Surface effects on hydrodynamic evolution

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ICPAQGP, 2023

Surface effects

Heavy ion collision with a first order equation of state -

- deconfined phase inside and confined phase outside
- temperature profile from the central maximum to zero outside along a phase boundary.
- at phase boundary order parameter will rapidly vary from deconfinement to confinement value
- a finite gradient energy of the order parameter field -> surface tension
- radial expansion -> expands phase boundary -> should feel resistance
- constrained radial flow for a system with a phase boundary

Addressing the surface effects in hydrodynamics

Fluid with a surface represented by the gradient energy of the order parameter field -

- hydrodynamics studies flow -> does not include the effect of a surface

- effective field theory with an appropriate order parameter can study evolution of surfaces -> does not study flow

- couple hydrodynamics and effective field theory

Coupling the order parameter field and the fluid

- Two systems - fluid and order parameter field - interacting with each other
- Evolution governed by the conservation of the energy - momentum tensor of the combined system with and equation of state for the fluid and an equation of motion for the order parameter field
- Assumption: the fluid is quarkless → use Polyakov loop effective field theory for the order parameter as well as the equation of state of the fluid.
- Assumption: no fluctuations in the order parameter field → imaginary component of the field is not excited during the evolution

Coupling the order parameter field and the fluid

$$\partial_\mu T^{\mu\nu} = 0$$

$$T^{\mu\nu}_{fluid} = (\epsilon + p) u^\mu u^\nu + p\eta^{\mu\nu}$$

$$T^{\mu\nu} = T^{\mu\nu}_{fluid} + T^{\mu\nu}_\phi$$

$$L(\phi, T) = \alpha T^2 \partial_\mu \phi \partial^\mu \phi - V(\phi, T)$$

$$T^{\mu\nu}_\phi = 2\alpha T^2 \partial^\mu \phi \partial^\nu \phi + \eta^{\mu\nu}(\alpha T^2 \partial_\beta \phi \partial^\beta \phi - V(\phi, T))$$

Assumption: T is constant between *t* and *dt*

$$\frac{\partial^2 \phi}{\partial t^2} - \nabla^2 \phi = -\frac{1}{\alpha T^2} \frac{\partial V(\phi, T)}{\partial \phi}$$

Eos of the fluid is calculated using this effective potential

$$V(\phi, T) = b_4 T^4 \left[-\frac{b_2(T)}{2} \phi^2 - \frac{b_3}{3} \phi^3 + \frac{1}{4} \phi^4 \right].$$

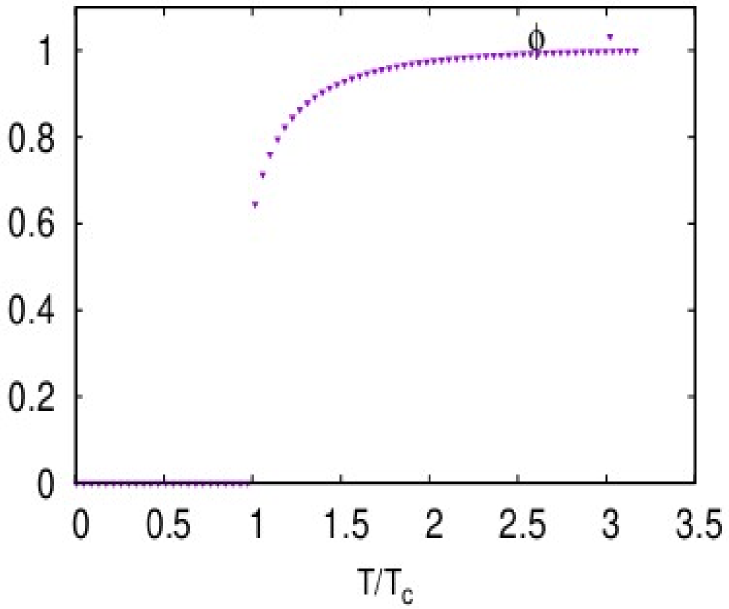
$$b_2(T) = (1 - 1.11\ T_c/T)\,(1 + 0.265\ T_c/T)^2\,(1 + 0.3\ T_c/T)^3 - 0.487$$

