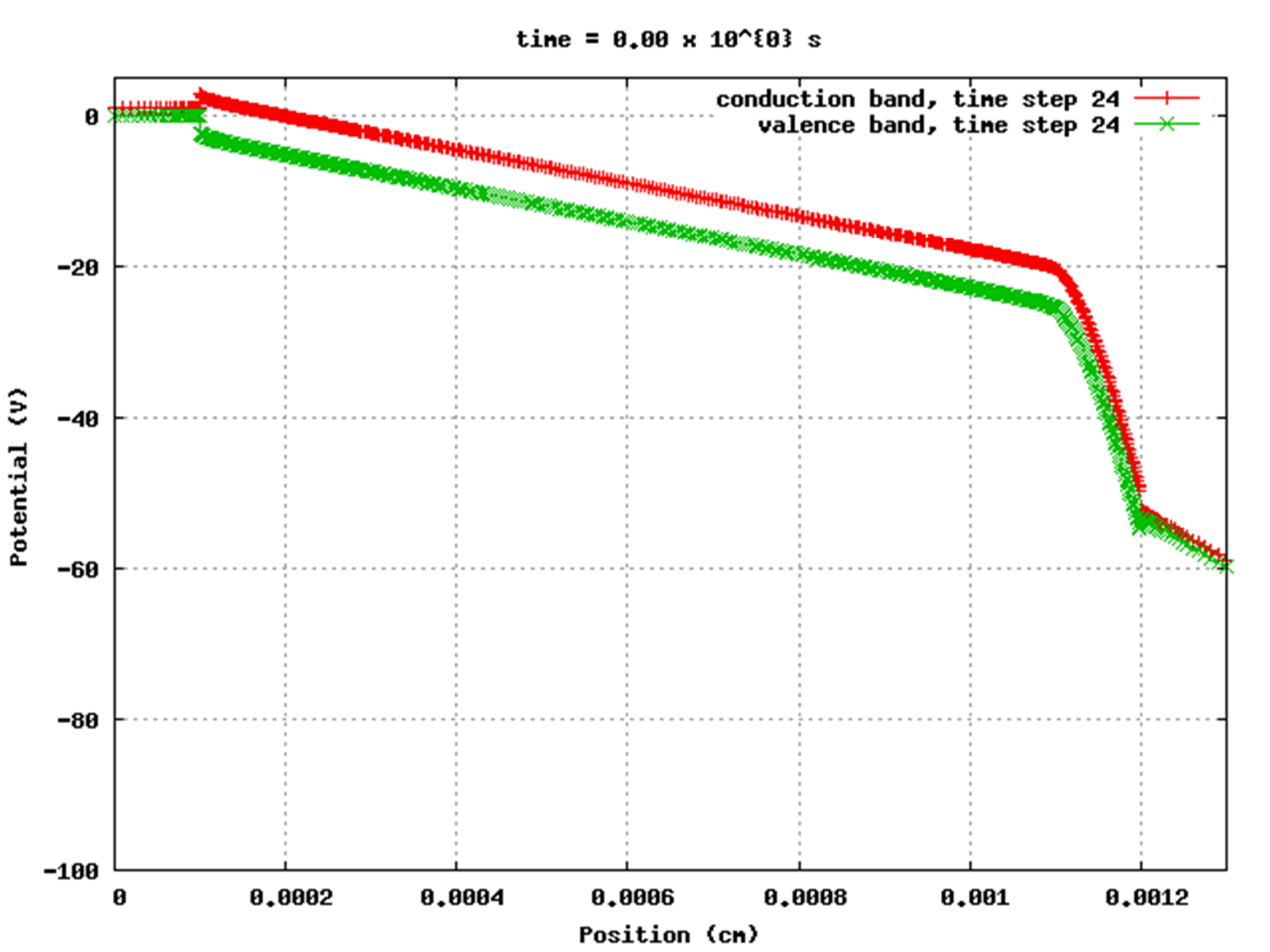

time = 0.00 x 10^{0} s
conduction band, time step 19
valence band, time step 19
0
-20
-40
-60
-80
-100
Potential (V)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)

