e+ stacking simulations update

Frank Zimmermann
on behalf of the POSIPOL Collaboration

Particular thanks to: Fanouria Antoniou, Robert Chehab, Maxim Korostelev, Masao Kuriki, Tsunehiko Omori, Yannis Papaphilippou, Louis Rinolfi, Junji Urakawa, Alessandro Variola, Alessandro Vivoli , Vitaly Yakimenko

ILC e+ Source Collaboration Meeting, Daresbury 2008

some Compton source history

Conceptual design of a polarised positron source based on laser Compton scattering – Snowmass'05
Sakae Araki *et al.* CARE-ELAN-DOCUMENT-2005-013, CLIC-NOTE-639, KEK-PREPRINT-2005-60, LAL-05-94, Sep 2005. 39pp.
Contributed to 2005 International Linear Collider Physics and Detector Workshop and 2nd ILC Accelerator Workshop, Snowmass, Colorado, 14-27 Aug 2005. e-Print: **physics/0509016**

Updates & improvements:
POSIPOL2006 Geneva
POSIPOL2007 Paris
POSIPOL2008 Hiroshima
CLIC2008 Geneva

physics/0509016
CARE/ELAN Document-2005-013
CLIC Note 639
KEK Preprint 2005-60
LAL 05-94
September 2, 2005

Conceptual Design of a Polarised Positron Source Based on Laser Compton Scattering
— *A Proposal Submitted to Snowmass 2005* —

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activity driven by J. Urakawa, T. Omori, M. Kuriki, A. Variola, K. Moenig, et al

Compton source basics

collide 1.3-1.8 GeV e- beam with laser pulse
stored in optical cavity (λ~1 μm);
yield ~ 0.2 γ/e- for <u>single 600 mJ cavity</u> *

convert Compton scattered photons to e+/e-,
and capture e+
yield ~ 0.01 e+/γ *

stack in accumulation ring
ex.: $6x10^{10}$ e-/bunch → 10^8 e+ → 40-60 stackings
needed to achieve $4.5x10^9$ e+ / bunch for CLIC;
unless we use several optical cavities like ILC

*Tsunehiko Omori, 11 October 2008

various scenarios

Compton sources

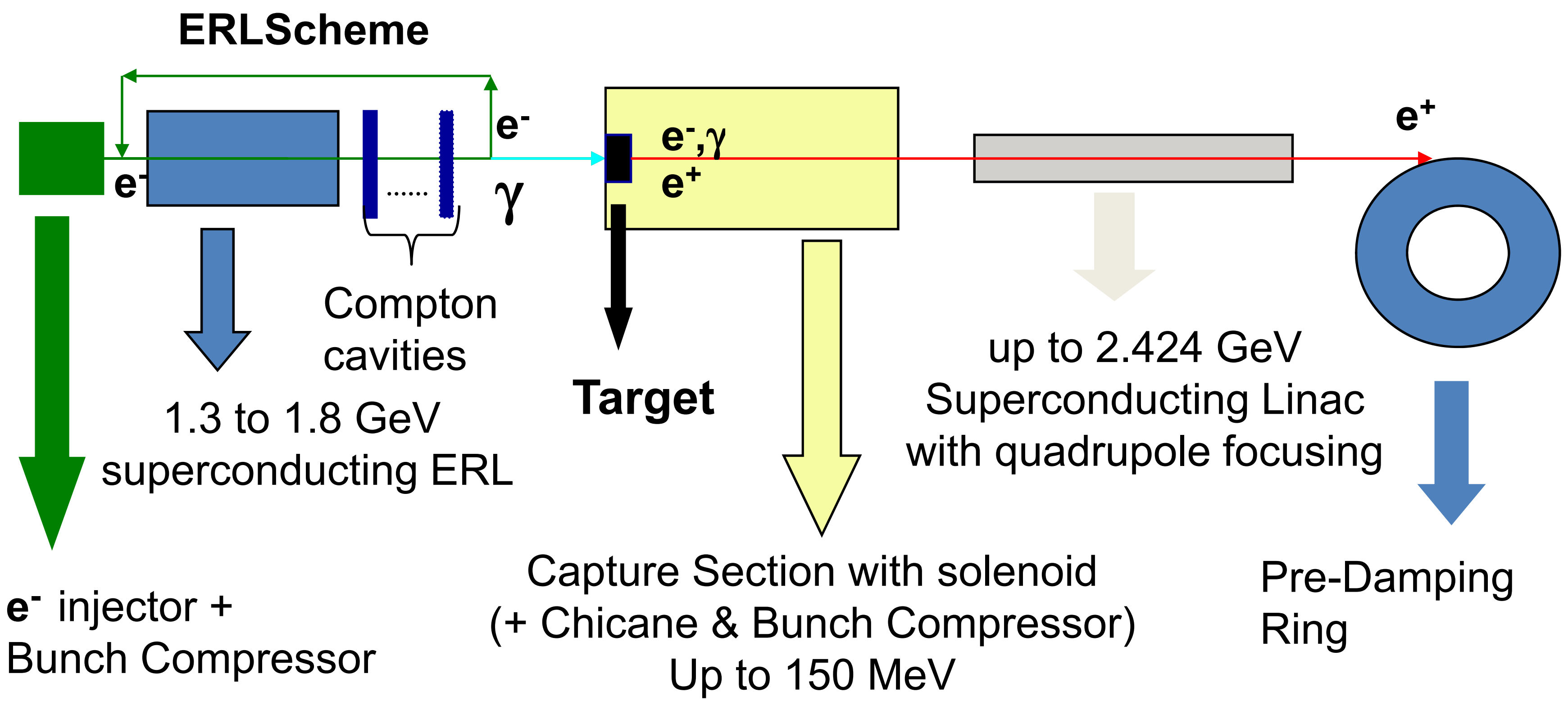
- **Compton ring – CR** (“pulsed”), or
- **Compton ERL – CERL** (“continuous”)

accumulation rings

- **ILC damping ring**
- **CLIC pre-damping ring**
- **dedicated accumulator ring?**

initial e+ parameters (from A. Vivoli's simulation)

parameter	value
#e+ / pulse	6.65 x 10^7
longitudinal edge emittance (10 x rms) at ~200 MeV	0.72 meV-s
transverse normalized edge emittance (10 x rms)	0.063 m-rad



ILC-CLIC comparison

- beam structure: CLIC has a **smaller bunch charge** (about 5x less) and **less bunches per pulse** (about 10x less) → ***relaxed laser parameters***
- **bunch spacing**: **0.5 ns (CLIC) instead of 2.8 ns (ILC)**
  → ***do not stack on every turn in every bucket***, but e.g. every 40th turn with 20 ns e- spacing
- damping ring; CLIC damping ring needs to produce beam with extremely small emittance, limited dynamic aperture; → **pre-damping ring** is required; ***we can use and optimize pre-damping ring for stacking polarized e+ from Compton source***
- CLIC **repetition rate is 50 Hz instead of 5 Hz** for ILC, but (pre-) damping ring damping times are more than 10 times shorter
  → *Compton scheme is easier for CLIC!*

