Future Colliders

W. Trischuk

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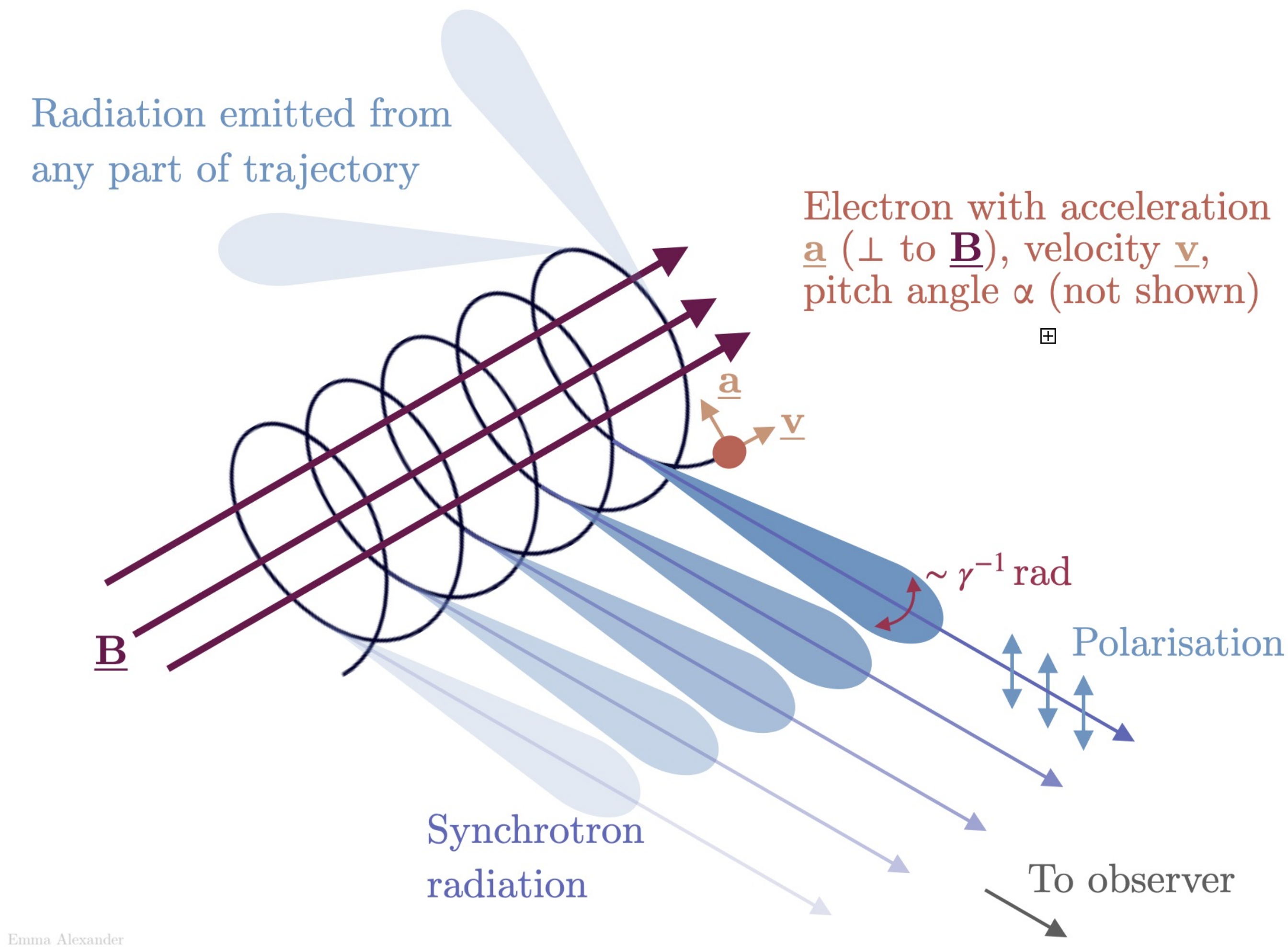
Synchrotron Radiation



A direct consequence of Maxwell's equations is that accelerated charged particles always emit electromagnetic radiation. Synchrotron radiation is the special case of charged particles moving at relativistic speed undergoing acceleration perpendicular to their direction of motion, typically in a magnetic field. In such a field, the force due to the field is always perpendicular to both the direction of motion and to the direction of field, as shown by the Lorentz force law.

The power carried by the radiation is found (in SI units) by the relativistic Larmor formula:[9][10]

$$P_\gamma = \frac{q^2}{6\pi\varepsilon_0 c^3} a^2 \gamma^4 = \frac{q^2 c}{6\pi\varepsilon_0} \frac{\beta^4 \gamma^4}{\rho^2},$$

where

- ε_0 is the vacuum permittivity,
- q is the particle charge,
- a is the magnitude of the acceleration,
- c is the speed of light,
- γ is the Lorentz factor,
- $\beta = v/c$,
- ρ is the radius of curvature of the particle trajectory.

The force on the emitting electron is given by the Abraham–Lorentz–Dirac force.

Jackson E&M
(Chapter 14)

