Multi-Parameter Optimization for an ERL injector

R. Hajima, R. Nagai (JAERI)

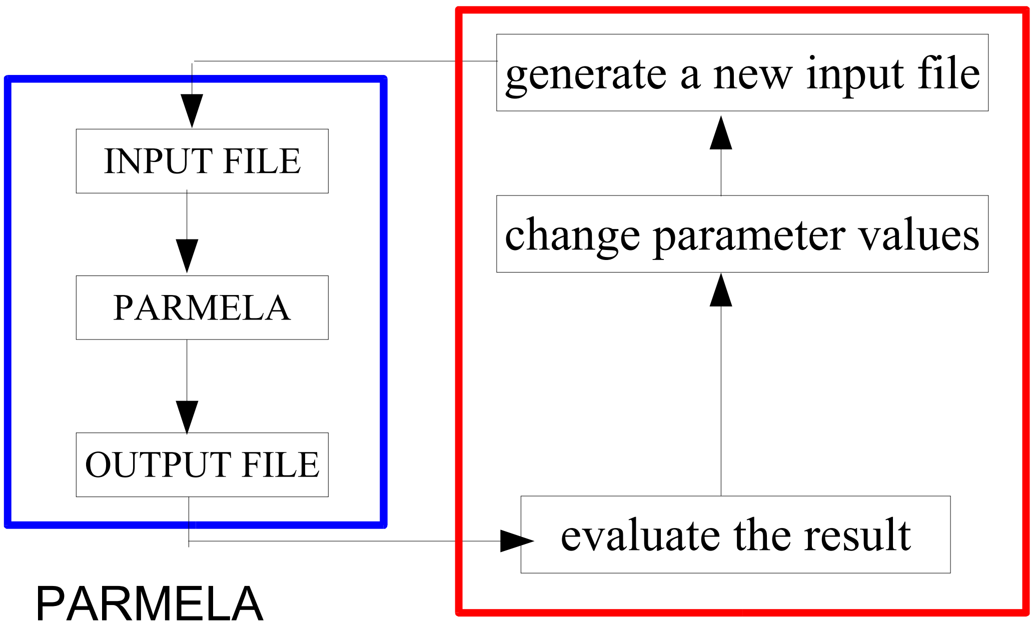
- Optimization with PARMELA
- Step-by-step optimization by down-hill simplex
- All-at-once optimization by simulated annealing

Multi-parameter optimization for an ERL injector

- We need to calculate
  - space charge effect
  - beam motion in a DC/RF gun, acc. structure, bending ...
  - transverse and longitudinal motion
- PARMELA seems applicable to these calculation.
- However, no optimization trick is available in PARMELA.
- Because particle tracking was a heavy task for computers, when PARMELA was developed
- In the 21st century, now, we have excellent PC's fast enough to repeat PARMELA runs many times.

The optimization is possible with PARMELA.

How to make parameter optimization with PARMELA



PARMELA
(Los Alamos ver.)

External Programs

a JAVA post-processor to evaluate the result.
- a part of old particle-tracking code.

R. Hajima, Proc. ICAP-98.

a PERL wrapper script to generate an input-file.

master input file

```
;# VARY SOL1 200 100 300
;# MAXLOOP 100
;# FIT ENX ENY + 2 POW
SOLENOID 10 5 1 SOL1
DRIFT 20 5 1
....
```

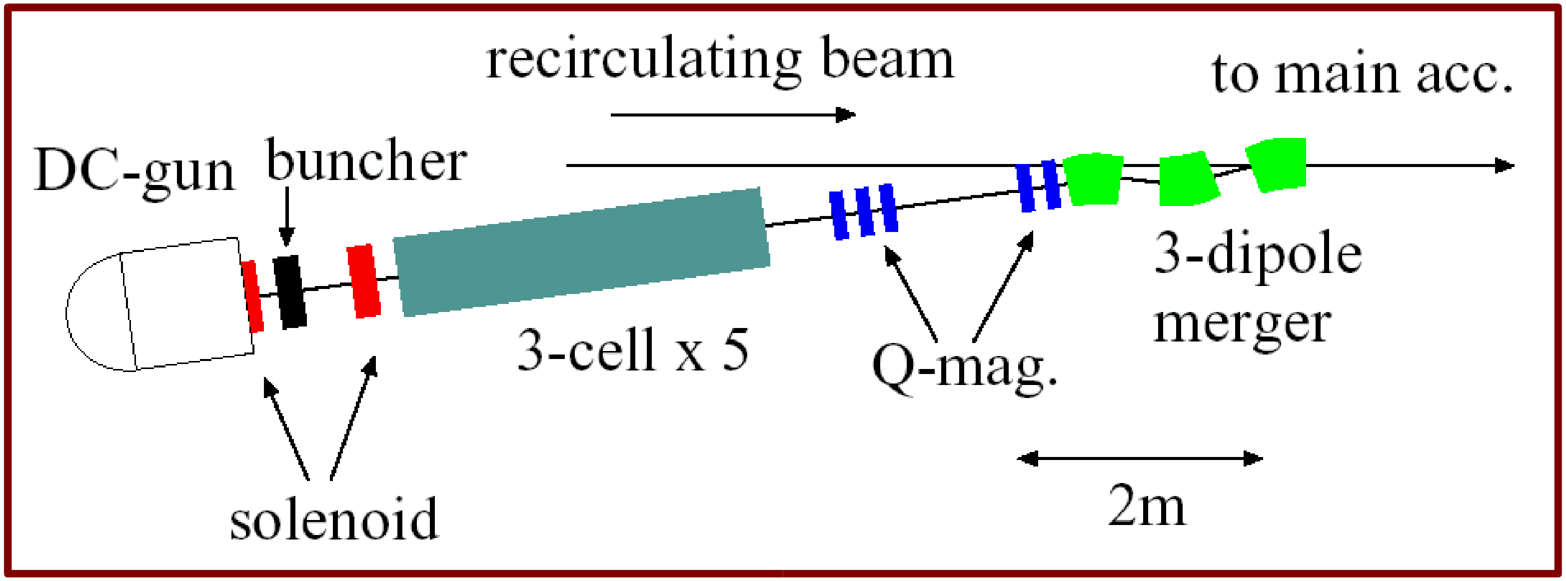
optimization commands are embedded in a PARMELA INPUT (master file).

specify parameters to vary

specify the target function with reverse Polish notation.

PARMELA INPUT for each run is generated dynamically from the master.

ERL injector



- parameters to change
  - transverse motion: solenoid x 2, Quad. x 5 = 7 parameters
  - longitudinal motion : buncher (A, ϕ), 3-cell (A, ϕ) x 5 = 12 parameters

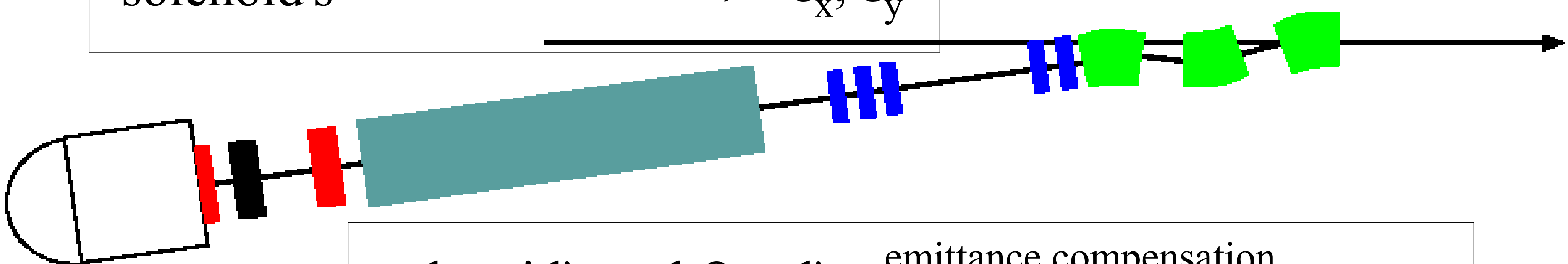
- position of elements, gun geometry, and drive laser are fixed.

