The report for the **Exchange Visit** in the frameworks of the
**EFS Program "Super-intense laser-matter interactions" (SILMI)** of

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in the research group led by Prof. Dimitri Batani

## The purpose of the visit

The research objectives of this proposal, concerns the study of ultra-high-intensity laser-matter interaction, in the target material, and the study of the heating of the target material induced by X-ray and fast electron propagation.

We were going to continue and to finish some steps of our work concerning the propagation of laser shocks in layered target, including the application to numerical description of experiments on equation of state (EOS). In particular we were going to finish some step of our previous work on porous carbon EOS, namely to study the possibility to estimate necessary conditions relative the shock stationarity and the influence of preheating. There was realized the collaborative work with some Italian and foreign colleagues, which included the development of experimental data and the work with computer simulations.

## Description of the work carried out during the visit

The equation of state (EOS) of carbon at high pressures is a subject of interest for several branches of physics, including astrophysics (the description of high-pressure phases is essential for realistic models of planets and stars [1,2], in particular for the explanation of large magnetic fields of giant planets such as Uranus and Neptune [3,4]), material science (carbon is a unique element due to its polymorphism and the complexity and variety of its state phases), applied engineering (first of all including inertial confinement fusion research), etc.

The important phenomenon of carbon metallization at high pressure has been predicted theoretically but until now there are difficulties with experimental proving. The first theoretical estimates [5] set the triple point for the transition among diamond, liquid metal, and solid metal at 1.7 Mbar and 3100 K, but this prediction was not in agreement with experimental [6, 7]. More recent works set the metallic transition at much larger pressures. At higher temperatures, liquid phases were predicted, going from non-metallic at low pressures to semi-metallic and metallic at high ones. The first experimental evidence of a liquid metallic phase was given in [8,9]. Nowadays, the most accepted phase diagram of carbon by Grumbach and Martin [10] sets the structural changes in liquid carbon from about fourfold to about sixfold coordination (metallic liquid) in the pressure range 4–10 Mbar.

To reach this liquid metallic phase in lab conditions is possible by the laser-driven shocks. Indeed due to momentum conservation from the laser ablation and plasma expansion in vacuum the material is pushed inside generating shock wave. The shock pressure (in Mbar) of such shocks can be estimated by [11]:

$$P = 11.6\left(I/10^{14}\right)^{3/4}\lambda^{-1/4}\left(A/2Z\right)^{7/16}\left(Z^{*}t/3.5\right)^{-1/8}, \qquad (1)$$

where $I$ is the laser intensity on target in W/cm$^2$, $\lambda$ is the laser wavelength in μm, and $A$, $Z$, and $Z^*$ respectively are the mass number, the atomic number, and the effective ionization degree of the target, and the time $t$ is in ns. So the intensities of the order of $10^{14}$ W/cm$^2$, which can be obtained quite easily, allows getting pressures of the order of 10 Mbar.

A large problem of the application of laser shock for the EOS measurements is in difficulties to obtain uniform high-quality profile. Really this problem was overcome only in ninetieth of XX century. [12-14] On of the technique, which was used in resent experiments on porous EOS [15] consist in application of Phase Zone Plates (PZP) [12], which allows eliminating the laser hot spots while getting an almost flat-top laser irradiation profile.

A general limitation of shock-wave EOS experiments is that shocks compress and heat the material at the same time, so pressure and temperature are not independent variables, and thereby only data on the Hugoniot curve of the material could be obtained. One way to overcome such a limitation is to use a sample with a reduced density (porous or foam target). This changes the initial conditions in the material so that data along different Hugoniot curves are obtained. In particular, by reducing the initial density of the sample, the same shock pressure $P$ will correspond to a higher temperature $T$ (or internal energy $E$) and a reduced final density.