(1) CLIC

- *Compton Ring or*
- *Energy Recovery Linac*

stacking simulations for CLIC CERL/CR scheme

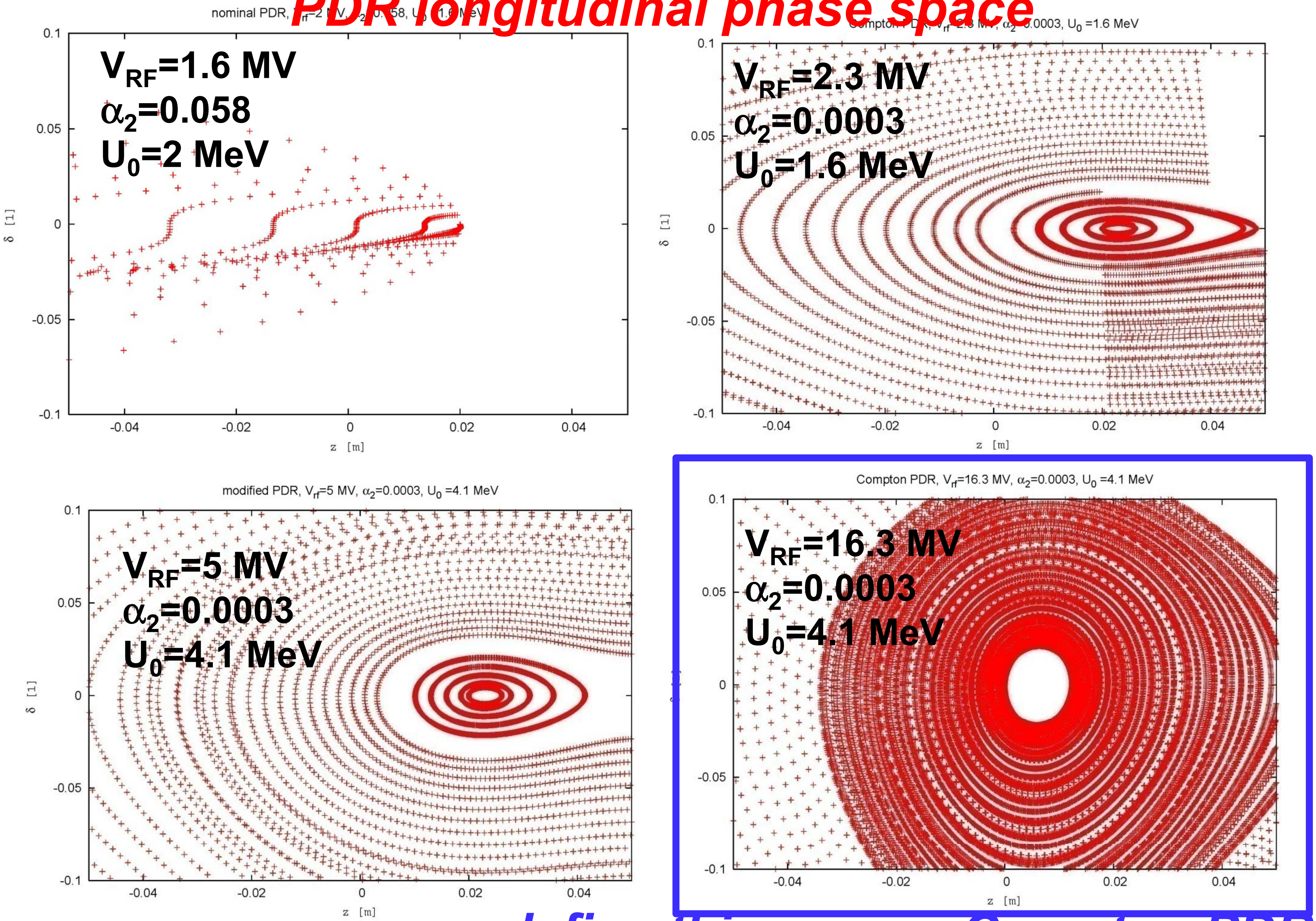
- **stacking is done in longitudinal phase space**
  RF bucket >> longitudinal edge emittance of injected e+
- **ingredients:** ***sinusoidal rf, momentum compaction, 2nd order momentum compaction, radiation damping, quantum excitation, initial e+ parameters*** [**A. Vivoli!**]
- injection septum placed at location with large dispersion; septum blade << transverse beam size
- **inject every 40th turn into same PDR bucket** (20 ns bunch spacing for e- beam; arranged by suitable CR/CERL-PDR circumference difference, e.g. 0.15 m); **fast small septum bump** at moment of injection (probably not needed)

CLIC-Compton Pre-Damping Ring Para's

parameter	value*	"Compton-PDR"
#bunches / train	312	
bunch spacing	0.5 ns	
final bunch charge	4.5×10^{9}	
circumference	251.6 m	
RF frequency	2 GHz	
harmonic number	1677	
RF Voltage	2 MV	**16.2 MV**
1st order momentum compaction	8.98×10^{-5}	
2nd order momentum compaction	0.058	**3×10^{-4}**
beam energy	2.424 GeV	
longitudinal damping time	1.25 ms	**0.5 ms**
equilibrium momentum spread	0.095%	**~0.12%**
equilibrium bunch length	0.786 mm	**~0.47 mm**

***Fanouria Antoniou, Yannis Papaphilippou, 9 October 2008**

PDR longitudinal phase space



define this as new Compton PDR!

CLIC-CERL injection scheme

continuous stacking at 50 MHz (T. Omori, A. Variola)

80 injections over 2400 turns (~2.7 ms)

injecting every 40th turn ($\Delta\phi_s$=0.50 x 2 π)

followed by 20647 turns (~17.3 ms) damping;

longitudinal damping time 0.5 ms

inject with constant offset δ, fast orbit bump at sept.

parameters of injected e+ bunchlets:

<Vivoli san's result: ~ 2.9 MeV at ~200 MeV

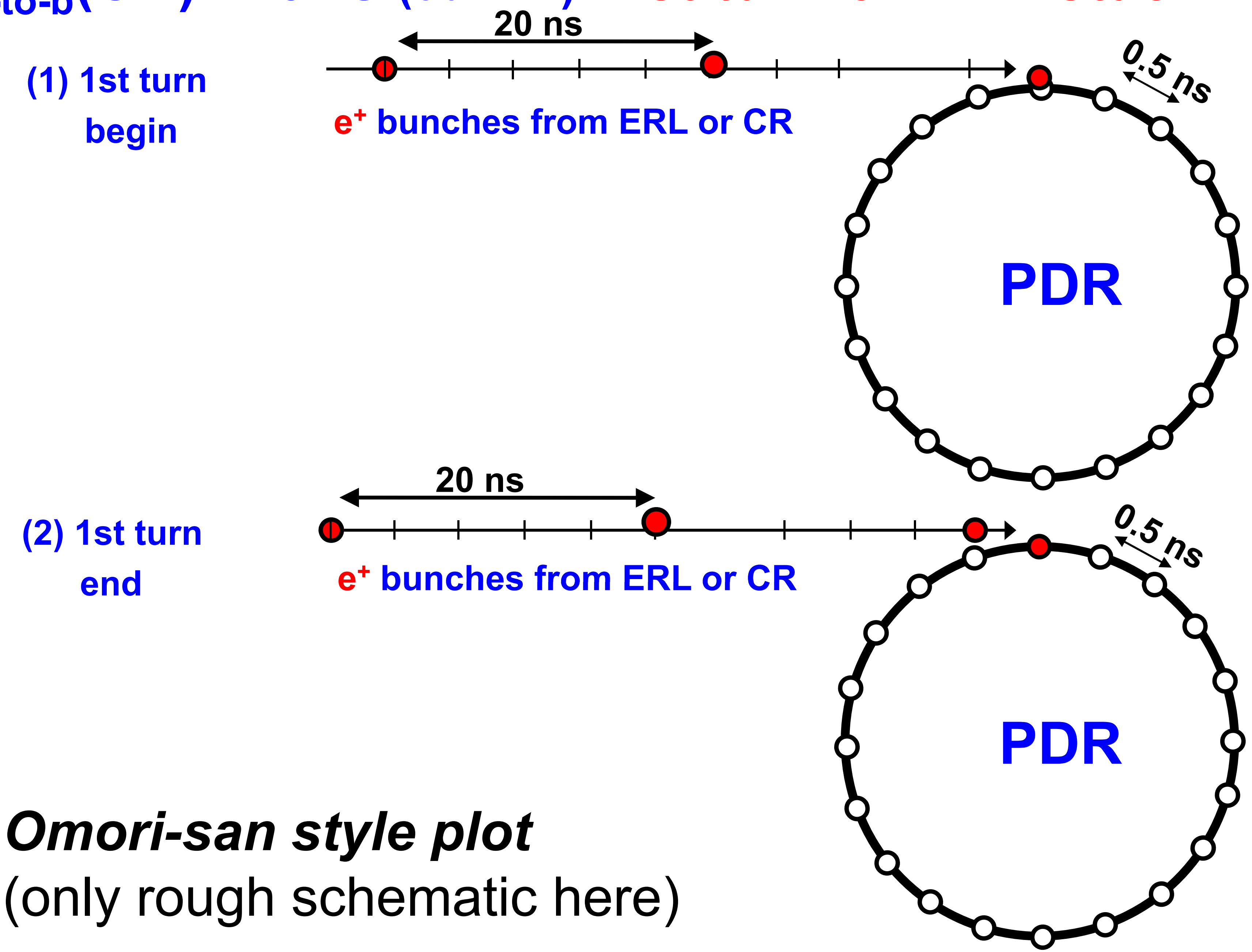
σ_{z0}=11.4 mm, $\sigma_{\delta 0}$=8x10^{-4} (2 MeV)

might require ***energy pre-compressor***

note:

Omori-san proposed injection on "unstable point"

