SSMB Online Workshop, Tsinghua, 2020-12

Beam Quality Preservation in a Triplet Bend Achromat (TBA) with stable optics

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2020-12

work to be submitted

Congratulations!

- Success of the phase I experiment
- Impressive progress on key physics and technology R&D
- More and more close to be reality
- Wish great success of planned SSMB project

work to be submitted

Before entering the topic

- The presented work has some similarity to the SSMB (strong focusing) lattice design

- SSMB lattice design: min. α_p (& high order) & min. partial α_p

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- This TBA design: min. α_p (& high order) & min. $\Delta\varepsilon$ (due to CSR)
  CSR: Coherent synchrotron radiation

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- This TBA design: min. α_p (& high order) & min. $\Delta\varepsilon$ (due to CSR)

CSR: Coherent synchrotron radiation

What we want: when a high quality beam (low emittance, short bunch length) passes thorough a beam line, one can keep the beam distribution in 3D space (except in d dimension) as much as possible.

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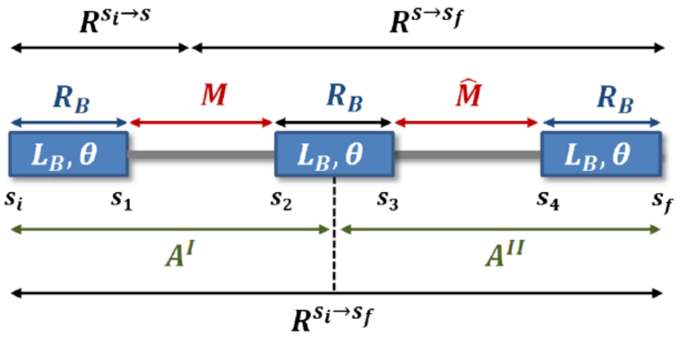
Previous TBA design study

- In Ref. [1], Venturini have designed a TBA satisfying
  - min. α_p (or R56 in Linac notation) & min. $\Delta\varepsilon$ (due to CSR)



$$R_B = \begin{pmatrix} 1 & L_B & 0 & L_B\theta/2 \\ 0 & 1 & 0 & \theta \\ \theta & L_B\theta/2 & 1 & L_B\theta^2/6 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad M = \begin{pmatrix} m_{11} & m_{12} & 0 & 0 \\ m_{21} & m_{22} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}.$$

[1] M. Venturini Phys. Rev. Accel. Beams 19, 064401 (2016).

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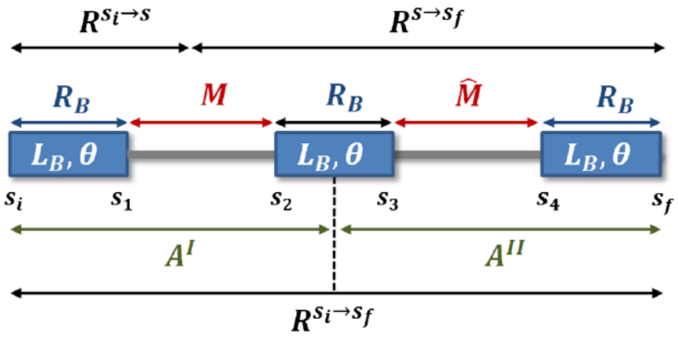

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To satisfy the above two conditions, the transfer matrix from the exit of the 1st dipole to the entrance of the 2nd dipole should have

$$m_{11} = 7/4$$
$$m_{12} = -9L_B/8$$
$$m_{21} = 15/(2L_B)$$
$$m_{22} = -17/4$$

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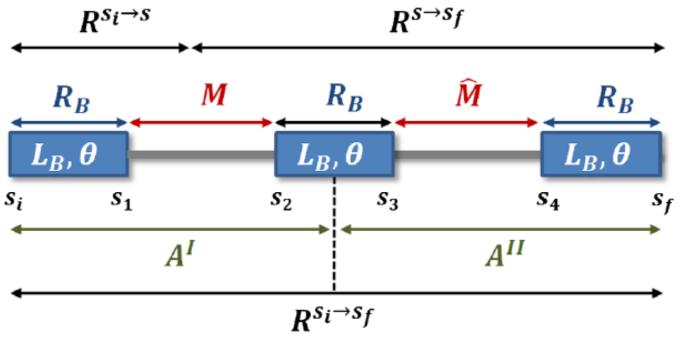

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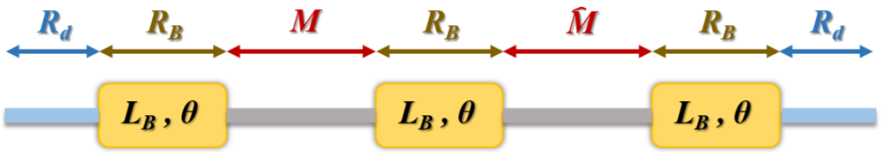
Transfer matrix of TBA:

$$\begin{pmatrix} \frac{139}{4} & \frac{117L_B}{8} & 0 & 0 \\ \frac{165}{2L_B} & \frac{139}{4} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

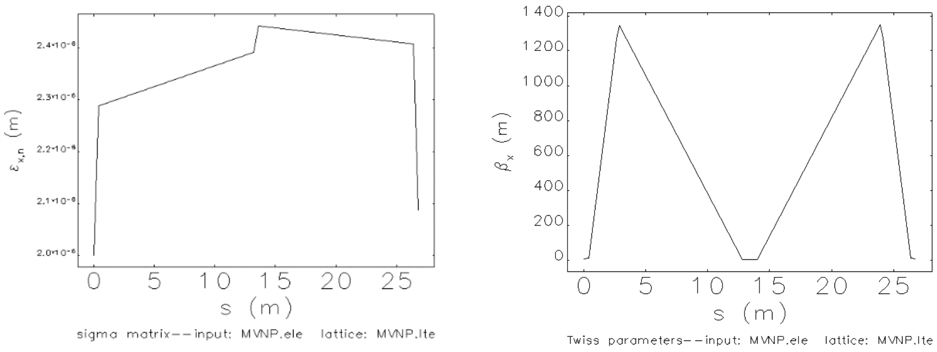
$\mathrm{Tr}(M_{total}) > 2$
Periodic optics stability criterion unsatisfied!

Not applicable to multi-TBA beamline

- If with only one of such cell with Tr(M) > 2, it is Ok.



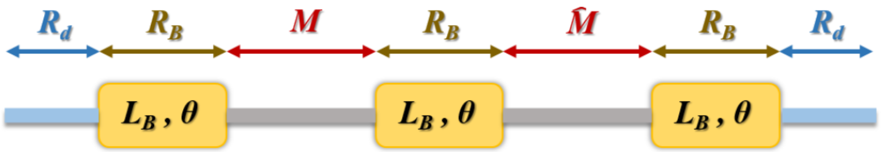
One TBA cell. left: emittance, right: β_x



work to be submitted

Not applicable to multi-TBA beamline

- If with only one of such cell with Tr(M) > 2, it is Ok.
- But, if having multi such cells, it will be difficult to control the optical functions and emittance growth.



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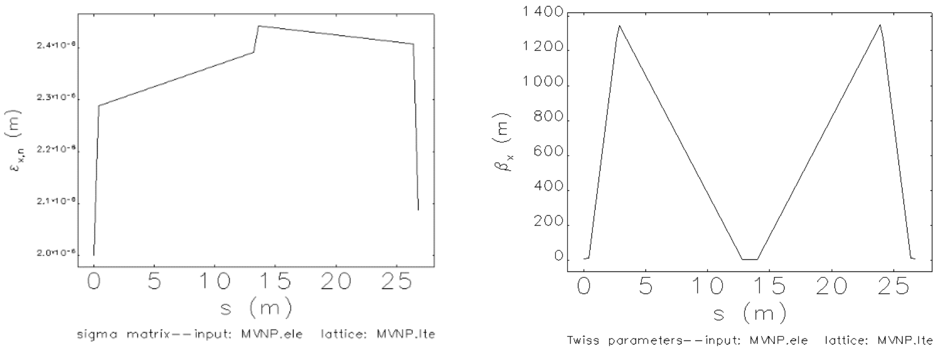
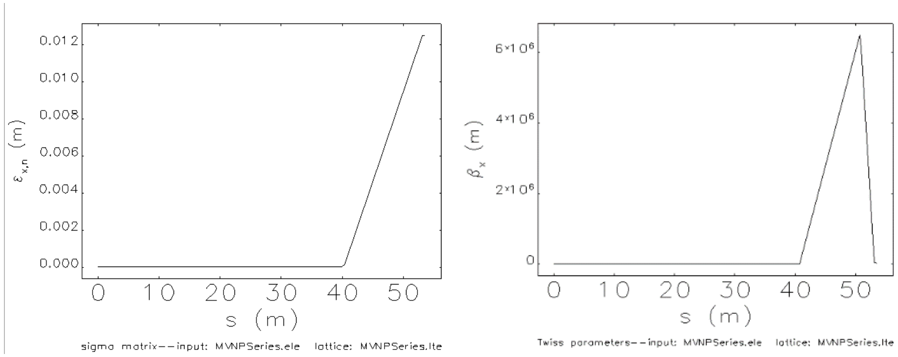


Two TBA cells. left: emittance, middle: β_x



If cell No. > 2, the effect is more significant

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CSR immune, isochronous & periodic stable?

