A HIGH REPETITION RATE X-RAY FEL USER FACILITY

–based on a compact wakefield accelerator –

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for the collaboration team (Sasha Zholents)

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  - D. Shchegolkov, E. Simakov (***LANL***),
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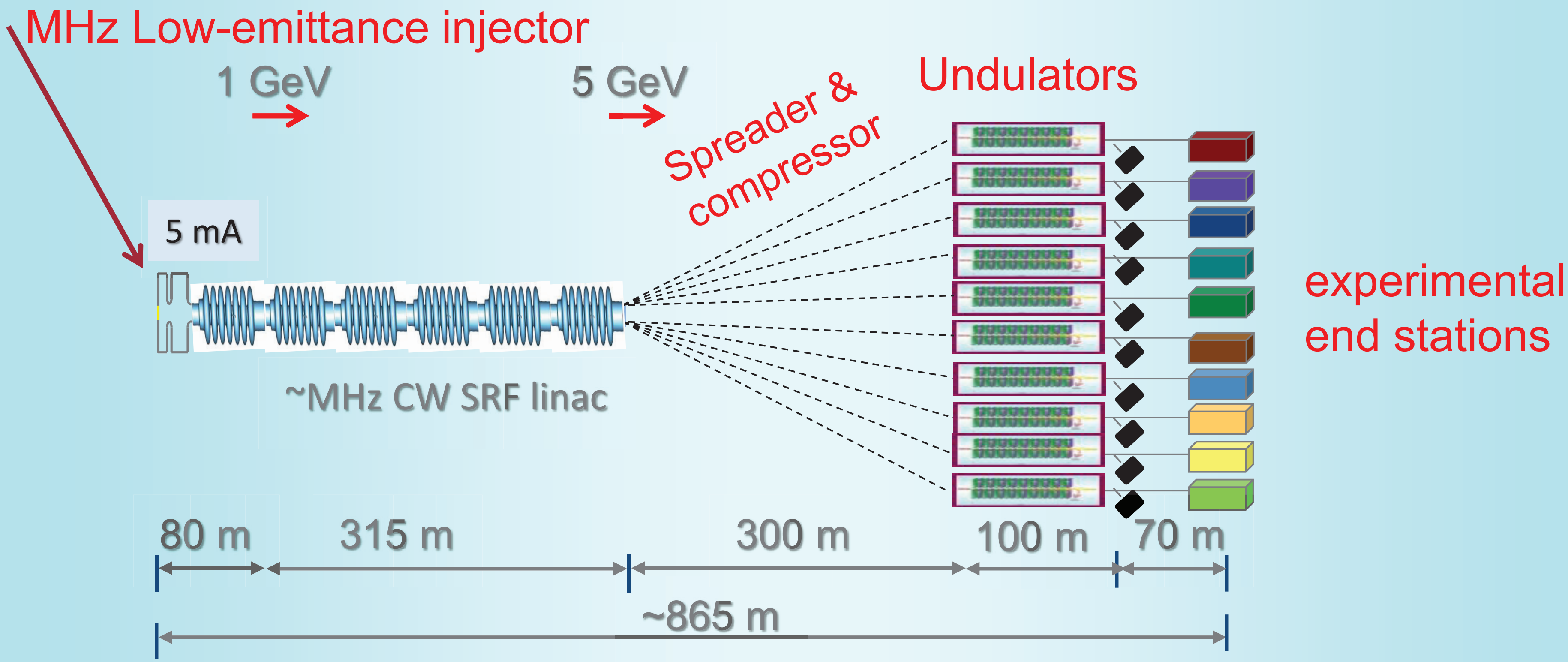
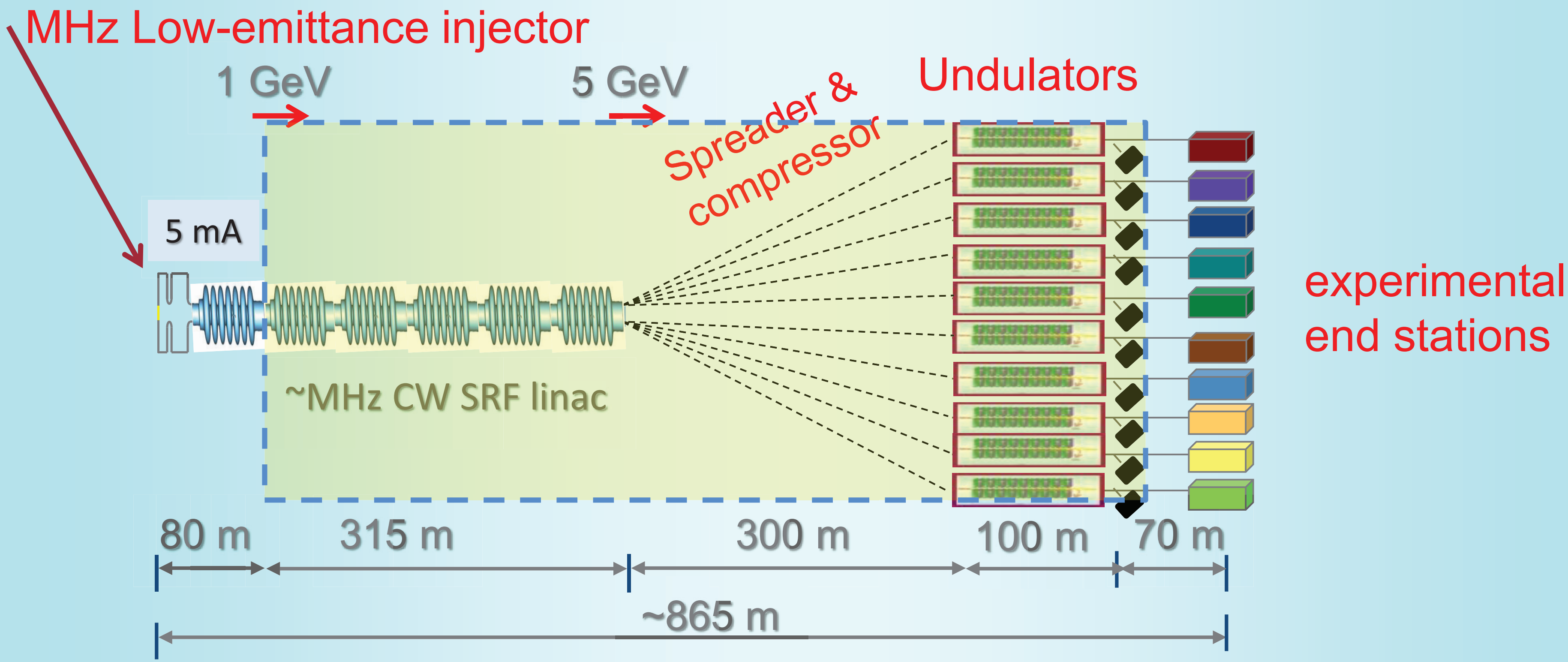
  - S. Siy, N. Behdad (***University of Wisconsin***)

High repetition rate multi-user X-ray FEL facility (SRF accelerator and Room Temp undualtors)



- Capable of serving ~2000 scientists/year
- Flexible x-ray beamlines: Tunable pulse length, Seeded, 2 color seeded, SASE

High repetition rate multi-user X-ray FEL facility (SRF accelerator and Room Temp undualtors)



- Capable of serving ~2000 scientists/year
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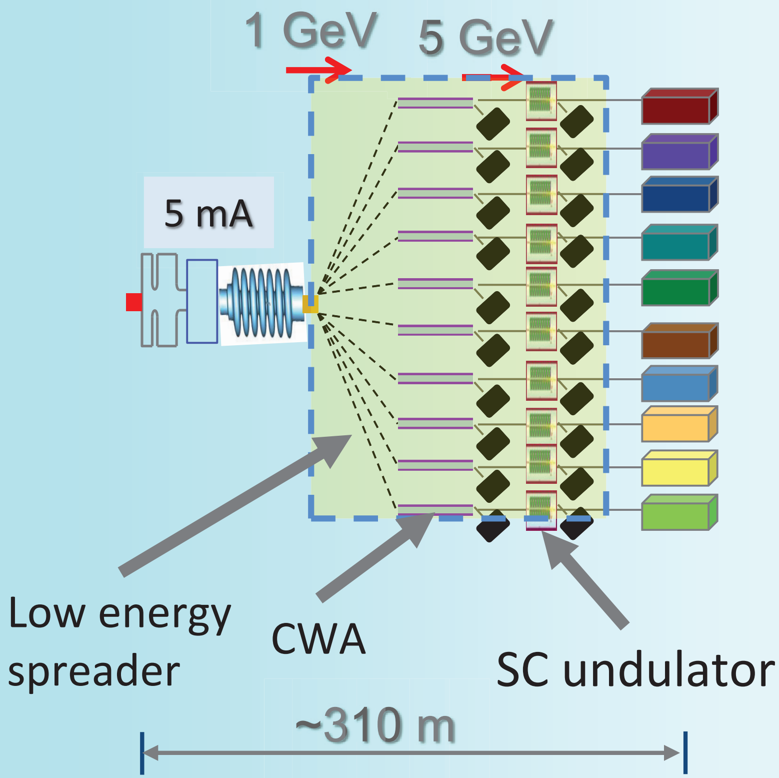
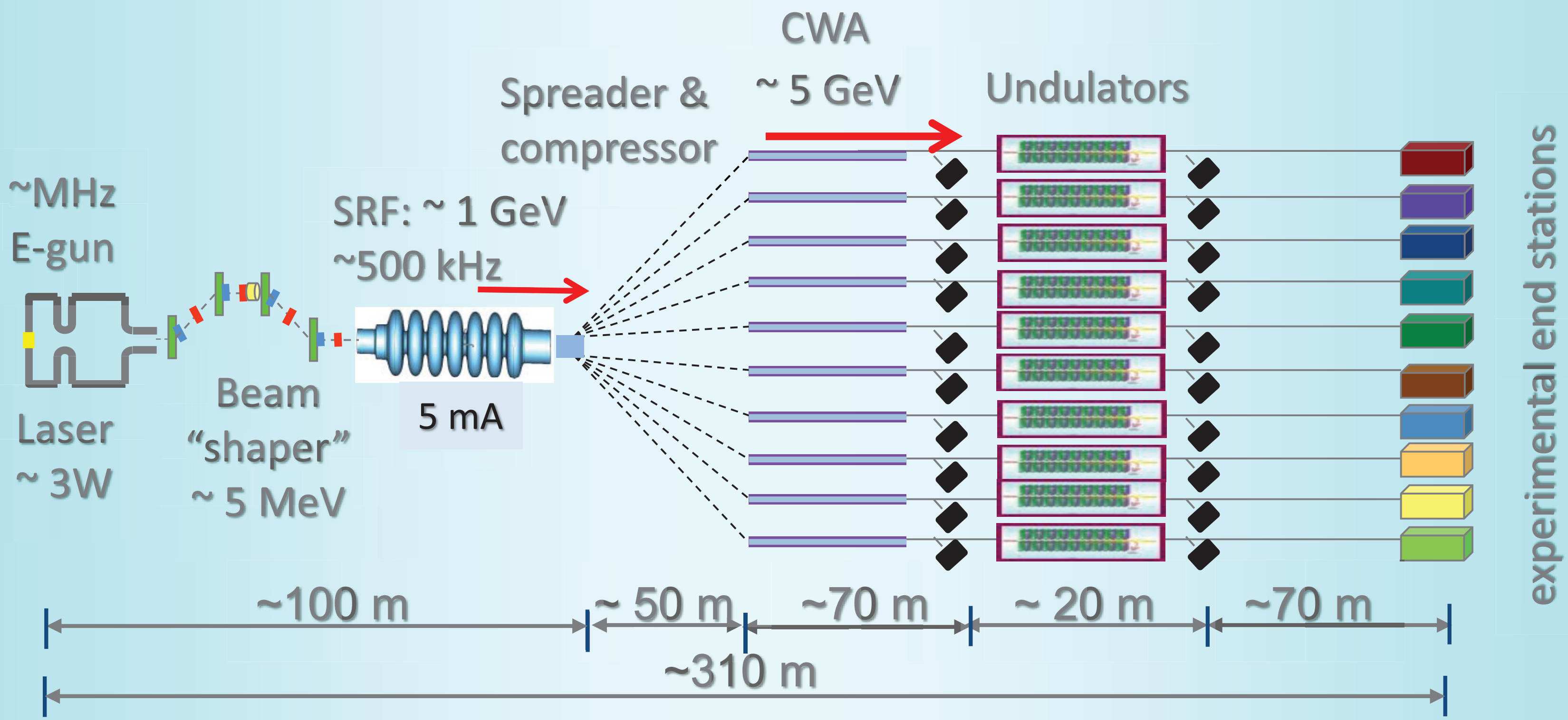
High repetition rate multi-user X-ray FEL facility (collinear wakefield accelerator and SC undualtors)



- **COMPACT**
  - Low energy spreader
  - CWA gradient ~ 100 MV/m
  - SC helical undulator
- **Low Cost**
  - Low energy spreader
  - CWA (passive room-temp accelerator)

- Capable of serving ~2000 scientists/year
- Flexible x-ray beamlines: Tunable pulse length, Seeded, 2 color seeded, SASE

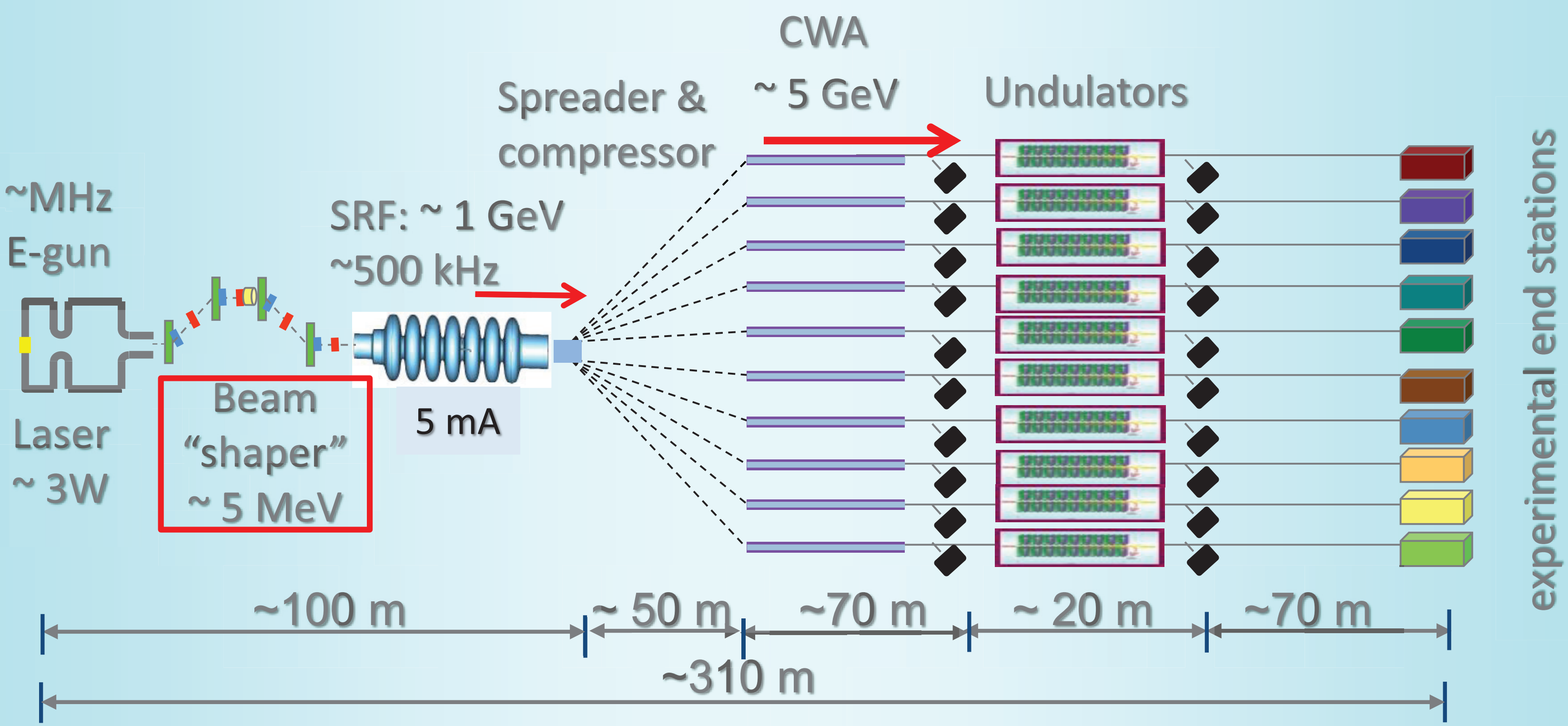
High repetition rate multi-user FEL facility based on Collinear Wakefield Accelerator



