Optical Tweezers

Draft Design

Jan 29, 2007

Changes

- Make light grey box frame around laser control panel that matches handles.
- Make grey supports looking like they are supporting the lens.
- Make control panel section that's title "Graphs" with radio buttons for None, Position Histogram, and Potential Energy Curve
- Make control panel section that's titled "Laser Display" as radio buttons
  - Beam
  - Electric field vectors
  - Beam with vectors

  Behavior would be that Beam was only option in fast mode, but other radio buttons became active in super-duper slow mode.
- Make control panel section that's titled "Bead's charges" as radio buttons
  - Hidden
  - Charge distribution
  - Excess charge only
- Rail-slider for laser
- Make lens with flat view

Changes meeting – w/ Wendy : June 4, 2007

- Reduce spacing between radio buttons
- Add “Ignore brownian motion” option, delete “show brownian force”
- Add ruler icon next to show ruler

Concepts

- Concepts for 1st panel: Physics of Tweezers
  - Light is oscillating, propagating electric field
  - Electric field induces a polarization of the bead. This polarization increases with strength of electric field, and changes direction with change in direction of E-field
  - Gradient in electric field and polarization of bead causes net force towards center (show force in x only???)
    - Show as balance of right hand side force and left hand side force
  - Bead is under constant brownian motion
    - Distance that bead travels is balance of brownian motion versus trap strength: $\frac{1}{2} k_B T = \frac{1}{2} k_{x\text{-trap}} \langle x^2 \rangle$
  - If bead is out of trap it will just undergo brownian motion.
  - ON FREEZE FIELDS OR PAUSE view, learning goal:
    - Moving bead around changes polarization of charges and net force on bead.
    - (DON"T DO THIS?) Allows you to let go and see behavior of bead in a "static" E-field
    - How to model this???
      - Static field you won't get k-trap … take example of when you are at zero e-field (no force).
      - (DO THIS) Possibly just allow them to move bead around during "PAUSE" (showing force vector) but not model motion of ball with static E-fields.

- Start-up ideas:
  - No bead?
  - Or bead out of beam … with wiggle me of move bead into laser?
  - Or bead doing brownian motion with no laser on and wiggle me to turn laser on?

Physics NOT shown…

- Right now cannot change radius of bead (could add to advanced features if important).

Physics of Tweezers

User Stories:

1) Trap force like a spring:
   a. User grabs bead and moves it horizontally. Sees force grow as distance from center grows. Always towards center
   b. User goes to advanced options and sets flow going. Calculates offset of bead in x versus flow force … 6 π η r v = k_trap_x*X. (They will have to estimate r of bead with ruler, viscosity and velocity are from controls.)
   c. Intensity control changes force.

2) Can control position of bead with laser:

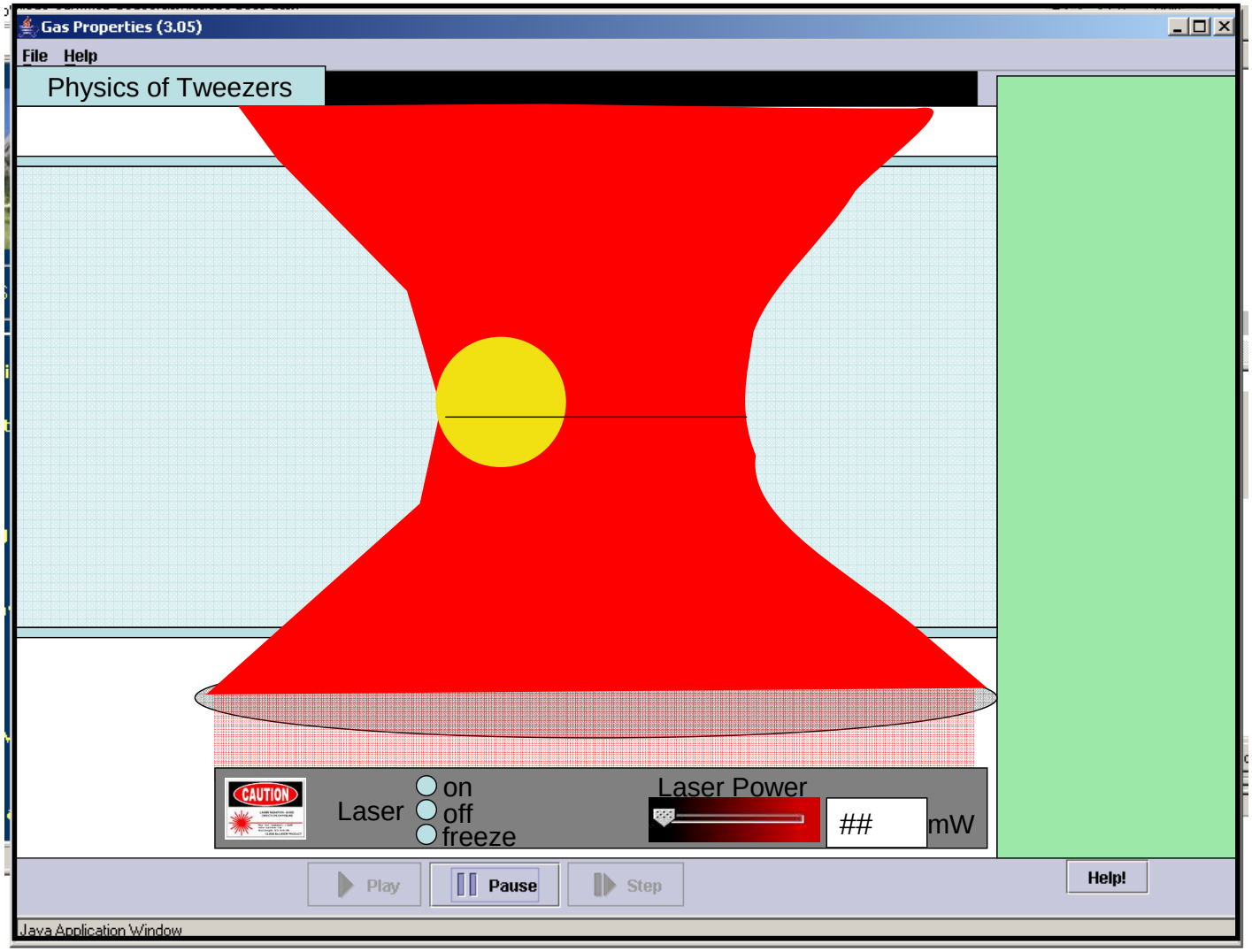
a. User grabs laser and drags it around seeing that bead will stay in laser beam unless user moves laser “stage” too fast. In which case bead will “pop” out of laser beam and just be doing brownian motion.
b. Intensity control changes speed at which bead pops out.

3) ETC… I can write a ton, but before I do I want to make sure this is what Chris wants.

Physics of Tweezers

Dimensions:
-Bead is 200nm
-Laser waist is 500 nm

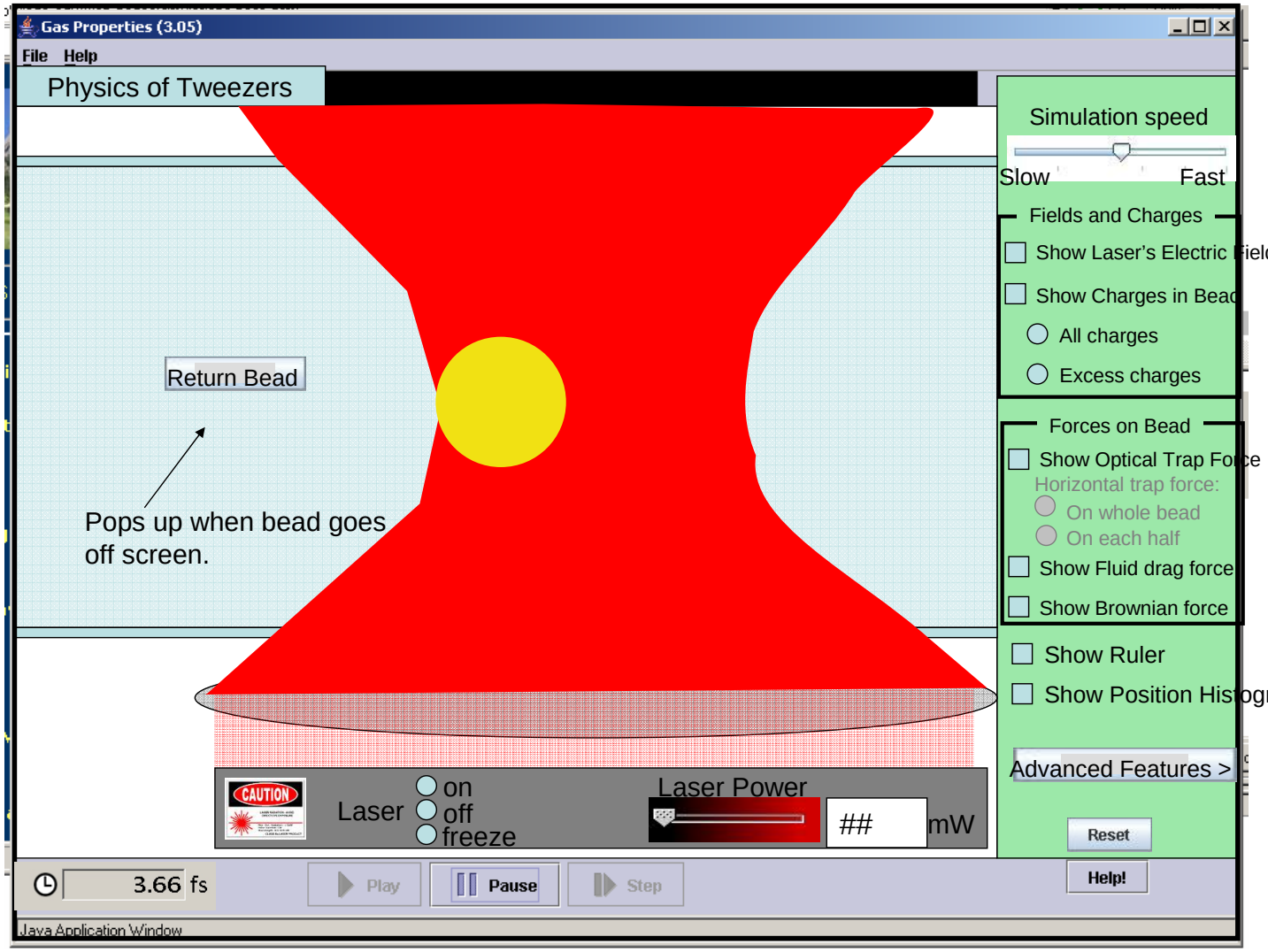
Look:
-Bead should have shading to look 3D
-Laser should have shading so that red looks like gaussian power distribution from left to right and weaker where broader beam. Red should get brighter with intensity.

