超级陶粲装置
Super Tau-Charm Facility

The 6th International Workshop on Future Tau Charm Facilities
FTCF, 2024, Guangzhou

Progress on physics design of the STCF Collider ring

Ye Zou
On behalf of the STCF collider ring accelerator physics group
University of Science and Technology of China
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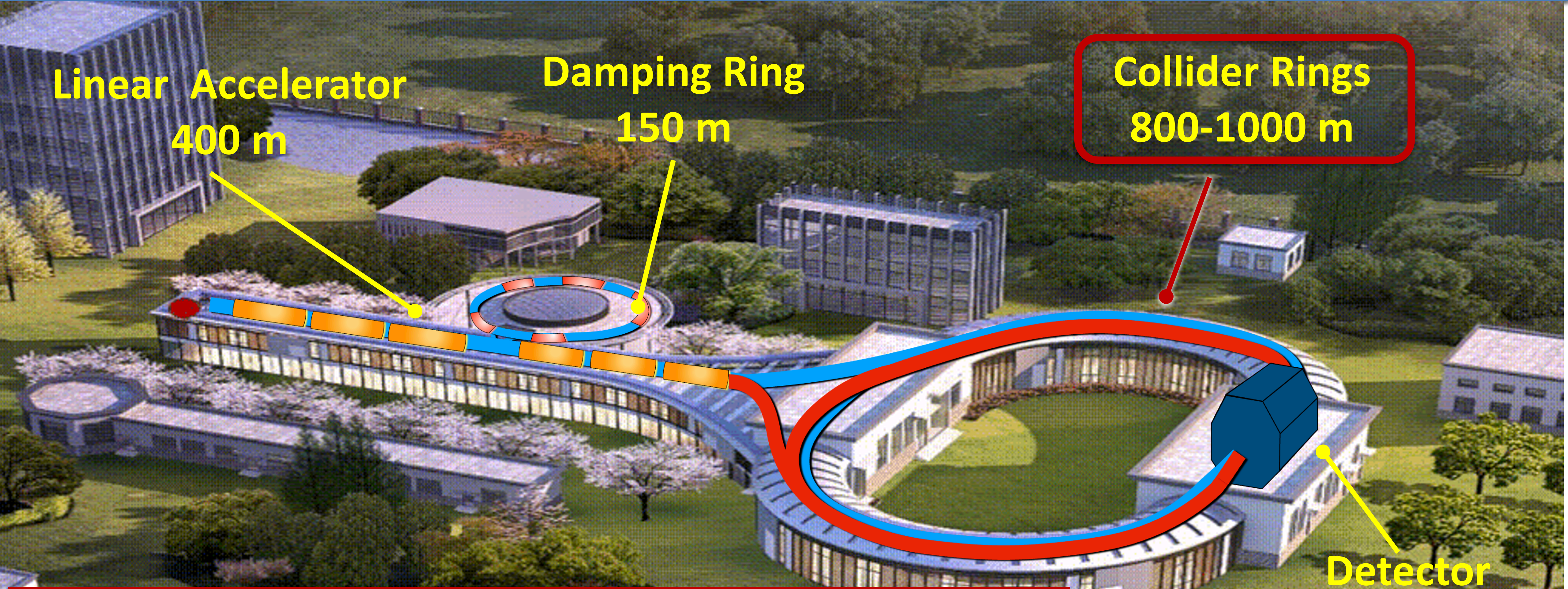
Outline

- ☐ Introduction of STCF collider ring
- ☐ Physics design of STCF collider ring
- ☐ Summary

Super Tau Charm Facility (STCF)



Design goals:

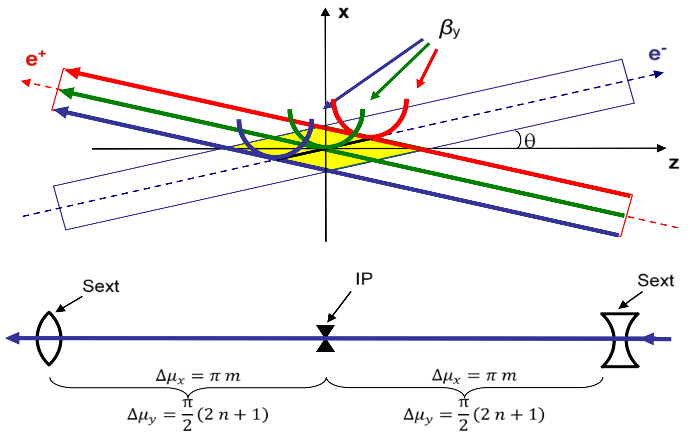
- E_{cm}= 2-7 GeV, $\mathcal{L} > 0.5\times10^{35}$ cm^{-2} s^{-1} @ 4 GeV
- Potential for upgrade to increase luminosity and realize polarized beam

Crab waist scheme at STCF

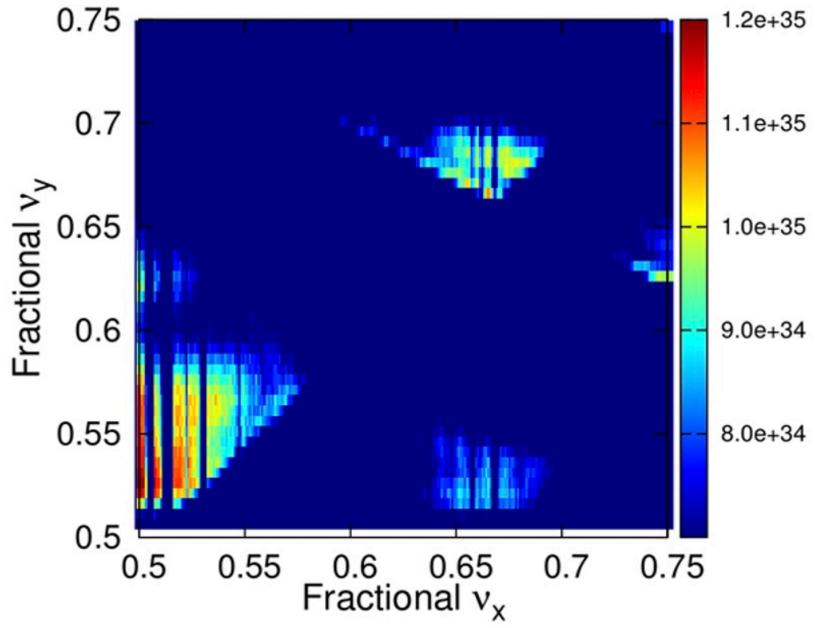
- STCF adopts crab waist scheme with crossing angle 2θ = 60 mrad
- Tune scan with beam-beam effect shows significant increase of luminosity with crab waist at STCF

$$L = \frac{\gamma n_b I_b}{2 e r_e \beta_y^*} \xi_y H$$

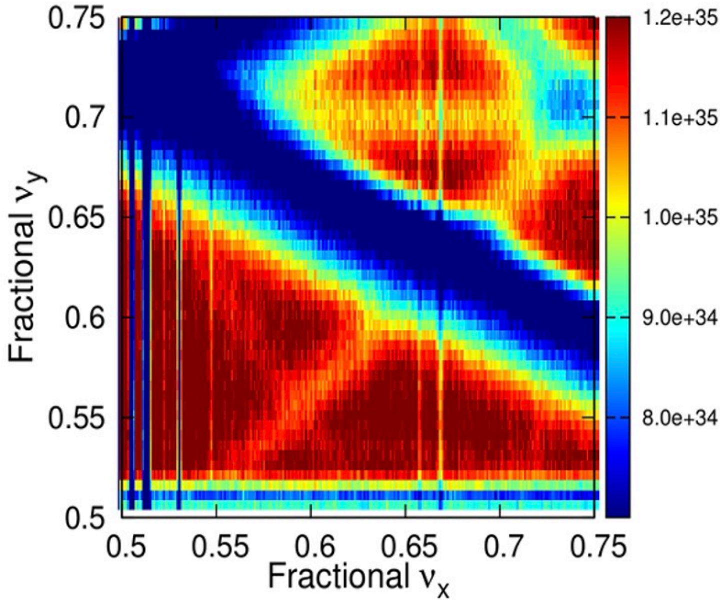
P. Raimondi, 2006



No crab waist



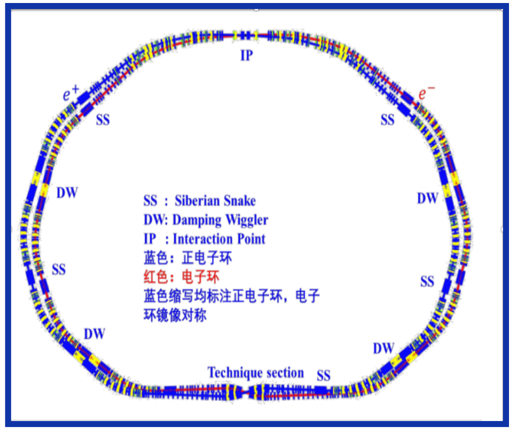
With crab waist



- Large Piwinski angle: $\varphi = \frac{\sigma_z}{\sigma_x} \tan\theta \gg 1$
- Small $\beta_y^* \approx \frac{\sigma_x}{\theta} \ll \sigma_z$ (hour-glass)

Lattice evolution of STCF

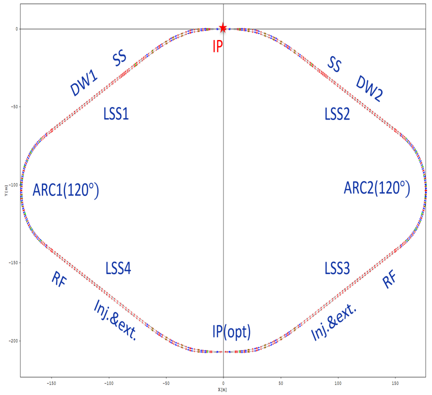
Main lattice scheme before early 2024



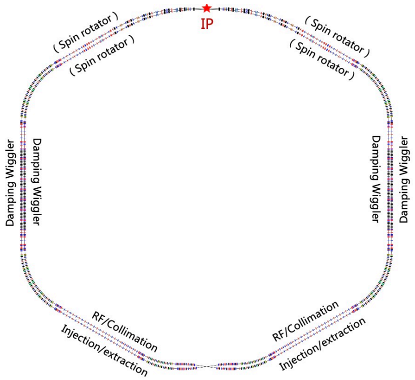
- Short circumference: ~650 m
- Not enough space for IR, ARC and SS

