Interfacing of Jet Energy-Loss Schemes with a 3D Hydrodynamic Medium

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- current status: jet-energy loss in a hydrodynamic medium
- development of a standardized interface
- the OSCAR2008H file format
- next steps

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

- Jet energy-loss calculations have reached a high level of technical sophistication (BDMPS, GLV, higher twist…), yet they employ a variety of rather 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: arXiv:0808.0908 [nucl-th]

Connecting high-p_t partons with the dynamics of an expanding QGP

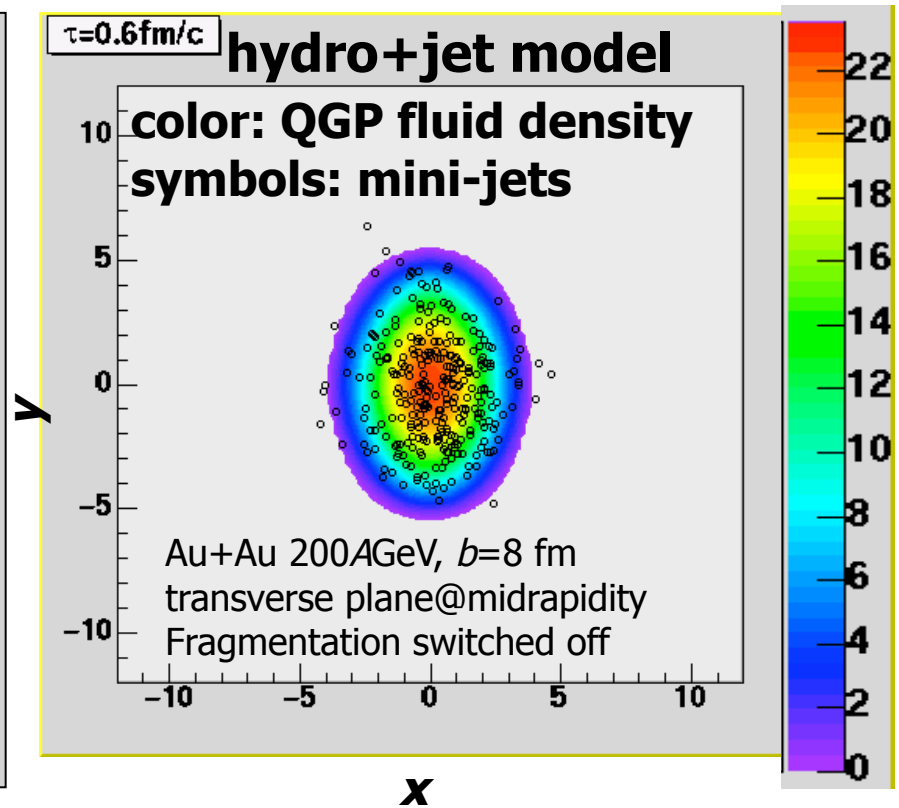
Hydro+Jet model

T.Hirano. & Y.Nara: Phys.Rev.**C66** 041901, 2002

- use GLV 1st order formula for parton energy loss (M.Gyulassy et al. '00)

$$\Delta E = C \int_{\tau_0} d\tau (\tau - \tau_0) \times \rho(\tau, \mathbf{x}(\tau)) \ln\left(\frac{2 p_0^\mu u_\mu}{\mu^2 L}\right)$$

- take Parton density $\rho(x)$ from full 3D hydrodynamic calculation



- 1st work combining realistic hydro and jet energy-loss
- good description of single-inclusive spectra and R_{AA}

Energy-Loss Implementation in 3D RFD

3D hydrodynamic evolution provides ε, T, γ and Γ_{QGP} as function of (τ,x,y,η)

BDMPS/ASW:

- define local transport coefficient along trajectory ξ (K as parameter to fix transport coefficient of medium): $\hat{q}(\xi) = K \cdot 2 \cdot \varepsilon^{\frac{3}{4}}(\xi)$

Higher Twist:

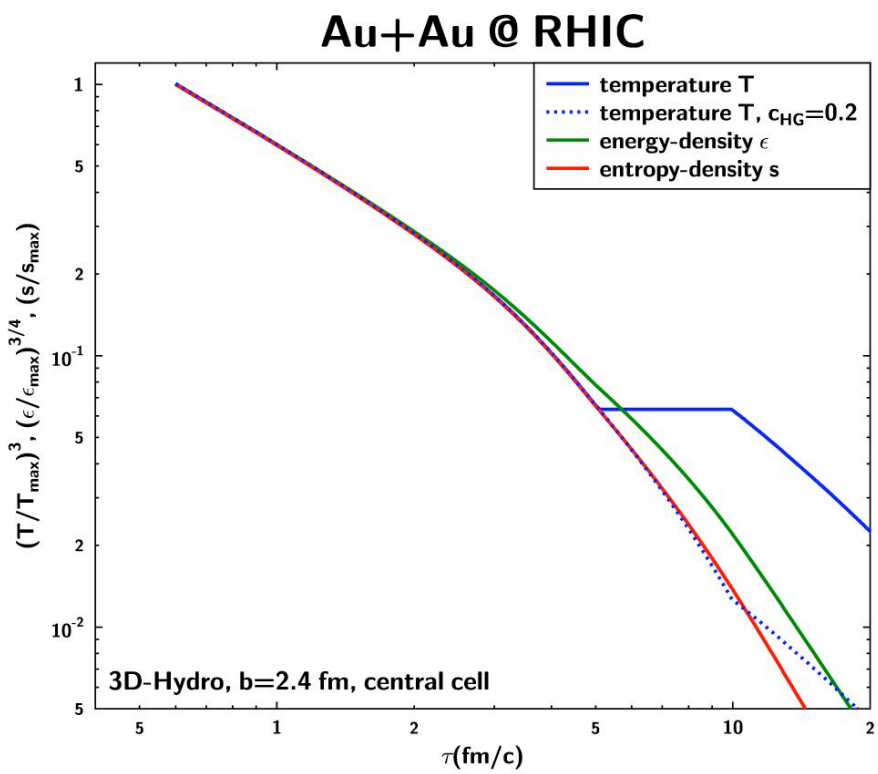
- fix starting value of q; hadronic phase can be taken into account via coefficient c_{HG}: $\hat{q}(\vec{r},\tau) = \hat{q}_0 \frac{\gamma(\vec{r},\tau)T^3(\vec{r},\tau)}{T_0^3}\left[\Gamma_{QGP}(\vec{r},\tau) + c_{HG}\left(1-\Gamma_{QGP}(\vec{r},\tau)\right)\right]$

AMY:

- evolution of jet-momentum distribution is obtained by solving set of coupled rate eqns, with transition rates depending on the coupling constant α_s, local temperature T and flow velocity γ ($q \sim T^3$)

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): $\varepsilon = \frac{\pi^2}{30} g_{DOF} T^4$



- common choices for scaling:

$$\hat{q} \sim T^3 \qquad \hat{q} \sim \varepsilon^{3/4} \qquad \hat{q} \sim s$$

➢ 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)

