

## PROGRESS IN DEVELOPMENT OF KHARKOV X-RAY GENERATOR NESTOR

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### ABSTRACT

The sources of the X-rays based on Compton scattering of intense Nd:YAG laser beam on electron beam circulating in a storage ring with beam energy 43 – 225 MeV is under construction in NSC KIPT. In the paper the progress in development and construction of Kharkov X-ray generator NESTOR is presented. The current status of the main facility system design and development are described. New scheme and main parameters of injection system are presented. The status of power supply system and control system is described. The facility is going to be in operation in the middle of 2007 and generated X-rays flux is expected to be of about  $10^{13}$  phot/s.

### INTRODUCTION

The paper is one out of regular progress reports of the supported by SfP NATO Grant #977982 project of NESTOR (New-generation Electron STORage Ring) X-ray generator based on Compton scattering of an intense laser beam on electron beam with low energy circulating in a storage ring [1-5]. Technical design report of the facility has been issued last year and design and development of the main facility systems has been continued during the year. By now bending magnets of the lattice and pilot specimens of quadrupole magnets were manufactured, new scheme of injection was designed, the first items of power supply system and control system were produced and are under examination. Elements of vacuum system are under design. Construction of facility foundation was finished by the end of May, 2005 and preparation of the whole operation room will be finished by the end of 2005 year.

### MAIN NESTOR FACILITY PARAMETERS

Radiation intensity and brightness are the main characteristics of any light source. Based on the strategy of maximum X-ray intensity with feasible parameters of technological systems the main NESTOR facility parameters were worked out (Table 1).

Table 1. The main NESTOR facility parameters.

Parameter	Value
Storage ring circumference, m	15.418
Electron beam energy range, MeV	40-225
Betatron tunes $Q_x, Q_z$	3.155; 2.082
Amplitude functions $\beta_x, \beta_z$ at IP, m	0.14; 0.12
Linear momentum compaction factor $\alpha_1$	0.01-0.078
RF acceptance, %	> 5
RF frequency, MHz	700
RF voltage, MV	0.3
Harmonics number	36
Number of circulating electron bunches	2; 3; 4; 6; 9; 12; 18; 36
Electron bunch current, mA	10
Laser flash energy into optical cavity, mJ	1
Collision angle, degrees	10; 150
Scattered photon energy (Nd laser, $\epsilon_{\text{las}} = 1.16$ eV), keV	6-900
Spectral brightness, phot/(s mm <sup>2</sup> mrad <sup>2</sup> 0.1%BW)	$5 \times 10^{12} - 5 \times 10^{13}$

## NESTOR ALLOCATION AND CONSTRUCTION PROGRESS

NESTOR X-ray source is constructed on the base of N-100 electron storage ring and is located in a building of 300 MeV linear accelerator complex. Such decision makes the total cost of the project much cheaper for the reasons of existed infrastructure using and absence of building construction costs. Layout of the NESTOR facility is presented in Fig.1. For new equipment allocation an old radiation shelter has been broken down and new one is going to be build. Old accelerators sections and N-100 storage ring were dismantled and new accelerator section, injection channel and magnetic system of the storage ring along with a laser system will be assembled as it is shown in the figure.

Under design and construction of the NESTOR ring foundation the total mass of equipment (of about 50 tones), geometric parameters and the strict requirements to installation errors of magnetic elements of the ring ( $\pm 75 \mu$ ) were taken into consideration.

