Electron Positron Collider Power Consumption & Performance Considerations

Frank Zimmermann, CERN

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Thanks to B. List, S. Belomestnykh, V. Shiltsev, J. Gao, A. Faus-Golfe, M. Biagini, M. Boscolo, R. Rimmer, T. Satogata, M. Koratzinos, E. Nanni, P. Raimondi, T. Raubenheimer, J. Seeman, V.N. Litvinenko, K. Oide


ias HKUST JOCKEY CLUB INSTITUTE FOR ADVANCED STUDY

IAS PROGRAM

High Energy Physics

February 12 – 16, 2023

Conference: February 14 – 16, 2023


eeFACT'22

Snowmass 2021

Snowmass 2021

AF03: EW/Higgs Facilities

report: https://arxiv.org/abs/2209.05827

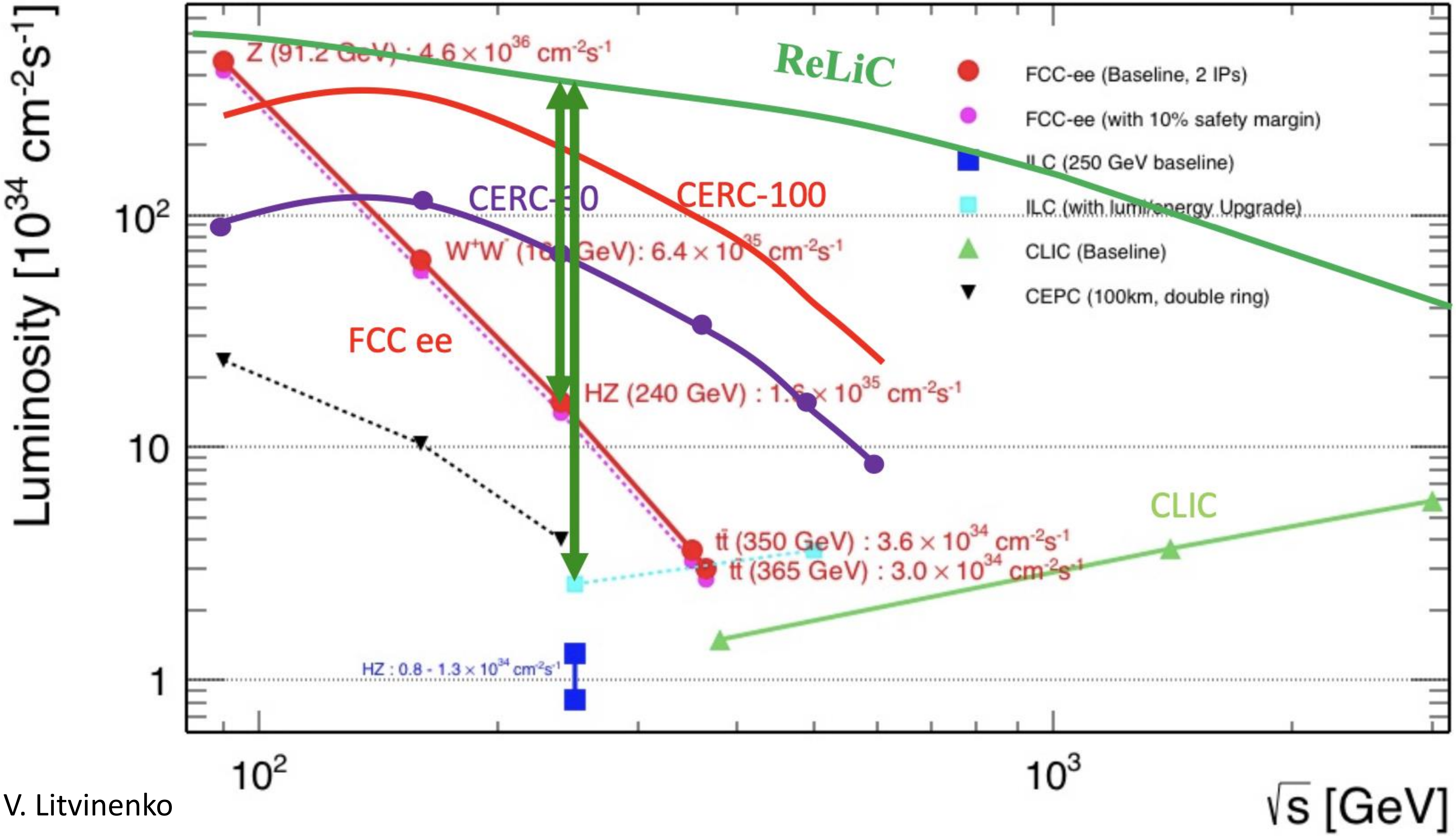
Co-Conveners

- Georg Hoffstaetter
- Qing Qin
- Angeles Faus-Golfe
- Frank Zimmermann

RELIC

Gain of 40 to 200 at HIGS energy

Snowmass 2021



V. Litvinenko

During the Snowmass Community Summer Study in Seattle, questions arose on the feasibility of power and luminosity numbers communicated for various collider proposals.

The Accelerator Frontier Implementation Task Force (ITF) had received many inputs on various collider concepts. The ITF specifically mentioned that they had not reviewed luminosity and power consumption projections (i.e., **the ITF used proponents' numbers of luminosity and power**).

The following **ICFA Workshop eeFACT'22, organized at Frascati in September 2022, was charged with** helping the broader accelerator and HEP community **by taking a look at the luminosity and power consumption projections for various e^+e^- Higgs factories and providing an "expert comparative evaluation" for them.**
Given the strength of the cohort of anticipated participants, such "independent" evaluation was expected to be very helpful.

A special session was set up during eeFACT'22, where representatives from all major proposals were invited to present and discuss their respective numbers and the underlying assumptions.

This effort resulted in a **dedicated paper, FRXAS0101, submitted to the proceedings of eeFACT'22. Key points** are reported here.

