Substantial theoretical and high-energy heavy-ion collision experimental efforts worldwide have been devoted to the investigation of strongly interacting matter under extreme conditions. At present, the RHIC and the LHC have been investigating the properties of the QCD matter at very high temperature and almost zero net baryon density. Lattice QCD data indicate a smooth crossover from hadronic to the quark-gluon matter [1] in this region of the QCD phase diagram. The region of high net-baryon density in the QCD phase diagram can be reached in the heavy-ion collision at relatively lower energies. Beam Energy Scan (BES) program of RHIC is currently studying large region of baryonic chemical potential. In the region of high net-baryon density a first order phase transition from hadronic to QGP phase is expected. The region of high net-baryon density will also be investigated at CERN-SPS with the upgraded NA49 detector (NA61-SHINE) using light and medium size beams. In future, Compressed Baryonic Matter (CBM) [2] experiment at Facility for Antiproton and Ion Research in Darmstadt will also cover the
high net-baryon density region of the QCD phase diagram. It is expected that beam ener-
gies between 30 and 40 AGeV (on fixed target), or $\sqrt{s}$ between 6 and 10 AGeV will
create the highest net-baryon densities in the laboratory [3].

5.1 The Facility for Antiproton and Ion Research

The Facility for Antiproton and Ion Research (FAIR) [2, 4] in Darmstadt, Germany
will provide unique research opportunities in the fields of atomic, nuclear, hadron and
plasma physics. There will be several experimental programs like Compressed Baryonic
Matter (CBM), anti-Proton ANnihilations at DArmstadt (PANDA), Nuclear Structure
Astrophysics and Reactions (NUSTAR). Figure 5.1 shows the FAIR together with the
existing layout of GSI facilities. FAIR includes a superconducting double-synchrotron
(SIS100/300) with a circumference of 1100 meters and with magnetic rigidities of 100
and 300 Tm, respectively. The upgraded existing accelerators at GSI like UNILAC and
SIS18 will serve as the injector. Figure 5.1 also shows the antiproton production target,
the proton linac, the superconducting fragment separator (Super-FRS), the collector ring
(CR), the rare isotope production target, the accumulator ring (RESR), the new experi-
mental storage ring (NESR), the high energy antiproton storage ring (HESR) along with
the experimental stations for CBM, plasma physics, radioactive ion beams (Super-FRS),
atomic physics, and low-energy antiproton and ion physics (FLAIR).

5.2 The Compressed Baryonic Matter (CBM) experiment at FAIR

The CBM experiment will start with initial beams from the $SIS$100 synchrotron. This
synchrotron will provide protons beam unto $E_{lab} = 29$ GeV, $Au$ unto 11 AGeV, nuclei
with $Z/A = 0.5$ unto 14 AGeV. Later SIS300 synchrotron will come with beam of pro-
tons unto 90 GeV, $Au$ unto 35 AGeV and nuclei with $Z/A = 0.5$ up to 45 AGeV [5].
Maximum beam intensity of CBM experiment will be $10^9$ $Au$ ions per second. The strat-
ey of CBM experiment is to perform measurements of almost all the particles produced
in nuclear collisions with unprecedented precision and statistics. These measurements
will be conducted in nucleus-nucleus, proton-nucleus and proton-proton collisions at dif-
ferent beam energies. For the identification of multi-strange hyperons, hypernuclei, par-
ticles with charm quarks and vector mesons decaying into lepton pairs requires very high
interaction rates and efficient background suppression. CBM experiment will not use
any external trigger system. Self-triggered read-out electronics, a high-speed data acquisition system, fast algorithms, radiation hard detectors are prerequisites for a successful operation of the experiment.

5.2.1 Diagnostic probes

Vector mesons like $\rho$, $\omega$ and $\phi$ mesons are produced continuously via $\pi\pi$ annihilation during the way of the reaction and decay either again into mesons, or into a pair of leptons. Since leptons are electromagnetically interacting, they are not affected by final-state interactions. Hence the dileptonic decay offers the possibility to look directly into the fireball. On the other hand, particles containing charm quarks are expected to be created in the very first stage of the reaction. Then, it is expected that D mesons and $J/\Psi$ mesons may serve as probes for the dense fireball. However, since their mass is large, their production probabilities are very small compared to lighter particles like pions. Those rair particles will also be identified via their leptonic decay channel. In order to compensate for the low yields of the rare particles, the measurements will be performed

Figure 5.1: Layout of the Facility for Antiproton and Ion Research (FAIR). This figure is taken from Ref. [4].
at an exceptionally high reaction rates (up to 10 MHz for certain observables).

