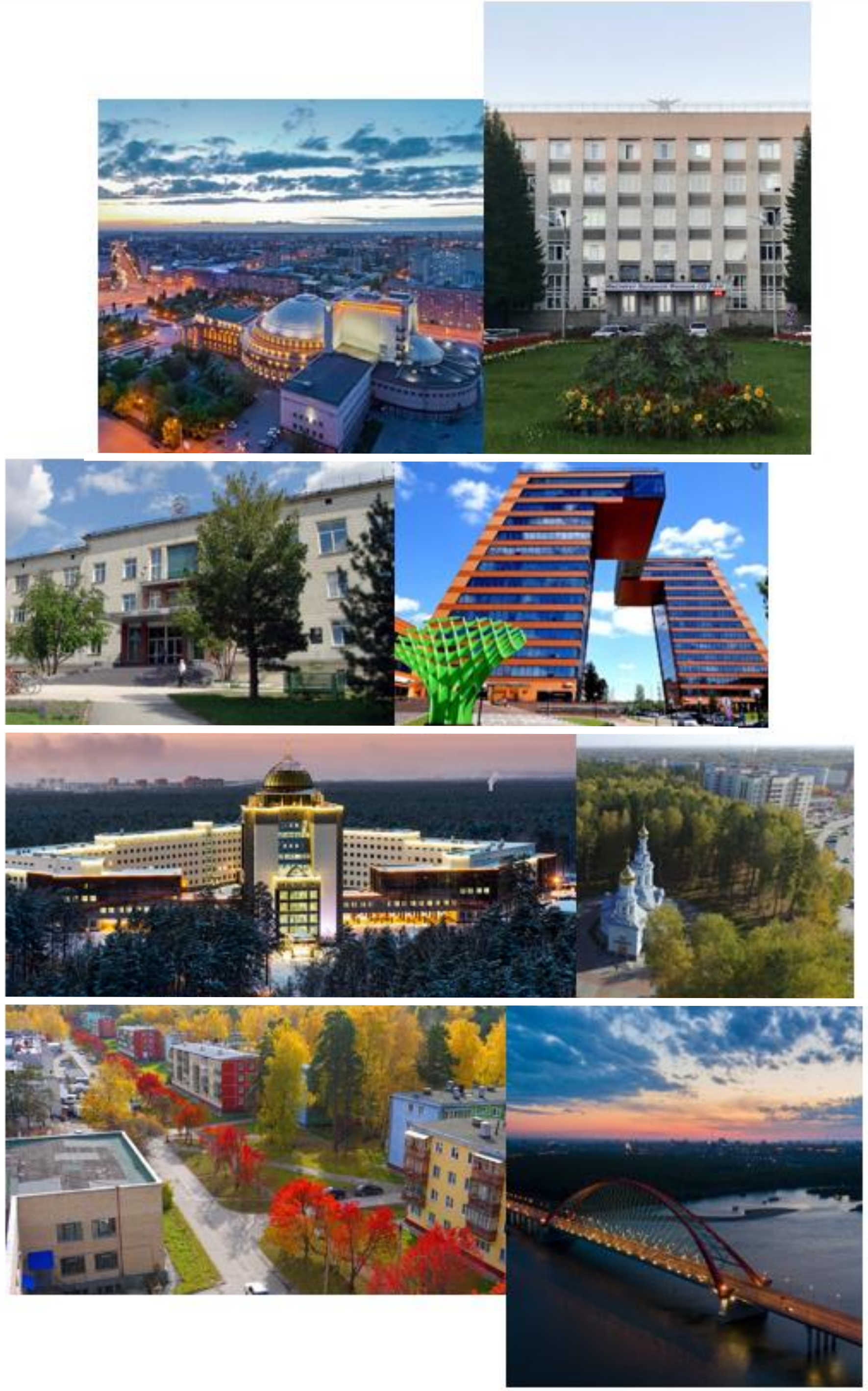

Storage ring for Novosibirsk low emittance light source SKIF

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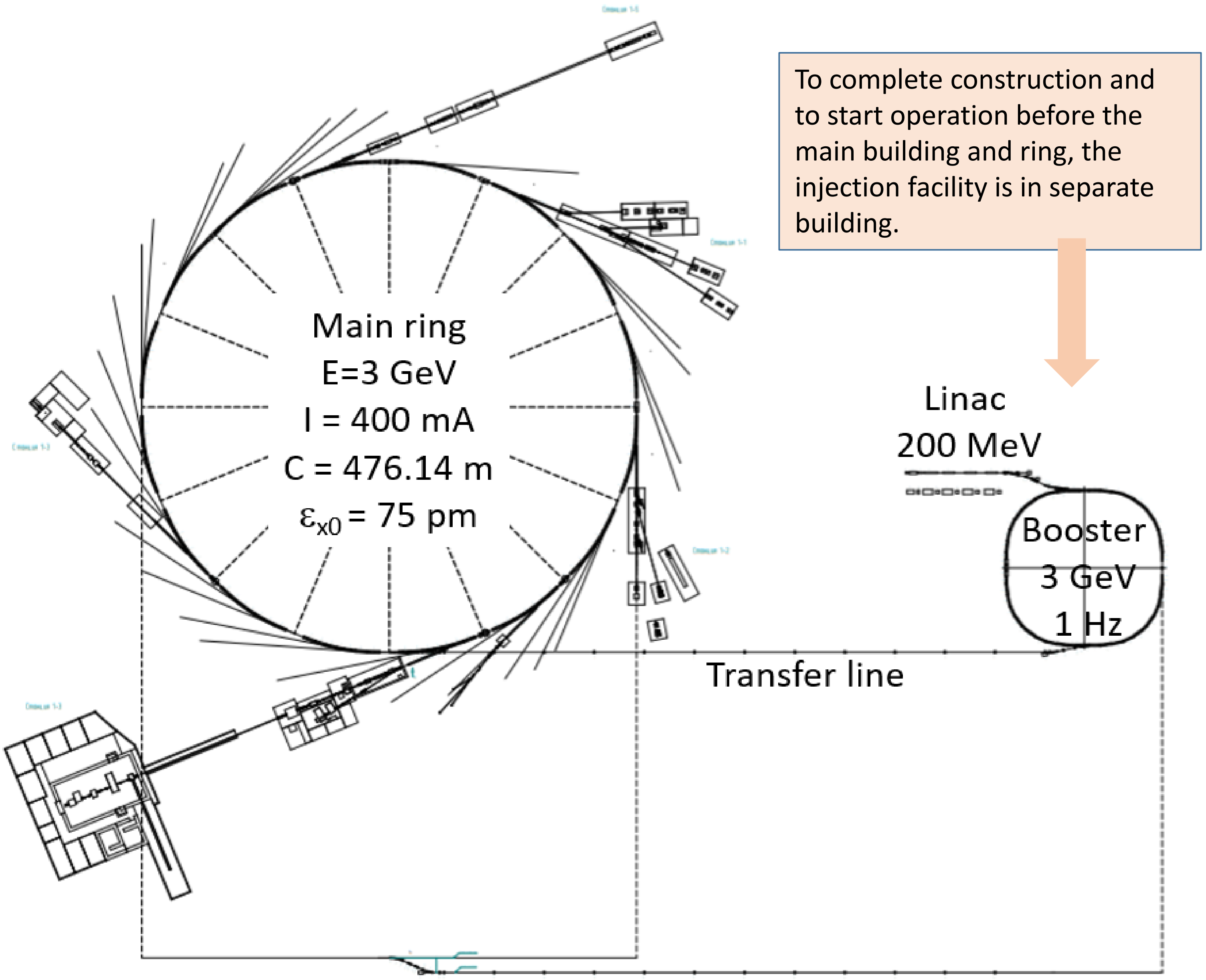
SKIF Session, 16 July 2020

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
- Simple, robust, proven solution when possible (reliability) (short construction term)

Configuration

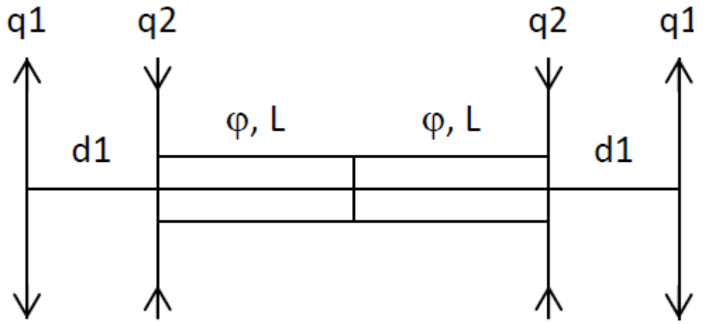
- Linear accelerator with maximum energy 200 MeV
- Small size booster synchrotron with maximum energy 3 GeV and orbit length 158.7 m
- Electron storage ring 16-fold symmetry with 3 GeV energy and 476 m circumference

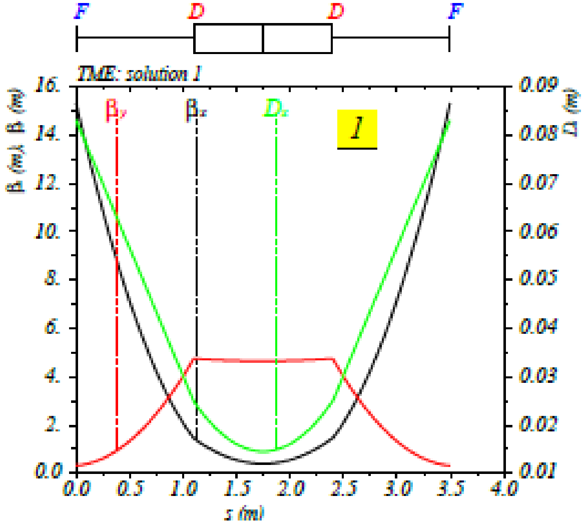


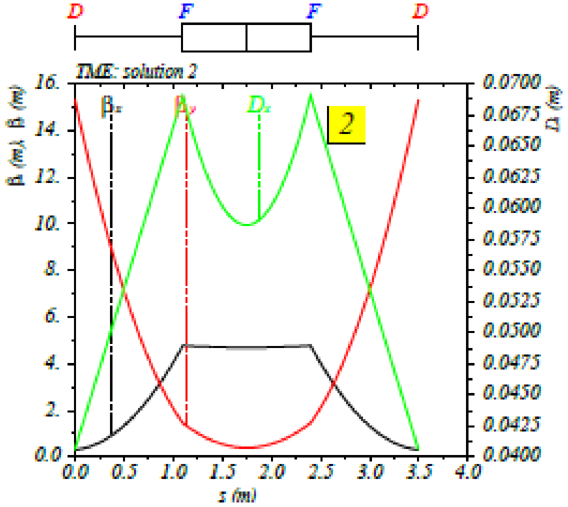
To complete construction and to start operation before the main building and ring, the injection facility is in separate building.

