THE DEVELOPMENT OF SYNCHROTRON RADIATION SOURCE OF NRC “KURCHATOV INSTITUTE”

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РУПАК2012, 24-28 сентября 2012г, СПб, ПЕТЕРГОФ

1978 –the contract on a creation in IAE of the complex of storage rings – first dedicated synchrotron radiation source was signed between IAE and INP.

Academician A.P. Aleksandrov, President of Academy of Sciences of the USSR, the director of IAE of I.V. Kurchatov

Academician A.N. Skrinsky, Director of INP of Siberian Branch of Academy of Sciences

Creation of specialized sources of SR in the USSR - Russia

- 3 stages:

1. 1982-1986. A start of work of the electron storage ring "Siberia-1", an achievement of design parameters of a SR source.

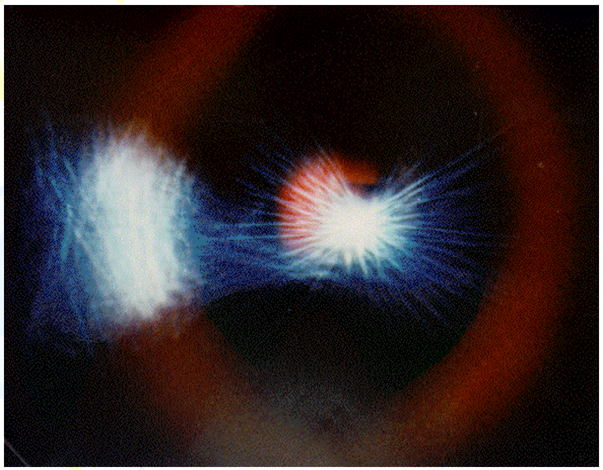
   1985. A 3-pole wiggler (shifter) was installed on "Siberia-1“: Bmax=4.3 T, λc=21,4 Å at 450 MeV;

   1985. An installation of first lithographic station on SR beamline from the wiggler, first works on lithography - IAE (Moscow), INP (Novosibirsk), NRIPP (Zelenograd);

   1985-1991. SR Research and technological works on "Siberia-1" in bld. 140 (IAE);

1 stage. Small storage ring «SIBERIA-1»

First SR beam from BM, 1983, bld.140.
Injector - Linac «Jet»



1992. Syberia-1 works in a new bld. 348 as a booster for Syberia-2 and a SR source of VUV and Soft X-ray spectrum.

Injector - new 80 MeV Linac.

- E = 0.45 GeV, I = 200 mA (340mA-max)
- Crit. Phot. En. - 0.21 keV (VUV, Soft X-ray)
- Diameter - 2.75 m
- Hor. emittance - $8.8 \cdot 10^{-7}$ m-rad
- Life time (100мА) – 1-1.5 hrs
- Stand. Bunch length - 30 cm
- SR pulse duration - 2.35 ns (FWHM)
- SR pulse frequency - 34.52 MHz

1986 г. Making a decision on construction of the new building №348 for the placement of Kurchatov SR Source.

05.05.1989. Building 348.
The shielding walls are under construction.

1992. New building №348 for KCSR

Creation of specialized sources of SR in the USSR - Russia

- 3 stages:

2. 1986-1991. Creation and commissioning of a new Linac - injector for "Siberia-1“, bld. 348.;

   1992. The beginning of “Siberia-1” operation with new Linac in new bld. 348.

3. 1986-1994. Creation and commissioning of "Siberia-2" – main SR source.

   1994-2004. An achievement of SR source "Siberia-2" design parameters, installation of SR beam lines and experimental stations, a carrying out of the researches.

1990. Linear Accelerator

Andreev`s structure – discs with radial supports and diaphragms with holes d=8.7 mm. Work on captured power, standing microwave of 2856MHz.

Electron gun: 40 kV, 4A, 18 ns

E = 80 MэВ, L = 6 m,

U=15 MeV/m, Rs=95 MHom/m,

Emittances < 10E-6 m-rad

I = 0.2 A, ΔE/E = 0.005

T < 15 нс, F rep = 1 Гц

Control room

Creation of specialized sources of SR in the USSR - Russia

- 3 stages:

3. 1986-1994. Creation and commissioning of "Siberia-2" – main SR source.

   1994-2004. An achievement of SR source "Siberia-2" design parameters, installation of SR beam lines and experimental stations, a carrying out of the researches.

2 stage: Creation of the dedicated electron storage ring "Siberia-2", 1986-1994.

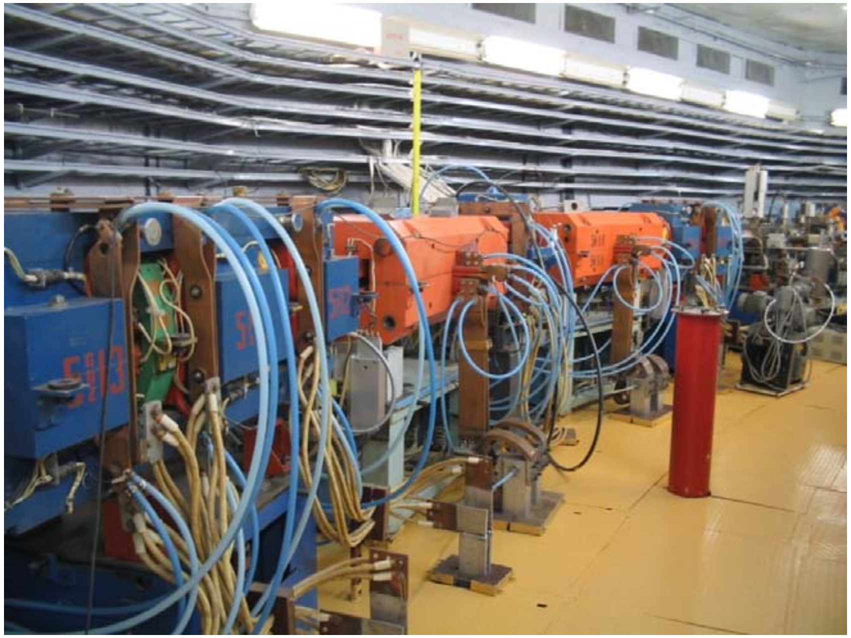
Initial requirements:

•The 2.5 GEV "Siberia-2" storage ring is the SR source providing bright and intensive photon beams in a range from visible light up to hard x-ray radiation.

•The magnetic structure of the storage ring should be optimized for installation of high field SC Wiggler for hard x-ray radiation and "undulators" for bright beams of UV and Soft SR radiation.

SR Source in X-ray spectrum

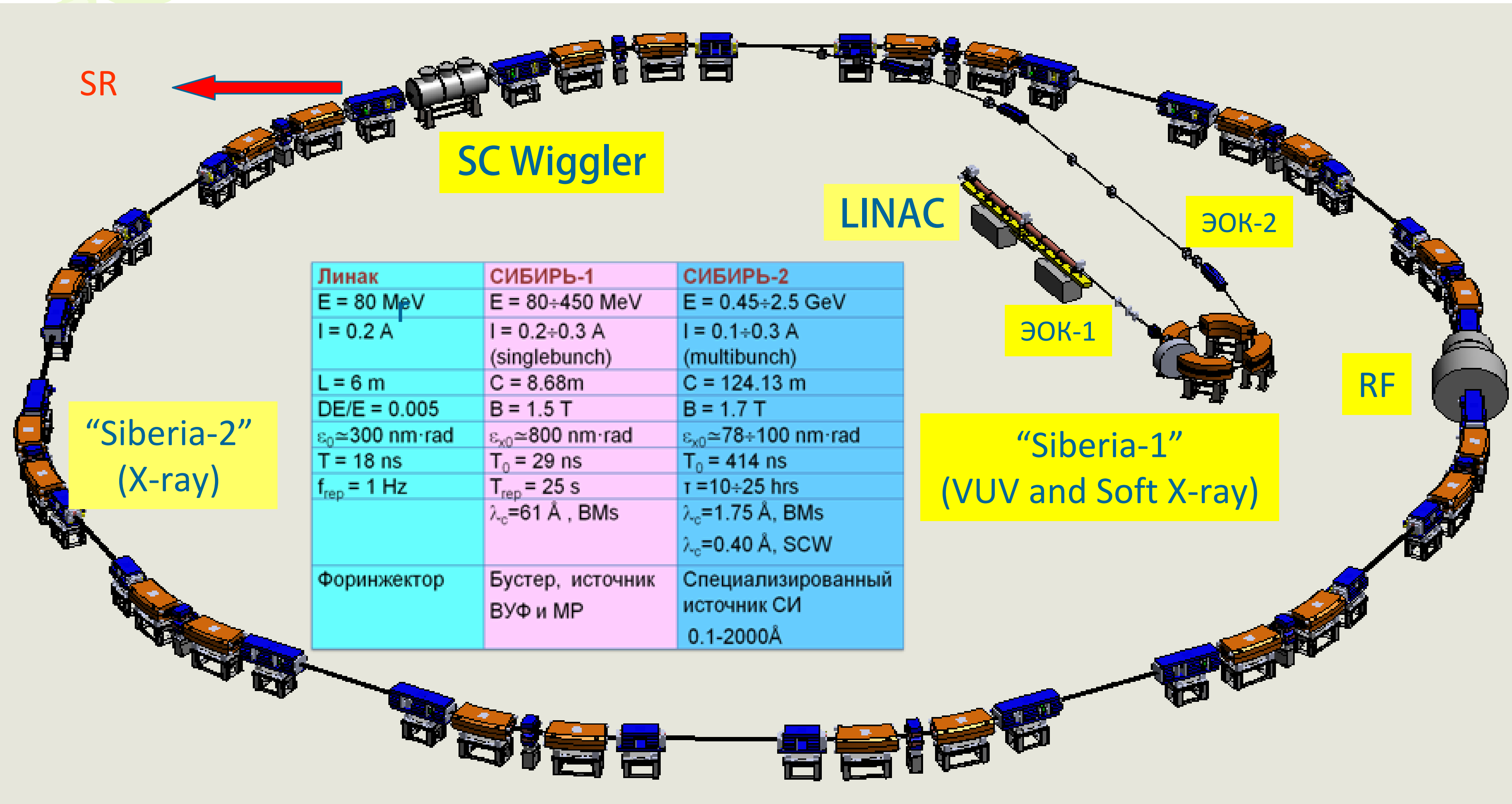
- E = 2.5 GeV,
- I = 100-300 mA
- BMs critical energy – 7.2 keV
- Diameter - 40 m
- Hor. emittance - (76-98) nm-rad
- Life time (100 mA) – 10 ÷ 14 hrs
- Stand. bunch length – 1.84 cm
- 39 SR beam lines (project)



1994 г. The installation of SIBERIA-2 is finished

Unified team of INP (Novosibirsk) and IAE (Moscow)

KCSR accelerator facility layout



Линак	СИБИРЬ-1	СИБИРЬ-2
E = 80 MeV	E = 80÷450 MeV	E = 0.45÷2.5 GeV
I = 0.2 A	I = 0.2÷0.3 A (singlebunch)	I = 0.1÷0.3 A (multibunch)
L = 6 m	C = 8.68m	C = 124.13 m
DE/E = 0.005	B = 1.5 T	B = 1.7 T
$\varepsilon_0 \simeq 300$ nm·rad	$\varepsilon_{x0} \simeq 800$ nm·rad	$\varepsilon_{x0} \simeq 78 \div 100$ nm·rad
T = 18 ns	T_0 = 29 ns	T_0 = 414 ns
f_{rep} = 1 Hz	T_{rep} = 25 s	τ =10÷25 hrs
	λ_c=61 Å , BMs	λ_c=1.75 Å, BMs λ_c=0.40 Å, SCW
Форинжектор	Бустер, источник ВУФ и МР	Специализированный источник СИ 0.1-2000Å

KCSR History on XXI century

On October 1, 1999.
Official Opening of KCSR

On April 18, 2007.
The nano-technological program and the organization of КCSRNT

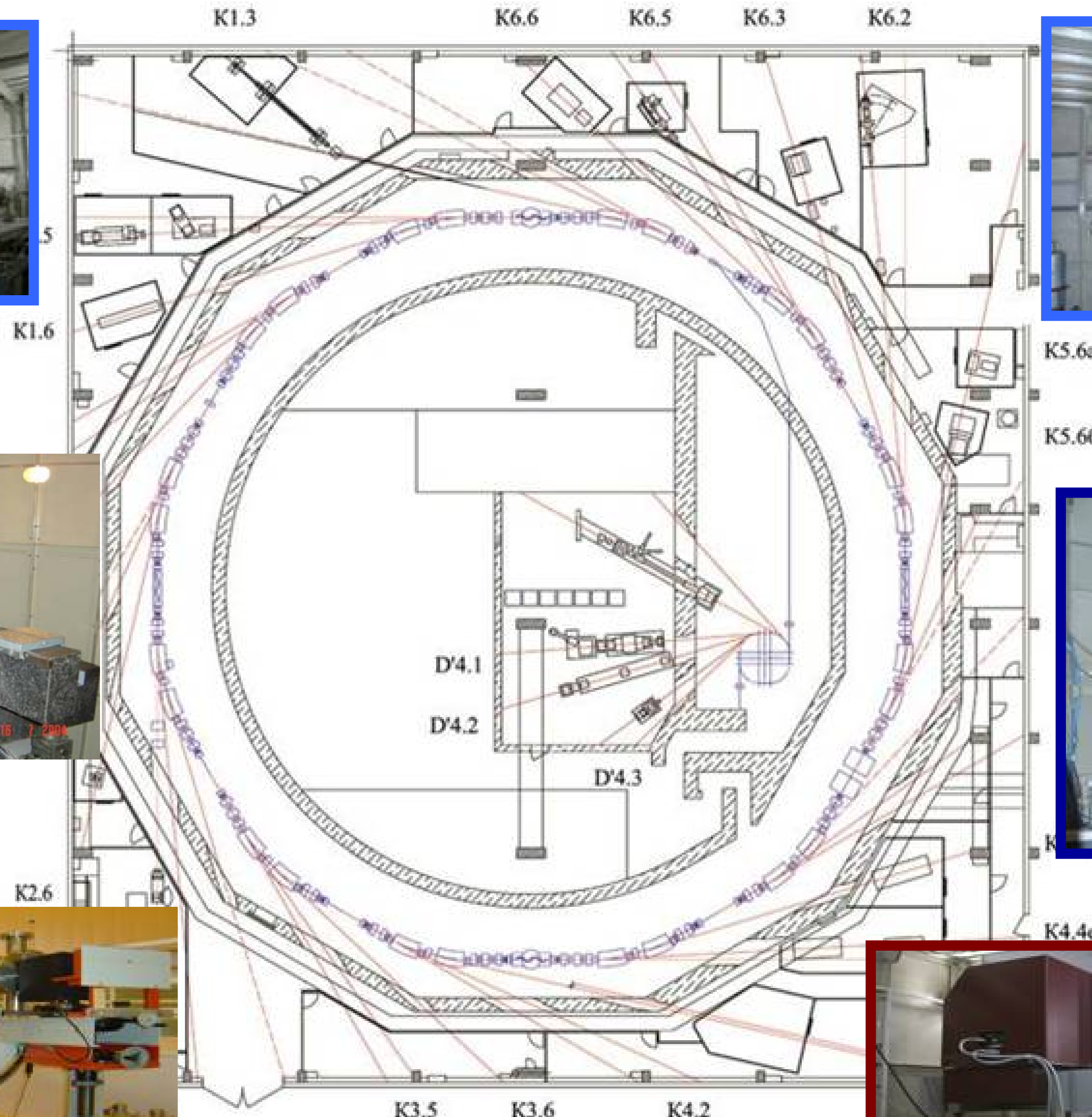
On September 30, 2009.
The Decree of the President about formation of National Research Center Kurchatov Institute.

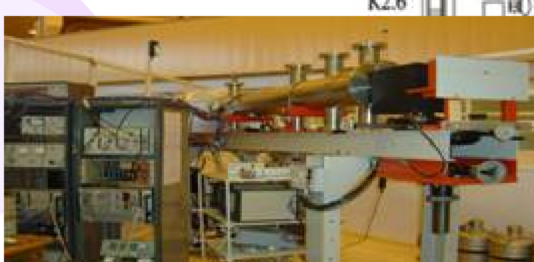
KCSR

- By the beginning of 2000-2002 in KCSR there were 13 experimental stations in a different stage of readiness, from them 10 stations - on the "Siberia-2" and 3 stations - on the "Siberia-1".
- The stations were started to work. They were produced by cooperation of several scientific organizations. Among them a leading role has played Institute of Crystallography of Academy of Sciences, creating more than a half of experimental stations or their most responsible elements: SR beamlines, monochromators, collimators, focusing devices, goniometers and so forth.

Large progress was achieved in increasing stored current at SIBERIA-2 during 2003-2004. Kurchatov SR Source operates close to the design parameters.

