CLIC scheme of polarized e+ source based on laser Compton scattering

Frank Zimmermann

POSIPOL2006, CERN, 26. April 2006

Thanks to
Eugene Bulyak, Peter Gladkikh,
Masao Kuriki, Klaus Moenig,
Tsunehiko Omori, Junji Urakawa,
Alessandro Variola

outline

(1) history of CLIC e+ source
(2) “new” Compton Scheme
(3) Snowmass’05 ILC Compton proposal
(4) CLIC-ILC differences
(5) CLIC scheme
(6) Compton ring
(7) laser system
(8) optical cavities
(9) e+ stacking, accumulator ring
(10) arguments for Compton source
(11) e- kick from laser collision
(12) summary

(1) history of CLIC e+ source

- 1997, conventional unpolarized source (L. Rinolfi); $W_{75}Re_{25}$ target hit by 2-GeV e- beam from linac; 67 kW beam power on target; yield 0.6 e+/e- at 200 MeV [CLIC Note 354]
- 2000, CLIC undulator source (T. Kamitani)

  L=150 m, B_u=1.76 T, λ_u=3.37 cm, E_1=20 MeV, ΔE=38.2 GeV at 1.5 TeV, addt'l rms energy spread σ_E/E~1.3×10^{-3}
- Snowmass 2001 (R. Assmann, F. Zimmermann)

  comparison of 4 schemes for producing polarized e+, identified old JLC Compton scheme as preferred option among the four [CLIC Note 501]
- 2005, new ILC Compton scheme (F. Zimmermann), adopted to CLIC parameters

(2) “new” Compton scheme

- ❖ polarized e+ source based on laser Compton scattering for the ILC was proposed at Snowmass 2005

- ❖ experimental tests at the ATF demonstrated production of 10^4 polarized e+ per bunch with 73%+/- 15%+/-19% polarization

- ❖ e+ stacking in the damping ring new feature proposed for the ILC

- ❖ γ stacking in high-finesse optical cavities relaxes laser requirements

Recent References

1) S. Araki et al, *"Conceptual Design of a Polarized Positron Source Based on Laser Compton Scattering – A Proposal Submitted to Snowmass 2005"*, KEK-Preprint 2005-60, CLIC Note 639, LAL 05-94 (2005)

→ ***ILC Compton scheme proposal at Snowmass'05***

2) T. Omori et al, *"Efficient Propagation of the Polarization from Laser Photons to Positrons Through Compton Scattering and Electron-Positron Pair Creation"*, Phys. Rev. Letters (2005)

→ ***Experimental Compton results from KEK/ATF***

3) E. Bulyak, P. Gladkikh, V. Skomorokhov, *"Synchrotron Dynamics in Compton X-Ray Ring with Nonlinear Compaction"*, in arXiv p. 5 physics/0505204v1 (2005)

→ ***Design of Compton Ring***

(3) Snowmass '05 proposal

proposal of a polarized e+ source based on laser Compton scattering for the ILC was presented at Snowmass 2005;
the same scheme can be adapted to CLIC

"POSIPOL collaboration"

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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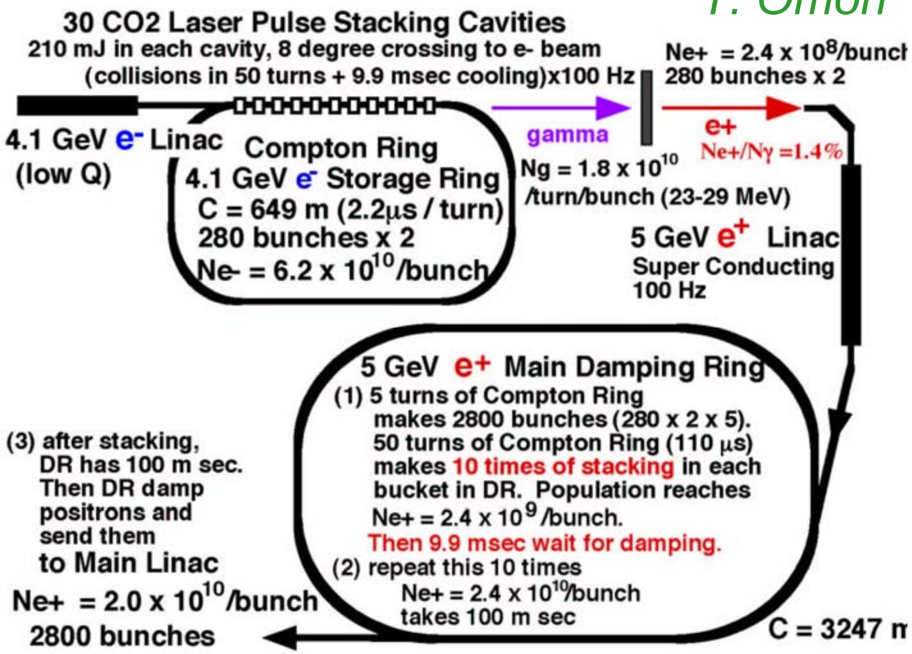
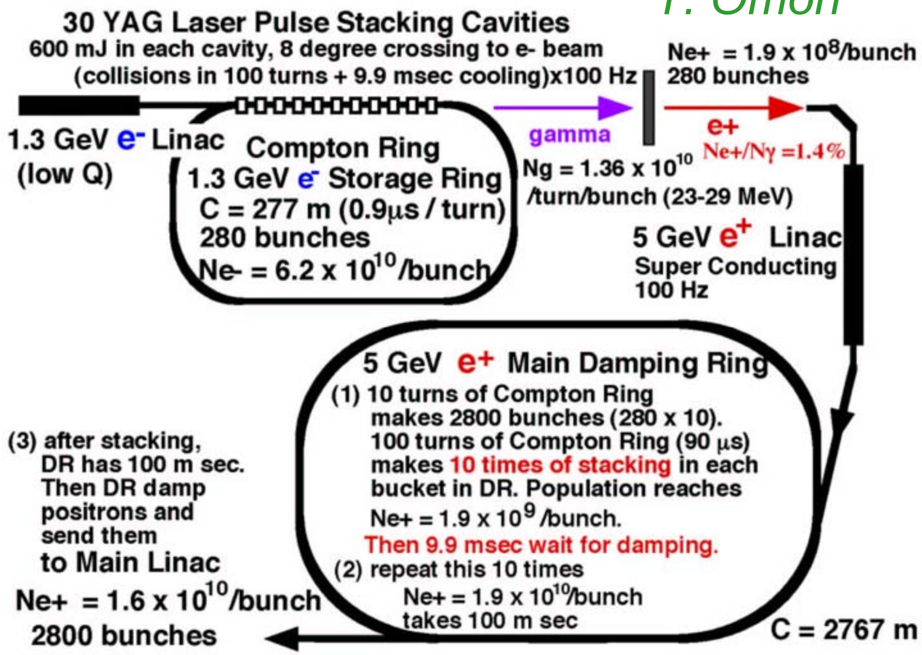
ILC pol. e+ source w. CO2 or YAG laser

- ILC Compton ring contains 30 coupled optical cavities
- 100 (50) turns in Compton ring result in 10x2800 bunches of pol. e+, accelerated in 100-Hz 5 GV pulsed s.c. linac
- bunches are stacked 10 times in each DR bucket; whole process is repeated 10x with 10-ms time for damping
- after 90 ms accumulation is completed; damping ring stores e+ bunches for 100 further ms before extraction