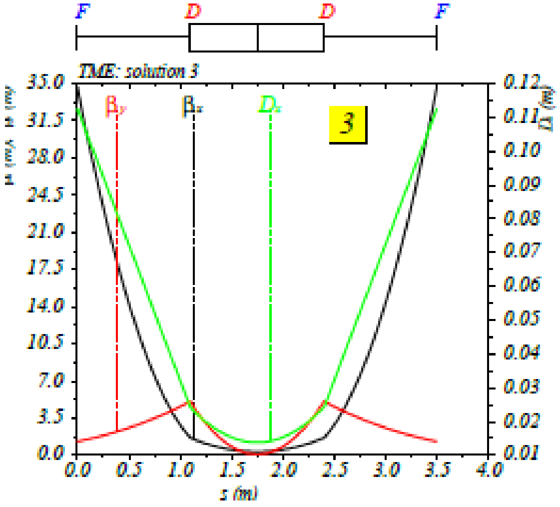
Basic cell choice (I)

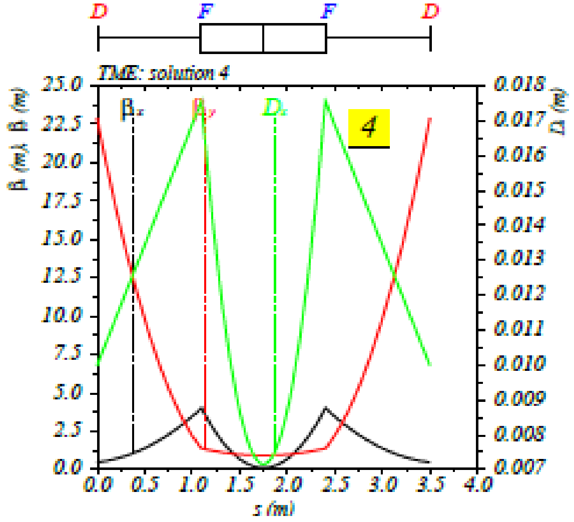
We need very low emittance but also low strength of quadrupoles and sextupoles and large dynamic aperture. A simple and compact magnet arrangement for low emittance allows 4 optical solutions





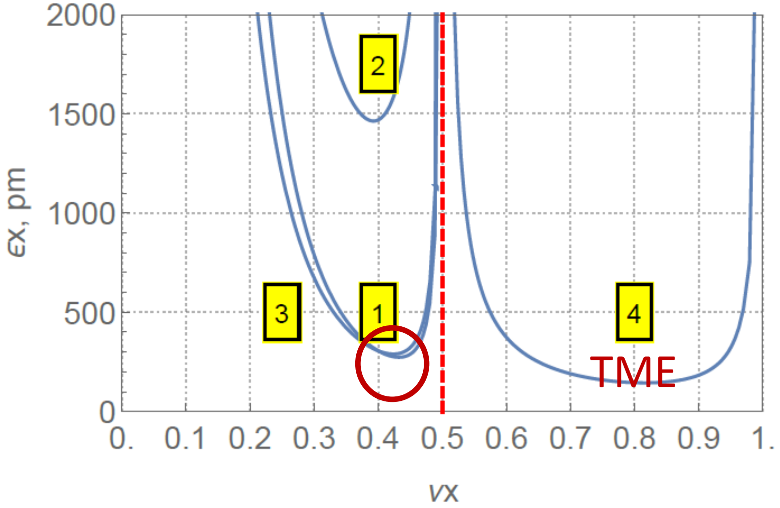






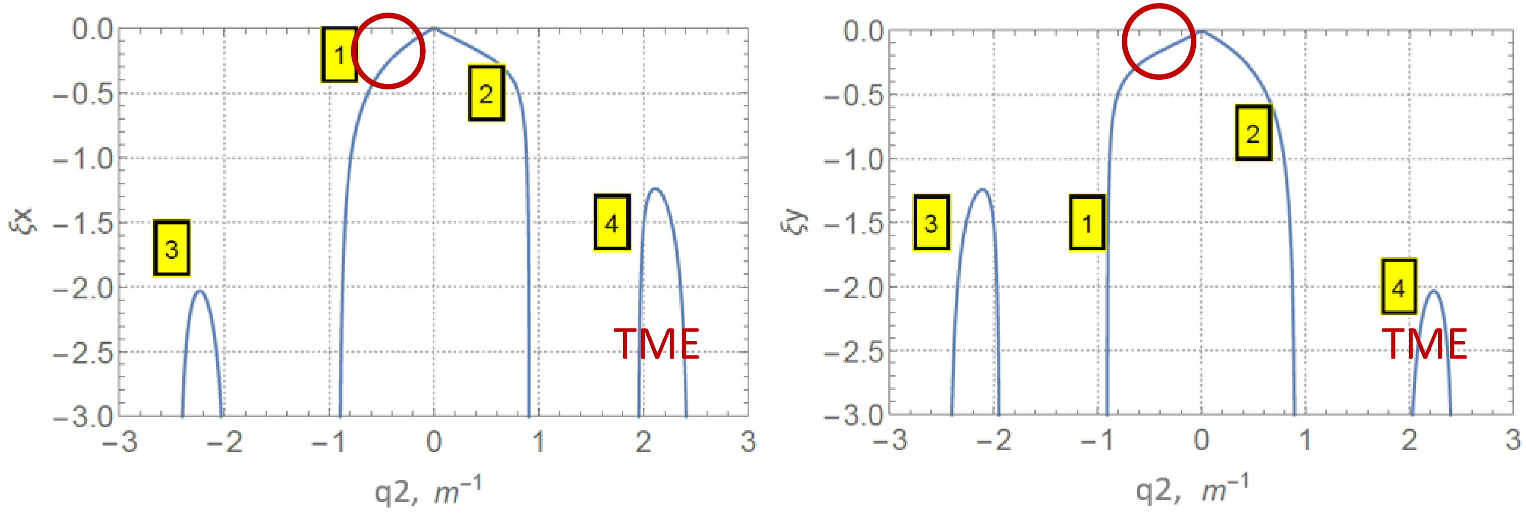
№	ν_x	ν_y	$q_1q_2q_2q_1$	Comment
1	0÷0.5	0÷0.5	FDDF	$\varepsilon_{x1min} \approx 2\varepsilon_{xTME}$. **Emittance OK, sextupoles low.**
2	0÷0.5	0÷0.5	DFFD	$\varepsilon_{x2min} \approx 10\varepsilon_{xTME}$. **Very large emittance.**
3	0÷0.5	0.5÷1	FDDF	$\varepsilon_{x3min} \approx 2\varepsilon_{xTME}$. **Strong vertical sextupole**
4	0.5÷1	0÷0.5	DFFD	Эмиттанс ε_{xTME}. **TME, very strong sextupoles, low DA**