Wikipedia

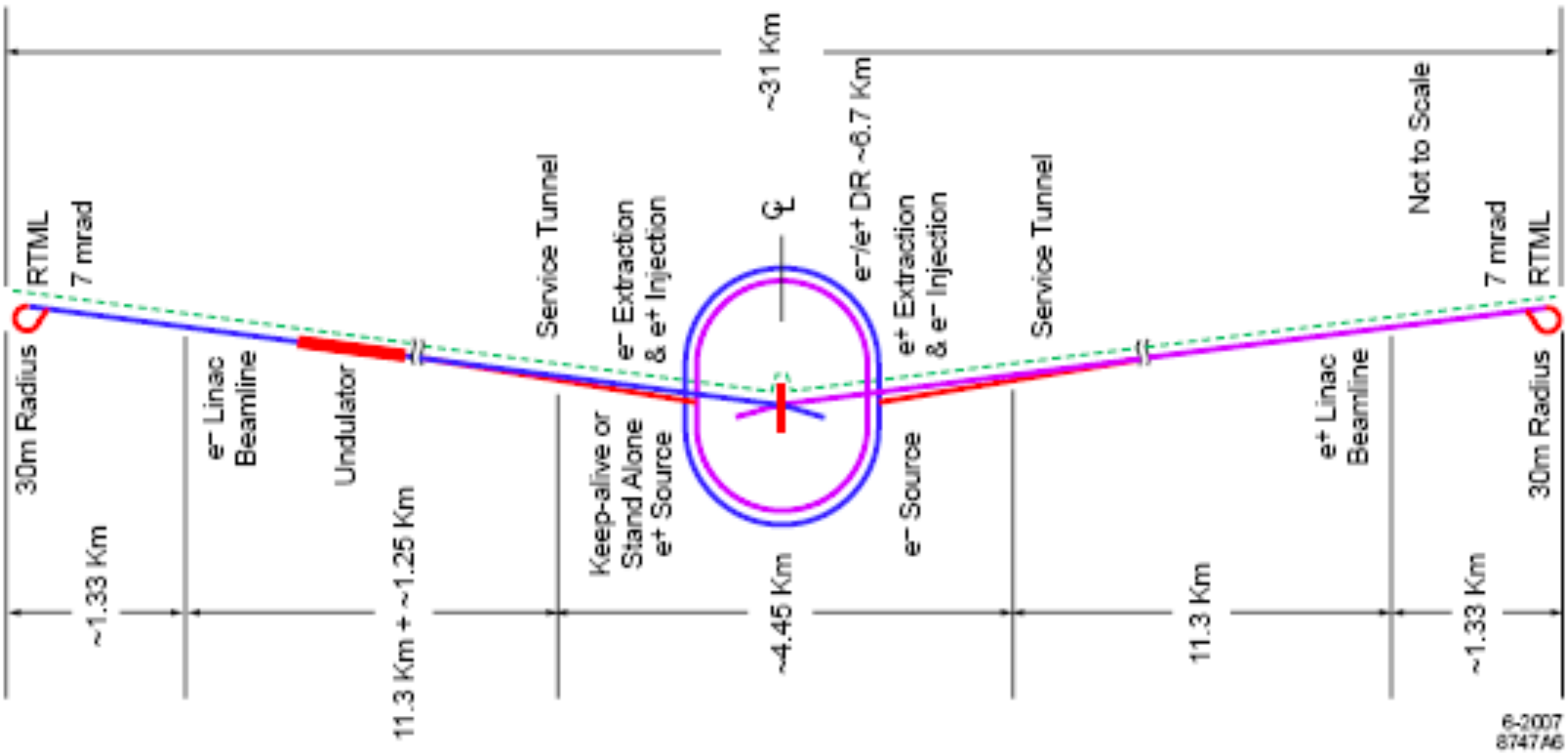
Lepton vs. Proton Colliders

- Colliding electrons
  - Puts all the beam energy in to the collision
  - Limited by energies you can reach
    - Circular electron colliders limited by synchrotron radiation
    - **Linear colliders** limited by only colliding each accelerated bunch once
- Colliding protons
  - Quarks/gluons on carry a fraction of beam energy
  - Synchrotron losses are much lower (go like γ^4)
    - Still non-negligible energy/power at LHC – ends up in superC magnets
- Colliding muons
  - Might be best of both worlds
    - Point like projectiles, 200x higher mass (10^9 less synchroton rad)
  - But muons only have a 2us lifetime…

Summary of Future Colliders

- ILC/CLIC comparison (Zimmerman: CERN-ATS-2010-056)
  - Linear colliders don‘t have synchrotron radiation limits
  - But can only use each accelerated bunch “once“.
- Circular colliders
  - Hadron machines (HE-LHC CDR: CERN-ACC-2018-0059)
  - Electron machines (Chinese Circular Collider)
- Muon collider
  - https://cerncourier.com/a/sketching-out-a-muon-collider/

ILC Layout



~31 Km
RTML
7 mrad
30m Radius
e⁻ Linac Beamline
Undulator
Service Tunnel
e⁻ Extraction & e⁺ Injection
Keep-alive or Stand Alone e⁺ Source
e⁻/e⁺ DR ~6.7 Km
e⁺ Extraction & e⁻ Injection
e⁻ Source
Service Tunnel
Not to Scale
e⁺ Linac Beamline
7 mrad
RTML
30m Radius
~1.33 Km
11.3 Km + ~1.25 Km
~4.45 Km
11.3 Km
~1.33 Km
6-2007
8747A6

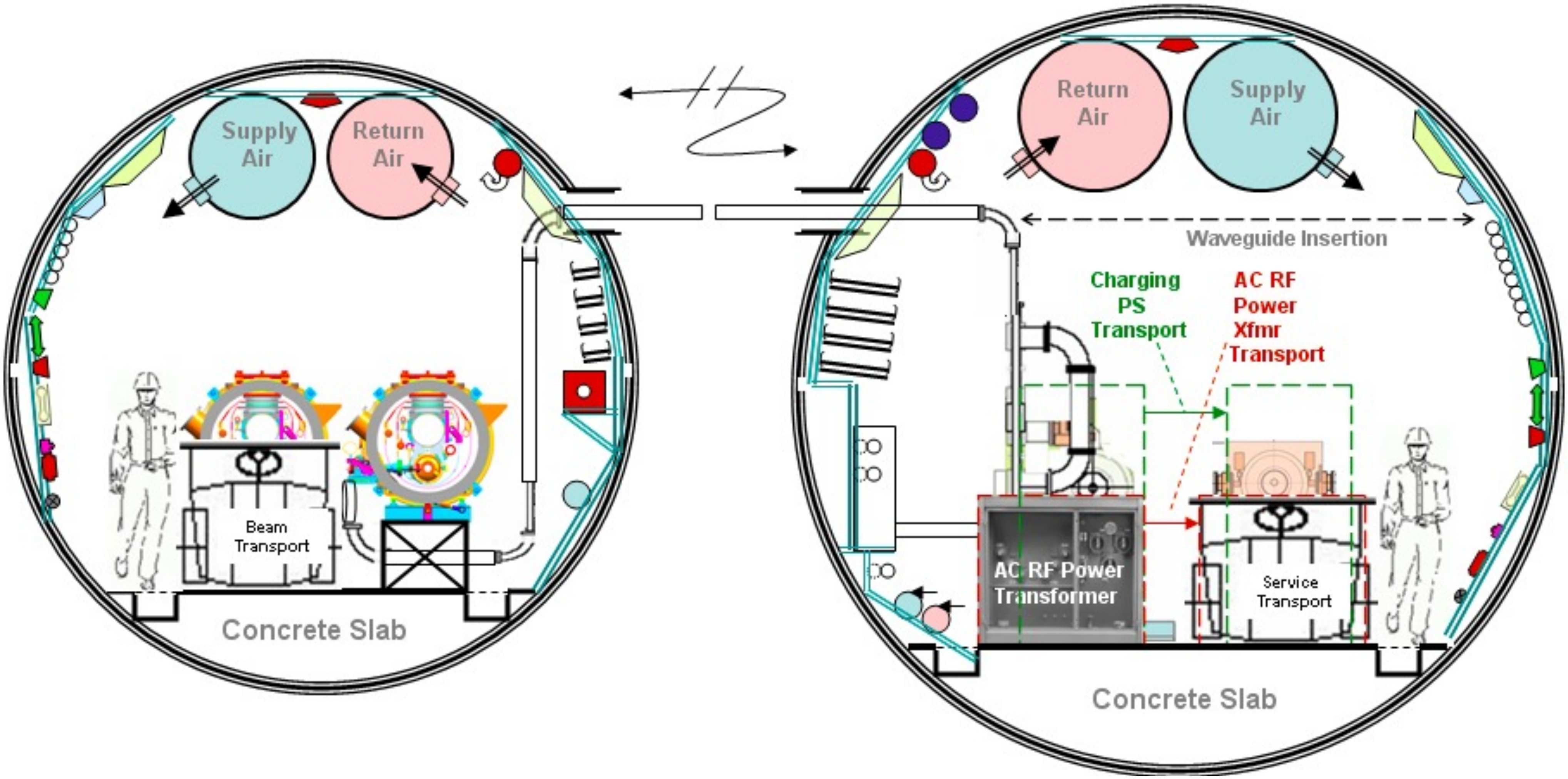
ILC/CLIC Comparsion

Table 14: CLIC and ILC parameters [61,65].

