Space charge compensation and optimal mergers

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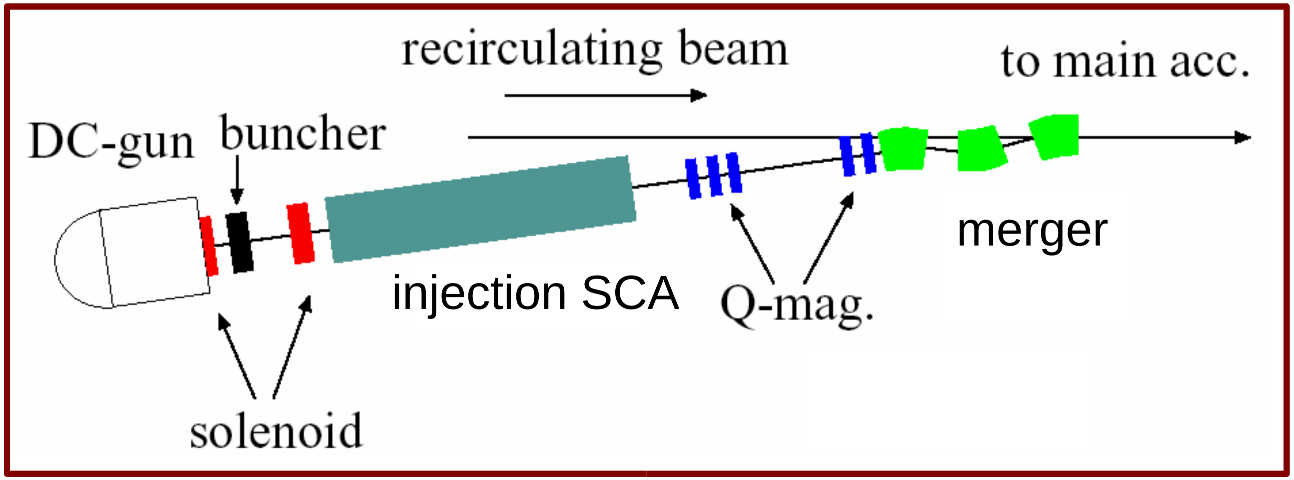
to answer the question:

How can space charge and other emittance diluting effects be compensated in an ERL, especially in the injector and merger ?

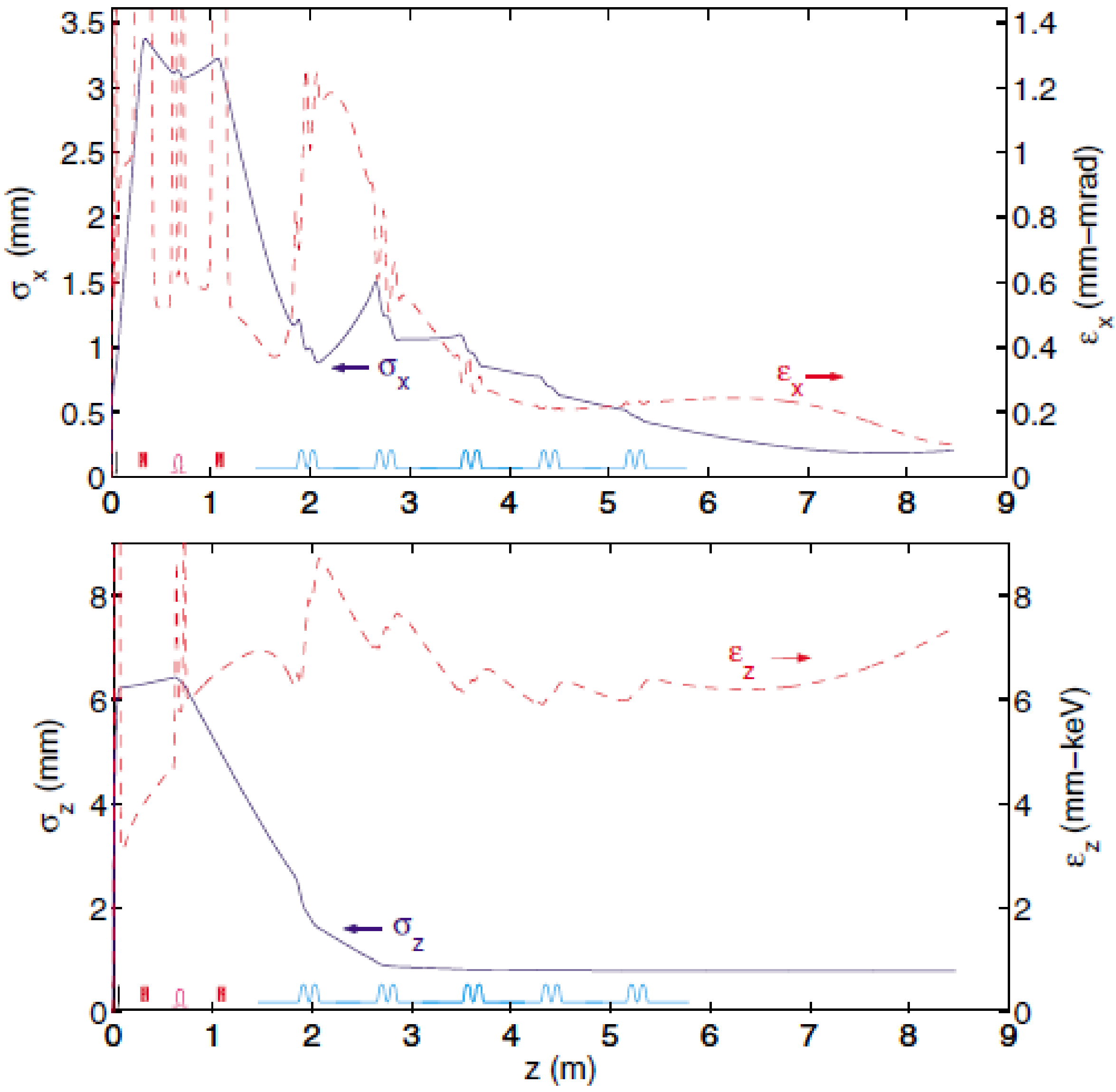
Injector Configuration and Parameters



- components
  - DC gun 500-750kV with NEA-GaAs photocathode
  - Injection SCA ~500kW = 100mA x 5MeV or 1-10mA x 15MeV
  - Merger dipoles and other focusing magnets

- operation modes
  - high-flux = 100mA (77pC x 1.3GHz), ε_n ~ 1mm-mrad
  - high-coherence = 10mA (7.7pC x 1.3GHz), ε_n ~ 0.1mm-mrad
  - ultra-fast = 1mA (1nC x 1MHz), ε_n ~ 5-10mm-mrad

