Possible e^- and e^+ sources for LHeC

Louis Rinolfi

Thanks to O. Brüning, A. Vivoli and F. Zimmermann

Linac-Ring Option for the LHeC

O. Brüning

Summary of Accelerator working group at the 1st LHeC workshop

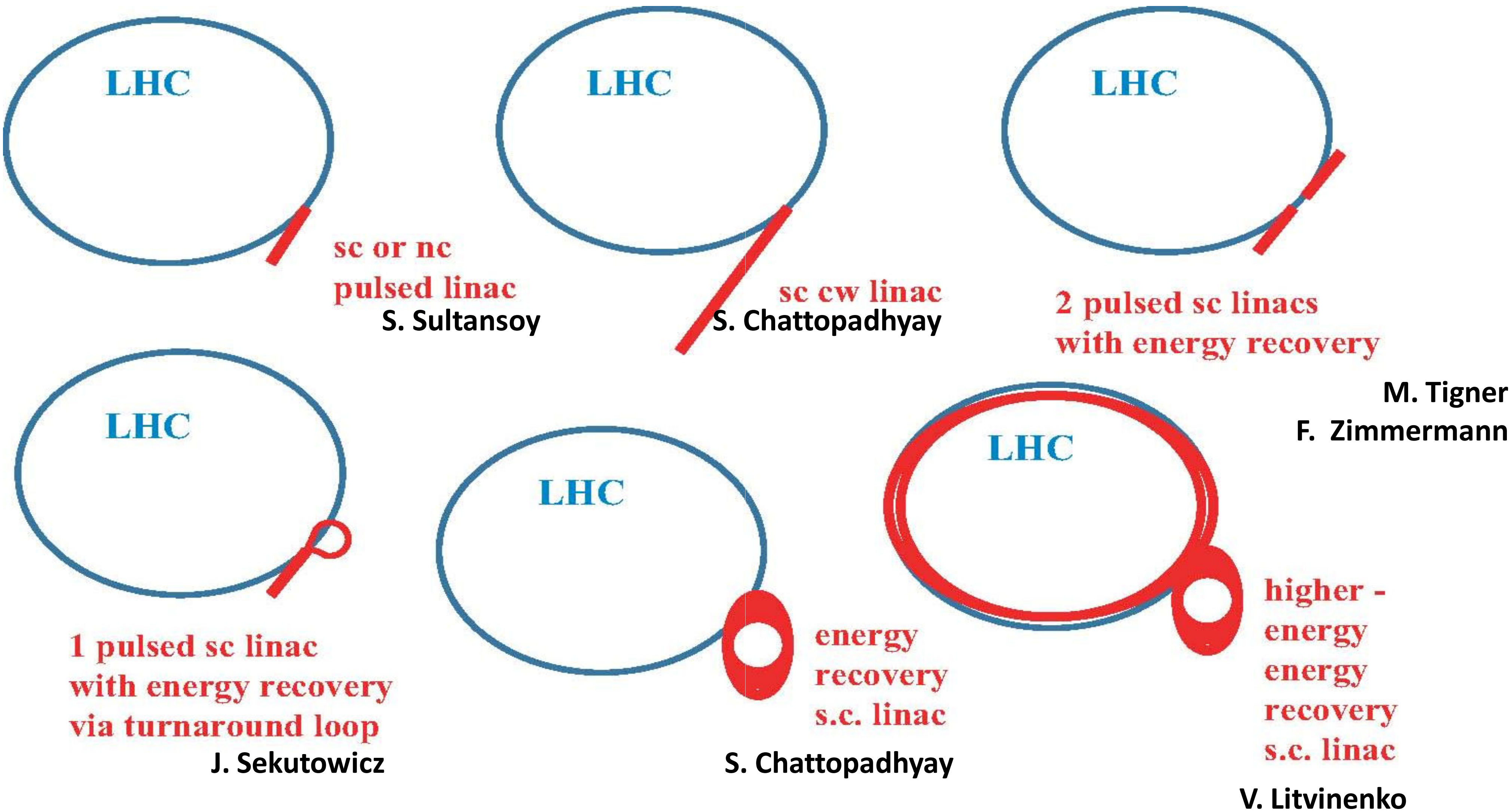
➔ new concept and not much experience (we need a 60+GeV linac, probably with CW operation and with energy recovery)

➔ this implies a lot of R&D and development of new tools / studies

➔ has the big advantage that it can largely decouple the construction from the LHC operation

➔ compatibility of positron operation with energy recovery?

LR scenarios

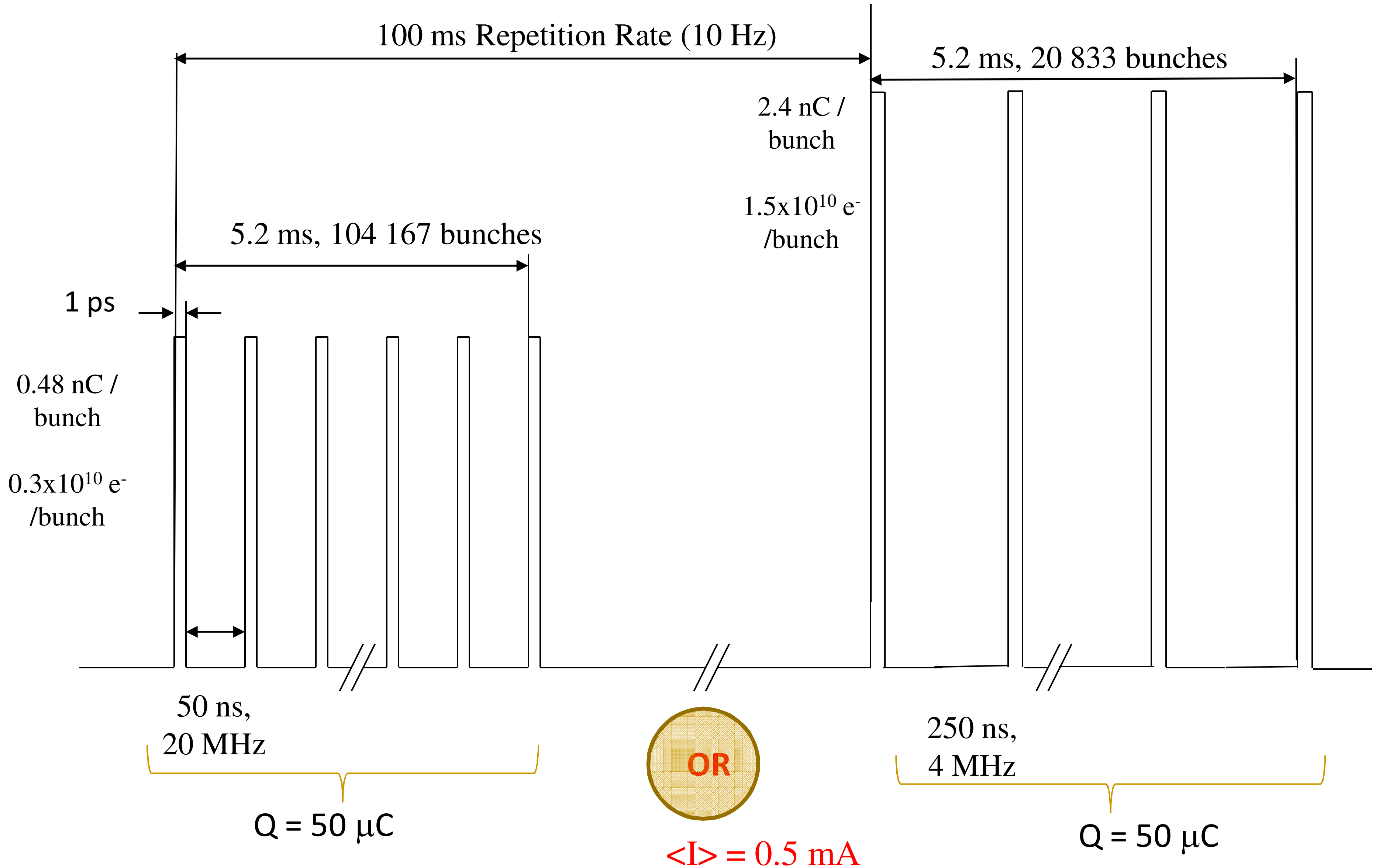


LHeC parameters

"The Large Hadron-Electron Collider (LHeC) at the LHC"
by F. Zimmermann et al. (27 co-authors)
PAC09 Conference, Vancouver, May 2009