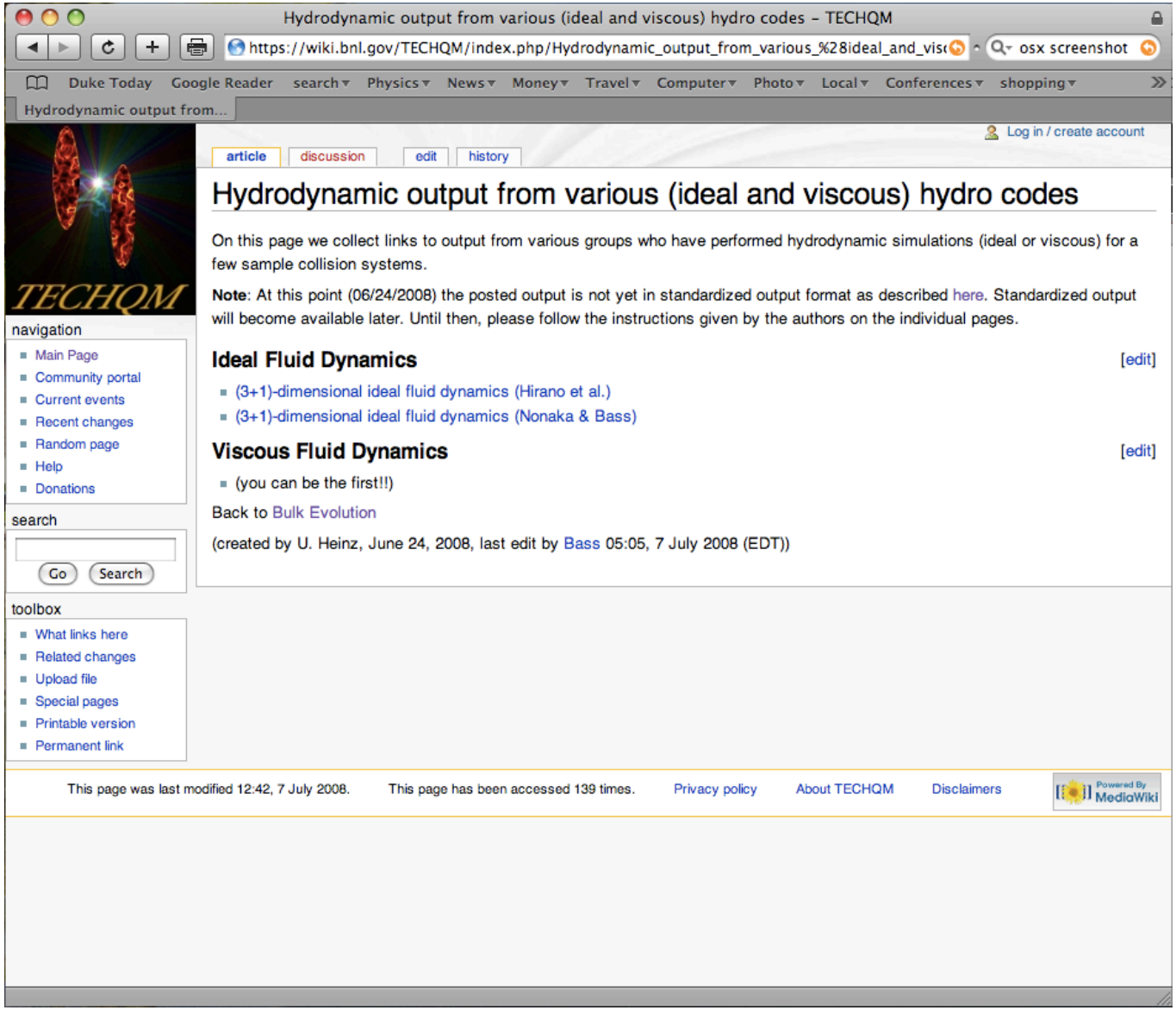
- different medium scaling can affect q by a factor of 2
- a clear difference persists among the different approaches, even when utilizing identical medium evolution & scaling and initial conditions
- the "correct" medium scaling relation is a priori not known, should hopefully be calculable from 1st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

Status at TECHQM May 2008

pragmatic to-do list:

- need interfaces which enable collaboration between developers of models for bulk evolution and practitioners of hard probe calculations (jets, photons, heavy-quarks) ✔
- define an OSCAR standard for the time-evolution and freeze-out hypersurface output of hydrodynamic models (needs to accommodate ideal/viscous parameters, Eulerian & Lagrangian grids and different coordinate frames) (✔)
- think about how to give credit to all significant contributors to a comprehensive calculation - medium and probe components/ practitioners should carry the same weight (citations not enough to support career of graduate student or postdoc!) ✗

Available Hydro Evolution Files



File vs. Interpolation Routine

Advantages of the standardized output file:

- easy to maintain, requires only moderate effort in implementation
- direct access to the raw data

Advantages of the standardized interface routines:

- ability to interpolate between the hydro cells and provide thermodynamic quantities as a smooth function of of position, no matter the structure of the underlying grid

Issues which would need to be resolved for interpolation routines:

- what information should be accessible via these routines?
- should the interpolation between the cells be conducted in a specific manner or is this free for the developer of the respective hydro to decide?
- are the routines to be supplied in FORTRAN or C or both?

