



Merging of jet-quenching with full event simulations

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- current status and open questions
- development of standardized interfaces:
 - the OSCAR2008H file format
 - common table format for hydro equation of state
- the PCM brick problem





Motivation

Jet-Medium Interactions

- Heavy-ion collisions at RHIC have produced a state of matter which behaves similar to an ideal fluid
- (3+1)D Relativistic Fluid Dynamics and hybrid macro+micro models are highly successful in describing the dynamics of bulk QCD matter
- A new generation of Parton Cascade Models is being developed for the same purpose (BAMPS...)
- Jet energy-loss calculations have reached a high level of technical sophistication (BDMPS, GLV, higher twist, AMY), yet they employ a variety of sometimes simple models for the evolution of the underlying deconfined medium...
- all conclusions to be drawn from jet energy-loss calculations are necessarily with respect to the nature of the medium assumed in the calculation
- need to treat medium and hard probes consistently and at same level of sophistication!
- same medium necessary for comparison of different energy-loss schemes and vice versa!



Current Status:

- Jet energy-loss and hydro

Hirano & Nara: Phys. Rev. **C66** (2002) 041901

Hirano & Nara: Phys. Rev. **C69** (2004) 034908

Renk, Ruppert, Nonaka & Bass: Phys. Rev. **C75** (2007) 031902

Majumder, Nonaka & Bass: Phys. Rev. **C76** (2007) 041902

Qin, Ruppert, Turbide, Gale, Nonaka & Bass: Phys. Rev. **C76** (2007) 064907

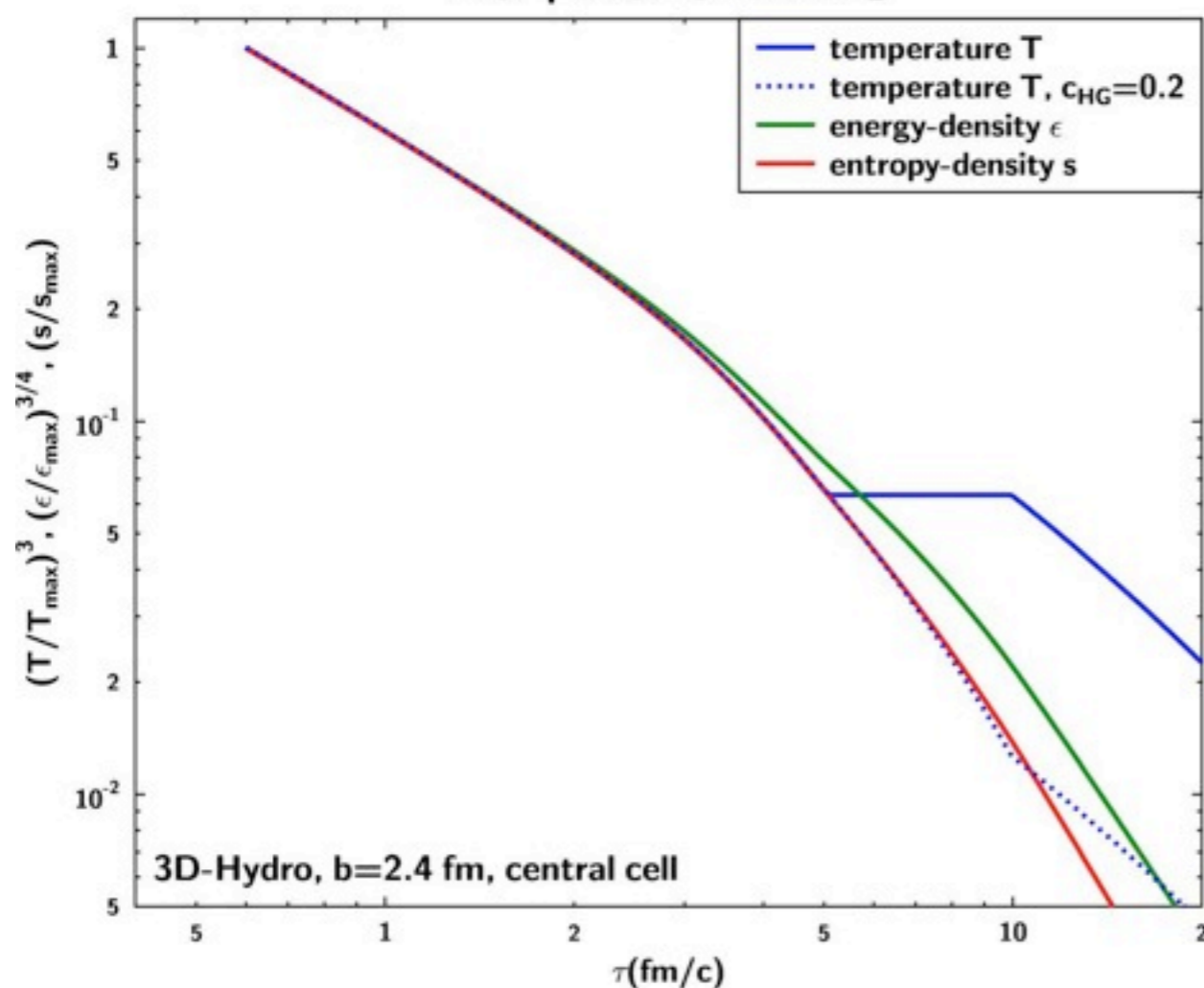
Bass, Gale, Majumder, Nonaka, Qin, Renk, Ruppert: Phys. Rev. **C79** (2009) 024901

Scaling with the Medium: T , ϵ or s ?