	LHeC-RR	LHeC-RL high lumi	LHeC-RL 100 GeV	LHeC-RL high energy
e^- energy at IP [GeV]	60	60	100	140
luminosity [10^{32} cm^{-2}s^{-1}]	29	$29^\dagger$ ($2.9^\ddagger$)	2.2	1.5
bunch population [10^{10}]	5.6	$0.19^\dagger$ ($0.02^\ddagger$)	0.3 (1.5)	0.2 (1.0)
e^- bunch length [μm]	~10,000	300	300	300
bunch interval [ns]	50	50	50 (250)	50 (250)
norm. hor.&vert. emittance [μm]	4000, 2500	50	50	50
average current [mA]	135	$7^\dagger$ ($0.7^\ddagger$)	0.5	0.5
rms IP beam size [μm]	44, 27	7	7	7
repetition rate [Hz]	CW	CW	10 [5% d.f.]	10 [5% d.f.]
bunches/pulse	N/A	N/A	~~71430~~	~~14286~~
pulse current [mA]	N/A	N/A	10	10
beam pulse length [ms]	N/A	N/A	5	5
cryo power [MW]	0.5	20	4	6
total wall plug power [MW]	100	100	100	100

LHeC-RL (100 GeV) beam structure flexibility



Generation of polarized electron

Comparison for e^- source parameters

Microbunch width $(t_p)_{LHeC} = (t_p)_{ILC}$ at the photocathode => Bunch compressor requested

Parameters	LHeC 100 GeV	LHeC 100 GeV	ILC 500 GeV	CLIC 500 GeV
Electrons/bunch (N_{e-})	0.3E10	1.5E10	~ 3E10	1E10
Charge / bunch (q_e)	0.48 nC	2.4 nC	4.8 nC	1.6 nC
Number of bunches (n_b)	104 167	20 833	2625	354
Width of bunch (t_p)	1 ns	1 ns	1 ns	~ 0.1 ns
Time between bunches (Δt_b)	50 ns	250 ns	~360 ns	0.500 ns
Width of pulse (T_B)	5.208 ms	5.208 ms	1 ms	0.177 ms
Pulse repetition rate (F_B)	10 Hz	10 Hz	5 Hz	50 Hz
Charge per pulse (C_B)	50 000 nC	50 000 nC	~12 600 nC	566 nC
Average current from gun (C_B x F_B)	0.5 mA	0.5 mA	0.063 mA	0.028 mA
Peak current of bunch (I_{peak})	0.48 A	2.4 A	4.8 A	16 A
Current density (1 cm radius)	0.15 A/cm^2	0.76 A/cm^2	1.5 A/cm^2	5 A/cm^2
Polarization	> 80%	> 80%	>80%	>80%

cw laser parameters for LHeC e^- source

$$E_L = \frac{hc}{q}\frac{Q}{\lambda \times QE}$$

$$E_L(J) = 1.24\times 10^{-6}\frac{Q(nC)}{\lambda(nm)\times QE}$$

λ ≈ 775 - 780 nm for GaAs photocathodes

QE ≈ 0.2 % (Nagoya, JLAB, SLAC)

η ≈ 70% for the bunching system

Parameters	Units	LHeC 100 GeV	CLIC 500 GeV
Laser energy on photocathode ($E_B = E_L / \eta$)	J	40 000 x10^{-6}	647x10^{-6}
Peak power ($P_p = E_B / T_B$)	W	7.7	3654
Average power ($P_a = E_B$ x F_B)	W	0.4	0.032
Repetition frequency (F_B)	Hz	10	50

Pulsed laser parameters for LHeC e^- source

$\lambda \approx$ 775 - 780 nm for GaAs photocathodes

QE $\approx$ 0.2 %

$\eta \approx$ 90%

Parameters	Units	LHeC 100 GeV	LHeC 100 GeV	CLIC 500 GeV
Micropulse repetition frequency (f_p)	MHz	20	4	2000
Micropulse length (t_p)	ns	0.1	0.1	0.1
Micropulse laser energy on photocathode ($E_B = E_L / \eta$)	J	0.4×10^{-6}	2.1×10^{-6}	1.3×10^{-6}
Micropulse peak power ($Pp = E_B / t_p$)	W	426	2133	13
Macropulse laser energy on photocathode ($E_m = E_B x\ n_b$)	J	0.044	0.044	460×10^{-6}
Macropulse peak power ($P_m = E_m / T_B$)	W	8.5	8.5	2600
Macropulse average power ($P_a = E_m \times F_B$)	W	0.440	0.440	23
Repetition frequency (F_B)	Hz	10	10	50

Simulations for ILC and CLIC e⁻ sources

F. Zhou / SLAC

Parameters	Units	ILC 500 GeV	CLIC 3 TeV
Gun voltage	kV	140	140
Injector energy	MeV	76	20
Initial charge at the gun	nC	5	1
Capture efficiency	%	94	88
Initial bunch length at the cathode	ns	1.3	156
Final bunch length (FWHM)	ps	20	14
Energy spread (FWHM)	keV	100	100
Normalized rms emittance	mm.mrad	40	22

Possible for LHeC 100 GeV
140
20 – 80
2.7
90
1
1
?
10 - 100

To produce ultra-short pulse beam with high charge (< 10 ps, @1 nC/bunch) is not yet successful

Low beam emittance with high charge (< 1 π.mm.mrad, @1 nC/bunch) is not yet realized

R&D is ongoing at SLAC (A. Brachmann, J. Sheppard, F. Zhou), JLAB (M. Poelker), Japan (T. Omori, M.Kuriki, N. Yamamoto), …

Some challenges for LHeC e^- source

Gun:

Reliable load locked gun

High voltage 100 kV - 350 kV

Photocathode:

Production of the full current (0.5 mA) with space charge and surface charge limits

