Beam Dynamics study by using Genetic Algorithms
and
the ELI-np case

Alberto Bacci – INFN-Milano

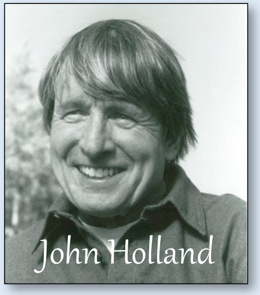
Outline

- **Genetic Algorithms (GAs) introduction**
  - Historical notes
  - Hints on What are & Why use GAs
  - Where: Genetic Algorithms in Beam Dynamics Optimization

- **GAs applied to Beam-Lines Optimization**
  - From Beam-Lines to Chromosomes
  - Following Genetic Laws: Fitness, Reproduction, Mutations, …
  - E.G.: SPARC beam line Optimization in Thomson case

- **The GIOTTO code**
  - The Data-Based DB
  - Inputs & Outputs
  - Fitness function (or Idoneity) definition
  - Optimizations & Statistics **on Specific Cases**:
    - ✓ **Ultra short bunches by Hybrid Velocity Bunching**
    - ✓ **Comb bunches distributions**
  - **Eli-np Case: The reference Working Point & Statistic**

Genetic Algorithms (GAs) introduction: **Historical Notes**



- 1970 John Holland - schemata theorem

- 1975 J. Holland publication: "Adaptation in Natural and Artificial Systems: An Introductory Analysis with Application to Biology, Control, and Artificial Intelligence". The Seminal work

- 1975 K. De Jong (J. Holland's student), Thesis: "An analysis of the behavior of a class of genetic adaptive systems". Broad applicability of GAs

- 1989 David Goldberg Book: "Genetic Algorithms in Search, Optimization, and Machine Learning"

  It deals with the topic at high level and is considered **a milestone in GAs story**. It reports techniques like Multi Objective GA (MOGA), today very current.

❑ Introduction: **What & Why**

What are Genetic Algorithms (GAs)

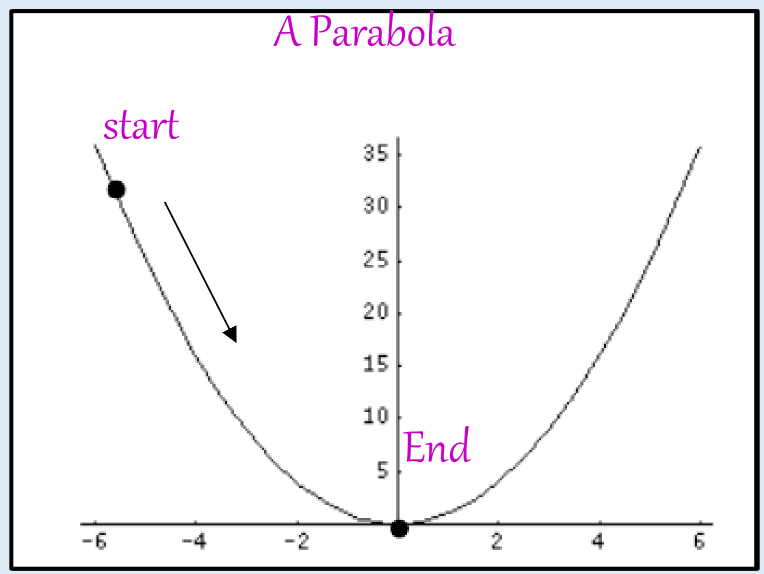
Searching procedures based on natural selections (genetic laws)

Why choosing GAs versus other techniques ...

A basic answer:

Newton-Raphson methods (and **many variants**) are based on local information.

The Scan moves in direction of “local maxima” or “local minima”



Why Genetic Algorithms **

Despite, Newton-Raphson methods can overcame the local solutions issue by some tricks ...

GAs are:

- naturally able to manage the local solution issue
- naturally parallelizable
- usable with a minimum mathematical effort

And, by empiric results,

show strong capability to manage problems where other methods fail

Genetic Algorithm Optimization Applied to Electromagnetics: A Review

Daniel S. Weile and Eric Michielssen, *Member, IEEE*

IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 45, NO. 3, MARCH 1997

** pros and cons in literature

❑ **Where:** Genetic Algorithms (GAs) in **Beam Dynamics Optimization -1**

GAs give strong advantages ...

- in multi-dimensional problems with variables strongly non linear correlated

A main example :

- Space Charge & its non-linear nature: correlates low energy beam-line parameters
- Also frozen beams (space charge off): Other complex situations

Example (1) Thomson/Compton Sources (e.g. SPARC_lab, STAR, ThomX, ELI-np, Munich Compact Light Source) **which ask for :**

For the spectral density: **1)** **very low DE/E**, **2)** **low Emit**

For the photon flux : **3)** Q_{bunch} as **high** as possible

❑ Where: … - 2

Example (2) Ultra short e-beams (e.g. SPARC_lab, LCLS, REAGE, XFEL, EUPRAXIA, …):

- Femtosecond light pulses (FEL/X-FEL), Atoms in chemical reactions, phase-transition, *Photosynthesis Water Splitting :* timescale 1-100 fs [2014 "first snapshots of water splitting" by LCLS; ScienceDaily; Nature]

- Plasma Wave Acceleration: λ_{plasma} order of 30-600 fs . The **Witness** much shorter, the **Driver** (pwfa) comparable to λ_{plasma}

- Femtosecond Electron Diffraction (FED)
  Molecular or atomic motion movies: phase transitions, …, . Timescale: few 10s of fs.
  Relativistic case: $E_b \approx 5$MeV, $Q_b \approx 100$fC, $\varepsilon_{tr}<0.1$ mm-mrad, $\sigma_z<30\mu$m (100fs)

- THz radiation (by CoTrRad)
  0.1 up to tens THz is of great interest for both longitudinal electron beam diagnostics (fs scale) and spectroscopy in pump-and-probe experiments ….

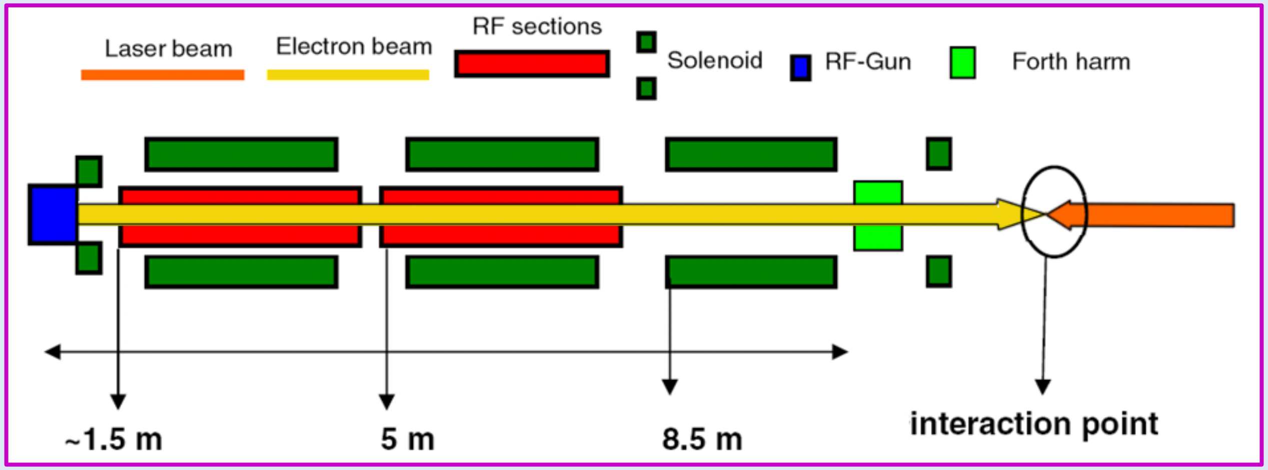
Genetic Algorithms applied to Beam-Line Optimization

❑ From Beam-Lines to Chromosomes

Genetic Laws work on Chromosomes ==> Chromosomes are made of genes (parameters)

Beam-Line = Parameters Array ==> One Chromosome

A Beam-Line



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Chromosome

Gene	Reference case
$dE_g / dz\ (MV/m)$	120
$\phi_g\ (°)$	0
$B_g\ (T)$	0.2707
$dE_1 / dz\ (MV/m)$	13.4
$\phi_1\ (°)$	-30
$B_1\ (T)$	0.12
$z_1\ (m)$	1.322
$dE_2 / dz\ (MV/m)$	6.55
$\phi_2\ (°)$	88
$B_2\ (T)$	0.1145
$z_2\ (m)$	5
$B_3\ (T)$	0.1145
$z_3\ (m)$	8.5
$\phi_{IVH}\ (°)$	180
$z_{IVH}\ (m)$	11.7

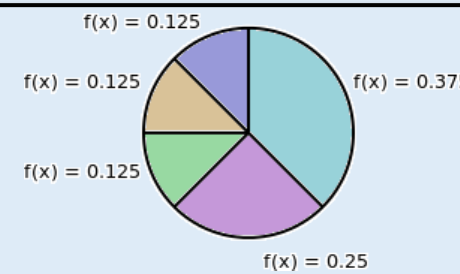
Following Genetic Laws: Fitness Function

Gene	Reference case
dE_g / dz (MV/m)	120
ϕ_g (°)	0
B_g (T)	0.2707
dE_1 / dz (MV/m)	13.4
ϕ_1 (°)	-30
B_1 (T)	0.12
z_1 (m)	1.322
dE_2 / dz (MV/m)	6.55
ϕ_2 (°)	88
B_2 (T)	0.1145
z_2 (m)	5
B_3 (T)	0.1145
z_3 (m)	8.5
ϕ_{IVH} (°)	180
z_{IVH} (m)	11.7

Starts from random generation

Rules to pass generation ➔ in generation:

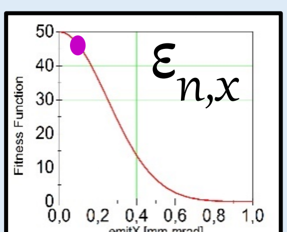
- Selection: bluffed Roulette wheel
- Mutations



.... & others methods & tricks. The rule: closest to Nature, best performances

Chromosomes Must be sorted by a Fitness function

$$\text{🏃} == 50 \cdot e^{-\left(\frac{eimtX}{0.35}\right)^2} + 50 \cdot e^{-\left(\frac{E_{spread}}{250}\right)^2}$$



