issues for e+ stacking in the rings

Frank Zimmermann

IWLC2010,

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thanks to Fanouria Antoniou, Eugene Bulyak, Peter Gladkikh, Yannis Papaphilippou, Louis Rinolfi, Junji Urakawa, Alessandro Variola, Alessandro Vivoli

various Compton-scheme scenarios

Compton sources

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

accumulation rings

- ILC damping ring – *optimized?*
- CLIC pre-damping ring - optimized
- two CLIC stacking rings - dedicated

ILC & CLIC parameters, differences & needs

	CLIC	ILC	comment
e+/bunch	**4.5×10^{9}**	**2×10^{10}**	
bunches/pulse	**312**	**2625**	
spacing in (P)DR	0.5 ns	(3-)6 ns	**CLIC cannot stack every bucket per turn**
stacking ring	**dedicated SRs or optimized pre-DR**	**optimized DR**	
beam energy	2.86 GeV (PDR)	5 GeV	
circumference	~400 m (PDR)	~6700 m (?)	
bucket area /π	28 meVs (PDR)	41 meV-s	
synchrotron tune	0.033 (PDR)	0.084	
RF frequency	2 GHz (PDR)	650 MHz	
RF voltage	20 MV (PDR)	36 MV	2009 assumption
momentum compaction	3.8×10^{-4} (PDR)	4.2×10^{-4}	2009 assumption
damping time	0.58 ms (PDR)	6.4 ms	2009 assumption
repetition rate	**50 Hz**	**5 Hz**	
e+ / second	**7×10^{13}**	**3×10^{14}**	

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 * (CLIC)
~1 γ/e- for several optical cavities (ILC)

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

example numbers:

	CLIC C-R	CLIC C-ERL	ILC C-R	ILC C-ERL
e-/bunch	6×10^9	10^9	3×10^{10}	10^9
#cavities	1	1	5	5
e+/collision	10^7	2×10^6	5×10^8	10^7
#stackings	**~500**	**~2000**	**~60**	**~2000**
e+/bunch	4.5×10^9	4.5×10^9	2×10^{10}	2×10^{10}

*Tsunehiko Omori, 11 October 2008

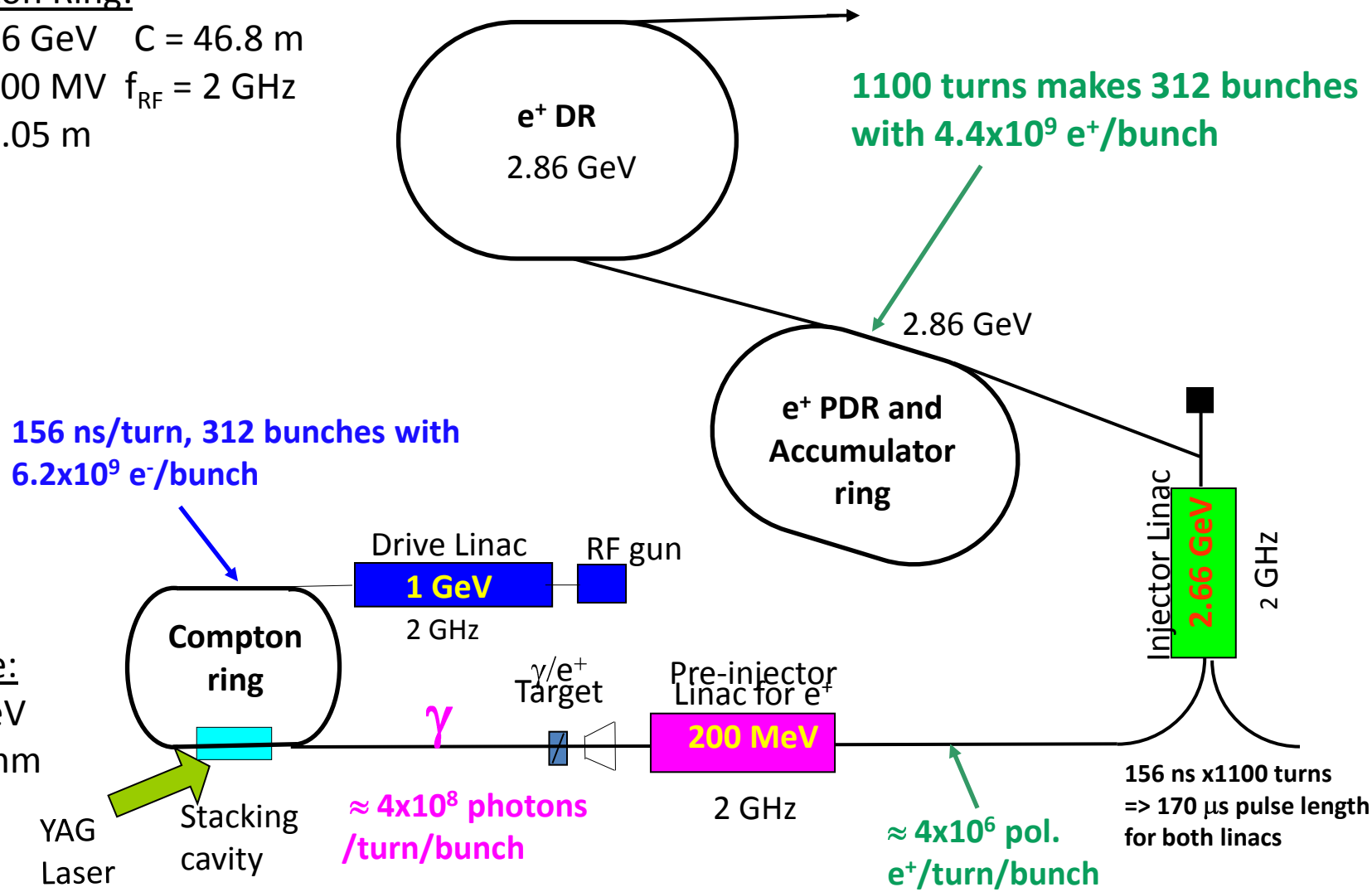
stacking approach

- most laser Compton sources (R-Ring, C-ERL) do not provide required e+ intensity / pulse
- **e+ must be accumulated over ~50-3000 "shots" in (pre-)damping or dedicated stacking ring**
- **longitudinal stacking**:
  - transverse emittance fills aperture
  - longitudinal aperture larger than injected emittance with low-α & high RF voltage
  - longitudinal damping rate is ~2x faster than transverse

Compton Ring Scheme for CLIC

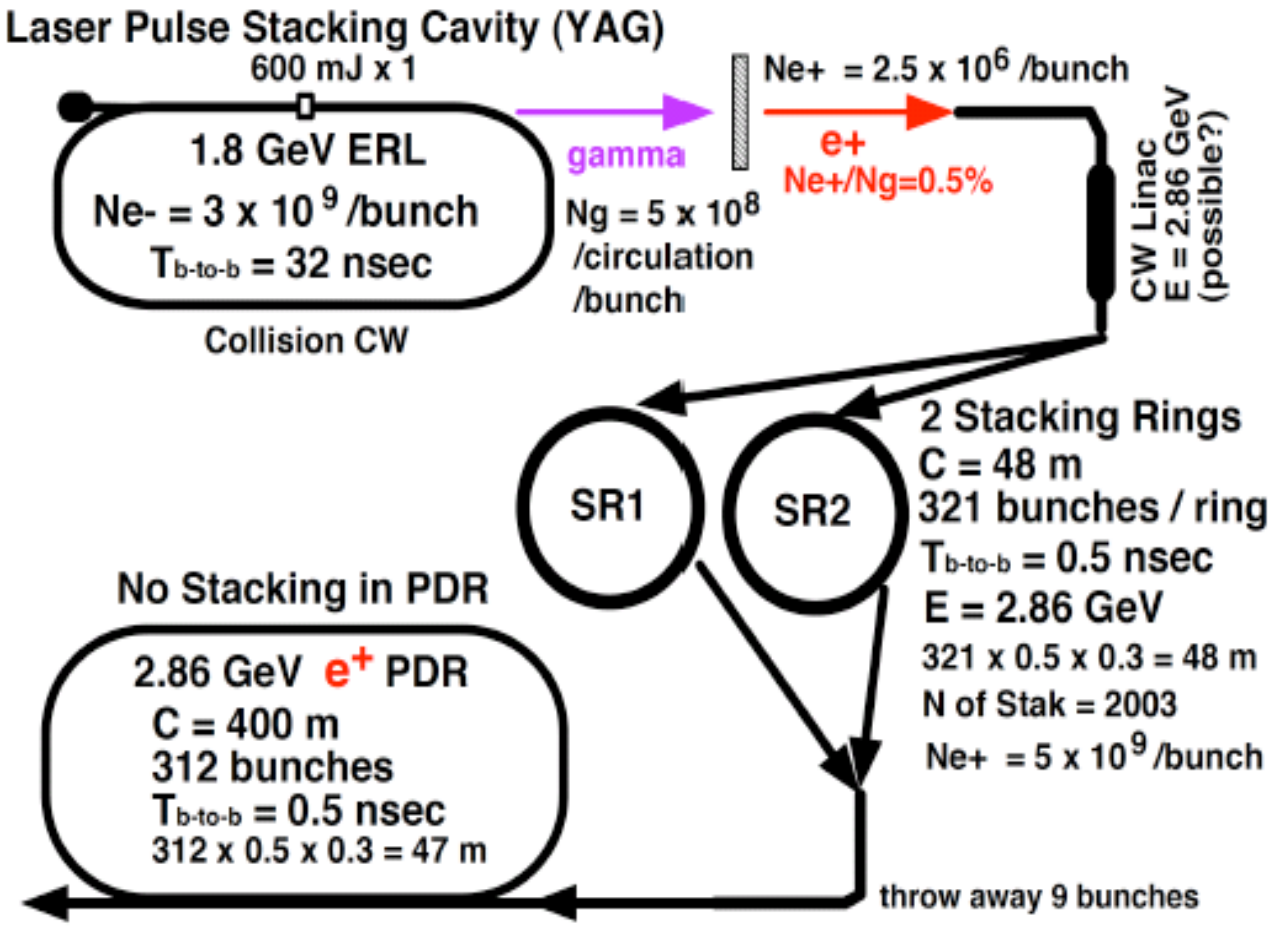
L. Rinolfi

Compton Ring:
E = 1.06 GeV C = 46.8 m
V_{RF} = 200 MV f_{RF} = 2 GHz
β_{CP} = 0.05 m



