Bunch compression techniques

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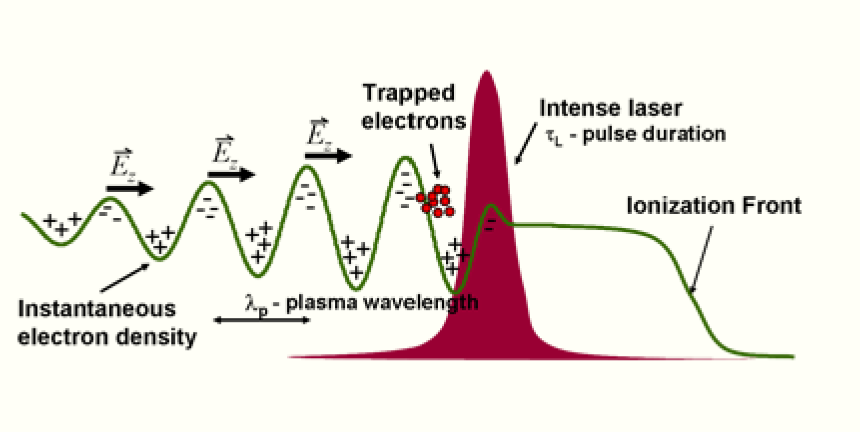
Why short bunches?

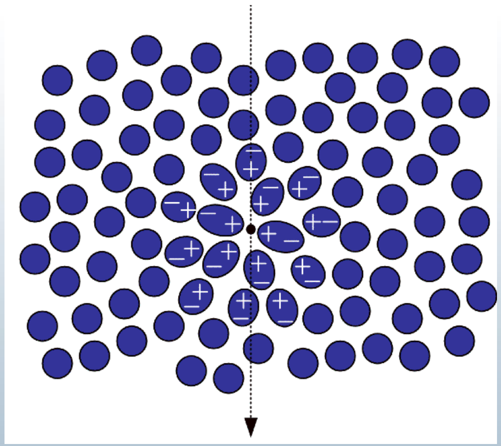
- **Plasma wakefield acceleration**
  - Waves are generated when a laser pulse propagates through the plasma and displaces background electrons through the ponderomotive force of the laser.
  - Beam bunches need to be shorter than the plasma wave length in order to maintain good quality
  - If to long it can cause emittance growth and energy spread

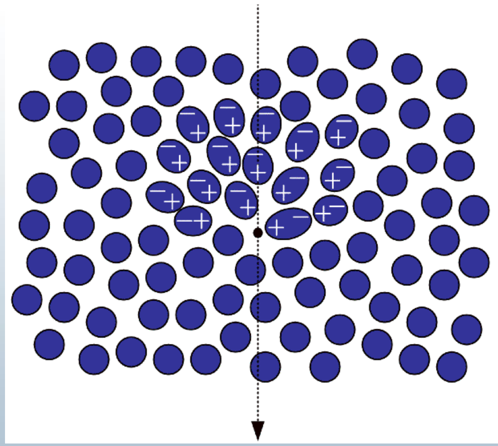


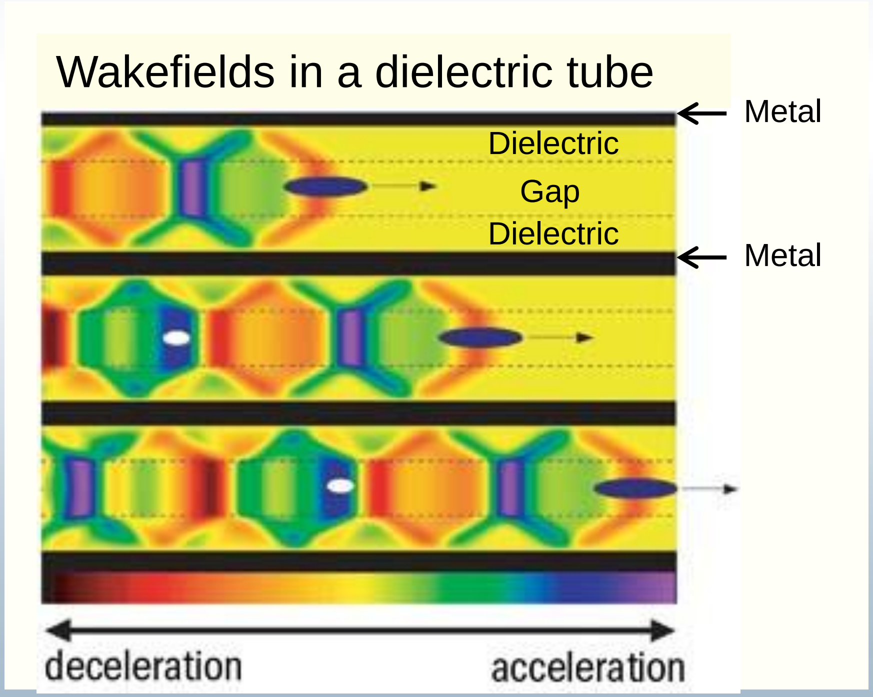
Bunches of ~ tenths of fs are desired!

Why short bunches?

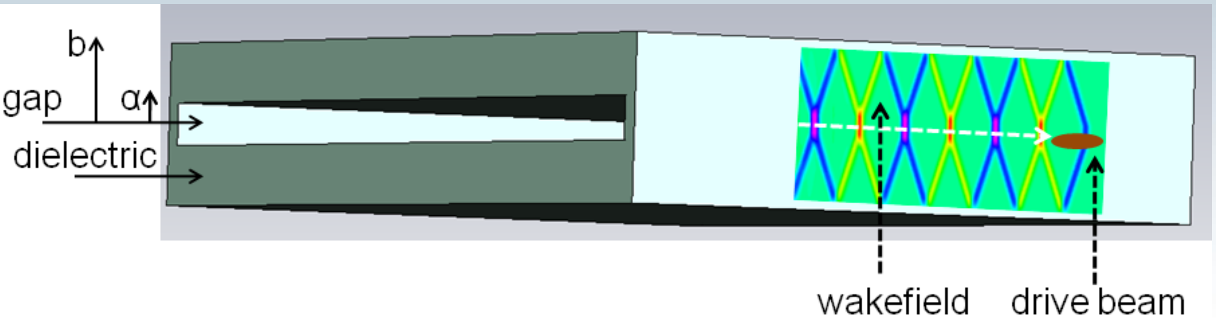
- **Dielectric wakefield acceleration**
  - A single driving bunch as it passes near the dielectric excites Cherenkov radiation which is reflected back to towards the center axis where a second beam is accelerated