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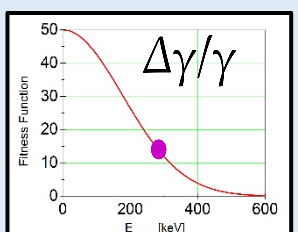
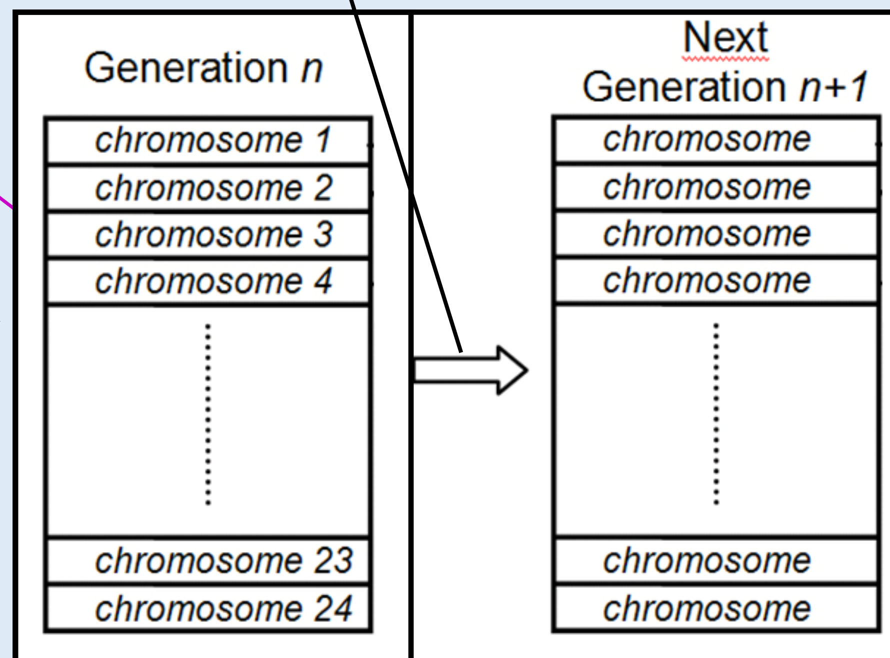
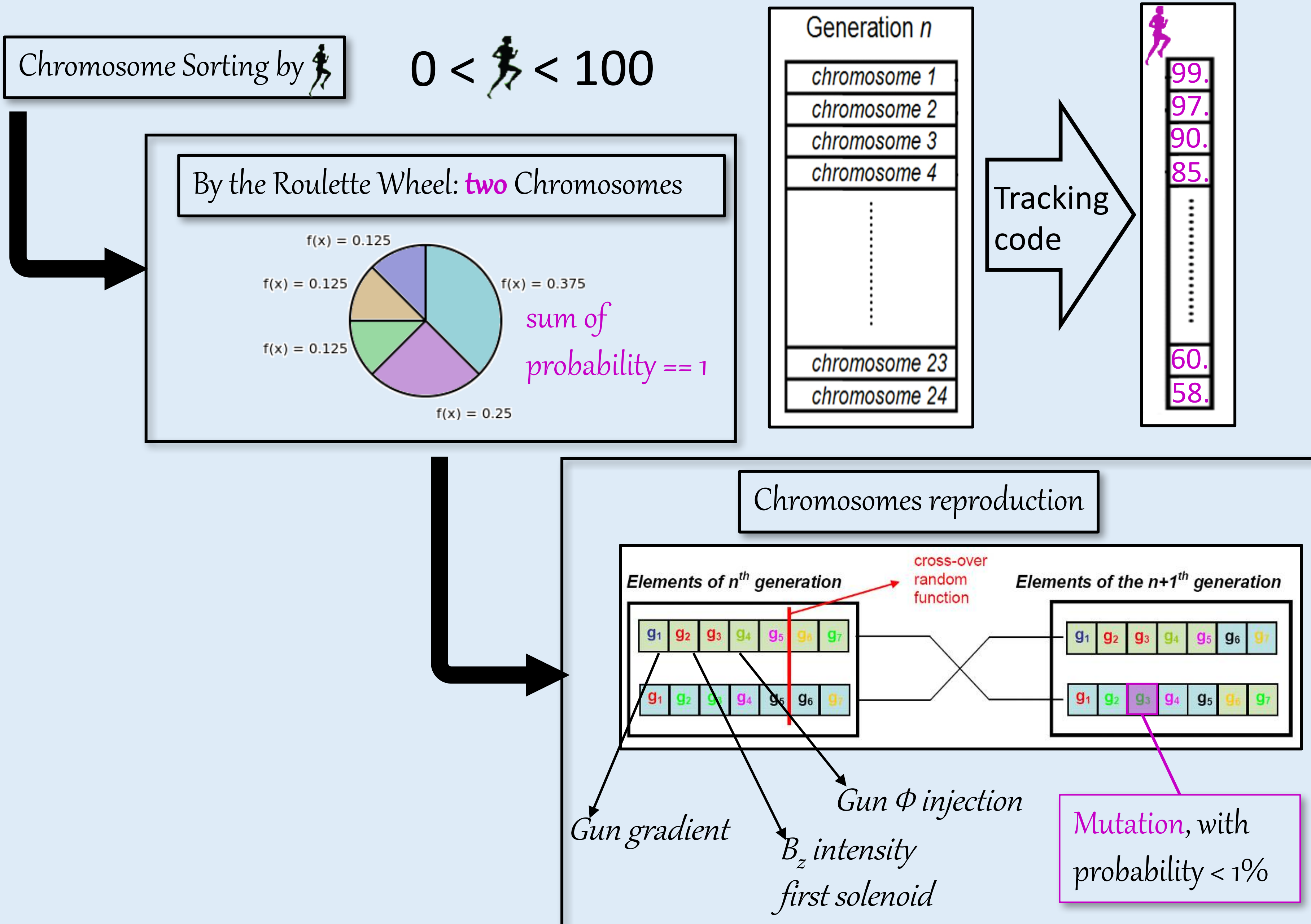




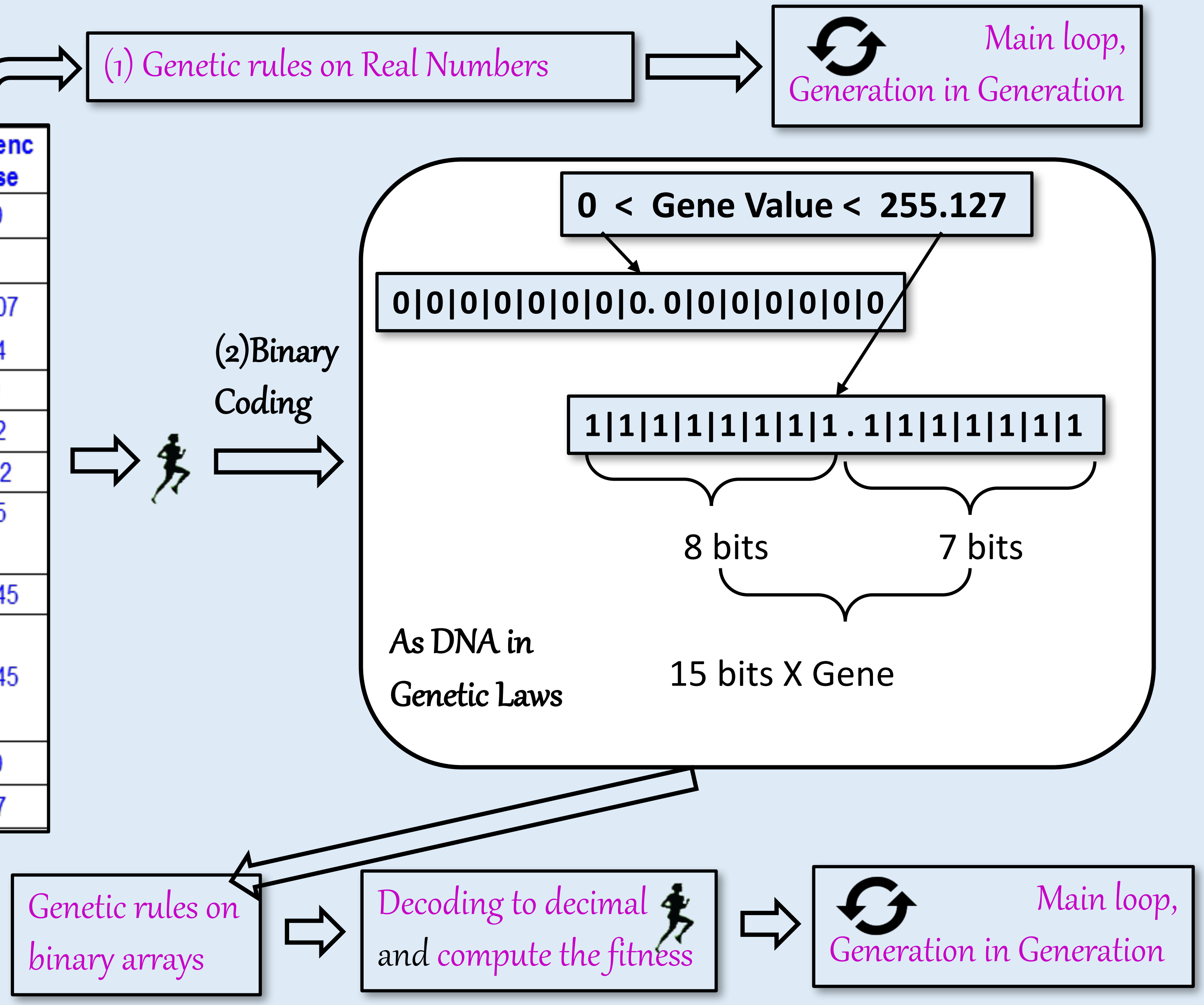
➢ Following Genetic Laws: Reproduction & Mutation



Following Genetic Laws: **Real coding** (1) and **binary coding** (2)

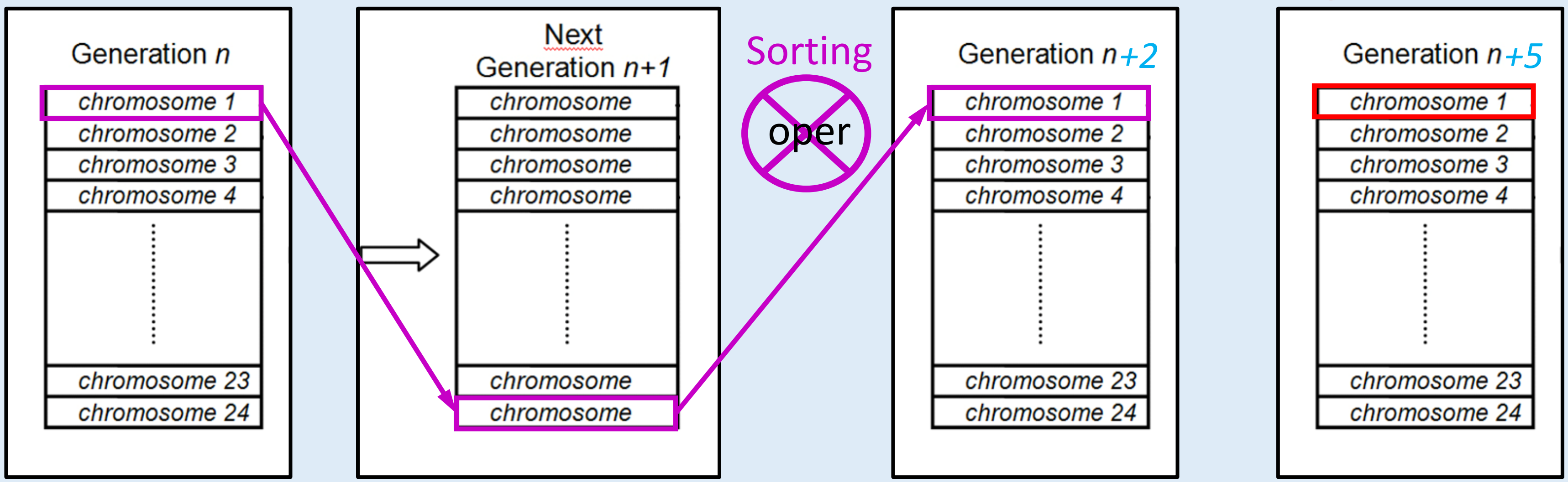
Chromosome

Gene	Reference case
dE_g/dz (MV/m)	120
ϕ_g (°)	0
B_g (T)	0.2707
dE_1/dz (MV/m)	13.4
ϕ_1 (°)	-30
B_1 (T)	0.12
z_1 (m)	1.322
dE_2/dz (MV/m)	6.55
ϕ_2 (°)	88
B_2 (T)	0.1145
z_2 (m)	5
B_3 (T)	0.1145
z_3 (m)	8.5
ϕ_{IVH} (°)	180
z_{IVH} (m)	11.7



➢ Following Genetic Laws: Elitism

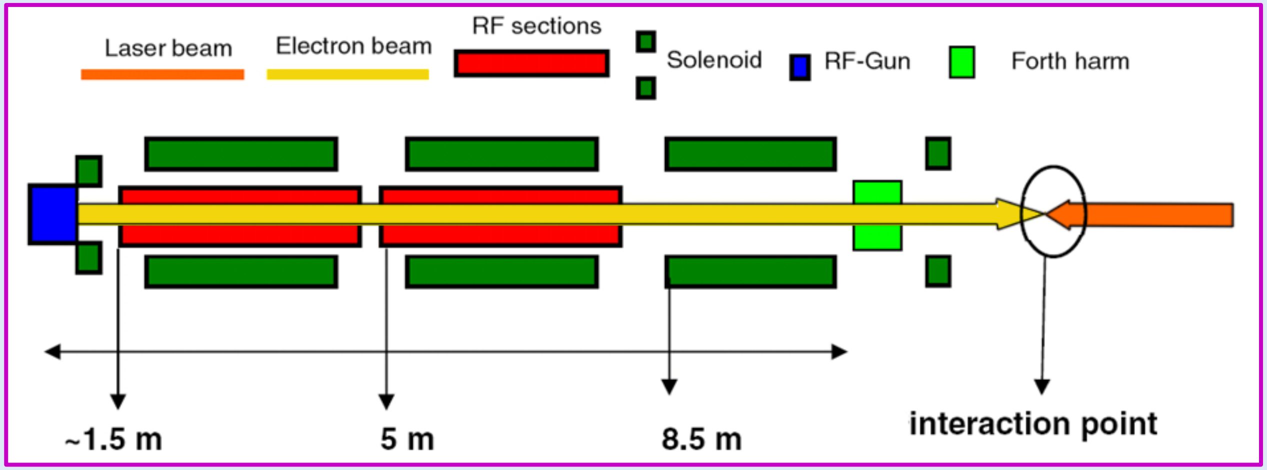
Concluding: *the elitism*



Nowadays "**quasi-classic**" optimization techniques

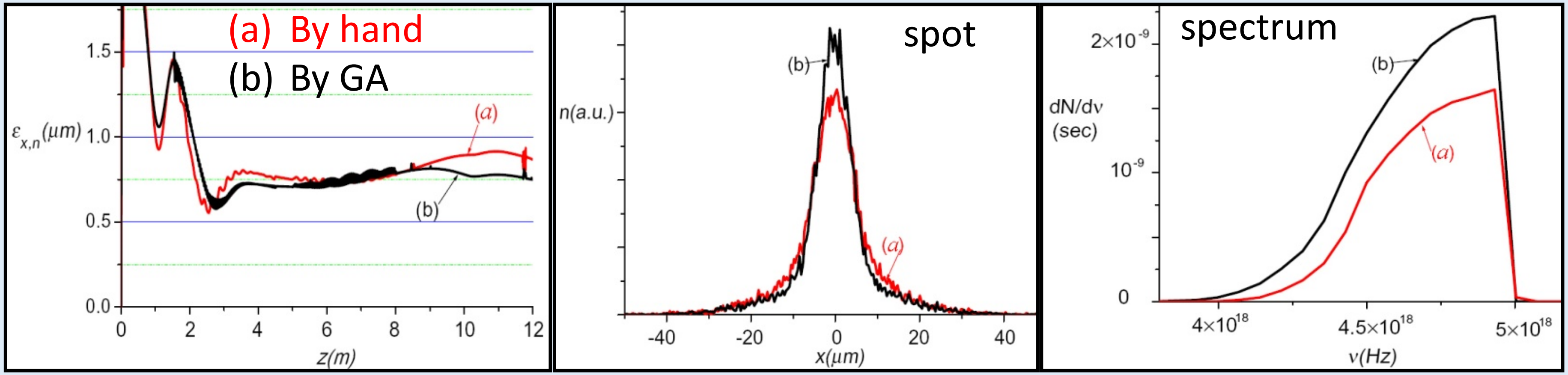
- *elitism*
- *advanced mutation operators*
- *hill climbing*
- *regeneration from best solutions*
- *… … …*
- & parallelization *quasi-mandatory*

