Stacking Issues for the CLIC Compton e+ Source

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

CLIC 2008, October 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

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

ILC Compton-source benchmark

- 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
  → ***CLIC Compton source is easier!***

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 single 600 mJ cavity *

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

stack in accumulation ring
ex.: 6x10^{10} e-/bunch $\rightarrow$ 10^{8} e+ $\rightarrow$ 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

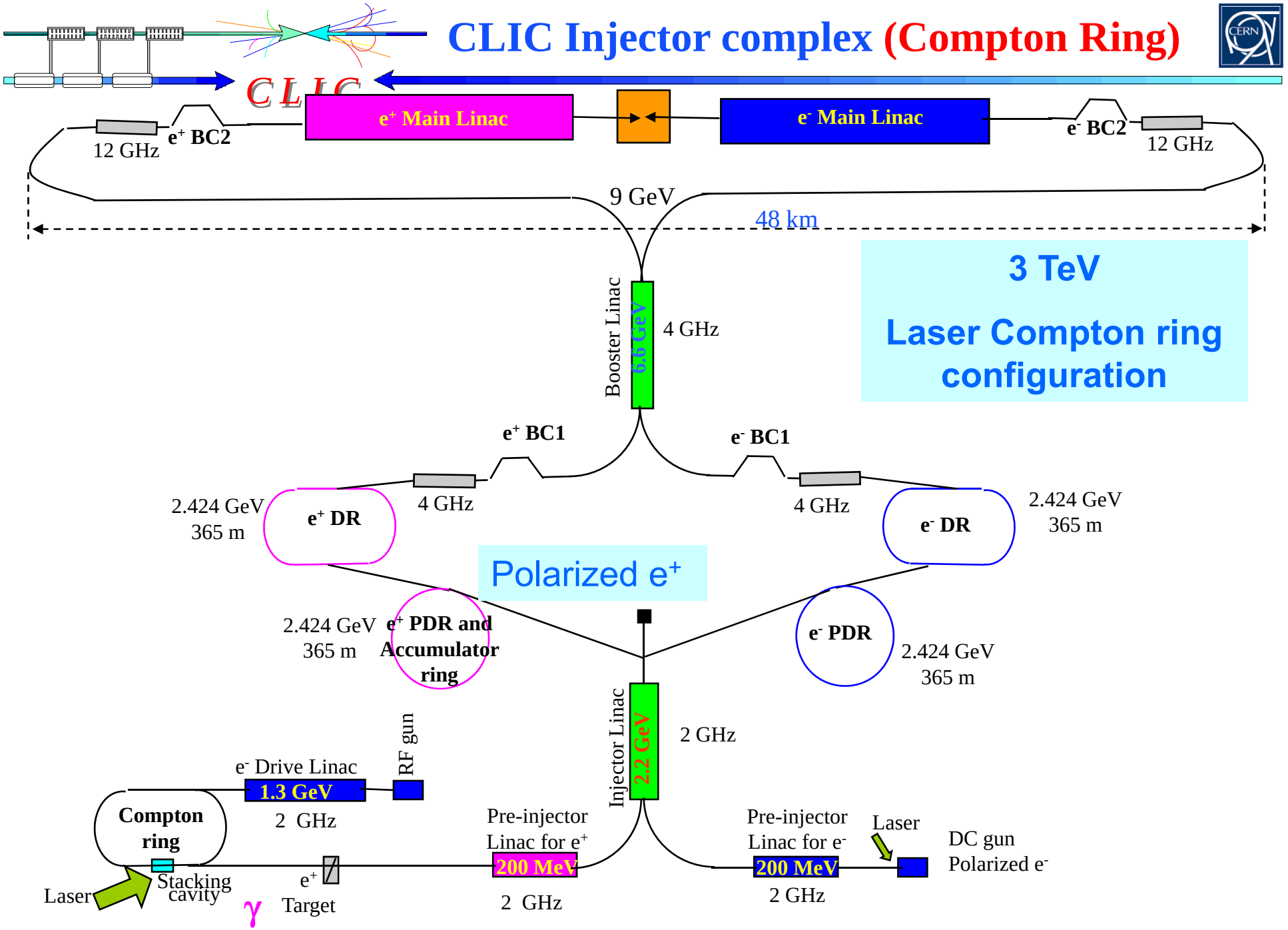
Compton sources

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

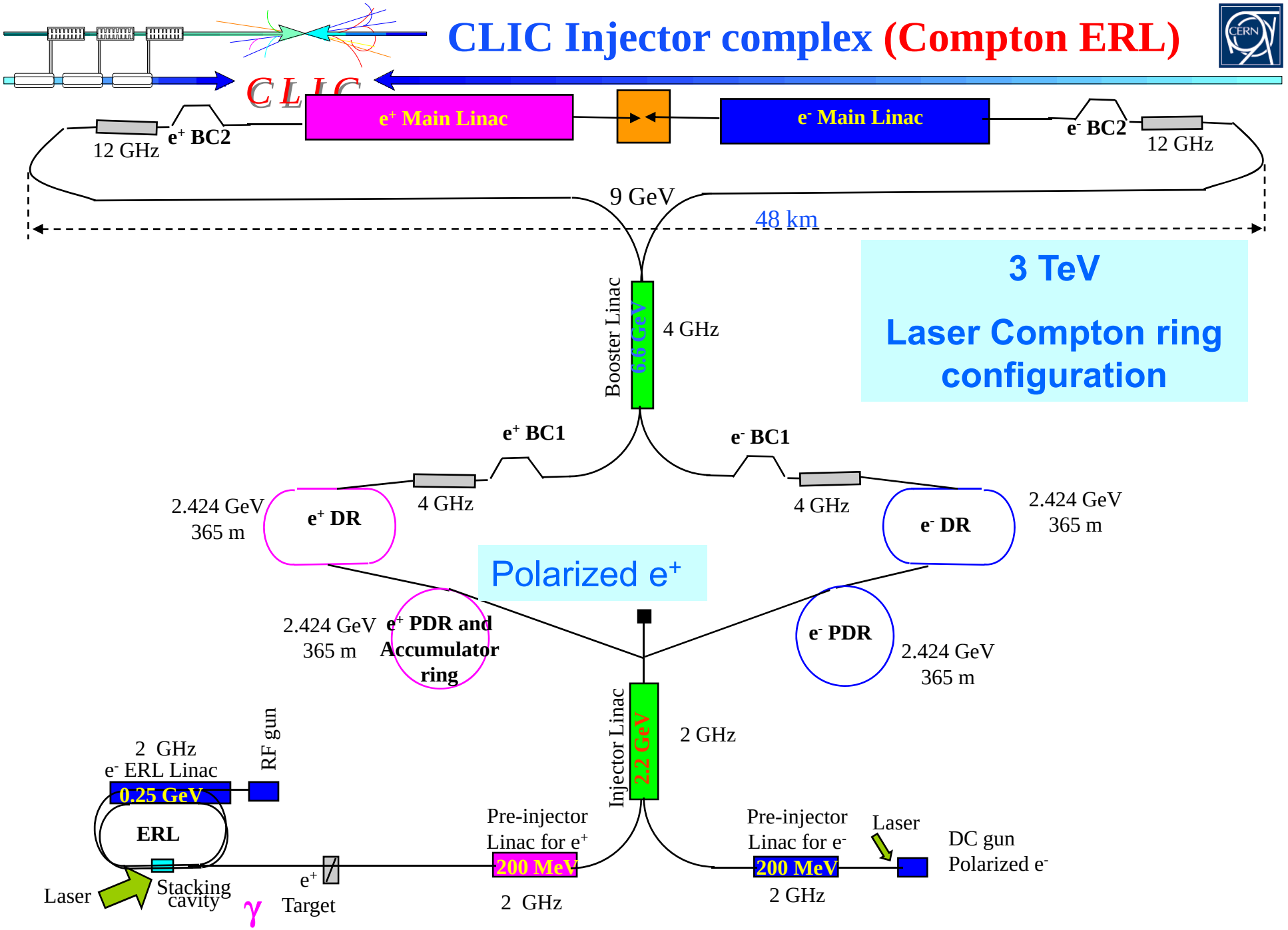
accumulation ring

- **CLIC pre-damping ring**
  or Compton-optimized PDR
- **CLIC damping ring ?**
- **dedicated stacking ring ?**

CLIC Injector complex (Compton Ring)

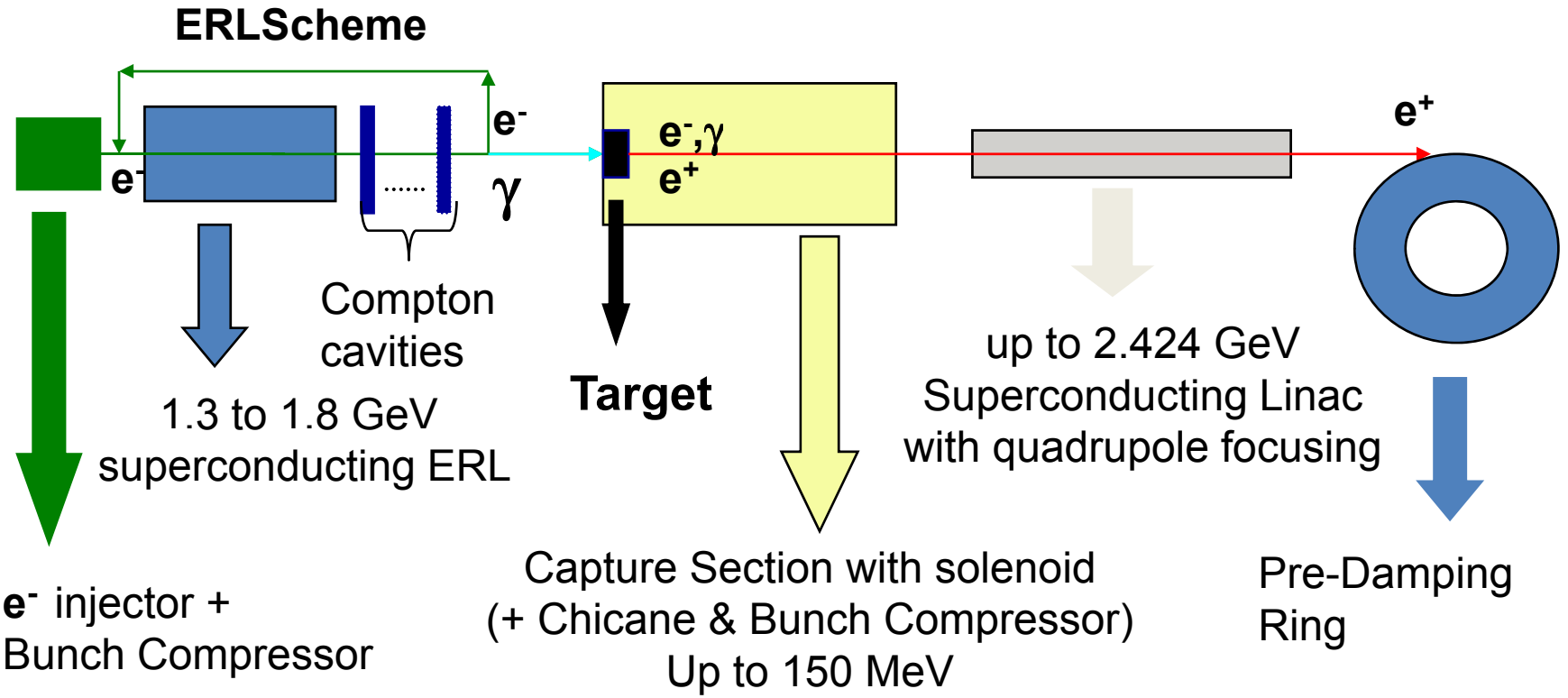


CLIC Injector complex (Compton ERL)



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



comment on longitudinal emittance

accelerating the e+ from 200 MeV to 5 GeV in 1.3 GHz linac may increase longitudinal emittance 4 times due to correlated energy spread from rf curvature and non-ideal initial bunch length (Vivoli, Rinolfi)

we do not need to accept this blow up for CLIC!

