# ASSESMENT OF OPPORTUNITY FOR

# A COLLINEAR WAKEFIELD ACCELERATOR FOR A MULTI BEAMLINE SOFT X-RAY FEL FACILITY

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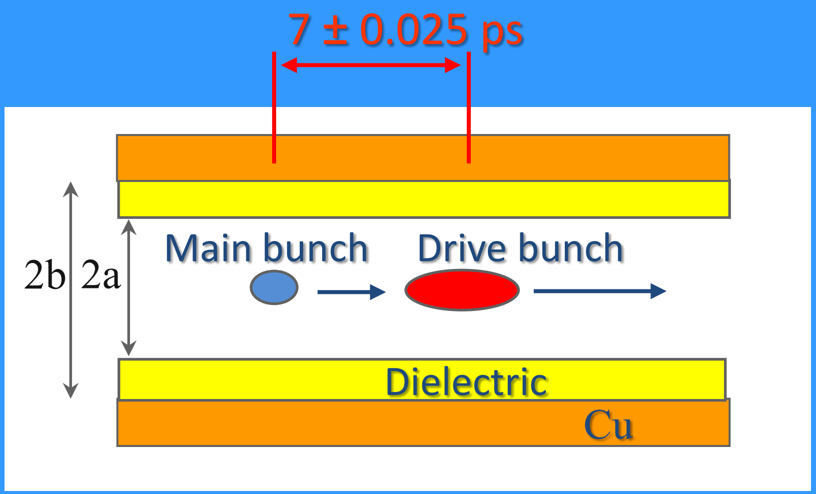
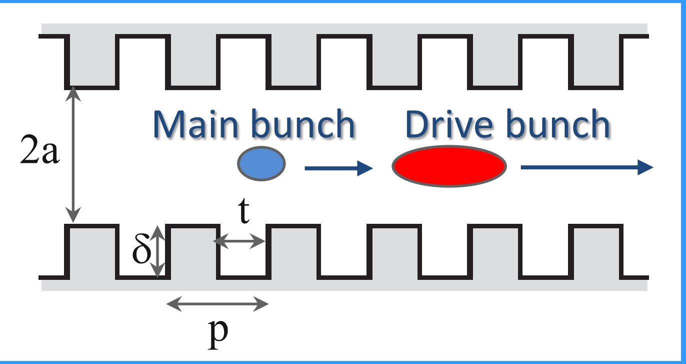
Many hurdles to overcome as you will see…

FEL2014 PSI 25-29 August 2014

# Collinear acceleration in a dielectric-lined or corrugated wall waveguide*

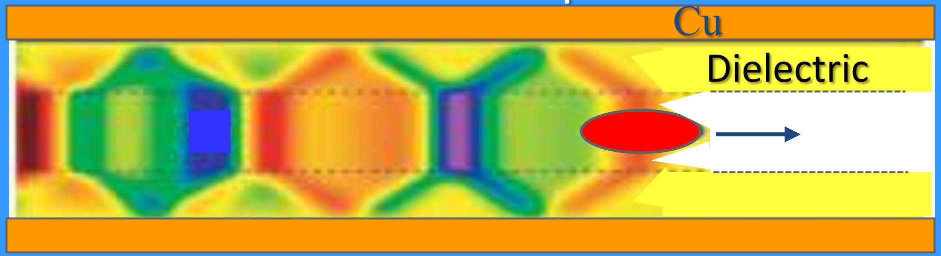



$|E_z| \sim Q/a^2$, $f_0 \sim 300$ GHz




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

Electric field map

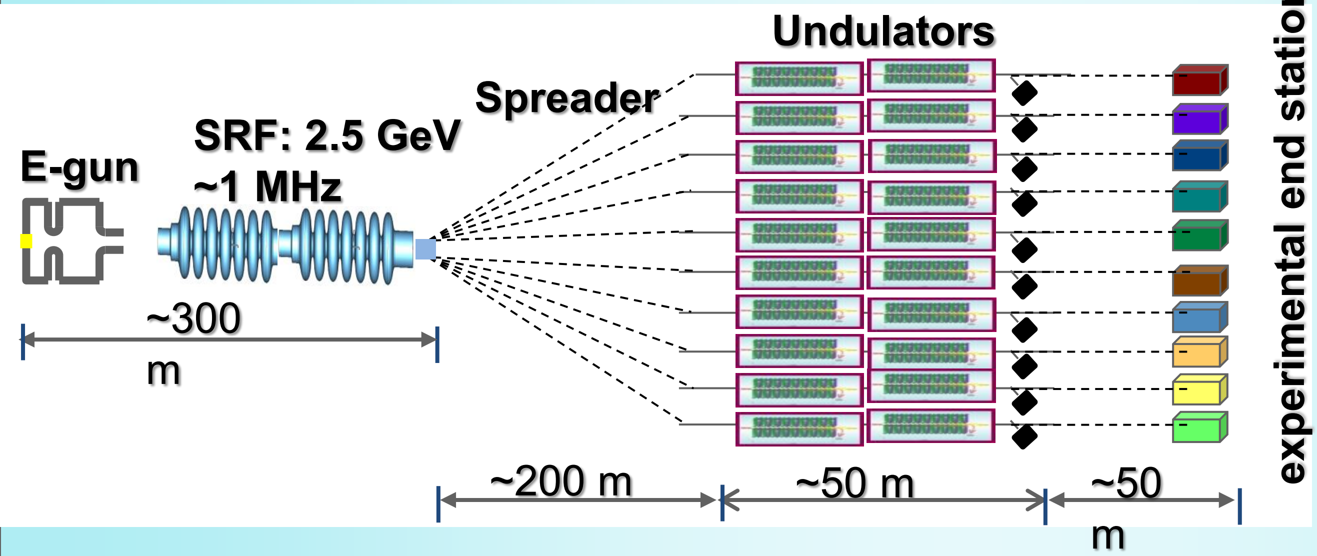



Phase velocity ~ c, group velocity = (0.7-0.9)c

- **Low cost device (likely)**
- **Potential for:**
  - **high field gradients**
  - **high wall plug power efficiency**
  - **high bunch repetition rate**

* W. Gai et al. Phys. Rev. Lett. 61, 2756,1988.

# A concept of a multi-user FEL facility

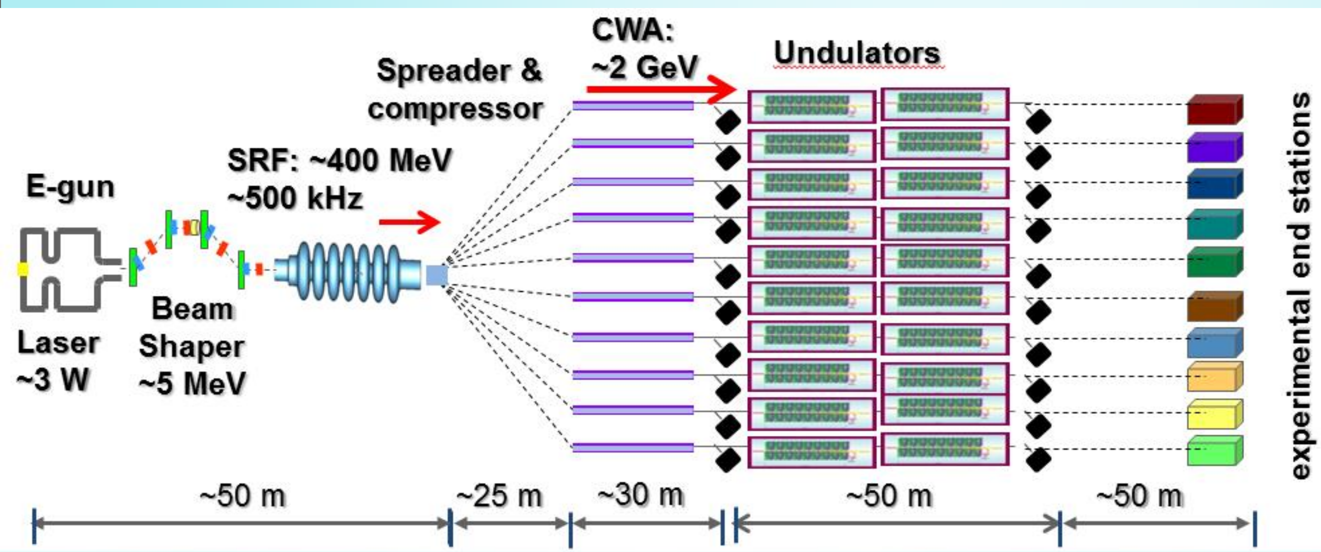



**Based on:**

**High repetition rate SRF linac (NGLS-like)**

⇩

**Collinear Wakefield Accelerator (CWA)**




- Low E spreader
- Up to 100 MV/m
- CWA imbedded in quadrupole wiggler
- Tunable *E* ~ a few GeV
- Tunable $I_{pk}$> 1KA
- Rep. rate ~50 kHz/FEL

**Compact** **Inexpensive** **Flexible**

# Beam shaper and why we need it

- Drive Bunch Shaping
  - Increase Transformer Ratio (Double triangle peak current distribution)
  - Reduce Beam Break Up (Parabolic current distribution)

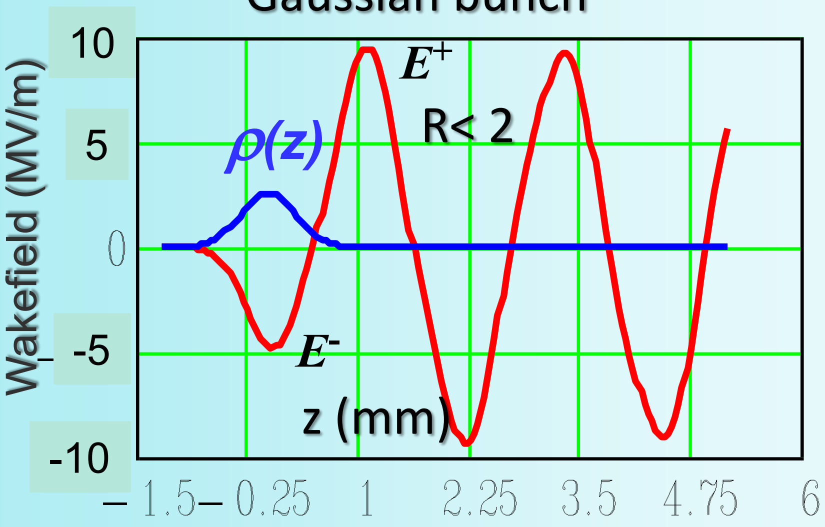
- Main Bunch Shaping
  - Reduce Energy Spread (Trapezoidal current distribution)

- Bunch Shaping Method
  - AWA Bunch Shaping Experiment

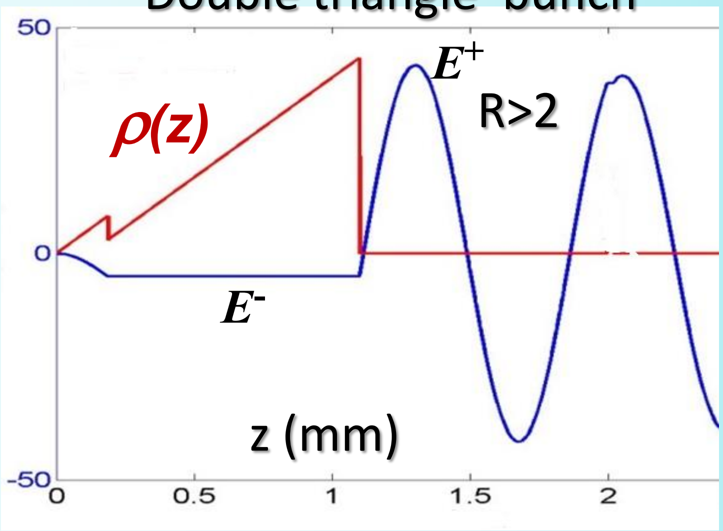
# Road map to a high energy gain acceleration: Transformer Ratio[1-4]

$$R = \frac{E^+}{E^-} = \frac{\text{(Maximum field behind the drive bunch)}}{\text{(Maximum field inside the drive bunch)}}$$

