MUTAC Review
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Muon Collaboration

Target Simulations

Roman Samulyak

Center for Data Intensive Computing
Brookhaven National Laboratory
U.S. Department of Energy

rosamu@bnl.gov

Talk outline

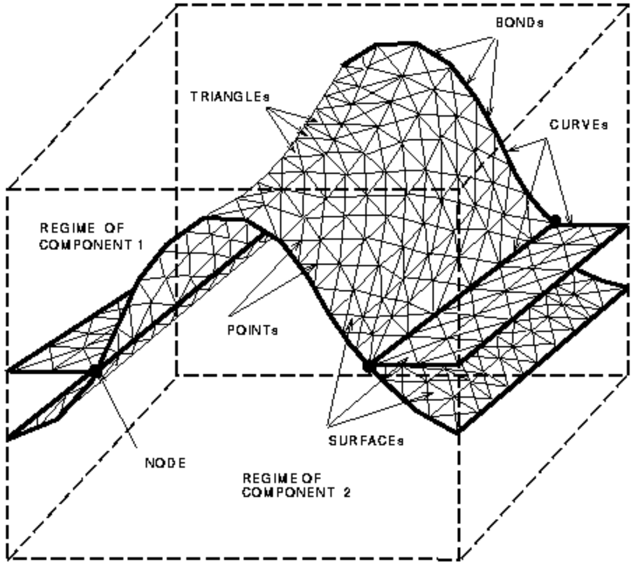
- Numerical simulation of the mercury jet interaction with a proton pulse; evolution of the Richtmyer-Meshkov type instability
- MHD simulations: stabilizing effect of the magnetic field
- EOS models for phase transition/cavitation
- Recent improvements of software capabilities
- Other current studies and research plans

