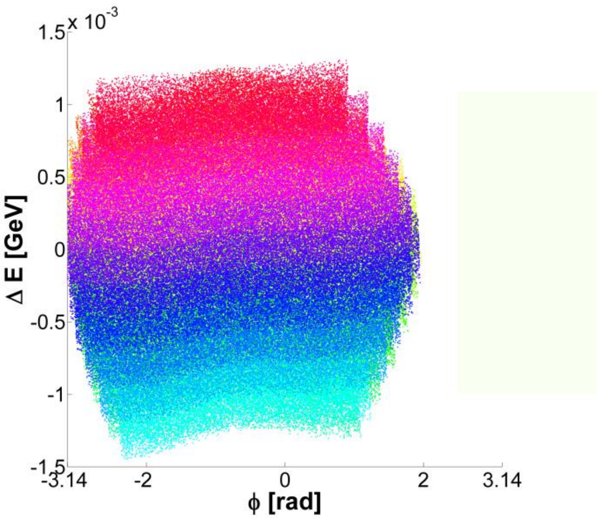
Longitudinal evolution of LHC beams in the PSB from Linac4

V. Forte

Acknowledgements: E. Benedetto, C. Carli, H. Damerau, A. Lombardi

Two ways for the longitudinal injection…

Longitudinal painting



Pros:

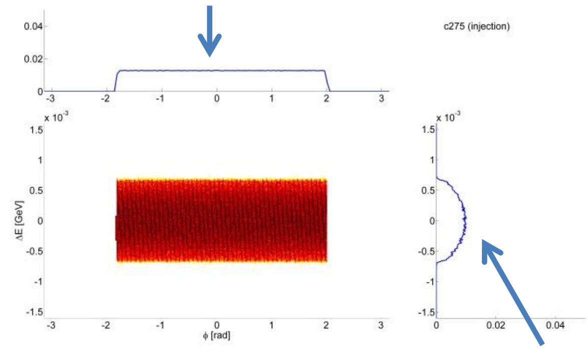
- *Uniform filling of the bucket with bunching factor optimization (good for space charge)*

Cons:

- *Slow modulation of E_0 vs. time -> min. 40 turns/injection to cover all the bucket*

No longitudinal painting

uniform



waterbag

Pros:

- *Easy implementation fixing ΔE and Linac4 chopping factor at injection.*
- *Less # turns / injection*

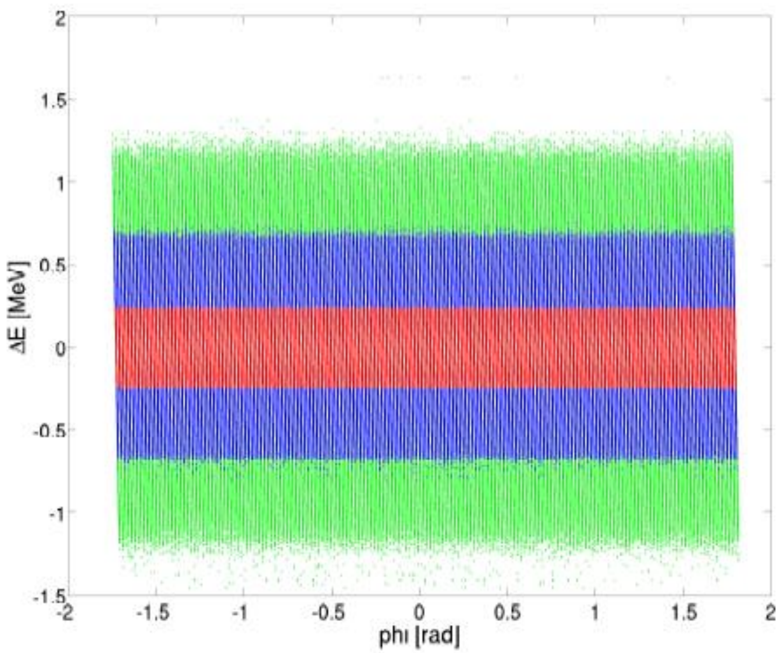
Cons:

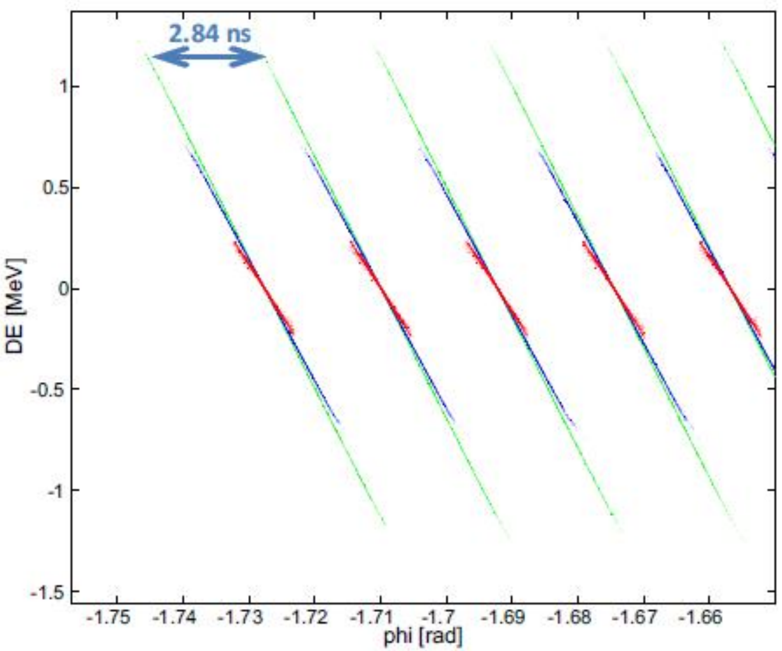
- *Non-uniform filling*

The Linac4 bunches in the PSB…

Alessandra provided different Linac4 bunches, with different ΔE, to evaluate the best one…

113 keV rms - 336 keV rms - 592 keV rms





$$Nr.\ of\ injected\ bunches = \frac{Desired\ intensity\ in\ the\ PSB}{Single\ bunch\ intensity}$$

From LIU specifications

1.14e9 p.* (assumption…corresponding to 80 mA from source. To be updated.)