Step-by-step optimization

we have adequate knowledge of beam dynamics.

buncher 3-cell —velocity bunching→ σ_z

solenoid's —emittance compensation→ $\varepsilon_x, \varepsilon_y$

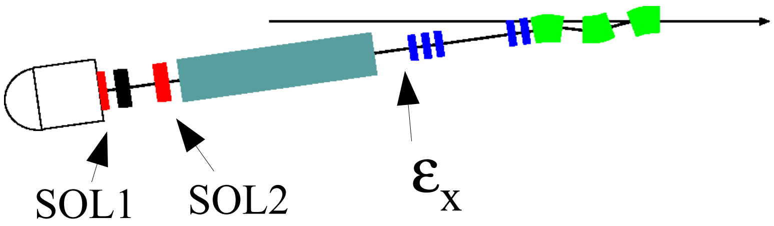


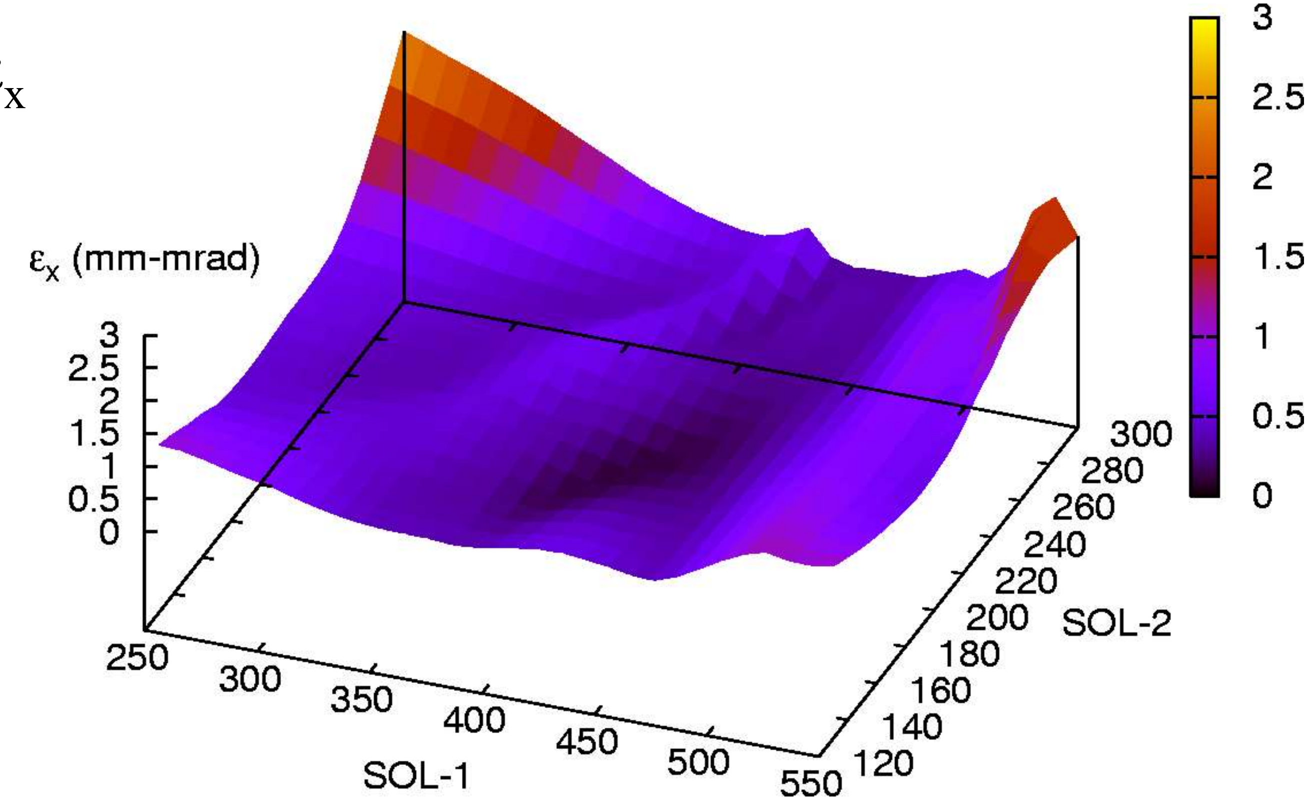
solenoid's and Quad's —emittance compensation→ $\varepsilon_x, \varepsilon_y$

optimizing the parameters step-by-step from the upstream.

repeating the procedure, if necessary.

Solenoid vs ε_x before the Quad's

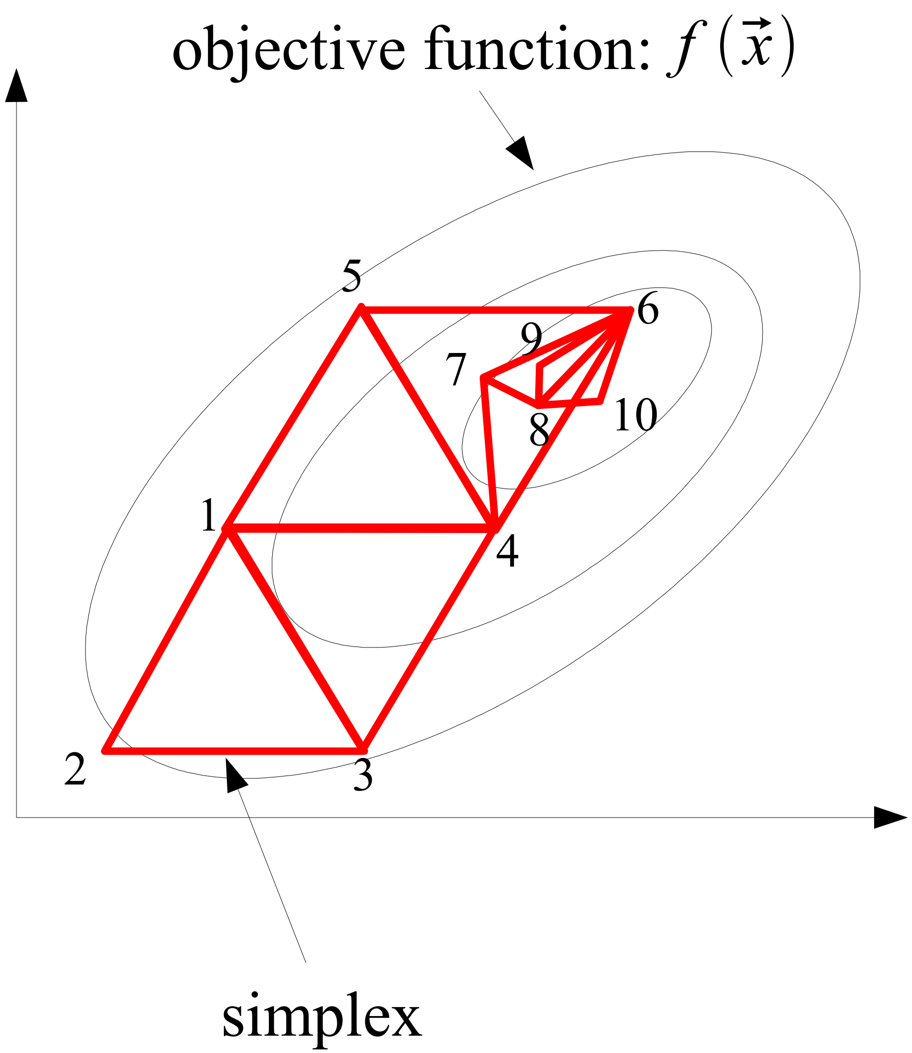




ε_x is a smooth function of SOL-1 and SOL-2.
But there are local minima.