5.2.2 Detectors/Components of CBM experiment

The CBM experiment comprises the following components:

5.2.2.1 Dipole magnet

The dipole magnet will be superconducting in order to reduce the operation costs. It has a large aperture of $\pm 25\degree$ polar angle, and provides a magnetic field integral of 1 Tm [6].

5.2.2.2 Micro-Vertex Detector (MVD)

The determination of the decay vertices of open charm particles requires detectors with excellent position resolution and a very low material budget in order to reduce multiple scattering. These requirements are met by Monolithic Active Pixel Sensors (MAPS). The pixel size will be between $18 \times 18 \mu m^2$ and $20 \times 40 \mu m^2$ [5]. For the latter size, a position resolution of $\sigma = 3.5 - 6 \mu m$ can be achieved. The goal of the detector development is to construct vacuum compatible MAPS detector stations with a total thickness of about $300 - 500 \mu m$ silicon equivalent for sensors and support structures, depending on the size of the stations. The MVD consists of 3 MAPS layers located 5, 10 and 15 cm downstream the target in the vacuum. This detector arrangement permits to determine the secondary decay vertex of a D mesons with a resolution of about $50 - 100 \mu m$ along the beam axis.

5.2.2.3 Silicon Tracking System (STS)

This detector system’s task is to measure the trajectories and momenta of charged particles originating from the zone of interactions of heavy-ion beams with nuclear targets. The charged particle multiplicity will be upto 700 per event within the detector acceptance. The STS [7] consists of 8 tracking layers of silicon detectors located at distances between 30 cm and 100 cm downstream of the target inside the field of dipole magnet. The required momentum resolution is of the order of $\Delta p/p = 1\%$. The concept of the STS tracking is based on silicon microstrip detectors on lightweight ladder-like mechanical supports. The sensors will be read out through multi-line micro-cables with fast electronics at the periphery of the stations where cooling lines and other infrastructure can be placed. The micro-strip sensors are double-sided with a stereo angle of $7.5\degree$, a strip pitch of $58\mu m$, strip lengths between 20 and 60 mm, and a thickness of $300\mu m$ of silicon. The micro-cables will be built from sandwiched polyimide-aluminum layers of several $10\mu m$ thickness.
5.2.2.4 Ring Imaging Cherenkov Detector (RICH)

The RICH detector [8] is designed to provide identification of electrons and suppression of pions in the momentum range below 10 GeV. This can be achieved using a gaseous RICH detector built in a standard projective geometry with a photo detector and focusing mirror elements. $\text{CO}_2$ with a pion threshold for Cherenkov radiation of 4.65 GeV will be used as radiator gas. This detector will be positioned behind the dipole magnet about 1.6 m downstream of the target. It will consist of a 1.7 m long gas radiator and two arrays of mirrors and photo detector planes. The mirror plane is divided horizontally into two arrays of spherical glass mirrors of area $4 \times 1.5 m^2$ each. The design of the photo detector plane is based on MAPMTs in order to provide high granularity, high geometrical acceptance, high detection efficiency of photons also in the near UV region and a reliable operation. Figure 5.2 shows the CBM experimental facility with the RICH detector.
5.2.2.5 Muon Chamber System (MUCH)

