EEX based Bunch Shaping Experiments at AWA

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for Gwanghui Ha (Ph.D. Thesis project)

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The 2nd Workshop on Applications of Dielectric Wakefield Accelerators to Next Generation X-ray Free Electron Laser Facilities.
Los Alamos, NM, December 5-6, 2013

DWFA driven XFEL Collaboration

- A group to investigate using Dielectric Wakefield Acceleration to drive X-ray-Free Electron Lasers.
- 3 institutions: ANL, LANL, FNAL
- Readytalk meetings held 1-2 times per month (Group started summer 2013)
- Mission:
  - Strawman Facility Layouts
  - Staging DWFA
  - Ultimate energy gain of a staged DWFA
  - Maximum repetition rate of a staged DWFA
  - Energy efficiency of a staged DWFA
  - Dielectric structure design and engineering
  - Control of the beam energy spread and chirp
  - BBU control and transverse wake fields
  - Tolerances, stability, reproducibility
  - Design of the demonstration experiment
  - Production of the optimal drive beam.

Topics discussed at meetings so far

High Repetition-Rate, Soft X-ray FEL User Facility

Capable of serving ~2000 scientists/year

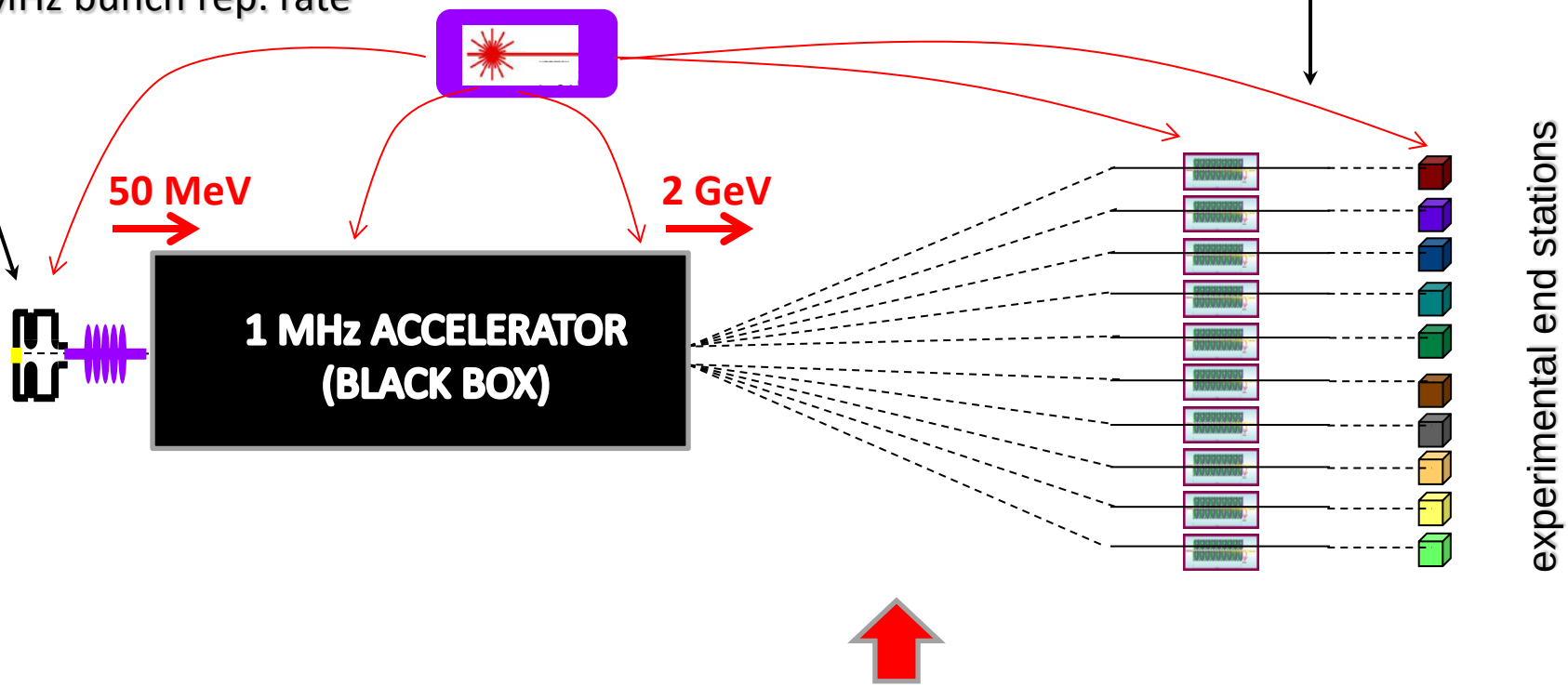
Flexible x-ray beamlines

- Tunable pulse length
- Seeded
- 2 color seeded
- SASE

Lasers linked with a fiber-optics time distribution network

Low-emittance injector:

- 1 MHz bunch rep. rate



Beam spreader

- 100 kHz bunch rep. rate

Multi-user soft x-ray FEL facility based on: SRF linac

Capable of serving ~2000 scientists/year

Lasers linked with a fiber-optics time distribution network

Flexible x-ray beamlines

- Tunable pulse length
- Seeded
- 2 color seeded
- SASE

Low-emittance injector:

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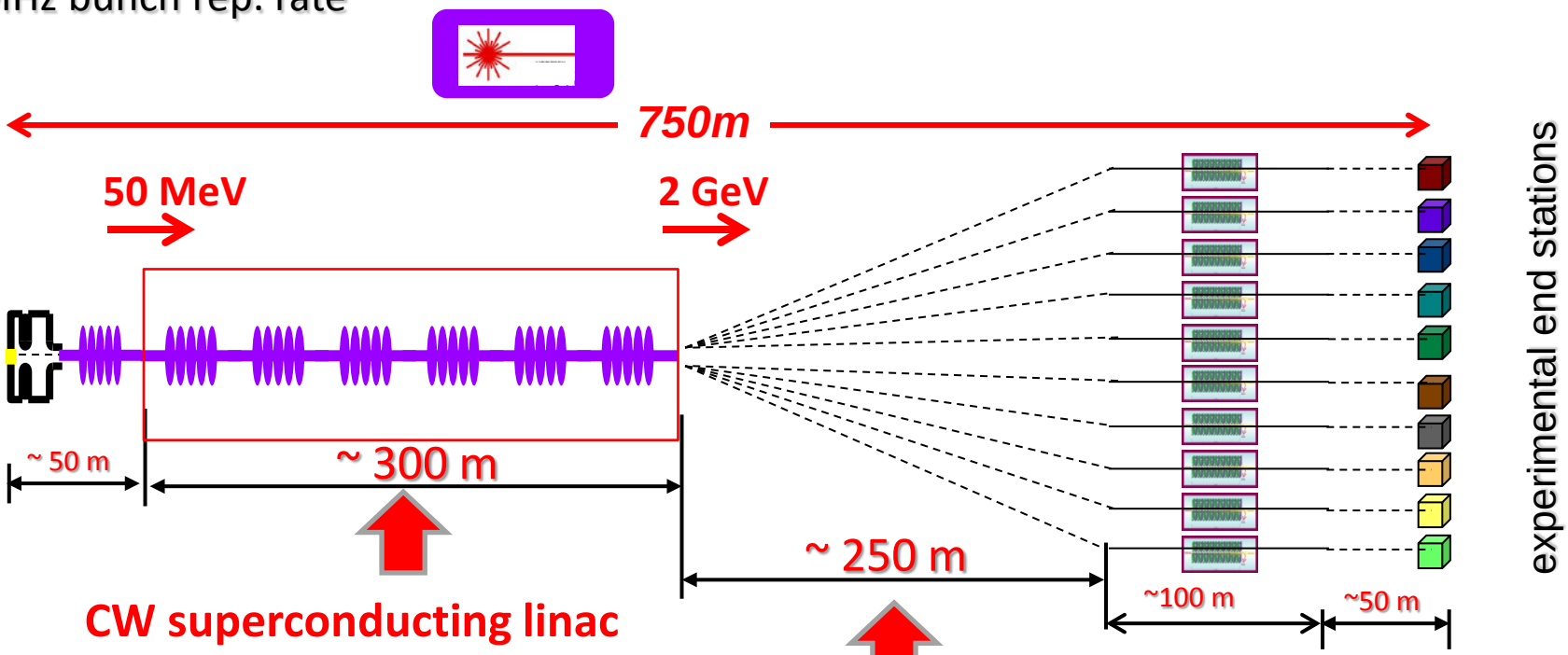


CW superconducting linac

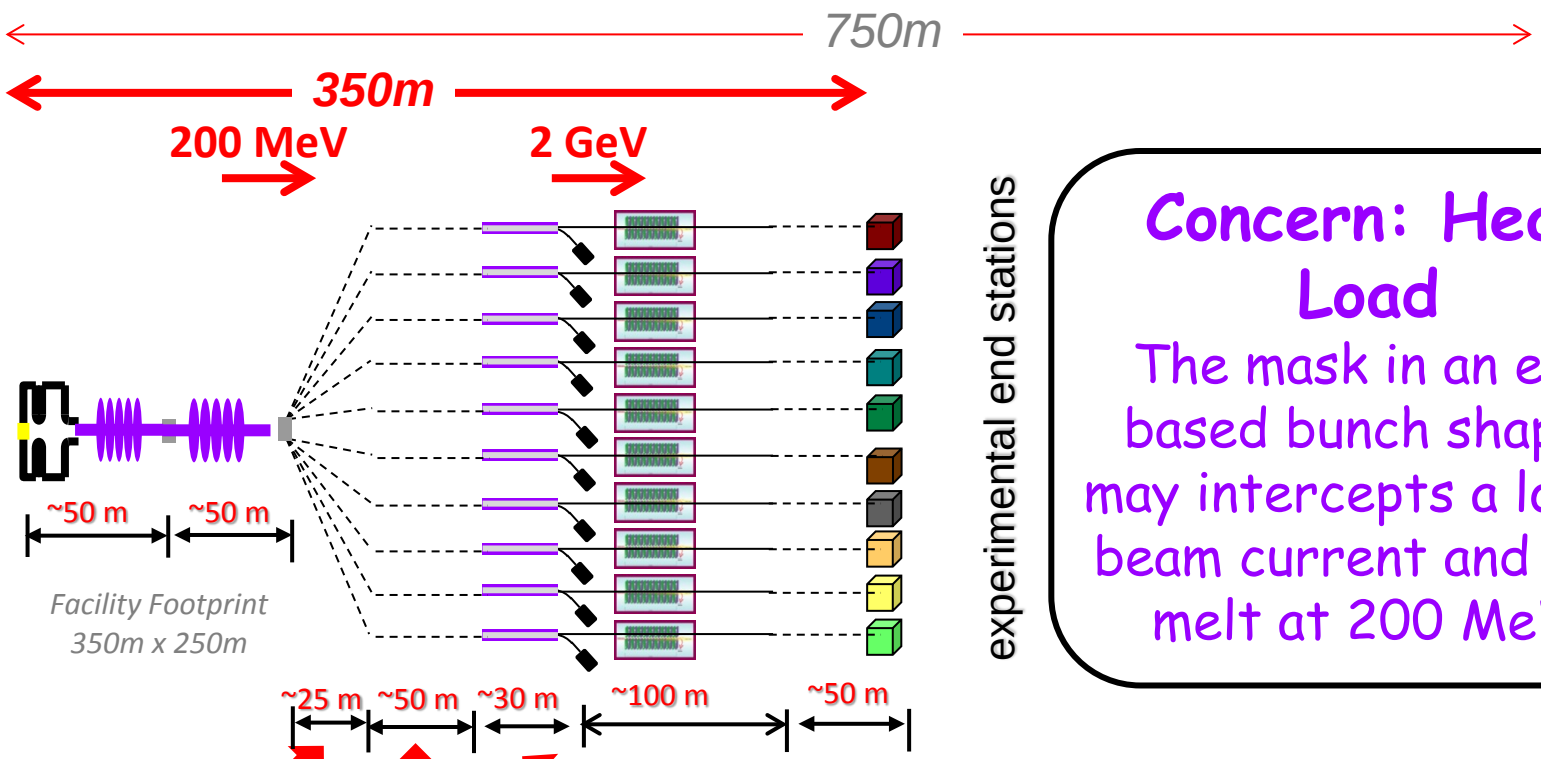
~1MHz bunch rep. rate
~2 GeV beam energy
~1 kA peak current

Beam spreader

- 100 kHz bunch rep. rate

Multi-user soft x-ray FEL facility based on: DWFA linac

Dielectric Wakefield Acceleration (DWFA) linac



Concern: Heat Load

The mask in an eex based bunch shaper may intercepts a lot of beam current and may melt at 200 MeV.