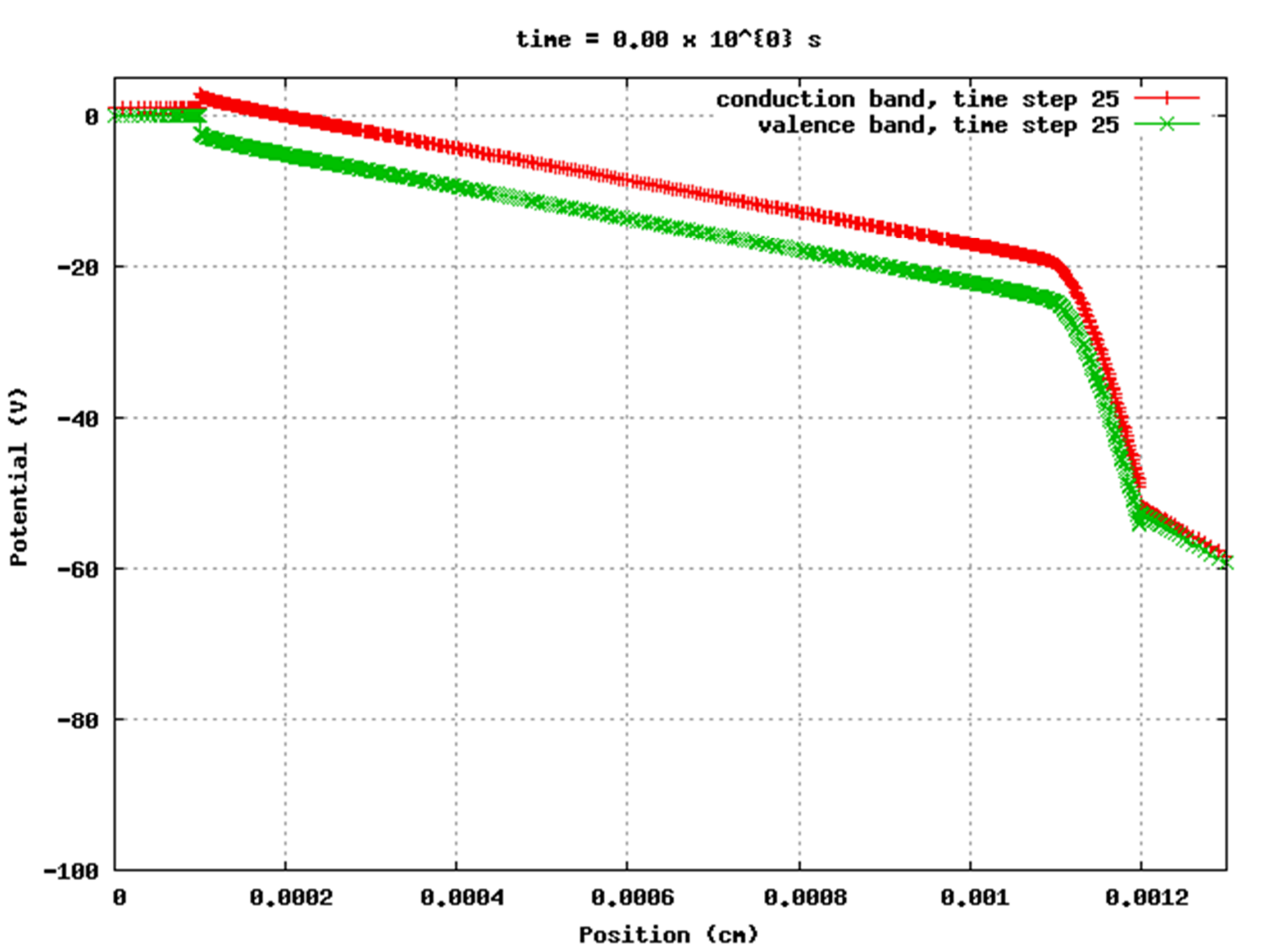

time = 0.00 x 10^{0} s
conduction band, time step 20
valence band, time step 20
0
-20
-40
-60
-80
-100
Potential (V)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)


time = 0.00 x 10^{0} s
conduction band, time step 21
valence band, time step 21
0
-20
-40
-60
-80
-100
Potential (V)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)


time = 0.00 x 10^{0} s
conduction band, time step 22
valence band, time step 22
0
-20
-40
-60
-80
-100
Potential (V)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)