One of the must fruitful experimental methods is based on the impedance mismatch technique and consists in simultaneous measuring of the shock velocity for two different materials (test and reference). The first one is the material with unknown EOS (carbon in our case) while the second one is a reference material (we have chosen aluminium, because its EOS is well known at high pressures [16]). The shock-wave measurements are realised by recording the emissivity of the rear side of the shocked target with time and space resolution. Using rear-face time-resolved imaging, we can experimentally determine the velocity of the shock propagating through the two steps $D_{\mathrm{Al}}$ and $D_{\mathrm{C}}$, corresponding to particle velocities $U_{\mathrm{Al}}$ and $U_{\mathrm{C}}$, respectively. If the EOS (and hence also the Hugoniot curve) of the base material (aluminium) is known, we can determine an EOS point for the test material (carbon). This is a ‘‘relative’’ measurement since it uses aluminium as a reference material. In order to find the EOS point for carbon, we consider the intersection in the $(P,U)$ plane of the line $P=\rho_{\mathrm{C}}D_{\mathrm{C}}U$, where $\rho_{\mathrm{C}}$ is the density of cold carbon, with the reflected shock polar drawn from the point $(P_{\mathrm{Al}}\,,U_{\mathrm{Al}})$.

The critical point of this method is the preheating of target caused by secondary X-rays and hot electrons. Such nonlinear physical phenomena take place at laser intensities ($I$) of the order of $10^{14}/\lambda^2$ W/cm$^2$, where $\lambda$ in mm is the laser wavelength. Propagation of the shock wave in an X-ray preheated medium involves several simultaneous processes, including the (i) impact of X-ray generation on shock pressure and (ii) changes in shock velocity due to target rear side expansion. Since hard X-rays and hot electrons are the principal causes of preheating of the material ahead of the shock wave, it is clear that intensities on target above this limit must be avoided in EOS experiments, but even in case of product ($I\lambda^2$) has order $10^{13}$ it is necessary to be careful in the interpretation of experiments. [17]

Other critical point is the necessity of the reaching of stationary conditions for the shock. Otherwise the measured shock velocity is not corresponded to Hugoniot parameters. Although many experiments [12–15] proved the possibility of creating spatially very uniform shocks in solids, the analysis of these factors is still urgent and open question.

The aim of our work was to make 1D simulation of the processes, having place in multi-layers targets, then to find the “times of shock arrival” for every step of target, reconstruct from these values the Carbon EOS, and finally compare it with both tabulated EOS, used in simulation, and experimental data. That gives a possibility: (i) to test the tabulated carbon EOS itself, (ii) to find the effect of above-mentioned phenomena (preheating and shock non-stationarity) on a possible systematic error in real experiments, (iii) to compare obtained data with resent experimental EOS results obtained for porous carbon [15], make more exact experimental data reducing estimated systematic error, and (iv) finally specify tabulate EOS taking into account new experimental data. In our resent paper [18] we have presented the EOS calculated by MQEOS for carbon with reduced density. In this paper we have concentrated for the second item of our common task, namely to analyze the effect of preheating and shock non-stationarity on a possible systematic error for the initial laser intensity ~ $10^{13}$-$10^{14}$ W/cm$^2$.

The typical scheme of present-day laser-driven EOS experiment with the considered target structure is shown in the figure 1. The sizes and configurations were considered like it was realised in some resent experiments. [15] The application of plastic (CH) base layer reduces the amount of X-rays and produces softer, hence less penetrating X-rays, strongly reducing preheating. [19] In discussed in this paper simulations there was considered the use of high-power Nd-laser with conversation to second harmonic ($\lambda$=0.526 $\mu$m).

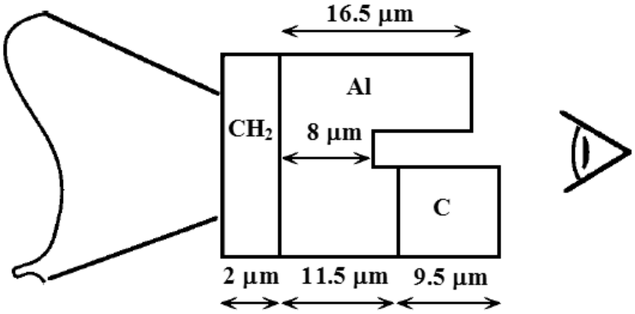

Fig.1 Sketch of the configuration of EOS measurements by impedance mismatch technique with the considered target. From the shock travelling time in these steps, measured in real experiments with a visible streak camera, the shock velocities $D_{Al}$ and $D_C$ are determined.

