Genetic Algorithms and their Applications in Accelerator Physics

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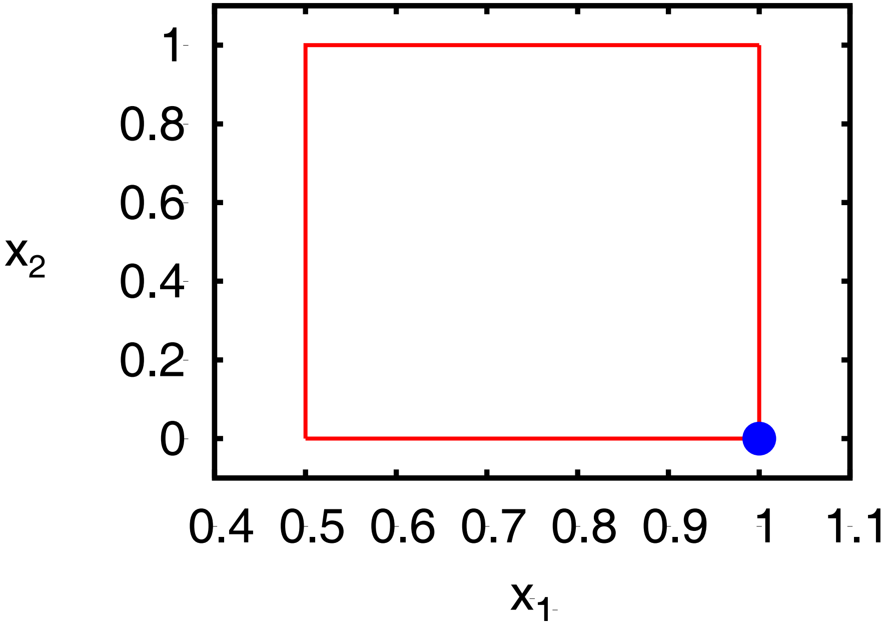
North American Particle Accelerator Conference
September 29 - October 4, 2013, Pasadena, CA

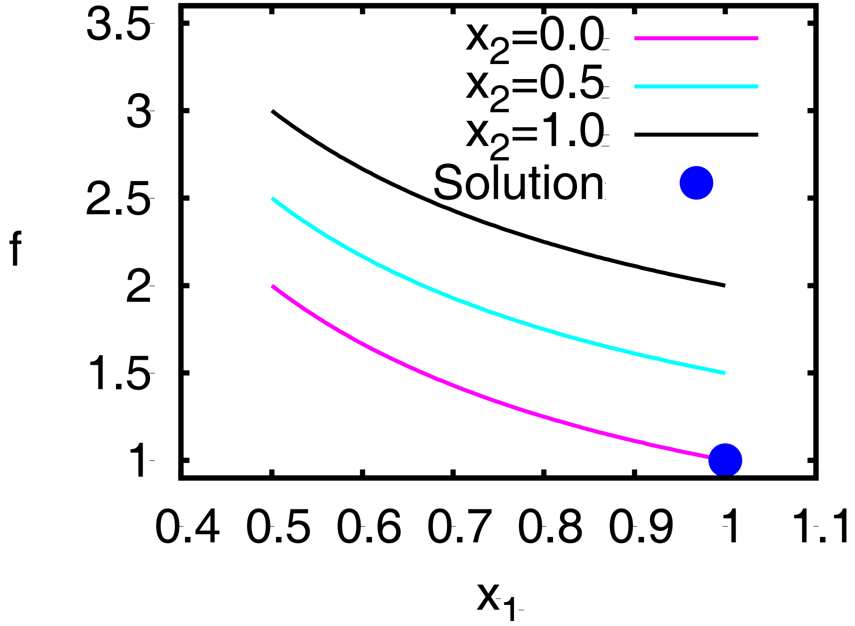
Outline

- Single and multi-objective problems
- Algorithms overview
- Tools
- Examples
  - Beamline component design
  - Real time and diagnostic uses
  - Machine optimization
    - Operational settings
    - Combined settings and element design
- Conclusion

Single-Objective Example



Decision space: x_2 vs. x_1 (red box and interior)



f vs. x_1 for fixed x_2

Minimize $f\left(x_1, x_2\right) = \frac{1}{x_1} + x_2$

One multi-dimensional objective

subject to $0.5 \le x_1 \le 1$

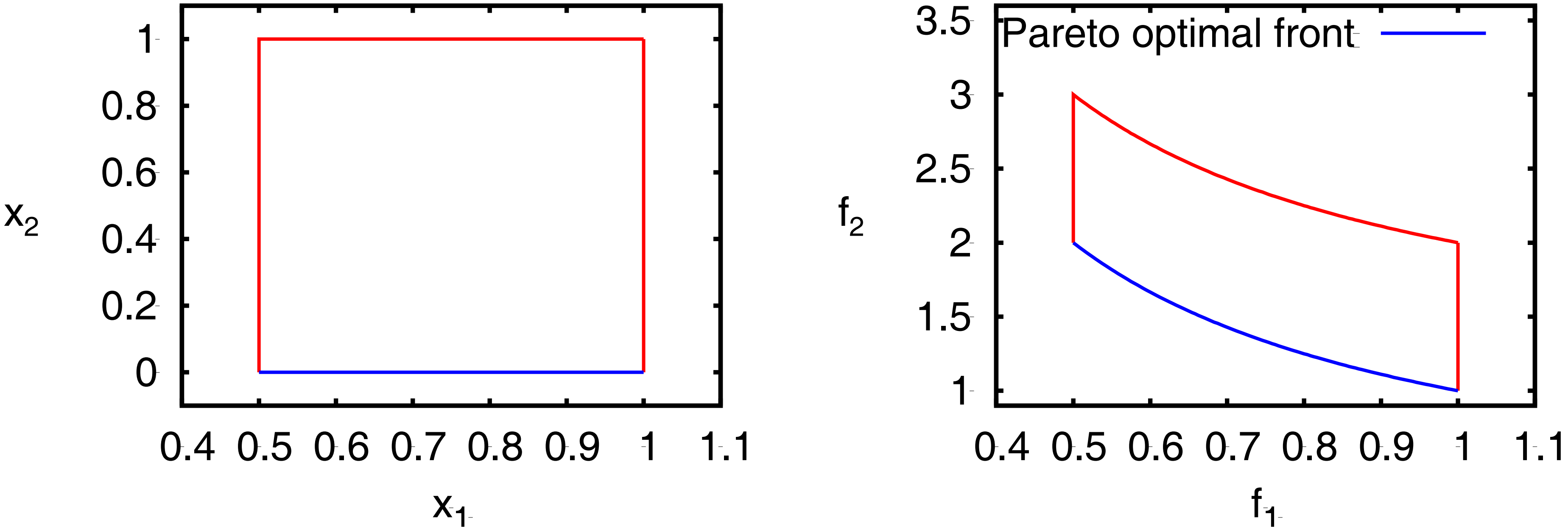
$0 \le x_2 \le 1$

Decision variable bounds constraints

Multi-Objective Example 1

Decision space: x_2 vs. x_1 (red and blue box and interior)

Search space: f_2 vs. f_1 (red and blue structure and interior)



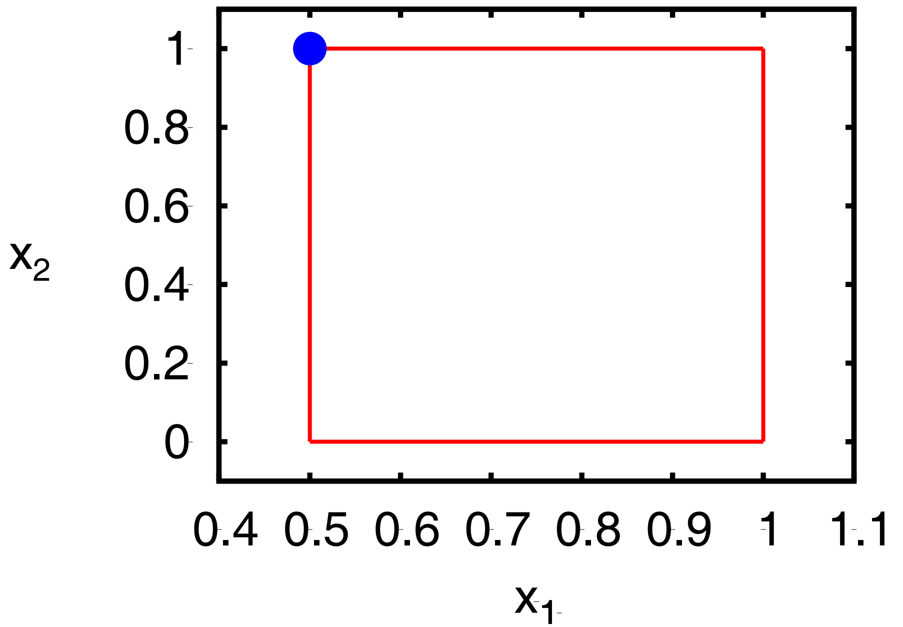
$$\begin{aligned} &\text{Minimize} && f_1(x_1, x_2) = x_1 \\ &\text{Minimize} && f_2(x_1, x_2) = \frac{1}{x_1} + x_2 \\ &\text{subject to} && 0.5 \le x_1 \le 1 \\ & && 0 \le x_2 \le 1 \end{aligned}$$

Two conflicting objectives

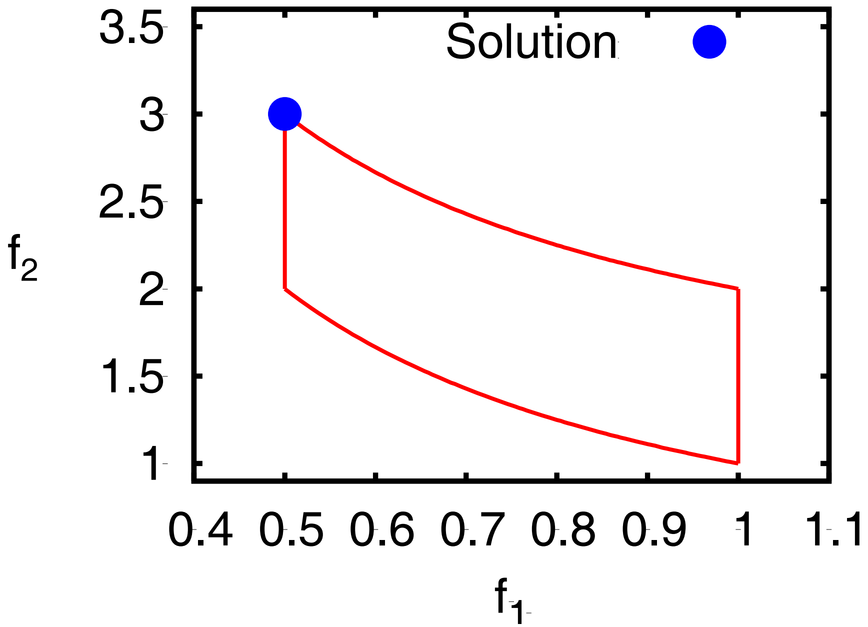
Decision variable bounds constraints

Multi-Objective Example 2

Decision space: x_2 vs. x_1
(red box and interior)



Search space: f_2 vs. f_1
(red structure and interior)



