Genesis /ALICE Benchmarking

Igor Zagorodnov

Beam Dynamics Group Meeting

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Genesis 1.3 (S.Reiche et al)

- only 3D
- 3D Cartesian field solver (ADI)
- Runge-Kutta integrator
- Dirichlet boundary conditions
- **transverse motion**
- many other physics
- parallel (MPI)

ALICE

- 1D/2D/3D
- 3D azimuthal field solver (Neumann)
- Leap-Frog integrator
- Perfectly Matched Layer
- **transverse motion**
- simplified model
- parallel (MPI)
- tested by me on the examples from the book of SSY

(~Saldin et al, 2000 „The Physics …“,)

XFEL Source Parameters

General properties of XFEL sources

- Operation at fixed electron energy 17.5 GeV
- Continuos covering of design wavelength range with three SASE FELs

Electron beam

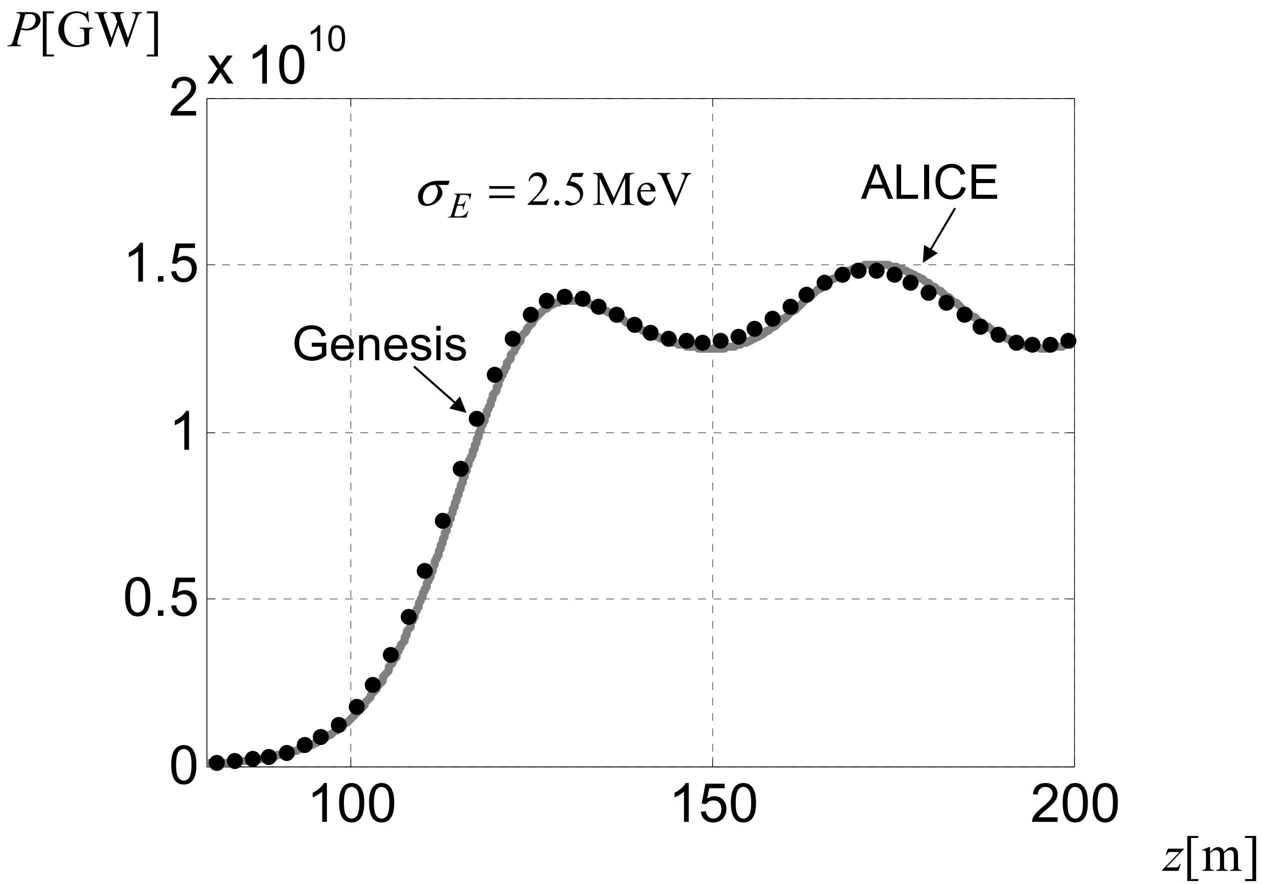
	Units	
Energy	GeV	17.5
Bunch charge	nC	1
Peak current	kA	5
Bunch length (rms)	μm	25
Norm. emittance (rms)	mm-mrad	1.4
Energy spread (rms)	MeV	1.5
# bunches p. pulse	#	3250
Repetition rate	Hz	10

2.5 MeV

Undulators:

	λ_r nm	λ_u mm	L_w m
SASE1	0.1	35.6	200
SASE2	0.1-0.4	48	260
SASE3	0.4-1.6	65	130
Possible XUV option			
SASE4	1.6-6.4	110	80

Genesis vs. ALICE / Energy Spread
(round Gaussian beam, Gaussian energy spread, **parallel motion only**)



SASE 2 parameters

$\lambda_s = 0.1\,\mathrm{nm}$

$C = 0$

$\sigma_r = 4.086\mathrm{e}\text{-}5\ \mathrm{m}$

W = 4 kW

How to simulate emmitance with laminar particle motion only?

$$\hat{\Lambda}_T{}^2 = \frac{\sigma_\varepsilon{}^2}{\rho^2 \varepsilon_0{}^2} \qquad \hat{\Lambda}_{emit}{}^2 = \frac{\gamma_{z0}^4 \varepsilon^2}{\rho^2 \beta^2}$$

