SAPPHiRE: a Gamma-gamma Higgs Factory based on the LHeC using lasers or FELs

Atoosa Meseck and Frank Zimmermann

Photon Beams 2017

Padua, 28 November 2017

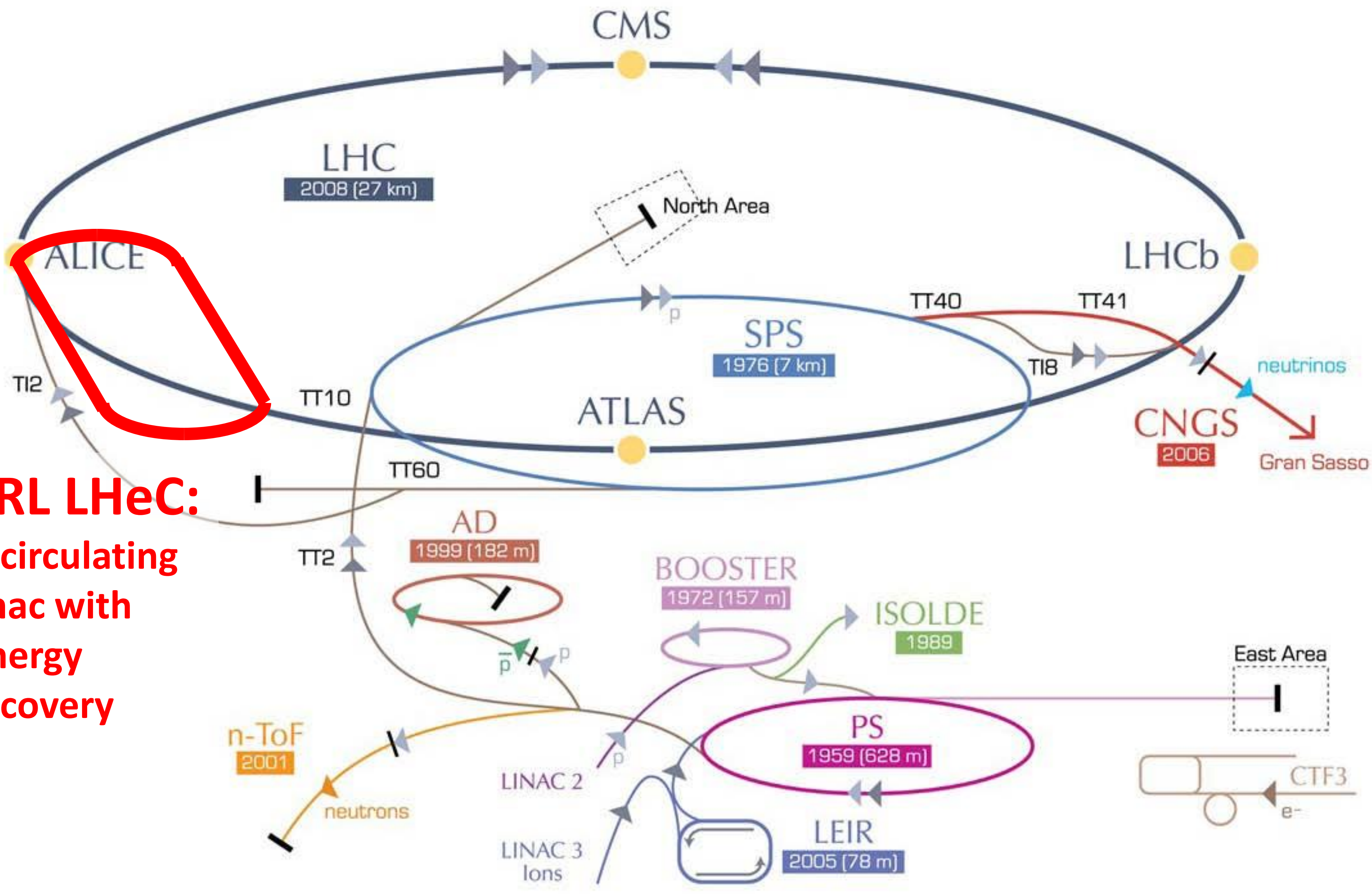
many thanks to

T. Takahashi and M. Zanetti

ARIES is co-funded by the European Commission in the HORIZON 2020 Research and Innovation programme under grant agreement no 730871.

LHeC

Large Hadron electron Collider (LHeC)
baseline design



ERL LHeC:
recirculating linac with energy recovery

LHeC Conceptual Design Report

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

A Large Hadron Electron Collider at CERN

Report on the Physics and Design
Concepts for Machine and Detector

LHeC Study Group
THIS IS THE VERSION FOR REFEREEING, NOT FOR DISTRIBUTION

LHeC CDR published in J. Phys. G: Nucl. Part. Phys. 39 075001 (2012)

http://cern.ch/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

~600 pages

LHeC Higgs physics

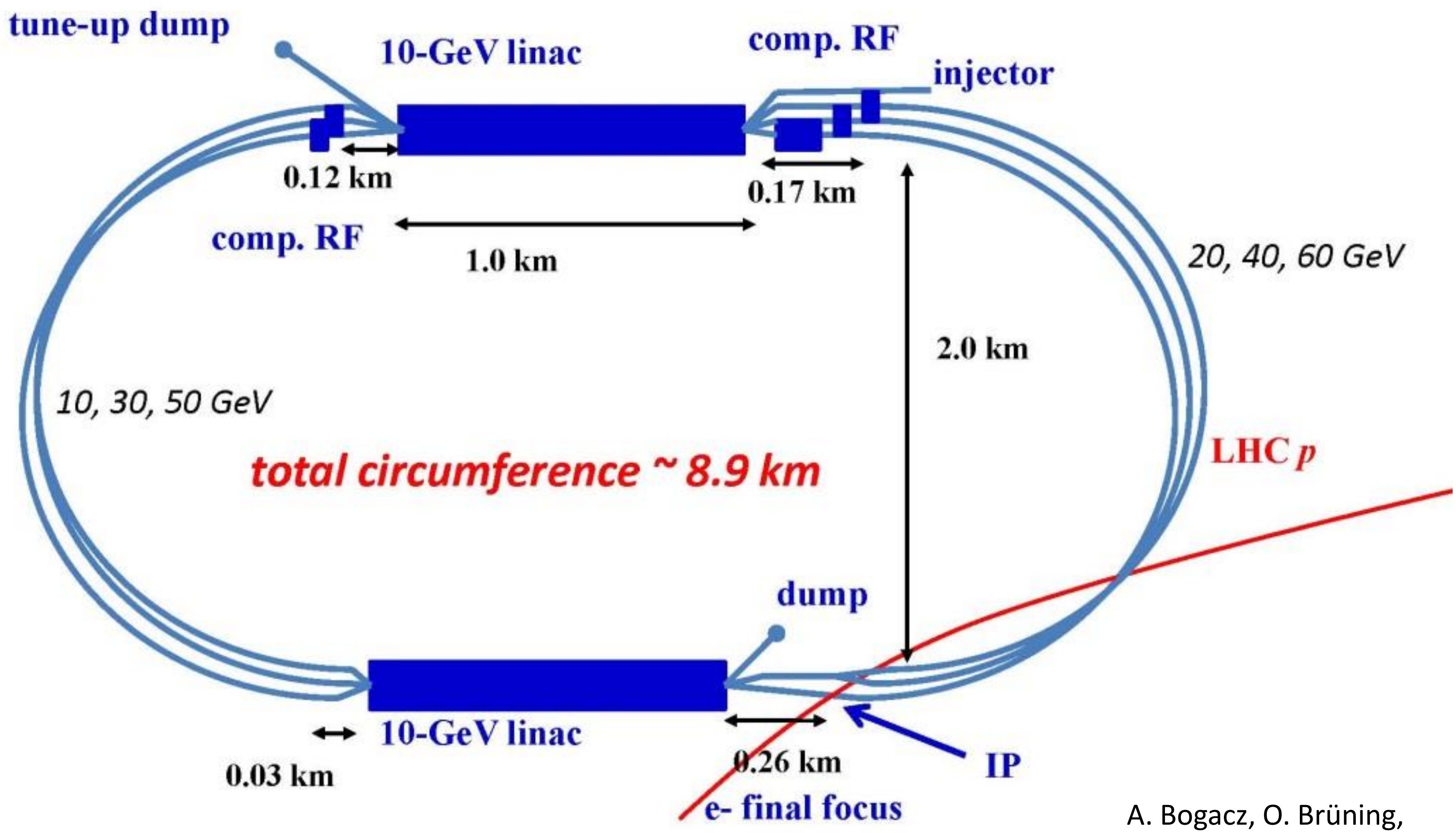
- precision coupling measurements
  ($Hb\bar{b}$, $H\gamma\gamma$, *H4l*,…)
- reduction of theoretical QCD-related uncertainties in *pp* Higgs physics
- potential to find new physics at the cleanly accessible *WWH* (and *ZZH*) vertices

LHeC baseline (& pushed) parameters

parameter [unit]	LHeC	
species	$e^{\pm}$	p, $^{208}Pb^{82+}$
beam energy (/nucleon) [GeV]	60	7000, 2760
bunch spacing [ns]	25, 100	25, 100
bunch intensity (nucleon) [10^{10}]	0.1 (0.2), 0.4	17 (22), 2.5
beam current [mA]	6.4 (12.8)	860 (1110), 6
rms bunch length [mm]	0.6	75.5
polarization [%]	90 (e^{+} none)	none, none
normalized rms emittance [μm]	50	3.75 (2.0), 1.5
geometric rms emittance [nm]	0.43	0.50 (0.31)
IP beta function $\beta^{*}_{x,y}$ [m]	0.12 (0.032)	0.1 (0.05)
IP rms spot size [μm]	**7.2 (3.7)**	**7.2 (3.7)**
synchrotron tune	-	0.0019
hadron beam-beam parameter	0.0001 (0.0002)	
lepton disruption parameter D	6 (30)	
hourglass reduction factor H_{hg}	0.91 (0.67)	
pinch enhancement factor H_D	1.35 (0.3 for e^{+})	
luminosity/ nucleon [10^{33} cm^{-2}s^{-1}]	**1 (10), 0.2**	

