eh Accelerator Prospects

FCC
hh ee he

Frank Zimmermann

for the FCC & LHeC teams

FCC Week 2015, Washington DC, 24 March 2015

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precursor: LHeC

DRAFT 1.0
Geneva, September 3, 2011
CERN report
ECFA report
NuPECC report
LHeC-Note-2011-003 GEN

LHeC

A Large Hadron Electron Collider at CERN

Report on the Physics and Design
Concepts for Machine and Detector

LHeC Study Group
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http://cern.ch/lhec

LHeC

LHeC Study Group

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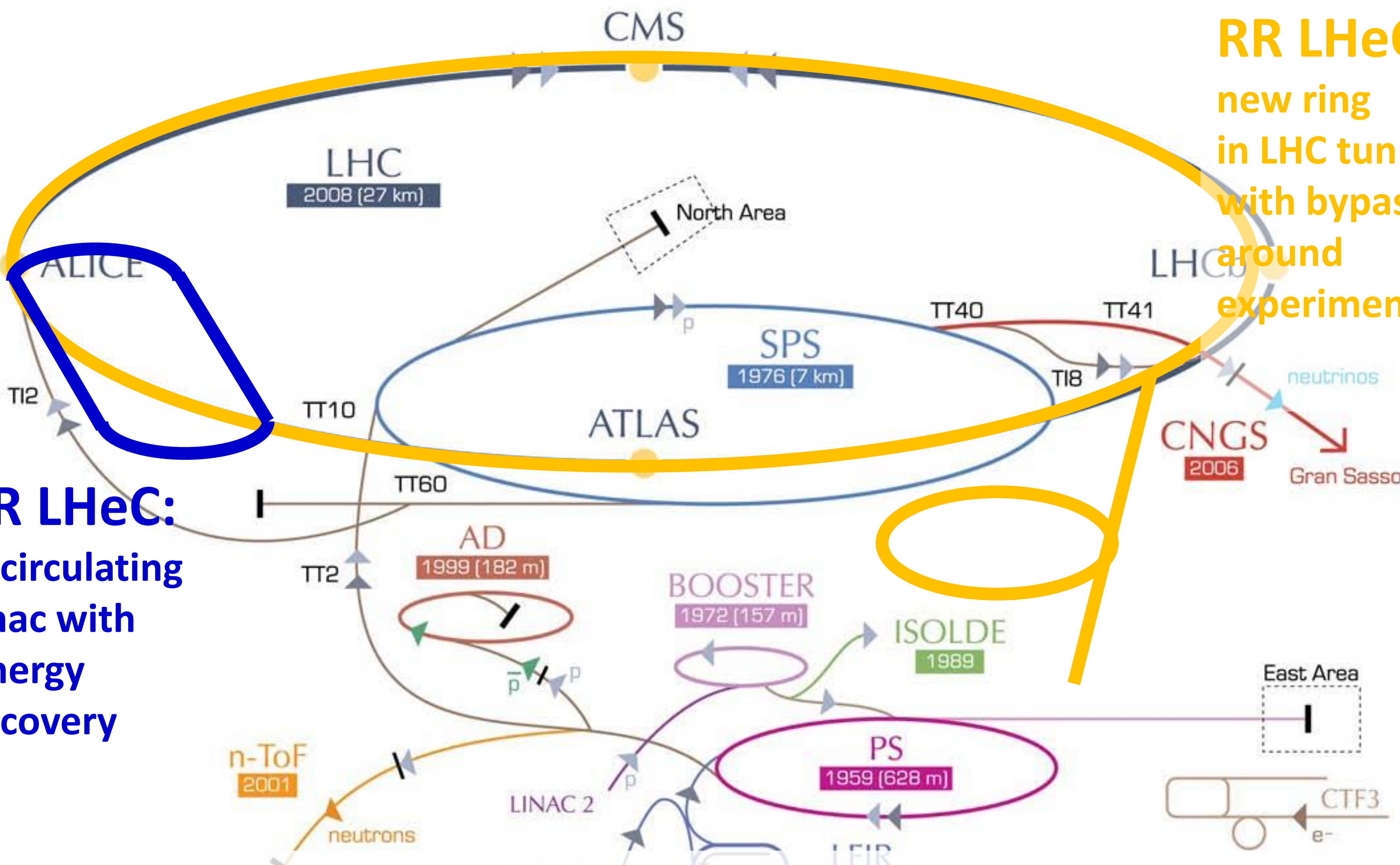
About 150 Experimentalists and Theorists from 50 Institutes
Tentative list