Minimize $f_1(x_1, x_2) = x_1$

Maximize $f_2(x_1, x_2) = \frac{1}{x_1} + x_2$

subject to $0.5 \le x_1 \le 1$

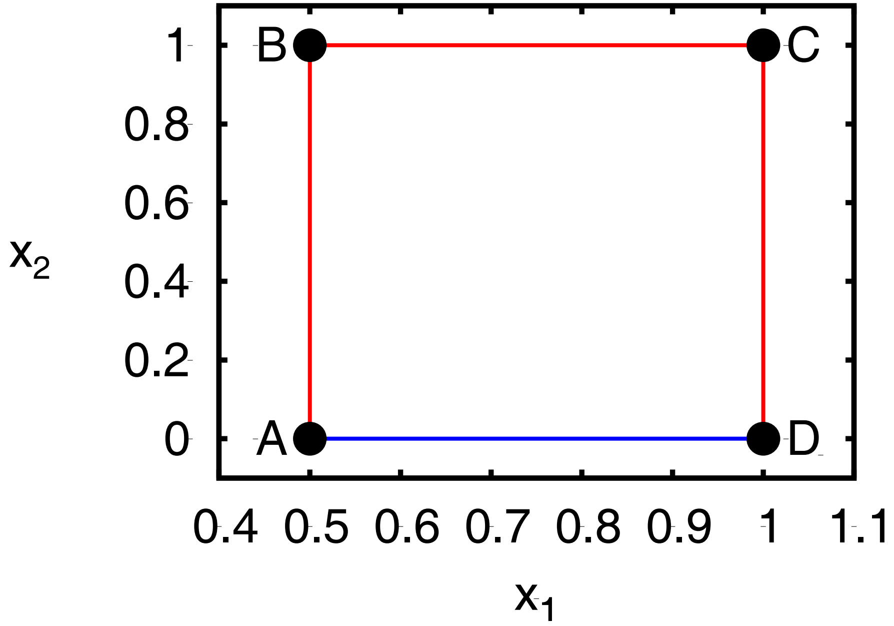
$0 \le x_2 \le 1$

Objectives do not conflict

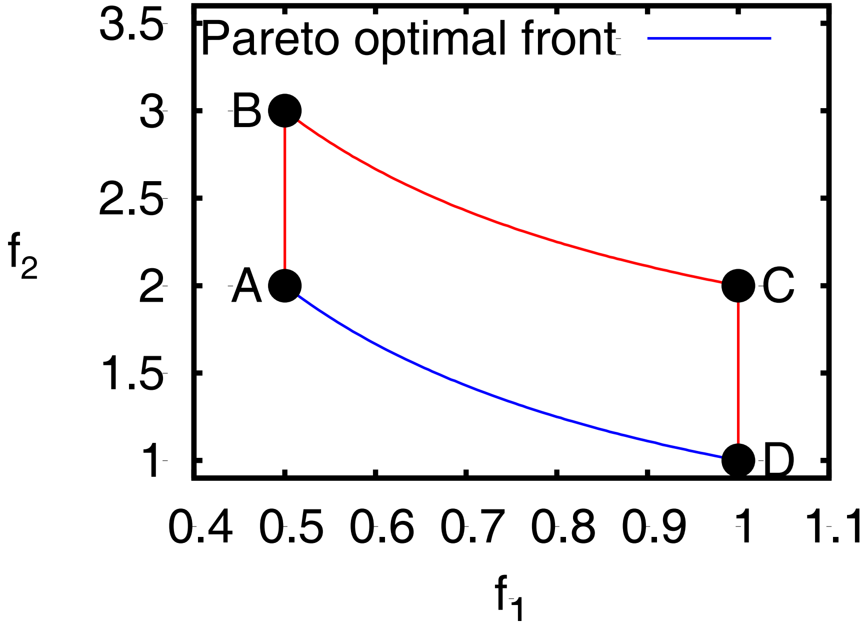
Decision variable bounds constraints

Multi-Objective Example 1

Decision space: x_2 vs. x_1



Search space: f_2 vs. f_1



- Dominance
  - An individual dominates another if it is better in at least one objective and no worse in the remainder
  - "Better" = "<" and "no worse" = "≤" for minimization
- Pareto optimality
  - Trade-offs between objectives
  - Non-dominated individuals that dominate at least one other individual

- For A, B, C, and D in f_2 vs. f_1
  - A dominates B and C but not D
  - D dominates C but not A and B
  - B and C do not dominate
  - A and D are non-dominated

  - Blue curve is Pareto optimal front
  - A and D are on the Pareto optimal front

Comparison to Standard Techniques

Iterative derivative based method

- Local optima
- Serial

Systematic parameter scan

- Global optima
- Parallelizable

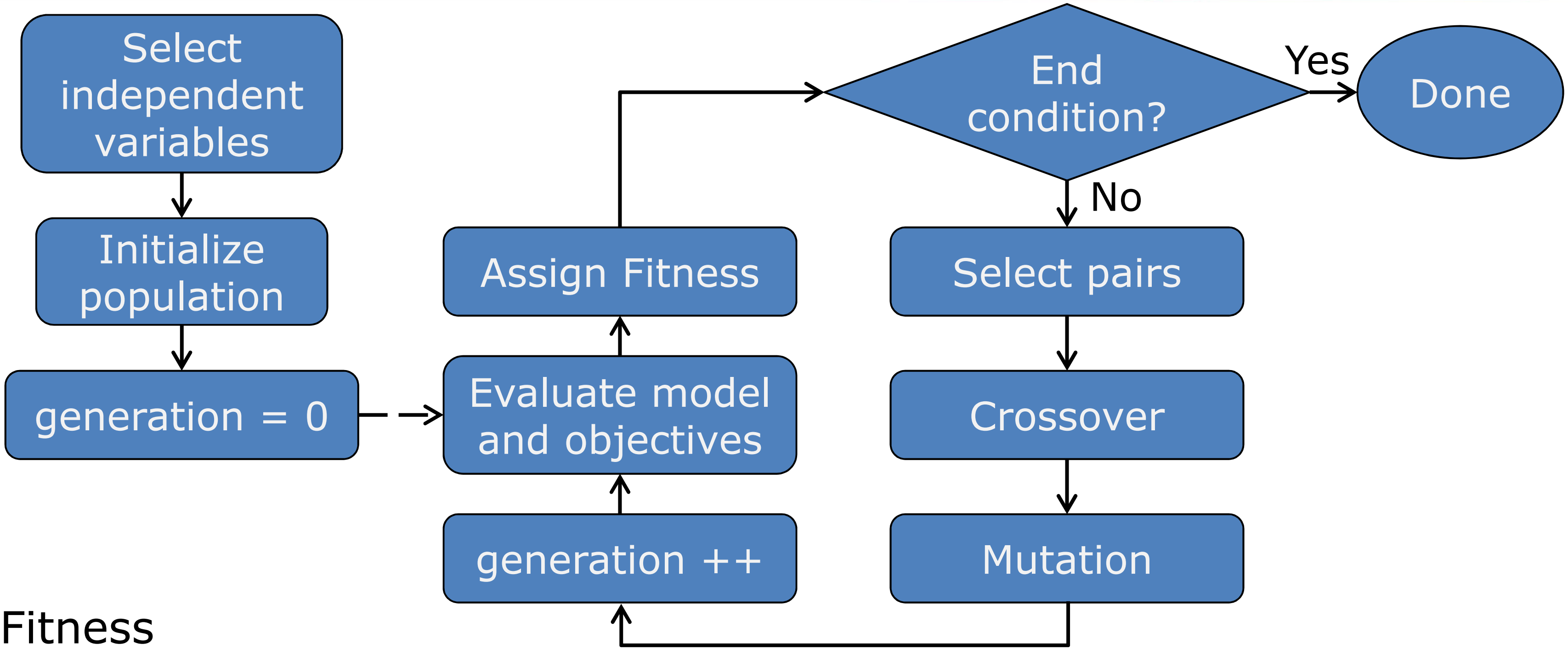
Genetic and Evolutionary Algorithms:

- Iterate through generations (new populations)
- Do not need/use derivatives
- Randomness in variable changes provides a mechanism to escape local optima

- Capable of locating global optima
- Interleave sampling parameter space and analyzing objective values
- Parallelizable

Genetic and Evolutionary Algorithms = smart parameter scans

General Processing Flow



Select independent variables

Initialize population

generation = 0

Evaluate model and objectives

Assign Fitness

End condition?

Yes

Done

No

Select pairs

Crossover

Mutation

generation ++

- Fitness
  - Function of objectives
  - Rank individuals
- Selection
  - Fitness-based competition
- Elitism
  - Preferential treatment for best individuals

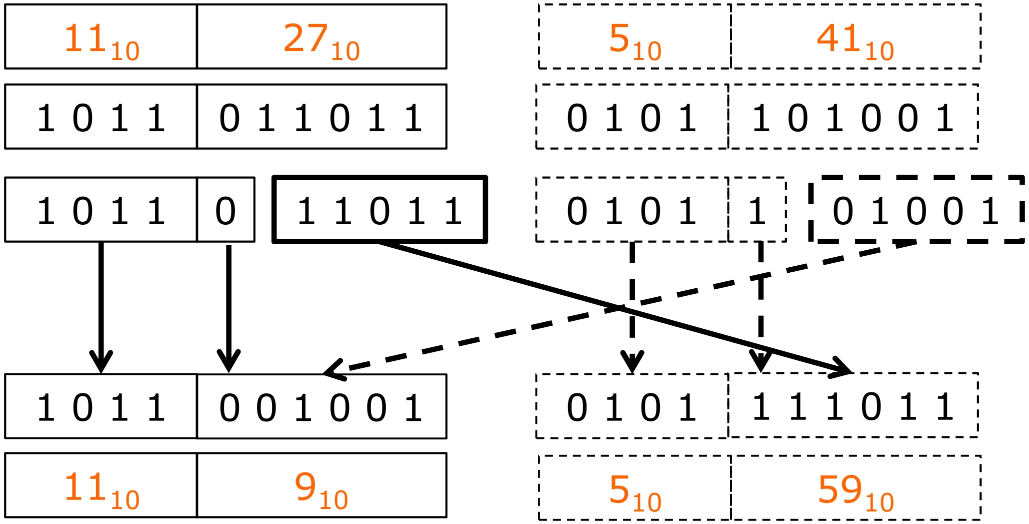
- Single-objective algorithm
  - Differential Evolution (DE) (R. Storn & K. Price, J. Global Optimization 11, 1997)
- Multi-objective algorithms
  - Elitist DE (J. Qiang et al, IPAC, 2013)
  - Non-dominated Sorting Genetic Algorithm II (NSGA-II) (K. Deb, IEEE Trans. Evolutionary Computing 6, 2002)
  - Strength Pareto Evolutionary Algorithm 2 (SPEA2) (E. Zitzler et al, EUROGEN, 2001)

Crossover or Recombination

Genetic Algorithm
Binary encoded strings

parent-1 2-gene chromosome

parent-2 2-gene chromosome



parent-1: 11_{10} | 27_{10}

1 0 1 1 | 0 1 1 0 1 1

1 0 1 1 | 0 | 1 1 0 1 1

parent-2: 5_{10} | 41_{10}

0 1 0 1 | 1 0 1 0 0 1

0 1 0 1 | 1 | 0 1 0 0 1

offspring-1: 1 0 1 1 | 0 0 1 0 0 1

11_{10} | 9_{10}

offspring-2: 0 1 0 1 | 1 1 1 0 1 1

5_{10} | 59_{10}

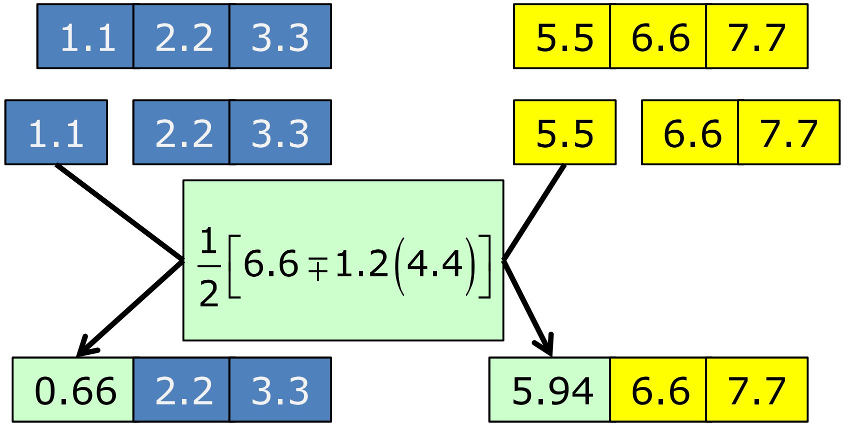
offspring-1 2-gene chromosome

offspring-2 2-gene chromosome

Evolutionary Algorithm
Real-valued vectors

parent-1 3-element decision vector

parent-2 3-element decision vector



1.1 | 2.2 | 3.3

5.5 | 6.6 | 7.7

1.1 | 2.2 3.3

5.5 | 6.6 7.7

$$\frac{1}{2}\left[6.6 \mp 1.2\left(4.4\right)\right]$$

0.66 | 2.2 | 3.3

5.94 | 6.6 | 7.7

offspring-1

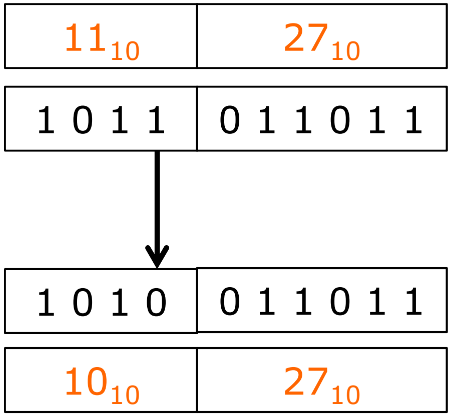
offspring-2

Probability density function
(Optionally, swap vector elements)