$T_{b\text{-}to\text{-}b}(CR)=20$ns (50MHz): 1st turn of PDR stacking



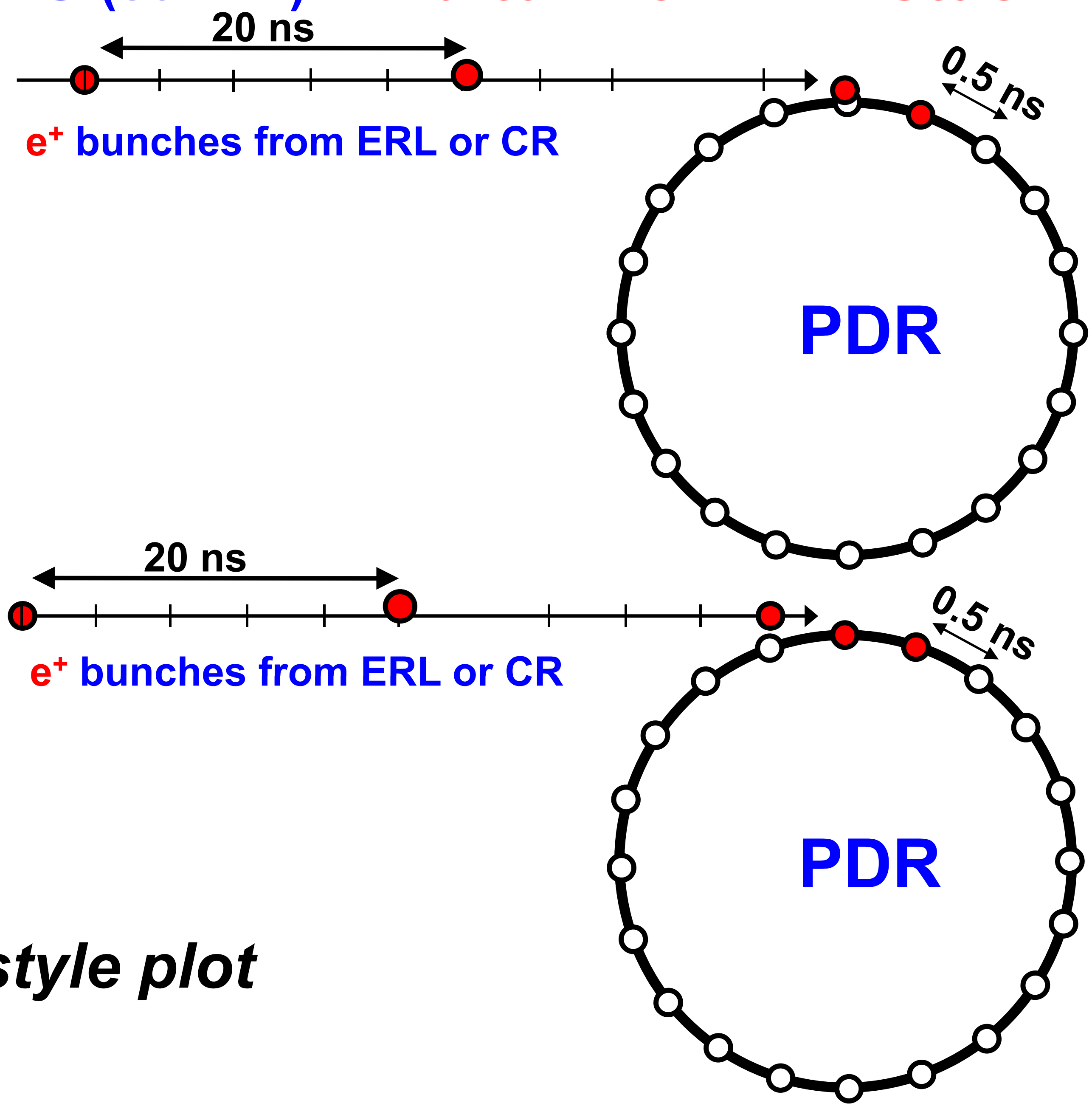
Omori-san style plot

(only rough schematic here)

