WAKEFIELD ACCELERATOR BASED COMPACT FEL LIGHT SOURCE

Alexander Zholents

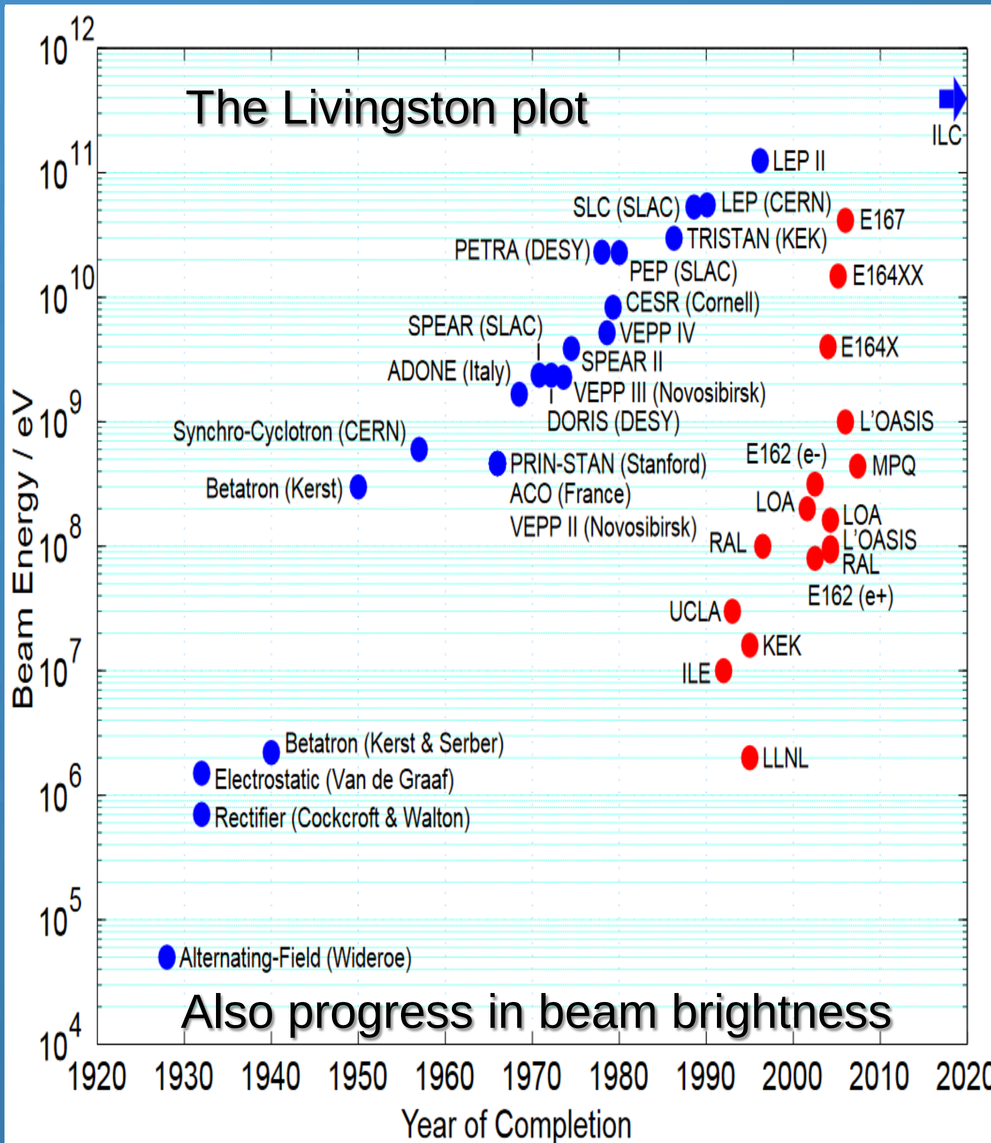
Argonne National Laboratory

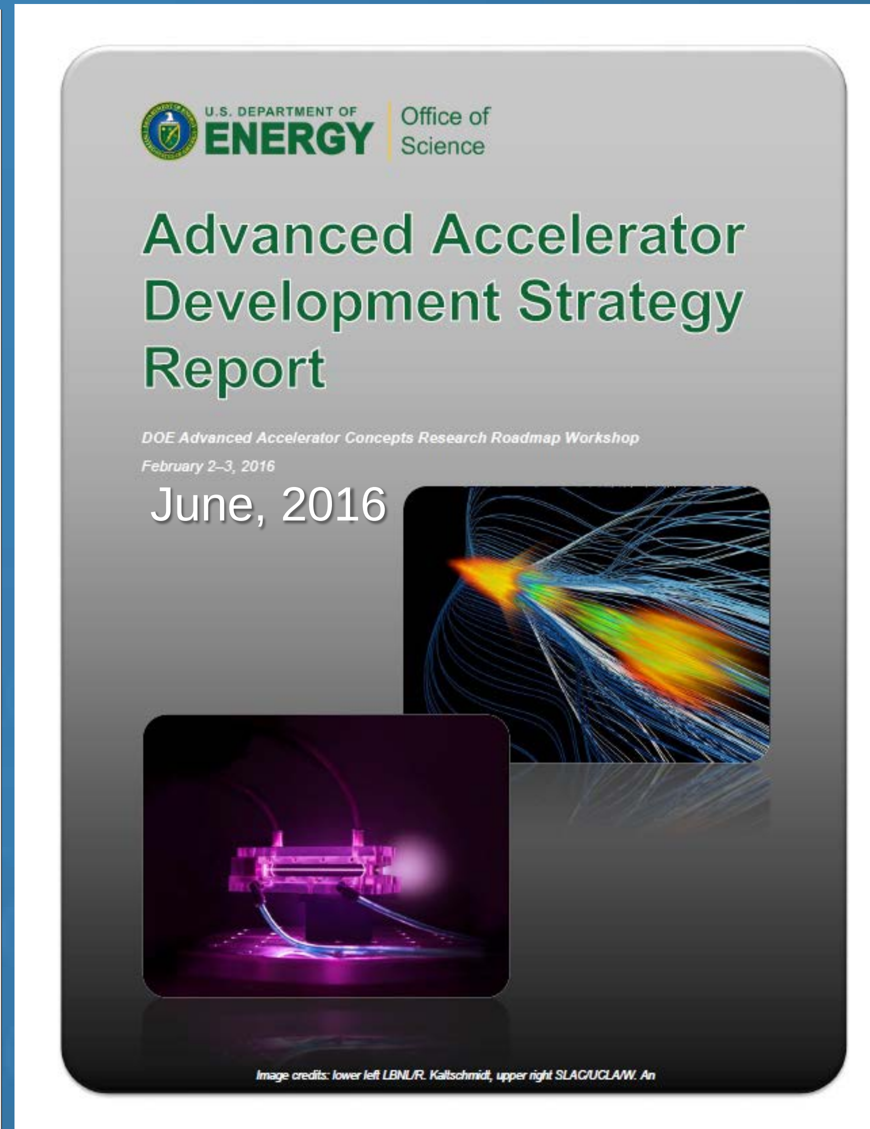
Seminar at Fermi National Accelerator Laboratory, December 13, 2016.

- Co-authors :
  - S. Doran, W. Gai, J. Power (***HEP/ANL***), W. Berg, Yu. Ivanyushenkov, R. Lindberg, Y. Sun, E. Trakhtenberg, I. Vasserman (***APS/ANL***), S. Baturin, C. Jing, A. Kanareykin, N. Strelnikov (***Euclid Techlabs***), D. Shchegolkov, E. Simakov (***LANL***), P. Piot (***NIU/Fermilab***), Q. Gao, C. Li (***Tsinghua University, China***), G. Ha (***Pohang University, Korea***)

A new era in accelerator development

ENGINE FOR DISCOVERIES




U.S. DEPARTMENT OF ENERGY | Office of Science

Advanced Accelerator Development Strategy Report

DOE Advanced Accelerator Concepts Research Roadmap Workshop

February 2–3, 2016

June, 2016

Image credits: lower left LBNL/R. Kaltschmidt, upper right SLAC/UCLA/W. An

http://www.ischebeck.net/media/Accelerator%20Physics/Advanced%20Accelerator%20Concepts/Livingston%20Plot/slides/Livingston%20without%20plasma%20accelerators%202007.html

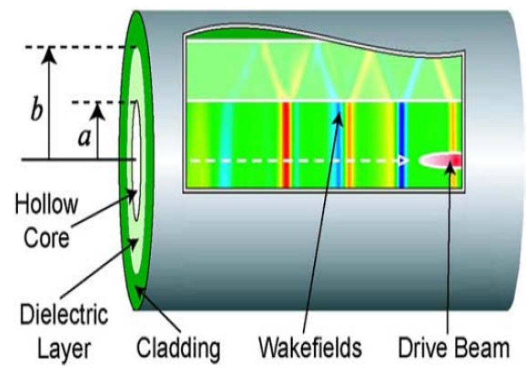
http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Advanced_Accelerator_Development_Strategy_Report.pdf

NEW ACCELERATOR TECHNOLOGIES

build the particle accelerator of the 21st century

LASER DRIVEN PLASMA WAKEFIELD ACCELERATOR	BEAM DRIVEN PLASMA WAKEFIELD ACCELERATOR	STRUCTURE-BASED WAKEFIELD ACCELERATOR

nature COMMUNICATIONS

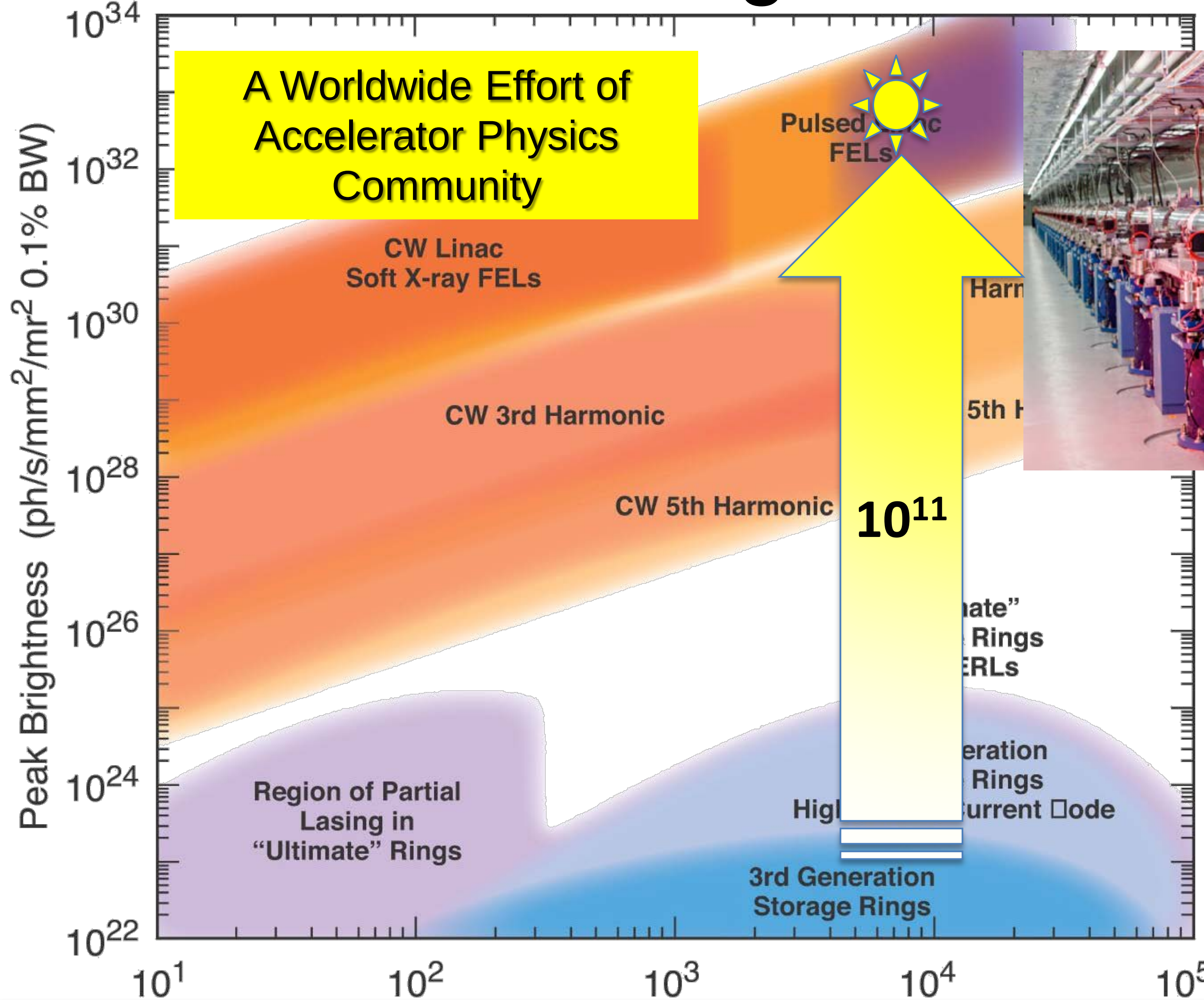


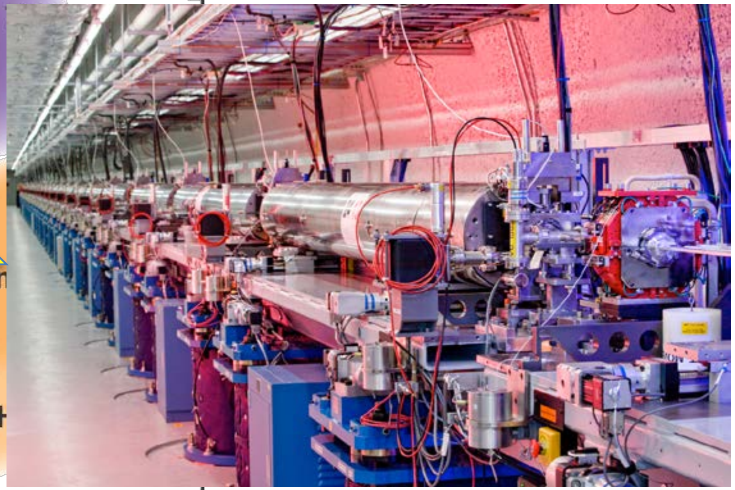
Many synergies across the technologies

FEL: LCLS Right Out of the Box

April 10, 2009

A Worldwide Effort of Accelerator Physics Community

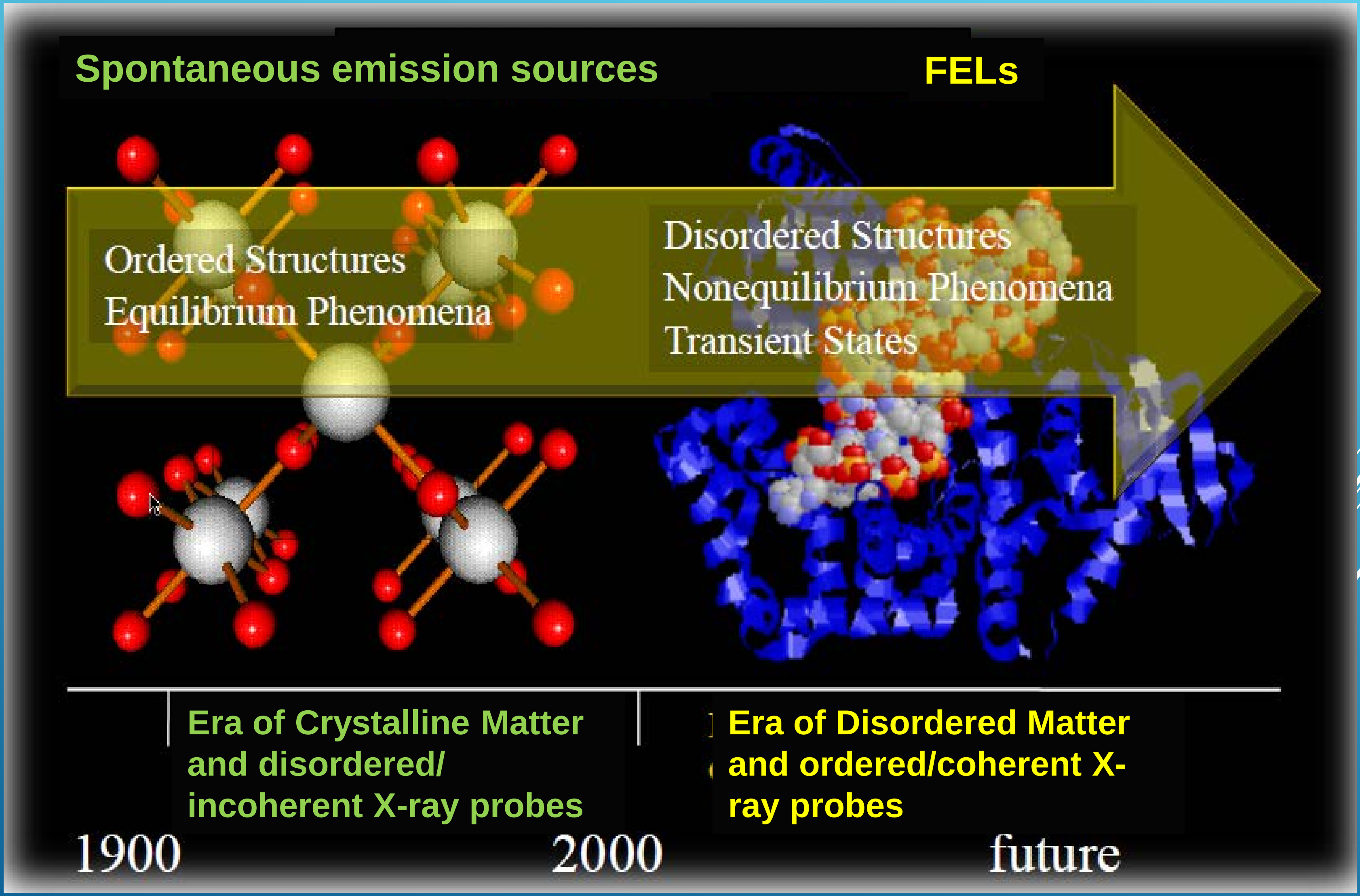




FLASH/DESY,
LCLS/SLAC,
FERMI/Trieste,
SACLA/Spring8

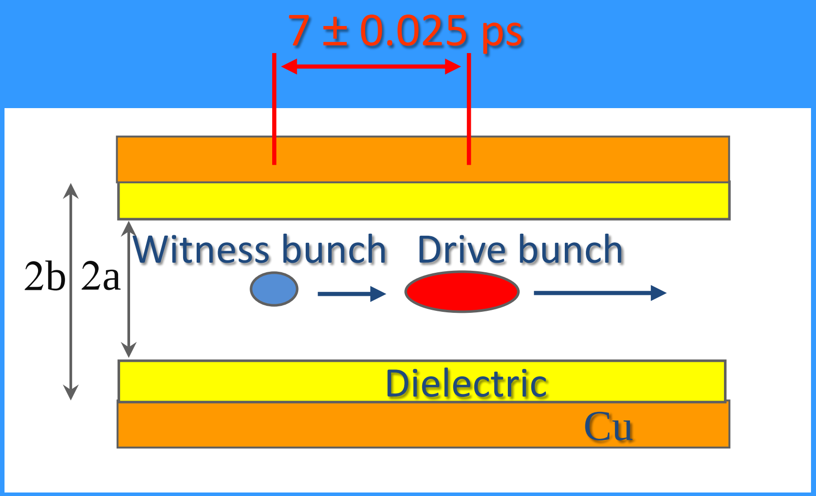
In commissioning: Pohang/Korea, in construction: PSI/Switzerland, XFEL/DESY

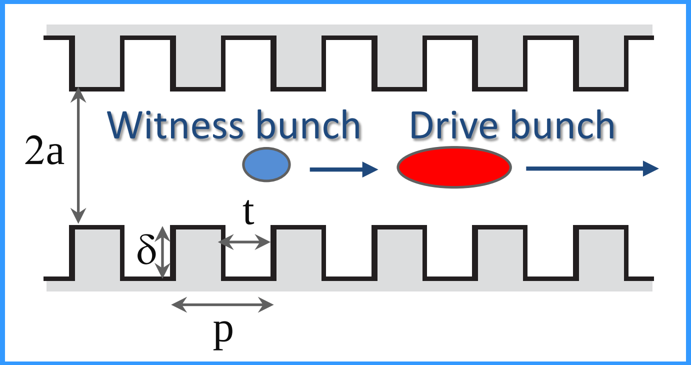
X-RAY LASER FOR PROBING OF MATTER



STRUCTURE-BASED ACCELERATORS

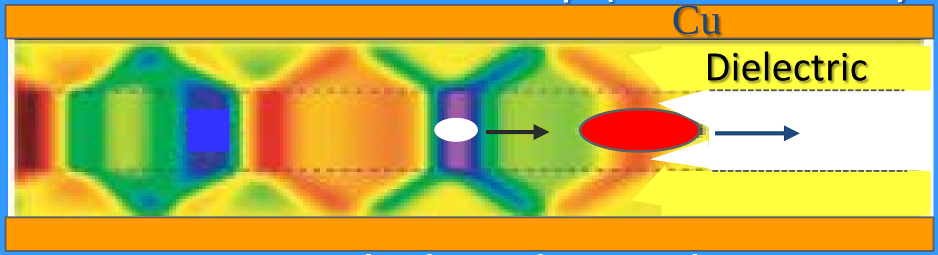
Beam acceleration in a collinear wakefield accelerator: hollow dielectric channel or corrugated wall waveguide





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

Electric field map (200-400 GHz)