eeFACT22 extension as mandated by Snowmass

task from the Snowmass process to

“*take a look at the luminosity and power consumption projections for various ee-Factories & provide expert comparative evaluation for them*.”

special session on Thursday evening and Friday morning

thanks to Marica Biagini, Vladimir Shiltsev, Tor Raubenheimer, Mike Koratzinos, Jie Gao, Angeles Faus-Golfe, …

Agenda of the special eeFACT'22 session

Thursday afternoon/evening, 15 Sept. 2022

Talks from the US

- Vladimir Litvinenko, **CERC** and **ReLiC**
- Emilio Nanni, **C^3**
- Sergey Belomestnykh, **HELEN**

Friday, 16 Sept. 2022

Talks from Europe and Asia

- Jie Gao, **CEPC**
- Frank Zimmermann, **FCC-ee**
- Steinar Stapnes, **CLIC**
- Benno List, **ILC**

survey table

Beam energy [GeV]
Average beam current [A or mA]
SR power [MW]

Collider cryo power [MW]
Collider RF power [MW]
Collider magnet power [MW]
Cooling & ventilation power [MW]
General services power [MW]
Injector cryo power [MW]
Injector RF power [MW]
Injector magnet power [MW]
Pre-injector power (where applicable)] [MW]
Detector power (if included) [MW]
Data center power (if included) [MW]
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Total power [MW]

Effective physics time per year for integrated luminosity [10^7 s]

every project provided this input

Table 2: Electrical power budgets for the proposed Higgs and Electroweak factory colliders, and, for comparison the EIC, based on invited contributions to the special session at eeFACT'22 [4]. NI: Not Included; NE: Not Estimated; –: Not Existing. ‡ILC parameters correspond to the luminosity upgrade. The total ILC power includes 4 MW margin, the one for HELEN 3.3 MW (here as part of the general services). *For HELEN, the "detector" number refers to the power required for the beam delivery system, machine detector interface, interaction region, and beam dumps, the "injector magnets" number to damping ring with wigglers. †For RELIC, the 2.5 GeV damping rings and transfer lines would use permanent magnets.