we apply “down-hill simplex" to the optimization.

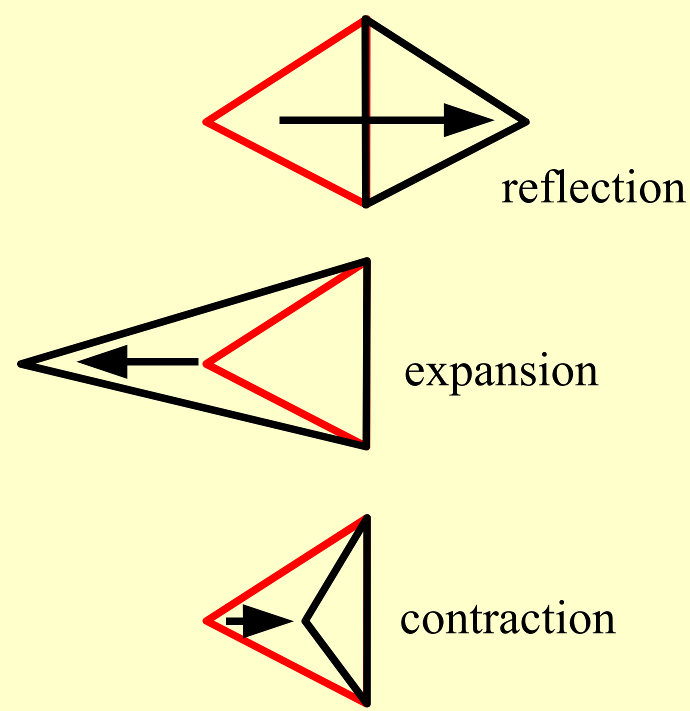
Down-hill simplex



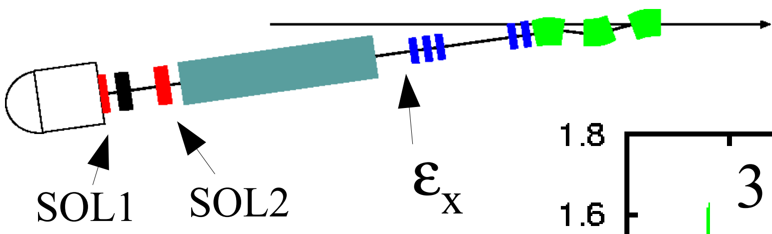
simplex is n-dimensional volume enclosed by (n+1)-points in n-dimensional phase space.

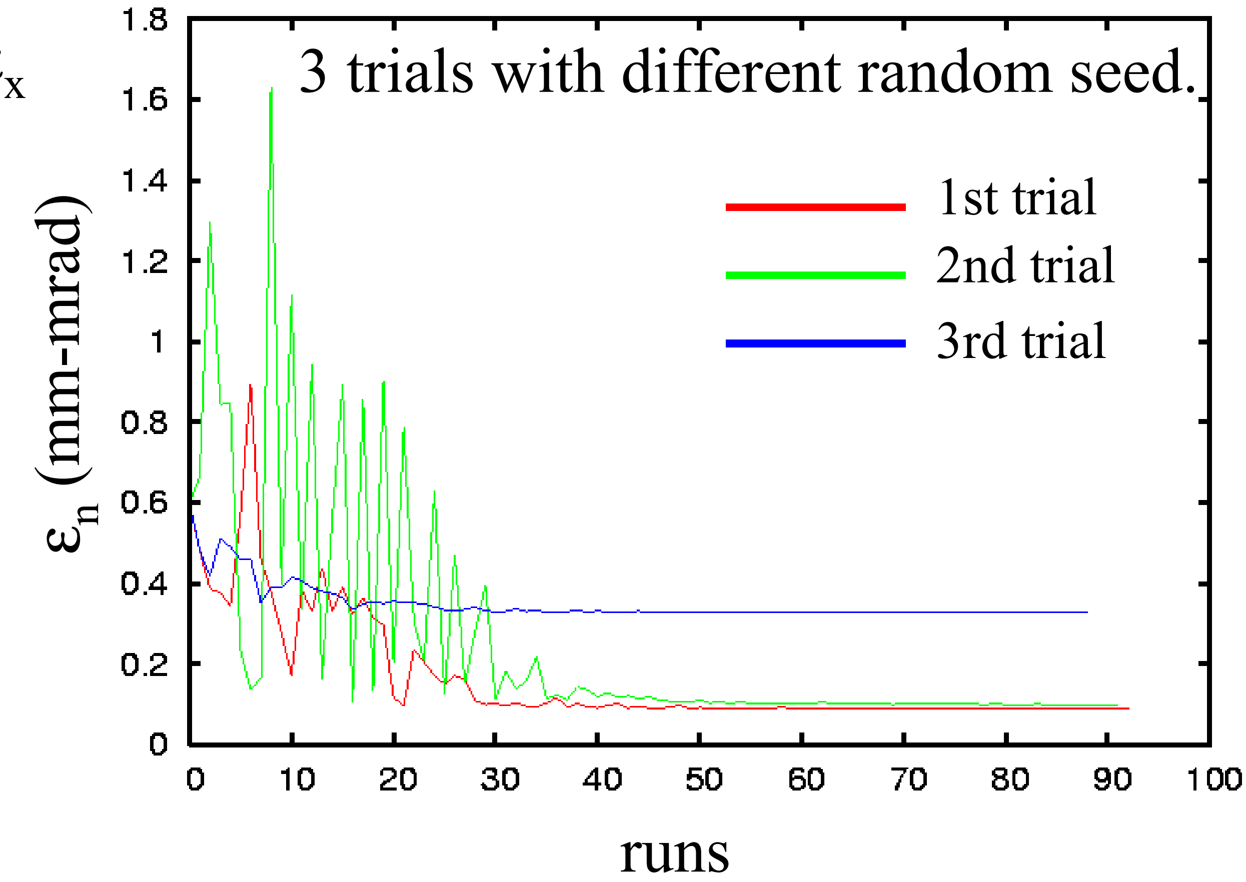
the objective function is evaluated at each point of the simplex.

searching a minimum through a series of steps:



Solenoid optimization by down-hill simplex





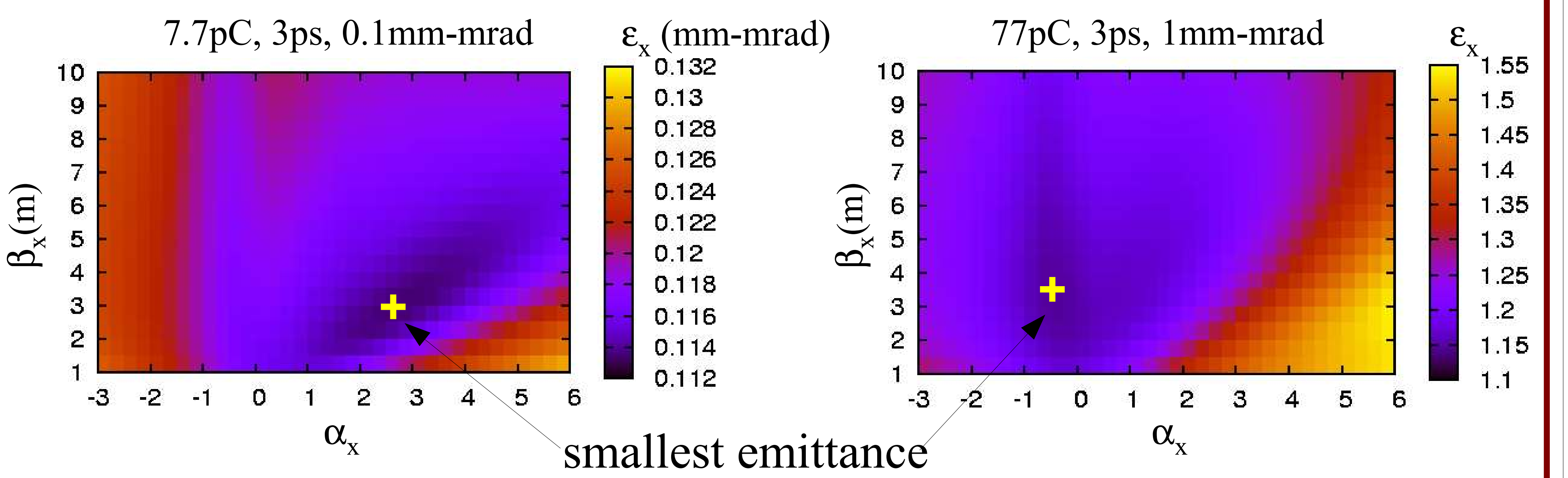
- emittance value is converged after 40-50 iterations.
- The 3rd trial may be trapped at a local minimum.
- After several runs, we can find optimum solenoid field.

Envelope matching in the merger

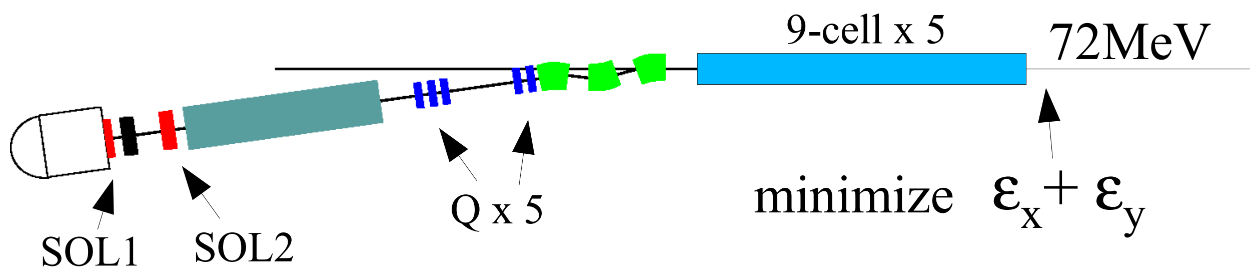
For the merger optimization by simplex method, we need an adequate set of initial parameters for the 5 quadrupole magnets.

We use "envelope matching" to find the initial values of quad's. (similar to the CSR case)

