Ultralow Emittance Light Sources

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Outline

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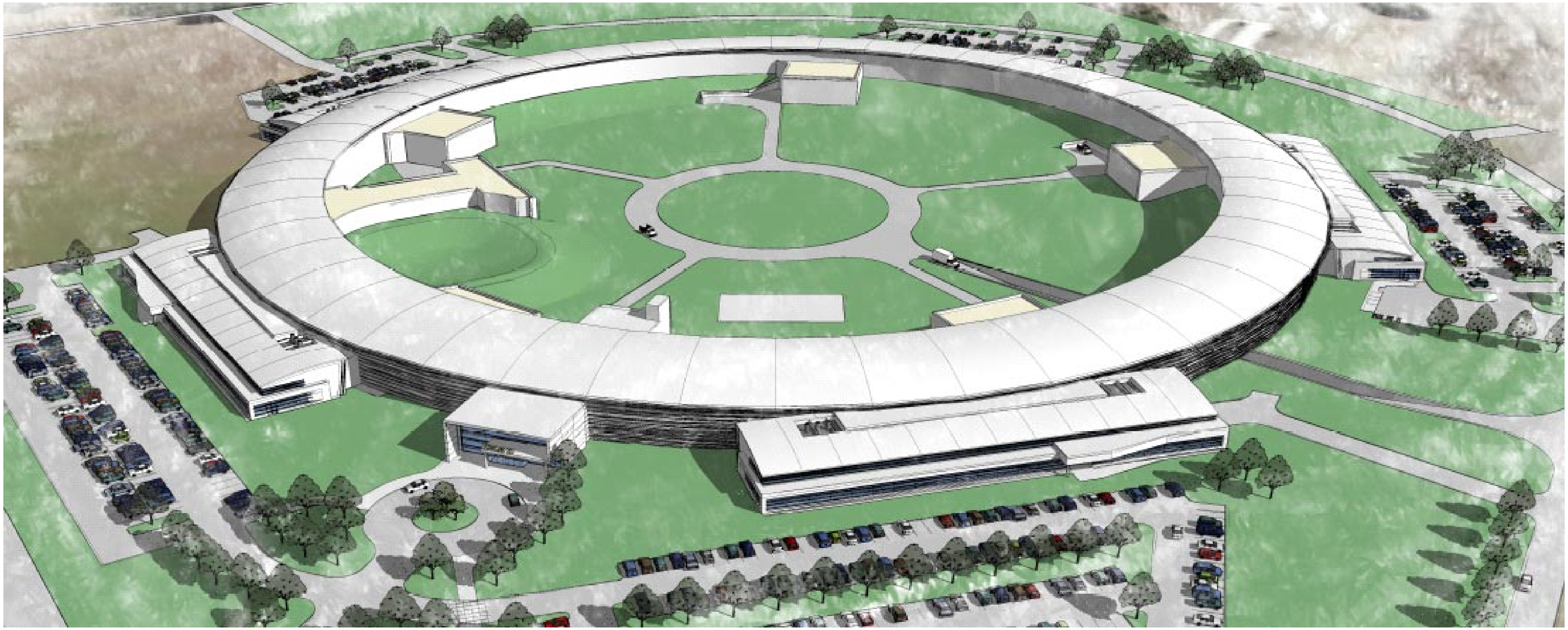
The Facility



Acknowledgements

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What's Known

- Dedicated third generation light sources: ~20 years of optimizations.
- The horizontal emittance (isomagnetic lattice) is given by

$$\varepsilon_x\ [\mathrm{nm\cdot rad}] = 7.84\times 10^3 \cdot \frac{(E\ [\mathrm{GeV}])^2 F}{J_x N_b^3}$$

N_b is the number of dipoles, $0 < J_x < 3$, $F \geq 1$. No dipole gradients => $J_x \approx 1$.

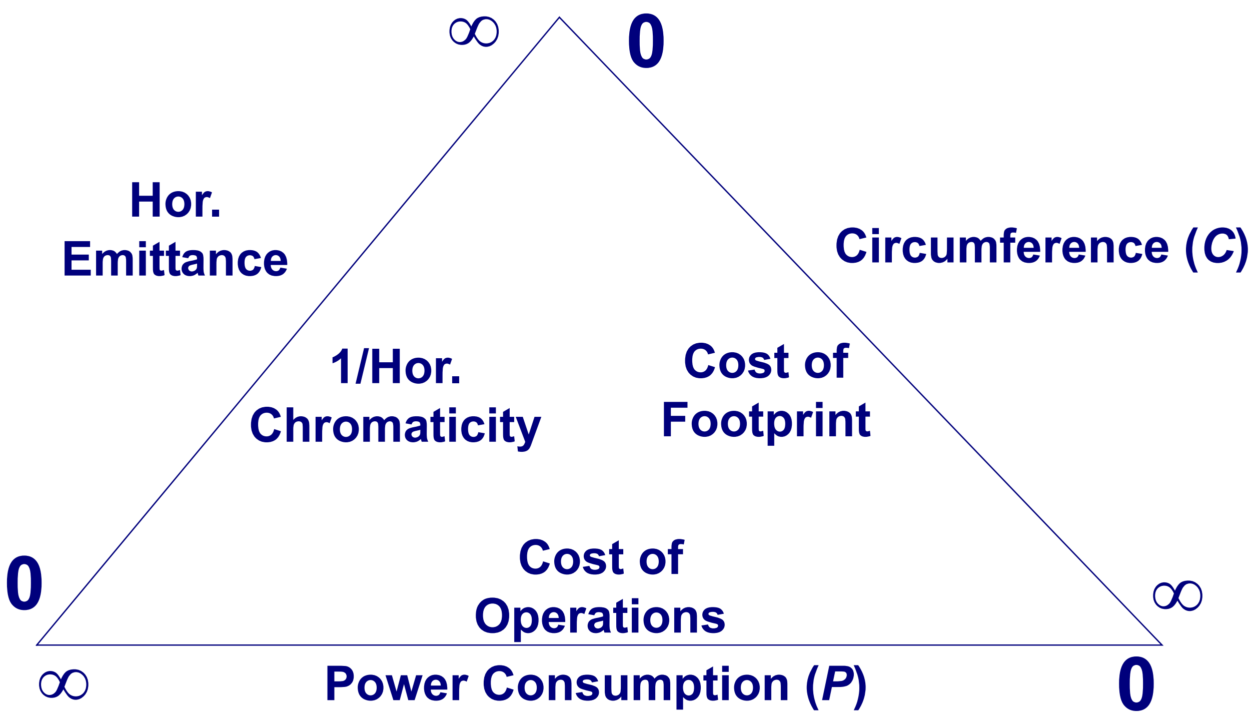
- Generalized Chasman-Green Lattices: DBA, TBA, QBA, 7-BA [1].
- Effective emittance => chromatic cells.
- Increasing N_b reduces ε_x but also reduces peak dispersion, which makes the chromatic correction less effective => "chromaticity wall" [2].
- Damping wigglers (DWs): damping rings and conversion of HEP accelerators [3,4].
- Mini-Gap Undulators (MGUs), Three-Pole-Wigglers (TPWs) inside DBA [5].

What's New

- Use of damping wigglers to reduce horizontal emittance and as high flux X-ray sources => achromatic cells and weak dipoles.
- Medium energy ring (3 GeV) with ~30 DBA cells.
- Vertical orbit stability requirements.
- Generalized higher order achromat.

