# SPACE CHARGE EFFECTS IN THE NICA COLLIDER RINGS

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*Abstract*

The **N**uclotron-based **I**on **C**ollider f**A**cility (NICA) is a new accelerator complex being constructed at JINR aimed to provide experiments with colliding heavy ions up to Au for experimental study of hot and dense strongly interacting baryonic matter and search for possible signs of the mixed phase and critical endpoint in the centre-of- mass energy range $\sqrt{s_{NN}}$ = 4-11 GeV. Two beam cooling systems – stochastic and electron will be used in the collider rings. Parameters of cooling systems, proposed scenario of operation and particular features of their design intended to achieve required average luminosity of the order of $10^{27}$cm$^{-2}$s$^{-1}$at high energies are presented in this report.

## INTRODUCTION

The goal of the NICA project is construction at JINR of the new accelerator facility that consist of [1]: cryogenic heavy ion source of Electron String type (ESIS) with 6T solenoid; source of polarized protons and deuterons, the existing linac LU-20 of Alvaretz type (energy up to 5 MeV/u); a new heavy ion linear accelerators RFQ-DTL (3 MeV/u); a new 600 MeV/u superconducting Booster-synchrotron placed inside the decommissioned Synchrophasotron yoke; the existing and modernized proton and heavy ion synchrotron Nuclotron (4.5 GeV/u maximum kinetic energy for ions with Z/A=1/3); the new system of beam transfer channels, and two new superconducting storage rings of the collider.

The facility will provide ion-ion (1-4.5 GeV/u), ion-proton collisions and collisions of polarized pp (5-12.6 GeV) and polarized dd (2-5.8 GeV) beams. The collider will have two interaction points. The Multi Purpose Detector (MPD) will be used for the first IP, the Spin Physics Detector will be used for the second one.

Collider operation at fixed energy without acceleration of the injected from the Nuclotron beam is considered. Beam storage at some optimum energy and slow acceleration in the collider (at field ramp rate < 1 T/s) is presumed as a reserve option. The maximum energy of the experiment is determined by the Nuclotron maximum magnetic rigidity of 45 T·m. The main purpose of the NICA facility is to provide the collider experiments with heavy ions (e.g. Au) at average luminosity of to $1\cdot10^{27}$ cm$^{-2}$ s$^{-1}$ in the maximally wide energy range up to 4.5 GeV/u.

Therefore we discuss only heavy ion mode of the facility operation and $^{197}$Au$^{+79}$ ions as the reference particles. The space charge effects in the high intensity ion beams are considered. The corresponding beam cooling technique is proposed for collider rings to achieve the required beam parameters.

## COLLIDER LUMINOSITY

Two collider rings have the maximum magnetic rigidity of 45 Tm corresponding to the maximum rigidity of Nuclotron. The rings are vertically separated (32 cm between axes) and use “twin aperture” superconducting magnets (dipole and quadrupoles) [2] except the common Interaction Region part. The maximum field in dipoles of 1.8 T and maximum gradient in quadrupoles of 23 T/m are chosen to avoid the saturation effects in iron yokes. Each ring consists of two bending arcs and two long straight sections representing the racetrack shape with the circumference of 503 m that is exactly two Nuclotron sizes. Collider ring optics is based on FODO periodic cell in arc, 12 cells per each arc. FODO optics shows its more preference in comparison with other optics from the view point of IBS rates, stochastic cooling time reserve for Intra Beam Scattering (IBS) suppression, more convenient scheme for beam injection [3]. In Fig. 1 the assembly of one ring is shown for ion mode of operation, where the layout of stochastic cooling system for that ring and electron cooling, RF systems for both rings are pictured.

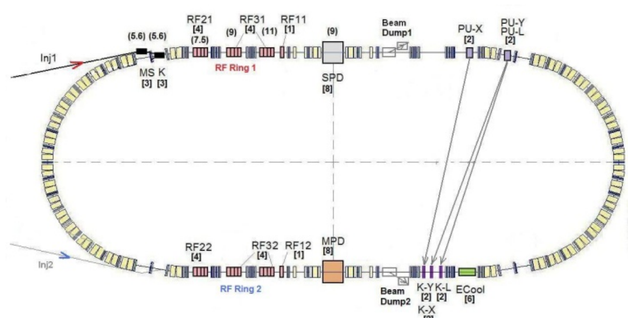


Figure 1: Collider ring composition.

