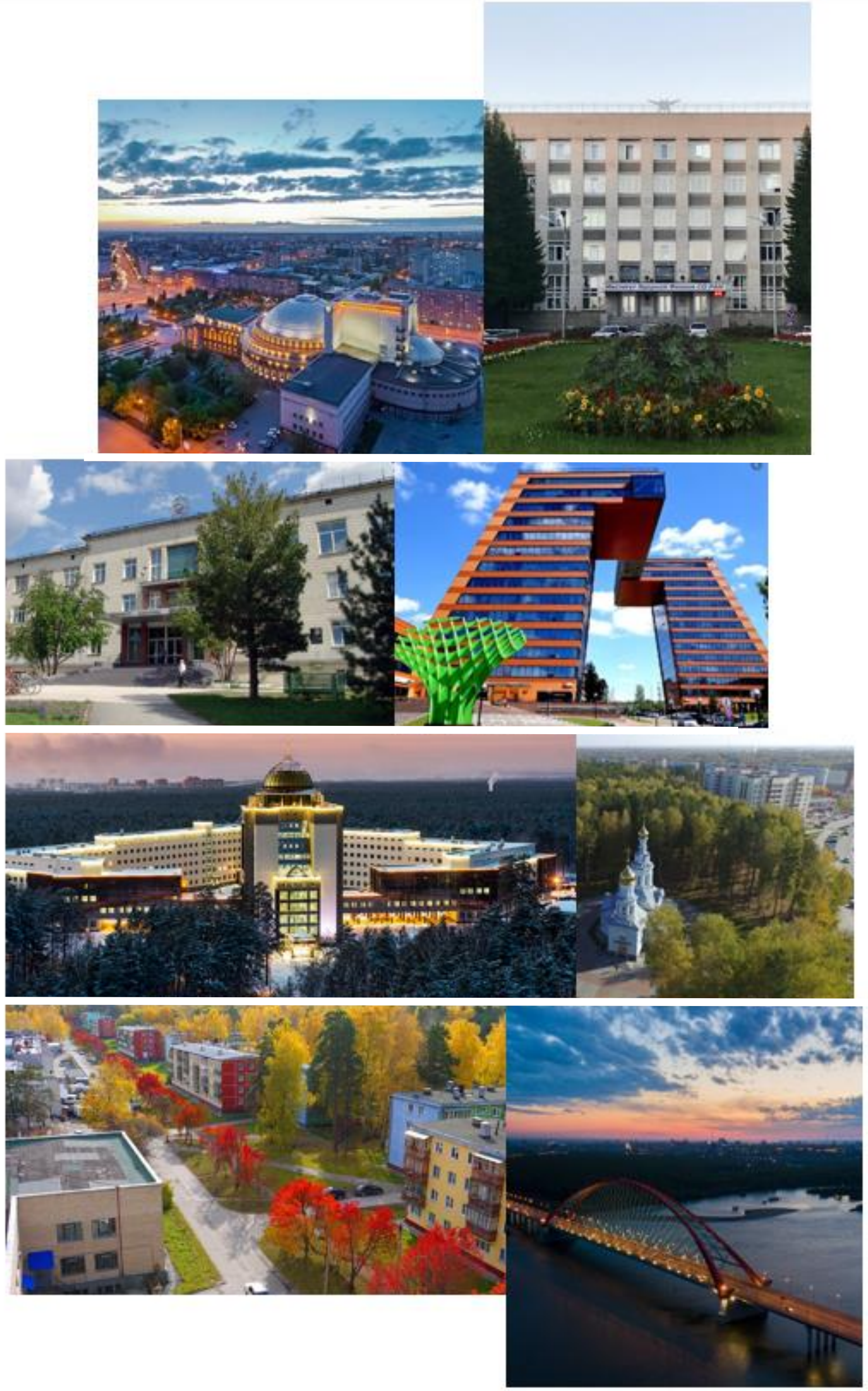


Storage ring for Novosibirsk low emittance light source SKIF

E. Levichev (on behalf of the SKIF team)

Budker Institute of Nuclear Physics/Boreskov Institute of Catalysis, Novosibirsk, Russia

LER-2020, 26-30 October 2020

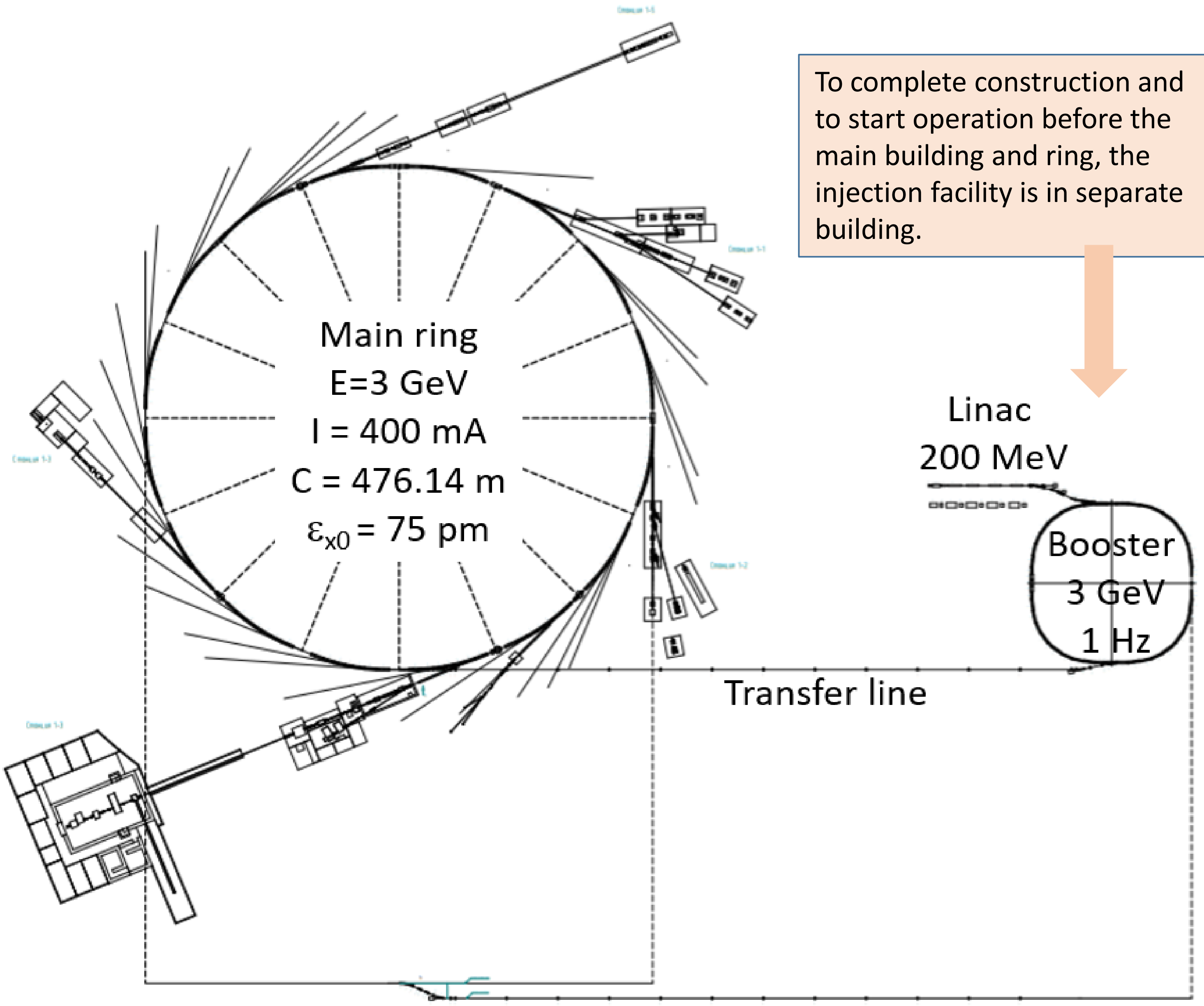
Specifications and constraints

- Beam energy 3 GeV (short construction term)
- Circumference < 500 m (available ground area)
- Natural horizontal emittance $\leq$100 pm (zero current, zero coupling, no IDs)
- Injection complex *à la* NSLS II (150-200 MeV linac and full energy small size booster synchrotron) (short construction term)
- Traditional off-axis horizontal plane injection with four-kicker bump (reliability)
- Sufficient number of beamlines (users requirements)
  - From wigglers and undulators (straight sections)
  - Hard X-ray from strong field dipoles
  - Soft X-ray and VUV from weak field magnets (important for catalysis and chemical users)
- Simple, robust, proven solution when possible (reliability) (short construction term)

Configuration

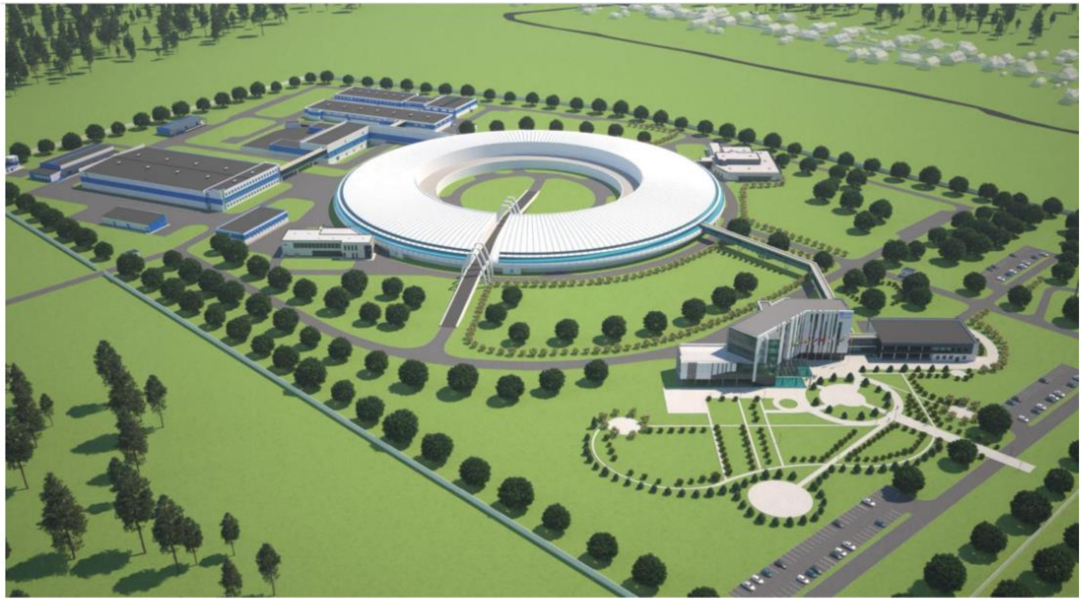
- Linear accelerator with maximum energy 200 MeV
- Small size booster synchrotron with maximum energy 3 GeV and orbit length 158.7 m
- Electron storage ring 16-fold symmetry with 3 GeV energy and 476 m circumference