Compact Beam Spreader

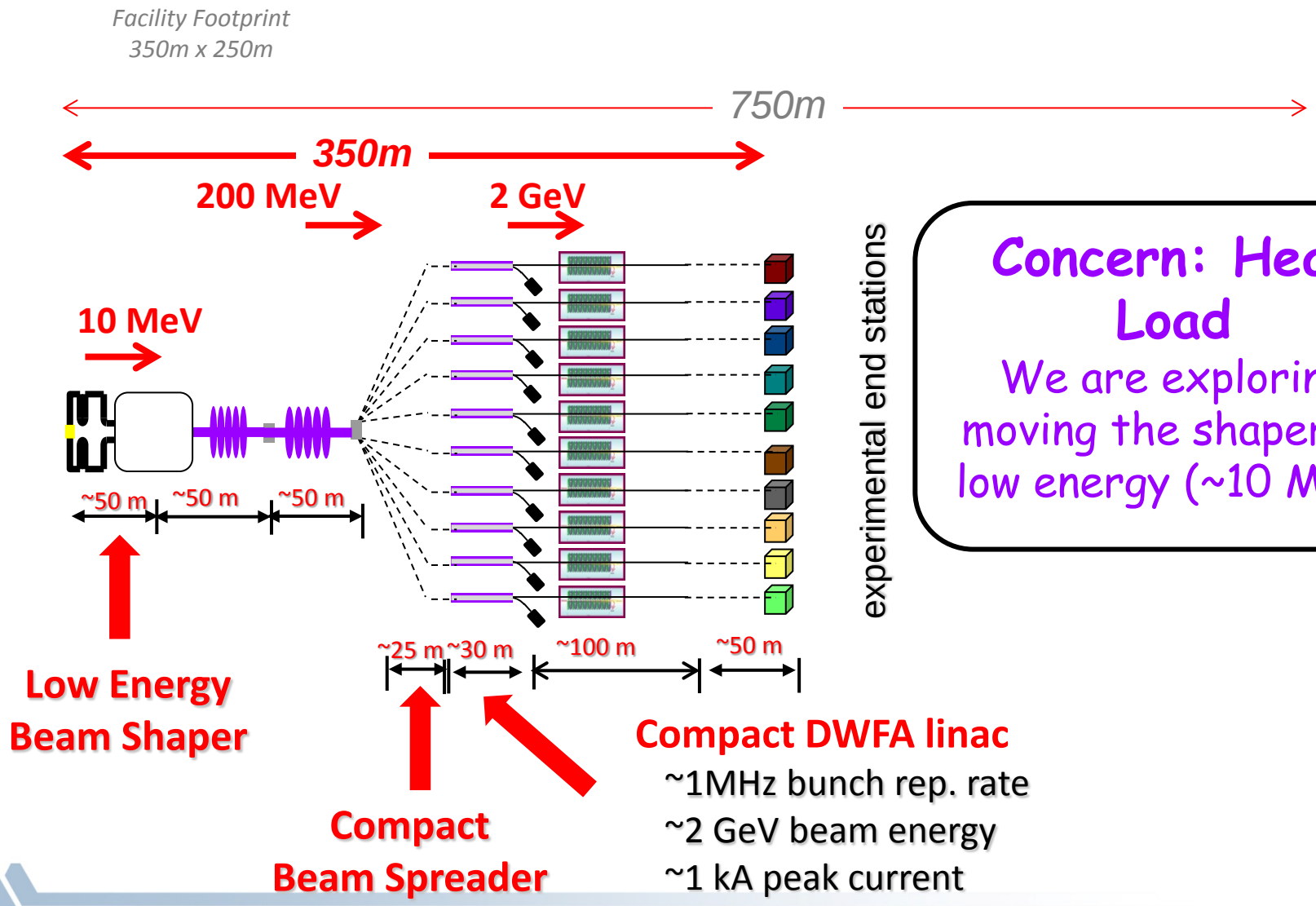
Beam Shaper

Compact DWFA linac

- ~1MHz bunch rep. rate
- ~2 GeV beam energy
- ~1 kA peak current

Multi-user soft x-ray FEL facility based on: DWFA linac

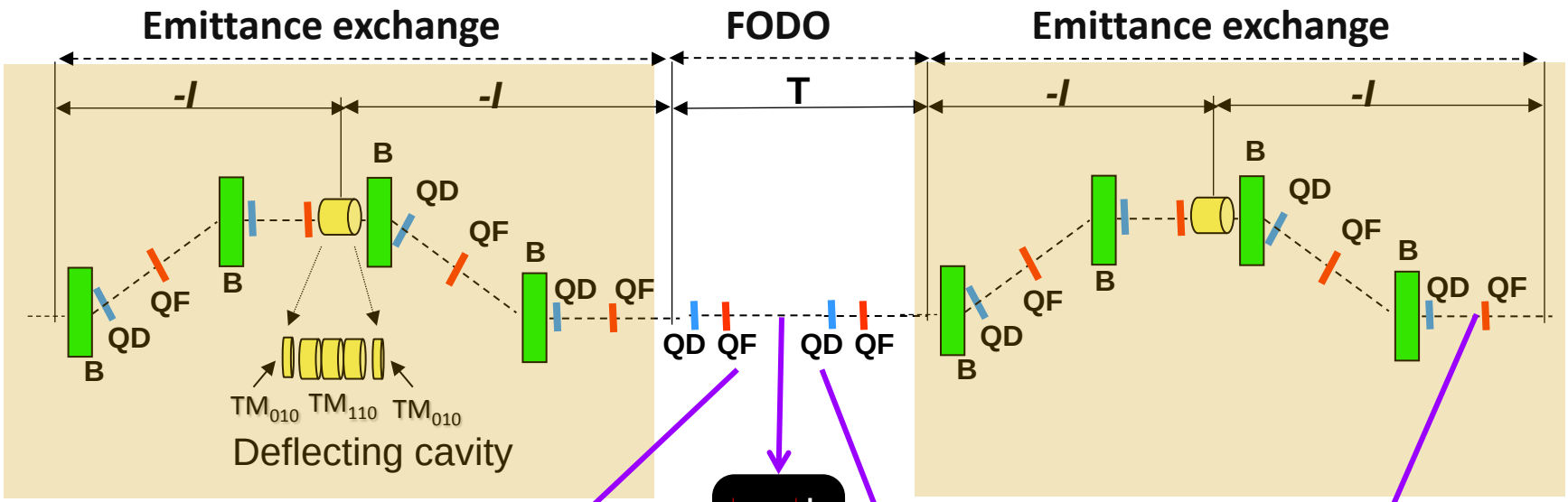
Dielectric Wakefield Acceleration (DWFA) linac



Concern: Heat Load

We are exploring moving the shaper to low energy (~10 MeV)

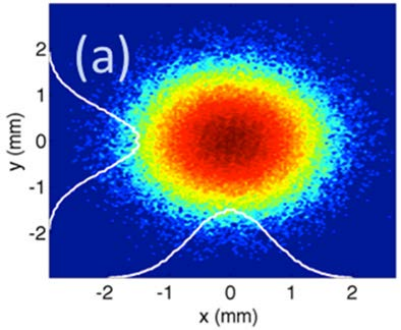
Double EEX technique:
a convenient tool for drive and witness bunch shaping



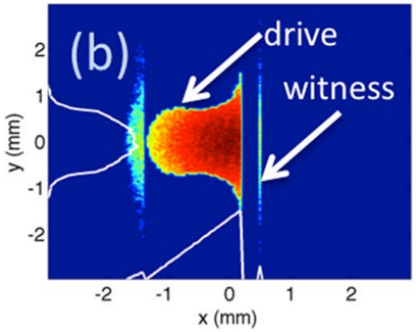
z →x emit. exch.

x →z emit. exch.

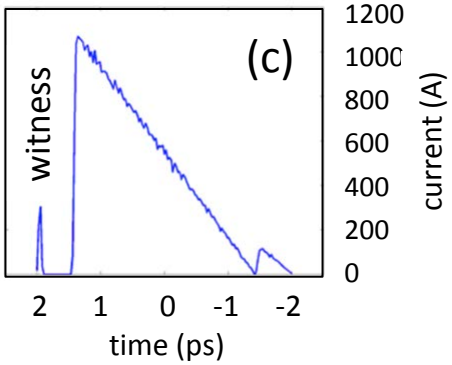
Before mask



After mask



At EEX exit

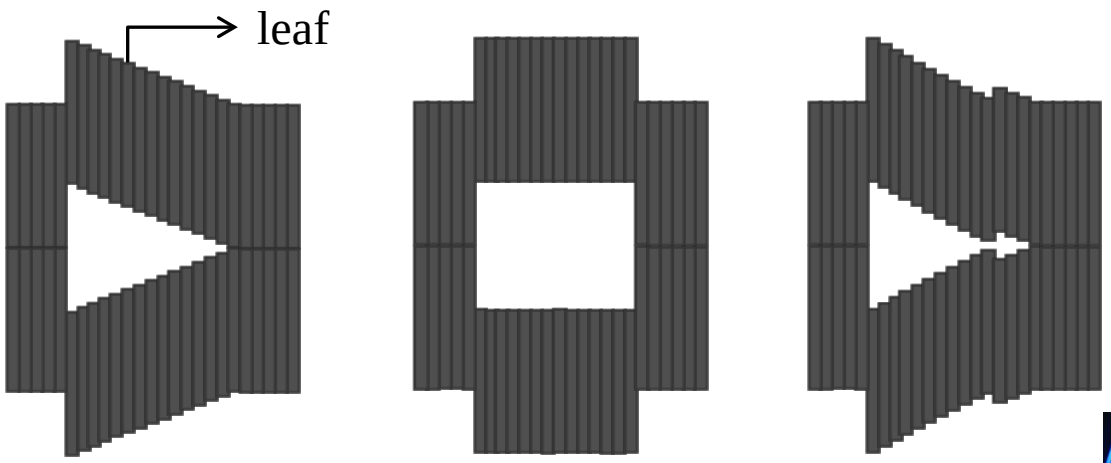


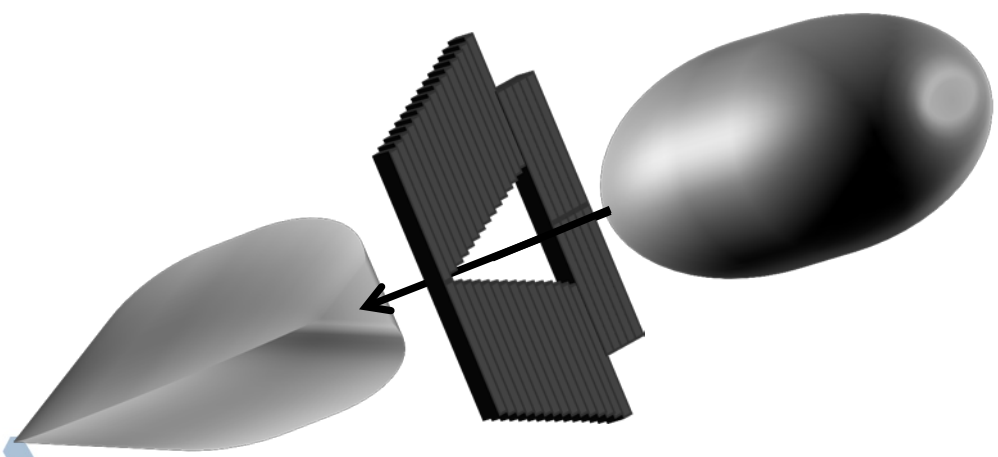
Drive and Witness from the same source bunch→ minimal timing jitter

General (nonlinear) shapes are possible

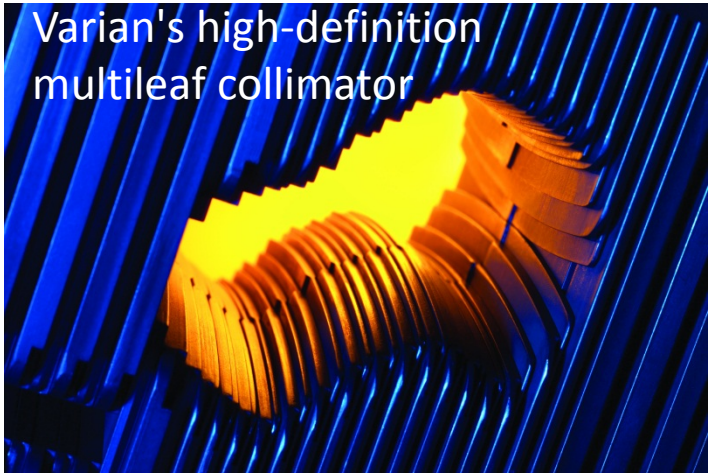
Multi-leaf collimator:

- Used in medical linacs to shape the x-rays
- Each vertical leaf moves independently





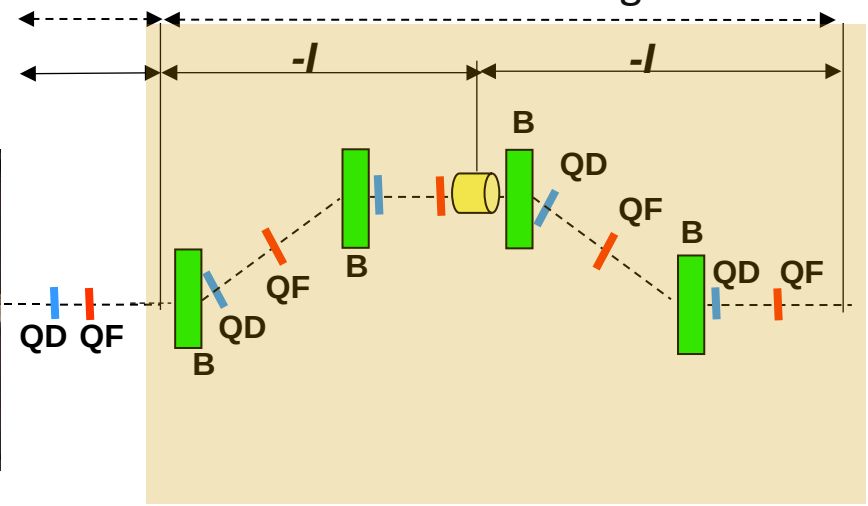
Multi-leaf collimator



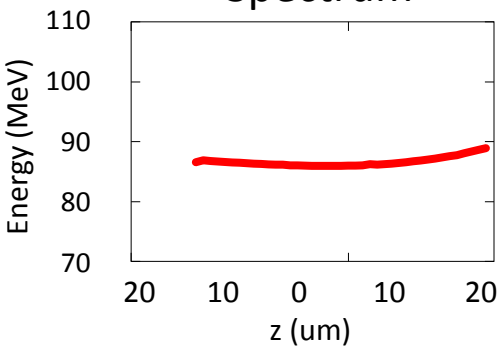
Feedback on desired witness and drive shape

Multi-leaf mask

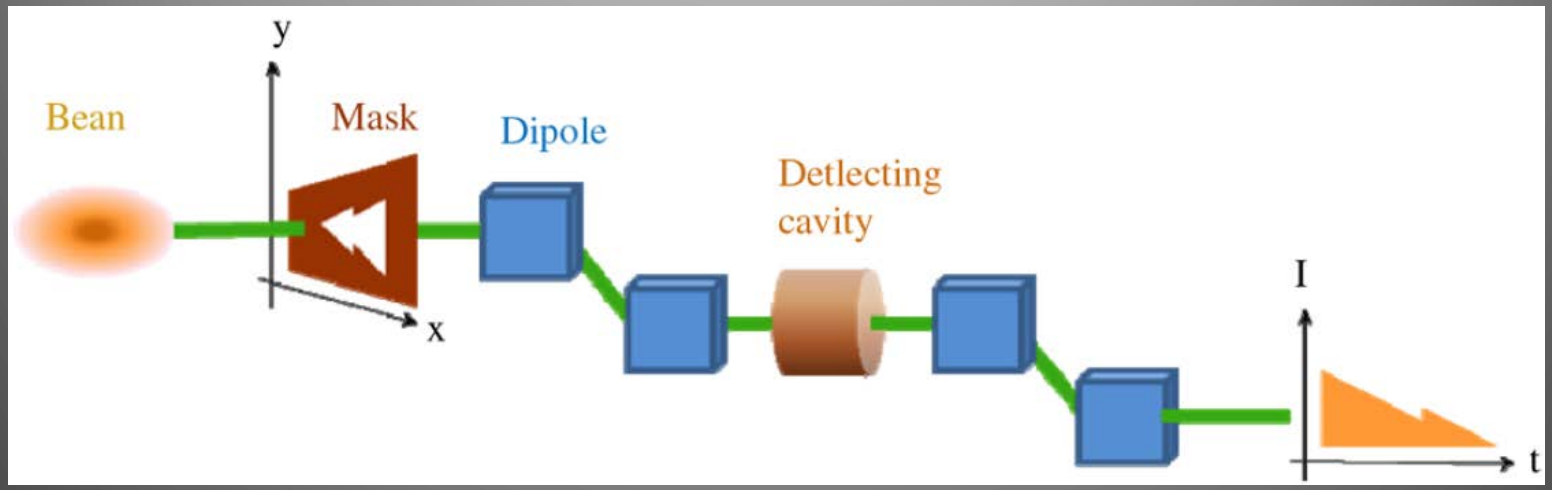
Emittance exchange



Measured Spectrum



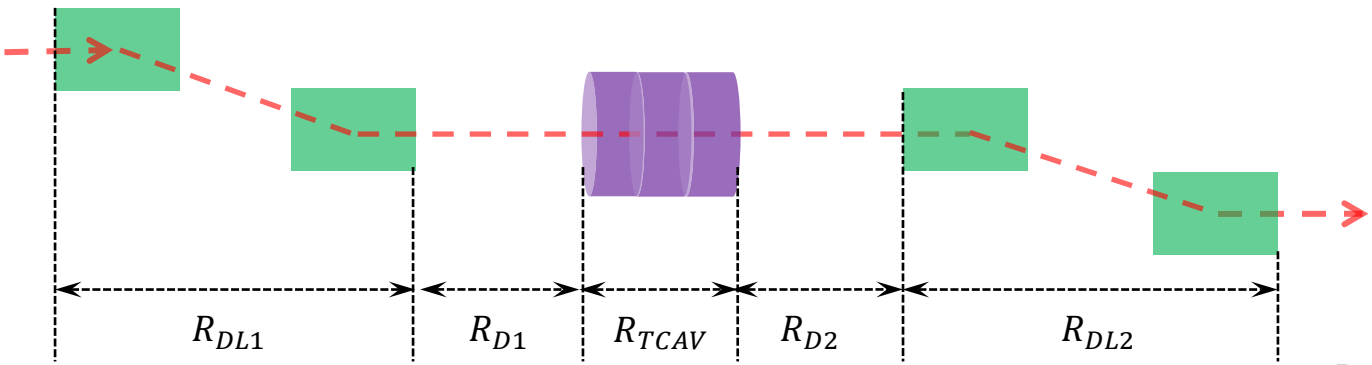
FEEDBACK



INTRODUCTION LONGITUDINAL BUNCH SHAPING WITH AN EEX BEAMLINE

Investigate EEX based bunch shaping at the Argonne Wakefield Accelerator

Transport matrix: Emittance exchanger



$$R_{DL1} = R_{DL2} = \begin{bmatrix} 1 & L & 0 & \eta \\ 0 & 1 & 0 & 0 \\ 0 & \eta & 1 & \xi \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_{D1} = R_{D2} = \begin{bmatrix} 1 & D & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_{TCAV}\ \text{(thin-lens)} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & 0 & 0 & 1 \end{bmatrix}$$