$$\hat{\Lambda}_{T,eff}^2 = \hat{\Lambda}_T^2 + a\hat{\Lambda}_{emit}^2$$

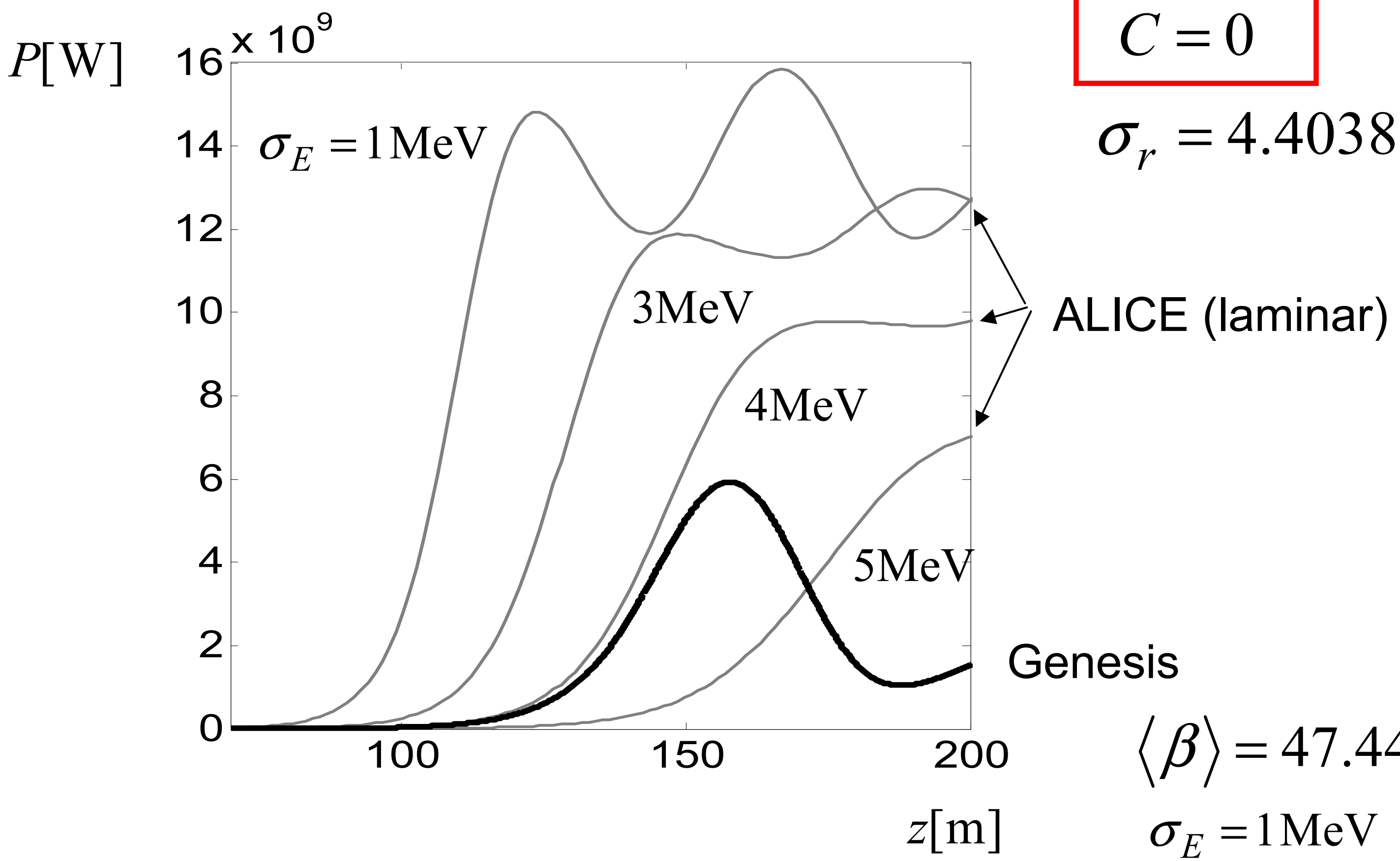
$a = \frac{1}{4}$ -E. Saldin et al, TESLA-FEL 95-02 (1995); S.Reiche PhD Thesis (1999).

$a = 1$ - E. Saldin et al, The Physics of Free Electron Lasers (2000)

$a = 2$ - E. Saldin et al, DESY 05-164 (2005)

$\varepsilon_n = 1.4 \text{ mm}\times\text{mrad}$

Genesis vs. ALICE / Emmitance
(round Gaussian beam, Gaussian energy spread)



$C = 0$

$\sigma_r = 4.4038\text{e-}005\text{m}$

$\langle \beta \rangle = 47.44\text{m}$

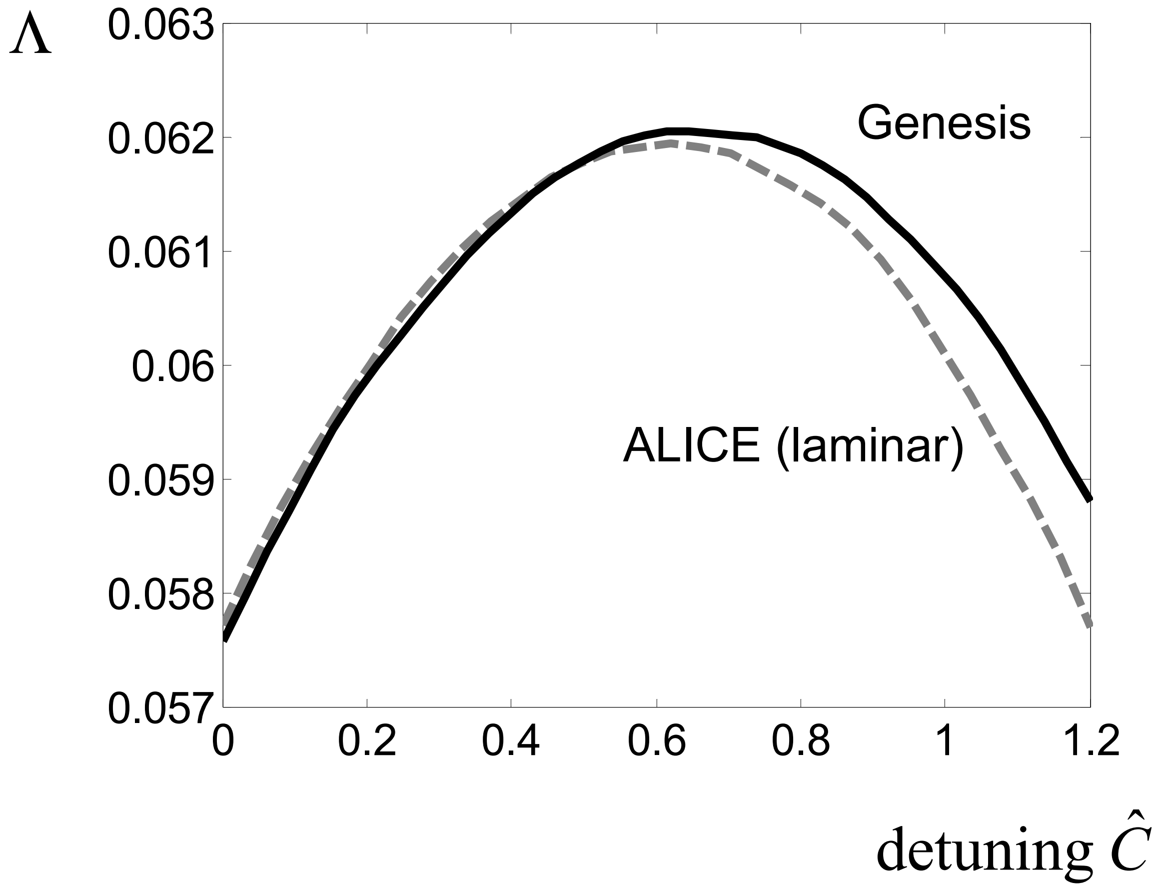
$\sigma_E = 1\text{MeV}$

$\varepsilon_n = 1.4 \text{ mm}\times\text{mrad}$

Genesis vs. ALICE (emittance parameter fit)

