future uses of the LHeC – motivation, ERL as γγ collider SAPPHiRE, as injector for FCC-ee ,or …

Frank Zimmermann

LHeC & FCC-eh workshop

CERN, 13 September 2017

many thanks to I. Chaikovska, F. Hug, S. Ogur, Y. Papaphilippou, D. Shatilov, V. Shiltsev,..

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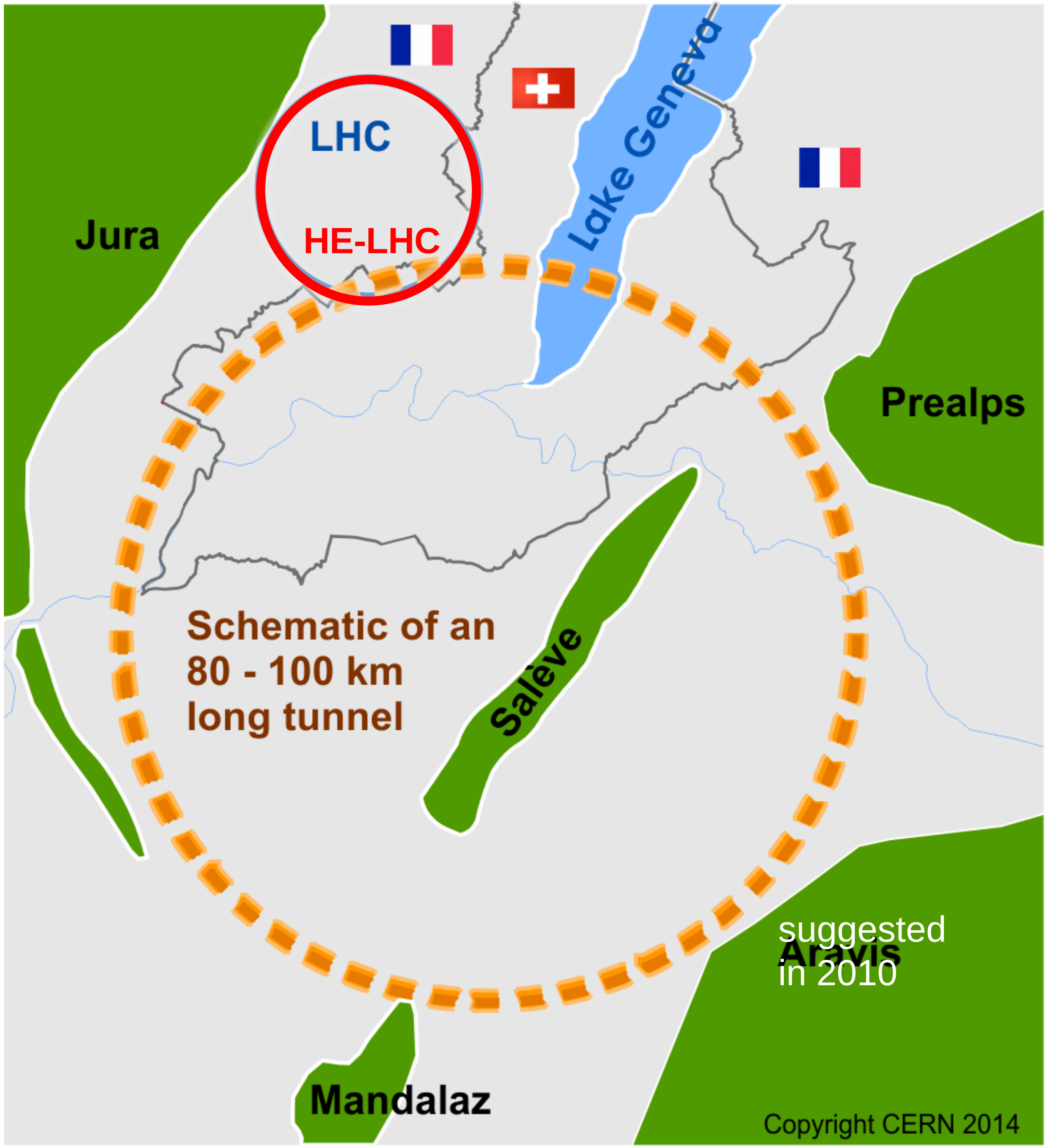
Future Circular Collider Study
Goal: CDR for European Strategy Update 2019/20

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

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

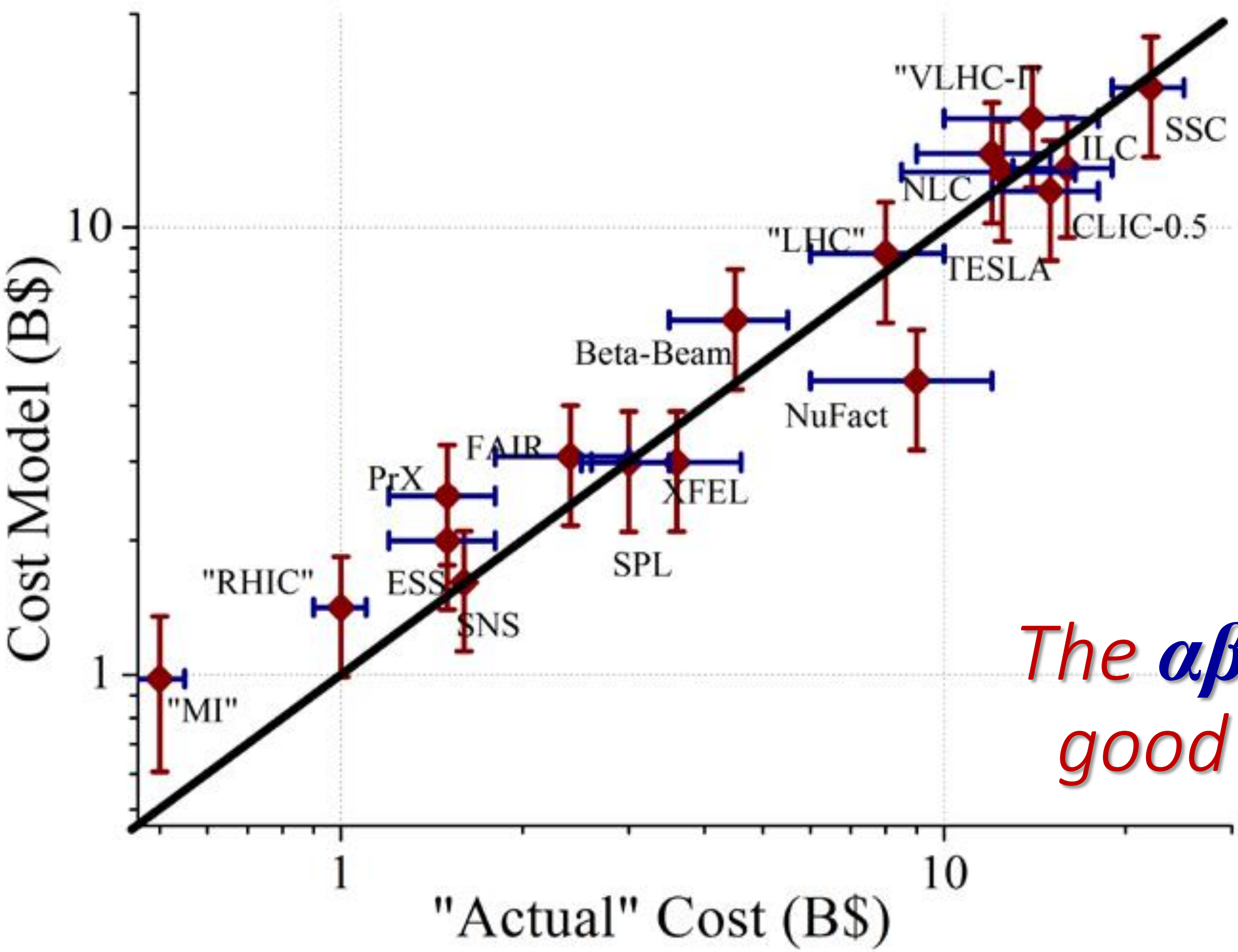
~16 T ⇒ 100 TeV *pp* in 100 km

- **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



project costs fitted by αβγ model

$Cost(TPC) = \alpha L^{1/2} + \beta E^{1/2} + \gamma P^{1/2}$



The ***αβγ****-model is good to +-30%*

V. Shiltsev

technology cost drivers

"SRF is the most expensive technology ever invented"

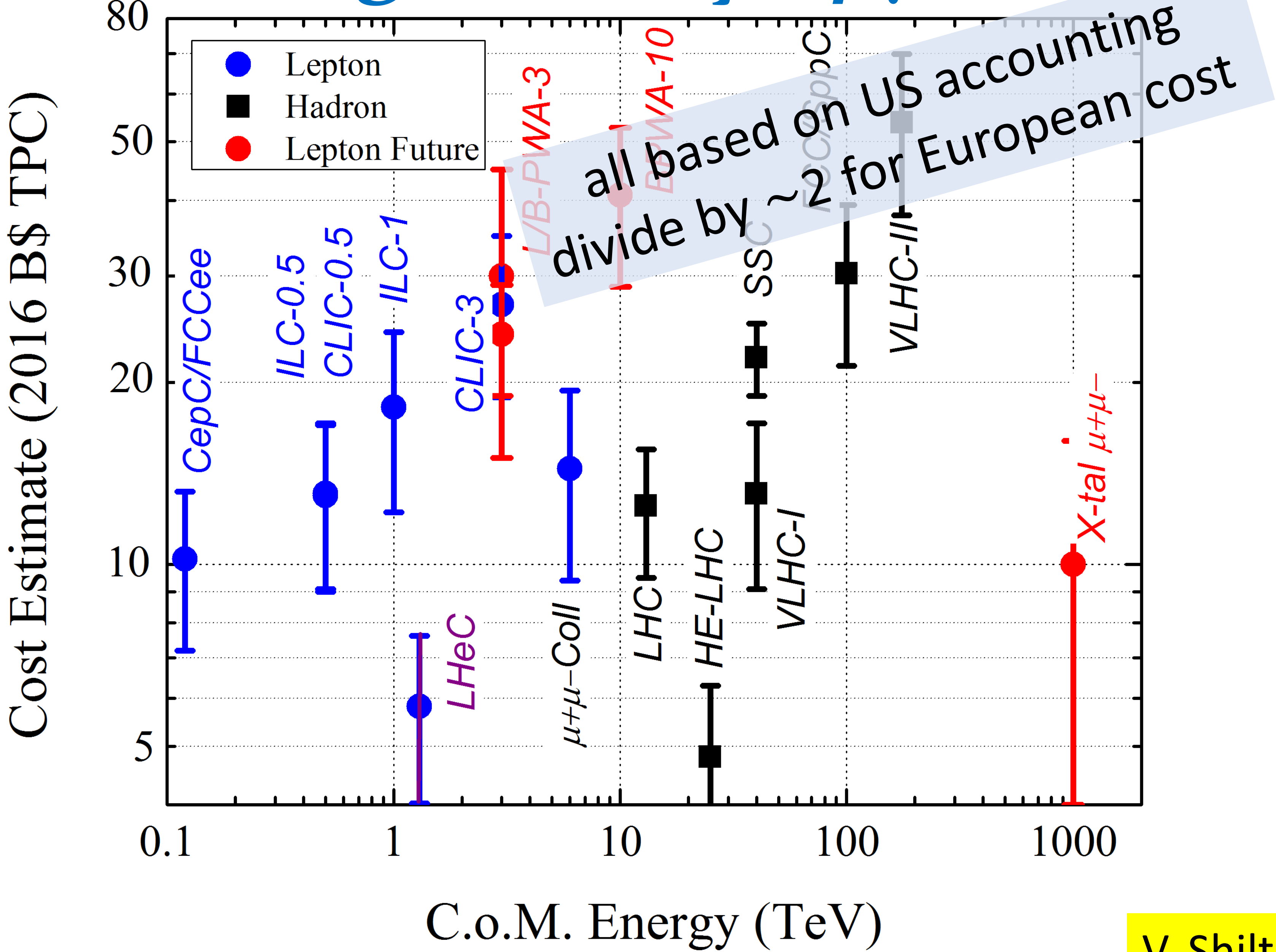
$\beta \approx$ 10 B$/sqrt(*E*/TeV)

