Multi Objective Genetic Optimization of Linac Beam Parameters for a Seeded FEL
[TUABC3]

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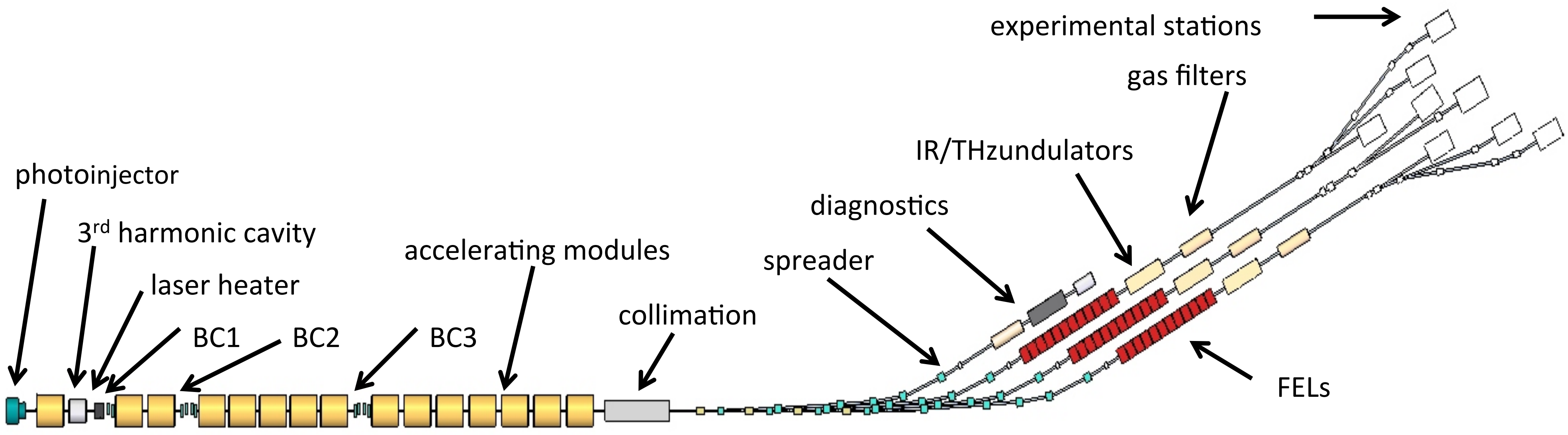
- FEL linac
  - generalities
  - case study: the New Light Source (NLS) setup
  - objectives and knobs for optimization
- Multi Objective Genetic Algorithm (MOGA) approach
  - start-to-end simulation
  - results on NLS 3BC case
  - variations with
    - fewer bunch compressors
    - different initial charge
- conclusion and future development

General Layout for an X-Ray FEL
electron Gun (n.c.)
L-band s.c. cavities (acceleration)
bunch compression (ph. space conditioning)
undulator (lasing)

High Quality Electron Beam	
energy:	few GeV
ε_N:	0.33 μm
$\Delta\gamma/\gamma$:	10^{-4}
I_{peak}:	~1kA



New Light Source (NLS) project [1]:

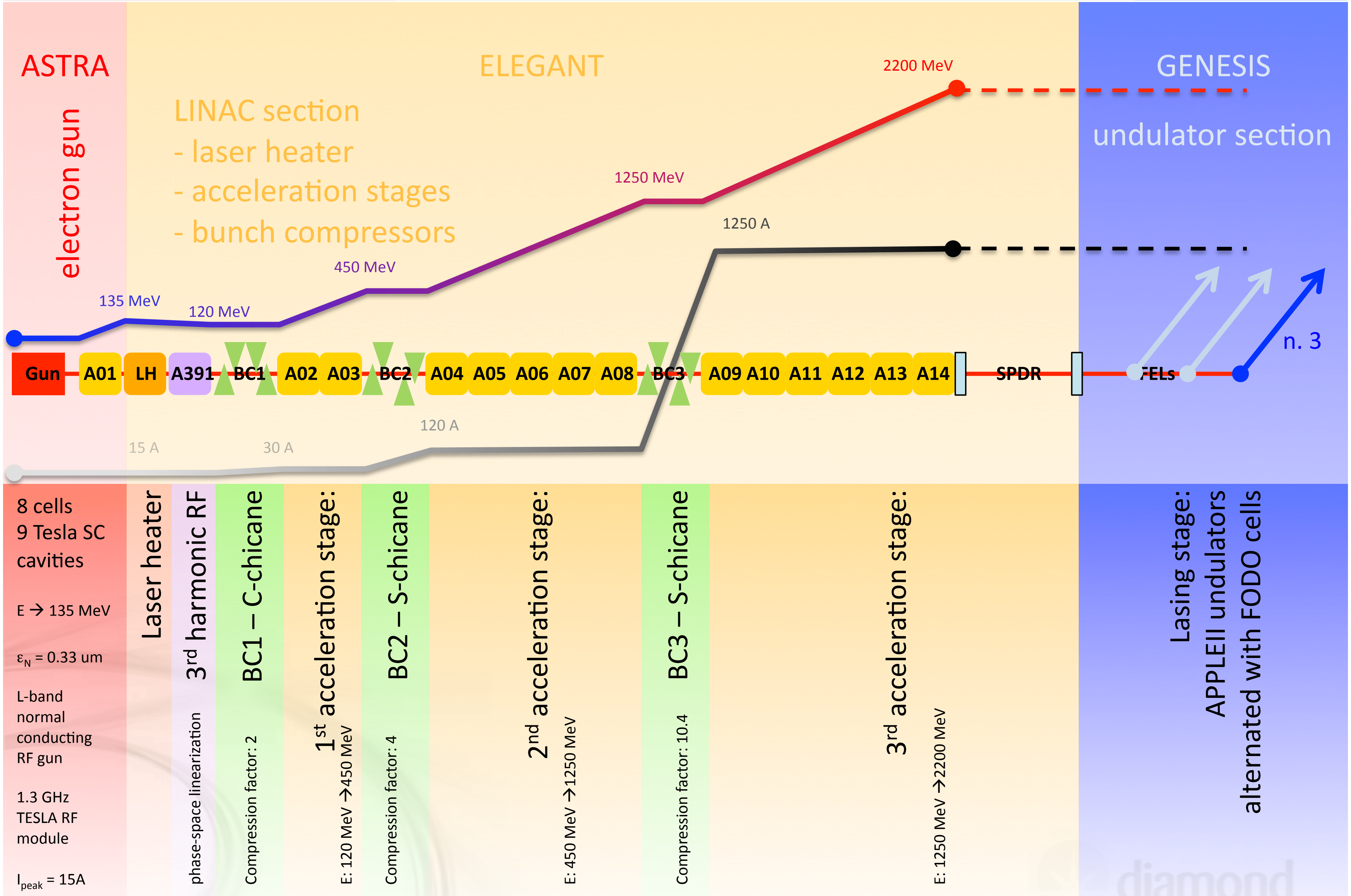
- advanced 4th generation X-ray source

- 3 seeded FELs @ different w.l.

- FEL-3: 1keV / 1.2nm (fundamental)

- 1 single LINAC

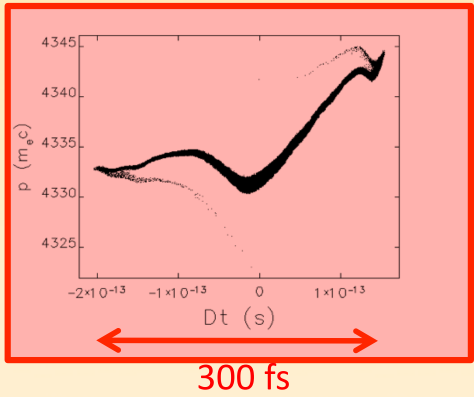
[1] NLS Conceptual Design Report (2010) in http://www.newlightsource.org.

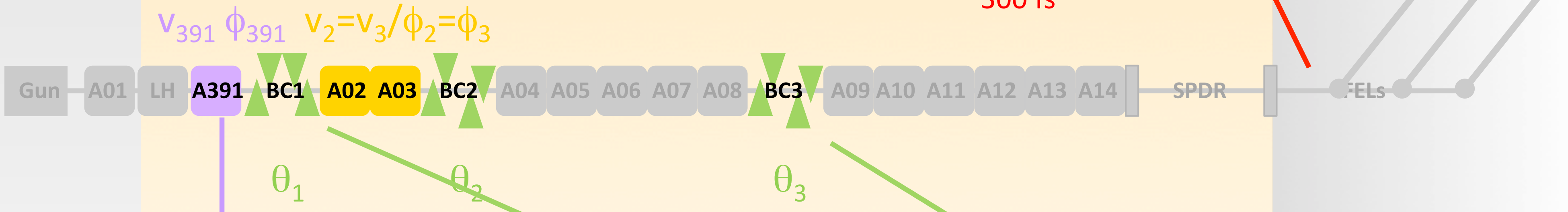

ASTRA
electron gun
ELEGANT
LINAC section
- laser heater
- acceleration stages
- bunch compressors
GENESIS
undulator section
2200 MeV
1250 MeV
1250 A
450 MeV
135 MeV
120 MeV
n. 3
Gun
A01
LH
A391
BC1
A02
A03
BC2
A04
A05
A06
A07
A08
BC3
A09
A10
A11
A12
A13
A14
SPDR
FELs
120 A
15 A
30 A
8 cells
9 Tesla SC
cavities
E → 135 MeV
εN = 0.33 um
L-band
normal
conducting
RF gun
1.3 GHz
TESLA RF
module
Ipeak = 15A
Laser heater
3rd harmonic RF
phase-space linearization
BC1 – C-chicane
Compression factor: 2
1st acceleration stage:
E: 120 MeV → 450 MeV
BC2 – S-chicane
Compression factor: 4
2nd acceleration stage:
E: 450 MeV → 1250 MeV
BC3 – S-chicane
Compression factor: 10.4
3rd acceleration stage:
E: 1250 MeV → 2200 MeV
Lasing stage:
APPLEII undulators
alternated with FODO cells

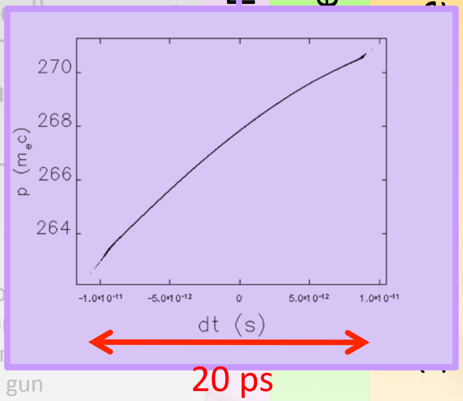
Choice of knobs

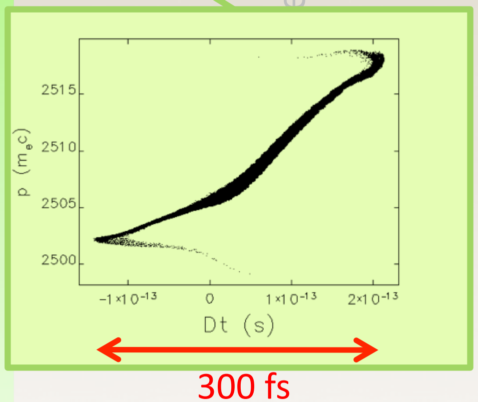
ASTRA | ELEGANT | GENESIS

LINAC section
- laser heater
- acceleration stages
- bunch compressors









θ_1 [10.47, 14.47] (°)

θ_2 [8.27, 12.27] (°)

θ_3 [5.9, 10.9] (°)

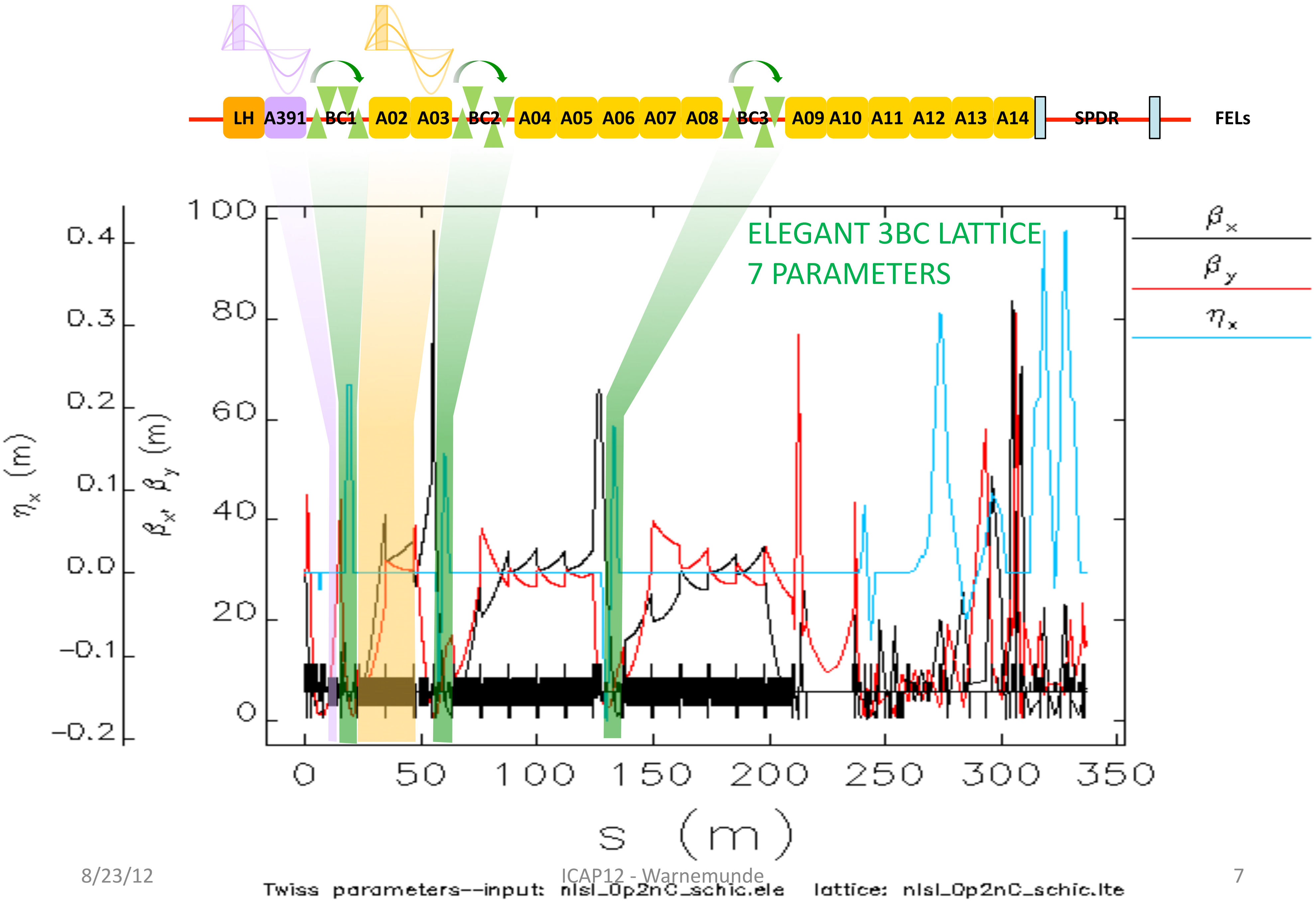
v_{391} [7.2, 9.0] (MV/m)
ϕ_{391} [170, 190] (°)

$v_2=v_3$ [19, 21] (MV/m)
$\phi_2=\phi_3$ [8, 12] (°)

undulator section

Lasing stage: APPLEII undulators alternated with FODO cells

- Warnemunde


LH
A391
BC1
A02
A03
BC2
A04
A05
A06
A07
A08
BC3
A09
A10
A11
A12
A13
A14
SPDR
FELs
ELEGANT 3BC LATTICE
7 PARAMETERS
β_x
β_y
η_x
η_x (m)
β_x, β_y (m)
s (m)
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
100
80
60
40
20
0
50
150
200
250
300
350
Twiss parameters--input: nlsl_0p2nC_schic.ele lattice: nlsl_0p2nC_schic.lte

Choice of objectives

Pierce parameter

$$\rho = \left[\frac{K^2 [JJ]^2}{32} \cdot \frac{k_p^2}{k_u^2} \right]^{1/3}$$

$$[JJ] = [J_0(\xi) - J_1(\xi)]$$

$$\xi = K^2 / (4 + 2K^2)$$

$$k_u = \text{und.wave number}$$

$$k_p = \sqrt{2 I_e / (\gamma^3 I_A \sigma_x^2)}$$

I_e = peak current

I_A = Alfven current

σ_x = rms beam size

Gain Length (1D)

$$L_g = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

Seeded FEL → bunch "uniformity"

$\sigma(L_g)$: RMS of L_g in a bunch

18 to 20 Lg to reach power saturation

Caveat: realistic beams spoils Lg!