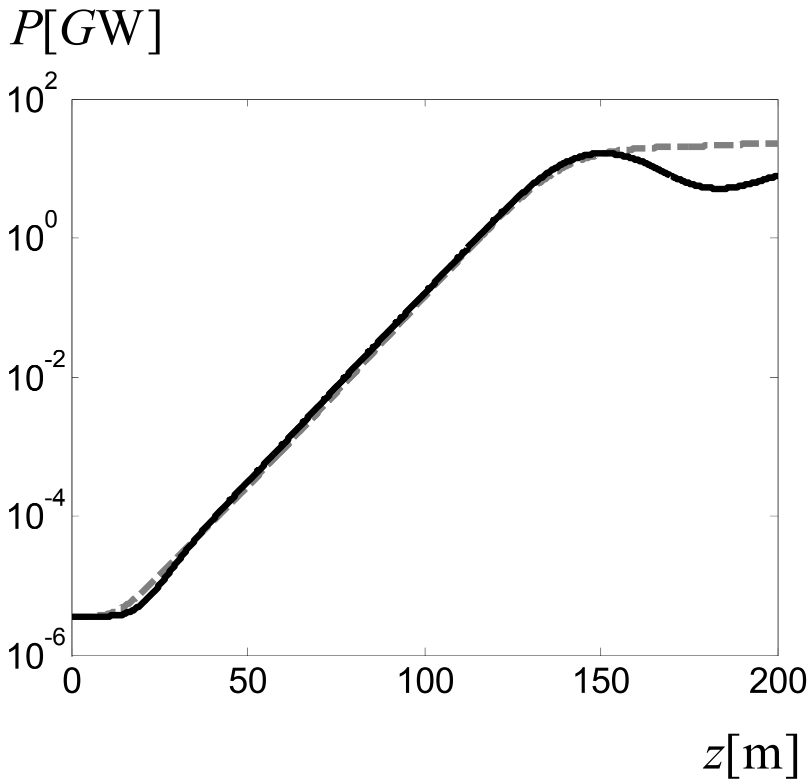
$a = 1.1$

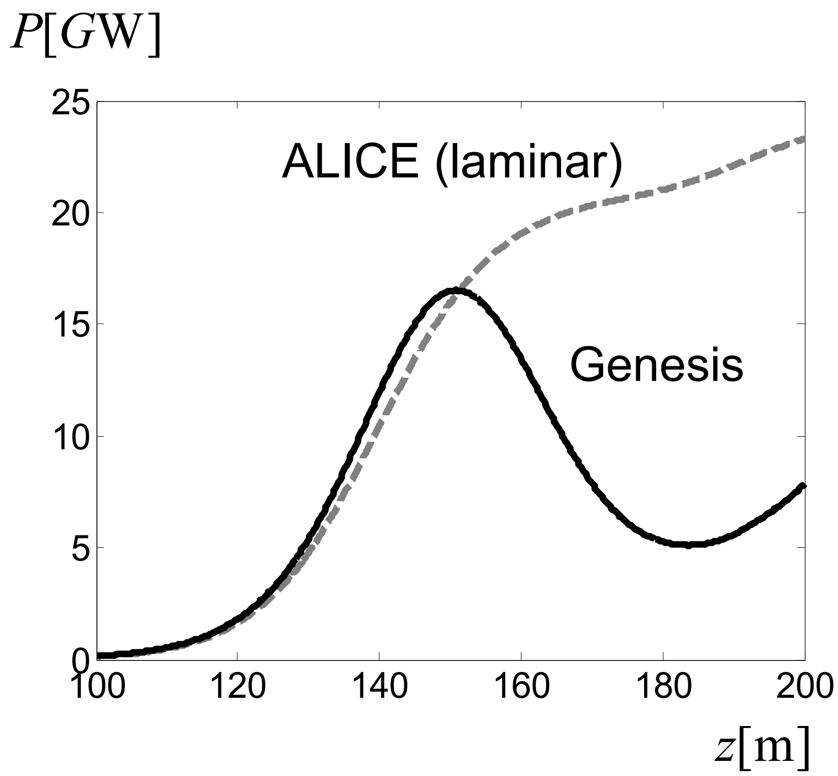
Field growth rate



Genesis vs. ALICE with laminar motion

$$a = 1.1$$





Detuning corresponds to maximal growth rate in linear regime

$$\Lambda(C_0) = \max_C \Lambda$$

The transverse motion has to be implemented in ALICE

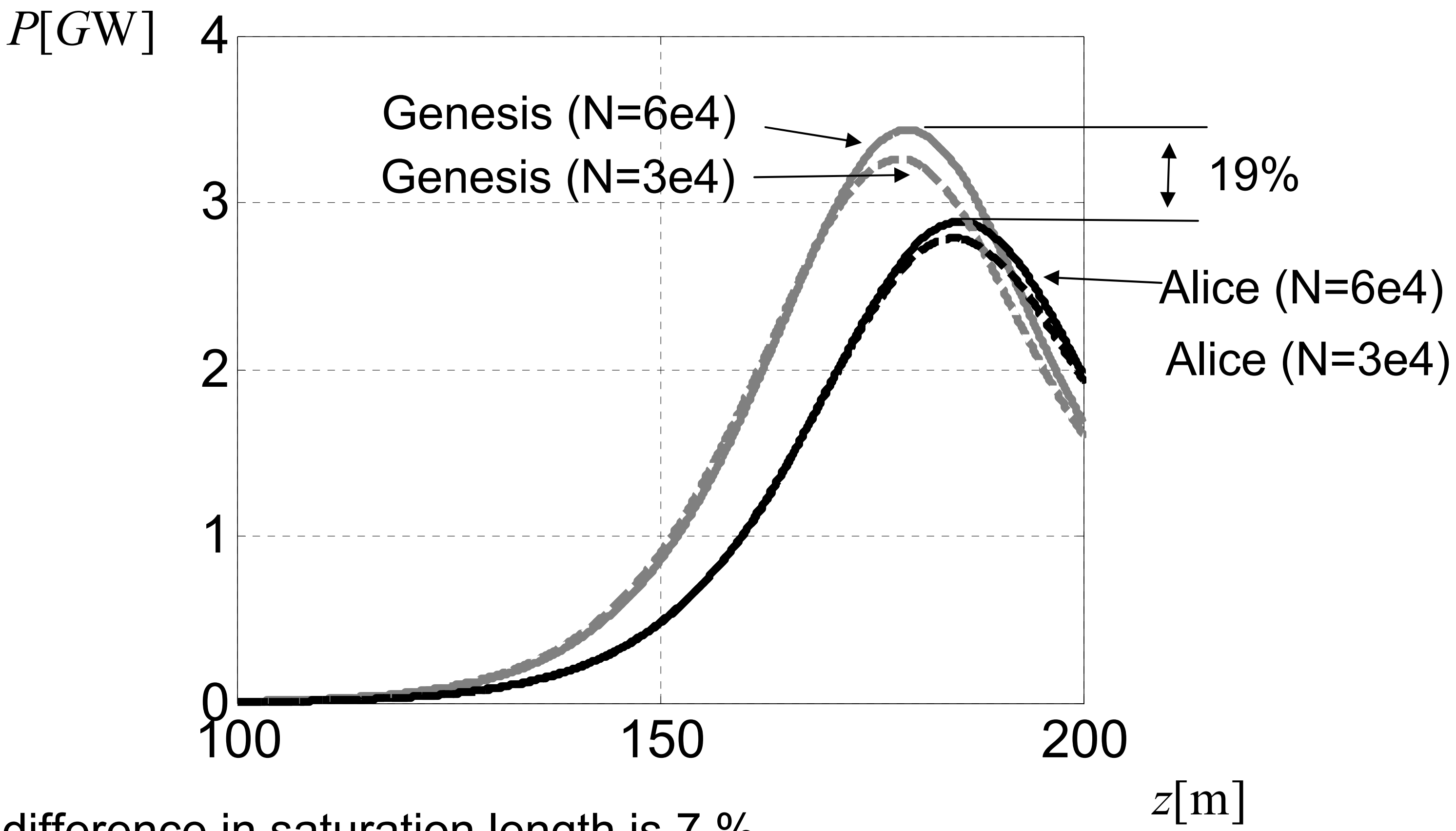
Genesis vs. ALICE
with transverse motion