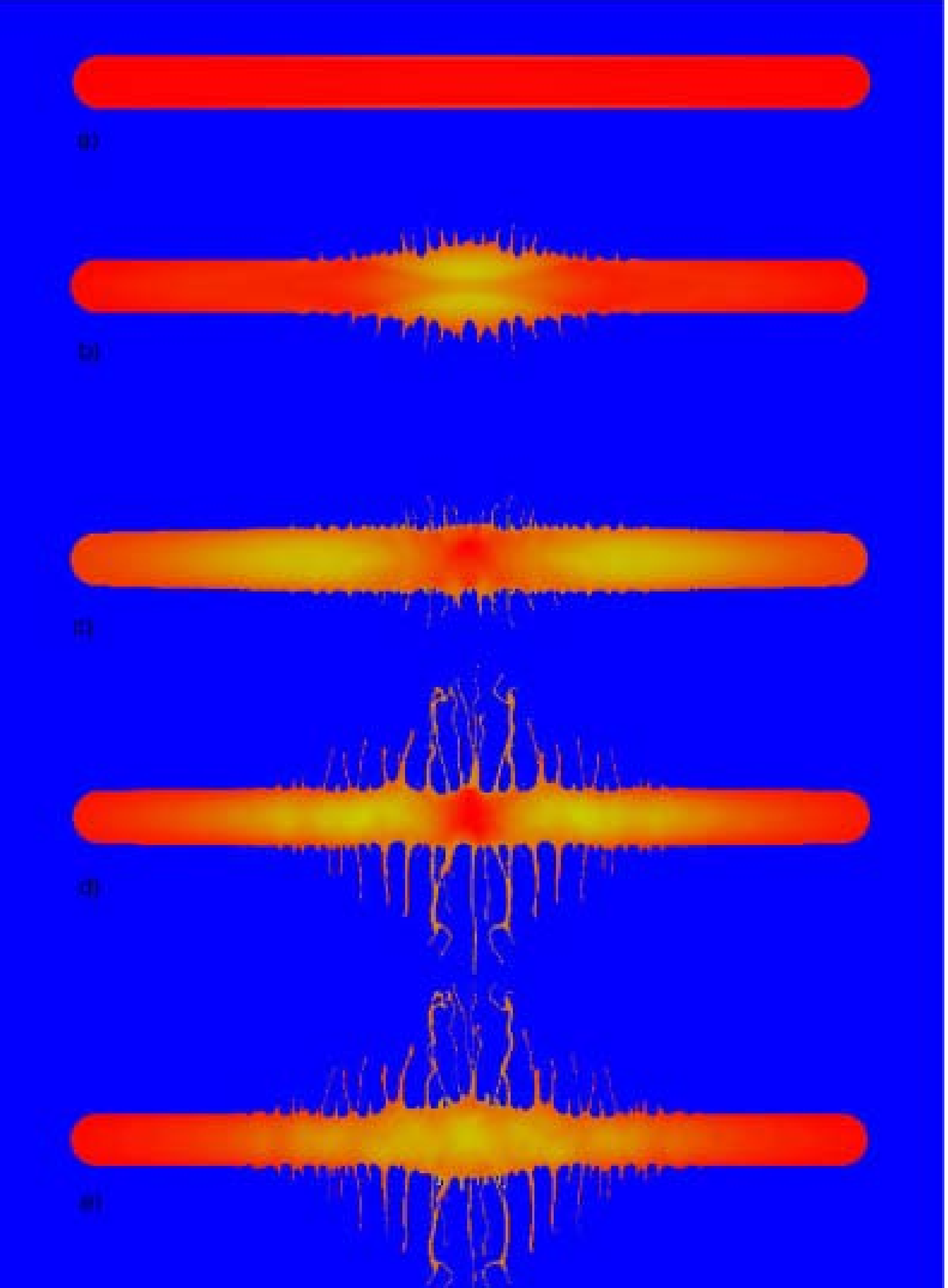
Numerical tool: the ***FronTier Code***

- FronTier is a parallel 3D magnetohydrodynamics code with free interface support.
- The FronTier code is based on front tracking, a conservative method with no numerical diffusion across interfaces.

FronTier features include

- Dynamic finite element grid generation with interface constrains for solving elliptic (MHD) problems.
- High resolution (shock capturing) interior hyperbolic solvers.
- Realistic equation of state models for liquids, including mercury. Phase transition support.





Mercury jet evolution due to the proton pulse energy deposition

Emax = 100 J/g, B = 0

a) Initial shape of the jet, t = 0;
b) Instabilities due to the second reflected shock wave, t = 80
c) Interaction of the third reflected shock wave with the surface, t = 90
d) Instabilities due to the third reflected shock wave, t = 118;
e) Interaction of the fourth reflected shock wave with the surface, t = 134.