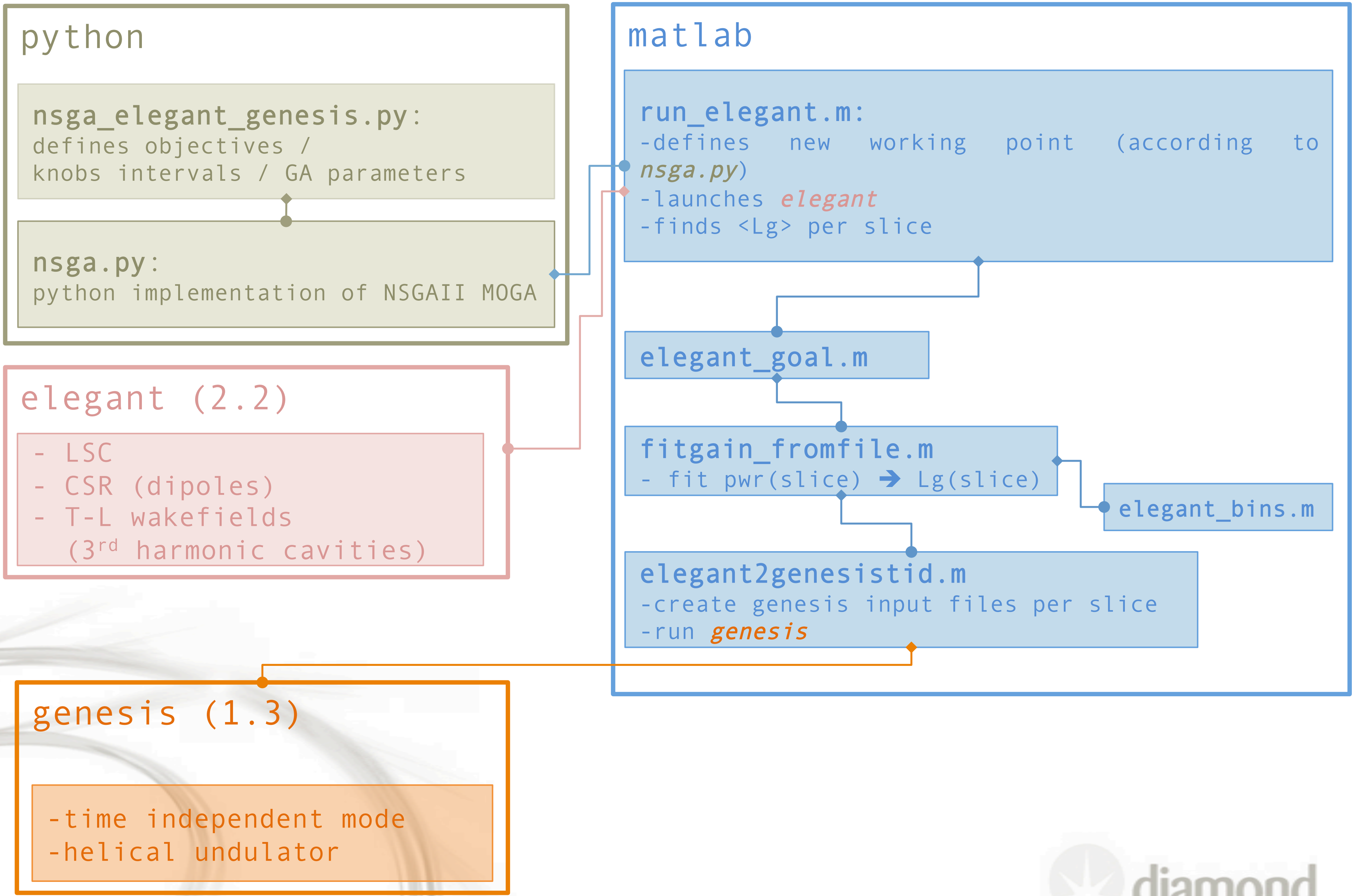
- semianalytical Xie parametrization [2]
- start-to-end simulation

[2] M. Xie, Proceedings of the 1995 Particle Accelerator Conference, Dallas (1995).

- Multi Objective Genetic Algorithm
  - used to tackle the problem of *conflicting objectives*
  - based on NSGAII algorithm [3]
  - effective: comparison with purely random search (see later)
- Strategy
  - ASTRA section: *fixed* (pre-optimized).
    - output beam at fixed charge injected into the LINAC (baseline 200pC)
  - ELEGANT section: *dynamic*.
    - knobs varied during optimization.
    - 100K particles sufficient for good characterization (*)
  - GENESIS section:
    - beam from ELEGANT injected and propagated through *undulator + FODO* structure.
    - ~~Time DEPENDENT mode challenging (time consuming in a MOGA)~~
    - Time INDEPENDENT scheme + sliced bunch analysis
    - Bunch ROI = 100 fs around centre of charge ← from time jitter studies
    - 40 slices (2.5 fs each): each fed into GENESIS

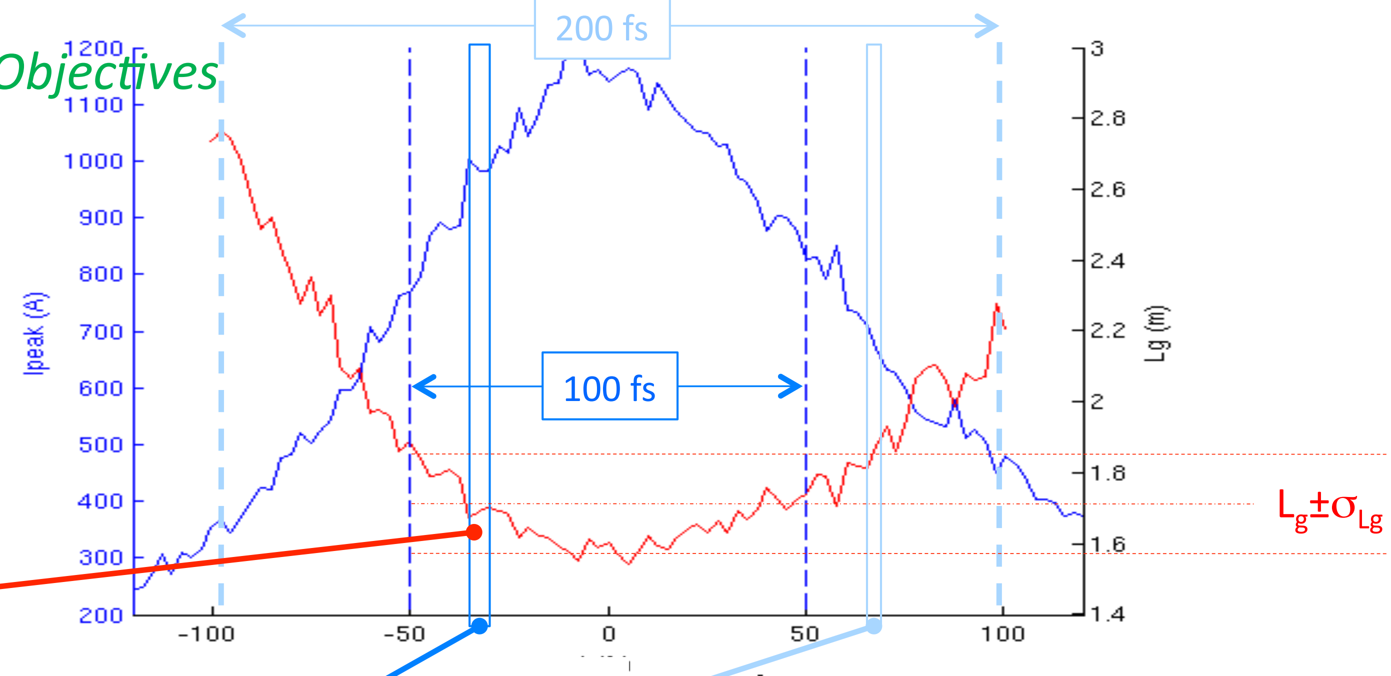
(*) quality preserved up to 2M particles

[3] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, IEEETrans. Evol. Comput. 6, 182 (2002).

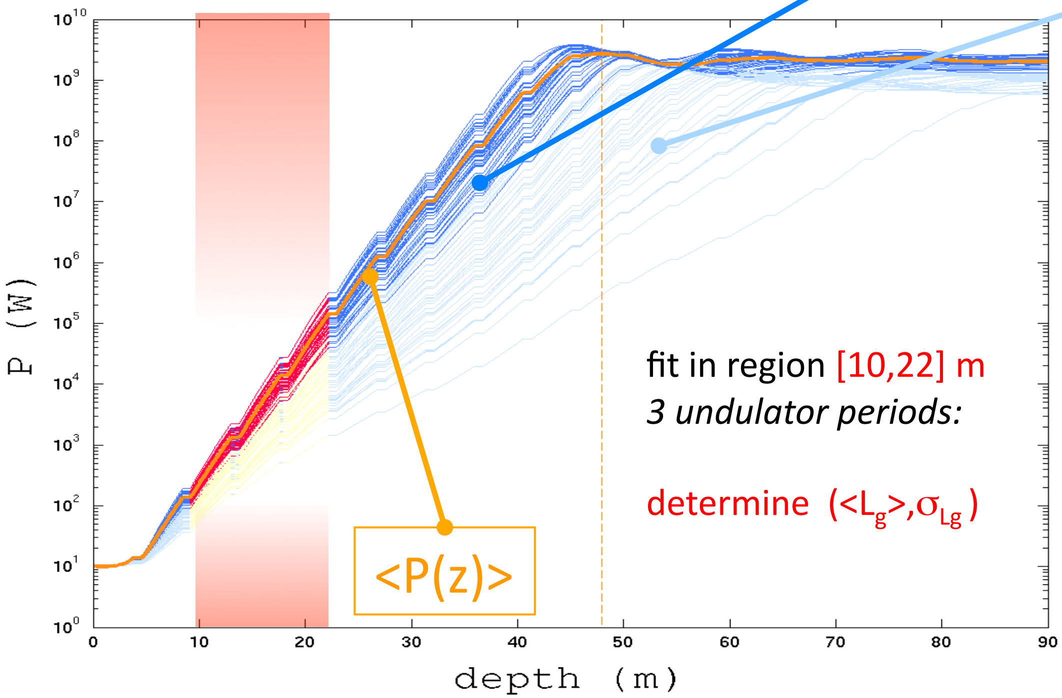

python
nsga_elegant_genesis.py:
defines objectives /
knobs intervals / GA parameters
nsga.py:
python implementation of NSGAII MOGA
elegant (2.2)
- LSC
- CSR (dipoles)
- T-L wakefields
(3rd harmonic cavities)
genesis (1.3)
-time independent mode
-helical undulator
matlab
run_elegant.m:
-defines new working point (according to nsga.py)
-launches elegant
-finds <Lg> per slice
elegant_goal.m
fitgain_fromfile.m
- fit pwr(slice) ➔ Lg(slice)
elegant_bins.m
elegant2genesistid.m
-create genesis input files per slice
-run genesis

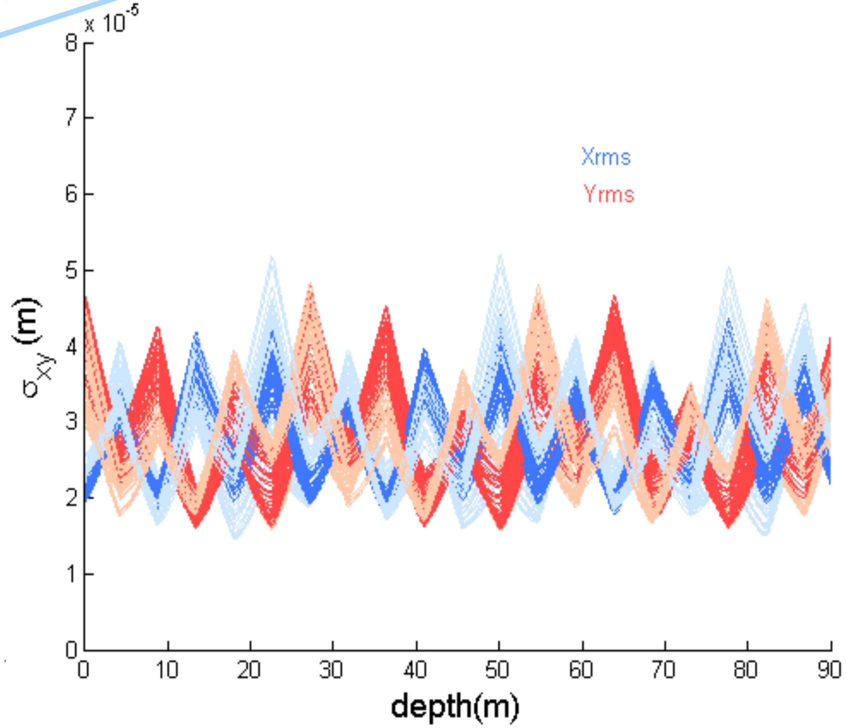
the AP Diamond Cluster	
30nodes: Xeon E5430 dual quad-core each	
2 Gb RAM / core	
200 TB Lustre File System	*high performance f.s. for linux cluster (GNU GPL v2 open license)*
Gigabit Ethernet (GbE)	*evolution of Fast Ethernet, frames transmission at 1 Gb/s*
4xDDR (20 gbps) infiniband for 24 nodes	*high performance communication link between processor nodes and I/O nodes*
Sun Grid Engine (SGE)	*batch queueing system*
Open MPI (Message Passing Interface)	*standard message passage system for parallel calculus*