- Three conditions instead of two conditions
  - min. α_p (or R56 in Linac notation) & min. $\Delta\varepsilon$ (due to CSR) & **$Tr(M_{total}) <= 2$**

work to be submitted

CSR immune, isochronous & periodic stable?

- Three conditions instead of two conditions
  - min. α_p (or R56 in Linac notation) & min. $\Delta\varepsilon$ (due to CSR) & **$Tr(M_{total}) <= 2$**

- After derivations (ignored here), we found a **new** solution

$$m_{11} = -2$$
$$m_{12} = 3L_B / 4$$
$$m_{21} = 0$$
$$m_{22} = -1/2$$

$$m_{11} = 7/4$$
$$m_{12} = -9L_B / 8$$
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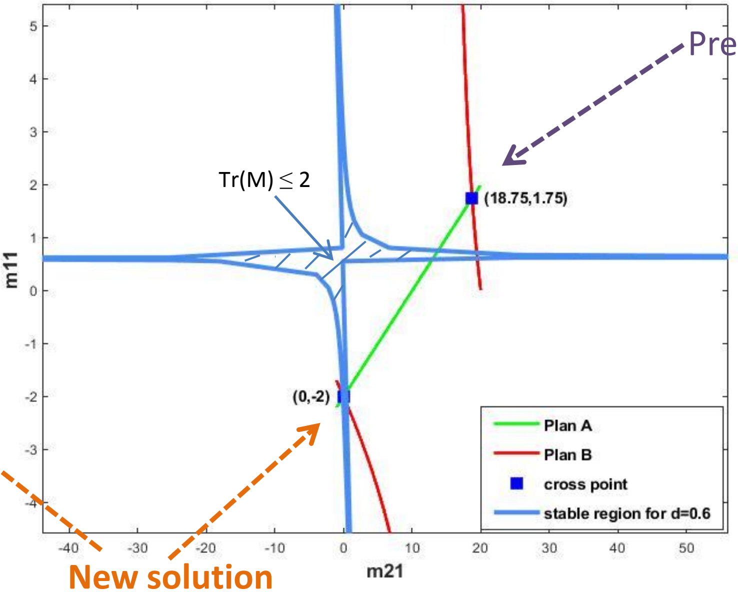
An example with L_B = 0.4 m