Laser pulse:
E = 1.164 eV
r = 0.005 mm
l = 0.9 mm

Compton ERL Scheme for CLIC



L. Rinolfi (CERN) and T. Omori (KEK)

ILC-CLIC e+ studies

14-May-2009

stacking scheme / simulation ingredients

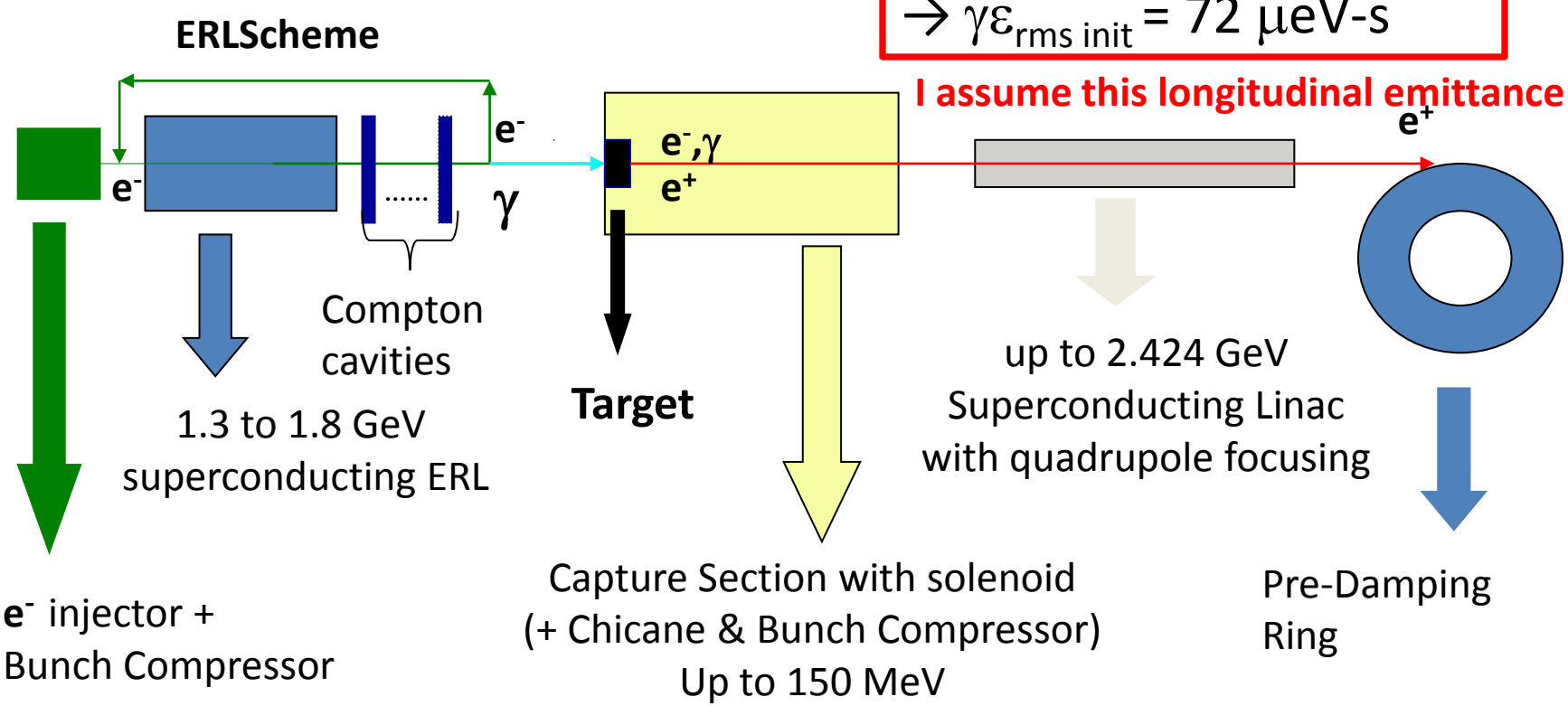
- **stacking in longitudinal phase space**
  RF bucket >> longitudinal edge emittance of injected e+
- **ingredients:** *sinusoidal rf, momentum compaction, 2nd order momentum compaction, radiation damping, quantum excitation, initial e+ parameters*
- injection septum placed at location with large dispersion; septum blade << transverse beam size
- **inject every Nth turn into same (P)DR bucket** (large bunch spacing for e- beam; arranged by suitable CR/CERL-PDR circumference difference, e.g. 0.15 m)
- either **fast septum bump/kick** or **static injection**

initial e+ parameters (A.Vivoli's ILC simulation,'08)