The MUCH [5] will be used to detect muons. The vector mesons like $\rho, \omega, \phi$ and $J/\Psi$, which decay into dimuons, will be identified by MUCH. The experimental challenge for muon measurements in heavy-ion collisions at FAIR energies is to identify low-momentum muons in an atmosphere of high particle densities. This concept is realised by dividing the hadron absorber into several layers, and placing triplets of tracking detector planes in the gaps between the absorber layers. The absorber or detector system is placed downstream of the STS which determines momentum of the particle. The design of the muon detector system consists of 6 hadron absorber layers. First one is made of 60 cm carbon and rest are made of irons $(20 + 20 + 30 + 35 + 100 \text{ cm thickness})$ and 18 gaseous tracking chambers placed in triplets behind each absorber piece. The challenge for the muon chambers and for the track reconstruction algorithms is the very high particle density up to a maximum of 0.3 hits/cm$^2$ per central event in the first detector layers after the first absorber. For a reaction rate of 10 MHz this hit density translates into a hit rate of 3 MHz/cm$^2$ [5]. Highly granulated Gas Electron Multiplier (GEM) detectors will be used for this purpose. Figure 5.3 shows the CBM experimental facility with the MUCH detector.
5.2.2.6 Transition Radiation Detector (TRD)

The TRD will be used to identify electrons and other charged particles [5]. This detector consisting of 3 detector layers located at approximately 5 m, 7.2 m and 9.5 m downstream the target. The total active detector area amounts to about 600 m$^2$. The TRD detector readout will be realized in rectangular pads giving a resolution of 300 – 500 $\mu$m across and 3 – 30 mm along the pad. Every second TRD layer is rotated by 90°. The TRD will be consists of Micro Wire Proportional Counter (MWPC) and GEM detectors.

5.2.2.7 Timing Multi-gap Resistive Plate Chambers (MRPC)

In time-of-flight (TOF) [9] technique, mass of the hadron is determined by estimating the time of flight, the particle momentum and the particle track length. The timing Multi-gap Resistive Plate Chambers (MRPC) consists of an array of resistive plate chambers. The TOF is located about 6 m downstream of the target for measurements at SIS100, and at 10 m at SIS300. The TOF wall covers an active area of about 120 m$^2$. The required time resolution is of the order of 80 ps. For 10 MHz minimum bias Au+Au collisions, the inner part of the detector has to work at rates up to 20 kHz/cm$^2$.

5.2.2.8 Electromagnetic Calorimeter (ECAL)

In order to reconstruct photons and neutral mesons ($\pi^0$, $\eta$) decaying into photons, a “shashlik” type calorimeter as installed in the HERA-B, PHENIX and LHCb experiments will be used [5]. The ECAL will be made of modules which consist of 140 layers of 1mm lead and 1mm scintillator, with cell sizes of $3 \times 3$ cm$^2$, $6 \times 6$ cm$^2$ and $12 \times 12$ cm$^2$. The shashlik modules can be arranged either in a tower geometry with variable distance from the target or as a wall.

5.2.2.9 Projectile Spectator Detector (PSD)

To determine the orientation of the reaction plane and the collision centrality, PSD will be used [5]. A very precise characterisation of the event class is of crucial relevance for the analysis of event-by-event observables. The study of collective flow requires a well-defined reaction plane which has to be determined by a method not involving particles participating in the collision. The detector is designed to measure the number of non-interacting nucleons (i.e., spectators) from a projectile nucleus in nucleus-nucleus collisions. The PSD is a full compensating modular lead-scintillator calorimeter which gives very good and uniform energy resolution. The calorimeter comprises 44 individual modules, each consisting of 60 lead/scintillator layers with a surface of $20 \times 20$ cm$^2$. The
scintillation light is read out via wavelength shifting (WLS) fibres by Multi-Avalanche Photo-Diodes (MAPD) with an active area of $3 \times 3$ mm$^2$ and a pixel density of $10^4$ /mm$^2$.

5.2.2.10 Data Acquisition System (DAQ)

High statistics measurements of particles with extremely small production cross sections require high reaction rates. The detectors of the CBM experiment, the online event selection systems, and the data acquisition will be designed for very high event rates up to 10 MHz, corresponding to a beam intensity up to $10^9$ ions/s and a 1% interaction target, for example [5]. Measurements with event rates of 10 MHz require online event selection algorithms which reject the background events by a factor of 100 or more. The event selection system will be based on a fast on-line event reconstruction running on a high-performance computer farm equipped with multi-core CPUs and graphics cards (GSI GreenIT cube). The track reconstruction, which is the most time-consuming stage of the event reconstruction will be performed on parallel track finding and fitting algorithms, implementing the Cellular Automaton and Kalman Filter methods.