Gaussian bunch



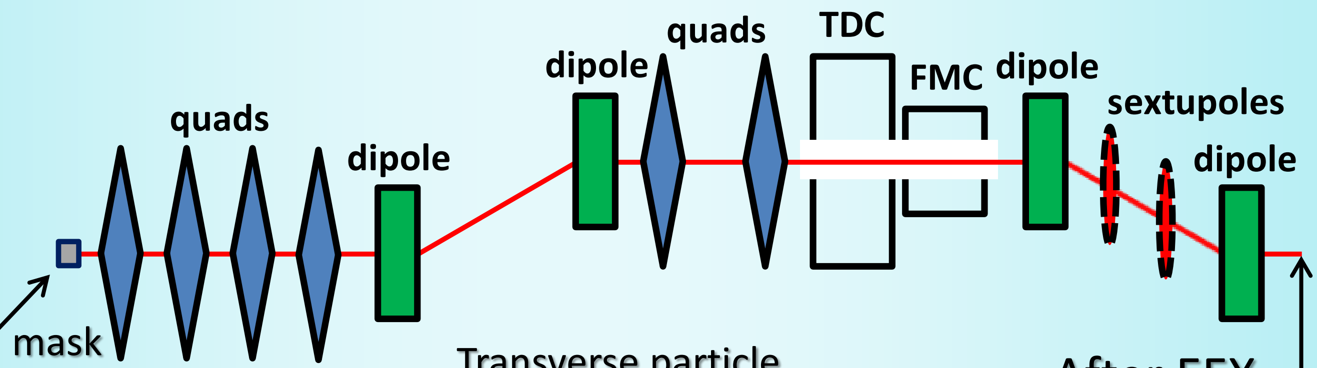

Double triangle bunch

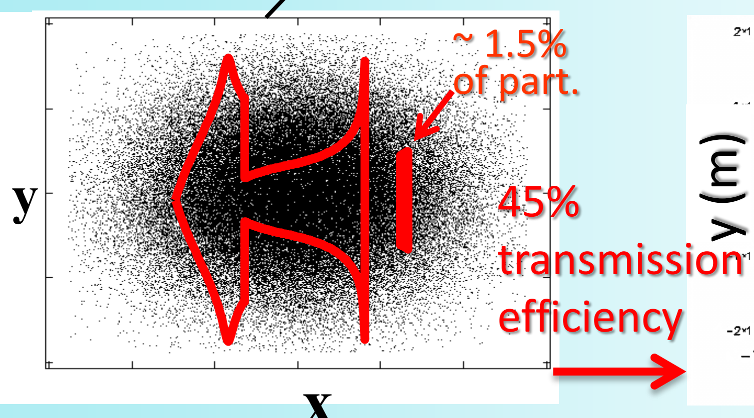


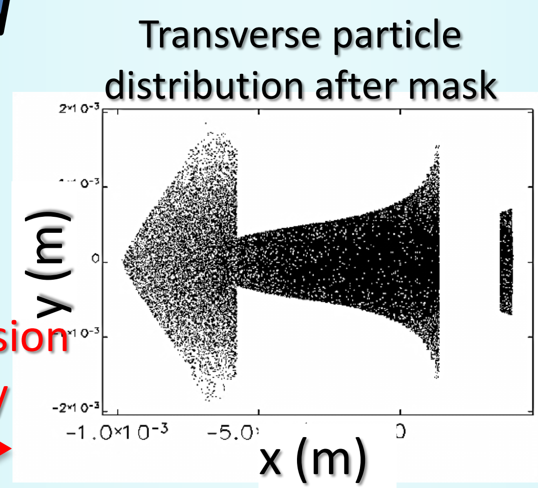

Goal is to extract maximum energy from drive bunch, up to 80%

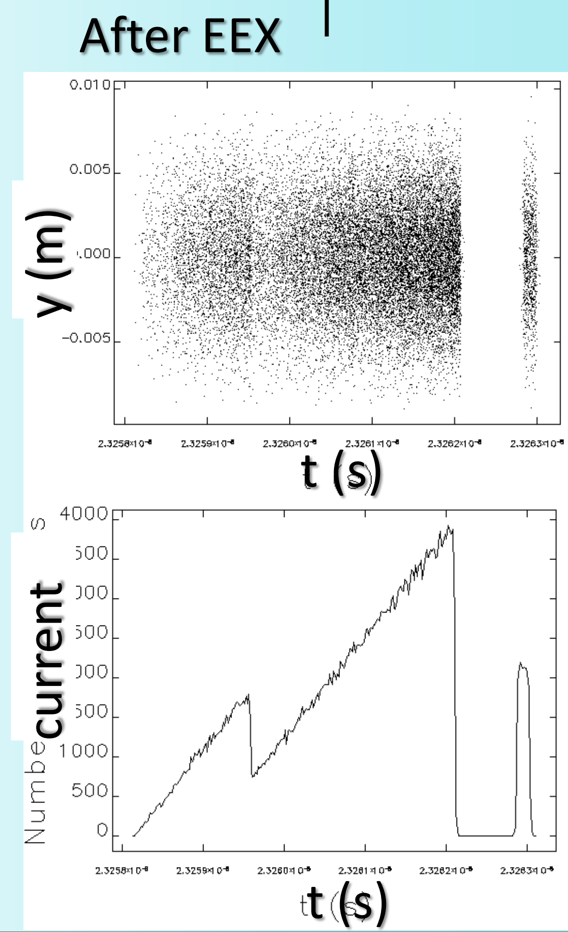

1) Bane et. al., IEEE Trans. Nucl. Sci. NS-32, 3524 (1985).
2) Schutt et. al., Nor Ambred, Armenia, (1989).
3) C. Jing, A. Kanareykin, J. Power, M. Conde, Z. Yusof, P. Shoessow, and W. Gai. Phys. Rev. Lett., v.98, pp. 144801-1,-4 2007.
4) C. Jing, J. G. Power, M. Conde, W. Liu, Z. Yusof, A. Kanareykin, and W. Gai. Phys. Rev ST-Accelerator Beams, v 14, pp. 021302-6, 2011.

# Drive bunch shaping using emittance exchange EEX



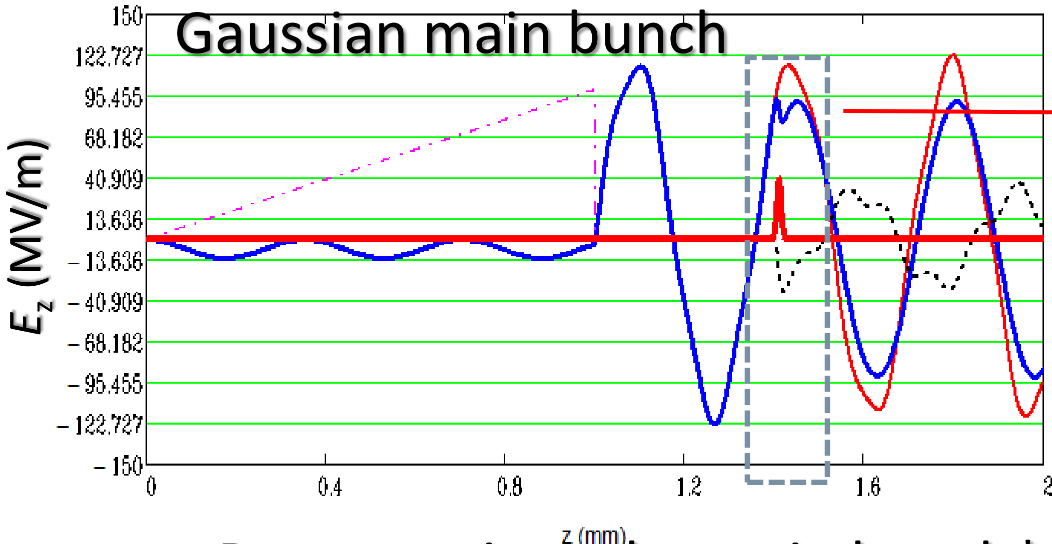



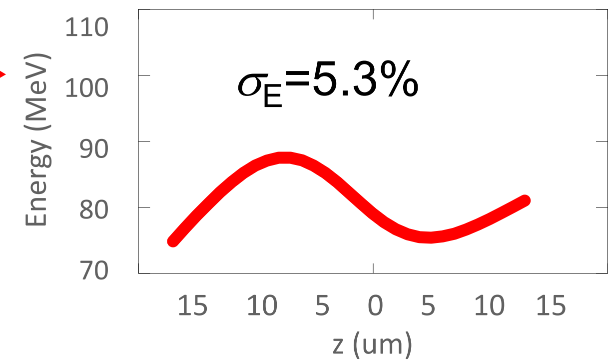

- ~25 kW is deposited on mask at low energy 5 MeV,
- i.e. below threshold energy for isotope production


M. Cornacchia and P. Emma, *Phys. Rev. ST Accel. Beams* 5, 084001 (2002)
P. Emma, *et al, Phys. Rev. ST Accel. Beams* 9, 100702 (2006)
D. Xiang and A. Chao, *Phys. Rev. ST Accel. Beams* 14, 114001 (2011)
Y. –E. Sun, *et al, Phys. Rev. Lett*. 105, 234801 (2010)
B. Jiang, *et al, Phys. Rev. Lett.* 106, 114801 (2011)
B. E. Carlsten, *et al, Phys. Rev. ST Accel. Beams* 14, 084403 (2011)
P. Piot, *et al, Phys. Rev. ST Accel. Beams* 14, 022801 (2011)
Shchegolkov and Simakov, *Phys. Rev. ST Accel. Beams* 17, 041301