centre-of-mass energy	ILC 500 GeV	CLIC 500 GeV	CLIC 3 TeV
total (peak 1%) luminosity [10^{34} cm^{-2}s^{-1}]	2(1.5)	2.3 (1.4)	5.9 (2.0)
repetition rate [Hz]	5	50	
loaded accelerating gradient [MV/m]	32	80	100
main linac RF frequency [GHz]	1.3	12	
particles per bunch [10^9]	20	6.8	3.7
bunch separation [ns]	370	0.5	
beam pulse duration [ns]	950,000	177	156
beam power / beam [MW]	10.8	4.9	14
horizontal/vertical IP beam size [nm]	639, 5.7	200, 2.3	40, 1.0
#hadronic events / crossing at IP	0.12	0.2	2.7
incoherent pairs at IP [10^5]	1.0	1.7	3.0
crossing angle [mrad]	14	18.6	20
beam delivery system length / beam [km]	2.23	1.87	2.75
total site length [km]	31	13	48
total electrical power consumption [MW]	230	130	415

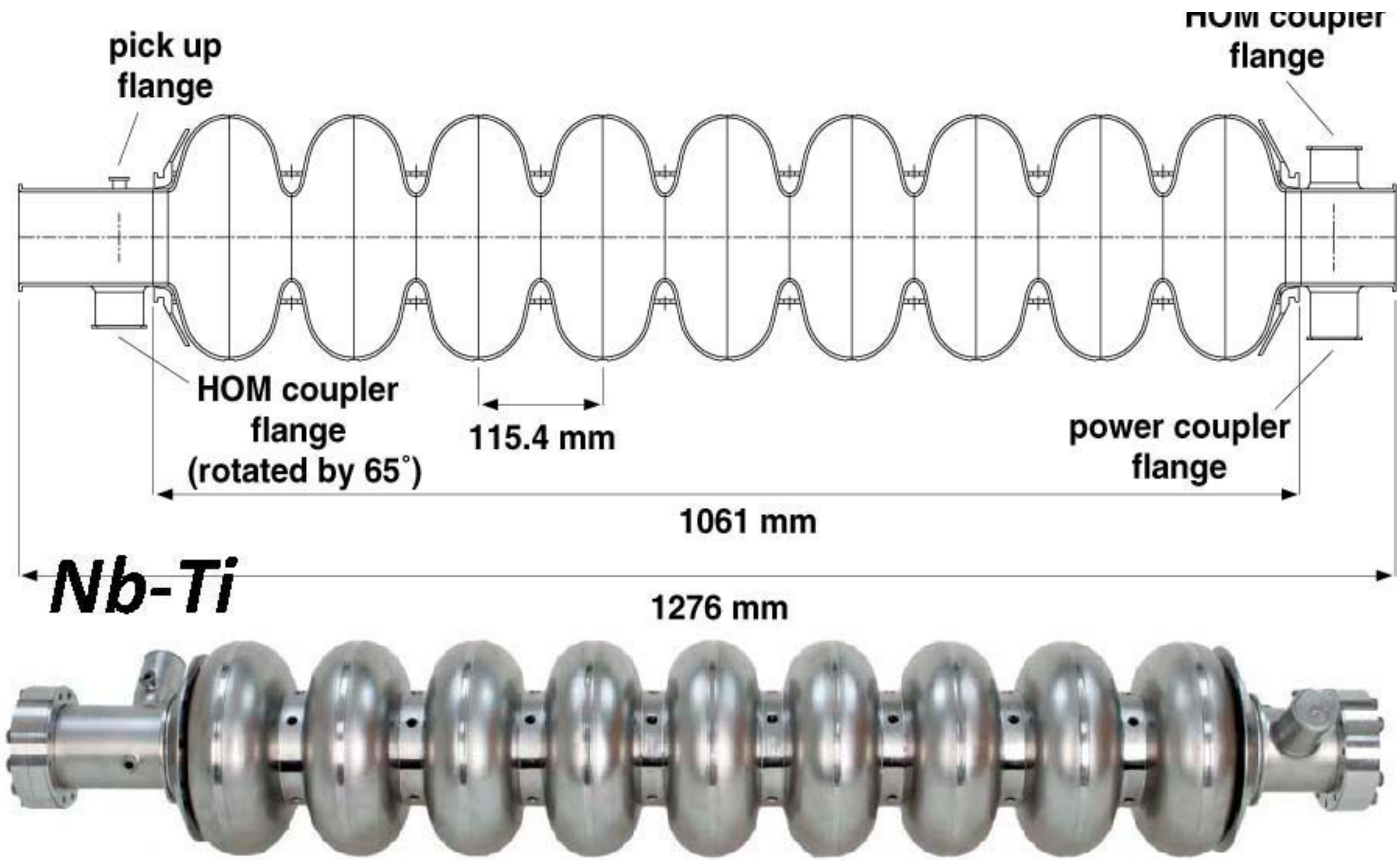
Parameters		units	ILC(RDR)	CLIC(3 TeV)
Injection / final linac energy	E_{Linac}	GeV	**25 / 250**	**9/ 1500**
Acceleration gradient	E_a	MV/m	**31.5**	**100**
Average beam current	I_b	μA	42	9
Peak RF power	$P_{in\ peak}$	MW/m	**0.37**	**275**
Average RF power	$\langle P_{in} \rangle$	kW/m	**2.9**	**3.7**
Initial / final horizontal emittance	ε_x	μm	8.4 / 9.4	0.38/0.66
Initial / final vertical emittance	ε_y	nm	24 / 34	4/20
RF pulse width	T_p	μs	**1565**	**0.24**
Repetition rate	F_{rep}	Hz	5	50
Number of particles in a bunch	N	10^9	20	3.7
Number of bunches / train	N_b		2625	312
Bunch spacing	T_b	ns	360	0.5
Bunch spacing per RF cycle	T_b / T_{RF}		468	6