Example of an ERL injector

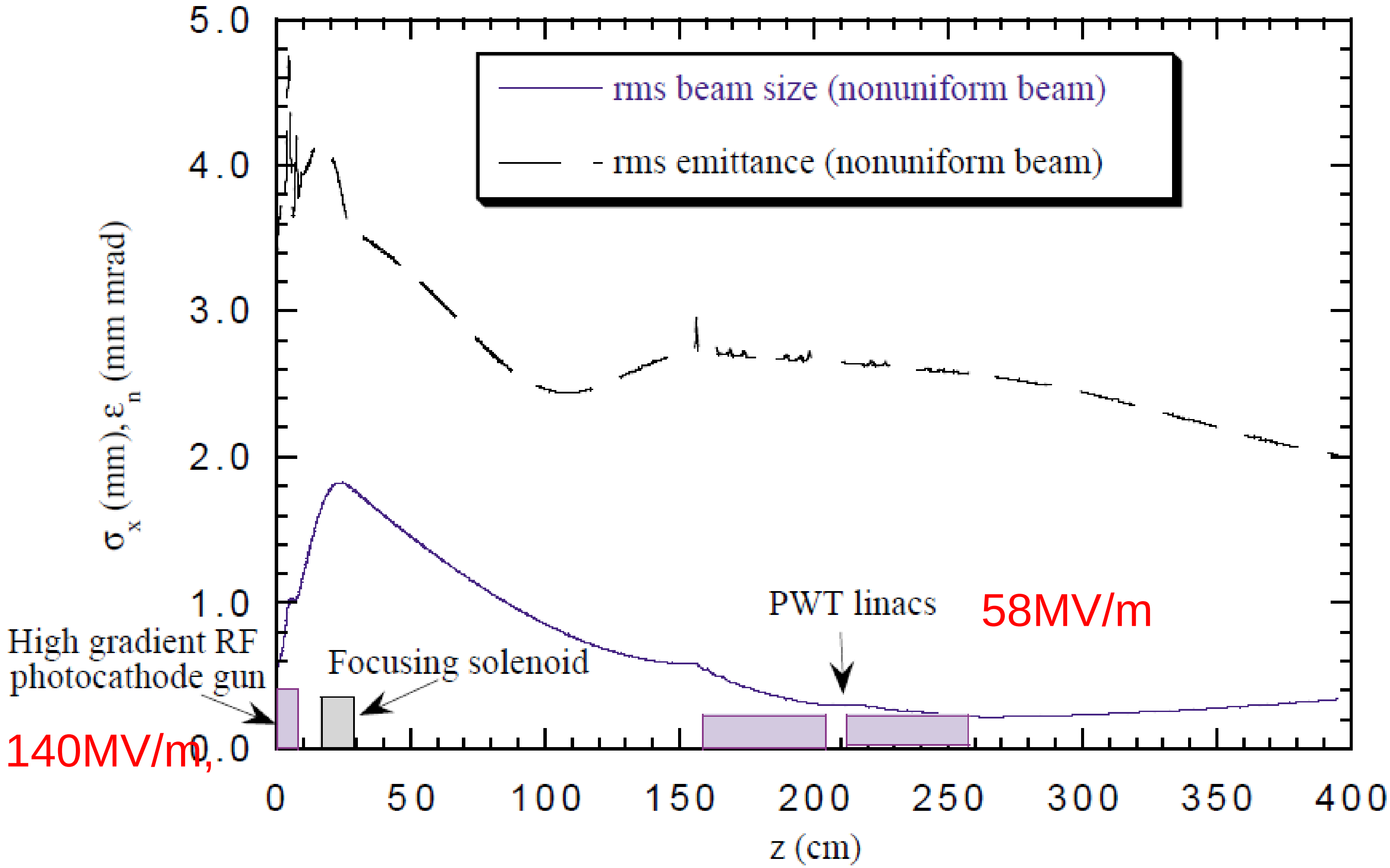


I. Bazarov and C. Sinclair
PRST-AB 8, 034202 (2005)

optimized for 80pC bunch

610kV gun
12.6MeV injector exit

Example of an XFEL injector



S. G. Anderson and J. B. Rosenzweig, PRST-AB 3, 094201

What are different ?

ERL injector with a DC gun	XFEL injector with an RF gun

ERL injector with a DC gun

gun

- low gradient and voltage

  10-15MV/m, 500-750kV

- there is no "RF emittance"

  -- DC gun based XFEL is proposed (SCSS)

injection Acc.

- low gradient and voltage

  1-3MV/m (effective), 5-15MeV

  limited by "input power / unit length"

- solenoid is prohibited due to SCA
- phase dependent focusing

  large effect at the 1st-cavity entrance

XFEL injector with an RF gun

gun

- high gradient and voltage

  140MV/m, 7MeV

- phase dependent transverse focusing

$$\varepsilon_{RF} = \frac{\alpha k^3 \sigma_x^2 \sigma_z^2}{\sqrt{2}}$$

Kwang-Je Kim, NIM-A275, 201 (1989)

injection Acc.