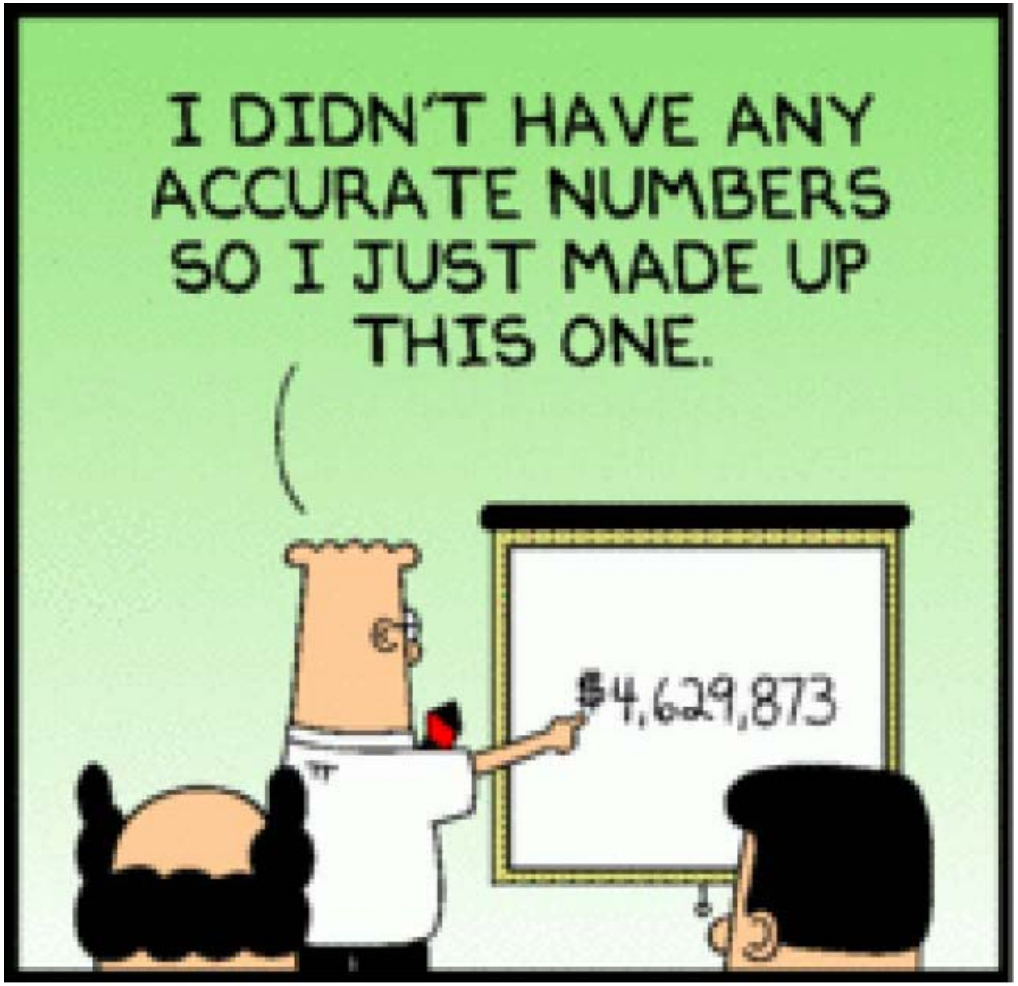
CLIC DR energy is 2.424 GeV → ½ blow up

use 700 MHz linac like SPL → ¼ blow up

+ if necessary optional bunch compression, higher harmonic RF, etc.

I assume preservation of normalized emittance

stacking simulations



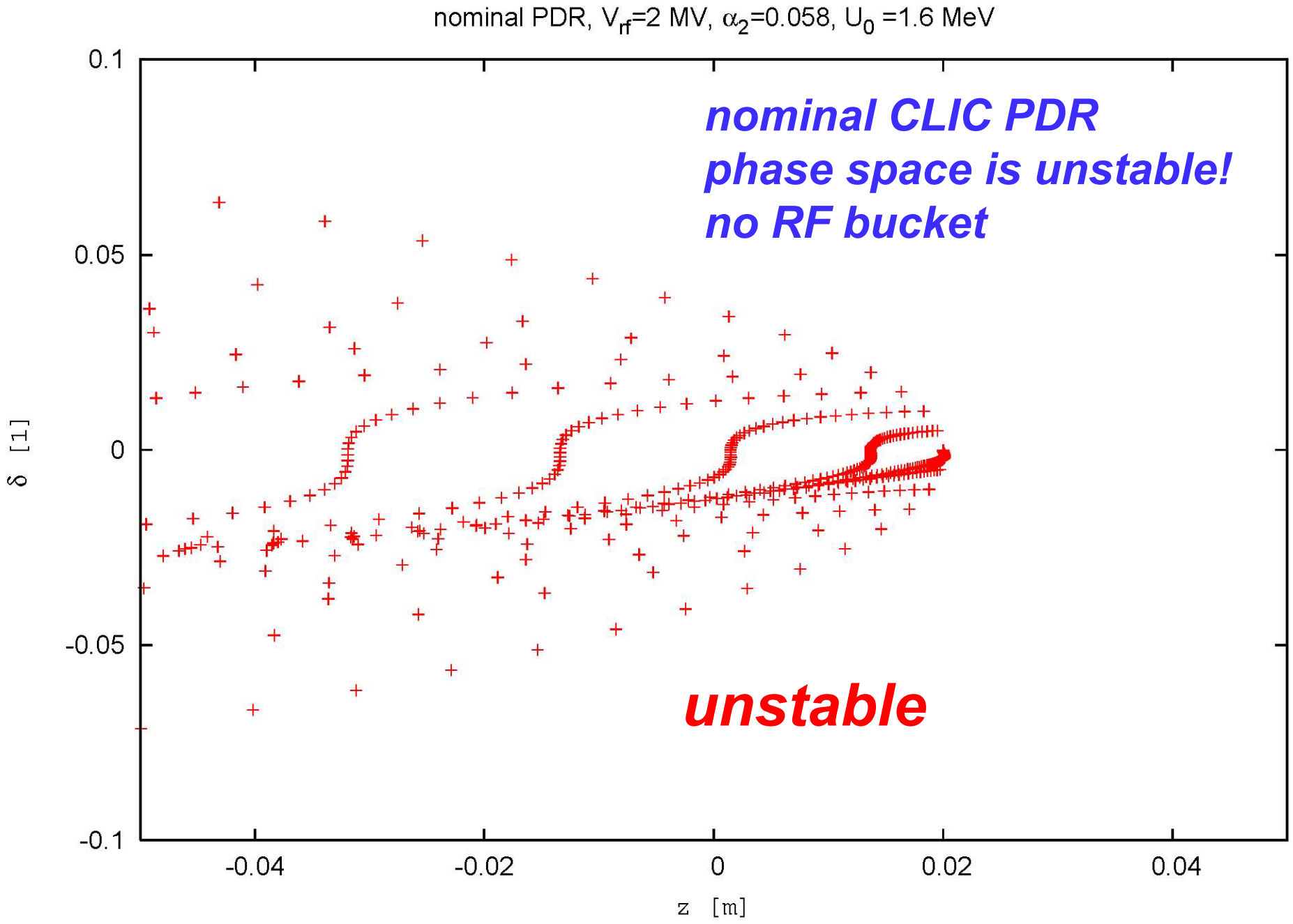
stacking simulations for CLIC CERL/CR scheme

- **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)

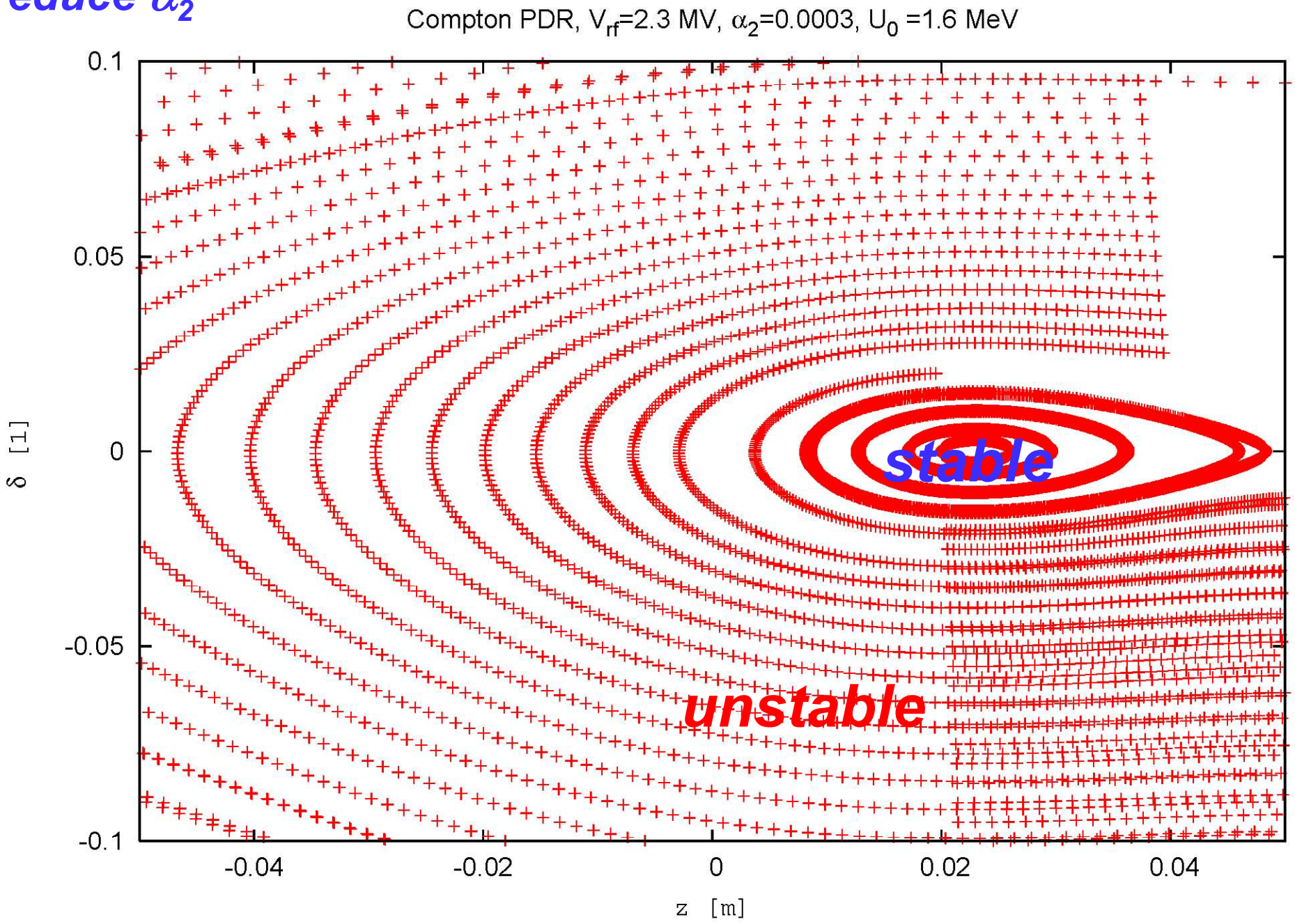
CLIC Pre-Damping Ring Parameters

parameter	value*
#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
1^{st} order momentum compaction	8.98×10^{-5}
2^{nd} order momentum compaction	0.058
beam energy	2.424 GeV
longitudinal damping time	1.25 ms
equilibrium momentum spread	0.095%
equilibrium bunch length	0.786 mm

