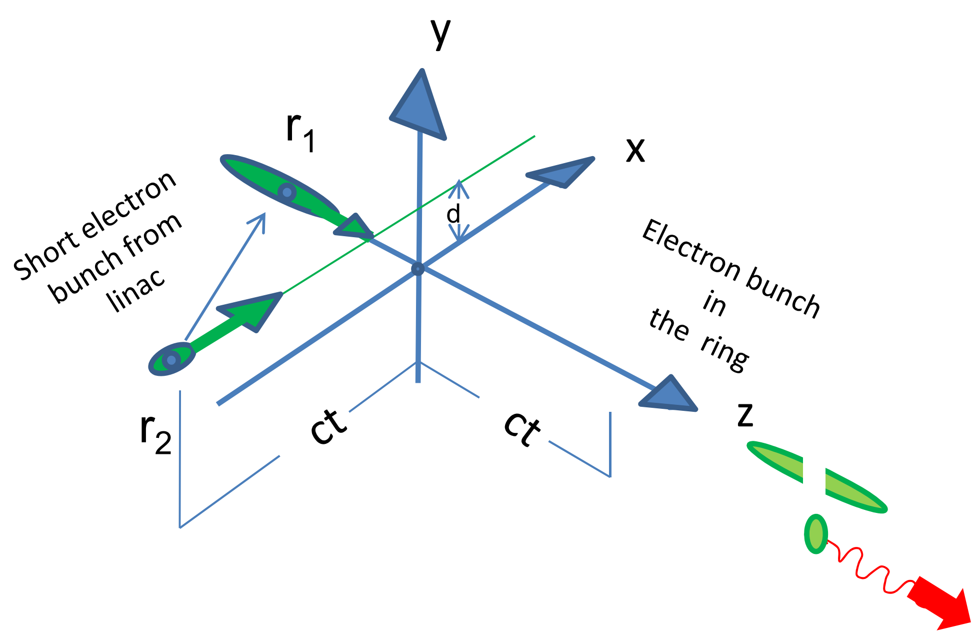
Femto-second X-ray Pulse Generation by Electron Beam Slicing



Basic Idea:

When short electron bunch from linac (5MeV, 100pC,100fs) passes above a storage ring bunch (30 ps), it kicks a slice (150fs) vertically.
(Ferdinand Willeke)

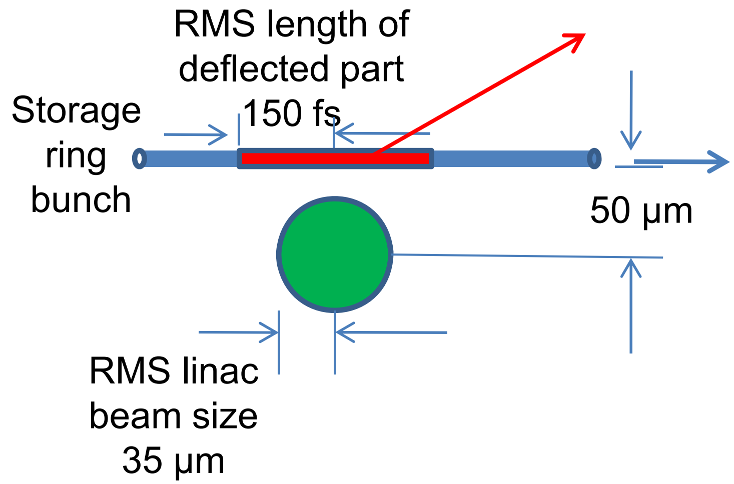
The radiation from short slice is separated from the core bunch.

