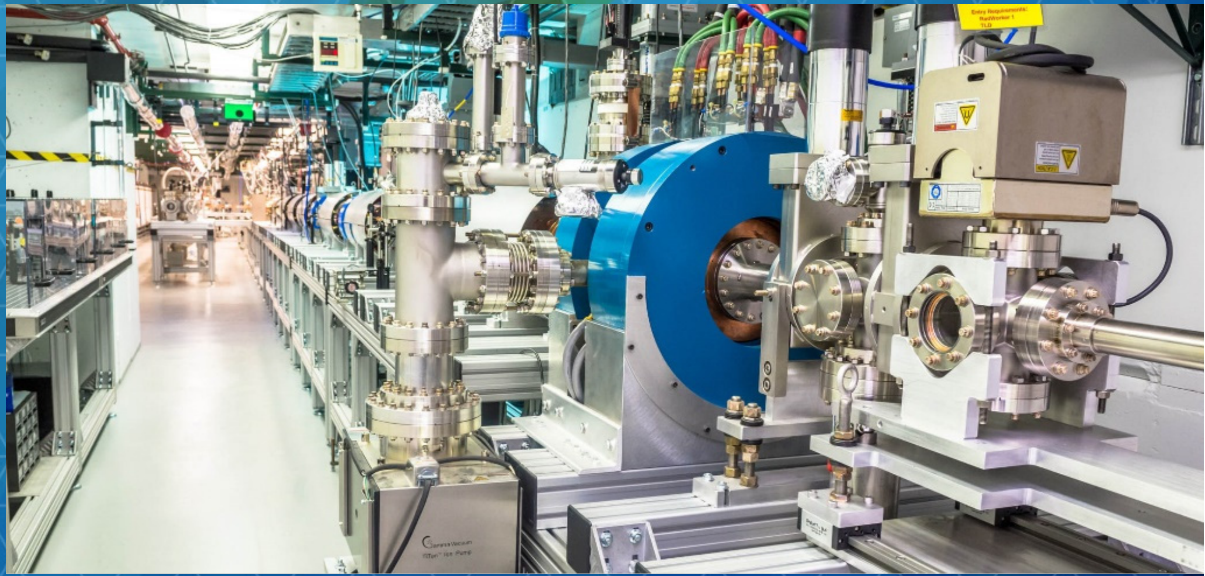
JUNE 15, 2022

LONGITUDINAL BUNCH SHAPING USING AN X-BAND TRANSVERSE DEFLECTING CAVITY
powered by wakefield power extractor at Argonne Wakefield Accelerator Facility (AWA)



SEONGYEOL KIM (SEONG-YEOL KIM) [1], CHUNGUANG JING [2], SERGEY KUZIKOV [3], JOHN POWER [1], ALEXIS BIBIAN [3], GONGXIAOHUI CHEN [1], SCOTT DORAN [1], ERNEST KNIGHT [3], WANMING LIU [1], PHILIPPE PIOT [4], ERIC WISNIEWSKI [1],

1. Argonne Wakefield Accelerator Group, Argonne National Laboratory
2. Euclid Beamlabs
3. Euclid Techlabs
4. Northern Illinois University

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Contents

❖ Motivation

❖ Principle of transverse deflecting cavity (TDC)-based bunch shaping

❖ X-band TDC shaping system configuration

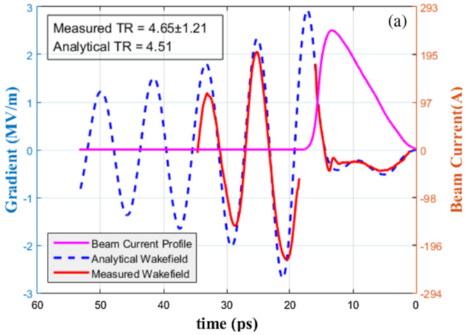
❖ Particle tracking simulation results

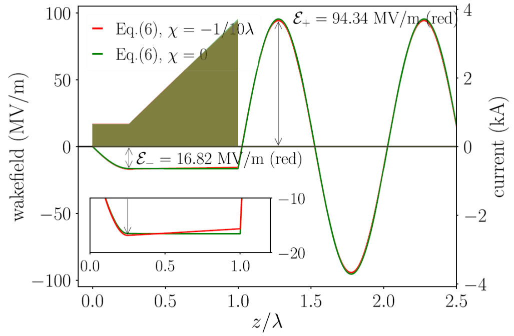
❖ Conclusion, future works

Motivation: Bunch shaping applications

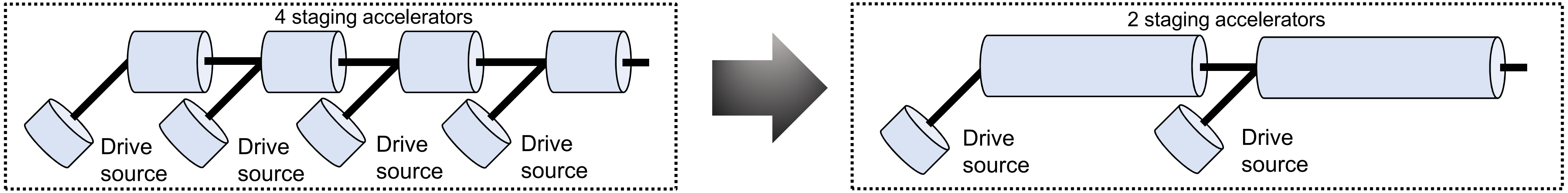
E.g., collinear (structure and plasma) wakefield accelerators,

- For high-transformer ratio: need a longitudinally shaped bunch
  - ➡ **e.g., triangle, doorstep**





- For high gradient: need high charge
  - ➡ **e.g., 10 nC of electron beam***

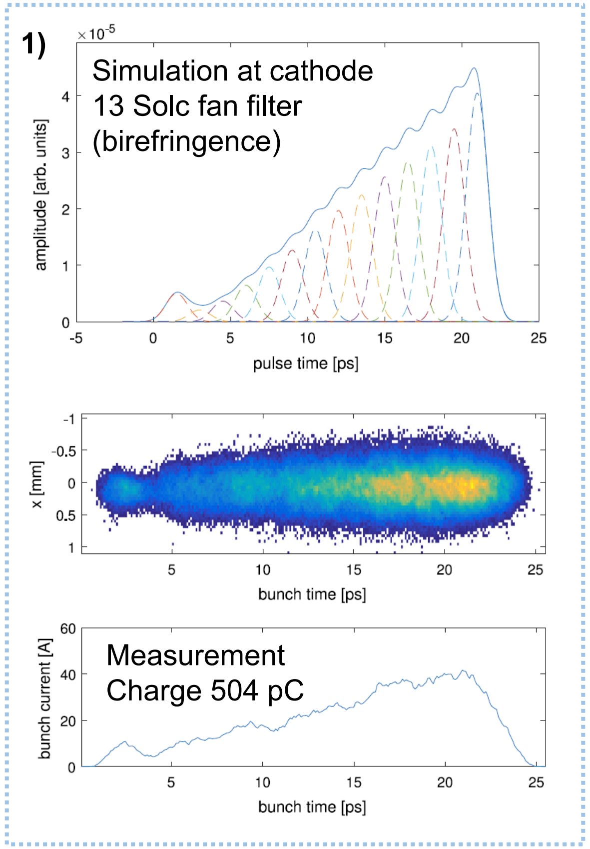


- **Wakefield Accelerator needs high-charge, shaped bunches**

- Q. Gao *et al.*, *Phys. Rev. Lett.* **120**, 114801, 2018
- R. Roussel *et al.*, *Phys. Rev. Lett.* **124**, 044802, 2020
- Wei Hou Tan *et al.*, *Phys. Rev. Accel. Beams.* **24**, 051303, 2021