Flexible: each beamline has its own accelerator

- Tunable electron beam energy
- Tunable peak current > 1 kA
- X-ray pulse rep. rate ~ 50 kHz per line

High repetition rate multi-user FEL facility based on Collinear Wakefield Accelerator



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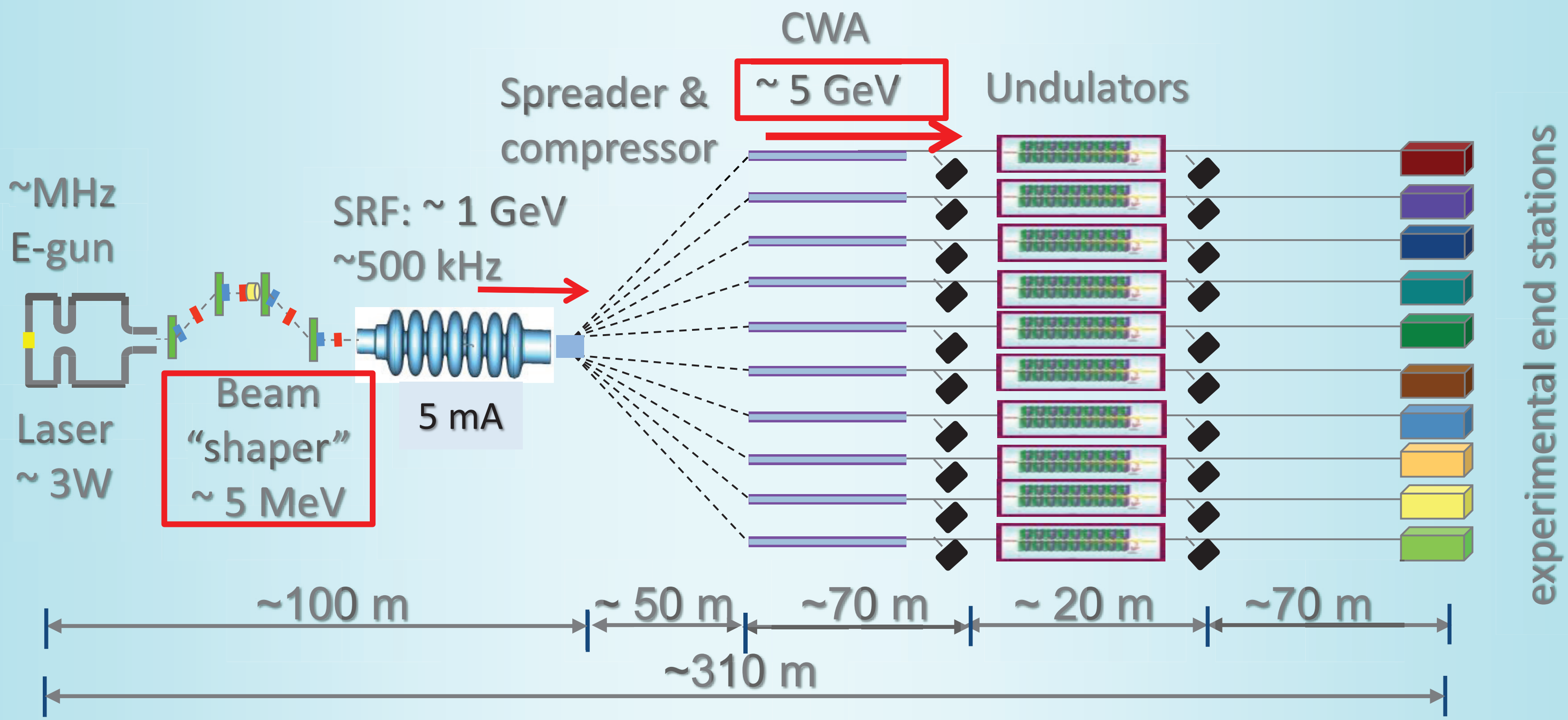
High repetition rate multi-user FEL facility based on Collinear Wakefield Accelerator



Flexible: each beamline has its own accelerator

- Tunable electron beam energy
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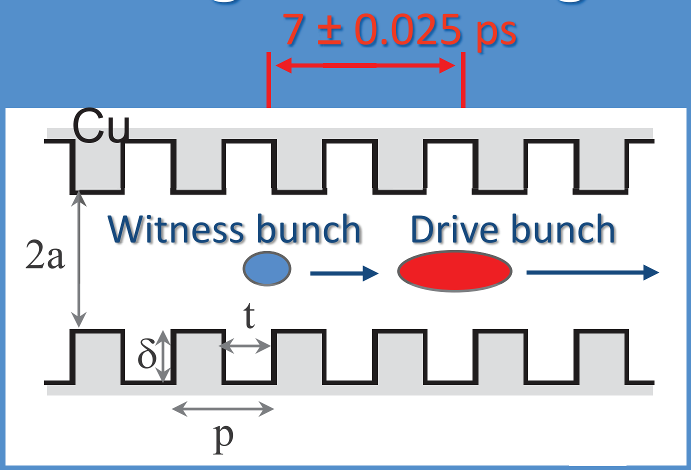
Collinear Wakefield Accelerator*

Structure WakeField Accelerator (SWFA)

Structures:

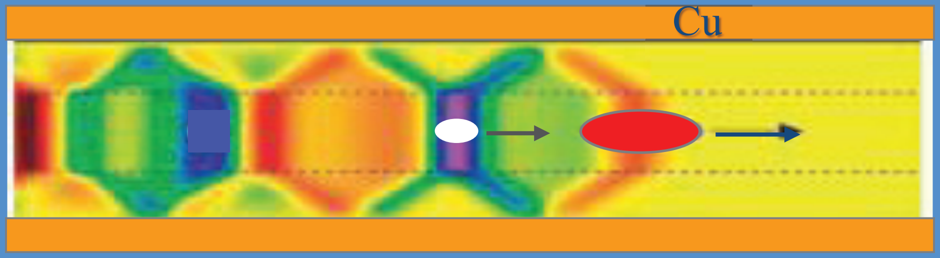
corrugated waveguide



a ~ 1mm, p ~ 0.3 mm, t ~ 0.2 mm, δ ~ 0.15 mm

dielectric waveguide

Electric field map (200-400 GHz)



group velocity = (0.7-0.9)c

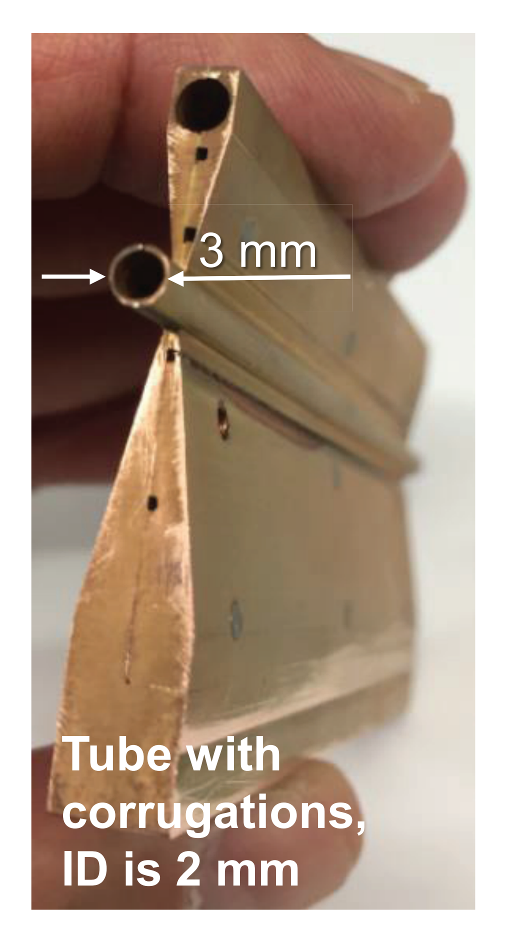
Beams:

- Bunch Shaping
- Drive and Witness bunches from the same "source" bunch → minimal timing jitter

*) G. A. Voss and T. Weiland, DESY M-82-10, 1982;
K. L. F. Bane, P. Chen, P. B. Wilson, SLAC-PUB-3662,1985;
W. Gai et al. Phys. Rev. Lett. 61, 2756,1988.

Potential of collinear wakefield accelerators

- Low cost device (likely)



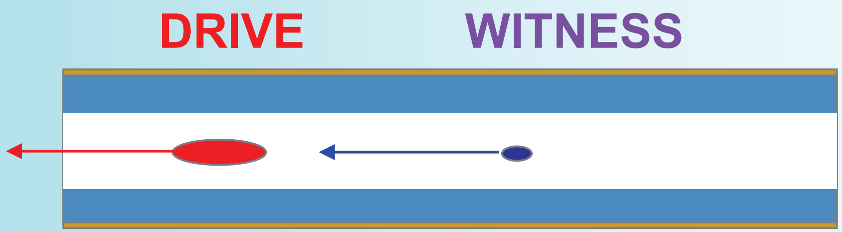
Main CWA accelerator component

- High field gradients
  - Up to ~ 200 MV/m
- High wall plug power efficiency
- High bunch repetition rate
  - Up to ~ 50 kHz (low energy SRF linac supplies drive and witness bunches)

COLLINEAR WAKEFIELD ACCELERATION FUNDAMENTALS

- Acceleration Gradient and Transformer Ratio
  - Drive Bunch Energy Utilization
- Efficiency & Cooling
- Beam Stability

The Wakefield Theorem and the Transformer Ratio



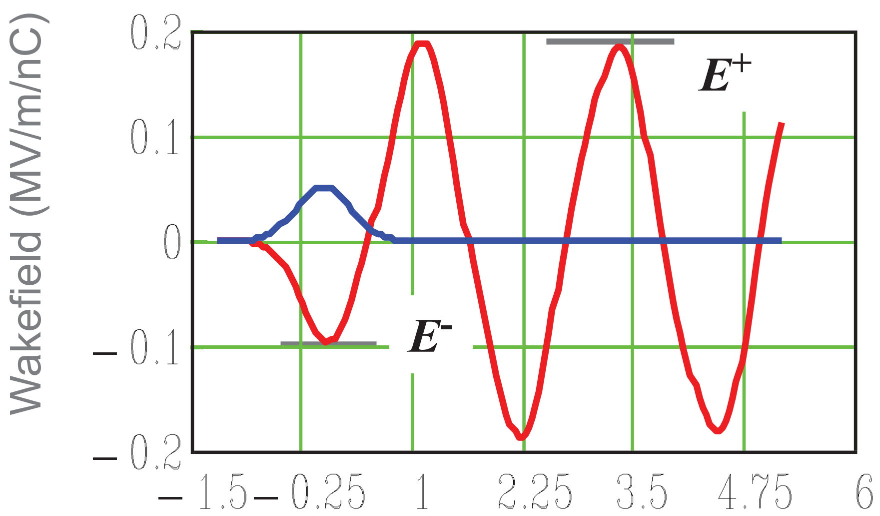
Collinear Dielectric Wakefield Acceleration

Transformer ratio

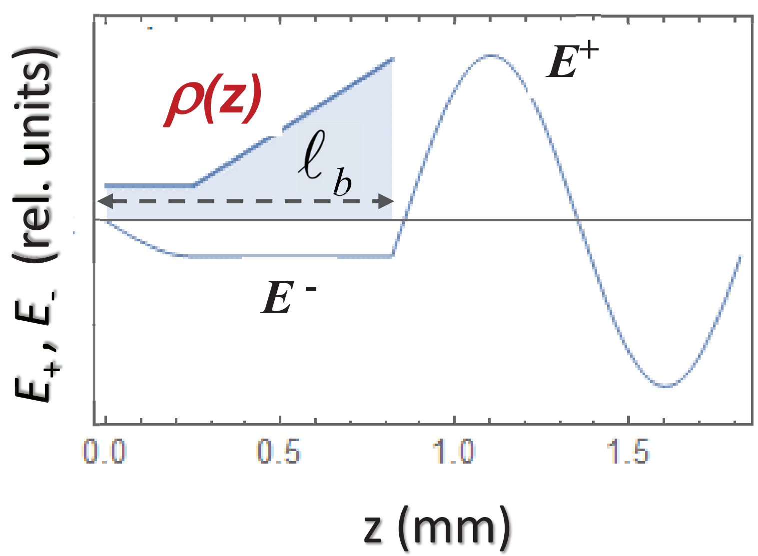
$$R = \frac{\max|E_+|}{\max|E_-|}$$

Wakefield Theorem: R<2 for symmetric bunches

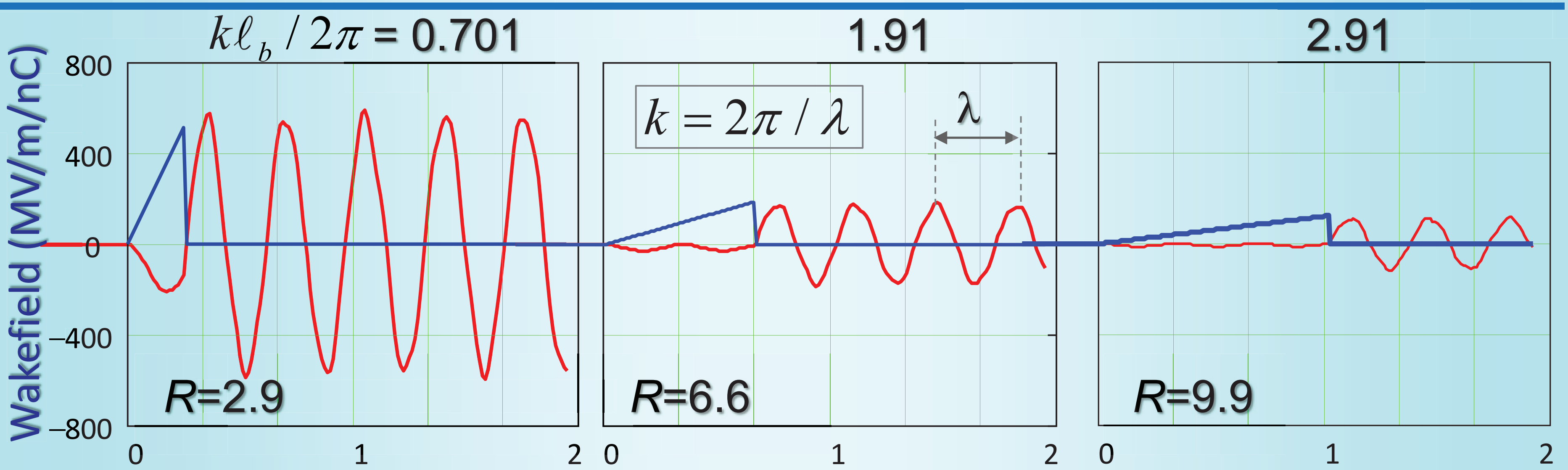
Symmetric distributions R< 2



Asymmetric distributions R>2



Tradeoff:
Acceleration Gradient (E_+) and Transformer ratio (R)*



*) J. Power, Presentation at 2011 Argonne Workshop on Dielectric Wakefield Accelerator;
S. Baturin, A. Zholents, PRAB, 061302 (2017).