High polarization: 80 % - 90%

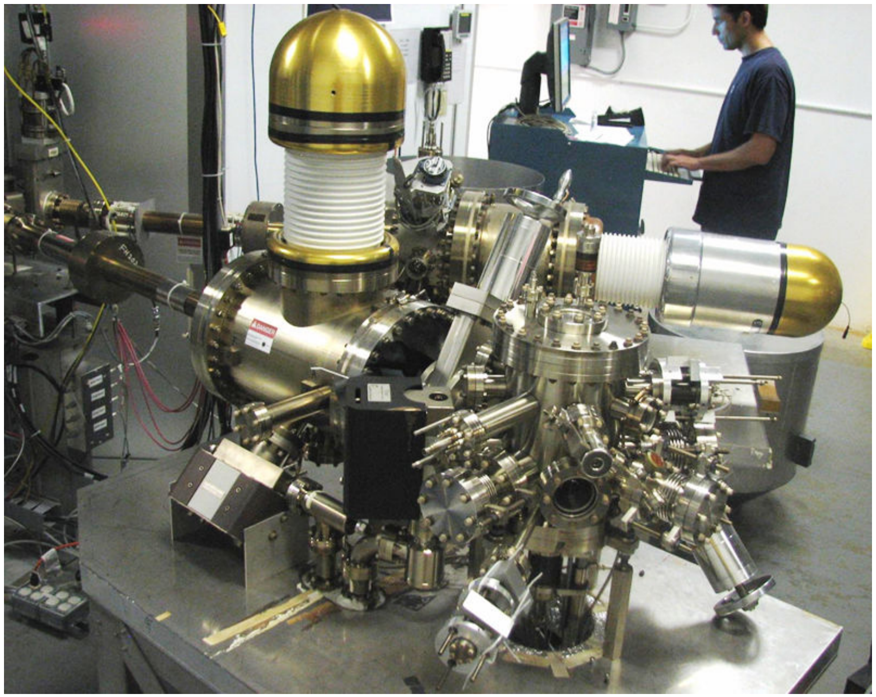
High Quantum Efficiency: 0.2 – 1 %

Long life time

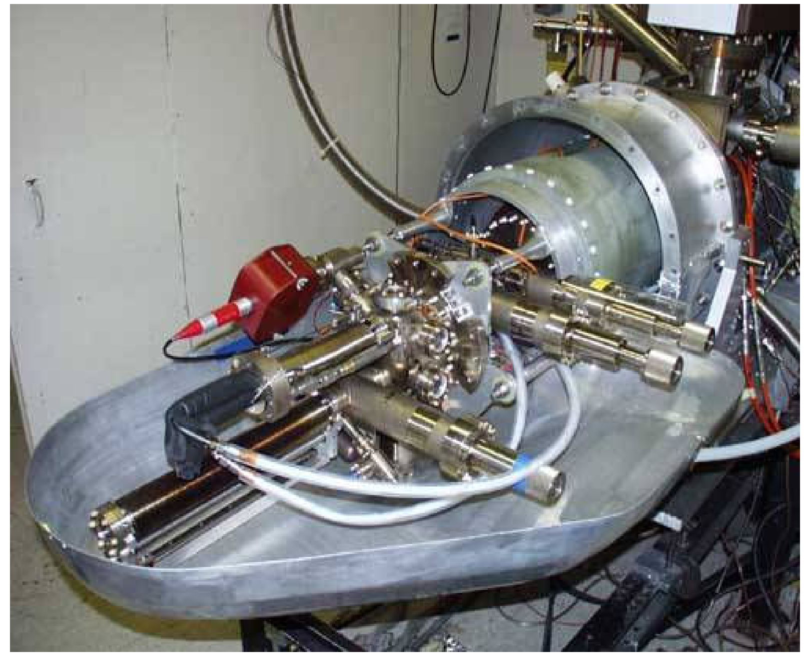
Laser:

Laser frequency:	4 to 20 MHz
Pulse length:	0.1 to 1 ns
Pulse energy:	~ 40 mJ

DC guns for polarized e^- source



JLAB   100 kV electron gun
(courtesy from M. Poelker)

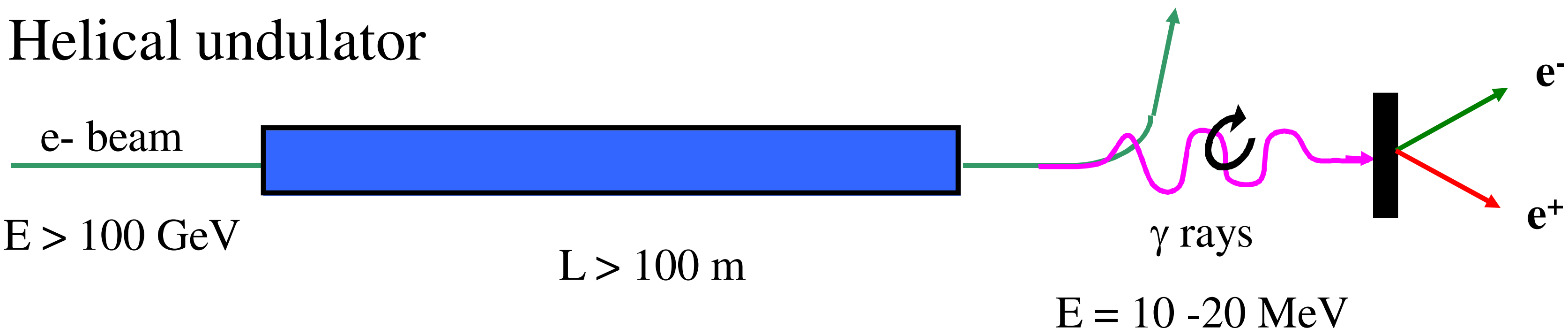


SLAC   120 kV electron gun
(courtesy from J. Sheppard)

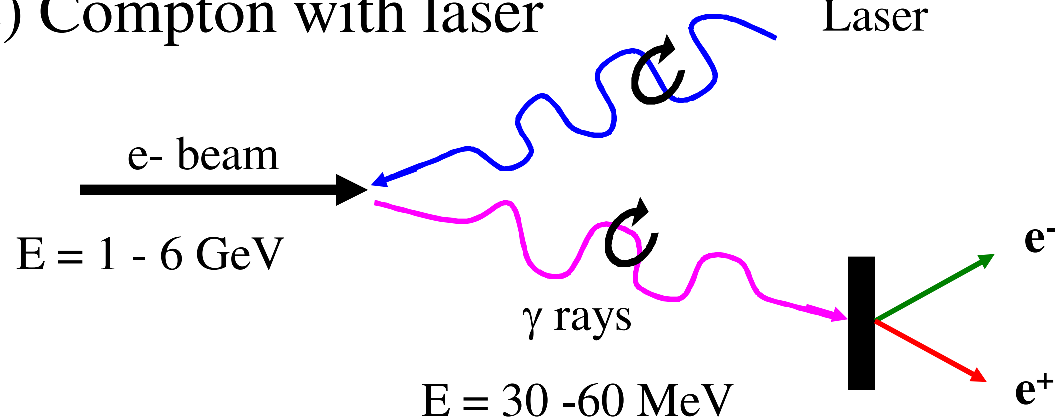
Generation of polarized positron

Two methods to produce polarized e^+

1) Helical undulator

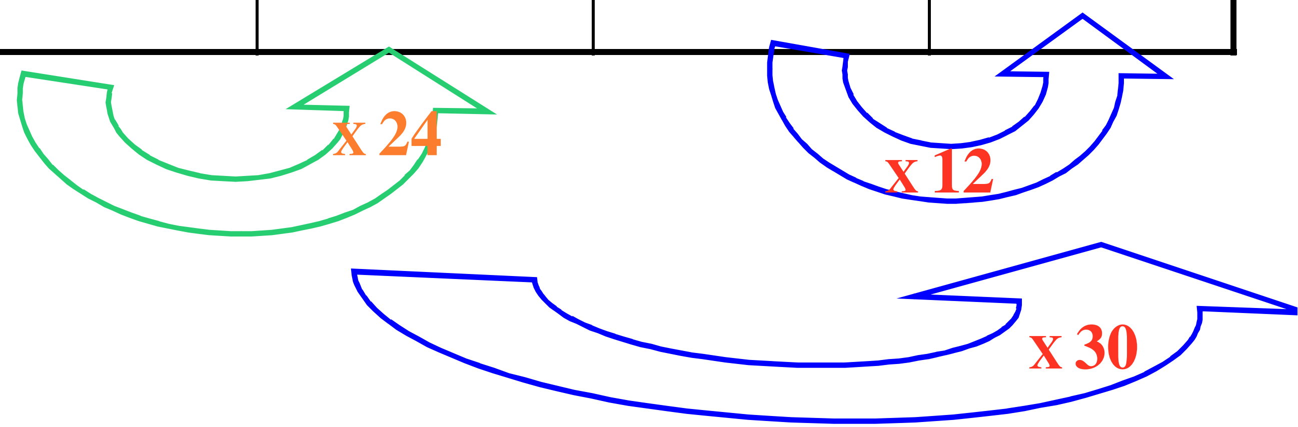


2) Compton with laser



Flux of e^+

	SLC	CLIC	ILC	LHeC
Positrons / bunch	3.5×10^{10}	0.64×10^{10}	2×10^{10}	1.5×10^{10}
Bunches / macropulse	1	312	2625	20833
Macropulse Rep Rate	120	50	5	10
Positrons / second	**0.042×10^{14}**	**1×10^{14}**	**2.6×10^{14}**	**31×10^{14}**