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

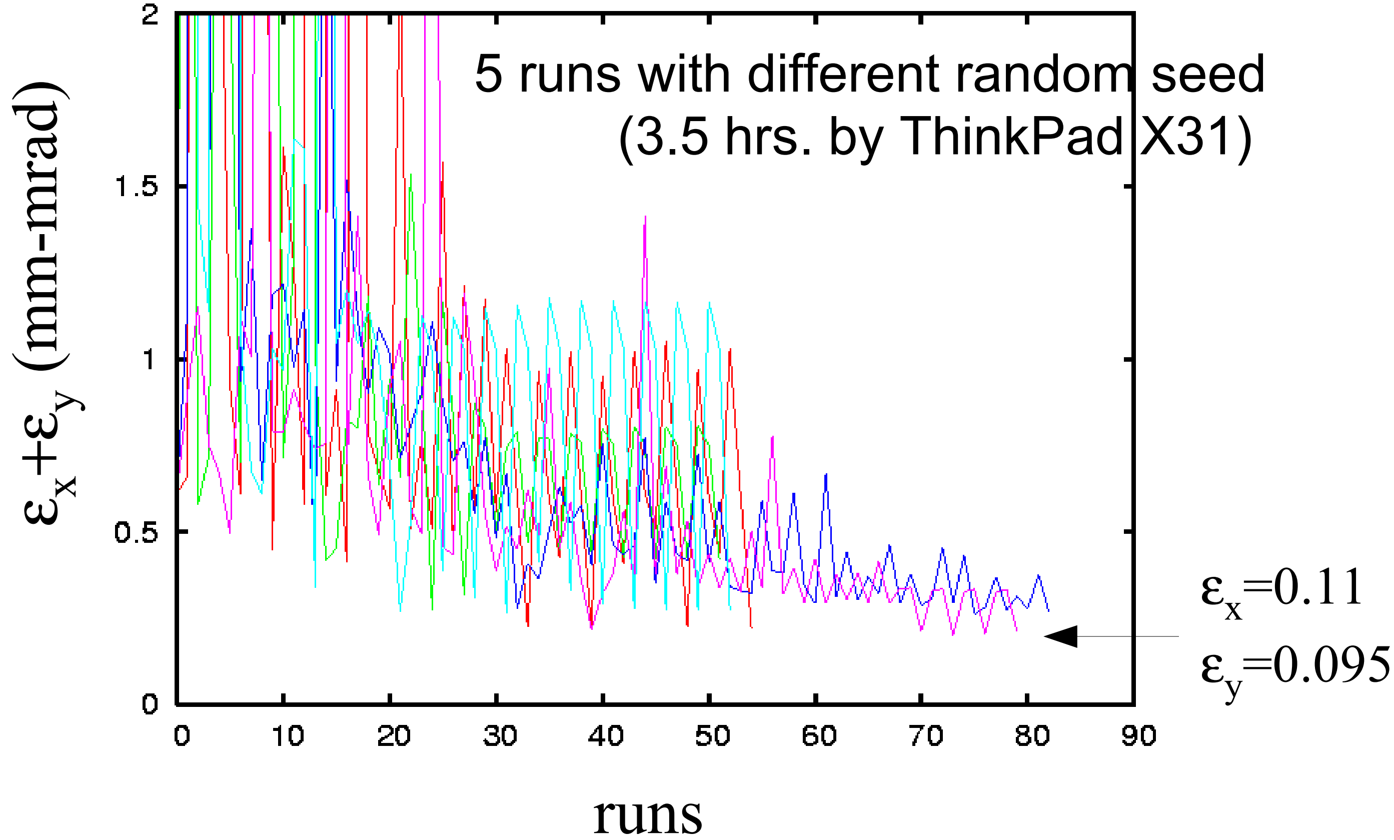


Solenoid and Quad optimization

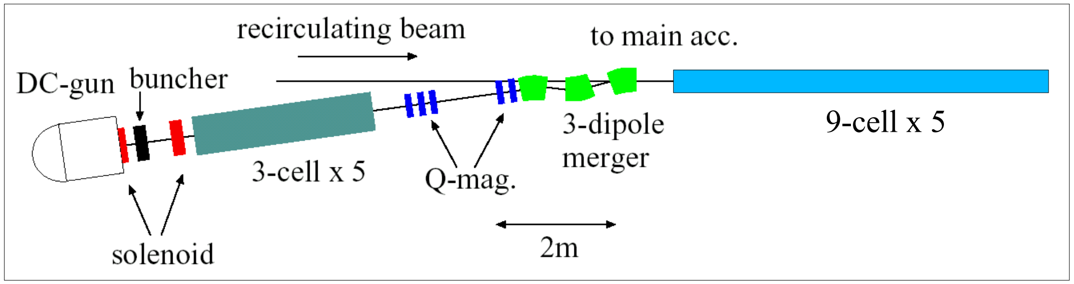


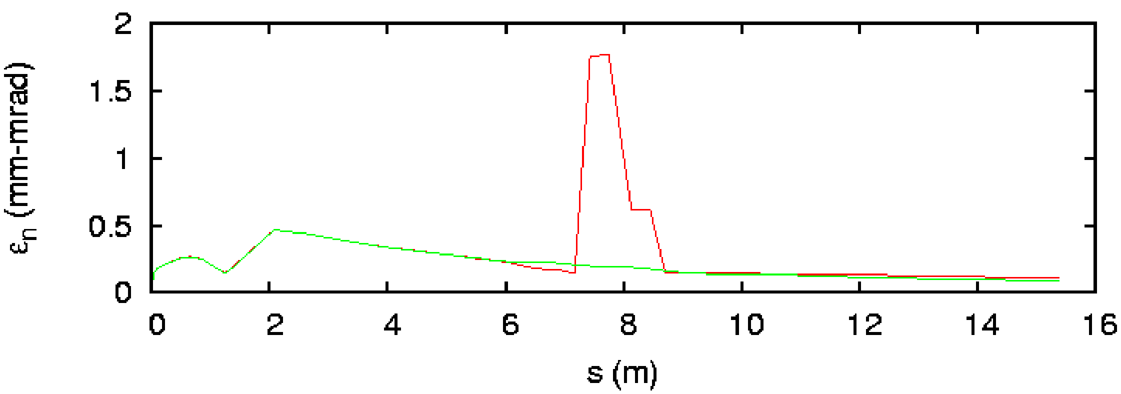
down-hill simplex with 7 parameters (2 Sol. + 5 Quad.)

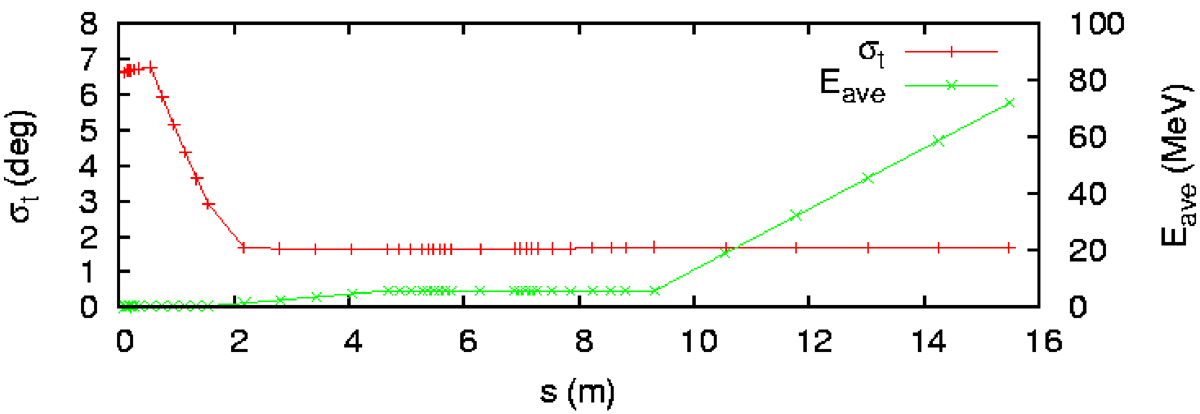
starting from the initial values obtained by envelope matching.



ERL injector optimized for a 7.7pC bunch







bunch charge 7.7pC (10mA)

cathode parameters
temperature 35meV
uniform in spatial r=0.5mm
thermal emittance = 0.065πmm-mrad
Gaussian in temporal σ_t= 14ps

at 72MeV (after 9-cell x 5)

$$\varepsilon_{n,x} = 0.105\,\pi \text{ mm-mrad}$$

$$\varepsilon_{n,y} = 0.094\,\pi \text{ mm-mrad}$$

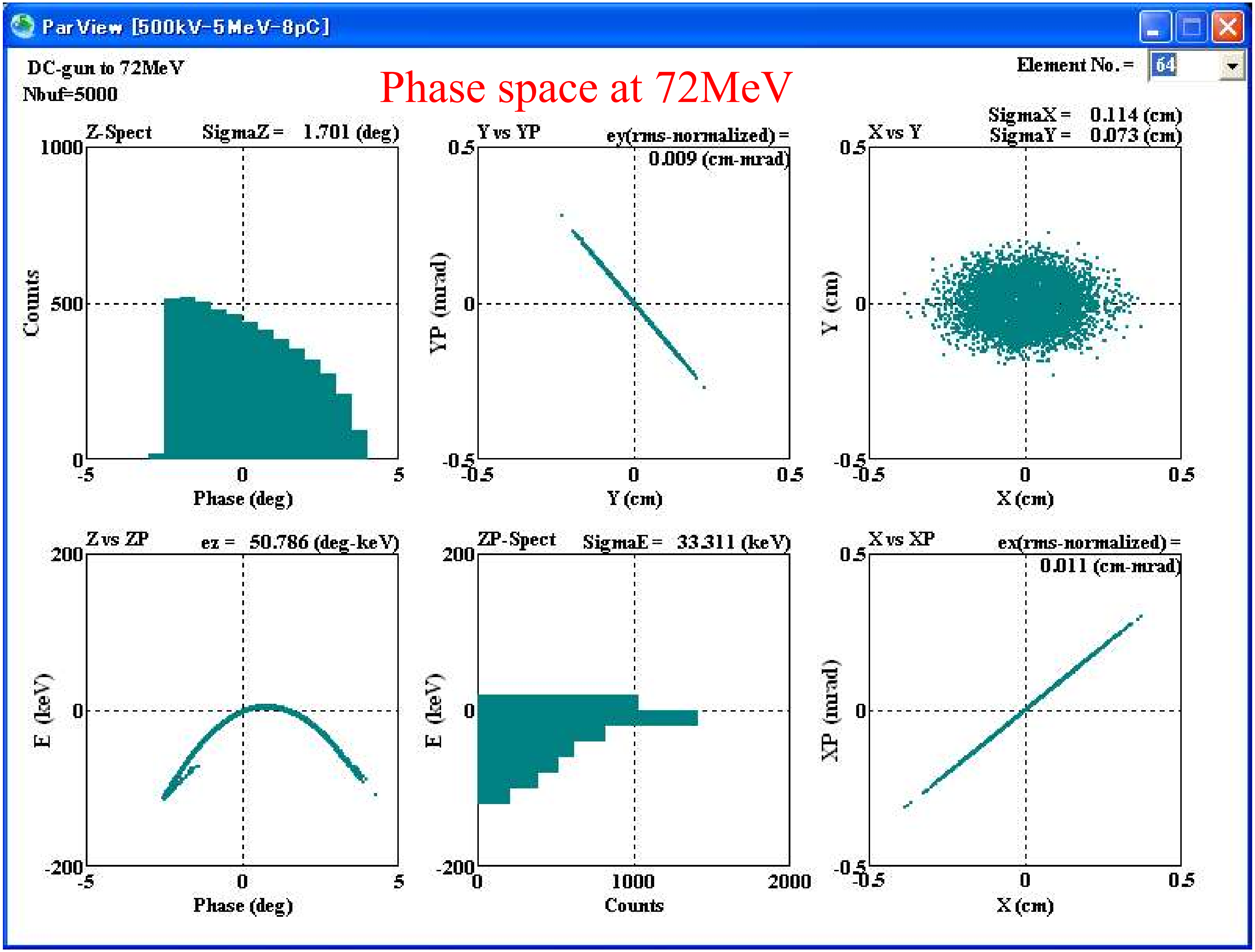
$$\varepsilon_z = 51 \text{ deg-keV}, \quad \sigma_t = 3.6 \text{ ps}$$

