Compact Electron Acceleration and Bunch Compression in THz Waveguides

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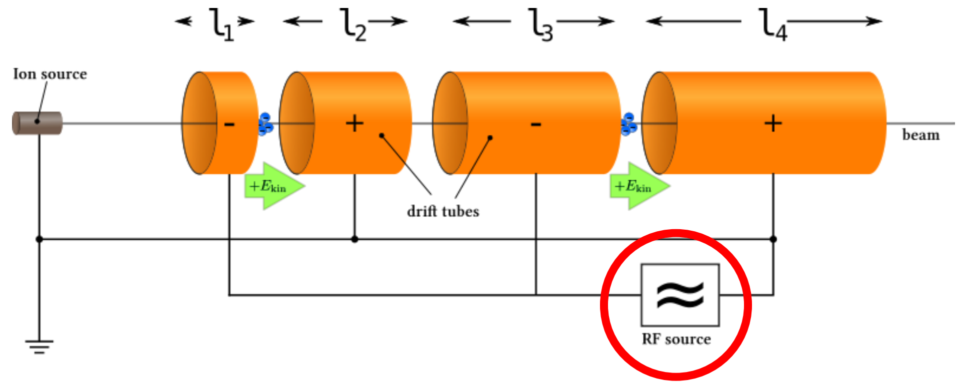
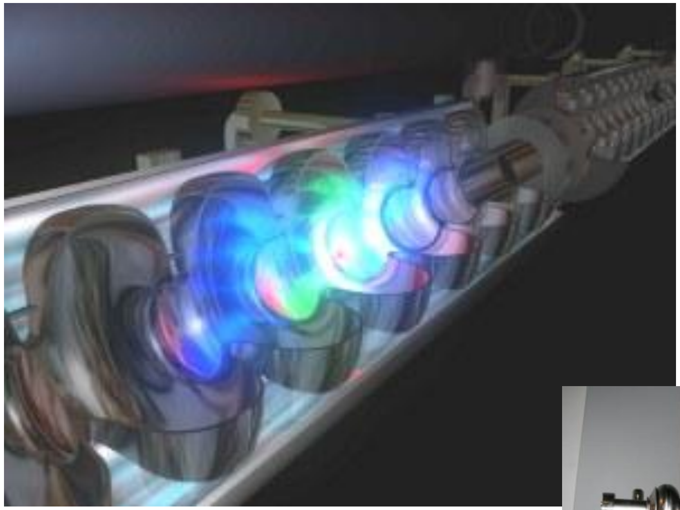
29. April 2014

- Motivation
- THz acceleration of electrons
- Bunch acceleration in THz waveguide
  - Optimization
  - Bunch calculations
- Bunch Compression in THz waveguides
  - Rectilinear compression
  - Bunch calculations
- Conclusion

1920s: Proposing the idea of acceleration using oscillating fields



Electron gains energy from cascaded cavities along the acceleration line.



The basic concept of the various modern accelerators

Motivation

Modern accelerators are based on RF technology and operate in this wavelength regime.

Is RF frequency domain the optimum choice for acceleration?

Some advantages:

- Available high-Q cavities
- Available efficient sources
- Acceleration of big bunches

Some disadvantages:

- Large dimensions for high energies
- Great number of devices for power supply

Decreasing the operation wavelength results in smaller required cavities.

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Less energy is needed for filling the cavities and acceleration.

Extensive studies were carried out recently on optical acceleration of particles.

PHYSICAL REVIEW E 70, 016505 (2004)

Optical Bragg accelerators

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(Received 4 November 2003; revised manuscript received 26 January 2004; published 23 July 2004)

Enhancing X-Ray Generation by Electron-Beam–Laser Interaction in an Optical Bragg Structure

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(Received 16 April 2008; published 12 January 2010)

SCALING LAWS OF A DIELECTRIC OPTICAL ACCELERATOR

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Problem: Small cross section of optical beams ⇒ acceleration of a very small amount of charge is feasible using laser-plasma acceleration.

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THz acceleration of particles seems to be a good candidate.

Motivation

The main challenges in this regime:

1. Large loss of the materials
2. Limited available THz *high power* sources

The second difficulty is recently tackled by using optical rectification techniques to design THz sources.

February 15, 2012 / Vol. 37, No. 4 / OPTICS LETTERS

Generation of sub-mJ terahertz pulses by optical rectification

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Received October 3, 2011; revised December 19, 2011; accepted December 21, 2011; posted December 23, 2011 (Doc. ID 155578); published February 8, 2012

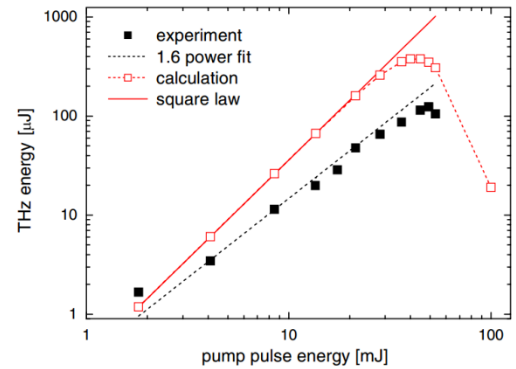

Fig. 1. (Color online) Measured and calculated THz energy versus pump energy.

Short THz pulses can be efficiently generated from a reasonable laser intensity.

We need to accelerate electrons using short pulses.

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We are no more in the continuous wave (CW) regime.