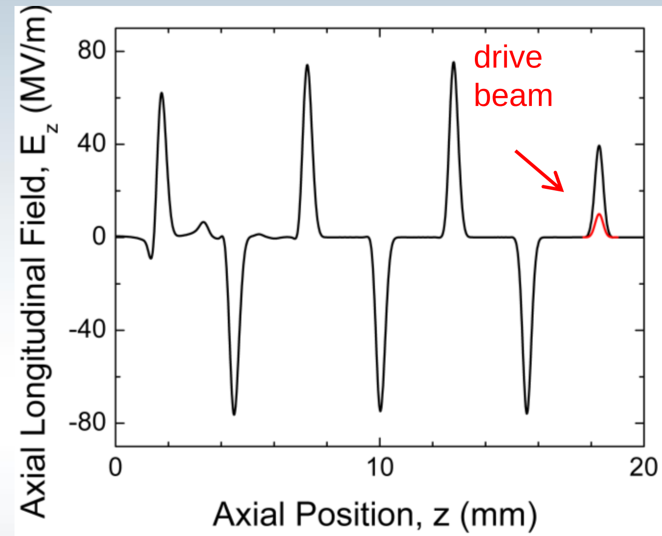






Dielectric wakefield aceleration



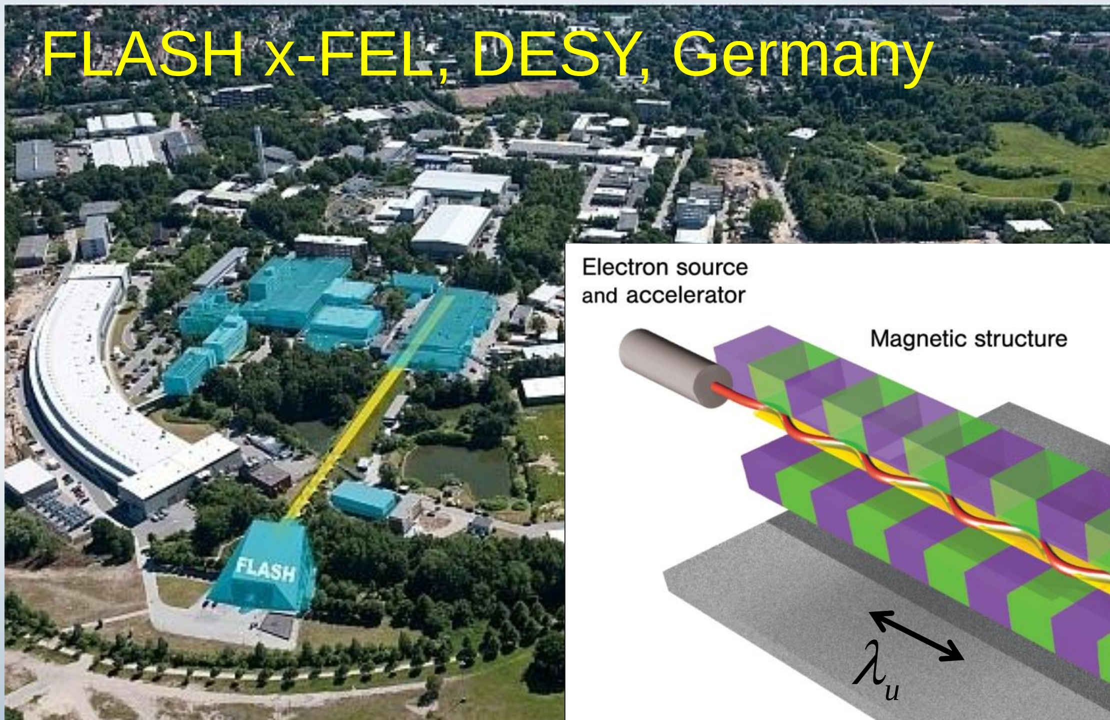


- Electron bunch drives Cerenkov wake in slab:
  - Wakefield accelerate the trailing bunch
  - Dependent on the structure properties and the bunch length
  - Peak accelerating field:

$$E_{z,acc} = \frac{Q}{\varepsilon_0 \left(a + 2\pi \sigma_z \frac{\varepsilon_r}{\sqrt{\varepsilon_r - 1}} \right)}$$

Why short bunches?

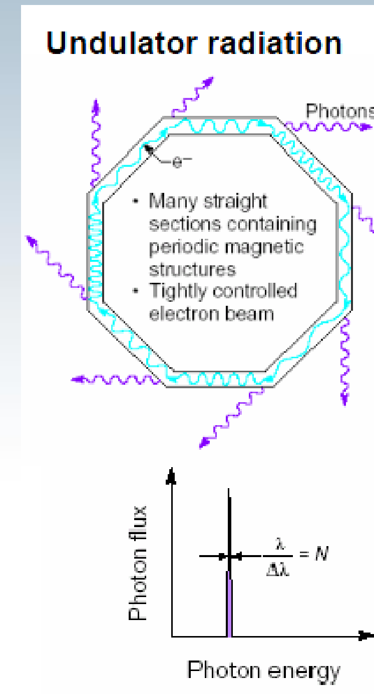
- **Free-electron lasers**

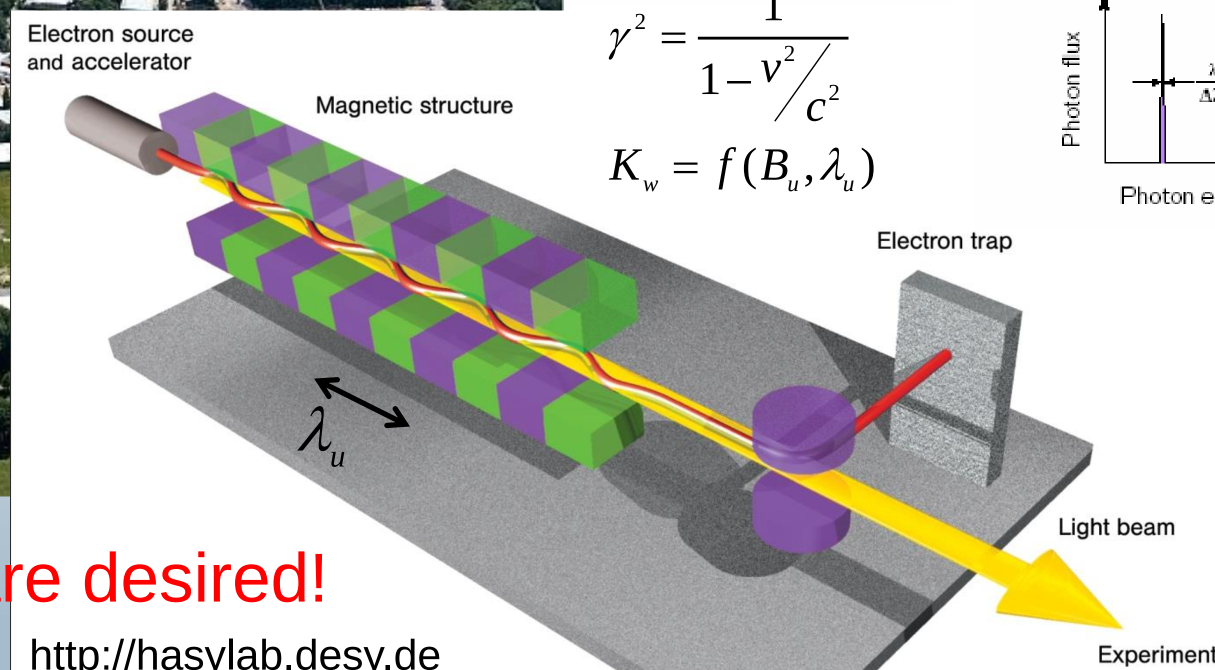


$$\lambda = \frac{\lambda_u}{2\gamma^2}(1 + K_w^2)$$

$$\gamma^2 = \frac{1}{1 - v^2/c^2}$$

$$K_w = f(B_u, \lambda_u)$$

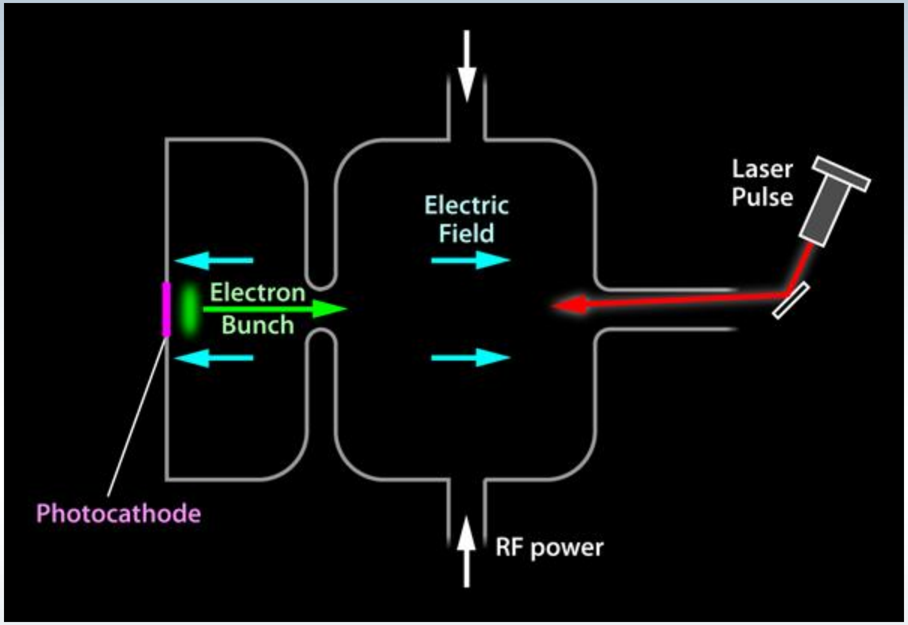




Bunches of ~ fs are desired!

http://hasylab.desy.de

How can we create them?

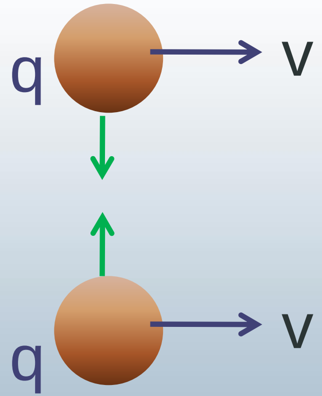


- First guess:
  - Generate short bunches directly from photo-injectors
- But there is problem….