IAC suggests circumference of 800~1000 m

V1, V2, 2024.05-2024.08

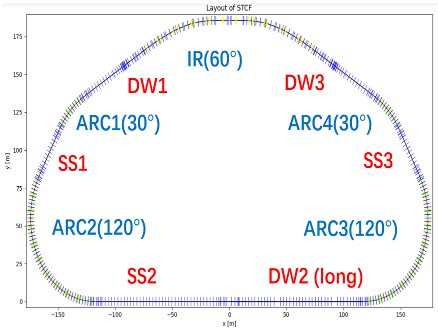


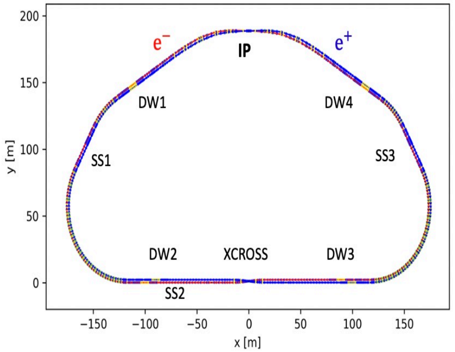
V3, V4, since 2024.09



Baseline scheme

- C: ~900 m
- Two-fold: second IP
- Spin rotator for polarized beam (upgrade)
- LSS for NC DW

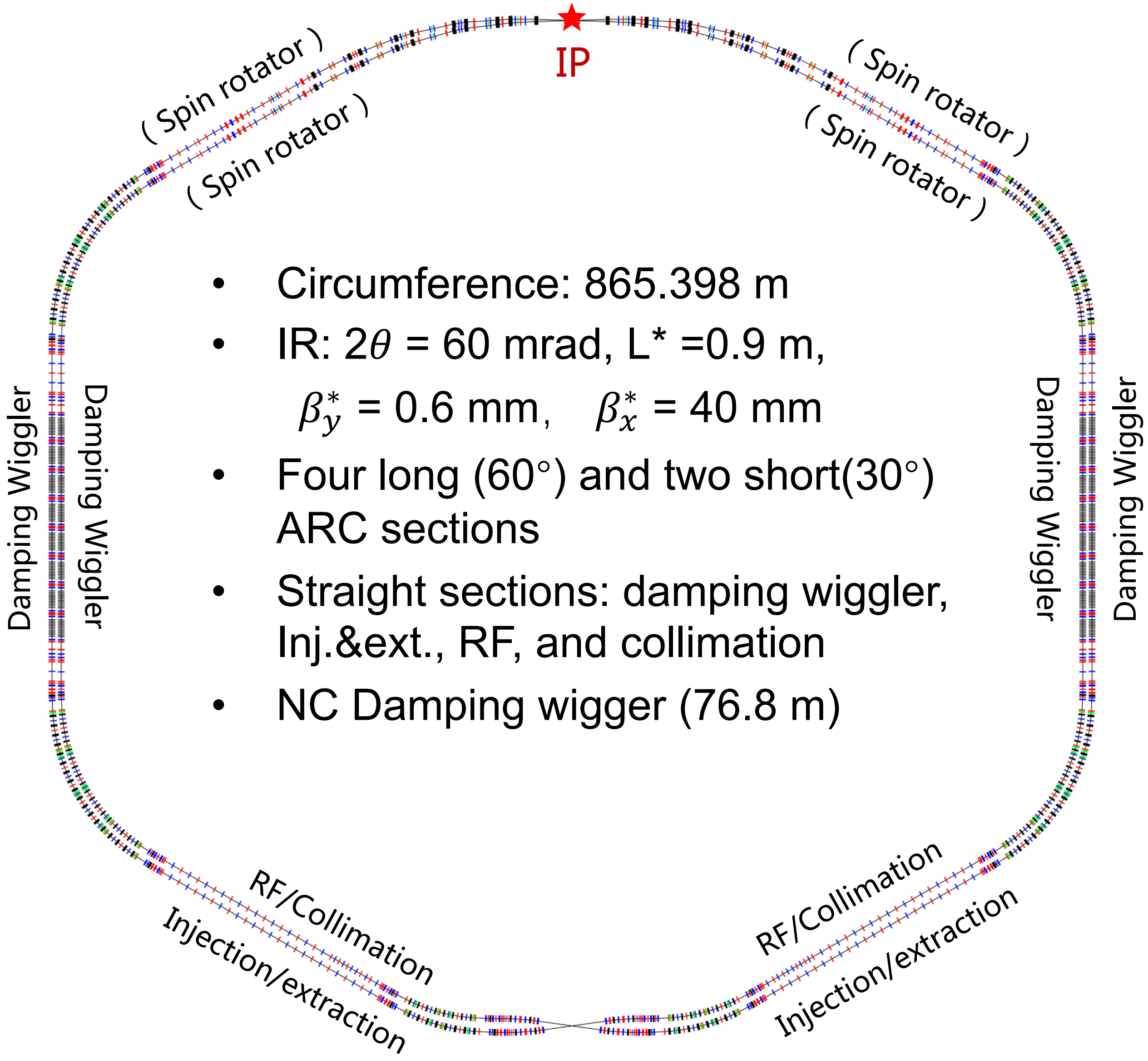




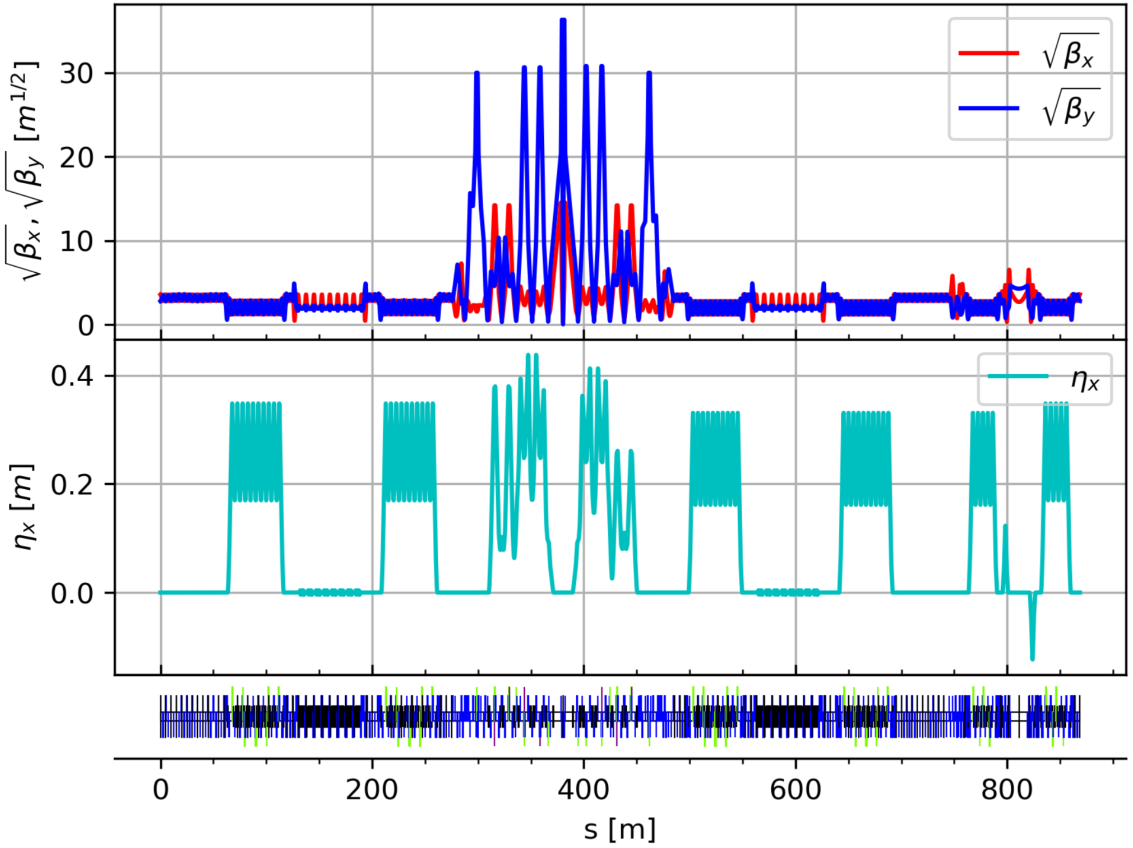
Alternative scheme

- C: ~900 m
- One-fold lattice
- Siberian Snake for polarized beam (upgrade)
- SC DW

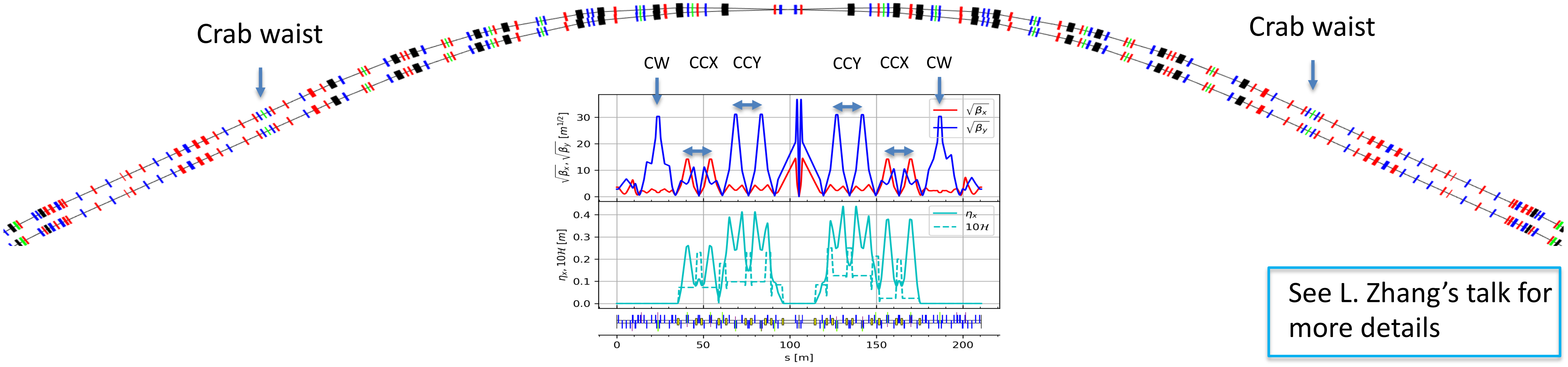
Lattice and layout of STCF



- Circumference: 865.398 m
- IR: 2θ = 60 mrad, L* =0.9 m,
  β_y^* = 0.6 mm, β_x^* = 40 mm
- Four long (60°) and two short(30°) ARC sections
- Straight sections: damping wiggler, Inj.&ext., RF, and collimation
- NC Damping wigger (76.8 m)



