STCF对撞环物理设计进展

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代表STCF对撞环加速器物理组

2025年超级陶粲装置研讨会

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设计目标和挑战

核心设计目标:

- CoM energy: 2-7 GeV
- Luminosity: > 0.5×10^{35} cm^{-2} s^{-1} @ 4 GeV

为了实现设计目标, 对撞环设计需要满足(@ 4GeV):

- Collision scheme: Large Piwinski angle + Crab-waist
- β_y^*: 0.6 mm to 1 mm
- Current: ~2 A
- Horizontal emittance: ~5 nm rad
- Touschek lifetime: > 200 s

主要挑战:

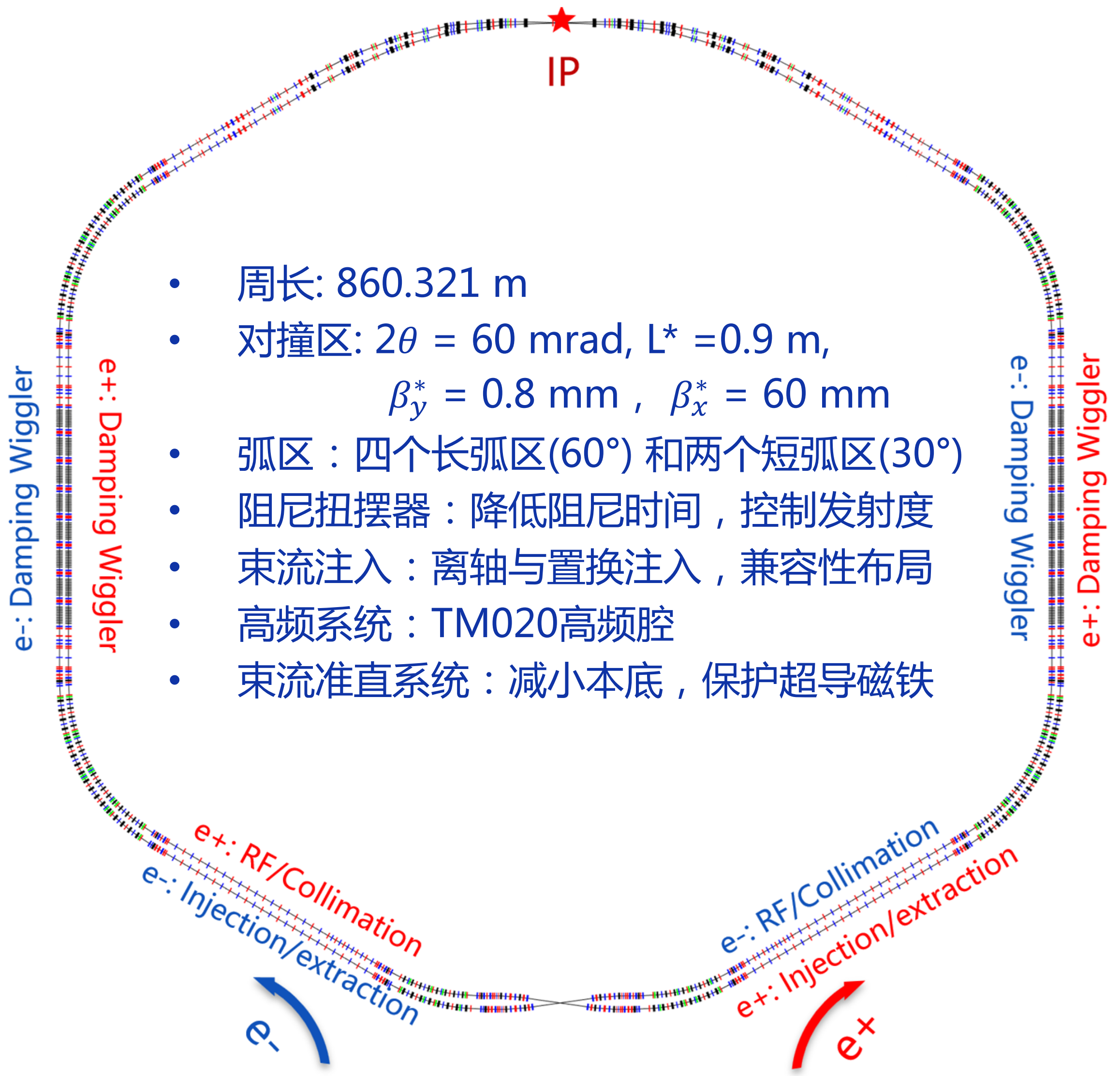
- Very strong nonlinear effect: small dynamic aperture and momentum acceptance
- High current, low energy, small emittance: strong collective effect (Touschek effect, IBS, beam-beam, impedance, etc.)
- Interplay of multiple physical processes
- Very short Touschek lifetime: Large beam loss, large background and SC magnets quenching

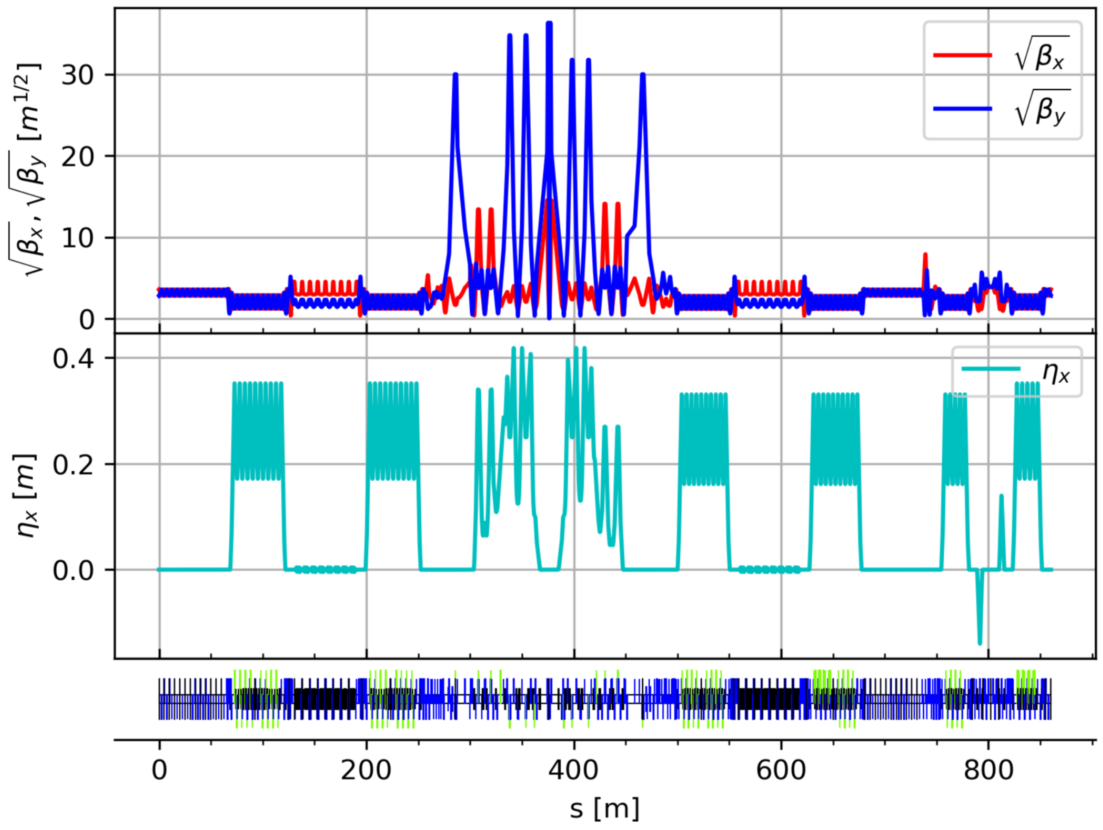
关键参数

Parameters	Units	2 GeV	1 GeV	1.5 GeV	3.5 GeV
Circumference, C	m	860.321			
Crossing angle, 2θ	mrad	60			
Hor. /Ver. beta function at IP, β_x^*/β_y^*	mm	60/0.8			
Hor./Ver. betatron tune		30.543/34.58	30.555/34.57		
Beam current, I	A	2	1.1	1.7	2
Hor. Emittance (SR/DW+IBS)	nm	8.79/4.63	2.2/5.42	4.94/3.82	26.9/26.91
Ver. Emittance (SR/DW+IBS)	pm	87.9/46.3	330/813	494/382	134.5/134.55
Ratio, $\varepsilon_y/\varepsilon_x$	%	1	15	10	0.5
Momentum compaction factor, α_p	10^{-3}	1.35	1.26	1.32	1.37
Energy spread (DW+IBS)	10^{-4}	7.8	6.18	6.93	10.02
Energy loss per turn (SR+DW), U_0	keV	543	106	267	1494
SR power per beam (SR+DW), P	MW	1.086	0.117	0.453	2.988
RF voltage	MV	2.5	0.75	1.2	6
Synchrotron tune, ν_s		0.0194	0.0146	0.0154	0.0228
δ_{RF}	%	1.68	1.44	1.35	1.88
Bunch length (Nature/0.1Ω+IBS)	mm	7.21/8.70	6.62/9.79	7.89/8.56	8.26/8.89
Hor./Ver. beam-beam parameter, ξ_x/ξ_y		0.005/0.095	0.005/0.023	0.004/0.033	0.003/0.032
Luminosity	$cm^{-2}s^{-1}$	9.4E+34	6.19E+33	2.09E+34	4.48E+34

Lattice布局和光学函数 (V4.3)

- 周长: 860.321 m
- 对撞区: 2θ = 60 mrad, L* =0.9 m,
  β_y^* = 0.8 mm， β_x^* = 60 mm
- 弧区：四个长弧区(60°) 和两个短弧区(30°)
- 阻尼扭摆器：降低阻尼时间，控制发射度
- 束流注入：离轴与置换注入，兼容性布局
- 高频系统：TM020高频腔
- 束流准直系统：减小本底，保护超导磁铁

