16th US-Japan Workshop on Fusion Neutron Sources for Nuclear Assay and Alternate Applications

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Simulations for Multiple-grid IEC

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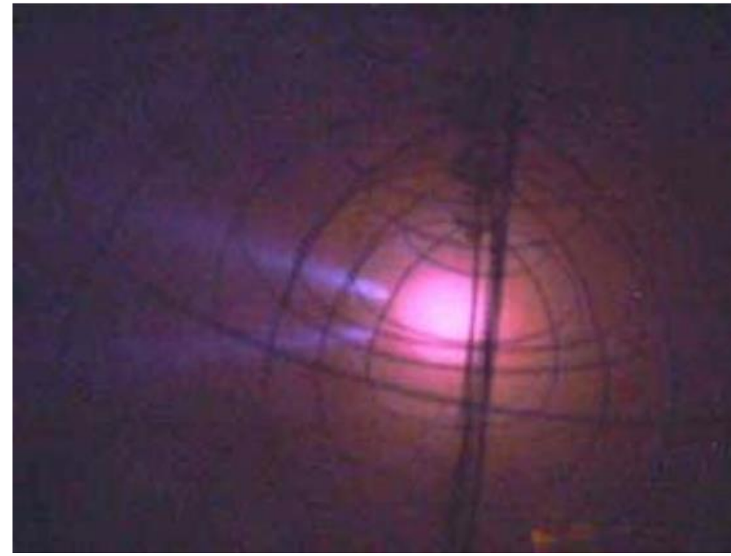
Multiple-grid IEC – brief history

Sedwick et al. used additional grids to focus ion beams and increase ion confinement time

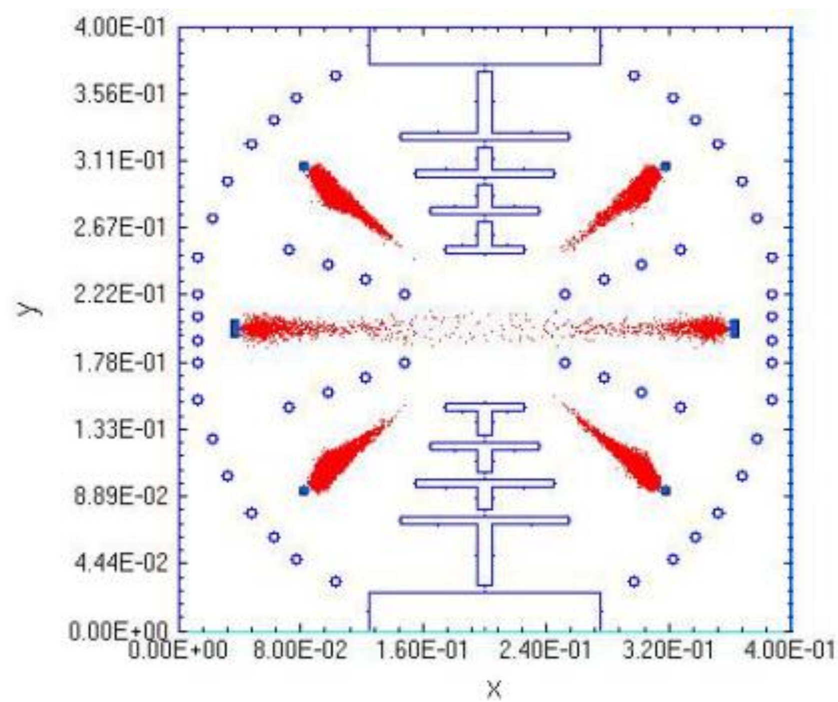


3 TAKEAWAYS:

1: **Ion lifetimes extended:** From 10's of passes to 10^3-10^6 passes

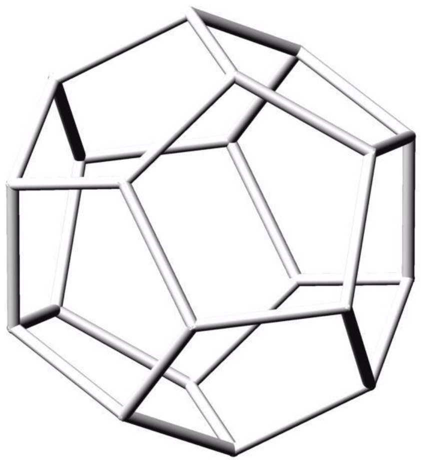
2: Greater confinement time
+ Counter-stream instability
+ IEC trap kinematics
= Ion bunching

3: **Bunch synchronization → Decreased thermalization**



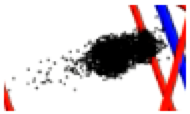
Multiple-grid IEC – current research

DODECAHEDRAL GRIDS



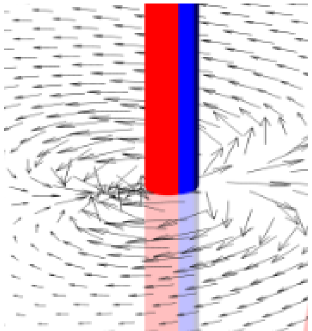
- **12 Faces → 6 beamlines**
- Highly symmetric
- Another possibility: **Truncated Icosahedron** (Soccer Ball)
- Feed-throughs?

ION BUNCHING



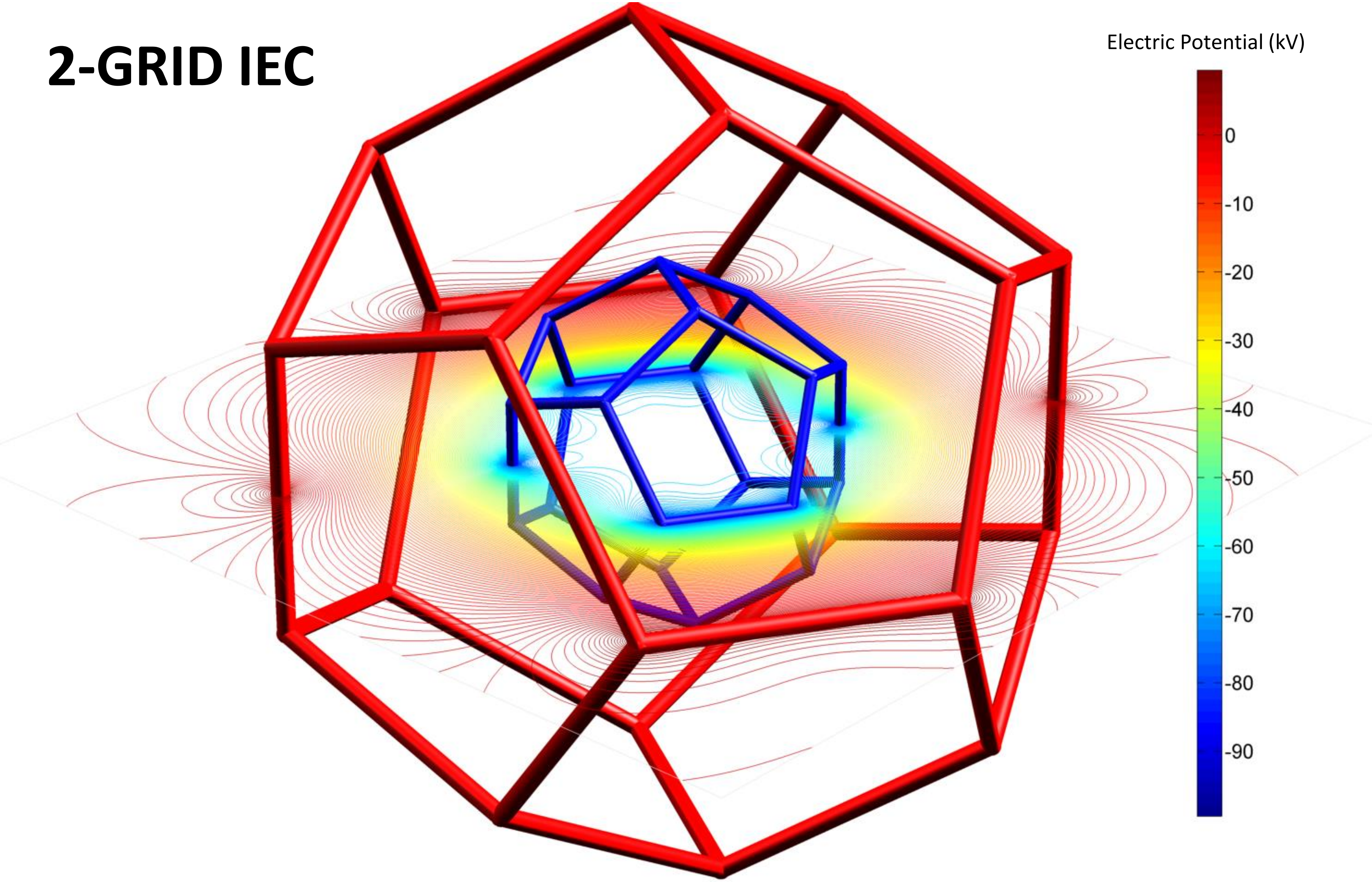
- Potential well can be shaped to encourage ion bunch cohesion