ILC tunnels

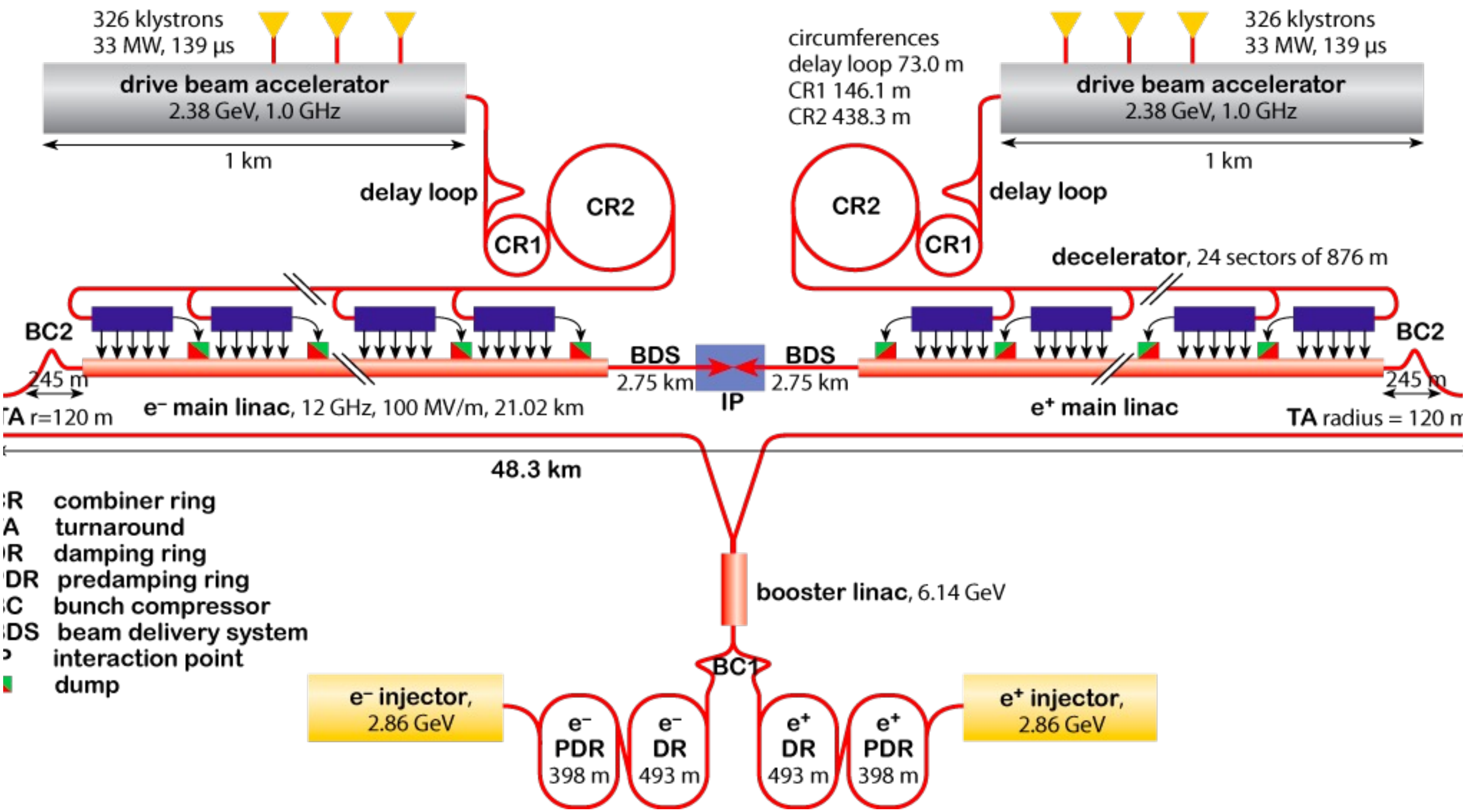


Supply Air
Return Air
Beam Transport
Concrete Slab
Return Air
Supply Air
Waveguide Insertion
Charging PS Transport
AC RF Power Xfmr Transport
AC RF Power Transformer
Service Transport
Concrete Slab

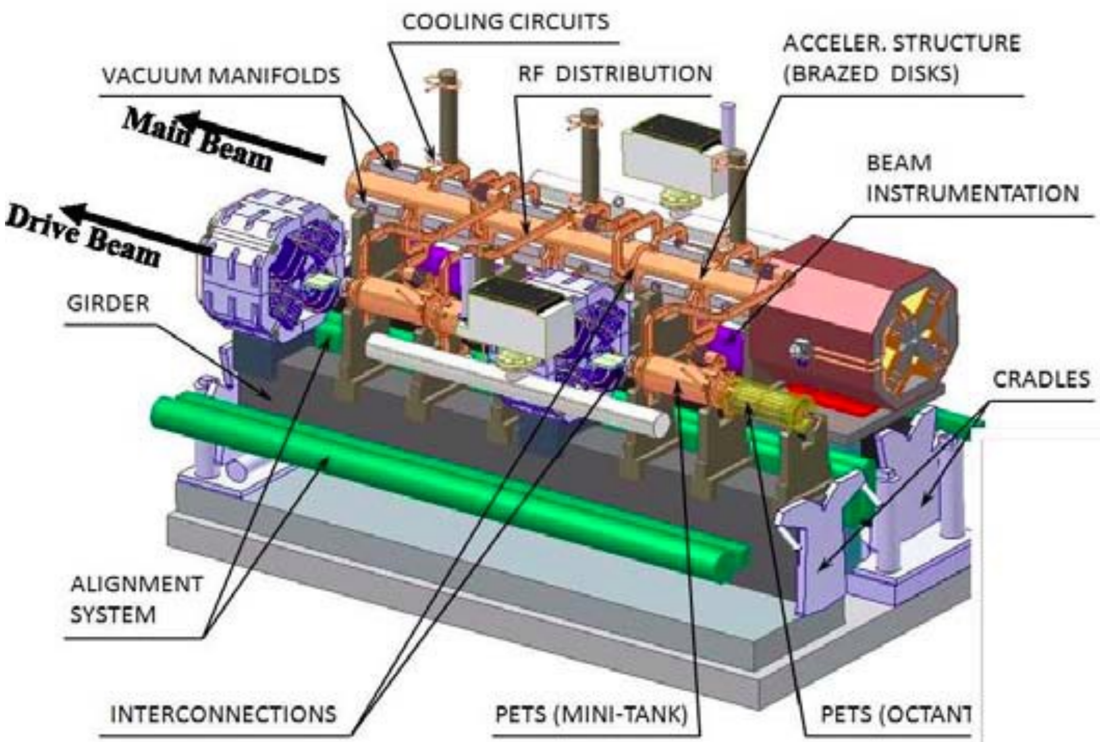
ILC Cavity

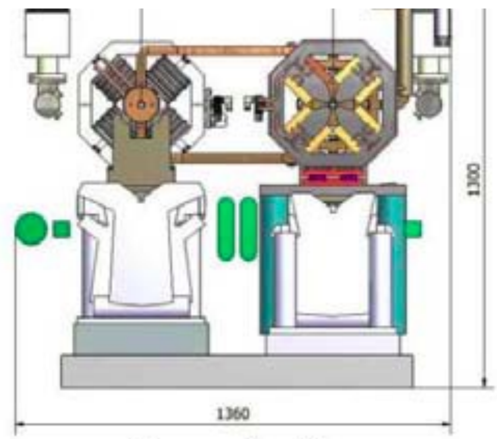

HOM coupler
flange
pick up
flange
HOM coupler
flange
(rotated by 65˚)
115.4 mm
power coupler
flange
1061 mm
Nb-Ti
1276 mm