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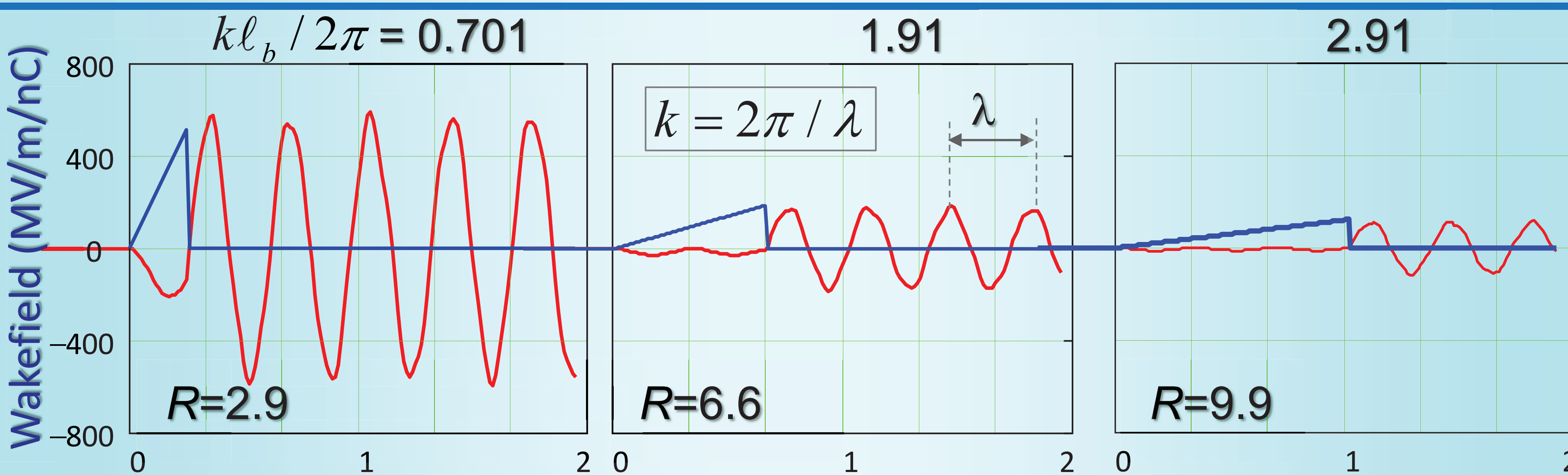
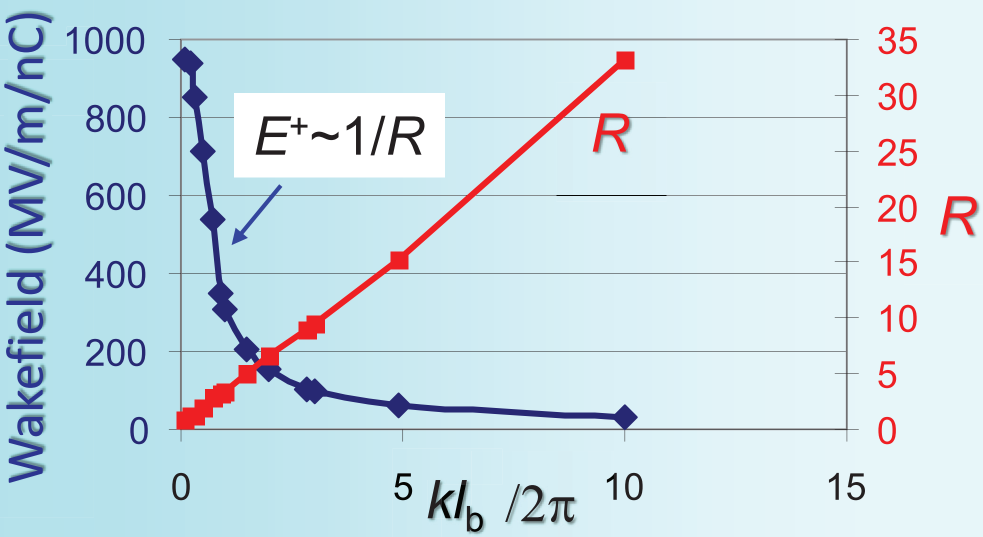




$$R \le \sqrt{1 + (kl_b)^2}$$

Ultimate accelerating field

$$\max|E_+| \le 2\kappa_{\|}|Q|\frac{2R}{1+R^2}$$

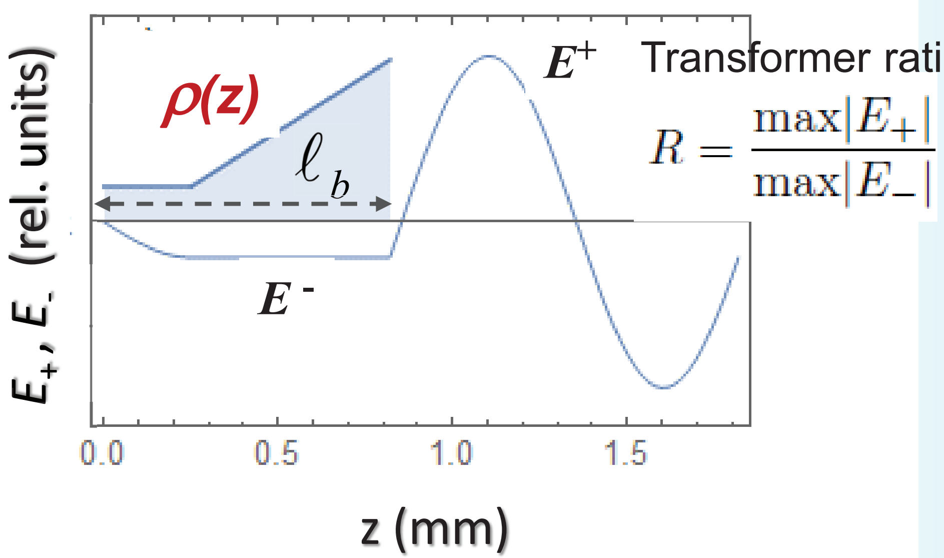
loss factor — total charge

*) J. Power, Presentation at 2011 Argonne Workshop on Dielectric Wakefield Accelerator; S. Baturin, A. Zholents, PRAB, 061302 (2017).

High energy gain by witness electron bunch

- Drive bunch utilization
  - Transformer Ratio (R = 5)
  - Extract maximum energy from drive bunch, (η = 80%)

"Door step triangle distribution" [1]



Other distributions possible [2]

$\Delta E_{witness} = R\,(\eta\, E_{drive})$

utilization of drive bunch energy E_{drive}

Example:

E_{drive} = 1 GeV
R = 5
$\eta = 0.8$
$E_{witness}$ = 5 GeV

1) K. Bane et. al., *IEEE Trans. Nucl. Sci.* NS-32, 3524 (1985).
2) F. Lemery, P. Piot, *Phys. Rev. Spec. Topics – Acc. and Beams*, 18, 081301 (2015).

Efficiency and Power Management

$$\text{Energy efficiency} \leq \eta \frac{Q_W}{Q_D} R$$

Q_W: witness bunch charge

Q_D: drive bunch charge

Example

for 50 kHz rep. rate

Assumptions:

$E_{drive} = 1$ GeV
$E_{witness} = 1$ GeV
$R = 5$
$\eta = 0.8$
$Q_D = 8$ nC
$Q_W = 0.3$ nC

⇨ Energy efficiency = 18%

Power management

1 GeV

Drive +witness in 415 kW →

Wakefield accelerator ~ 50 m

→ 75 kW witness out

5 GeV

↓ 80 kW drive

200 MeV

Efficiency and Power Management

$$\underline{\text{Energy efficiency}} \leq \eta \frac{Q_W}{Q_D} R$$

witness bunch charge (Q_W)

drive bunch charge (Q_D)

Example

for 50 kHz rep. rate

Assumptions:

E_{drive} = 1 GeV
$E_{witness}$ = 1 GeV
R = 5
η = 0.8
Q_D = 8 nC
Q_W = 0.3 nC

⇨ Energy efficiency = 18%

Power management

1 GeV

Drive +witness in 415 kW →

Wakefield accelerator ~ 50 m

Power load ~ 20 W/cm

5 GeV

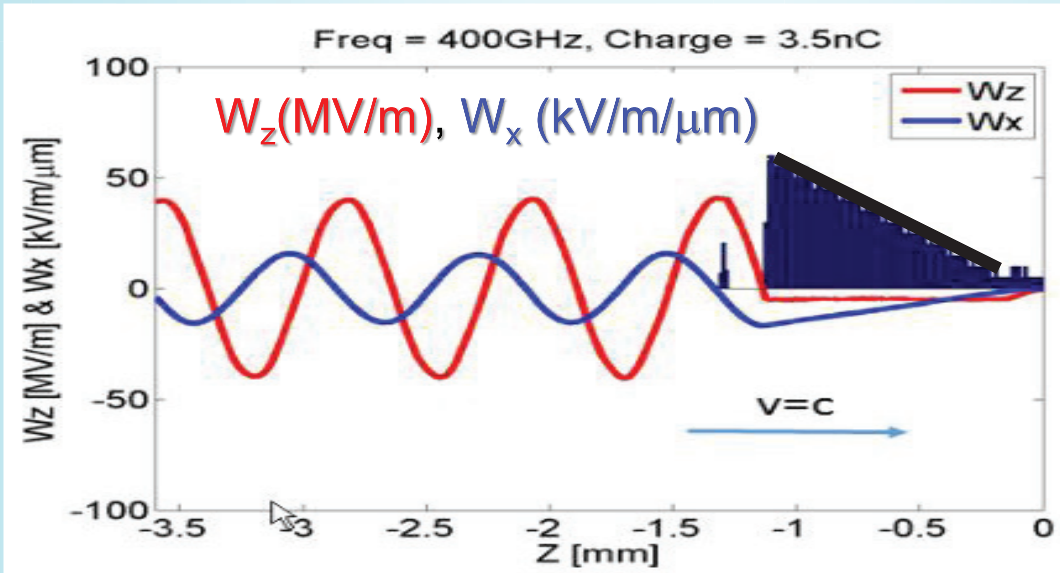
→ 75 kW witness out

↓ 80 kW drive

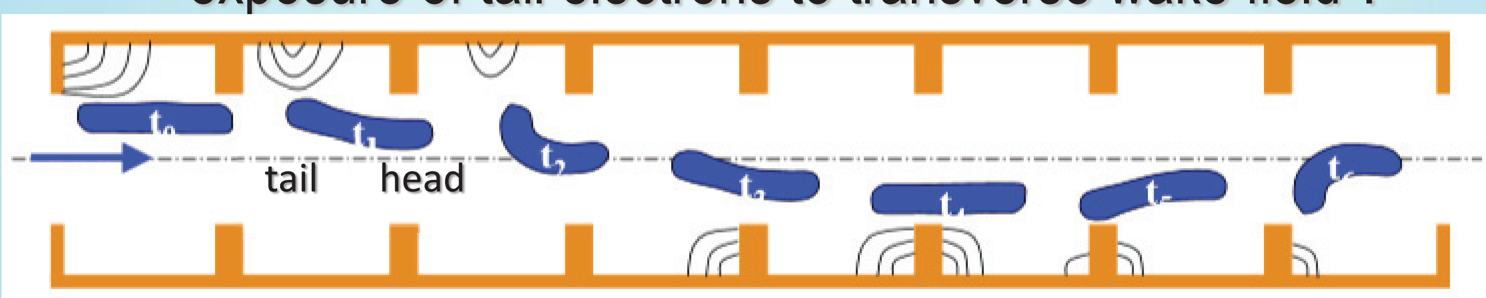
200 MeV

Beam Stability

Transverse wakefields: $W_x \sim 1/(ka^4)$ (to be compared with $W_z \sim 1/a^2$)



Beam breakup instability arises from continuous exposure of tail electrons to transverse wake field*.



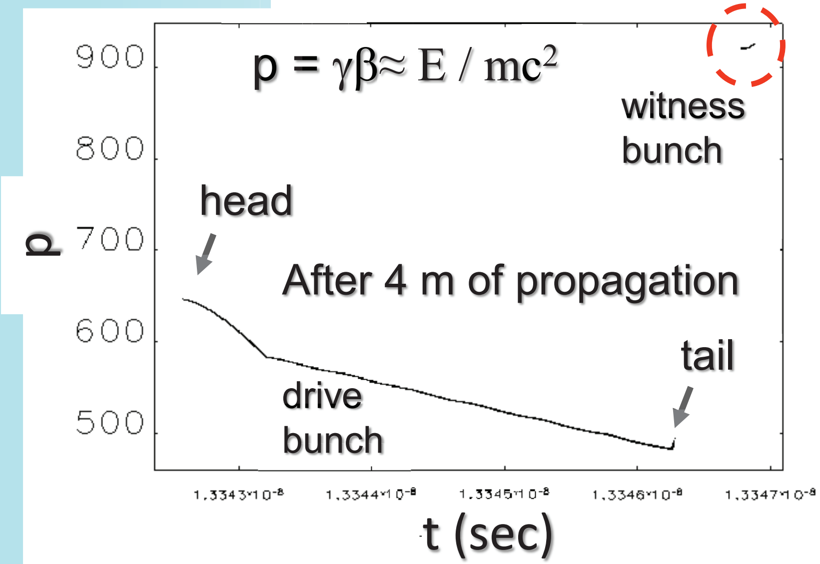
Snapshots of a single bunch traversing a SLAC structure

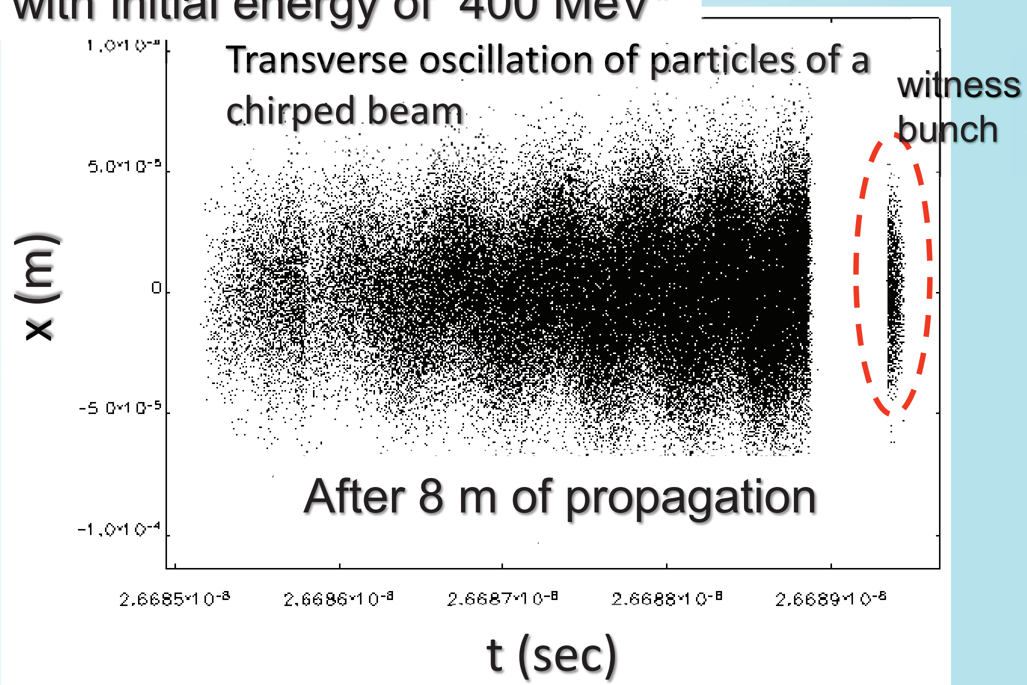
*) A.Chao, "Physics of collective beam instabilities in high energy accelerators", New York: Wiley.

Balakin-Novokhatsky-Smirnov (BNS) damping of BBU

- Use FODO channel to guide the drive bunch in CWA
- Produce "chirp" in the betatron tune along the drive bunch using the energy "chirp", and
- Force tail to oscillate out of phase from the head, thus mitigating the impact of transverse wake fields.

Illustration for drive bunch with initial energy of 400 MeV*





Initial energy chirp ~15 % (peak-to-peak)

Particles of different energies have different oscillation periods in the FODO lattice

*) Shchegolkov, Simakov, Zholents, IEEE Trans. on Nuclear Sci., vol. 63, (2016)804.