MAGNETIC CORE

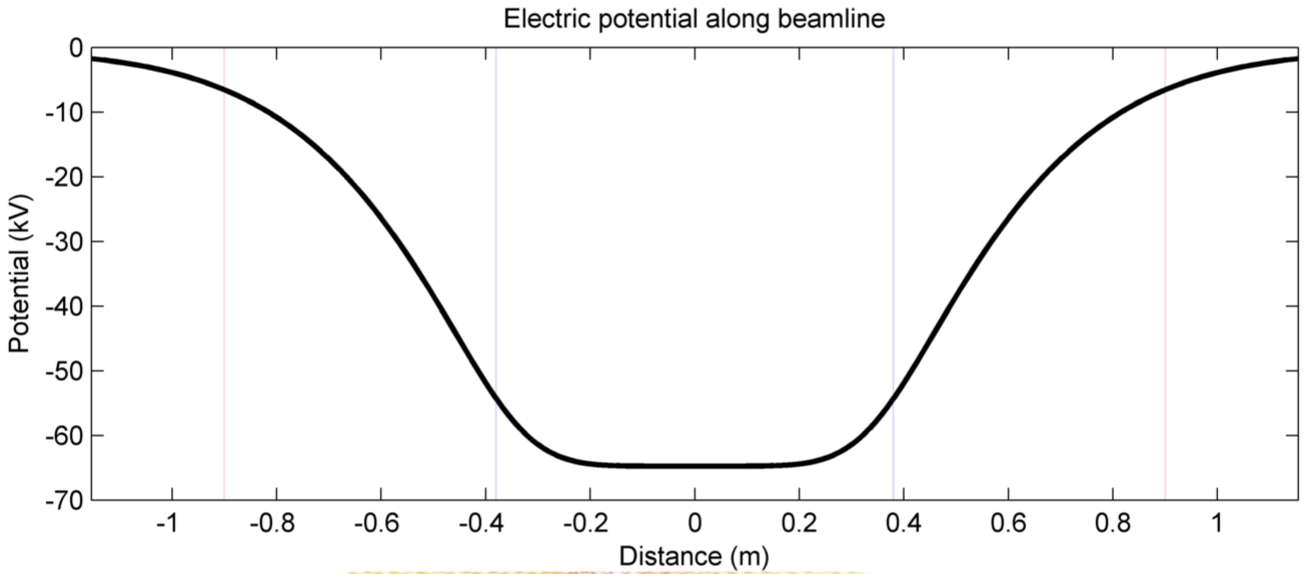


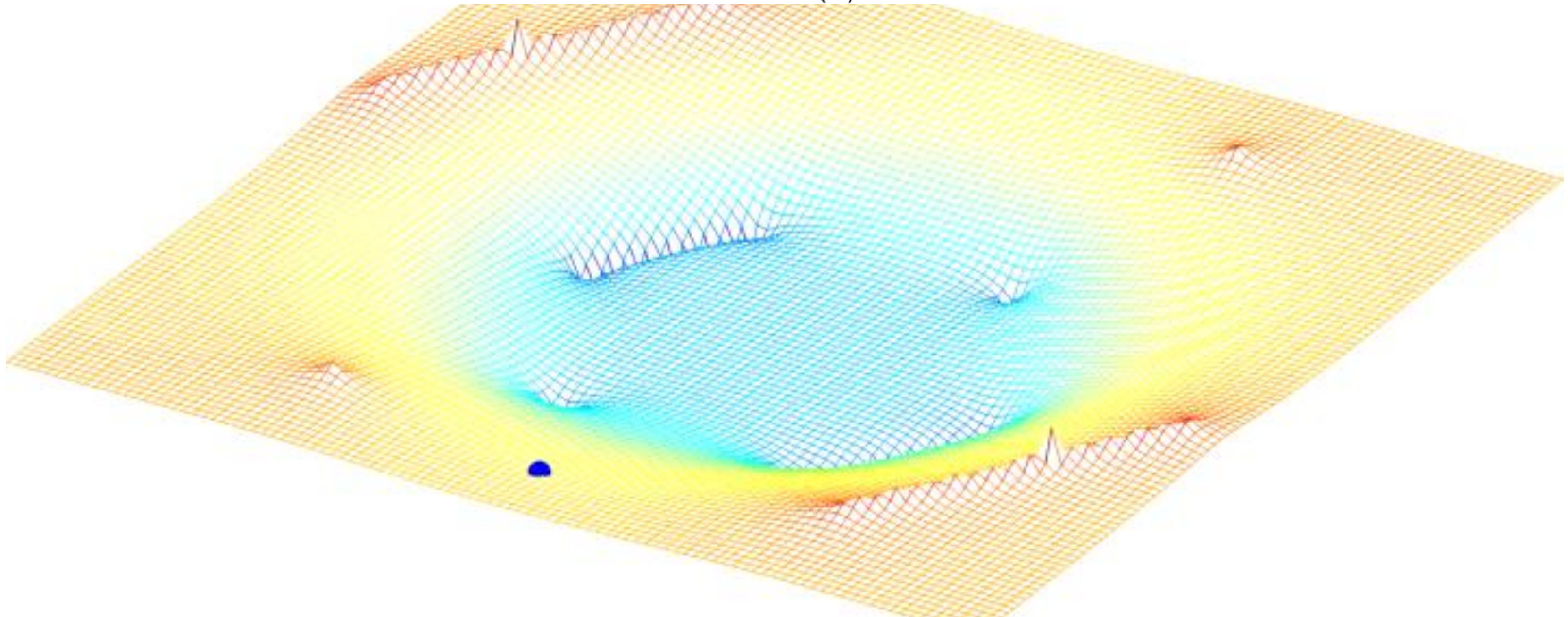
- Confinement of electrons in the core

2-GRID IEC

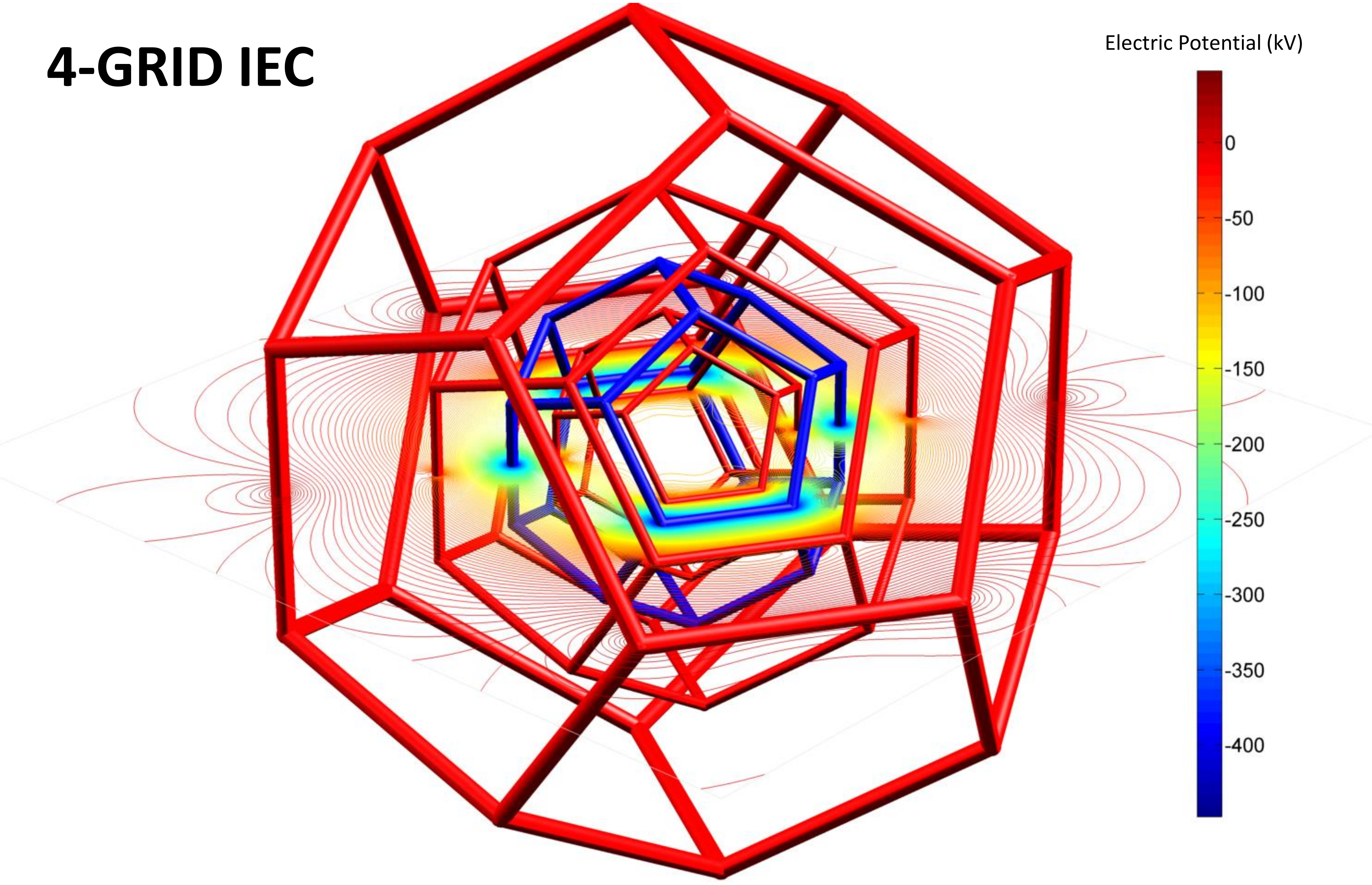


2-GRID IEC

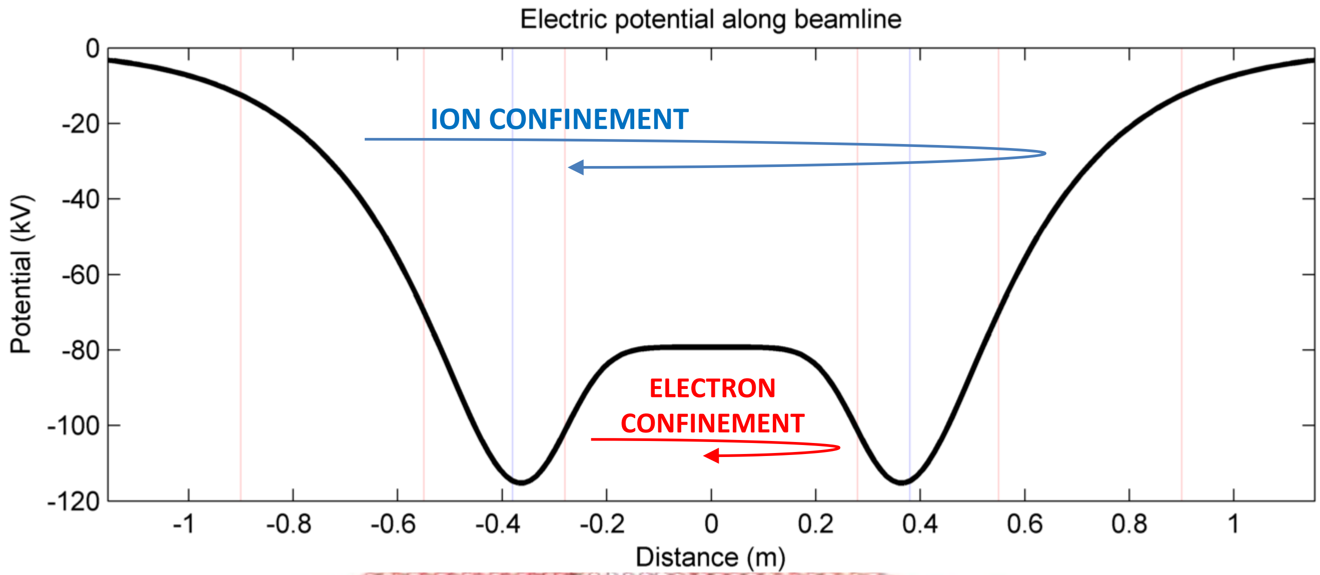

Electric potential along beamline
Potential (kV)
0
-10
-20
-30
-40
-50
-60
-70
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Distance (m)

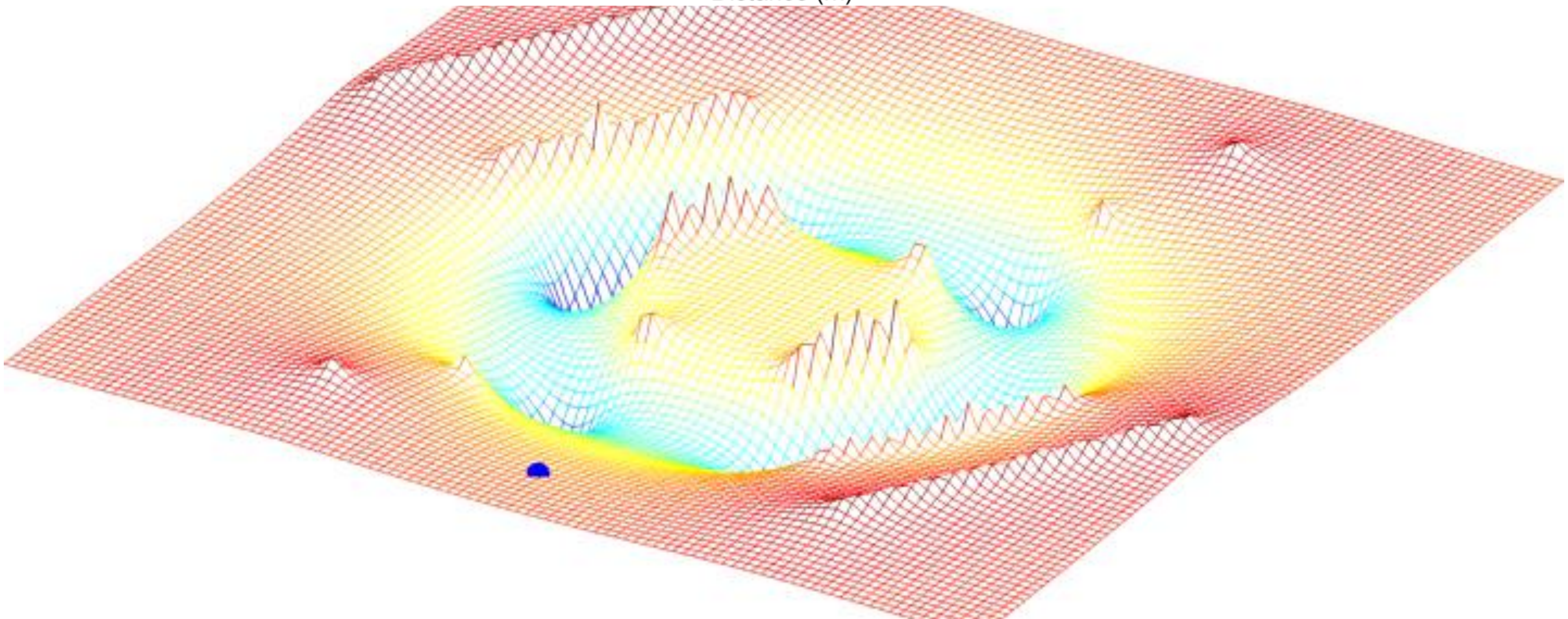


4-GRID IEC



4-GRID IEC

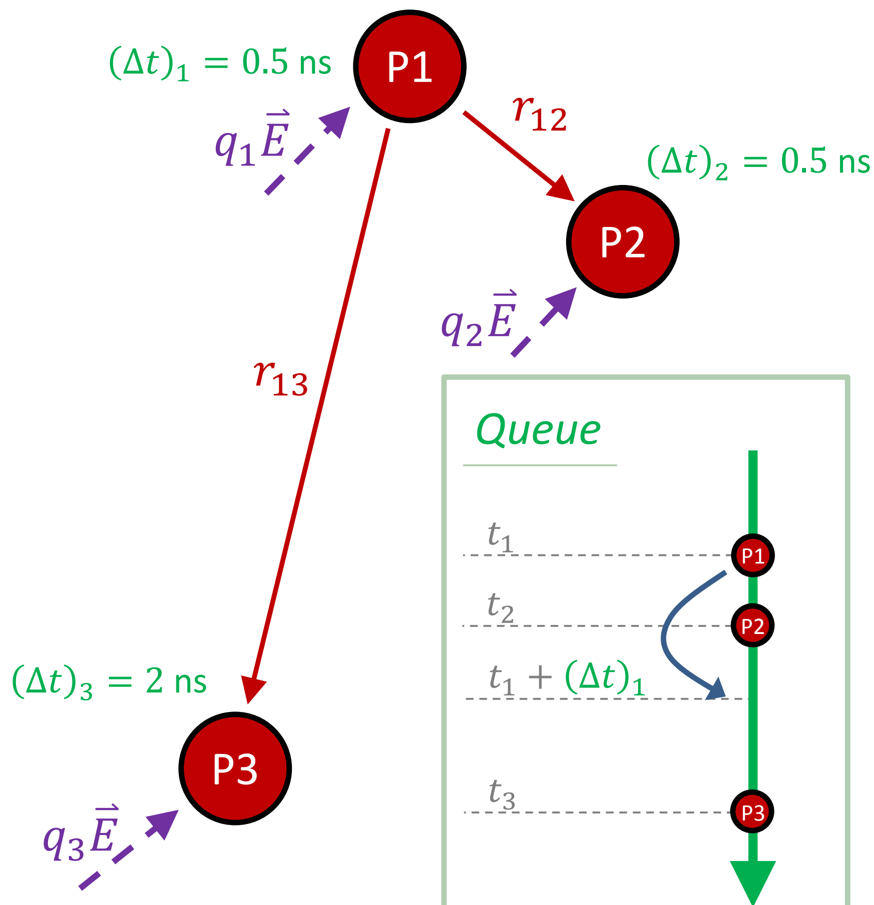

Electric potential along beamline
ION CONFINEMENT
ELECTRON
CONFINEMENT
Potential (kV)
0
-20
-40
-60
-80
-100
-120
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Distance (m)