$T_{b\text{-}to\text{-}b}$(CR)=20 ns (50MHz): 2nd turn of PDR stacking

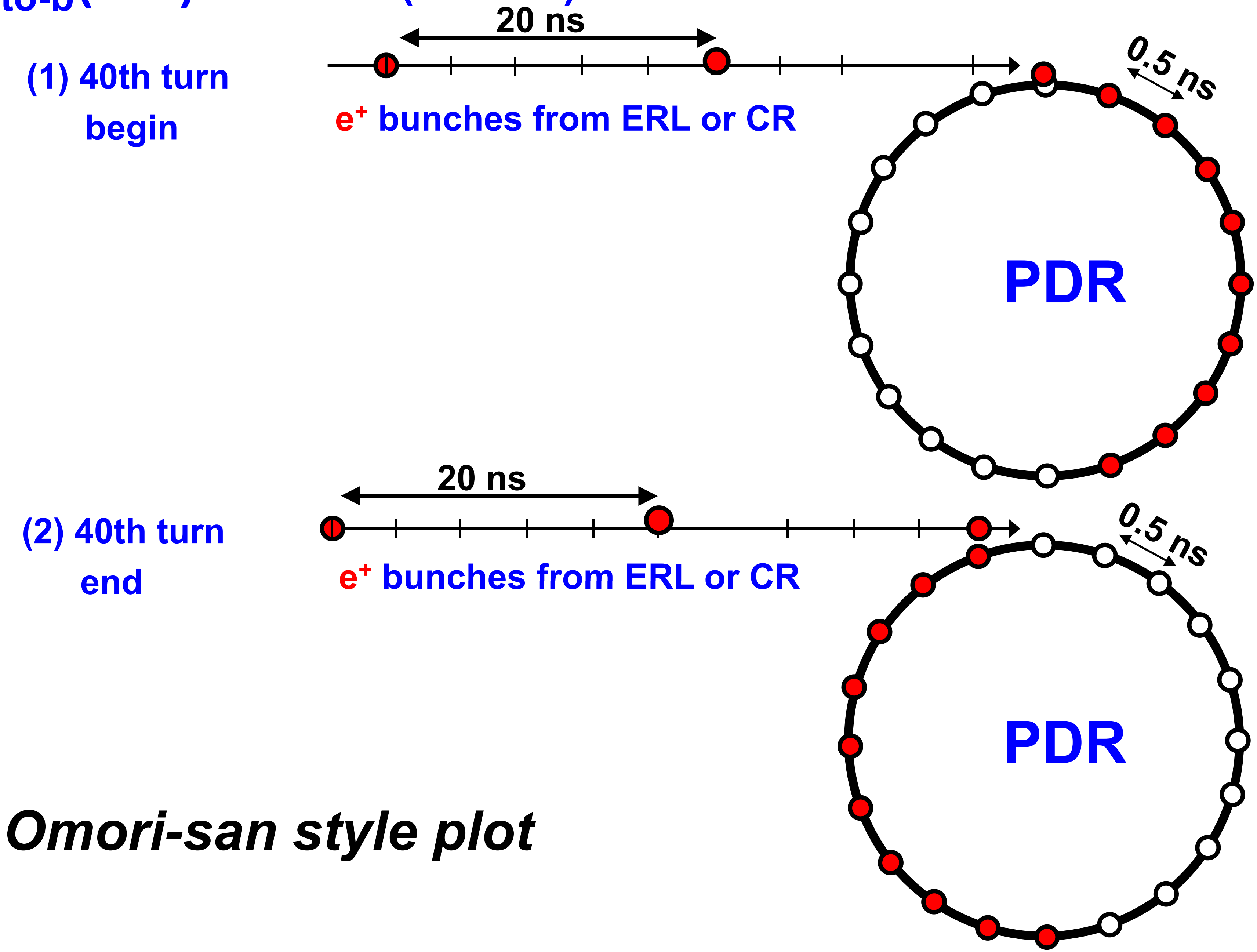
(1) 2nd turn begin

(2) 2nd turn end



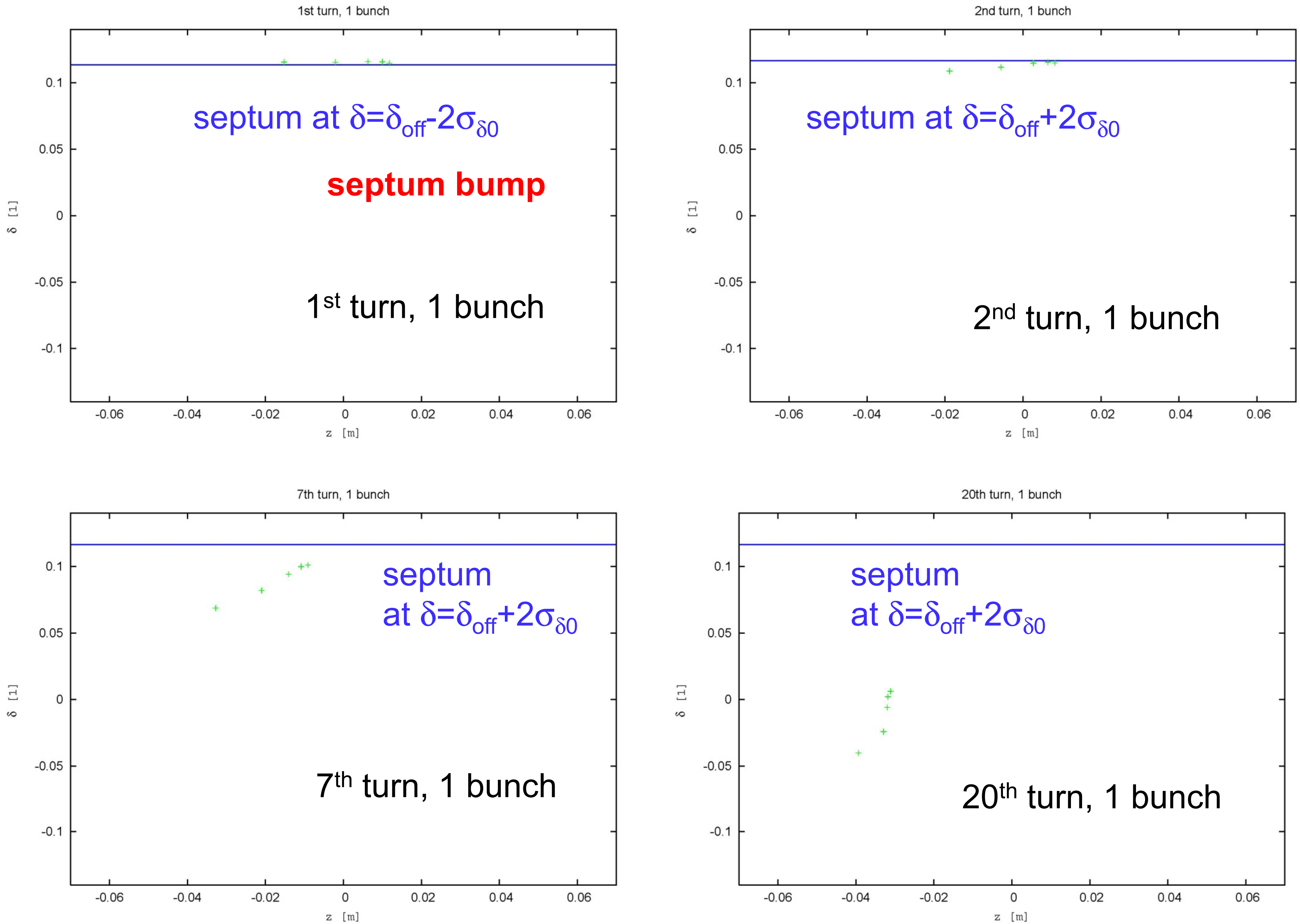
Omori-san style plot

$T_{b\text{-}to\text{-}b}$(CR)=20ns (50MHz): 40th turn of PDR stacking

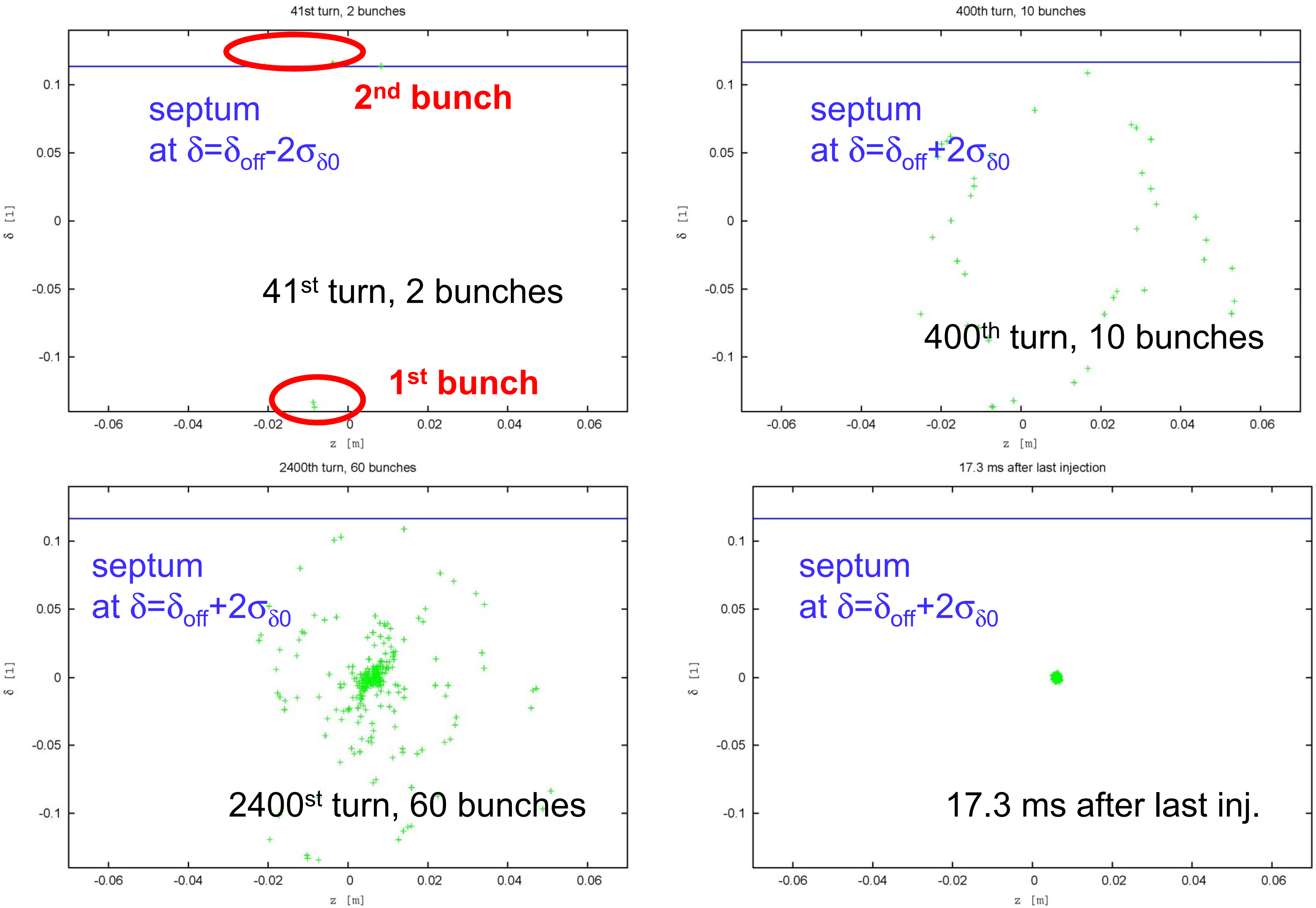


Omori-san style plot

CLIC PDR stacking simulation, example, δ_{off}=11..5%



CLIC PDR stacking simulation, example, δ_{off}=11..5%



conditions for this stacking scheme to work:

$$E_{loss}\ \text{(1 synchrotron period)} > 4\,\sigma_{E0}$$

in our example:

328 MeV > 8 MeV

easily fulfilled

no septum bump needed if:

$$\Delta E\ \text{(1 turn)} > 4\,\sigma_{E0}$$

treatment of synchrotron radiation

R. Siemann, HEACC 1988

model A

$$z_{new} = z_{old} e^{-T_0/\tau_{\|}} + \xi \sqrt{2\left(1 - e^{-T_0/\tau_{\|}}\right)} \sigma_{z,eq}$$

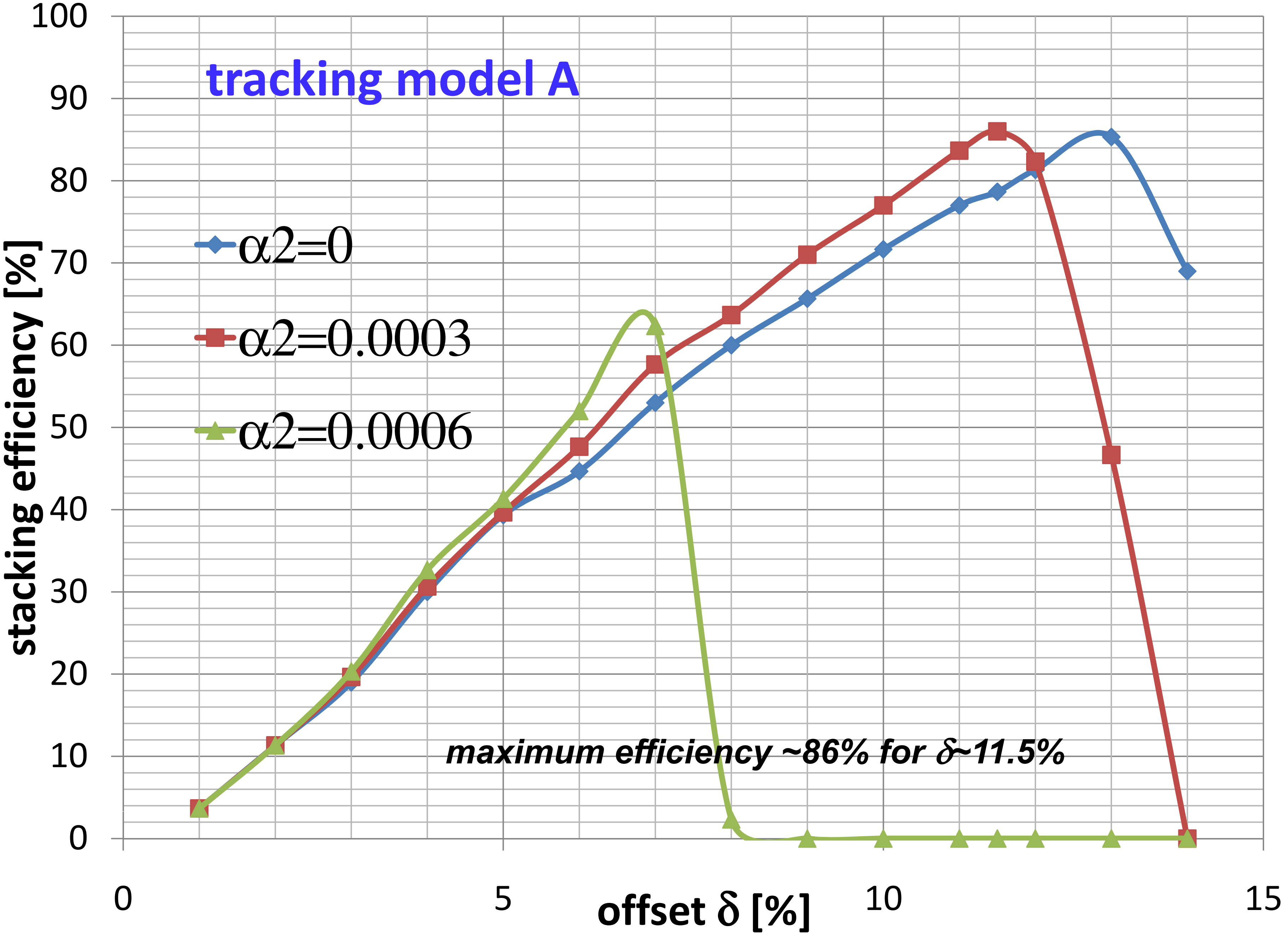
$$\delta_{new} = \delta_{old} e^{-T_0/\tau_{\|}} + \xi \sqrt{2\left(1 - e^{-T_0/\tau_{\|}}\right)} \sigma_{\delta,eq}$$