Interaction region



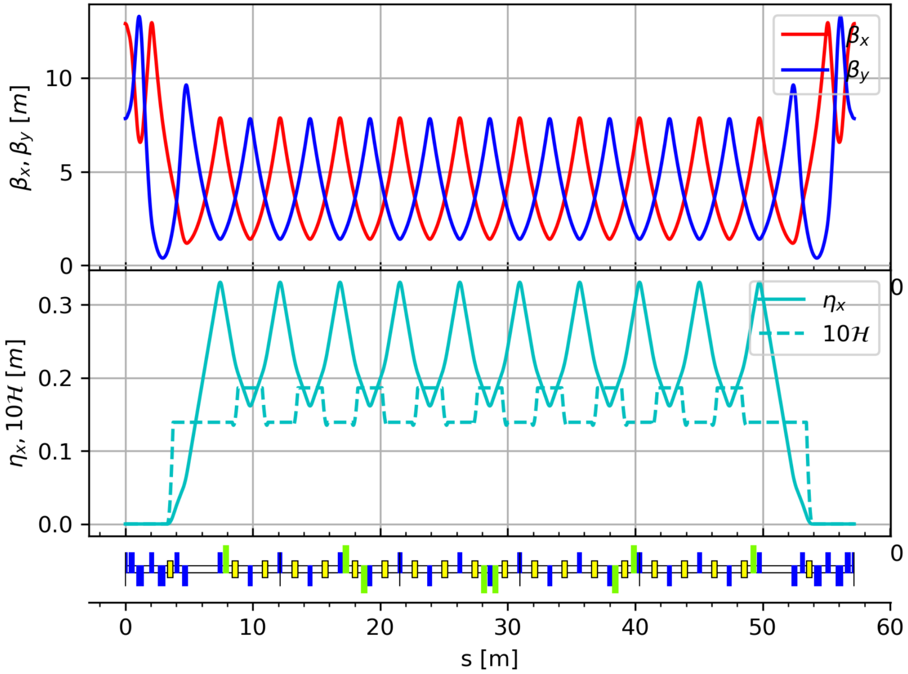
See L. Zhang's talk for more details

- Modular design：FFT、CCY、CCX、CS、MS
- FFT：large crossing angle（θ=60 mrad），Flat beam collision ，bunch size compression at IP（$\sigma_y = 135$ nm，$\sigma_x = 16$ μm ），β function at IP（$\beta_y^* = 0.6$ mm， $\beta_x^* = 40$ mm）
- Local chromaticity correction（CCY/CCX）: large β, large dispersion，appropriate phase advance
- Crab sextupole（CS）： appropriate phase advance and strength（$\nu_x = 12\pi$，$\nu_y = 11\pi$，k_2 =17.16 m^{-3} ）
- MADX and SAD for design and optimization

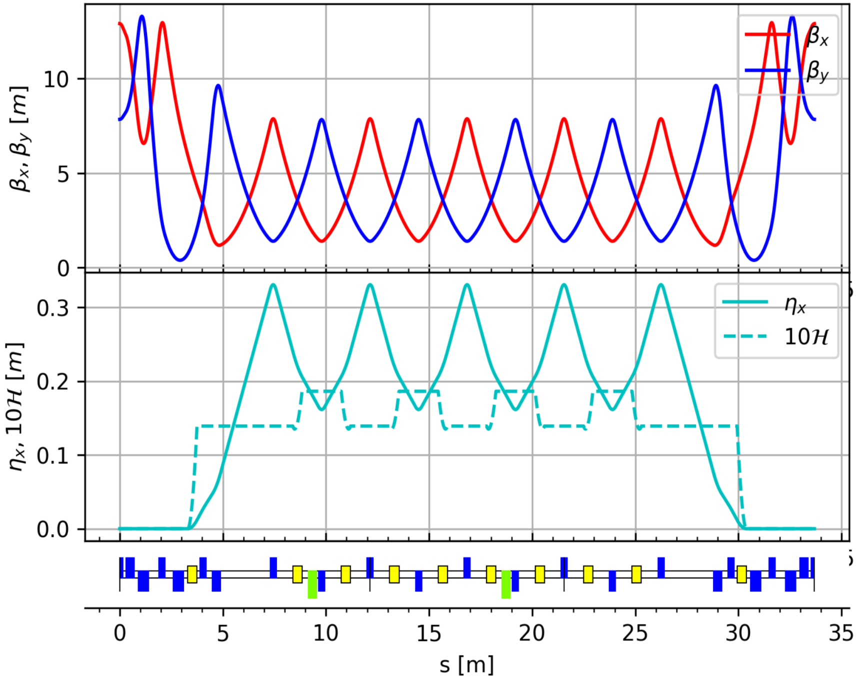
$$K2L = \pm \frac{1}{2\theta\beta_y^*\beta_y}\sqrt{\frac{\beta_x^*}{\beta_x}}$$

ARC

Long arc section

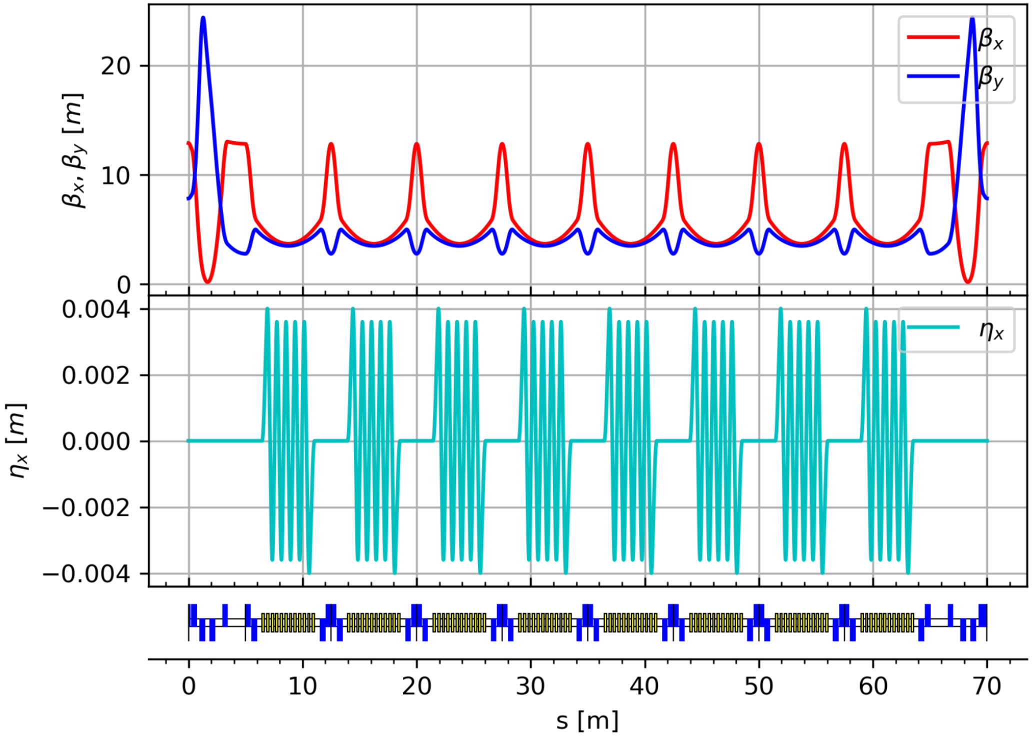


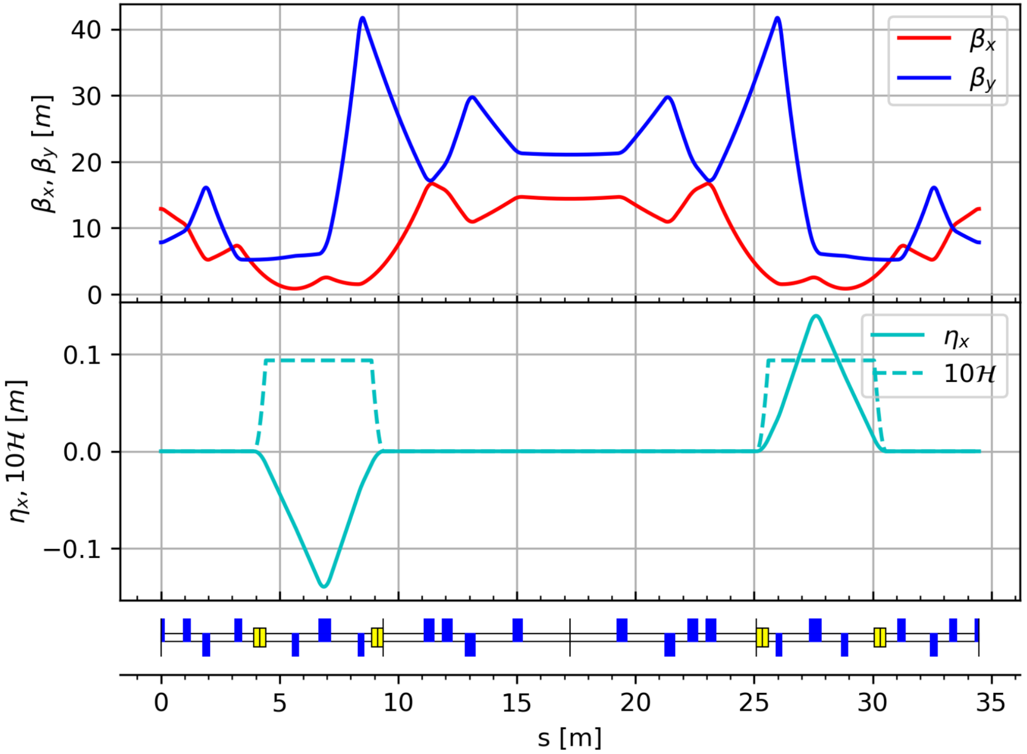
Short arc section



- Long arc section: 9×FODO cell, 6° bending angle, 90° phase advance, 4 pairs of sextupoles (2 SDs + 2 SFs), 180° phase advance (-I, non-interleaved)
- Short arc section: 4×FODO cell, 6° bending angle, 90° phase advance, 1 pairs of sextupoles (SD), 180° phase advance (-I, non-interleaved)