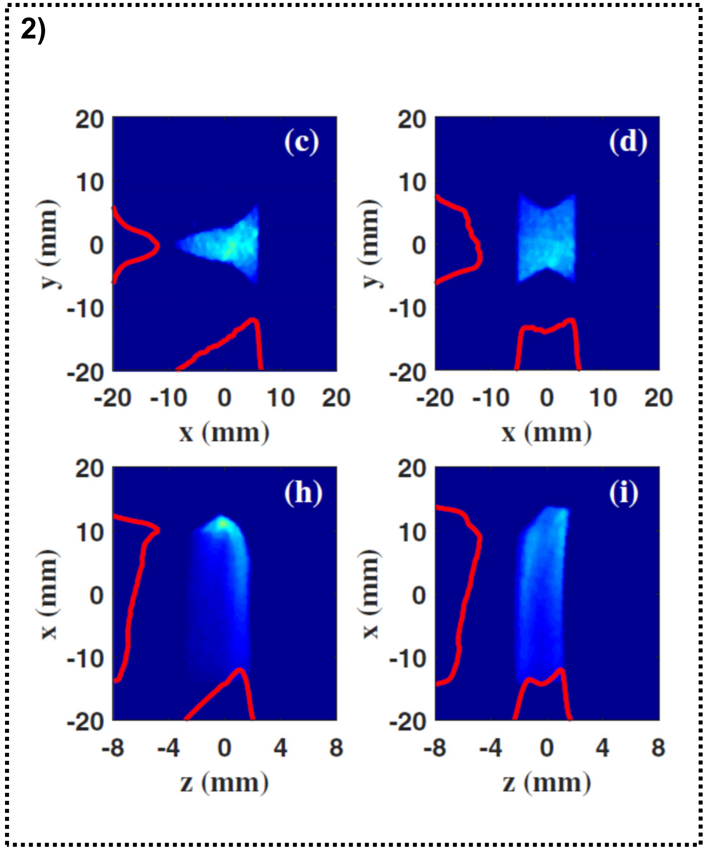
* ~100 MeV

Motivation: The challenge of shaping high charge bunches



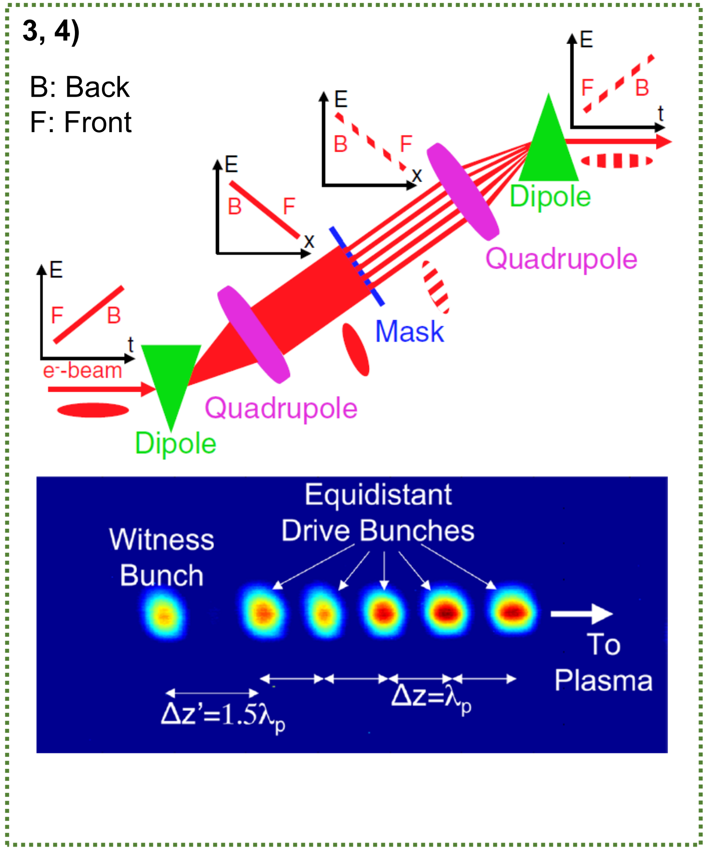
Laser shaping:

For high charge and short UV length: strong space charge at cathode



Shaping with Emittance Exchange (EEX)

For high charge: strong CSR effect



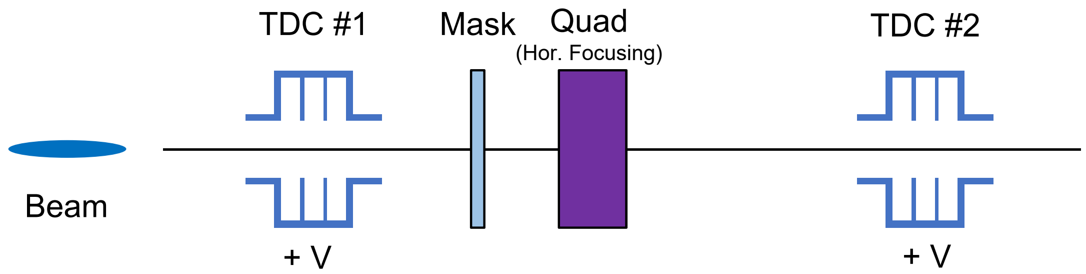
Correlation-based shaping:

For high charge: strong CSR effect

- 1) G. Loisch *et al.*, *Nucl. Inst. Meth. Phys. Res. A* **909**, 107-110, 2018.
- 2) G. Ha *et al.*, *Phys. Rev. Lett.* **118**, 104801, 2017
- 3) P. Muggli *et al.*, *Phys. Rev. Lett.* **101**, 054801, 2008.
- 4) P. Muggli *et al.*, *Phys. Rev. ST Accel. Beams* **13**, 052803, 2010.

High quality bunch shaping for high charge beam: Minimization // suppression of collective effects

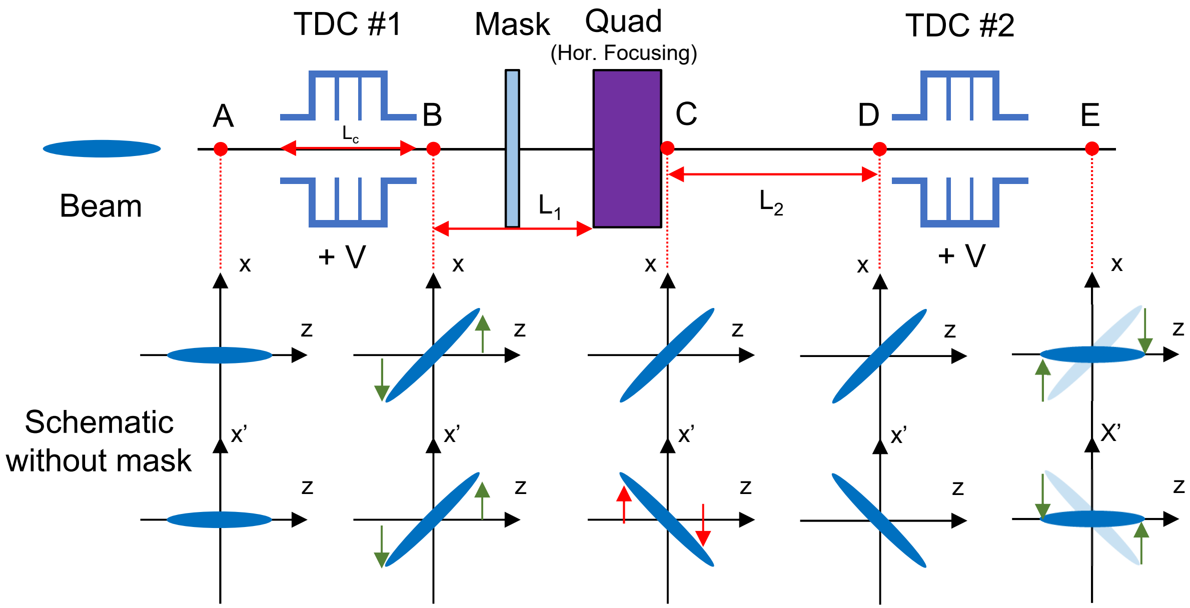
A solution to high-Q shaping: TDC-based bunch shaping*



- **Straight line**: No dipole magnet used ➡ CSR effects are not present
- Relativistic beam used: **space charge effects are less considered**

- *E. Kur *et al.*, Rep. No. LBNL-2670E, 2009.
- *G. Ha *et al.*, *Phys. Rev. Accel. Beams* **23**, 072803, 2020.
- J. Qiu *et al.*, *Ultramicroscopy* **161**, 130-136, 2016.
- Du Ying Chao *et al.*, *Chinese Phys* **36**, 151, 2012.