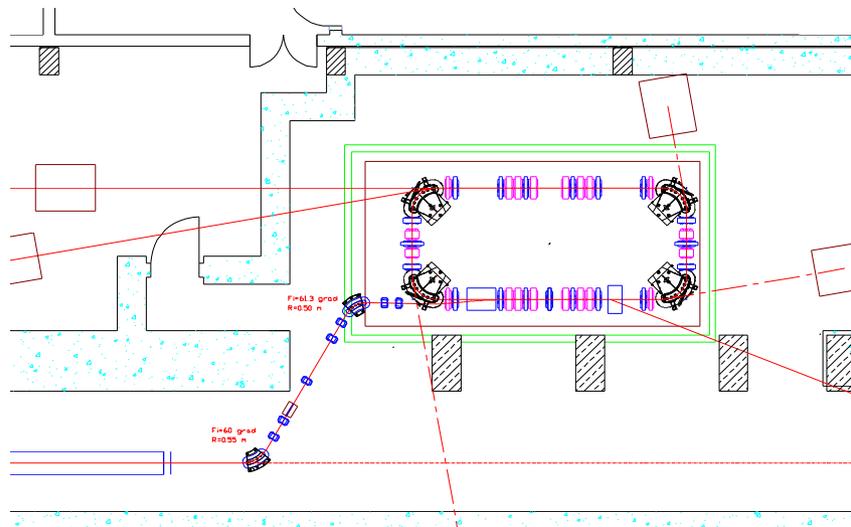


Figure 1: NESTOR facility layout.

Under design and construction of the NESTOR ring foundation the total mass of equipment (of about 50 tones), geometric parameters and the strict requirements to installation errors of magnetic elements of the ring ( $\pm 75 \mu$ ) were taken into consideration.

For maximum reducing of mechanical vibrations from outside sources the foundation is disconnected from other foundations and constructions of the accelerator complex and other surrounding equipments. The foundation is the separate reinforced concrete solid parallelepiped with size  $6.690 \times 3.335 \times 1.200$  m which is set on the river sand pillow of 0.5 m thickness. Sand fills and flanks area around the foundation. In the foundation body a tunnel for cables with size of  $800 \times 600$  mm is set. The general view of the foundation is presented in Fig 2.



Figure 2: General view of the NESTOR ring foundation.

In the foundation metal inserts are installed and a load-bearing metal frame of the ring is assembled to them. Metal inserts are two structural channels with size  $120 \times 52 \times 7.8$  mm each which lain in parallel with the storage ring axes and will be configured as two closed ring (Fig. 2). The distance between structural channels is 500 mm and its value meets to base distance between a **NESTOR** bending magnet supports.

## MAGNETIC LATTICE OF THE NESTOR FACILITY

The detail description of the magnetic lattice of the NESTOR storage ring is presented in [6, 7]. The lattice corresponds to racetrack. Long straight section with IP is dispersion free while dispersion on opposite long straight section is non-zero. The designed lattice includes 4 dipole magnets with combined focusing functions, 20 quadrupole magnets and 19 sextupoles (9 with horizontal-vertical correction, 4 with octupole component of magnetic field). Such huge number of magnetic elements as for compact storage ring with low electron beam energy is dictated by very specific and contradictory requirements to RF acceptance value, beam size at the IP and chromatic effects strength. It is supposed the reference orbit correction system will be used 12 pick-up monitors and 9 correctors. The system will provide as well global reference orbit correction along circumference with accuracy better than  $240 \mu$  as local corrections at the IP.

## MAGNETIC ELEMENTS OF NESTOR

NESTOR bending magnets have been manufactured. The bases for the new magnets were N-100 dipole magnets. Fig. 3 shows view of the NESTOR bending magnet yoke after reconstruction.



Figure 3: NESTOR bending magnet after reconstruction.

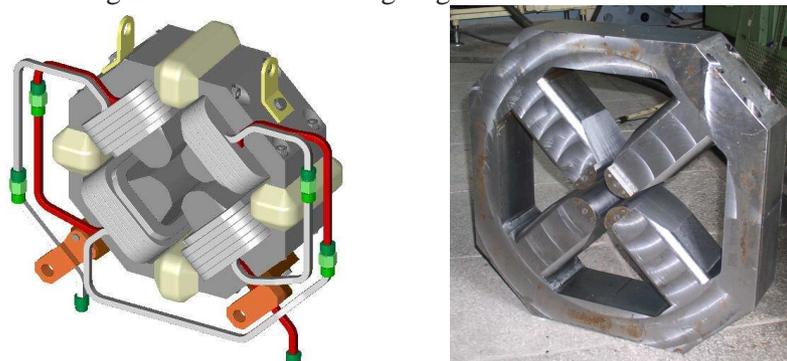


Figure 4: NESTOR quadrupole magnet

Quadrupole magnets of three different size-types but with similar design are under manufacturing. Fig. 4 shows 3D drawing and view of a yoke of the NESTOR quadrupole and Table 4 lists the main magnet parameters. The main quadrupole coils are wound with copper rectangular pipe ( $10 \times 10$  mm) with inner diameter of 7 mm. All quadrupoles are connected in series with bending magnets. To meet parameters of quadrupoles and bending magnets additional low current coils are provided (Fig. 3). NESTOR magnet parameters are listed in [5].