Experimental station of KCSR





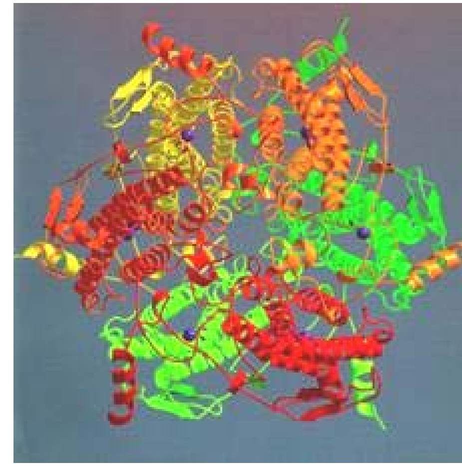
2002 - 2005 . 10 X-Ray stations at “Siberia-2”

SR STATION	SR STATION full NAME
X-Ray cinema	Station for a high-speed low-angular difractometry
CTM	Station of low-angular dispersion
Lengmuir	Station of research of bioorganic films on a liquid surfa
Mediana	Station of complex researches on medical diagnostics
Protein	Station of a protein crystallography
ПРО	Station of a x-ray crystallography and physical materials science
ПРО	Station of x-ray refraction optics
ПРО	Fluorescent EXAFS spectrometer
ПРО	Station of deep x-ray lithography
ПРО	Station of precision x-ray optics

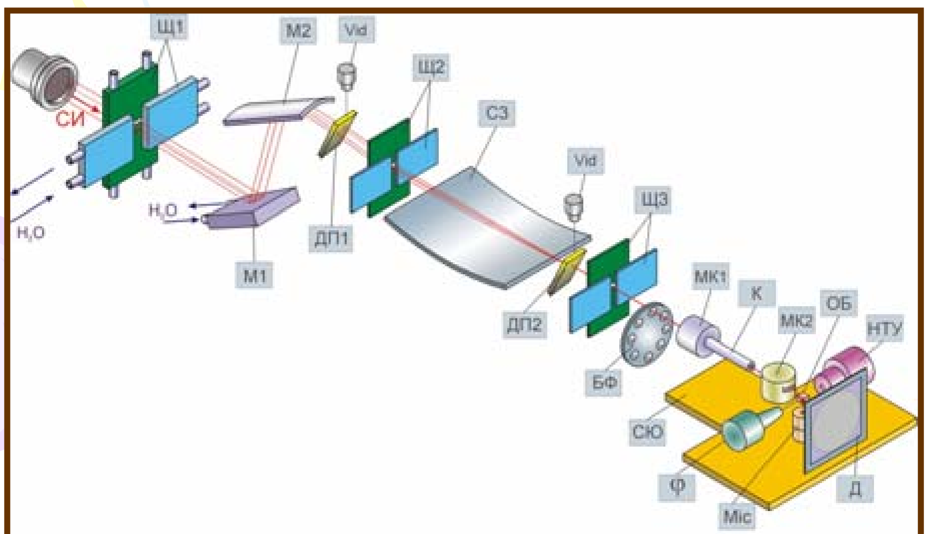
3 VUV stations on “Siberia-1

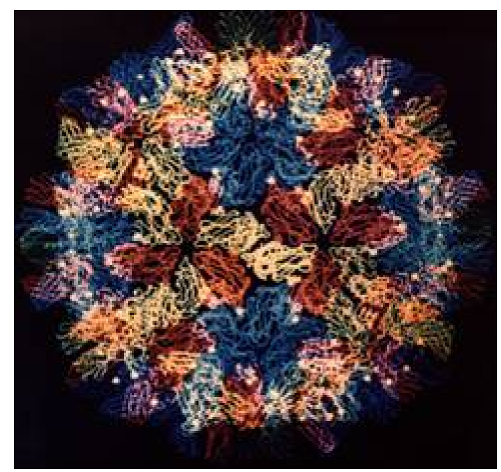
SR STATION	SR STATION full NAME
PES	Station photoelectron spectroscopy
SPECTR	Station of condensed conditions
LOCUS	Station of luminescent and optical researches

“Protein crystallography”



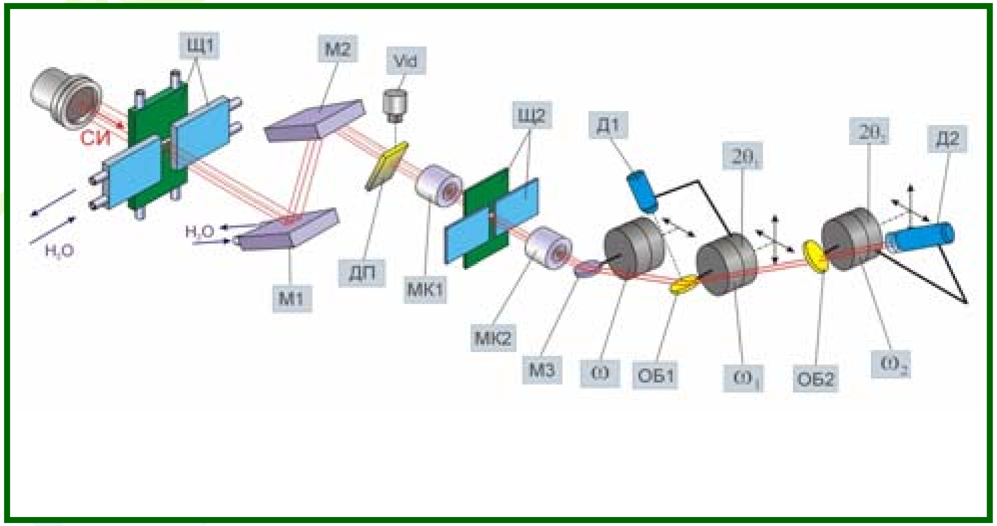
Catalase
Thermus thermophilus

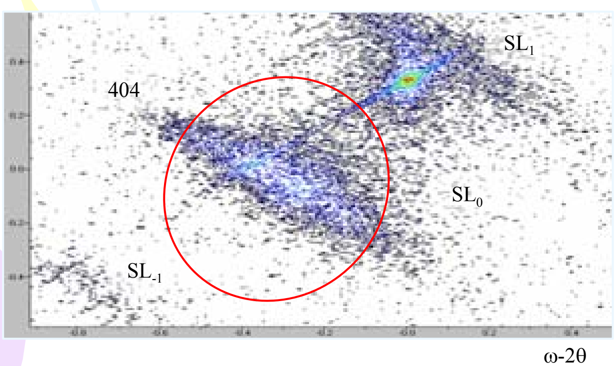




Virus
Carnation Mottle

“X-Ray crystallography and material science”

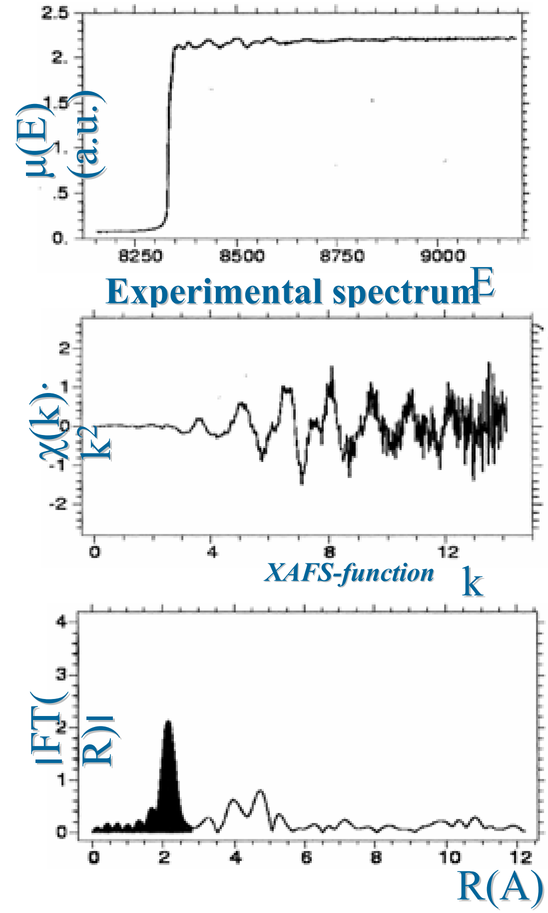




Diffuse scattering at quantum dots nanostructure in InAs/GaAs

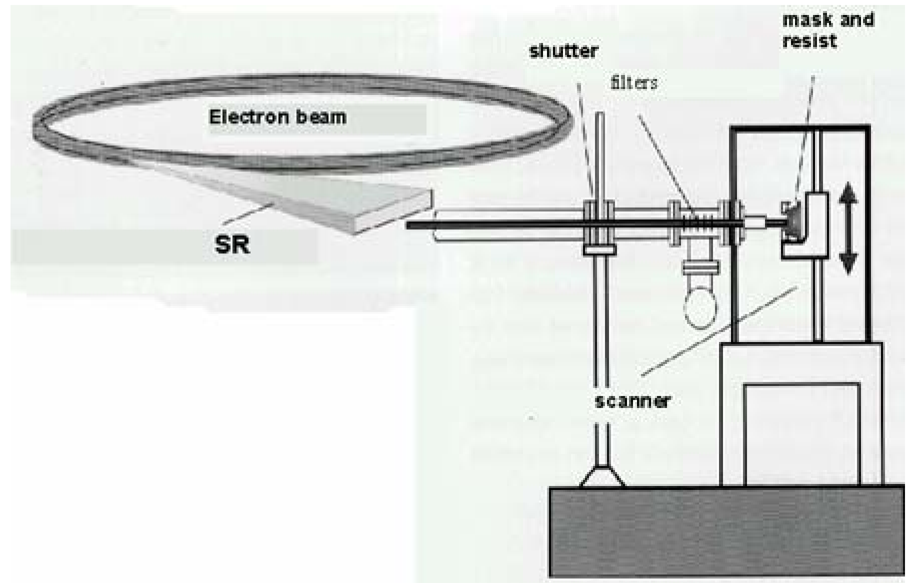
“EXAFS-spectroscopy”

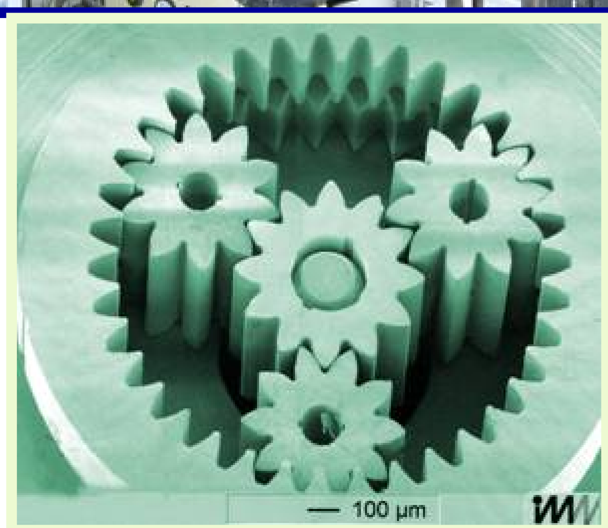
- **X-ray spectroscopy near absorption edges of various chemical elements**

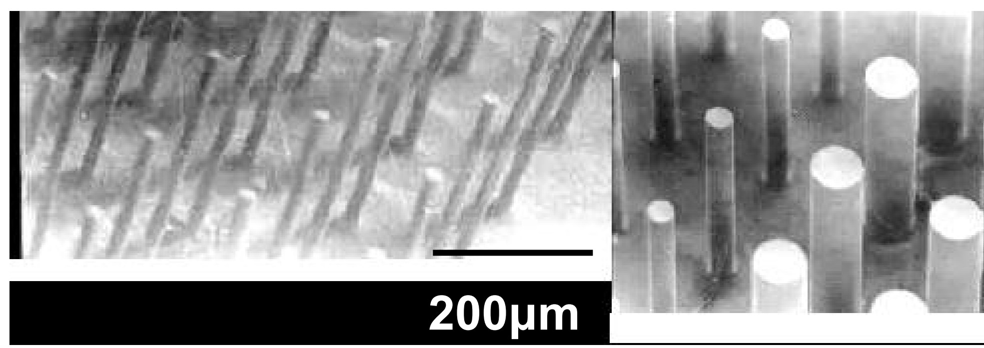


EXAFS in
Cr (32.11%) Mo(1.28%) Ni alloy

"LIGA"- technology

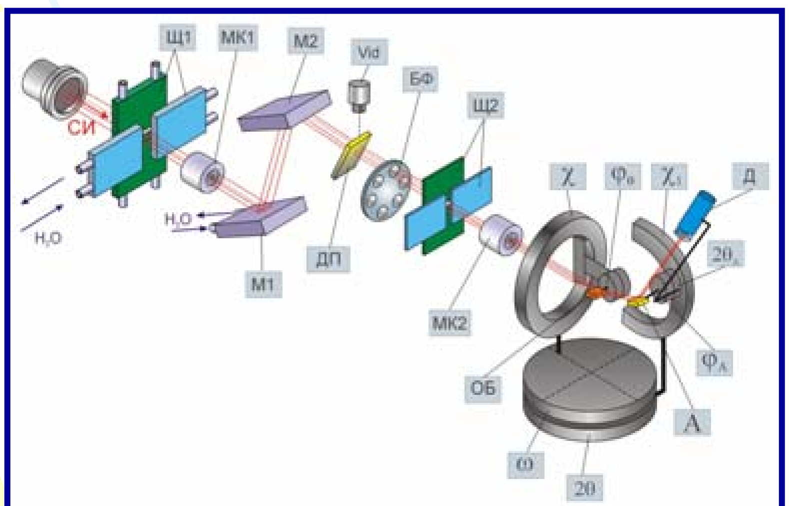




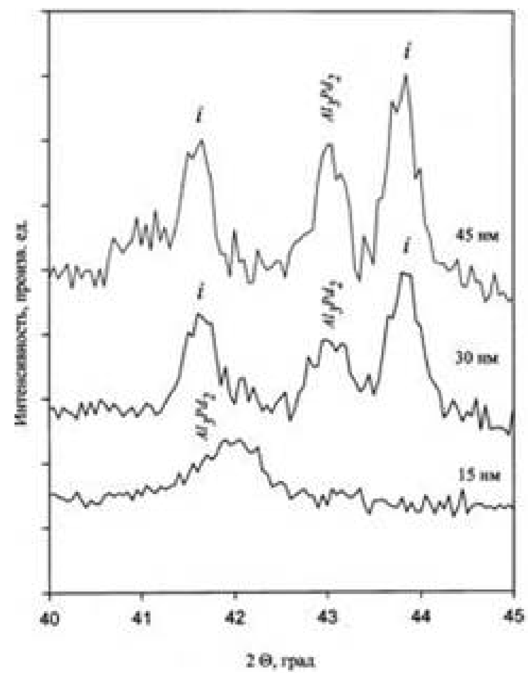


SU-8 resist,
t= 0.8-1.1mm,

“X-Ray precise optics”



- Double and triple crystal diffraction
- Multi waves surface diffraction
- X-ray standing waves



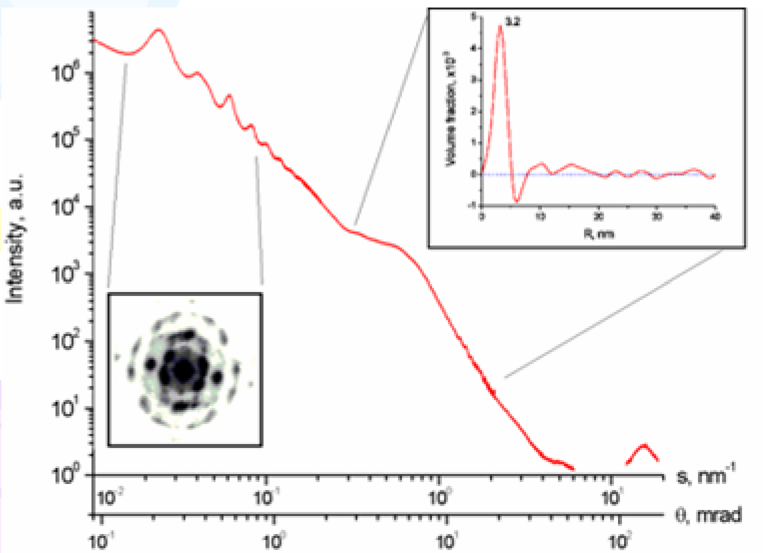
45 nm

30 nm

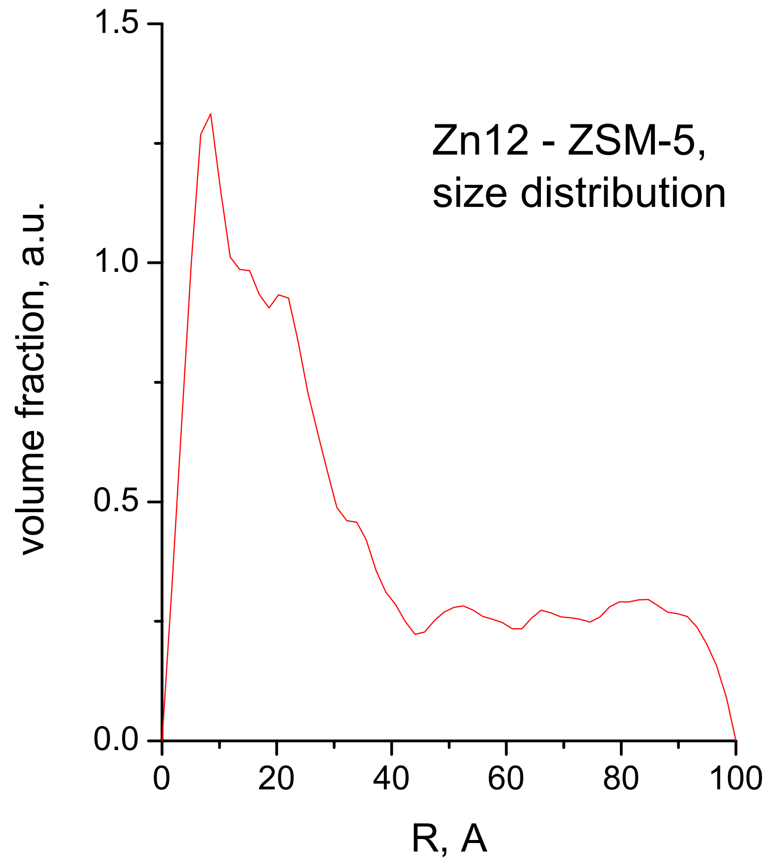
15 nm

Diffraction in nanofilms of quasicrystals Al71Pd21Re8.