TDC-based bunch shaping*



With linear transfer matrix

- At "B" position, horizontal position and divergence are

$$x_B = x_i + L_c x_i' + \frac{L_c}{2}\kappa z_i$$

TDC length

$$x_B' = x_i' + \kappa z_i$$

$$\boxed{\kappa = \frac{eV_\perp}{pc}\frac{2\pi}{\lambda}}$$

TDC strength

Generate linear x-z correlation due to TDC kick

- At "D" point (entrance of second TDC),

$$\left(-\frac{L_2}{f_1}+1\right)$$

$$x_D = a x_i + \left[a(L_1+L_c)\right]x_i' + \boxed{\left[\frac{a}{2}L_c\kappa_1 + a\kappa_1(L_1+L_2)\right]z_i}$$

z-component

$$x_D' = -\frac{1}{f}x_i + \left(-\frac{(L_c+L_1)}{f}+1\right)x_i' + \boxed{\left(-\frac{L_c\kappa_1}{2f}+\kappa_1\left(-\frac{L_1}{f_1}+1\right)\right)z_i}$$

Due to quadrupole magnet, longitudinal phase space is rotated (and ready for removal of z-x, z-x' correlations from second TDC)

- *E. Kur *et al.*, Rep. No. LBNL-2670E, 2009.
- *G. Ha *et al.*, *Phys. Rev. Accel. Beams* **23**, 072803, 2020.
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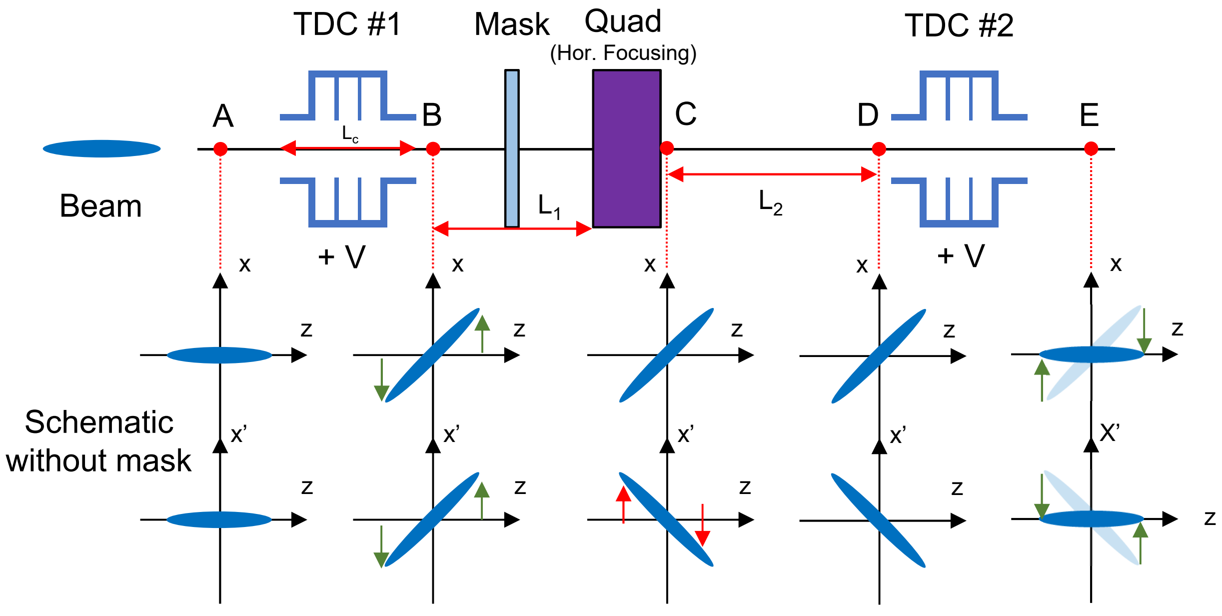
TDC-based bunch shaping*



At second TDC with positive kick, transverse-longitudinal correlations are cancelled out, and longitudinal beam is shaped by the installed mask

With linear transfer matrix

- At "B" position, horizontal position and divergence are

$$x_B = x_i + L_c x_i' + \frac{L_c}{2}\kappa z_i$$

TDC length

$$x_B' = x_i' + \kappa z_i$$

$$\boxed{\kappa = \frac{eV_\perp}{pc}\frac{2\pi}{\lambda}}$$ TDC strength

Generate linear x-z correlation due to TDC kick

- At "D" point (entrance of second TDC), $\left(-\frac{L_2}{f_1}+1\right)$

$$x_D = ax_i + [a(L_1+L_c)]\,x_i' + \boxed{\left[\frac{a}{2}L_c\kappa_1 + a\kappa_1(L_1+L_2)\right] z_i}$$ z-component

$$x_D' = -\frac{1}{f}x_i + \left(-\frac{(L_c+L_1)}{f}+1\right)x_i' + \boxed{\left(-\frac{L_c\kappa_1}{2f} + \kappa_1\left(-\frac{L_1}{f_1}+1\right)\right) z_i}$$

Due to quadrupole magnet, longitudinal phase space is rotated (and ready for removal of z-x, z-x' correlations from second TDC)

TDC-Shaping condition

(thin lens quad)

$$f_1 = \frac{\left(L_1+\frac{L_c}{2}\right)\left(L_2+\frac{L_c}{2}\right)}{L_1+L_2+L_c}$$

$$\kappa_2 = \frac{2L_1+L_c}{2L_2+L_c}\kappa_1$$

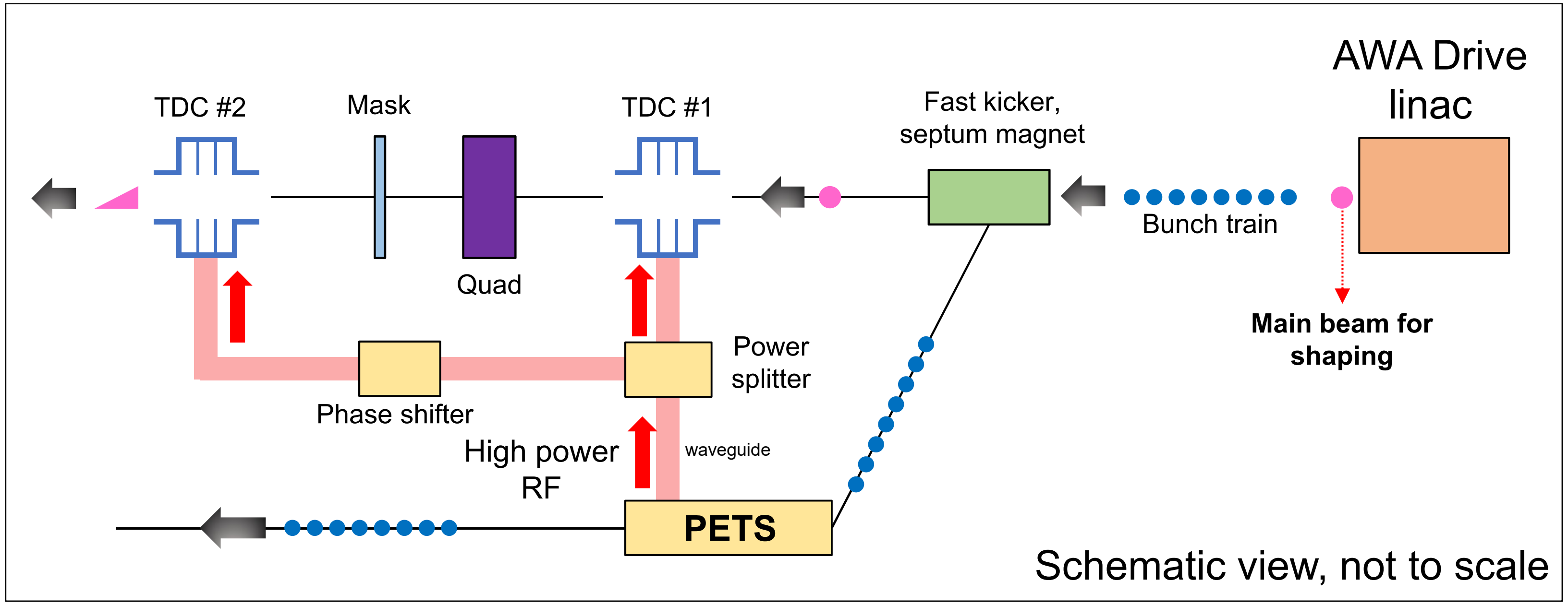
- *E. Kur *et al.*, Rep. No. LBNL-2670E, 2009.
- *G. Ha *et al.*, *Phys. Rev. Accel. Beams* **23**, 072803, 2020.
- J. Qiu *et al.*, *Ultramicroscopy* **161**, 130-136, 2016.
- Du Ying Chao *et al.*, *Chinese Phys* **36**, 151, 2012.