5.2.3 Summary of CBM experiment

The CBM experiment will create a medium of high net-baryon density. A first order phase transition from hadronic to QGP medium is expected to observe in this experiment. CEP is also expected to be observed in this experiment. Since reaction rate will be very large, rare particles like $J/\Psi$ can be measured precisely. Medium modification of low mass vector mesons will expected to provide valuable information about the dense baryonic matter. A careful analysis of the dilepton yield might provide information about the thermal fireball. For the successful operation of this experiment, require self-triggered readout electronics, high-speed DAQ and radiation hard fast electronics.

5.3 Dilepton as a probe of QGP

In the chapter 1 we have mentioned various probes which may help to study the properties QGP. Among these signals fluctuations-correlations, quarkonium suppression, strangeness enhancement, collective flow, photons, dileptons are the most important. Out of them photons and dileptons are the cleanest signals, since they are electromagnetically interacting particles. The mean free path of the photons and leptons exceed the size of the system formed by the heavy ion collisions and hence, they come out of the system.
immediately after their production, carrying the information about the system. In this chapter, we want to study dilepton contribution resulting from the interaction between secondary partons in a locally thermalized QGP \((q + \bar{q} \rightarrow l^+ + l^-)\) at FAIR energy. These dileptons will be useful for detector simulation for CBM experiment at FAIR. Dilepton will also be produced from the thermalized hadronic system. However, we will concentrate on thermal dileptons from QGP system only. In heavy-ion collisions, there are other sources of dileptons like dilepton from heavy quarkonium decay. Drell-Yan contribution during initial \(q\bar{q}\) collisions will also be present there. This contribution is present even in \(pp\) collisions. Among different sources, thermal dilepton, described above, is expected to serve as a probe to the QGP and therefore, it is very important to study this contribution.

### 5.3.1 Thermal dilepton production in a static QGP medium

It is assumed that in heavy-ion collisions at ultrarelativistic energies the initial temperature \(T_i\) and chemical potential \(\mu_i\) become so large that the QGP will be formed. After formation of QGP, the system expands in all possible directions. As a result, temperature and / or baryonic chemical potential decrease. In QGP phase, dileptons are produced dominantly from quark-antiquark annihilation process. In this process, a quark interacts with an antiquark to form a virtual photon which afterwards decays into lepton pair. The number of dilepton produced per unit four-volume is

\[
\frac{dN_{l^+l^-}}{d^4x} = N_c N_s^2 \sum_{f=1}^{N_f} \frac{(e_f)^2}{e} \int \frac{d^3p_1 d^3p_2}{(2\pi)^6} f_1(E_1) f_2(E_2) \sigma(M) v_{12} \tag{5.1}
\]

where \(N_c, N_s\) are color and spin degeneracy factors respectively, \(N_f\) is the number of flavor, \(e_f\) is the electric charge of a quark with flavor \(f\), \(v_{12}\) is the relative velocity between quark and antiquark. \(f_1(E_1)\) and \(f_2(E_2)\) are the quark and antiquark distribution function respectively, where

\[
f(E) = \frac{1}{e^{(E+\mu)/T} + 1} \tag{5.2}
\]

the \((-)\) and \((+)\) sign correspond to the distribution function for quark and antiquark respectively.

\(\sigma(M)\) is the cross section of the process \(q\bar{q} \rightarrow l^+l^-\) and for massless initial particles the expression is given by

\[
\sigma(M) = \frac{4\pi}{3} \frac{\alpha^2}{M^2} \sqrt{(1 - \frac{4m_l^2}{M^2})(1 + \frac{2m_l^2}{M^2})}, \tag{5.3}
\]

where \(\alpha = \frac{1}{137}\) is the fine structure constant, \(m_l\) is the rest mass of the lepton and \(M\) is the invariant mass of the dilepton.
In case of massless quark and antiquark, the number of dileptons produced per unit dilepton invariant mass squared $M^2$, per unit four-volume, is given by [10]

$$
\frac{dN_{l^+l^-}}{dM^2d^4x} = N_c N_s^2 \sum_{f=1}^{N_f} \left( \frac{e_f}{e} \right)^2 \frac{\sigma(M)}{2(2\pi)^4} M^2 f_1(\varepsilon) F_2 \left( \frac{M^2}{4\varepsilon} \right) \left( \frac{2\pi}{w(\varepsilon)} \right)^{1/2}. \quad (5.4)
$$