“Small angle scattering”

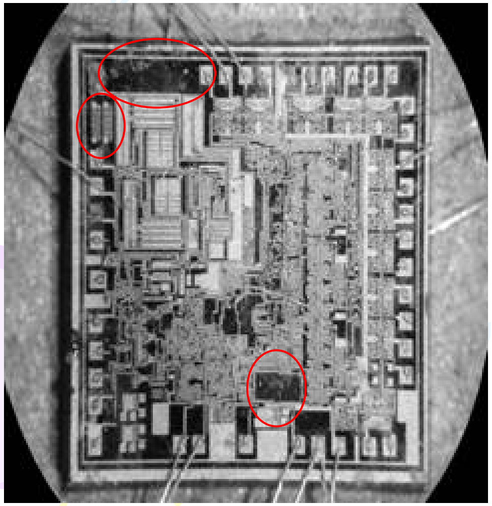


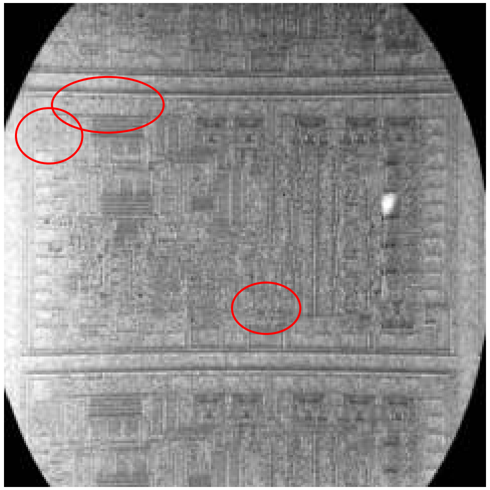
Small-angle scattering at nanostructure (photonic crystal)



Size distribution of the particles ZnO

“Difraction topography”

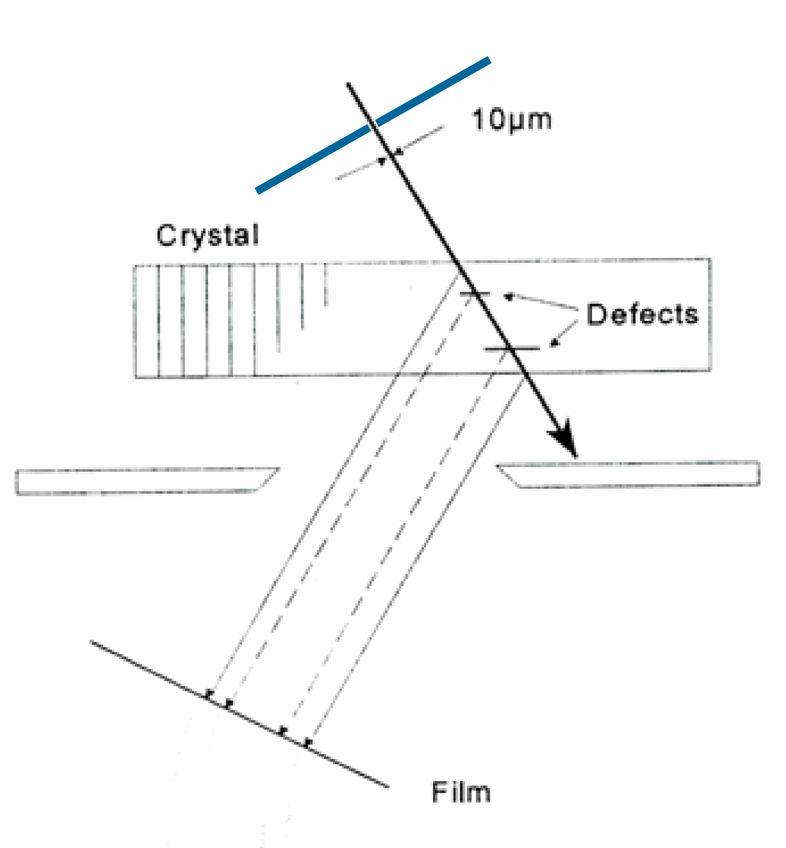




Diffraction topography for microelectronics

Dislocation in Nd2-xCexCuO4-y

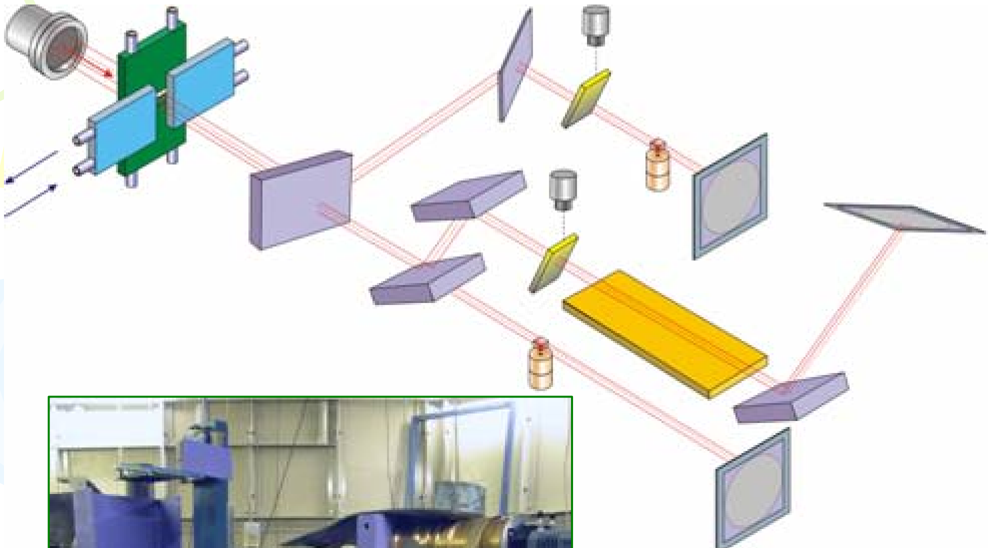
Difraction topography, visualisation of domen structure



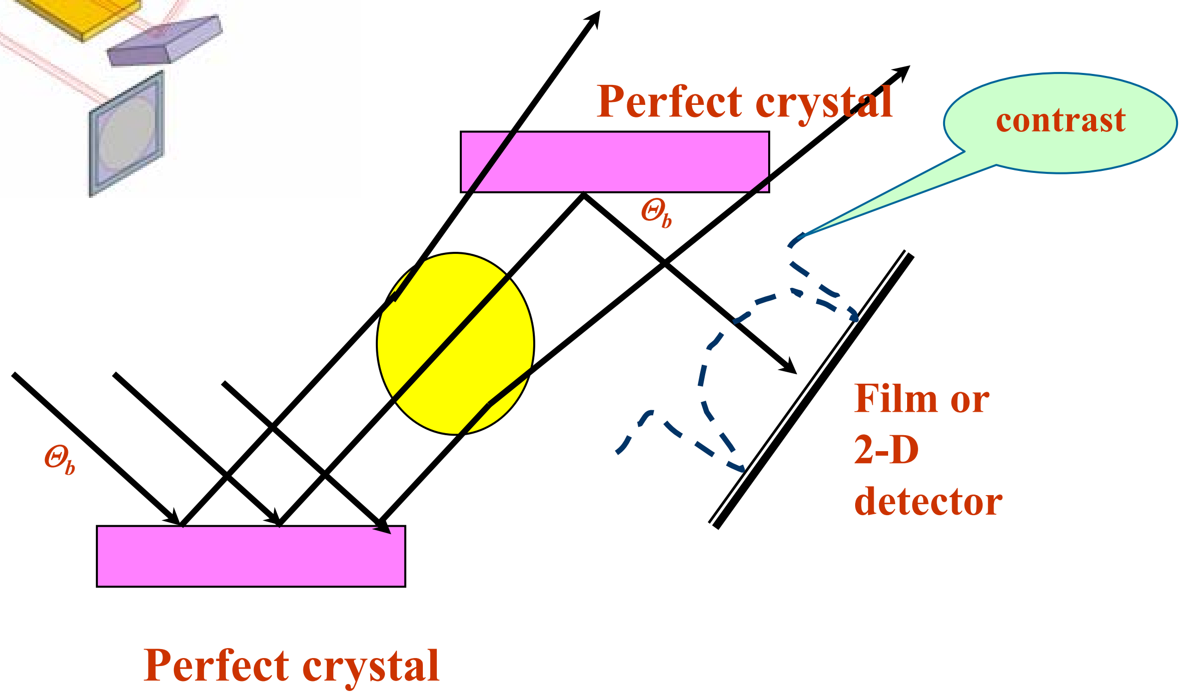
SR section topography of hematite crystal

SR topographies at saturated magnetic field (a) and without field (б).

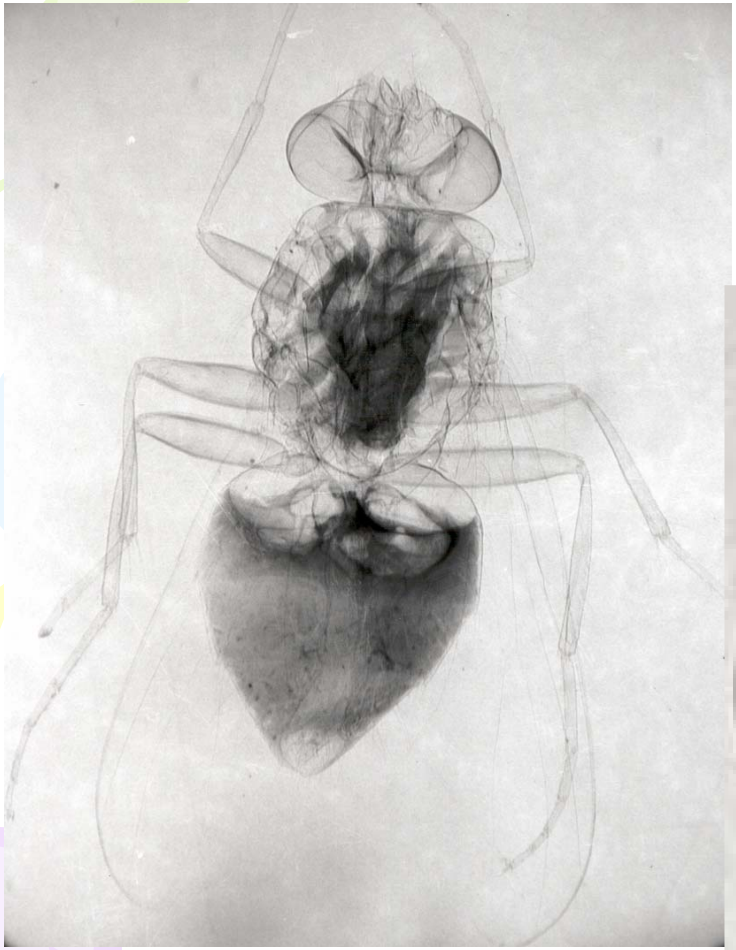
"Medical diagnosis"

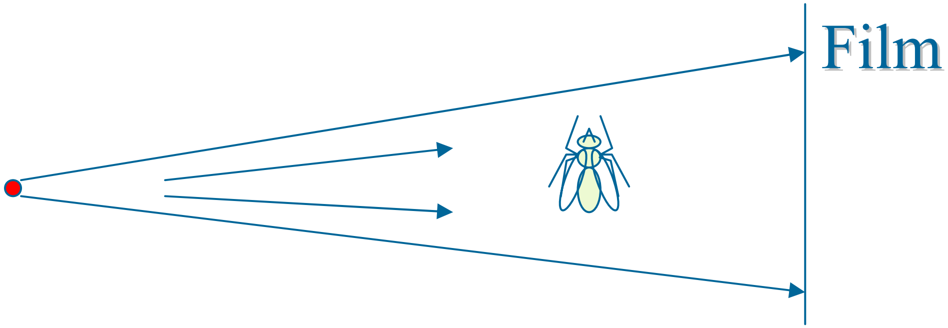


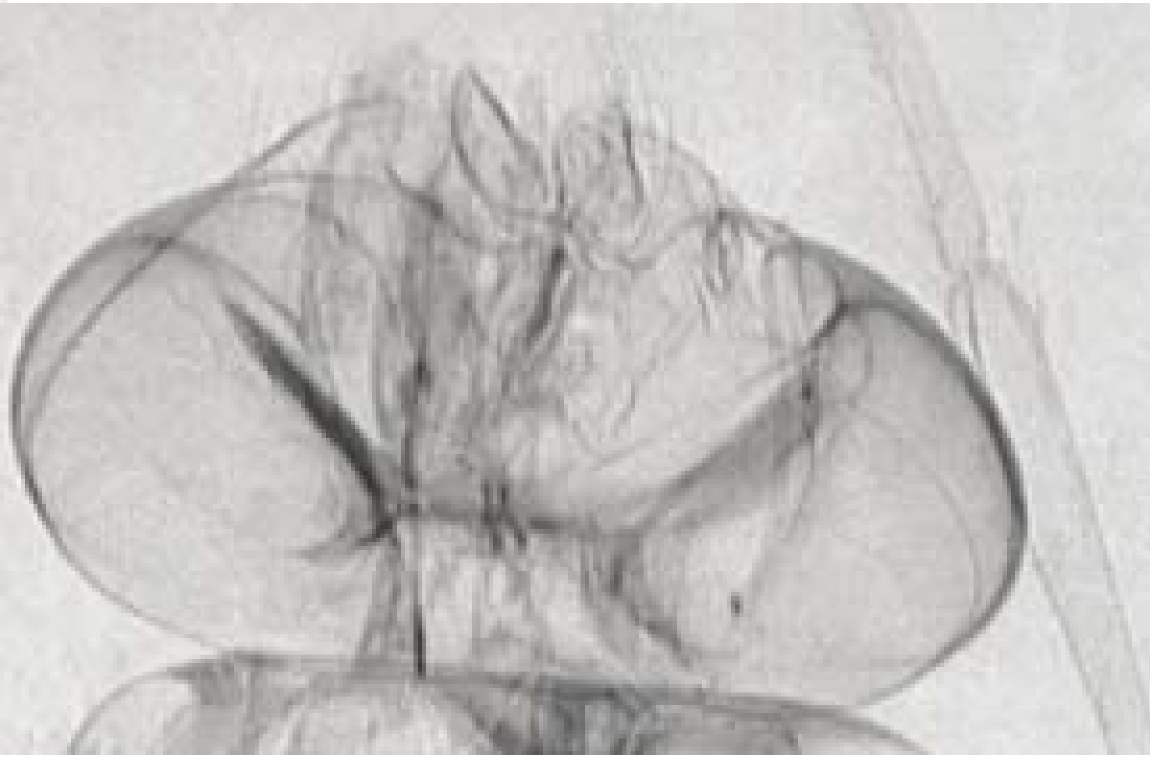
Radiography with refraction contrast



"Medical diagnostics"