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 (intial conditions, grid size, collision geometry) to allow for post-processing and analysis

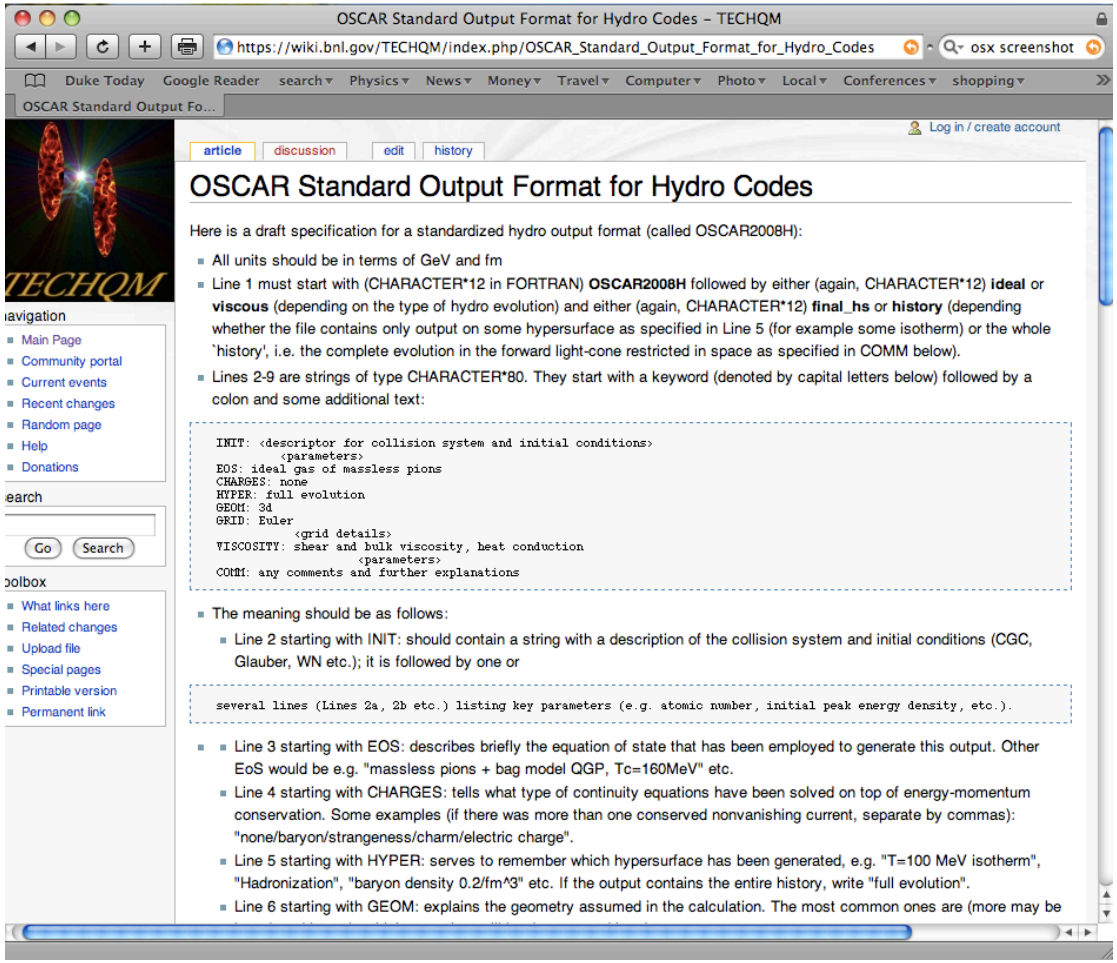
Prototype Developers:

- 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

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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

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current status:

- first draft 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 -0.57157676649
    0    1    0    0  0.6000000000000000E+00 -0.1110000000000000E+02 -0.1140000000000000E+02 -0.1140000000000000E+02   0.0000   0.0000   0.0350   0.0000 -0.56141639813
    0    2    0    0  0.6000000000000000E+00 -0.1080000000000000E+02 -0.1140000000000000E+02 -0.1140000000000000E+02   0.0000   0.0000   0.0350   0.0000 -0.55098764096
    0    3    0    0  0.6000000000000000E+00 -0.1050000000000000E+02 -0.1140000000000000E+02 -0.1140000000000000E+02   0.0000   0.0000   0.0350   0.0000 -0.54028621153
    0    4    0    0  0.6000000000000000E+00 -0.1020000000000000E+02 -0.1140000000000000E+02 -0.1140000000000000E+02   0.0000   0.0000   0.0350   0.0000 -0.52930809772
    0    5    0    0  0.6000000000000000E+00 -0.9900000000000000E+01 -0.1140000000000000E+02 -0.1140000000000000E+02   0.0000   0.0000   0.0350   0.0000 -0.51804959555
    0    6    0    0  0.6000000000000000E+00 -0.9600000000000000E+01 -0.1140000000000000E+02 -0.1140000000000000E+02   0.0000   0.0000   0.0350   0.0000 -0.50650734767
    0    7    0    0  0.6000000000000000E+00 -0.9300000000000001E+01 -0.1140000000000000E+02 -0.1140000000000000E+02   0.0000   0.0000   0.0350   0.0000 -0.49467838343
    0    8    0    0  0.6000000000000000E+00 -0.9000000000000000E+01 -0.1140000000000000E+02 -0.1140000000000000E+02   0.0000   0.0000   0.0350   0.0000 -0.48256016033
    0    9    0    0  0.6000000000000000E+00 -0.8699999999999999E+01 -0.1140000000000000E+02 -0.1140000000000000E+02   0.0000   0.0000   0.0350   0.0000 -0.47015060663
    0   10    0    0  0.6000000000000000E+00 -0.8400000000000000E+01 -0.1140000000000000E+02 -0.1140000000000000E+02   0.0000   0.0000   0.0350   0.0000 -0.45744816485
    0   11    0    0  0.6000000000000000E+00 -0.8100000000000000E+01 -0.1140000000000000E+02 -0.1140000000000000E+02   0.0000   0.0000   0.0350   0.0000 -0.44445183579
    0   12    0    0  0.6000000000000000E+00 -0.7800000000000000E+01 -0.1140000000000000E+02 -0.1140000000000000E+02   0.0000   0.0000   0.0350   0.0000 -0.43116122274
    0   13    0    0  0.6000000000000000E+00 -0.7500000000000000E+01 -0.1140000000000000E+02 -0.1140000000000000E+02   0.0000   0.0000   0.0350   0.0000 -0.41757657550
    0   14    0    0  0.6000000000000000E+00 -0.7200000000000000E+01 -0.1140000000000000E+02 -0.1140000000000000E+02   0.0000   0.0000   0.0350   0.0000 -0.40369883362
    0   15    0    0  0.6000000000000000E+00 -0.6900000000000000E+01 -0.1140000000000000E+02 -0.1140000000000000E+02   0.0000   0.0000   0.0350   0.0000 -0.38952966844
    0   16    0    0  0.6000000000000000E+00 -0.6600000000000000E+01 -0.1140000000000000E+02 -0.1140000000000000E+02   0.0000   0.0000   0.0350   0.0000 -0.37507152342
    0   17    0    0  0.6000000000000000E+00 -0.6300000000000000E+01 -0.1140000000000000E+02 -0.1140000000000000E+02   0.0000   0.0000   0.0350   0.0000 -0.36032765203
    0   18    0    0  0.6000000000000000E+00 -0.6000000000000000E+01 -0.1140000000000000E+02 -0.1140000000000000E+02   0.0000   0.0000   0.0350   0.0000 -0.34530215267
    0   19    0    0  0.6000000000000000E+00 -0.5700000000000000E+01 -0.1140000000000000E+02 -0.1140000000000000E+02   0.0000   0.0000   0.0350   0.0000 -0.33000000000
```

To-Do List

- prototype 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?

The End