DW and Crossing section





- Normal conducting damping wiggler
- Triplet cell: flexible adjust β function
- Small β function in both Hor./Ver. planes

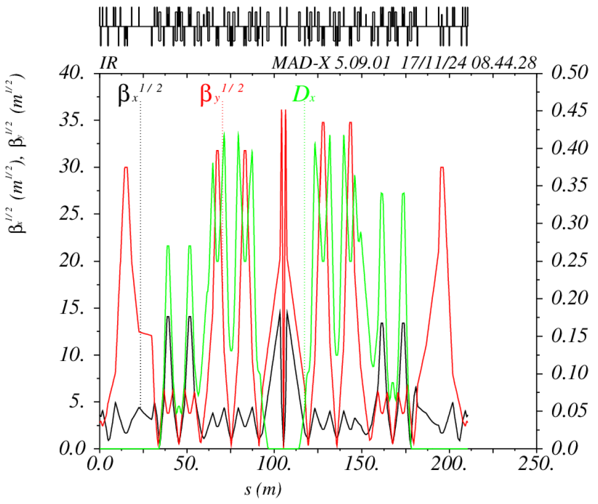
- Two pairs of bending magnets (bending angle: 6°)
- Separation in horizontal plane with 2 m

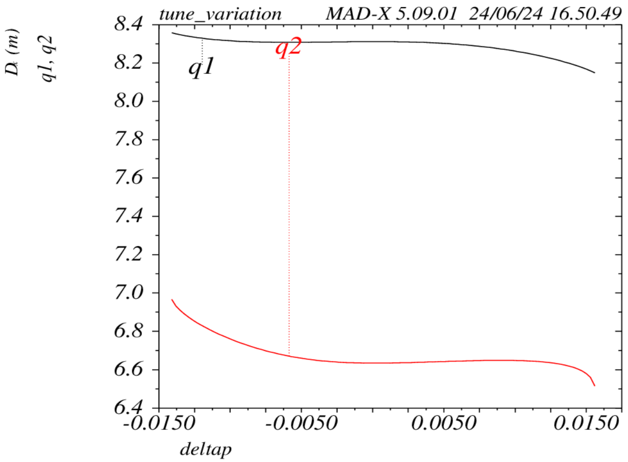
Nonlinear optimization: IR

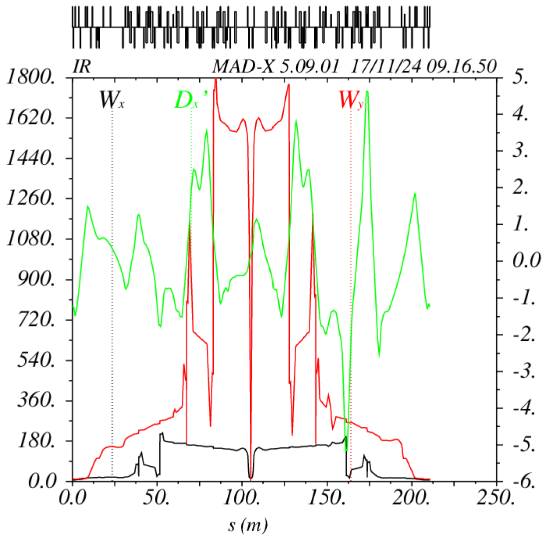
See L. Zhang's talk for more details

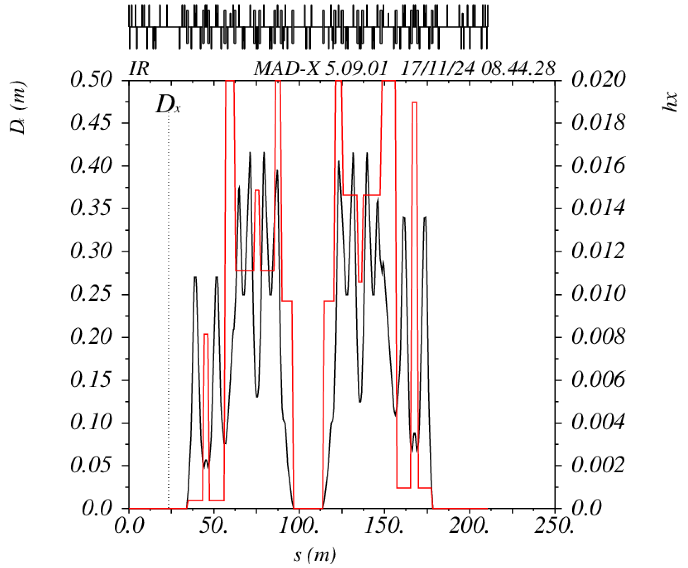
$$Q(\delta) = Q_0 + \frac{\mathrm{d}Q}{\mathrm{d}\delta}\delta + \frac{1}{2}\frac{\mathrm{d}^2Q}{\mathrm{d}\delta^2}\delta^2 + \frac{1}{6}\frac{\mathrm{d}^3Q}{\mathrm{d}\delta^3}\delta^3 + \frac{1}{24}\frac{\mathrm{d}^4Q}{\mathrm{d}\delta^4}\delta^4 + \cdots$$

- Use sextupoles (SY1 and SX1) at CCY and CCX to correct 1st order Chromaticity
- Use the fine-tuning phase advance of SY1 and SX1 to IP to correct 2nd order Chromaticity
- Use SY3 and SX3 at the 1st and 2nd image points of IP to correct 3rd order Chromaticity
- Tuning the phase advance between the crab sextupole and final quadrupole to minimizes the Montague function at crab to increase off-momentum DA



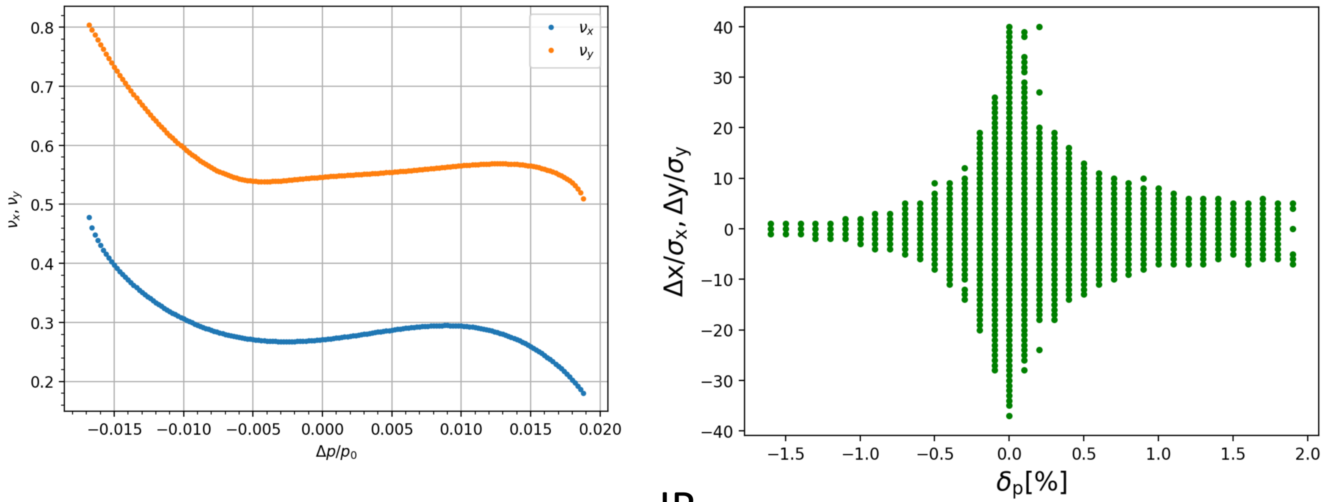




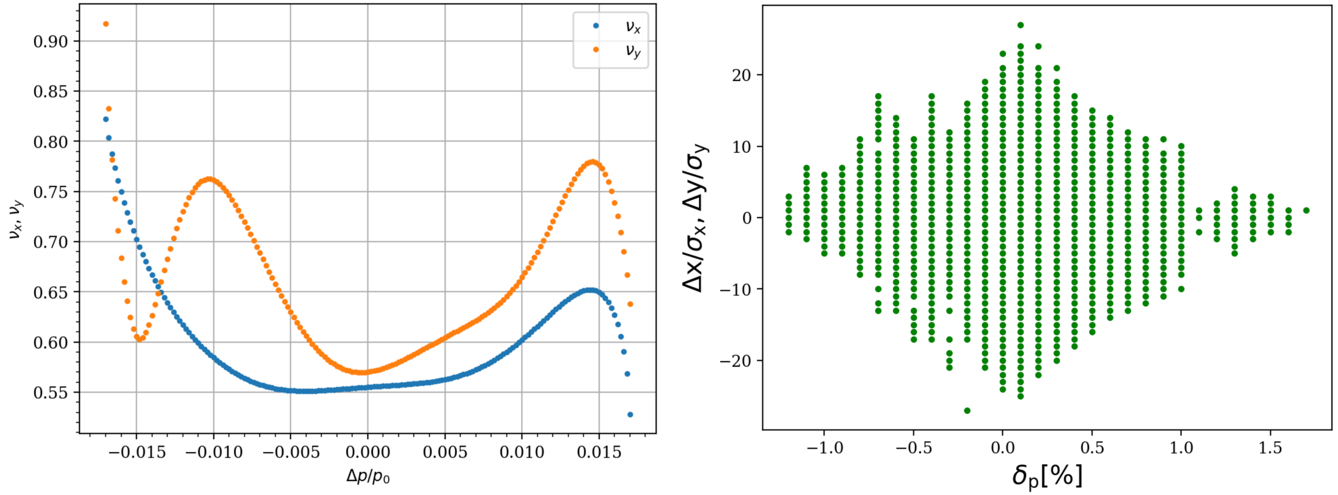


Nonlinear optimization: MOGA

- ATPY code developed by T. Liu
- MOGA (NSGAII) to do the nonlinear optimization
- Variables: sextupole strength, phases between IR and non-IR
- Constraints: Hor. / Ver. Chromaticity
- Targets: dynamic aperture and momentum bandwidth
- DA optimization goes very slow, firstly optimize $\mathrm{d}\mu_x/\mathrm{d}J_x$, $\mathrm{d}\mu_x/\mathrm{d}J_y$, $\mathrm{d}\mu_y/\mathrm{d}J_y$
- Preliminary results, still ongoing