T. Omori

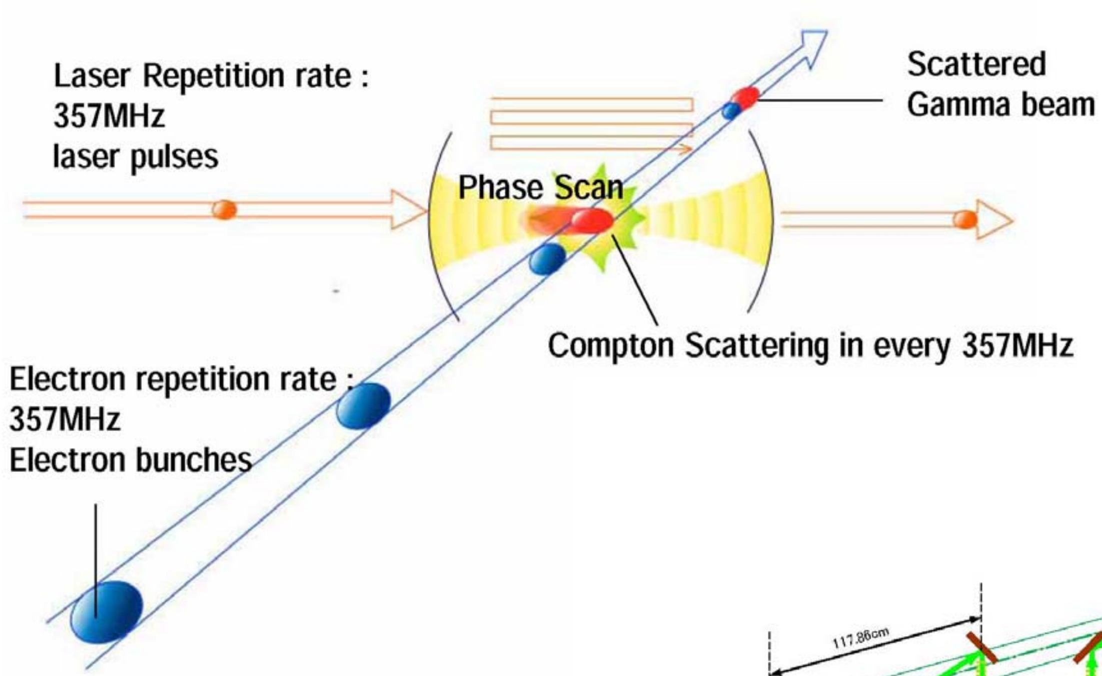


T. Omori

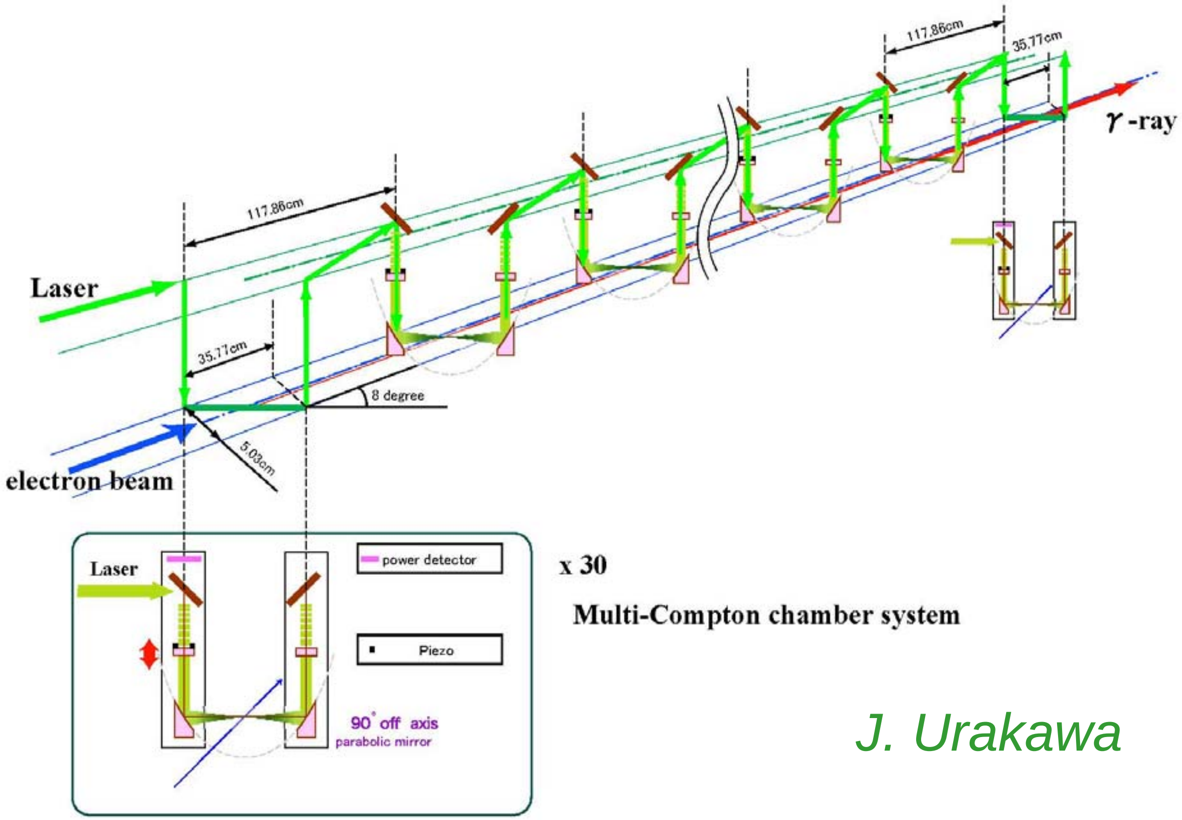


Compton IP for ILC

J. Urakawa



ILC multi-IP chamber



J. Urakawa

Compton-based e+ source for CLIC - ***Why?***

- either ILC or CLIC could be realized depending on physics case and cost

- CLIC differs from ILC in beam parameters, damping ring, bunch spacing, and repetition rate
  → several aspects of e+ source become easier

- recommendation by Yokoya san at NB'05 to use Compton source at CLIC (but not at ILC)

for simplicity consider only YAG laser case, since it facilitates injection linac & lowers Compton-ring energy

(4) CLIC – ILC differences

- beam structure: CLIC has a **smaller bunch charge** (about 10x less) and **less bunches per pulse** (about 20x less) → relaxed laser parameters

- **bunch spacing** in DR: **0.533 ns instead of 2.8 ns**
  → layout of optical cavities more challenging
  → multiple pulses stored in one cavity?

- 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 150 Hz instead of 5 Hz** for ILC

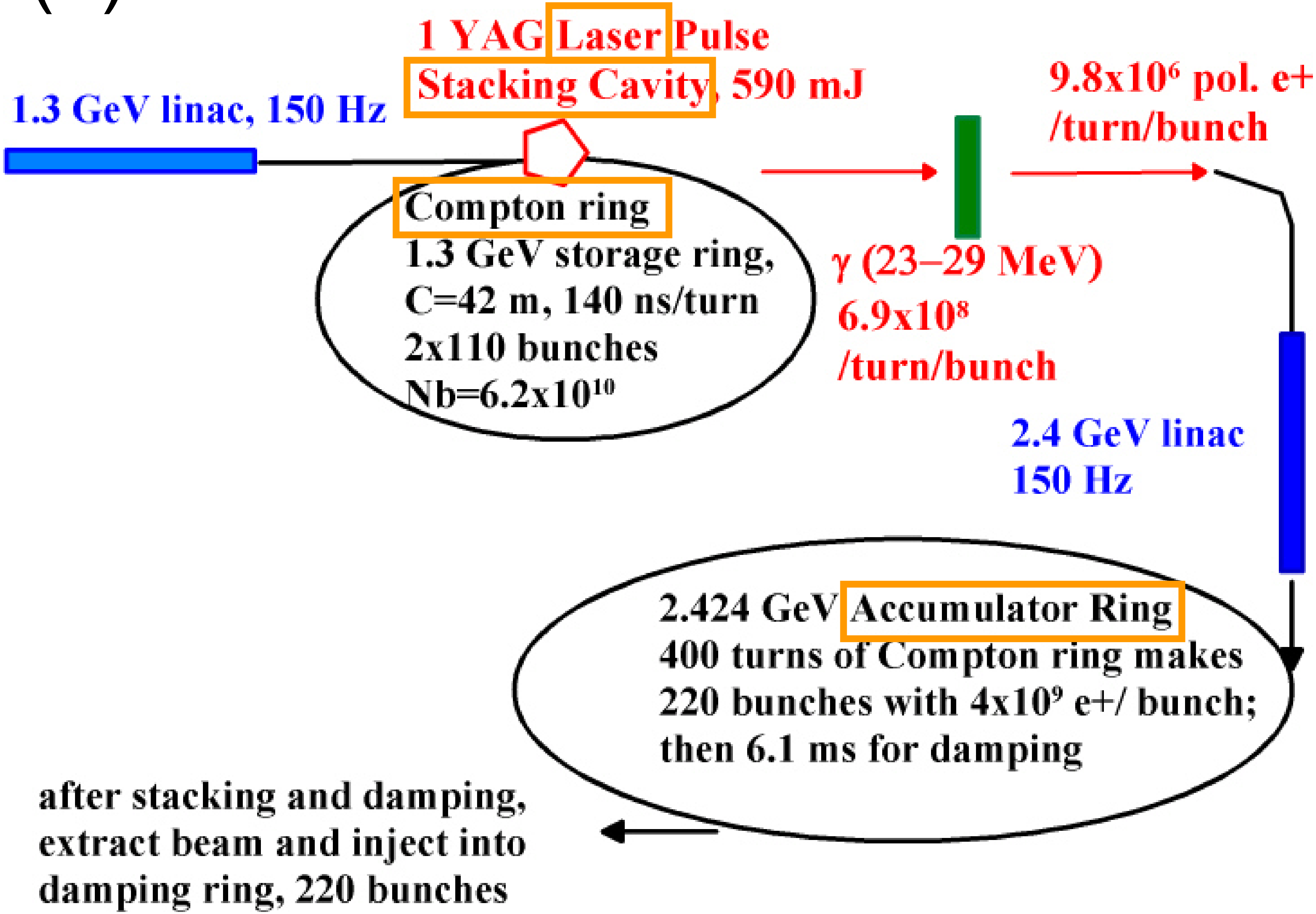
CLIC and ILC Damping Ring Parameters

parameter	CLIC	ILC (OTW/PPA)
energy	2.424 GeV	5 GeV
circumference	360 m	3230 m (or ~6 km)
bunch population	2.56×10^9	2×10^{10}
bunches/train	110	280
intertrain gap	flexible	80 missing bunches
# trains/pulse	2	10
bunch spacing	0.533 ns	3.077 ns
hor.norm.emittance	550 nm	8 μm
rf frequency	1.875 GHz	650 MHz
vert.norm. emittance	3 nm	20 nm
rms bunch length	1.54 mm	6 mm
rms energy spread	0.126%	0.14%
repetition rate	150 Hz	5 Hz

as consequence of these differences,
we can significantly reduce number of laser cavities in the CLIC Compton ring, ideally *to one* (a case which was already demonstrated at ATF)

this may considerably *simplify design of Compton ring, laser hardware, and operation*

(5) CLIC scheme



tentative polarized e+ source parameters for CLIC & ILC

parameter	CLIC	ILC
energy	1.3 GeV	1.3 GeV
circumference	42 m	277 m
rf frequency	1.875 GHz	650 MHz
bunch spacing	0.16 m	0.923 m
# bunches stored	220	280
bunch population	6.2×10^{10}	6.2×10^{10}
#optical cavities	1	30
photons/bunch/turn	2.8×10^{9}	5.8×10^{10}
photons 23.2 MeV-29 MeV	6.9×10^{8}	1.36×10^{10}
pol. e+ /bunch/turn	9.8×10^{6}	1.9×10^{8}
#injections/bunch	400	100
total # e+/pulse	$(5.6\text{-}8.6) \times 10^{11}$	5.3×10^{13}
total # e+/second	$(8.4\text{-}12.9) \times 10^{13}$	2.7×10^{14}