Thanks to all and to
CERN, ECFA, NuPECC

LHeC CDR (~600 pages)
published in 2012

LHeC scenarios & baseline



RR LHeC:
new ring in LHC tunnel, with bypasses around experiments

LR LHeC:
recirculating linac with energy recovery

At 2012 CERN-ECFA-NuPECC LHeC workshop ERL-LHeC was selected as baseline (*RR installation challenging, LHC interference*)

LHeC → LHeC Higgs Factory

parameter [unit]		
species	***e-***	***p***
beam energy (/nucleon) [GeV]	60	7000
bunch spacing [ns]	25	25
bunch intensity (nucl,) [10^{10}]	**0.1 → 0.4**	**17→ 22**
beam current [mA]	**6.4 → 25.6**	**860 → 1110**
normalized rms emittance [μm]	50 → **20**	**3.75 → 2.5**
geometric rms emittance [nm]	**0.43 → 0.17**	**0.50 → 0.34**
IP beta function $\beta_{x,y}$* [m]	**0.12 → 0.10**	**0.10 → 0.05**
IP rms spot size [μm]	7.2 → **4.1**	7.2 → **4.1**
lepton *D* & hadron ξ	**6 → 23**	**0.0001→ 0.0002**
hourglass reduction factor H_{hg}	0.91→ **0.80**	
pinch enhancement factor H_D	1.35	
luminosity/nucl. [$10^{33}cm^{-1}s^{-1}$]	**1.3 → 14.4**	

FCC-he key parameters

$e^{\pm}$ energy = 60 (→200?) GeV

p **energy = 50 TeV** (or equiv. *A* energy)

#IPs = 1, goal $\boldsymbol{L \geq 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}}$