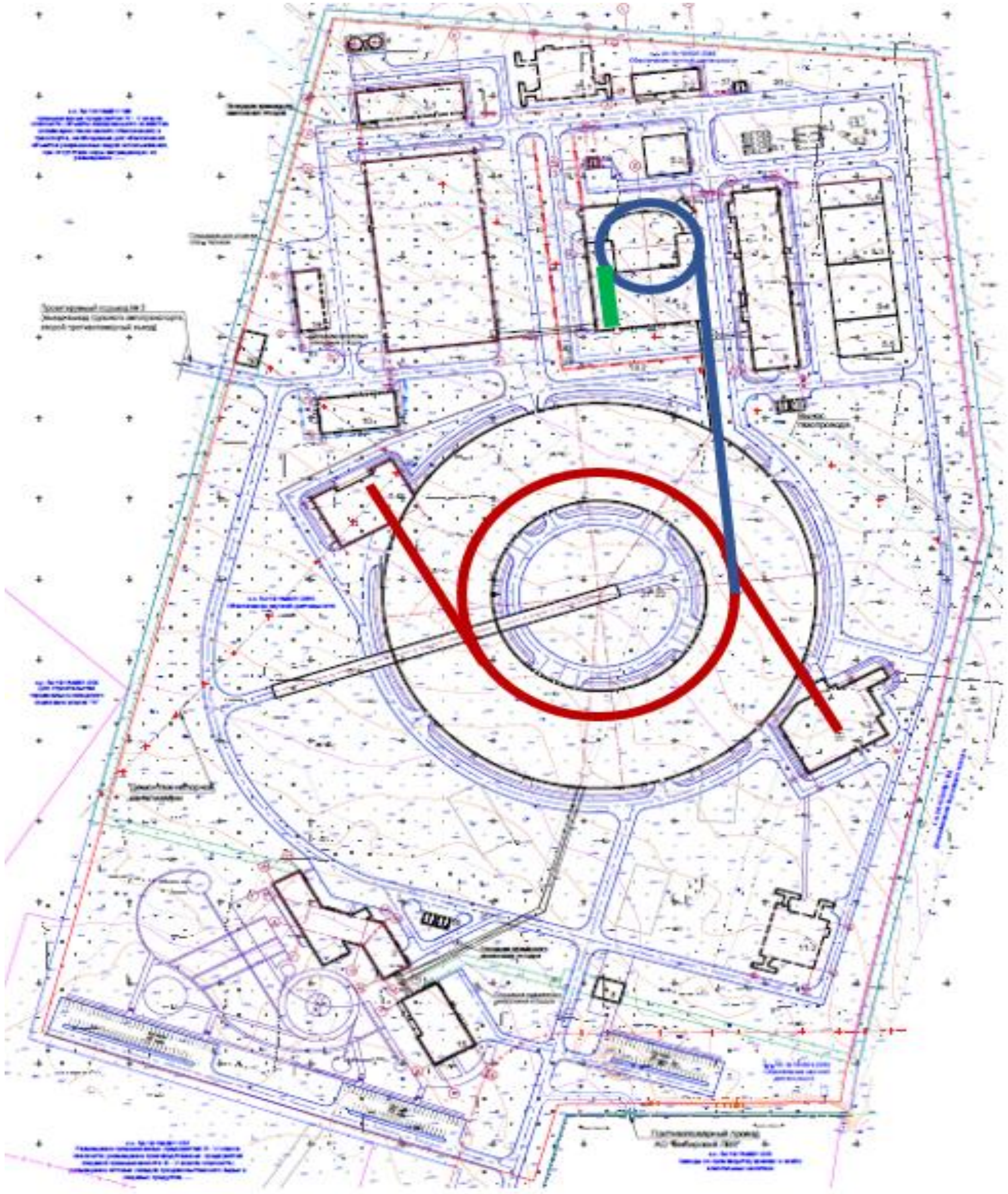
To complete construction and to start operation before the main building and ring, the injection facility is in separate building.



