Multivariate Optimization of High Brightness High Current DC Photoinjector

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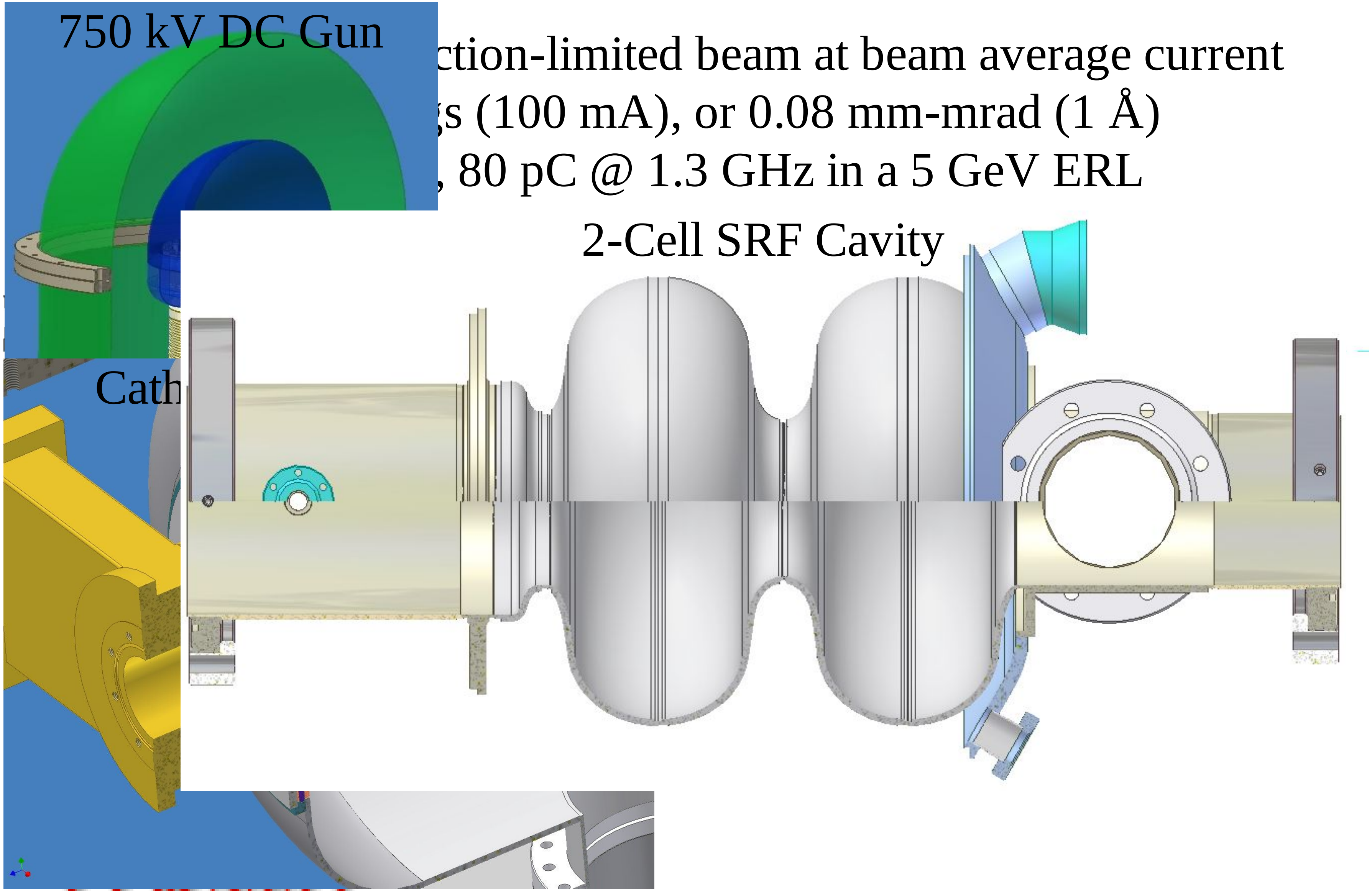
Talk Outline:

- Motivation
- Evolutionary Algorithms
- Optimization Results

ERL Injector

ction-limited beam at beam average current
s (100 mA), or 0.08 mm-mrad (1 Å)
, 80 pC @ 1.3 GHz in a 5 GeV ERL



750 kV DC Gun

Cath

2-Cell SRF Cavity

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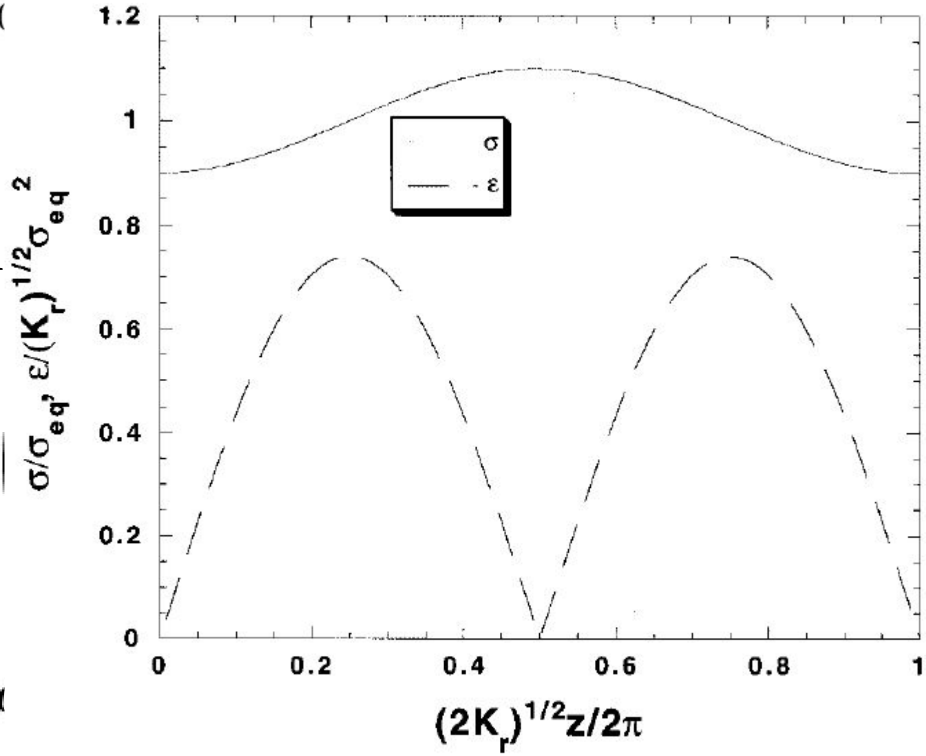
Emittance ‘compensation’ concept (PRE **55**, 7565)

$$\sigma''+K_r\sigma=\frac{I}{2I_{(}}+\frac{\epsilon^2_{n,\mathrm{th}}}{}.$$

$$\epsilon_{n,\mathrm{th}}(\zeta)\equiv\frac{\beta\gamma}{}\sqrt{\langle r^2\rangle_\zeta\langle r'^2\rangle_\zeta-\langle rr'\rangle^2_\zeta}$$