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

$\rightarrow \gamma\varepsilon_{rms\ init} = 72\ \mu eV\text{-}s$

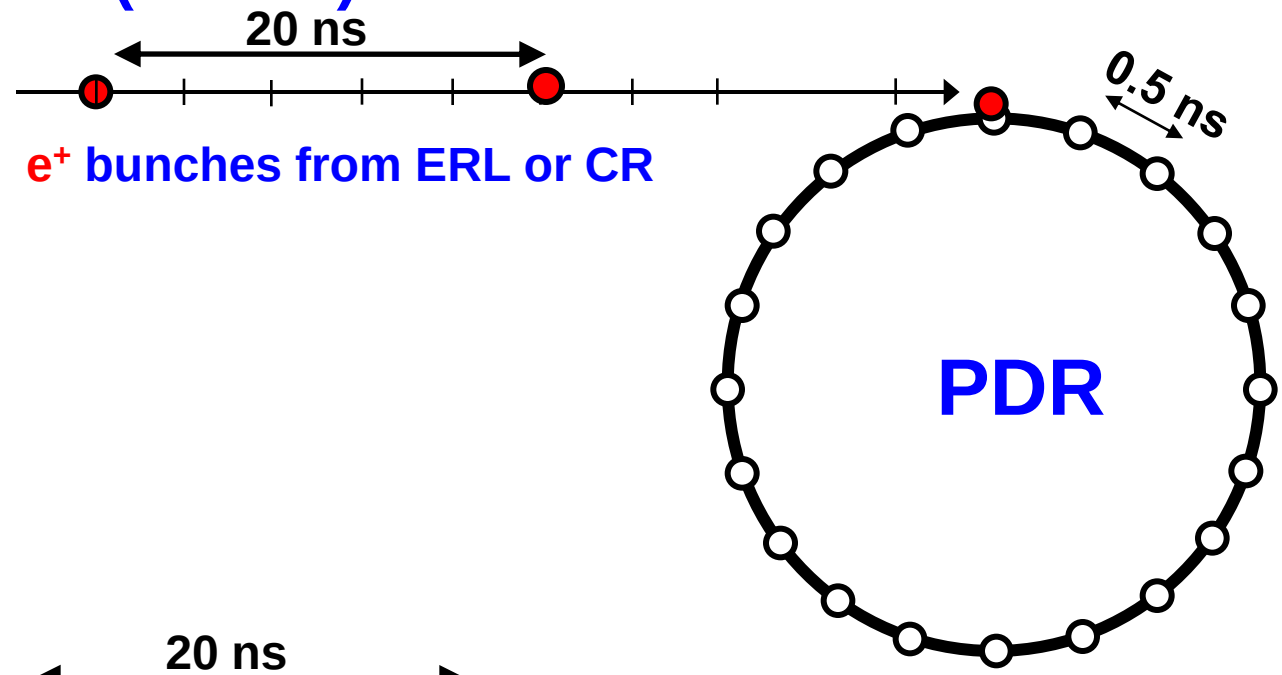
I assume this longitudinal emittance



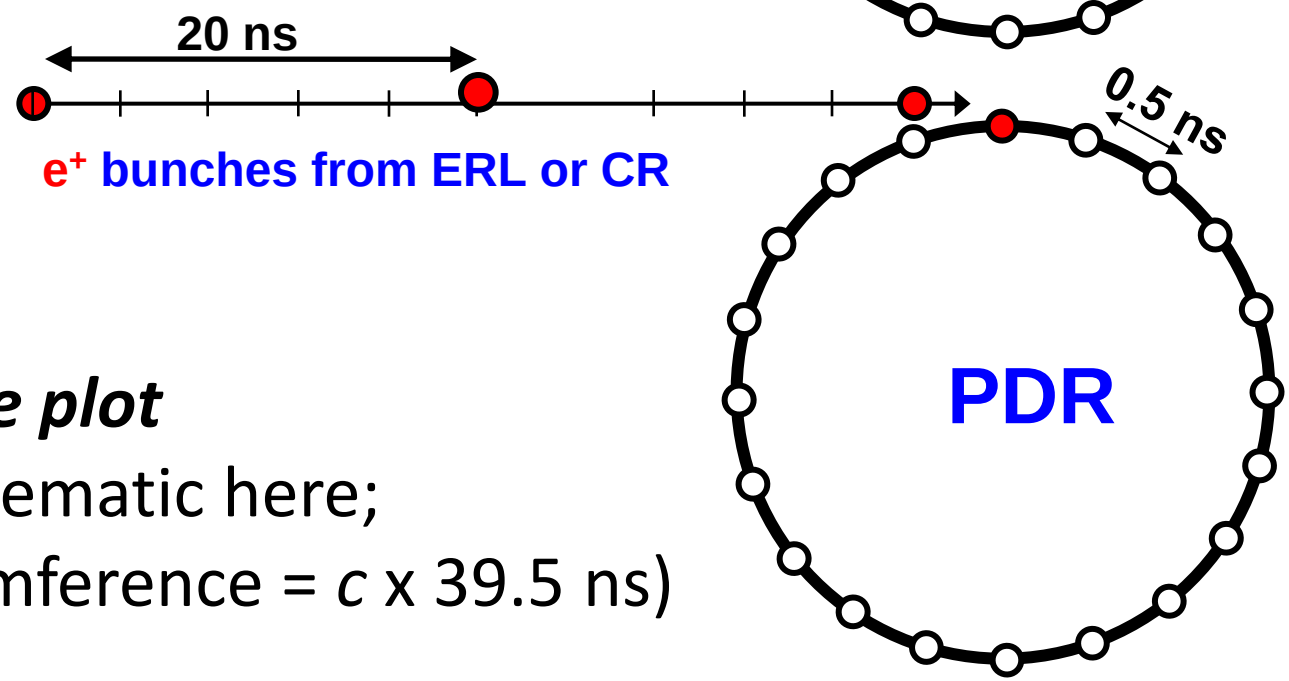
need similar simulation for CLIC

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

(1) 1st turn begin



(2) 1st turn end

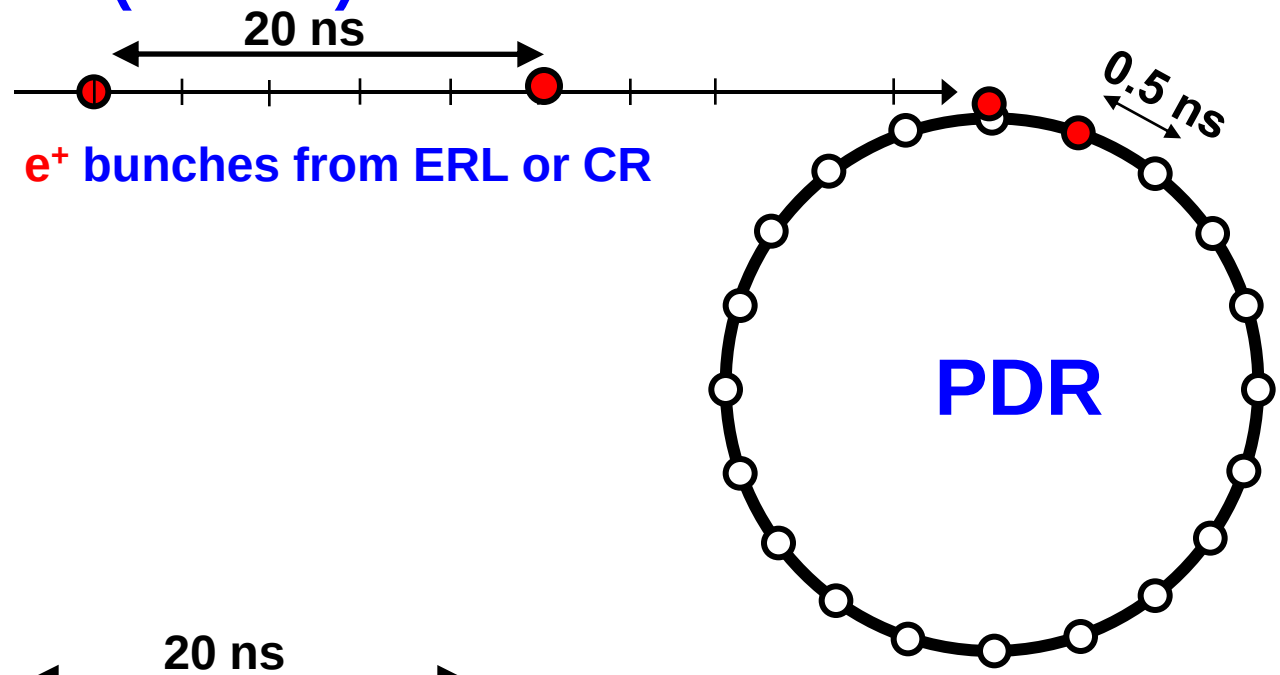


Omori-san style plot

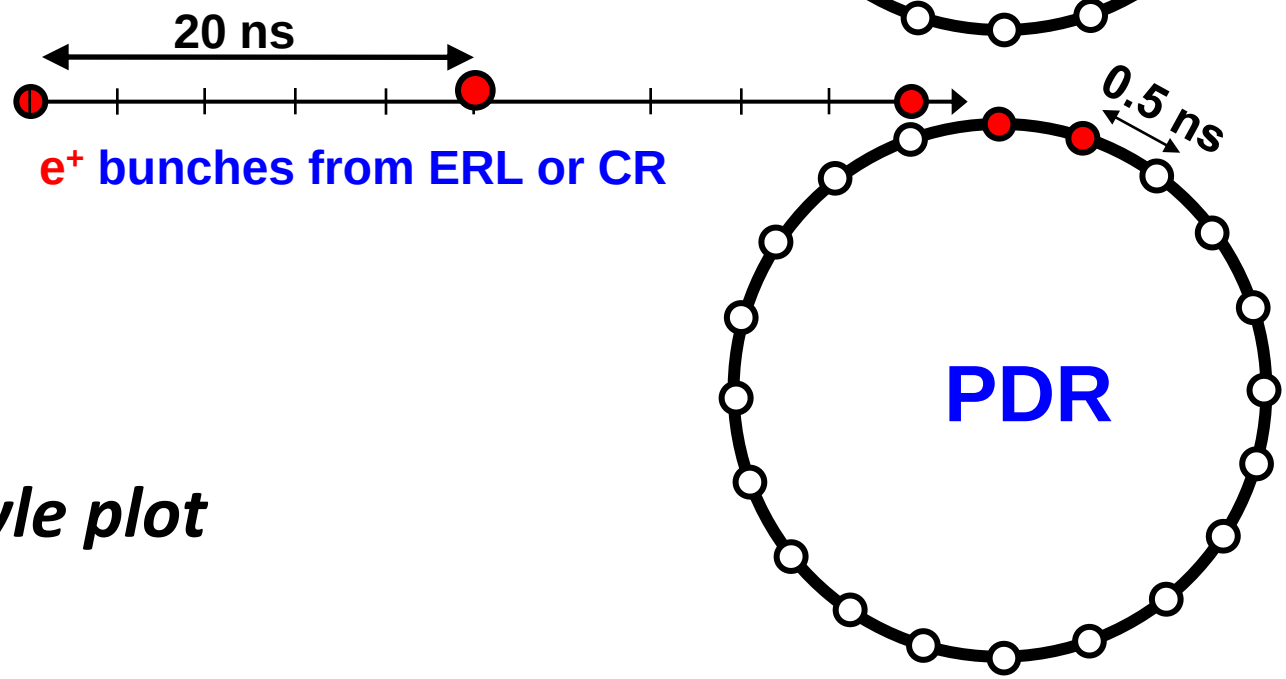
(only rough schematic here;
take ring circumference = *c* x 39.5 ns)