Determination of Objectives

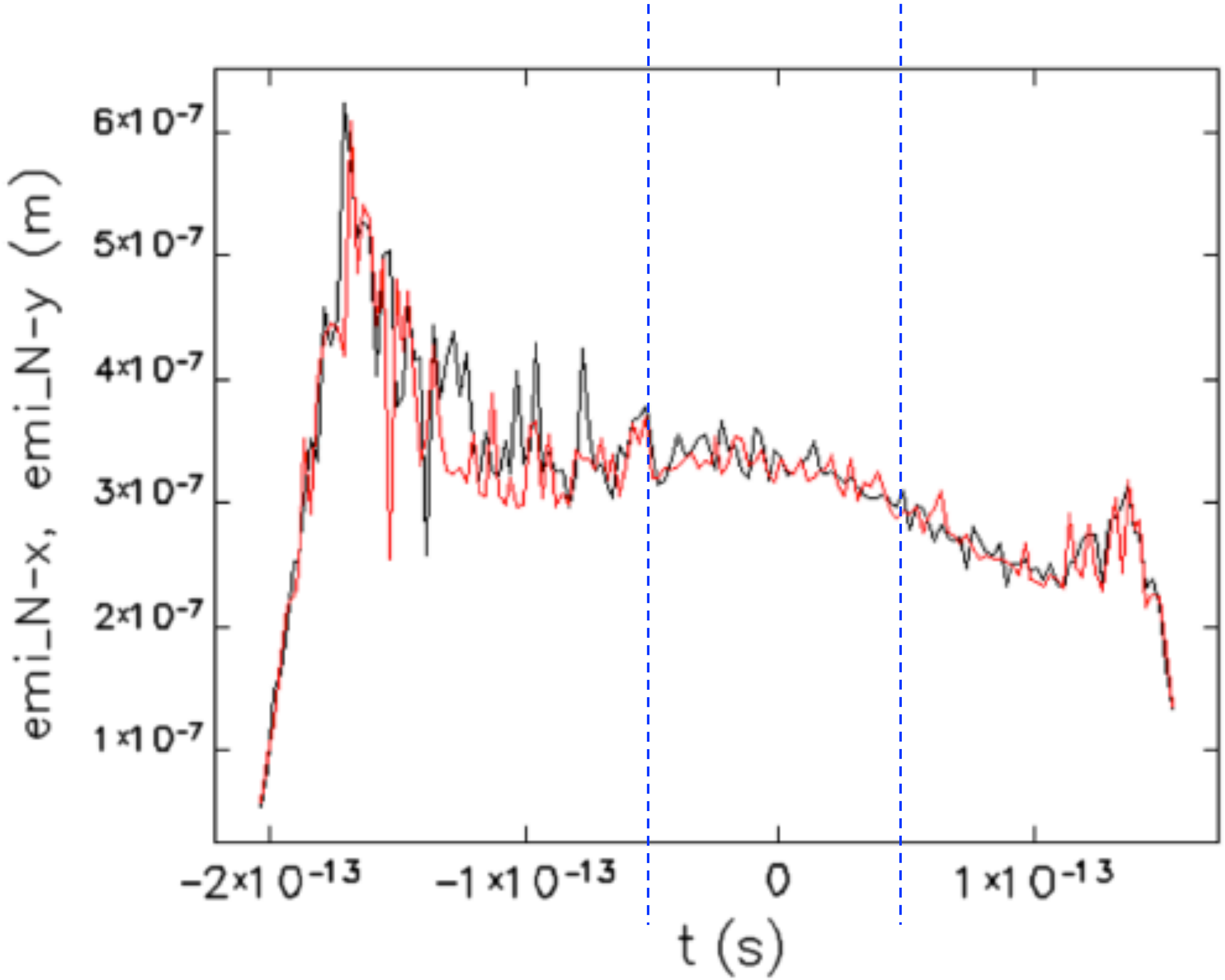


$$P \propto \exp\left(\frac{z}{L_g}\right)$$



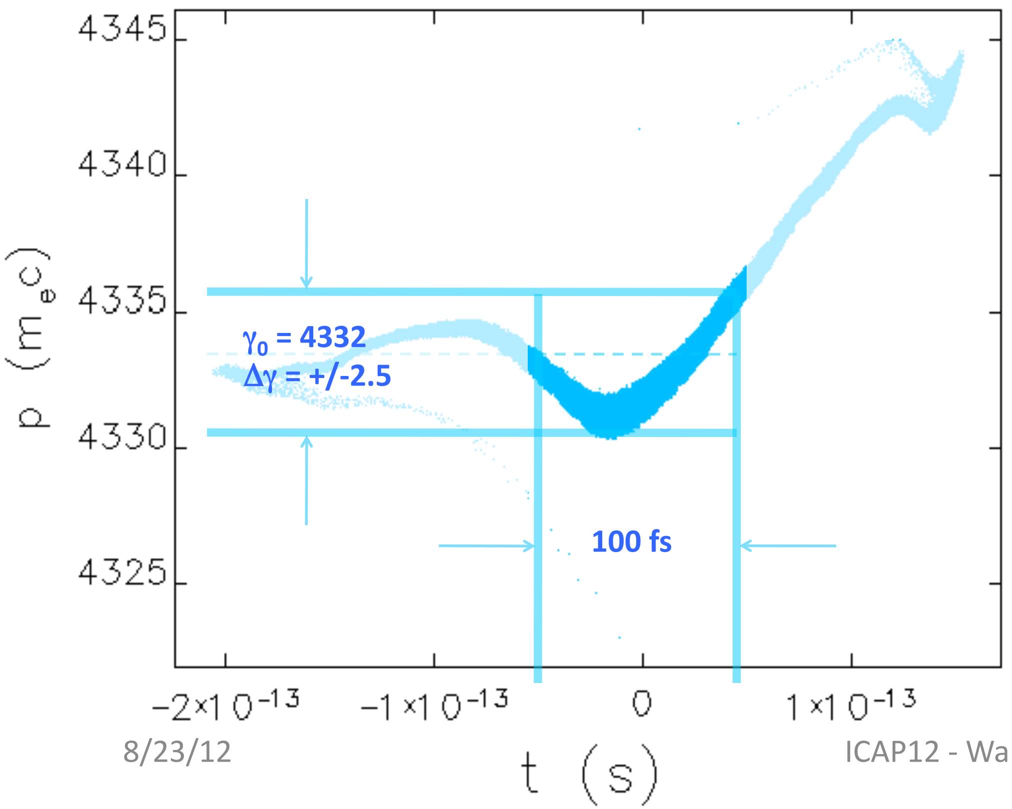


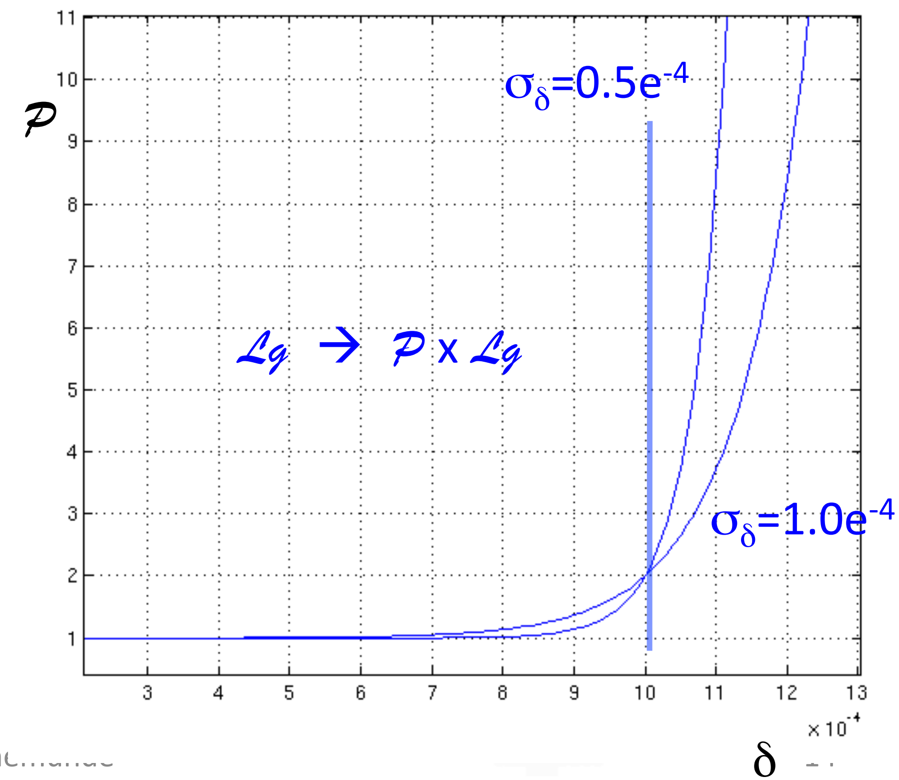
Normalized Emittance



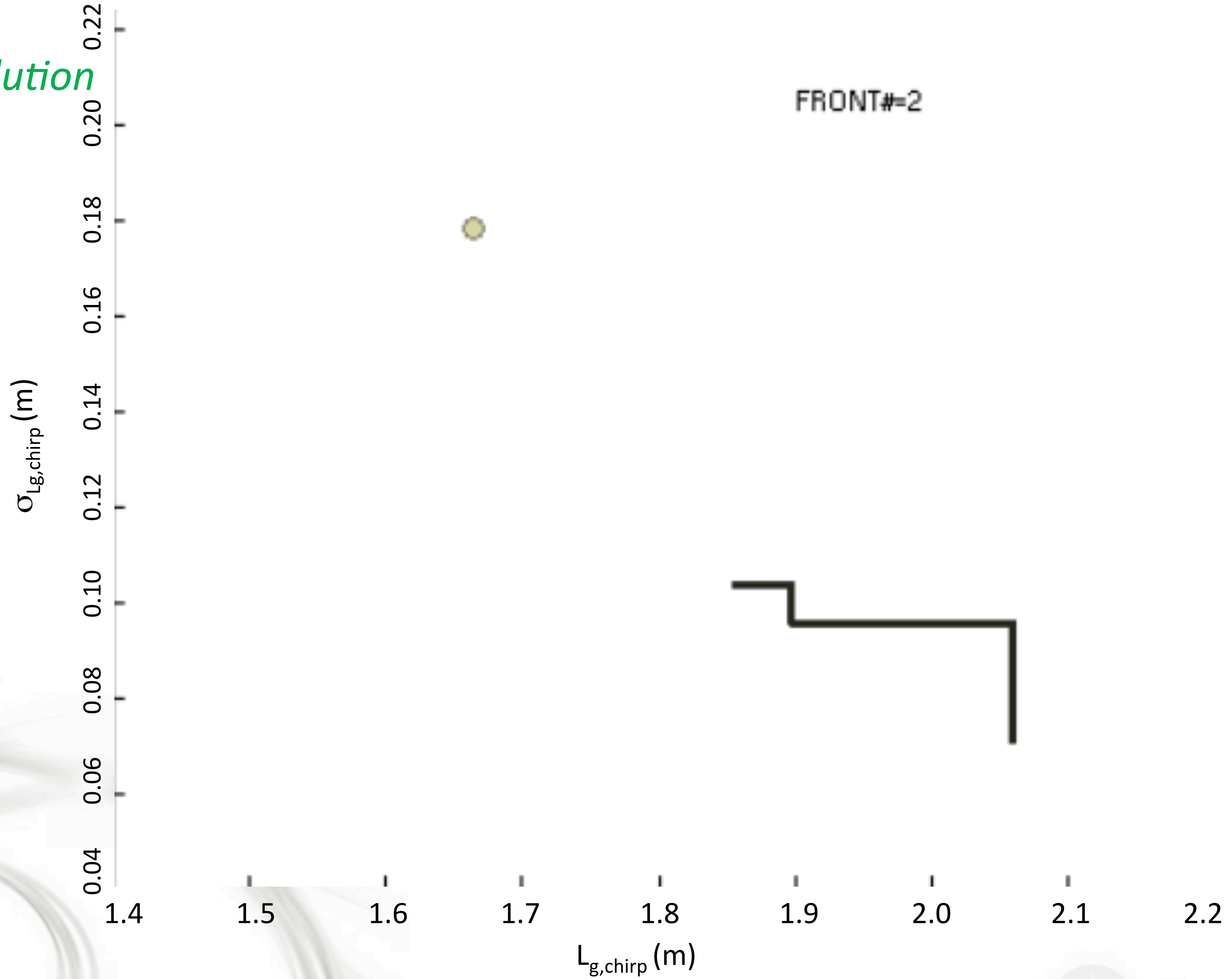
Energy chirp control – Penalty Function

$$\begin{cases} \mathcal{P} = 1 + exp\left[\dfrac{(\delta_n - \delta_{MAX})}{\sigma_\delta}\right], \\ \delta_n = \dfrac{\gamma_n - \gamma_o}{\gamma_o}, \\ \delta_{MAX} = 1‰, \sigma_\delta = 0.5 \times 10^{-4}. \end{cases}$$