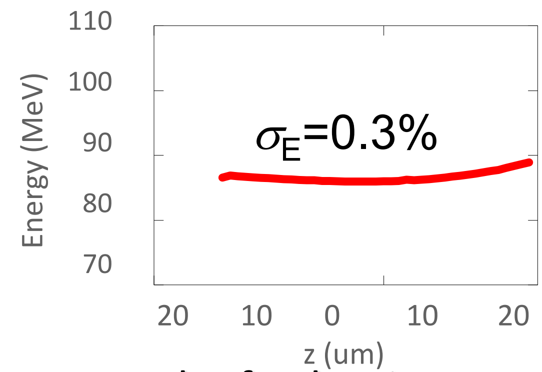
# Main Bunch Shaping

## Reduce correlated energy spread in the main bunch



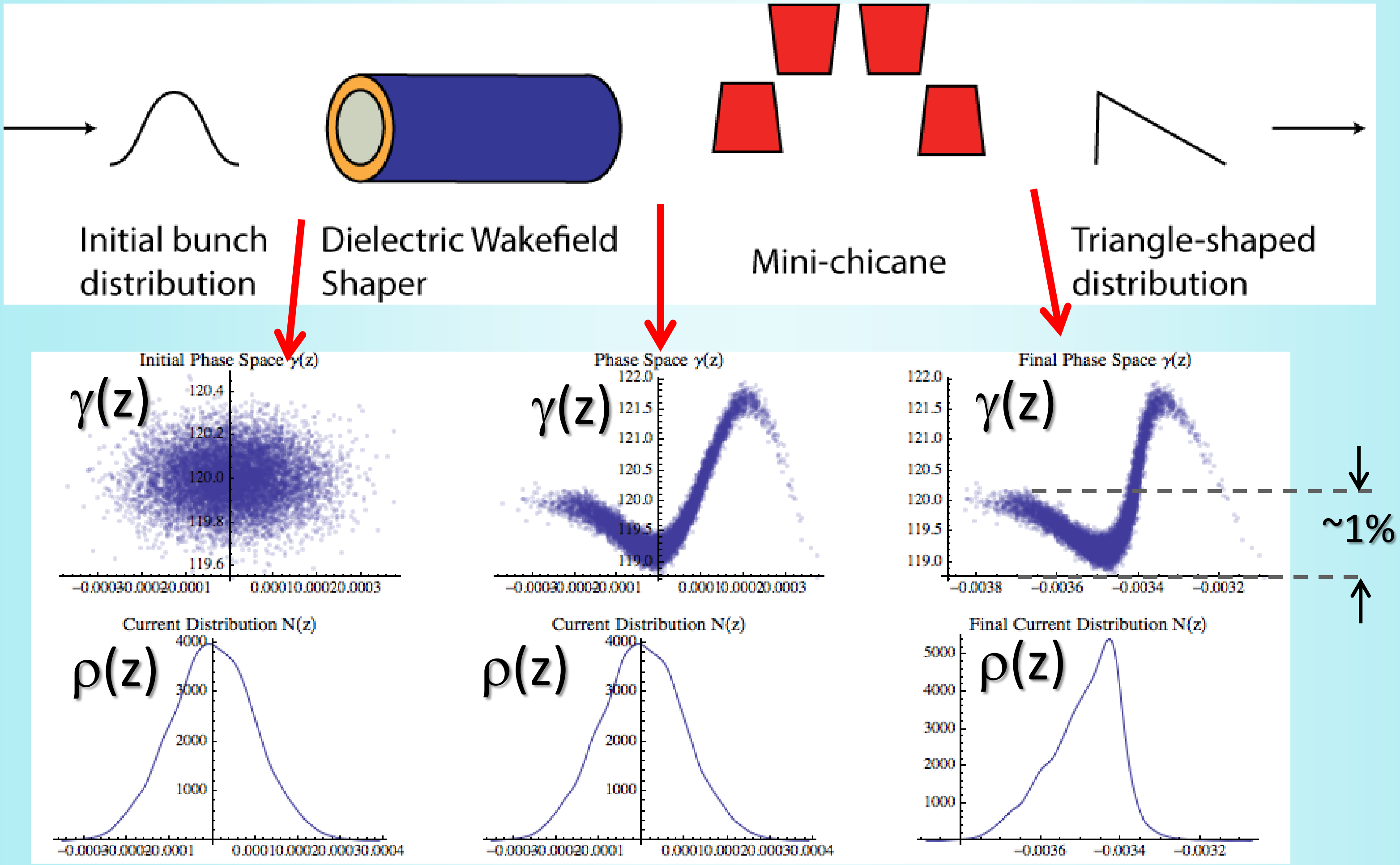

Reverse triangular main bunch*


Can be further improved

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

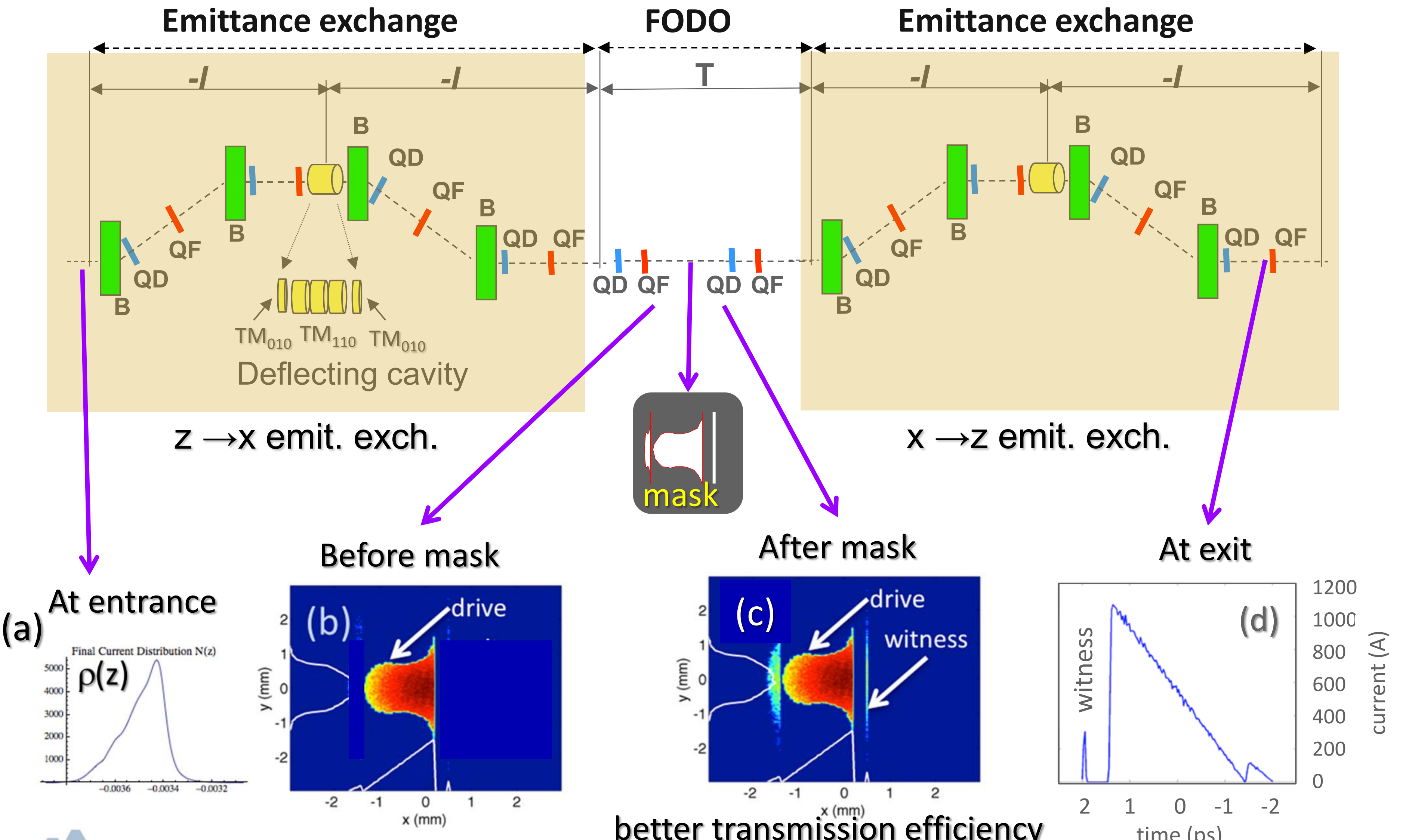
# Drive bunch shaping using self-wakefields*




Bunch shaping with photocathode laser is also an option

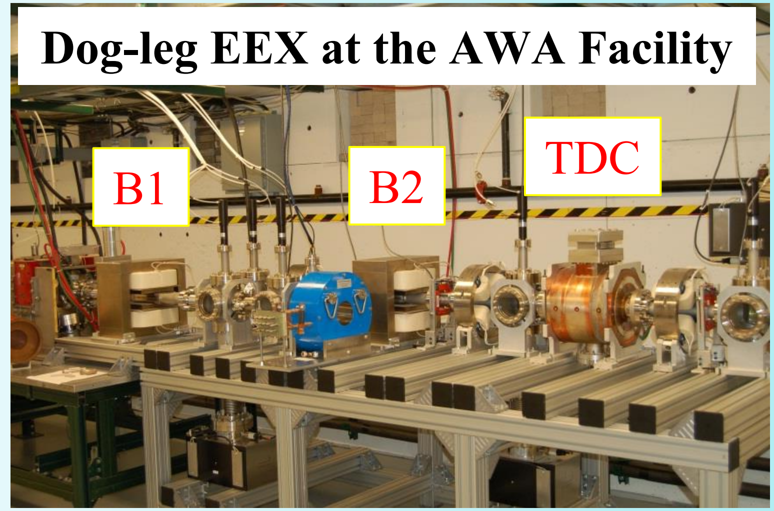
*) G. Andonian, Advanced Accelerator Workshop - AAC 2014, San Jose, (2014)

# Self-wakefield shaping can be made more precise using Double EEX technique

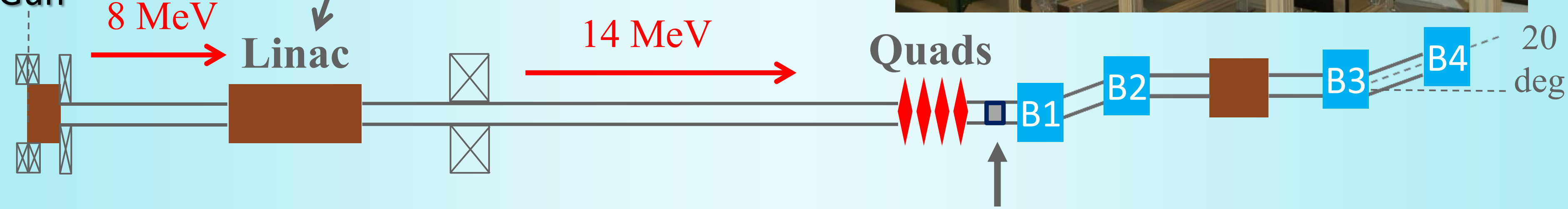


# AWA experiment is focused on bunch shaping demonstration

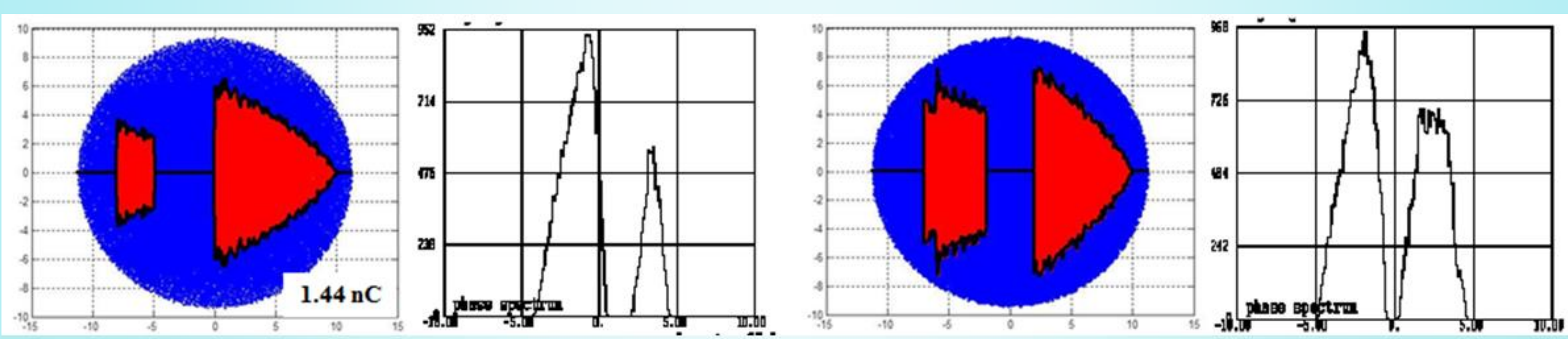
Beamline installation: Fall 2014
First beam: Winter 2015