model B

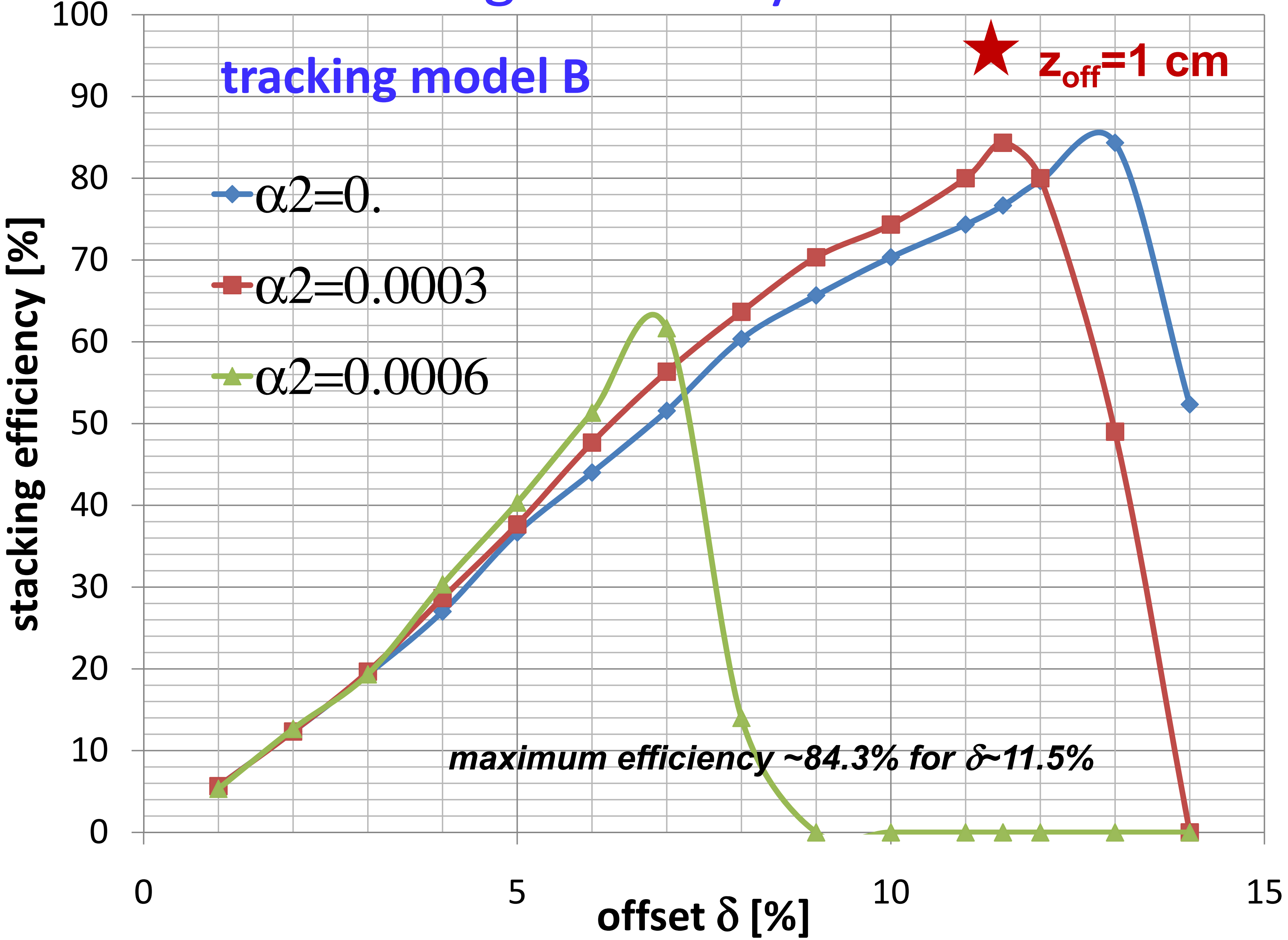
$$z_{new} = z_{old}$$

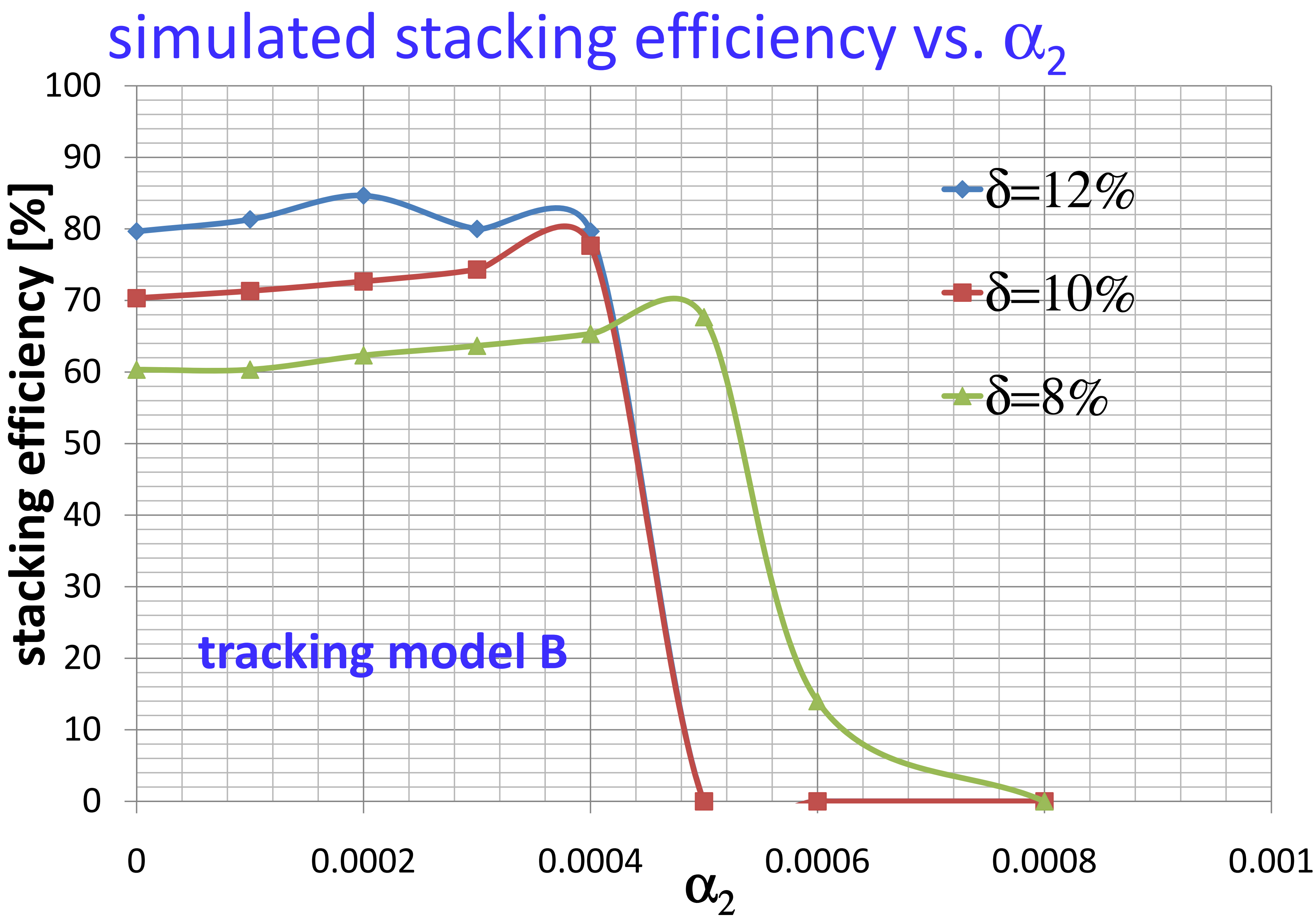
$$\delta_{new} = \delta_{old} e^{-2T_0/\tau_{\|}} + \xi \sqrt{2\left(1 - e^{-2T_0/\tau_{\|}}\right)} \sigma_{\delta,eq}$$

