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

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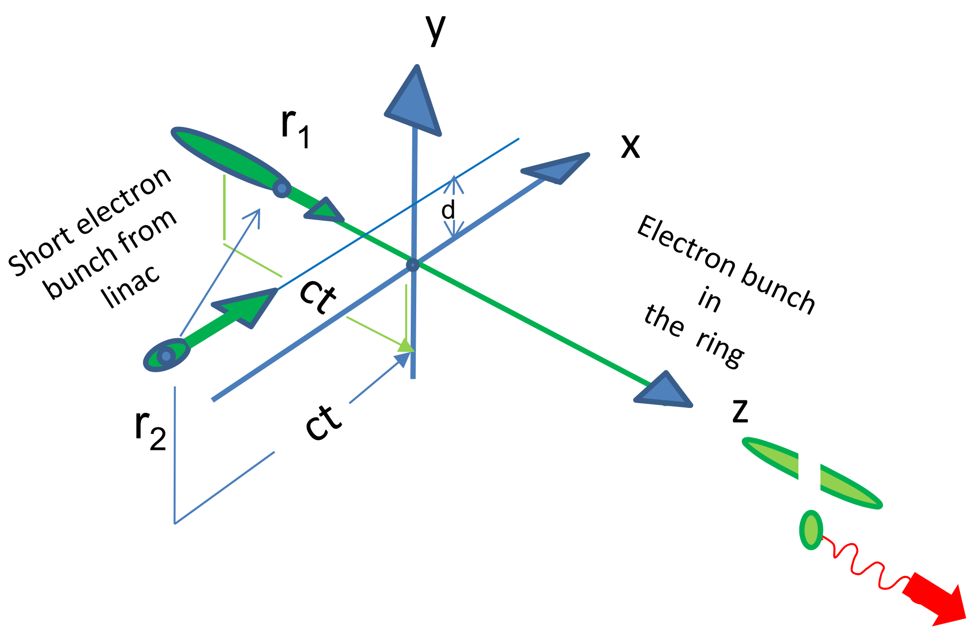


Basic Idea:
When short electron bunch from linac (5MeV, 50pC,100fs) passes above a storage ring bunch (30 ps), it kicks a slice (150fs) vertically.
(Ferdinand Willeke)

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

Advantages when compared to other schemes respectively may be a complimentary approach

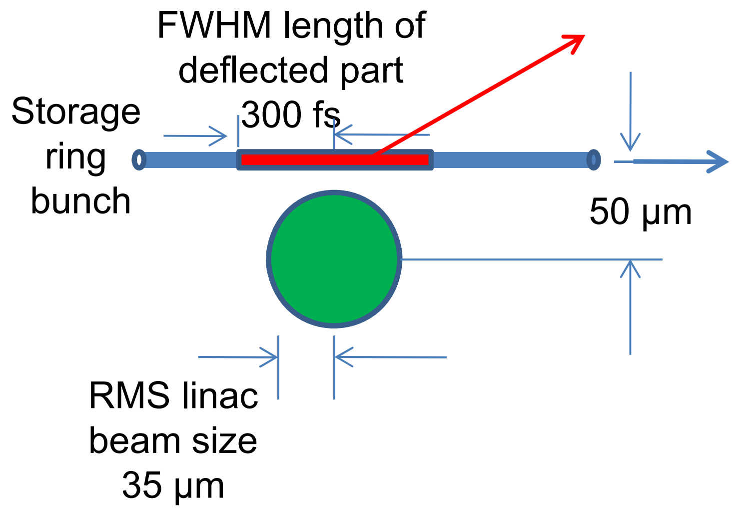
- Need much smaller space in storage ring for interaction point, compared with crab cavity
- Pulse length (150fs) much shorter than crab cavity method (1-2ps)
- The flux per pulse may be increased significantly compared with laser slicing (> x 6-10)
- Rep rate can be higher than laser slicing (100kHz-1 MHz compared with 1-10kHz)
- 10^3~10^4 of magnitude higher rep. rate, more stable than LCLS for short x-ray pulse

Estimate of Basic Parameters of the Slicing Beam

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

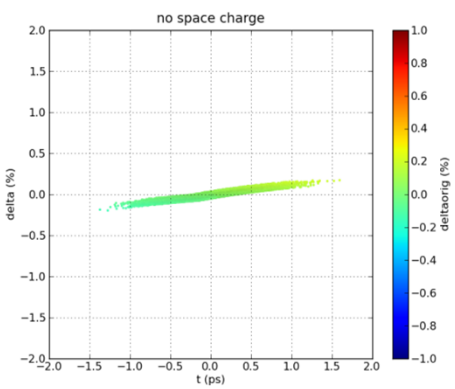
- Energy 5 MeV, 50pC, 100fs bunch
- ϵ_n= 5μm, β=2.5mm,f=25cm,
- Deflection θ=3.3 μrad
- Core separation 5 σ require θ =3 μrad with β_y=25m
- Length of deflected part ~2 × 150fs

