Other Uses of ERL based LHeC

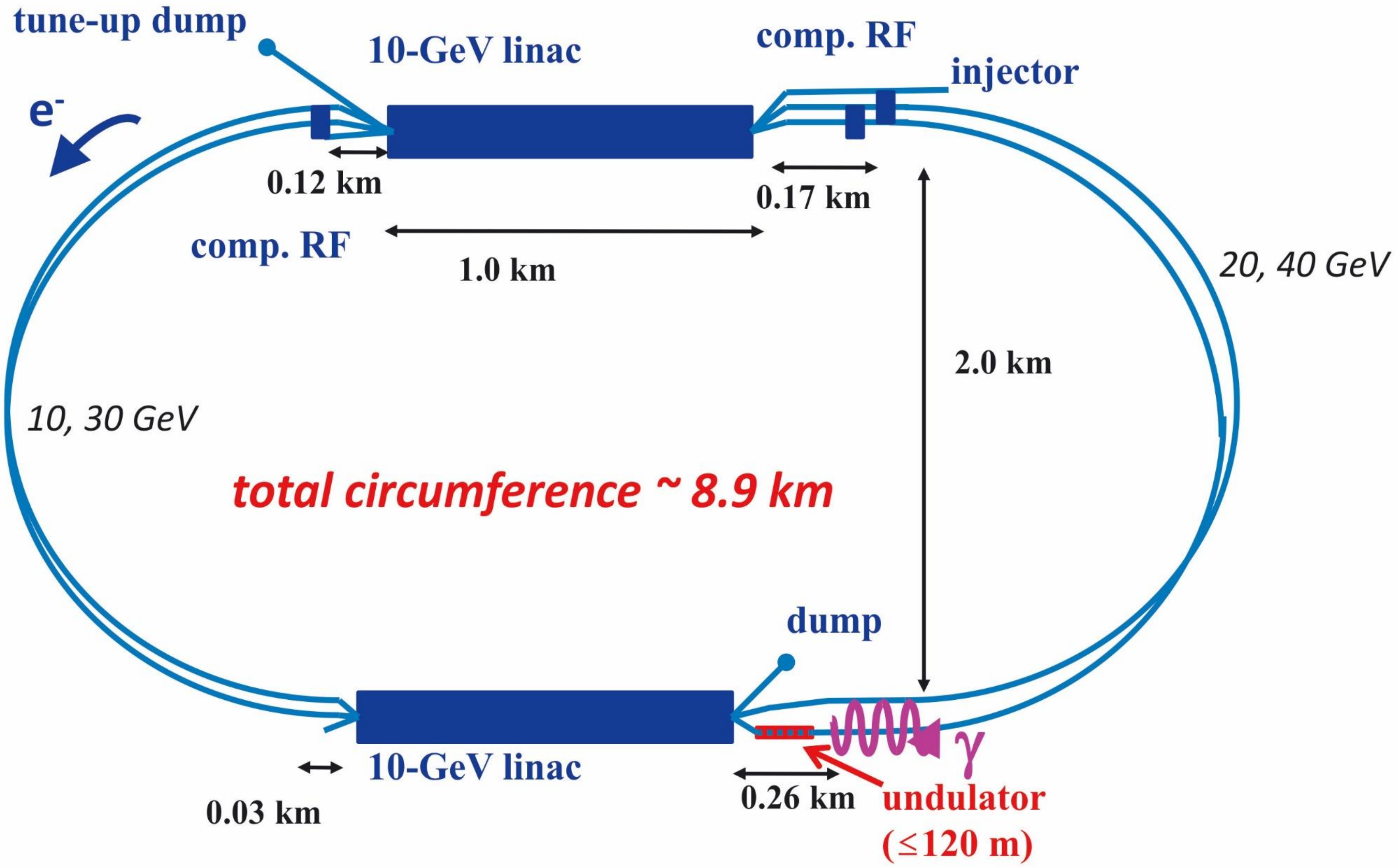
1. LHeC-FEL **Zafer Nergiz**, Frank Zimmermann, Husnu Aksakal
2. $\gamma\gamma$ Higgs factory SAPPHiRE

Atoosa Meseck, Frank Zimmermann

"Electrons for the LHC" workshop,

LAL Orsay, 28 june 2018

LHeC recirculating linac reconfigured for FEL operation



The main LHeC-ERL electron beam parameters.

Parameters	Unit	Value
energy	GeV	40.0
relativistic gamma		78277.9
electrons per bunch		3×10^9
rms bunch length	μm	7
peak beam current	kA	8.2
average beam current	mA	~20
normalized emittance	μm	0.5
bunch spacing	ns	25
rms energy spread	%	0.1

optimum match: $\varepsilon_N \leq \frac{\gamma\lambda}{4\pi}$

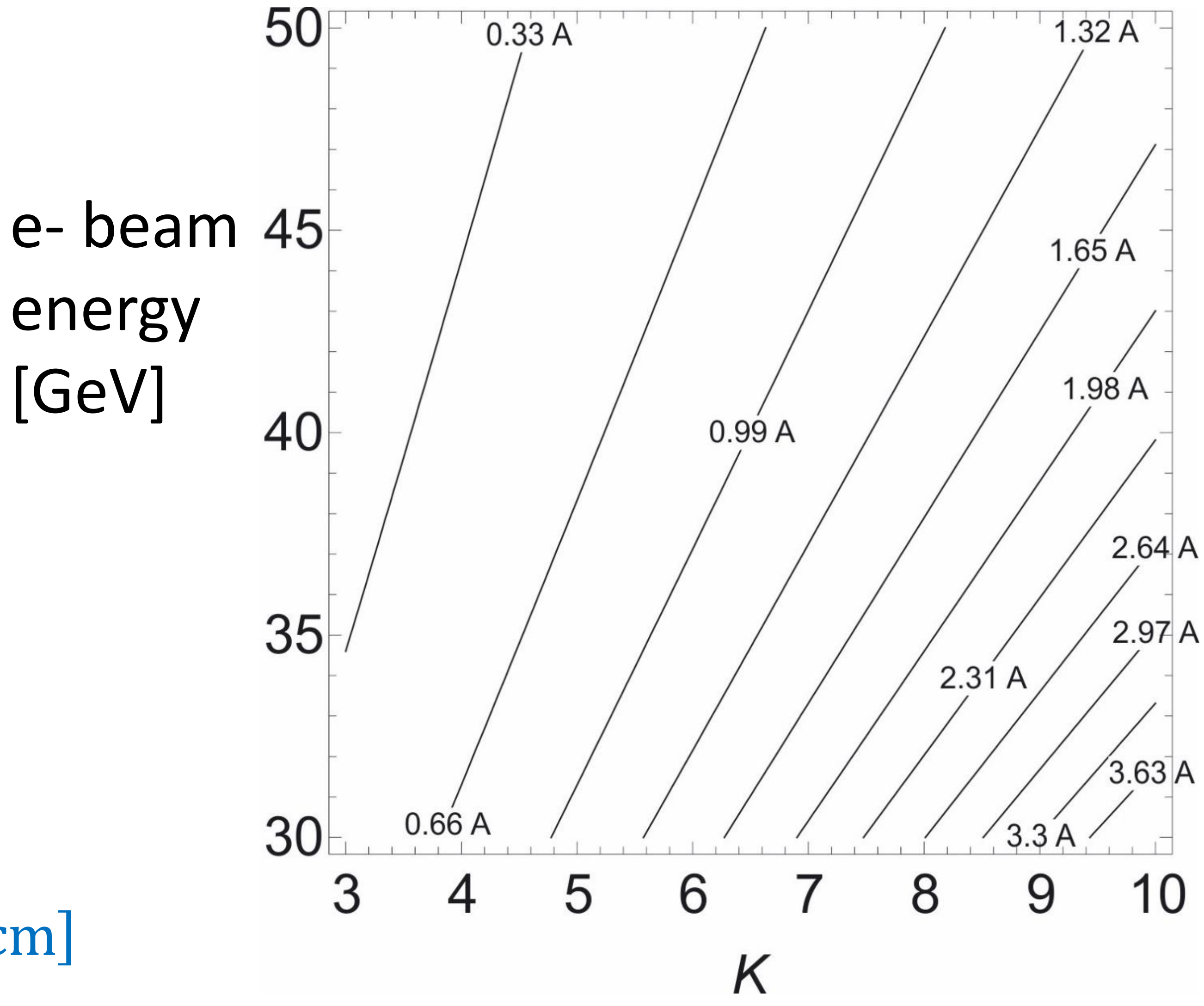
✓ OK for sub-Angstrom wavelengths

Parameters of some operating ERL-based FELs at lower beam energy.

facility	BINP[3]	JAEA[4]	JLAB[5]
beam energy [MeV]	20	17	120
peak current [A]	3000	35	300
average current [mA]	100	8	8
photon wavelength [μm]	40	22	1.6
average FEL power [W]	500	1	10,000
pulse duration [ps]	50	0.32	0.17

LHeC-FEL goal: hard X-ray FEL radiation in the range between 0.45 Å and 2.2 Å

LHeC FEL wavelength (contours) as a function of electron beam energy (vertical axis) and undulator parameter (horizontal axis).