Global Optimization

1. Horizontal emittance (natural): damping $\leftrightarrow$ diffusion (fundamental limit is IBS).
2. Optimize (for Insertion Devices (IDs)) [6]:



$$\varepsilon_x \sim \frac{1}{R^2 \cdot P}$$

R bend radius

Challenges

Non-linear dynamics:

- Medium energy: control of Touschek life time and momentum aperture.
- 30 DBA cells: control of tune footprint.
- Control of impact of DWs and IDs: include leading order nonlinear effects from DWs in Dynamic Aperture (DA) optimizations.
- Optics requirements for IDs and top-up injection: introduce alternating straights with high- and low horizontal beta function <-> reduced symmetry (30 -> 15).
- DBA: momentum dependence of optics functions => number of chromatic sextupole families.

Technical

- Weak dipoles: introduce TPWs (adjacent to the dipoles) => control of peak beta functions and horizontal dispersion.
- Vertical orbit stability: sub micron => pushing the state-of-the-arts [7,8].

Lattice Parameters

Energy	3 GeV
Circumference	791.5 m
Beam Current (I_b)	500 mA
Bending Radius (R)	25.0 m
Dipole Energy Loss (U_0)	286.5 keV
Emittance (ε_x, ε_y): bare/w. 8 DWs	(2.1, 0.01)/(0.6, 0.01) nm·rad
Momentum compaction	0.00037
RMS Energy Spread: bare/w. 8 DWs	0.05/0.1%
Working point (ν_x, ν_y)	(32.4, 16.3)
Chromaticity (ξ_x, ξ_y)	(-100, -42)
Peak Dispersion ($\hat{\eta}_x$)	0.45 m
Beta Function (β_x, β_y): long/short straight	(18, 3)/(3, 3) m

Intrabeam Scattering (IBS)

Equilibrium

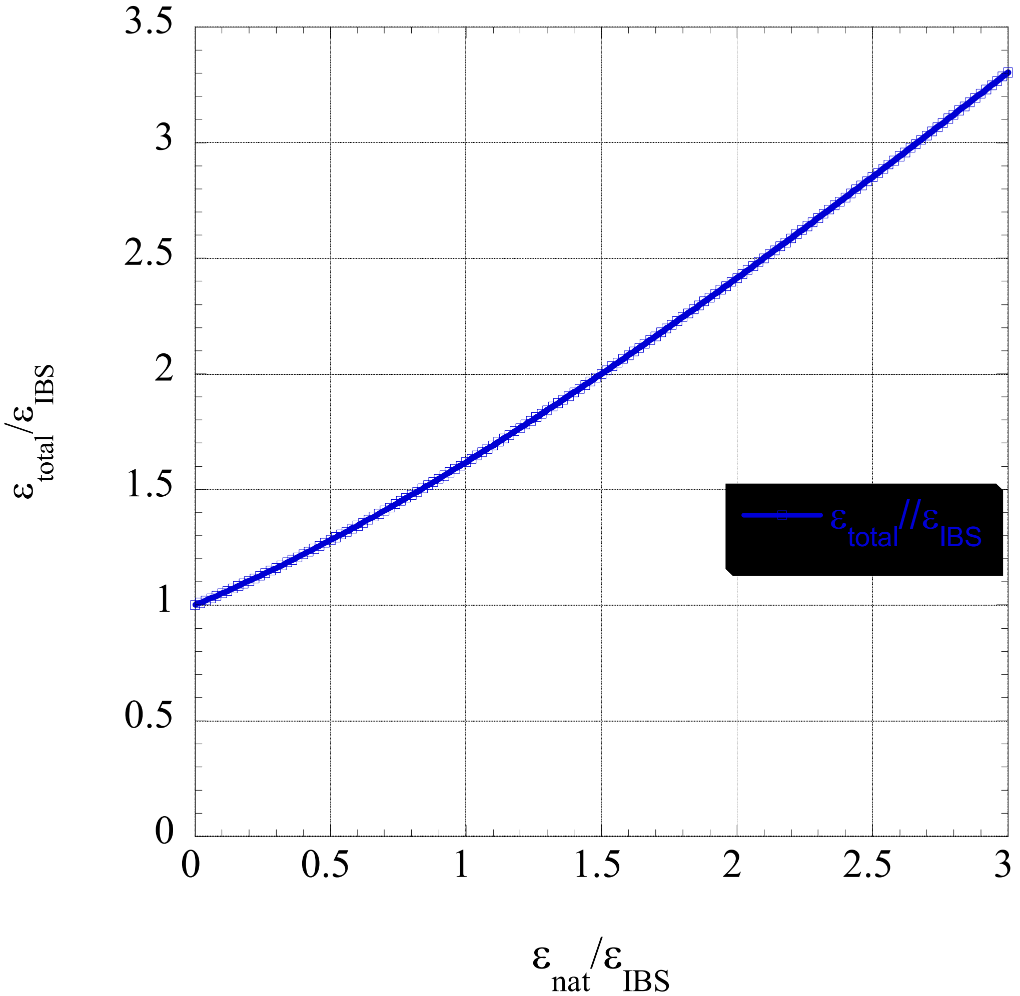
$$\varepsilon_x = \varepsilon_x^{\mathrm{SR}} + \varepsilon_x^{\mathrm{IBS}} = \tau_x(E^{\mathrm{SR}})\langle \mathcal{H} \cdot (D_\delta^{\mathrm{SR}}(R) + D_\delta^{\mathrm{IBS}})\rangle,$$

$$\sigma_\delta^2 = \tau_\delta(E_{\mathrm{SR}})(D_\delta^{\mathrm{SR}}(R) + D_\delta^{\mathrm{IBS}})$$

where

$$\delta \equiv \frac{E - E_0}{E_0}, \qquad \mathcal{H} \equiv \tilde{\eta}^{\mathrm{T}}\tilde{\eta}, \qquad \bar{\eta} \equiv \begin{bmatrix} \eta_x \\ \eta'_x \end{bmatrix}, \qquad \tilde{\eta} \equiv A^{-1}\bar{\eta}, \qquad A^{-1} = \begin{bmatrix} 1/\sqrt{\beta_x} & 0 \\ \alpha_x/\sqrt{\beta_x} & \sqrt{\beta_x} \end{bmatrix}$$

IBS Trade-Off



Touschek Lifetime

Cross section (Møller scattering) × phase space density [9]

$$\frac{1}{\tau_{1/2}} = \frac{r_e^2 c_0 N_e}{8\pi\gamma^3\sigma_s}\frac{1}{C}\oint_C \frac{F\left[\left(\frac{\hat{\delta}(s)}{\gamma\sigma_{x'}(s)}\right)^2\right]}{\sigma_x(s)\sigma_z(s)\sigma_{x'}(s)\hat{\delta}(s)}ds$$