Mutation

Genetic Algorithm
Binary encoded strings

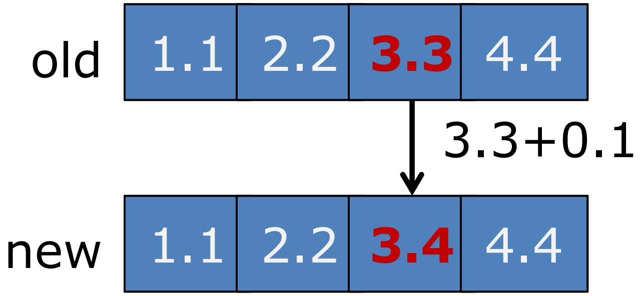
2-gene chromosome



Mutated 2-gene chromosome

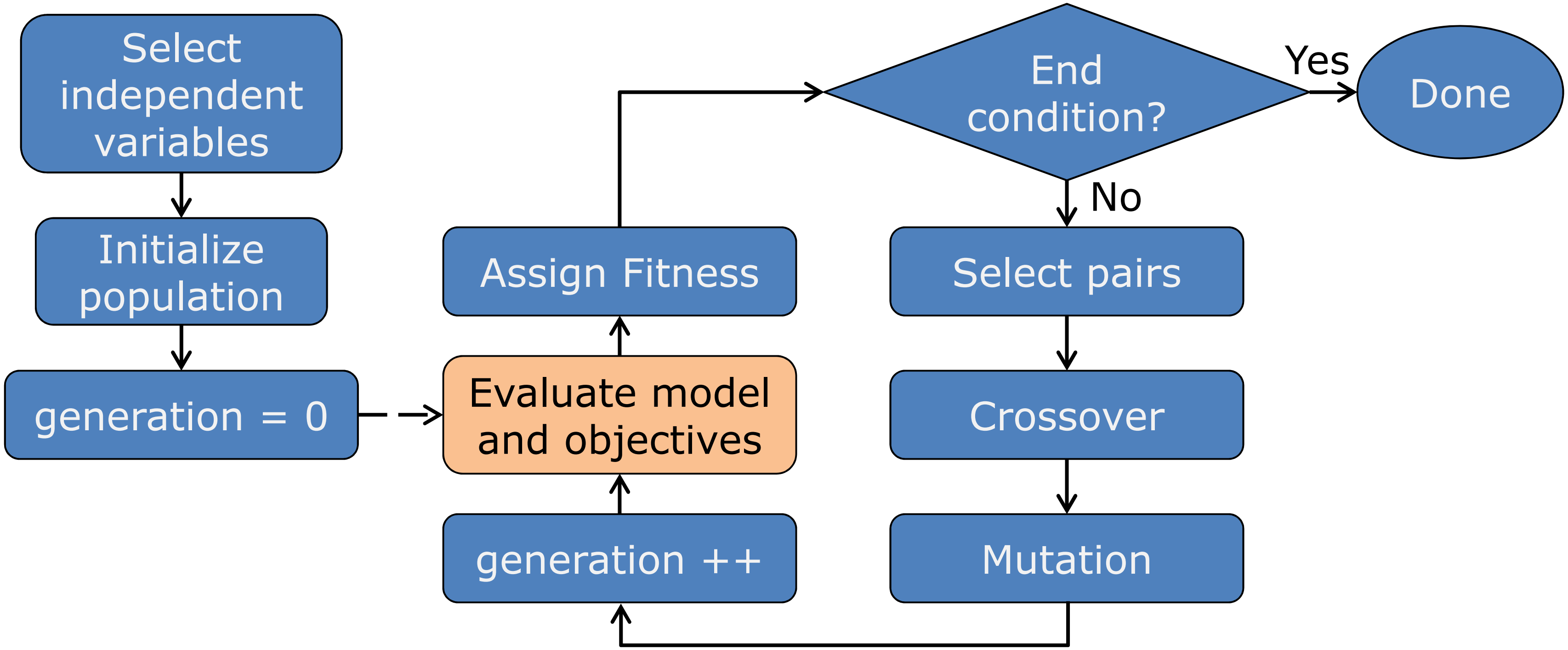
Evolutionary Algorithm
Real-valued vectors

4-element decision vector



Probability density function

Tools



Select independent variables

Initialize population

generation = 0

Evaluate model and objectives

Assign Fitness

End condition?

Yes

Done

No

Select pairs

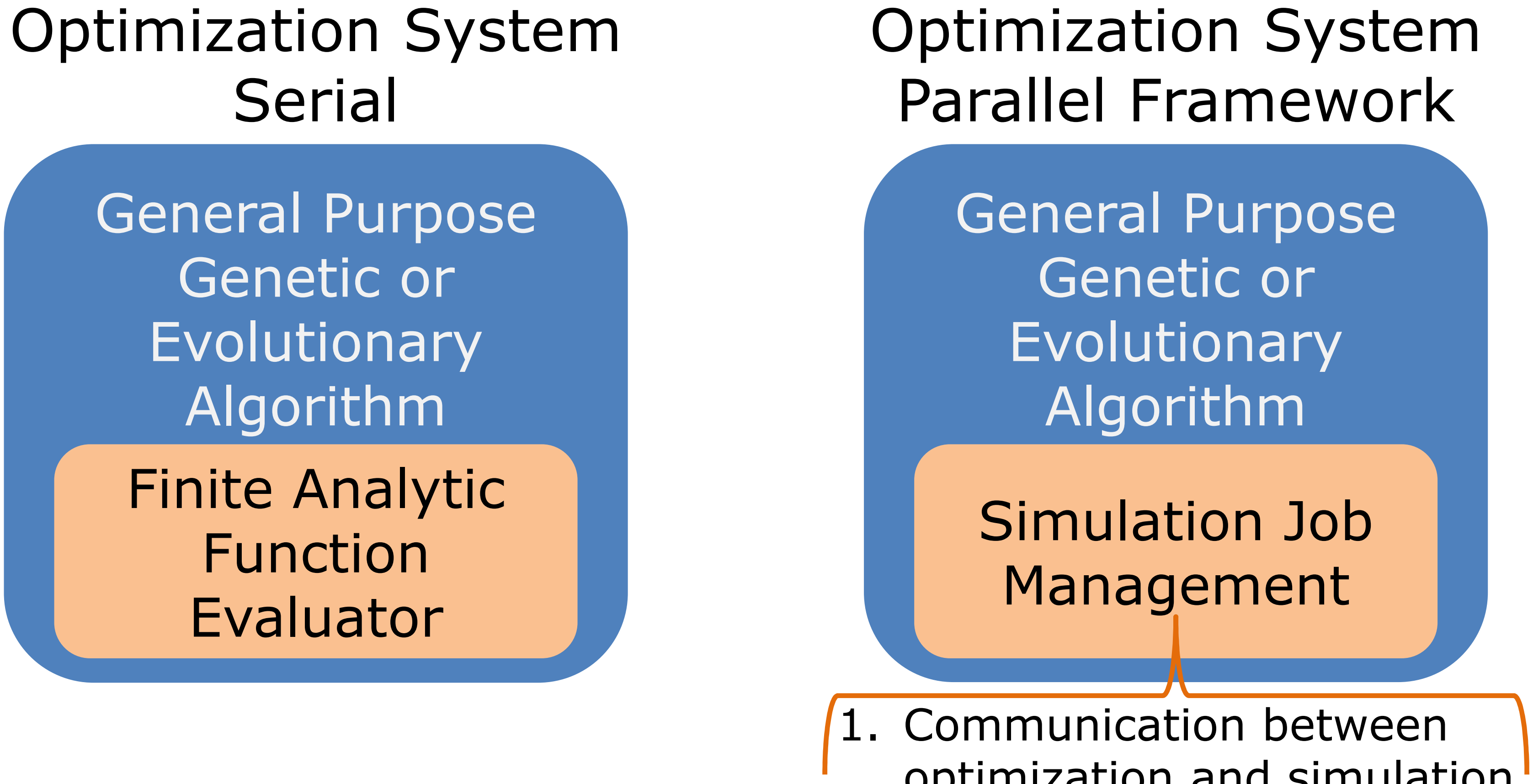
Crossover

Mutation

generation ++

Tools

Model execution time
Serial vs. parallel evaluation of population individuals



Optimization System
Serial

General Purpose Genetic or Evolutionary Algorithm

Finite Analytic Function Evaluator

Optimization System
Parallel Framework

General Purpose Genetic or Evolutionary Algorithm

Simulation Job Management

1. Communication between optimization and simulation
2. Simulation job dispatch

Tools

Tool	Lab	Features	Algorithm
Alternate PISA* (I.V. Bazarov & C.K. Sinclair, PRST-AB 8, 2005)	Cornell University	Interface to ASTRA Particle distribution generation	SPEA2 NSGA-II
APISA variant (C. Gong & Y.-C. Chao, ICAP, 2012)	TRIUMF	General purpose Objectives derived from multiple sources Parallel and concurrent simulations	SPEA2
APISA variant (A. Hofler et al, PRST-AB 16, 2013)	Jefferson Lab	Interfaces to ASTRA and Poisson Superfish Straight line RF gun cavity description	SPEA2
APISA variant (A. Hofler et al, PRST-AB 16, 2013)	Jefferson Lab	General purpose Script-based	SPEA2
geneticOptimizer (M. Borland & H. Shang, 2007)	ANL	General purpose Script-based	NSGA-II
OPT-PILOT (A. Adelmann et al, ICAP, 2012)	PSI	General purpose Generalized job dispatch system Python GUI to view fronts	NSGA-II

*PISA=A Platform and Programming Language Independent Interface for Search Algorithms, S. Bleuler et al, Evolutionary Multi-Criterion Optimization, 2003.

Tools

Simulation suite	Lab	Algorithm
TAO (D. Sagan & J.C. Smith, PAC, 2005)	Cornell University	Differential Evolution
COSY-GO (K. Makino & M. Berz, ICAP, 2006)	MSU	Custom
G-optimizer in TRACK (B. Mustapha & P.N. Ostroumov, ICAP, 2009)	ANL	SPEA2
GeneticTRACY (C. Sun et al, PAC, 2011)	LBNL	NSGA-II
elegant MOGA (M. Borland, APS LS-287, 2000)	ANL	NSGA-II
Symbolic beam propagator (S.N. Andrianov et al, IPAC, 2011)	St. Petersburg State University	Custom

- **Libraries: PGAPack** (D. Levine, ANL-95/18, 1996) and **pikaia** (P. Charbonneau & B. Knapp, NCAR/TN-418+IA, 1995)
- **Sources for large numbers of computing nodes:**
  - Analysis farms
  - High performance computing clusters
  - Underutilized desktop computers (**APISA** and **Condor** (J.D.A. Smith et al, PAC, 2009))
  - Cloud computing

Beamline Component Design

Superconducting magnet coil design tool

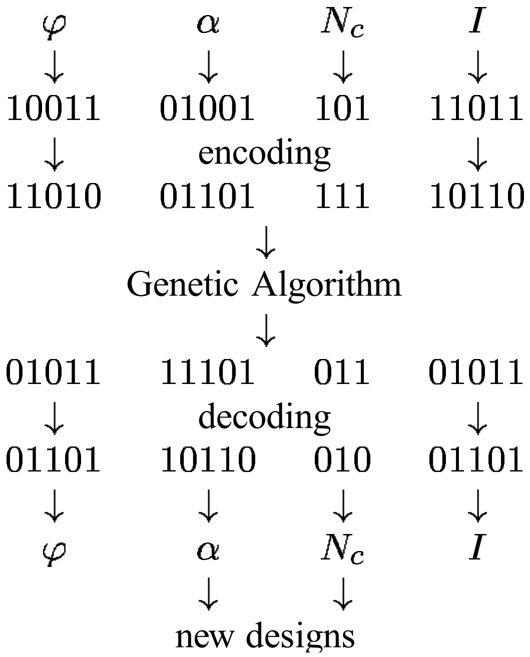
- Pareto optimality

N_c=number of turns per coil block

α=block positioning

φ=inclination angles of the blocks

I=current in each turn (to guarantee solutions do not exceed load-line limit of superconducting wires (depends on local magnetic field))



$\varphi \quad \alpha \quad N_c \quad I$

↓ ↓ ↓ ↓

10011 01001 101 11011

↓ encoding ↓

11010 01101 111 10110

↓

Genetic Algorithm

↓

01011 11101 011 01011

↓ decoding ↓

01101 10110 010 01101

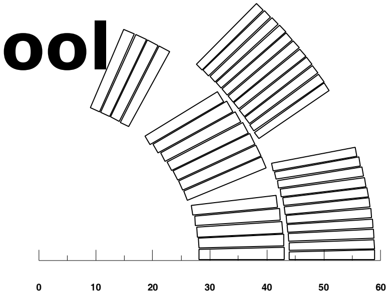
↓ ↓ ↓ ↓

$\varphi \quad \alpha \quad N_c \quad I$

↓ ↓

new designs

Gray Encoding



5-block alternative to the classical 5 block design

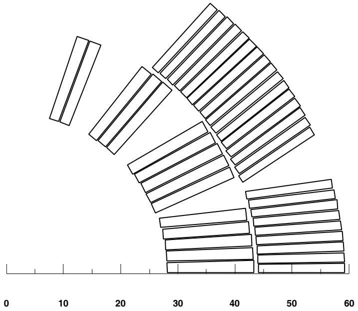


Figure 6: 6-block (40 turns) design (V6-1)

