Near Real-time Simulations of Large Group B Fluidized Beds with a Low Order Bubble Model

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Outline of today's presentation

- **Emergent Behavior**
  - What Is it?
  - Why should we be interested?
- **Model background**
  - Multi-bubble models
  - Recent improvements to Halow-Daw model
- **Emergent Behavior with the Halow-Daw model**
  - Central/multiple channel formation & "cell" formation in 3D beds (Square, Circular and deep square)
  - Long time scale dynamics

General Characteristics of Systems with Emergent Behavior

- **Multiple interacting copies of limited number of “agents”**
- **Agent configuration changes with time**
- **Interactions constrained, often non-linear**
- **Collective behavior not predictable from behavior of “average” agent**

Examples of emergent behavior

- **Flocking birds**
- **Traffic flow**
- **Social insects**
- **Solids circulation, gas plumes, slugging in fluidized beds**

Common theme: Complex, global behavior arises from interaction of agents following simple rules

Modeler's challenge: Who are the agents, what are the simple rules?

Why use agent-based models?

- **Despite increases in computation speed, detailed models are still not fast enough for large parametric studies, large physical problems and are really far-fetched for real time studies**
- **Agent-based models can provide the following:**
  - Capture essential global features
  - Reveal connection between physics at agent level and large scales (separate essential physics from details)
  - Simple - so they run much faster

Why model emergent behavior in fluidized beds?

- **Large-scale global features can dominate bulk mixing, heat transfer**
- **Global features can be used as diagnostics for small-scale phenomena (e.g., detecting onset of solids stickiness or agglomeration by shifts in solids circulation)**
- **Global features are critical to validation of detailed CFD codes and low-order models can help interpret physical reasons for code/experiment differences**
- **Better understanding of global dynamics may lead to new control strategies (e.g., how does solids circulation affect agglomeration, how does distributor design affect circulation)**
- **Low-order models are extremely fast and that can be used for very large beds and on-line diagnostics/control**

Multi-Bubble Models for Group B Fluid Beds

- **Multi-bubble models around since the 60s**
- **In multi-bubble models, the "Agents" are bubbles**
- **Halow & Daw model features:**
  - **Bubble interaction correlations from capacitance imaging**
  - **Fortran code structured for fast simulation (improved)**
  - **Can explore long term dynamics (including "emergent" behavior)**
  - **Flexible construction allows addition of new interaction rules, constraints (improved)**