$C = 0$ I=5KA

P0 = 4 kW N_λ ~10 400

$\sigma_E = 2.5\,\mathrm{MeV}$ $\lambda_s = 0.1\,\mathrm{nm}$

$\sigma_r = 4.086\text{e-}5\ \mathrm{m}$



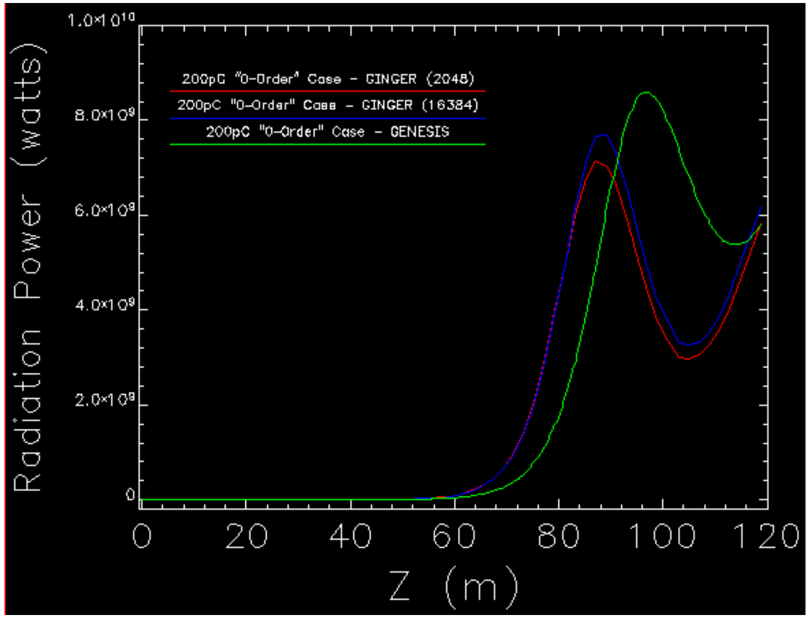
The difference in saturation length is 7 %.
The difference in power gain is 19 %.

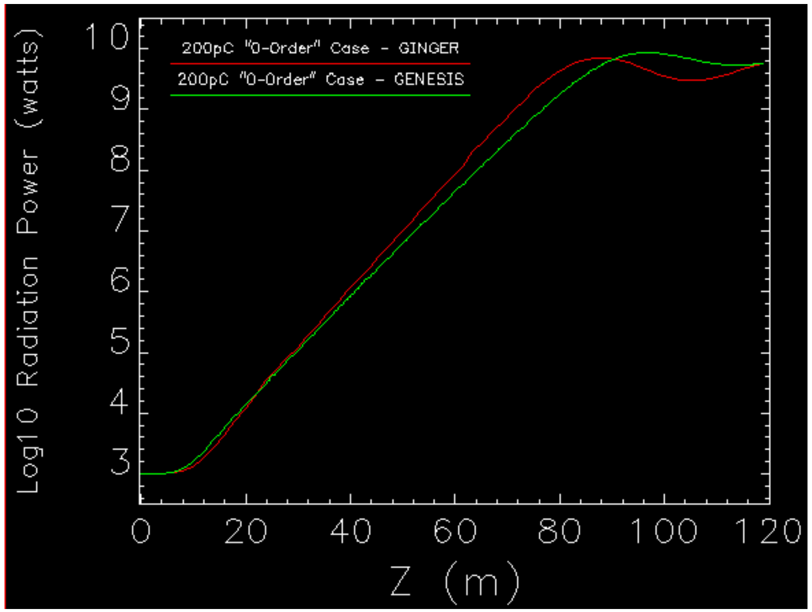
The difference **does not reduce** with changing of the discrete model parameters ?!.

GINGER/GENESIS results for “0-order” 200-pC case

Observations:

- Again, GENESIS shows slightly longer gain length, 10-m later saturation but 15% higher power
- Again, GINGER shows deeper post-saturation power oscillation
- Little sensitivity (2 m, 7%) in GINGER results to 8X particle number increase
- Possible reasons for differences:
  - ➢ bugs
  - ➢ slight differences in initial e-beam properties (*e.g.* mismatch)
  - ➢ grid effects (e.g. outer boundary)
  - ➢ ???

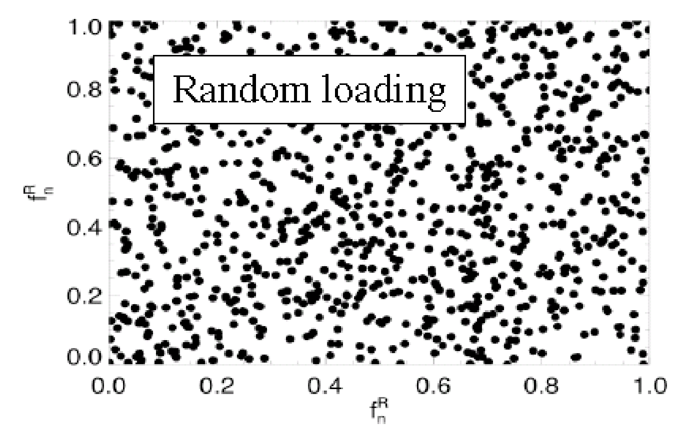


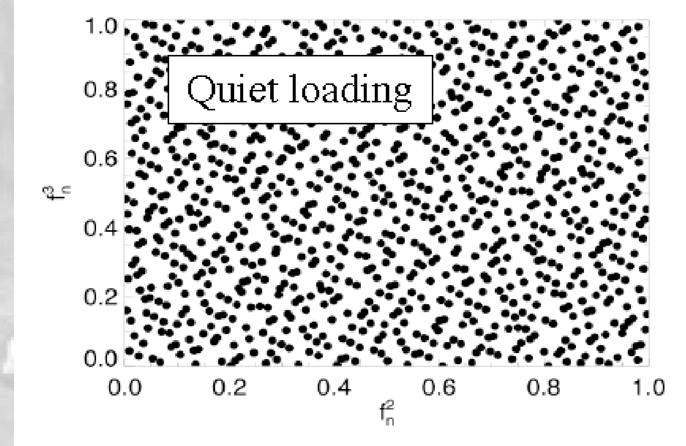


William M. Fawley, ICFA 2003 Workshop on Start-to-End Numerical Simulations of X-RAY FEL’s

Phase Space Loading

Smooth filling phase space with Hammersley sequences:





Algorithm (n should be prime number to avoid correlation)

Count	n-base number (n=2)	Invert digit	Convert back
1	1	0.1	0.5
2	10	0.01	0.25
3	11	0.11	0.75
4	100	0.001	0.125
…	…	…	

A brief introduction to the three dimensional, time dependent code Genesis 1.3, brought to the people by Sven Reiche in the year 2002 anno domino.