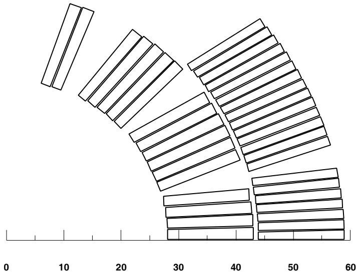
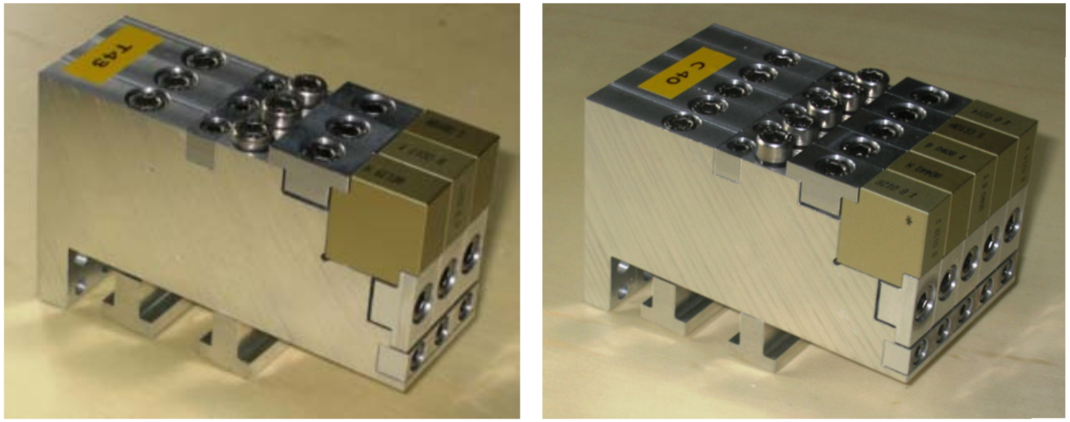


Figure 7: 6-block (38 turns) design (V6-3)

S. Ramberger & S. Russenschuck, EPAC, 1998

Beamline Component Design



3 and 5 magnet modules for APPLE undulator

Shimming results for a SOLEIL APPLE-II undulator

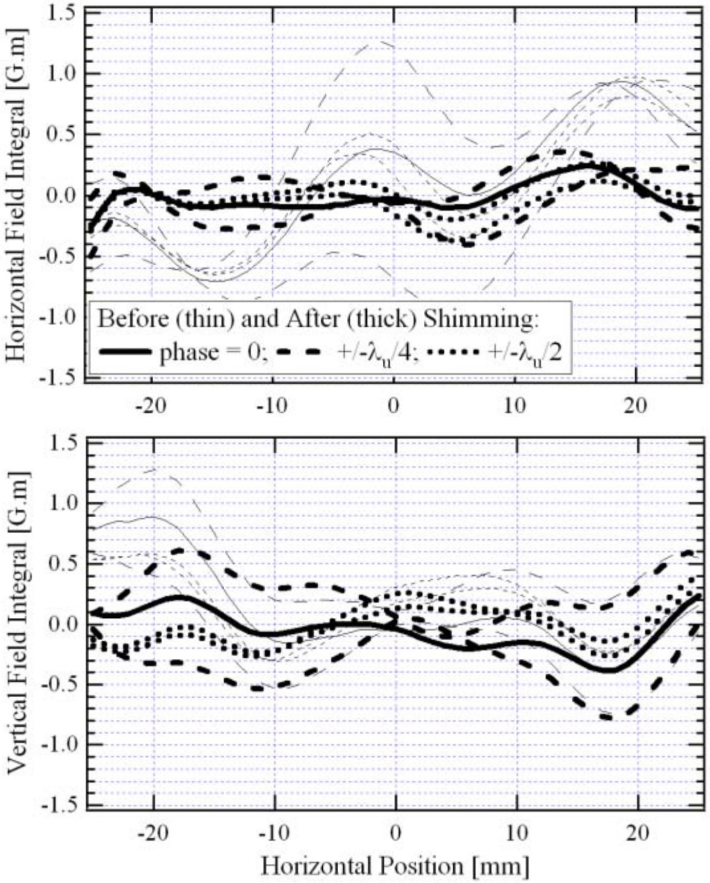


Figure 4: Horizontal and vertical field integrals before and after “virtual” shimming of HU52-LUCIA.

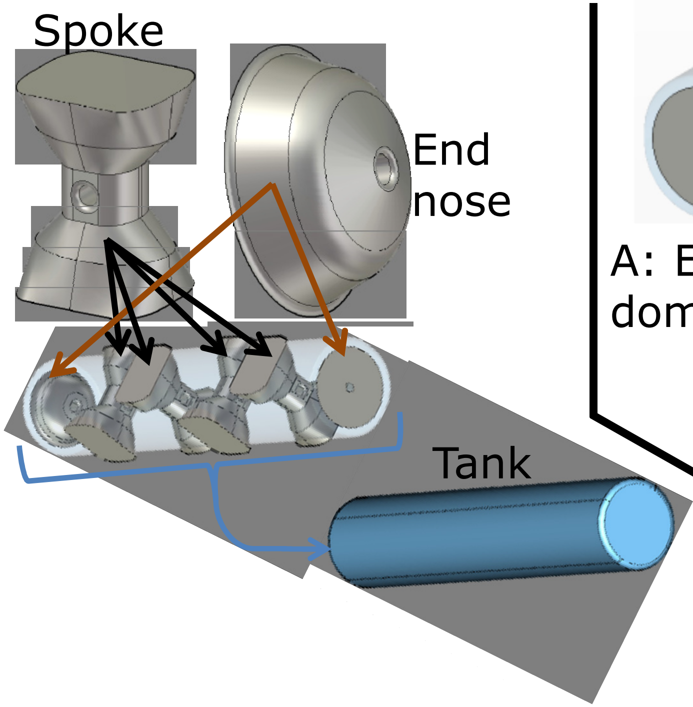
Wiggler/Undulator construction

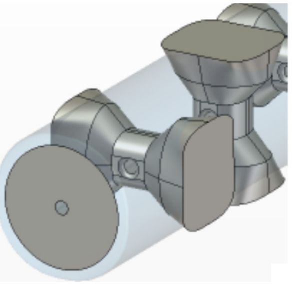
- Component magnet
  - ordering
  - shimming (transverse displacements)
  - magic fingers (trim magnet) adjustments
- SOLEIL, FERMI@Elettra, CLIO

R. Hajima et al, NIMA 318, 1992
F. Briquez et al, EPAC, 2006
M. Musardo et al, EPAC, 2008
O. Chubar et al, EPAC, 2008
J.-M. Ortega et al, IPAC, 2012

Beamline Component Design

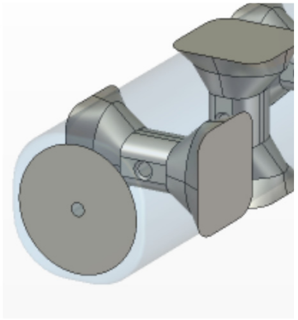
Spoke cavity

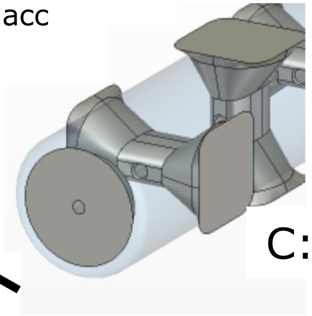




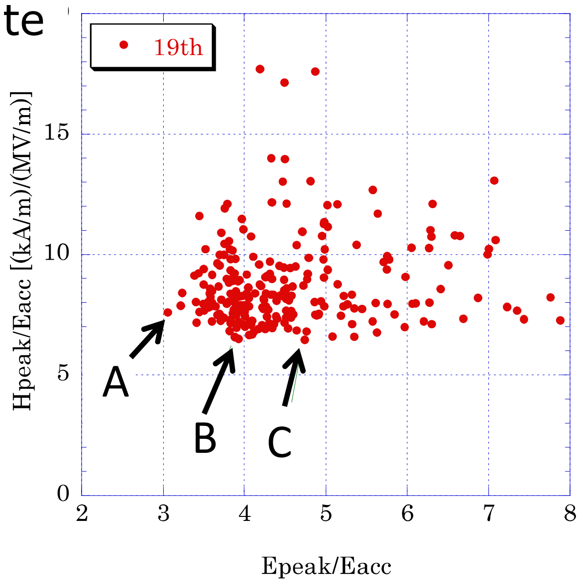
A: E_{peak}/E_{acc} dominant

B: Intermediate

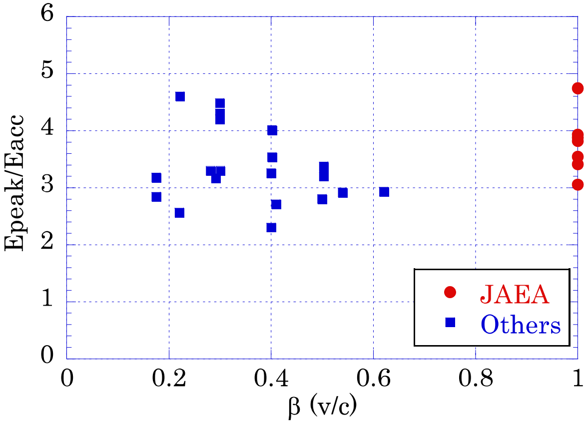


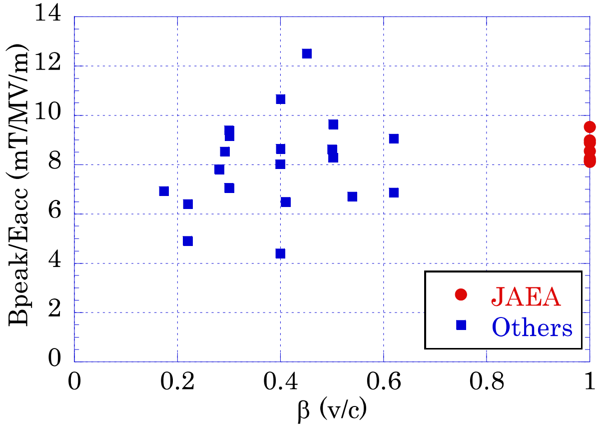


C: H_{peak}/E_{acc} dominant



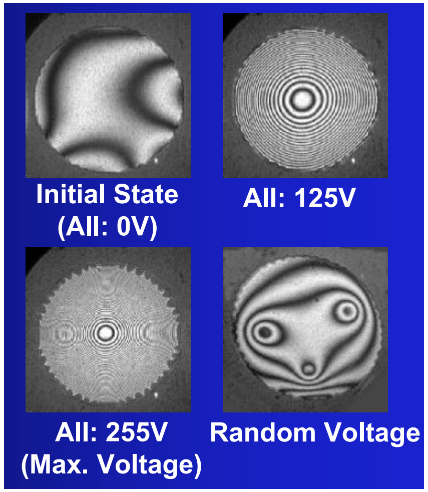
Optimized β=1 geometries (red) comparable to existing β<1 designs (blue)