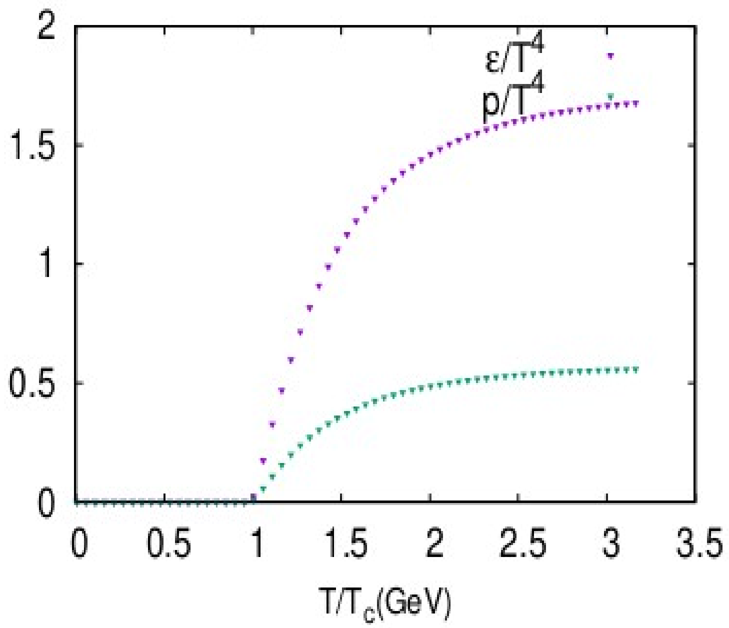
Coupling the order parameter field and the fluid

- Mechanism of feed back between the order parameter field and the fluid – temperature of the fluid.
- Polyakov effective potential is a function of temperature -> field evolution will depend on the local temperature.
- Local temperature is a function of the energy density and temperature of the fluid.

- In order to avoid double counting of the pressure, we do not consider the potential in the energy momentum tensor of the field. The surface is only represented by the gradient energy of the order parameter field.