- how does the transport coefficient scale with the thermodynamic properties of the medium? Does the choice of T , ϵ or s matter? (a priori not known, but should be calculable)

- EoS for ideal QGP (ideal gas of ultrarelativistic bosons): $\epsilon = \frac{\pi^2}{30} g_{DOF} T^4$

Au+Au @ RHIC



- common choices for scaling:

$$\hat{q} \sim T^3 \quad \hat{q} \sim \epsilon^{3/4} \quad \hat{q} \sim s$$

- identical results only for **ideal QGP**

- for non-ideal EoS, value of q will be affected by choice of scaling variable, in particular if energy-loss persists into hadronic phase
- choice of $c_{HG}=0.2$ mimics scaling with entropy-density s

Quantitative Comparison:

- define local transport coefficient along trajectory ξ for all three approaches and compare initial maximum value q_0 :

$$\hat{q}(\xi) = \hat{q}_0 \cdot \Gamma(\xi) \quad \text{with } \Gamma = \left(\frac{T}{T_0} \right)^3, \left(\frac{\varepsilon}{\varepsilon_0} \right)^{3/4}, \left(\frac{s}{s_0} \right)$$

- for ASW, use Baier formula:

$$\hat{q}_0 = 2K \cdot \varepsilon_0^{\frac{3}{4}}$$

- For AMY use:

$$\hat{q}_0 = C \left(\frac{g^2}{4\pi} \right) T_0^3 \frac{8 \times 16\pi}{9}$$

q_0 [GeV ² /fm]	ASW	HT	AMY
T	10	2.3	4.1
ε	18.5	4.5	X
s		4.3	X

(all values quoted for a gluon jet)

- different medium scaling can affect q by a factor of 2
- a clear difference persists among the different approaches, even when utilizing identical medium evolution & scaling and initial conditions
- the “correct” medium scaling relation is a priori not known, should hopefully be calculable from 1st principles QCD



A Common Output Format for Hydrodynamic Models



Available Hydro Evolution Files

Hydrodynamic output from various (ideal and viscous) hydro codes - TECHQM

https://wiki.bnl.gov/TECHQM/index.php/Hydrodynamic_output_from_various_%28ideal_and_viscous%29_hydro_codes

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Hydrodynamic output from...

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Hydrodynamic output from various (ideal and viscous) hydro codes

On this page we collect links to output from various groups who have performed hydrodynamic simulations (ideal or viscous) for a few sample collision systems.

Note: At this point (06/24/2008) the posted output is not yet in standardized output format as described [here](#). Standardized output will become available later. Until then, please follow the instructions given by the authors on the individual pages.

Ideal Fluid Dynamics [\[edit\]](#)

- (3+1)-dimensional ideal fluid dynamics (Hirano et al.)
- (3+1)-dimensional ideal fluid dynamics (Nonaka & Bass)

Viscous Fluid Dynamics [\[edit\]](#)

- (you can be the first!!)

[Back to Bulk Evolution](#)

(created by U. Heinz, June 24, 2008, last edit by [Bass](#) 05:05, 7 July 2008 (EDT))

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The OSCAR2008H Standard

- follows the spirit of the OSCAR initiative
- OSCAR1997A output format for particle based codes still in use
- 2 output file specifications:
 - full time evolution file
 - final freeze-out hypersurface
- format needs to be flexible enough to accommodate different geometries, dimensionalities, ideal vs. viscous etc...
- should contain all relevant information on calculation (initial conditions, grid size, collision geometry) to allow for post-processing and analysis