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Pulse Acceleration of Electrons should be studied.

Let us consider one electron experiencing a pulse with a longitudinal Gaussian field:

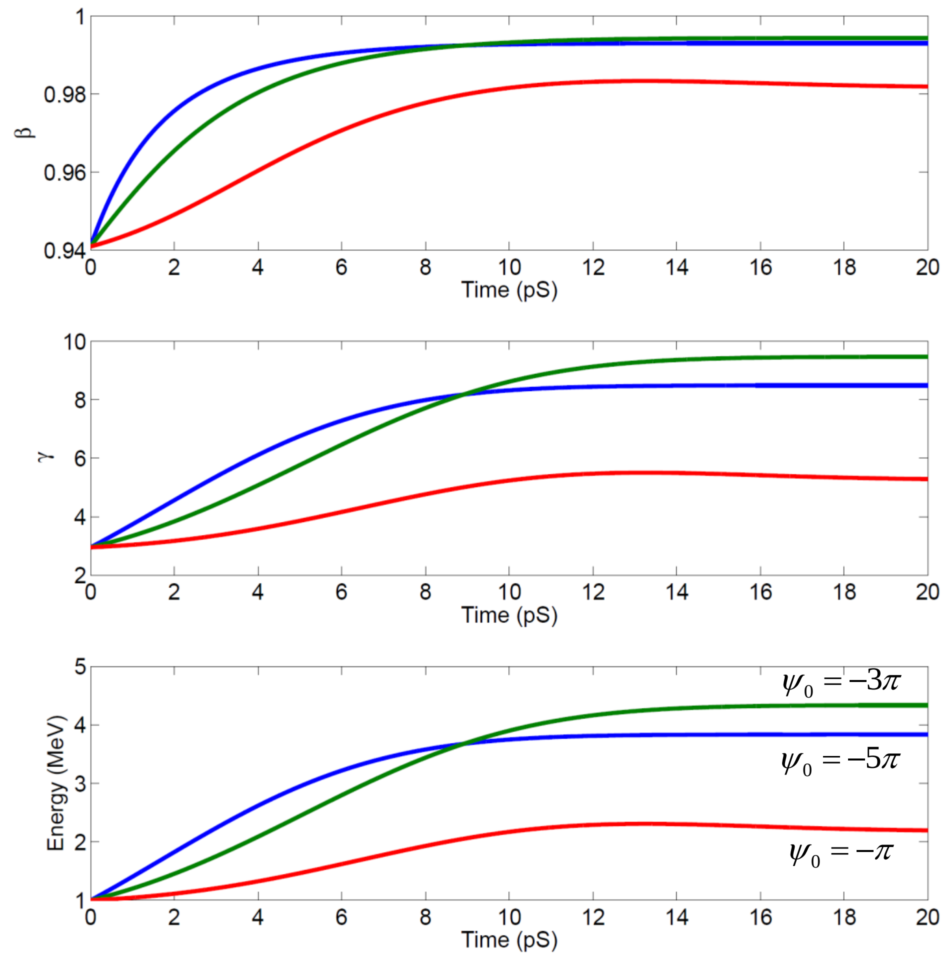
$$\begin{aligned} \frac{d\beta}{dt} &= -\frac{eE_0}{mc\gamma^3} \exp\left[-4\ln 2\left(\frac{t - z/v_g}{\tau}\right)^2\right] \cos(\omega t - kz + \psi_0) \\ \frac{dz}{dt} &= \beta c, \qquad \text{with} \qquad z|_{t=0} = z_0 \quad \text{and} \quad \beta|_{t=0} = \beta_0 \end{aligned}$$

THz Acceleration of Electrons

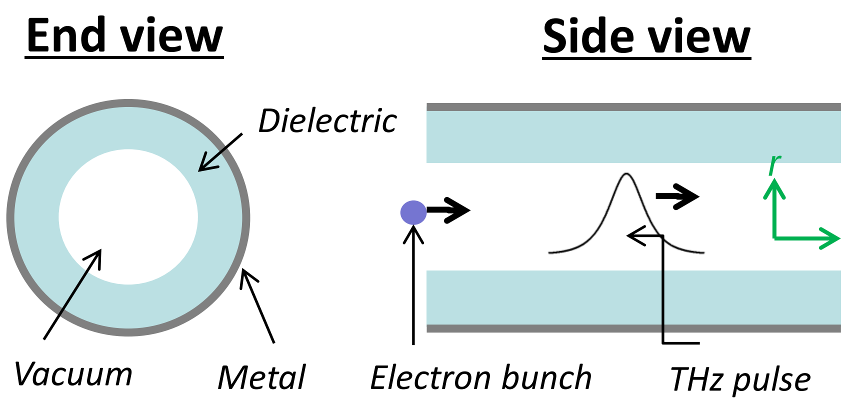
In contrast to the CW regime, we solve the equations numerically.