Equation of state



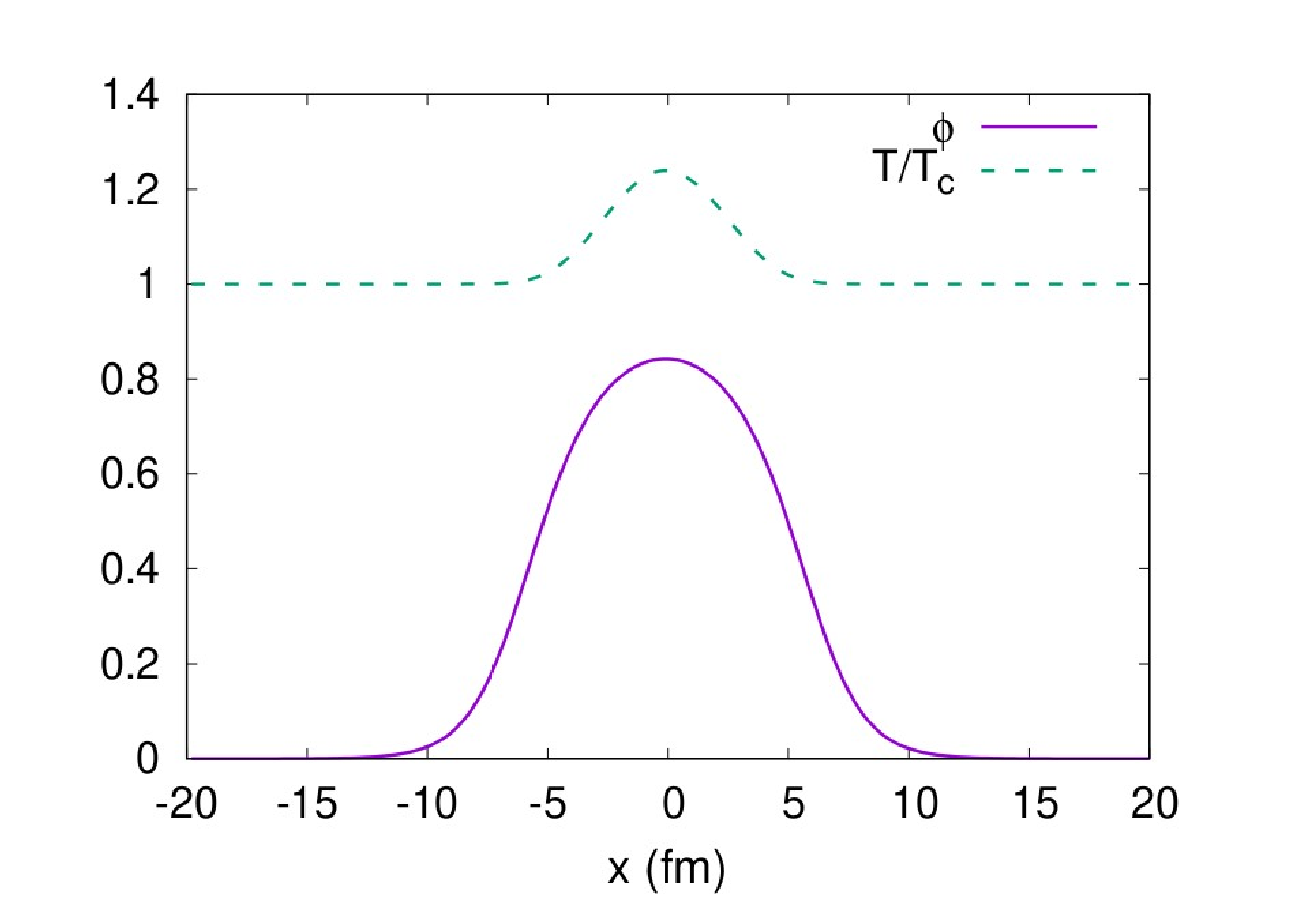


Assumption: Outside the fluid is confined phase at $T = T_c$

More assumptions

- No Bjorken flow
- Azimuthal symmetry
- Initial energy density profile → Gaussian which tends to the corresponding value at transition temperature at large r

Initial profile



Numerical steps

- Given the initial temperature profile, calculate the order parameter field.
- Calculate the corresponding energy momentum tensor and evolve

$$\partial_\mu T^{\mu\nu}_{fluid} = -\partial_\mu T^{\mu\nu}_{\phi}$$

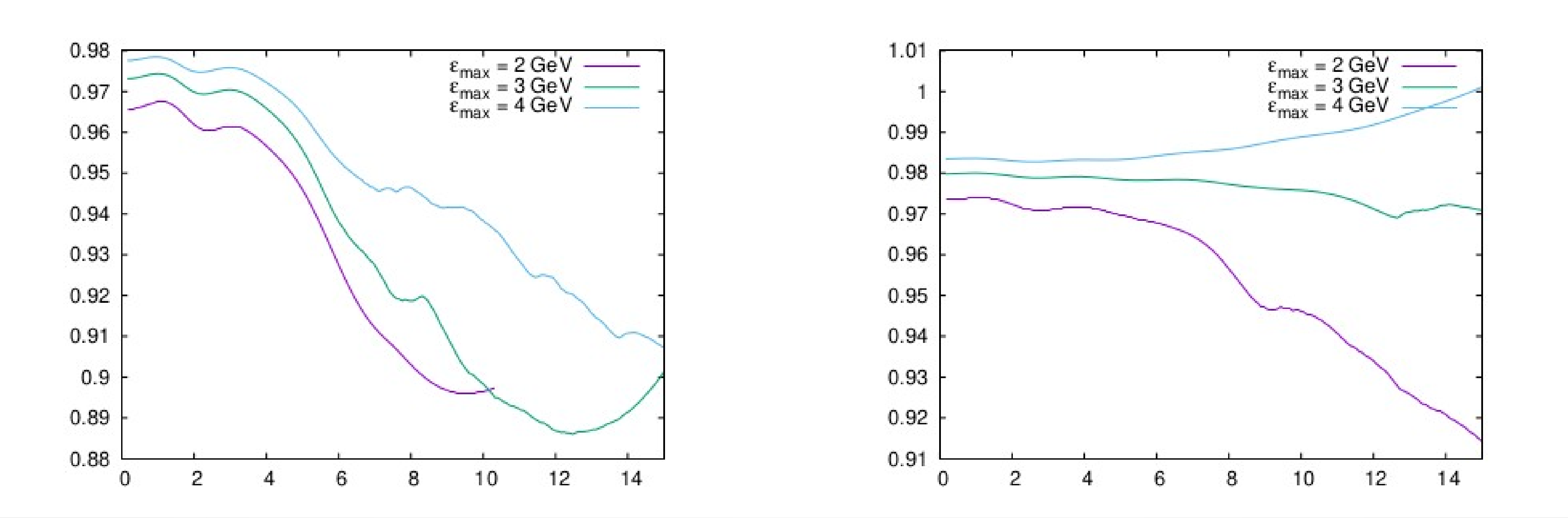
- Energy density, pressure, velocity profile and temperature are calculated for the fluid
- The Polyakov loop profile is calculated by evolving the corresponding equation of motion.