simulated stacking efficiency vs. initial δ offset



simulated stacking efficiency vs. initial δ offset



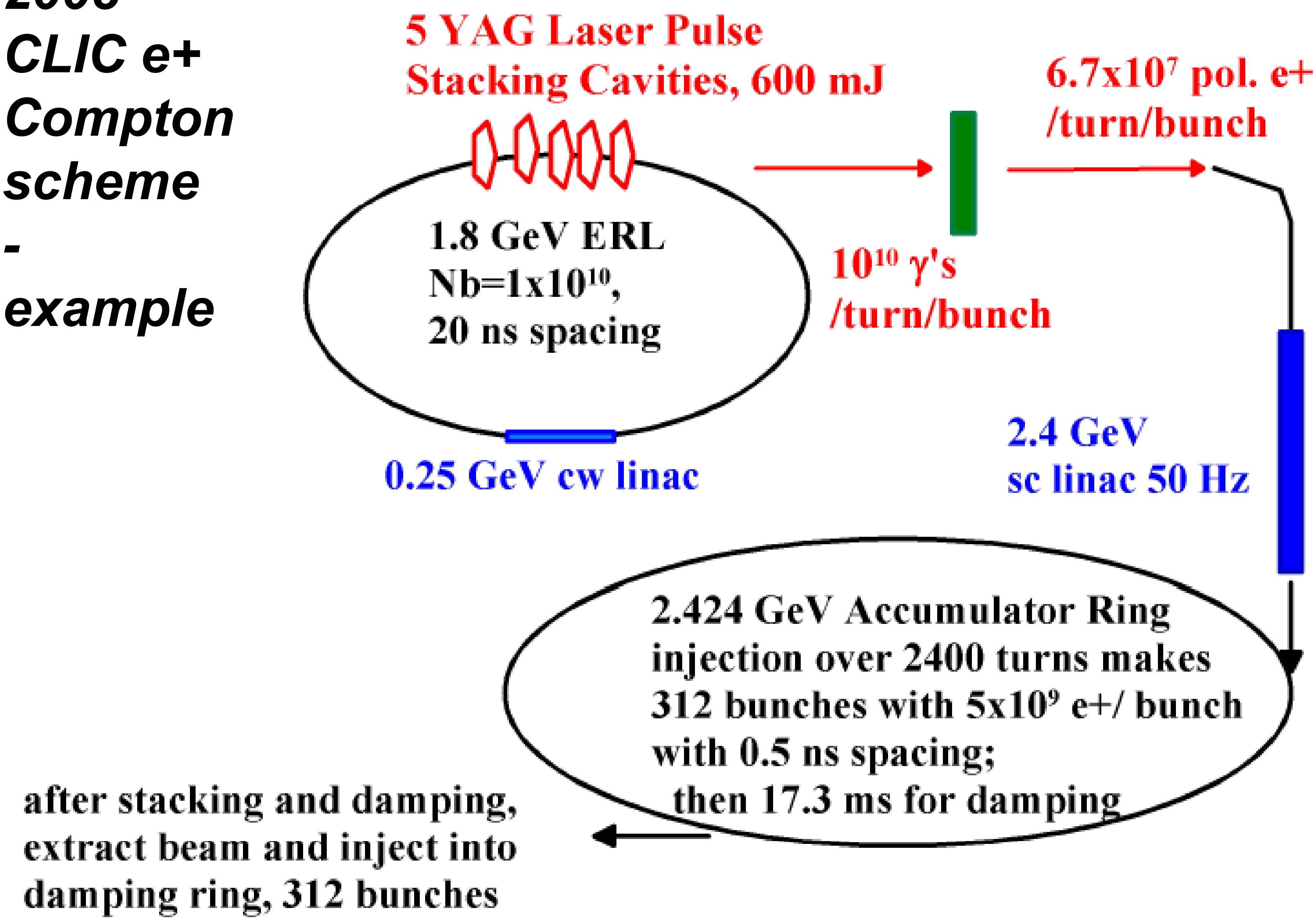


simulated stacking efficiency vs. α2
stacking efficiency [%]
100
90
80
70
60
50
40
30
20
10
0
0
0.0002
0.0004
0.0006
0.0008
0.001
α2
δ=12%
δ=10%
δ=8%
tracking model B

Compton source megatable - 1	ILC-DR Snowmass '05 proposal	**ILC 2008 – Compton "CR-B"**	**ILC 2008 – Compton "CERL-B"**	CLIC pre-DR 2007 (NLC 2004)	**CLIC 2008 (& CLIC CERL Compton vers.)**
beam energy	5 GeV	5 GeV		1.98 GeV	2.424 GeV
circumference	3223 m	6695 m		230.93 m	251.6 m
particles per extracted bunch	$2.4x10^{10}$	$2.0x10^{10}$		$4.0x10^{9}$	$4.5x10^{9}$
rf frequency	650 MHz	650 MHz		2 GHz	2 GHz
harmonic number	6983	14516		1540	1677
no. trains stored in the ring	10 (10/pulse)	52.5 (52.5/pulse)		4 (1/pulse)	1
#bunches/train	280	50		312	312
bunch spacing	4.202 ns	6.15 ns		0.5 ns	0.5 ns
gap between trains	80 (336 ns)	~50 ns		73 (36.5 ns)	682.7 ns
#e+ / injection	$2.4x10^{8}$	$6.65x10^{7}$	$6.65x10^{7}$	$6.65x10^{7}$	$6.65x10^{7}$
#turns btw inj. in 1 bucket	1	2	5	40	40
injections/bucket per cycle	10	30	1020 (cont.)	3	80 (cont.)
injection frequency	~240 MHz	80 MHz	32 MHz	~50 MHz	50 MHz
full cycle length	200 ms	200 ms	200 ms	80 ms	20 ms
time between inj. periods	10 ms	10 ms	-	1.9 ms	-
#turns between cycles	930	450	(5155)	2470	(20647)
length of one inj.period	0.107 ms	1.34 ms	114 ms	0.046 ms	2.6837 ms
TI=total # injections/bucket	100	300	1020	60	80
ST=store time after last inj.	109 ms	97 ms	86 ms	42 ms	17.3163 ms
IP=interval with inj. periods	91 ms	103 ms	(114 ms)	38 ms	(2.6837 ms)
energy loss/turn	5.5 MeV	**8.7x2 MeV**	**8.7x2 MeV**	0.803 MeV	1.63MeV (4.08 MeV)
longitudinal damping time $\tau_{\parallel}$	10 ms	**6.4 ms**	**6.4 ms**	2 ms	1.25 ms (0.5 ms)

Compton source megatable - 2	ILC-DR Snowmass '05 proposal	ILC 2008- **Compton "CR-B"**	ILC 2008- **Compton vers. "CERL-B"**	CLIC pre-DR 2007 (NLC 2004)	**CLIC 2008 (& CLIC CERL Compton vers.)**
transv. normalized edge emittance at inj. (10x rms)	0.05 rad-m	0.063 rad-m		0.063 rad-m	0.063 rad-m
transv. normalized dynamic aperture (Ax+Ay)gamma	>>0.05 rad-m?	0.4 rad-m		0.2 rad-m	0.2 rad-m?
rms bunch length at injection	3 mm	**9 mm**	**11.4 mm**	3.8 mm	11.4 mm
rms energy spread at injection	0.14%	**0.06%(3MeV)**	**0.04%**	0.28%	0.08% [2 MeV]
final rms bunch length	6 mm	**5.2 mm**		5.12 mm	0.79 mm (0.47 mm)
final rms energy spread	0.14%	**0.091 %**		0.089%	0.095% (0.12%)
longit. "edge" emittance at inj.	0.7 meV-s	0.72 meV-s		0.72 meV-s	0.73 meV-s
rf voltage	20 MV	**36 MV**		1.72 MV	**2 MV (16.3 MV)**
momentum compaction	3×10^{-4}	4.2×10^{-4}		1.69×10^{-3}	**9×10^{-5}**
2nd order mom. Compact.	1.3×10^{-3}	-		-	**5.8×10^{-2} (3×10^{-4})**
synchrotron tune	0.0356	**0.084**		0.0188	**0.0045 (0.0127)**
bucket area	292 meV-s	**129 meV-s**		10 meV-s	12meVs (234meVs)
ICM=bckt area/edge emit. /π	133	**57**		4	**(102)**
RMIN=TI/ICM	0.75	18		15	(0.59)
IP/RMIN/$\tau_{\parallel}$	12	**1**		1.3	**(9.1)**
IP/RACT/$\tau_{\parallel}$	0.09	**0.15**		0.31	**(0.09)**
synchronous phase	15.58°	**28.97°**		26.47°	**(14.49°)**
separatrix phases 1&2	164.42 °, -159.19 °	**151.03 °, -82.64 °**		153.53 °, -95.66 °	**(165.51 °, -163.83 °)**
max. momentum acceptance	+/-2.7%	+/- 1.6%		+/- 1.0%	+/-1.6% (+/- 13%)
injection offset δ,z	ramped in δ	ramped in d	+1.5%,0.01m	ramped in δ	(+13.20%, 0 m)
simulated stacking efficiency	**82%**	**97.2%**	**91%**	not comp.	**95.5%**
final # positrons / bunch	**2×10^{10}**	**1.94×10^{10}**	**6×10^{10}**	not comp.	**5.1×10^{9}**