The collider operation in luminosity range of $10^{26}\div10^{27}$ cm$^{-2}$ s$^{-1}$ allows to perform experiments to measure all hadrons comprising multi-strange hyperons, their phase-space distributions and collective flows.

For identical colliding bunches of round shape cross-section the peak luminosity can be written as

$$L = \frac{N_i}{4\pi\varepsilon\beta^*} F_{coll} f_{HG}(\sigma_s, \beta^*), \qquad (1)$$



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where $N_i$ is number ions per bunch, $\varepsilon$ is transverse r.m.s. unnormalized emittance, $\beta^*$ is the value of the beta-function in the collision point, $\sigma_s$ is the r.m.s. value of the longitudinal bunch length, $F_{coll}$ is the collision repetition rate, and so called "hour-glass effect" is calculated by the following formula:

$$f_{HG}(\sigma_s, \beta^*) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{+\infty} \frac{\exp(-u^2)du}{(1+(u\sigma_s/\beta^*)^2)}, \quad (2)$$

The maximum acceptable bunch number is limited by the requirement to avoid the parasitic collisions in the interaction region and equal to 23 bunches in each ring.

The bunch length should be small enough to avoid the "hour glass effect" and to provide the luminosity concentration in the central part of the MPD detector. When the bunch size $\sigma_s$ much less than the beta-function in IP $\beta^*$ the "hour-glass" function $f_{HG}$ closing to unit. But the very small bunch length increases the bunch peak current and thus increases the tune shift and risk of coherent instability. Therefore the compromise $\sigma_s$ value for the collider is chosen to be about 60 cm.

The collider design has to provide the project luminosity and its maintenance during long time required for physics experiments. That includes the formation of high intensity and low emittance beams and support the necessary ion beam life time.

Intense beam life time is limited mostly by the beam space charge effects, which could be estimated by the "tune shift criteria". The main and most strong criterion is the betatron oscillation tune shift, *"Laslett tune shift"*:

$$\Delta Q_{Las} = \frac{Z^2}{A} \cdot \frac{r_p N_i}{\beta^2 \gamma^3 4\pi\varepsilon} \cdot F_{SC} F_b, \; F_b = \frac{C_{ring}}{\sigma_s \sqrt{2\pi}}, \quad (3)$$

where $Z$ and $A$ are ion charge and mass number, $r_p$ is proton classic radius, $N_i$ is ion number per bunch in the bunched ion beam, $\beta$, $\gamma$ are the ion Lorentz factors, $F_b$ is bunch factor, $C_{ring}$ is the collider ring circumference, $\sigma_s$ is r.m.s. bunch length ($\sigma$-value for Gaussian beam), $\varepsilon$ is the ion beam "geometrical" transverse emittance. The second criterion, so called "beam-beam parameter" describes betatron tune shift caused by scattering of ion in the electromagnetic field of encountering ion bunch:

$$\xi = \frac{Z^2}{A} \cdot \frac{r_p N_b (1+\beta^2)}{4\pi\beta^2\gamma\varepsilon} \quad (4)$$

For practical estimations the numerical criterion for the beam stability is used. That is total acceptable betatron tune shift:

$$\Delta Q_{total} = \Delta Q_{Las} + n_\xi \xi \le 0.05, \quad (5)$$

where $n_\xi = 2$ is number of interaction points and limiting value of 0.05 is chosen for betatron tune working point of the collider. The relations between luminosity and tune shift from the beam intensity and emittance can be represented from the formulae above (1-3) as following:

$$L \propto \frac{N_i^2}{\varepsilon} \cdot \varepsilon \cdot f_1(E_i) \cdot f_{HG}, \qquad \Delta Q_{total} \propto \frac{N_i}{\varepsilon} \cdot f_2(E_i), \quad (6)$$

where $E_i$ is ion energy, $f_1$ , $f_2$ are the functions describing energy dependence of parameters, $f_{HG}$ is hour-glass effect function.