Results

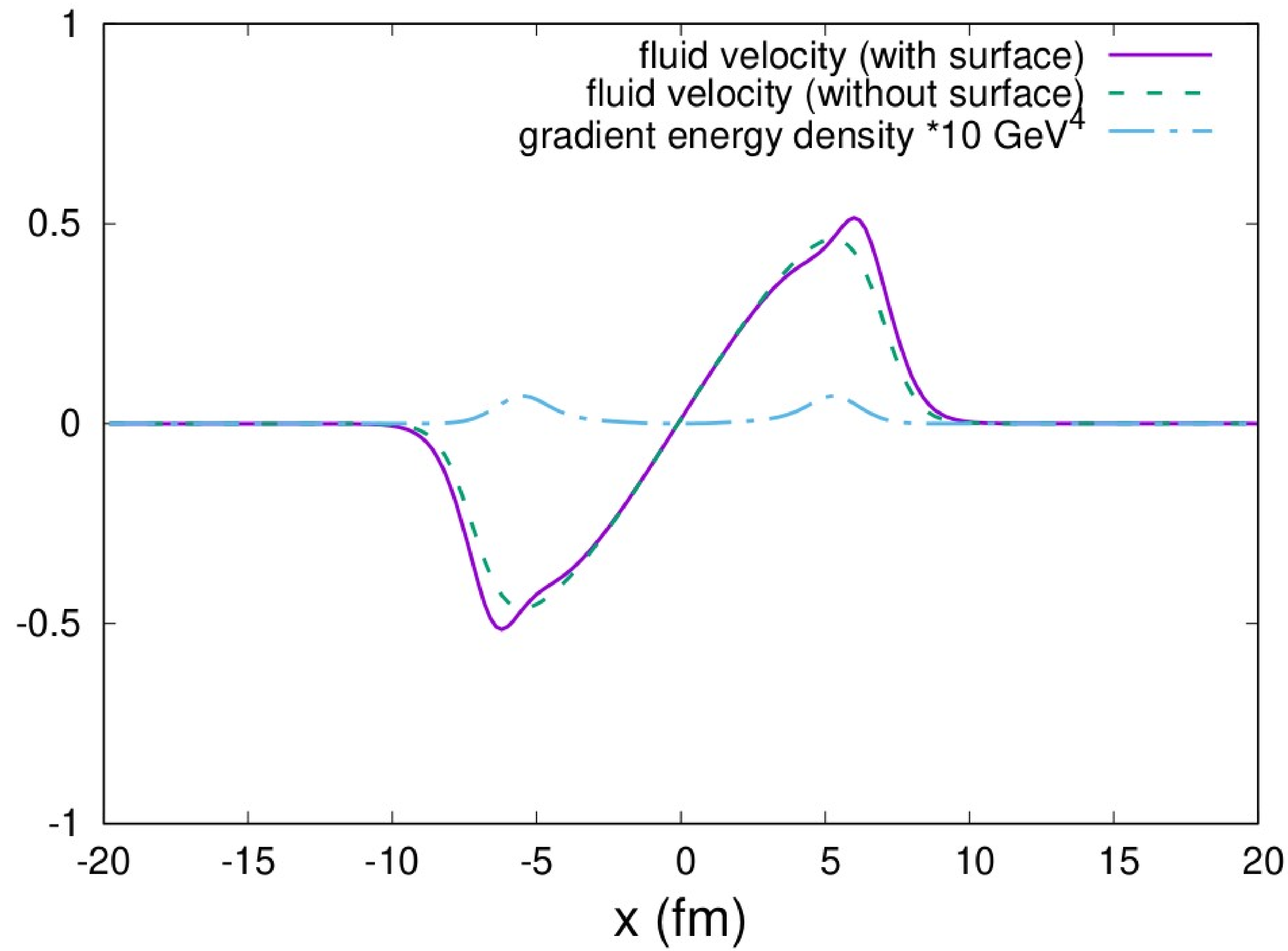
Central collision

$$\langle v_r \rangle = \frac{\langle \gamma \sqrt{v_x^2 + v_y^2} \rangle}{\langle \gamma \rangle}$$

Evolution of the ratio of radial flow with and without phase boundary effect with different radii (2 and 3 fm respectively) of the initial Gaussian.