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

(1) 2nd turn begin



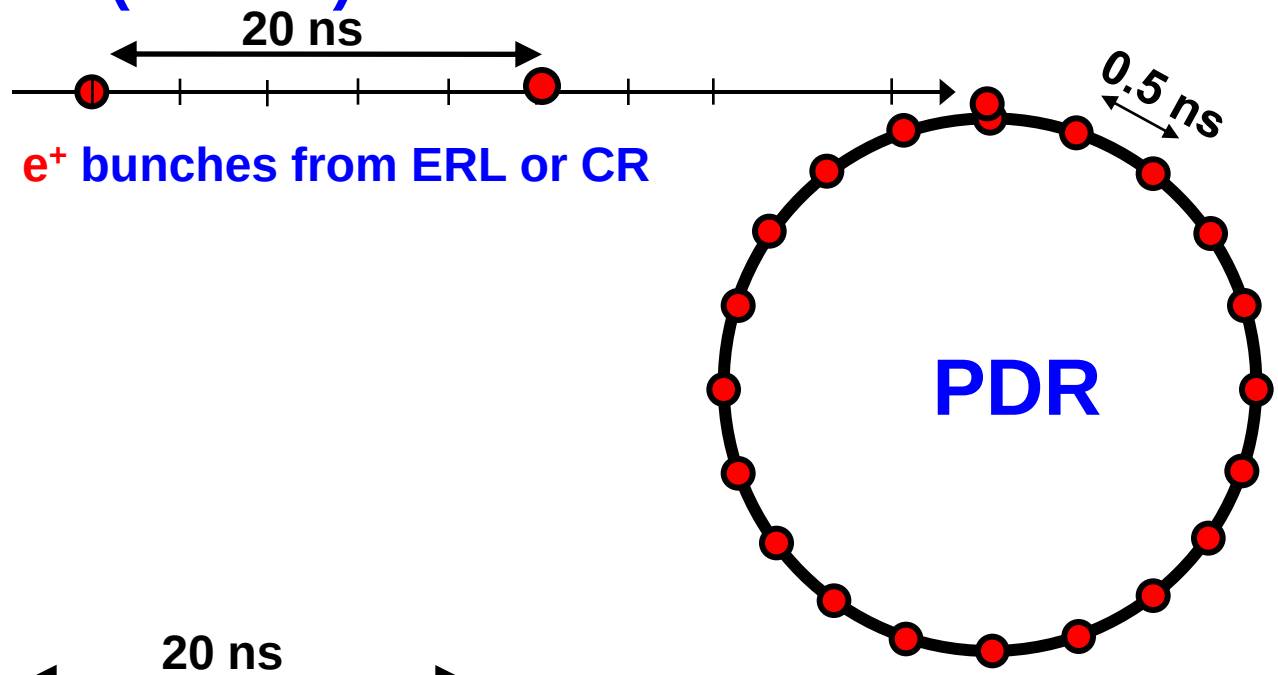
(2) 2nd turn end



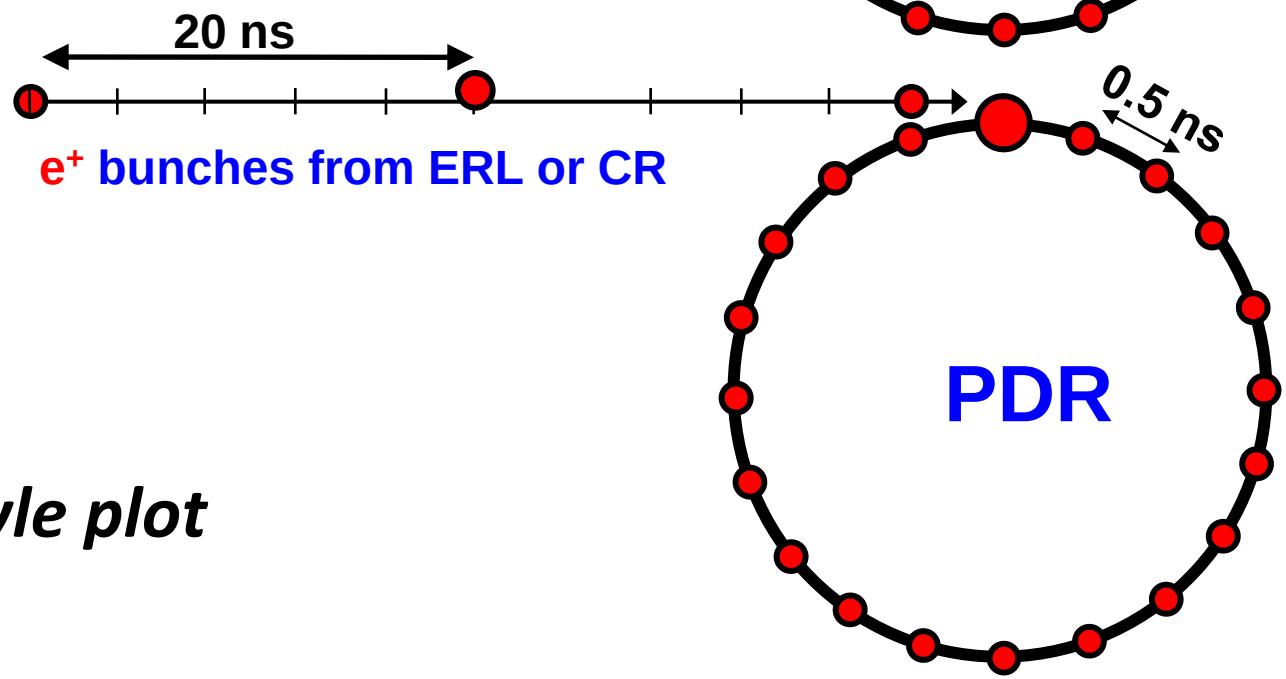
Omori-san style plot

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

(1) 40th turn begin

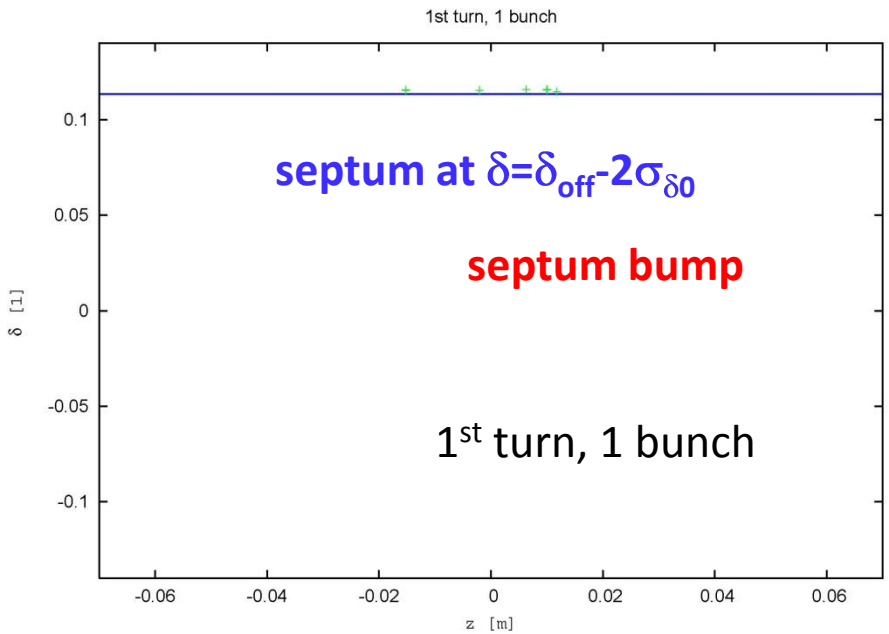


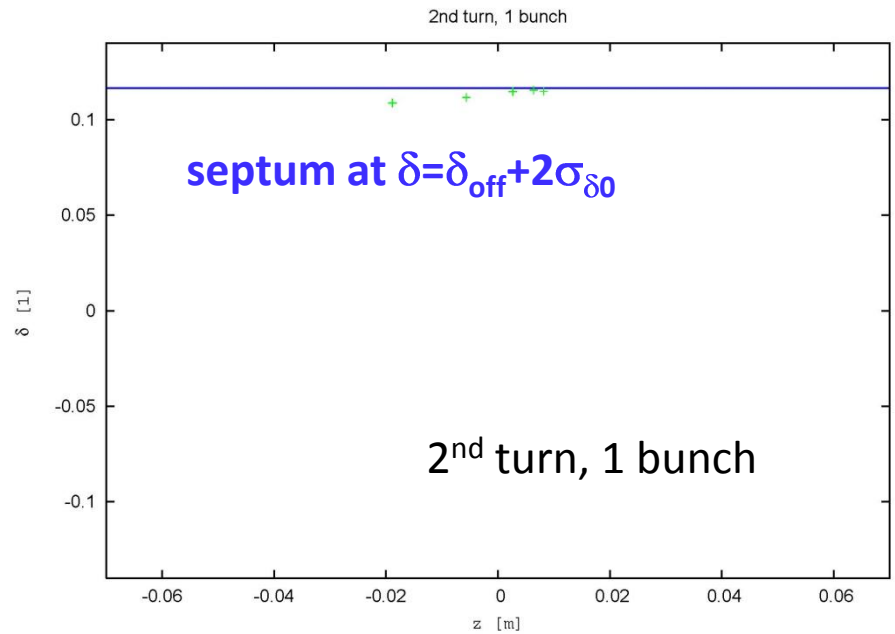
(2) 40th turn end

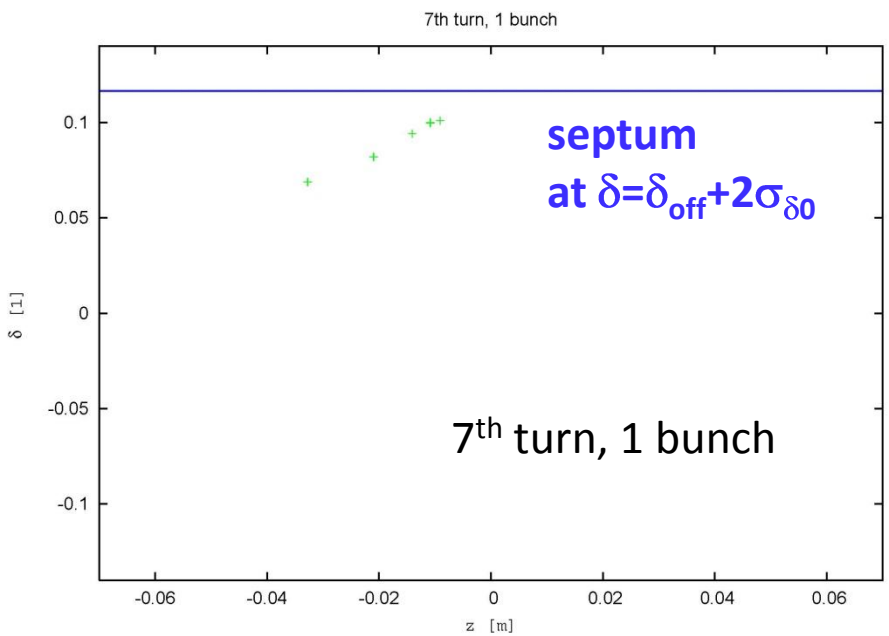


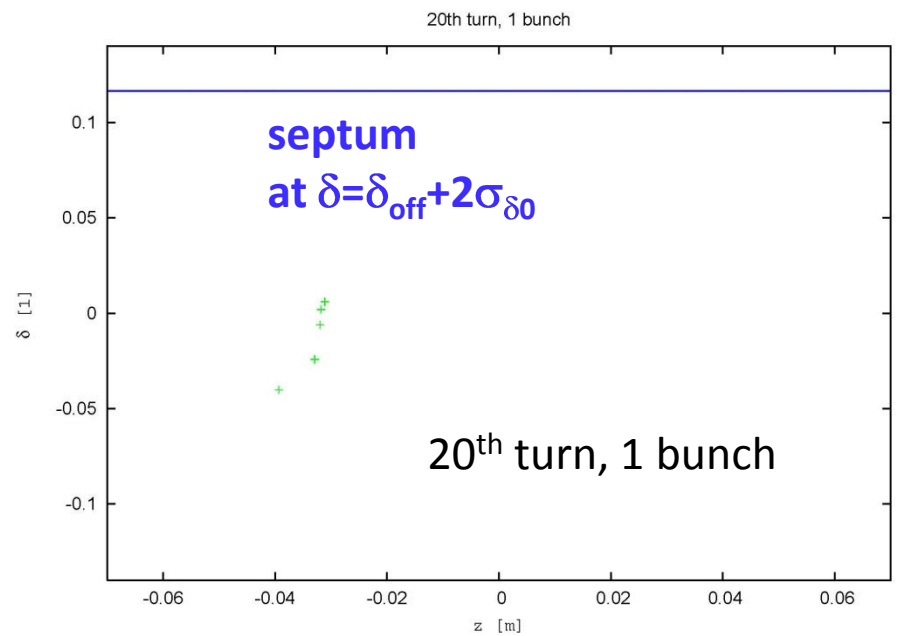
Omori-san style plot

CLIC PDR stacking simulation, example, δ_{off}=11.5%

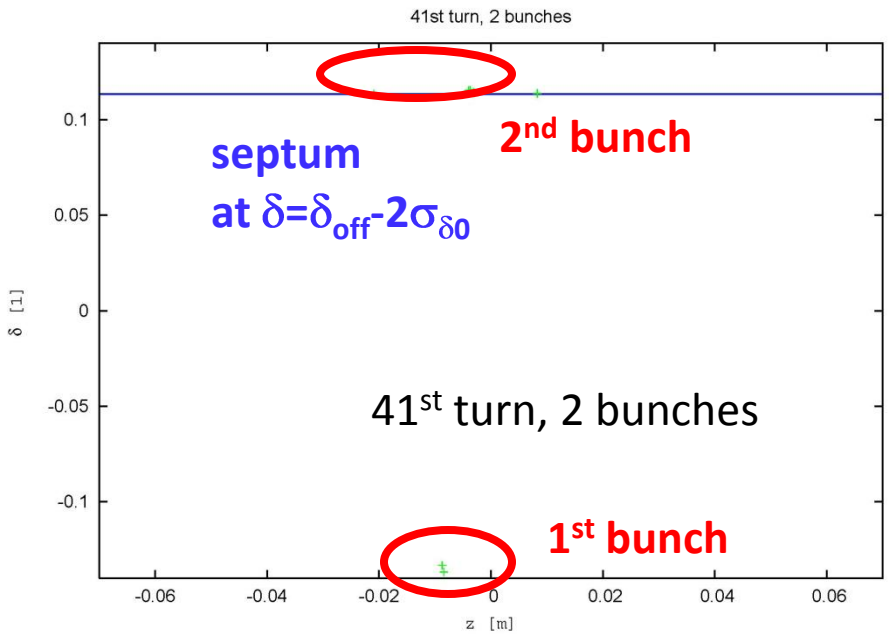


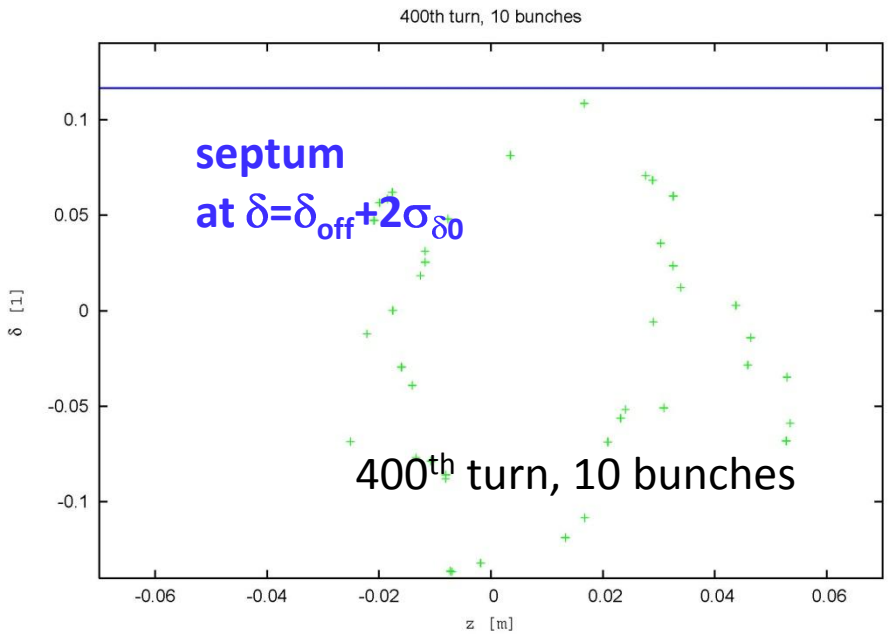


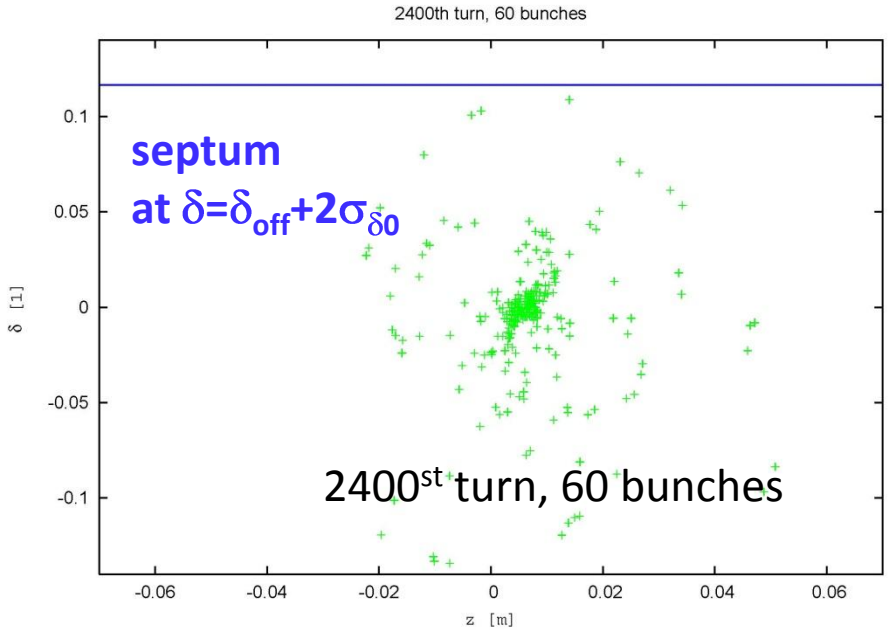


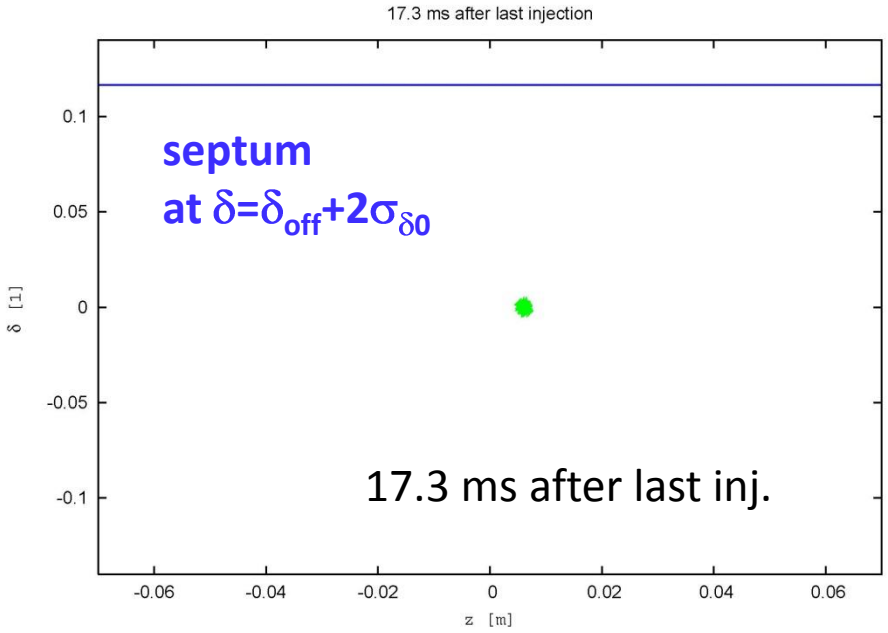


CLIC PDR stacking simulation, example, δ_{off}=11.5%









treatment of synchrotron radiation

R. Siemann, HEACC 1988

model A

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

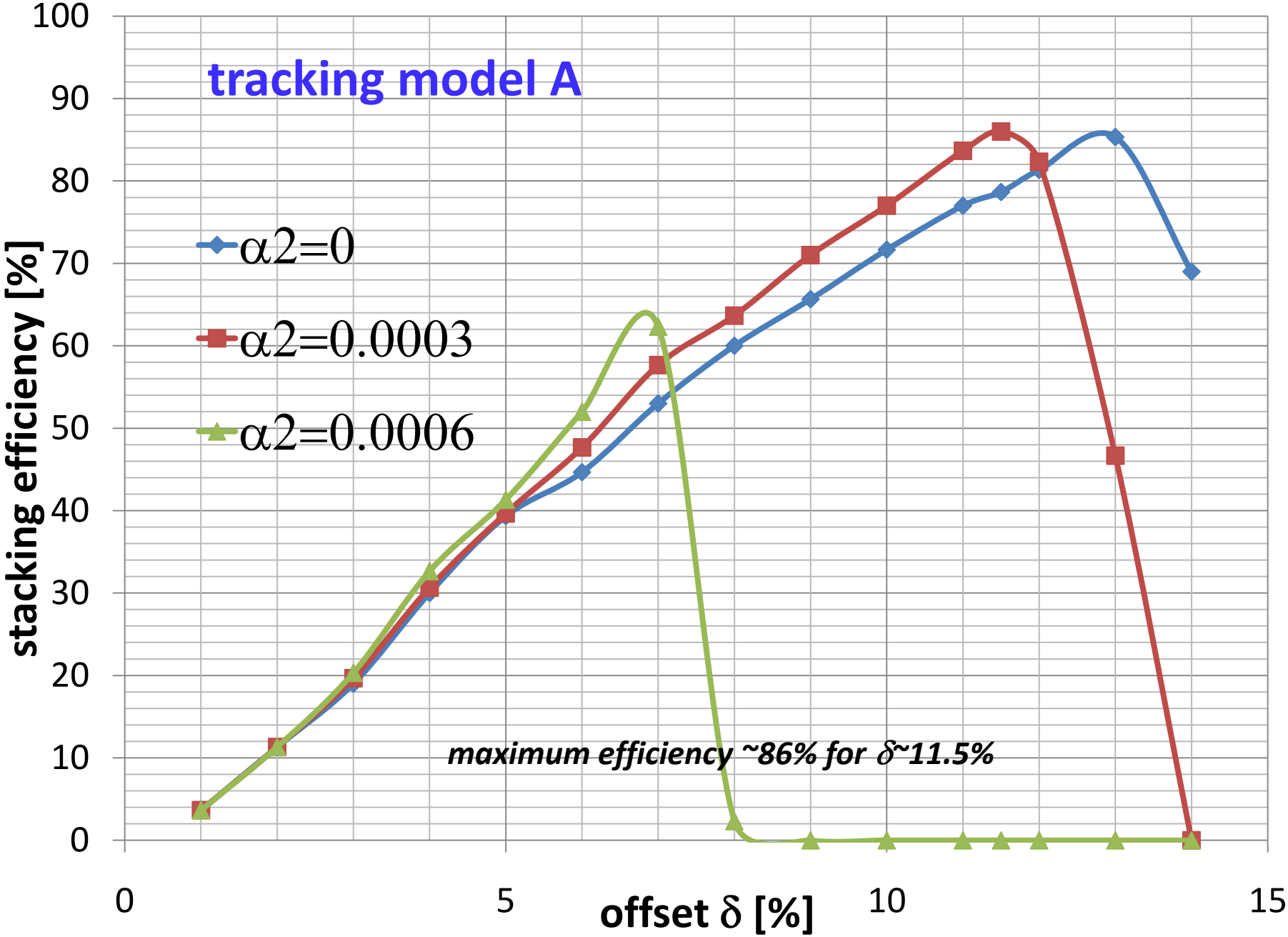
$$\delta_{new} = \delta_{old} e^{-T_0/\tau_{||}} + \xi \sqrt{2\left(1 - e^{-T_0/\tau_{||}}\right)}\, \sigma_{\delta,eq}$$