A Stability Recipe for CWA*

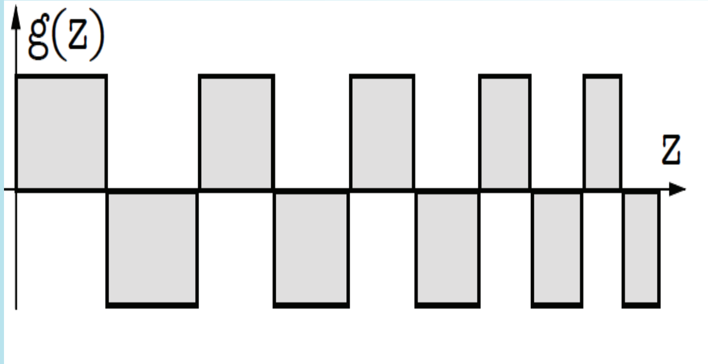
Ingredient 1: Adaptive focusing

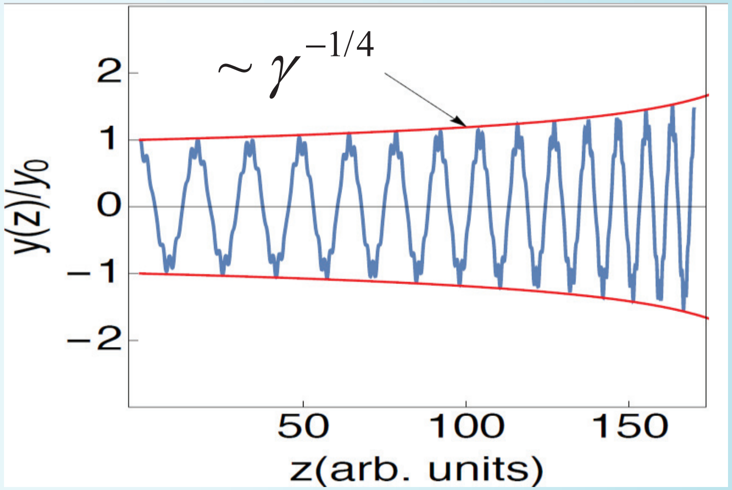
- Change the quadrupole length according to

$$L = L_0\sqrt{1-\alpha z},$$

with beam deceleration $\gamma(s,z) = \gamma_0\left[1-\alpha z\right]$

and keep the magnetic field gradient at a maximum





*) Baturin, Zholents, "Stability condition for the drive bunch in a collinear wakefield accelerator", arXiv:1709.08583v2

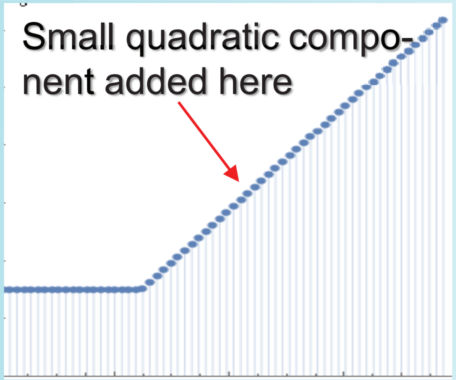
A Stability Recipe for CWA* cont’t

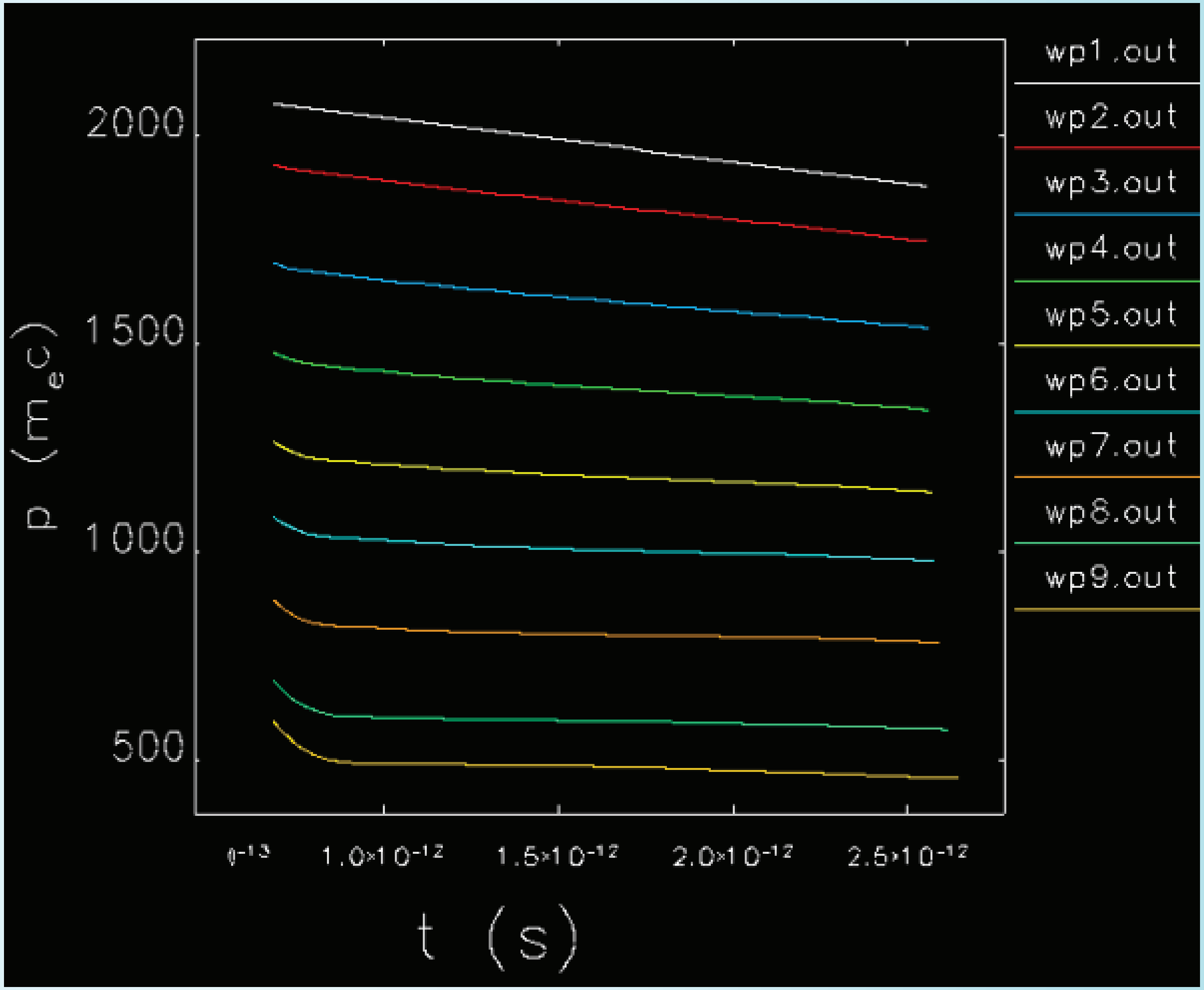
Ingredient 2: Adaptive energy chirp

Keep relative energy chirp constant

$$\frac{\Delta\gamma}{\gamma_z} = \text{const}$$

Accomplish it by employing the longitudinal wakefield and special peak current distribution in the drive bunch.





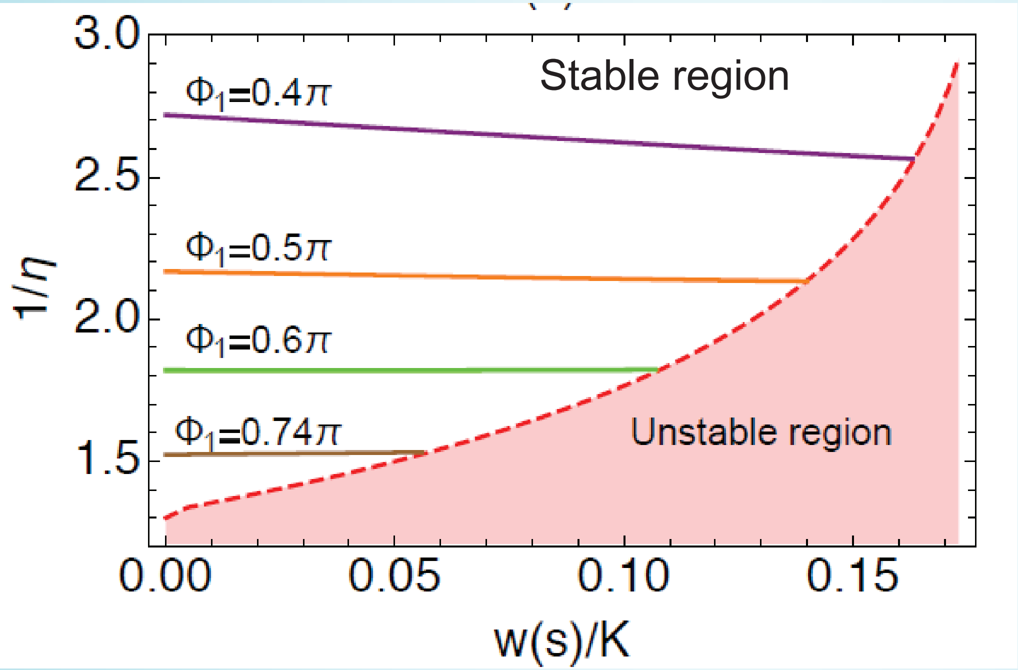
Demonstration of the adaptive energy chirp using *elegant* code

A Stability Recipe for CWA* cont't

Ingredient 3: Select energy chirp within the stability "window"

$$\frac{1}{\eta}\frac{2}{ka}\frac{\max\left|E_{+}\right|}{cB_{0}} \leq \left|\frac{\Delta\gamma}{\gamma_{z}}\right| \leq \frac{1}{\eta}\frac{w(s)}{K}$$

quadrupole pole tip field



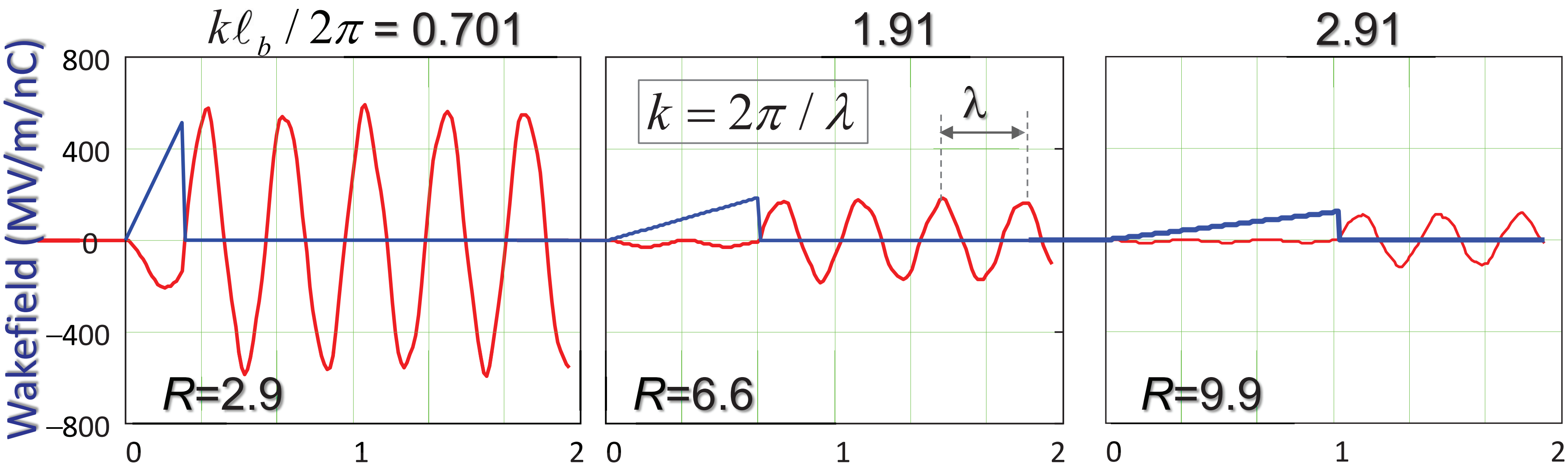
Φ_1 is the betatron phase advance of the head electron in FD focusing cell

BUNCH SHAPING

1. Manipulating wakefields via bunch shaping
2. Methods of bunch shaping
   - Emittance Exchange
   - photocathode laser-based
   - self-wakefields,

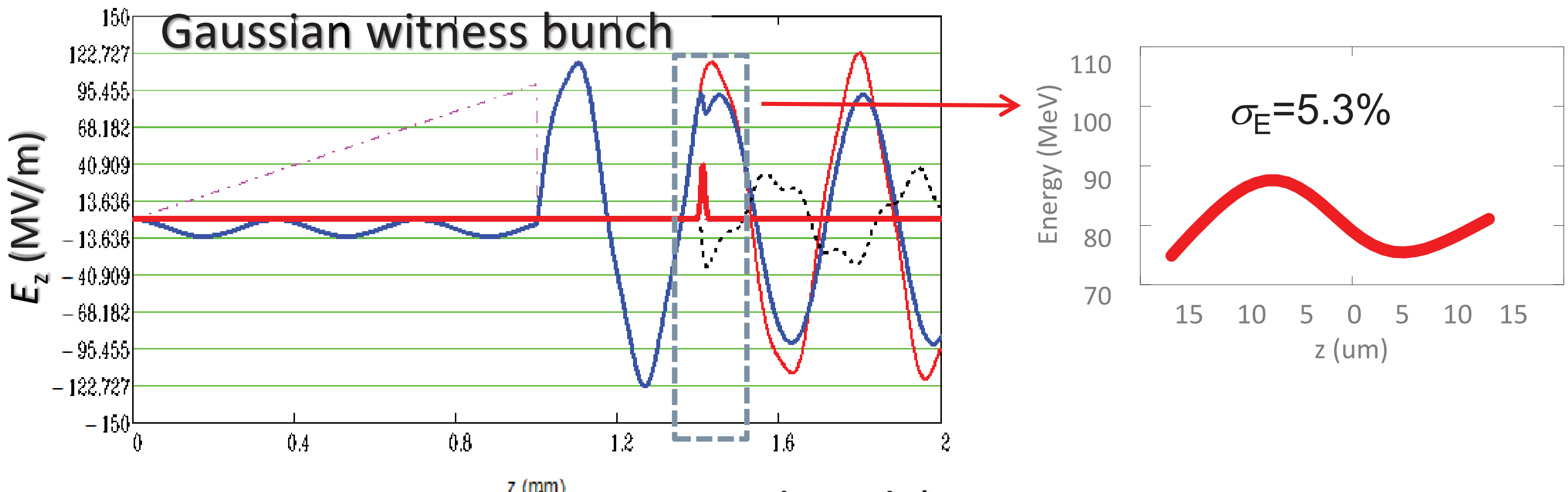
Q: Why do we want to control the bunch shape?

A: Drive bunch shape controls the drive bunch wakefield to control transformer ratio **R** and acceleration gradient **E_z.**

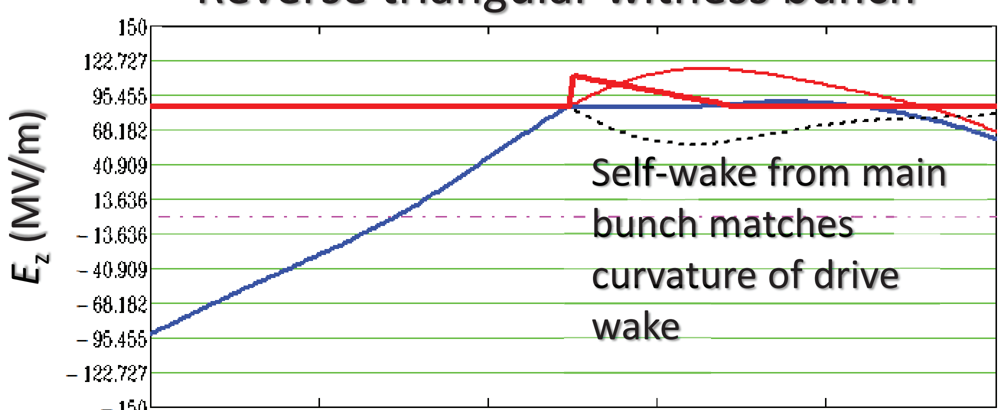


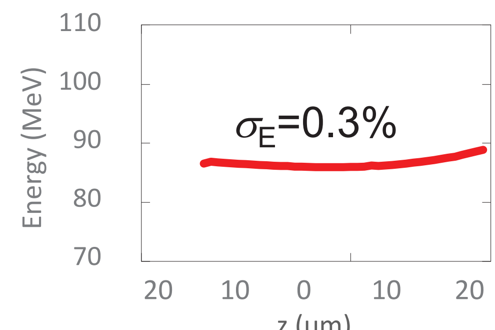
Q: Why do we want to control the bunch shape?

A: Witness bunch shape controls the witness bunch wakefield to reduce its correlated energy spread.