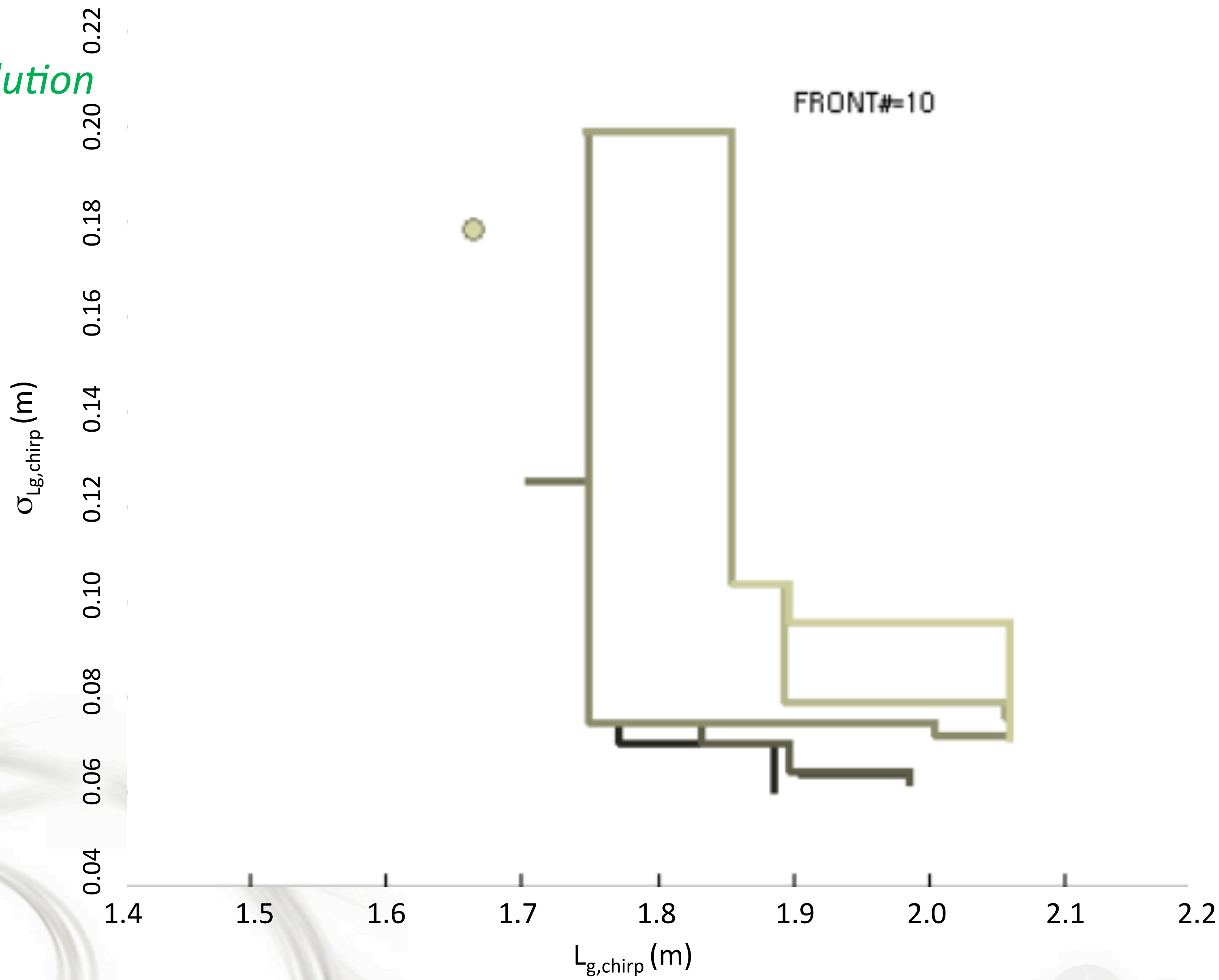




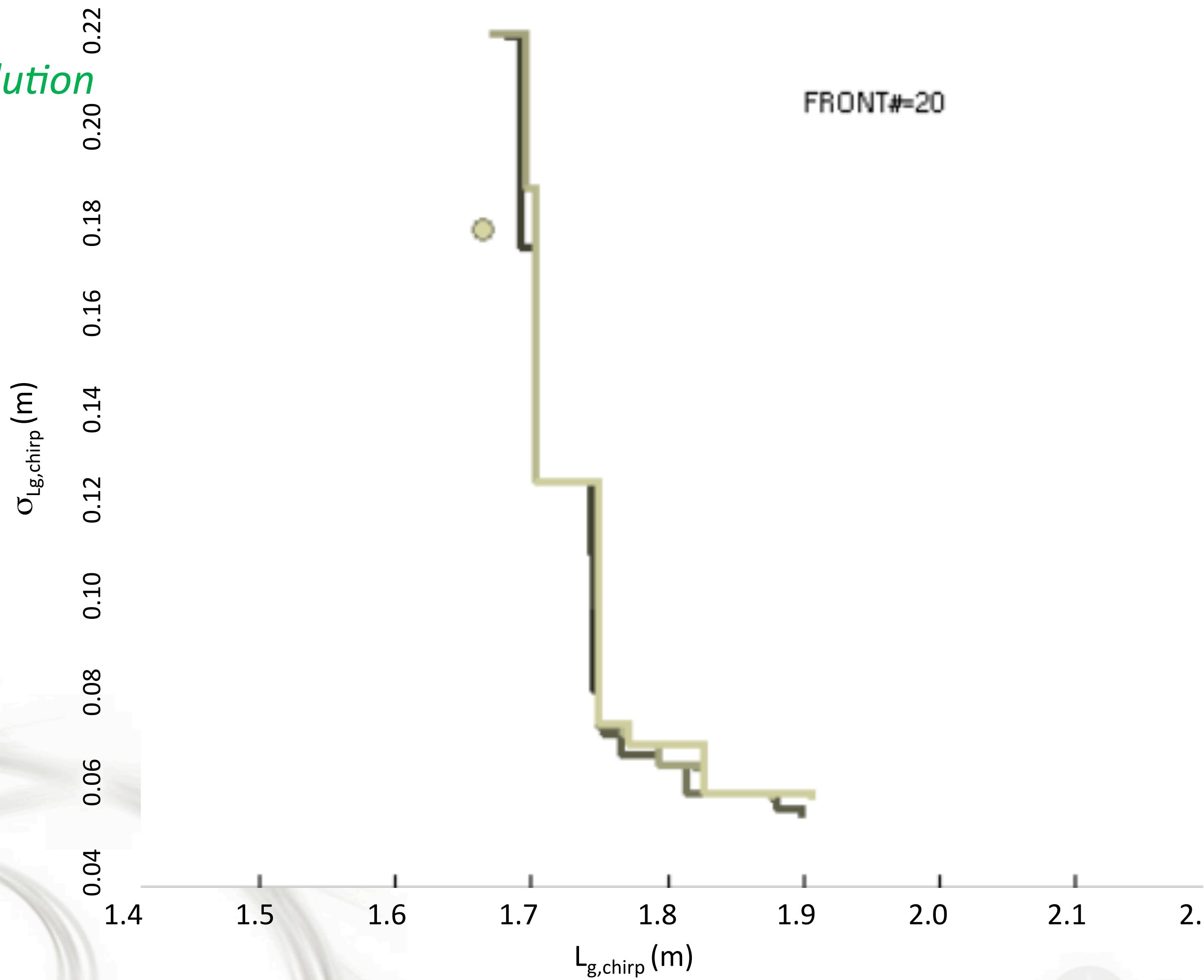
Front Evolution



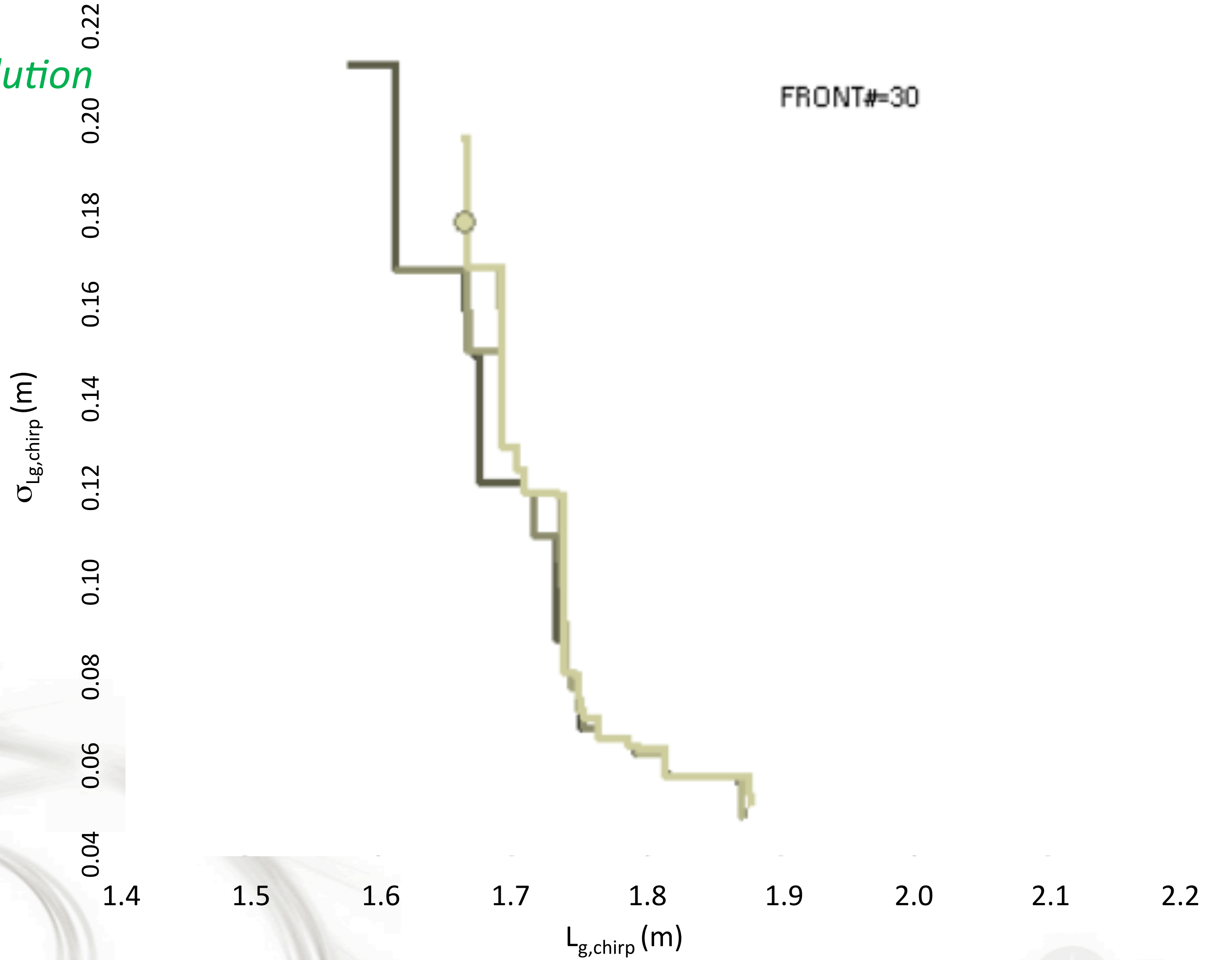
Front Evolution



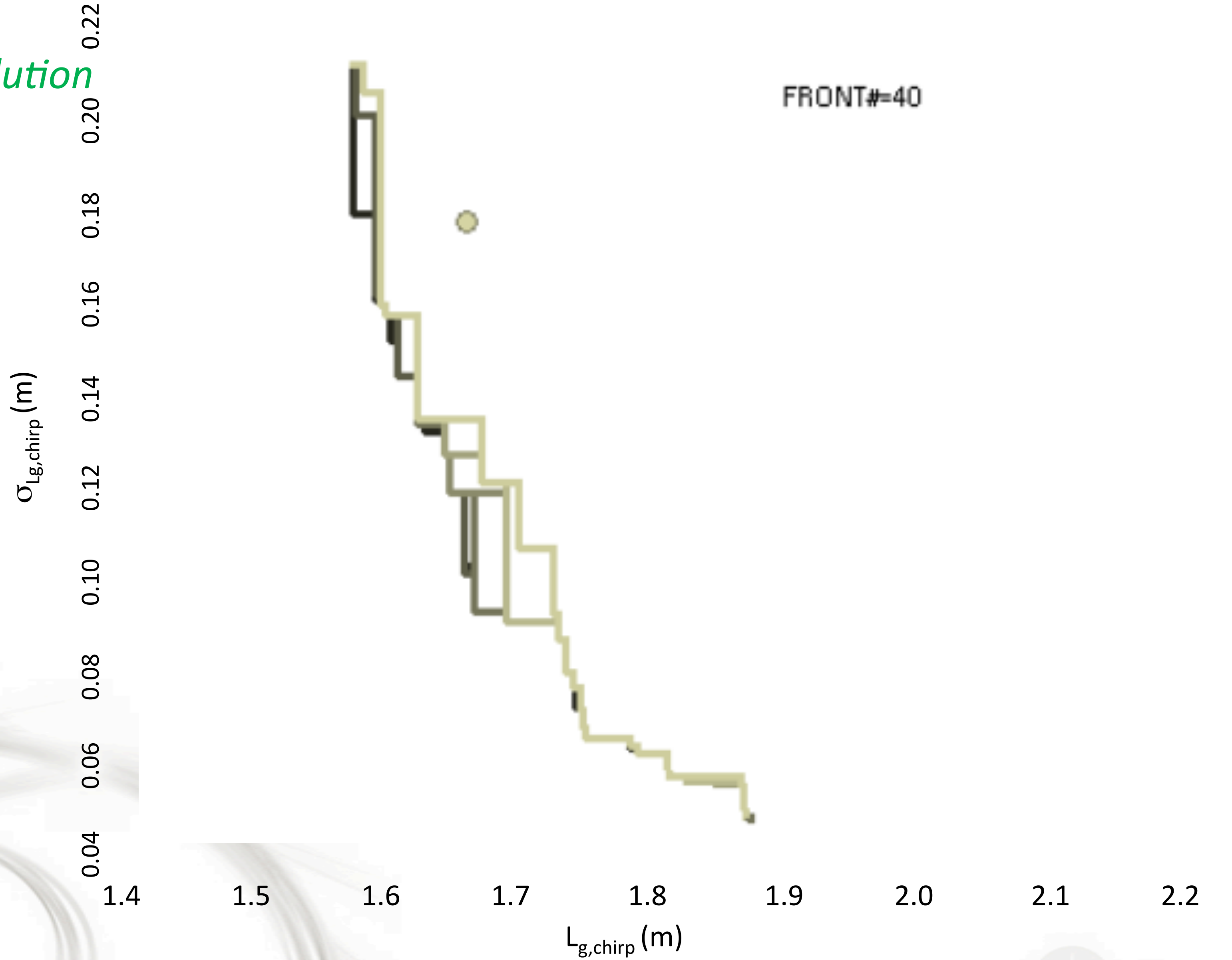
Front Evolution



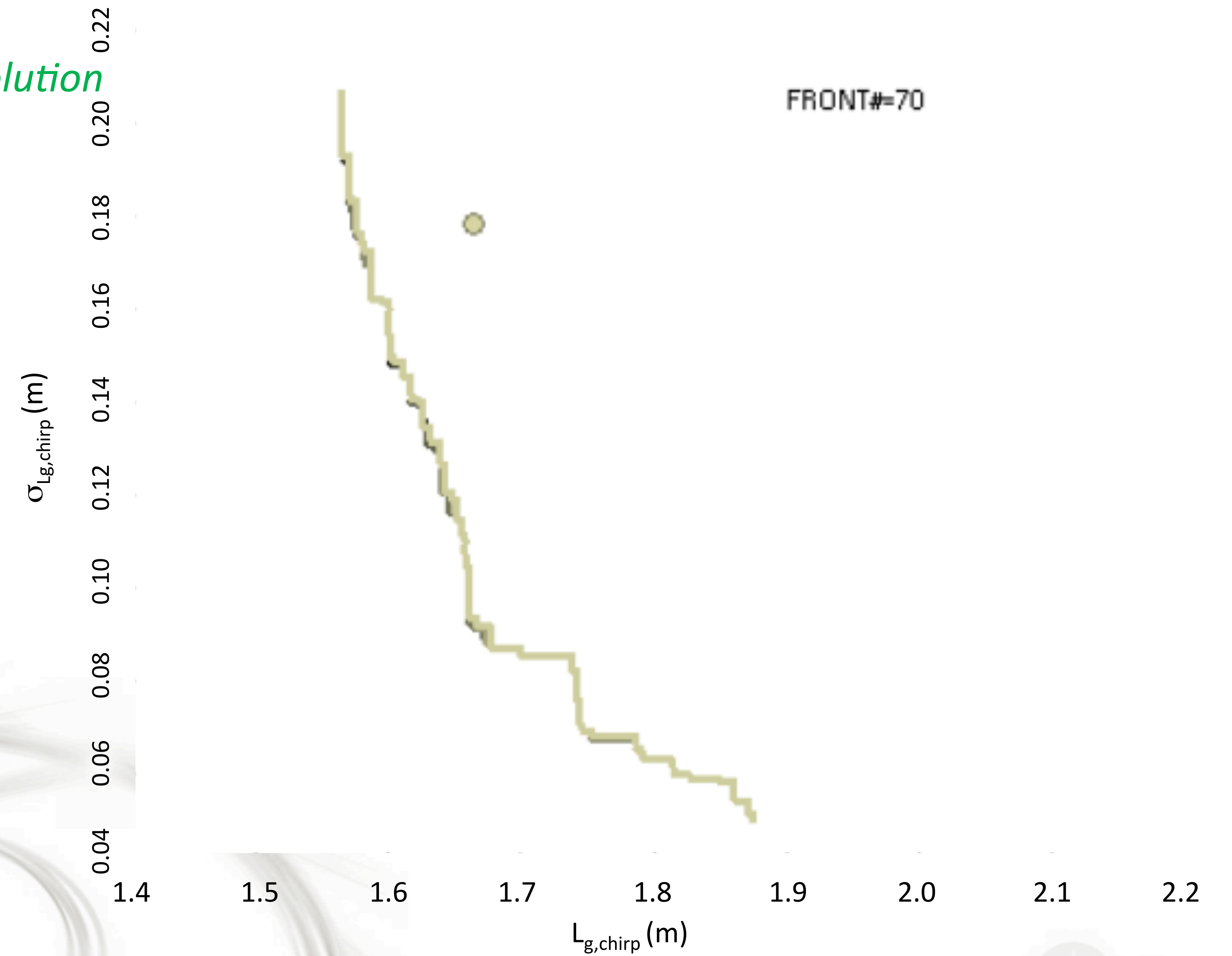
Front Evolution



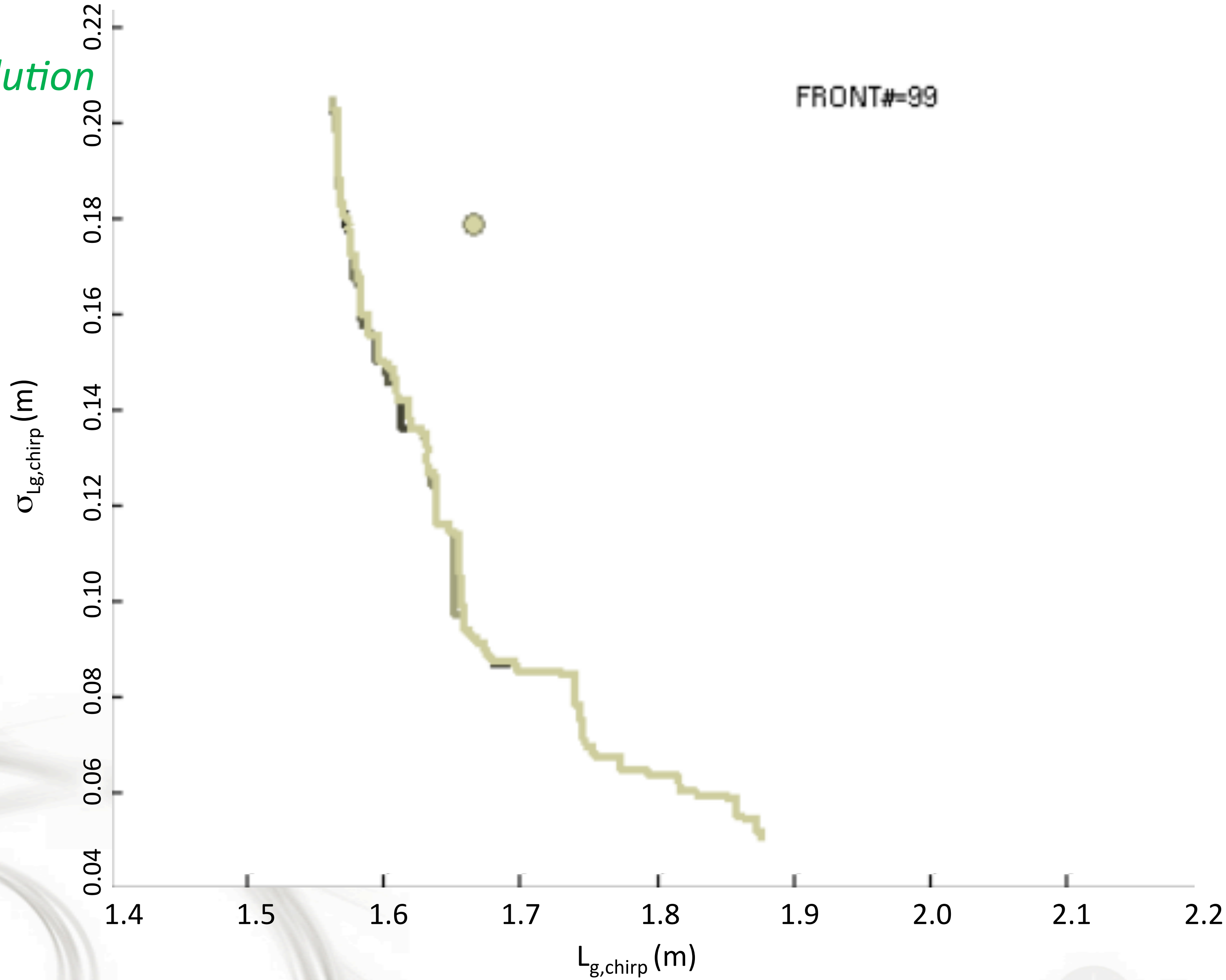