Beam size determine slice length

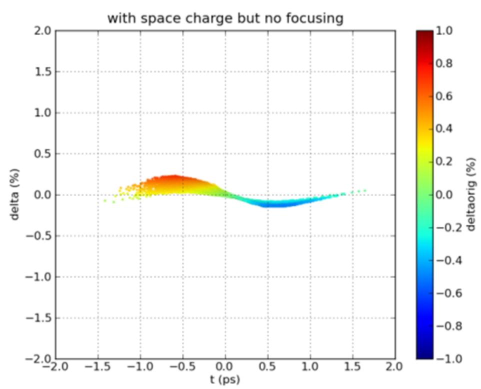


How to generate chirp for low energy compressor

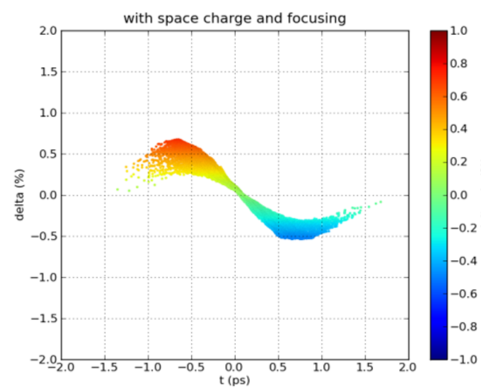
- Photo-cathode gun output has small chirp at low charge
- Space charge generate negative chirp---head has higher energy than tail
- Focus the beam to use space charge to increase the chirp