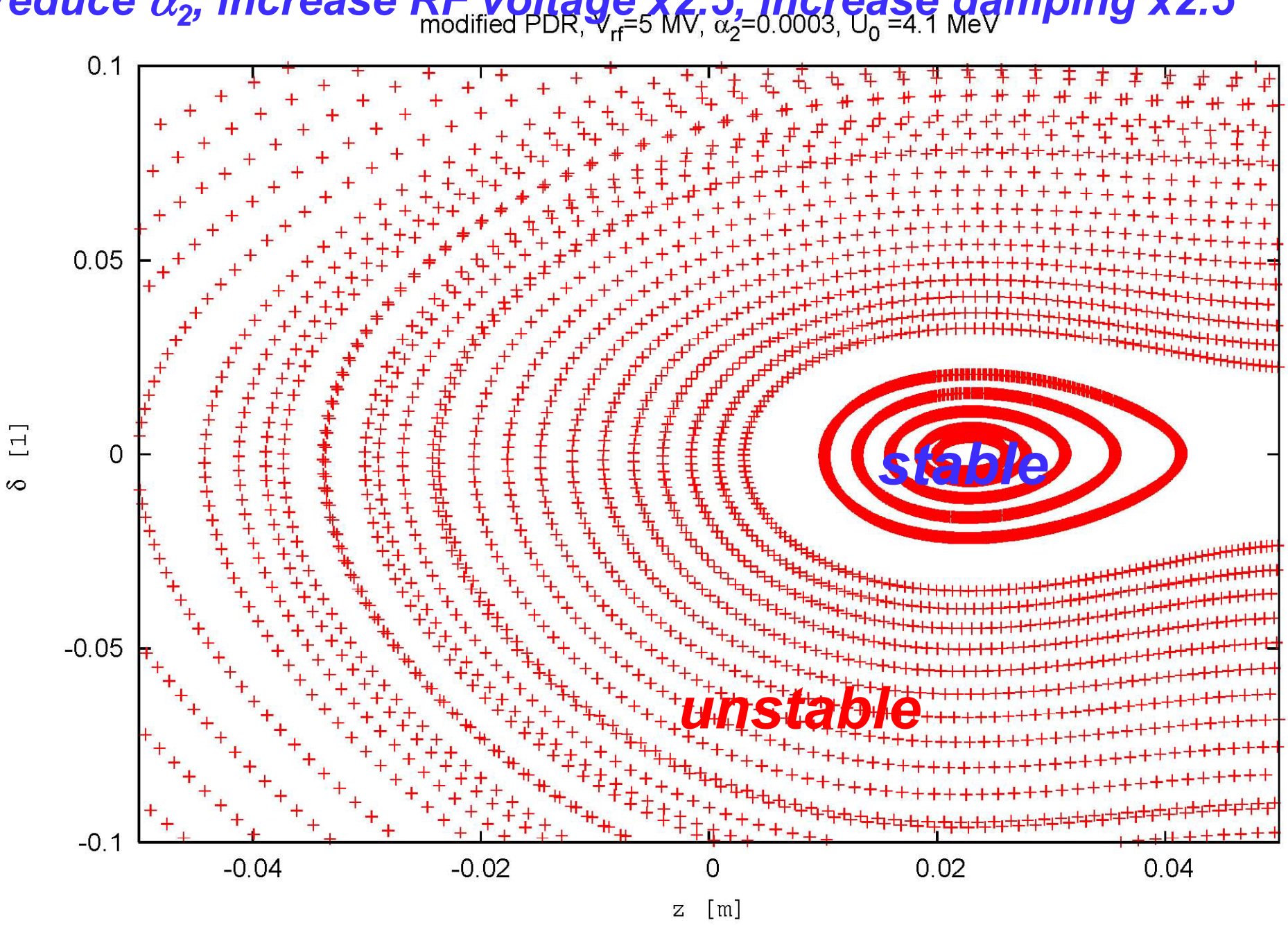
*Fanouria Antoniou, Yannis Papaphilippou, 9 October 2008


nominal PDR, V_{rf}=2 MV, α_2=0.058, U_0 =1.6 MeV
nominal CLIC PDR
phase space is unstable!
no RF bucket
unstable
0.1
0.05
0
-0.05
-0.1
δ [1]
-0.04
-0.02
0
0.02
0.04
z [m]

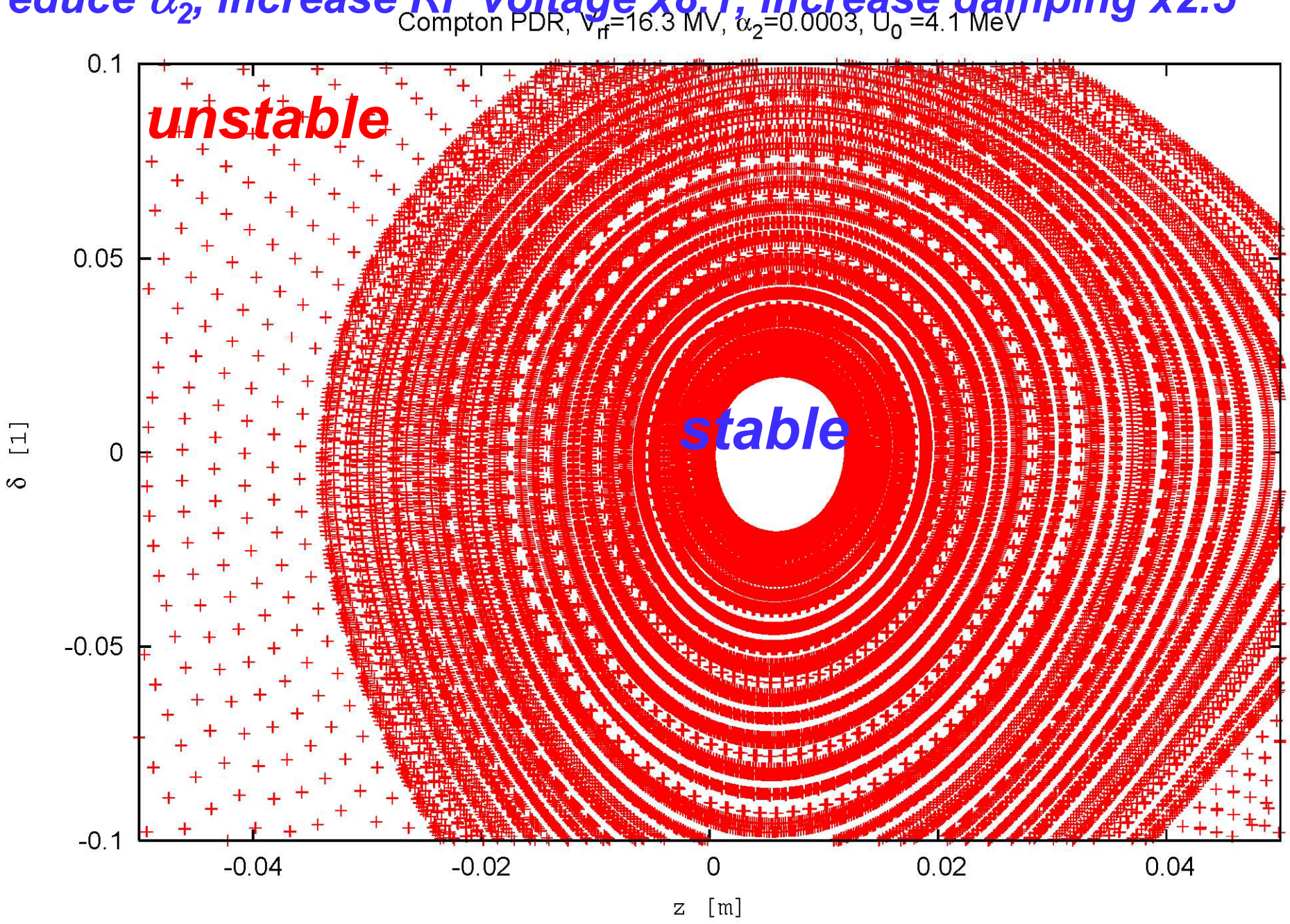
reduce α_2



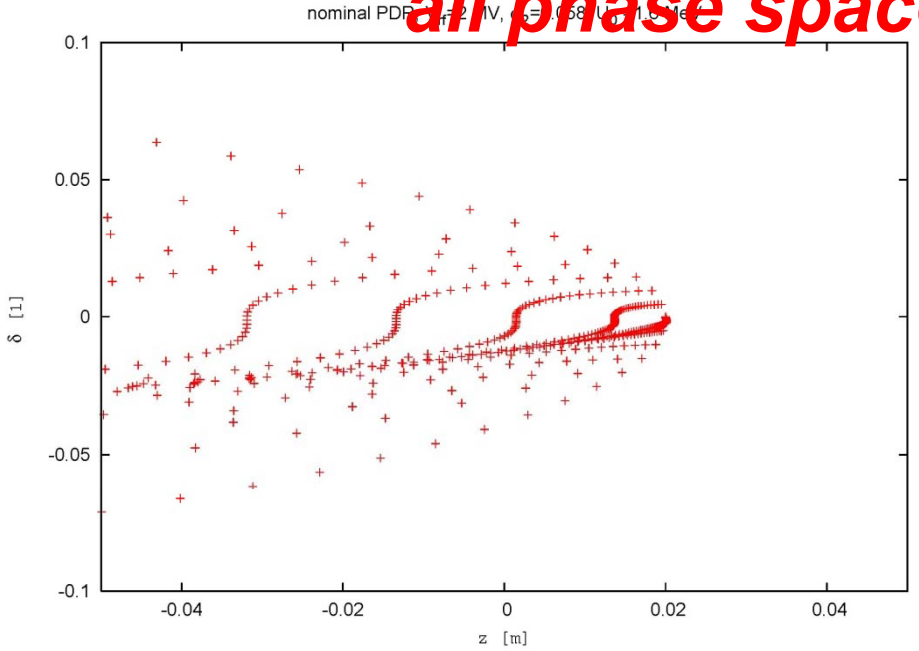
reduce α_2, increase RF voltage x2.5, increase damping x2.5