Proposal	CEPC		FCC-ee		CERC		C^3	HELEN	CLIC	ILC‡	RELIC		EIC
Beam energy [GeV]	120	180	120	182.5	120	182.5	125	125	190	125	120	182.5	10 or 18
Average beam current [mA]	16.7	5.5	26.7	5	2.47	0.9	0.016	0.021	0.015	0.04	38	39	0.23–2.5
Total SR power [MW]	60	100	100	100	30	30	0	3.6	2.87	7.1	0	0	9
Collider cryo [MW]	12.74	20.5	17	50	18.8	28.8	60	14.43	–	18.7	28	43	12
Collider RF [MW]	103.8	173.0	146	146	57.8	61.8	20	24.80	26.2	42.8	57.8	61.8	13
Collider magnets [MW]	52.58	119.1	39	89	13.9	32	20	10.40	19.5	9.5	2	3	25
Cooling & ventil. [MW]	39.13	60.3	36	40	NE	NE	15	10.50	18.5	15.7	NE	NE	5
General services [MW]	19.84	19.8	36	36	NE	NE	20	6.00	5.3	8.6	NE	NE	4
Injector cryo [MW]	0.64	0.6	1	1	NE	NE	6	1.96	0	2.8	NE	NE	0
Injector RF [MW]	1.44	1.4	2	2	NE	NE	5	0*	14.5	17.1	192	196	5
Injector magnets [MW]	7.45	16.8	2	4	NE	NE	4	13.07*	6.2	10.1	0†	0†	5
Pre-injector [MW]	17.685	17.7	10	10	NE	NE	–	13.37	–	–	NE	NE	10
Detector [MW]	4	4.0	8	8	NE	NE	NE	15.97*	2	5.7	NE	NE	NI
Data center [MW]	NI	NI	4	4	NE	NE	NE	NI	NI	2.7	NE	NE	NI
Total power [MW]	259.3	433.3	301	390	89	122	150	110.5	107	138	315	341	79
Lum./IP [10^{34} cm^{-2}s^{-1}]	5.0	0.8	7.7	1.3	78	28	1.3	1.35	2.3	2.7	200	200	1
Number of IPs	2	2	4 (2)	4 (2)	1	1	1	1	1	1	2	2	1 (2)
Tot. integr. lum./yr [1/fb/yr]	1300	217.1	4000 (2300)	670 (340)	10000	3600	210	390.7	276	430	79600	79000	145
Eff. physics time / yr [10^7 s]	1.3	1.3	1.24	1.24	1.3	1.3	1.6	2.89	1.2	1.6	2	2	1.45
Energy cons./yr [TWh]	0.9	1.6	1.51	1.95	0.34	0.47	0.67	0.89	0.6	0.82	2	2.2	0.32

Annual power consumption in TWh numbers does not look fully consistent across various machines.
As an **example, for the FCC-ee**, the annual power consumption is higher than the product of instantaneous power and effective physics time, since **power needs during annual hardware commissioning, beam commissioning, operational down times, technical stops, machine development periods and shutdowns are also taken into account** [J.-P. Burnet], as sketched in the following Table.