(6) Compton ring

e- bunch length at C-IP	5 mm?
e- rms hor./vert. beam size	25, 5 μm
e- beam energy	1.3 GeV
e- bunch charge	10 nC
laser photon energy	1.164 eV
rms laser radius	5 μm
rms laser pulse width	0.9 mm
laser pulse energy	592 mJ
no. of laser cavities	1
crossing angle	~10 degrees
photons in cavity pulse	3.2×10^{18}
polarized γs per bunch & turn	6.9×10^{8}
positron yield e+/γ	0.014

Compton parameters

$x=0.023$, $E_{\gamma,max}=30$ MeV

$$\sigma_C \approx \sigma_T = \frac{8\pi}{3} r_e^2$$

→ laser-photon scattering probability

in 1 collision < 10^{-8}

→ *pulse depletion from scattering negligible*

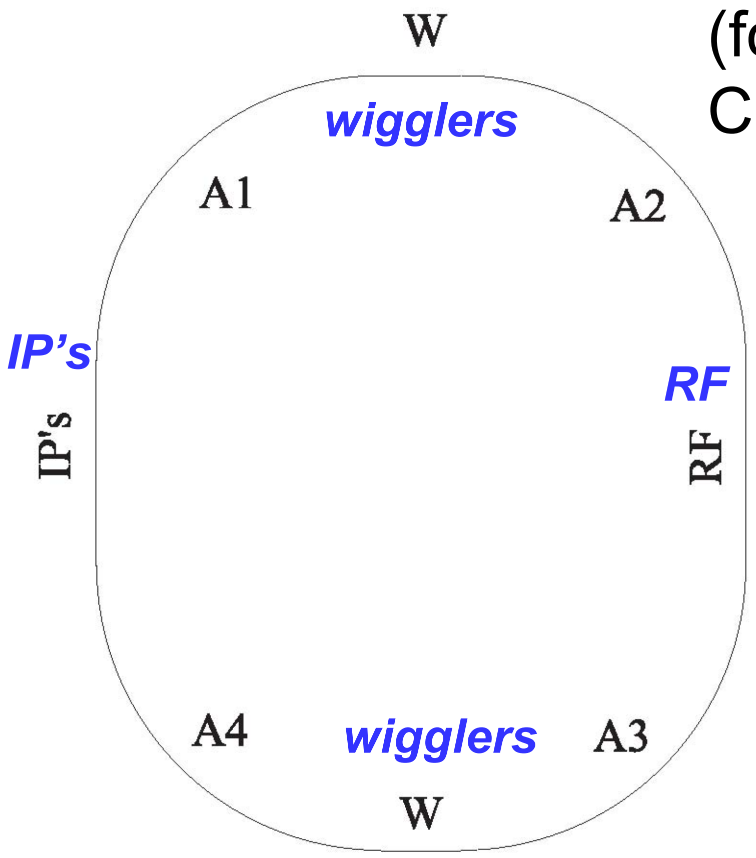
$$\xi^2 = \frac{2 n_\gamma r_e^2 \lambda}{\alpha} \approx 0.02 << 1$$

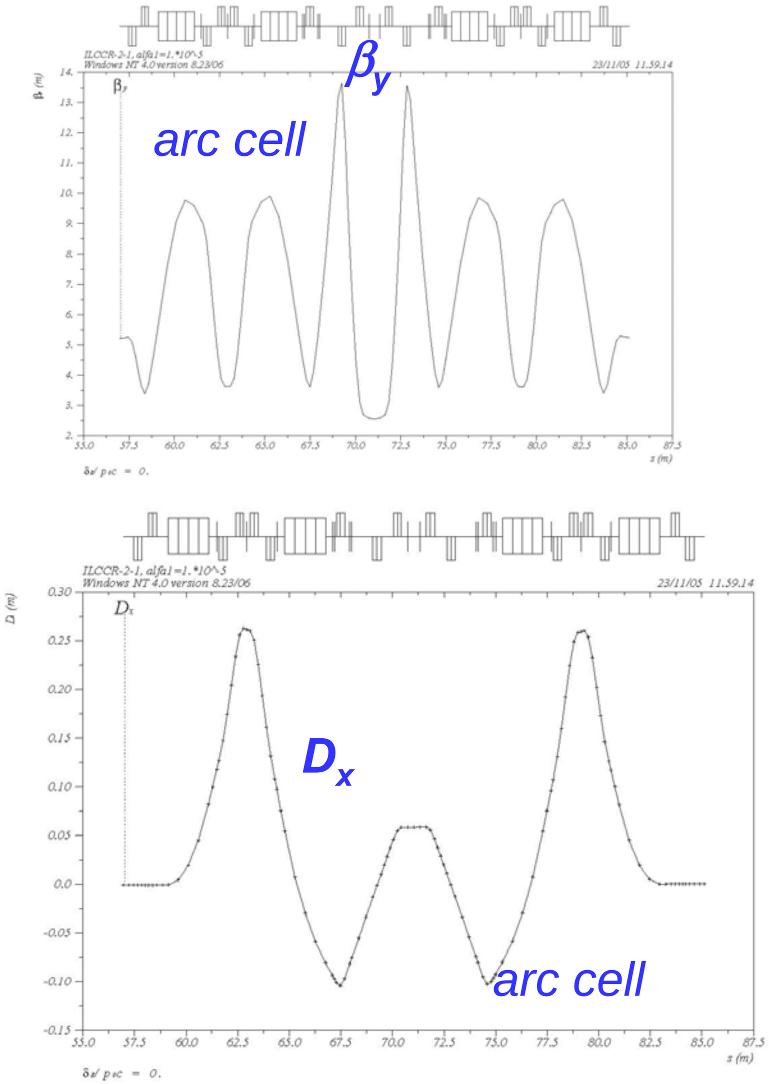
→ *nonlinear Compton effect not important*

Compton ring lattice design

P. Gladkikh
E. Bulyak

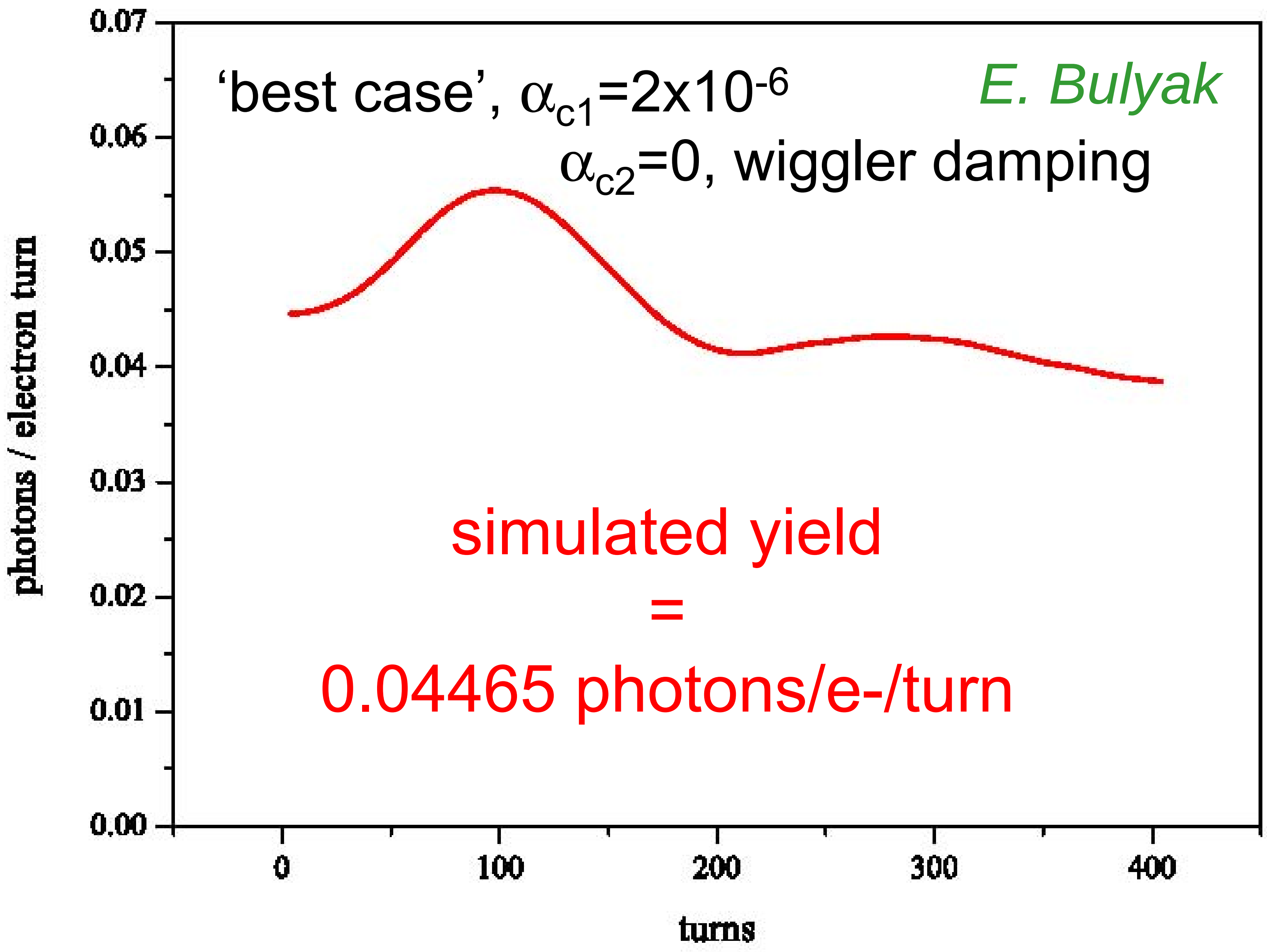
(for ILC, CO_2 laser)