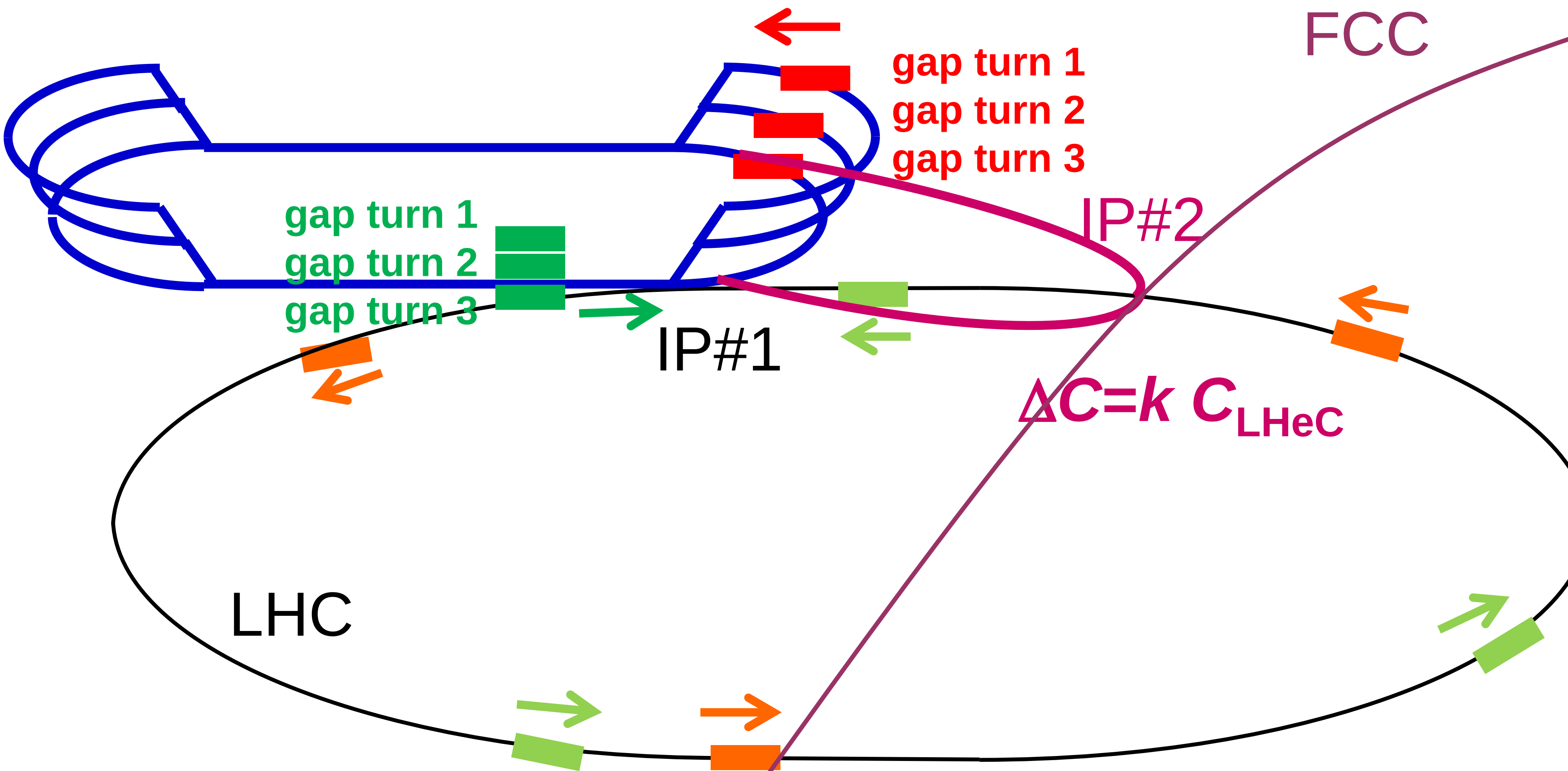
to measure Higgs self coupling

spot size determined by *p*

options for FCC-he:

1) ***e^-*** **from** ***LHeC (or other) ERL***
2) $e^{\pm}$ from *FCC-ee*
   (if co-existing with *FCC-hh*)

LHeC ion gaps & circumference



$C_{LHeC}=C_{LHC}/n$

future: $C_{LHeC}=C_{FCC}/m$

m, *n* (=3 or 4), *k*: integer

FCC-he linac-ring luminosity

luminosity of LR collider:

(round beams)

H_D~1.3

D. Schulte
LHeC2010

$$L = \frac{1}{4\pi e}\frac{N_{b,p}}{\varepsilon_p}\frac{1}{\beta_p^*} I_e H_{hg} H_D$$