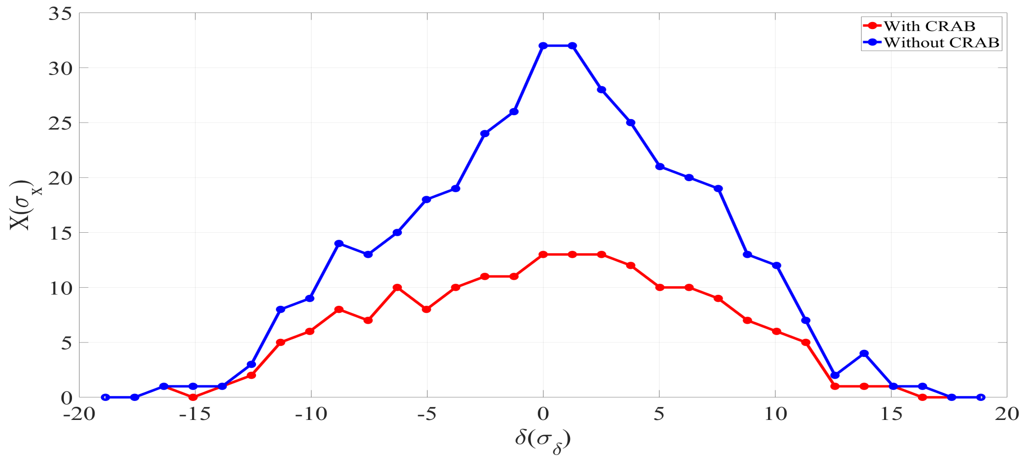


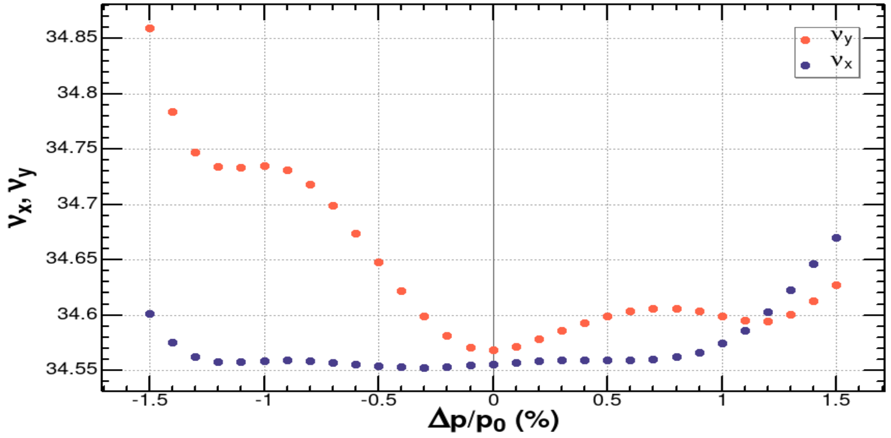
IR



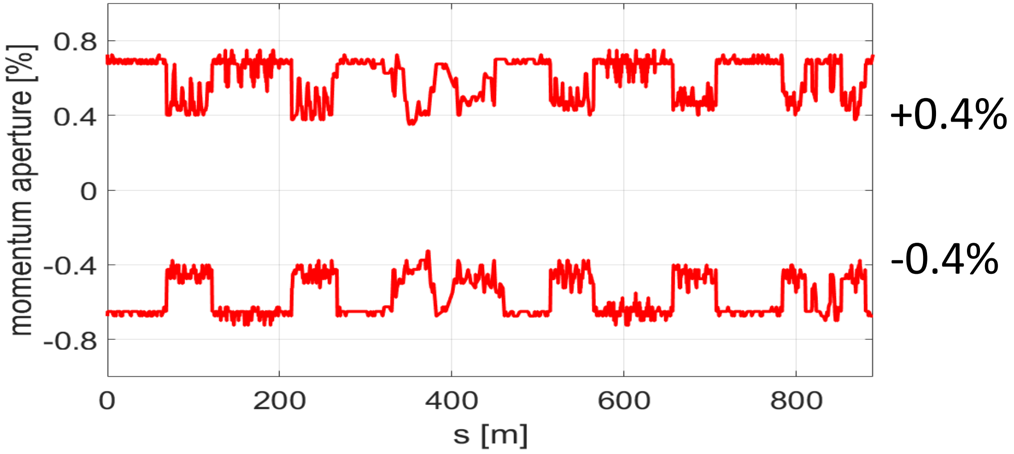
Collider ring

Dynamic aperture (6D)





$$\delta(s) = \frac{R}{\eta(s) + \sqrt{\mathcal{H}(s)\beta_x(s)}}$$



- Dynamic aperture/Touschek lifetime varies greatly w/o crab sextupoles
- Strong nonlinear effect from crab sextupoles
- Possible solutions: extra sextupoles within crab sextupoles?

	With Crab(6D)	Without Crab(6D)
Touschek lifetime	**115 s**	**210 s**

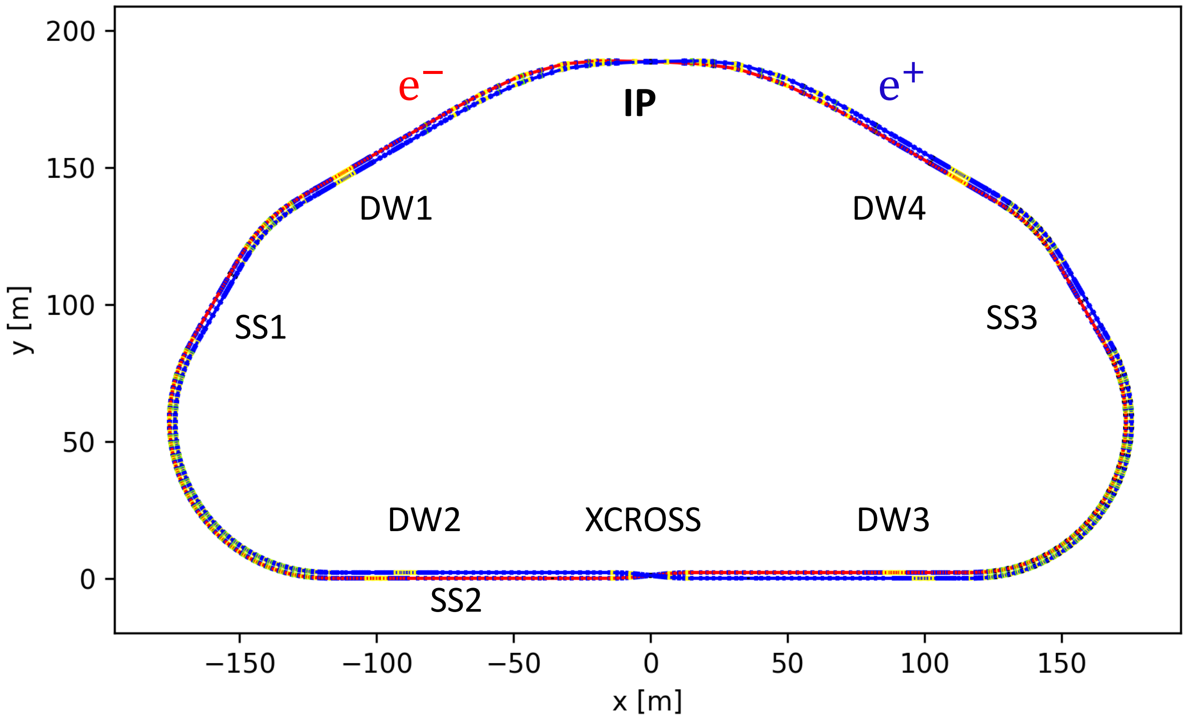
Key parameters (V3)

Parameters	Units	2 GeV	1 GeV	1.5 GeV	3.5 GeV
Circumference, C	m	865.398			
Crossing angle, 2θ	mrad	60			
RF frequency, f_{rf}	MHz	499.7			
Hor. /Ver. beta function at IP, β_x^*/β_y^*	mm	40/0.6 → 60/0.8 (V4)			
L*	m	0.9			
Coupling, $\boldsymbol{\varepsilon_y/\varepsilon_x}$	%	0.5			
Hor./Ver. betatron tune		32.555/34.570	32.555/36.570	32.555/34.570	33.555/34.570
Beam current, I	A	2	1.5	1.7	2
Emittance (DW, IBS) , Hor./Ver.	nm	4.57/0.023	12.46/0.06	7.12/0.035	29.35/0.15
Energy loss per turn (SR+DW), U_0	keV	541	106	266	1477
SR power per beam (SR+DW), P	MW	1.082	0.159	0.452	2.954
RF voltage	MV	3	1	2	6
Synchrotron tune, ν_s		0.0217	0.0173	0.0203	0.0232
δ_{RF}	%	1.87	1.69	1.86	1.86
Bunch length (0.1Ω, IBS)	mm	8.43	9.79	8.56	8.89
Hor./Ver. beam-beam parameter, ξ_x/ξ_y		0.0037/0.105	0.0041/0.095	0.0041/0.108	0.0019/0.026
Luminosity	$cm^{-2}s^{-1}$	1.34E+35	4.19E+34	8.67E+34	4.69E+34

Alternative lattice scheme

T. Liu

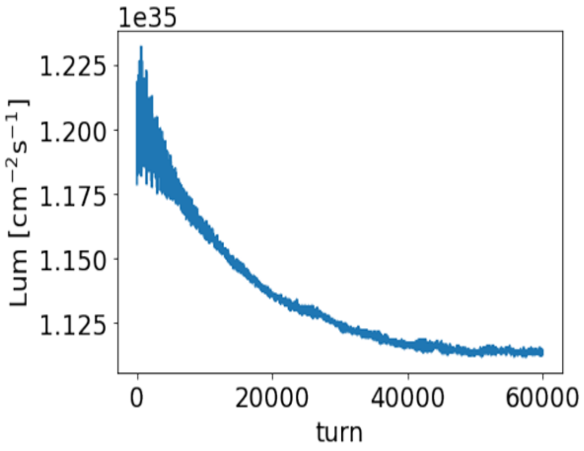
- L: $1.04\times10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ @ 2 GeV
- Touschek lifetime ~160 s (double ring)
- Optimization is still ongoing.