$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

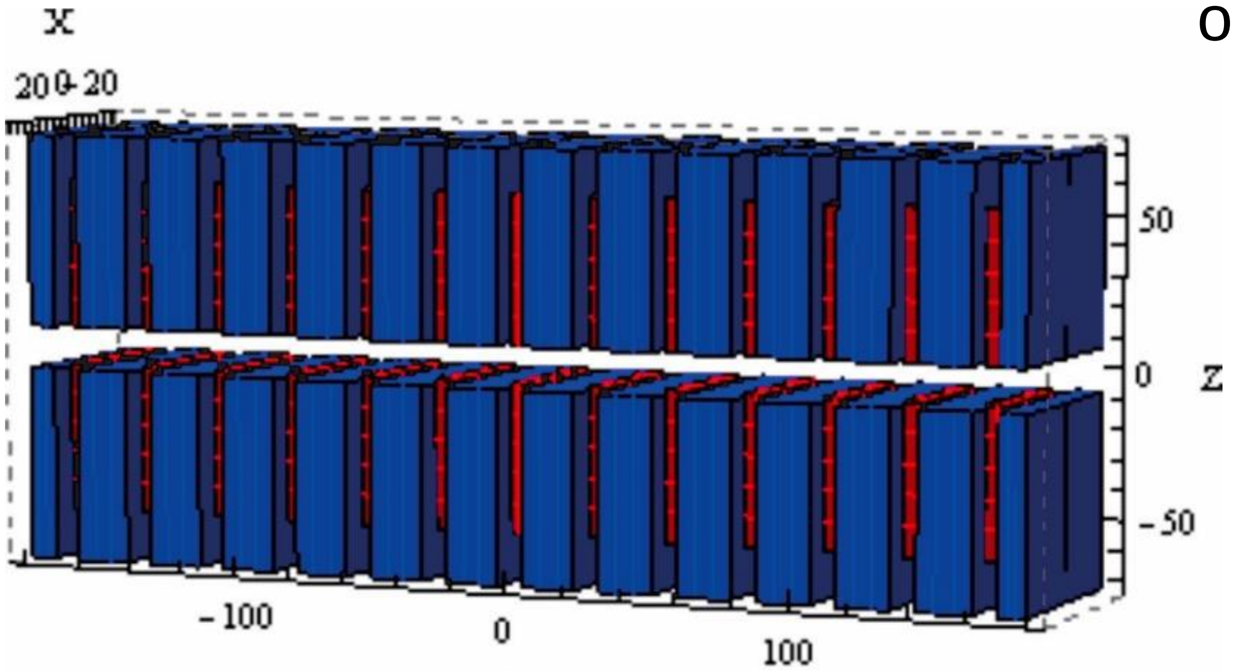
$$K = 0.934\, B\ [\mathrm{T}]\ \lambda_u[\mathrm{cm}]$$

$\lambda_u = 5.5$ cm

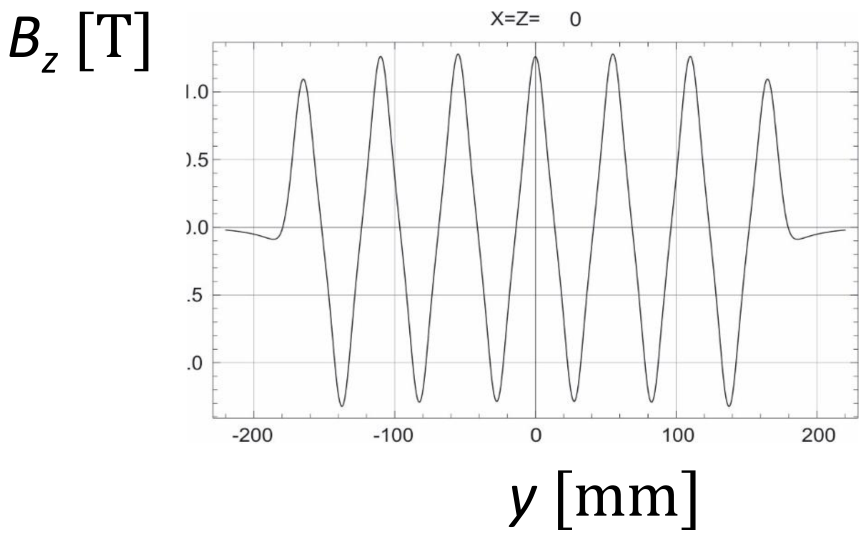
Main parameters of the LHeC-FEL undulator.

parameter	value
period length (cm)	5.5
number of period	61
total length (m)	120
minimum gap (mm)	7.2
"undulator parameter" K	4.2–9.9
wavelength range (Å)	0.45–2.24

Magnet arrays of undulator. Permanent magnet elements are in blue and the iron poles in red. All units are in mm. Only first few periods shown.



Vertical magnetic field along the axis of the U55 undulator for a gap of 12.4 mm; only a few periods shown.

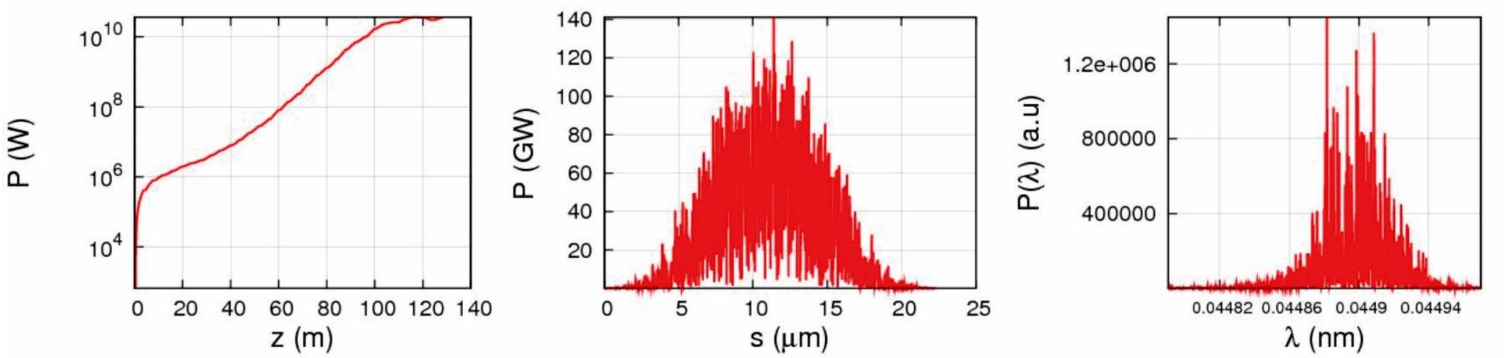


Genesis simulation results

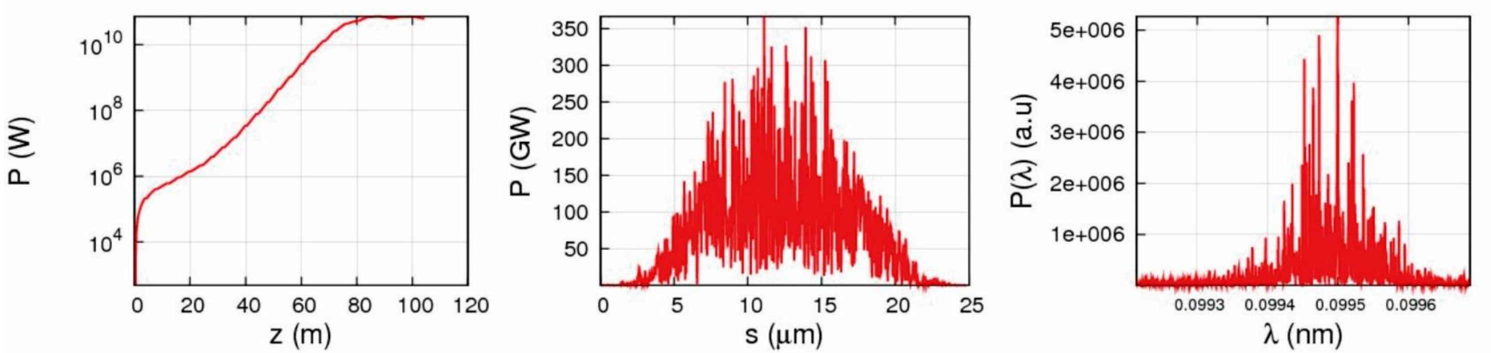
evolution of the pulse power along the undulator

spatial (temporal) profile of the radiation pulse

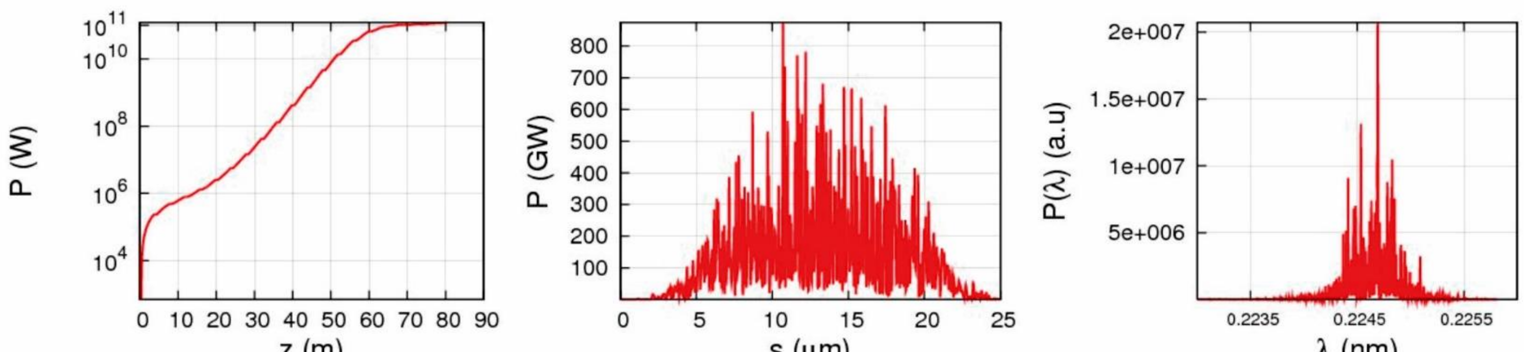
wavelength spectrum of the radiation



for λ=0.45 Å (K = 4.24)



for λ=1 Å (K = 6.5)

