

BRAHMS Decadal Planning Document

The BRAHMS Collaboration

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1.Introduction

The BRAHMS collaboration has prepared this response to the request from RHIC management for a decadal plan. Our goals for the next few years were outlined in our August 2003 Beam Use Proposal. Here we repeat some of that document while giving some perspective on scheduling and responding to the PAC recommendations. Additional details of our plans can be found in the BRAHMS Beam Use proposal. We extend the Beam Use Proposal discussion with some ideas currently being developed for a new, forward-physics program at RHIC.

With the significant achievements already made by the BRAHMS experiment, it should be possible to complete the program initially described in the experiment's CDR in the next few years. As an introduction to our future plans, we summarize what has been accomplished and what still remains from our initial experimental program. New physics discoveries from BRAHMS and the other RHIC experiments will strongly influence our physics program in the extended period envisioned by this decadal plan. Already, based on these new physics opportunities, we are planning extensions to our baseline program focusing on high- p_t and high- y physics, while retaining the survey nature of the investigations in the near term. We also plan to exploit the current BRAHMS system to measure transverse asymmetries in polarized proton-proton collisions.

The data obtained by BRAHMS in the initial running at RHIC can be characterized as having achieved a first mapping of the global features of the Au-Au, d-Au and pp reactions. Systematic studies of rapidity density of charged hadrons [1,2] and hadron to anti-hadron ratios at $\sqrt{s_{NN}}=130$ and 200 GeV [3,4] severely constrain dynamical models. The ratios data establish that a system is formed in ultrarelativistic heavy-ion collisions that is consistent with being in chemical equilibrium over a wide rapidity range. Nuclear modification factors in Au-Au and d-Au collisions at $\sqrt{s_{NN}}=200$ GeV have been studied through

measurements of transverse momentum spectra [5] in both the mid- and forward-rapidity regions leading to the surprising observation of high-momentum particle suppression away from midrapidity. Properties of the longitudinal dynamics such as baryon transport and energy stopping have been determined from the net proton rapidity distributions at $\sqrt{s_{NN}}=200$ [6], and from yields of charged hadrons vs. rapidity at $\sqrt{s_{NN}}=200$ GeV [7].

Physics Program

The BRAHMS experiment has unique capabilities for precise momentum determination and particle identification. The forward spectrometer (FS) is the only device within the family of RHIC experiments that can identify charged hadrons up to rapidity $y \sim 4$. It covers a large momentum and transverse momentum range. The excellent Particle Identification (PID) and angular coverage of the Mid-Rapidity Spectrometer (MRS) extends and complements measurements by the other RHIC detectors, and provides comparisons between mid-rapidity and forward-rapidity spectra with the same experiment setup. Despite the small solid angles of the spectrometers, p_t spectra of identified particles can be measured up to ~ 4 GeV/c with a readily obtainable integrated luminosity. The physics topics that BRAHMS intends to address in the coming years are discussed below. The program is mainly focused on issues that can be uniquely addressed by BRAHMS by studying the hot and dense system formed in heavy ion collisions in a systematic way as function of system size, collision energy, centrality and rapidity.

Heavy-ion Collisions

High- p_t suppression

A tool for understanding the initial partonic state is the study of identified high- p_t hadrons over a range of rapidities. BRAHMS is uniquely capable of studying the evolution of the high- p_t components of hadronic spectra over several units of rapidity. Recently all RHIC experiments have reported suppression of high- p_t spectra compared to expectations from pp collisions near mid-rapidity at both 130 GeV and 200 GeV. BRAHMS also observes this suppression at $y \sim 2$. The suppression may result from the energy loss of quarks and gluons passing through a dense partonic system. The continued suppression out to $y=2$ provides information on the longitudinal extent of this dense system. An intriguing possibility recently highlighted by BRAHMS measurement of the d+Au nuclear modification factor at $y \sim 3.2$ is that the suppression at forward rapidities may also result in part from parton saturation effects in the initial state. In the next set of measurements for Au+Au collisions we will explore the suppression signature at even larger rapidity to study the effect of density and, possibly, initial state saturation.

The study of particle spectra in the p_t range of 1-4 GeV/c will help in the understanding of initial scattering (Cronin) effects, gluon saturation, shadowing and jet quenching effects. The relative importance of these

processes depends on energy, rapidity and the mass of the collision system. Systematic studies may disentangle effects related to a ‘cold’ versus a ‘hot’ medium, and to the density of the medium.