$$Nr.\ of\ turns = \frac{Nr.\ of\ injected\ bunches}{Bunches\ per\ turn}$$

To be determined

* Linac4 Technical Design Report - CERN.AB.2006.084 ABP/RF – page 6

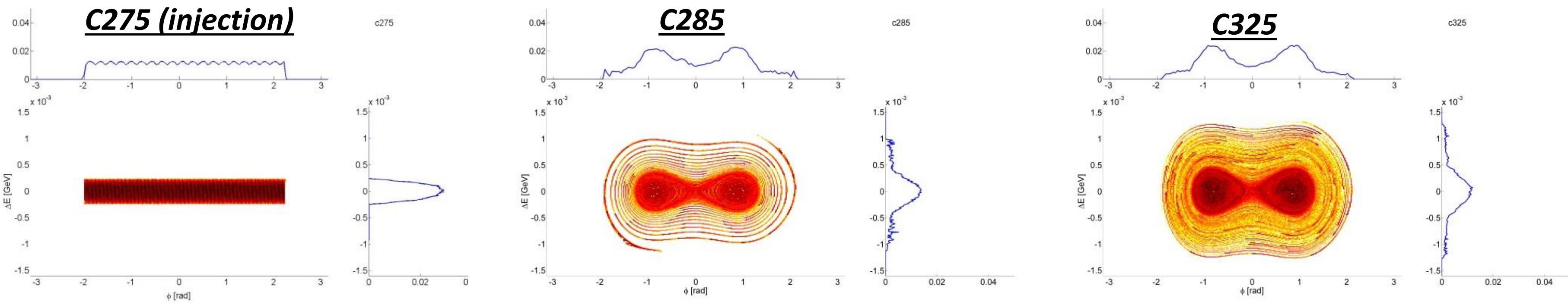
PSB Upgrade
LIU Project

Injection without energy modulation

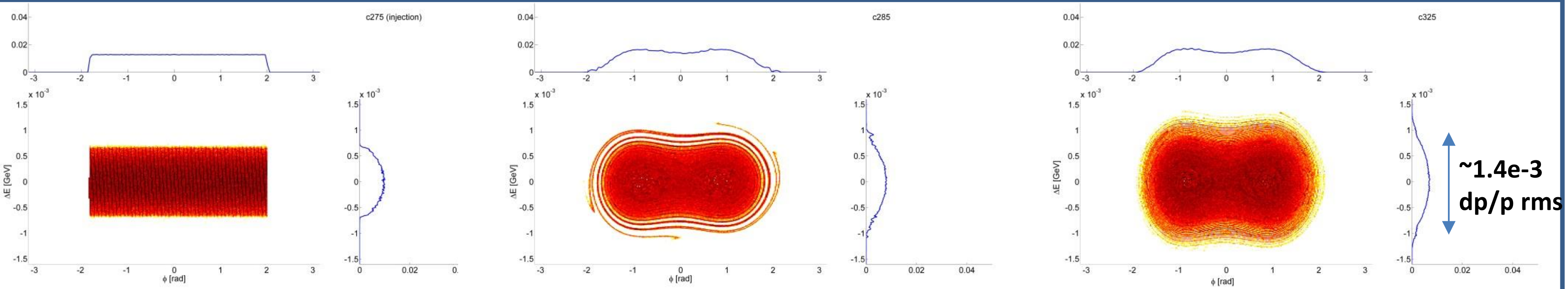
From single Linac4 bunches it is possible to create injection structures for the PSB, for optimizing…

- **the bunch length to minimize the number of turns injected.**
- **the energy spread to minimize filamentation and peaks in linear density.**

ESME simulations without longitudinal space charge



Min-max 0.5 MeV (113 keV RMS) – 0.19 eVs (rms%) - 0.38e-3 dp/p rms – total bunch length 690 ns – 243 Linac4 bunches



Min-max 1.74 MeV (336 keV RMS) - **1.1e-3 dp/p rms** – total bunch length **625 ns** – 220 Linac4 bunches

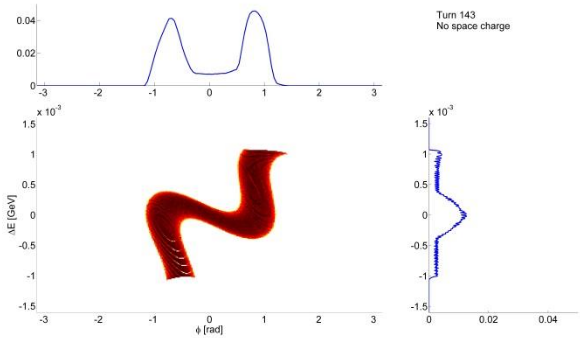
References:
C. Carli, R. Garoby - ACTIVE LONGITUDINAL PAINTING FOR THE H- CHARGE EXCHANGE INJECTION OF THE LINAC4 BEAM INTO THE PS BOOSTER - AB-Note-2008-011 ABP

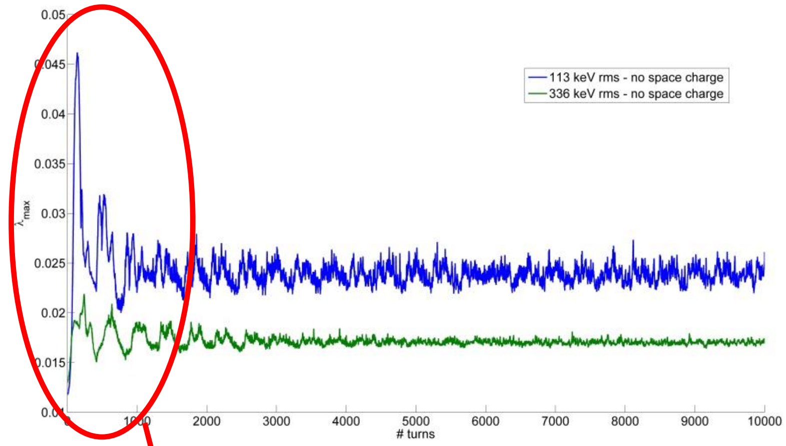
Injection without energy modulation

- **113 keV rms** -> increase in top linear density of a factor 4 during the first 150 turns .
- **336 keV rms** -> nicer and smoother behavior in top linear density (lower) .
- **592 keV rms** -> increase of turns around 60% to fit in the PSB bucket (max 139 Linac 4 bunches/turns), w.r.t. the previous cases (not under further consideration).