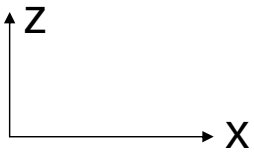


Basic idea:
-Bead in liquid undergoes brownian motion
-Laser beam ON puts force on bead that pulls it toward center of laser beam .. “traps it”
-Liquid is viscous so causes bead to always moves at terminal velocity (Force ~ velocity NOT
Force ~ acceleration).

Physics of Tweezers

Sim speed = FAST (Shows only time averaged forces on bead)





Laser force is like a SPRING force:
F_trap_x= k_trap_x*delta_x
F_trap_z= k_trap_z*delta_z
Delta x = distance from center in x
Delta z = distance from center in z

Trap force goes to zero if bead is

Force on bead given by k_trap:
k_trap_x = Power/11400
Power in mW, k_trap_x in pN/nm
k_trap_x is independent of z.

Power goes from 0 mW to 1000 mW

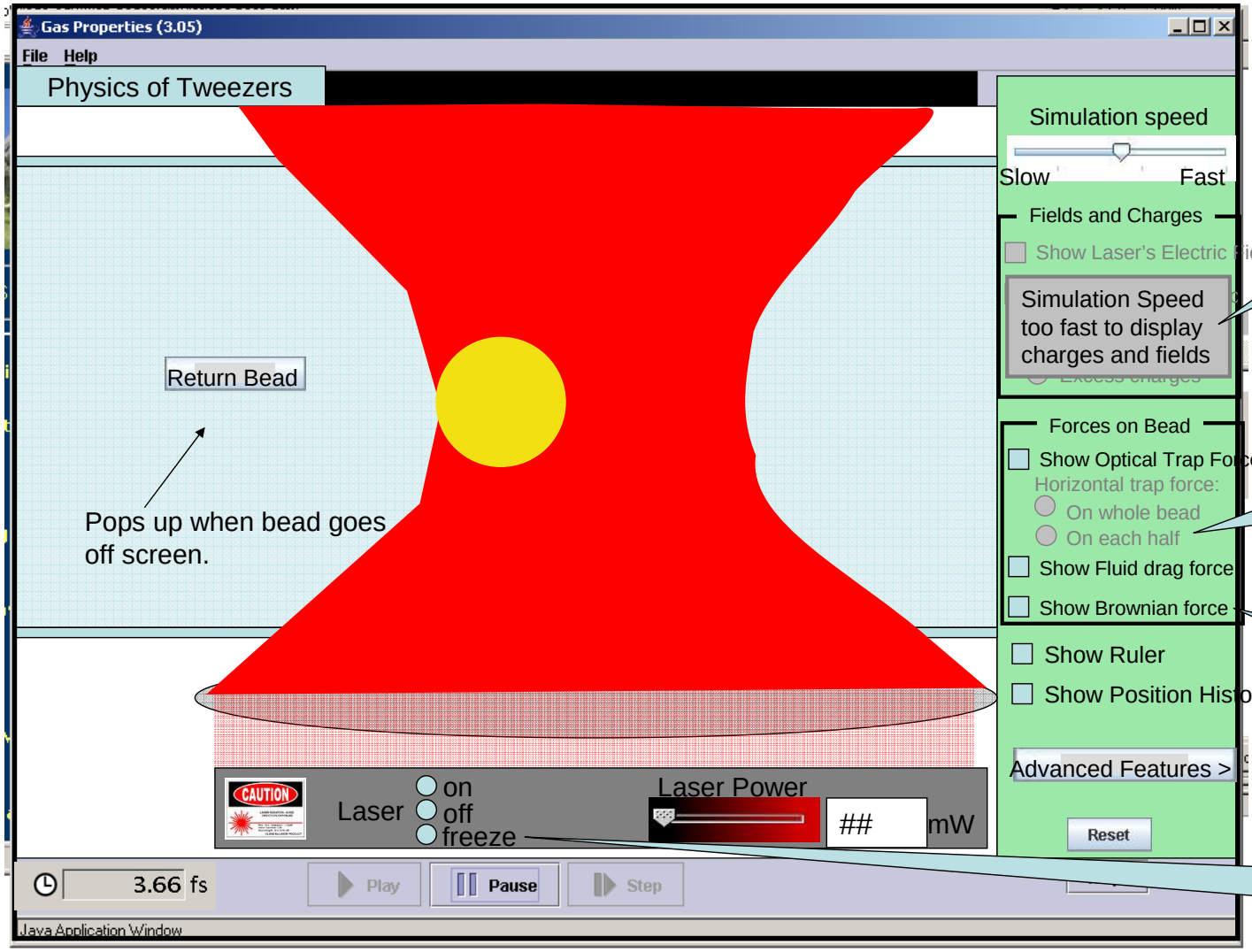
k_trap_z = k_trap_x / 5.6

F_drag = γ*velocity
(γ = drag coefficient, will be adjustable through viscosity in advanced features
F_brownian = small random kicks

Model check: If No force … (laser off) diffuses ~1 bead diameter in 1 sec

Physics of Tweezers

Sim speed = FAST (Shows only time averaged forces on bead)



If sim speed is fast, have message appear in this part of control panel that says cannot display this now.

Grey out this control if sim speed too fast to display fields and charges.

Is it reasonable to display Brownian motion forces?? Need to check modeling.

May want "laser freeze" or just use "pause" button if can allow dragging bead around if that is active?

Physics of Tweezers

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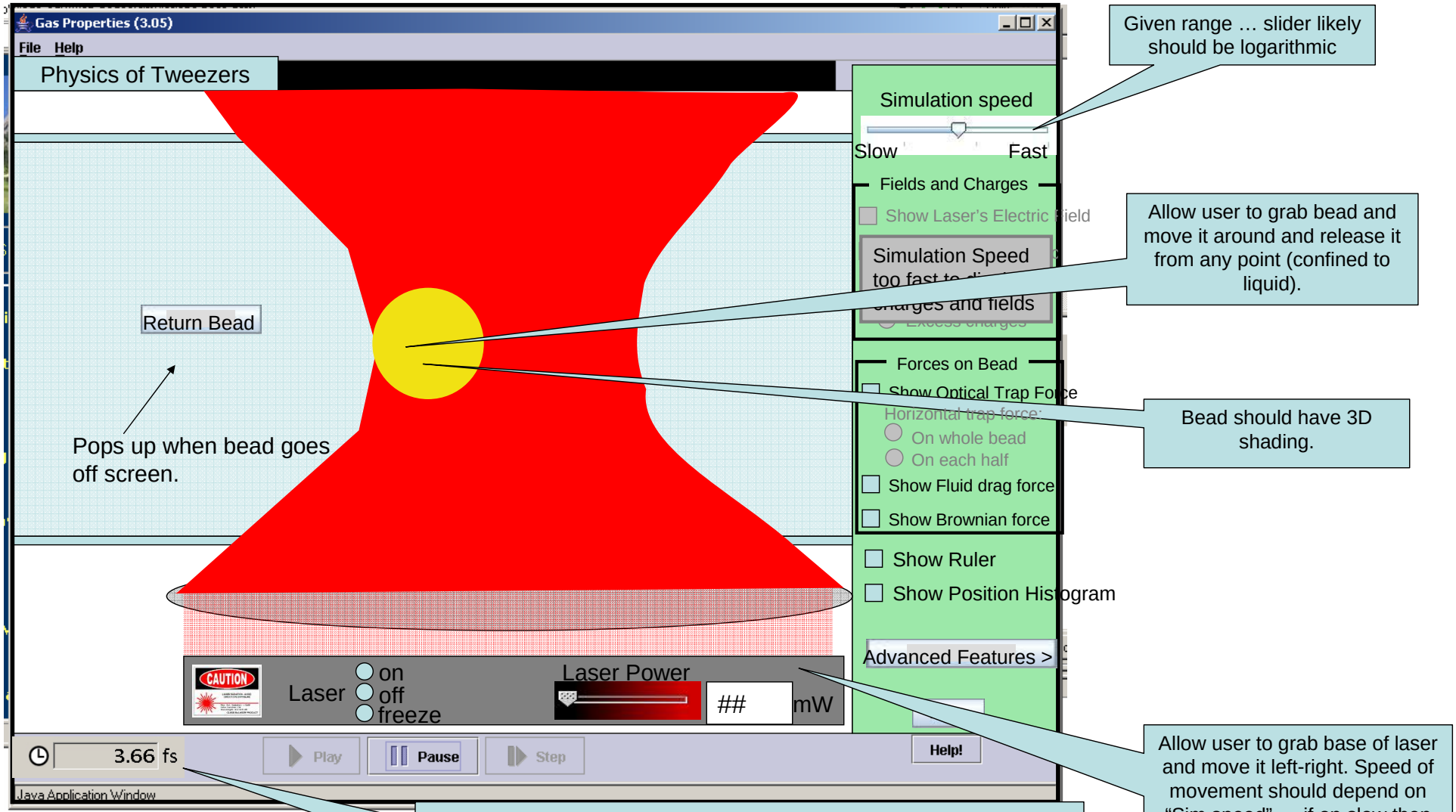