## INJECTION SYSTEM

It is supposed that on the first stage NESTOR will use the 60 MeV accelerator section with the main parameters are listed in [5].

Injection channel is “nearly parallel displacement” scheme with bending angles in line magnets  $\varphi_{B1}=60^\circ$  and  $\varphi_{B2}=-61^\circ$ . The final parallel displacement of the beam is fulfilled with inflector (see Fig. 1). As a base for the channel the classic 5 lenses scheme of parallel displacement was chosen for the reason of its flexible focusing properties. Such achromatic scheme can provide focusing with linear and angle enlargement factor values are equal near 1, so called “T” optics.

We have chosen D-F-D-F-D focusing variant for such scheme provides better beam focusing in the vertical plane. Since final part of the injection channel after parallel displacement (bending magnet fringe field,

quadrupole and inflector) is a dispersion system the parallel displacement part of the injection channel has to compensate the dispersion produced with the final part. The results of the injection channel calculations are presented in Fig. 5. As one can see the injection channel provides beam transportation from linac to the storage ring with required parameters.

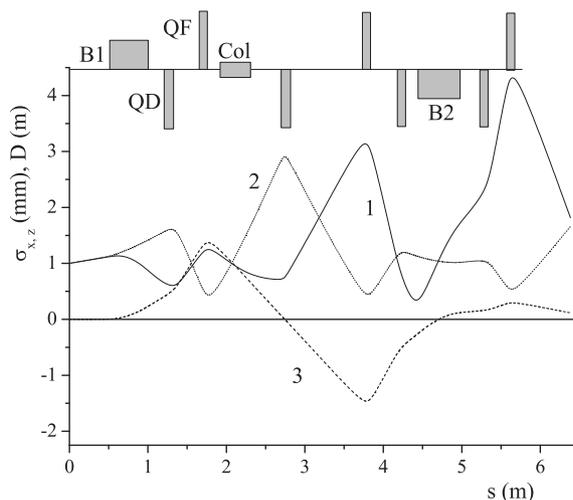


Figure 5: NESTOR injection channel lattice element allocation and injected beam envelopes: (1)-horizontal, (2)-vertical.

Single turn horizontal injection will be performed by means of three fast pulsed electromagnetic deflectors. Fast switches will regulate the voltage on the deflectors. The output of the switches will be matched to the complex load of the deflectors [5]. Two blocks of the deflectors will be based on existed two sections of N-100 deflector.

## VACUUM SYSTEM

The vacuum system of the storage ring NESTOR is intended for production and maintaining of average pressure  $\leq 5 \times 10^{-9}$  Torr in all operation modes with storage current up to 1 A. To provide mentioned above pressure of residual gas both concentrated, and distributed pumping equipment were considered under design of NESTOR bending magnet vacuum chamber. Main units of the chamber are (see Fig. 6): 1 is channel for circulating electron beam which has ellipse profile with axes  $79 \times 27$  mm<sup>2</sup>, with a bending radius equal to 500 mm; 2 is channel for SR beam extraction in the visible and ultra-violet range of radiation spectrum which is ended with a window made of quartz glass or sapphire; 3 is channel for Compton radiation beam extraction; 4 is channel for NEG pump installation; 5 are channels joined to a tract of a circulating electron beam, cameras, intended for a warm-up; 6 are sockets of pipes for installation of ion pumps (MPH) such as TRION-150 or NMD-0,16, manometric converters MI-27 and PMM-46, leak valves, analyzer of a mass - spectrometer.

As the material for manufacturing of cameras leaf of a stainless steel 316L (according to classification of the USA) with parameters: thickness is 20 mm, contents of carbon of about 0.03 %, factor of a magnetic permeability  $\mu_0 < 1,005$  (for inductions 0.1 T) was selected. It is supposed that each camera will be manufactured from two trough-shaped parts and welded with argon-arc welding.