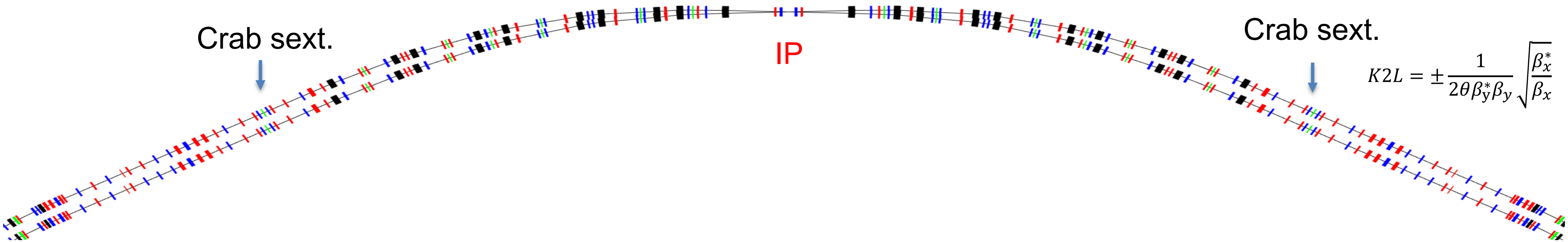




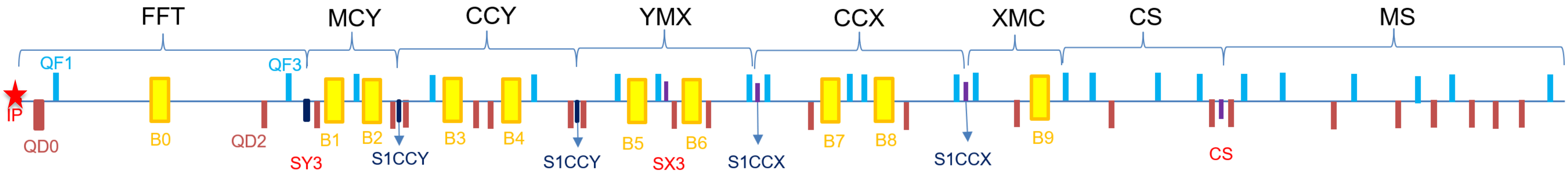
对撞区光学设计

详见张林浩报告

- Modular design → flexible for optics adjustment and local chromaticity correction
  - Final Focus Telescope (FFT), Chromaticity Correction (CCY、CCX), and Crab Sextupoles (CS)
  - FFT: small β function (β_y^* =0.8 mm, β_x^* =60 mm) and bunch size at IP (σ_y= 190 nm, σ_x =17 μm)
  - CCY/CCX: sextupole pairs, large β, large dispersion, exact –I map →reduce sextupole strength
  - CS: phase advance to IP (μ_x = 6π, μ_y = 5.5π); $\beta_y >> \beta_x$ →reduce sextupole strength (k_2 =16.94 m^{-3})
  - IR Bending angle 60°: weak bending magnet (B0) closest to IP, to avoid synchrotron radiation at IP



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



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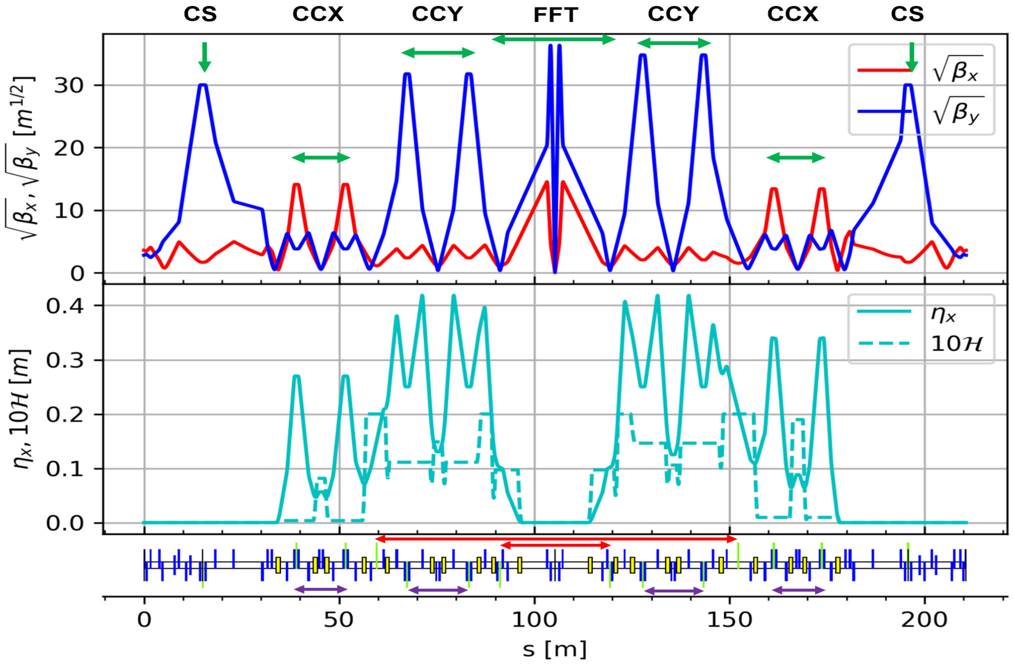
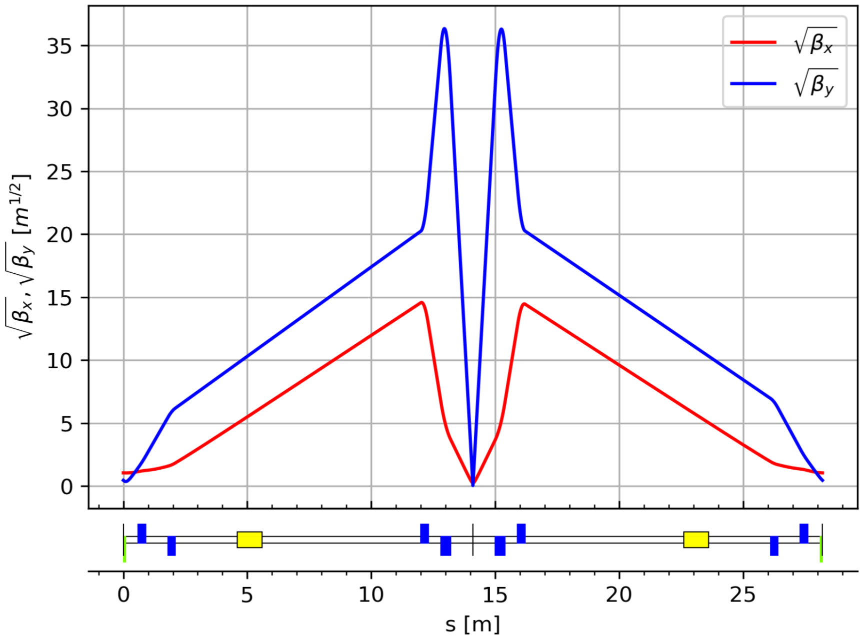
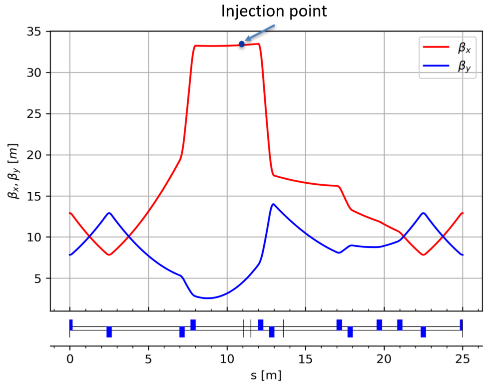


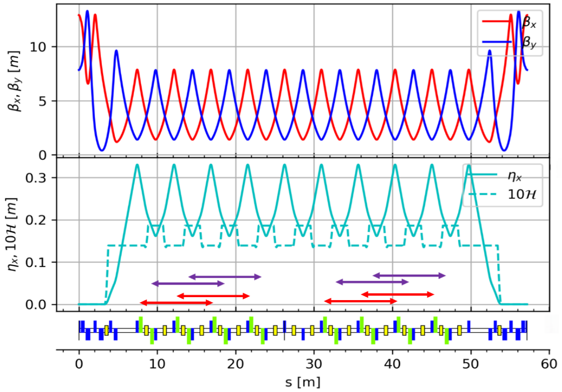
Final Focus Telescope



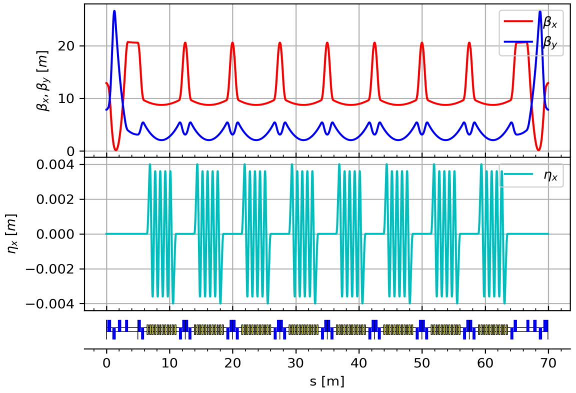
非对撞区光学设计

- 弧区采用标准 FODO 单元 → 90° phase advances, 40 pairs of sextupoles (20 SDs+20 SFs), exact -I map
  - 也在考虑具有更高灵活度的弧区结构（optional）: 可以在更大范围调节发射度和动量压缩因子
- 常温Damping wiggler：采用 triplet cell，可以灵活调节DW长度, beta X/Y
- 交叉段采用两组弯转磁铁, 水平分离约 2 m
- 注入段采用离轴与置换兼容的光学设计