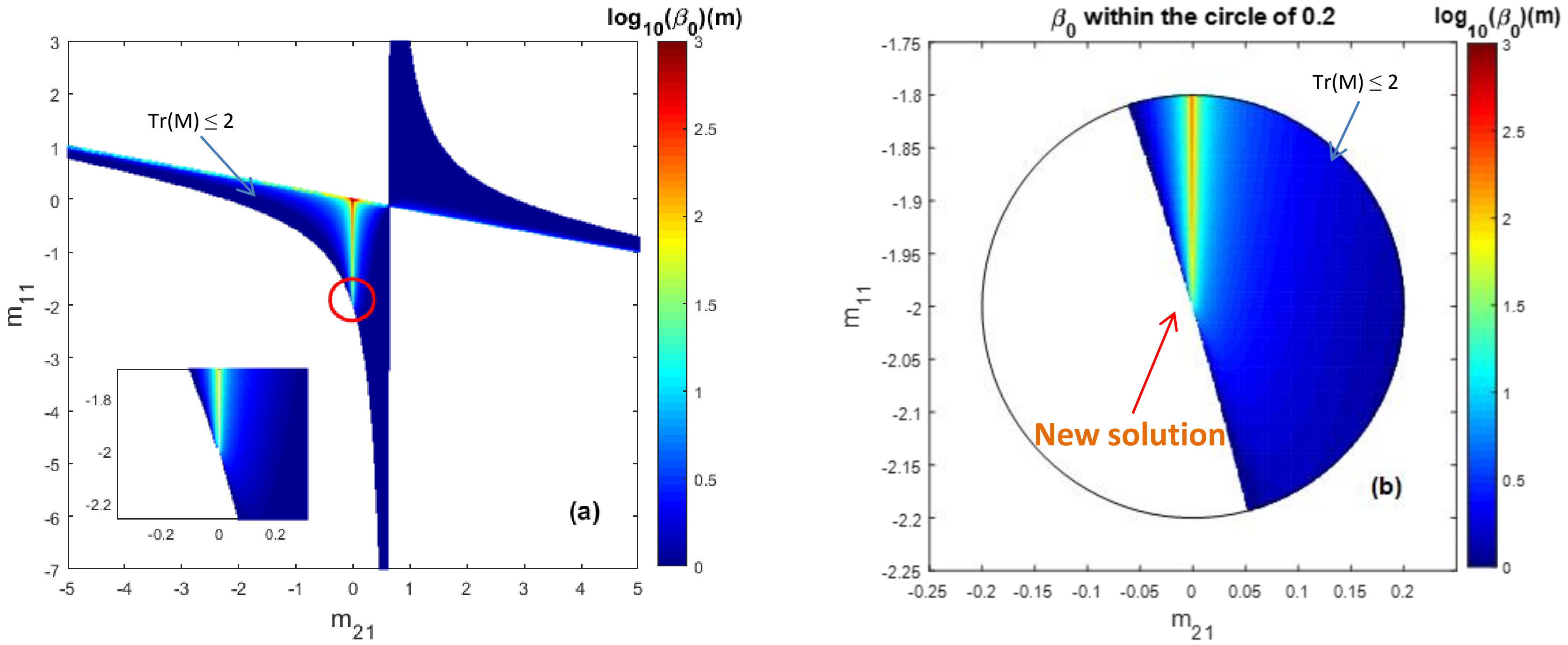
Previous solution

New solution

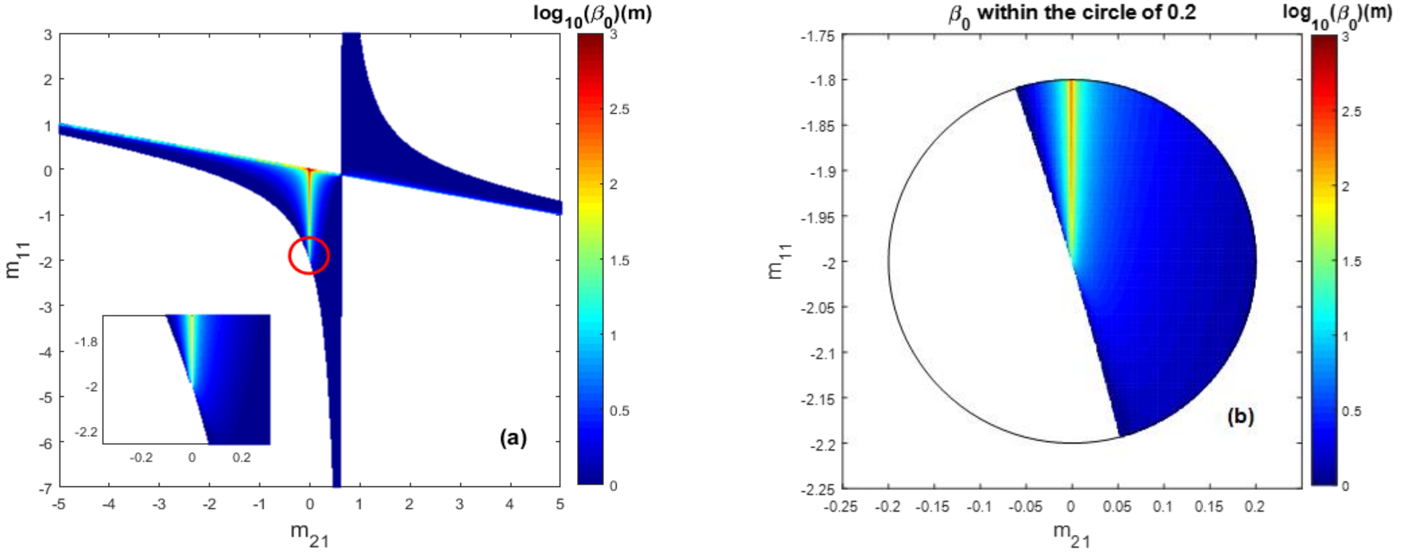
work to be submitted

The new solution: a singular point

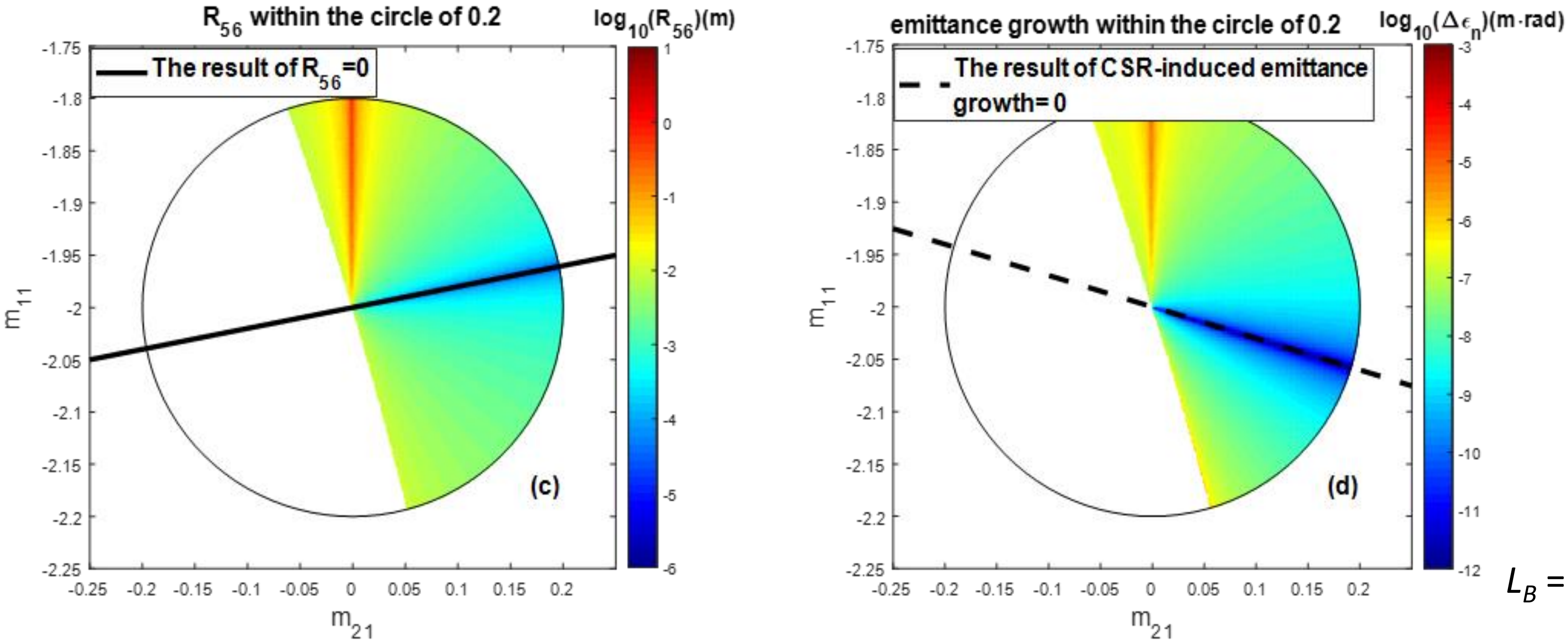
- An example with L_B = 0.4 m



- Exactly at the point (m_{11}, m_{21}[m^{-1}]) = (-2, 0), the periodic beta functions are very large or even unstable.



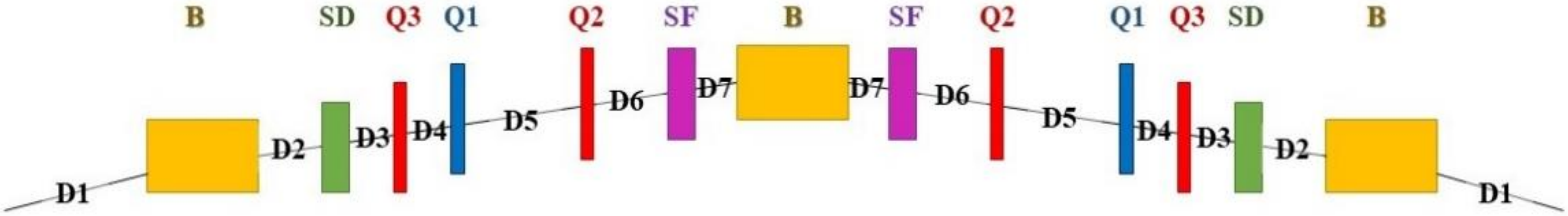
- But near the point, one can find solutions satisfying periodic stability criterion, and having small R56 and small emittance growth induced by CSR.



L_B = 0.4 m

Verified w/ practical lattice optimization

- To verify this result, we did PSO optimization of practical lattice, with eight variables and two objectives: α_p (and high α_p) & $\Delta\varepsilon$ due to CSR
- Of course, some practical constraints were considered, to ensure the periodic optical parameters are at a reasonable level.



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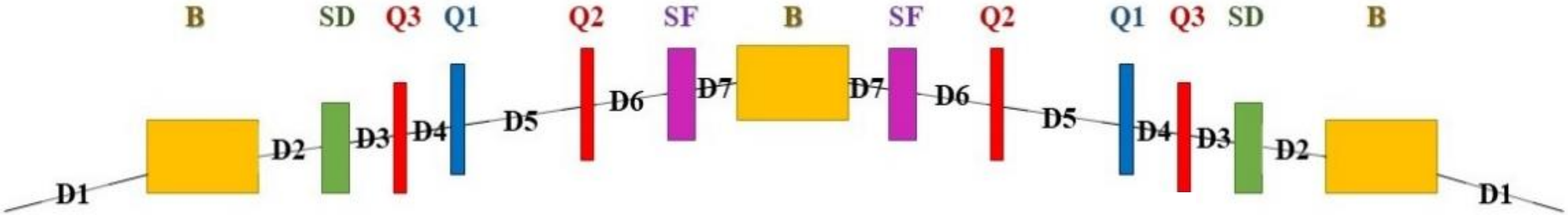

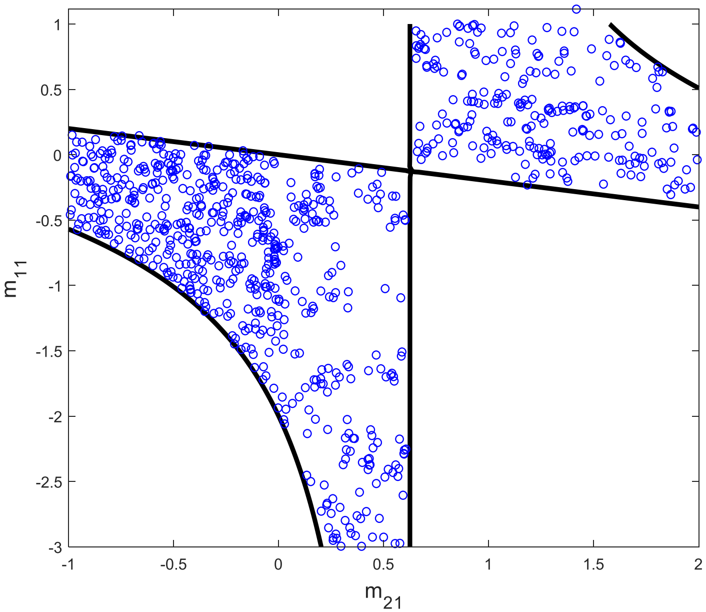

Generate initial seeds distributed approximately uniformly in (m_{11}, m_{21}) space

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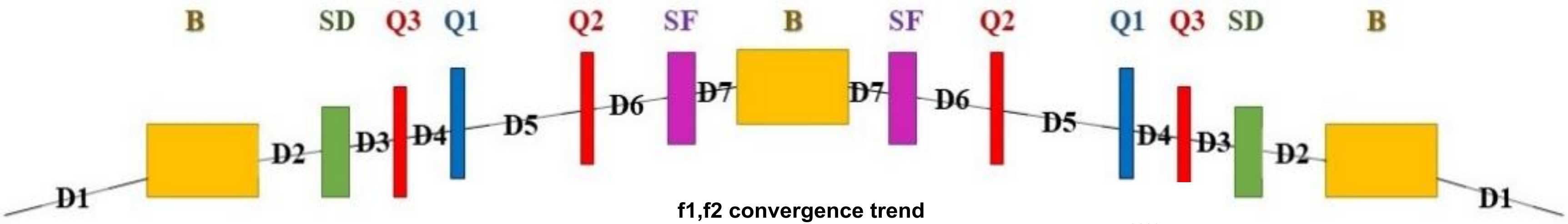
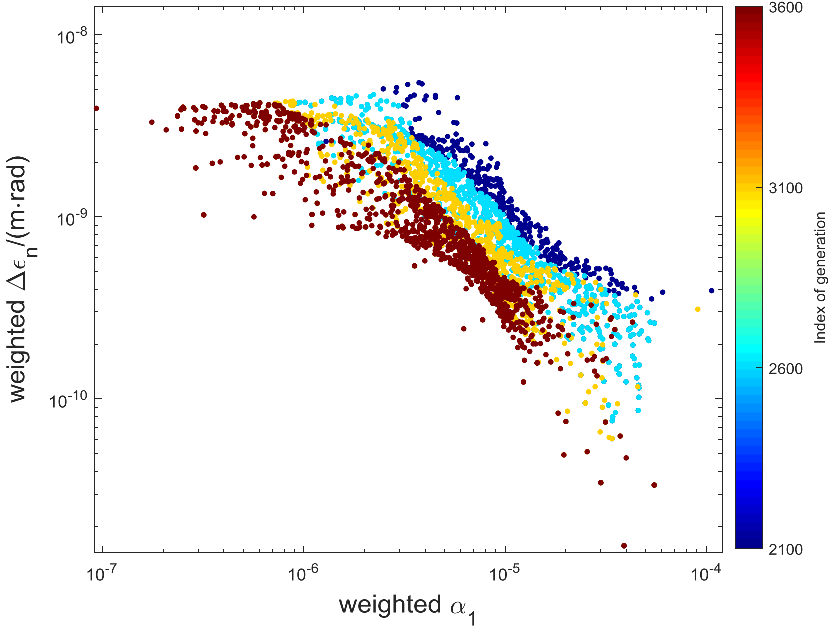