Compton sources

1) **Compton Ring:** long bunch length; large charge; burst collision => cooling time

- Storage ring
- Laser stacking cavities
- Stacking ring for e^+ (low γ flux and $Ne^+ / N_\gamma < 1\%$)

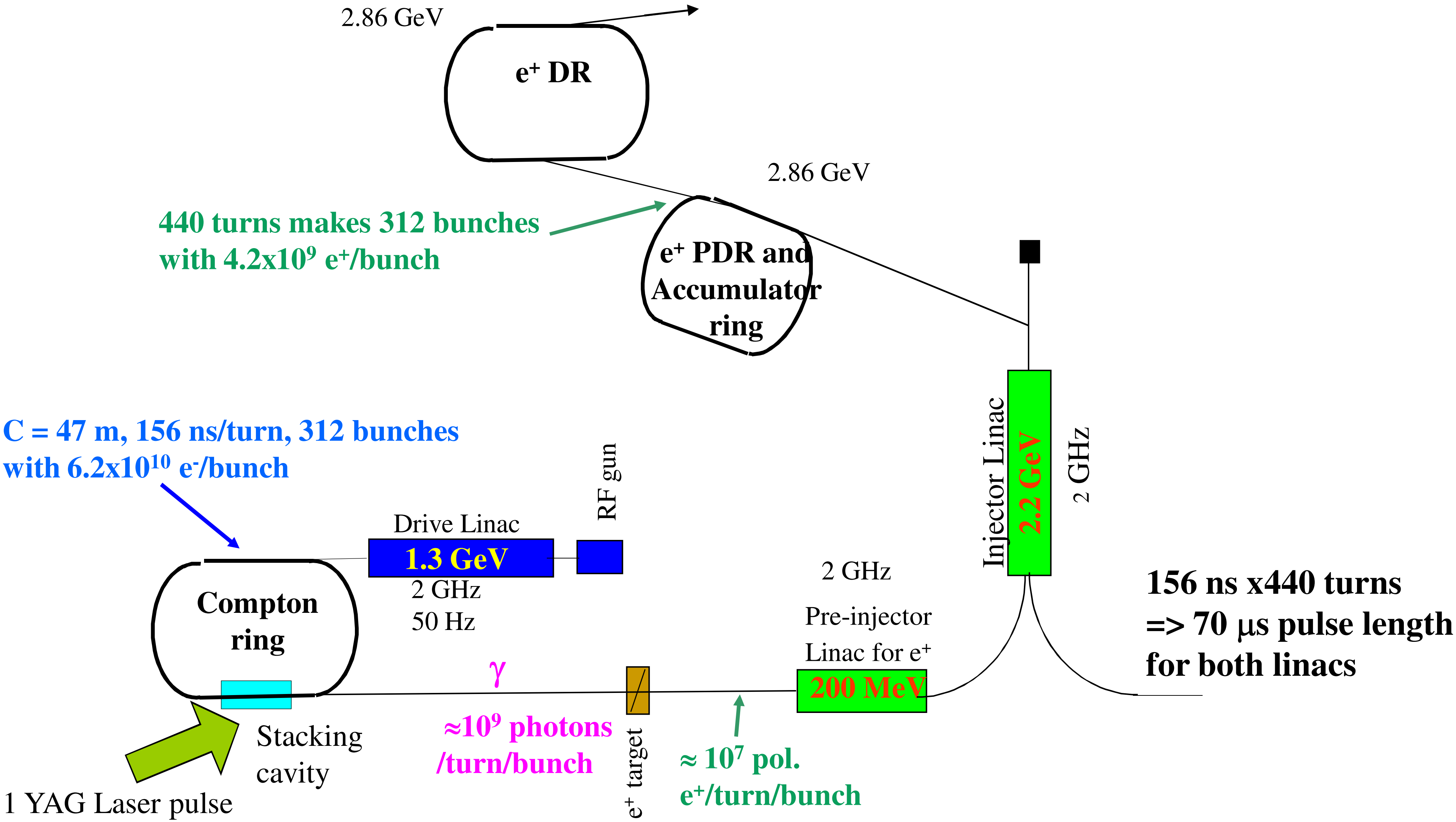
2) **Compton ERL:** short bunch length, small charge, CW => trade off between charge and rep. rate

- Energy Recovery Linac (sc)
- Laser stacking cavities
- Stacking ring for e^+ (low γ flux and $Ne^+ / N_\gamma < 1\%$)

3) **Compton Linac:**

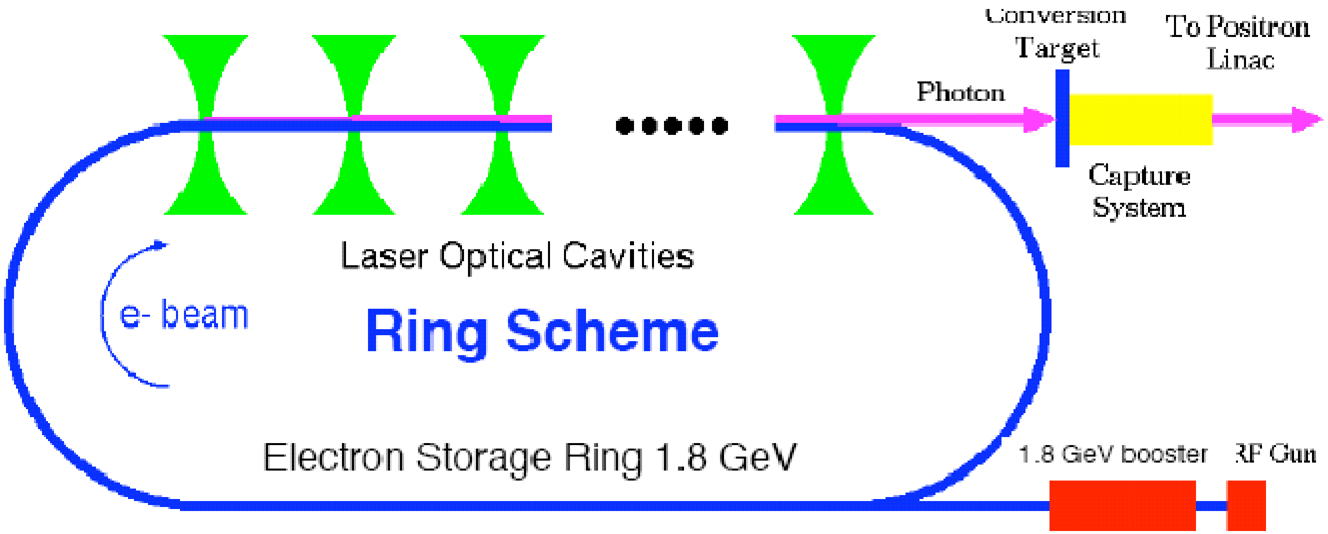
- Linac at few GeV energy (4 - 6 GeV) and powerful laser (CO_2 or YAG)
- Several optical cavities for interaction points but without laser stacking
- No stacking ring for e^+