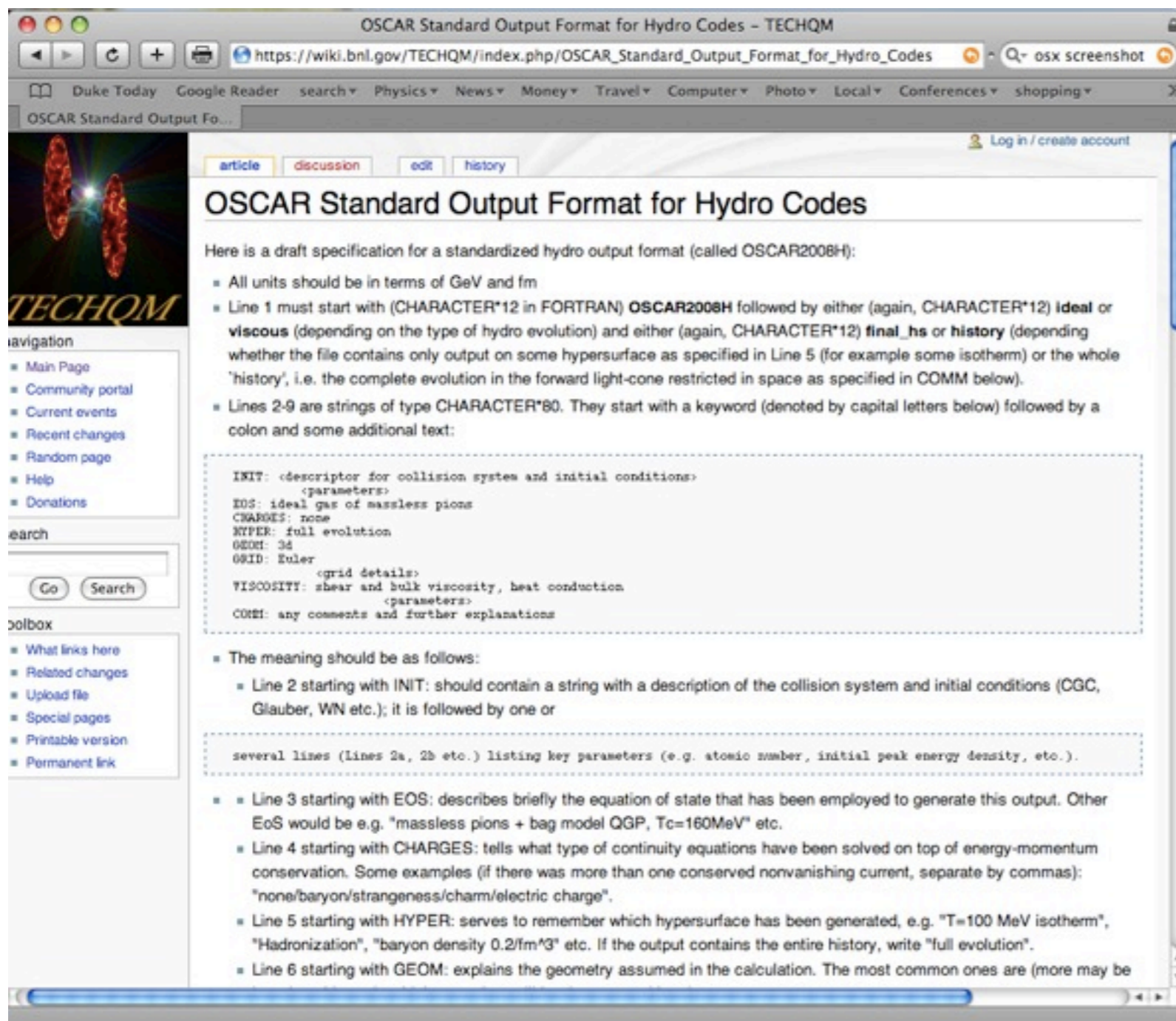
Prototype Developers:

- S.A. Bass & C. Nonaka
- H. Song & U. Heinz
- (T. Hirano)

Pledged Supporters:

- D. Molnar & P. Huovinen
- P. Romatschke
- D. Teaney & K. Dusling
- Frankfurt Group

OSCAR2008 Specifications



OSCAR Standard Output Format for Hydro Codes - TECHQM

https://wiki.bnl.gov/TECHQM/index.php/OSCAR_Standard_Output_Format_for_Hydro_Codes

OSCAR Standard Output Fo...

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OSCAR Standard Output Format for Hydro Codes

Here is a draft specification for a standardized hydro output format (called OSCAR2008H):

- All units should be in terms of GeV and fm
- Line 1 must start with (CHARACTER*12 in FORTRAN) **OSCAR2008H** followed by either (again, CHARACTER*12) **ideal** or **viscous** (depending on the type of hydro evolution) and either (again, CHARACTER*12) **final_hs** or **history** (depending whether the file contains only output on some hypersurface as specified in Line 5 (for example some isotherm) or the whole 'history', i.e. the complete evolution in the forward light-cone restricted in space as specified in COMM below).
- Lines 2-9 are strings of type CHARACTER*80. They start with a keyword (denoted by capital letters below) followed by a colon and some additional text:

```

INIT: <descriptor for collision system and initial conditions>
      <parameters>
EOS: ideal gas of massless pions
CHARGES: none
HYPER: full evolution
GEOM: 3d
GRID: Euler
      <grid details>
VISCOSITY: shear and bulk viscosity, heat conduction
      <parameters>
COMM: any comments and further explanations
  
```

- The meaning should be as follows:
 - Line 2 starting with INIT: should contain a string with a description of the collision system and initial conditions (CGC, Glauber, WN etc.); it is followed by one or several lines (Lines 2a, 2b etc.) listing key parameters (e.g. atomic number, initial peak energy density, etc.).
 - Line 3 starting with EOS: describes briefly the equation of state that has been employed to generate this output. Other EoS would be e.g. "massless pions + bag model QGP, Tc=160MeV" etc.
 - Line 4 starting with CHARGES: tells what type of continuity equations have been solved on top of energy-momentum conservation. Some examples (if there was more than one conserved nonvanishing current, separate by commas): "none/baryon/strangeness/charm/electric charge".
 - Line 5 starting with HYPER: serves to remember which hypersurface has been generated, e.g. "T=100 MeV isotherm", "Hadronization", "baryon density 0.2/fm^3" etc. If the output contains the entire history, write "full evolution".
 - Line 6 starting with GEOM: explains the geometry assumed in the calculation. The most common ones are (more may be

current status:

- posted on TECHQM website
- prototype implementations by Song/Heinz and Bass/Nonaka

next steps:

- need to use files in regular workflow to find shortcomings in specifications
- once usability has been established, specifications will be finalized