Evolved over 3000 generations

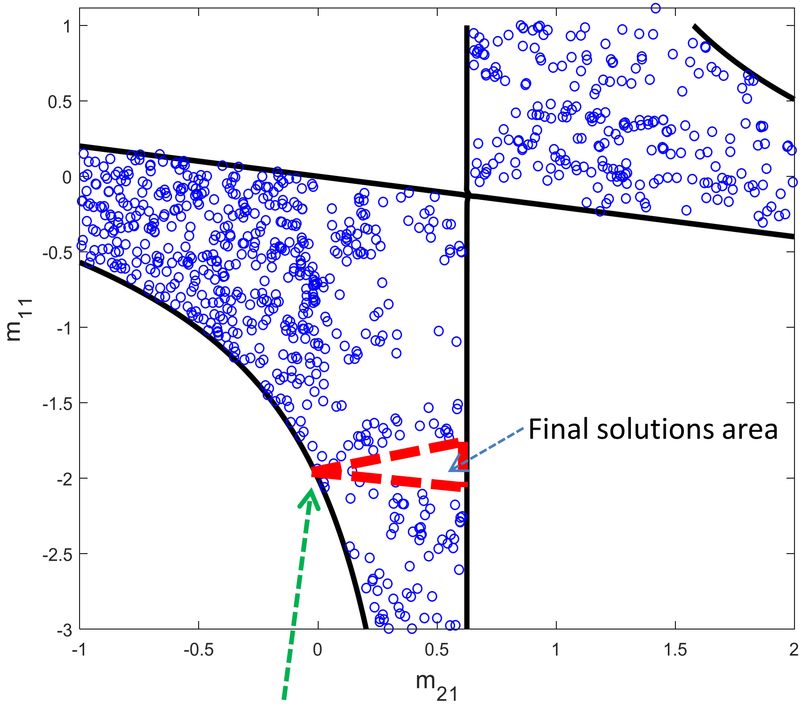

f1,f2 convergence trend

Verified w/ practical lattice optimization

- Final solutions converged to a small area close to the point (m_{11}, $m_{21}[m^{-1}]$) = (-2, 0)

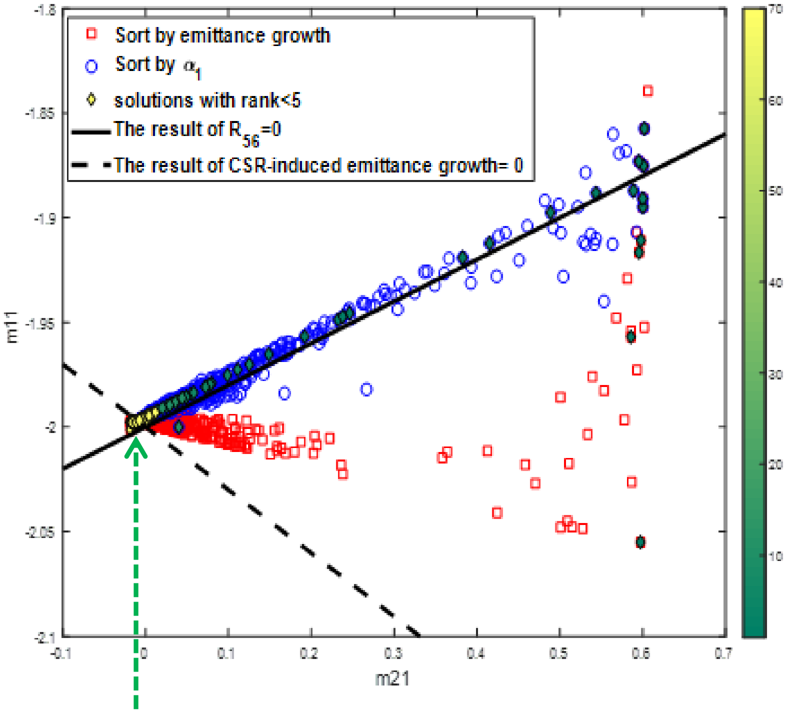
- **Accord with the analytical prediction very well**

Initial solutions



(m_{11}, $m_{21}[m^{-1}]$) = (-2, 0)

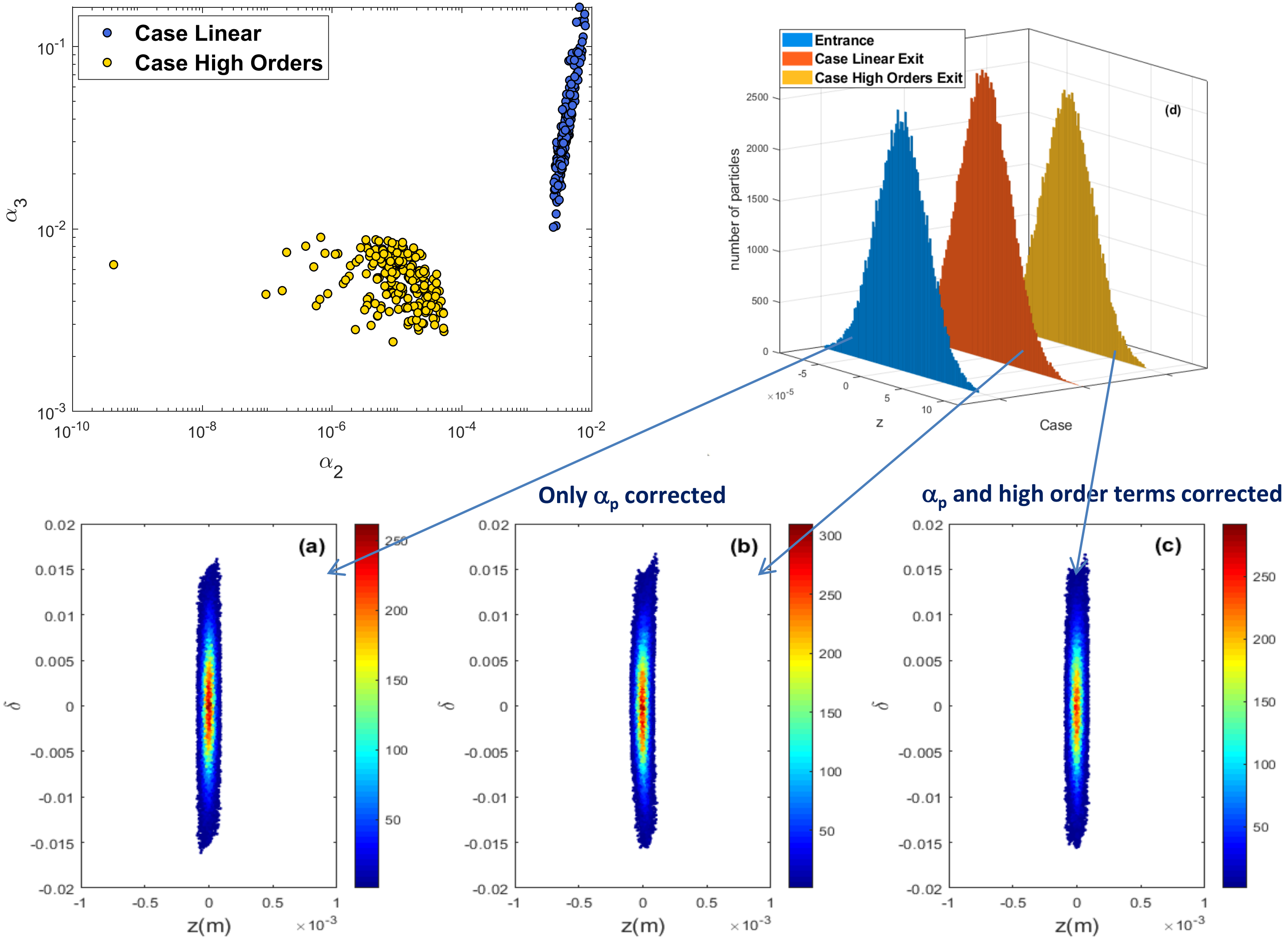
Final solutions



(m_{11}, $m_{21}[m^{-1}]$) = (-2, 0)