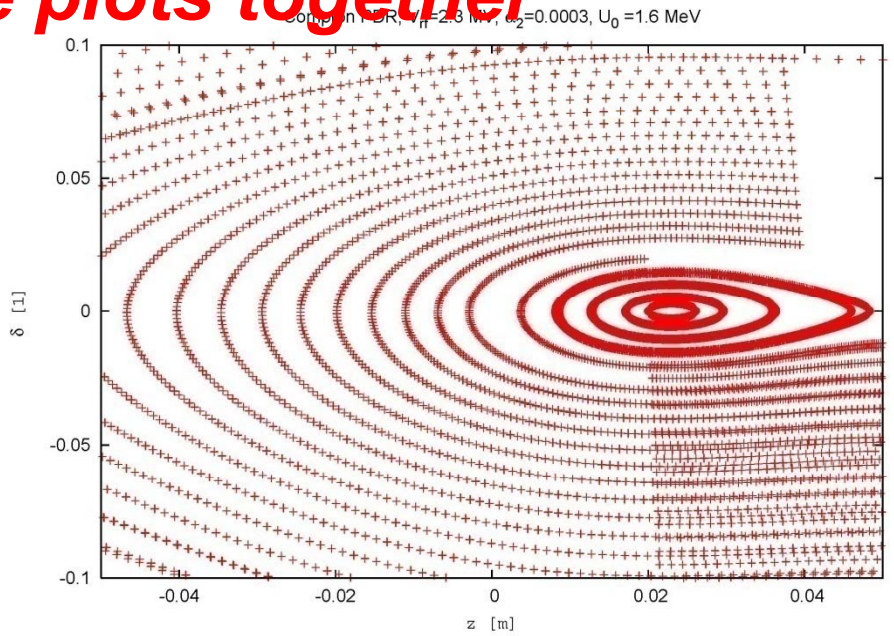


reduce α_2, increase RF voltage x8.1, increase damping x2.5

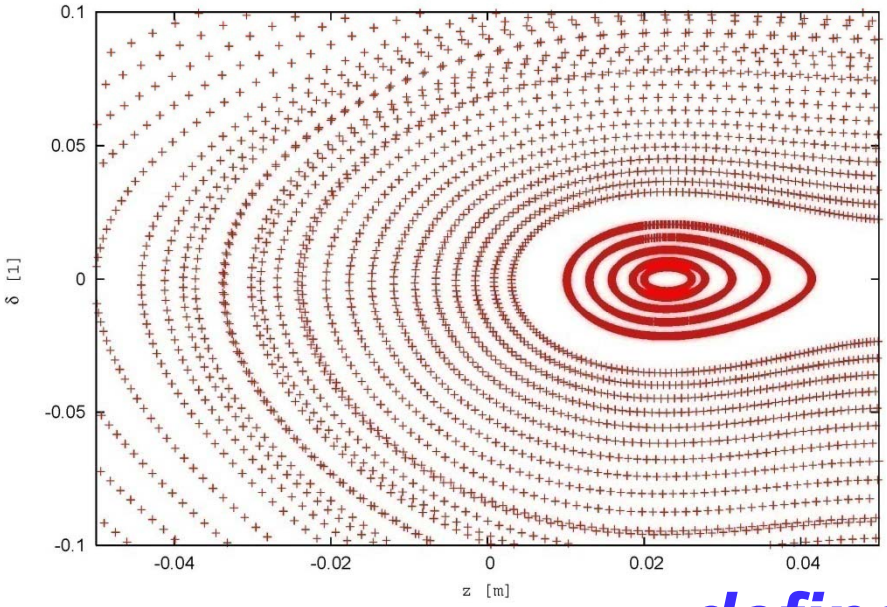


all phase space plots together

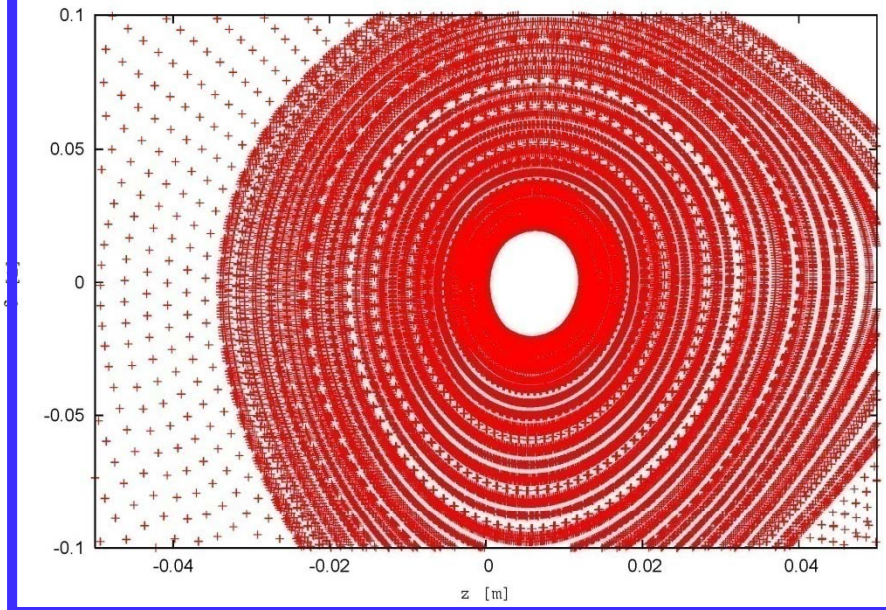




modified PDR, V_{rf}=5 MV, α_2=0.0003, U_0 =4.1 MeV



Compton PDR, V_{rf}=16.3 MV, α_2=0.0003, U_0 =4.1 MeV



define this as new Compton PDR!

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**
1^{st} order momentum compaction	8.98×10^{-5}	
2^{nd} 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**

stacking parameters for ILC and CLIC - 1	ILC-DR Snowmass '05 proposal	**ILC 2008 – Compton vers. "CERL-B"**	CLIC pre-DR 2007 (NLC 2004 design)	**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	2.4×10^{10}	2.0×10^{10}	4.0×10^{9}	4.5×10^{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	2.4×10^{8}	6.65×10^{7}	6.65×10^{7}	6.65×10^{7}
#turns between injections in 1 bucket	1	5	40	40
injections/bucket per cycle	10	1020 (cont.)	3	80 (cont.)
injection frequency	~240 MHz	32 MHz	~50 MHz	50 MHz
full cycle length	200 ms	200 ms	80 ms	20 ms
time between injection periods	10 ms	-	1.9 ms	-
#turns between cycles	930	(5155)	2470	(20647)
length of one injection period	0.107 ms	114 ms	0.046 ms	2.6837 ms
TI=total # injections/bucket	100	1020	60	80
ST=store time after last injection	110 ms	86 ms	42 ms	17.3163 ms
IP=time interval with injection periods	90 ms	(114 ms)	38 ms	(2.6837 ms)
energy loss/turn	5.5 MeV	**8.7x2 MeV**	0.803 MeV	1.63MeV (4.08 MeV)
longitudinal damping time $\tau_{\parallel}$	10 ms	**6.4 ms**	2 ms	1.25 ms (0.5 ms)

stacking parameters for ILC and CLIC - 2	ILC-DR Snowmass '05 proposal	ILC 2008- **Compton vers. "CERL-B"**	CLIC pre-DR 2007 (NLC 2004 design)	**CLIC 2008 (& CLIC CERL Compton vers.)**
transv. normalized edge emittance at injection (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	**11.4 mm**	3.8 mm	11.4 mm
rms energy spread at injection	0.14%	**0.04% (2 MeV)**	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	$3x10^{-4}$	$4.2x10^{-4}$	$1.69x10^{-3}$	**$9x10^{-5}$**
2^{nd} order momentum compaction	$1.3x10^{-3}$	-	-	**$5.8x10^{-2}$ ($3x10^{-4}$)**
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=bucket area / long. edge emit. /π	133	**57**	4	**(102)**
RMIN=TI/ICM	0.75	18	15	(0.59)
IP/RMIN/$\tau_{\|\|}$	12	**1**	1.3	**(9.1)**
IP/RACT/$\tau_{\|\|}$	0.09	**0.15**	0.31	**(0.09)**
synchronous phase	15.58^{o}	**28.97^{o}**	26.47^{o}	**(14.49^{o})**
separatrix phases 1&2	164.42^{o}, -159.19^{o}	**151.03^{o}, -82.64^{o}**	153.53^{o}, -95.66^{o}	**(165.51^{o}, -163.83^{o})**
max. momentum acceptance	+/-2.7%	+/- 1.6%	+/- 1.0%	+/-1.6% (+/- 13%)
injection offset δ,z	ramped in δ	+1.5%, 0.01 m	ramped in δ	(+13.20%, 0 m)
simulated stacking efficiency	**82%**	**91%**	not computed	
final # positrons / bunch	**$2x10^{10}$**	**$6x10^{10}$**	not computed	

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:

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

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

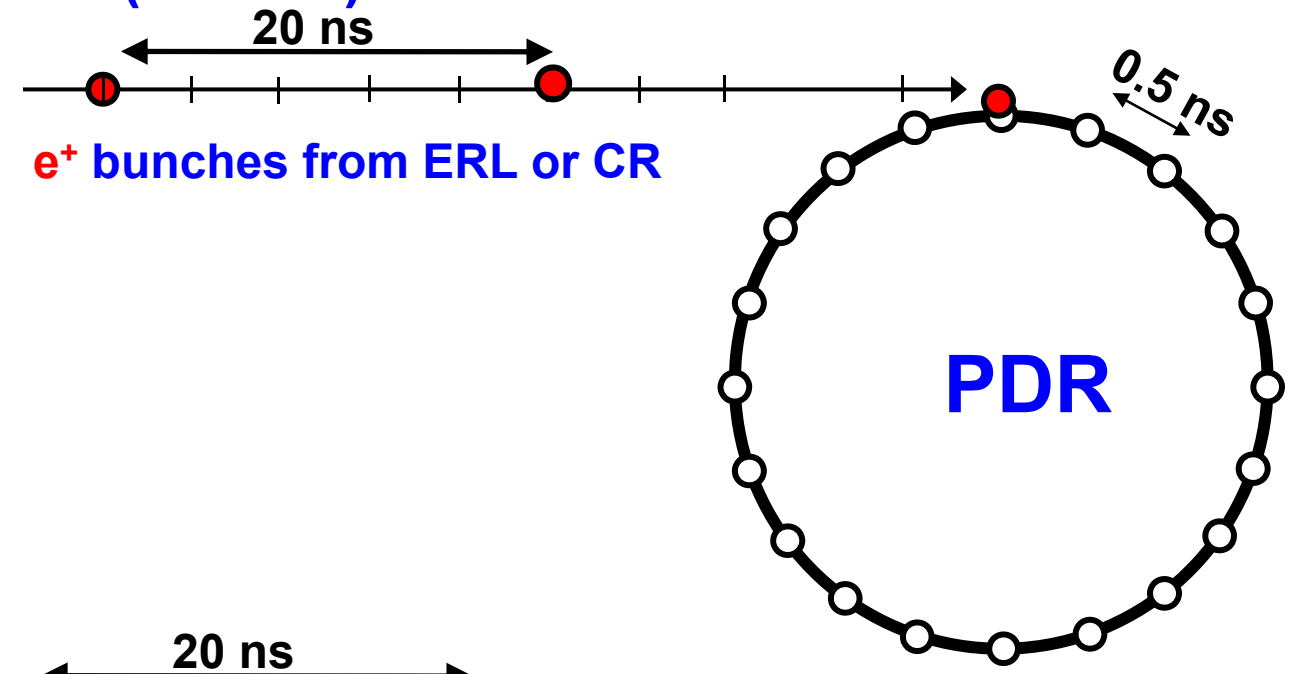
might require ***energy pre-compressor***

note:

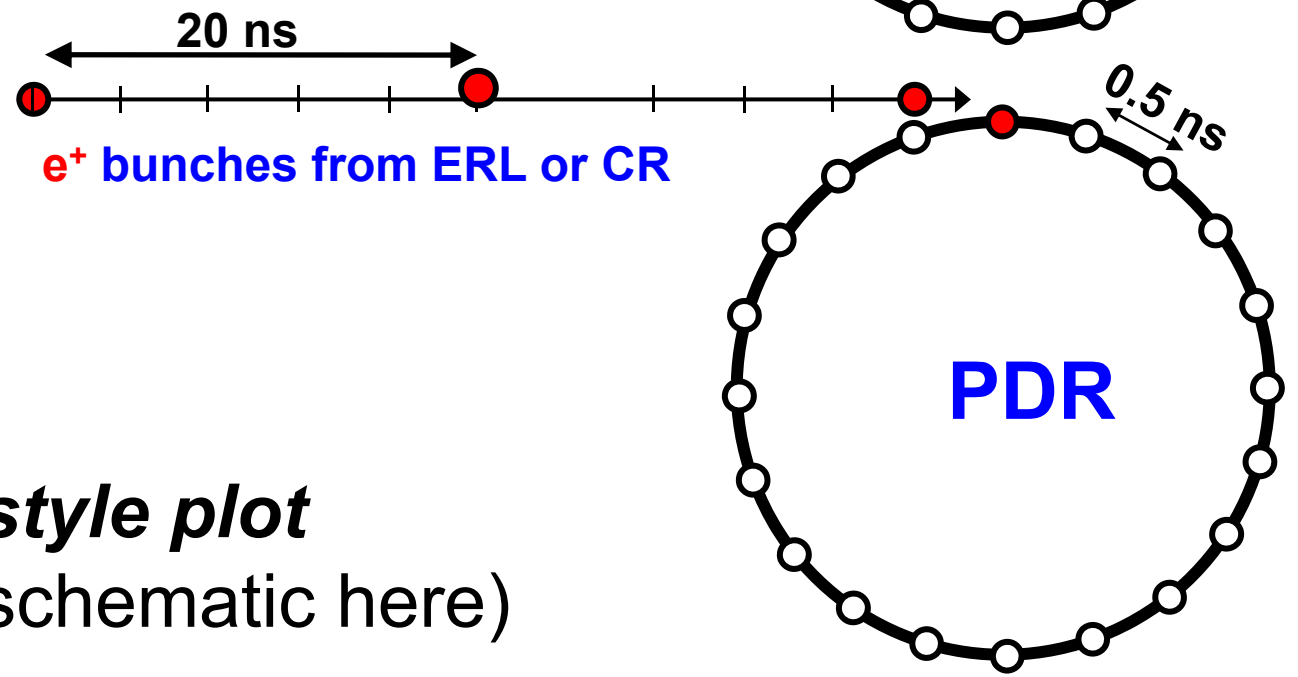
Omori-san proposed injection on "unstable point"

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

(1) 1st turn begin



(2) 1st turn end

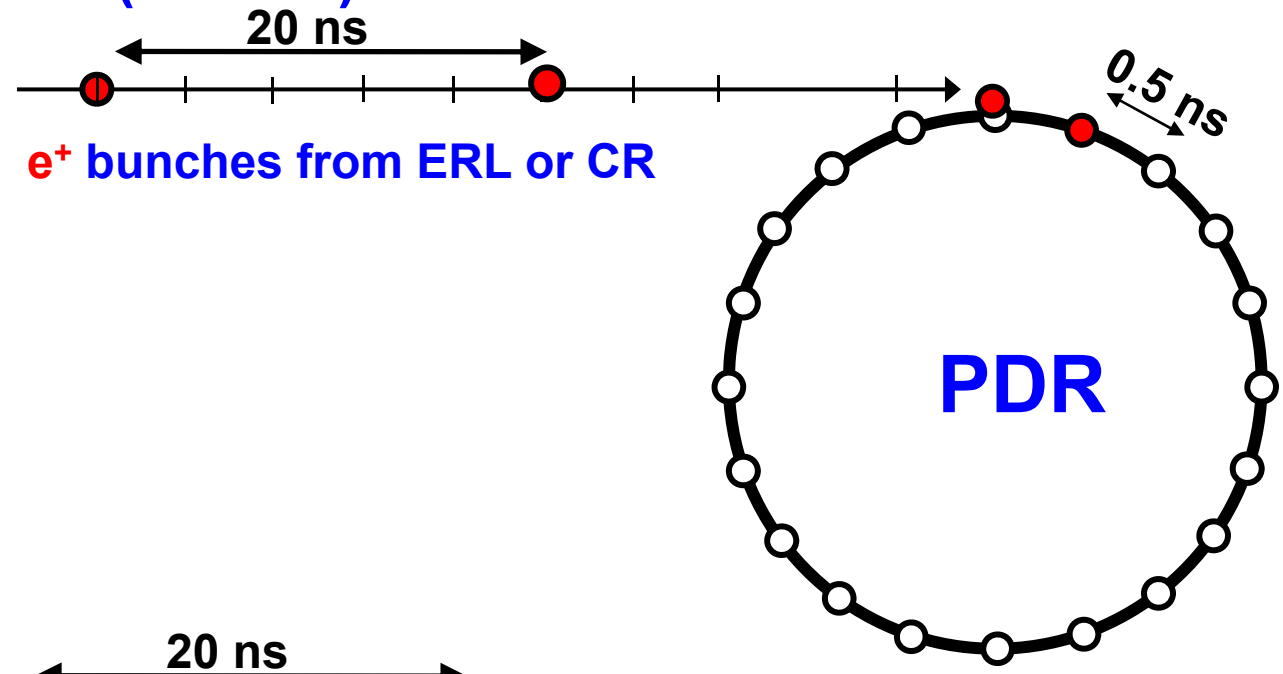


Omori-san style plot

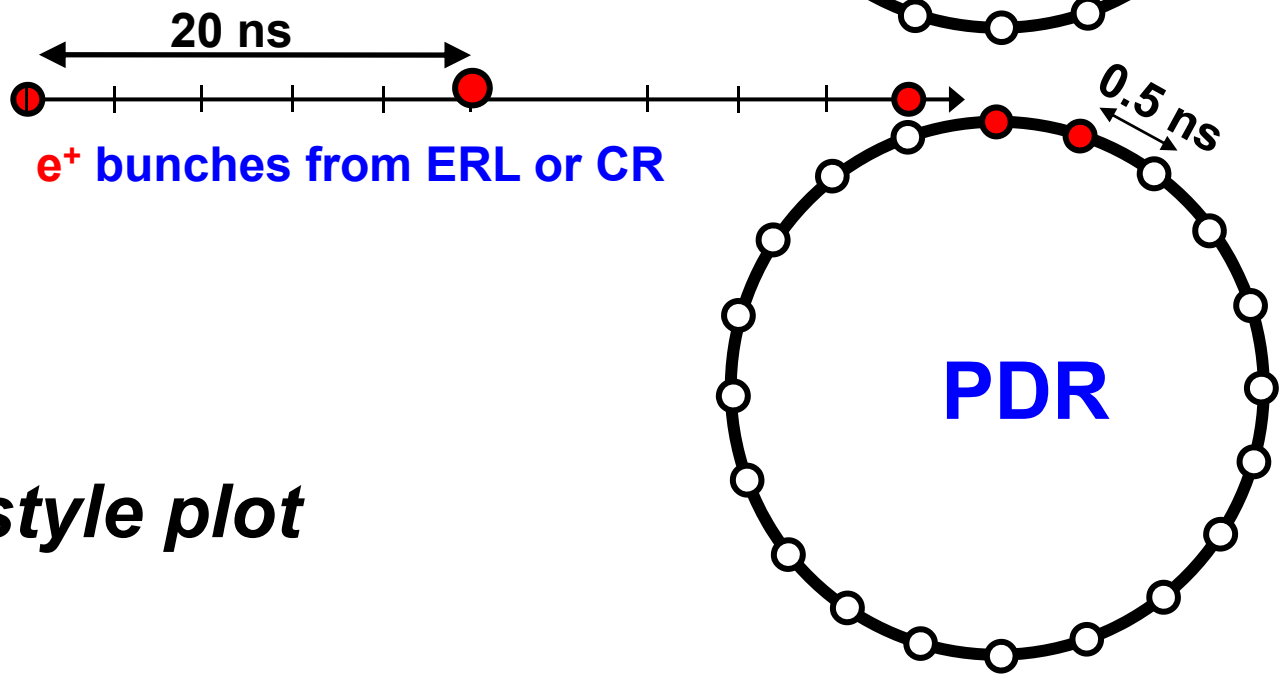
(only rough schematic here)

