Multivariate Optimization of High Brightness High Current DC Photoinjector

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Talk Outline:

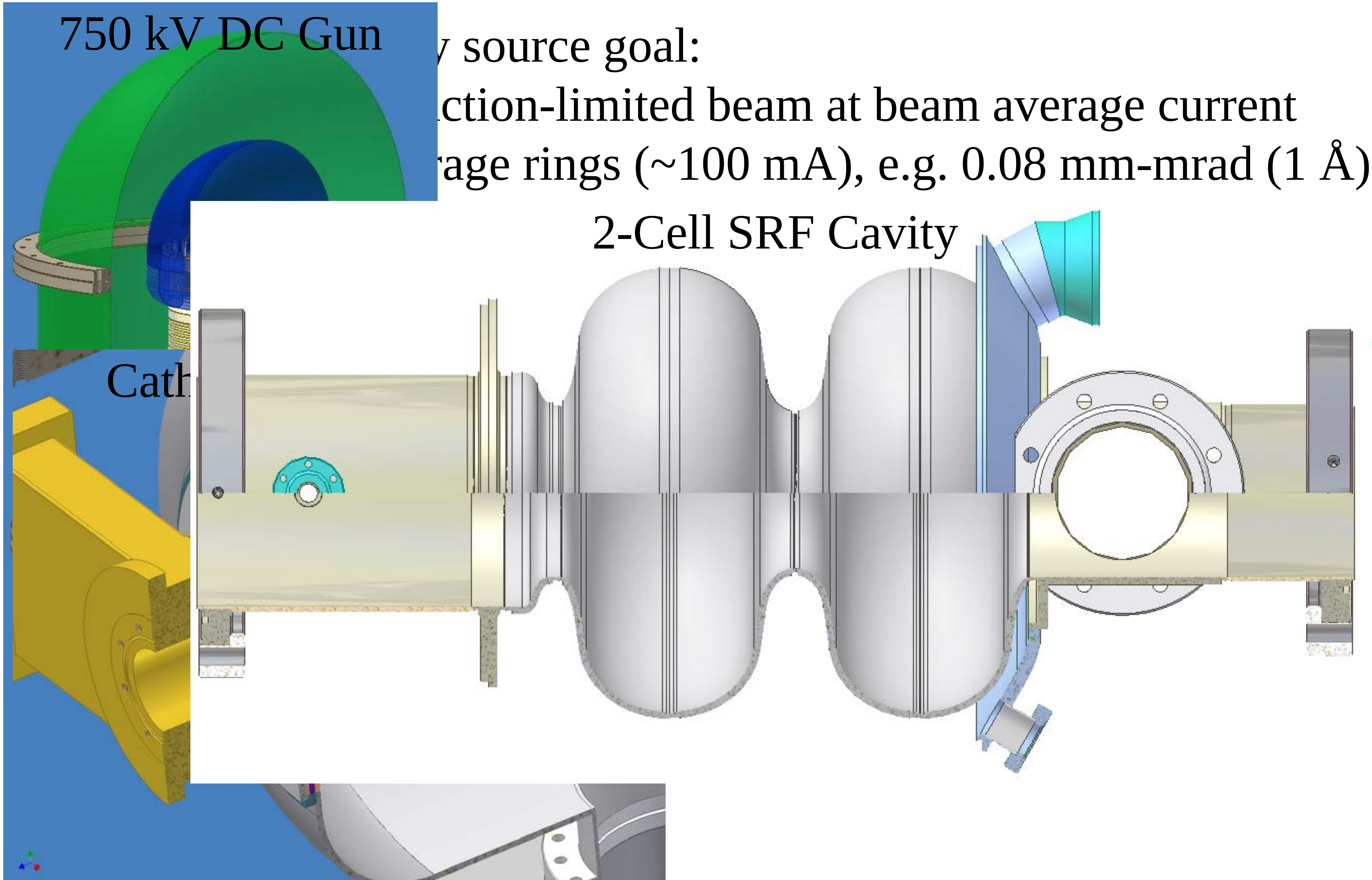
- Motivation
- Parallel Evolutionary Algorithms
- Results & Outlook

Cornell ERL Injector Project

y source goal:

ction-limited beam at beam average current

rage rings (~100 mA), e.g. 0.08 mm-mrad (1 Å)



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

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New approach

Need to do things faster?