focusing



Needle beam

$\sigma_{\mathrm{eq}}(g(\zeta))=|$

on for slice

δ $)=0$ or

oscillation frequency current independent

$$\delta\sigma''(\zeta)+2K_r\delta\sigma(\zeta)=0,$$

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Doing it faster

- work harder
- work smarter
- get help

- processor speed
- algorithms
- parallel processing

Solution: use parallel MOGA

***M**ulti**O**bjective **G**enetic **A**lgorithm*

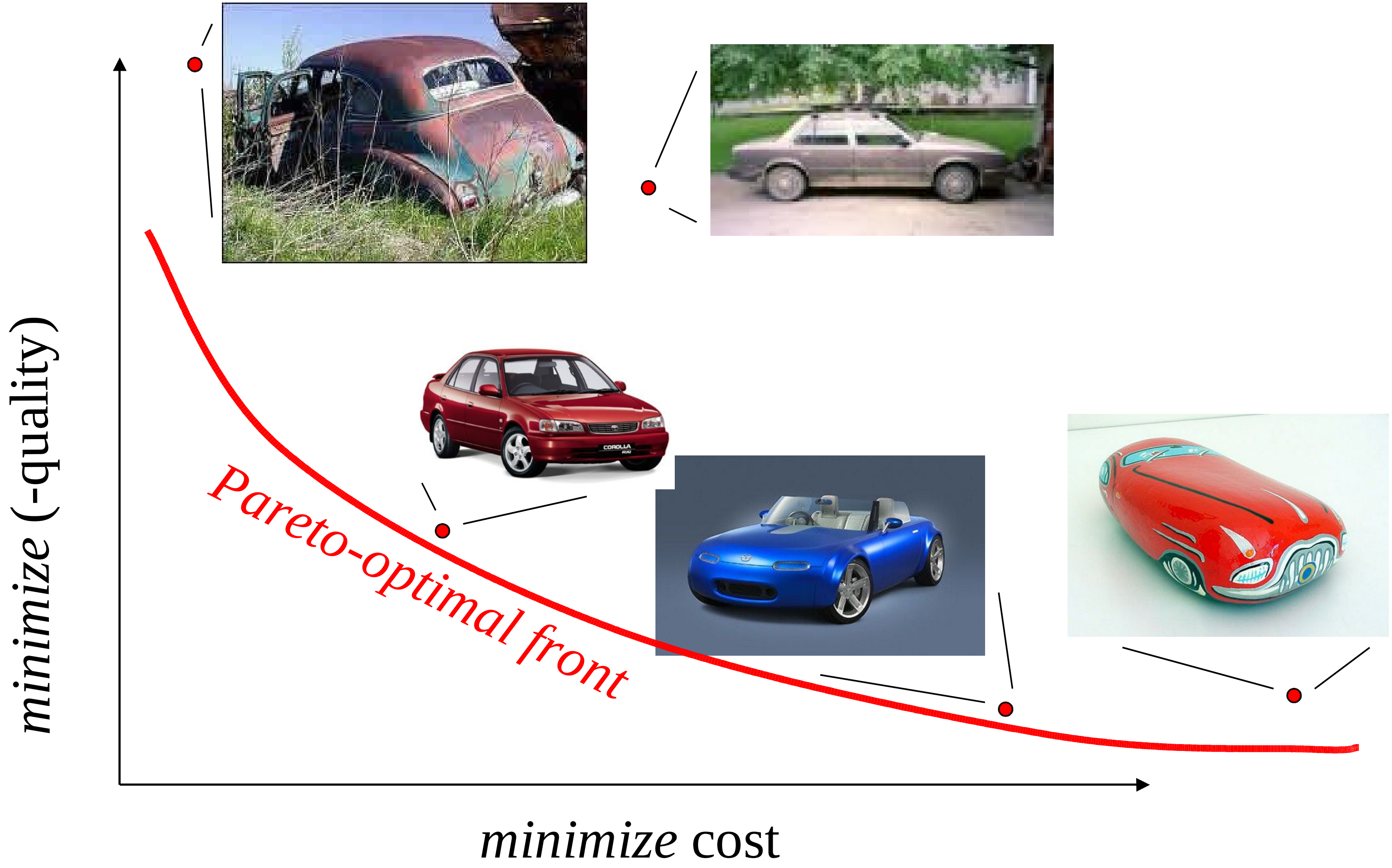
- throw in all your design variables
- map out whole Pareto front, i.e. obtain multiple designs all of which are optimal
- use realistic injector model with your favorite space charge code

Conventional Way to Design an Injector

- Cut the number of decision variables to some reasonable number (2-4) perhaps by using a simplified theoretical model to guide you in this choice
- **Large regions of parameter space remain unexplored**
- Optimize the injector varying the remaining variables with the help of a space-charge code to meet a fixed set of beam parameters (e.g. emittance at a certain bunch charge and a certain length)
- **One ends up with a *single-point* design without capitalizing on beneficial trade-offs that are present in the system**

Primary challenge in exploring the full parameter space is computational speed

MultiObjective Optimization



Multi-Objective Optimization Problem

$$\left.\begin{array}{lll}\text{maximize} & f_m(x_1, x_2, \ldots, x_n), & m = 1, 2, \ldots, M; \\ \text{subject to} & g_j(x_1, x_2, \ldots, x_n) \geq 0, & j = 1, 2, \ldots, J; \\ & x_i^{(\mathrm{L})} \leq x_i \leq x_i^{(\mathrm{U})}, & i = 1, 2, \ldots, n. \end{array}\right\}$$

Definition 1. *A solution* $\boldsymbol{x}_a$ *is said to dominate the other solution* $\boldsymbol{x}_b$ *if the solution* $\boldsymbol{x}_a$ *is not worse than* $\boldsymbol{x}_b$ *in all objectives and* $\boldsymbol{x}_a$ *is strictly better than* $\boldsymbol{x}_b$ *in at least one objective. In other words,* $\forall m \in 1, 2, \ldots, M$: $f_m(\boldsymbol{x}_a) \geq f_m(\boldsymbol{x}_b)$ *and* $\exists m' \in 1, 2, \ldots, M$: $f_{m'}(\boldsymbol{x}_a) > f_{m'}(\boldsymbol{x}_b)$.

Definition 2. *Among a set of solutions* $\mathcal{P}$*, the nondominated subset of solutions* $\mathcal{P}'$ *are those that are not dominated by any member of the set* $\mathcal{P}$.

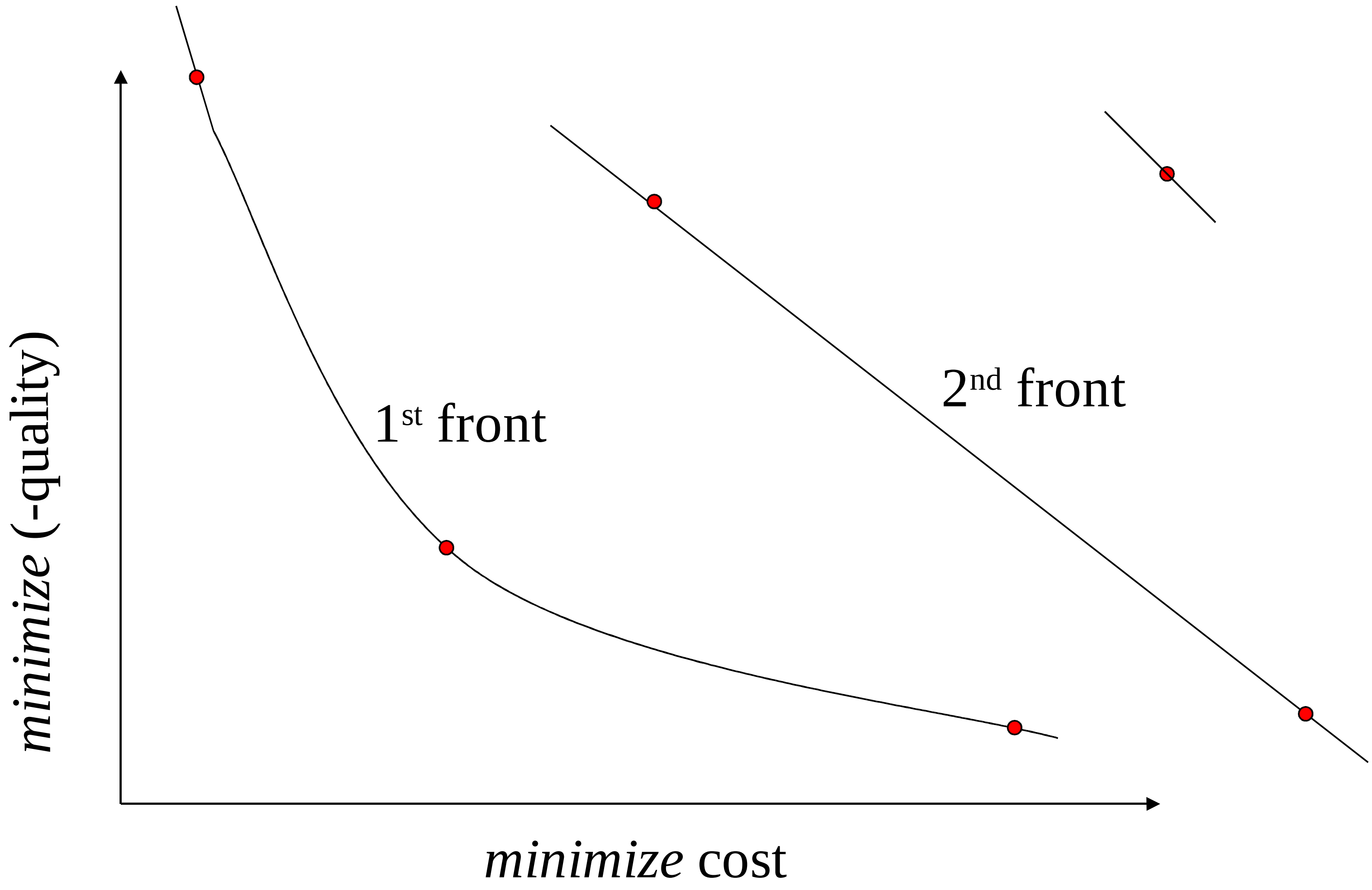
When the set $\mathcal{P}$ is the entire search space resulting nondominated set is called the *Pareto-optimal set.*