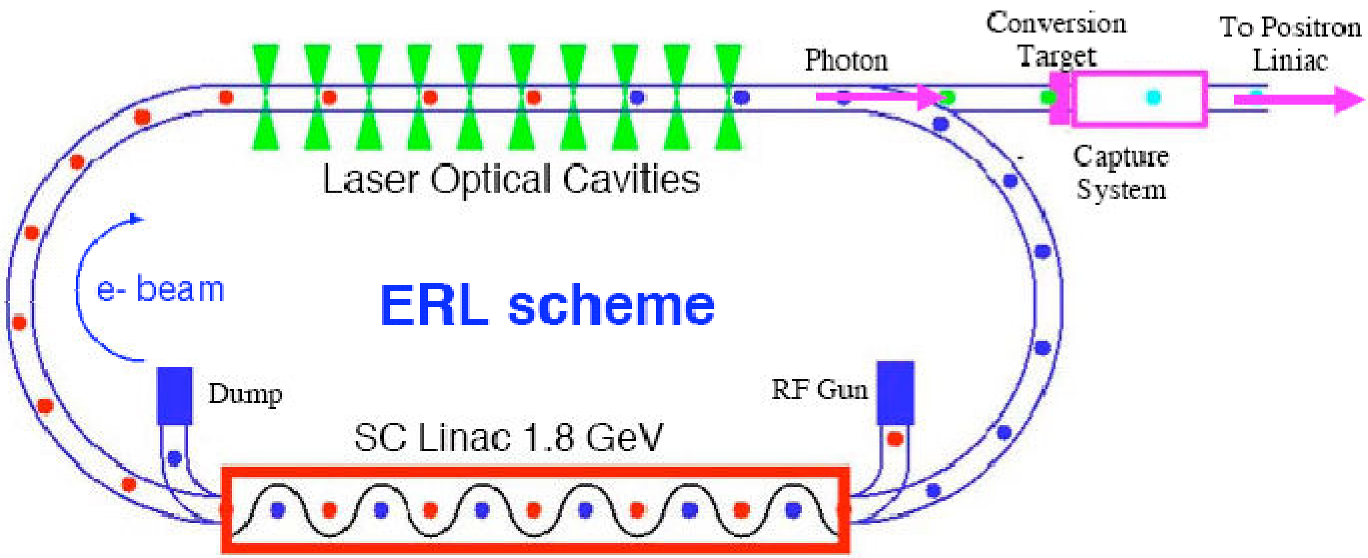
CLIC Compton scheme



Compton Ring and Compton ERL for ILC

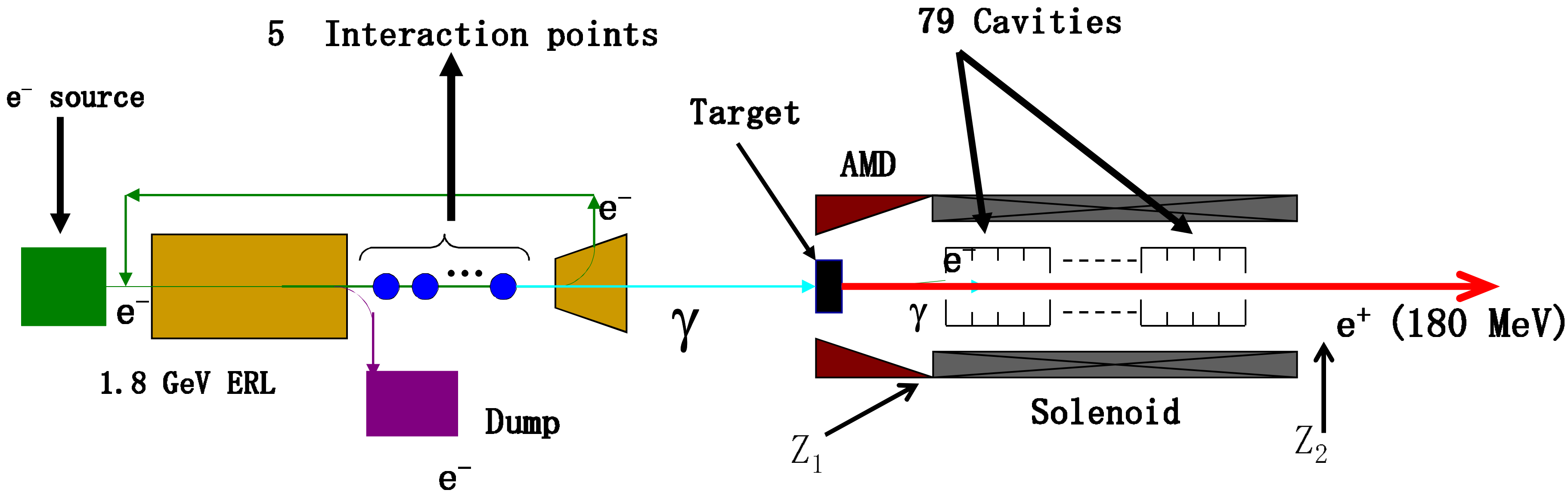
T. Omori / KEK





Scheme of the capture section for ILC

A. Vivoli



Longitudinal position m	N e^+ 10^5	ε_x (rms) π mm mrad	ε_y (rms) π mm mrad	<E> MeV	σ_E MeV	σ_z (rms) mm	ε_z (rms) cm MeV
$Z_1 = 0.050$	2866	434	433	20.15	11.08	7.9	7.29
$Z_2 = 57$	1591	20	19	164.39	24.24	10.76	9.65

Useful $\gamma\varepsilon$ (rms) = 6400 mm.mrad

Transverse emittance too large:

=> Damping Ring

=> or collimation => reduce e^+ yield

σ_t (rms)= 36 ps

Bunch length too long => Bunch compressor

Considerations about e^+ target

Classical target material:	Tungsten (W)
Density:	19.25 g/cm^3
PEDD(*):	35 J/g
Radiation length (χ_o):	3.44 mm

Simulations done with EGS code for a W target (and ILC pulse):
Photon beam mean energy ~ 30 MeV (from ERL Compton)
Studied length = 0.4 χ_o = 1.4 mm

Results :
0.830 MeV deposited in a volume of ~ 32 mm^3
PEDD = 2.2 x 10^{-13} J/g / photon
$\Rightarrow 1.6 \times 10^{14}$ photons per macropulse maximum on the target

Target damages by:
- Energy deposition
- Acoustic shock wave
- Temperature rise

Assuming N_{e+}/N_γ ~ 2 % => 3.2 x 10^{12} e^+ captured
with transverse emittances of $\gamma\varepsilon$ = 6500 mm.mrad

If we want $\gamma\varepsilon$ = 65 mm.mrad, a rough linear scaling => 3.2 x 10^{10} e^+ are captured

To be compared to 3.1 x 10^{14} e^+ requested per macropulse => Needs stacking !!!

(*) PEDD =Peak Energy Deposition Density. This value defines a limit where the target brakes

My preliminary conclusions for the LHeC e^+ source

1) Due to the large number of bunches (between 20 000 and 100 000), it seems difficult to implement a Damping Ring either to perform e^+ stacking or to reduce transverse emittances or to do both.

