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The lattice with variation of negative momentum compaction factor for high-resolution mode of HESR

Requirements to HESR lattice:

- **wide momentum range** $.5 \div 15$ **GeV/c**

- **beam stability in high-resolution mode** $\delta p / p \approx 10^{-4} \div 10^{-5}$ **in whole energy range**

- **maximum luminosity on the target**

- **minimum particles losses** ➔

Therefore:

- **corrected chromaticity by arc's sextupoles**

- **sufficiently large dynamic aperture after sextupole correction**

- **dispersion free straight sections**

- **minimum influence of non-linear tune shift in target point**

For stability the only solution is negative momentum compaction factor:

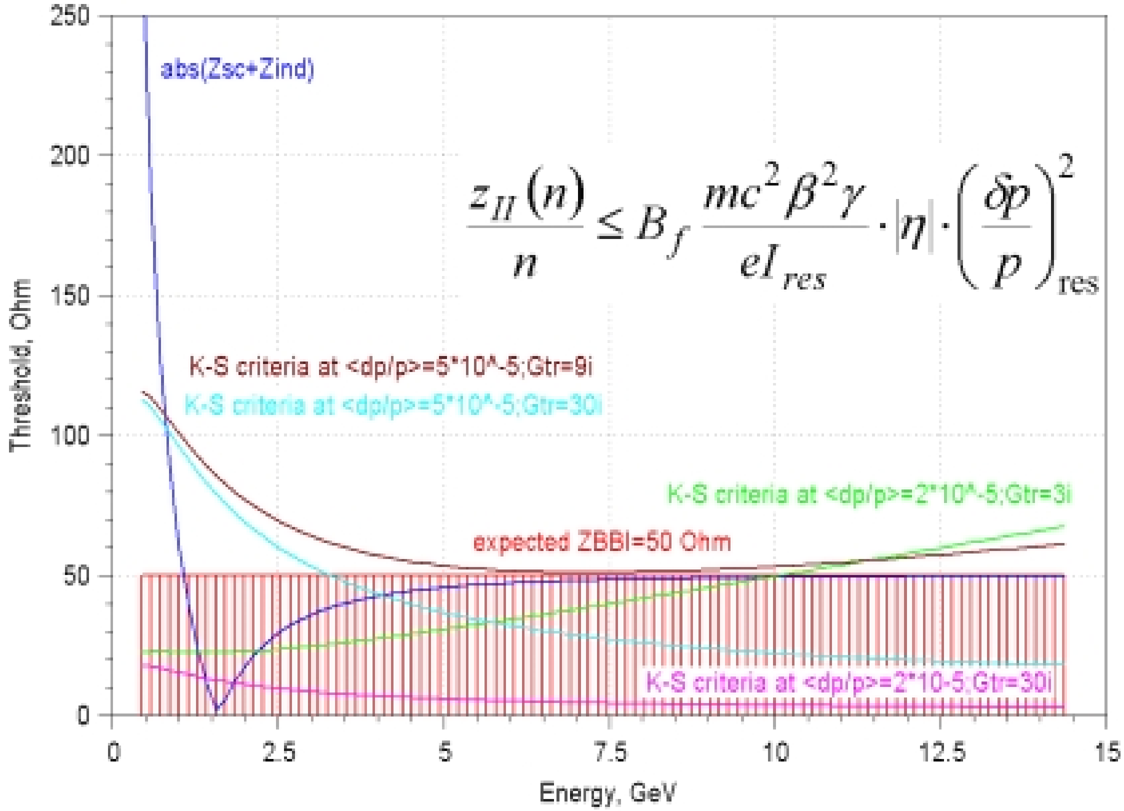
$$\alpha = 1/\gamma_t^2 < 0 \Rightarrow |\eta| = 1/\gamma^2 + 1/\gamma_t^2$$

It provides higher Keil-Schnell threshold:

$$Z_{KS} \approx B_f \frac{mc^2 \beta^2 \gamma}{eI_c} \cdot |\eta| \cdot \left(\frac{\delta p}{p} \right)^2$$

First estimation of PANDA insertion into Longitudinal BBI is ~40 Ohm!!!

BBI limit



For momentum $\delta p / p \sim 10^{-4}$ and $\alpha > 0$ the beam is unstable in whole range of energy.

Only since $\alpha < -0.012$ the lattice satisfies to Keil-Schnell criteria for beam with $(\delta p / p) = 5 \cdot 10^{-5}$

and for $(\delta p / p) = 2 \cdot 10^{-5}$ in region $0 \div 15$ GeV we have to adjust $\alpha \approx -0.12$.

Negative Momentum Compaction Factor(MCF)

$$\mathrm{D}'' + \mathrm{K}(\tau)\mathrm{D} = \frac{1}{\rho(\tau)} \Rightarrow \text{"}\rho\text{"}-\text{modulation} \Rightarrow$$

$$\text{where } K(\tau) = \frac{eG(\tau)}{p}$$

$$D(\tau) \sim Ae^{i\nu_x\tau} + \frac{B}{\nu_x^2 - S^2} e^{iS\tau} + \frac{1}{\overline{R}} \Rightarrow$$

$$\alpha = \int \frac{D(\tau)}{\rho(\tau)} d\tau \sim \frac{B^2}{\nu^2 - S^2} + \frac{1}{\nu_x^2}$$

In lattice with super periodicity close to eigen frequency $S - \nu_x << S, \nu_x$ **the dispersion is determined by second term and MCF can be negative.**

However, using the conception of pseudo-second order achromat for arc the ρ modulation is not enough

$$D'' + K_0(\tau)D = \frac{1}{\rho(\tau)} + \varepsilon K_0(\tau)\frac{\Delta G}{G}(\tau)\cdot D$$

ρ – modulation

Gradient modulation

In result:

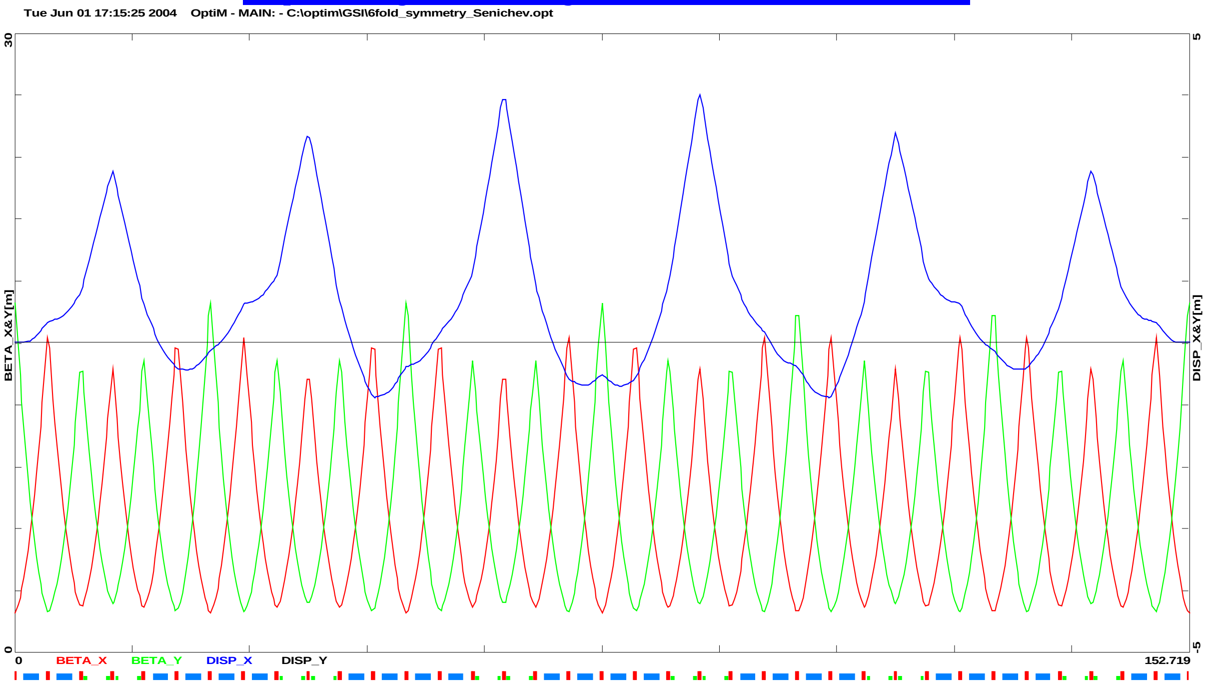
$$\alpha = \frac{1}{\nu_x^2}\left(1 - \frac{1}{4\left(\frac{nS}{\nu_x} - 1\right)} \cdot \left(\frac{g_n}{1 - \left(\frac{nS}{\nu_x} - 1\right)^2} - \frac{r_n}{r_0}\right)^2\right)$$

where

$$\varepsilon \frac{\Delta G}{G} = \sum_{n=0}^{\infty} g_n \cos n\phi s;$$

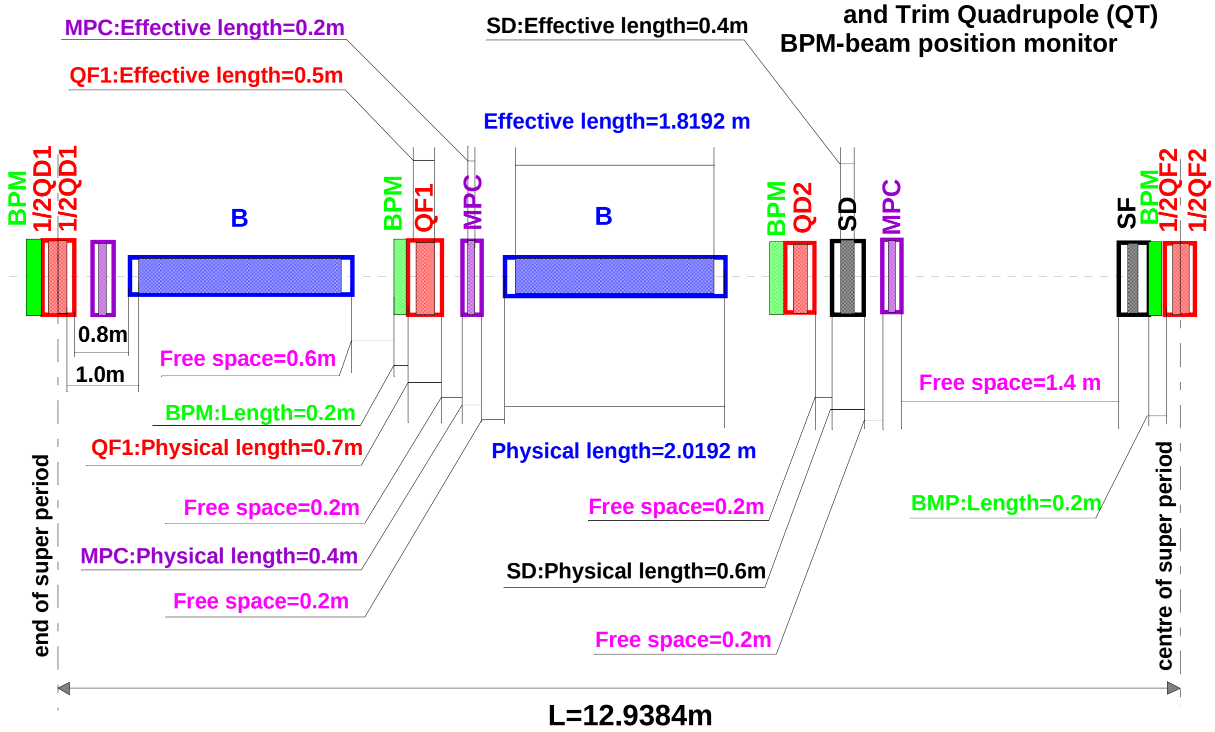
$$\frac{1}{\rho(s)} = r_0 + \sum_{n=1}^{\infty} r_n \cos n\phi s$$

6 fold symmetry ARC LATTICE:

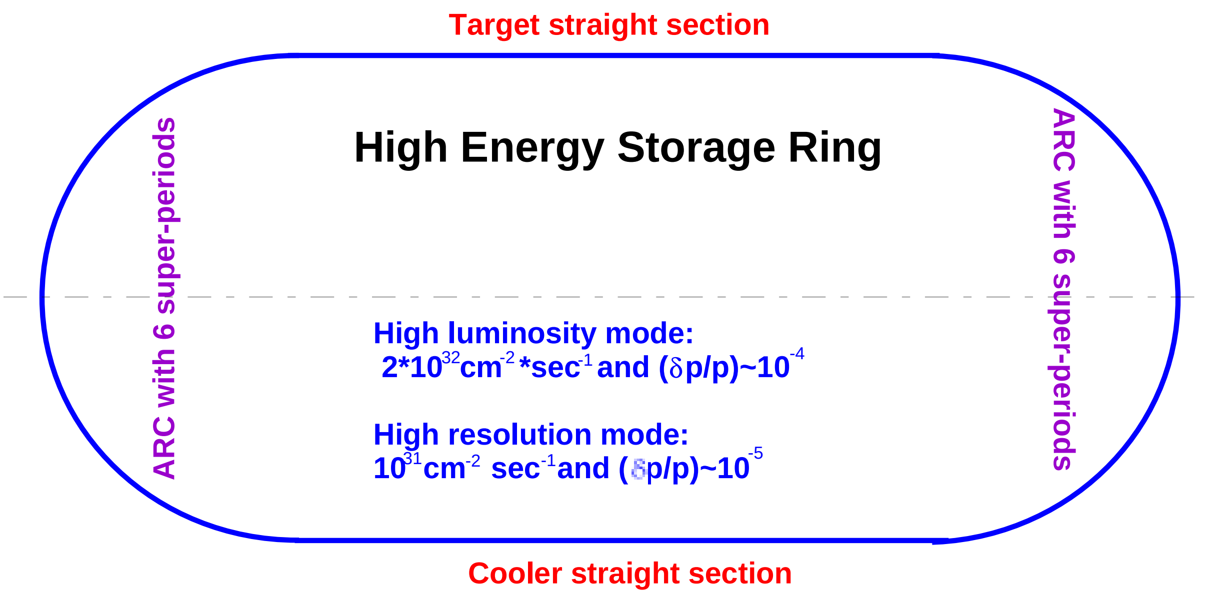


Half-Superperiod:

B -bend magnet
QD -defocusing quadrupole
QF -focusing quadrupole
SD -defocusing sextupole
SF -focusing sextupole
MPC-multipole corrector including Orbit Corrector Dipole (OCD) and Trim Quadrupole (QT)
BPM-beam position monitor



HESR:


Target straight section
High Energy Storage Ring
ARC with 6 super-periods
ARC with 6 super-periods
High luminosity mode:
2*10^32 cm^-2 *sec^-1 and (δp/p)~10^-4
High resolution mode:
10^31 cm^-2 sec^-1 and (δp/p)~10^-5
Cooler straight section

Separated tunes $\nu_{x,y}$ and MCF α control

Optimised ratio between g_n and r_n is determined, when next inequalities reach maximum:

MCF control →

$$\frac{\partial \alpha}{\partial G_{QF2}} > \frac{\partial \alpha}{\partial G_{QD2}} >> \frac{\partial \alpha}{\partial G_{QF1}} \approx \frac{\partial \alpha}{\partial G_{QD1}}$$

X tune control →

$$\frac{\partial \nu_x}{\partial G_{QF1}} > \frac{\partial \nu_x}{\partial G_{QF2}} >> \frac{\partial \nu_x}{\partial G_{QD1}} \approx \frac{\partial \nu_x}{\partial G_{QD2}}$$

Y tune control →

$$\frac{\partial \nu_y}{\partial G_{QD1}} \approx \frac{\partial \nu_y}{\partial G_{QD2}} >> \frac{\partial \nu_y}{\partial G_{QF1}} \approx \frac{\partial \nu_y}{\partial G_{QF2}}$$

Dynamic Aperture

DA is determined mostly by strength of sextupoles =>

Sextupole strength is determined by total chromaticity =>

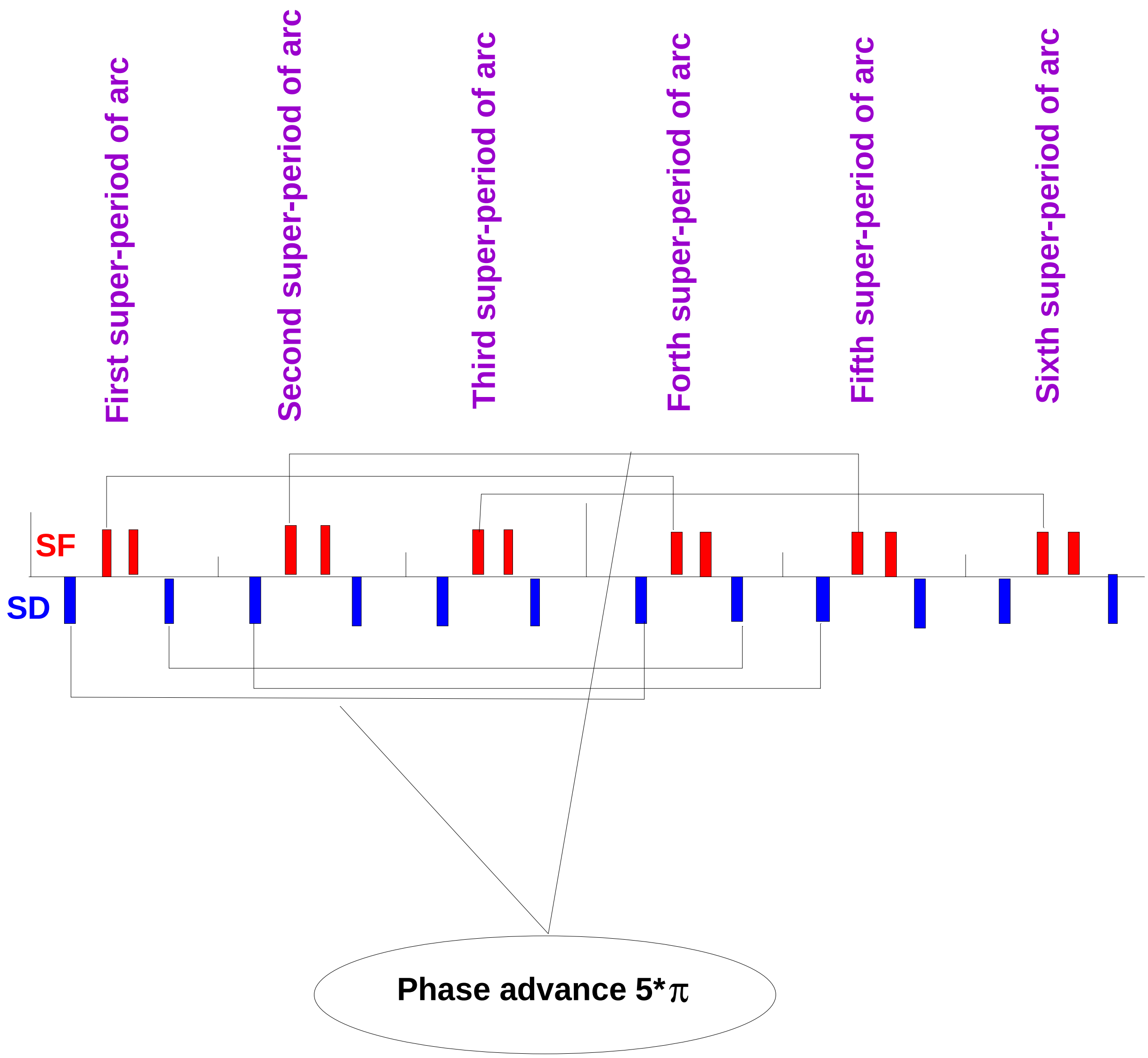
Total chromaticity is determined by arc and straight section chromaticity =>

Arc chromaticity is determined by gradient modulation (that is by MCF)