System size dependence

Light-ion collisions such as Fe-Fe will allow us to study hot nuclear systems with ~ 10 to 100 participants. This region of system sizes is not easily studied with Au-Au collisions since it is very difficult to accurately determine the number of participants for peripheral events. With a light projectile such as Fe the matter length for suppression of high- p_t particles is about half of that in Au-Au collisions, but likely with quite similar energy densities. This will be very useful for studying models of particle production but perhaps more importantly will allow us to study high- p_t suppression as a function of system size. BRAHMS can study this effect at $\sqrt{s_{NN}} = 200$ GeV. Finally it would be interesting to see if the coalescence radius decreases significantly when we reduce the number of participants by a large factor.

Energy systematic of heavy-ion collisions

The study of the energy dependence of global reaction properties such as baryon stopping and strangeness production has generally led to an increased understanding of the reaction mechanism and the system characteristics. The highest SPS energy is 17 GeV, and the lowest RHIC data that are well studied are at 130 GeV. There is significant stopping at SPS while at RHIC energies the nuclei are much more transparent. An intermediate energy such as 63 GeV for which some, albeit lower statistics and less systematic data exists for pp collisions at the ISR, would add well into the overall systematic understanding. At this energy BRAHMS can measure into the fragmentation region and can explore both stopping and the complete shape of produced mesons spectra, as well as limiting fragmentation for identified particles. This will place additional stringent limits on the theoretical understanding of stopping, energy loss, transparency, and the equation of state. The rapid disappearance of high- p_t jet-like particles unfortunately makes a study of high- p_t suppression at lower energy statistically very difficult with BRAHMS, but we can make a measurement up to ~ 4 GeV/c at $y \sim 1$.

Bulk properties

In Run II BRAHMS measured spectra of identified hadrons from which rapidity densities, $\langle p_t \rangle$, and spectral shapes were deduced. These results were used for the study of transverse flow and longitudinal dynamics for the reaction. Particle ratios as a function of rapidity were analyzed within the statistical model framework to determine the baryon and strangeness chemical potentials, and the chemical and thermal freeze-out temperatures as a function of rapidity. From the proton and antiproton rapidity densities we can deduce the net energy loss of the beam and projectile. In addition, global charged particle pseudorapidity densities have been measured using the BRAHMS global detectors. Together, these measurements strongly constrain models in terms of their longitudinal development. We will extend the

spectral measurements to the highest rapidities allowed by the forward spectrometer and beam line geometry (2.3°), which will allow us to better determine the net-proton distribution and to place even more stringent constraints on theoretical models. The analysis of radial and elliptic flow gives access to information on the temporal and spatial development of pressure within the hot, strongly interacting system. We will establish the reaction plane in non-central collisions by a reconfiguration of our Si multiplicity array; this may open up a new dimension for BRAHMS' study of heavy-ion collisions by measuring the full three dimensional cross section, $d^3N/d\phi dp_T dy$, and R_{AA} factors. Such studies will be essential in determining the equation of state of the hot, dense, and presumably partonic state of matter produced at RHIC.

Particle correlations

Interferometry and nucleon and anti-nucleon coalescence allow us to measure the spatial properties of the final state of the system as it breaks up. The ‘‘HBT puzzle’’ at RHIC is the striking similarity of the outward and sideward correlation functions and the lack of any dependence of the radii on $\sqrt{s_{NN}}$. NA44 at SPS has combined π , k and p interferometry and coalescence measurements to determine the transverse flow of the Pb-Pb system [10] at $\sqrt{s_{NN}}=17$ GeV. However, at high expansion velocities which reach the speed of sound in the medium, as may occur at RHIC, one would expect hydrodynamics to break down and, indeed, some evidence for this effect in high- p_T pion interferometry may be seen. We will study coalescence at both high rapidity and at higher p_T values to address these issues. The data for the HBT analysis will be obtained in conjunction with other measurements. Combining interferometry and coalescence volume information with single-particle momentum spectra will allow us to measure the density of particles in phase space [11]. Integrating this density can reveal the entropy of the system. Finally comparing the formation of nuclear clusters and anti-clusters will help us understand the time interval between hadronization and thermal freeze-out.