For each simulation of experimental EOS investigation by impedance mismatch technique we have realised 3 different 1D sub-simulations for targets: (i) CH-Al (2 $\mu$m + 8 $\mu$m), (ii) CH-Al (2 $\mu$m + 16.5 $\mu$m), and (iii) CH-Al-C (2 $\mu$m + 11.5 $\mu$m + 9.5 $\mu$m). For each of sub-simulation there was found the time of the shock arrival to the rear target surface, like it should be reached in real experiment. Afterward from these 3 times of arrival there were calculated 2 shock velocity $D_{Al}$ and $D_C$ for aluminium and carbon correspondently. Then using the known shock polar and Hugoniot-Rankine relation for momentum conservation ($P=\rho DU$) for aluminium we have found the point ($U_{Al}$, $P_{Al}$) corresponding to $D_{Al}$. Afterward using the known relaxation curve for aluminium from the point ($U_{Al}$, $P_{Al}$) up to relation $P=\rho_C D_C U$ (momentum conservation for carbon) we have found the point ($U_C$, $P_C$) which should correspond to shock polar for carbon.

For the realisation of simulations we have applied hydrocode MULTI (multigroup radiation transport in multilayer foils) [20]. We have used the SESAME equation of state for aluminium, porous carbon EOS calculated by MPQEOS [21, 22] with a reduced initial density (1.6 g/cm$^3$) [16] and the SNOP opacities [23]. The flux limiter was taken with the usual value $f$=0.06, since it is well known that this value can well reproduce experimental results [24].

Let us see the figures 2, which presents the dependences of pressure in the sub-simulations CH-Al-C (2 $\mu$m + 11.5 $\mu$m + 9.5 $\mu$m) the dependences of pressure from spatial coordinate for a set of times. We can see that for relatively small intensities in order of $10^{13}$ W/cm$^2$ for simulations without account of radiation transport, the pressures obtained from the shock velocities are corresponded to real shock pressure in each material at least in first approximation. For the intensity 2 $10^{13}$ W/cm$^2$ the shock pressure remain close to constant for aluminium from -10 $\mu$m (the end of first aluminium step), and for all carbonic part, but it is not impartial for 2 $10^{14}$ W/cm$^2$. Let us also to see in fig. 3, which demonstrates dependences of pressure (solid line) and density (dotted line) from spatial coordinate for the time of the shock arrival in the Al-C border. It is important that in the presence of radiation transport (and it is certainly presents in any real experiment) the density profile of tested material stopped to be uniform. The initial density of tested material in the boarding can be lower or upper, that it was before.