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

(1) 2nd turn begin



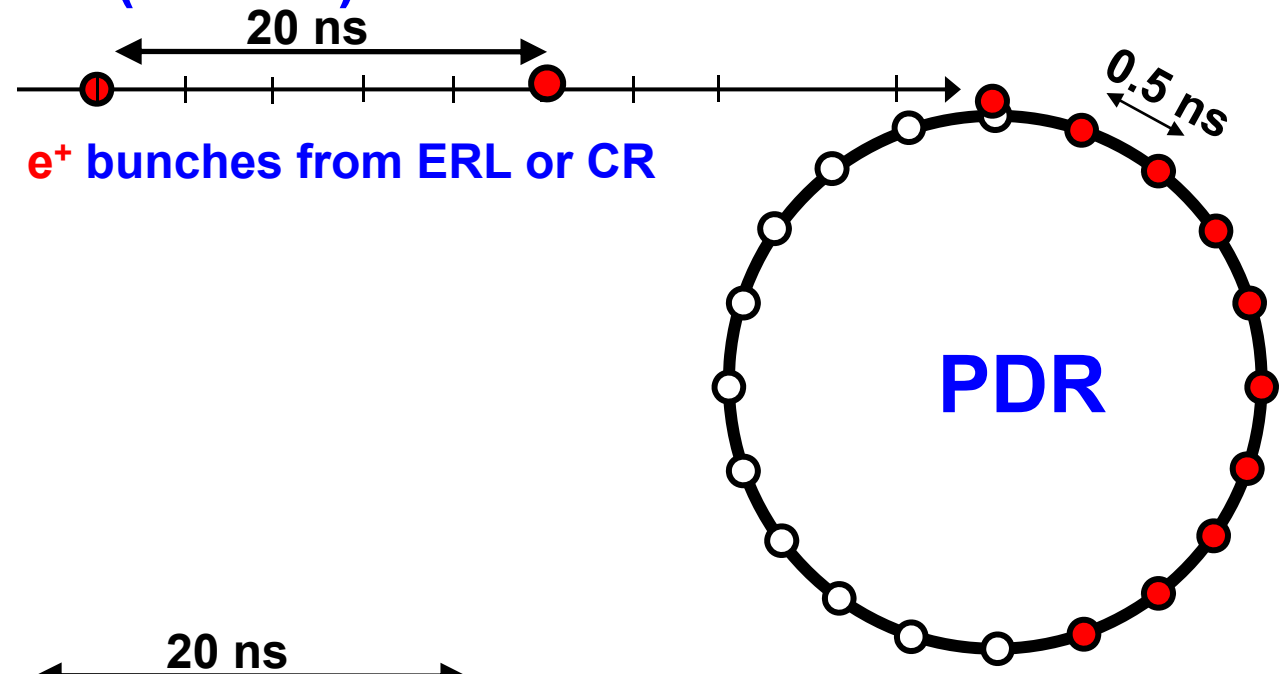
(2) 2nd turn end



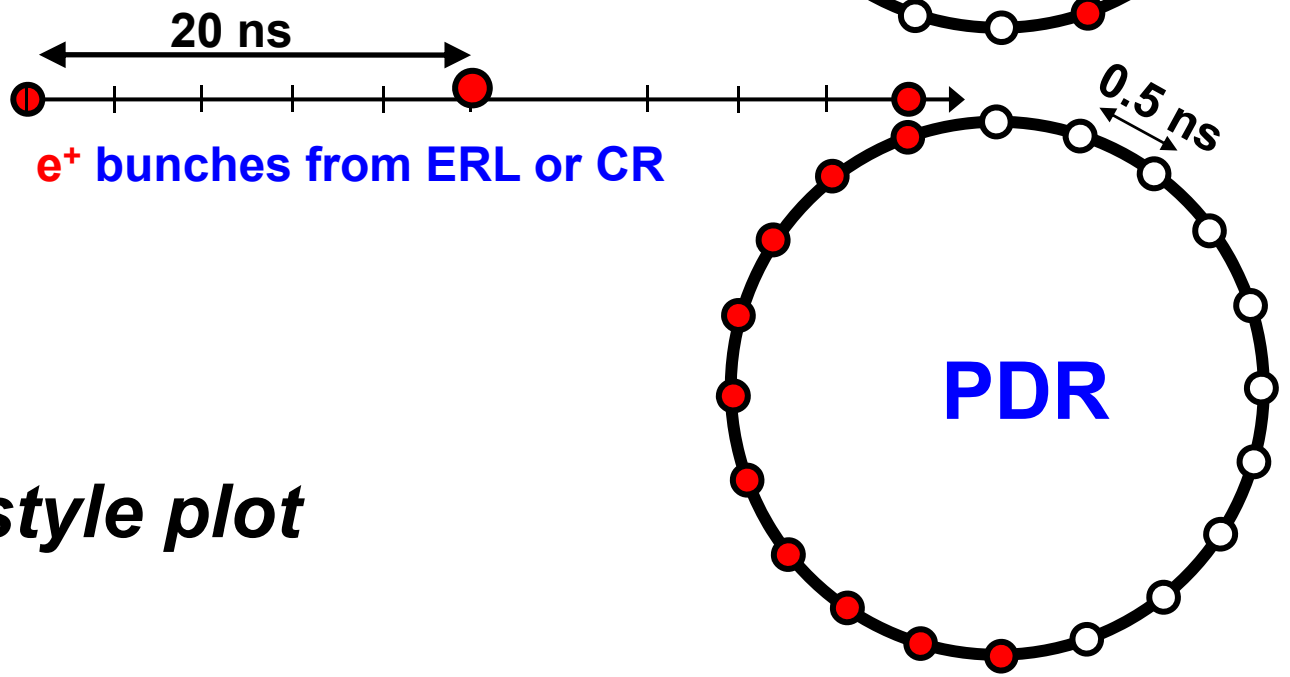
Omori-san style plot

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

(1) 40th turn begin

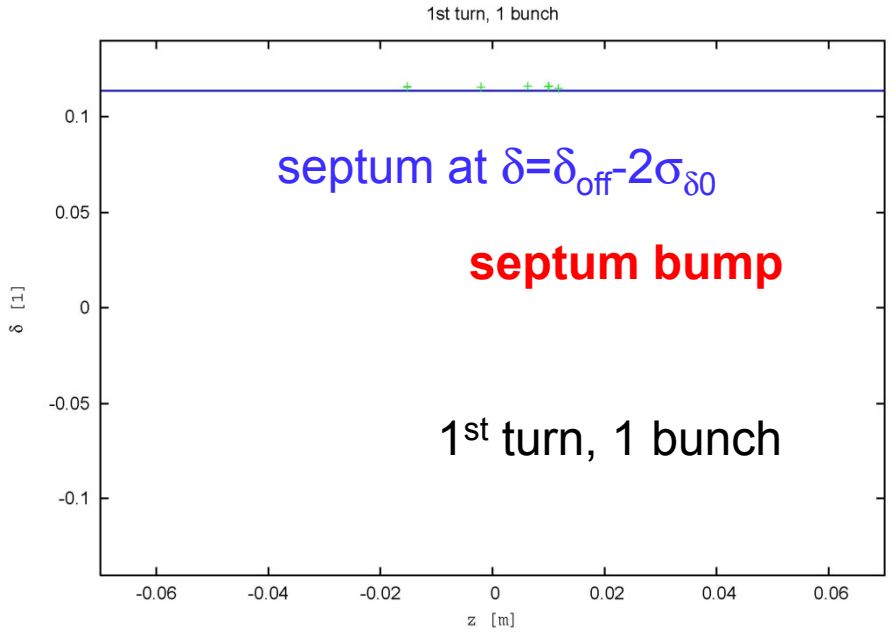


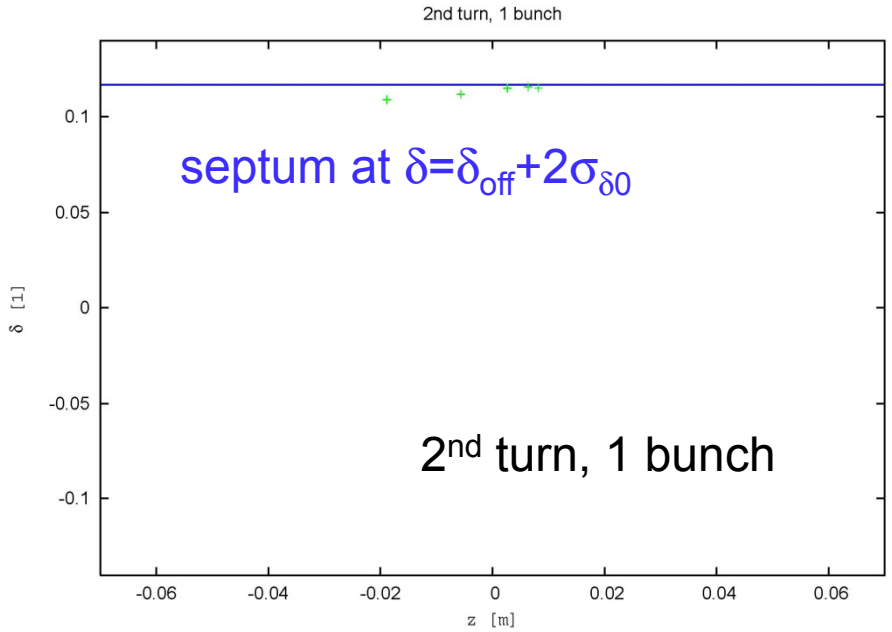
(2) 40th turn end

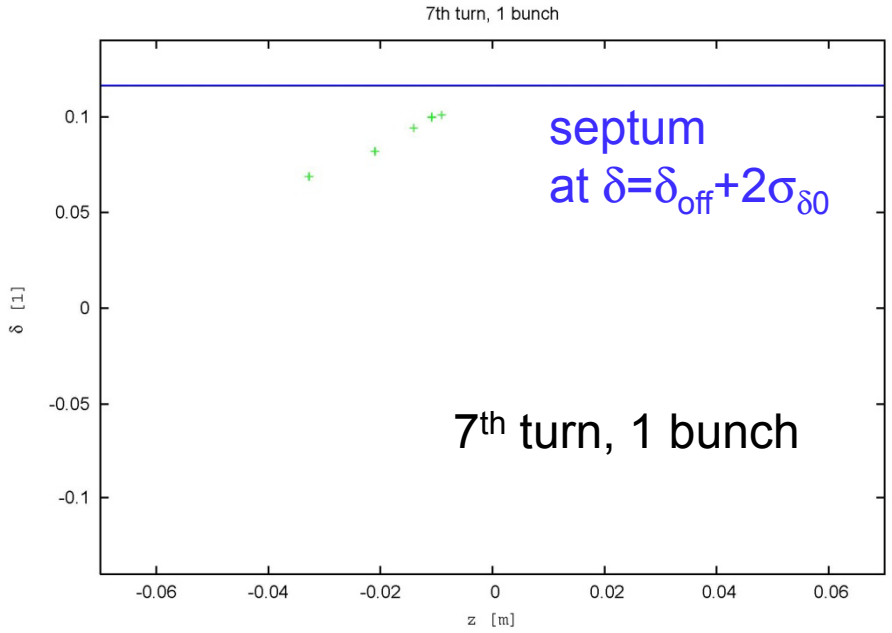


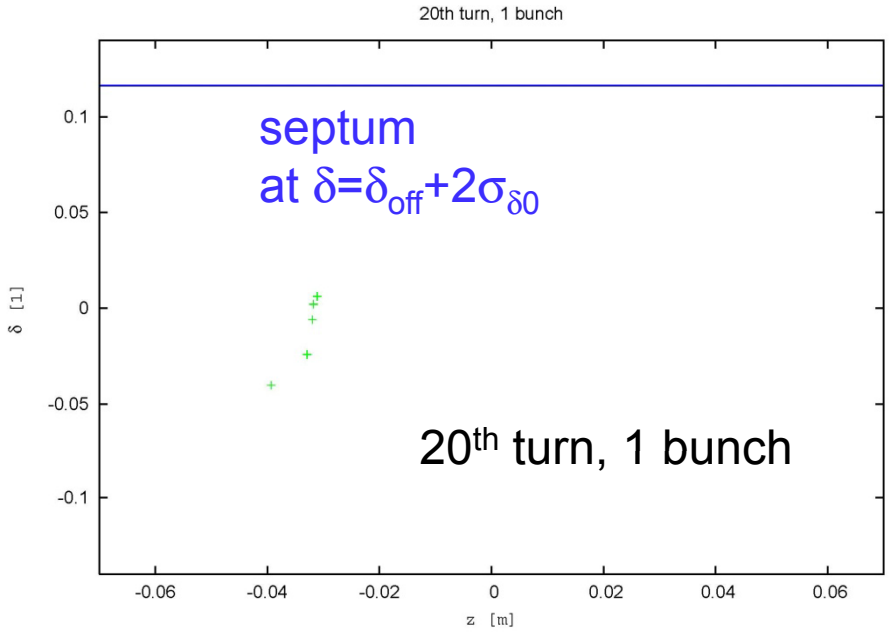
Omori-san style plot

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

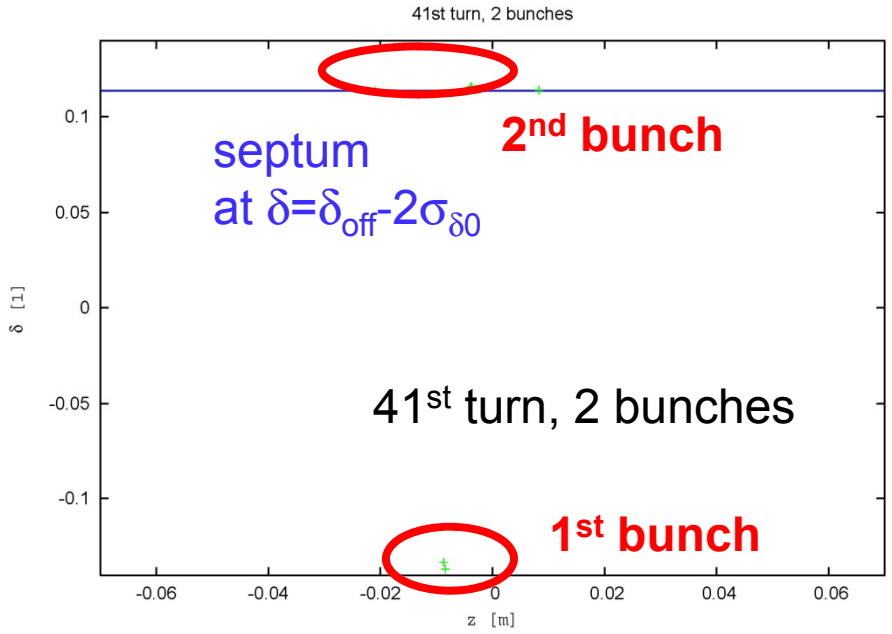


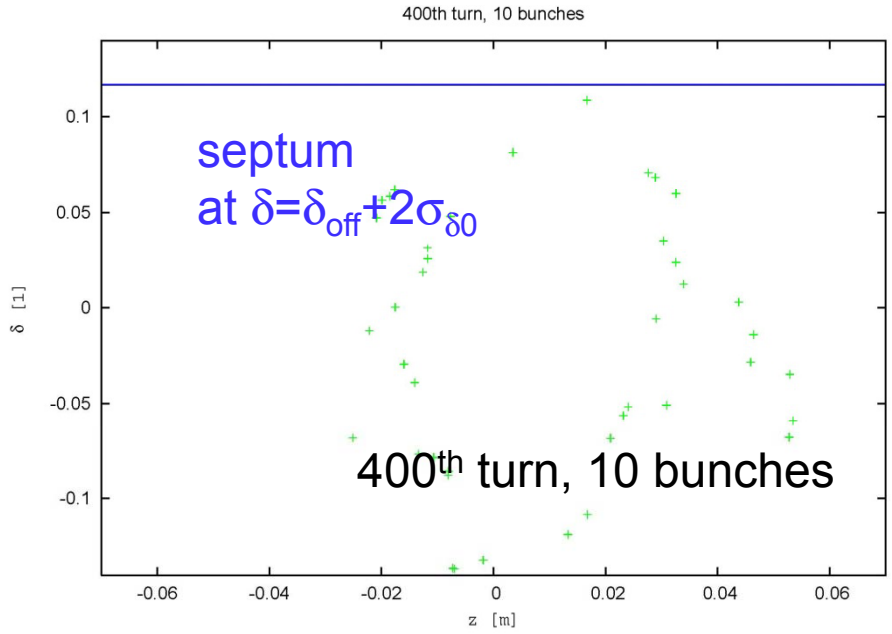