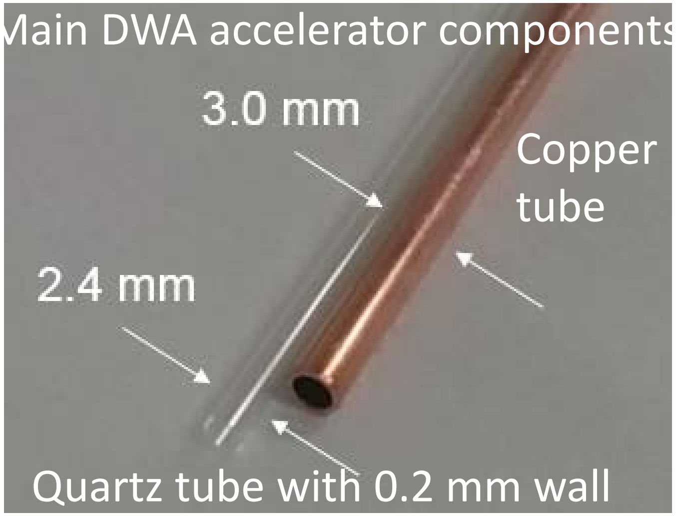


group velocity = (0.7-0.9)c

*) 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 Structure-Based Accelerators

- **Low cost device (likely)**

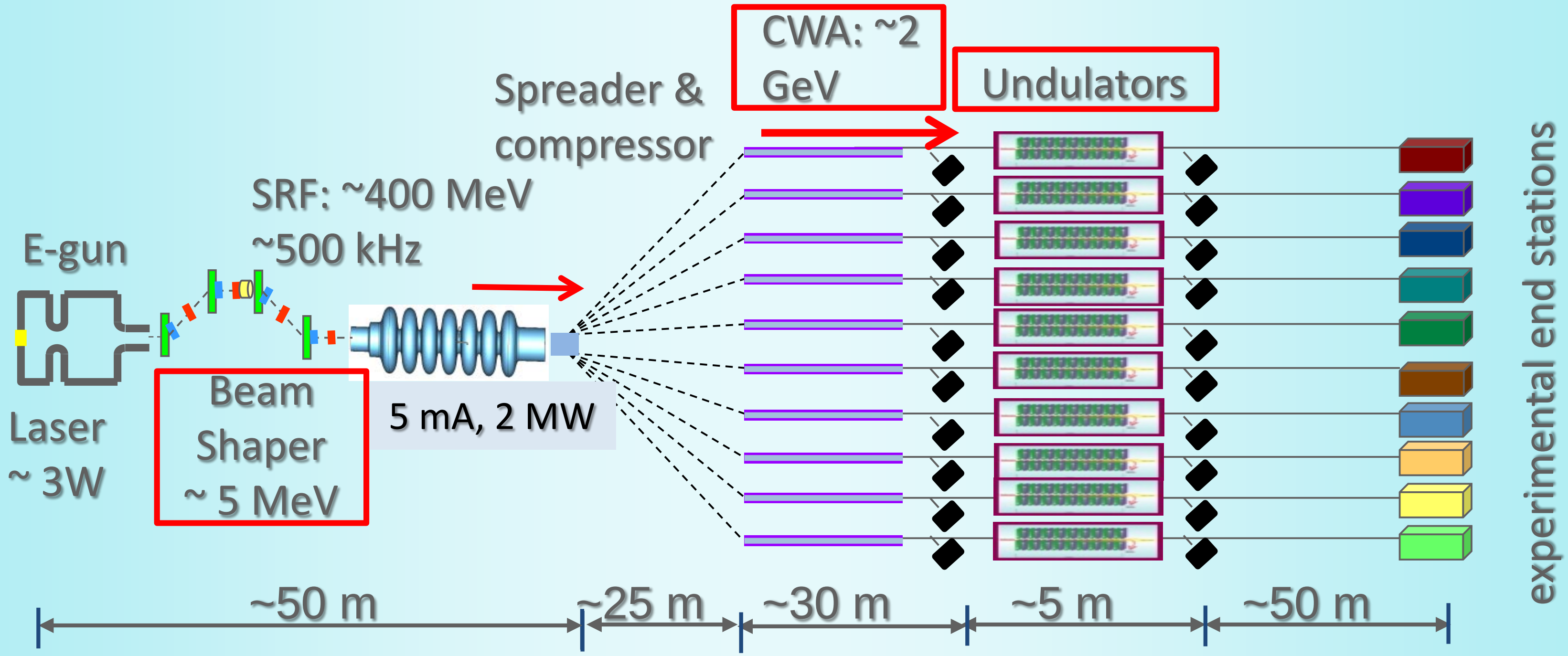


- **High field gradients[1)]**
- **High wall plug power efficiency**
- **High bunch repetition rate[2)]**

1. **Accelerating gradient ~ 300 MV/m has been demonstrated at FACET (SLAC)***
2. **SRF linac can be used for a drive beam**

*) B. O'Shea *et al.*, Nature Communications, September 2016

A concept of a high repetition rate multi-user FEL facility based on Collinear Wakefield Accelerator



Flexible: each beamline has its own accelerator

- Low energy spreader
- Accelerating gradient ~ 100 MV/m
- Tunable electron beam energy
- Tunable peak current > 1 kA
- X-ray pulse rep. rate ~ 50 kHz to each experiment

SOME FUNDAMENTALS

Wake Field and Transformer Ratio

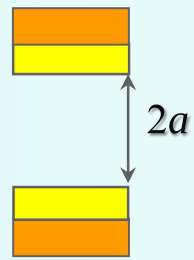
Wake field

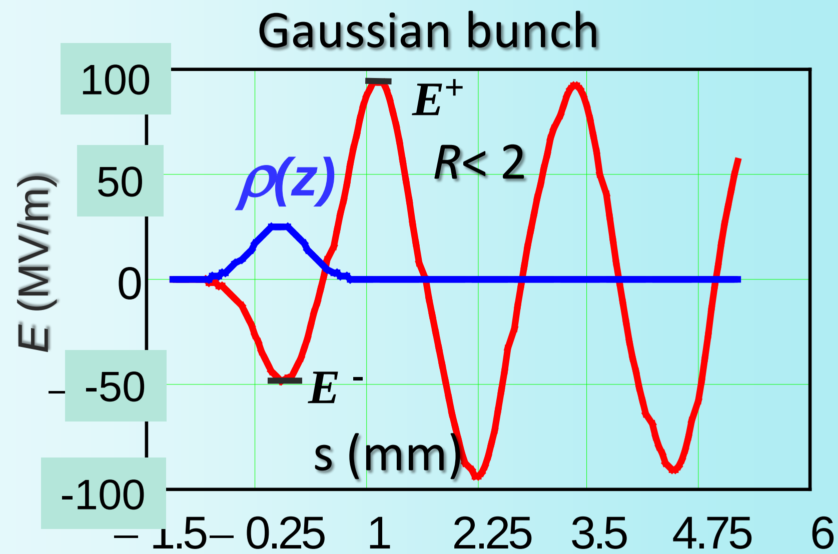
Drive bunch longitudinal density

$$E(s) \propto \int_{-\infty}^{s} \rho(s')G\left(s-s'\right)ds'$$

Green's function, i.e. point charge wake field

$$G\left(s\right) \approx \frac{4}{a^2}\cos\left(ks\right)$$



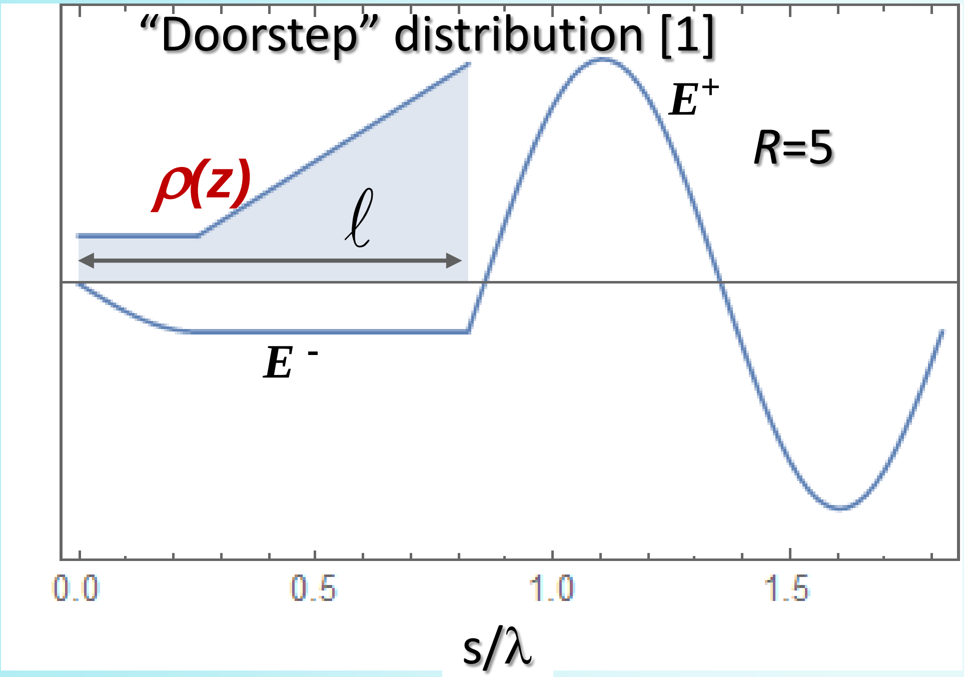


Transformer ratio[1)]

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

Energy Gain by Witness Electron Bunch

Goal is to extract maximum energy from drive bunch, up to η=80%, and obtain highest energy for the witness bunch



Other distributions possible, see also [2]

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

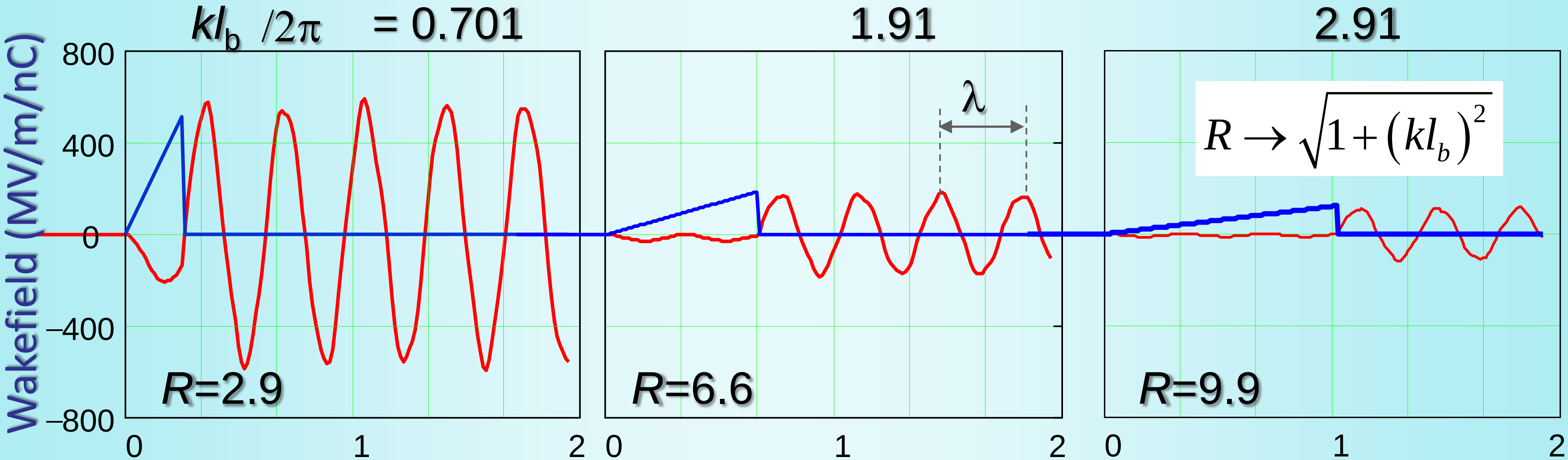
Efficiency of utilization of drive bunch energy E_{drive}

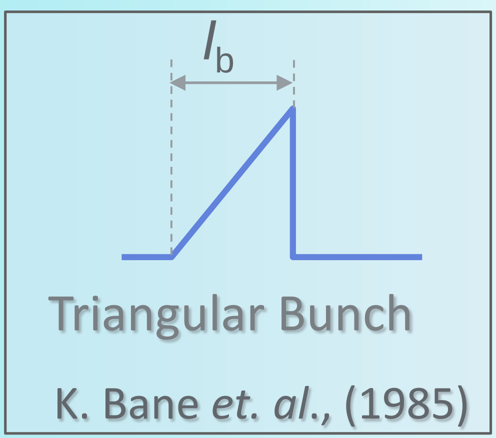
Example:

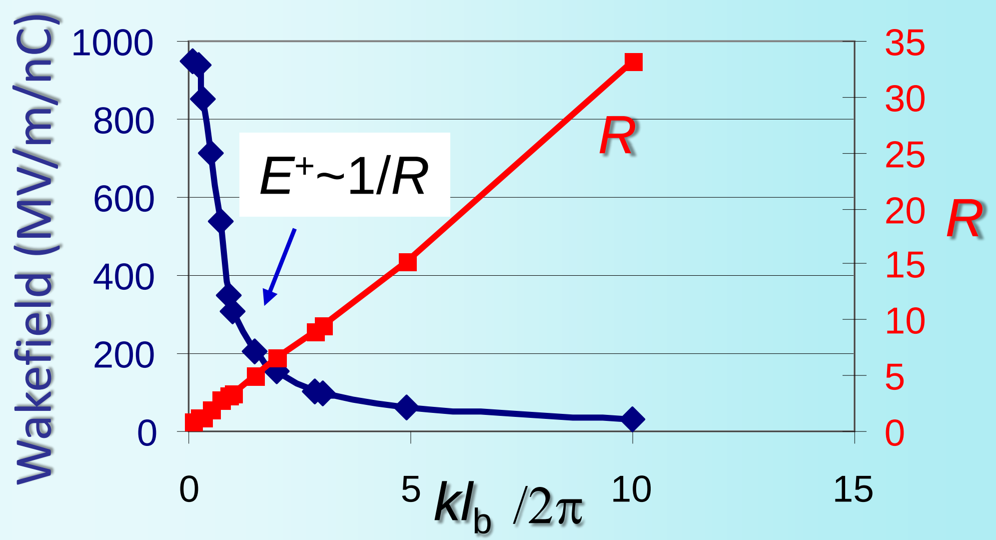
E_{drive} =400 MeV
R = 5
η = 0.8
$\Delta E_{witness}$= 1.6 GeV

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).

Transformer Ratio and Acceleration (2)







J. Power, Presentation at 2011 Argonne Workshop on Dielectric Wakefield Accelerator

Energy Efficiency and Power Management

$$\text{Efficiency} \leq \frac{Q_W E^+ L}{Q_D E^- L} = \frac{Q_W}{Q_D}\eta R$$

witness bunch charge

drive bunch charge

For

E_{drive} = 400 MeV
$E_{witness}$ = 400 MeV
R = 5
η = 0.8
Q_D = 8 nC
Q_W = 0.3 nC

efficiency = 15%

Power management

400 MeV

Drive +witness

166 kW in

at 50 kHz rep. rate

Wakefield accelerator ~ 20 m

Power loss 52 W/cm

2 GeV

30 kW witness

out

32 kW drive

80 MeV

Three basic rules of the collinear wakefield accelerator

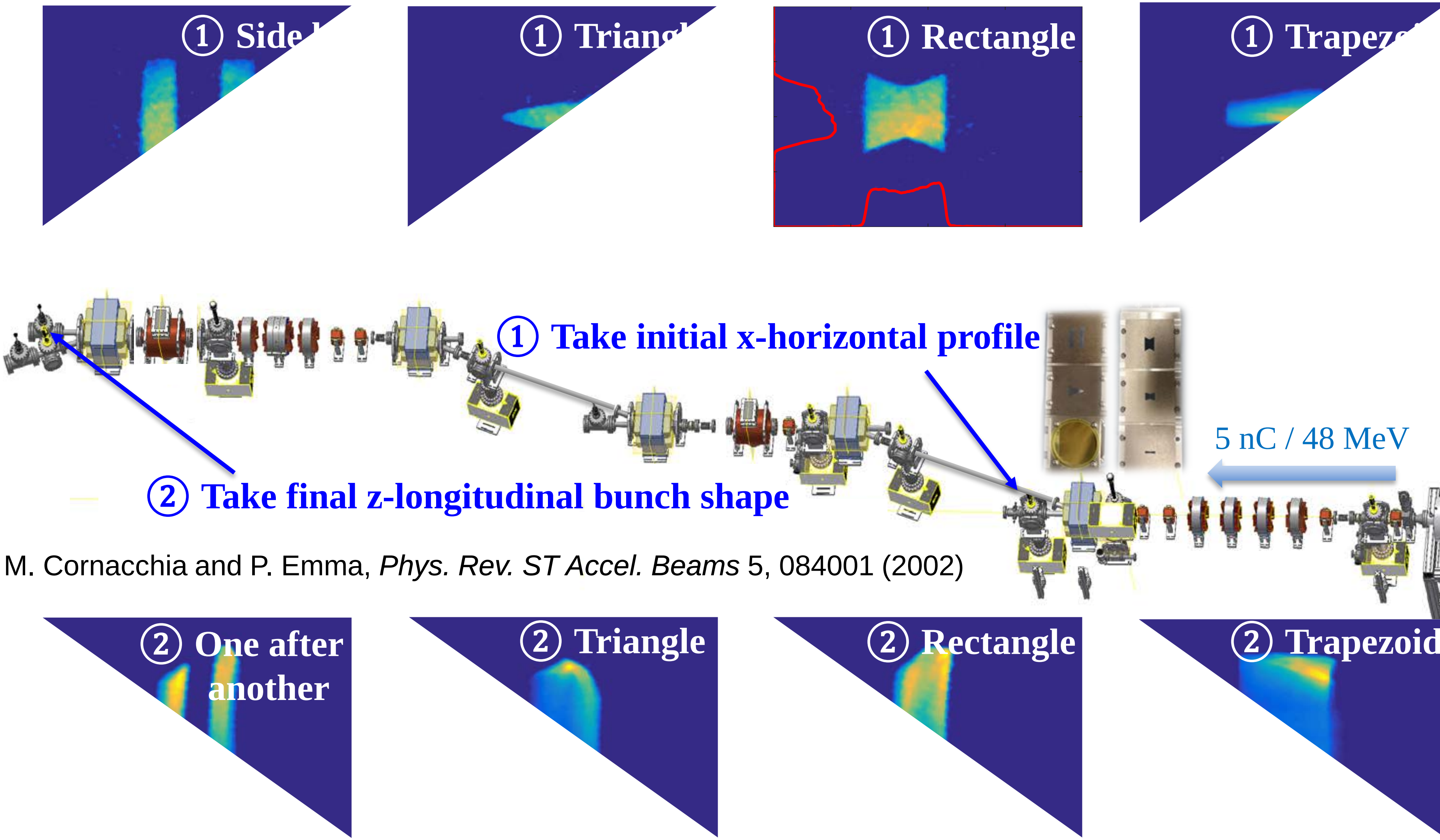
Efficient CWA have to:

- trade a high energy gain for a high transformer ratio,
- use bunch shaping to obtain constant decelerating field inside the drive bunch,
- maintain stable drive bunch until it almost completely decelerated.