TDC-based
LONGITUDINAL BUNCH SHAPING STUDY AT THE AWA FACILITY

10 nC triangular shaped bunch

TDC bunch shaping study at the AWA Facility*

- ➢ AWA's high-power, short-pulse RF source **(400 MW at 10 ns**)**: X-band (11.7 GHz) Power Extractor and Transfer Structure (**PETS**)
- ➢ Short-pulse advantage: enhanced breakdown limit → much higher gradient on structure → reduction on shaping system length



- ➢ *C. Jing, Integrated High Efficiency Bunch Shaping Techniques For SWFA, SBIR project
- ➢ C. Jing et al., Electron acceleration through two successive electron beam driven wakefield acceleration stages, *Nucl. Inst. Meth. Phys. Res. A* **898**, 2018.
- ➢ ** C. Jing, Short-pulse wakefield structure R&D for high-gradient and high-efficiency acceleration, LCWS2021, 2021.

TDC bunch shaping study at the AWA Facility*

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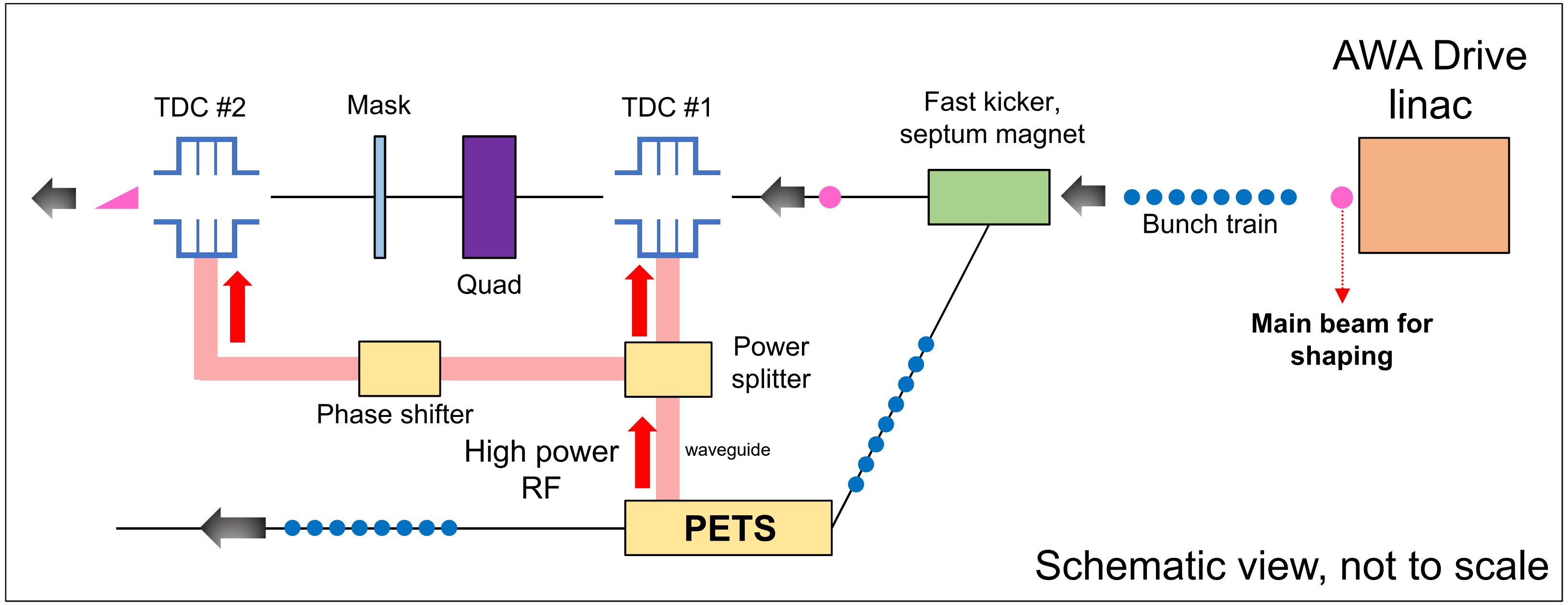


Purpose: feasibility study of the X-band TDC-based longitudinal bunch shaping

Target: Triangular shaped bunch with 10 nC at 10 ps of full bunch length

- *C. Jing, Integrated High Efficiency Bunch Shaping Techniques For SWFA, SBIR project
- C. Jing et al., Electron acceleration through two successive electron beam driven wakefield acceleration stages, *Nucl. Inst. Meth. Phys. Res. A* **898**, 2018.
- ** C. Jing, Short-pulse wakefield structure R&D for high-gradient and high-efficiency acceleration, LCWS2021, 2021.

X-band TDC

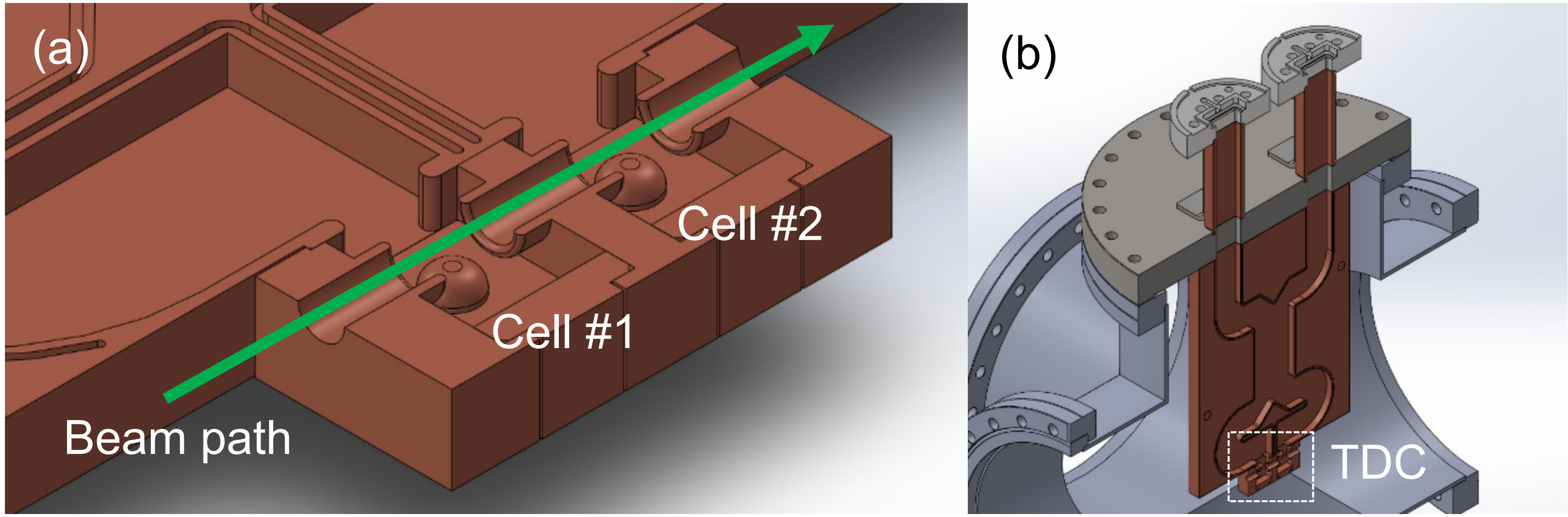
- Operation frequency: **11.7 GHz**
- Fundamental mode: **TE11**