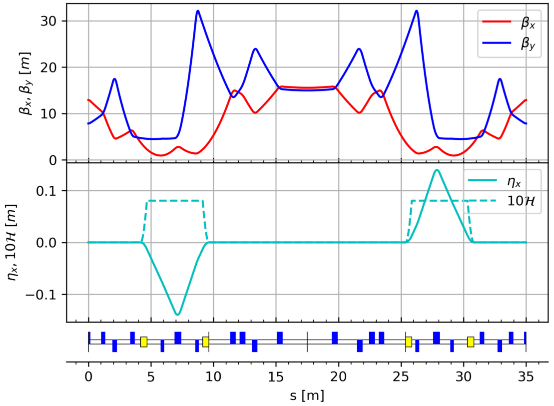




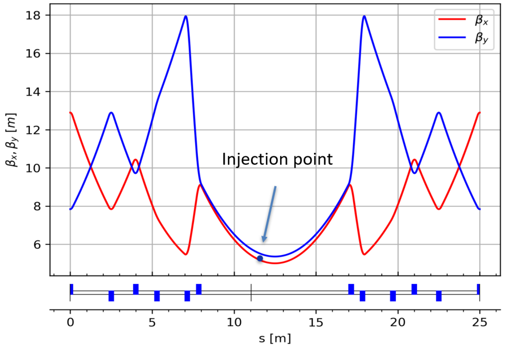
弧区



Damping wiggler段



交叉段

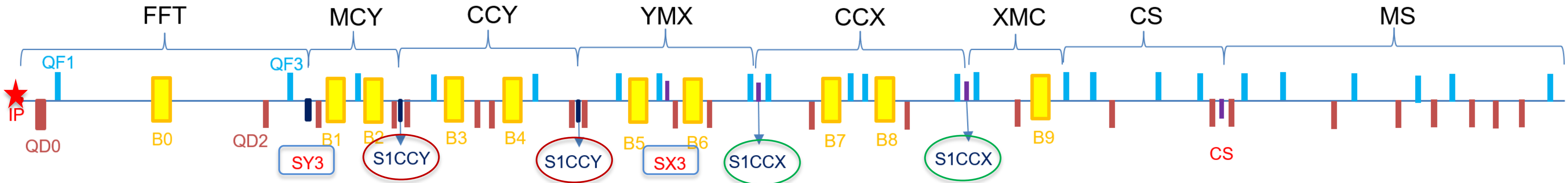


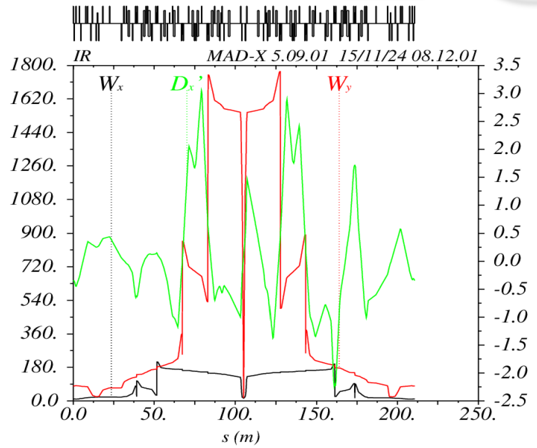
上图：离轴注入
下图：置换注入

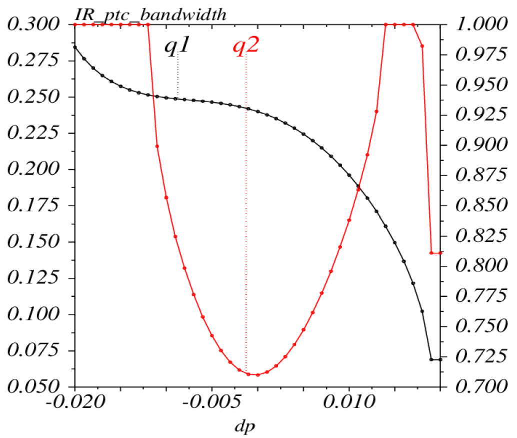
非线性优化策略

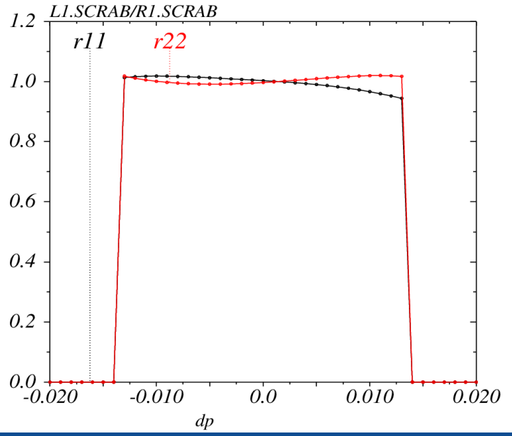
详见张林浩报告

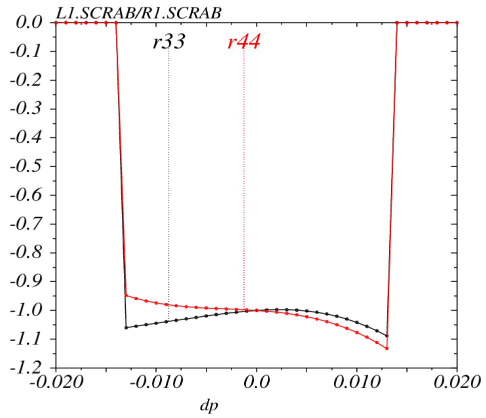
- Local chromaticity correction (up to 3rd order) → to increase momentum bandwidth
  - 1st-order chromaticity: S1CCY and S1CCX main sextupole pairs with -I map;
  - 2nd-order chromaticity: fine-tuning phase advance of S1CCY and S1CCX to IP;
  - 3rd-order chromaticity: SY3 and SX3 at the 1st and 2nd image points of the IP.
- Optimize Montague function at IP and CS to enhance off-momentum beam dynamics
- Optimize the map between CRAB sextupoles, as linear as possible with δ varying







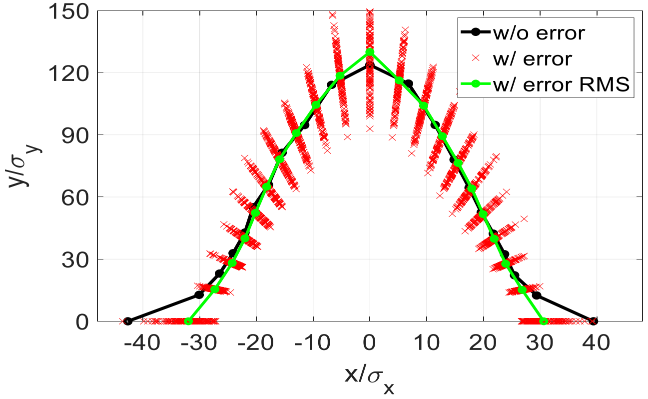


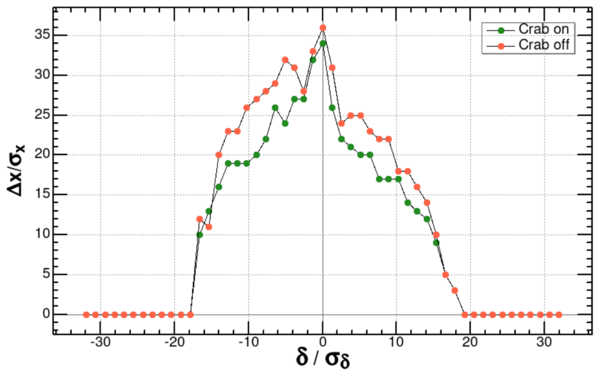


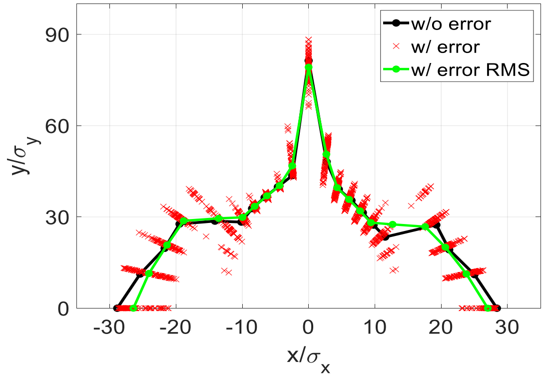
非线性优化

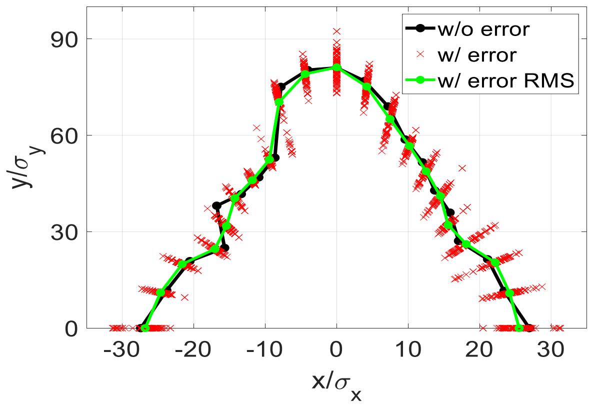
详见张林浩报告

- MADX/SAD for the lattice design, **PAMKIT** for global nonlinear optimization
- Optimization procedure:
  - Variables: sextupole strengths (IR: 6 pairs, arcs: 40 pairs)
  - Constraints: first-order chromaticity and key resonance driving terms
  - Objectives: dynamic aperture and momentum acceptance
  - During optimization, crab sextupoles always on
  - On-momentum DA: Hor. > 30σ_x,Ver. >120 σ_y; off-momentum DA: >15σ_x @ 10 σ_δ
- Fringe fields effects:
  - add octupole coils near FF quadrupole magnets
  - On-momentum DA: Hor. > 25σ_x,Ver. >80 σ_y; off-momentum DA: >10σ_x @ 10 σ_δ