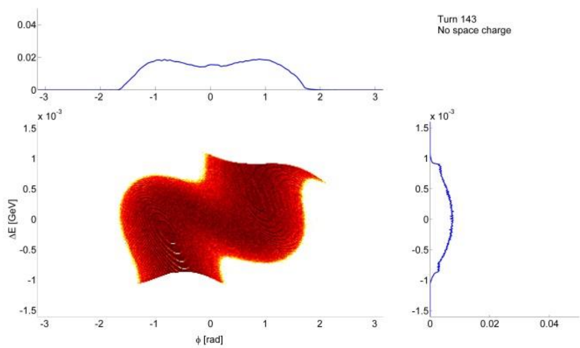
__After 143 turns__

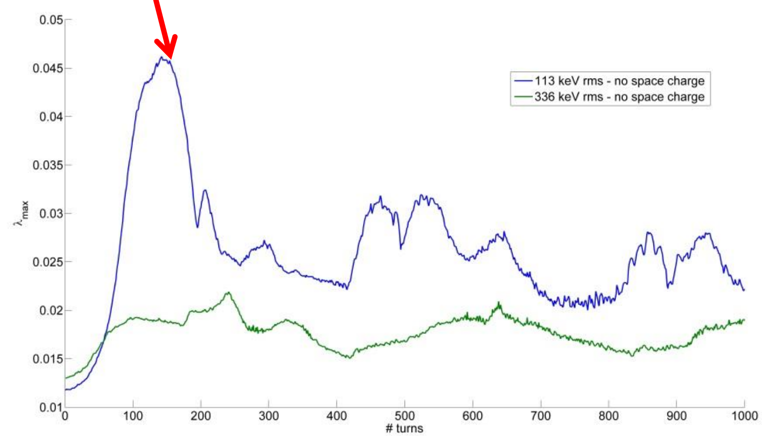
__113 keV rms__





__336 keV rms__





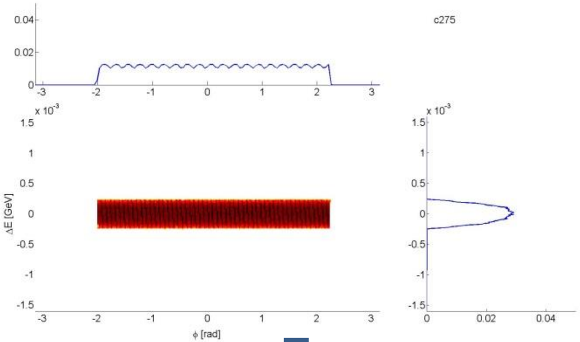
PSB Upgrade
LIU Project

Longitudinal space charge effect

- **The longitudinal "islands" creation is an intensity-dependent phenomenon (increases with intensity).**
- **It happens when the space charge module is activated in ESME .**

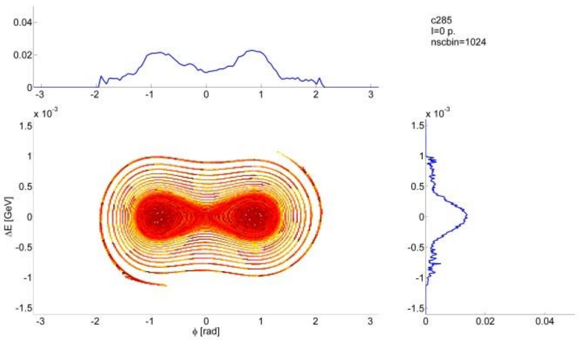
<u>C275 (injection)</u>

<u>113 keV rms</u>

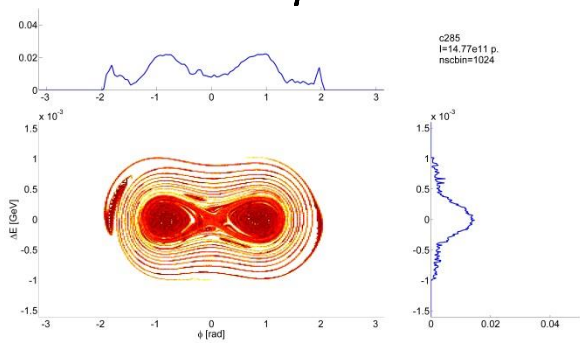


<u>C285</u>

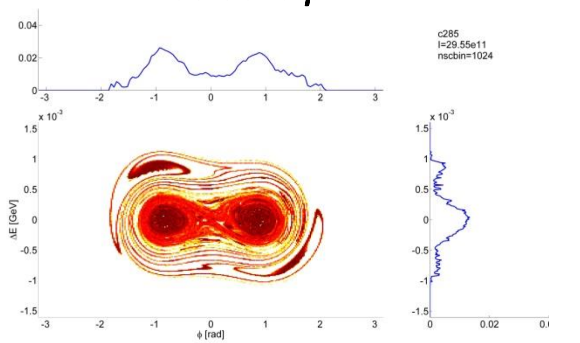
I=0



I=147.7e10 p.



I=295.5e10 p.