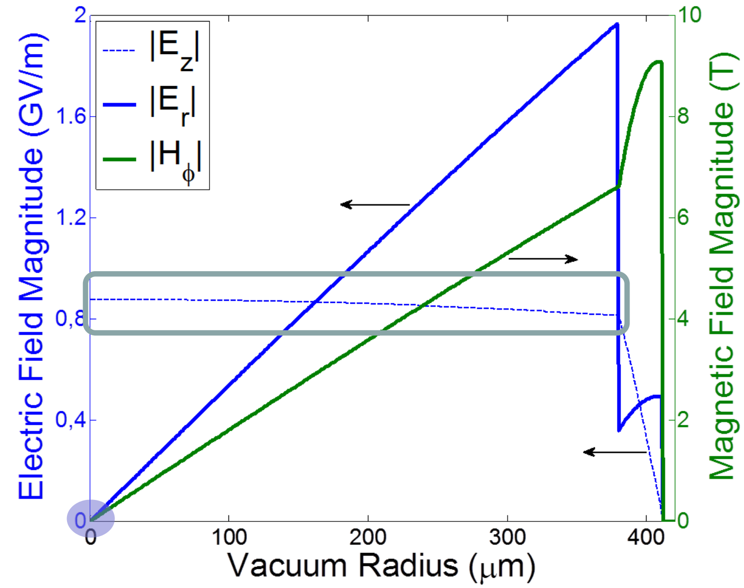
Let us assume the following parameters:

Accelerating field	$E_0 = 1.5\mathrm{GV/m}$
Phase velocity	$v_p = 0.99c$
Group velocity	$v_p = 0.53c$
Operation frequency	$f = 600\mathrm{GHz}$
Pulse duration	$\tau = 5/f$
Initial energy	$KE_0 = 1\mathrm{MeV}$



Good for some applications such as compact X-ray sources and electron diffraction imaging



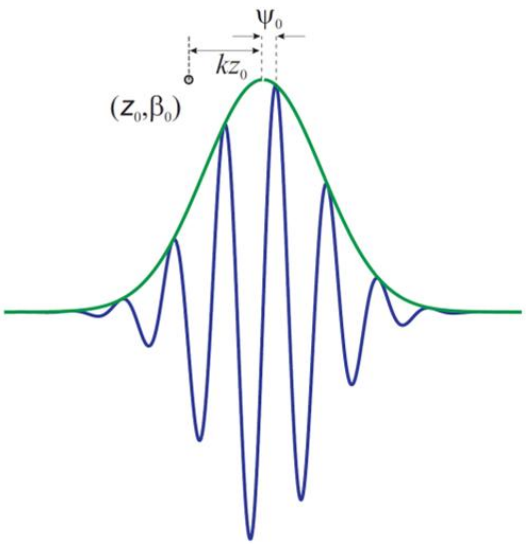


Uniform longitudinal field at b=1

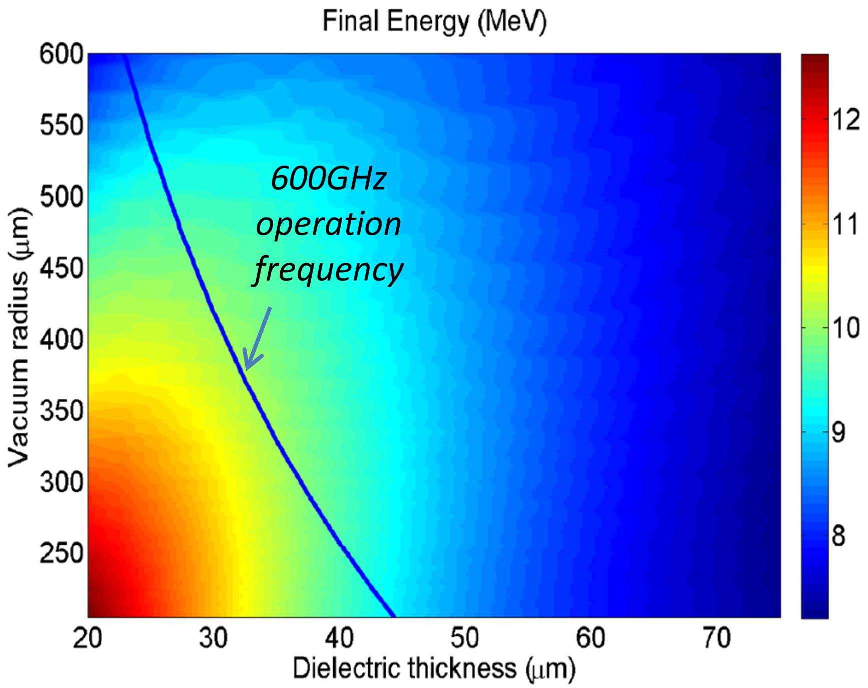
$$E(z,r,t) = E_0 J_0\left(\sqrt{k_0^2 - \beta^2} r\right) e^{-\alpha z} \Re\mathfrak{e} \left\{ \frac{\tau \exp\left[-2\ln 2\left(\frac{(t - z/v_g)^2}{\tau^2 - j4\ln 2 \cdot \mathrm{GVD} \cdot z}\right)\right]}{\sqrt{\tau^2 - j4\ln 2 \cdot \mathrm{GVD} \cdot z}} e^{j(\omega t - kz + \psi_0)} \right\}$$

