



清华大学
Tsinghua University

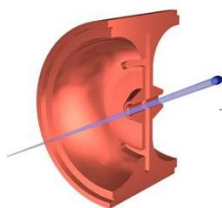
先进光源物理研讨会

稳态微聚束储存环纵向强聚焦物理设计

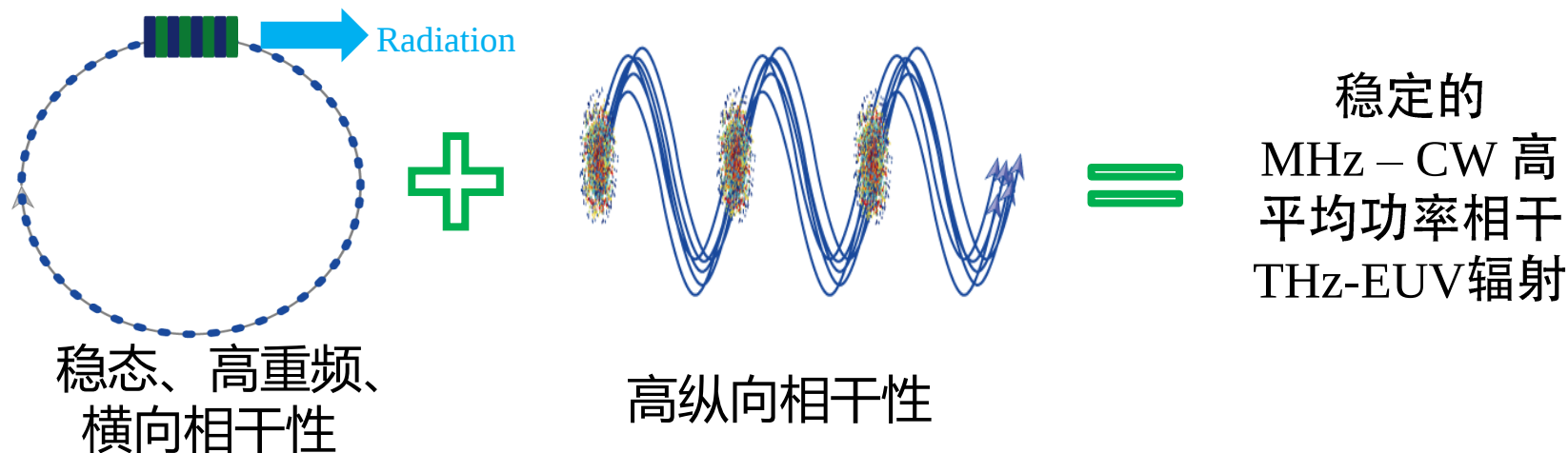
Design of Longitudinal Strong Focusing SSMB Ring

张 耀

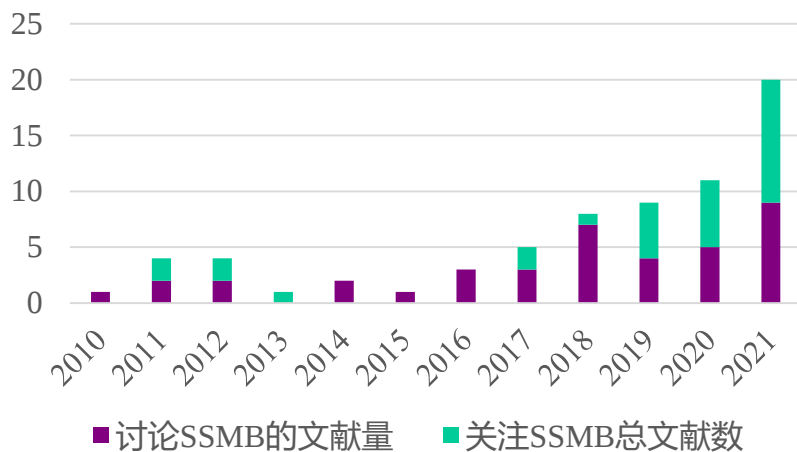
2022年08月21日



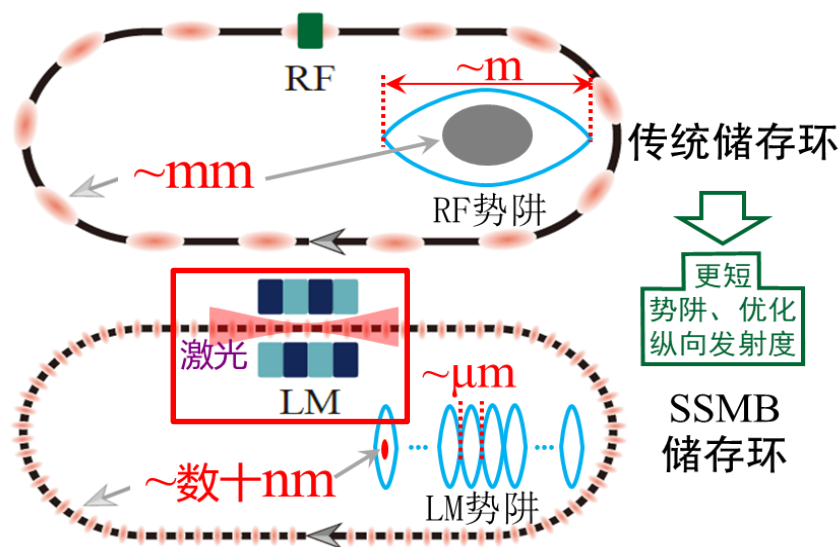
Accelerator Laboratory of Tsinghua University