$$R_{EEX} = R_{DL2} \cdot R_{D2} \cdot R_{TCAV} \cdot R_{D1} \cdot R_{DL1}$$

$$= \begin{bmatrix} R_{11} & R_{12} & R_{15} & R_{16} \\ R_{21} & R_{22} & R_{25} & R_{26} \\ R_{51} & R_{52} & R_{55} & R_{56} \\ R_{61} & R_{62} & R_{65} & R_{66} \end{bmatrix} = \begin{bmatrix} 0 & 0 & k(L+D) & \eta + k\xi(L+D) \\ 0 & 0 & k & k\xi \\ k\xi & \eta + k\xi(L+D) & 0 & 0 \\ k & k(L+D) & 0 & 0 \end{bmatrix}$$

Applications

1. **Emittance Exchange →**

before

$$\boldsymbol{\Sigma}_b = \begin{bmatrix} \boldsymbol{\Sigma}_x & 0 \\ 0 & \boldsymbol{\Sigma}_z \end{bmatrix}$$

after

$$\boldsymbol{\Sigma}_a = \begin{bmatrix} \mathbf{B}\boldsymbol{\Sigma}_x\mathbf{B}^T & \mathbf{0} \\ \mathbf{0} & \mathbf{C}\boldsymbol{\Sigma}_z\mathbf{C}^T \end{bmatrix}$$

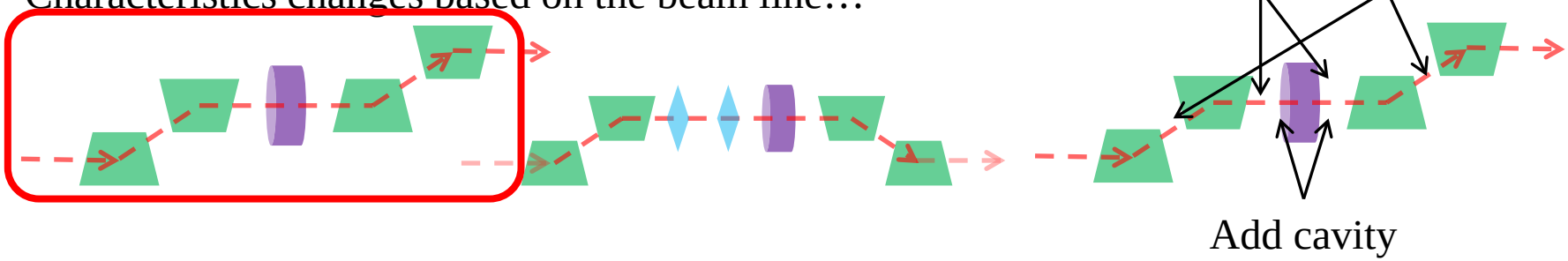
2. **Bunch Shaping →**

$$z_f = k\xi x_i + \{\eta + k\xi(L + D')\}x'_i$$

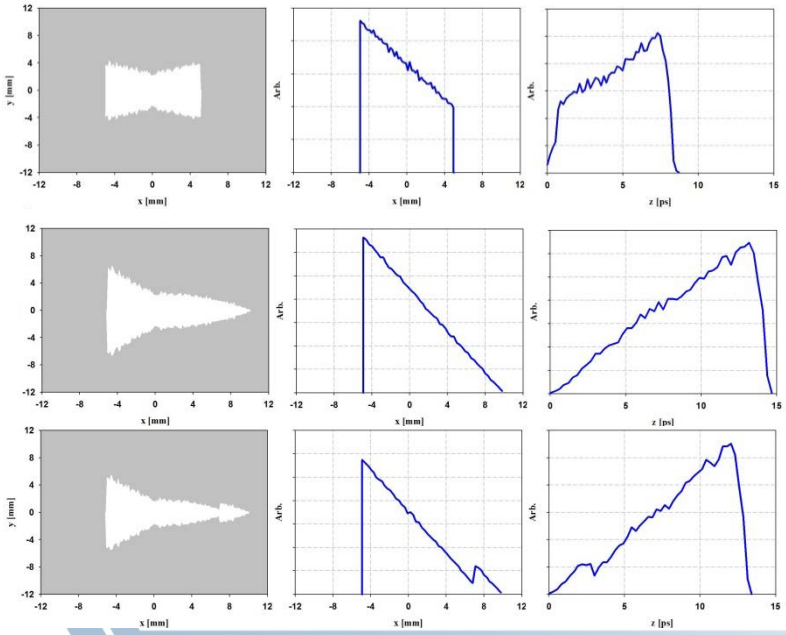
Three ways to control the shaping process

1. Beam line

Characteristics changes based on the beam line…



2. Shape of the Mask



3. Initial beam conditions

- Beam line still have many weak points. It will be modified.
- Mask shape will be determined based on the first order theory.
- We will focus on the initial beam conditions for the shaping.
- Details in the next slides…

Limitations of the Bunch Shaping eex-based beamline

What realistic effects disturb the shaping process??

Simplest case

1. Uniform distribution / zero emittance / thin-lens / 1st order /no SC/ no CSR

2. **Non-Uniform distribution** / zero emittance / thin-lens / 1st order/no SC/ no CSR

3. Non-Uniform distribution / **finite emittance** / thin-lens / 1st order/no SC/ no CSR

4. Non-Uniform distribution / finite emittance / **thick-lens** / 1st order/no SC/ no CSR

5. Non-Uniform distribution / finite emittance / thick-lens / 1st & **2nd order** /no SC/ no CSR

6. Non-Uniform distribution / finite emittance / thick-lens / 1st & 2nd order/ **SC**/no CSR

7. Non-Uniform distribution / finite emittance / thick-lens / 1st& 2nd order/ SC/ **CSR**

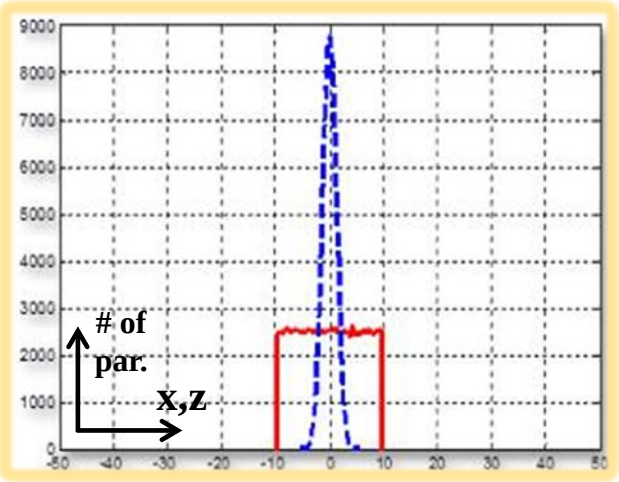
Realistic case

1. Uniform distribution / zero emittance / thin-lens / 1st order /no SC/ no CSR

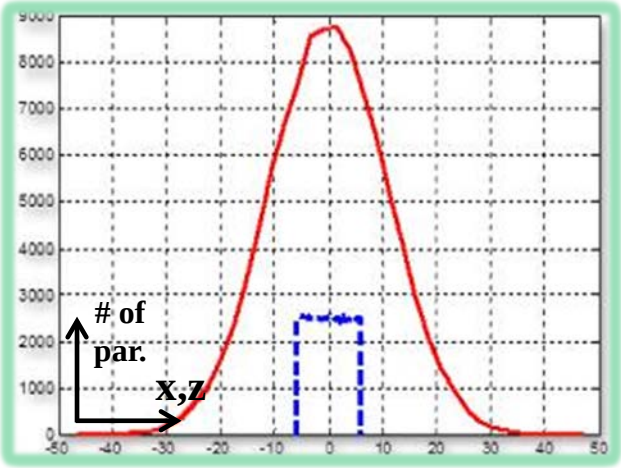
Horizontal profile
Current profile

Simplest case

Entrance



Exit



If we have quasi-linearity between x_i and x'_i and the expression for z_f

$$\left[x'_i \sim -\frac{\alpha_x}{\beta_x} x_i\right]$$

$$z_f = k\xi x_i + \{\eta + k\xi(L+D)\}x'_i$$

Then the final Current profile at the exit follows horizontal profile at the entrance

$$z_f = \left\{k\xi - \frac{\alpha_x}{\beta_x}\{\eta + k\xi(L+D)\}\right\} x_i$$

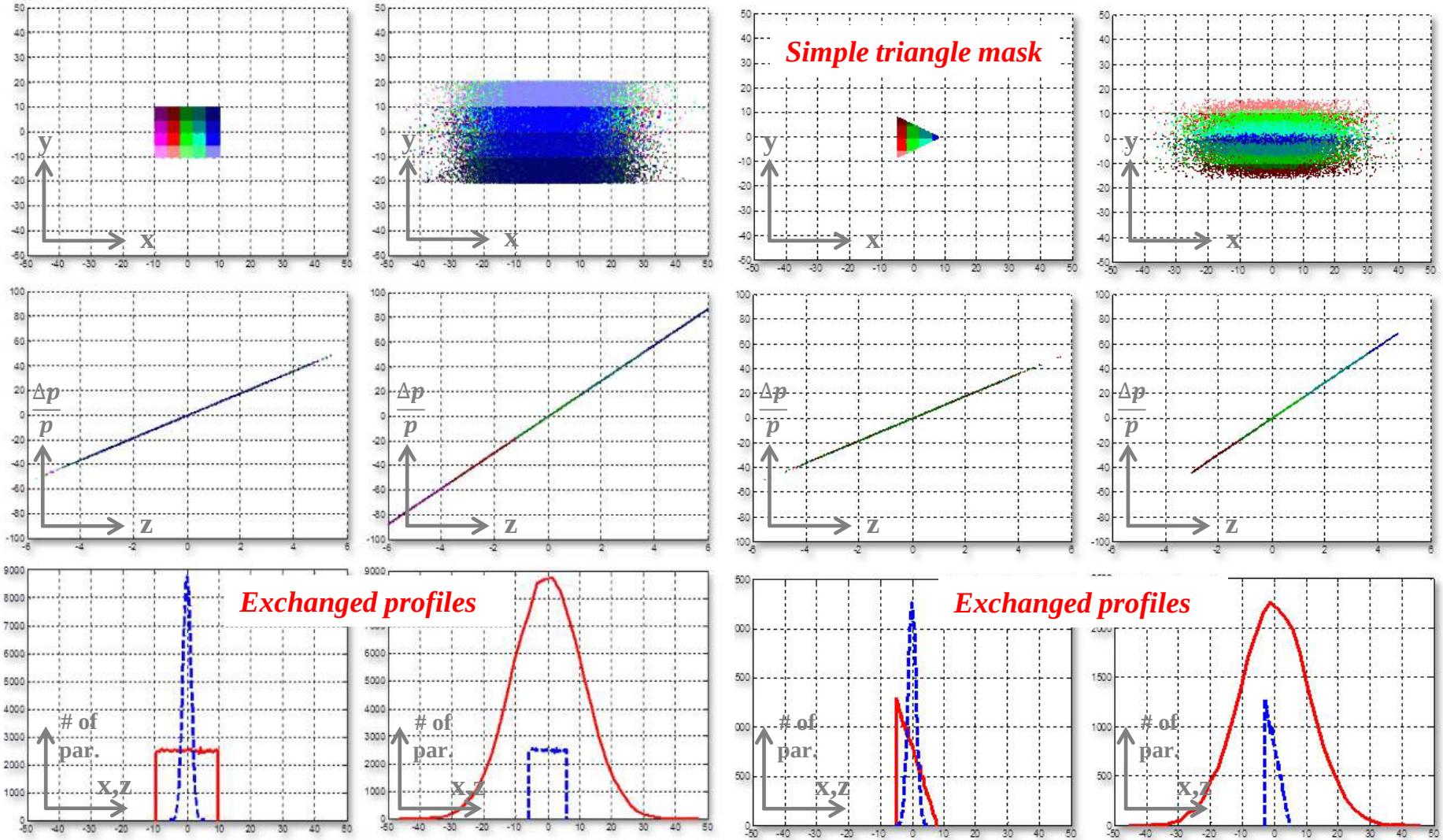
1. Uniform distribution / zero emittance / thin-lens / 1st order /no SC/ no CSR