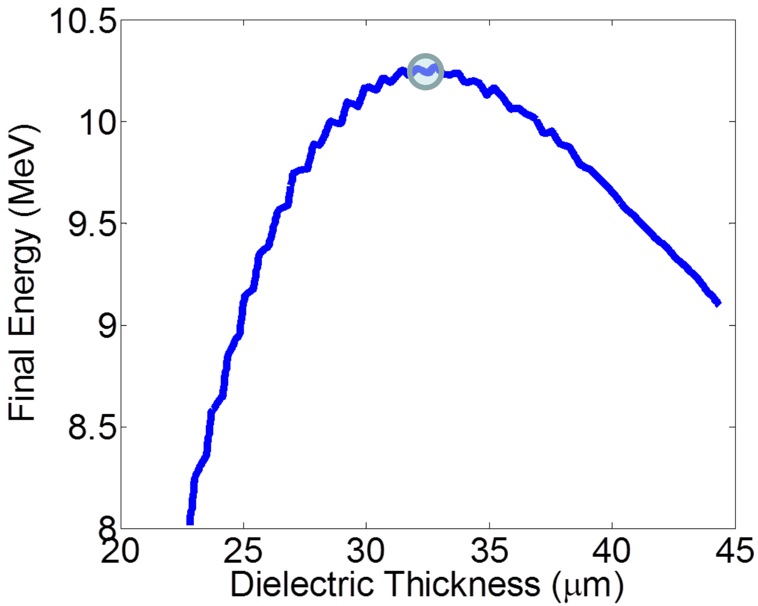
Optimization

- Very many parameters are involved in the acceleration level of electrons: v_p, v_g, GVD, a, z_0 and ψ_0
- Best fitness function for optimization: *final energy of one electron*
- We numerically solver the problem of one electron.
- Final energy of the electron is used as the figure of merit for the group of parameters.



$$\begin{aligned}\beta_{n+1} &= \beta_{n-1} - \frac{2eE(z,0,t)\delta t}{mc\gamma_n^3} \\ z_{n+1} &= z_{n-1} + 2\beta_n c\delta t\end{aligned}$$





Optimum frequency of optical rectification is assumed to be 600GHz.

Vacuum radius 380μm

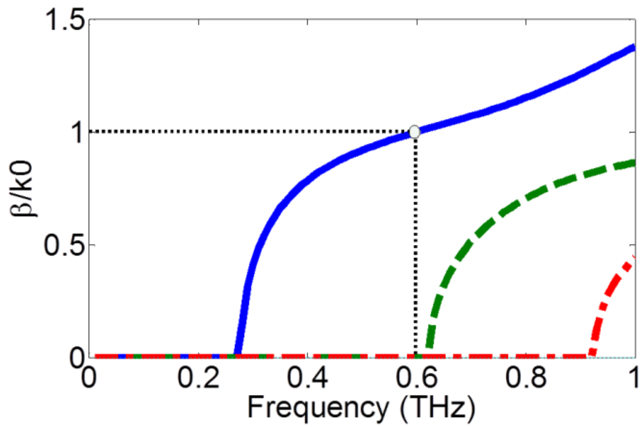
Dielectric thickness 32μm

Electron bunch acceleration

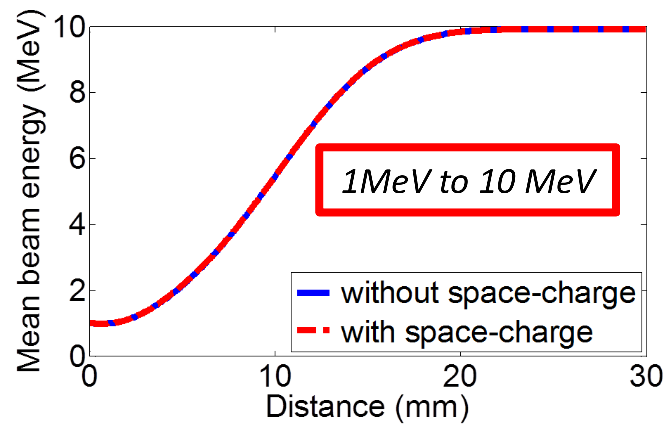
- Update of electron motion with time: Cash-Karp Runge-Kutta method
- Generating a bunch of electrons with Gaussian distribution: Box-Muller method.
- Very large number of particles (10^7): we use *macro-particles*.
- We consider the following initial condition:
  - Mean initial energy = 1MeV
  - Initial energy spread = 0.1%
  - Initial bunch spread is a cube of $30\mu m \times 30\mu m \times 30\mu m$

THz Acceleration in waveguides

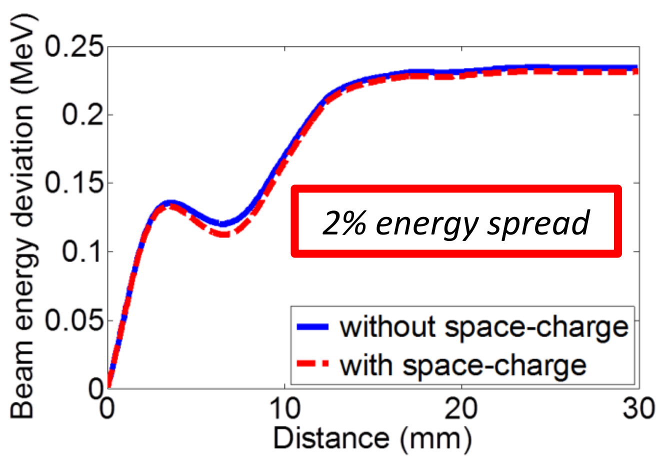
Dispersion curve



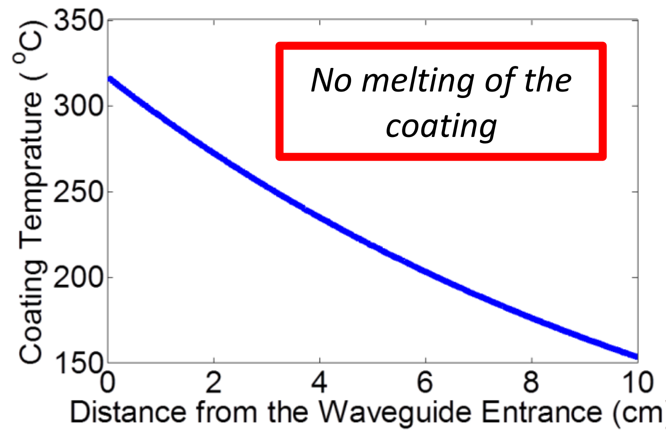
Energy of a bunch (20mJ THz pulse)