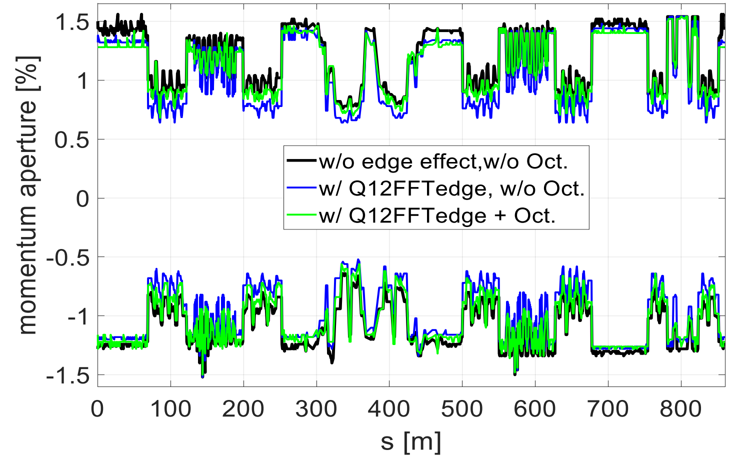


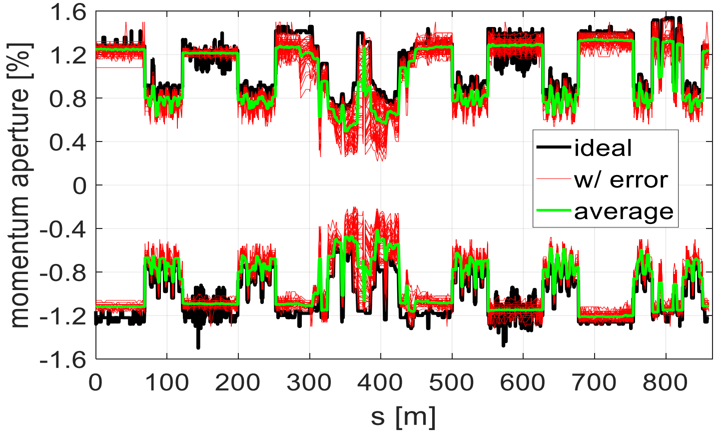
LMA 与 Touschek 寿命

- Local momentum acceptance (LMA) evaluated by Elegant
- Lower H function to increase LMA by linear optics design
- Integration of FF quadrupole fringe fields significantly degrades LMA
- With octupole compensation, the LMA recovers a lot
- Touschek lifetime: > 300s with crab sextupoles on and fringe fields compensation with ideal lattice and >220s with errors

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

Touschek Lifetime (s)	Ideal lattice	with errors
w/o edge effect	351	283
w/ edge effect	242	166
w/ edge effect and octupoles	309	226





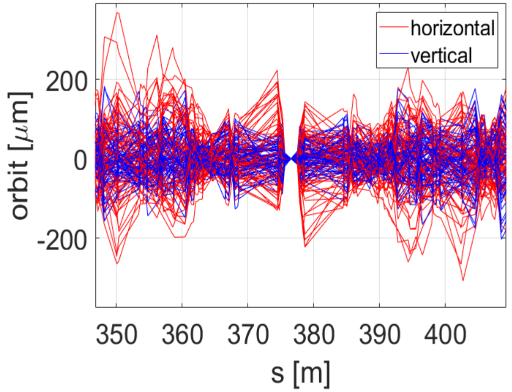
- Double-checked by Anton Bogomyagkov from BINP

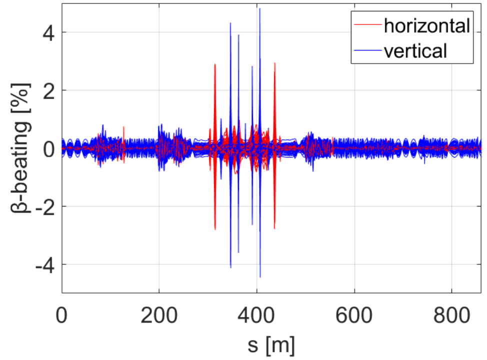
误差分析与校正

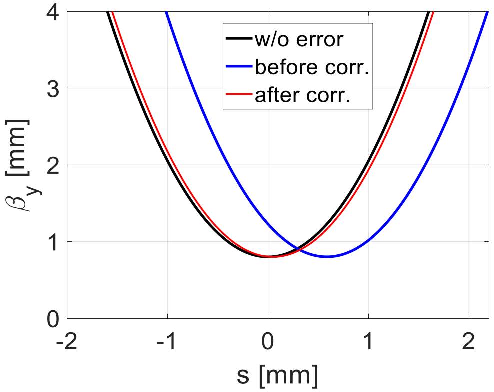
详见杨鹏辉报告

- Analyze the errors of the ring and add BPMs and correctors for correction
- BPM and corrector layout:
  - Place BPMs and correctors next to quadrupoles; 405 BPM in each ring.
  - QF: CORx; QD: CORy; Sextupole: double-plane corrector and skew quadrupole;
- Misalignment Errors:
  - FFT doublet: more strictly than other quadrupoles
  - IR sextupoles: more strictly than sextupoles in the Arc
- Correction strategy
  - First turn trajectory correction
  - Orbit and dispersion correction the whole ring and IP (SVD+DFS)
  - Optics and coupling correction (LOCO)
  - β_y^* correction: K-modulation

	Δx (μm)	Δy (μm)	Δs (μm)	$\Delta\theta_x$(mrad)	$\Delta\theta_y$ (mrad)	$\Delta\theta_s$ (mrad)
Dipole	**100**	**100**	**100**	**0.1**	**0.1**	**0.1**
Quadrupole	**50**	**50**	**100**	**0.1**	**0.1**	**0.1**
FFT doublet	**30**	**30**	**100**	**0.1**	**0.1**	**0.1**
Arc/IR Sextupole	**50/30**	**50/30**	**100**	**0.1**	**0.1**	**0.1**





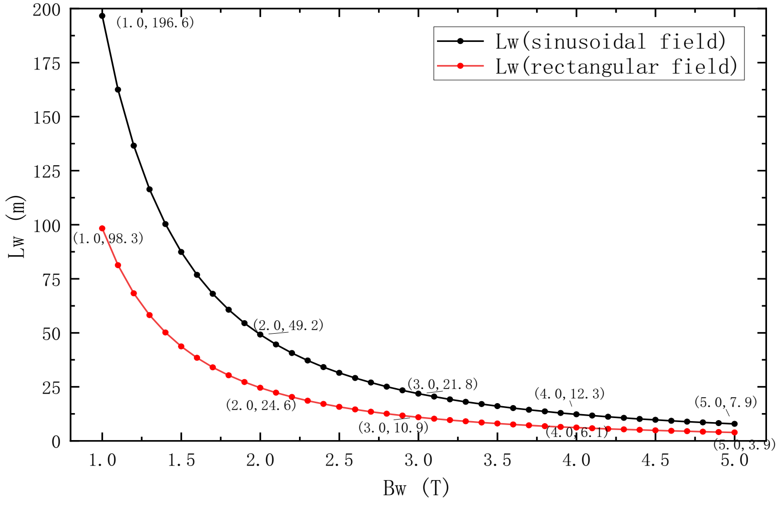


误差分析与校正

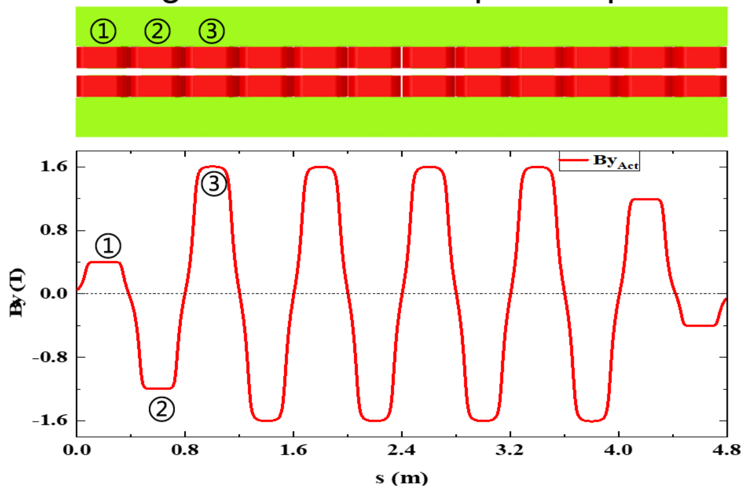
详见杨鹏辉报告

	Global	@IP
Hor./Ver. orbit, MAX (μm)	371/328	0.52/0.10
Hor./Ver. orbit, RMS (μm)	48.3/47.6	0.17/0.034
Hor./Ver. dispersion deviation, MAX (mm)	7.0/1.8	0.81/0.04
Hor./Ver. dispersion deviation, RMS (mm)	0.48/0.17	0.35/0.014
Hor./Ver. β-beat, MAX (%)	3.0/3.8	0.12/0.86
Hor./Ver. β-beat, RMS (%)	0.13/0.17	0.04/0.29
Hor./Ver. tune shift, MAX ($\times 10^{-4}$)	0.21/2.5	
Couling factor MAX/RMS ($\times 10^{-5}$)	7.9/2.8	

- Damping wiggler （DW）
  - Reducing damping time and emittance control，damping time < 30 ms, ε_x ~ 5 nm rad
  - Room temperature DW has been adopted as baseline → mature technology
  - the total DW length is proportional to B_w^{-2}, higher B_w is favorable ，1.6 T -> 1.9 T，76.8 m -> 54.5 m
  - The period length λ_w affects the field shape, large λ_w is more efficient for damping，0.8m -> 0.6m
  - An even-pole (2N) with a pole sequence of {+1/4, -3/4, +1, -1, ..., +1, -1, +3/4, -1/4}.