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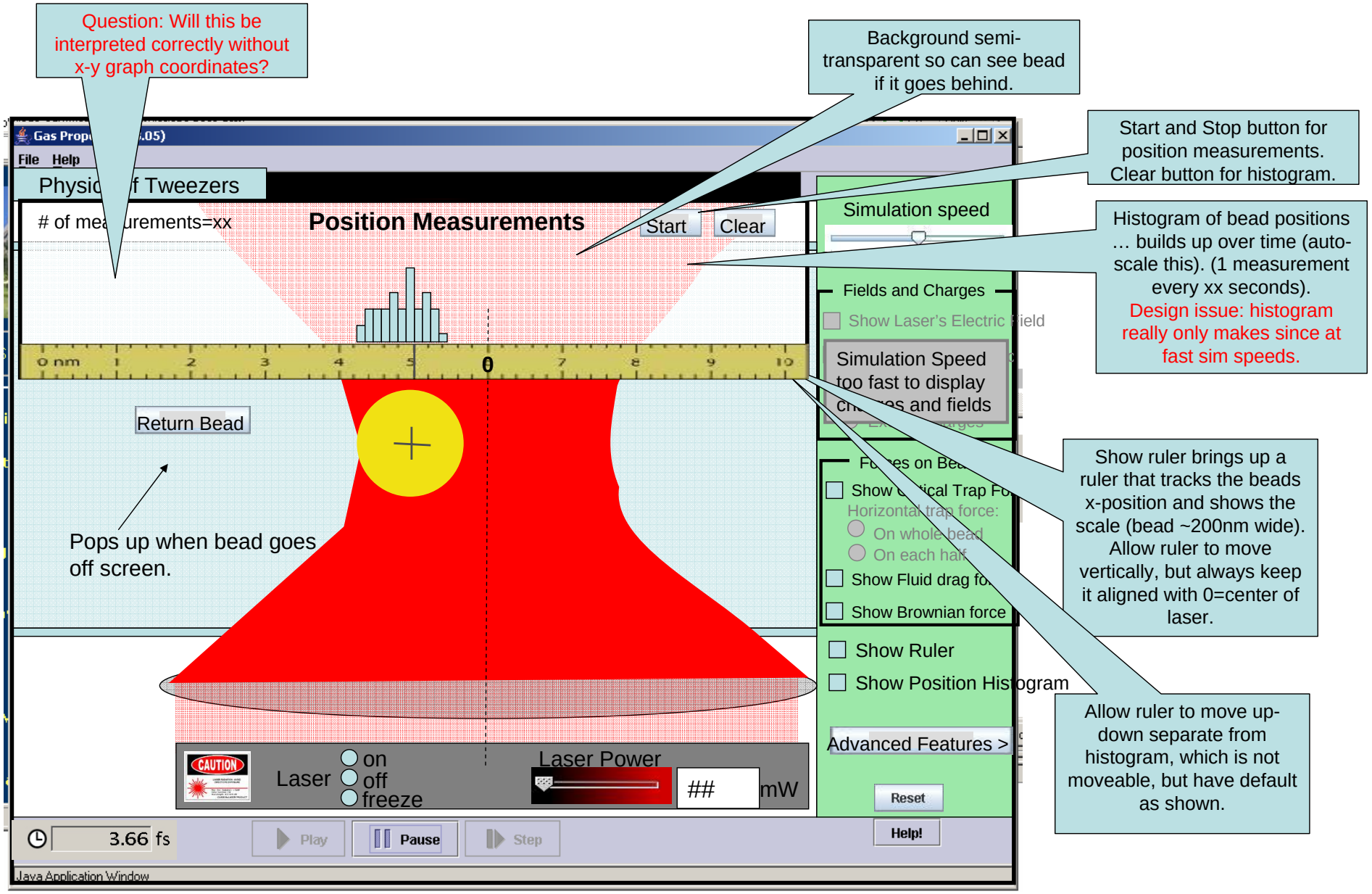
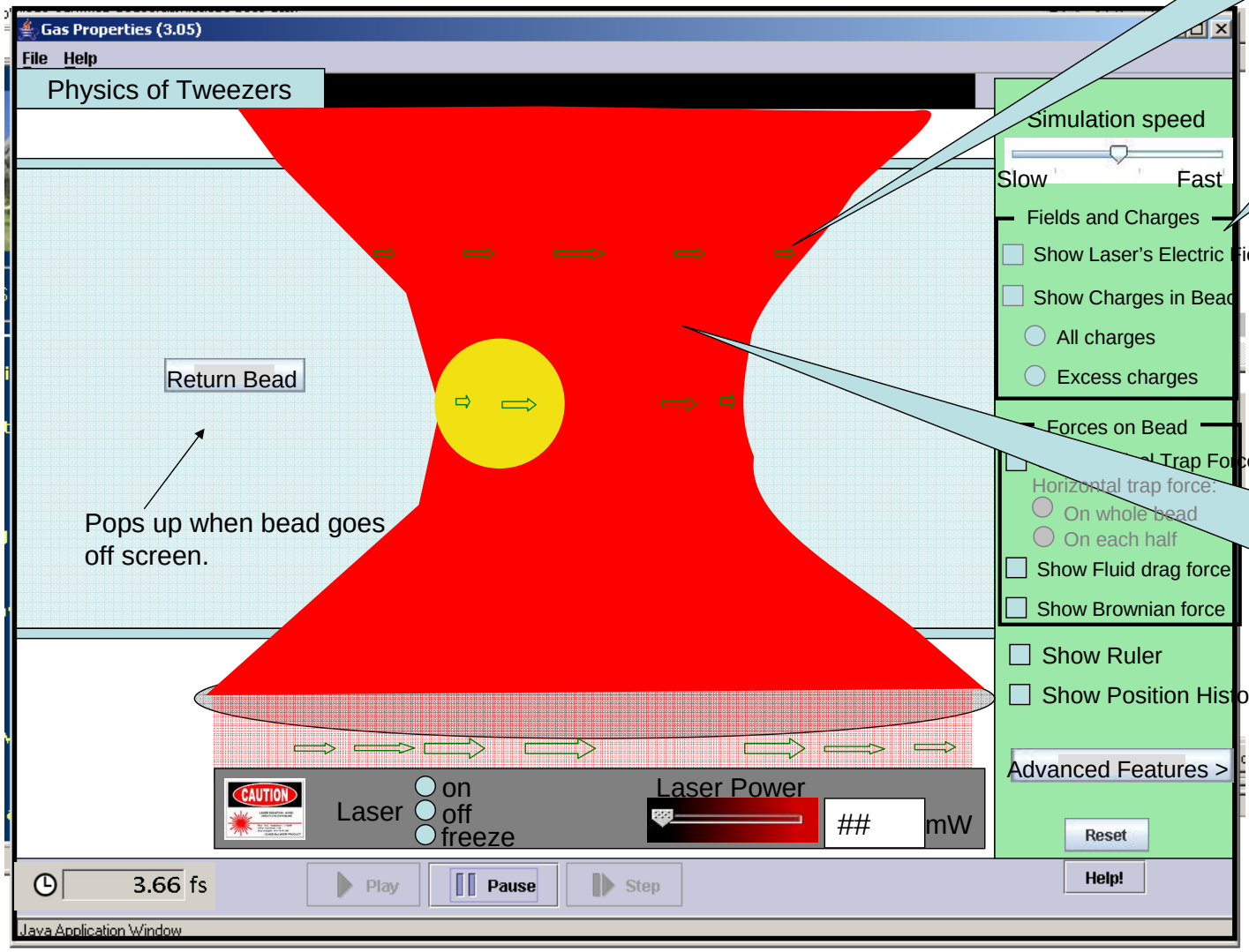


Physics of Tweezers

Sim speed = SLOW (show E-field and charges.)