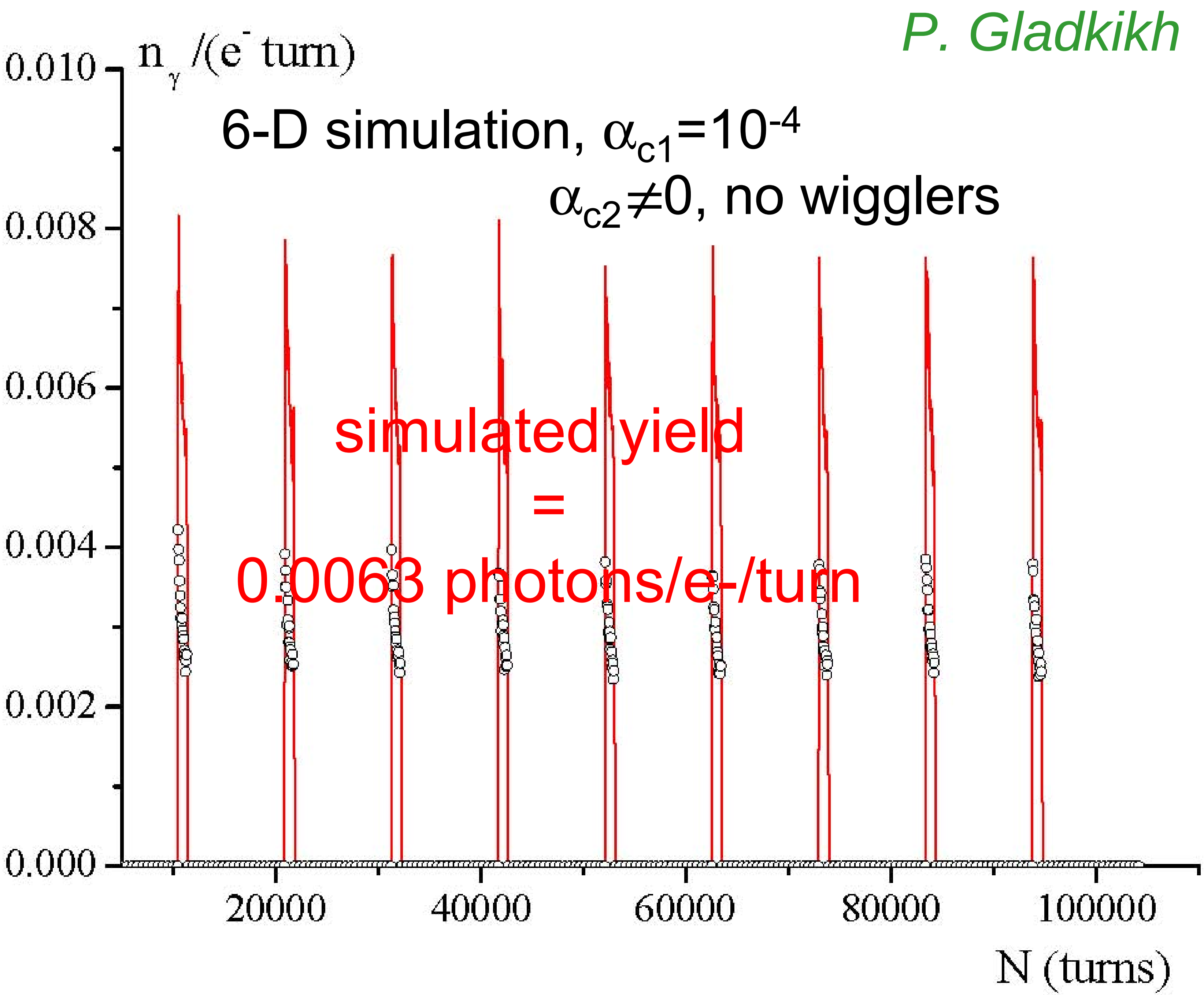


CLIC Compton ring parameters:

- for rms e- size ~ 10 μm, need C>100 m
- increased bunch spacing to 4 λ_{rf}~64 cm, allows crossing angle ϕ~10^o and reduces heat load on mirrors



simulated photon yield as a function of turn number for continuous interaction with the 590-mJ YAG laser pulse over 400 turns



P. Gladkikh
n_γ /(e⁻ turn)
6-D simulation, $\alpha_{c1}=10^{-4}$
$\alpha_{c2}\neq0$, no wigglers
simulated yield
=
0.0063 photons/e-/turn
0.010
0.008
0.006
0.004
0.002
0.000
20000
40000
60000
80000
100000
N (turns)

problem with CLIC YAG ring: large energy spread

P. Gladkikh

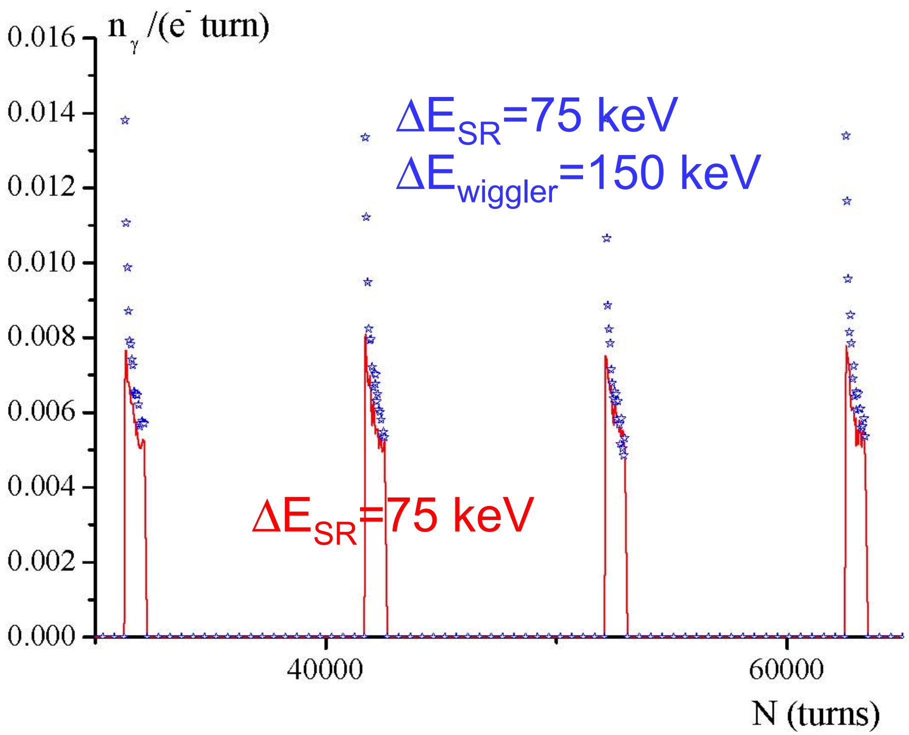
requires large momentum acceptance of 7-8%; reducing laser power & increasing turn number does not help

remedies:

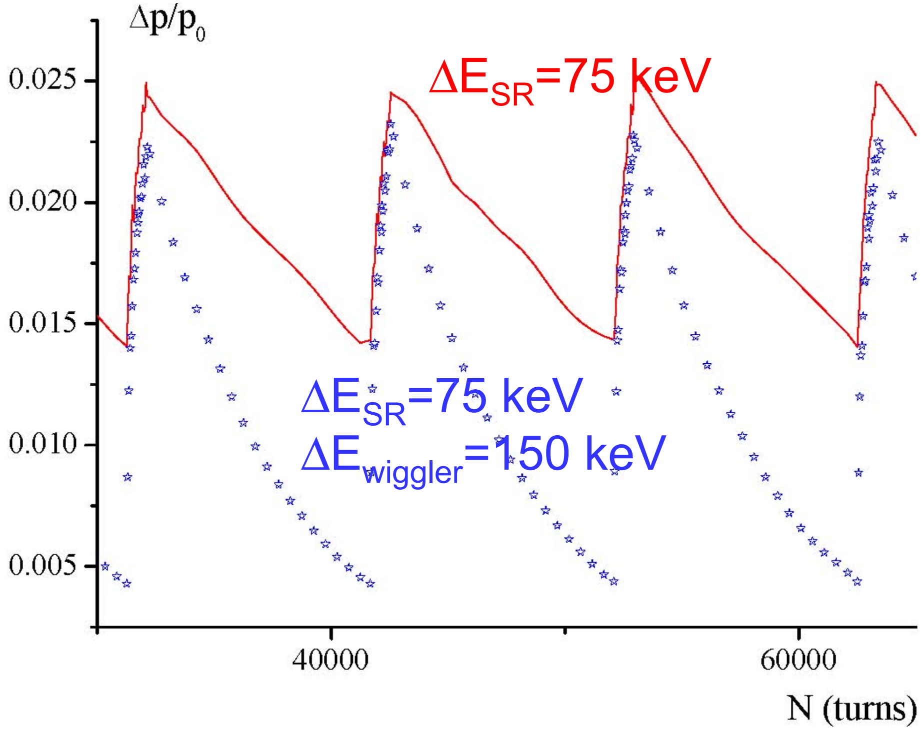
- decreasing turn number and increasing electron bunch number (leading to larger circumference)
- and/or introduction of additional damping using wigglers
- or CO_2 laser as for ILC (CLIC ring still easier)

additional damping by wigglers increases yield & reduces energy spread

number of photons



energy spread



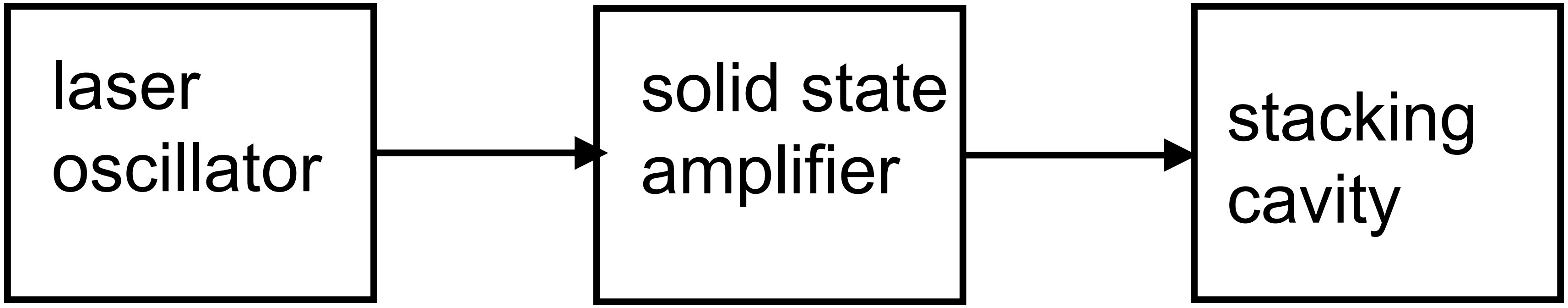
P. Gladkikh

many other improvements of Compton rings considered for more difficult ILC conditions; these would also boost CLIC performance:

- rf phase manipulation
- low & nonlinear momentum compaction
- pulsed momentum compaction lattice
- optimized lattice design

Eugene Bulyak & Peter Gladkikh

(7) laser system



170 nJ
10 ps FW
117 MHz
20 W

600 µJ,
gain 3500,
ATF: 10^4
(ATF rf gun)
CPMA

600 mJ,
factor 1000 enhancement,
ATF: 300 (pulsed laser wire)
ATF: 1000 (cw laser wire),
e.g., 16 pulses in 1.3-m cavity

J. Urakawa

tentative YAG laser parameters for CLIC & ILC

parameter	CLIC	ILC
laser pulse duration	57 μs	90 μs
rest between Compton cycles	6.1 ms	9.9 ms

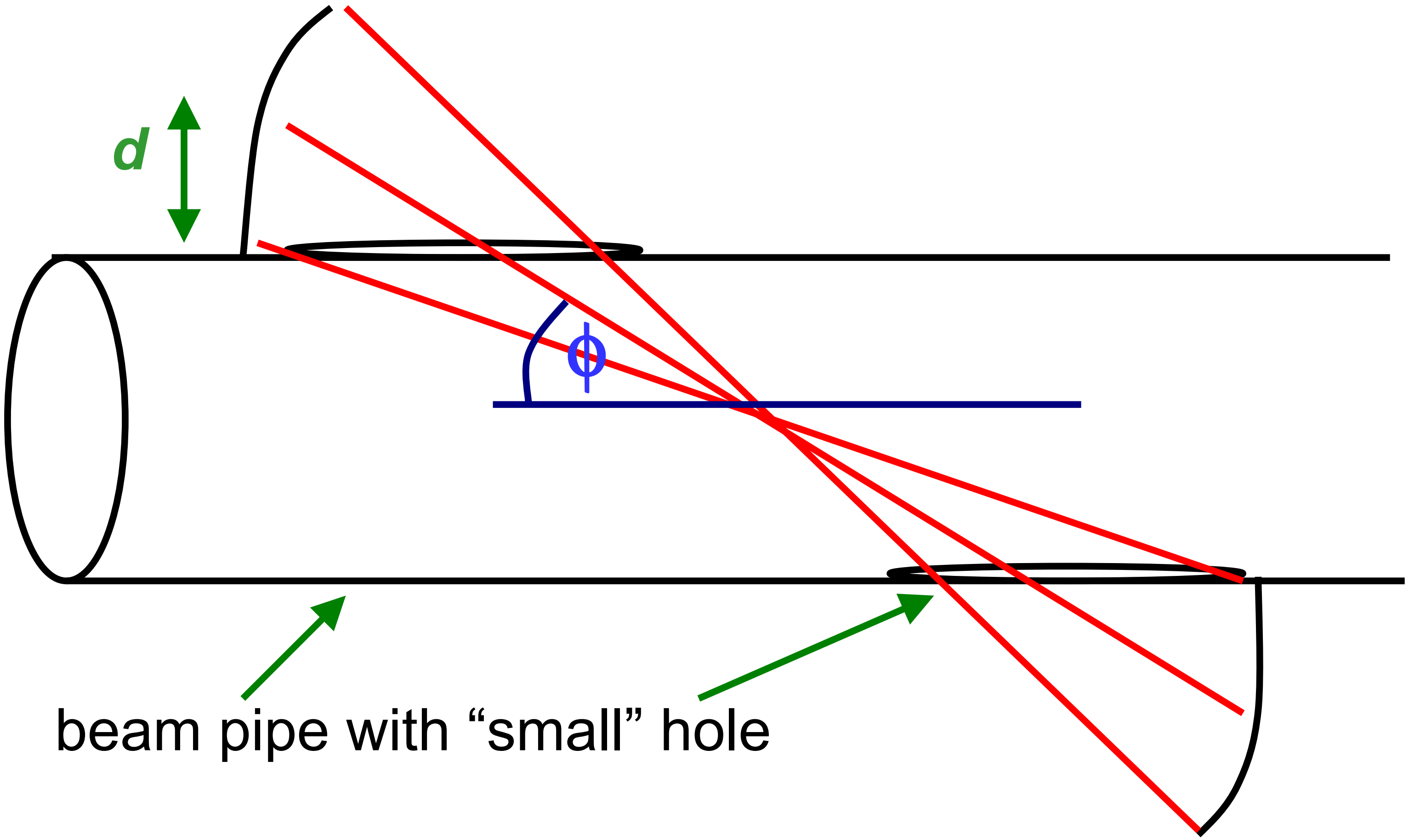
laser parameters: ATF (existing), JLC, ILC, CLIC

parameter	ATF	JLC '99	ILC	CLIC
pulse energy	0.1 mJ (rf gun) 400 mJ (e+)	350 mJ	6 mJ 2.1 mJ	0.6 mJ
pulses / second	~1200, 3	7×10^5	4.2×10^7?	1.3×10^7
type	YAG YAG (2nd)	CO2	YAG CO2	YAG
average total power	0.12 W? 1.2 W?	245 kW	250 kW 88 kW	8 kW

laser options

- YAG laser with pulse energy >0.6 mJ & smaller quality factor for optical cavity
- CO_2 laser with 0.21 mJ / pulse (alternative ILC scheme)
- continuous mode laser operation (fiber laser?) at ~50 MHz with 10 μJ / pulse and higher quality factor 10^4-10^5 (LAL) *A. Variola*
- feedback on laser (LAL) and/or on optical cavity (KEK)

(8) optical cavity



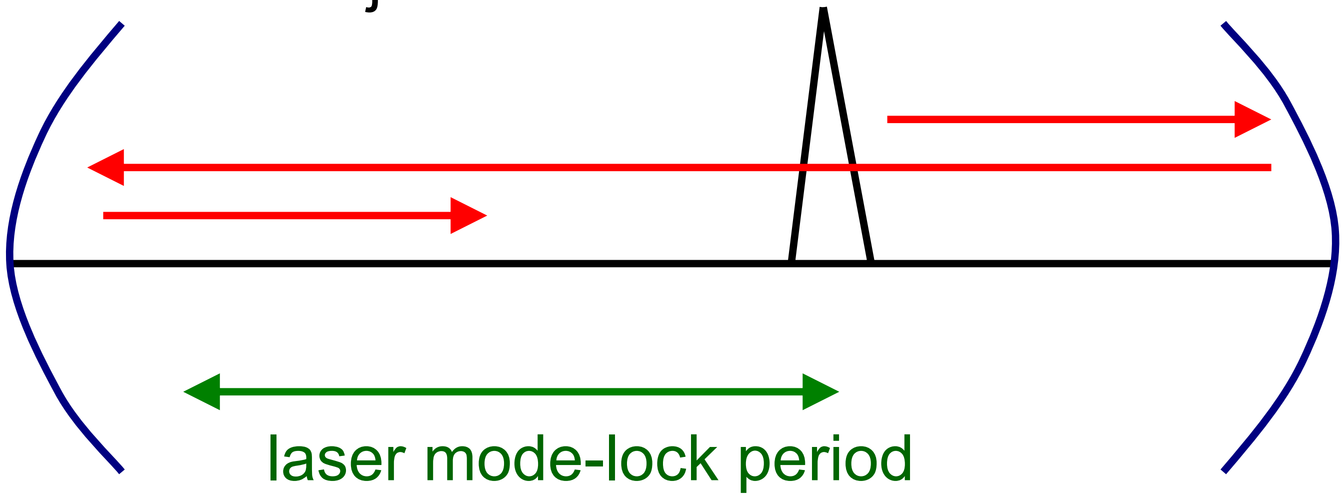
cavity length $l \sim d/\phi$

$d \sim 25$ mm, $\phi \sim 10^{o} \rightarrow l \sim 28$ cm
(3-4 pulses)