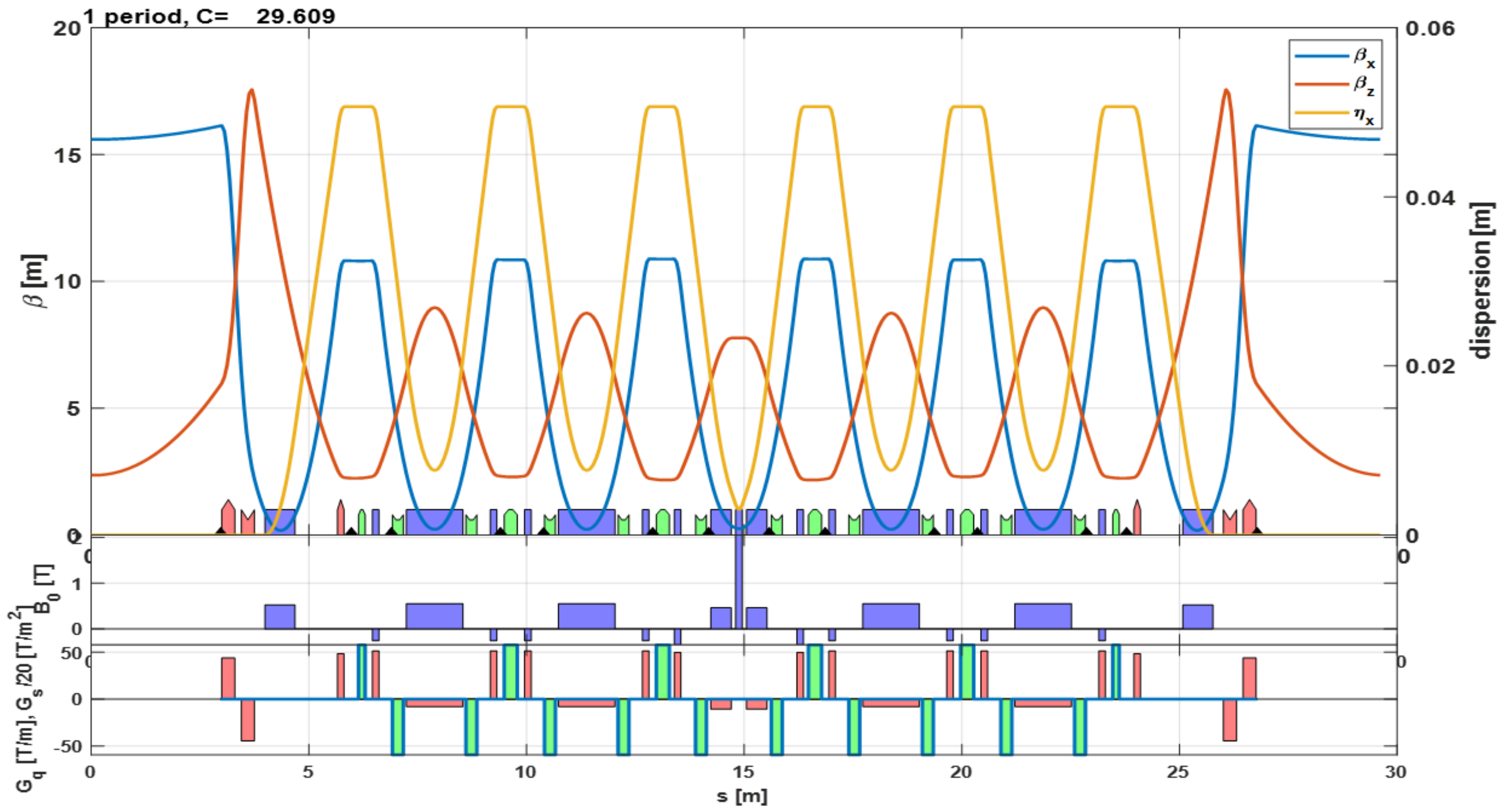
SKIF Location: Kol’tsovo Science Town

Site and architecture



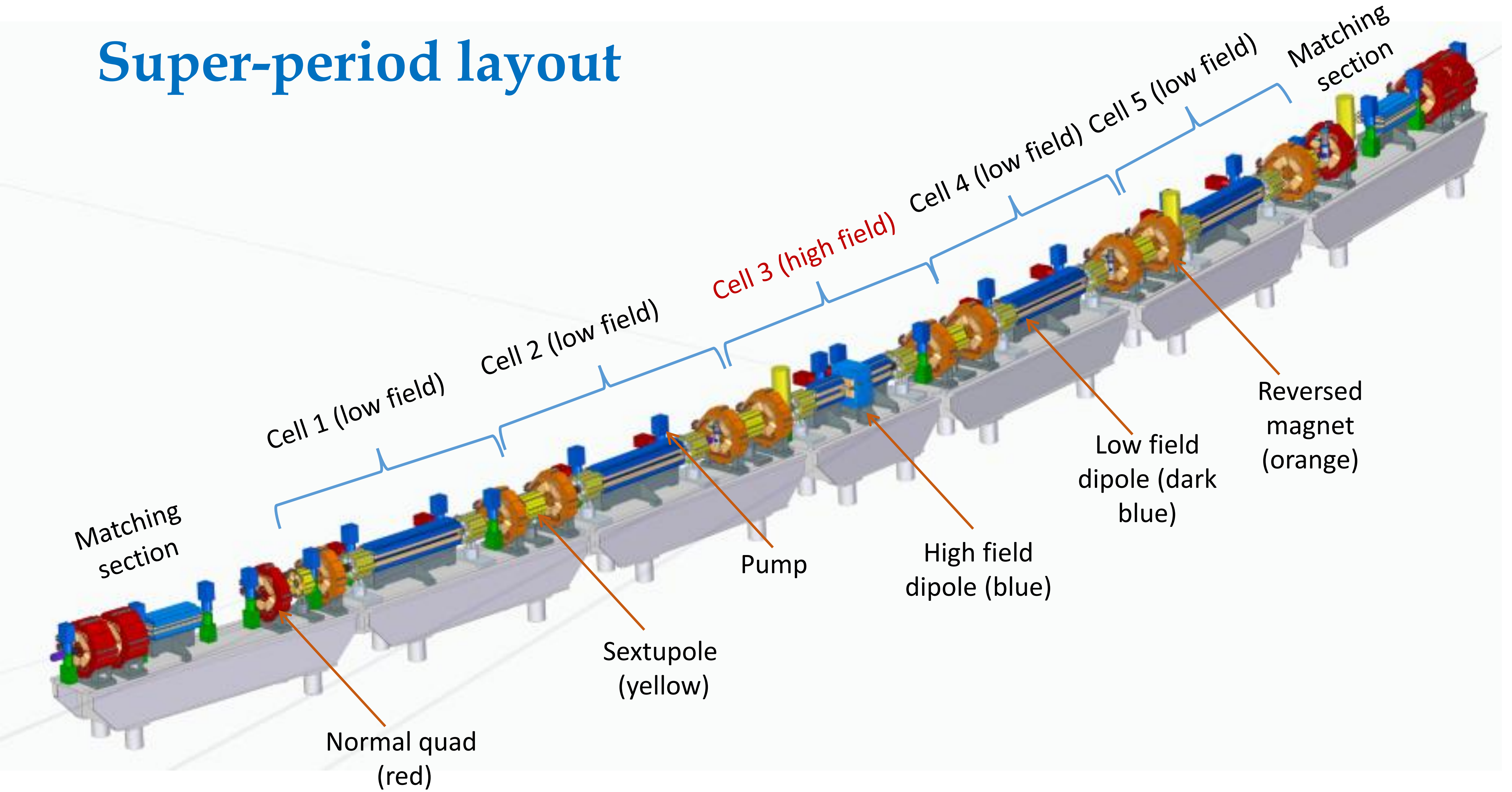


Super-period optics and parameters



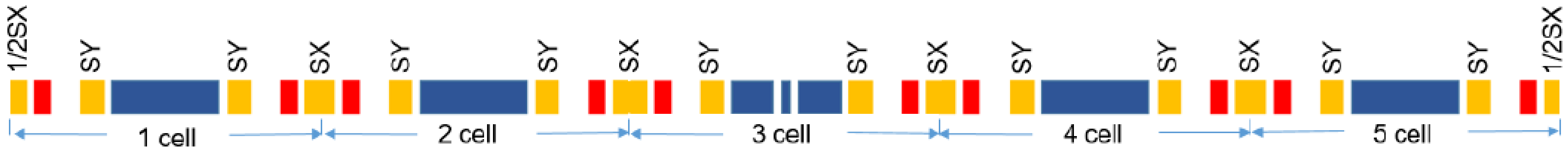
Energy, GeV	3
Symmetry	16
Circumference, m	476.14
Revolution period, µс	1.588
Horizontal emittance, pm	73.2
Energy spread	$1 \cdot 10^{-3}$
E loss per turn, keV	536
Betatron tunes, (*x*/*y*)	50.806 / 18.84
Compaction factor	$7.64 \cdot 10^{-5}$
Natural chromaticity, (*x*/*y*)	–149/–55
RF harmonic number	567
RF frequency, MHz	357
RF voltage, MV	0.77
Energy acceptance	±3 %
Synchrotron tune	$1.13 \cdot 10^{-3}$
Natural bunch length, mm	5.3
Partitions, (*x*/*e*)	1.94/1.06
Damping times, (*x*/*e*), ms	9.2/16.7

Super-period layout



Chromaticity correction

(ξ_x/ξ_y) =- 149/- 55

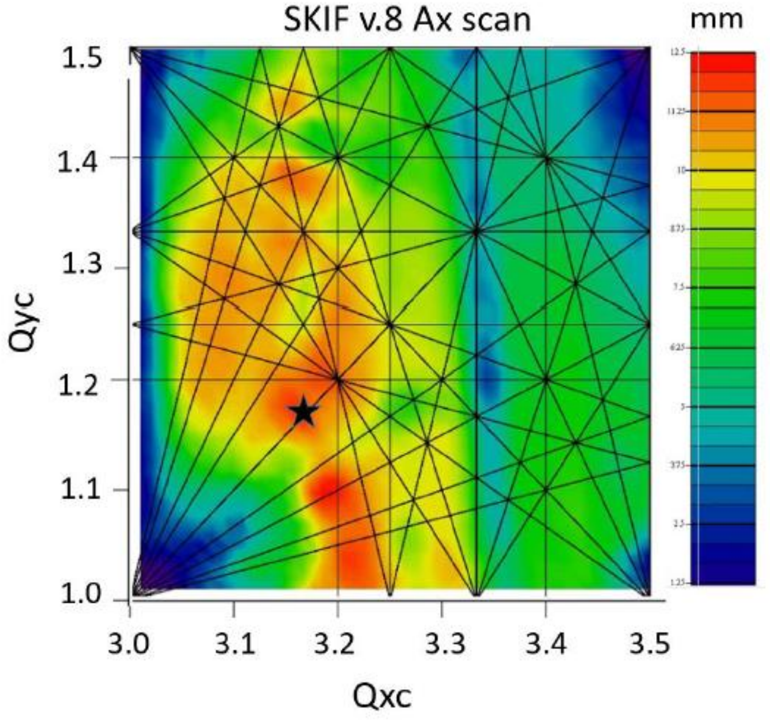


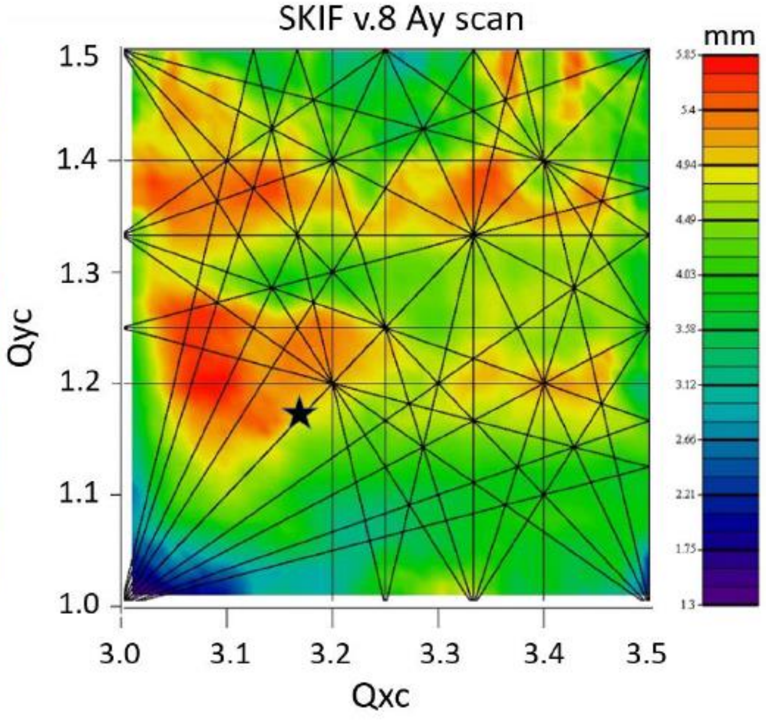
	l, м	B''_{nom}, Т/м^2	$(K_2 l)_{nom}$, м$^{-2}$	B''_{max}, Т/м^2	$(K_2 l)_{max}$, м$^{-2}$
SY	0.25	–2379	–59.48	–2800	–70
SX	0.30	2313	69.39	2800	84
1/2SX	0.15	2313	34.70	2800	42

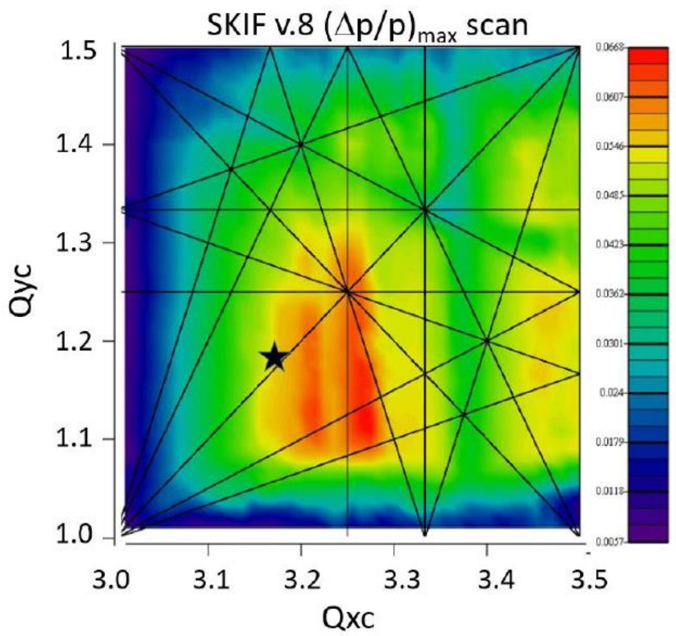
We use only two sextupole families to compensate natural chromaticity and optimize dynamic aperture and momentum acceptance. No other multipoles (octupoles or harmonic sextupoles) are applied.