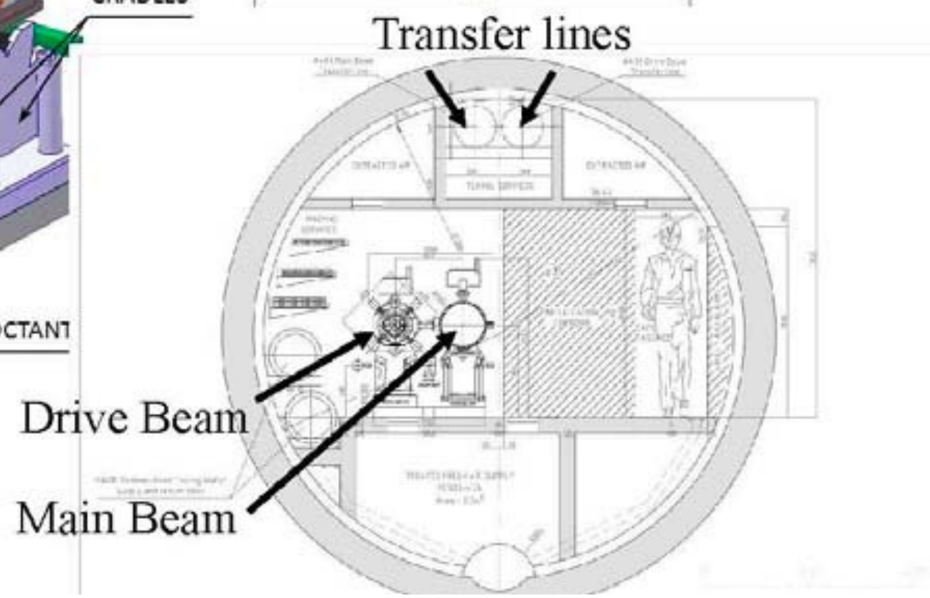
CLIC Layout


326 klystrons
33 MW, 139 μs
drive beam accelerator
2.38 GeV, 1.0 GHz
1 km
delay loop
CR2
CR1
circumferences
delay loop 73.0 m
CR1 146.1 m
CR2 438.3 m
326 klystrons
33 MW, 139 μs
drive beam accelerator
2.38 GeV, 1.0 GHz
1 km
delay loop
CR2
CR1
decelerator, 24 sectors of 876 m
BC2
245 m
A r=120 m
e⁻ main linac, 12 GHz, 100 MV/m, 21.02 km
BDS
2.75 km
IP
BDS
2.75 km
BC2
245 m
e⁺ main linac
TA radius = 120 m
48.3 km
R combiner ring
A turnaround
R damping ring
DR predamping ring
C bunch compressor
DS beam delivery system
interaction point
dump
booster linac, 6.14 GeV
BC1
e⁻ injector,
2.86 GeV
e⁻ PDR 398 m
e⁻ DR 493 m
e⁺ DR 493 m
e⁺ PDR 398 m
e⁺ injector,
2.86 GeV

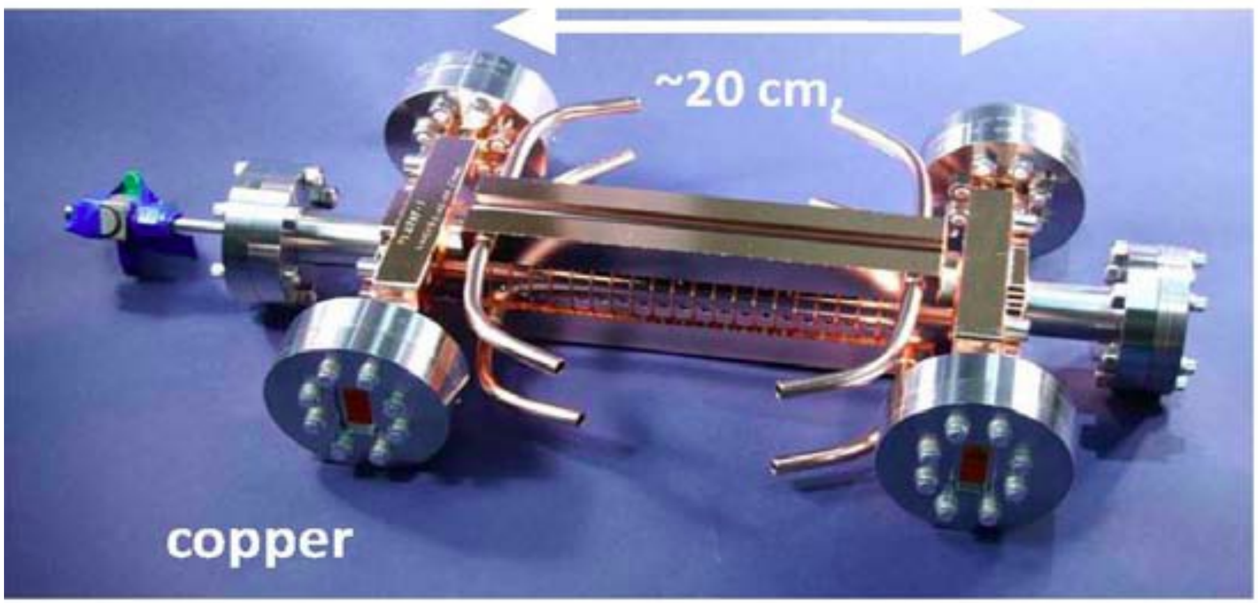
CLIC Layout

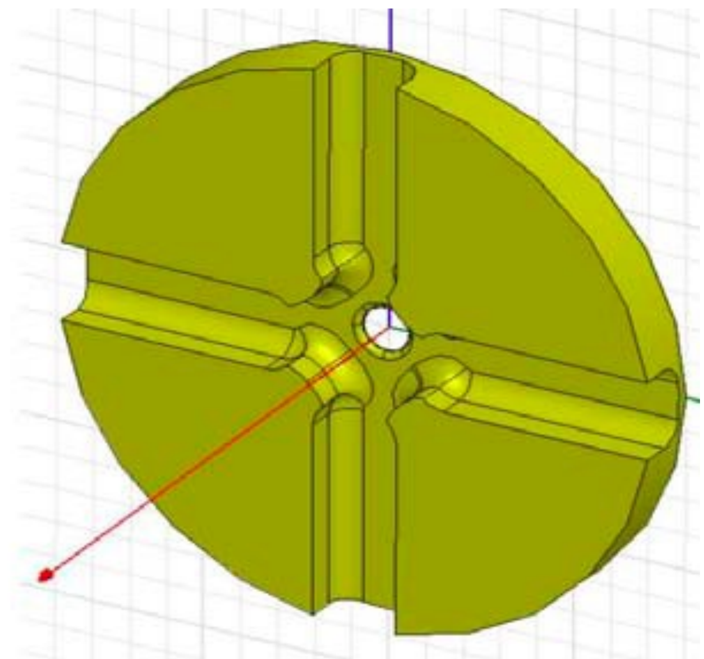

COOLING CIRCUITS
VACUUM MANIFOLDS
RF DISTRIBUTION
ACCELER. STRUCTURE
(BRAZED DISKS)
Main Beam
Drive Beam
BEAM
INSTRUMENTATION
GIRDER
CRADLES
ALIGNMENT
SYSTEM
INTERCONNECTIONS
PETS (MINI-TANK)
PETS (OCTANT