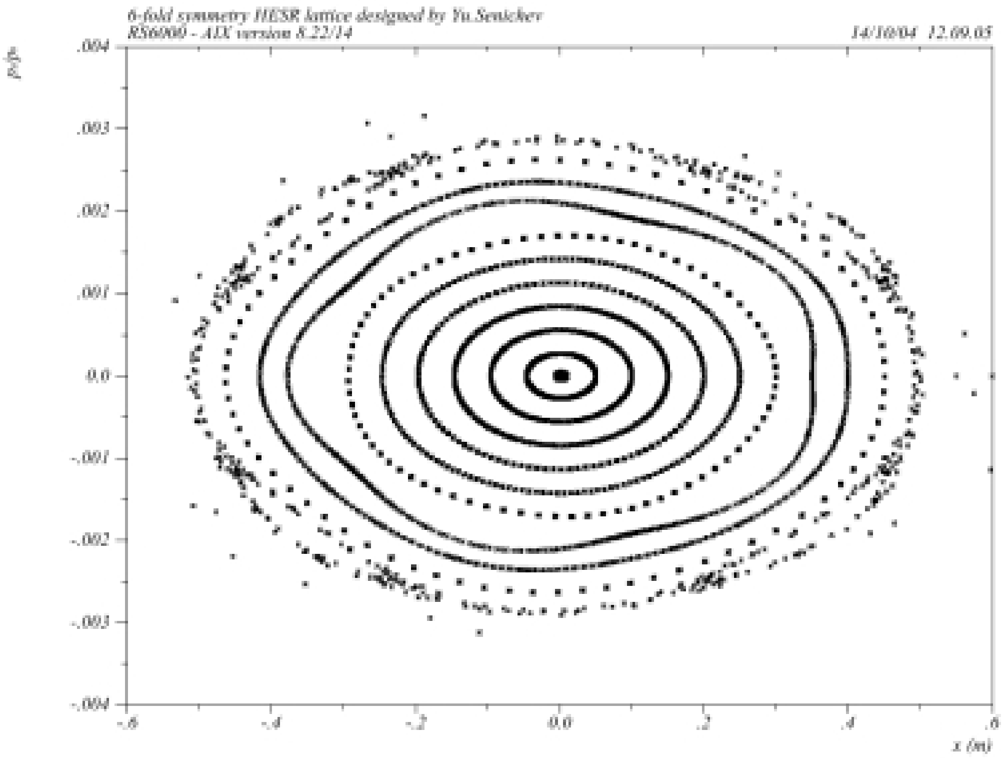
Straight section chromaticity is determined by beam spot size on target

Nevertheless, the maximum normalized chromaticity was numerically determined and it is limited by $\xi_{x,y} \approx -2.0 \div 2.2$ **(for 6 fold symmetry** $Q_{x,y} \approx 24 \div 26$**)**