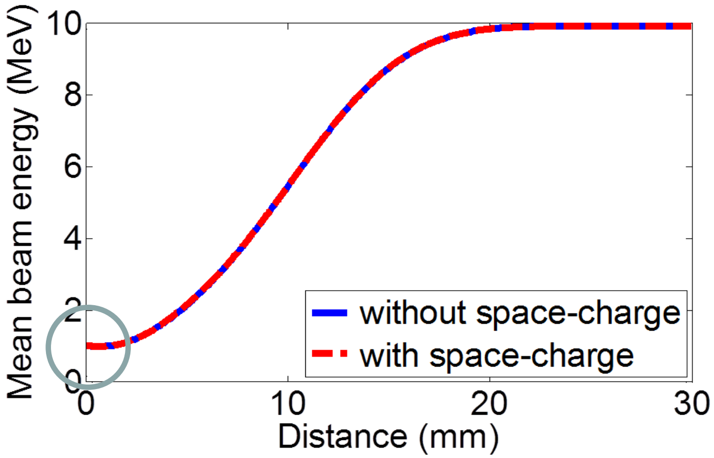
Energy spread in a bunch



Temperature of the coating



Energy of a bunch (20mJ THz pulse)



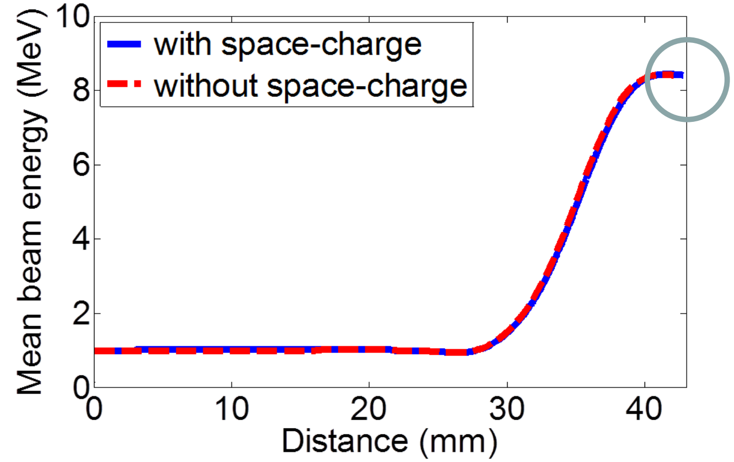
Electron is injected in a point within the pulse

It is not possible practically

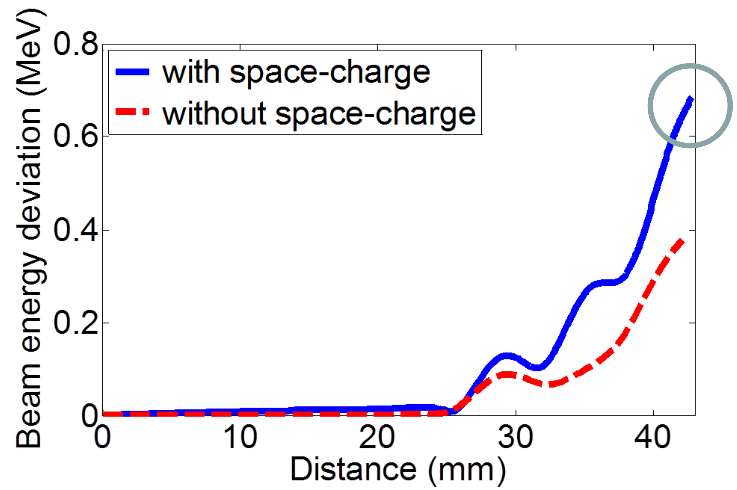
A rule of thumb

Practically achievable results are 10% lower than the theoretical optimum point.

Acceleration to 8.5MeV



9% energy spread

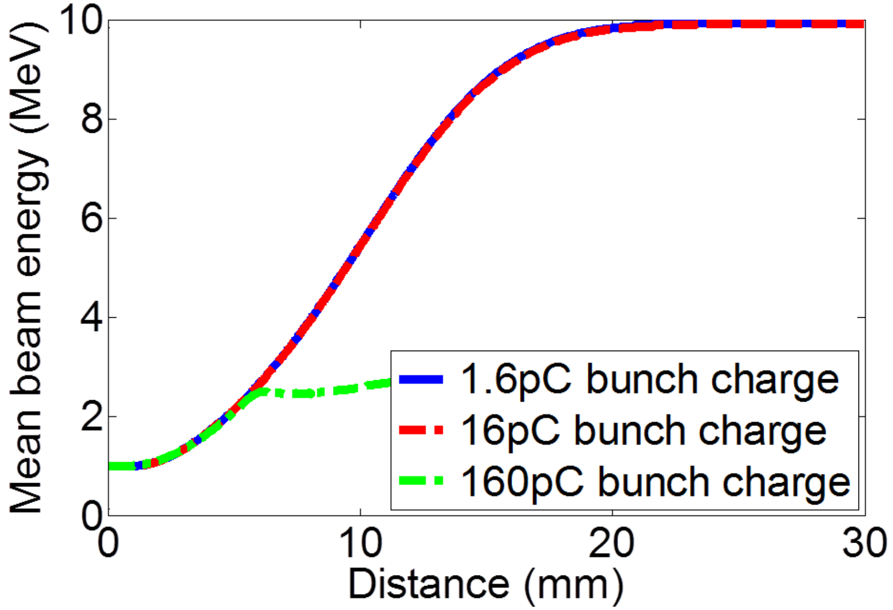


Amount of charge we can accelerate in the waveguide?

