FCC – towards more luminosity

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Frank Zimmermann, CERN


photo: J. Wenninger

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Alert: this talk was not endorsed by FCC or CERN management !

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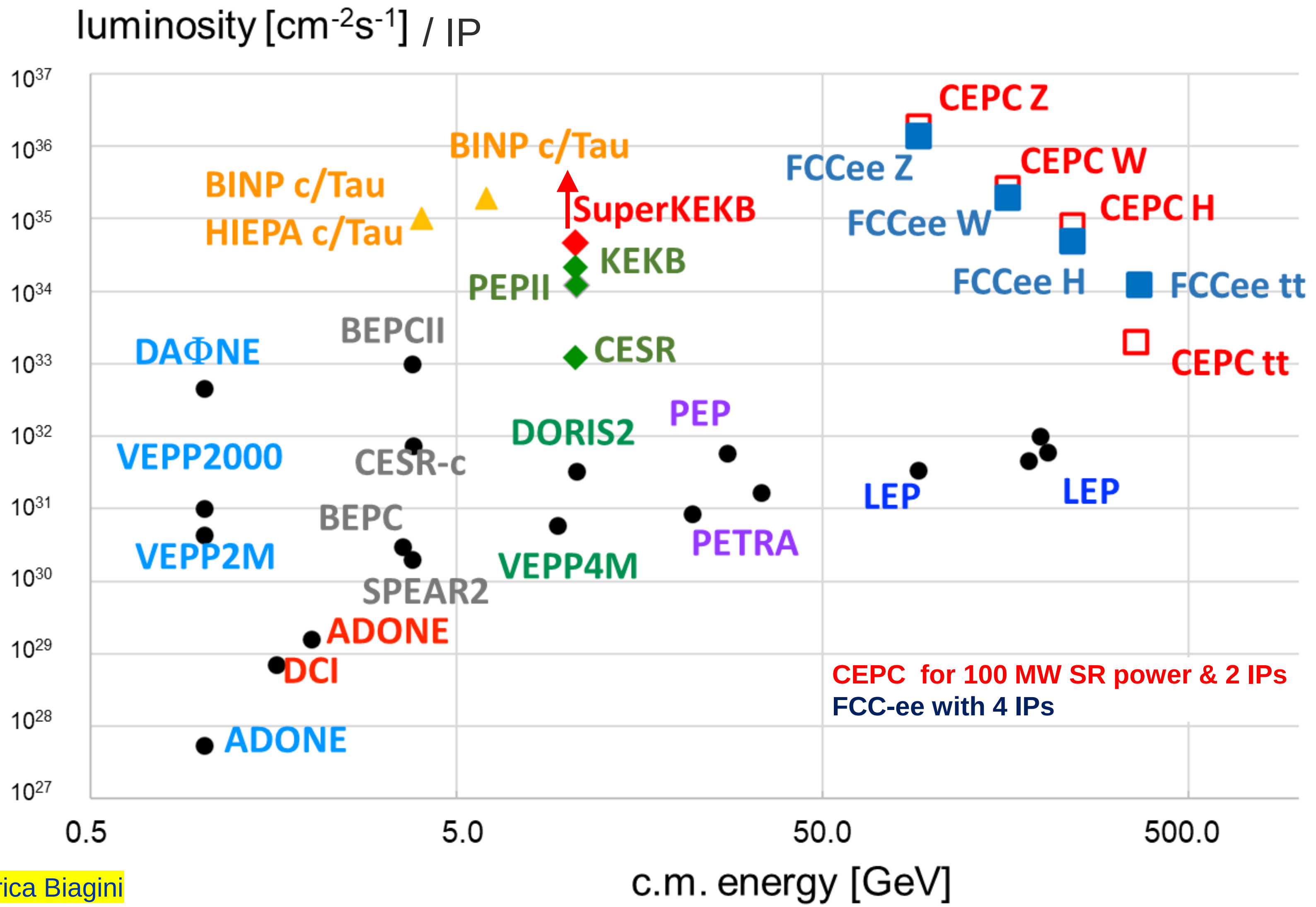
FUTURE CIRCULAR COLLIDER
Innovation Study