Intra beam scattering (IBS) is the main problem defining the intense ion beam life time of the NICA collider. Both electron and stochastic cooling are proposed for IBS suppression. Maximum achievable luminosity is reached at the bunch emittance and intensity corresponding to the space charge limit. In such a regime an increase of the bunch intensity allows increasing the luminosity at the same value of the tune shift. To keep the constant tune shift the beam emittance has to be increased proportionally to the bunch intensity and the luminosity is scaled linearly with the ion number. The maximum luminosity is reached when the bunch phase volume corresponds to the ring acceptance when the total space charge tune shift reaches a resonant value 0.05. This is so called *"Space Charge Dominated Regime"* (SC DR). Using the above Formulae (6) one can derive the simple relations between parameters:

$$L \propto \Delta Q_{total}^2 \cdot \varepsilon \cdot f_3(E_i) \cdot f_{HG}, \qquad N_i \propto \Delta Q_{total} \cdot \varepsilon \cdot f_4(E_i). \quad (7)$$

One can see that maximum luminosity is achieved if beam emittance $\varepsilon$ has maximum, i. e. coincides with the ring acceptance.

For some requirements the luminosity can be limited by detector performance reasons. Then one can optimise the SC DR decreasing equilibrium emittance and $N_b$ (Fig. 2). Such an optimisation can be done with variation of $N_b$ number. In the case of limited luminosity one can also avoid SCD regime decreasing ion number and allowing, by weakening cooling force, the beam emittance keeping $\Delta Q_{total}$ below resonant value. We call it "*IBS Dominated Regime"* (IBS DR) when equilibrium state is provided with equality IBS and cooling rates: $\tau_{IBS} = \tau_{cool}$.

Then at fixed luminosity one could rewrite the relations (6) as following:

$$N_i \propto \sqrt{L \cdot \varepsilon} \cdot f_4(E_i, \beta^*, \sigma_s), \qquad \Delta Q_{total} \propto \sqrt{\frac{L}{\varepsilon}} \cdot f_5(E_i, \beta^*, \sigma_s) < \Delta Q_{max} (= 0.05). \quad (8)$$



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From these proportions one can see that minimum $\Delta Q_{total}$ corresponds to maximum emittance, i. e. full acceptance filling with ions. Simultaneously, it gives us maximum $\tau_{IBS}$ at relatively increased ion number (Fig. 3).