The Argonne Wakefield Accelerator Facility (AWA) 14 MeV beamline

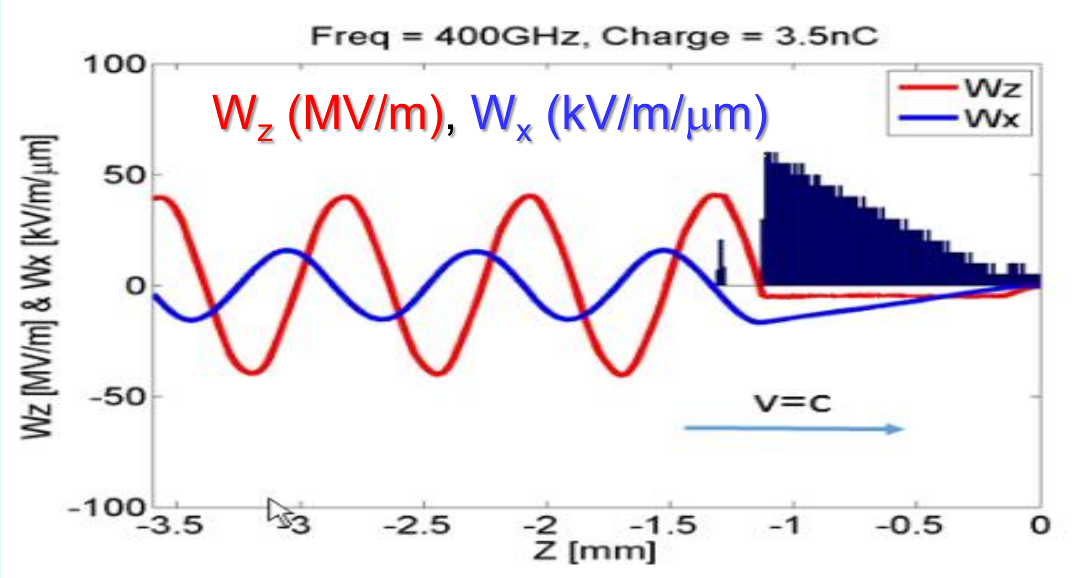



Multiple masks on motorized actuator will be used to study the bunch shaping capability of the dog-leg type EEX beamline



# Drive Bunch Beam Break Up Instability

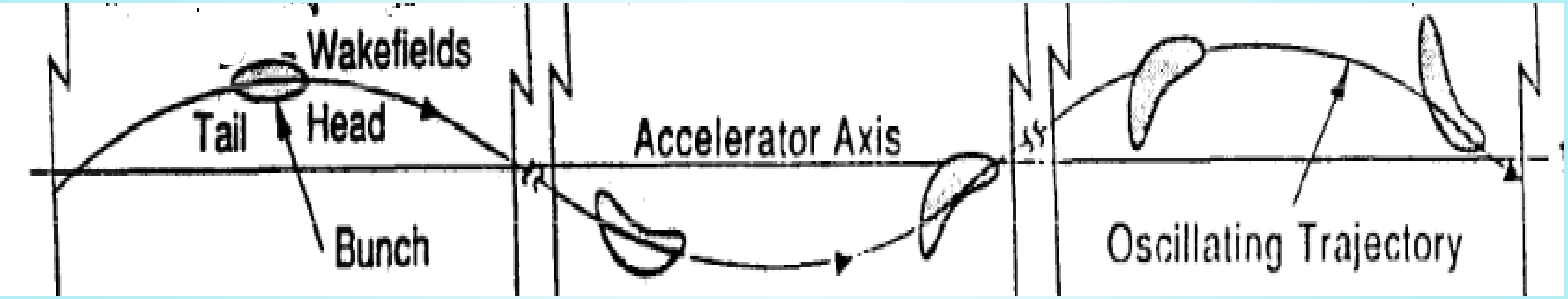
Examples of longitudinal and transverse wakefield functions




$W_z \sim Q/a^2$

$W_\perp \sim Q/a^3$

Cumulative collective instability arises from continuous exposure of tail electrons to transverse wake field*

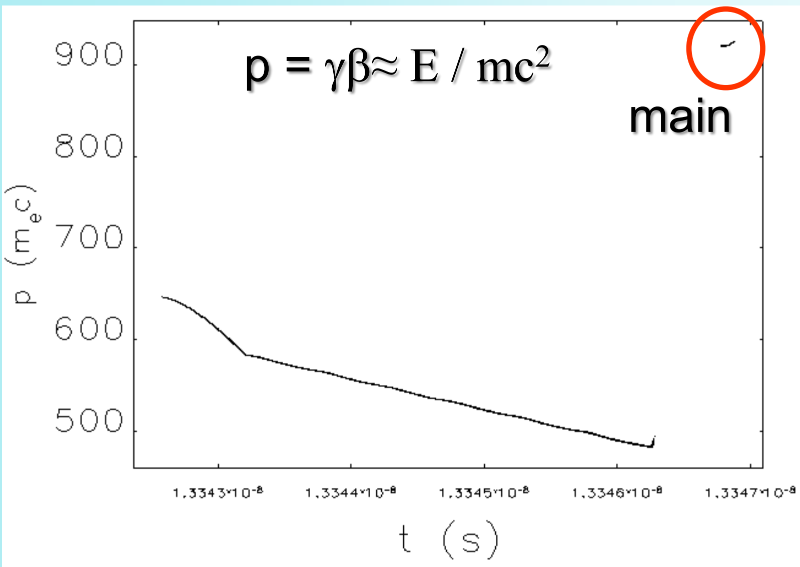


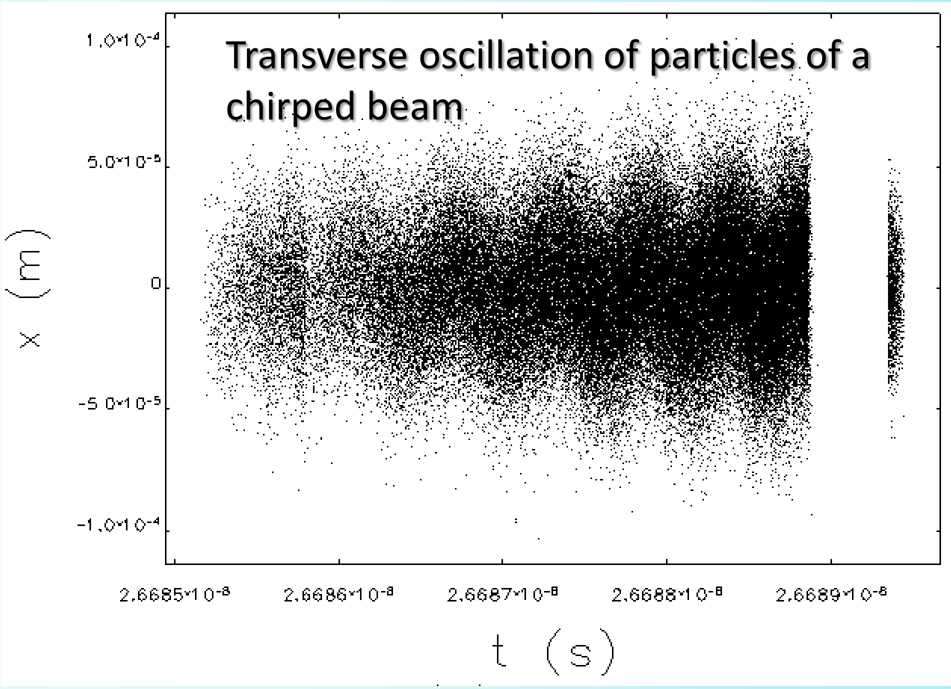

*) A.Chao, "Physics of collective beam instabilities in high energy accelerators", New York: Wiley.

# Balakin-Novokhatsky-Smirnov (BNS) damping of BBU

- Produce "chirp" in the betatron tune along the electron bunch using the energy "chirp", and
- Force tail to oscillate faster than head, thus averaging the impact of transverse wake fields.

After 4 m of DWA

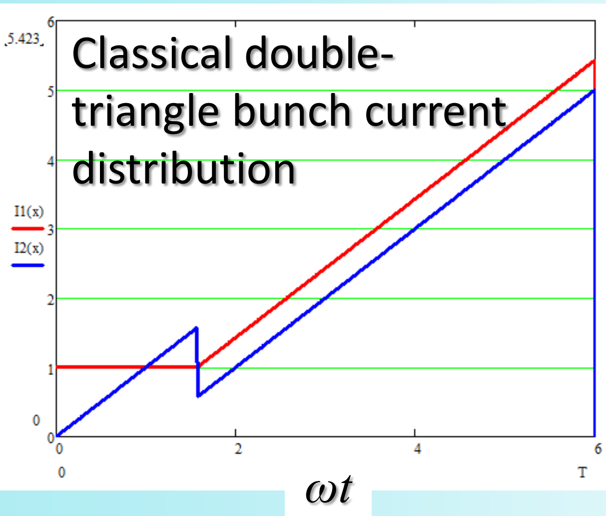


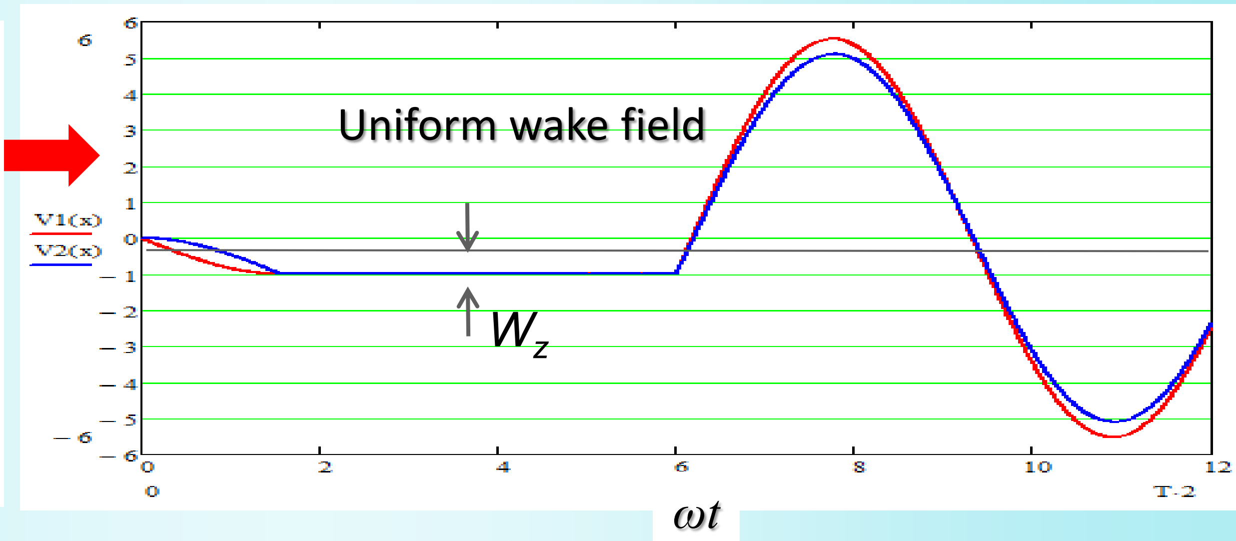




Initial energy chirp ~15 % (peak-to-peak)

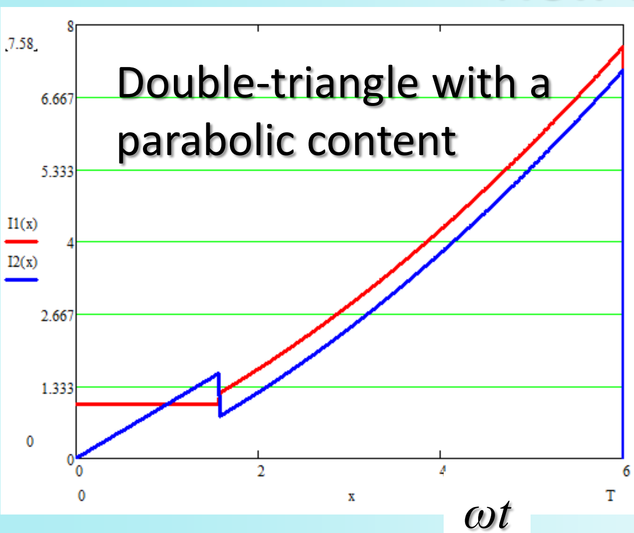
Particles of different energies have different oscillation periods in the FODO lattice