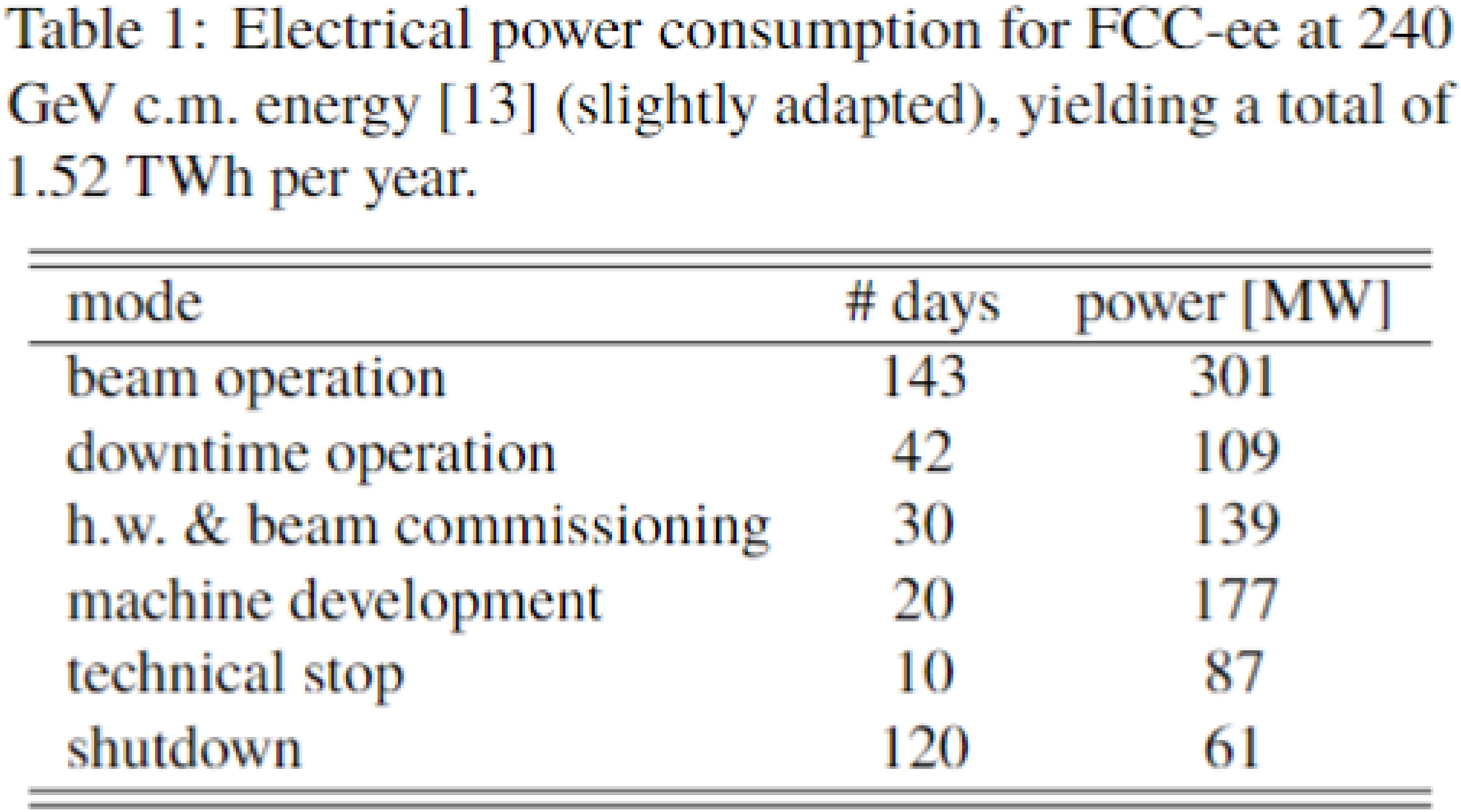


Table 1: Electrical power consumption for FCC-ee at 240 GeV c.m. energy [13] (slightly adapted), yielding a total of 1.52 TWh per year.

mode	# days	power [MW]
beam operation	143	301
downtime operation	42	109
h.w. & beam commissioning	30	139
machine development	20	177
technical stop	10	87
shutdown	120	61

Static Heat Loads

Concerning static heat loads, the best values from LCLS-II cryomodules are reported to be 5 times larger than those which had been assumed for the ILC. Based on operational experience, the 2-K static heat load per 8-cavity cryomodule is expected to be about 11 W for LCLS-II-HE, which is about two times higher than the value of 6 W estimated for LCLS-II in 2014, and an order of magnitude higher than the **static heat load per cryomodule of 1.32 W at 2 K, which had been predicted for the ILC in 2017**.

LCLS-II may still have some cryogenic issues to resolve.

A more appropriate comparison is with the European E-XFEL. For this E-XFEL, a static heat load of 6.1 W was measured per linac cryomodule. Consequently, **in the latest ILC estimates, a static heat load of 6 W per cryomodule is assumed**, consistent with actual E-XFEL experience.