- work harder
- work smarter
- get help

→

- processor speed
- algorithms
- parallel processing

Solution: use parallel MOGA

Multi***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

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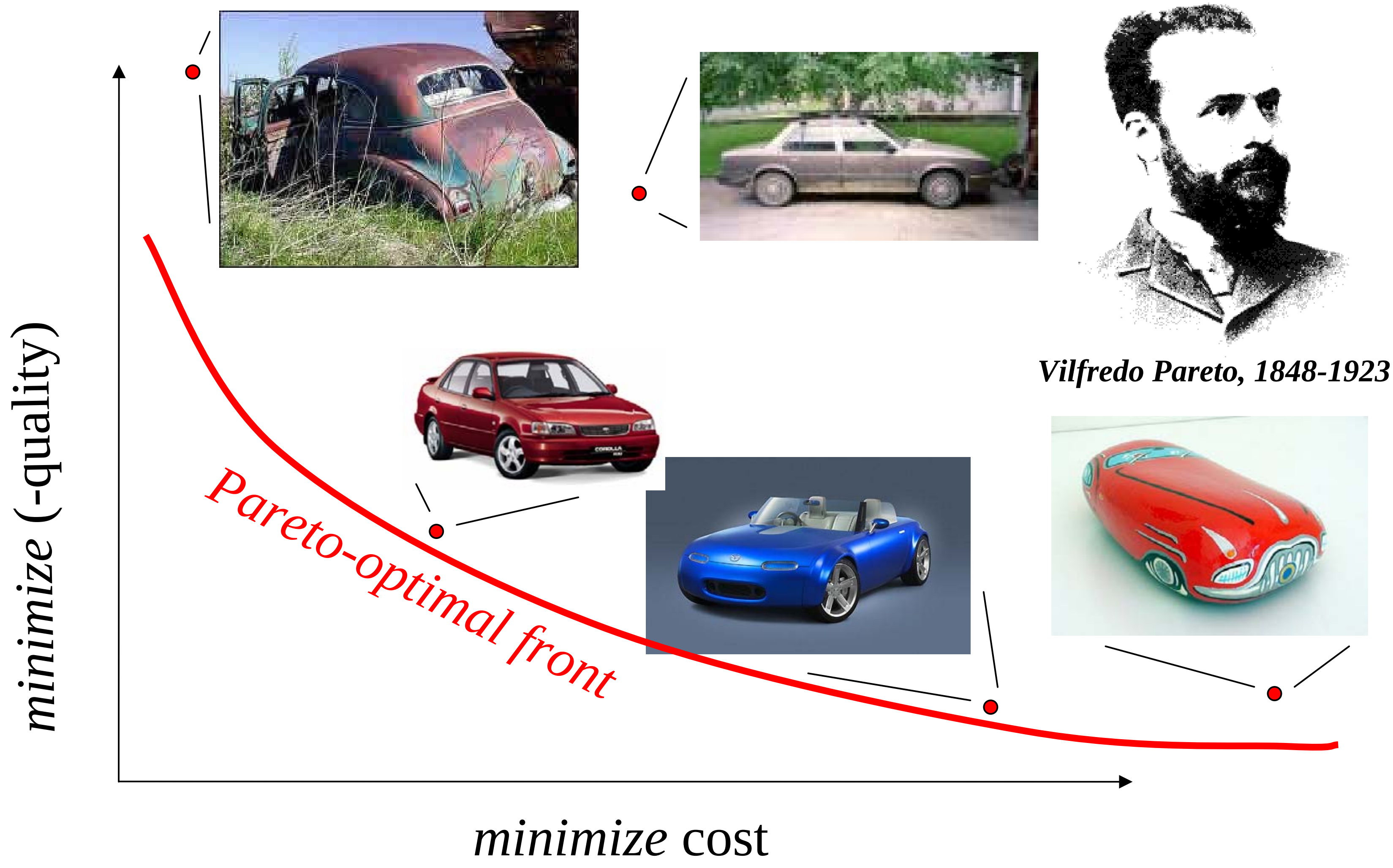
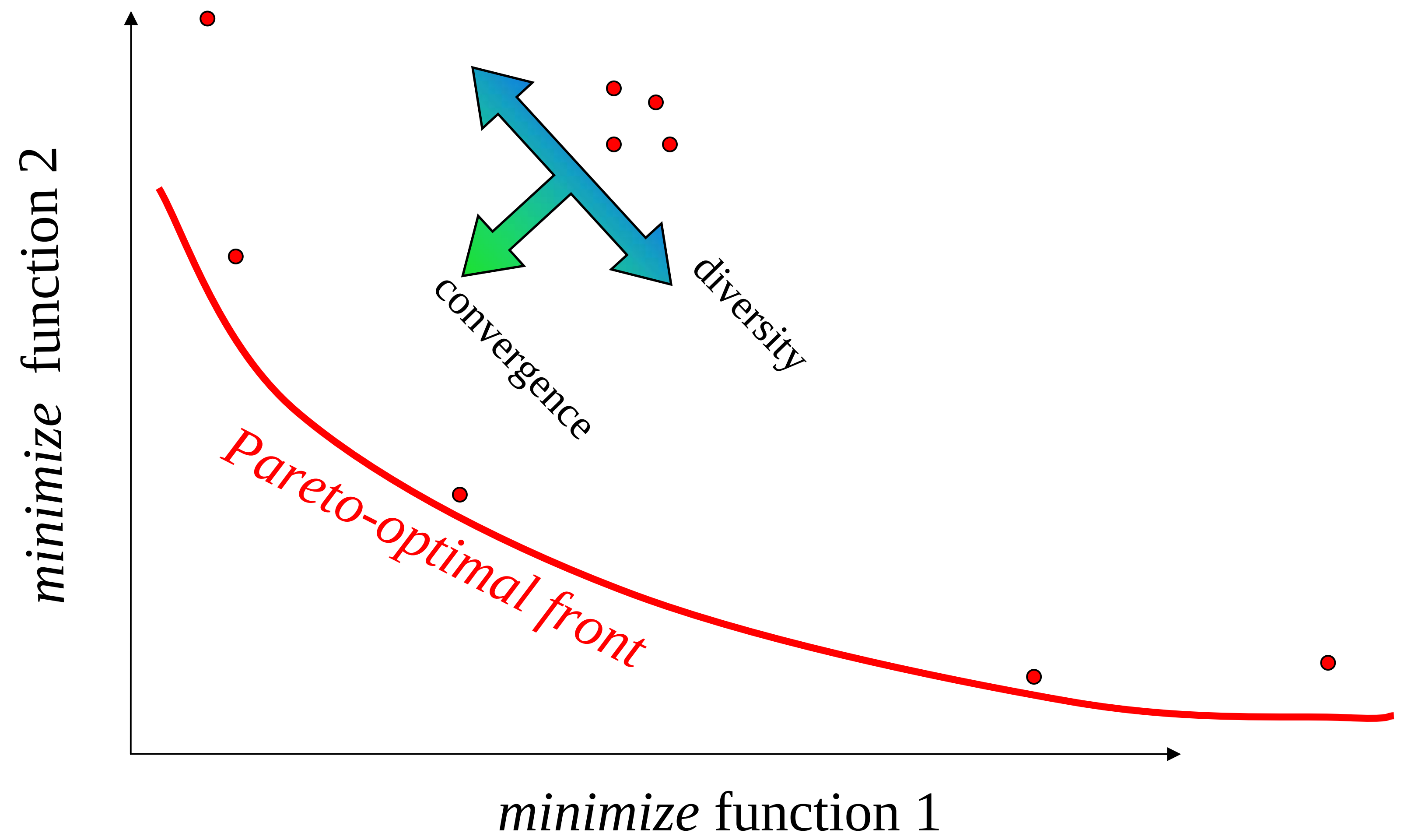
MultiObjective Optimization