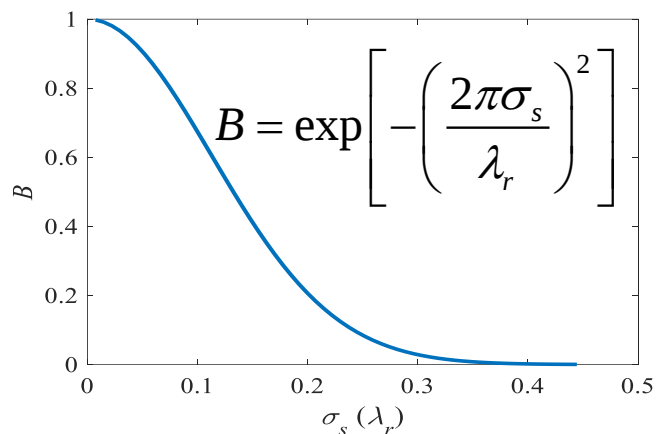


SSMB关注度的发展



SSMB的核心 在储存环全环内或者局部地方产生 稳态的超短束团

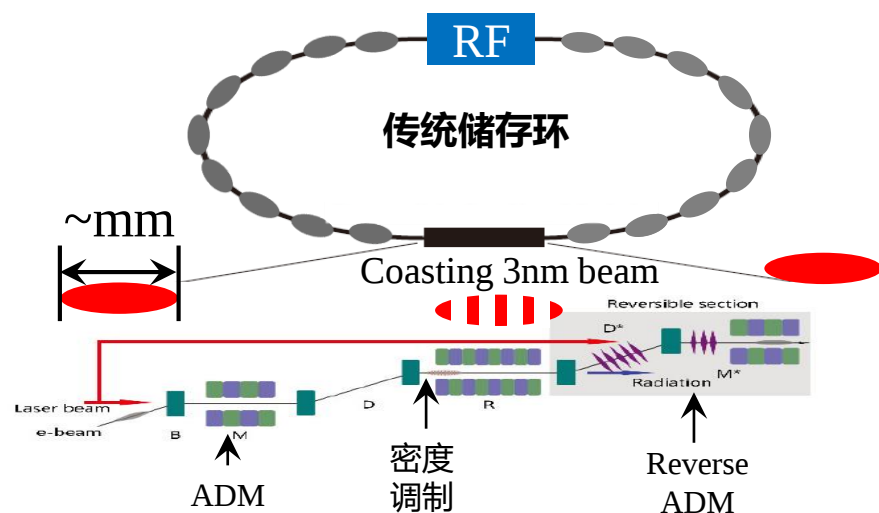




$$\lambda_r = 13.5 \text{ nm} \longleftrightarrow \sigma_s < 3 \text{ nm}$$

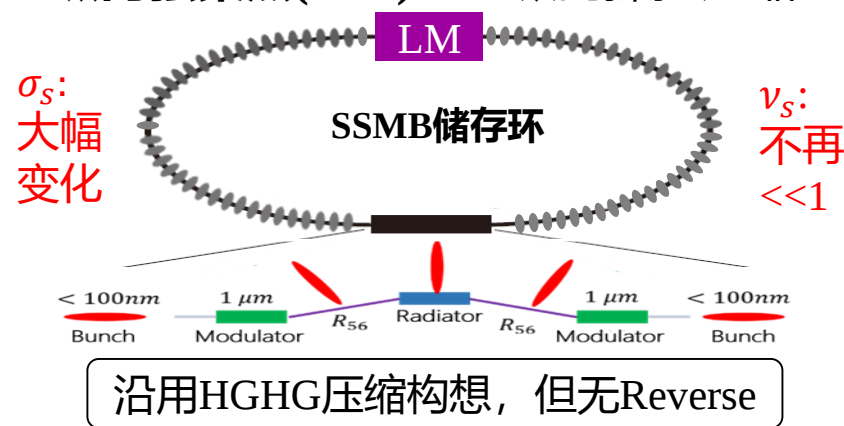
典型储存环束长
亚毫米~厘米量级

Reversible

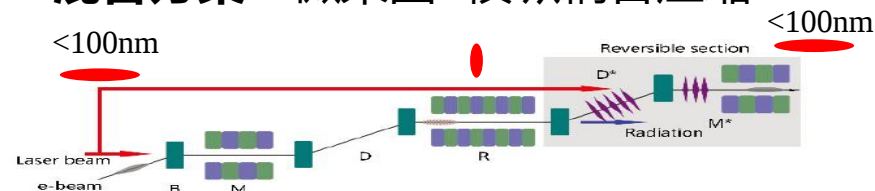


采用PEHG/ADM等可实现高次谐波的聚束方案 + 能量调制、反调制的精确抵消

纵向强聚焦(LSF): 纯纵向操控压缩



混合方案: 微束团+横纵耦合压缩



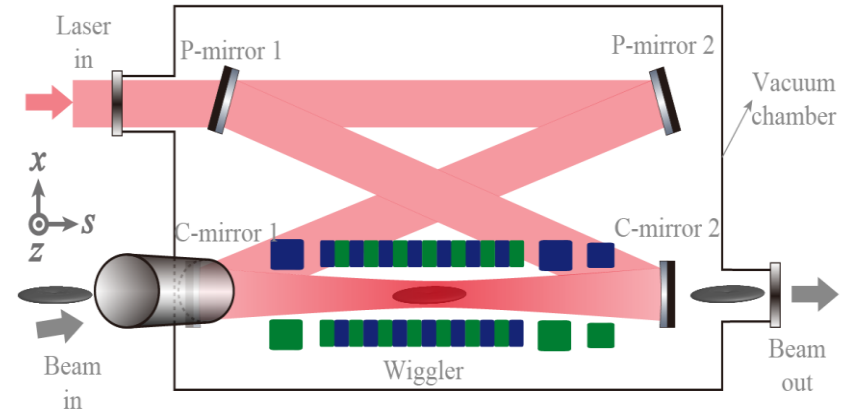
- 波长在微米级的能量调制，比RF更强的调制强度
- 微米级长度的纵向bucket
- 与RF主要存在两方面的区别