Without space-charge: unlimited
With space-charge: limited

What is the limit?

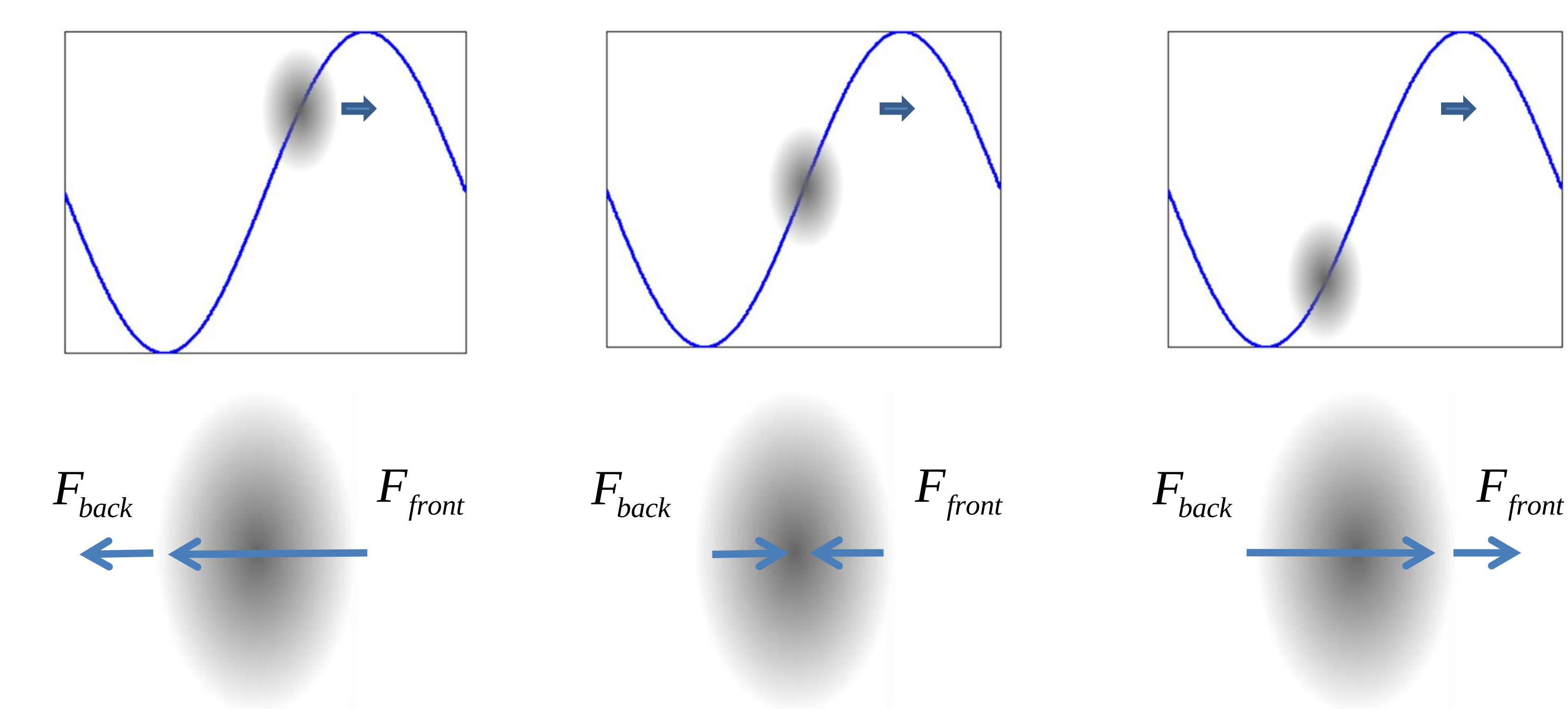
We stop a macro-particle as soon as it hits the walls of the accelerator.



16pC is by far more than what we need.