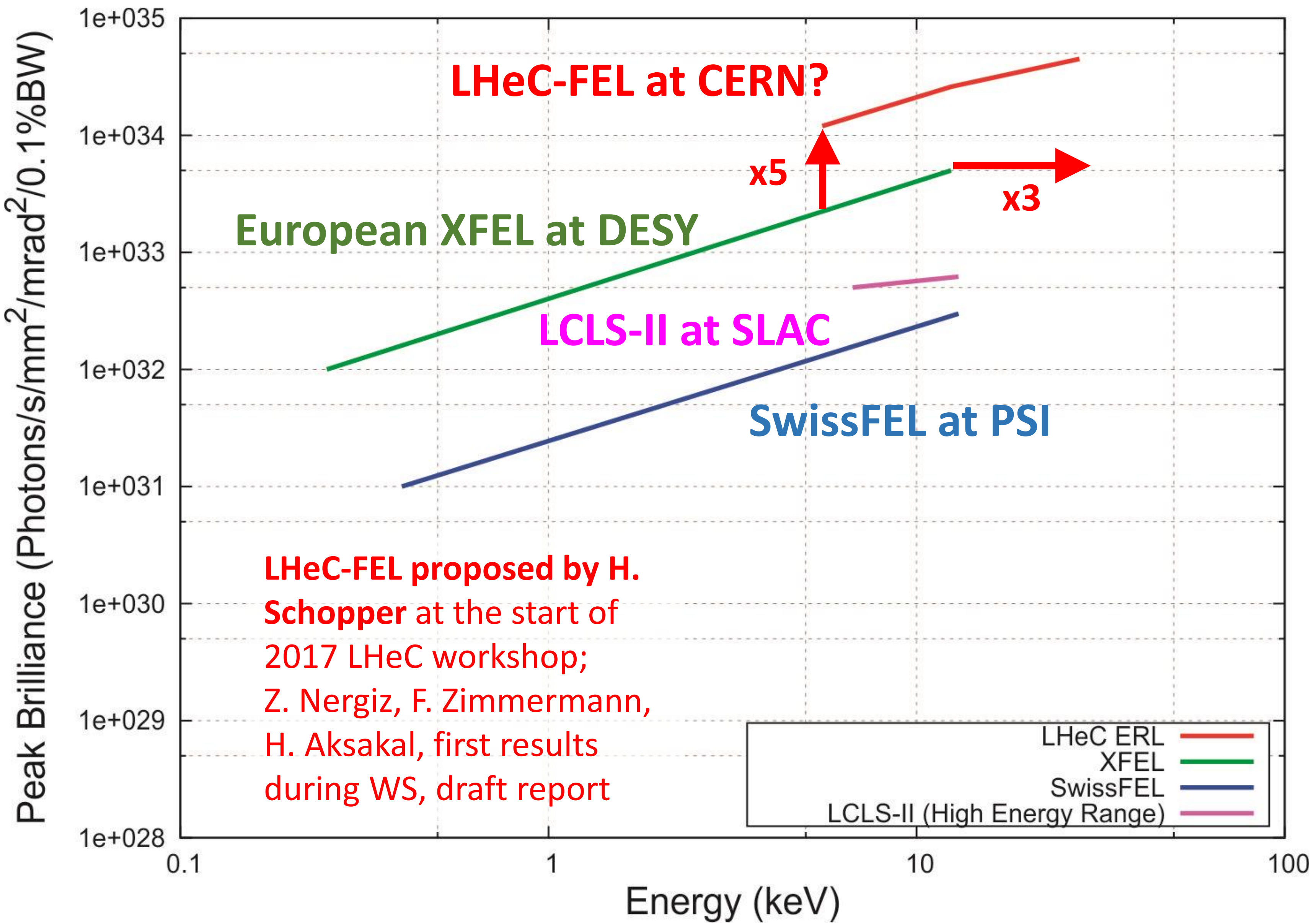


for λ=2.24 Å (K = 9.9)

LHeC-FEL radiation parameters derived from simulations. The peak-power values were obtained by averaging the simulated power over the length of the pulse ($\pm\sigma_z$). The unit for the corrresponding peak and average brilliance (B) is equal to photons/mm^2/mrad^2/s/0.1%bw.

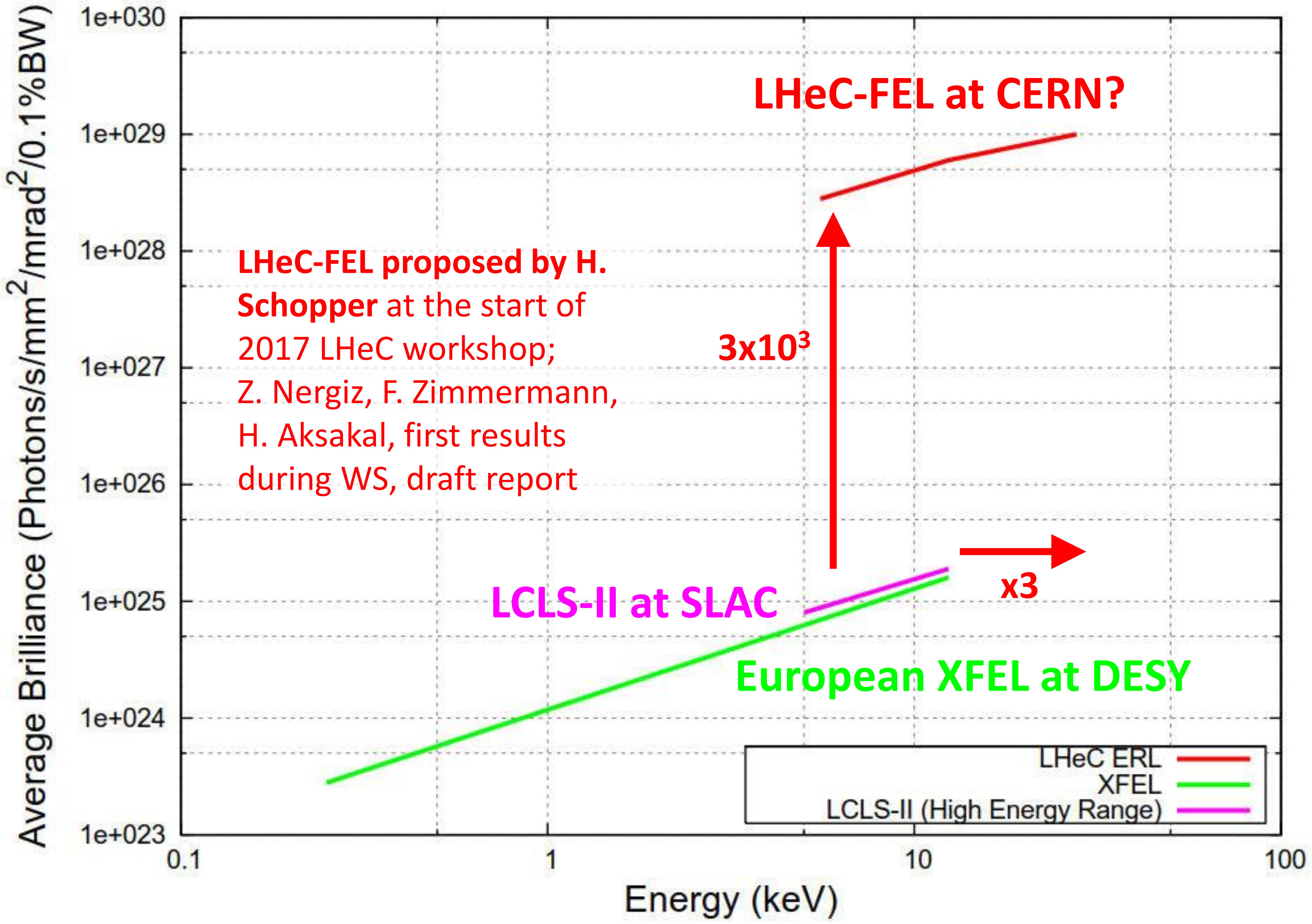
parameters	Unit	K=4.24	6.5	9.9
electron energy	GeV	40	40	40
wavelength	nm	0.045	0.1	0.225
photon energy	keV	27.7	12.41	5.54
saturation length	m	110	85	70
peak power	GW	40	65	120
pulse duration	fs	60	60	60
bandwidth	%	0.04	0.05	0.09
photons per pulse	#	5.2×10^{11}	2.5×10^{12}	7.8×10^{12}
peak brilliance	B	4.5×10^{34}	2.6×10^{34}	1.2×10^{34}
average brilliance	B	1.0×10^{29}	6.0×10^{28}	2.8×10^{28}