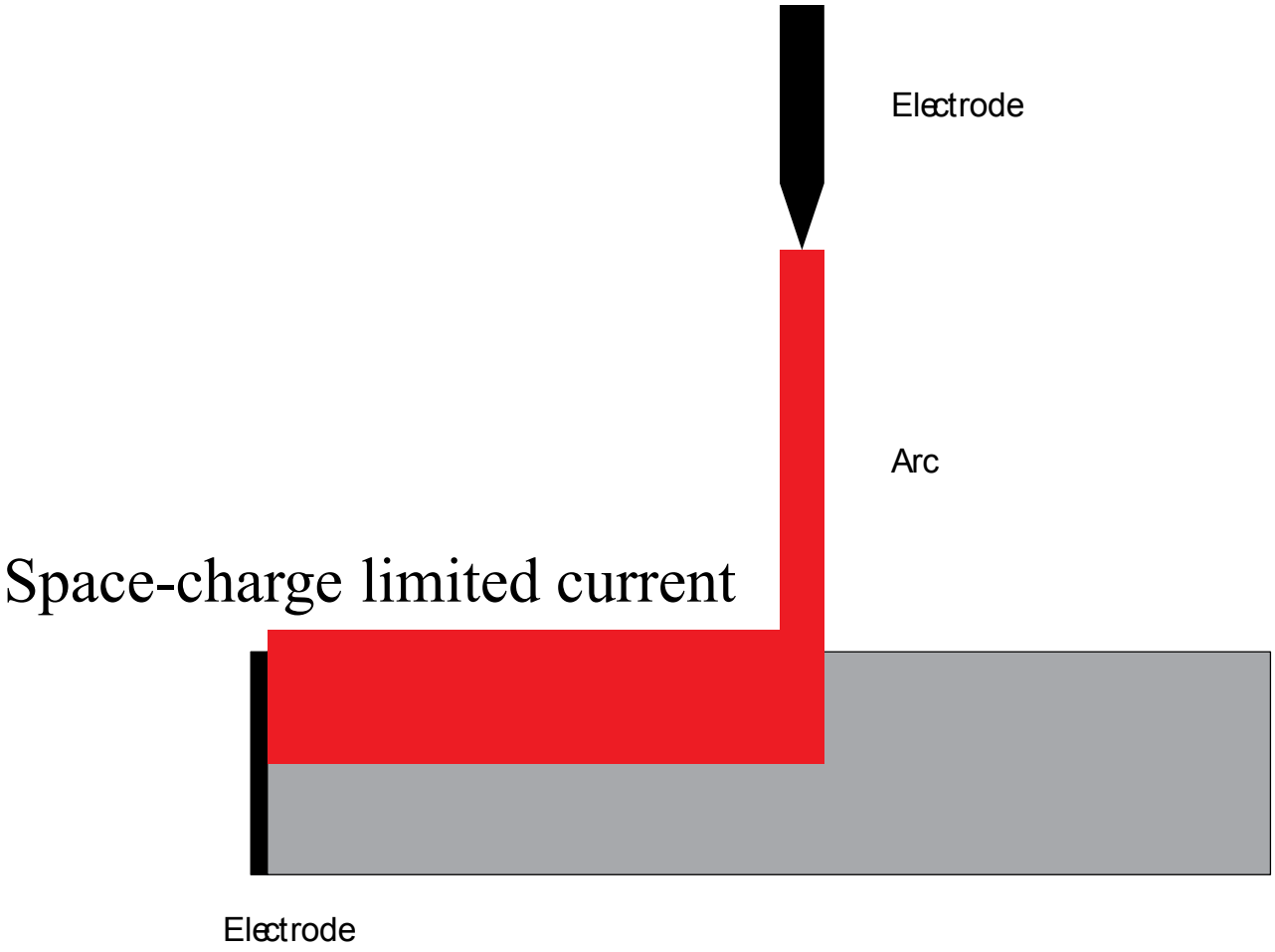

time = 0.00 x 10^{0} s
conduction band, time step 23
valence band, time step 23
Potential (V)
0
-20
-40
-60
-80
-100
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)


time = 0.00 x 10^{0} s
conduction band, time step 24
valence band, time step 24
Potential (V)
0
-20
-40
-60
-80
-100
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)


time = 0.00 x 10^{0} s
conduction band, time step 25
valence band, time step 25
Potential (V)
0
-20
-40
-60
-80
-100
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
Position (cm)