E.G.: SPARC beam line Optimization in Thomson case



Old Kind of Fitness Function

$$F_{fitness} = \frac{1}{\varepsilon_{x,n} \cdot \frac{\Delta\gamma}{\gamma}}$$



“MAXIMIZING THE BRIGHTNESS OF AB ELECTRON BEAM BY MEANS OF A GENETIC ALGORITHM”
A. Bacci, C. Maroli, V. Petrillo, A. Rossi, L. Serafini - NIMB 263 (2007) 488-496

The
GIOTTO code

GIOTTO - Genetic Interface for OpTimising Tracking with Optics

- **WAS BORN** in 2008; Language: Fortran 90/95
- **USE** for Optimization of Generic Code's Parameters or for Statistical (Jitters) Analysis
- **INPUTS** based on NameList & on two internal DataBase
- **CAN** easily Drive different codes:

  Now: ASTRA's Generator, ASTRA, QFluid (Plasma acceleration, A. Rossi modifications)
- **Current Version (Ver. 10.0):**

  Linux 64 bit; Windows 64 – (compilers **gfortran** or **INTEL fortran**)

  Parallelized with OPEN-MPI (Linux), MS-MPI or INTEL MPI (Windows)

  Used @ PSI (S. Bettoni) and tested at Desy-Pitz
- **Code and Documentations:**

  URL: http://pcfasci.fisica.unimi.it/Pagine/GIOTTO/GIOTTO.htm (server down, pardon!)

  Exist an User manual for version 8.5 2012 (needs updates)

GIOTTO – Genetic Interface for OpTimising Tracking with Optics

From 2008 up to day, the code is grew in power and capability

Optimization techniques: elitism; advanced mutation operators; hill climbing; ant colony regeneration from best solutions

user freely defined by Astra outputs:
Targets: bunch PosZ or **Time**, **En**, **En_{spread}**, **SigZ**, **Xemit**, **sigX**, **divergX**, **Yemit**, ….

Important GIOTTO's features:

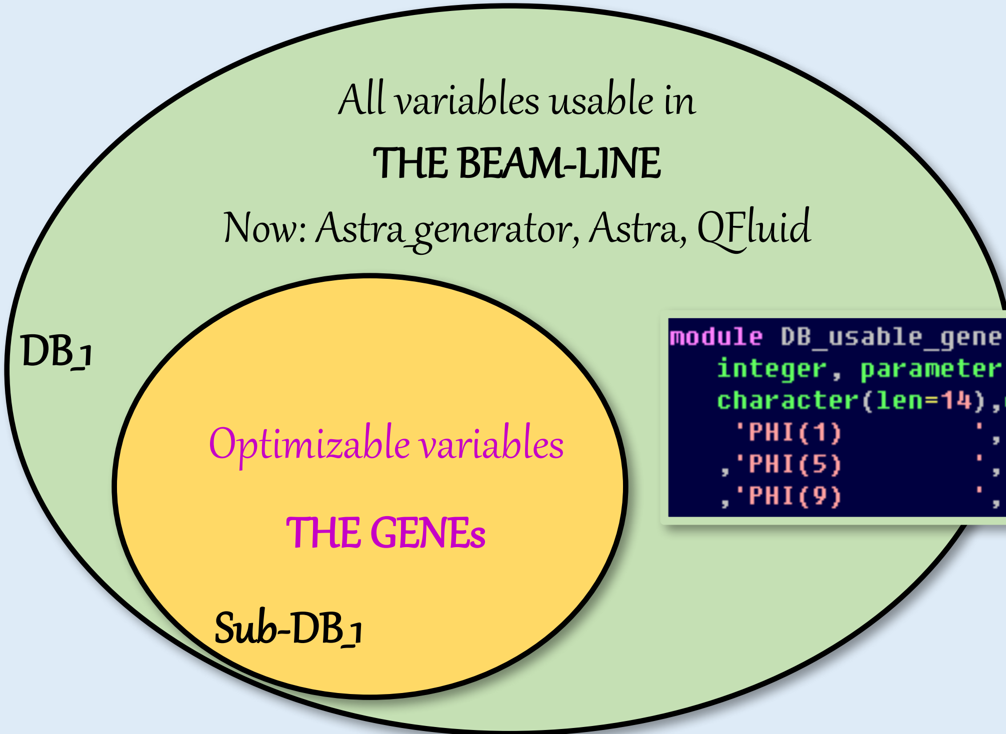
Every NameList 's variables can be used as a GENE (optimizable) **&** Any code working with NameList is directly importable in GIOTTO.
ASTRA e.g. : **Phi(1)**…Phi(50), **MaxE(1:50)**, **MaxB(1:50)**, **sig_x (laser cathode)** ,**sig_clock (Laser @ cathode)**, …, … (no limit on the number)

Constraints freely defined by the user (under test)

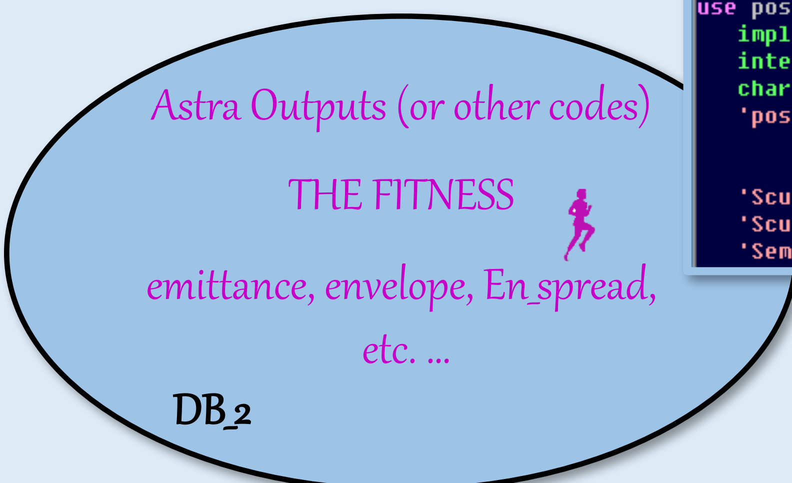
Switch from Optimizations to Statistical analysis is really EASY

Jitters sampling interval: Uniform or Gaussian

➢ GIOTTO's Data-Bases




```
module DB_usable_gene
   integer, parameter :: DB_extension=269
   character(len=14),dimension(DB_extension) :: DB_genes=(/&   !da inseri
    'PHI(1)         ','PHI(2)         ','PHI(3)         ','PHI(4)         '&
   ,'PHI(5)         ','PHI(6)         ','PHI(7)         ','PHI(8)         '&
   ,'PHI(9)         ','PHI(10)        ','PHI(11)        ','PHI(12)        '&
```




```
module charge_rpn_idon      !rpn reverse polish notation
use post_processors
   implicit none
   integer,parameter,private :: DB_out_dim=107
   character(len=10),dimension(DB_out_dim),private :: DB_out=(/&
   'posZ      ','time      ','En        ','sigZ      ','DEn       ','emitZ
                            'Xmed      ','sigX      ','divergX   ','emitX
                            'Ymed     ','sigY     ','divergY  ','emitY     ','
   'Scurr(1)  ','Scurr(2)  ','Scurr(3)  ','Scurr(4)  ','Scurr(5)  ',&
   'Scurr(6)  ','Scurr(7)  ','Scurr(8)  ','Scurr(9)  ','Scurr(10) ',&
   'SemitX(1) ','SemitX(2) ','SemitX(3) ','SemitX(4) ','SemitX(5) ',&
```

➢ GIOTTO's INPUT FILE

GINxx.xx.ini is divided in two parts:

1) One NameList (&GA) giving all the directive to GIOTTO
2) Three keyNames defining: CONSTRAINTS, FITNESS and GENES

1)

```
&GA
Astra_in='Astra_23_Jan2014.exe','pls-start.in'
....
.....
/
```

2)

```
==============================From here Key_Names==============================
==================(lines after one blank-record are comments)==================
===============================================================================
[constr01]
sigZ En * sqr emitZ sqr sigX * / 5300 * 1 >

[constr02]
sigZ En * sqr emitZ sqr sigX * / 6300 * 10 >

[idoneity] !must be used the Reverse Polish Notation
emitX 2.5 / sqr -1. * exp 50 *
sigZ 0.150 / sqr -1. * exp 50 * +
sigX 2.5 / sqr -1. * exp 50 * +

!Gene(i)___Delta___JoinGenes(i:i+N)___u-uniform___g-gaussian___JoingSign
[genes]
sig_clock    0.2E-3    1      u     1   0.0 0
SIG_x        0.02      1      u     1   0.0 0
MaxB(1)      0.08      1      u     1   0.0 0
MaxB(2)      0.08      1      u     1   0.0 0
```

➢ GIOTTO's INPUT FILE: &GA NameList

```
&GA
Astra_in='Astra_23_Jan2014.exe','pls-start.in'
Gener_in='generator_Mar2013.exe','generator-start1.in'
Genes_number=7  !max value is 40
pop_size=8      !must to be a multiple of the nodes numbers
generations_number=410

keepADistribution=.false. !".f." start from "Gener_in", ".t." from Distribution
keepInParameters=.true.
!".t." the chrom in the first gen;".f." All rnd, the chrom as central values

!***********************Turn on and Control the constraints
 constraints=.false. !if "true" turn-on constraints--------
 minimumZ=1.0 !this is valid for all constraints
 constr_number=2 !max number of contraints is 10
 constr_name='[constr01]','[constr02]'
 lower_Zbound=1.6,5.0,16.0  !intervals where the constraint is valid
 upper_Zbound=25.0,25.0,25.0

!****************Post processor for COMB bunch distributions*******************
 LaserComb=.false. !if true Gener_in is a generator input with SPIKES namelist--
 !if "true" uses "ID_bunch_LC" for the spikes analysis and compute the Fitness--
 LaserComb_PostPro=.false.
 PostPro_in_index=0012

!***********************Forced Optimization Process*************
 step_OP_forced=25
 variation_x100=5.0 !Best Cromosom Variation %. Every "step_OP_forced"----------
 !-----variation in % is halved----untill "step_OP_forced" X "Step2Start_x100"--
 Step2Start_x100=4
!***************************Statistical Analysis********************************
 statistic=.false.
 Runs_Number=360      !must be a multiple of the pop_size
/
```

Under developing (it slows down heavily GIOTTO)