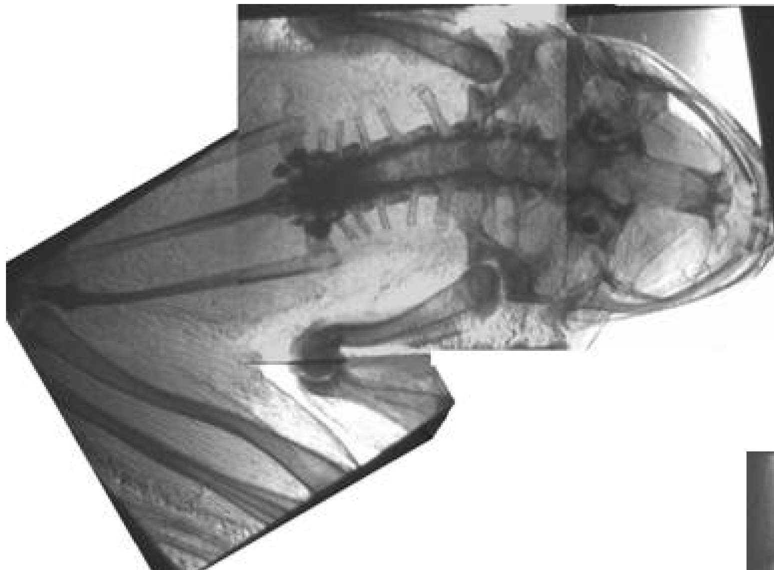






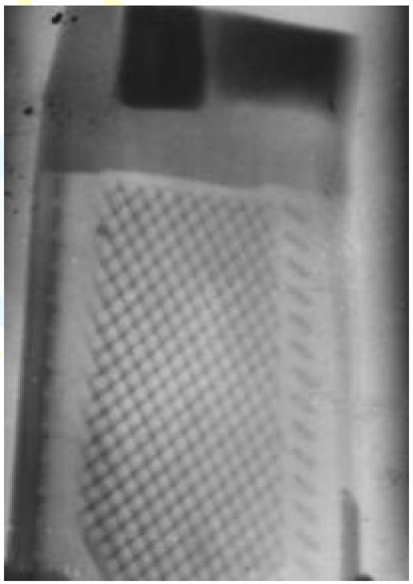
Refraction radiography

Refraction radiography

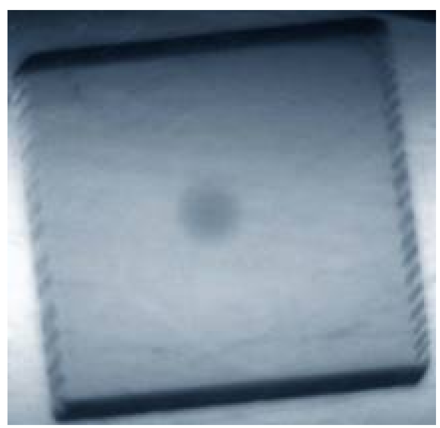


Refraction contrast

Absorption contrast



turbine blade



mography pmamhantom

Vacuum ultraviolet stations

photoelectron spectroscopy

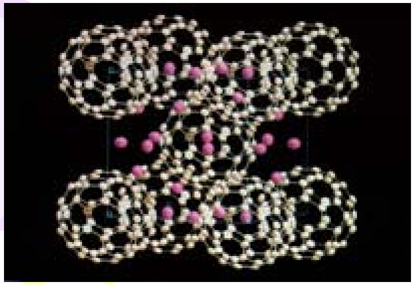
E ~ 3 ÷ 35 eV

VUV Luminescence and Absorption

E ~ 3,5 ÷ 25 eV

Optical Investigations of Dielectrics

E ~ 3 ÷ 40 eV (SN)
E ~ 30 ÷ 200 eV (TMG)



- **Fullerenes C60F48,**
- **Tokamak T-10 Smooth Hydrogenated Carbon Erosion Films,**
- **BaFCl-Eu, AlPO4, Y2O2S-Tb, Gd2O2S-Tb, La2O2S-Tb, ….**
- **Quasicrystals Al-Fe-Cu, PbMoO4, ZnWO4,…**

Reconstruction of a building for KCSR

August 2009

On April 18, 2007. **The nano-technological program and the organization of KCSRNT**

March 2008

August 2007

Additional building , reconstruction of existing building, essential increasing of the useful surfaces for SR beam lines and experimental stations.

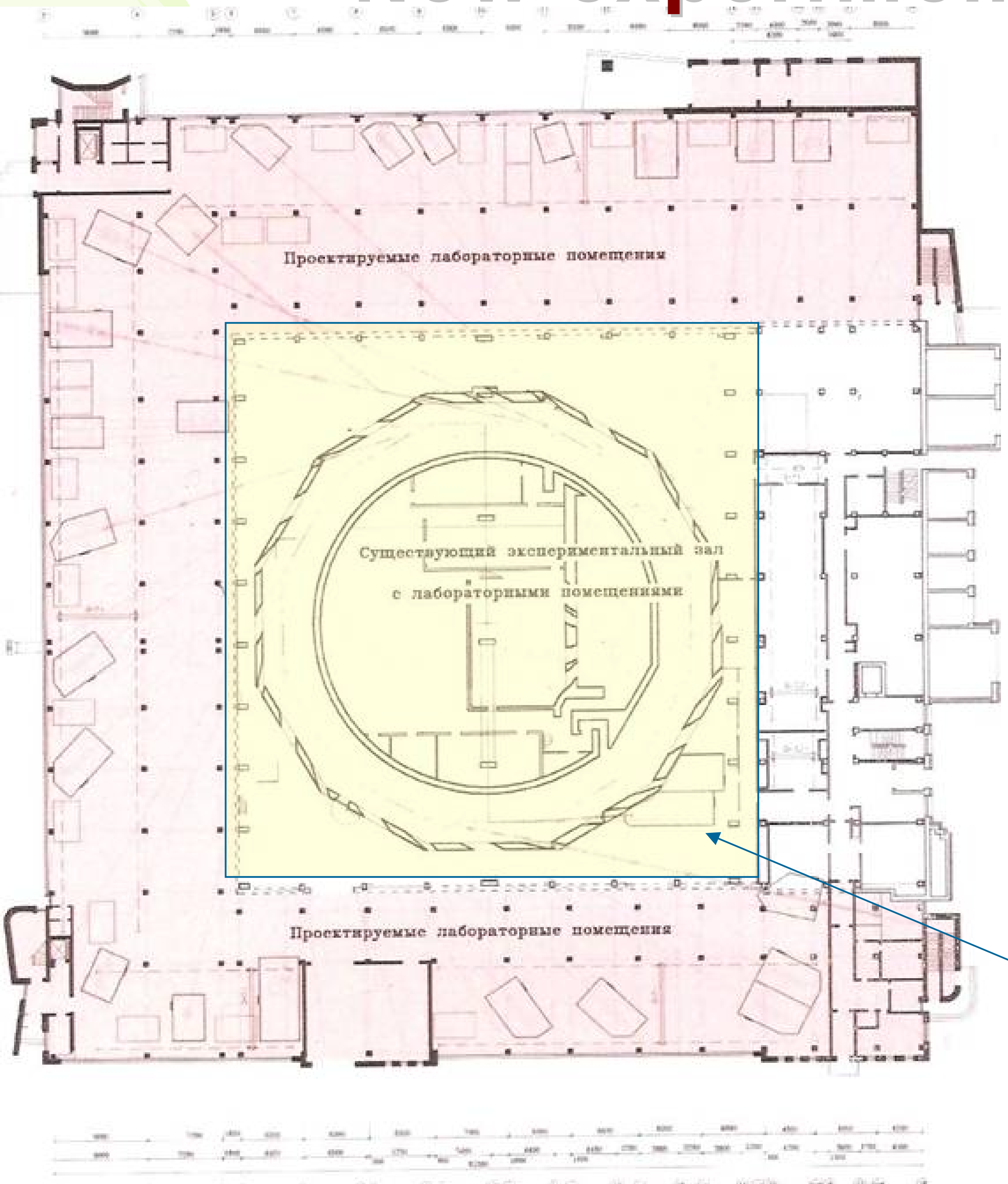
2007-2009

	Before reconstruction	*After reconstruction*
Experimental hall area, m^2	*950*	*4 850*
Office area, m^2	*512*	*4 643*
Total surface, m^2	*6 026*	*16 756*

Main scientific directions

- **Nanodiagnostics and material science** (nuclear structure, macromolecular structure, nanofilms, heterostructures, superlattices, nanoclusters, low dispersive materials, quantum points, radiating defects, carbon nanostructures, nanocomposites and so forth)
- **Nanotechnologies** (molecular and beam epitaxy, equipment Lengmuir-Blodgett and so forth)
- **Biotechnologies** (a protein crystallography, bioorganic films on a liquid surface and so forth)
- **Microsystem equipment** (LIGA – technology). Basic researches (materials at ultrahigh pressure, "space" crystals, x-ray optics and so forth)
- **Live systems and nuclear medicine** (new methods of medical diagnostics, supramolecular structure of biological tissue and liquids and so forth).
- **Double technologies** (nondestructive control of responsible products, judicial examination and so forth). Metrological providing of nanotechnologies (spectroradiometry, metrology of layered structures and so forth)

New experimental area



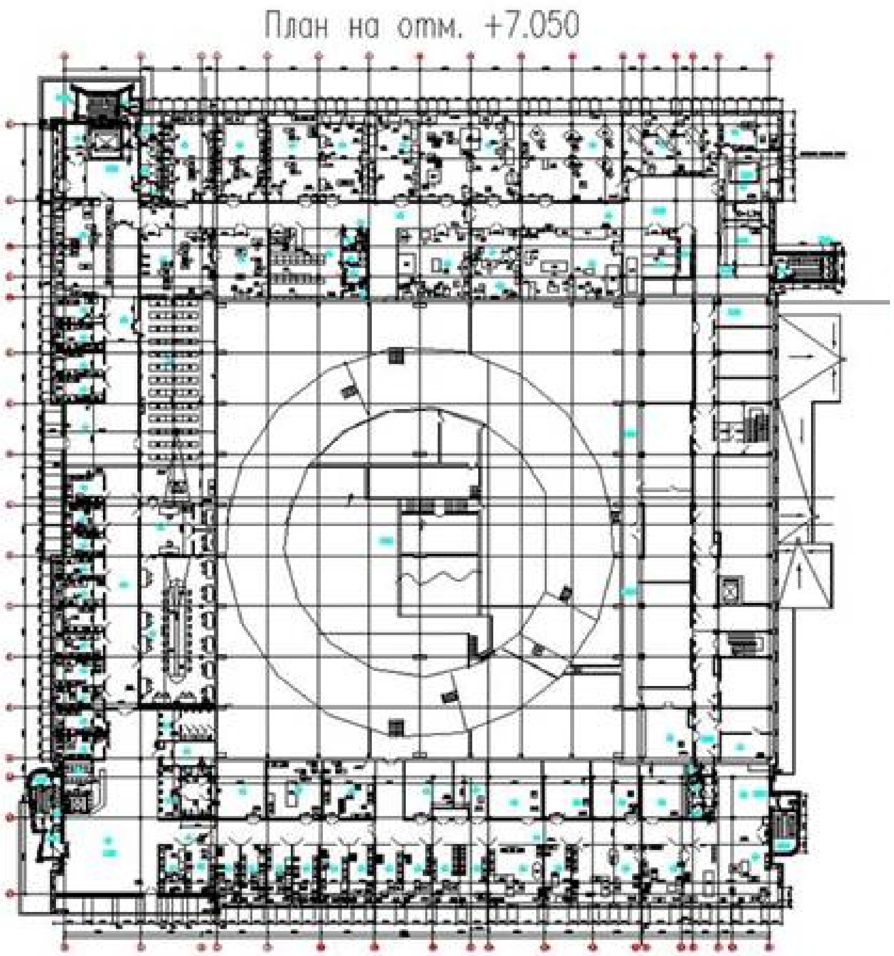
S = 4 850 кв.м.

S = 950 кв.м.

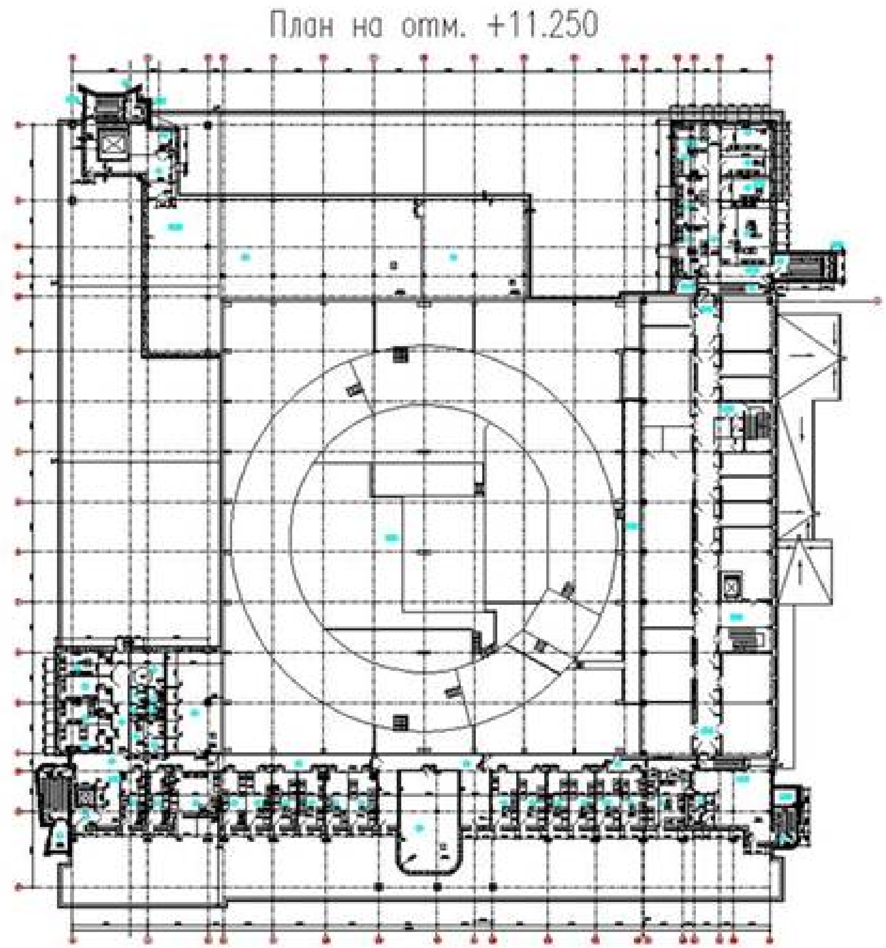
Old hall

First floor. Clean experimental zones

New rooms for employees and users of S=16 000 sq.m.