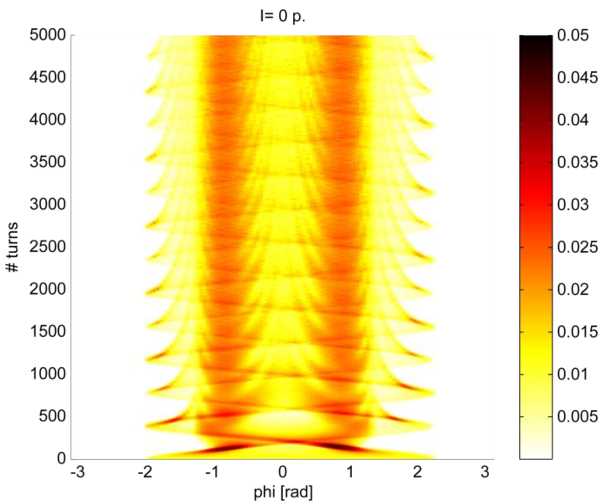


PSB Upgrade
LIU Project

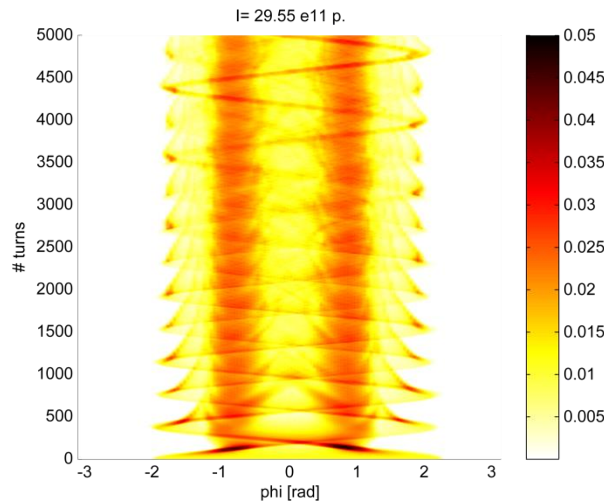
Longitudinal space charge effect

*Simulations with all intensity in one shot

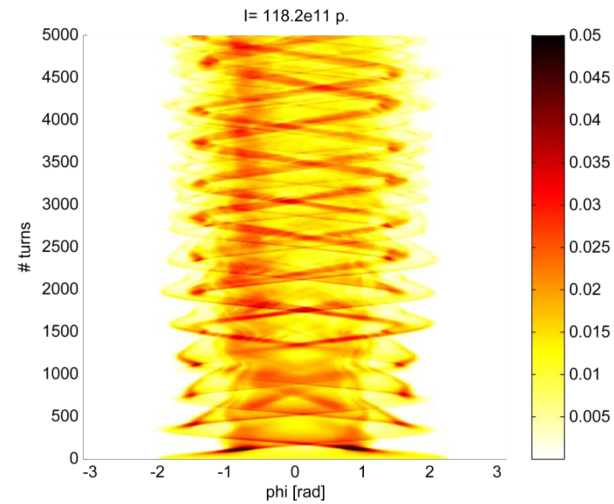
ESME simulations with longitudinal space charge



I=0 p.



I=295.5e10 p.



I=1182e10 p.

Initial bunch length = 690 ns
(239 Linac4 bunches)
Initial ΔE rms= 113 keV
b/a=30/11

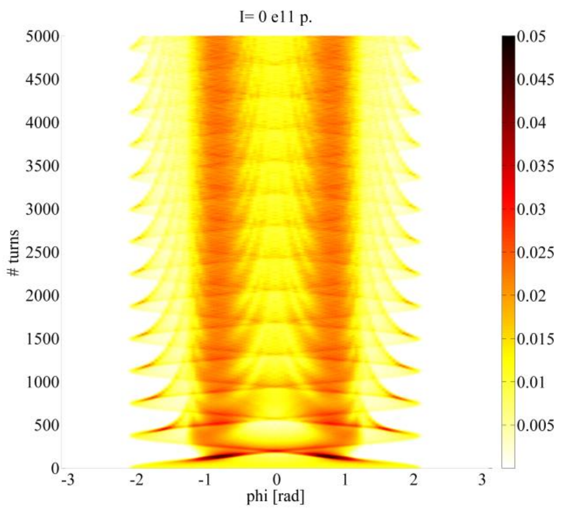
The longitudinal space charge field:

$$V_i = -\frac{\left(1 + 2\ln\left(\frac{b}{a}\right)\right)R}{2\epsilon_0\gamma^2}\lambda'$$

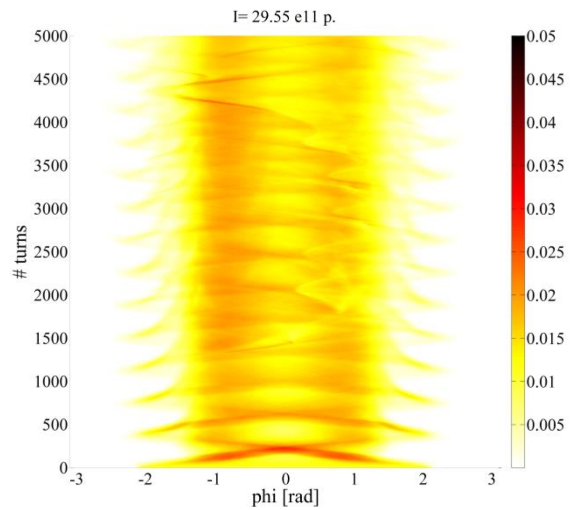
PSB Upgrade
LIU Project

Longitudinal space charge effect

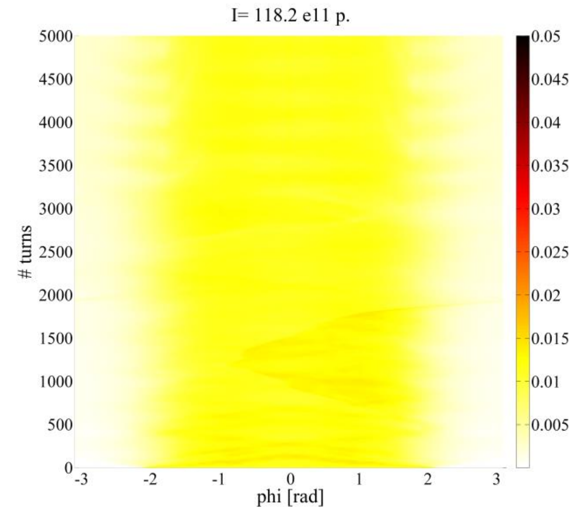
PyOrbit simulations with longitudinal space charge (no acceleration)



I=0 p.



I=295.5e10 p.



I=1182e10 p.

PyOrbit simulations show different results (to be understood).

Summary and conclusions

- Different bunch trains from Linac4 have been tracked in the PSB for several turns at injection.
- In particular 3 structures with ΔE = 113 keV, 336 keV and 592 keV have been analysed more in detail. The structure at 592 keV requires 60% more turns for a given intensity, because it must be much shorter to fit in the bucket: max 139 Linac4 bunches per turn, instead of 220 (336keV) or 243 (113keV).
- The best solution in terms of bigger bunch length and smaller linear density is the one with **336 keV rms** injected (halfway solution).
- Problems with longitudinal space charge can raise for high intensity beams (PyOrbit and ESME simulations, to be understood). Also ln(b/a) has an impact.
- Important is to optimize the "rectangle" shape -> New simulations are on-going for small changes in the initial conditions (w.r.t. to the 336 keV case).