Extra Slides

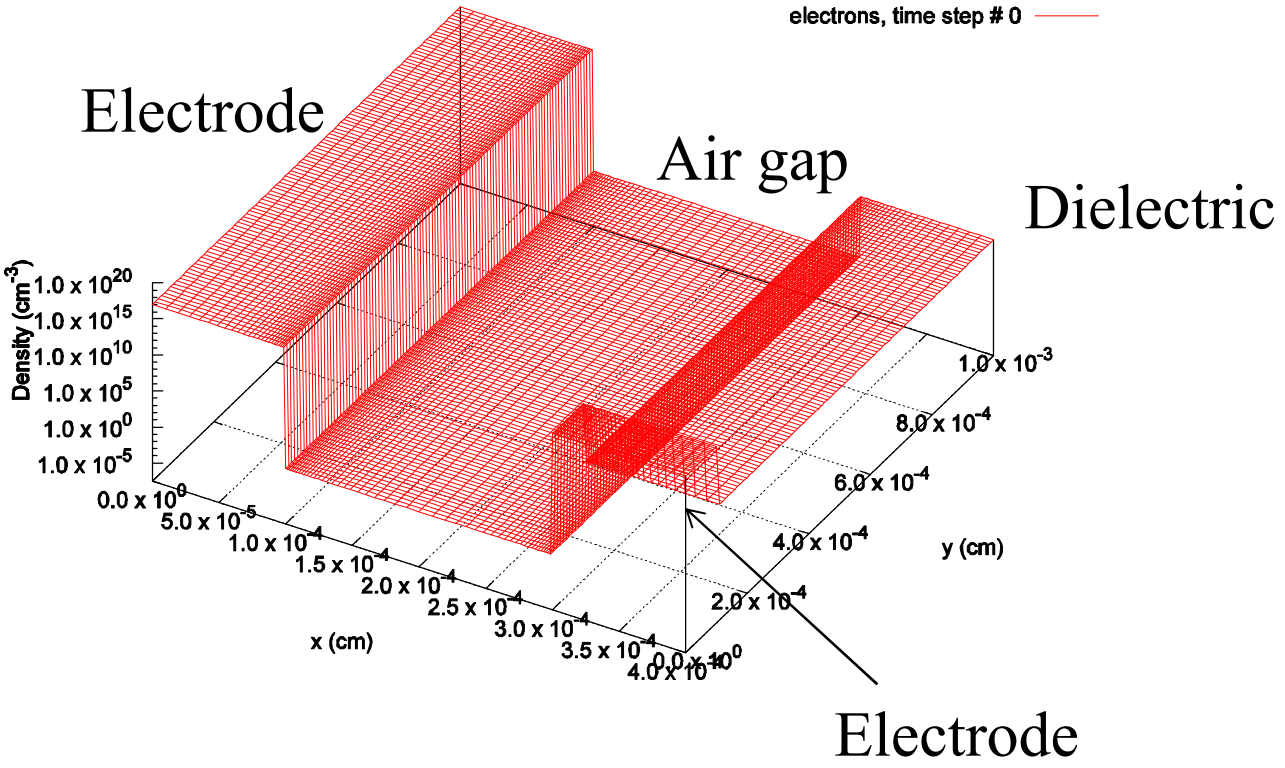
Idealized Experiments: Lateral



REOS results will illustrate the stages

Sandia National Laboratories

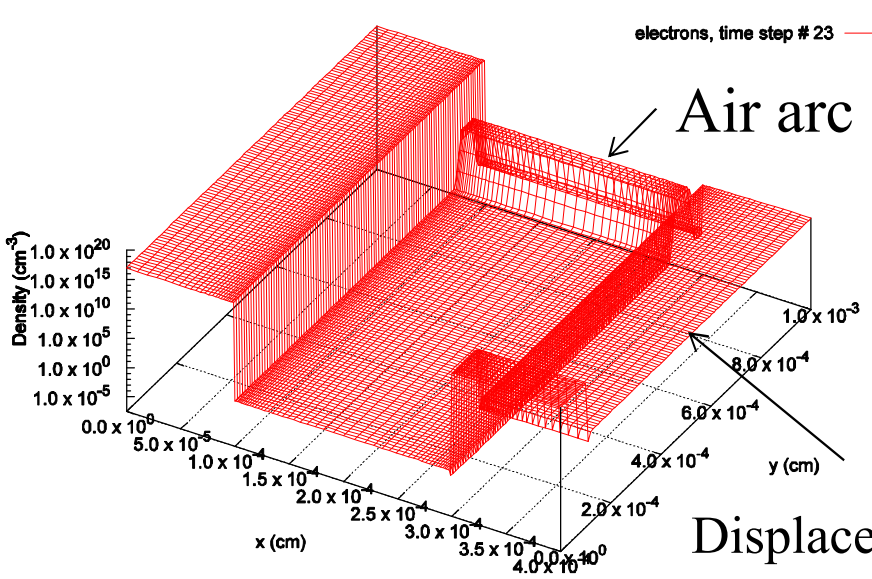