1. low charge -> very small chirp



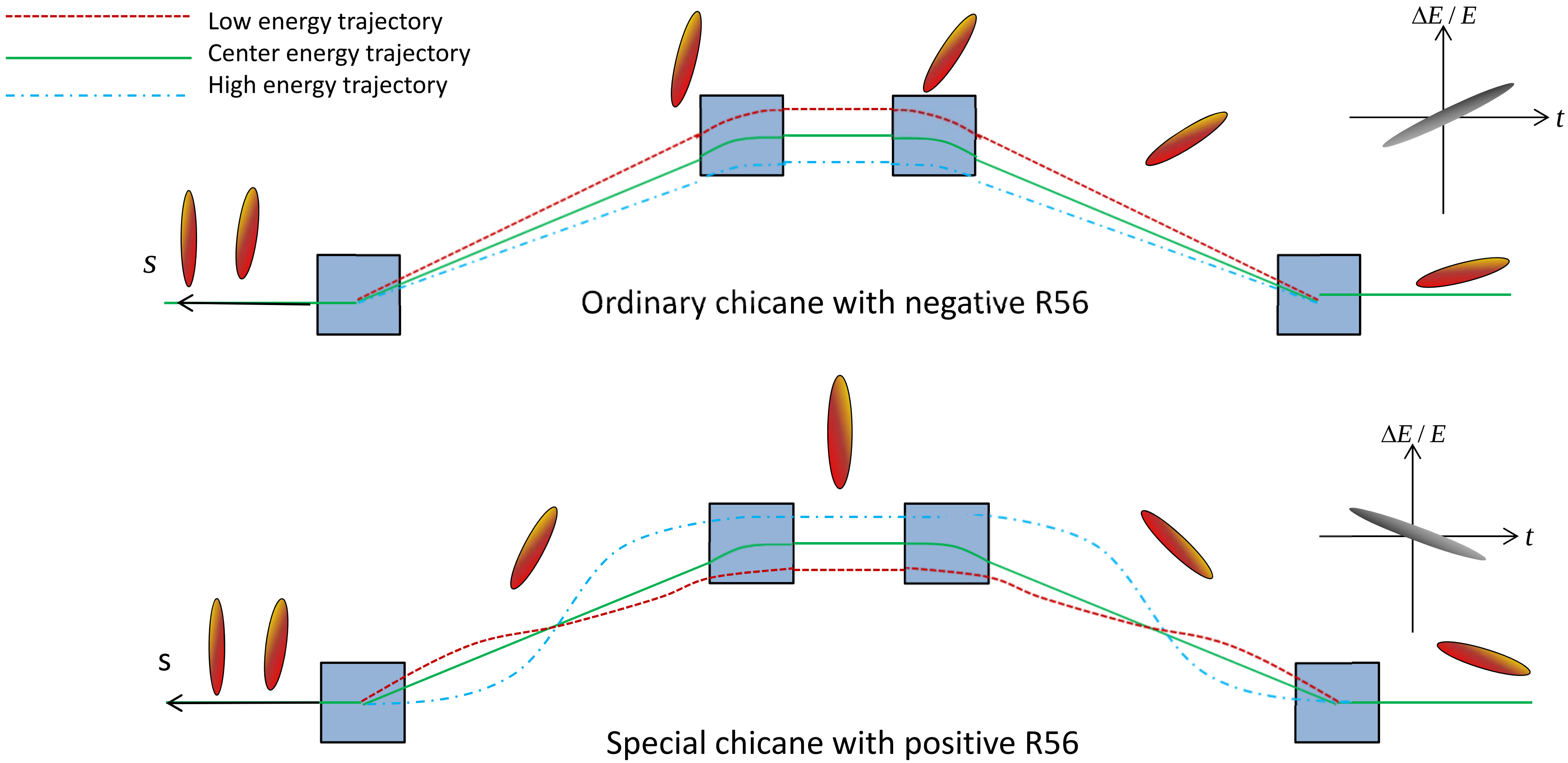
2.100pC, small negative chirp



3. Focusing → required chirp ~1%/ps

Chicane for negative chirped bunch

- For ordinary chicane, tail has higher energy, go through shorter path length to catch up with head → negative R56 (path length change per unit energy increase)
- For our case, head has higher energy due to space charge, needs longer path
- Use quads to flip the trajectory after bend to increase path length for electrons with higher energy--- positive R56



Chicane for negative chirped bunch

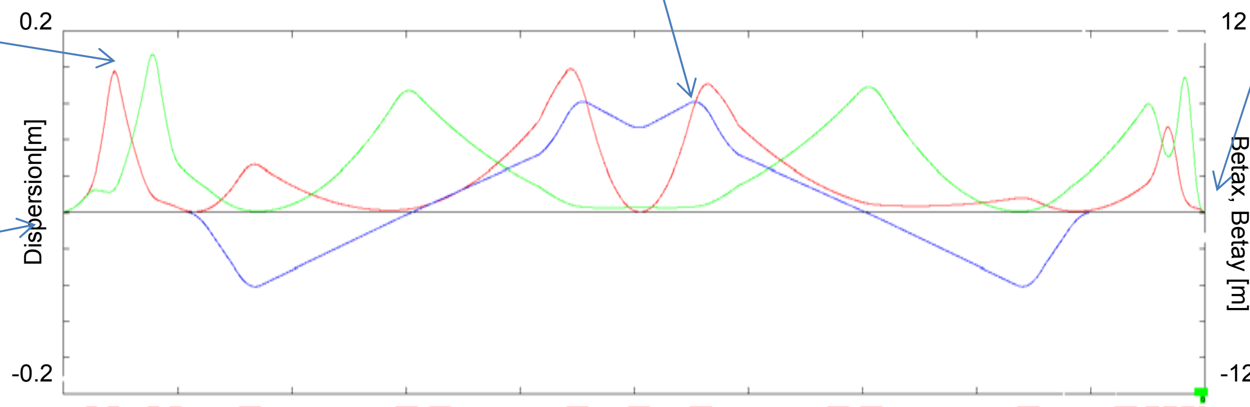
- Small chirp → large R56→large beta function→ large beam size→ particles with large transverse oscillation lag behind→ long bunch length → need smaller R56→ we need larger chirp→ strong focusing before entrance to the chicane (against intuition, we use space charge instead of avoid it)
- Found we need 1% chirp in 1 ps and R56=15mm
- Realized we need to overcome R56 of drift space, -10mm/m. For 5 meter beamline we need additional 50mm of R56→R56=65mm

beta function is controlled <10m

Dispersion is reduced to 12cm

100fs at focal point—satisfactory when space charge is neglected

Focusing before entrance to chicane increased the chirp to 1%/ps



Use ELEGANT to design linear lattice as first step (without space charge effect)
To reach R56=65mm. Lattice is as close as possible to maintain symmetry. This help control beta maximum.