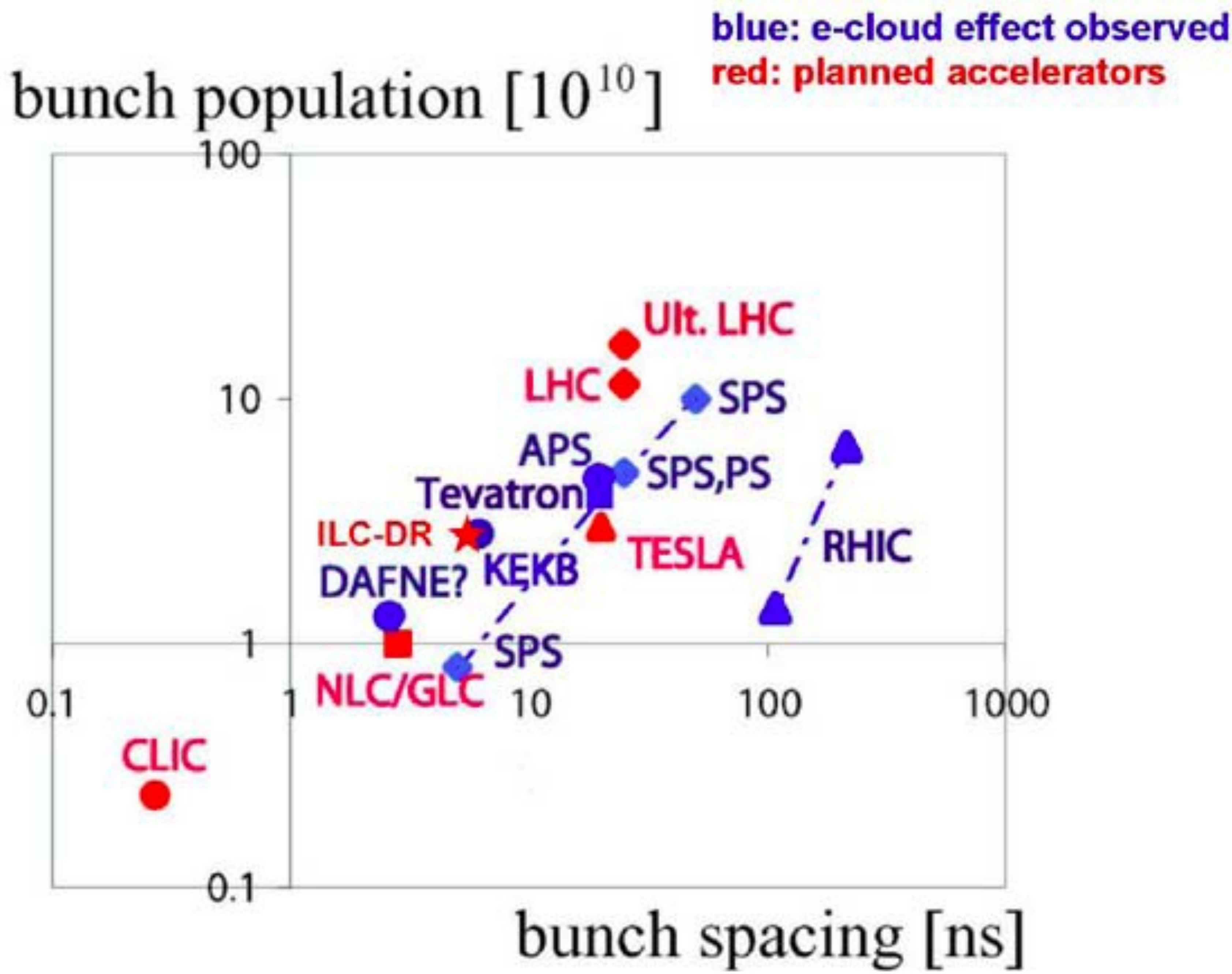

1300
1360


Transfer lines
Drive Beam
Main Beam

CLIC RF structure







blue: e-cloud effect observed
red: planned accelerators
bunch population [10^{10}]
100
10
1
0.1
0.1
1
10
100
1000
Ult. LHC
LHC
SPS
APS
SPS,PS
Tevatron
ILC-DR
KEKB
TESLA
RHIC
DAFNE?
SPS
NLC/GLC
CLIC
bunch spacing [ns]

CLIC e^- beam time structure

L. Rinolfi

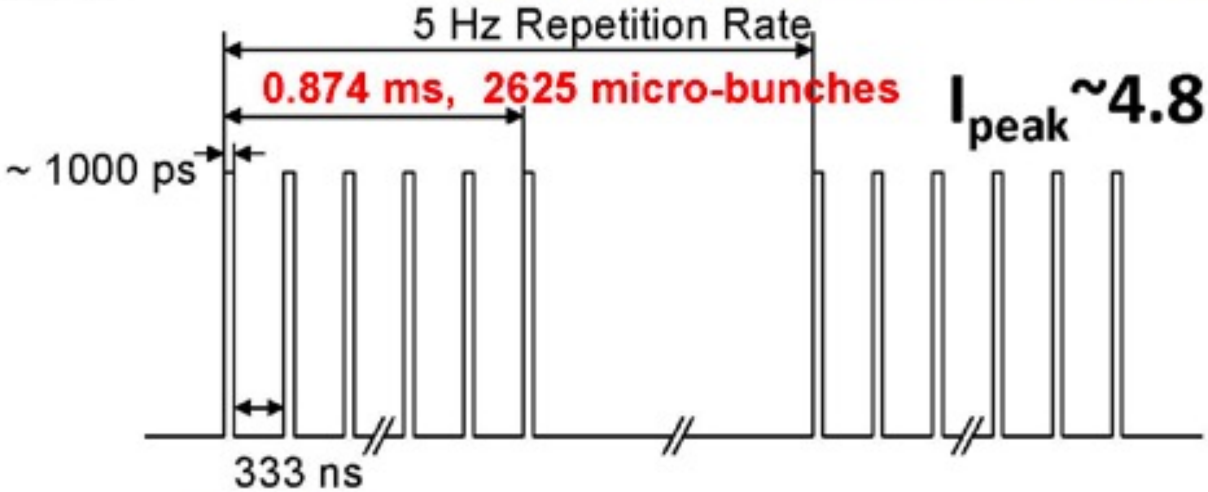
I_{peak}~9.6 A

1.999 GHz

$(\Delta I/I)_{\text{bunch to bunch}} \leq 1\%$ $(\Delta I/I)_{\text{pulse to pulse}} \leq 0.2\ \%$

not to scale!