- **Two independent cavities are placed**, powered by using 3-dB coupler

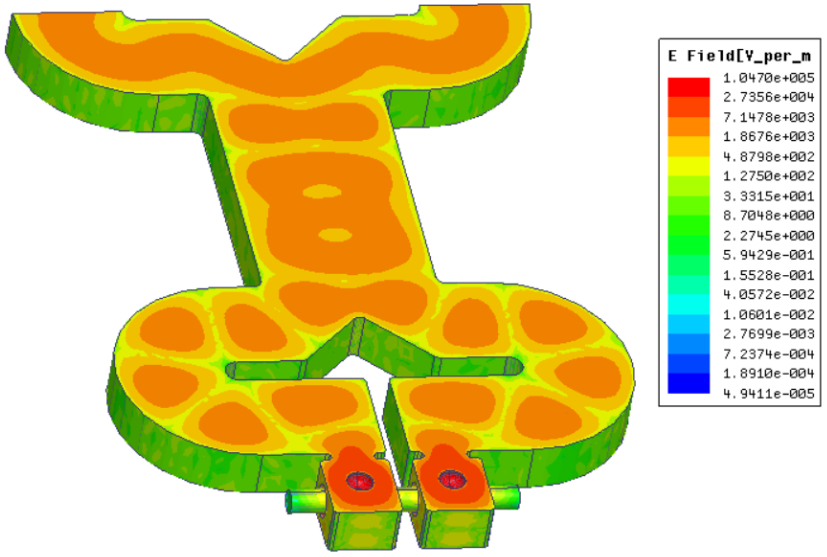
- **Phase difference:** $\pi/2$, for synchronization of streaking mode at each cell, distance between cell to cell is 19.2 mm

- **Nominal peak E_x: 100 MV/m** (can be increased by using more power from the PETS with > 400 nC drive beam)

Installation inside the chamber

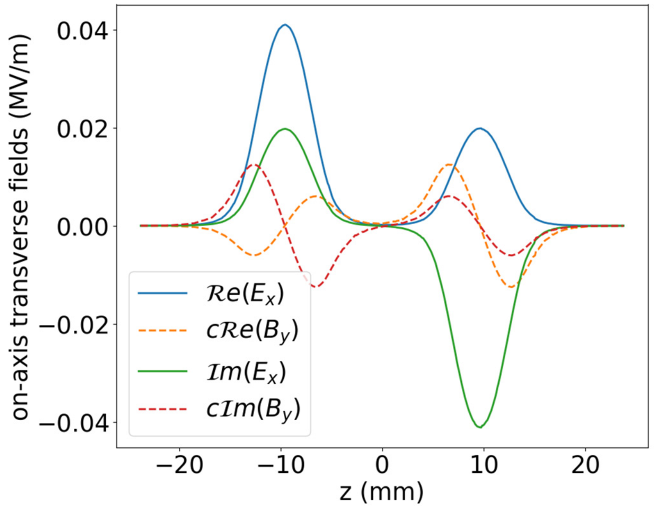


2-cell TDC (Sergey K)

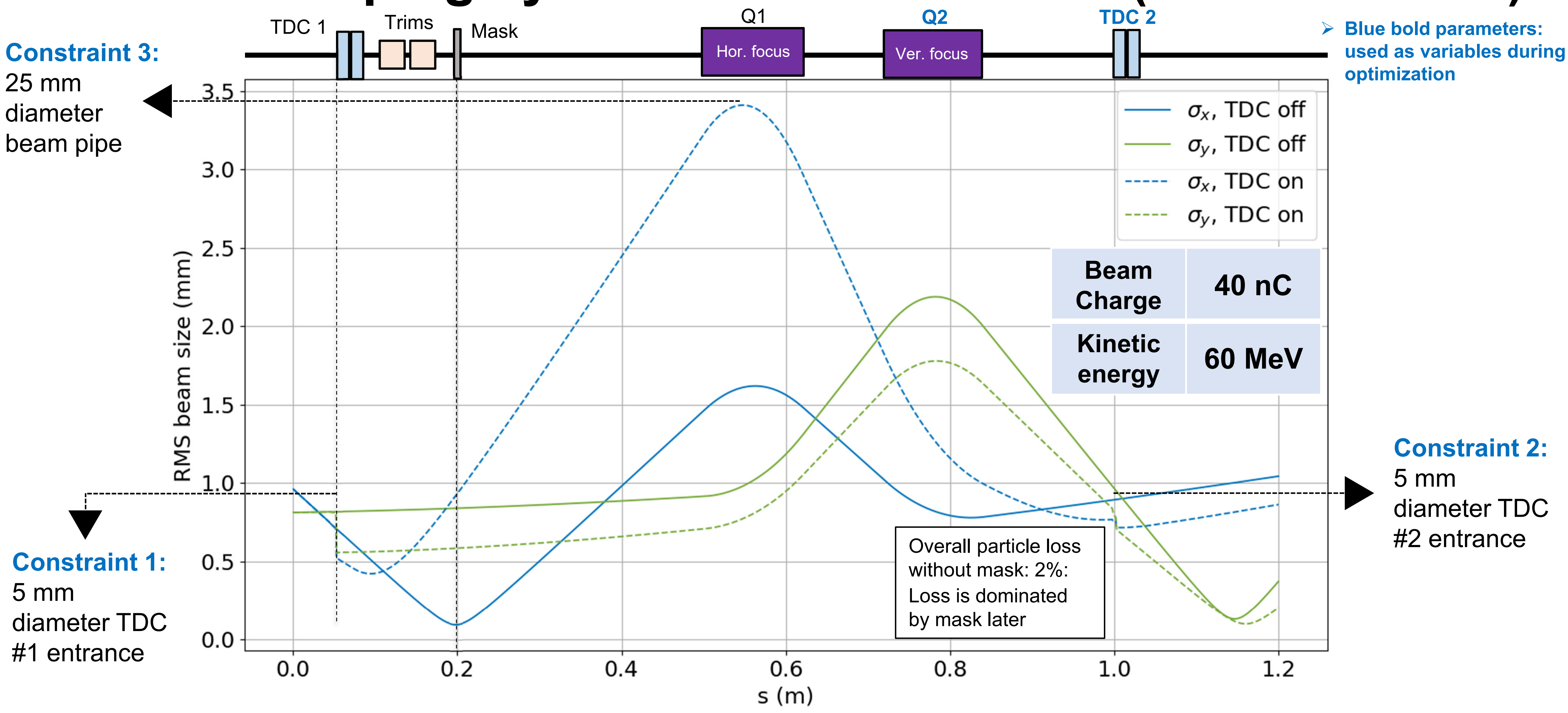


Cell 1 **Cell 2**

Field distribution



AWA TDC shaping system: beamline lattice (no mask used)

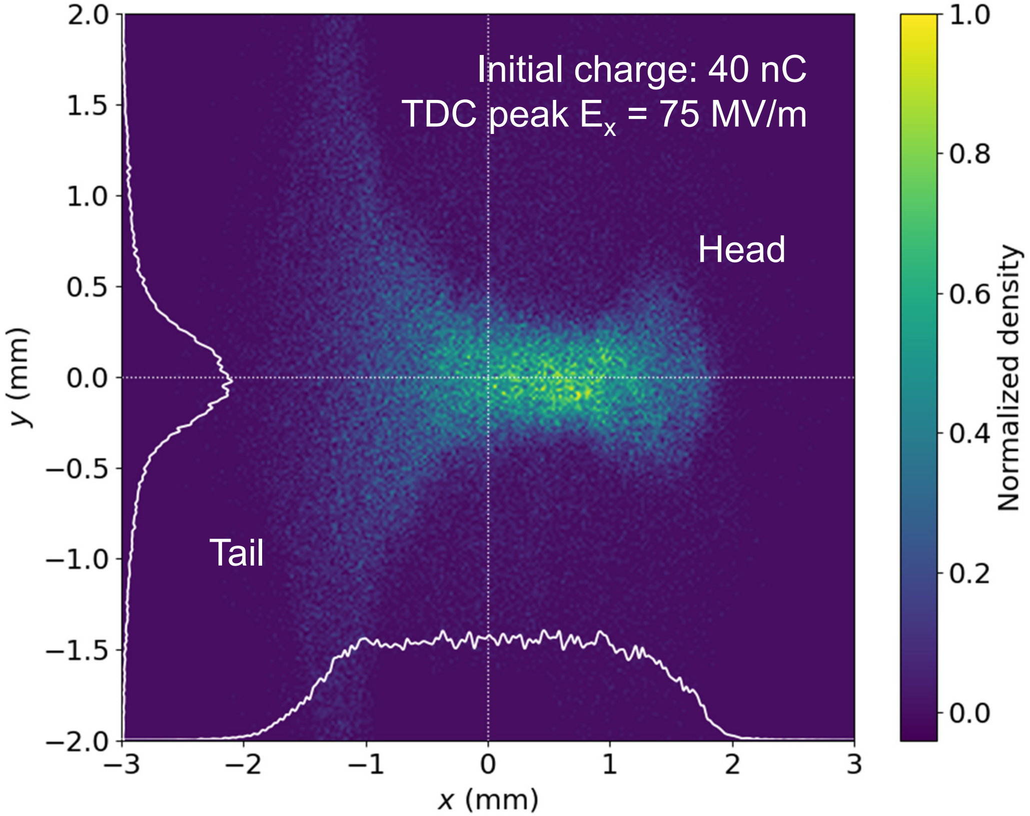


- Blue bold parameters: used as variables during optimization

- **Initial beam parameters**: obtained from s-to-e **OPAL simulation (3D space charge)** including drift-quadrupole line
- **Optimization goal:** (1) satisfy TDC-shaping condition; (2) beam small at mask; while satisfy beam-scarping constraints