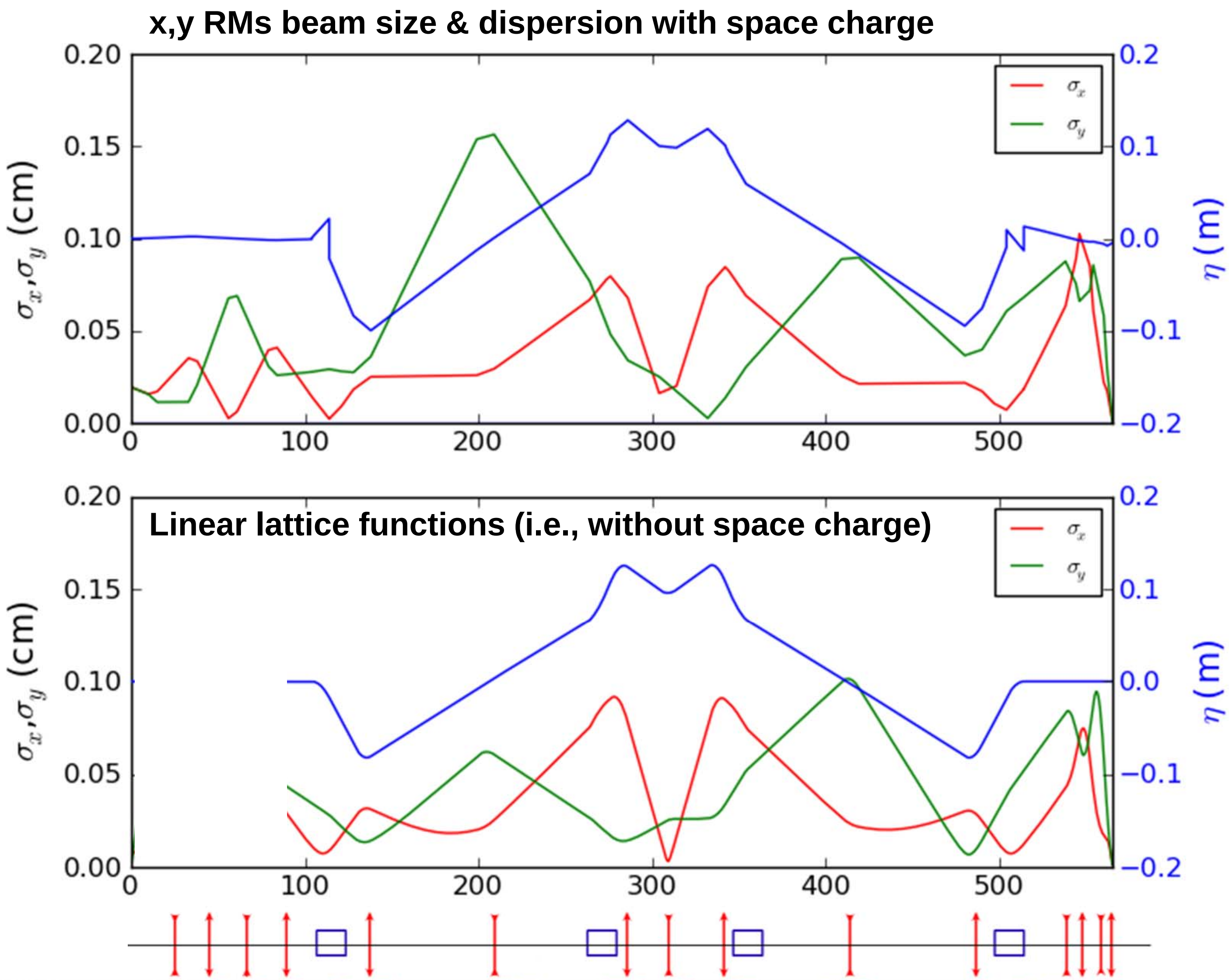
Move these quads close to bends to limit betax while reaching desired dispersion

Bending increased to 20 degree from initial design of 10

Space charge effect

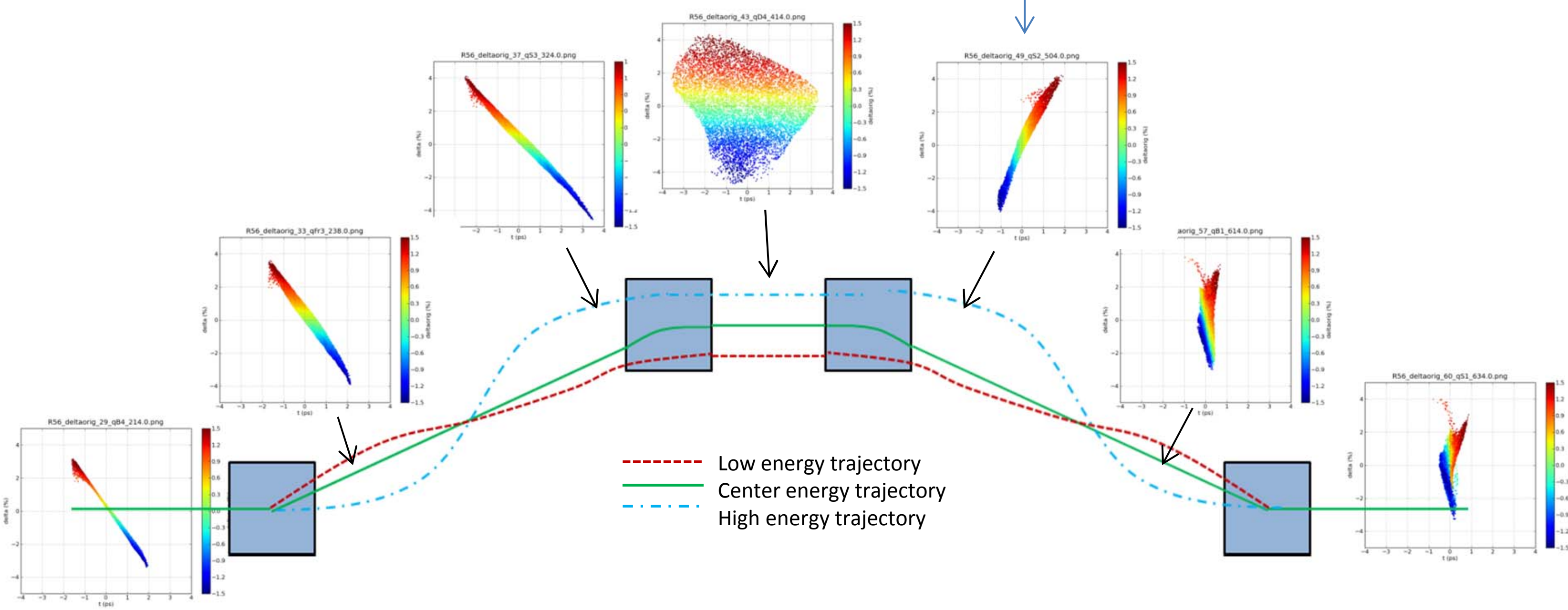
- **Turn on space charge, simulated by the code PARMELA, 3-D blow up:**
  - **Beam size increased from 30μ →500μ**
  - **Bunch length increased from 100fs → 1ps**
- **Particle energy is no longer constant →**
  - **Dispersion and beta function lost meaning**
- **Found a way to represent these functions**
  - **Averaged trajectories within selected initial energy ranges give equivalent dispersion**
  - **Averaged trajectories within selected initial emittance ranges give equivalent beta function**
- **Adjust the quads to return the “dispersion function” and “beta function” to be approximately same as the case without space charge.**
- **Gradually turn on the space charge from 1 pC to 10 pC and start to use optimization procedure in python to optimize these functions**