"only plasma acceleration is even more expensive"

$\beta \approx$ XX B$/sqrt(*E*/TeV)

V. Shiltsev

predicting costs by αβγ model



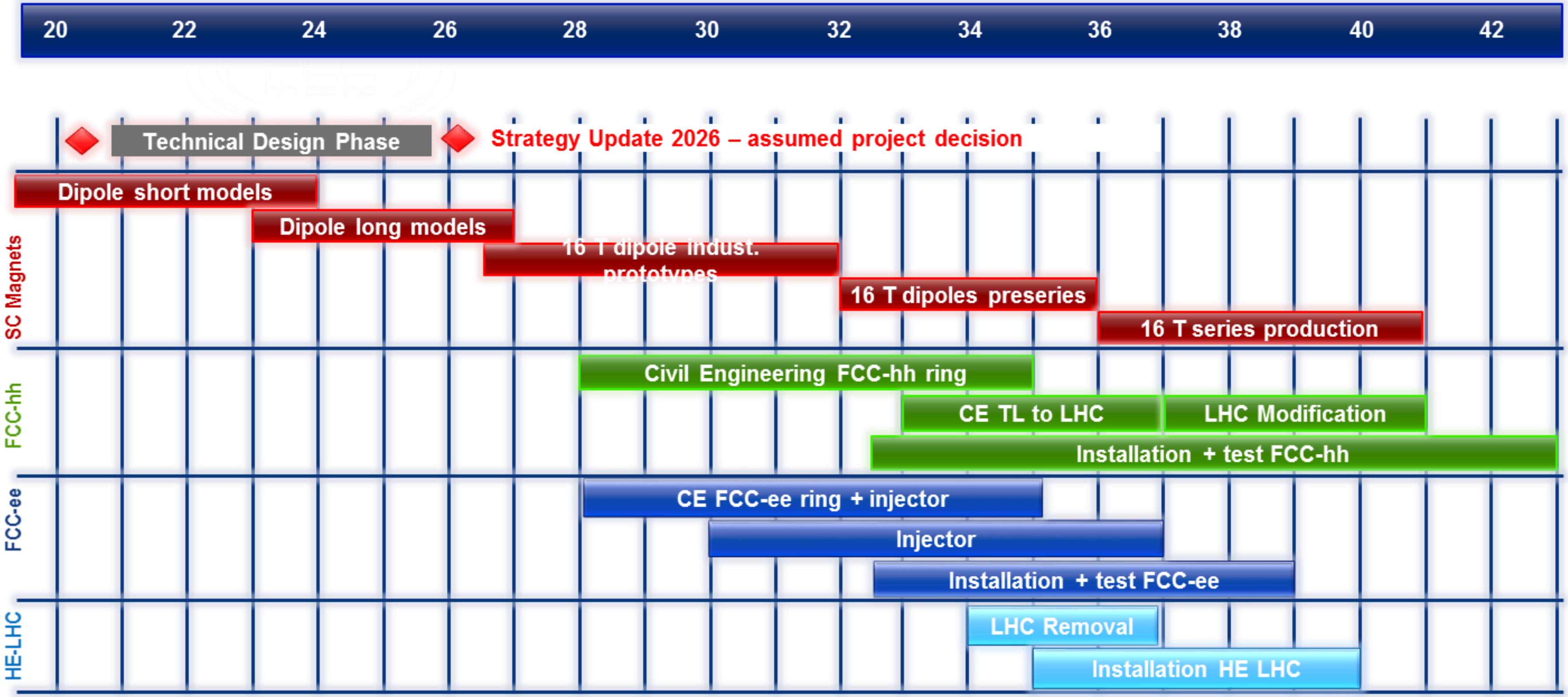
V. Shiltsev

V. Shiltsev

3 recipes to lower the cost of future highest-energy colliders

- reduce the technology cost
  - LHeC: *N* doping etc.
- build on a site with existing injector complex
  - or make LHeC part of the complex
- consider staging (see next!)

FCC Fastest Possible Technical Schedule

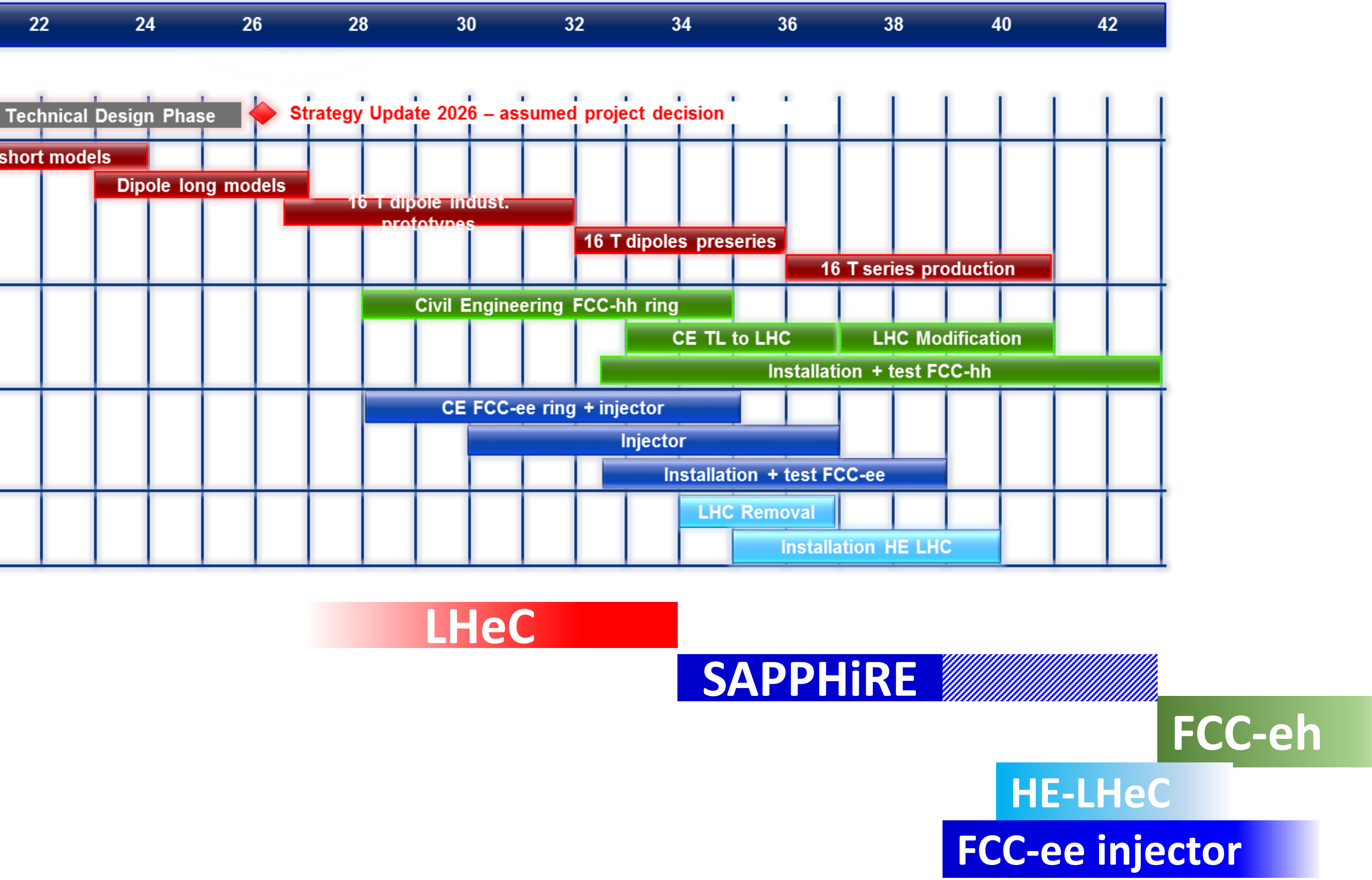


technical schedule defined by magnets program and by CE
→ earliest possible physics starting dates:

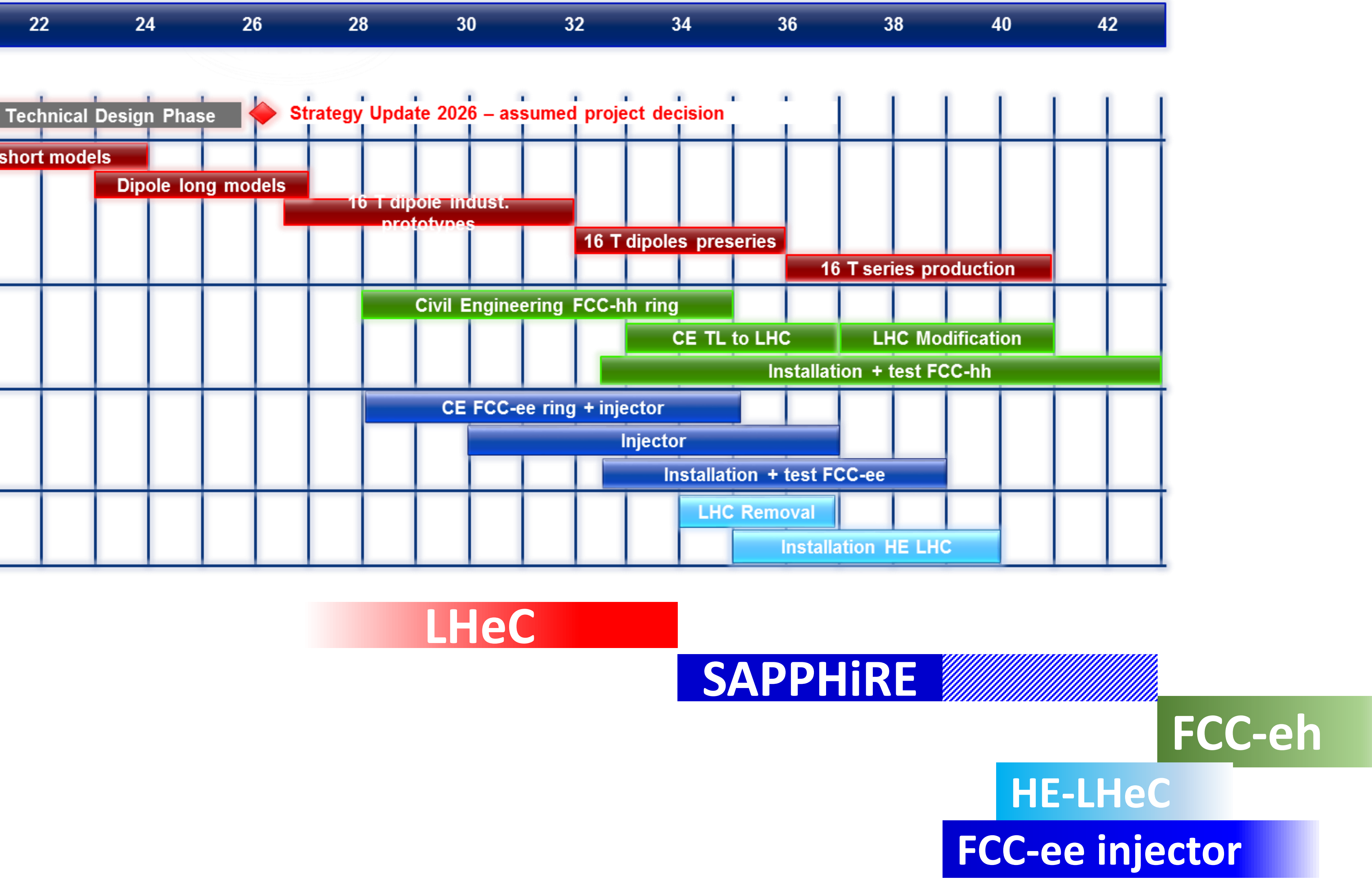
- FCC-hh: 2043
- FCC-ee: 2039
- HE-LHC: 2040 (with HL-LHC stop at LS5 / 2034)