Reverse triangular witness bunch*



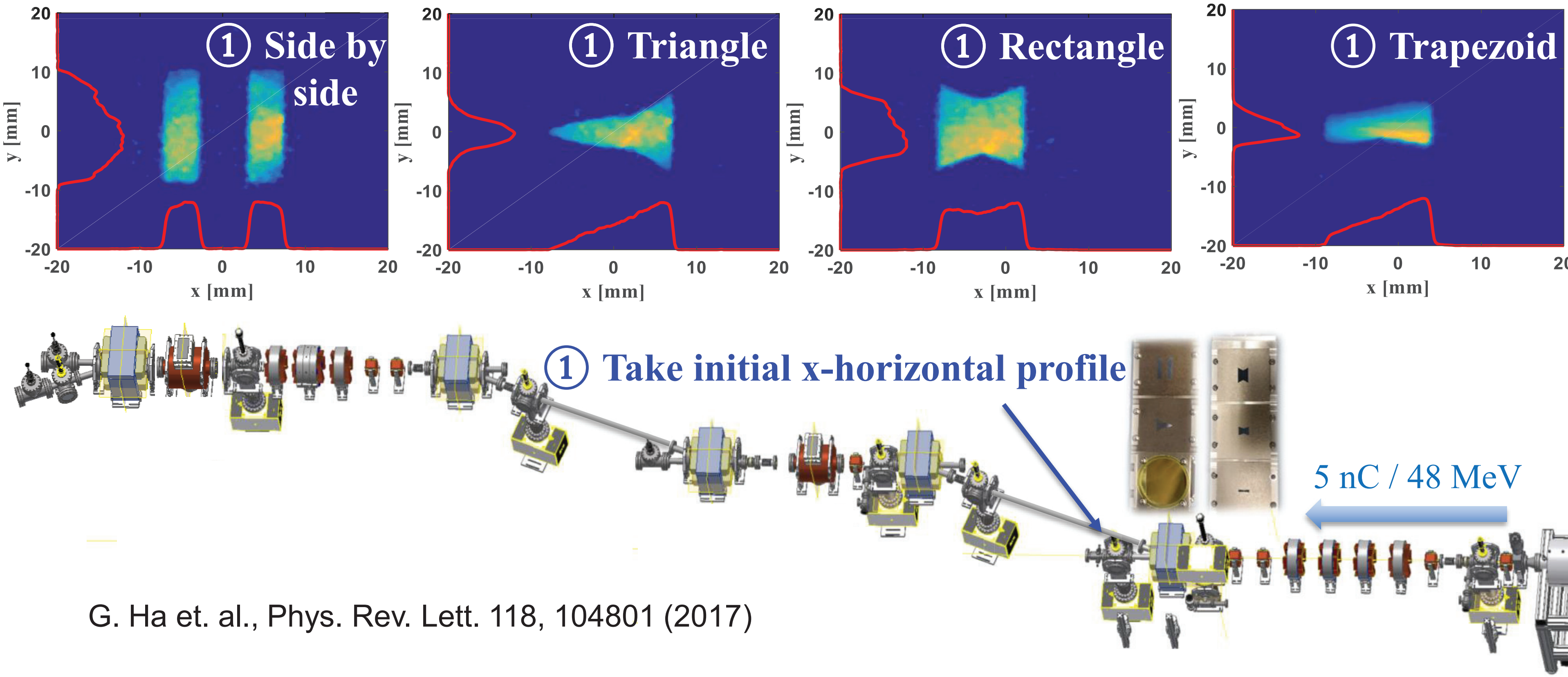


Can be further improved

*) T. Katsouleas et al., Particle Accelerators, 1987, Vol. 22, pp. 81-99

Emittance Exchange Beamline Converts Transverse Shaping to Longitudinal Shaping

EXPERIMENT
AWA/ANL



G. Ha et. al., Phys. Rev. Lett. 118, 104801 (2017)

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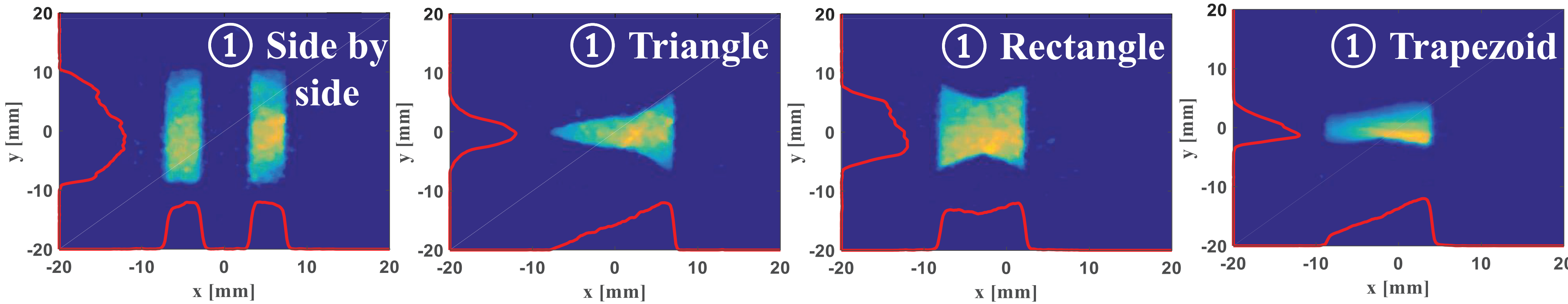

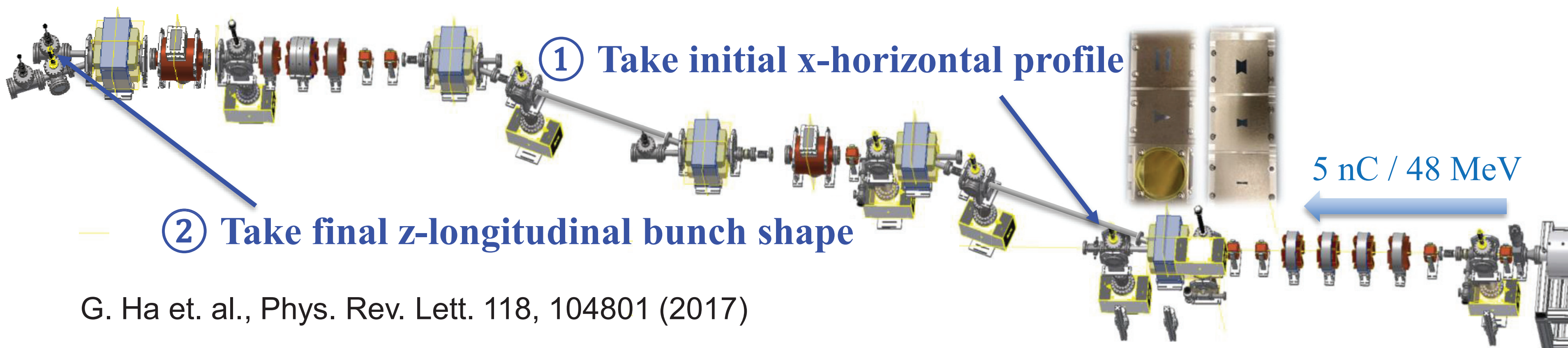

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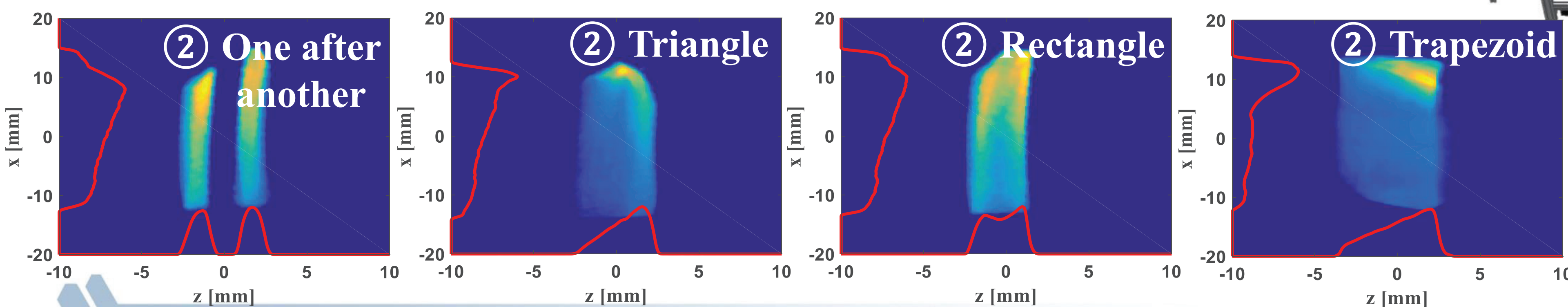
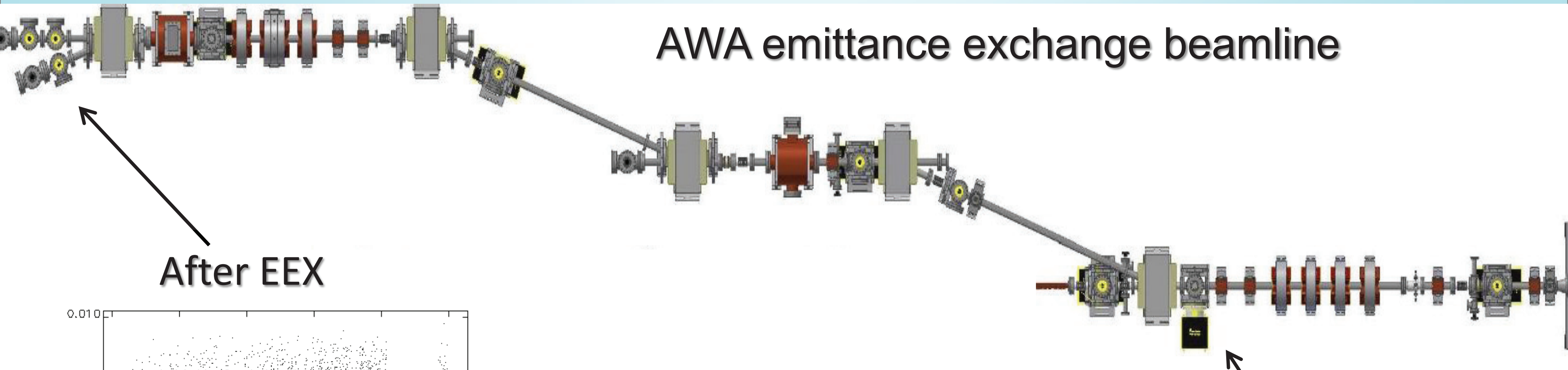
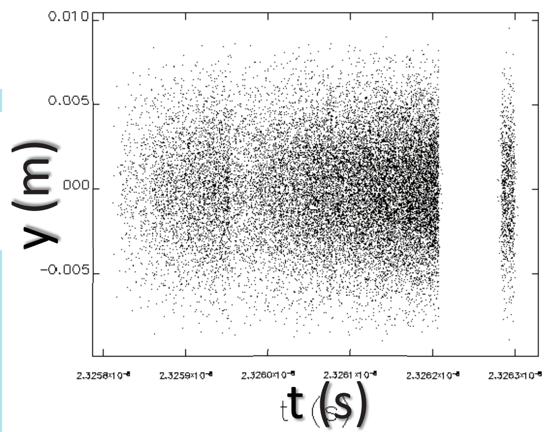


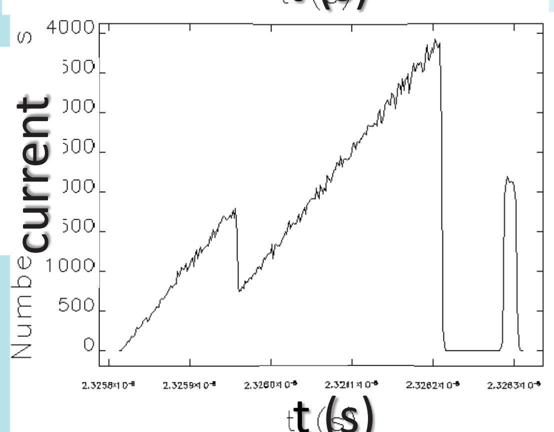
Masks (~100 μm of W)

YAG

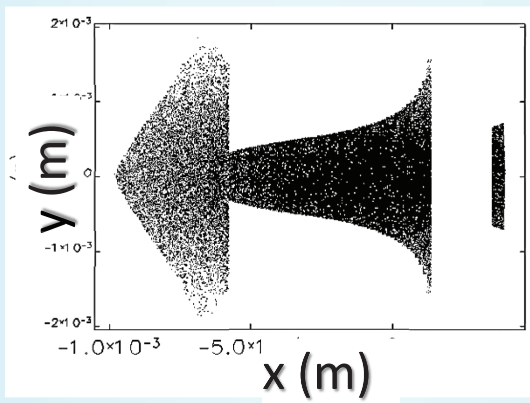
Problematic at a high bunch repetition rate



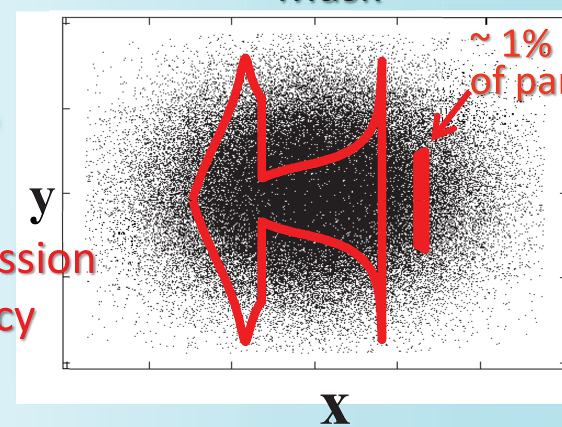




Transverse particle distribution after mask

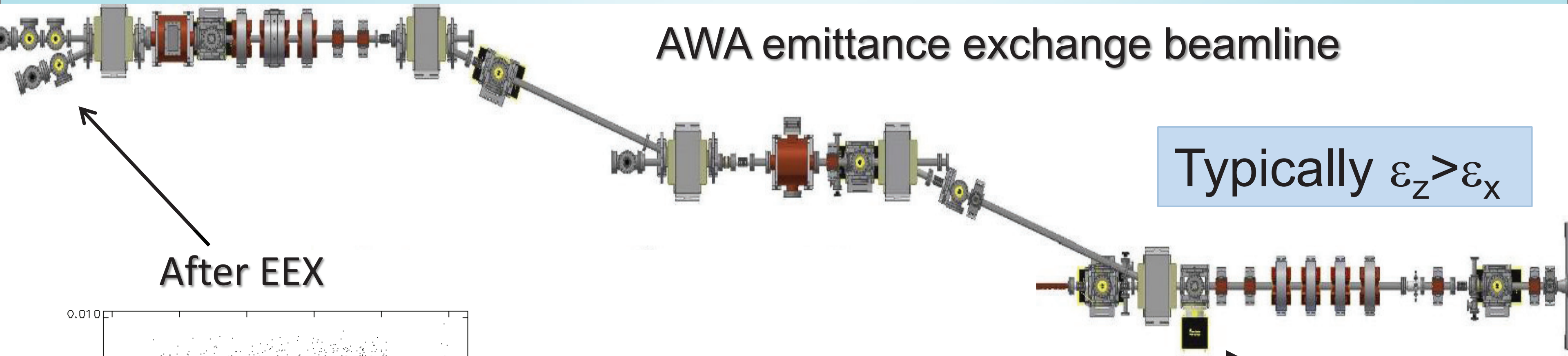


40% transmission efficiency

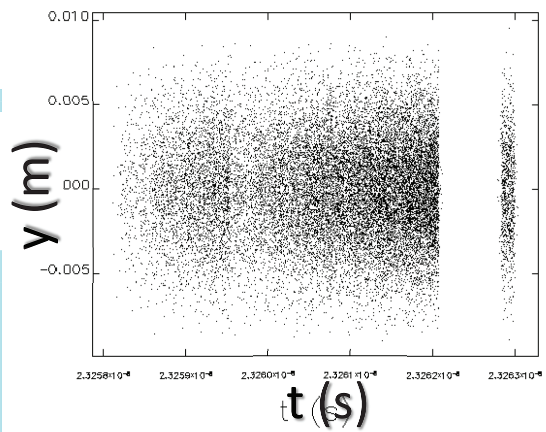


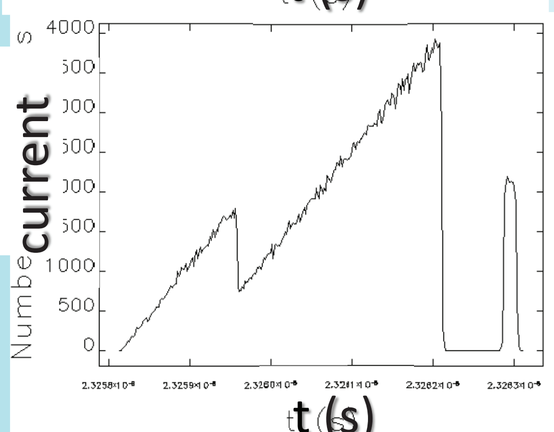
~ 60 kW will be deposited on a mask, even at a low energy 5 MeV (below threshold for isotope production)

Problematic at a high bunch repetition rate



Typically $\varepsilon_z > \varepsilon_x$





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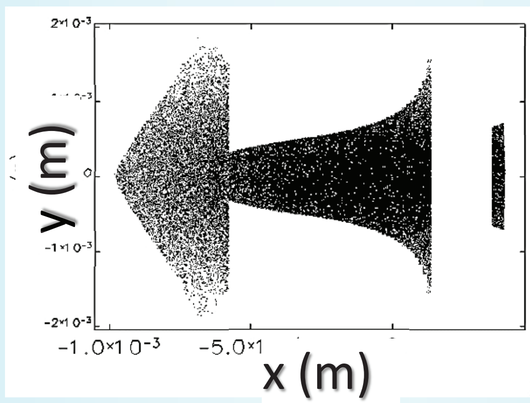