We have just seen that choosing N points uniformly randomly in an n-dimensional space leads to an error term in Monte Carlo integration that decreases as $1/\sqrt{N}$. In essence, each new point sampled adds linearly to an accumulated sum that will become the function average, and also linearly to an accumulated sum of squares that will become the variance (equation 7.6.2). The estimated error comes from the square root of this variance, hence the power $N^{-1/2}$.

Numerical Recipes in C

The Art of Scientific Computing

Second Edition

How good is a Sobol' sequence, anyway? For Monte Carlo integration of a smooth function in n dimensions, the answer is that the fractional error will decrease with N, the number of samples, as $(\ln N)^n/N$, i.e., almost as fast as $1/N$. As an example, let us integrate

About advantages of the „quiet start“ see, for example, in

Bridsall C.K., Langdon A.B., Plasma Physics via Computer Simulations, 1991
Dawson J.M, Particle simulation of Plasmas // Reviews of Modern Physics, 1983

Properties of the Normal macroparticle distribution

$$\sigma_4 = 3\sigma_2 \qquad \delta = \frac{|\sigma_4 - \tilde{\sigma}_4|}{\sigma_4} 100\%$$

	N_{trans}	δ_x, %	δ_y, %	δ_{px}, %	δ_{py}, %
Genesis	7500	**1.5**	**7.5**	5.1	5.8
	15000	**4.1**	**4.7**	4.1	3.2
ASTRA	7500	**1.6**	**4.2**	0.43	2.3
	15000	**0.4**	**3.3**	0.62	1.9
Alice	7500	**0.8**	**1.0**	0.8	0.8
	15000	**0.4**	**0.4**	0.5	0.5

Properties of the Normal macroparticle distribution

	N_{trans}	Rxy	Rpxpy	Rxpy	Rypx
Genesis	7500	**8e-3**	2e-2	5e-3	8e-3
	15000	**8e-3**	1e-2	1e-3	3e-3
ASTRA	7500	**4e-3**	7e-3	5e-3	5e-3
	15000	**5e-3**	4e-3	6e-3	4e-3
Alice	7500	**1e-3**	2e-3	8e-4	2e-3
	15000	**5e-4**	1e-3	5e-4	8e-4

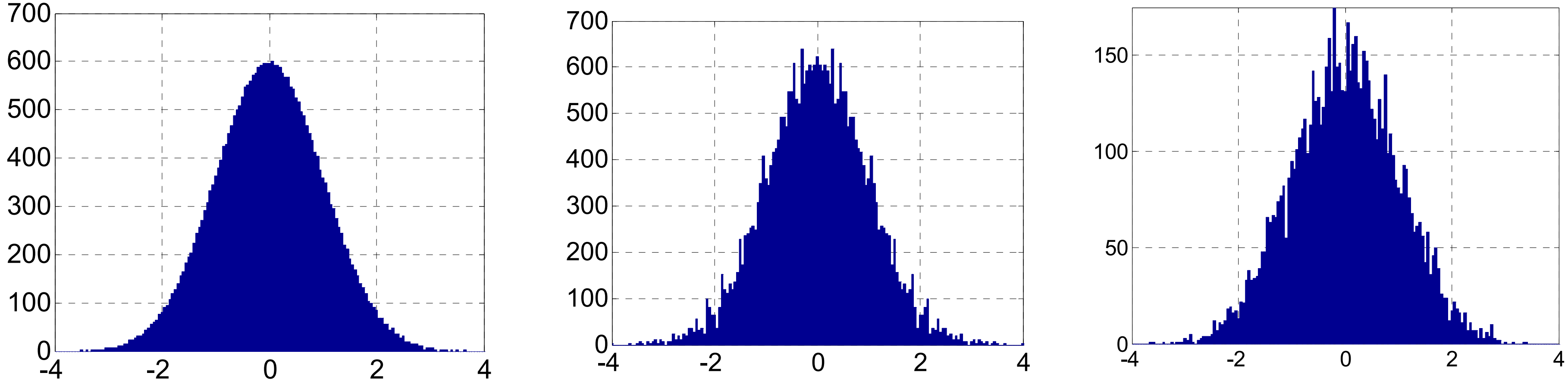
$$R_{\alpha\beta} = \frac{\mathrm{cov}(\alpha, \beta)}{\sigma_\alpha \sigma_\beta}$$

Quiet start ?

$n = 4 * N_{trans}$ ALICE

$n = 4 * N_{trans}$ Genesis

N_{trans} ASTRA



y / σ_y y / σ_y y / σ_y

$$N_{trans} = 7500$$

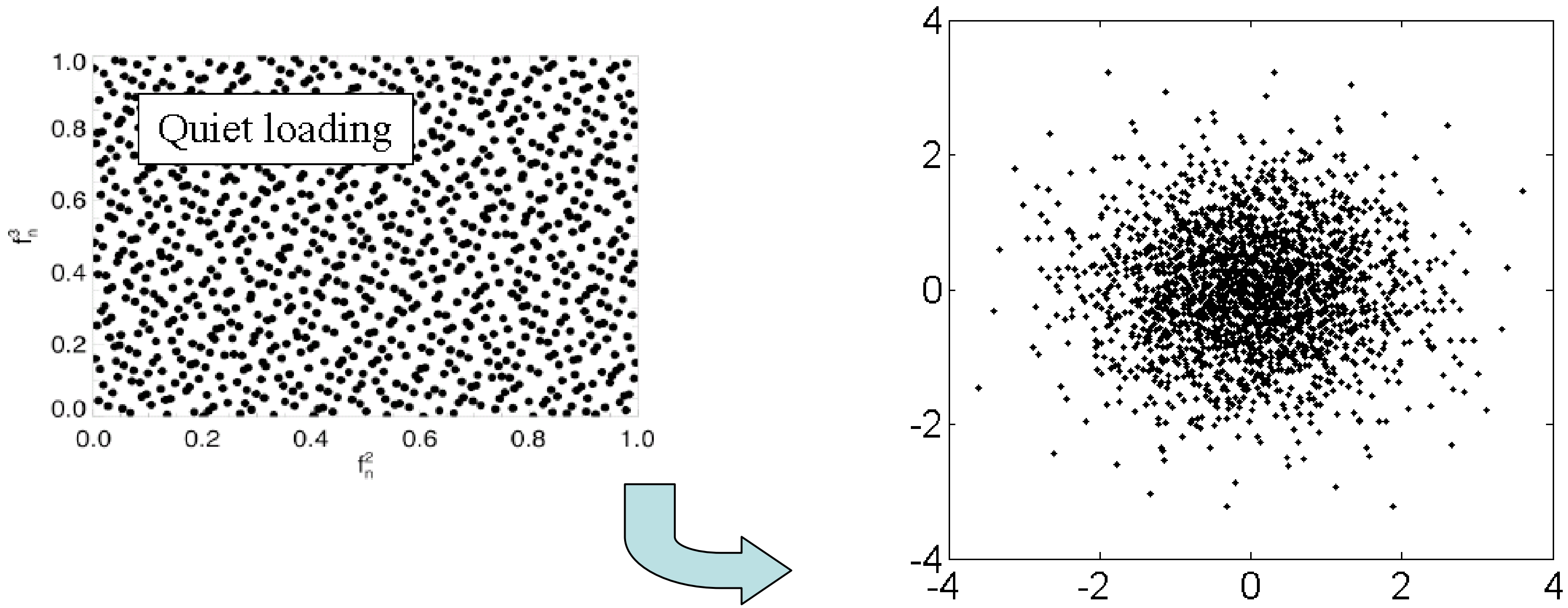
clustering

What is the reason?