Vilfredo Pareto, 1848-1923

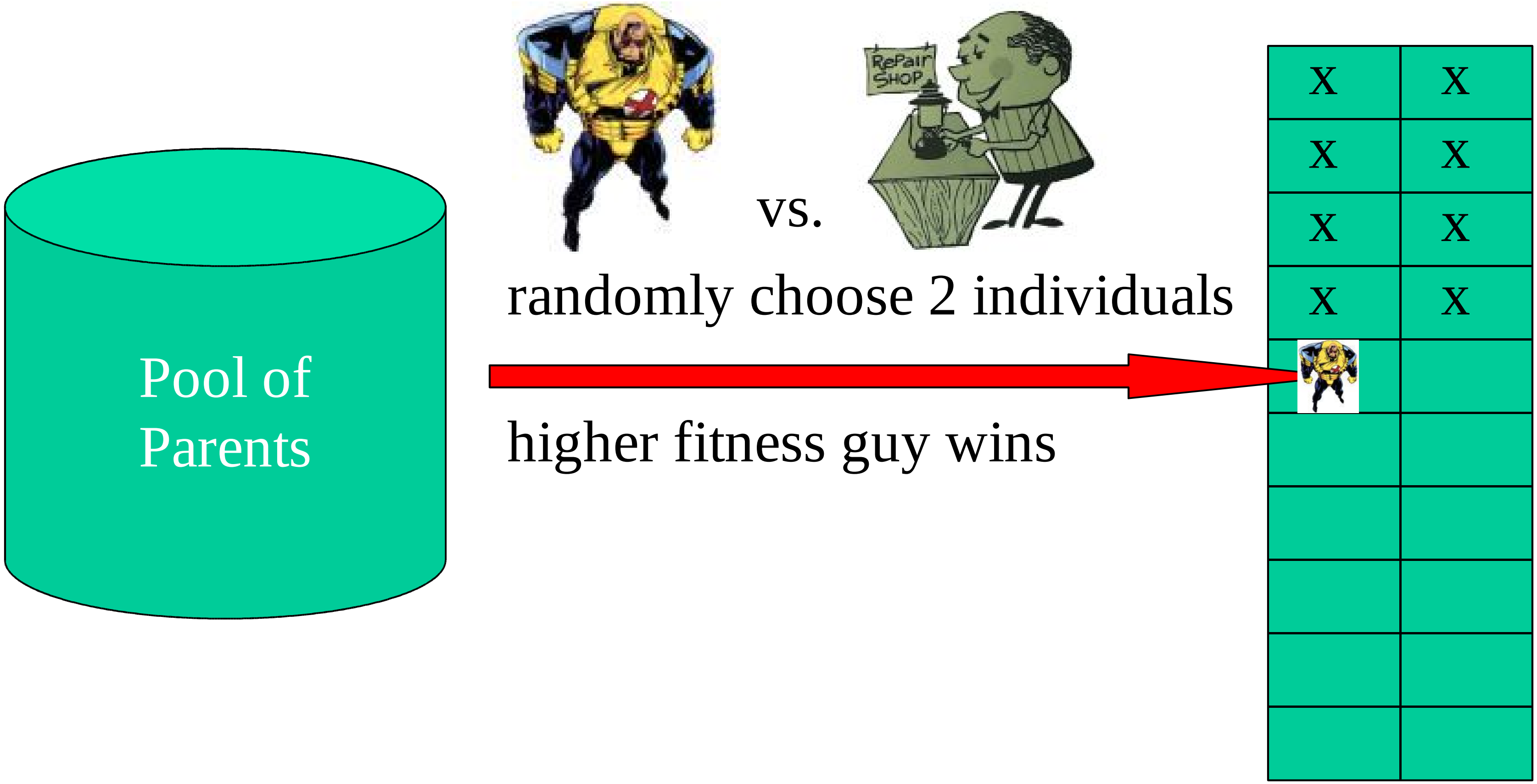
MOGA

1. Initialize population
2. Evaluate objective functions / constraints
3. Assign fitness to all individuals (convergence & diversity)
4. Stochastically choose a subset for mating pool (higher fitness being preferred)
5. Apply crossing and mutation operators to generate offspring
6. Evaluate objectives / constraints for the offspring
7. 'Good' solutions make it to the next generation
8. Repeat from step 3.

Fitness: e.g. NSGA-II



Binary Tournament



Pool of Parents

vs.

randomly choose 2 individuals

higher fitness guy wins

Cross-over operator: e.g. SBX

Figure: Probability distribution of children solutions with distant parents.