In Eq. 5.4

$$
F_2(E) = - \int_{\infty}^{E} f_2(E') dE',
$$

$\varepsilon(M)$ is the root of the equation

$$
\frac{d}{dE} [\ln f_1(E) + \ln F_2 \left( \frac{M^2}{4E} \right)]_{E=\varepsilon} = 0,
$$

and is given by

$$
\varepsilon = \frac{M}{2} \left[ \frac{1 + e^{(\varepsilon-\mu)/T}}{\ln(1 + e^{-(M^2/(4\varepsilon) + \mu)/T})(1 + e^{(M^2/(4\varepsilon) + \mu)/T})} \right]^{1/2}. \quad (5.7)
$$

The most important point of the above equation is that the both left hand side and right hand side contain $\varepsilon$. So for a particular $T$ and $\mu$ we have to solve this equation to get $\varepsilon$. For $\mu = 0$ and $M >> T$, an approximate solution of $\varepsilon$ is

$$
\varepsilon \approx M/2,
$$

and the quantity within the square bracket is approximately unity.

The quantity $w(\varepsilon)$ in Eq. 5.4 is

$$
w(\varepsilon) = - \left[ \frac{d^2}{dE^2} [\ln f_1(E) + \ln F_2 \left( \frac{M^2}{4E} \right)] \right]_{E=\varepsilon},
$$

and the expression is

$$
w = \frac{4}{MT} \left[ \left( \frac{M^2}{4\varepsilon} \right)^3 \frac{1 + [1 + \frac{\varepsilon}{2\varepsilon}] e^{-(\varepsilon-\mu)/T}}{(1 + e^{-(\varepsilon-\mu)/T}) \ln(1 + e^{-(M^2/(4\varepsilon) + \mu)/T})(1 + e^{(m^2/4\varepsilon + \mu)/T})} \right], \quad (5.10)
$$

For $\mu = 0$ and $M >> T$, an approximate solution of $w$ is

$$
w \approx \frac{4}{MT}. \quad (5.11)
$$

### 5.3.2 Thermal dilepton using Bjorken Hydrodynamic model

Till now we have calculated dilepton production for static plasma, i.e., temperature and the chemical potential of the system are held fixed. However, temperature and the chemical potential of the system will decrease as a function of proper time during the evolution
CHAPTER 5. THERMAL DILEPTON AT FAIR

of the system. So we have to consider some dynamics of the system. For simplicity, we assume one-dimensional Bjorken hydrodynamical model [11] where it is assumed that in heavy-ion collisions the system expands mainly in beam direction in a boost-invariant way. Thermodynamical quantities like temperature, pressure do not depend on rapidity. But they depend on proper time \( \tau = \sqrt{(t^2 - z^2)} \). Though the Bjorken model is expected to be valid for ultrarelativistic energies (LHC, RHIC) one can assume it can be used at SPS and FAIR energies as well [12].

In case of one-dimensional Bjorken expansion \( d^4x = \pi R_A^2 \tau d\tau dy \), where \( R_A \) is the radii of the colliding nuclei, \( y \) is the fluid rapidity. Integrating Eq. 5.4 over \( d^4x \) we get

\[
\frac{dN_{l^+l^-}}{dM} = \int 2M \left( \frac{dN_{l^+l^-}}{dM^2 d^4x} \right) d^4x.
\]  

(5.12)

So,

\[
\frac{dN_{l^+l^-}}{dM dy} = \int 2M(N_cN_s^2 \sum_{f=1}^{N_f} \left( \frac{e_f}{e} \right)^2 \frac{\sigma(M)}{2(2\pi)^4} M^2 f_1(\varepsilon) F_2 \left( \frac{M^2}{4\varepsilon} \right) \left( \frac{2\pi}{w(\varepsilon)} \right)^{1/2} \pi R_A^2 \tau d\tau.
\]  

(5.13)