Functions defined to represent beam size and dispersion when space charge dominated

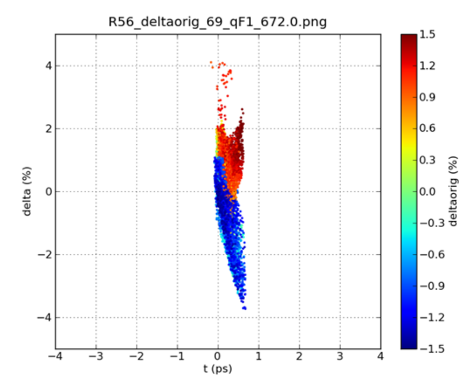


Magnets are adjusted to return to similar shape as linear case while charge is gradually turned on

- To overcome drift space’s negative R56, we need over compress in the middle of the compressor
- After the middle of the chicane the head becomes the tail, the energy spread starts to decrease
- Lattice is almost symmetric



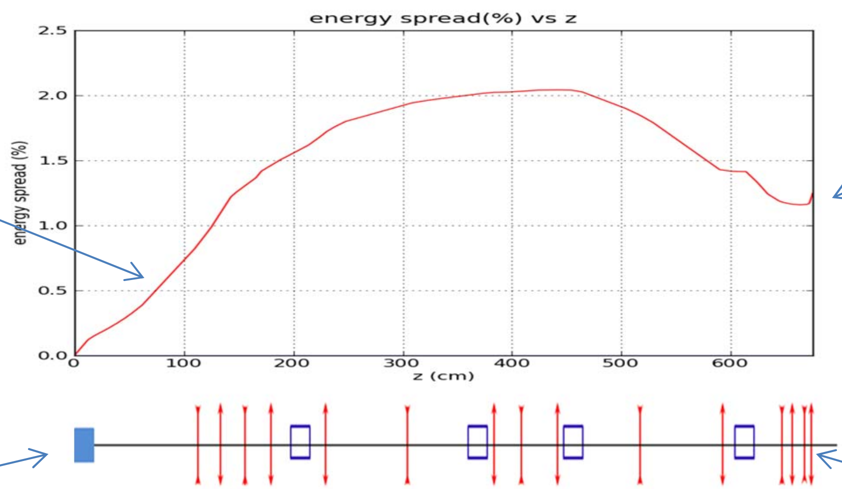
- at the focal point, due to Liouville's theorem, longitudinal phase space is conserved →
- increased energy spread can lead to smaller bunch length
- Strong focusing at the entrance to chicane can increase energy spread
- Increase solenoid strength in RF gun for strong focusing → shorter bunch length
- space charge effect can be used to compensate its damages



Energy spread increase due to space charge effect is reversible

- Energy spread change caused by space charge was not as harmful as initially expected
  - When energy spread increased, the required quad strength and dipole strength to bend the trajectory for high energy particles are reduced so it returns to the same trajectory as if there is no space charge
- Energy spread increase in this case is not an irreversible process

Strong focusing Increases energy spread



Increase final energy spread so bunch length is shorter

RF-gun

Final focal point

Parameters for the Slicing Beam
Based on performance of bunch compressor at 5 MeV