Particle-particle Discrete Event Simulation

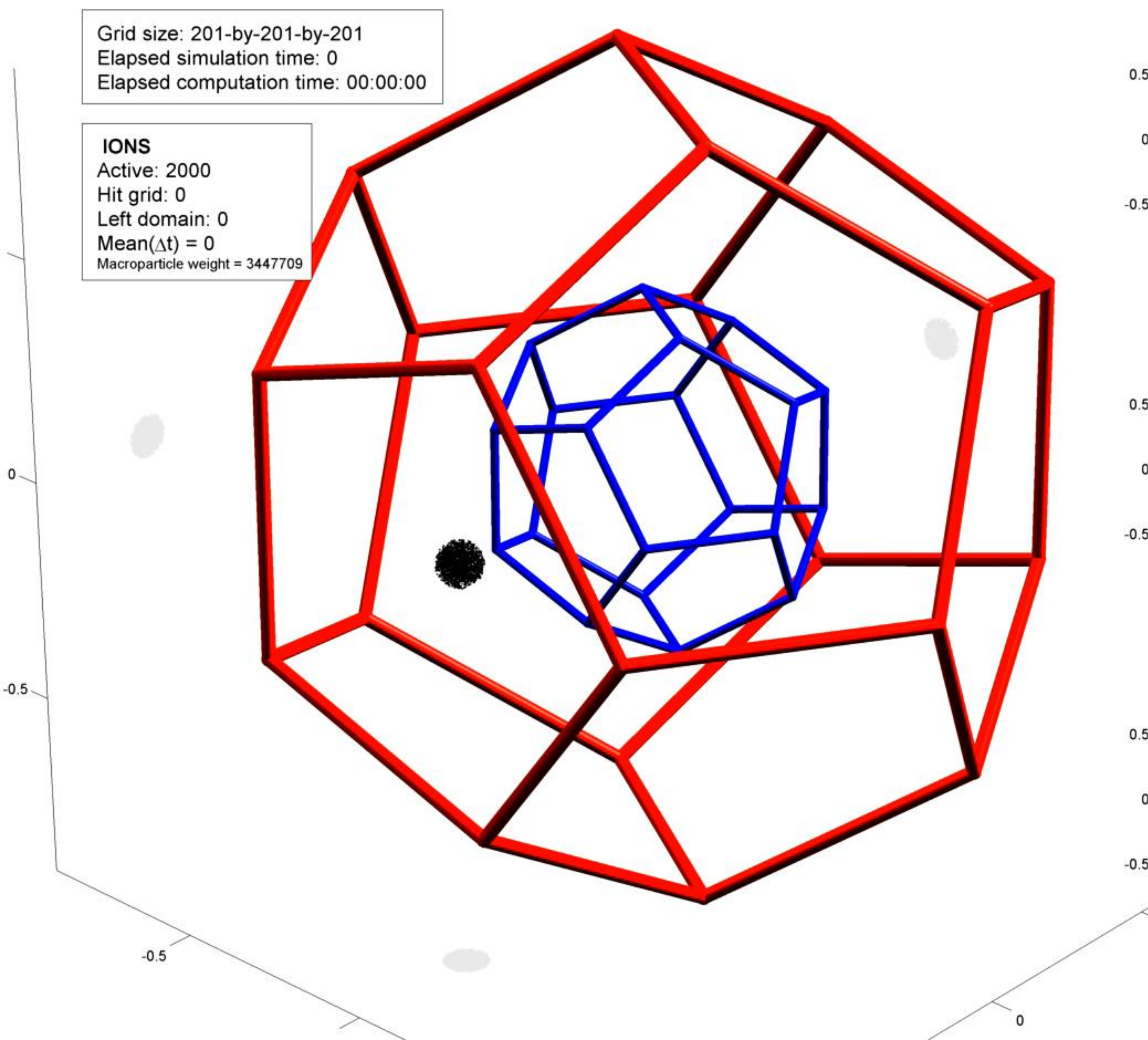
$$\vec{a}_i = -\frac{1}{4\pi\epsilon_0}\frac{q_i}{m_i}\sum_{j\neq i}\frac{q_j}{r_{ij}^3}\vec{r}_{ij} + \frac{q_i}{m_i}\vec{E}$$

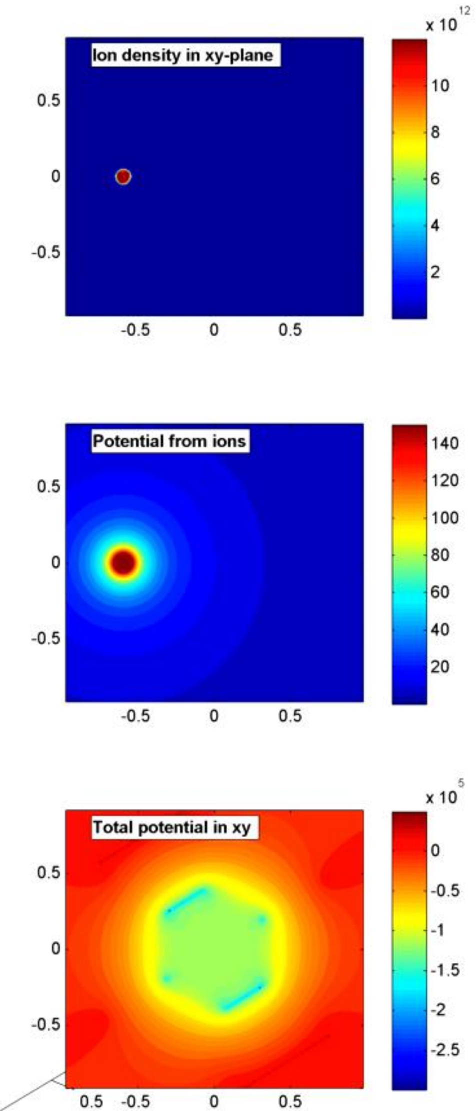
- **Inter-particle forces are calculated directly** (N-body simulation)
  - No need to solve Poisson's equation at each time step
- **No global time-step**, each particle is assigned its own time-step depending on its velocity and acceleration
  - Coulomb collisions are modeled directly by decreasing the time-step values of colliding particles.
- Static E&M fields are calculated once at the beginning of the simulation



2-GRID Particle-particle simulation

LOW DENSITY BUNCH



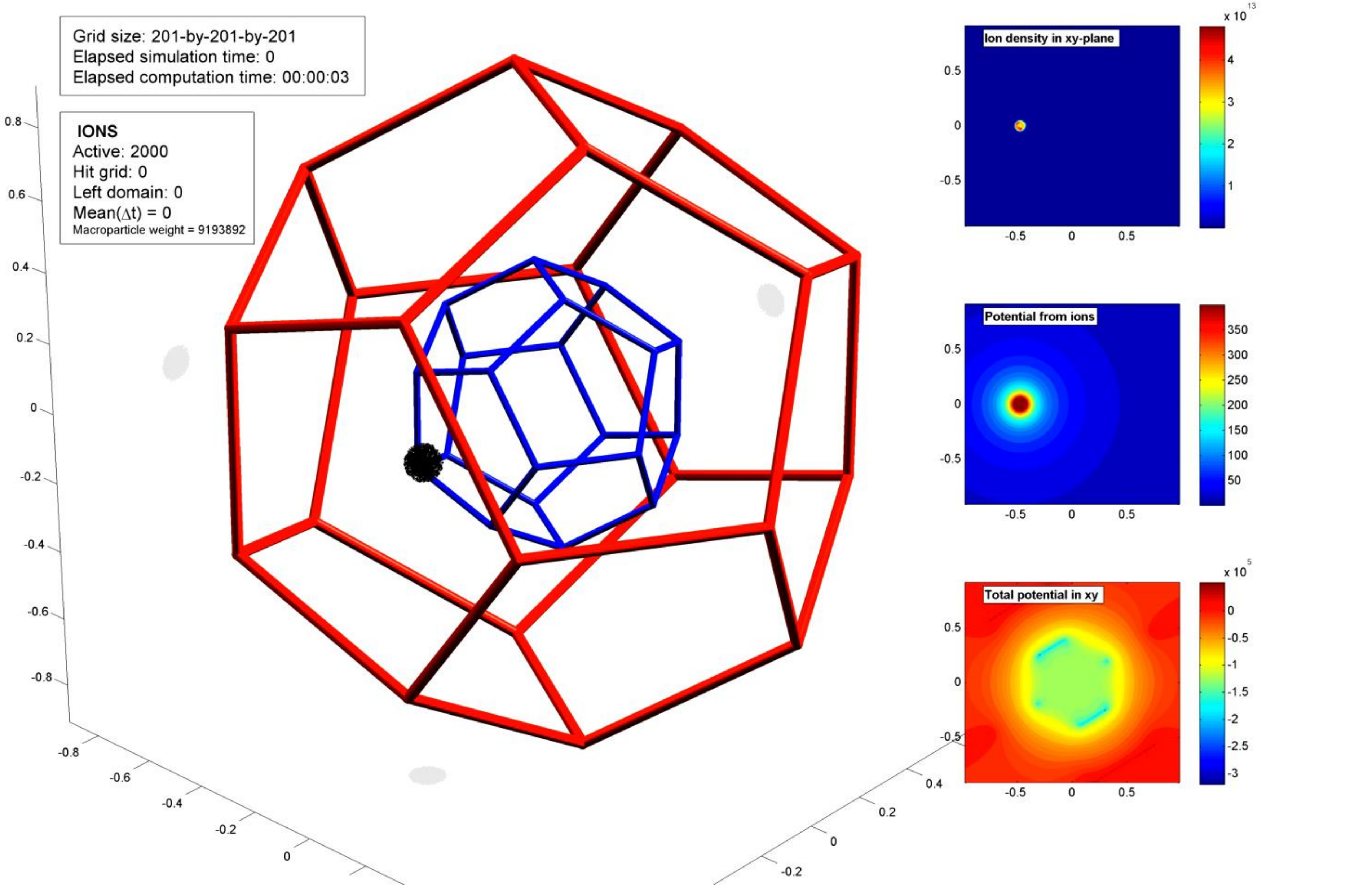


2-GRID Particle-particle simulation

What happens if we increase the density of the ion bunch?

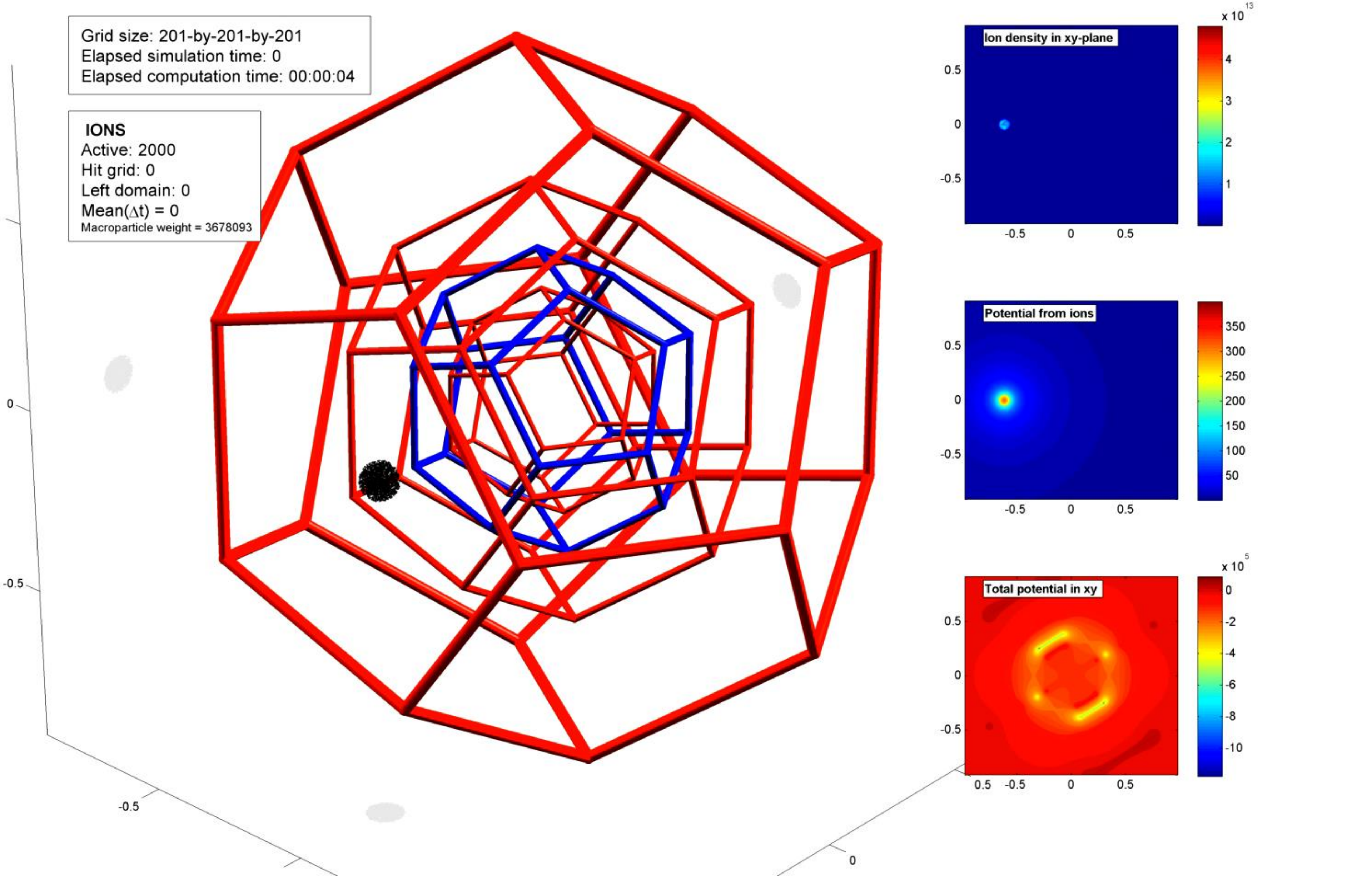
2-GRID Particle-particle simulation

HIGHER DENSITY BUNCH



4-GRID Particle-particle simulation

SAME DENSITY AS PREVIOUS SLIDE



Ion Bunching – The Kinematic Criterion

Ions near the **back** of the bunch are **decelerated** by the Coulomb repulsion from the bunch

Energy **decreases**

Period must also **decrease** to prevent ions from “running away”

Kinematic criterion:

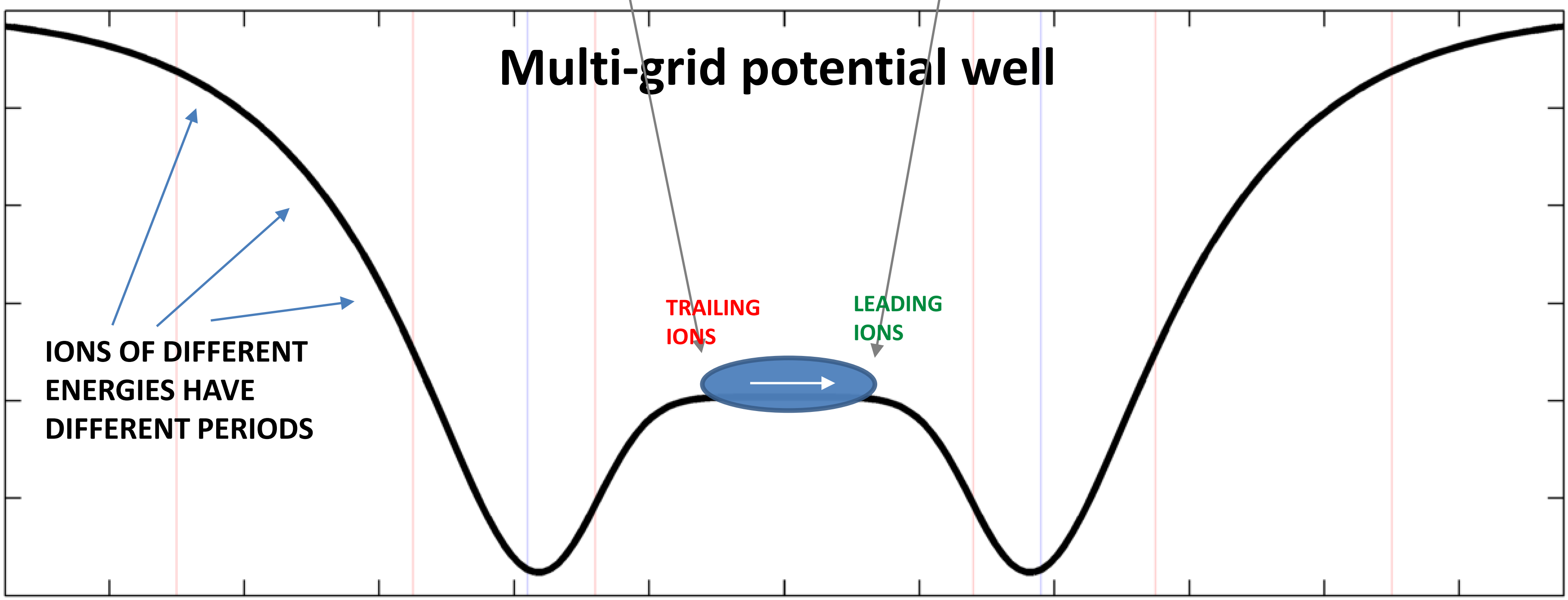
$$\frac{dT}{dE} \geq 0$$

T: Period
E: Ion Energy (KE+PE)

Ions in the **front** of the bunch are **accelerated** by the Coulomb repulsion from the bunch

Energy **increases**

Period must also **increase** to prevent ions from “running away”



Ion Bunching – The Kinematic Criterion

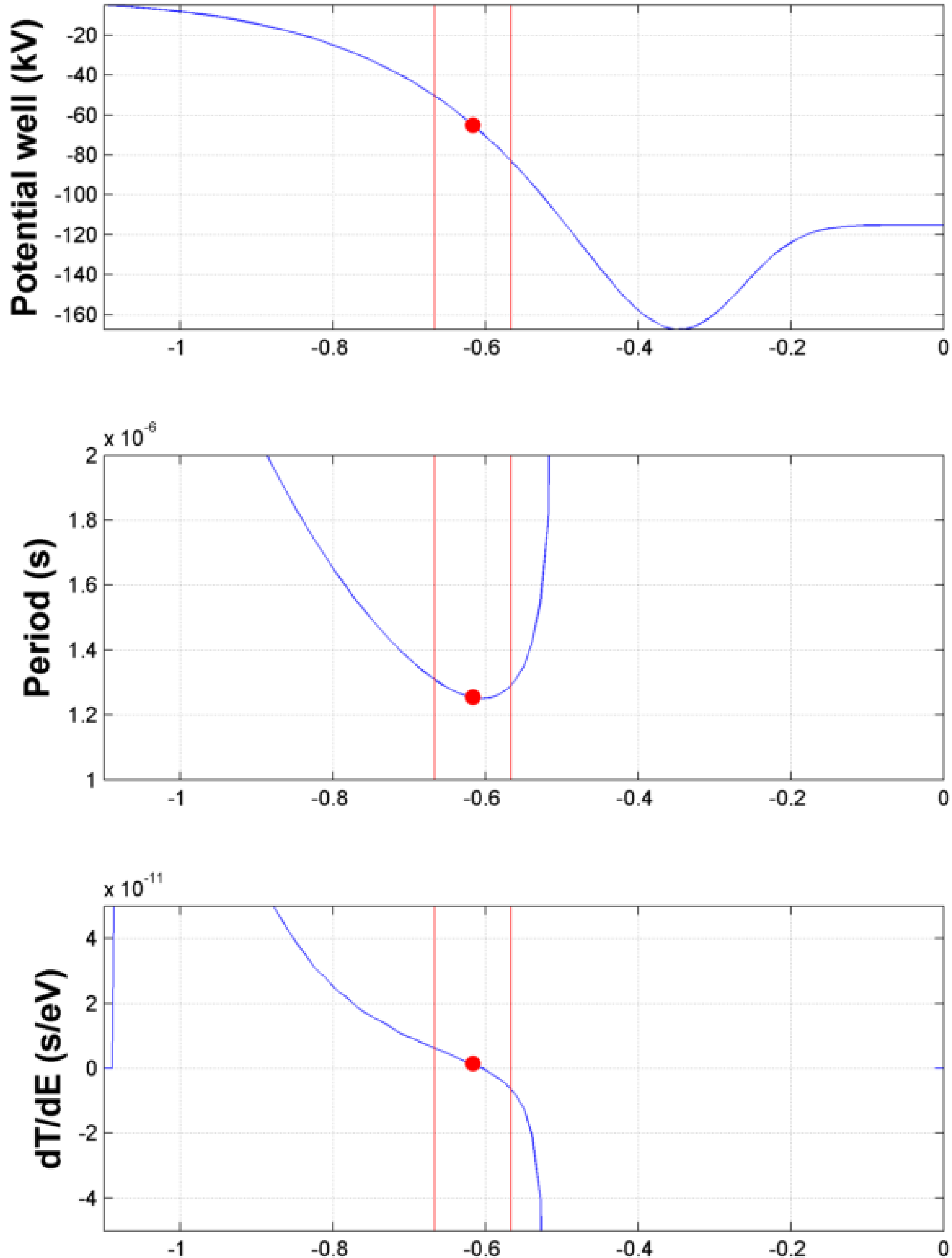
Kinematic criterion: $\frac{dT}{dE} \geq 0$

But $\frac{dT}{dE}$ can't be too large either!

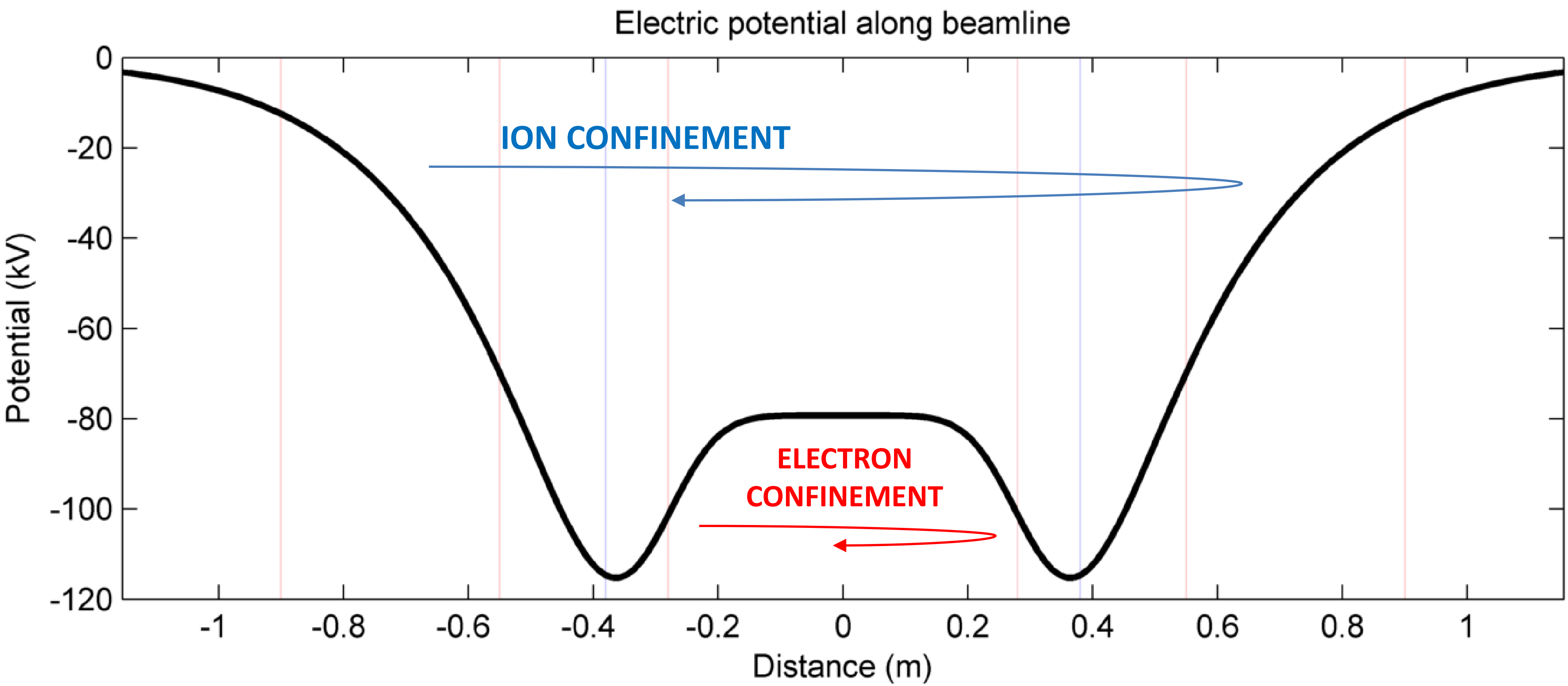
Conditions have to be just right for ions to coalesce into bunches

FUTURE WORK:

"Sculpting" the IEC well to encourage bunch cohesion

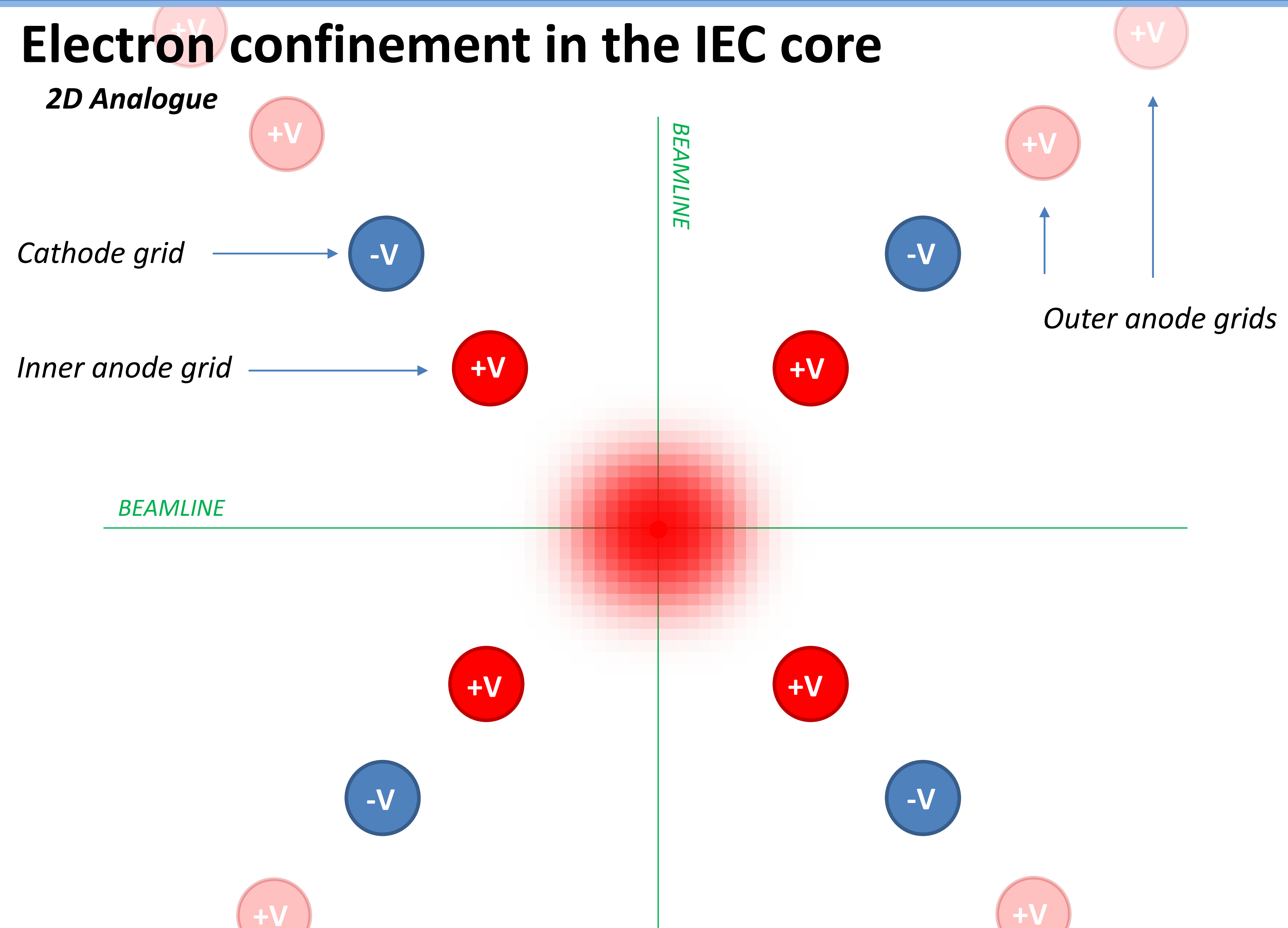


Electron confinement in the IEC core

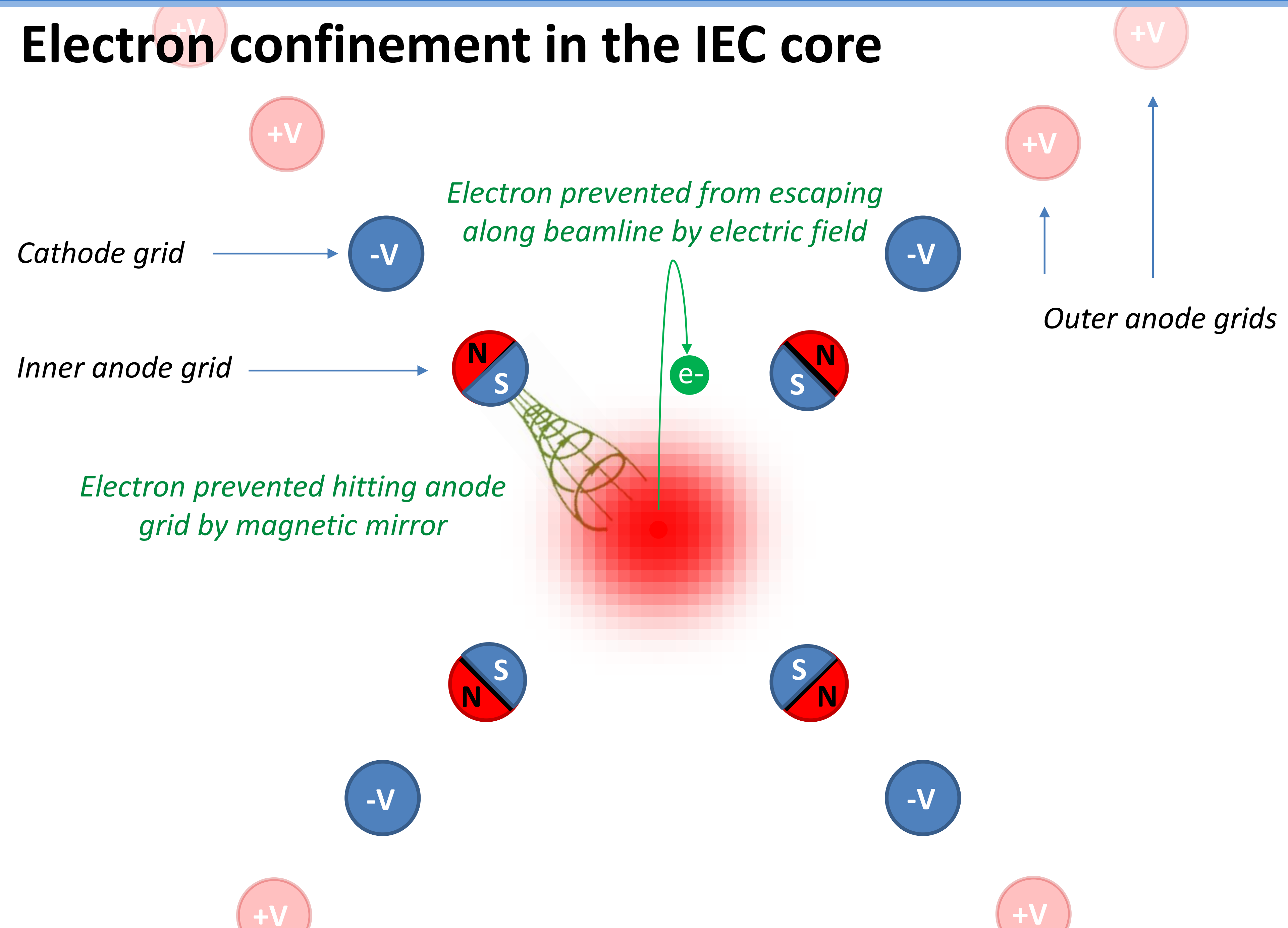


Electron confinement in the IEC core

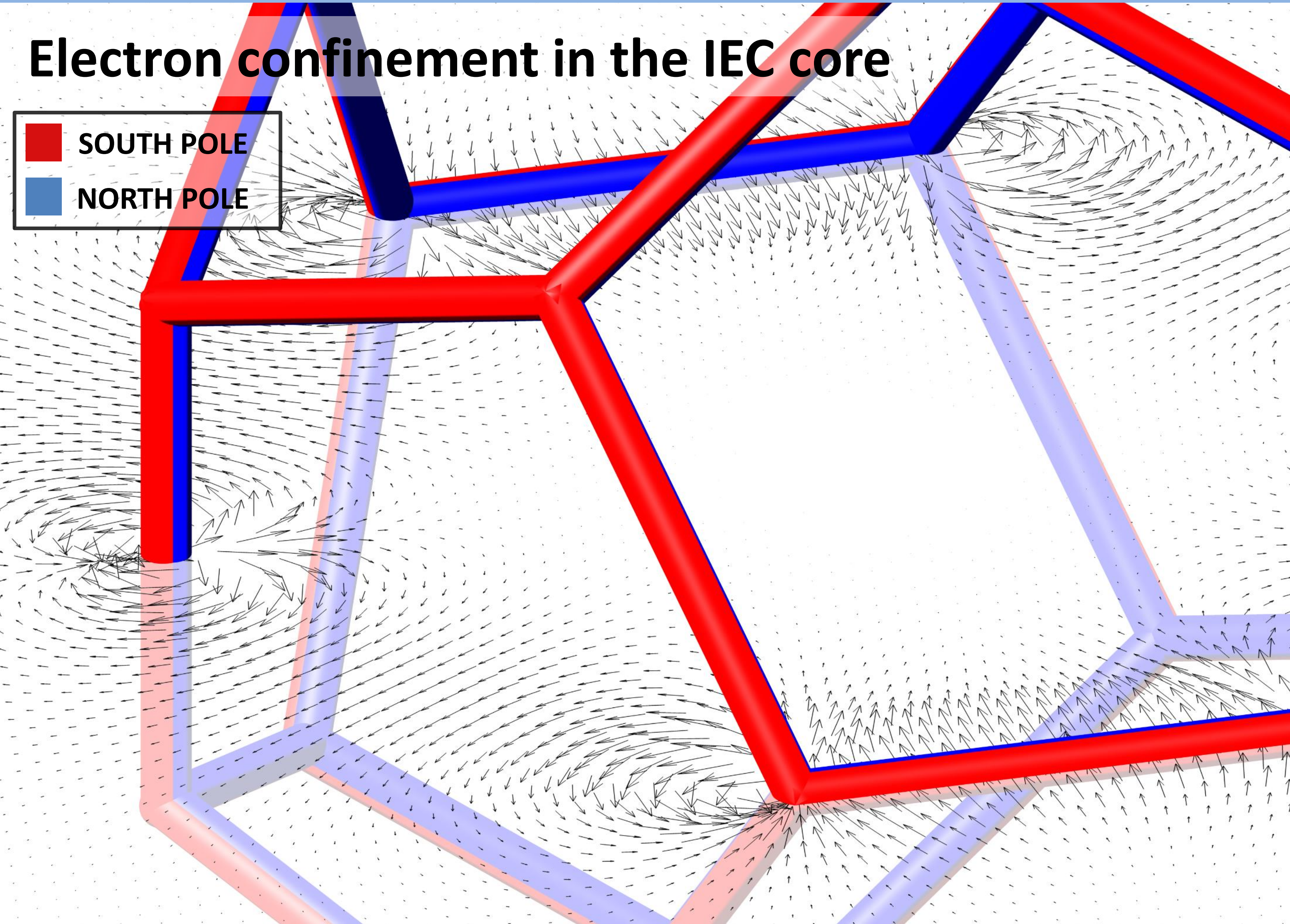
2D Analogue



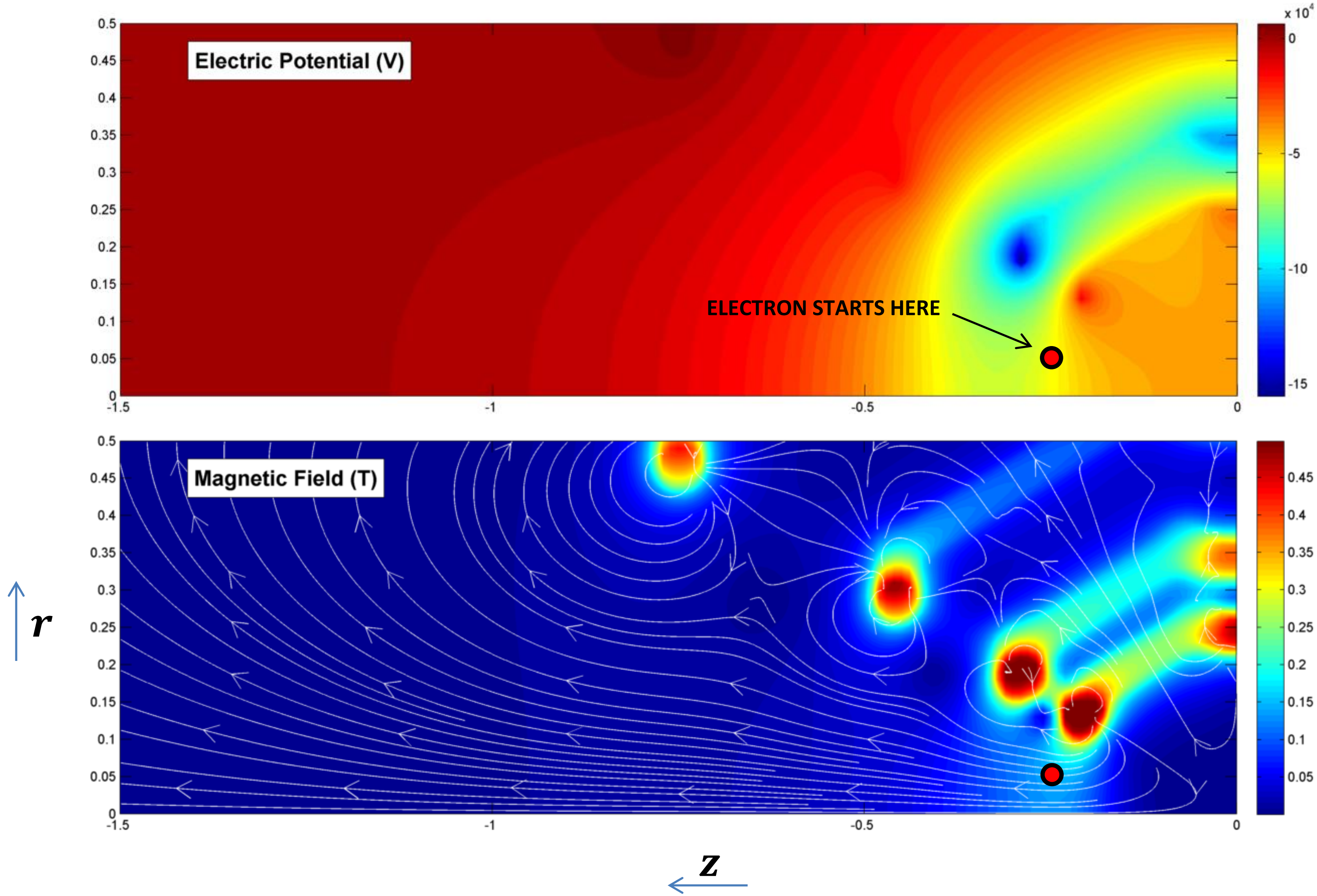
Electron confinement in the IEC core



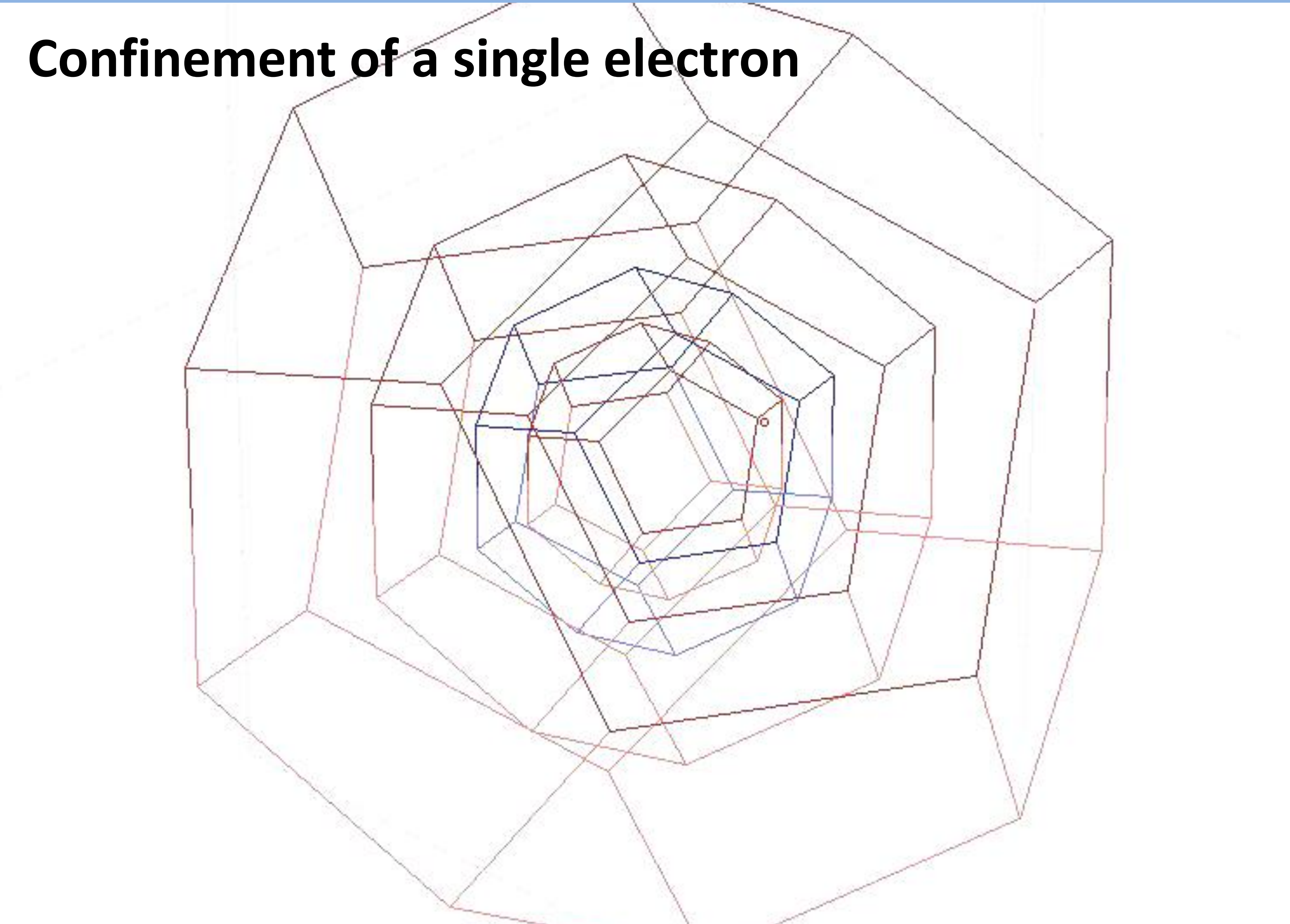
Electron confinement in the IEC core



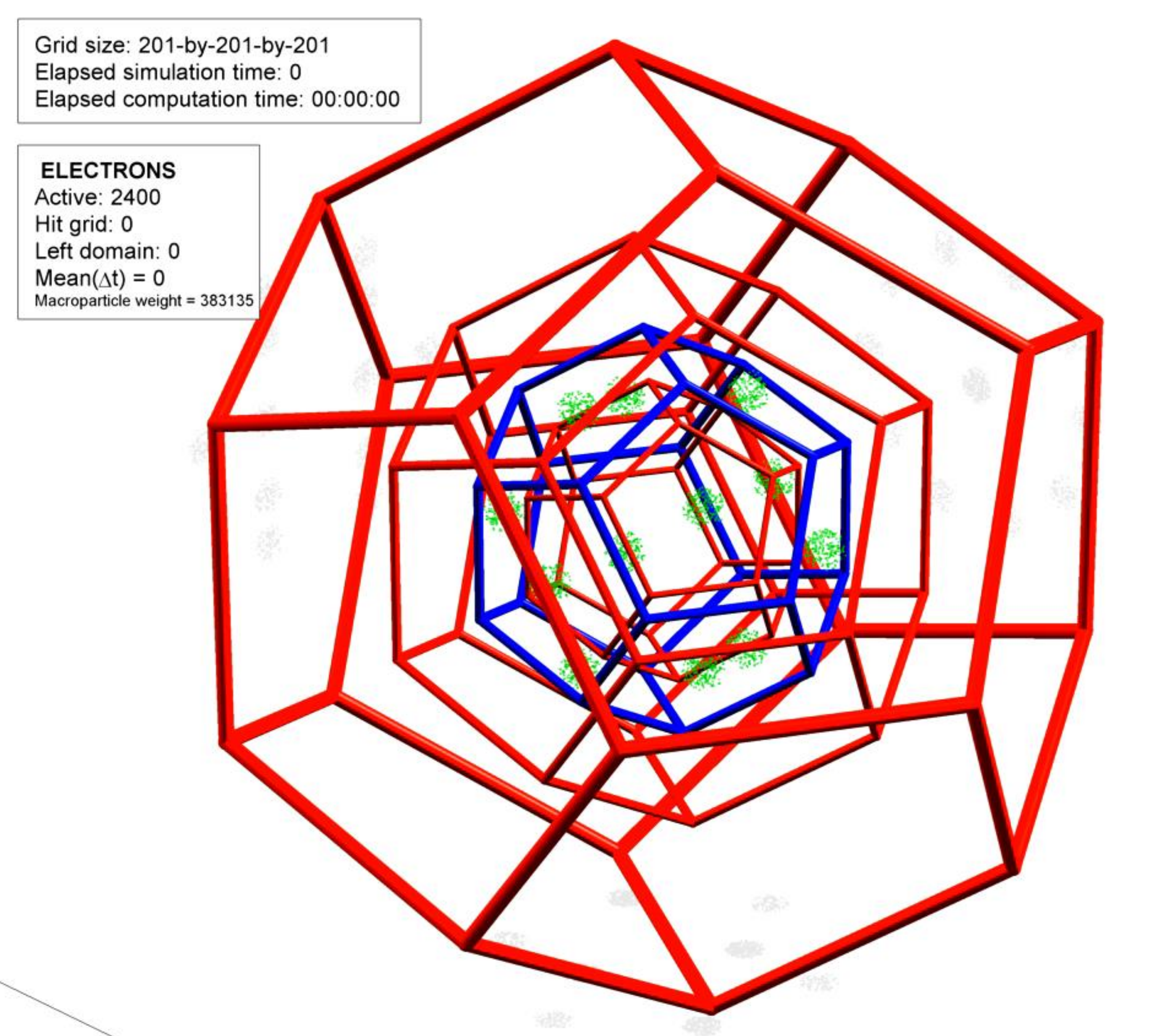
Approximate E&M fields along a beampath

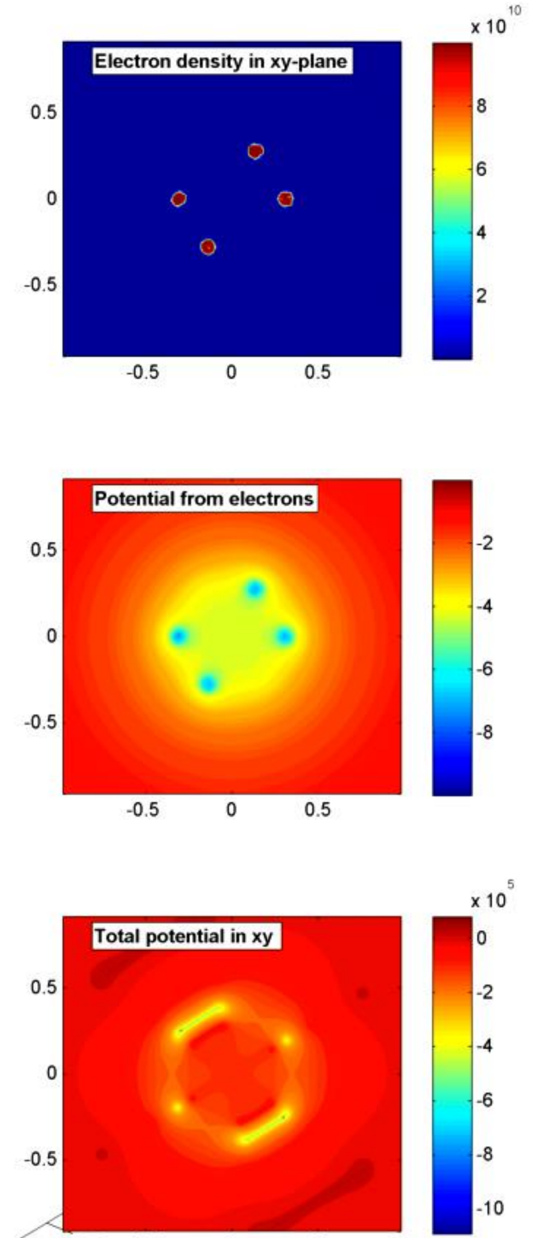


Confinement of a single electron



Confinement of many electrons





Disadvantages of the particle-particle discrete event simulation

- Computation time scales as N^2
- Only suitable (at this point) for modeling one species at a time (ions or electrons) for short timescales
- To model both species at once we need a hybrid PIC model