APPENDIX

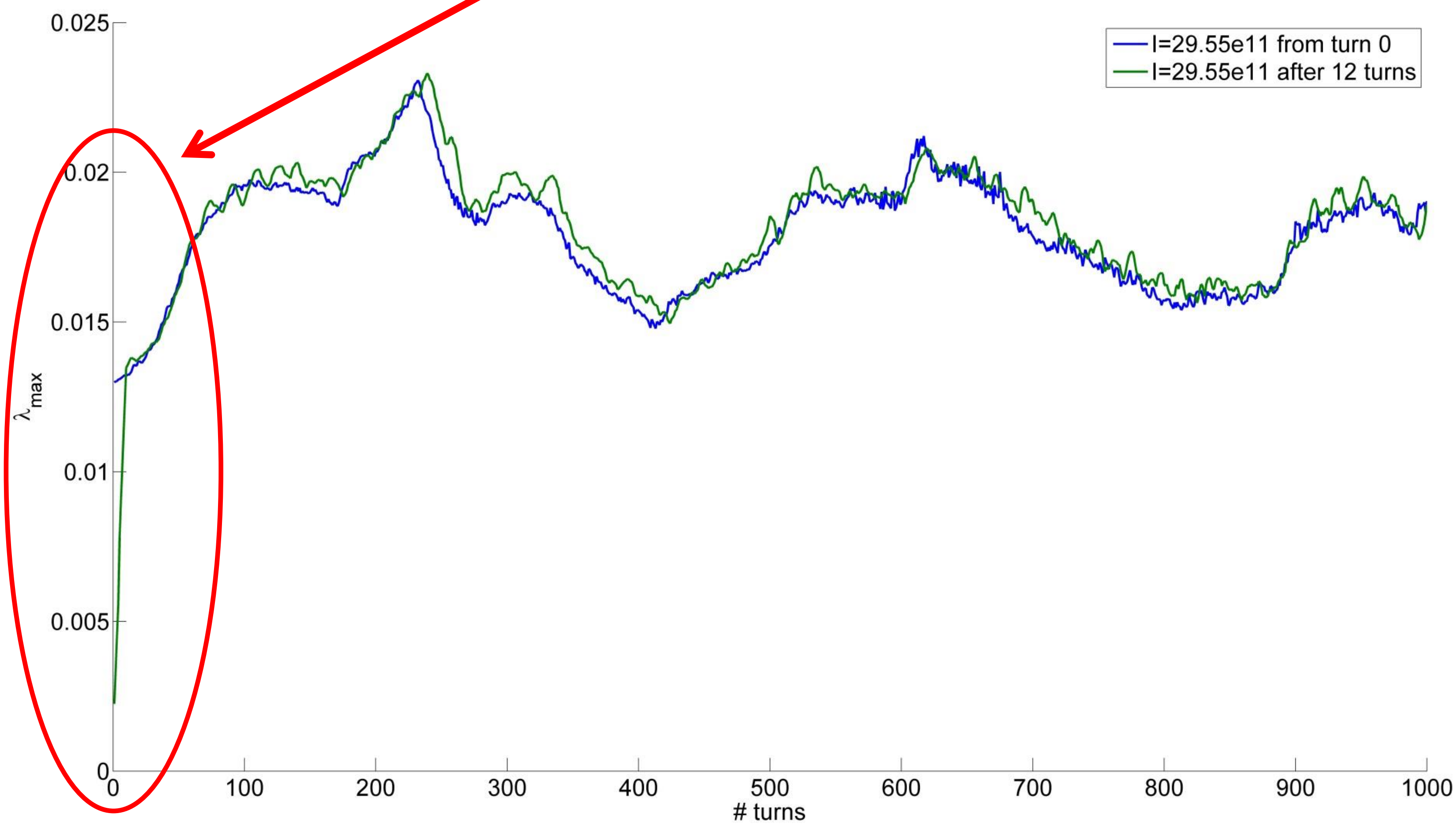
Linac4 Technical Design Report - CERN.AB.2006.084 ABP/RF – page 6

Table 1.2: Linac4 beam parameters

Ion species	H^-
Output energy	160 MeV
Bunch frequency	352.2 MHz
Max. rep.-rate	2 Hz
Beam pulse length	400 μs
Max. beam duty cycle	0.08%
Chopper beam-on factor	62%
Chopping scheme	222/133 full/empty buckets
Source current	80 mA
RFQ output current	70 mA
Linac current	40 mA
Average current	0.032 mA
Beam power	5.1 kW
No. particles per pulse	1.00×10^{14}
No. particles per bunch	1.14×10^{9}
Source transverse emittance	0.2 π mm mrad
Linac transverse emittance	0.4 π mm mrad

Why do we inject all the intensity in 1 turn in our simulations (not real condition)?

Injecting in 1 shot in simulations does not show much differences w.r.t. to the multiturn injection in terms of linear density (at least for small nr. of turns)