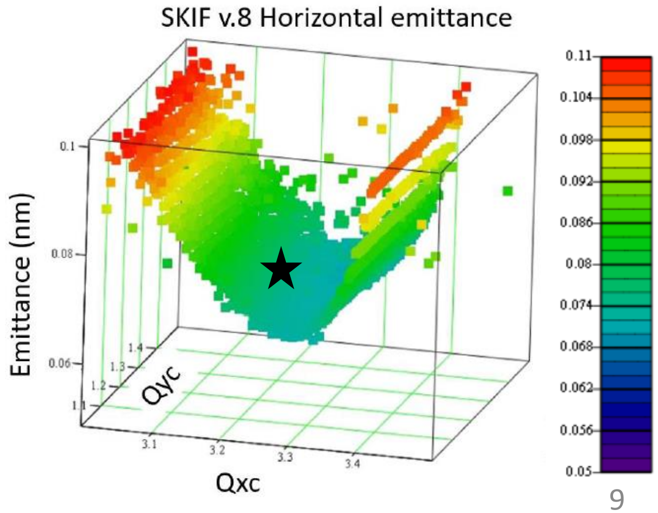
Dynamic aperture scan for one super-period

Tunes are for one super-period. ★ Chosen tune point



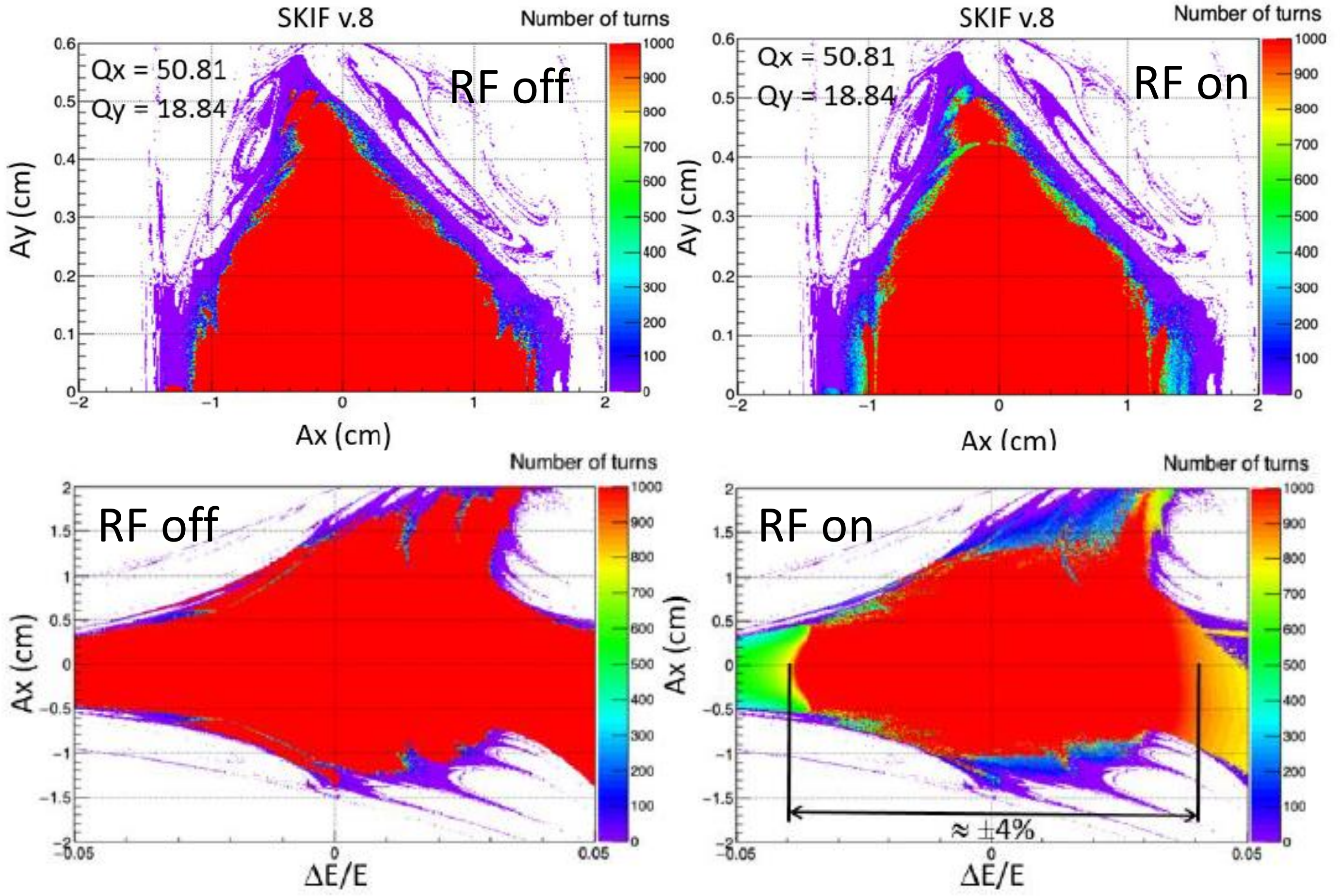




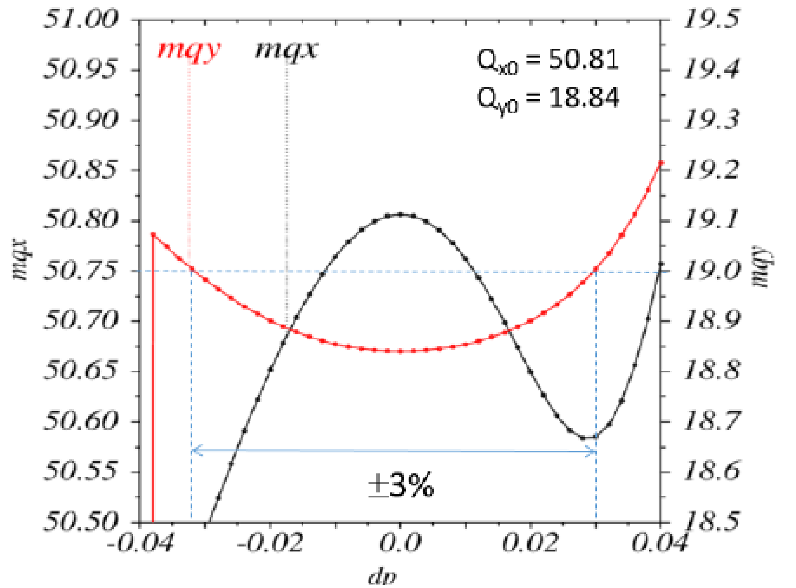


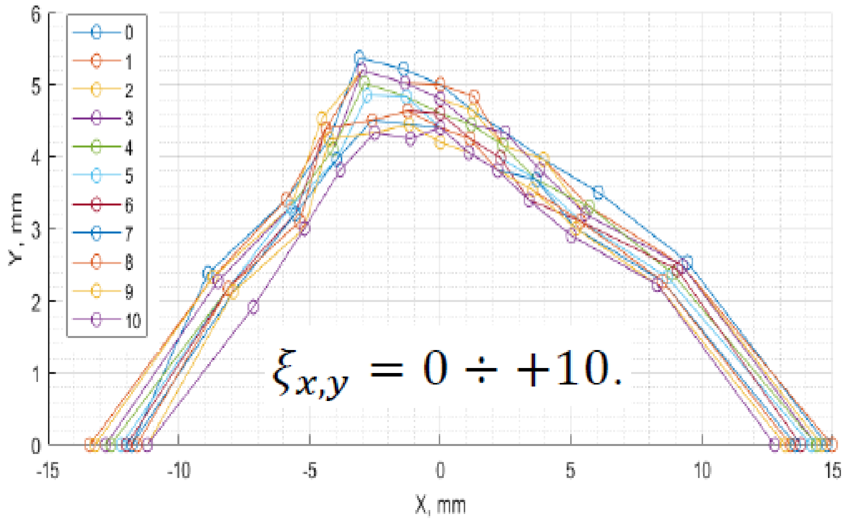
Betatron tunes, phase advances between chromatic sextupoles and their strength were carefully adjusted to maximize dynamic aperture and momentum acceptance.

Dynamic aperture and momentum acceptance



Survival plots. Red is stable during 1000 revolutions. Only two sextupole families are enough to get sufficient dynamic aperture and momentum acceptance. $\beta_x = 15.6$ м, $\beta_y = 2.4$ м

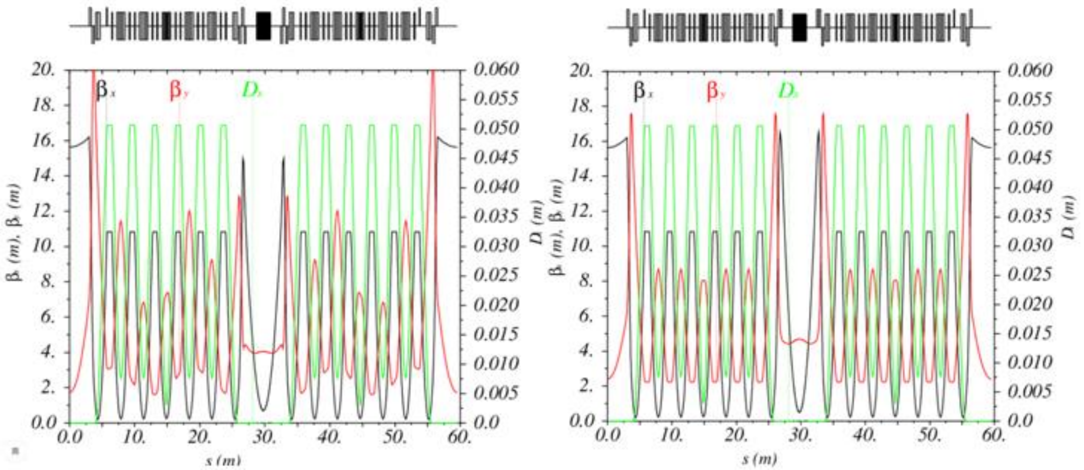




Insertion devices

To extend the spectrum in the hard X-ray region, we plan to use superconducting IDs.