Basic cell choice (II) Solution 1

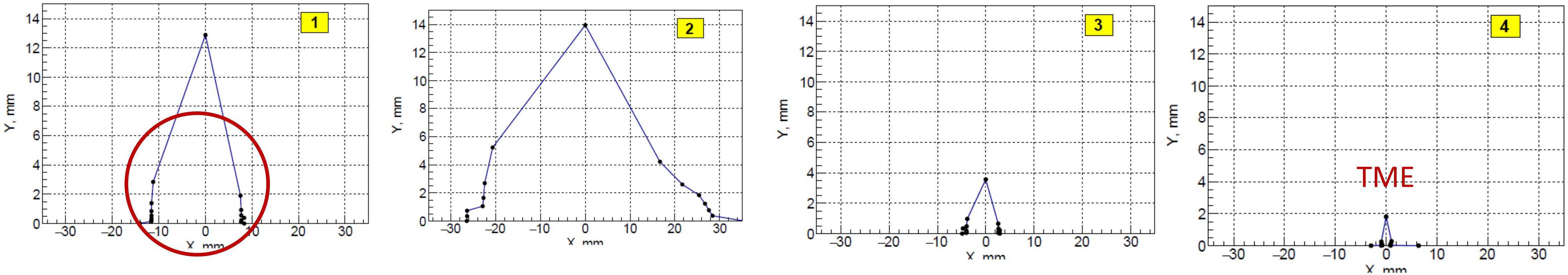


Emittance for four solutions

Our choice

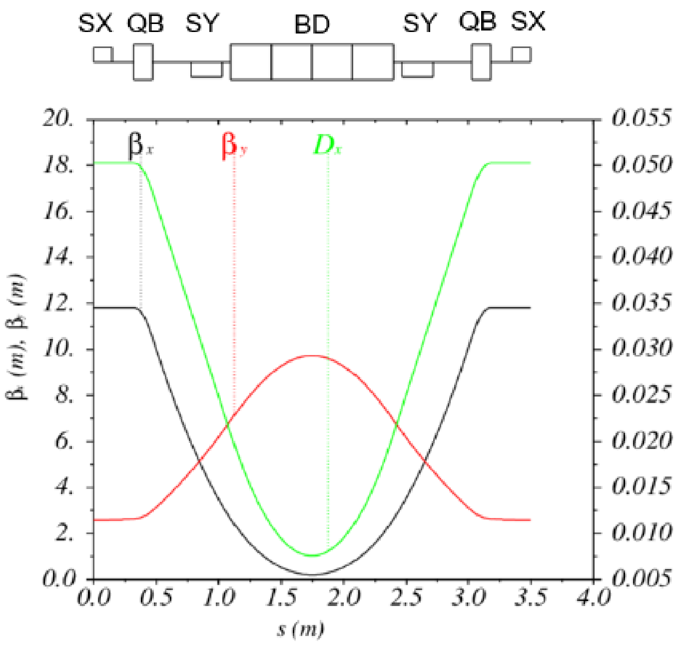


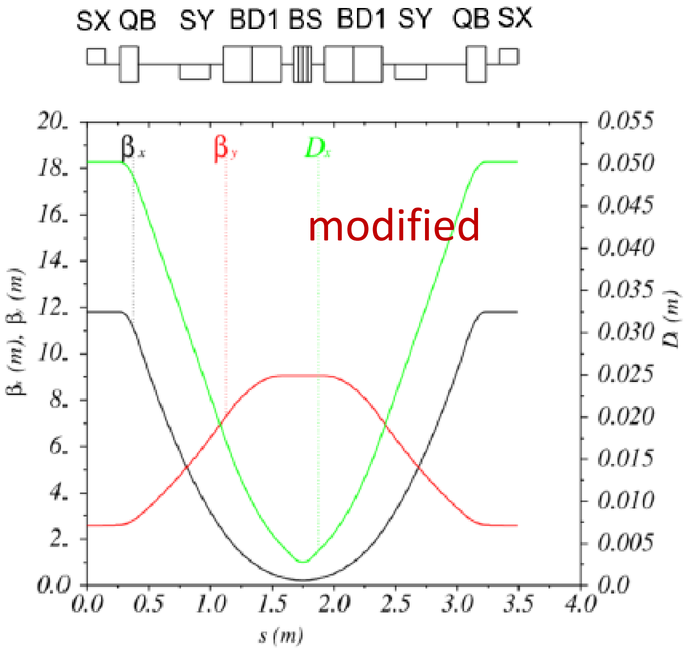
Chromaticity (x, y) for four solutions



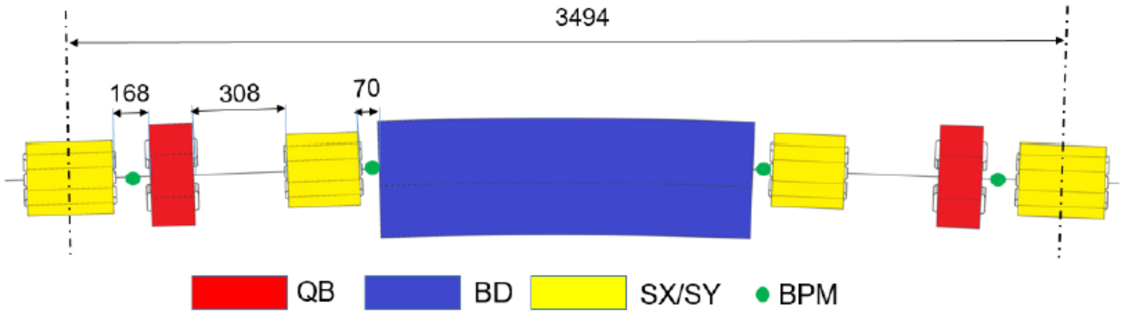
Dynamic apertures for four solutions

SKIF basic cell

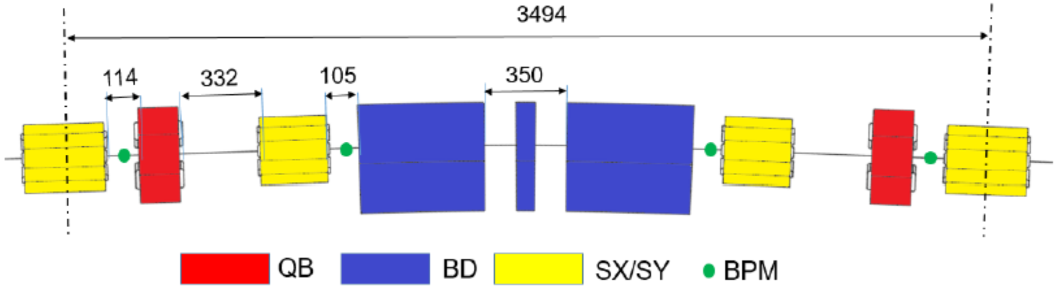



modified

BD: low field (0.55 T) low gradient (-7.9 T/m)
BD1: low field (0.53 T) low gradient (-10.7 T/m)
BS: high field (2 T) flat
QB: shifted (-5 mm) quad (51 T/m) (reverse bend)
SX: hor sextupole (2313 T/m^2)
SY: ver sextupole (-2379 T/m^2)

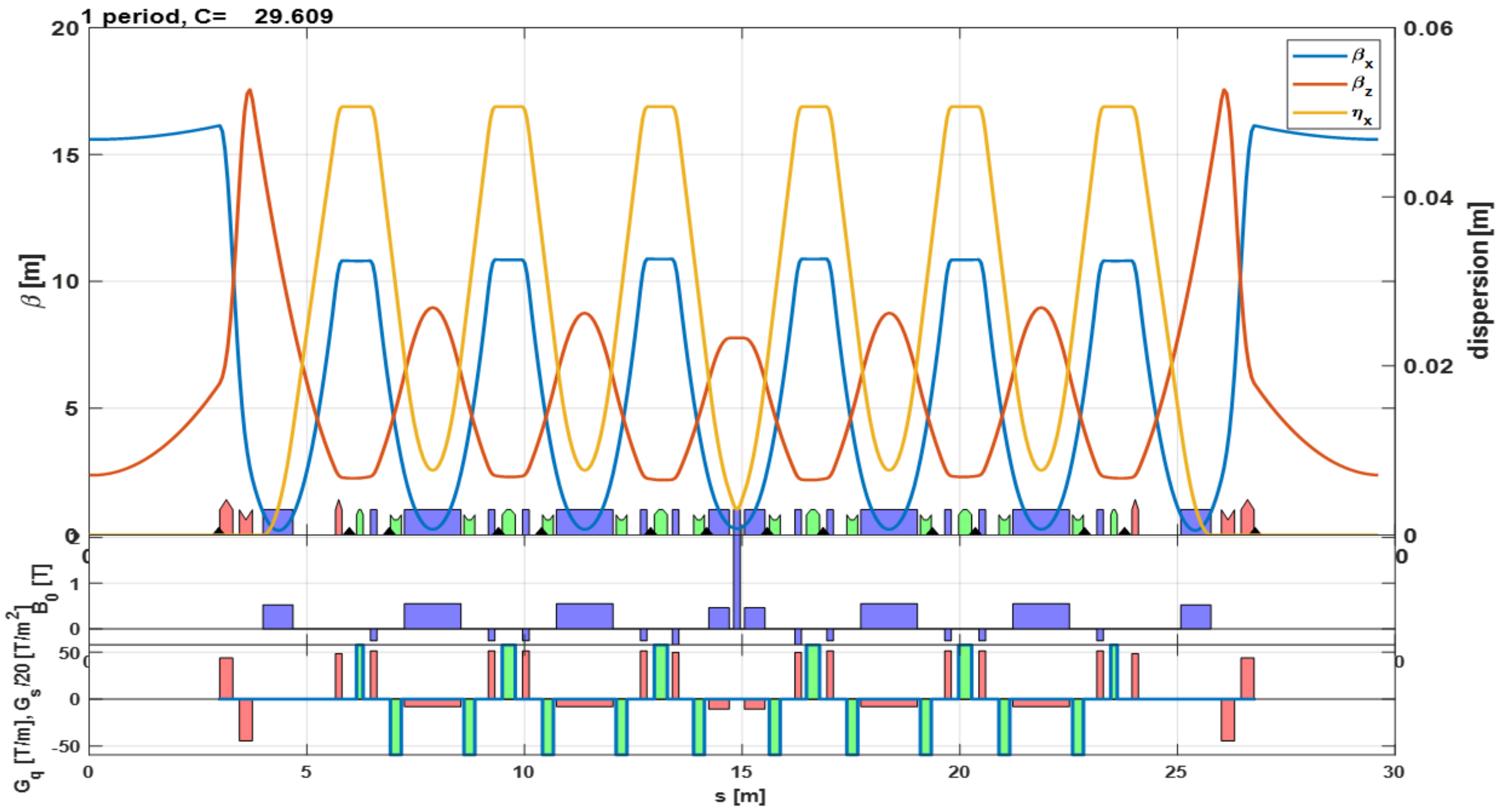


low field magnet cell (4 per super-period)



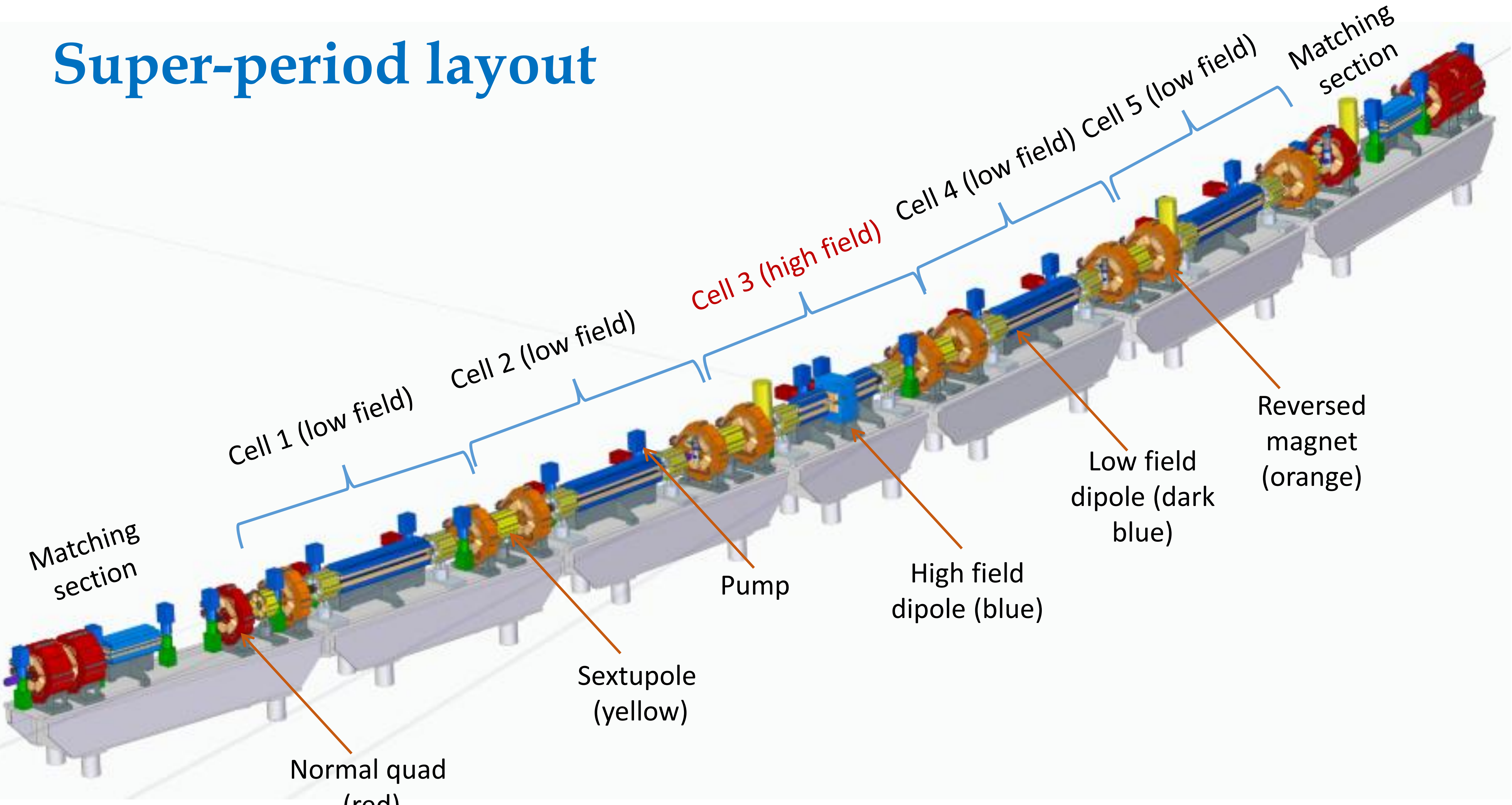
high field magnet cell (1 per super-period)

Super-period optics and parameters



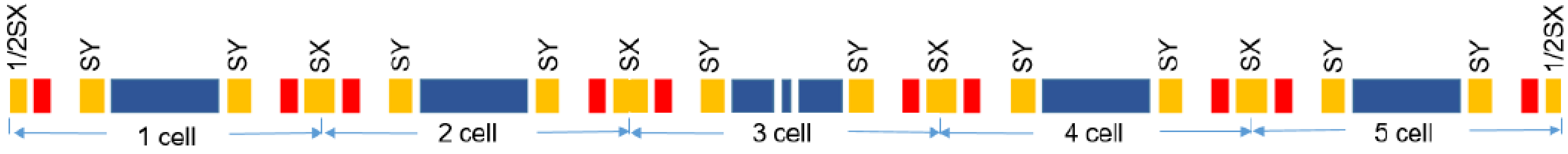
Energy, GeV	3
Symmetry	16
Circumference, m	476.14
Revolution period, μc	1.588
Horizontal emittance, pm	73.2
Energy spread	$1\cdot10^{-3}$
E loss per turn, keV	536
Betatron tunes, (*x*/*y*)	50.806 / 18.84
Compaction factor	$7.64\cdot10^{-5}$
Natural chromaticity, (*x*/*y*)	–149/–55
RF harmonic number	567
RF frequency, MHz	357
RF voltage, MV	0.77
Energy acceptance	±3 %
Synchrotron tune	$1.13\cdot10^{-3}$
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