model B

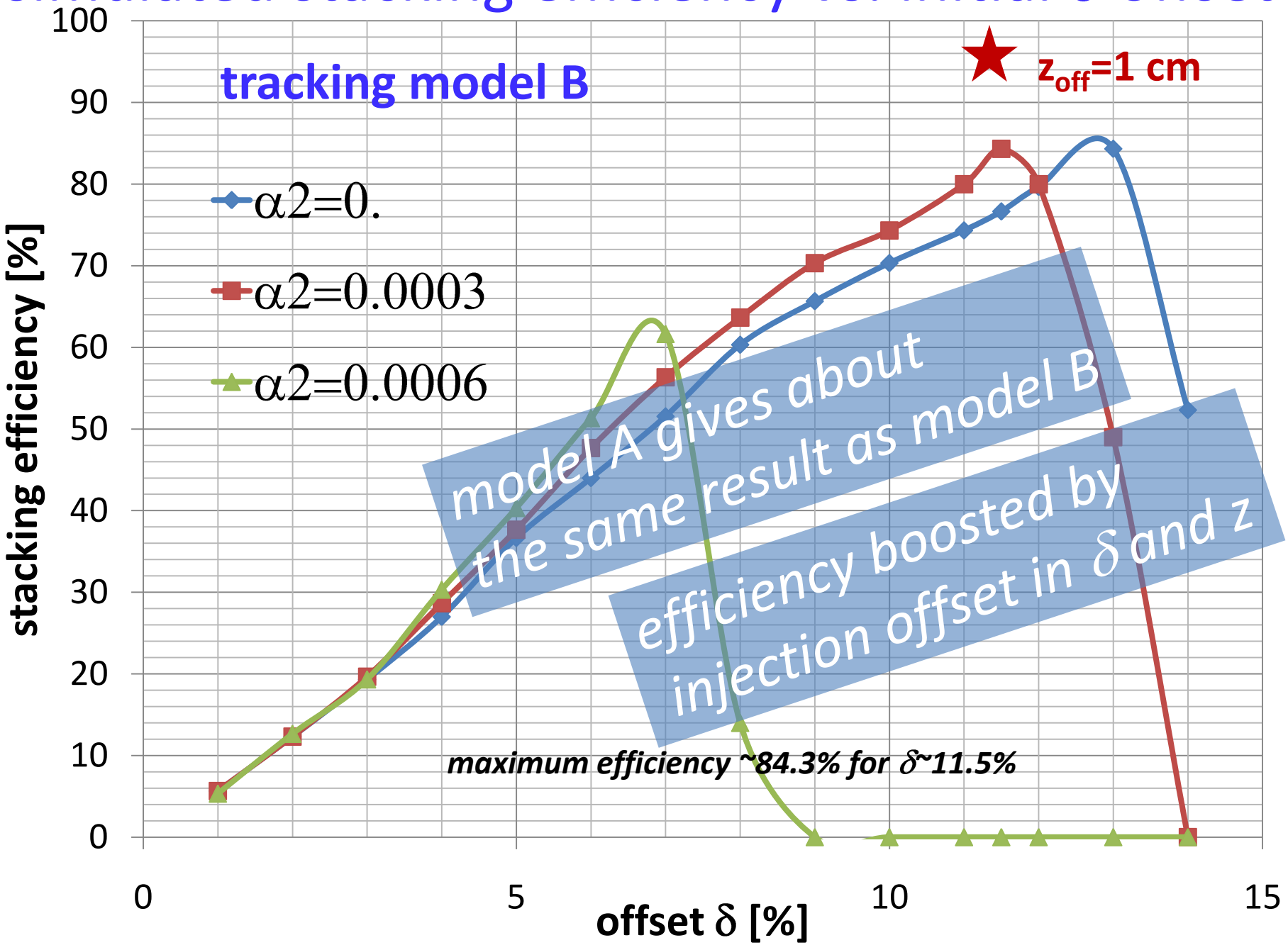
$$z_{new} = z_{old}$$

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

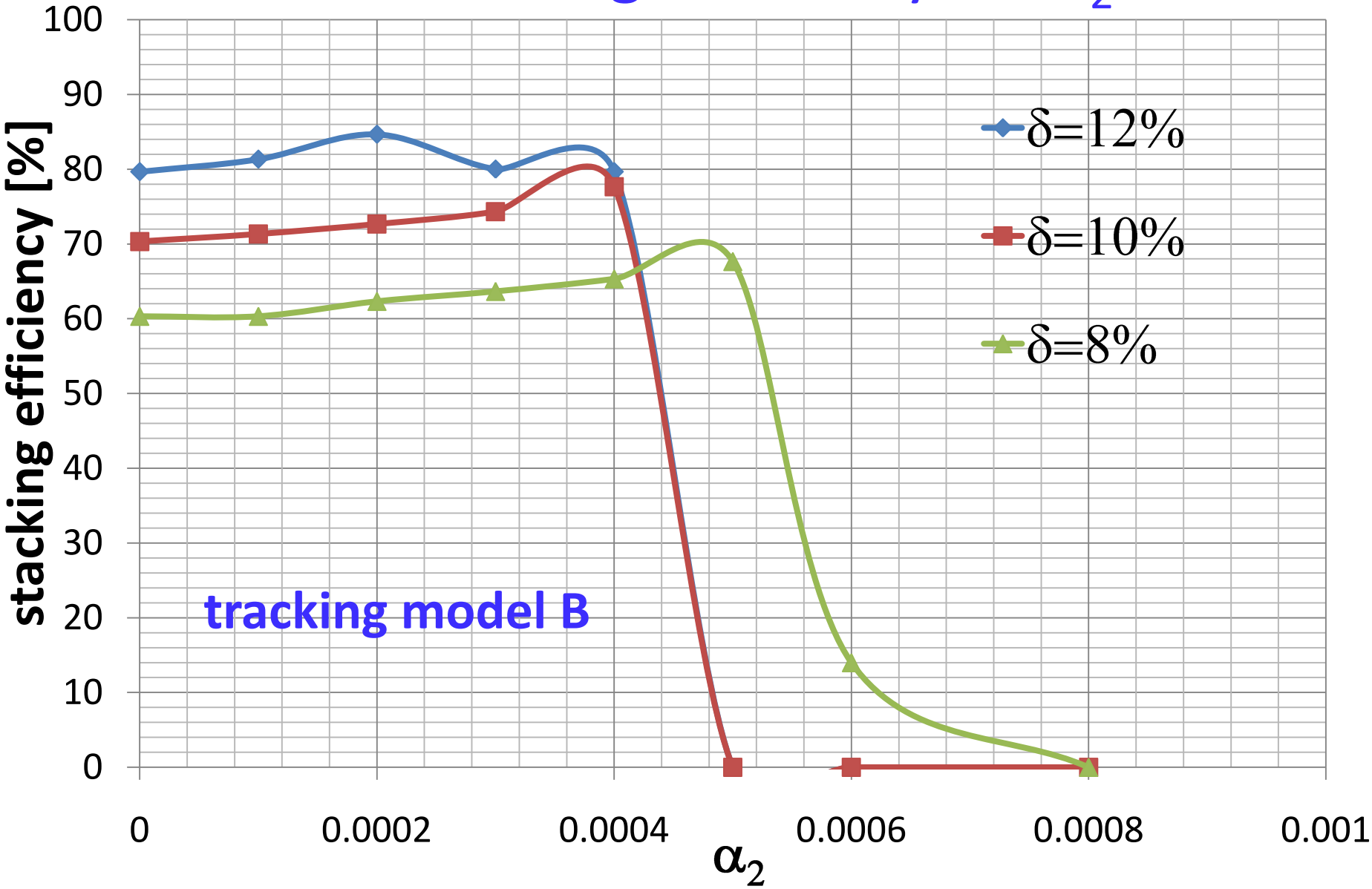
simulated stacking efficiency vs. initial δ offset



simulated stacking efficiency vs. initial δ offset



simulated stacking efficiency vs. α_2



Compton source megatable - 2008	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	2.4×10^{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}	6.65×10^{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)

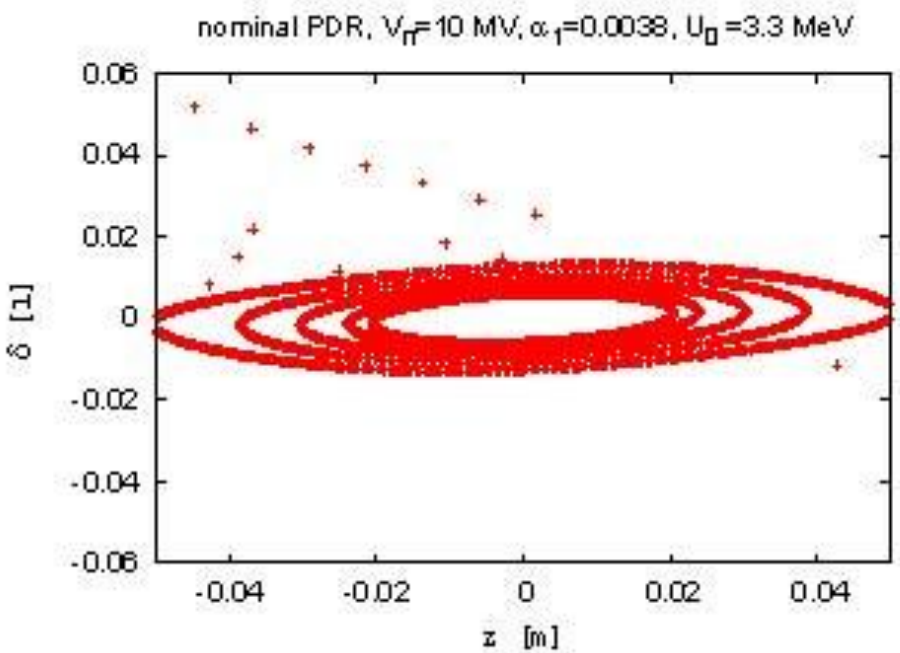
Compton source megatable - 2008	ILC-DR Snowmass '05 proposal	ILC 2008- **Compton "CR-B"**	ILC 2008- **Compton vers. "CERL-B"**	CLIC pre-DR 2007 (NLC 2004)	**CLIC 2008 (& CLIC CERL Compton vers.)**
transv. normalized edge emittance at inj. (10x rms)	0.05 rad-m	0.063 rad-m		0.063 rad-m	0.063 rad-m
transv. 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%**	**~95%**	**~94%**	not comp.	**95.5%**
final # positrons / bunch	**2×10^{10}**	**1.94×10^{10}**	**6×10^{10}**	not comp.	**5.1×10^{9}**