№	Experimental station	ID	B (T)	λ_w (mm)	N_{per}	P_{SR} (kW)
1-1	Microfocus (5-47 keV)	SCU	1.2	15.6	128	7.2
1-2	Structural analysis (5-40 keV)	SCU	1.2	15.6	128	7.2
1-3	Fast dynamic processes (15-100 keV)	SCW	4	33.7	60	75
1-4	XAFS and magnetic dichroism (2.5-35 keV)	SCU	1.2	15.6	128	7.2
1-5	Hard X-ray imagine (25-200 keV)	SCW	4	33.7	60	75
1-6	Photoelectron spectroscopy (0.01-2 keV)	EMU	0.5	100/200	20/10	1.8



Before correction

After correction

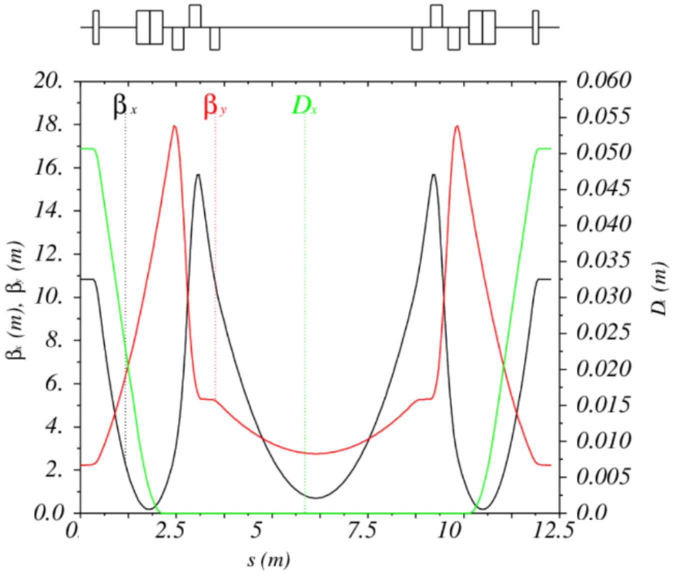
Optics with 1 SCW

Parameter	Bare	1U	1W	2W	3W
ε_{xtot}, pm	73	72	74	75	76
$\sigma_E/E \cdot 10^3$	1.03	1.02	1.24	1.32	1.36
ΔE/turn, keV	534	548	720	904	1090
U_{RF}, MV	0.85	0.85	1.1	1.27	1.48
$J_{x/s}$	1.94/1.06	1.91/1.09	1.68/1.32	1.55/1.45	1.46/1.54
$\tau_{x,y,s}$, ms	9/18/17	9/17/16	8/13/10	7/10/7	6/9/6

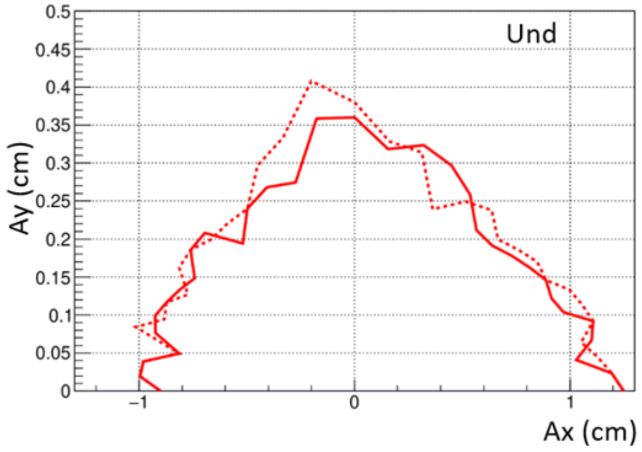
For baseline lattice, the emittance does not depend on IDs.

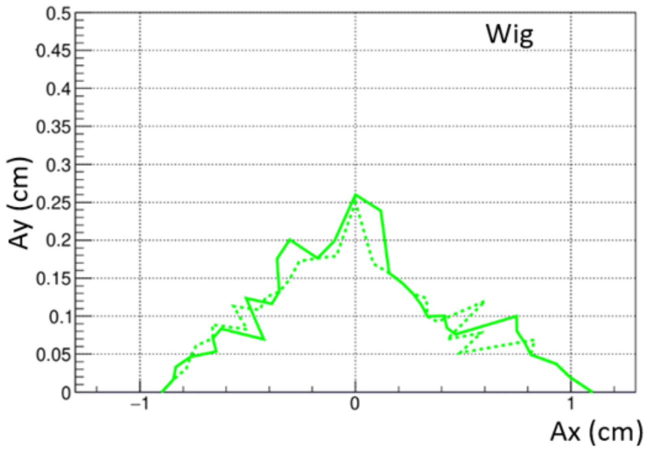
IDs, alternative drift optics

Low β_x in the wiggler section allows additional emittance reduction. For beta control we need quadrupole triplets instead of doublets.



Parameter	Bare	1W	2W	3W
ε_{xtot}, pm	73	61	54	48
$\sigma_E/E{\cdot}10^3$	1.03	1.24	1.32	1.36
ΔE/turn, keV	534	720	904	1090
U_{RF}, MV	0.85	1.1	1.27	1.48
$J_{x/s}$	1.94/1.06	1.68/1.32	1.55/1.45	1.46/1.54
$\tau_{x,y,s}$, ms	9/18/17	8/13/10	7/10/7	6/9/6





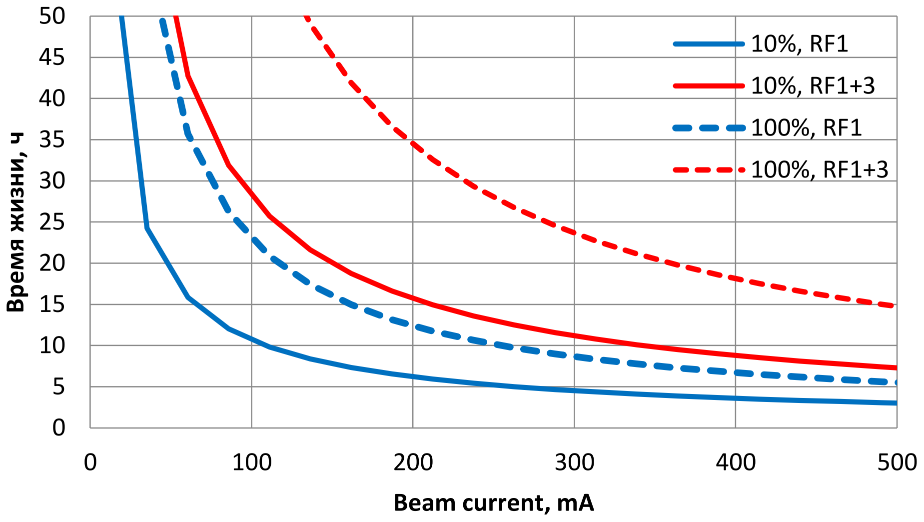
Strong field IDs influence the DA (through the optical symmetry breaking). Mitigation of such influence is under way.

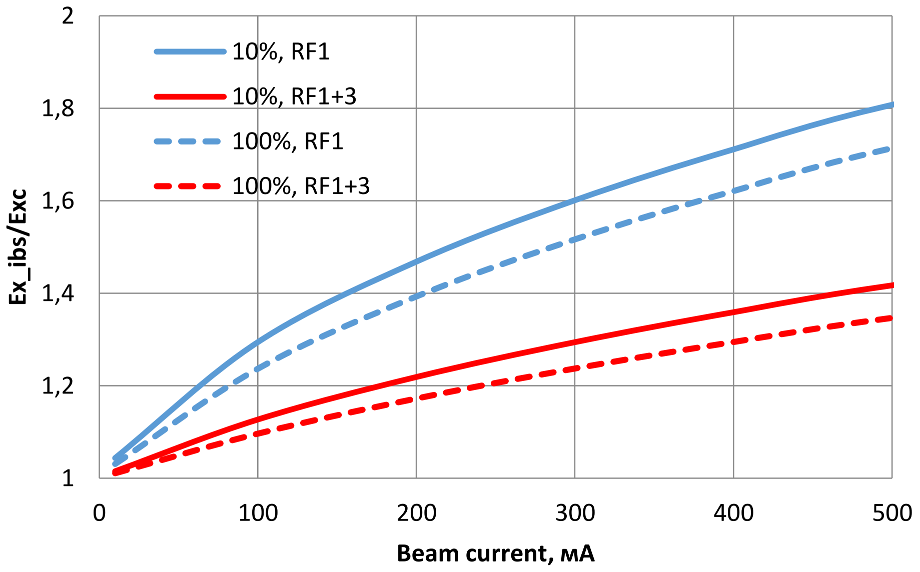
IBS bare lattice

400 mA in 510 bunches, U_0=534 keV/turn, V_{RF}=0.845 MV ($\Delta E/E=\pm3\%$)

RF1 – main accelerating system, RF1+3 – third harmonic RF elongate the bunch threefold.

	10%		100%	
	RF1	RF1+3	RF1	RF1+3
ε_{x0}, pm	72.7			
$\varepsilon_{xcoupled}$, pm	66		36	
ε_{xIBS}, pm	113	90	59	47
ε_{yIBS}, pm	11	9	59	47
$\sigma_E/E \times 10^4$ (0/IBS)	10.3/12.4	10.3/11.4	10.3/11.4	10.3/10.9
σ_l (mm) (0/IBS)	5.3/5.9	15.8/16.2	5.3/5.4	15.8/15.4
τ_{TIBS} (hours)	3.2	7.9	6.2	17





IBS with IDs

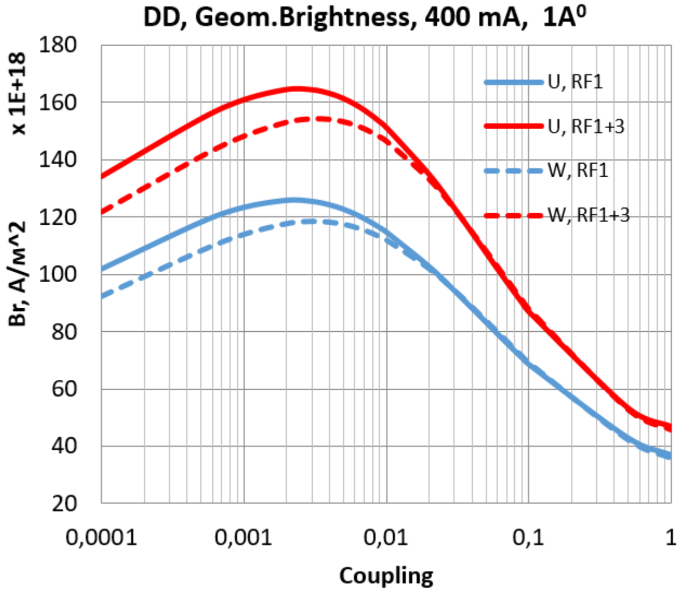
"Reduced or geometrical" brightness (depends on the electron beam parameters):