Quiet start ?

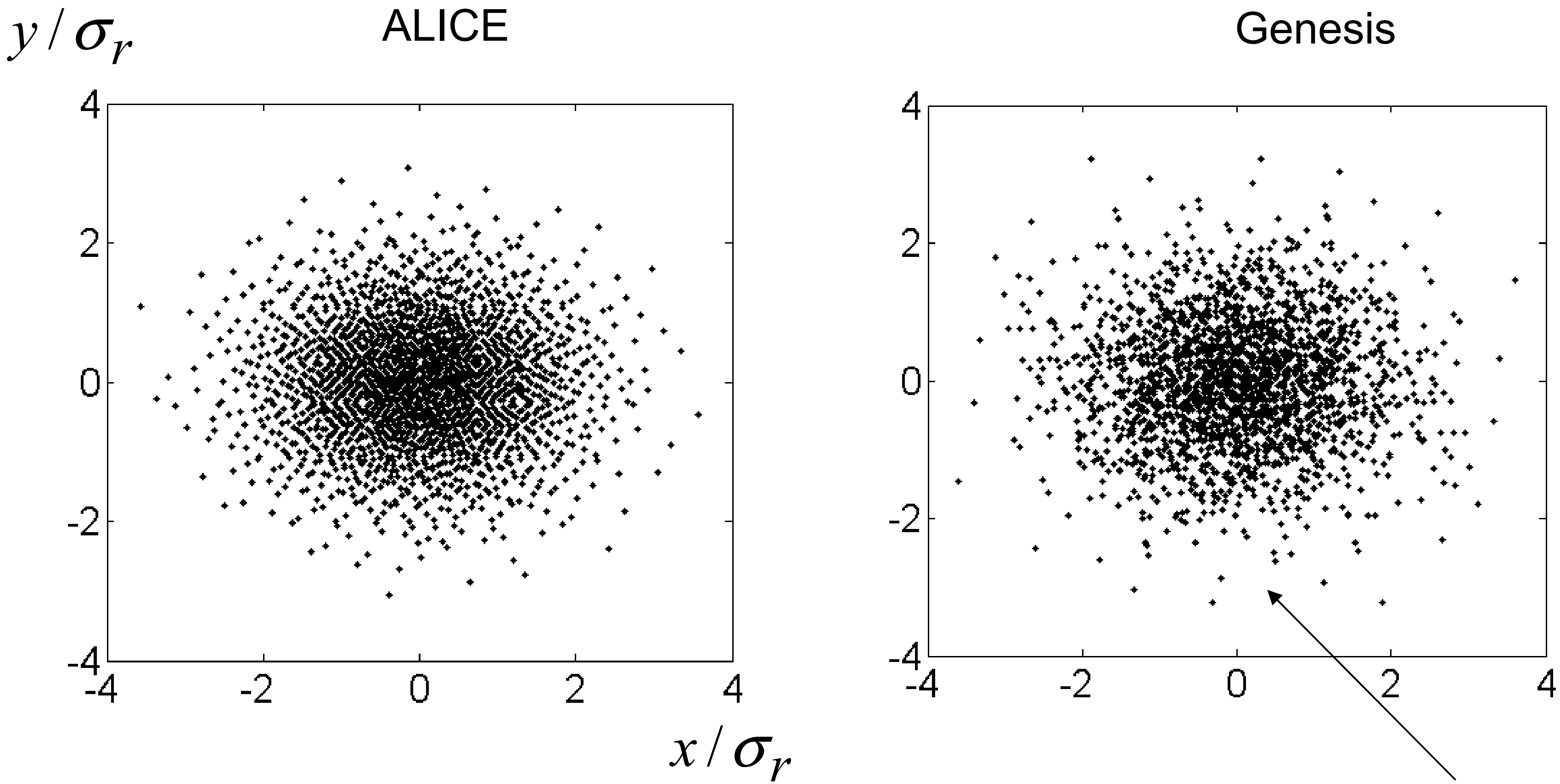
Uniform

Normal



The polar form of Box-Muller algorithm (in Genesis) maps the „quiet“ uniform distribution in a clustered normal distribution.

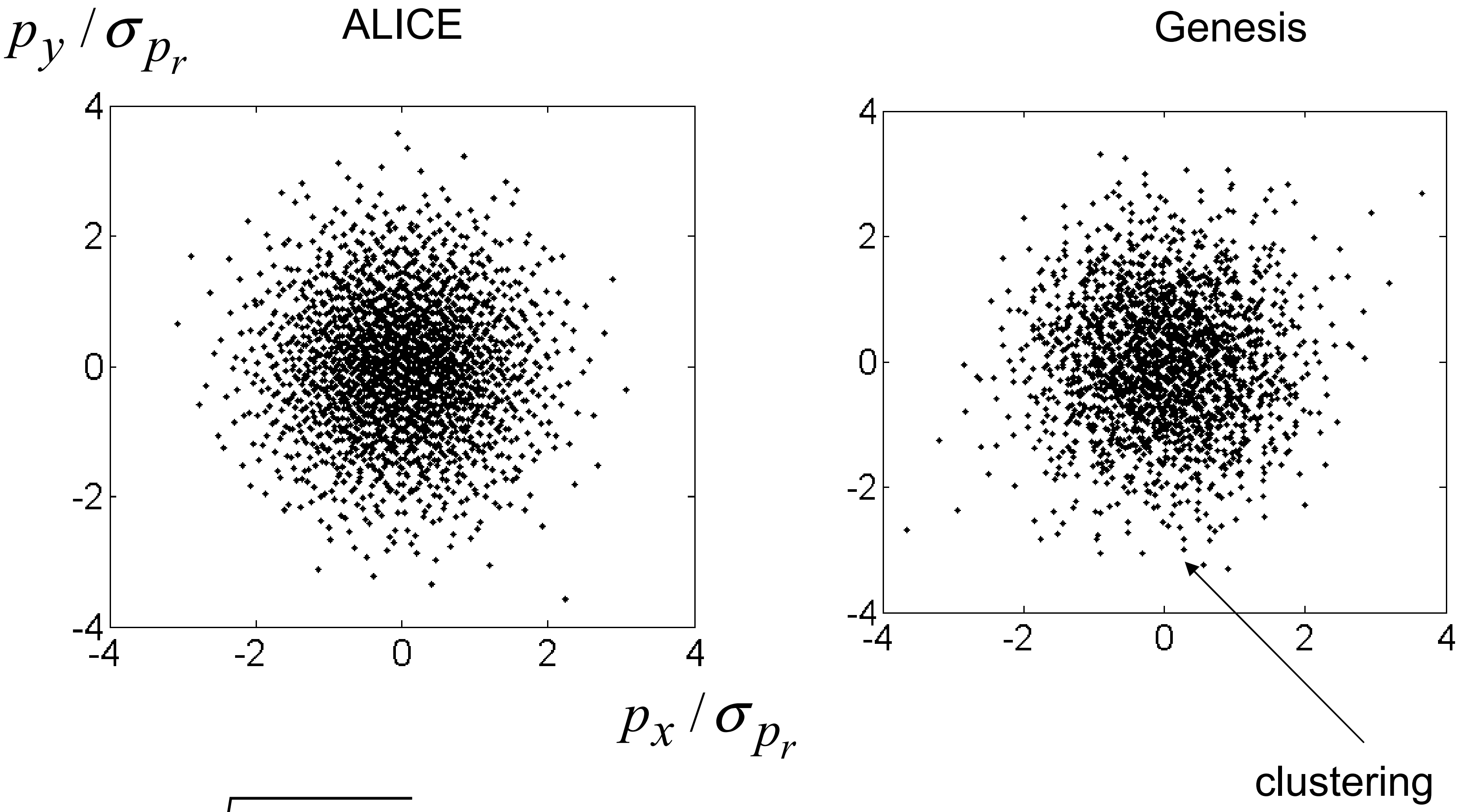
Quiet start ?