where

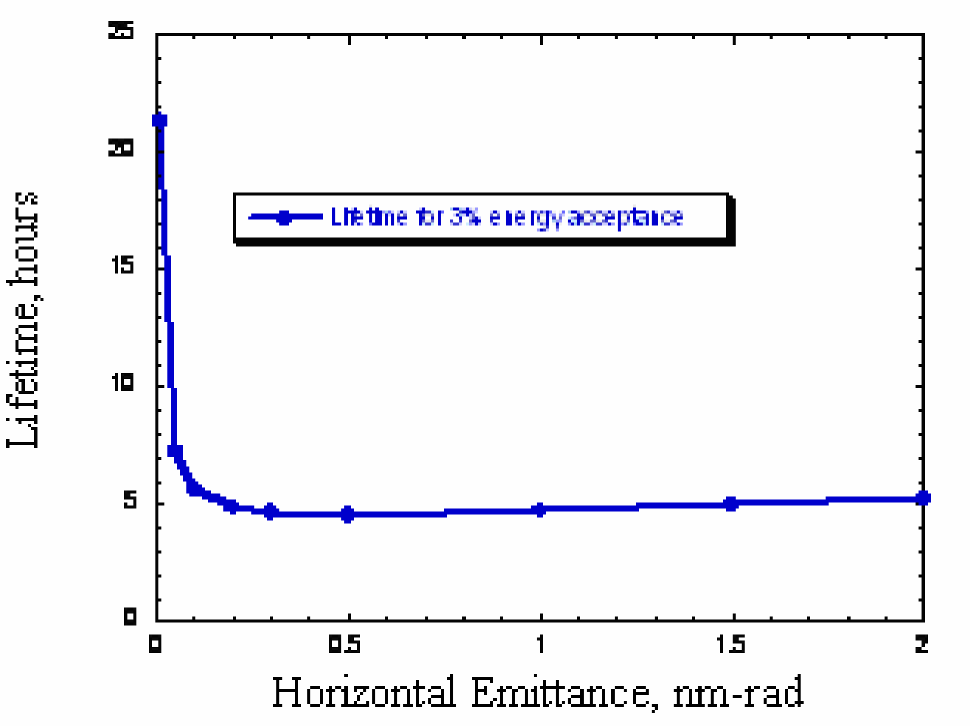
$$F(x) = \frac{1}{2}\int_0^1 \left[\frac{2}{u} - \ln\left(\frac{1}{u}\right) - 2\right]e^{-x/u}du$$

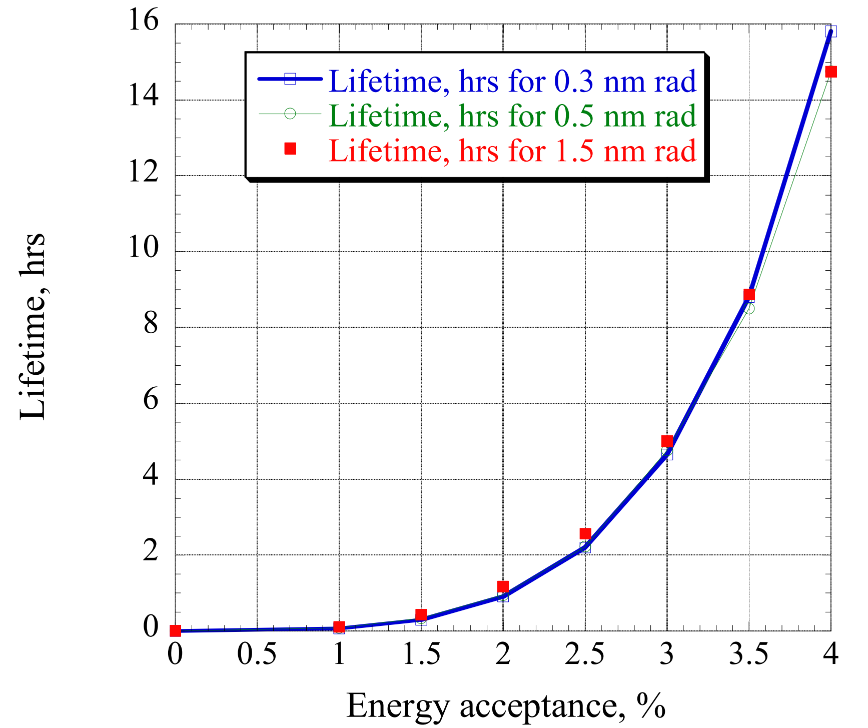
r_e classical electron radius, N_e no of electrons/bunch, σ_s rms bunch length,

C circumference, $\sigma_x(s)$, $\sigma_z(s)$ horizontal- and vertical rms beam size,

$\sigma_{x'}(s)$ horizontal rms beam divergence, $\hat{\delta}(s)$ momentum acceptance.

Touschek Life Time Trade-Offs



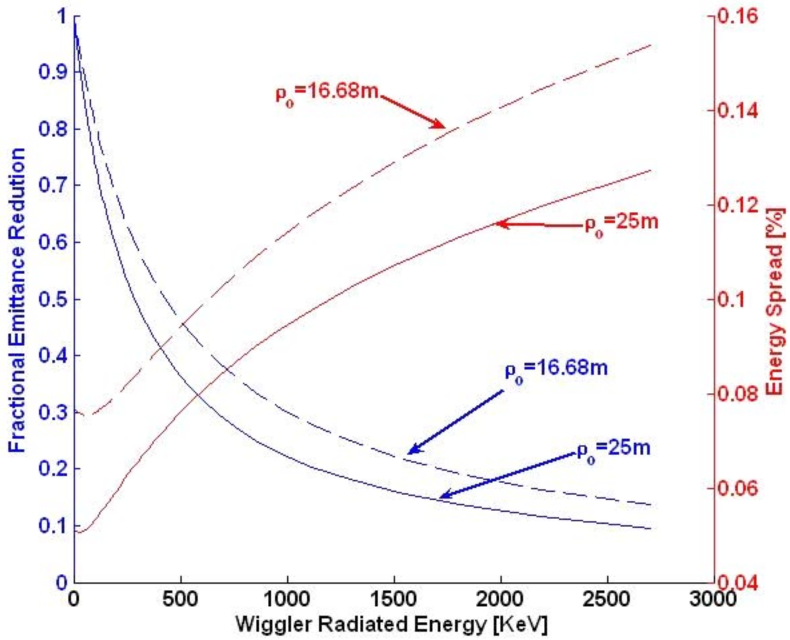


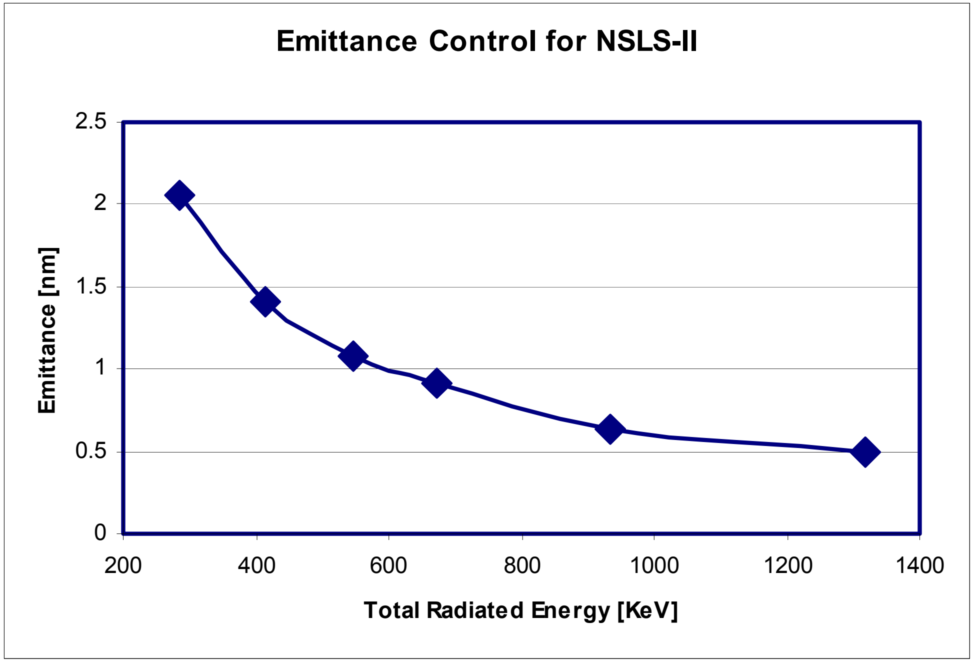
Damping Wigglers

The natural horizontal emittance scales with the radiated power

$$\frac{\varepsilon_w}{\varepsilon_0} \approx \frac{U_0}{U_0 + U_w}, \qquad \frac{\delta_w}{\delta_0} = \sqrt{\frac{1 + \frac{8}{3\pi}\frac{B_w}{B_0}\frac{U_w}{U_0}}{1 + \frac{U_w}{U_0}}}$$