M. Benedikt

fitting the LHeC

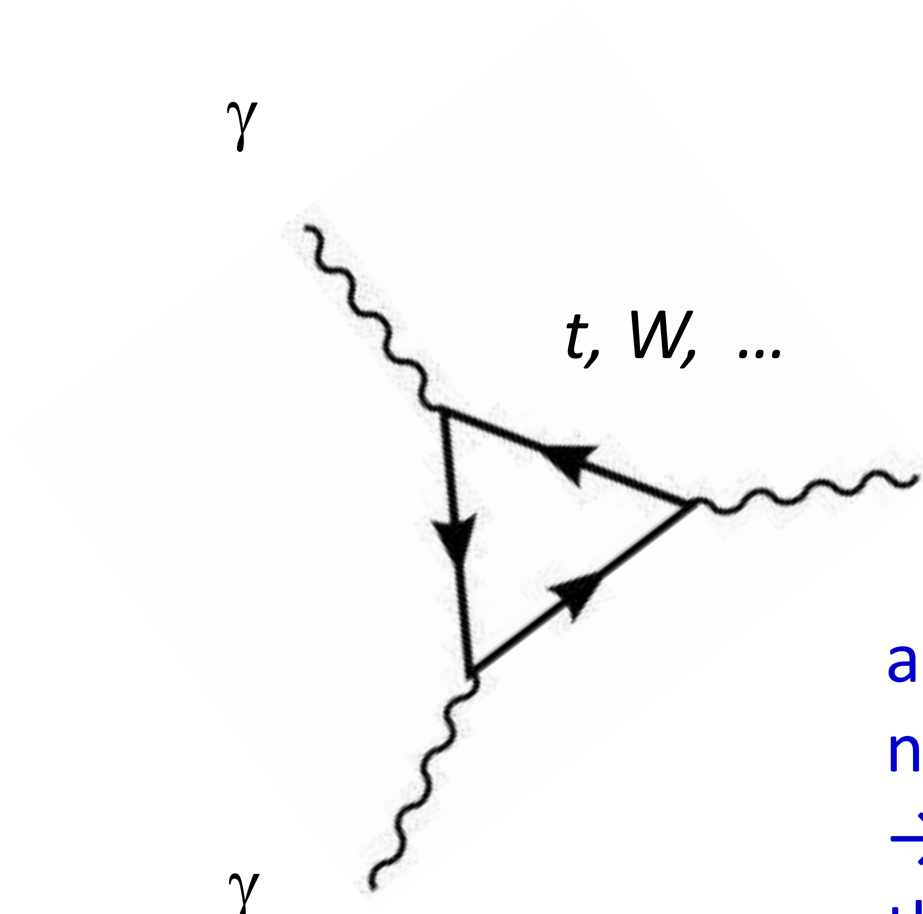


fitting the LHeC




SAPPHiRE

a new type of collider?

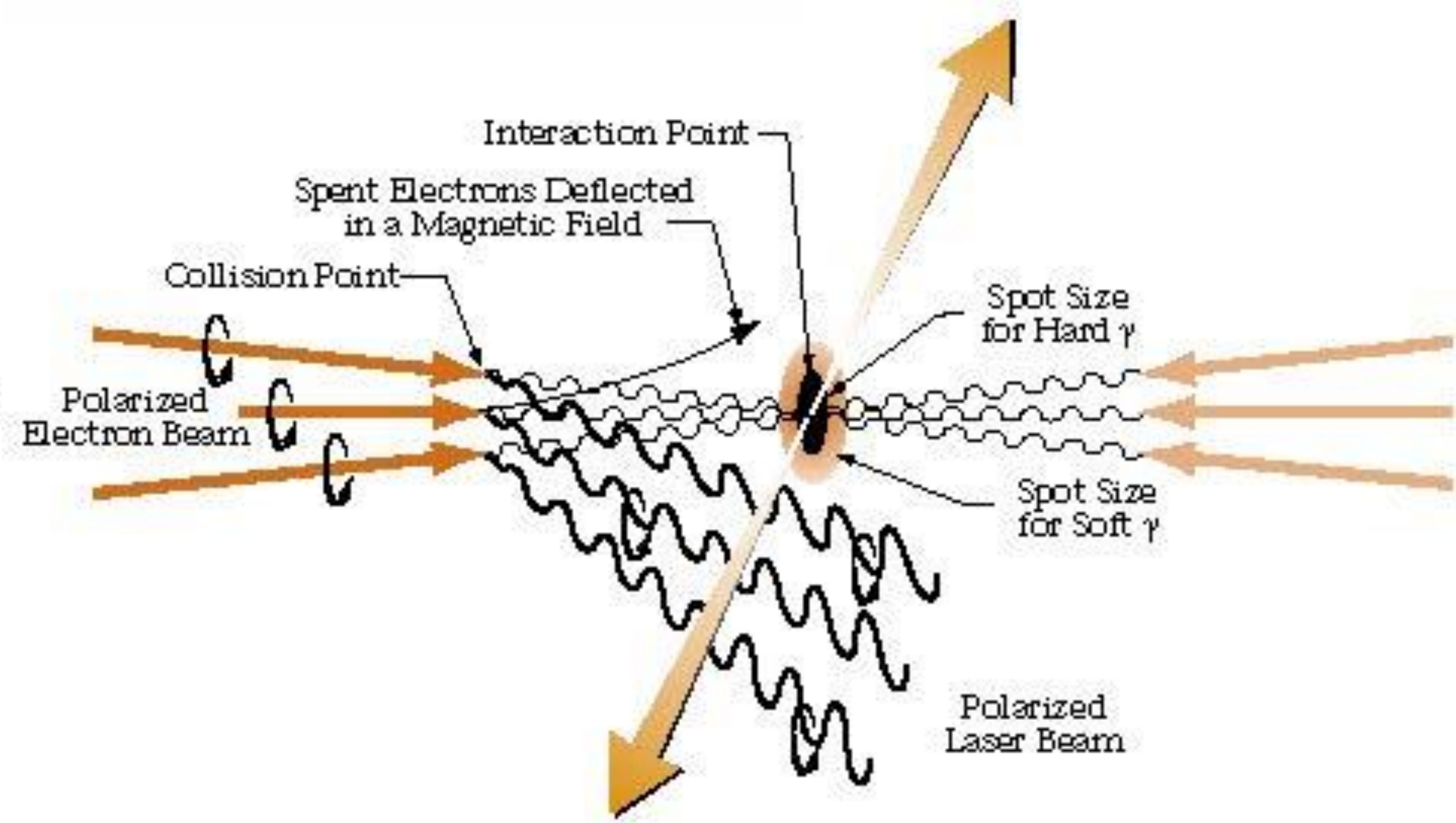


s-channel production;
lower energy;
no e^+ source

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

γγ collider Higgs factory

γγ collider based on e^-



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)

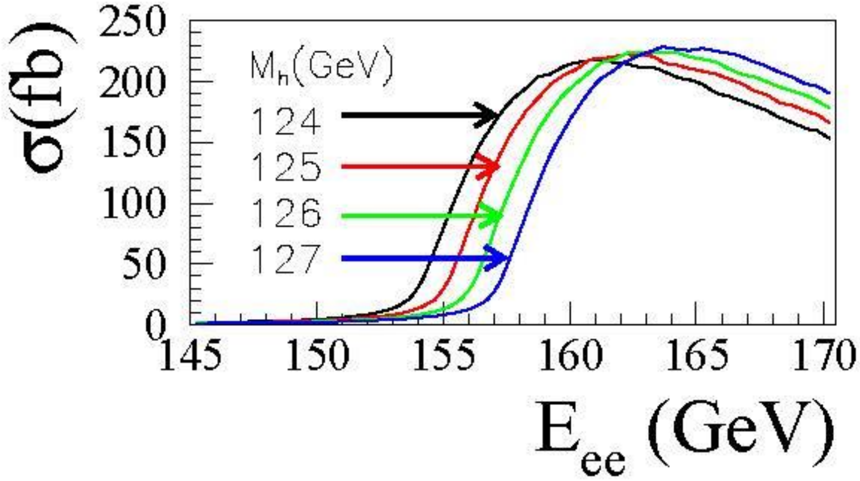
with $E_{beam} \approx 80$ GeV: $E_{\gamma,max} \approx 66$ GeV

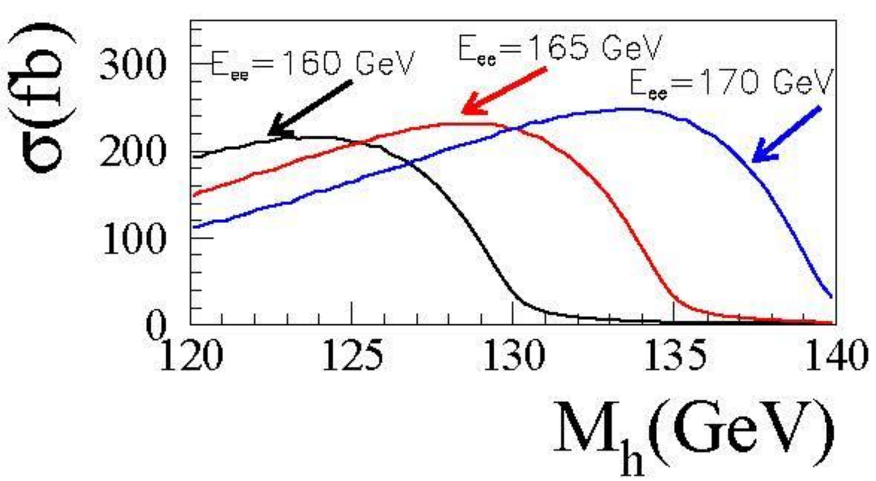
$E_{CM,max} \approx 132$ GeV

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

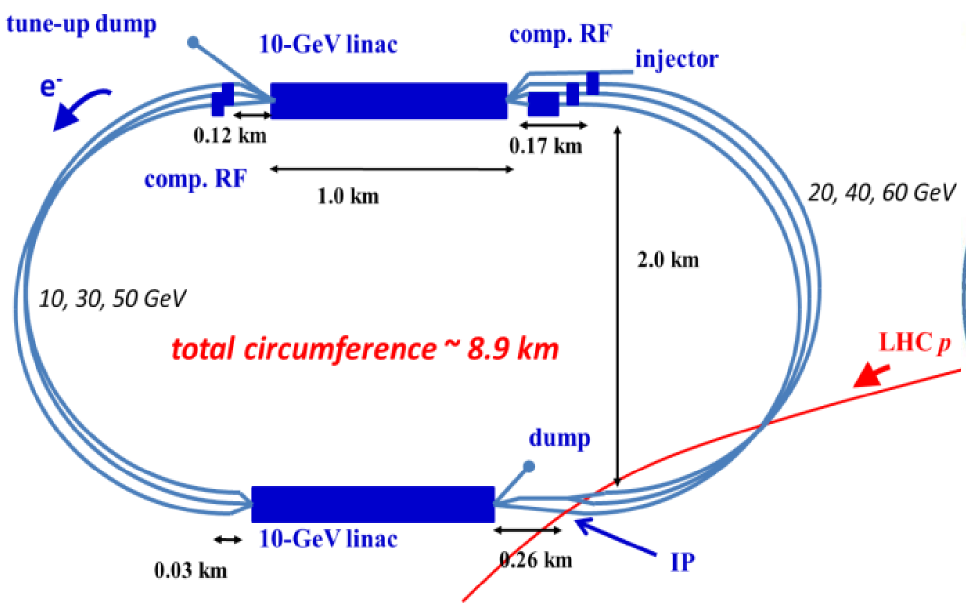




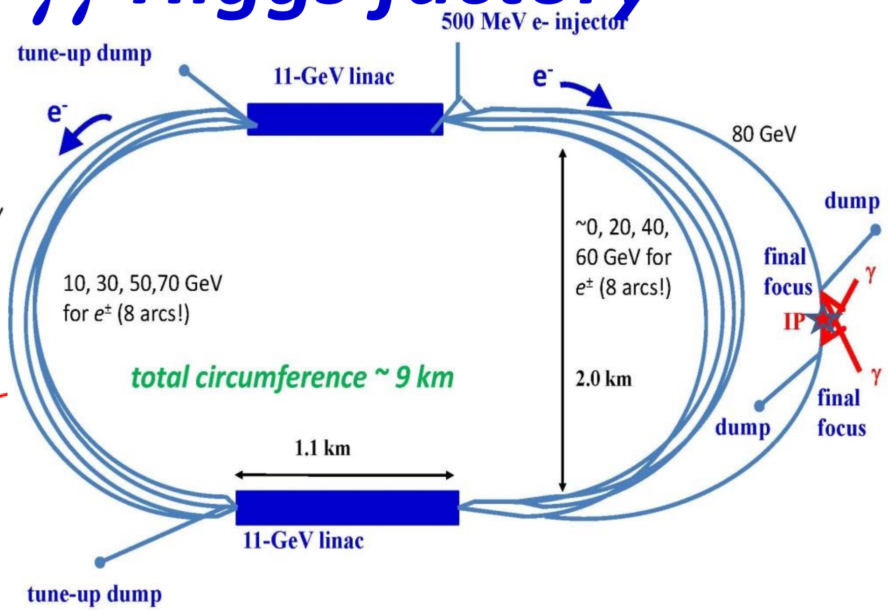
Left: The cross sections for $\gamma\gamma \rightarrow h$ *for different values of* M_h *as functions of* $E_{CM}(e^-e^-)$.
Right: The cross section for $\gamma\gamma \rightarrow h$ *as a function of* M_h *for three different values of* $E_{CM}(e^-e^-)$.
Assumptions: electrons have 80% longitudinal polarization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