Space-Charge effect

- Two charges q experience repulsive electrostatic Coulomb force, F_E

- If they travel with a velocity v, they are equivalent to two current wires I=qv and attract each other by their magnetic fields

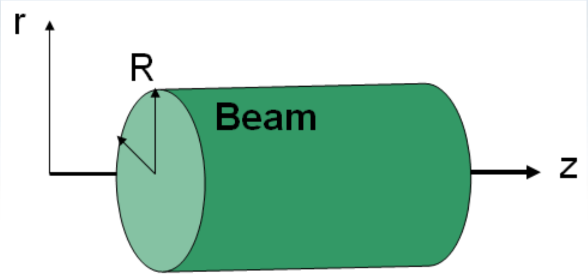


- Combined force: $F = \left(1 - \frac{v^2}{c^2}\right) F_E$

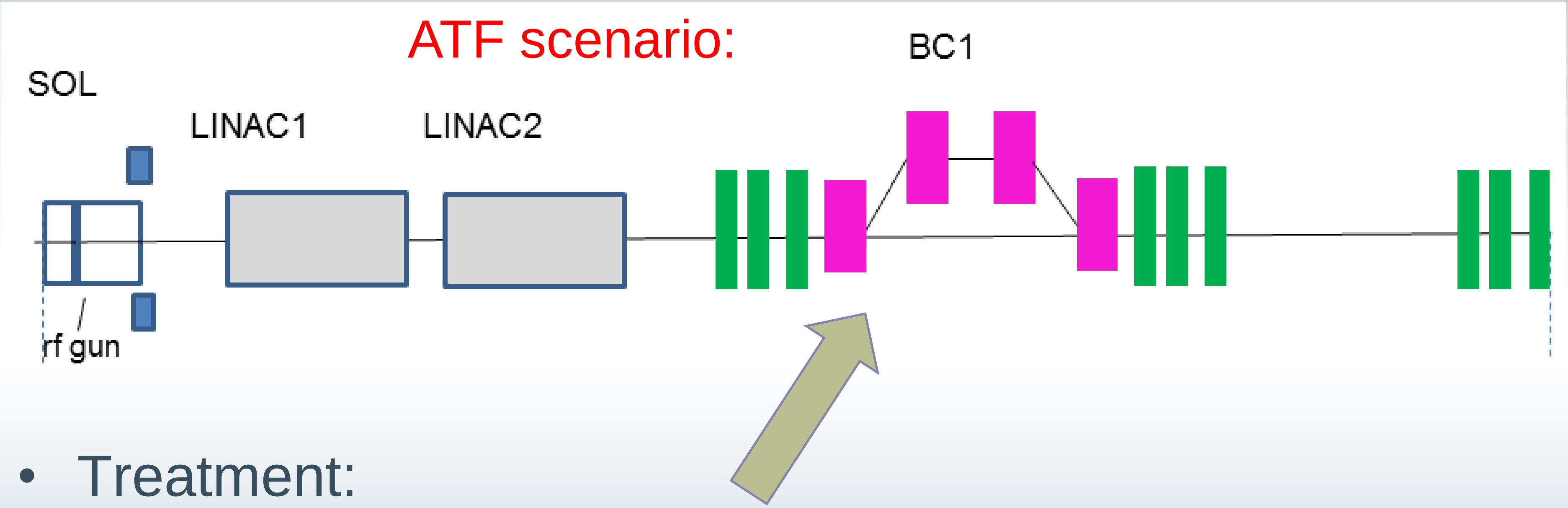
- SC force is repulsive and can severely deteriorate the beam quality

Space-charge effect: Quantitative

- Beam can be treated as a "continuous" charged medium
- Gauss' Law: $E_r = \dfrac{Ir}{2\pi\varepsilon_0 R^2 v}$
- Ampere's Law: $B_\theta = \dfrac{\mu_0 Ir}{2\pi R^2} = \dfrac{vE_r}{c^2}$
- Lorenz Force Law: $F_{r,sc} = q(E + v \times B) = \dfrac{qI}{2\pi\gamma^2\varepsilon_0 v R^2} r = C(R)r = \dfrac{qE_r}{\gamma^2}$
- SC force is pushing the particles out
- SC can be strong near the beam source (small gamma)
- SC negligible at high energies!

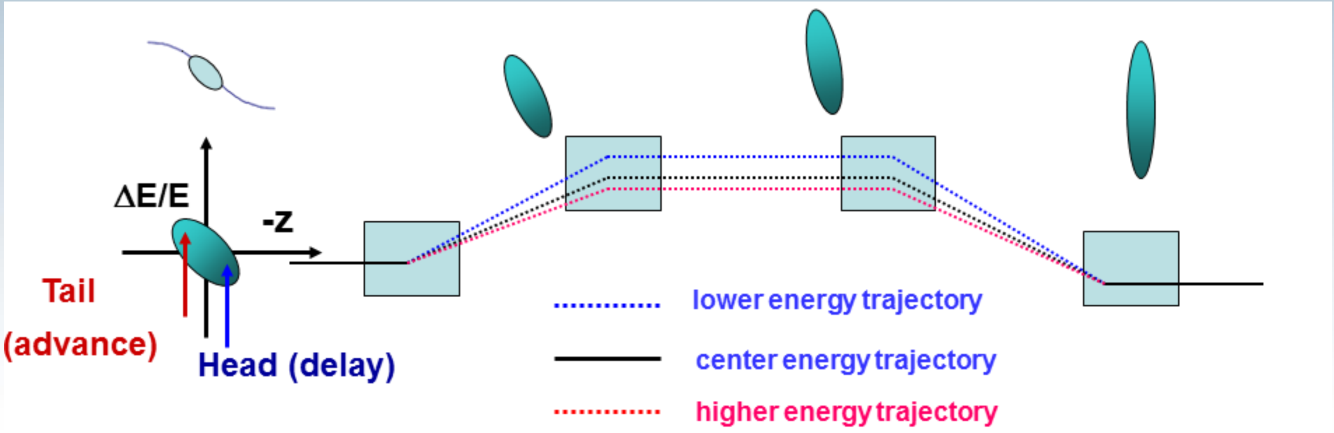


Bunch Compressors



- Treatment:
  - Use a magnetic bunch compressor just after the beam has gained some energy and the effect of space-charge becomes negligible.
  - Routinely used at the ATF

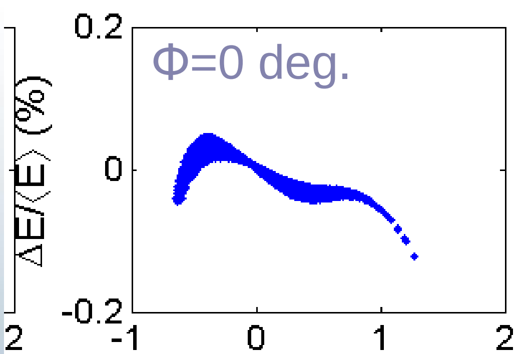
Magnetic bunch compression principle



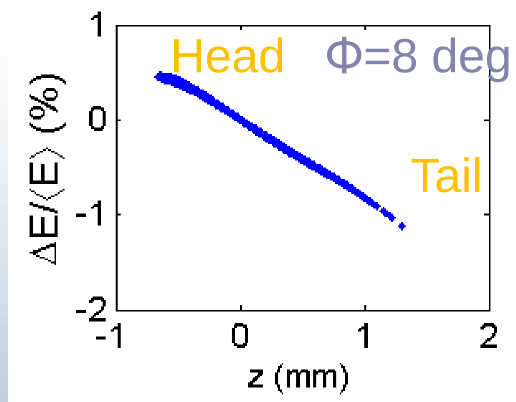
- Beam compression can be achieved:
  - By introducing an energy position correlation along the bunch with an RF section at zero crossing of voltage
  - Passing the beam through a region where path length is energy dependent
- To compress, trajectory in a dispersive region must be shorter for the tail of the bunch that is for the head!

Energy-time correlation at the ATF

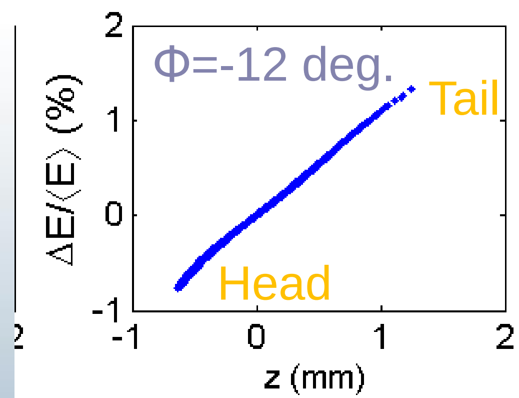
- Upstream of the compressor we have a rf linac
- Its phase can be adjusted in order to introduce energy-time correlation