Horizontal profile
Current profile

Simplest case

w\o Mask | **w\ Mask**

Entrance | **Exit** | **Entrance** | **Exit**

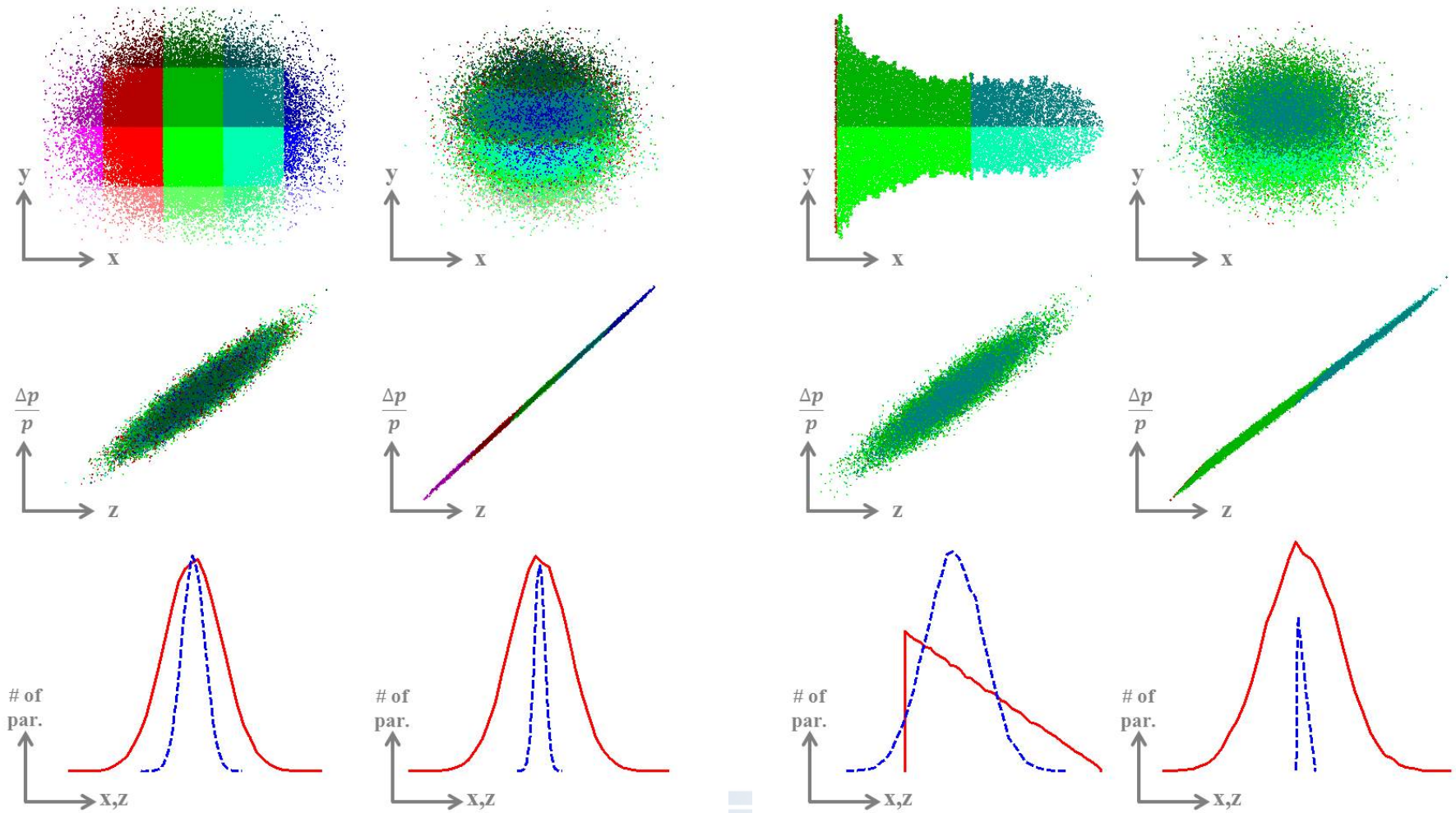


2. Non-Uniform distribution / zero emittance / thin-lens / 1st order/no SC/ no CSR

Horizontal profile
Current profile

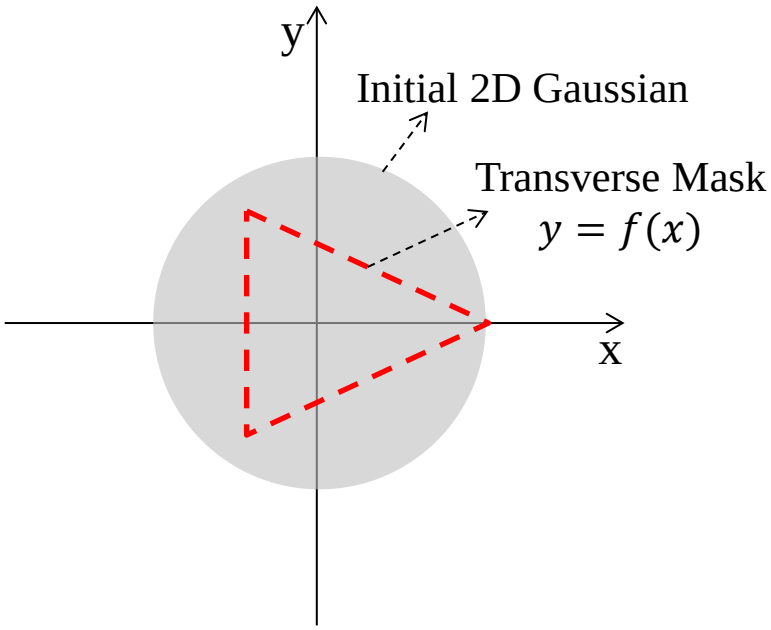
Cannot use Triangular Mask Shape

Gaussian Distribution w\o Mask | **Gaussian Distribution w\ Mask**



2. Non-Uniform distribution / zero emittance / thin-lens / 1st order/no SC/ no CSR

Determine Mask Shape



Initial 2D population

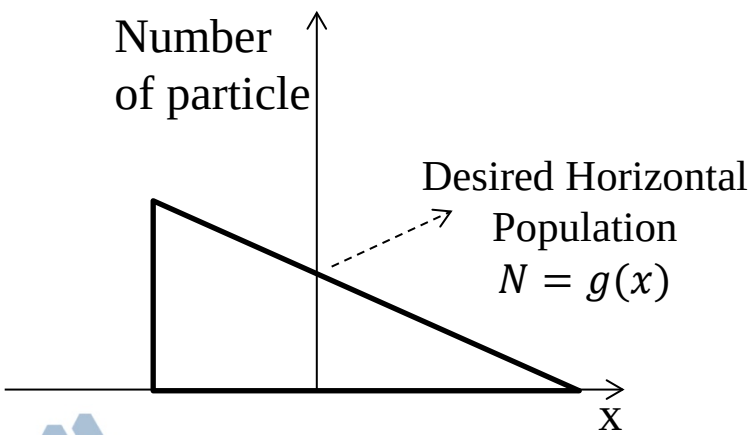
$$N(x,y) = \frac{N_{tot}}{2\pi\sigma_x\sigma_y}\, e^{-\left\{\frac{x^2}{2\sigma_x{}^2}+\frac{y^2}{2\sigma_y{}^2}\right\}}$$

Initial horizontal population

$$N(x) = \frac{N_{tot}}{\sqrt{2\pi}\,\sigma_x}\, e^{-\frac{x^2}{2\sigma_x{}^2}}\, erf\left\{\frac{f(x)}{\sqrt{2}\sigma_y}\right\}$$

Required shape of the transverse mask

$$\mathrm{f}(x) = \sqrt{2\,\pi}\,\sigma_y\, inverf\left\{\sqrt{2\pi}\,\sigma_x \frac{\mathrm{g(x)}}{N_{tot}} \exp\left(\frac{x^2}{2\sigma_x{}^2}\right)\right\}$$

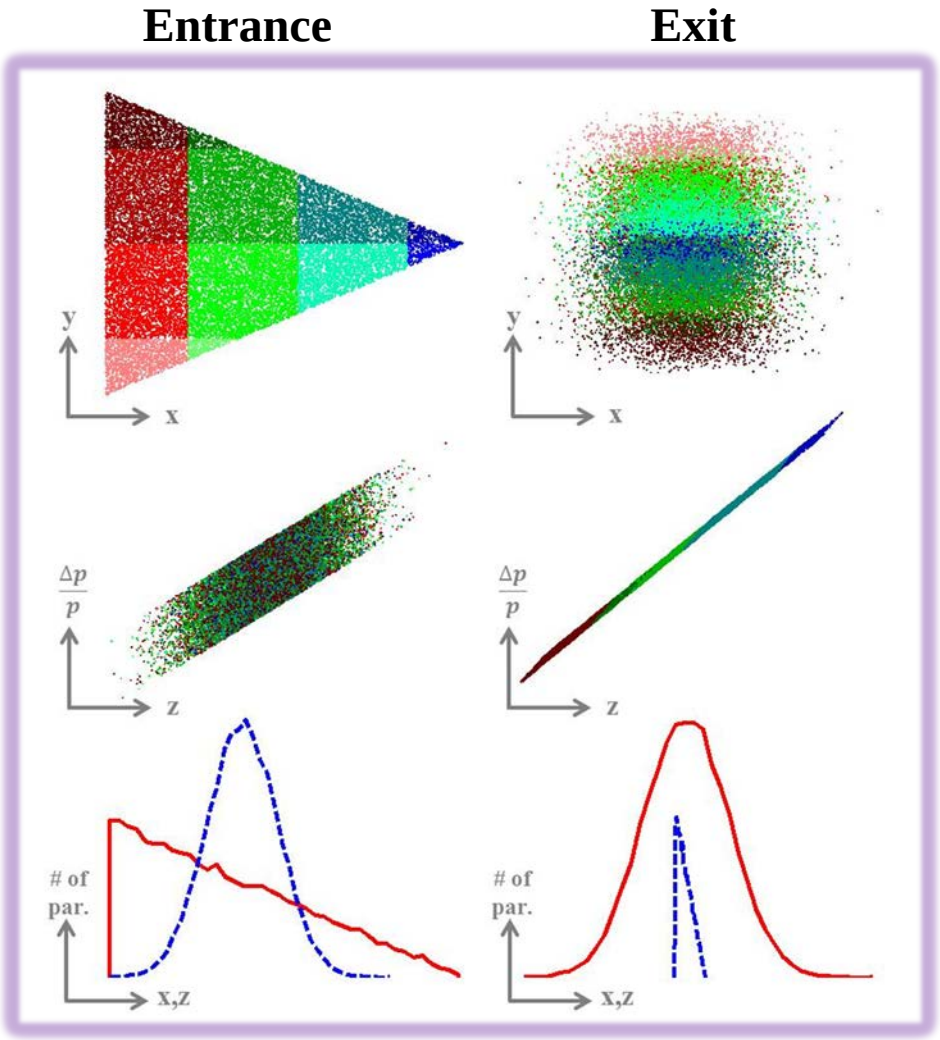


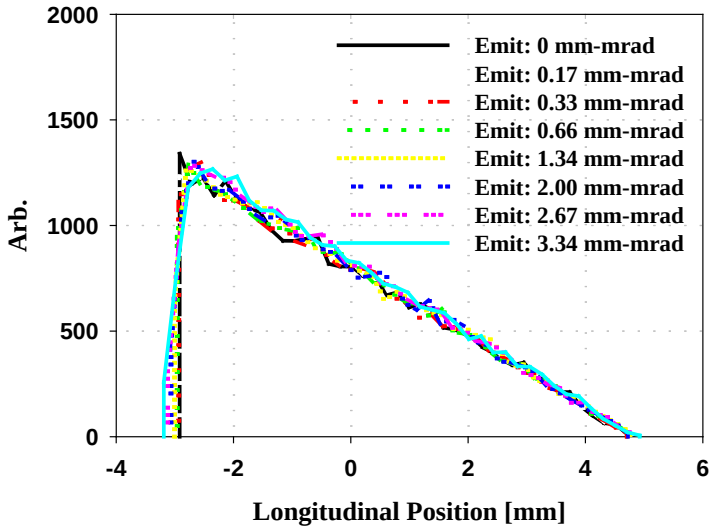
- Current initial population is not a Gaussian.
- The shape of the mask is determined numerically.

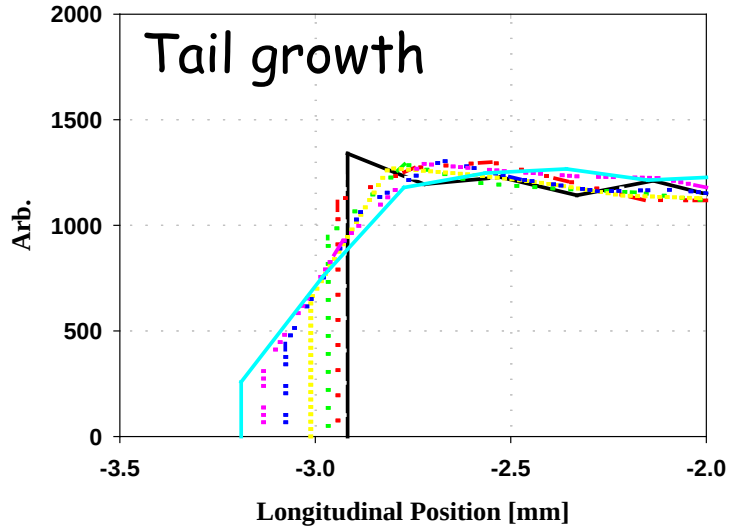
Relation between f, g and N

$$g(x) = 2\int_0^{f(x)} N(x,y)\;\; dy$$

3. Non-Uniform distribution / finite emittance / thin-lens / 1st order/no SC/ no CSR







Tail growth caused by overlap of R52 and Δx'

$$z_f = k\xi x_i + \{\eta + k\xi(L + D)\}x'_i$$

solution →

- R52=0
- Minimize emittance
- Increase beam size

4. Non-Uniform distribution / finite emittance / thick-lens / 1st order/no SC/ no CSR

$$R_{EEX} = \begin{bmatrix} 0 & \boxed{\frac{L_c}{4}} & k(L+D+\frac{L_c}{4}) & \eta + k\xi(L+D+\frac{L_c}{4}) \\ 0 & 0 & k & k\xi \\ k\xi & \eta + k\xi(L+D+\frac{L_c}{4}) & \frac{L_c}{4}k^2\xi & \frac{L_c}{4}k^2\xi^2 \\ k & k(L+D+\frac{L_c}{4}) & \frac{L_c}{4}k^2 & \frac{L_c}{4}k^2\xi \end{bmatrix}$$

$$R_{TCAV} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & 0 & 0 & 1 \end{bmatrix}$$

$$R_{TCAV} = \begin{bmatrix} 1 & L_c & kL_c/2 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & kL_c/2 & \boxed{k^2L_c/4} & 1 \end{bmatrix}$$

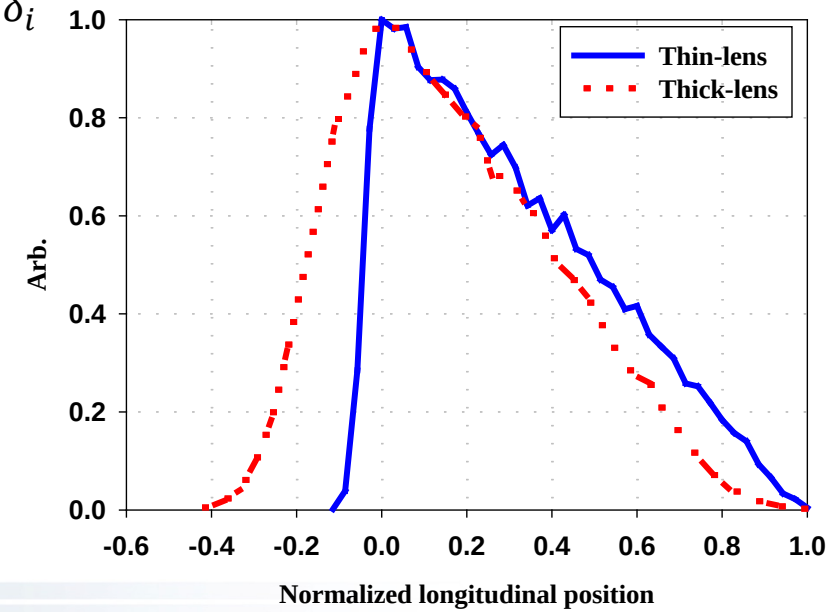
- The thick-lens terms significantly affect both the tail and the head

$$z_f = k\xi x_i + \{\eta + k\xi(L+D)\}x'_i s \ + \frac{L_c}{4}k^2\xi z_i + \frac{L_c}{4}k^2\xi^2\delta_i$$