Front Evolution



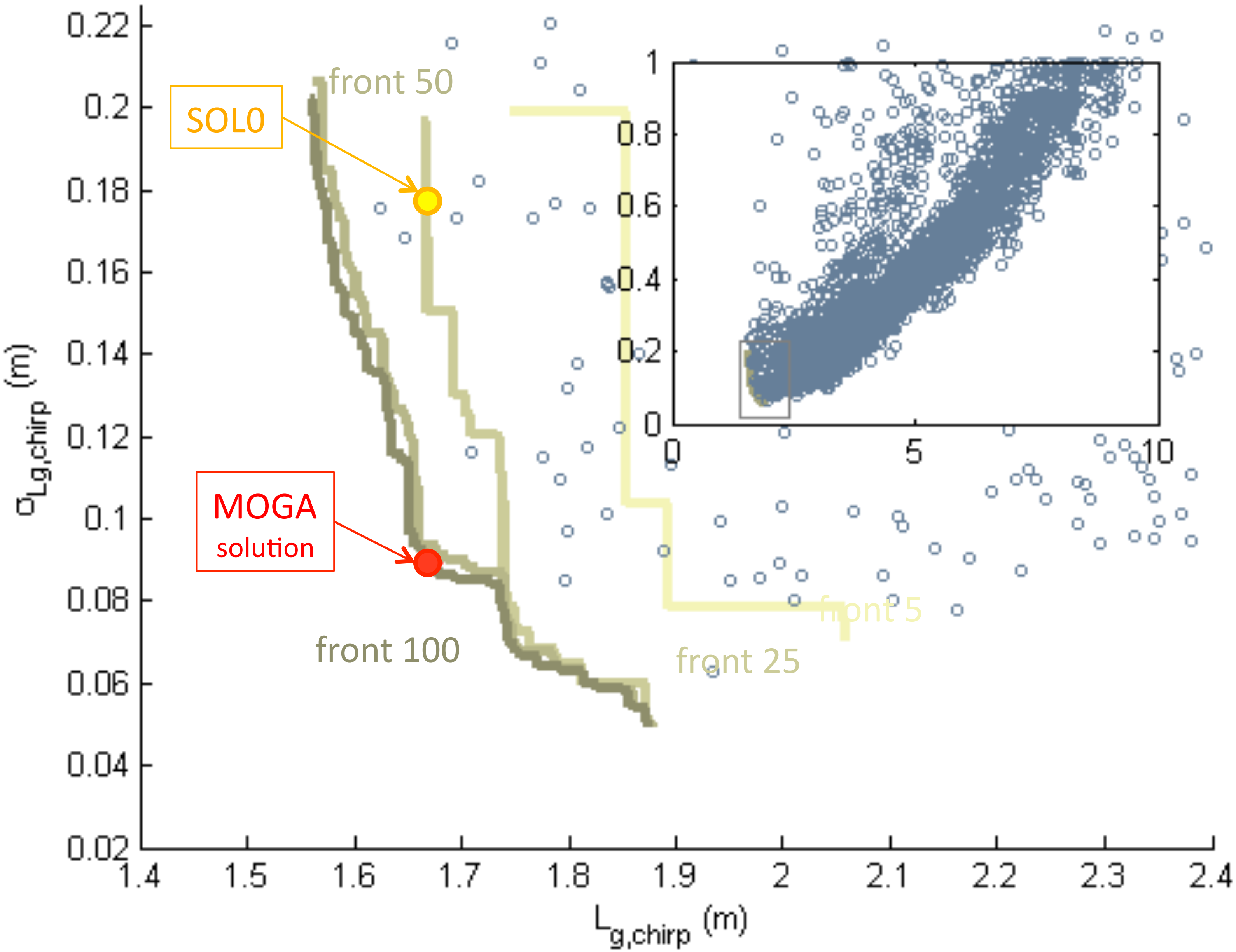
Front Evolution

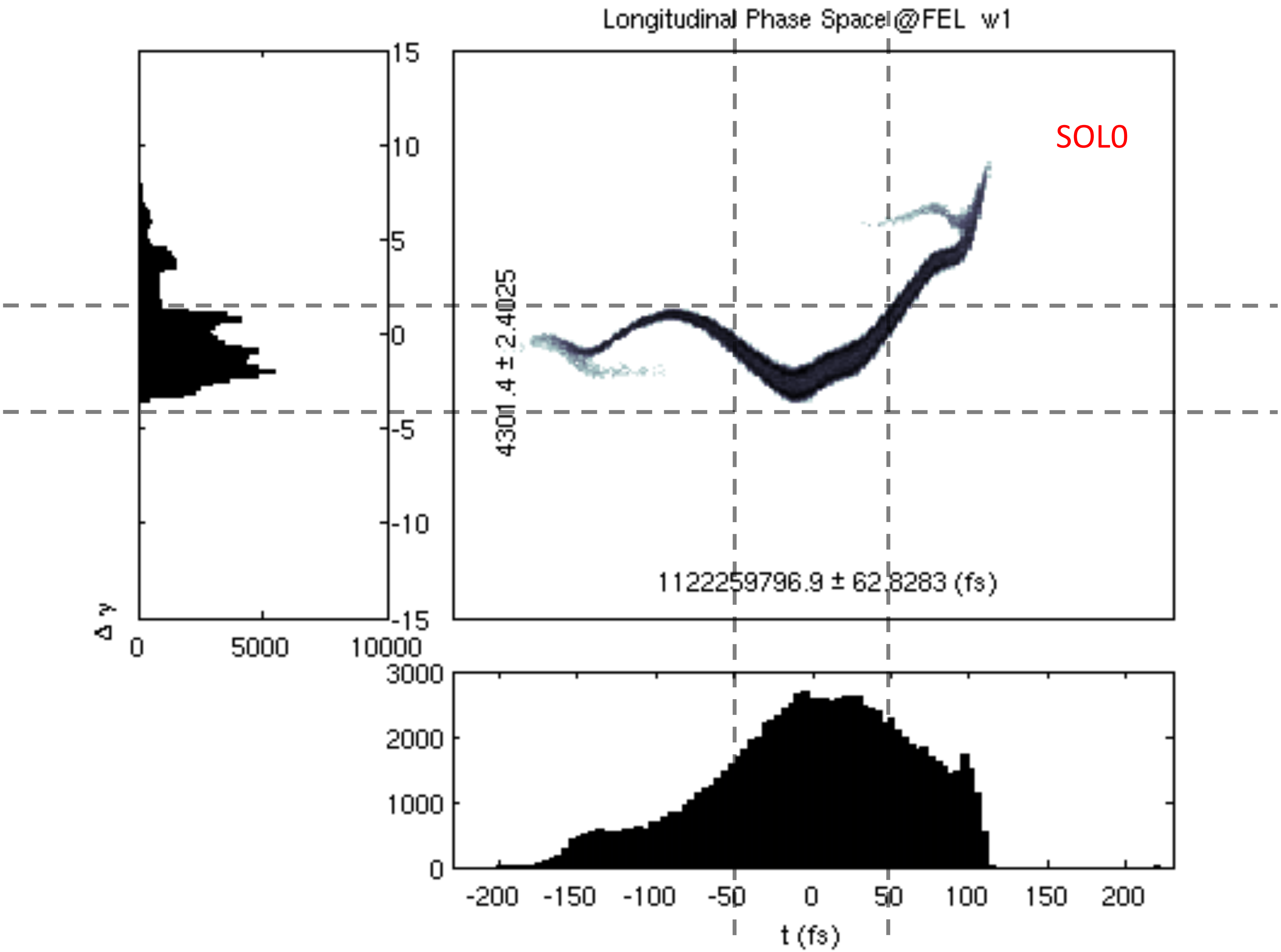


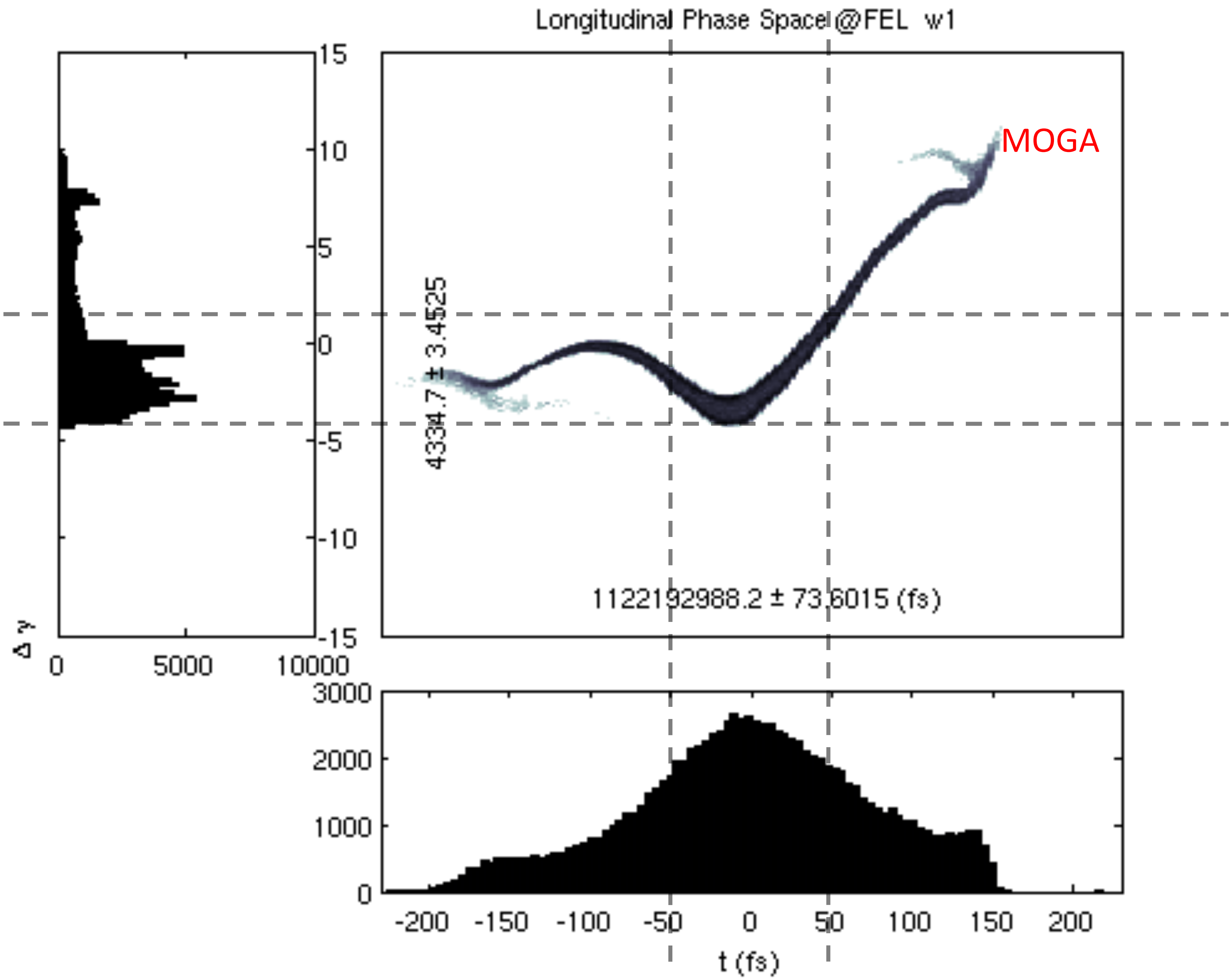
Front Evolution

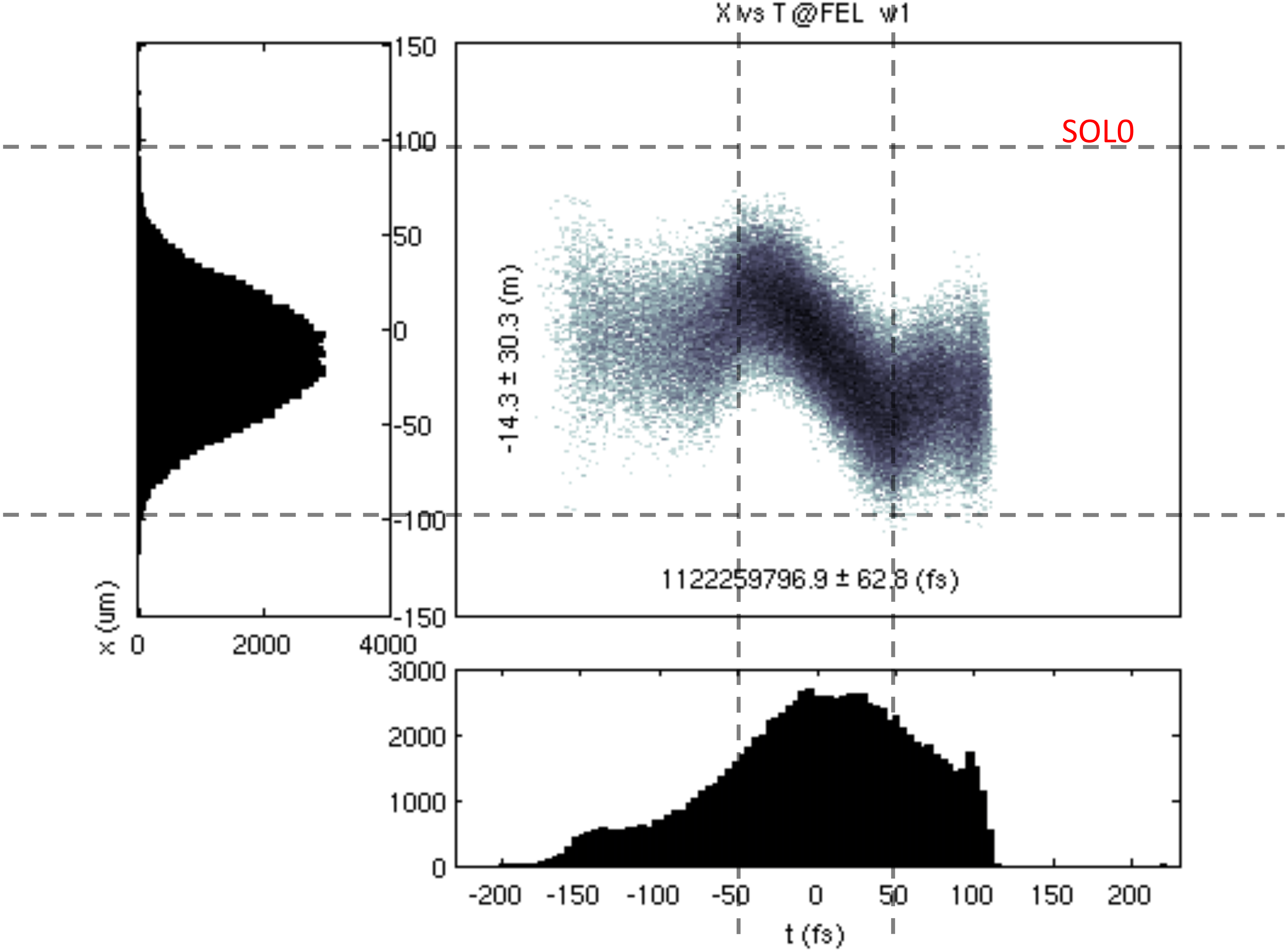


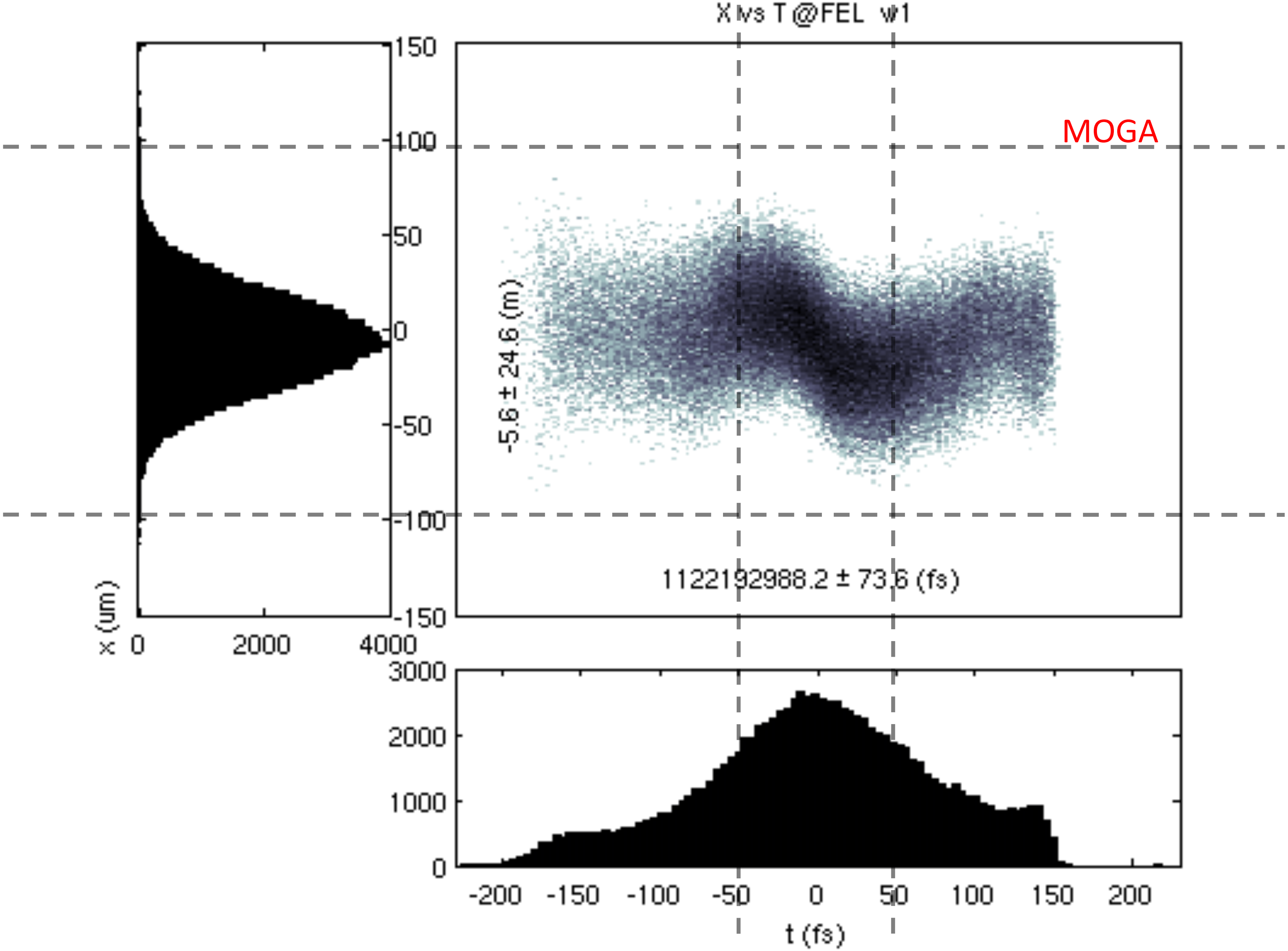
Pareto fronts (-) (from NSGAII) vs purely random search (o)