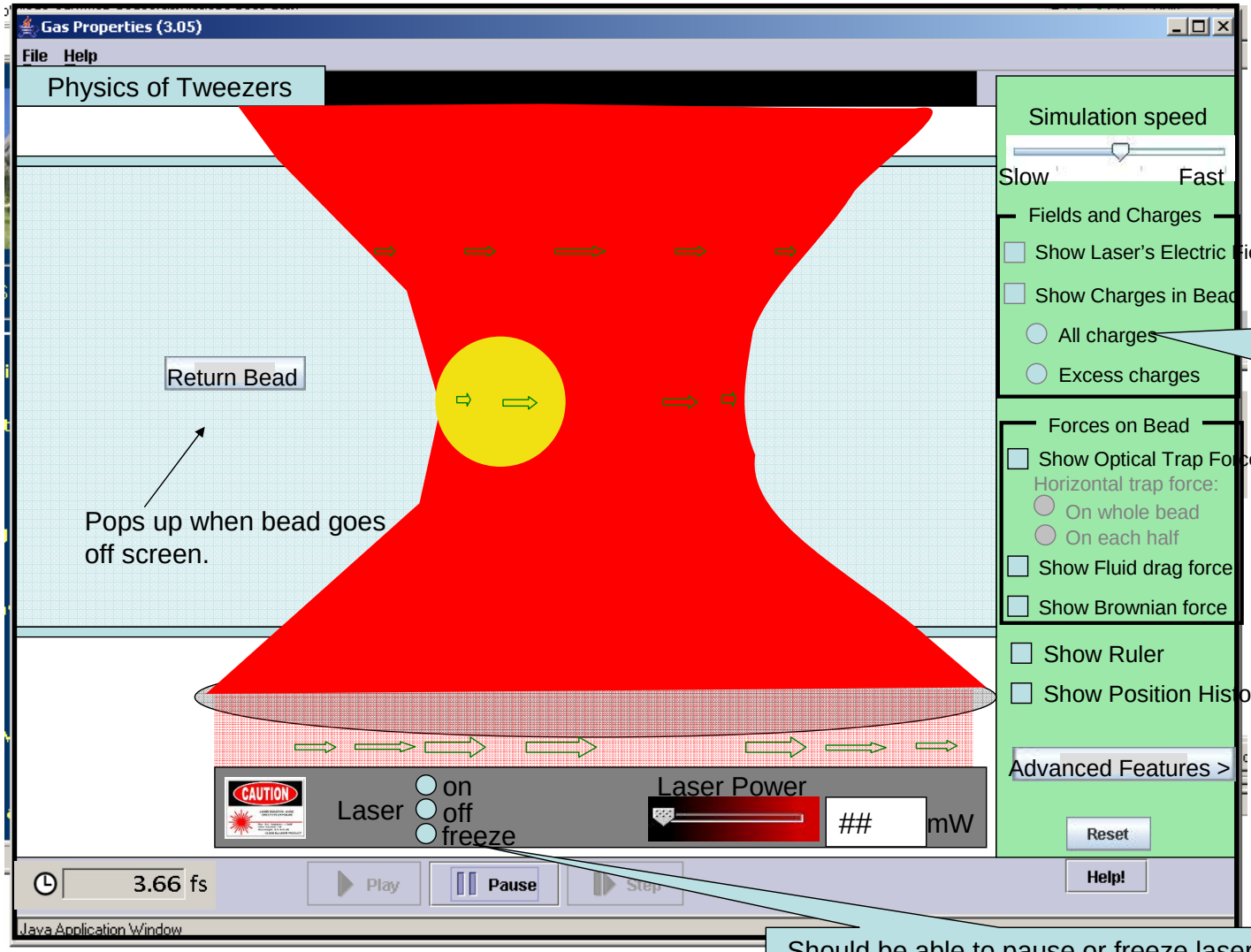
E-field displayed as vectors on even grid that maps laser area (as in radio wave sim). Fading and size changes with strength

If sim speed slow enough, then allow these options. Slow enough means: about 1 sec = 10-15 sec of sim time

Wavelength of laser shows up in e-field grid… what wavelength do folks trap at, or do we just use He-Ne wavelength since laser is shown as red here?
He-Ne = 632 nm.
Actually is IR: 1064 nm

Physics of Tweezers: Page 1

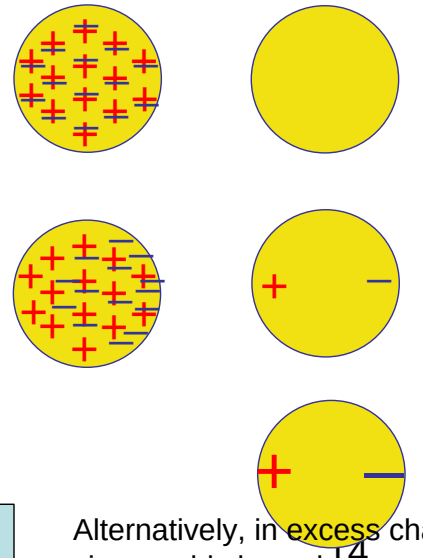
Sim speed = SLOW (show E-field and charges.)



The extent to which the bead is polarized will depend on electric field, stronger = more polarized. So as "zero" in e-field passes through, you will see no polarization. This will be Hollywood-ed since we only want qualitative idea.

Show charges should put grid of + and – charges, with –'s that moves slightly with E-field (creating polarization):

All charge view: Excess charge view:

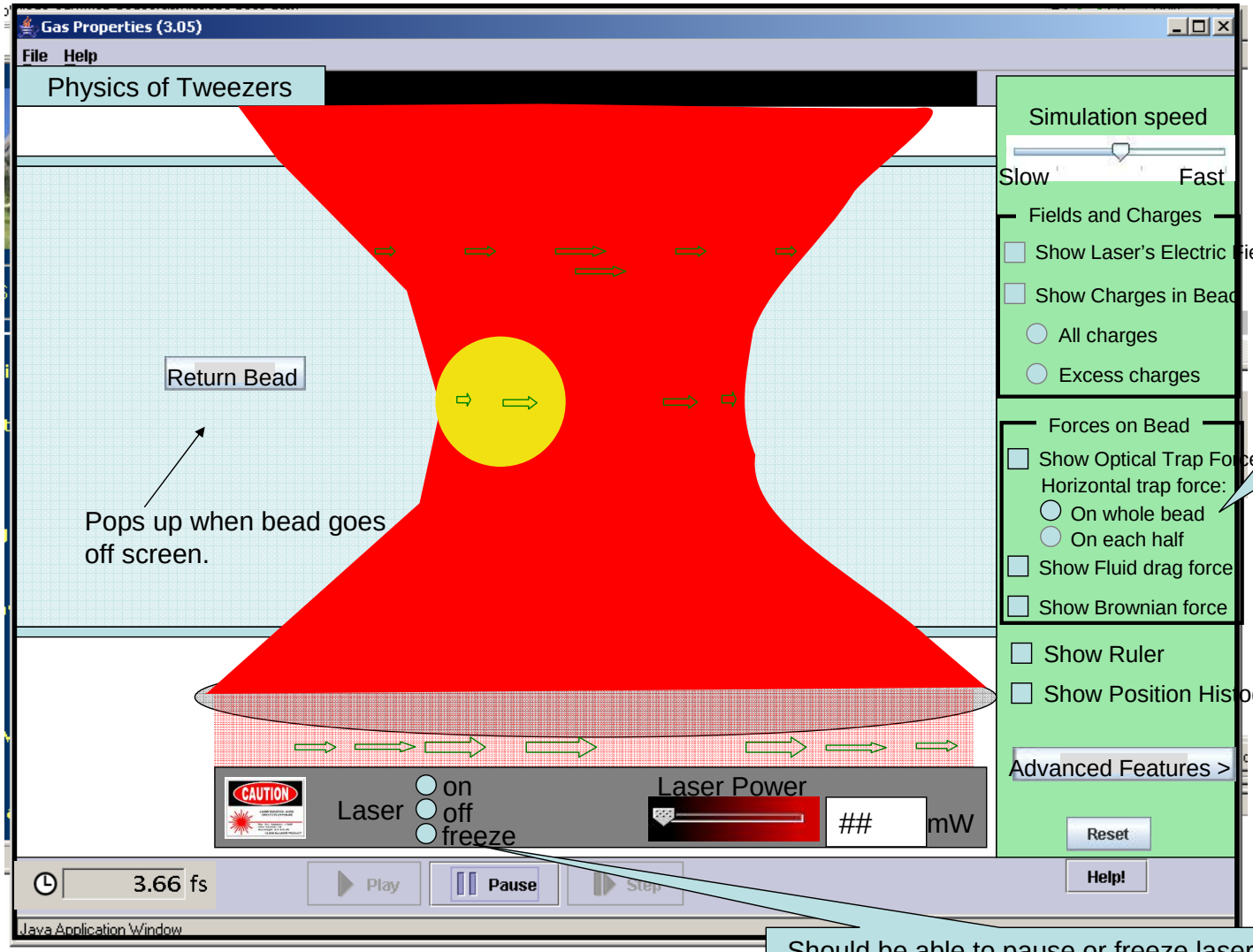


Should be able to pause or freeze laser and move bead about to see how charges and forces are different depending where you are in the beam.

Alternatively, in excess charge view could show charges all same size but more on each sic as excess charge increases.

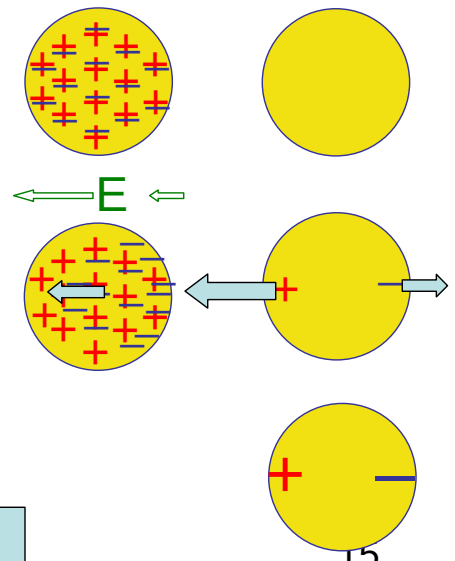
Physics of Tweezers

Sim speed = SLOW (show E-field and charges.)