- This effect can be suppressed by setting last two terms equal to zero

$$\frac{L_c}{4}k^2\xi z_i + \frac{L_c}{4}k^2\xi^2\delta_i = 0$$

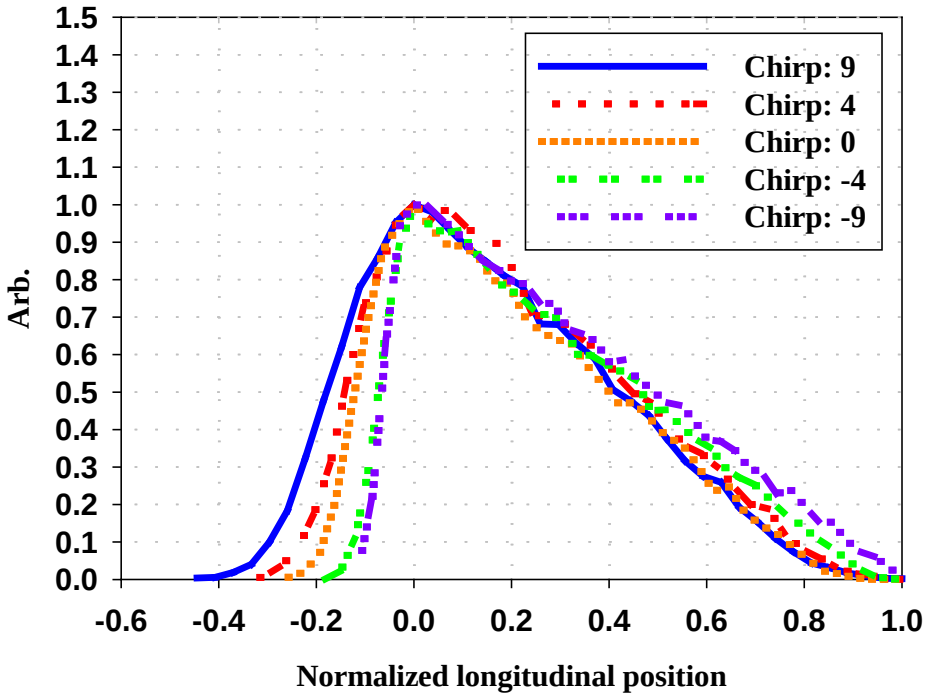
Soln: chirp = $\frac{z_i}{\delta_i} = -\frac{1}{\xi}$

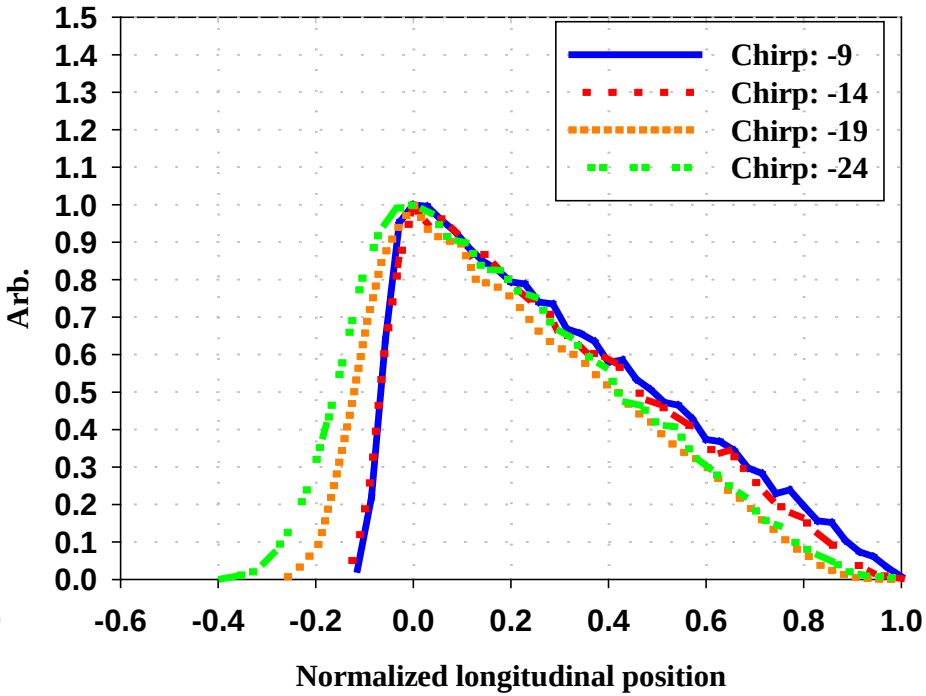


4. Non-Uniform distribution / finite emittance / thick-lens / 1st order/no SC/ no CSR

Suppression of thick-lens effect

- $R_{56} = R_{55} \times \xi$
- Longitudinal chirp of $-1/\xi$ can suppress the thick-lens effect.
- Chirp near -9 has short tail, and tail length increases as chirp changes.



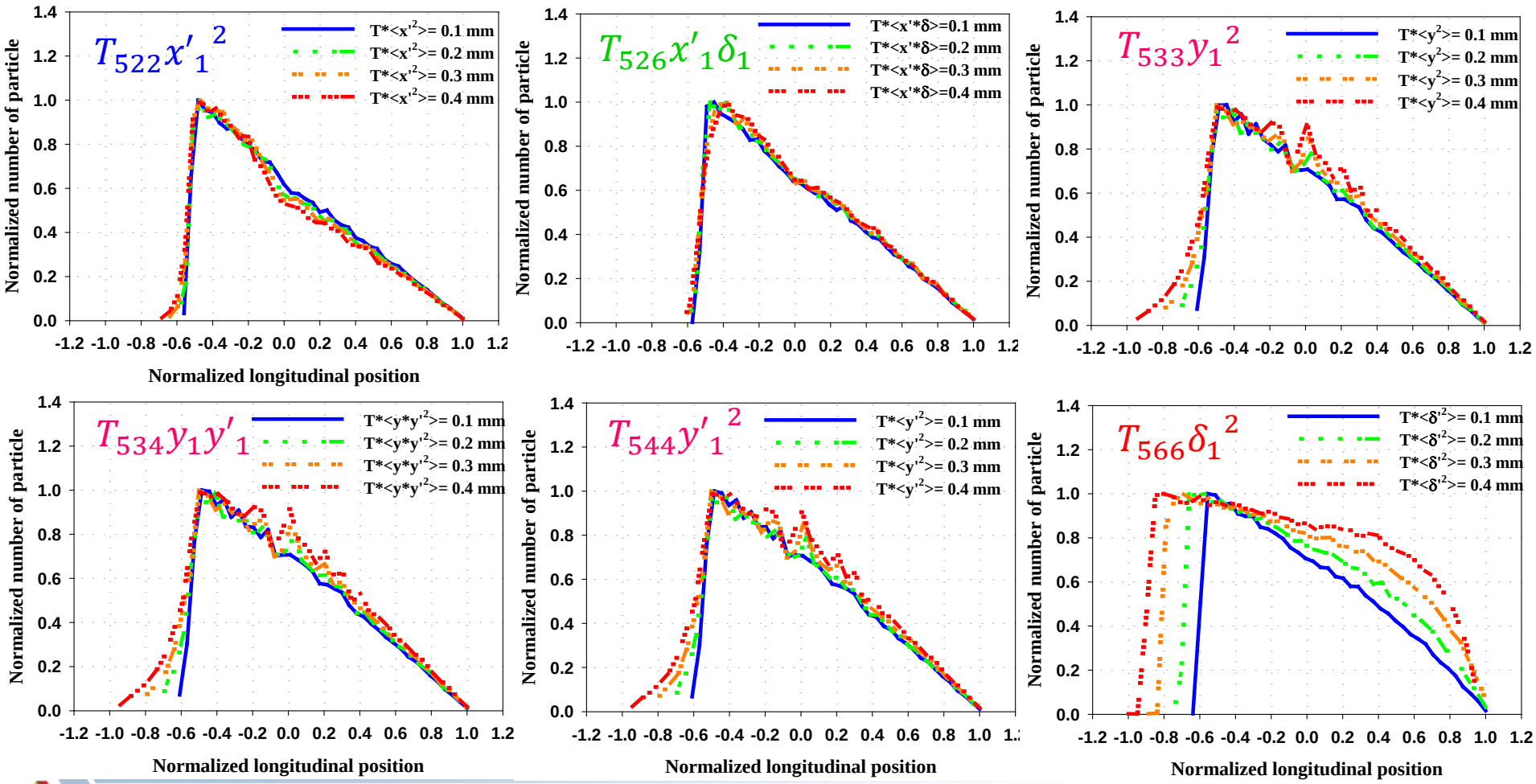


5. Non-Uniform distribution / finite emittance / thick-lens / 1st & **2nd order** /no SC/ no CSR

- This change mostly happens when the beam passes the second dog-leg.

Dominant term

$$z_f = [R_{52}x'_1 + R_{55}z_1 + R_{56}\delta_1] + [T_{533}{y_1}^2 + T_{534}y_1y'_1 + T_{544}{y'_1}^2 + T_{522}{x'_1}^2 + T_{526}x'_1\delta_1 + T_{566}{\delta_1}^2]$$



5. Non-Uniform distribution / finite emittance / thick-lens / 1st & **2nd order** /no SC/ no CSR

$T_{566}\delta_1{}^2$

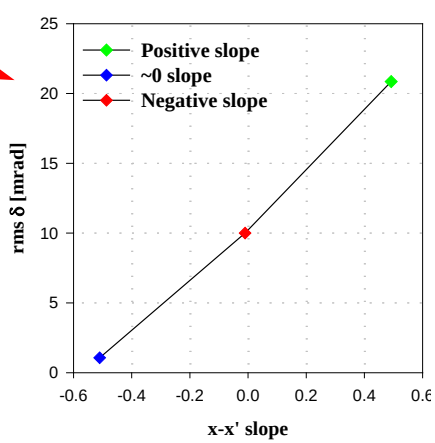
→ Directly linked with the current profile at the exit
→ Makes convex head
→ No tail

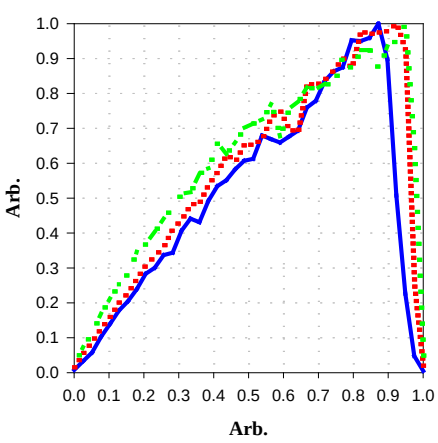
$$z_f = k\xi x_i + \{\eta + k\xi(L+D)\}x'_i$$
$$\delta_1 = kx_i + k(L+D)x'_i$$

- We could reduce T566 by adding elements to the beamline but …
- We want to reduce the energy spread at the entrance of the 2nd dog-leg.

$$\delta_1 = kx_i + k(L + D + L_c/4)x'_i + (L_c/4)k^2 z_i + (L_c/4)k^2\xi\delta_i$$

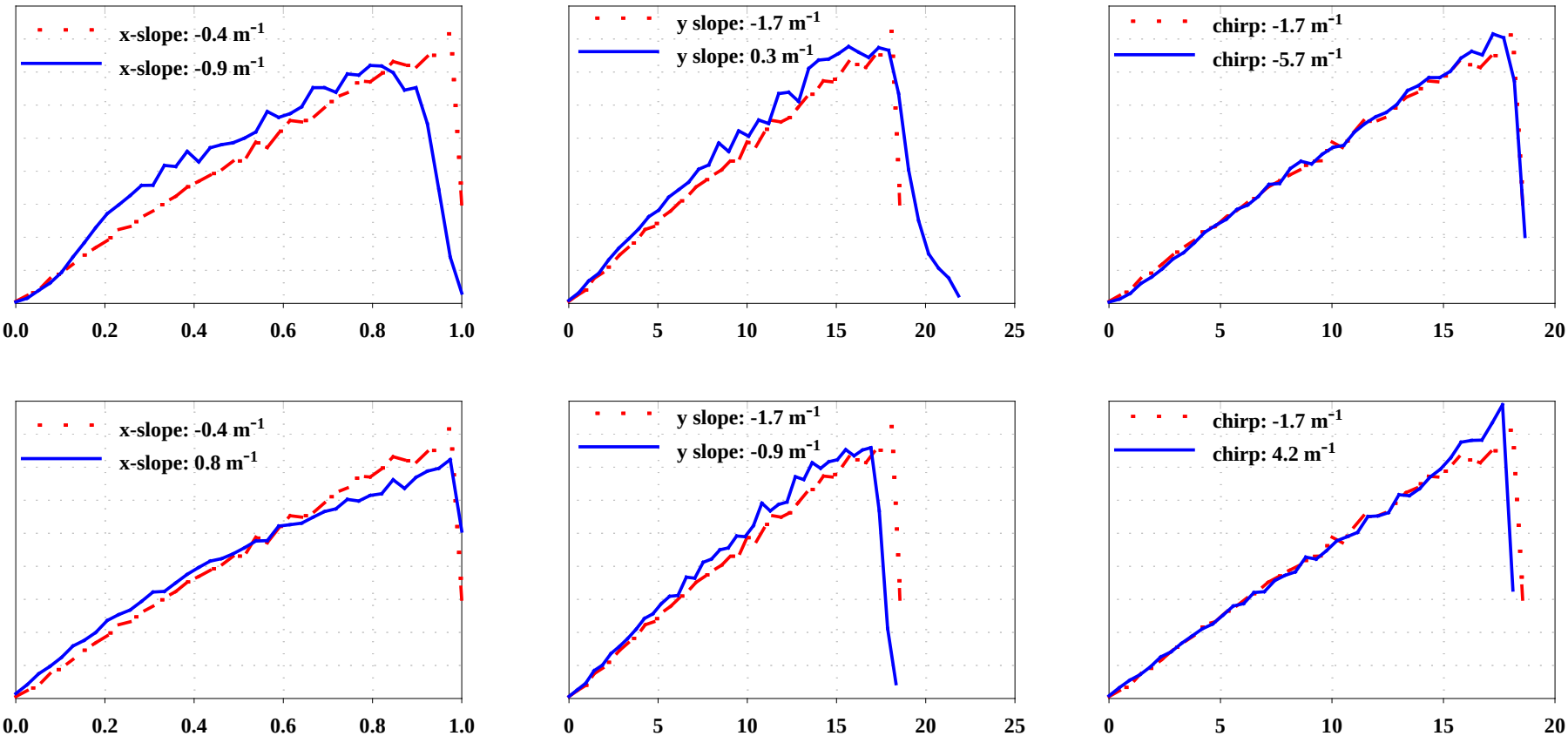
- Appropriate initial **<u>slope and chirp</u>** will reduce the energy spread δ_1.