LHeC ERL layout

two 10-GeV SC linacs, 3-pass up, 3-pass down; 6.4 mA, 60 GeV e^-'s collide w. LHC *p*/ions, e^- RF grad ~20 MV/m, 720 or 800 MHz



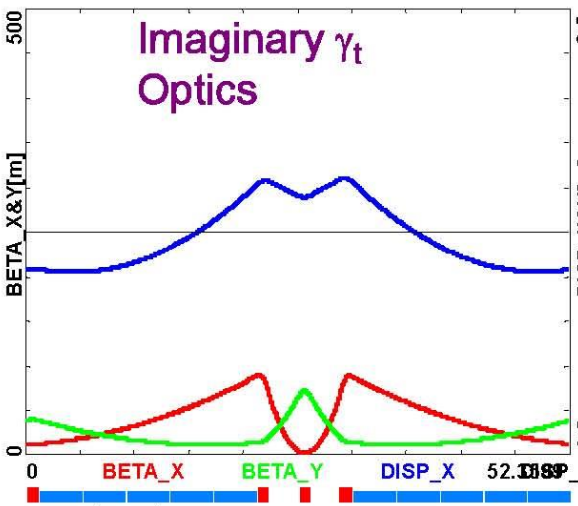
(C=1/3 LHC allows for ion clearing gaps)

A. Bogacz, O. Brüning,
M. Klein, D. Schulte,
F. Zimmermann, et al

LHeC: 3 passes, flexible momentum compaction arc lattice building block: 52 m long cell with 2 (10) dipoles & 4 quadrupoles

LHeC flexible momentum compaction cell; tuned for small beam size (low energy) or low $\Delta\varepsilon$ (high energy)

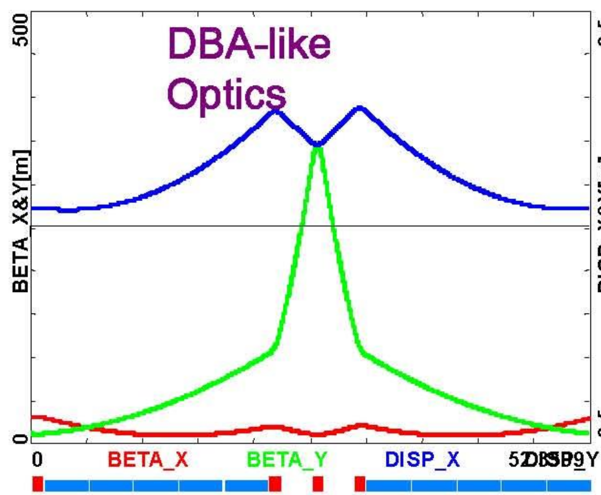
Arc 1 , Arc2



$$\langle H \rangle = 8.8 \times 10^{-3}\ m$$

limit chamber size
(>12 σ at 25 mm diameter)

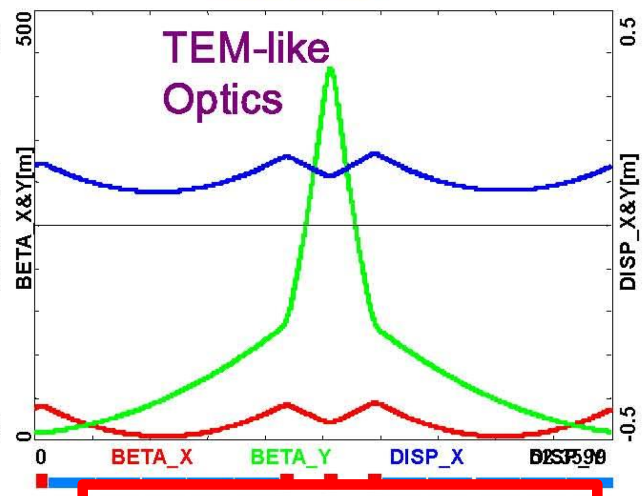
Arc 3, Arc 4



$$\langle H \rangle = 2.2 \times 10^{-3}\ m$$

Alex Bogacz

Arc5, Arc 6



$$\langle H \rangle = 1.2 \times 10^{-3}\ m$$

factor of 18 smaller than FODO

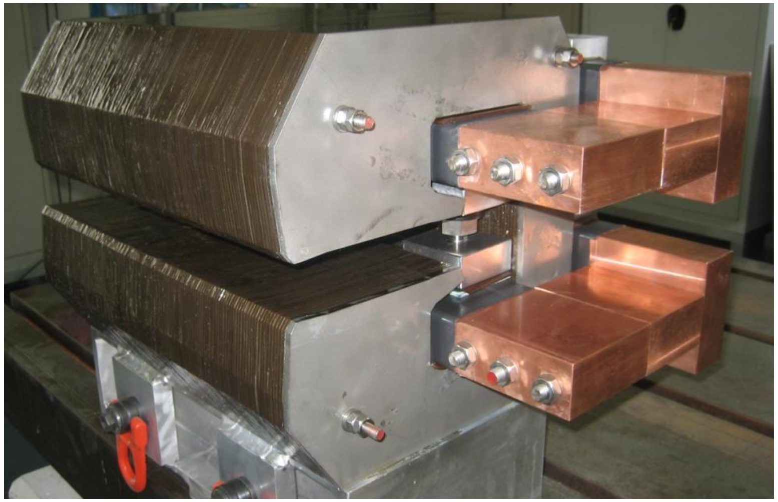
limit emittance growth

prototype arc magnets

eRHIC dipole model (BNL)

5 mm gap
max. field 0.43 T (30 GeV)

LHeC dipole models (BINP & CERN)



25 mm gap
max. field 0.264 T (60 GeV)

RF cavity development

5-cell 800 MHz cavity, JLAB prototype for LHeC, FCC-ee (top mode) & FCC-eh

optimized for high current operation

JLAB,
October 25, 2017

F. Marhauser et al

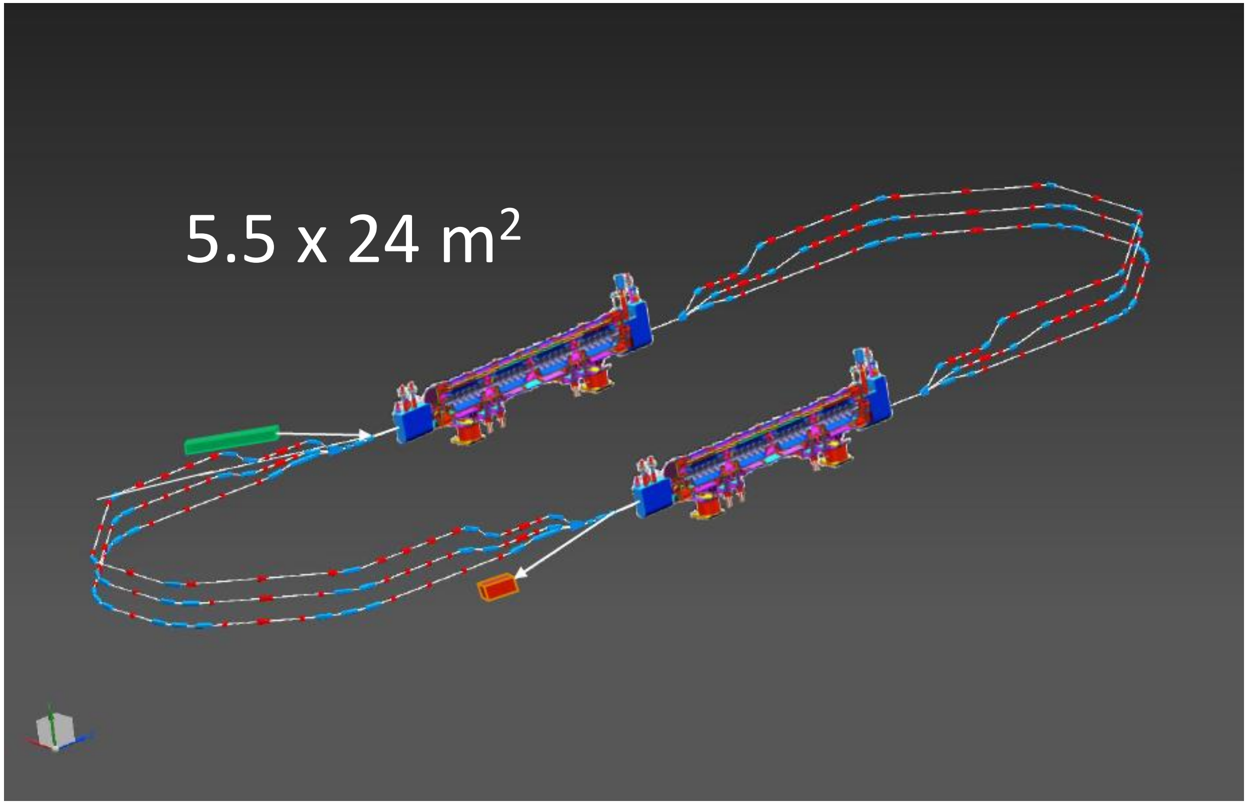
PERLE @ Orsay Test Facility

BINP, CERN, Daresbury/Liverpool, Jlab, Orsay +..