Lateral Breakdown



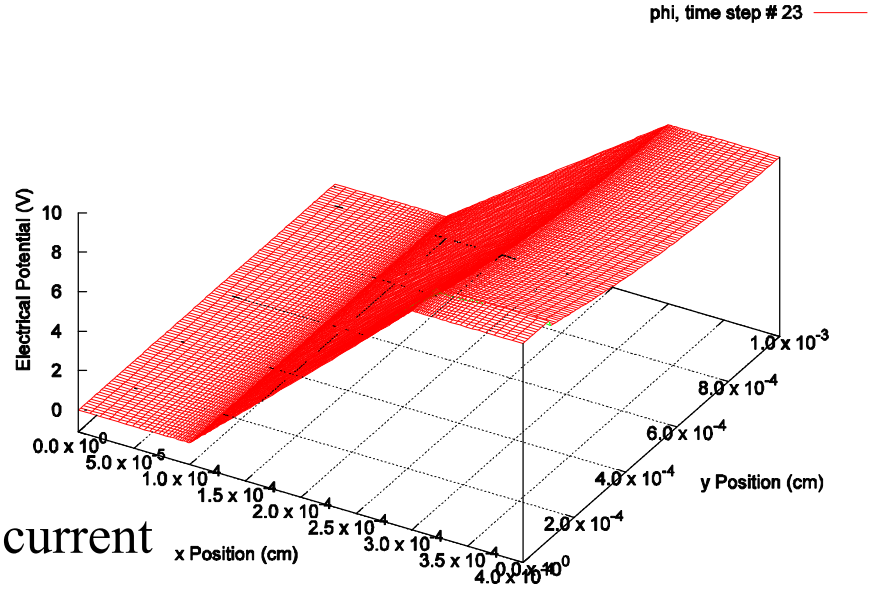
Dielectric constant: 80

Sandia National Laboratories

Early Stage of Air Breakdown

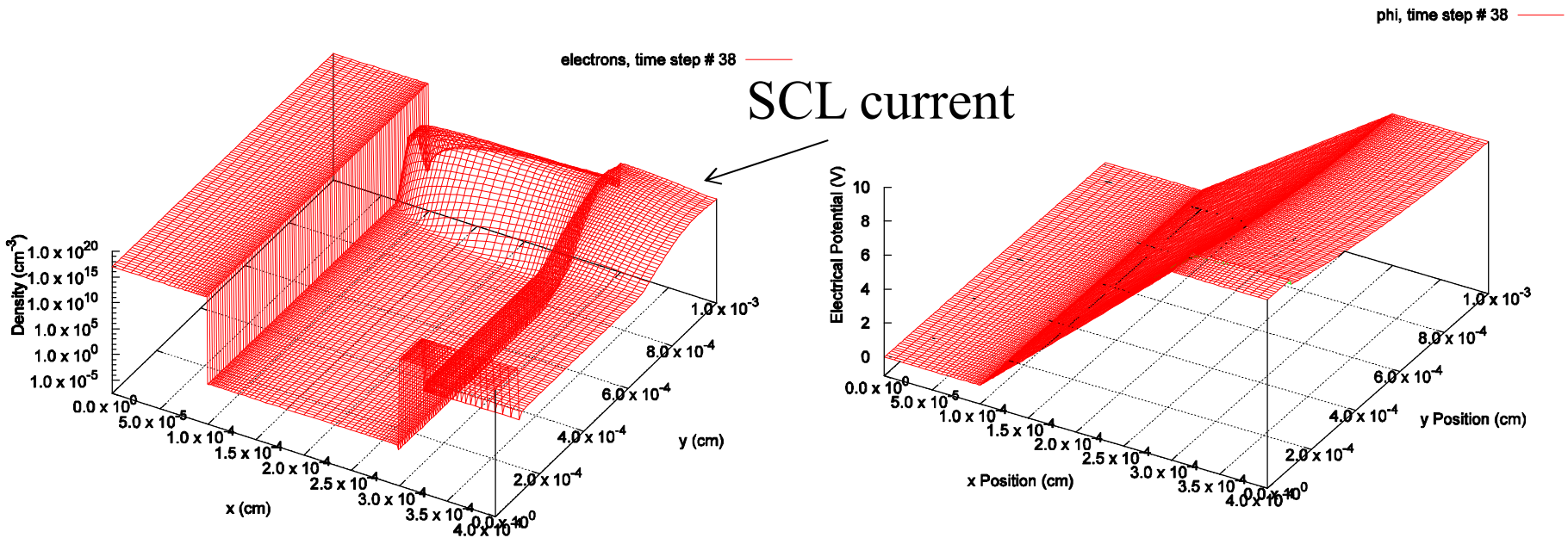