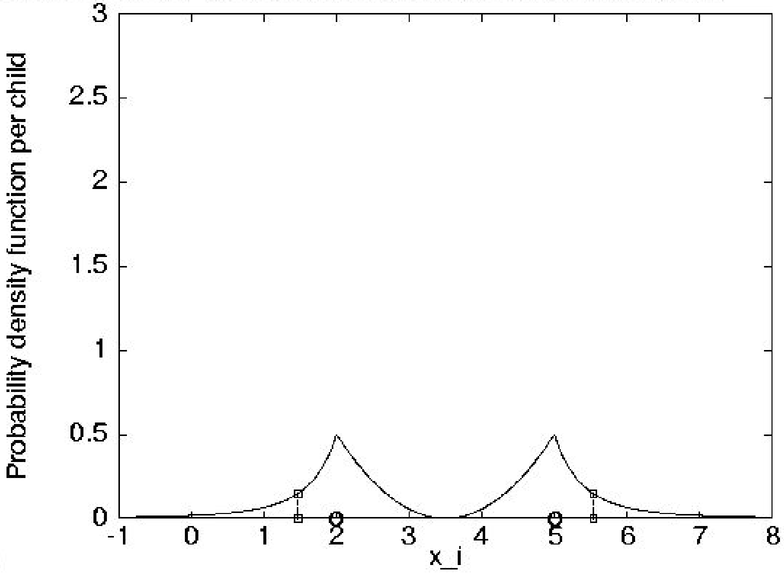
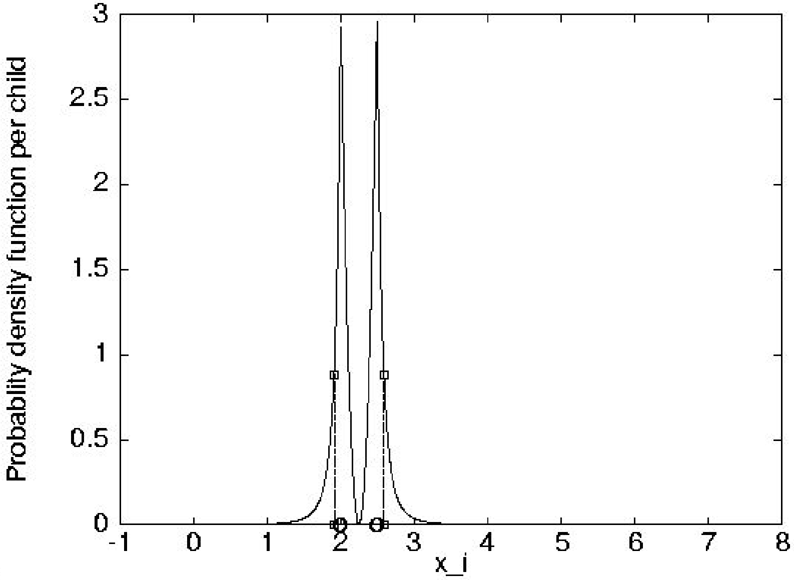
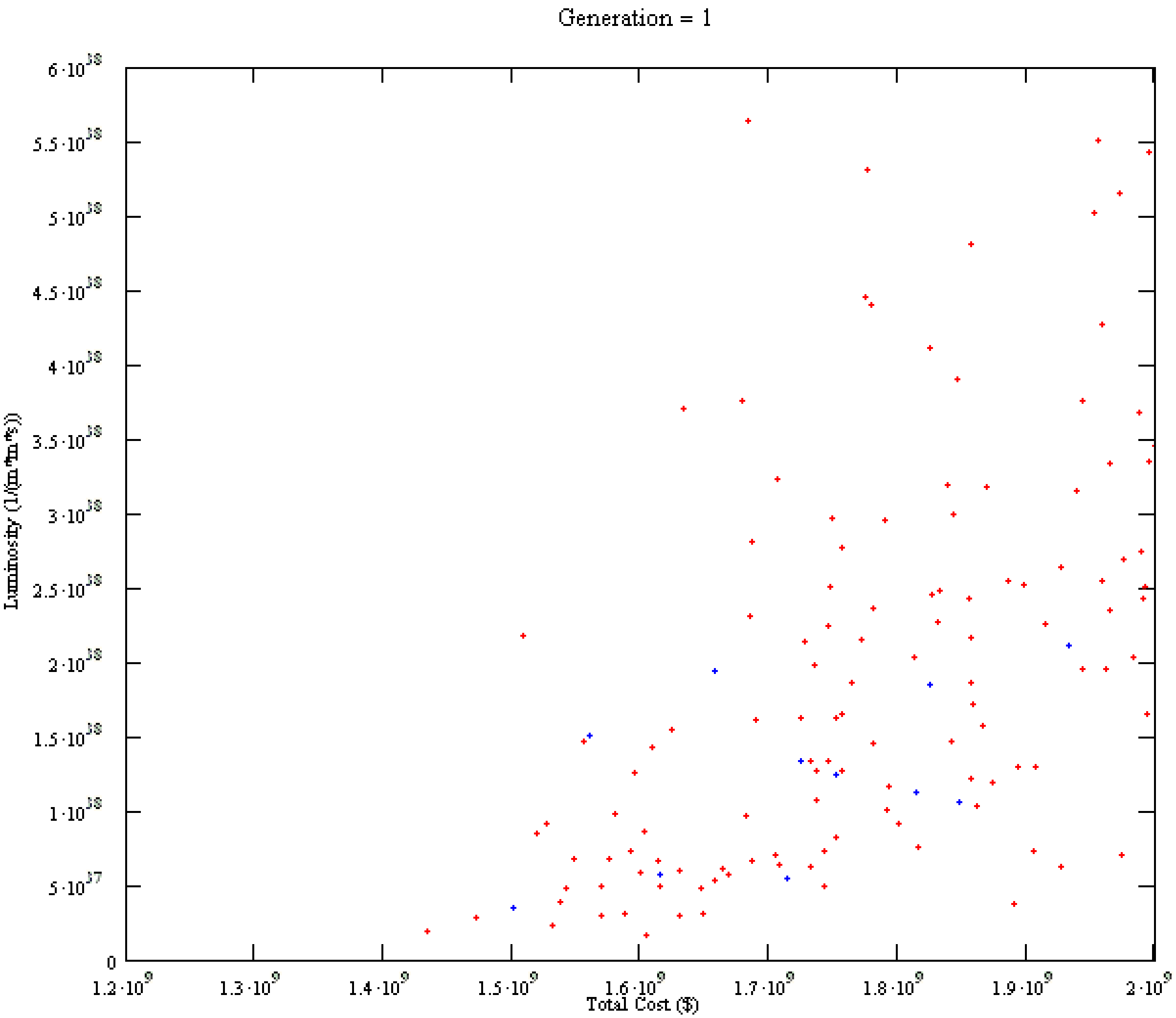


Figure: Probability distribution of children solutions with closely spaced parents.



- takes in 2 parents and produces 2 children
- preserves fine structure of data

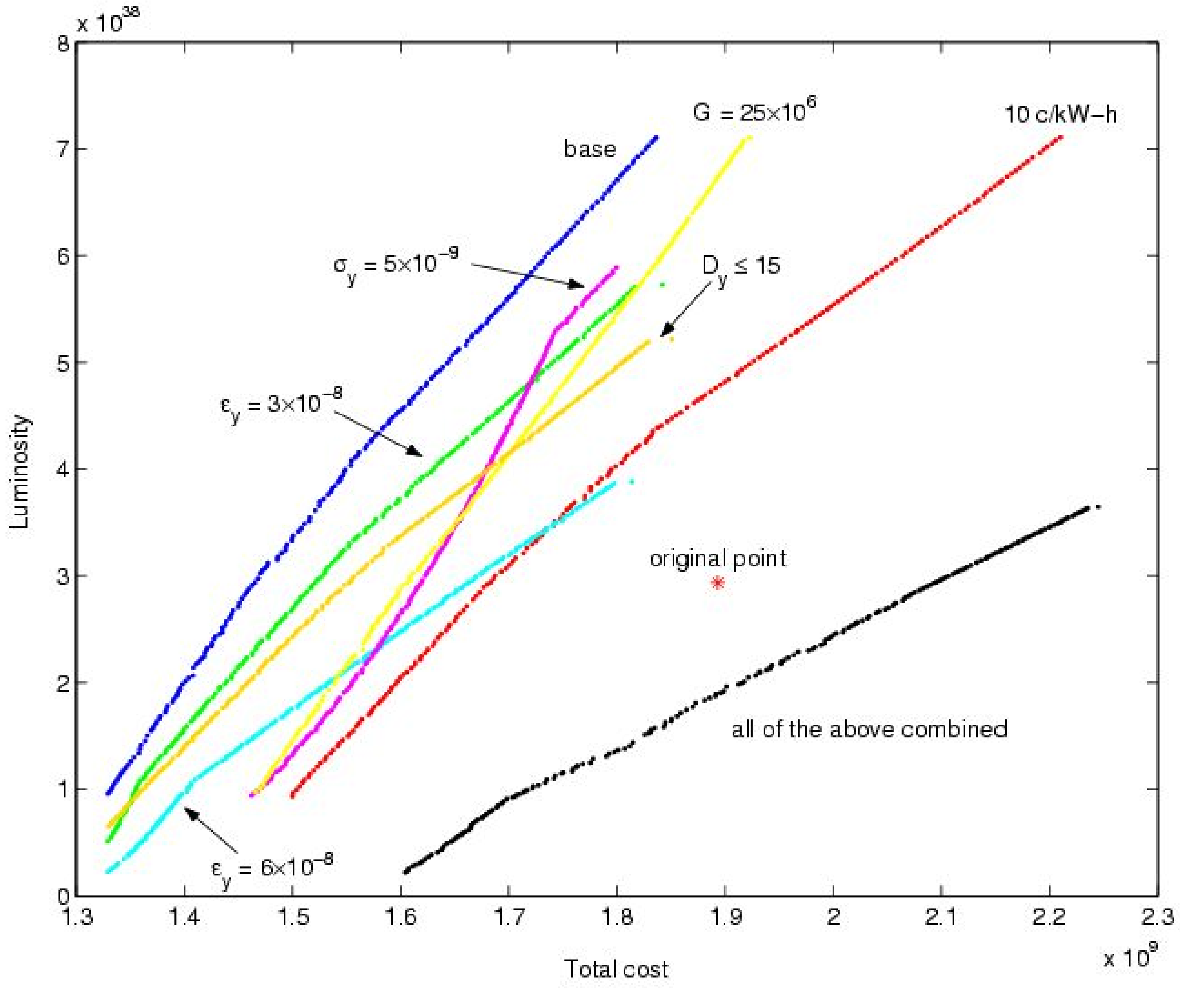
Example: Linear Collider



maximize **Luminosity**

minimize **Total Cost**

Example: Linear Collider (contd.)