5. Non-Uniform distribution / finite emittance / thick-lens / 1st & **2nd order** /no SC/ no CSR

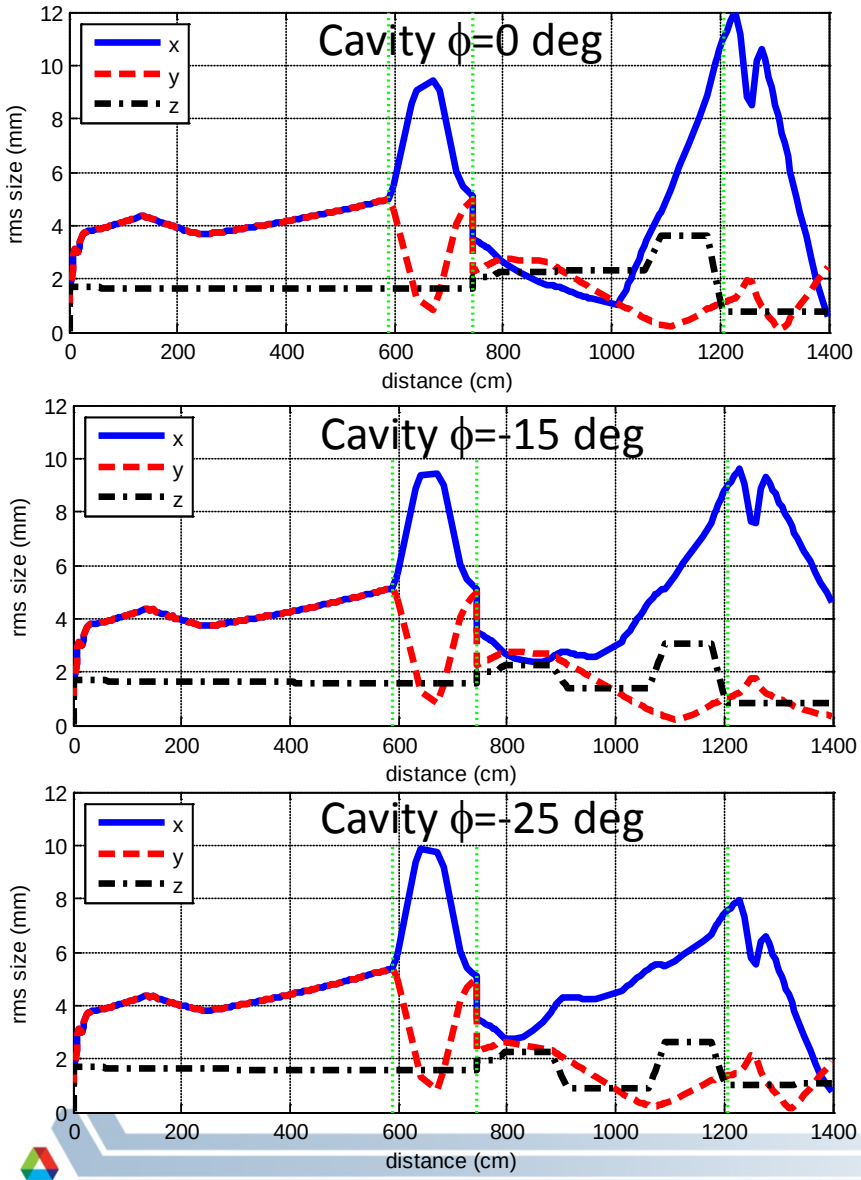
$T_{566}{\delta_1}^2$ $T_{533}{y_1}^2$ $T_{534}y_1{y'}_1$ $T_{544}{y'_1}^2$ $T_{526}{x'}_1\delta_1$ $T_{522}{x'_1}^2$

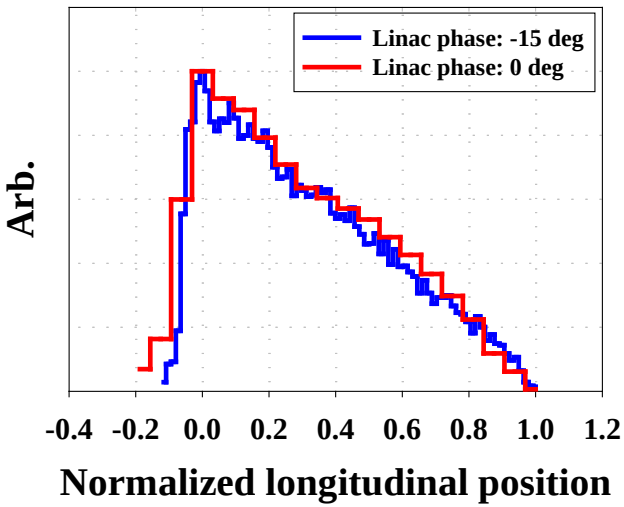


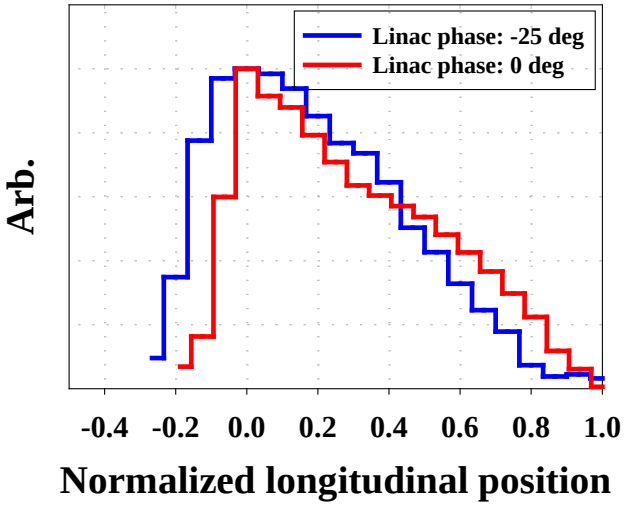
Conclusion: The 2nd order effects can be mostly suppressed with the proper choice:

- x-x' slope (most important)
- y-y' slope (weak effect)
- longitudinal chirp.

6. Non-Uniform distribution / finite emittance / thick-lens / 1st & 2nd order/ **SC**/no CSR



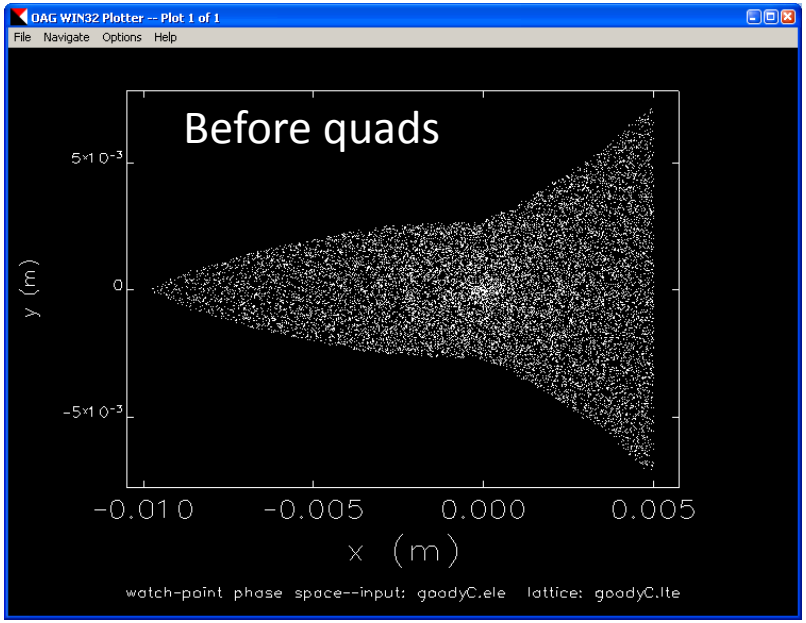


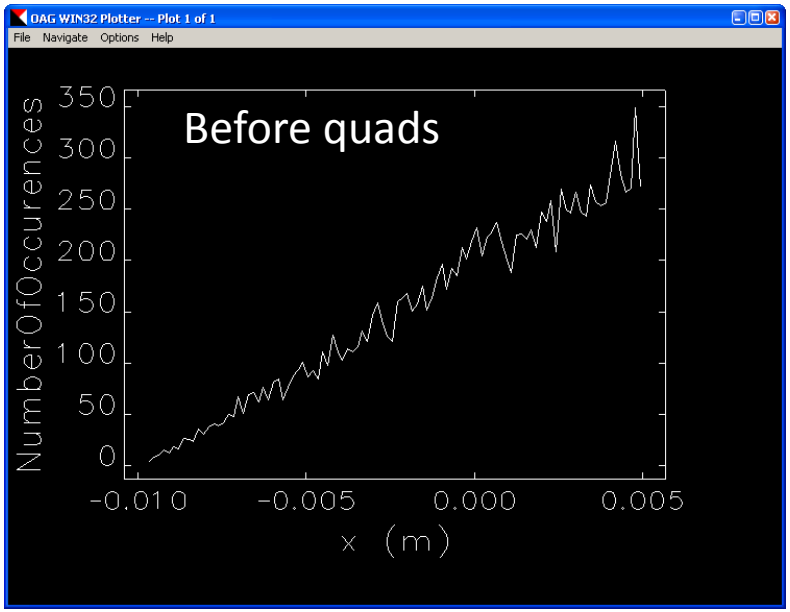


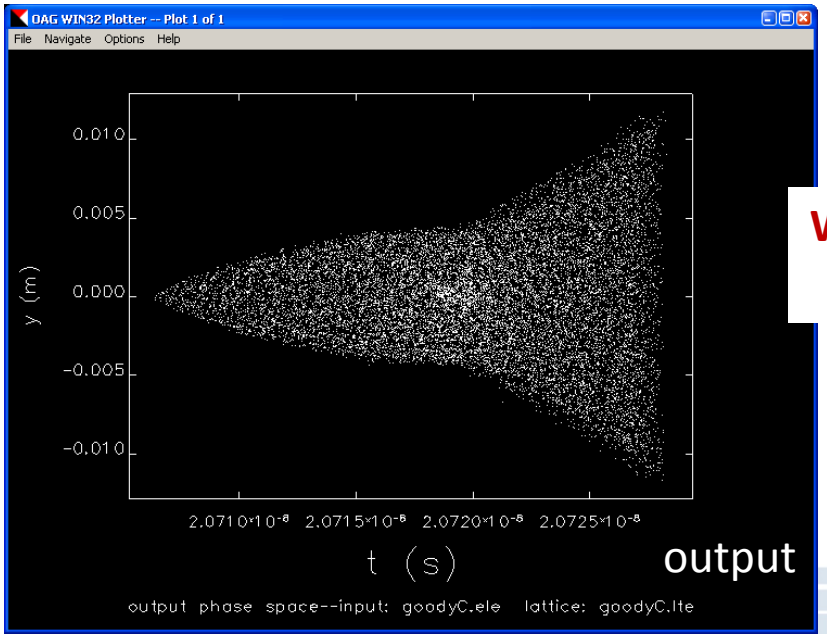
Best chirp for SC is opposed to previous; therefore chirp is a compromise

Non-Uniform distribution / finite emittance / thick-lens / 1st& 2nd order/ SC/ **CSR**

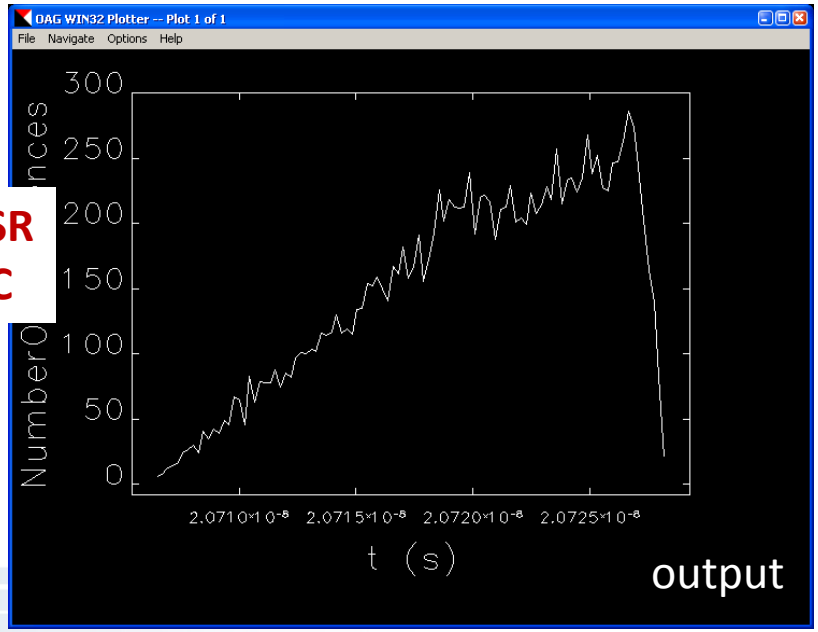
D. Shchegolkov (LANL)







WITH CSR and LSC

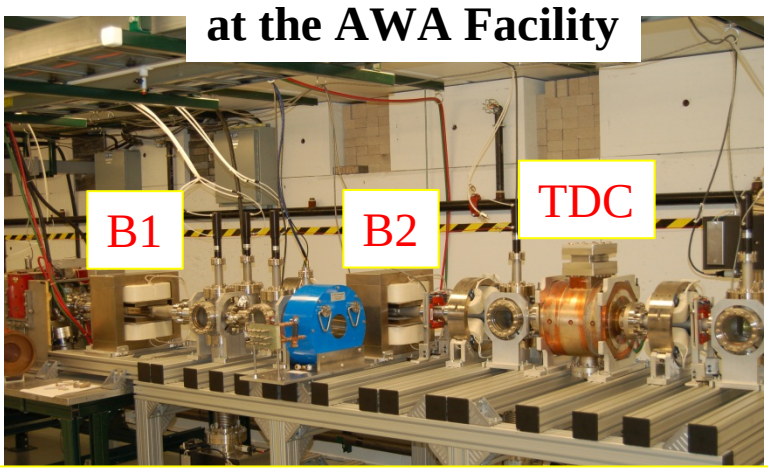


BEGINNING EXPERIMENTAL STUDIES 1:

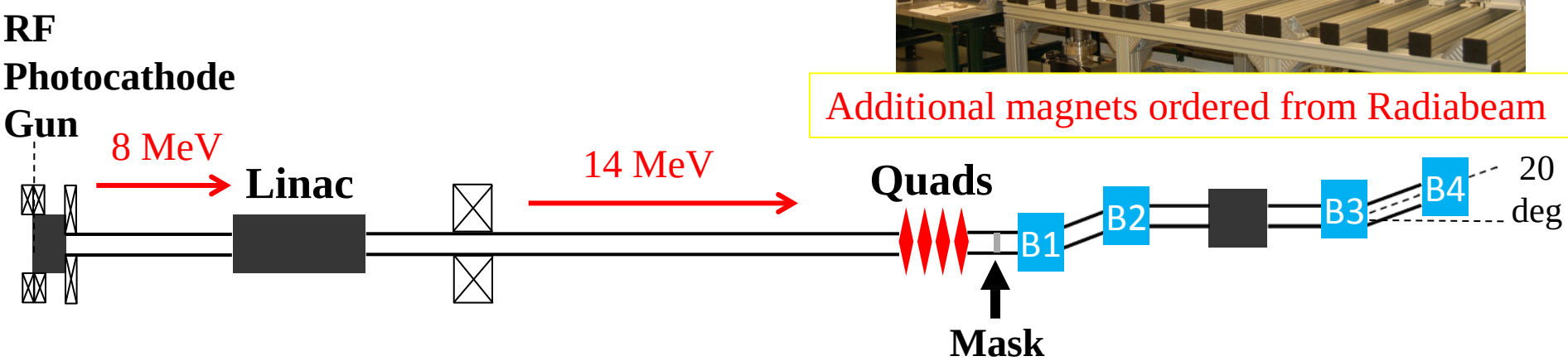
Demonstrate EEX based bunch shaping at the Argonne Wakefield Accelerator

Demonstrate bunch shaping using a double-dog leg EEX beamline

The
Argonne Wakefield Accelerator Facility
→ Low Energy (14 MeV) beamline



Additional magnets ordered from Radiabeam

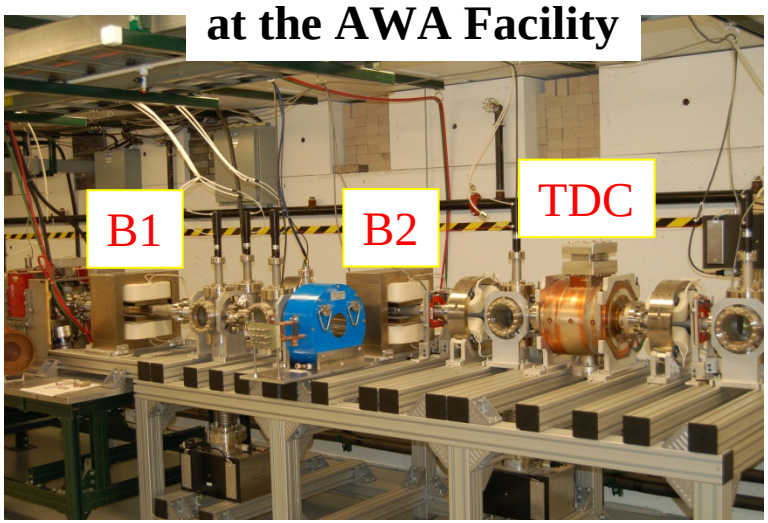


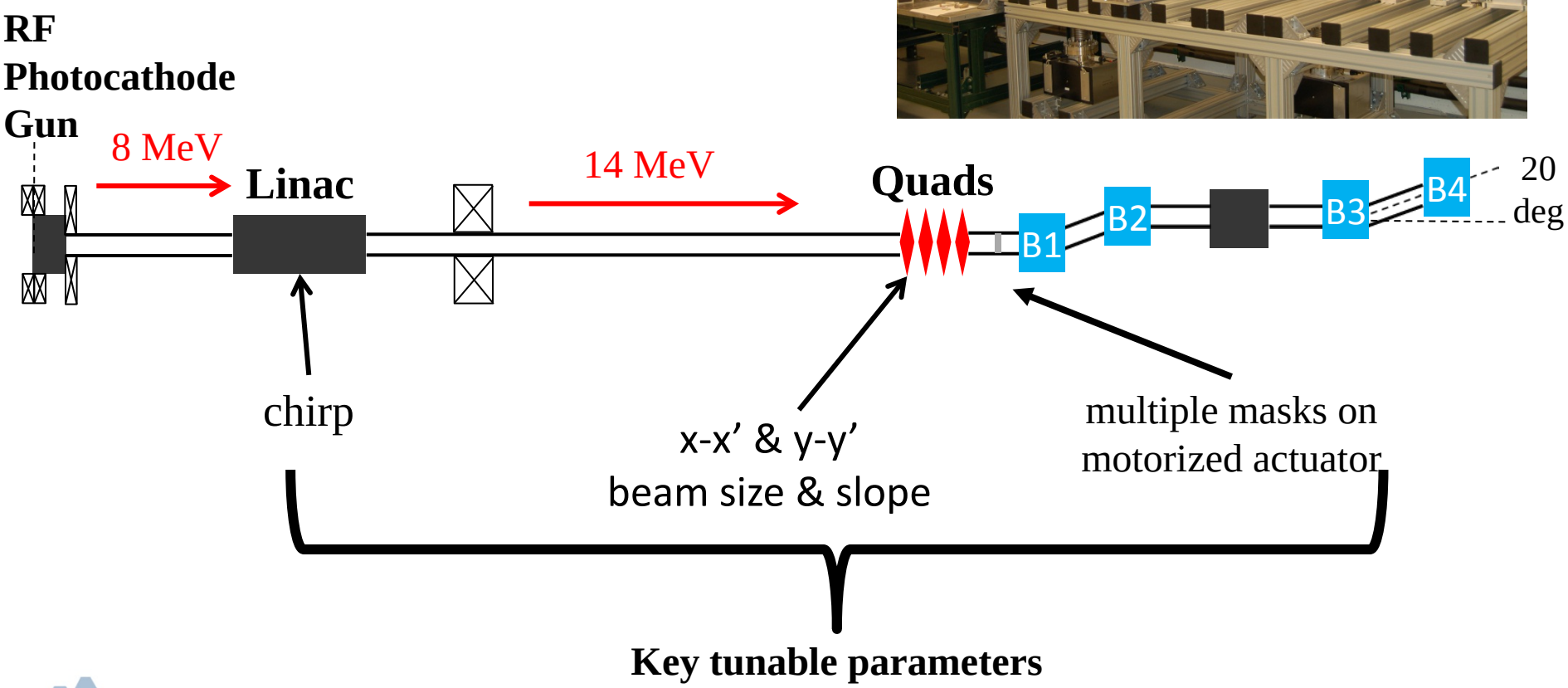
Initial experimental goals:

- Demonstrate bunch shaping and compare measured shape to 1st order theory
- Measure EEX transfer matrix
- Study 2nd order effects in beamline
- Study space charge effects in beamline

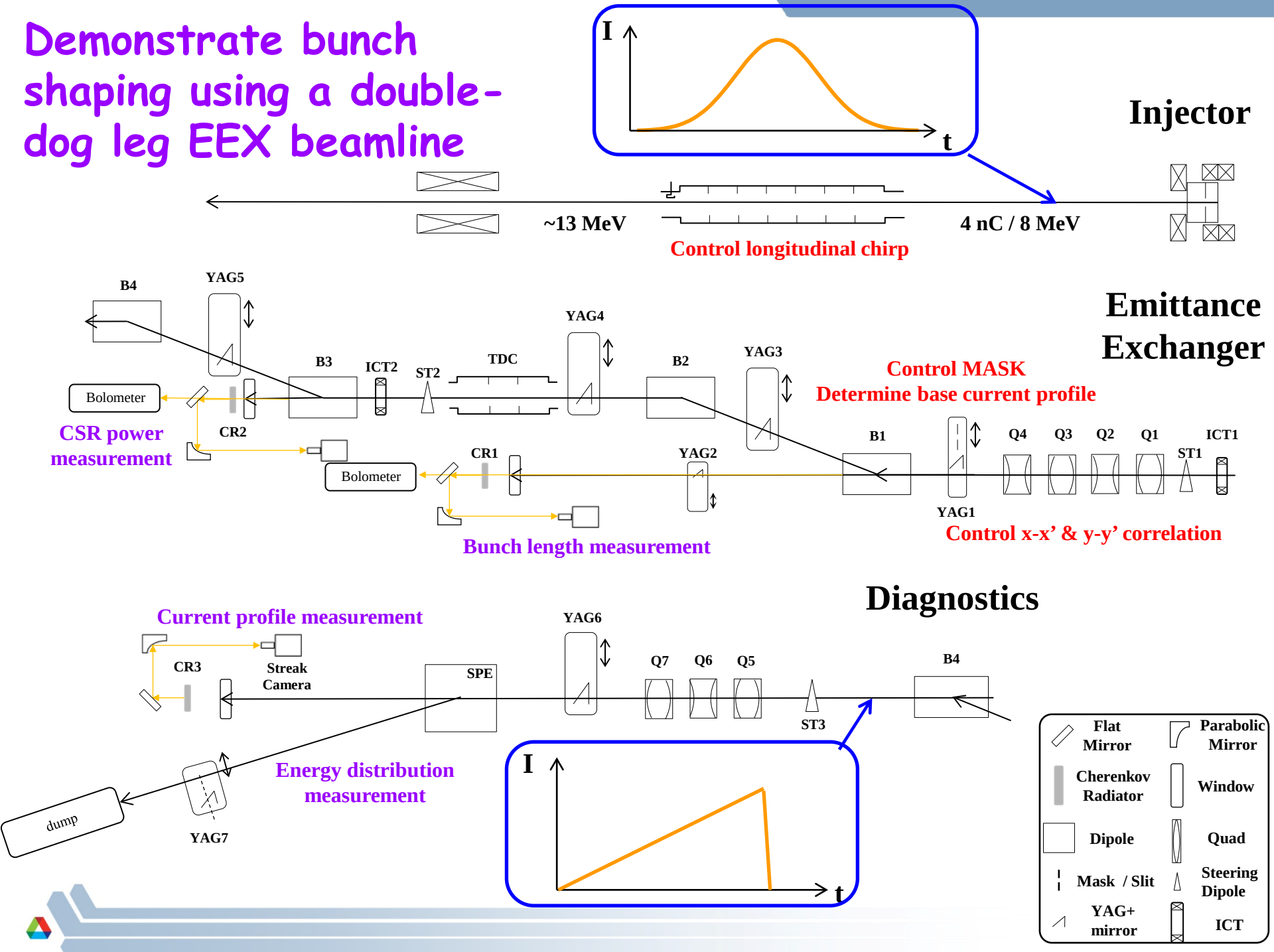
Demonstrate bunch shaping using a double-dog leg EEX beamline