Usually few variables are used

Optimization
Rarely needs changes

Fitness & Genes

➢ GIOTTO INPUT FILE: Key_Names

```
==============================From here Key_Names==============================
=================(lines after one blank-record are comments)=================

!**********************Equation in Reverse Polish Notation**********************
!-----Variables that can be used are:------------------------------------------
!-----PosZ time En DEn sigZ emitZ Xmed sigX divergX emitX Ymed sigY------------
!-----divergY emitY------------------------------------------------------------
!******************************************************************************
[constr01]
sigZ En * sqr emitZ sqr sigX * / 5300 * 1 >

[constr02]
sigZ En * sqr emitZ sqr sigX * / 6300 * 10 >

[idoneity] !must be used the Reverse Polish Notation
emitX 2.5 / sqr -1. * exp 50 *
sigZ 0.150 / sqr -1. * exp 50 * +
sigX 2.5 / sqr -1. * exp 50 * +

emitX 0.4 - 0.05 / sqr -1. * exp 50 * sigZ 0.280 - 0.01 / sqr -1. * exp 50 * +
sigX sigY - 1.0 / sqr -1. * exp 50 * + Xmed 1000 - 10.0 / sqr -1. * exp 50 * +
SemitX(1) 4 / sqr -1 * exp SemitX(2) 4 / sqr -1 * exp
Sdist(1) 380E-6 - 100E-6 / sqr -1 * exp 50 * +

!Gene(i)___Delta___JoinGenes(i:i+N)___u-uniform___g-gaussian___JoingSign
[genes]
sig_clock    0.2E-3    1      u     1   0.0 0
SIG_x        0.02      1      u     1   0.0 0
MaxB(1)      0.08      1      u     1   0.0 0
MaxB(2)      0.08      1      u     1   0.0 0
Phi(1)       2.0       1      u     1   0.0 0
Phi(2)       2.0       1      u     1   0.0 0
Phi(3)       10.0      1      u     1   0.0 0

MaxE(5)      5.0       1      u     1   0.0 0
c_pos(5)     0.05      1      u     1   0.0 0
Q_grad(4)    0.002     1      u     1   0.0 1 Q_grad(6) 0
Zstop        0.05      1      u     1   0.0 0
```

Rarely needed

Definition

Comments

GENES Definition

Comments

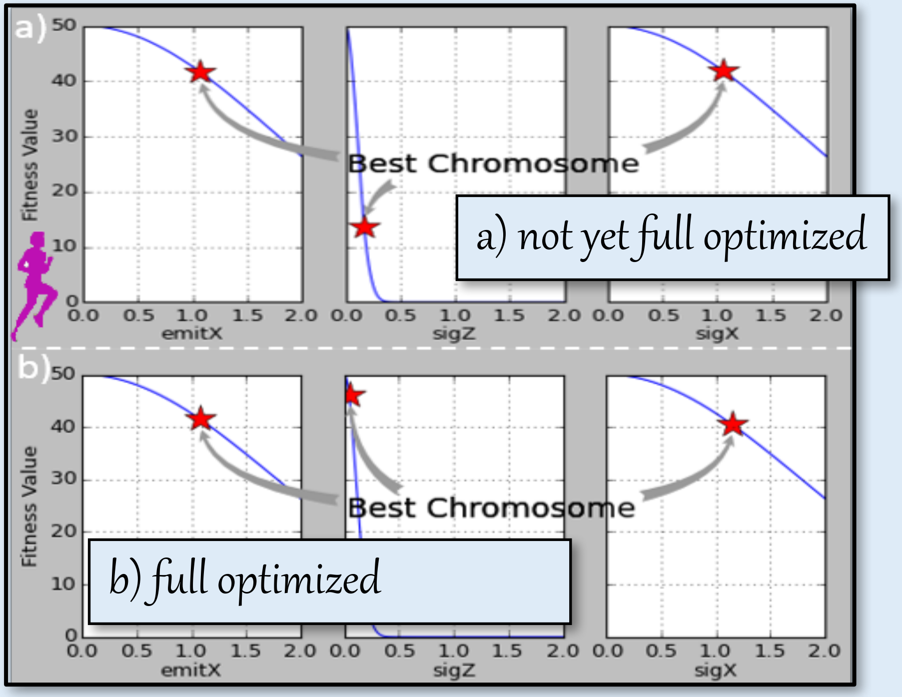
GIOTTO: FITNESS FUNCTION

```
[idoneity] !must be used the Reverse Polish Notation
emitX 2.5 / sqr -1. * exp 50 *
sigZ 0.150 / sqr -1. * exp 50 * +
sigX 2.5 / sqr -1. * exp 50 * +
```

Reverse Polish Notation: Opers Follow Operands

- 3 4 + = 7
- Stack based operation
- Does not need brackets

$$= 50 \cdot e^{-\left(\frac{emitX}{2.5}\right)^2} + 50 \cdot e^{-\left(\frac{sigZ}{0.15}\right)^2} + 50 \cdot e^{-\left(\frac{sigX}{2.5}\right)^2}$$



Fitness Funciont strategy to Cope with Multi Objectives Problems (MO):

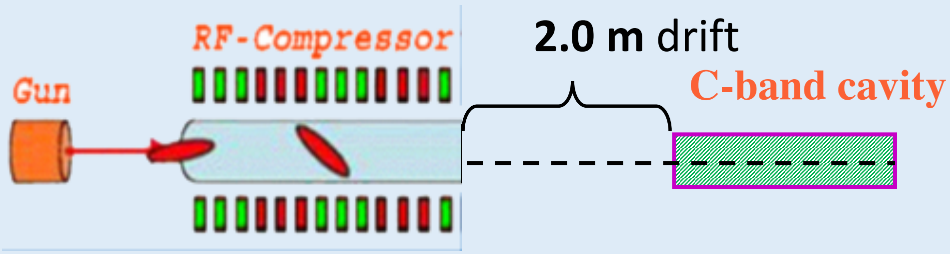
- One Single Criterium per Equation piece (Objectives Wights)
- To be close to the Goal mean close to the Gaussian Curve Top
- The 'Far region' (referring to optimization) has to be on the maximum Gaussin slope
- change the FF in real time (ander implementation)

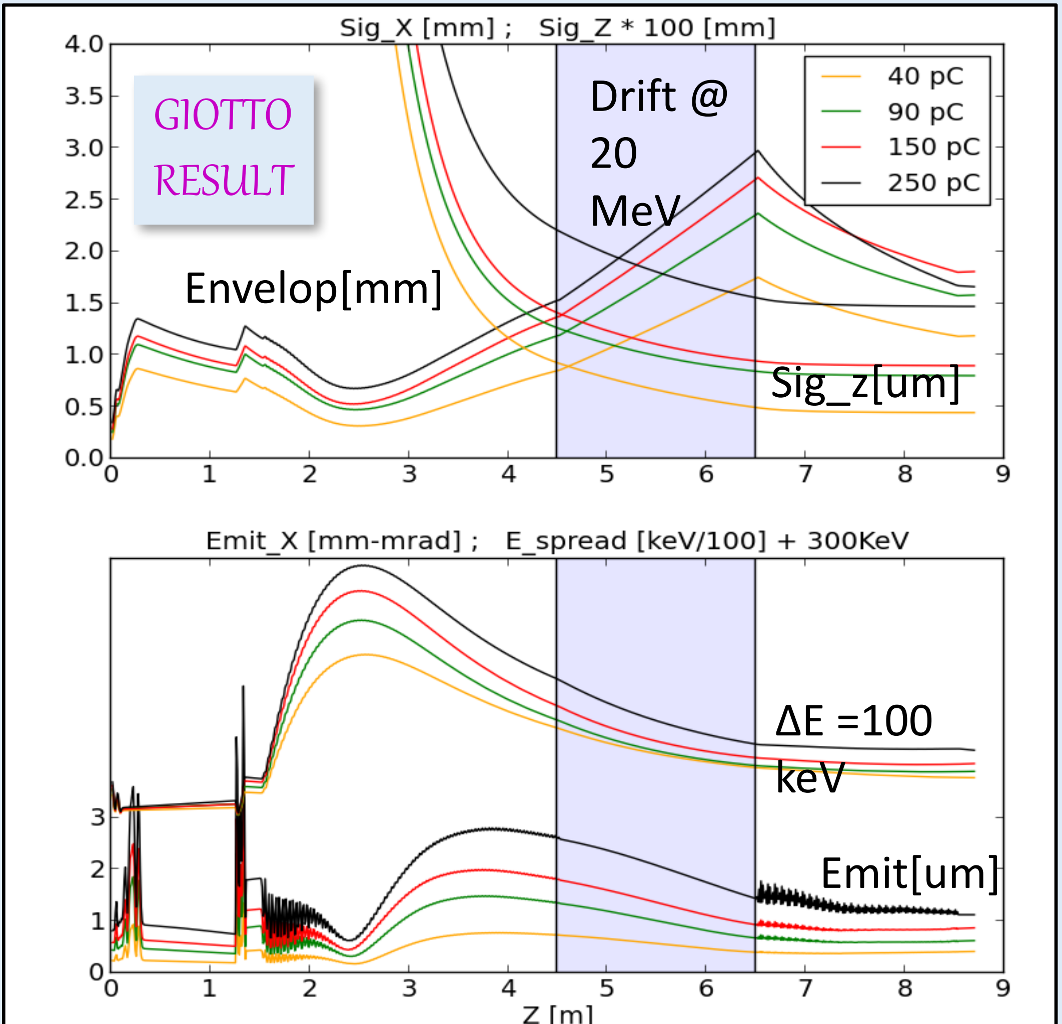
GIOTTO

Optimization &

Statistical analysis

Beam-Line Optimization for: ultra short, ultra cold, High brightness bunches





GOALS:

- Low Emittance
- Low Energy Spread
- femptosec. Sig Z

A Beam-Line studied with:

- Experience
- An Ad hoc GIOTTO use

GENES in the Optimization:

- Gun:
  - (1) Phase & (2) Solenoid (B_z)
- TW cavity (RF- Compressor):
  - (3) Phase & (4) Solenoids
- C-band cavity: (5) Phase

GIOTTO OUTPUT: RISULTATI.TXT

```
[idoneity] !must be used the Reverse
emitX 1.2 / sqr -1. * exp 100 *
sigZ 0.016 / sqr -1. * exp 400 * +
DEn 200.0 / sqr -1. * exp 50 * +
```

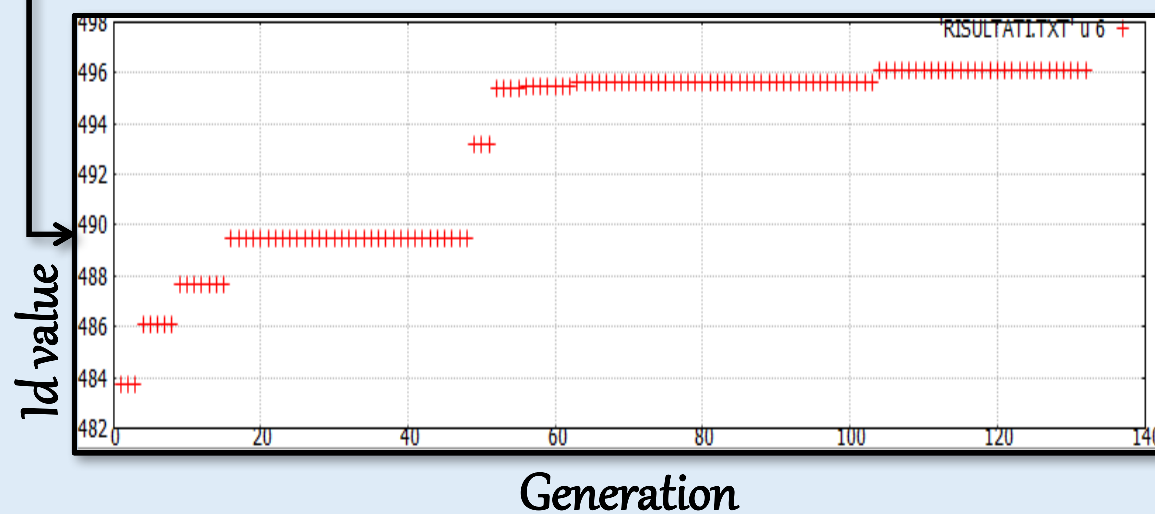
GENES

```
[genes]
MaxB(1)    0.003    1  u  1  0.0 0
MaxB(2)    0.01     1  u  1  0.0 0
Phi(1)     1.2      1  u  1  0.0 0
Phi(2)     1.5      1  u  1  0.0 0
Phi(3)     1.5      1  u  1  0.0 0
```