MultiObjective Genetic Algorithm

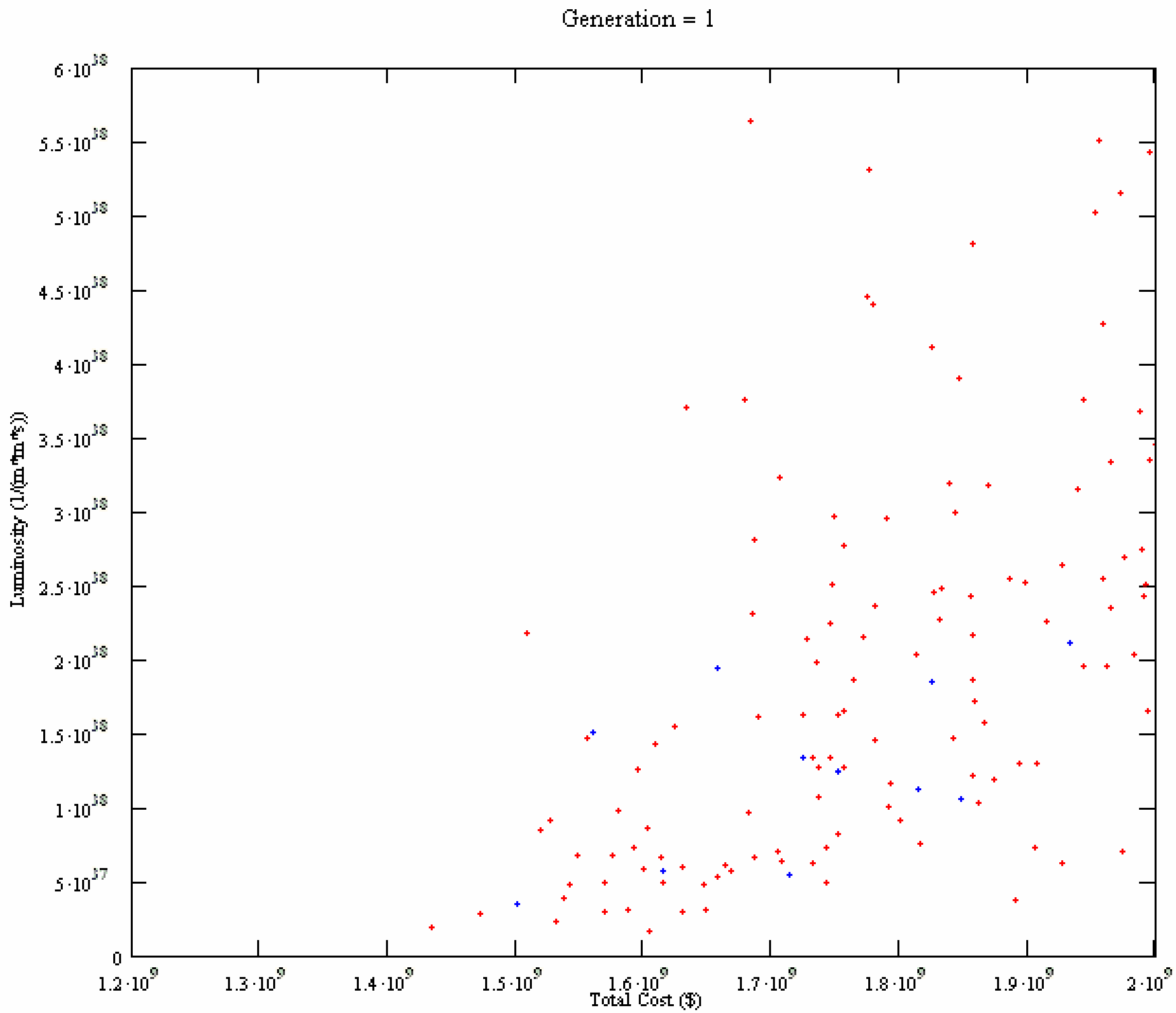
1. Initialize population
2. Evaluate objectives / constraints
3. Apply **selection** to create mating pool (subset)
4. Apply **crossing** operators to generate **offspring**
5. **Mutate** offspring
6. Evaluate objectives / constraints for the offspring
7. 'Good' solutions make it to the next generation
8. Repeat from step 3.

Selection Pressure



Example: Linear Collider Optimization

maximize **Luminosity**



minimize **Total Cost**

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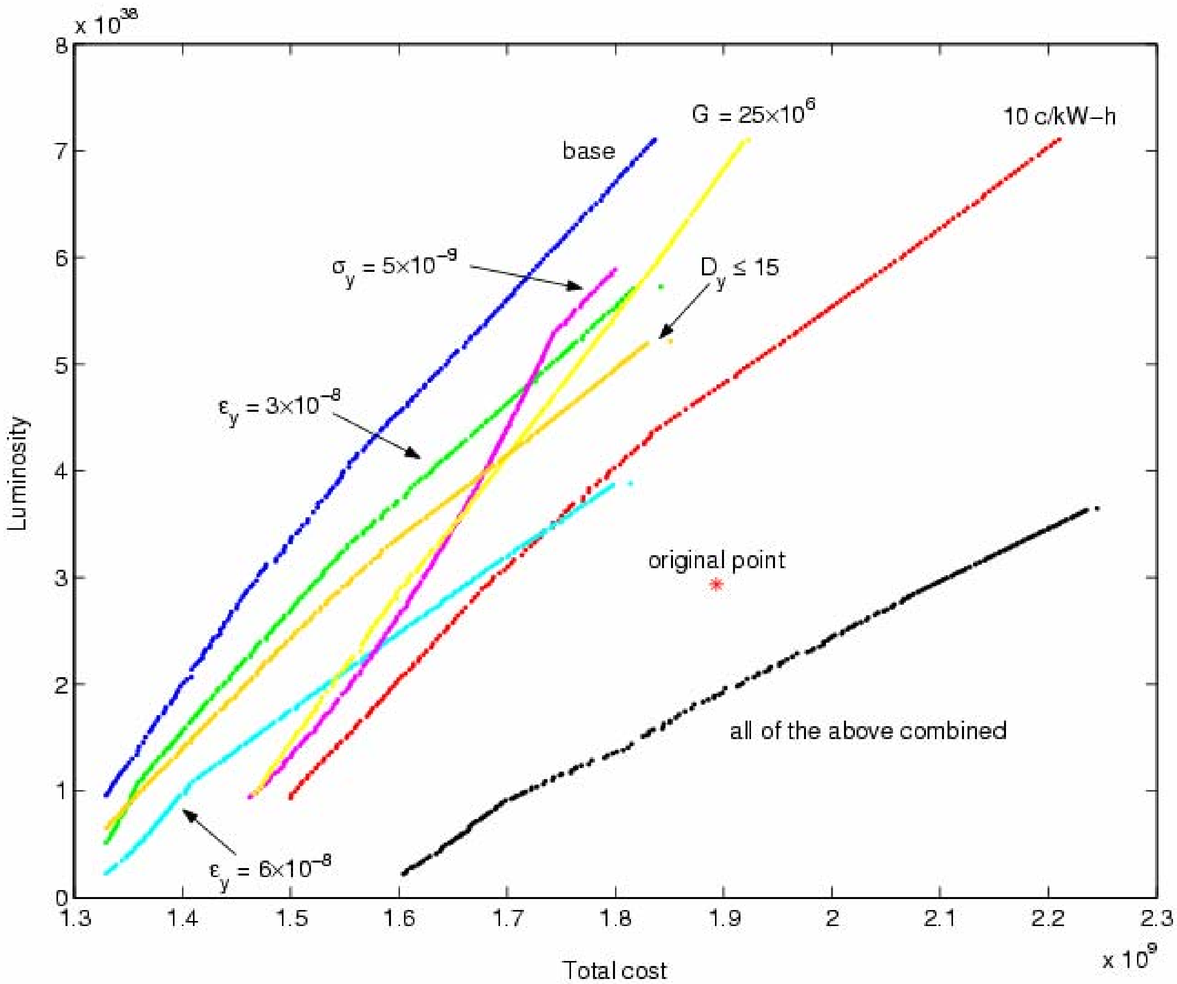
Example: Linear Collider Optimization (contd)