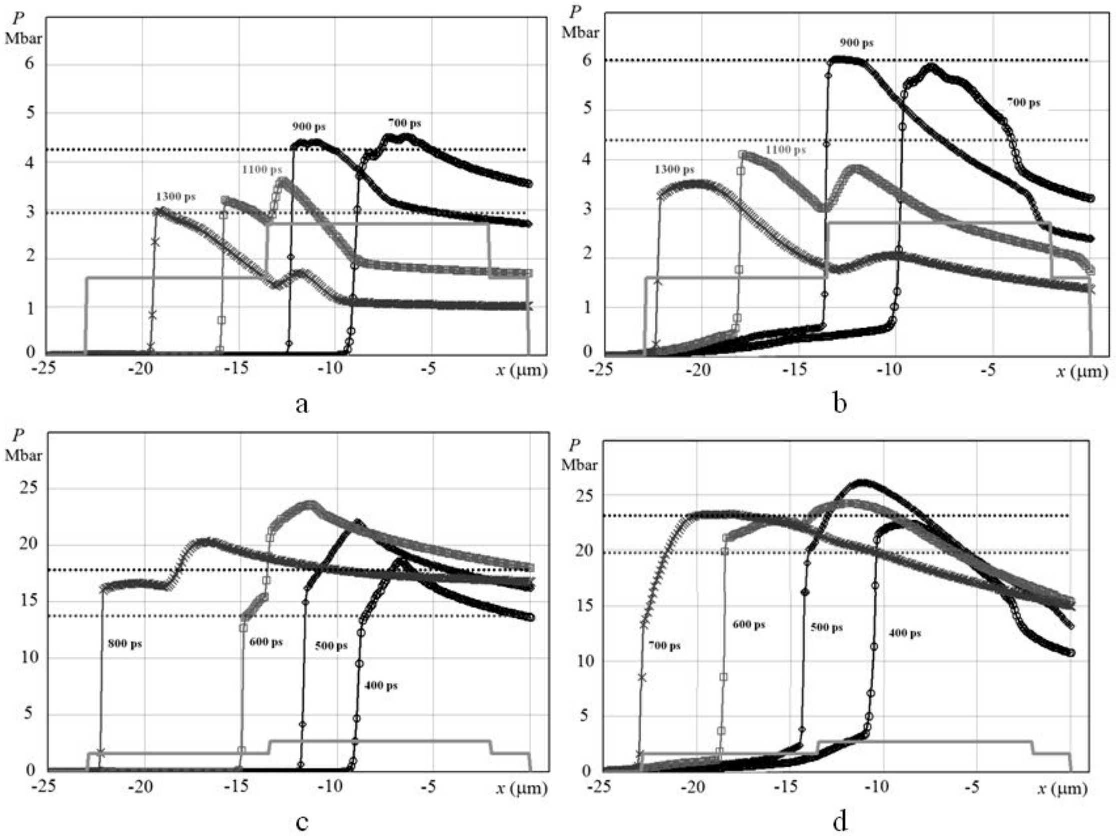

Fig 2. The dependences of pressure from spatial coordinate for a set of times. Gray solid rectangular polygon corresponds to spatial dependence of initial target density (g/cm$^3$). The simulation made without (left) and with (right) account of radiation transport for initial laser intensity about 2 10$^{13}$ W/cm$^2$ (upper), and 2 10$^{14}$ W/cm$^2$ (lower) Gaussian profile, pulse duration $\tau_{FWHM}$=0.6 ns were considered.

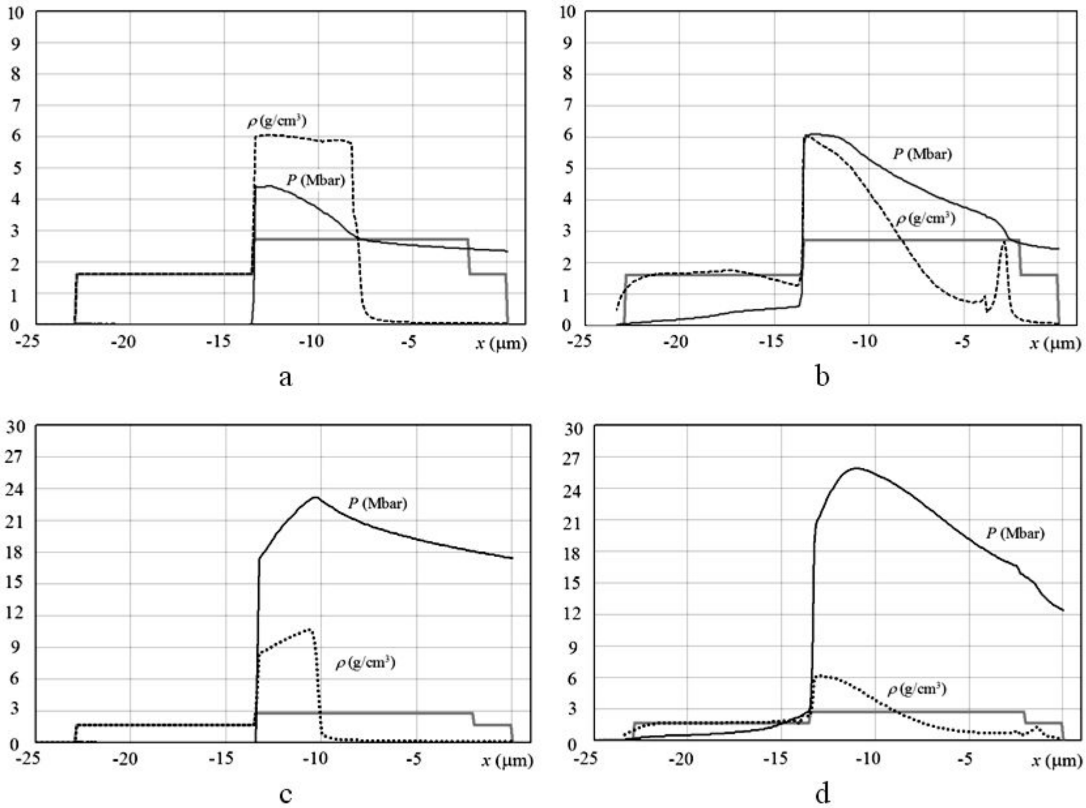

Fig 3. The dependences of pressure (solid line) and density (dotted line) from spatial coordinate for the time of the shock arrival in the Al-C border. Gray solid rectangular polygon corresponds to spatial dependence of initial target density (g/cm$^3$).