THz Compression in waveguides

Rectilinear Compression



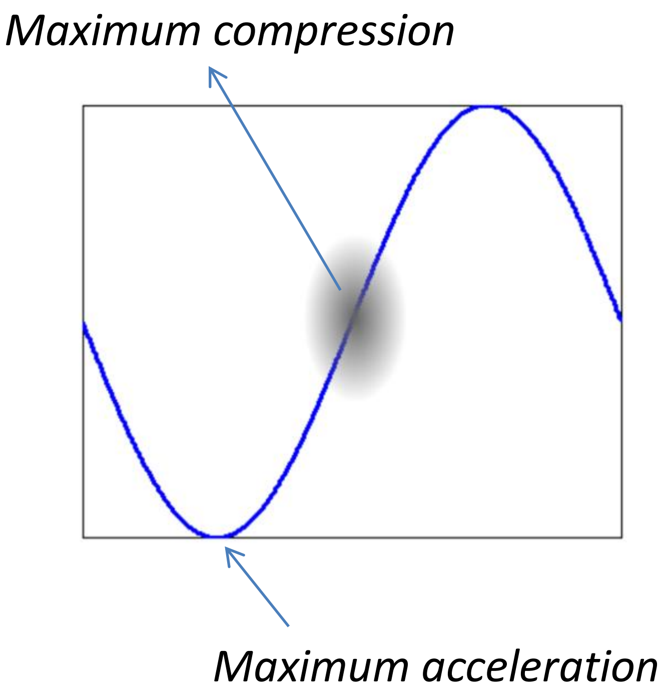
Compression and deceleration

Maximum Compression

Compression and acceleration

THz Compression in waveguides

- Compressed bunches: desired for the good quality in the applications
- Electron bunches can be compressed using THz pulses
- Simultaneous acceleration and compression is possible.
- For compression, the acceleration level needs to be sacrificed.
- Main obstacle against bunch compression: *space-charge forces*

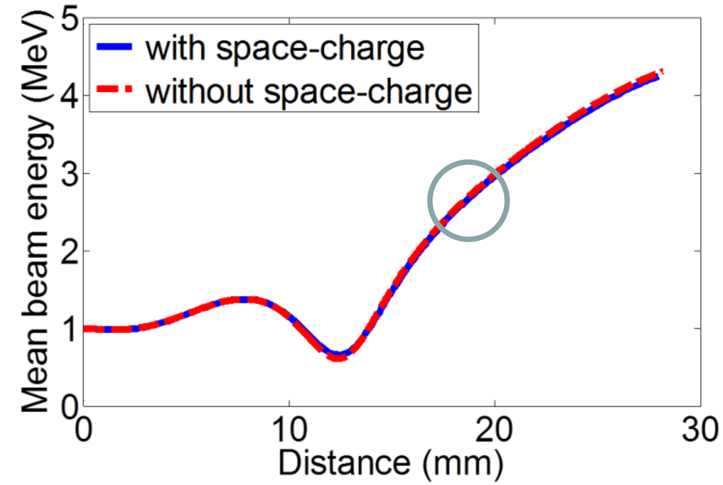


We study the simultaneous bunch acceleration and compression in THz waveguides.

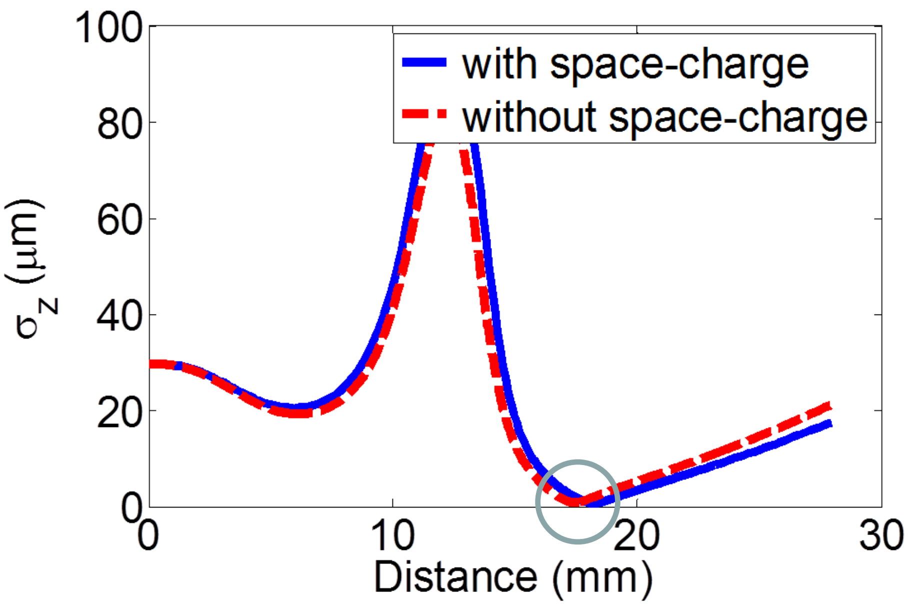
THz Compression in waveguides

- Mean initial energy = 1MeV
- Initial energy spread = 0.1%
- Initial bunch spread is a cube of 30μm×30μm×30μm
- 20mJ 10 cycle THz pulse