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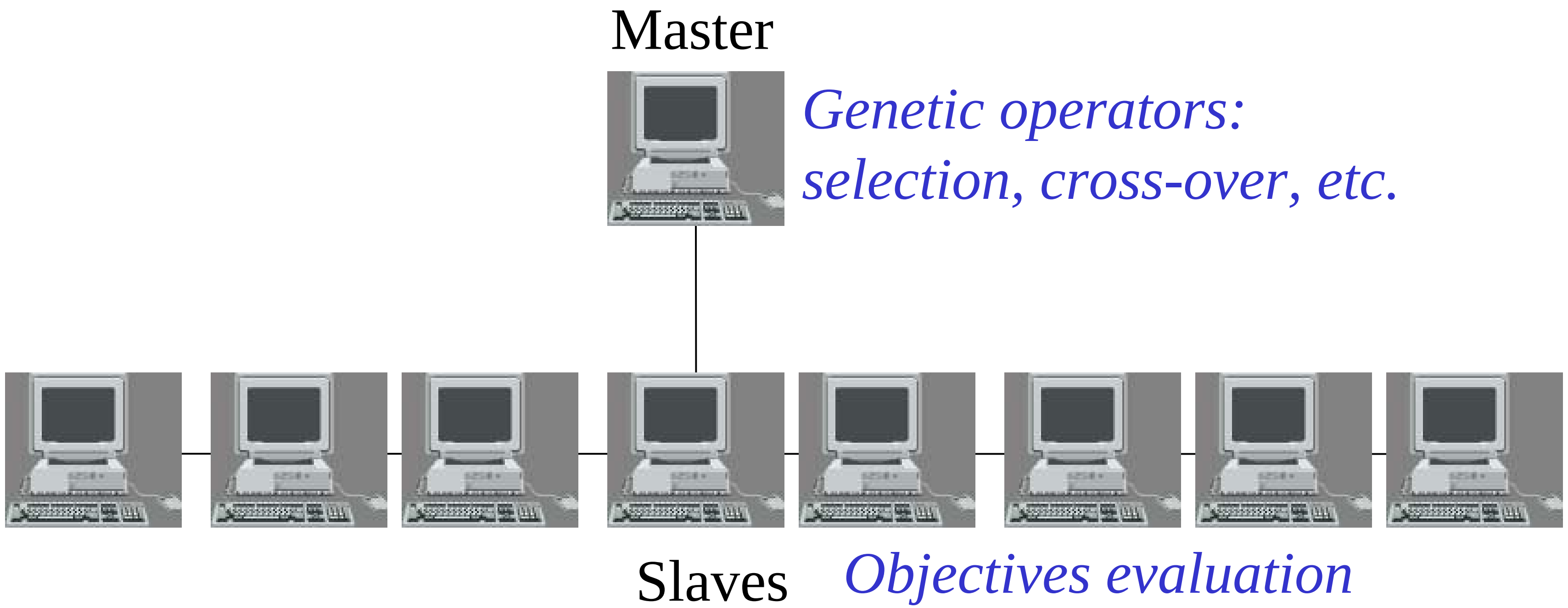
Parallelizing Genetic Algorithms



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

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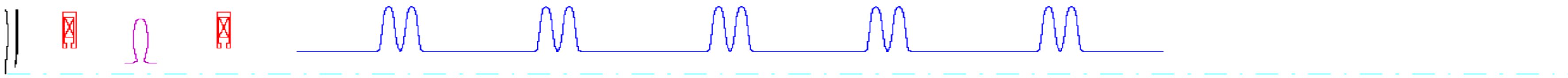
Cornell ERL injector: decision variables



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} x 2

Total: 22-24 dimensional parameter space to explore

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Injector Performance

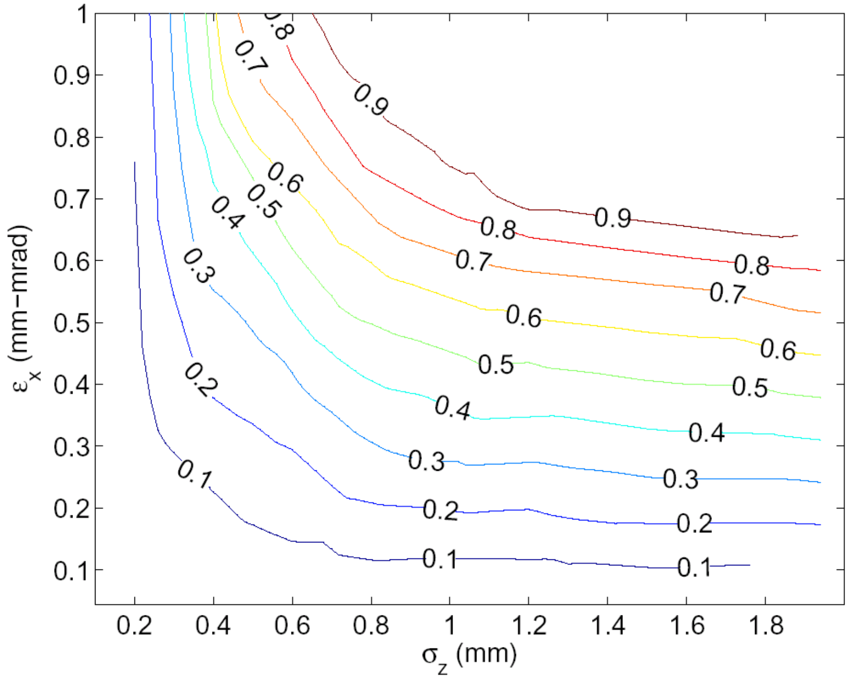

FIG. 10: Transverse emittance vs. bunch length for various charges in the injector (nC).