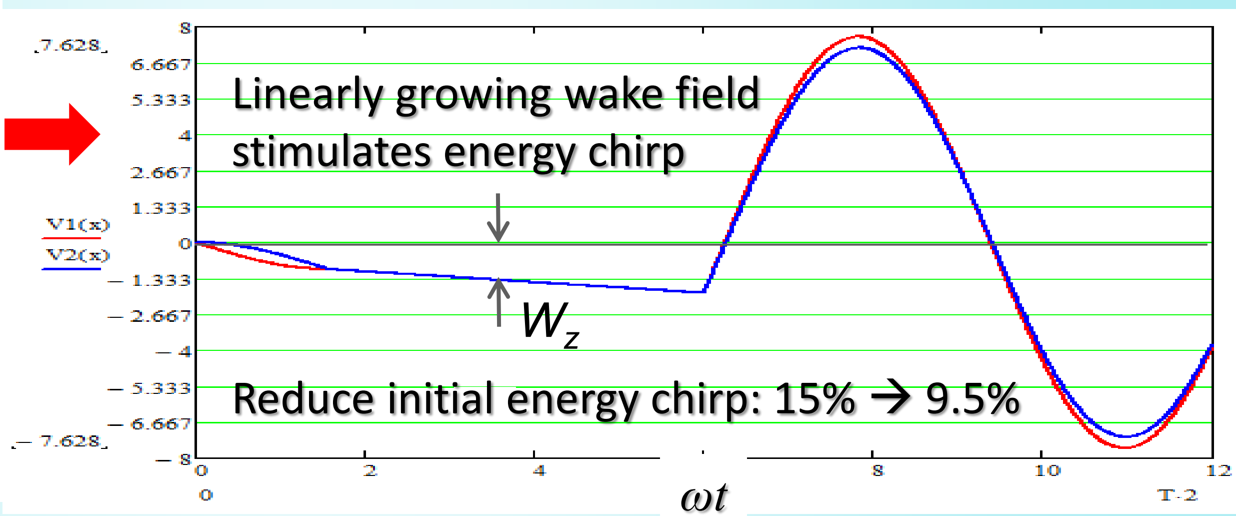
# Customizing the drive bunch current to reduce the required initial energy chirp



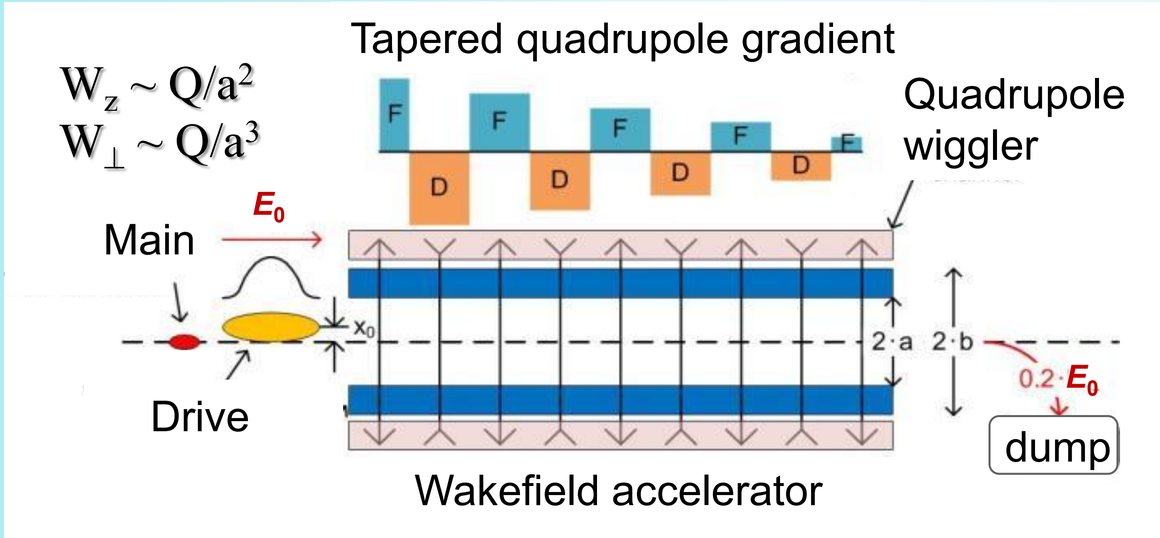




## New bunch current distribution



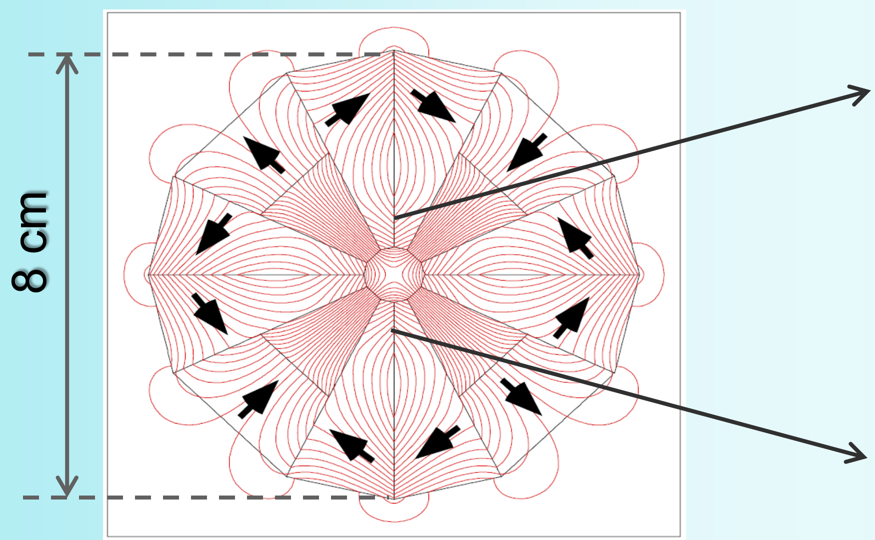



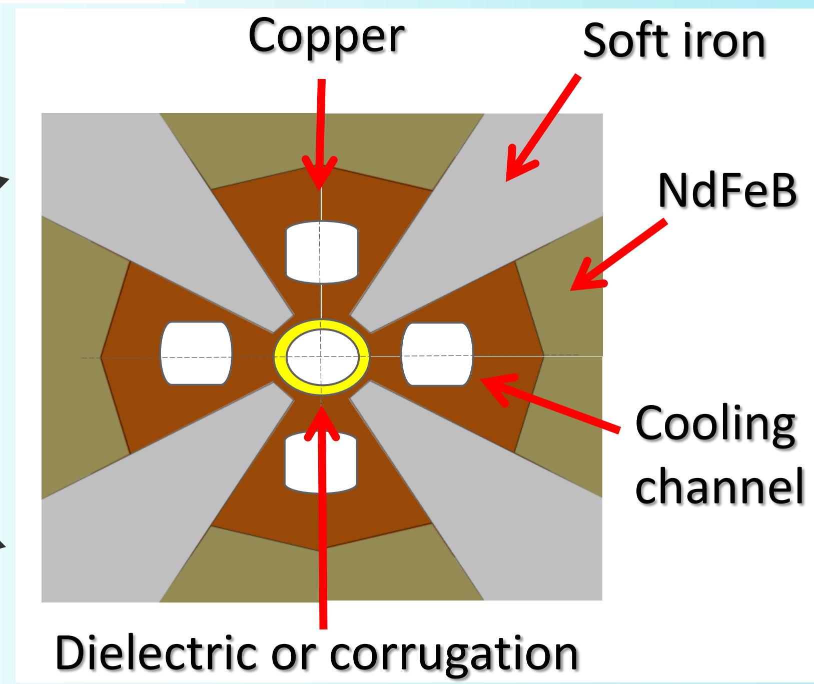
# Estimates using two particle BBU model*




Dielectric tube with copper cladding imbedded into *quadrupole wiggler*

High gradient permanent magnet quad

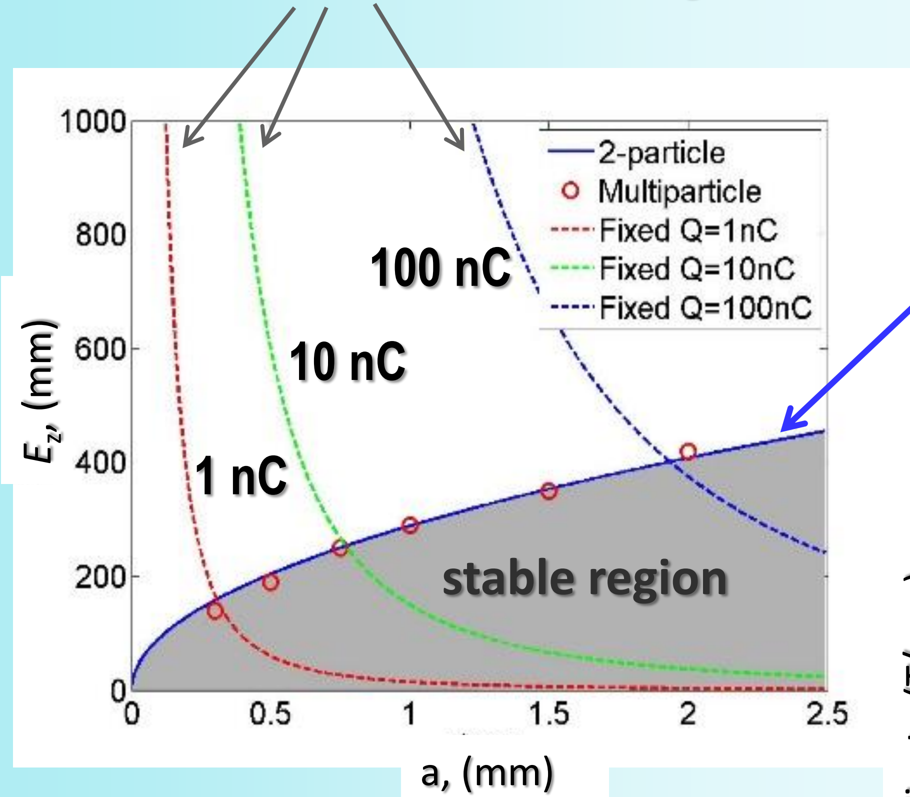



*) C Li et al., to be published

# Maximum attainable energy gain*

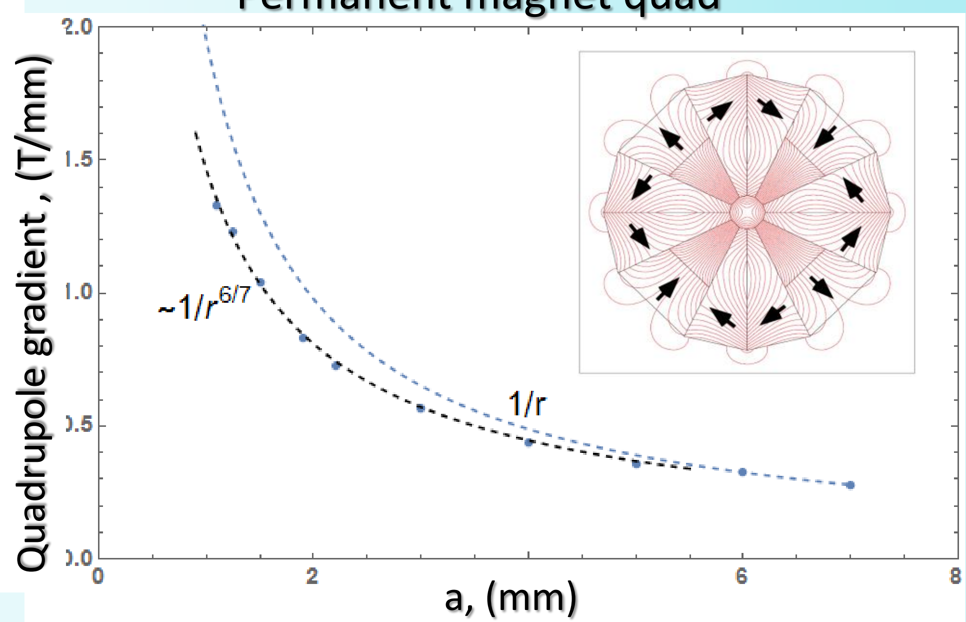
**Field scales ~ 1/$a^2$ when BBU is ignored**