No chirp



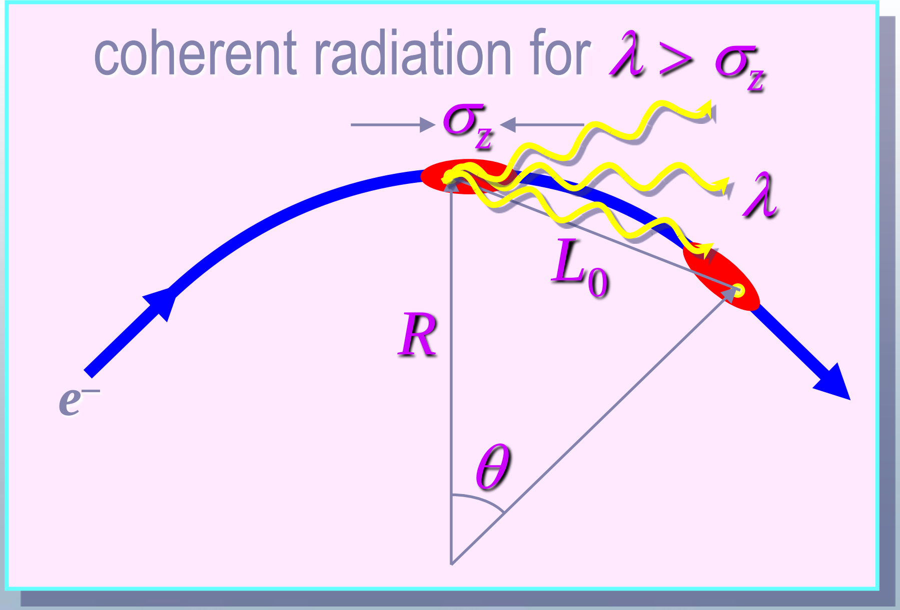
Wrong direction



Optimum

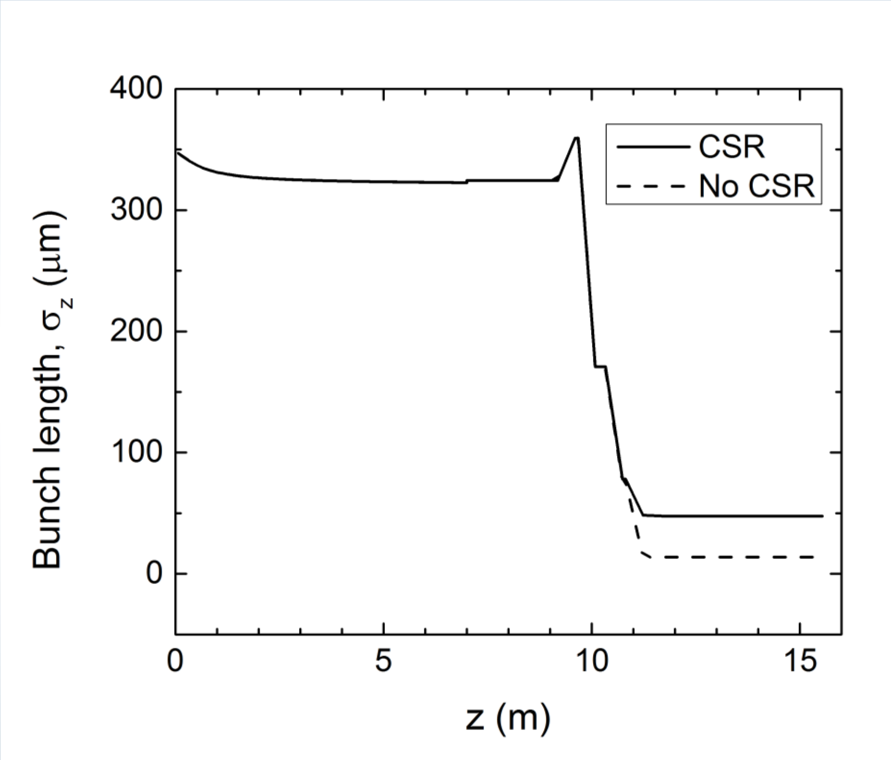
Bad news: Coherent synchrotron radiation

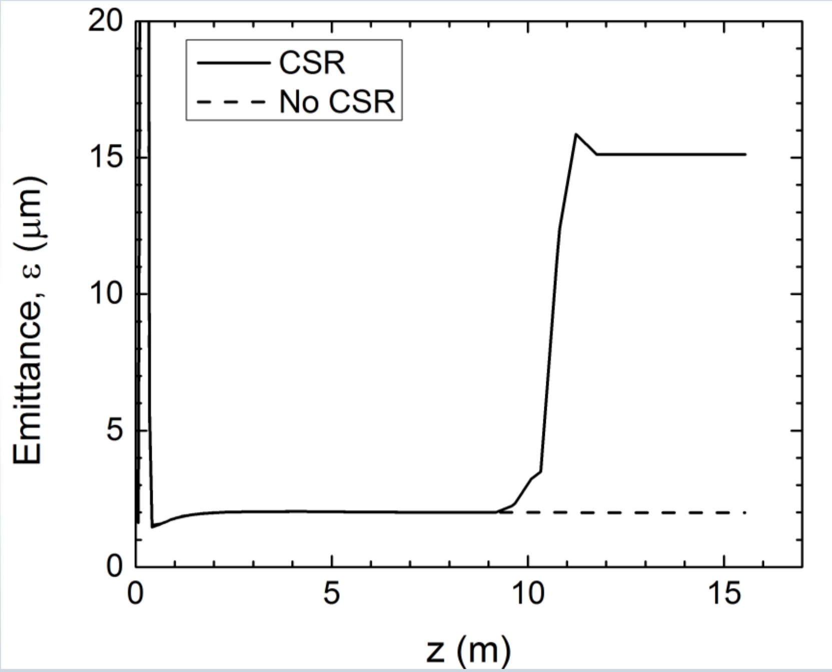
- CSR occurs when the bending of a relativistic electron beam allows the synchrotron radiation emitted by the tail of the micro-bunch to "catch up" with the head electrons.
- It induces an energy redistribution along the bunch which in turn causes emittance dilution.



Can be an issue in magnetic bunch compressors!

Chicane at the ATF for optimum

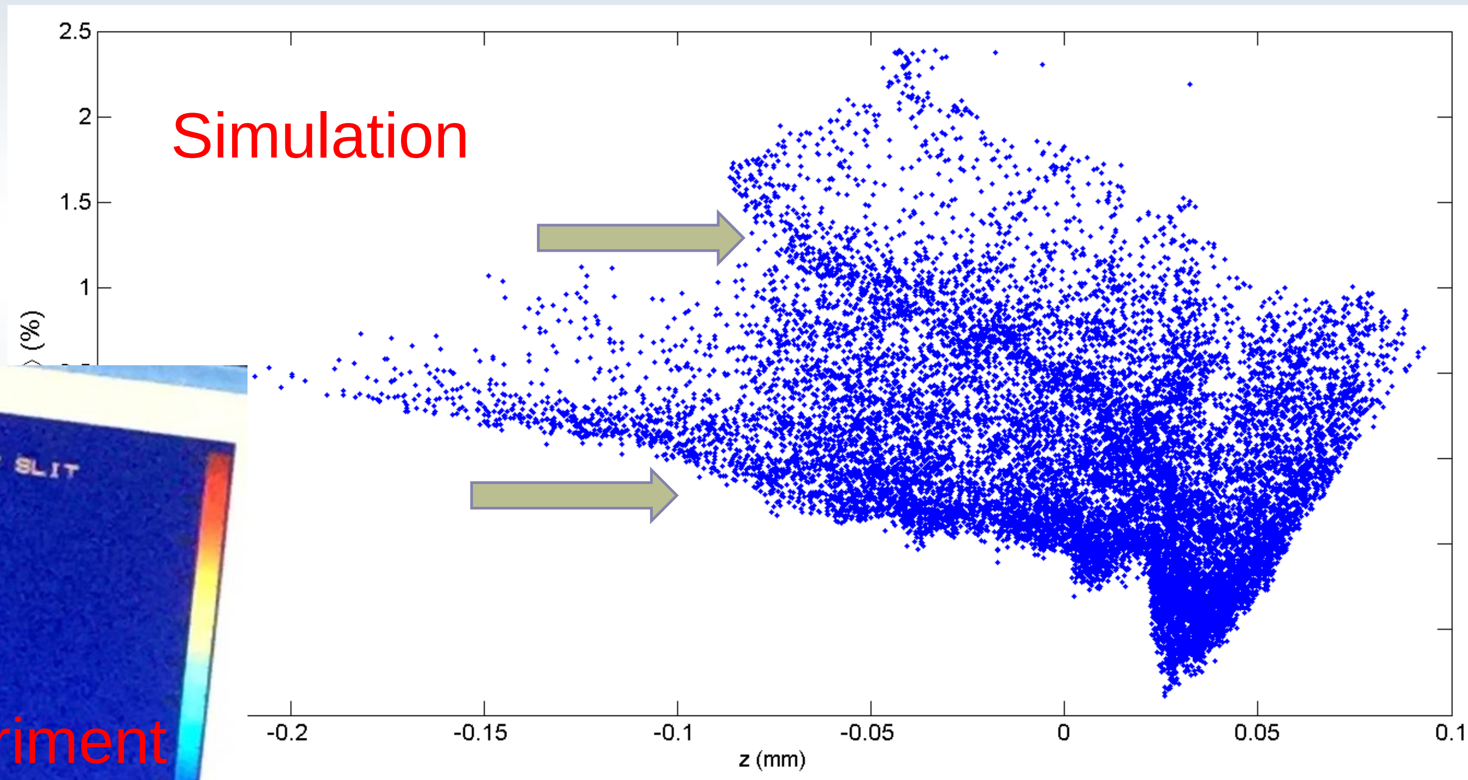


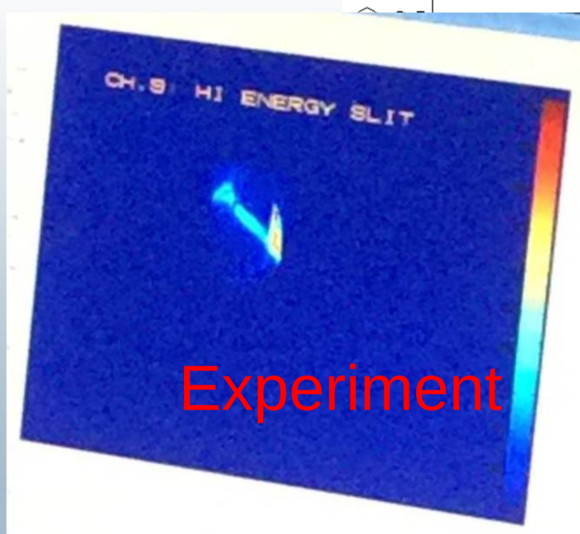


- Without CSR chicane compresses the beam to 1:30 ratio
- CSR causes severe emittance growth