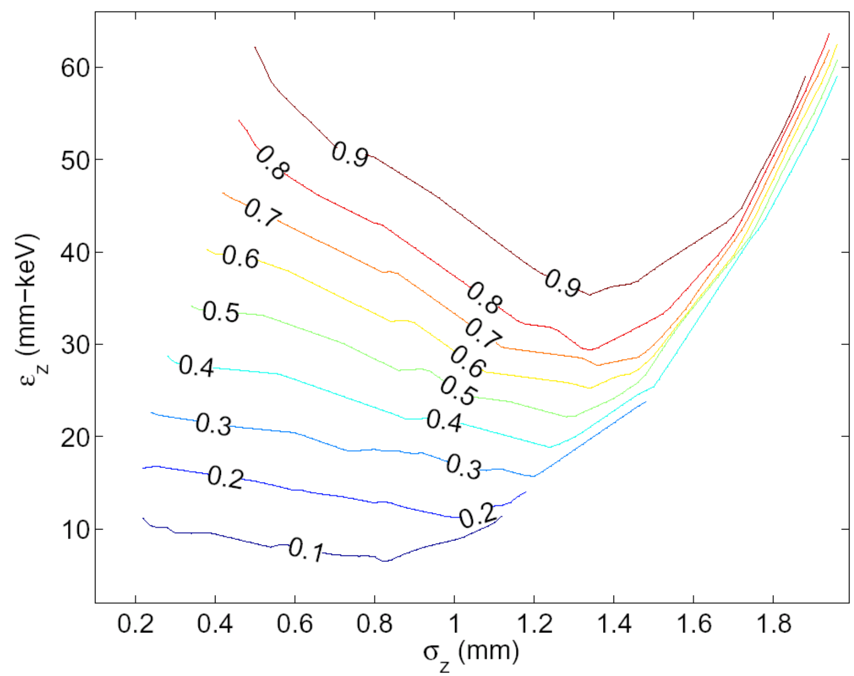

FIG. 11: Longitudinal emittance vs. bunch length for various charges in the injector (nC).

Takes several 10^5 simulations

$$\varepsilon_\perp[\text{mm-mrad}] \approx q[\text{nC}]\,(0.73 + 0.15/\sigma_z[\text{mm}]^{2.3})$$

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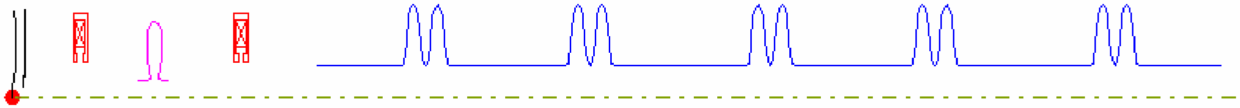
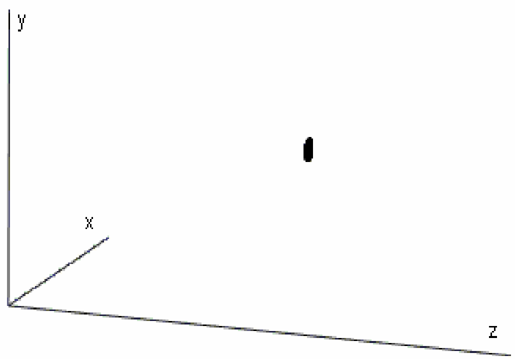
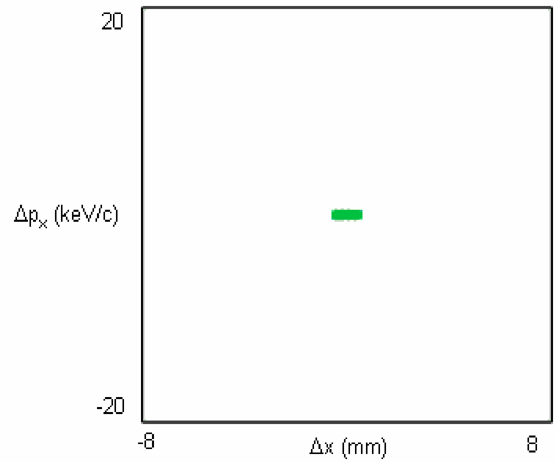
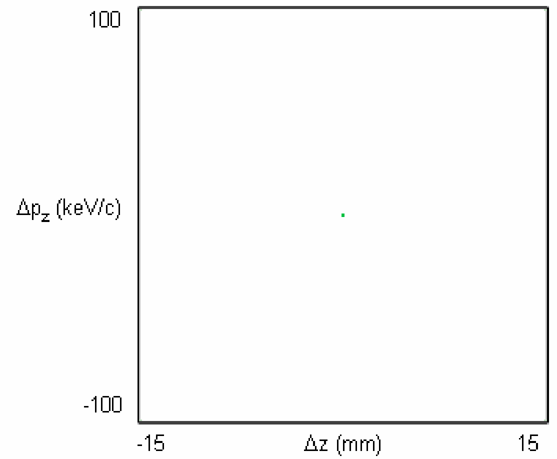
80 pC per bunch (animation)