$(\xi_x/\xi_y) =-149/-55$

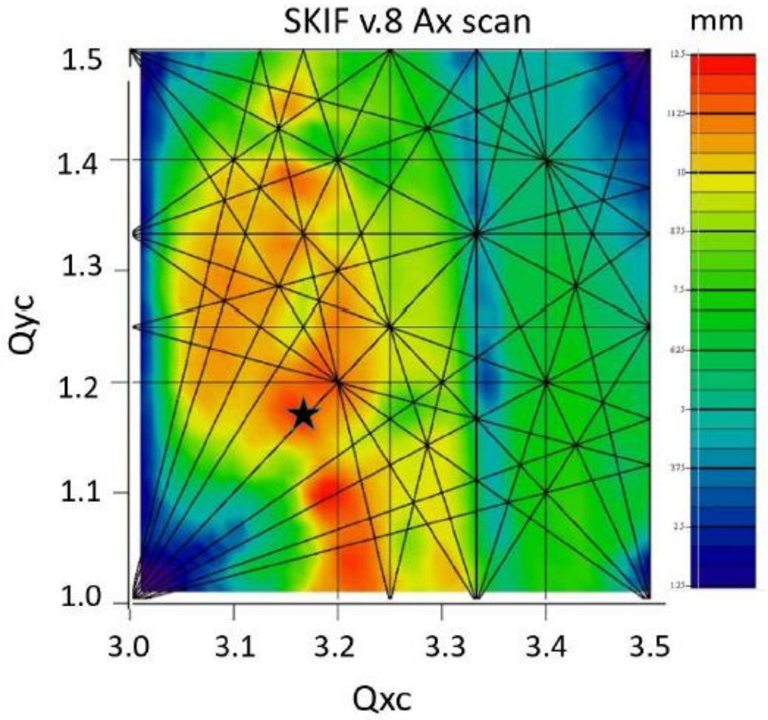


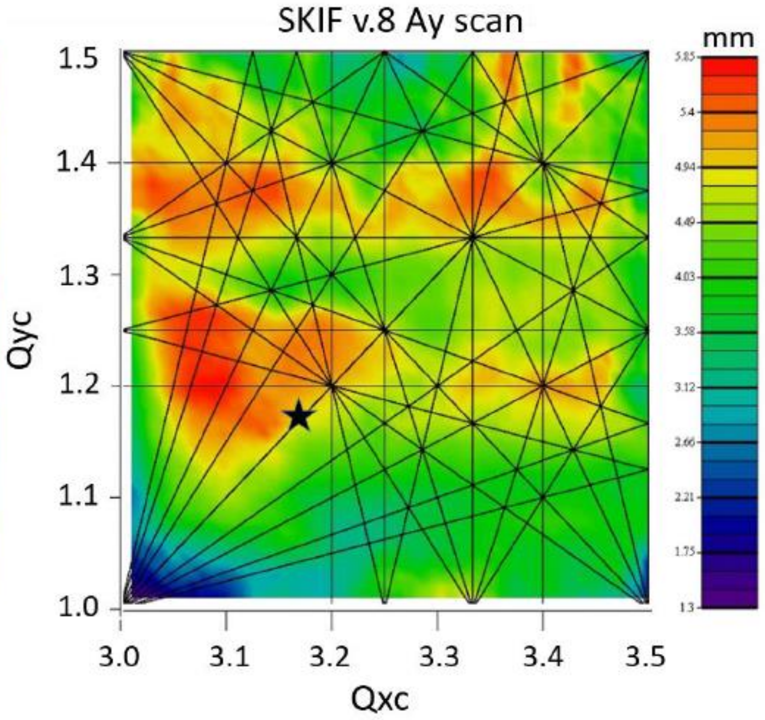
	l, м	B''_{nom}, T/м^2	$(K_2 l)_{nom}$, м$^{-2}$	B''_{max}, T/м^2	$(K_2 l)_{max}$, м$^{-2}$
SY	0.25	–2379	–59.48	–2800	–70
SX	0.30	2313	69.39	2800	84
1/2SX	0.15	2313	34.70	2800	42

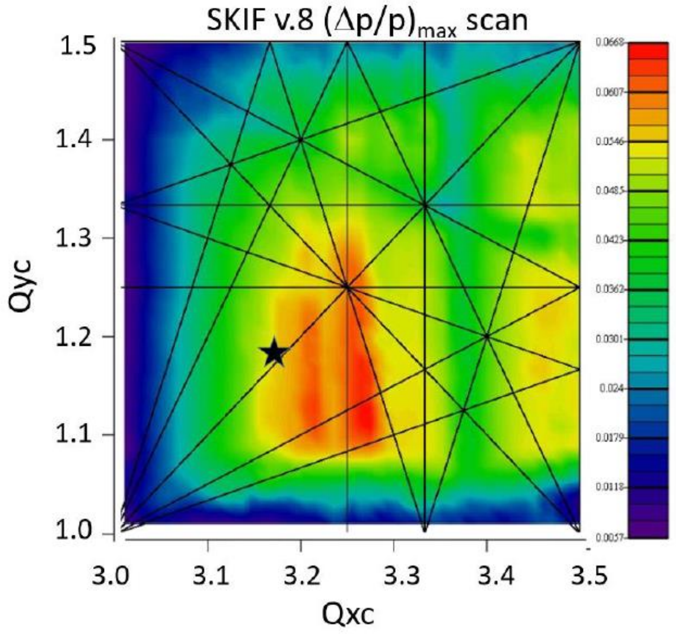
We use only two sextupole families to compensate natural chromaticity and optimize dynamic aperture and momentum acceptance. No other multipoles (octupoles or harmonic sextupoles) are applied.

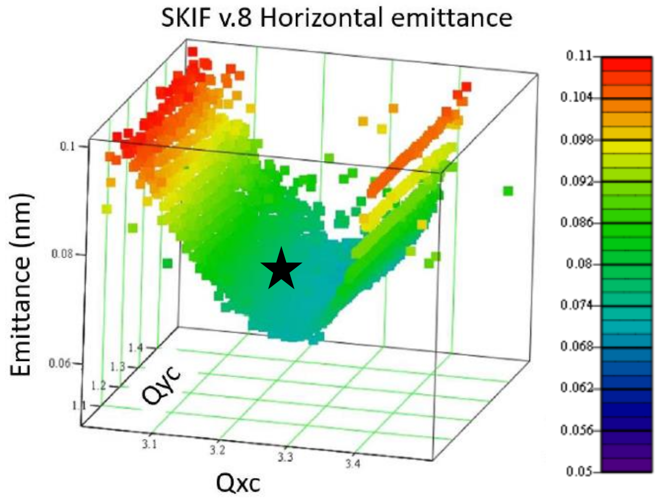
Dynamic aperture scan for one super-period

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



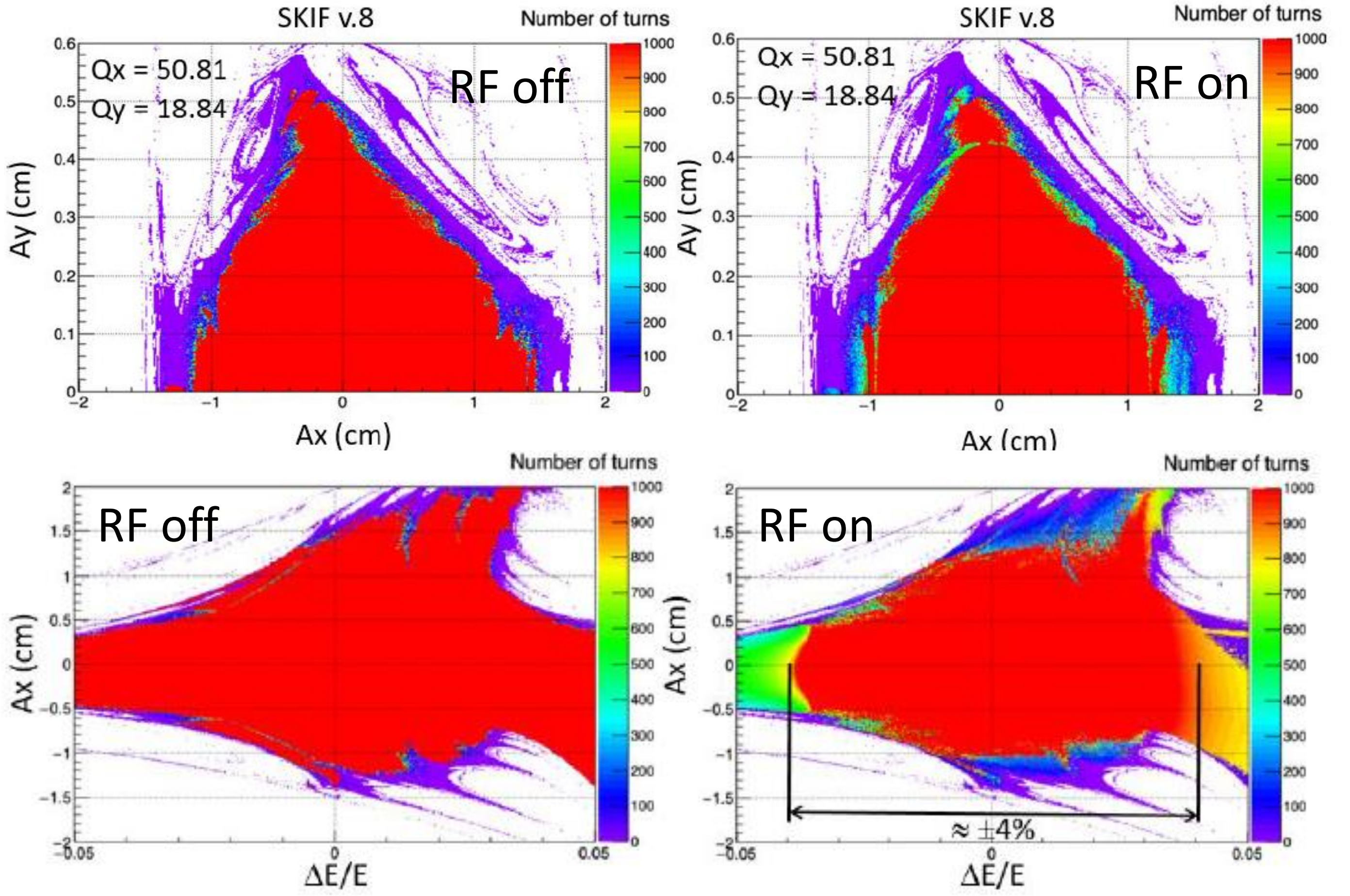


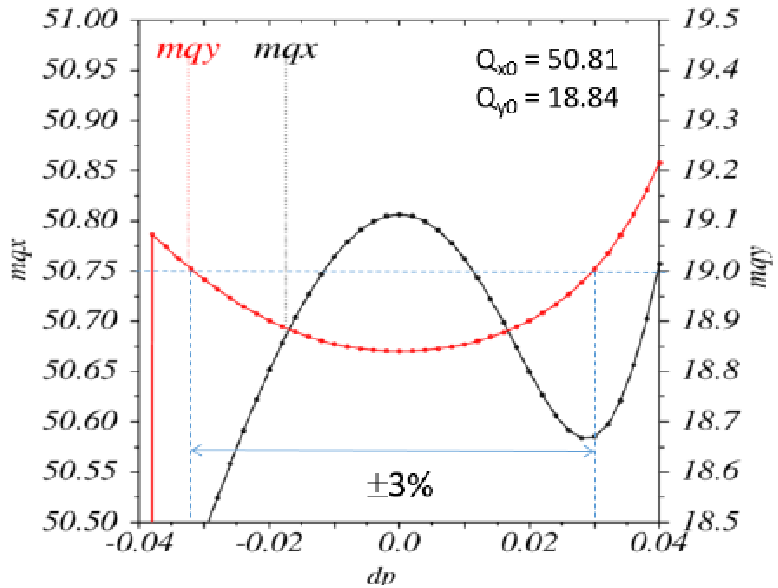


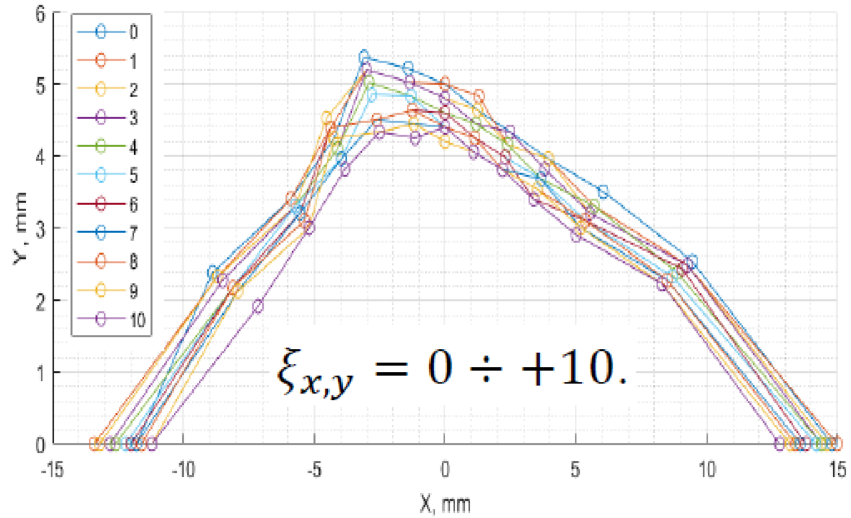


Betatron tunes, phase advances between chromatic sextupoles and their strength were carefully adjusted to maximize dynamic aperture and momentum acceptance.