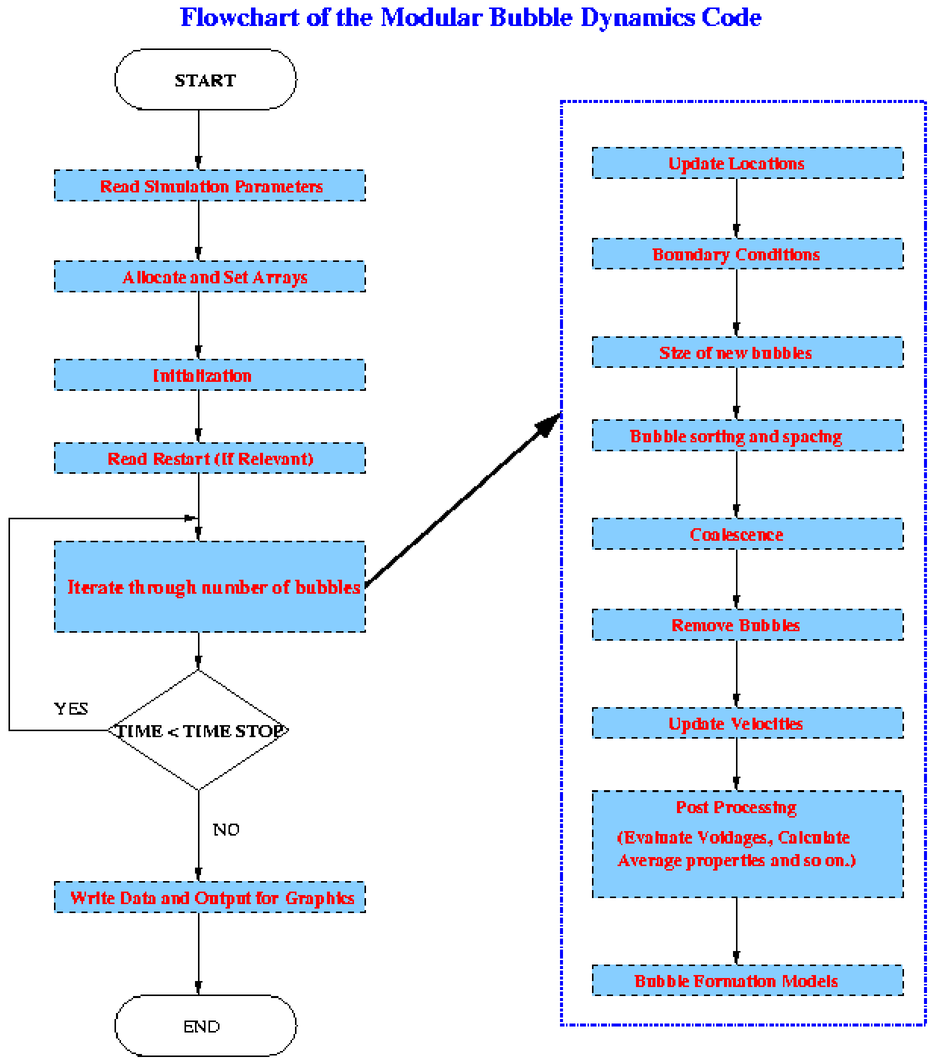
Two Bubble Interactions

- Trailing gas bubbles in liquids are experimentally observed to speed up when approaching lead bubbles (wake effect)
- A different mechanism was observed from capacitance imaging of fluid beds:
  - Solids moving around bubble expand
  - Expansion “relaxes” over time
  - When other bubbles encounter expansion “trails” they accelerate along them

Update on improvements to the code

- **Converted Basic code to modular & portable F90 code**
- **Profiled code and efficiency improved by 2 orders of magnitude**
- **Ability to track thousands of bubbles => Large fluidized beds of industrial scale can be simulated**
- **Code can be parallelized to give much faster turn around time and real-time simulations possible**