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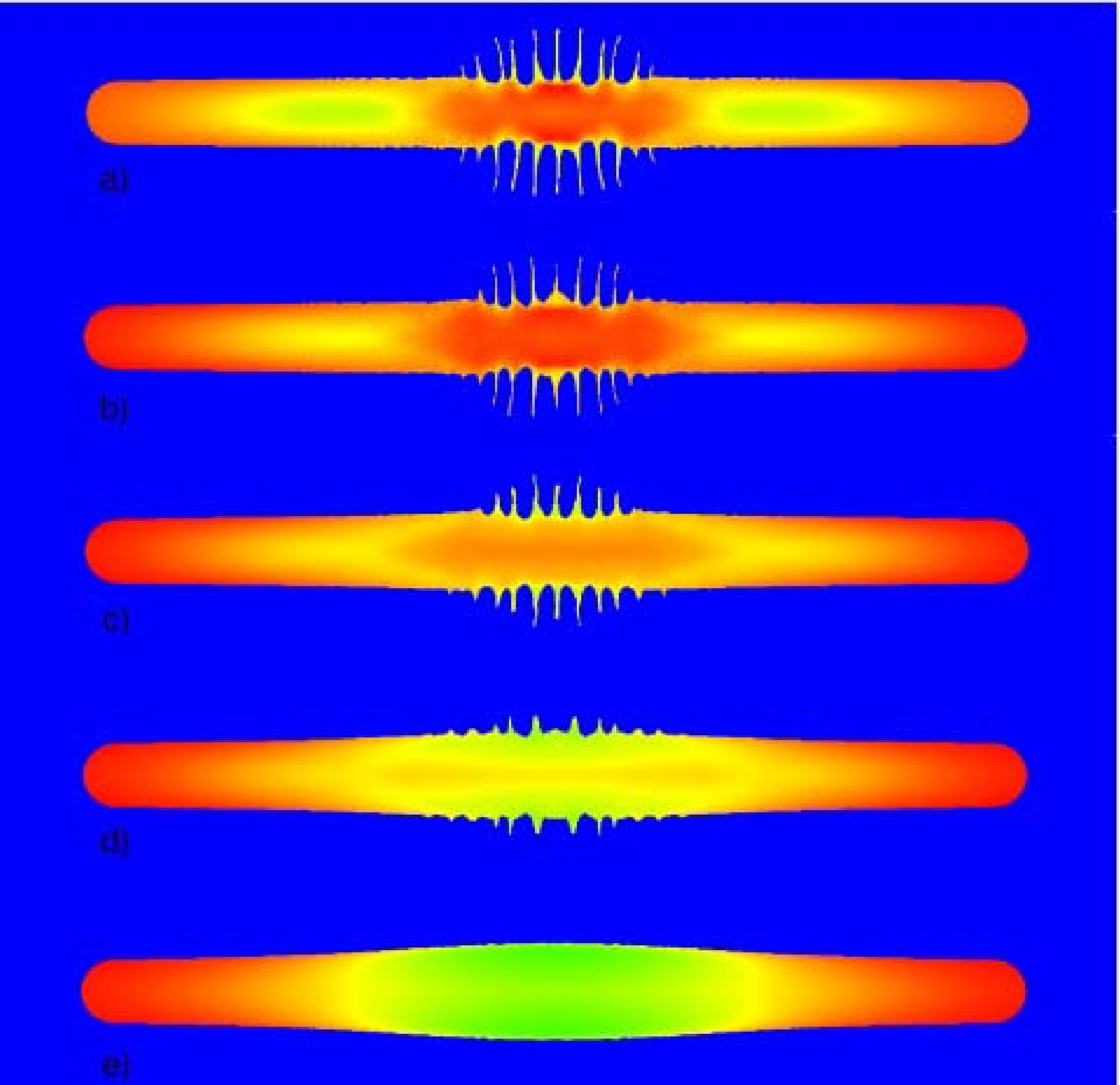
MHD simulations: stabilizing effect of the magnetic field.



a) B = 0
b) B = 2T
c) B = 4T
d) B = 6T
e) B = 10T.

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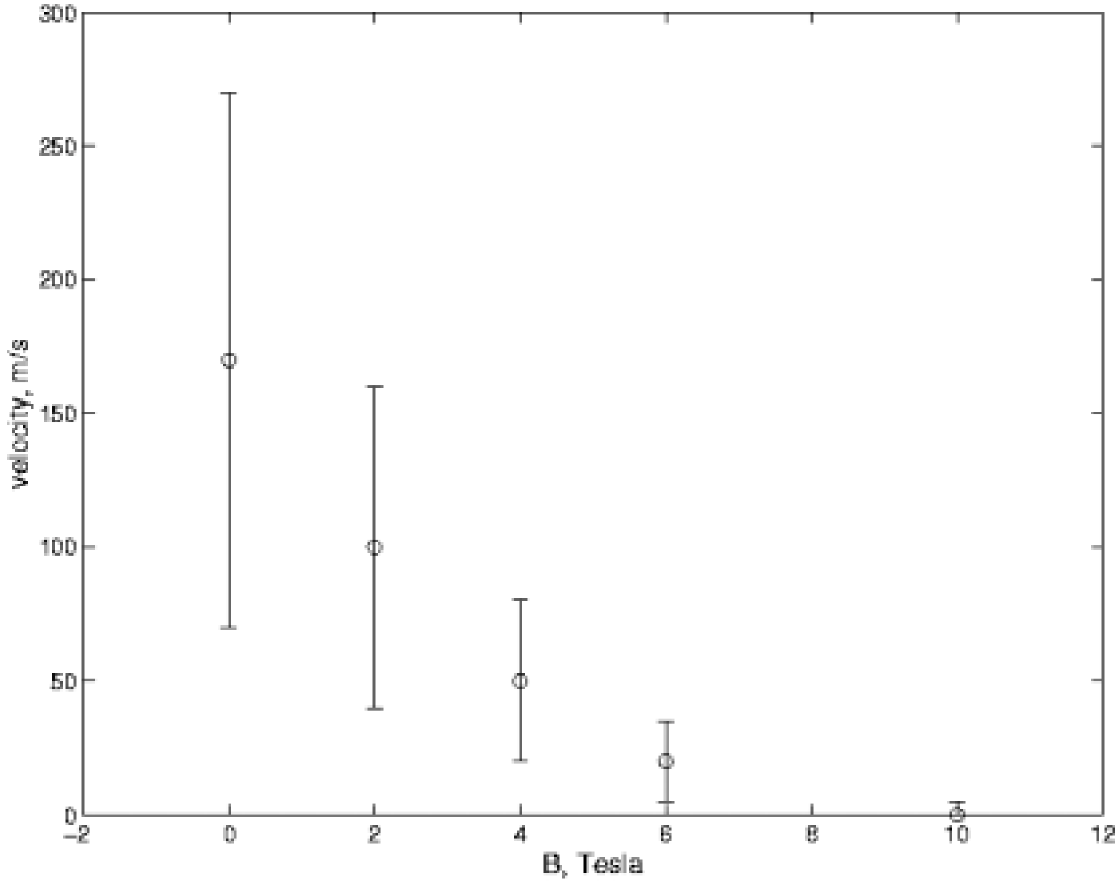
Velocity of jet surface instabilities in the magnetic field