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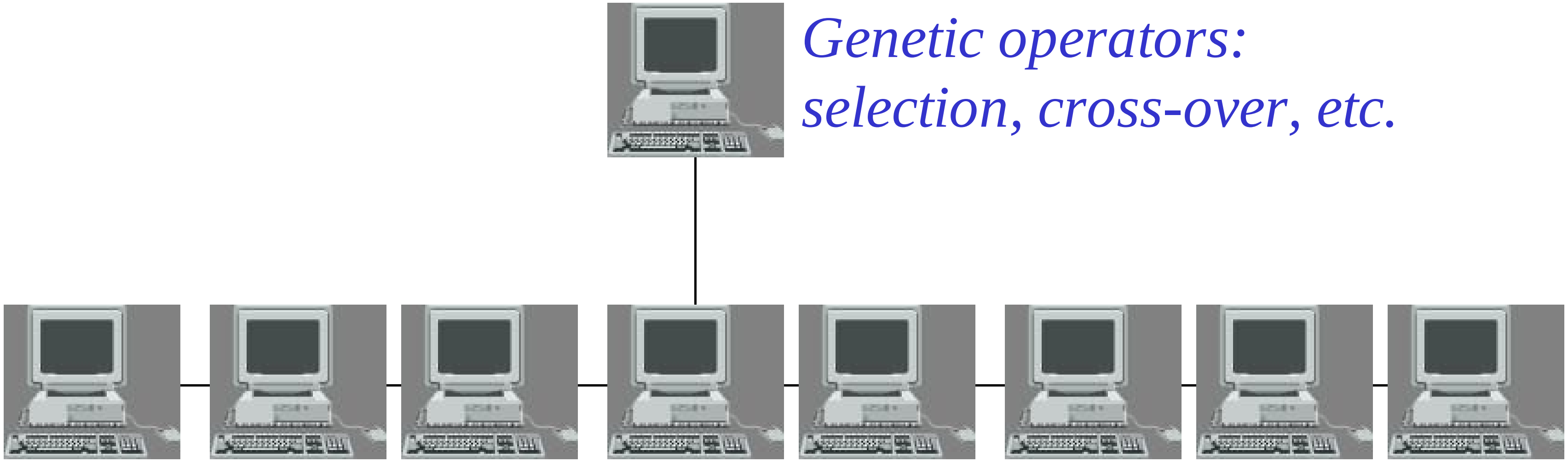
Parallel MOGA



Master

Genetic operators:
selection, cross-over, etc.

Slaves

Objectives evaluation

- no need for low-latency broadband network
- wall clock time is very close to that of truly parallel configuration, i.e. $1/t = 1/t_1 + 1/t_2 + \ldots 1/t_n$

Injector: Decision Variables

Fields:
DC Gun Voltage (300-900 kV)
2 Solenoids
Buncher
SRF Cavities Gradient (5-13 MV/m)
SRF Cavities Phase

Positions:
2 Solenoids
Buncher
Cryomodule

Bunch & Photocathode:
$E_{thermal}$
Charge

Laser Distribution:
Spot size
Pulse duration (10-30 ps rms)
{tail, dip, ellipticity} × 2

Total: 22-24 dimensional parameter space to explore

Injector Performance ($E_{thermal}$ = 35 meV, aka GaAs @ 780 nm)

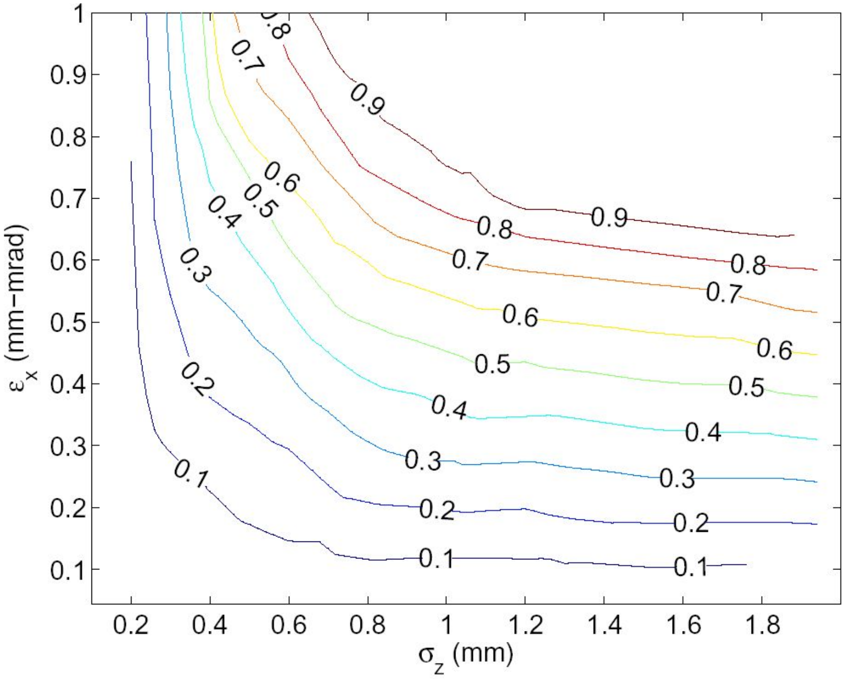


FIG. 10: Transverse emittance vs. bunch length for various charges in the injector (nC).

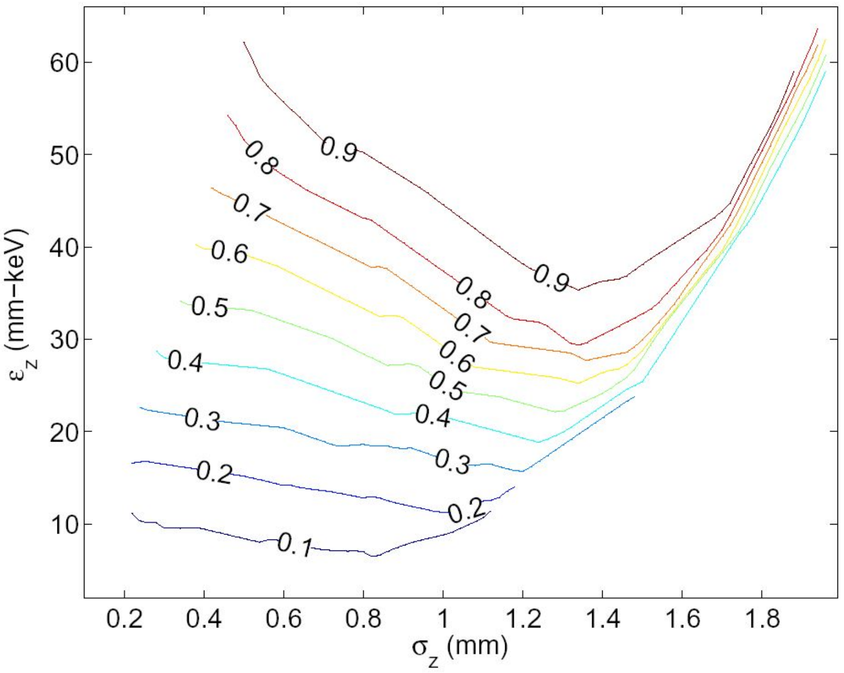
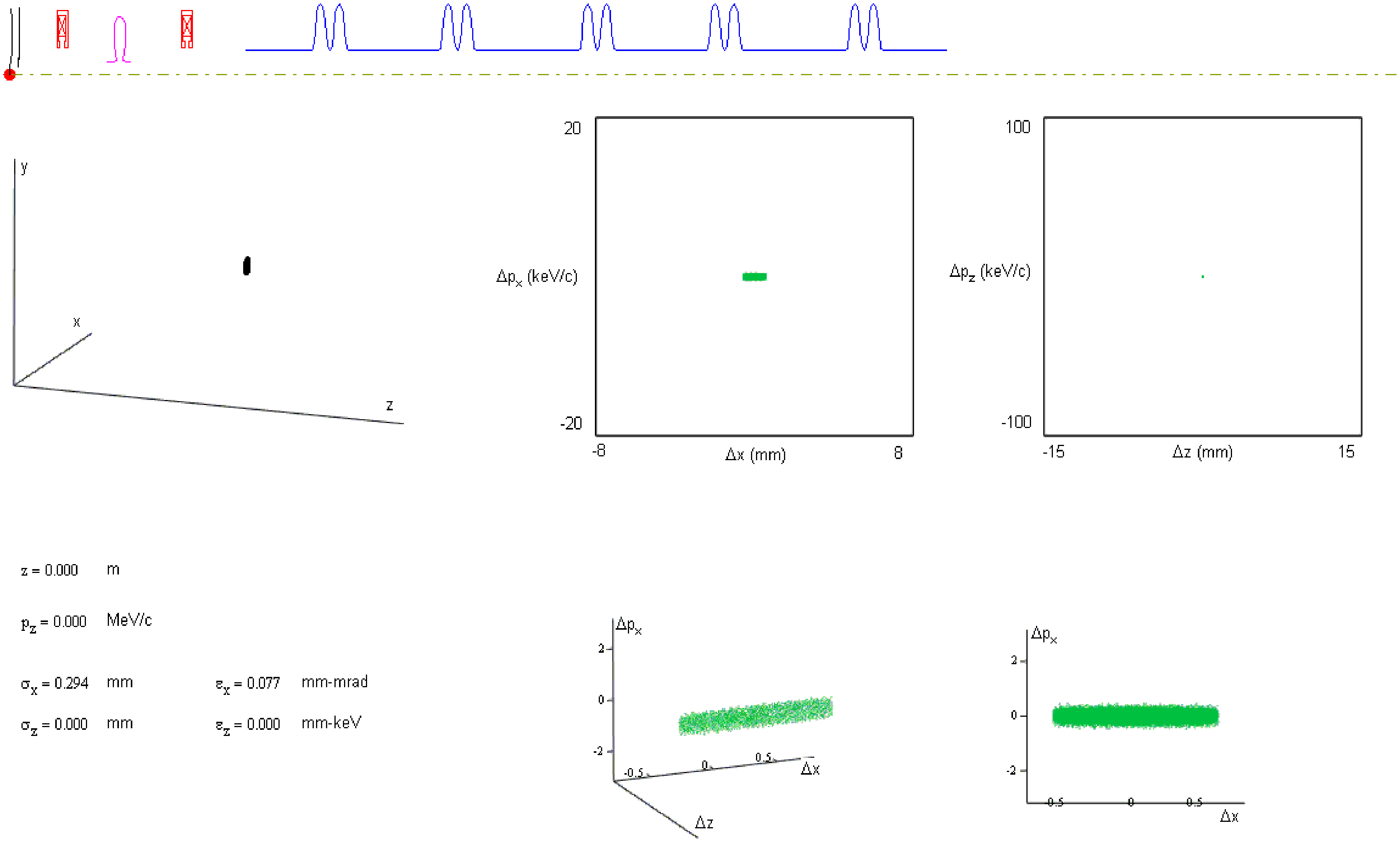