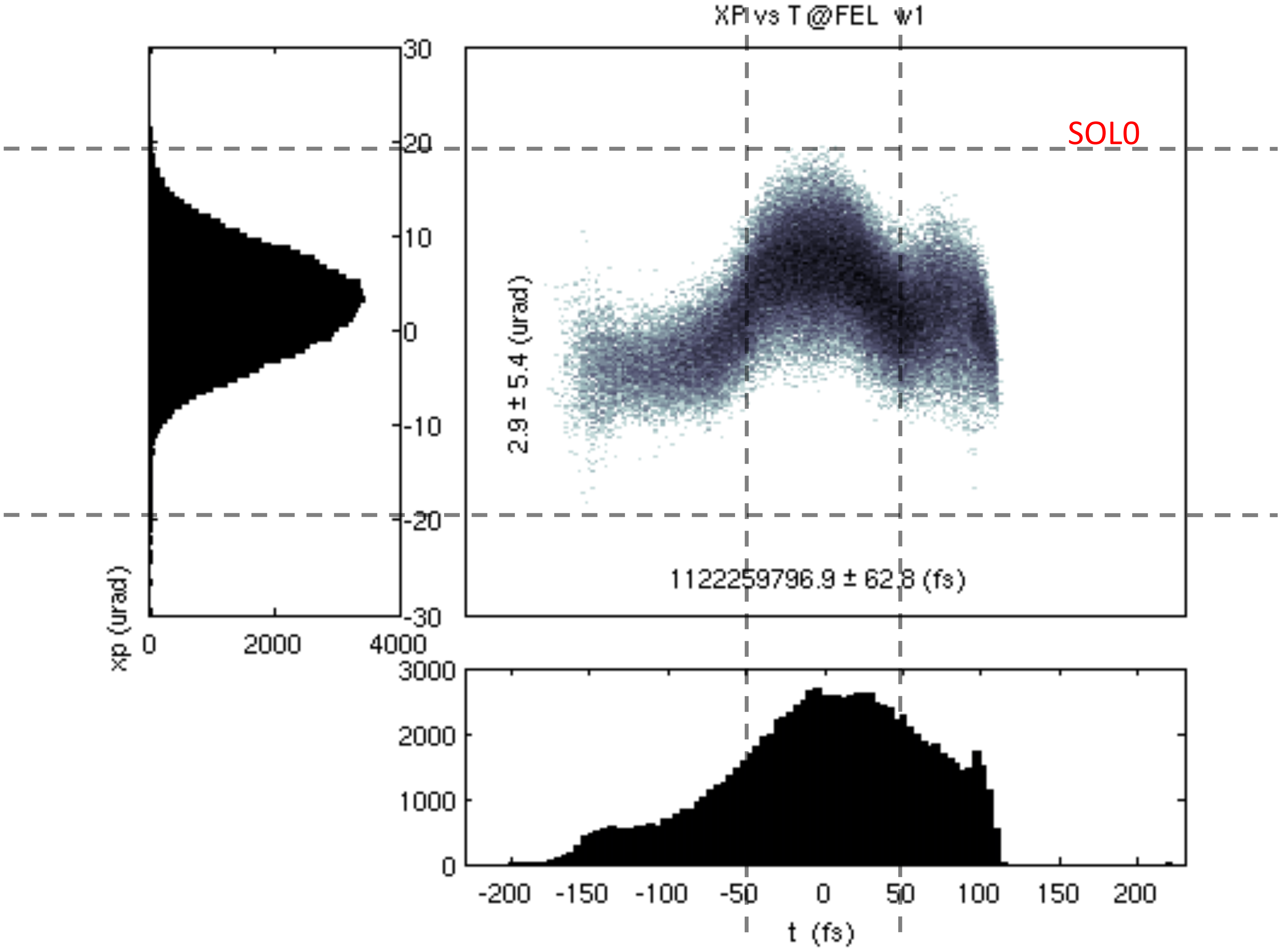

Longitudinal Phase Space @FEL w1
SOL0
4301.4 ± 2.4025
1122259796.9 ± 62.8283 (fs)
Δ γ
0
5000
10000
15
10
5
0
-5
-10
-15
3000
2000
1000
0
-200
-150
-100
-50
0
50
100
150
200
t (fs)

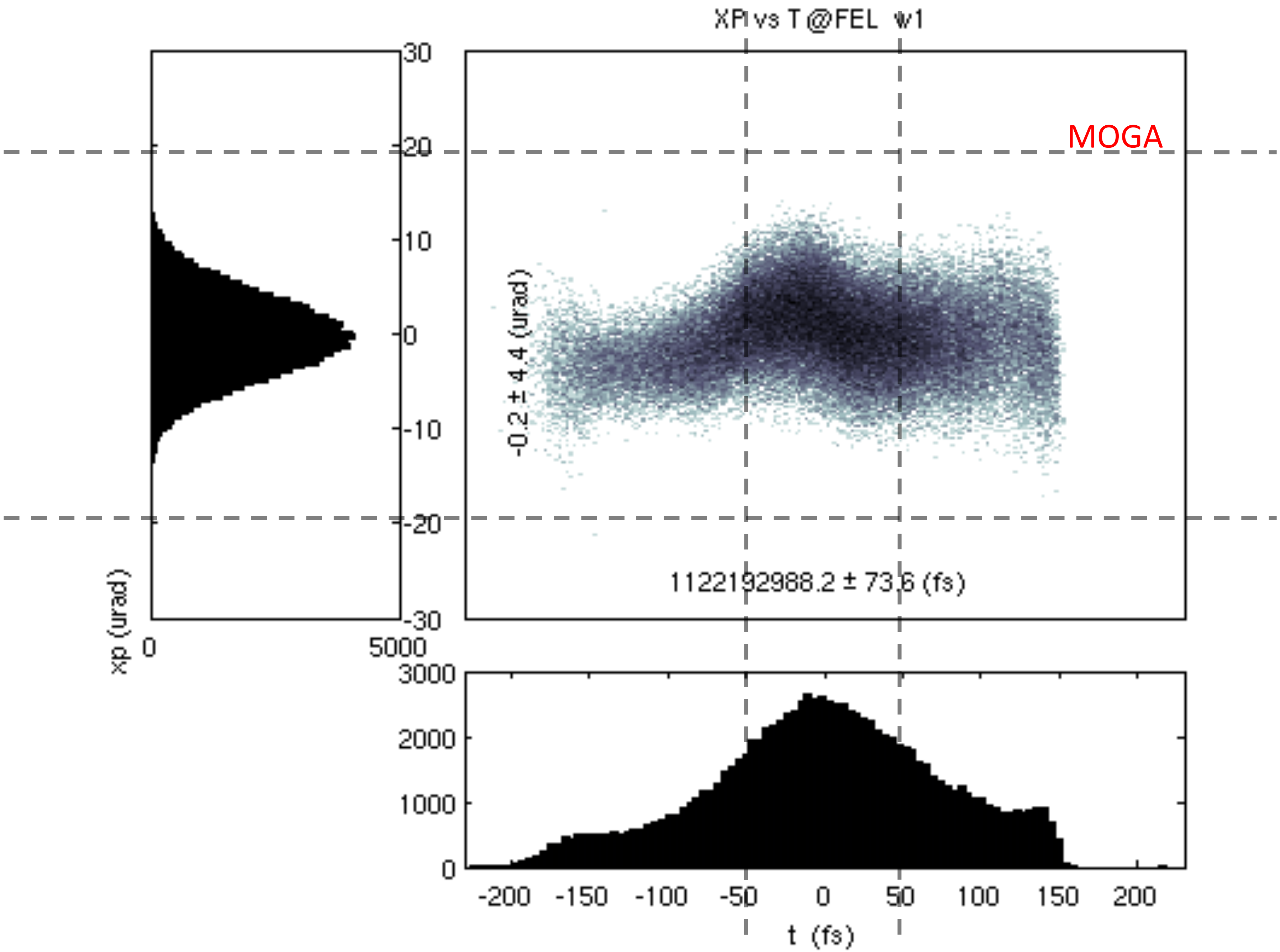

Longitudinal Phase Space @FEL w1
MOGA
4334.7 ± 3.4525
1122192988.2 ± 73.6015 (fs)
Δ γ
t (fs)
15
10
5
0
-5
-10
-15
0
5000
10000
3000
2000
1000
-200
-150
-100
-50
50
100
150
200

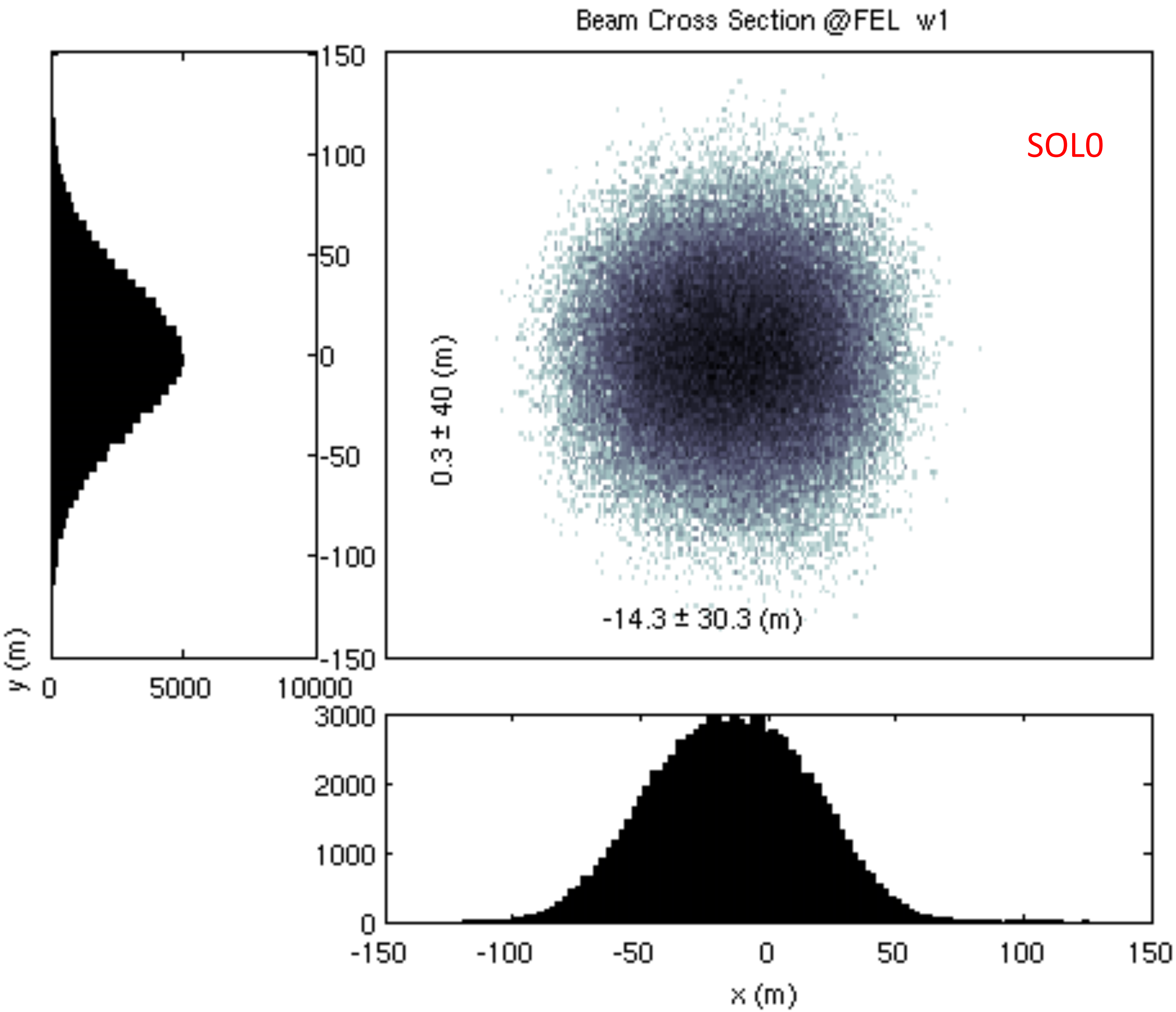

X vs T @FEL w1
SOL0
-14.3 ± 30.3 (m)
1122259796.9 ± 62.8 (fs)
x (um)
150
100
50
0
-50
-100
-150
0
2000
4000
3000
2000
1000
0
-200
-150
-100
-50
0
50
100
150
200
t (fs)