Damping Wiggler Trade-Offs





Optics Design Guidelines

The traditional approach, i.e., to first design the linear optics and then attempt to control the DA is inadequate for high performance lattices e.g. [10-11]. For a streamlined approach, the nonlinear effects must be considered from the start [12]. In particular, the following guidelines have been provided (the numbers have evolved with time) [13]:

- horizontal chromaticity per cell, $\xi_x \leq 3.5$,
- horizontal peak dispersion $0.3\ \mathrm{m} \leq \eta_x \leq 0.5$,

and

	Hor and Ver Dynamic Acceptance [mm·mrad]	Hor DA [mm]	δ [%]
Bare Lattice (2.5 D.O.F.)	~25	± 20	± 2.5
"Real" Lattice (3 D.O.F.)	~20	± 15	± 2.5

Optics Constraints

The DBAs have ~6 constraints:

- **linear achromat ($\eta_x = \eta'_x = 0$ at the entrance),**
- **small emittance ($\min(\mathcal{H}) \Rightarrow (\alpha_x, \beta_x)$ fixed at the entrance),**
- **and symmetric ($\alpha_{x,y} = 0$ at the center).**

Similarly, the long- and short matching sections have 10 constraints:

- **symmetric ($\alpha_{x,y} = 0$ at the center),**
- **$\beta_{x,y}$ at the center,**
- **and the cell tune $\nu_{x,y}^{\text{cell}}$.**

On the other hand, the lattice has only 8 quadrupole families.

Generalized Higher Order Achromat

- Introduce two chromatic sextupole families and choose the cell tune for N super cells $\mathcal{M}$ such that

$$\mathcal{M} = \mathcal{M}_1 \mathcal{M}_2 \ldots \mathcal{M}_N, \qquad \mathcal{M}_k = \mathcal{A}^{-1} e^{:h:} \mathcal{R} \mathcal{A}, \qquad \mathcal{R}^N = \begin{bmatrix} I & 0 \\ 0 & \pm I \end{bmatrix}$$

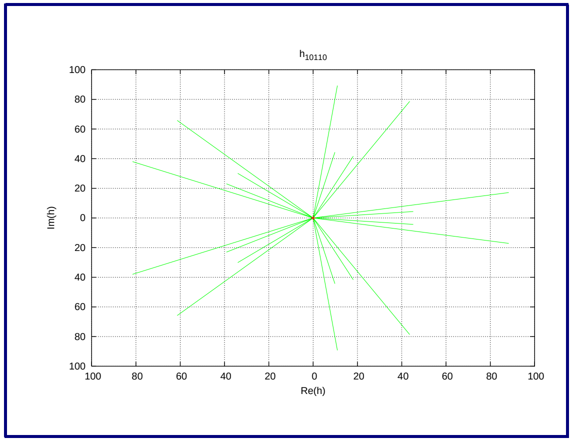
In particular, so that resonances up to 4th order

$$n_x \nu_x + n_y \nu_y = n, \qquad |n_x| + |n_y| \le 4$$

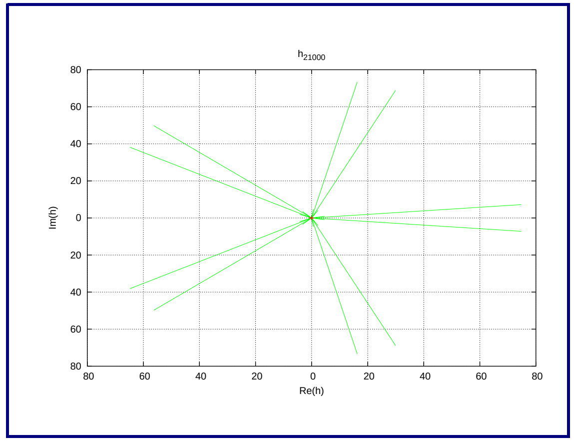
are cancelled (by symmetry):

- Control the residual amplitude dependent tune shift and free up the choice of working point by adding geometric sextupoles [SLS].
- Control the residual nonlinear chromaticity by adding chromatic multipole families as needed.
- Optimize dynamic- and momentum aperture (from tracking) by joint minimization of the driving terms and variation of the cell tune.

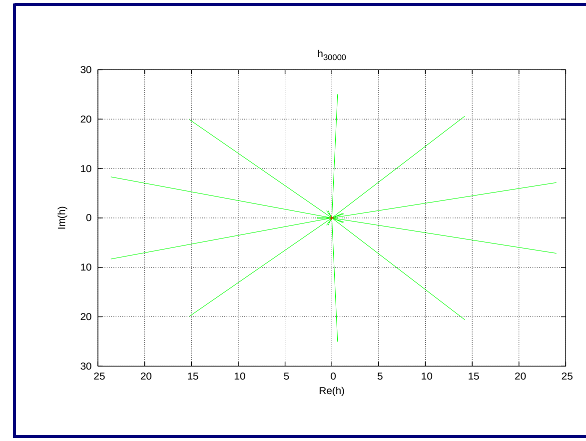
A 5-Cell Second Order Achromat (2 chrom families)