peak brilliance, LHeC-FEL compared with state-of-the-art

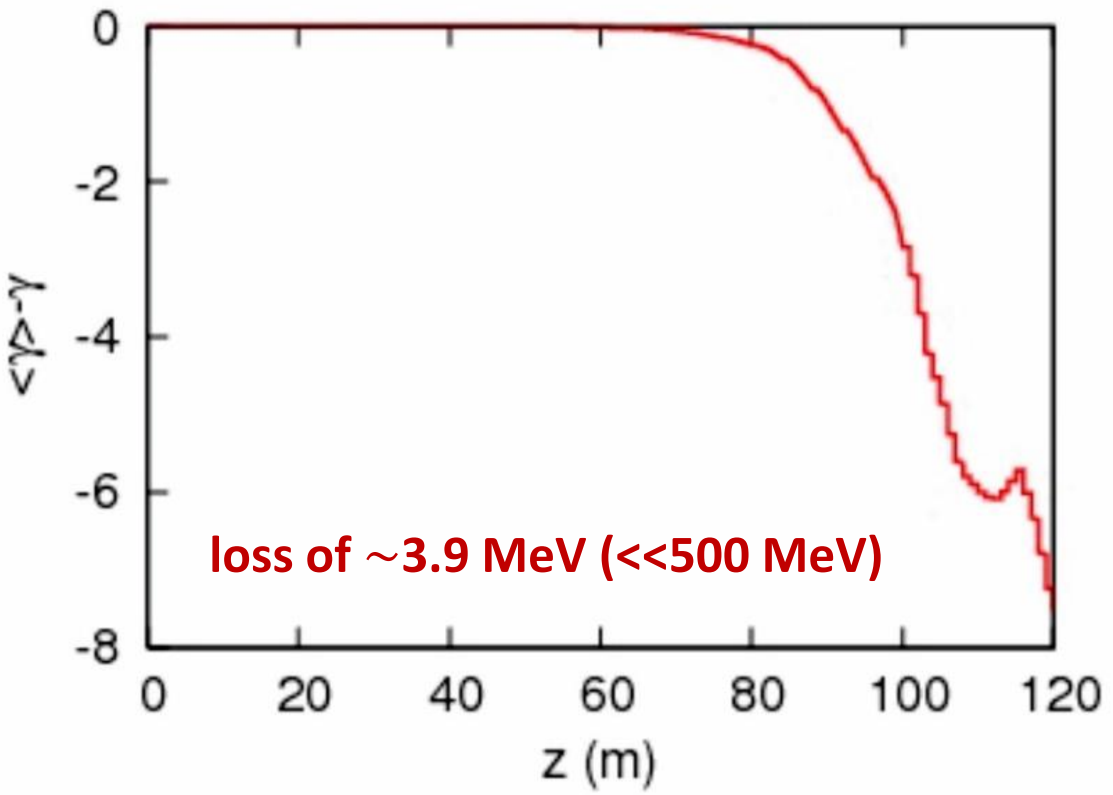


highlight ARIES WP6.5 workshop *LHeC/FCC-eh*

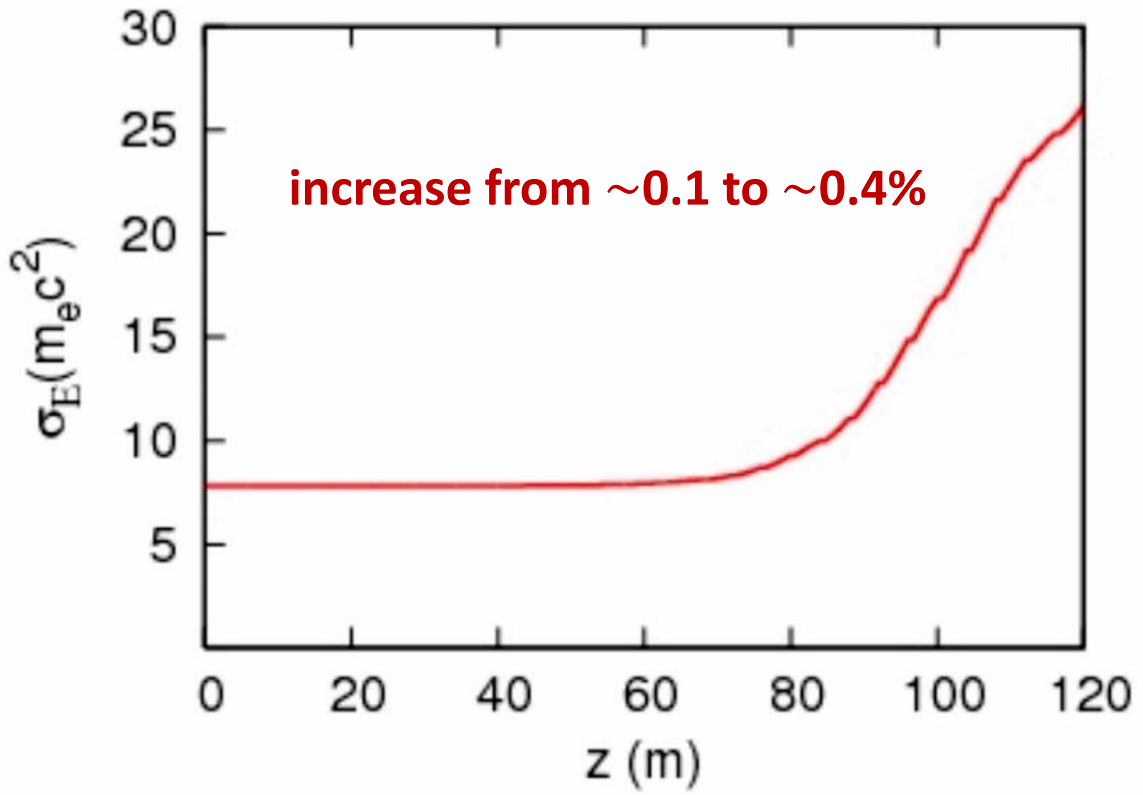
average brilliance, **LHeC-FEL** compared with state-of-the-art



evolution of the electron energy loss in units of gamma along the undulator region



evolution of the electron beam energy spread in units of the electron rest mass energy along the undulator region



→ no problem for energy recovery

LHeC-FEL Conclusions

- 40 GeV LHeC can produce SASE FEL radiation in (sub-) Angstrom wavelength regime at exceedingly high peak power and brilliance
- both peak and average brilliance far exceed other, existing or proposed X-ray FELs; e.g. at λ=0.45 Å, peak power 120 GW, peak brilliance 4.5×10^{34} photons/mm^2/$mrad^2$/s/0.1%bw
- beam is cw with 25 ns bunch spacing, translating into a remarkable average brilliance
- self seeding and tapered undulator would yield even better performance

References for LHeC –FEL

[1] Z. Nergiz, F. Zimmermann, H. Aksakal, 'Free electron laser based on the Large Hadron electron Collider,' draft report

[2] H. Schopper, suggestion during the 2017 LHeC/FCC-eh workshop (2017), https://indico.cern.ch/event/639067

[3] J. Sekutowicz et al., Phys. Rev. ST Accel. Beams 8, 010701 (2005)

[4] Tech. Rep. SLAC-I-060-003-000-02-R003 (2011)

[5] M. Altarelli et al., Tech. Rep. DESY 2006-097 (2006)

[6] R. Ganter et al., Tech. Rep. PSI Bericht Nr. 10-04 (2010)

[7] J. Galayda (2015), BESAC Presentation

[8] S. Reiche et al., Genesis User's Manual (2004), available at http://genesis.web.psi.ch/.