Reconfiguring *LHeC* → *SAPPHiRE*

LHeC-ERL



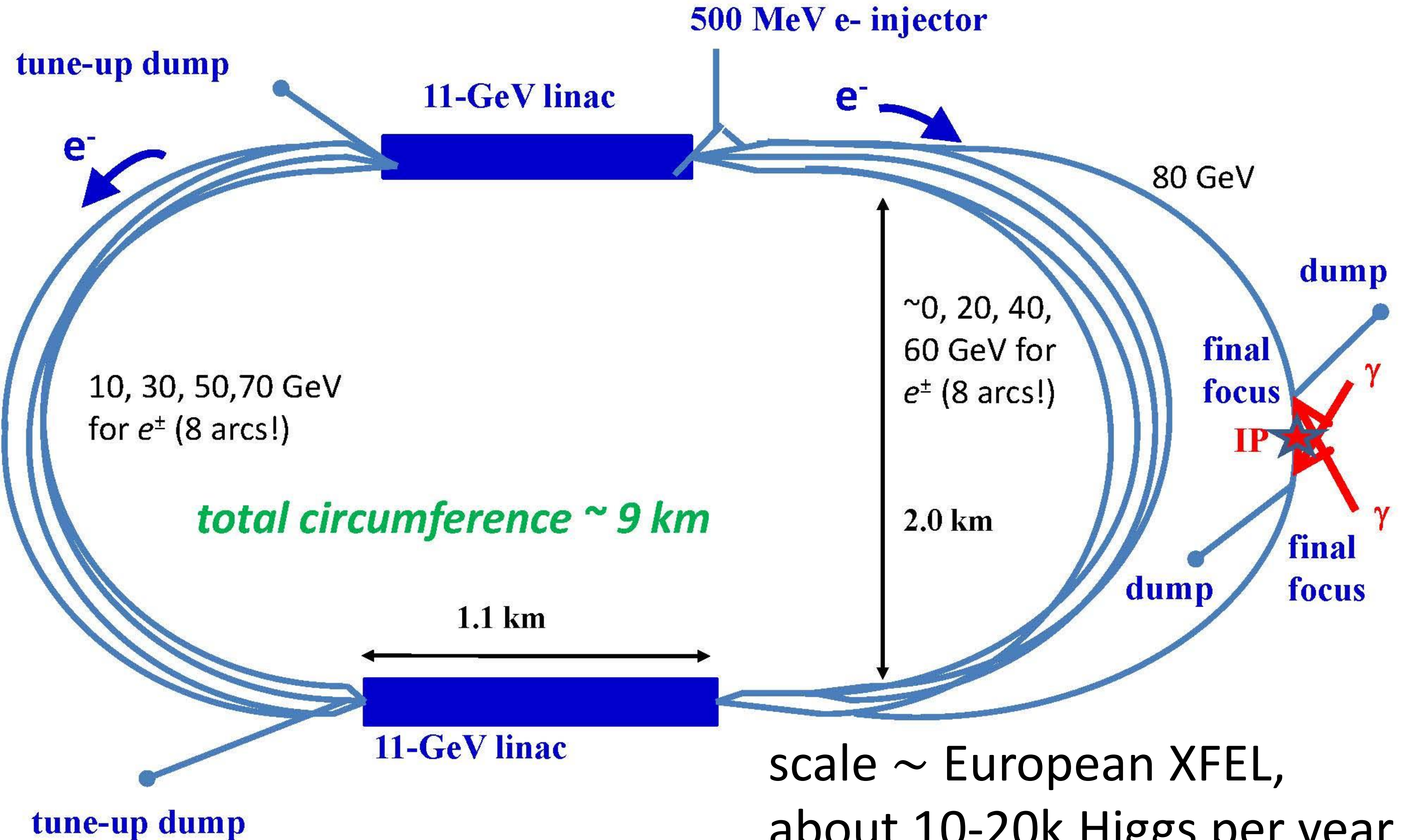
*SAPPHiRE**
γγ Higgs factory



*Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons

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

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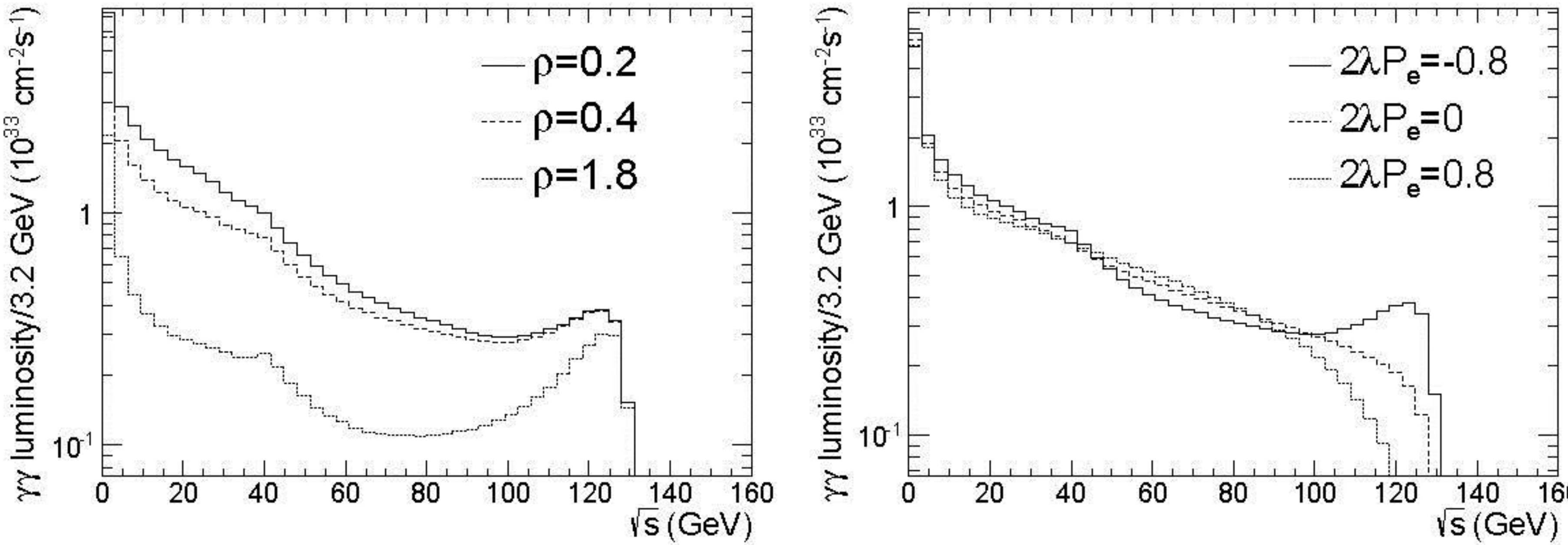
SAPPHiRE $\gamma\gamma$ luminosity

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 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

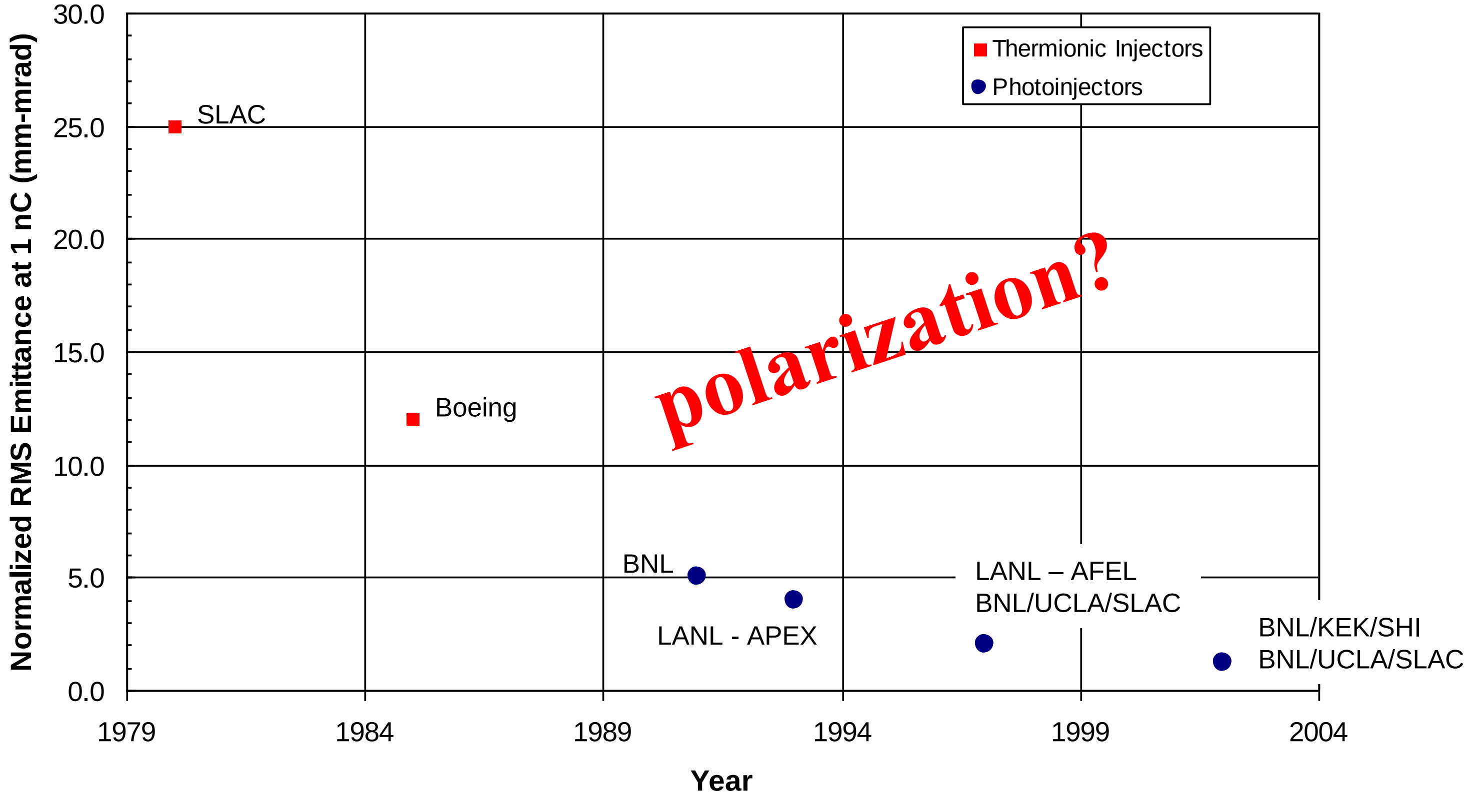
flat polarized electron source

- 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

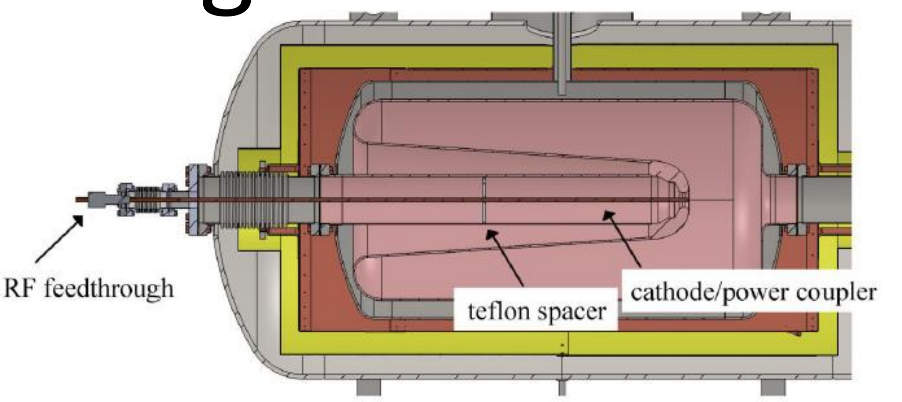
*Für **2013** wollen wir die 2. Version der SRF-Gun in Betrieb nehmen. Das neue Cavity erreichte im Test am Jlab ein Peakfeld von 43 MV/m. Mit diesen Werten sollten wir **1 nC Ladung mit 500 kHz Reprate im CW** (0.5 mA average current) erreichen. Die Emittanz könnte etwa **2 µm** sein. Auf **1 µm** könnte 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