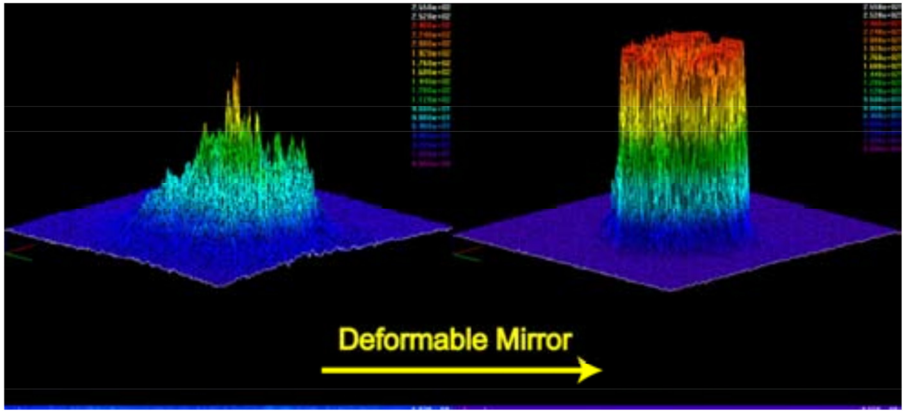


M. Sawamura et al, SRF, 2011

Real Time and Diagnostic Uses



Deformable mirror patterns for various control voltage settings



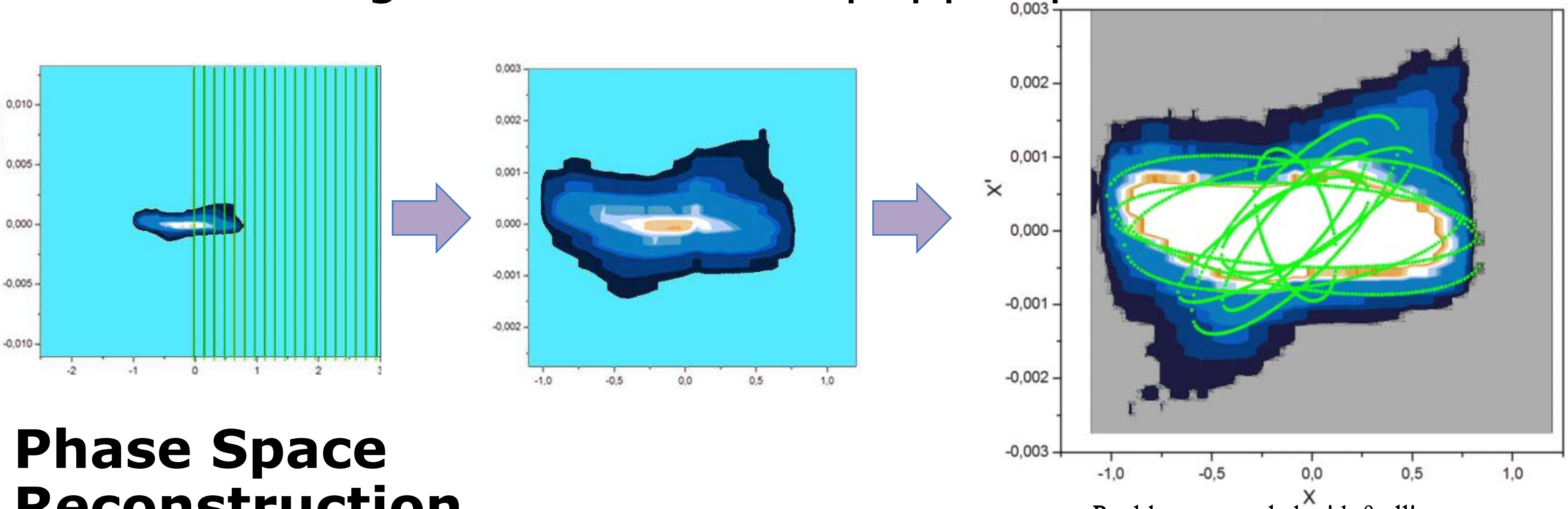
Spatial laser profile shaping

- **Spatial laser profile shaping**
  - Genetic algorithm to control deformable mirror
    - 59 mirror actuators = 59 control voltages (0-255 V)
  - Fitness function: weighted sum of 9 features from measured laser profile and calculated beam characteristics
  - Gaussian or flattop profile
  - 1 hour to optimize

H. Tomizawa et al, LINAC, 2004
H. Tomizawa et al, FEL, 2007

Real Time and Diagnostic Uses

Emittance diagnostic: movable pepper pot



Real beam sampled with 8 ellipses

Phase Space Reconstruction

- Beam is an ensemble of sub-beams of different intensity
  - Model in projected phase space as union of N ellipses
- Intensity distribution
- Variables
  - Twiss parameters for N ellipses
  - Centroid position
- Maximize
  - Intensity/f(geometric emittance area)

A. Bacci, SPARC/EBD-07/004, 2007
E. Chiadroni, FEL, 2007

Operational Settings

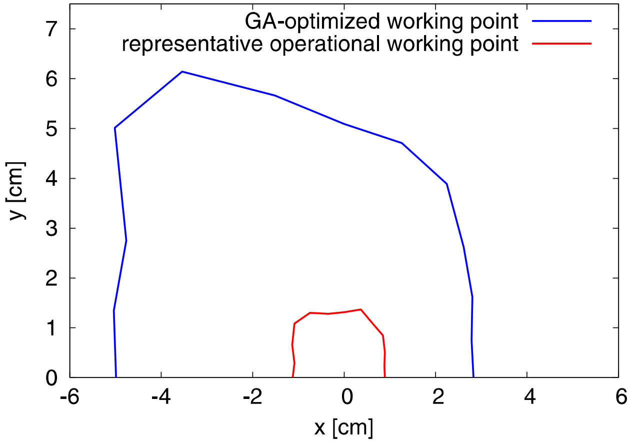
- Given a machine design (layout), four main uses for Genetic and Evolutionary Algorithms
  - Establish performance of design
  - Demonstrate a technology is suited for an application
  - Improve performance of existing machine
  - Determine settings to avoid operational problems

Operational Settings

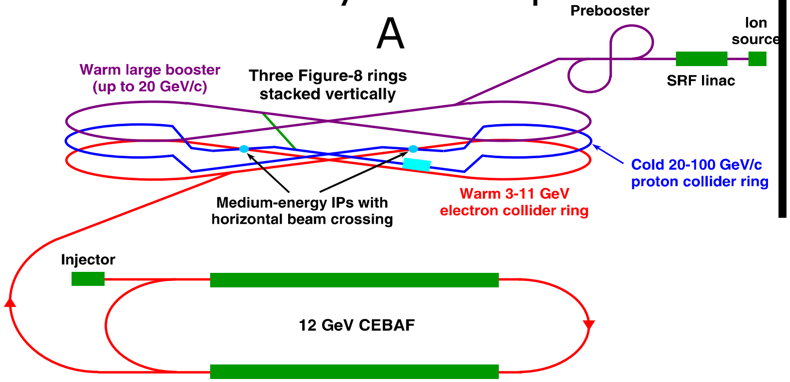
Establish performance:

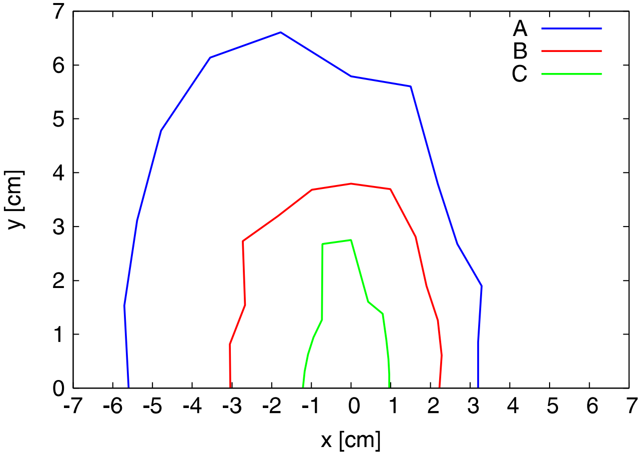
Collider ring dynamic aperture and momentum acceptance

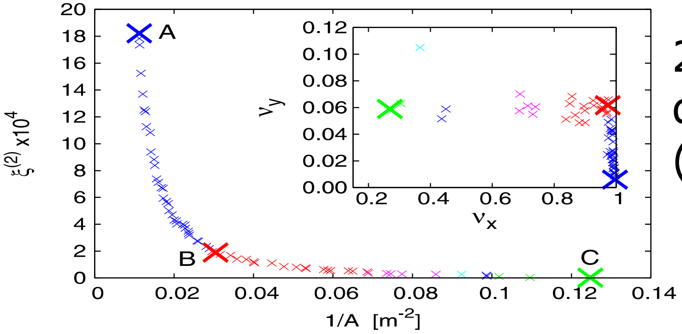
Vary betatron tunes for the beam (ν_x,ν_y)



Single objective:
Maximize dynamic aperture A







Two objectives:

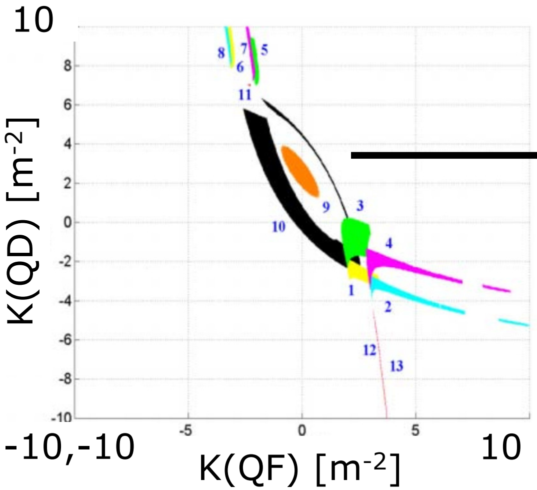
1. Maximize momentum acceptance to minimize 2nd-order chromatic function ξ^2
2. Maximize area of dynamic aperture *A* (minimize 1/*A*)

A.S. Hofler et al, PRSTAB 16, 2013

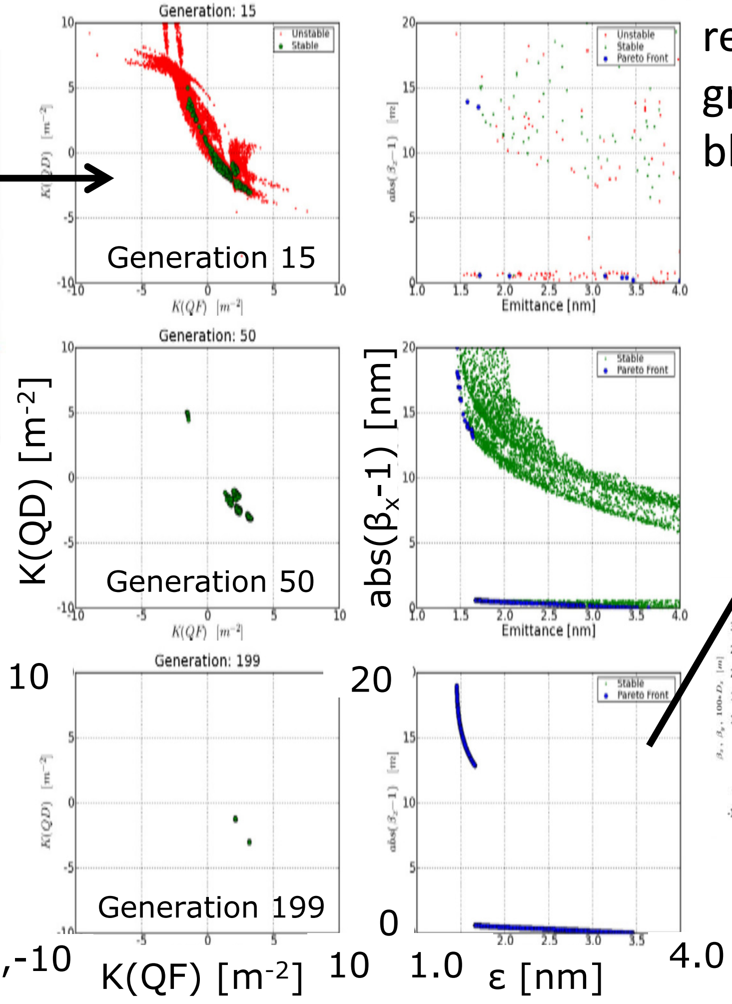
Operational Settings

Improve performance of existing machine:

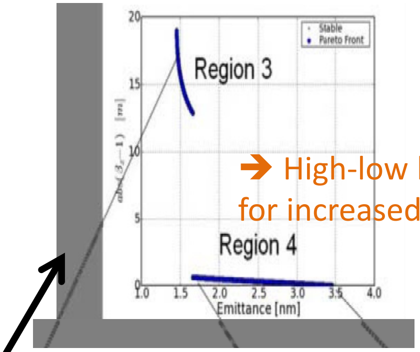
Optimizing magnetic lattice in a storage ring



GLobal Analysis of all Stable Settings (GLASS)