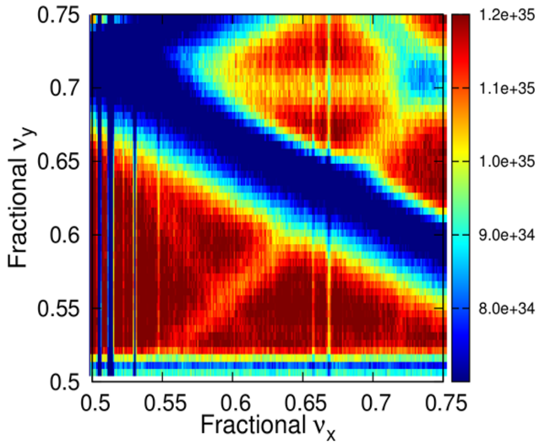


Parameters	Units	STCF
Optimal beam energy, E	GeV	2
Circumference, C	m	885.23
Crossing angle, 2θ	mrad	60
Revolution period, T	μs	2.953
Horizontal emittance, $\varepsilon_x/\varepsilon_y$	nm	5.93/0.030
Coupling, k		0.50%
Beta functions at IP, β_x/β_y	mm	40/0.6
Beam size at IP,σ_x/σ_y	μm	15.41/0.133
Betatron tune, $\nu_x\ /\nu_y$		33.554/32.571
Momentum compaction factor, α_p	10^{-4}	12.424
Energy spread, σ_e	10^{-4}	9.68
Beam current, I	A	2
Number of bunches, n_b		738
Particles per bunch, N_b	10^{10}	5.0
Single-bunch charge	nC	8.0
Energy loss per turn, U_0	keV	383.77
Damping time, $\tau_x/\ \tau_y/\ \tau_z$	ms	30.77/30.77/15.39
RF frequency, f_{RF}	MHz	499.3331295
Harmonic number, h		1476
RF voltage, V_{RF}	MV	1.8
Synchrotron tune, ν_z		0.016
Bunch length, σ_z	mm	10.6
RF bucket height, δ_{RF}	%	1.47
Piwinski angle, ϕ_{pwi}	rad	20.6
Beam-beam parameter, ξ_x/ξ_y		0.0023/0.081
Hour-glass factor, F_h		0.886
Luminosity, L	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.04×10^{35}

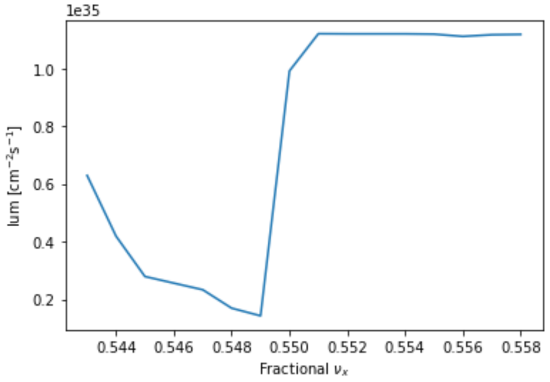
Beam-beam effect and luminosity optimization

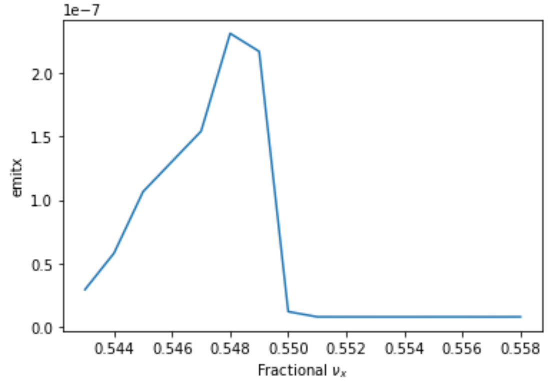
- Studies of incoherent and coherent beam-beam effects for STCF
- Optimizing ring parameters, adjusting beam-beam tune shift, and finding stable operating points with high luminosity





- ➢ The luminosity remains stable at around 1.12e35 in the range of 0.551–0.558.
- ➢ The current design parameters of STCF are far from the beam-beam limit
- ➢ The impact of X-Z instability is relatively small in the STCF_V3 lattice.
- ➢ The current X-Z oscillation period is relatively large, v_z=0.0217 > 5 ξ_x (0.0037).



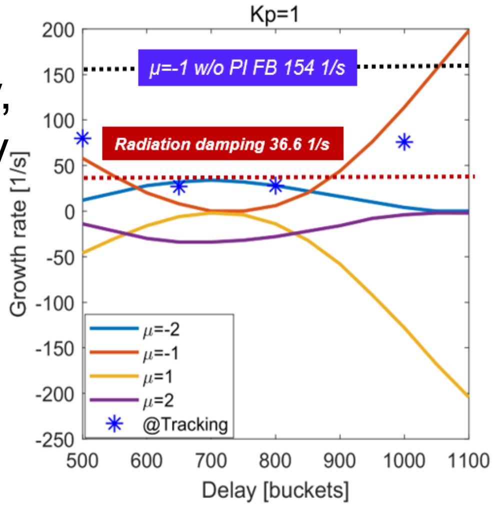


See S. Li's talk for more details

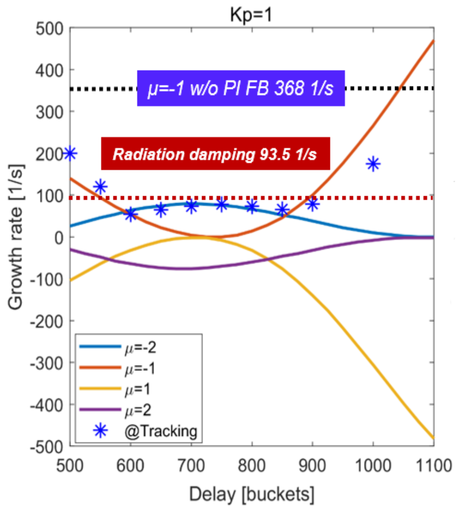
Synchrotron beam dynamics

- STCF currently adopts the TM020 RF cavity, due to high quality factor (Q) and a relatively low R/Q value;
- Studies show the coupling beam instability caused by the fundamental mode can be fully suppressed by selecting appropriate low-level PI feedback parameters
- The growth rate of coupled beam instability caused by high-order modes exceeds the radiation damping rate, and longitudinal feedback is needed to suppress it
- The thermal power need to be absorbed of the high-order mode absorber.

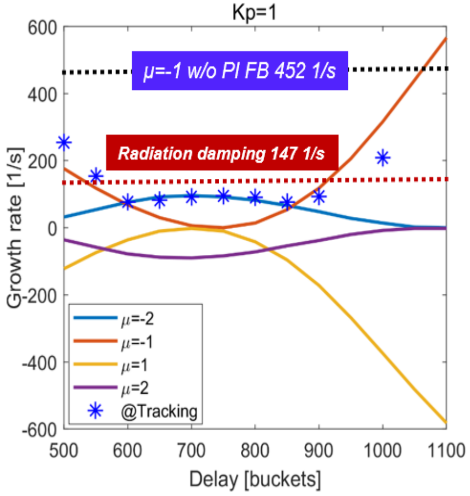
1 GeV

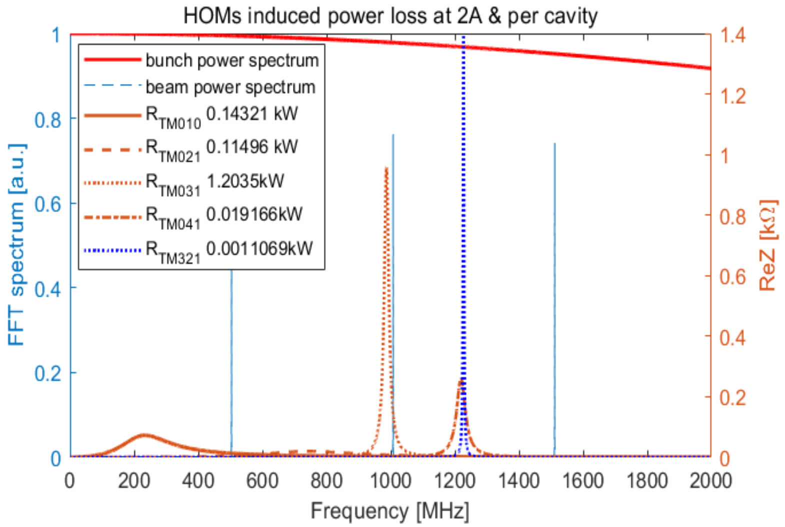


2 GeV



3.5 GeV





Sum Power = 2.7 kW

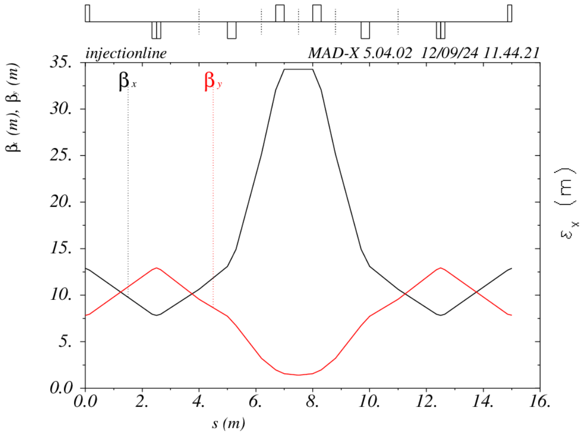
Absorb power@[1f+1e]*685+72e

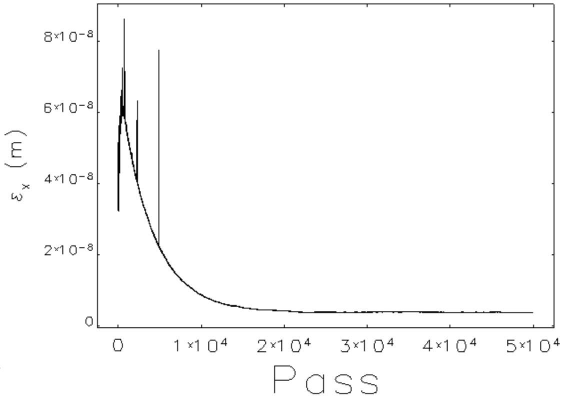
See T. He's talk for more details

Beam injection

- Off-axis injection and swap-out injection

	Off-axis injection		Swap-out injection	
Beam lifetime[s]	200			
Lowest luminosity	95%	90%	95%	90%
Bunch number	678（48%，bunch spacing 4 ns）			
Beam current [A]	2			
Circulating beam charge [nC]	8.5			
Injection beam charge [nC]	1.5		8.5	
Single-bunch charge [nC]	0.425	0.85	8.35	8.35
Injection efficiency	> 29%	> 57%	> 98%	
Injection emittance [nmrad]	< 6		~ 20-40	
Injection time [s]	10.26	21.07	10.26	21.07