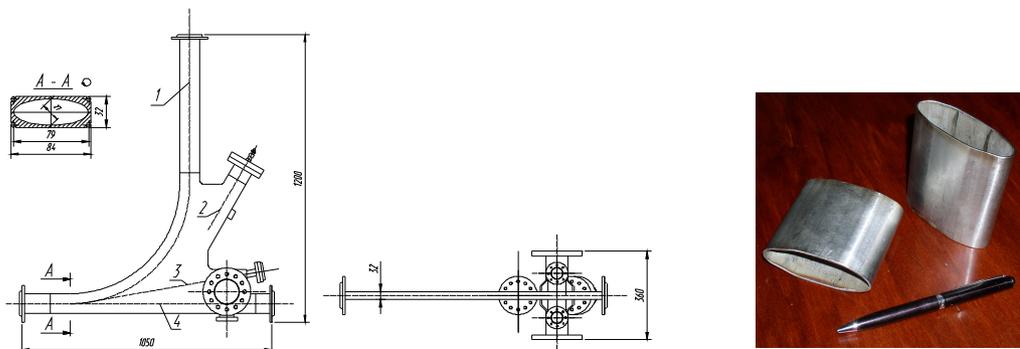


Figure 6: The bending magnet vacuum chamber for X-ray generator "NESTOR"

## LASER OPTICAL SYSTEM

Originally, the laser-optical system (LOS) of NESTOR was featured to provide the following parameters of the laser photon beam in the interaction point (IP):

- number of photons per pulse  $5 \times 10^{15}$
- laser pulse energy  $1 \text{ mJ}$
- pulse duration  $\leq 10 \text{ ps}$
- pulse repetition rate  $58 \text{ MHz}$
- transverse size  $0.1 \text{ mm}$

To obtain the required number of laser photons in the IP we considered pulse trapping from the low power Nd mode-locked laser ( $\lambda=1.064 \mu\text{m}$ ) in the resonance optical system, the simplest one being Fabry-Perot cavity.

For the time being, we have analyzed the effects of mode matching between the laser cavity (LC) and pulse-stacking Fabry-Perot cavity (PSC) upon the stored pulse width and stored power [8]. It was supposed that we can neglect the dispersion and nonlinear effects in the laser cavity, and the LC was presented with an equivalent 2-mirror cavity. The effect of the following parameters was studied: i) PSC length, ii) curvature radius of the LC mirrors, iii) reflectivity of the PSC mirrors and iii) laser-pulse width.

The calculations show that consideration of the wave-front curvature and dispersion in the PSC mirrors results in the following:

- Maximal power enhancement factor is achieved when the laser carrier frequency coincides with the definite axial mode frequency of the PSC, namely with that second to the fundamental mode, i.e., when the shift between resonance frequencies of LC and PSC is equal to the free spectral range (FSR).
- LOS with the short PSC ( $L=0.42\text{m}$ ) ensures better characteristics of the stored pulse than the long PSC originally considered ( $L=2.52\text{m}$ ).
- For the PSC with moderate-reflectivity mirrors ( $R=0,999$ ) the mismatch by 2-3 FSR is admissible without essential deterioration of power enhancement factor (see Fig. 7), while it is not admissible for the super-high-reflectivity (SHR) mirrors ( $R=0,9999$ ). This hampers realization of the scheme with SHR mirrors.
- The stored pulse is essentially widened (a factor of 2÷3) against the incident laser pulse in PSC with SHR mirrors.
- With increasing of the laser-pulse length from 7 ps (a typical pulse-length for the commercially available lasers of IC series) to 20ps the considered effects are drastically reduced.

These results imply that for the case of PSR with SHR mirrors both cavity lengths have to differ by one half of the laser wavelength, and these conditions have to be maintained during all period of generation. This task is the present state-of-the-art of laser optics technology, and it requires much efforts, both financial and scientific, to develop a laser pulse stacking system with power enhancement factors up to  $10^4$ . The power gain factor, which is the ratio of intensities of the stored and incident photon pulses, integrated over pulse duration, is presented in the Fig. 7.

These issues together with the experimental results [9] give us confidence in developing of the LOS with moderate-reflectivity mirrors, which will provide power gains up to 1000.