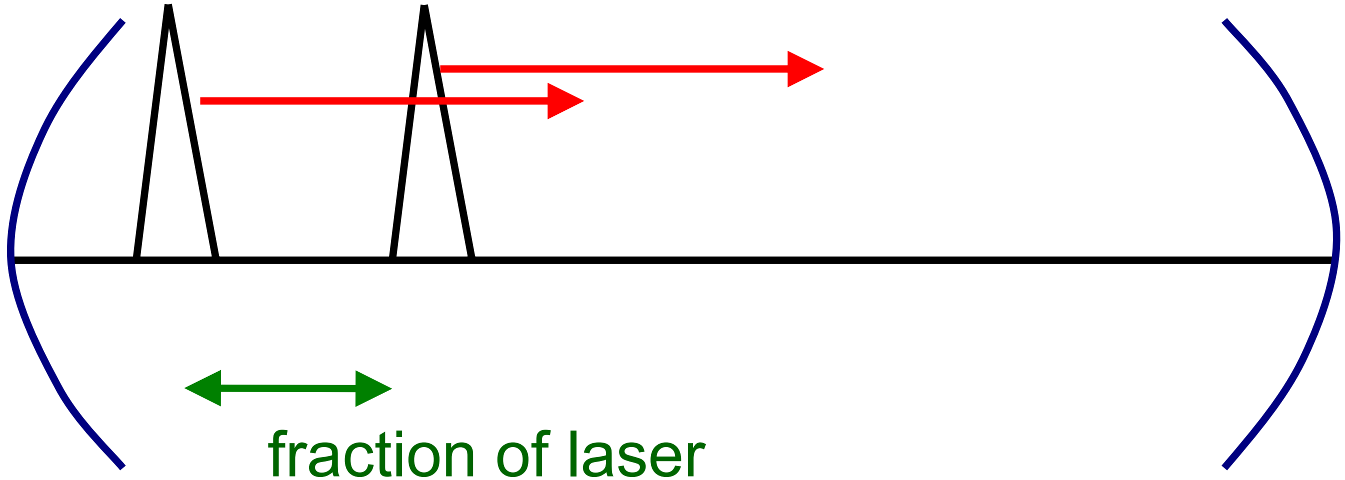
J. Urakawa
KEK/ATF scheme

laser frequency multiplication

1st laser bunch injected



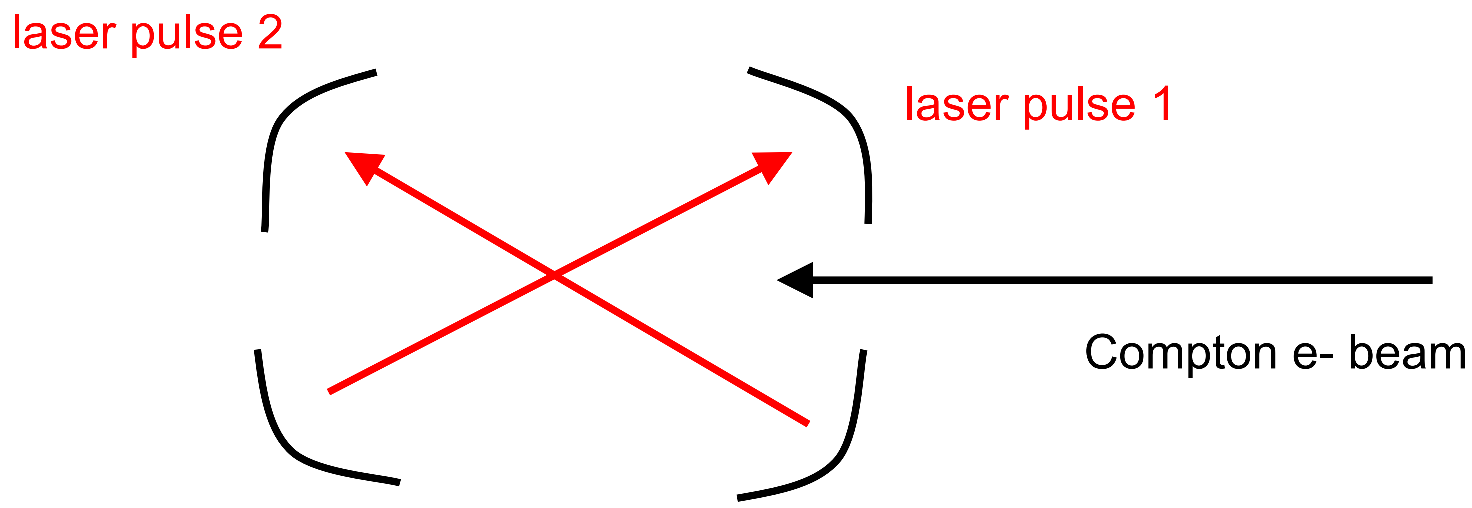
nth laser bunch injected



fraction of laser
mode-lock period
~0.533 ns

(note: short distance not
needed if we increase bunch
spacing in Compton ring)

another method for short bunch spacing



higher collision frequency with independent laser pulses in several larger optical cavities

A. Variola, LAL

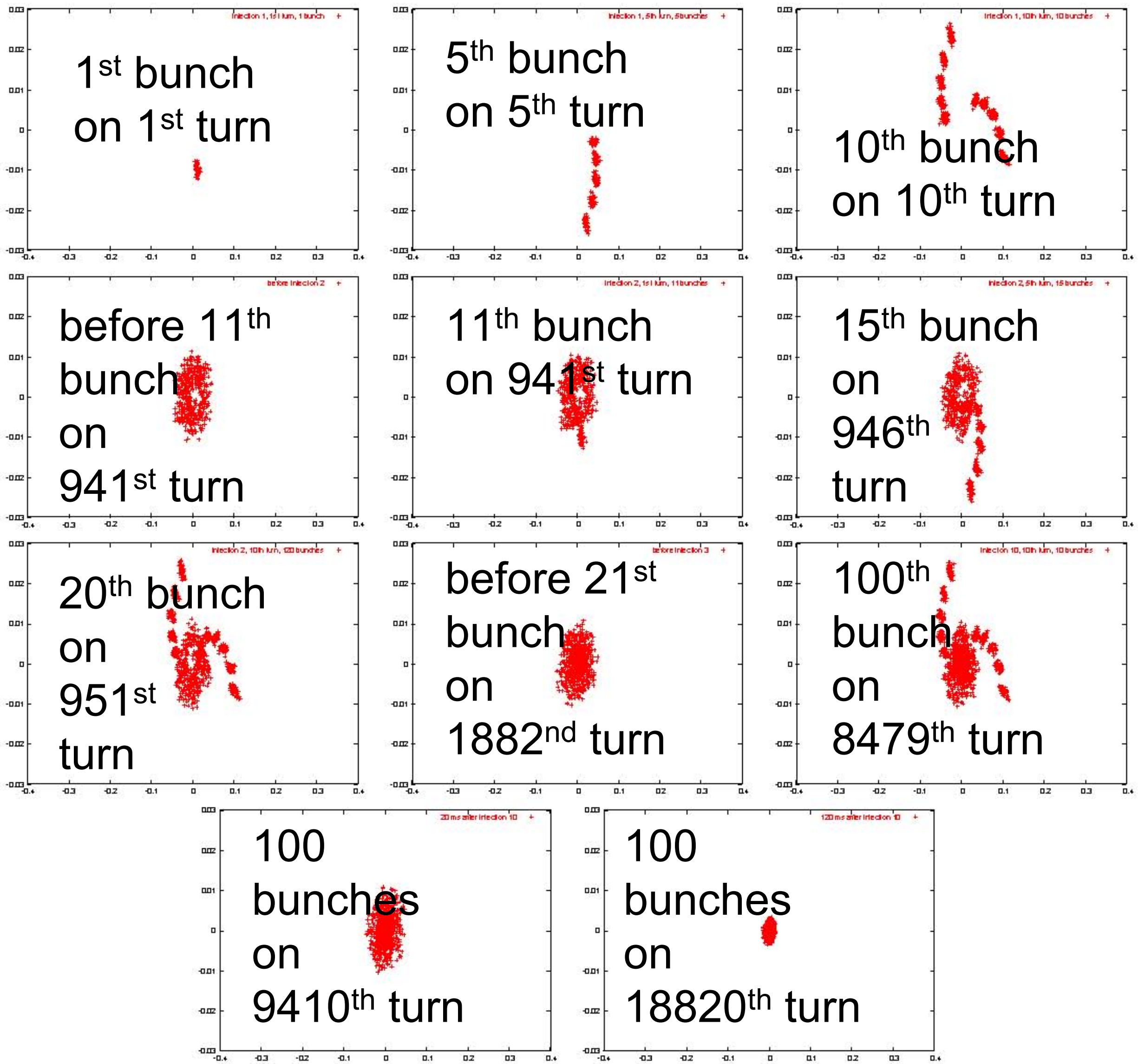
(9) e+ stacking

features of e+ accumulator ring:
large acceptance
fast damping

economic solution for ILC:
use one or three 6-km main damping rings

CLIC approach:
pre-damping ring (required in any case)

e+ stacking



stacking in 3-km ILC DR
– longitudinal phase space

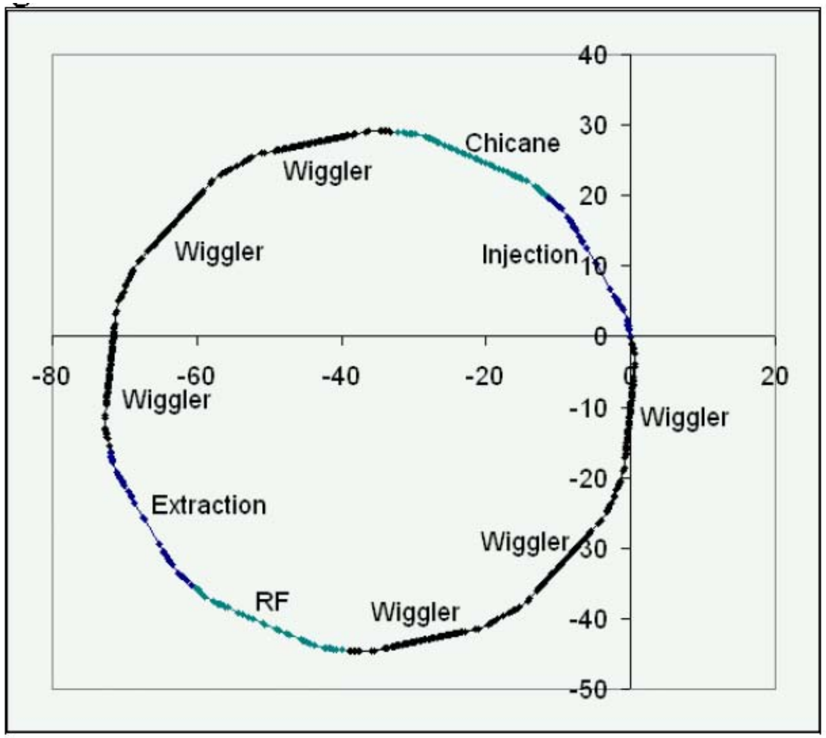
ILC scheme:
10 turn injection into the same bucket of main DR (at different δ); followed by 10 ms damping, this is repeated 10 times!