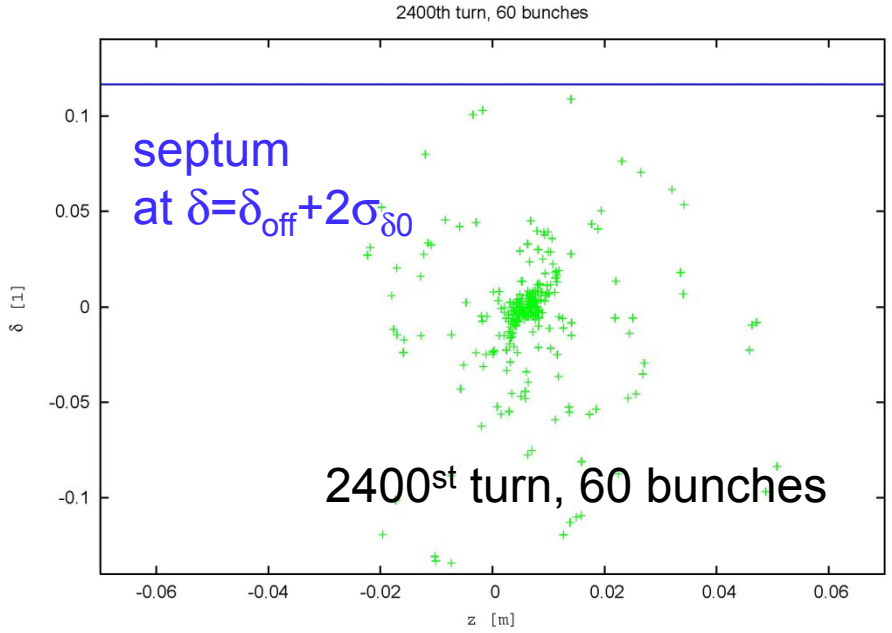


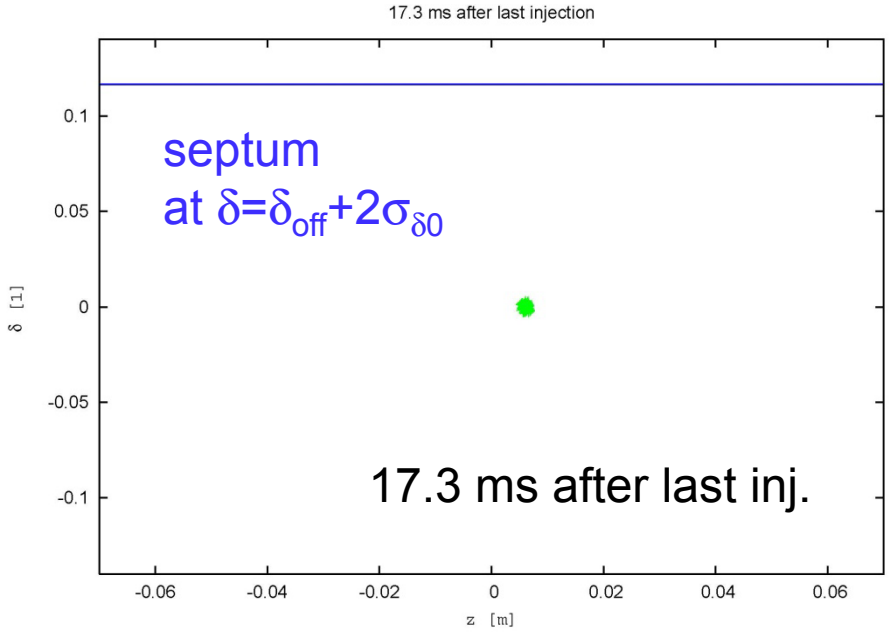


CLIC PDR stacking simulation, example, δ_{off}=11..5%









conditions for this stacking scheme to work:

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

in our example:

328 MeV > 8 MeV

easily fulfilled

no septum bump needed if:

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

treatment of synchrotron radiation

R. Siemann, HEACC 1988

model A

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

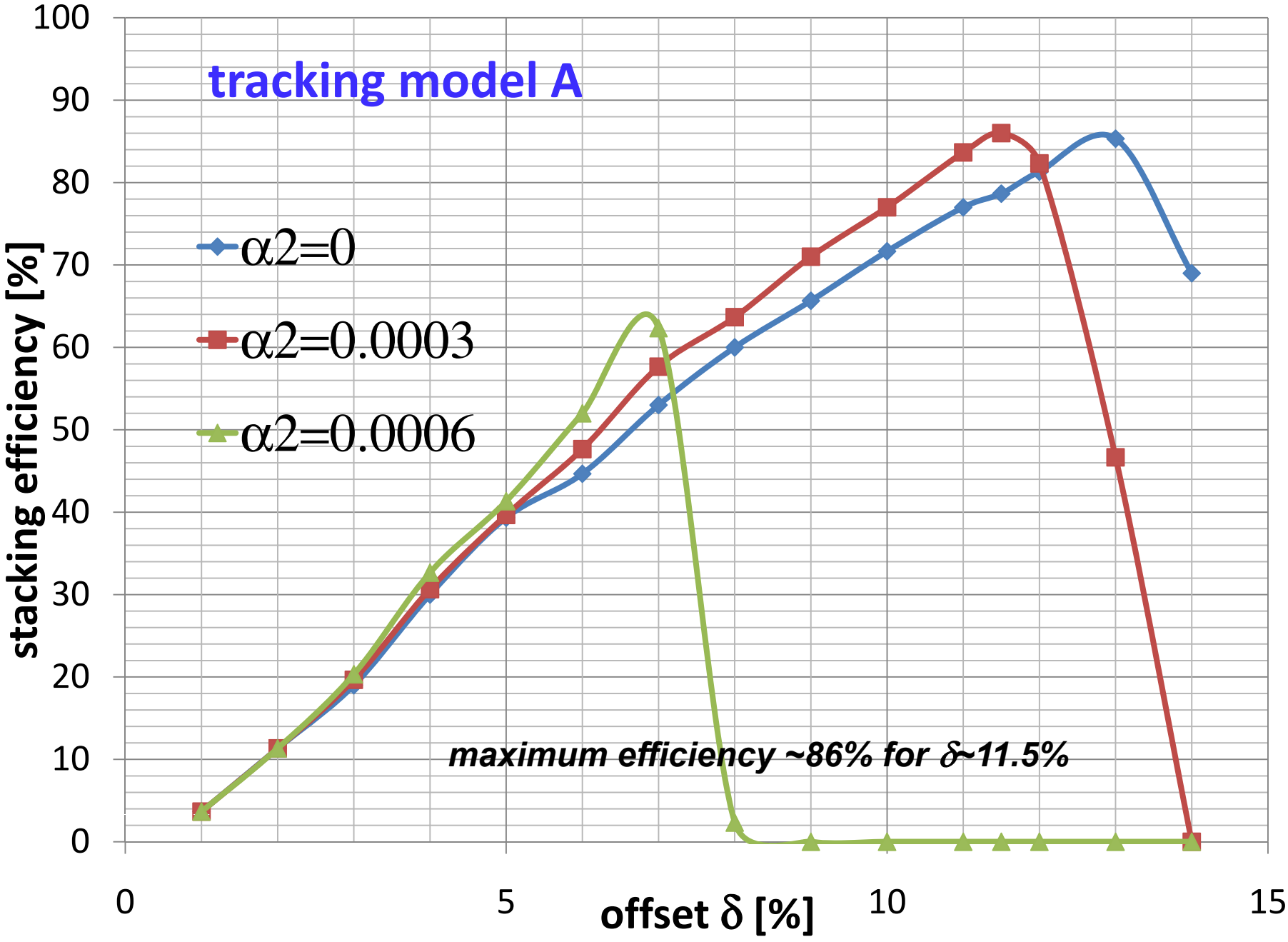
$$\delta_{new} = \delta_{old} e^{-T_0/\tau_{\|}} + \xi \sqrt{2\left(1 - e^{-T_0/\tau_{\|}}\right)} \sigma_{\delta,eq}$$