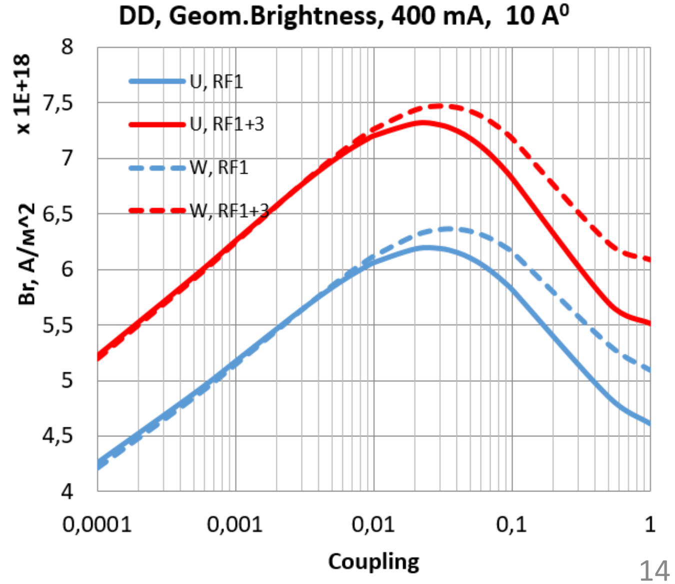
$$Br(\lambda) = \frac{n_b I_b}{\Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}} = \frac{n_b I_b}{\sqrt{\sigma_x{}^2+\sigma_r{}^2}\sqrt{\sigma_{x'}{}^2+\sigma_{r'}{}^2}\sqrt{\sigma_y{}^2+\sigma_r{}^2}\sqrt{\sigma_{y'}{}^2+\sigma_{r'}{}^2}},$$

$$\Sigma^2_{x,y}(I_b) = \beta_{x,y}\varepsilon_{x,y}(I_b) + \left(\frac{\sqrt{2\lambda L}}{4\pi}\right)^2, \quad \Sigma^2_{x'y'}(I_b) = \frac{\varepsilon_{x,y}(I_b)(1+\alpha_{x,y}{}^2)}{\beta_{x,y}} + \left(\sqrt{\frac{\lambda}{2L}}\right)^2$$

400 mA in 510 bunches, κ = 10%, B_{r1} and B_{r10} – "geometrical brightness" for λ = 1 Å and λ = 10 Å.

	SCU		SCW		10SCU+2SCW	
	RF1	RF1+3	RF1	RF1+3	RF1	RF1+3
U, MeV	0.55		0.72		1.07	
V_{rf}, MV	0.864		1.06		1.44	
ε_{x0} | $\varepsilon_{xcoupled}$, pm	71.6| 65.1		74.1| 67.3		67.2|61.1	
ε_{xIBS}, pm	112.8	89.2	106.8	85.7	99.5	78.9
$\sigma_E/E\times10^4$	10.2		12.4		12.3	
$(\sigma_E/E)_{ibs}\times10^4$	12.3	11.3	13.5	12.9	13.1	12.7
σ_l (mm)	4.8	14.3	5.3	16.1	4.7	14.3
σ_{l_IBS} (mm)	5.8	15.9	5.8	16.8	5.1	14.7
τ_{TIBS} (hours)	3.2	7.7	3.3	8.6	2.7	7.3
B_{r1} (A/m^2) $\times10^{-18}$	58.0	75.6	62.3	80.2	66.8	86.4
B_{r10} (A/m^2) $\times10^{-18}$	5.2	6.2	5.8	6.7	5.7	6.8





Emittance and lifetime with IBS

- For bare baseline lattice with 400 mA in 510 bunches, 10% coupling, ±3% energy acceptance (V_{RF} = 0.845 MB), horizontal emittance increases from 73 pm to 113 pm. Touschek lifetime is 3.2 hours.
- Threefold bunch elongation reduces the emittance to 90 pm and increases Touschek lifetime up to 7.9 hours.
- 100 % coupling provides $\varepsilon_x = \varepsilon_y = 50 \div 60$ pm and doubles lifetime. However, the "geometrical" brightness reduces by factor 1.5÷2 (for the radiation wavelength region 1÷10 Å).
- For "premium" configuration (10 SCU + 2 SCW) $\tau_{TIBS} \geq$ 5 hours for V_{RF} = 1.4 MB (without coherent losses and other collective effects).
- For "premium" configuration, 10% coupling, threefold bunch elongation and 400 mA in 510 bunches the minimum horizontal emittance is 78.9 pm.
- For the radiation wavelength region 1÷10 Å maximum "geometrical" brightness is for the coupling range $\kappa \approx$ 0.5÷5%.

COD correction I

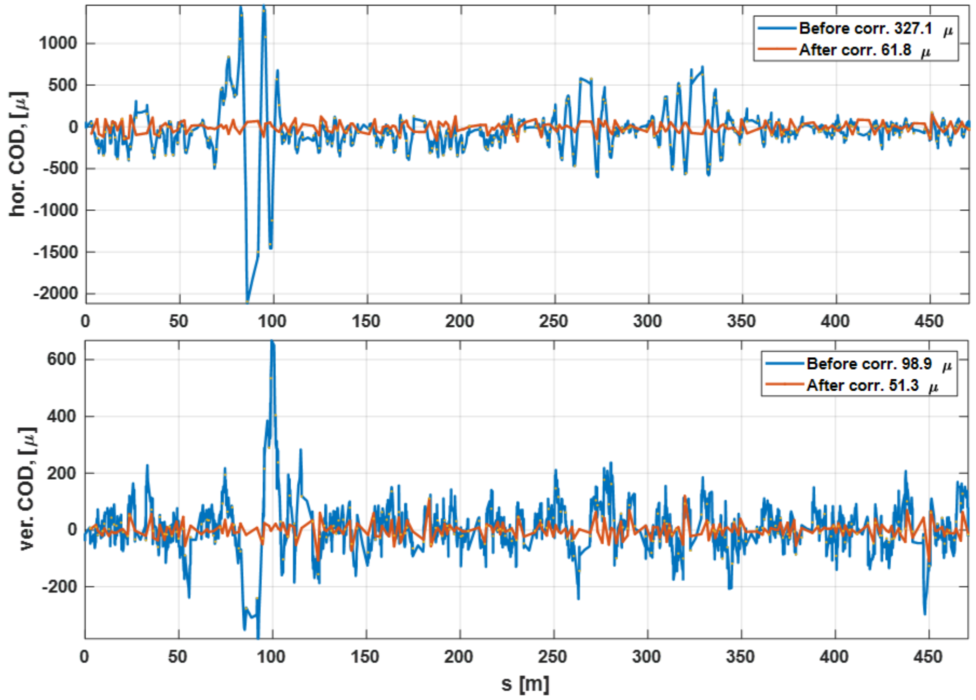
Even small COD in strong sextupoles generates significant optical and coupling errors reducing the dynamic aperture. An algorithm to corrects the orbit, optics and coupling is as following:

- Distribute random displacement in all elements (transverse 85 um and 150 um, longitudinal 1 mm, rotation around all three axes 200 μrad)
- Correct the COD at 14×16=224 BPMs using 128 steering magnets (96 in sextupoles plus 32 individual)
- Correct the beta-functions beating and tune point using 256 gradient correctors in sextupoles (!)
- Correct the coupling using 256 skew-gradient correctors in sextupoles

	σ_x, μm	σ_y, μm	σ_s, μm	σ_ψ, μrad
Quadrupoles	30	30	150	200
Sextupoles	30	30	150	200
Dipoles	30	30	300	200
Girders	80	80	150	200

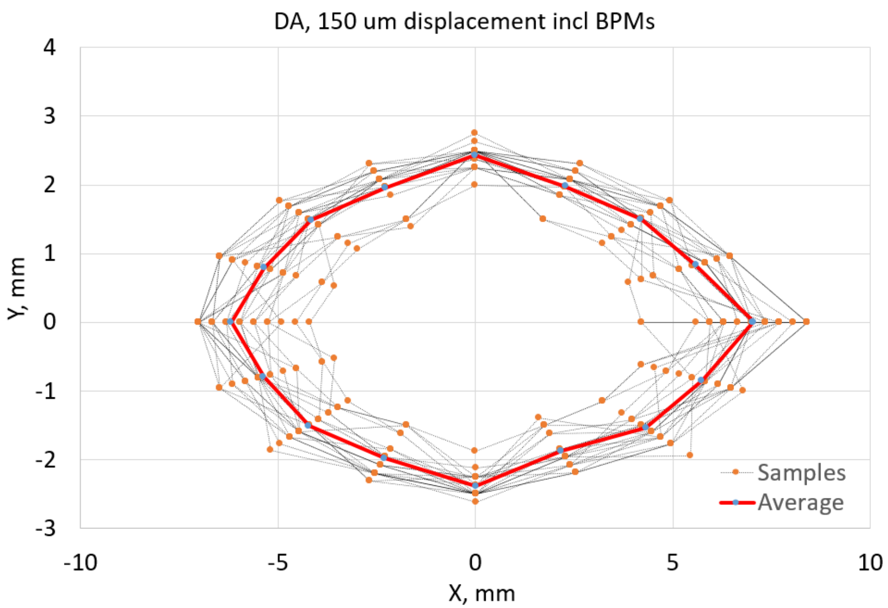
$$Effective\ displacement = \sqrt{80^2 + 30^2} \approx 85\ um$$