Block Diagram of the New Code



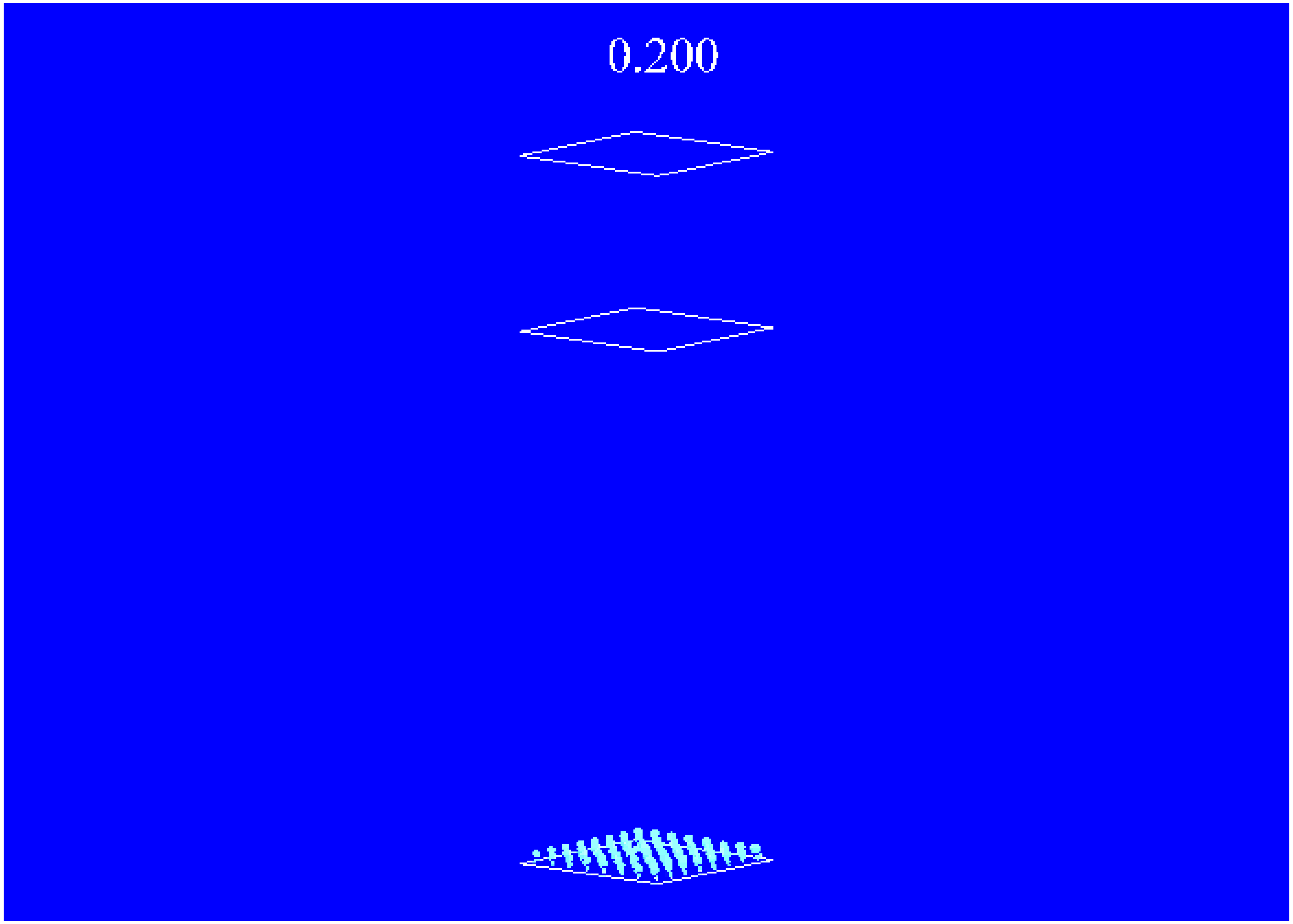
Characteristics of Calculation

- **One equation for each bubble in bed so number of equations can be large (100s or 1000s) and changes with time**
- **Each equation is first order ODE**
- **Equations nonlinearly coupled through separation distances**
- **Formation, coalescence, surface change affects the number of equations**
- **Readily solved by direct simulation.**

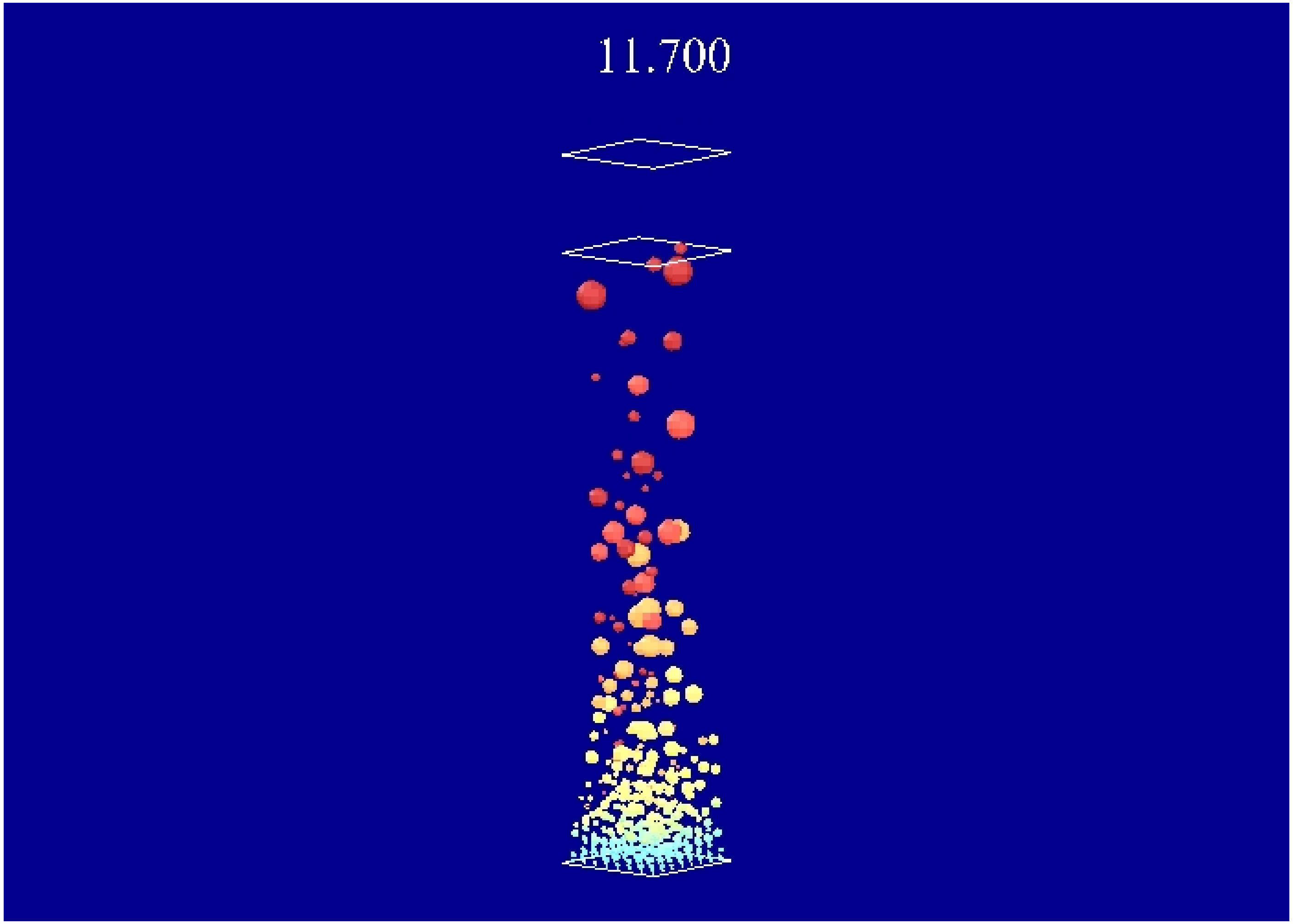
3-D Square Bed

- **200 cm width bed**
- **Bed L/D equal to 3.0**
- **U_{mf} = 6 cm/sec**
- **U/U_{mf} = 2**
- **2.5 cm bubbles released at randomly from distributor**
- **Spacing of Tuyeres (injectors) = 25 cm**