Implementation

OSCAR2008H file header:

```
OSCAR2008H  ideal      final_hs
INIT: Glauber + Wounded Nucleon
INIT: b=      2.4000 n_B,0=      0.0100 e_0=  300.0000
INIT: r_b/c=      0.8000 sigma_h      1.4000 eta_0=      2.0000
INIT: rad0 =      6.3800 rho0 =      0.1688 delta =      0.5400 sigma =      4.2000
EOS: Bag Model QGP + HRG
CHARGES: baryon
HYPER: T=110.0 MeV isotherm
GEOM: 3d
GRID: Lagrange
  20000 101 101 121    1    0    0
      0.600 10000.600    -15.000    15.000    -15.000    15.000    -18.000    18.000
VISCOSITY: none
COMM: (c) C. Nonaka & S.A. Bass
COMM: Phys.Rev.C75:014902 (2007)
```



OSCAR2008H ideal history

INIT: Glauber + Wounded Nucleon

INIT: b= 2.4000 n_B,0= 0.1500 e_0= 40.0000

INIT: r_b/c= 0.6000 sigma_h 1.5000 eta_0= 0.5000

INIT: rad0 = 6.3800 rho0 = 0.1688 delta = 0.5400 sigma = 4.2000

EOS: smooth cross-over with tri-critical point

CHARGES: baryon

HYPER: full evolution

GEOM: 3d

GRID: Lagrange

100000 77 77 77 1 0 0

0.600 10000.600 -11.400 11.400 -11.400 11.400 -11.400 11.400

VISCOSITY: none

COMM: (c) C. Nonaka & S.A. Bass

COMM: Phys.Rev.C75:014902 (2007)

0	0	0	0	0.6000000000000000E+00	-0.1140000000000000E+02	-0.1140000000000000E+02	-0.1140000000000000E+02	0.0000	0.0000	0.0350	0.0000	-0.57157676
0	1	0	0	0.6000000000000000E+00	-0.1110000000000000E+02	-0.1140000000000000E+02	-0.1140000000000000E+02	0.0000	0.0000	0.0350	0.0000	-0.56141639
0	2	0	0	0.6000000000000000E+00	-0.1080000000000000E+02	-0.1140000000000000E+02	-0.1140000000000000E+02	0.0000	0.0000	0.0350	0.0000	-0.55098764
0	3	0	0	0.6000000000000000E+00	-0.1050000000000000E+02	-0.1140000000000000E+02	-0.1140000000000000E+02	0.0000	0.0000	0.0350	0.0000	-0.54028621
0	4	0	0	0.6000000000000000E+00	-0.1020000000000000E+02	-0.1140000000000000E+02	-0.1140000000000000E+02	0.0000	0.0000	0.0350	0.0000	-0.52930809
0	5	0	0	0.6000000000000000E+00	-0.9900000000000000E+01	-0.1140000000000000E+02	-0.1140000000000000E+02	0.0000	0.0000	0.0350	0.0000	-0.51804959
0	6	0	0	0.6000000000000000E+00	-0.9600000000000000E+01	-0.1140000000000000E+02	-0.1140000000000000E+02	0.0000	0.0000	0.0350	0.0000	-0.50650734
0	7	0	0	0.6000000000000000E+00	-0.9300000000000001E+01	-0.1140000000000000E+02	-0.1140000000000000E+02	0.0000	0.0000	0.0350	0.0000	-0.49467838
0	8	0	0	0.6000000000000000E+00	-0.9000000000000000E+01	-0.1140000000000000E+02	-0.1140000000000000E+02	0.0000	0.0000	0.0350	0.0000	-0.48256016
0	9	0	0	0.6000000000000000E+00	-0.8699999999999999E+01	-0.1140000000000000E+02	-0.1140000000000000E+02	0.0000	0.0000	0.0350	0.0000	-0.47015060
0	10	0	0	0.6000000000000000E+00	-0.8400000000000000E+01	-0.1140000000000000E+02	-0.1140000000000000E+02	0.0000	0.0000	0.0350	0.0000	-0.45744816
0	11	0	0	0.6000000000000000E+00	-0.8100000000000000E+01	-0.1140000000000000E+02	-0.1140000000000000E+02	0.0000	0.0000	0.0350	0.0000	-0.44445183
0	12	0	0	0.6000000000000000E+00	-0.7800000000000000E+01	-0.1140000000000000E+02	-0.1140000000000000E+02	0.0000	0.0000	0.0350	0.0000	-0.43116122
0	13	0	0	0.6000000000000000E+00	-0.7500000000000000E+01	-0.1140000000000000E+02	-0.1140000000000000E+02	0.0000	0.0000	0.0350	0.0000	-0.41757657
0	14	0	0	0.6000000000000000E+00	-0.7200000000000000E+01	-0.1140000000000000E+02	-0.1140000000000000E+02	0.0000	0.0000	0.0350	0.0000	-0.40369883
0	15	0	0	0.6000000000000000E+00	-0.6900000000000000E+01	-0.1140000000000000E+02	-0.1140000000000000E+02	0.0000	0.0000	0.0350	0.0000	-0.38952960
0	16	0	0	0.6000000000000000E+00	-0.6600000000000000E+01	-0.1140000000000000E+02	-0.1140000000000000E+02	0.0000	0.0000	0.0350	0.0000	-0.37507152
0	17	0	0	0.6000000000000000E+00	-0.6300000000000000E+01	-0.1140000000000000E+02	-0.1140000000000000E+02	0.0000	0.0000	0.0350	0.0000	-0.36032765
0	18	0	0	0.6000000000000000E+00	-0.6000000000000000E+01	-0.1140000000000000E+02	-0.1140000000000000E+02	0.0000	0.0000	0.0350	0.0000	-0.34530215

To-Do List for Output Format

- developers need to work with format to ensure its practicability/usability
- OSCAR2008H should be finalized by next TECHQM workshop
- accepted use policy for output files needs to be defined
- should TECHQM consider supplying analysis tools for the output?
- start work on interpolator routines:
 - use native or OSCAR2008 format?
 - which quantities should be provided?
 - which programming languages to support?
 - specify interpolation algorithm?