Cryoplant Efficiency

The cryoplant efficiencies at various existing facilities, like LHC, JLAB, and SLAC can be compared with the target efficiency for future projects. The **LHC cryoplant efficiency at 1.9 K is 900 W/W** (that is the number of Watt at room temperature required for removing one Watt at 1.9 K). For a proposed 8 GeV SC proton linac at Fermilab a cryo efficiency at 2 K of 790 W/W is considered. The **ILC will further improve the 2-K cryoplant efficiency to 700 W/W**.

Collision Spot Size

The difference of the vertical spot size observed at the KEK/ATF-2 facility from expected value, especially at nominal $\beta^*{}_x$, and its dependence on bunch intensity, resembles earlier findings at the SLC and at the FFTB. The present ATF-2 optics is much relaxed compared with the design, which should greatly lower the optical aberrations. **The ATF-2 would offer an opportunity to characterize the higher-order aberrations with beam and to compare them with model predictions.**

Positron Needs

Traditional linear colliders lose all particles after 1 collision

For circular colliders and ERL based colliders, unavoidable losses occur due to radiative Bhabha scattering and beamstrahlung

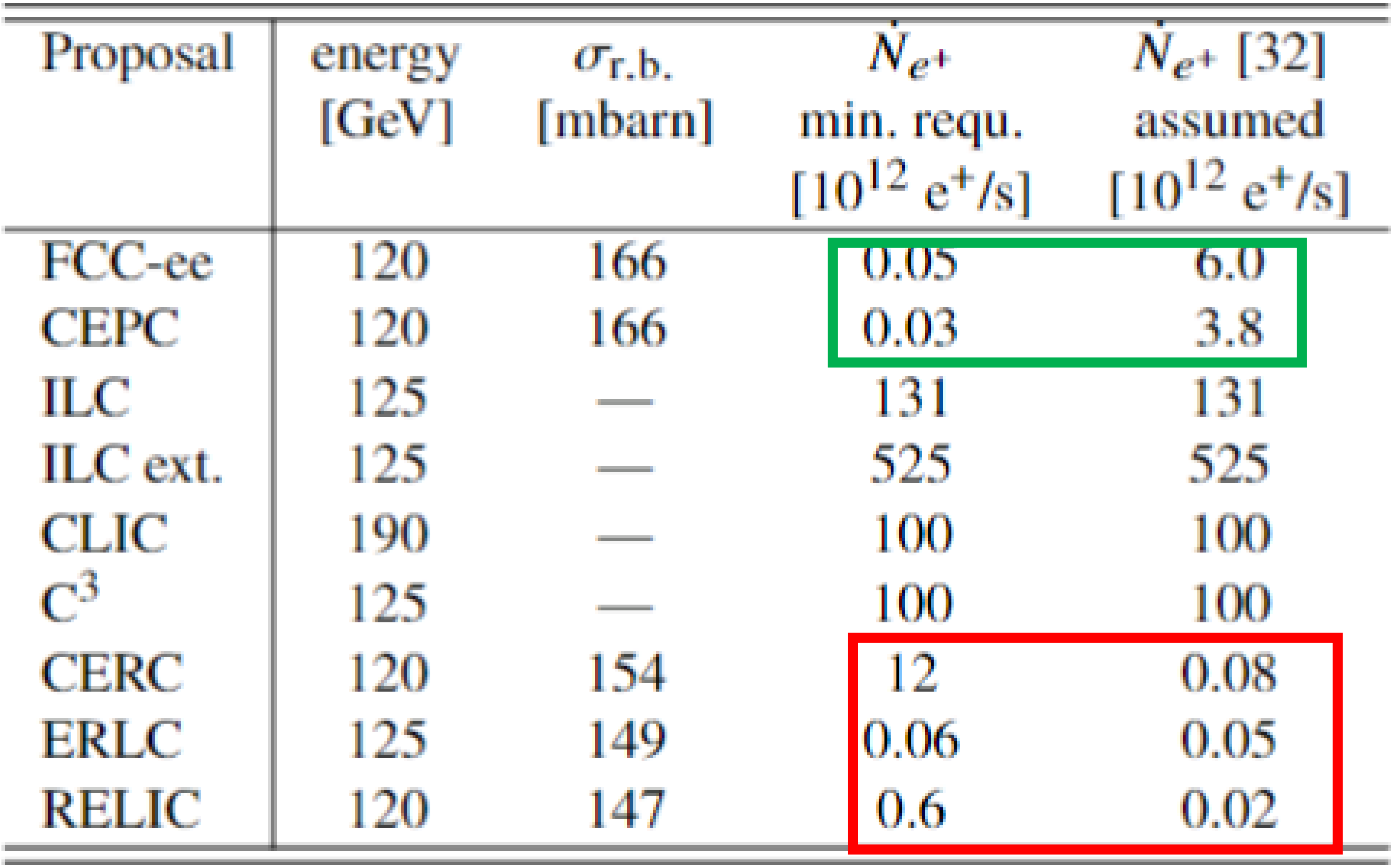
Radiative Bhabha scattering:

- simulation program BBBREM and formalism developed by Burkhardt and Kleiss for LEP, includes cut-off on momentum transfer related to average distance between beam particles
- other treatment by Kotkin and Serbo with cutoff related to transverse beam size

exact theory and numbers to be revised

either way, cross section depends on IP parameters

J. Seeman reviewed project e^+ rates compiled by ITF



Proposal	energy [GeV]	$\sigma_{\text{r.b.}}$ [mbarn]	$\dot{N}_{e^+}$ min. requ. [10^{12} e$^+$/s]	$\dot{N}_{e^+}$ [32] assumed [10^{12} e$^+$/s]
FCC-ee	120	166	0.05	6.0
CEPC	120	166	0.03	3.8
ILC	125	—	131	131
ILC ext.	125	—	525	525
CLIC	190	—	100	100
C^3	125	—	100	100
CERC	120	154	12	0.08
ERLC	125	149	0.06	0.05
RELIC	120	147	0.6	0.02

Cross section for particle loss due to radiative Bhabha scattering, $\sigma_{\text{r.b.}}$, as computed by BBBREM considering an energy acceptance of 2% and a cut-off based on the Burkhardt-Kleiss parameter *d*, the resulting minimum positron production rates required for different circular and ERL based colliders ("min. requ."), compared with project assumptions compiled for Snowmass'21 ("assumed"). In case of linear colliders without particle recovery, like ILC and CLIC, the required ("min. requ.") positron rate directly follows from bunch charge and bunch collision rate.

FCC-ee and CEPC: significant margins thanks to the fact that the maximum injector production rate is specified for the more demanding running on the Z pole

For RELIC, loss rate due to radiative Bhabha scattering a ~25x higher than production rate hitherto assumed; for CERC the loss rate is 100x higher than production rate → injector designs may need to be modified