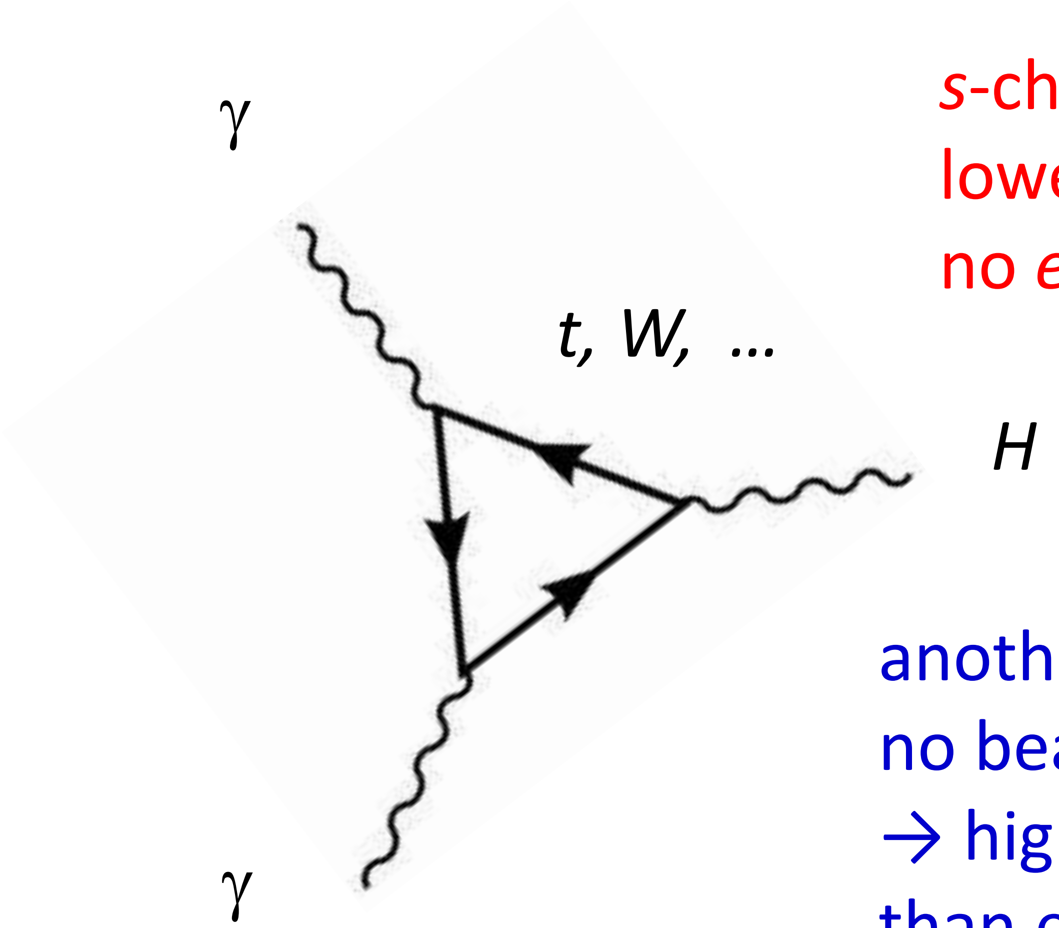

SAPPHiRE++

Photon Beams, Padua

27-28 November 2017

state-of-the-art in $\gamma\gamma$ colliders, Compton sources, γ factories

a new type of collider

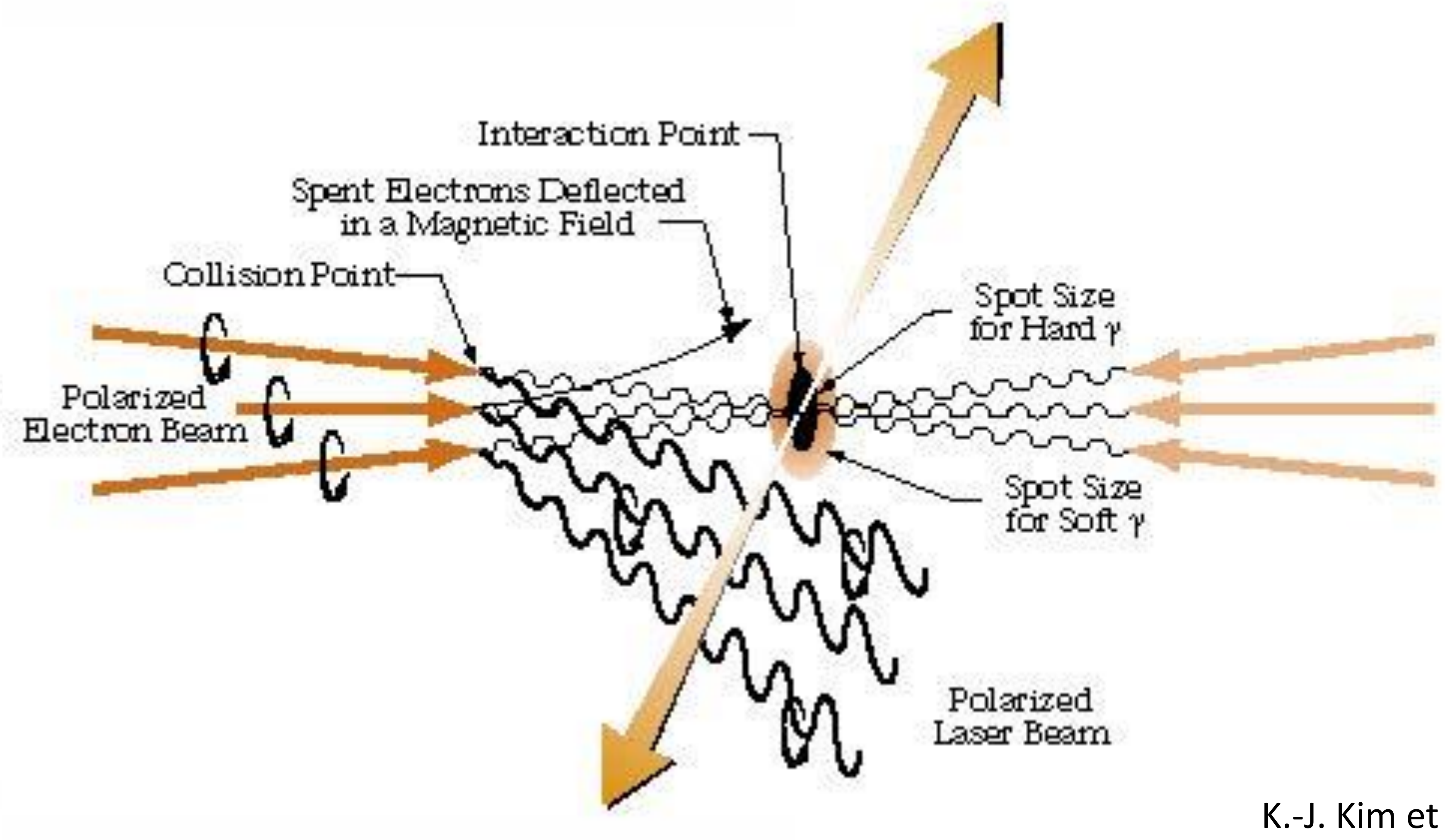


s-channel production;
lower energy;
no e^+ source

another advantage:
no beamstrahlung
→ higher energy reach
than e^+e^- colliders

γγ collider Higgs factory

$\gamma\gamma$ collider based on e^-

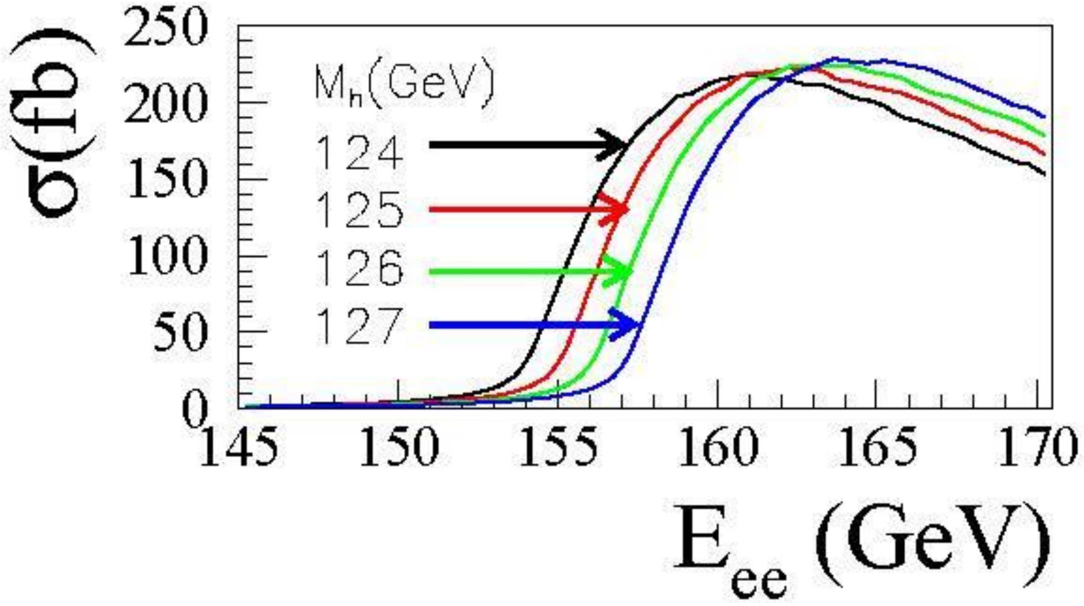


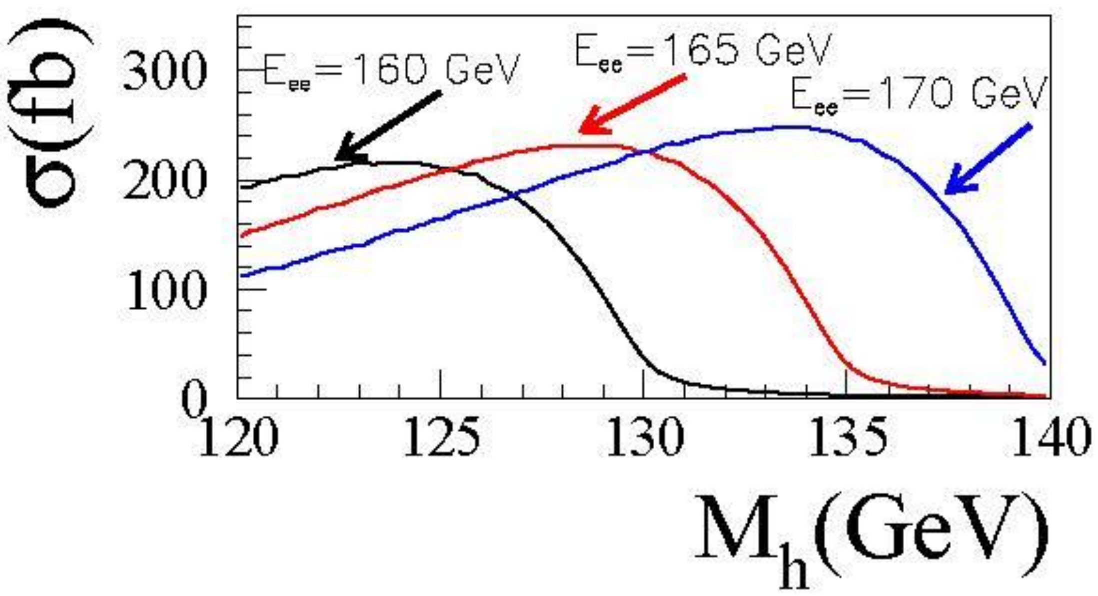
K.-J. Kim et al.