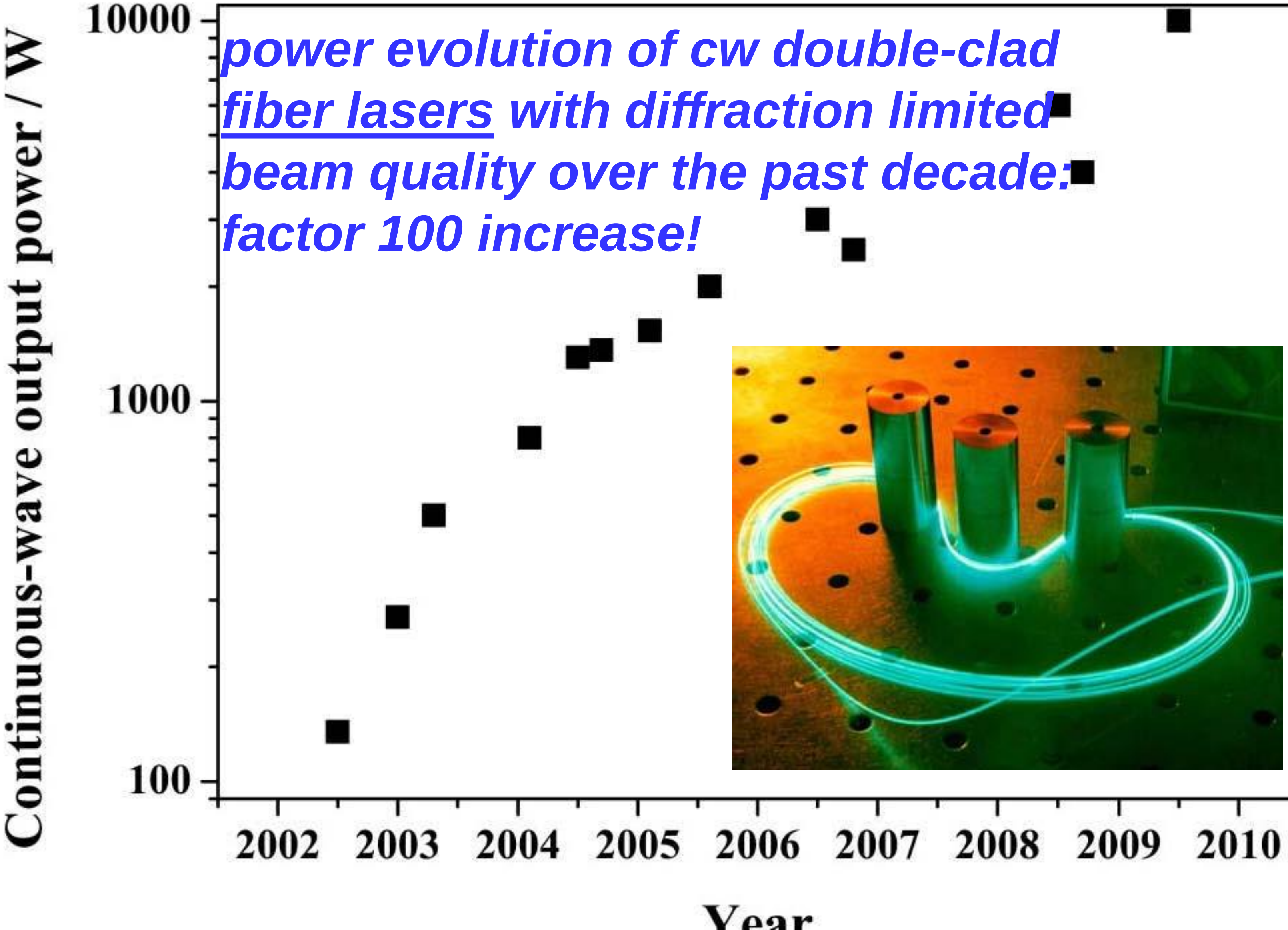
recent e$^-$ gun progress (LHeC/FCC-eh)

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)
$\gamma\varepsilon < 25$ μm (!?), 20 mA

laser progress: example fiber lasers

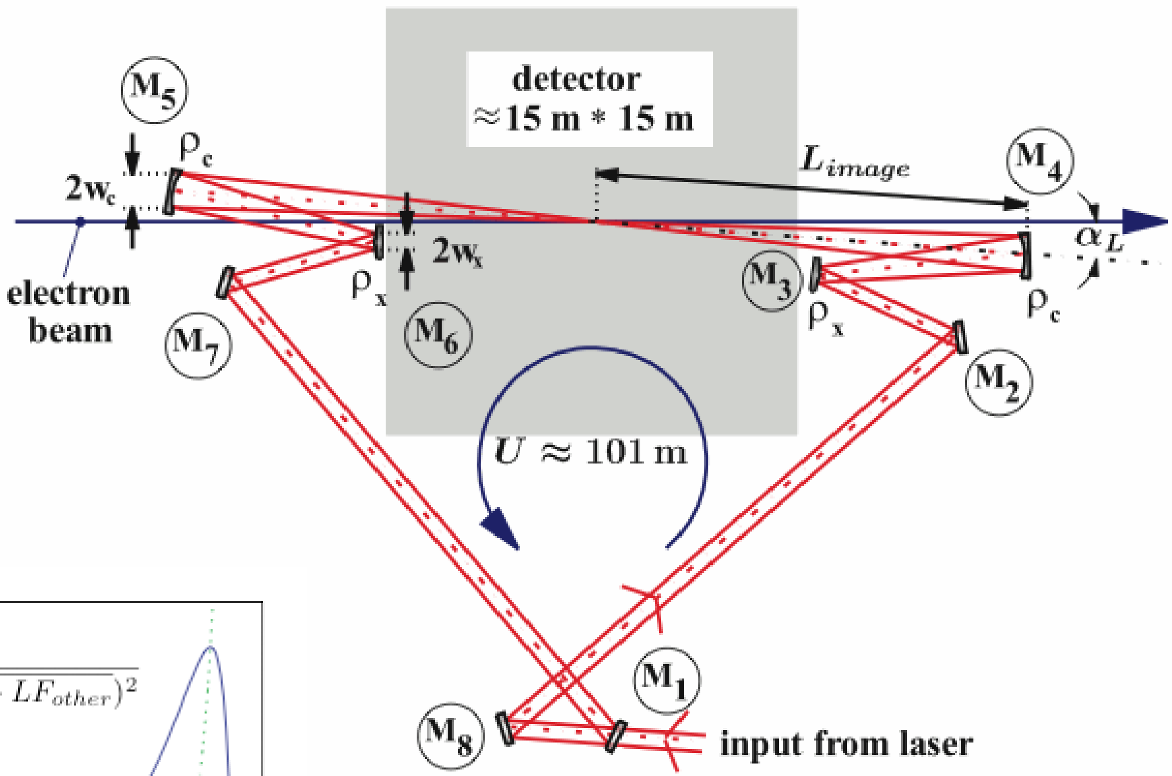


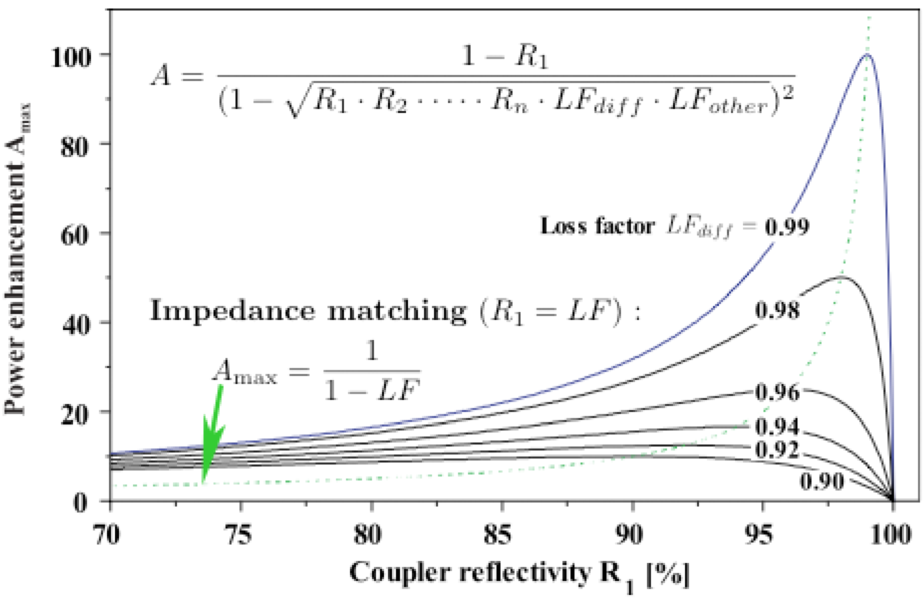
Source: Fiber lasers and amplifiers: an ultrafast performance evolution, Jens Limpert, Thomas Schreiber, and Andreas Tünnermann, Applied Optics, Vol. 49, No. 25 (2010)

passive optical cavity

→

relaxed laser parameters

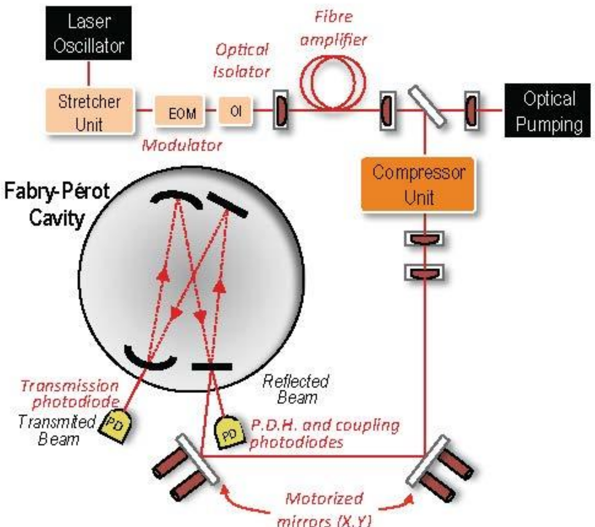




K. Moenig et al, DESY Zeuthen

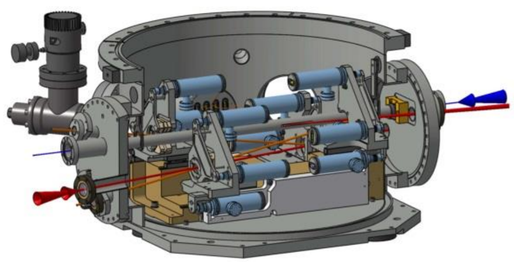
LAL *MightyLaser* experiment at **KEK-ATF**

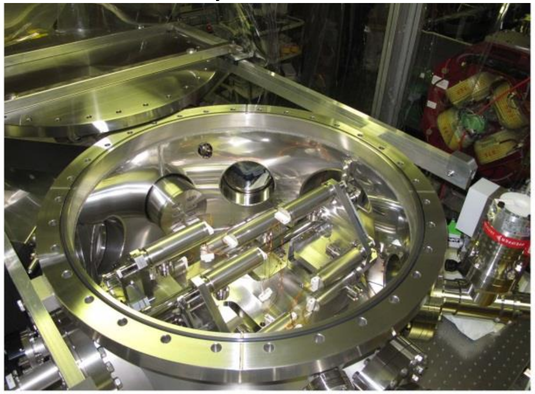
non-planar high finesse four mirror Fabry-Perot cavity;
first Compton collisions observed in October 2010