MANIPULATING WAKEFIELDS VIA BEAM SHAPING

Emittance Exchange Beamline Converts Transverse Shaping to Longitudinal Shaping

EXPERIMENT AWA/ANL



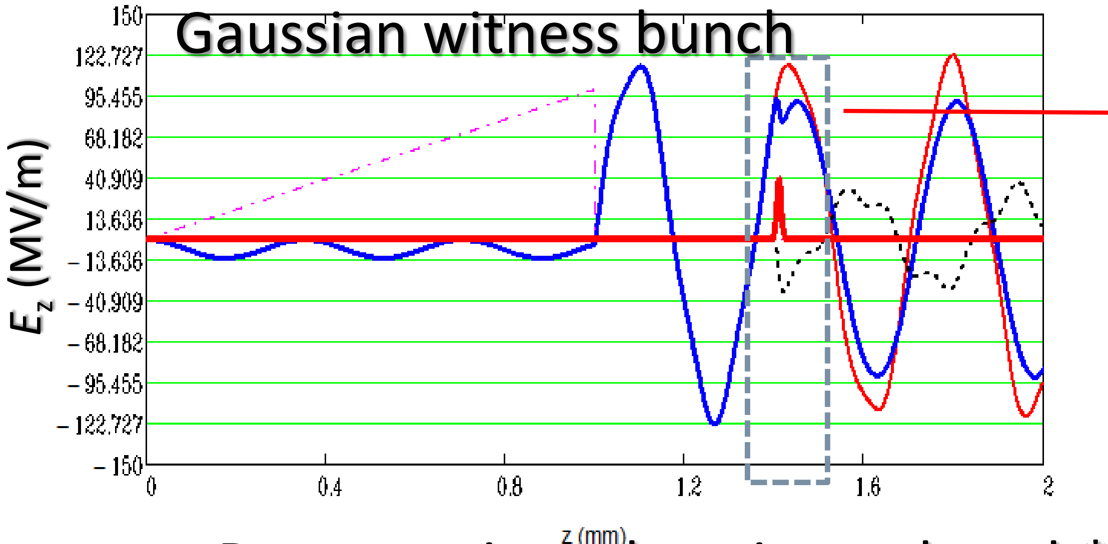
M. Cornacchia and P. Emma, *Phys. Rev. ST Accel. Beams* 5, 084001 (2002)

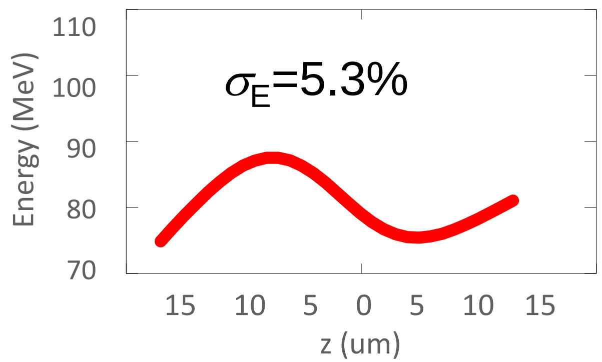
Masks (~100 μm of W)

YAG

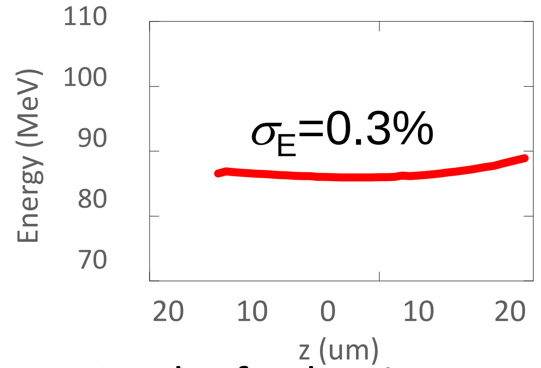
Witness Bunch Shaping

Reduce correlated energy spread in the witness bunch





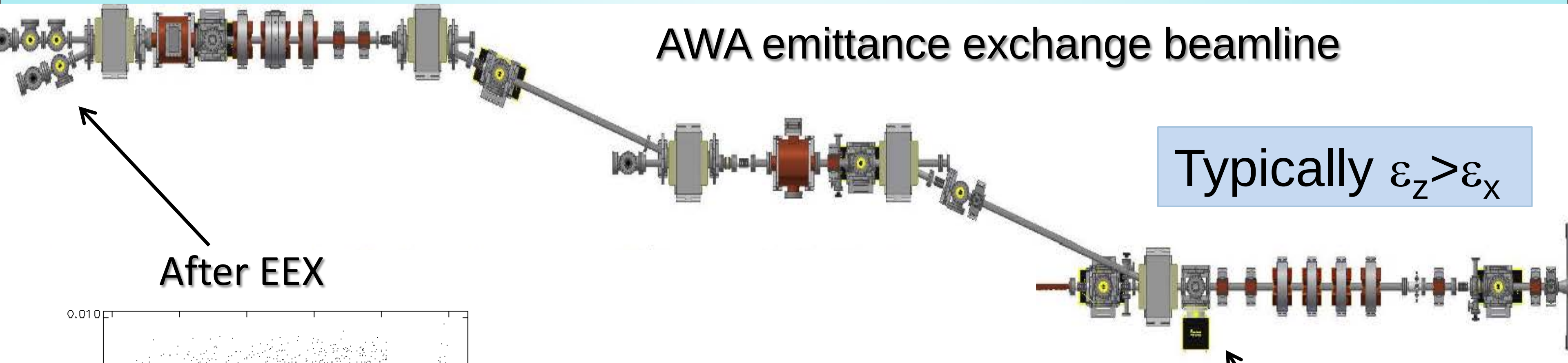
Reverse triangular witness bunch*

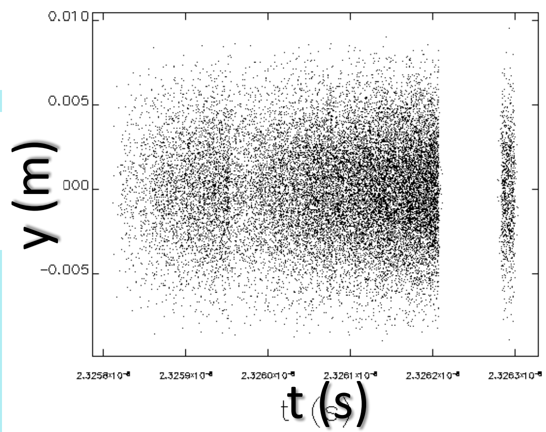


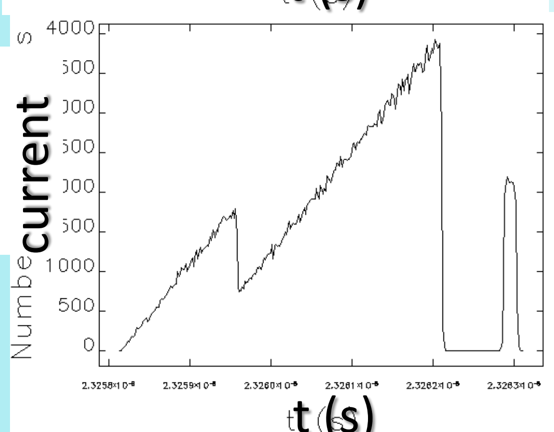
Can be further improved

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

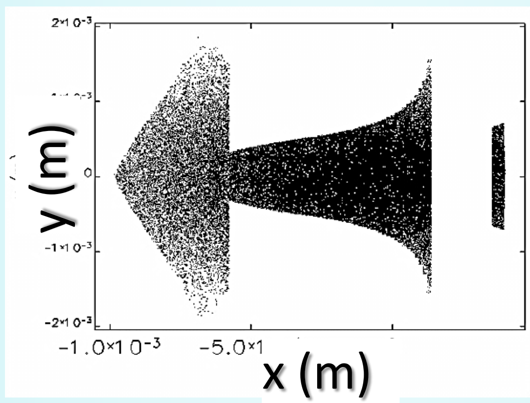
Problem at a high bunch repetition rate

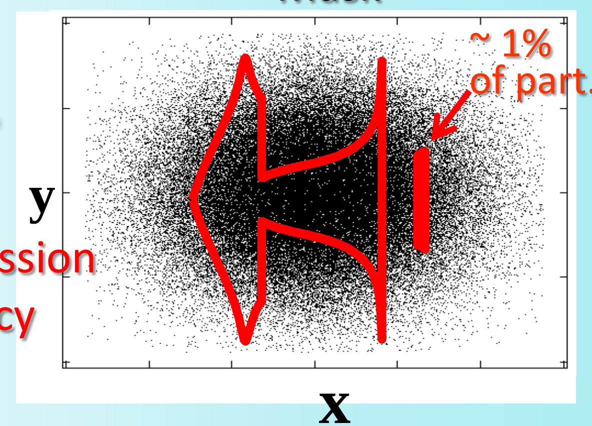






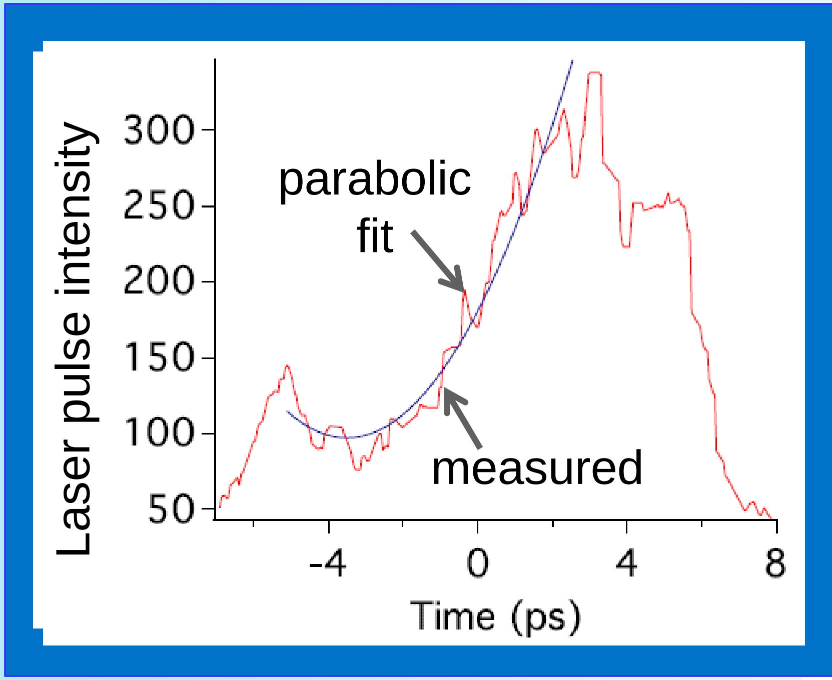
Transverse particle distribution after mask

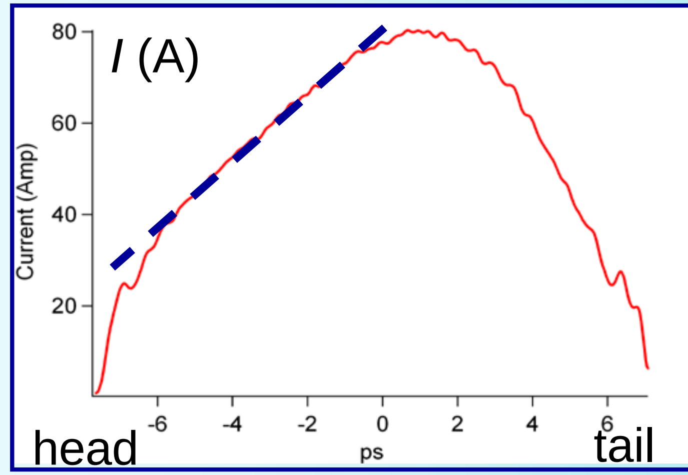




~ 60 kW will be deposited on a mask, even at a low energy 5 MeV (below threshold of material activation)

Drive bunch shaping using photocathode laser *)

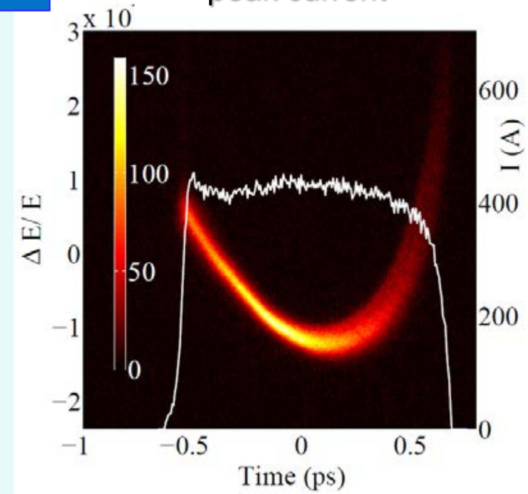




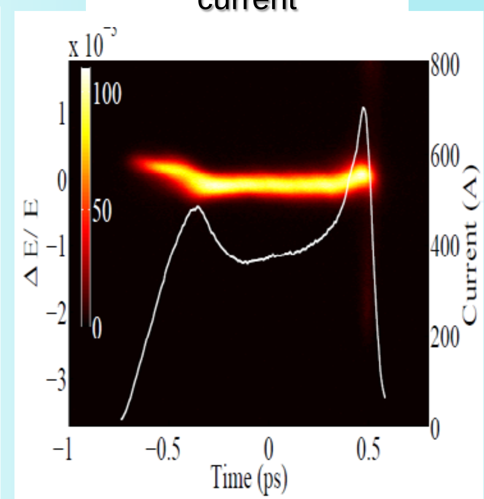
At the end of the injector at 100 MeV

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

Without ramped peak current

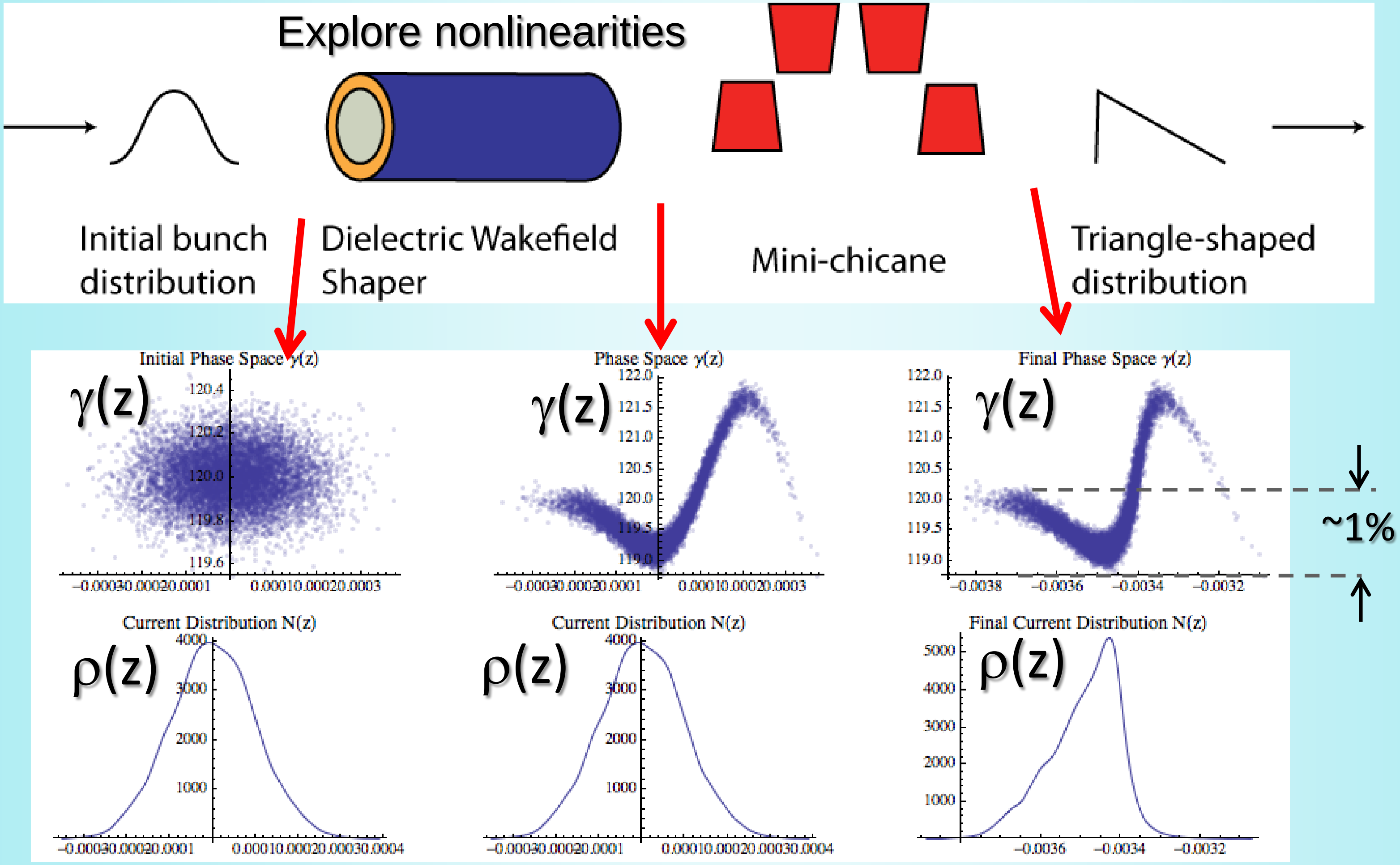


With ramped peak current



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

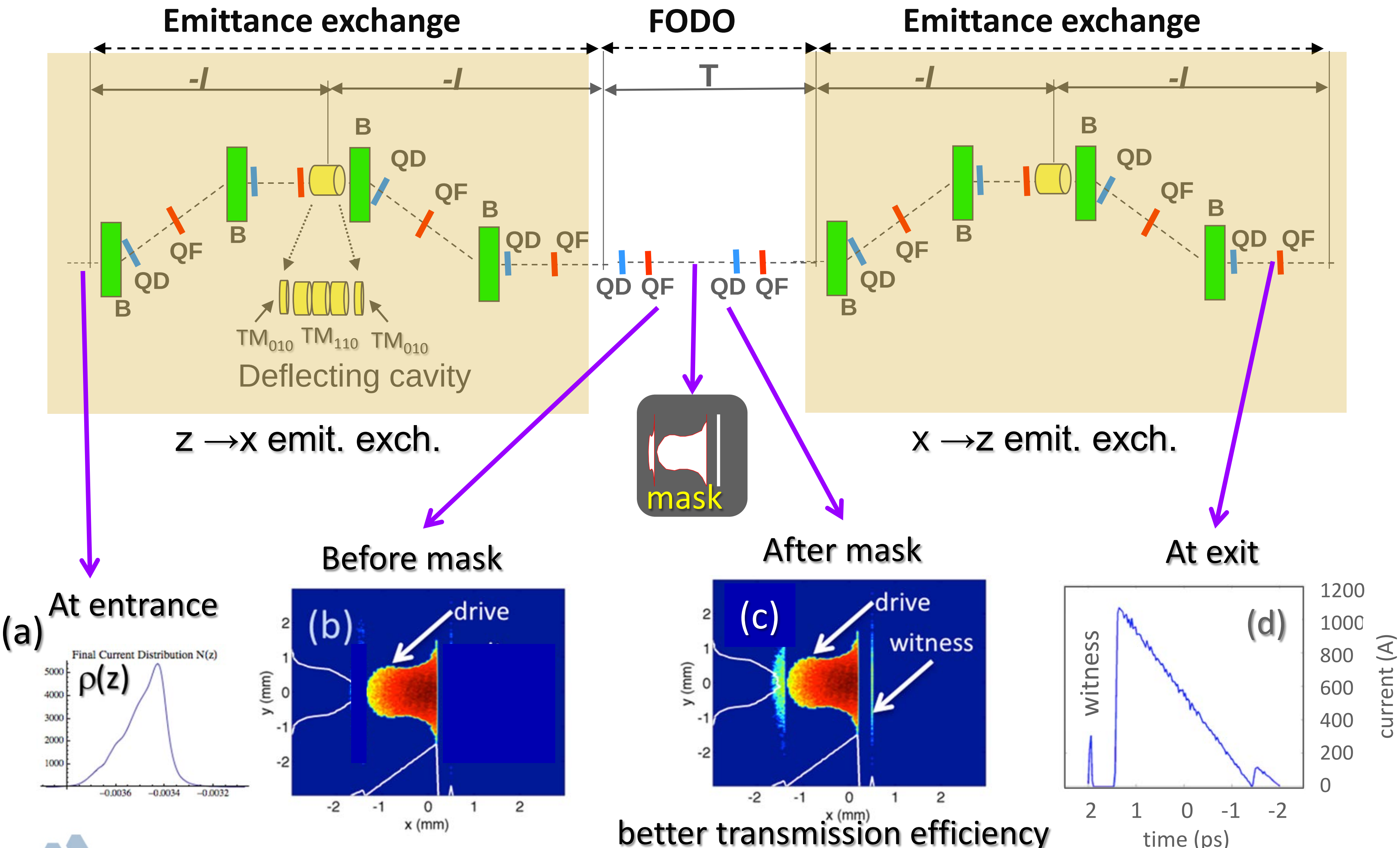
Drive bunch shaping using self-wakefields*



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

Make it more precise using Double EEX*)

funded project for AWA

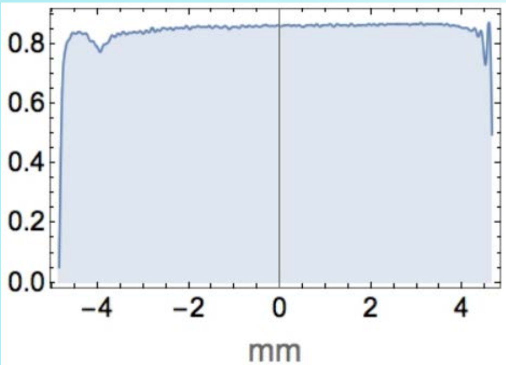


*) A. Zholents and M. Zolotorev (LS-327/APS, 2010)

Bunch Shaping Using the Entire Accelerator

S. Baturin, work in progress

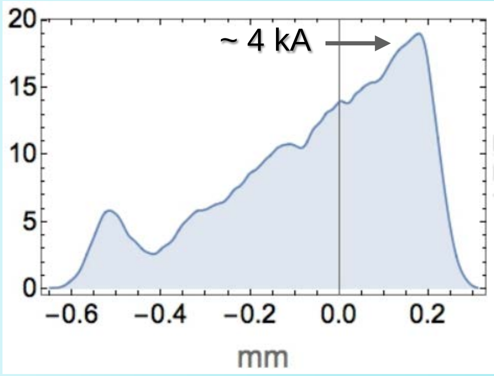
Uses no masks

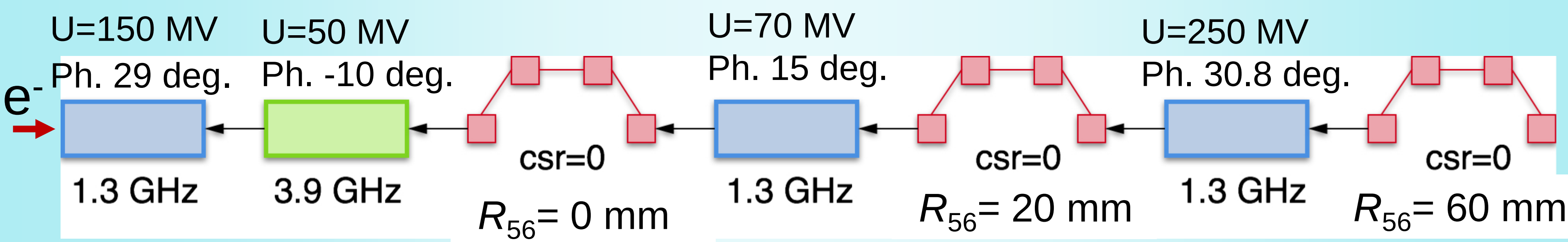


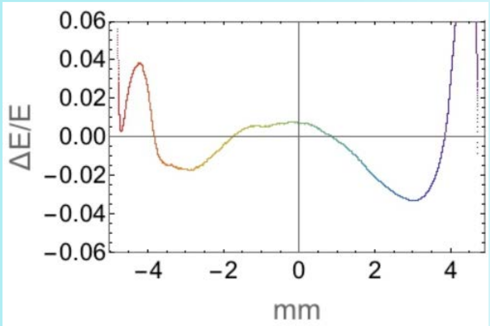
← ~ 200 A

Time reversible tracking

~ 4 kA →





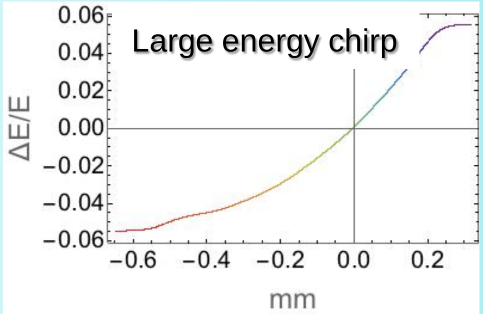


Drive bunch In

Includes:

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

CSR is next

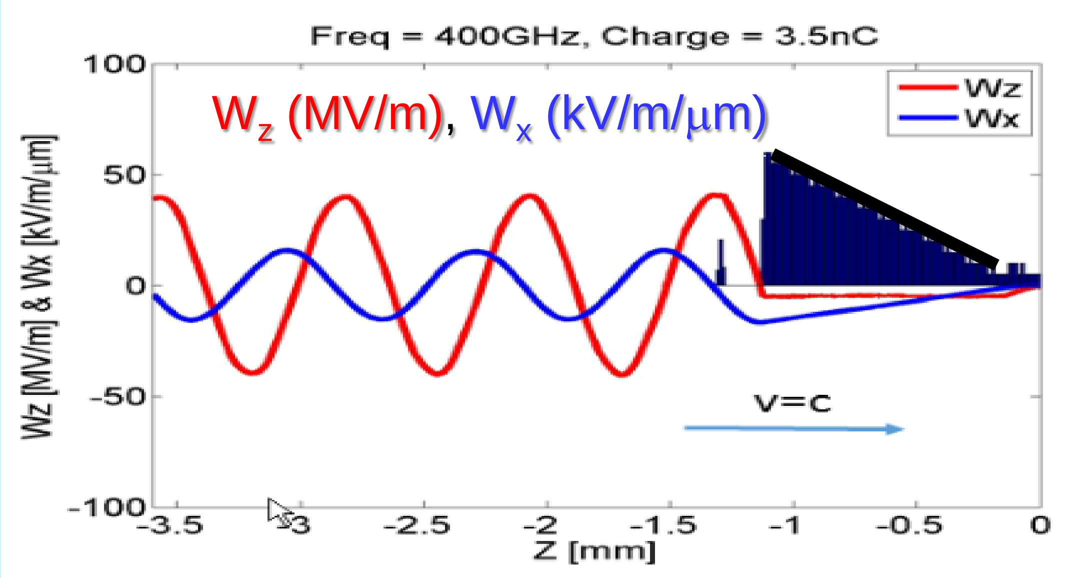


Drive bunch Out

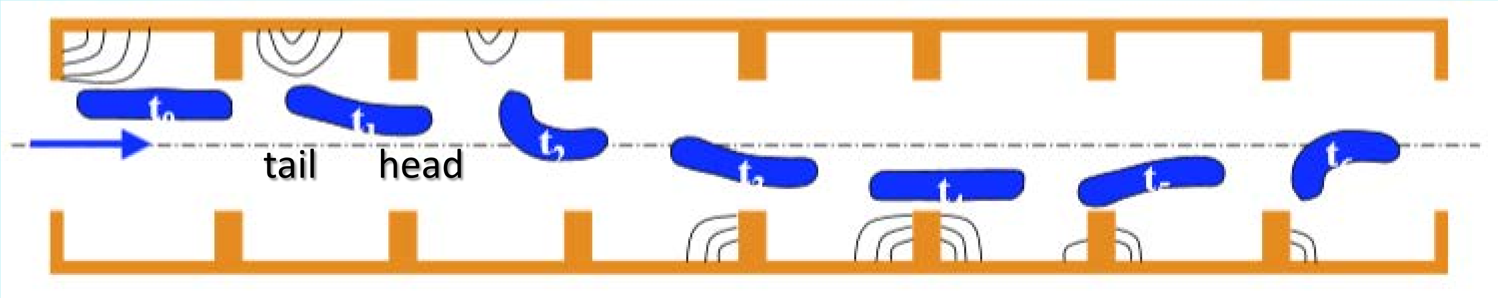
BEAM BREAKUP INSTABILITY

Drive Bunch Beam Breakup Instability (BBU)

Examples of longitudinal and transverse wakefields ($W_z \sim 1/a^2$, $W_x \sim 1/a^3$)



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



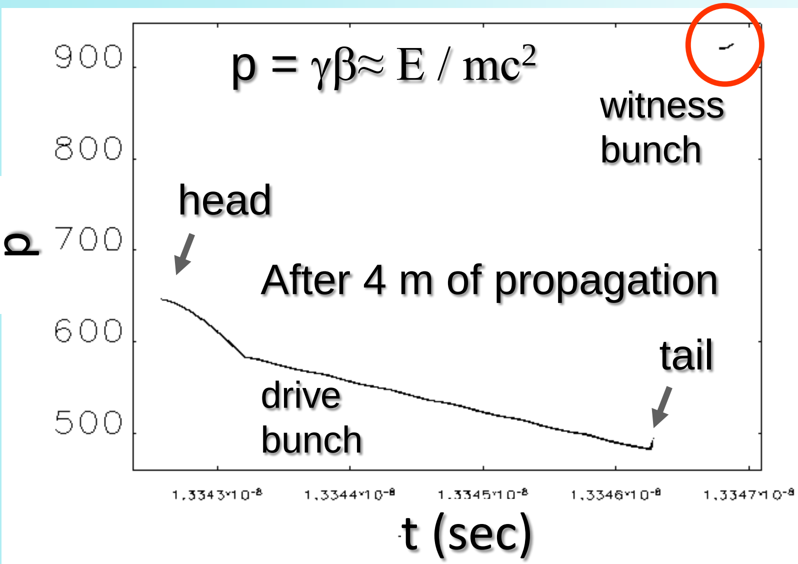
Snapshots of a single bunch traversing a SLAC structure

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

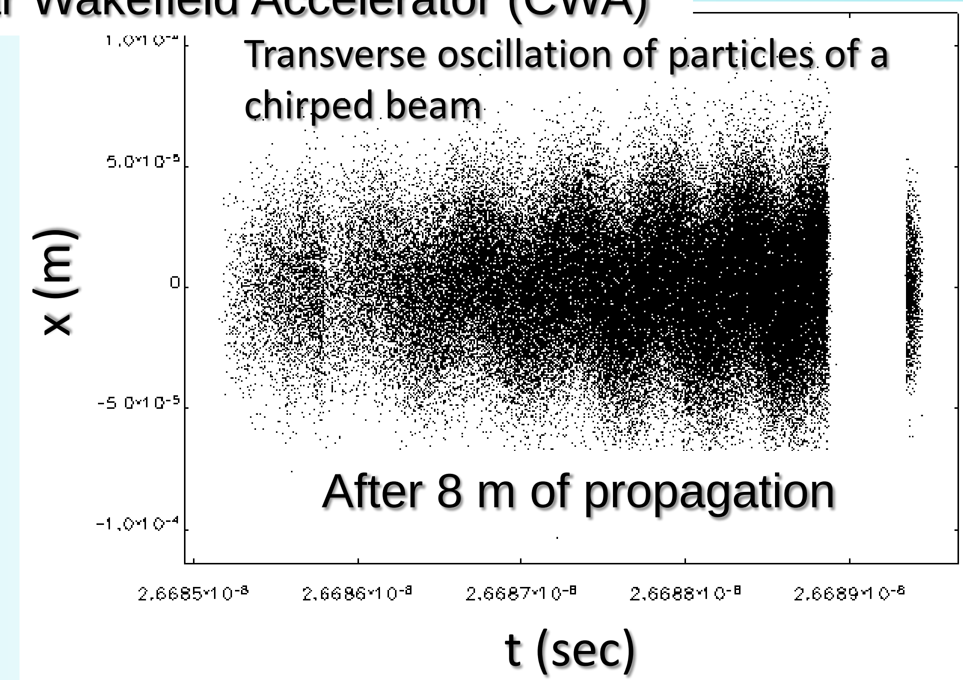
Balakin-Novokhatsky-Smirnov (BNS) damping of BBU

- Use FODO channel
- Produce “chirp” in the betatron tune along the electron 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 Colinear Wakefield Accelerator (CWA)



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

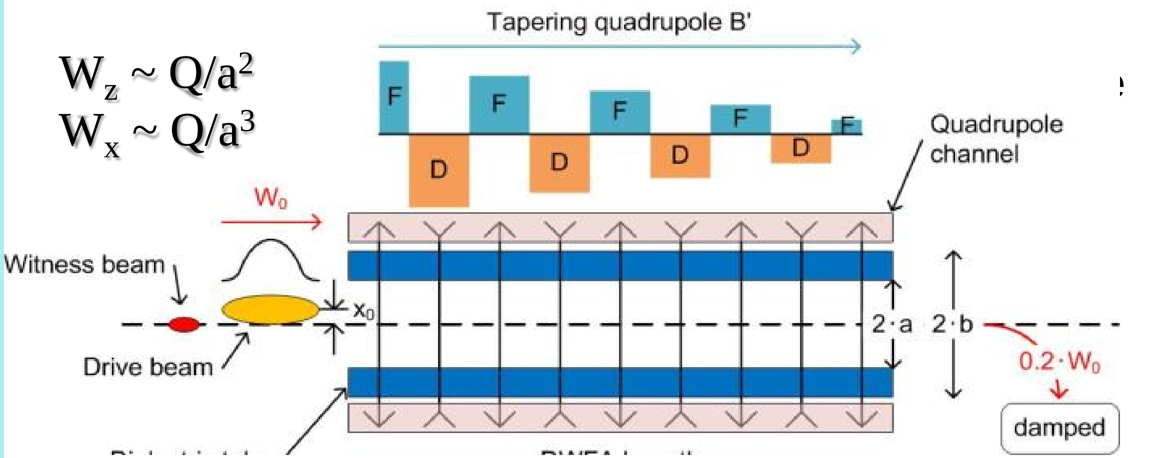


Particles of different energies have different oscillation periods in the FODO lattice

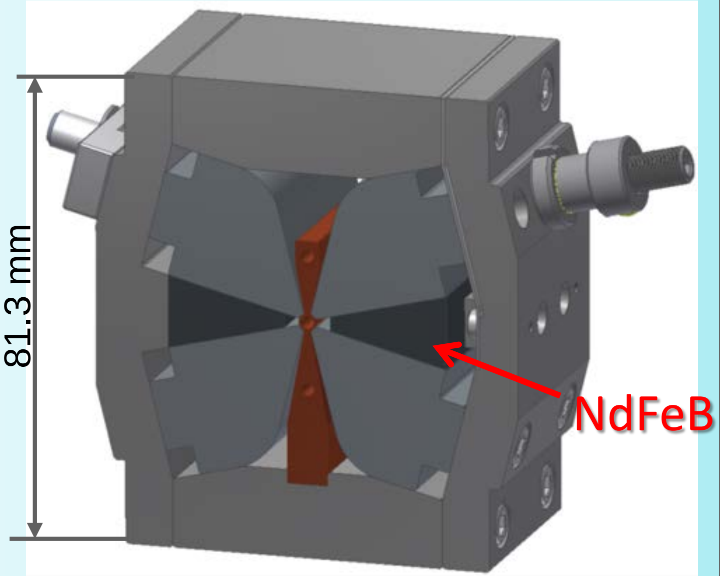
FODO channel (quadrupole wiggler) to control BBU

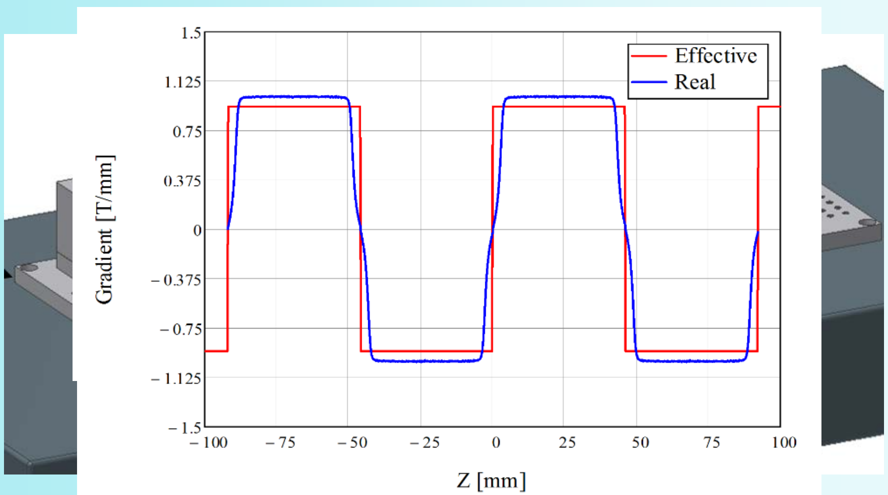
Wakefield accelerator

$$W_z \sim Q/a^2$$
$$W_x \sim Q/a^3$$



Wakefield accelerator imbedded into *quadrupole wiggler*





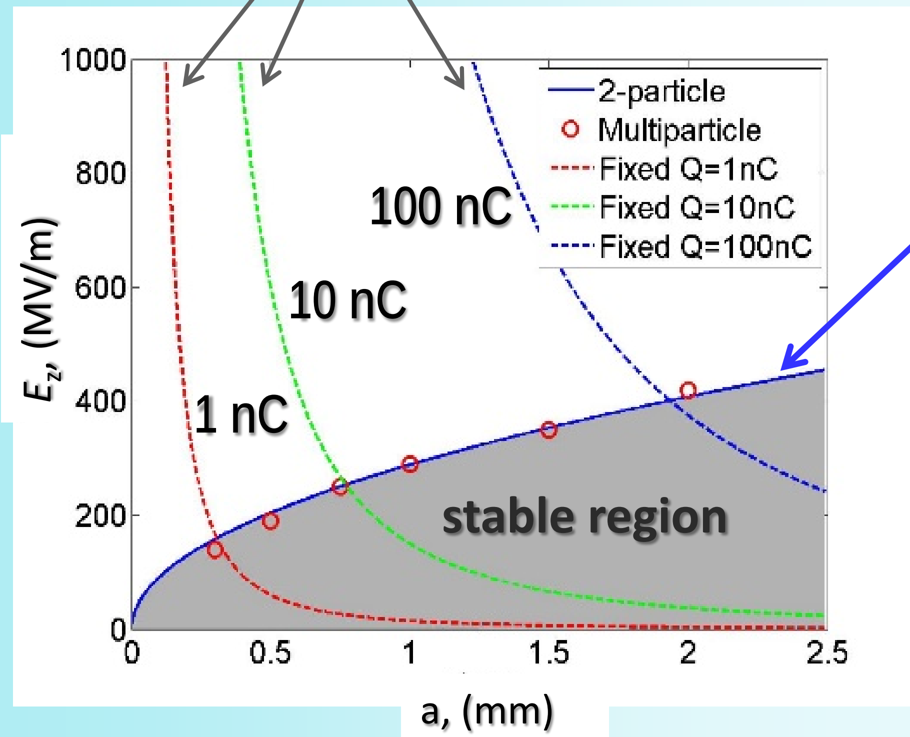
High gradient hybrid quad

- 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.

Maximum energy gain is defined by the quad strength

E_z scales ~ $1/a^2$

$W_z \sim 1/a^2$
$W_x \sim 1/a^3$



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

Obtained using a two-particle model, this envelope is defined by the maximum attainable quadrupole gradient at each bore radius*.

E_z scales as ~ $a^{1/2}$ on a boarder line of a stability region

Control of BBU instability favors larger radius

*) C. Li, W. Gai, C. Jing, J. G. Power, C. X. Tang, A. Zholents, PRST-AB, 17, 091302 (2014)

Similarity with a Hollow Plasma Channel

PHYSICS OF PLASMAS **20**, 123115 (2013)

Beam loading in a laser-plasma accelerator using a near-hollow plasma channel

C. B. Schroeder, C. Benedetti, E. Esarey, and W. P. Leemans
Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

(Received 20 May 2013; accepted 3 December 2013; published online 23 December 2013)

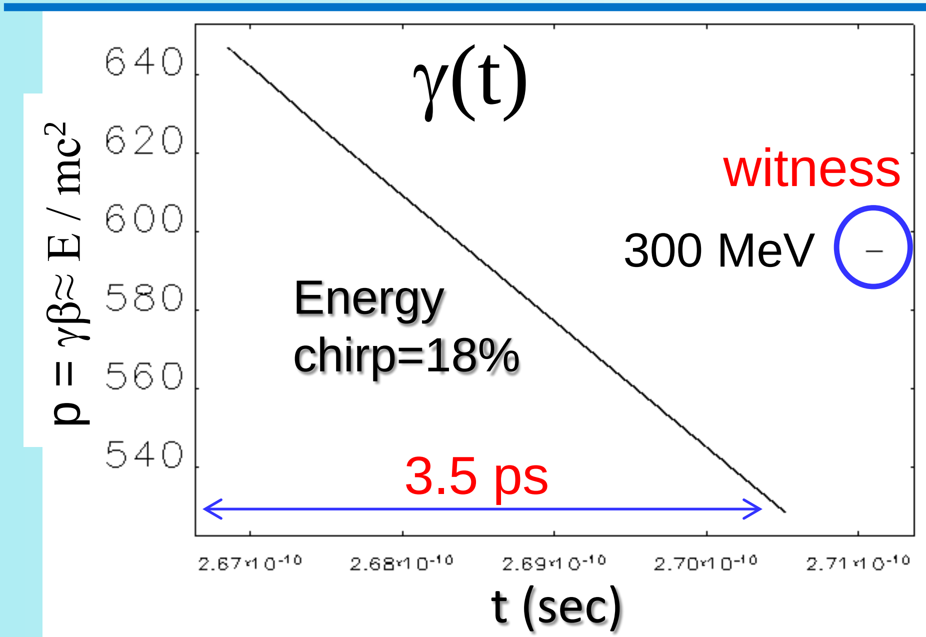
Beam loading in laser-plasma accelerators using a near-hollow plasma channel is examined in the linear wake regime. It is shown that, by properly shaping and phasing the witness particle beam, high-gradient acceleration can be achieved with high-efficiency, and without induced energy spread or emittance growth. Both electron and positron beams can be accelerated in this plasma channel geometry. Matched propagation of electron beams can be achieved by the focusing force provided by the channel density. For positron beams, matched propagation can be achieved in a hollow plasma channel with external focusing. The efficiency of energy transfer from the wake to a witness beam is calculated for single ultra-short bunches and bunch trains. [http://dx.doi.org/10.1063/1.4849456]

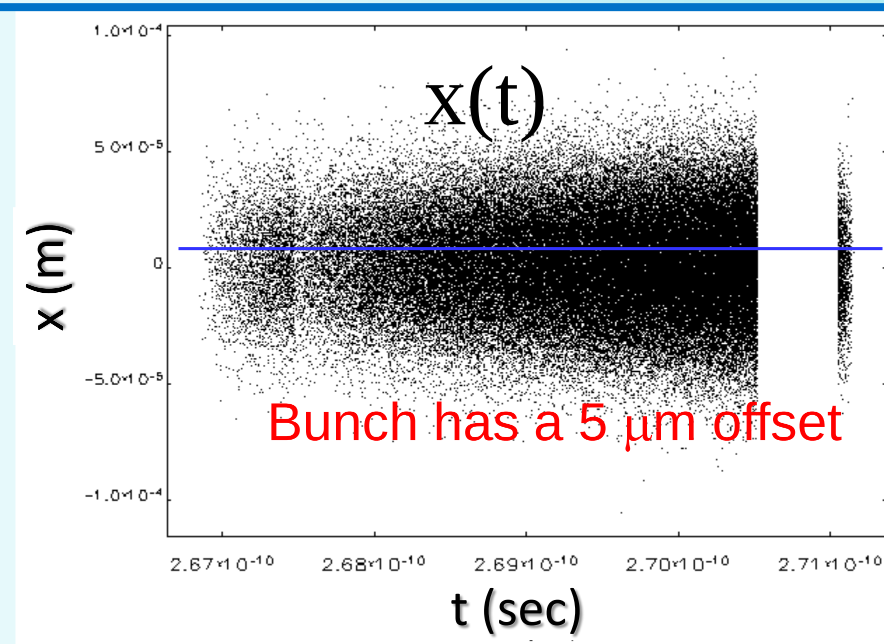
provide a defocusing force to a positron beam. For a relativistic positron beam, one would operate using a hollow plasma channel ($n_c = 0$) and rely on external focusing. Strong focusing could be achieved by using permanent magnetic quadrupoles positioned around the plasma channel structure.