- high gradient and voltage

  ~50MV/m, 100-150MeV

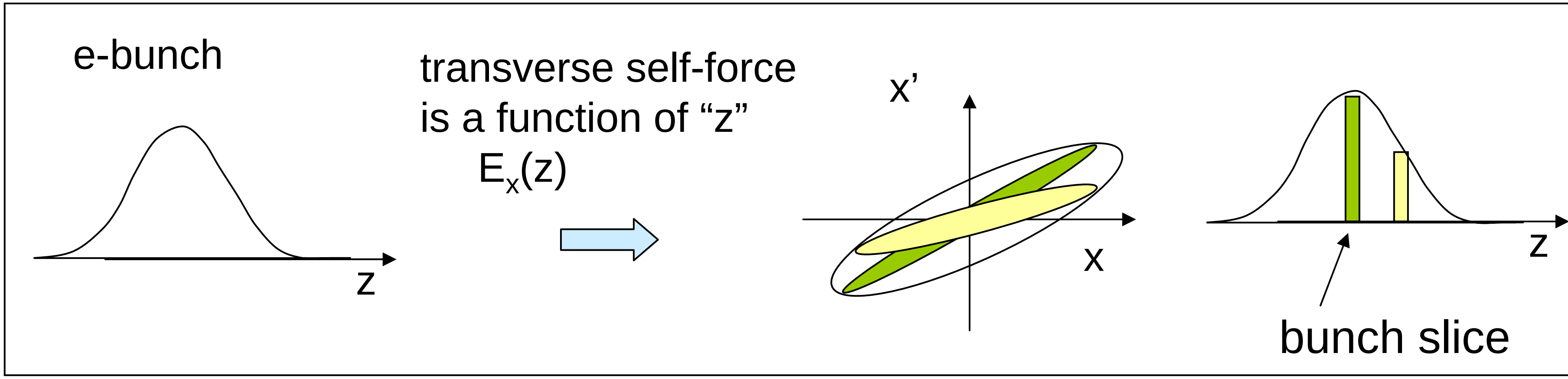
- solenoid can be applied

  --necessary for velocity bunching

- negligible phase dependent focusing

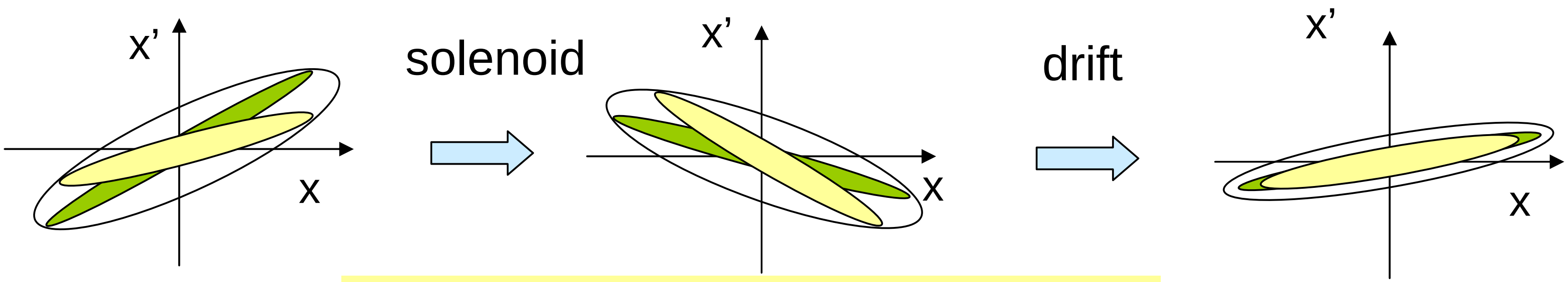
  beam energy is already high enough

emittance growth by transverse space charge force



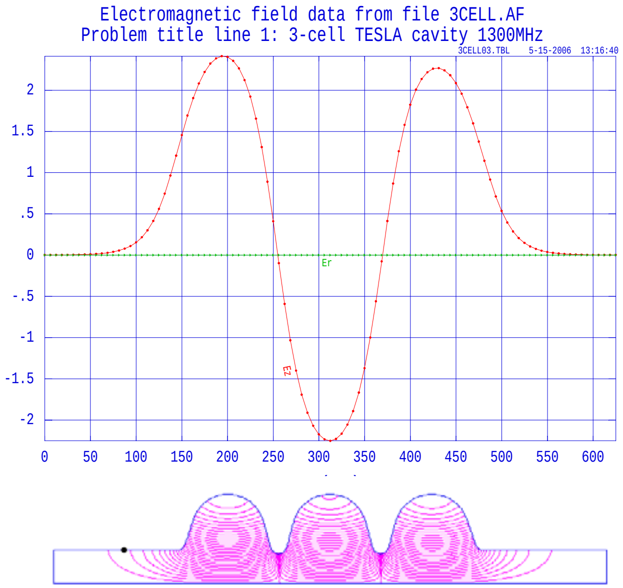
total emittance grows, but slice emittace is preserved
emittance compensation is possible

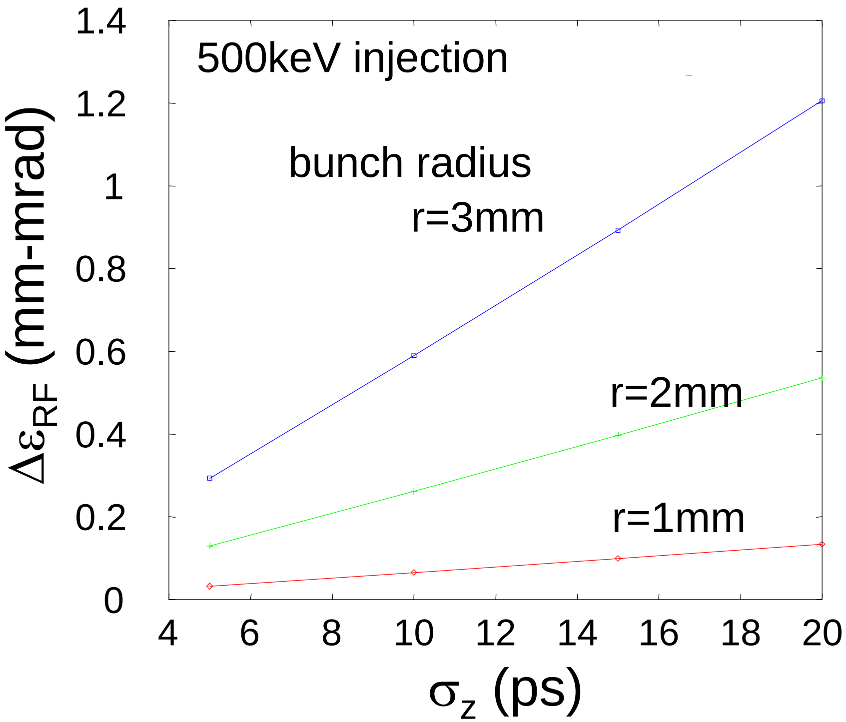
B.E. Carlsten, NIM-A285, 313 (1989).
S. G. Anderson and J. B. Rosenzweig, PRST-AB 3, 094201 (2000)



emittance compensation by solenoid

"RF emittance growth" at injection SCA



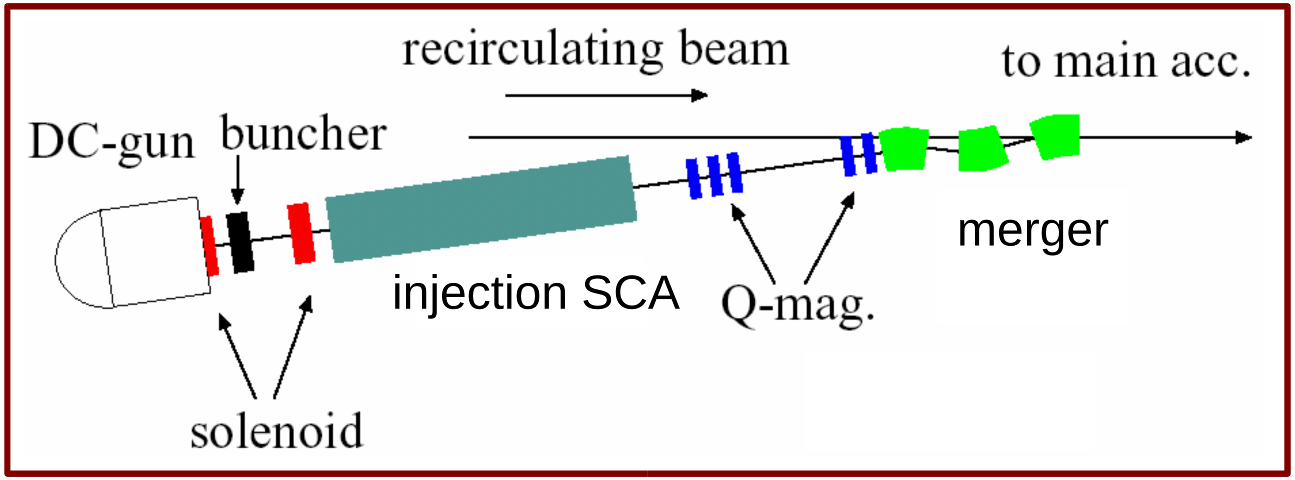


no space charge assumed = only RF emittance growth

injection phase is chosen for maximum energy gain, 1MeV

⟶ scaling : $\Delta\varepsilon_{RF} \propto \sigma_r^2 \sigma_z$ (depending on the fringe field profile)