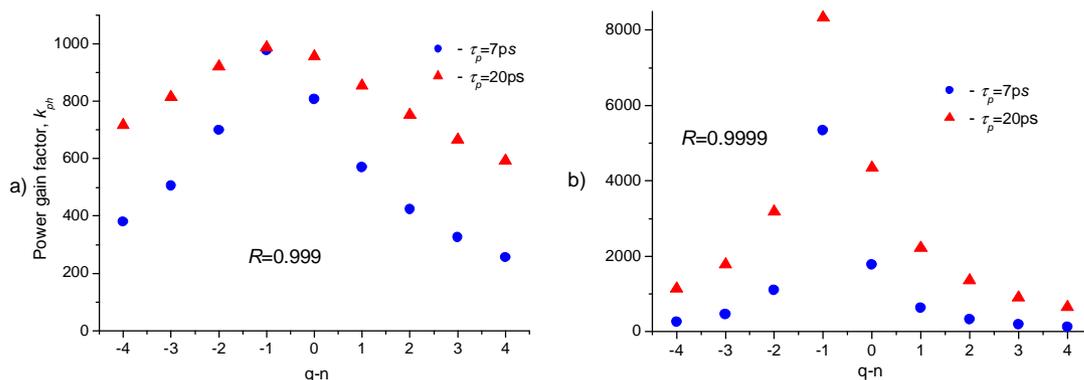


Figure 7: Power gain factor as a function of the cavity mode shift  $q-n$  for medium reflectivity mirrors (a) and SHR mirrors (b). Mode shift by unity corresponds to the difference in the cavity lengths of  $\lambda$ .

## POWER SUPPLY AND CONTROL

To keep required value of current with stability of about  $10^{-4}$  a system of power supply and stabilization with motor-generator as execution unit is under design. In the power supply system which are under design and development all facility units are combined in groups with different power supply sources. Bending and quadrupole magnets are connected in series and are powered by motor-generator with total power 110 kW (maximal load current output 478 A, output voltage 230 V, rotation speed 1470 per minute). Sextupole magnets and correcting coils of all magnets will be connected with separate controlled power supply sources of low power. Control of system parameters will be carried out with IBM type computer through ETHERNET. Control signals through CAMAC controller will be translated to a crate pathway.

Few blocks were designed for control and detuning of currents in magnetic element coils. Block of motor-generator control allows to work as well in automatic (through CAMAC pathway) as handle regime with keyboard. It is supposed that such scheme of power supply system will provide current stability of about  $2.0 \cdot 10^{-5}$ .

## REFERENCES

- [1] E. Bulyak et al, "Compton scattering in the 100 MeV Kharkov storage ring," PROC. PAC-99, June, 1999, New York, USA, v.2, pp. 3122-3124.
- [2] P. Gladkikh et al, "Lattice design for the compact X-ray source based on Compton scattering," Proc. Of EPAC-2000, Vienna, Austria, pp. 696-698.
- [3] E. Bulyak et al, "Compact X-ray Source Based on Compton Backscattering," NIM A, 2002, # 487, pp. 241-248.
- [4] A. Agafonov et al, "Spectral Characteristics of an Advanced X-ray Generator at the KIPT Based on Compton Back-Scattering", Proc. SPIE48th annual meeting, August, 2003, San Diego, USA.
- [5] V. Androssov et al, "Status of Kharkov X-ray Generator based on Compton Scattering NESTOR", Proc. of EPAC 2004, pp.2412-2414.
- [6] P. Gladkikh et al, "Lattice of NSC KIPT Compact Intense X-ray Generator NESTOR," EPAC-2004, Lucerne, Switzerland, pp. 1440-1442.
- [7] P. Gladkikh, "Lattice and beam parameters of compact intense x-ray sources based on Compton scattering", Physical Review Special Topics - Accelerators And Beams **8**, 050702 (2005), 10p.
- [8] V.A. Androssov, I.M. Karnaukhov, Yu.N. Telegin, "Coherent stacking of laser pulses in a high-Q optical cavity for accelerator applications", e-preprint: <http://arxiv.org/list/physics/0407028>, 2004, 11p.
- [9] R.J. Loewen, "A compact Light Source: Design and Technical Feasibility Study of a Laser-Electron Storage Ring X-ray Source", SLAC-R-632, SLAC, Stanford University, Stanford, 2003, 105p.