Second floor.
Offices, laboratories, conference hall

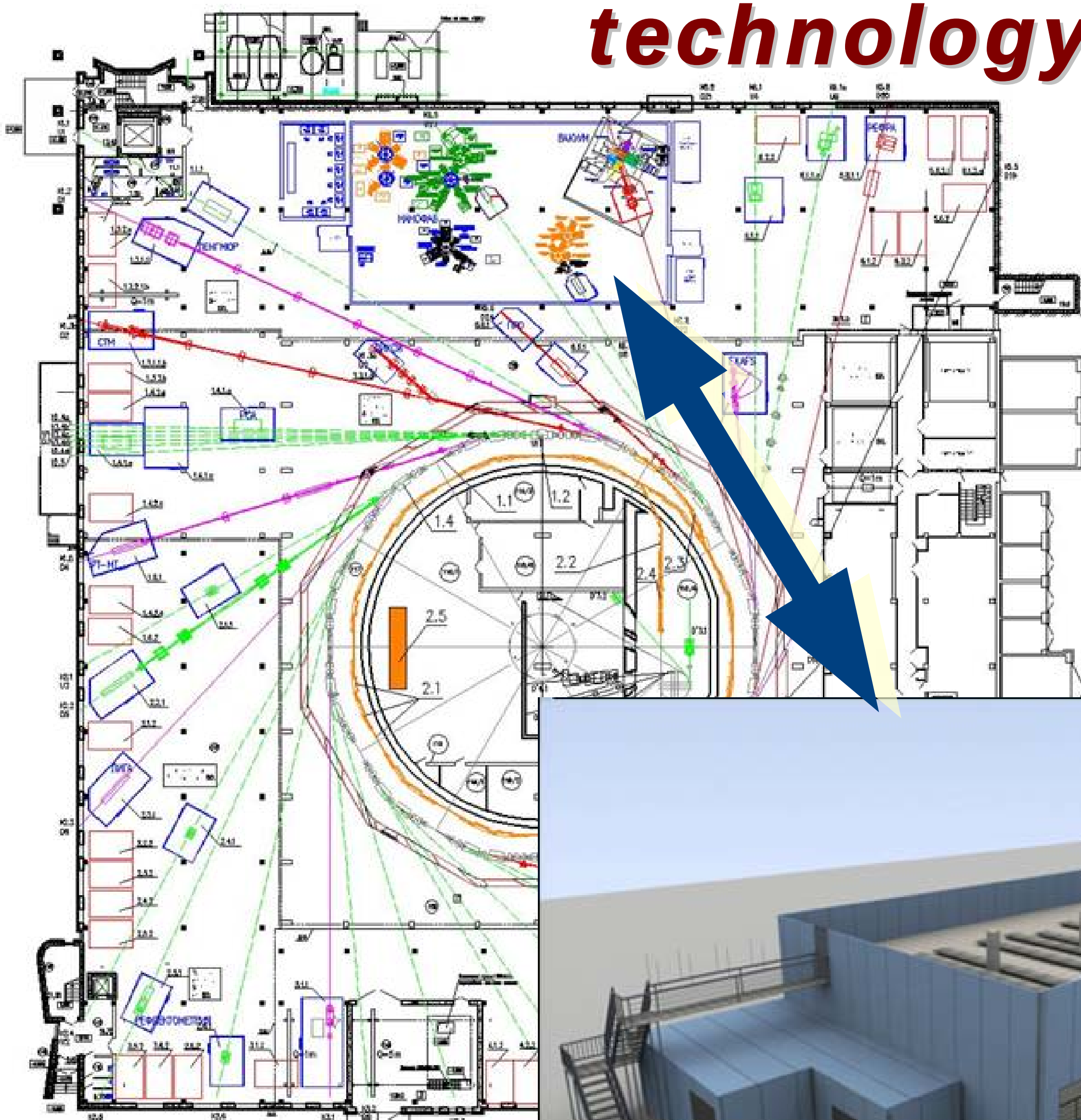


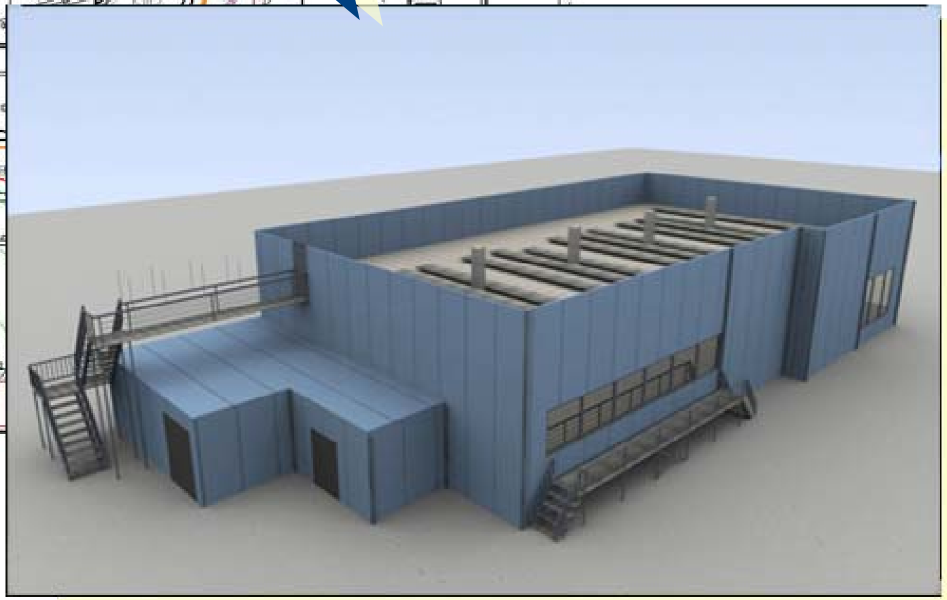
Third floor.
Rooms of users

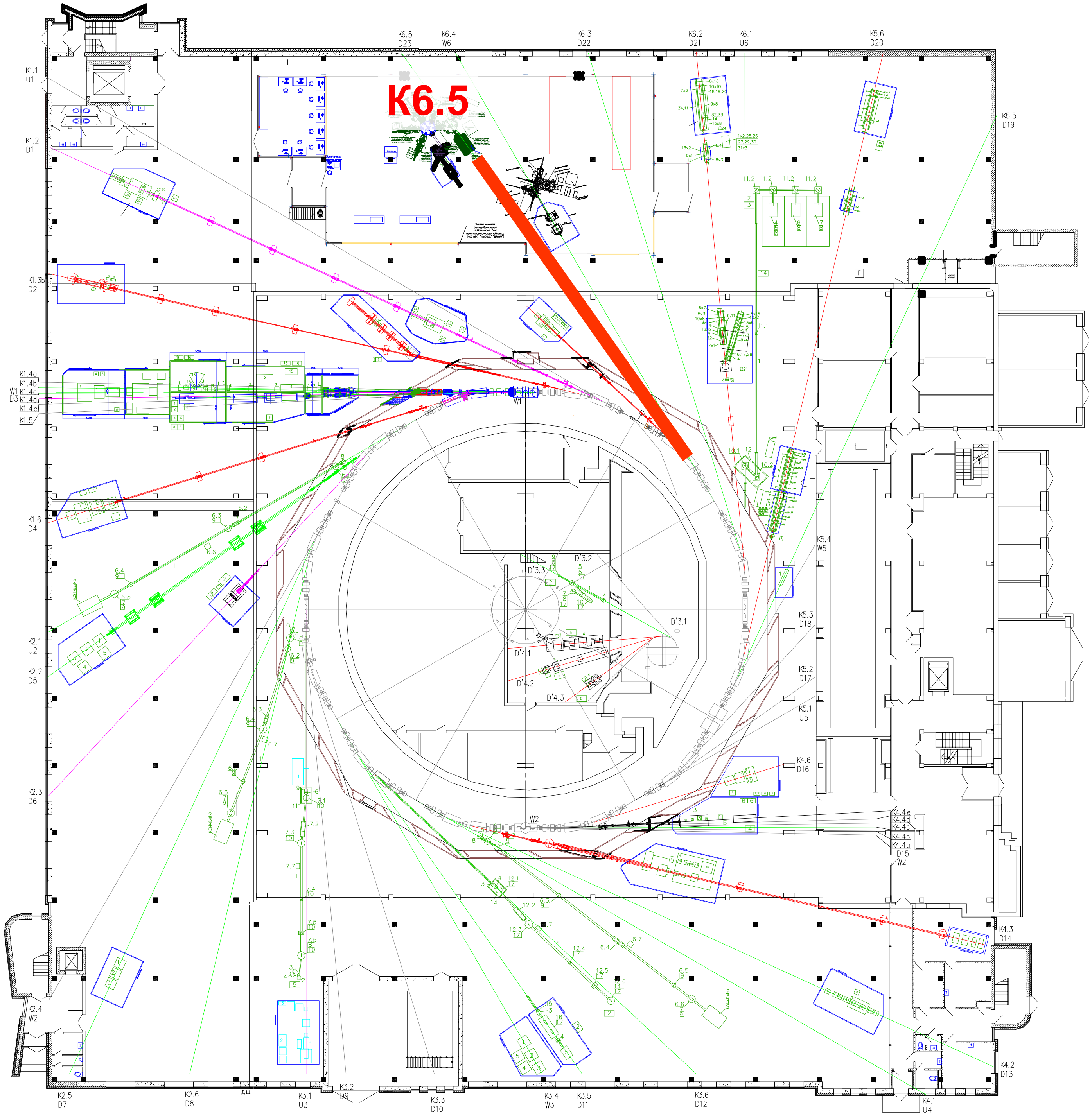
Third floor.
Living rooms for SR users.

Second floor. Halls for carrying out scientific meetings

Clean rooms. MEMS and NEMS technology



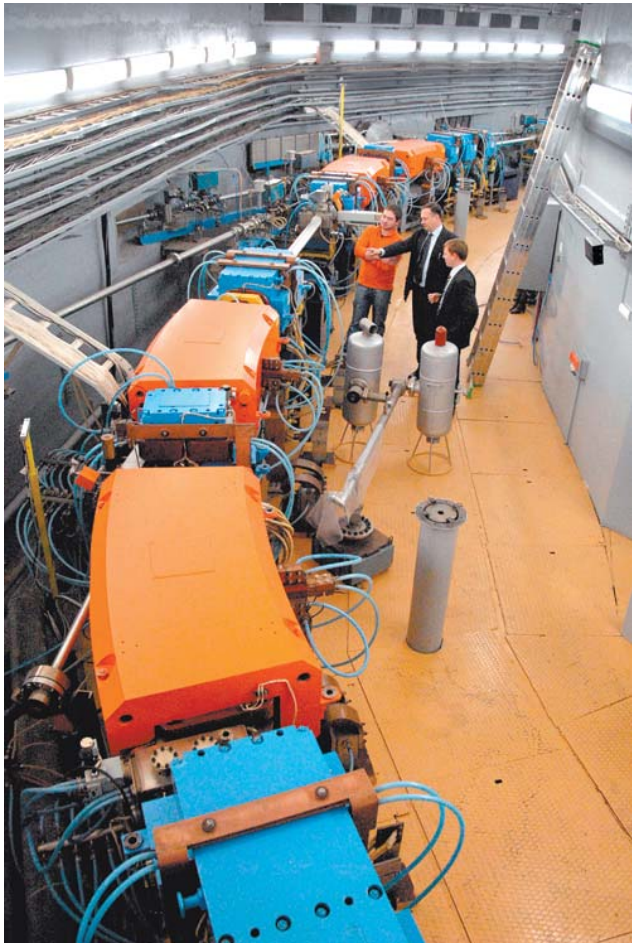



K6.5
K6.5 D23
K6.4 W6
K6.3 D22
K6.2 D21
K6.1 U6
K5.6 D20
K5.5 D19
K1.1 U1
K1.2 D1
K1.3b D2
K1.4a
K1.4b
W1 K1.4c
D3 K1.4d
K1.4e
K1.5
K1.6 D4
K2.1 U2
K2.2 D5
K2.3 D6
K2.4 W2
K2.5 D7
K2.6 D8
K3.1 U3
K3.2 D9
K3.3 D10
K3.4 W3
K3.5 D11
K3.6 D12
K4.1 U4
K4.2 D13
K4.3 D14
K4.4e
K4.4d
K4.4c
K4.4b
K4.4a
D15
W2
K4.6 D16
K5.1 U5
K5.2 D17
K5.3 D18
K5.4 W5
W1
W2
D'3.1
D'3.2
D'3.3
D'4.1
D'4.2
D'4.3

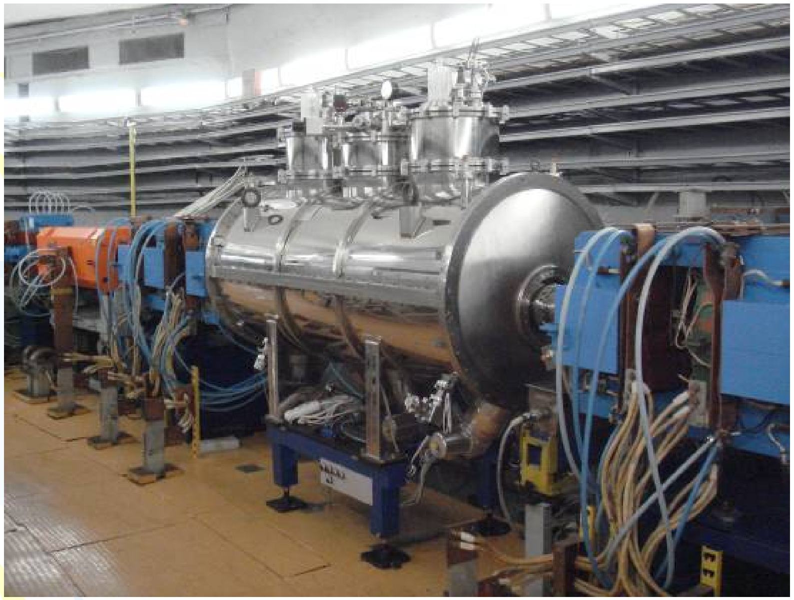
Modernization of SR Source in KCSR, 2007-2012

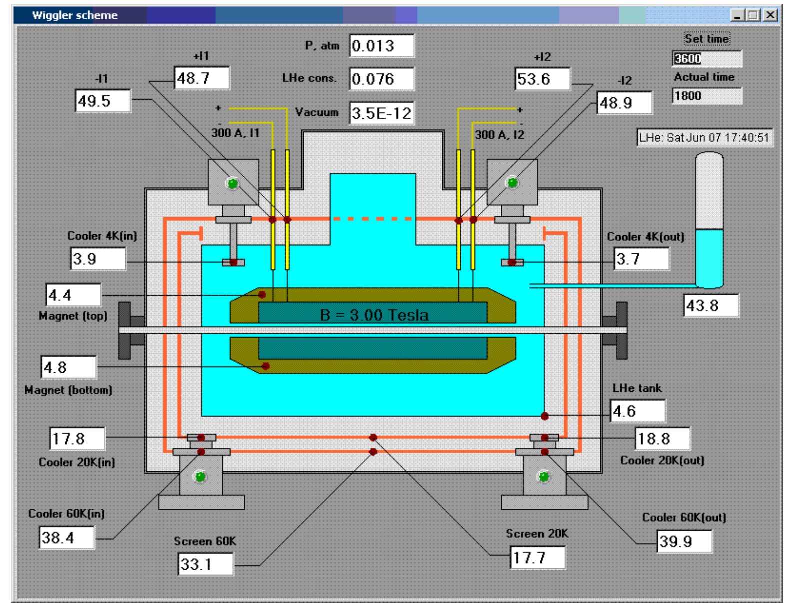
1. Improvement of consumer parameters of KCSR SR beams:
- Photon flux increasing, an accumulation of large electron current at small apertures;
- Lifetimes of the electron and photon beams;
- A time and space stability of the photon flux;
- Enlargement of spectral range of SR source based on new insertion devices installation on Siberia-2 storage ring.

2) Reliability of work of KCSR



December 2007. The installation of Superconducting Wiggler: B=7.5T, 19+2 poles. *KCSR + BINP, Novosibirsk*