Common Table Format for Hydro Equation of State

Motivation

- one of the main goals for the measurement of high p_T hadrons and/or jets is their capability to act as well-calibrated probes of the properties of the medium, aka the “full event”
- ambiguities arise from multiple sources, among them the sensitivity to the Equation of State
- only a controlled variation of individual modeling components will allow for the disentanglement of the different sensitivities and the unambiguous determination of the medium properties
- focus here on the sensitivity to the Equation of State in (v)RFD calculations:
 - a common format for tabulating the EoS would allow for easy interchange of different EoS in (v)RFD calculations and would thus enable systematic comparisons on the EoS sensitivity to the bulk evolution and to jet energy-loss calculations
 - such a format would also provide an efficient interface to the Lattice community for dissemination of their results to the transport community



Current Status & To-Do List

current status:

- solicitation for description of current status on EoS treatment and proposals for a new standard treatment sent out to TECHQM community in 6/2009
- feedback received from a subset of practitioners (Ohio State, Purdue, Frankfurt)
- still waiting to hear from more community members

to-do list:

- develop prototype for common EoS table based on community feedback
 - needs to be able to work for ideal and viscous RFD
 - needs to be able to treat full chemical equilibrium and PCE
- create repository for different EoS tables on TECHQM website
- lobby for community-wide adoption of standard



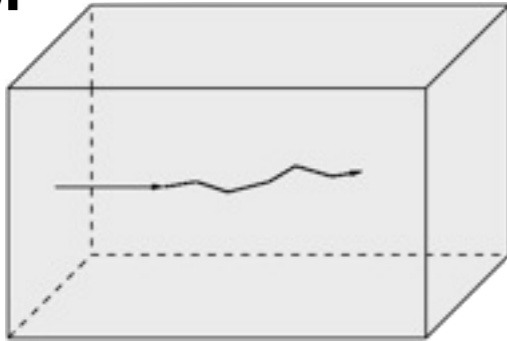
The PCM Brick Problem

Motivation

- Parton Cascade Models are microscopic transport models based on the Boltzmann Equation - they describe the full time-evolution of a system of deconfined partons (quarks and gluons) at high density and temperature
 - PCMs offer the unique ability to not only describe the evolution of the jet as it interacts with the medium, but also the response of the medium to the jet on a microscopic level
 - a number of PCM implementations exist, each with their unique set of features and limitations, due to the algorithms employed to solve the Boltzmann eqn. and to deal with issues such as covariance, detailed-balance and radiative corrections
 - the differences in the PCM implementations pose a challenge for the extraction of robust physics conclusions from these calculations
 - a set of standard benchmarks will allow for
 - the comparison of the different PCM implementations among each other under controlled conditions
 - the comparison with analytic solutions, e.g. of the QGP brick problem
 - the verification of specific physics features, e.g. the implementation of the LPM effect
- **the PCM brick problem**

PCM Brick Problem: Setup

Box Setup:



- define a box of 5 fm length w/ periodic boundary conditions
- populate box with an ensemble of thermal gluons at $T=300, 400, 500$ or 600 MeV
- insert a hard gluon w/ initial momentum $p_x=50, 100, 200, 300, 400$ GeV and track its evolution through the medium

Cross Section:

- use a Debye-screened elastic gg cross-section:

$$\frac{d\sigma}{dq_{\perp}^2} = \frac{9\pi\alpha_s^2}{(q_{\perp}^2 + m_D^2)^2}$$

- choose Debye-mass to be:

$$m_D^2 = \frac{24}{\pi}\alpha_s T^2$$

- use a fixed coupling: $\alpha_s=0.3$

Desired Calculations:

- distribution of momentum transfers
- energy-loss as function of distance traveled
- energy-loss transport coefficient defined as:

$$\hat{q} = \frac{1}{l_x} \sum_{i=1}^{N_{coll}} (\Delta p_{\perp,i})^2$$

Optional Extensions:

- full QGP: study flavor-dependence
- heavy quark energy-loss
- radiative energy-loss
- medium response: conical flow, correlations



Current Status & To-Do List

The brick problem for Parton Cascade Codes - TECHQM

https://wiki.bnl.gov/TECHQM/index.php/The_brick_problem_for_Parton_Cascade_Codes#Desired_Calculations:

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The brick problem for Parton Cascade Codes

Contents [hide]

- 1 The Brick Problem for Parton Cascade Codes
 - 1.1 Basic Setup:
 - 1.2 Box Definition:
 - 1.3 Cross Sections:
 - 1.4 Desired Calculations:
 - 1.5 Results:

The Brick Problem for Parton Cascade Codes

The brick for Parton Cascades aims at providing a set of benchmarks for Parton Cascade Codes. In particular it allows for the calculation of elastic (collisional) energy-loss in a controlled environment in the framework of microscopic transport models (and for those models incorporating gluon splitting, radiative energy-loss can be addressed as well). Currently the setup described here is a proposal to the TECHQM community on how to formulate such a Brick for PCMs - it has been worked out through a collaboration of the Duke and Frankfurt groups and will hopefully be adopted by the greater community in the near future.