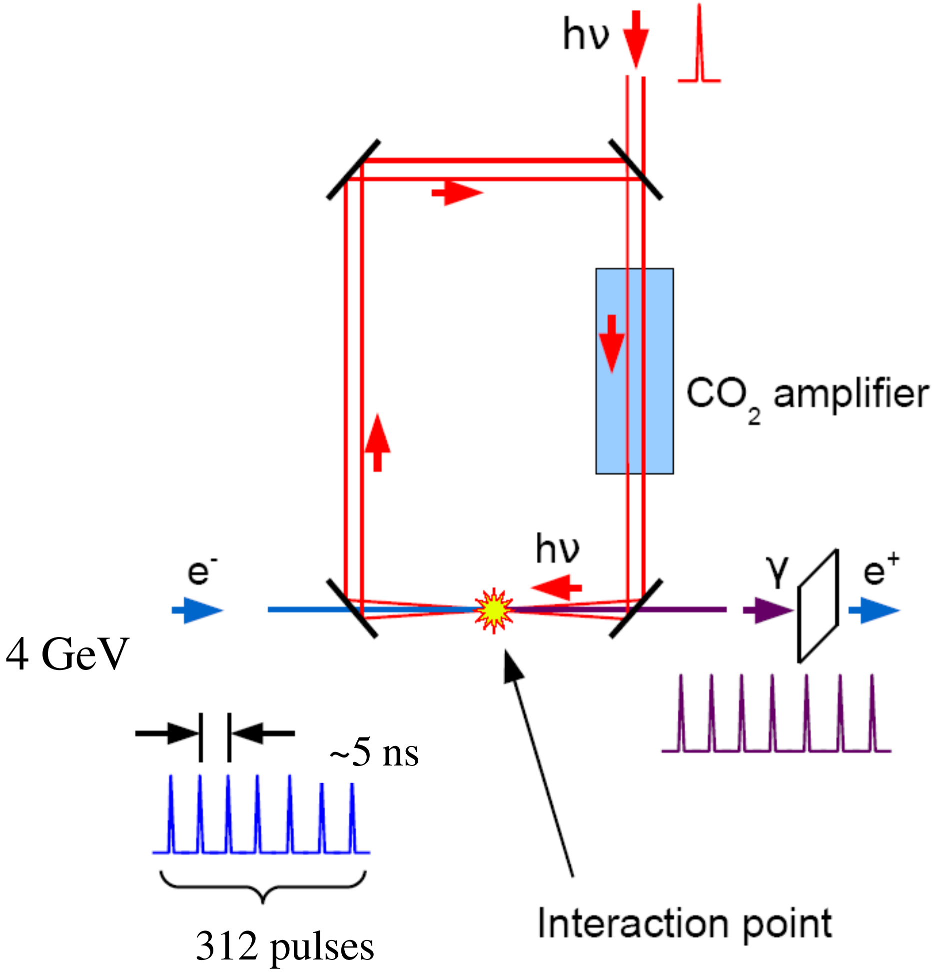
2) Due to the large amount of energy requested to produce one LHeC e^+ macropulse, a single classical target will be destroyed and therefore seems excluded. However one could imagine several rotating targets working in parallel => technology challenge + reliability issues.

3) Unless smart ideas are found, the Compton Ring and the Compton ERL do not seems suitable for the LHeC polarized e^+ source with the present parameters.

4) Compton Linac and Undulator schemes remain possible solutions.

5) Can we envisage an unpolarized e^+ source for the LHeC ?

Compton Linac for e^+ source



$N_\gamma / N_{e-} = 1$ (demonstrated at BNL)

$N_{e+} / N_\gamma = 0.02$ (expected)

i.e. ≈ 50 gammas to generate 1 e^+

<u>Data for CLIC:</u>

$N_{e+} = 6.4 \times 10^9$ / bunch ~ 1 nC

$N_{e-} = 0.32 \times 10^{12}$ / bunch ~ 50 nC

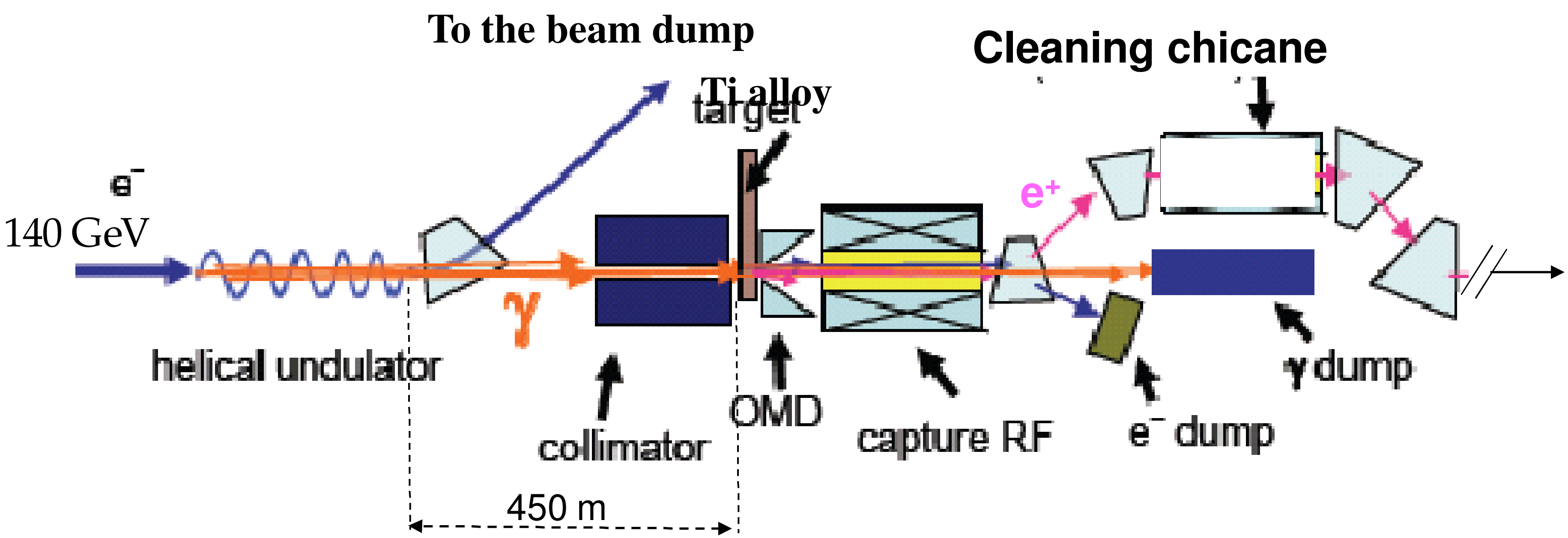
With 5 nC / e^- bunch and 10 Compton IP's

=> 1 nC / e^+ bunch

For LHeC, one would need to increase the number of targets/capture sections working in parallel in order to reach the requested intensity.
=> Cost and reliability issues

See talk of V. Yakimenko / BNL

Possible LHeC undulator based on ILC scheme



Undulator (to be optimized):

K = 0.5 - 0.75

λ_u = 1 - 1.5 cm

L = 100 m

OMD:

B = 7T - 0.5T

L = 20 cm

Pre-Injector Linac:

G = 10 MV/m

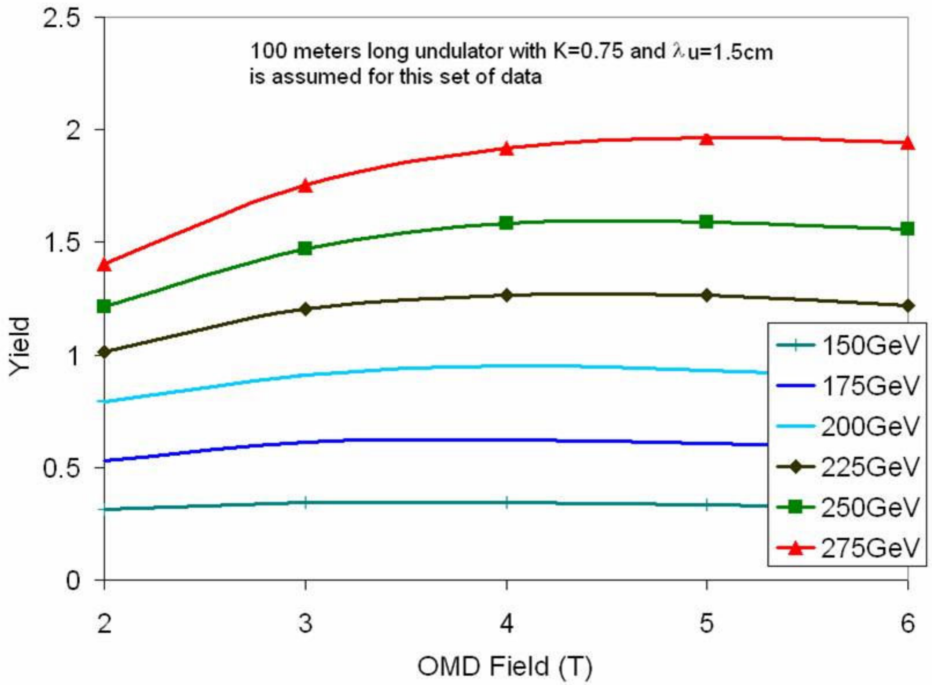
f = 1.3 GHz

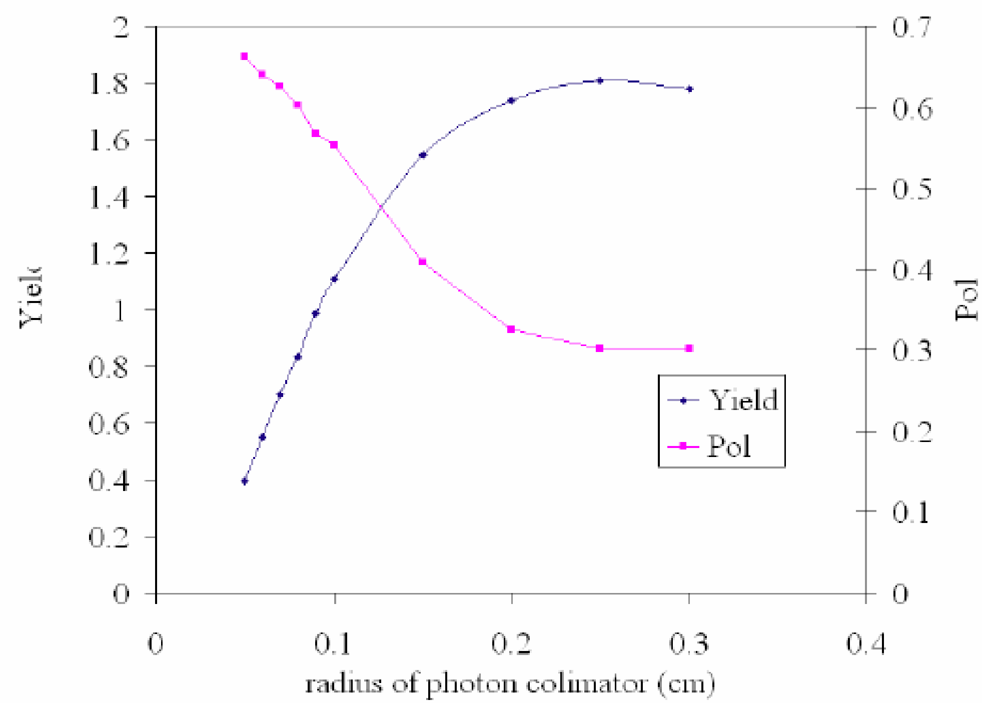
E = 200 MeV

Bo = 0.5 T

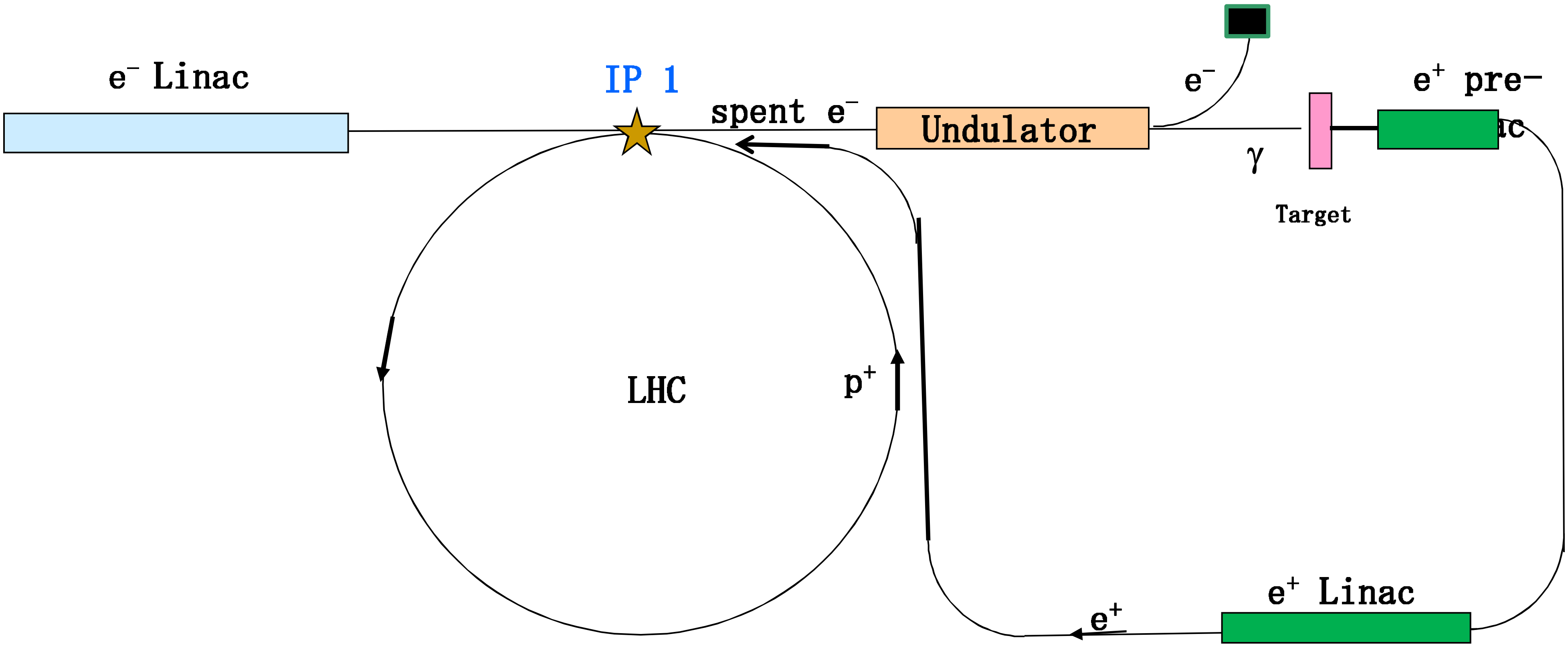
Results of simulations for an undulator

W. Gai, W. Liu / ANL





Proposal for LHeC with Undulator

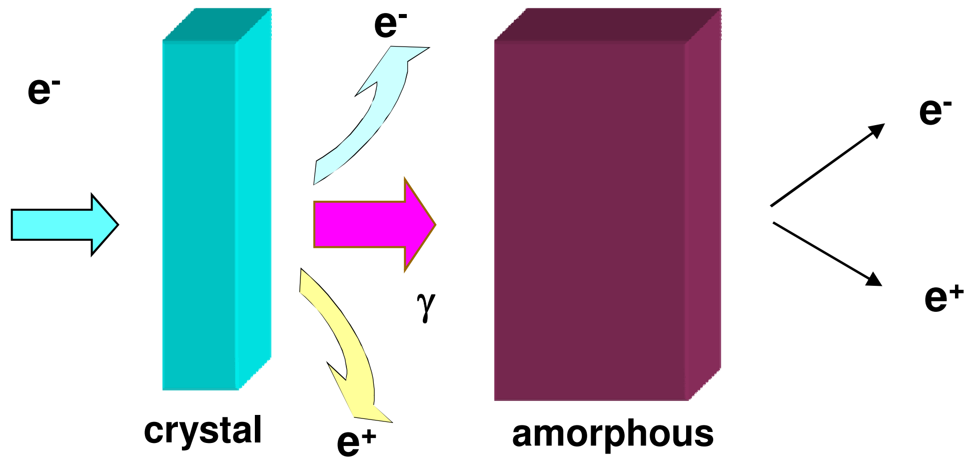


Unpolarized e^+ based on hybrid targets for CLIC

Electron beam on the crystal:
- energy = 5 GeV
- beam spot size = 2.5 mm

> First target is a crystal oriented along <111> axis where channeling process occurs

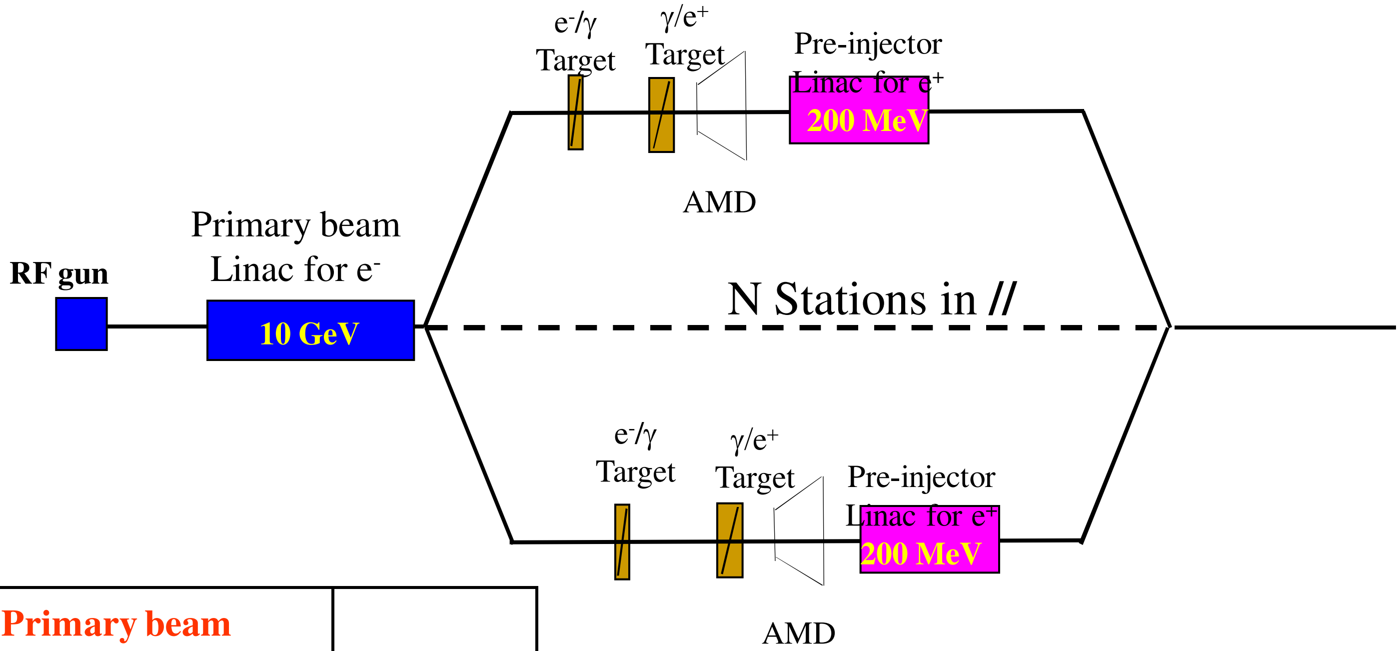
> Second target is amorphous.



Target		Crystal	Amorphous
Material		W	W
Length	mm	1.4	10
Beam power deposited	kW	0.2	7.5
Deposited P / Beam Power	%	0.2	8
Energy lost per volume	10^9 GeV/mm^3	0.8	2
Peak energy deposition density (PEDD)	J/g	6.8	18

Simulations by O. Dadoun / LAL and V. Strakhovenko / BINP

A possibility for unpolarized e^+ at LHeC



Primary beam	
Primary beam energy	10 GeV
Nb e^- / bunch	1.5×10^9
Nb bunches / pulse	20 000
Nb e^- / pulse	3×10^{13}
Pulse length	5 ms
Beam power	480 kW
Bunch length	1 ps

Target @ 1 station	
Yield (e^+ / e^-)	2
Crystal thickness	1 mm
Amorph. thickness	6 mm
Distance crystal-amorph.	3 m
Nb e^+ / bunch	3×10^9
PEDD / target	30 J/g

e^+ @ 5 stations	
Beam energy	200 MeV
Nb e^+ / bunch	15×10^9
Nb bunches / pulse	20 000
Nb e^+ / pulse	3×10^{14}
Bunch spacing	250 ns

Some challenges for LHeC e^+ source

1) Unpolarized e^+ with several parallel target stations