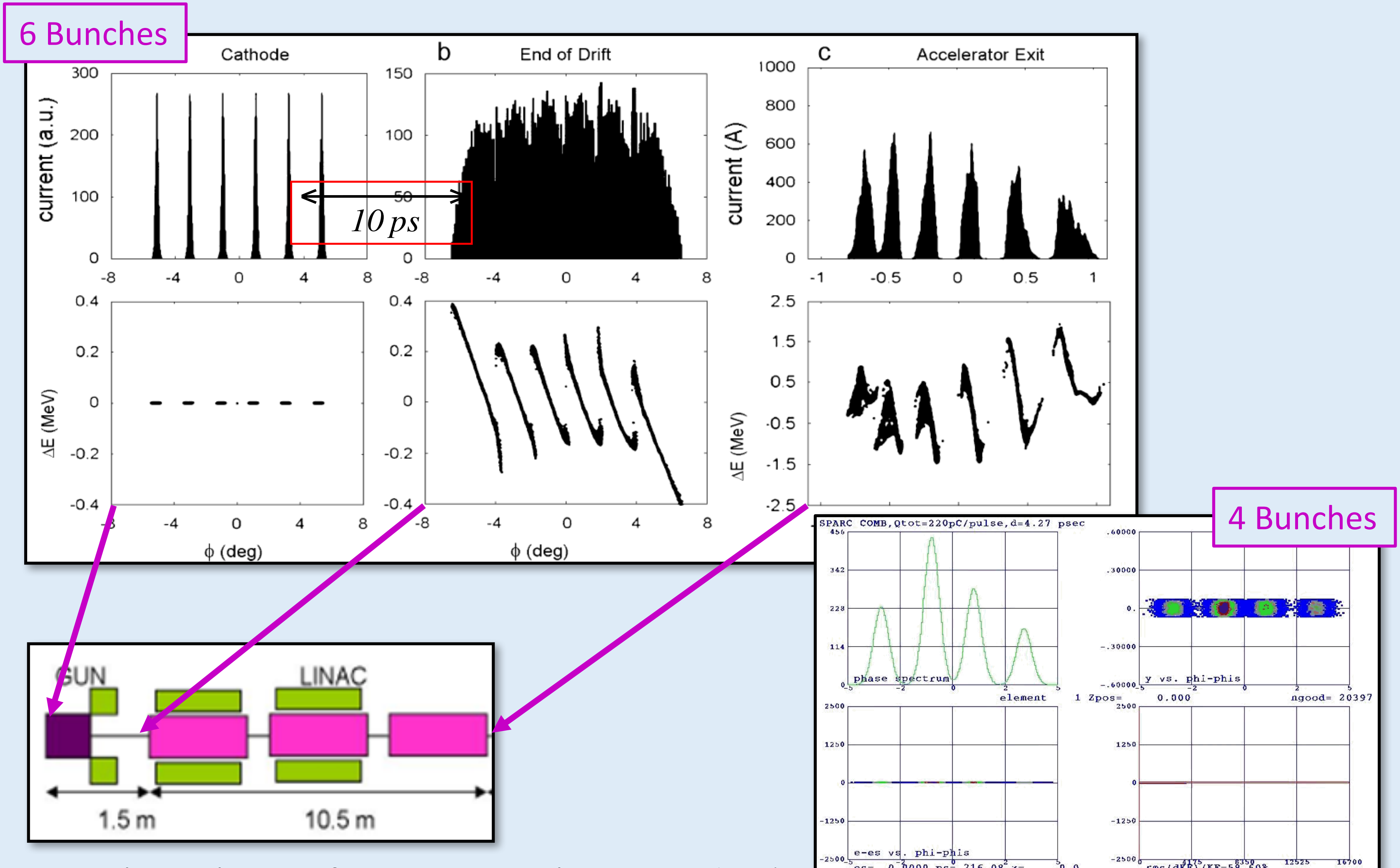
RISULTATI.TXT

								Emit	sigZ	ΔE
1	MAXB(1)	MAXB(2)	PHI(1)	PHI(2)	PHI(3)	***id_best***	***id_worst***	emitX	sigZ	DEn
2	3.33234E-01	5.76714E-02	2.34351E+00	1.91001E+02	-8.48726E+01	4.83694E+02	7.83022E+01	5.79140E-01	5.08770E-03	7.80340E+01
3	3.33234E-01	5.76714E-02	2.34351E+00	1.91001E+02	-8.48726E+01	4.83694E+02	1.72762E+02	5.79140E-01	5.08770E-03	7.80340E+01
4	3.33234E-01	5.76714E-02	2.34351E+00	1.91001E+02	-8.48726E+01	4.83694E+02	3.32879E+02	5.79140E-01	5.08770E-03	7.80340E+01
5	3.33234E-01	5.76714E-02	2.18337E+00	1.90543E+02	-8.50834E+01	4.86096E+02	3.06747E+02	6.46100E-01	4.62500E-03	7.56980E+01
6	3.33234E-01	5.76714E-02	2.18337E+00	1.90543E+02	-8.50834E+01	4.86096E+02	3.27456E+02	6.46100E-01	4.62500E-03	7.56980E+01
7	3.33234E-01	5.76714E-02	2.18337E+00	1.90543E+02	-8.50834E+01	4.86096E+02	2.90264E+02	6.46100E-01	4.62500E-03	7.56980E+01
8	3.33234E-01	5.76714E-02	2.18337E+00	1.90543E+02	-8.50834E+01	4.86096E+02	2.92544E+02	6.46100E-01	4.62500E-03	7.56980E+01
9	3.33234E-01	5.76714E-02	2.18337E+00	1.90543E+02	-8.50834E+01	4.86096E+02	3.01542E+02	6.46100E-01	4.62500E-03	7.56980E+01
10	3.33234E-01	5.76714E-02	2.34351E+00	1.90543E+02	-8.50834E+01	4.87645E+02	4.29286E+02	6.16760E-01	4.63930E-03	7.69790E+01
11	3.33234E-01	5.76714E-02	2.34351E+00	1.90543E+02	-8.50834E+01	4.87645E+02	4.31203E+02	6.16760E-01	4.63930E-03	7.69790E+01
12	3.33234E-01	5.76714E-02	2.34351E+00	1.90543E+02	-8.50834E+01	4.87645E+02	4.40076E+02	6.16760E-01	4.63930E-03	7.69790E+01
13	3.33234E-01	5.76714E-02	2.34351E+00	1.90543E+02	-8.50834E+01	4.87645E+02	4.40076E+02	6.16760E-01	4.63930E-03	7.69790E+01

Best Chromosome of the Generation N.5



Beam-Line STATISTIC for Laser Comb (ECHO Bunch Generations)

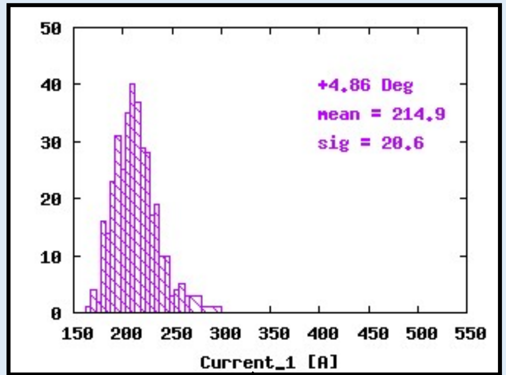


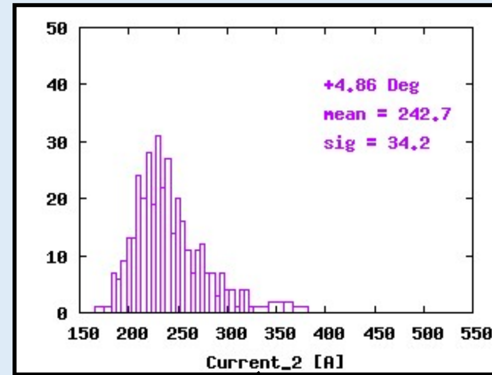
- P.O.Shea et al., Proc. of 2001 IEEE PAC, Chicago, USA (2001) p.704.
- M. Ferrario. M. Boscolo et al., Int. J. of Mod. Phys. B, 2006 (Taipei 05 Workshop)

Beam-Line STATISTIC for Laser Comb – TWO Bunches case : Current Statistic

```
!***************************Statistical Analysis*******
statistic=.true.
Runs_Number=360        !must be a multiple of the pop_size
!*****************************************************
```

```
[genes]
phi(1)      0.9        1       g      1
phi(2)      0.9        1       g      1
```





360 cases

bacci@pcsimul2:~/Doc_Lavoro/08_SPARC/03_LaserComb/02_Simulazioni/05_Giotto/02b_Titti_comparison/02_result_p5

	posZ	time	En	sigZ	DEn	emitZ	zXEpMed	Xmed
5								
6	12.0000000	40.1020012	127.5899963	0.1931200	315.2000122	49.8079987	181.1999969	-0.0012153
7	12.0000000	40.0989990	127.5899963	0.1988300	287.4100037	47.6329994	158.7799988	-0.0011859
8	12.0000000	40.1010017	127.5999985	0.1907200	329.6600037	51.0439987	192.4600067	-0.0012634
9	12.0000000	40.0989990	127.5899963	0.2004300	282.3500061	47.5709991	152.9400024	-0.0012552
10	12.0000000	40.0999985	127.5899963	0.2022500	275.6199951	47.2900009	145.9199982	-0.0012090
11	12.0000000	40.0970001	127.6399994	0.1682500	445.8599854	58.4290009	279.6300049	-0.0011903

sigX	divergX	emitX	xXxpMed	Ymed	sigY	divergY	emitY
0.1552100	0.0777850	1.6316000	0.0655140	0.0003971	0.1546800	0.0778750	1.6328000
0.1575600	0.0799780	1.5186000	0.0701300	0.0004734	0.1574000	0.0801450	1.5223000
0.1577300	0.0770300	1.7099000	0.0637480	0.0002847	0.1572100	0.0771520	1.7097000
0.1560300	0.0800730	1.4665999	0.0707510	0.0005361	0.1559900	0.0802450	1.4737000
0.1585100	0.0807810	1.4794000	0.0716900	0.0005785	0.1585100	0.0810230	1.4844000
0.1906800	0.0691680	2.5023999	0.0452270	0.0004415	0.1896900	0.0691130	2.5088999
0.1604000	0.0805670	1.5132999	0.0712350	0.0005018	0.1602400	0.0807310	1.5175000

yXypMed	Scurr01	Scurr02	SemtX01	SemtX02	SemtY01	SemtY02	Sdist01	Sdist02
0.0655090	216.6100006	234.6699982	1.0002000	1.6055000	1.0131000	1.5854000	0.0003813	0.0000000
0.0702470	227.5399933	218.2200012	1.0061001	1.6256000	1.0204000	1.6002001	0.0003928	0.0000000
0.0638020	209.6300049	244.7700043	1.0125999	1.7193000	1.0254000	1.7012000	0.0003765	0.0000000
0.0708450	230.9100037	215.6799927	0.9868600	1.6118000	1.0041000	1.5850000	0.0003960	0.0000000
0.0718970	234.2200012	212.6699982	1.0067000	1.6318001	1.0206000	1.6045001	0.0003997	0.0000000
0.0446640	170.4299927	359.5400085	1.0303000	1.6545000	1.0482000	1.6513000	0.0003305	0.0000000

GIOTTO
and the ELI-NP case

ELI-NP LINAC machine

Beam Dynamic features

Electron Linac design to drive bright Compton back-scattering gamma-ray sources
A. Bacci, D. Alesini, P. Antici, M. Bellaveglia, R. Boni et al.
J. Appl. Phys. 113, 194508 (2013); **online:** http://dx.doi.org/10.1063/1.4805071

The Peculiar Gamma Ray Source features

Photon energy	*MeV*	0.2-19.5
Spectral Density	*ph/sec.eV*	$0.8\text{-}4 \cdot 10^{4}$
Bandwidth (rms)	%	≤0.5
# photons per shot within FWHM bdw.		$\leq 2.6 \cdot 10^{5}$
# photons/sec within FWHM bdw.		$\leq 8.3 \cdot 10^{8}$
Source rms size	*μm*	10 - 30
Source rms divergence	*μrad*	25 - 200
Peak Brilliance	$(N_{ph}/sec \cdot mm^2 mrad^2 \cdot 0.1\%)$	10^{20} - 10^{23}
Radiation pulse length	(rms, *psec*)	0.7 - 1.5
Linear Polarization	%	> 99
Macro rep. rate	*Hz*	100
# of pulses per macropulse		≤32
Pulse-to-pulse separation	*nsec*	16

In next page,
how to reach these parameters

ELI-NP Injector *merit factors*

The Emittance

Maximization of electron density into transverse phase space :

$$\eta \equiv \frac{Q_b}{{\varepsilon_n}^2}$$

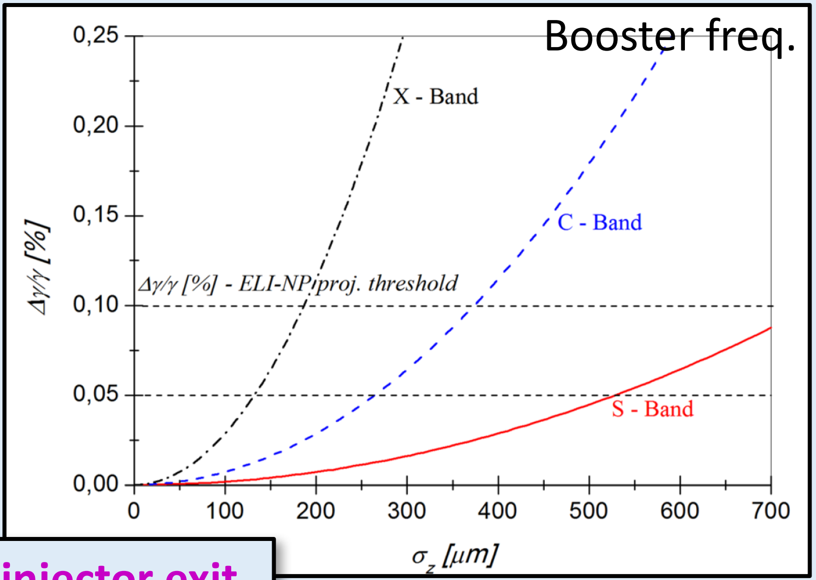
==> means ==> very low emittance~ **0.4 mm-mrad**