2008
CLIC e+
Compton
scheme
-
example



(2) ILC - Compton Ring

similar assumptions as for Snowmass'05

- **stacking in longitudinal phase space**
- ingredients: sinusoidal rf, momentum compaction, radiation damping and quantum excitation
- injection septum placed at location with large dispersion; septum blade << transverse beam size
- between successive injections orbit at the septum is varied with fast bumper magnets
- energy of injected beam is ramped such that the **transverse septum position is always separated by 2 $\sigma_{\delta 0}$ from injected beam centroid**

ILC-CR injection scheme

- ILC 2008: **inject every second turn (80 MHz) into the same bucket - 30 times; then wait 10 ms (~450 turns, ~1 damping time) and repeat 9 times; total injections/bucket: 300**; synchrotron phase advance between two injections: 0.134
- simulation result (February'08) :

  35% loss / cycle, total loss 76%!

improving ILC-CR stacking efficiency

possible approaches not yet used:

- ❑ smaller momentum compaction factor
- ❑ reduced synchrotron tune
- ❑ larger interval between cycles

(but nominal interval already too long for vertical damping – Vitaly Yakimenko's comment; see next slide)

ILC DR "*trouble*" (Vitaly Yakimenko)

final $\gamma\varepsilon_{y,rms}$=0.017 micron
initial $\gamma\varepsilon_{y,rms}$=6 mm

minimum store time T_{store} follows from
$0.017*\exp(2\ T_{store}/\tau_y)\ \mu m=6000\ \mu m$

→ $T_{store} > 6.4\ \tau_y$=164 ms
leaving only 36 ms for stacking

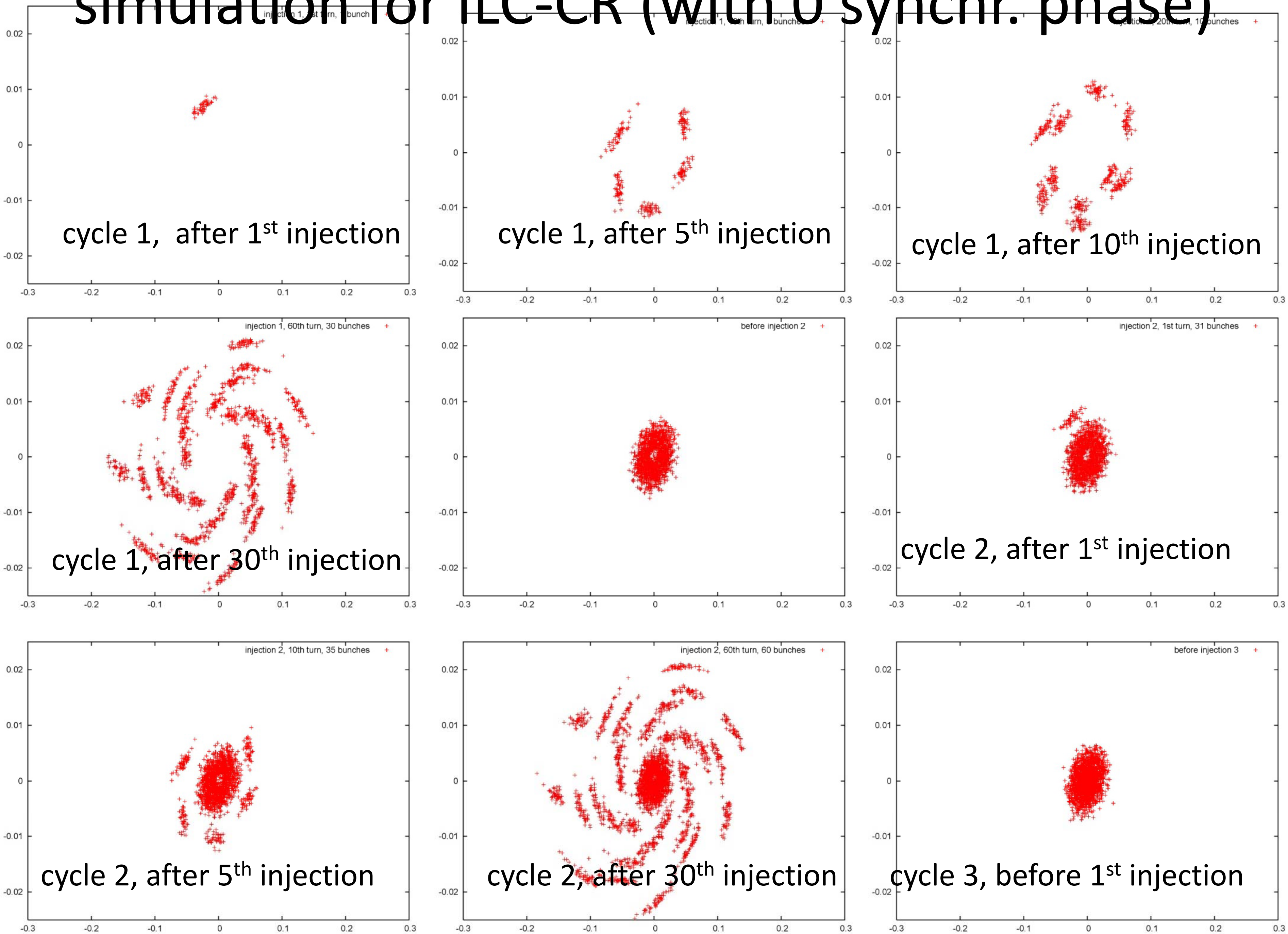
improving ILC-CR stacking efficiency

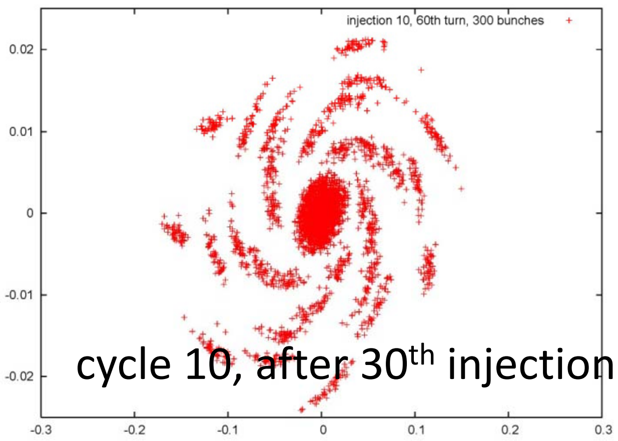
methods chosen:

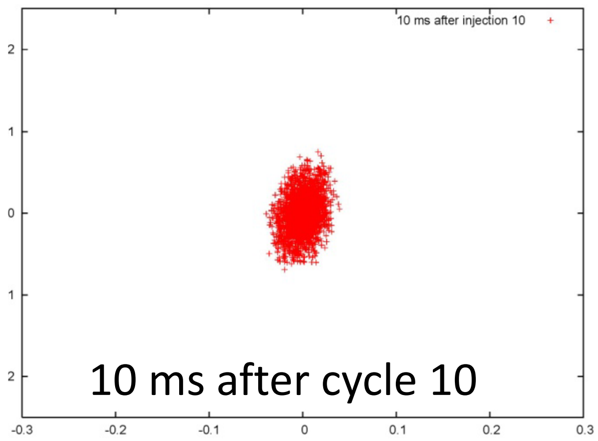
- ✓ **energy pre-compression [x3] (R. Chehab)**
- ✓ **addt’l DR wigglers for faster damping [x2]**
- ✓ **larger rf voltage [x 1.5 or more!]**