work to be submitted

High order α_p also optimized



Only α_p corrected

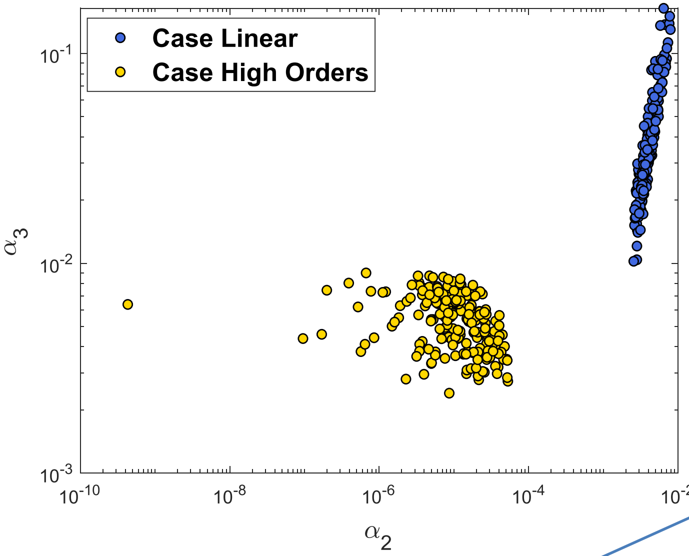
α_p and high order terms corrected

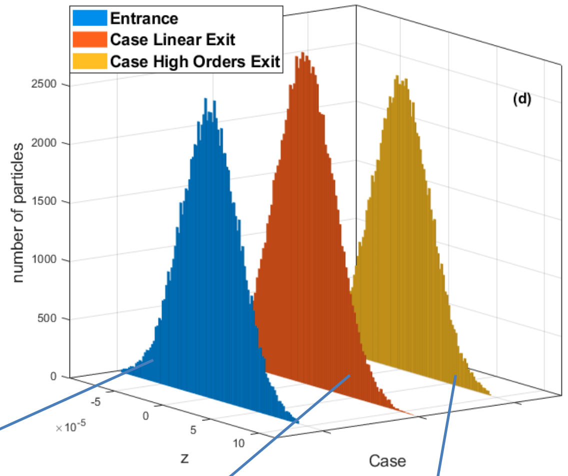
beam distribution
at entrance of TBA

beam distribution
at the exit of TBA

beam distribution
at the exit of TBA

High order α_p also optimized





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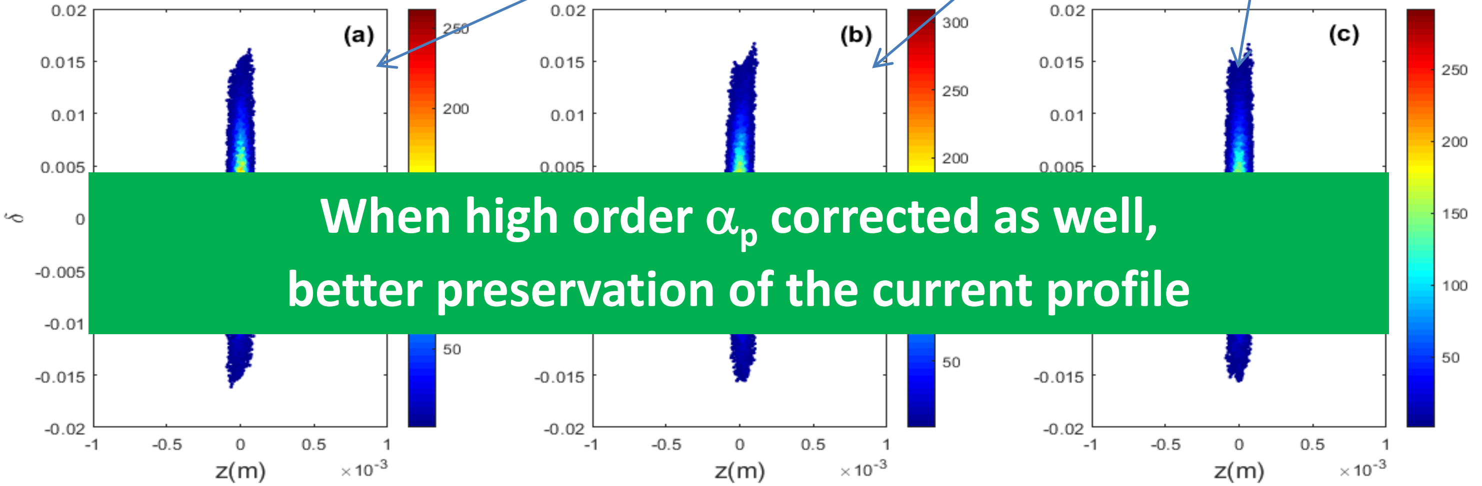


When high order α_p corrected as well,
better preservation of the current profile

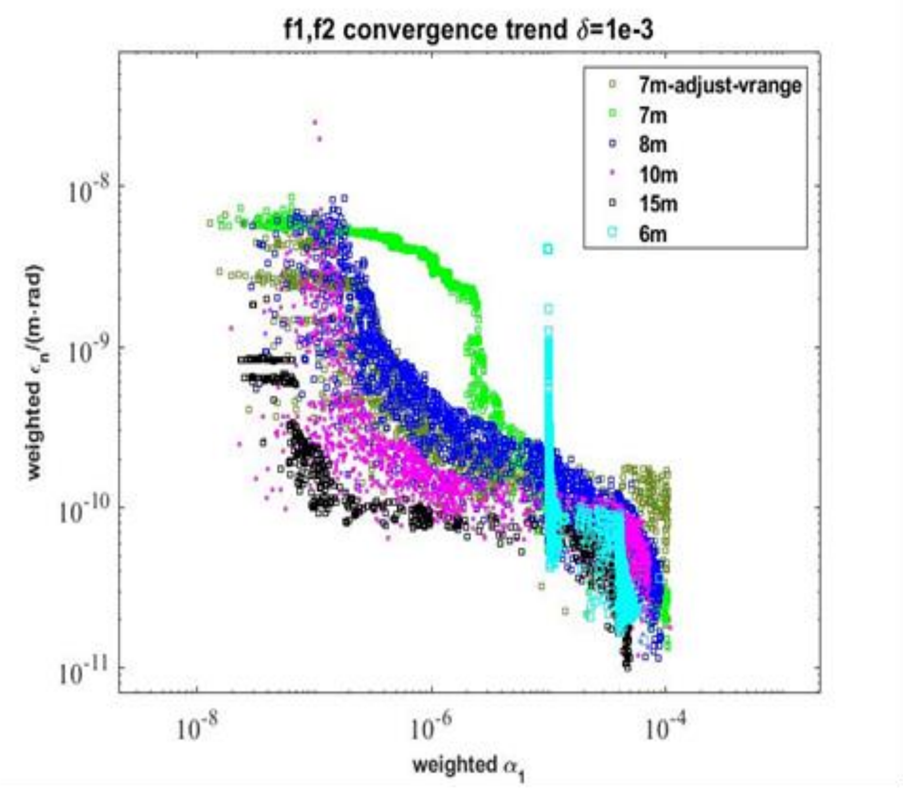
beam distribution
at entrance of TBA

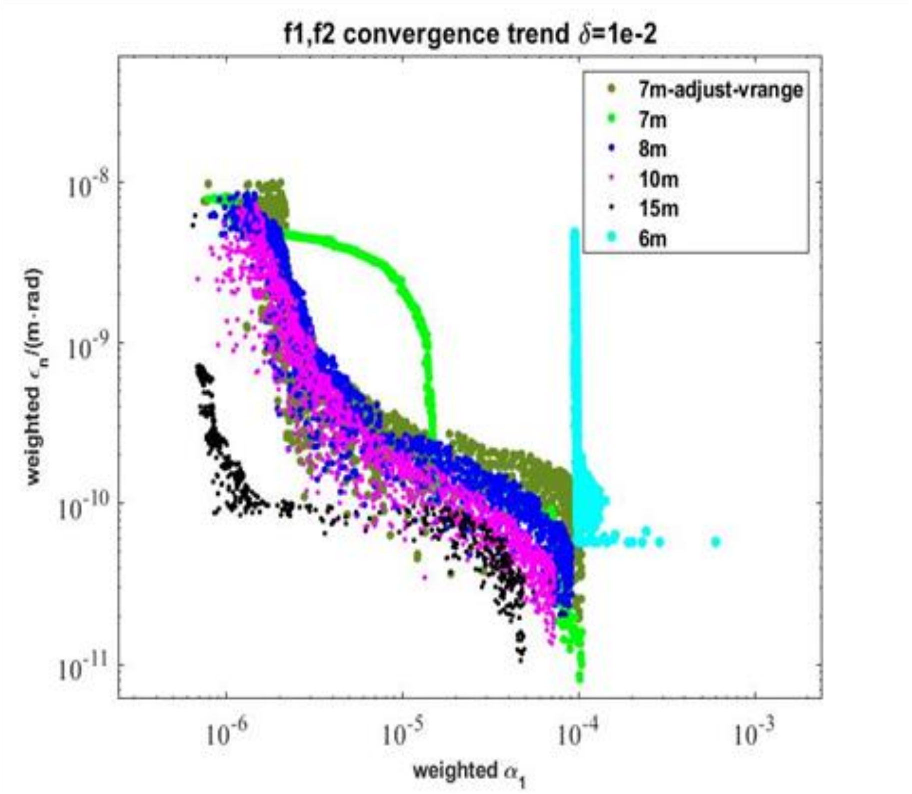
beam distribution
at the exit of TBA

beam distribution
at the exit of TBA

Further practical lattice optimization

- For 1 GeV beam, such a TBA can be realized with a cell length of about 8 m.