Displacement current

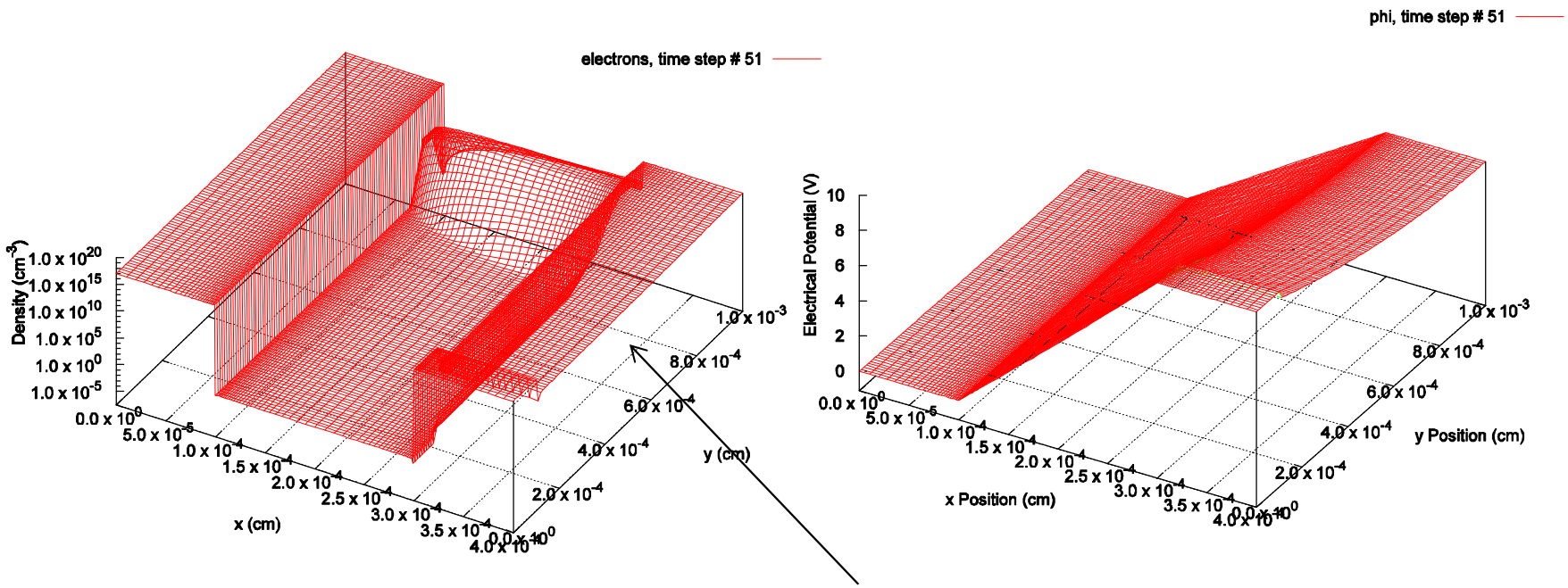


Sandia National Laboratories

Intermediate Stage



Late Stage



Large SCL current

Joule heating from a large SCL current causes electrothermal breakdown