To calculate the above-mentioned quantity we have to know the initial time of the expansion of the fireball as well as the dependency of temperature and chemical potential of the system with time for which we have to know the equation of state of the system. It is assumed that the hydrodynamic expansion starts when the two Lorentz-contracted nuclei have passed through each other. Initial time of hydrodynamical expansion can be estimated using the Eq. 5.14 (and is assumed to be at least 1 fm) [13]

\[
t_i = 2R \sqrt{\frac{2m_N}{E_{lab}}}.
\]  

(5.14)

where \( \gamma \) is the Lorentz-contraction factor, \( v \) is the velocity of the nuclei, \( m_N \) is the nucleon mass and \( E_{lab} \) is the kinetic energy of the beam. Within this time, all initial baryon-baryon scatterings have progressed and also the energy deposition has taken place. This is the earliest probable time where thermalization might be achieved [14]. However in our calculations, we use initial time of expansion of the fireball as 1 fm which is assumed to be the earliest time [13] of the expansion.

Now we will discuss the calculation of initial temperature and chemical potential of the system. In Bjorken picture, one can show that at \( z = 0 \),

\[
\frac{ds}{dy} = \pi R^2 \tau s,
\]  

(5.15)

where \( s \) is the entropy density. For non dissipative and inviscid fluid \( \tau s = \) constant. Therefore in Bjorken scenario \( \frac{ds}{dy} = \) constant [15]. If we assume that the entire evolution of the
fireball from the initial time $\tau_i$ till the freeze-out time $\tau_f$ is strictly adiabatic and a negligible amount of entropy is generated during phase transition from QGP to hadronic phase then we can write

$$\frac{ds}{dy_i} = \frac{ds}{dy_f}. \quad (5.16)$$

To calculate entropy density we have to know the partition function of the system. In fact, any thermodynamic quantity can be calculated once we know partition function of the system. The partition function ($Z$) for a thermalized system is given by

$$\ln Z = \frac{V g}{(2\pi)^3} \int_0^\infty \pm d^3p \ln[1 \pm \exp((-p - \mu)/T)], \quad (5.17)$$

where $V$ is the system size, $g$ is the degeneracy and the upper and lower sign corresponds to fermions and bosons respectively. Here we consider massless relativistic particles. The $\ln Z$ for QGP system can be written as

$$(\ln Z)_{\text{QGP}} = (\ln Z)_g + (\ln Z)_q + (\ln Z)_{\bar{q}}, \quad (5.18)$$

where $(\ln Z)_g$, $(\ln Z)_q$ and $(\ln Z)_{\bar{q}}$ are the contributions of gluon, quark and anti-quark part respectively. Pressure can be calculated from the partition function using the relation $P = T \frac{\partial}{\partial V} (\ln Z)$.

For a QGP system, pressure can be written as,

$$P_{\text{QGP}} = T \frac{\partial}{\partial V}(\ln Z)_{\text{QGP}} = P_g + P_q + P_{\bar{q}}, \quad (5.19)$$

where $P_g$, $P_q$ and $P_{\bar{q}}$ are the pressures for the gluon, quark and anti-quark part respectively. For gluonic part

$$P_g = T \frac{\partial}{\partial V}(\ln Z)_g = -\frac{T g_g}{(2\pi)^3} \int_0^\infty d^3p \ln[1 - \exp(-p/T)]$$

$$= g_g \frac{\pi^2 T^4}{90}, \quad (5.20)$$

where the degeneracy factor for gluon $g_g$ is 16. The quark and anti-quark contribution to the pressure can be written as [16]

$$P_q + P_{\bar{q}} = T \frac{\partial}{\partial V}(\ln Z_q + \ln Z_{\bar{q}})$$

$$= -\frac{T g_q}{(2\pi)^3} \int_0^\infty d^3p \ln[1 + \exp(-(p - \mu)/T)]$$

$$+ \frac{T g_{\bar{q}}}{(2\pi)^3} \int_0^\infty d^3p \ln[1 + \exp(-(p + \mu)/T)]$$

$$= g_q \left(\frac{7\pi^2 T^4}{360} + \frac{\mu^2 T^2}{12} + \frac{\mu^4}{24\pi^2}\right), \quad (5.21)$$
where \( g_q = g_{\bar{q}} = 12 \) for two flavor quarks and anti-quarks. Therefore for QGP,

\[
P_{QGP}(T, \mu) = g_{QGP} \frac{\pi^2 T^4}{90} + g_q \left( \frac{\mu^2 T^2}{12} + \frac{\mu^4}{24\pi^2} \right),
\]