CSR effect (ELEGANT)

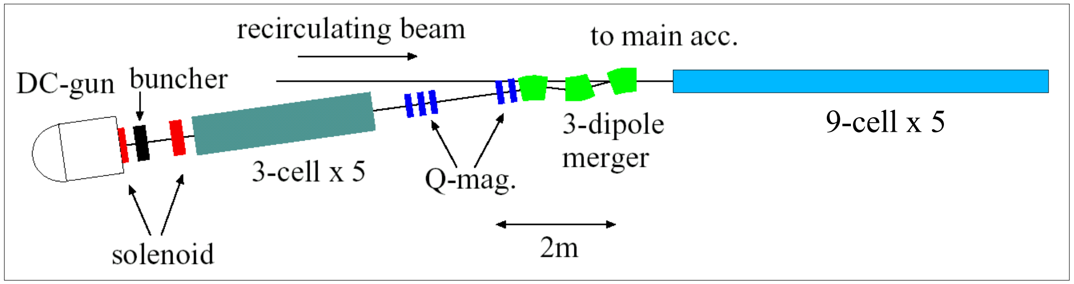
$$\Delta\varepsilon_{n,x} = 0.003\,\pi \text{ mm-mrad}$$

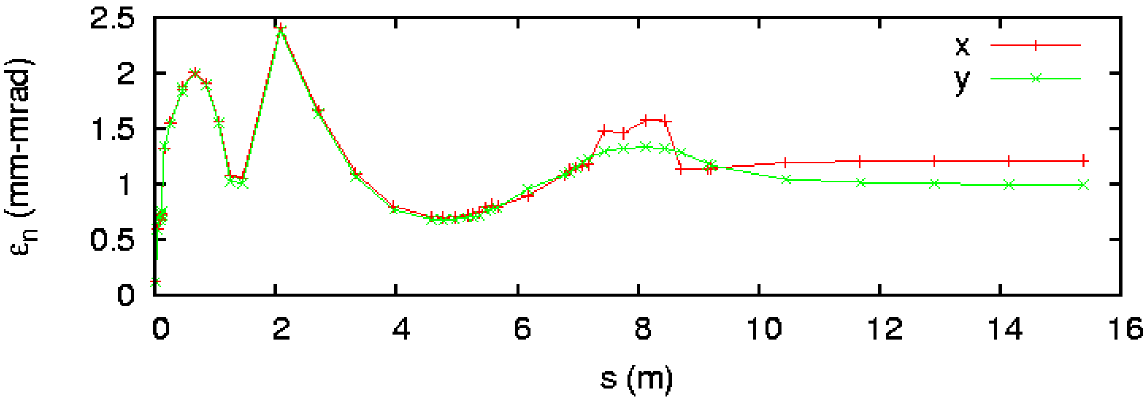
$$\varepsilon_{n,x} = \sqrt{0.105^2 + 0.003^2} \simeq 0.105\,\pi \text{ mm-mrad}$$

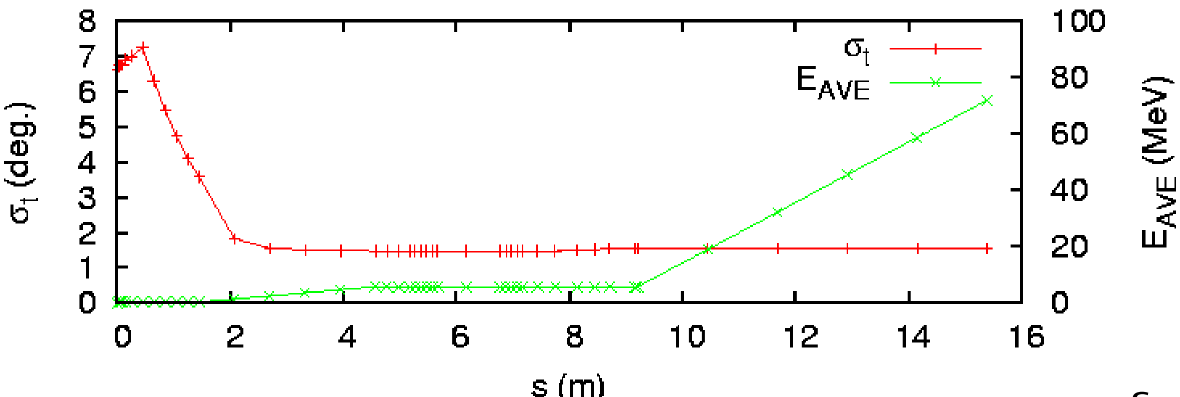
ERL injector optimized for a 7.7pC bunch