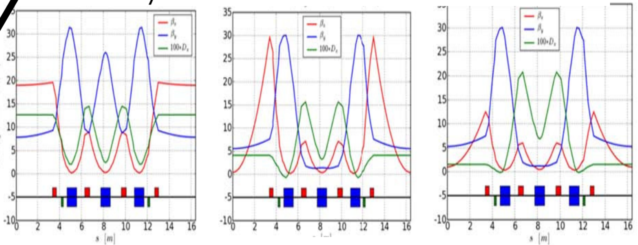


red: unstable
green: stable
blue: Pareto front



➔ High-low beta optics for increased brightness

β_x, β_y, 100*D_x [m] -10-35 m



s [m] 0-16 m

red: β_x, blue: β_y, green: D_x

L. Yang et al, EPAC, 2008

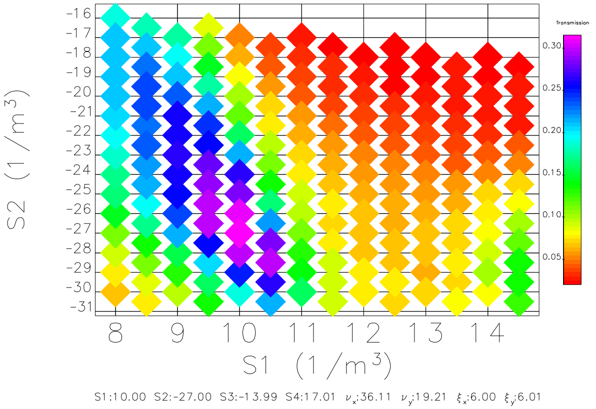
Operational Settings

Improve performance of existing machine:

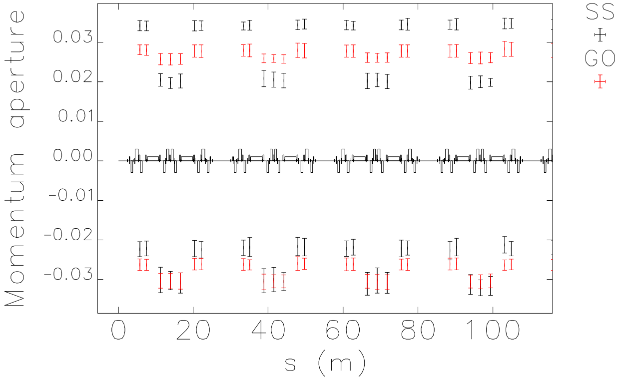
Optimizing dynamic and momentum apertures in a storage ring

Momentum aperture

Transmission

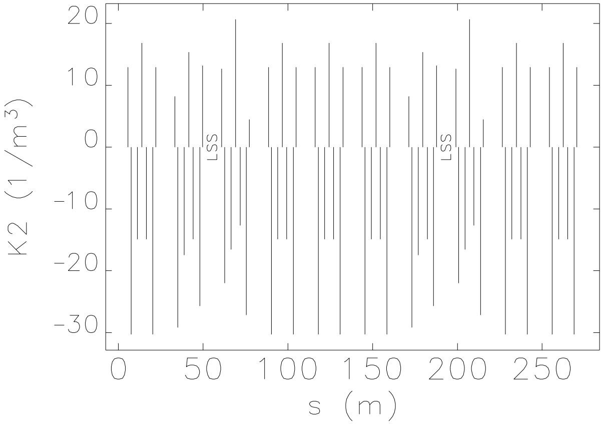


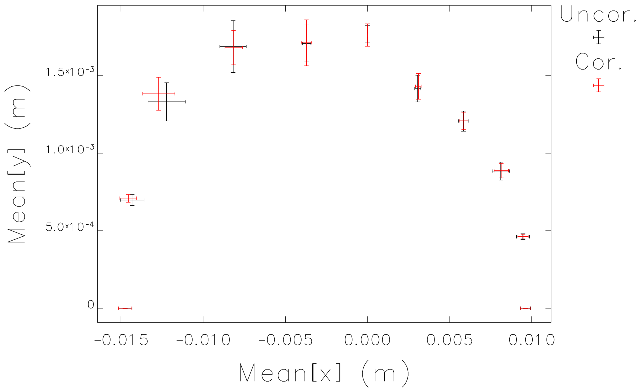
Sextupole scan



Sextupole scan and genetic optimization comparison

Dynamic aperture
Upgrade for long straight sections (LSSs)





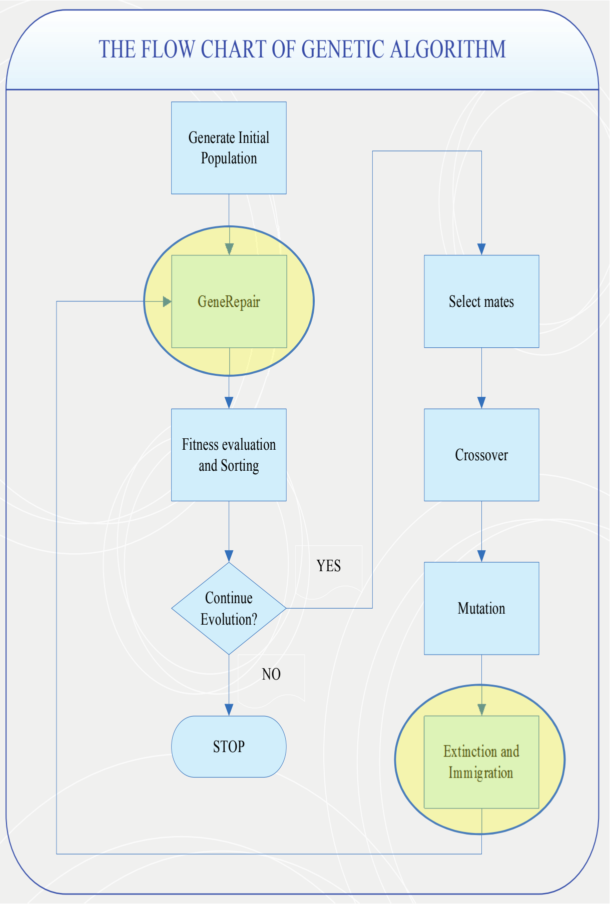
- APS lattice optimization: ~30% increase in lifetime
- LSS optimization: asymmetric sextupole distribution is useful and works
- Vet optimized solutions with realistic error ensembles
- Direct methods (based on particle tracking) for determining dynamic and momentum apertures

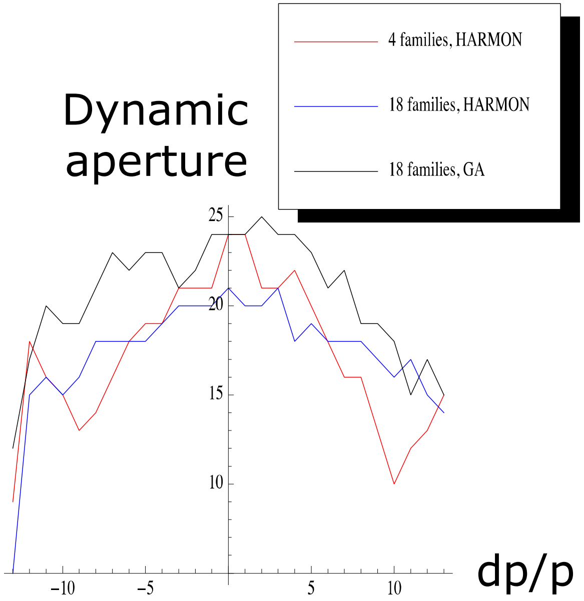
M. Borland et al, PAC, 2009

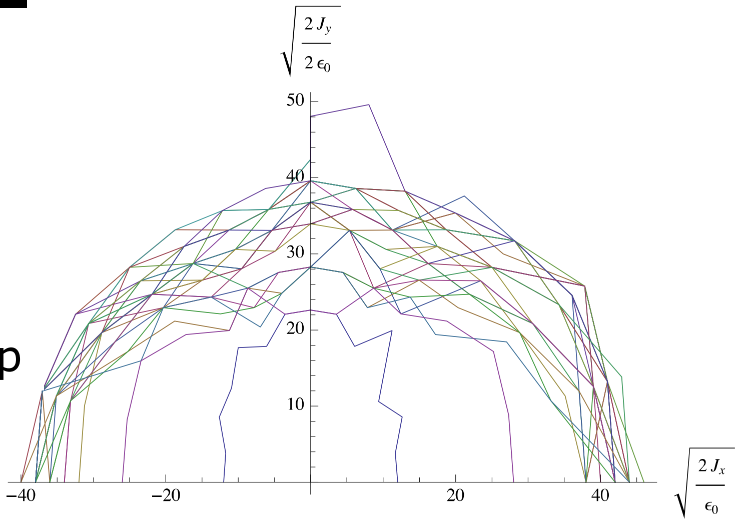
Operational Settings

Improve performance of existing machine:

Optimizing chromatic sextupoles in a storage ring




Dynamic aperture



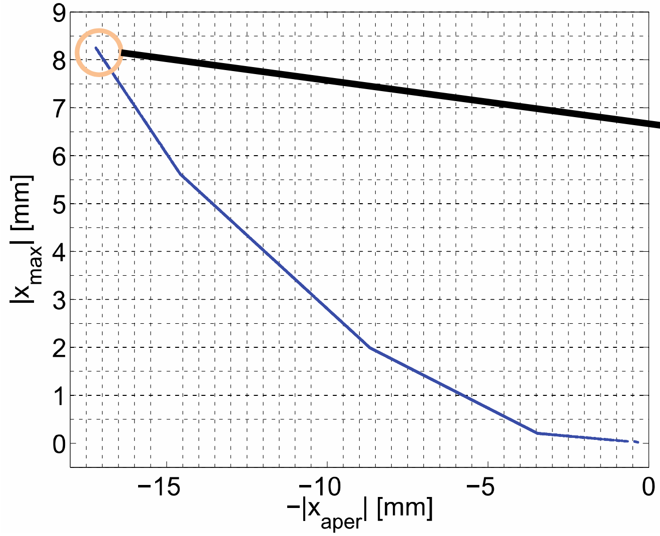
Dynamic aperture in transverse plane

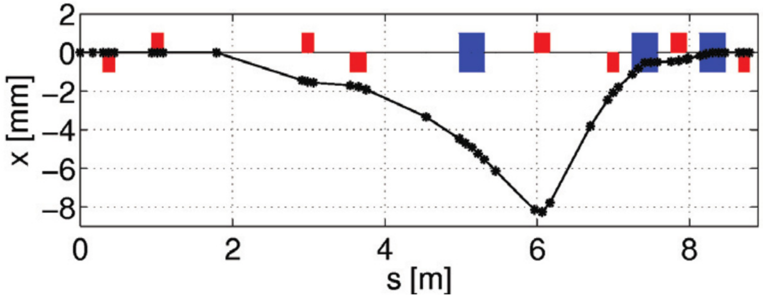
Z. Duan & Q. Qin, IPAC, 2011

Operational Settings

Avoid operational problems:

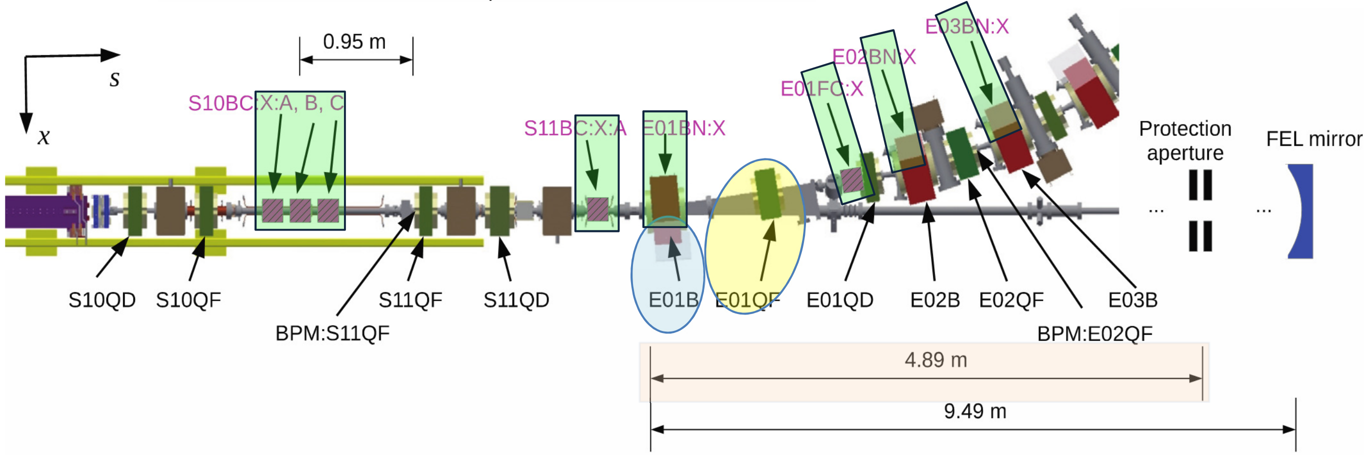
Orbit bump for free electron laser mirror protection





Two objectives:

1. Maximize $-|x_{aper}|=-|x_i+4.89\ [\mathrm{m}]x_i'|$
2. Minimize $|x_{max}|$

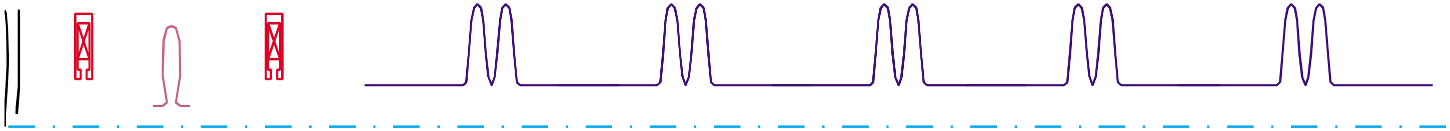


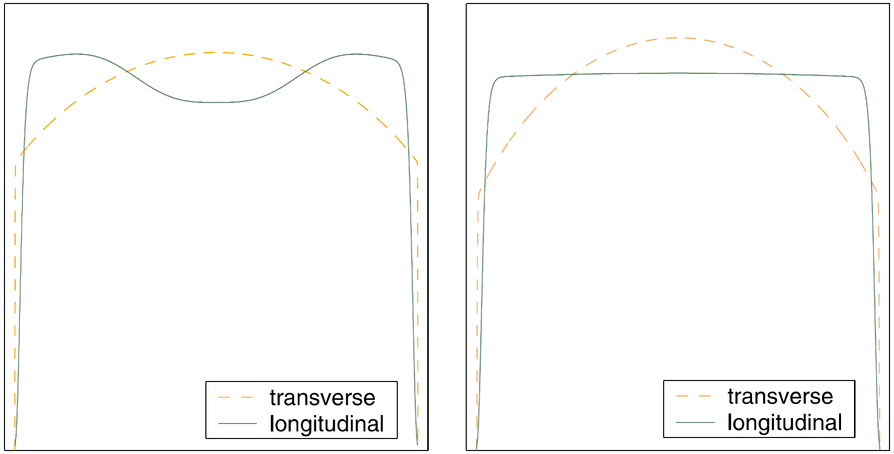
Constraints:
Maximum corrector magnet kick angles

H. Hao et al, IPAC, 2013

Combined Settings and Beamline Element Design

ERL injector: D.C. gun, solenoid, buncher, solenoid, 5 2-cell SC cavities





Initial particle distributions: 80 pC and 0.8 nC

- Vary
  - Particle distribution characteristics
  - Peak field for magnets and RF elements
  - RF phases
  - Relative element spacing
- Optimize beam properties
- Demonstrated power of Pareto optimality

I.V. Bazarov & C.K. Sinclair, PRSTAB 8, 2005

Parameter	Ref. [13]	This work	Units
Charge	80	80	pC
Laser spot size (rms)	0.6	0.3	mm
Laser pulse duration (rms)	20	11	ps
dc gun voltage	500	750	kV
Buncher voltage	116	126	kV
SRF cavity 1 gradient	9.8	5.5	MV/m
SRF cavities 2–5 gradient	7.2	10.6	MV/m
SRF cavity 1 phase	10	43	°
Solenoid 1 peak field	0.058	0.077	T
Solenoid 2 peak field	0.040	0.043	T
Solenoid 1 position	0.29	0.26	m
Solenoid 2 position	1.00	1.12	m
Buncher position	0.80	0.57	m
SRF cavity 1 position	1.80	1.90	m
Transverse emittance (rms)	0.82	0.14	mm mrad
Bunch length (rms)	0.80	0.78	mm
Longitudinal emittance (rms)	8.7	6.2	mm keV
Kinetic energy	10.6	12.6	MeV

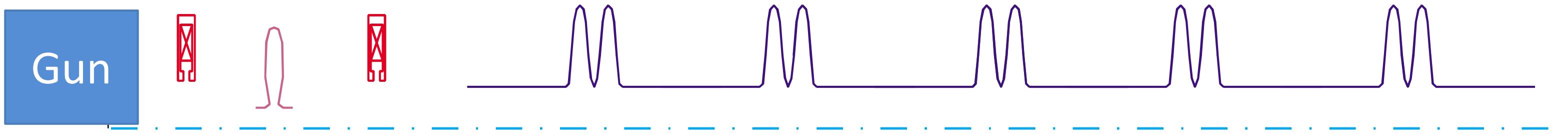
Damping ring design

- Create and compare optics designs fitting in a ring of a given circumference

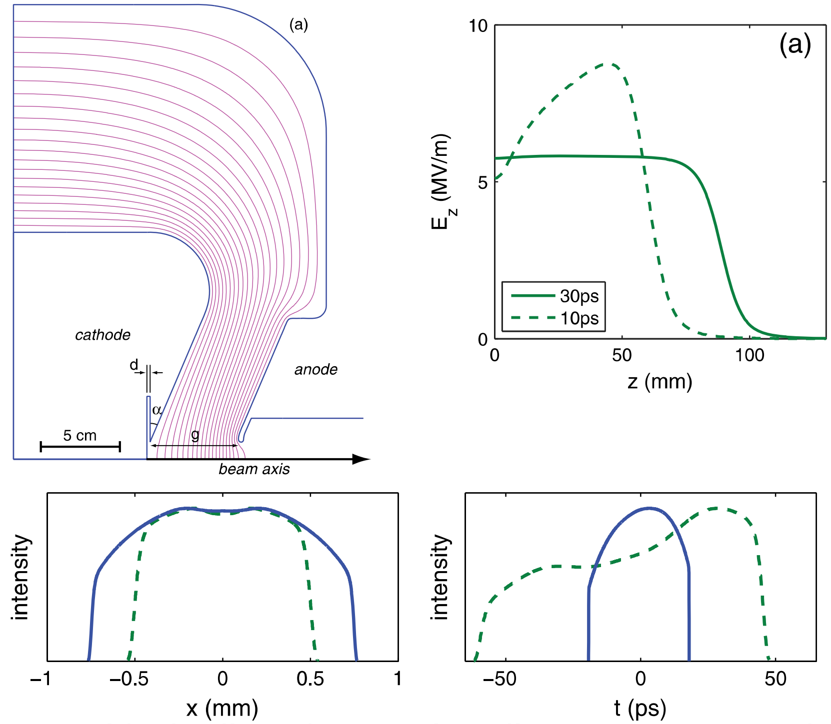
L. Emery, PAC, 2005

Combined Settings and Beamline Element Design

ERL injector: gun, solenoid, buncher, solenoid, 5 2-cell superconducting cavities

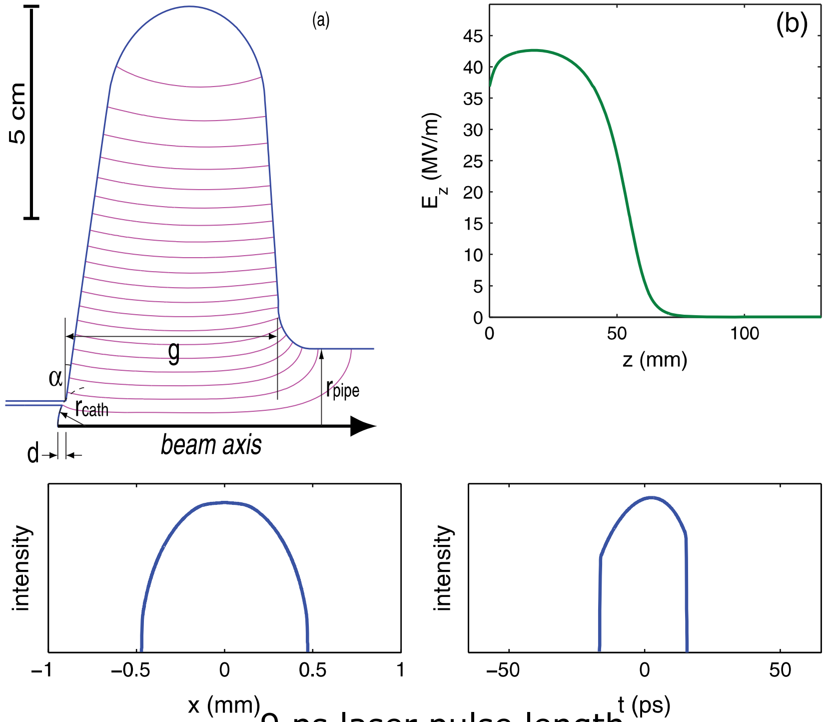


DC gun geometry



10 ps (dashed) and 30 ps (solid) laser pulse length

1-cell SRF gun geometry



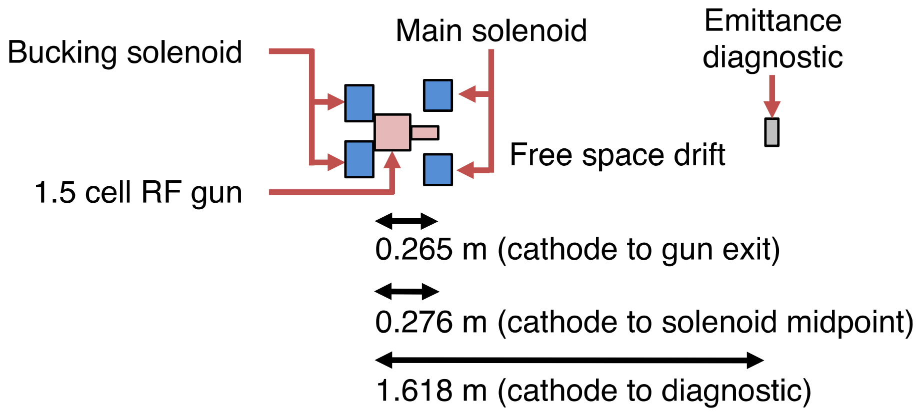
9 ps laser pulse length

I.V. Bazarov et al, PRSTAB 14, 2011

Combined Settings and Beamline Element Design

Radio frequency gun injector:

bucking solenoid (off), RF gun, solenoid, drift



Bucking solenoid

Main solenoid

Emittance diagnostic

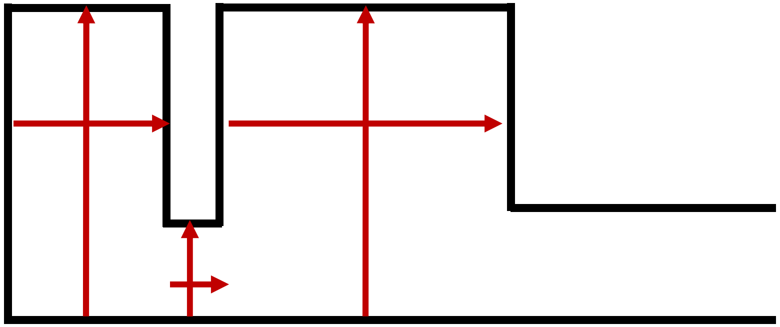
Free space drift

1.5 cell RF gun

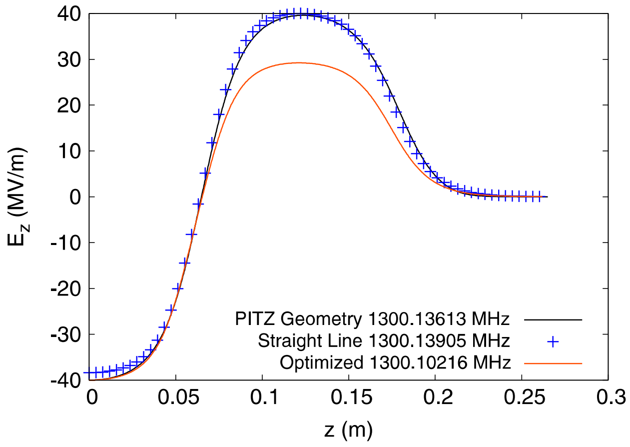
0.265 m (cathode to gun exit)

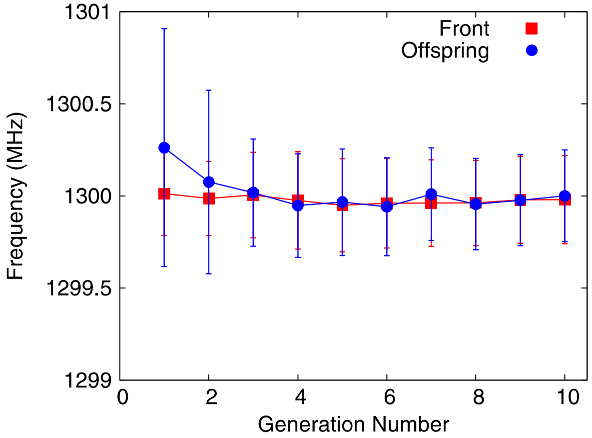
0.276 m (cathode to solenoid midpoint)