400 MeV, 3 turns, 20 mA, 802 MHz

CDR published in J Phys G [arXiv:1705. 08783]

intensity 100 x ELI: technology, beam dynamics, physics



M. Klein

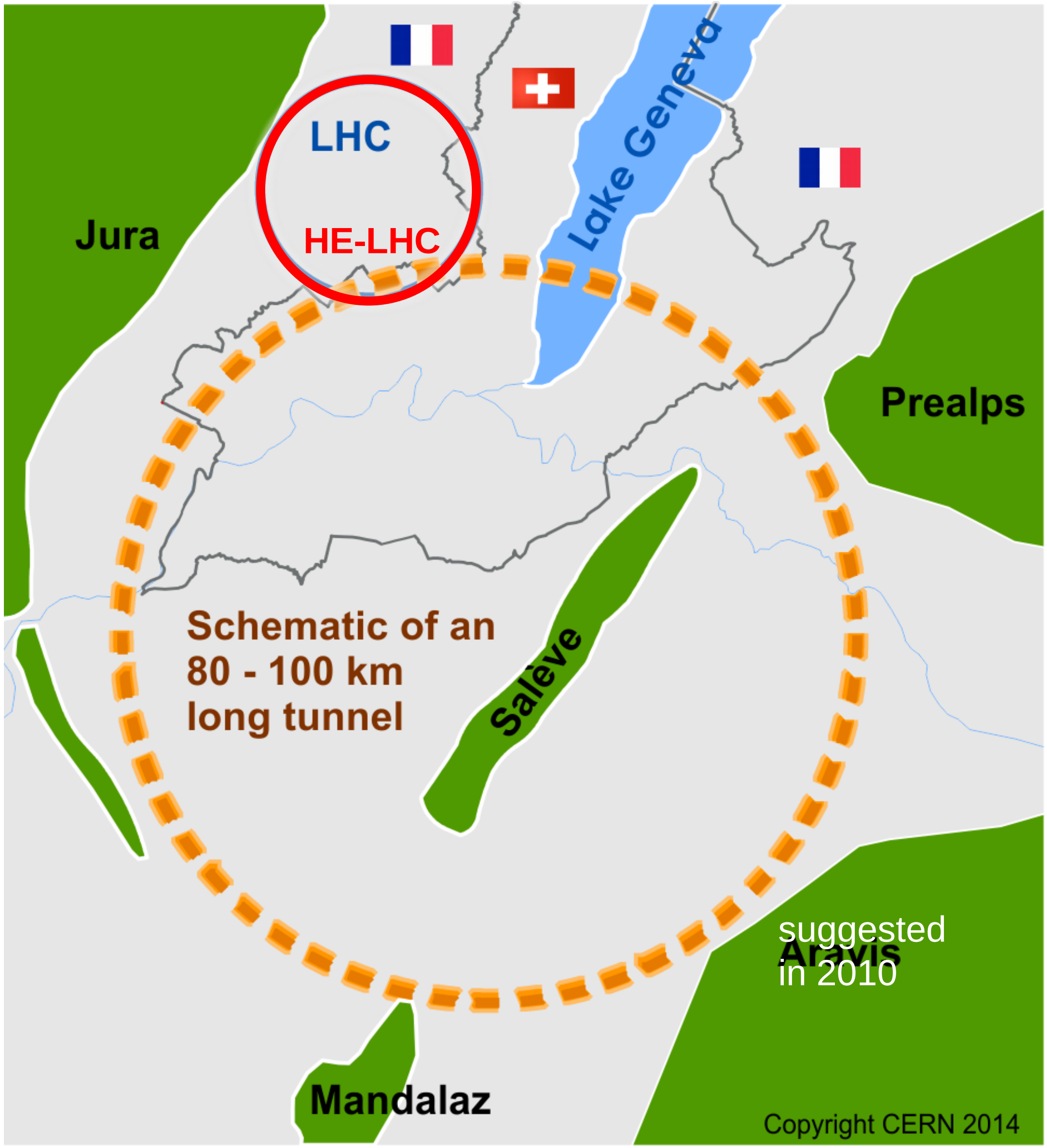
Future Circular Collider Study
Goal: CDR for European Strategy Update 2019/20

international FCC collaboration (CERN as host lab) to design:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area, site specific
- ***e⁺e⁻* collider (*FCC-ee*),** as a possible first step
- ***p-e* (*FCC-he*) option,** one IP, FCC-hh & ERL
- **HE-LHC** w *FCC-hh* technology



A Baseline for the FCC-he

Oliver Brüning[1], John Jowett[1], Max Klein[1,2],
Dario Pellegrini[1], Daniel Schulte[1], Frank Zimmermann[1]
[1] CERN, [2] University of Liverpool

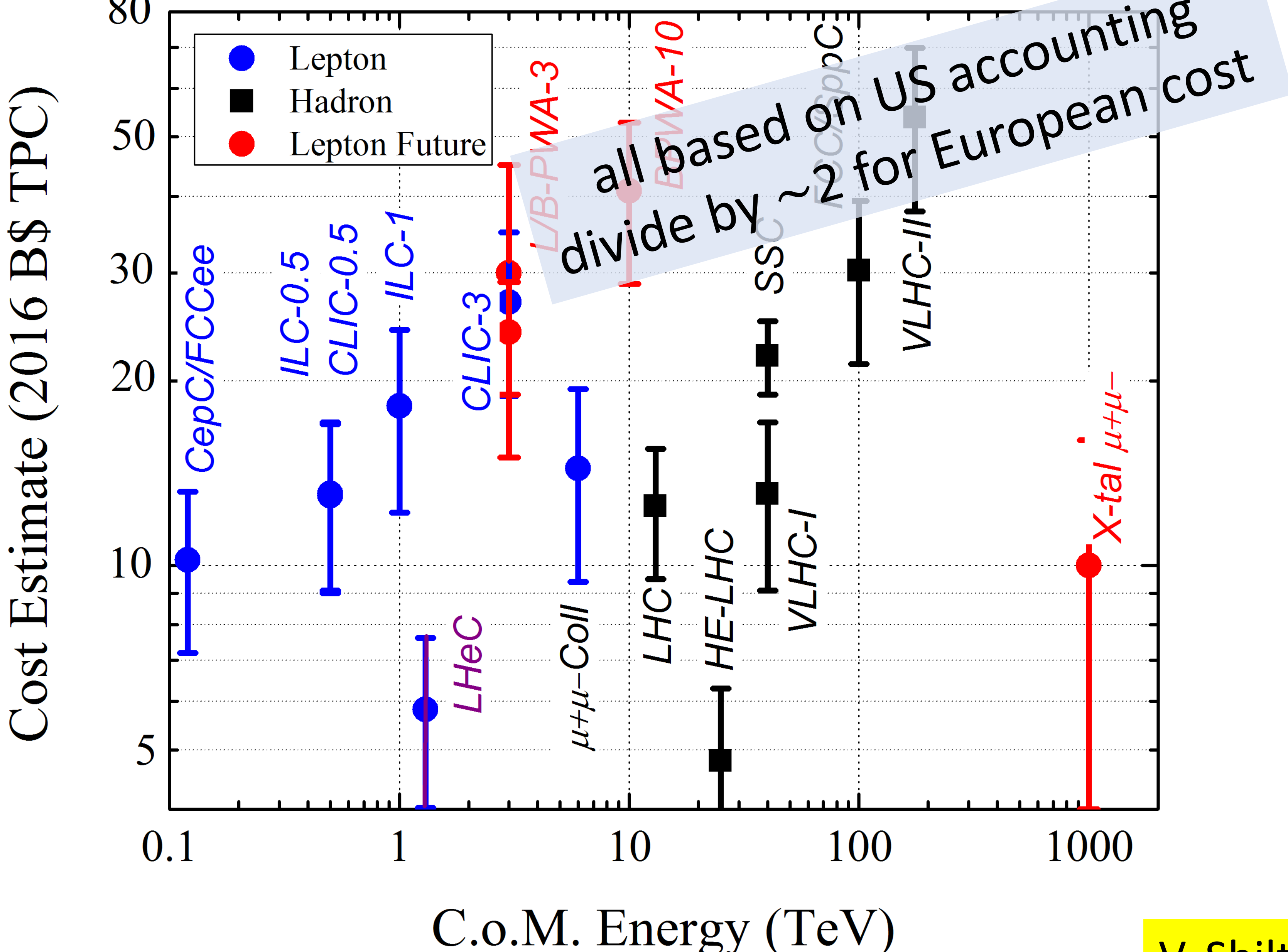
April 6^{th}, 2017

the same ERL at three ep colliders

Table 1: Baseline parameters and estimated peak luminosities of future electron-proton collider configurations for the electron ERL when used in concurrent *ep* and *pp* operation mode.

parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2
electrons per bunch [10^9]	1	2.3	3.0	3.0
electron current [mA]	6.4	15	20	20
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3	1.3
proton filling H_{coll}	0.8	0.8	0.8	0.8
luminosity [10^{33}cm^{-2}s^{-1}]	1	8	12	15