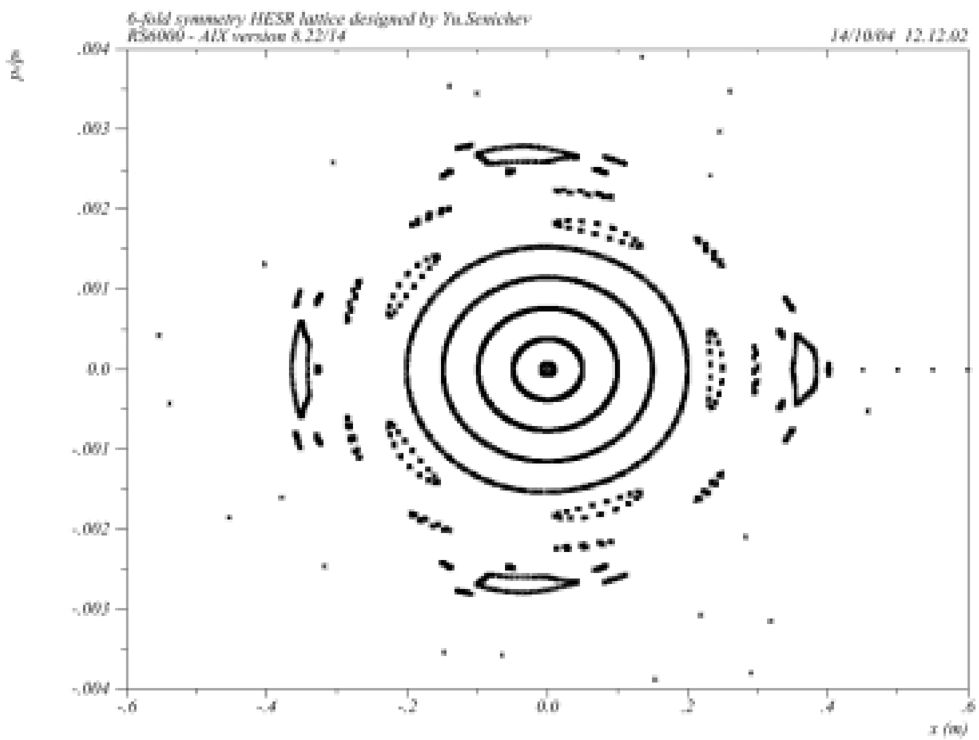
Sextupole Scheme Correction



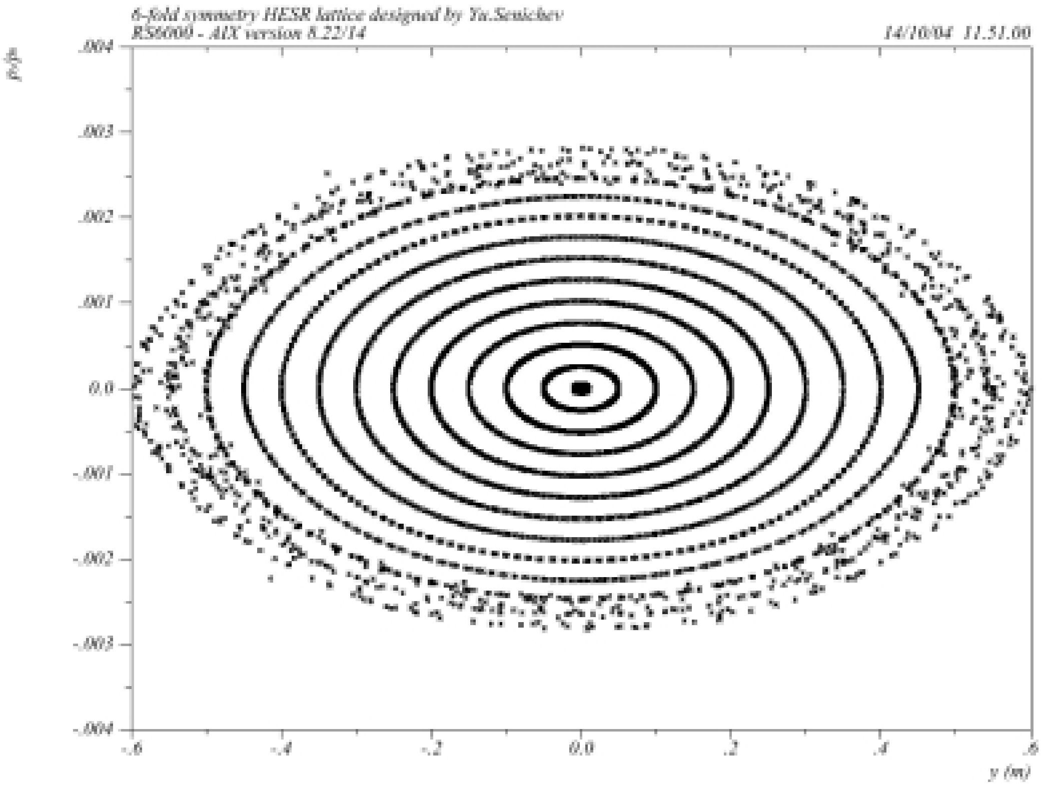
X plane with momentum deviation –0.5%



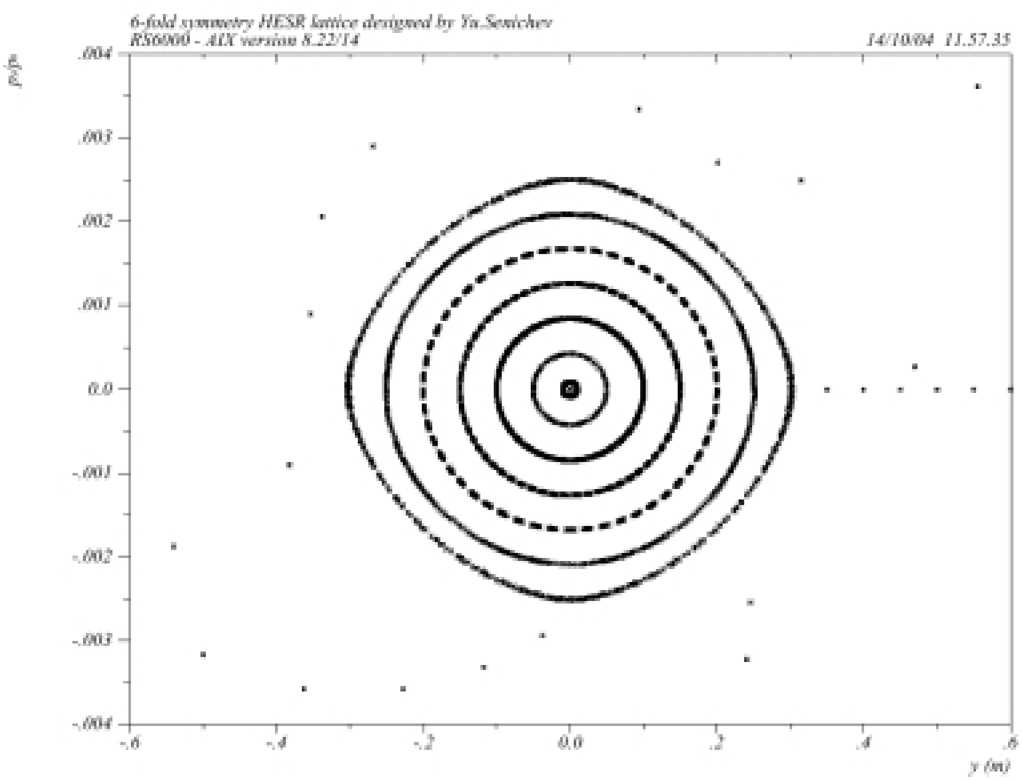
X plane with momentum deviation 0.5%



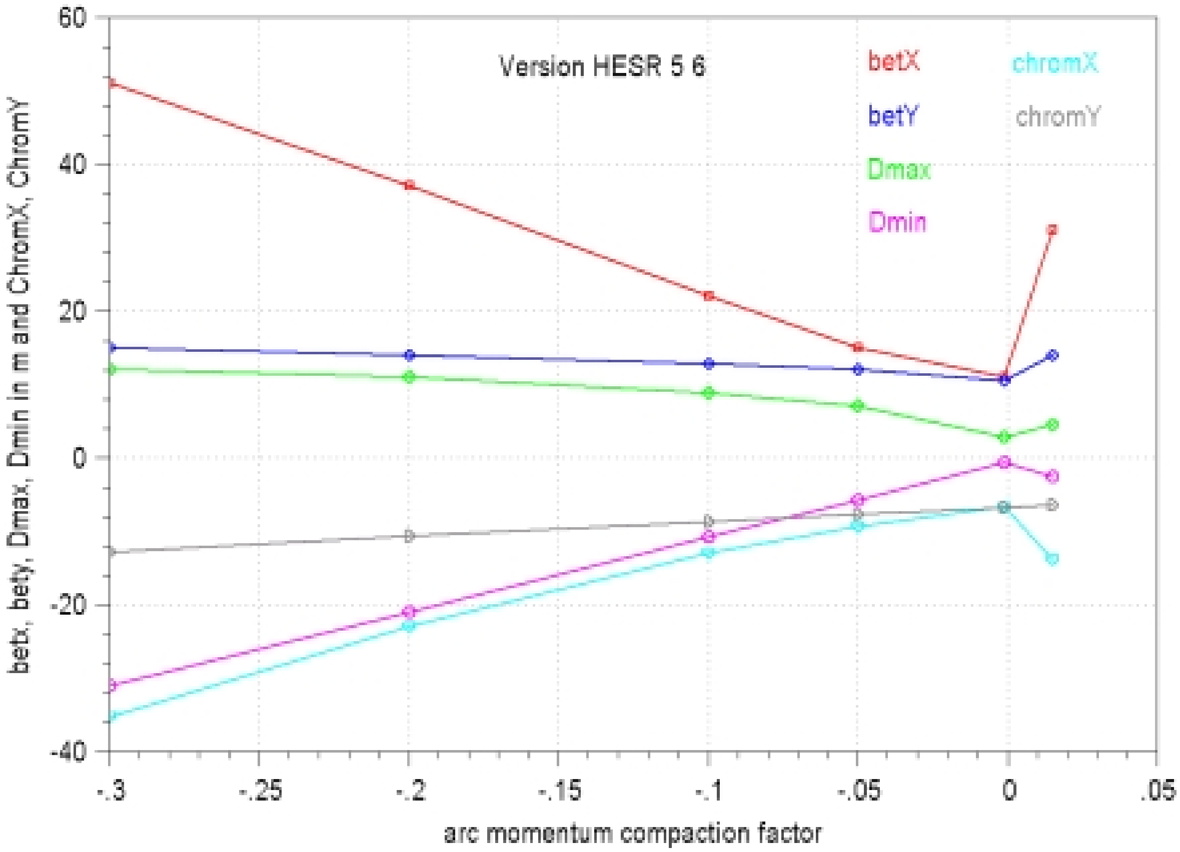
Y plane with momentum deviation –0.5%

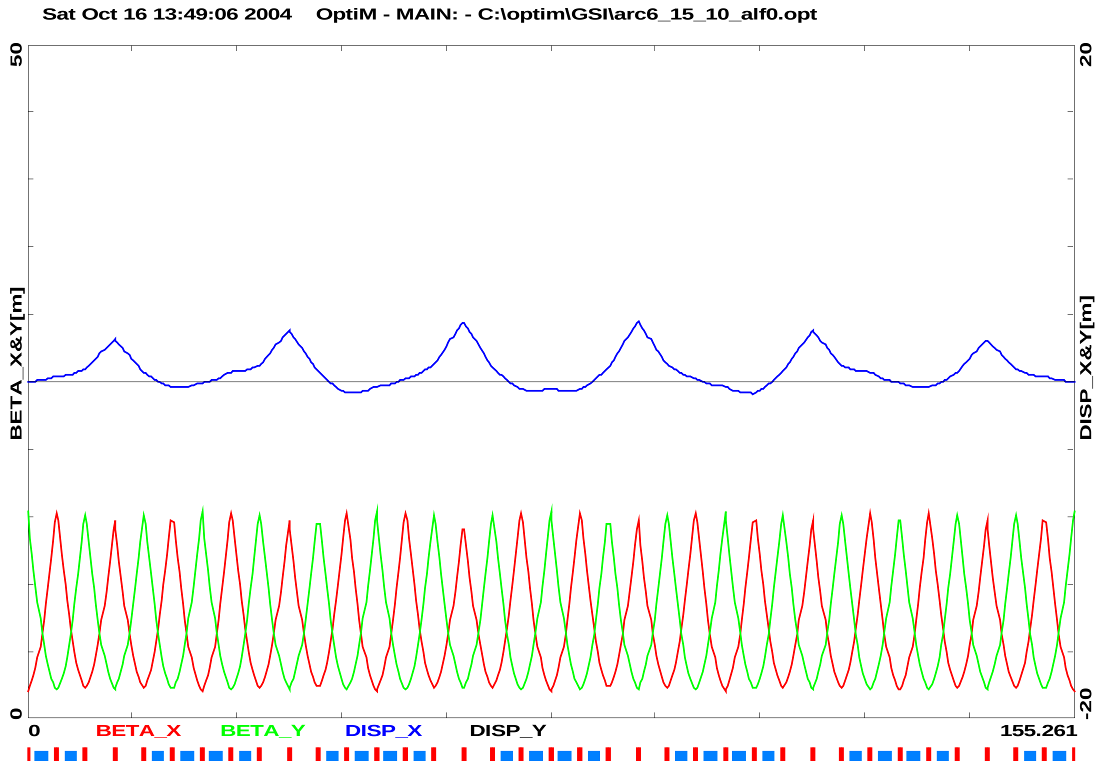


Y plane with momentum deviation 0.5%

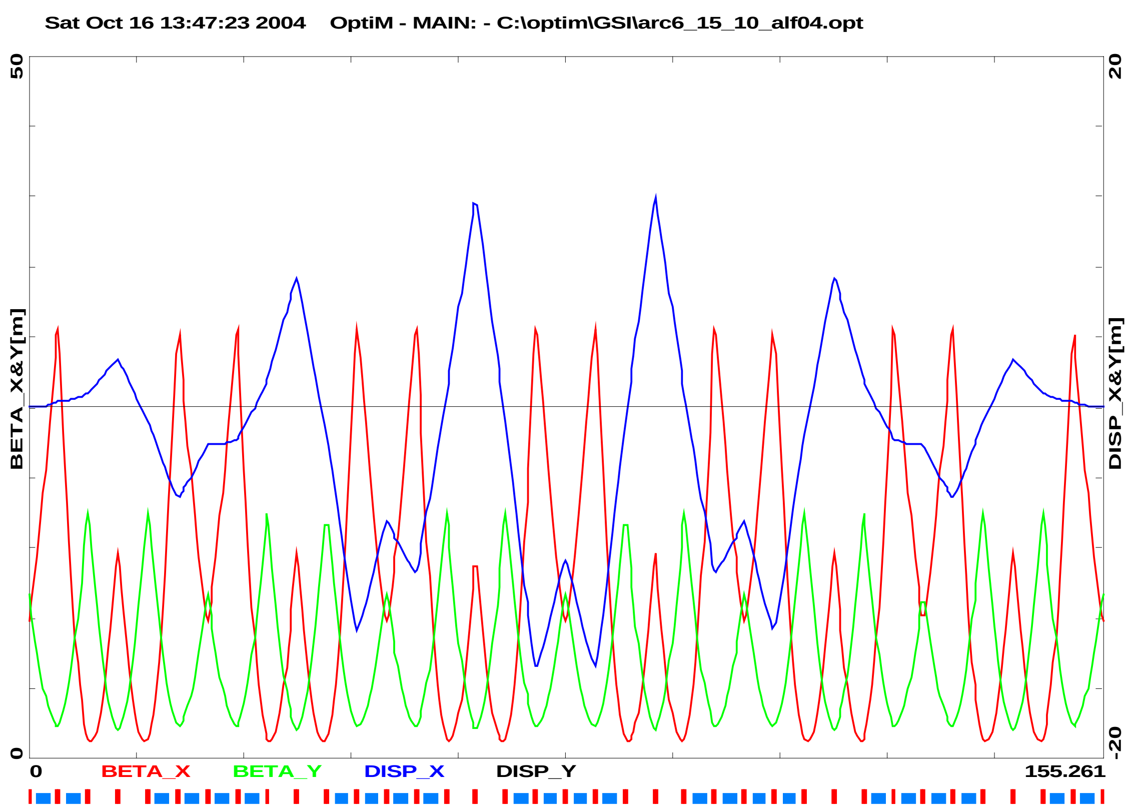


TWISS parameters vs Gamma Transition



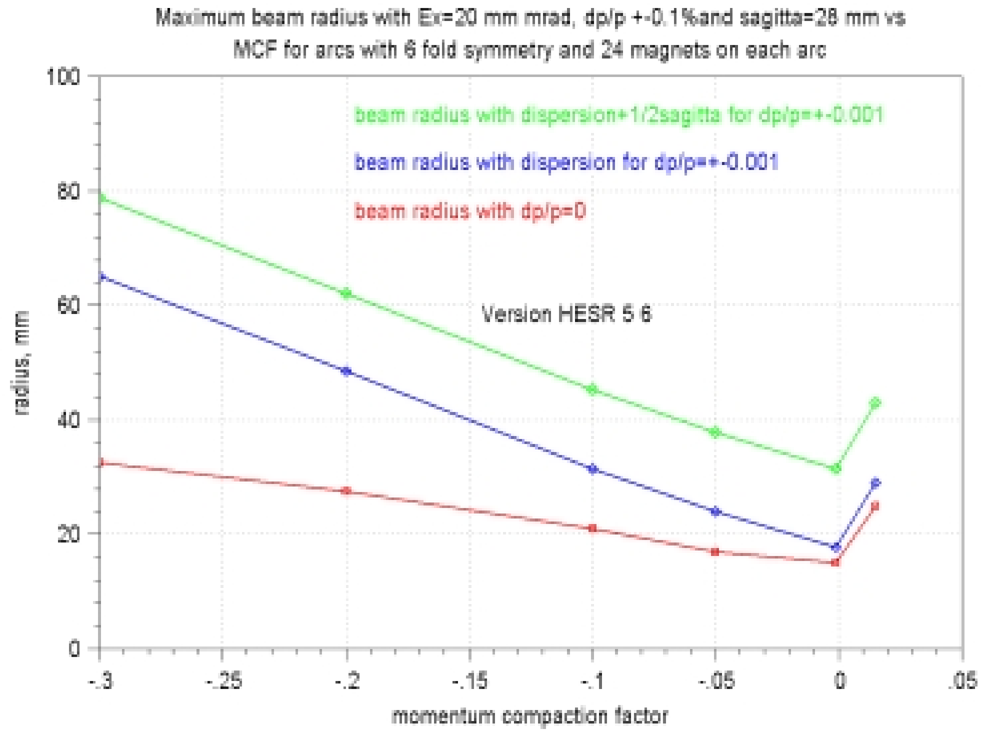


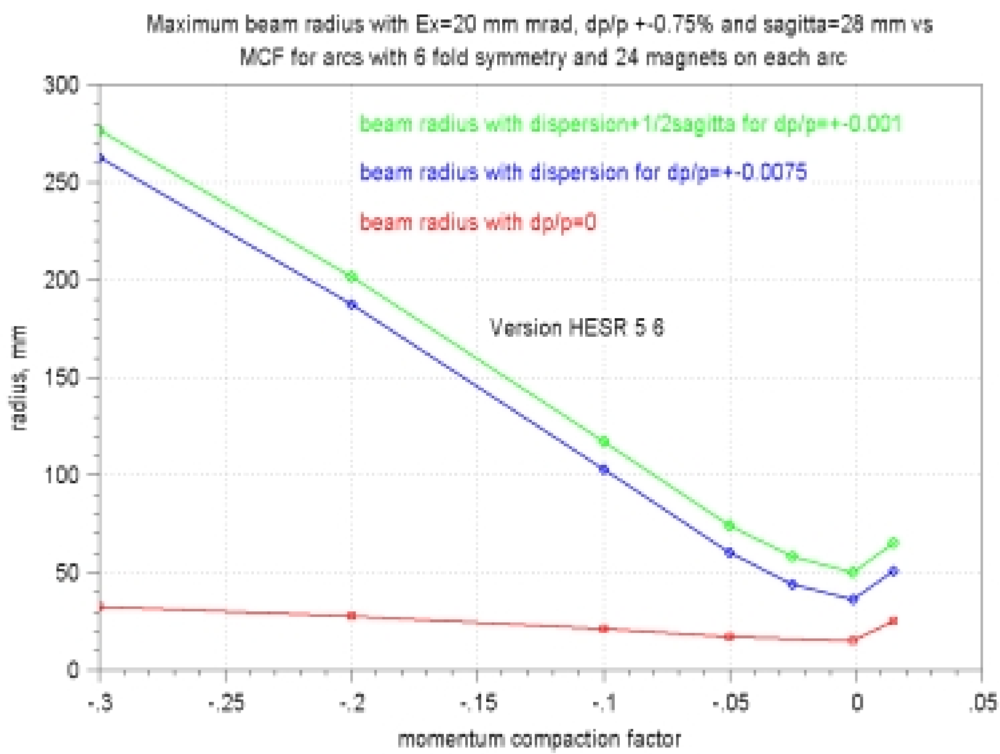