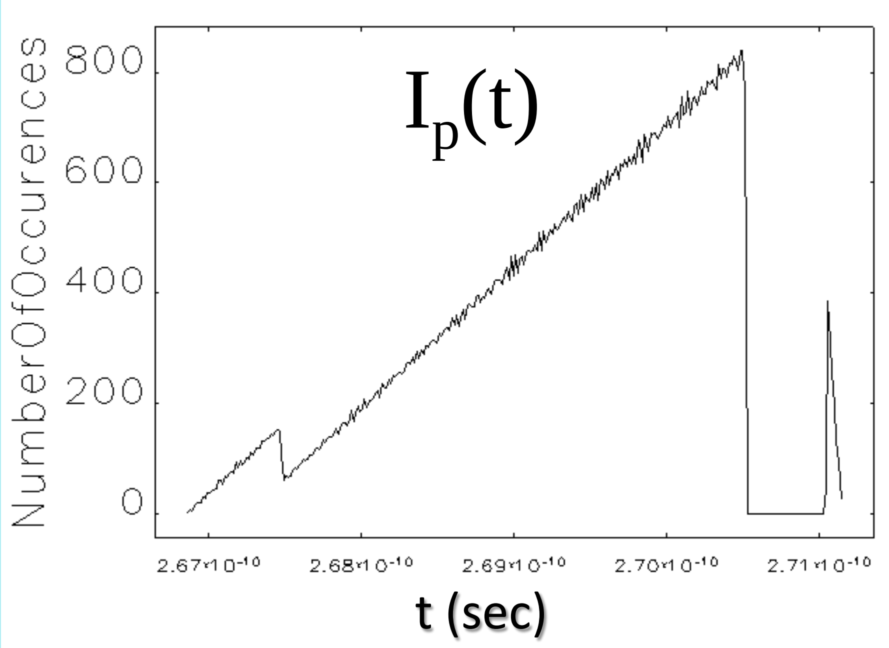
Study cases

	Case I	Case II
Fundamental mode Freq. (GHz)	400	300
ID (mm)	1.5	2
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
Witness bunch charge (pC), length (μm)	50, 5	250, 10
Total DWA length (m)	~40	~20
Drive beam dump energy (MeV)	~ 70 MeV	80 MeV
Drive beam to main beam efficiency (%)	8.6	15.5
Witness beam energy gain (GeV)	1.5	1.6

Illustration using 3.5 nC drive and 50 pC witness bunches



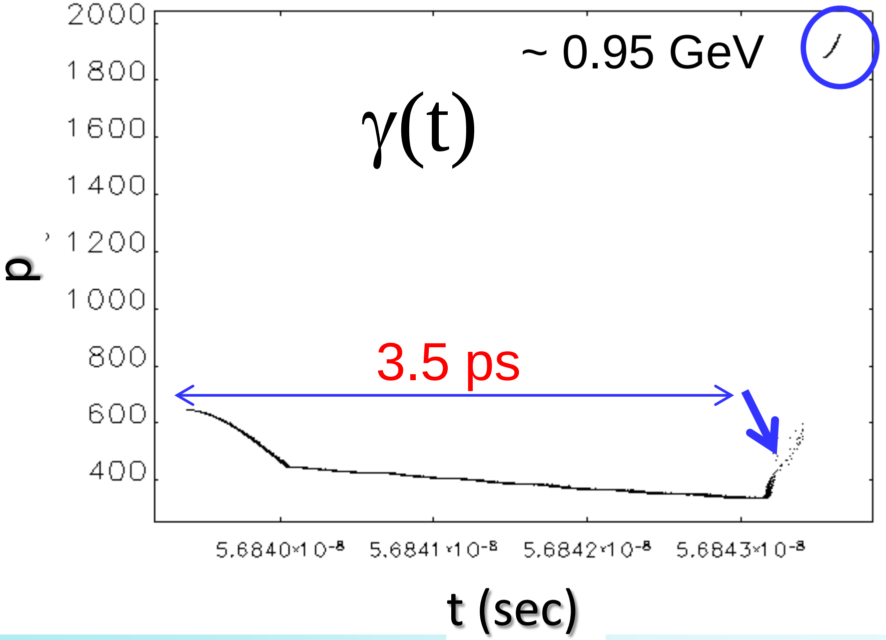


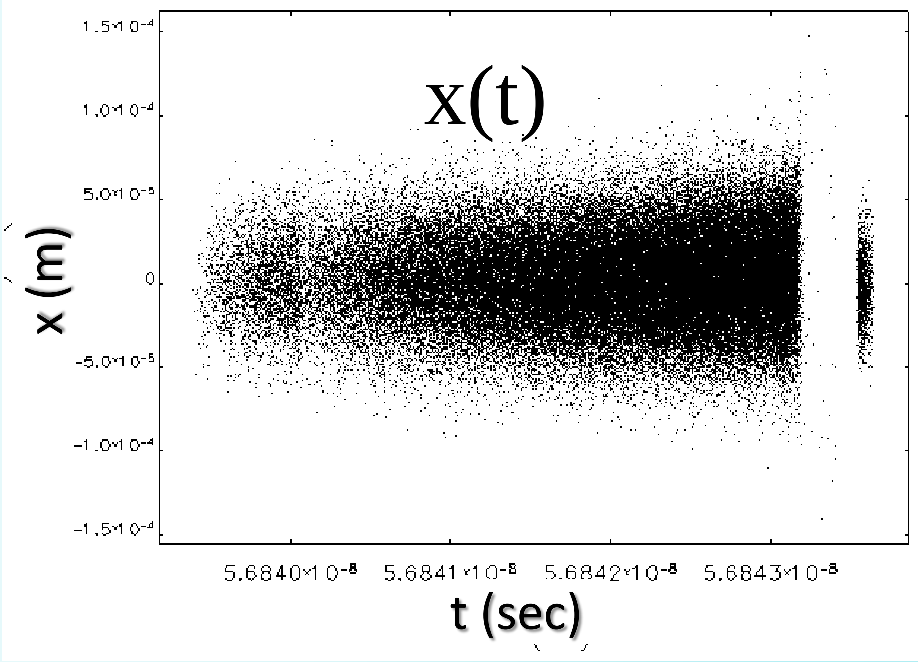


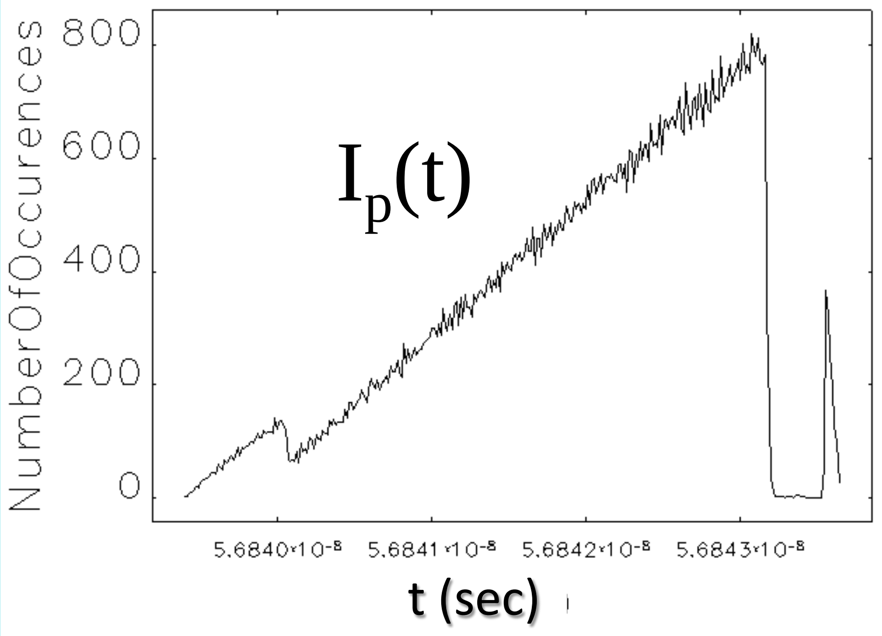
0 m

Space charge effects are not included

Illustration cont'd



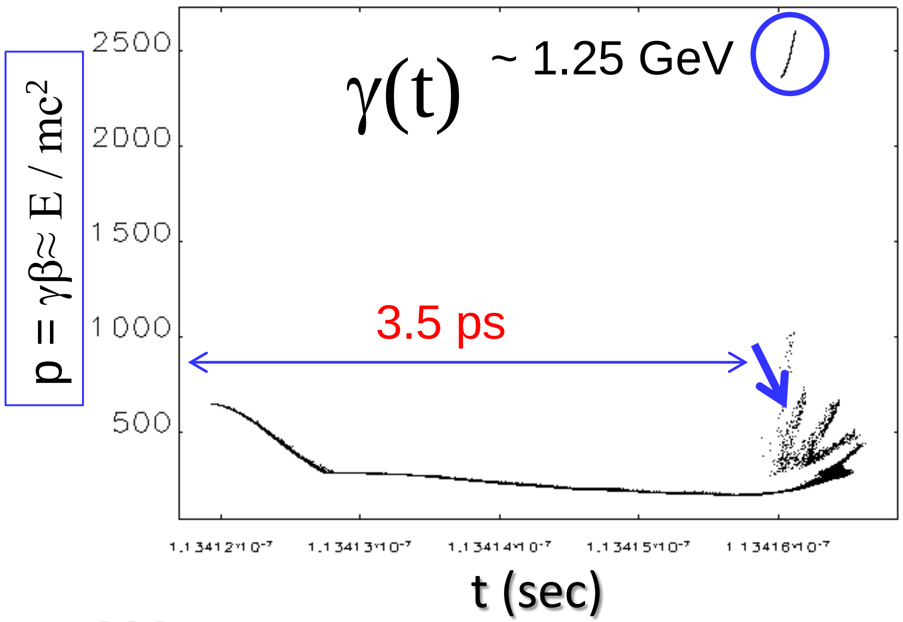


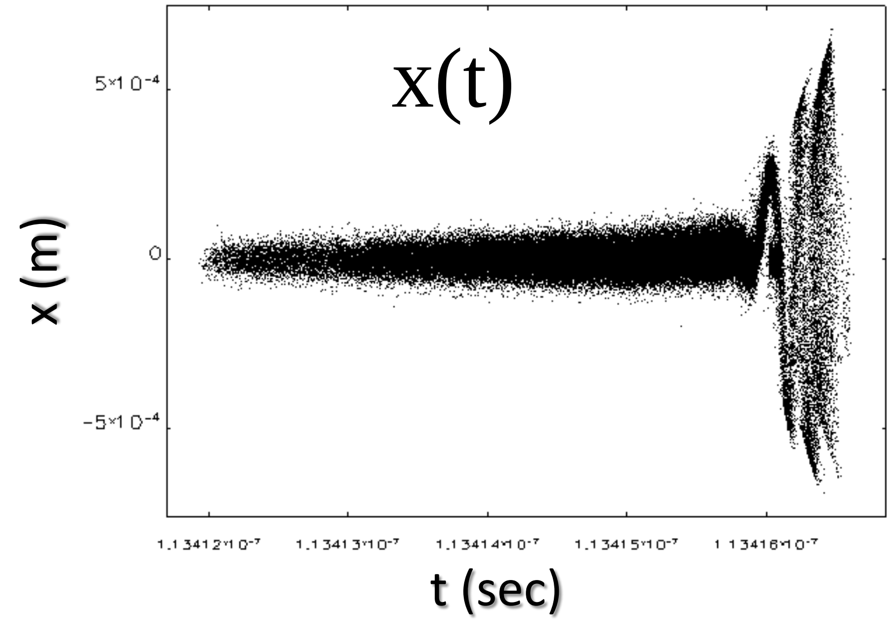


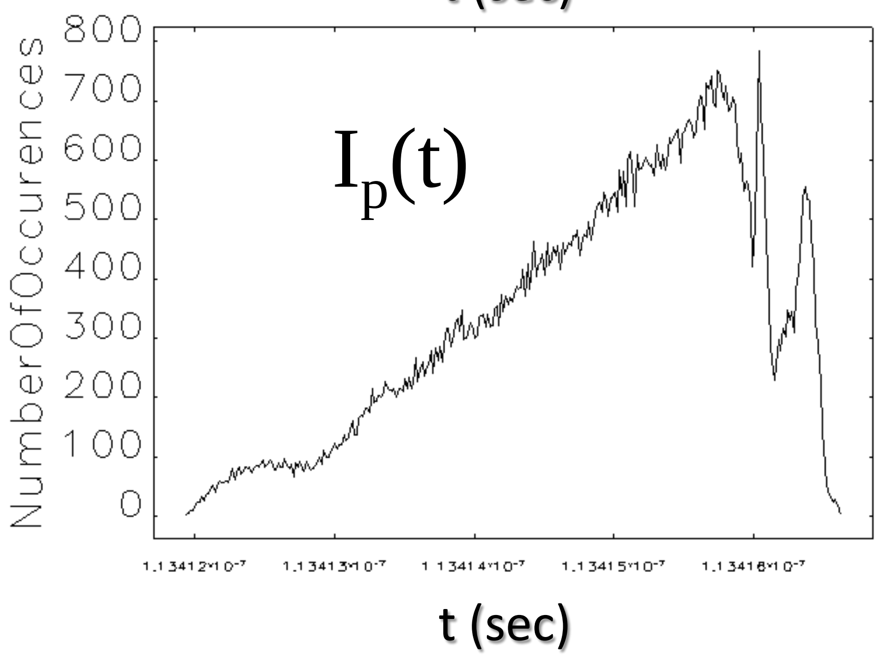
the drive bunch tail develops lagging and sees the wake's accelerating field

after 17 m

Illustration cont'd





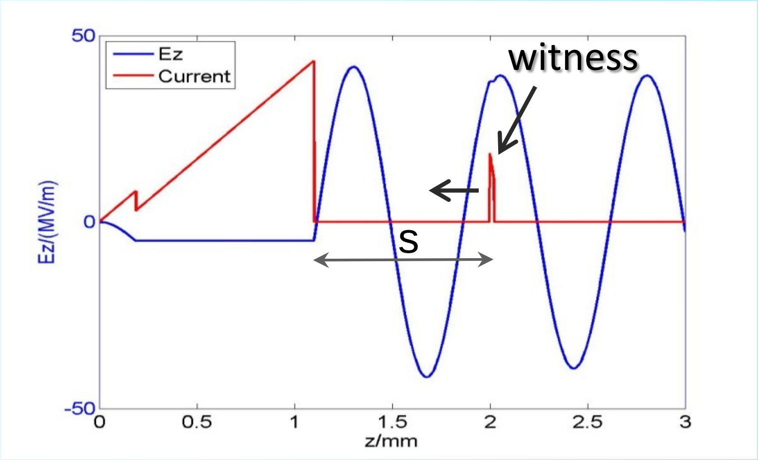


Drive bunch and witness bunch separation decreases because of their different energies

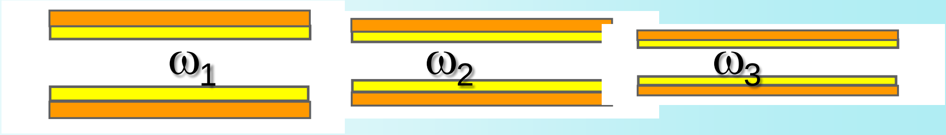
after 34 m

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)

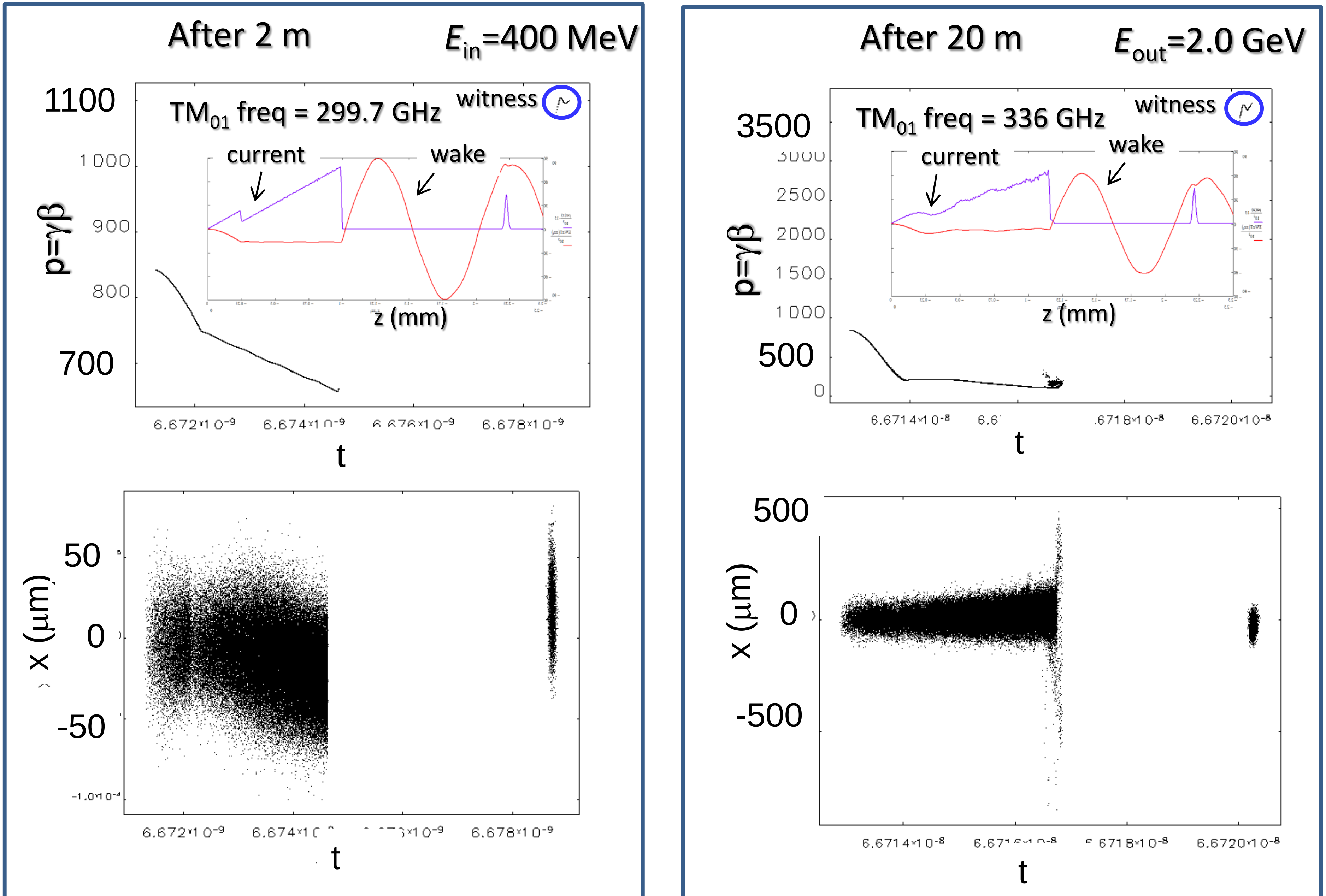


$\omega_1 < \omega_2 < \omega_3$

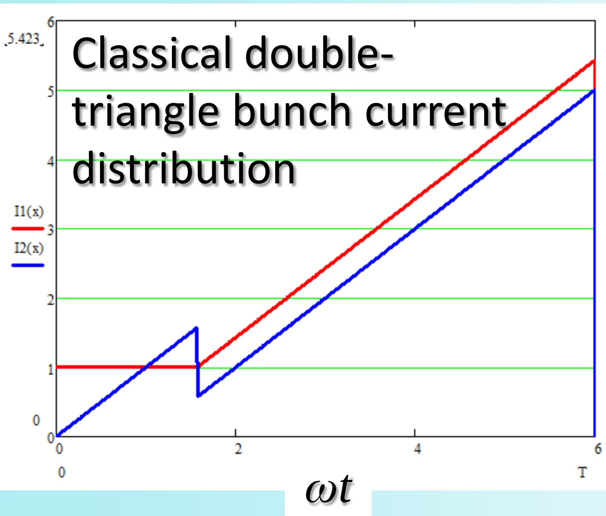
frequency adaptive channel

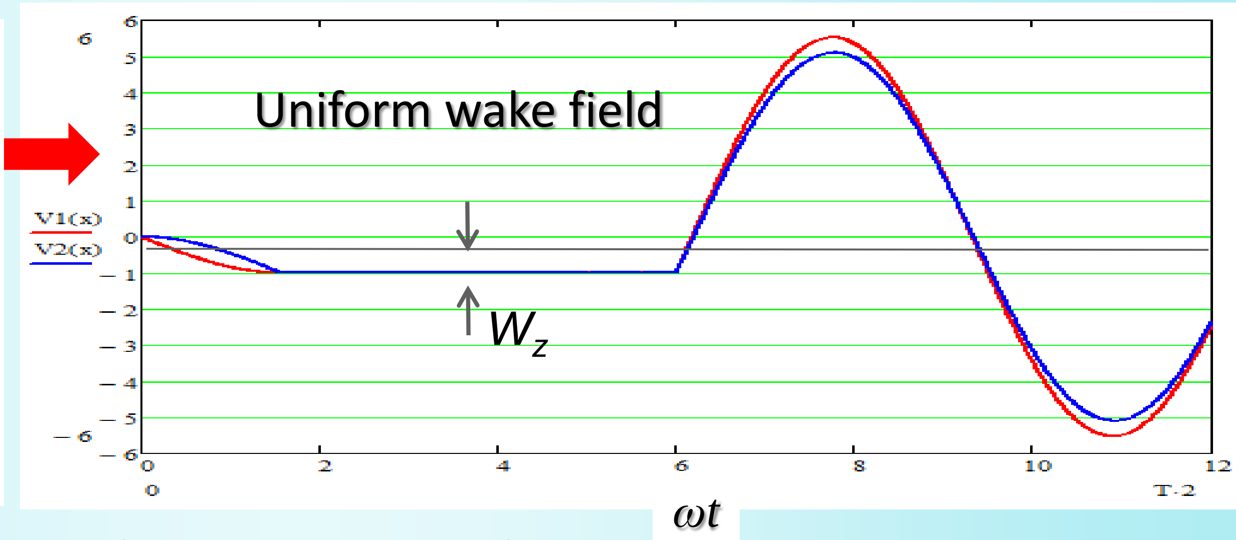
- Use drive bunch with higher energy (affects facility cost and energy efficiency)