Magnetic field and 12 pairs of poles



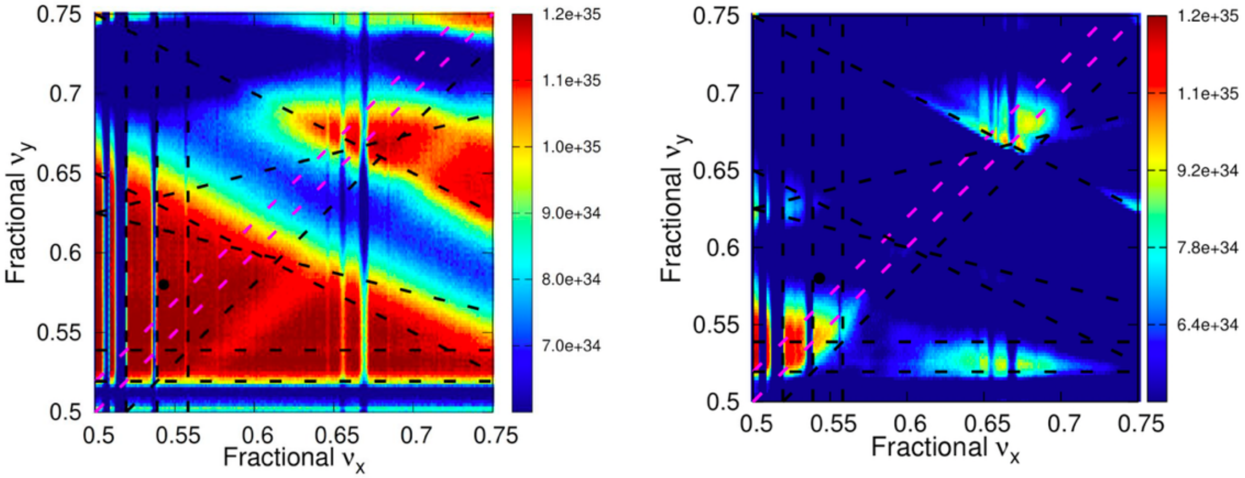
Parameter	Value
Beam energy (GeV)	1.0 – 3.5
Wiggler length (m)	4.8
Peak field (T)	1.6
Period length (m)	0.8
Magnetic gap (mm)	50
Number of wigglers per ring	16
Total wiggler length per ring (m)	76.8

束-束相互作用

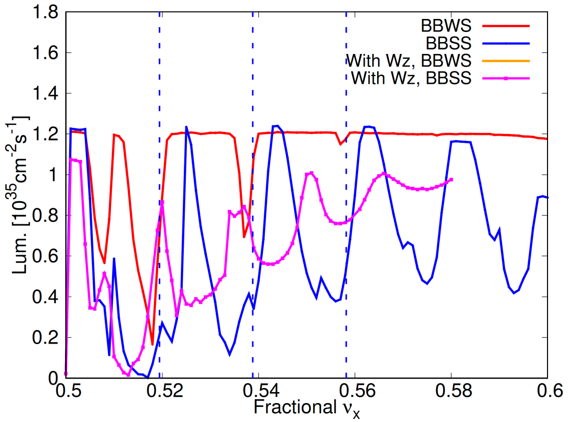
详见李桑丫报告

- 束束相互作用
  - Crab waist方案可以有效提高峰值亮度，但是无法抑制Synchrobetatron共振和相干X-Z不稳定性: $\nu_z/\xi_x \gtrsim 3$
  - 相干 X-Z 不稳定性对亮度性能有显著影响 -> 考虑增加 ν_z 以及减小β_x^* 来抑制X-Z不稳定性
  - 工作点选取: $0.5 + n\nu_z < [\nu_x] < 0.5 + (n+1)\nu_z$ with $n = 1\ or\ \ 2$
  - 纵向阻抗将共振范围变宽 (ν_z spread) 同时会降低共振强度 (Landau damping)
  - 强强模拟给出带Lattice后亮度会有所降低，仍然可以达到1×10^{35} cm^{-2} s^{-1}

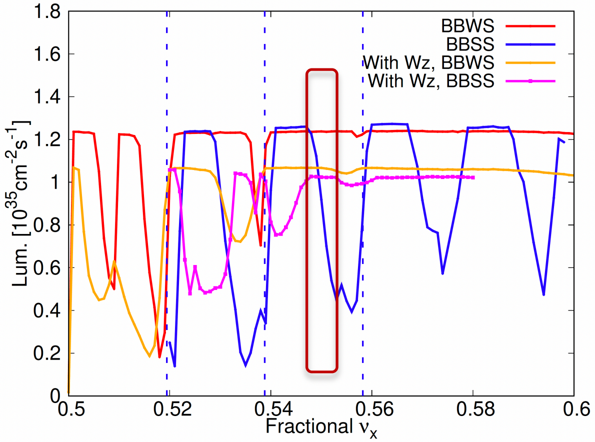
Weak-strong simulations with and without CW



β_x^* = 60 mm



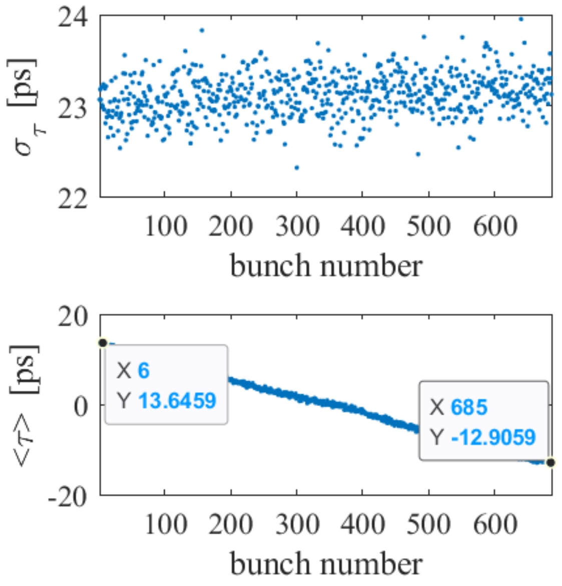
β_x^* = 40 mm



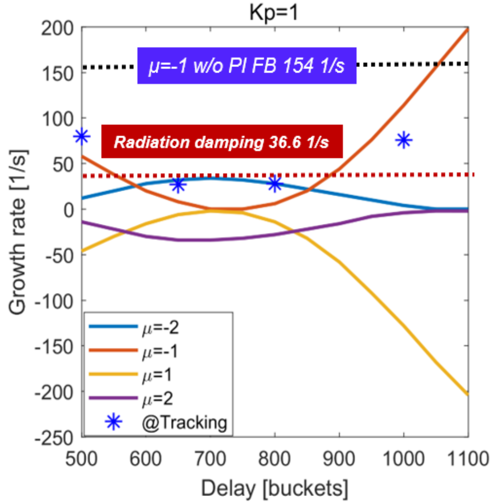
束-腔相互作用

详见李伟伟报告

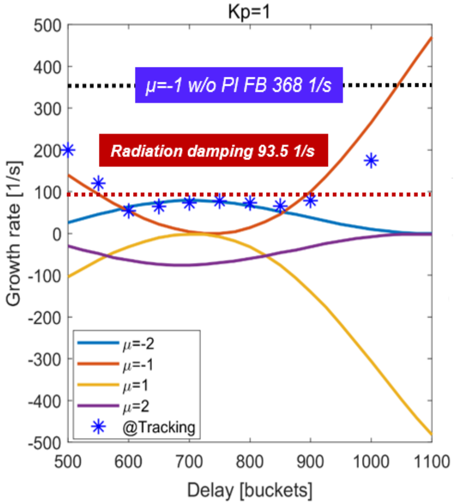
- STCF选择TM020高频腔，高品质因子（Q），低R/Q值
- 研究TM020腔基模和高次模产生的耦合束团不稳定性及其抑制措施
- 对于基模产生的耦合束团不稳定性，可以通过低电平PI反馈来进行充分抑制
- 高次模产生的耦合束团不稳定性增长率超过了阻尼率，需要通过纵向反馈来达到抑制效果（1ms）
- 瞬态束流负载效应导致束团质心位置变化约±13 ps：对亮度影响不大