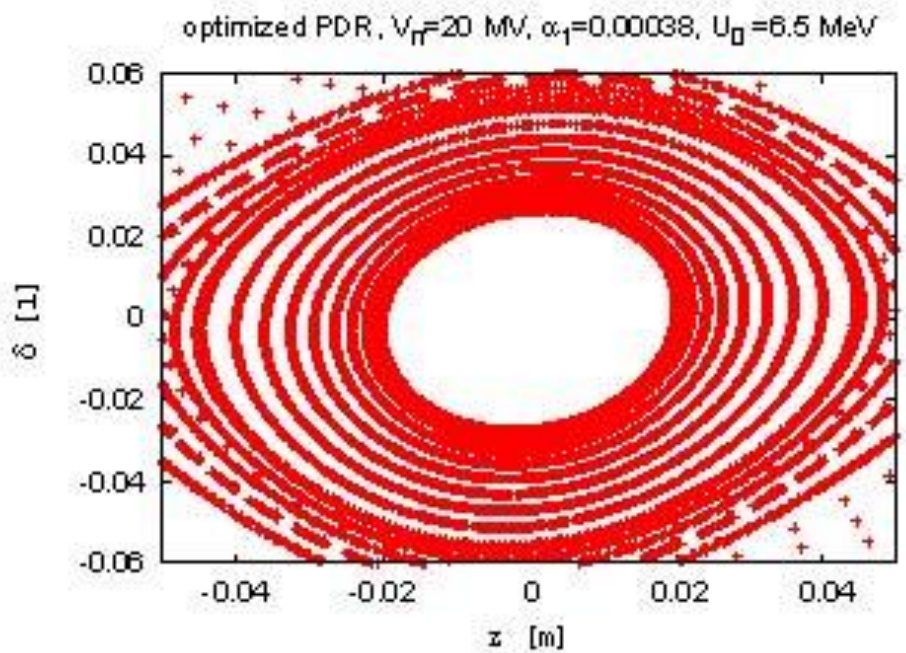
stacking is helped by:

- **short damping time**
- small longitudinal emittance
- **large ring momentum acceptance**

  (low α, low α_2, large V_{RF}, higher harmonic rf)
- energy pre-compression
- off-phase off-energy injection
- long time between injections
- long time for final damping

longitudinal phase space of CLIC PDR





PDR design

[F. Antoniou, Y. Papaphilippou]

optimized for stacking

[F.Z. et al, PAC2009]

condition for fast septum-bump scheme:

ΔE_{loss} (1 synchrotron period) > 4 σ_{E0}
or $\Delta E_{loss} > 4\,(\sigma_{E0} + E\,\sigma_{z0}\,Q_s/(\alpha_c C))$ (conservative)

in our example for CLIC PDR:

328 MeV (80 turns) > 8 MeV

easily fulfilled

no septum bump needed if:

ΔE (1 turn) > 4 σ_{E0}

static injection

conditions for static injection scheme :

ΔE_{loss} (1 synchrotron period)
$> 4\,(\sigma_{E0} + E\,\sigma_{z0}\,Q_s/(\alpha_c C))$ [e.g. ~ 0.02 E]

no septum bump needed if

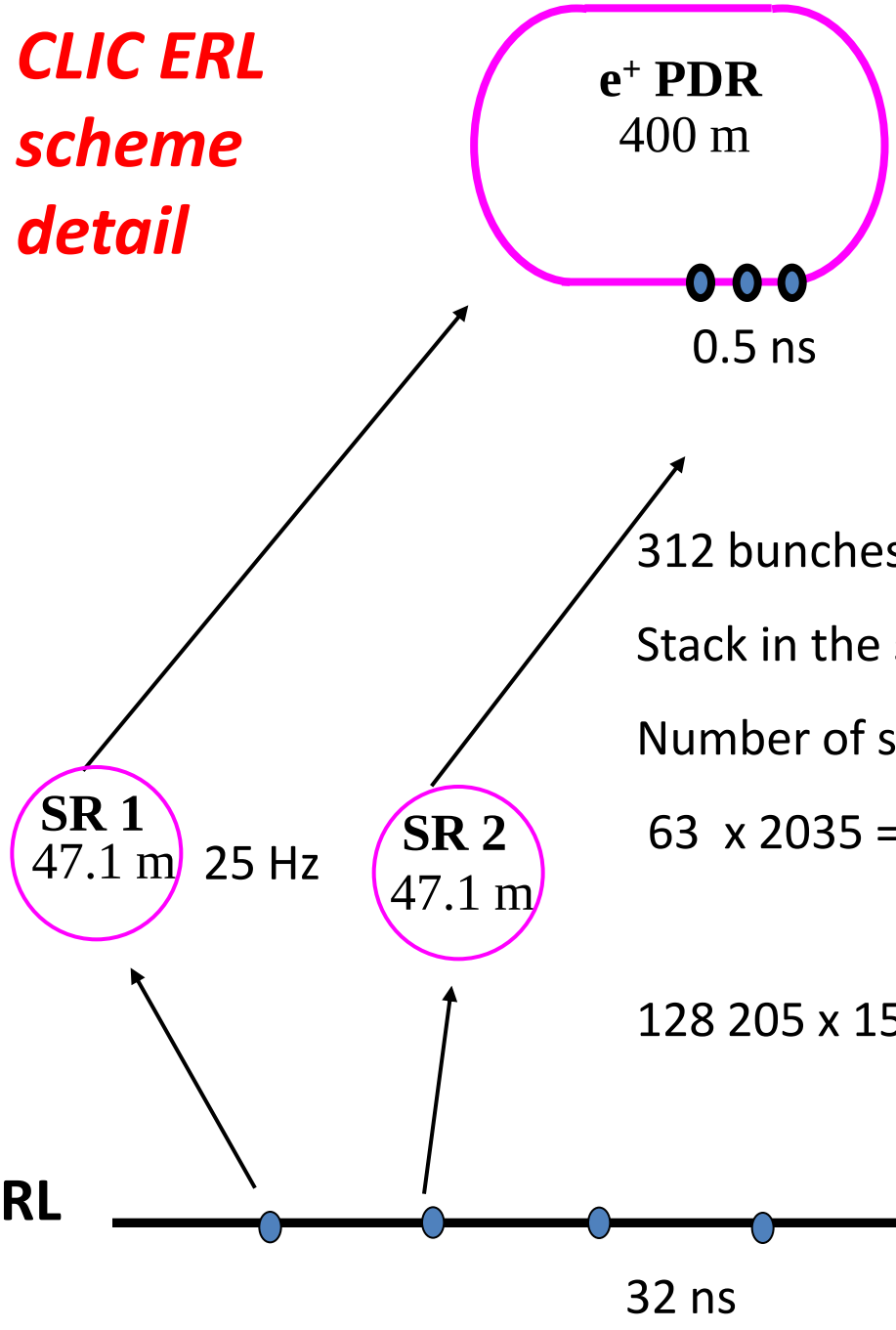
$\Delta E_{sync.osc.}$ (1 turn) ~ $2\pi\,Q_s\,\delta E_{inj} > 4\,\sigma_{E0}$

example for CLIC-ERL SRs:

$\Delta E_{loss/turn}$ = 3.5 MeV, σ_{E0}/E =0.0028,
σ_{z0}~7 mm, Q_s~0.05, $\delta E_{inj}/E$~0.081 (!)

both conditions fulfilled

CLIC ERL scheme detail



312 bunches / train

1 train / ring

50 Hz

throw away 2 bunches

312 bunches spaced by 0.5 ns => 156 ns / turn

Stack in the same bucket every 63th turn

Number of stacking in the same bucket: 2035

63 x 2035 = 128 205 turns

(64x2003=128192)

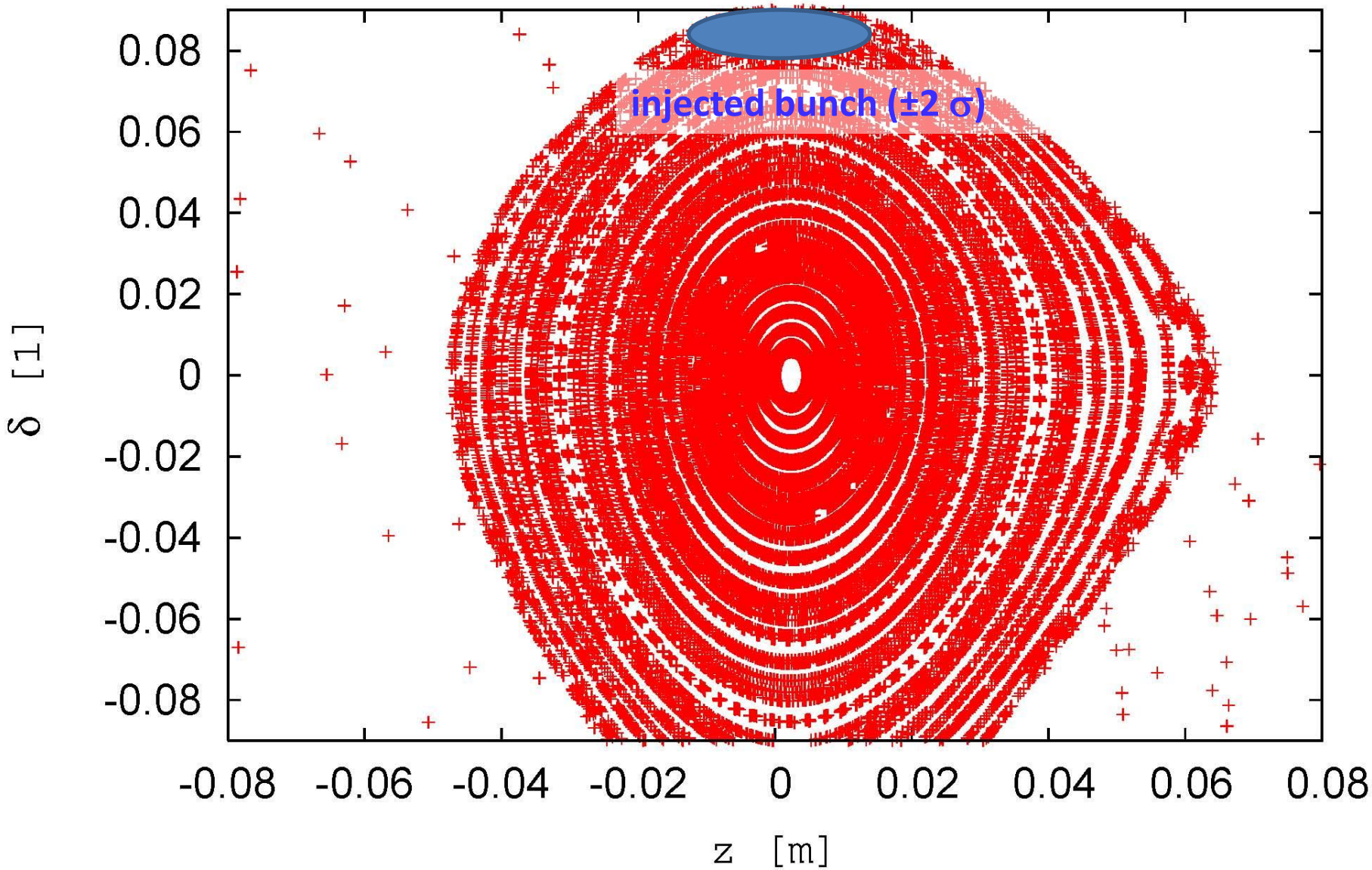
128 205 x 156 ns = 20 ms

(314 bunches, every 63th turn)