How solenoids work in an ERL injector



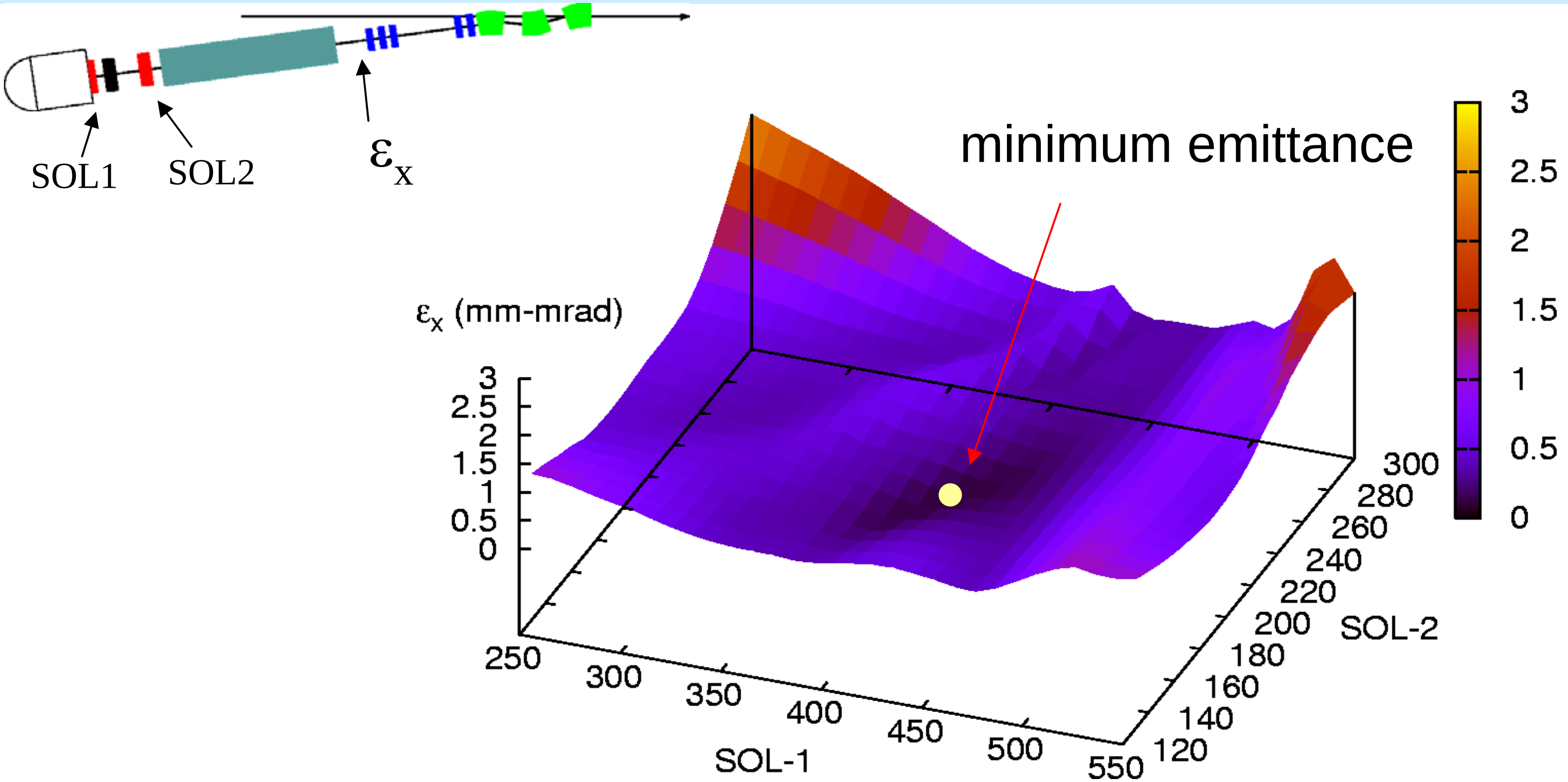
solenoids are necessary for

1. minimizing ε_{SC} by emittance compensation technique
2. minimizing ε_{RF} by controlling radial size at the buncher and the entrance of injection SCA.

⇨ { we need two solenoid.
we need to optimize both position and field of solenoid.

1 and 2 are incompatible, but there must be a solution to minimize $\varepsilon_{SC}+\varepsilon_{RF}$.

Solenoid field vs ε_x after the injection SCA

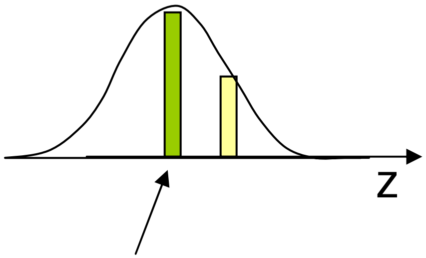


ε_x is a smooth function of solenoid field,
and there is a set of solenoid field to minimize the emittance.

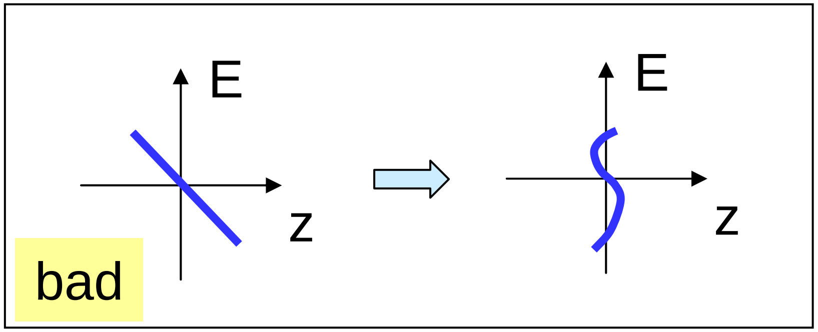
Here, we fix the position of solenoids.
See Bazarov's simulation, which changes the position and field of solenoids.
PRST-AB 8, 034202 (2005)

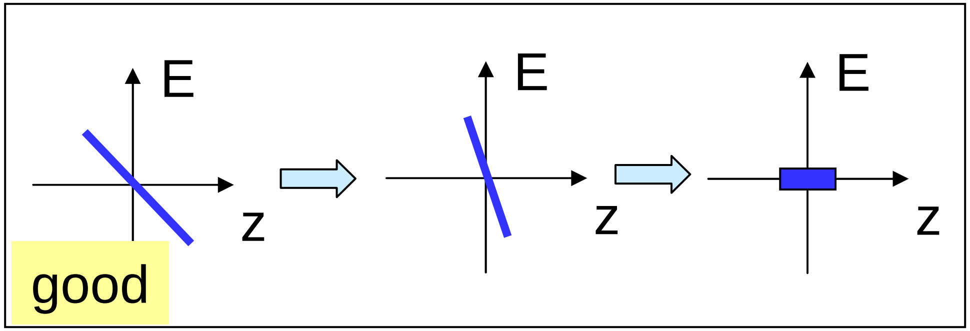
emittance compensation and bunch compression

In the emittance compensation scheme,
it is essential to keep the order of bunch slices.



In the injection SCA, emittance compensation is performed during bunch compression.