- 纵向传输矩阵

$$\text{RF} \quad \begin{pmatrix} 1 & 0 \\ \pm h & 1 \end{pmatrix}$$

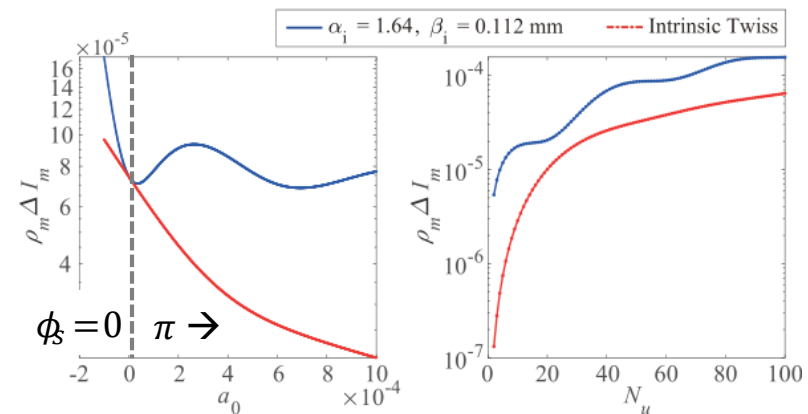
$$\text{LM} \quad \begin{pmatrix} \cos \Delta \psi & \frac{2 \sin \Delta \psi}{\nu_m k} \\ -\frac{\nu_m k \sin \Delta \psi}{2} & \cos \Delta \psi \end{pmatrix}$$

- ν_m : LM单周期纵向tune advance
- $\Delta \psi = 2\pi N_u \nu_m$: LM纵向phase advance

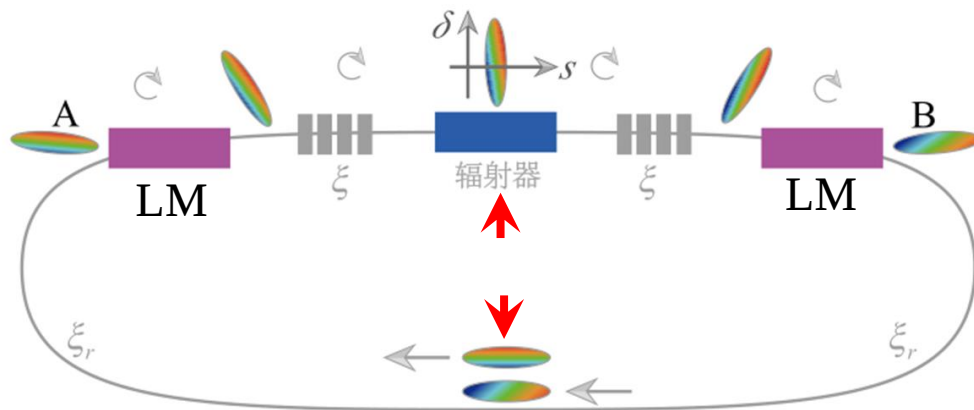


- 对纵向发射度的贡献

无



- $\phi_s = \pi$ 时，激光功率↑， ΔI_m ↓ 0.1~10
- $\phi_s = 0$ 时，激光功率↑， ΔI_m ↑ 皮米



➤ 线性化的纵向单圈map

$$T_R = \begin{pmatrix} 2\varphi\varphi_r - 1 & \frac{2\varphi}{h}(\varphi\varphi_r - 1) \\ 2h\varphi_r & 2\varphi\varphi_r - 1 \end{pmatrix}, \quad \beta_R = \frac{1}{|h|} \sqrt{\frac{\varphi(1 - \varphi\varphi_r)}{\varphi_r}} = \left| \frac{\varphi}{h} \tan(\pi\nu_z) \right|, \quad \sigma_{zR} = \sqrt{\epsilon_z \beta_R}$$

$$T_{Ro} = \begin{pmatrix} 2\varphi\varphi_r - 1 & \frac{2\varphi_r}{h}(\varphi\varphi_r - 1) \\ 2h\varphi & 2\varphi\varphi_r - 1 \end{pmatrix}, \quad \beta_{Ro} = \frac{1}{|h|} \sqrt{\frac{\varphi_r(1 - \varphi\varphi_r)}{\varphi}} = \left| \frac{\varphi_r}{h} \tan(\pi\nu_z) \right|, \quad \sigma_{zRo} = \sqrt{\epsilon_z \beta_{Ro}}$$

➤ 压缩系数

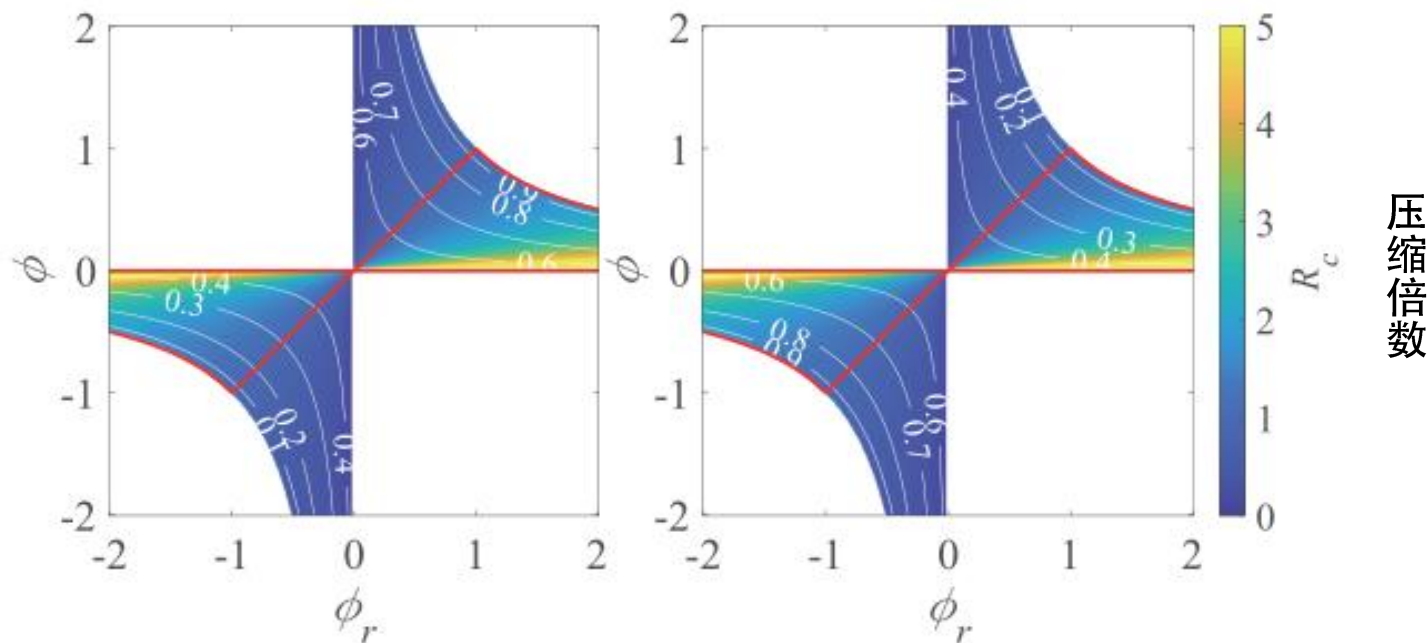
$$R_c = \frac{\sigma_{sRo}}{\sigma_{sR}} = \sqrt{\frac{\beta_{Ro}}{\beta_R}} = \sqrt{\frac{\varphi_r}{\varphi}} \quad \text{条件: } R_c > 1$$