So, we can conclude that it is quite rough approximation to consider stationary shock especially for large laser intensities > $10^{14}$ W/cm$^2$, and although it can give appropriable results, it is necessary to be careful with conclusions. The non-agreement of latest experimental data [15] with existed theoretical predictions could also be a result of regular error based by non-stationarity of shock in tested region based both in X-ray-preheating and non-flattop laser profile.

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## Description of the main results obtained

We have numerically investigated the experimental impedance mismatch techniques to study the EOS of porous carbon. Finally we can conclude the principal possibly a porous carbon EOS measurements up to laser intensities of order $10^{14}$ W/cm$^2$ (in second or third harmonics of Nd-laser). But the radiation transport account is important for the correct description shock propagation and can qualitatively change the common results. The full results will be reported and publicized soon.

## Future collaboration with host institution

This visit was a step of a longtime collaboration between visitor and host University started in 2004. We are going to continue our joint work in area of investigation of high-power laser-matter interaction.

## Projected publications/articles resulting or to result from the grant (ESF must be acknowledged in publications resulting from the grantee’s work in relation with the grant).

The visit is just finished, so the publication of results in good peer-reviewed journals (we have planned to realize at least 2) will be realized in 2010-2011.

We are going to present the report contained the acknowledgements to SILMI in frameworks of this visit in the conferences:

1. International School “Towards Fusion Energy” Kudowa Zdroj, Poland, June 8-12, 2010
2. 24th Symposium on Plasma Physics and Technology June 14-17, 2010, Czech Technical University, Faculty of Electrical Engineering Technicka 2, Prague 6, Czech Republic
3. 37th Conference on Plasma Physics” of European Physical Society, Dublin. Ireland, 21-25 June 2010
4. Fourth International Conference on Superstrong Fields In Plasmas, October 2010, Sunday 3 to Saturday 9, Villa Monastero, Varenna, Italy

etc.