Dynamic aperture and momentum acceptance





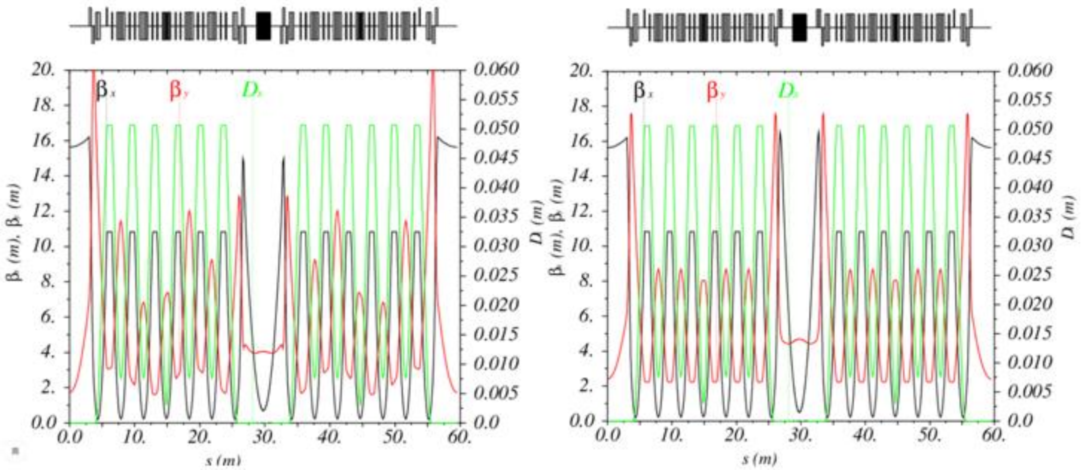


Survival plots. Red is stable during 1000 revolutions. Only two sextupole families are enough to get sufficient dynamic aperture and momentum acceptance. $\beta_x = 15.6$ м, $\beta_y = 2.4$ м

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

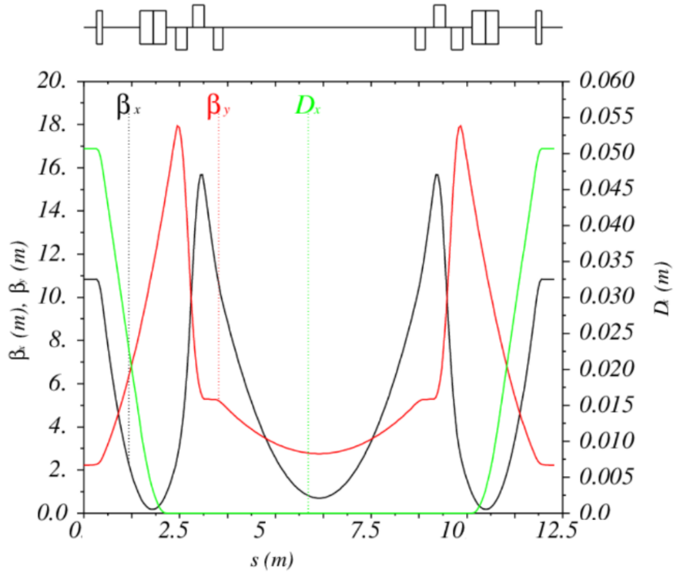
Optics with 1 SCW

Parameter	Bare	1U	1W	2W	3W
ε_{xtot}, pm	73	72	74	75	76
$\sigma_E/E\cdot10^3$	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.

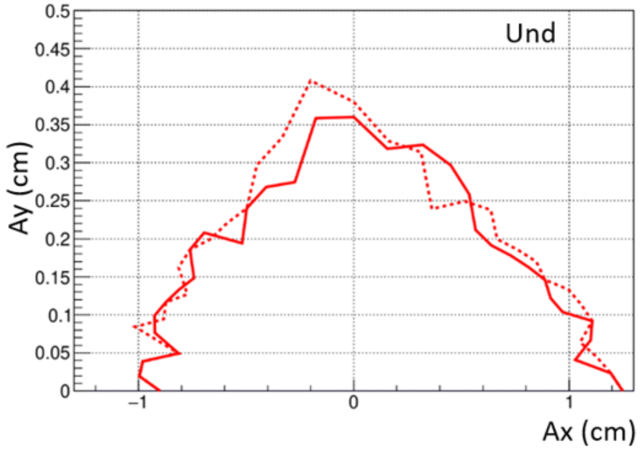
IDs, alternative drift optics

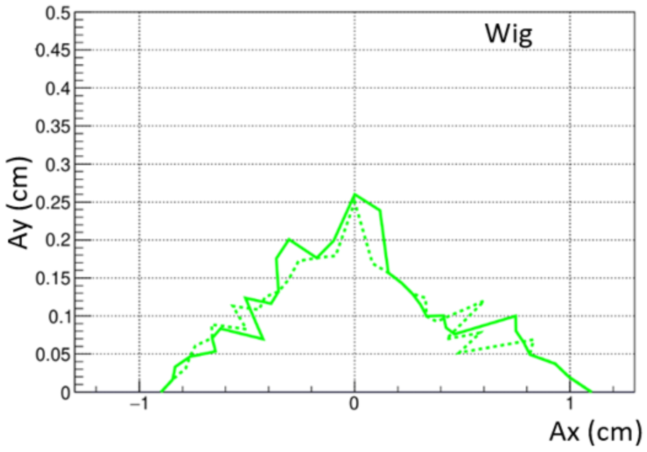
Low β_x in the wiggler section allows additional emittance reduction. For beta control we need quadrupole triplets instead of doublets.



Parameter	Bare	1W	2W	3W
ε_{xtot}, pm	73	61	54	48
$\sigma_E/E\cdot10^3$	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.

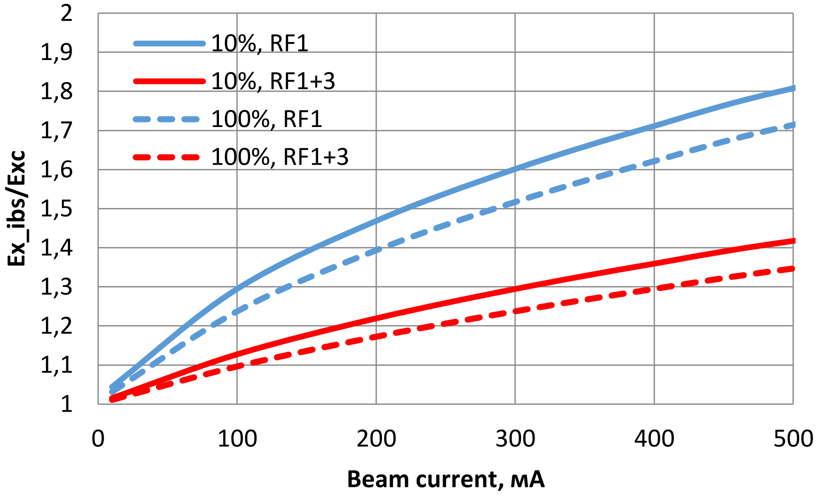


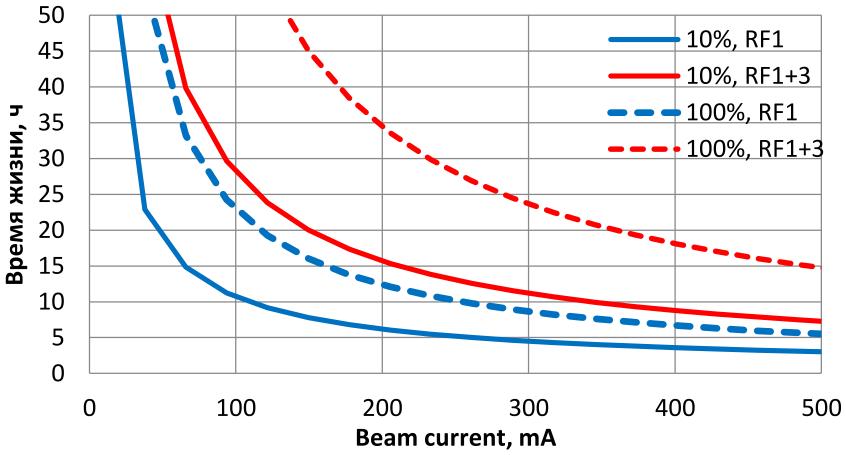


IBS bare lattice

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

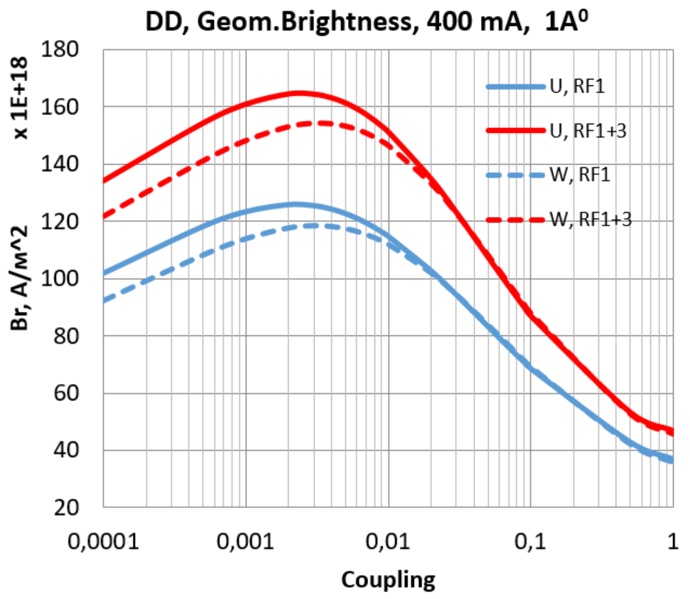
“Geometrical” brightness (depends on the electron beam parameters):