CLIC:
250-400 turn injection into the same bucket, no repetition

CLIC uses pre-damping ring optimized for e+ accumulation

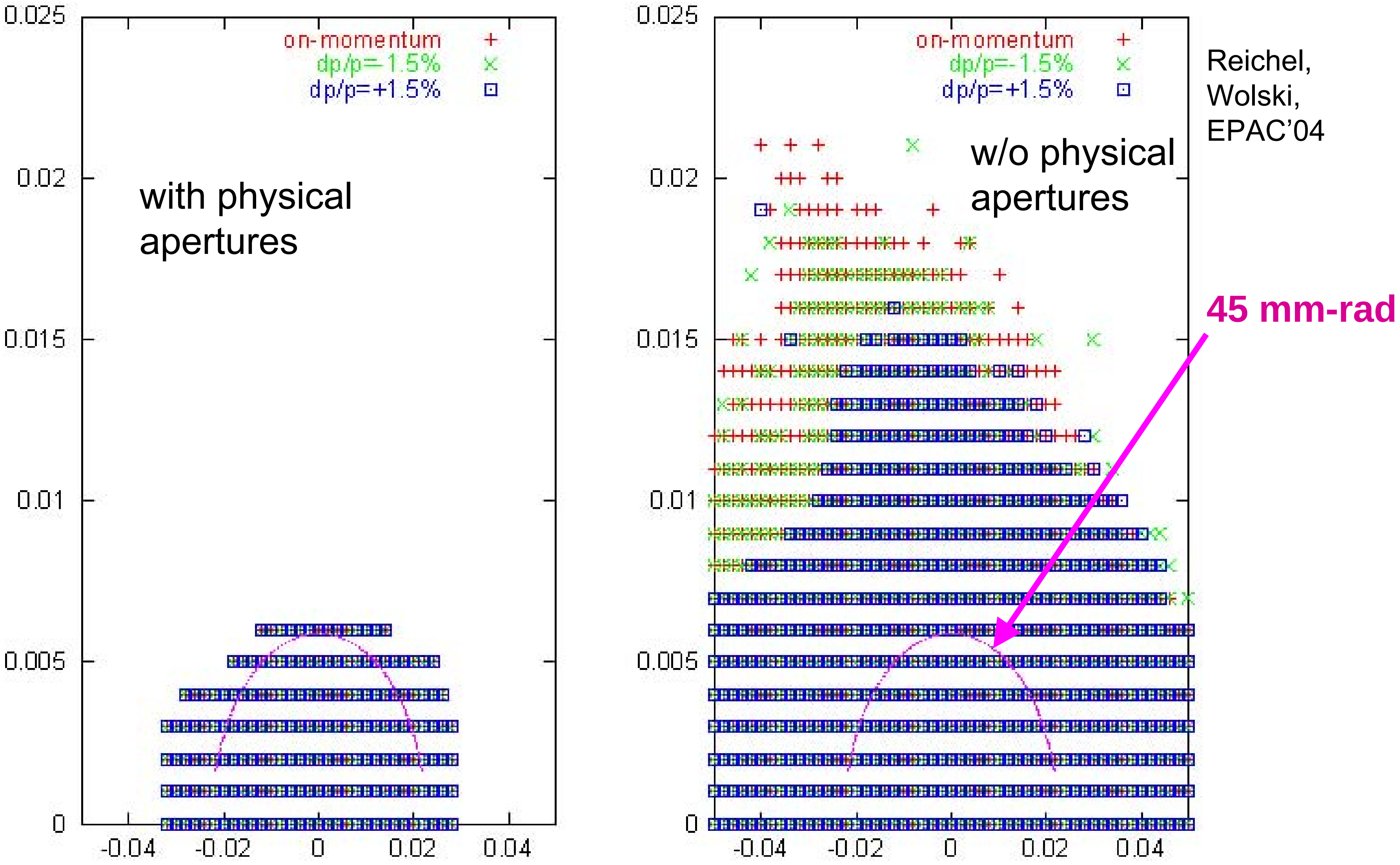
CLIC e+ stacking in pre-damping ring

- pre-DR can be optimized for accumulation independently of DR constraints
- may adopt NLC pre-DR design of Wolski (EPAC’02) and Reichel & Wolski (EPAC’04)



10-fold symmetric DBA structure;
optimized for large acceptance;
wiggler damping ~2x arc damping
beam energy ~2 GeV
circumference ~200 m
bunch spacing ~0.4 m
damping time ~3.5, 2 ms
repetition rate ~100-150 Hz

injected e+ rms emittance ~2 mm-rad, edge emittance ~20 mm rad?



dynamic aperture for particles with zero & +/-1.5% $\delta p/p$

(10) arguments for Compton source

- *KEK-ATF proof-of-principle experiment*
- *future R&D at ATF & DAFNE*
- rapid advances in *lasers* & optical cavities
- several 10s of *Compton X-ray sources are under development across the globe* for medical & biological applications
- does not couple e+ and e- arms of collider
- does not impact main beam
- *adequate for CLIC* e+ charge requirements

Past Compton source R&D at ATF

arXiv:hep-ex/0508026
KEK Preprint 2005-56
Phys. Rev. Lett. **96**, 114801 (2006)

Efficient propagation of the polarization from laser photons to positrons through Compton scattering and electron-positron pair creation

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Abstract

We demonstrated for the first time the production of highly polarized short-pulse positrons with a finite energy spread in accordance with a new scheme that consists of two-quantum processes, such as inverse Compton scattering and electron-positron pair creation. Using a circularly polarized laser beam of 532 nm scattered off a high-quality, 1.28 GeV electron beam, we obtained polarized positrons with an intensity of 10^4 e^+/bunch. The magnitude of positron polarization was determined to be $73 \pm 15(\text{sta}) \pm 19(\text{sys})\%$ by means of a newly designed positron polarimeter.

Proposal for Study of High Intensity Multi-Bunch γ-Ray Generation by Compton Scattering at ATF

T. Omori, T. Takahashi et al, April 2006

- design & fabricate laser pulse stacking cavity with high enhancement factor and small spot size
- design collision point which realizes minimal collision angle
- install a laser pulse stacking cavity into ATF damping ring and demonstrate γ-ray generation

(later? coupled cavities with feedback control?)

Letter of Intent for EU FP7 JRA proposal on ‘positron polarized (POSIPOL) sources’

Technological R&D

- high-power & high-repetition rate **lasers**
- Fabry-Perot **optical cavities** in pulsed regime
- polarimetry

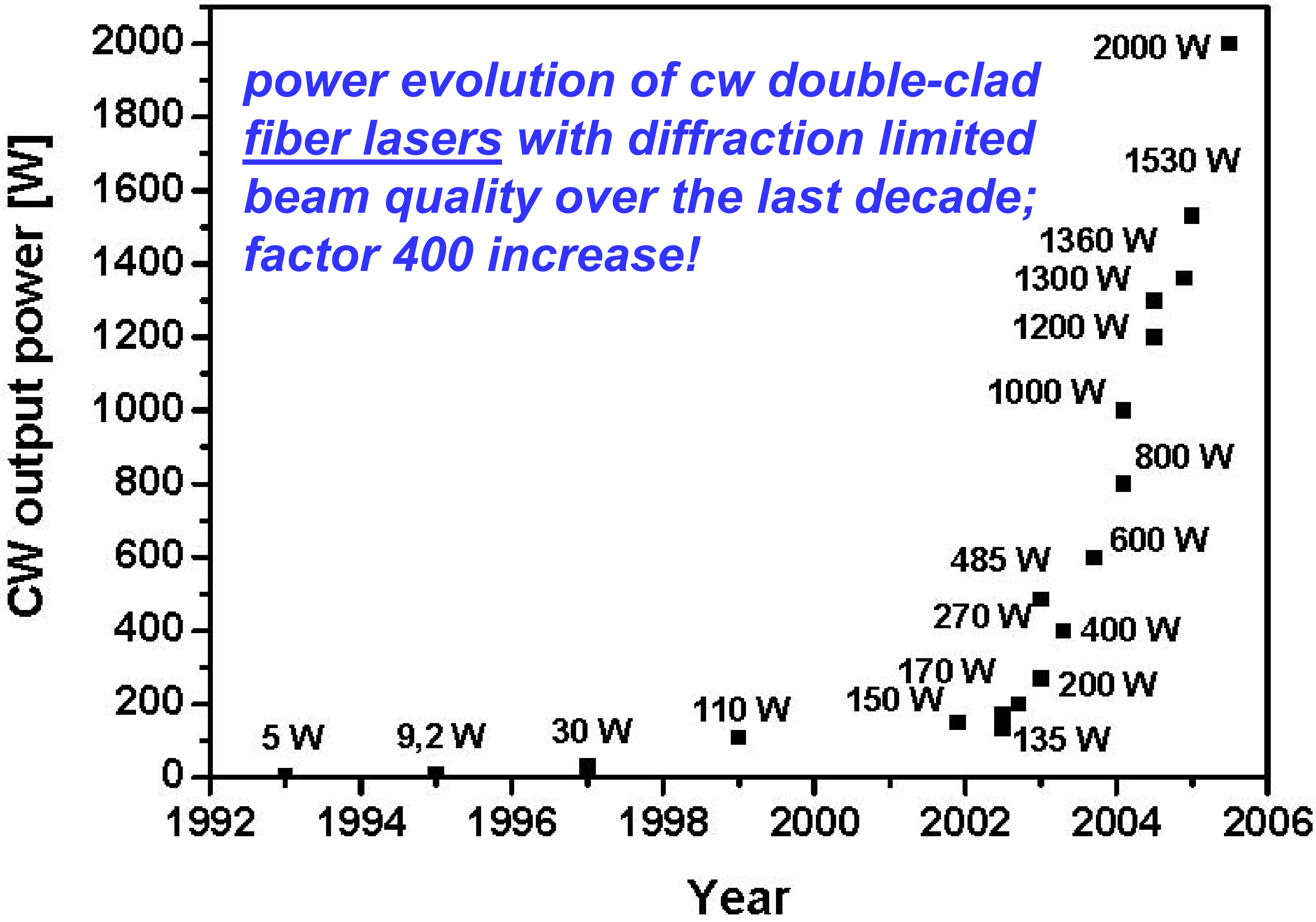
Design Study

- parameters optimization
- **Compton ring** design
- **collection system design**
- **multiple injection** schemes