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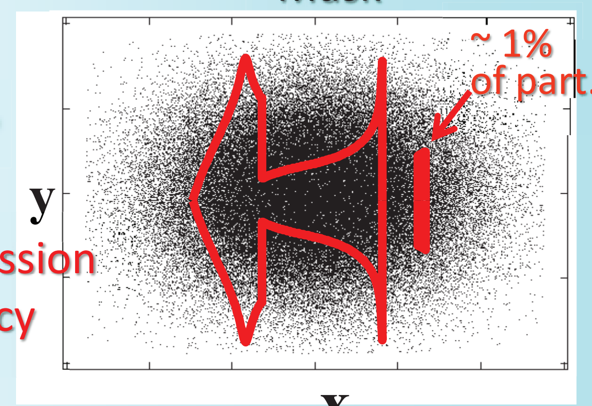
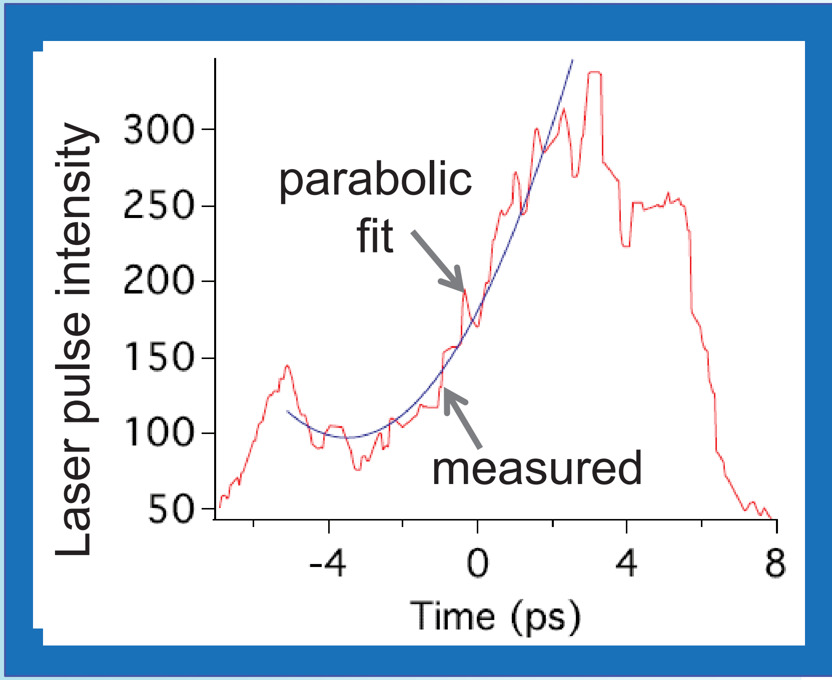
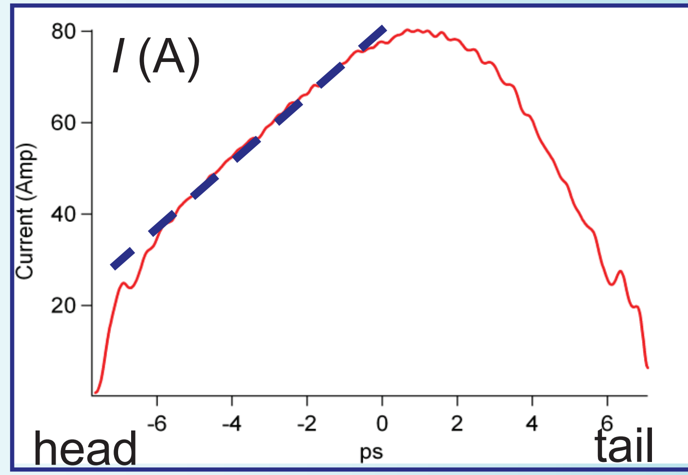


~ 60 kW will be deposited on a mask, even at a low energy 5 MeV (below threshold for isotope production)

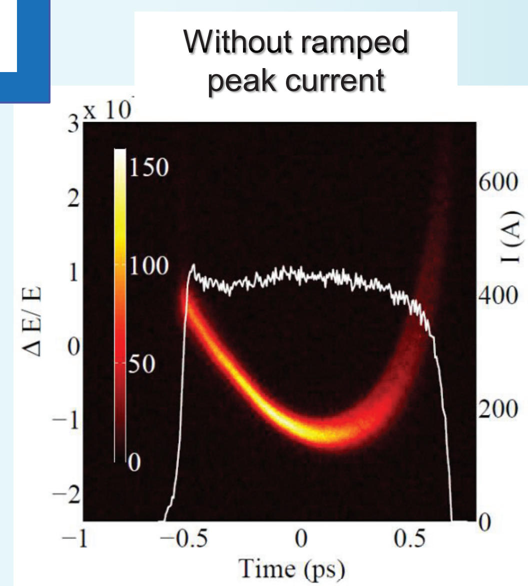
Drive bunch shaping using photocathode laser *)

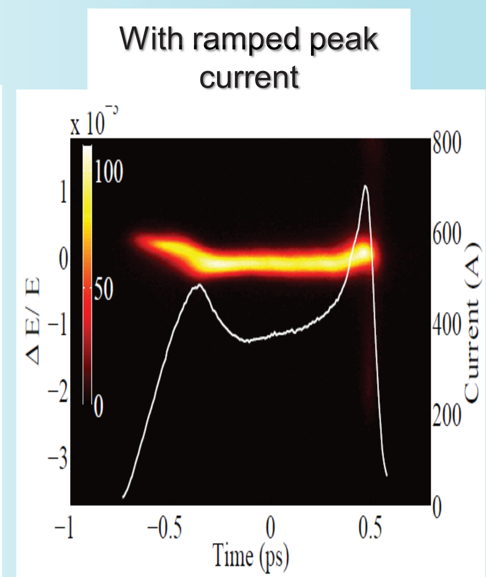




At the end of the injector at 100 MeV

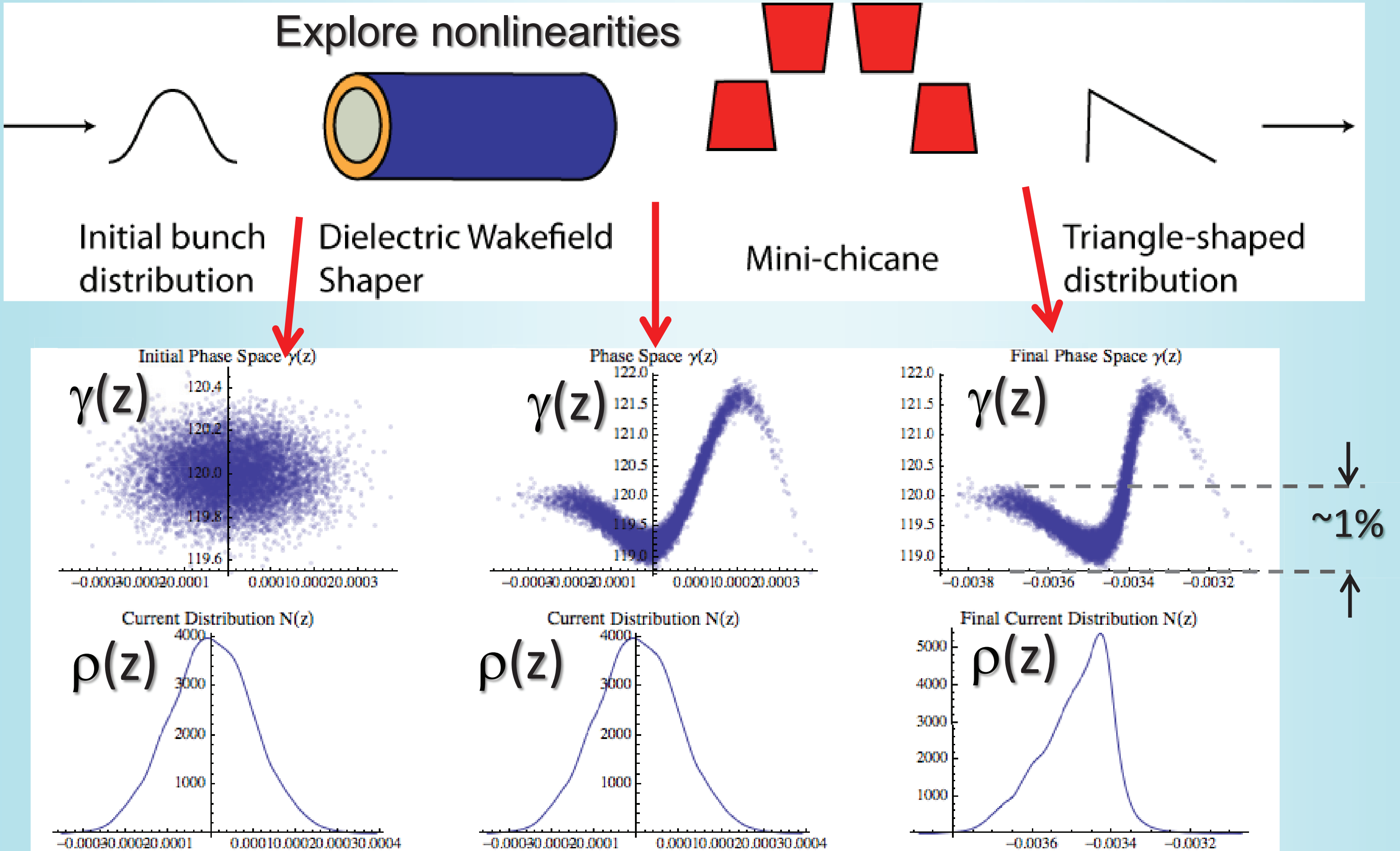
… was proposed to remove significant quadratic energy chirp at the end of the FERMI FEL linac





*) Cornacchia, Di Mitri, Penco, Zholents, *Phys. Rev. ST-AB*, 9, 120701(2006);
Penco, Danailov, Demidovich, Allaria, et al.,Phys. Rev. Lett, 112, 044801 (2014).

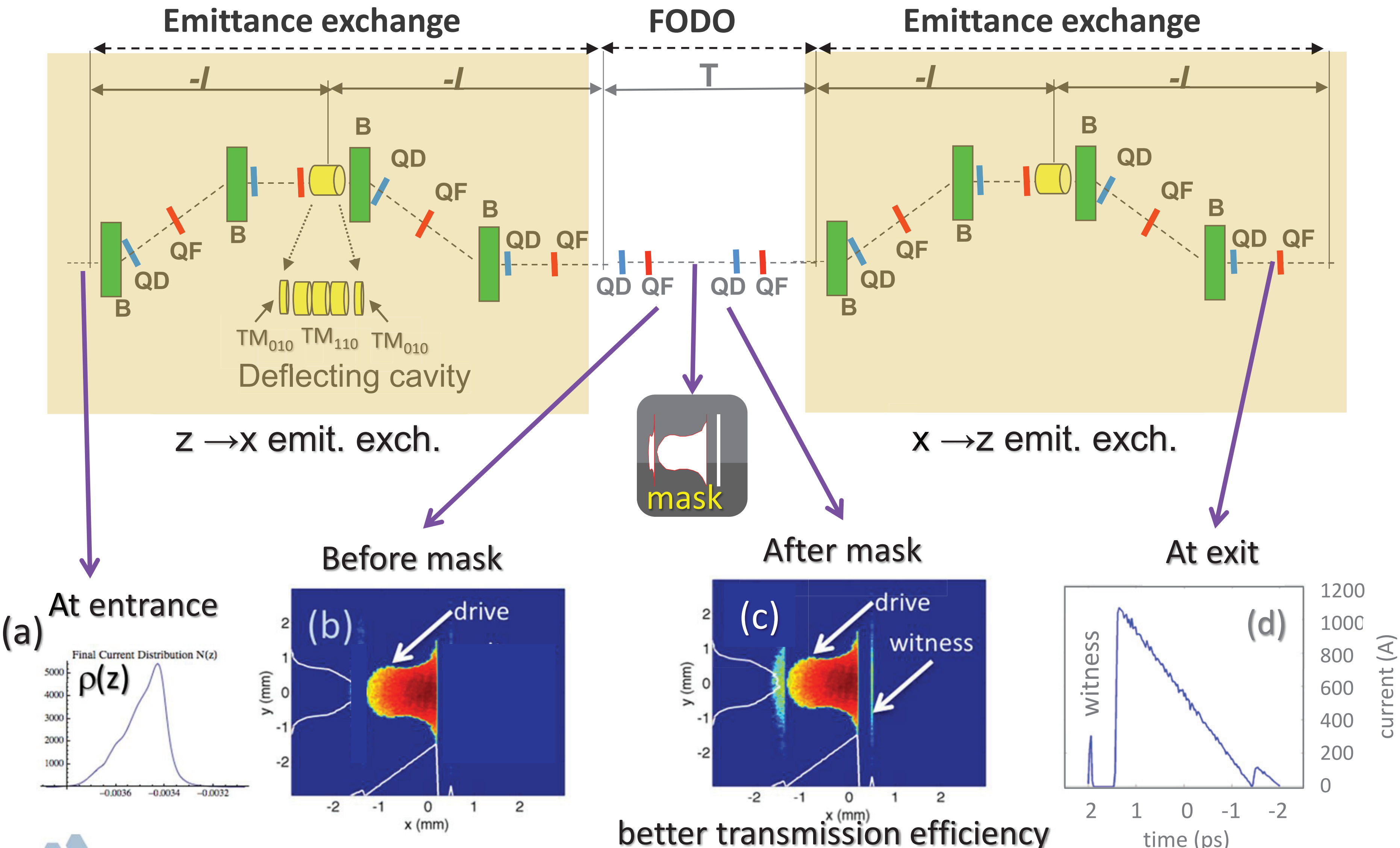
Drive bunch shaping using self-wakefields*



*) G. Andonian, Advanced Accelerator Workshop - AAC 2014, San Jose, (2014)

Make it more precise using Double EEX*)

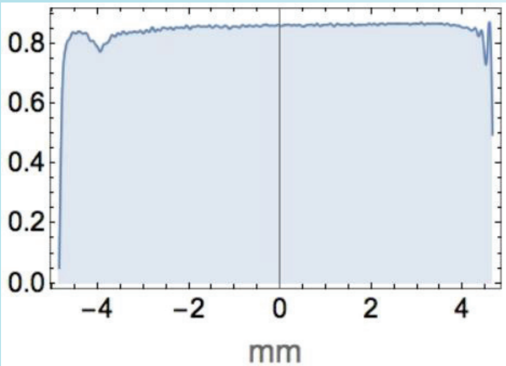
Under installation at the Argonne Wakefield Accelerator (AWA) facility



*) A. Zholents and M. Zolotorev (LS-327/APS, 2010)