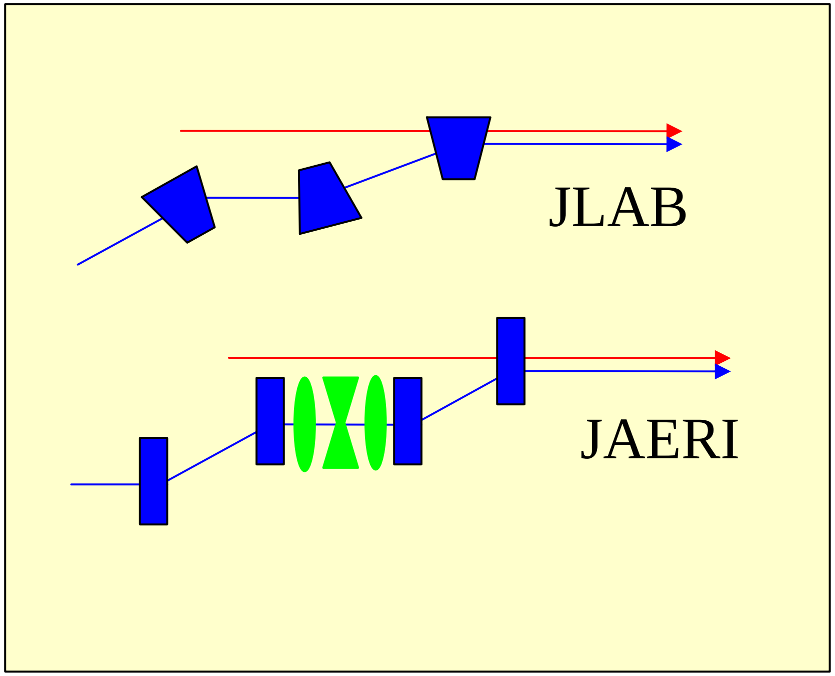


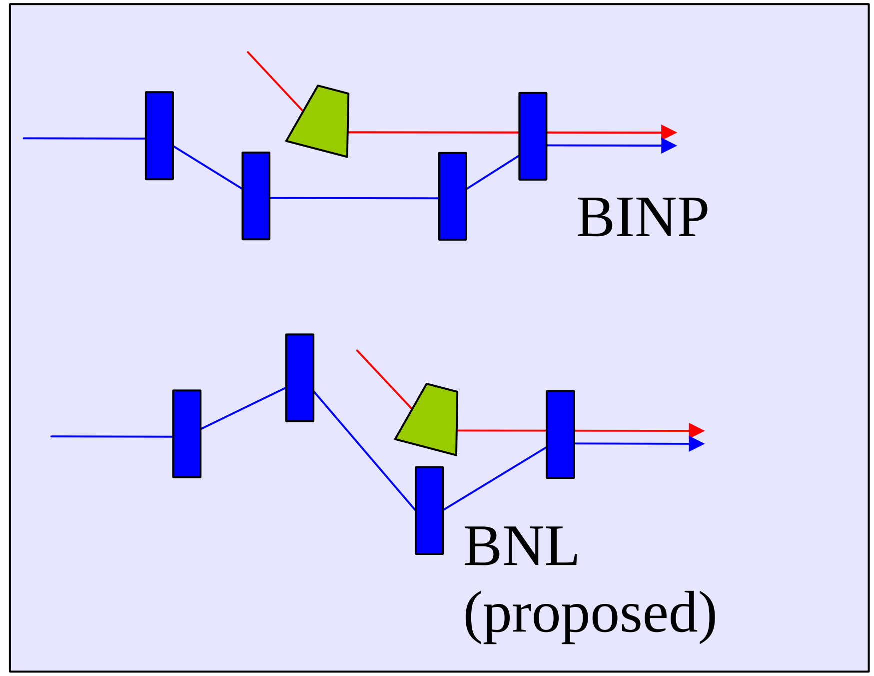
Over compression destroys the emittance compensation.

we must avoid longitudinal mixing of bunch slices

see an example of PARMELA run

Merger Configuration





"slide injection"

injection / recirculation are tilted or shifted.

“in-line injection"

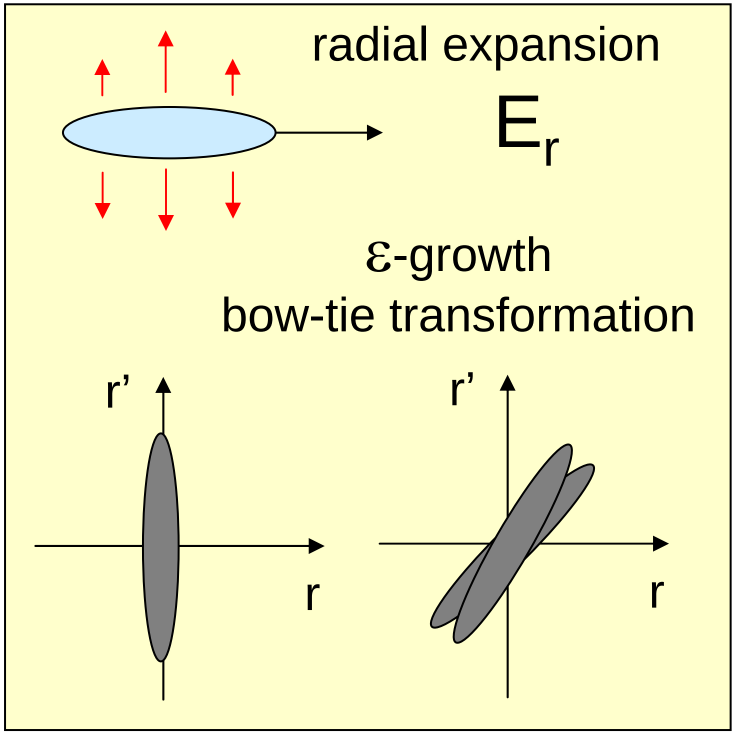
injection / recirculation are in line.

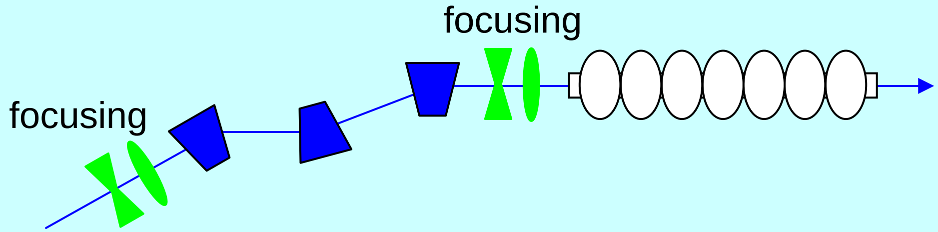
Emittance growth in a merger (1)

transverse space charge force

- injected bunches are not solid enough – still feel space charge force
- radial expansion by transverse space charge force.

$$k_p^2 = 4\pi n_b / \gamma^3 \beta^2 \qquad \text{77pC, 3ps, 5MeV} \qquad k_p \sim 0.5 m^{-1}$$