FCC-ee – 2^{nd} highest luminosity collider



Marica Biagini

~ same accelerator design as twin machine CEPC

a few differences

	FCC-ee	CEPC
#IPs	4 or 2	2
collider SRF up to ZH	400 MHz, 1- & 2-cell, Nb/Cu, 4.5 K	650 MHz, 2-cell, Nb, 2 K
collider SRF ttbar	800 MHz 5-cell, Nb, 2 K	650 MHz, 5-cell, Nb, 2 K
booster SRF	800 MHz 5-cell, Nb, 2 K	1.3 GHz, 9-cell, Nb, 2 K
top-up	in collider	in booster

risks of lower luminosity

trends from mid-term review

- **reduce linac rep rate from 400 to 200 Hz**
- **stainless steel chamber for booster**
- **replace 1-cell Z cavities by 2-cell cavities (the same cavities as for W and ZH)**
- **..**

all this is bad news for luminosity … ☹

most demanding : operation at the Z

Mid-term parameters

K. Oide

11200 bunches / beam

injection at 2x200 Hz = 400 Hz

time to fill the booster = 11200/400 s = 28 s

up + top + down ramp ~ 1s

A. Vanel

total cycle time 30 s

we can inject the same beam every 60 s or 1 minute

beam lifetime: 15 minutes

intensity change at 200 Hz injection (400 Hz rep rate)

$$\Delta N/N \sim e^{-1/15} \sim 0.936\ (> 6\%)$$

if we injected at 100 Hz, we would have

$$\Delta N/N \sim e^{-2/15} \sim 0.875\ (> 12\%)$$

at 100 Hz with rad. Bhabha lifetime (22 min) only:

$$\Delta N/N \sim e^{-2/22} \sim 0.91\ \ (\sim 9\%)$$

D. Shatilov required, for the "bootstrapping" injection,
to keep the intensity within +/-5%
and this without any errors

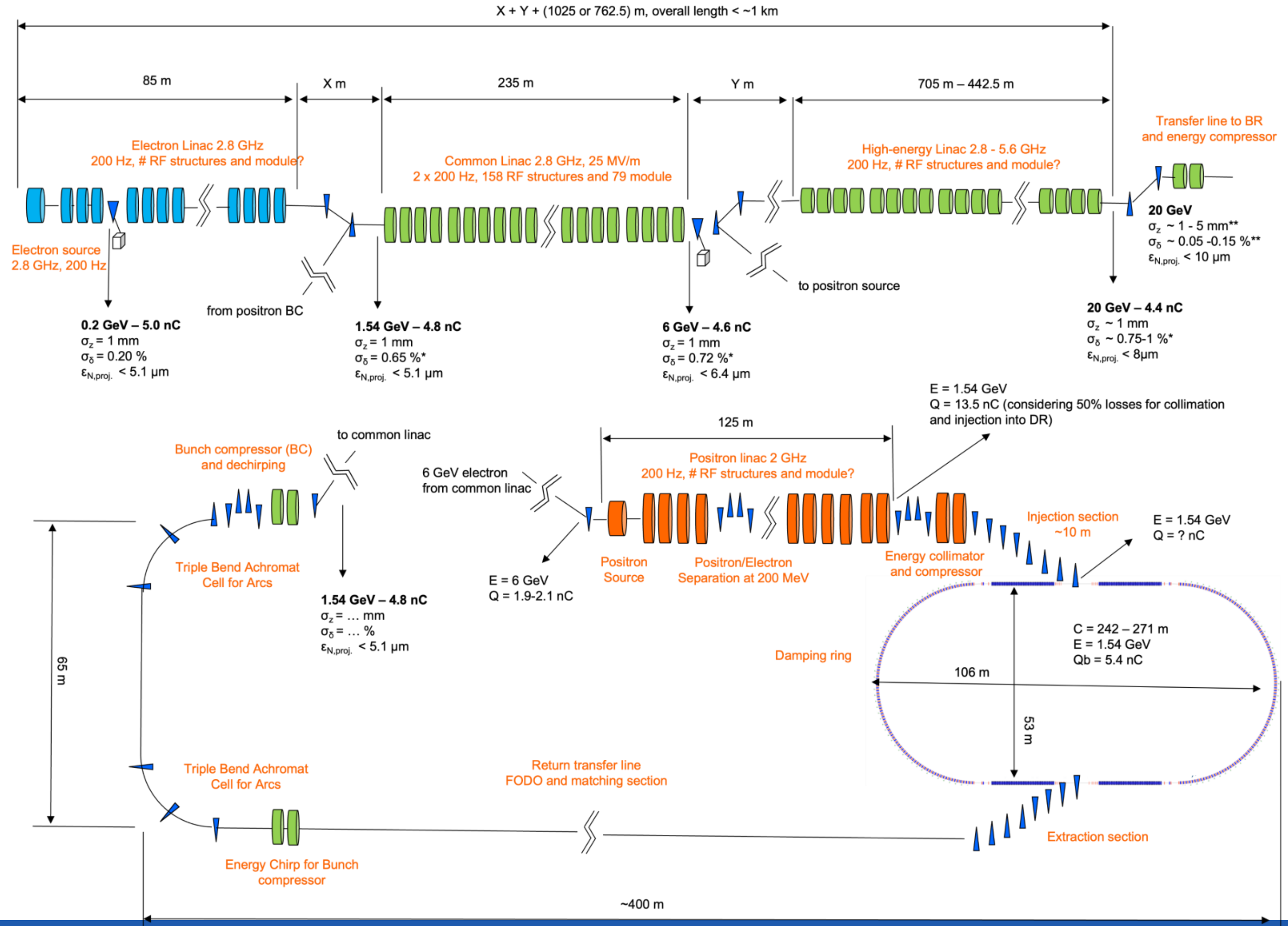
→ how can we lower the linac rep rate below 400 Hz,
while keeping the baseline rate of injection ?