FIG. 11: Longitudinal emittance vs. bunch length for various charges in the injector (nC).

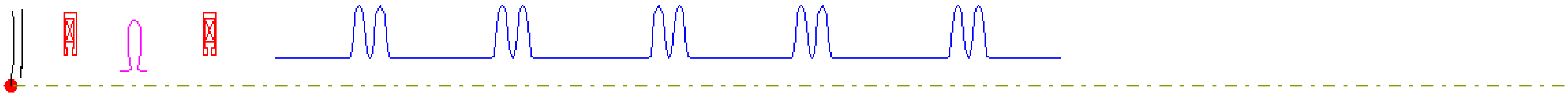
Takes several 10^5 simulations

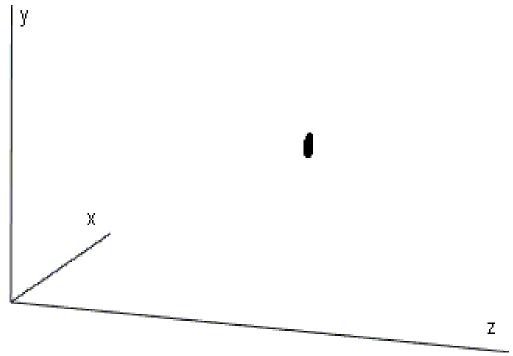
Closer Look: 80 pC

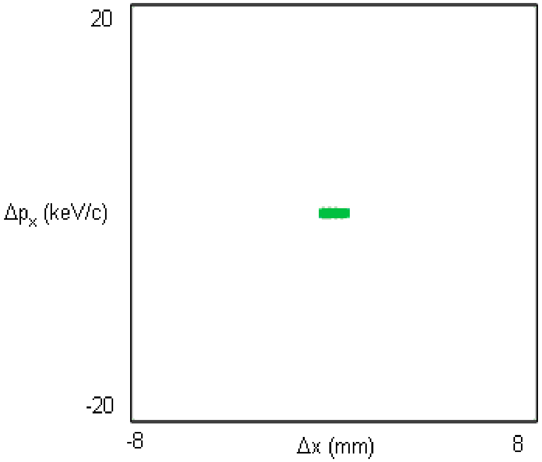


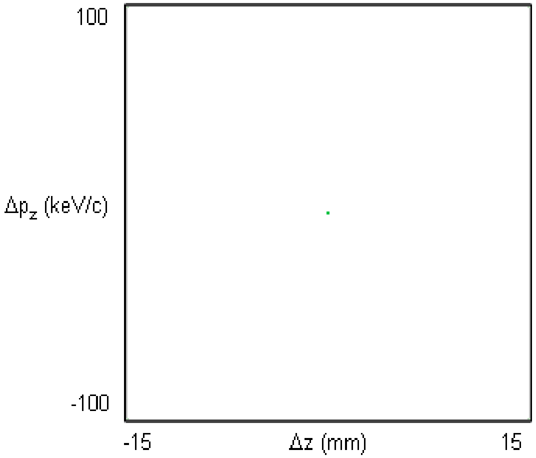
```
z = 0.000     m

pz = 0.000    MeV/c

σx = 0.294    mm          εx = 0.077    mm-mrad

σz = 0.000    mm          εz = 0.000    mm-keV
```

Closer Look: 0.8 nC







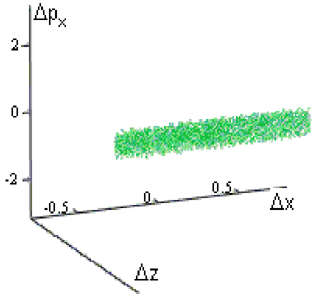


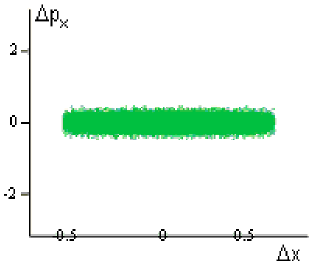
$z = 0.000$ m

$p_z = 0.000$ MeV/c

$\sigma_x = 0.294$ mm $\qquad \varepsilon_x = 0.077$ mm-mrad

$\sigma_z = 0.000$ mm $\qquad \varepsilon_z = 0.000$ mm-keV





Envelopes

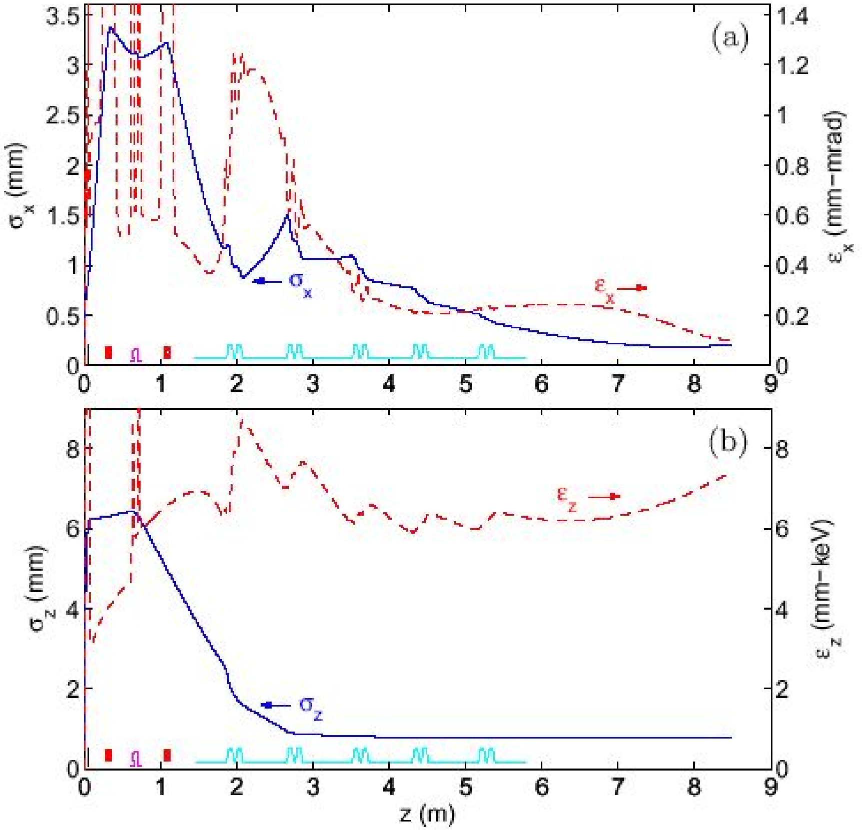


FIG. 3: Beam evolution in the injector for 80 pC bunch charge: transverse (a) and longitudinal (b) emittances (dashed) and sizes (solid) vs. position in the injector.