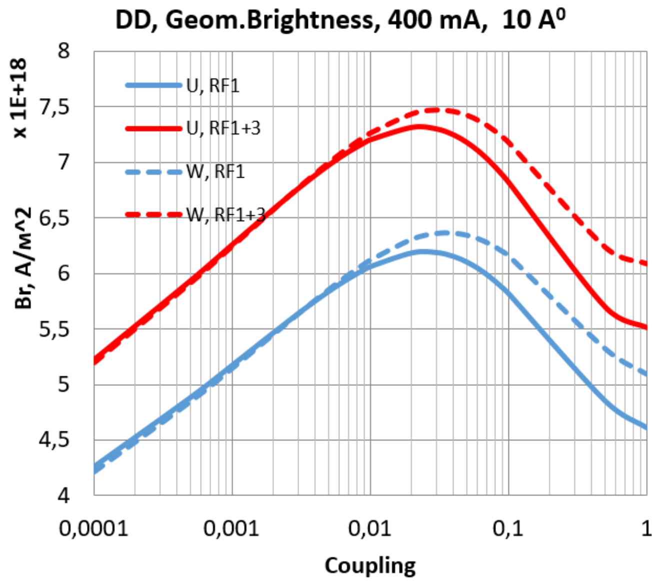
$$Br(\lambda) = \frac{n_b I_b}{\Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}} = \frac{n_b I_b}{\sqrt{{\sigma_x}^2+{\sigma_r}^2}\sqrt{{\sigma_{x'}}^2+{\sigma_{r'}}^2}\sqrt{{\sigma_y}^2+{\sigma_r}^2}\sqrt{{\sigma_{y'}}^2+{\sigma_{r'}}^2}},$$

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

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


DD, Geom.Brightness, 400 mA, 1A^0


DD, Geom.Brightness, 400 mA, 10 A^0

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 $\kappa \approx 0.5 \div 5\%$.

Collective instabilities issues

A low-emittance storage ring has specific features in its design, like a strong lattice, low dispersion and momentum compaction, narrow apertures and consequently a larger geometric impedance, and other, potentially leading to limitation of the beam intensity.

Impedance	Beam Effects	Possible Cures/Remedies
Longitudinal broad-band impedance	Uncontrolled bunch lengthening Microwave instability	Controlled bunch lengthening using passive/active harmonic cavities
Transverse broad-band impedance	Head-tail instability Transverse mode coupling instability	Bunch length control (see above). Chromatic head-tail damping. Feedback
Longitudinal narrow -band impedance	Longitudinal coupled-bunch instability	HOM dampers. HOM frequency shifters. Control of RF cavity temperature. Feedback
Transverse narrow -band impedance	Transverse coupled-bunch instability	Bunch length control. Chromatic head-tail damping. Nonlinear decoherence. Feedback
Ion-related effects	Transverse coupled-bunch instability Emittance growth	Better vacuum. Bunch train shaping. Feedback

A comprehensive study of collective effects in SKIF is under way. The preliminary assessment of the upper bounds for critical impedance elements is compatible with the design beam intensity, keeping in mind that ~2÷3-fold bunch lengthening seems to be acceptable for this light source. A complete evaluation of the machine impedance budget should be a constant concern. A modern experience with bunch-by-bunch feedback systems must be studied and implemented.

Any assistance welcome!

COD correction I

Even small COD in strong sextupoles generates significant optical and coupling errors reducing the dynamic aperture.

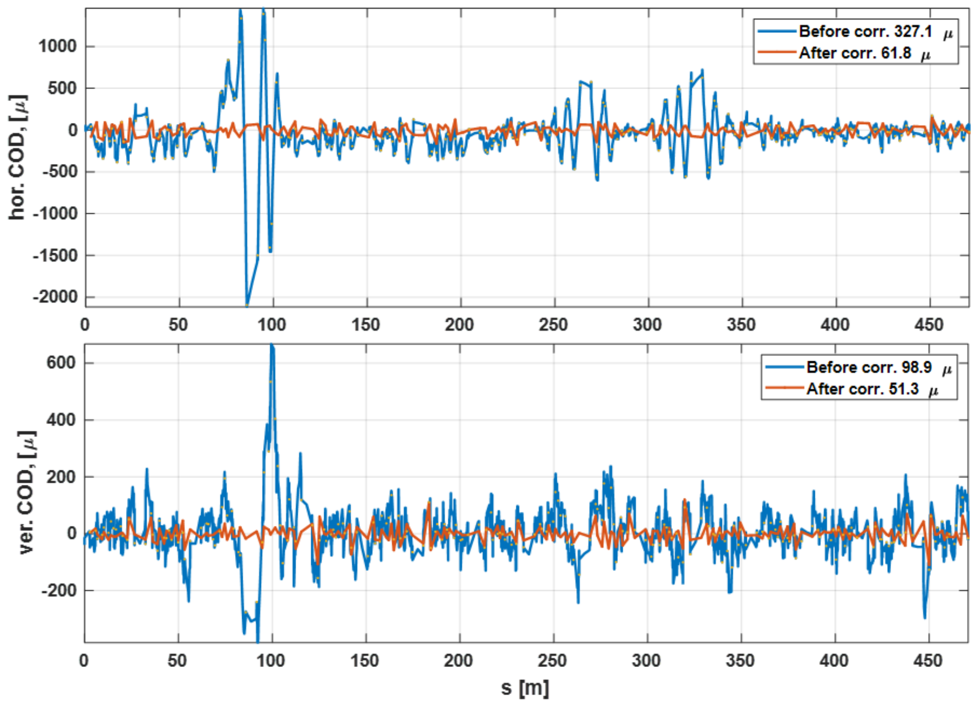
An algorithm to corrects the orbit, optics and coupling is as following:

- 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

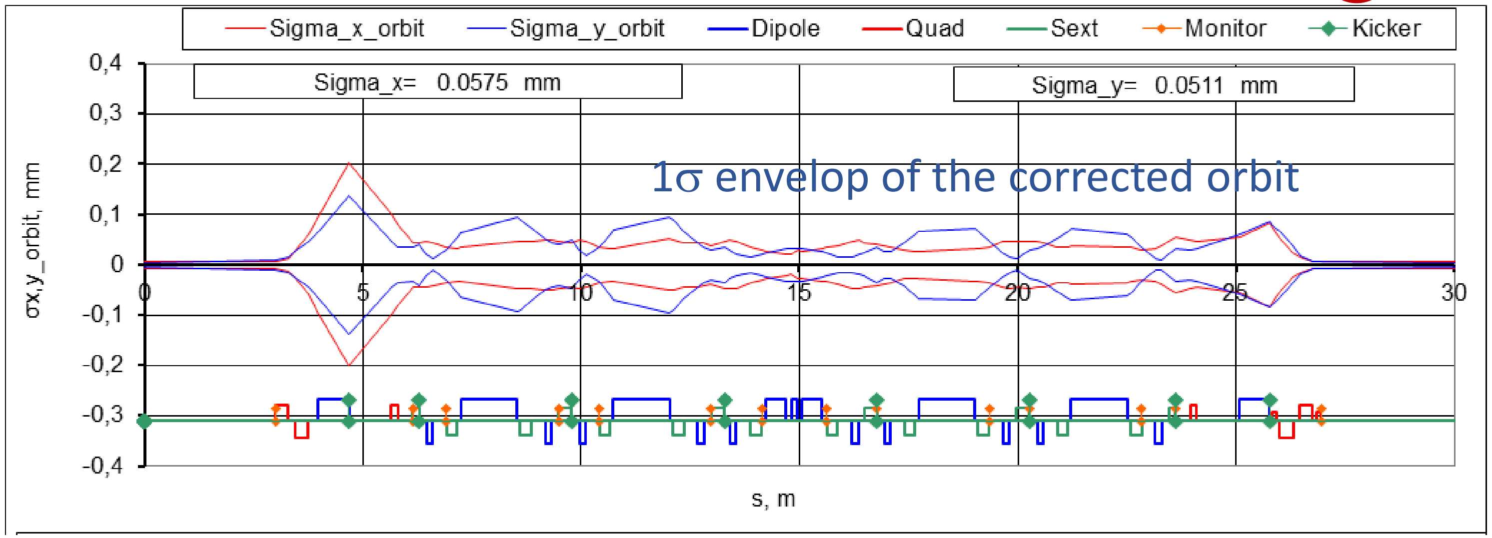
$$Effective\ displacement = \sqrt{80^2 + 30^2} \approx 85\ um$$

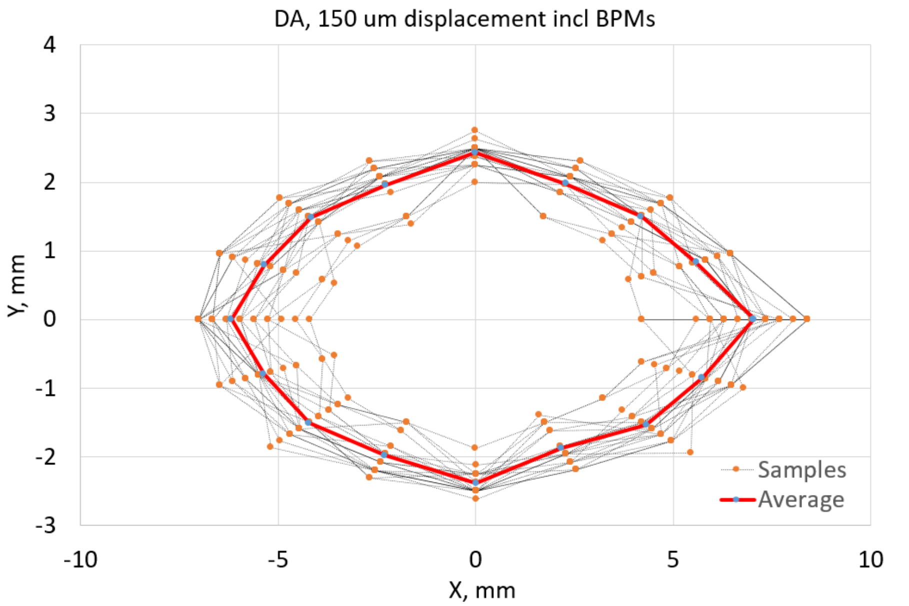
COD after first turn and after final correction