Basic Setup:

The basic setup of the problem is to have gluonic matter in a box in thermal equilibrium at a given temperature. Then a hard probe, i.e. a gluon, will be shot through the box at a given initial energy/momentum and its energy (or energy-loss) will be measured as a function of distance (along its trajectory) and as a function of its initial energy.

Box Definition:

- the box should be a cube of 5 fermi length with periodic boundary conditions, i.e. a gluon leaving the box at $x=+5$ fm, would re-enter the box at $x=0$ fm with the same momentum.
- gluons will be initialized according to a thermal momentum distribution at a density of $\kappa = N/V = (16/\pi^2)T^3$
- the box will be initialized at temperatures $T=300, 400, 500$ and 600 MeV

Cross Sections:

- a Debye-screened elastic glue-gluon cross section will be used - just as in expression (1) of [arXiv 0711.0961 \[nucl-th\]](#)
- the Debye mass is chosen to be $m_D^2 = (24/\pi)\alpha_s T^2$ (i.e. calculated for Boltzmann particles) with the coupling constant fixed to $\alpha_s = 0.3$
- a minimum c.m. energy cut-off for a parton-parton collision is set to be $\Lambda_{QCD} = 200$ MeV

Desired Calculations:

- insert an on-shell gluon into the medium with an initial momentum of 50 GeV, 100 GeV, ... up to 400 GeV in 100 GeV increments, have it propagate through the box (with periodic boundary conditions the probe may propagate arbitrary distances) and measure E vs. x with x being the distance traveled along its trajectory (alternatively one may measure E vs. time, even though this may not be as accurate for comparing to the analytic formula)
- measure the sum of all p_{\perp}^2 kicks the parton accumulates and divide it by the pathlength traveled. This provides a measure for

$$\hat{q} = 1/l_x \sum_{i=1}^{N_{coll}} (\Delta p_{\perp,i})^2$$

the transport coefficient

- these calculations are to be performed with the aforementioned 2-2 elastic glue-gluon scattering cross section
- subsequently, take a 200 GeV gluon and propagate it through the box at temperatures $T=300, 400, 500$ and 600 MeV, performing the same analysis
- optionally (if the code is capable of doing so), the calculations can be repeated with 2-3 processes activated as well - this will need to be fleshed out at a later date...

Results:

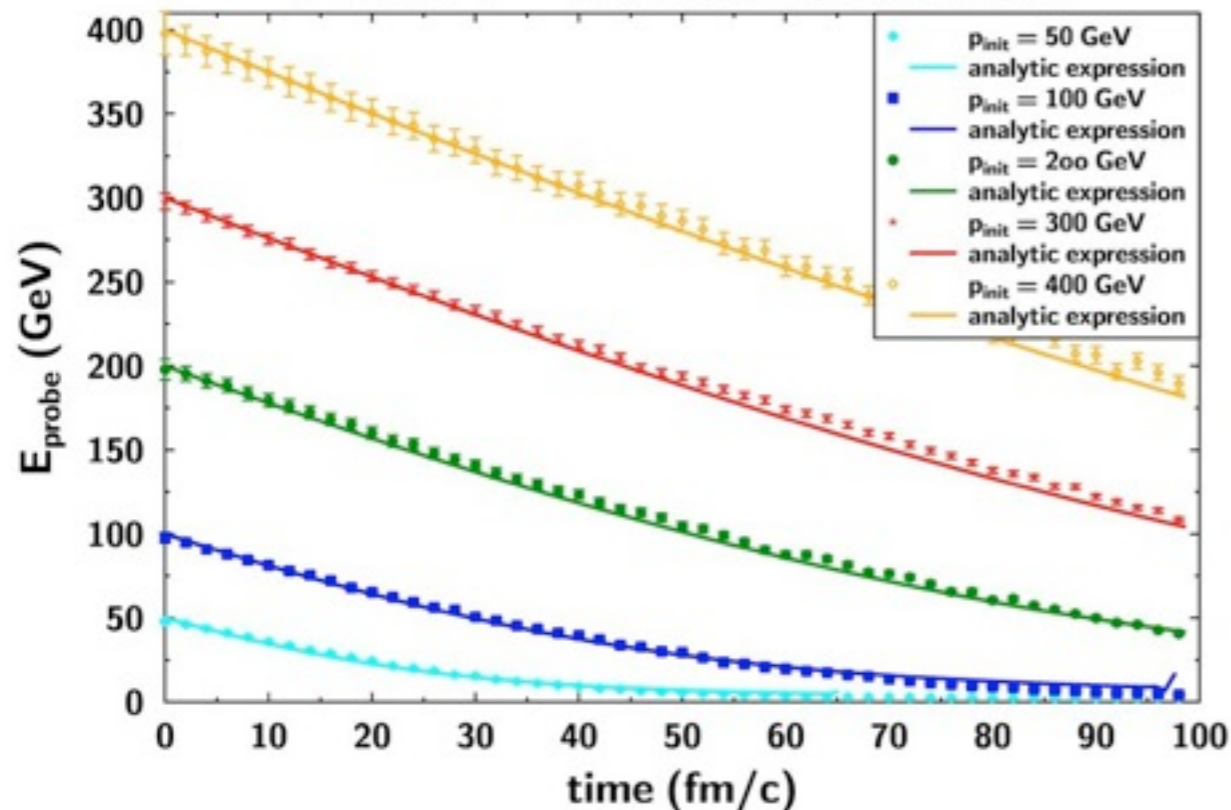
- First results for the Andong Parton Cascade code APC