➤ 纵向tune

$$\cos(2\pi\nu_s) = 2\phi\phi_r - 1$$

➤ 稳定性条件

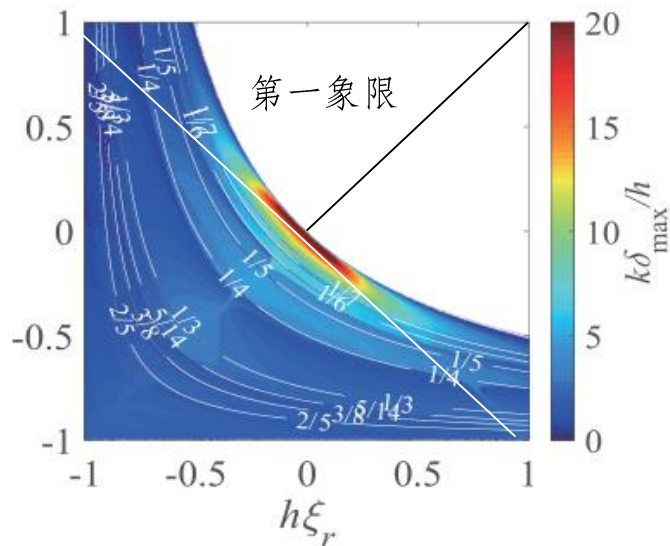
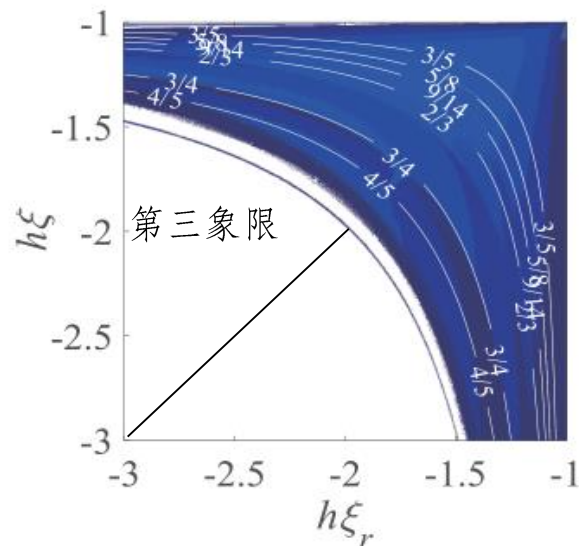
$$0 < \phi\phi_r < 1$$



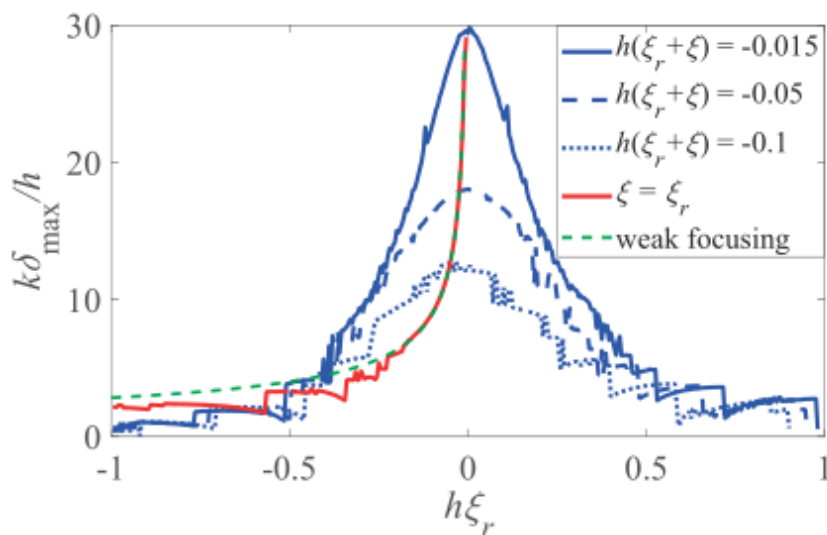
稳定的参数空间 (左: $h > 0$; 右: $h < 0$)

- 压缩倍数极大和极小的区域，纵向tune均靠近0.5，处于不稳定的边缘
- 压缩系数 $R_c > 1$ 导致一半参数可取

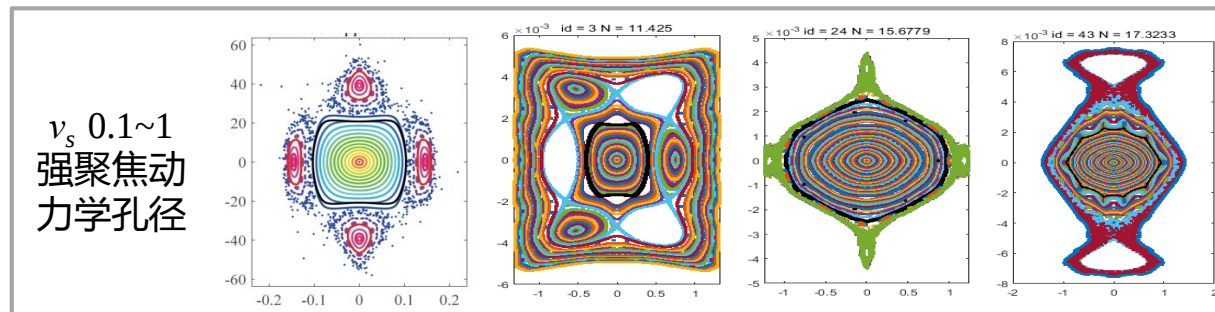
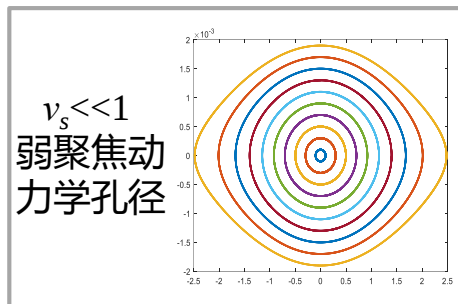
纵向动力学孔径