Hybrid Particle-in-cell model

IONS → PARTICLES

ELECTRONS → FLUID

Long-timescale simulation requires **time-steps based on the ion motion**

→

Assume electrons reach a **thermalized steady-state** at each time-step ($\frac{dn_e}{dt} = 0$)

Hybrid Particle-in-cell model

Currently using the following governing equations:

Interested in steady-state solution

CONTINUITY

$$\cancel{\frac{\partial n_e}{\partial t}} + \nabla \cdot (n_e \vec{v}) = S$$

VELOCITY

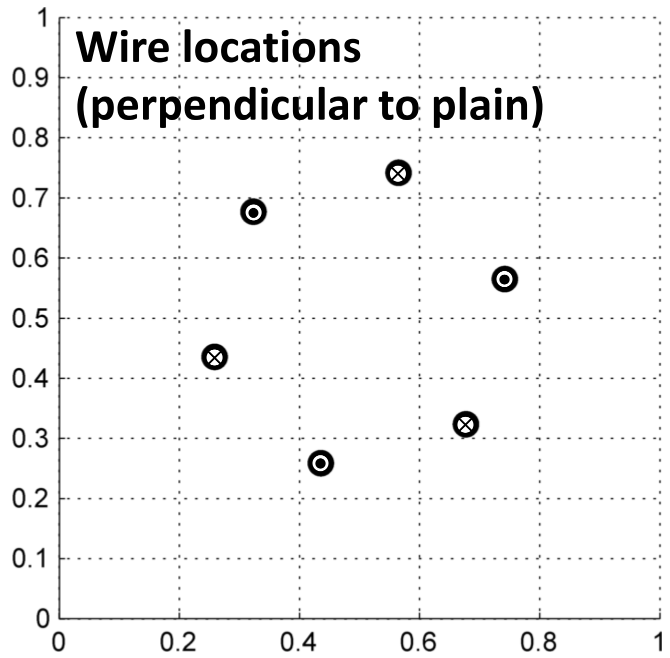
$$\cancel{\frac{\partial \vec{v}}{\partial t}} + (\vec{v} \cdot \nabla)\vec{v} = \frac{e}{m_e}(\nabla\Phi + \vec{v} \times \vec{B})$$

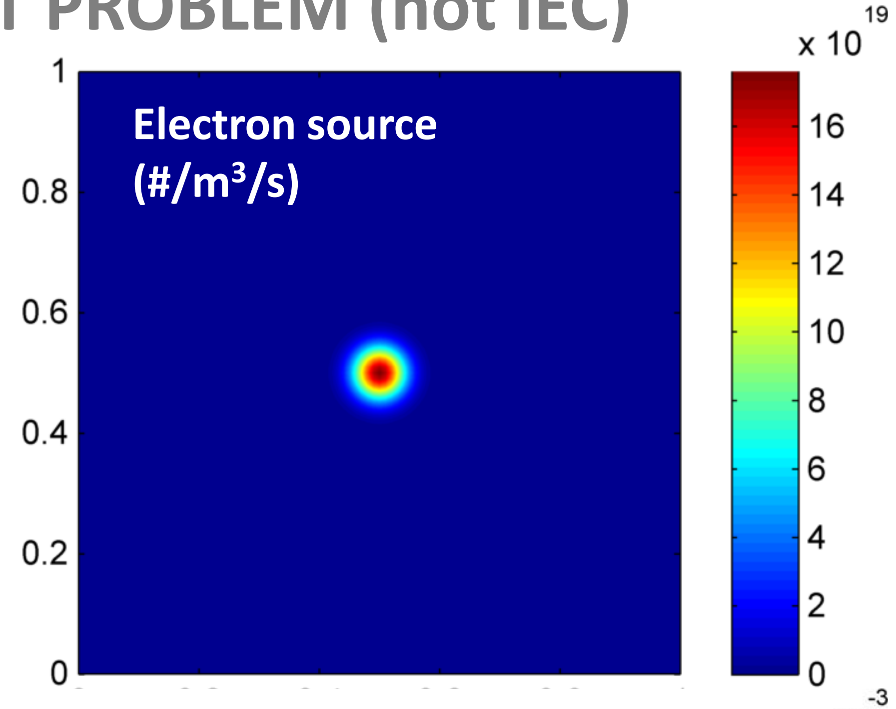
POISSON'S

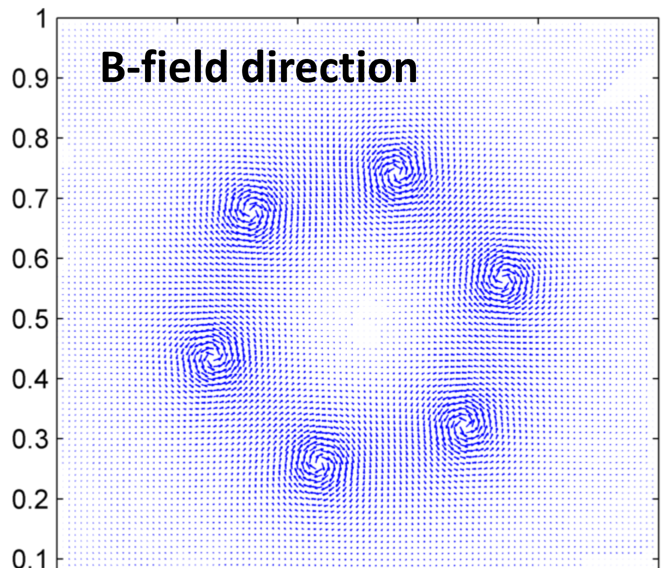
$$\nabla^2 \Phi = \frac{e}{\epsilon_0}(n_e - n_i)$$

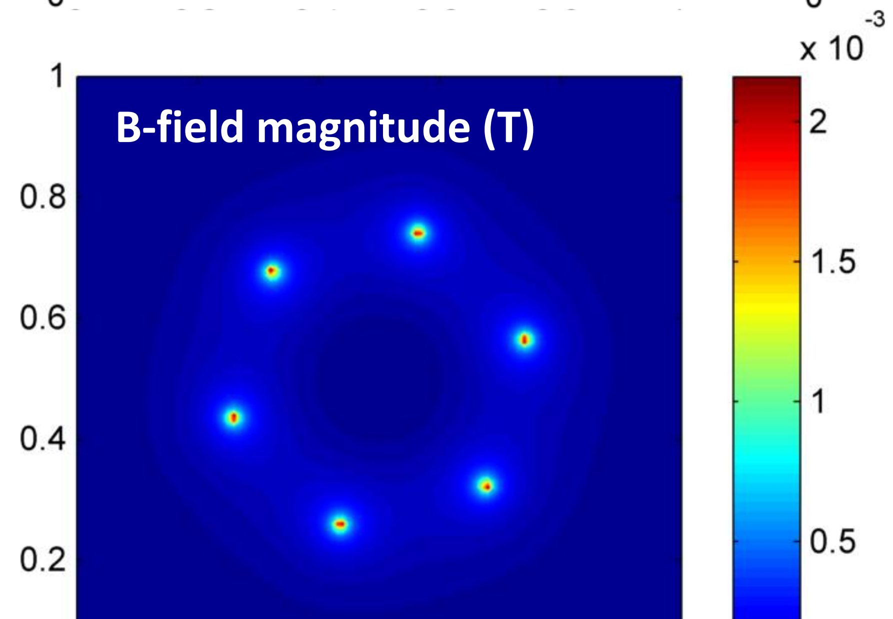
But first we'll test the time-stepping solution