(created by Steffen A. Bass on July 7th 2008, last edited by Muller 08:37, 7 July 2008 (EDT))

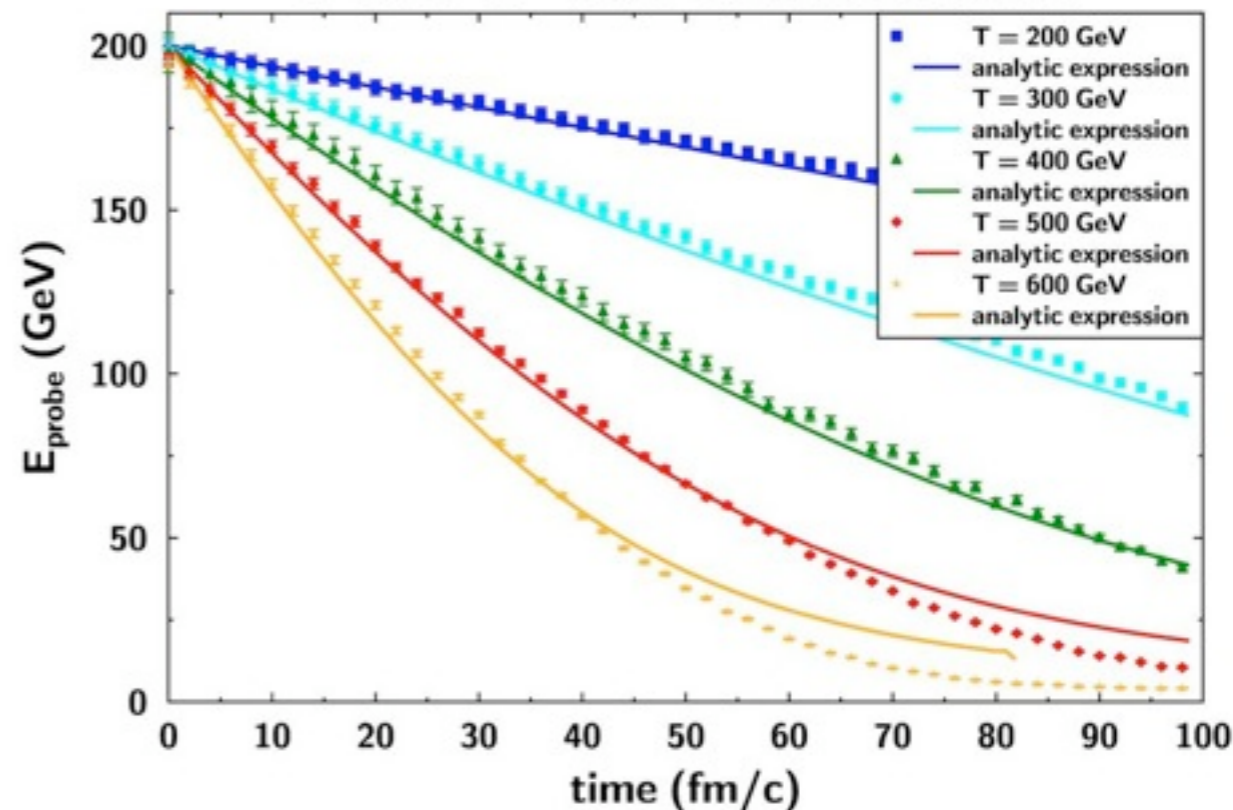
- full specifications of the PCM brick problem have been posted on the TECHQM website
- several groups have pledged to undertake the calculations and compare results (Duke, Frankfurt, Andong)
- ▶ need to publicize this effort for wider adoption

Energy- & Temperature Dependence

PCM: T=400 MeV, bin. coll.



PCM: E=200 GeV, bin. coll.