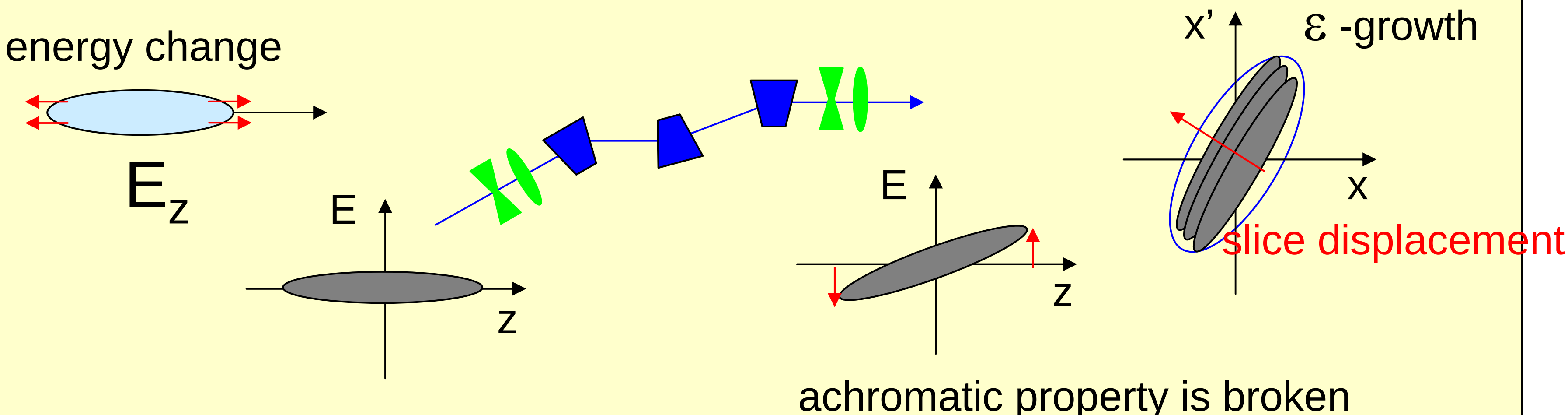




- emittance compensation scheme must be optimized across the merger.
- dipoles introduce "x-y asymmetry"
- quadrupoles are necessary

Emittance growth in a merger (2)

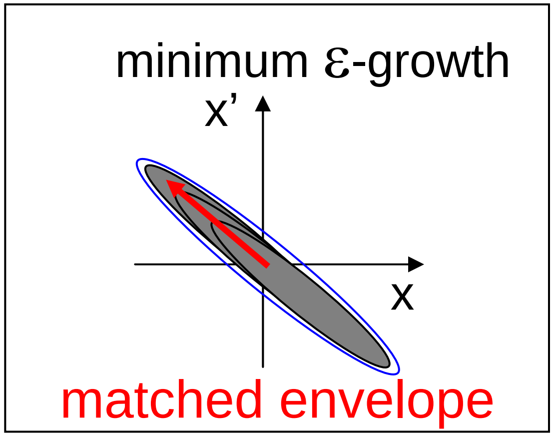
longitudinal space charge force



see for example, B.E. Carlsten et al., IEEE QE **27**, 2580 (1991).

emittance compensation by envelope-matching

- matching the space-charge kick to the beam ellipse.
- similar to the CSR case.
- is it compatible with ε-compensation for E_r?



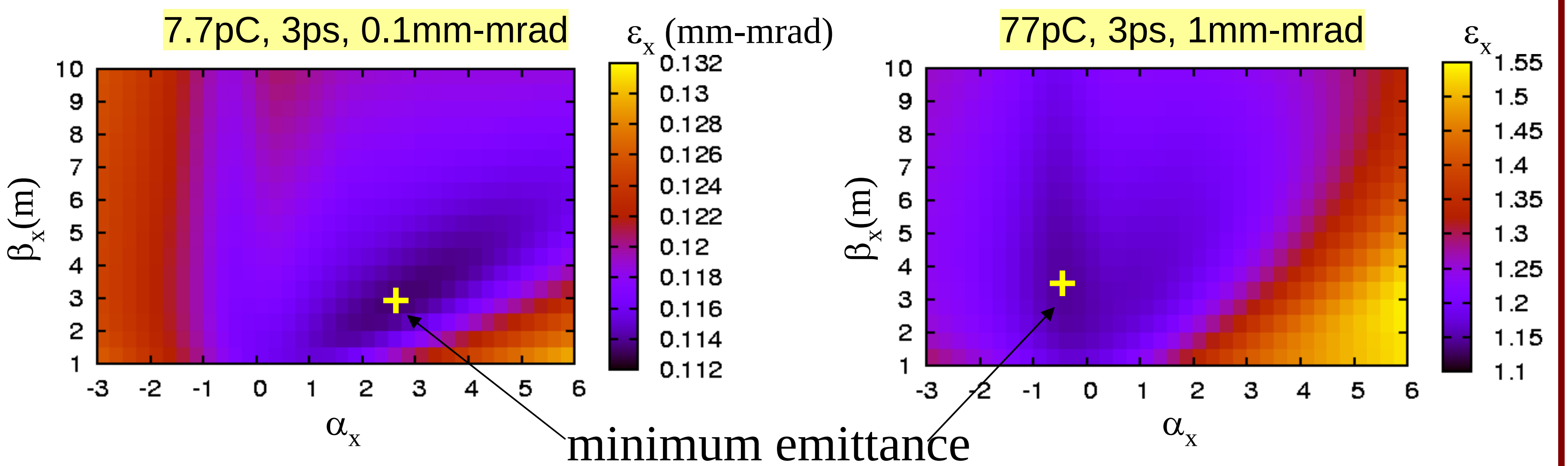
Optimum injection to a 3-dipole merger

optimum envelope = minimize “TSC effect + LSC effect”
= emittance compensation + matched envelope

TSC: transverse space charge, LSC: longitudinal space charge.

this optimum envelope is a function of bunch parameters.

PARMELA runs for the merger (3 dipoles) with varying α_x, β_x at the merger entrance.



How to design an ERL injector

The goal is

- minimize TSC and RF effects in the gun and injection SCA.
- obtain linear bunch compression (no over-compression)
- minimize TSC and LSC effects in the merger.