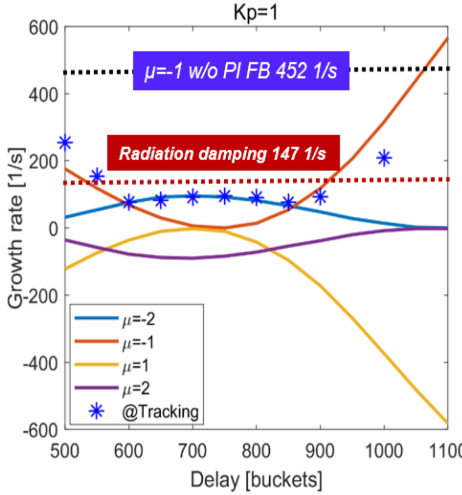
1 GeV

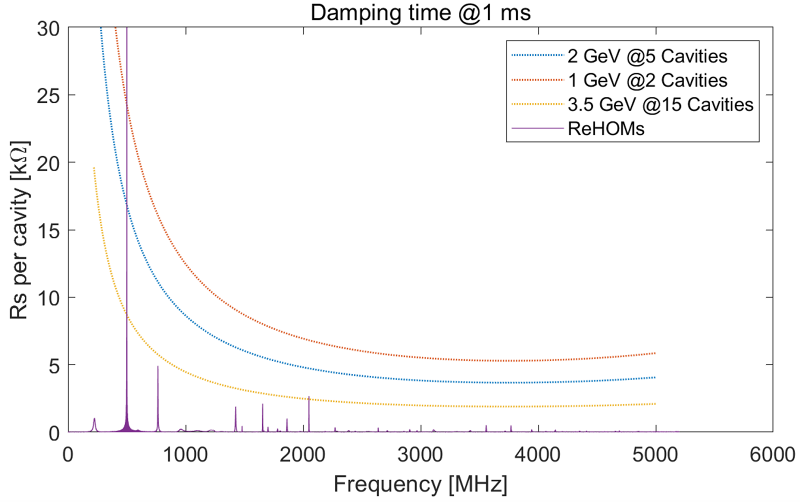


2 GeV



3.5 GeV





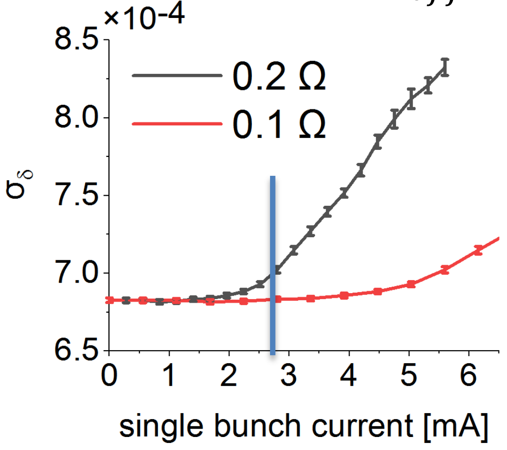
阻抗驱动的集体效应

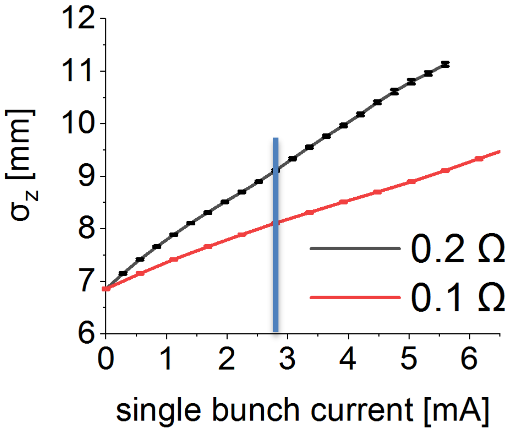
详见李伟伟报告

- 纵向微波不稳定性
  - 采用简单的宽带谐振子（BBR）模型估算 @ 2 GeV
  - 有效阻抗选取 0.2 Ω 和 0.1 Ω
  - 准确计算依赖于具体阻抗建模
  - 需严格控制阻抗预算

Keil-Schnell-Boussard criterion:

$$I_{th}\left|\frac{Z_{\parallel}}{n}\right|_{eff} < \frac{(2\pi)^{\frac{3}{2}}E_0\alpha_p\sigma_\delta^2\sigma_z}{C}$$





Single bunch current [mA] @ 2 GeV

- 横向耦合模式不稳定性TMCI

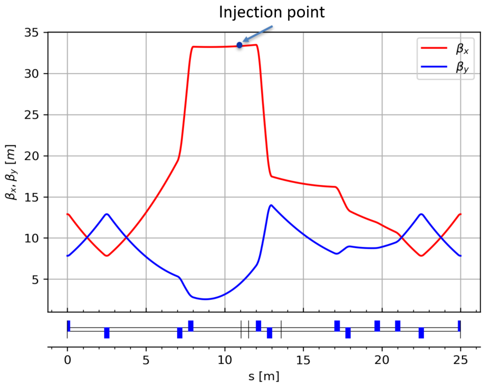
$$I_{th} = \frac{4\pi\nu_s(E_0/e)}{T_0\sum_i \beta_{y,i}k_{y,i}} \rightarrow \sum_i \beta_{y,i}k_{y,i} < 78\ \mathrm{kV/pC/m}$$

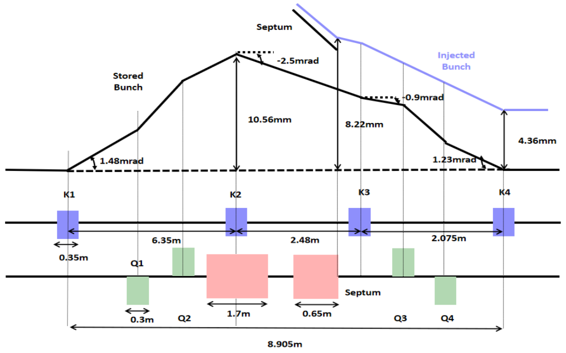
  - 限制单束团流强阈值
  - 准直器起主导作用
  - 后面根据准直器的阻抗模型进行计算

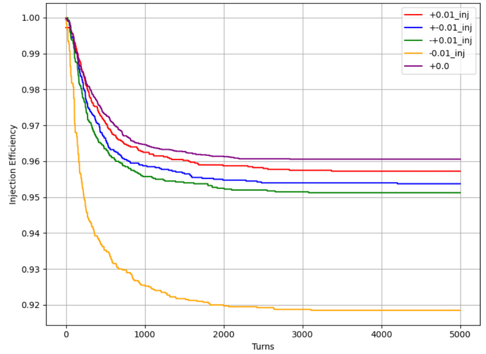
- 电阻壁不稳定性
  - 假设全环 25 mm半径铝制真空室 -> 不稳定增长率 1.6 ms^{-1}
  - 采用横向逐束团反馈进行抑制

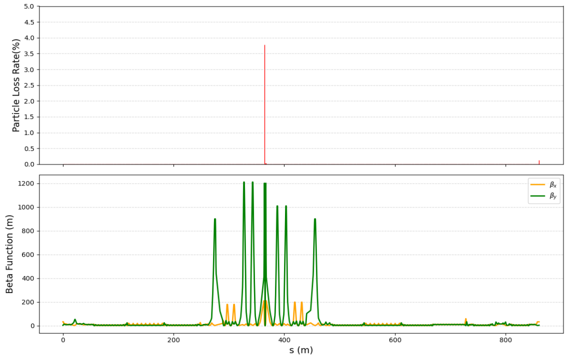
束流注入-离轴注入

- 兼容离轴与置换注入的光学设计，前期采用离轴注入，后期切换到置换注入
- 离轴注入: 技术成熟，注入器相对简单；需大动力学孔径，造成对撞区束流损失，增大本底
  - 切割磁铁+凸轨磁铁
  - 注入效率: ~95% (ideal) → ~70% (考虑septum漏场和注入位置误差)
  - 束流主要损失在对撞点上游超导四极铁处
  - 需通过束流准直系统准直丢失粒子







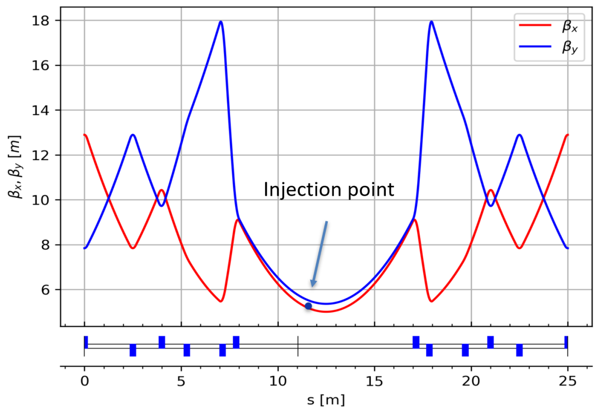


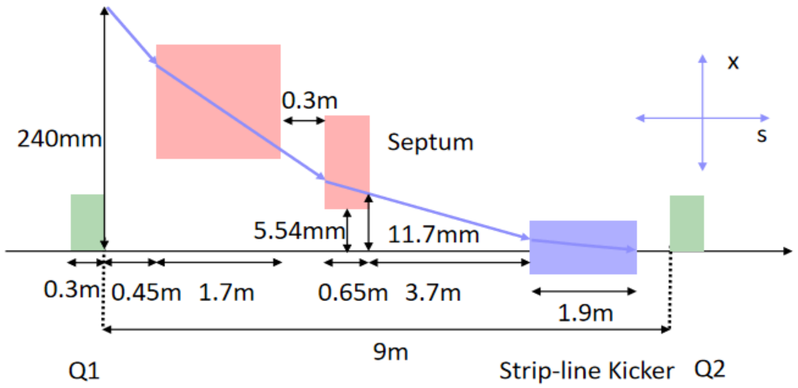
参数名称	数值
注入点环内/环外β_x [m]	33.34/11.53
注入束角度 [mrad]	-2.45
注入点凸轨高度 [mm]	3.86
注入点凸轨角度 [mrad]	-2.50
凸轨回落后注入束位置 [mm]	4.36
凸轨持续时间 [圈]	1
凸轨磁铁长度 [mm]	350
凸轨磁铁最大偏转角度 [mrad]	<3.5
凸轨磁铁磁场强度 [Gs]	< 1167
薄切割板高度 [mm]	5.54
薄切割板厚度 [mm]	1.0
薄切割磁铁机械长度/有效长度 [mm]	0.65/0.6
薄切割磁铁磁场强度 [Gs]	5500
薄切割磁铁偏转角度 [mrad]	28
厚切割板厚度 [mm]	2.0
厚切割磁铁机械长度/有效长度 [mm]	1.7/1.3
厚切割磁铁磁场强度 [Gs]	9900
厚切割磁铁偏转角度 [mrad]	110