•Slice pulse length ~2×185fs FWHM

Energy 5 MeV, 50pC, 166fs bunch

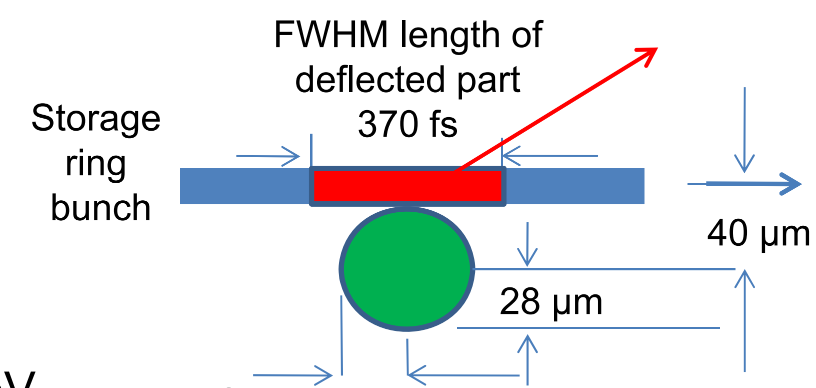
Beam size determine slice length

•Angular separation $5\ \sigma_\theta$

Core σ_θ=0.6 μrad with β_y=25m

Deflection θ=3.3 μrad

Radiator at β_y=1m, deflect θ =16 μrad



•Single pulse photon flux

S=10^{15} photons/sec/0.1%BW, U20, 8keV

Slice 0.3ps out of 30ps bunch=1% fraction

revolution time 2.6μs, 1000 bunches, 500mA

$10^{15} \times$ 0.3ps/30ps $\times$ 2.6μs/1000= 2.6×10^4

2.6×10^4 photons/0.1%BW bunch current 0.5mA

16×10^4 photons/0.1%BW 3mA camshaft

•Flux 2.6×10^9 photons/sec/0.1%BW

with rep. rate 100kHz

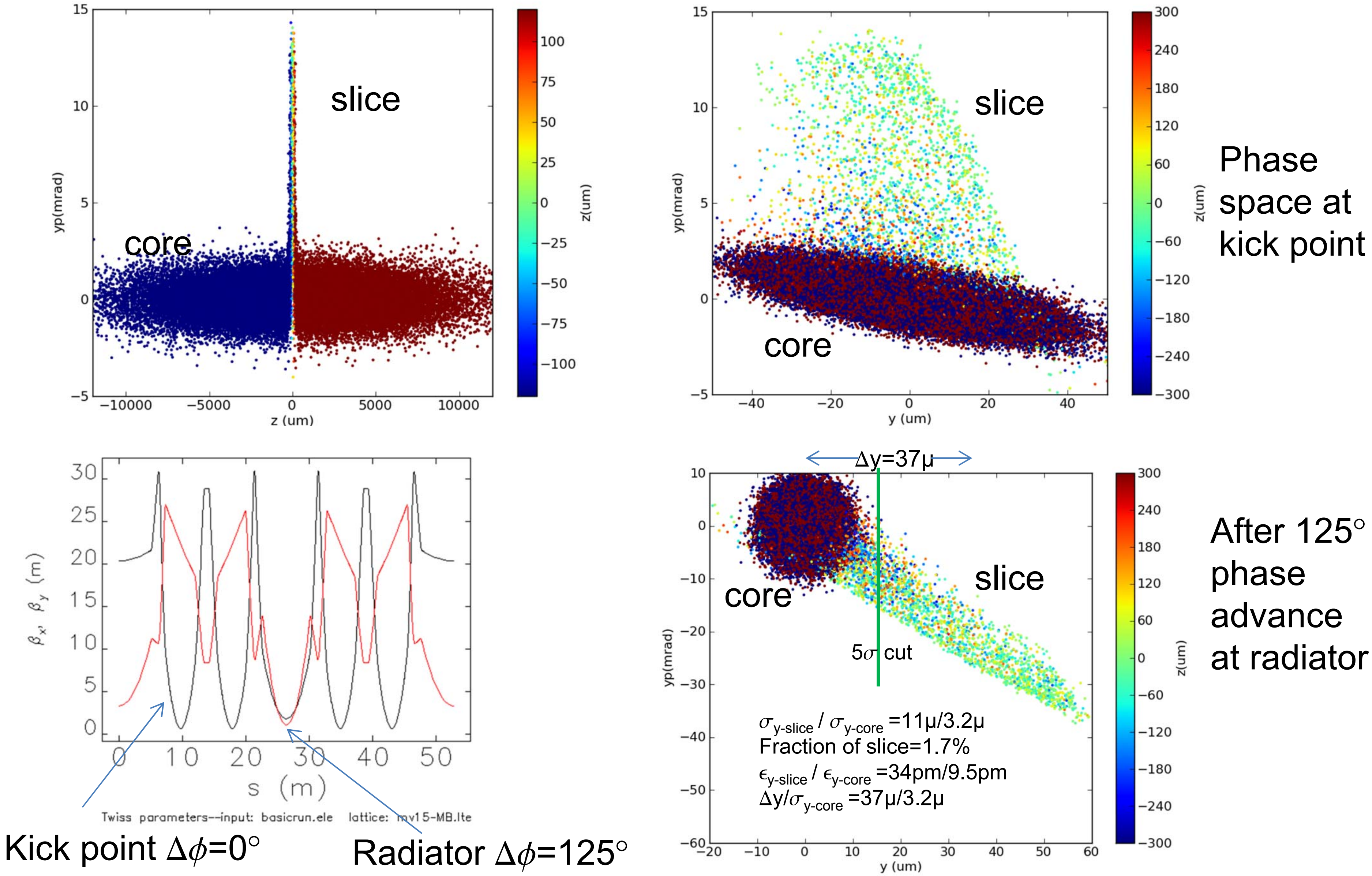
vertical emittance increase 8% (to be discussed later)