Energy spectrum in the ATF

- Both simulation and experiment illustrate a beam break up after the pass of the chicane





Bunch compression

- Can we compensate CSR? How?
- Solution
  - Perform only modest compression with a magnetic bunch compressor
  - Use an alternative technique to further compress the beam

Hybrid solution

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A hybrid approach for generating ultra-short bunches for advanced accelerator applications

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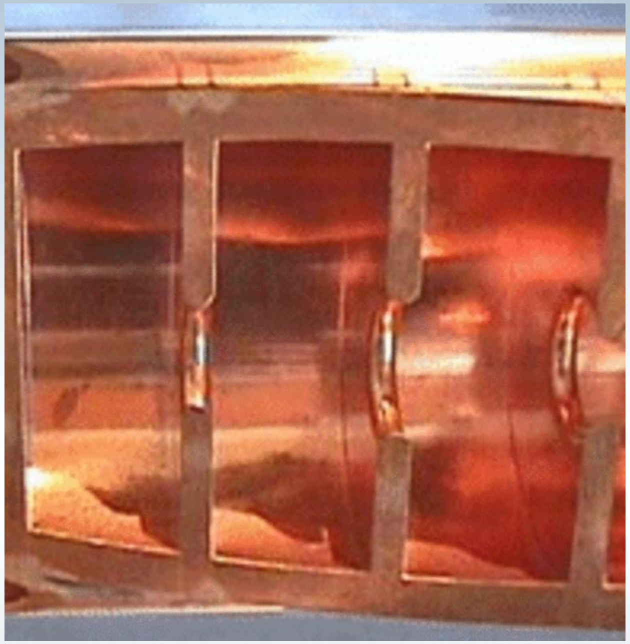
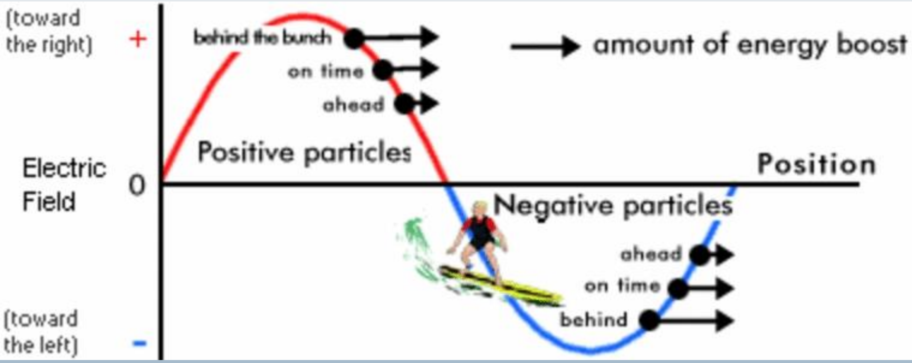
ABSTRACT

Generation of electron beams with high phase-space density, short bunch length and high peak current is an essential requirement for future linear colliders and bright electron beam sources. Unfortunately, such bunches cannot be produced directly from the source since forces from the mutual repulsion of electrons would destroy the brilliance of the beam within a short distance. Here, we detail a beam dynamics study of a two-stage compression scheme that can generate ultra-short bunches without degrading the beam quality. In the first stage, a magnetized beam is compressed with a velocity bunching technique in which the longitudinal phase space is rotated so that electrons on the bunch tail become faster than electrons in the bunch head. In the second stage, the beam is further compressed with a magnetic chicane. With the aid of numerical simulations we show that our two-staged scheme is capable to increase the current of a 50 pC bunch by a notable factor of 100 (from 15 A to 1.5 kA) while the emittance growth can be suppressed to 1% with appropriate tailoring of the initial beam distribution.

- In today's homework you will be asked to reproduce some of the results of this paper.

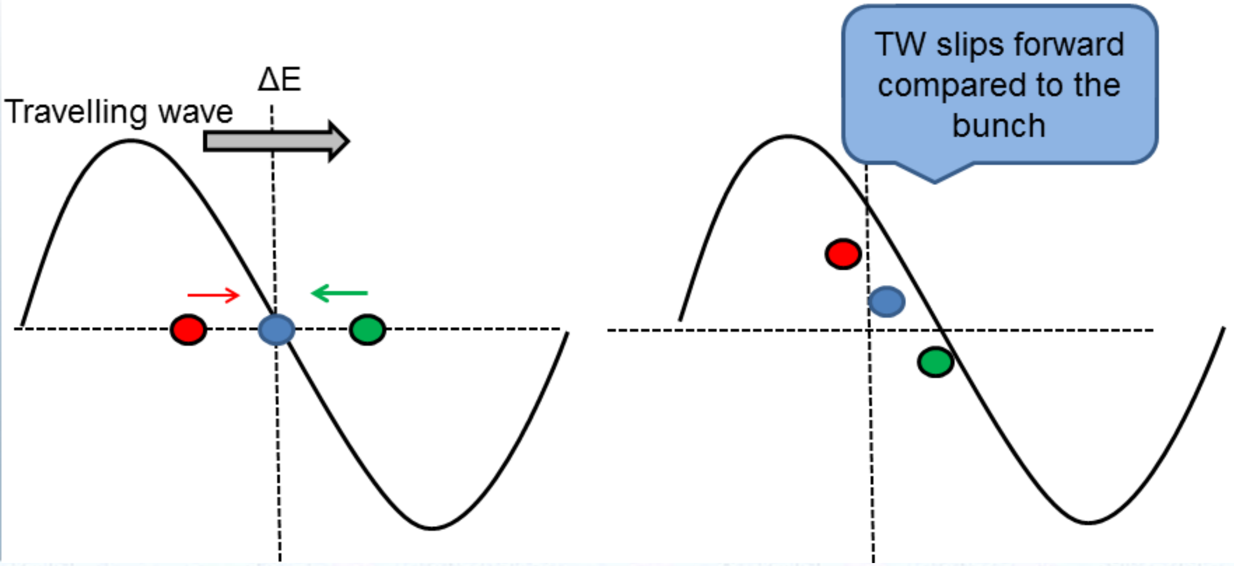
Recall concept of RF Cavities





Introduction to velocity bunching

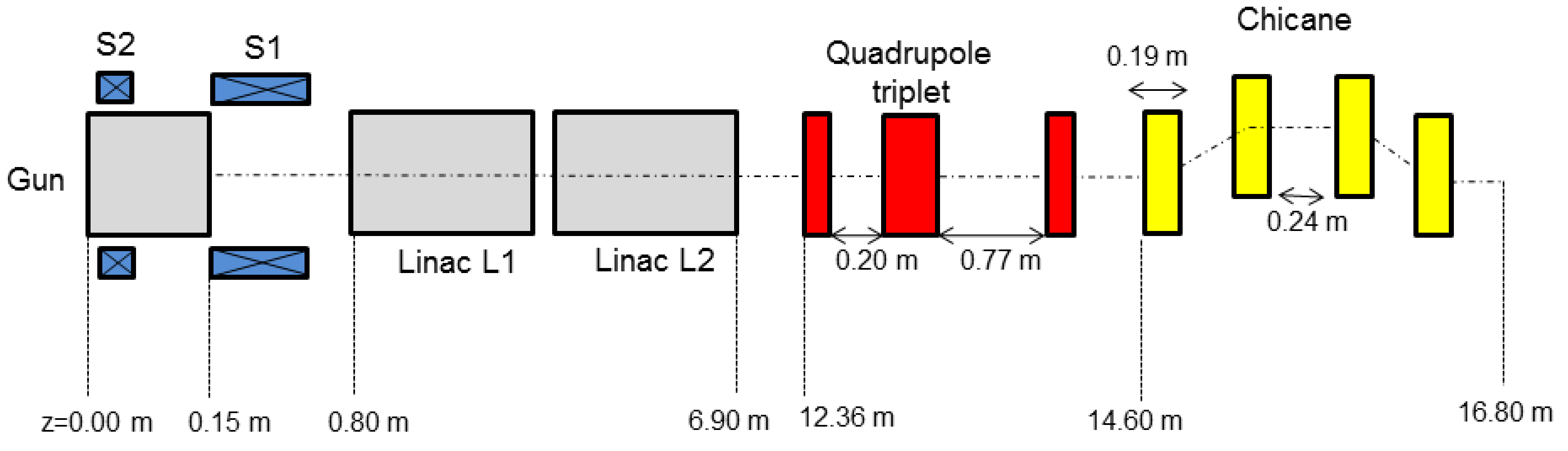
- The beam is injected in a long accelerating structure at zero crossing field phase
- Injection at low energies where the beam is slower than the phase velocity of the rf wave
- Compression and acceleration will take place at the same time within the same linac section



Pros & Cons

- Some benefits:
  - Compression without CSR effects
  - Economic: acceleration & compression at the same linac
- Some challenges:
  - Can cause emittance growth
  - Asymmetric beam profiles
  - Reduces the overall energy
- In this talk, I will show you some features of the VB technique.