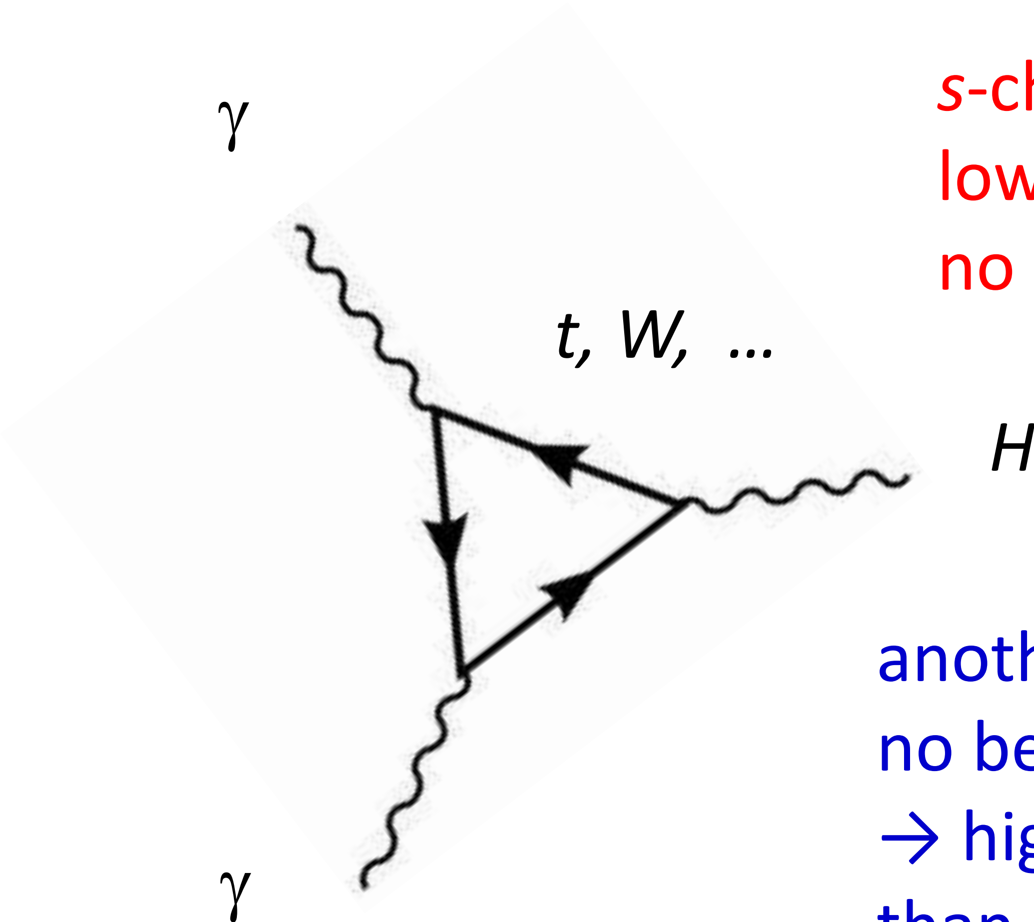
predicting costs by αβγ model



V. Shiltsev


SAPPHiRE

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

LHC – *the first photon collider!*

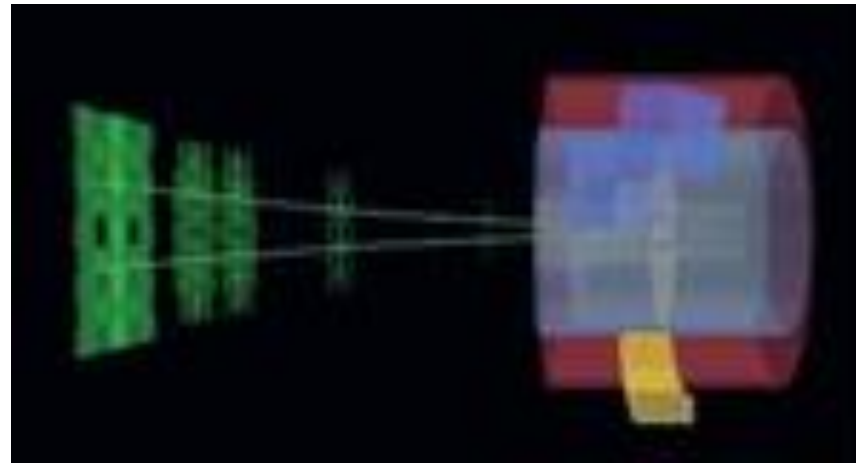
CERN COURIER

Nov 6, 2012

Using the LHC as a photon collider

ALICE

The protons and nuclei accelerated by the LHC are surrounded by strong electric and magnetic fields. These fields can be treated as an equivalent flux of photons, making the LHC the world's most powerful collider not only for protons and lead ions but also for photon-photon and photon-hadron collisions (*CERN Courier* October 2007). This is particularly so for beams of multiply charged heavy-ions, where the number of photons is enhanced by almost four orders of magnitude compared with the singly charged protons (the photon flux is proportional to the square of the ion charge).

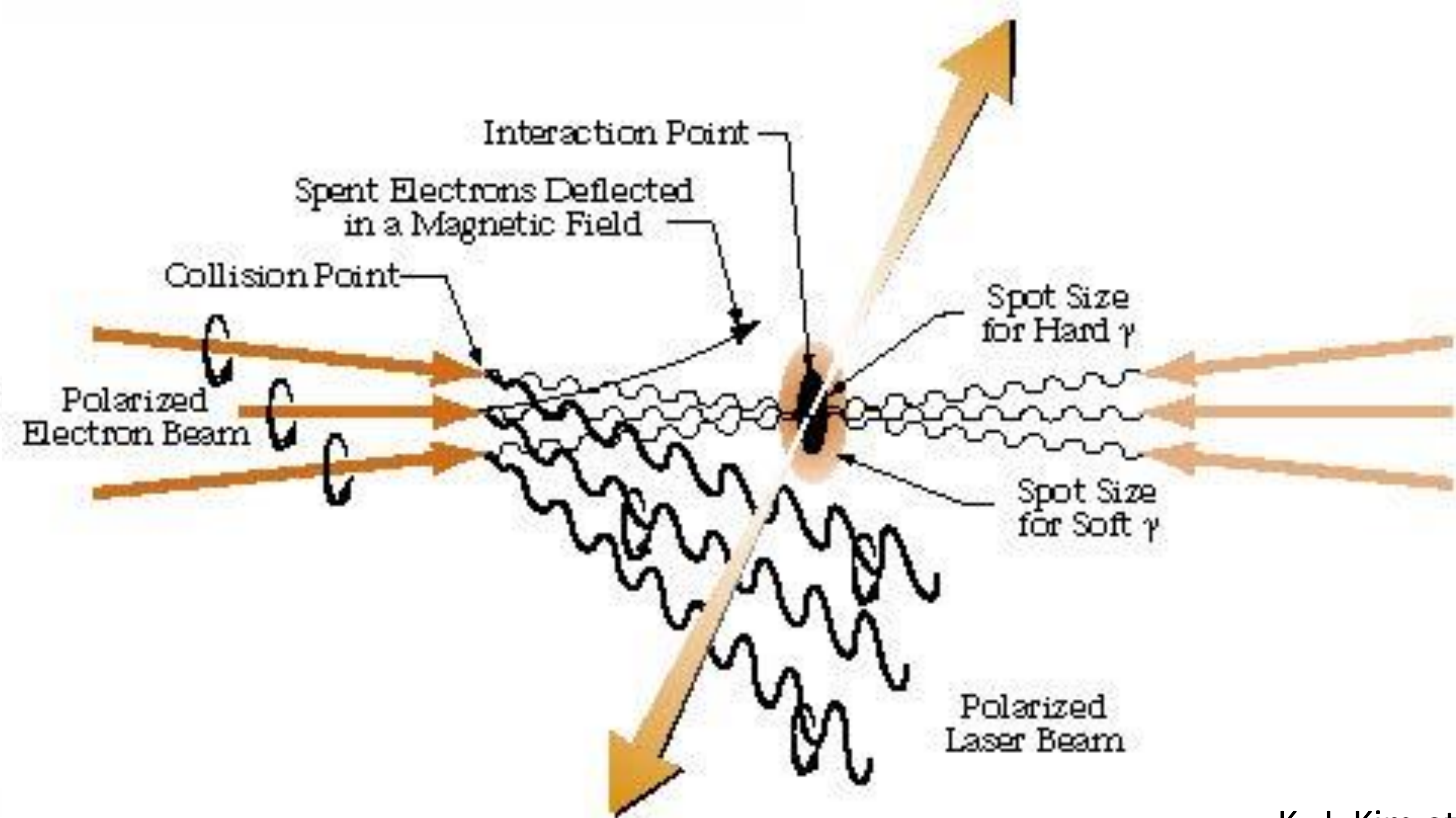


ultra-peripheral photon-photon interaction in *Pb-Pb* collisions at ALICE

CERN Courier, November 2012

thanks to John Jowett

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



K.-J. Kim et al.

combining photon science & particle physics!

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 occurs)

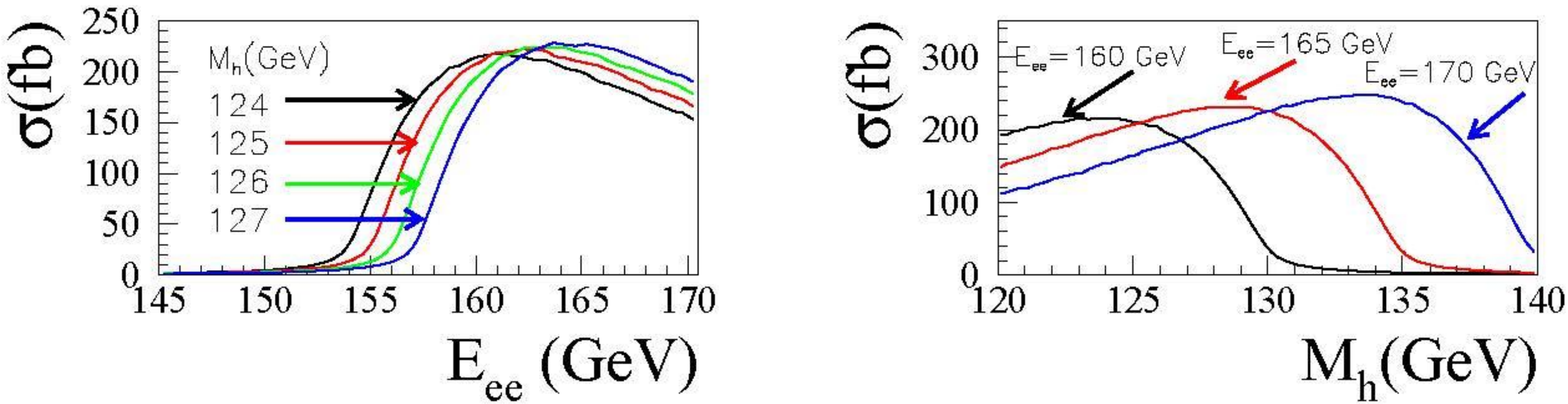
with $E_{beam} \approx 80$ GeV: $E_{\gamma,max} \approx 66$ GeV