highest proton beam brightness available

smallest possible proton β* function:
- reduced *l**
- squeeze only one *p* beam

average e^- current limited by energy recovery efficiency

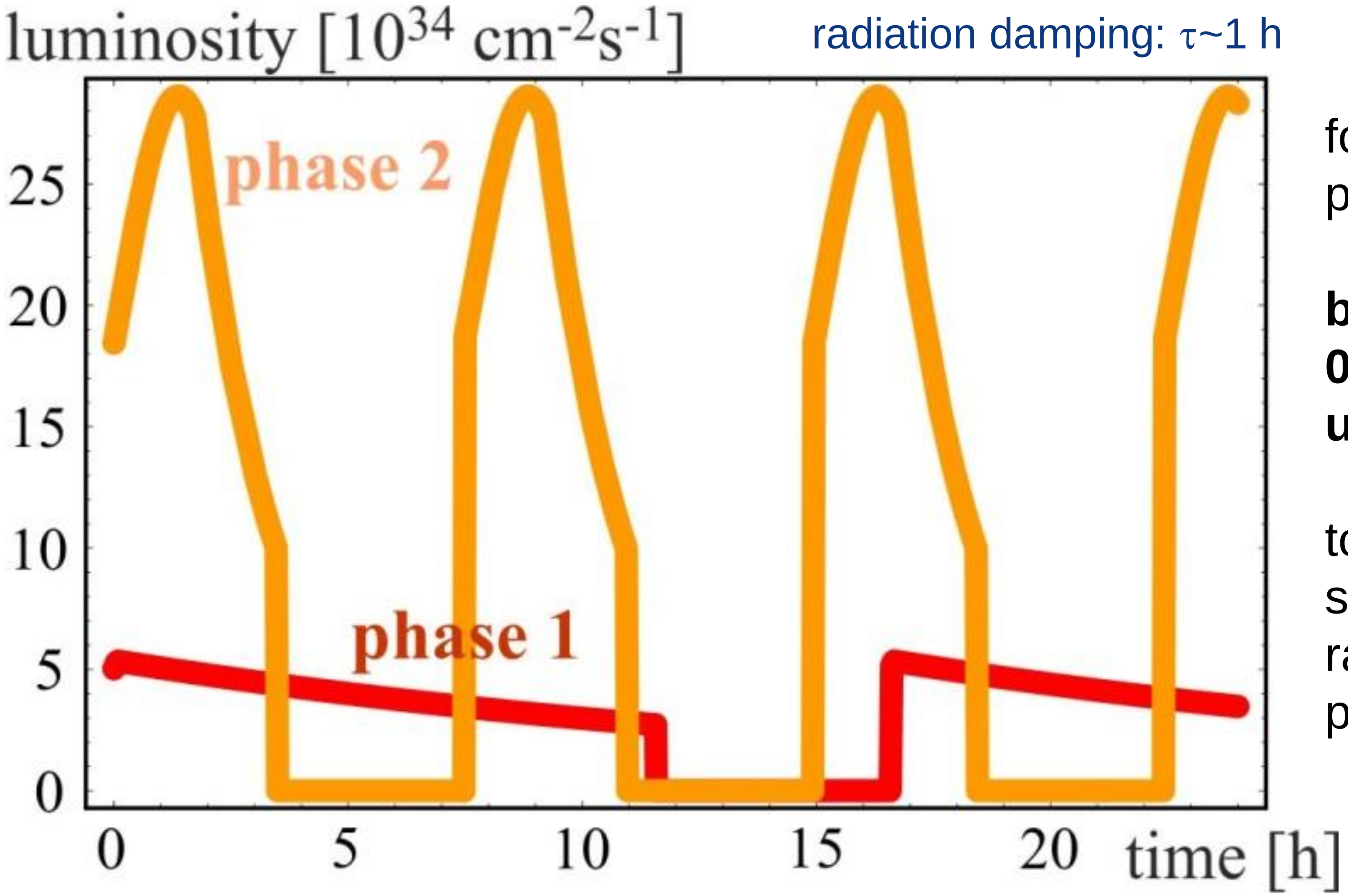
I_e=25.6 mA (HF)

maximize geometric overlap factor
- head-on collision
- small e- emittance

θ_c=0

H_{hg}≥0.7

FCC-hh phases 1 & 2



radiation damping: τ~1 h

for both phases:

beam current 0.5 A unchanged!

total synchrotron radiation power ~5 MW.

phase 1: β^*=1.1 m, ΔQ_{tot}=0.01, t_{ta}=5 h → phase 2: β^*=0.3 m, ΔQ_{tot}=0.03, t_{ta}=4 h