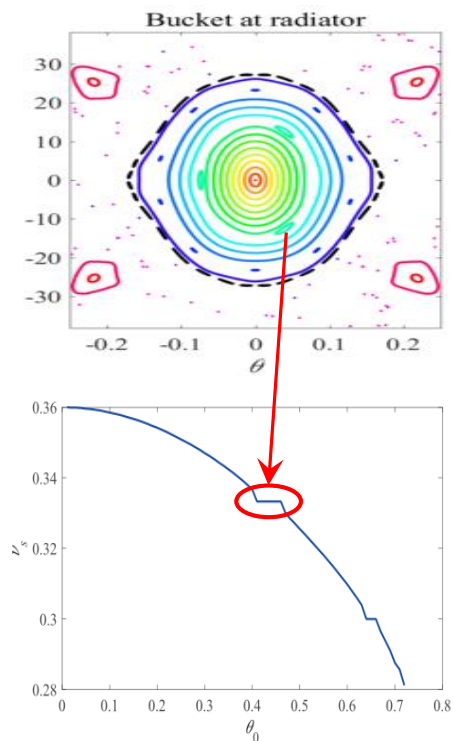
- 第三象限 R_{56} 较大动力学孔径小
- $h\xi_r$ 和 $h\xi$ 较小（准等时环）时的动力学孔径较大
- 两个特殊方向：
 - ① $\xi_r + \xi = 2R_{56}$ ：强聚焦段和主环 r_{56} 相消
 - ② $\xi_r = \xi$ ：单RF的双周期模式



纵向动力学孔径



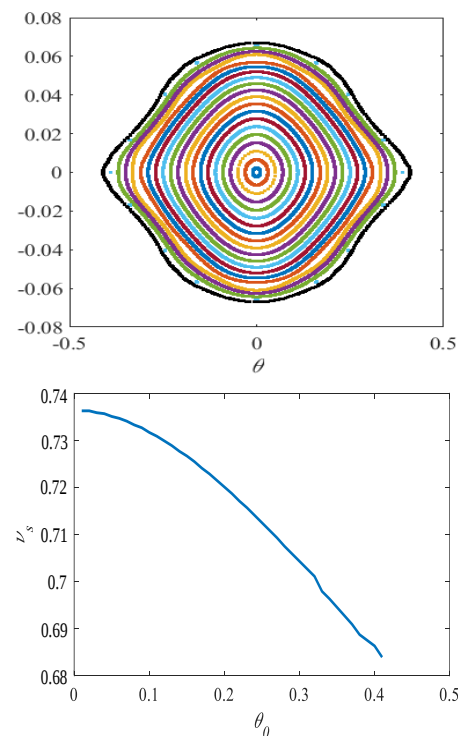
纵向动力学孔径中的Amplitude Dependent Tune Shift (ADTS)



v_s 共振线:

$$\left(\frac{1}{2}, \frac{2}{5}, \frac{3}{8}, \frac{5}{14}, \frac{1}{3}, \frac{1}{4}, \frac{1}{5}, \frac{1}{6}, \frac{1}{8} \right)$$

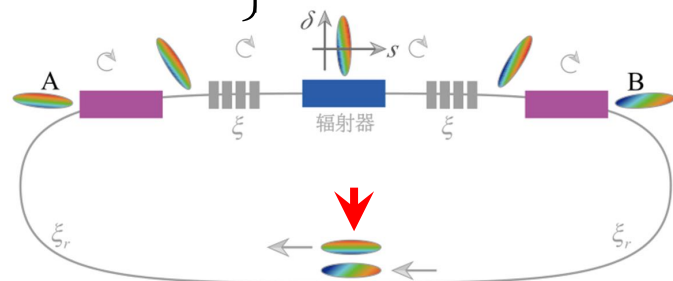
- 遇共振线时可能会出现共振小岛
- 好的纵向动力学孔径: 干净、无共振小岛



$$\epsilon_z = \frac{C_0 \gamma_c^5}{2D_z} \left\{ \frac{2\pi}{\rho_c^2} \left[\frac{1}{\gamma_{Ro}} + \xi_r^2 \gamma_{Ro} \right] - f_{lat} \gamma_{Ro} + 2\Delta I_m \right\}$$

➤ 在 $\nu_z \rightarrow 0$ 或者0.5两个极限下的束长和能散

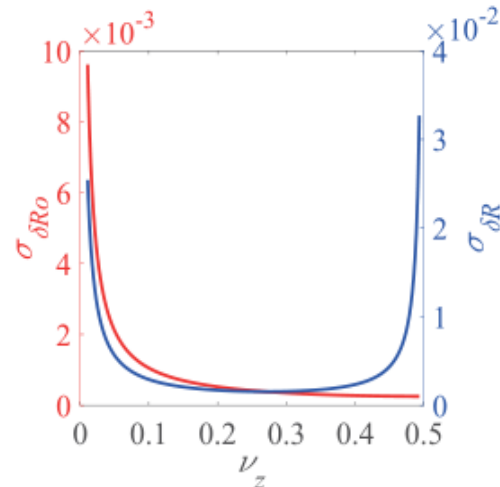
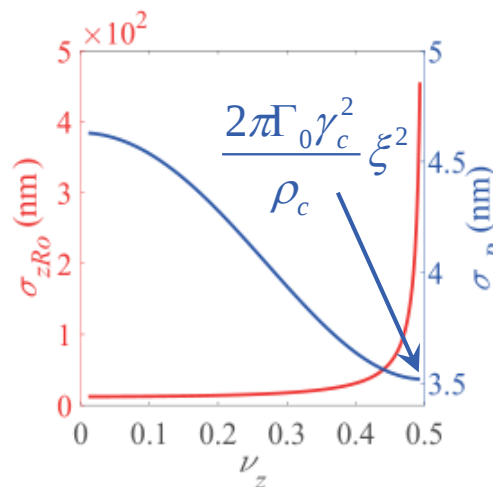
- 如果束长收敛，能散必定发散；反之亦然
- 较高压缩倍数和较大动力学孔径在 $\nu_z = 0.5$ 附近，束长不易改变，能散发散