$E_{CM,max} \approx 132$ GeV

E_{photon} ~3.53 eV , λ~351 nm

Higgs $\gamma\gamma$ production cross section

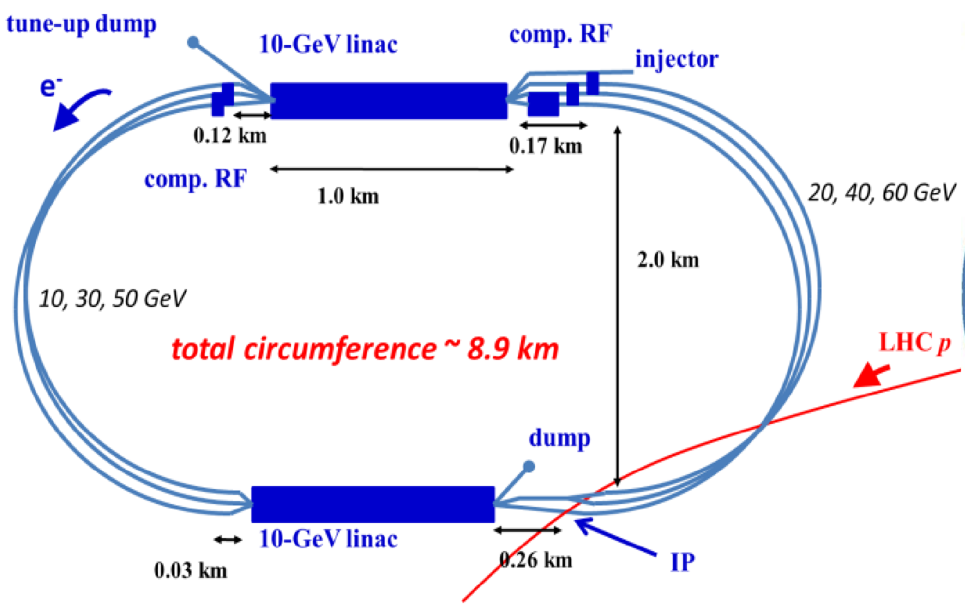
S. A. Bogacz, J. Ellis, L. Lusito, D. Schulte, T. Takahashi, M. Velasco, M. Zanetti, F. Zimmermann, 'SAPPHiRE: a Small Gamma-Gamma Higgs Factory,' arXiv:1208.2827



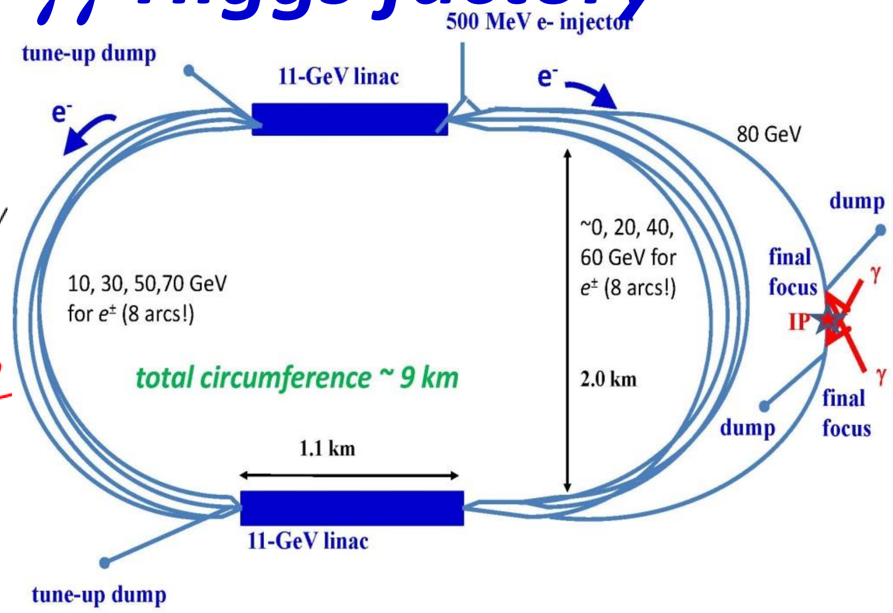
Left: The cross sections for $\gamma\gamma \rightarrow h$ *for different values of* M_h *as functions of* $E_{CM}(e^-e^-)$.
Right: The cross section for $\gamma\gamma \rightarrow h$ *as a function of* M_h *for three different values of* $E_{CM}(e^-e^-)$.
Assumptions: electrons have 80% longitudinal polarization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

Reconfiguring *LHeC* → *SAPPHiRE*

LHeC-ERL



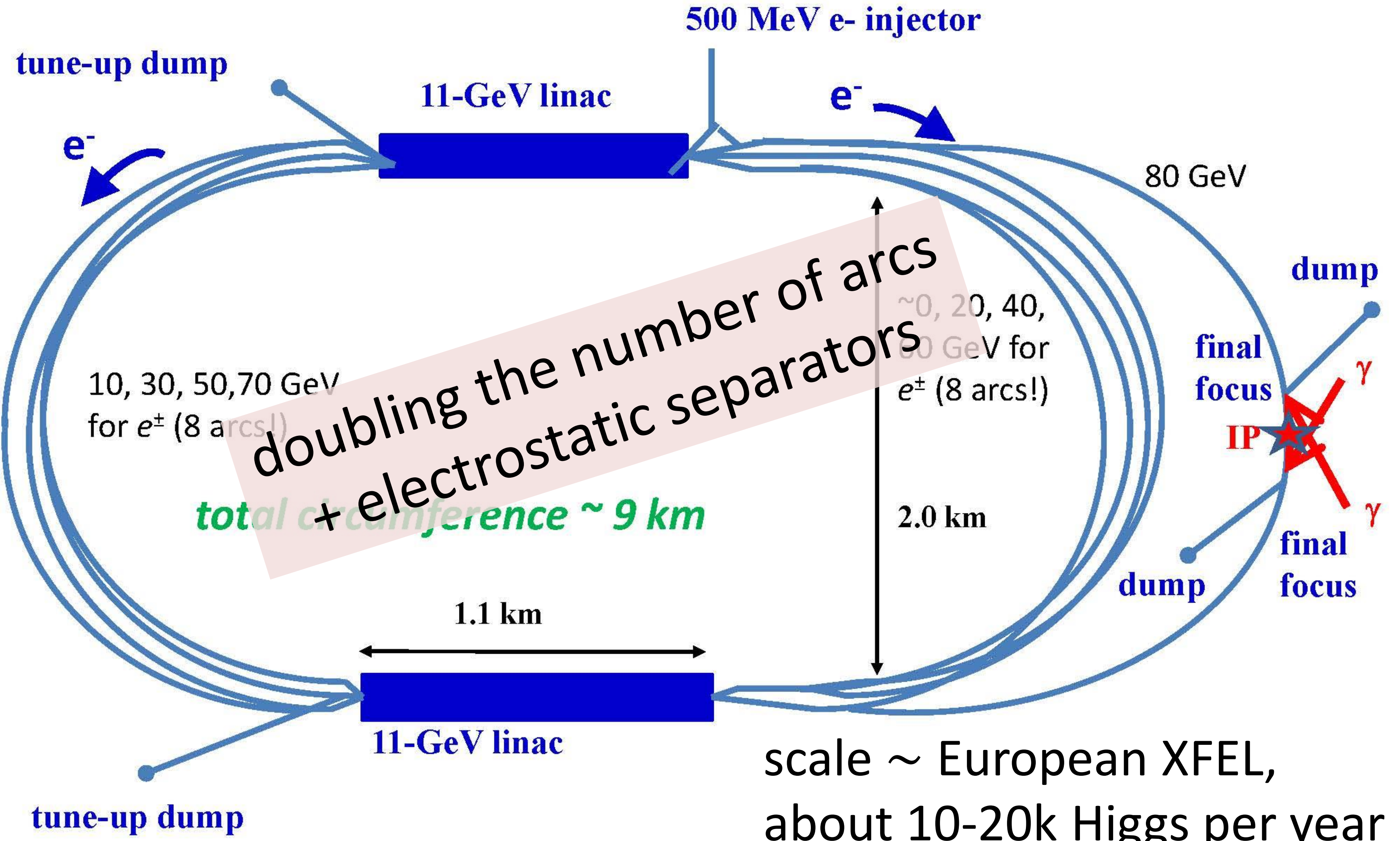
*SAPPHiRE**
γγ Higgs factory



***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 $\gamma\gamma$ 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	symbol	value
total electric power	P	100 MW
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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

photon pulse properties & luminosity

Table 2: *Example parameters for the CLICHE mercury laser system [3], and for the SAPPHiRE laser system, assuming* $\mathcal{L}_{ee} = 4.8 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$ *and* $\mathcal{L}_{ee} = 2.2 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$*, respectively.*

from arXiv 1208.2827

Variable	Symbol	CLICHE [3]	SAPPHiRE
Laser beam parameters			
Wavelength	λ_L	0.351 μm	0.351 μm
Photon energy	$\hbar\omega_L$	3.53 eV = 5.65×10^{-19} J	3.53 eV
Number of laser pulses per second	N_L	$169400\,\mathrm{s^{-1}}$	$200000\,\mathrm{s^{-1}}$
Laser peak power	W_L	2.96×10^{22} W/m^2	6.3×10^{21} W/m^2
Laser peak photon density		5.24×10^{40} photons/m^2/s	1.1×10^{40} photons/m^2/s
Photon beam			
Number of photons per electron bunch	N_γ	9.6×10^9	1.2×10^{10}
$\gamma\gamma$ luminosity for $E_{\gamma\gamma} \geq 0.6 E_{CM}$	$\mathcal{L}_{\gamma\gamma}^{peak}$	3.6×10^{33} cm^{-2}s^{-1}	3.6×10^{33} cm^{-2}s^{-1}

recent simulation by T. Takahashi (21 November 2017):