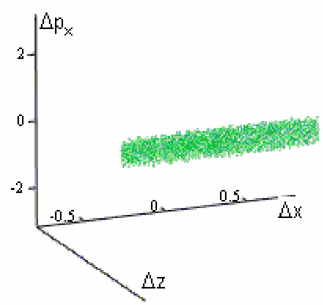


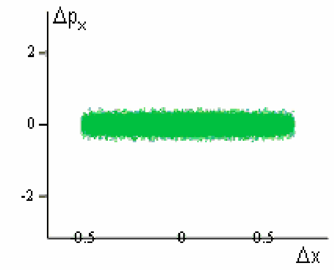
z = 0.000 m

p_z = 0.000 MeV/c

σ_x = 0.294 mm ε_x = 0.077 mm-mrad

σ_z = 0.000 mm ε_z = 0.000 mm-keV





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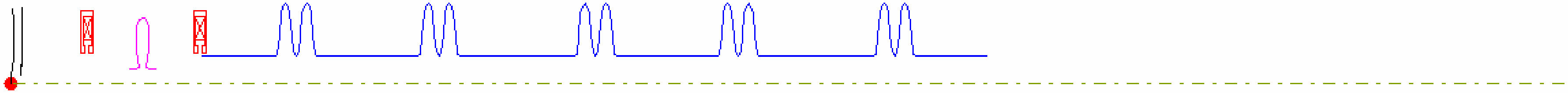
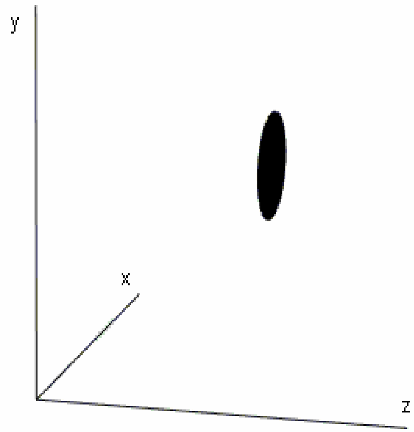
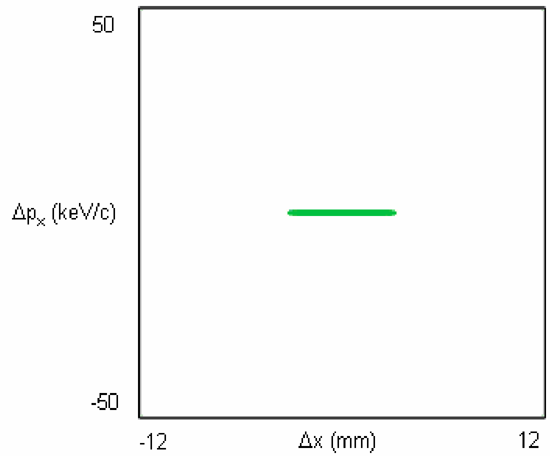
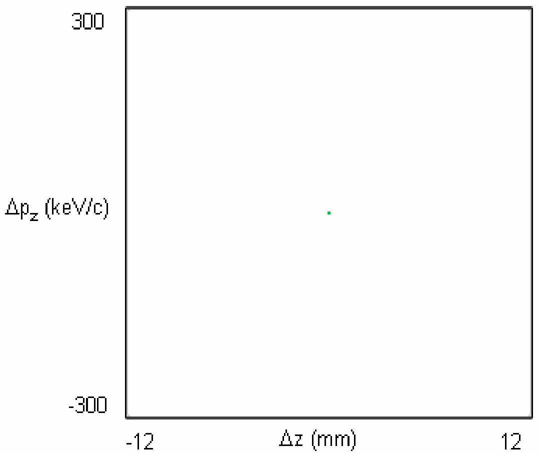
0.8 nC per bunch (animation)









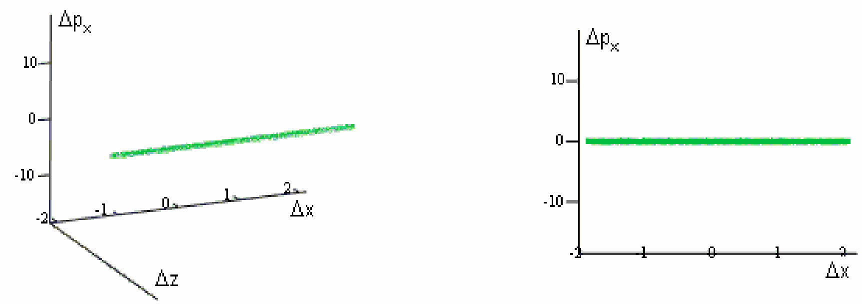
$z = 0.000$ m

$p_z = 0.000$ MeV/c

$\sigma_x = 1.629$ mm $\quad \varepsilon_x = 0.425$ mm-mrad

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

Zoomed in transverse phase space



Laser Pulse Shaping

0.8 nC

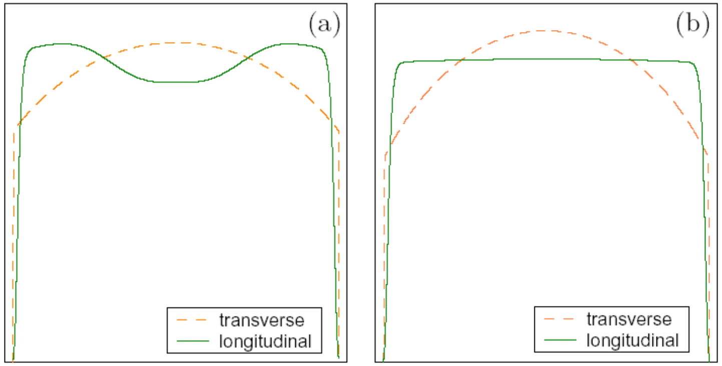


FIG. 6: Initial distribution profiles corresponding to minimal emittance at the end of the injector for (a) 80 pC and (b) 0.8 nC cases.

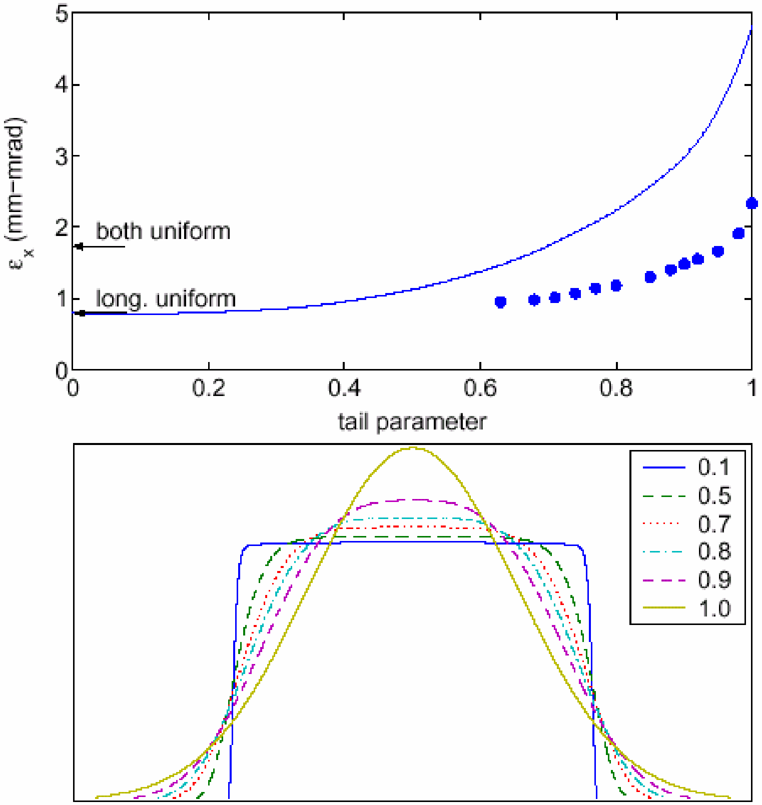


FIG. 8: 0.8 nC: emittance sensitivity (solid curve) to the longitudinal profile changes (top) and the corresponding profile shapes (bottom).

