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

Our source goal:

- Production-limited beam at beam average current
- Similar to storage rings (~100 mA), e.g. 0.08 mm-mrad (1 Å)

2-Cell SRF Cavity
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*
New approach

Need to do things faster?
- work harder
- work smarter
- get help
- processor speed
- algorithms
- parallel processing

Solution: use parallel MOGA

MultiObjective Genetic Algorithm

- 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
MultiObjective Optimization

minimize cost

minimize (-quality)

Pareto-optimal front

Vilfredo Pareto, 1848-1923
Multi-Objective 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

\[ \text{minimize function 1} \]

\[ \text{minimize function 2} \]

Pareto-optimal front

diversity

convergence
Example: Linear Collider Optimization

\[ \text{minimize} \quad \text{Total Cost} \]

\[ \text{maximize} \quad \text{Luminosity} \]
Example: Linear Collider Optimization (contd)
Parallelizing Genetic Algorithms

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. $1/t = 1/t_1 + 1/t_2 + \ldots + 1/t_n$
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:**
- $E_{\text{thermal}}$
- Charge

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

**Total: 22-24 dimensional parameter space to explore**
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*

$$\varepsilon_{\perp}\text{[mm-mrad]} \approx q\text{[nC]} \left(0.73 + 0.15/\sigma_z[\text{mm}]^{2.3}\right)$$
80 pC per bunch (animation)

\[ z = 0.000 \text{ m} \]

\[ p_x = 0.000 \text{ MeV/c} \]

\[ \sigma_x = 0.294 \text{ mm} \quad \epsilon_x = 0.077 \text{ mm-mrad} \]

\[ \sigma_z = 0.000 \text{ mm} \quad \epsilon_z = 0.000 \text{ mm-keV} \]
0.8 nC per bunch (animation)

\[ \sigma_x = 0.000 \text{ m} \]
\[ \sigma_z = 0.000 \text{ MeV/c} \]
\[ \sigma_{xz} = 1.639 \text{ mm} \]
\[ \sigma_{xz} = 0.423 \text{ mm-mrad} \]
\[ \sigma_{xz} = 0.000 \text{ mm-keV} \]

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).
0.8 nC per bunch (animation)
At low gun voltage the layout is very crowded before the 1st SRF cavity.
Thermal Energy of the photocathode

\[ \sigma_z < 0.9 \text{ mm} \]

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.
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]
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?  
  10% difference in the following  
  10\(^{-3}\) difference in K.E.  

| Parameter | 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 |