3-D Square Bed Cell Formation example

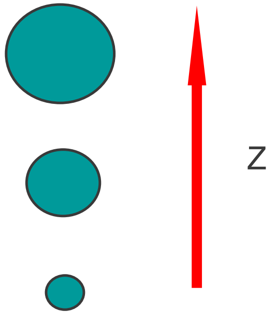


Bubble dynamics in 3D Deep Square Bed



Reason for Channel Formation

Bubbles Grow along the chain due to coalescence as the trailing bubbles accelerate towards the leading



Bubbles Grow large enough and also due to instabilities, perturb from the straight line to influence the neighboring chains

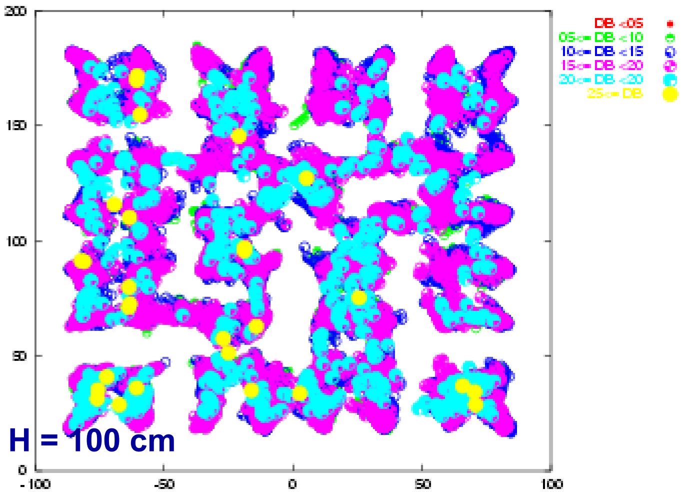
Interacting chains can create rise to even larger bubbles due to coalescence

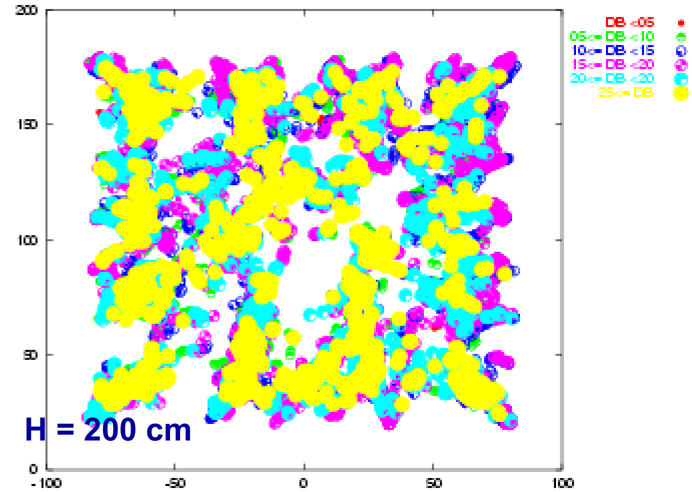
Bubbles rise with very high velocities and their influence is not felt far below and stabilization of the chains takes place. The process is repeated again. This reverse process can be viewed as series of bifurcations.