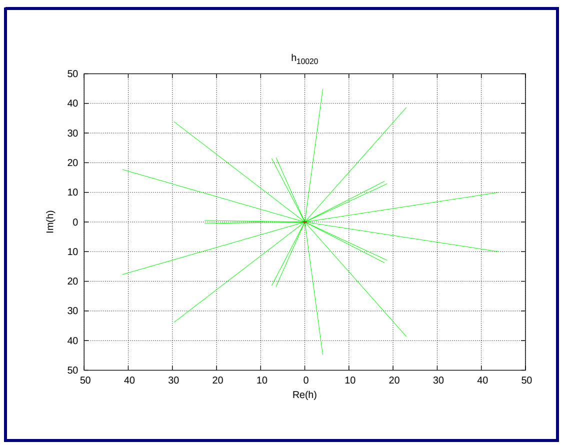
h_{10110}



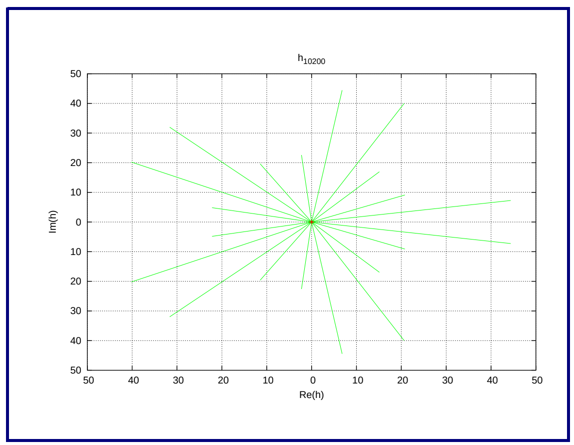
h_{21000}



h_{30000}



h_{10020}



h_{10200}

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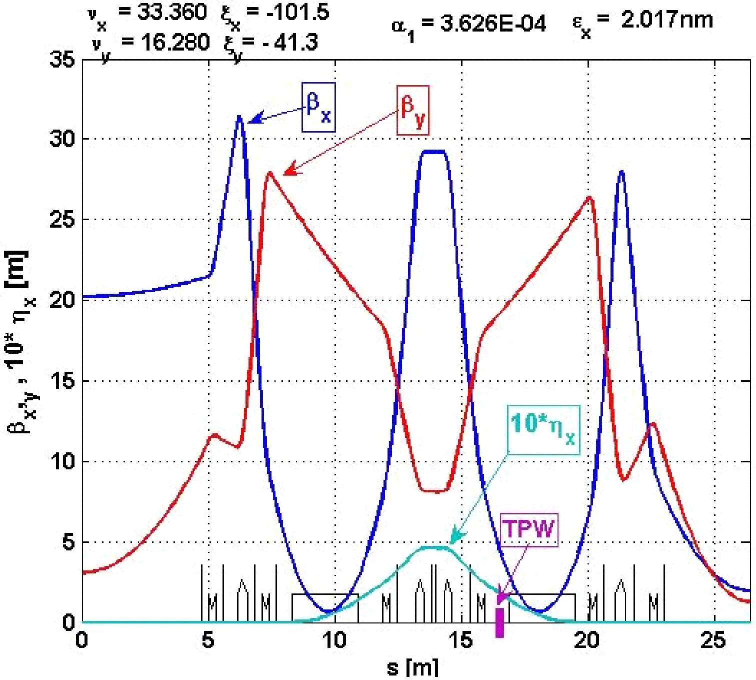
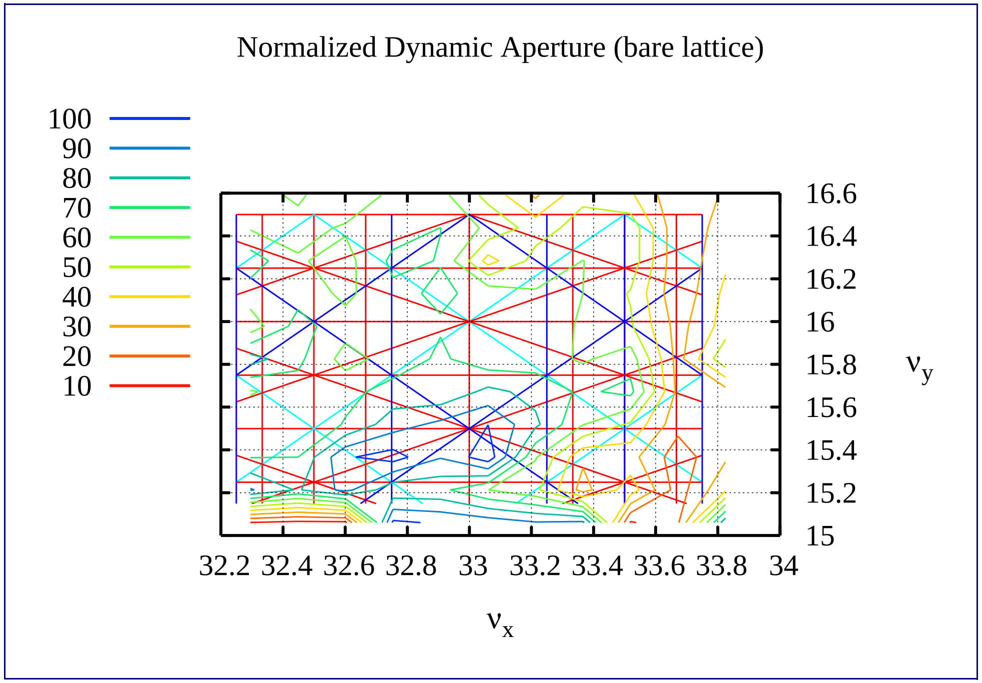
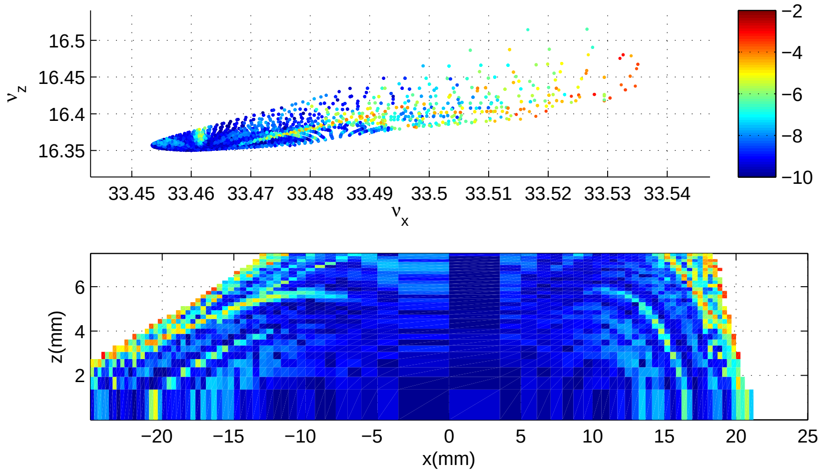
Linear Optics and Tune Scan

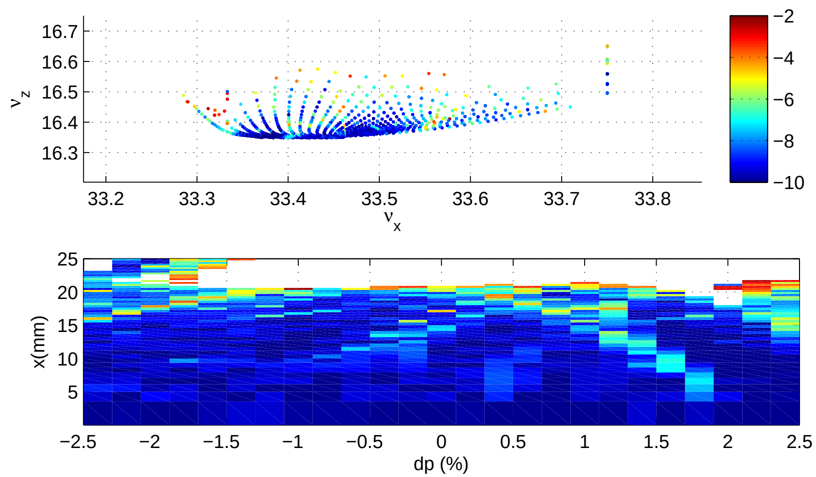


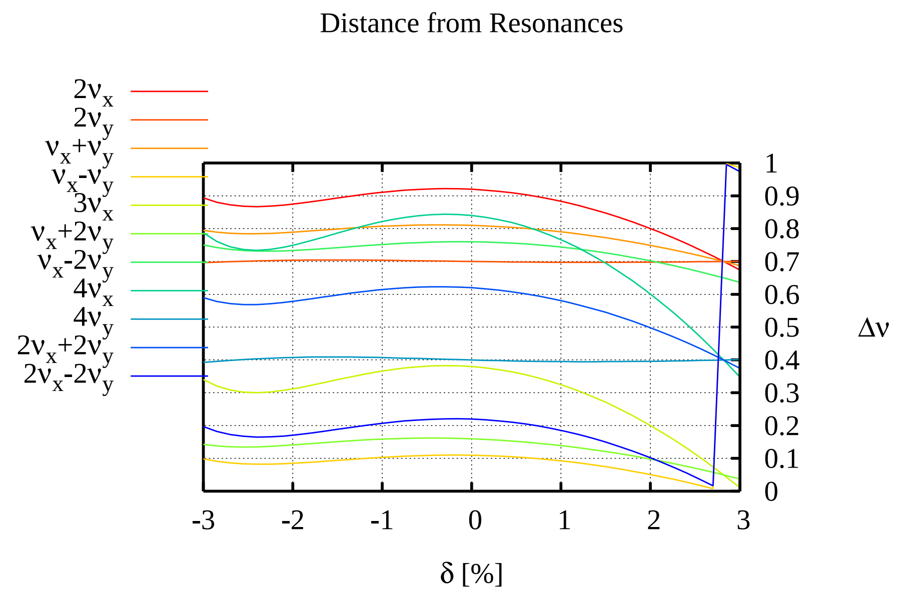


- An 11×11 grid of working points is obtained that meets optics requirements.
- For each working point, the driving terms are minimized and a weighted average of the dynamic- and momentum aperture ($DA/\sqrt{\beta_x \beta_y}$) is computed by tracking.