束流注入-置换注入

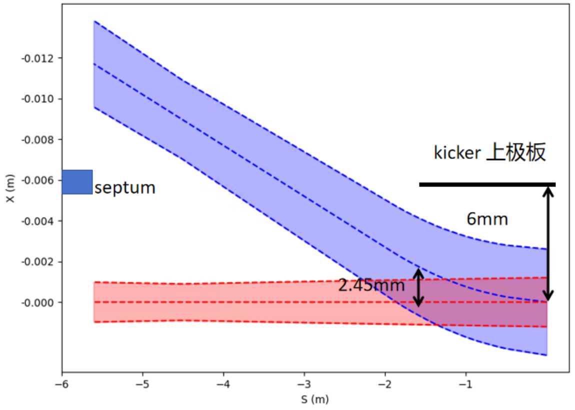
➢ 置换注入: 对动力学孔径需求低，束流本底噪声减少；注入器复杂且造价高

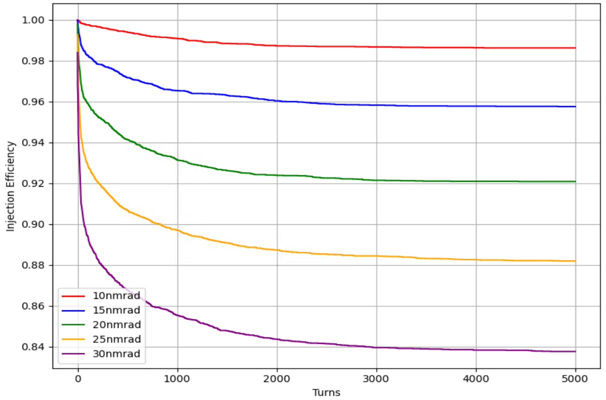
- 切割磁铁+条带型超快冲击磁铁，与离轴注入采用相同的切割磁铁设计
- 垂直发射度对注入效率影响较大，小于15 nmrad





参数名称	数值
冲击磁铁长度 [mm]	300
冲击磁铁偏转角度 [mrad]	0.5
冲击磁铁极板间距 [mm]	12
模块数量	5
上升/平顶/下降时间 [ns]	2/2/2
好场区 [mm]	±5
注入束进入冲击磁铁的位置 [mm]	2.45
电压幅值 [kV]	> 17.5
束团注入频率 [Hz]	30
薄切割板高度 [mm]	5.54
薄切割板厚度 [mm]	1.0
薄切割磁铁机械长度/有效长度 [mm]	0.65/0.6
薄切割磁铁磁场强度 [Gs]	5500
薄切割磁铁偏转角度 [mrad]	28
厚切割板厚度 [mm]	2.0
厚切割磁铁机械长度/有效长度 [mm]	1.7/1.3
厚切割磁铁磁场强度 [Gs]	9900
厚切割磁铁偏转角度 [mrad]	110





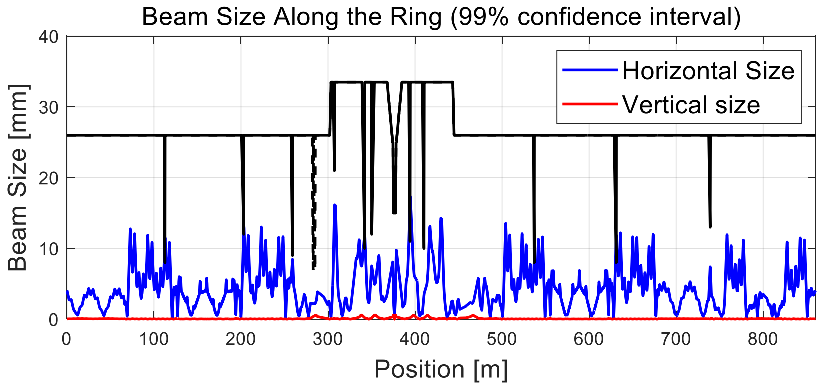
束流准直系统

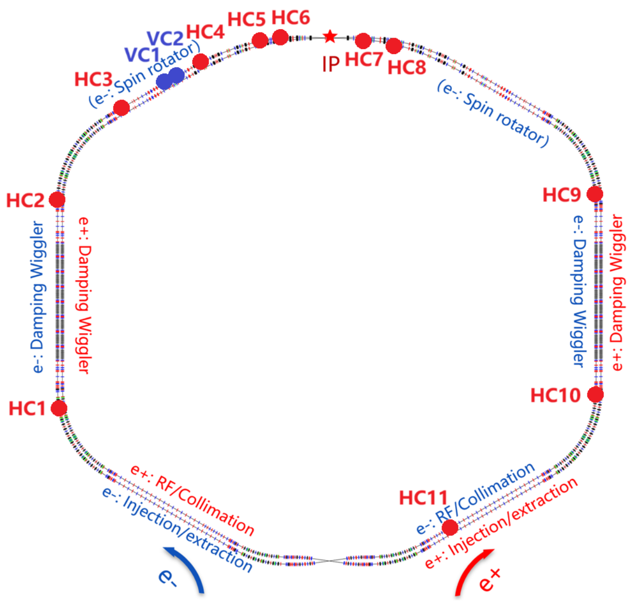
- 束流损失问题具有非常大的挑战(high luminosity, short Touschek lifetime)
- 束流损失机制研究: Touschek scattering effect, beam injection, beam-beam effect, beam-gas effect, beam sudden loss

Touschek scattering effect: calculate off-momentum optical function and beam size → Collimators are favorable to set at large beam size, optimize collimator number, gaps, materials.

- Each ring is equipped with 11 horizontal collimators and 2 vertical collimators.
- The minimum half gap is 7 mm.

Off-momentum beam size (-1%)



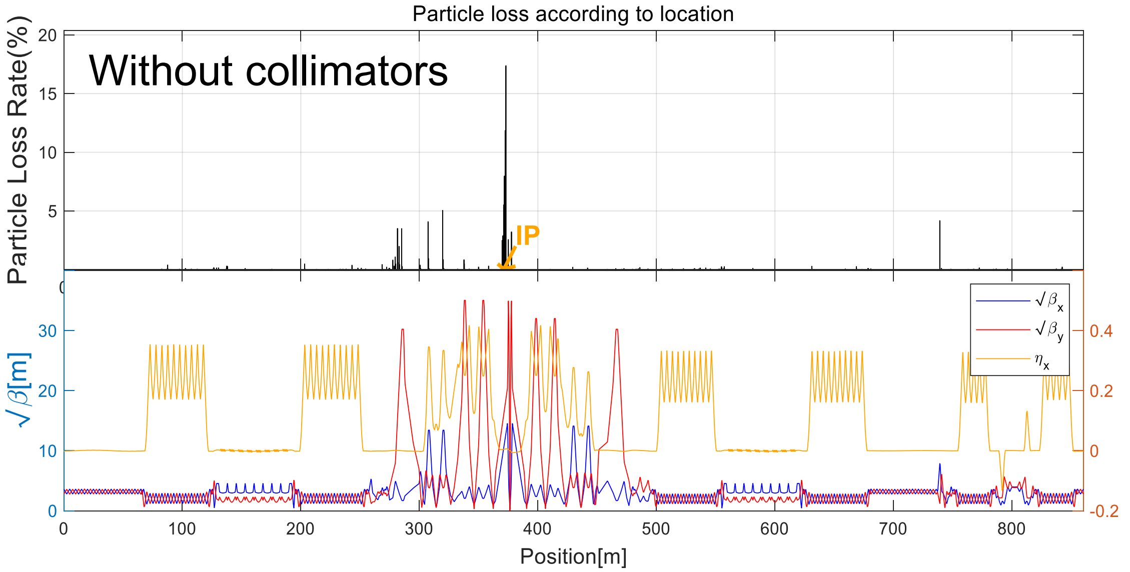


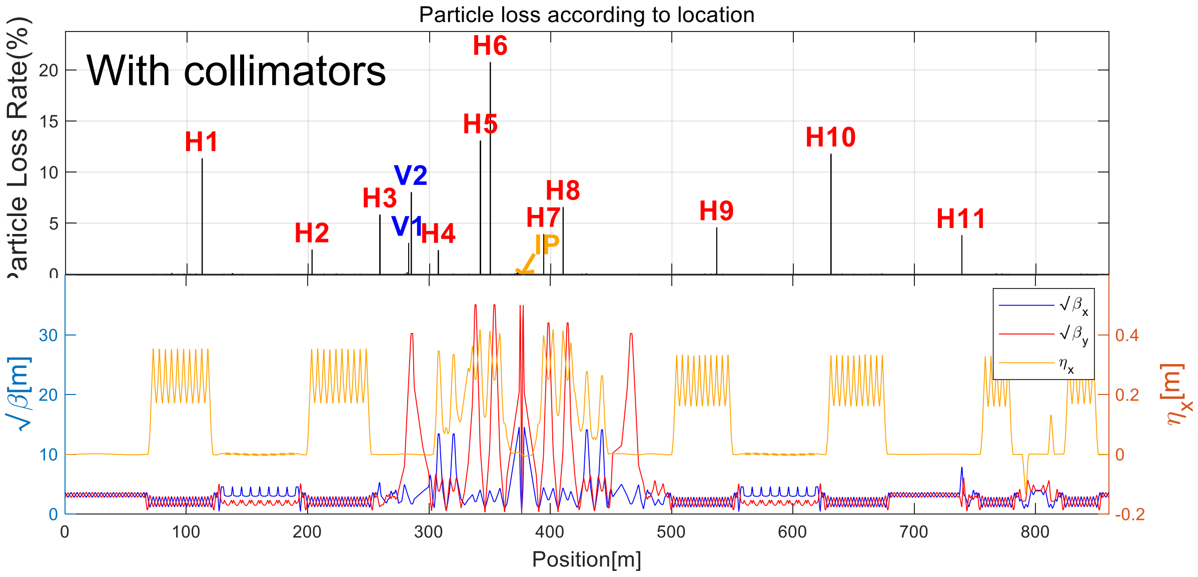
Collimator	Half gap [mm]	Half gap [*σ]	Position [m]	$\beta_{x/y}$[m]
HC1	8	24.10	112.62	8.03
HC2	12	36.29	203.18	7.98
HC3	9	25.14	259.15	27.68
HC4	21	23.31	307.34	161.11
HC5	10	23.55	342.05	15.99
HC6	12	28.65	350.23	15.34
HC7	11	26.09	394.21	18.91
HC8	10	23.23	410.23	18.36
HC9	8	25.48	536.91	7.52
HC10	8	25.47	631.15	7.57
HC11	13	24.27	739.09	61.99
VC1	7	49.38	282.87	1.53
VC2	7	34.54	285.06	1.61

Touschek 散射准直模拟结果

Without collimators：
- Approximately 58.2% of particle losses occur in IR (370 ~ 380 m);
- About 11.2% of losses occur in the CCX section upstream of the IR (300 ~ 320 m);
- Around 13.4% of particle losses happen near the crab sextupole magnet before the IR (270 ~ 290 m).