$$\sigma_r = \sqrt{\sigma_x \sigma_y}$$

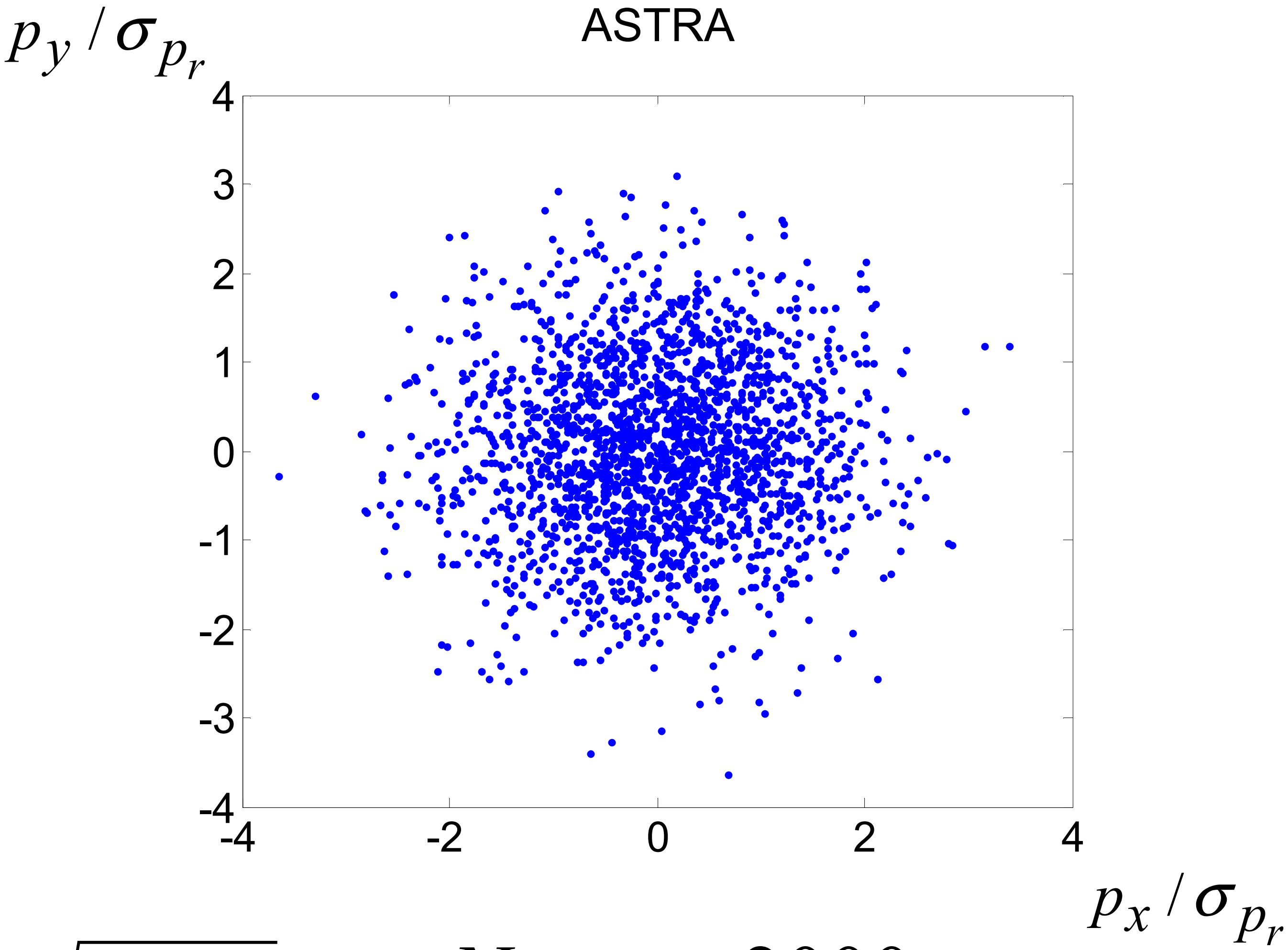
$$N_{trans} = 2000$$

Quiet start ?