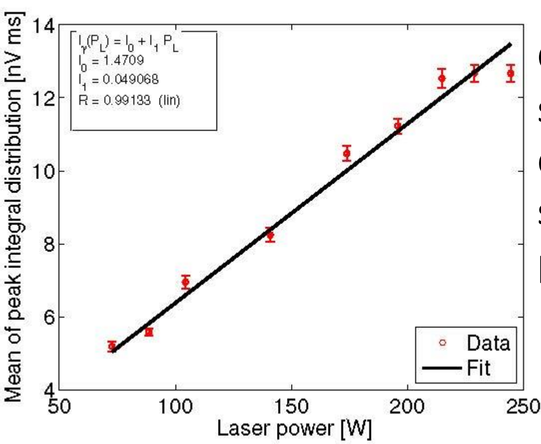
Optical system used for laser power amplification and to inject laser into FPC

I. Chaikovska, N. Delerue, A. Variola, F. Zomer et al

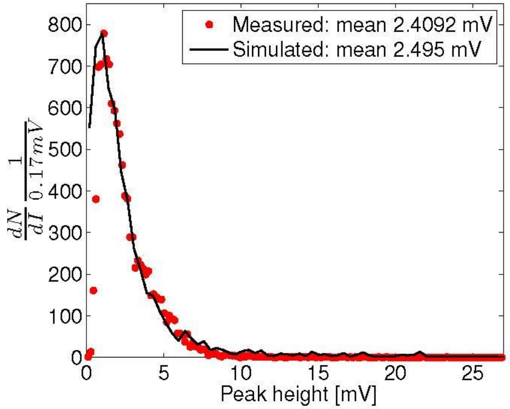




Vacuum vessel for Fabry-Perot cavity installed at ATF



Gamma ray spectrum for different FPC stored laser power

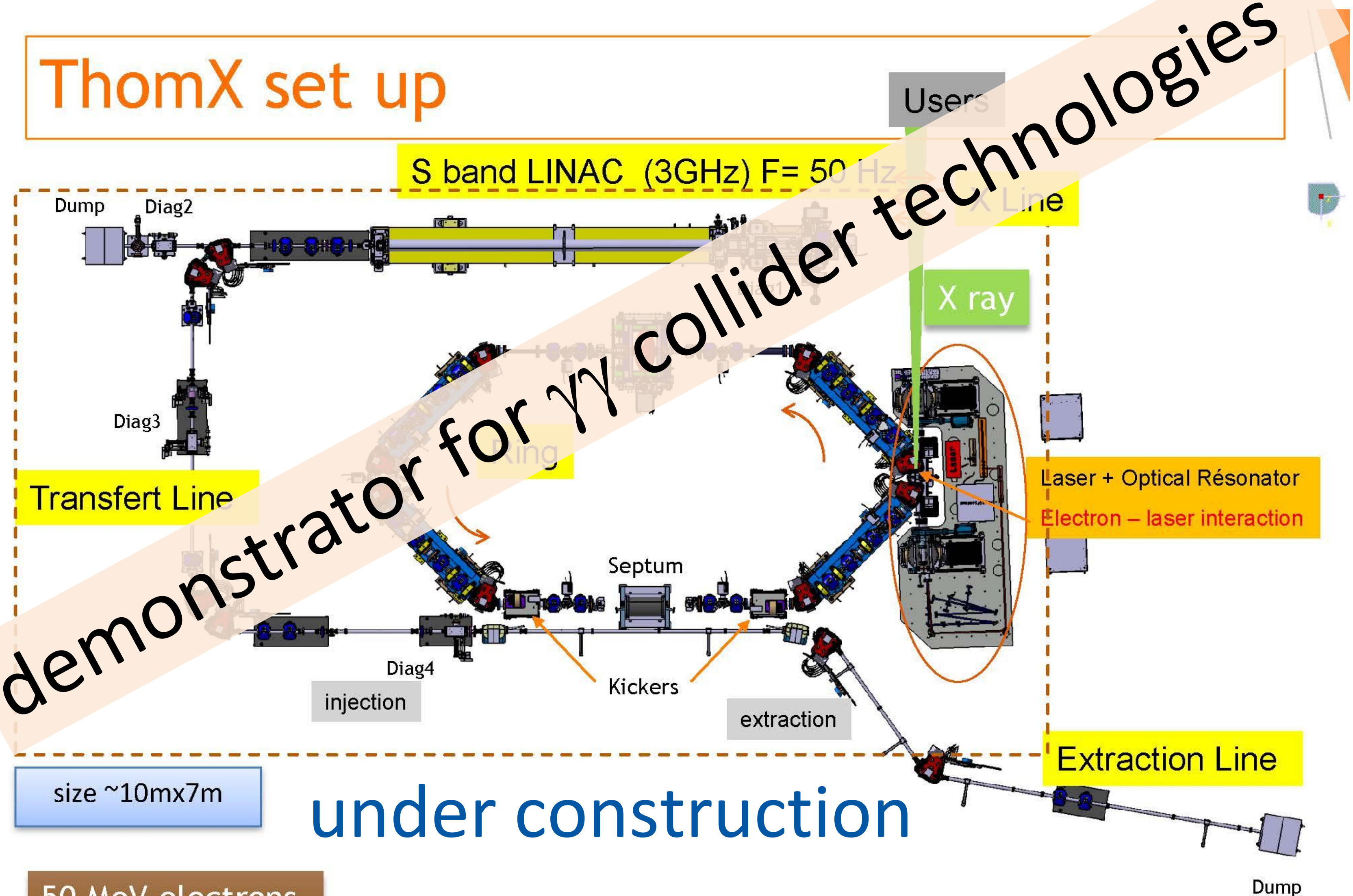


Comparison of measured and simulated gamma-ray energy spectra from Compton scattering

Plan: improve laser and FPC mirrors & gain several orders

I. Chaikovska, PhD thesis to be published

ThomX at LAL – commissioning in 2018



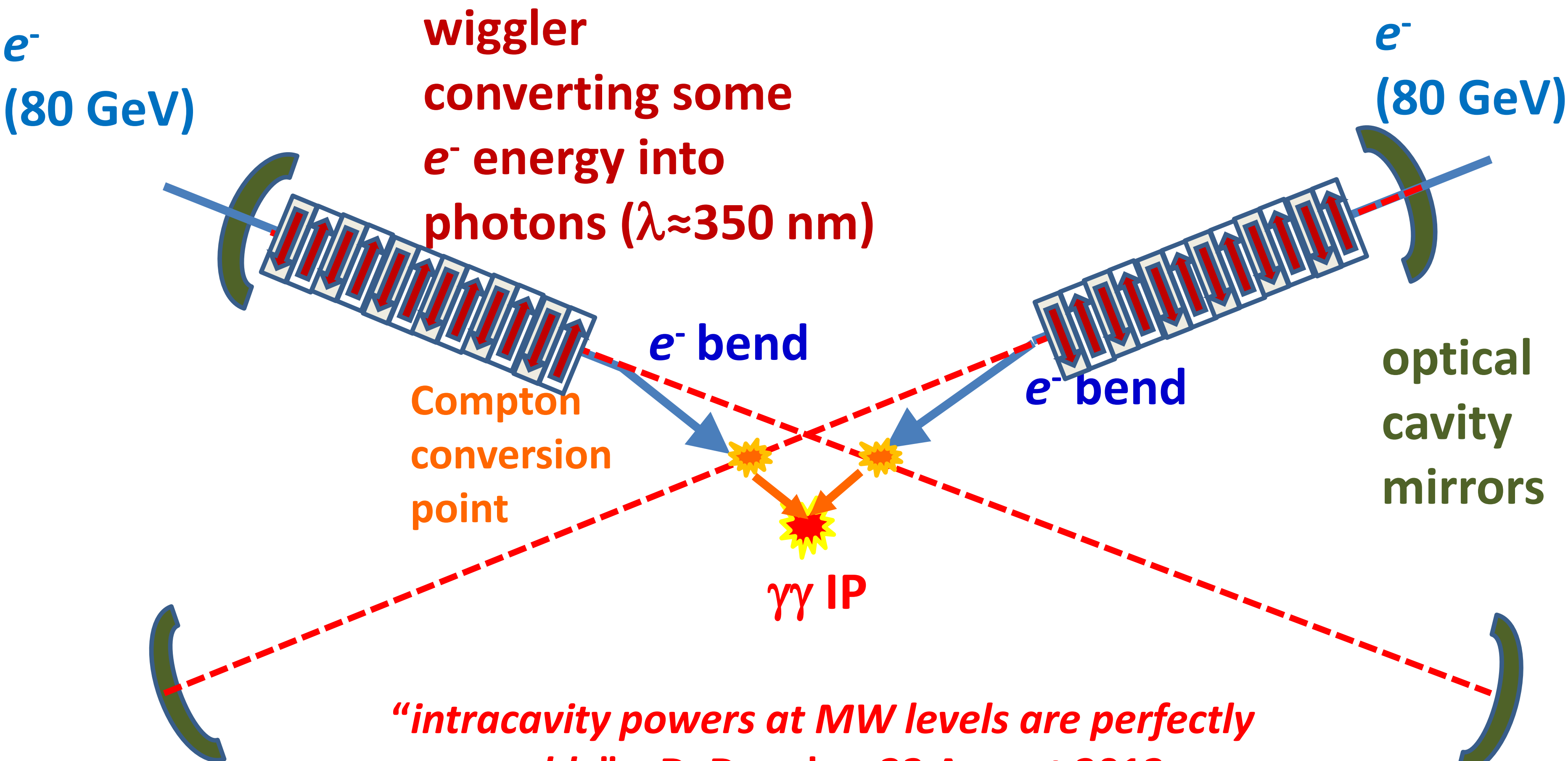
under construction

50 MeV electrons

upgrade to 70 MeV forseen

H. Monard

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



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

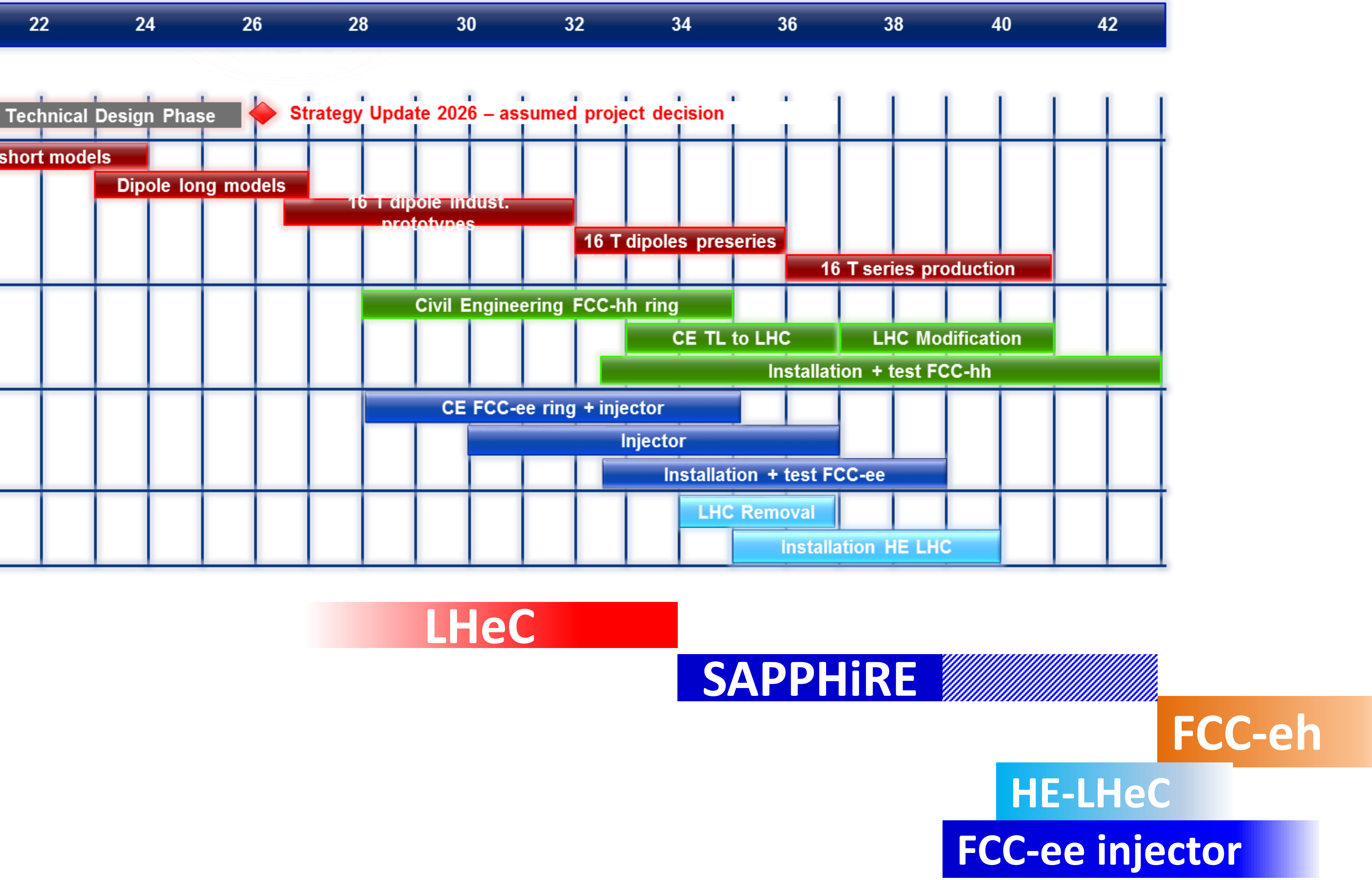
example:
λ_u=200 cm, B=0.625 T, L_u=100 m, $U_{0,SR}$=0.16 GeV, 0.1%P_{beam}≈25 kW