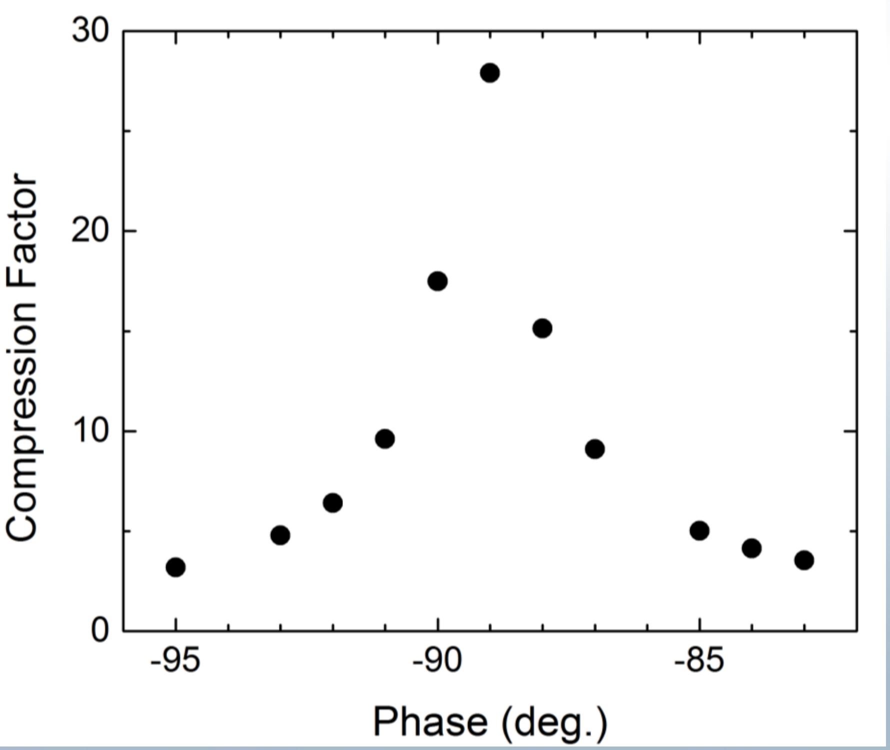
Beamline schematic

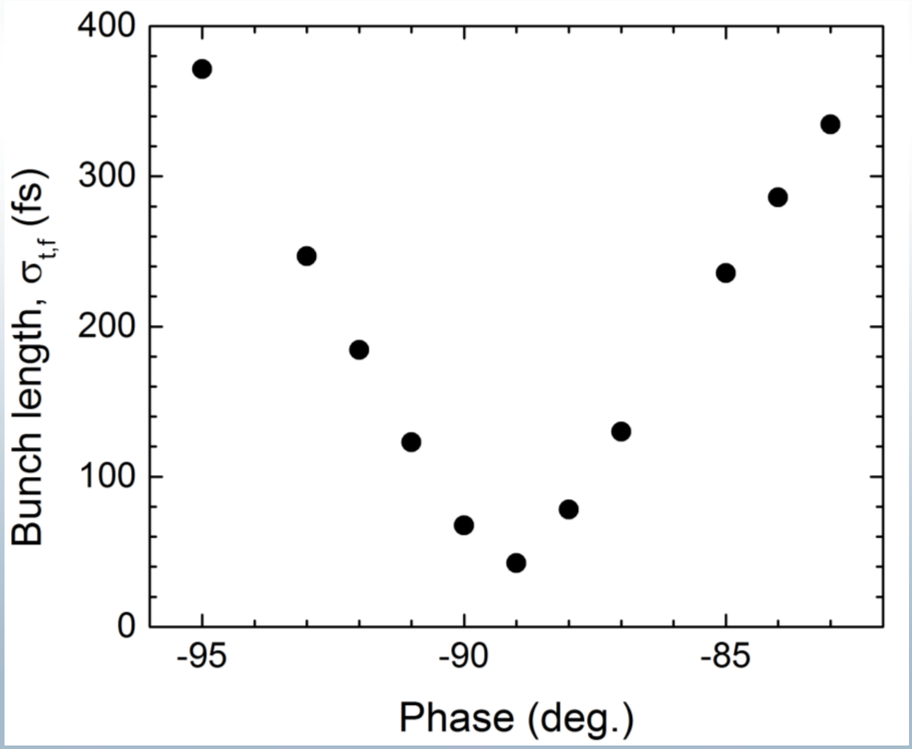


- S1: Emittance compensation solenoid
- S2: Magnetized beam solenoid
- Quadrupole triplet that can be switched to “skew” to generate the flat beam
- Phase of the linacs L1, L2 can be adjusted to create a “chirp” sufficient for compression at the chicane

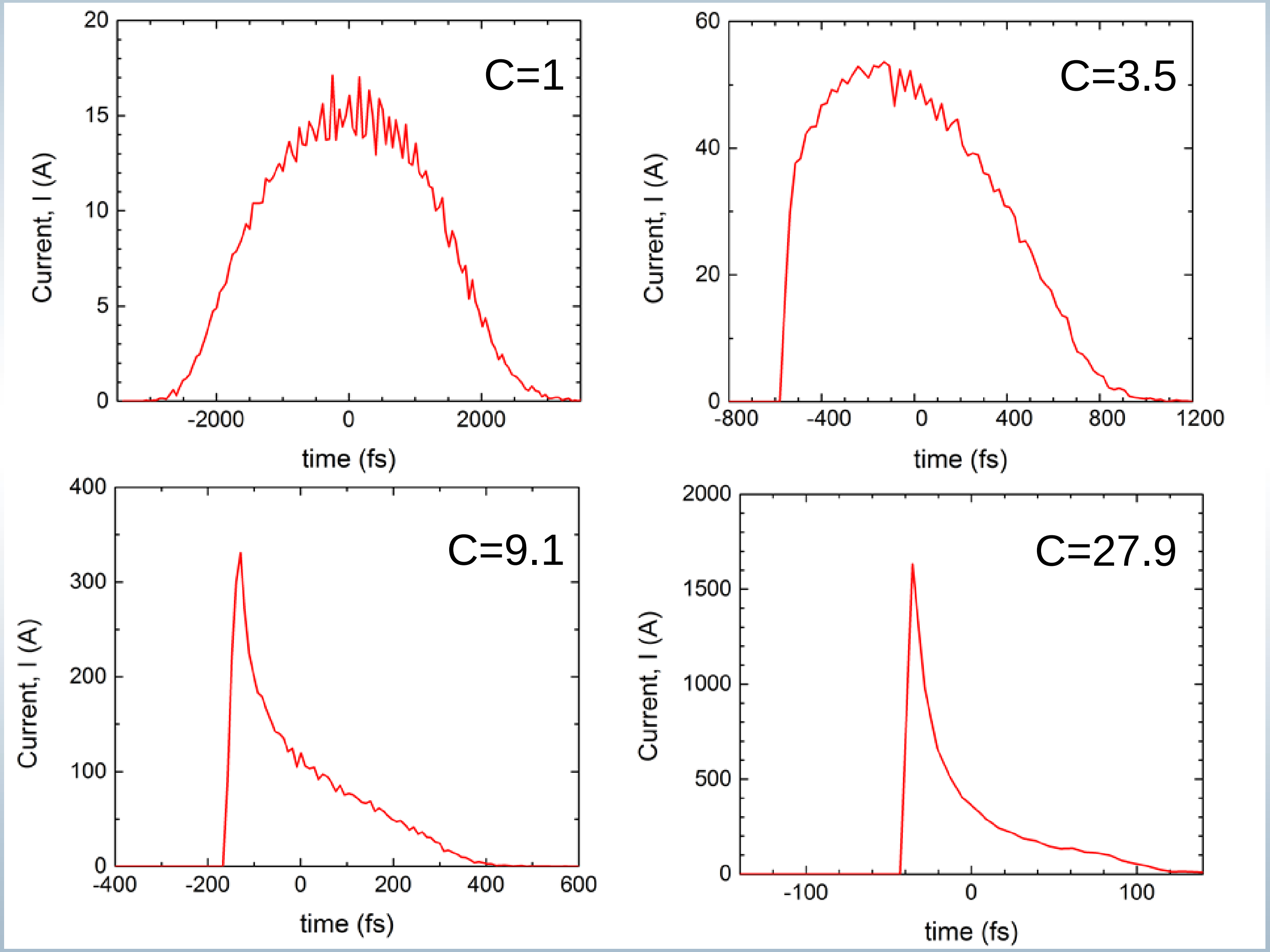
Velocity Bunching (50 pC)

- Vary phase of first linac (L1)
- Keep L2 on crest ($\phi=0^0$)
- Turn off magnetic bunch compressor (BC)