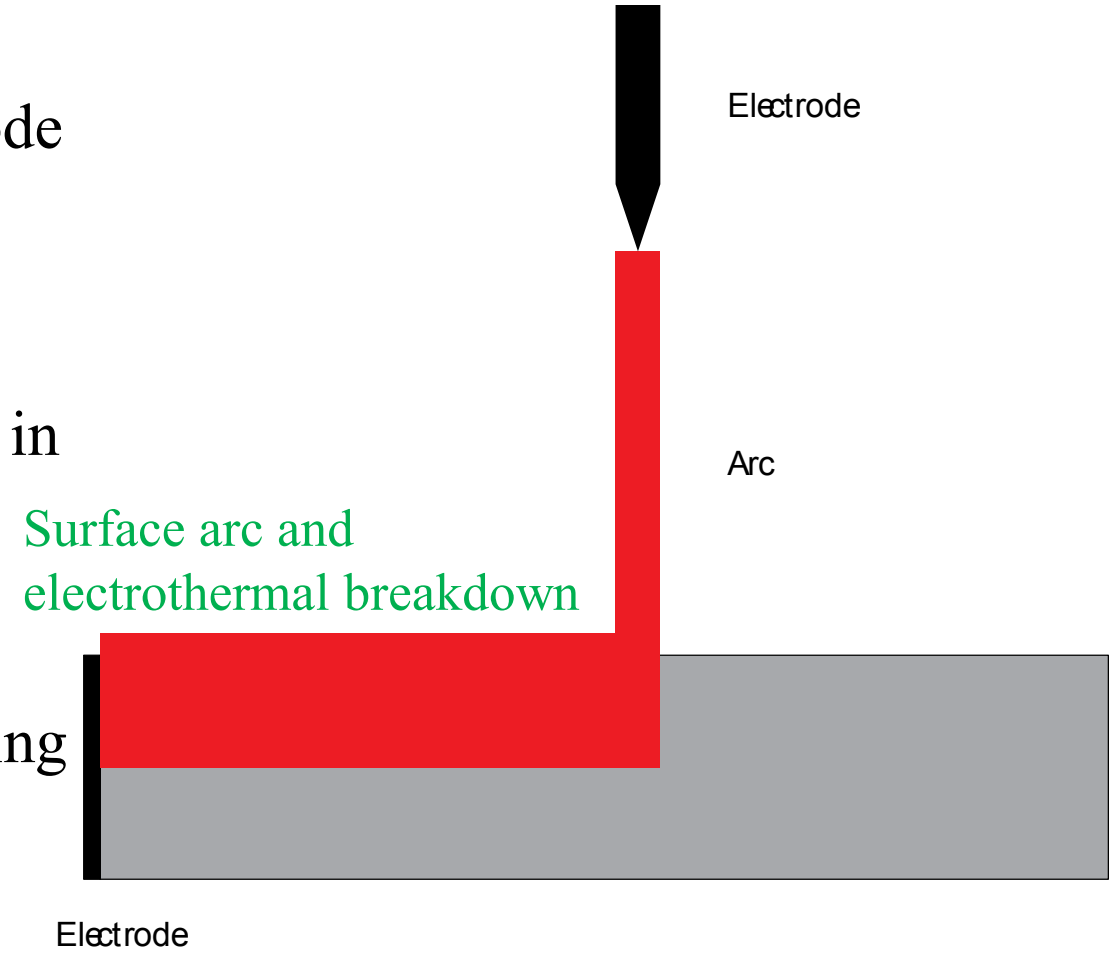
Sandia National Laboratories

Summary

Short times: The insulating dielectric acts like an electrode to cause air breakdown