Nucleon-Nucleus (d-Au) collisions

Recent results from HERA have shown that at very small x gluons may fuse together. This raises the possibility that at RHIC the soft gluons from different nuclei may fuse to form a Colored Glass Condensate (CGC) [9]. Although the prediction from this model at mid-rapidity is not consistent with the d-Au data at $y=0$ it is still possible that the CGC may be observed at forward rapidities in d-Au collisions. BRAHMS collected a sample of d-Au at higher rapidities during Run III. The analysis of these d-Au has revealed features, i.e., an R_{dA} factor at $\eta \sim 3.2$ that is significant below 1 at $p_T \sim 2.5$ GeV/c, that are consistent with the qualitative predictions of the CGC picture and are in contrast to the prediction by Vitev [10]. Although it is too early to rule out models that do not include gluon saturation, the preliminary results suggest additional d-Au running may be a high priority in the coming years.

Proton-proton collisions

Transverse Spin Asymmetries for charged hadrons.

In addition to these heavy-ion topics the collaboration is developing the tools for measuring and analyzing the charged pion asymmetry at higher x_F values in polarized p-p reactions. Towards this end we have established a collaboration with the RBRC spin group.

The E704 experiment at Fermilab observed large ($\sim 30\%$) single-spin transverse asymmetries in pion production at forward angles from p-p collisions at $\sqrt{s}=19.4$ GeV [11,12]. Because pQCD predicts only small effects, these observations spurred significant theoretical study. Presently, it is recognized that, with the inclusion of intrinsic transverse momentum, k_T , pQCD calculations can predict the observed asymmetries based on, for example, the Sivers effect [13] (spin dependence of the k_T distribution of the proton), the Collins effect [14] (final state interactions of a transversely polarized quark fragmenting into a pion), twist-three contributions beyond the leading power picture [15], or a combination of these three effects. With precise measurements of these asymmetries at the higher \sqrt{s} of RHIC (200 GeV), it is possible to discern between these explanations because the predictions of each one exhibit different dependence on the energy. During Run II and Run III, the STAR experiment measured this asymmetry for forward neutral pions [16] and found that it was as large as (if not slightly larger than) those observed by the E704 experiment. Given the excellent PID and momentum resolution achievable with the BRAHMS forward spectrometer, we propose to measure these asymmetries for positive and negative pions over the x_F region up to ~ 0.45 ($y \sim 4$) during Run IV and Run V in order to provide a complete measurement of these quantities. In addition, we intend to measure the charged kaon asymmetries during Run V and Run VI. These measurements will test the expectations based on the partonic content of the initial and final particles, namely that the positive kaon and pion asymmetries should be roughly equal because the production process for both mesons is expected to be dominated by the valence u-quark and (2) the negative kaon asymmetry should be zero since the negative kaon is an all-sea object and the sea is essentially un-polarized [17]. If merited, we will also explore the p_t dependence of the asymmetry at fixed x_F in subsequent runs.

Completion of Survey program

The Run II and Run III pp program yielded some results relevant for a general survey of elementary collisions at $\sqrt{s}=200$ GeV to be contrasted with Au-Au at the same energy. Unfortunately, the statistics obtained at relative high- p_t (3-4) and at large rapidity (2,3) were marginal and were only for a single charge state (negative). The Pythia model predicts quite significant differences between π^+ and π^- , but there is little experimental data for identified particle at larger rapidities to support these predictions. The results

are of importance for understanding the high- p_t suppression observed in heavy-ion collisions and, consequently, we wish to extend our earlier measurements.

3. Planning for coming run periods

Under optimal conditions our core program can be carried out in the next three years with the currently projected number of running weeks available to RHIC ¹. The constraints and impact on the physics program imposed by the time needed to set up and develop luminosity are severe. Compromises imposed by the needs of the other RHIC experiments could stretch the time needed to complete the survey program. The proposed program prioritizes the heavy-ion program over the p-p and d-Au to ensure this is carried out primarily in the next two running periods.

It is well understood that RHIC and all of the experiments are looking in detail at various options for the coming runs periods based on various scenarios of funding and the distribution of time between running, accelerator improvement projects, detector R&D and upgrades. The following section does not attempt to discuss the various options but merely summarizes the desired physics measurements, with details on luminosities given in the beam use proposal.