LHeC HF → FCC-he (phase 1)

parameter [unit]		FCC-hh
species	***e-***	***p***
beam energy (/nucleon) [GeV]	60	7000→ **50000**
bunch spacing [ns]	25	25
bunch intensity (nucl,) [10^{10}]	**0.4**	**22→ 10**
beam current [mA]	**25.6**	**1110 → 500**
normalized rms emittance [μm]	20	**2.5 → 2.2**
geometric rms emittance [nm]	**0.17**	**0.34 → 0.04**
IP beta function $\beta_{x,y}$* [m]	**0.10 → 0.07**	**0.05 → 0.3**
IP rms spot size [μm]	4.1 → **3.5**	4.1 → **3.5**
lepton *D* & hadron ξ	**23 → 16**	**0.0002→0.0002**
hourglass reduction factor H_{hg}	0.80→ **0.88**	
pinch enhancement factor H_D	~1.35	
luminosity/nucl. [$10^{33}cm^{-1}s^{-1}$]	**14.4 → 9.9**	

LHeC HF → FCC-he (phase 2)

parameter [unit]		FCC-hh
species	***e-***	***p***
beam energy (/nucleon) [GeV]	60	7000→ **50000**
bunch spacing [ns]	25	25
bunch intensity (nucl,) [10^{10}]	**0.4**	**22→ 10**
beam current [mA]	**25.6**	**1110 → 500**
normalized rms emittance [μm]	20 → **10**	**2.5 → 0.75**
geometric rms emittance [nm]	**0.17→0.085**	**0.34 → 0.014**
IP beta function $\beta_{x,y}$* [m]	**0.10→0.048**	**0.05 → 0.3**
IP rms spot size [μm]	4.1 → **2.0**	4.1 →**2.0**
lepton *D* & hadron ξ	**23 → 48**	**0.0002→0.0007**
hourglass reduction factor H_{hg}	0.80→ **0.80**	
pinch enhancement factor H_D	~1.35	
luminosity/nucl. [$10^{33}cm^{-1}s^{-1}$]	**14.4 → 27.6**	

polarized e^- beams?

SLC had a polarized e^- beam,

80% polarization, **1 μA average current**

issues for 26 mA: space charge and photocathode surface charge limit, laser parameters,…

ongoing R&D efforts:

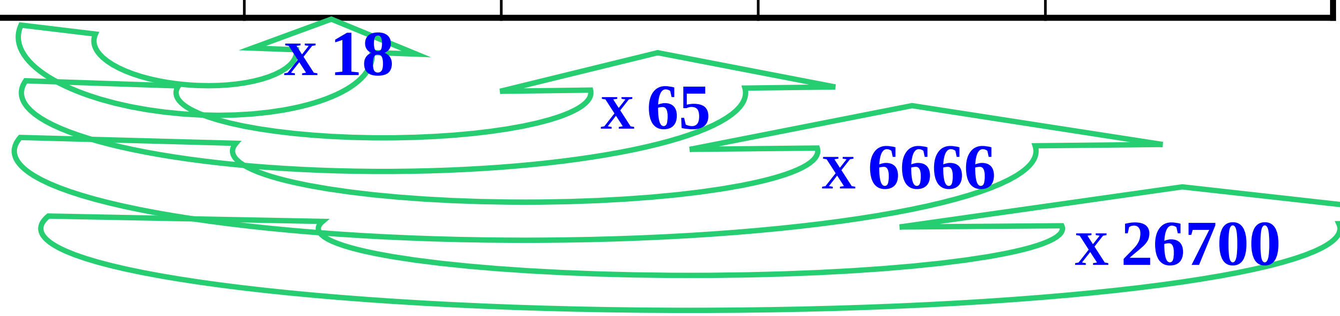
low-emittance DC guns (MIT-Bates, Cornell, SACLA, JAEA, KEK…) [E. Tsentalovich, I. Bazarov, …]

polarized SRF guns (FZD, BNL,…)