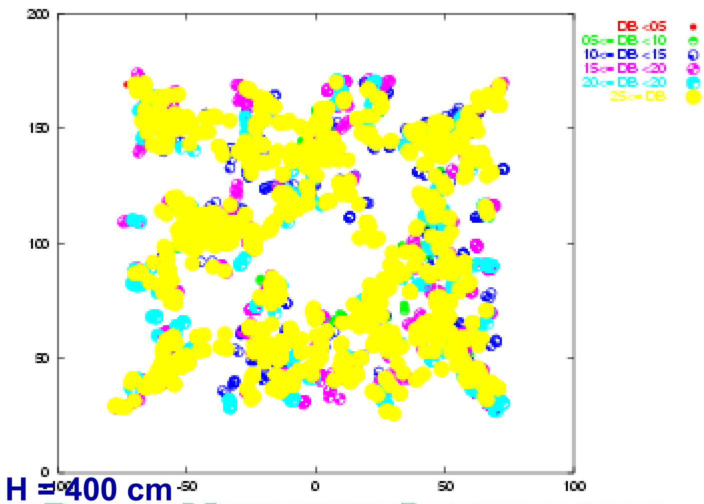
Cell-Like Formation in 3-D Square Beds

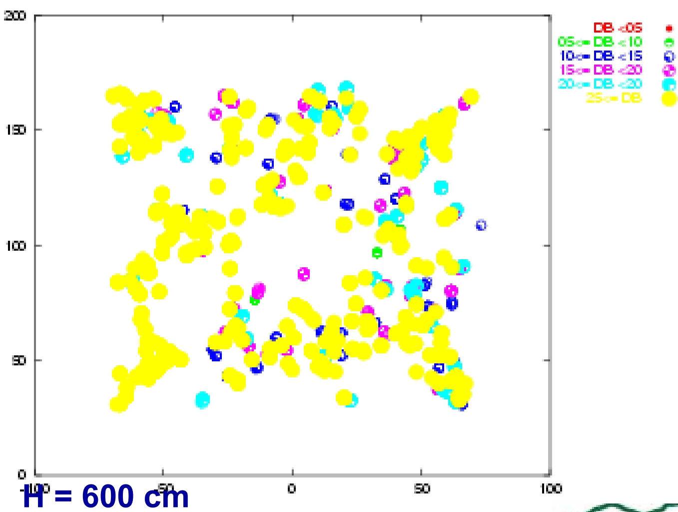
- **Initially, first bubbles in bed rise up and collect a chain of bubbles behind them**
- **Bubbles in chains coalesce and grow larger**
- **If chains overlap they can merge**
- **When a lead bubble reaches surface that chain may shift and follow another bubble**
- **Bubbles on the outside, can only shift inward.**
- **Outer edge moves inward until a rapidly draining channel is formed.**
- **Process has long time scale dynamics**