Au-Au collisions at 200 GeV

- Collect high statistics for high- p_t spectra at $y \sim 2.5$ and $y \sim 3.5$ for both charge states. Flow measurements to $p_t \sim 3$ GeV/c with centrality-dependent v_2 measurements up to about $p_t \sim 2$ GeV/c.
- Supplement existing lower p_t data where needed.
- Perform simultaneous coalescence measurements at $y \sim 2.5$. The simultaneous measurements in the MRS will concentrate on higher field running at $y \sim 1$ to collect higher p_t data at $y \sim 1$ utilizing the new Cherenkov for pion identification.

This set of measurements is estimated to require $\sim 240 \mu\text{b}^{-1}$ delivered to IP2. This is not what is planned for Run-4, where the call for $300 \mu\text{b}^{-1}$ delivered to Phenix will result in $\sim 100 \mu\text{b}^{-1}$ for BRAHMS because of the difference in β^* at the two IPs. The collaboration is in the process of prioritizing the program, and will evaluate progress during the run.

Au-Au at lower $\sqrt{s_{NN}}=63$ GeV

- High- p_t measurement at $y \sim 1$. (MRS)
- Survey of net-proton, kaon and π distributions utilizing the FS.

¹ The overall request for BRAHMS baseline program, i.e., for the coming few years, is based on the physics outlined above and translates to the following requested delivered luminosities to BRAHMS. This

Fe-Fe at full energy

- High-pt measurements with identified charged hadrons at $y \sim 1$ and 2.5 .
- These runs will result in a rapidity distribution for net-protons (baryons), establish the particle composition at the two rapidities, and explore strangeness production as a function of rapidity.

p-p at 200 GeV

- Transverse asymmetry measurements for π^+ and π^- at $x_F \sim 0.2$ to 0.4 .
- Completion of reference pp spectra in particular at $\eta \sim 2.2$ and $\eta \sim 4$.

Scheduling Considerations

The BRAHMS collaboration has a strong preference, in part because of the commitments that the Danish and Norwegian groups have to ALICE (which is expected to start taking physics data in 2008, but with construction completed before then), and in part because the physics program is part of the RHIC heavy-ion survey and discovery phase, that the heavy-ion program be given priority for the next few years, with the polarized pp program during this time emphasizing development and measurements requiring only short run periods. This was reflected in the distribution of beams and run lengths given in the detailed request for the next 3 run periods in the Beam Use Proposal as Table 1. After the actual execution of the Run-4 Au-Au period we will evaluate the need for additional requests of Au-Au at full energy.

Future Extensions and Summary

In the Beam Use Proposal and here we have outlined a set of measurements for the next 3 years where BRAHMS can contribute significantly and uniquely to the RHIC heavy ion program through systematic studies with Au-Au at full energy, at a lower energy of $\sqrt{s_{NN}} = 63$ GeV, and with a lighter species mapping properties of high- p_t suppression and particle production over a wide rapidity range. In addition we envision measurements of transverse spin asymmetries for π^+ and π^- .

The new preliminary result from BRAHMS presented at the DNP meeting in Tuscon for the nuclear modification factor R_{dAu} at large rapidities demonstrates that the present understanding of the reaction mechanisms for particle production at large rapidity and high-pt is not well understood. Such

is done under the assumptions that in Run IV the IP-2 is at β^* of 3. With a very modest upgrade of power supply distribution in the triplet a β^* of 2 can be achieved in subsequent years.

measurements, particularly for the d(p)-A system and extended to higher p_t , could help establish the saturation scale and how important saturation effects are at RHIC. Discussions have been initiated on a new, focused, forward-physics experiment to be implemented after completion of the BRAHMS baseline program. The physics possibilities were discussed at a recent one-day workshop for “Forward Physics at RHIC”². Such a program could encompass an extended study of “saturation physics”, opportunities in spin physics, and a more detailed mapping of the phase diagram for the media created in RHIC collisions. Current discussions consider upgrades to the existing BRAHMS facility to increase solid angle coverage, or new detectors dedicated to answer specific questions that are not addressed by the current RHIC detectors.

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² Program and presentations can be found at <http://www4.rcf.bnl.gov/~videbaek/fphar/Index.html>