work to be submitted

Another outcome: mitigate MBI effect

- Another outcome is that we find near the point, the microbunching instability (MBI) can be well controlled.
- According to the previous MBI studies [2], to mitigate the MBI effect, it is preferred to have
  - **phase advance close to integer times of π between adjacent dipoles**
  - **moderate beta function**

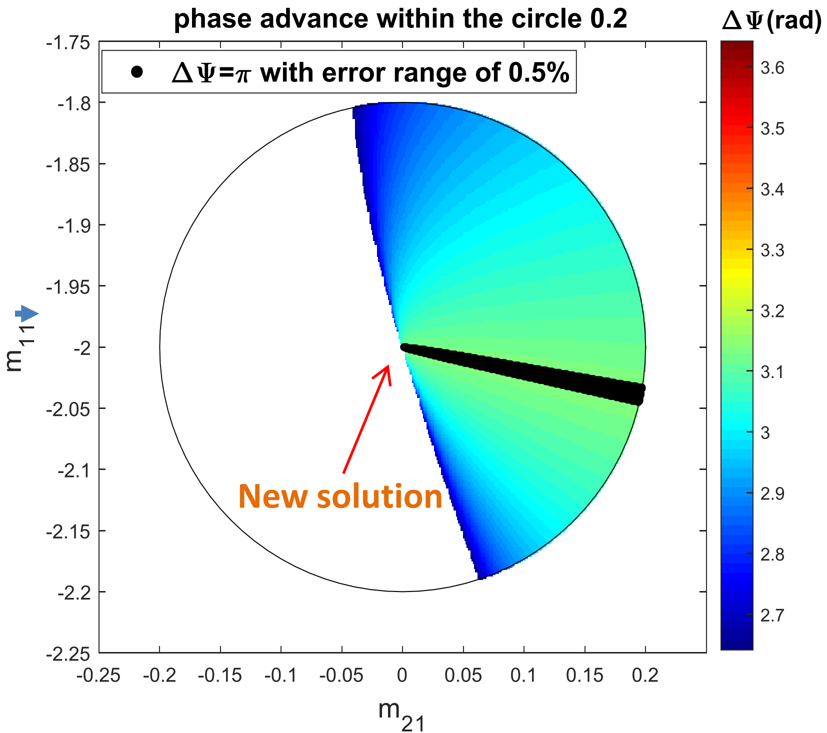
[2] Tsai, C.-Y., S. Di Mitri, D. Douglas, R. Li, and C. Tennant. “Conditions for Coherent-Synchrotron-Radiation-Induced Microbunching Suppression in Multibend Beam Transport or Recirculation Arcs.” *Physical Review Accelerators and Beams* 20, no. 2 (February 22, 2017): 024401.

work to be submitted

Another outcome: mitigate MBI effect

- Another outcome is that we find nearby the point, the microbunching instability (MBI) can be well controlled.
- According to the previous MBI studies [2], to mitigate the MBI effect, it is preferred to have
  - **phase advance close to integer times of π between adjacent dipoles**
  - **moderate beta function**

Near the point, the phase advance of the adjacent dipoles in the TBA cell is intrinsically close to π.

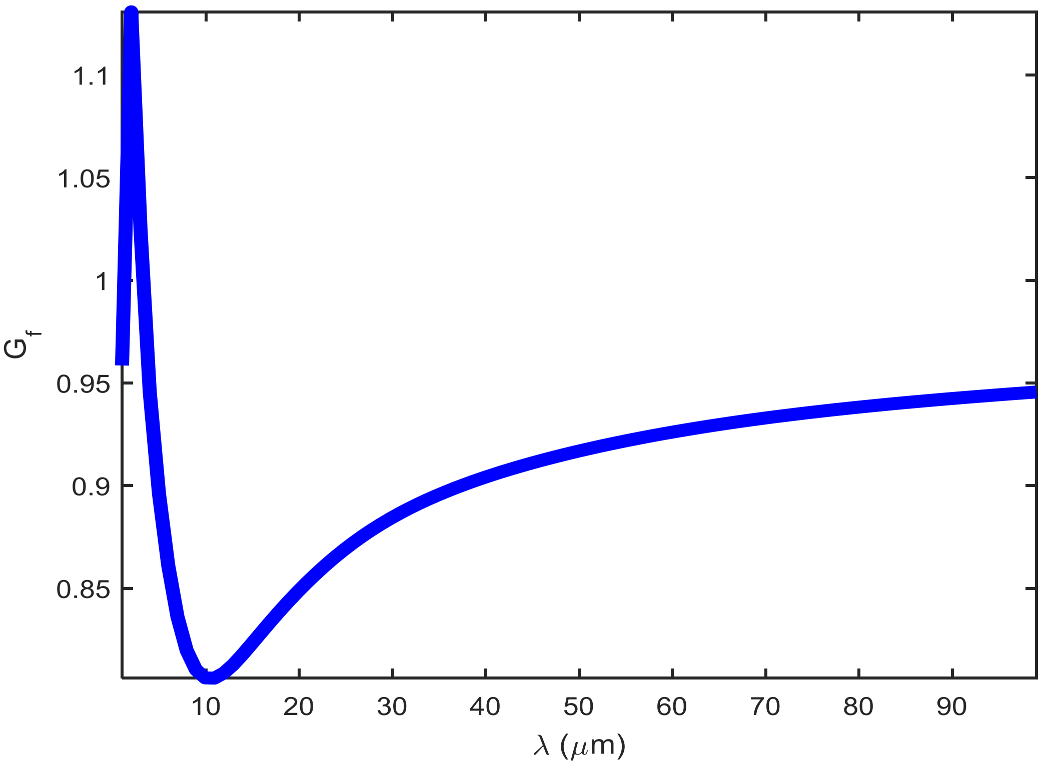

phase advance within the circle 0.2

[2] Tsai, C.-Y., S. Di Mitri, D. Douglas, R. Li, and C. Tennant. “Conditions for Coherent-Synchrotron-Radiation-Induced Microbunching Suppression in Multibend Beam Transport or Recirculation Arcs.” *Physical Review Accelerators and Beams* 20, no. 2 (February 22, 2017): 024401.

work to be submitted

Another outcome: mitigate MBI effect

- Studies showed that even with 30 repetitive TBA cells (totally 360 degrees), the MBI gain factor can be well controlled to a sufficiently small level.



work to be submitted

Summary

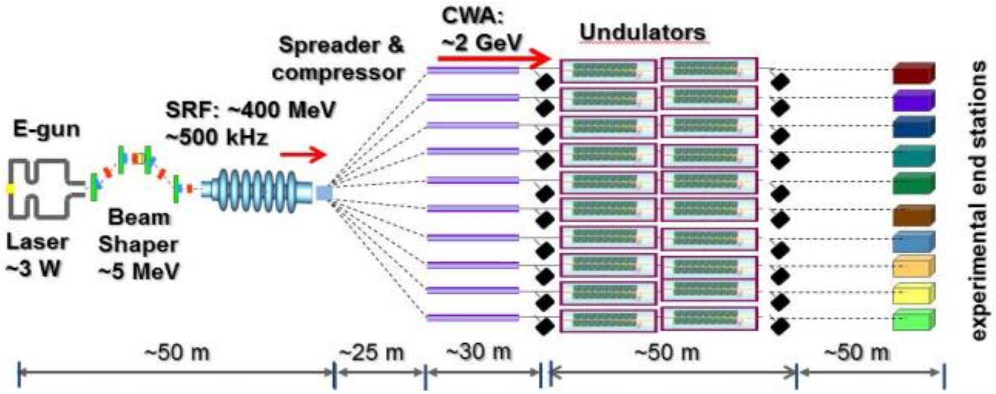
- This study suggests **a new direction of TBA cell design** which could promise **low α_p** (and higher order terms) and **small emittance growth** induced by CSR, and satisfy the **periodic stability criterion**.