Bunch shaping using the entire accelerator

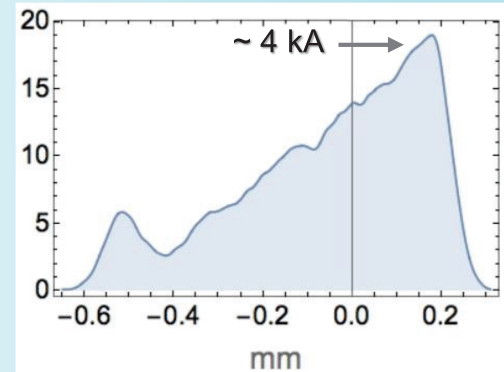
Uses no masks

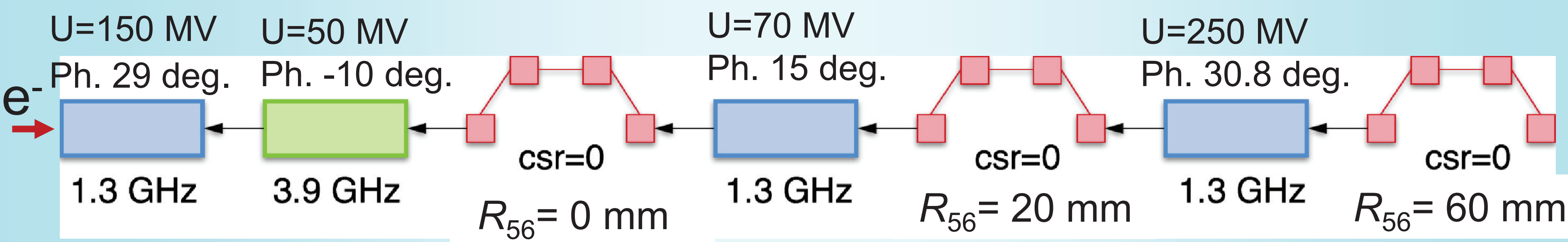


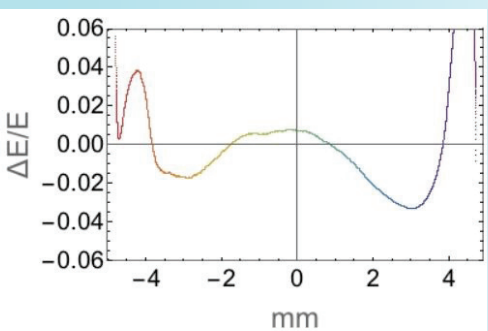
← ~ 200 A

Time reversible tracking

~ 4 kA →



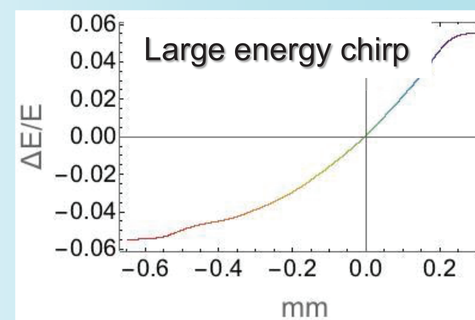




Drive bunch In

Includes:
- Wakefields
- Long. space charge
- T_{566}

CSR is next

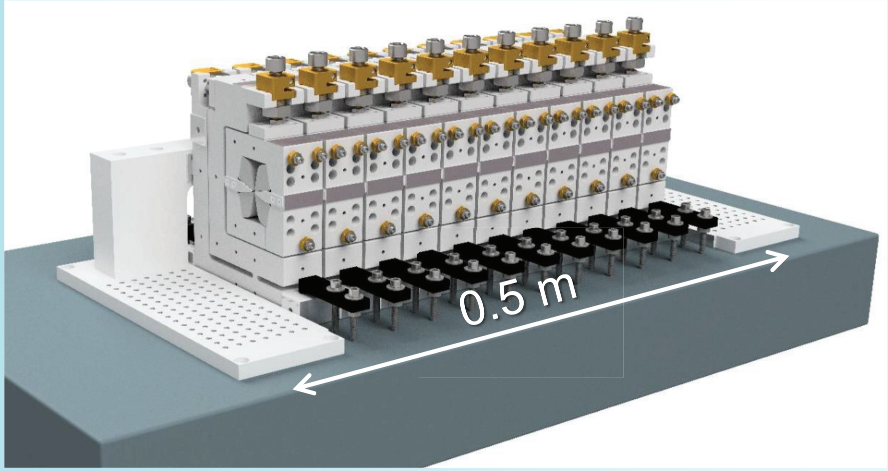


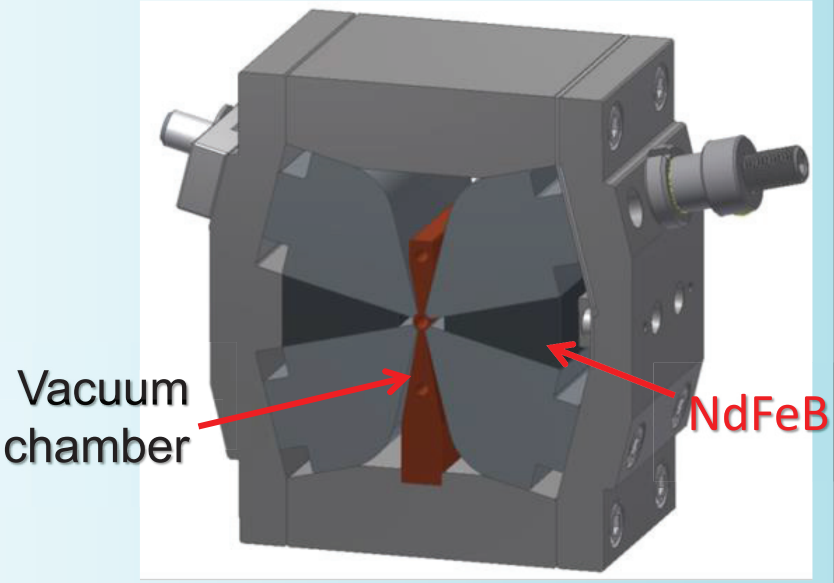
Drive bunch Out

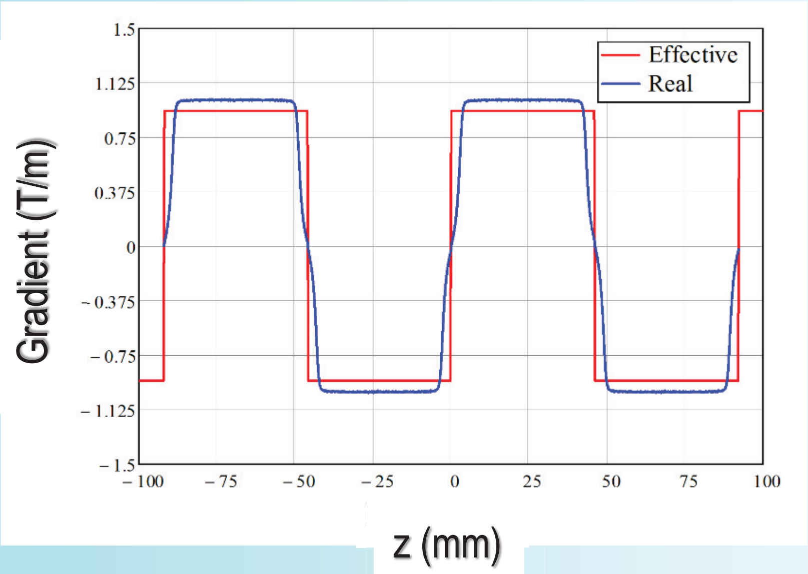
PROTOTYPING AND EXPERIMENTING

Accelerator module

Quadrupole wiggler: array of focusing (F) and defocusing (D) quadrupoles





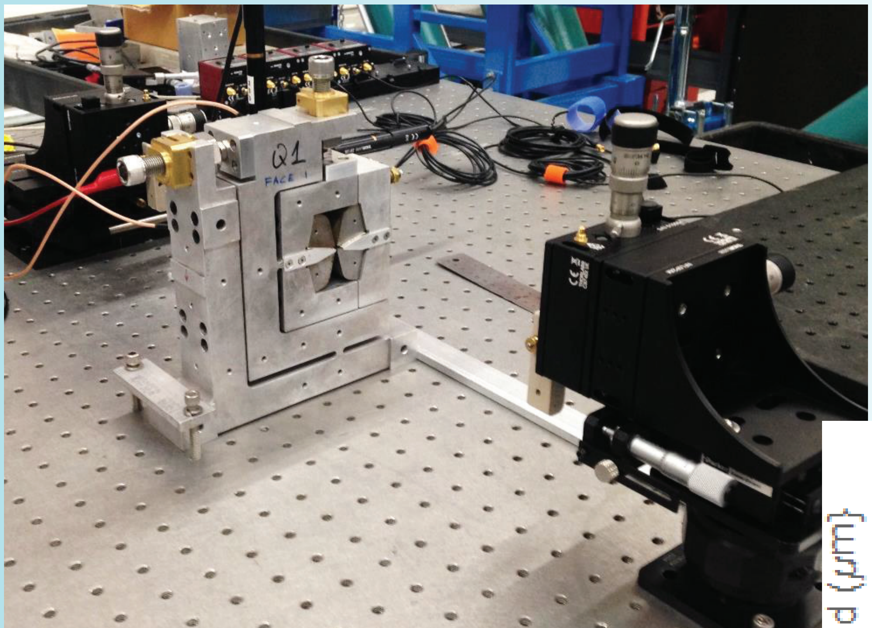


High gradient hybrid quad

- Bore radius = 1.5 mm.
- Peak gradient = 0.96 T/mm.
- Sub-micron precision in the magnetic center position.
- Length = 40 mm.
- Weight = 2.5 kg.
- Magnetic force between top and bottom parts = 30.5 kg.

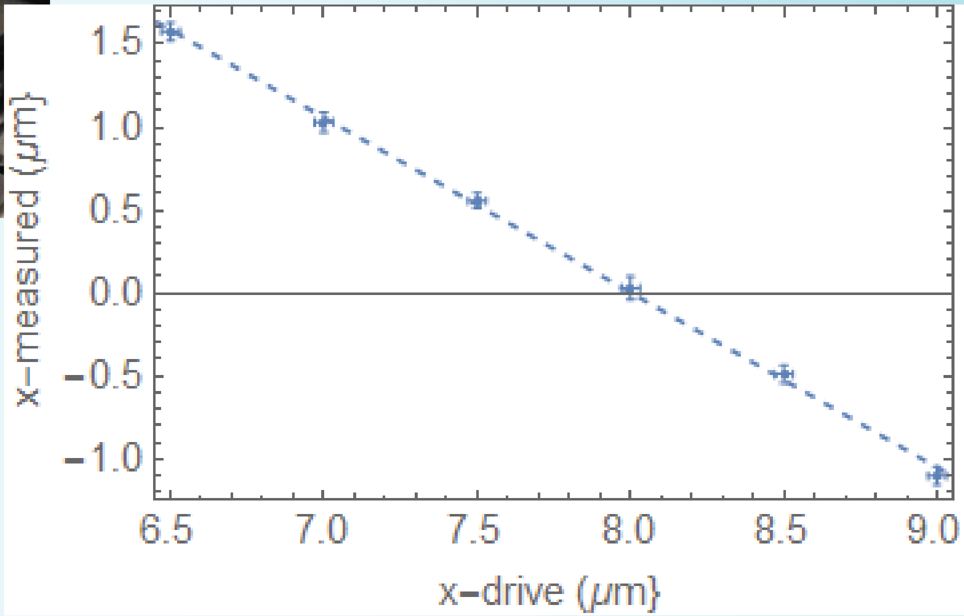
Quadrupole wiggler

Requirement: quad-to-quad misalignment tolerance ≤ 1 μm

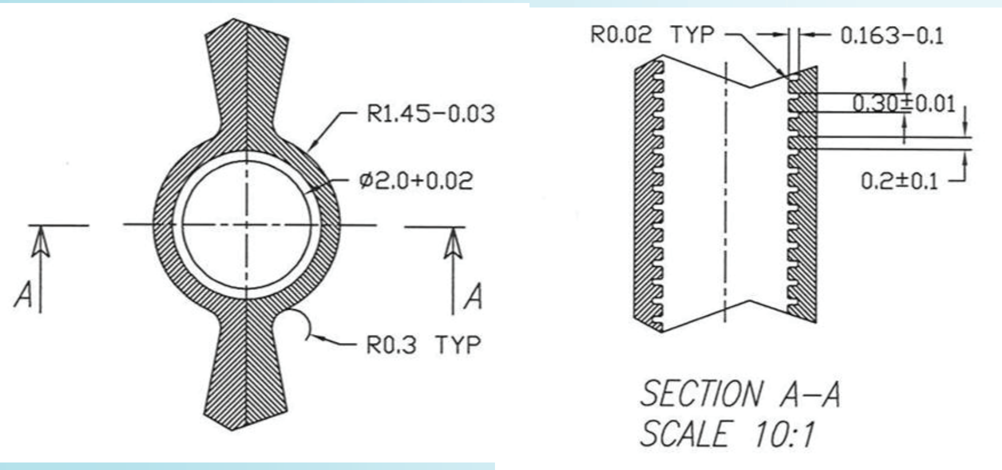


Demonstrated: sub-micrometer accuracy in determination of the magnetic center

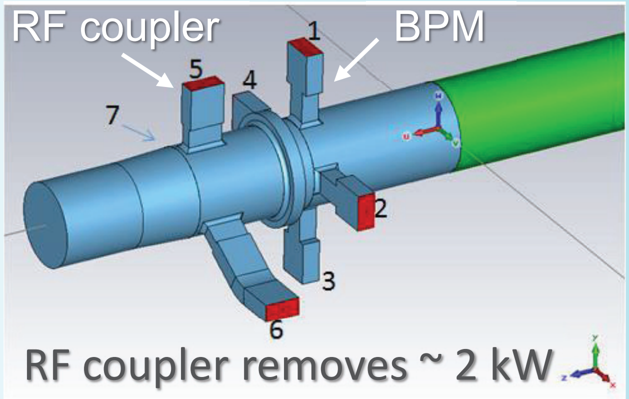
Prototype quadrupole on the bench for magnetic measurements



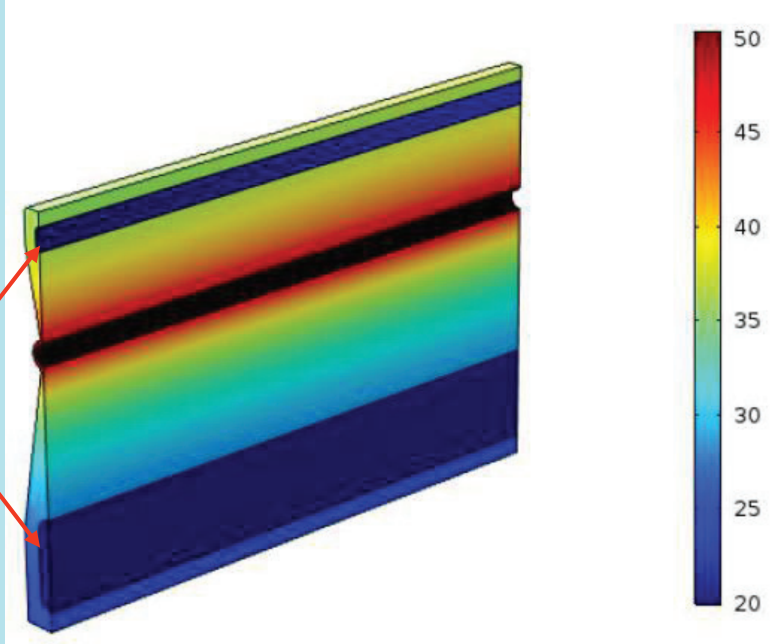
Vacuum chamber



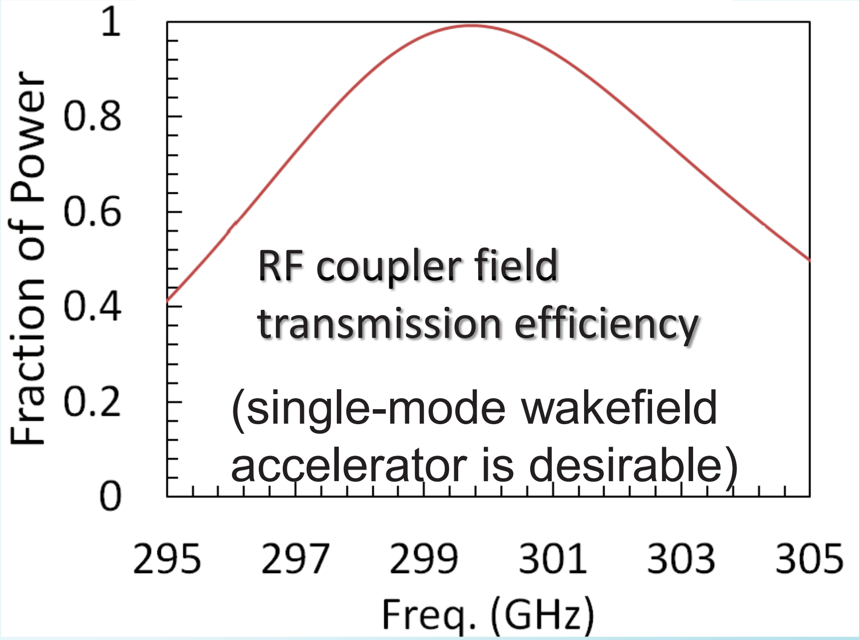
RF main mode and HOM coupler every 0.5 m