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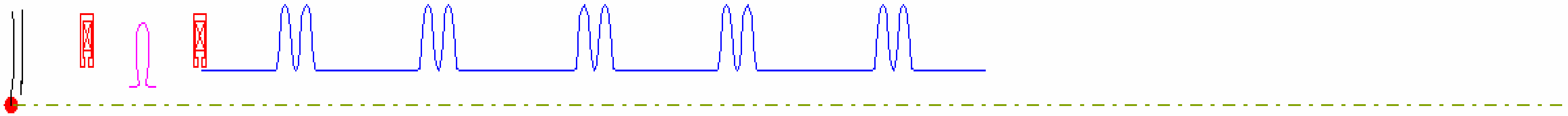
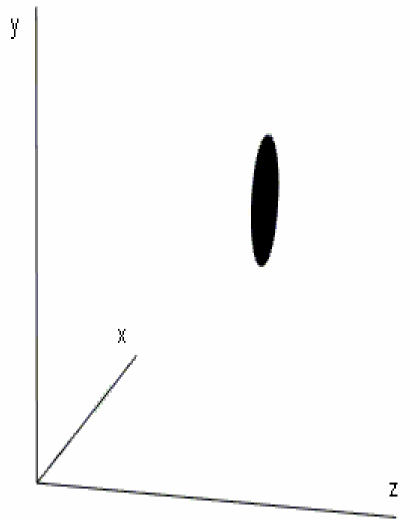
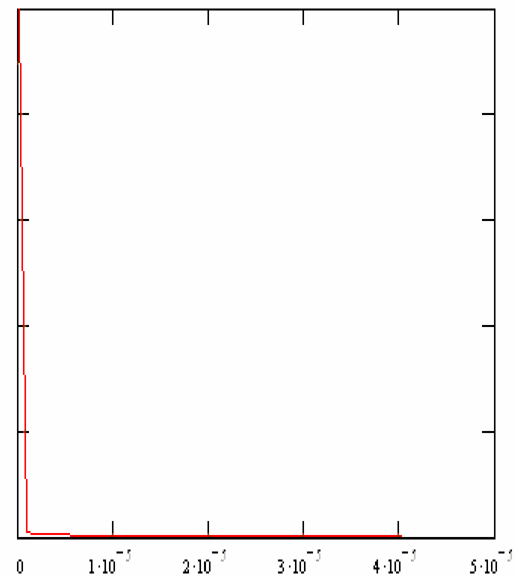
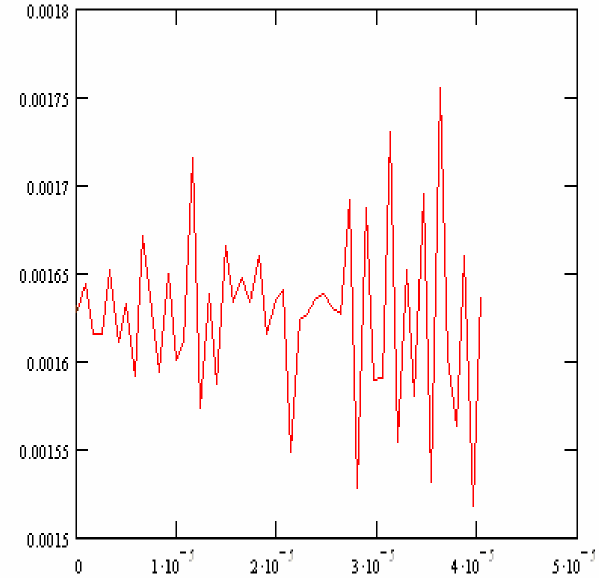
0.8 nC per bunch (animation)







Longitudinal Profile (abscissa slice position in m)



(y-axis) Slice Rms size (m) vs. (x-axis) slice coordinate (m)