risk mitigations to be studied

- reduce linac rep rate from 400 to 200 Hz
  - new layout without common linac
  - operation with 4 bunches / pulse
- stainless steel chamber for booster
  - larger aperture
  - Cu lamination
  - more cycles with fewer bunches / cycle
- replace 1-cell Z cavities by 2-cell cavities (the same cavities as for W and ZH)
  - efficient HOM damping for 2-cell cavities
  - one fundamental power coupler per cell ?

- new optics (Raimondi) with larger momentum acceptance?

injector layout baseline



common linac
1.54 GeV → 6 GeV;
400 Hz rep rate,

total S-band linac
length 1150 m

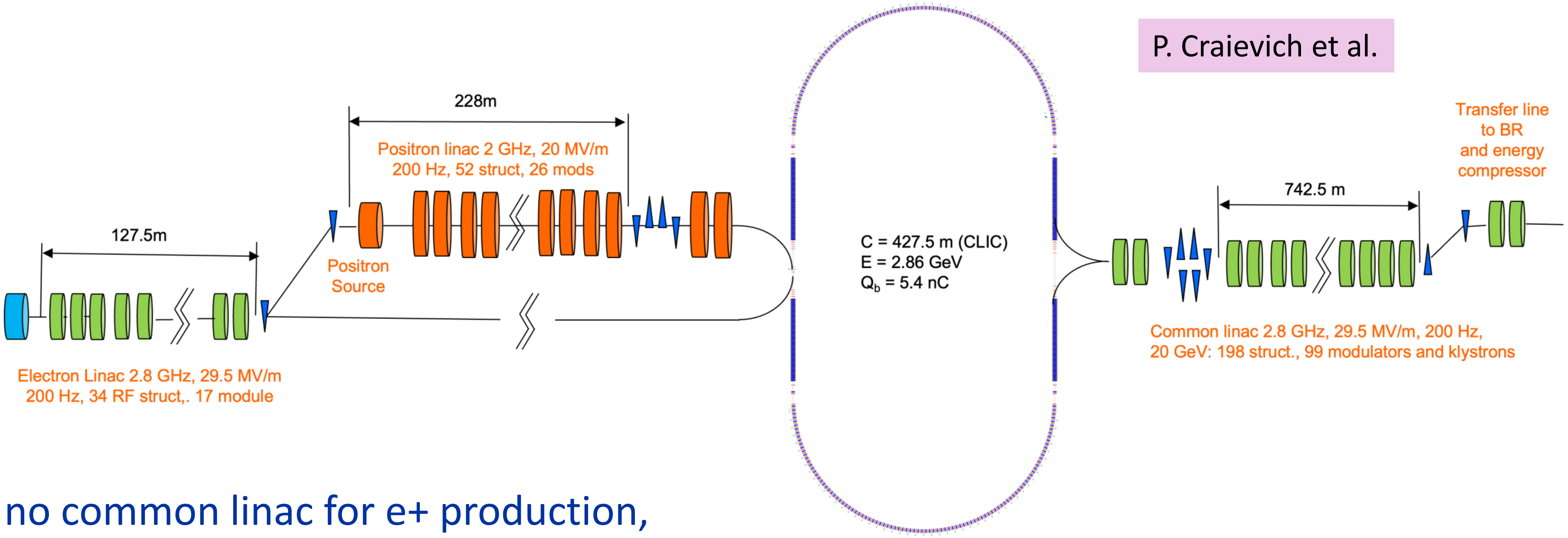
DR energy 1.54 GeV

e^+ production at 6 GeV

P. Craievich et al.

alternative injector layout

P. Craievich et al.



no common linac for e+ production,

200 Hz linac rep rates,

total S-band linac length 1095 m,

DR energy 2.86 GeV,

e^+ production at 2.86 GeV

luminosity constraints

injector rate limitation for Z running – factor <2 margin

SR power limit – luminosity could be increased in proportion to SR power

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beamstrahlung limit

$$\frac{1}{\rho} \propto \frac{\xi_y}{L_i}\sqrt{\frac{\varepsilon_y}{\beta_y^*}}$$

beam-beam tune shift limit

$$\xi_y = \frac{N_b r_e}{2\pi\gamma}\frac{\beta_y^*}{\sigma_x\sigma_y\sqrt{1+\Phi^2}}$$

constraint from coherent beam-beam instability

$$\xi_x < Q_s$$

change emittances?
reduce beta *?

note:
if we keep ε_y/β_y^* constant, ρ and ξ_y are unchanged

Mid-term Review Parameters	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch spacing [ns]	25			
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
SR power [MW]	100	100	100	100
total RF voltage 400/800 MHz [GV]	0.080/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	141	20	5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha [min]	22	16	14	12
beam lifetime (q+BS+lattice) [min]	50	42	100	100