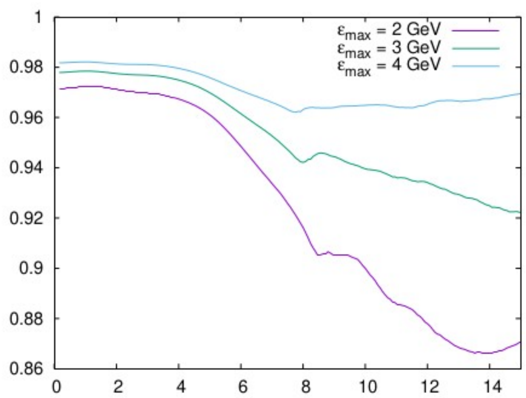


Velocity profile

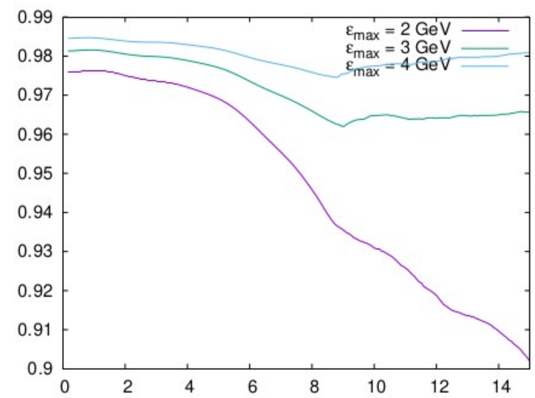


Results: non-central collisions

Evolution of ratio of momentum anisotropy with and without phase boundary. Figures (a), (b) and (c) have major axes 3 fm, 4 fm and 5 fm respectively for the ellipsoid when the minor axis is 2 fm for all.

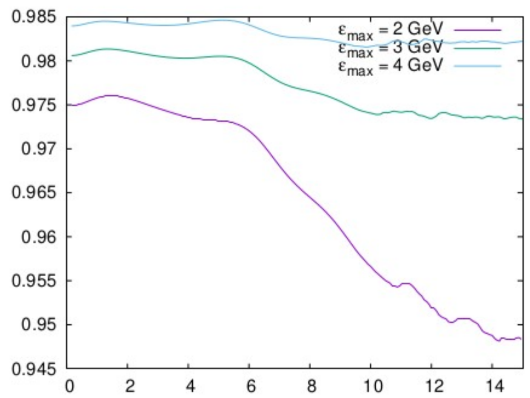


(a)



(b)

$$\epsilon_p = \frac{\langle T^{xx} - T^{yy} \rangle}{\langle T^{xx} + T^{yy} \rangle}$$



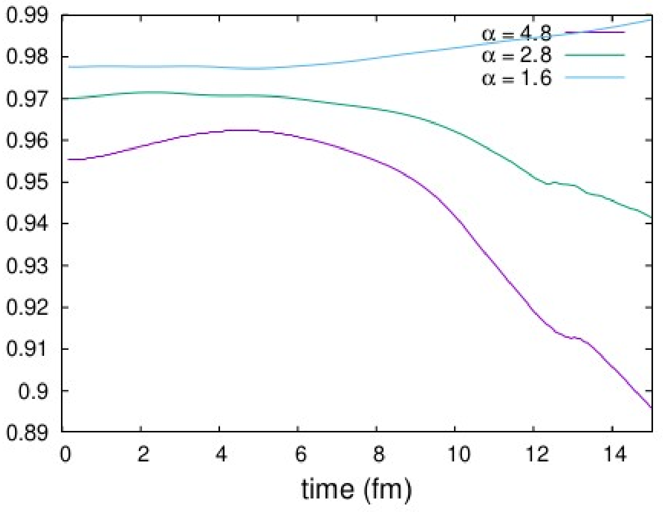
(c)

Surface tension effect

The surface tension of the phase boundary can be obtained from the Euclidean action corresponding to the order parameter Lagrangian

$$\sigma = 2\sqrt{\alpha}T \int_0^{\phi_d} d\phi \sqrt{V(\phi, T)}$$

ϕ_d is the Polyakov loop expectation value in the deconfined phase



Ratio of radial flow with and without phase boundary effect. The initial energy density is 2 GeV/fm^3 and the Gaussian width is 4 fm.

Summary

Heavy ion collision with a first order equation of state -

- deconfined phase inside and confined phase outside
- at phase boundary order parameter will rapidly vary from deconfinement to confinement value
- a finite gradient energy of the order parameter field -> surface tension
- expansion -> expands phase boundary -> feels resistance
- Radial flow and momentum anisotropy will be smaller due to this resistance
- The suppression decreases with increase in size and increase in initial energy density
- The suppression increases with an increase in surface tension

Thank you