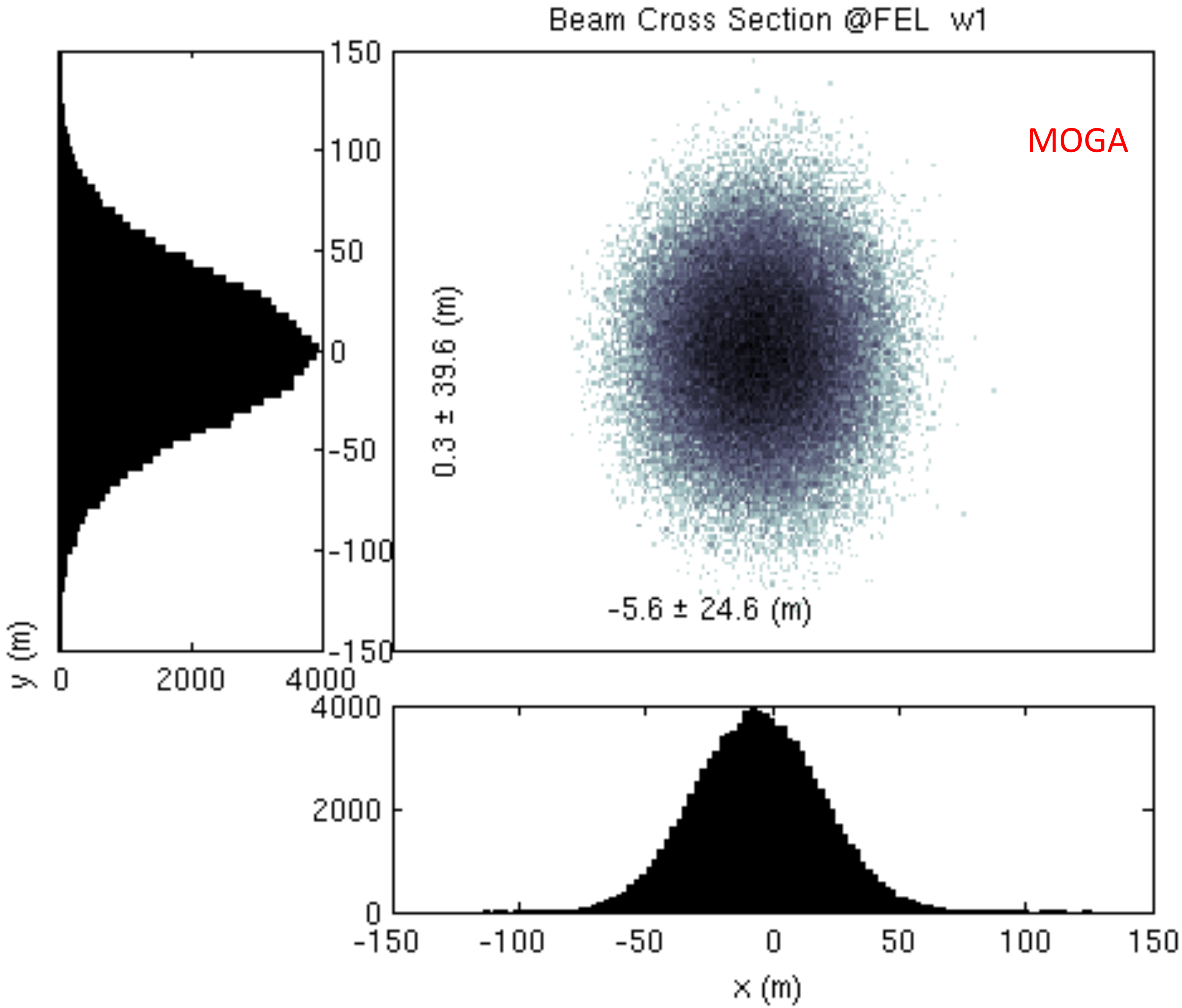


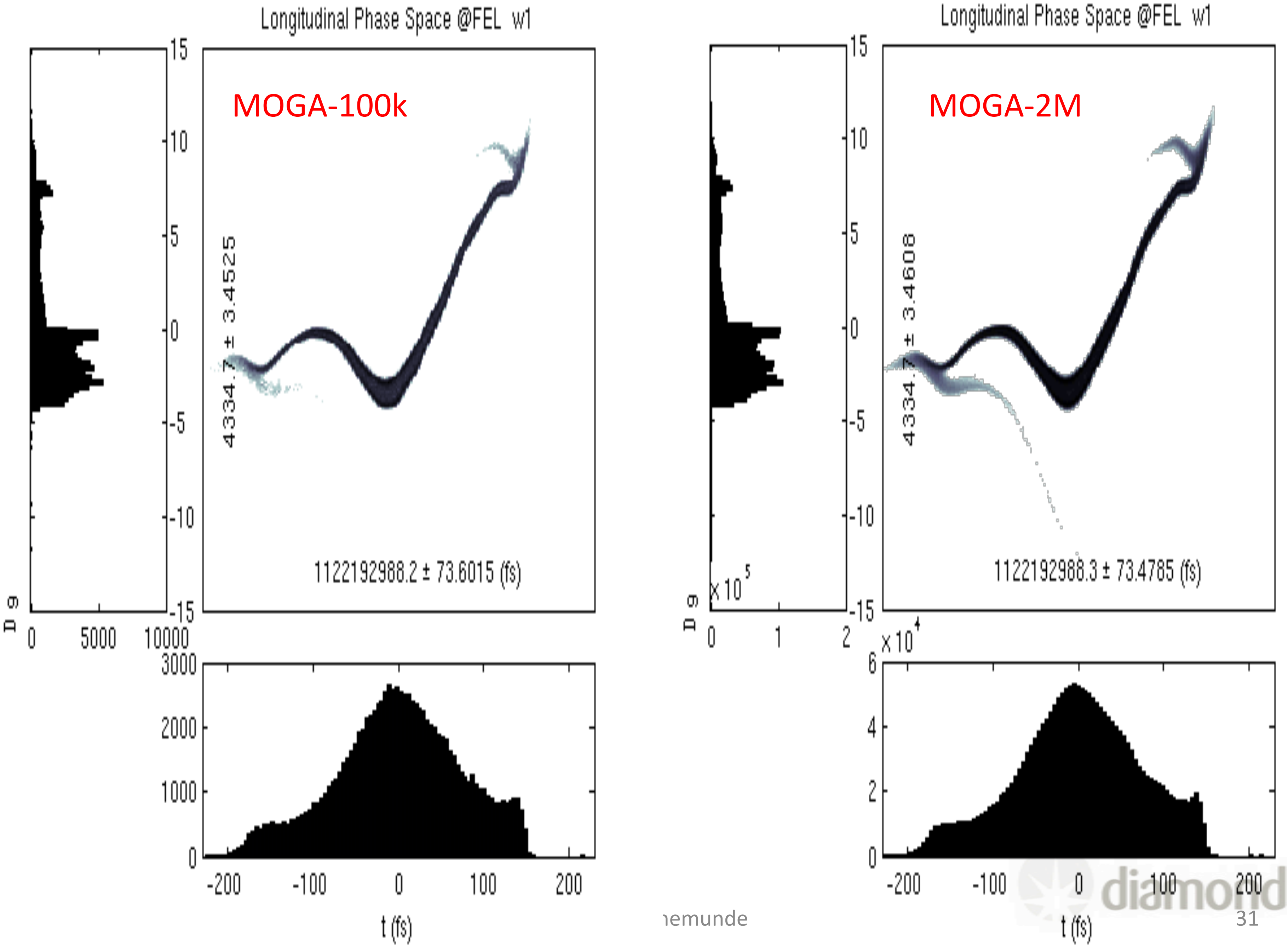
X1vs T @FEL w1
MOGA
-5.6 ± 24.6 (m)
1122192988.2 ± 73.6 (fs)
x (um)
t (fs)
150
100
50
0
-50
-100
-150
0
2000
4000
3000
2000
1000
0
-200
-150
-100
-50
0
50
100
150
200

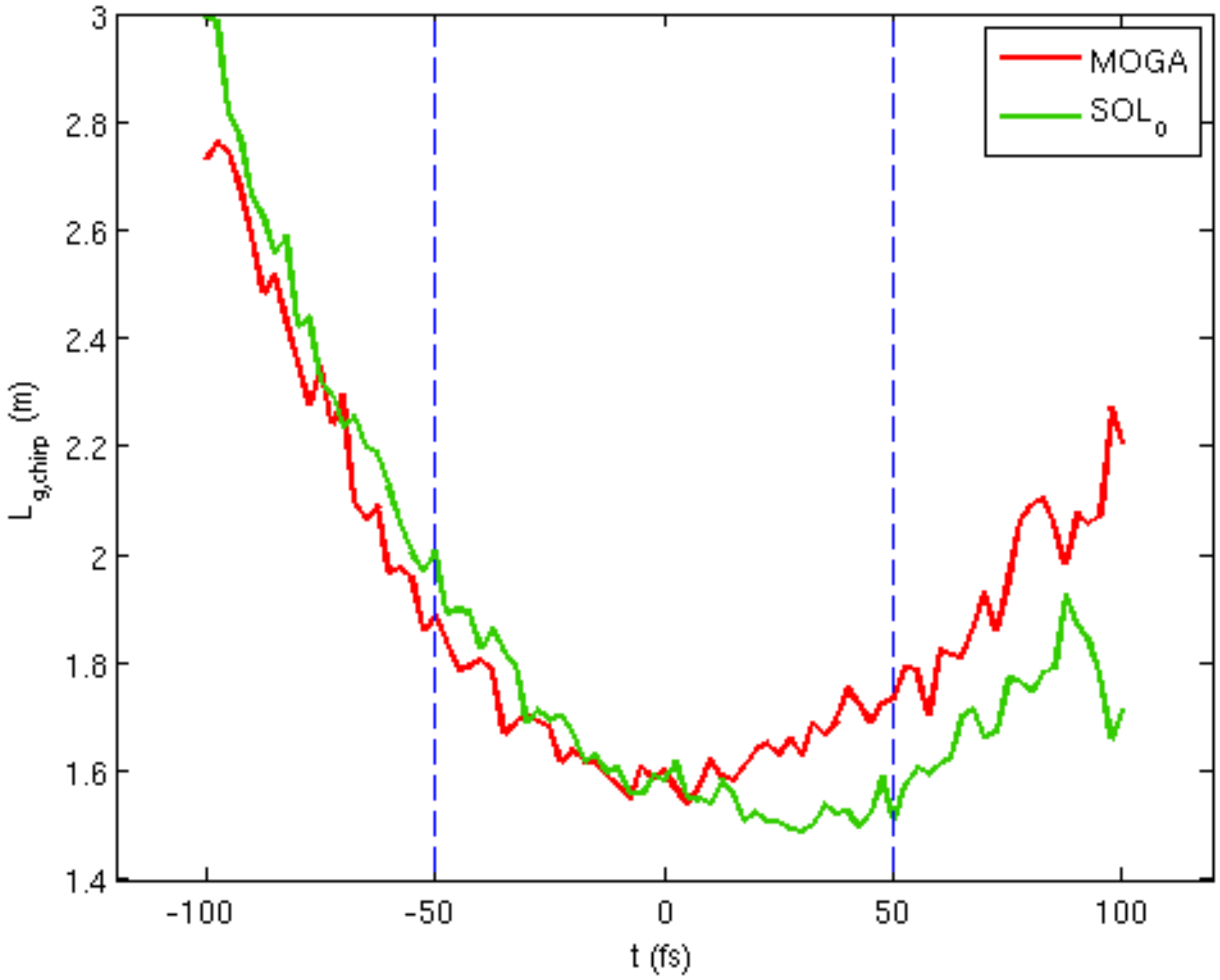

XP vs T @FEL w1
SOL0
xp (urad)
0
2000
4000
30
20
10
0
-10
-20
-30
2.9 ± 5.4 (urad)
1122259796.9 ± 62.8 (fs)
3000
2000
1000
0
-200
-150
-100
-50
0
50
100
150
200
t (fs)

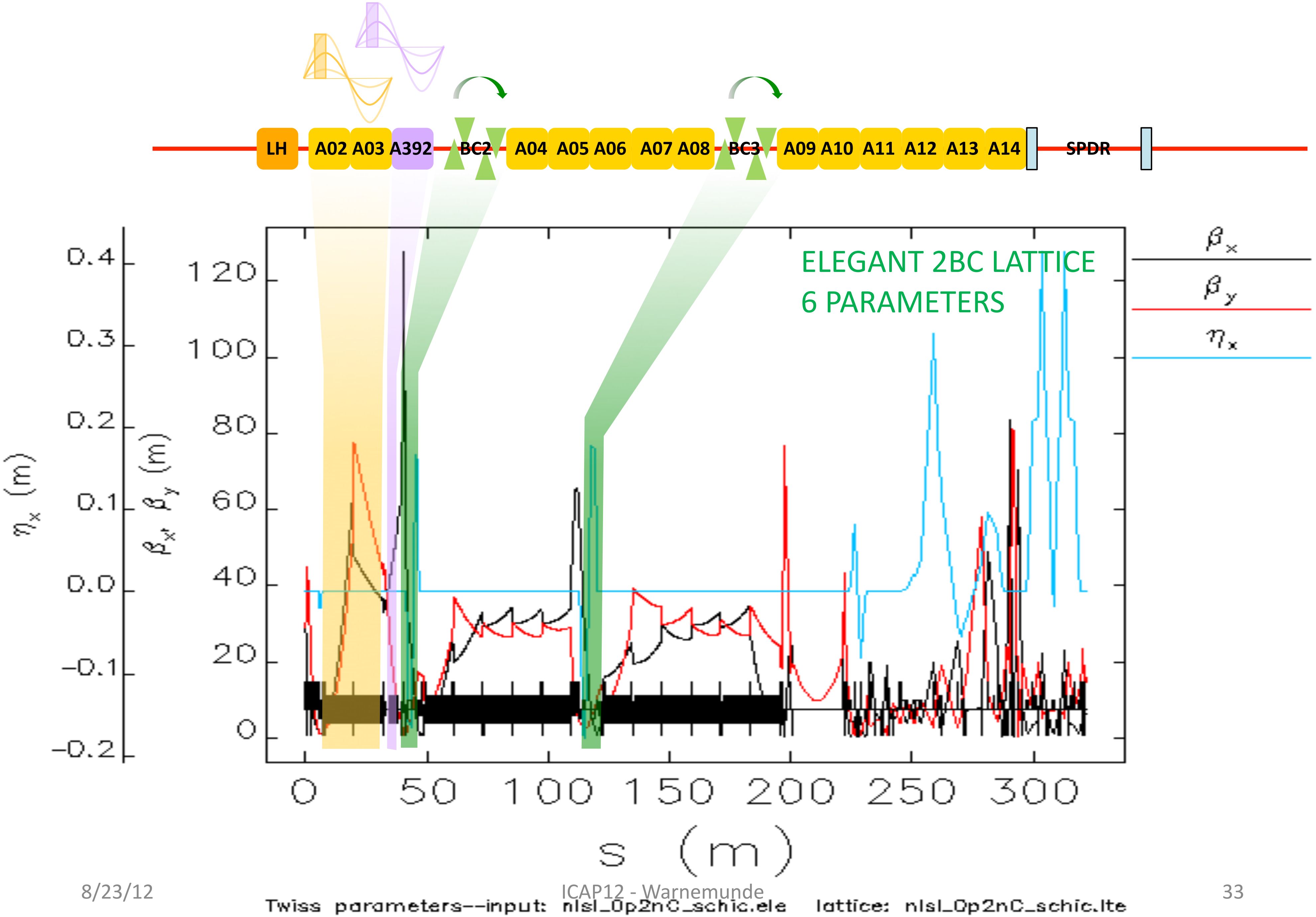

XP vs T @FEL w1
MOGA
-0.2 ± 4.4 (urad)
1122192988.2 ± 73.6 (fs)
xp (urad)
t (fs)
30
20
10
0
-10
-20
-30
0
5000
3000
2000
1000
0
-200
-150
-100
-50
0
50
100
150
200


Beam Cross Section @FEL w1
SOL0
0.3 ± 40 (m)
-14.3 ± 30.3 (m)
y (m)
x (m)
150
100
50
0
-50
-100
-150
0
5000
10000
3000
2000
1000
-150
-100
-50
0
50
100
150

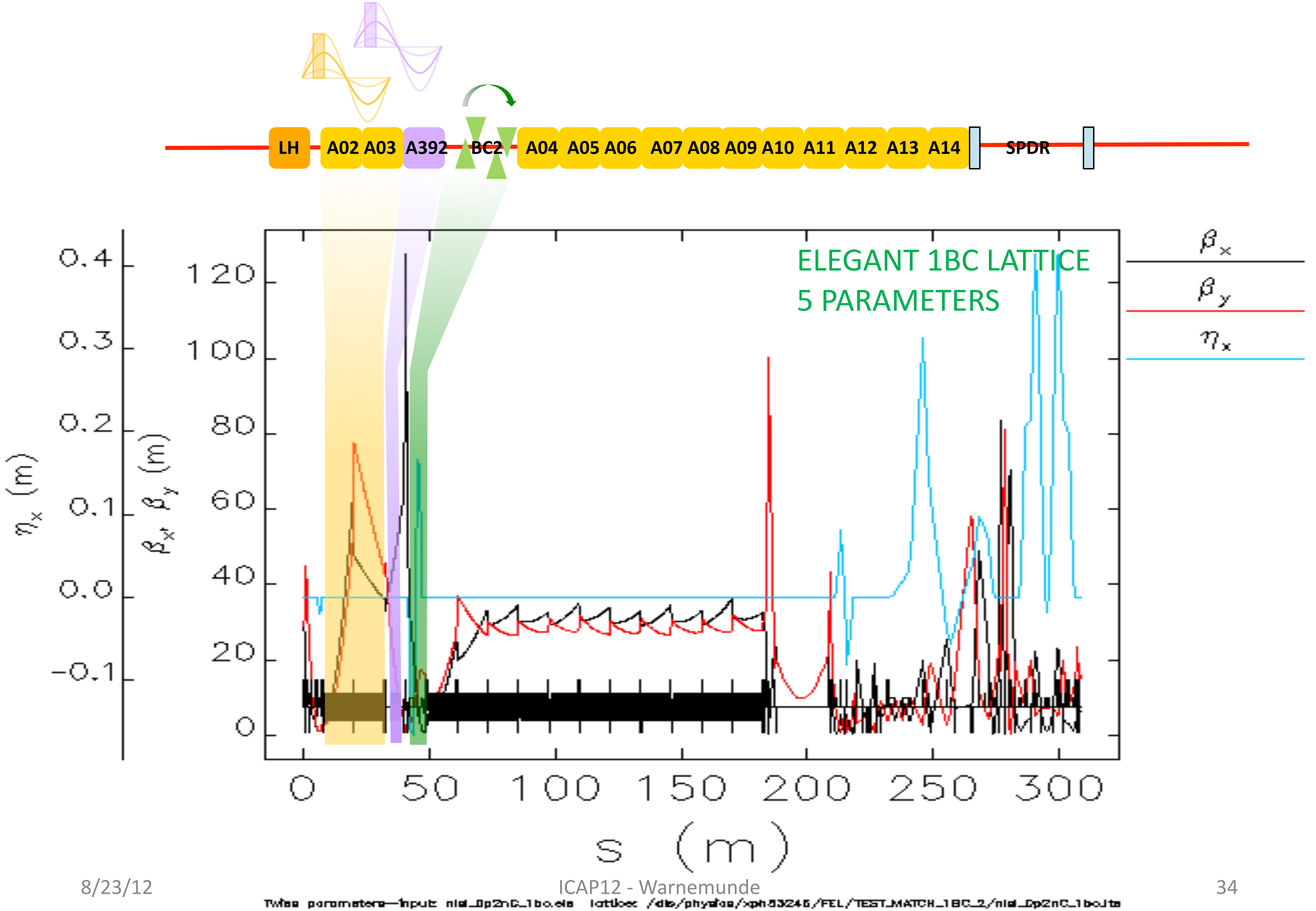

Beam Cross Section @FEL w1
MOGA
0.3 ± 39.6 (m)
-5.6 ± 24.6 (m)
y (m)
x (m)
150
100
50
0
-50
-100
-150
0
2000
4000
-150
-100
-50
0
50
100
150