The
Argonne Wakefield Accelerator Facility
→ Low Energy (14 MeV) beamline



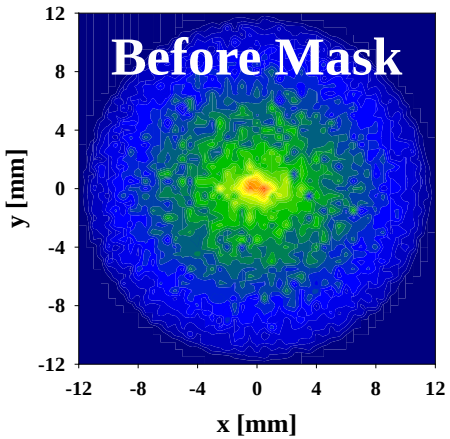


Demonstrate bunch shaping using a double-dog leg EEX beamline



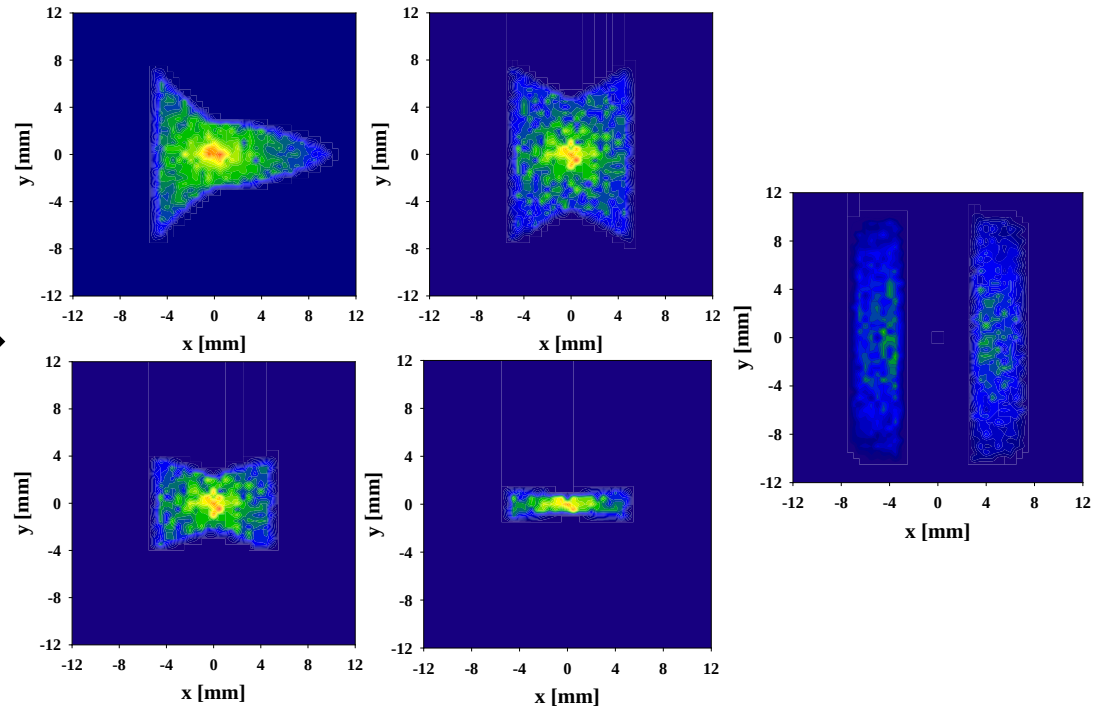
Experiment I - Shaping ability of Masks

Multiple masks used to study bunch shaping



Apply

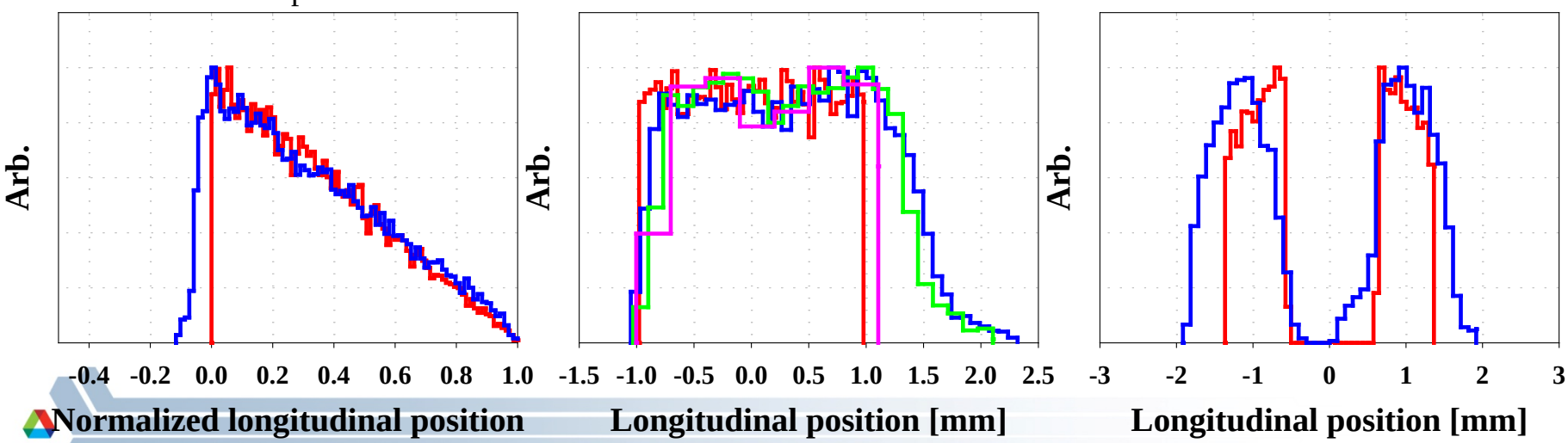
Mask



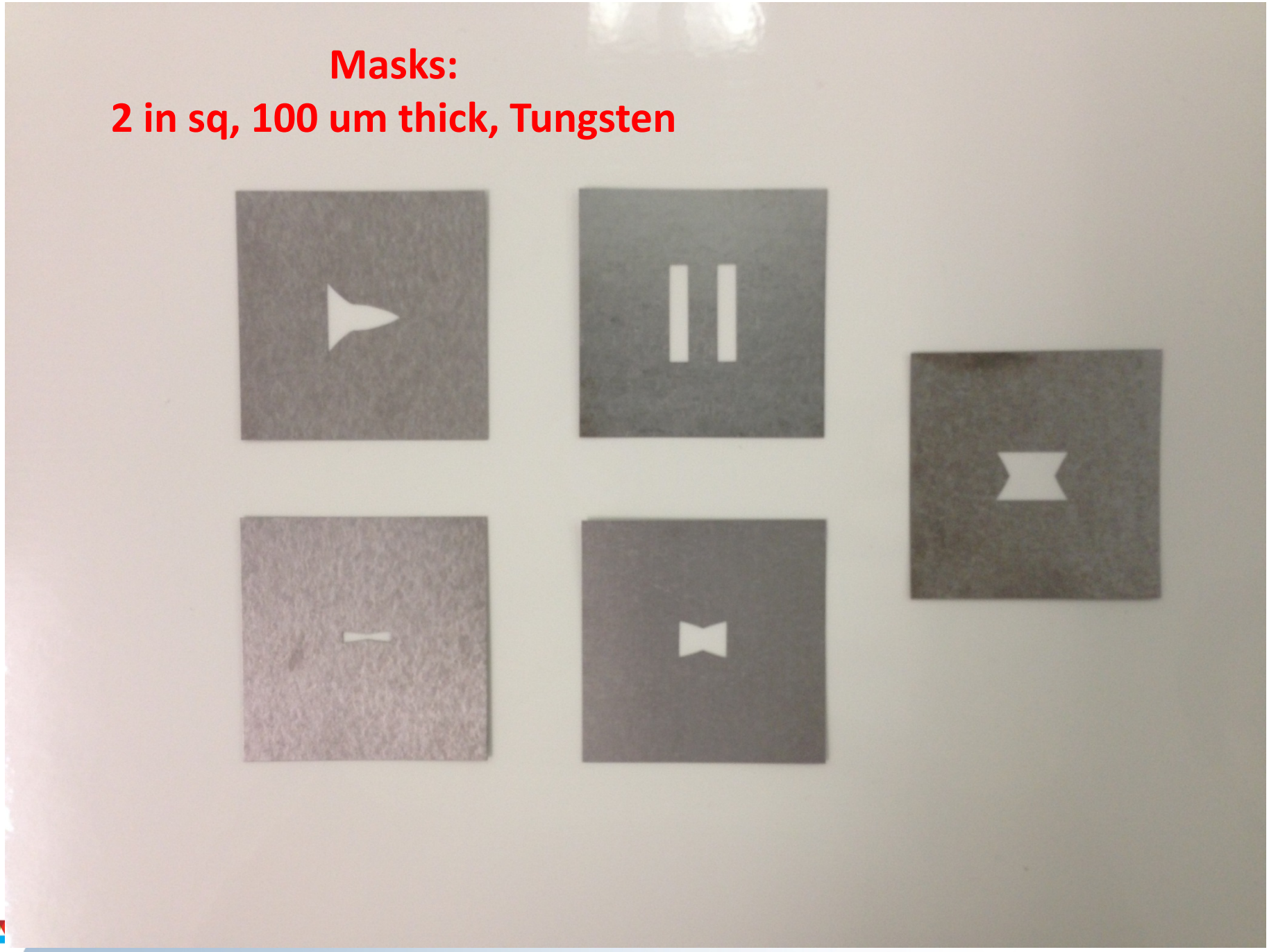
PARMELA Simulation results

Horizontal profile after the mask

Final current profile



Masks:
2 in sq, 100 um thick, Tungsten

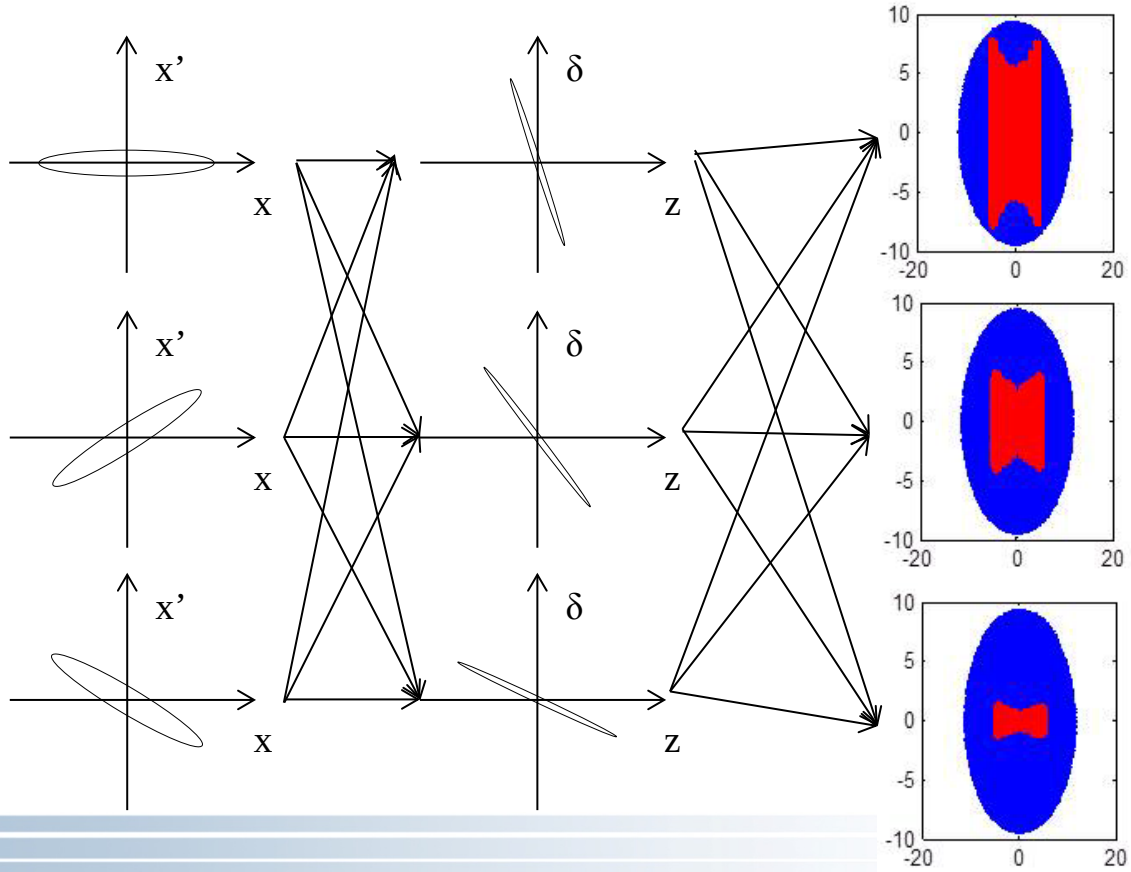


Experiment II - Shaping ability of Beam Parameters

Goal 1. Find relations between initial beam condition and shaped current profile

2. Observe the effect of space-charge

- **Set nominal parameters:** x-x' slope, y-y' slope, longitudinal chirp, and charge.
- **Vary one parameter at a time:** with quadrupoles, rf cavity phase, and mask.
- **Observe the current profile and energy profile.**



Experiment II - Shaping ability of Beam Parameters

Goal 1. Find relations between initial beam condition and shaped current profile

2. Observe the effect of space-charge

What is the best chirp??

A compromise between suppressing 2nd order vs. SC effects.

EXAMPLE

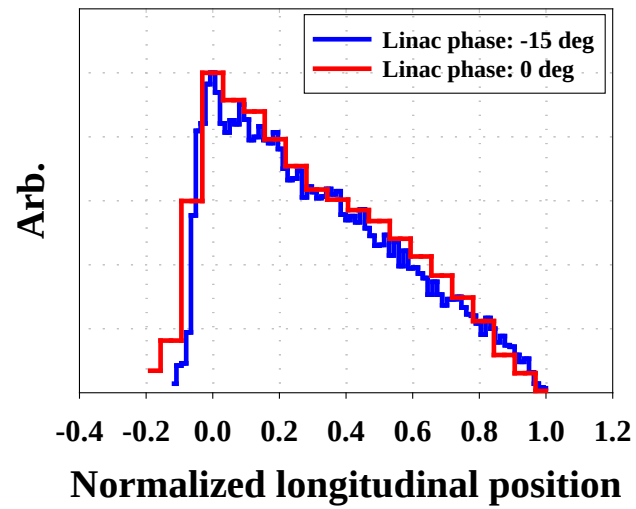
PARMELA Simulation results

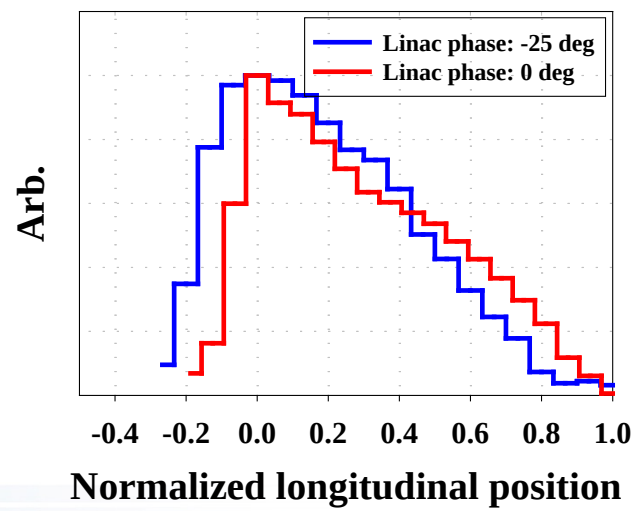
1. linac phase ϕ= -30 deg ➔ suppress 2nd order effect
2. linac phase ϕ=0 deg ➔ suppress SC effect (long bunch length)

Compromise: linac phase ϕ=15 deg

*linac phase ϕ= -30 deg (chirp = $-1/\xi$ = -7)

*linac phase ϕ= 0 deg (chirp = $-1/\xi$ = -2)



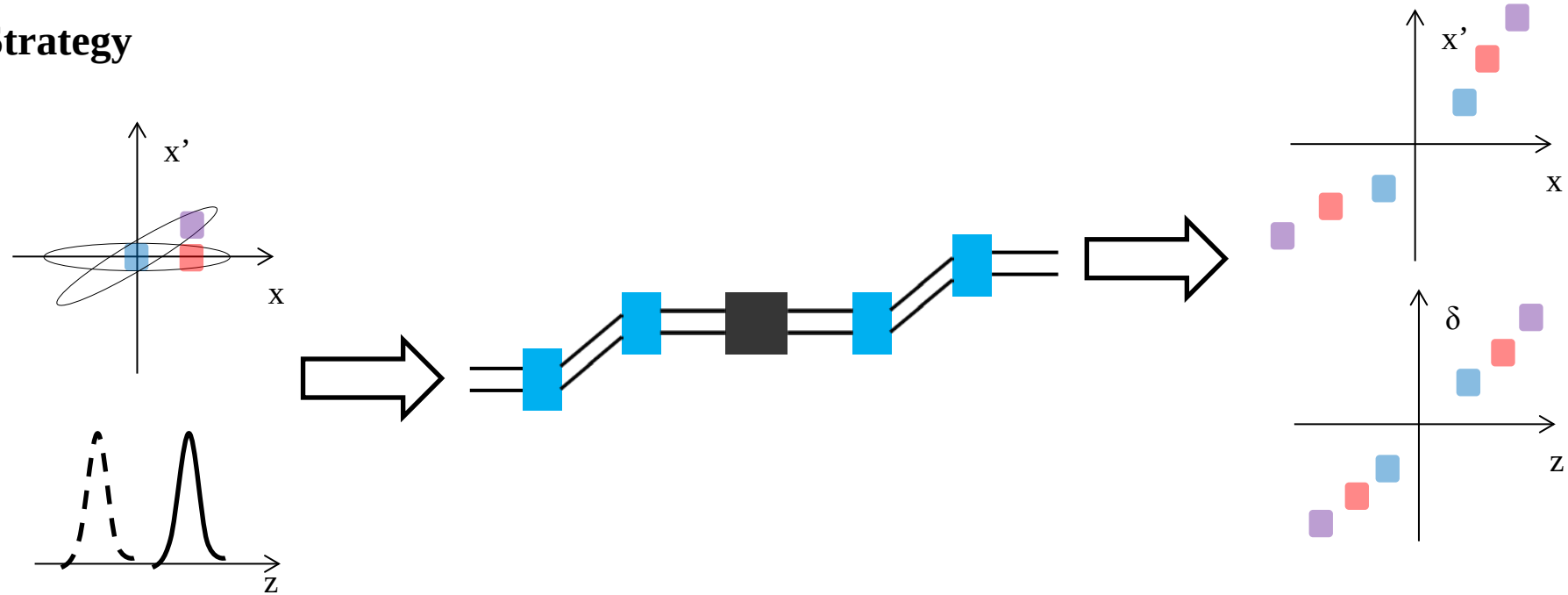


Experiment III - Transport matrix measurement

Goal

1. Experimentally measure the transport matrix
2. Analyze space-charge effect and CSR effect in the emittance exchanger

Strategy



1. Initially give the longitudinally two bunch which are very close.
2. Make the beam like a color part in the figure using the quad and slit-like mask.
3. Compare the horizontal and longitudinal beam positions, divergence, and energy of each color.

Summary

- **The concept: High Repetition-Rate, Soft X-ray FEL User Facility**
  - 10 DWFAs linacs driven by a single SRF linac
  - 10 FEL lines @ 100 kHz rep. rate.
  - Compact, Inexpensive, and Flexible
- **A working group has started feasibility studies**
- **Bunch Shaping Experiments to start Spring 2014**
  - Study the fundamental structure (double dogleg eex)
  - Explore the limits of the shaping process
- **We welcome collaborators and new ideas!**