Showing forces on bead… now these options are available (when sim speed is slow enough).
Optical trap force will grow and strink depending on where you are in E-field wave cycle.
(Only show horizontal force ???
Detailed physics of vertical force is not apparent with this model)

All charge view: Excess charge view:



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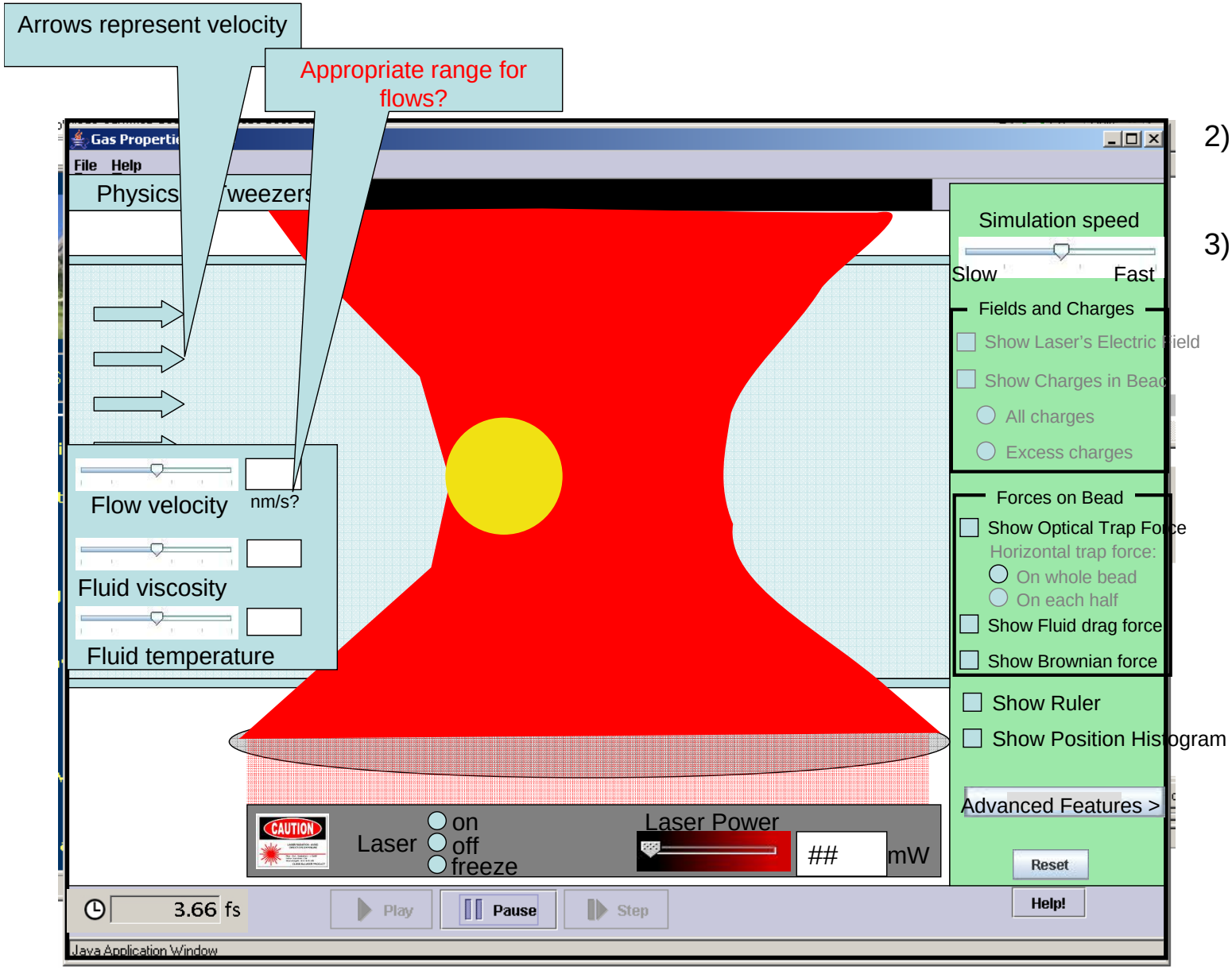
Physics of Tweezers

Sim speed = SLOW (show E-field and charges.)



When any one of advanced options is selected then:

1) Sim speed skips to "fast" and if students try to readjust, does not allow student to go to slow speeds.
2) Fields & charges grey out, Horizontal forces grey out.
3) Bead and laser return to default location.

Advanced Features >

- Control Fluid and Flow
- Show change in momentum model for trap force
- Show potential energy graph

If Control Fluid and Flow selected, options at left appear:

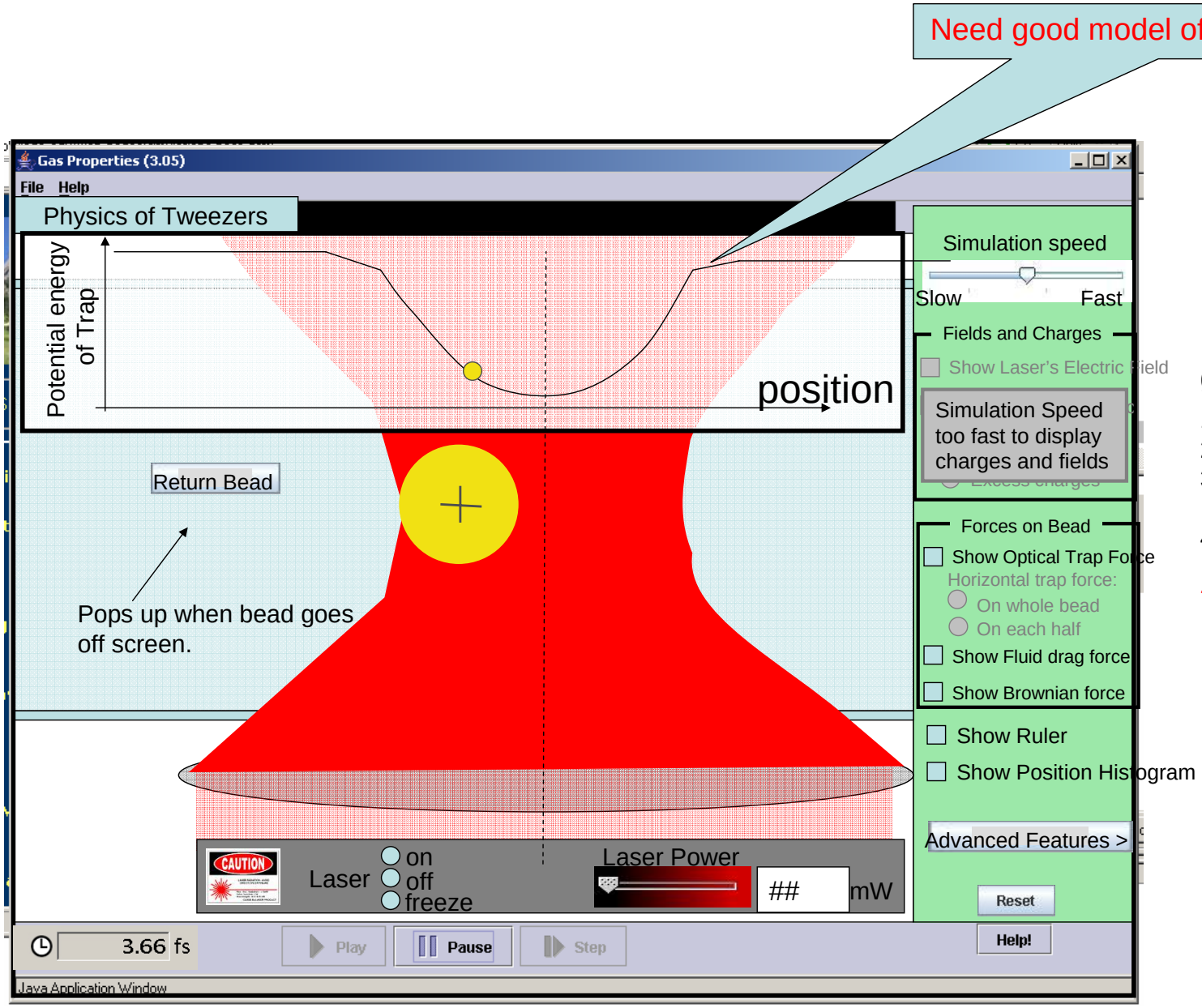
$F_{drag} = \gamma * velocity$

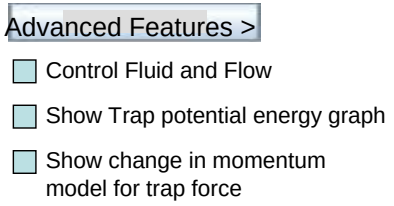
$\gamma = 6 \pi \eta r$

(η = viscosity … will be adjustable).
r=radius of bead (not adjustable)
v=velocity of fluid relative to bead.

Temperature, will adjust $F_{brownian}$.