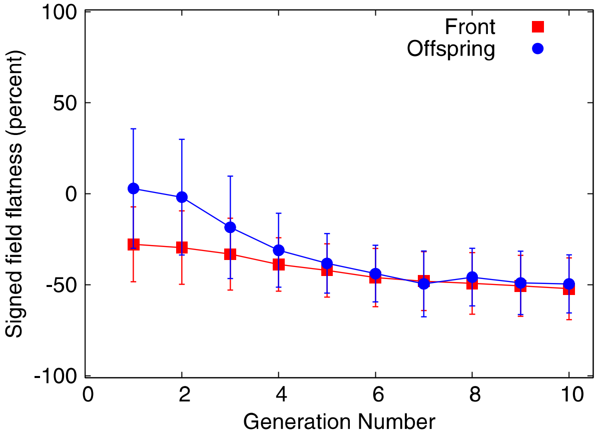
1.618 m (cathode to diagnostic)



Vary cavity dimensions and use inequality constraints to “tune” cavity



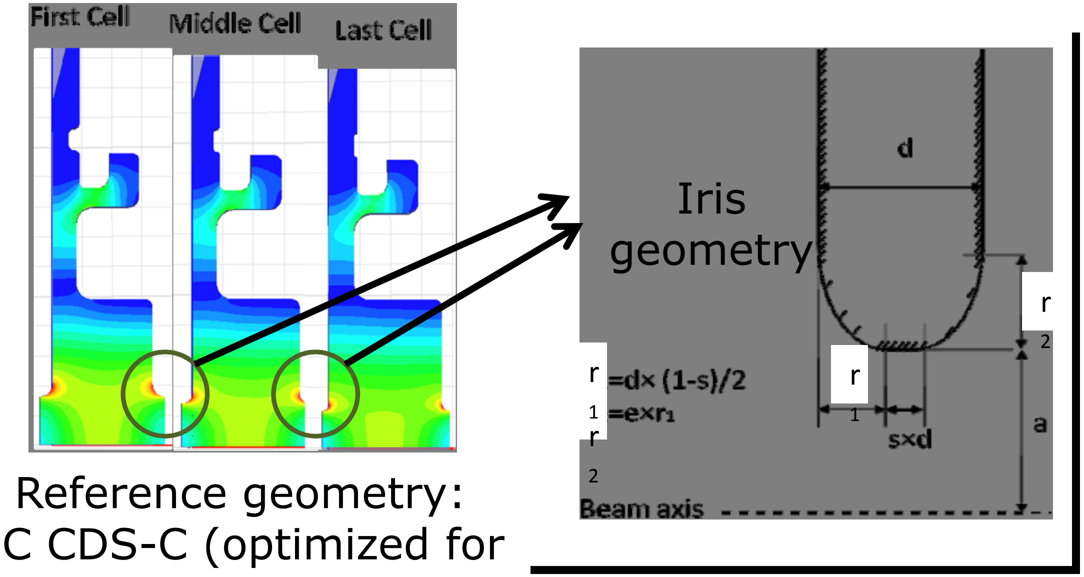




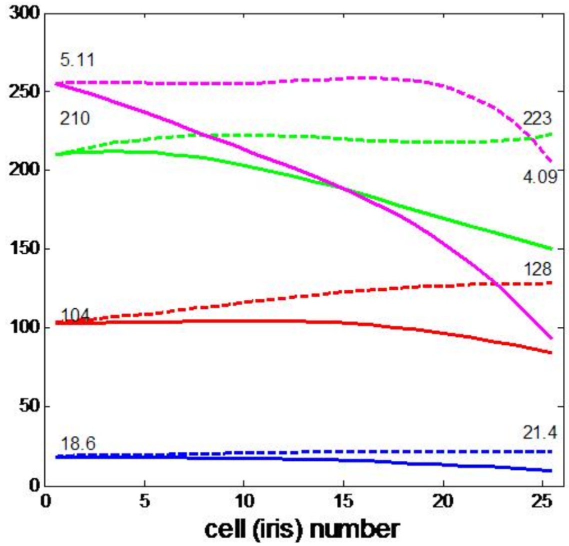
A.S. Hofler et al, PRSTAB 16, 2013

Combined Settings and Beamline Element Design

Choke-mode damped RF linac structure



Reference geometry:
CLIC CDS-C (optimized for higher order mode damping)
24 cells in a unit



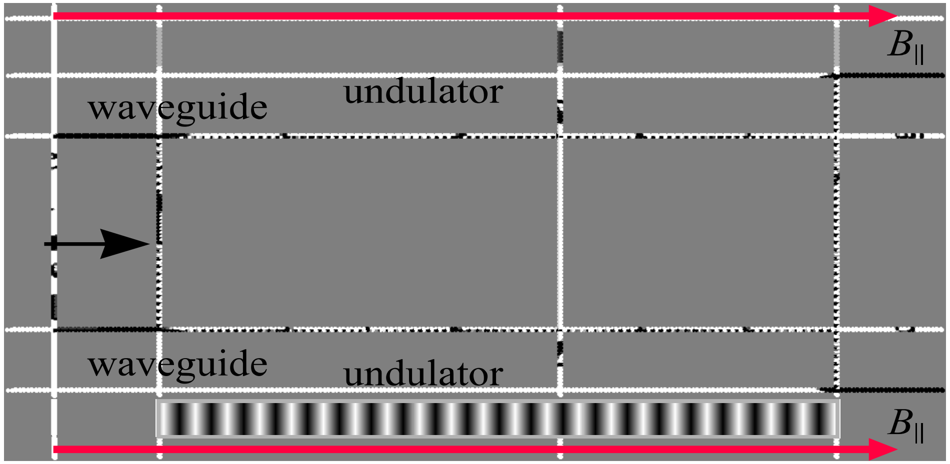
New CDS-D (solid) vs. CDS-C (dashed)
Red: accelerating gradient (MV/m)
Green: maximum surface electric field (MV/m)
Blue: pulsed temperature (K)
Magenta: maximum modified Poynting vector (x50, MW/mm²)

Parameters	CDS-D	CDS-C
Bunch population (10^9)	4.50	3.72
Bunch luminosity ($10^{34}m^{-2}$)	1.43	1.22
Peak input power (MW)	79.3	67.5
Filling time (ns)	60.8	72.4
RF-Beam efficiency (%)	26.0	24.2
Maximum surface field (MV/m)	223	246
Maximum Sc (MW/mm^2)	5.17	5.72
Maximum pulsed temperature rise (K)	22.0	23.0

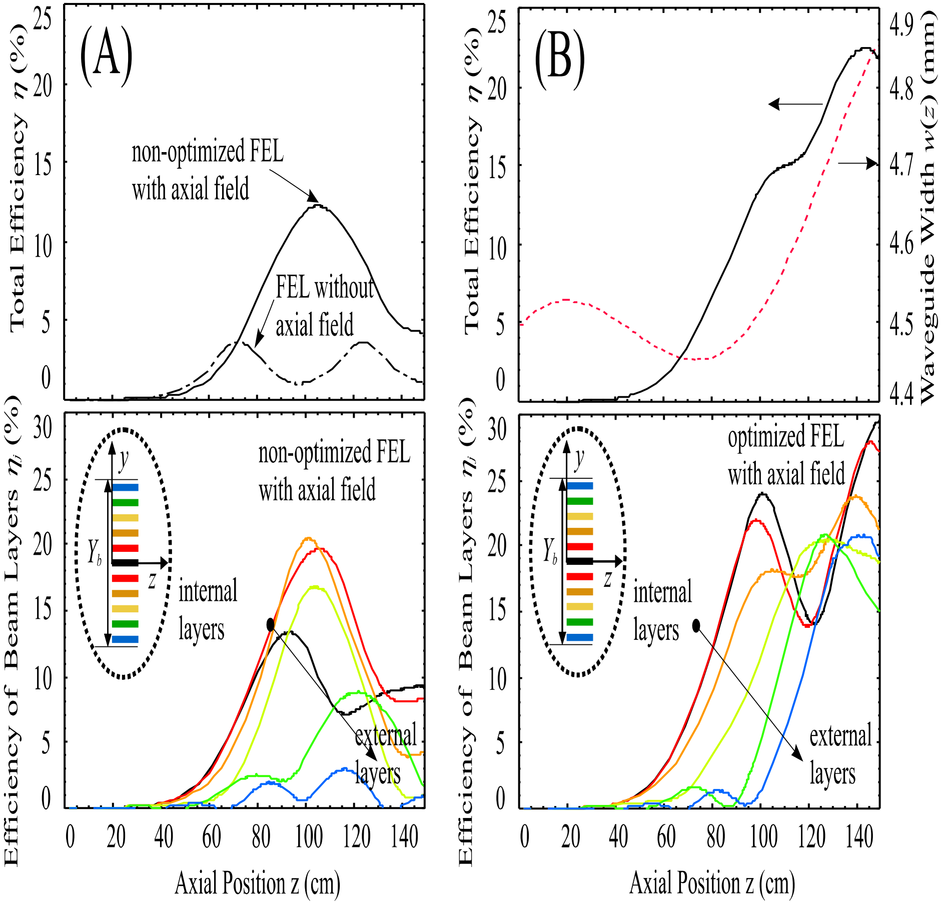
H. Zha et al, IPAC, 2013

Combined Settings and Beamline Element Design

Free electron laser with irregular waveguide



Planar FEL amplifier cross section x=0



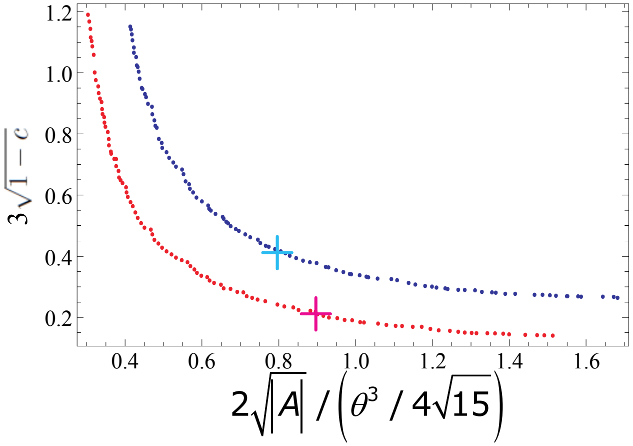
Sheet beam (1 mm x 2 cm) represented in layers (oval insets)

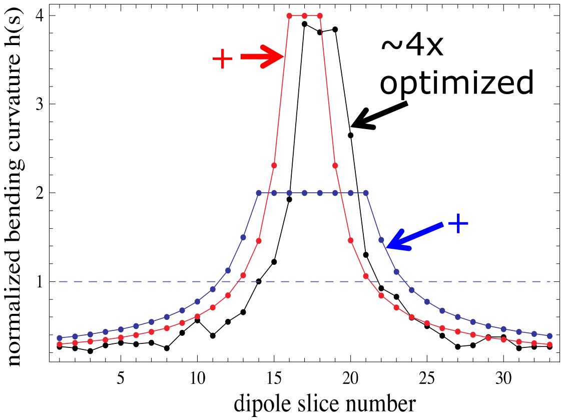
- Improve efficiency by adjusting waveguide wall profile
- A) Fixed width waveguide
  - Adding $B_{||}$ increases efficiency
- B) Optimized waveguide wall with $B_{||}$

V. Goryashko, FEL, 2010

Combined Settings and Beamline Element Design

Dipole field profile for storage ring





dash: reference dipole (1 m long with 10 m bending radius)

blue: maximum field 2x higher than reference

red: maximum field 4x higher than reference

+ single objective solution for TME

Theoretical minimum emittance for a dipole:

$$\varepsilon = \frac{C_q \gamma^2}{J_x} F_{\min}$$

Minimum emittance

$$F_{\min} = 2\sqrt{|A|}\left\{\begin{array}{l} 1 \\ \dfrac{1}{\sqrt{1-c}} \end{array}\right.$$

Under achromatic conditions

Theoretical (TME)

where $|A|$ and c are determined by the dipole.

- Non-uniform dipole model
  - Series of uniform dipole slices with independent ρ(s)
  - Bending curvature h(s)=1/ρ(s)
- Minimize $2\sqrt{|A|}$ and $\sqrt{1-c}$
- For uniform dipole with bending angle θ :

$$2\sqrt{|A|} \approx \theta^3 / 4\sqrt{15}\,;\ c \approx 8/9$$

C.-X. Wang et al, IPAC, 2010

Conclusion

- Basic GA and EA overview
  - flexibility to solve multi-objective optimizations
  - ability to identify inherent trade-offs between objectives
- GAs and EAs are well established in accelerator physics
  - variety of applications and tools
  - explosive growth in automated system optimizations
    - complex in dynamics
    - large number of variables

Thank you for your attention.