Performance of Compressor vs. Energy, Charge

Increase linac energy to increase charge and reduce bunch length

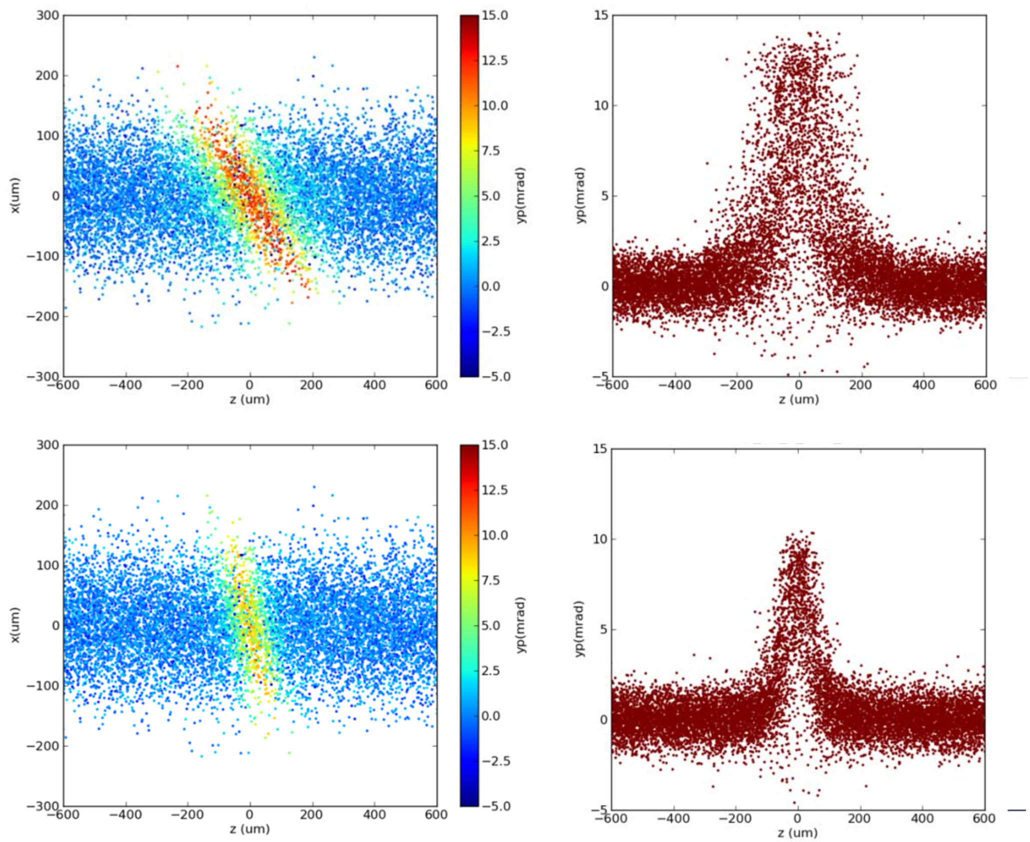
case	Charge[pC]	Energy[MeV]	Bunch length[fs]	Rms beamsize x[um]	Rms beamsize y[um]
1	50	5	166	31	28
2	100	12	110	34	31
3	150	12	122	32	22

A specific example of storage ring beam slice profile
Use 12MeV beam with 150 pC, at d=31µm from high energy beam center
Showing 37µm positional and 22 µrad angular separation at radiator