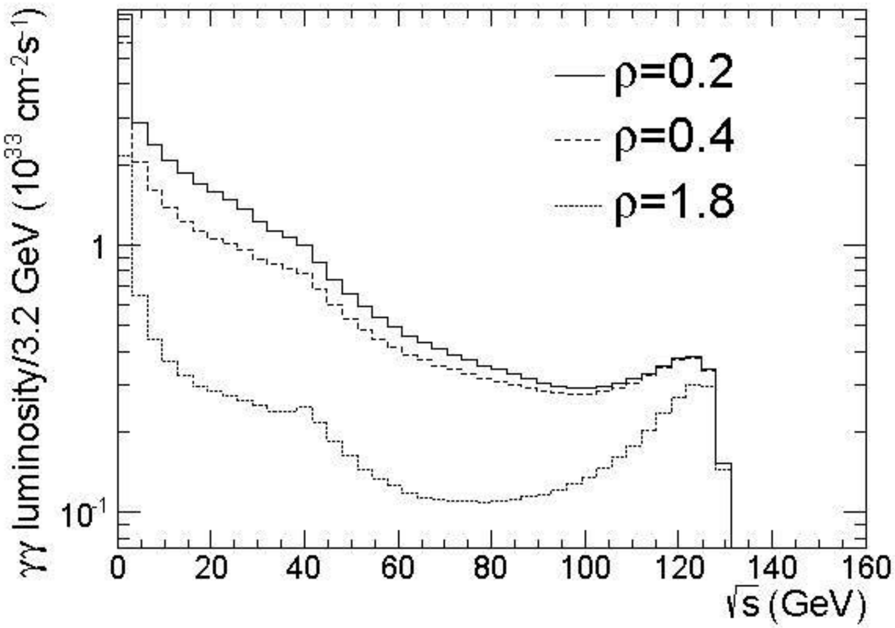
wave length 0.351 micron, pulse energy 2 J, pulse length 2 ps, spot size 2.89 micron

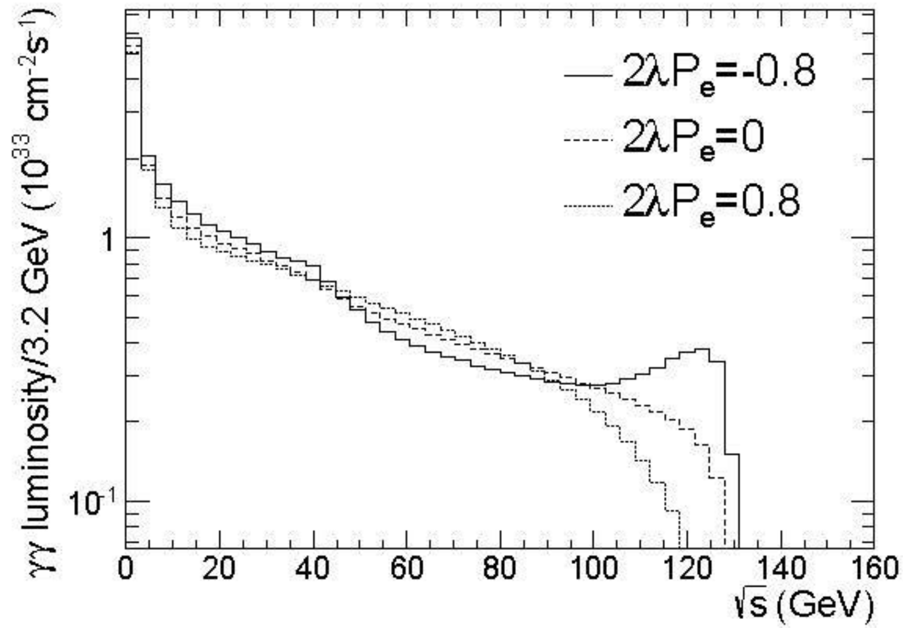
yielding; $7.6\mathrm{x}10^{21}$ Watt/m^2 , $1.3\mathrm{x}10^{40}$ /m^2/s

200 kHz x 2 Joule = 400 kW intracavity power

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

Energy loss and energy spread on multiple passes

The energy loss per arc is $\Delta E_{arc}\,[\mathrm{GeV}] = 8.846 \times 10^{-5}\,\frac{(E\,[GeV])^4}{2\rho[\mathrm{m}]}$

For **ρ=764 m** (LHeC design) the energy loss in the various arcs is summarized in the following table. *e*⁻ lose about 4 GeV in energy, which can be compensated by increasing the voltage of the two linacs from 10 GV to 10.5 GV. We take 11 GV per linac to be conservative.

beam energy [GeV]	ΔE_{arc} [GeV]	$\Delta\sigma_E$ [MeV]
10	0.0006	0.038
20	0.009	0.43
30	0.05	1.7
40	0.15	5.0
50	0.36	10
60	0.75	20
70	1.39	35
80	1.19	27
total	**3.89**	**57 (0.071%)**

Emittance growth

The emittance growth is $\Delta\varepsilon_N = \frac{2\pi}{3}\frac{C_q r_e}{\rho^2}\gamma^6\langle H\rangle$

with C_q=3.8319x10^{-13} m, and ρ the bending radius.

For LHeC RLA design with l_{bend}=10 m, and ρ=764 m, <H>=1.2x10^{-3} m [Bogacz et al]. At 60 GeV the emittance growth of LHeC optics is 13 micron, too high for our purpose, and extrapolation to 80 GeV is unfavourable with 6th power of energy. From L. Teng we also have **scaling law $< H > \propto l_{bend}^3/\rho^2$** , which suggests that **by reducing the cell length and dipole length by a factor of 4 we can bring the horiz. norm. emittance growth at 80 GeV down to 1 micron**.

$\Delta\varepsilon_{N,x} \leq 1$ μm: reduced LHeC cell length 52 → 13 m will do

Valery Telnov thinks this scaling is too optimistic

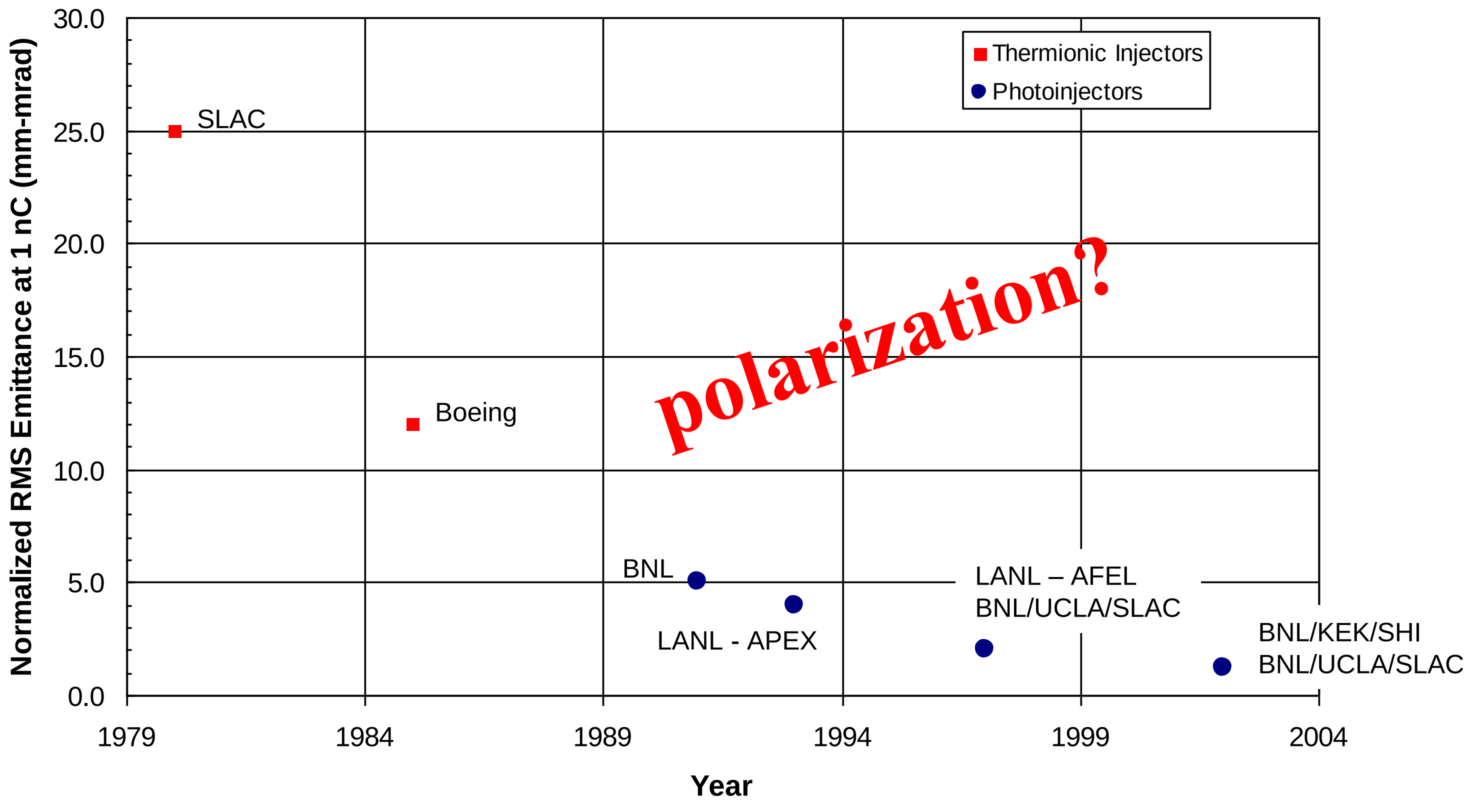
flat polarized electron source

- target $\varepsilon_x/\varepsilon_y$ ~ 10
- flat-beam gun based on flat-beam transformer concept of Derbenev et al.
- starting with $\gamma\varepsilon$~4-5 μm at 0.5 nC, injector test facility at **Fermilab A0 line achieved emittance ~40 μm horizontally and 0.4 μm vertically, with $\varepsilon_x/\varepsilon_y$~100**
- for SAPPHiRE **we only need $\varepsilon_x/\varepsilon_y$~10, but at three times larger bunch charge (1.6 nC) and smaller initial $\gamma\varepsilon$~1.5 μm**
- these parameters are within the present state of the art (e.g. the LCLS photoinjector routinely achieves 1.2 μm emittance at 1 nC charge)
- however, **we need a polarized beam**…