3-D Square Bed Cell Formation example

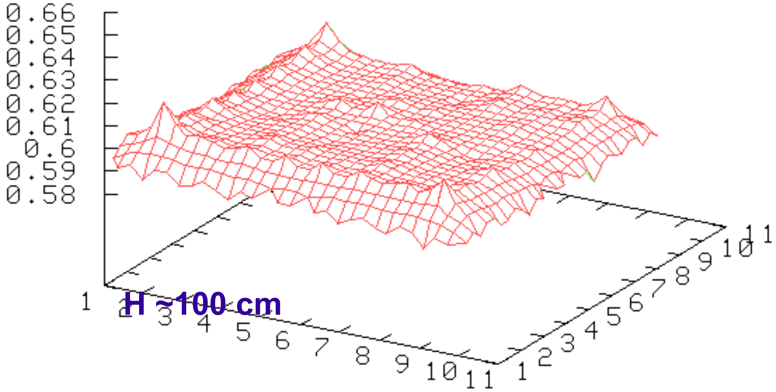




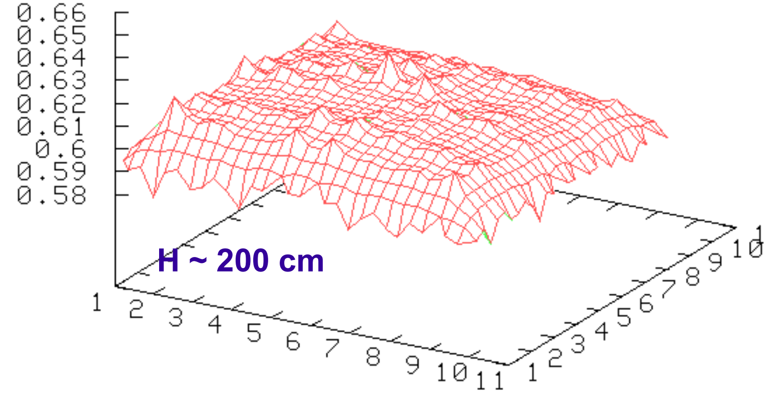




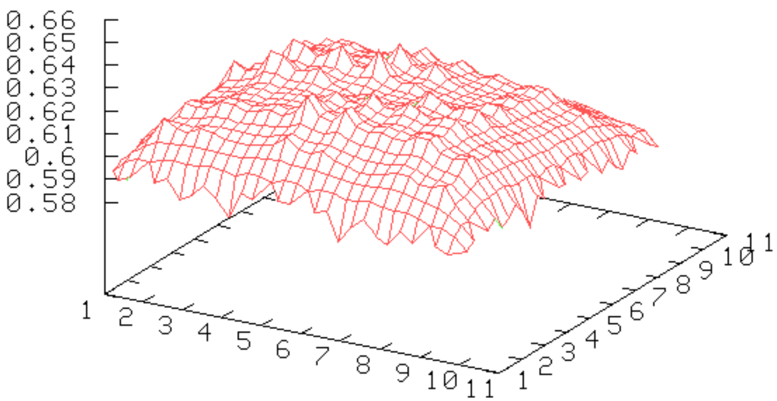
3-D Square Bed Cell Formation example



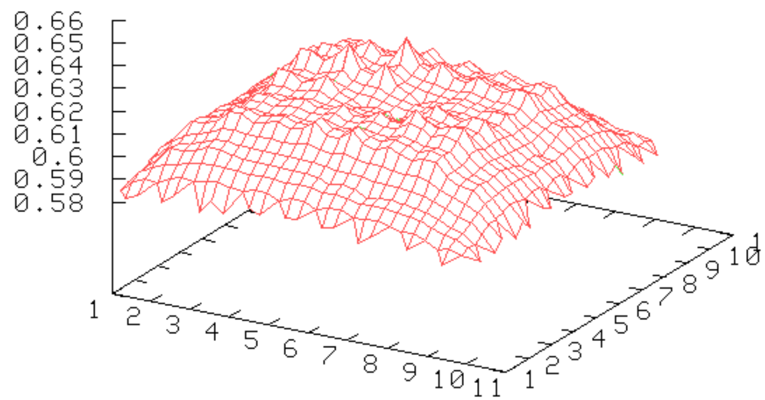
H ~100 cm



H ~ 200 cm



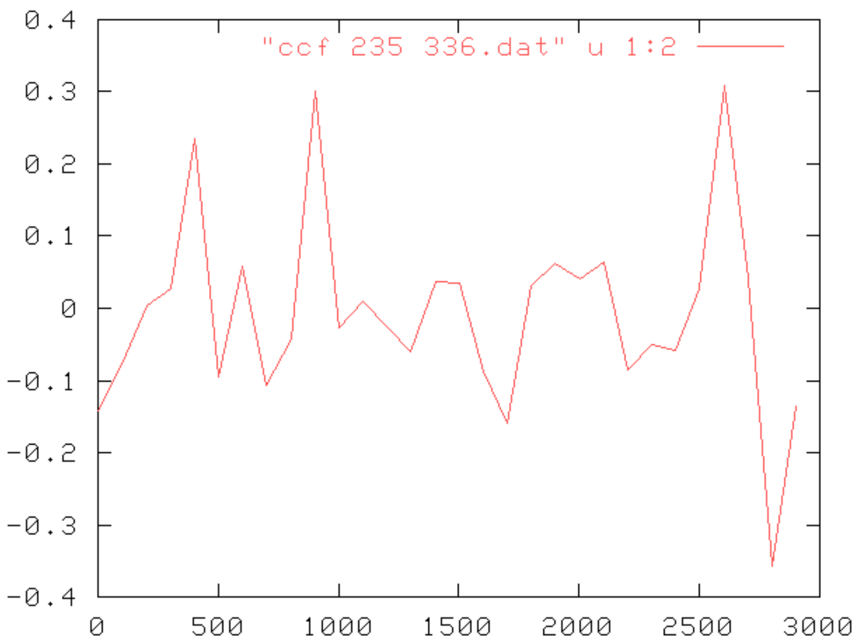
H ~ 400 cm



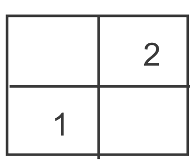
H ~ 600 cm

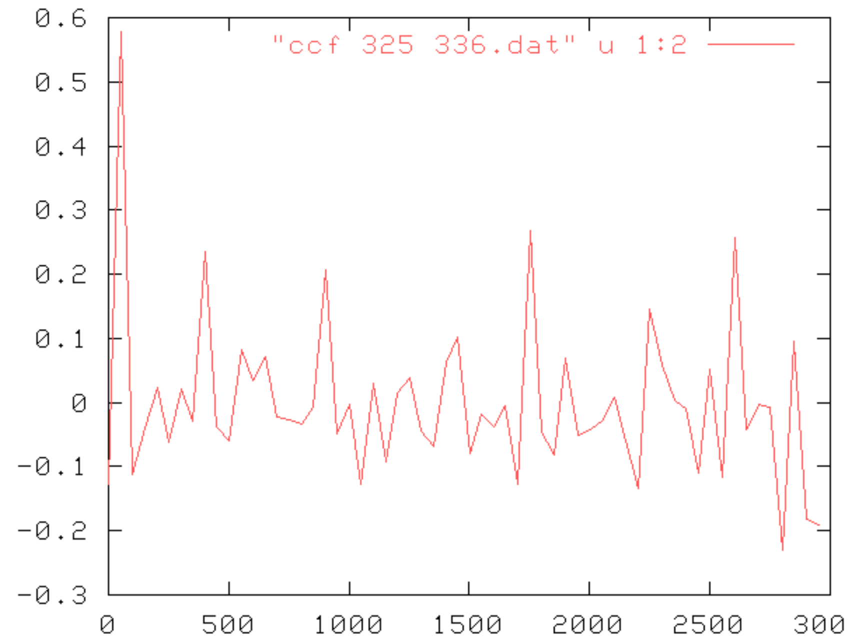
3-D Square Bed Cell Formation example

Cross-correlation of void fraction

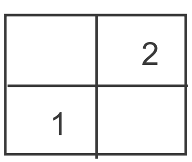


Location 1 (200 cm, 300 cm, 500 cm)
Vs. Location 2 (300 cm, 300 cm, 600 cm)