The Energy Spread

Minimization of the energy spread: the **source spectral density require $\Delta\gamma/\gamma < 0.1\%$**, we have chosen a conservative threshold of 0.05 %

Energy Spread by **RF curvature**:

$$\left.\frac{\Delta\gamma}{\gamma}\right|_{rms} \approx 2\left(\pi f_{RF}\frac{\sigma_z}{c}\right)^2$$

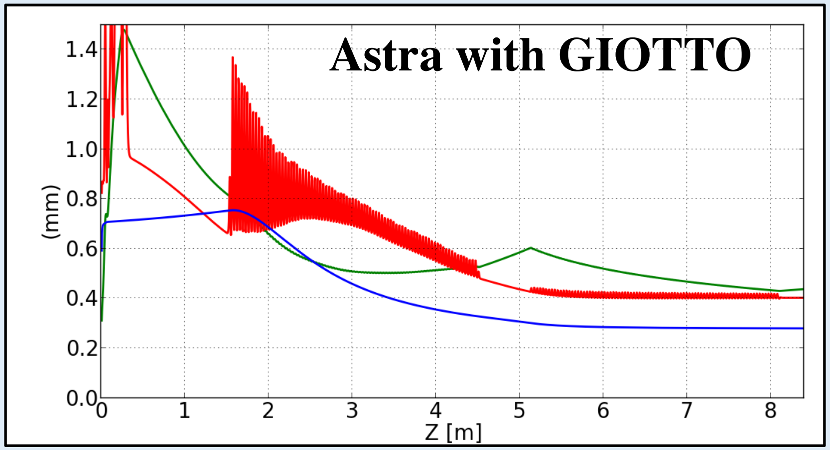


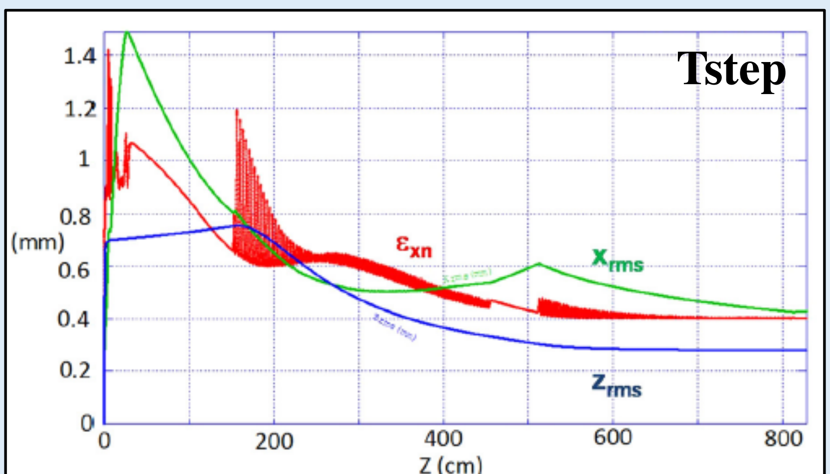
σ_z < 280 µm @ the injector exit

Result: GIOTTO optimization on merit factors (booster's injector)

Comparison using **Tstep** (a Parmela heir) & **Astra** codes

1) A space charged dominated region needs a double check
2) Astra gives the possibility to use Giotto (Giotto improves 30-60 %)





Astra

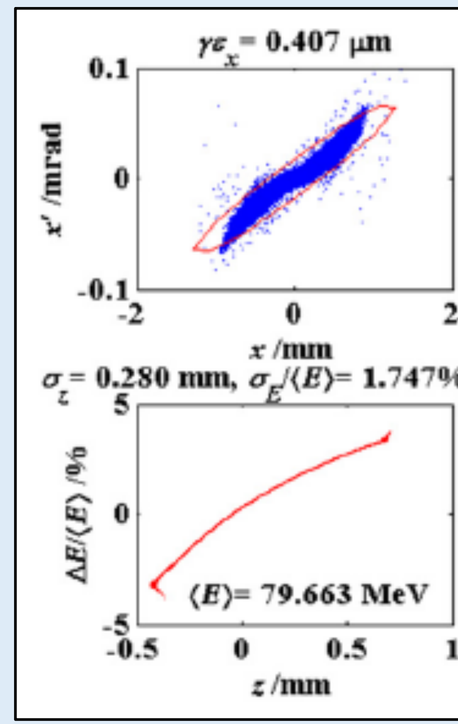
γε =0.4 μm

<E>=79.8 MeV

σ_z= 0.279 mm

σ_E/<E> = 1.65%

Tstep



Injector jitters analysis

a full S2E:

Injector → C Booster → γ-Source

Astra → Elegant → Cain

ELI-NP booster's Injector Jitters (**9 parameters**)

Jitters kept in Consideration in GIOTTO:

RF:

- 200 fs Phase (overestimated): **(1)** Gun & **(2,3)** TW cavities (S- band)
- 2‰ in pick field: **(4)** Gun & **(5,6)**TW cavities (S- band)

laser:

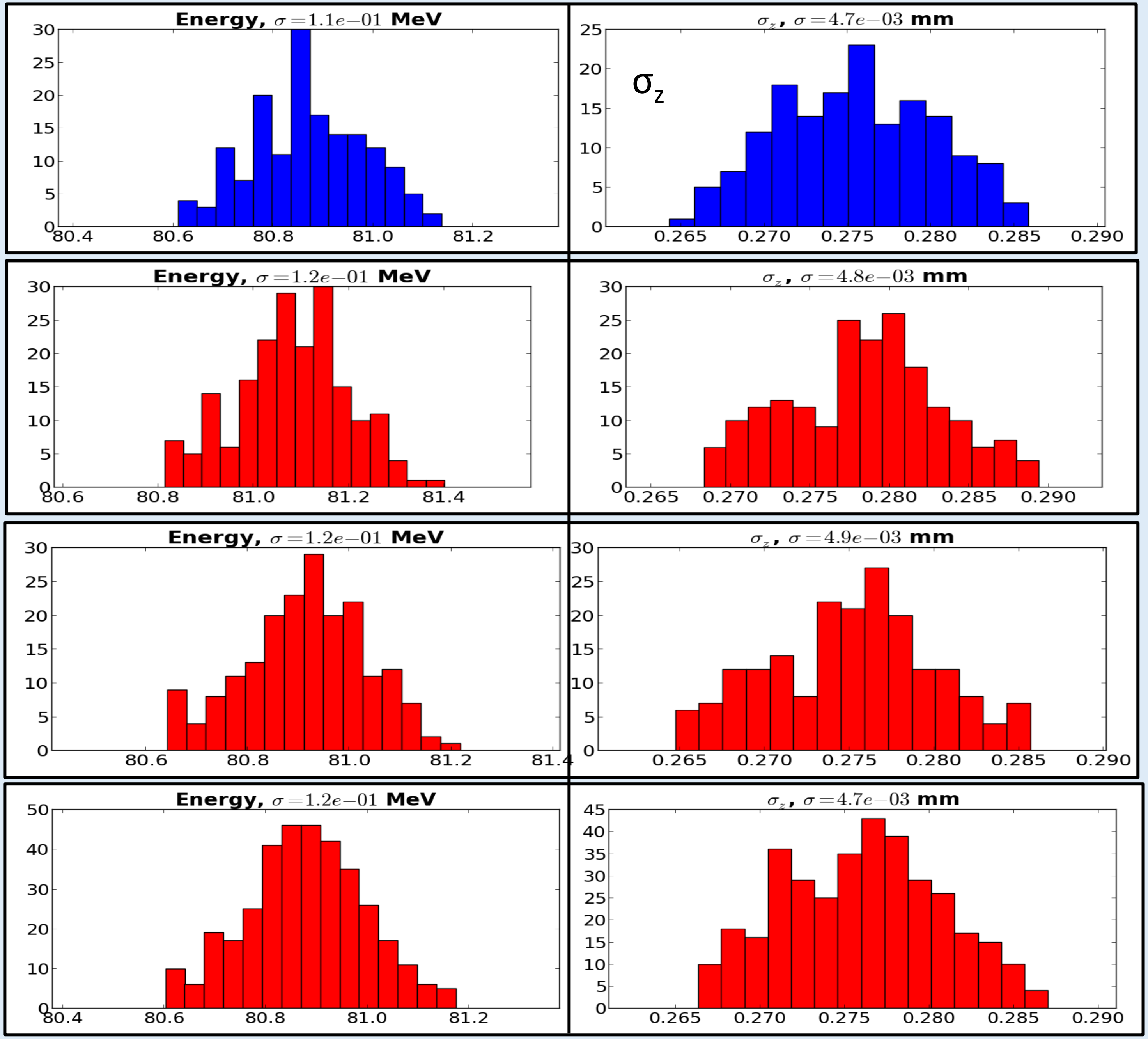
- **(7)** 200 fs arrival time
- **(8)** 20 μm pointing instabilities (on cathode)
- **(9)** 5% energy fluctuation (Charge fluctuation)

Different Machines:

+/- 70 μm as misalignments for: RF Cavities, Gun Solenoid, TW Solenoid

Uniform distributions Jitters; a very conservative choice

ELI-NP Injector Jitters Analysis – Energy & Bunch length



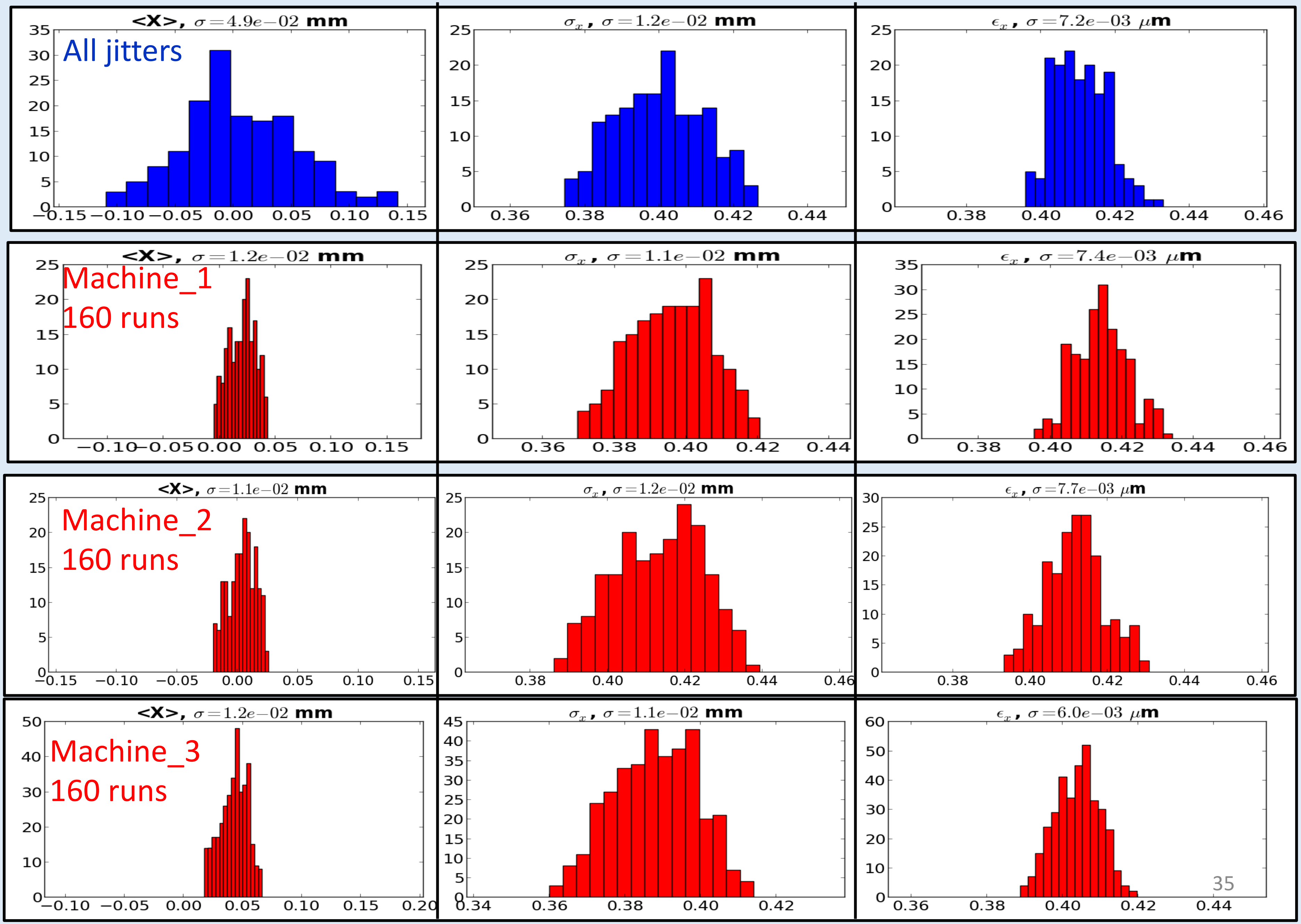
All jitters

Machine_1
160 runs

Machine_2
160 runs

Machine_3
160 runs

ELI-NP Injector Jitters Analysis – Centroid, Envelope, Emittance



In Conclusion

Genetic Algorithms show **great promise** in the **Beam Dynamics** optimization and **problem solution**.