Physics of Tweezers: Page 1



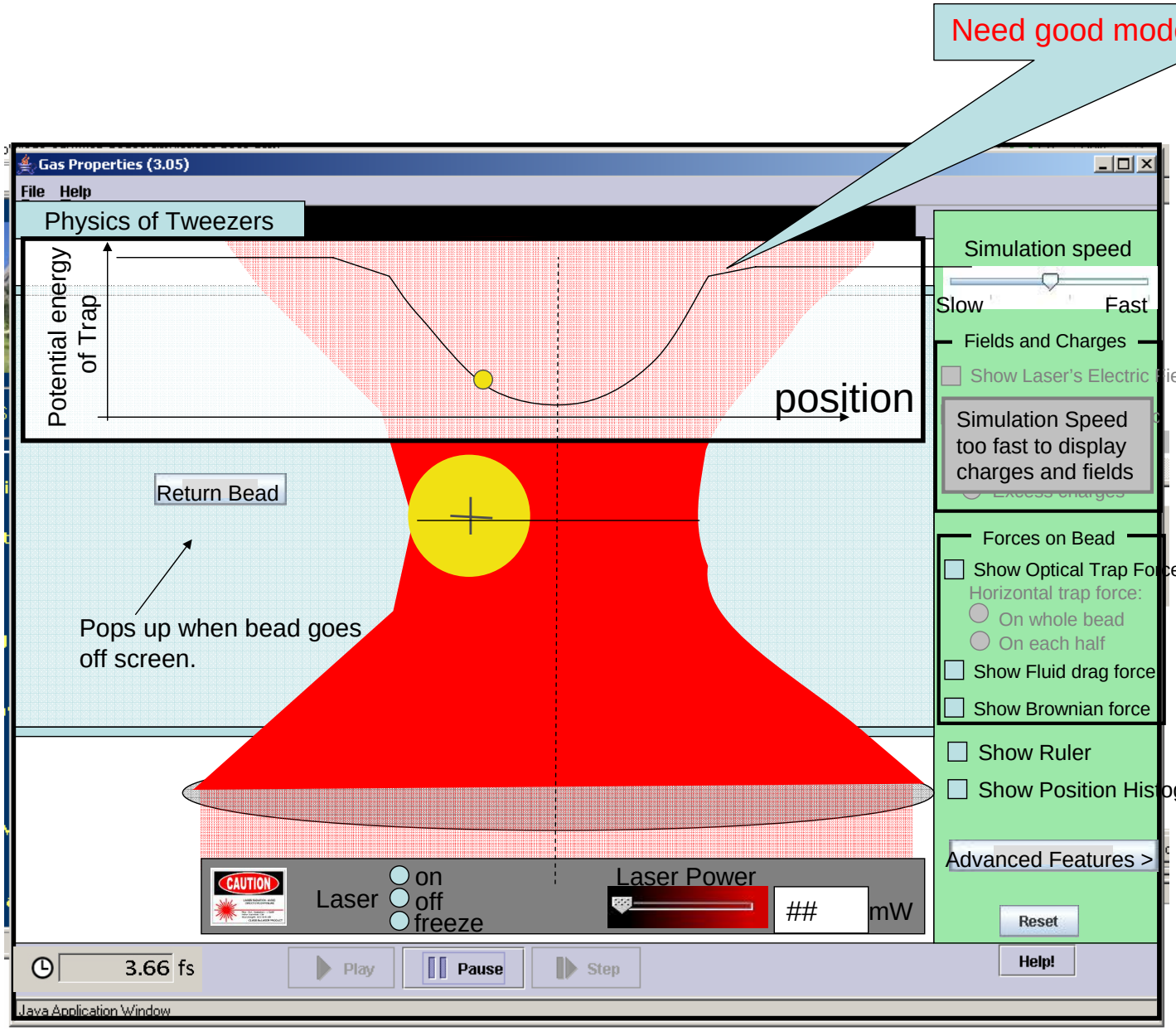


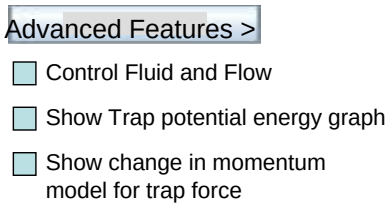
If Show potential energy graph checked:

1) Graph appears at top
2) Curve shows ½ kx_trap*x^2
3) Little image of bead where bead is in x.
4) NO Units on PE curve

??? What to do with PE curve if person grabs bead and moves it up and down? Should whole curve shift up and down by appropriate amount? (That is k_x_trap is independent of x, but PE does go UP as bead moves vertically.).

Physics of Tweezers



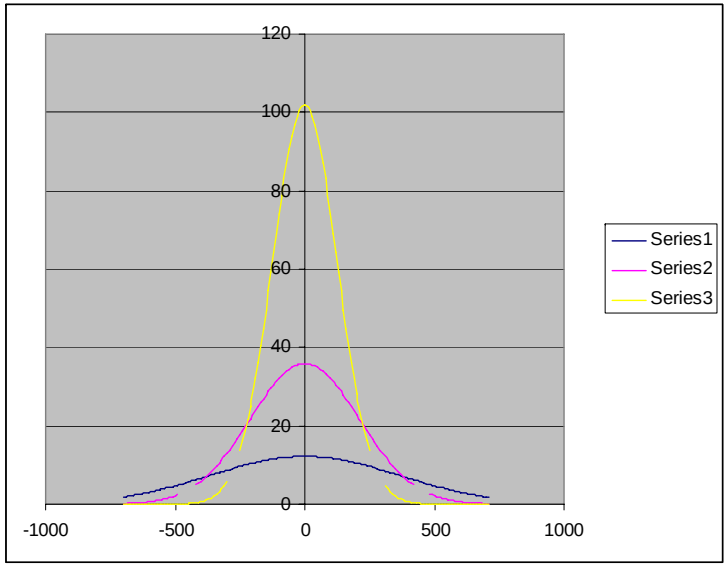


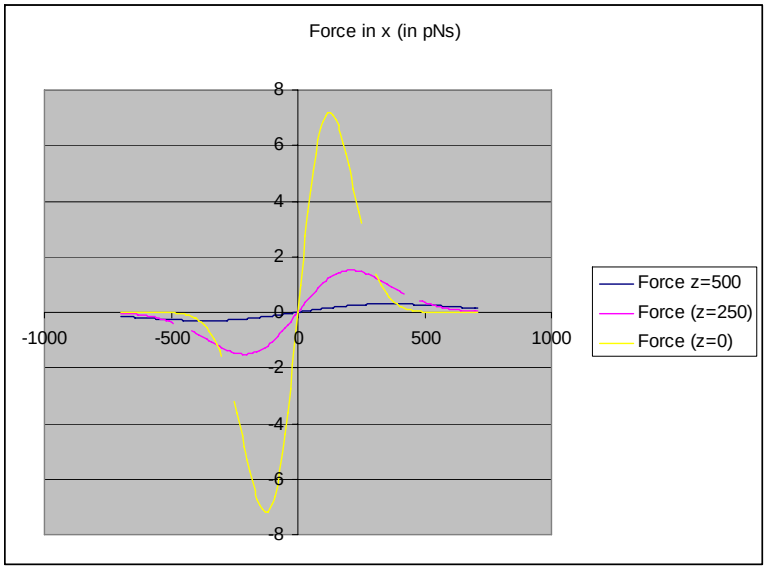
If Show change in momentum model for trap force …

DO NOT HAVE GOOD PICTURE FOR THIS YET! But in general will show two laser light rays bending through bead and how bead changes momentum of the light by changing the direction of the beam.

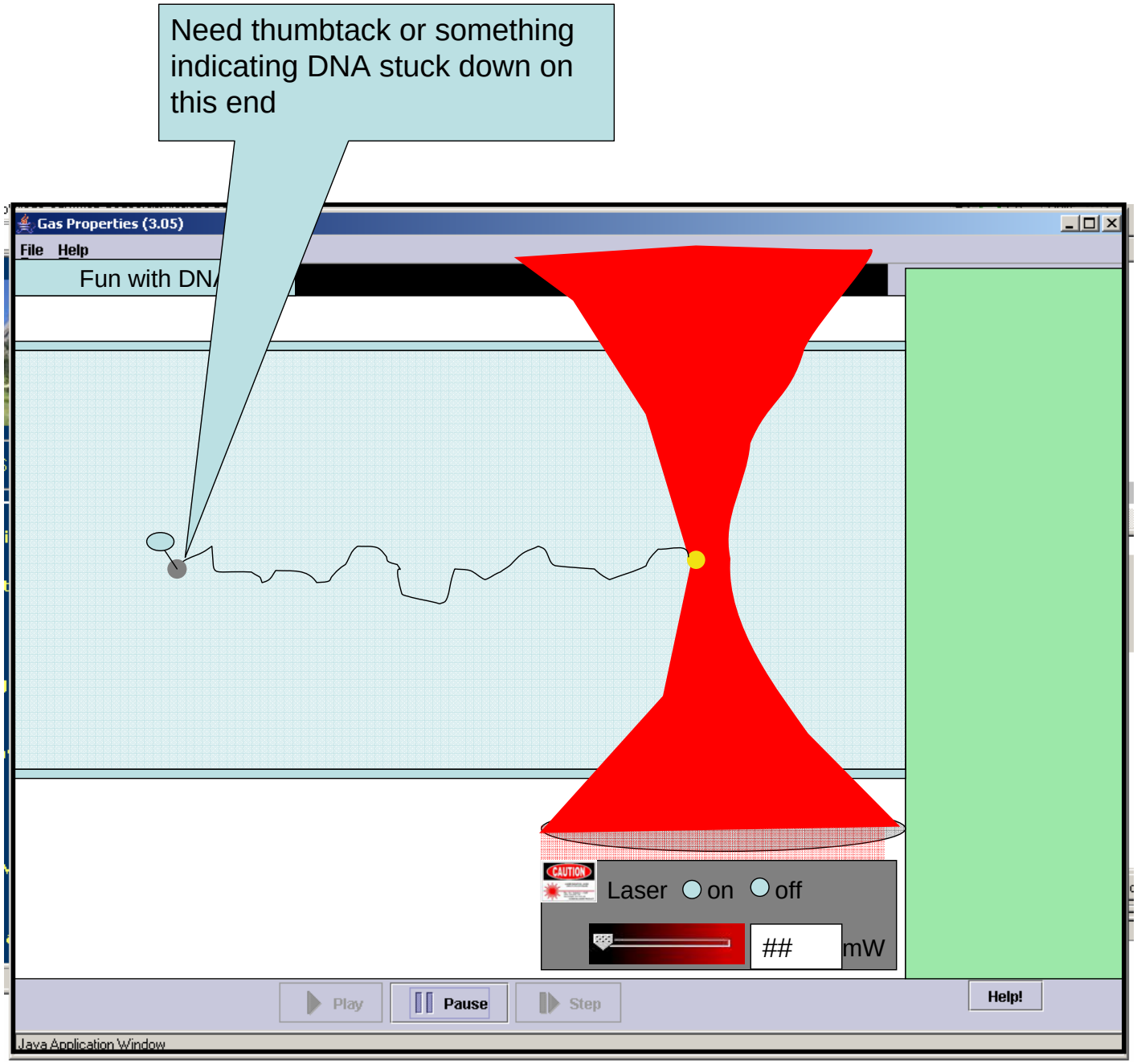
Models

- Laser beam profile …
  - Model with hyperbola
  - Model shaded intensity with a gaussian
    - http://www.rp-photonics.com/gaussian_beams.html