Tracking results using 8nC drive and 250pC witness bunch

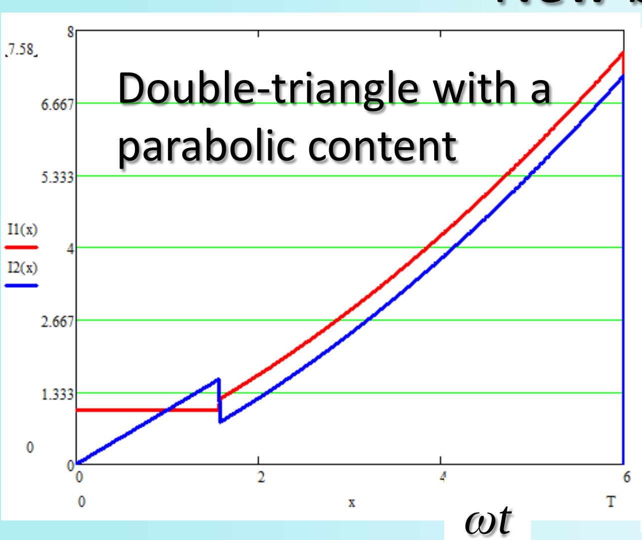


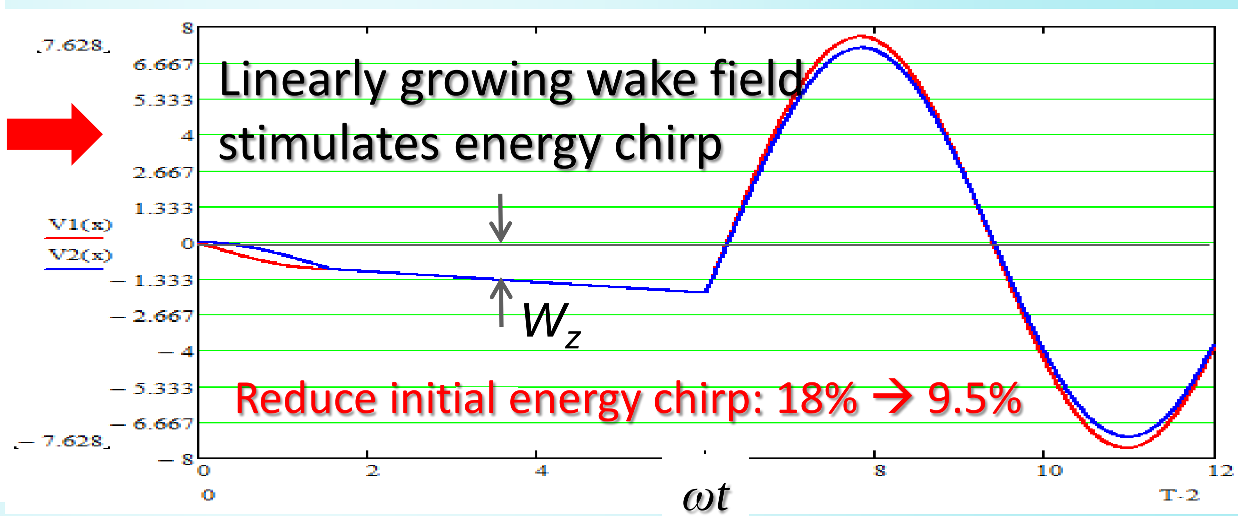
Further Customizing Drive Bunch Distribution: accommodating smaller initial energy chirp



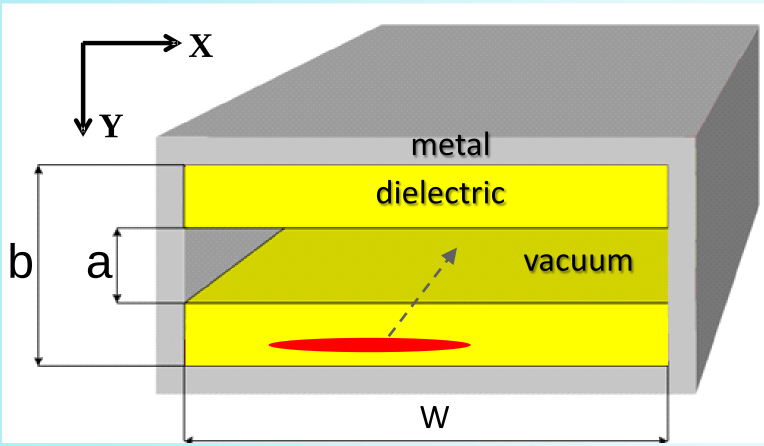


New bunch current distribution

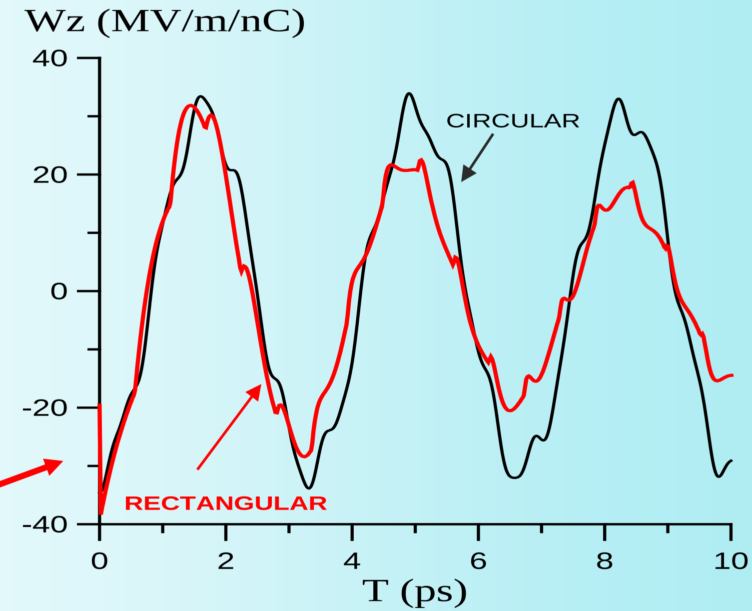


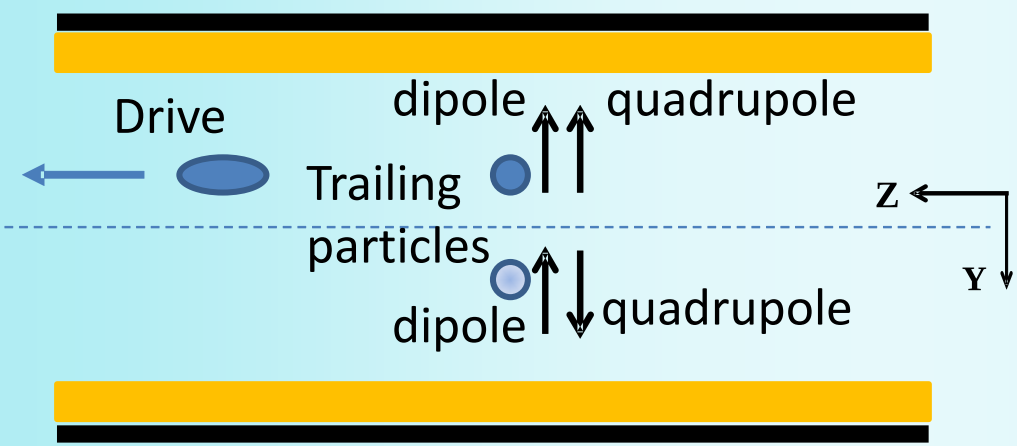


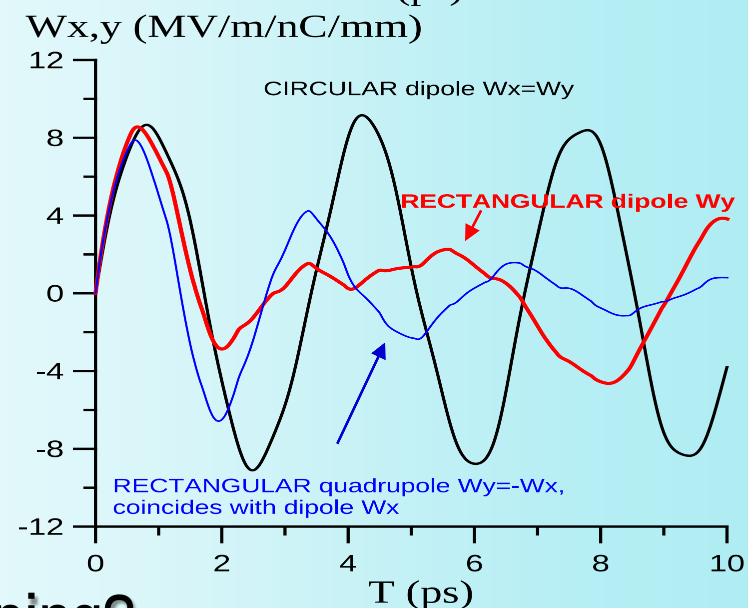
Planar waveguide (weaker dipole wake for a flat bunch)



(a=1.5 mm, b = 1.584 mm, W=8 mm, ε=5) selected to obtain the same W_z as in the circular geometry



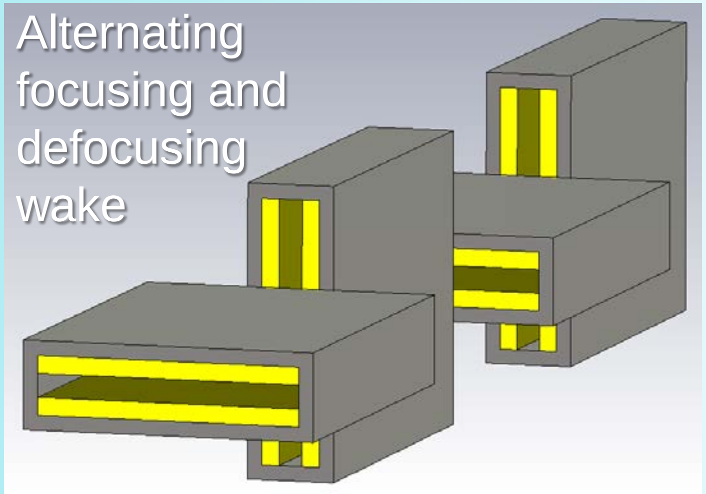


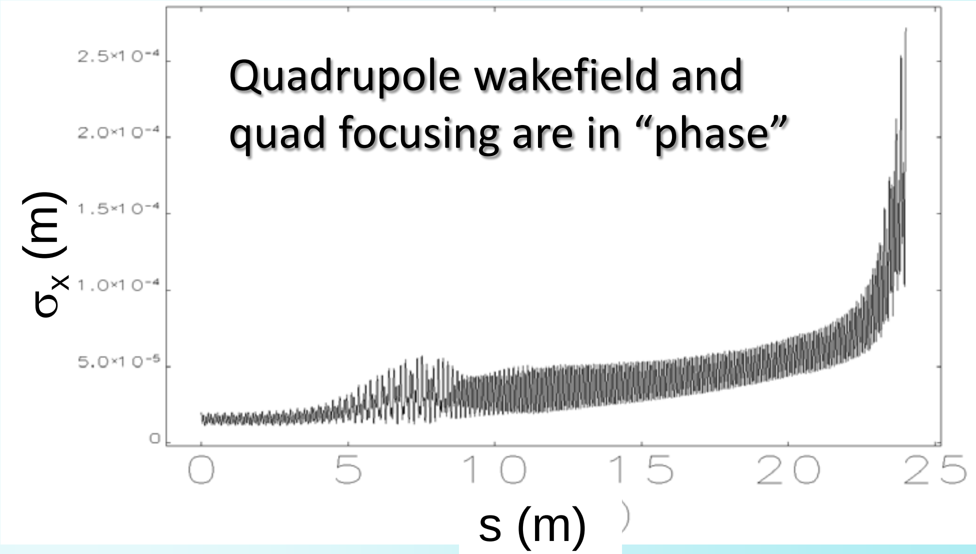


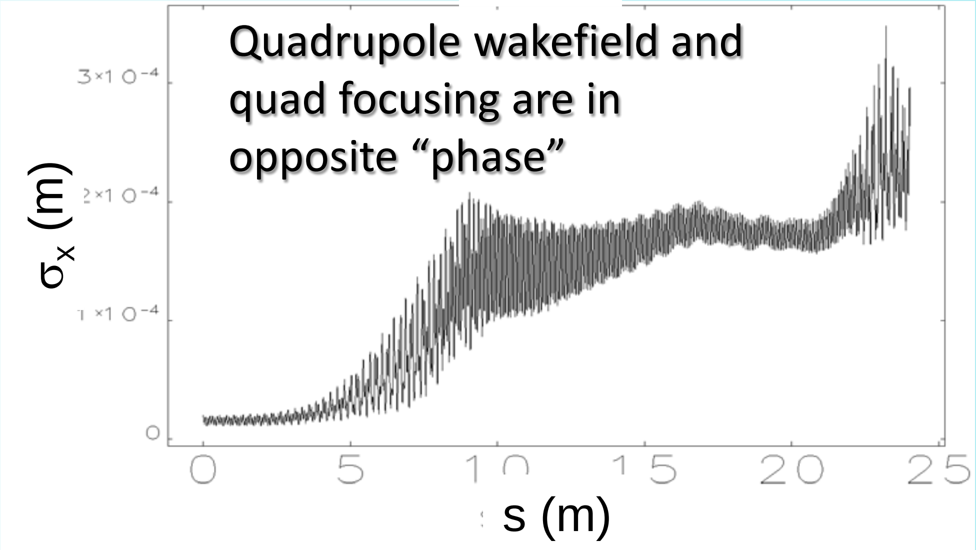
Even on-axis drive bunch will excite the quadrupole wake

Can quadrupole wake produce BNS-like damping?

Is there confinement by a quadrupole wake?







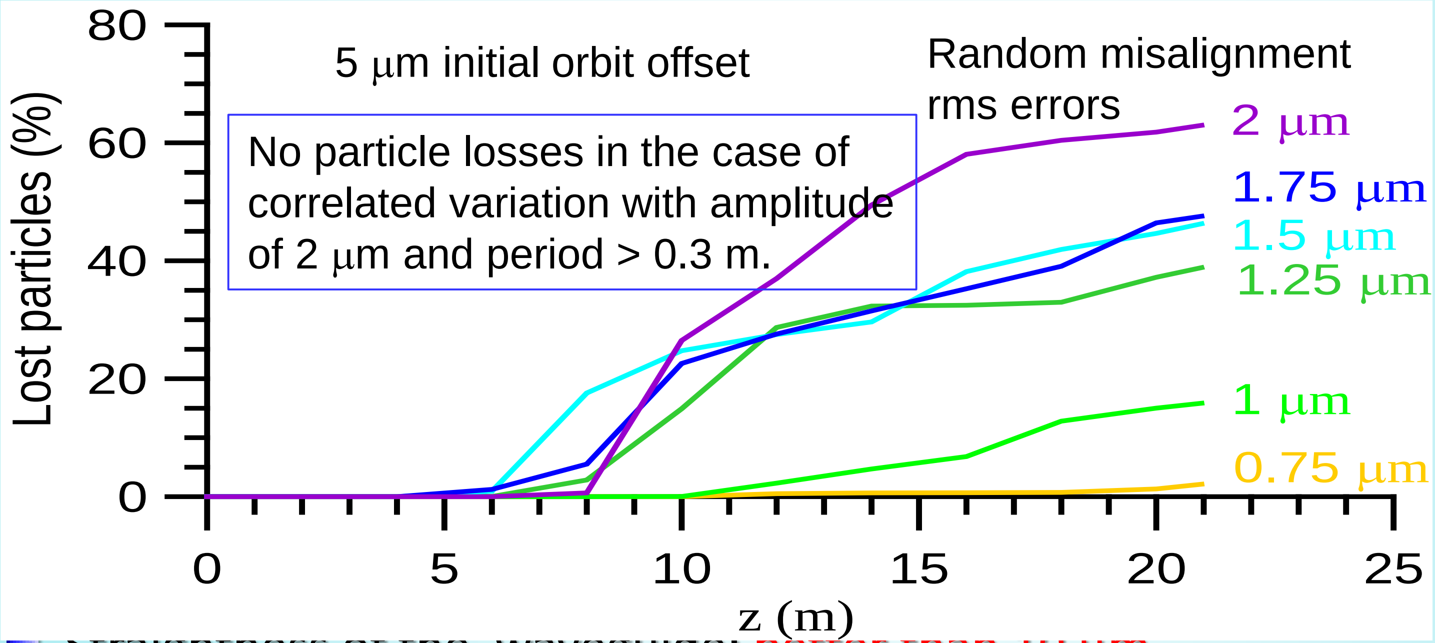
Not much.
Although slightly weaker quads can be used to control BBU *)

*) Shchegolkov, Simakov, Zholents, IEEE Trans. on Nucl. Science, **63**, 804(2016)

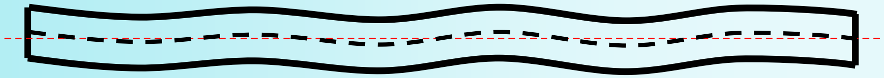
PROTOTYPING AND EXPERIMENTING

Tolerances

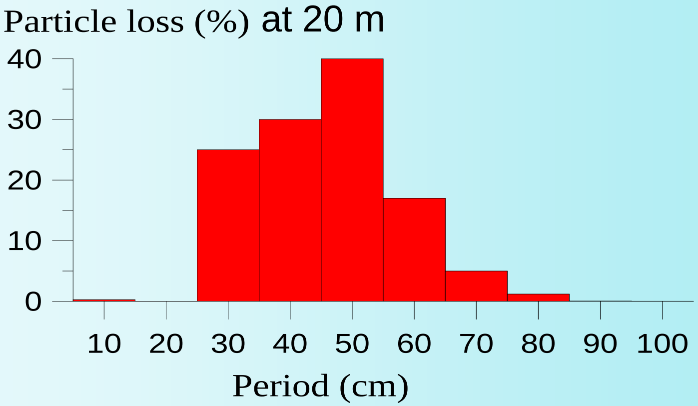
- Misalignment of FODO quadrupoles (or trajectory) < 1 μm



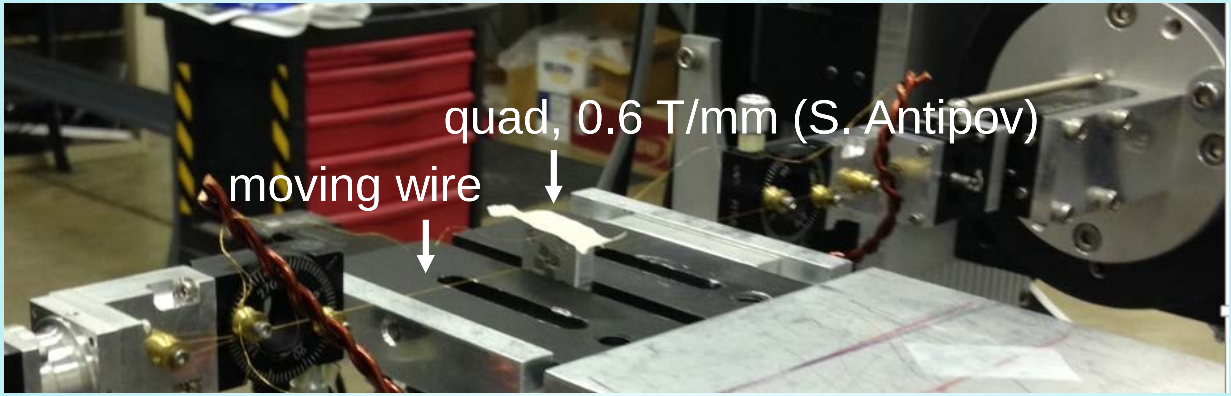
- Straightness of the waveguide: better than 10 μm

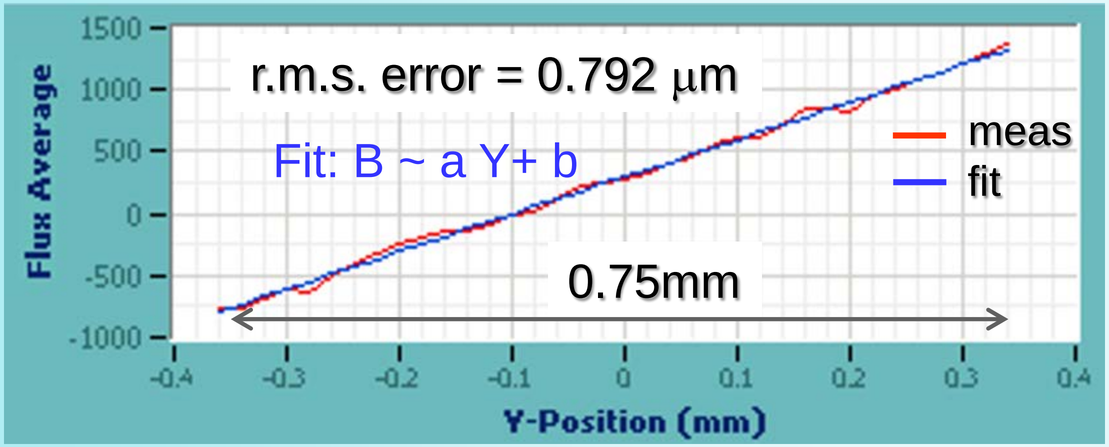


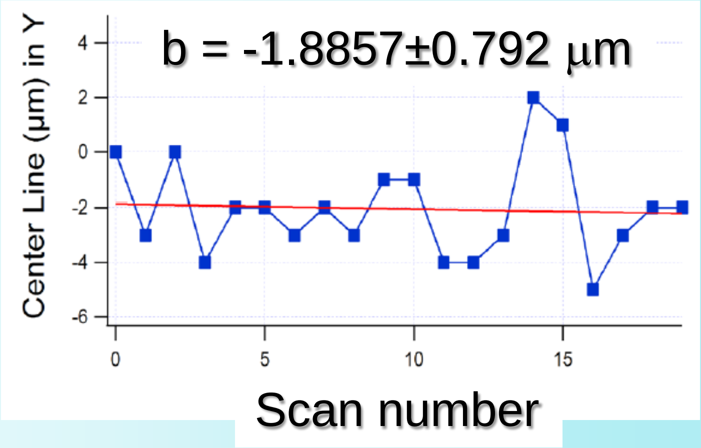
Maximum amplitude is 10 μm and the period is varied