Parameters for 150 MW SR power	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1905	206	40	7.4
number bunches/beam	16800	2670	660	90
bunch spacing [ns]	<18			
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
SR power [MW]	150	150	150	150
total RF voltage 400/800 MHz [GV]	0.080/0	1.0/0	2.1/0	2.1/9.4
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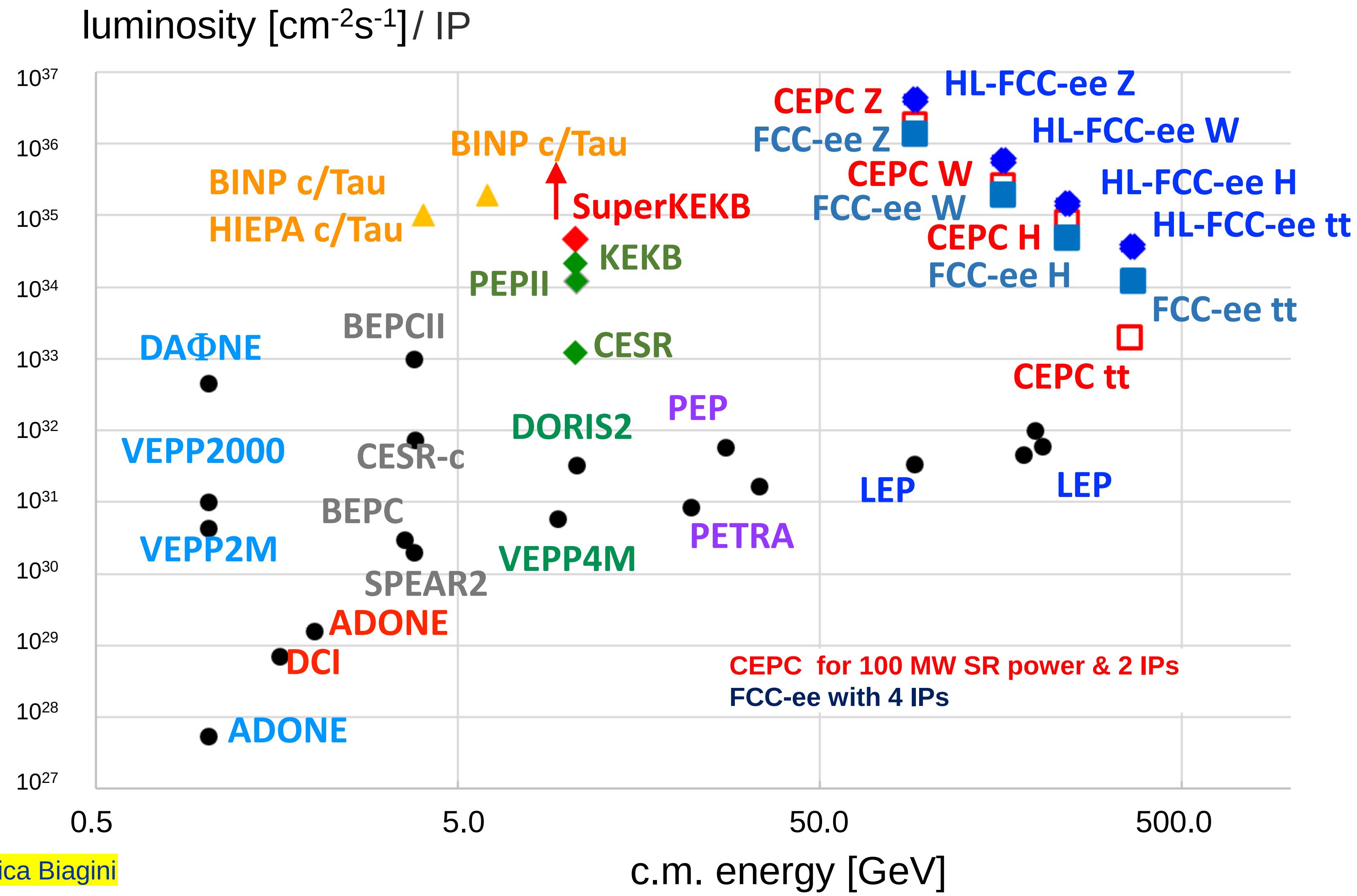
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	212	30	7.5	1.88
total integrated luminosity / IP / year [ab^{-1}/yr]	25	3.6	0.9	0.23
beam lifetime rad Bhabha [min]	22	16	14	12
beam lifetime (q+BS+lattice) [min]	50	42	100	100

Parameters for smaller β_y* & ε_y	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch spacing [ns]	25			
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
SR power [MW]	100	100	100	100
total RF voltage 400/800 MHz [GV]	0.080/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.35	0.5	0.5	0.8
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.0	1.1	0.7	0.8
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	18	24	20	26
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]	282	40	10.0	2.5
total integrated luminosity / IP / year [ab^{-1}/yr]	34	4.8	1.2	0.3
beam lifetime rad Bhabha [min]	11	8	7	6
beam lifetime (q+BS+lattice) [min]	50	42	100	100

Parameters for 150 MW SRP and smaller β_y* & ε_y	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1905	206	40	7.4