With collimators：
- Beam loss within ±20 m of the IP is approximately 1.3%;
- The remaining particles not intercepted by the collimators are uniformly distributed in the arc sections and DW regions;
- The collimation efficiency reaches 97.3%.





Beam loss distribution: (left) without collimators; (right) with collimators.

总结与展望

- STCF 核心目标: CoM energy range 2~7 GeV, 0.5×10^{35} cm^{-2} s^{-1} @ 4 GeV, Touschek lifetime > 200 s
- Lattice设计和非线性动力学优化
  - Lattice设计（V4.3）: 线性光学和非线性优化
  - 考虑准则误差和高阶场误差，并进行校正
  - Luminosity: ~1×10^{35} cm^{-2} s^{-1} @ 4 GeV
  - Touschek lifetime: >300 s with ideal lattice and >230 s with errors @ 4 GeV
- 束流集体效应
  - Crab waist方案可以有效提高对撞亮度 (1×10^{35} cm^{-2} s^{-1}), 需要避免出现X-Z不稳定性 (ν_z=0.0194 > 3 ξ_x (0.005)), smaller β_x^* is favorable (40 mm)
  - 模拟中发现空间电荷效应，影响不是很严重
  - 需严格控制阻抗预算
- 下一步工作：
  - 第5版lattice设计：减小β_x^* ，缩短DW长度，缩短周长
  - 继续深入研究束流动力学，进一步提高动力学孔径，动量接受度，从而提高Touschek寿命
  - 建立阻抗预算，深入研究束流集体效应
  - 继续研究束流注入引出、束流准直系统

周例会

Home » Experiments » STCF » Accelerator » Collider Ring Group Meeting (CRAP)

Collider Ring Group Meeting (CRAP)

输入您的搜索词

对撞环物理设计组会

2025年7月

- 7月02日 STCF Collider Ring Physics Weekly Meeting

2025年6月

- 6月25日 STCF Collider Ring Physics Weekly Meeting
- 6月18日 STCF Collider Ring Physics Weekly Meeting
- 6月11日 STCF Collider Ring Physics Weekly Meeting

以前的65个事件。 显示

STCF Collider Ring Physics Weekly Meeting

星期三 2025年6月18日 14:00 → 16:50 Asia/Shanghai

说明 腾讯会议链接：https://meeting.tencent.com/dm/Jq04JyPO6CW2

#腾讯会议：452-9293-2730

14:00 → 14:05	唐靖宇-本周情况通报	5m
14:05 → 14:10	邹野-CRAP 系统主要信息	5m
14:10 → 14:40	注入引出进展 报告人: 泽 于 2025.6.18.pptx	30m
14:40 → 15:05	对撞区crab-waist对束流效果 报告人: 虞焓 金 jinyuhan_20250618...	25m
15:05 → 15:25	束束相互作用进展 报告人: 德民 周 20250618_BB(1).pdf	20m
15:25 → 15:45	各子任务进展报告	20m
15:45 → 15:55	会议纪要 STCF-对撞环物理设...	10m

会　议　纪　要

STCF 对撞环物理设计周例会　　2025 年 6 月 18 日

会议形式：线下（科技实验楼东楼 1603 会议室）

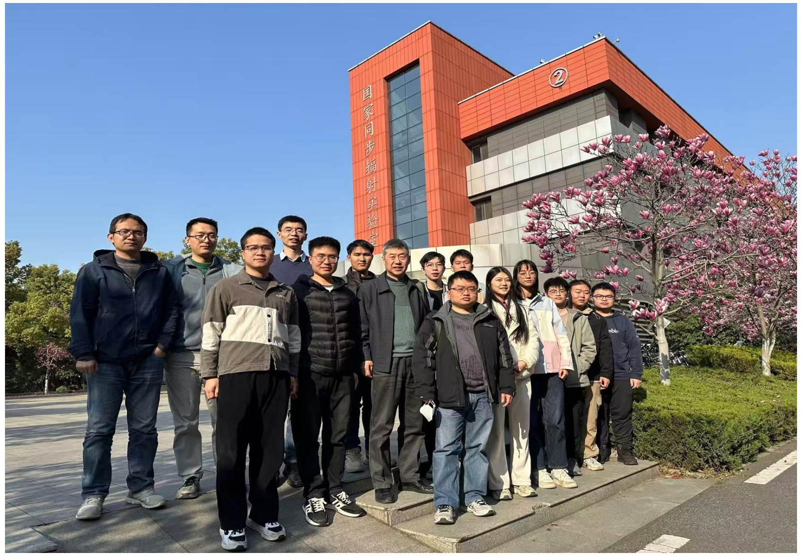
时间：2025 年 6 月 18 日 14:00-17:00

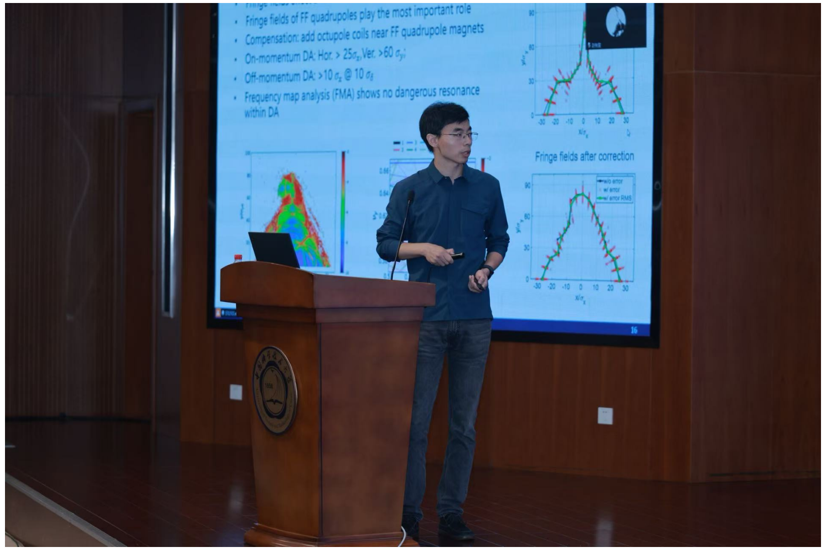
腾讯会议：807-5464-4247

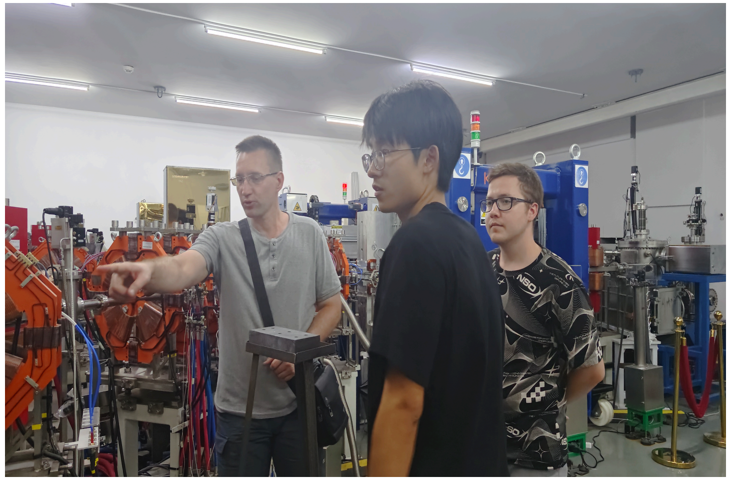
参会人员：

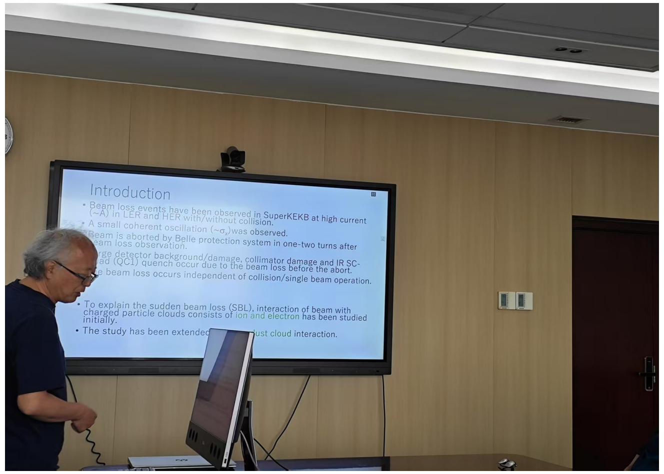
- 线下参加：唐靖宇、邹野、刘涛、张林浩、李桑丫、莫钛豪、李航洲、周昊、梁文姝、高嘉俊、金虞焓
- 线上参加：吴英志、原有进、周德民、彭海平、樊宽军、王磊、蔡承颖、常铭轩、于泽、鲍楗聪、李伟伟、何天龙、杨鹏辉、罗箐
- 请假：无
- 主持人：邹野
- 记录和纪要整理： 莫钛豪/张林浩

Acknowledgments









请各位专家批评指正！