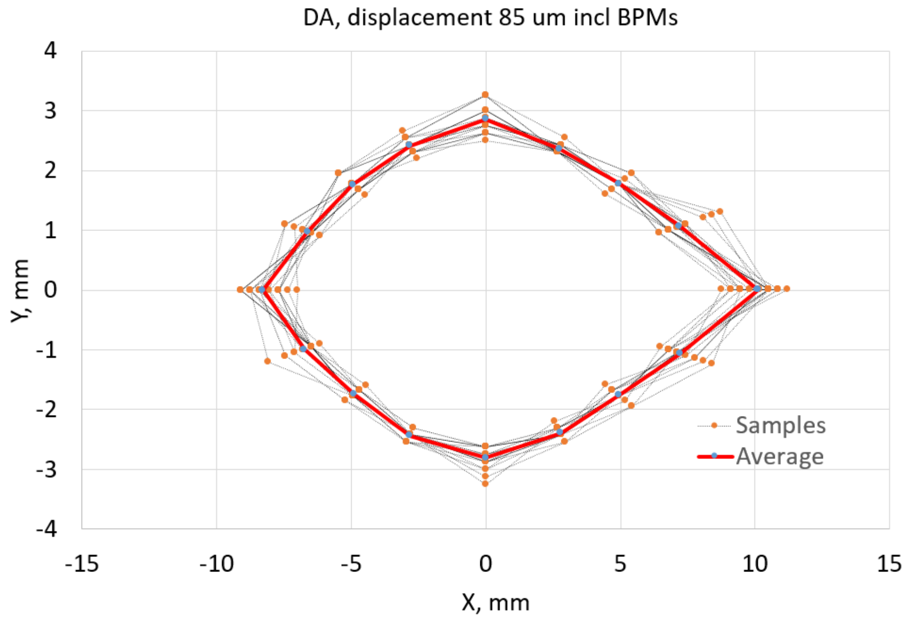


COD correction II

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

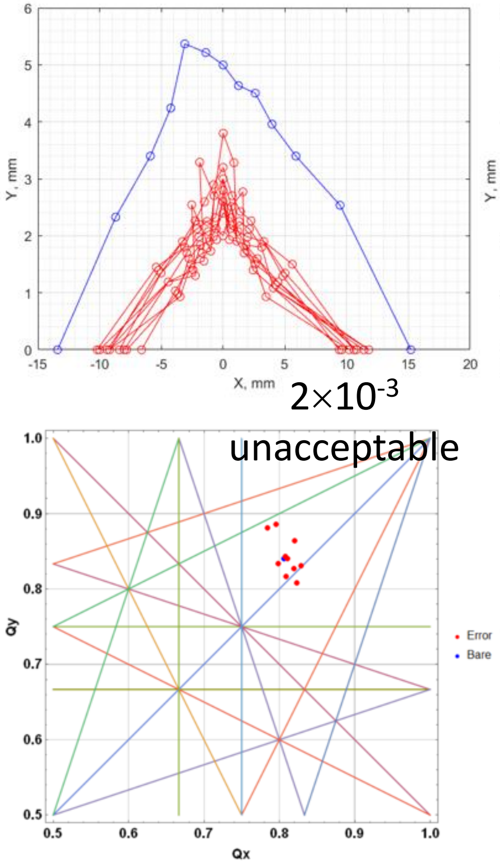

1σ envelop of the corrected orbit


DA, 150 um displacement incl BPMs


DA, displacement 85 um incl BPMs

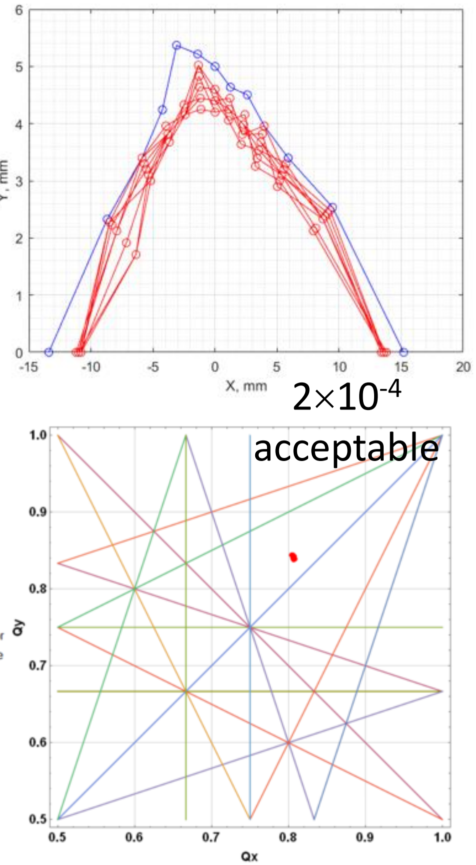
Multipole errors

Random quadrupole errors



2×10^{-3}

unacceptable



2×10^{-4}

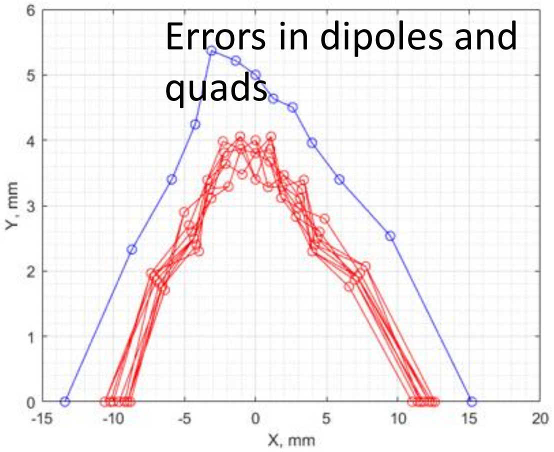
acceptable

Multipole errors in dipoles and quadrupoles ($\times10^{-4}$)

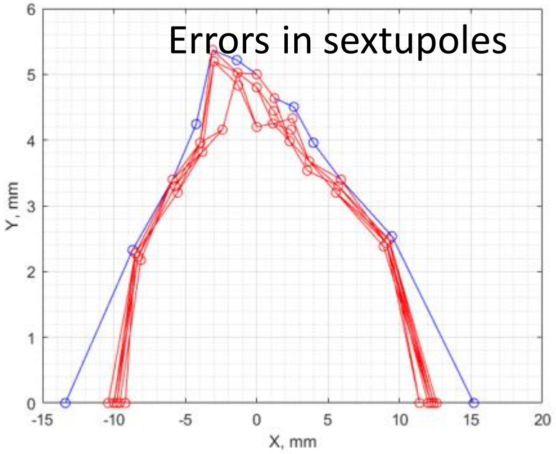
n	$(\mathrm{norm})_n$	$(\mathrm{skew})_n$
2	-	-
3	3	3
4	3	3
5	1	-
6	3	-
10	3	-
14	1	-

Multipole errors in sextupoles ($\times10^{-4}$)

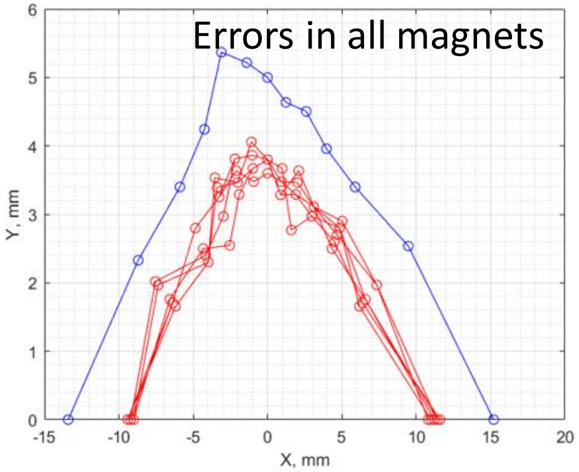
n	$(\mathrm{norm})_n$	$(\mathrm{skew})_n$
4	4	4
5	8	
9	20	
15	20	



Errors in dipoles and quads



Errors in sextupoles



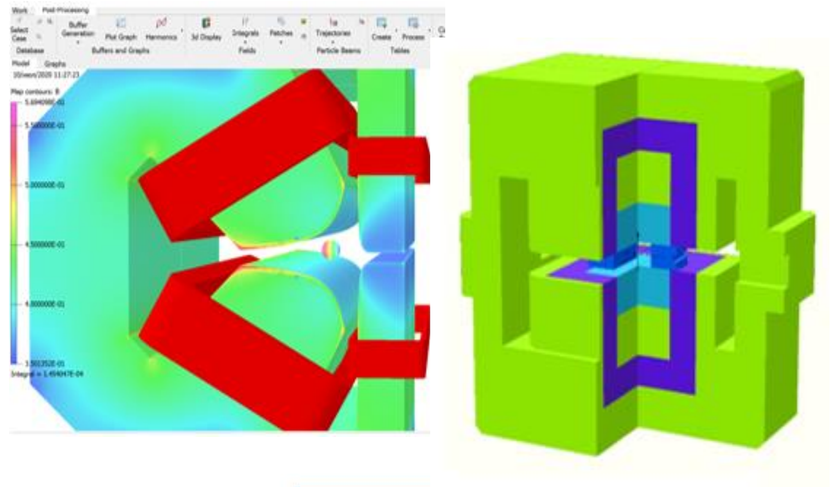
Errors in all magnets

Preliminary results. Work in progress.

Magnets

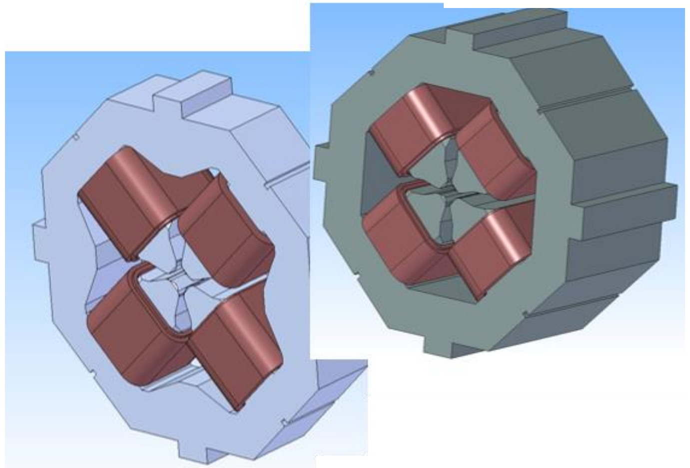
Dipoles

Magnet	No	L, m	ϕ°	ρ, m	B, T	K_1, m^{-2}	G, T/m
BD1	64	1.30	4.12	18.07	0.553	-0.791	-7.91
BD2	32	0.47	1.245	21.62	0.526	-1.074	-10.74
BM	32	0.69	2.079	19.01	0.526	-	-
BP	16	0.148	1.74	4.87	2.05	-	-



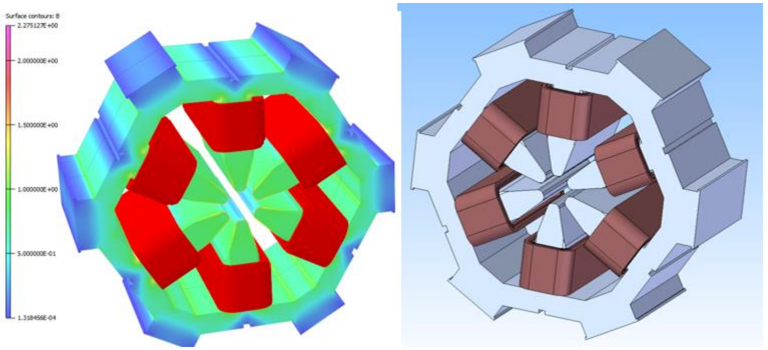
Quadrupoles

Magnet	No	L, m	ϕ°	ρ, m	B, T	K_1, m^{-2}	G, T/m
QD	32	0.3	-	-	-	-4.456	-44.56
QF1	32	0.3	-	-	-	4.397	43.97
QF2	32	0.15	-	-	-	4.866	48.66
QF3	128	0.15	-0.221	-38.84	-0.257	5.152	51.52
QF4	32	0.15	-0.3	-28.66	-0.349	4.987	49.87



Sextupoles

Magnet	No	L, m	K_2, m^{-3}	B'', T/m
SF1	32	0.15	231.309	2313.09
SD	160	0.25	-237.939	-2379.39
SF2	64	0.3	231.309	2313.09