number bunches/beam	16800	2670	660	90
bunch spacing [ns]	<18			
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
SR power [MW]	150	150	150	150
total RF voltage 400/800 MHz [GV]	0.080/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.35	0.5	0.5	0.8
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.0	1.1	0.7	0.8
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	18	24	20	26
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]	423	60	15.0	3.8
total integrated luminosity / IP / year [ab^{-1}/yr]	51	7.2	1.8	0.45
beam lifetime rad Bhabha [min]	11	8	7	6
beam lifetime (q+BS+lattice) [min]	50	42	100	100

“HL-FCC-ee” – highest luminosity collider !



Marica Biagini

Conclusions

- the alternative injector layout looks attractive and could support higher luminosity at reduced linac repetition rate
- possible path to increasing the FCC-ee luminosity by a factor 2-3 at all energies, by decreasing β_y^* along with ε_y, and/or by raising SR power, respecting all other relevant constraints
- a good optics and excellent optics control will be essential
- increasing luminosity at Z is most challenging; vertical design emittance from IR solenoids should be minimised (presently ~0.5 pm for 4 IPs at Z, Mike Koratzinos, arXiv 2101.05704); at Z also e-cloud could limit #bunches
- there might be other ways to boost the FCC-ee luminosity (hor. emittance, crossing angle, hor. beta*, bunch length, bunch charge etc.)