MPSCW: NbTi coils

E=2.5 GeV, I=0.1-0.3 A

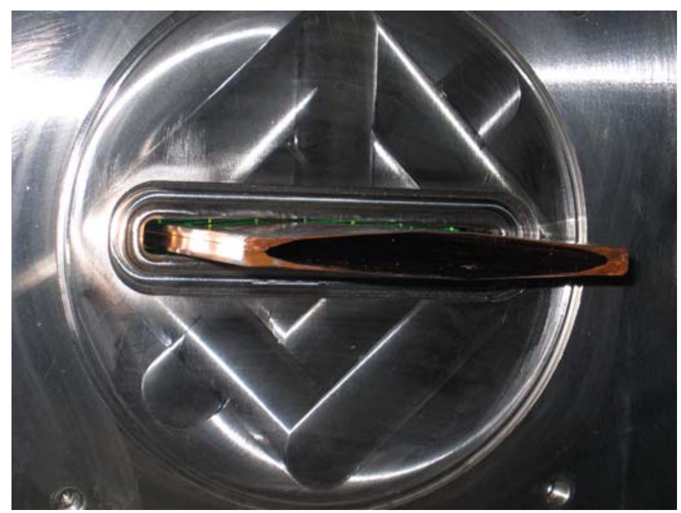
B= 3 - 7.5 T, Npoles=19+2

λwig = 164 mm, Eph crit. = 31.2 keV

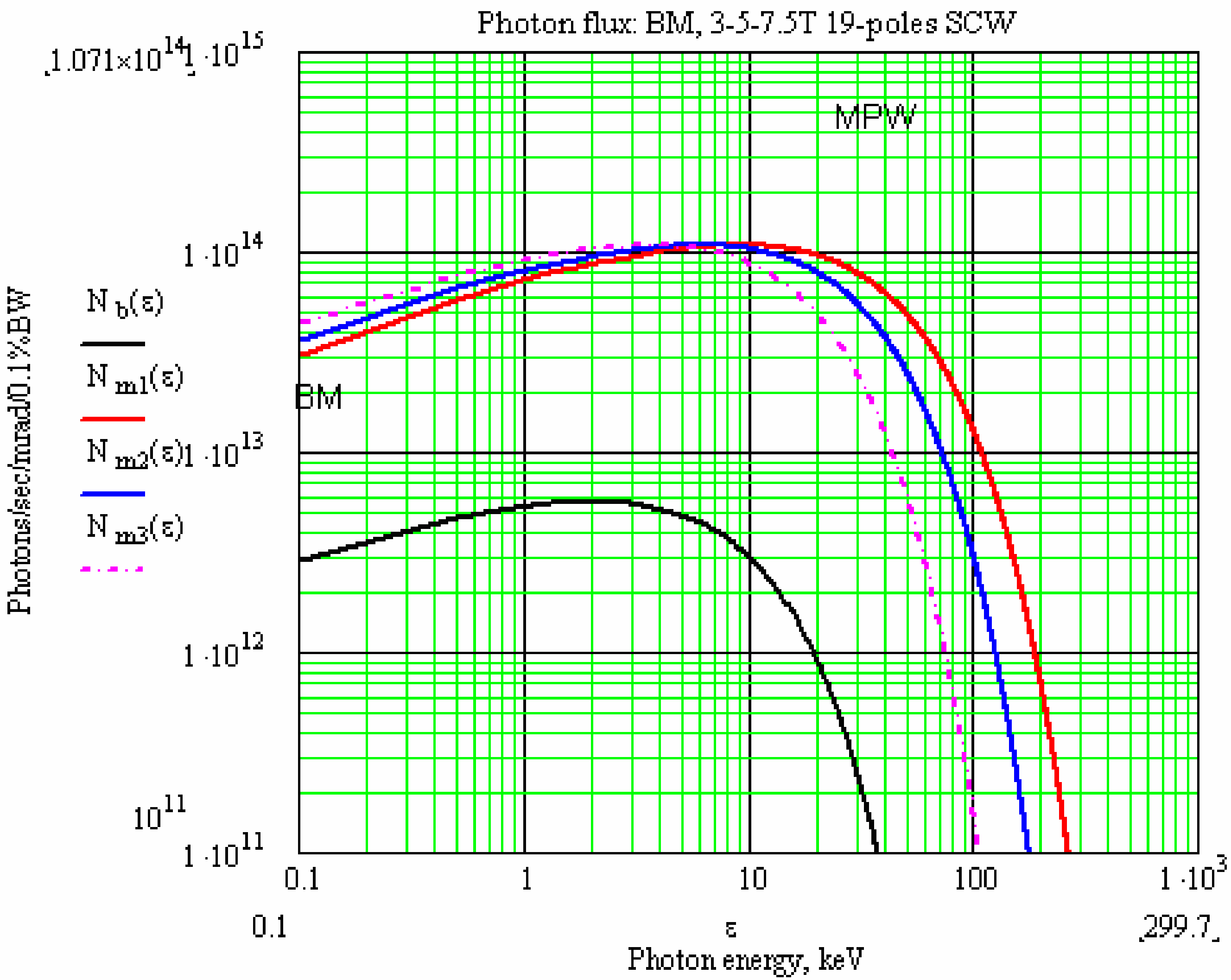
Flux = (10^{14}-10^{12}) ph/s/0.1%BW

Eph = 5 - 200 keV , Θx max = ± 23.5 mrad

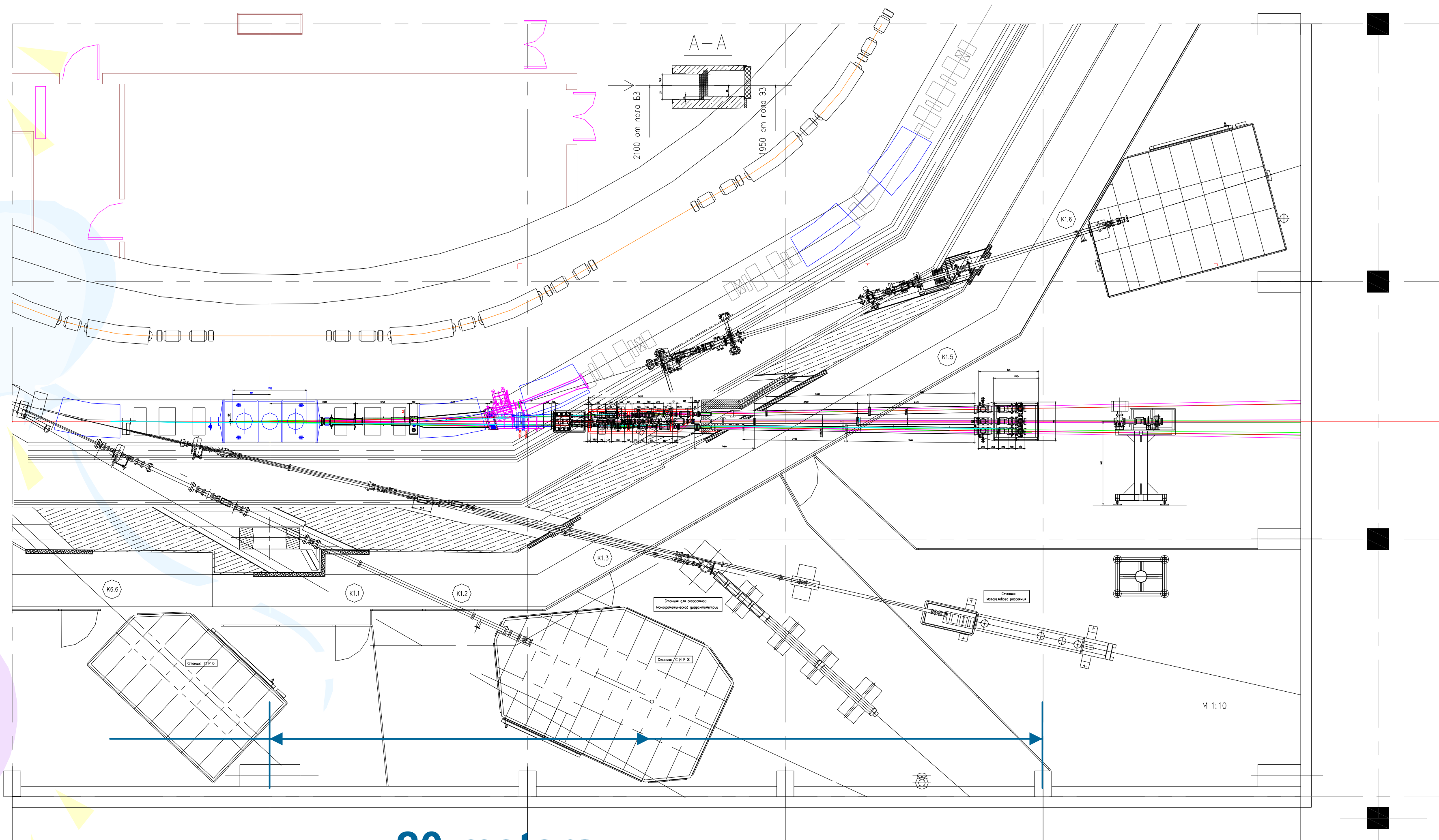
Ptot (100 mA) = 36.5 kW



SR Spectral Flux from 3-5-7.5 T SCW and 1.7 T BM. E=2.5 GeV, I=0.1A



Extraction of SR from SC wiggler into 3 photon lines



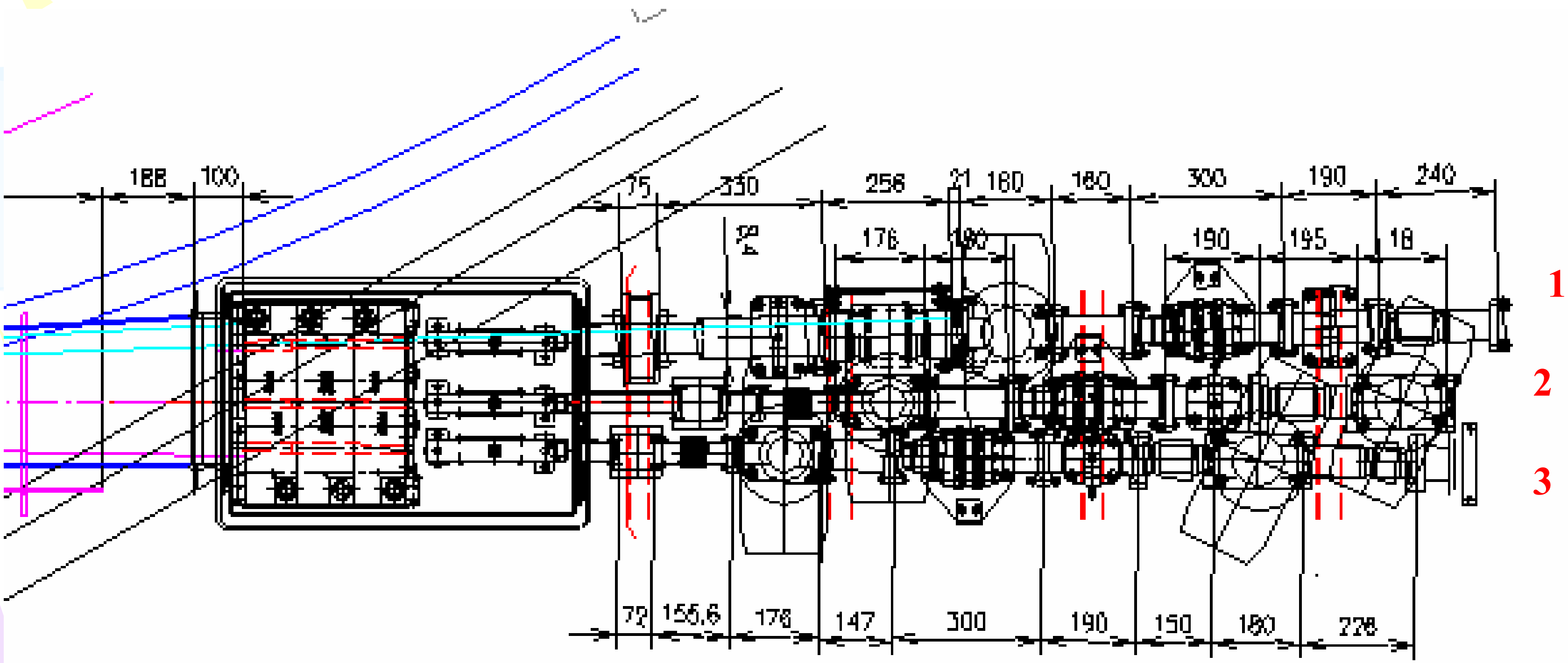
20 meters

SR Beam lines19-poles 7.5 T SCW:

1. RSA: (-17 ± 1) mrad;

2. Extremale state: upto 150 keV, λc = 0.4 Å , P = 940 W/mrad, (0 ± 1) mrad;

3. RS-MCD: (13.3 ± 1)mrad



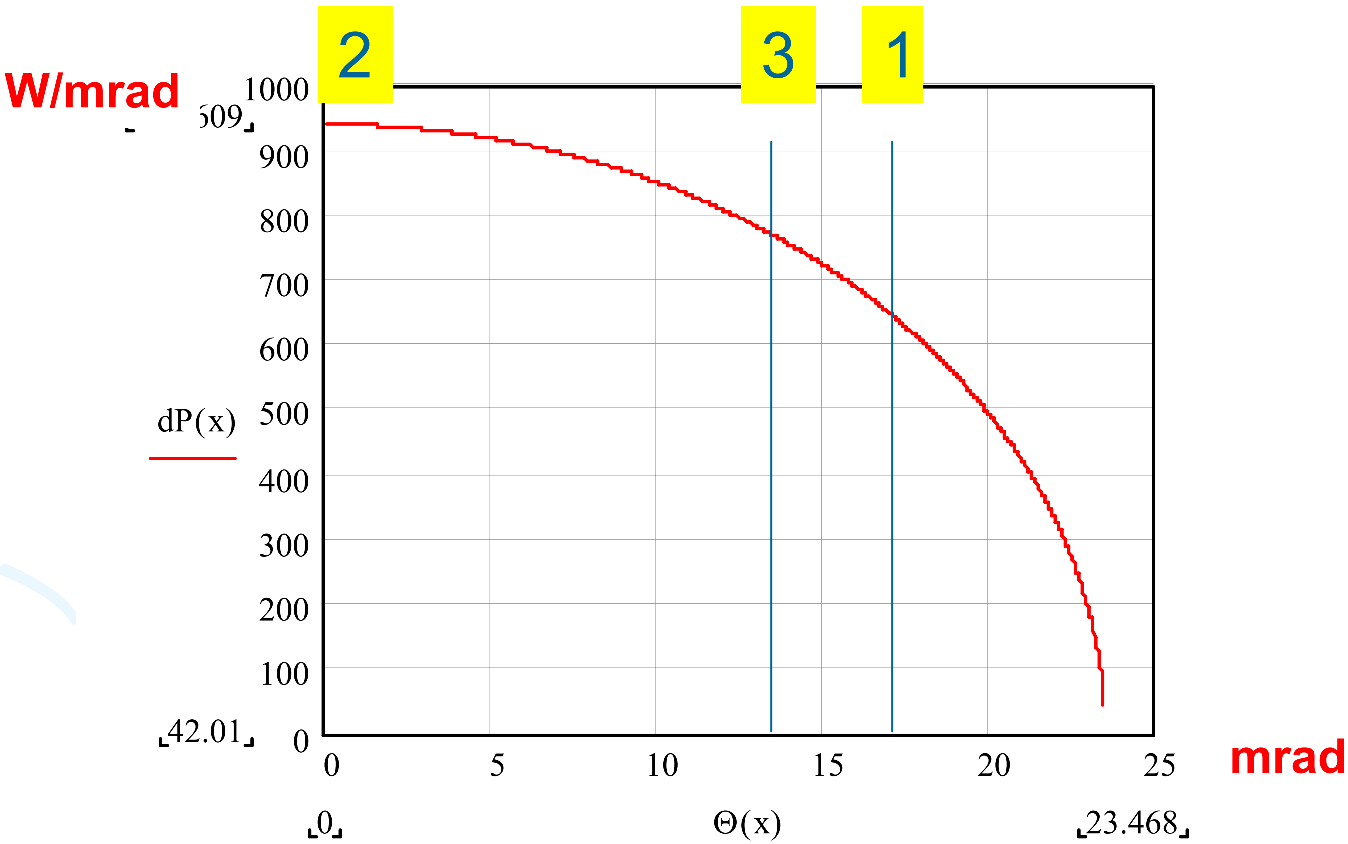
Power density angle distribution of SR from 19-pole SC wiggler E = 2.5 GeV, I = 0.1A, B = 7.5 T

$$\frac{dP}{d\Theta}\left[\frac{W}{mrad}\right] = 4.22 \cdot E^3[GeV] \cdot B_m[T] \cdot I[A] \cdot \sqrt{1-(\Theta/\Theta_m)^2} \cdot N_{poles}$$

1. «RSA»:
(-17 ± 1) mrad,
λc = 0.58 Å,
P = 650 W/mrad

2. «Hard X-Ray»
(0 ± 1) mrad,
Up to 150 keV,
λc = 0.4 Å ,
P = 940 W/mrad,

3. «RS-MCD»:
(13.3 ± 1)mrad,
λc = 0.5 Å,
P = 760 W/mrad



Wiggler influence on general beam parameters of SIBERIA-2

Parameters	Without wiggler	With wiggler 7.5 T
Energy	2.5 GeV	2.5 GeV
Horizontal emittance	***98 nm·rad***	***64.7 nm·rad***
Betatron tune shifts, $\Delta Q_{x,z}$	-	0, 0.05
Radiation loss per turn	***685 keV***	***1041 keV***
Orbit compaction factor	0.01036	0.01036
Energy dispertion, σ_E/E	***0.000953***	***0.00133***
Damping times: τ_x, τ_z, τ_s	3.15, 3.02, 1.48 ms	2.05, 1.99, 0.98 ms
RF-voltage amplitude	1.2 MV (current value)	***1.61 MV*** (for the same energy acceptance)

2007-2009. RF system of Siberia-2 upgrade (KCSR + BINP)

Figure 1.

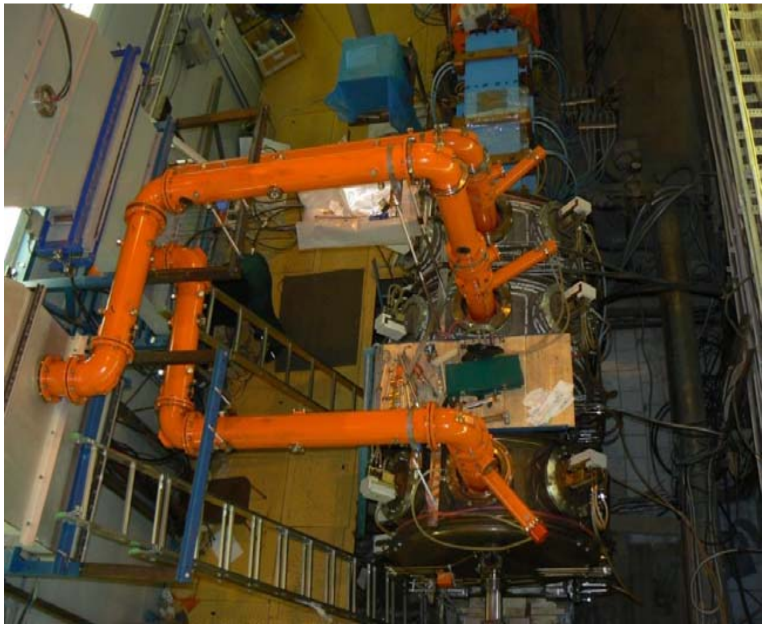


Figure 2.

•Fig.1. (5.11- 28.12).2007. Replacement 181 MHz cavity № 2 on 2 new cavities: New RF control electronics; 2 New feeders; New RF computer control for automation processes.