Basic Parameters of the Slicing Beam

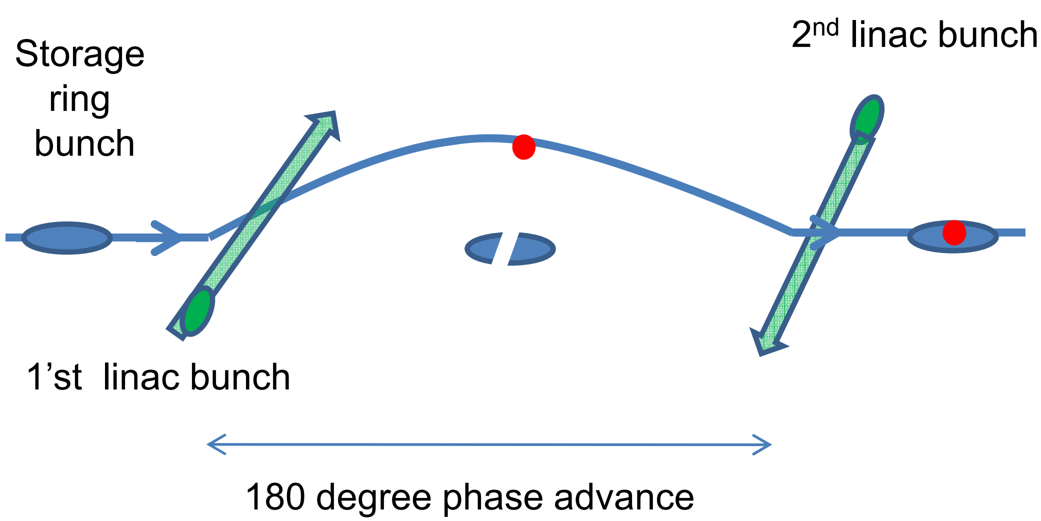
Require: * **high rep. rate,**
*** low energy,**
*** small focused beam size,**
*** short bunch length**

Beam size determine slice length

- Energy 5 MeV, 100pC, 100fs bunch
- ϵ_n= 5μm, β=2.5mm,f=25cm,
- Deflection θ=7 μrad
- Core separation 5 σ require only θ =3.5 μrad
- Length of deflected part ~150fs

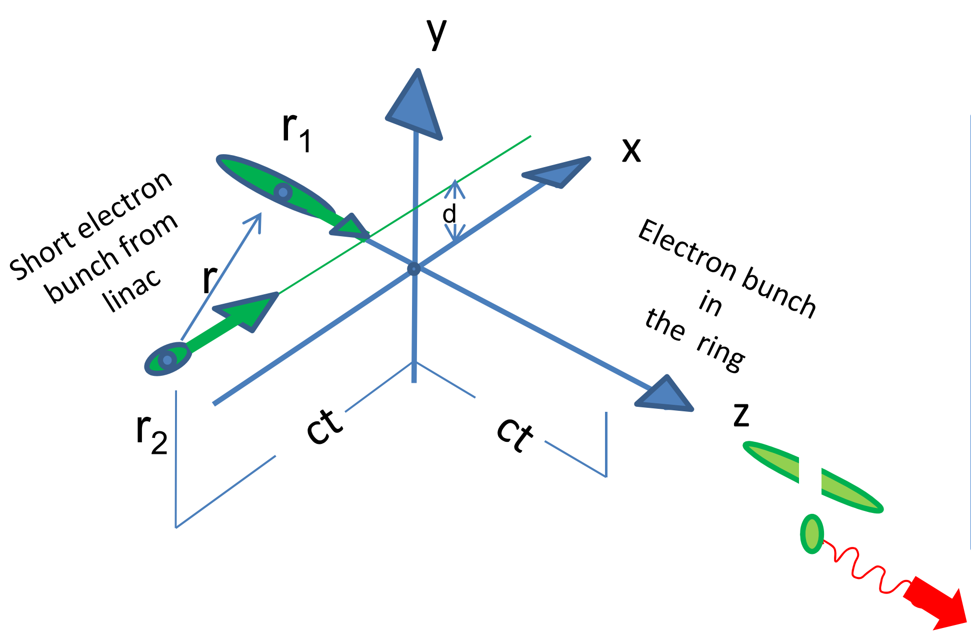


Two linac bunches required for a local bump for the kicked electrons in storage ring



The requirement: time jitter between two bunches << 100 fs
The use of local bump makes it possible to achieve high rep. rate

The achievable pulse length in beam-slicing is determined by the pulse length and cross section of slicing low energy beam➔ **need strong focusing**



The force exerted by electron in linac bunch at r_2 on electron in storage ring at r_1 is:

$$\vec{r} = \vec{r}_1 - \vec{r}_2 = (x_1 - (x_2 + ct), y_1 - (y_2 + d), (z_1 + ct) - z_2)$$

$$\vec{F} = \frac{N_2 e^2}{4\pi\varepsilon_0} \frac{\gamma_2}{s^3} \begin{pmatrix} x + \beta_1 \beta_2 z \\ y \\ z \end{pmatrix}$$

$$s = (\gamma_2^2 x^2 + y^2 + z^2)^{\frac{1}{2}}$$

After **integration over the crossing time and the 3-D profile** of the linac bunch, we obtained a formula for the kick angle received by a single electron in the storage ring bunch