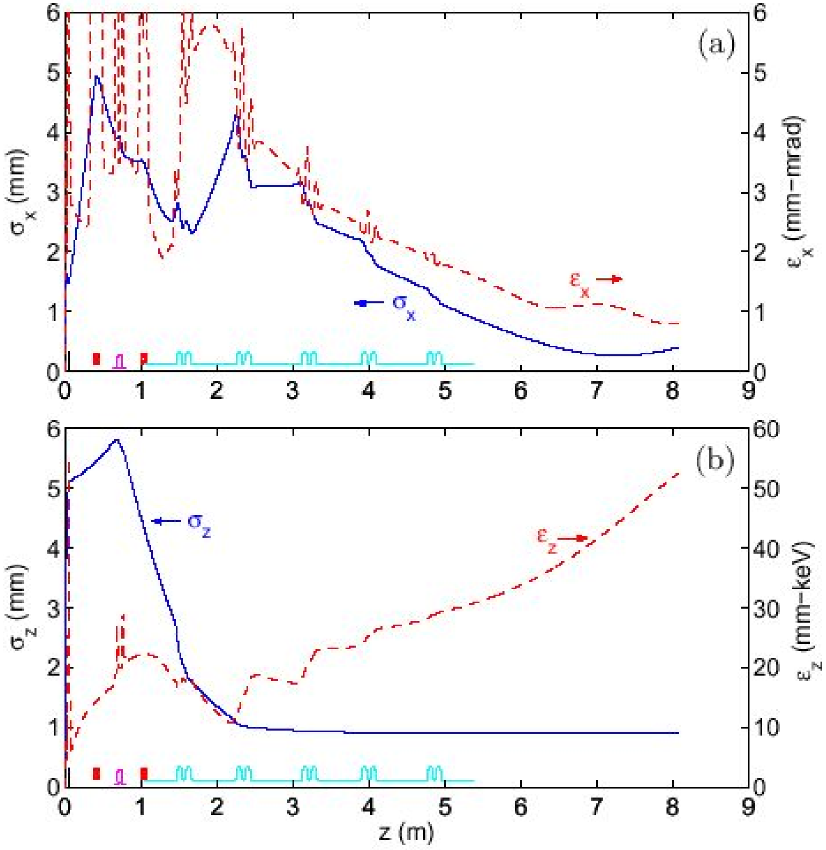


FIG. 4: Beam evolution in the injector for 0.8 nC bunch charge: transverse (a) and longitudinal (b) emittances (dashed) and sizes (solid) vs. position in the injector.

Extremely High Gun Voltage?

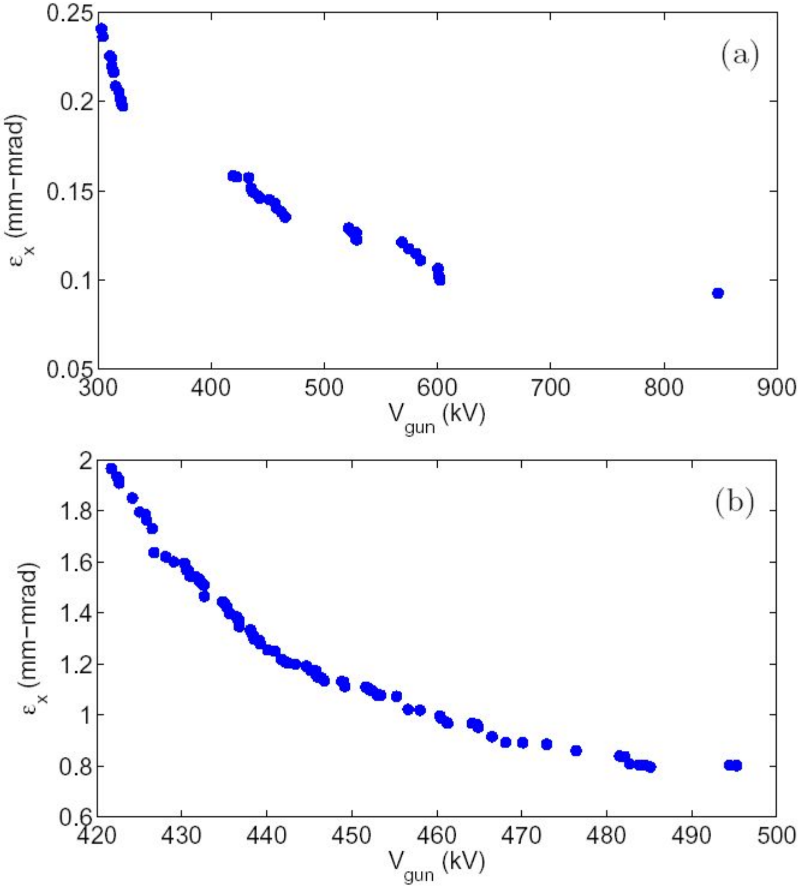
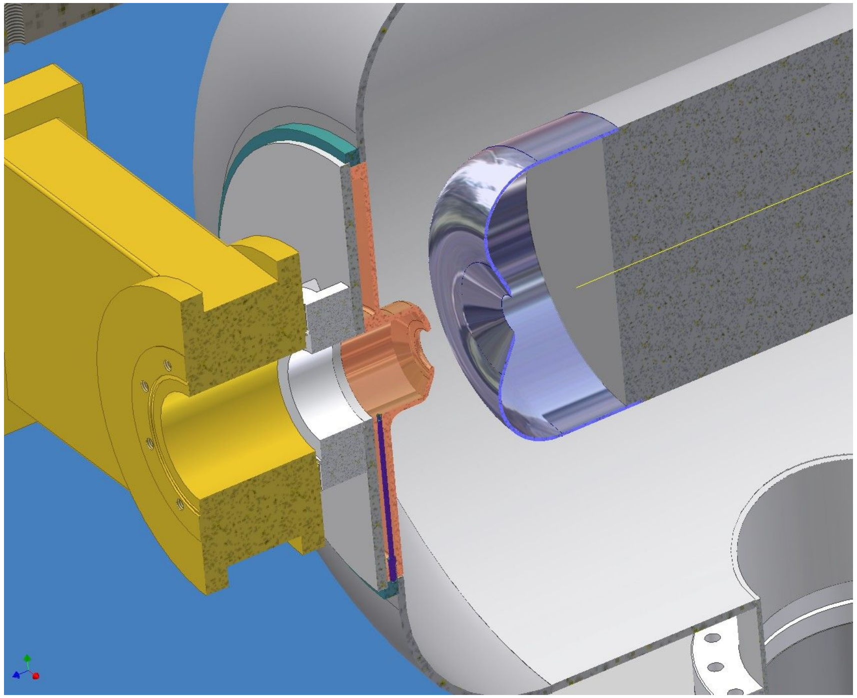


FIG. 5: Emittance vs. voltage in the gun for (a) 80 pC and (b) 0.8 nC bunch charges. The average bunch length corresponding to these calculations was (a) 0.8 mm and (b) 0.9 mm.



Pulse Shaping: 80 pC

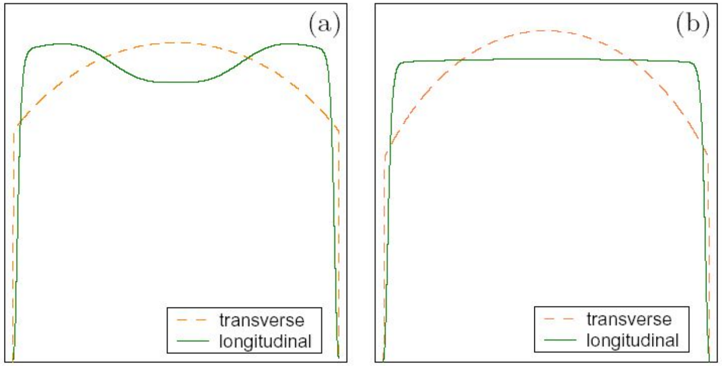


FIG. 6: Initial distribution profiles corresponding to minimal emittance at the end of the injector for (a) 80 pC and (b) 0.8 nC cases.