Crossing angle of slicing and Slice pulse length

90°

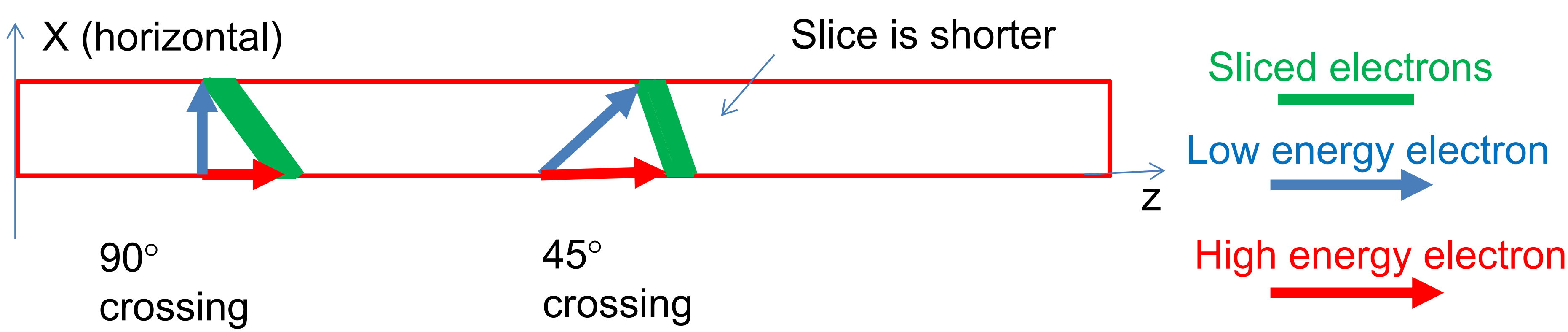


45°

Result:

σ_t =270fs
$\sigma_{y\text{-slice}} / \sigma_{y\text{-core}}$ =11μ/3.2μ
Fraction of slice=1.7%
$\epsilon_{y\text{-slice}} / \epsilon_{y\text{-core}}$ =34pm/9.5pm
$\Delta y/\sigma_{y\text{-core}}$ =37μ/3.2μ

σ_t =150fs
$\sigma_{y\text{-slice}} / \sigma_{y\text{-core}}$ =6.9μ/3.2μ
Fraction of slice=0.9%
$\epsilon_{y\text{-slice}} / \epsilon_{y\text{-core}}$ =19pm/9.5pm
$\Delta y/\sigma_{y\text{-core}}$ =29μ/3.2μ



Rep. rate limitation due to vertical emittance increase

One angular kick of 5 σ_θ with a slice of 300 fs in a 30 ps bunch increases ϵ_y by

$$\frac{0.3ps}{30ps} \times 5^2 \times \frac{1}{2}\epsilon_y = 12\% \, \epsilon_y$$

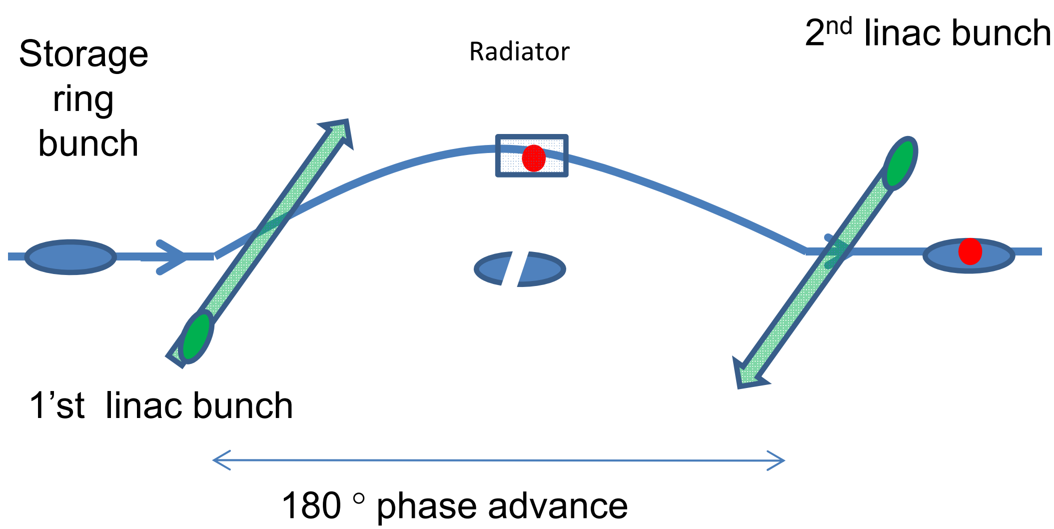
with rep. rate f for one bunch, increase rate is f $\times$ 12%,

Emittance increase is f $\times$ 12% $\times \tau$, τ =damping time =10ms

If f=100Hz, get 12% increase

For 1000 bunches with evenly distributed kicks, 12% tolerance on ϵ_y increase, rep. rate limit is 100kHz. APS experiences show tolerance on ϵ_y may be much larger.

Two linacs bunces to form a local bump for the kicked electrons in storage ring
Can reduce emittance increase with increased rep. rate. Challenge to be studied



Summary:
It is possible to achieve the following:

- **Small space used in storage ring**
- **High fraction: slice is 1% of core**
- **Use low energy beam 5-12MeV**
- **High rep rate 100kH-1MHz**
- **Pulse length 150fs**

End