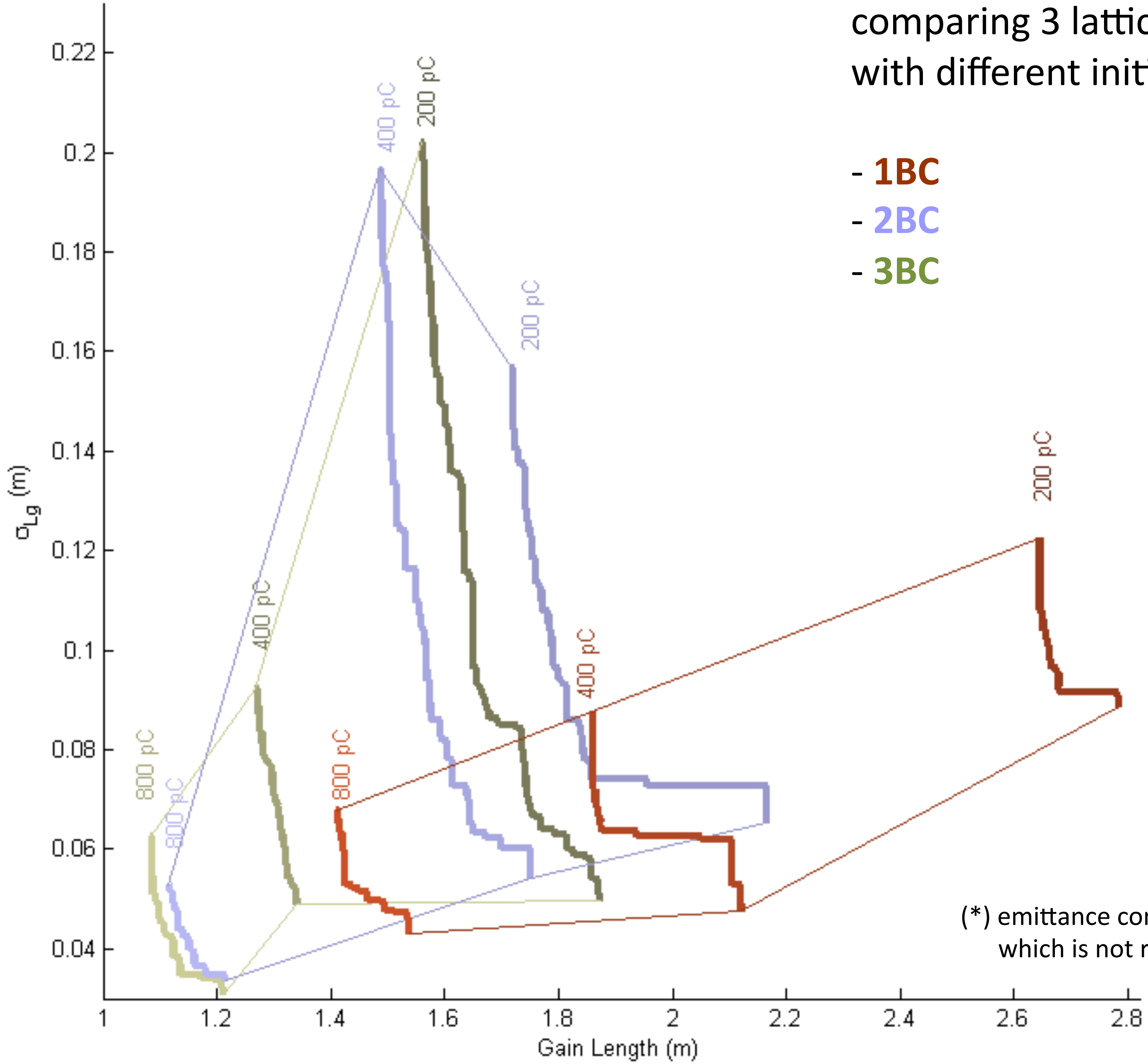

Longitudinal Phase Space @FEL w1
MOGA-100k
4334.7 ± 3.4525
1122192988.2 ± 73.6015 (fs)
t (fs)
Longitudinal Phase Space @FEL w1
MOGA-2M
4334.7 ± 3.4608
1122192988.3 ± 73.4785 (fs)
t (fs)


MOGA
SOL0
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
-100
-50
0
50
100
t (fs)
L g,chirp (m)



LH
A02 A03 A392
BC2
A04 A05 A06 A07 A08
BC3
A09 A10 A11 A12 A13 A14
SPDR
ELEGANT 2BC LATTICE
6 PARAMETERS
η_x (m)
β_x, β_y (m)
s (m)
β_x
β_y
η_x
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
120
100
80
60
40
20
0
0 50 100 150 200 250 300
Twiss parameters--input: nlsl_Op2nC_schic.ele lattice: nlsl_Op2nC_schic.lte


LH
A02 A03
A392
BC2
A04 A05 A06 A07 A08 A09 A10 A11 A12 A13 A14
SPDR
ELEGANT 1BC LATTICE
5 PARAMETERS
β_x
β_y
η_x
η_x (m)
β_x, β_y (m)
s (m)



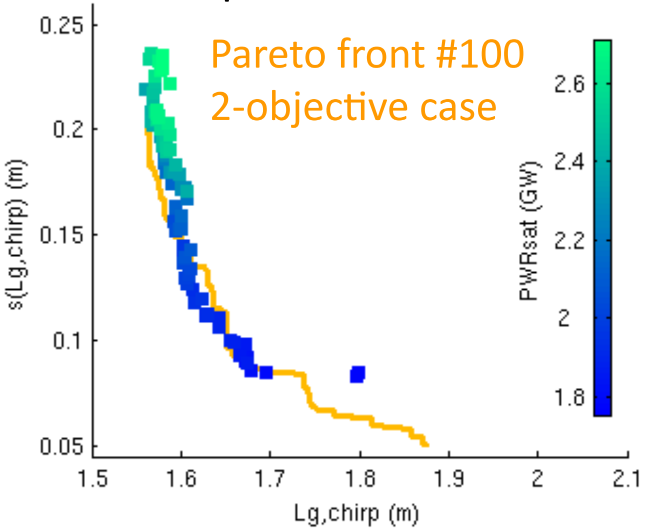
comparing 3 lattices
with different initial charges(*)

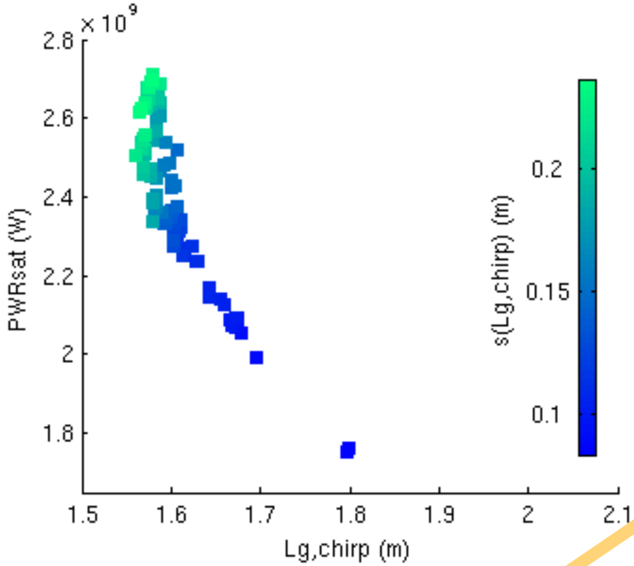
- **1BC**
- **2BC**
- **3BC**

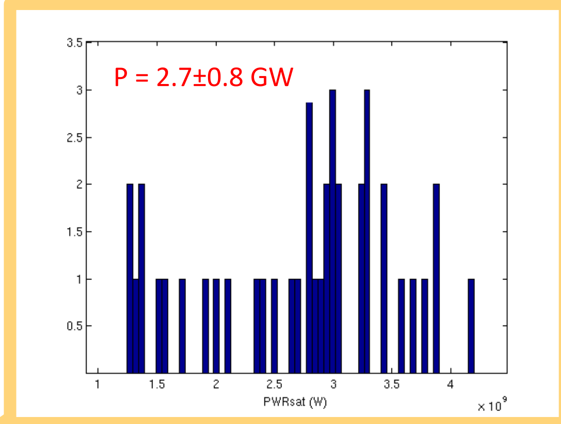
(*) emittance constant in all cases
which is not realistic in general

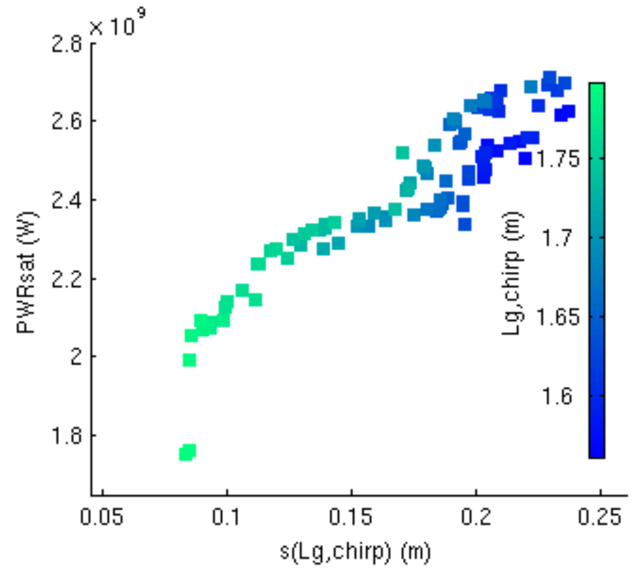
optimization over **3 objectives:** (L_g, σ_{L_g}, PWR_{sat})

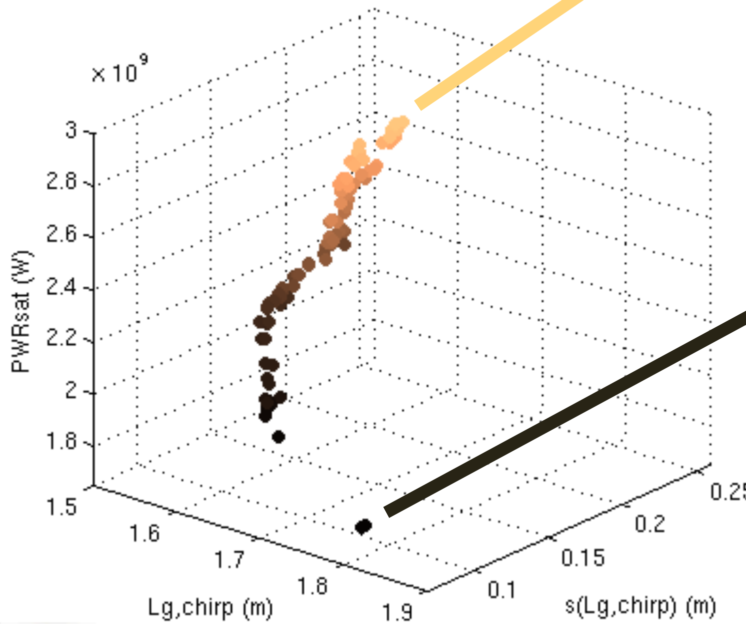
3BC / 200 pC

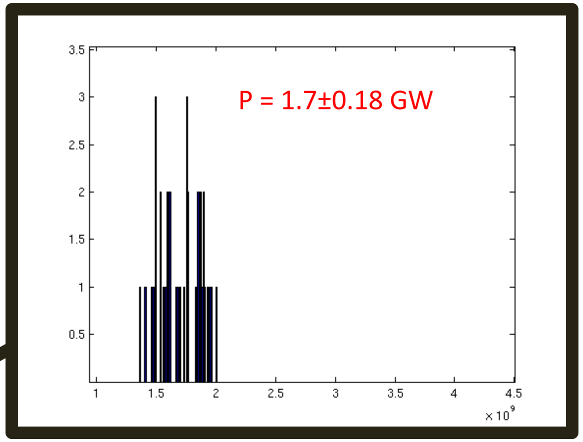












Conclusions

- start-to-end simulation for a linac driven FEL

- optimization with Multi Objective Genetic Algorithm (NSGAII)
    - knobs: BC and cavities (V,phase)
    - objectives (in view of a seeded case): (L_g, σ_{Lg})

- use of parallel computing: AP-Diamond cluster
    - genesis in time independent mode + slice analysis (reduce cpu time)

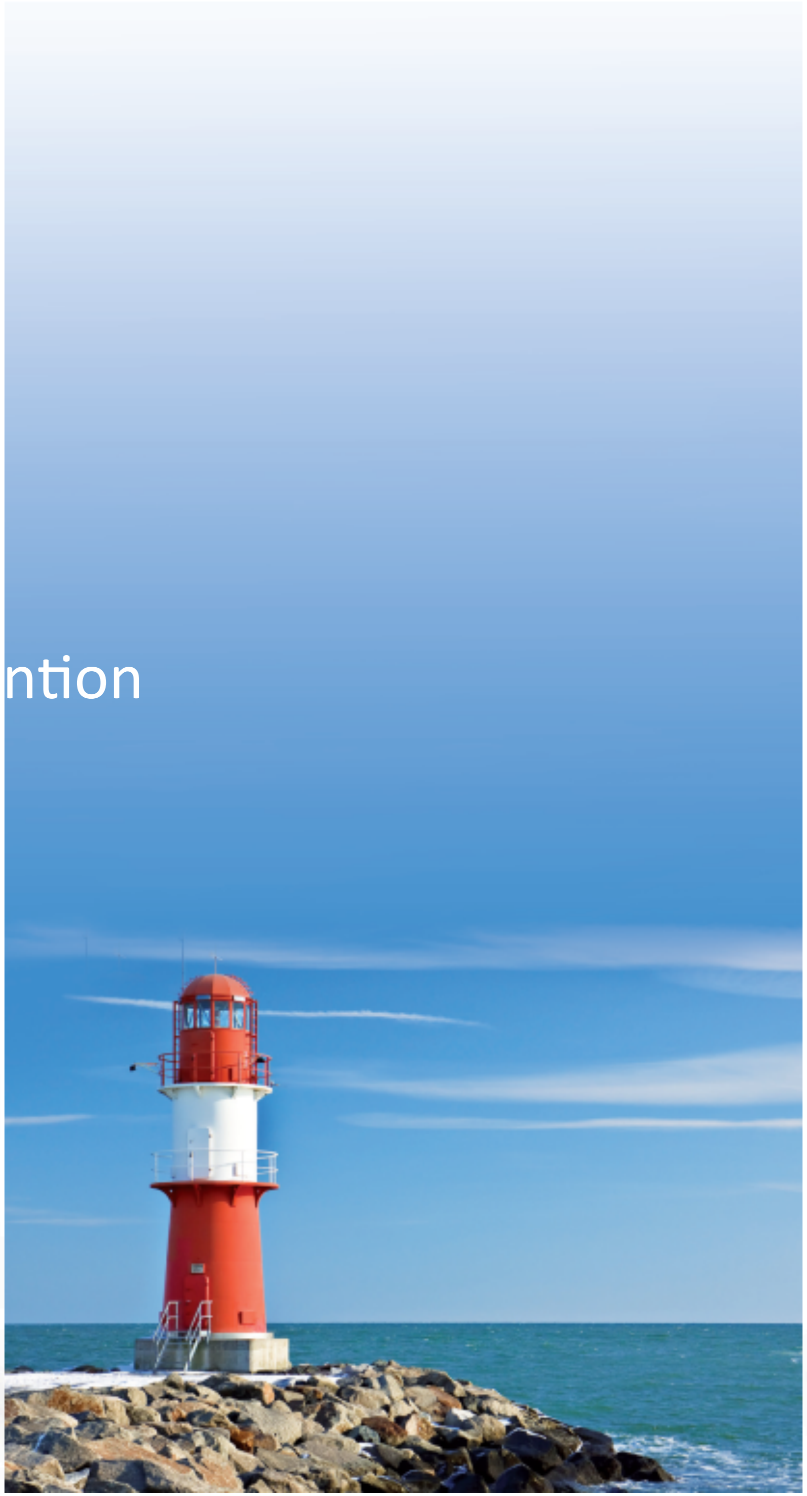
- multi-package, multi-code implementation:
    - python / matlab / elegant / genesis / astra

- results:
    - MOGA effective both in time and results (comparison with pure random search)
    - comparison with other lattices (3BC / 2BC / 1BC)
    - test with different initial beam charge
    - flexibility: case with 3 objectives shown (Lg, sLg, P(saturation))

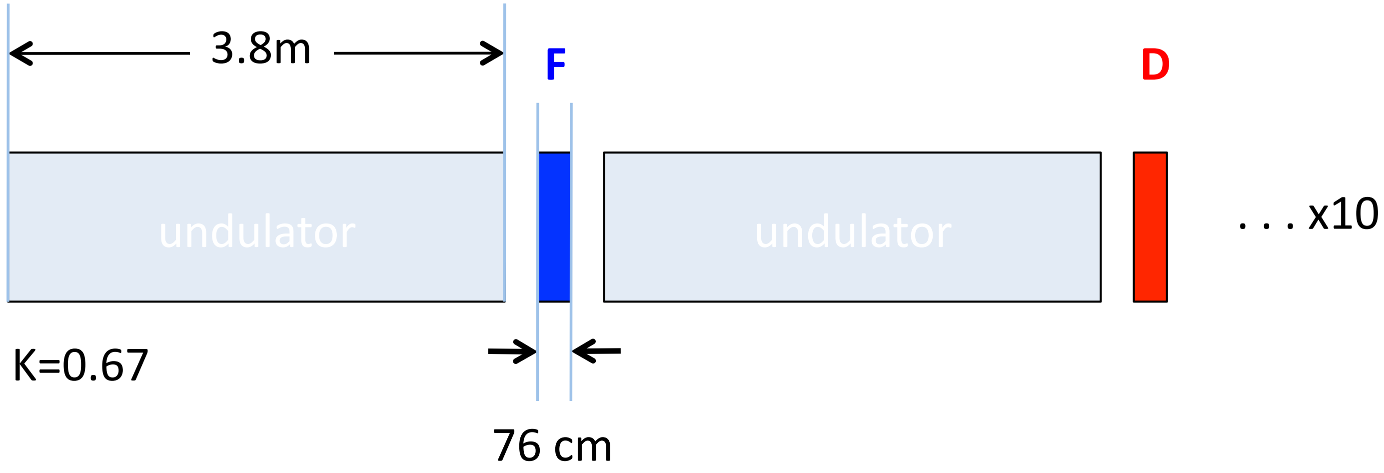
Future developments

- use of genesis in time dependent mode ➔ computing time !
- introduction of other objectives (bandwidth)

Thanks for your attention



FEL structure



Time Dependent simulation (SASE mode)