$$\sigma_{\delta Ro}^2 \Big|_{\nu_z \rightarrow 1/2} = \frac{C_0 \gamma_c^5}{2D_z} \left(\frac{2\pi}{\rho_c^2} + 2C_{m\beta} \right);$$

$$\sigma_{zR}^2 \Big|_{\nu_z \rightarrow 0} = \frac{(\xi + \xi_{mH})^2}{(\xi_r + \xi_{mH})^2} \sigma_{zRo}^2 \Big|_{\nu_z \rightarrow 0};$$

$$\sigma_{zR}^2 \Big|_{\nu_z \rightarrow 1/2} = (\xi + \xi_{mH})^2 \sigma_{\delta Ro}^2 \Big|_{1/2}$$

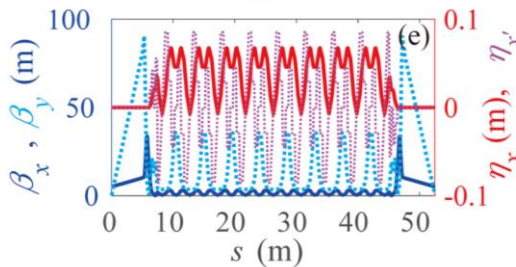
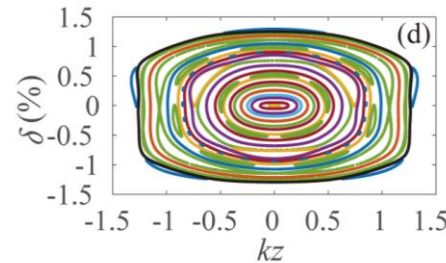
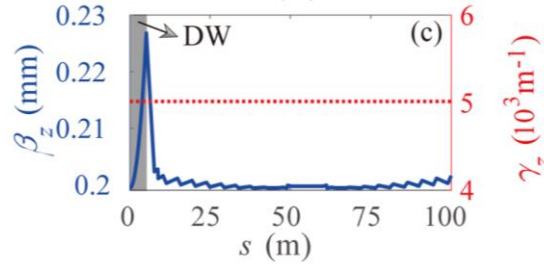
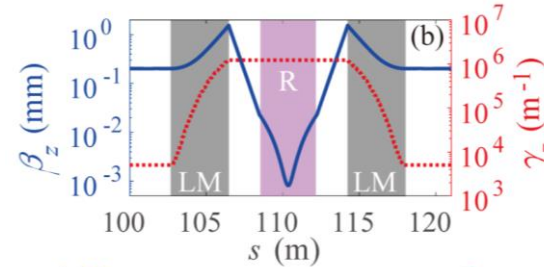
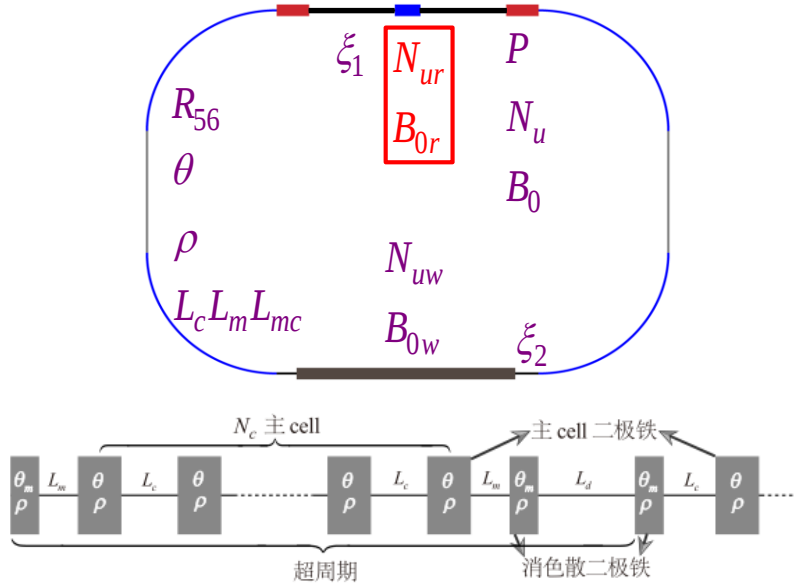


- LM本身对发射度的贡献和其 R_{56} ，导致压缩更困难
- 但LM本身对纵向阻尼系数的贡献对此压缩过程难度有所改善
- 增加damping wiggler，提高单圈的辐射损失，增大 D_z 以降低纵向发射度

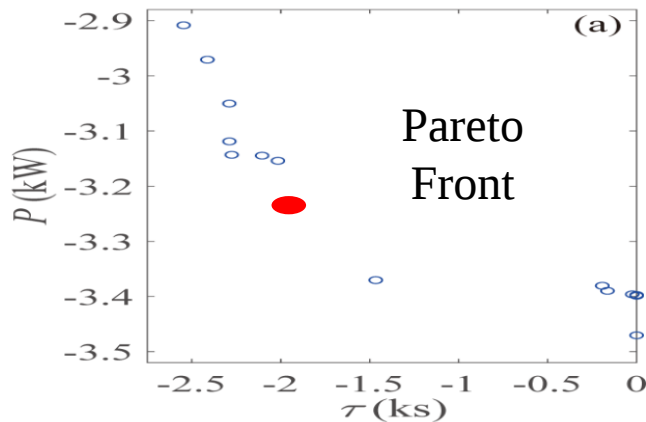
SSMB纵向强聚焦储存环初步设计

10

2LMs+DW+11BA(4 supper cells)