Frequency Map and Resonance Avoidance





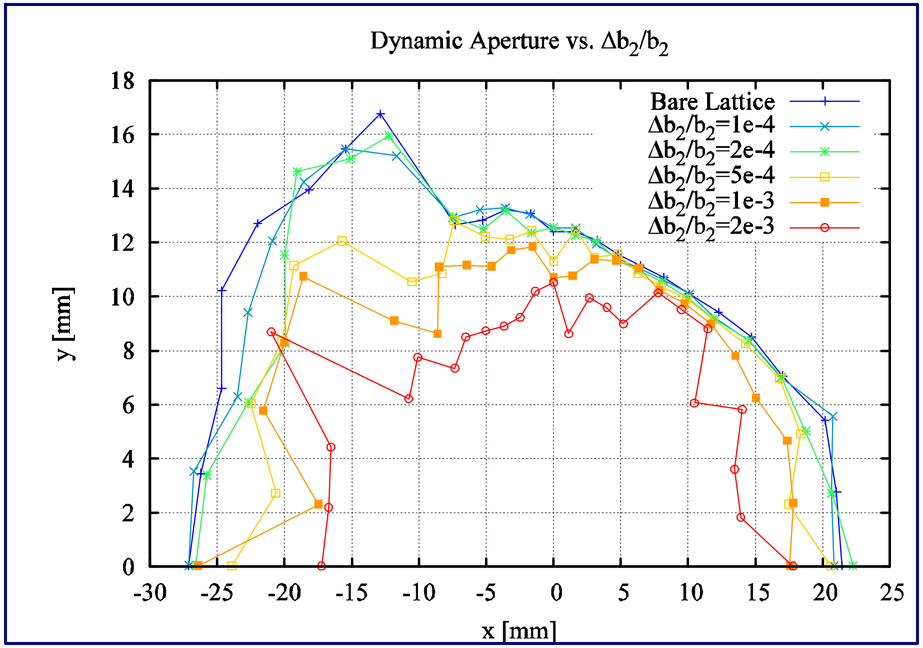


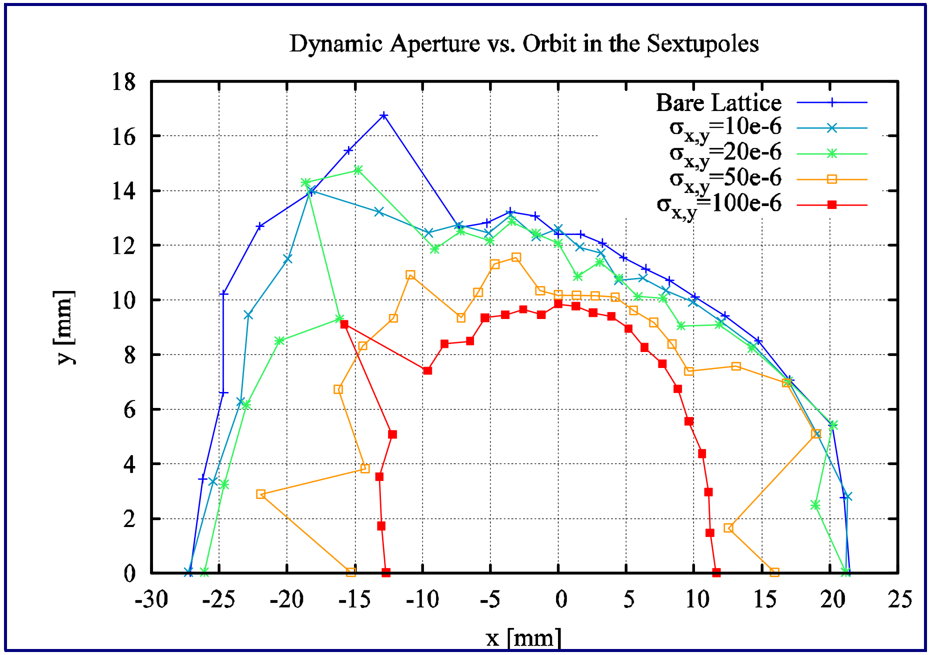
without DWs.

Optics Tolerances

Estimated tolerances

Parameter	$\Delta b_2 / b_2$	$(\Delta\beta_{x,y}/\beta_{x,y})_{\mathrm{rms}}$	$(\Delta\nu_{x,y})_{\mathrm{rms}}$	$(\Delta x_{\mathrm{cod}}, \Delta y_{\mathrm{cod}})_{\mathrm{rms}}$
Tolerance	$\sim 5\times10^{-4}$	~(2%, 3%)	~(0.003, 0.002)	~(50, 50) μm





Impact of Insertion Devices

The averaged Hamiltonian is (planar)

$$\langle H \rangle_{\lambda_w} = \frac{p_x^2 + p_y^2}{2(1+\delta)} + \left(\frac{B_w}{B\rho}\right)^2 \frac{\cosh^2(k_y y)}{4k_z^2(1+\delta)} - \delta + O(p_{x,y})^4, \qquad k_y = k_z = \frac{2\pi}{\lambda_w}$$

To leading order one obtains

$$\Delta\nu_y = \frac{1}{8\pi}\left(\frac{B_w}{B\rho}\right)^2 \langle \beta_y \rangle L_w, \qquad \frac{\partial \nu_y}{\partial J_y} = \frac{\pi}{4}\left(\frac{B_w}{B\rho}\right)^2 \frac{\langle \beta_y^2 \rangle L_w}{\lambda_w^2}$$

Since $\beta(s) = \beta_0[1 + (s/\beta_0)^2]$, optimum beta for min impact is:

stay clear => $\beta_0 = L/2$, linear optics => $\beta_0 = L/2\sqrt[4]{3}$,

nonlinear dynamics => $\beta_0 = L/2\sqrt[4]{5}$.

Conclusions

- The "chromaticity wall" has been avoided by using damping wigglers. Furthermore, these turned out to be useful high-flux X-Ray sources.
- The emittance can be reduced as the facility evolves.
- The nonlinear effects are taken into account for the optics design. In particular, by providing guidelines for chromaticity per cell and peak dispersion.
- The dynamic- and momentum aperture are improved by implementing a generalized higher order achromat. It is optimized by a joint optimization of the driving terms and working point.
- The ultimate-low emittance limit can be reached by this approach. It is a matter of power consumption and circumference.