TWISS parameters at $\gamma_{tr} = \infty$



TWISS parameters at $\gamma_{tr} = 3i$

Beam radius


Maximum beam radius with Ex=20 mm mrad, dp/p +-0.1%and sagitta=28 mm vs
MCF for arcs with 6 fold symmetry and 24 magnets on each arc
beam radius with dispersion+1/2sagitta for dp/p=+-0.001
beam radius with dispersion for dp/p=+-0.001
beam radius with dp/p=0
Version HESR 5 6
radius, mm
momentum compaction factor
100
80
60
40
20
0
-.3
-.25
-.2
-.15
-.1
-.05
0
.05


Maximum beam radius with Ex=20 mm mrad, dp/p +-0.75% and sagitta=28 mm vs
MCF for arcs with 6 fold symmetry and 24 magnets on each arc
beam radius with dispersion+1/2sagitta for dp/p=+-0.001
beam radius with dispersion for dp/p=+-0.0075
beam radius with dp/p=0
Version HESR 5 6
radius, mm
momentum compaction factor
300
250
200
150
100
50
0
-.3
-.25
-.2
-.15
-.1
-.05
0
.05

Effects of residual dispersion and chromaticity

$$\varsigma_{\Sigma} = \varsigma_{arc} + \varsigma_{cool} + \varsigma_{\text{target}}$$

After correction chromaticity up to zero by ARCs sextupoles we have:

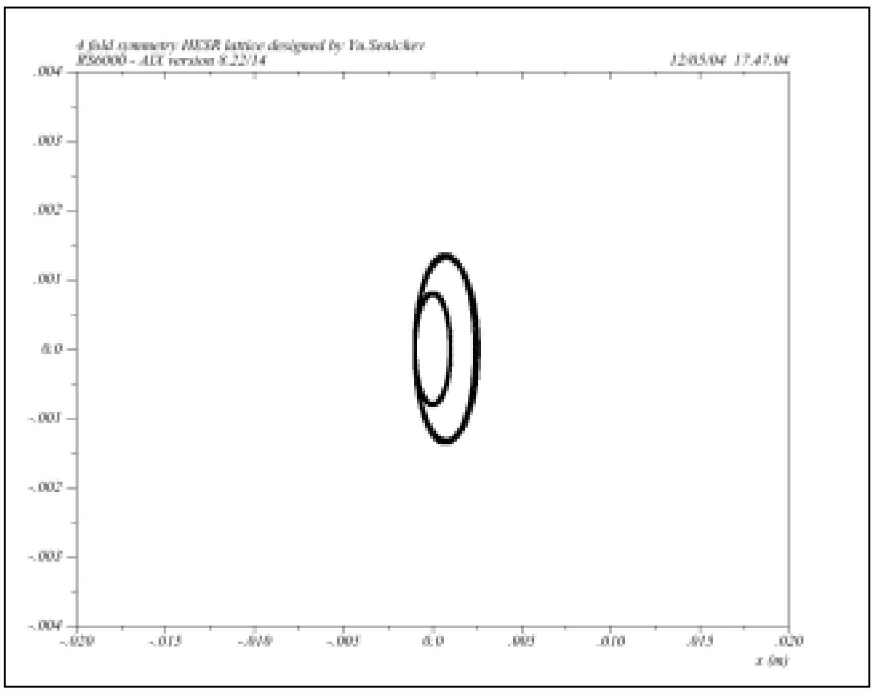
$$\varsigma_{arc} = -(\varsigma_{cool} + \varsigma_{\text{target}})$$