model B

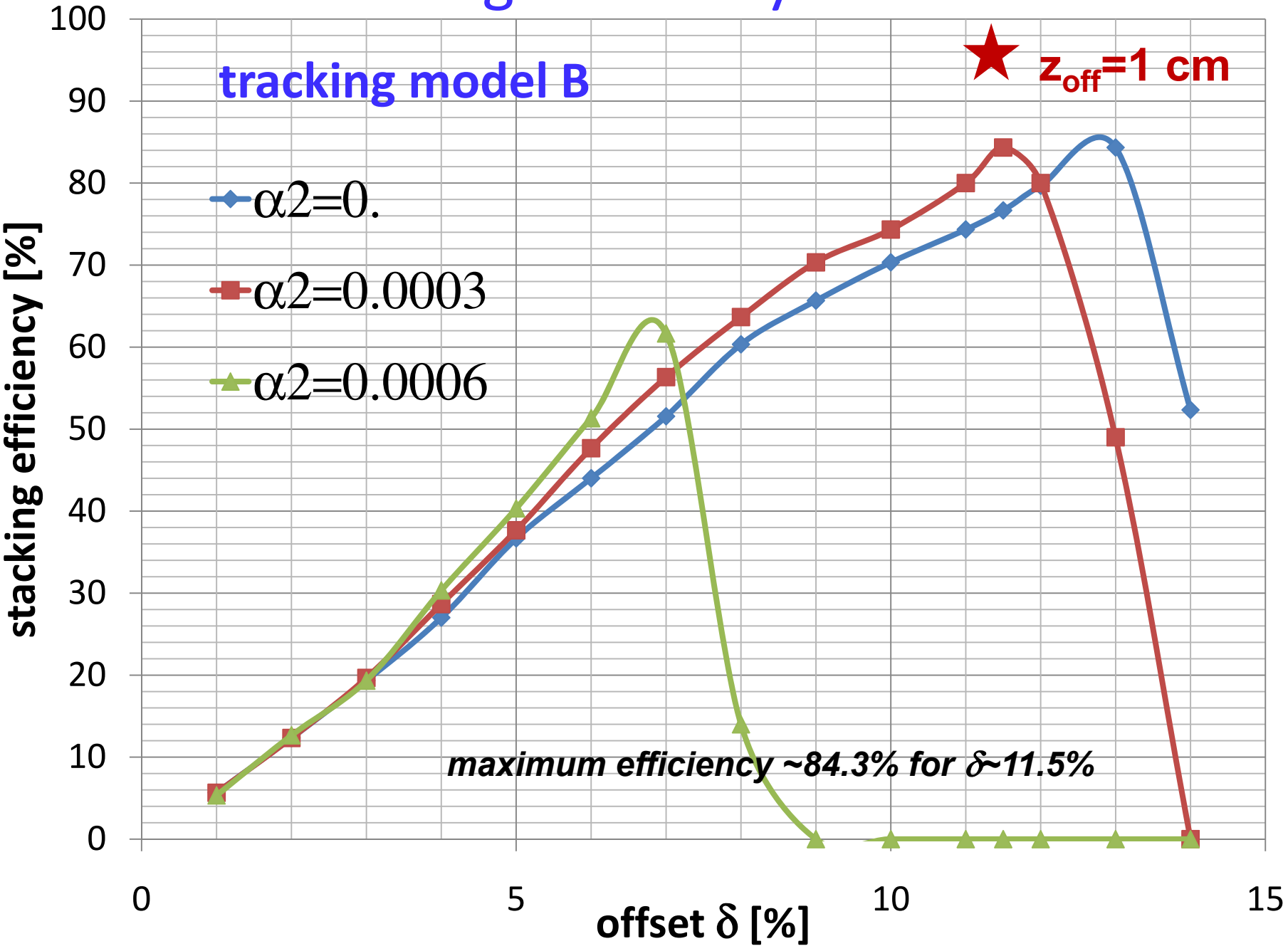
$$z_{new} = z_{old}$$

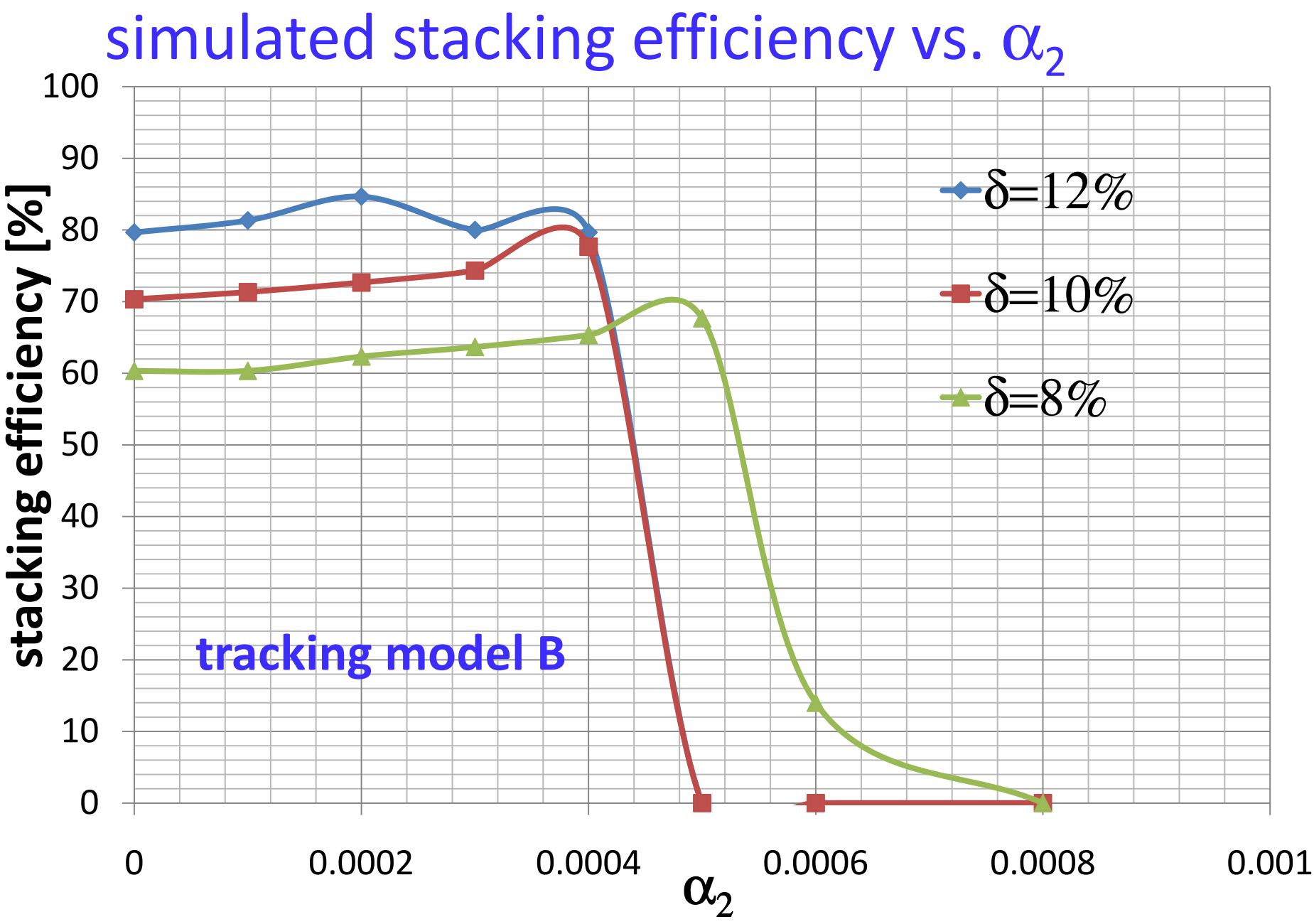
$$\delta_{new} = \delta_{old} e^{-2T_0/\tau_{\|}} + \xi \sqrt{2\left(1 - e^{-2T_0/\tau_{\|}}\right)} \sigma_{\delta,eq}$$

simulated stacking efficiency vs. initial δ offset



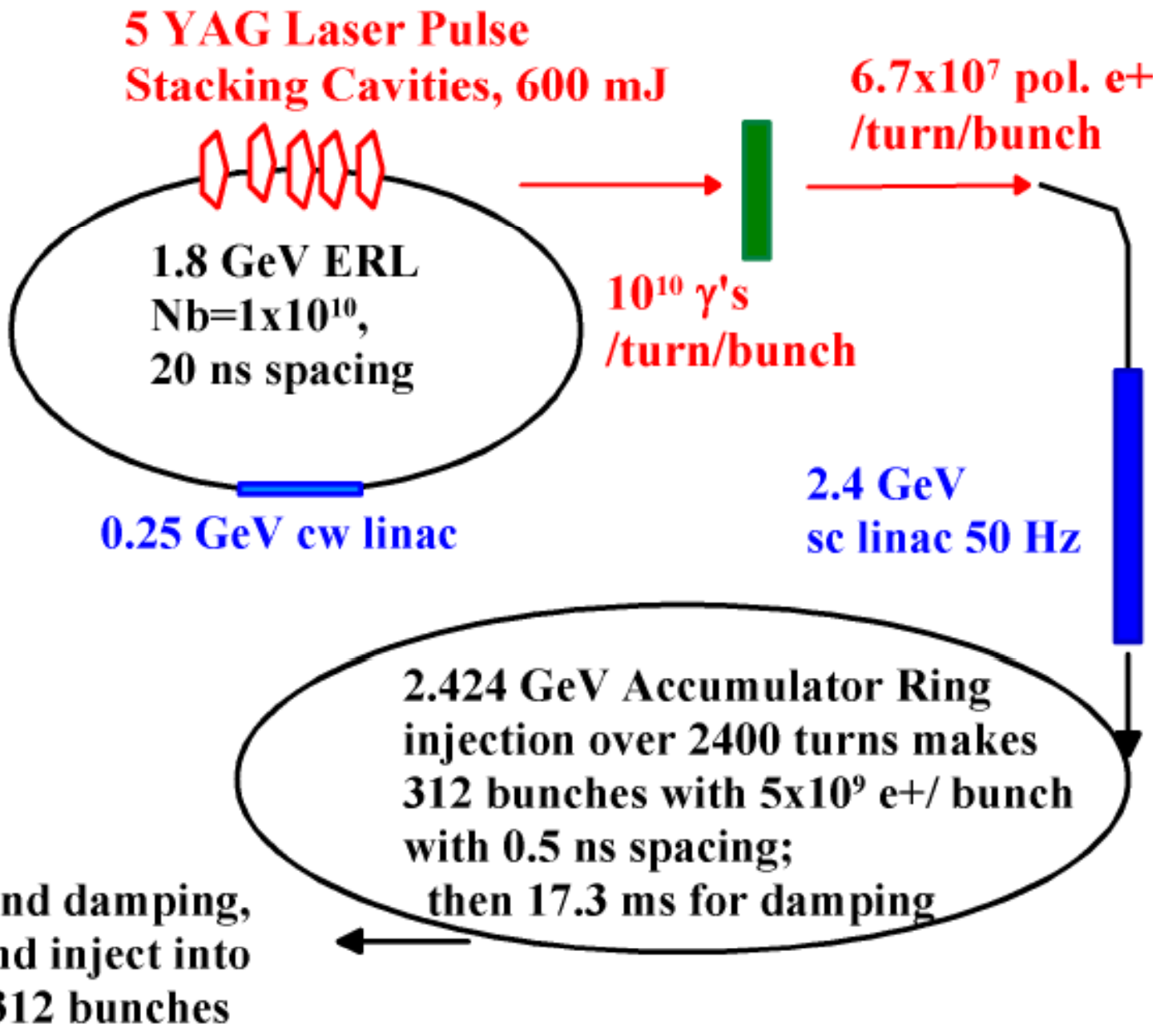
simulated stacking efficiency vs. initial δ offset




simulated stacking efficiency vs. α_2
stacking efficiency [%]
100
90
80
70
60
50
40
30
20
10
0
0
0.0002
0.0004
0.0006
0.0008
0.001
α_2
δ=12%
δ=10%
δ=8%
tracking model B

stacking parameters for ILC and CLIC – 2*	ILC-DR Snowmass '05 proposal	ILC 2008-**Compton vers. "CERL-B"**	CLIC pre-DR 2007 (NLC 2004 design)	**CLIC 2008 (& CLIC CERL Compton vers.)**
transv. normalized edge emittance at injection (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	**11.4 mm**	3.8 mm	11.4 mm
rms energy spread at injection	0.14%	**0.04% (2 MeV)**	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	$3x10^{-4}$	$4.2x10^{-4}$	$1.69x10^{-3}$	**$9x10^{-5}$**
2^{nd} order momentum compaction	$1.3x10^{-3}$	-	-	**$5.8x10^{-2}$ ($3x10^{-4}$)**
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=bucket area / long. edge emit. /π	133	**57**	4	**(102)**
RMIN=TI/ICM	0.75	18	15	(0.59)
IP/RMIN/$\tau_{\|\|}$	12	**1**	1.3	**(9.1)**
IP/RACT/$\tau_{\|\|}$	0.09	**0.15**	0.31	**(0.09)**
synchronous phase	15.58^{o}	**28.97^{o}**	26.47^{o}	**(14.49^{o})**
separatrix phases 1&2	164.42^{o}, -159.19^{o}	**151.03^{o}, -82.64^{o}**	153.53^{o}, -95.66^{o}	**(165.51^{o}, -163.83^{o})**
max. momentum acceptance	+/-2.7%	+/- 1.6%	+/- 1.0%	+/-1.6% (+/- 13%)
injection offset δ,z	ramped in δ	+1.5%, 0.01 m	ramped in δ	(+13.20%, 0.01 m)
simulated stacking efficiency	**82%**	**91%**	not computed	**95.5%**
final # positrons / bunch	**$2x10^{10}$**	**$6x10^{10}$**	not computed	**$5.1x10^{9}$**

2008 CLIC e+ Compton scheme - example



some conclusions

- CLIC Compton source using ERL or CR
- e+ emittance preservation after capture
- CLIC PDR parameters adapted for stability and stacking, $\alpha_2 \downarrow\downarrow$ $V_{RF} \uparrow$
- stacking simulation: 95% efficiency with off-momentum off-phase injection
- PDR off-momentum dynamic aperture must be adequate (huge!)
- quite some flexibility (# optical cavities vs. e- bunch charge)
- but a few challenges for PDR design

thank you for your attention!