ERL injector optimized for a 77pC bunch







bunch charge 77pC (100mA)

cathode parameters

temperature 35meV

uniform in spatial r=1.5mm

thermal emittance 0.2 πmm-mrad

Gaussian in temporal σ_t= 14ps

at 72MeV (after 9-cell x 5)

$$\varepsilon_{n,x} = 1.22\,\pi\ \text{mm-mrad}$$

$$\varepsilon_{n,y} = 0.99\,\pi\ \text{mm-mrad}$$

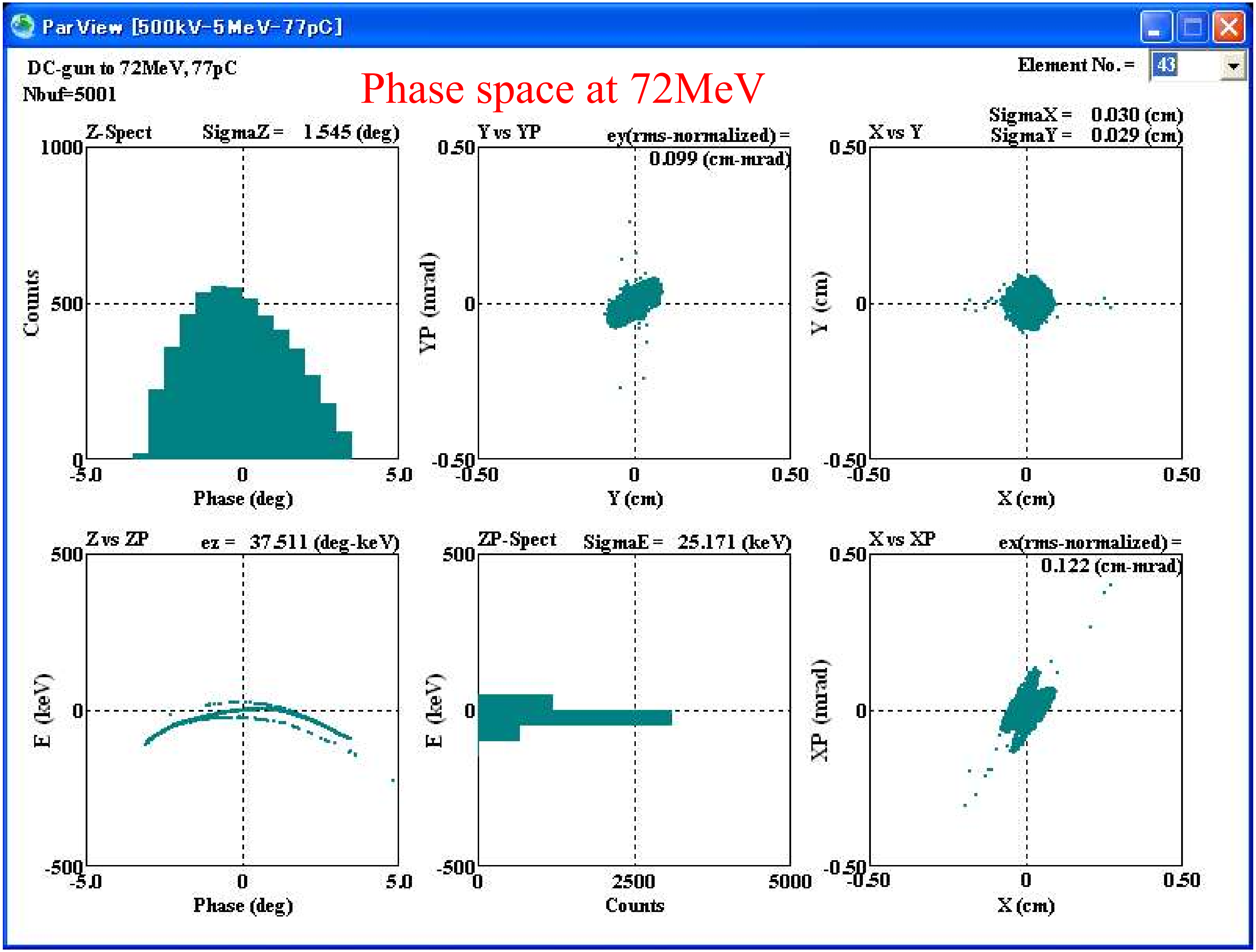
$$\varepsilon_z = 38\ \text{deg-keV}, \quad \sigma_t = 3.3\ \text{ps}$$

CSR effect (ELEGANT)

$$\Delta\varepsilon_{n,x} = 0.089\,\pi\ \text{mm-mrad}$$

$$\varepsilon_{n,x} = \sqrt{1.22^2 + 0.089^2} \simeq 1.22\,\pi\ \text{mm-mrad}$$

ERL injector optimized for a 77pC bunch



Optimization without any knowledge a priori

simulated annealing (SA)

- analogy to the annealing process

  = metal cooling and freezing into a minimum energy crystalline structure.

- random search for down-hill, but accept up-hill results with a probability

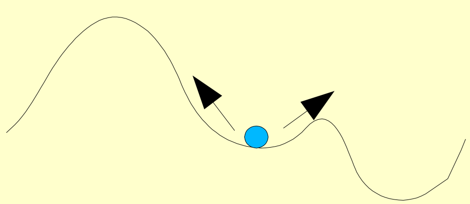
$$p = \exp\left(-\frac{\delta f}{T}\right)$$