GIOTO has been applied successfully to:

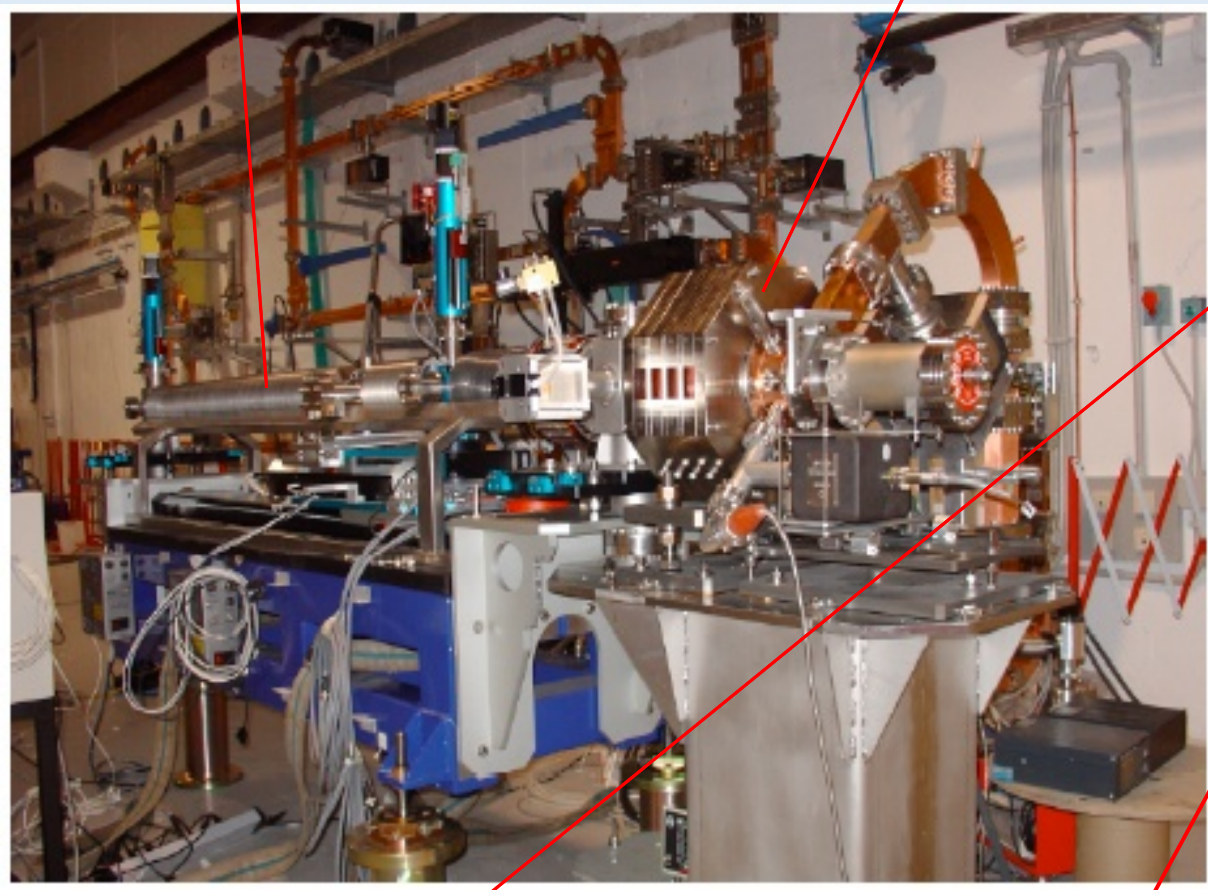
- refine known beam lines, with improvements around 20-40 % (in the performances)
- have been used to find completely new schemes, as in case of the hybrid velocity bunching

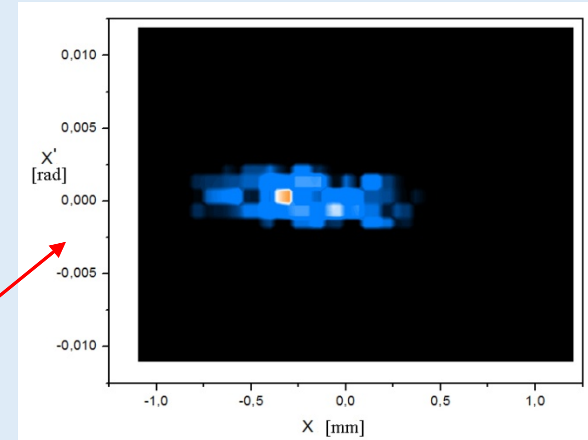
Thanks for your attention

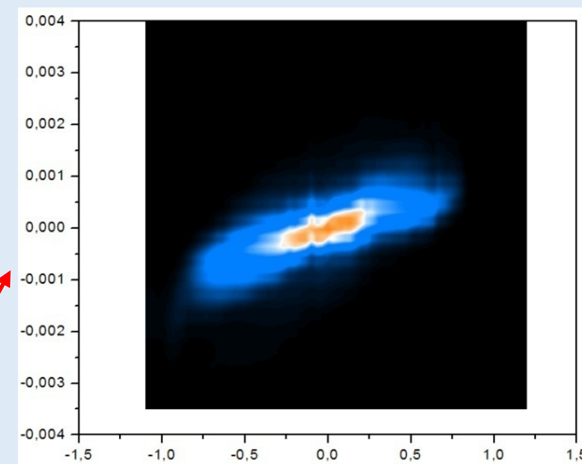
Demand of EXTREME HIGHT QUALITY electron beams doesn't stop and often it makes necessary to cope with strong space charge

Beam-Line optimization is Nowadays really a critical issue

Emittanzometro RF-Gun 1.6 S-band 120 MV/m



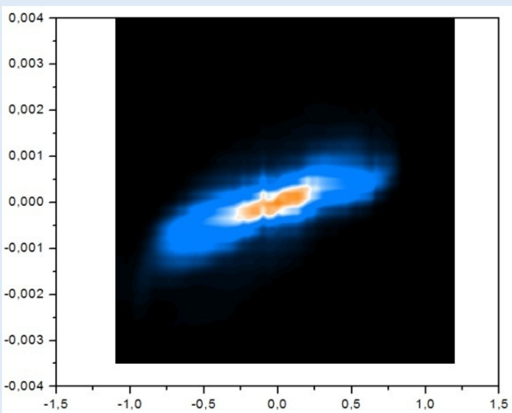


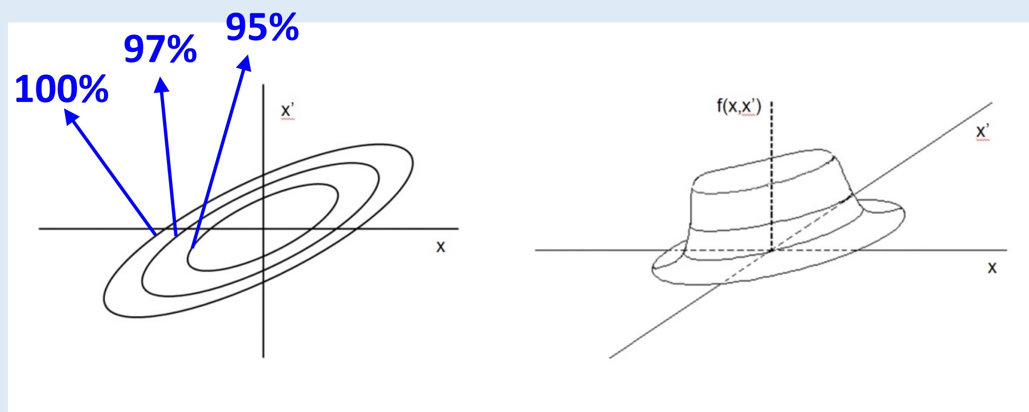


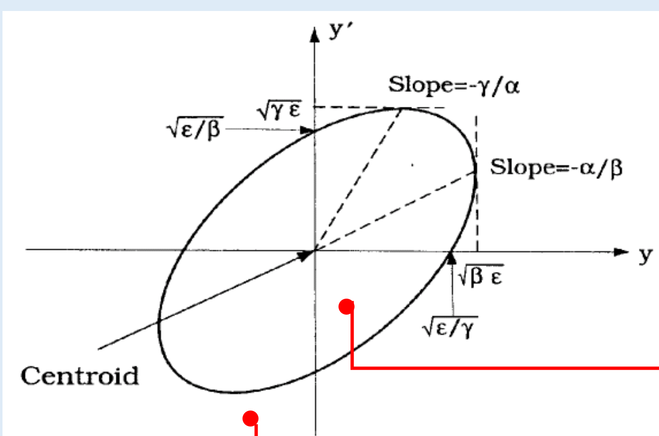
Emittanzometro's data are handled by a dedicate algorithm that return an **intensity matrix** PhaseSpace.txt (successively **interpolated** to increase the definition)

Emittance in Real Beam

Since real beams usually do not have well defined boundaries, a method for calculating the emittance, is to choose a specific density contour, in the phase space, that represents from the **50% (worst cases)** up to the **98-99% (best cases)** of the whole bunch charge (or integrated intensity). Within this density contour and under certain conditions, such emittance satisfies the Liouville's theorem and thus is conserved







$$\gamma x^2 + \beta y^2 + 2\alpha xy = \varepsilon$$

$$\gamma\beta - \alpha^2 = 1$$

$$\varepsilon = \frac{area}{\pi}$$

GMESA normalization

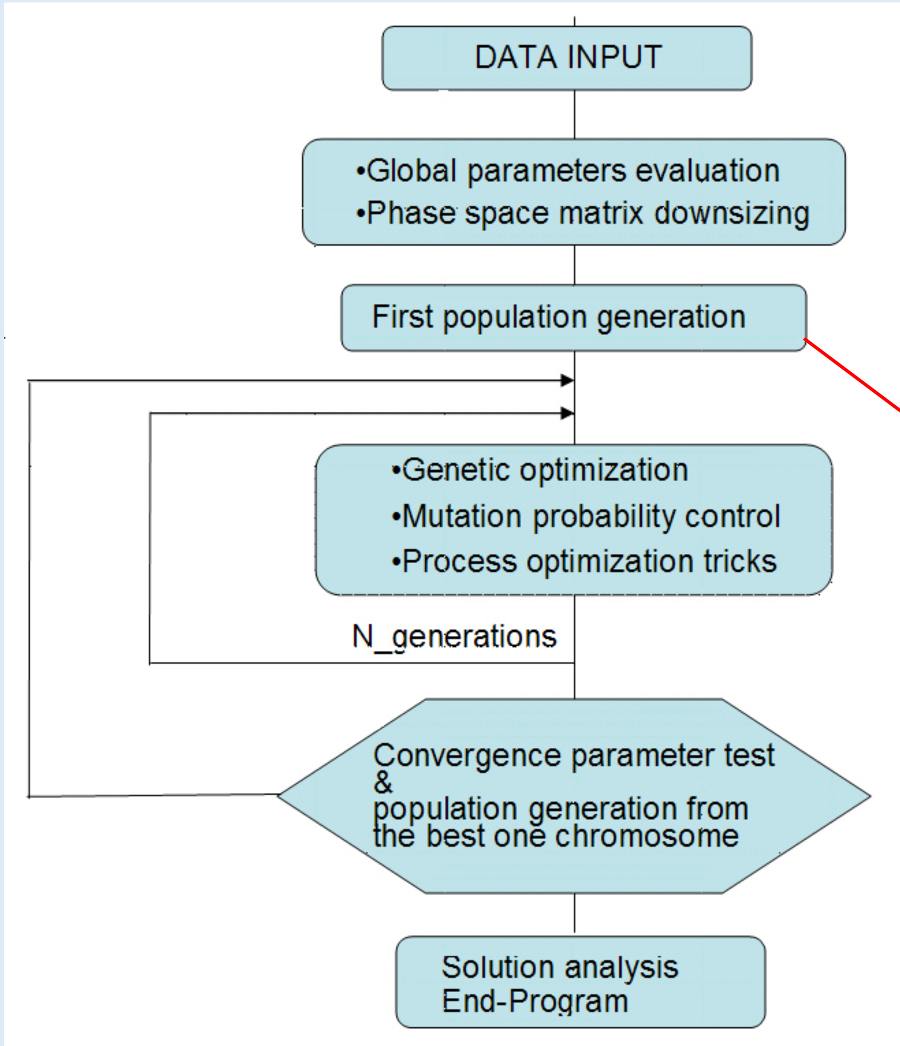
$$gx^2 + by^2 + 2axy = 1$$

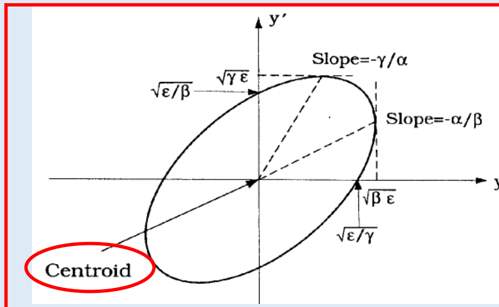
$$gb - a^2 = \frac{1}{\varepsilon^2}$$

$$g = \frac{\gamma}{\varepsilon}, \quad b = \frac{\beta}{\varepsilon}, \quad a = \frac{\alpha}{\varepsilon}$$