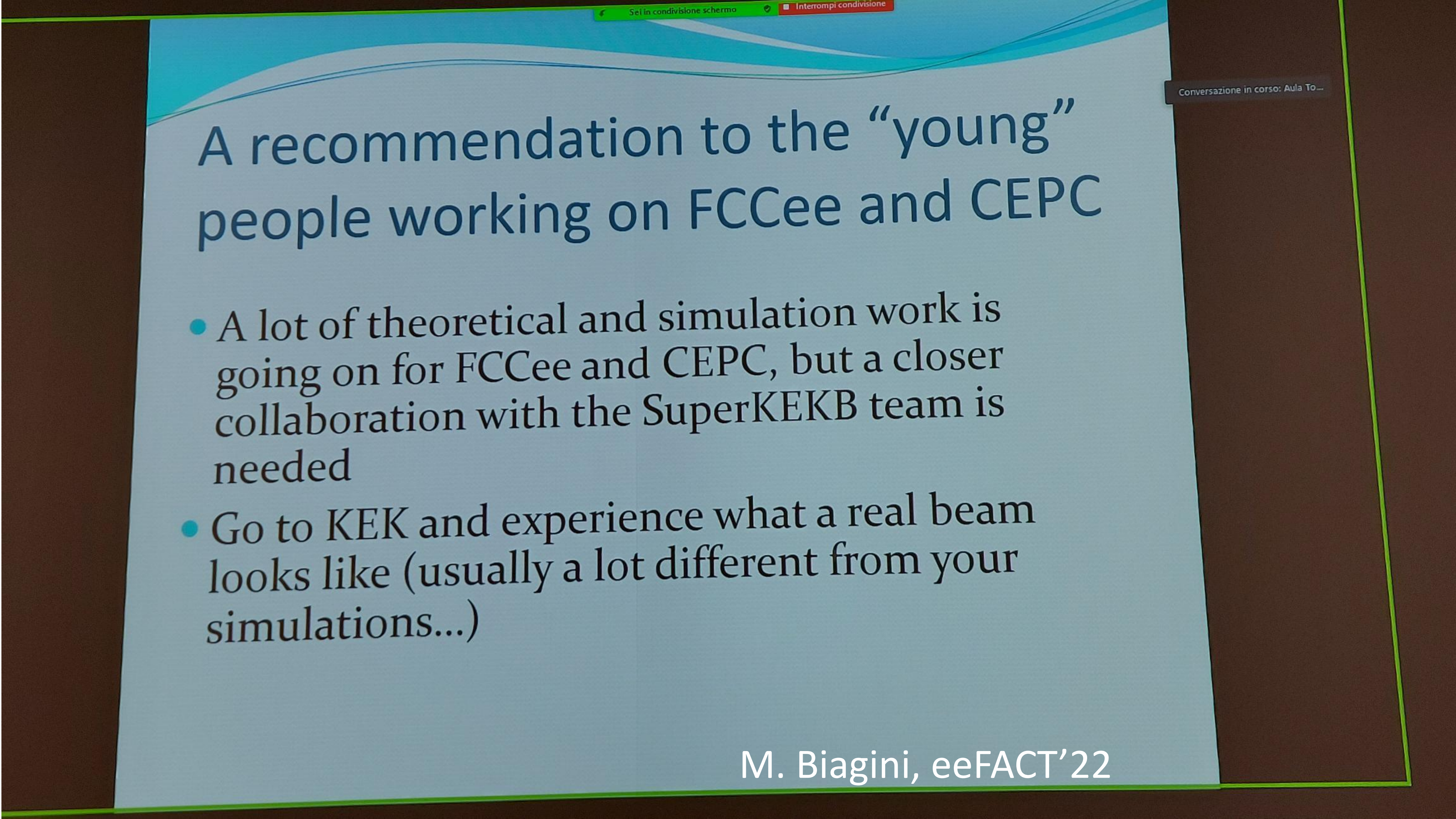
respective cross sections still need to be validated, and possibly updated, before definite conclusions can be drawn

Predicting Performance

More mature projects (ILC, CLIC, FCC-ee, CEPC) have fairly established and reviewed performance figures backed by detailed simulations, although of course all projects are working towards increasing performance.
The newer projects (e.g., RELIC, CERC) do not yet have reviewed performance figures, neither detailed simulations demonstrating how to achieve them.

Past experience with the SLC, which after ten years of operation reached about half of its nominal luminosity, **present-day struggles with obtaining the SuperKEKB design luminosity**, and, on the other hand**, actual luminosities exceeding design values at previous machines like LEP, PEP-II and KEKB**, highlight the **importance of a fair and thorough evaluation of the luminosity risks and of the luminosity potentials**.

The corresponding work needs to be continued !



A recommendation to the "young" people working on FCCee and CEPC

- A lot of theoretical and simulation work is going on for FCCee and CEPC, but a closer collaboration with the SuperKEKB team is needed
- Go to KEK and experience what a real beam looks like (usually a lot different from your simulations...)

M. Biagini, eeFACT'22