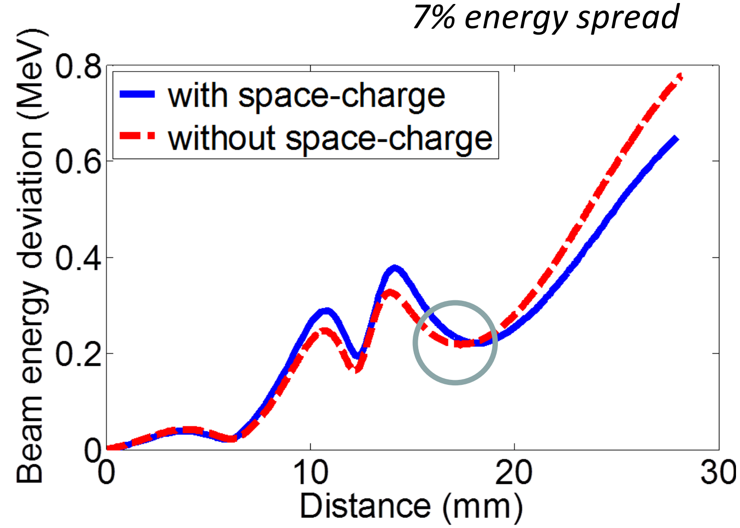
Acceleration to 3MeV



50 times bunch compression



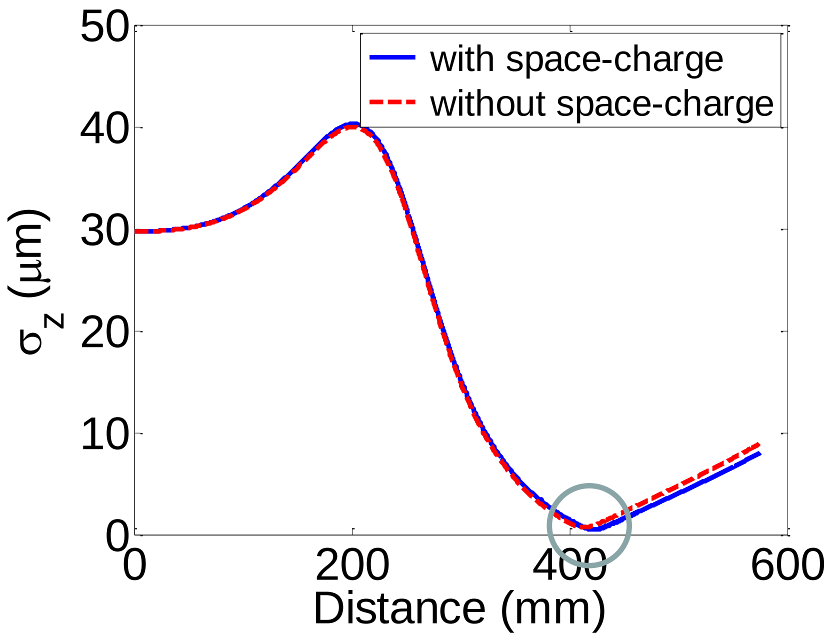
7% energy spread



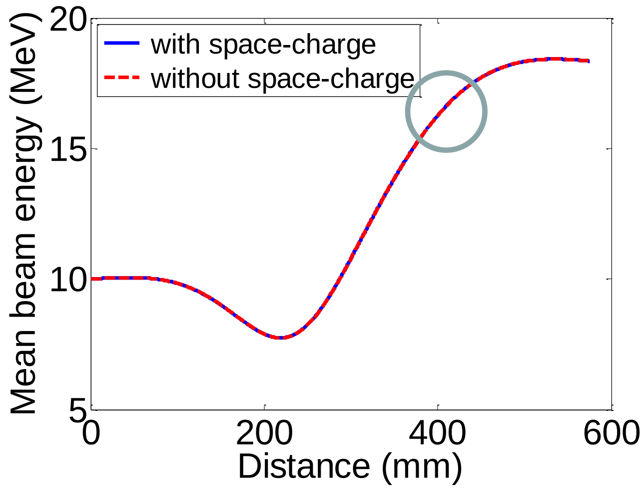
THz Compression in waveguides

- Mean initial energy = 10MeV
- Initial energy spread = 0.1%
- Initial bunch spread is a cube of 30μm×30μm×30μm
- 20mJ 100 cycle THz pulse

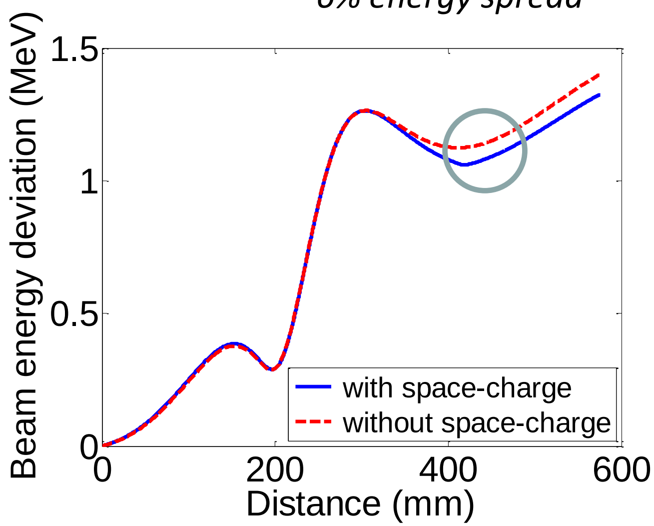
62 times bunch compression



Acceleration to 17MeV



6% energy spread



Conclusion

- With the emergence of high power THz sources, THz acceleration seems to be a promising candidate for compact devices.
- Cylindrical Dielectric-loaded metal waveguides are able to produce the acceleration gradient needed in many applications.
- With a 20mJ-10cycle THz pulse, an electron bunch can be accelerated from 1MeV to ~9MeV.
- The same device can be used for compressing the electron bunch based on rectilinear compression.
- 50 times Compression of a 1MeV bunch and 62 times compression of a 10MeV bunch are demonstrated.
- More details about the results:

Wong, Liang Jie, Arya Fallahi, and Franz X. Kärtner. "Compact electron acceleration and bunch compression in THz waveguides." Optics express 21, no. 8 (2013): 9792-9806.

Acknowledgement

Prof. Franz X. Kärtner and **Liang Jie Wong**
Research Laboratory of Electronics (RLE), MIT
Center for free-electron laser science (CFEL), DESY

Thank you for your attention