Intermediate times: Space charge limited current flows in the solid dielectric

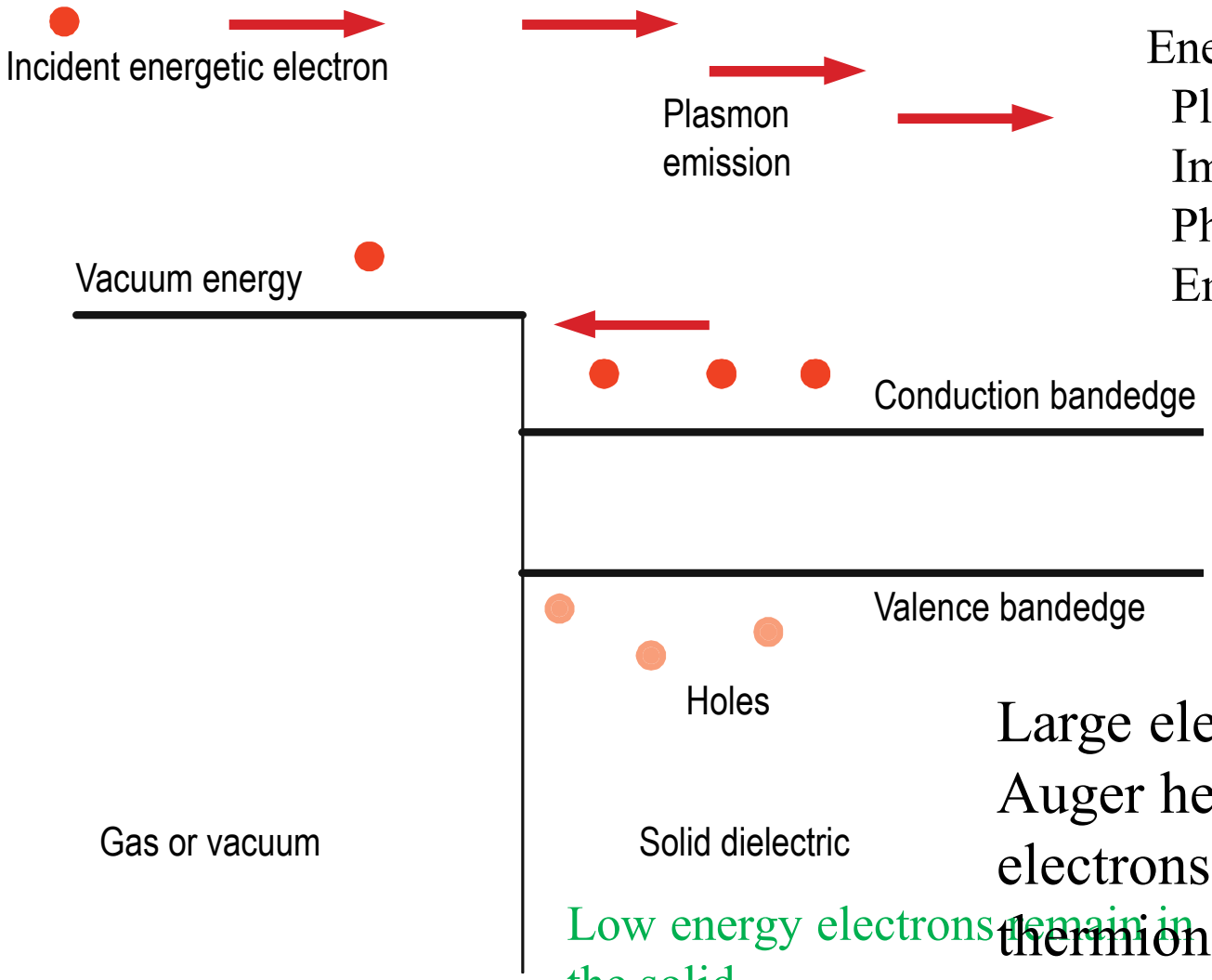
Long times: Electrothermal breakdown from Joule heating



Summary

- **Electrical breakdown with high dielectric constant materials**
  - **The solid dielectric appear metallic at short times**
  - **Electrical breakdown in the solid dielectric**
    - **Space-charge limited (SCL) current flows**
    - **SCL current causes Joule heating that increases the conductivity**
    - **Electrothermal breakdown occurs at long times**

Secondary Electron Emission (SEE): Basic Phenomena



Energy relaxation processes
- Plasmon emission
- Impact ionization
- Phonon emission
- Emission from the solid

Large electron density causes Auger heating. The hot electrons are released by thermionic emission

Low energy electrons remain in the solid

Radiation Effects in Oxides and Semiconductors (REOS) Calculations

- **Features**
  - **Transport**
  - **Energy relaxation**
  - **Chemical reactions**
  - **Heteromaterial interfaces**
- **Emphasis**
  - **Physics**
  - **Simple geometry**
- **Method**
  - **Inject electrons and holes in the RHS insulating region**
  - **Include energy relaxation processes that control the temperature**
  - **Follow evolution in space and temperature**

Sandia National Laboratories

SEE Calculations: Structure

Metal-insulator-insulator-metal