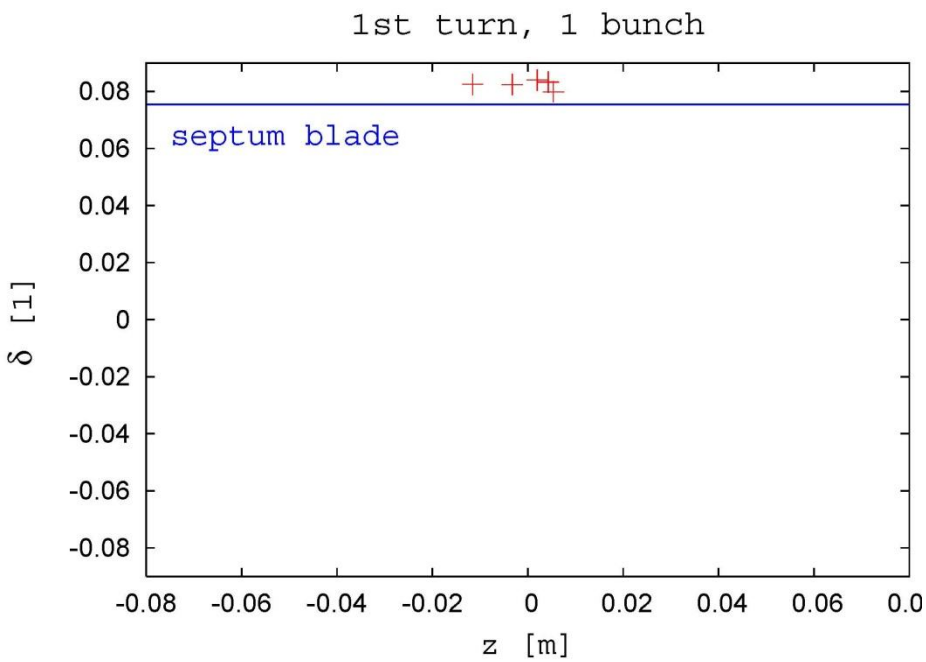
SLC Damping Ring as Prototype Stacking Ring	Units	SLC Damping Ring	CLIC SR1 and SR2 (for one ring)
Circumference	m	35.28	46.82
Energy	GeV	1.19	1
Charge at injection (1 / bunch)	10^9	50	0.0025
Charge at extraction (1/ bunch)	10^9	50	4.4
Norm. rms equil. emittance (x, y)	mm-mrad	30, 2	30, 2
Transverse damping times	ms	~3.7	0.09
Equilibrium bunch length	mm	6.5	4.0
Equilibrium energy spread	10^{-4}	9	12
Longitudinal damping time (ms)	ms	1.5	**0.045**
Momentum comp. factor (1st order)	-	0.0147	0.006
Momentum comp. factor (2nd order)	-	?	~0.024
RF voltage	MV	0.82	**35.0**
RF frequency	MHz	714	2000
Harmonic number		84	312
Synchrotron tune		0.012	**0.102**
Synchronous phase		6.7^o	5.7^o

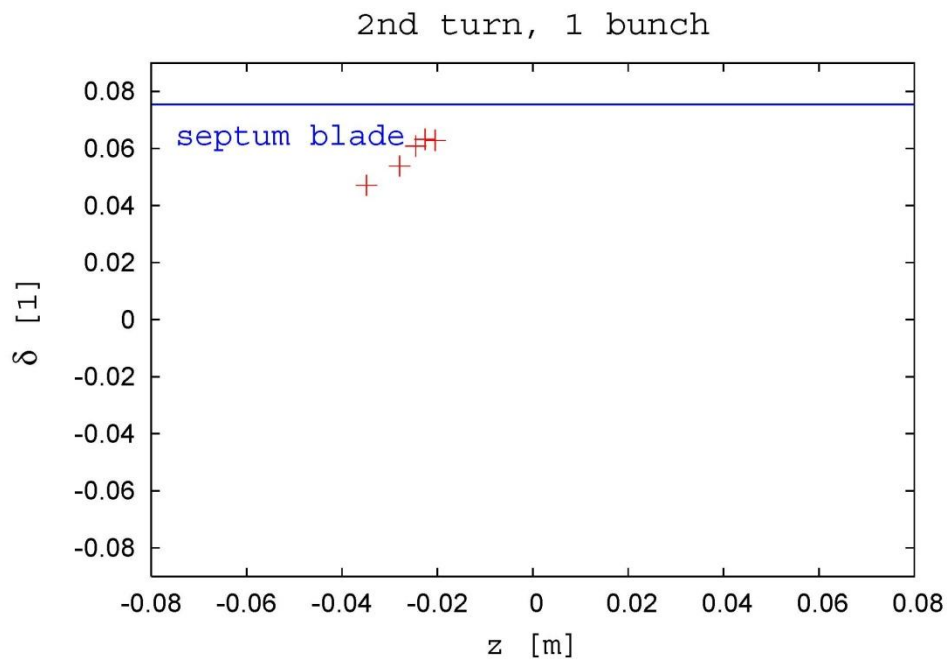
phase space of stacking ring

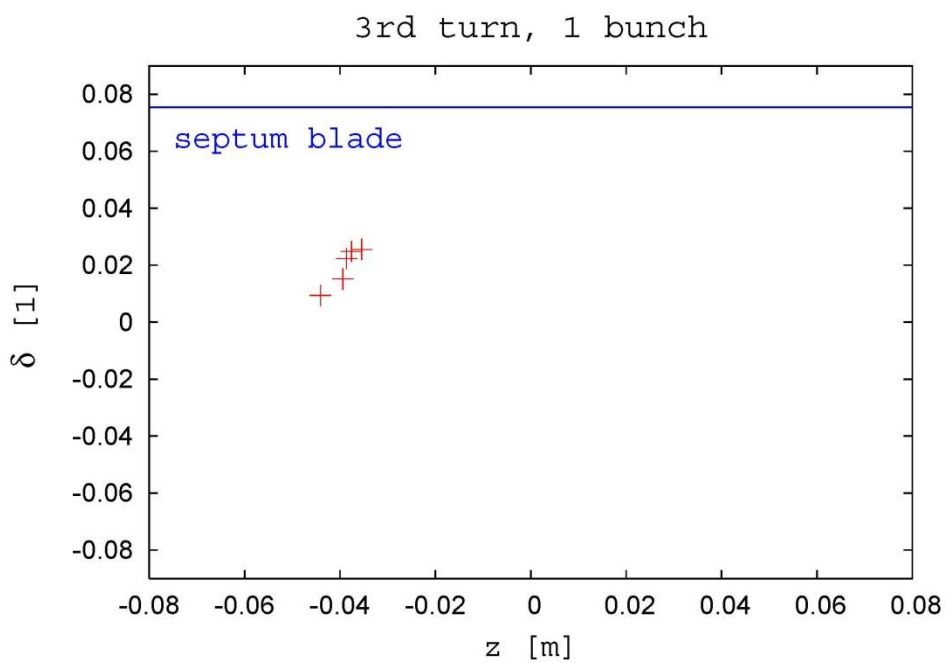
nominal SR, V_{rf}=35 MV, α_1=0.006, α_2=0.024, U_0 =3.5 MeV



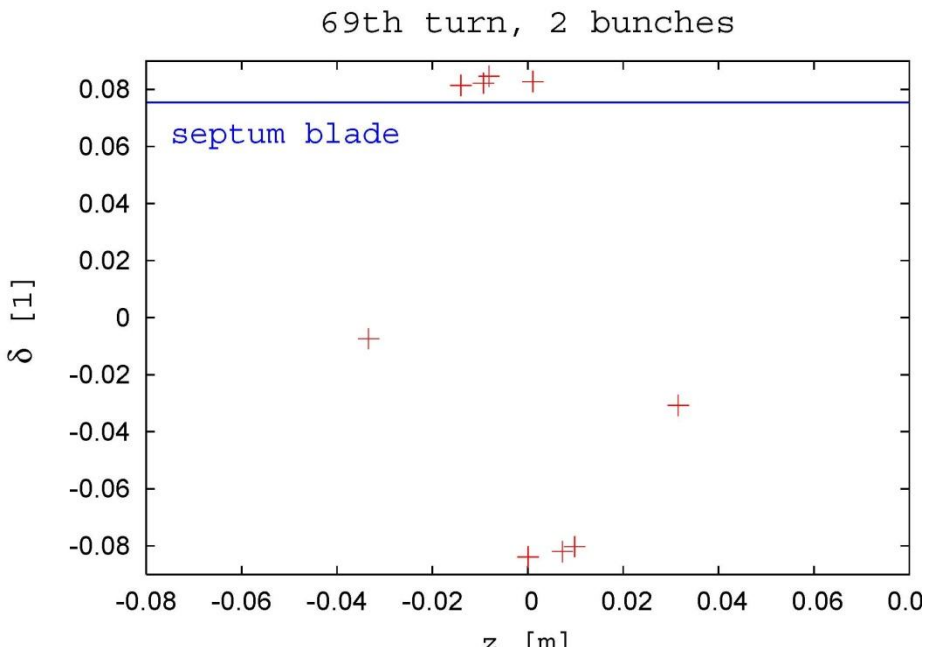
the first few turns after injection bunch #1