$$gx^2 + bx'^2 + 2axx' < 1$$

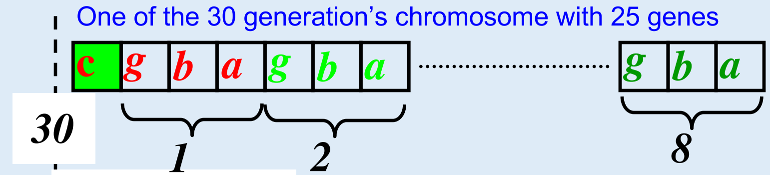
$$gx^2 + bx'^2 + 2axx' > 1$$

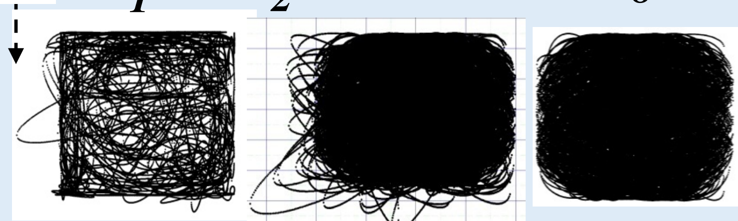




$$gx^2 + by^2 + 2axy = 1$$

$$g = \frac{\gamma}{\varepsilon},\ b = \frac{\beta}{\varepsilon},\ a = \frac{\alpha}{\varepsilon}$$



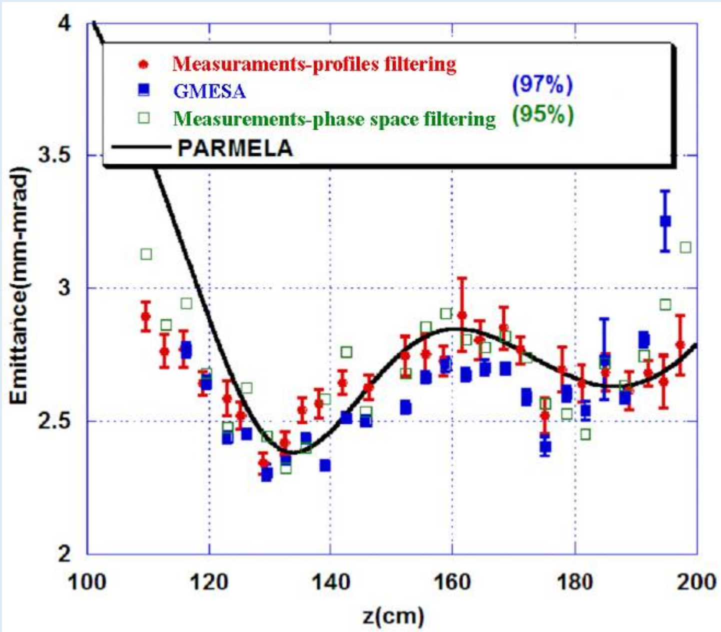


The space phase ellipse's sampling is a thorny issue as uniformity and dimension. A **shuffled** uniform random generator is used.

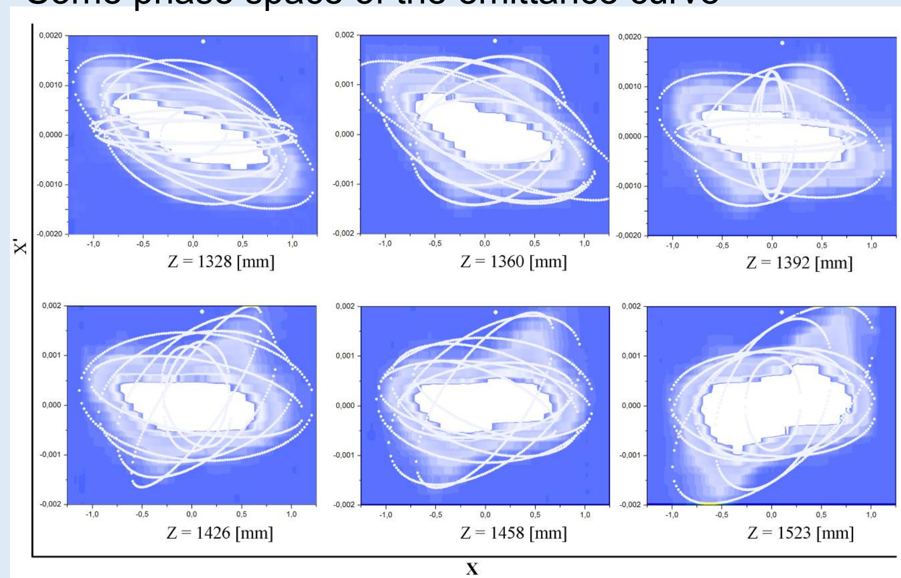
$$F_{fitness} = \frac{I}{A_d}$$

Data analysis at SPARC - *Some relevant results*

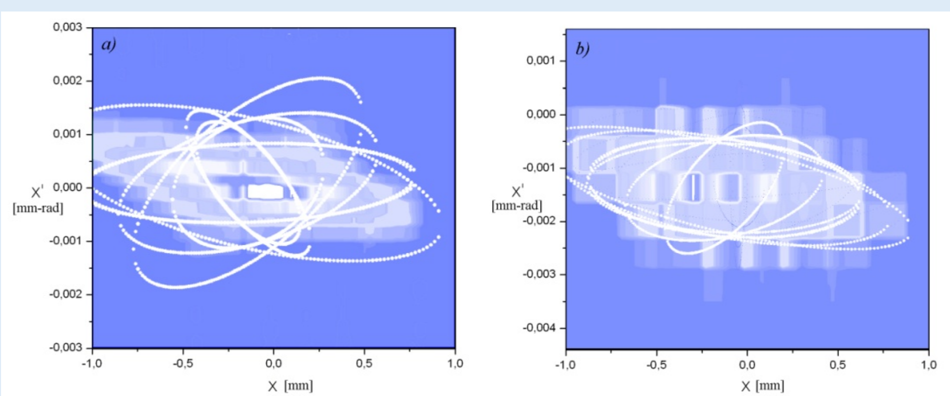
One of the more significant curve - analyzed also with two other methods - that shows a strongly marked double minimum



Some phase space of the emittance curve



From first tests the code seemed to be able to analyze the rough phase space images, not yet interpolated

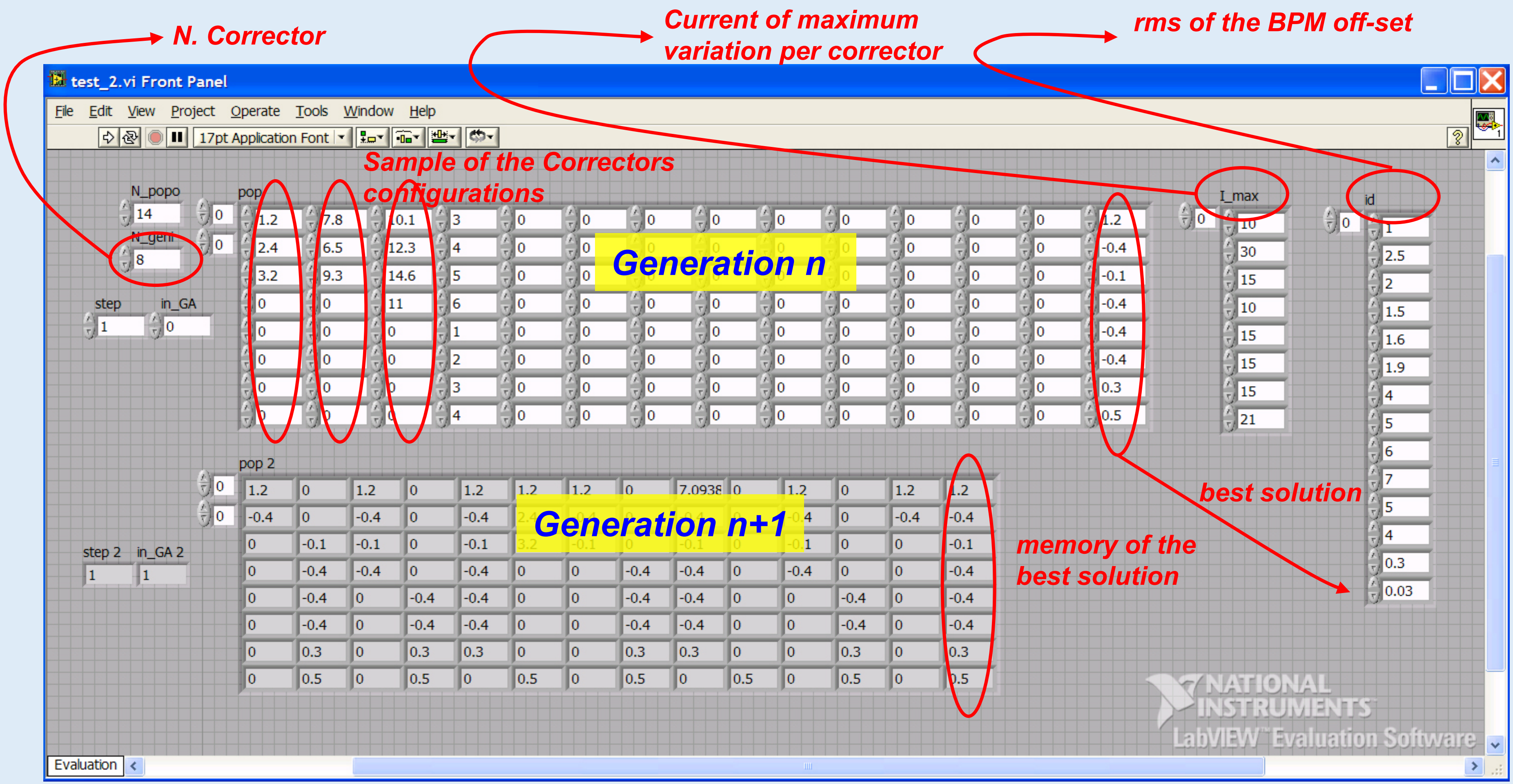


An output file

```
Coordinate del centro dell'ellissi:
X_c= 3.67236547E-02 X'_c= 7.84265576E-05
Emittanza rms al 100% della matrice centrata in 0,0= 2.23044437E-04
Emittanza rms al 100% della matrice centrata in X_c,Y_c= 2.23232026E-04

EQ. ELLISSE  1 :
2.01641560 *X^2+2* 296.490082 *X*X'+ 2428111.25 X'^2= 1
gamma= 2.01641560    gamma-normalizzato =  9.19580809E-04
beta= 2428111.25    beta-normalizzato =  1107.33350
alfa= 296.490082    alfa-normalizzato =  1107.33350
emittanza analitica =  4.56047273E-06

EQ. ELLISSE  8 :
1.98872209 *X^2+2* -296.490082 *X*X'+ 863863.063 X'^2= 1
gamma= 1.98872209    gamma-normalizzato =  1.55765051E-03
beta= 863863.063    beta-normalizzato =  676.613770
alfa= -296.490082    alfa-normalizzato =  676.613770
emittanza analitica =  7.83241936E-06

Percentuale della carica raccolta= 97.0004120 %
Emittanza rms unione dell'ellissi - [massima stima] - non normalizzata =  2.09415637E-06  [mm-mrad]
Emittanza rms senza l'Area_buio   - [minima stima] - non normalizzata =  2.06715064E-06  [mm-mrad]
Area_Intensita'_nulla =  2.27432990 [% dell'Area numerica totale]
Area numerica= 5.23847807E-05 Emittanza numerica A_num/pi= 1.66745926E-05 [mm-mrad]
```

BPM and Genetic control of the steering correctors *A code to compute the rms emittance of high brightness electron beams*

Developing of a dynamic link library (dll), in fortran 90, that can interface with LabView



from simulations it converges to 0.200 mm of maximum off-set after 80 generation

Considering 2s to test each configuration → 36 minutes

The real world could be faster

ant colony optimization