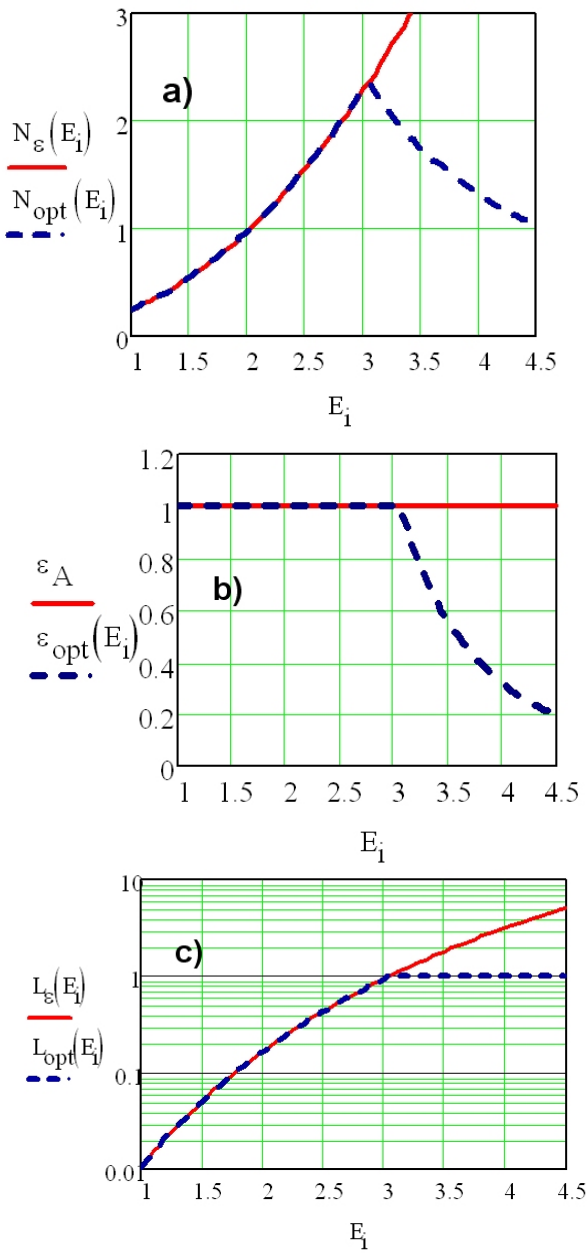


Figure 2: SC dominated regime: ion number per bunch (a), beam emittance (b) and luminosity (c) versus ion energy in two cases: full acceptance if filled with ions (red solid curves) and luminosity is limited (blue dash curve); the ring acceptance = 40 π·mm·mrad, units: $[N_i]$= $10^9$, $[\varepsilon]$= π·mm·mrad, , $[L] = 10^{27}$ $cm^{-2}\cdot s^{-1}$.

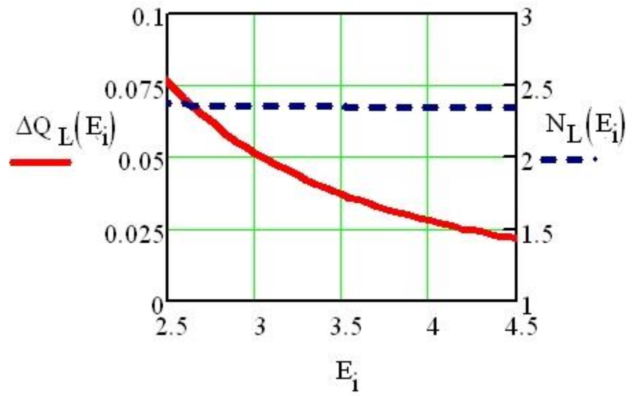


Figure 3: IBS dominated regime; beam tune shift $\Delta Q_{total}$ (red solid curve) and ion number per bunch $N_i$ (blue dash curve) at constant luminosity $L = 1\cdot10^{27}$ $cm^{-2}\cdot s^{-1}$ and beam emittance of 1.0 π·mm·mrad; $[N_i] = 10^9$.

The chromaticity correction scheme in the collider rings provides the transverse dynamic aperture of order 130 π·mm·mrad and relative momentum deviation acceptance of ±1%. The transverse emittances were chosen from the condition of equal heating rates due to IBS. The parameters for this IBS dominating regime are shown in Table 1, where the IBS heating rates were calculated [4] for the chosen momentum spread and transverse r.m.s. emittances of about 1 π mm·mrad. The transverse 6 r.m.s. beam acceptance corresponds to the ring geometric acceptance of 40 π mm·mrad.

Table 1: Collider Beam Parameters and Luminosity

| | | | |
|---|---|---|---|
| Ring circumference, m | 503.04 | | |
| Number of bunches | 23 | | |
| Rms bunch length, m | 0.6 | | |
| β-function in the IP, m | 0.35 | | |
| FF lenses acceptance | 40π mm mrad | | |
| Long. acceptance, Δp/p | ±0.010 | | |
| Gamma-transition, $\gamma_{tr}$ | 7.091 | | |
| Ion energy, GeV/u | 1.0 | 3.0 | 4.5 |
| Ion number per bunch | 2.7e8 | 2.4e9 | 2.2e9 |
| Rms Δp/p, $10^{-3}$ | 0.62 | 1.25 | 1.65 |
| Rms emittance, hor/vert, (unnorm), π·mm·mrad | 1.1/ 1.01 | 1.1/ 0.89 | 1.1/ 0.76 |
| Luminosity, $cm^{-2}s^{-1}$ | 1.1e25 | 1e27 | 1e27 |
| IBS growth time,sec | 190 | 700 | 2500 |



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## COOLING STRATEGY

The application of beam cooling methods in the collider ring [5] has the purposes of beam accumulation using cooling-stacking procedure and luminosity preservation during experiments.

The beam accumulation in the collider is proposed to be realized in the longitudinal phase space with application of RF barrier bucket (BB) technique. This provides the independent optimization of the bunch intensity, bunch number and the control of the beam emittance and momentum spread during bunch formation. The goal of beam accumulation could be achieved with electron beam cooling or stochastic cooling systems with reasonable technical parameters, because of rather low linear particle density. Numerical simulations of the accumulation process with account of longitudinal fields of the beam space charge shown that the stacking of required particle number can be realized at efficiency of about 90%.