combining photon science & particle physics!

Higgs $\gamma\gamma$ production cross section

S. A. Bogacz, J. Ellis, L. Lusito, D. Schulte, T. Takahashi, M. Velasco, M. Zanetti, F. Zimmermann, ‘SAPPHiRE: a Small Gamma-Gamma Higgs Factory,’ arXiv:1208.2827





Left: The cross sections for γγ → h *vs* M_h *as functions of* E_{CM}(e-e-).
Right: The cross section for γγ→ h *vs* M_h *for three different values of* E_{CM}(e-e-).
Assumptions: e- have 80% longitudinal polarization and lasers are circularly polarized, so that produced photons are highly circularly polarized at their maximum energy.

which beam & photon energy / wavelength?

$$E_{\gamma,max} = \frac{x}{1+x} E_{beam}$$

$$x = \frac{4E_e\omega_L}{m_e^2}\cos^2\frac{\theta}{2}$$

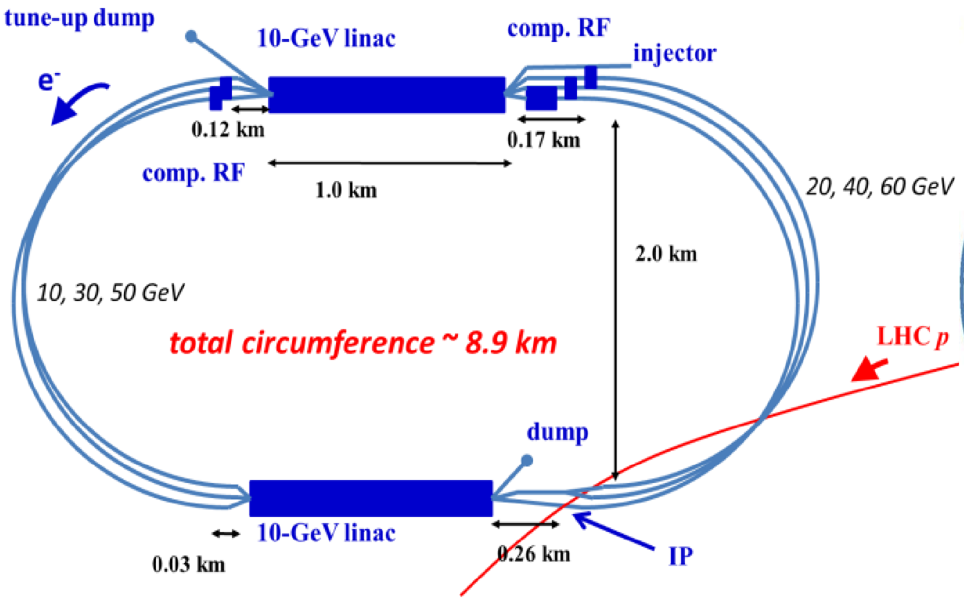
example $x \approx 4.3$ (for x>4.83: coherent pair production)

with $E_{beam} \approx$ 80 GeV: $E_{\gamma,max}$ ≈66 GeV, $E_{CM,max}$ ≈ 132 GeV

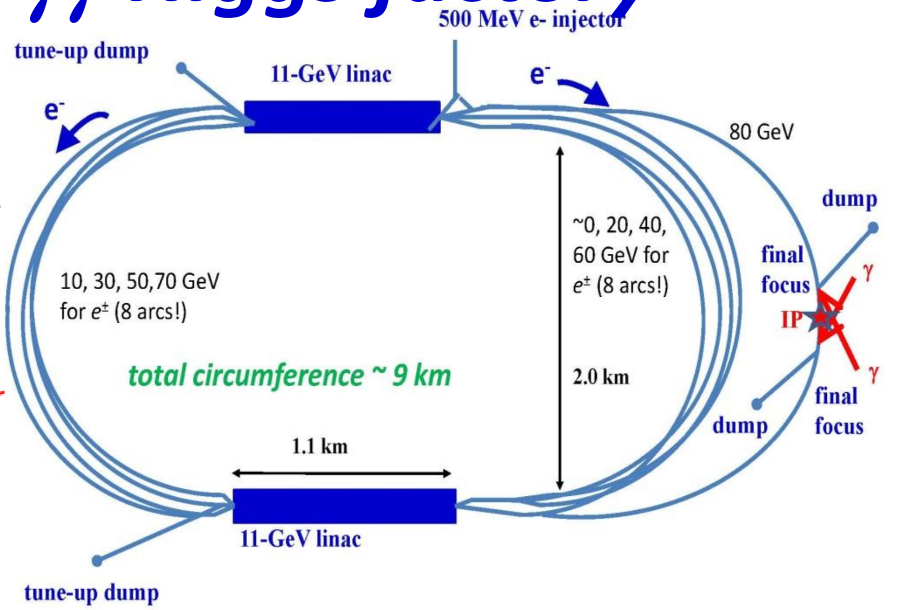
E_{photon} ~3.53 eV , λ~351 nm

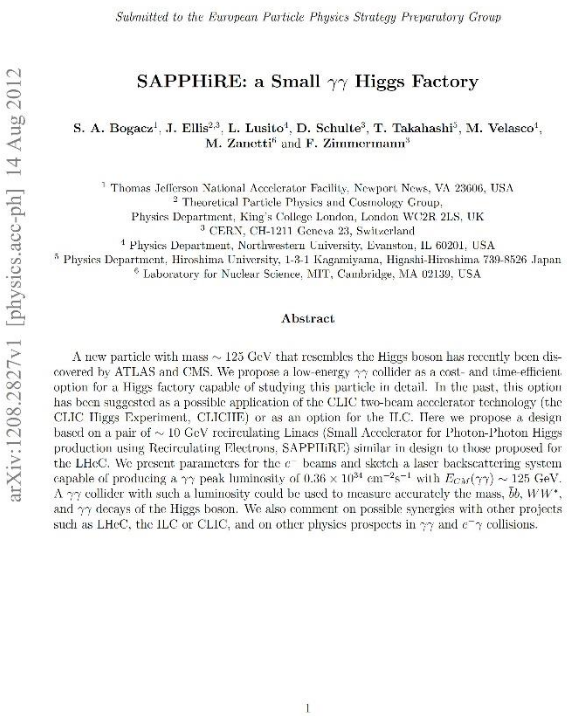
Reconfiguring *LHeC* → *SAPPHiRE*

LHeC-ERL



*SAPPHiRE**
γγ Higgs factory





arXiv:1208.2827v1 [physics.acc-ph] 14 Aug 2012

Submitted to the European Particle Physics Strategy Preparatory Group

SAPPHiRE: a Small $\gamma\gamma$ Higgs Factory

S. A. Bogacz[1], J. Ellis[2,3], L. Lusito[4], D. Schulte[3], T. Takahashi[5], M. Velasco[4], M. Zanetti[6] and F. Zimmermann[3]

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[4] Physics Department, Northwestern University, Evanston, IL 60201, USA
[5] Physics Department, Hiroshima University, 1-3-1 Kagamiyama, Higashi-Hiroshima 739-8526 Japan
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Abstract