$$\sigma_{p_r} = \sqrt{\sigma_{p_x} \sigma_{p_y}}$$

$$N_{trans} = 2000$$



$$\sigma_{p_r} = \sqrt{\sigma_{p_x} \sigma_{p_y}}$$

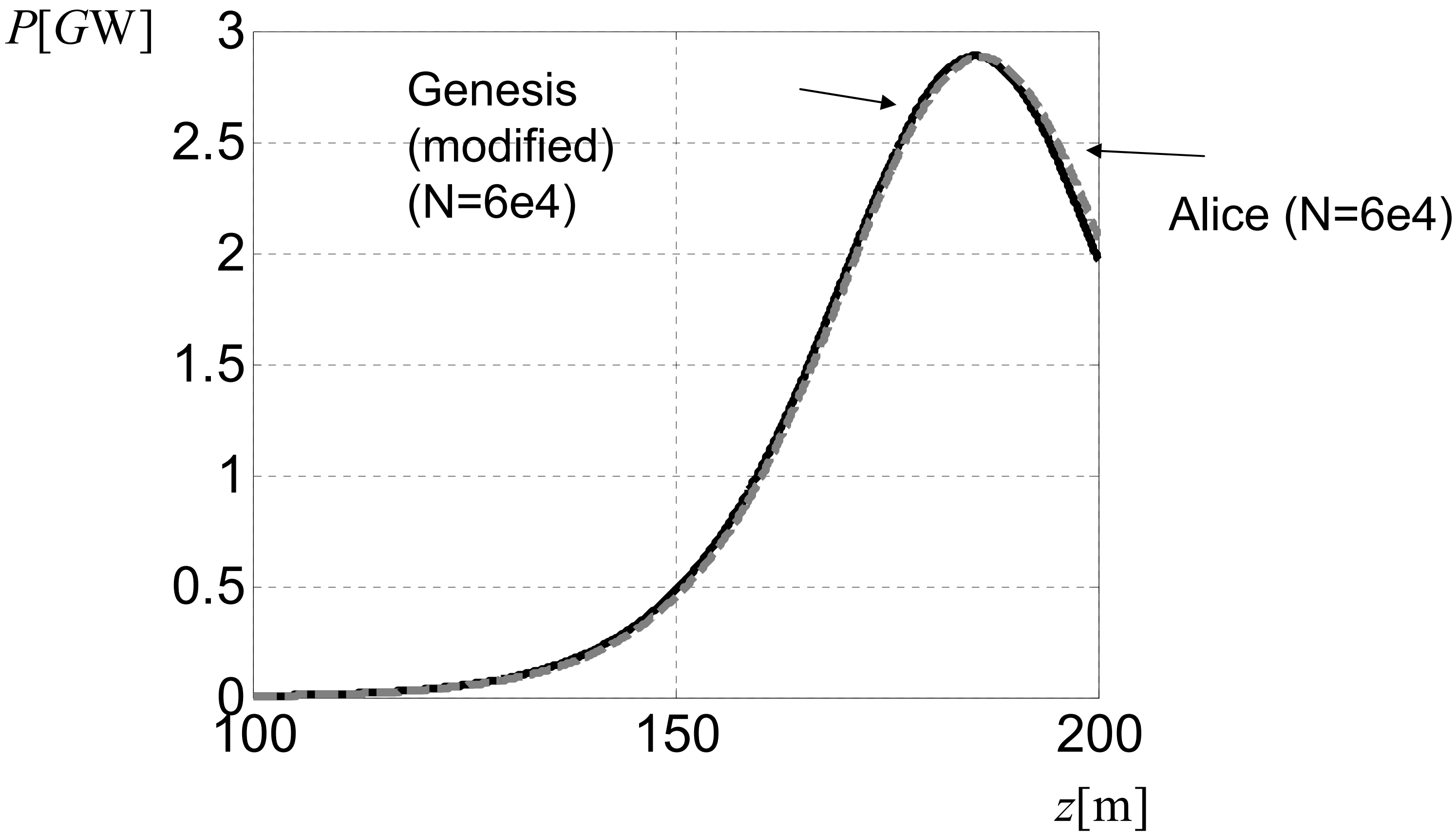
$$N_{trans} = 2000$$

Modified Genesis vs. ALICE with transverse motion

$C = 0$

P0 = 4000 Watt

$\sigma_E = 2.5\,\mathrm{MeV}$



The transformation used in ALICE

It uses the straightforward transformation by inverse error function

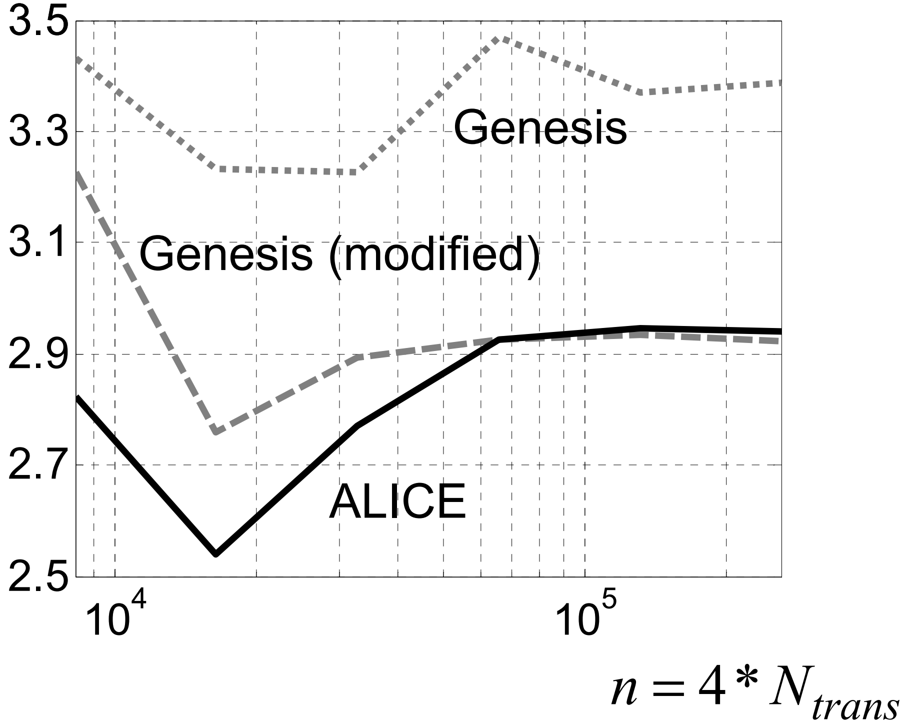
$$Y_i = \sigma\sqrt{2}\,\mathrm{erf}^{-1}(2X_i - 1) + \mu$$

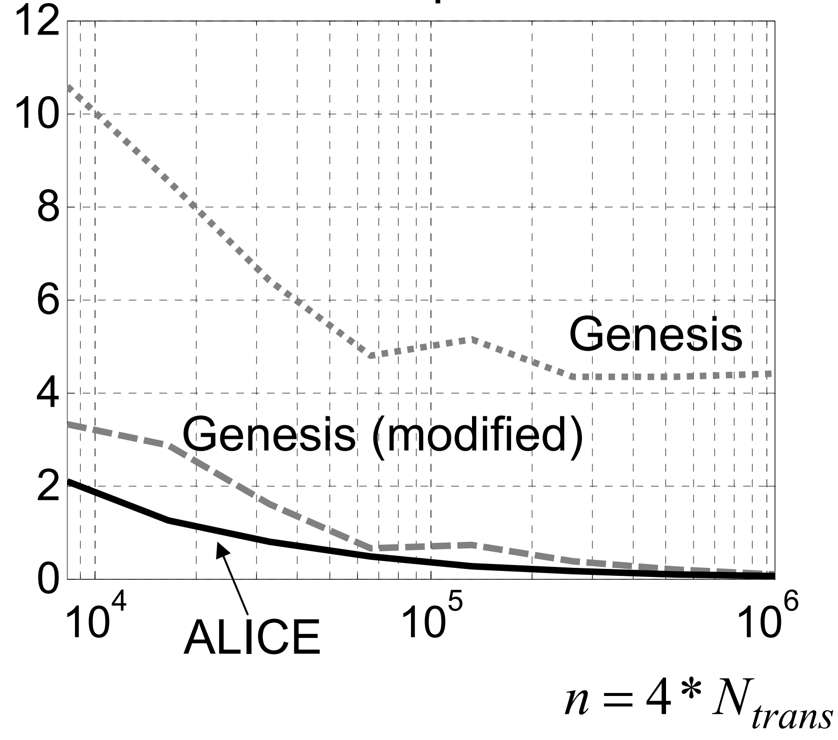
It transforms the uniform distribution X_i (0,1) to the normal distribution Y_i (μ, σ).
This transformation does not destroy the „quiet start“.

Convergence

$P[GW]$ at saturation

$$\delta = \frac{|\sigma_4 - \tilde{\sigma}_4|}{\sigma_4} 100\%$$





Genesis:	Hammersley and Box-Mueller
Genesis (modified):	Hammersley and the inverse error function
ALICE:	Sobol and the inverse error function

$\sigma_E = 2.5\,\mathrm{MeV}$

$C = 0$

$\lambda_s = 0.1\,\mathrm{nm}$

I=5KA

N_λ ~10 400