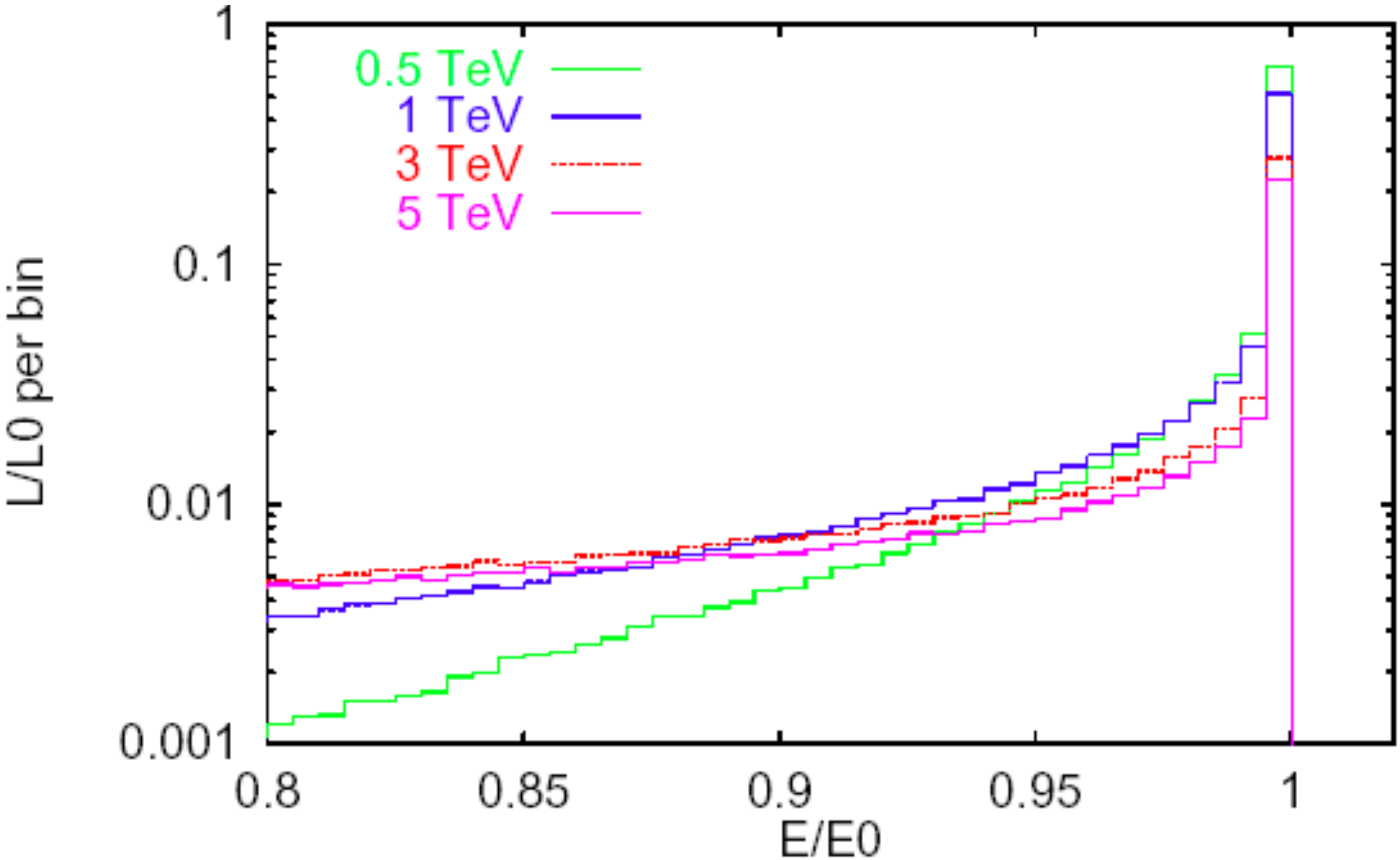
ILC e^- beam time structure



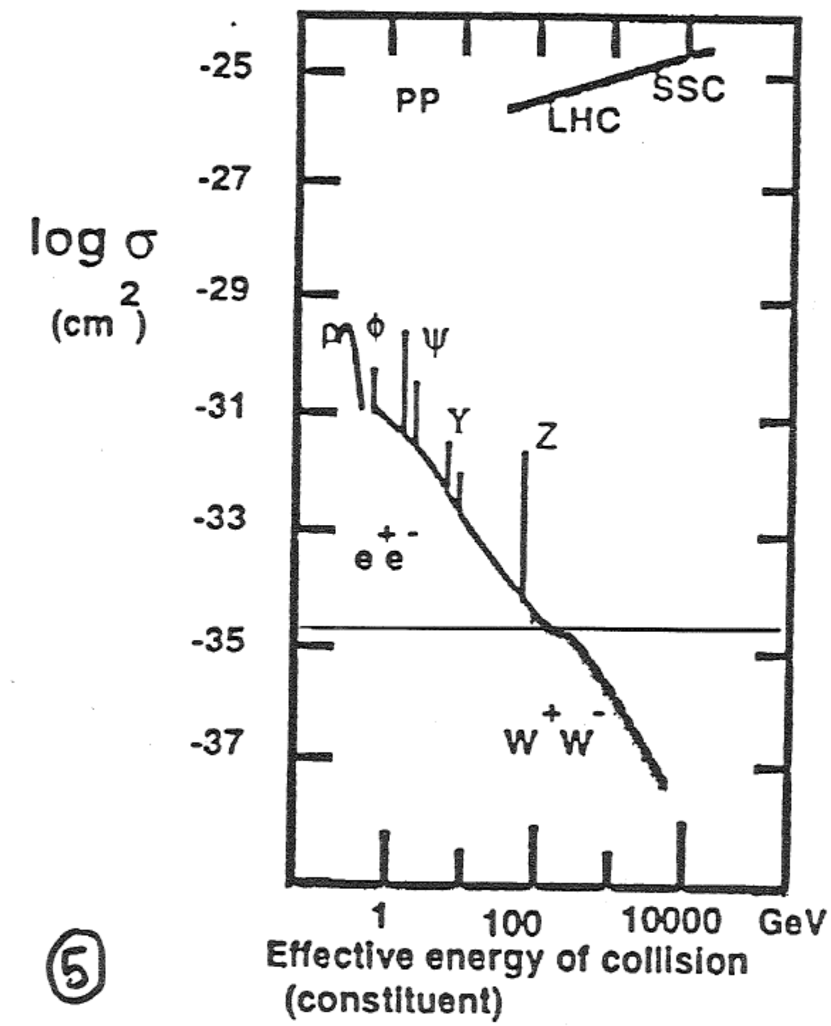
I_{peak}~4.8 A

3 MHz $(\Delta I/I)_{\text{bunch to bunch}} \leq$? % $(\Delta I/I)_{\text{pulse to pulse}} \leq$? %

Collision Energy Dispersion (CLIC)