Valery Telnov stressed this difficulty

normalized emittance for 1 nC has been reduced from tens of μm to 1 μm

Bruce Carlsten, SPACE CHARGE 2013



LCLS scaling: $\varepsilon_n = 1\,(\mu\text{m})\sqrt{q(\text{nC})}$

PITZ scaling: $\varepsilon_n = 0.7\,(\mu\text{m})\sqrt{q(\text{nC})}$

can we get ~ 1-nC polarized e^- bunches with ~1 μm emittance?

long-standing R&D efforts:

low-emittance DC guns

(MIT-Bates, Cornell, SACLA?, JAEA, KEK, Daresbury, …)

[E. Tsentalovich, I. Bazarov, B. Militsyn, et al]

polarized SRF guns (FZD, BNL, …)

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

Cornell DC gun

*The answer is a **qualified 'yes'.** Presently we have demonstrated 90% emittances of **0.5mm-mrad at 80pC/bunch and 0.2mm-mrad at 20pC/bunch for 2ps rms bunches** with the gun voltage and photocathode we are using. The scaling with charge is bunch_charge^(1/2) meaning that **numbers around 2-3 mm-mrad should be doable from our gun today [for 1-2 nC charge].***
*We are working on **further improving our gun and laser shaping, expecting to halve the emittance even when using the same photocathodes** we have today. Better photocathodes automatically translate into smaller emittances and many pursue this venue as well*

Ivan Bazarov, 7 Nov 12

SACLA pulsed "DC" gun

*I think **our gun almost meets your requirement** except for the repetition rate*

Hitoshi Tanaka, 7 Nov 12

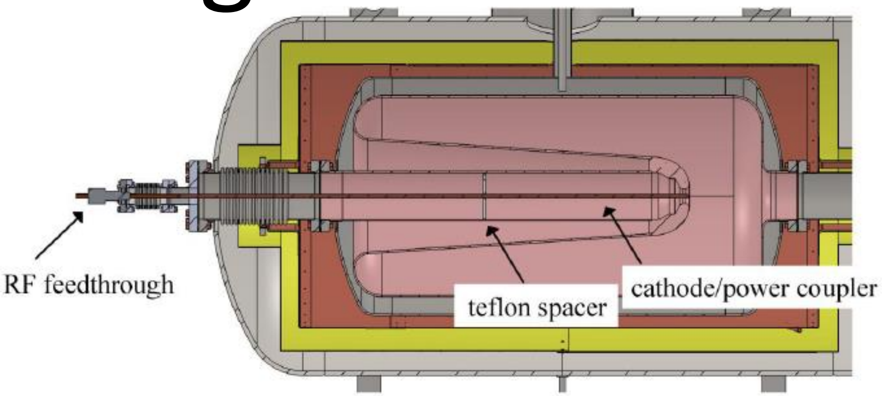
Rossendorf polarized SRF gun

*Für **2013** wollen wir die 2. Version der SRF-Gun in Betrieb nehmen. Das neue Cavity erreichte im Test am Jlab ein Peakfeld von 43 MV/m. Mit diesen Werten sollten wir **1 nC Ladung mit 500 kHz Reprate im CW** (0.5 mA average current) erreichen. Die Emittanz könnte etwa **2 µm** sein. Auf **1 µm** könnte man etwa kommen, wenn wir **vom Gausslaser zum Flat-top** übergehen (analog zu PITZ/XFEL gun).*
*Mit der Inbetriebnahme der 2. Gun, wird dann auch das Kathodentransfersystem ausgetauscht, und wir denken dann auch die **GaAs-Kathoden** zu testen. Ergebnisse dann **im Jahr 2014**.*

Jochen Teichert, 12 Nov 12

BNL QWT polarized SRF gun

simulations of 5 µm emittance
***at 10 nC** with 112 MHz gun*



Tor Raubenheimer, 14 Nov 2012

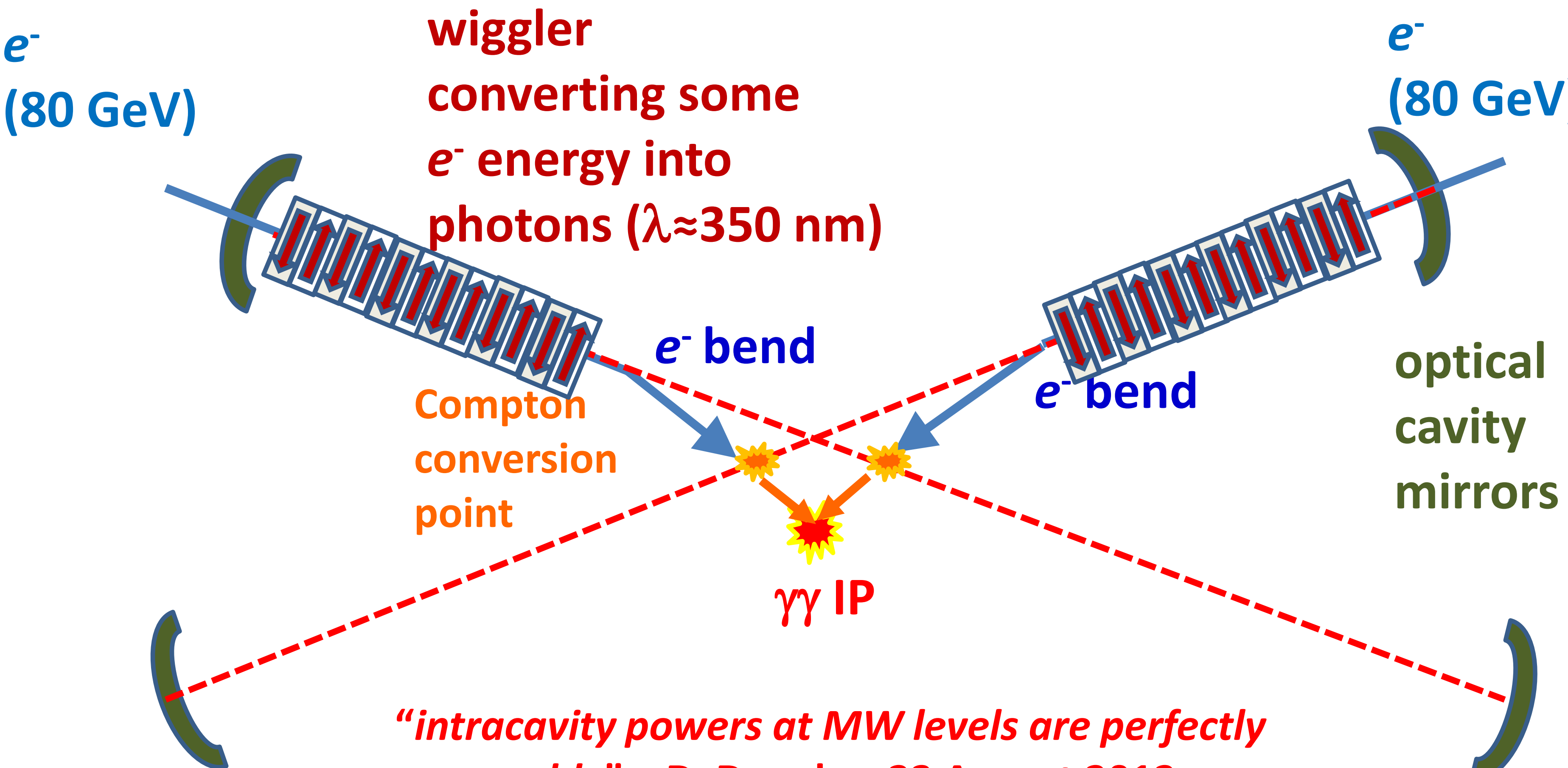
recent e^- gun progress (since 2012)

cryogenic photocathodes (L. Cultrera et al., Cornell, PRST-AB 18, 113401 (2015); F. Hug)

DC gun for CBETA (K. Smolenski, Cornell; E. Jensen) – delivered 75 mA (!) 2.6 days lifetime @ 65 mA

PERLE gun design (Daresbury, B. Militsyn, T. Noakes) $\gamma\varepsilon < 25\ \mu m$ (!?), 20 mA

self-generated FEL γ beams (instead of laser)?



***"intracavity powers at MW levels are perfectly reasonable"* – D. Douglas, 23 August 2012**

example:
λ_u=200 cm, B=0.625 T, L_u=100 m, $U_{0,SR}$=0.16 GeV, 0.1%P_{beam}≈25 kW