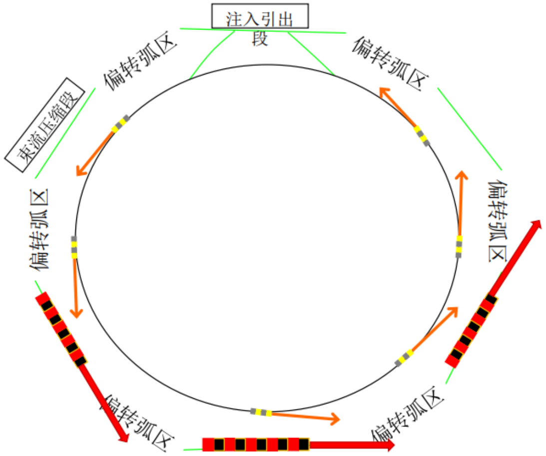
- It is also found that such a design is helpful in **mitigating the MBI effect**.

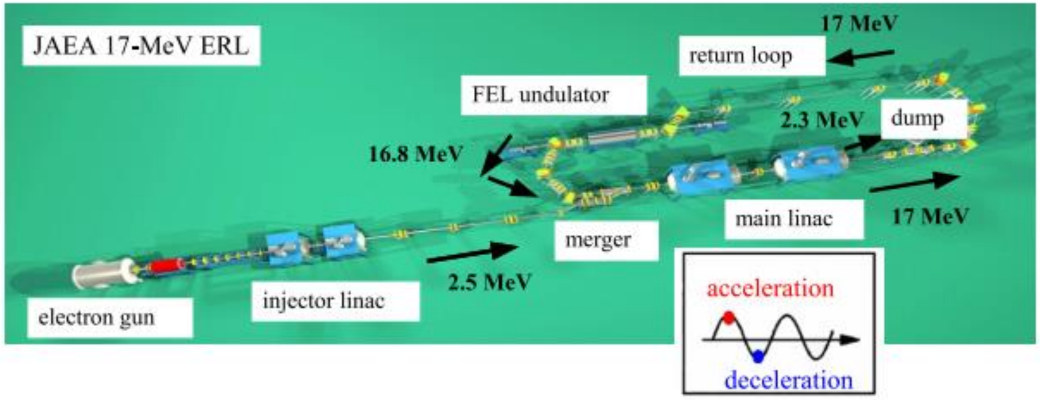
work to be submitted

Summary

- We hope such a TBA design would be helpful in different accelerator beam line designs.







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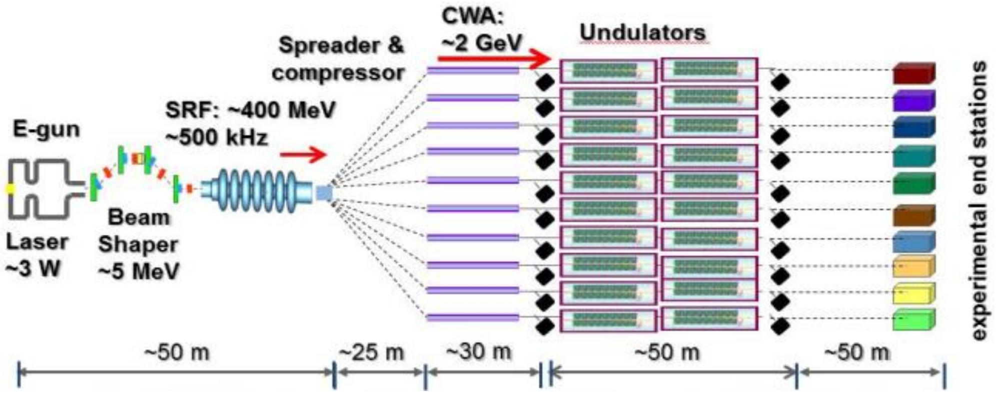

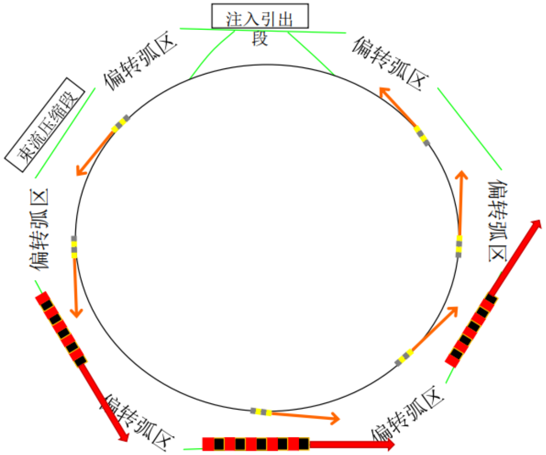

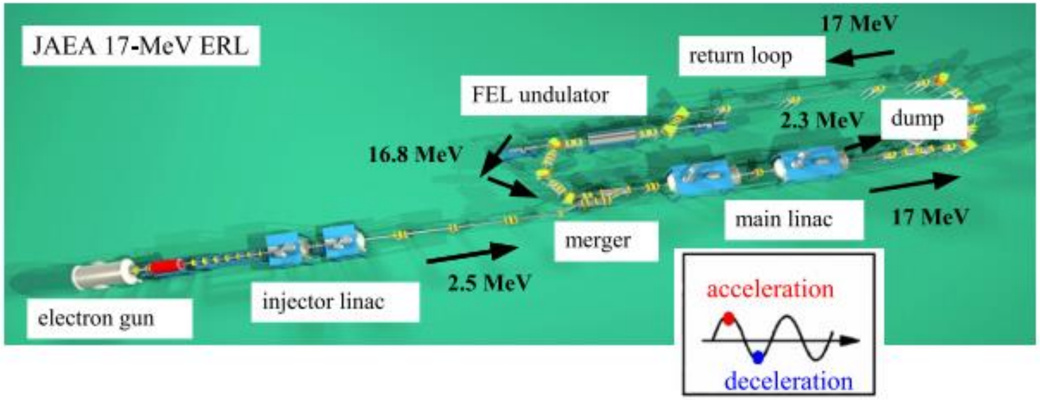

Thanks!

- backups

longitudinal dynamics

纵向相空间动力学：考虑非线性项

$$\boldsymbol{z_f = z_i + R_{56}\delta_i + T_{566}\delta_i^2 + U_{5666}\delta_i^3 + O\left(\delta_i^4\right)}$$

$$\alpha_1 = \frac{1}{L_0}\oint \frac{\eta_1(s)}{\rho}ds$$

$$\boldsymbol{\Delta\mathrm{L} = R_{56}\delta_i + T_{566}\delta_i^2 + U_{5666}\delta_i^3 + O\left(\delta_i^4\right)}$$

$$\alpha_2 = \frac{1}{L_0}\int \frac{\eta_1'(s)}{2} + \frac{\eta_2(s)}{\rho}ds$$

$$\boldsymbol{\frac{\Delta L}{L_0} = \alpha_1\delta_i + \alpha_2\delta_i^2 + \alpha_3\delta_i^3 + O\left(\delta_i^4\right)}$$

$$\boldsymbol{\alpha_1 \to 0}$$
$$\boldsymbol{\alpha_2 \to 0}$$

$$\begin{pmatrix} R_{11} & R_{12} & R_{13} & R_{14} & R_{15} & R_{16} \\ R_{21} & R_{22} & R_{23} & R_{24} & R_{25} & R_{26} \\ R_{31} & R_{32} & R_{33} & R_{34} & R_{35} & R_{36} \\ R_{41} & R_{42} & R_{43} & R_{44} & R_{45} & R_{46} \\ R_{51} & R_{52} & R_{53} & R_{54} & R_{55} & R_{56} \\ R_{61} & R_{62} & R_{63} & R_{64} & R_{65} & R_{66} \end{pmatrix}$$

work to be submitted

CSR effect

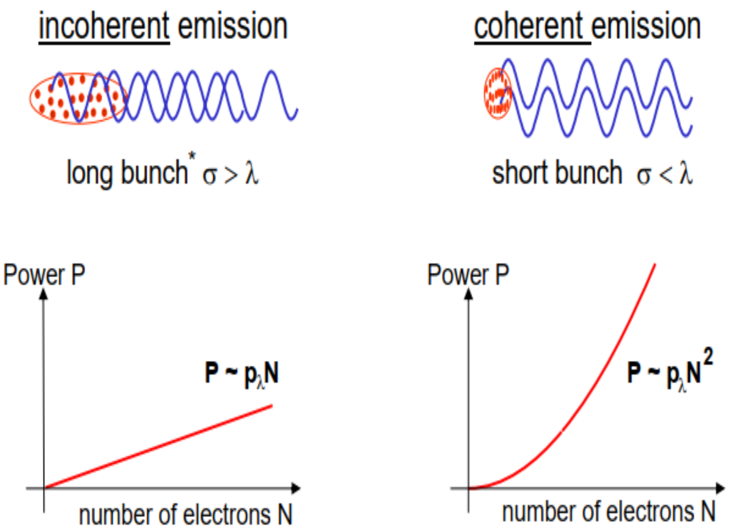

图1. Coherent Synchrotron Radiation(CSR)效应的物理图像[1]