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Equation of state models for liquids implemented in FronTier

- Stiffened polytropic EOS for one phase fluid (supports the fluid tension/negative pressures)

- SESAEME tabular EOS for mercury

- Analytical model for an isentropic EOS with the phase transition/cavitation support

Analytical model: Isentropic EOS with phase transitions

- A homogeneous EOS model

- Gas (vapor) phase is described by the polytropic EOS reduced to an isentrope.

$$P = (\gamma_0 - 1)E\rho,$$

$$T = \frac{P}{R\rho},$$

$$S = (\log P - \gamma_0 \log \rho)\frac{R}{\gamma_0 - 1}.$$

$$S = const \Rightarrow$$

$$P = \eta\rho^{\gamma}, \quad E = \frac{\eta}{\gamma - 1}\rho^{\gamma-1}, \quad T = \frac{\eta}{R}\rho^{\gamma-1},$$

$$\text{where} \quad \eta = \exp\left(\frac{S(\gamma-1)}{R}\right)$$

Isentropic EOS: the mixed phase

- The mixed phase (vapor/liquid coexistence) is described as follows:

$$P(\rho) = P_l^{sat} + P_{vl}\,\mathrm{log}\left[\frac{\rho_v a_v^2\left(\rho_l + \alpha\left(\rho_v - \rho_l\right)\right)}{\rho_l\left(\rho_v a_v^2 - \alpha\left(\rho_v a_v^2 - \rho_l a_l^2\right)\right)}\right],$$

$$E(\rho) = \int_{\rho_v^{sat}}^{\rho} \frac{P}{\rho^2}\, d\xi,$$

where

$$P_{vl} = \frac{\rho_v a_v^2 \rho_l a_l^2\left(\rho_v - \rho_l\right)}{\rho_v^2 a_v^2 - \rho_l^2 a_l^2},$$

and α is the void fraction: $\alpha = \dfrac{\rho - \rho_l}{\rho_v - \rho_l}.$

Isentropic EOS: the liquid phase

- The liquid phase is described by the stiffened polytropic EOS:

$$P = (\gamma - 1)\rho(E + E_\infty) - \gamma P_\infty,$$

$$T = \frac{P + P_\infty}{R\rho},$$

$$S = \left(\log(P + P_\infty) - \gamma_0 \log\rho\right)\frac{R}{\gamma_0 - 1}.$$

$$S = const \Rightarrow$$

$$P = \eta\rho^\gamma - P_\infty,$$

$$E = \frac{\eta}{\gamma - 1}\rho^{\gamma-1} + \frac{P_\infty}{\rho} - E_\infty, \quad T = \frac{\eta}{R}\rho^{\gamma-1},$$