H_2O

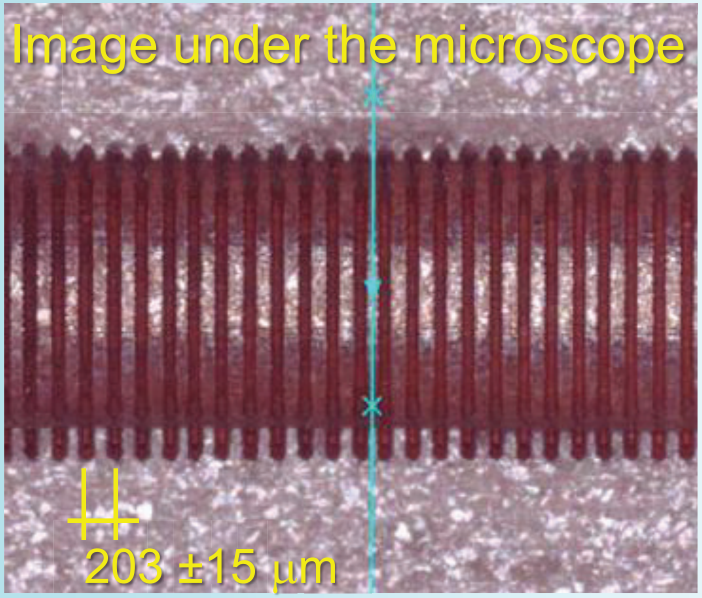


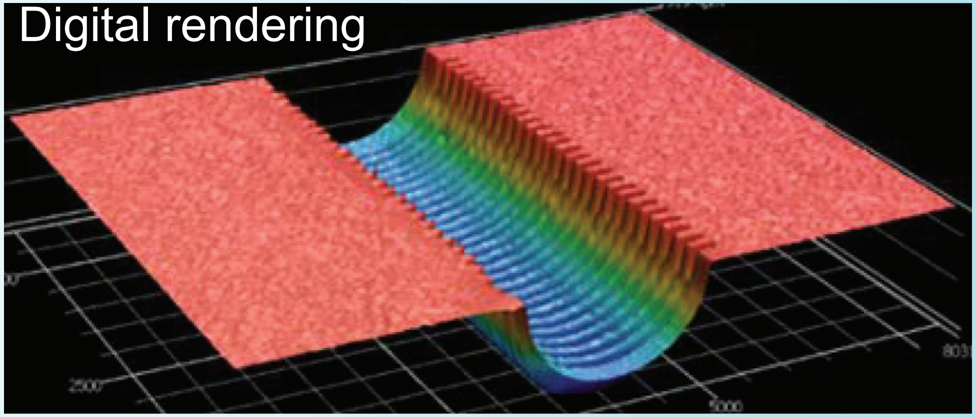
Power loss in Cu 20 W/cm

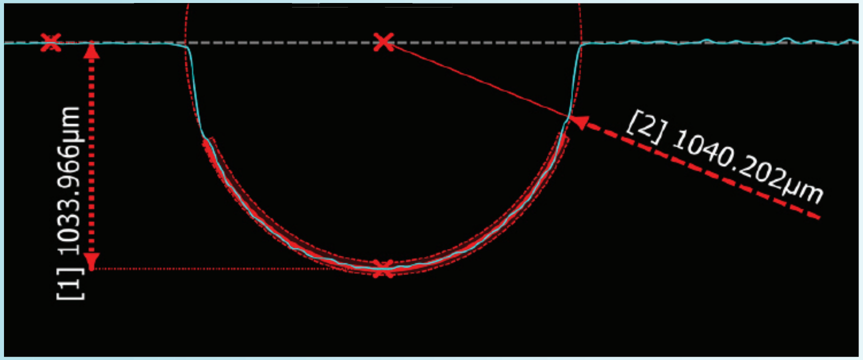


Vacuum chamber cont'd

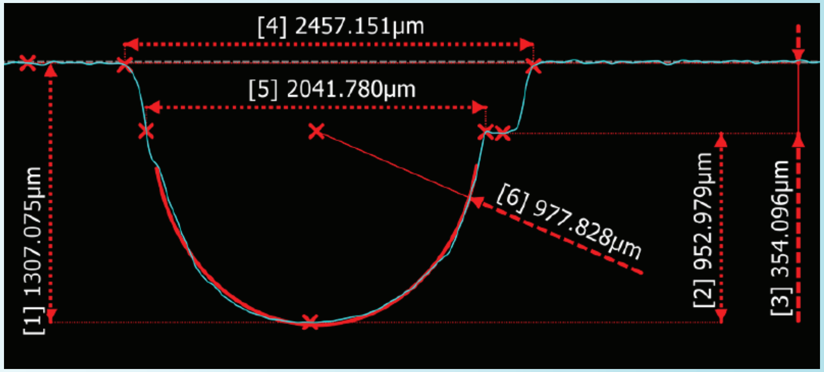
Making the waveguide with small corrugations: work in progress





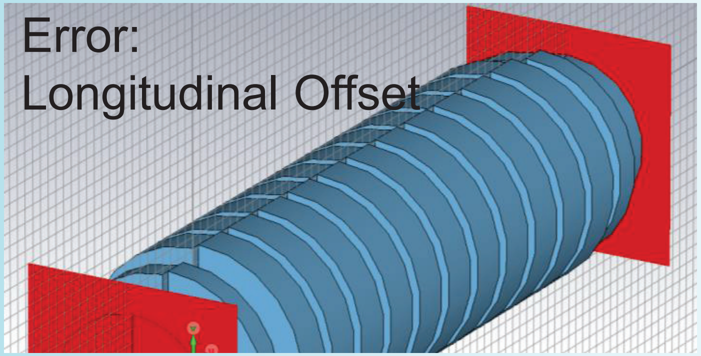


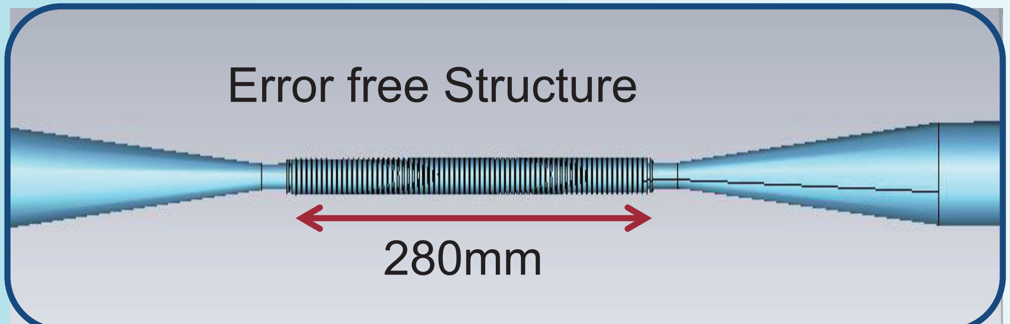
Cross-sectional profile through a raised tooth marked by the blue line in the above photo.

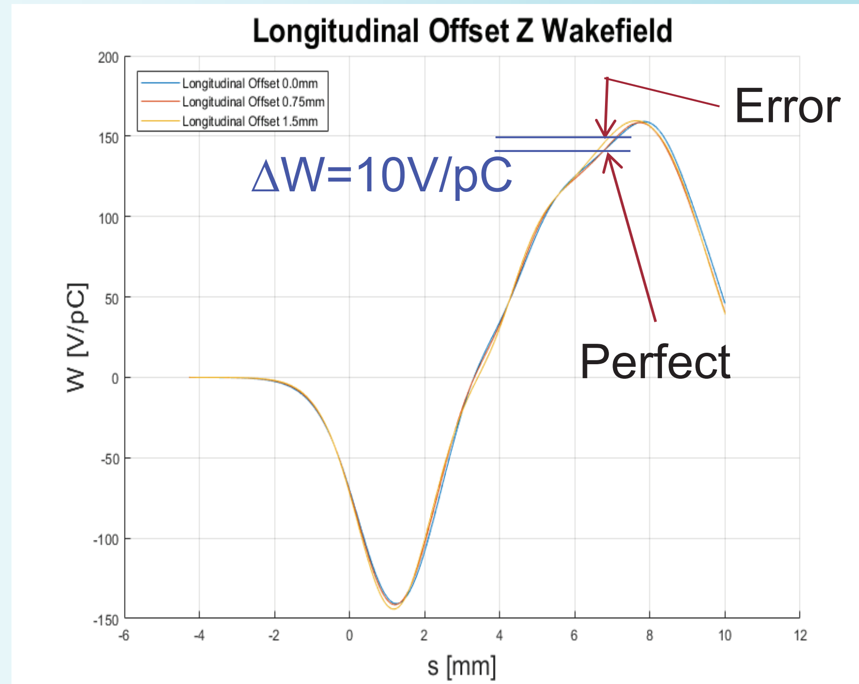


Cross-sectional profile through a groove.

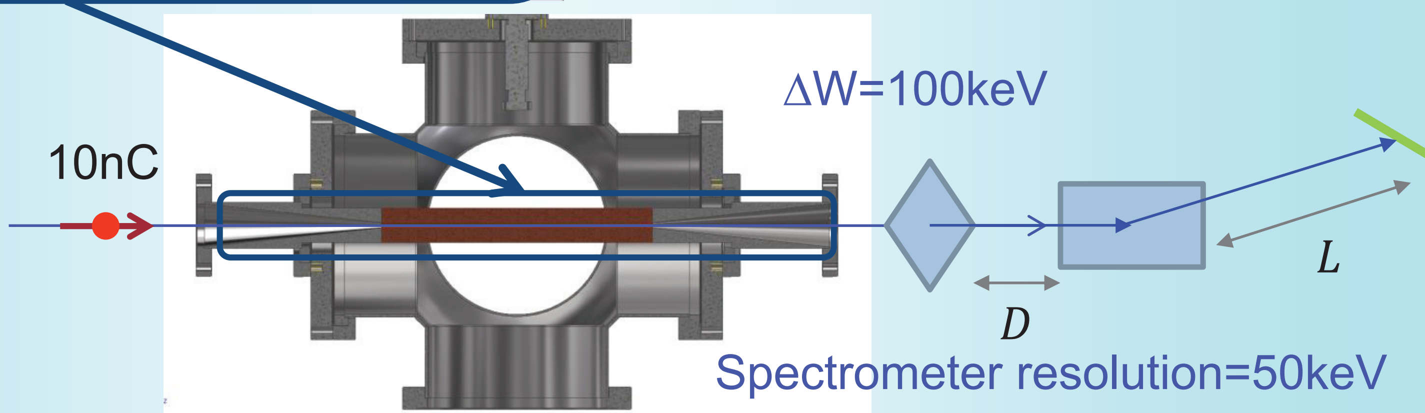
Scaled up experiment at the Argonne Wakefield Acceleratorr (AWA) Facility: Tolerance Study







Beam test to measure longitudinal wakefield



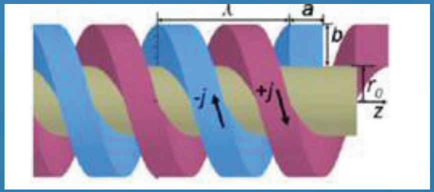
FREE-ELECTRON LASER

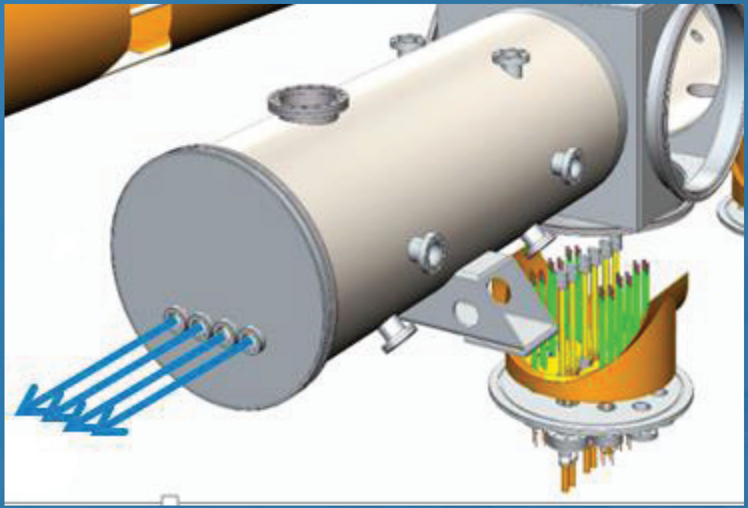
Small period undulator

... allows obtaining the same radiation wavelength using the electron beam with less energy (shorter and less expensive Linac)

$$\lambda_{x-ray} = \frac{\lambda_{undulator}}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

A promising technology is a helical superconducting undulator

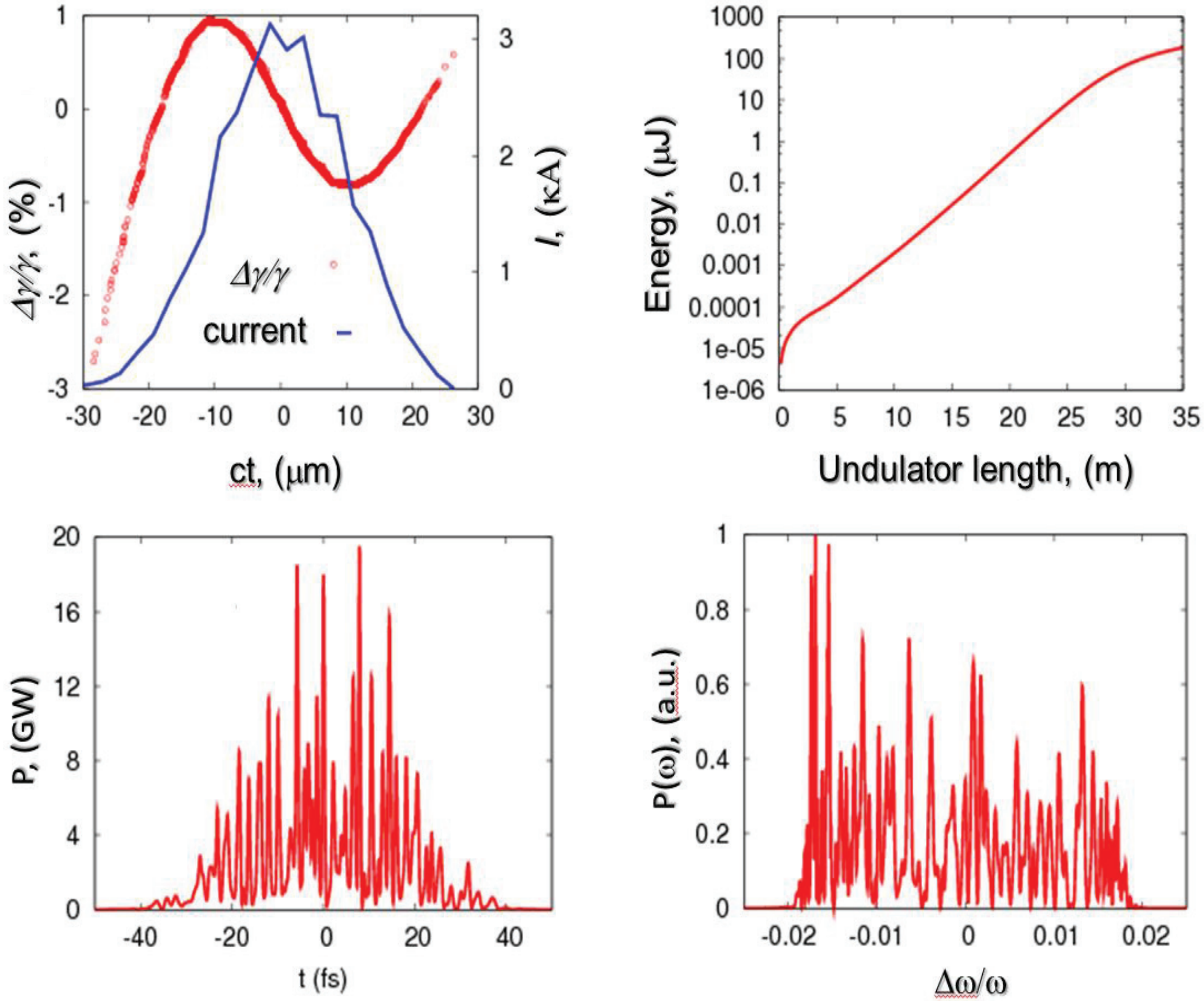




- Innovative concept of multiple helical undulators sharing one cryostat
- Supplemental helical quadrupole winding will ensure a superior FEL performance
- Expected period ~ 10 mm (for 2 mm vacuum bore)

FEL simulations (illustration)

Undulator period, cm	1.8
Undulator parameter, K	1.0
Energy, GeV	1.88
Charge, pC	250
Current, kA	3
Emitt, μm	1
RMS energy spread, %	0.3
Pierce parameter,	0.01
X-ray wave-length, nm	1
Peak power, GW	5
Bandwidth, %	3.8



Conclusion

- Making progress towards a High Repetition Rate, Multiuser, X-ray FEL Facility.
- Collinear wakefield accelerator
  - Limiting factors for accelerating gradients are defined
  - High accelerator efficiency is favored over the high acceleration gradient
  - Accelerator design mitigating BBU of the drive bunch has been proposed
- Beam shaping and obtaining high transformer ratio has been demonstrated
- Prototyping of the accelerator components is quickly progressing
- Small period superconducting undulators are considered