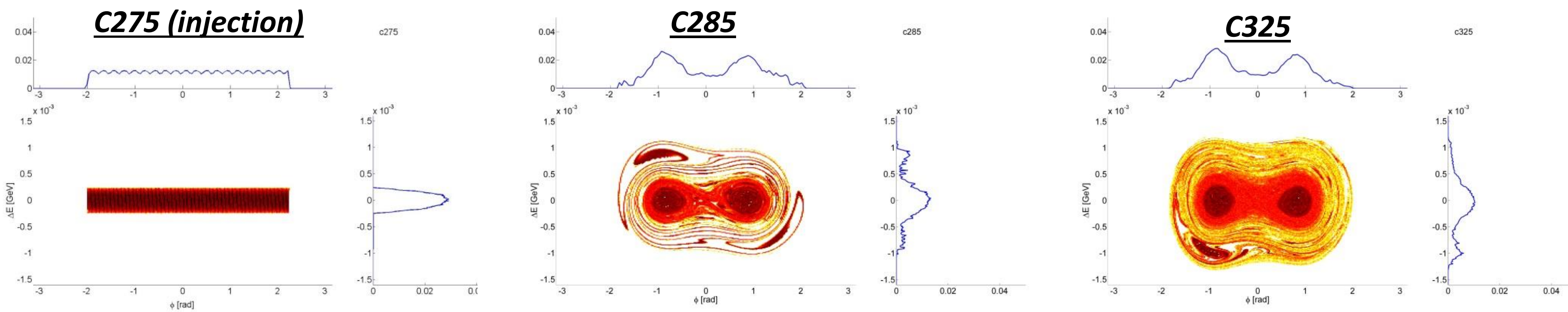


PSB Upgrade
LIU Project

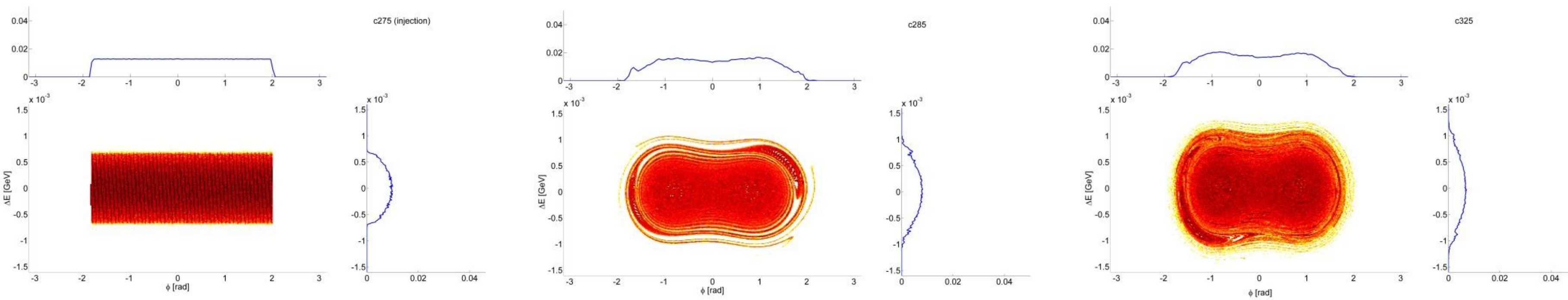
Linac4 chopped bunches injection in the PSB without energy modulation

- **Optimize…**
  - **the bunch length to minimize the number of turns injected in the PSB for a certain intensity.**
  - **the energy spread to minimize filamentation and peaks in linear density.**

ESME simulations (I=29.55e11)



Min-max 0.5 MeV (113 keV RMS) - 0.38e-3 dp/p rms – 690 ns – 243 Linac4 bunches



Min-max 1.74 MeV (336 keV RMS) - 1.1e-3 dp/p rms – 625 ns – 220 Linac4 bunches

<u>To inject 1.65e12 p. in the PSB -> 6.6 turns</u>

(@ 220 Linac4 bunches/turn and 1.14e9 p.p.bunch)

Reference:

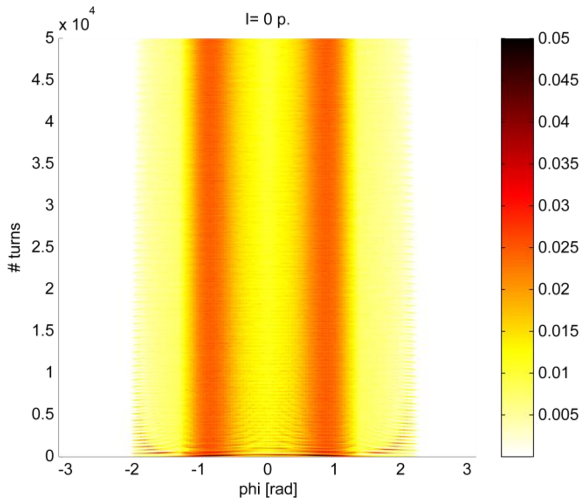
C. Carli, R. Garoby - ACTIVE LONGITUDINAL PAINTING FOR THE H- CHARGE EXCHANGE INJECTION OF THE LINAC4 BEAM INTO THE PS BOOSTER - AB-Note-2008-011 ABP

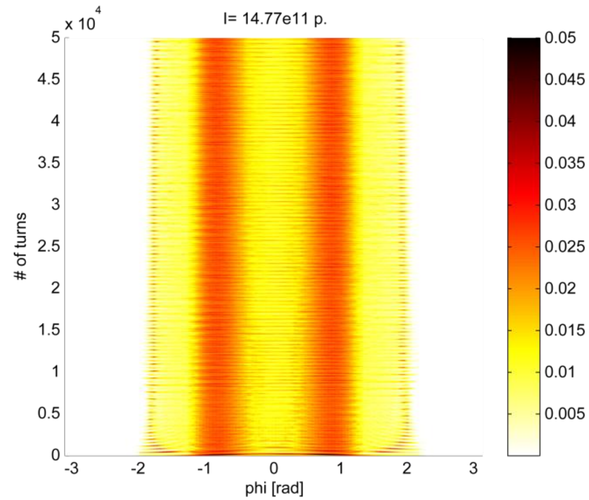
Why is it not possible to have high intensity AND small transverse profiles?

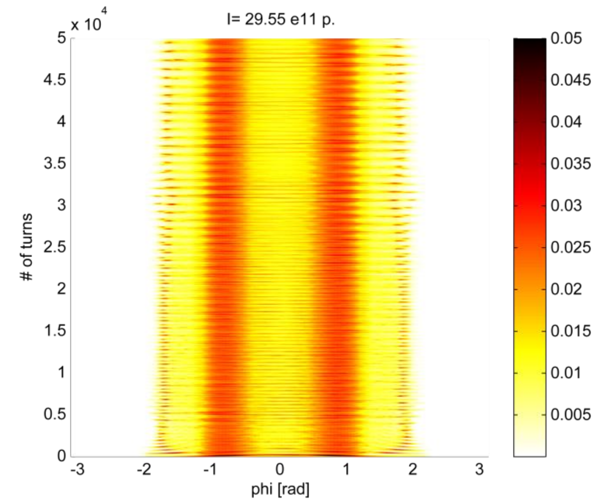
PSB Upgrade
LIU Project

ESME simulations with longitudinal space charge (long term simulations)