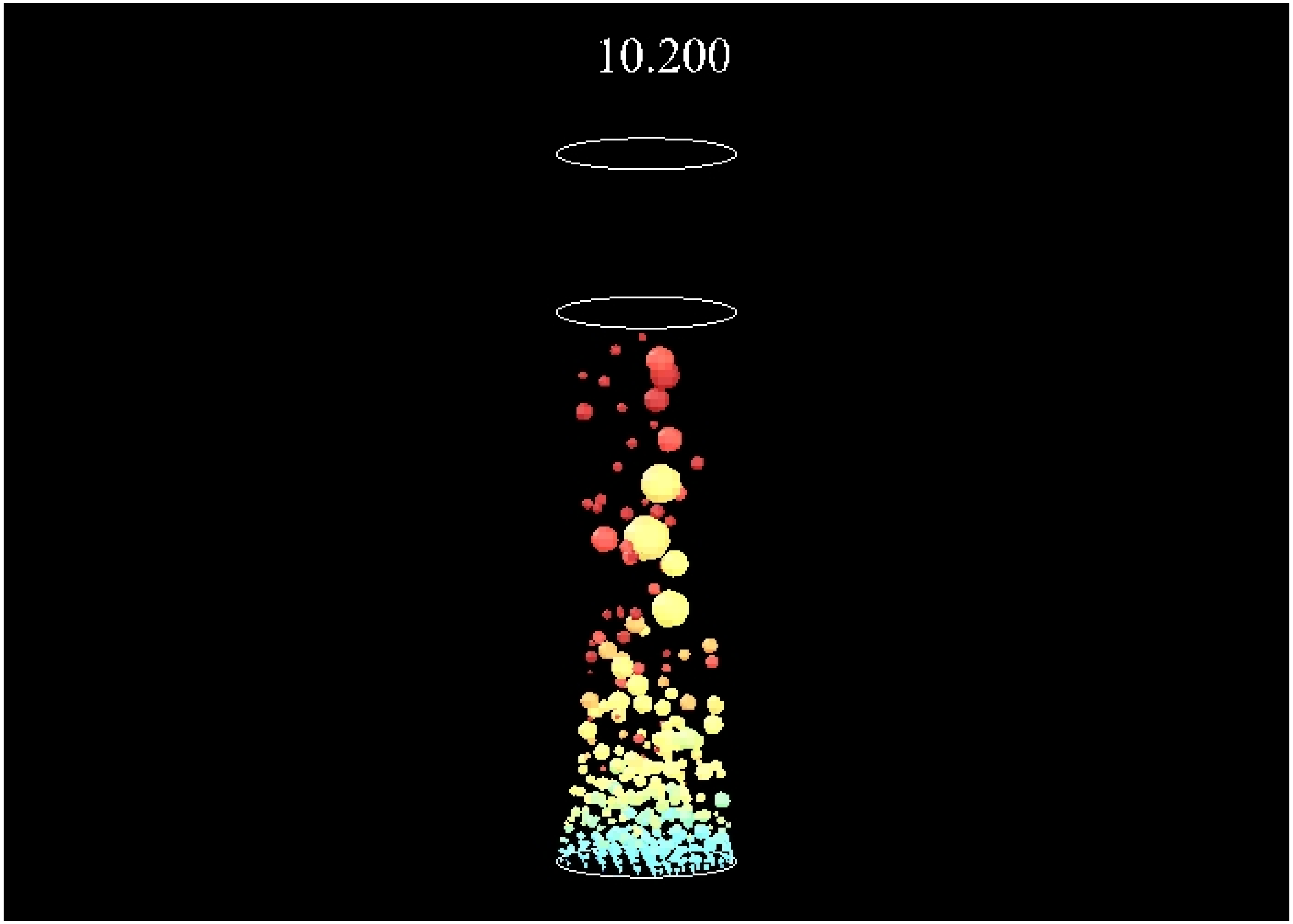
Location 1 (300 cm, 200 cm, 500 cm)
Vs. Location 2 (300 cm, 300 cm, 600 cm)



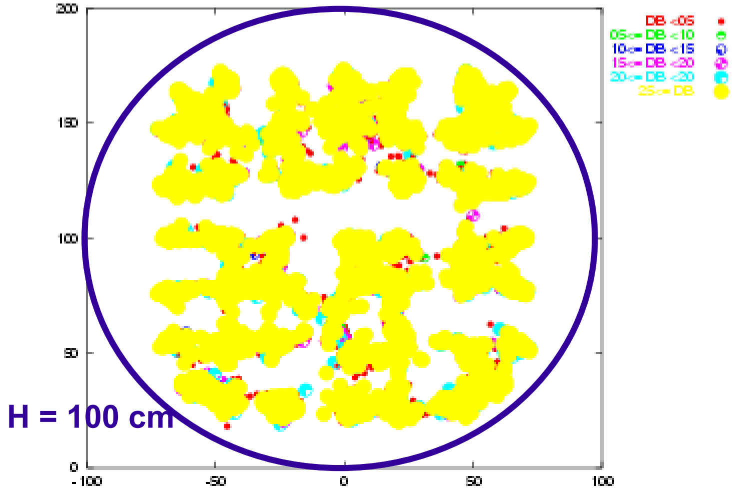
An Example:
Bubble dynamics in 3D Circular Bed