(5.22)

where \( g_{QGP} = (g_g + \frac{2}{3} g_q) \). For two flavor system \( g_{QGP} = 37 \). The entropy density of the same system can be calculated as

\[
s_{QGP}(T, \mu) = \frac{1}{V} \frac{\partial}{\partial T} (T \ln Z)_{QGP} V,\mu = \frac{37\pi^2 T^3}{90} + 2\mu^2 T.
\]

(5.23)

Again \( \frac{ds}{dy} \) can be written as, \( \frac{ds}{dy} = \frac{ds}{dn} \frac{dn}{dy} \). It can be shown that \( \frac{ds}{dn} = 3.6(4.2) \) for ideal bosons (fermions) at high \( T \) with \( \mu = 0 \). Using Eq. 5.15, the Eq. 5.16 can be written as

\[
s_i(T_i, \mu_i) = \frac{1}{\pi R^2 \tau_i} \left( \frac{ds}{dn} \frac{dn}{dy} \right)_f.
\]

(5.24)

where \( s_i \) is the entropy in QGP phase (Eq. 5.23) at temperature \( T_i \) and chemical potential \( \mu_i \). It can be seen that the above equation relates \( T_i \) and \( \mu_i \) with \( \frac{dn}{dy} \). However since there are two unknown \( T_i \) and \( \mu_i \), another information is needed. In Bjorken scenario one can also show that at \( z = 0 \)

\[
\frac{dn_b}{dy} = \pi R^2 n_b \tau.
\]

(5.25)

and \( n_b \tau = \text{constant} \), where \( n_b \) is the net-baryon density and is given by

\[
n_b(T, \mu) = \frac{1}{3} n_q = \frac{1}{3} n_q \left( \frac{1}{3} \frac{T}{V} \left( \frac{\partial}{\partial \mu} (\ln Z)_{QGP} \right)_{V,T} = \frac{1}{3} \frac{\partial P_{QGP}}{\partial \mu}\right)
\]

\[
= \frac{2\mu T^2}{3} + \frac{2\mu^3}{3\pi^2},
\]

(5.26)

where \( n_q \) is the quark density. The factor three is due to the fact that there are three quarks in a baryon.

Therefore in Bjorken picture, \( \frac{dn_b}{dy} = \text{constant} \). As a result one can connect \( \frac{dn_b}{dy} \) at initial time with that of freeze-out time by the relation

\[
\left( \frac{dn_b}{dy} \right)_i = \left( \frac{dn_b}{dy} \right)_f.
\]

(5.27)

Here we assume that net-baryon density does not change during phase transition from QGP to hadronic phase. Therefore

\[
n_b(T_i, \mu_i) = \frac{1}{\pi R^2 \tau_i} \left( \frac{dn_b}{dy} \right)_f.
\]

(5.28)
If initial time ($\tau_i$) of hydrodynamic expansion is known then it is possible to calculate $T_i$ and $\mu_i$ from Eqs. 5.24 and 5.28 using $\frac{dn}{dy}$ and $\frac{dn_b}{dy}$. However in an experiment $\frac{dn}{dy}$ and $\frac{dn_b}{dy}$ are not measured. In experiments we can have the information about multiplicity of charge particles and net-proton. Using statistical thermal model one can relate total particle multiplicity with total charge particle multiplicity and net-baryon with net-proton and therefore we can calculate $\frac{dn}{dy}$ and $\frac{dn_b}{dy}$.

To know the time evolutions of $T$ and $\mu$, we have used the Eqs. $n_b \tau = \text{constant}$ (conservation of net-baryon number) and $\varepsilon \tau^{1+c_s^2} = \text{constant}$ (conservation of energy density) where $\varepsilon$ is the energy density of the system, $c_s$ is called velocity of sound. Value of $c_s^2 = \frac{1}{3}$ for ideal relativistic system.