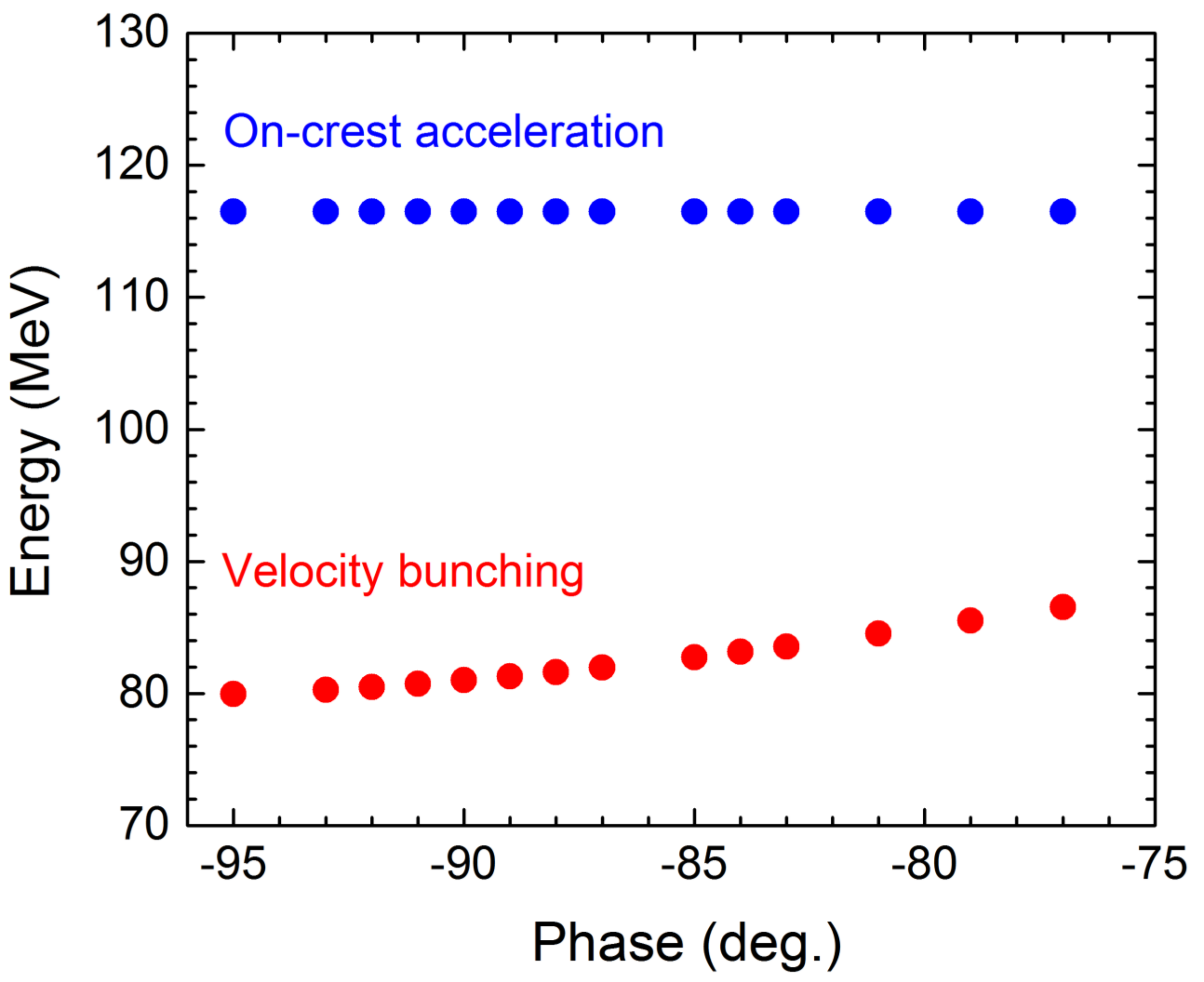
Beam profiles after linac L2



C is the compression factor

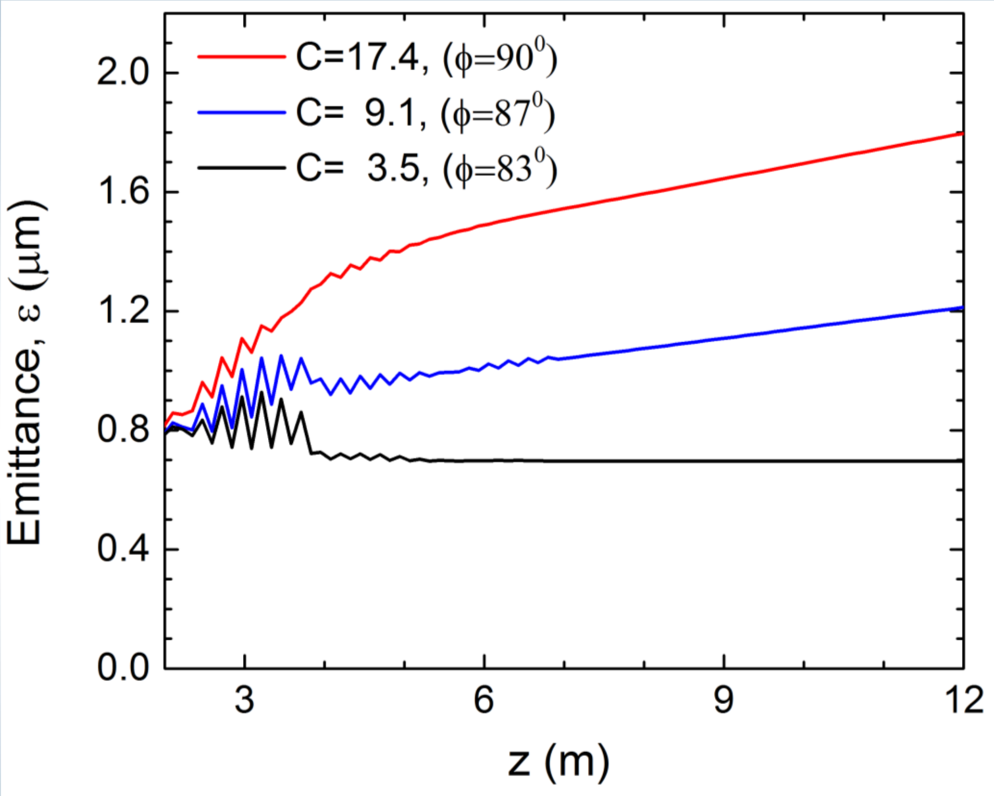
- Unfortunately, peaked current distributions have long tails

Energy



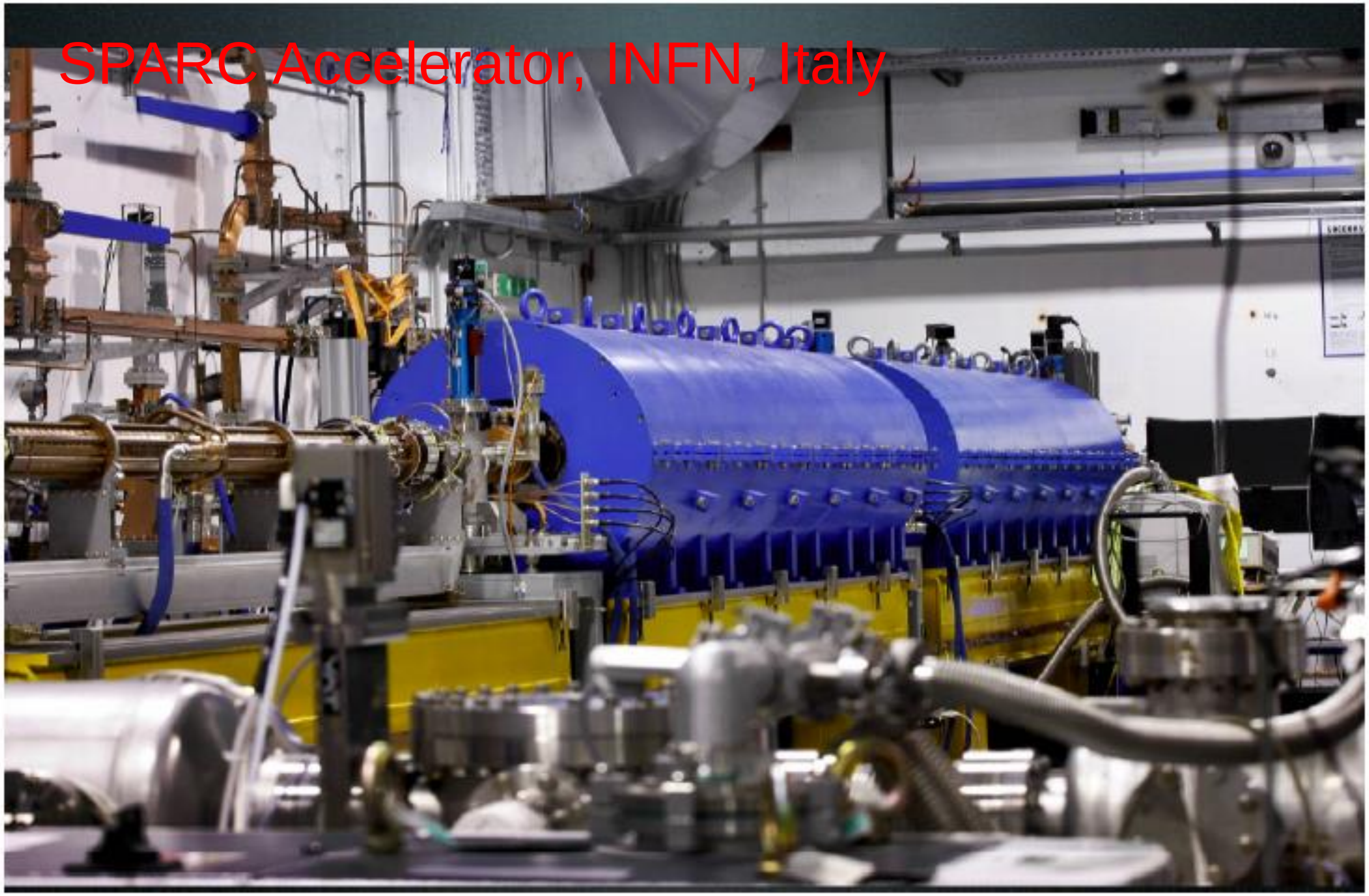
- VB causes a ~30% drop in the final energy