[J. Teichert, J. Kewisch, et al]

positrons? *e⁺* source requirements

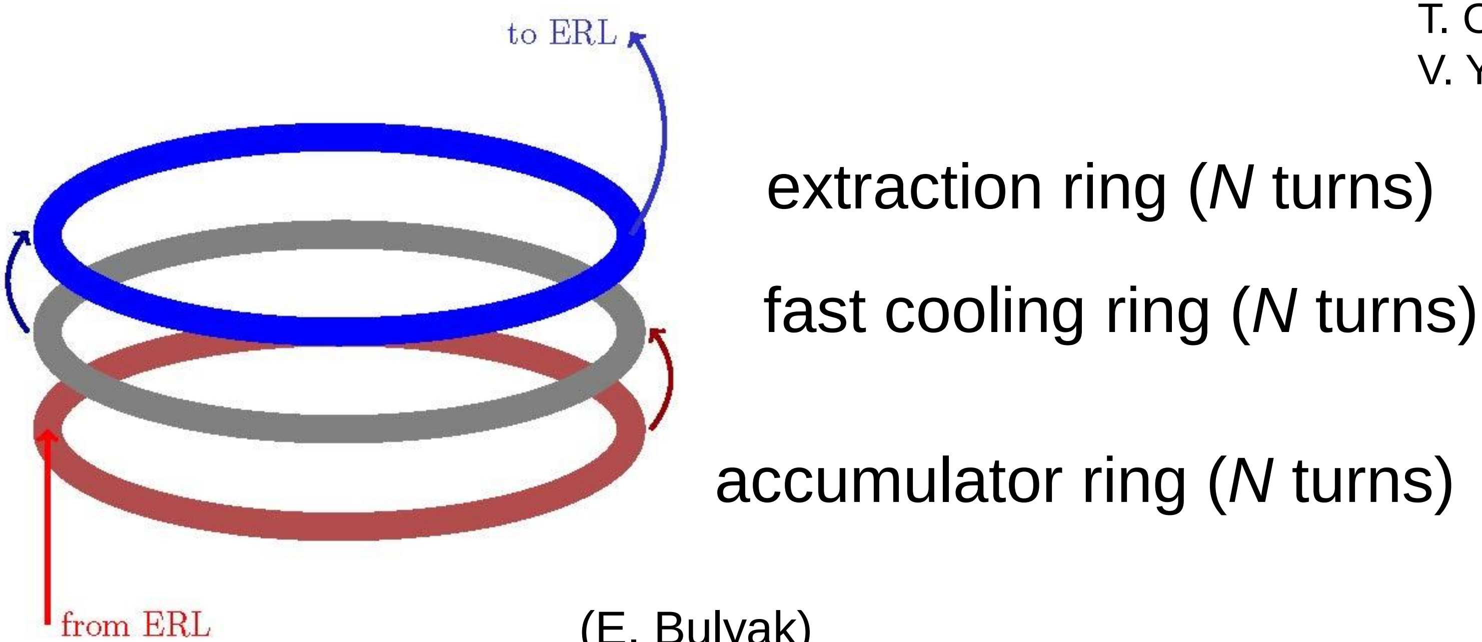
	SLC	CLIC (3 TeV)	ILC (RDR)	LHeC	LHeC HF/ FCC-he
Energy	1.19 GeV	2.86 GeV	5 GeV	60 GeV	60 GeV
e^+/ bunch at IP	40×10^9	3.72×10^9	20×10^9	1×10^9	4×10^9
e^+/ bunch before DR inj.	50×10^9	7.6×10^9	30×10^9	N/A	N/A
Bunches / macropulse	1	312	2625	N/A	N/A
Macropulse repet. rate	120	50	5	CW	CW
Bunches / second	120	15600	13125	40×10^6	40×10^6
e^+ / second	**0.06×10^{14}**	**1.1×10^{14}**	**3.9×10^{14}**	**400×10^{14}**	**1600×10^{14}**



L. Rinolfi

possible e^+ source options

- **recycle** e^+ together with energy, multiple use, damping ring in SPS tunnel w $\tau_\perp$~2 ms (D. Schulte) (Y. Papaphilippou)
- Compton ring, Compton ERL, coherent pair production, or undulator for high-energy beam
- 3-ring transformer & cooling scheme (H. Braun, E. Bulyak, T. Omori, V. Yakimenko)