•Fig.2. October 2009.The installation 3-rd new 181 MHz cavity instead of old one.

Shortening of an electron bunch in SIBERIA-1

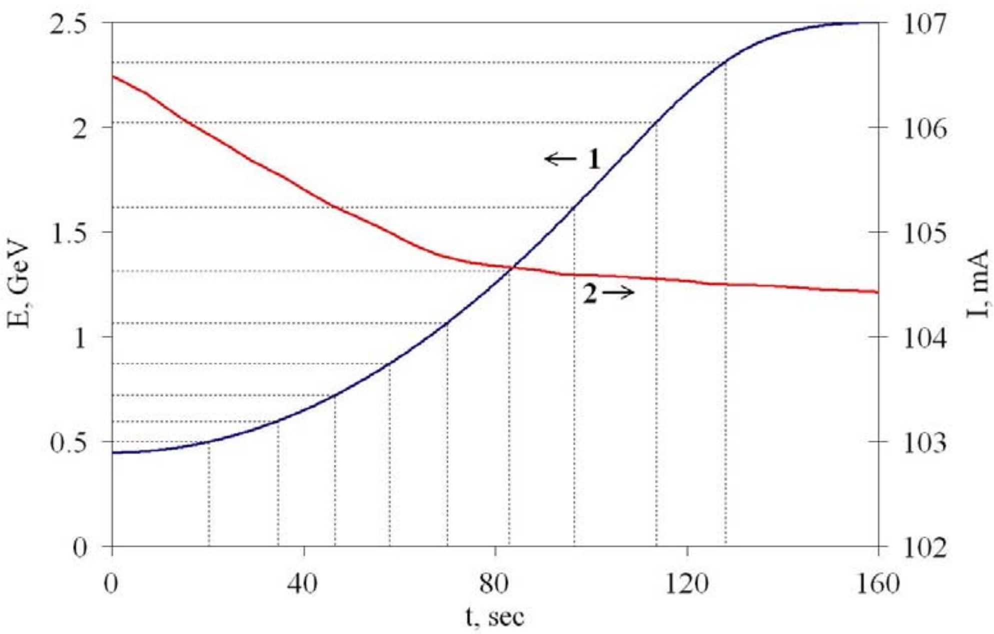
- In 2008 on the SIBERIA-1 a new pulse output septum – magnet with more homogeneous distribution of a magnetic field was established. The increase in ejection factor of an electron current from SIBERIA-1 in EOC-2 to 70 % was received as a result.
- The following step on increase in ejection efficiency of electrons to SIBERIA-2 was made in 2011 when the RF generator of Siberia-1 was powered for the purpose of increase in accelerating tension at RF resonator of 34.5 MHz. from 15 kV to 30 kV.
- Now less than in 0.1 second before release of electrons with energy of 450 MeV the RF generator current is charply increased and, at the RF cavity invariable tune, the electric voltage on the cavity jumps from 15 kV to nearly 30 kV, leading to bunch shortening to

$$6\sigma \approx 130\text{cm} < \lambda_{181\text{MGz}} = 165.6\text{ cm}.$$

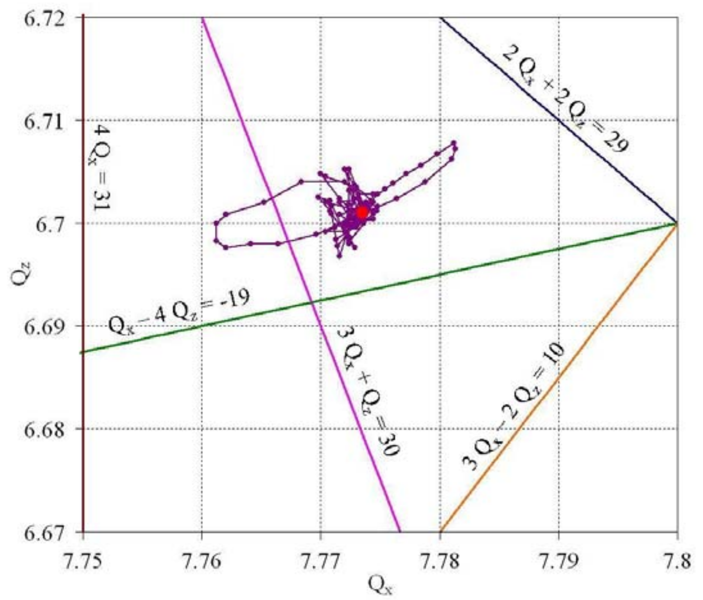
This action stabilizes a capture percentage in Siberia-2.

Energy ramping at Siberia-2 (WEPPD008)

Whole process takes 2 min.40 s, beam losses doesn’t exceed 2 – 3 %, betatron tune shifts are less than 0.015.



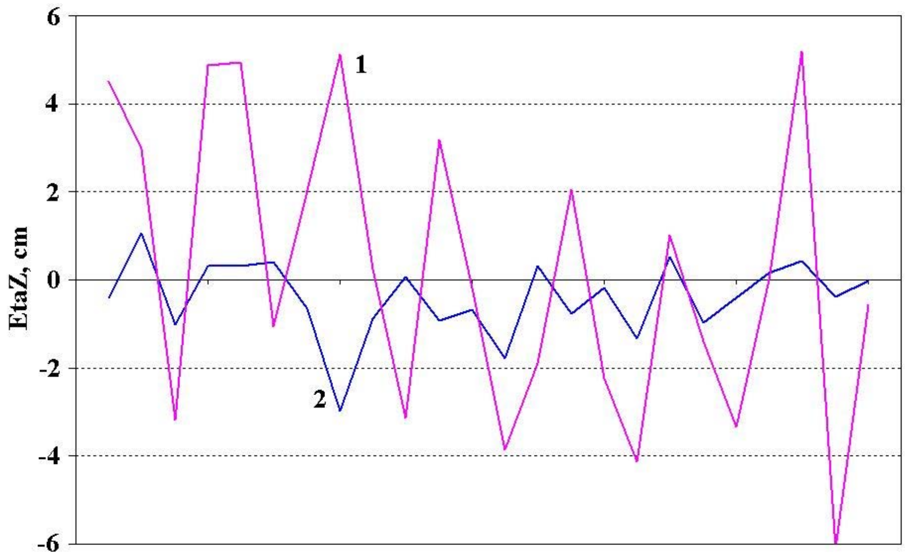
Energy growth (1) and electron current changing (2) during energy ramping (19/04/12). Dotted lines correspond to regime borders.



Betatron tune shifts during energy ramping. Red point corresponds to initial (and final) working point. Largest tune shifts occurred in the last regime.

VERTICAL SIZE OF AN ELECTRON BEAM AT SIBERIA-2 due to vertical dispersion and betatron coupling (WEPPD007)

Vertical dispersion function at SIBERIA-2 BPMs before correction (1) and after it (2).



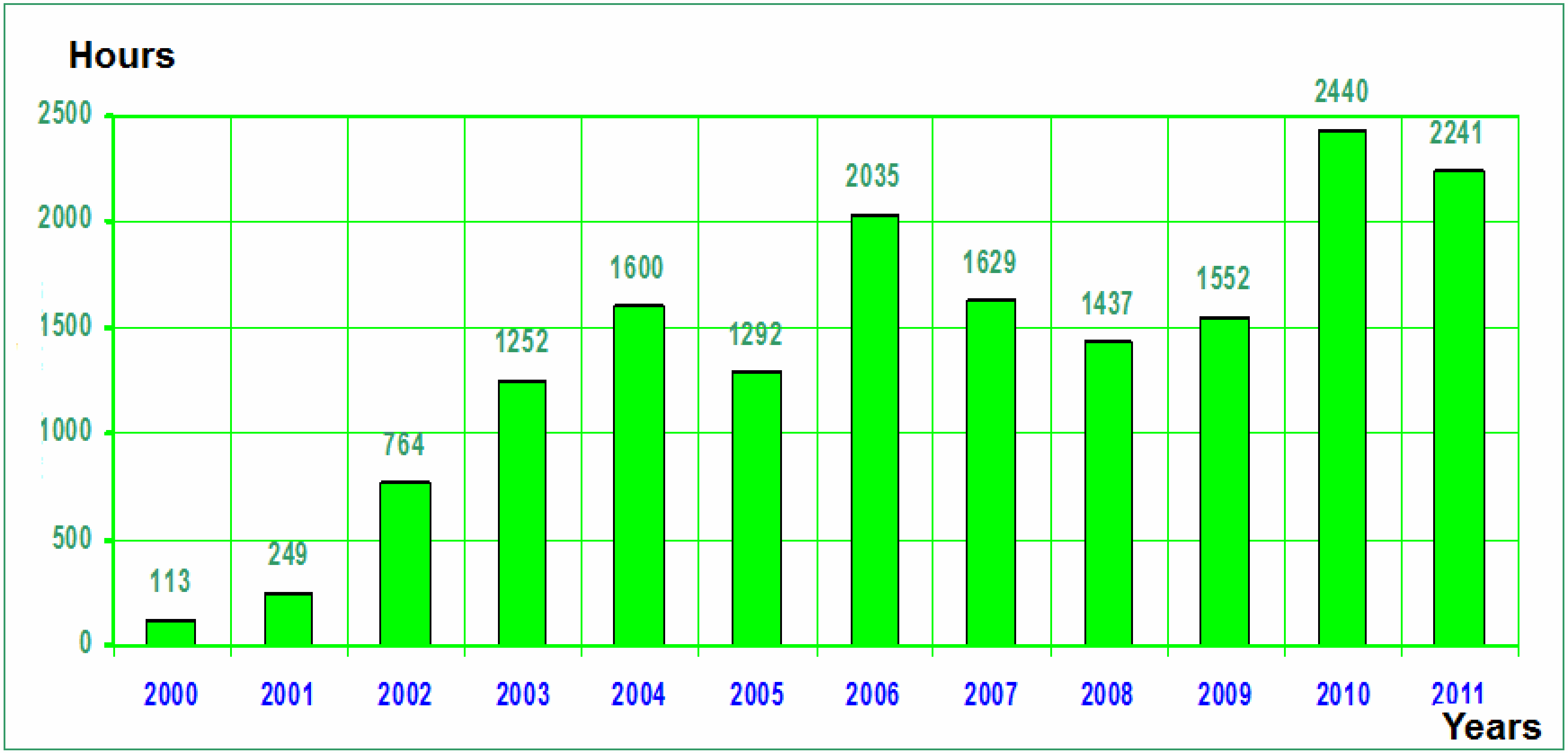
•The new commutation in the families of the skew-quadrupole lenses allowed to reduce currents (and, hence, the field) needed to compensate the betatron coupling.

Thus, *vertical emittance due to coupling can be reduced to an amount not exceeding 0.01% from the horizontal one.*

•*The correction of the vertical dispersion function led to 3.5 times lower ηz value at BPM azimuths.*

All these factors provide a substantial decrease of the electron beam vertical size in radiation points of the bending magnets.

Statistics of work of SR Source for users, 2000-2011.



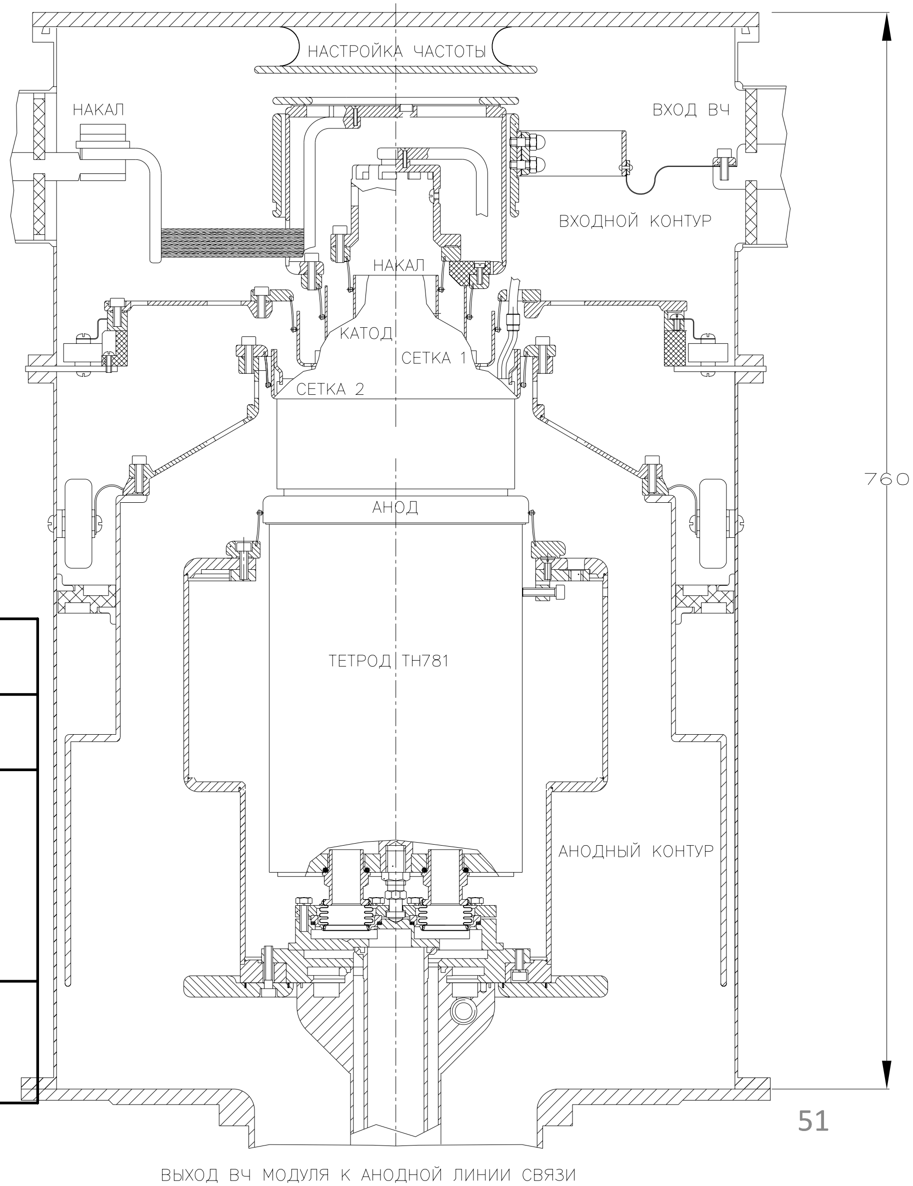
Operation of KCSR SR source in 2011-2012 (1/2)

	Jan.-Dec. 2011	Jan.-Dec. 2011	Jan.-June 2012	Jan.-June 2012
Parameter	SIBERIA-1	SIBERIA-2	SIBERIA-1	SIBERIA-2
Total operation time, hrs: min	3175:37	3914:06	2371:18	2371:24
EXPERIMENT				
Duration, hrs: min	100:15	2241:09	42:39	1074:03
% relative to total operation time	3%	57%	2%	45%
Max. current, мA	299.3	191.1	299.5	127.7
Average current, мA	118.3	83.1	116.6	46.0
Total collected integral, A*hrs	343.1	994.6	348.3	1045.9
Current integral per period, A*hrs	11.867	186.176	5.000	49.300
Life time at 100 mA, hrs: min	0:32	26:11	1:56	38:29
Life time at 50 mA, hrs: min	2:27	41:38	1:11	50:50
INJECTION	12%	6%	10%	5%
Tuning of facilities		9%	34%	24%
Duty mode (other works)		28%	54%	25%

RF system modernization of Siberia-2
2012-2013.

- Change of the RF generating lamps GU101A on the new type of generating lamps (6 powerful tetrodes TH781) with pyrolitic graphite grides (Contract with THALES, France).
- Warranty period of service at these lamps of 3500 hours.
- Target cascades of generators will be modified (contract with BINP, Novosibirsk).