Test Facility Experiments

- validation at **ATF & DaΦne** accumulation ring

A. Variola, LAL



Source: Fiber Based High Power Laser Systems,
Jens Limpert, Thomas Schreiber, and Andreas Tünnermann

Compton X-ray sources

Lyncean Technologies (Ron Ruth & Co.), Palo Alto
HIGS, Duke University
BNL-ATF
KEK-ATF
BINP ROKK-1M facility
Spring-8
LLNL/UCLA (PLEIADES)
ALS, LBNL
NIRS Chiba/U. Tokyo/KEK – coronary arteriography
…

rapidly evolving field with huge synergy!

Since 2004 Lyncean Technologies is constructing the Compact Light Source (CLS), … specifically designed to bring state-of-the-art protein structure determination to the university or industrial laboratory - but it has also promised a broad impact across the spectrum of x-ray science.
Unlike the stadium-sized synchrotron light sources, the Compact Light Source will fit into a typical university x-ray lab.
The **reduction in scale and cost is a factor of 200** – made possible by ***using a laser beam instead of the "undulator" magnets*** of the large synchrotrons.
On March 2, 2006, Ronald Ruth, Ph.D., president of Lyncean Technologies, announced that the ***CLS prototype is up and running and has just produced its first X-ray beams.***

Medical Devices News, 6 March 2006

Reference: Ron D. Ruth, Zhirong Huang, "Laser Electron Storage Ring," Phys. Rev. Lett. 80, 976 (1998)

(11) e- kick from laser collision

A.Mikhailichenko, Snowmass 2005

kick of order 5x10^{-6} rad, beam misses laser bunch at second interaction; *effect the same for YAG and CO2 laser*

A.Mikhailichenko, Cornell CLNS 05/1942

same statement, but numbers differ by factors ~2 from before

K. McDonald, *"...some fundamental limitations of this method seem to be underappreciated by its proponents…"* 20.12.05

E. Bulyak et al., "Comments on 'One Comment to the KEK's Positron Production Scheme' by A. Mikhailichenko", August 2005

only 3% electrons scatter, scattered e- receive kick of 3x10^{-6} rad for YAG laser and 10 times less for CO2 laser; partial steady-state transverse emittance ~2 times smaller than natural one

effect of e-γ collision on transverse emittance

R.D. Ruth, Z. Huang, "Laser Electron Storage Ring," Phys. Rev. Lett. 80, 976 (1998), "Radiative Cooling of Relativistic Electron Beams," PAC99 (1999).

$$\frac{\Delta\varepsilon}{\varepsilon} \approx \frac{32\pi}{10}\left(\frac{r_e^2 \lambda_C E_L}{Z_R \lambda_L^2 mc^2}\right)\frac{\beta}{\varepsilon} \approx 4\times10^{-3}$$

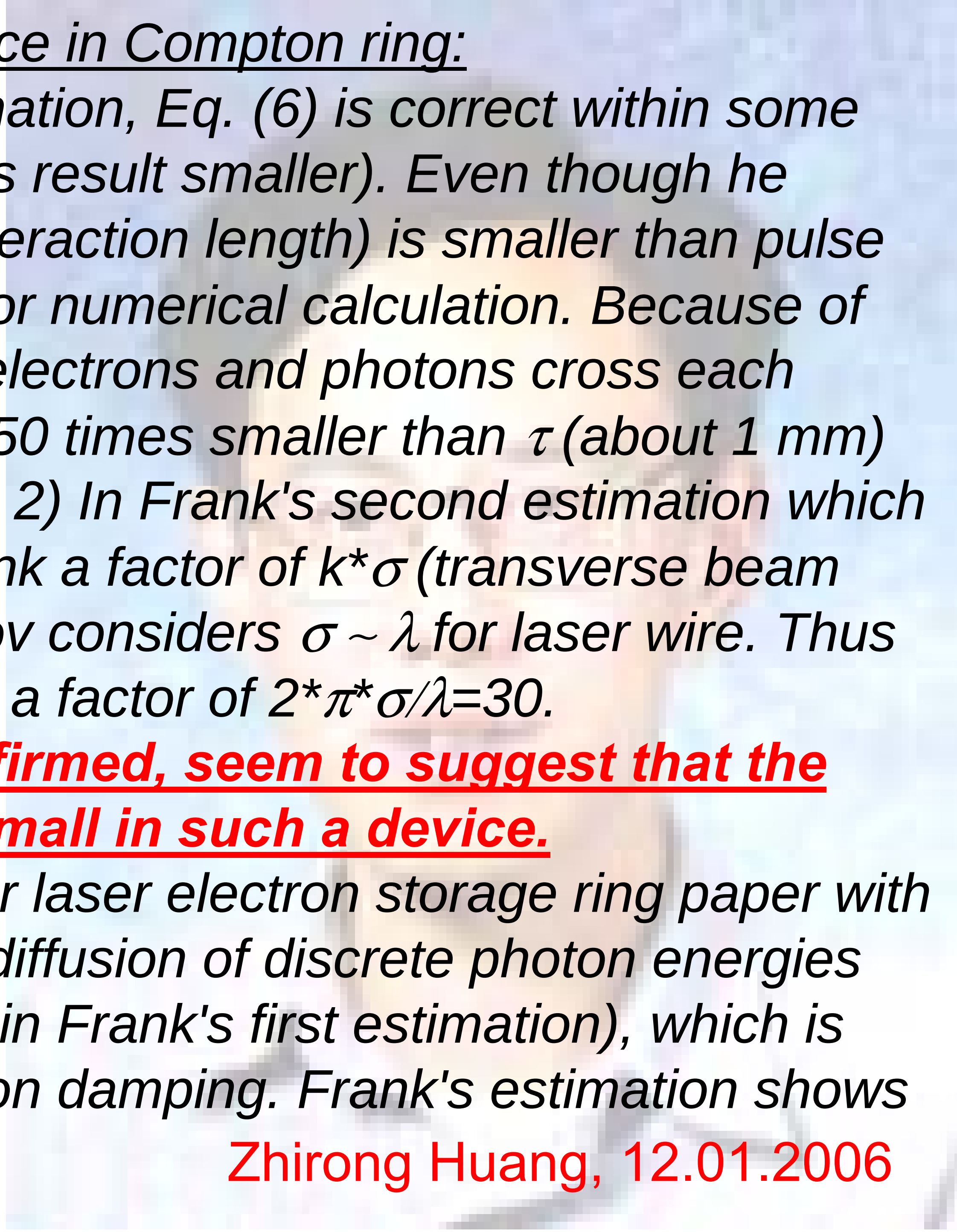
(YAG laser case, >100 times smaller for CO2)

V.I. Telnov, "Is a Laser 'Wire' a Non-Invasive Method?", Nanobeam'02 ICFA Advanced Beam Dynamics Workshop, Lausanne (2002)

$$\frac{\Delta P_\perp}{P_\perp} \approx \frac{k_{prob}}{\alpha\gamma^2}\sqrt{\frac{\beta}{\varepsilon}} \approx 0.015$$

(YAG laser case, 10 times smaller for CO2)

using β=0.25 m, ε=0.5 nm, k_{prob}~1/30



"<u>What I think about emittance in Compton ring:</u>
1) In Mikhailichenko's estimation, Eq. (6) is correct within some factor of 2 (which makes his result smaller). Even though he recognizes L_{eff} (effective interaction length) is smaller than pulse length τ, he still plugs in τ for numerical calculation. Because of the crossing angle (not all electrons and photons cross each other), I estimate L_{eff} to be 50 times smaller than τ (about 1 mm) at 8 degree crossing angle. 2) In Frank's second estimation which uses Telnov's formula, I think a factor of $k*\sigma$ (transverse beam size) is missing since Telnov considers $\sigma \sim \lambda$ for laser wire. Thus the result will be smaller by a factor of $2*\pi*\sigma/\lambda=30$.
<u>These corrections, if confirmed, seem to suggest that the ponderomotive force is small in such a device.</u>
The emittance growth in our laser electron storage ring paper with Ron comes from quantum diffusion of discrete photon energies (with Compton wavelength in Frank's first estimation), which is counterbalanced by radiation damping. Frank's estimation shows this is also small."

Zhirong Huang, 12.01.2006

(12) summary

- CLIC e+ / pulse ~ 1/100 ILC number
- scaled-down Compton source (→ single Compton IP) looks attractive
- open questions:
  - laser system
  - optical cavity
  - Compton ring
  - 6-D e+ distribution
  - stacking in pre-damping ring

feasibility & optimization


thank you
for your attention!