⇩

numerical studies show modestly acceptable results

I. Bazarov, C. Sinclair, PRST-AB 8, 034202 (2005)
R. Hajima. R. Nagai, NIM-A557, 103-105 (2006)

analytical studies give a good insight

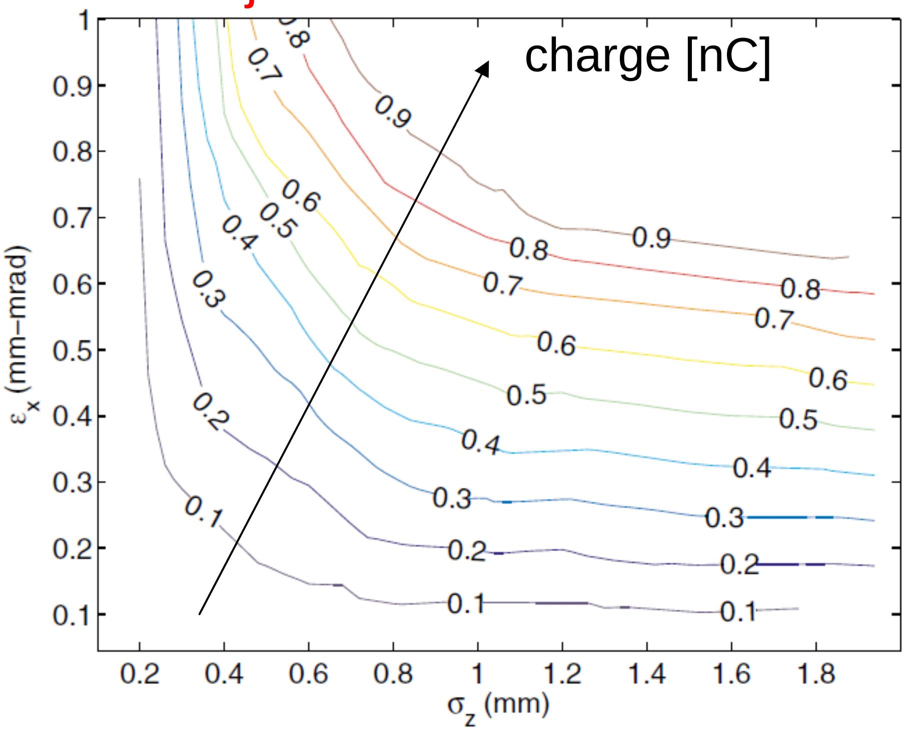
V.N. Litvinenko, R. Hajima and D. Kayran, NIM-A557, 165-175 (2006)

However, we must notice untouched critical issues:

asymmetric external field (SCA main coupler, HOM …)
self field in a curved path
effects of trapped ions (charge neutralization, tune shift …)