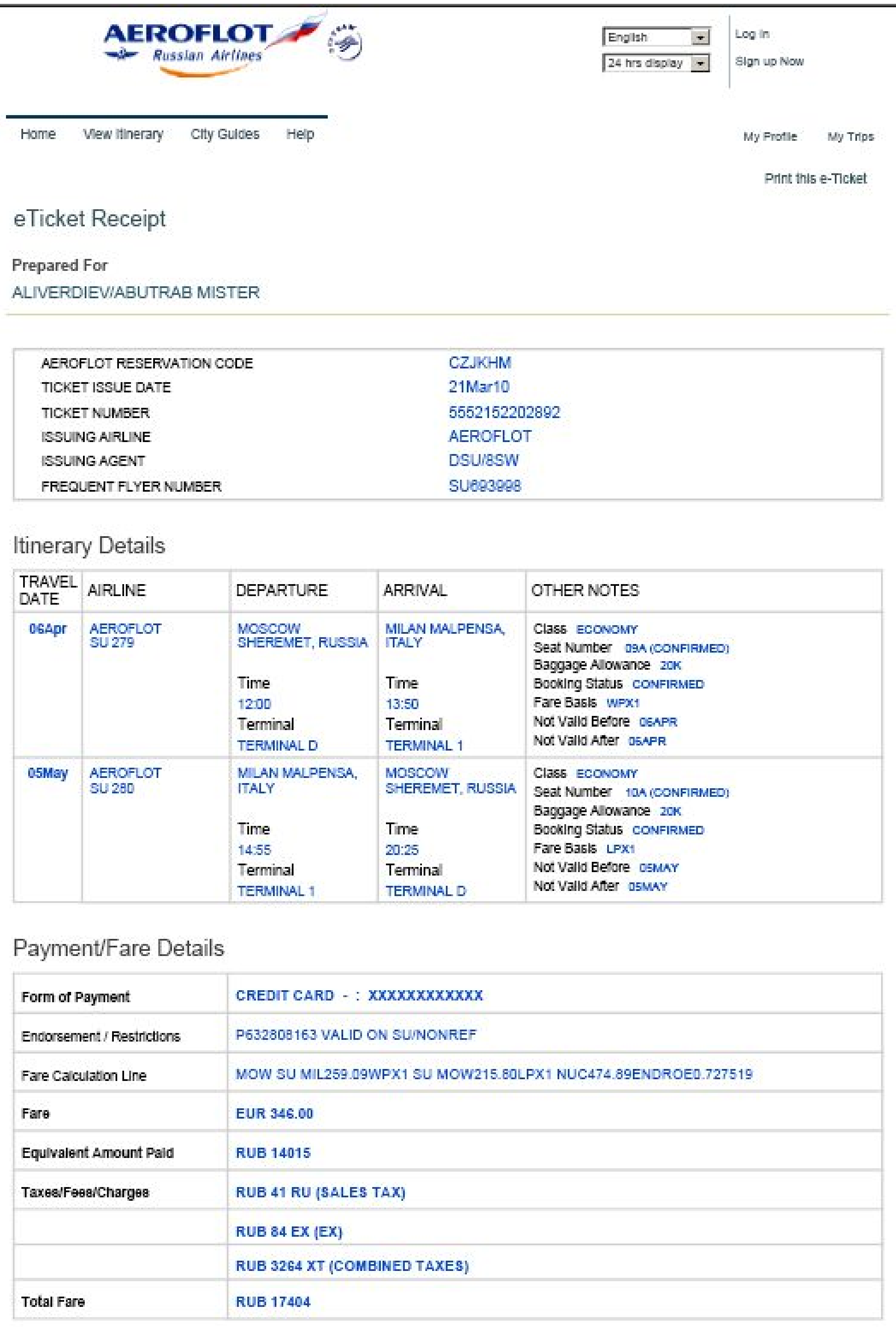
## Other comments

The one-month visit was planned 1-30 April, but by the reason the University was closed from 1 up to 6 April coursed by Easter holiday, we a little shift the time of visit from 6 April up to 5 May (30 days) of stay in Milan. The minimal time of transport connection between Makhachkala (home-town of visitor) and Milan is 1-3 days. So, the real time of visit was started 5 April and finished 8 May.

The total cost of travel was
346 Euro Moscow-Milan-Moscow air-ticket,
132 Euro (5250 Russian Rubles) Makhachkala-Moscow air-ticket,
52 Euro (2052 Russian Rubles) Moscow-Makhachkala train-ticket,
11+11=22 Euro tickets Malpensa airport – Milan – Malpensa airport,
7 Euro (250 Russian Rubles) – tickets town-airport in Moscow.

So, the total travel cost was 560 Euro (more than 400 Euro, that it was planned).

The copies of tickets are attached.



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| TICKET NUMBER | 5552152202892 |
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## Itinerary Details

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| 06Apr | AEROFLOT<br>SU 279 | MOSCOW SHEREMET, RUSSIA<br>Time<br>12:00<br>Terminal<br>TERMINAL D | MILAN MALPENSA, ITALY<br>Time<br>13:50<br>Terminal<br>TERMINAL 1 | Class ECONOMY<br>Seat Number 09A (CONFIRMED)<br>Baggage Allowance 20K<br>Booking Status CONFIRMED<br>Fare Basis WPX1<br>Not Valid Before 06APR<br>Not Valid After 06APR |
| 05May | AEROFLOT<br>SU 280 | MILAN MALPENSA, ITALY<br>Time<br>14:55<br>Terminal<br>TERMINAL 1 | MOSCOW SHEREMET, RUSSIA<br>Time<br>20:25<br>Terminal<br>TERMINAL D | Class ECONOMY<br>Seat Number 10A (CONFIRMED)<br>Baggage Allowance 20K<br>Booking Status CONFIRMED<br>Fare Basis LPX1<br>Not Valid Before 05MAY<br>Not Valid After 05MAY |

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| **Taxes/Fees/Charges** | **RUB 41 RU (SALES TAX)** |
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| | **RUB 3264 XT (COMBINED TAXES)** |
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