**Field scales as ~ $a^{1/2}$ (BBU).**

**This envelope is defined by the attainable quadrupole gradient at a given bore radius.**

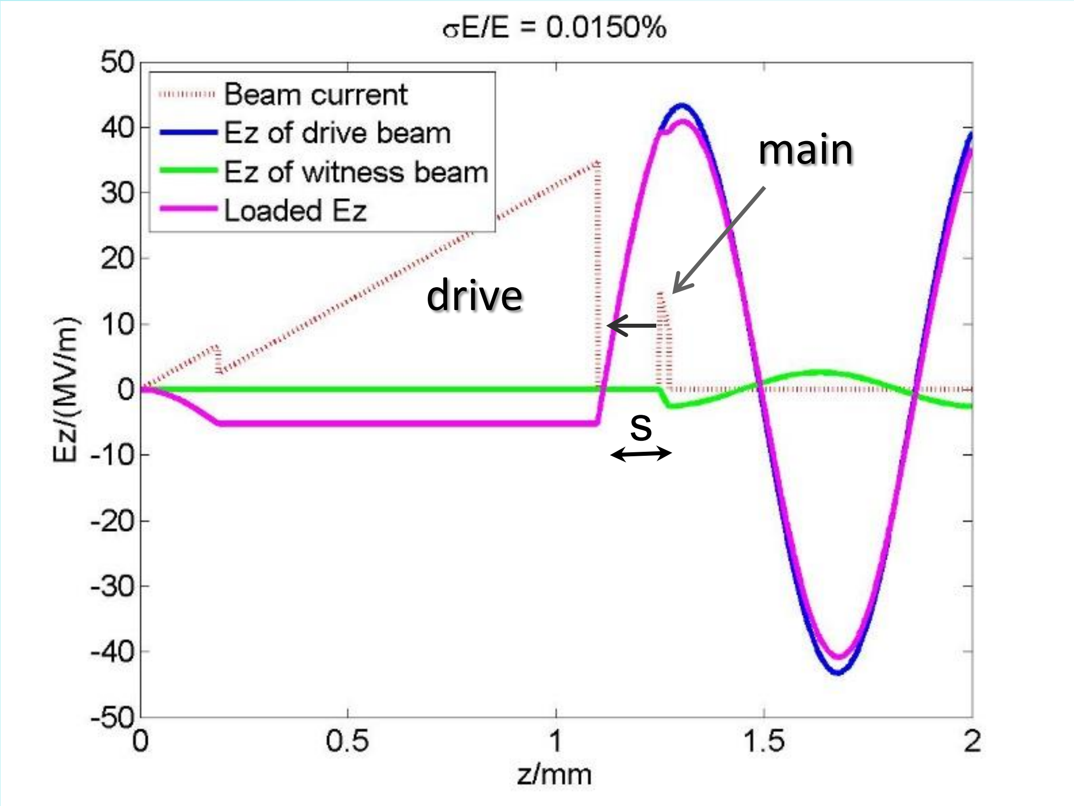
Permanent magnet quad**




***) Gaussian peak current distribution of the drive bunch is assumed**

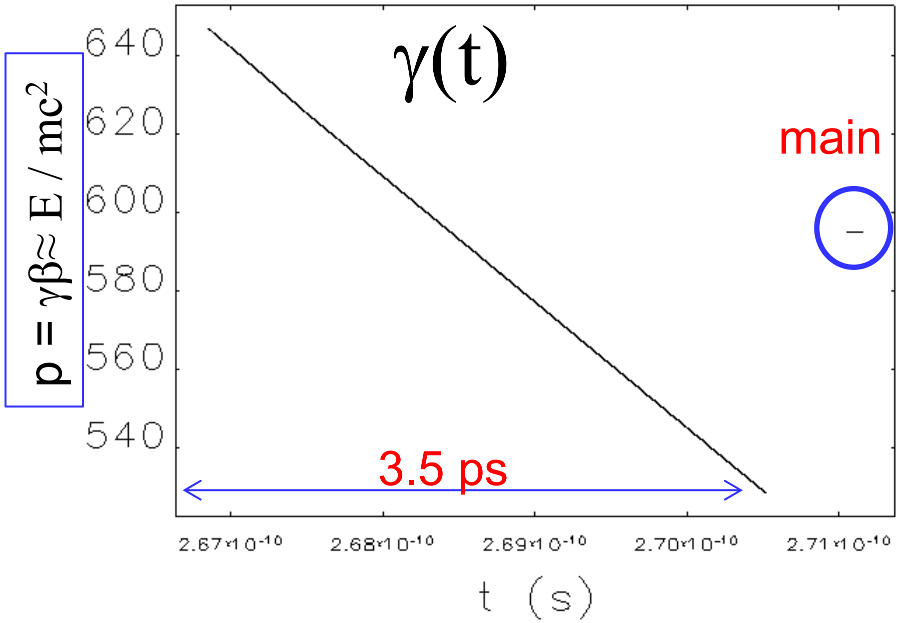
**) Abliz, Vasserman, Zholents, to be published