Electron fluid model – TEST PROBLEM (not IEC)





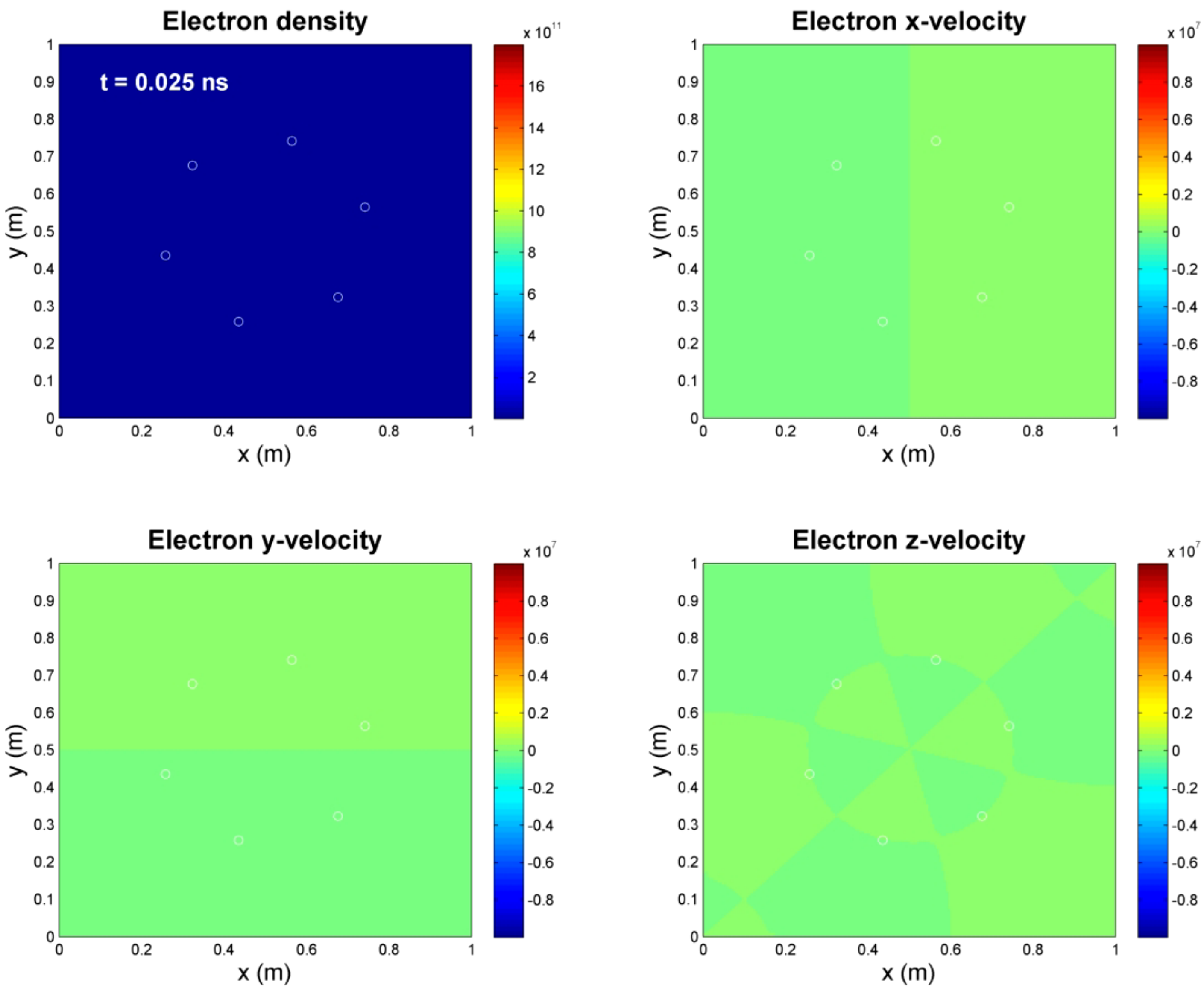




Electron fluid model

Simple 2D test problem:

- ***Magnetic field created by current-carrying wires***
- ***Electron Source in Center***



Electron fluid model

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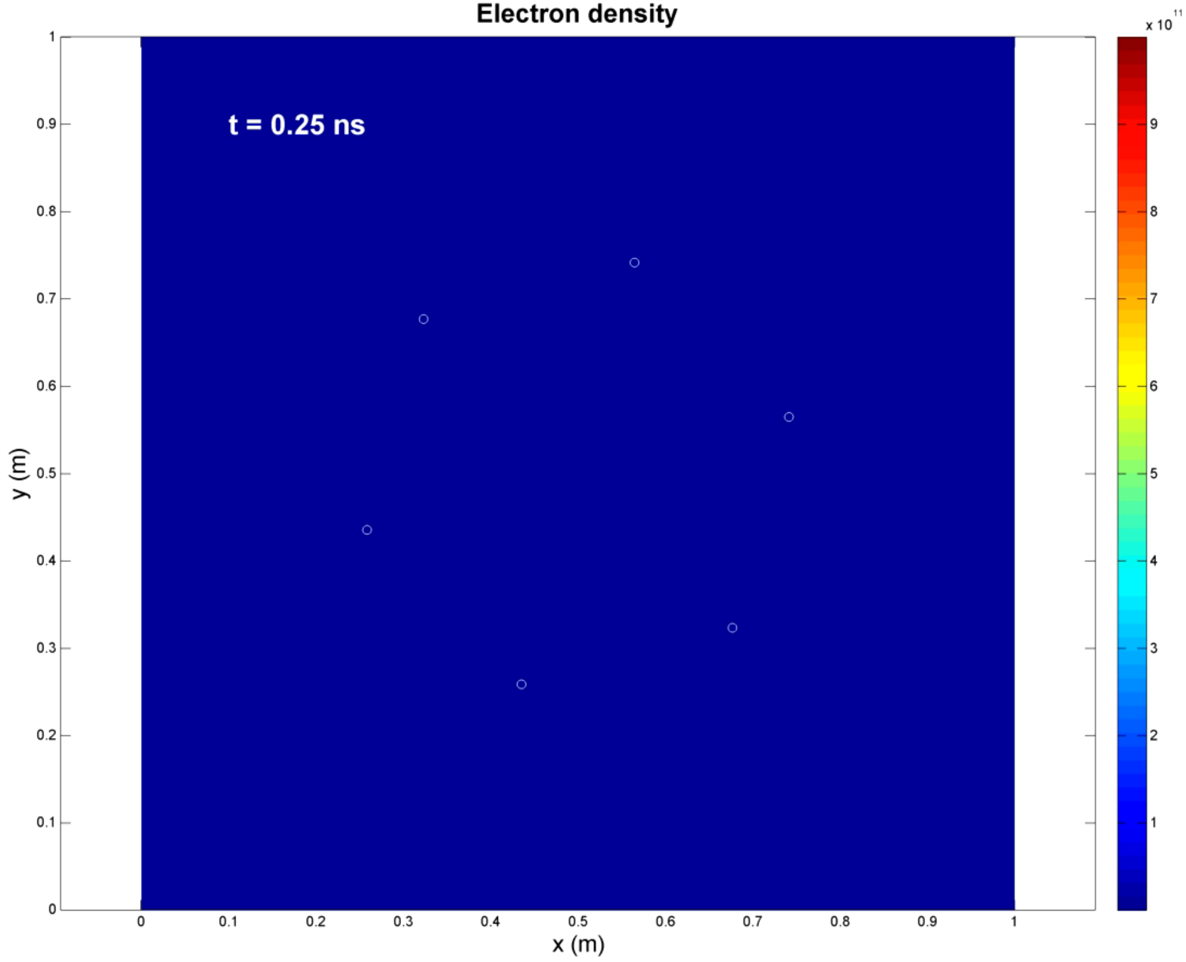
Comparison with particle-in-cell model with same conditions



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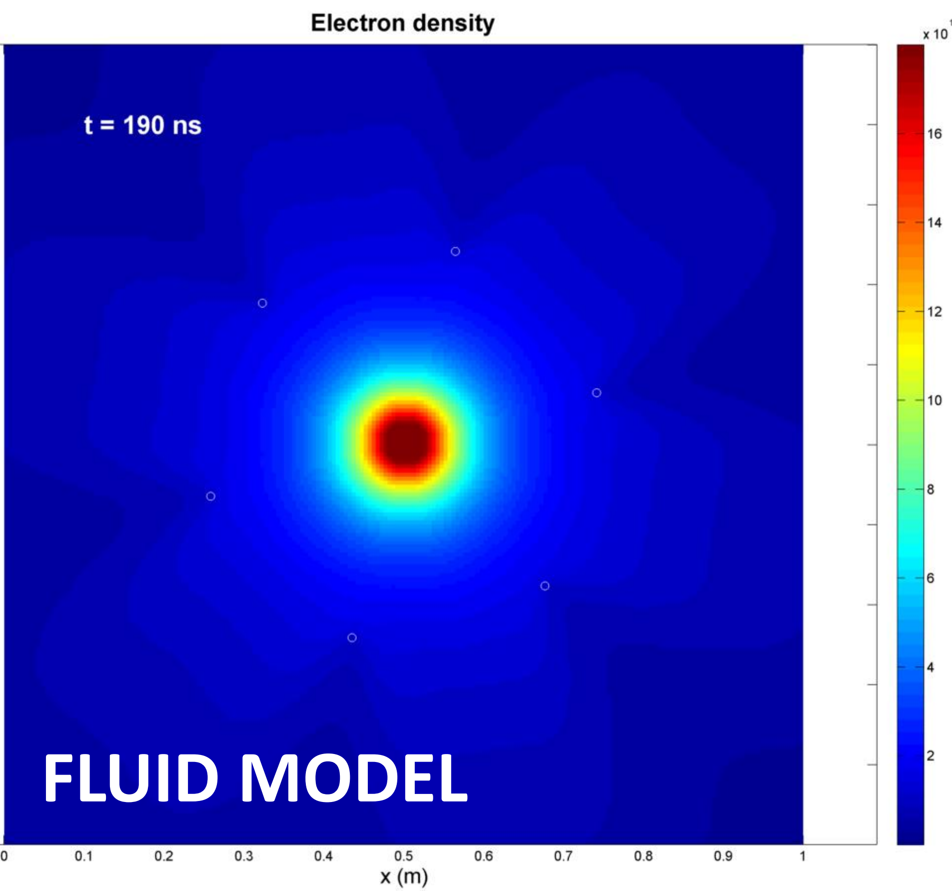
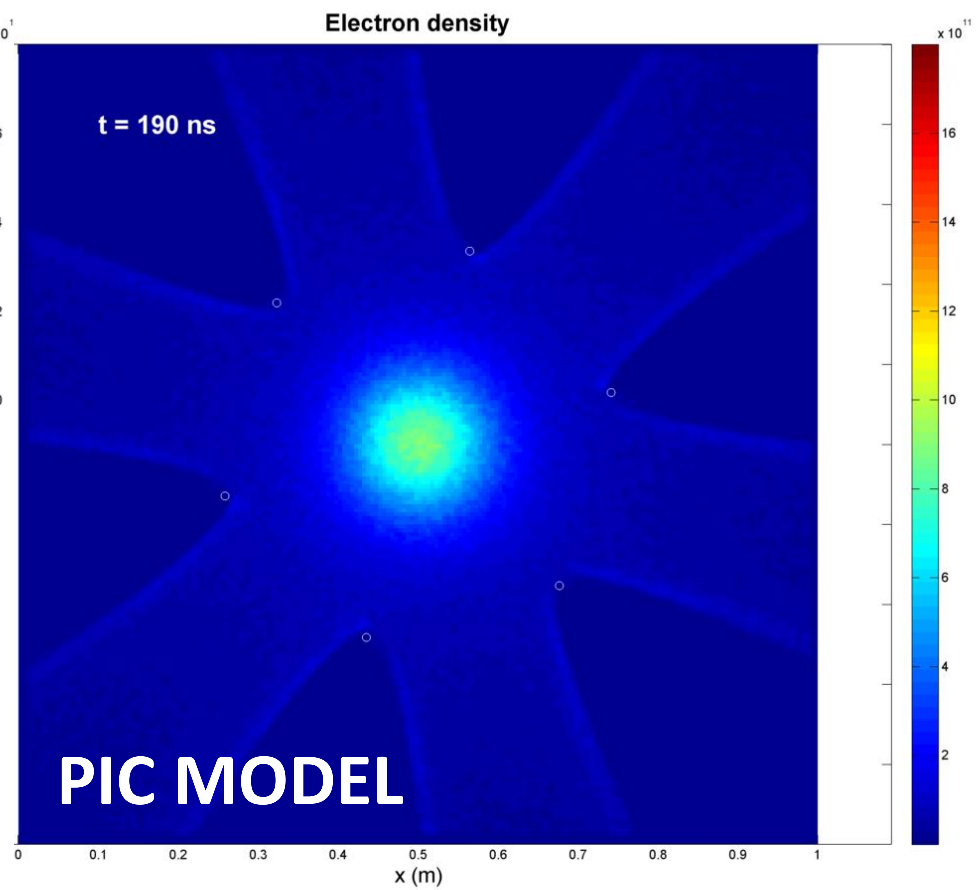
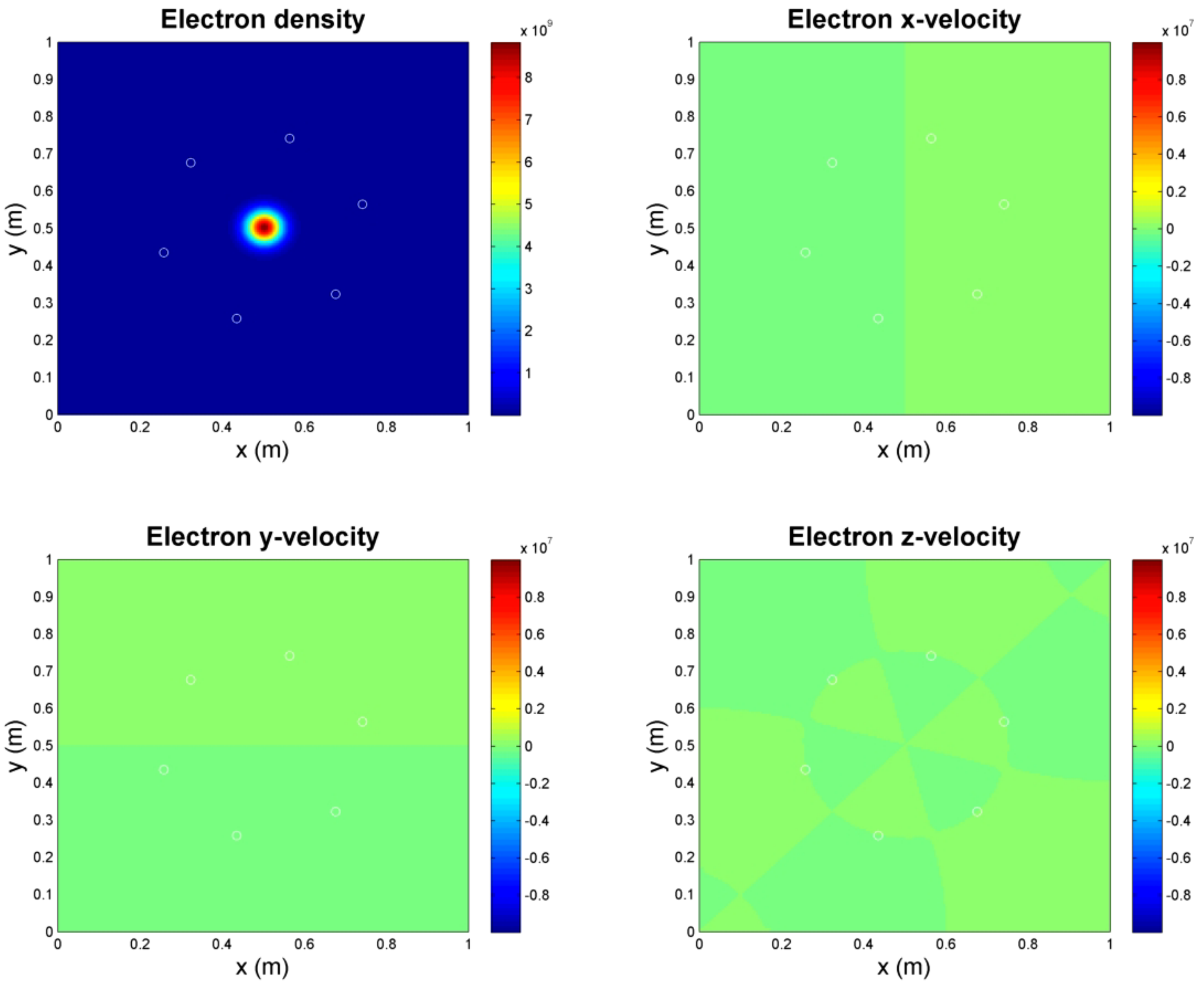