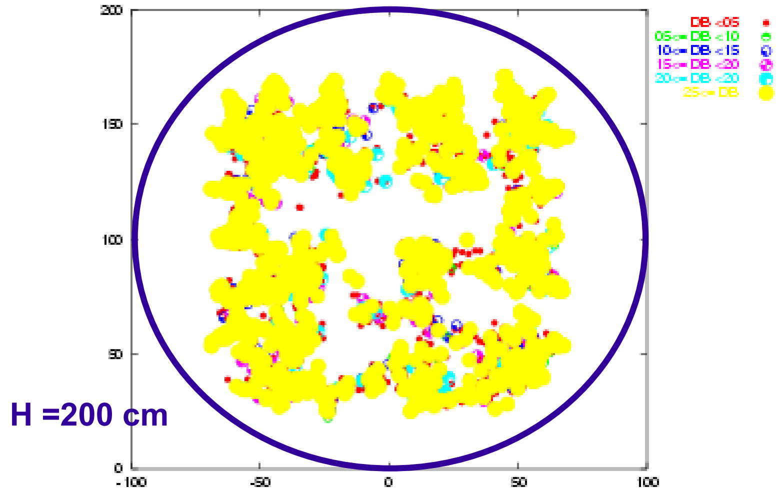
- **200 cm diameter bed**
- **Bed L/D equal to 3.0**
- **U_{mf} = 6 cm/sec**
- **U/U_{mf} = 2.0**
- **2.5 cm bubbles released at randomly from distributor**
- **Spacing of Tuyeres (injectors) = 25 cm**

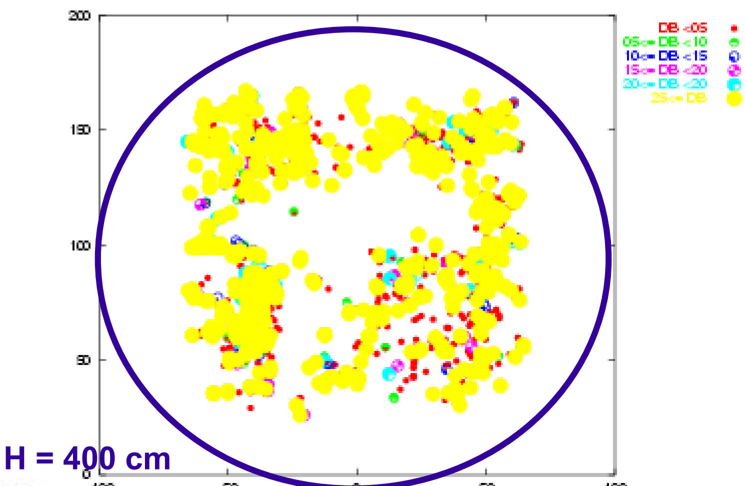
Bubble dynamics in 3D Circular Bed

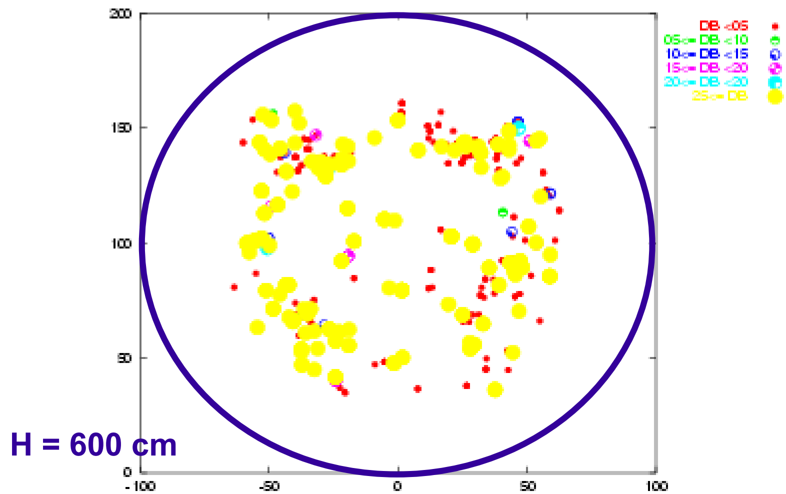


Bubble Distribution in 3D Circular Bed









Bubble Model Forms “Cells”

- **Number of Channels depends on**
  - Bed Width
  - Excess Gas Velocity
  - Initial Bubble size
  - Initial bubble release grid
  - Bed shape
  - Bed Depth

Conclusions

- **Efficient bubble model has been employed to simulate large fluidized beds**
- **Emergent behavior present in simple bubble model**
- **Tendency of bed to form channel(s) can be explained as an emergent behavior - more detailed studies will be performed in near future**
- **Long term dynamics predicted by simple bubble model**