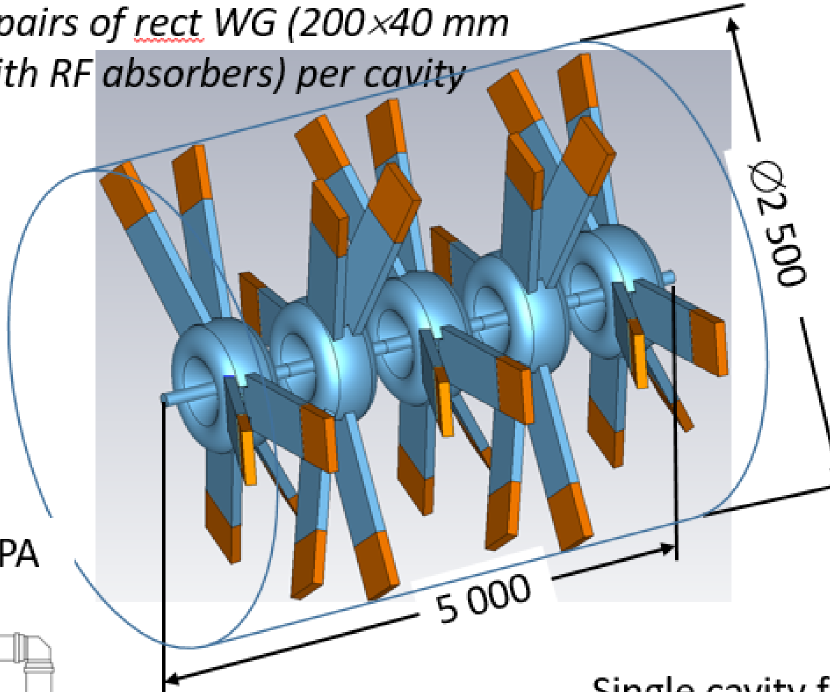


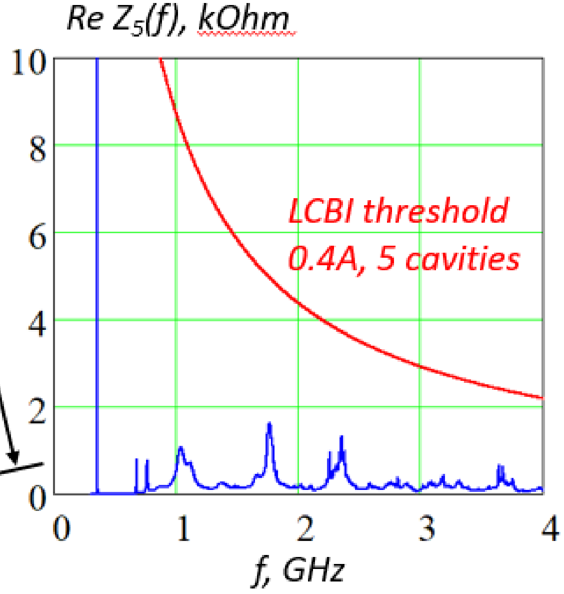
RF system

	Booster	*Main Ring*	
f_{rf}, MHz	*357*	*357*	*1071*
$V_{acc\ tot}$, MV	*1*	*1.8*	*0.35*
$N_{cavities}$	*3*	*5*	*3*
Cav. type	*NC*	*NC*	*NC*
HOM damping	*Yes*	*Yes*	*No*
Load type	*WG*	*WG*	

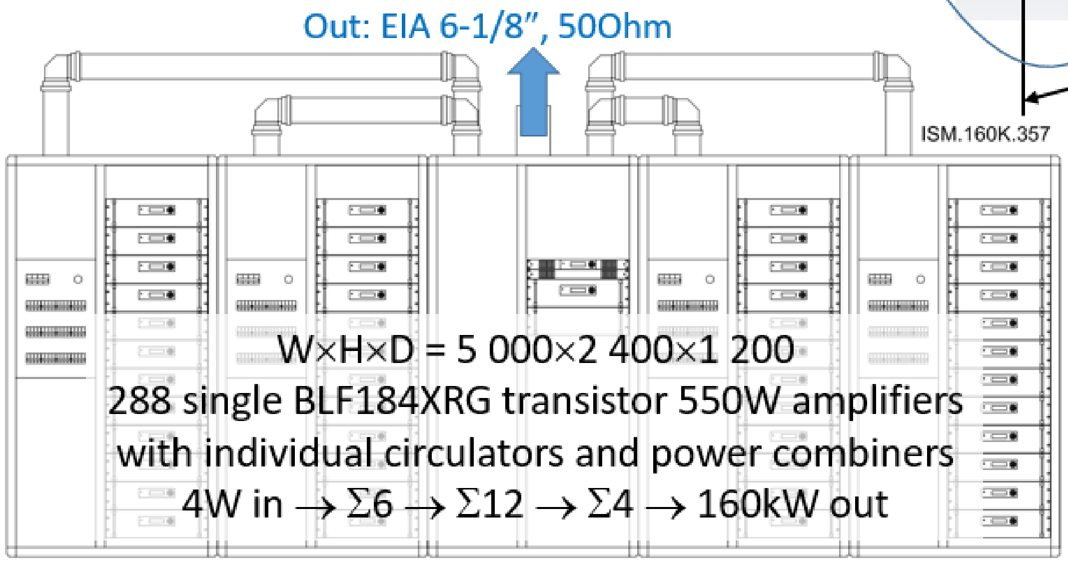
Main Ring accelerating module of 5 independently driven cavities

3 pairs of rect WG (200×40 mm with RF absorbers) per cavity





Main Ring single cavity 357 MHz / 160 kW CW SSPA



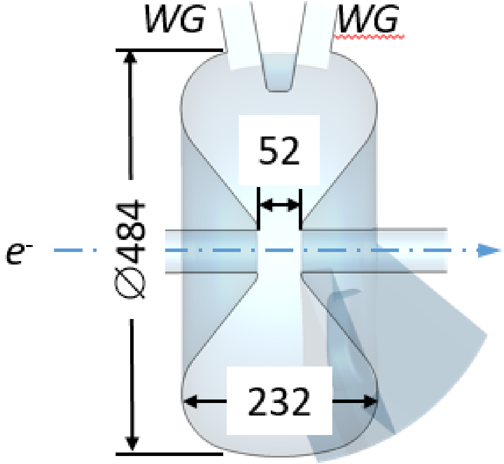
W×H×D = 5 000×2 400×1 200

288 single BLF184XRG transistor 550W amplifiers with individual circulators and power combiners

4W in → Σ6 → Σ12 → Σ4 → 160kW out

Booster cavity SSPA: 1/4 of the Main Ring SSPA

Single cavity fundamental mode data



f_0, MHz	*357*
R/Q, Ohm	*108*
Q_0	*20 000*
$R/Q \cdot Q_0$, MOhm	*2.16*
$V_{acc\ 1}$, kV	*360*
P_{Cu}, kW	*30*
$P_{S\ max}$, W/cm^2	*16*

Vacuum system: basic approaches

Vacuum lifetime for 1 nTorr

Process	Lifetime [h]
Elastic (Rutherford)	43
Inelastic (bremsstrahlung)	66
Total	**26**

- Vacuum lifetime: > 10h (dynamic pressure of CO ≤ 2.5 nTorr).
- Absorption of 200 kW of SR.
- Low impedance design.
- Material: aluminum alloys 6063.
- Connections like in SuperKEKB, compensators like in PEPII type, BPMs like in MAX4/SIRIUS/Diamond.
- Cryo-pump or distributed NEG coating in the narrow aperture straight sections.
- Lumped compact combined pumps in the arcs. Expected conditioning time 3÷6 months. Advantage in compare to the NEG coating is unbaked system, less sensitive to micro-leaks, low wall impedance.

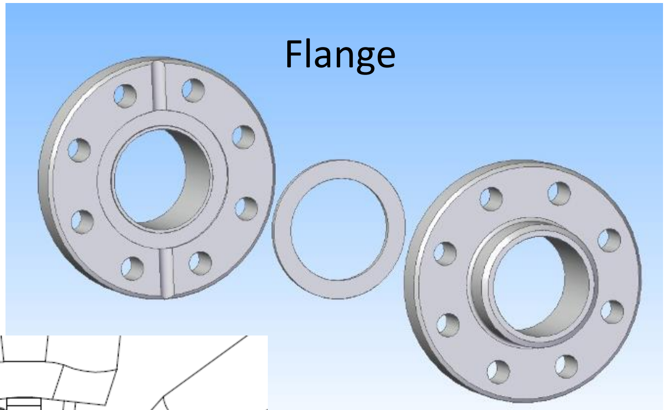
Vacuum system design

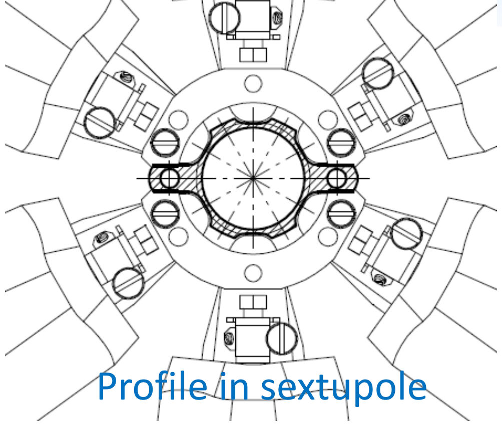
Design requirements:

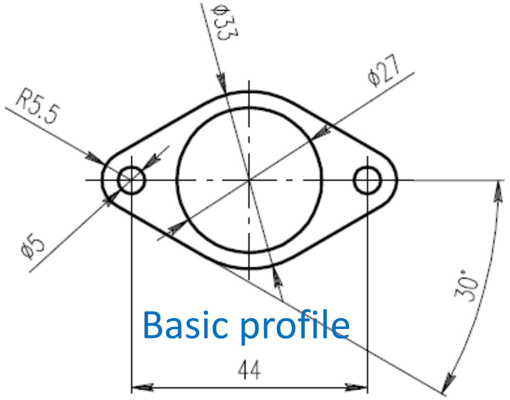
Inner diameter of beam pipe, *d* [mm]	27
Average distance between pumps, *L* [m]	1
Total number of lumped pumps per arc	24
Pumping speed of one pump for CO [l/s]	120
Average photon flux [ph/s/m] at I=0.4A, E=3 GeV	2E18
Initial/final desorp.coeff. [mol./ph] for CO	1E-2/0.8E-6
Average photon dose for conditioning [ph/m]	1.4E25 (777 Ah)
Lifetime at I=0.4 A during conditioning [h]	3
Calculated conditioning duration [s] (worst case)	**8E6 (~3 months)**

Status:

- All profiles are defined. BINP is ready for ordering.
- Beam pipes are defined by BPMs and e-ph beams branching points positioning.
- Universal port and flange connections are designed.
- Design of smooth flange connection for prototyping is completed.
- Bellow units is based on the PEP-II design.
- Parameters of crotch-absorbers are defined. Design follows the ESRF absorbers.
- Beam pipe gate valves (32 pieces) with RF contacts will be BINP design.

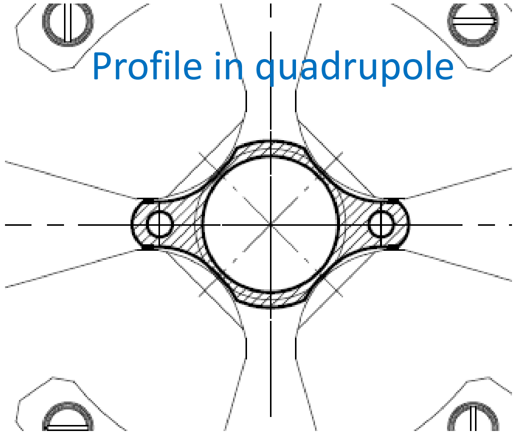

Flange


Profile in sextupole



Basic profile


Universal port


Profile in quadrupole

Conclusions

- 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!