OPAL simulation result: Triangular shape

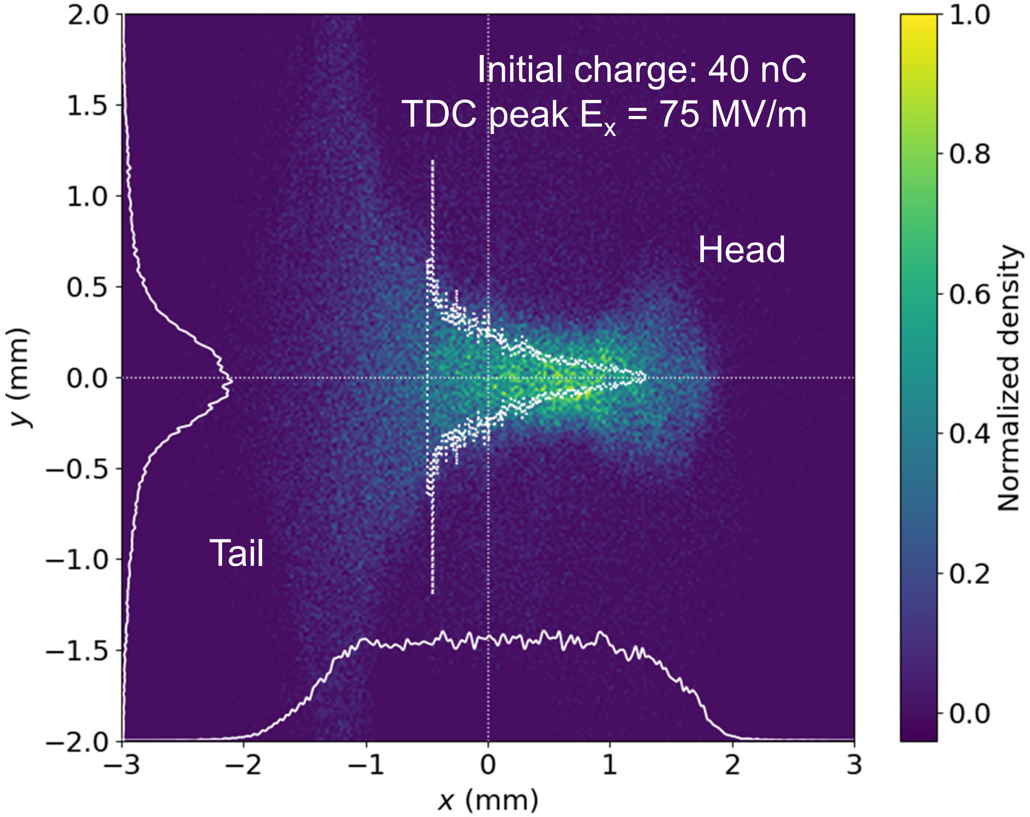
Transverse Profile



- **Before mask**: Beam is kicked horizontally due to TDC → projection of z-slice into x-y plane

OPAL simulation result: Triangular shape

Transverse Profile

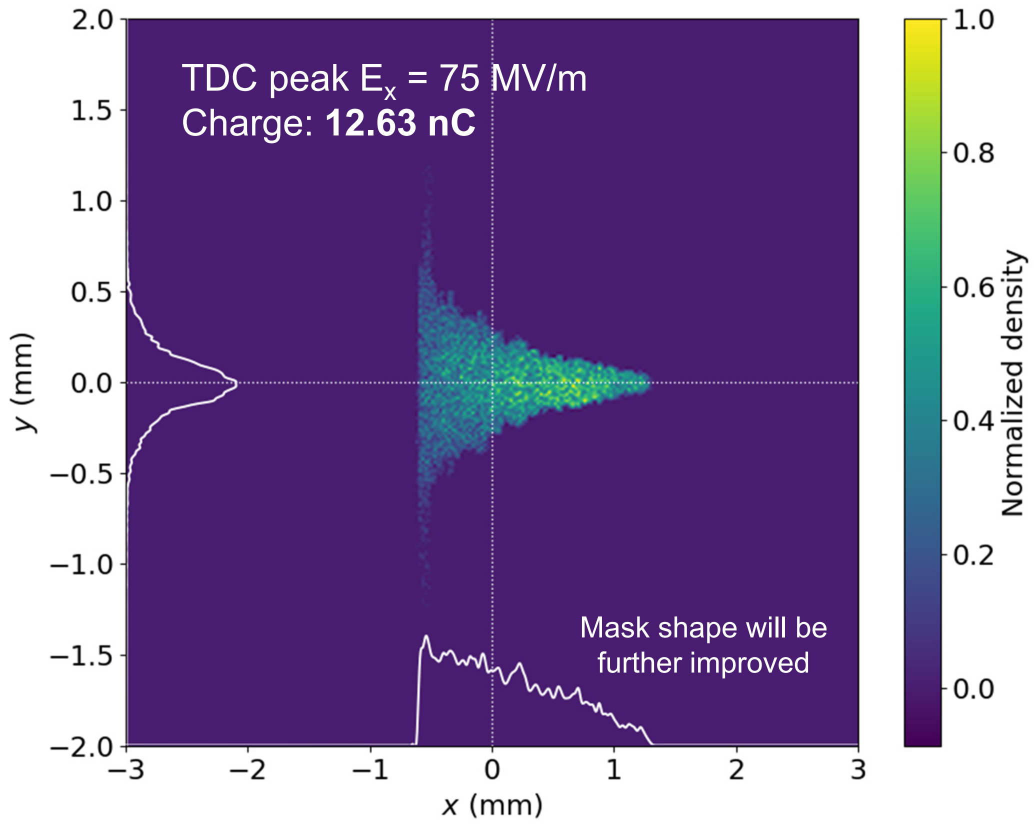


- **Before mask**: Beam is kicked horizontally due to TDC → projection of z-slice into x-y plane