Scaled formula shows the importance of small beam size for angle and time resolution

Kick angle is determined by scaled beam size and vertical distance d:

$$\theta = \frac{e q_2 Z_0 c}{2\pi E_1} \frac{\gamma_2}{\sqrt{\gamma_2^2+1}} \frac{1}{\sqrt{2}\sigma_y} f(\rho, \bar{u}_1, \bar{y}_1)$$ ← need small σ_y

$$\bar{y}_1 = \frac{d - y_1}{\sqrt{2}\sigma_y}$$ ← need small d

$$\rho = \sqrt{\frac{\gamma_2^2}{\gamma_2^2+1} \frac{\sigma_x^2+\sigma_z^2}{\sigma_y^2}}$$ ← need σ_x σ_z ~σ_y

$$\bar{u}_1 = \frac{x_1 + z_1}{\sqrt{2(\sigma_x^2+\sigma_z^2)}}$$ ← need small σ_x σ_z to have short pulse

$$f(\rho, \bar{u}_1, \bar{y}_1) = \int_0^\infty \mathrm{Re}[w(\bar{u}_1 + \bar{y}_1)][e^{-(\rho y - \bar{y}_1)^2} - e^{-(\rho y + \bar{y}_1)^2}]dy$$

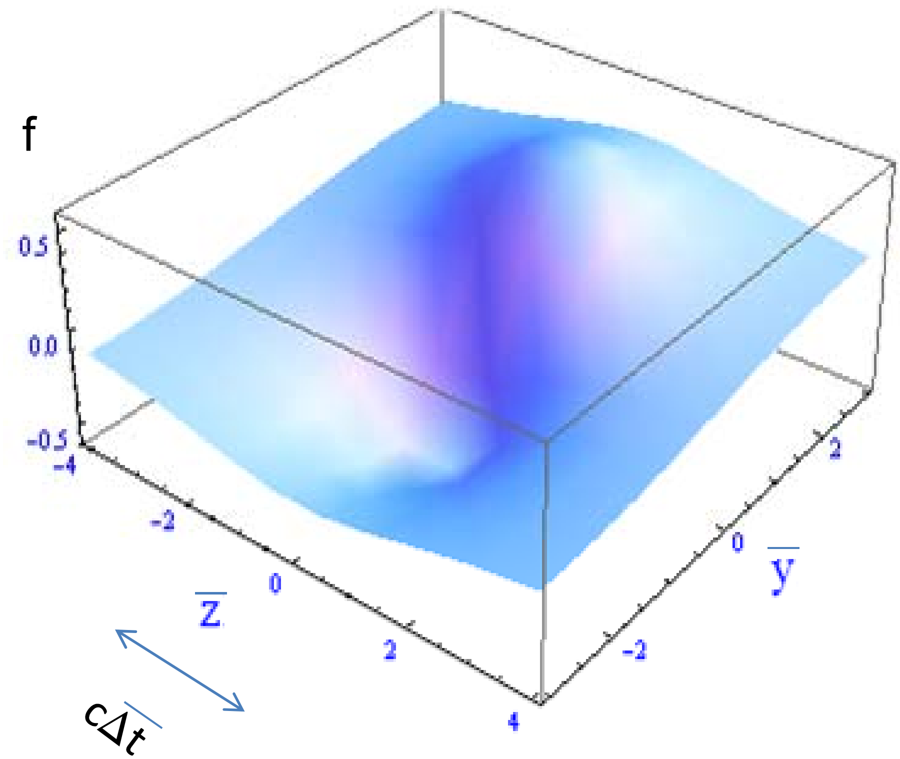
w is the error function

Scaled formula shows the importance of small beam size for angle and time resolution

f profile gives scaled dependence of kick angle on vertical distance and slicing length