Energy density for ideal QGP can be calculated as

$$\varepsilon_{QGP}(T, \mu) = -\frac{1}{V} \frac{\partial}{\partial(1/T)} \ln(Z_{QGP})_{\mu/T}$$ (5.29)

We have already shown the expressions of $n_b$ (Eq. 25) and $\varepsilon$ (Eq. 28). They depend on temperature and chemical potential. Therefore the temperature and chemical potential of the system at a particular time can be calculated using the relations $n_b \tau = (n_b \tau)_i$ and $\varepsilon \tau^{1+c_s^2} = (\varepsilon \tau^{1+c_s^2})_i$ and using the information of initial conditions $T_i$ and $\mu_i$.

### 5.3.3 Results

Using the available experimental data of heavy ion collisions ($R \sim 6.3$ fm) near $\sqrt{s} = 8$ GeV [17, 18], we have estimated $T_i$ and $\mu_{b_i}$ as 181 MeV and 1034 MeV respectively. In Fig. 5.4 we have shown variation of temperature and baryonic chemical potential with time. Here we have assumed that the system is in QGP phase till $\varepsilon = 0.6$ GeV/fm$^3$ which
corresponds to four times the nuclear density ($150 \text{ MeV/fm}^3$) which is comparable to the values obtained from UrQMD model [13]. It can be seen that the system belongs to the QGP phase up to $\tau = 3.8 \text{ fm}$. Further, since we are using $c_s^2 = 1/3$, cooling law is same as $T^3 \tau = \text{constant}$ and $\mu^3 \tau = \text{constant}$.

In Fig. 5.5 we have shown the time evolution of pressure, energy density and entropy density and net-baryon density. All these quantities decrease with time since temperature and chemical potential decrease with time.

In the Fig. 5.6 we have shown distribution of invariant mass of thermal dilepton. This thermal dilepton produces a continuum in invariant mass distribution. It can be seen that $dN/(dMdy)$ is non-zero in the invariant mass region from 0.2 to 1.7 GeV for muon and from 0 to 1.7 GeV for electron. The Magnitude of $dN/(dMdy)$ is slightly higher for electronic contribution compared to muonic contribution.

Now we will discuss application of these calculations in simulation for CBM experiment at FAIR. For CBM experiment, muon detector system consists of segmented absorbers with tracking chamber triplets placed in between the absorber segments [19].
Figure 5.6: Dilepton invariant mass distribution at FAIR energy.

Figure 5.7: A schematic view of MUCH layout

Figure 5.8: Reconstructed invariant mass of di-muons.
Since total absorber thickness is divided into thinner segments, this system allows identifying muons over a wide range of momenta depending on the number of absorber segments that the particles have passed through. Using those theoretical calculations we have generated four-momentum of $\mu^+$ and $\mu^-$ and used them in simulation in CBMROOT. To use this, we have used FairAsciiGenerator as our primary event-generator. Geometry which is used in this simulation is SIS300. There are 6 absorbers, first one made of 60 cm carbon and rest made of irons (20 + 20 + 30 + 35 + 100 cm) (Fig. 5.7). There are 6 tracking stations sandwiched between absorber layers. Each tracking station consists of the triplet of detector layers resulting in the number of layers to be 18. However, for low mass vector mesons, only first 15 detector layers will be used. After passing through absorbers and detectors, we have reconstructed the invariant-mass of muon pairs. We have used several cuts like hits in MUCH detectors $\geq 14$, hits in STS detectors $\geq 4$ and $\chi^2 < 3$. We have compared reconstructed invariant-mass of muon pairs coming from low mass vector mesons $\rho$ and $\omega$. For generating $\rho$ and $\omega$, we have used pluto event generator [20]. In Fig. 5.8 we have shown the reconstructed invariant mass of di-muons. It can be seen that in low mass region thermal part is buried inside low-mass vector mesons. However, they are important in the intermediate mass region.

5.3.4 Summary

We have estimated initial temperature, chemical potential as well as time evolution of them at FAIR energy. Further, we have estimated thermal dilepton yield from a QGP source at FAIR energy and used them in simulation for the CBM experiment at FAIR. This is the dominating contribution of dilepton from thermal QGP source. Finally, we have compared reconstructed muons with low mass vector mesons. We have seen that thermal dilepton from QGP source is not important at low mass region where low mass vector-mesons dominate. However they are important in the intermediate mass region.

Bibliography


CHAPTER 5. THERMAL DILEPTON AT FAIR