LHC typical intensities

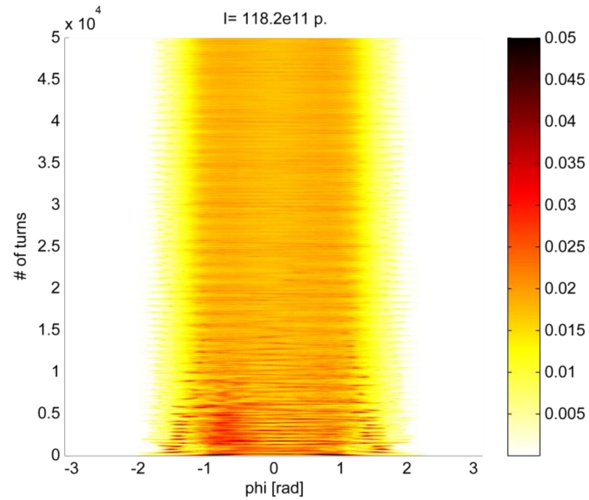






~ISOLDE typical intensities

Initial bunch length = 680 ns (239 Linac4 bunches)
Initial ΔE rms= 113 keV
b/a=30/11



The longitudinal space charge field:

$$V_i = -\frac{R g_0 \lambda'}{2 \varepsilon_0 \gamma^2},$$

where $g_0 = (1+2\ln(b/a))$, b is the vacuum chamber radius and a is the beam radius, λ' is the longitudinal charge density gradient, ε_0 is the permittivity of free space, γ is the relativistic factor and $2\pi R$ is the circumference of the ring.

* BUNCH SHORTENING EXPERIMENTS IN THE FERMILAB BOOSTER AND THE AGS

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***Simulations with all intensity in one shot**

LIU target beam parameters

PSB

		N (10^{11} p)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
LIU	Standard	29.55	1.55	0.16	1.4	650	$1.8 \cdot 10^{-3}$	(0.55, 0.66)
	BCMS	14.77	1.13	0.16	1.4	650	$1.8 \cdot 10^{-3}$	(0.35, 0.44)
HL-LHC		34.21	1.72	0.16	1.4	650	$1.8 \cdot 10^{-3}$	(0.58, 0.69)

PS (double injection)

		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
LIU	Standard	28.07	1.63	2.0	3.00	205	$1.5 \cdot 10^{-3}$	(0.16, 0.28)
	BCMS	14.04	1.19	2.0	1.48	135	$1.1 \cdot 10^{-3}$	(0.19, 0.31)
HL-LHC		32.50	1.80	2.0	3.00	205	$1.5 \cdot 10^{-3}$	(0.18, 0.30)

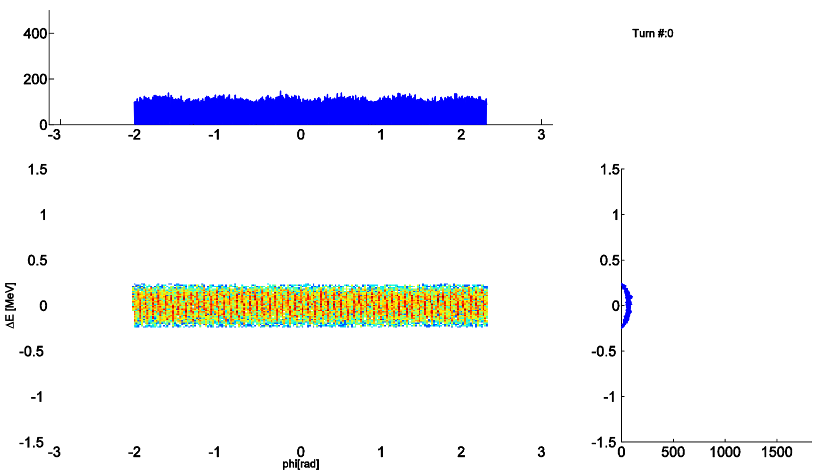
SPS (several injections)

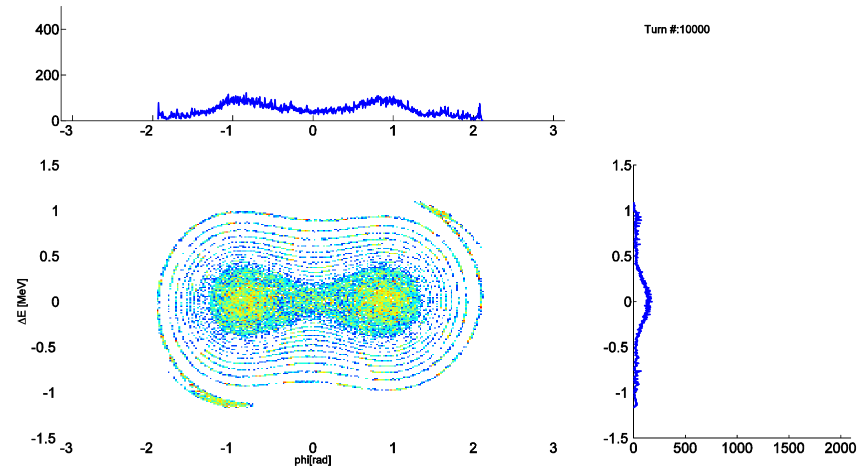
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	p (GeV/c)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
LIU	Standard	2.22	1.71	26	0.37	3.0	$1.5 \cdot 10^{-3}$	(0.09, 0.16)
	BCMS	2.22	1.25	26	0.37	3.0	$1.5 \cdot 10^{-3}$	(0.12, 0.21)
HL-LHC		2.57	1.89	26	0.37	3.0	$1.5 \cdot 10^{-3}$	(0.10, 0.17)

LHC

		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	p (GeV/c)	ϵ_z (eVs/b)	B_l (ns)	bunches/train
LIU	Standard	2.00	1.88	450	0.60	1.65	72
	BCMS	2.00	1.37	450	0.60	1.65	48
HL-LHC		2.32	2.08	450	0.65	1.65	72