OPAL simulation result: Triangular shape

Transverse Profile

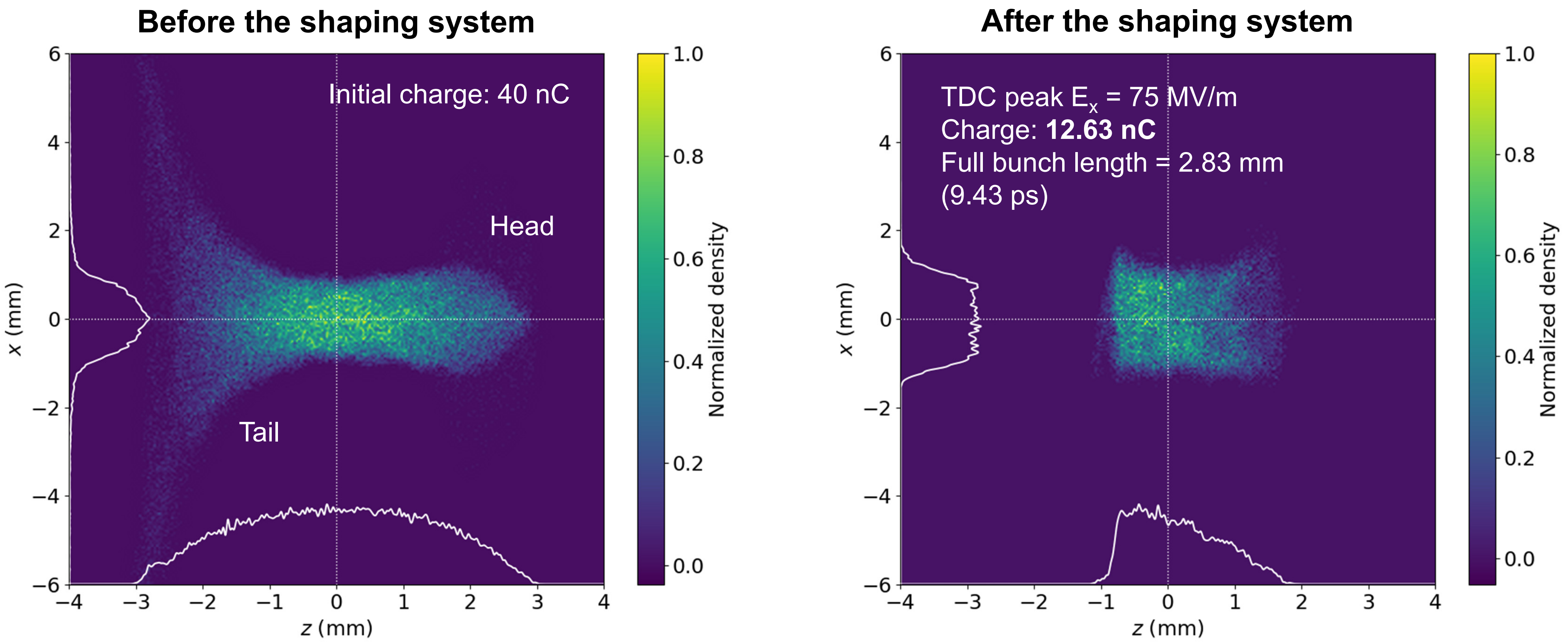
after the mask



- **Before mask**: Beam is kicked horizontally due to TDC ➡ projection of z-slice into x-y plane
- **After mask:** longitudinal density distribution is cut following the mask shape

OPAL simulation result: Triangular shape

Longitudinal Profile

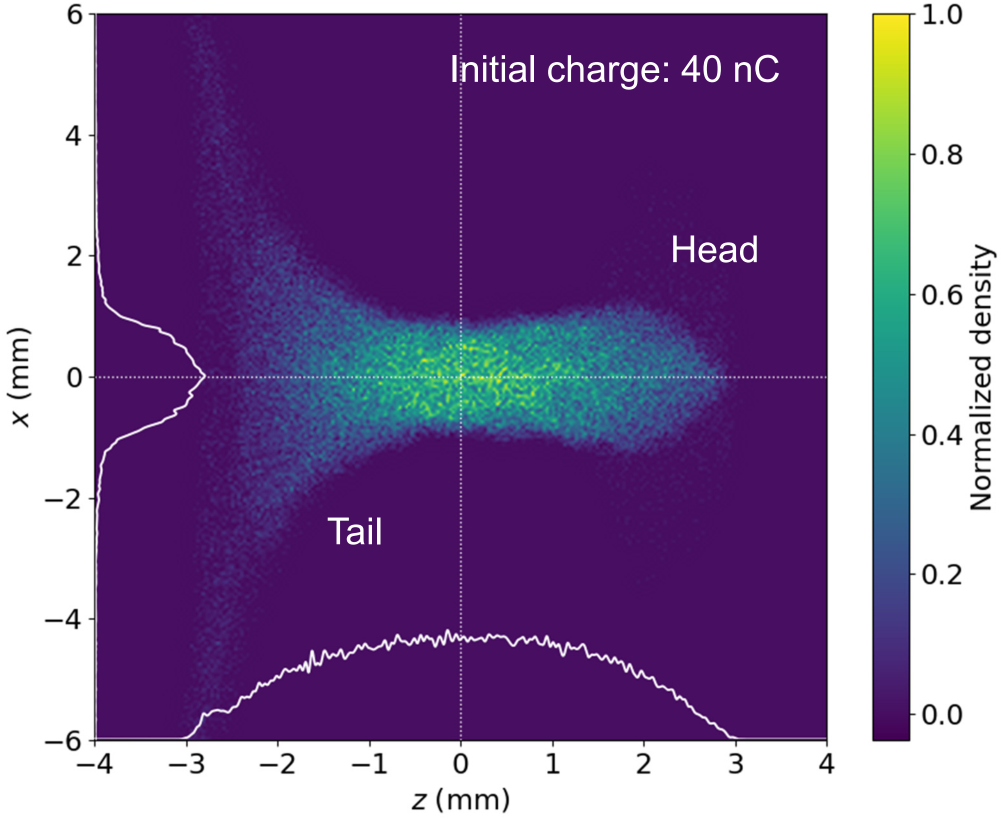


➢ **Parameters after system**: satisfy all target parameters (longitudinal shape, beam charge, bunch length)

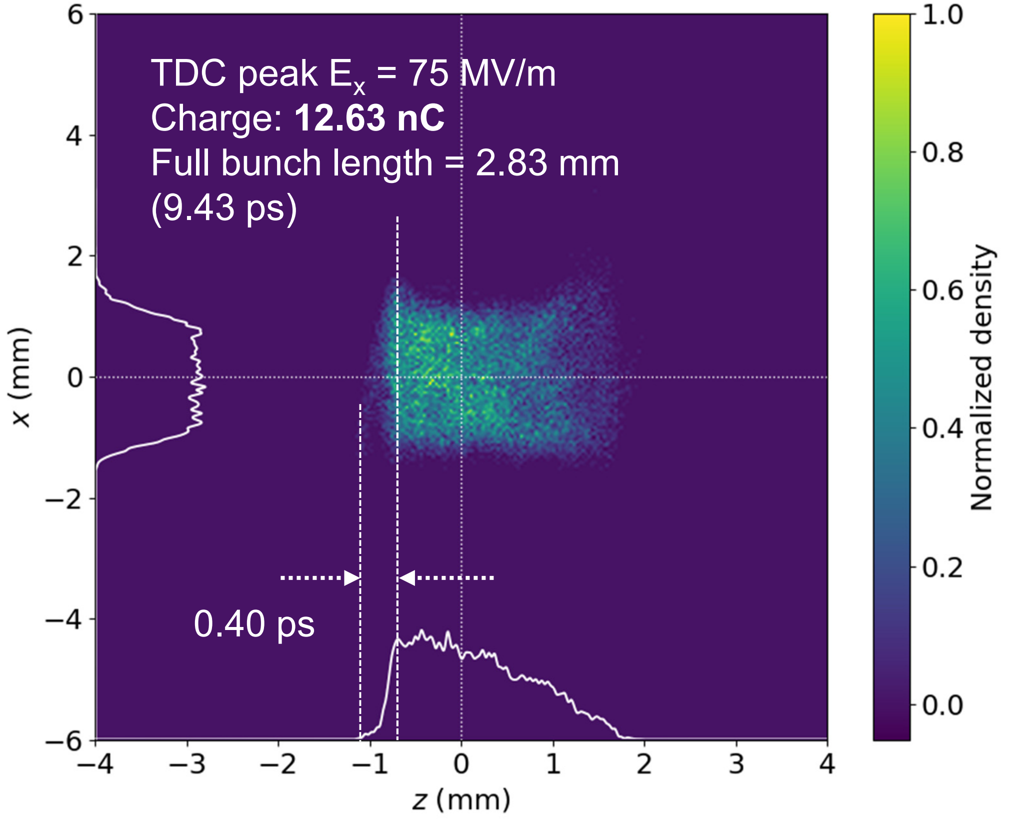
OPAL simulation result: Triangular shape