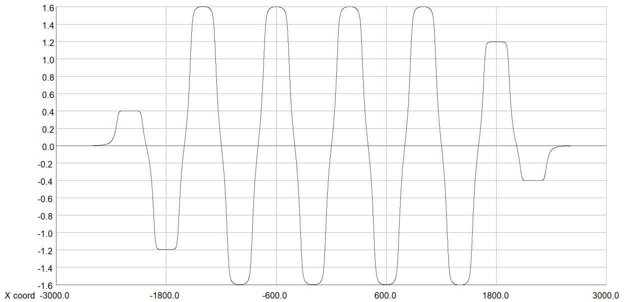


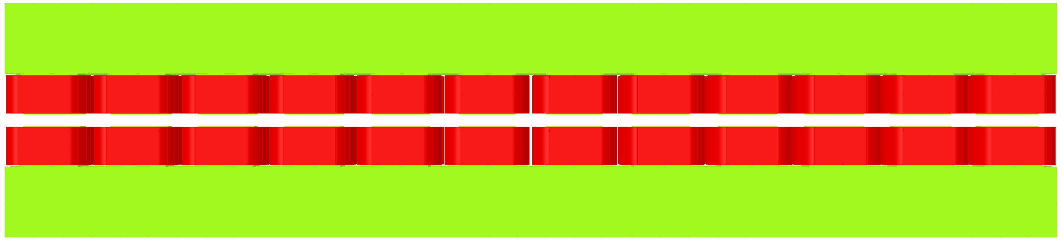
- The equilibrium emittance is 3.68nmrad
- Setting the actual Septum as the physical aperture limit, about 1% of the particles are lost in the first turn, resulting in a final injection efficiency of 85% （ Ideal case ）
- The design and simulation of swap-out injection will be carried out in subsequent work

Damping wigger

- Damping wiggler can be used to reduce damping time, adjust emittance and energy spread
- Nonlinear effect of DW can be minimized by shimming or increasing the width of the polar

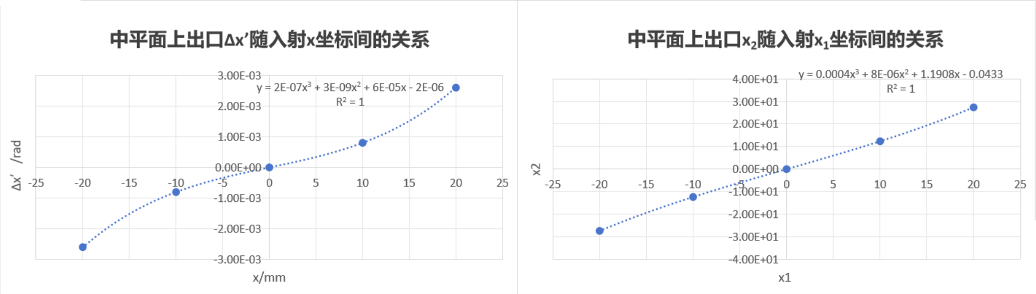
12 pairs of poles, field configuration: {+1/4, -3/4, +1, -1, ... +1, -1, +3/4,-1/4}



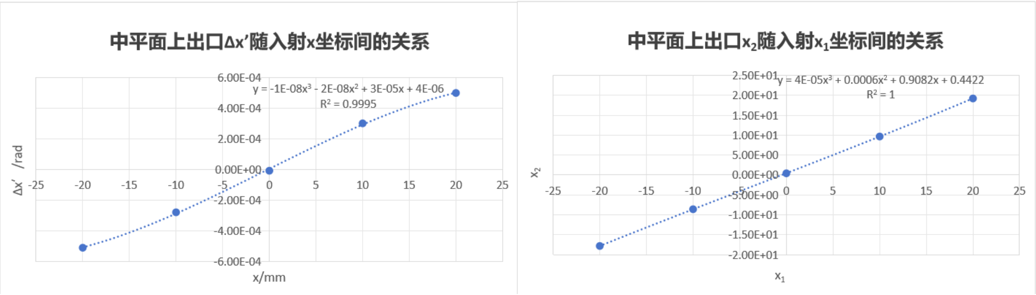


DW parameter	Value
Number	16
Effective length (m)	4.8
Period length (m)	0.8
No. of periods	6
Peak field (T)	1.6
Gap (mm)	50
Beam clearance (mm）	2*(20x13)
Good field width (mm, 1%)	40

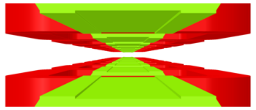
时情况(2GeV)：



采用垫补时情况(2GeV)：No shimming and with shimming



垫补方式（用于减少六极场分量对束流的影响）：

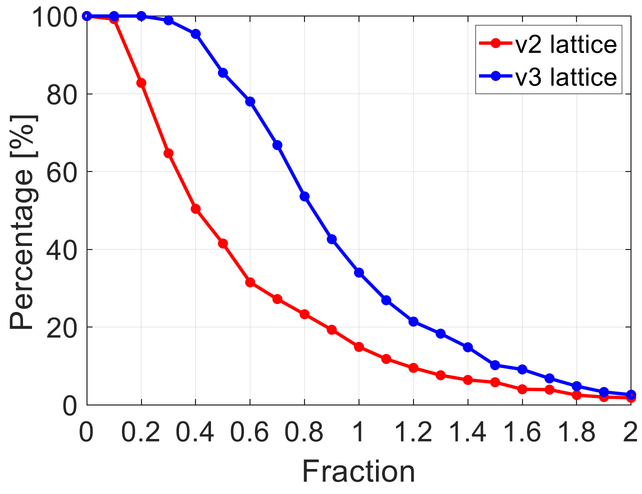


在100mm宽的极面两侧各加了一个20mm×1.5mm的矩形。

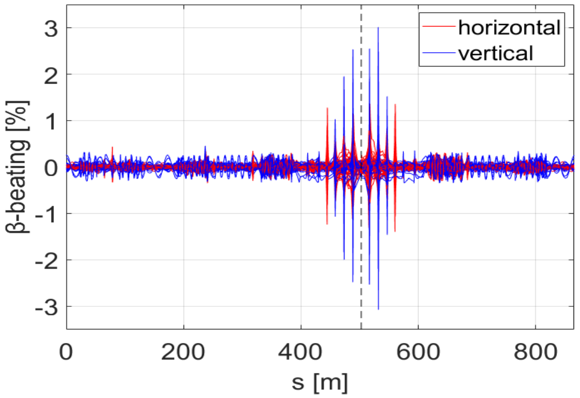
Error effect study

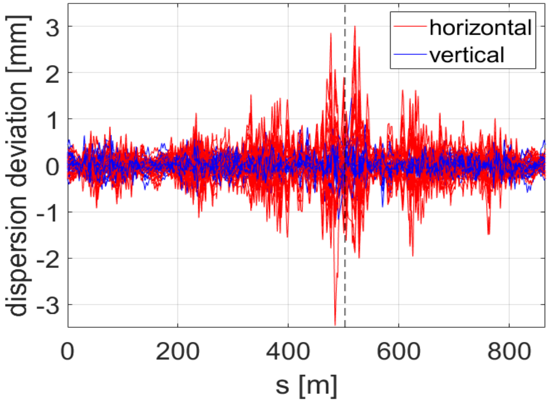
BPM、corrector and skew quadrupole layout:
(1) Place BPMs and correctors next to quadrupoles; 402 BPM in each ring.
(2) QF: CORx; QD: CORy; Sextupole: double-plane corrector;
(3) Place skew quadrupoles in sextupoles and some multi-function magnets.

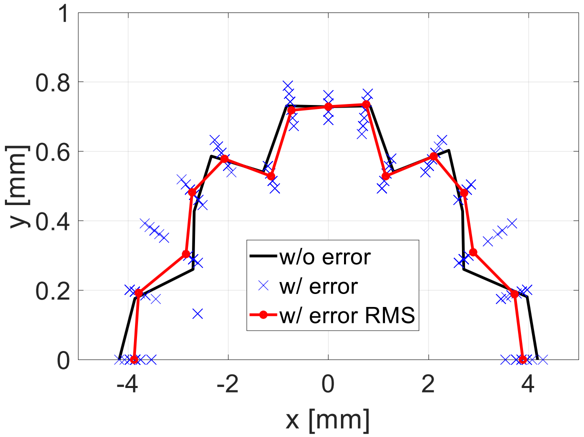
	Δx (μm)	Δy (μm)	Δs (μm)	$\Delta\theta_x$(mrad)	$\Delta\theta_y$ (mrad)	$\Delta\theta_s$ (mrad)	Field error
Dipole	75	75	100	0.1	0.1	0.1	0.02%
Quadrupole	75	75	100	0.1	0.1	0.1	0.02%
Sextupole	75	75	100	0.1	0.1	0.1	0.02%



Orbit	Before(mm)	After(μm)
X Max	1.1	214
Y Max	2.7	294
X RMS	0.11	35
Y RMS	0.16	45