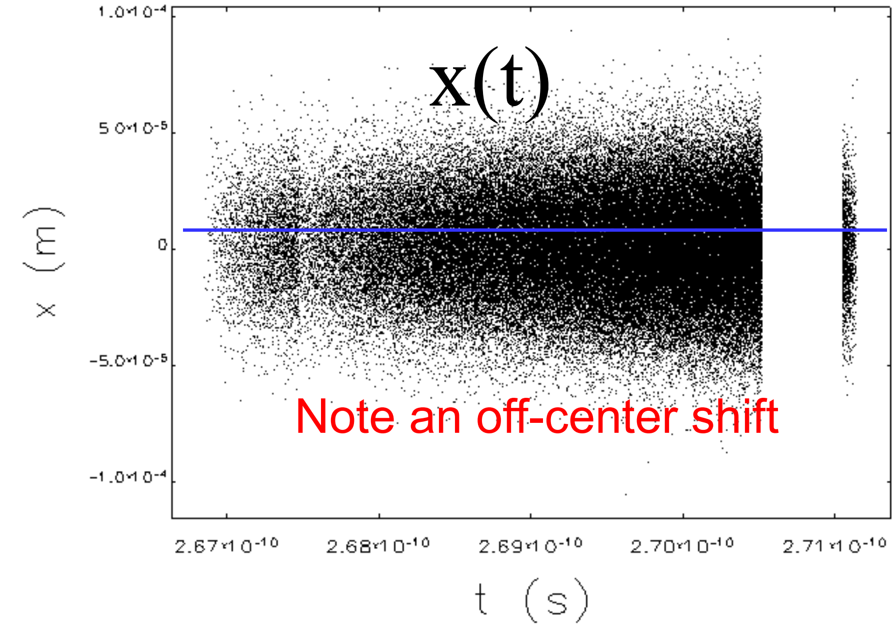
# Slippage effect

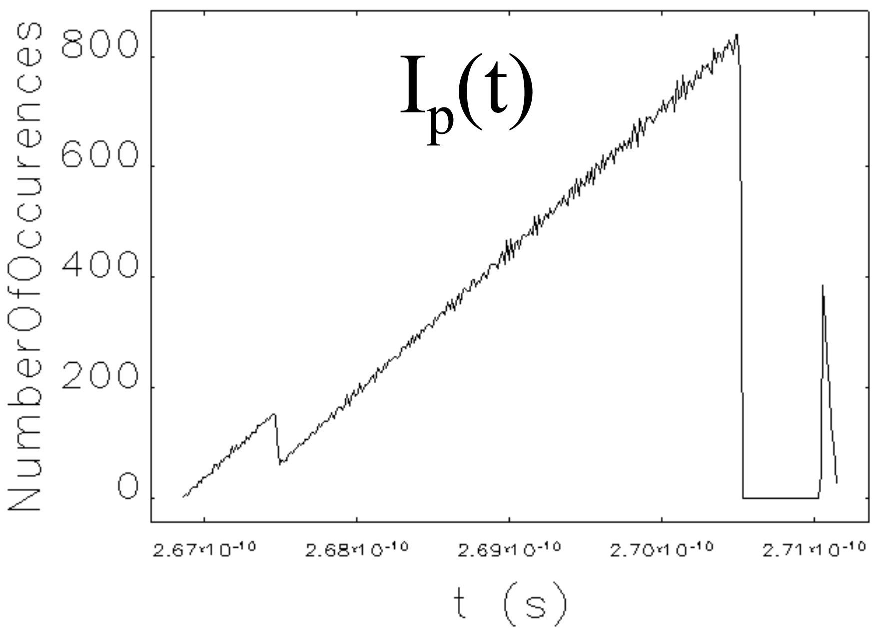



Drive-to-main bunch separation decreases because of their different energies

# Illustration

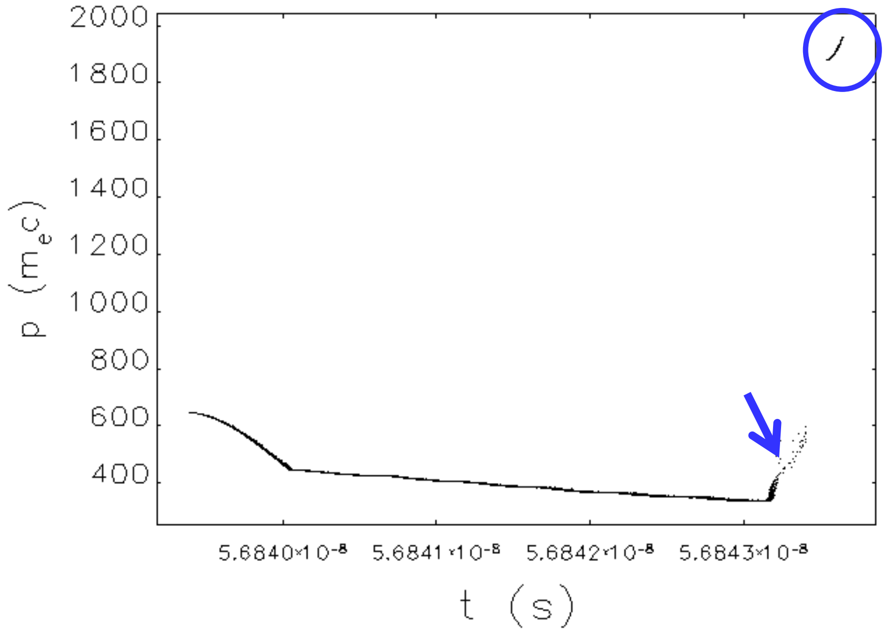


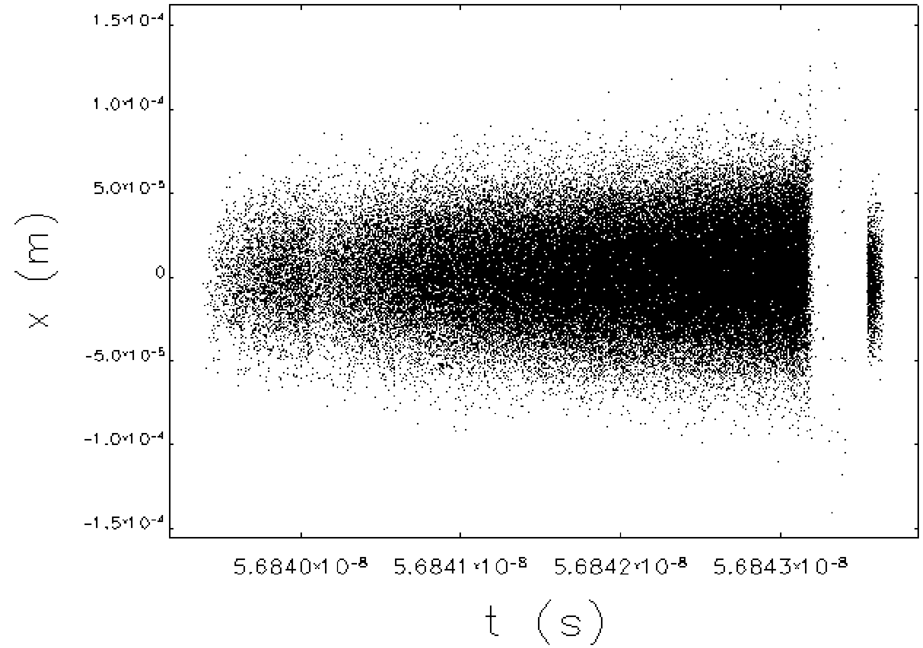




0 m

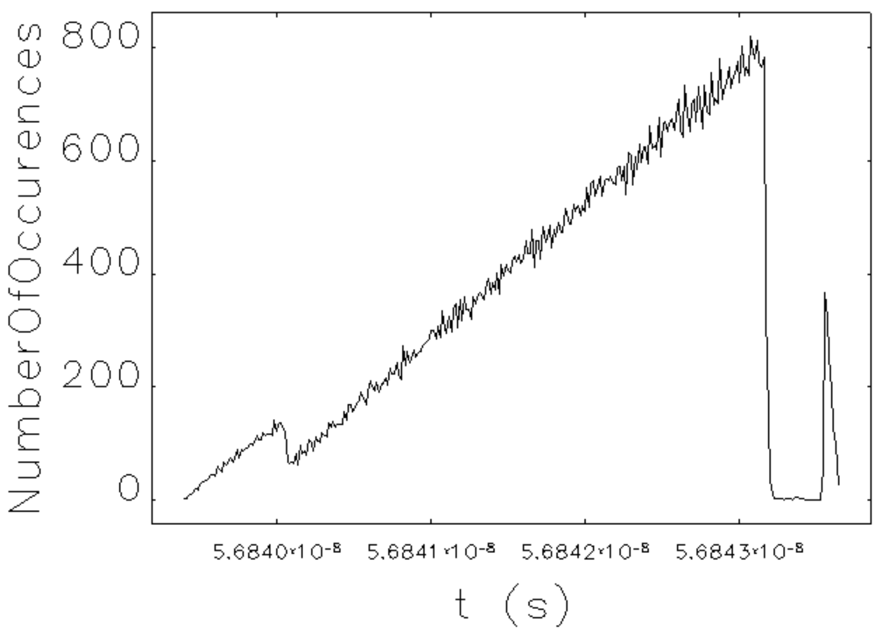
Space charge effects are not included



2000
1800
1600
1400
1200
1000
800
600
400
p (m_e c)
5.6840×10-8 5.6841×10-8 5.6842×10-8 5.6843×10-8
t (s)

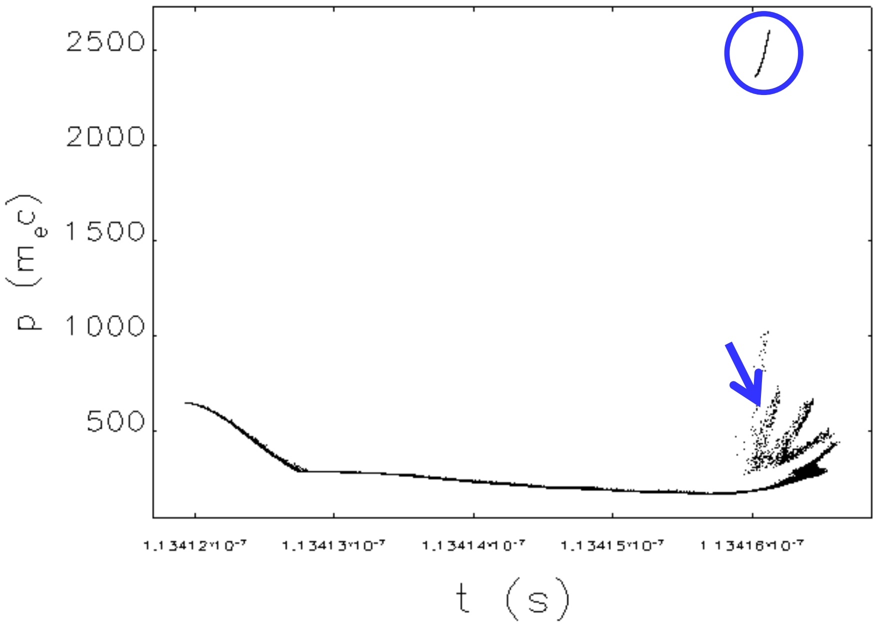



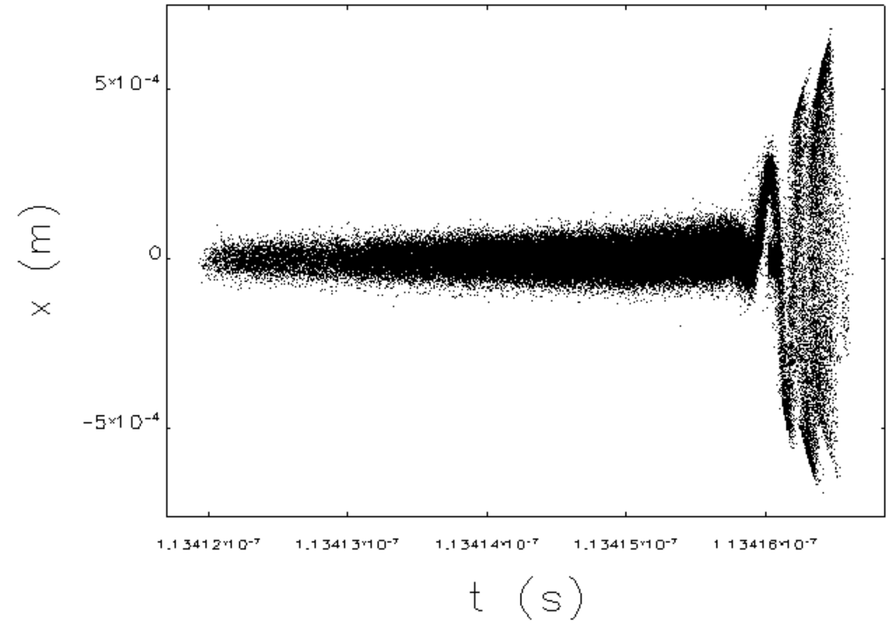
1.5×10-4
1.0×10-4
5.0×10-5
0
-5.0×10-5
-1.0×10-4
-1.5×10-4
x (m)
5.6840×10-8 5.6841×10-8 5.6842×10-8 5.6843×10-8
t (s)

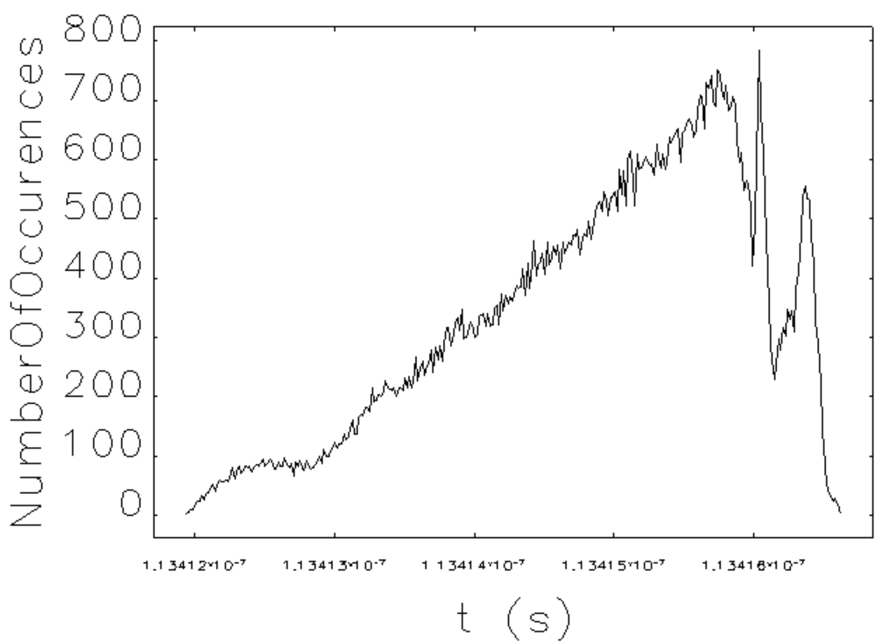



800
600
400
200
0
NumberOfOccurences
5.6840×10-8 5.6841×10-8 5.6842×10-8 5.6843×10-8
t (s)


17 m



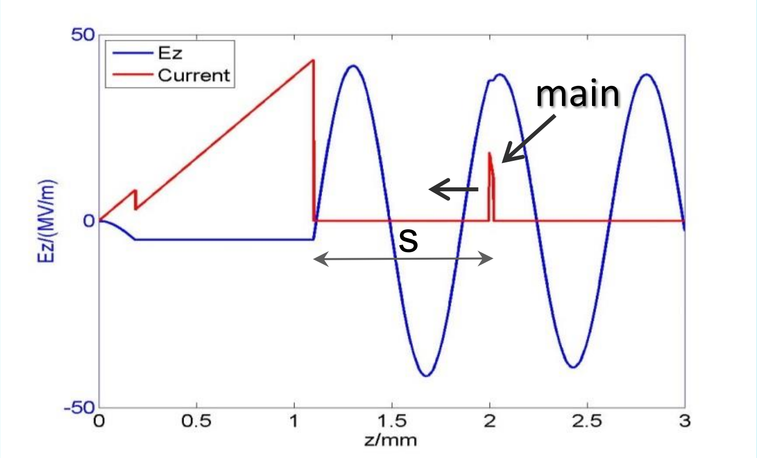




# 34 m

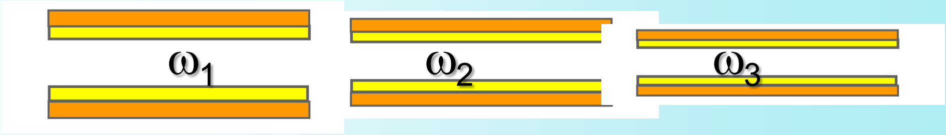
- the drive beam tail decelerates,
- gets a lag, and
- sees the wake’s accelerating field

# Problem mitigation

- Move main bunch to second maximum (can be difficult if done using the mask)




- Make adaptive frequency channel and always keep main bunch at or near to the maximum (easy)