$z = 0.000$ m

$p_z = 0.000$ MeV/c

$\varepsilon_x = 0.426$ mm-mrad

$\varepsilon_z = 0.006$ mm-keV

$\sigma_x = 1.629$ mm

$\sigma_z = 0.006$ mm

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Gun Voltage

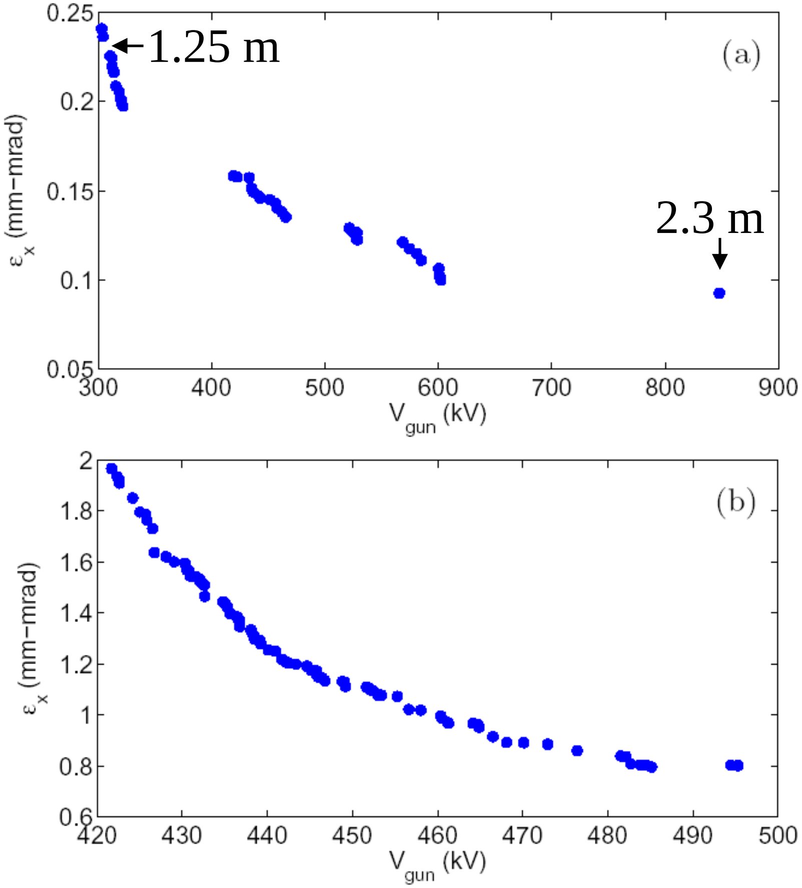
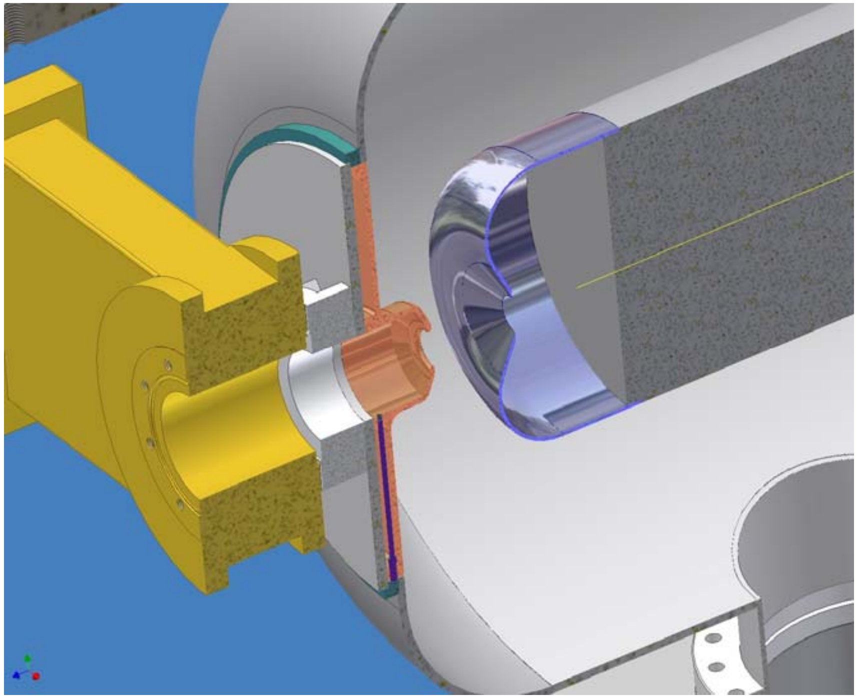


FIG. 5: Emittance vs. voltage in the gun for (a) 80 pC and (b) 0.8 nC bunch charges. The average bunch length corresponding to these calculations was (a) 0.8 mm and (b) 0.9 mm.

$\sigma_z < 0.9$ mm



At low gun voltage the layout is very crowded before the 1st SRF cavity

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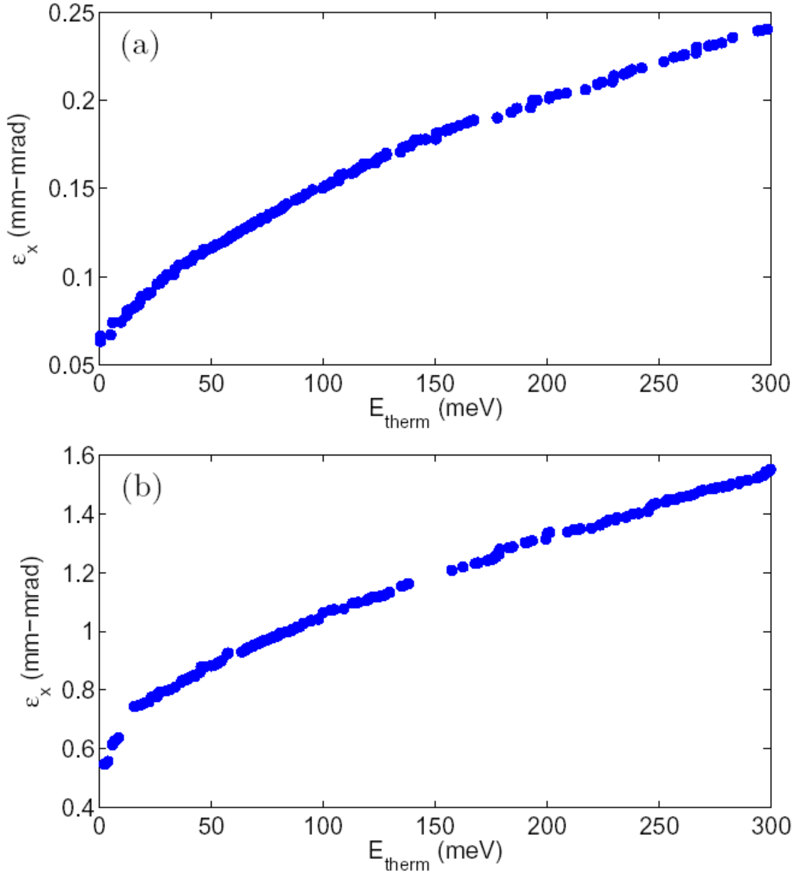
Thermal Energy of the photocathode



$\sigma_z < 0.9$ mm

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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Outlook

Cornell Theory Center:
an Intel/Windows cluster complex consisting of more than 1500 processors

- Work in progress to setup Parmela for parallel
- We should be able to simulate the whole injector including the merger and the first cryomodule

- **We will be able to compare these simulations with actual beam measurements in the foreseeable future at Cornell**

Acknowledgements

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

- MacCHESS for their 2 clusters
- whole LEPP/CLEO for their Linux desktops

For more details see our paper (Bazarov and Sinclair) in *PRST AB* [to appear in March (or April) issue of 2005]

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Two questions…

- Number 1: Is the result reproducible with another space charge code?

Yes. PARMELA essentially reproduces the beam envelope & emittance of ASTRA (the code used in these optimizations)

- Number 2: How sensitive are these solutions? *e.g. @0.1 nC*

	10 % difference in the following			*10^{-3} difference in K.E.*	
Trms	24%	sigmaz*	BunPhase	1.2°	deltaE
Vgun	0.5%	deltaE	Cav1Phase	0.8°	K.E.
LPhase	2.4°	K.E.	Cav2Phase	1.5°	K.E.
Vbun	2.4%	deltaE	Ecav1	1.0%	K.E.
B1	0.8%	sigmax	Ecav2	0.5%	K.E.
B2	2.1%	sigmax	XYrms	3.5%	epsilonx
			LIntensity	7.4%	epsilonx