(E. Bulyak)

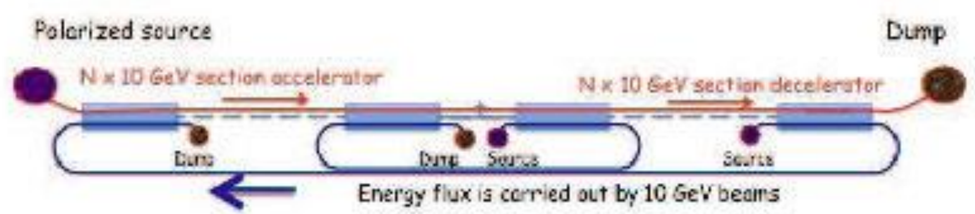
ERL energies beyond 60 GeV?

obstacle: synchrotron radiation

- larger tunnel, e.g. ERL in LHC 27 km tunnel
- or ERL installed in100-km FCC tunnel
- linear ERL with lower-energy transfer

  beams (similar to CLIC)

V. Litvinenko



- suppress or avoid the radiation ?!
  - muon ERL?
  - tiny aperture with SC chambers?

(hypothetical) ring-ring luminosity

assuming flat beams

$$L \approx \frac{\gamma_e}{2 e r_e} \frac{I_e \xi_e}{\beta_y^*}$$

average e⁻ current limited by synchrotron radiation

$I_e \sim 1/E^4$, e.g.

I_e=500 mA at 60 GeV

I_e=30 mA at 120 GeV

maximum beam-beam tune shift increases with energy $\xi \sim E^{1.2}$

electron β* function: limited by

hourglass effect at small values

and by tune shift at high values

collider parameters	FCC-ee single ring		protons
species	$e^{\pm}$	$e^{\pm}$	p
beam energy [GeV]	60	120	50000
bunches / beam	10600	1360	10600
bunch intensity [10^{11}]	0.94	0.46	[illegible]
beam current [mA]	480	30	[illegible]
rms bunch length [cm]	0.15	0.12	[illegible]
rms emittance [nm]	2.1 (x)	[illegible]	[illegible]
$\beta_{x,y}$*[mm]	7.4	[illegible]	...0/200
$\sigma_{x,y}$* [μm]	[illegible]	[illegible]	equal
beam-b. paramete[r]	[illegible]	...13	0.008
hourglass red[uction]	[illegible]	~0.48	
CM energy [TeV]	...5	4.9	
luminosity[10^{34}cm...]	**8.7**	**0.9**	

a ring-ring collider could have higher luminosity, higher energy reach, positrons, and some polarization.

but large disruption (D>30) and hourglass effect (H_{hg}<0.5) would call for careful study

wall plug power (lepton branch)

	linac-ring	ring-ring
total RF voltage	10 GV	0.5 GV
RF gradient	20 MV/m	12 MV/m
cryogenics (dynamic load)	14 MW (Q_0=4x10^{10})	0.2 MW (Q_0=4x10^{10})
RF operation & microphonics control	12 MW (401 MHz)	<5 MW?
addt'l RF power to compensate SR losses	96 MW (I_e=25.6 mA)	~100 MW
injector	7 MW	7 MW?
magnets (arcs + IR)	4 MW	4 MW?
total	~133 MW	~114 MW

similar power levels

conclusions

- *FCC-he* can be based on the *LHeC-HF ERL*
- peak luminosities L>1-3x10^{34} $cm^{-2}s^{-1}$ with 60 GeV e^-
- 80-90% polarized e^- collisions may be possible, perhaps at lower luminosity (polarized e^-gun current)
- e^+ operation looks challenging; it would most likely need to be based on recycling the positrons
- SRF & power sources development aligned with *FCC-ee* / *FCC-hh* RF R&D (same frequency, similar RF gradients,…)
- options for higher-energy ERLs naturally fit
- FCC-he baseline parameters still to be released!