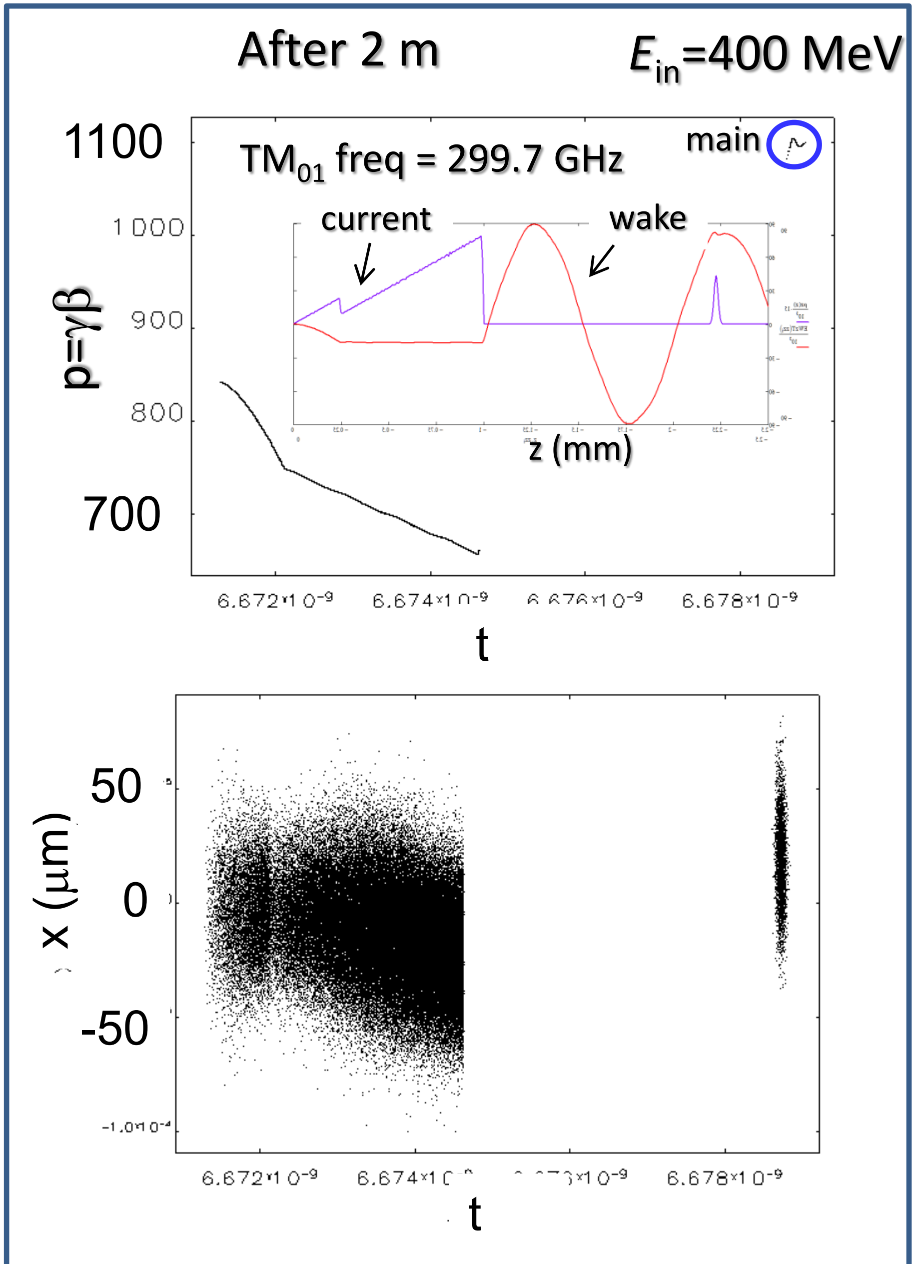

$\omega_1 < \omega_2 < \omega_3$

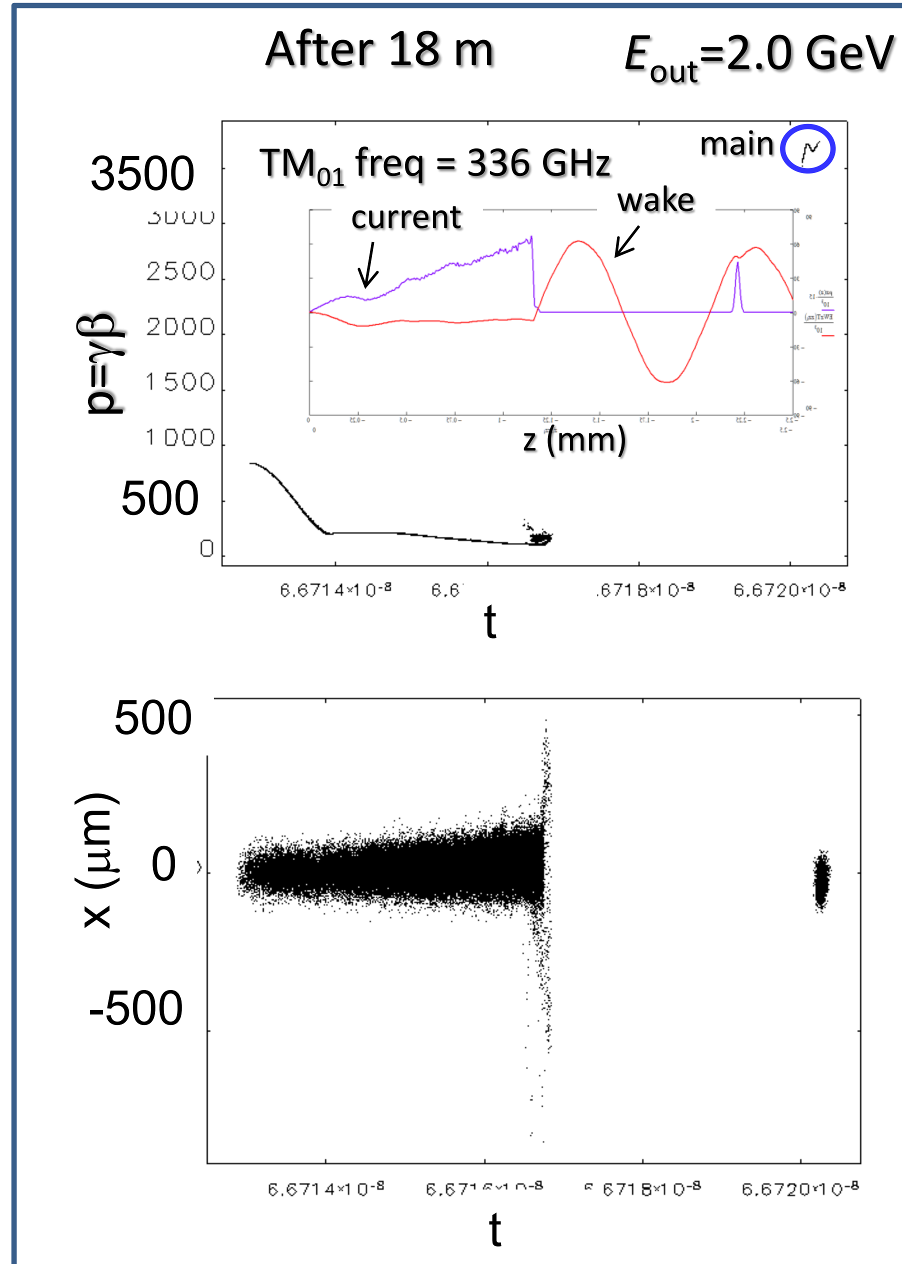
- Use drive bunch with higher energy (affects facility cost and energy efficiency)

# Study cases

| | Case I | Case II |
|---|---|---|
| Fundamental mode Freq. (GHz) | 400 | 300 |
| ID (mm), OD(mm), Length(cm) | 1.5, 1.59, 10 | 2, 2.12, 10 |
| Drive bunch charge (nC) | 3.5 | 8 |
| Double triangular bunch length (mm) | 1 | 1 |
| Drive/main bunch energy (MeV) | 300 | 400 |
| Bunch rep. rate (kHz) | 100 | 50 |
| Peak Accelerating Field (MV/m) | 42 | 90 |
| Power dissipation without and with THz field coupler per unit length (W/cm) | 19, 5.4 | 54, 10.8 |
| Transformer ratio | 8 | 5 |
| Main bunch charge (pC), length (μm) | 50, 5 | 250, 10 |
| Total DWA length (m) | ~40 | ~20 |
| Drive beam use, dump energy (MeV) | 80%, ~ 70 | 80%, 80 |
| Drive beam to main beam efficiency (%) | 8.6 | 15.5 |
| Main beam energy gain (GeV) | 1.5 | 1.6 |

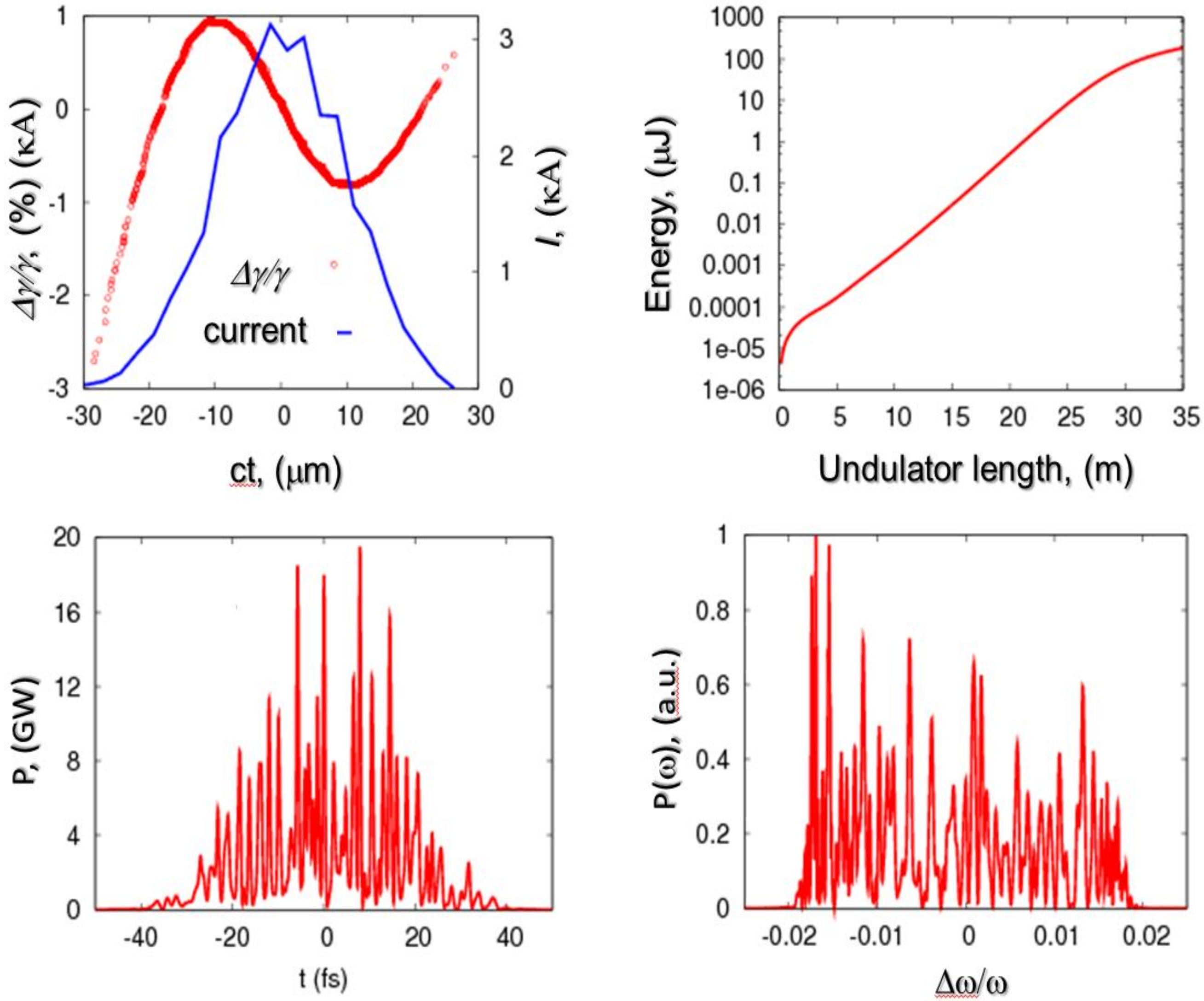
# Result of tracking for 8nC drive and 250 pC main bunch



# 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 |



# Summary

- High repetition-rate, soft X-ray FEL user facility
  - 10 CWAs linacs driven by a single 400 MeV SRF linac
  - 10 FEL lines @ 50 kHz bunch repetition rate
  - Compact, inexpensive, and flexible
- Progress
  - Drive bunch shaping (triangular + quadratic component)
  - Control of beam breakup instability
    - Quadrupole wiggler, adaptive frequency channel
  - Small “main bunch” energy spread
- Future development
  - improving transmission efficiency through the mask – important
  - accounting for space charge effects
  - maintaining trajectory straightness (~ 1 μm) - vital
  - modular design: quadrupole wiggler, vacuum chamber, heat load/ cooling , BPMs, rf couplers, etc. - critical