Measurement of quad's magnetic center with a sub-μm precision*







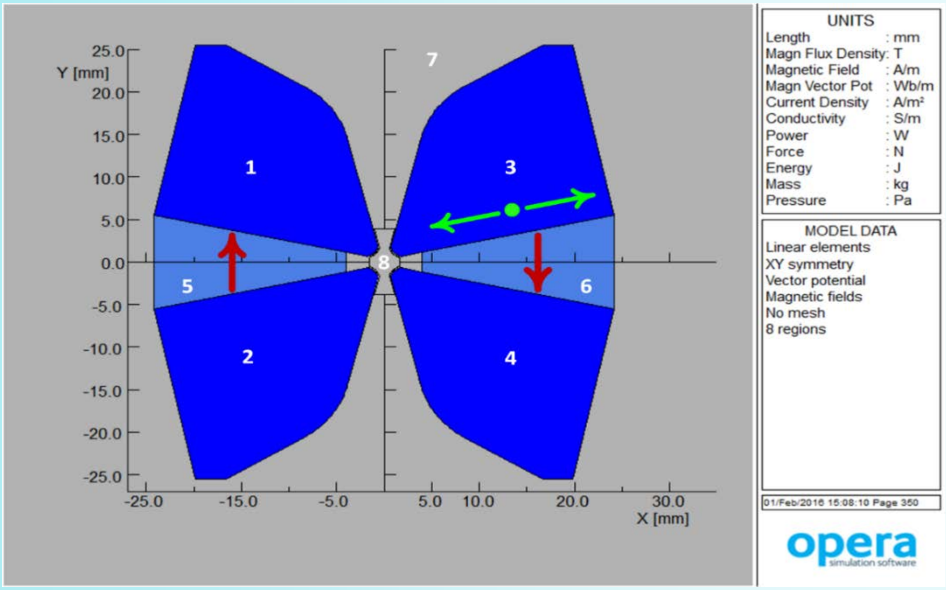
Transverse field distribution in 0.75-mm aperture quad

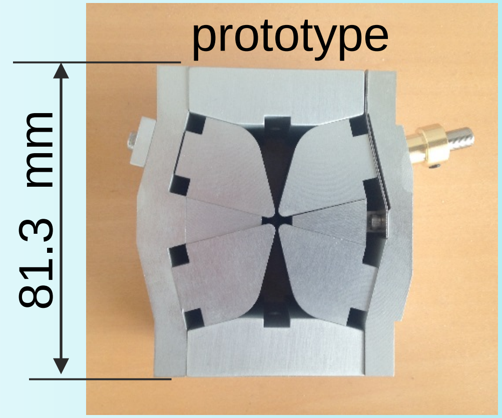
Pulsed wire technique will be used for a quadrupole wiggler

*) I. Vasserman, J. Xu, APS MD-TN-2016-003

Adjustment of quad's magnetic center with a sub-μm precision*

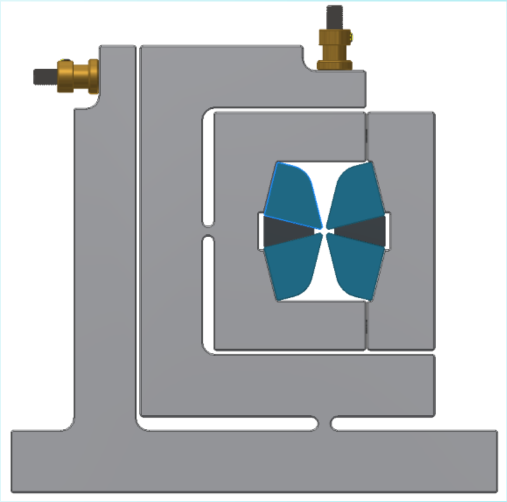
First variant





±50 μm adjustments of the magnetic poles 1 and 3 shift magnetic center by ±24 μm in x and ±6 μm in y

Second variant

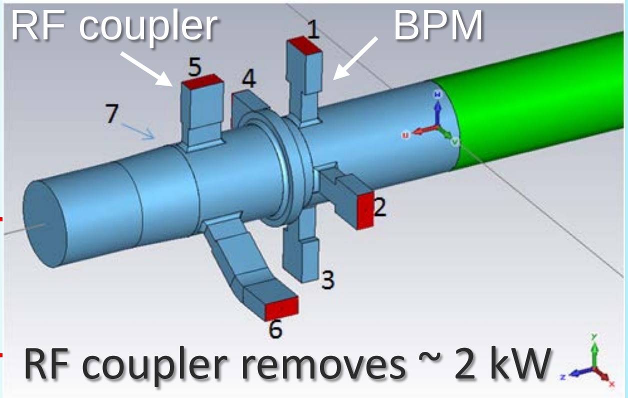


*) Design team:
Doran, Shiroyanagi. Strelnikov, Trakhtenberg, Vasserman , Xu, Zholents

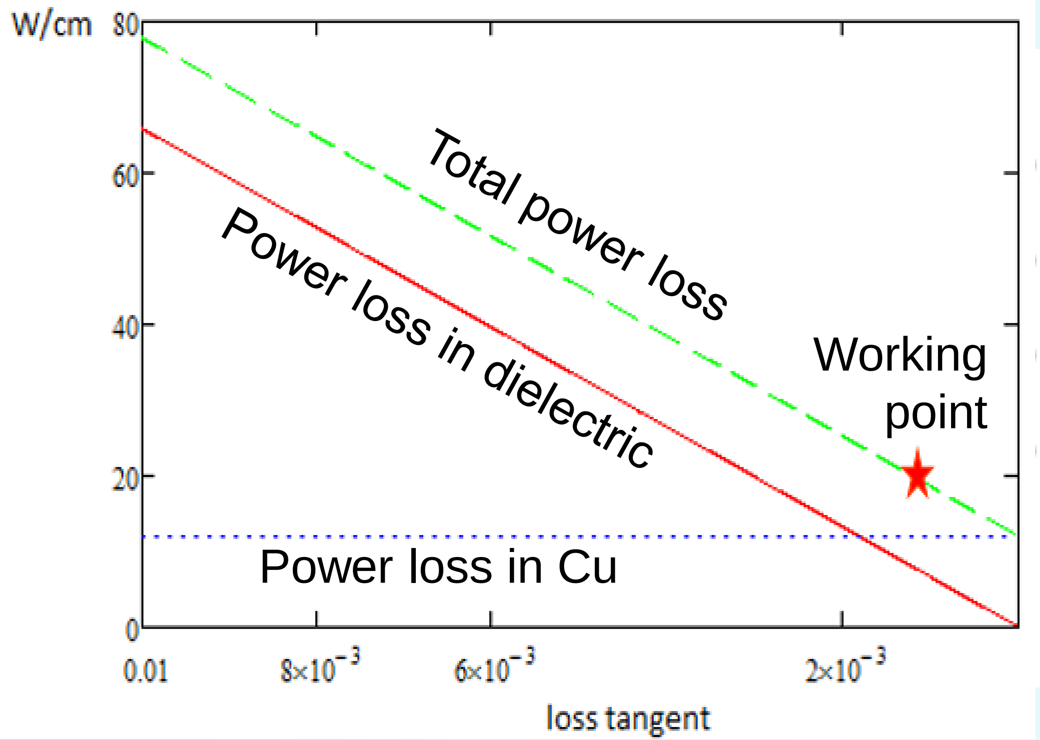
Vacuum chamber

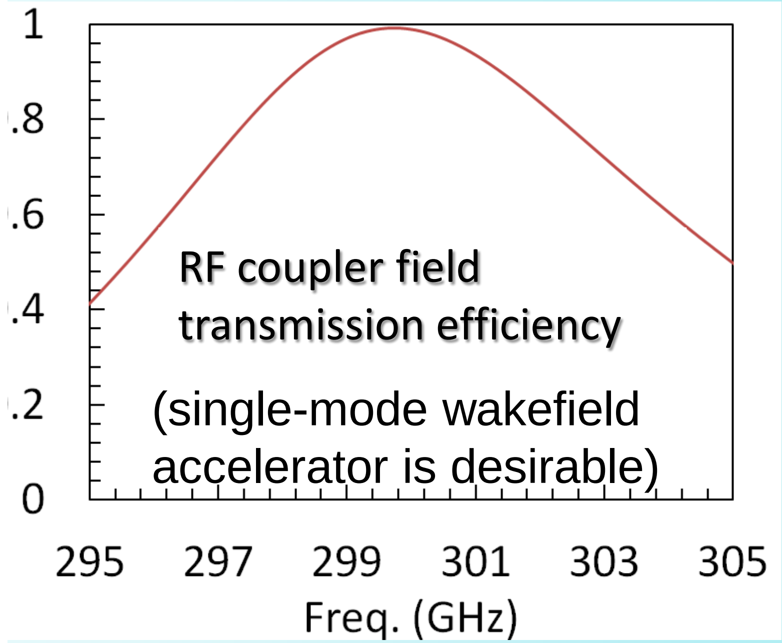
Q_drive	8	nC
Q_witness	0.3	nC
f_rep	50	kHz
E_drive	400	MeV
R	5	
P_wall_loss	20	W/cm

RF main mode and HOM coupler every 0.5 m



Beam power in: (160 kW drive + 6 kW witness)
Beam power out: (32 kW drive + 30 kW witness)





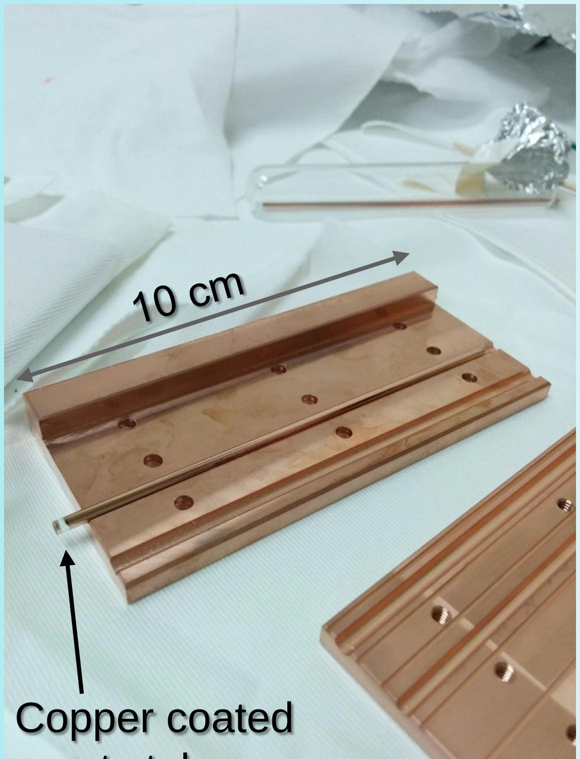
Dielectric Lined Waveguide

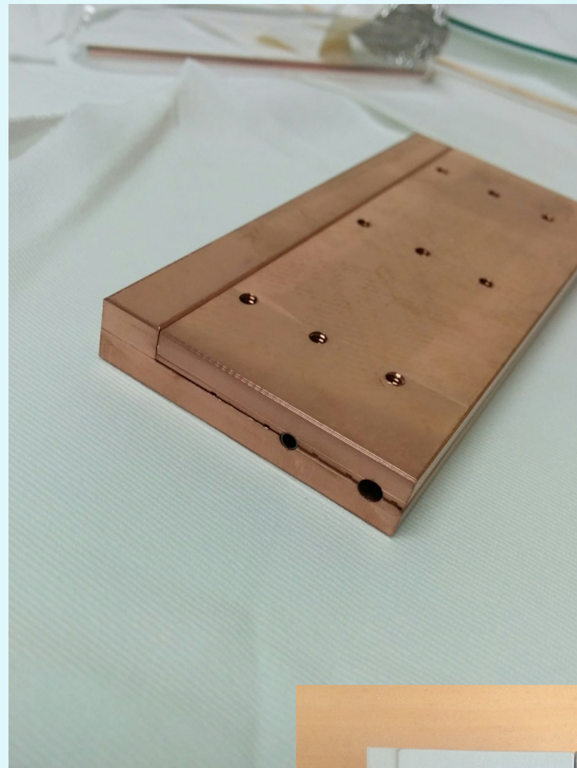
Dielectric Charging by Loss Electrons

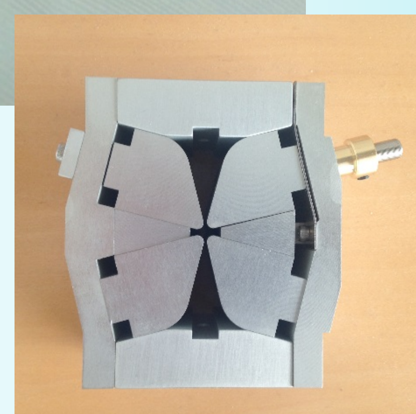
- Provide surface conductivity
  - TiN ultrathin film (<10 nm) coating

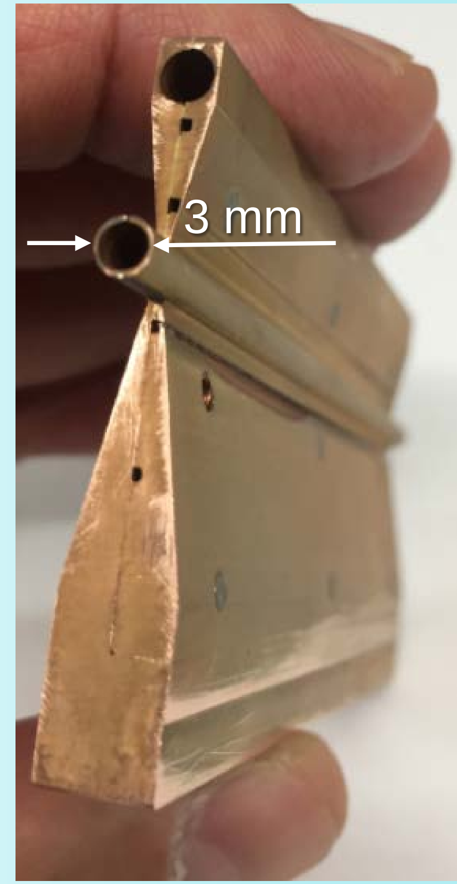
- Drain charge from the bulk
  - Material by design: attain properties of perfect dielectric at THz frequencies and DC conductivity
  - Candidate material: zinc metaniobate ($ZnNb_2O_6$), works at (10-150) GHz
  - Explore CVD diamond with doping

Vacuum chamber prototyping









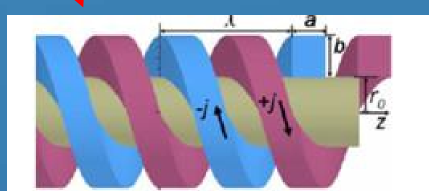
FEL

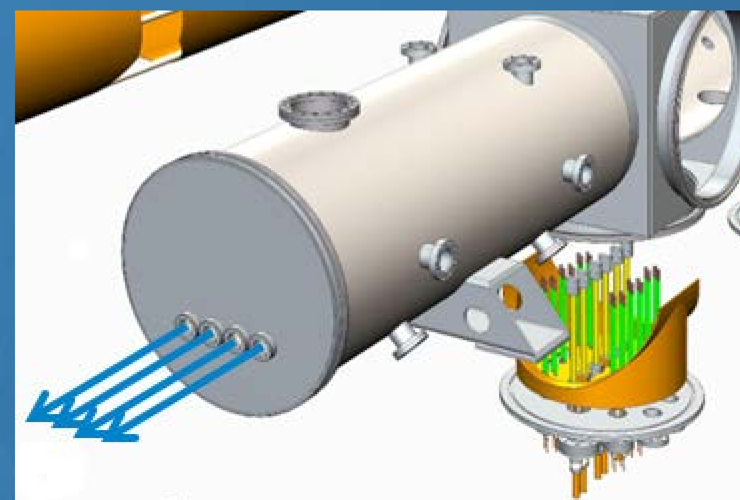
Small Period Undulator

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

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

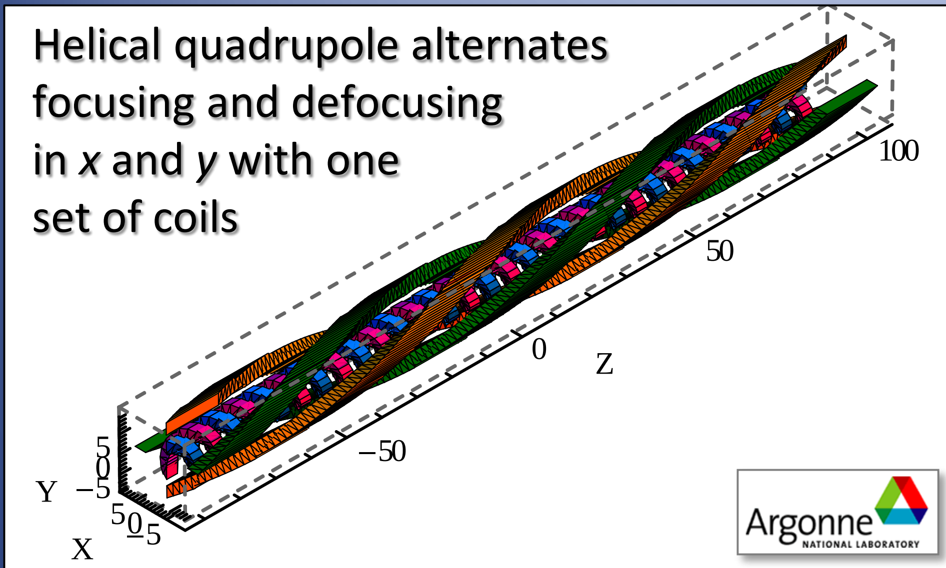
A promising technology is a helical superconducting undulator

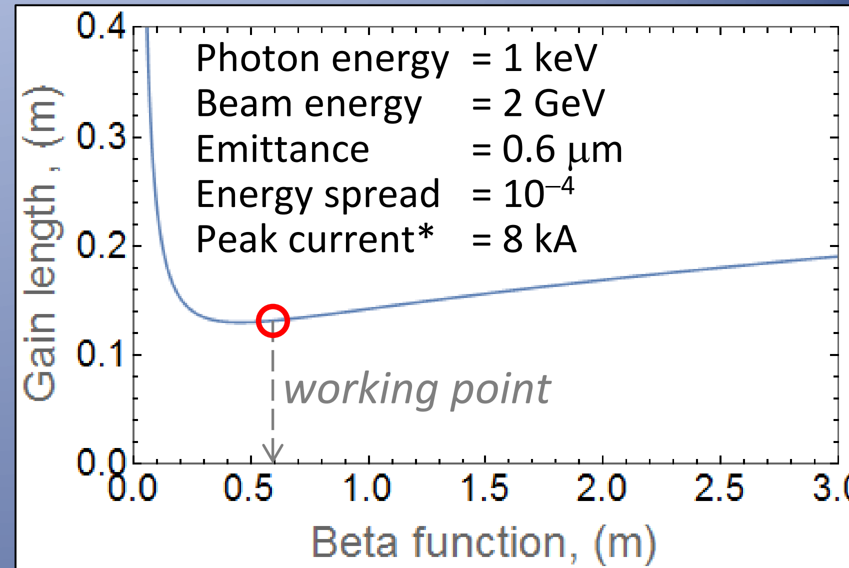




- Innovative concept of multiple helical undulators sharing one cryostat
- Supplemental helical quadrupole winding will ensure a superior FEL performance
- Expected period ~ 10 mm (for 2 mm vacuum bore)

Helical Undulator Combined with Helical Quadrupole





Soft x-ray gain-length (Ming-Xie).

Soft x-ray FEL und. parameters with $\beta = 0.6$ m.