Electron fluid model

With increased B-field

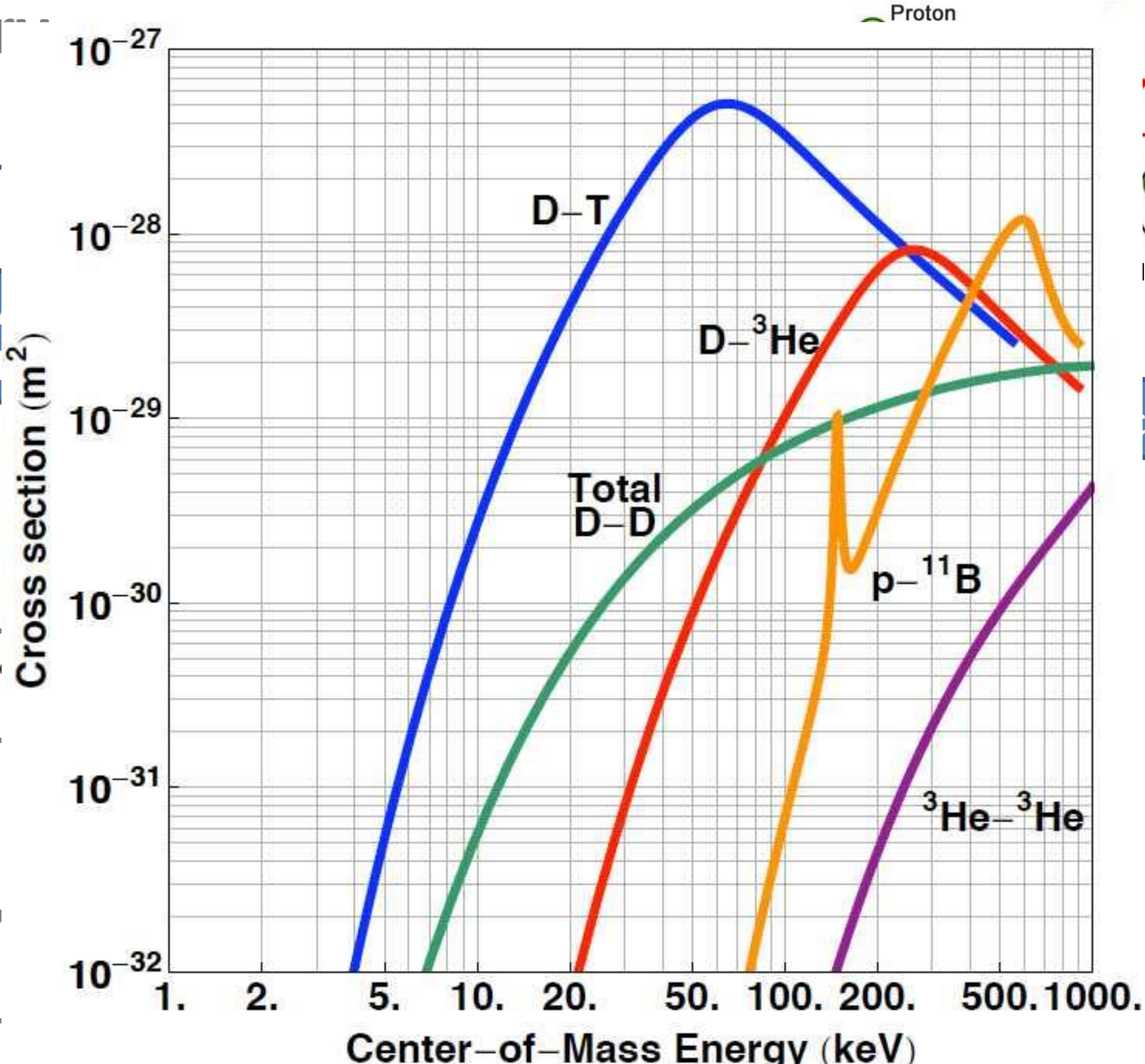


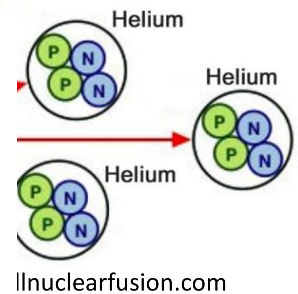
Summar

Pathway to r

ION BEA
FOCUSI

Reduce i
grid collis





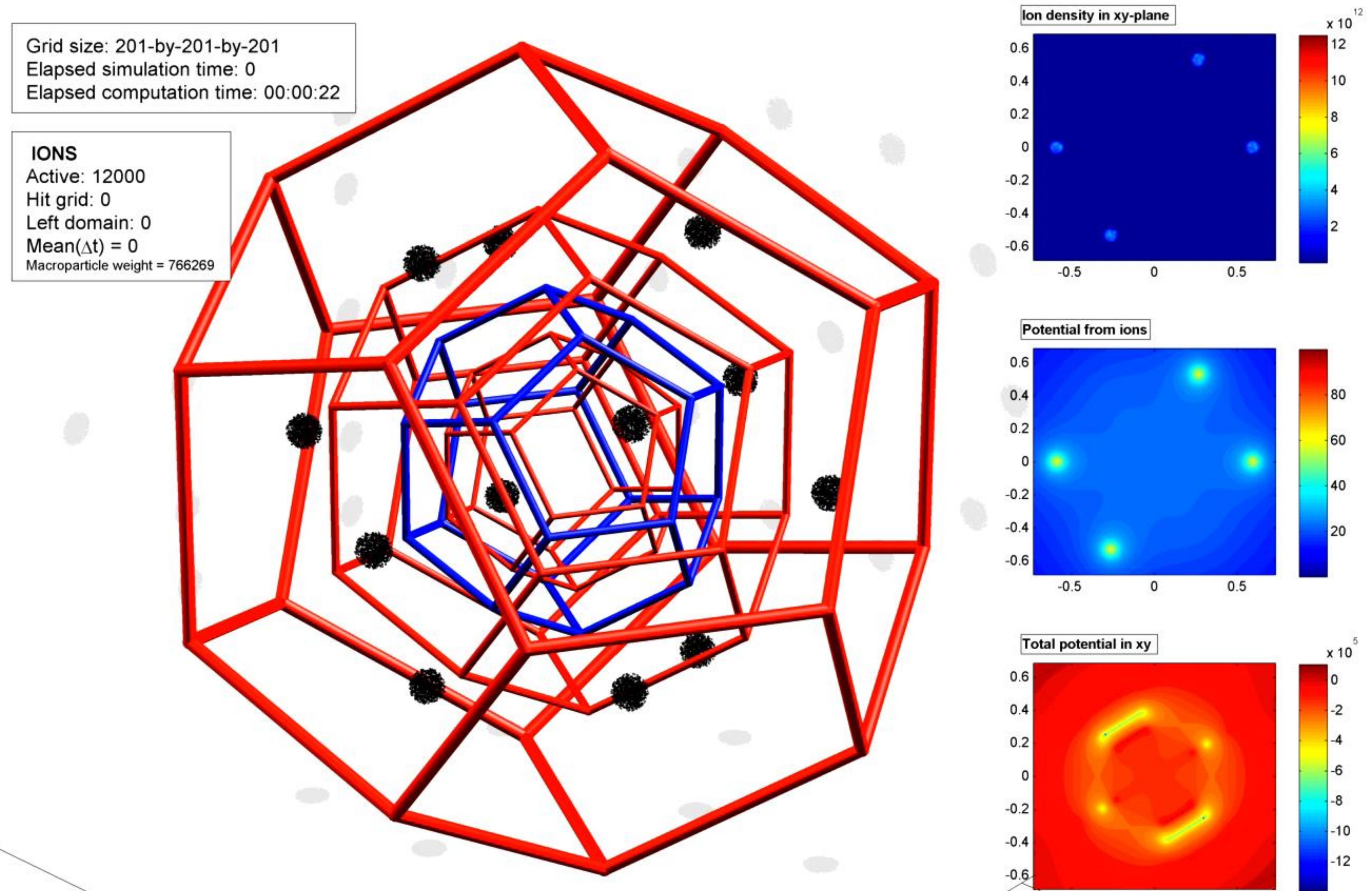
p-^{11}B fuel

THERMALIZATION

REDUCE
BREHMSSTRAHLUNG LOSSES

DIRECT ENERGY
CONVERSION

The End


Grid size: 201-by-201-by-201
Elapsed simulation time: 0
Elapsed computation time: 00:00:22
IONS
Active: 12000
Hit grid: 0
Left domain: 0
Mean(Δt) = 0
Macroparticle weight = 766269
Ion density in xy-plane
x 10^12
Potential from ions
Total potential in xy
x 10^5

DENSITY $$\frac{\partial n}{\partial t} + \frac{\partial}{\partial x}(nv) = S$$

VELOCITY $$\frac{\partial v}{\partial t} + \frac{\partial}{\partial x}(v^2) = \frac{e}{m}\frac{\partial}{\partial x}\Phi$$

POTENTIAL $$\frac{\partial^2}{\partial x^2}\Phi = \frac{e}{\epsilon_0}n$$

Using the **Roe scheme** (basically a selective upwind scheme) for density and velocity:

$$\frac{\partial u_i}{\partial t} + \frac{1}{2\Delta x}\left\{\underbrace{(\Gamma_{i+1} - \Gamma_{i-1})}_{\text{Central differencing}} \underbrace{- \left|\frac{\Gamma_{i+1} - \Gamma_i}{u_{i+1} - u_i}\right|(u_{i+1} - u_i) + \left|\frac{\Gamma_i - \Gamma_{i-1}}{u_i - u_{i-1}}\right|(u_i - u_{i-1})}_{\text{Upwind correcting terms}}\right\} = S_i$$

For STEADY STATE: can't take the derivatives of absolute values:

$$\frac{\partial u_i}{\partial t} + \frac{1}{2\Delta x}\left\{(\Gamma_{i+1} - \Gamma_{i-1}) - \left|\frac{\Gamma_{i+1} - \Gamma_i}{u_{i+1} - u_i}\right|(u_{i+1} - u_i) + \left|\frac{\Gamma_i - \Gamma_{i-1}}{u_i - u_{i-1}}\right|(u_i - u_{i-1})\right\} = S_i$$

Use approximation: $|x| \approx \sqrt{x^2 + a^2}$ with small enough a

In our case, a is a velocity