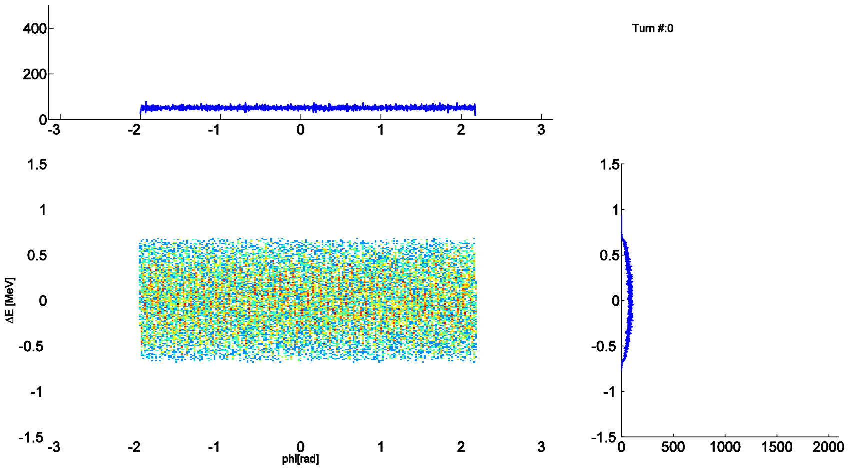
113 keV

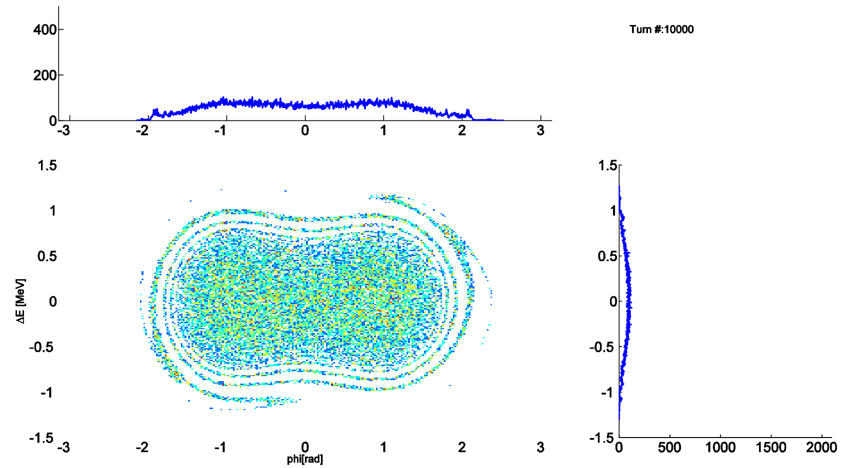




Energy spread (rms)	336keV	
	C275 (injection)	C285
# microbunches x turn	249 (chopping factor 70.1 %)	
Δp/p (rms)	0.38e-3	1.32e-3
Emittance (95%)	1.19 eVs	1.19eVs
Total bunch length	706 ns	628 ns
Bunching factor	0.6	0.35

336 keV

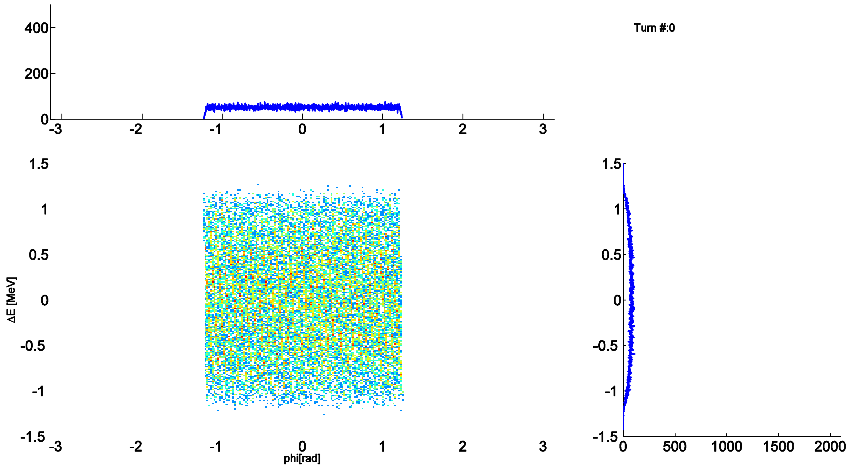


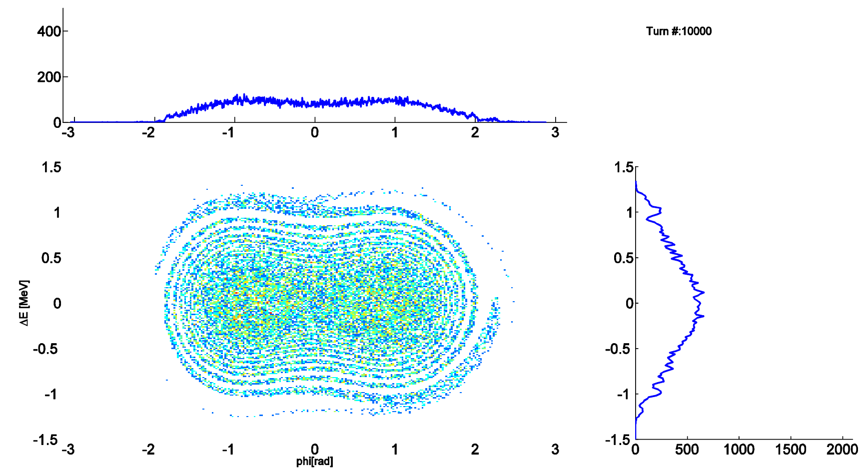


Energy spread (rms)	336keV	
	C275 (injection)	C285
# microbunches x turn	236* (chopping factor 66.5 %)	
Δp/p (rms)	1.1e-3	1.43e-3
Emittance (95%)	1.13 eVs	1.12 eVs
Total bunch length	671 ns	651 ns
Bunching factor	0.64	0.47

***instead of 220 (slide nr. 4)**

592 keV





Energy spread (rms)	592keV	
	C275 (injection)	**C285**
# microbunches x turn	139 (chopping factor 39.1%)	
Δp/p (rms)	2e-3	2.3e-3
Emittance (95%)	1.23 eVs	1.22 eVs
Total bunch length	396 ns	643 ns
Bunching factor	0.37	0.47

* Divergent due to particles out of acceptance