scheme developed with Z. Huang

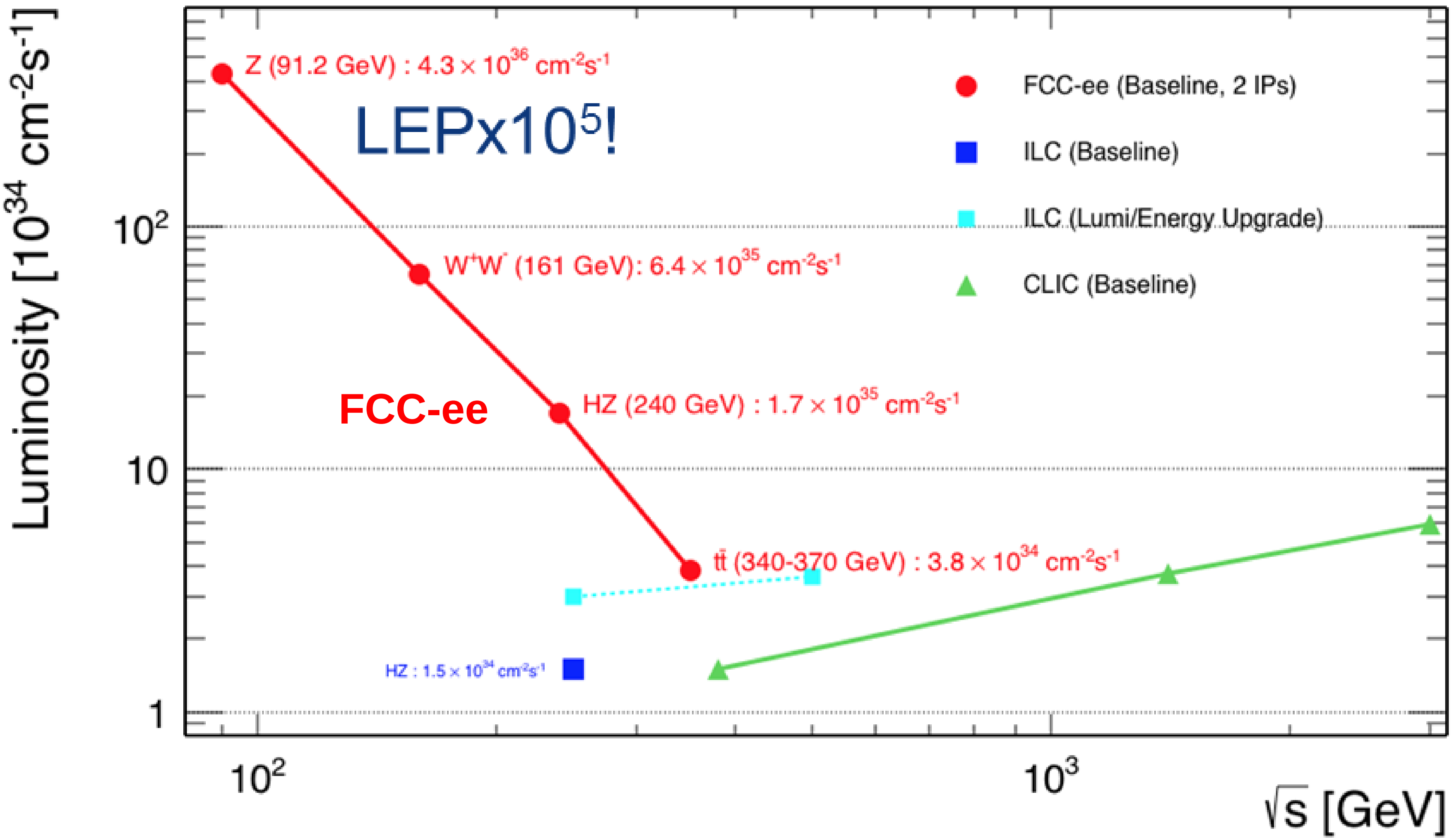
SAPPHiRE R&D items

- $\gamma\gamma$ interaction region
- large high-finesse optical cavity
- high repetition rate laser
- FEL in unusual regime
- separation scheme for beams circulating in opposite directions
- polarized low-emittance e^- gun
- detector

fitting the LHeC



total luminosity of proposed future e^+e^- colliders



FCC-ee

A. Blondel, Lepton-Photon 2017

Y. Papaphilippou

FCC-ee injector parameters (summer 2017)

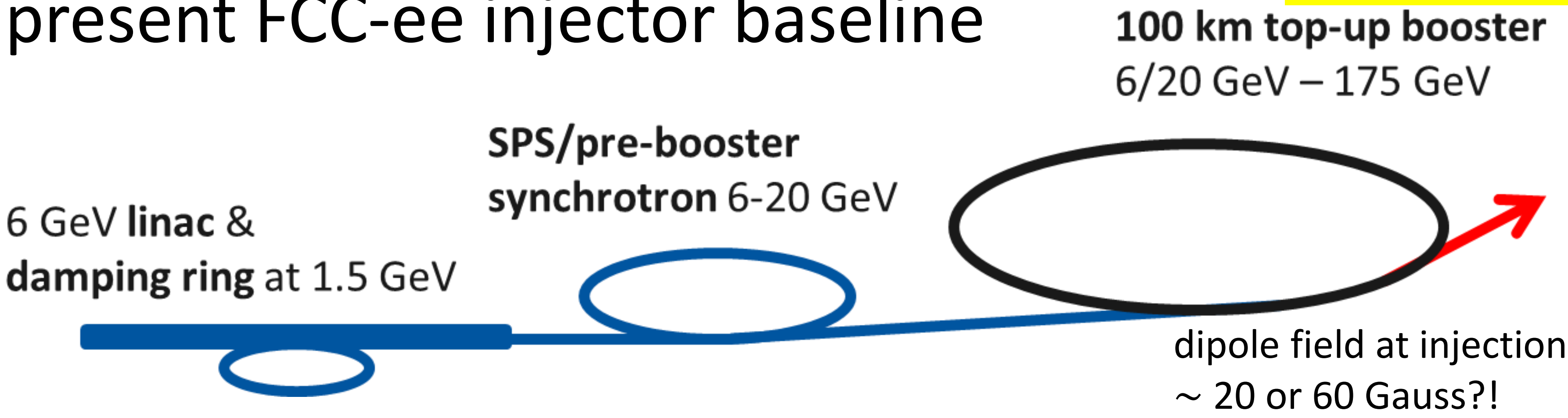
Accelerator	FCCee-Z		FCCee-W		FCCee-H		FCCee-tt	
Energy [GeV]	45.6		80		120		175	
Type of filling	Full	Top-up	Full	Top-up	Full	Top-up	Full	Top-up
LINAC # bunches, with 2.8 GHz RF	2		1					
LINAC repetition rate [Hz]	200		100					
LINAC/SPS bunch population [10^{10}]	2.5	0.25	1.25	0.25	1.11	0.44	2.55	1.28
# of LINAC injections	244	3538	364		59		64	
SPS bunch spacing [ns]	2.5		40		390		360	
# SPS cycles	10		20		14		1	
SPS # of bunches	488	7076	364		59		64	
SPS cycle time [s]	1.72	18.19	4.14		1.09		1.14	
SPS duty factor	0.79	0.94	0.91		0.15	0.70	0.16	
BR # of bunches	4880	70760	7280		826	826	64	
BR cycle time [s]	20.2	184.9	88.8		21.3		7.1	
#of BR cycles	29	1	4	1	8	1	10	1
# of injections/collider bucket	2	1	4	1	8	1	10	1
Total number of bunches	70760		7280		826		64	
Filling time (both species) [sec]	1171.6	369.8	710.4	177.6	340.2	42.5	142.8	14.3
Injected bunch population [10^{10}]	4.0	0.2	4.0	0.2	7.1	0.35	20.4	0.10

maximum current needed: 0.8 μA e- 0.8 μA e+

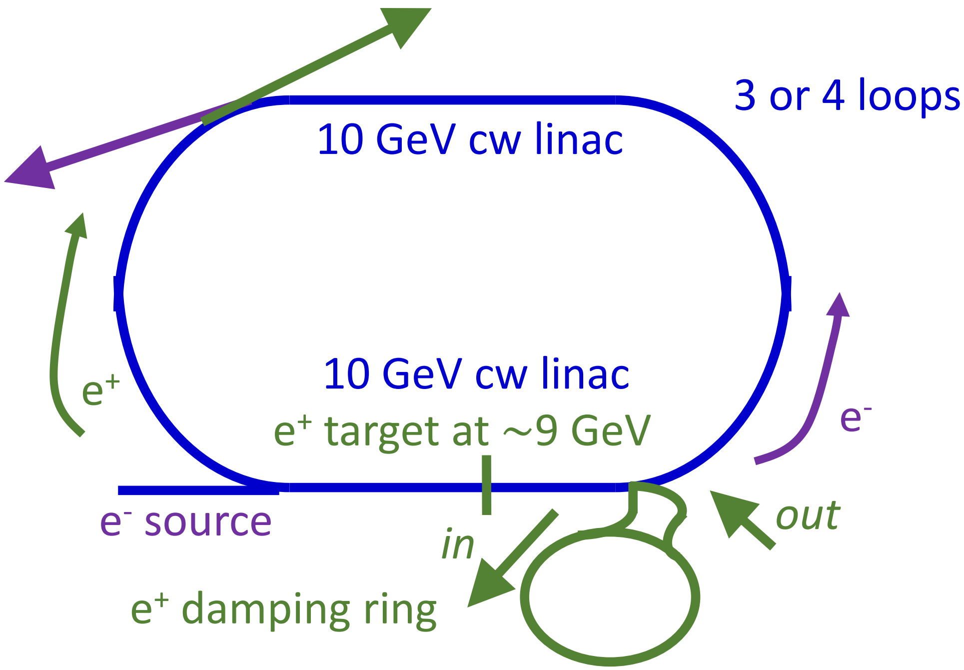
~1000x lower than LHeC w/o energy recovery!