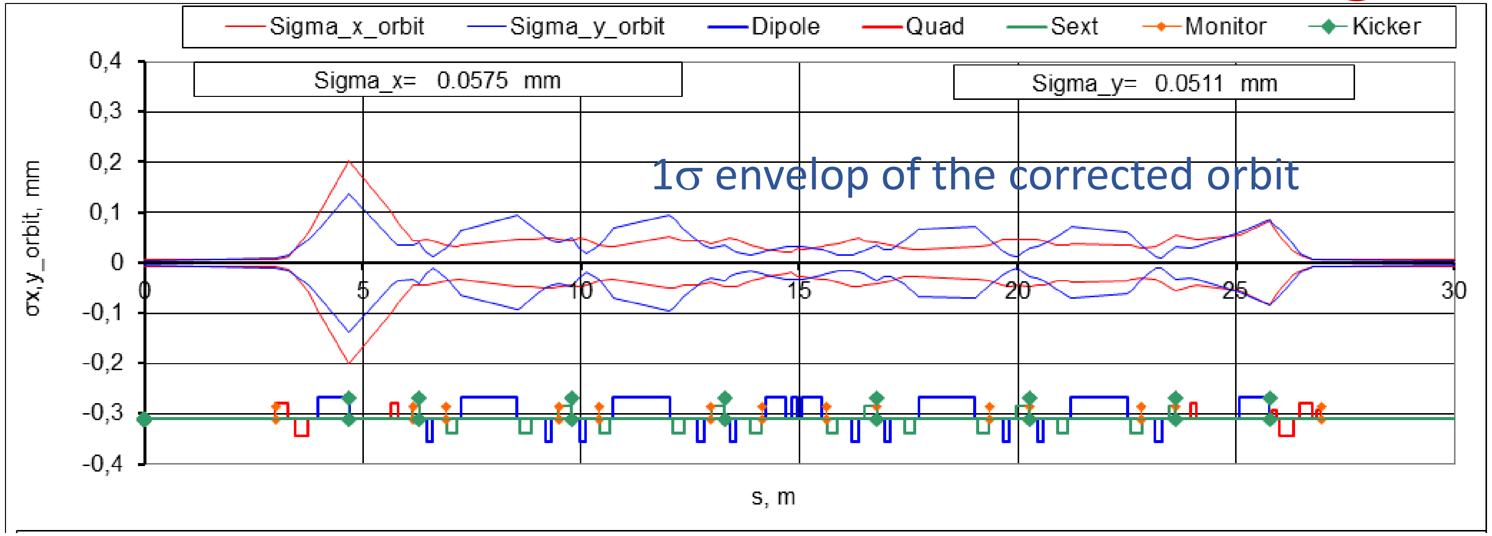
COD after first turn and after final correction

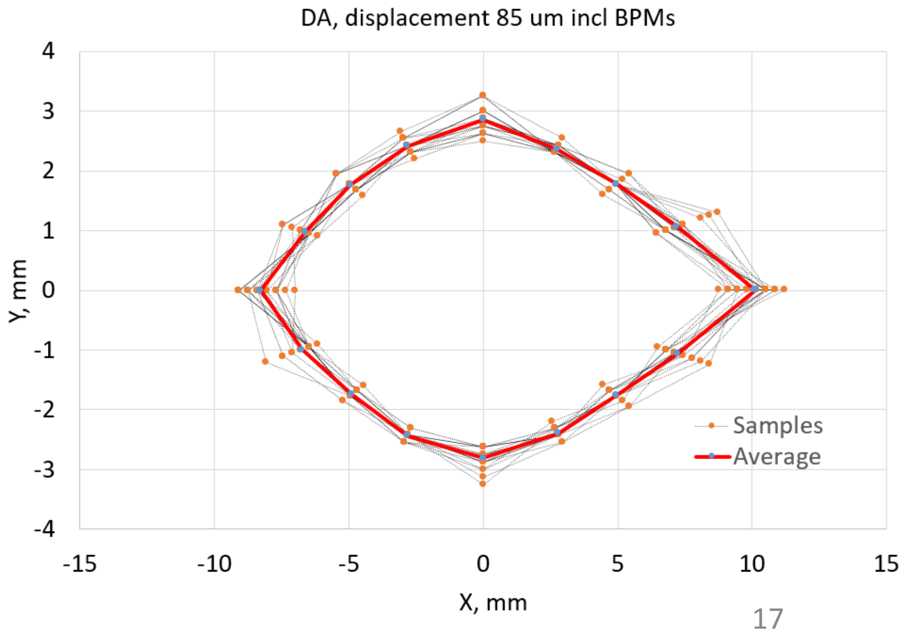


COD correction II

Rms alignment errors, µm	150	150	85	85
BPM alingment errors	No	Yes	No	Yes
Residue horizontal rms COD, µm	94	136	58	78
Residue vertical rms COD, µm	81	138	51	80
Horizontal emittance, pm	76.11±2.8	76.65±3.4	76.17±1.7	76.04±1.8
Average coupling, %	0,12	0,21	0,05	0,07
Horizontal average DA left/right, mm	-7.3 / +8.4	-6.2 / +7.0	-8.3 / +10.1	-7.5 / +8.7
Vertical average DA, mm	2.6	2.4	2.9	2.6
Residue rms beta beating, %	4	8	2	3
Residue rms vertical dispersion, mm	0,19	0,3	0,12	0,17
Maximum of rms corrector kick, mrad	0,49	0,52	0,28	0,32
Maximum of rms gradient corrector, м-1	0,034	0,049	0,024	0,023
Maximum of rms skew-gradient corrector, м-1	0,014	0,019	0,008	0,012

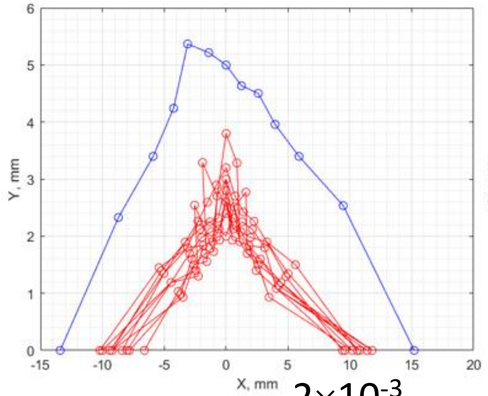




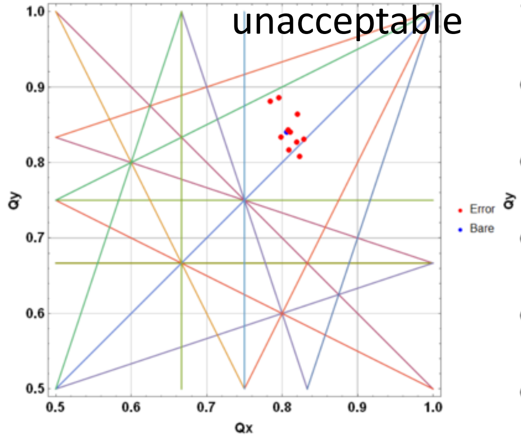


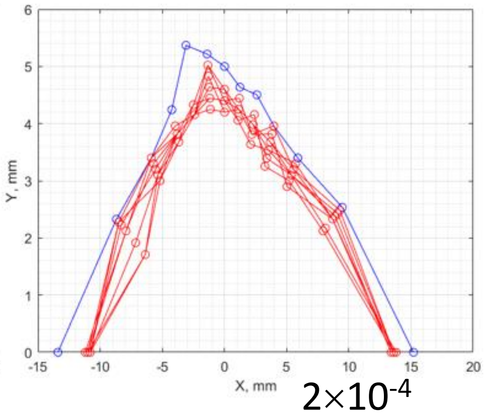
Multipole errors

Random quadrupole errors

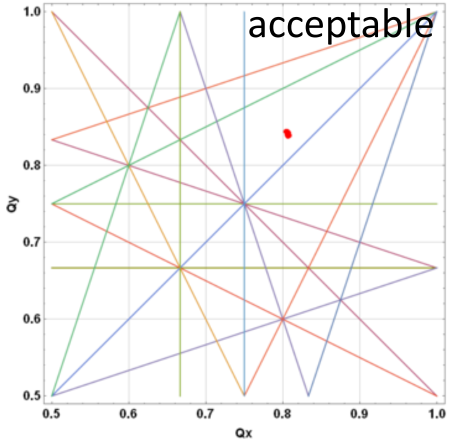


2×10^{-3} unacceptable





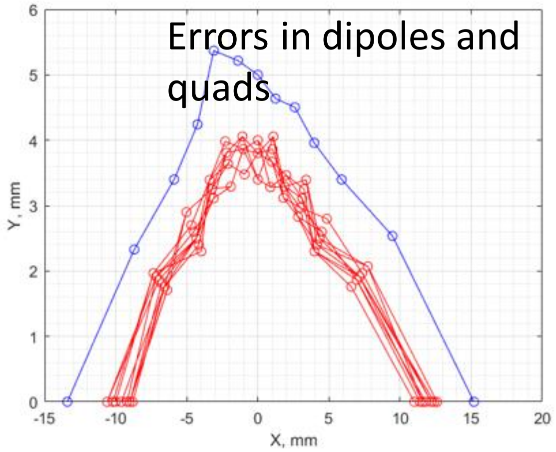
2×10^{-4} acceptable



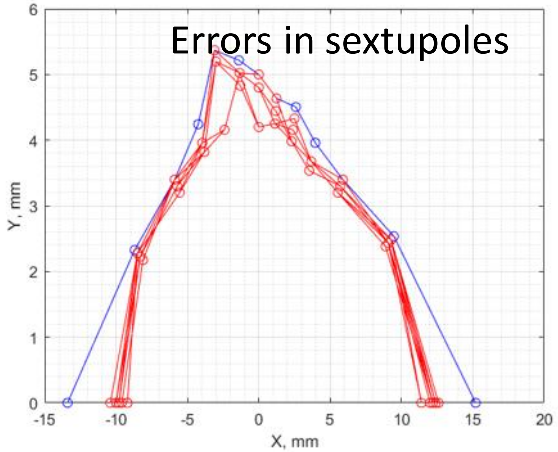
Multipole errors in dipoles and quadrupoles ($\times10^{-4}$)		
n	$(norm)_n$	$(skew)_n$
2	-	-
3	3	3
4	3	3
5	1	-
6	3	-
10	3	-
14	1	-

Multipole errors in sextupoles ($\times10^{-4}$)		
n	$(norm)_n$	$(skew)_n$
4	4	4
5	8	
9	20	
15	20	