and

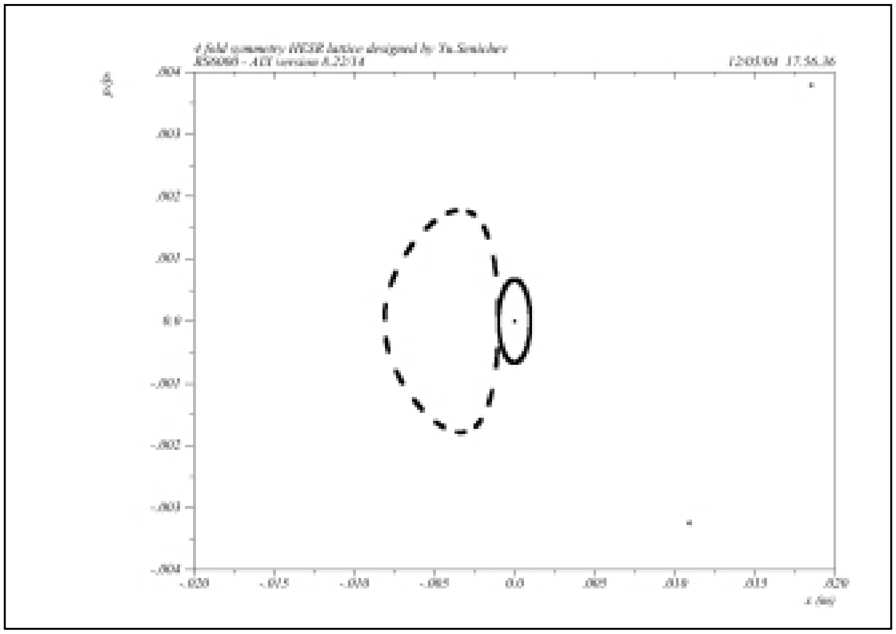
$$\nu_{arc} = \nu_{arc}\Big|_{\Delta p/p=0} \pm \frac{\Delta p}{p} \cdot \left|\varsigma_{cool} + \varsigma_{\text{target}}\right|$$

It means we violate the condition for the dispersion suppressing and we get the residial dispersion.

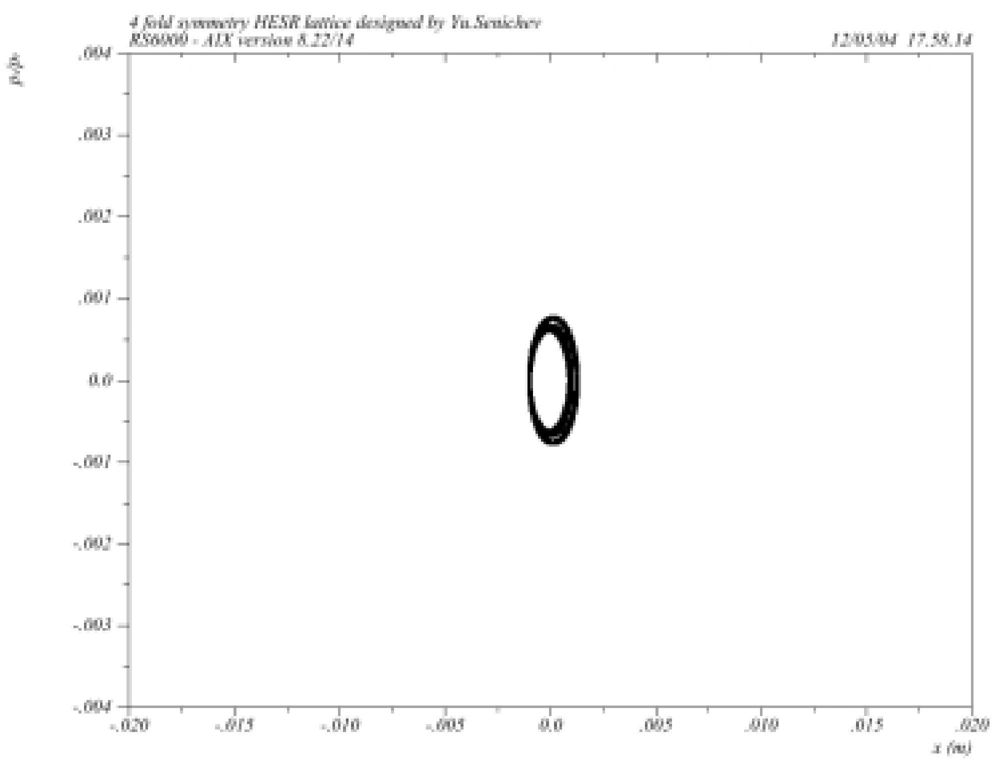
For instance, in lattice with $\alpha = -0.02$ **and dp/p=0.0075 we have the smearing of the beam on target➔**



In lattice with $\alpha = -0.15$ **and dp/p=0.0075 we have the smearing of the beam on target➔**



In lattice with $\alpha = -0.15$ **and dp/p=0.0005 we have the smearing of the beam on target➔**



The chromaticity is compensated on arcs only

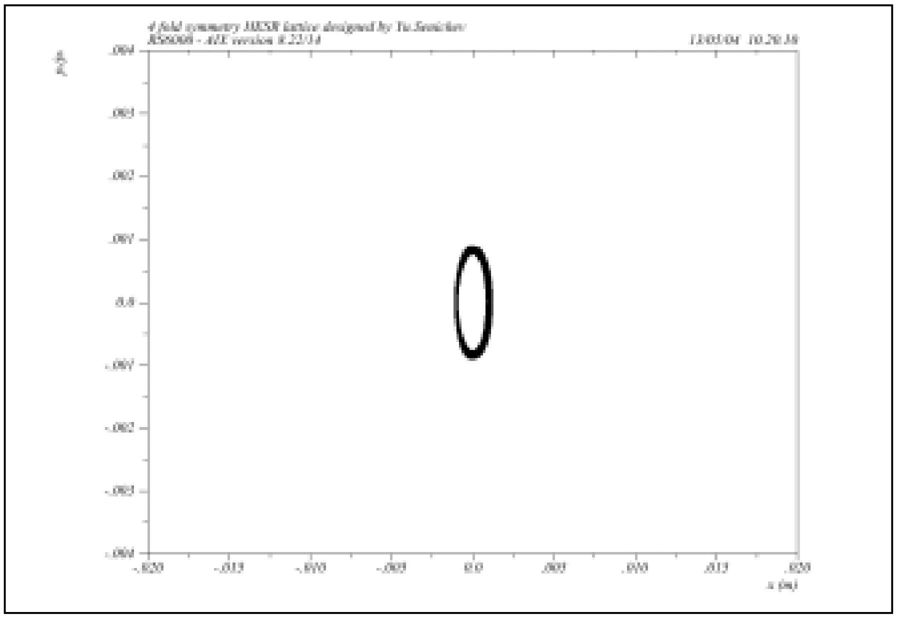


Table of HESR main parameters

Parameters	6-fold symmetry
Arc length, m	155.26
Number of arcs	2
Superperiods number of one arc S_{arc}	6
Total circumference, m	574.5
Possible region adjustment of α for arcs	$0.03 \div -0.3$
Possible region adjustment γ_{tr}/α for whole ring	$8.5 \div i2.7$ $0.015 \div -0.15$
Betatron tune of ring $\nu_{x,y}^{ring}$	12.16; 12.18
Magnets number per one arc	24
Effective length of magnet, m and max field,T	1.82; 3.6 T
Bend angle, degrees	7.5
Sagitta, m	0.0297
Maximum magnetic bending power, Tm	50
Quadrupoles number per one arc	37
Effective length of quadrupole, m	0.5
Quadrupole families number	3
Maximum gradient in quadrupoles, T/m	60

CONCLUSION

1. **Optimized arcs of HESR give the possibility to work in wide region of momentum compaction factor** $\alpha \approx 0.05 \div -0.15$**, using gradient variation with 3 quadrupoles families.**

2. **The straight sections have to be optimized to get minimum total chromaticity.**