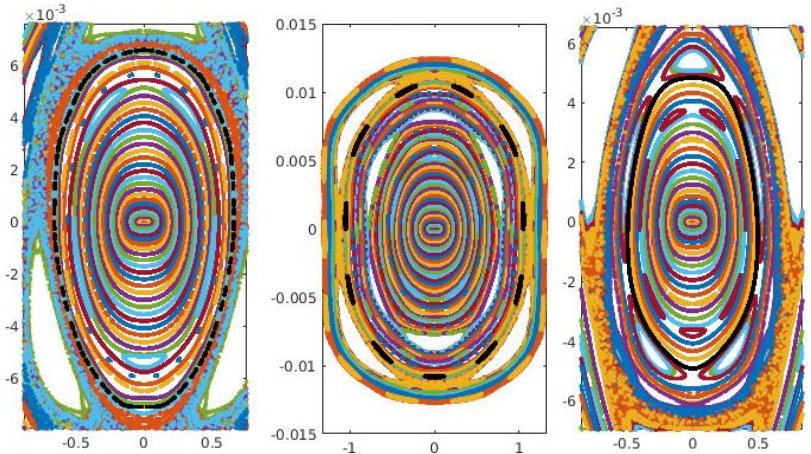
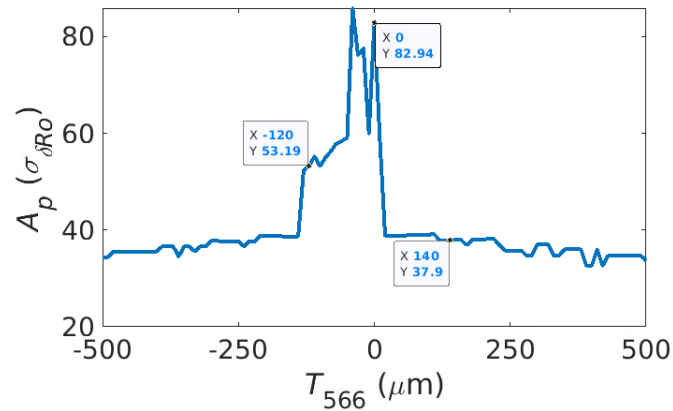


MOGA(目标: 辐射功率/Touschek寿命, 17变量)

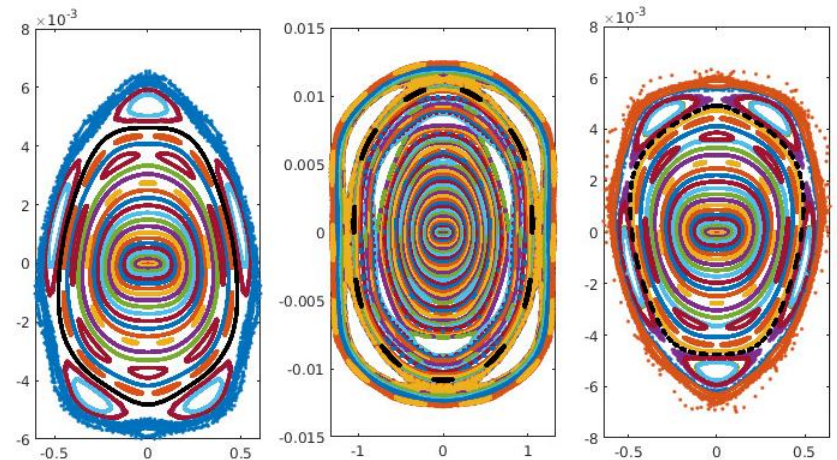
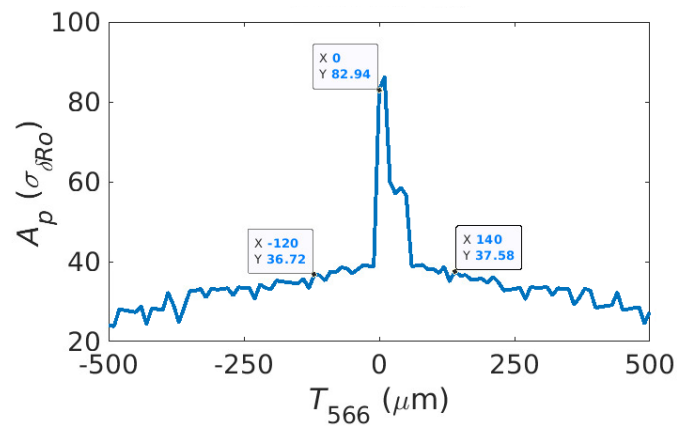


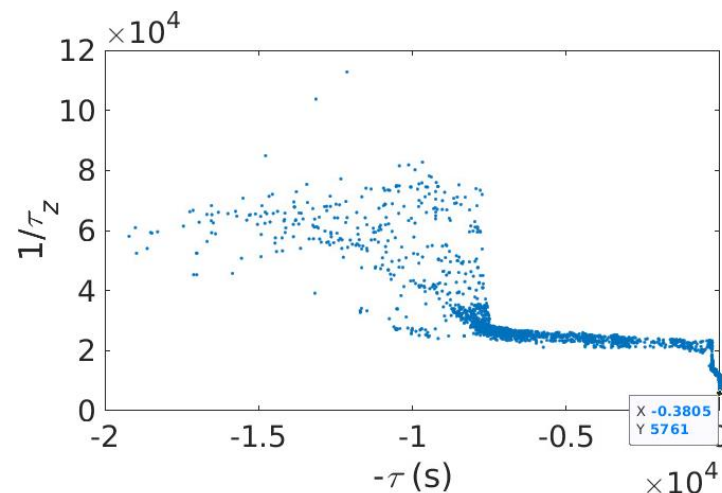
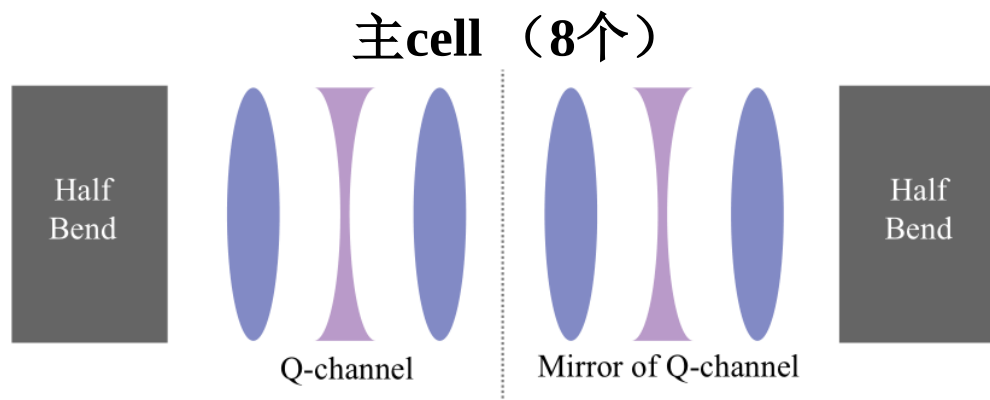
Paras.	Value
P_{laser}	300 MW
ε_x	24 pm
ε_s	4.68 pm
σ_{srad}	2.10 nm
σ_{drad}	2.20E-3
σ_{sring}	28.30 nm
σ_{dring}	1.65E-4
Iwidth	1.09E-2
τ_{DL}	388 ms
U_0	756 eV
I	1 A
τ_{touschek}	2000 s
P_{EUV}	3200 W