S. Ogur et al.

present FCC-ee injector baseline



LHeC: perfect FCC-ee injector!



very flexible, powerful injection can boost luminosity performance

higher e^+ yield (~9 vs 4.5 GeV)

no need for pre-booster,

no need for top-up booster at Z and W;

simpler top up booster or 2nd ERL for H and top

parameter D. Shatilov	Z	W	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	175
arc cell optics	60/60	90/90	90/90	90/90
momentum compaction [10^{-5}]	1.48	0.73	0.73	0.73
horizontal emittance [nm]	0.27	0.28	0.63	1.34
vertical emittance [pm]	1.0	1.0	1.3	2.7
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	2
length of interaction area [mm]	0.42	0.5	0.9	1.95
tunes, half-ring (x, y, s)	(0.569, 0.61, 0.0125)	(0.577, 0.61, 0.0115)	(0.565, 0.60, 0.0180)	(0.553, 0.59, 0.0343)
longitudinal damping time [ms]	414	77	23	7.5
SR energy loss / turn [GeV]	0.036	0.34	1.72	7.8
total RF voltage [GV]	0.10	0.44	2.0	9.5
RF acceptance [%]	1.9	1.9	2.3	5.0
energy acceptance [%]	1.3	1.3	1.5	2.5
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.153	0.099 / 0.151	0.147 / 0.192
bunch length (SR / BS) [mm]	3.5 / 12.1	3.3 / 7.65	3.15 / 4.9	2.45 / 3.25
Piwinski angle (SR / BS)	8.2 / 28.5	6.6 / 15.3	3.4 / 5.3	1.0 / 1.33
bunch intensity [10^{11}]	1.7	1.5	1.5	2.7
no. of bunches / beam	16640	2000	393	48
beam current [mA]	1390	147	29	6.4
luminosity [10^{34} cm^{-2}s^{-1}]	**>200**	**>30**	**>7**	**>1.6**
beam-beam parameter (x / y)	0.004 / 0.133	0.0065 / 0.118	0.016 / 0.108	0.095 / 0.157
luminosity lifetime [min]	70	50	42	39
time between injections [sec]	122	44	31	32
allowable asymmetry [%]	±5	±3	±3	±3
required lifetime by BS [min]	29	16	11	12
actual lifetime by BS ("weak") [min]	> 200	20	20	24
$e^{\pm}$ current for required lifetime [μA]	**0.26**	**0.05**	**0.014**	**0.003**

a few comments:

LHeC w/o energy recovery can continually produce 1 mA e^+ and e^- beam current, >1000x the current required for FCC-ee baseline

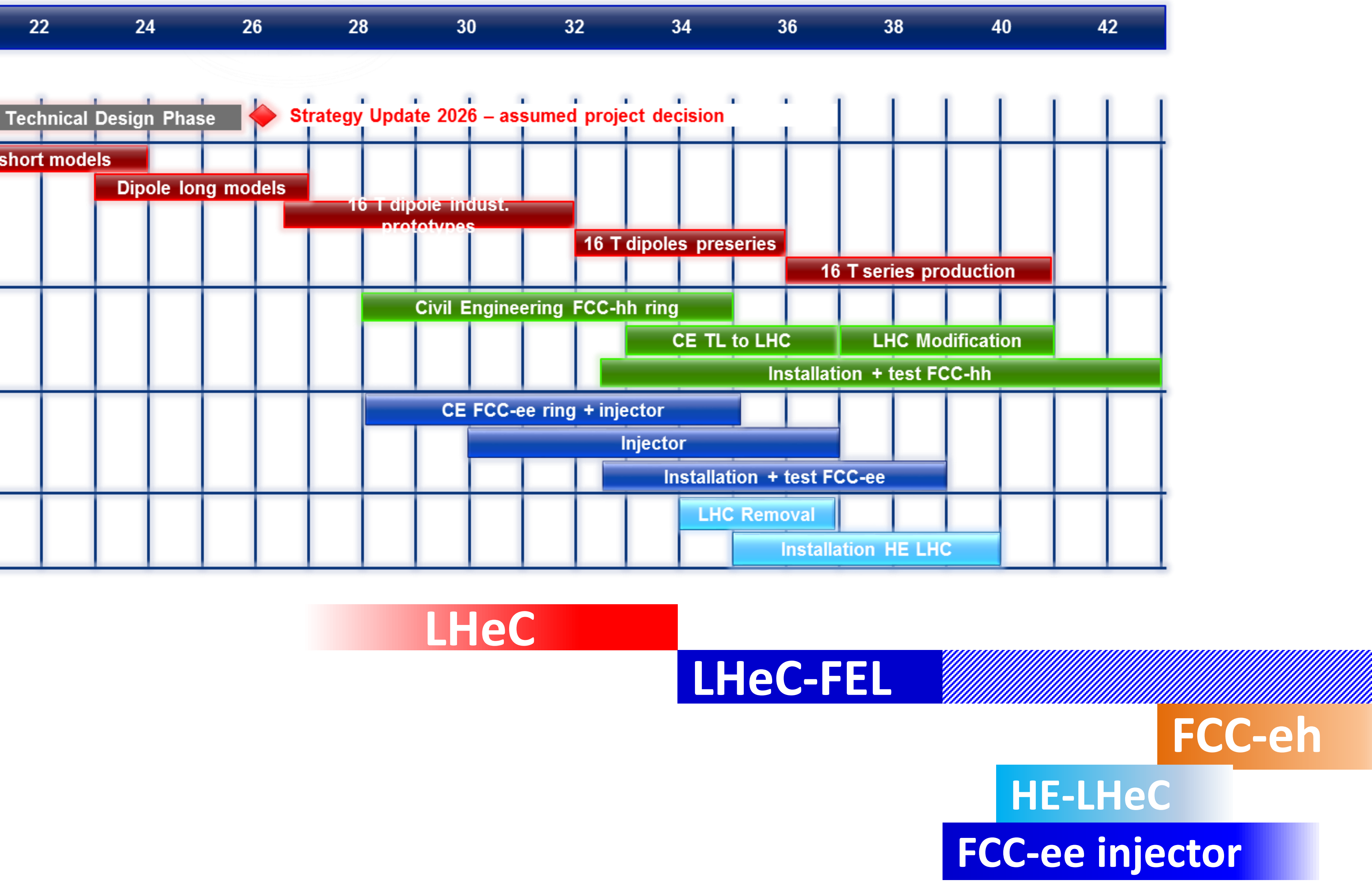
for 9 GeV e^- energy on target (LHeC) the e^+ yield is ~2x higher than for 4.5 GeV (present FCC-ee baseline)

Iryna Chaikovska, LAL

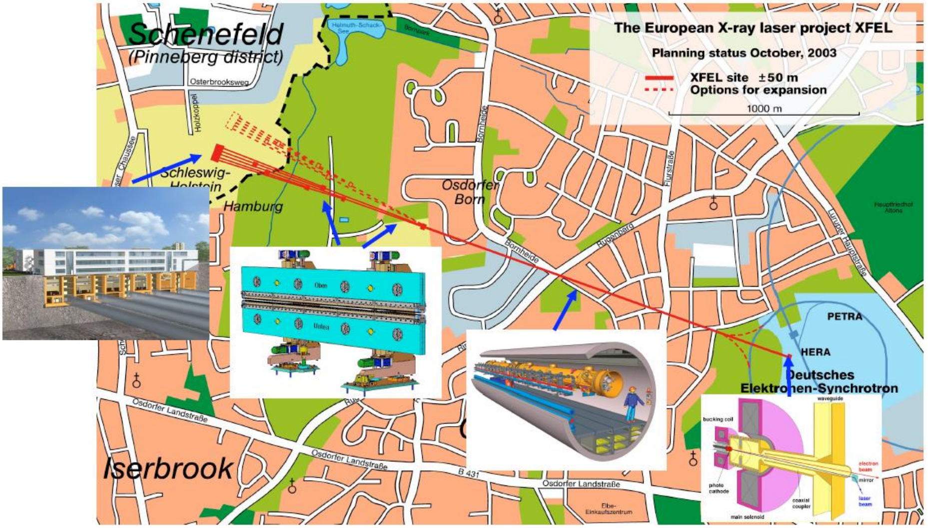
with a much more precise injection colliding-bunch charge asymmetry can be reduced and luminosity be increased from anywhere between a few percent (Dmitry Shatilov, BINP) and perhaps a factor of 2 (F.Z.)

we may still need a top-up booster ring to go above 80 GeV; but energy swing is much lower and injection field poses no problem anymore; alternatively we could add a few more RLA return lines in the collider tunnel

fitting the LHeC

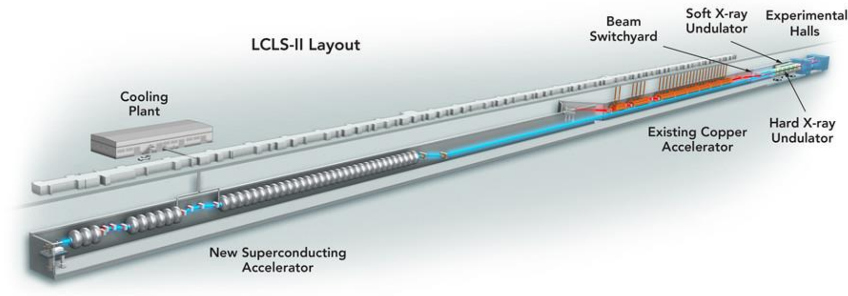


European XFEL, Hamburg, 2017



up to ~20 GeV, pulsed,
0.03 mA, up to 24 keV photons

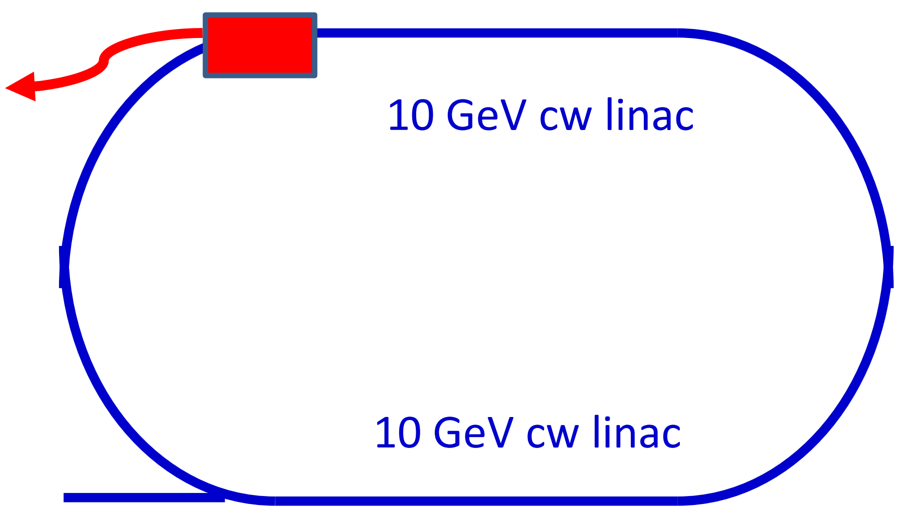
LCLS-II, SLAC, 2021?



up to ~4 GeV, cw, 0.06 mA,
up to 5 keV photons

H. Schopper

LHeC-FEL



up to 60 GeV,
~25 mA,
1 MeV photons?

3-15x higher beam energy
(10-200x higher γ energies),
300-600x higher current

conclusions

- LHeC + SAPPHiRE + HE-LHC + FCC-ee + FCC-eh are all tantalizing projects
- ERL complex offers natural staging scenarios and an optimum utilization of resources
- SAPPHiRE and LHeC = some of the cheapest possible options to further study the Higgs – but, esp. SAPPHiRE, not easy
- (HE-)LHeC & FCC-eh = discovery machines
- LHeC's RLA = the perfect FCC-ee injector
- LHeC-FEL = a great leap for X-ray science!

ARIES APEC workshop on "Compton sources, gamma-gamma colliders and gamma factories" - Padua, 2 days, November or December 2017

Organizers: Marco Zanetti (INFN Padua), Frank Zimmermann (CERN)

Programme Committee (tentative and tbc):
Luca Serafini, INFN Milano; Alessandro Variola, INFN-LNF & ELI; Witek Krasny, LNPHE Paris; Fabian Zomer, LAL Orsay ; Noboru Sasao, Okayama U.; Massimo Ferrario, INFN-LNF; Zhirong Huang, SLAC; Valery Telnov, BINP & NSU; Weiren Chou, IHEP Beijing; Yoann Zaouter, Amplitude Systemes; ...

ARIES APEC Task 6.6 "Far Future Concepts & Feasibility"

ARIES

THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION

HORIZON 2020

APEC

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