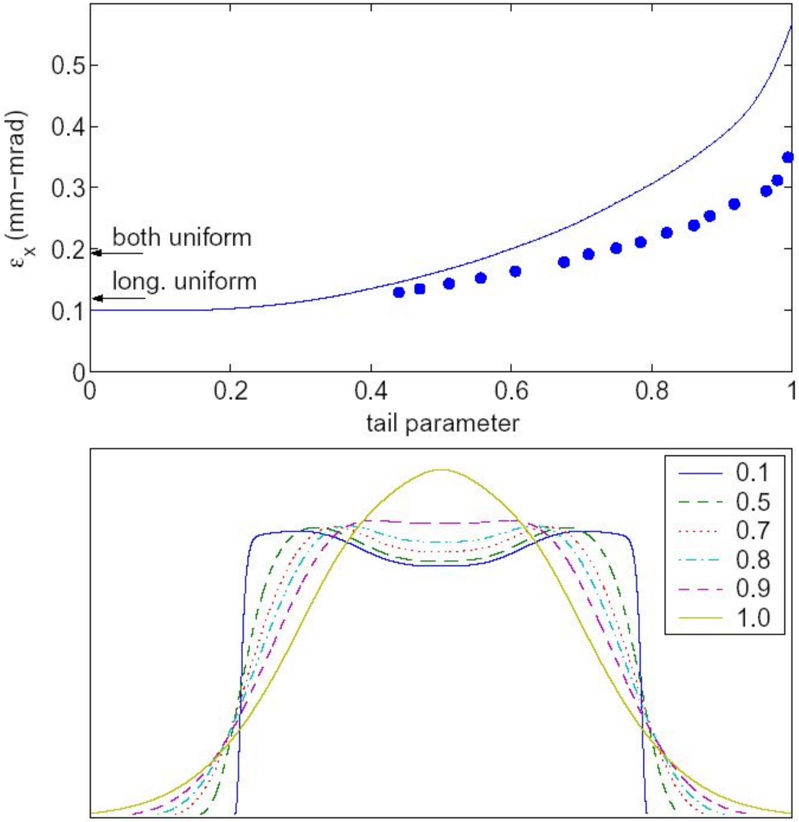


FIG. 7: 80 pC: emittance sensitivity (solid curve) to the longitudinal profile changes (top) and the corresponding profile shapes (bottom).

Pulse Shaping: 0.8 nC

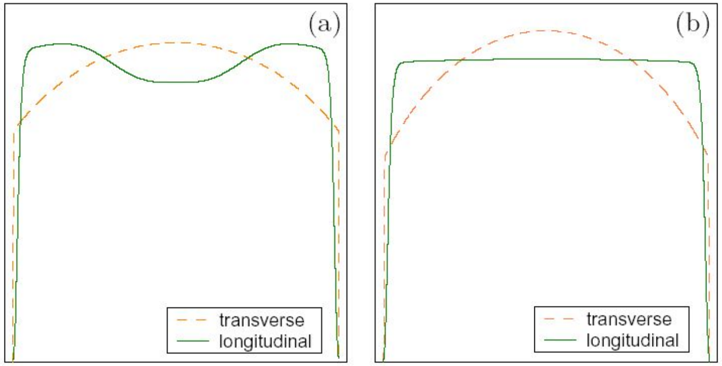


FIG. 6: Initial distribution profiles corresponding to minimal emittance at the end of the injector for (a) 80 pC and (b) 0.8 nC cases.

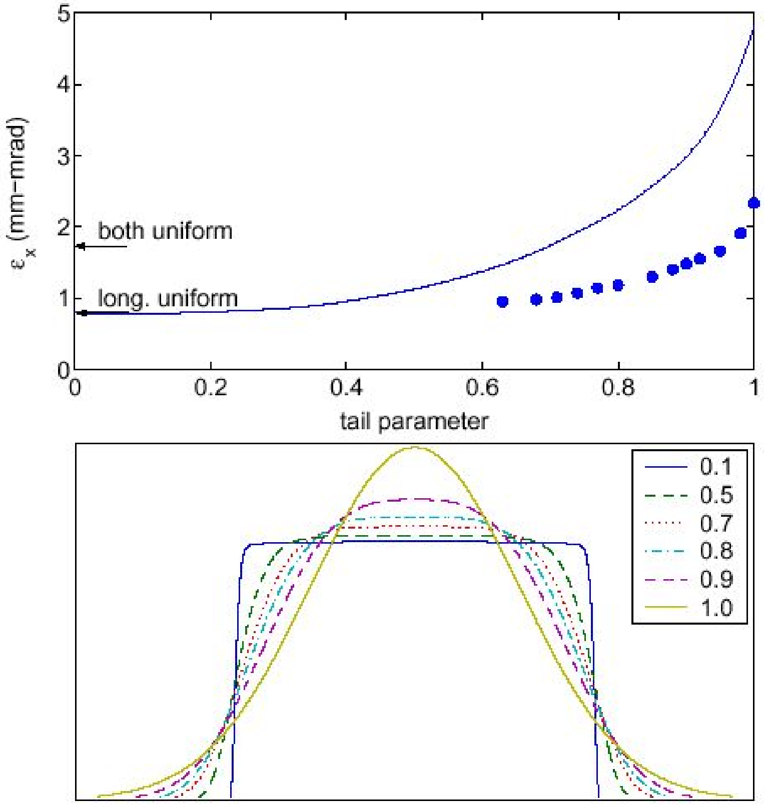


FIG. 8: 0.8 nC: emittance sensitivity (solid curve) to the longitudinal profile changes (top) and the corresponding profile shapes (bottom).

Thermal Energy of the Photocathode

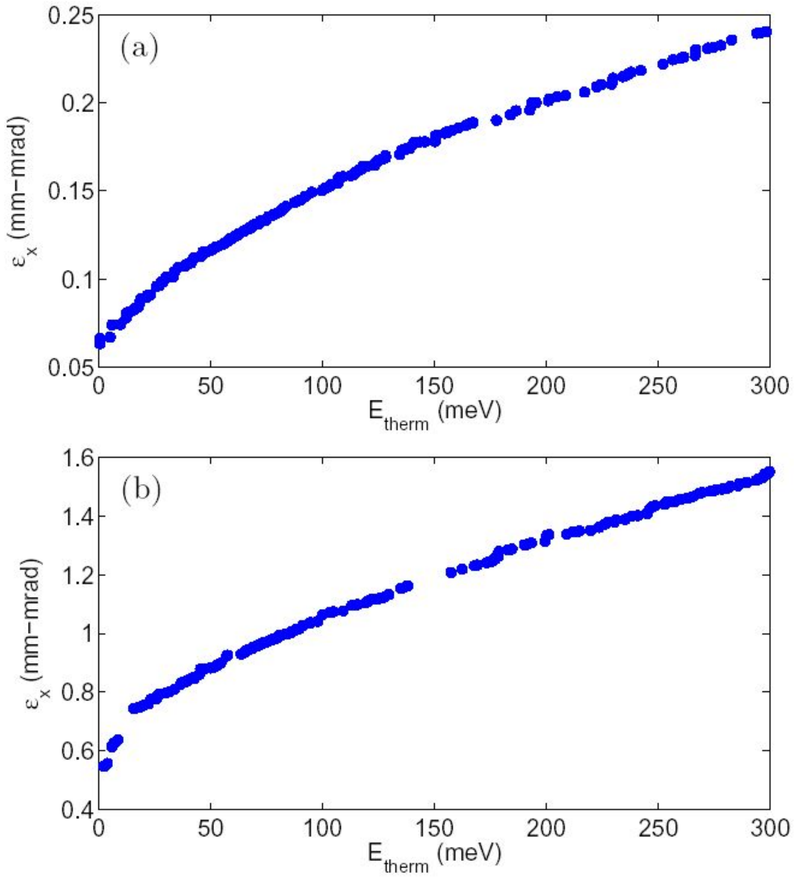


FIG. 9: Effect of thermal energy of the photocathode on the emittance of the injector for (a) 80 pC and (b) 0.8 nC charges respectively.

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Summary

- DC gun based injector can be operable in wide range of parameters with good simulated emittances: 0.1 mm-mrad @ 80 pC and 0.7 @ 1 nC
- Fields required for such performance are modest
- Parallel MOGA is a powerful tool which should and will be widely used in the accelerator field
- There are many outstanding issues with regards to tuning injector to its maximum performance + merge section to the main accelerator

Acknowledging the following individuals

- algorithm development with Igor Senderovich
- injector optimizations with Charlie Sinclair
- ILC stuff with Hasan Padamsee

Whole LEPP/CLEO for their Linux desktops
CHESS 2 clusters (before they were hacked)