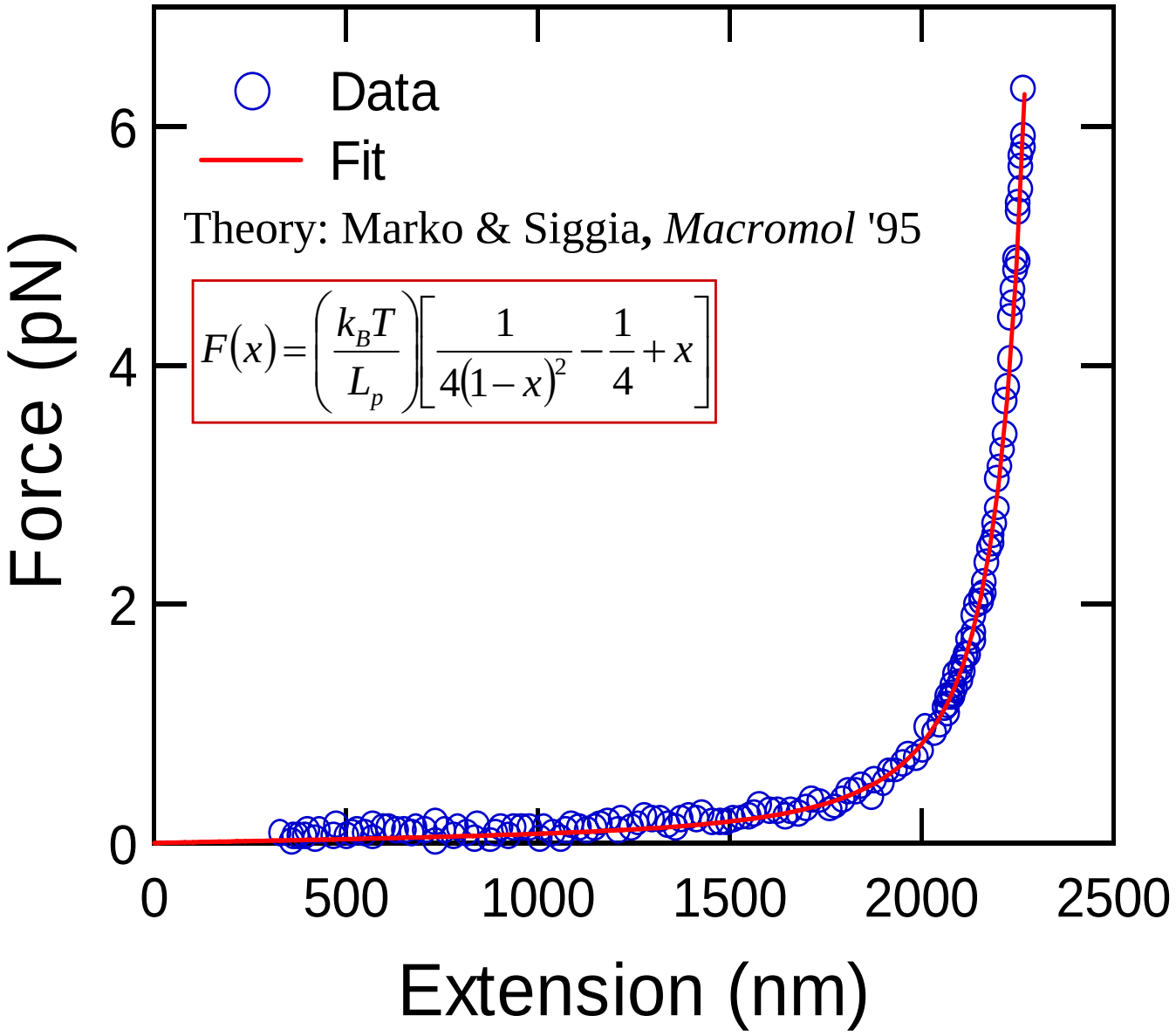
Fun with DNA: Panel Two



Basic idea:
-DNA with a bead on one end.
-Laser ON will trap bead.
-Can stretch DNA out … it pulls back against F_trap on bead.
-If bead pops out of trap, see DNA recoil due to random walk.
-Same deal with viscous conditions, so $F_{drag}=\gamma v$
-Can manipulate bead directly with mouse, or by moving trap laser horizontally.

Single DNA molecules are well characterized

- Enables rate determination



Explanation of graph

k_B= boltzman constant
T = temperature in K
L_p= Persistence length (measure of bending stiffness)
… how long it looks straight for (50 nm for double stranded dna)
… single stranded dna ~1nm

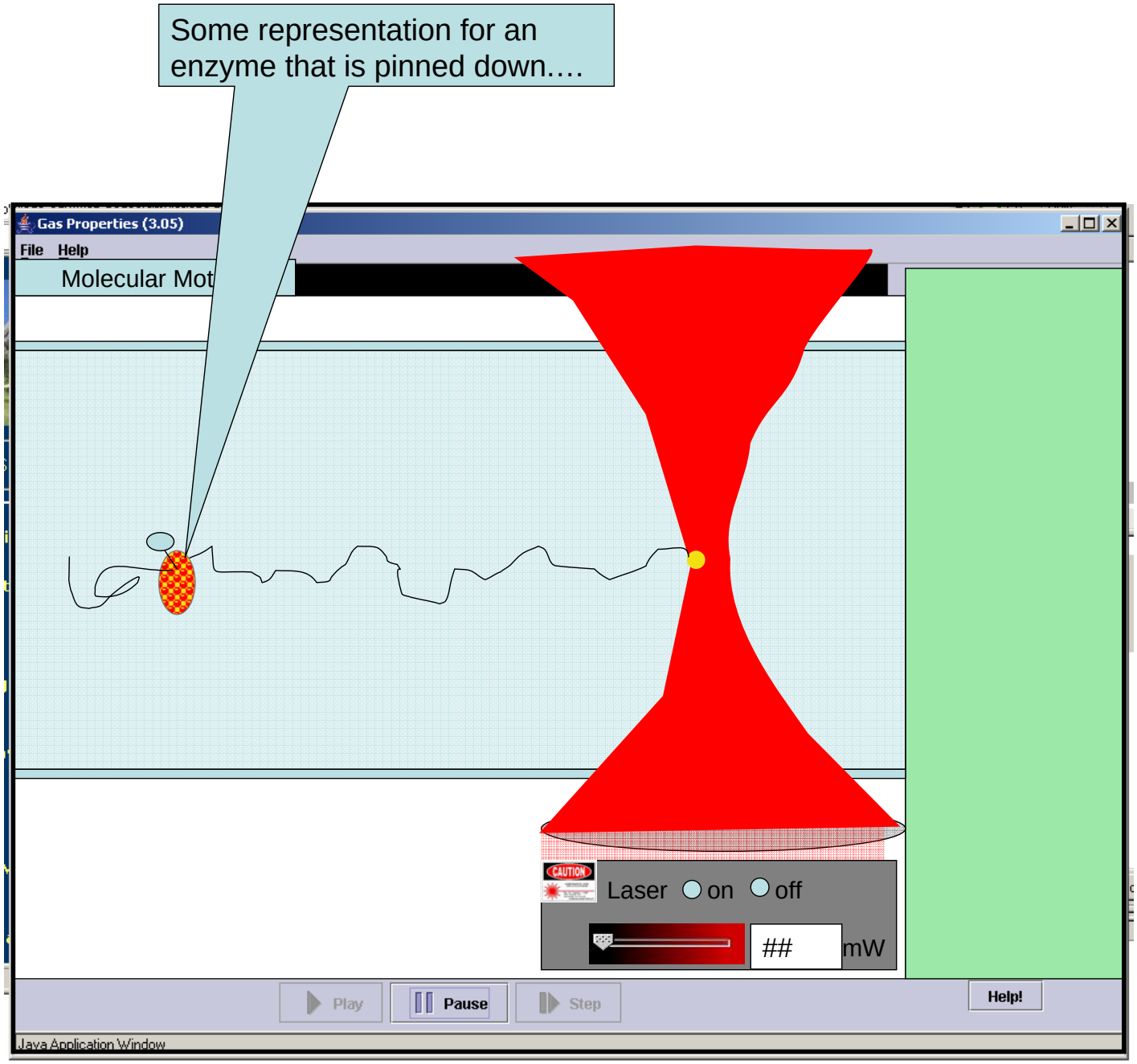
k_bT = 4.1 pN-nm for 293K
L_p= 50 nm

So k_bT=4.1 * T/293K (gives pN-nm)

x = extension/total length of dna
= end-to-end between beads / contour length of dna

Picture shown for
2413 nm dna strand

Molecular Motors: Panel Three



Basic idea:
-Similar to DNA panel, accept now:
-Enzyme pulls on DNA (walks it to left) if ATP (food) is present.
– Force that enzyme pulls with can be measured using laser trap.
-Can now set trap to “maintain constant force” so that it tracks RATE at which enzyme moves DNA along.

Molecular Motors: Panel Three

Basic idea:
-Similar to DNA panel, accept now:
-Enzyme pulls on DNA (walks it to left) if ATP (food) is present.
-Force that enzyme pulls with can be measured using laser trap.

Remove controls:
1) Fluid flow
New controls:
1) ATP level:
-Slider for ATP level;
-Start with trying arbitrary units between 0 and 10.
-Propose to have this in the fluid on the play area
-Tom: Is linear scale for this enough? Graphs show logarithmic scale, but I would prefer linear if the point is clear enough.

2) Botton (of alternative) labeled “hold trap force constant” which if pressed changes to “stop holding trap force constant”
-Possible locations: in “Forces on bead” section OR on laser control panel (since this is what you would control to hold trap force constant)
-Requirements: if user changes something about the laser (grabs and moves it or changes laser power OR grabs and moves bead then button will toggle so no longer holding trap force constant … this needs to be a big enough change that users notice! Button color changes or something.).