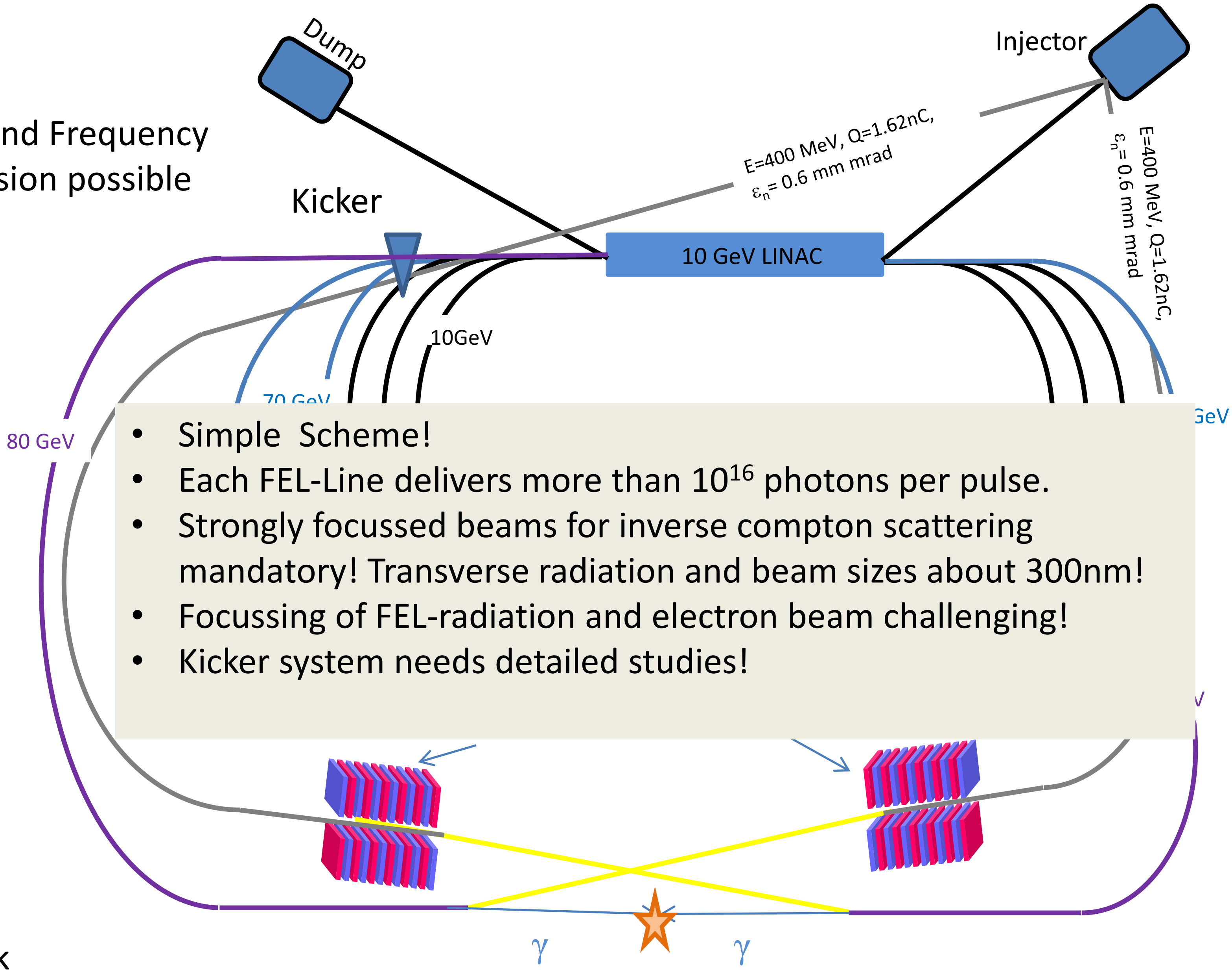
scheme developed with Z. Huang

recent improvements (A. Meseck):

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

Generic Recirculator based γγ –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!

A. Meseck

$Q_b := 1.62 \cdot nC$ bunch charge

$\sigma_z := 324 \cdot \mu m$ bunch length $\sigma_t := \frac{\sigma_z}{c}$ $I := \frac{Q_b}{\sigma_z} \cdot \frac{c}{\sqrt{2 \cdot \pi}}$ $\sigma_t = 1.081 \cdot ps$ $I = 598.001 \cdot A$

$\beta := 1.10 \cdot m$ Average β function in undulator

$E := 0.400 \cdot GeV$ Electron beam energy $\gamma := \frac{E}{m_0 \cdot c^2}$ $\gamma = 782.779065$

$\delta E := 0.24 \cdot MeV$ Energy spread $\delta E = 0.06 \cdot E \cdot \%$ $\sigma_\gamma := \frac{\delta E}{m_0 \cdot c^2}$ $\frac{\sigma_\gamma}{\gamma} = 6 \times 10^{-4}$

$\varepsilon_n := 0.60 \cdot \mu m$ Normalized emittance

$B_u := 0.8353 \cdot T$ peak undulator field strength $K := \frac{1}{\sqrt{2}} \cdot \frac{e_0 \cdot B_u \cdot \lambda_u}{2 \cdot \pi \cdot m_0 \cdot c}$ $K = 2.75752$

$\lambda_u \equiv 5.0 \cdot cm$ undulator period

$\lambda_s(\gamma, K) = 351.04\,nm$ $E_\Phi(\lambda_s(\gamma, K)) = 3.532 \cdot eV$

$\rho\left(\gamma, K, I, \frac{\varepsilon_n}{\gamma}, \beta\right) = 0.011$

$L_{sat}\left(\gamma, K, I, \frac{\varepsilon_n}{\gamma}, \beta, \frac{\sigma_\gamma}{\gamma}\right) = 4.392m$

$P_{sat}\left(\gamma, K, I, \frac{\varepsilon_n}{\gamma}, \beta, \frac{\sigma_\gamma}{\gamma}\right) = 3.67 \cdot GW$

$\frac{P_{sat}\left(\gamma, K, I, \frac{\varepsilon_n}{\gamma}, \beta, \frac{\sigma_\gamma}{\gamma}\right)}{I \cdot \frac{E}{e_0}} = 1.534\%$

$N_\Phi\left(\gamma, K, I, \frac{\varepsilon_n}{\gamma}, \beta, \frac{\sigma_\gamma}{\gamma}, \sigma_t\right) = 1.757 \times 10^{16}$

$\Lambda_T\left(\gamma, K, I, \frac{\varepsilon_n}{\gamma}, \beta, \frac{\sigma_\gamma}{\gamma}\right) = 0.053$

$B\left(\gamma, K, I, \frac{\varepsilon_n}{\gamma}, \beta\right) = 0.035$

$L_g\left(\gamma, K, I, \frac{\varepsilon_n}{\gamma}, \beta, \frac{\sigma_\gamma}{\gamma}\right) = 0.205m$

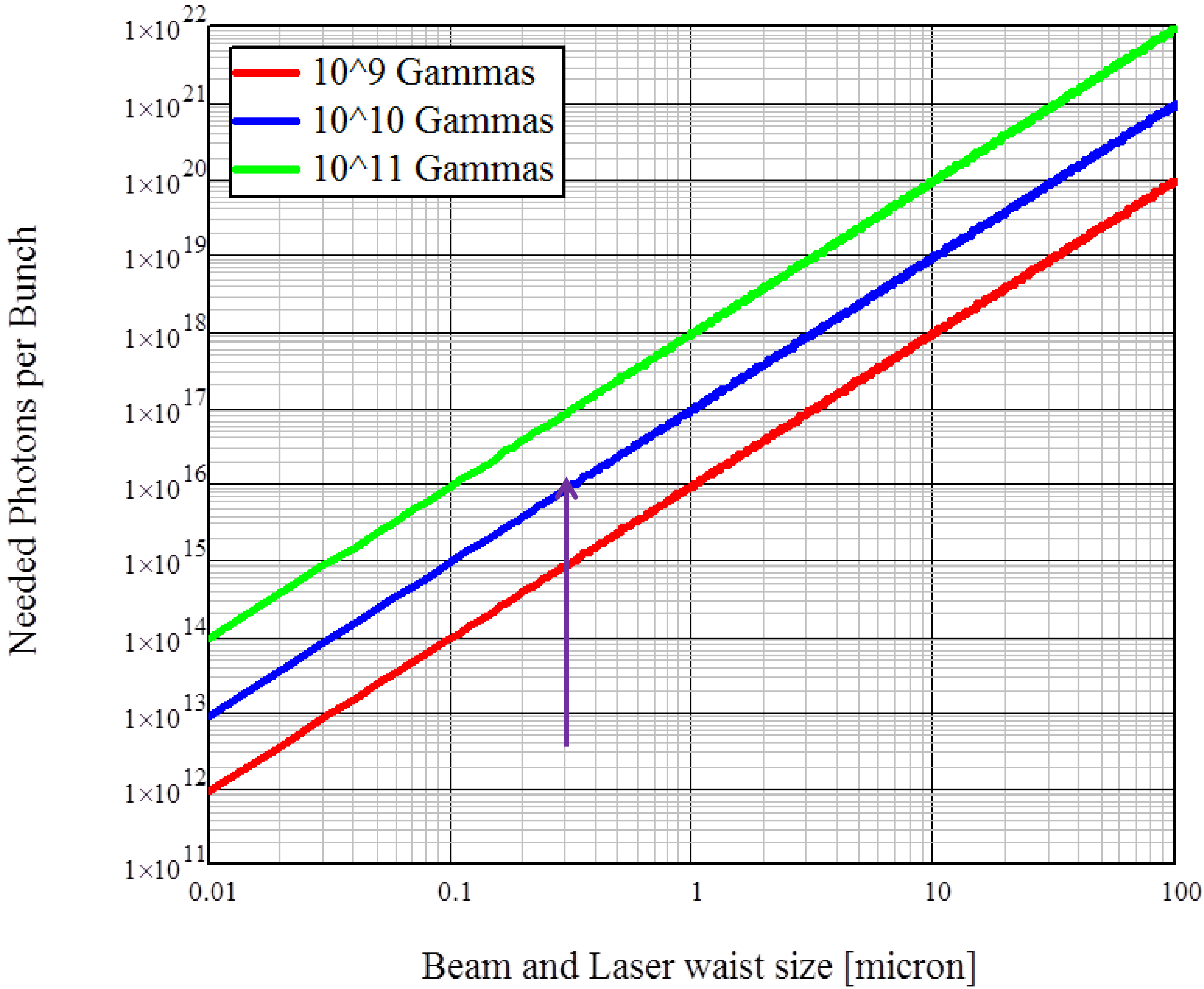
$\frac{N_\Phi\left(\gamma, K, I, \frac{\varepsilon_n}{\gamma}, \beta, \frac{\sigma_\gamma}{\gamma}, \sigma_t\right)}{\sigma_{xy}\left(\frac{\varepsilon_n}{\gamma}, \beta\right)^2} \cdot 0.2MHz = 4.168 \times 10^{30}\, m^{-2} \cdot s^{-1}$

$\sigma_{xy}\left(\frac{\varepsilon_n}{\gamma}, \beta\right) = 2.904 \times 10^{-5}\, m$

A. Meseck

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

using formla 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

conclusions

- SAPPHiRE = one of the cheapest possible options to further study the Higgs
- 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 FEL option available

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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[3] J. Abelleira Fernandez et al, 'A Large Hadron Electron Collider at CERN - Report on the Physics and Design Concepts for Machine and Detector,' Journal of Physics G: Nuclear and Particle Physics 39 Number 7 (2012) arXiv:1206.2913 [physics.acc-ph].

[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

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

[7] T. Takahashi, private communication, 21 November 2017

[8] A. Meseck, numerous private communications