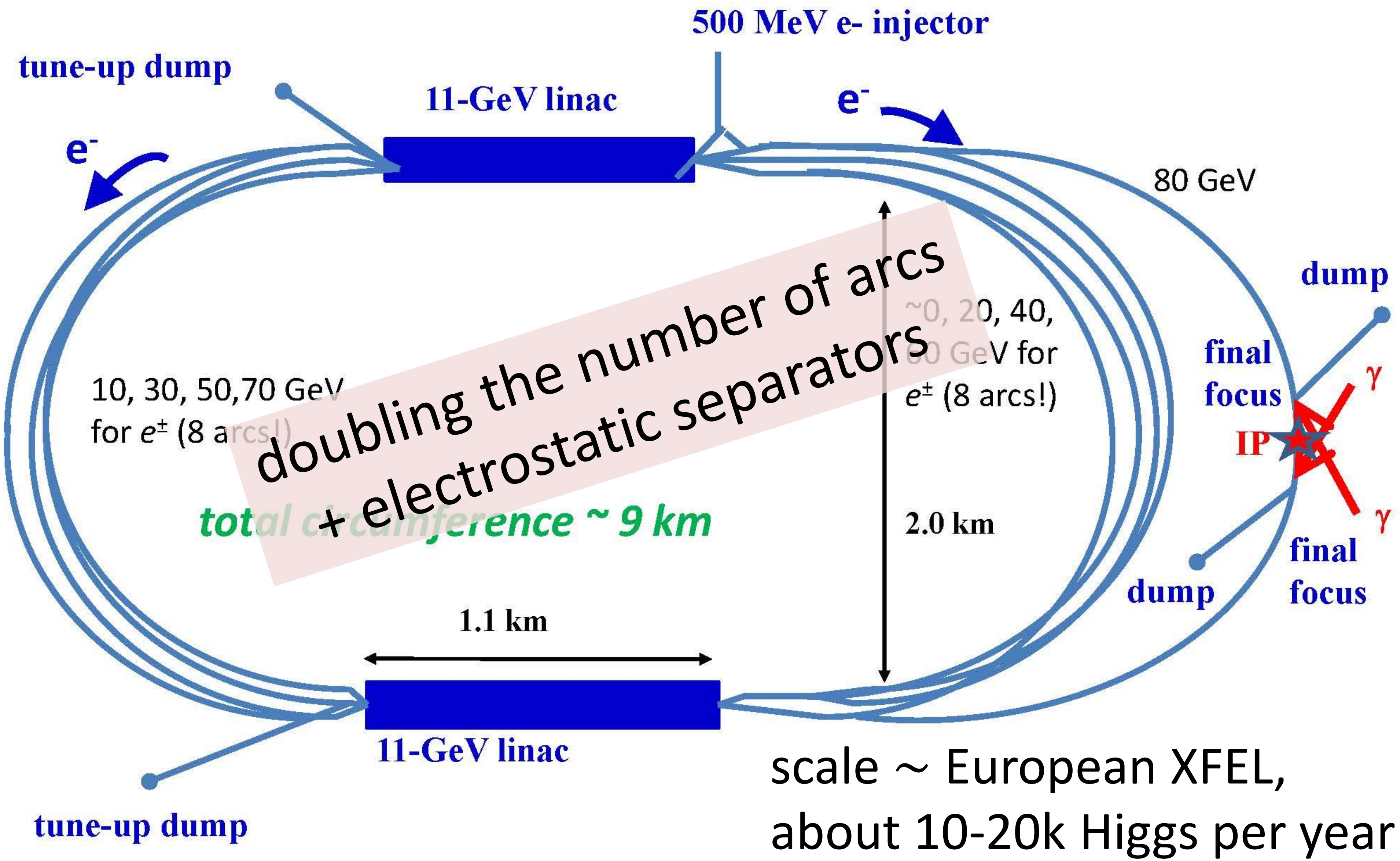
A new particle with mass ~ 125 GeV that resembles the Higgs boson has recently been discovered by ATLAS and CMS. We propose a low-energy $\gamma\gamma$ collider as a cost- and time-efficient option for a Higgs factory capable of studying this particle in detail. In the past, this option has been suggested as a possible application of the CLIC two-beam accelerator technology (the CLIC Higgs Experiment, CLICHE) or as an option for the ILC. Here we propose a design based on a pair of ~ 10 GeV recirculating Linacs (Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons, SAPPHiRE) similar in design to those proposed for the LHeC. We present parameters for the e^- beams and sketch a laser backscattering system capable of producing a $\gamma\gamma$ peak luminosity of 0.36×10^{34} cm^{-2}s^{-1} with $E_{CM}(\gamma\gamma) \sim 125$ GeV. A $\gamma\gamma$ collider with such a luminosity could be used to measure accurately the mass, $\bar{b}b$, WW^*, and $\gamma\gamma$ decays of the Higgs boson. We also comment on possible synergies with other projects such as LHeC, the ILC or CLIC, and on other physics prospects in $\gamma\gamma$ and $e^-\gamma$ collisions.

1

***S**mall **A**ccelerator for **P**hoton-**P**hoton **Hi**ggs production using **R**ecirculating **E**lectrons

S. A. Bogacz, J. Ellis, L. Lusito, D. Schulte, T. Takahashi, M. Velasco, M. Zanetti, F. Zimmermann, 'SAPPHiRE: a Small Gamma-Gamma Higgs Factory,' arXiv:1208.2827

SAPPHiRE: a Small γγ Higgs Factory



scale ~ European XFEL,
about 10-20k Higgs per year

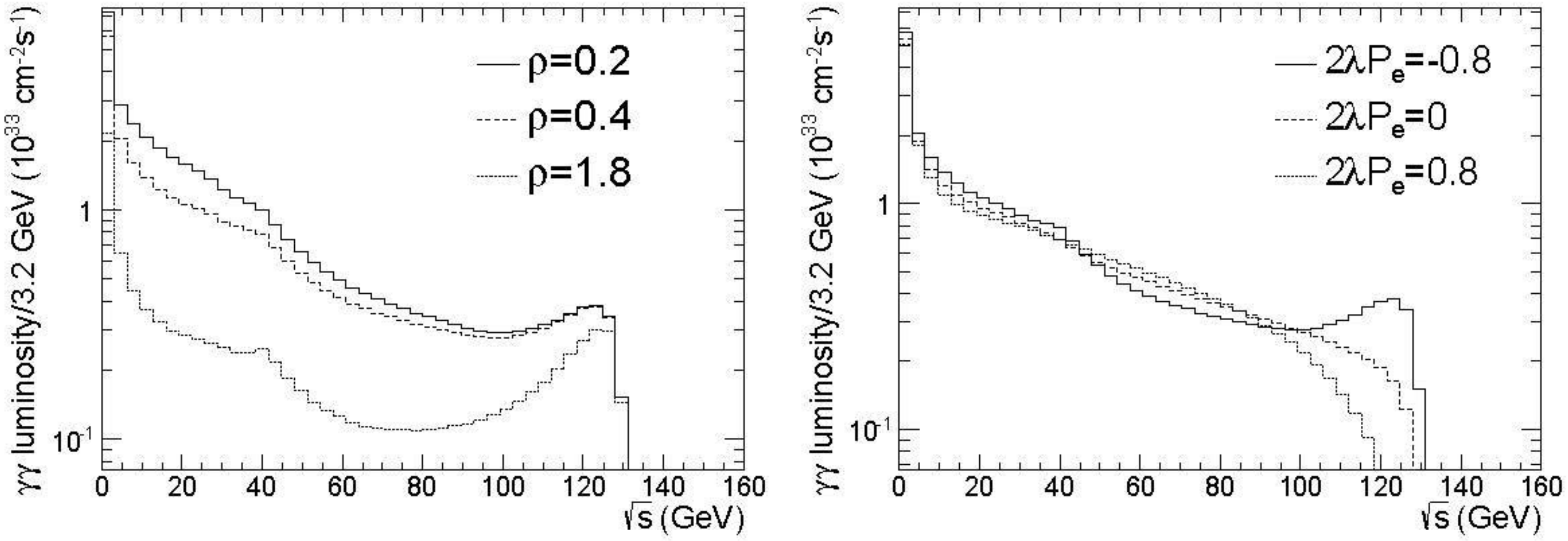
SAPPHiRE: Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons

SAPPHiRE	symbol	value
total electric power	P	100 MW
beam energy	E	80 GeV
beam polarization	P_e	0.80
bunch population	N_b	10^{10}
repetition rate	f_{rep}	200 kHz
bunch length	σ_z	30 μm
crossing angle	θ_c	≥20 mrad
normalized horizontal/vert. emittance	$\gamma\varepsilon_{x,y}$	5,0.5 μm
horizontal IP beta function	β_x^*	5 mm
vertical IP beta function	β_y^*	0.1 mm
horizontal rms IP spot size	σ_x^*	400 nm
vertical rms IP spot size	σ_y^*	18 nm
horizontal rms CP spot size	σ_x^{CP}	400 nm
vertical rms CP spot size	σ_y^{CP}	440 nm
e^-e^- geometric luminosity	L_{ee}	2×10^{34} cm^{-2}s^{-1}