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Back-up Slides

Damping Wigglers

The natural horizontal emittance scales with the radiated power

$$\frac{\varepsilon_w}{\varepsilon_0} = \frac{1+f}{1+\frac{U_w}{U_0}} \approx \frac{U_0}{U_0+U_w}, \qquad \frac{\delta_w}{\delta_0} = \sqrt{\frac{1+\frac{8}{3\pi}\frac{B_w}{B_0}\frac{U_w}{U_0}}{1+\frac{U_w}{U_0}}}, \qquad \frac{U_w}{U_0} = \frac{L_w}{4\pi\rho_0}\left(\frac{B_w}{B_0}\right)^2$$

where

$$f \cong \frac{2C_q\gamma^2}{3\pi^2\varepsilon_0}\frac{L_w\rho_0}{\rho_w^3}\left[\frac{1}{5}\left(\frac{K_w}{\gamma}\right)^2\langle\beta_x\rangle + \frac{\eta_{x0}^2}{\beta_{x0}} + \beta_{x0}\eta'_{x0}{}^2\right], \qquad \frac{K_w}{\gamma} = \frac{\lambda_w}{2\pi\rho_w}, \qquad C_q = 3.8\times10^{-13},$$

$$\beta_x(s) = \beta_{x0}\left[1+\left(\frac{s}{\beta_{x0}}\right)^2\right], \qquad \eta_x(s) = \frac{1}{\rho_w}\left(\frac{\lambda_w}{2\pi}\right)^2\left(1-\cos\left(\frac{2\pi s}{\lambda_w}\right)\right) + \eta_{x0} + \eta'_{x0}s$$

Control of Optics

Control of linear optics perturbation from IDs:

- **optics response matrix**

$$\left[\frac{\Delta\beta_i}{\beta_i}, \ldots, \Delta\mu_i, \ldots, \Delta\nu_x, \Delta\nu_y\right]^{\mathrm{T}} = \boldsymbol{T}(\beta, \mu)[\Delta \boldsymbol{b}_{2,1}, \ldots, \Delta \boldsymbol{b}_{2,N_{\mathrm{Q}}}]^{\mathrm{T}}$$

Control of vertical beam size:

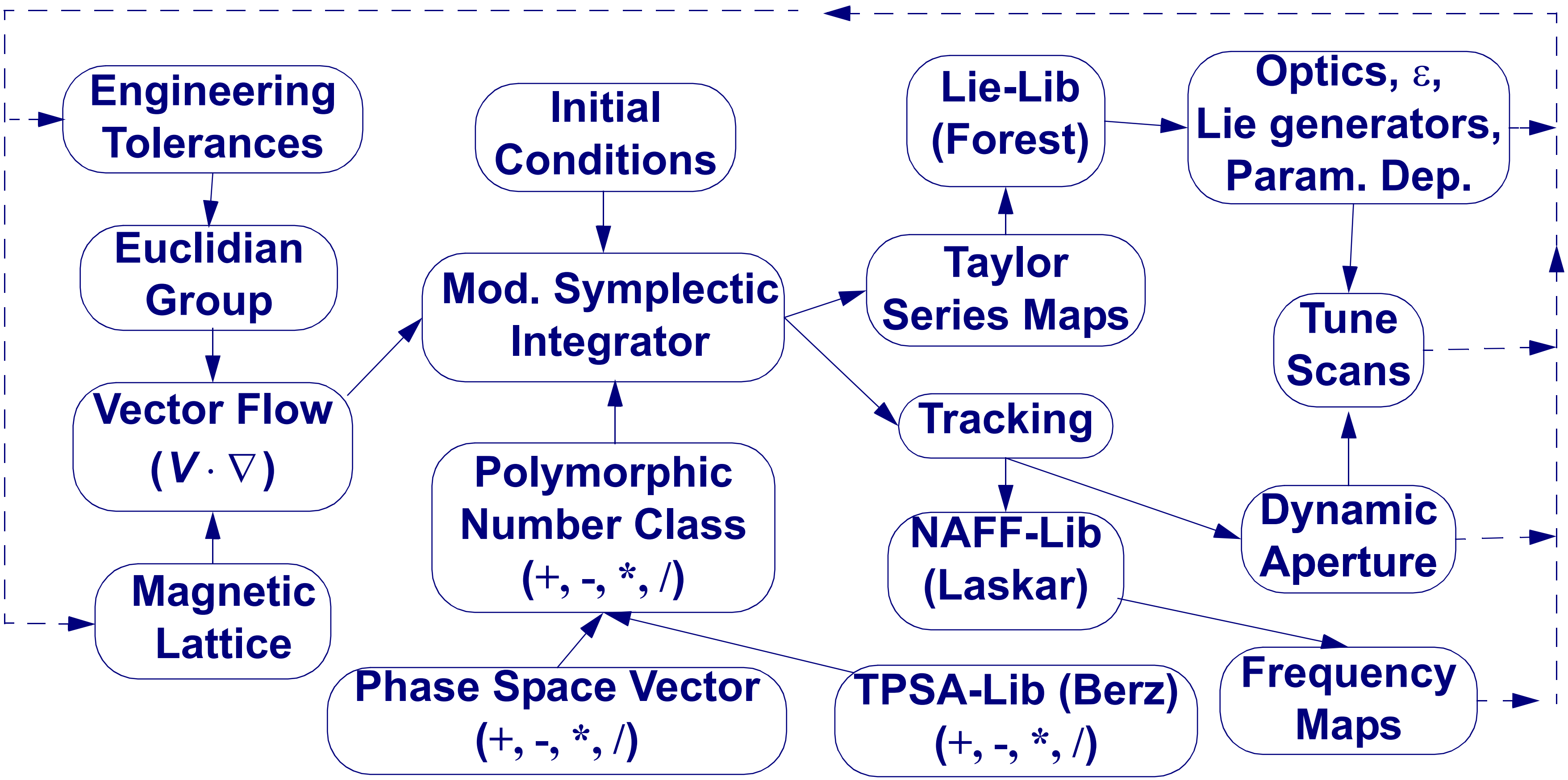
- **beam response matrix**

$$\left[\frac{\partial \boldsymbol{x}_i}{\partial \boldsymbol{p}_{y,k}}, \ldots, \frac{\partial \boldsymbol{y}_i}{\partial \boldsymbol{p}_{x,k}}, \ldots, \Delta\eta_{y,i}, \ldots\right]^{\mathrm{T}} = \boldsymbol{U}(\beta, \mu)[\Delta \boldsymbol{a}_{2,1}, \ldots, \Delta \boldsymbol{a}_{2,N_{\mathrm{SQ}}}]^{\mathrm{T}}$$

- **Include dispersion wave, if needed [14].**

Invert *T*, *U* by SVD, compute, and apply the corrections (i.e., like orbit correction).