Emittance dilution



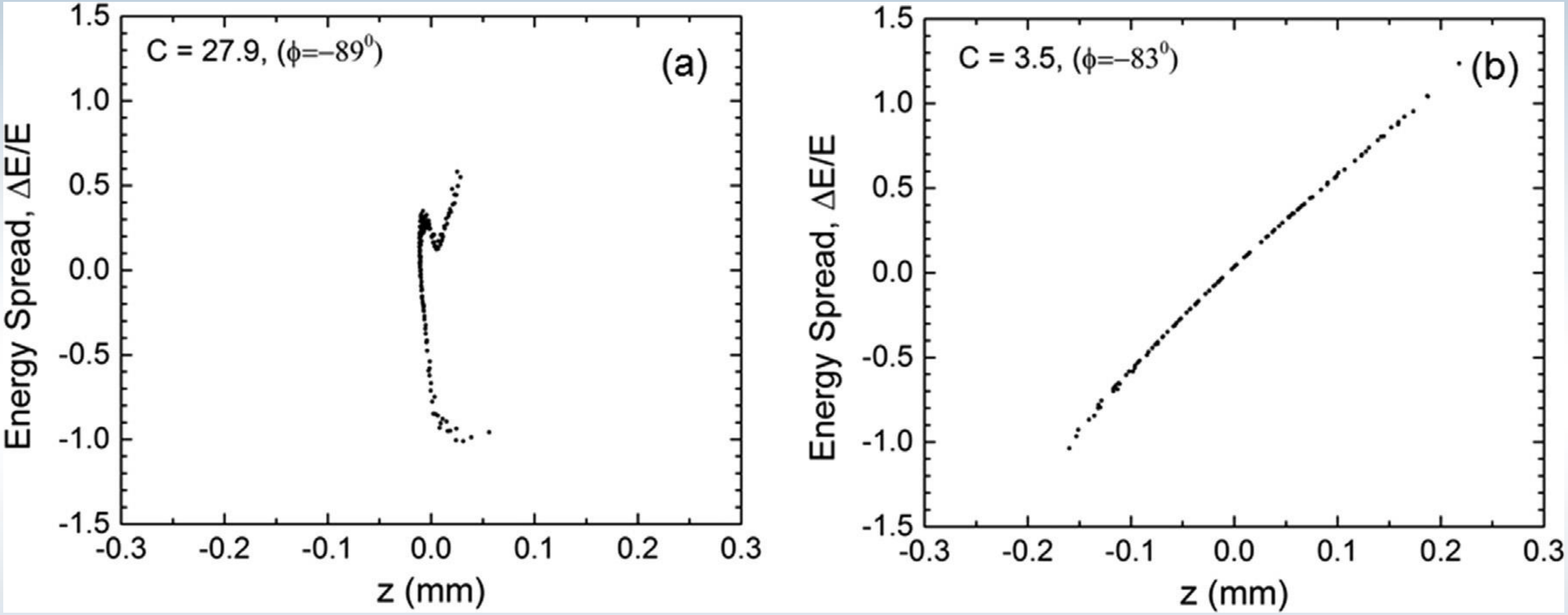
- High C's cause emittance growth
  - Mitigated with a solenoid around the linac (see Ferrario et al. PRL 104, 054801, 2010)

Treatment of emittance dilution



- Ferrario et al. PRL 104, 054801, 2010) – not done in this study

Energy-time correlation

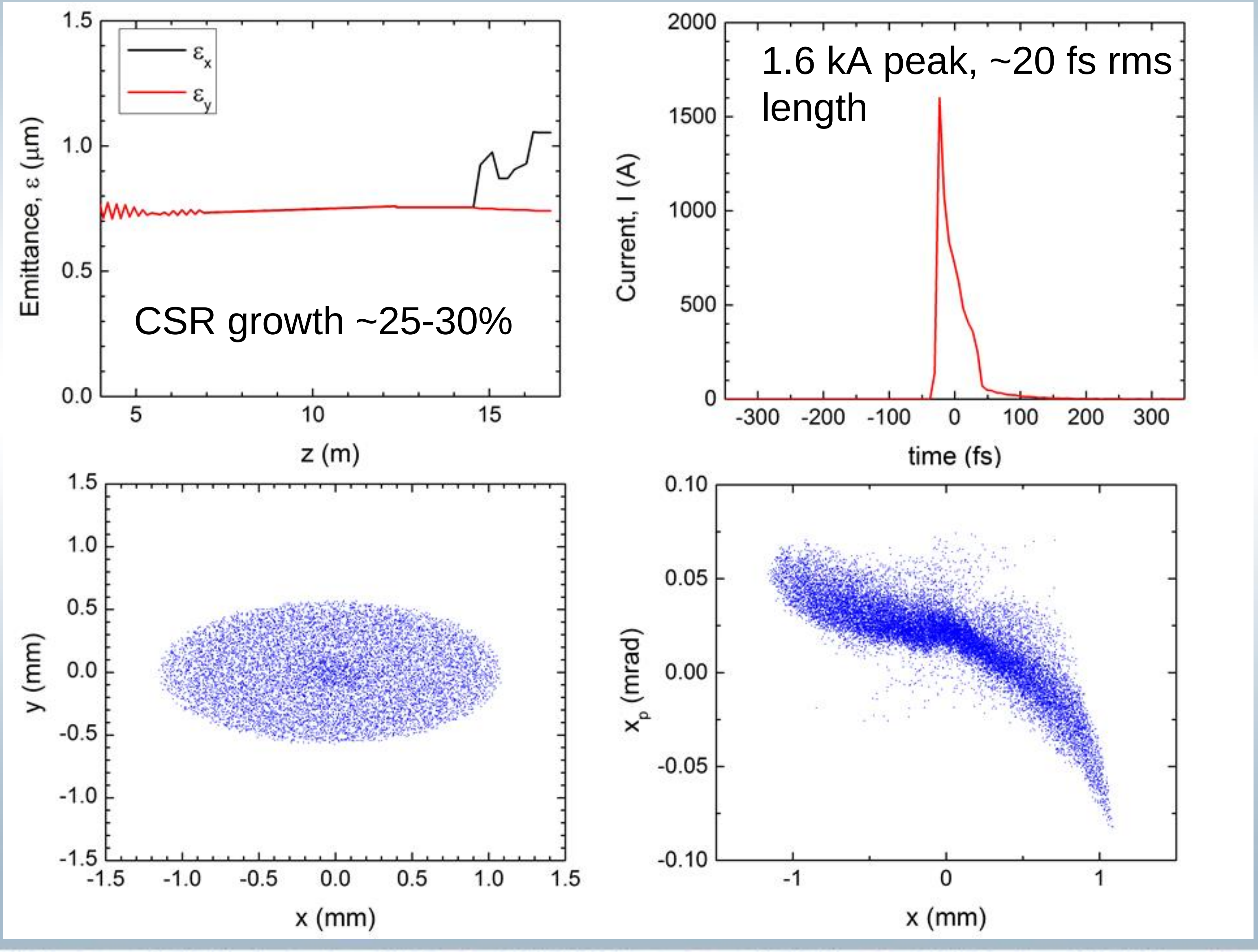


- Low C's preserve linearity on energy time correlation
- Required for magnetic compression

What we learn so far…

- Aggressive compression with VB creates highly asymmetric profiles and emittance growth
- Moderate compression provides satisfactory results
  - Less emittance growth
  - Less asymmetry in the profiles
- Aggressive magnetic bunch compression creates CSR
- Solution
  - Do modest compression with both VB and BC
  - If combined, they can generate ~fs buches with minimum distortion

ATF compression scenario…



Homework

- I have showed a scheme to produce, high peak current, ultra short bunches, with a combination of a velocity bunching and magnetic bunch compression
- In today's computer lab you will use ASTRA to demonstrate Velocity Bunching for the ATF beamlines