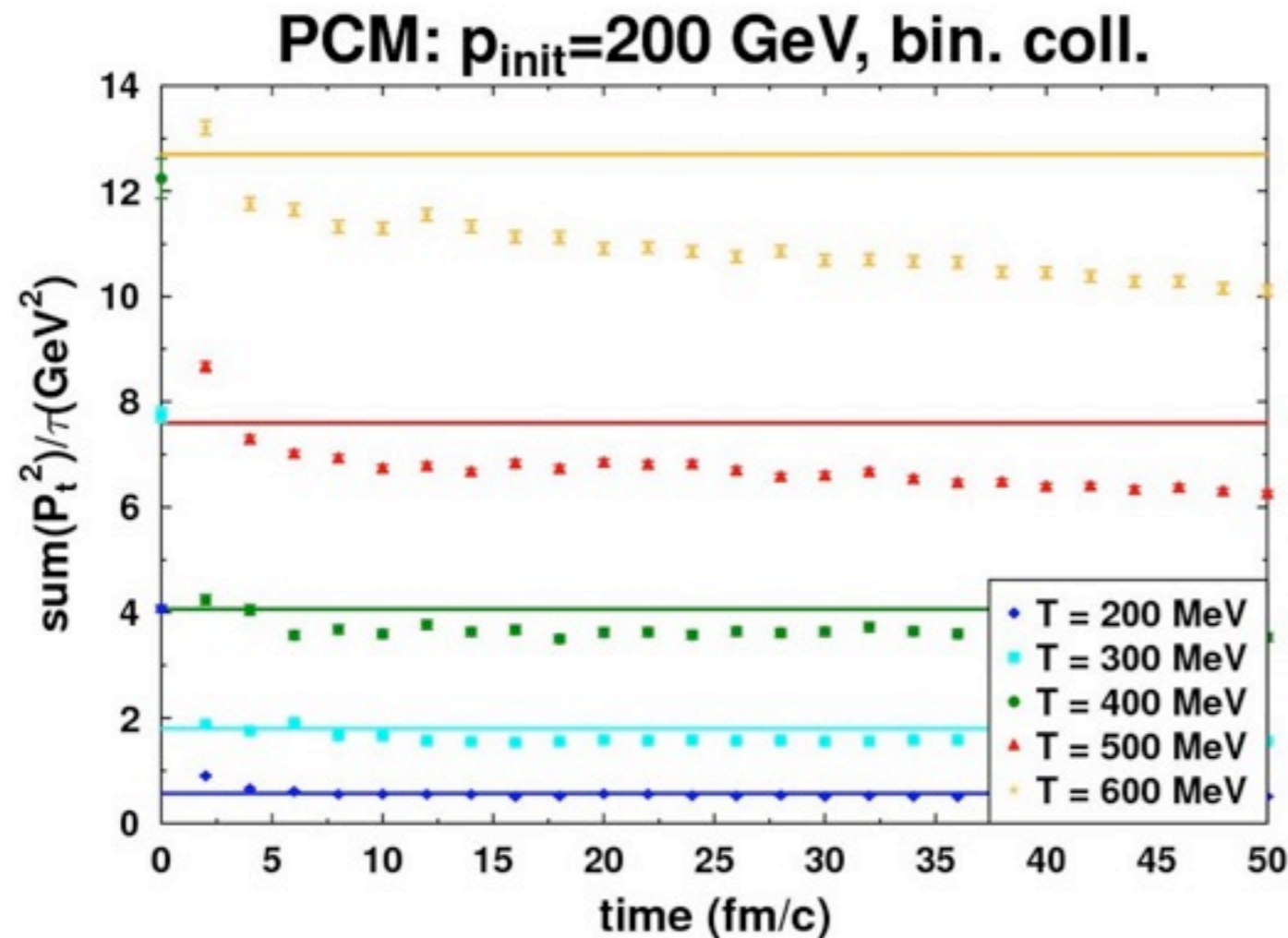


- the PCM brick calculations can be compared to the analytic expression for collisional energy-loss of light quarks/gluons:

$$E_p(x) = E_p(0) - x \frac{\alpha_s C_2 m_D^2}{2} \ln \left[\frac{\sqrt{E_p(x) T}}{m_D} \right]$$

- excellent agreement with analytic expression over time-scale of 40+ fm/c
- caveat of current calculation: uses time instead of path-length - this may account for deviations at longer times & high temperatures

Energy-loss transport coefficient



- definition of \hat{q} for microscopic transport models:

$$\hat{q} = \frac{1}{l_x} \sum_{i=1}^{N_{\text{coll}}} (\Delta p_{\perp,i})^2$$

- the PCM brick calculations can be compared to the analytic expression of \hat{q} for light quarks/gluons:

$$\hat{q} = \frac{C_2 g^2 T m_D^2}{2\pi} \ln \left[\frac{\sqrt{E_p T}}{m_D} \right]$$

- good agreement with analytic expression for lower temperatures $T=200-400$ MeV
- caveat of current calculation: uses time instead of path-length - this may account for deviations at higher temperatures

Summary

The Merging of jet-quenching with full event simulations is greatly facilitated by the development of standardized interfaces and benchmarks:

- the OSCAR2008H file format
 - allows for a standard interface between jet energy-loss calculations and (v)RFD evolution files
 - implementation nearly complete, awaits widespread adoption by community
- common table format for RFD equation of state
 - important for systematic comparisons on the sensitivity to the EoS of various observables, will help to disentangle ambiguities between different physics quantities characterizing the system
 - provides an interface to the Lattice-Gauge community
- the PCM brick problem
 - provides a benchmark for the comparison of the different PCM implementations among each other under controlled conditions
 - allows for the comparison with analytic solutions, e.g. of the QGP brick problem
 - enables the verification of specific physics features, e.g. the implementation of the LPM effect



The End

Motivation

- one of the main goals for the measurement of high p_T hadrons and/or jets is their capability to act as well-calibrated probes of the properties of the medium, aka the “full event”
- ambiguities arise from multiple sources:
 - different formalisms for the treatment of hard probe - medium interactions yield different values for characteristic medium properties, e.g. \hat{q}
 - sensitivity to the initial state (e.g. CGC vs. Glauber)
 - nature & treatment of pre-equilibrium phase of medium
 - sensitivity to the Equation of State
 - ideal vs. viscous treatment of medium in RFD, i.e. sensitivity to transport-coefficients, such as the bulk- and shear-viscosity
 - treatment of the hadronic phase: ideal RFD, PCE, hadronic afterburner...
- only a controlled variation of individual modeling components will allow for the disentanglement of the different sensitivities and the unambiguous determination of the medium properties
- focus here on the sensitivity to the Equation of State in (v)RFD calculations:
 - a common format for tabulating the EoS would allow for easy interchange of different EoS in (v)RFD calculations and would thus enable systematic comparisons on the EoS sensitivity to the bulk evolution and to jet energy-loss calculations
 - such a format would also provide an efficient interface to the Lattice community for dissemination of their results to the transport community