2) Devices for Undulator scheme (Helical undulator magnet, dumps,…)
3) Devices for Compton Linac (High power linac, cavities at IP, powerful laser systems,…)
4) Photon collimators
5) Targets issues (Heat load dynamics, beam energy deposition, shock waves, breakdown limits, activation, ….)
6) Adiabatic Matching Device (AMD)
7) Capture and acceleration sections (Transport and collimation of large emittances)
8) Find out a maximum e^+ yield (Trade off between yield, polarization and emittances)
9) Polarization issues (Analyze systematic errors of polarization measurements)
10) Development of codes + efficient use of existing codes (EGS4, FLUKA, Geant4, PPS-Sim, …)
11) Integration issues for the target station (remote handling in radioactive area)
12) Radioactivity issues
13) ……..

Summary

- The LHeC e^- source is challenging, still requires R&D but is doable.

- The LHeC polarized e^+ source is extremely demanding. The e^+ flux is 12 times more than ILC and 30 times more than CLIC. No reliable solution exists yet for polarized e^+ for both projects. This needs a strong R&D program. However several paths would be possible for a future solution.

- Fortunately many synergies exist with other projects (e.g. LHC upgrade, CLIC, ILC, eRHIC,…). Intense studies are ongoing for ILC and CLIC.

- Can the Physics considers unpolarized e^+ in a first stage ?

- In order to propose good and realistic e^- and e^+ sources for the LHeC Conceptual Design Report for 2010, the collaboration from other institutes is crucial.