Case for ρ=1

Scaled parameters should be ~ 1

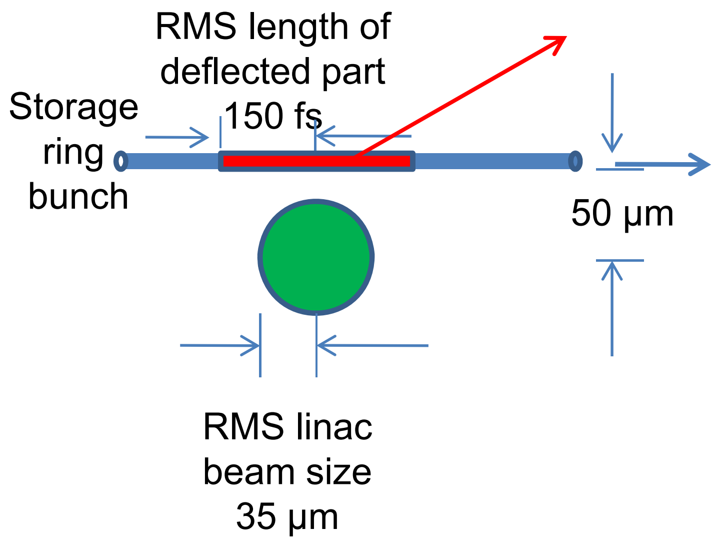


Slicing length ⇔ Time resolution ⇔ width of f profile in z direction

Kick angle ⇔ distance in y direction

Typical Parameters

Beam size determine slice length



$$q_2 = 100\,pC \quad Z0 = 377\Omega \quad E_1 = 3GeV$$

$$E_2 = 5MeV \quad \gamma_2 \approx 10$$

$$\varepsilon_n = 5\mu m \quad \varepsilon = \varepsilon_n / \gamma_2 = 0.5\mu m$$

$$\beta = 2.5mm \quad \sigma_y = \sqrt{\beta\varepsilon} = 36\mu m \quad d = \sqrt{2}\sigma_y = 50\mu m$$

$$\sigma_z = 15\mu m \quad (\sim 50\, fs)$$

$$\theta_{\max} = \frac{eq_2 Z_0 c}{2\pi E_1} \frac{\gamma_2}{\sqrt{\gamma_2^2+1}} \frac{1}{\sqrt{2}\sigma_y}$$

$$= \frac{e \times 100\,pC \times 377\Omega}{2\pi 3GeV} \frac{3\times 10^8 m/s}{50\mu m} = 12\mu rad$$

$$\rho = \sqrt{\frac{\gamma_2^2}{\gamma_2^2+1} \frac{\sigma_x^2+\sigma_z^2}{\sigma_y^2}} = 1.1 \quad f = 0.6$$

$$\theta = \theta_{\max} f = 12\mu rad \times 0.6 = 7\mu rad$$

Require: **high rep. rate, low energy, small focused beam size, short bunch length**

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Advantage when compared to other schemes:

- Need much smaller space in storage ring for interaction point, compared with crab cavity
- Pulse length (150fs) much shorter than crab cavity method (1-2ps)
- The flux per pulse may be increased significantly compared with laser slicing (> x 6-10)
- Rep rate can be many orders of magnitude higher than laser slicing (>10 MHz compared with 1-10kHz)
- 10^4~10^5 of magnitude higher rep. rate, more stable than LCLS for short x-ray pulse

Proposal: Proof of principle experiment Demonstration of Slicing Beam Parameters using test at SDL

test focusing in space charge dominated regime

Challenges and Questions

•What is a realistically high rep. rate
•lowest feasible energy beam to reduce RF power in e-gun and cost
•For low energy beam, space charge effect blow up 3-D beam size limit time resolution
•Estimate shows space charge makes bunch length changing rapidly at focal point
•Low energy beam may have larger relative energy spread → large chromatic focusing error
•We need to reduce energy spread by removing energy chirp by linac
•We can also carry out chromatic correction to reduce beam size
•To lower cost we need to reduce linac section used for removing energy chirp
•To lower cost we need to find a balance between energy chirp removing, chromatic correction and space charge effect in strong focusing
•These combined effects are complicated, we need both simulation and experimental test

Proof -of-Principle Experiment at SDL

First Step:

•Demonstrate focusing system for low energy beam

•Study chromatic correction to further reduce focusing size, for pulse length to be <150fs

Importance:

•Ultra-short x-ray pulse in storage ring is in demands

•Test and improve new method

Future possible collaboration:

• High rep. rate RF gun may need collaboration with other labs

•Testing new method on a storage ring

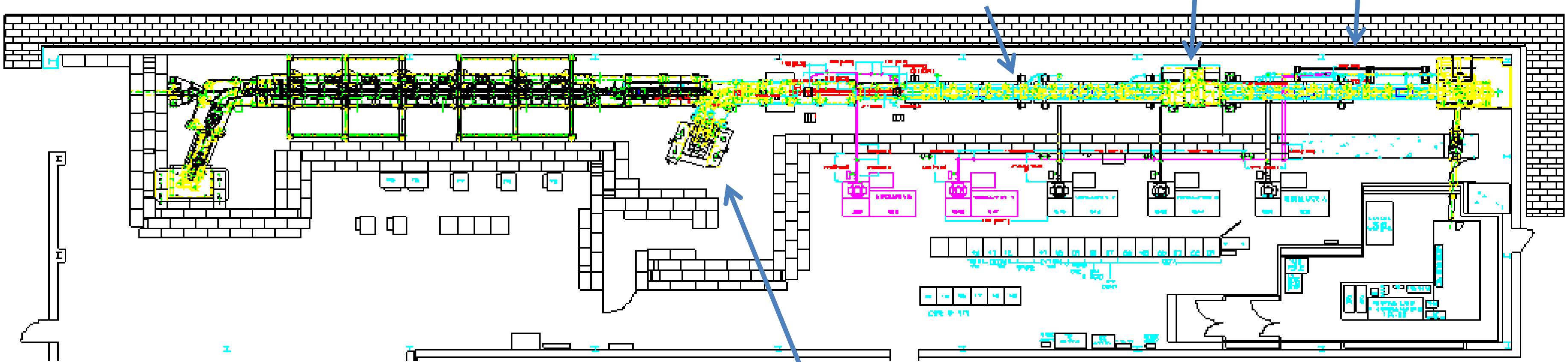
Fu**ture step:**

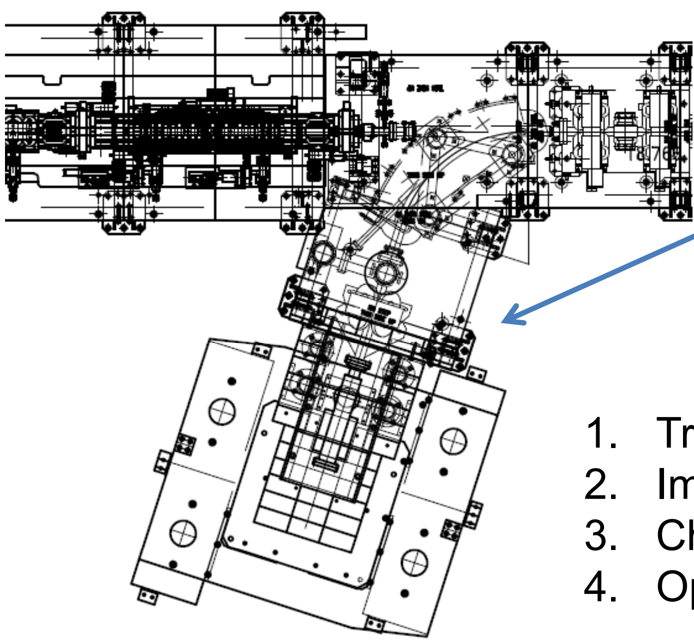
Demonstration of femto-slicing at SDL: **bring two bunches from two e-guns to crossing point.**

Goal of first step:

- Determine the basic parameters---energy, charge, focal point size, bunch length at focal point
- Find how much we need to remove the energy chirp of the linac bunch to optimize chromatic correction, or, can we avoid this?
- Full simulation of focusing including space charge effect on 3-D blow-up and chromatic correction
- Design the focusing system and the diagnostics of beam size and bunch length at the focal point
- Experimentally confirm the basic parameters

Test focusing at SDL





End of beam dump after the dipole , space for a set of quads and sextupoles for focusing with chromatic correction

Experiment steps:

1. Transport beam from e-gun to dipole with low energy (5MeV)
2. Implement focusing system with diagnostics
3. Characterize beam size and bunch length
4. Optimize beam and study its relation to energy chirp