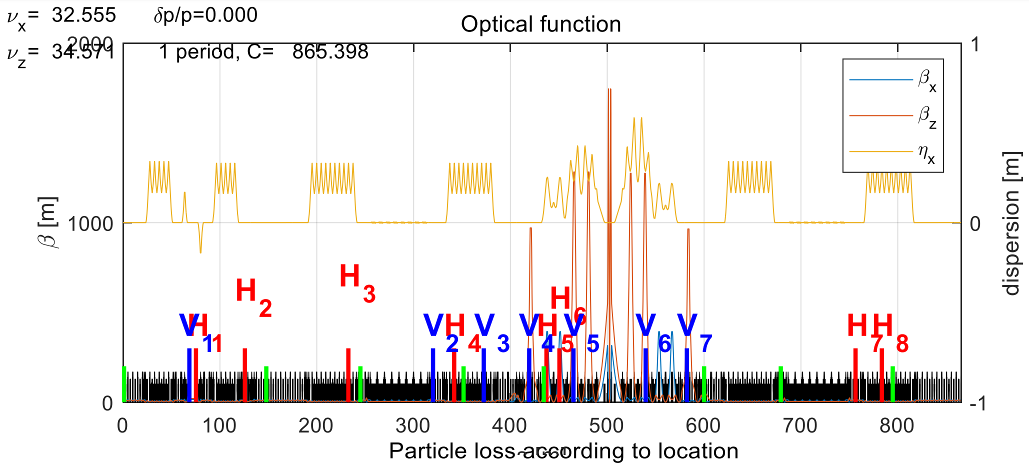


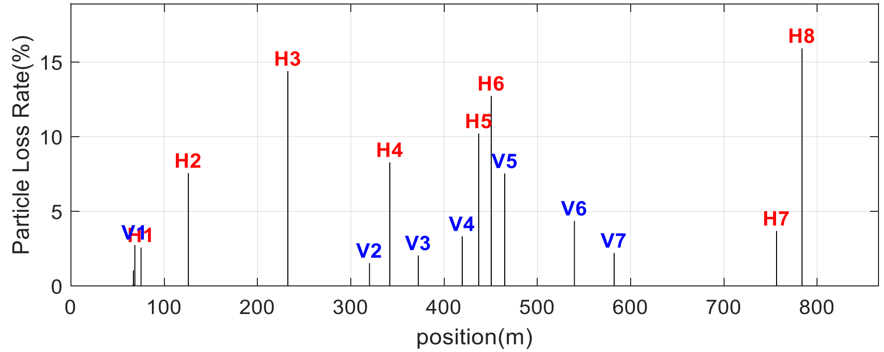
Beam collimation

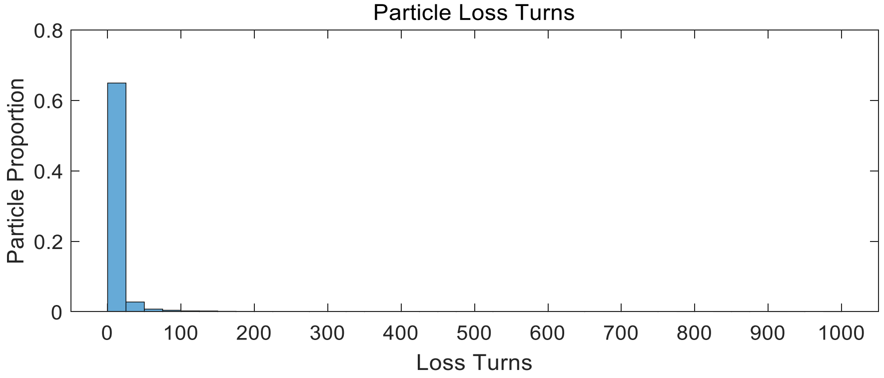
Collimator	Half Aperture /mm	Half Aperture /σ	Position/m	Space/m	Loss Rate/%
H1	8	24.27	75.25	3.4	2.55
H2	8	17.42	125.79	1.6	7.54
H3	7	20.27	232.63	0.8	14.37
H4	6	17.37	341.92	0.8	8.26
H5	20	12.38	437.21	2.8	10.19
H6	15	9.30	450.61	2.8	12.71
H7	8	26.84	756.40	2.2	3.66
H8	6	16.96	783.57	0.835	15.90
V1	10	262.44	68.45	3.4	2.73
V2	6	254.41	320.08	2.2	1.51
V3	8	349.94	372.47	0.8	2.02
V4	15	81.11	419.41	2	3.30
V5	12	41.39	465.11	2.8	7.51
V6	10	34.59	539.71	2.8	4.34
V7	8	43.43	582.21	2	2.19
				Total	98.79

Simulation Set:
800,000 particles , 1000 turns
±2% energy deviation (randomly)
8 scattering points (marked in green)

- Simulations were performed using AT (Accelerator Toolbox). The results are shown in the figure.
- About 99% of the lost particles are lost at collimators, and no particle loss occurs within ±37 m of IP.







Summary

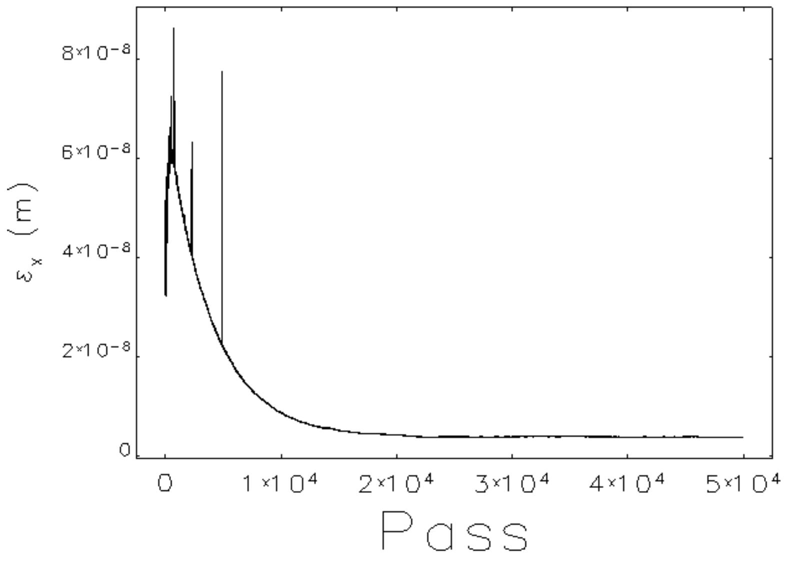
- We have a good progress of lattice design for STCF collider ring since early this year.
- The nonlinear effect of the lattice is very challenging, in particular in the IR region.
- Studies on beam-beam effect, synchrotron dynamics, beam injection, beam collimation, and error effects are progressing gradually.

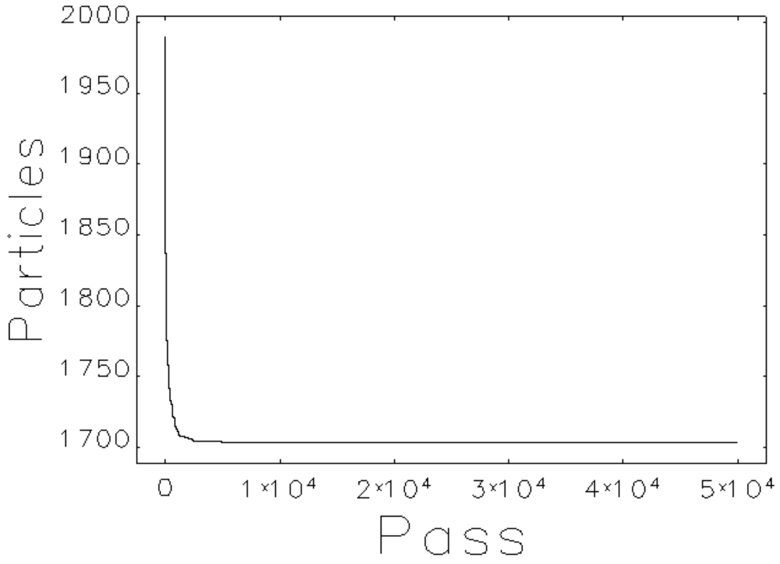
Backup slides

Beam injection

Progress in off-axis injection simulation

- Stored bunch beam stay clear：$4\sigma_s$=4×0.446 mm
- Injected bunch beam stay clear：$4\sigma_i$ =4×0.273 mm
- Septum width Ds：$1\sigma_s$=0.446 mm
- The distance between Septum and center orbit：$4\sigma_s$+Ds+2×$4\sigma_i$=4.414 mm
- Injection point Bump height：2.63 mm，angle：-0.5 mrad
- Injected bunch angle：-0.47 mrad
- The center position of the injected bunch after bump fall：3.322 mm





Instabilities

- Bunch lengthening due to impedance：

Zotter equation：

$$\left(\frac{\sigma_z}{\sigma_{z0}}\right)^3 - \frac{\sigma_z}{\sigma_{z0}} = -\frac{cI_b}{4\sqrt{\pi}\eta_p\omega_0\sigma_{z0}\sigma_{\delta 0}^2 E_0/e}\mathrm{Im}\left(\frac{Z_\parallel}{n}\right)_{\mathrm{eff}}$$

Effective impd 0.2 Ω，Ib=2.8 mA
Vrf= 2MV → $\sigma_z = 10.6$ mm
Vrf= 3MV → $\sigma_z = 8.9$ mm

- Resistive-wall instability：

$$\frac{1}{\tau_{\min}} = \frac{I_0 ecC}{4\pi^2\nu_y E_0 b^3}\sqrt{\frac{Z_0 c}{2\sigma\omega_0\left(1-\mathrm{frac}(\nu_y)\right)}}$$

Vacuum Material：Al、 b=25 mm

growing time 1.6 ms
can be suppressed by feedback

- CSR instability threshold = 2 mA @ 2 GeV
- Parallel-plates shielding steady-state model
- Gap：2h=50 mm; $\rho = 10$ m
- By particle tracking simulation

TMCI threshold：

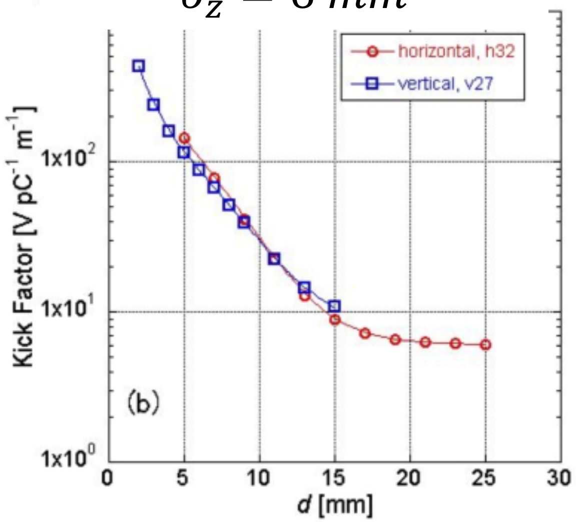
$$I_{th} = \frac{4\pi\nu_s(E_0/e)}{T_0\sum_i \beta_{y,i}k_{y,i}}$$

Transverse impdence：

$$\sum_i \beta_{y,i}k_{y,i} < 78 \ \mathrm{kV/pC/m}$$

SKEKB-type Collimation

$\sigma_z = 6\,mm$



Other studies on impdance modelling、e-cloud 、impedance & beam-beam coupling are on going.

International collaboration

- BINP visit: A. Bogomyagkov, M. Skamorokha, K. Kariukina, and N.Chepurnoi.
- KEK: Demin Zhou, Omi, et al.