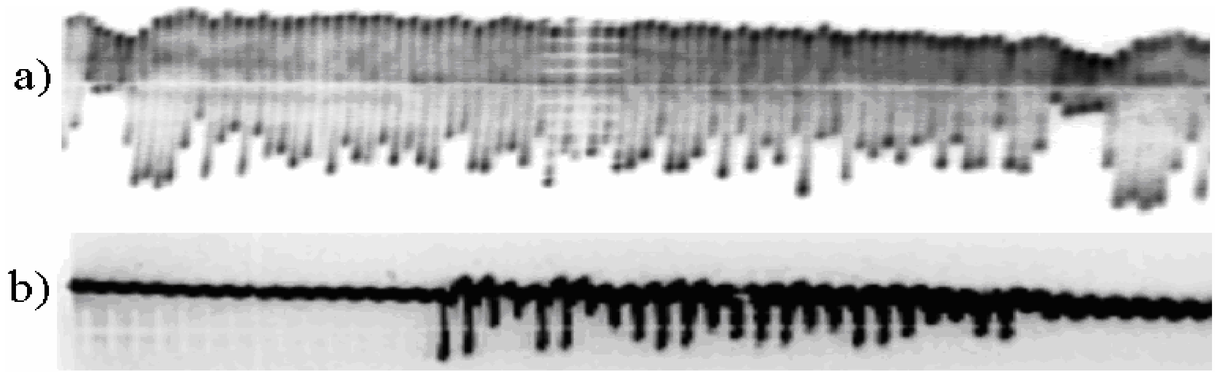
Electron energy	E_{MAX}	GeV	2.5
Beam current	$I_{B\ MAX}$	A	0.29
SR losses from: BMs; BMs and SCWs	ΔE_{BMs} ΔE_{BM+WIG}	keV/ turn	681 1021
Accelerating voltage	$2U_1+U_2$	kV	1500



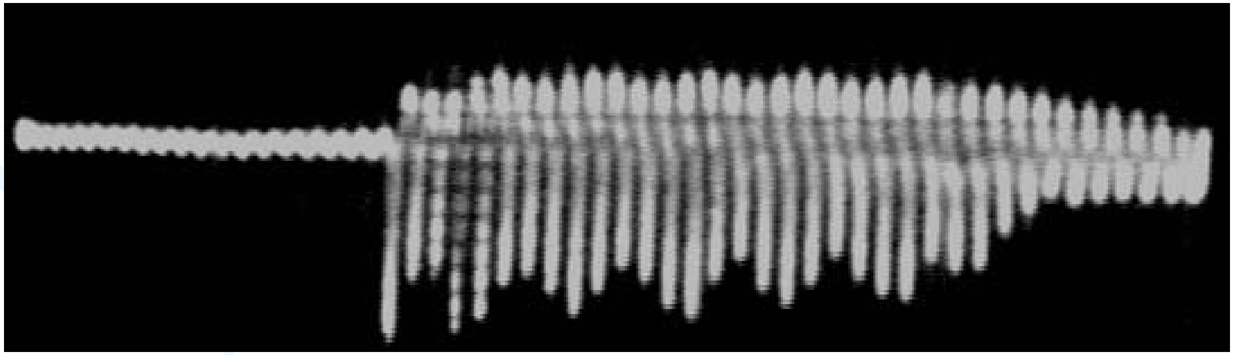
Modernization.
Electron beam diagnostics
on storage ring Siberia-2. 2011-2013

1. System of measurement of an equilibrium orbit of electrons "Orbit (KCSR and LIBERA, Slovenia, 2012г).
2. Feedback system for suppression of coherent betatrone oscillations. (KCSR and LIBERA, Slovenia, 2012г).
3. System of broadband feedback for suppression of coherent synchrotron oscillations. (LIBERA, Slovenia, 2012г).
4. SR beam line and station for optical observation of an electron beam (KCSR and BINP, Novosibirsk, 2012-April 2013).

The need in the feed-back systems on the storage ring Siberia-2



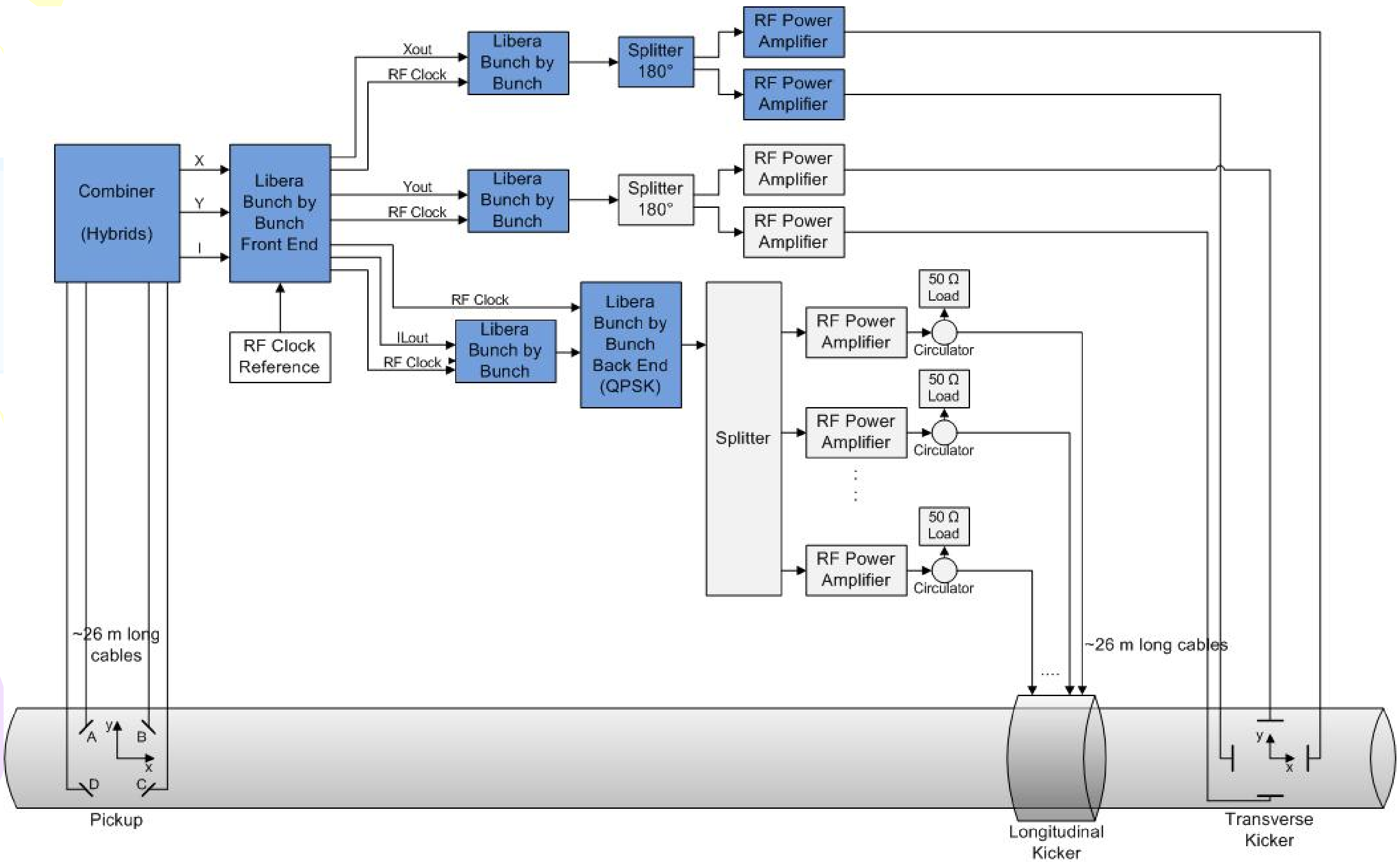
The typical picture of bunches filling when injection process



Modulation of the particle number in the bunches when instability arises during the energy ramping.

The scheme of BbB transverse and longitudinal feedback for SIBERIA-2.

(April 2012, Libera, Slovenia)

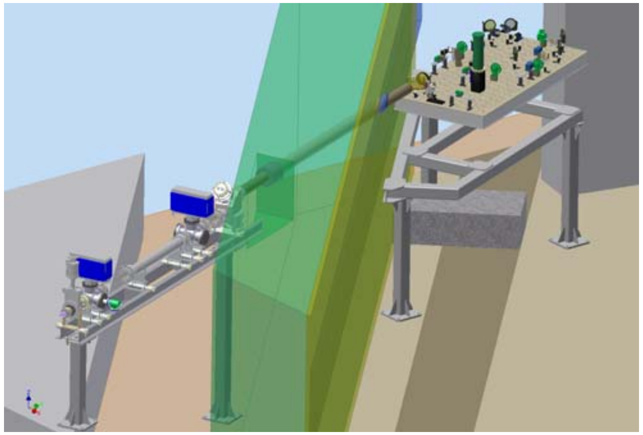


CREATION of Electronics for the orbit and current measurement at Siberia-2 (LIBERA, Slovenia 2012г)

Parameters of the “ORBIT” system	Units	Value
BPMs number	-	24
The electron current in multi-bunch regime	mA	0.1-400
The electron current in single bunch regime	мА	0.1-150
Number of the bunches	-	1-75
Space resolution at turn-by-turn measurements: for average beam current: 100 mA; 5 мА	μm	10; 50
Space resolution with measurement duration mor than 5 ms for average beam current of 5-300 mA	μm	1

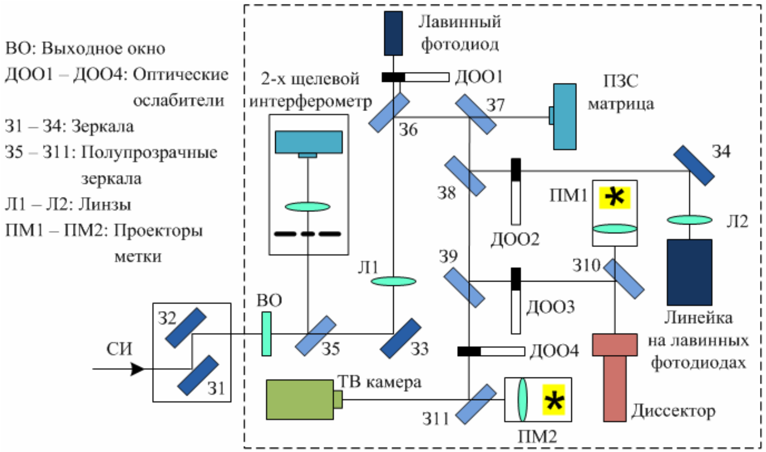
CREATION. Stations of continuous optical supervision outside of tunnel
(KCSR+BINP SB RAS, April 2013)

Existed optical system of electron beam observation inside of tunnel of SIBERIA-2



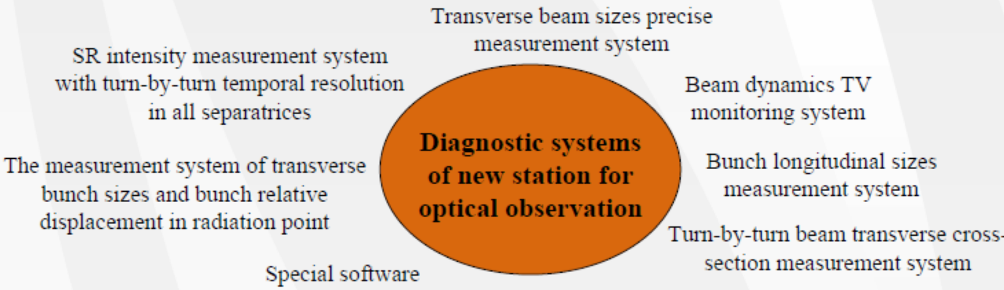
Drawing of a new optical station and beam line

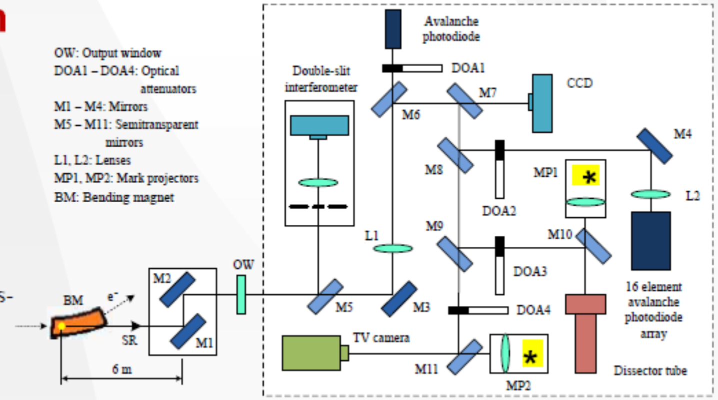
- By April, 2013 on Siberia-2 the special vacuum SR beam line will be mounted to release a visible range of SR out of limits of shielding wall of Siberia-2 storage ring where an optical bench with electronics of optical supervision (a CCD - matrix, φ - dissector, the 2-slit interferometer, the photomultiplier, TV) with high spatial and temporary resolution will be installed .



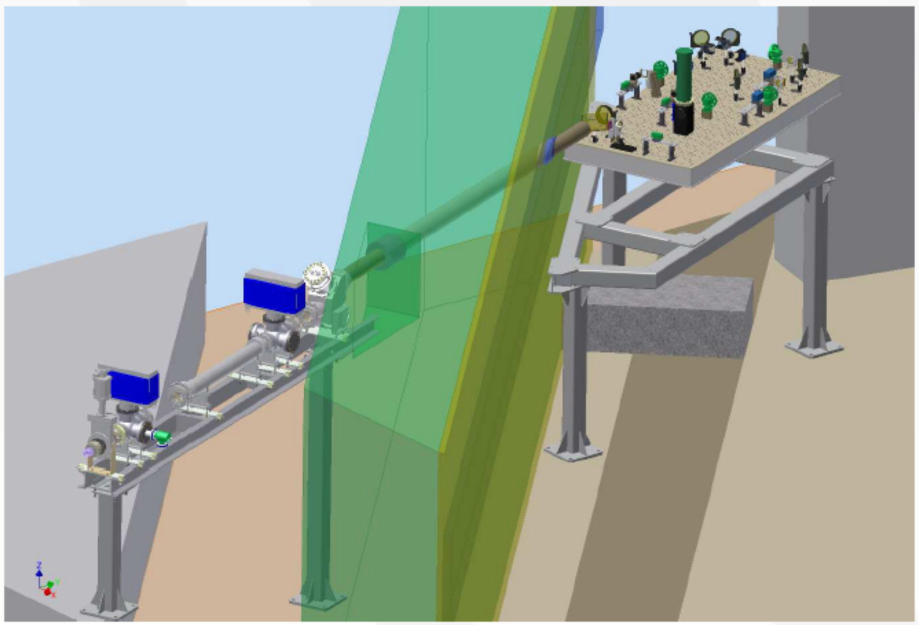
Scheme of a new optical station equipment

Diagnostic systems of optical observation station





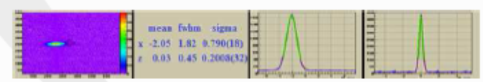
Block-scheme of the optical observation station measurement part at SIBERIA-2 storage ring.



Transverse beam sizes precise measurement system based on the double-slit interferometer serves to measure bunch transverse sizes with resolution 1 μm.

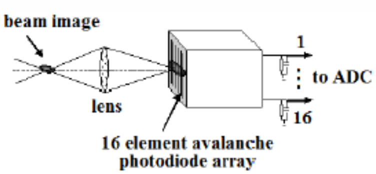
SR intensity measurement system with turn-by-turn temporal resolution in all separatrices contains an avalanche photodiode functioning as photodetector. For the increase of diagnostic dynamic range a discrete optical attenuator DOA1 is used which consists of a set of neutral light filters with attenuation rate ranging from 10 to 10^6 with a step of 10.

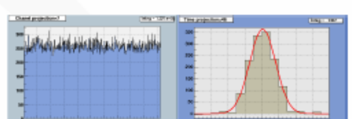
The measurement system of transverse bunch sizes and bunch relative displacement in radiation point contains CCD-matrix which can operate in continuous and pulse modes. The result of computer processing of signal from CCD-matrix is a visual two-dimension image of electron beam cross-section, x- and y- curves of electron density distribution within beam, FWHM, position of electron beam centre.



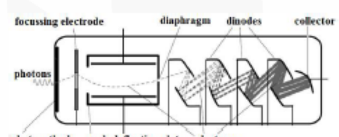
Beam dynamics TV monitoring system based on a TV camera is used for transferring the electron beam cross-section image to the video monitor.

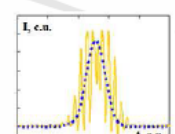
Turn-by-turn beam transverse cross-section measurement system serves the purpose of measuring x- and y- distribution of electron density within a chosen bunch, betatron and synchrotron oscillation frequency (defined by way of Fourier analysis of bunch dipole oscillations triggered by kick) as well as investigating x- or y- dynamics of beam shape in a chosen separatrix. The system comprises a measuring linear photo-receiver based on 16 avalanche photodiodes, optical attenuator and lens.





Bunch longitudinal sizes measurement system includes dissector tube with electrical focussing and deflection, DOA4 and mark projector. Dissector tube is also used for the diagnostic of longitudinal multibunch instability caused by electron bunches interaction with high modes of cavity electromagnetic field.





Special software will allow for automated monitoring and control of electron beam parameters. Graphical user interface will enable the operator to control system operation modes, to change the detectors parameters, to scan, to process and to archive the data.

POWER SUPPLIES and CS MODERNIZATION

1. Generators (nano - and micro second) pulse tension for system of injection of an accelerating complex (JSC Imp. Tekhnologii, Ryazan, KCSR).
2. The electronic equipment of the control for power supplies of Siberia-2 storage ring magnets (it is possible in 2013).
3. Modernization of CS of accelerator complex "Siberia". Stage 2 (RT Soft, 2012).Stage 3. (RT Soft, 2013)