If this button is active AND enzyme is moving the DNA strand, then LASER itself would move appropriately in x to maintain the Fdna as being the same given change in contour length of the DNA molecule as the enzyme moves it.
Knowing how far in x to move the laser is determined by keeping the following ratio constant:
ratio = extension/total length of dna
= end-to-end between beads / contour length of dna
So you’ll have (end-to-end x distance)_new = (end-to-end x distance_old/contour length_old) *contour_length_new
And you’ll want to move the laser over by:
end-to-end x distance _old – end-to-end x distance_new.

Forces from the enzyme's perspective:
-Fdna determines current "load" on enzyme.
-So, Fdna and ATP will determine velocity with which it moves DNA along
From bead's perspective:
-Bead model is the same as panel 2 (Fdna and Ftrap) just that Fdna and Ftrap will increase as the DNA moves through the enzyme.

Model:
Velocity of DNA moving through enzyme as function of [ATP] and F_dna
Also will need to go to 10x current max sim speed on this panel.

Velocity = V_Max * [ATP]/([ATP]+KM)
KM is a function of the Force_dna (in pN)
V_max is a function of F_dna (in pN)
[ATP] goes from 0 to 10
V_max = d2*c1/(c2+c3*e^(F*c4))

KM = d1*(c6+c7*e^(F*c8))/(c2+c3*e^(F*c4))

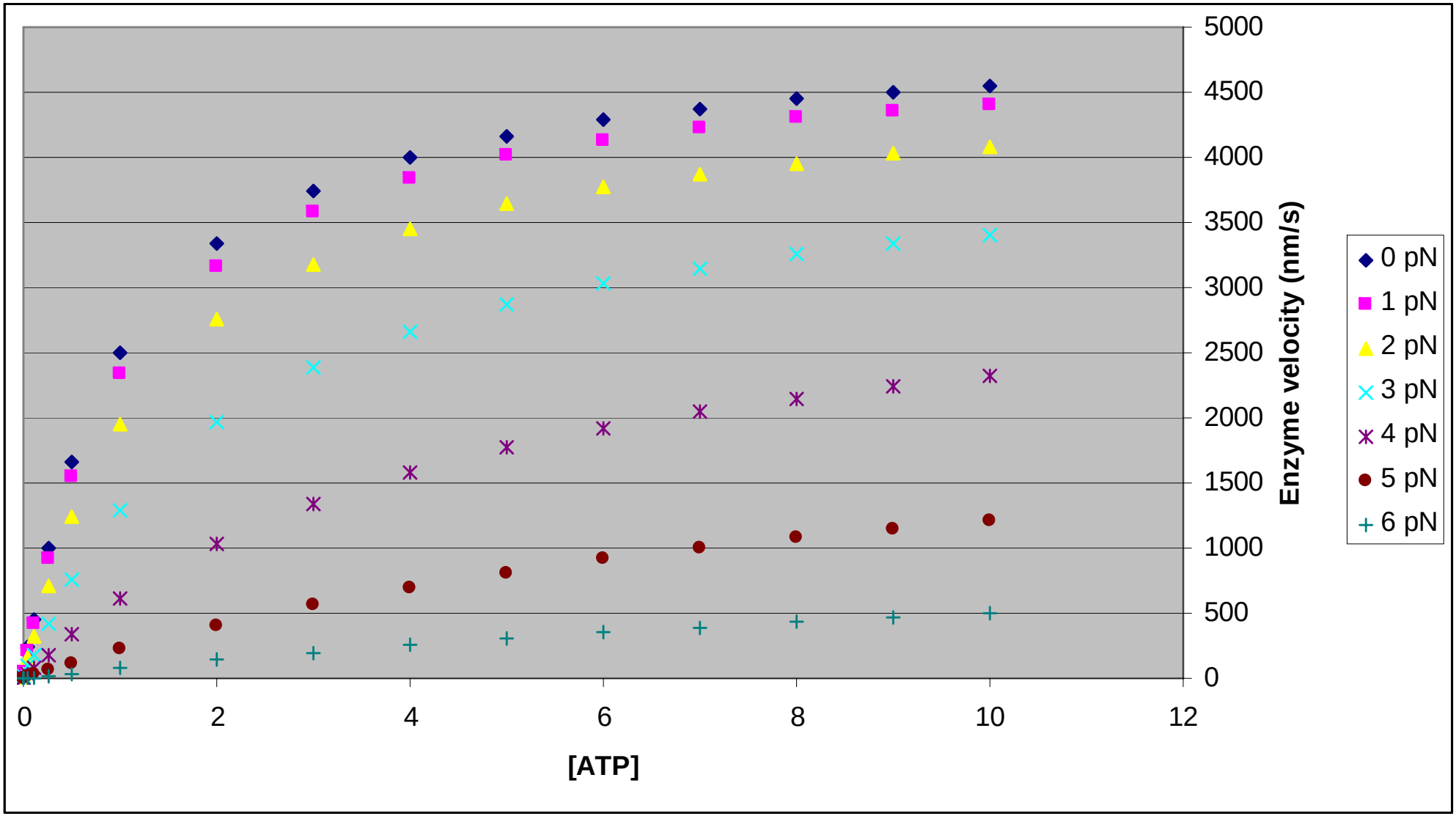
d2 = 5000 nm/s (make this and others easily changeable)

d1	2.281
c5	2.1
c6	2
c7	0.1
c8	1.2
c1	4.79
c2	4.7
c3	0.09
c4	0.82

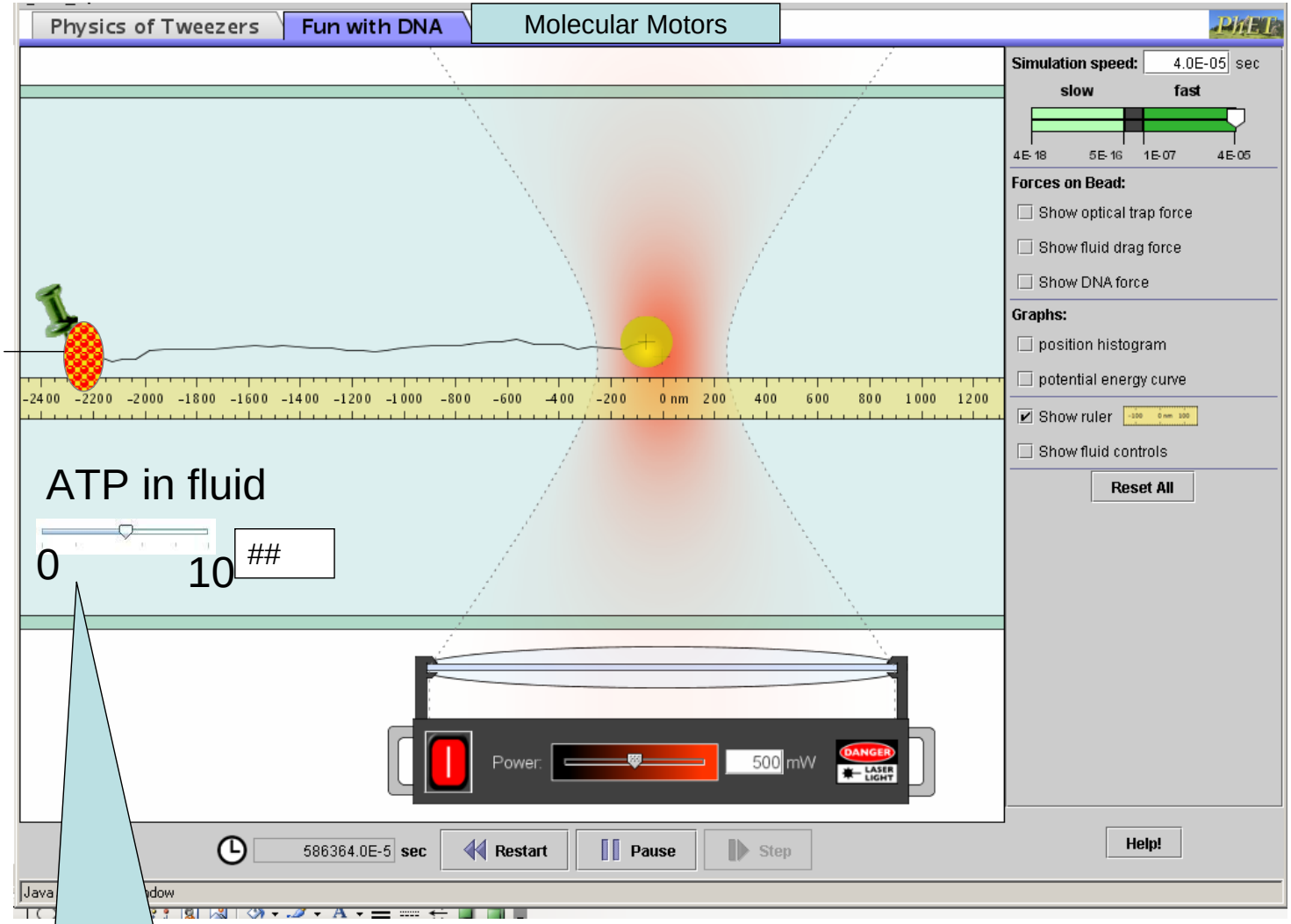
Where F is the dna force (either created using hand manipulation of bead or created using trap itself)
All of these parameters should be set up to make easy changes if needed … we are not modeling an exact enzyme here, just trying to get the general dependencies correct.

Velocity – decreases as load (trap force) increases
And velocity increases as ATP concentration increases.

ISSUE for TOM: we are not modeling the "stall" force (where the enzyme will just stop
Stall force should depend on ATP concentration


5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Enzyme velocity (nm/s)
0
2
4
6
8
10
12
[ATP]
0 pN
1 pN
2 pN
3 pN
4 pN
5 pN
6 pN

Molecular Motors: Panel Three



Control ATP conc in fluid … arbitrary units (may possibly want real units in end?)

Other issues Tom brought up:
Biochemical step vs mechanical step as rate limiting force
If biochemical is rate limiting, increase in force will not immediately change rate.