During the experiment using the electron beam and stochastic systems should cover the whole energy range to provide the maximum achievable luminosity at low energies and the value about $1\cdot10^{27}$ $cm^{-2}$ $s^{-1}$ at maximum energies. In equilibrium between IBS and cooling the luminosity life time is limited by ion interaction with residual gas. The mean luminosity is close to the peak value because the beam life time is much longer than beam preparation time. In this regime the cooling times have to be equal to the IBS heating times for all degrees of freedom (Fig. 4) . In SC dominating regime at low energies the way to increase luminosity is to provide cooling times sufficiently shorter than the IBS times.

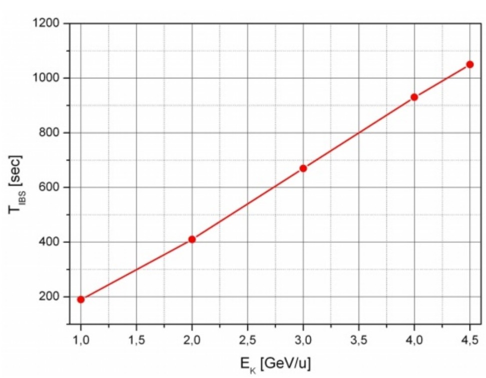


Figure 4: Expected IBS heating times at maximum luminosity.

The stochastic cooling is assumed to be used in the collider to preserve the required luminosity at the energy range from 3 to 4.5 GeV/u. For the higher energies cooling times of about 500 s could be achieved by stochastic cooling system at bandwidth of 3 GHz. The chosen lattice allows to optimize the pickup and kicker positions to provide small partial slip factor from pickup to kicker in the total energy range. For preferable Palmer method of longitudinal cooling the pickup is located in the arc section near the dispersion function maximum. The kicker is located in the long straight section, 140 m downstream from pickup (Fig. 5, 6). The choosing stochastic cooling system bandwidth from 3 to 6 GHz provides the cooling time two-three times shorter than IBS ones (Fig. 7).

*The electron cooling* is used to completely suppress IBS heating at low energy and provide the collider operation in the SC DR. In this case at small momentum spread the transverse emittance can be sufficiently larger, than determined by equi-partitioning condition. Therefore the luminosity at small energy can be sufficiently increased in comparison with IBS DR. For the reasonable technical parameters of the electron cooler the estimated cooling times [5] are shown for total energy range in Fig. 8. In the energy range from 3 to 4.5 GeV/u the cooling times are slightly shorter than expected IBS heating times and are comparable to stochastic cooling times. However at small energies the cooling times are about 20 times shorter than IBS heating times and the electron cooling is strong enough to provide space charge dominated regime of the collider operation. The problem of ion recombination with cooling electron has to be solved for effective cooling application.

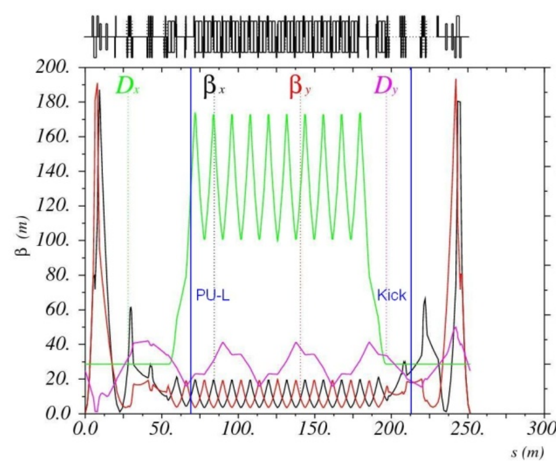


Figure 5: Betatron and dispersion functions over the half of the collider ring. Positions of the longitudinal pick-up and kicker for stochastic cooling are shown.