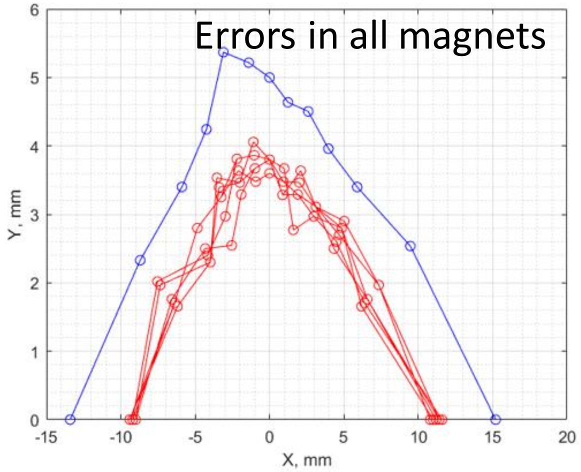
Errors in dipoles and quads



Errors in sextupoles



Errors in all magnets



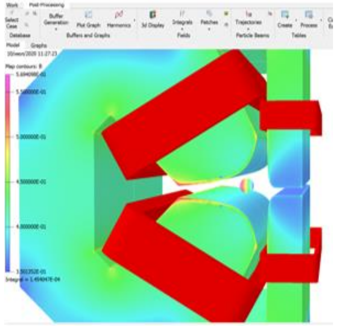
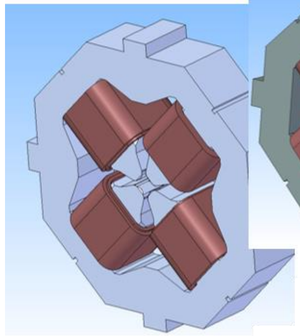
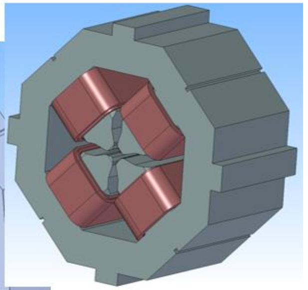
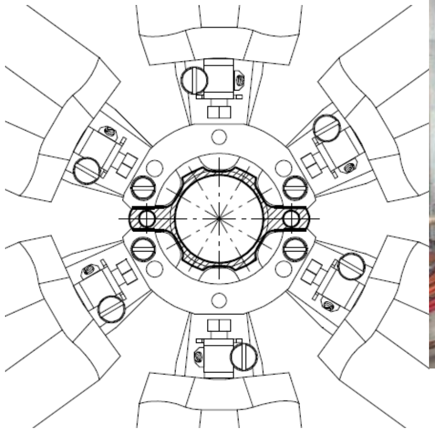
Preliminary results. Work in progress.

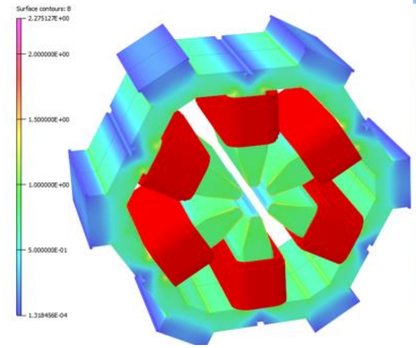
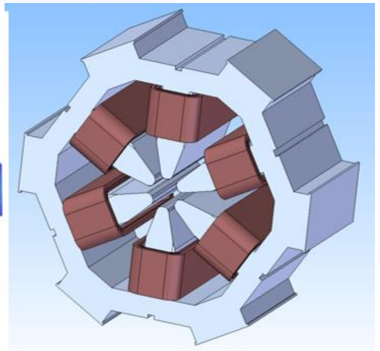
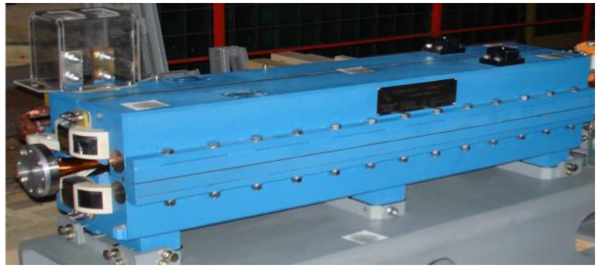
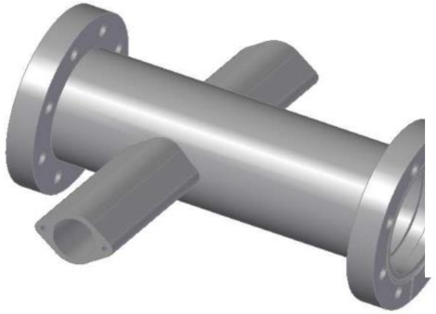
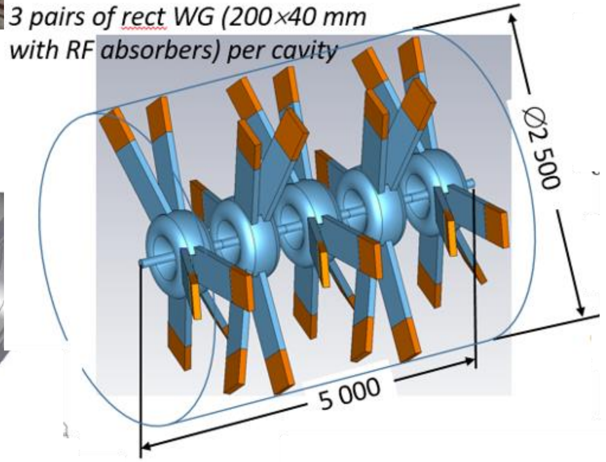
Status

- **Financial:** The SKIF host **Boreskov Institute of Catalysis** received the budget from the government. The contract with the SKIF producer **Budker INP** will be signed in the beginning of November.
- **Organizational:** new scientific organization (lab, institute) will be arranged based on the SKIF project. Team recruiting is going on (now we have around 60 staff members).
- **Infrastructure development:** site investigation and general design are ready, detailed design is under way, a construction company is chosen and plans to start ground work in April 2021.
- **Accelerator science:** general issues (optics, dynamics, lifetime, errors and misalignments, etc.) have completed. IDs influence and collective effects are still in progress.
- **Accelerator technology:** The injector (the linac like we have at BINP for colliders and the booster that follows the NSLS II booster design) is ready for production. The storage ring systems are under design, we plan first orders in the beginning of 2021.

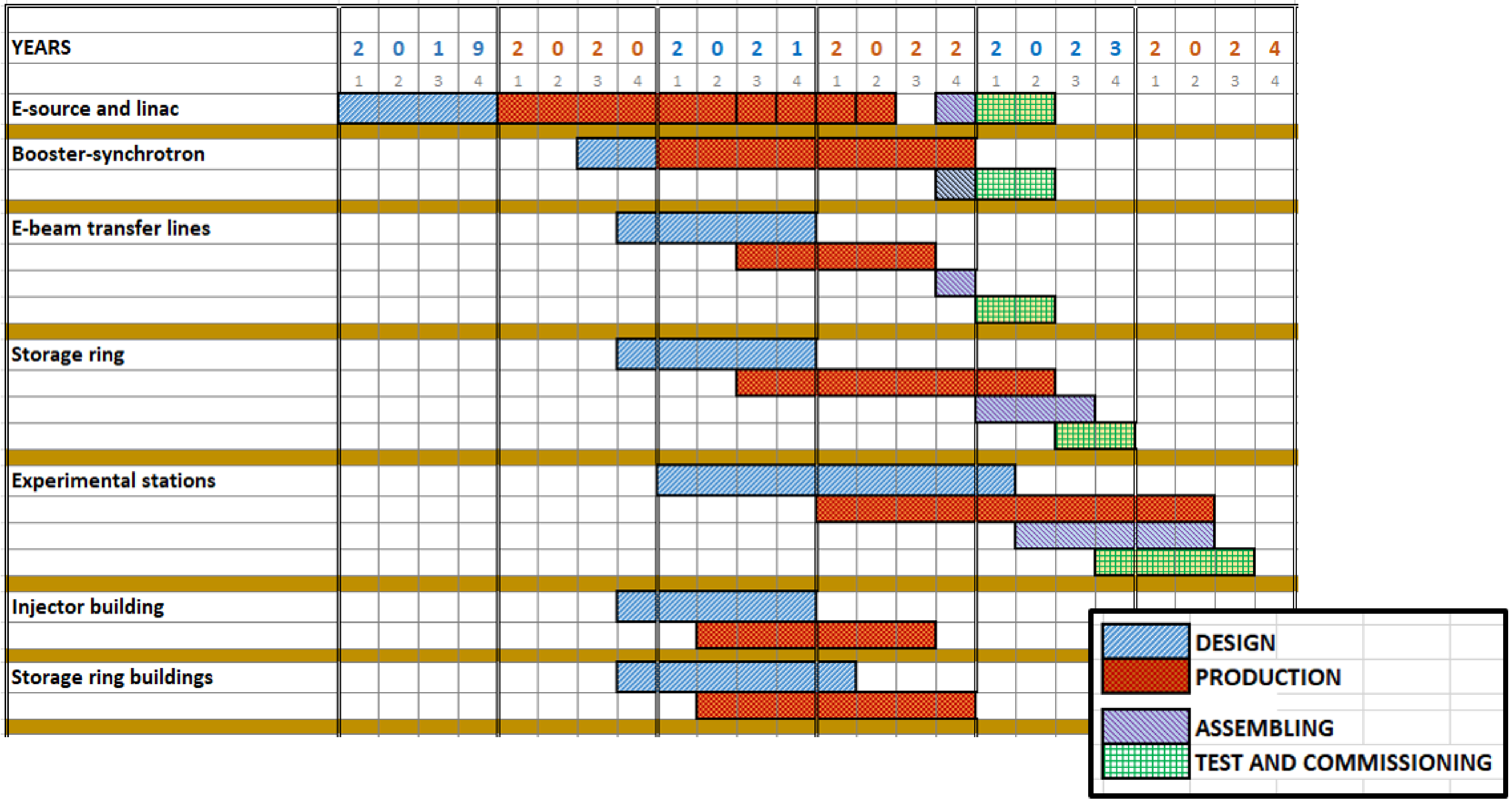
Status (illustration mix)



Timeline



YEARS
2019
2020
2021
2022
2023
2024
1 2 3 4
E-source and linac
Booster-synchrotron
E-beam transfer lines
Storage ring
Experimental stations
Injector building
Storage ring buildings
DESIGN
PRODUCTION
ASSEMBLING
TEST AND COMMISSIONING

Conclusion

- Design of the new Novosibirsk 4th generation light source SKIF provides natural emittance 73 pm for 3 GeV beam energy and 476 m orbit length.
- Only two sextupole families provide dynamic aperture and momentum acceptance sufficient for good beam lifetime and tradition well-proven injection.
- SKIF has 16 6-m-long straight sections (14 are for IDs). Optical functions in the straight sections are optimized to accommodate strong field IDs.
- 30 beam lines are foreseen: 14 are from IDs, 8 high field permanent magnets (2.1 T) and 8 from regular cell magnets (0.5 T).
- Magnet types are minimized for the cost and production time saving.
- For all major systems the R&D is completed and design stage is started.

We would highly appreciate collaboration with mature SR labs all over the world!