$$\text{where} \quad \eta = \exp\left(\frac{S(\gamma - 1)}{R}\right)$$

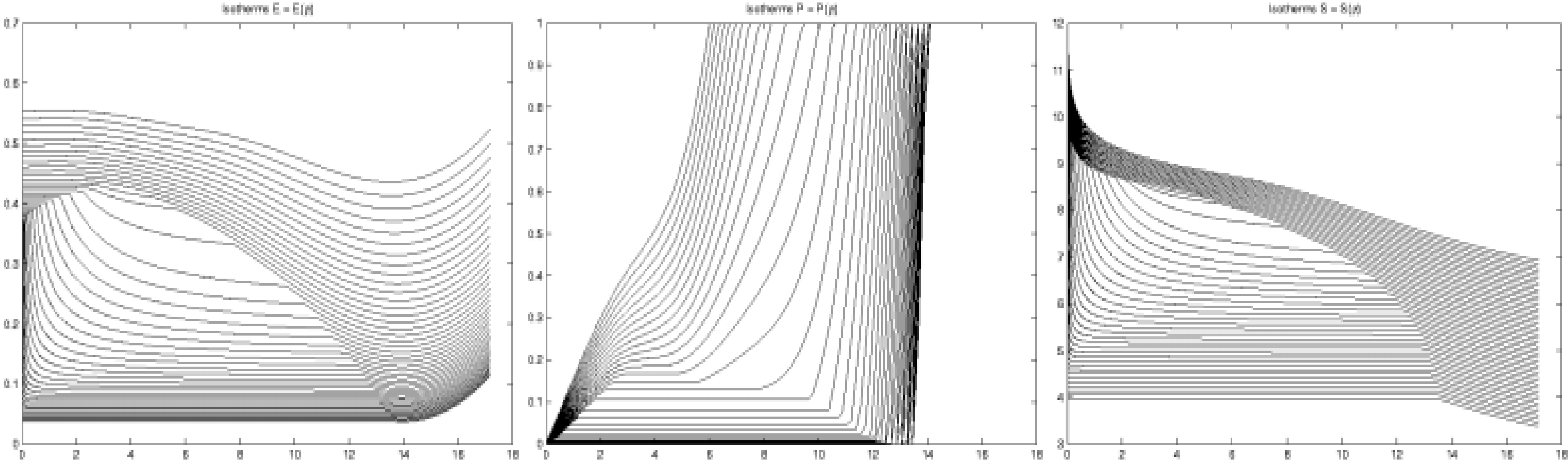
Improvement of EOS models with phase transition/cavitation support and software development

- Ability to reproduce properties of real mercury along an isentrope. Ability to model mercury with impurities by modifying EOS parameters

- Enabling the capability of the EOS model to work with the MUSCL solver (Monotonic Upstream Centered Difference Scheme for Conservation Laws) and different Riemann solvers (important if strong shocks and rarefaction waves are present in the system).

- Preconditioned iterative solver of a wire basket problem for solving in parallel the elliptic (MHD) problem.

Thermodynamic properties of mercury (ANEOS data)



Isotherms of the specific internal energy, pressure and entropy as functions of density are shown in a large density – temperature – pressure domain which includes liquid, vapor and mixed phases.

Applications of two phase isentropic EOS

- Local studies of the cavitation in strong rarefaction waves. The main aim is to reproduce quantitatively results of CERN targetry experiments and the evolution of the mercury jet.

- Numerical simulation of wave dynamics in the SNS target container.

- Current MHD studies: Numerical simulation of a mercury jet in a transverse magnetic field. Benchmark of our MHD code using experimental data (Sandia APEX related experiments with lithium jets and films, paper by S. Oshima, R. Yamane et al.)

Research plans

- EOS related research:

- Further work on the analytic isentropic two phase EOS

- Develop an analytic eos model using nonequilibrium thermodynamics approach

- Studies of shock waves and the cavitation in mercury in the presence of a magnetic field

- New 2D and 3D simulations of target related problems: jets in magnetic fields, nozzle influence, CERN targetry experiments etc.