multivariate optimization

multi-objective GA

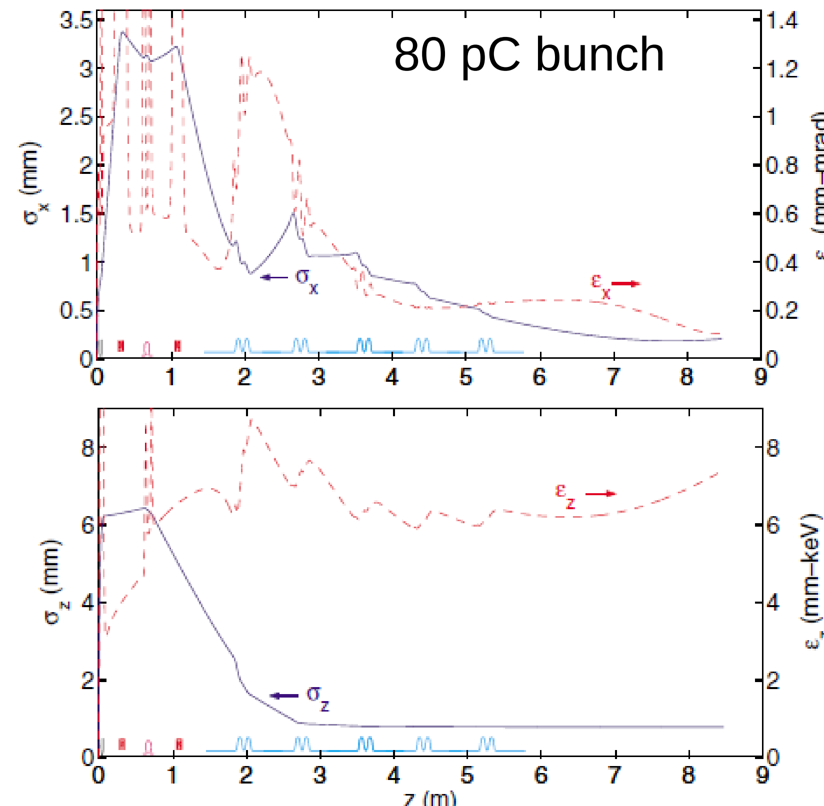


$$\varepsilon_n = Q(0.75 + 0.15/\sigma_z^{2.3})$$

I. Bazarov, C. Sinclair
PRST-AB 8, 034202 (2005)

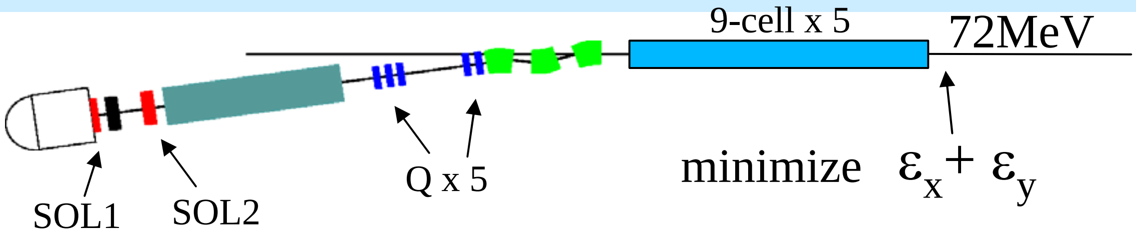
cathode temperature = 35 meV

610 kV gun, 12.6 MeV injector



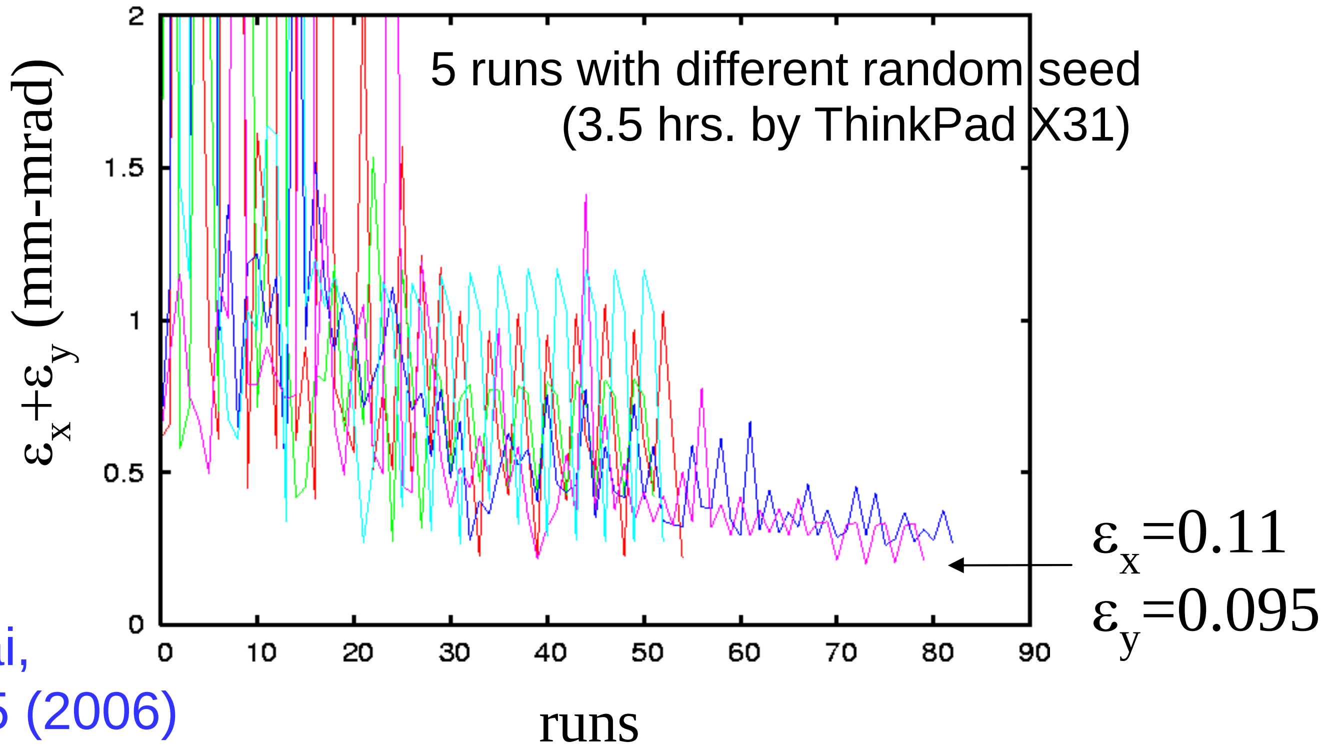
100mA, 0.1mm-mrad is possible

Solenoid and Quad optimization



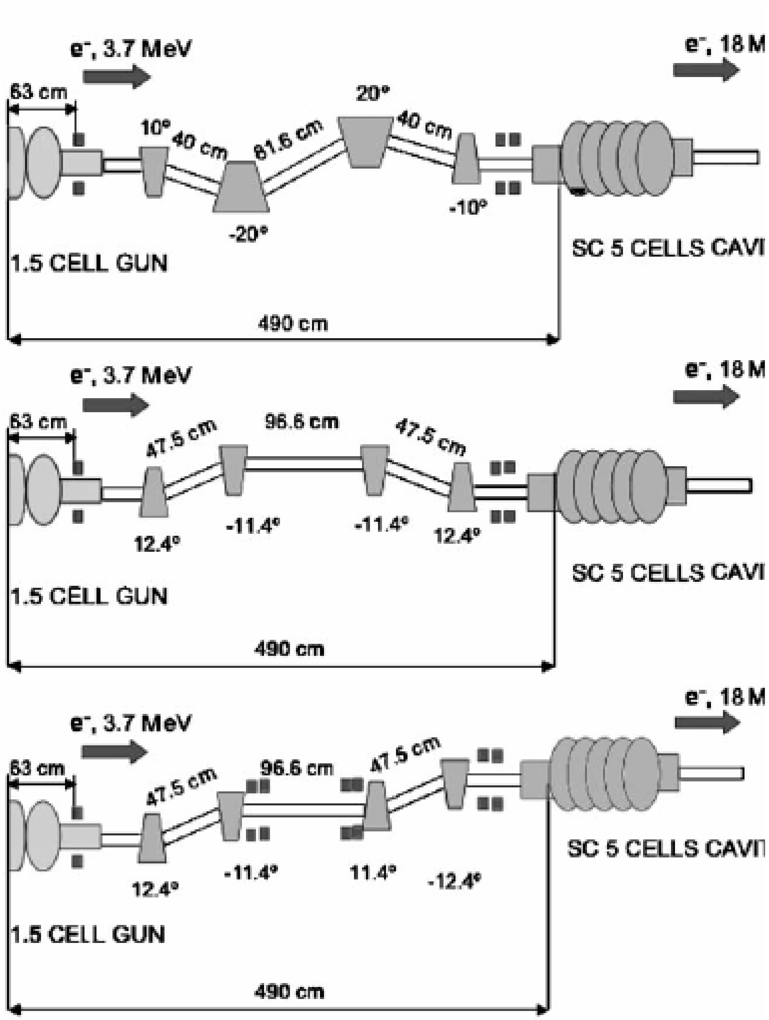
down-hill simplex with 7 parameters (2 Sol. + 5 Quad.)

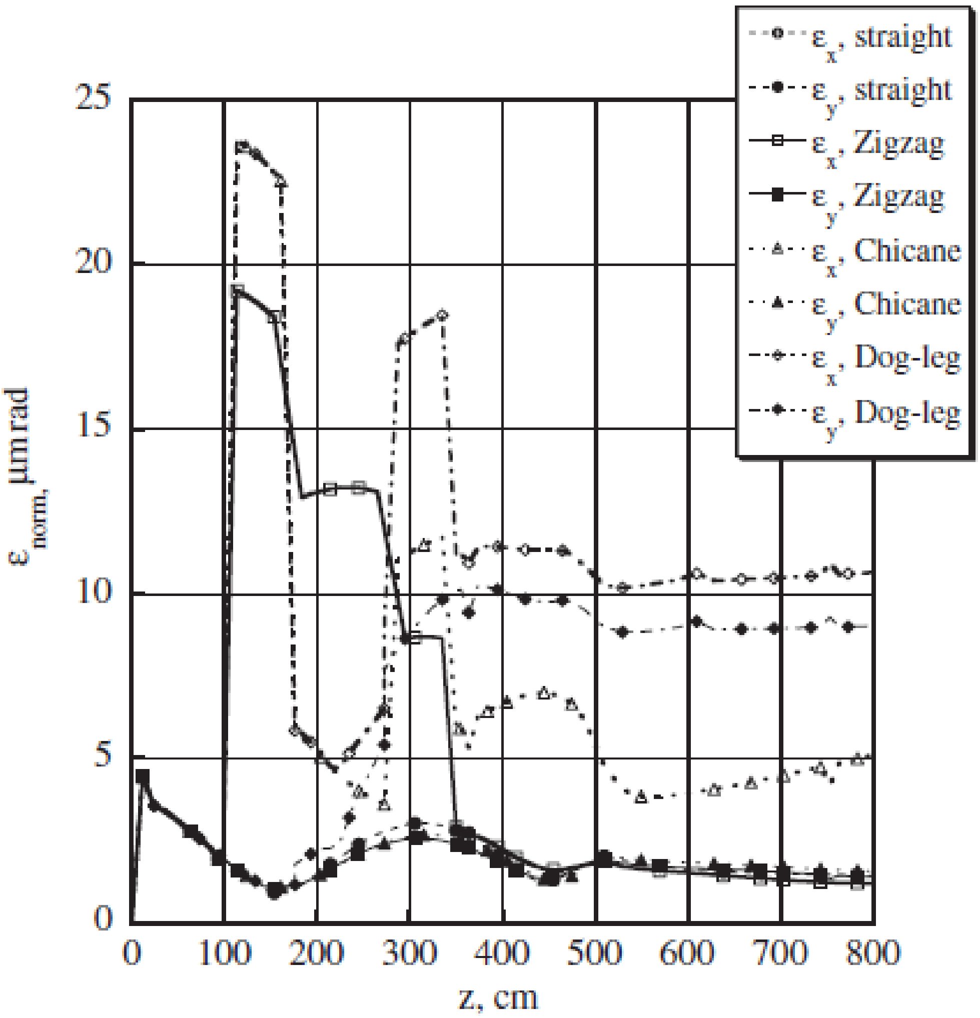
starting from the initial values obtained by envelope matching.



R. Hajima. R. Nagai,
NIM-A557, 103-105 (2006)

Comparison of 3 mergers





V.N. Litvinenko, R. Hajima and D. Kayran, NIM-A557, 165-175 (2006)