Longitudinal Profile

Before the shaping system



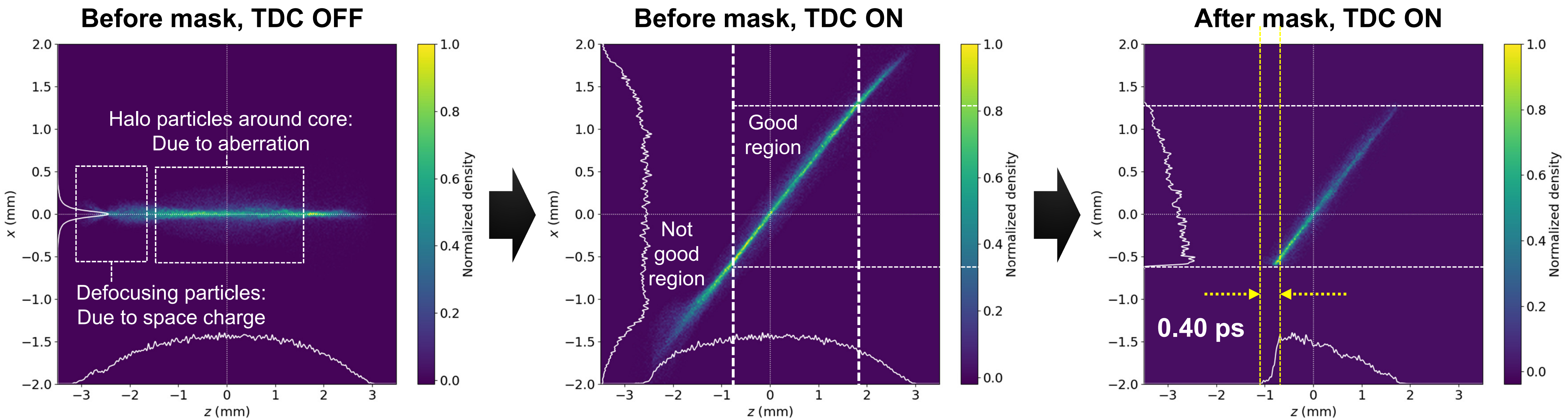
After the shaping system



- **Shaping quality (quantity):** 0.4 ps, due to horizontal beam size at mask and emittance (50 mm mrad)

OPAL simulation result: <u>Triangular shape</u>

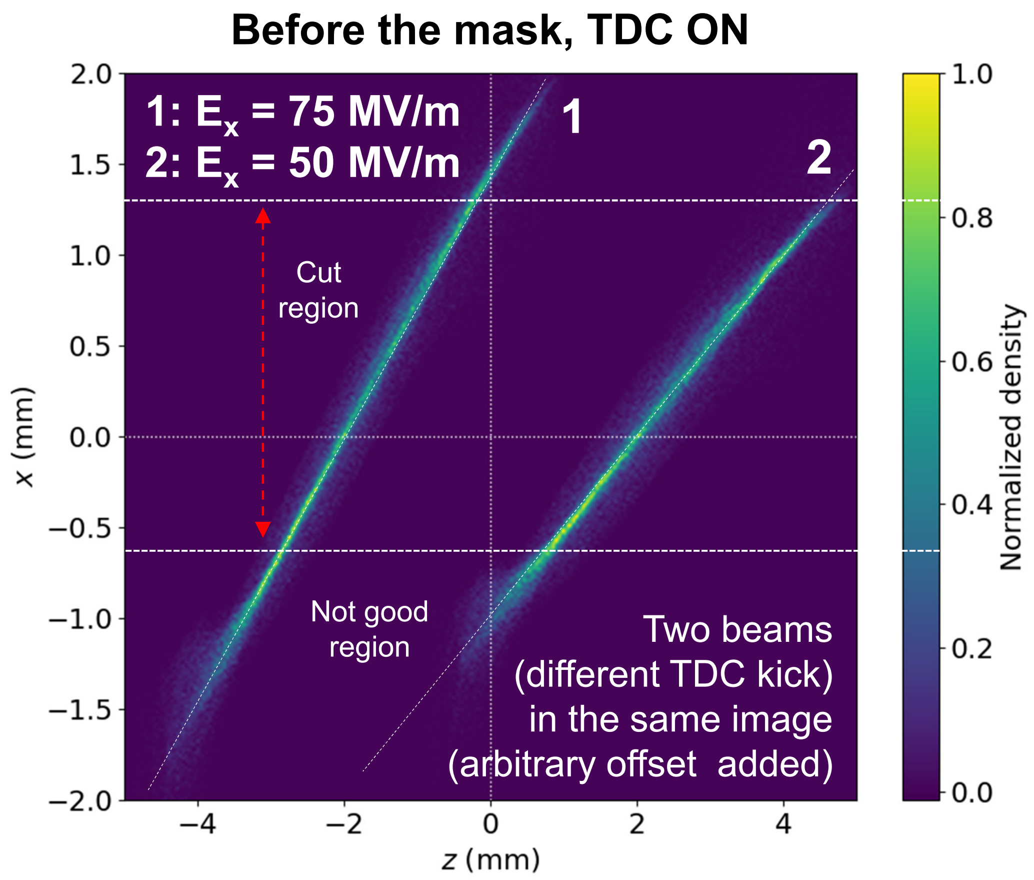
Longitudinal Profile

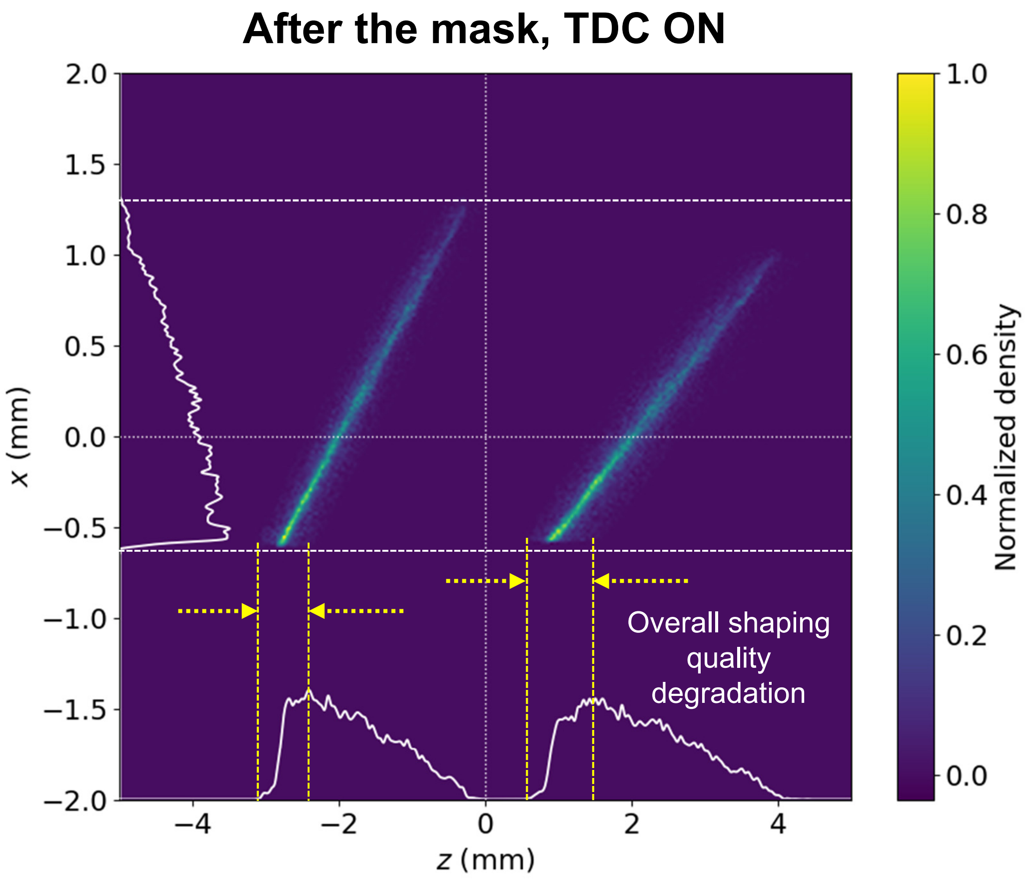


- ➢ Key point for the quality of the bunch shaping:
  - ❑ **small horizontal beam size and emittance (divergence) at mask position (without TDC)**

- ➢ Consideration of **space charge force (low-energy regime), second-order aberration (energy spread correlation), and matching of horizontal slice phase space** are necessary for quality preservation

OPAL simulation result: Triangular shape





Shaping quality was improved by strong TDC kick

Conclusion and future works

- TDC-based shaping is promising technique of beam manipulation
  - **No CSR effects** are present
  - Masking is performed when the beam energy reaches relativistic: **space charge effects is mitigated**

- Numerical simulations demonstrate that such the TDC-based shaping system **could provide bunch with current profile relevant to advanced acceleration concepts**
  - → target shape and parameters could be reached using the AWA drive-beam accelerator
  - → further work on producing more complex shapes is underway **(e.g., doorstep, bunch train)**

- The limitation related to **charge loss** could be alleviated by combining this technique with a coarsely pre-shaped electron beam **(e.g., produced via photocathode laser shaping)**