average beam current 2x0.3 mA

SAPPHiRE $\gamma\gamma$ luminosity

M. Zanetti

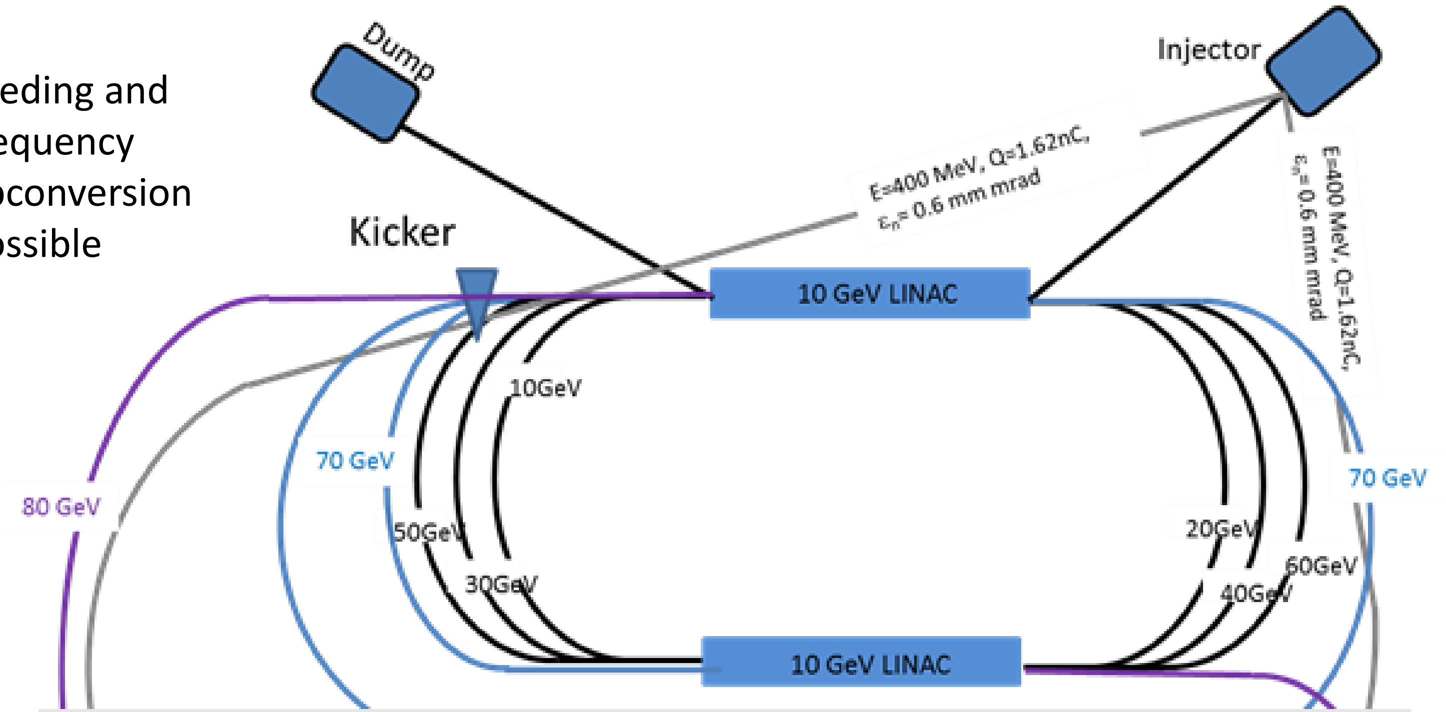


luminosity spectra for SAPPHiRE as functions of $E_{CM}(\gamma\gamma)$, computed using Guinea-Pig for **three possible normalized distances** $\rho \equiv l_{CP\text{-}IP}/(\gamma\sigma_y^*)$ (left) and **different polarizations of in-coming particles** (right)

$\rho=1 \leftrightarrow l_{CP\text{-}IP} \sim 2$ mm

improving the SAPPHiRE $\gamma\gamma$ Higgs factory

seeding and frequency upconversion possible



- Simple Scheme!
- Each FEL-Line delivers more than 10^{16} photons per pulse.
- Strongly focussed beams for inverse compton scattering mandatory! Transverse radiation and beam sizes about 300nm!
- Focussing of FEL-radiation and electron beam challenging!
- Kicker system needs detailed studies!

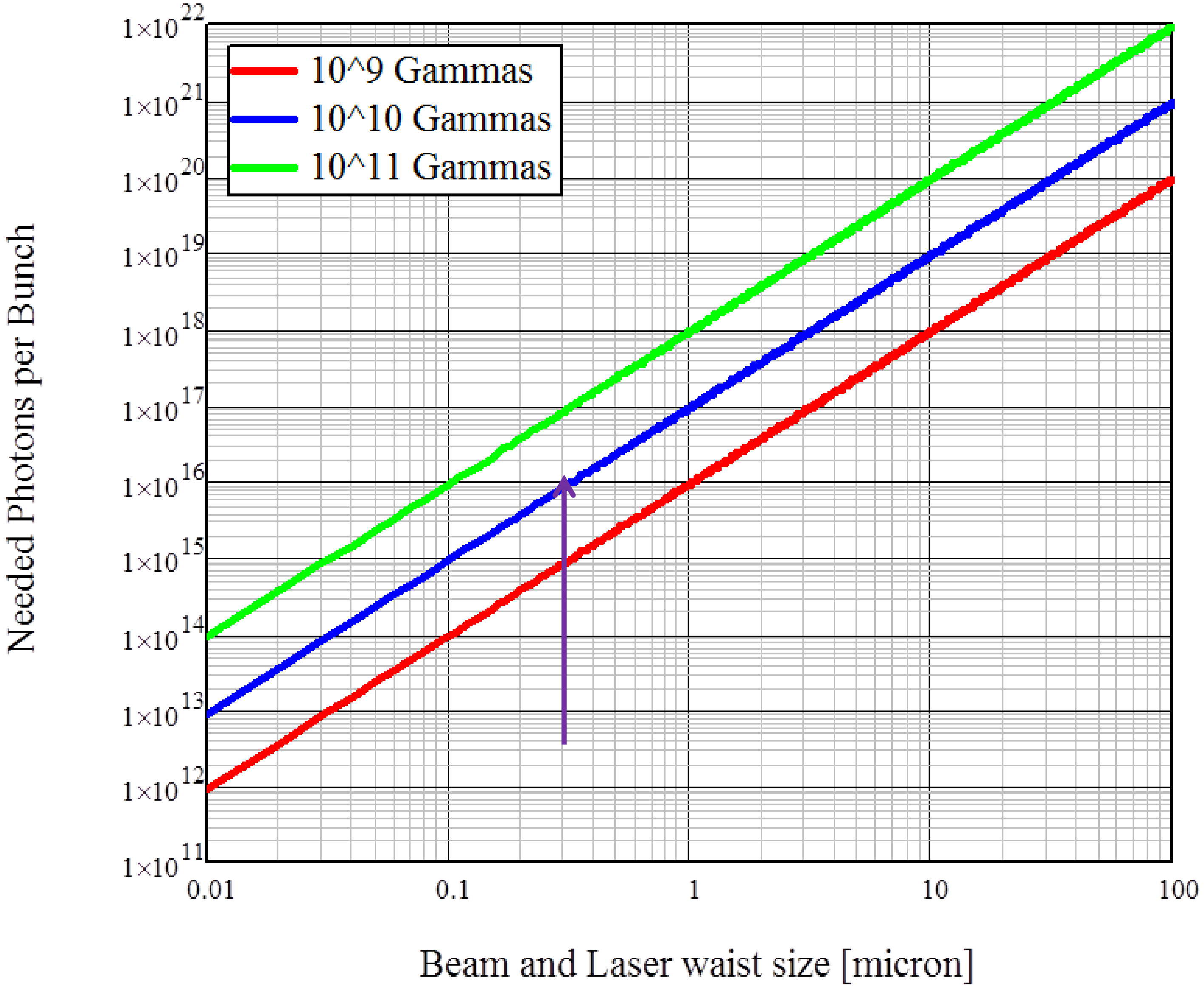
Generic recirculator-based $\gamma\gamma$ Higgs factory with two FELs (A. Meseck).

2017 innovations
(A. Meseck/ HZB):

- beam circulating only in one direction
  - applicable to both laser and FEL schemes
- refined FEL scheme driven by separate low-energy beams

required number of 3.5 eV photons per bunch as a function the beam dimension at the collision point for different gamma yields

using formula from PhD thesis of C. Curatolo (2016)



A. Meseck

SAPPHiRE R&D items

- $\gamma\gamma$ interaction region & spent e-
- large high-finesse optical cavity & high repetition rate laser
  - or *FEL implementation*
- *fast kicker*
  - or separation scheme for beams circulating in opposite directions
- polarized low-emittance e^- gun
- separation of spent beam after conversion

SAPPHiRE Conclusions

- SAPPHiRE = one of the cheapest possible options to further study the Higgs ; a serendipitous additional use of the LHeC RLA !
- a **refined scheme with fast kicker and bypass** avoids beam circulating in opposite direction and reduces the number of return loops by factor 2
- specific laser + optical cavity system meeting the requirements to be developed
- **alternative attractive FEL option**

References for LHeC and SAPPHiRE:

[1] S. A. Bogacz, J. Ellis, L. Lusito, D. Schulte, T. Takahashi, M. Velasco, M. Zanetti, F. Zimmermann, 'SAPPHiRE: a Small Gamma-Gamma Higgs Factory,' arXiv:1208.2827

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[4] Yuhong Zhang, 'Design Concept of a γ–γ Collider-Based Higgs Factory Driven by Energy Recovery Linacs,' JLAB Technote JLAB-TN-12-053, 31 October 2012

[5] E. Nissen, 'Optimization of Recirculating Linacs for a Higgs Factory,' prepared for HF2012

[6] J. Limpert, T. Schreiber, A. Tünnermann, 'Fiber lasers and amplifiers: an ultrafast performance evolution,' Applied Optics, Vol. 49, No. 25 (2010)

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[8] A. Meseck, numerous private communications