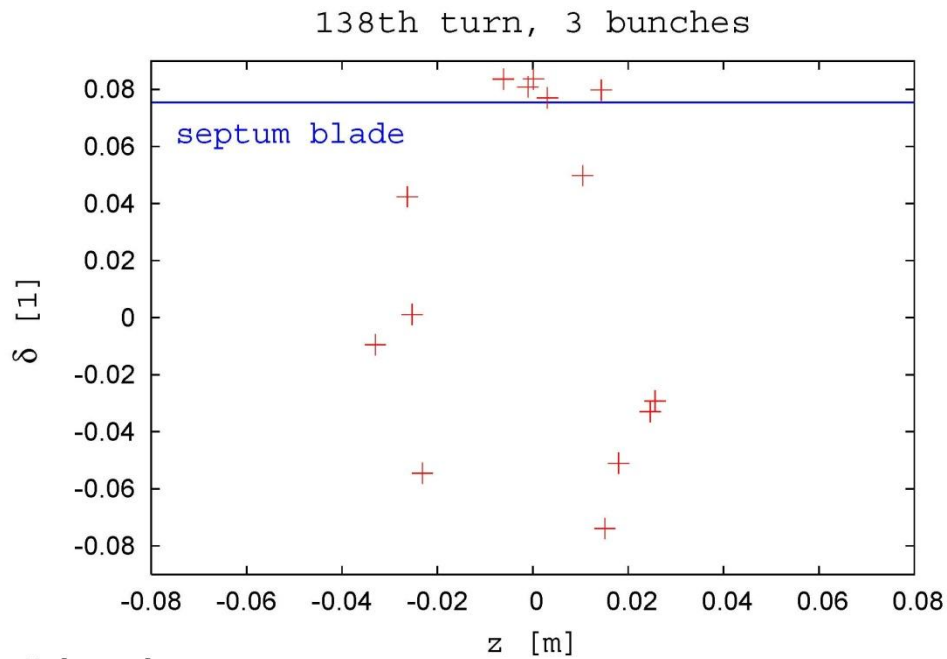


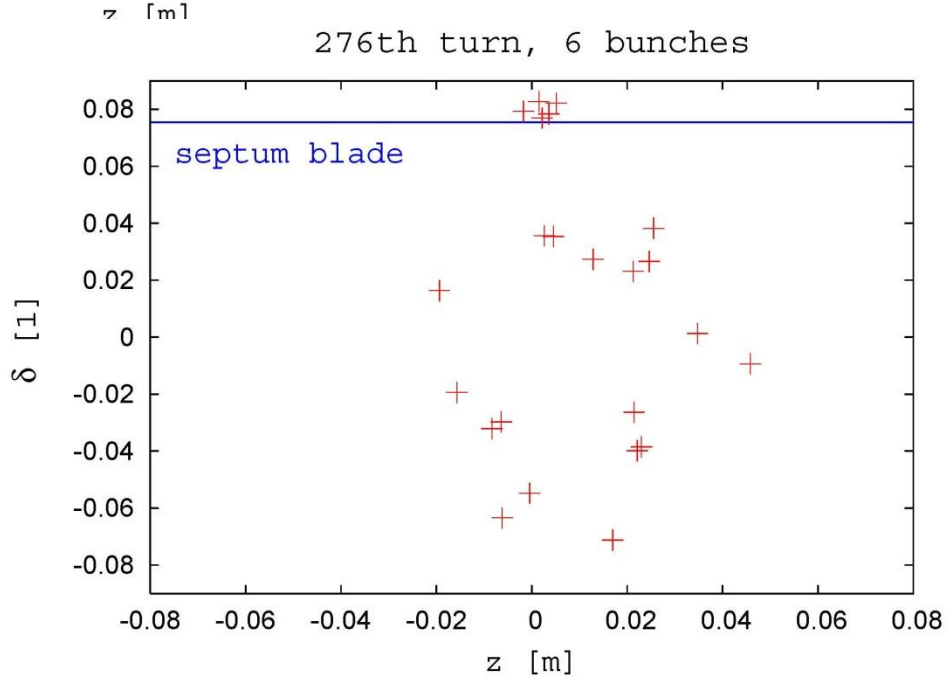




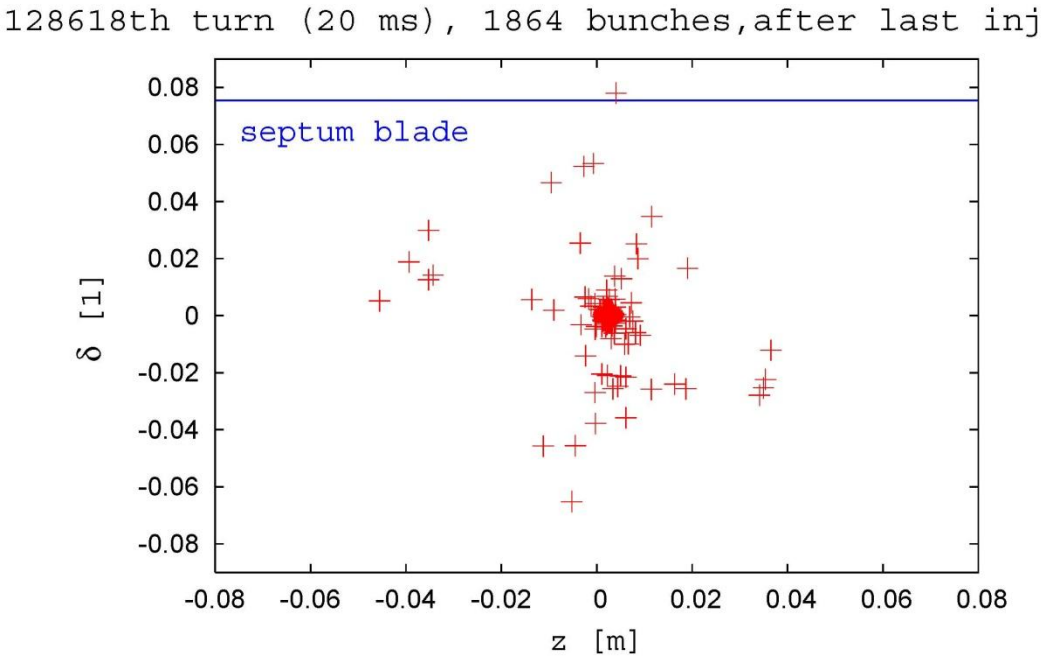
injecting bunches # 2, 3 and 6

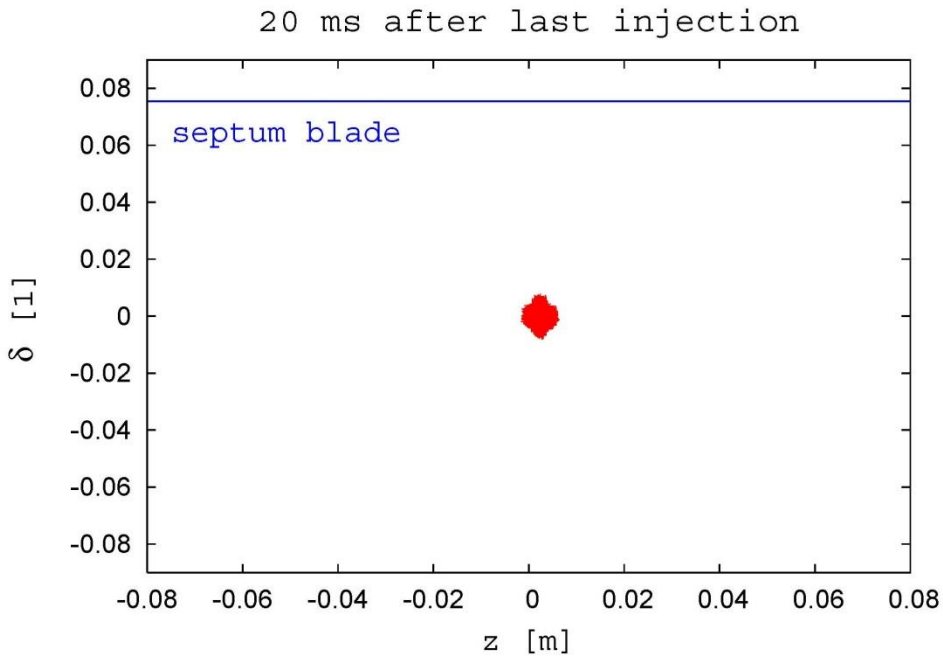






after injecting the last bunch (# 1864)

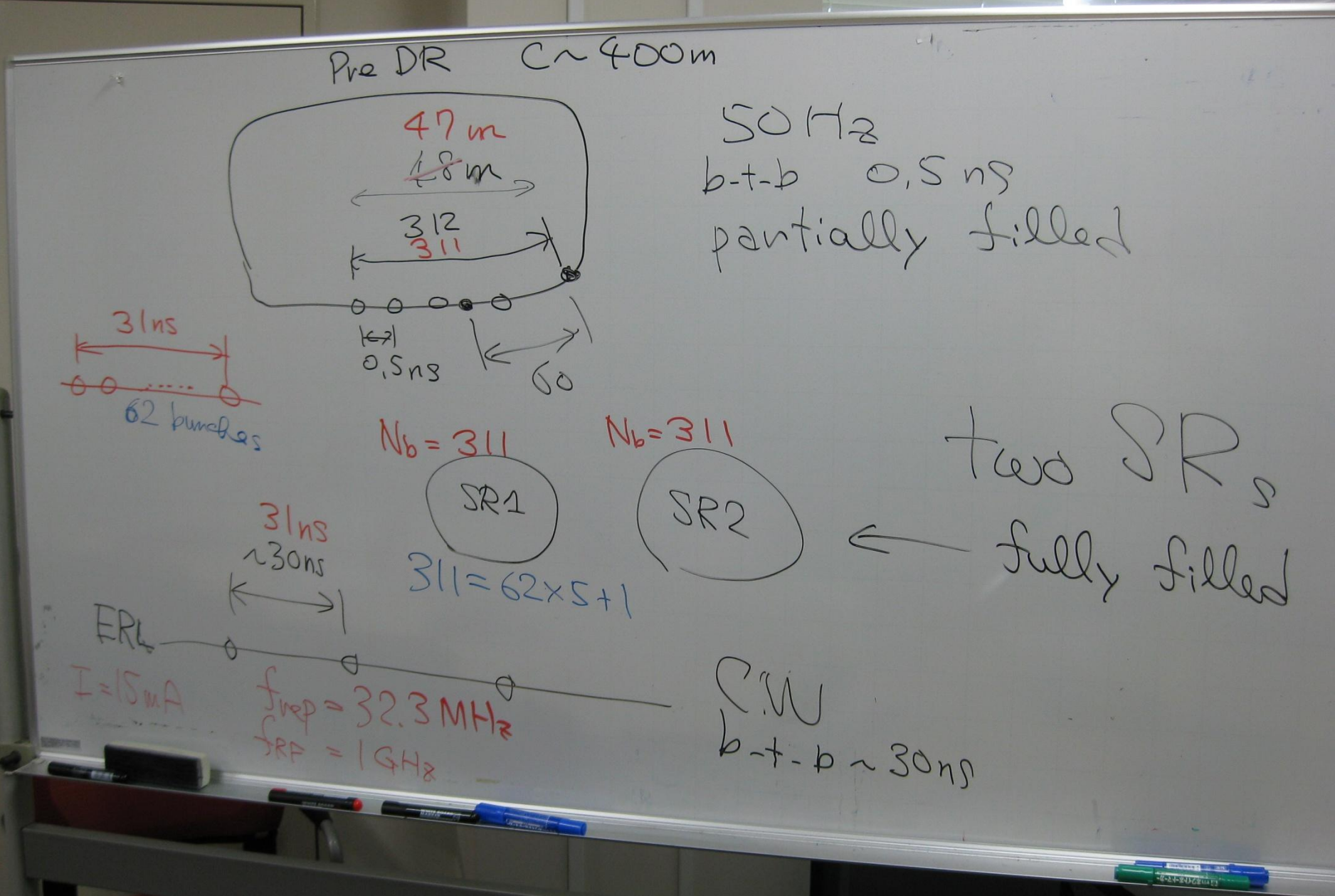




simulations summary

	# injections	$\tau_{\parallel}$ [ms]	σ_{δ} [MeV]	efficiency	
ILC-CR/DR	300	6.4	3	**95%**	
ILC-CERL/DR	1020	6.4	0.5	**94%**	***E* pre-compression**
CLIC-CR/PDR	80	0.58	2	**>95%**	***E* pre-compression**
CLIC-CERL/PDR	80	0.58	2	**>95%**	***E* pre-compression**
CLIC-CERL/SRs	~2000	**0.05**	2.8	**>95%**	**very short damping time**

“Face-to-face” meeting on polarized e+ source for CLIC with Urakawa san and Omori san, 8 July 2010, 14:00

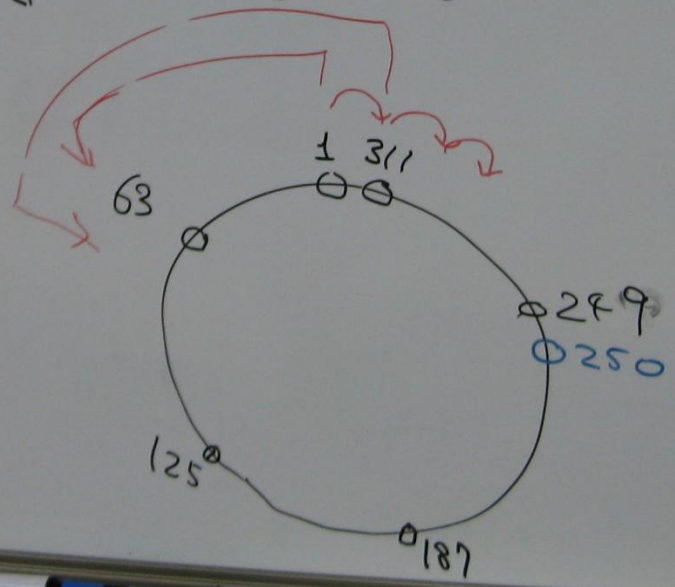


white board writings by Omori san

定表 (7月)

16	金	
17	土	
18	日	
19	月	
20	火	例定
21	水	16:30-17:30 定
22	木	
23	金	
24	土	
25	日	
26	月	
27	火	
28	水	16:30-17:30 AAT定例会議.
29	木	
30	金	
31	土	

1st	1	63	125	187	249
2nd	311	62	124	186	248
3rd	310	61	123	185	247
⋮					
61st	252	2	64	126	188
62nd	251	1	63	125	187
63rd	250	311	62	124	186



face-to-face discussion with Omori san and Urakawa san -

highlights:

- use **stacking-ring ring circumference equal to 63x5-1=314 [0.5 ns]** (throwing away two bunches) instead of 64x5+1=321 (throwing away nine bunches)
- use **two stacking rings with alternating injections (turn by turn)** to **relax the damping-time requirement by a factor of 2**
- **electron charge in Compton ERL** is a free parameter, keeping ERL beam current constant – ***this may be used to relax damping time!***

After the meeting Junji Urakawa asked the **Ukrainian collaborators Eugene Bulyak and Peter Gladkikh to design a CLIC (laser) stacking ring with the required short damping time (~100 μs)**.

They have made progress ever since
(several emails with Louis Rinolfi / week).

conclusions

fast bump and static injection schemes

simulated longitudinal stacking efficiency > 95% for all cases (ILC, CLIC; C-ERL, C-Ring; (P)DR, SRs)

large off-momentum dynamic aperture up to δ_{inj}~10% (!) is required

- off-momentum transverse dynamic aperture !?
- *E* pre-compression [R. Chehab] and/or fast damping (~50 μs for CLIC SRs)

open questions

lattice design for stacking rings (FFAG option?)

wiggler or laser and RF for stacking ring

stacking-optimized parameters for P(DR)s

impedance & stability for 10s of MV RF?
(K. Yokoya)

nonlinear wigglers damping large amplitudes?

laser-collision with dispersion
(E. Bulyak) → “Maxwell's demon”!

thank you for your attention!