主环非线性



LSF段非线性





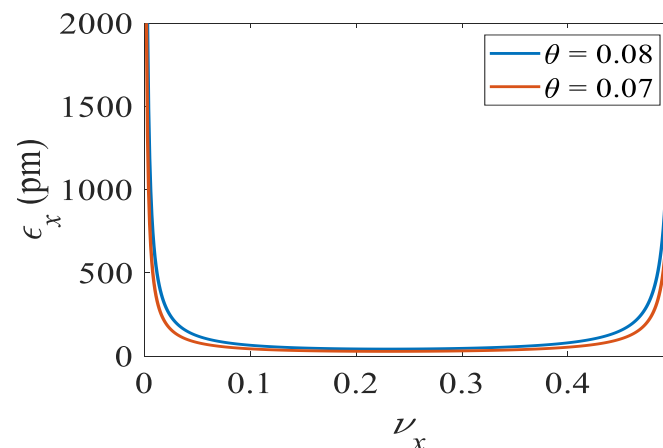
问题： 纵向IBS增长率无法降低 $\leftarrow$ 增大横向发射度，同时维持纵向束长

- 非线性：六极铁相位要求， $\nu_x = N/8$
- 纵向发射度： R_{56} & η_c ，以及二极铁中心处 $\eta'_c = 0$

$$\beta_{xc} = \left| \frac{\eta_c - \rho(1 - \cos \theta_H)}{\sin \theta_H} \tan(\pi \nu_x) \right|$$

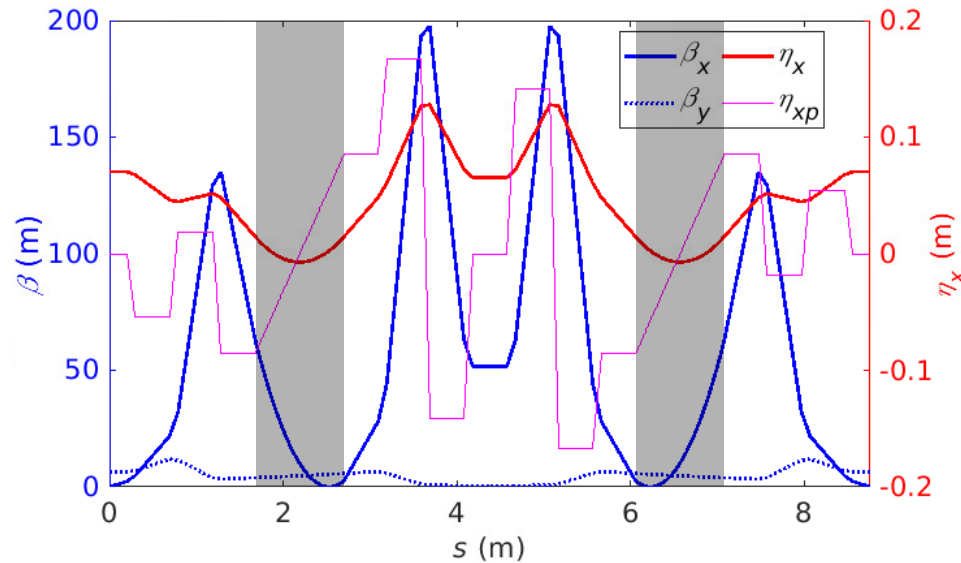
$$\Delta I_5 = \int \frac{\gamma_x \eta^2 + 2\alpha_x \eta \eta' + \beta_x \eta'^2}{|\rho|^3 (s)} ds$$

这意味着 $\epsilon_x(\theta_H, \nu_x)$



CFB η_c
or η'_c
not β_{xc}
 α_{xc}

- $\alpha_{xc}=0, \eta'_c=0$ 为 ϵ_x 的最小化条件
- $\eta'_c=0$ 为 ϵ_z 的最小化条件
- 每个主cell R_{56} 的要求



优化后, 利用 SLIM 方法, $\epsilon_x = 4.2 \text{ nm}$ $\frac{1}{\tau_z} = 57 \text{ s}^{-1}$

THU SSMB纵向强聚焦储存环拟采用双LM纵向强聚焦的方案在辐射点处实现长度小于三纳米的微束团，并产生以此产生大功率极紫外辐射

- LM是实现SSMB的关键器件，但相比RF，它的纵向传输矩阵不同，且会对横纵向发射度有贡献
- 对双LM纵向强聚焦方案分析后，发现在 $v_z \rightarrow 0$ 或者0.5两个极限下，纵向发射度趋于发散。但辐射点处较短的束长出现在 $v_z \rightarrow 0.5$ ，此时能散趋于发散
- 利用MOGA对THU SSMB纵向强聚焦储存环进行了初步设计，可实现的束长约2.1nm，Touschek寿命在2000s水平，辐射功率约3.2kW，且对 T_{566} 的容忍度较好
- 在保证纵向发射度的情况下，打破主cell二极铁中心处 $\alpha_{xc}=0$ 的条件可更好的增加横向稳态发射度，降低纵向IBS增长率

**感谢聆听！
请批评指正！**