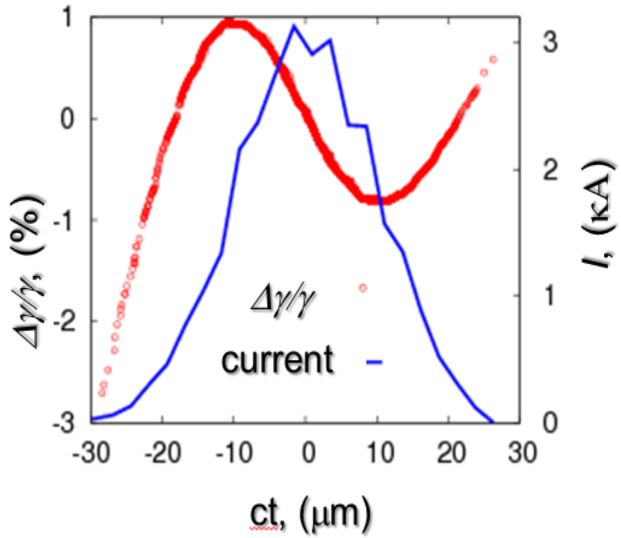
Parameter	dipole helical coils	quadrupole helical coils
Period length (mm)	12	900
Vacuum bore diameter (mm)	2	-
Winding bore diameter (mm)	3	12
Peak magnetic field (kG)	13.4	-
Peak field gradient (kG/cm)	-	15.4

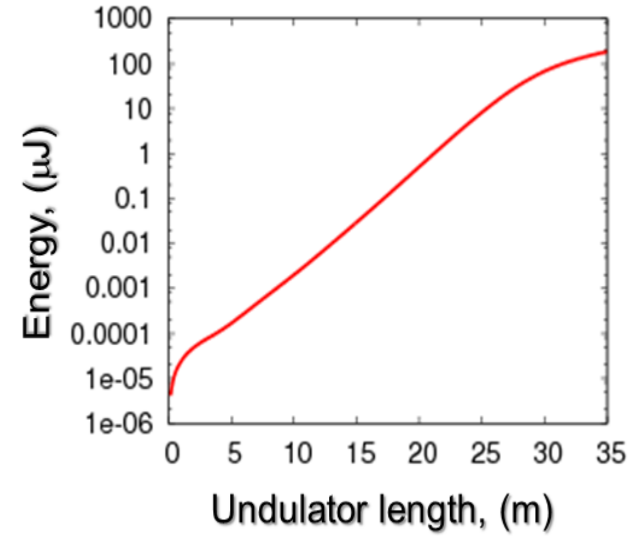
A small beta-function in the undulator helps to realize the full potential of ESASE

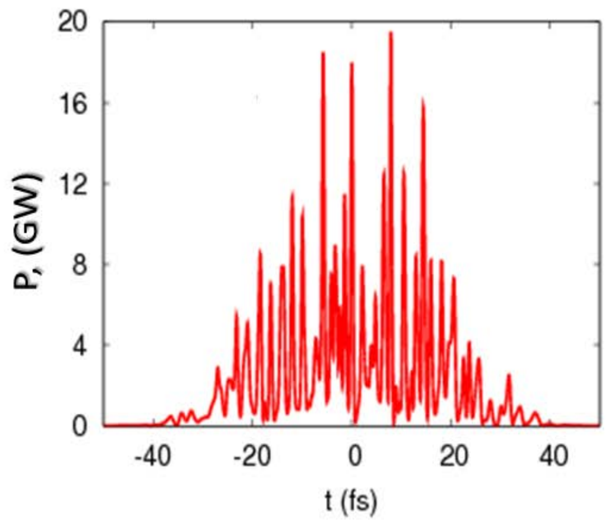
* after ESASE current enhancement ×8

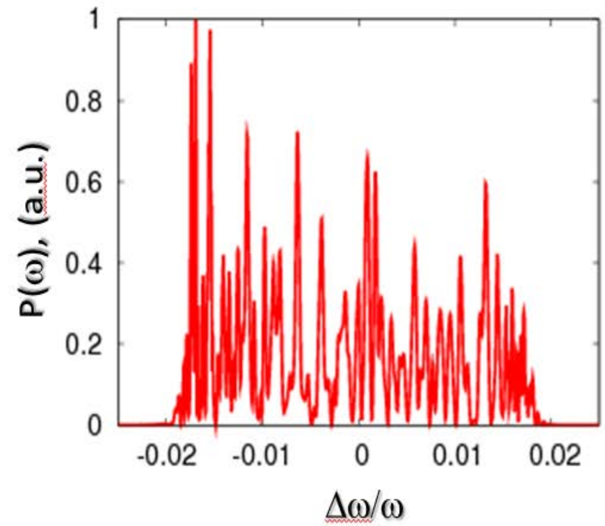
FEL simulations (illustration)

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







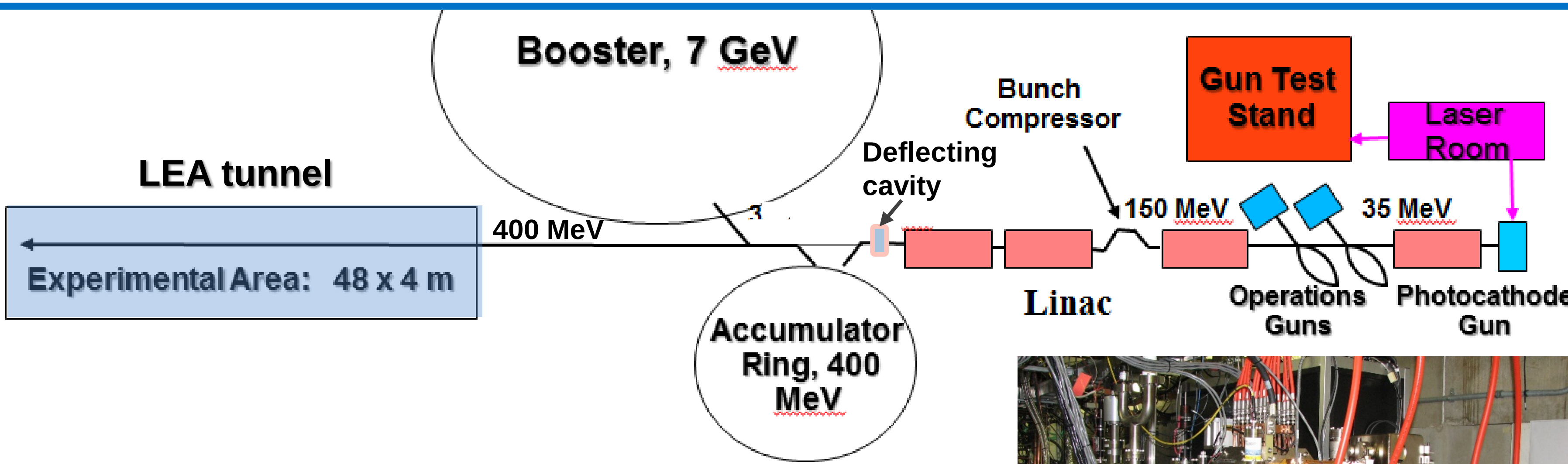


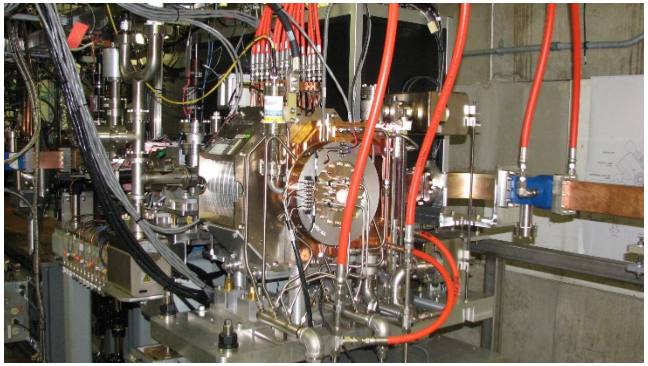
NEAR TERM PLANS

"You must first understand where you are and where you need to go."

-From *The Art of War* by Sun Tzu

Linac Extension Area at APS





PCgun installed at the head of the Linac

Beam parameters in LEA tunnel

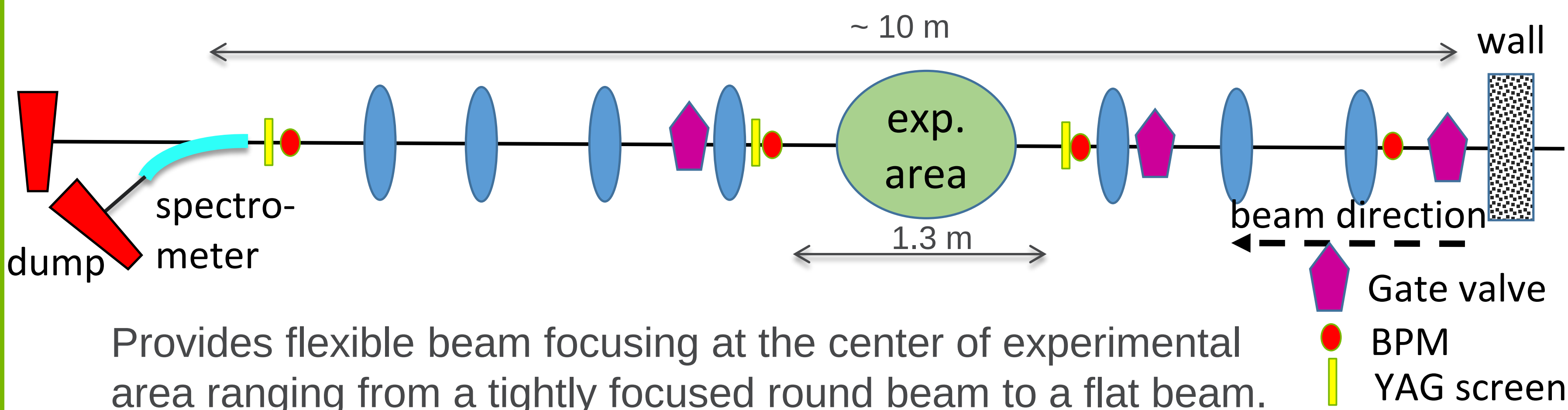
Electron beam energy	300-450 …500 MeV
Electron bunch charge	50 – 500 … 1000 pC
Beam emittance	0.5 – 1.5 mm-mrad
Beam energy spread	250 – 500 keV
Bunch length	100 – 1000 fs
Bunch rep. rate	6 – 30 Hz

Laser (Nd:Glass)

Wavelength	1053 nm
Pulse energy	2 – 5 mJ
Pulse length	1 – 4 ps

LINAC EXTENSION AREA (LEA)

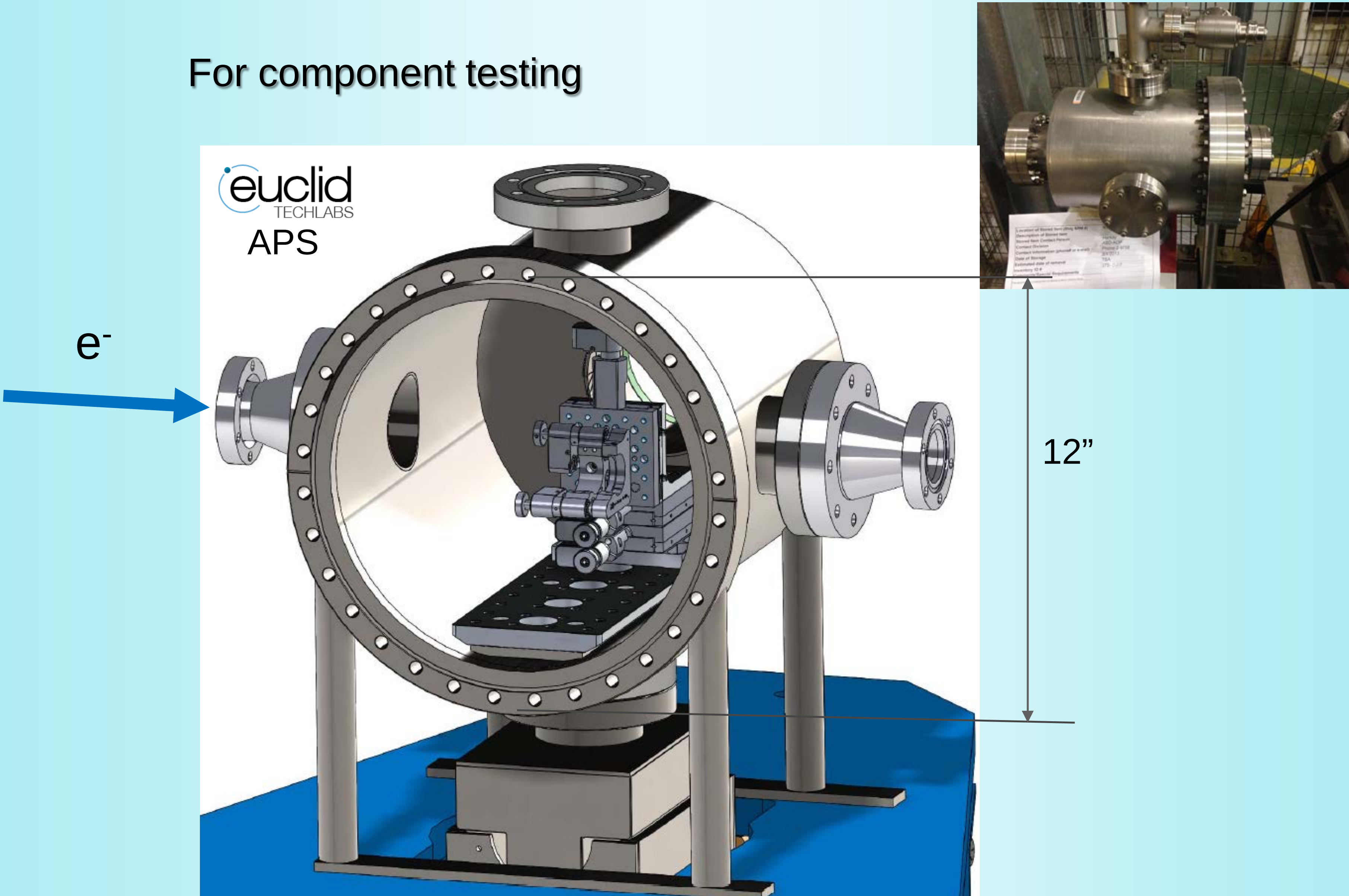
Reconfiguring the existing beamline with both old and new components



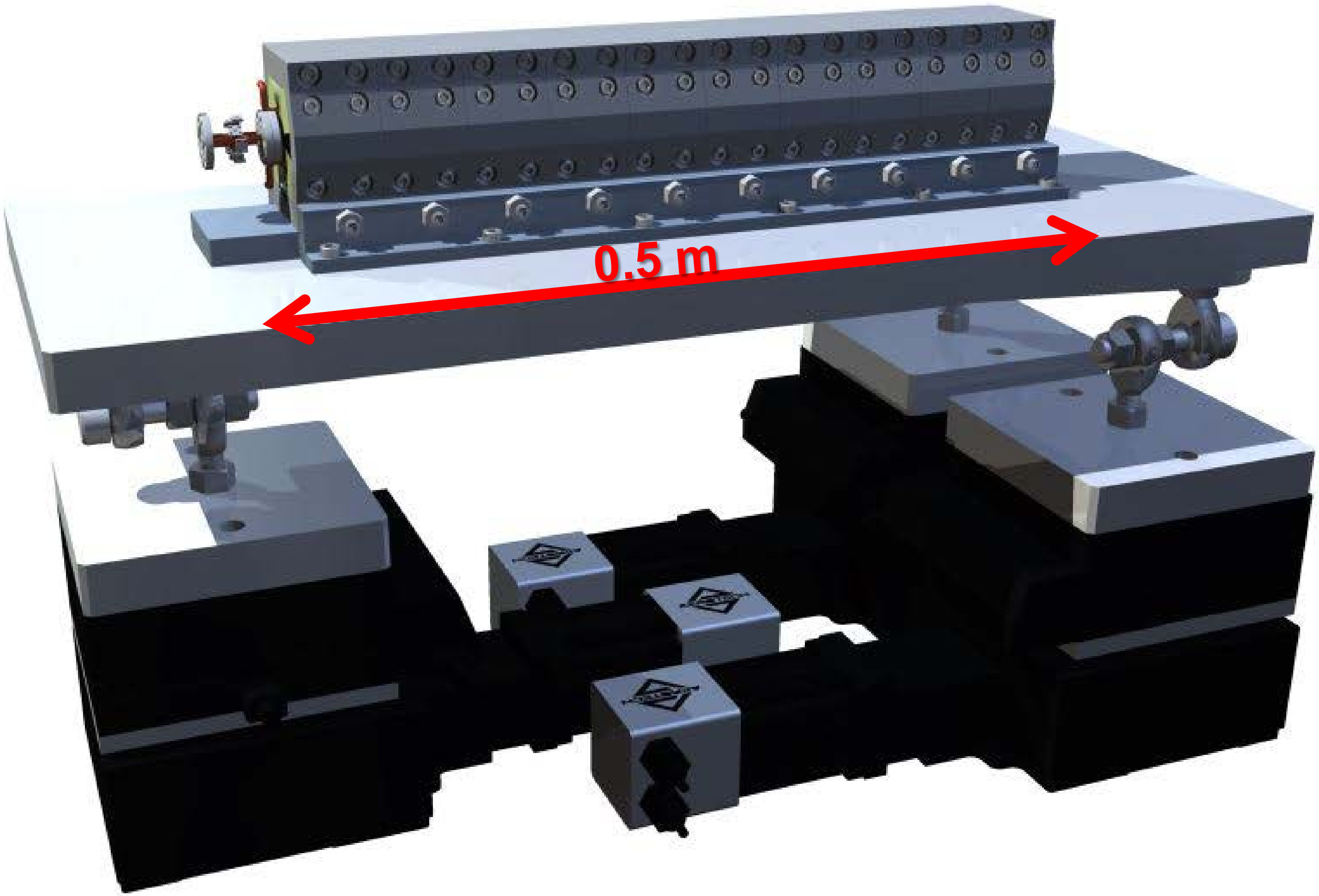
Provides flexible beam focusing at the center of experimental area ranging from a tightly focused round beam to a flat beam.

Experimental Chamber

For component testing



The initial goal is to build a 0.5 m long accelerator unit and test it in LEA tunnel using APS injector linac

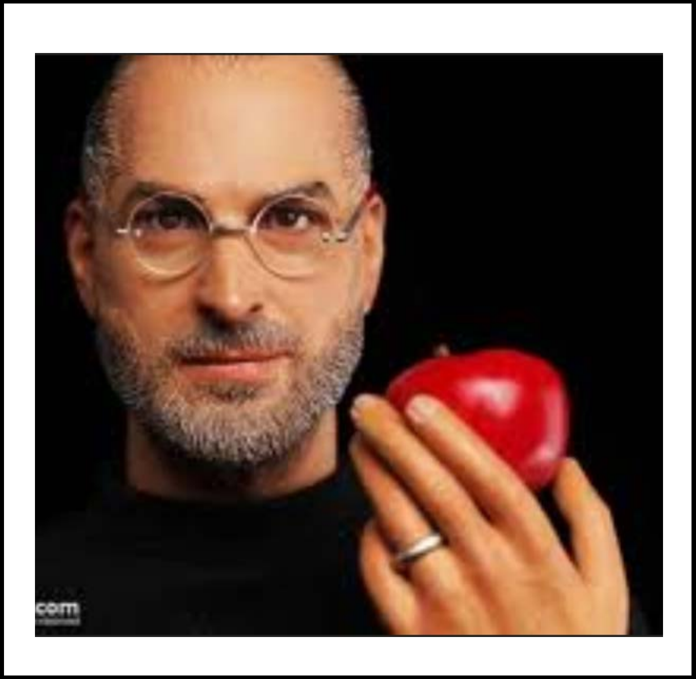


Will test:
alignment tolerance <0.75 μm rms quad-to-quad and <2 μm rms module-to-module

LONG TERM PLANS

“The best way to predict the future is to invent it”

Steve Jobs



A Preliminary Roadmap to a Compact FEL Facility

2016	2018	2020	2022	2024	2026	2028	2030

- **Continued Discovery and Innovations**
- **Structure or Plasma Wakefield accelerator**

Main accelerator

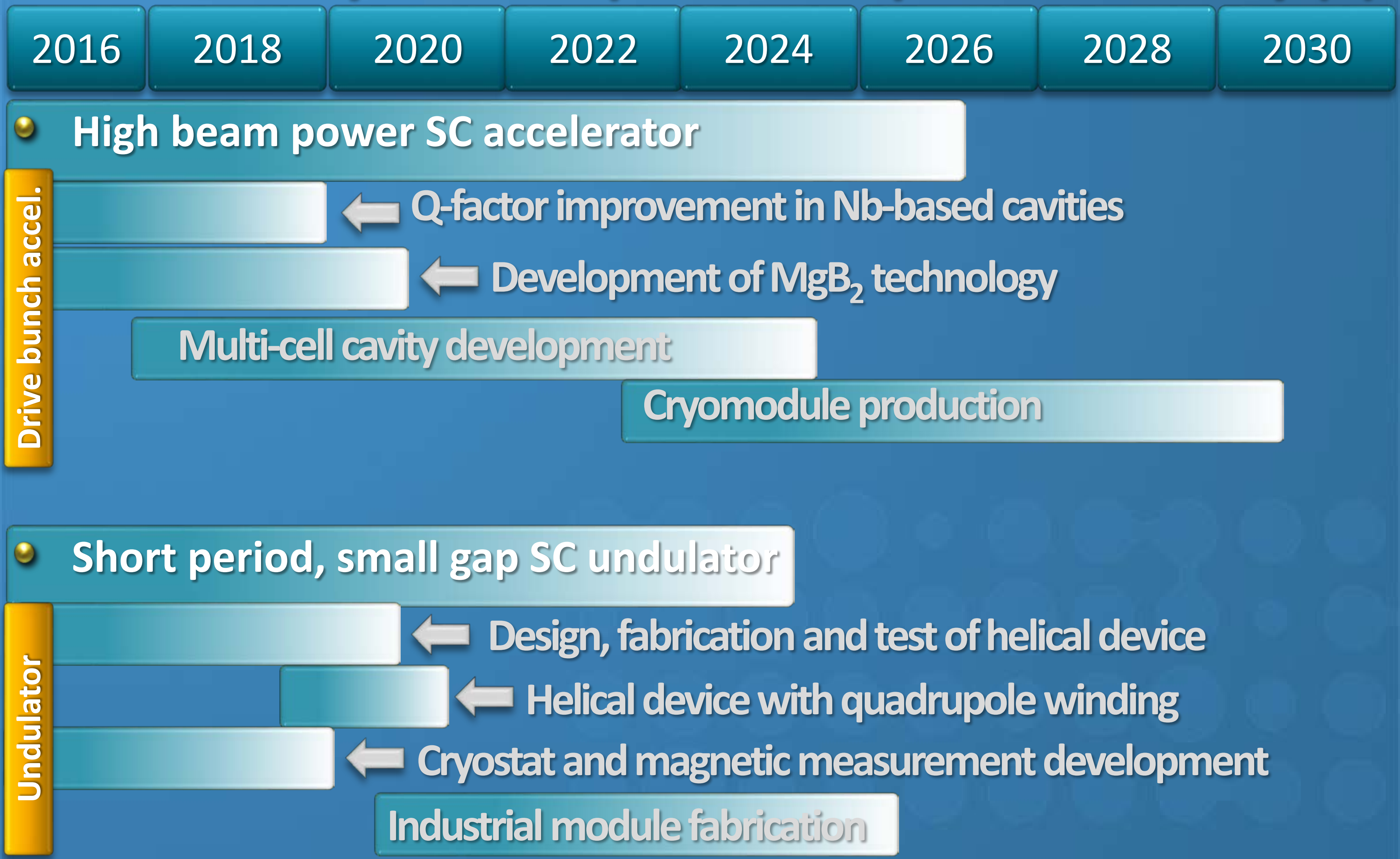
- Concept development
- Design of the accelerator module
- Prototyping and testing
- Single stage accelerator for soft x-rays
- More stages, hard x-rays

- **Electron source**

Injector

- High charge, high repetition rate electron gun
- Drive and witness beam shaping and manipulation
- Demonstration of high transformer ratio
- Full scale prototype

A Preliminary Roadmap to a Compact FEL Facility (2)



A Preliminary Roadmap to a Compact FEL Facility (3)

2016	2018	2020	2022	2024	2026	2028	2030

SASE, Seeded FELs

- **Continued FEL developments**
  - Innovation and modeling
  - Adapting FEL to wakefield accelerator
  - Seeded FELs prototyping and testing
  - Single stage accelerator for soft x-rays

In place of conclusion

Are you looking for a challenging task?
Join the effort!

Thank you for your attention