δf : increase in the objective function

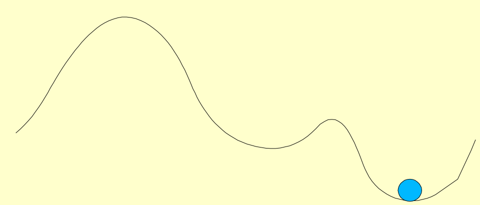
T : control parameter = temperature

high temperature → cool down → low temperature

easy to escape from a local minimum



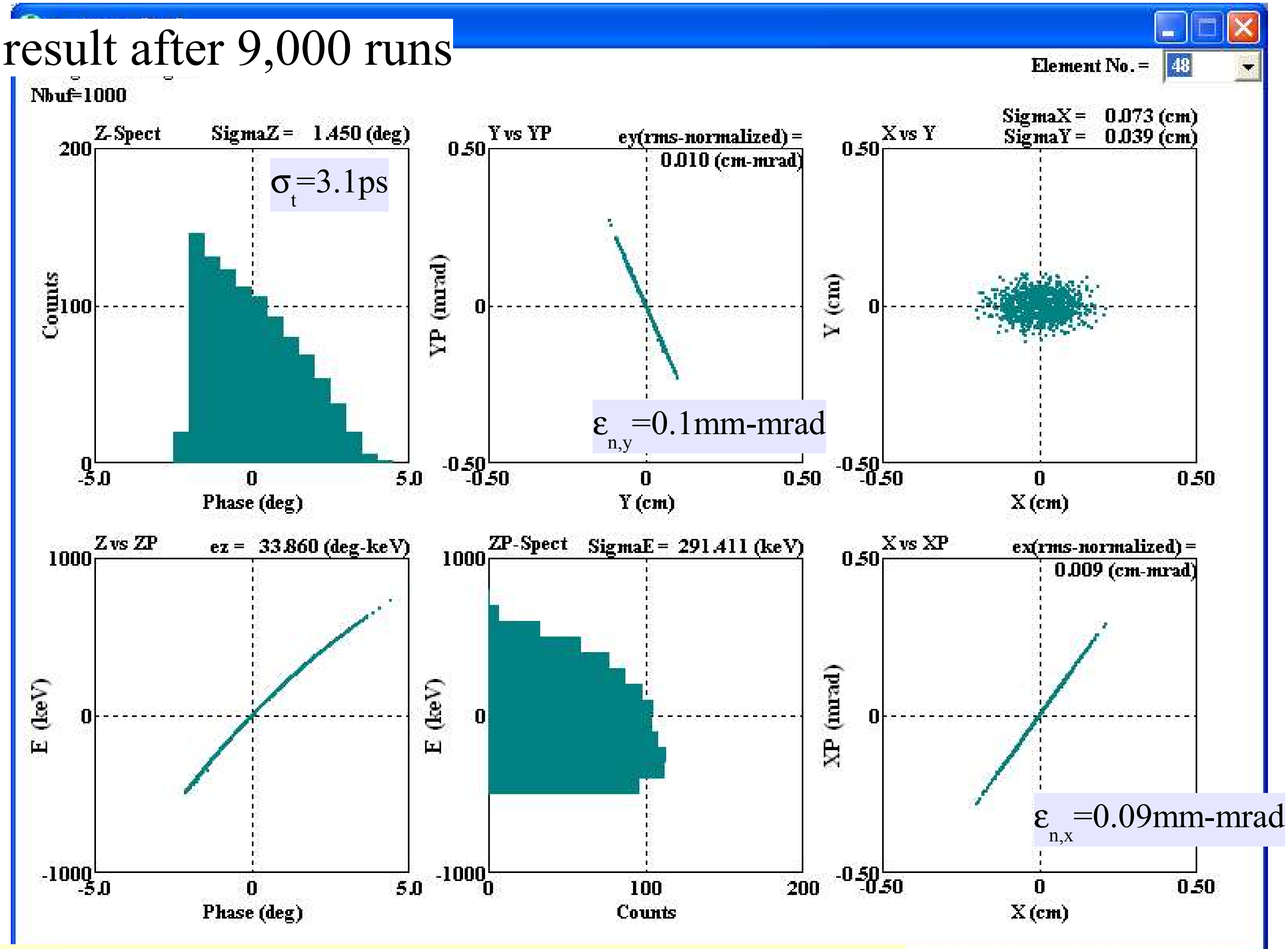
converge into a global minimum



Optimization by Simulated Annealing

7.7pC bunch, targeting σ_t=3ps, ε_n=0.1mm-mrad at 70MeV

best result after 9,000 runs

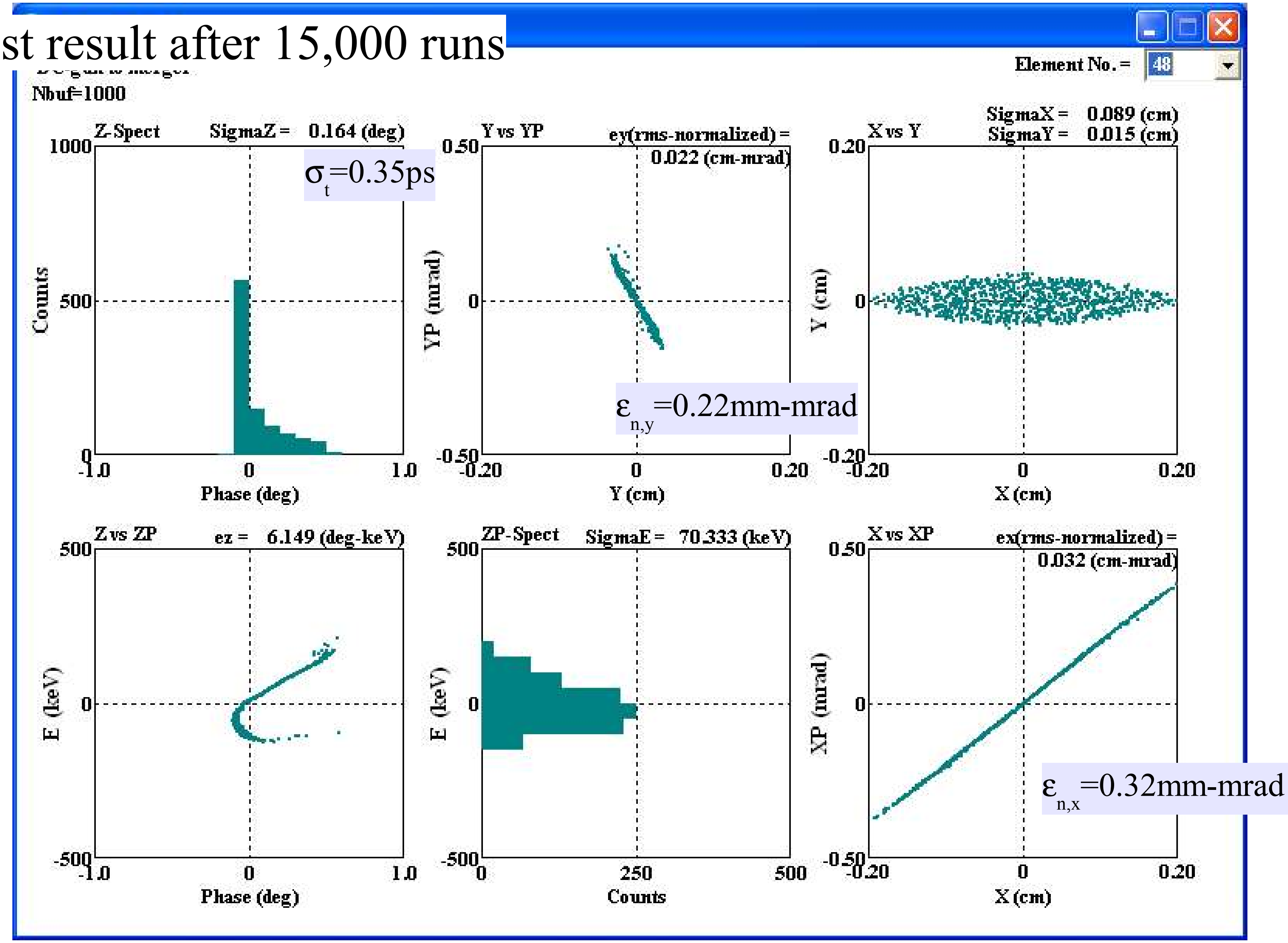


energy spread can be reduced if 9-cell phase is tuned manually.

Optimization by Simulated Annealing

7.7pC bunch, targeting σ_t=0.3ps, ε_n=0.1mm-mrad at 70MeV

best result after 15,000 runs



Summary

- multi-parameter optimization by extended-PARMELA
- step-by-step optimization works well

  500kV gun + 5MeV injector + 70MeV acc.

  ε_n ~ 0.1mm-mrad for 7.7pC

  ε_n ~ 1mm-mrad for 77pC

- all-at-once optimization by simulated annealing also works well

  setting an appropriate objective function is a key.
  many runs (~10^4) are necessary.

SA and GA in accelerator applications

Simulated Annealing

7 articles in NIMA
7 articles in RSI
35 articles in JACOW

Optimizing beam optics

solenoid for magnetized beam
J. Kewisch et al., EPAC-2004.
low-energy ion beam line
R. Baartman et al., PAC-1997.
fitting in a beam simulation code
M,D'yachkov et al., PAC-2001.
orbit control in 12GeV PS
Y. Hitaka et al., EPAC-2004.
beam collimator optimization
D.I. Kaltchev et al., PAC-1997.

Sorting undulator magnets

M.S. Curtin et al., NIMA-272, 187 (1988).
many other papers.

Genetic Algorithm

19 articles in NIMA
8 articles in RSI
19 articles in JACOW

Optimizing beam optics

Ring COD
S. Smith et al., EPAC-2004.
ERL linac focusing
R. Nagai et al, PAC-2003
Ring injector.
D. Schirmer et al., PAC-1995.

Optimizing SC magnet

S. Ramberger et al, EPAC-1998..

Sorting undulator magnets

R. Hajima et al, NIMA-318, 822 (1992)

Shaping laser pulses for an RF gun

S. Cialdi et al, NIMA-526, 239 (2004)

Optimizing a triode gun

C.X. Gu et al, NIMA-519, 90 (2004)