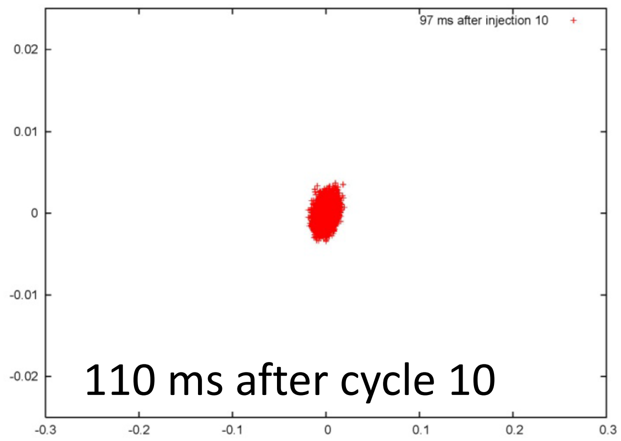
→ 2008 ILC DR Compton version

simulation for ILC-CR (with 0 synchr. phase)









~ 2.8% of injected e+ are lost!

similar loss fraction for single cycle

→ stacking efficiency ~97.2%

(but for 0 synchronous phase)

questions & comments for ILC-CR

- 2x3 km ring is option from Andy Wolski; it could reduce the damping times by factor 2, if we do not reduce the length of the wigglers

- ring parameters can be considered somewhat flexible; at present parameters are optimized for the undulator based source

- can we reduce initial energy spread to 2 MeV rms?

- option of pre-damping ring for ILC?

(3) ILC - Compton Energy Recovery Linac

ILC-CERL injection scheme - A

continuous stacking (ERL option),~27MHz (Omori san, Variola san) **850 injections** over 5100 turns (inject every 6th turn), followed by 5155 turns (~100 ms) damping; damping time 6.4 ms;

inject with constant offset δ=1.2% ↔ ***<Vivoli san's result: ~ 2.9 MeV***

σ_z=9 mm, $\sigma_{\delta 0}=1\times 10^{-4}$ (0.5 MeV, small!!): **63.7% loss**

Omori san asked about "unstable point" injection

offset **δ=1.2% or 0.4%, z=0.1 m**: **99.8% loss**

offset δ=0.2%, z=-0.1 m: 99.9% loss

offset δ=0.5%, z=0.01 m: 72.8% loss

offset δ=0.7%, z=0.01 m: 50% loss!! Method works!?

offset δ=0.8%, z=0.01 m: 41.8% loss!

offset **δ=0.9%, z=0.01 m**: 36.7% loss! 63% efficient

ILC-CERL injection scheme - B

over 6 turns synchrotron phase advance ~0.5!?
perhaps better inject every 5th turn?!

again continuous stacking (ERL option), **~32 MHz, 1020 injections** over 5100 turns (inject every 5th turn), followed by 5155 turns (~100 ms) damping; damping time 6.4 ms;

inject with constant offset δ=0.9%, z=0.01 m

σ_z=9 mm, $\sigma_{\delta 0}$**=1x10^{-4}** (0.5 MeV, small!!): **36% loss**

offset **δ=1.0%, z=0.01 m**: **33% loss**

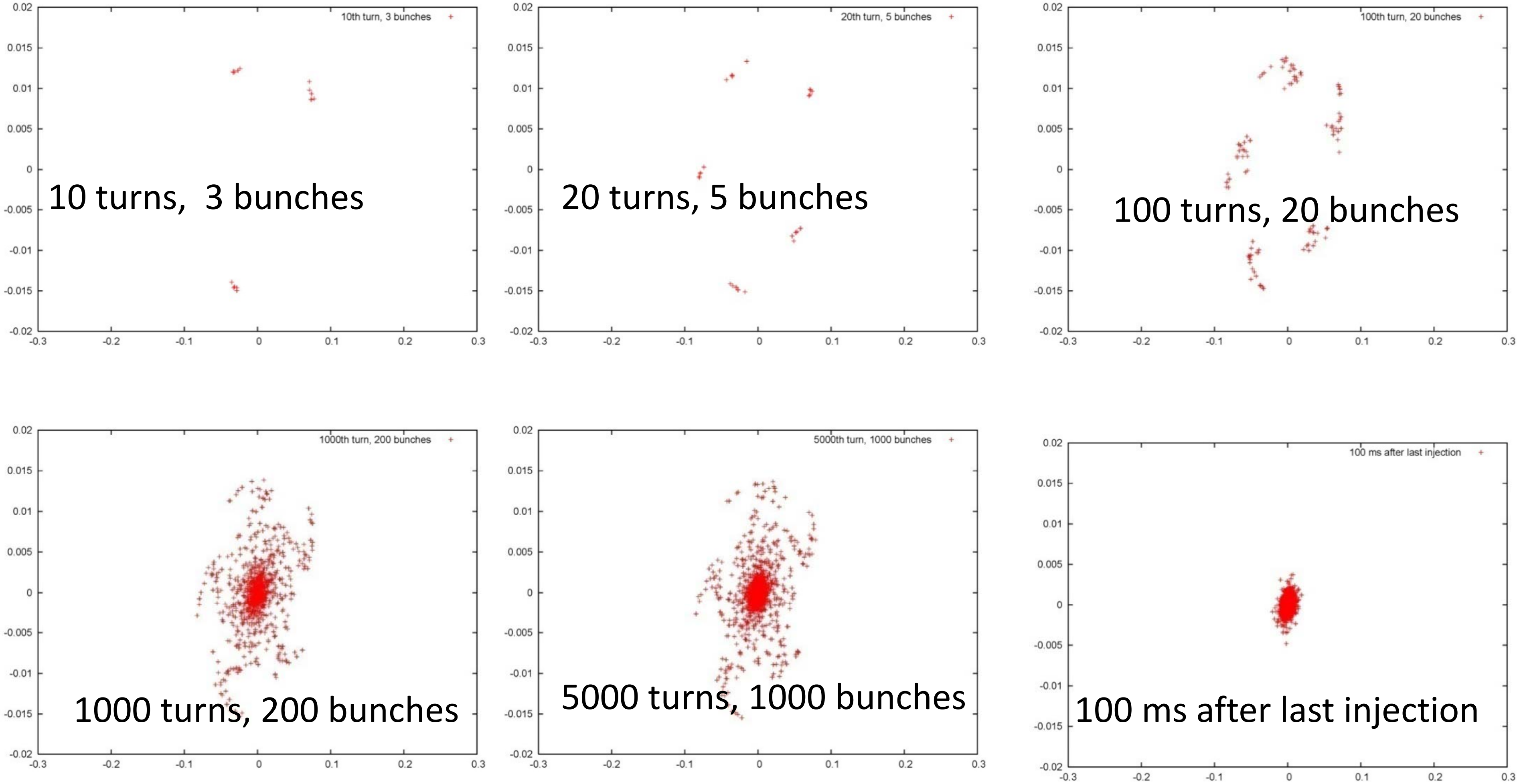
offset **δ=1.2%, z=0.01 m**: **27% loss! 73% efficient**

offset **δ=1.3%, z=0.01 m**: **23% loss! 77% efficient**

offset **δ=1.4%, z=0.01 m**: **16% loss! 84% efficient**

offset **δ=1.5%, z=0.01 m**: **9% loss! 91% efficient!**

simulation for ILC-CERL (with 0 synchr. phase)



→ stacking efficiency ~91%
(but for 0 synchronous phase)

(4) summary & outlook

some conclusions

- CLIC/ILC Compton source w ERL or CR
- e+ emittance preservation after capture
- CLIC PDR & ILC DR parameters adapted for stability and stacking, $\alpha_2\downarrow\downarrow$ $V_{RF}\uparrow$, $\tau_{||}\downarrow$
- stacking simulation: >90% efficiency with off-momentum off-phase injection
- (P)DR off-momentum dynamic aperture must be adequate (huge! >several %)
- quite some flexibility (# optical cavities vs. e- bunch charge)
- but a few challenges for PDR &DR design

stacking is helped by:

- short damping time
- small energy spread (which value is possible?)
- large ring momentum acceptance
  (low α, low α_2, large V_{RF})
- sufficient store time

simulation results:

97% for ILC-CR (300 inj's, σ_δ=3 MeV spread)
91% for ILC-CERL (1020 inj's! σ_δ=0.5 MeV)
95.5% for CLIC-CR/CERL (80 inj's, σ_δ=2 MeV)
last 2 with energy pre-compression - ***Compton version of ILC-DR acceptable? #e+ / pulse for CERL schemes? ILC cases to be redone (ϕ_s)***

next steps & ideas:

- repeat ILC simulations with nonzero synchronous phase!; stacking efficiency might be (much) smaller unless we can go to still higher rf voltage; CLIC example for high efficiency w. correct model
- determine “optimum” (pre-)DR parameters
- optimize **synchrotron tune, opt.** α_1, α_2
- **energy pre-compressor**
- combined **longitudinal/transverse** stacking
- **off-momentum dynamic aperture**

thank you for your attention!

please join the Compton adventure