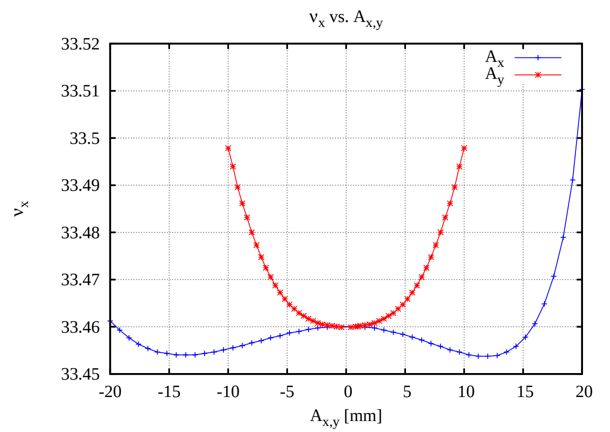
The Polymorphic Tracking Code (PTC)

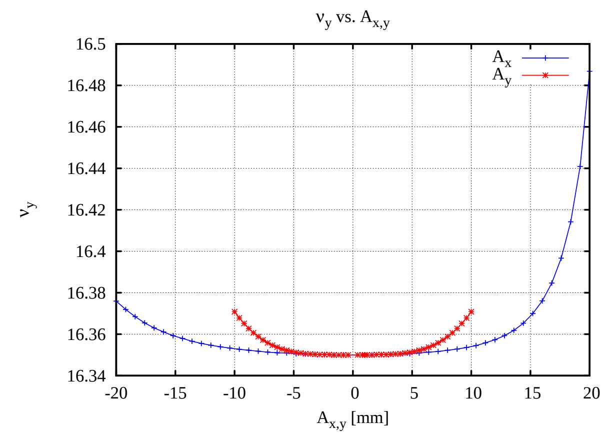


A 10-Cell Third Order Achromat

Cell	$\square_x$	$\square_y$	$\square_x$	$2\square_x$	$3\square_x$	$2\square_y$	$\square_x-2\square_y$	$\square_x+2\square_y$	$4\square_x$	$4\square_y$	$2\square_x-2\square_y$	$2\square_x+2\square_y$
1	2.200	1.050	2.20	4.40	6.60	2.10	0.10	4.30	8.80	4.20	2.30	6.50
2	4.400	2.100	4.40	8.80	13.20	4.20	0.20	8.60	17.60	8.40	4.60	13.00
3	6.600	3.150	6.60	13.20	19.80	6.30	0.30	12.90	26.40	12.60	6.90	19.50
4	8.800	4.200	8.80	17.60	26.40	8.40	0.40	17.20	35.20	16.80	9.20	26.00
5	11.000	5.250	11.00	22.00	33.00	10.50	0.50	21.50	44.00	21.00	11.50	32.50
6	13.200	6.300	13.20	26.40	39.60	12.60	0.60	25.80	52.80	25.20	13.80	39.00
7	15.400	7.350	15.40	30.80	46.20	14.70	0.70	30.10	61.60	29.40	16.10	45.50
8	17.600	8.400	17.60	35.20	52.80	16.80	0.80	34.40	70.40	33.60	18.40	52.00
9	19.800	9.450	19.80	39.60	59.40	18.90	0.90	38.70	79.20	37.80	20.70	58.50
10	22.000	10.500	22.00	44.00	66.00	21.00	1.00	43.00	88.00	42.00	23.00	65.00

Tune Footprint





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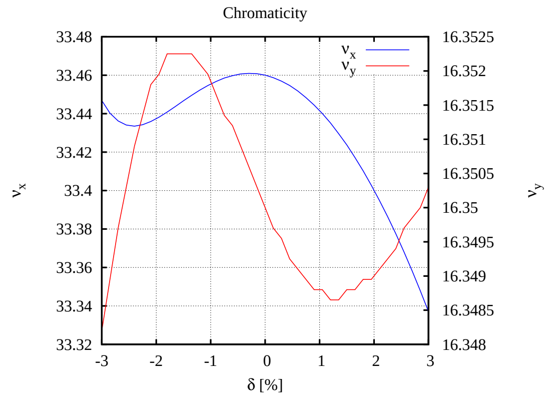

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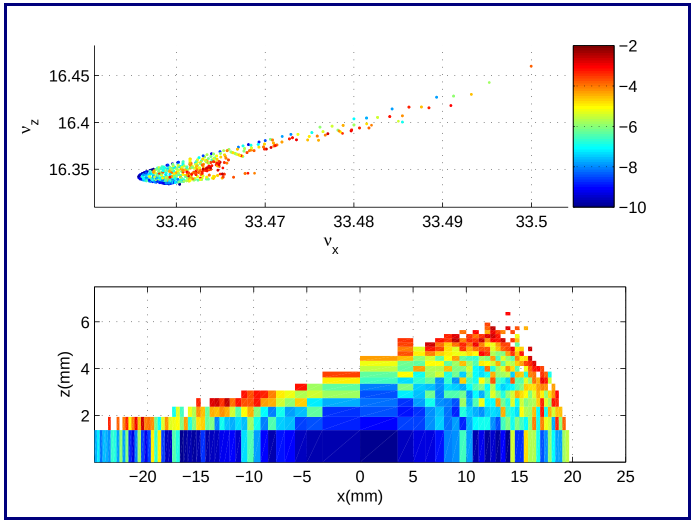
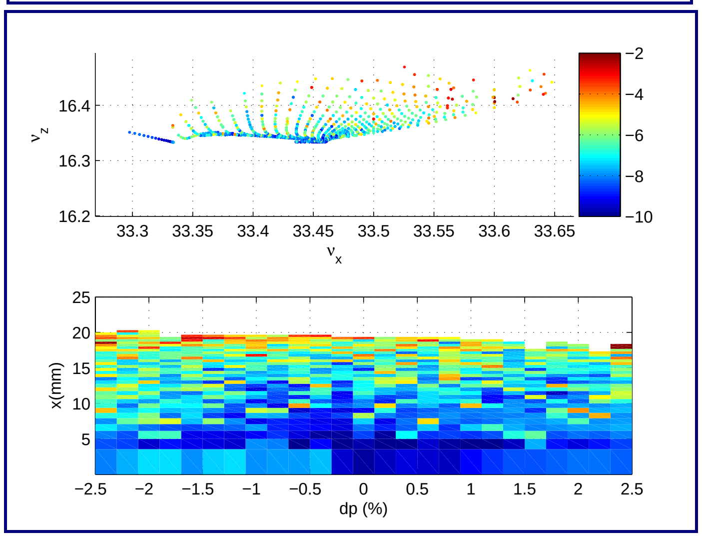
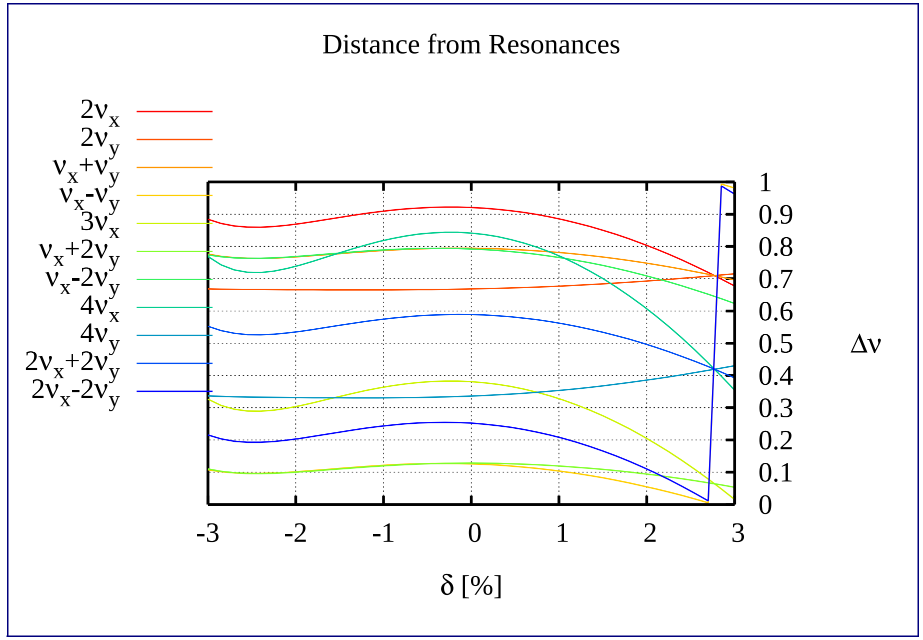
Frequency Map and Resonance Avoidance (w DWs)







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