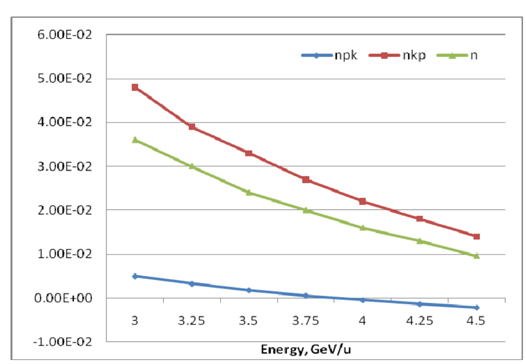


Figure 6: Total and partial slip-factors (from pick-up to kicker and from kicker to pick-up) as a function of ion energy.

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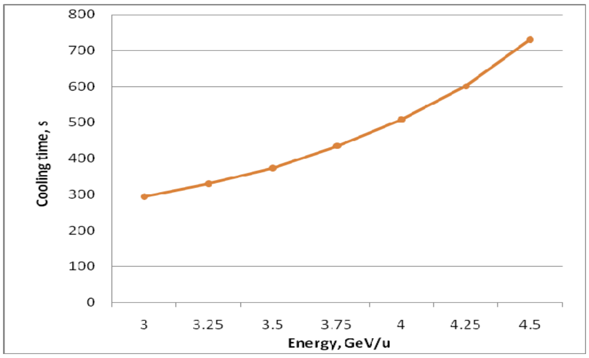


Figure 7: Stochastic cooling time as a function of the ion energy for bandwidth 3-6 GHz.

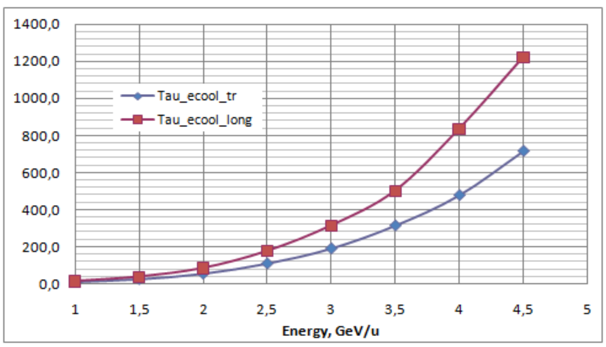


Figure 8: Electron beam cooling times dependences on the ion beam energy.

## CONCLUSION

The collider rings of the NICA accelerator complex have the particular operating features described in this report: SC and IBS dominated regimes. The application of the cooling methods is only way to realize the required collider luminosity parameters. The proposed cooling scenario includes: electron beam cooling in the energy range from 1 to 3 GeV/u can provide short cooling times at the SC dominated regime; the stochastic cooling technique is more preferable in the range 3-4.5 GeV/u where luminosity $1\cdot10^{27}$ $cm^{-2}$ $s^{-1}$ can be obtained in IBS dominated regime (Fig. 9).

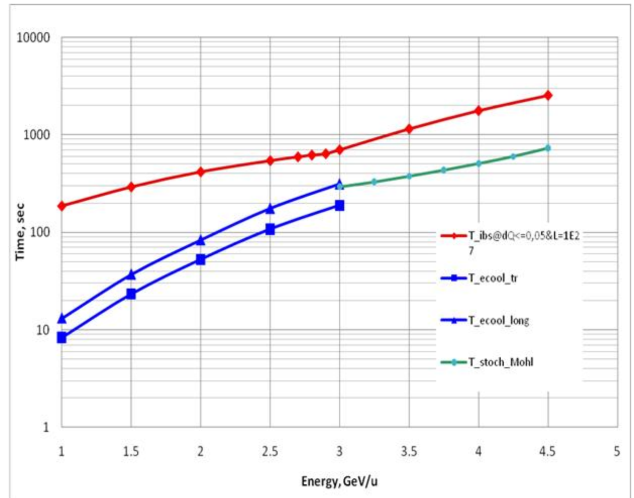


Figure 9: IBS growth times in the IBS dominated regime, electron cooling times (<3 GeV/u) and stochastic cooling time (≥3 GeV/u).

The NICA project has passed the phase of concept formulation and now it is under development of the working project, manufacturing and construction of the prototypes. It includes the design and construction of electron cooling system for the collider (collaboration with BINP, FZJ) and elaboration of stochastic cooling system (with FZJ, FNAL, CERN). The project realization plan implies a staged construction and start of the facility commissioning in 2017.

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