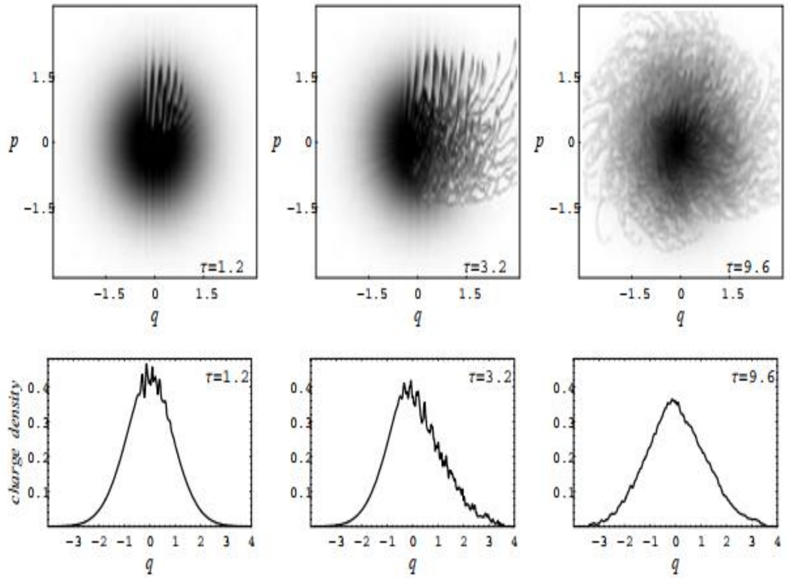

图2. CSR效应引起的束团相空间分布与束团密度分布图像[2]

$$I_b > \frac{\pi^{1/6}}{\sqrt{2}} \frac{ec}{r_0} \frac{\gamma}{\rho^{1/3}} \alpha \delta_0^2 \sigma \frac{1}{\lambda^{2/3}}$$

CSR bursting 流强不稳定阈值[3]

[1] G. Wüstefeld, BESSY, Short Bunches & CSR, EPAC'08, June 23rd. 2008

[2] Marco Venturini, Robert Warnock, Ronald Ruth, and James A. Ellison Phys. Rev. ST Accel. Beams 8, 014202 – Published 28 January 2005

[3] J. M. Byrd, W. P. Leemans, A. Loftsdottir, B. Marcelis, Michael C. Martin, W. R. McKinney, F. Sannibale, T. Scarvie, and C. Steier Phys. Rev. Lett. 89, 224801 – Published 8 November 2002

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CSR cancellation in TBA

- Model

  2D CSR kick model

- Requirements

  1) achromatic condition

  2) CSR cancellation

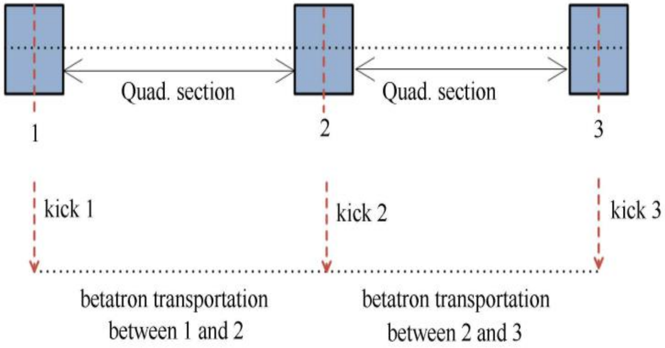
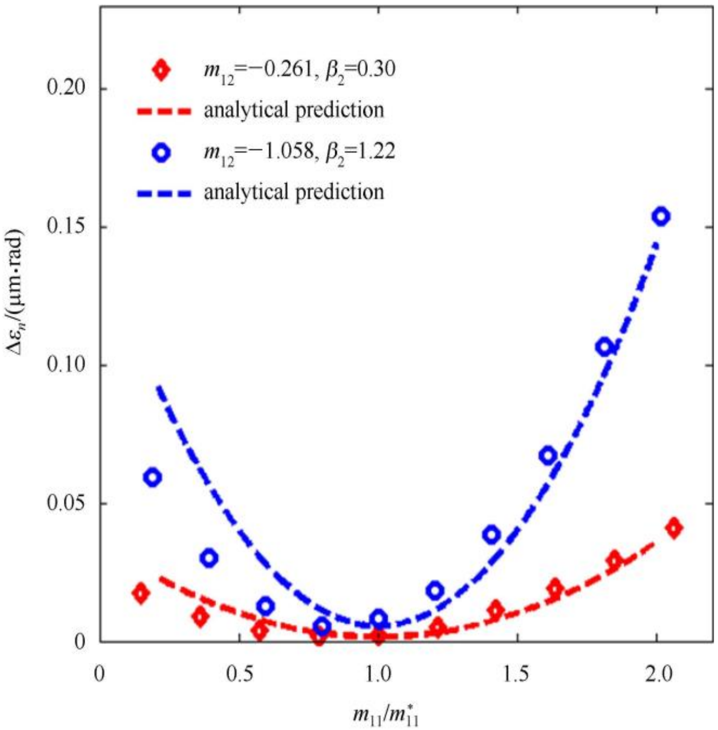


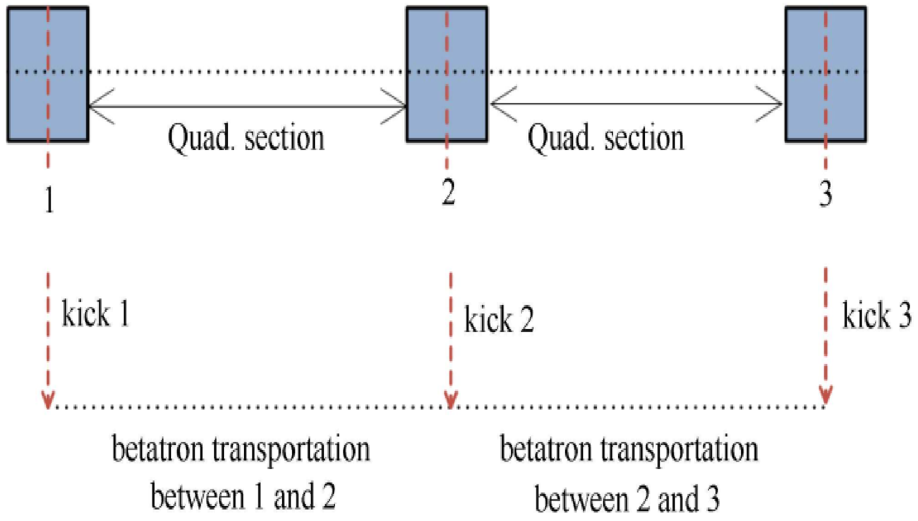
Fig. 1. Schematic layout of a symmetric TBA and the corresponding physical model of the CSR effect in a TBA with three point-kicks.



$$M_{12}=\begin{pmatrix} -\frac{r_2\rho+2m_{12}(\theta_1+\theta_2)S_1}{2r_1\rho} & m_{12} \\ \frac{1}{m_{12}}\left(\frac{r_2S_2}{4r_1S_1}+\frac{m_{12}(\theta_1+\theta_2)S_2}{2r_1\rho}-1\right) & -\frac{S_2}{2S_1} \end{pmatrix}, \quad (16)$$

[4] Huang, Xiyang & Jiao, Yi & Xu, Gang & Cui, Xiaohao. (2015). Suppression of the emittance growth induced by coherent synchrotron radiation in triple-bend achromats. Chinese Physics C. 39. 10.1088/1674-1137/39/5/057001

2D CSR kick model



$$\mathbf{x}_{\mathbf{f,rms}} \to 0$$
$$\mathbf{x'}_{\mathbf{f,rms}} \to 0$$

CSR效应引起的粒子坐标偏差：

$$X_k = \begin{pmatrix} x_k \\ x'_k \end{pmatrix} = \begin{pmatrix} \rho^{4/3} k[\theta\cos(\theta/2) - 2\sin(\theta/2)] \\ \sin(\theta/2)\left(2\delta + \rho^{1/3}\theta k\right) \end{pmatrix}$$

CSR效应引起的发射度增长：

$$\varepsilon = \sqrt{\left(\varepsilon_0\beta_f + x_{f,rms}^2\right)\left(\varepsilon_0\gamma_f + x'^2_{f,rms}\right) - \left(\varepsilon_0\alpha_f - x_{f,rms}^2 x'^2_{f,rms}\right)^2} = \sqrt{\varepsilon_0^2 + \varepsilon d\varepsilon}$$

$$d\varepsilon = \gamma_f x_{f,rms}^2 + 2\alpha_f x_{f,rms} x'_{f,rms} + \beta_f x'^2_{f,rms}$$

work to be submitted

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