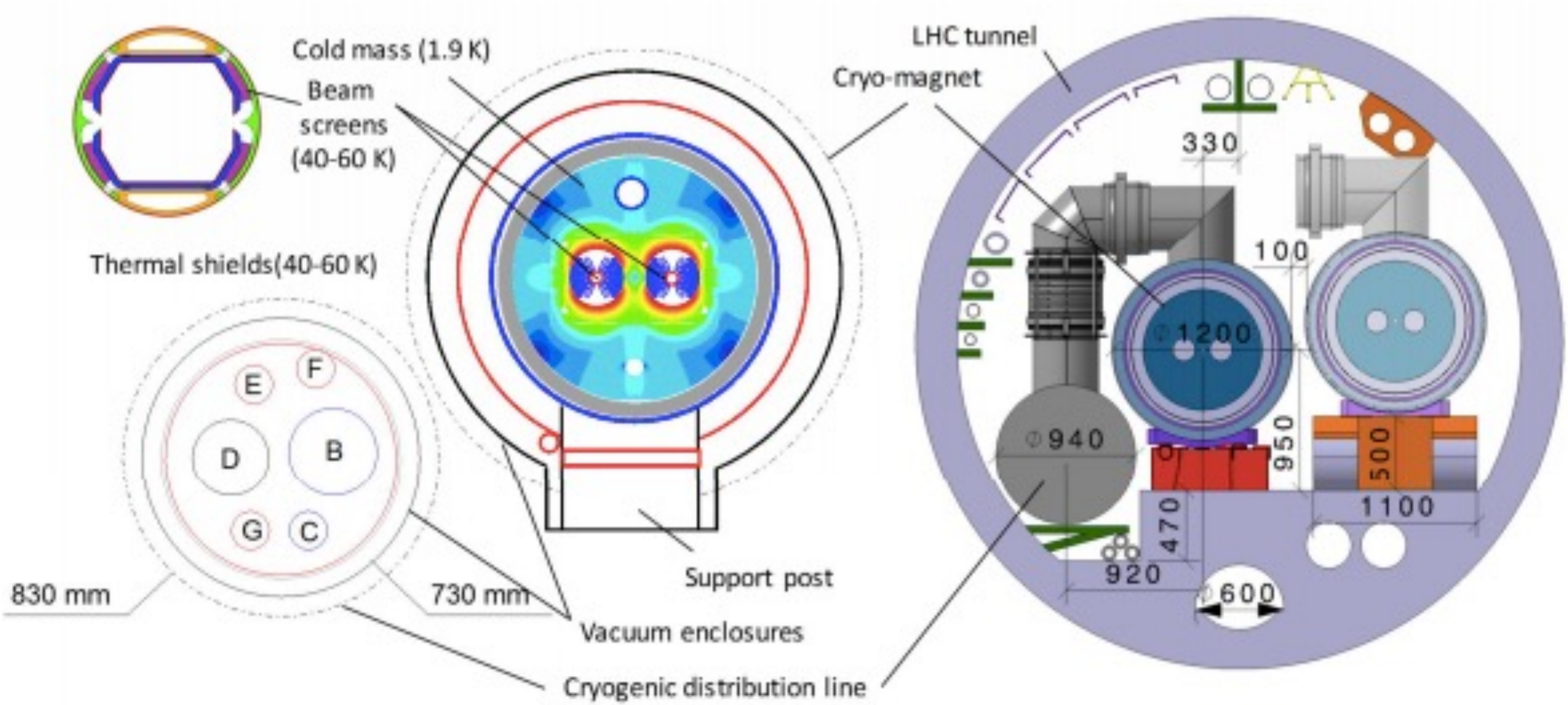


Future Hadron Colliders

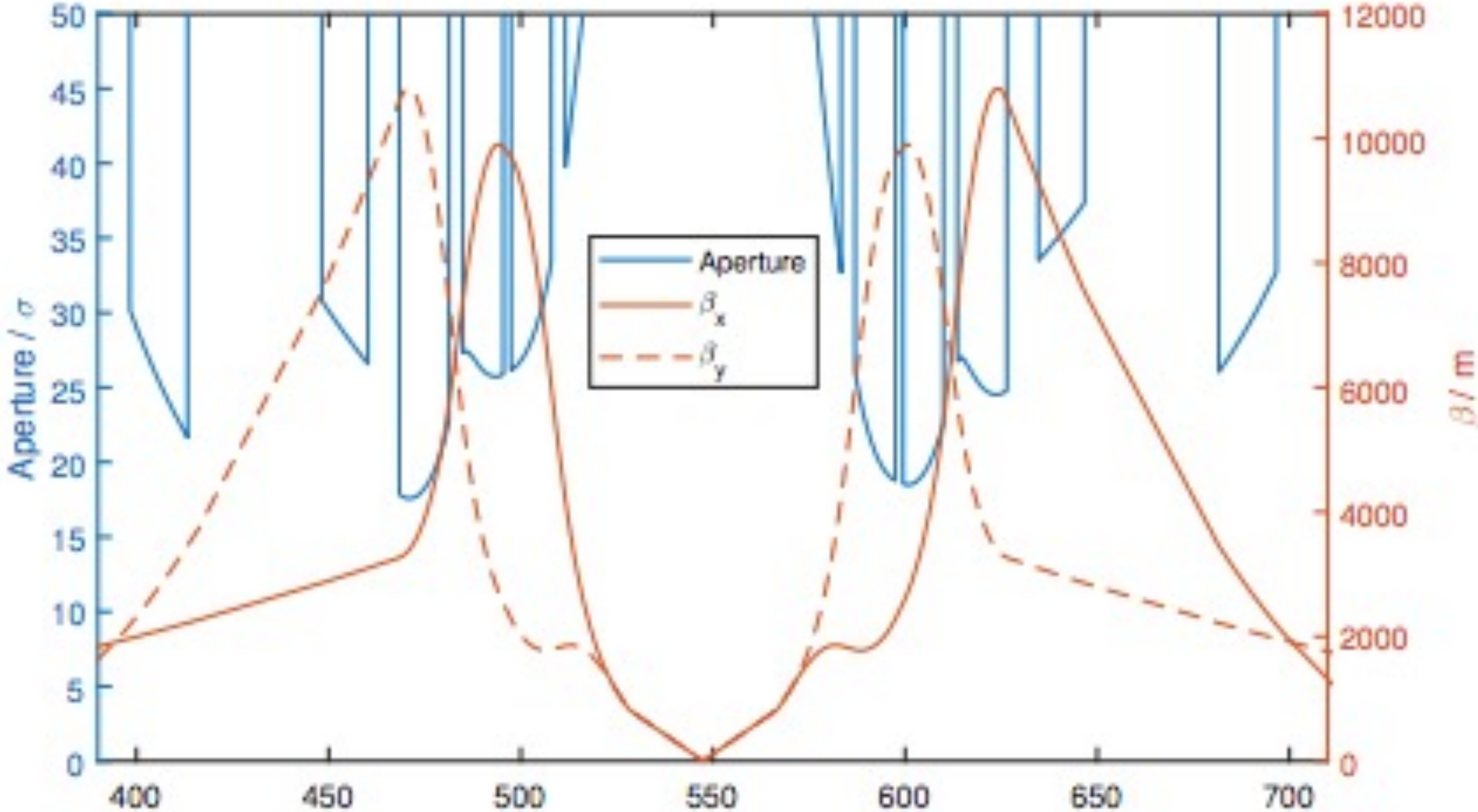


Parameter	**Unit**	FCC-hh		**HE-LHC**	(HL-)LHC
Centre-of-mass energy	TeV	100		27	14
Injection energy	TeV	3.3		1.3 (0.9, 0.45)	0.45
Peak arc dipole field	T	16		16	8.33
Circumference	km	97.8		26.7	26.7
Straight-section length	m	1400		528	528
Beam current	A	0.5		1.12	(1.12) 0.58
Bunch population	10^{11}	1.0		2.2	(2.2) 1.15
Number of bunches / beam	—	10400		2808	(2760) 2808
RF voltage	MV	32		16	(16) 16
RMS bunch length	mm	~ 80		90	(90) 75.5
Longitudinal emittance ($4\pi\sigma_z\sigma_E$)	eVs	$\sim$8		4.2	2.5
Bunch spacing	ns	25		25	25
Norm. transv. rms emittance	μm	2.2		2.5	(2.5) 3.75
IP beta function $\beta^*_{x,y}$	m	1.1	0.3	0.45	(0.15) 0.55
Initial rms IP beam size $\sigma^*_{x,y}$	μm	6.7	3.5	9.0	(7.1 min.) 16.7
Half crossing angle	μrad	37	100	165	(250) 142.5
Peak luminosity per IP	10^{34} cm^{-2}s^{-1}	5	30	16	(5, levelled) 1
Peak no. of events / crossing	—	170	1000	460	(135) 27
RMS luminous region	mm	53	49	57	(68) 45
Stored energy / beam	GJ	8.4		1.4	(0.7) 0.36
SR power / beam	kW	2400		100	(7.3) 3.6
Transv. emittance damping time	h	1.1		3.6	25.8
No. of high-luminosity IPs	—	2	2	2	(2) 2
Initial proton burn-off time	h	17	3.4	2.5	(15) 40
Allocated physics time / year	days	160	160	160	160 (160)
Average turnaround time	h	5	4	5	4 (5)
Optimum run time	h	11.6	3.7	5.3	(18–13) $\sim$10
Accelerator availability	—	70%	70%	75%	(80%) 71%
Nominal luminosity per day	fb^{-1}	2.0	8.0	4.5	(1.9) 0.4
Luminosity per year (160 days)	fb^{-1}	≥ 250	≥ 1000	500	(350) 55

Dipole magnets



Beam envelope near IP



Synchrotron radiation screens

Table 2.2: Synchrotron radiation (SR) characteristics in the arcs of LHC, HE-LHC and FCC-hh.

Parameter	**LHC**	**HE-LHC**	**FCC-hh**
Linear SR power [W/m]	0.25	5.5	35
Linear photon flux [10^{16} photons/m/s]	5	27	15
Critical photon energy [eV]	44	320	4300

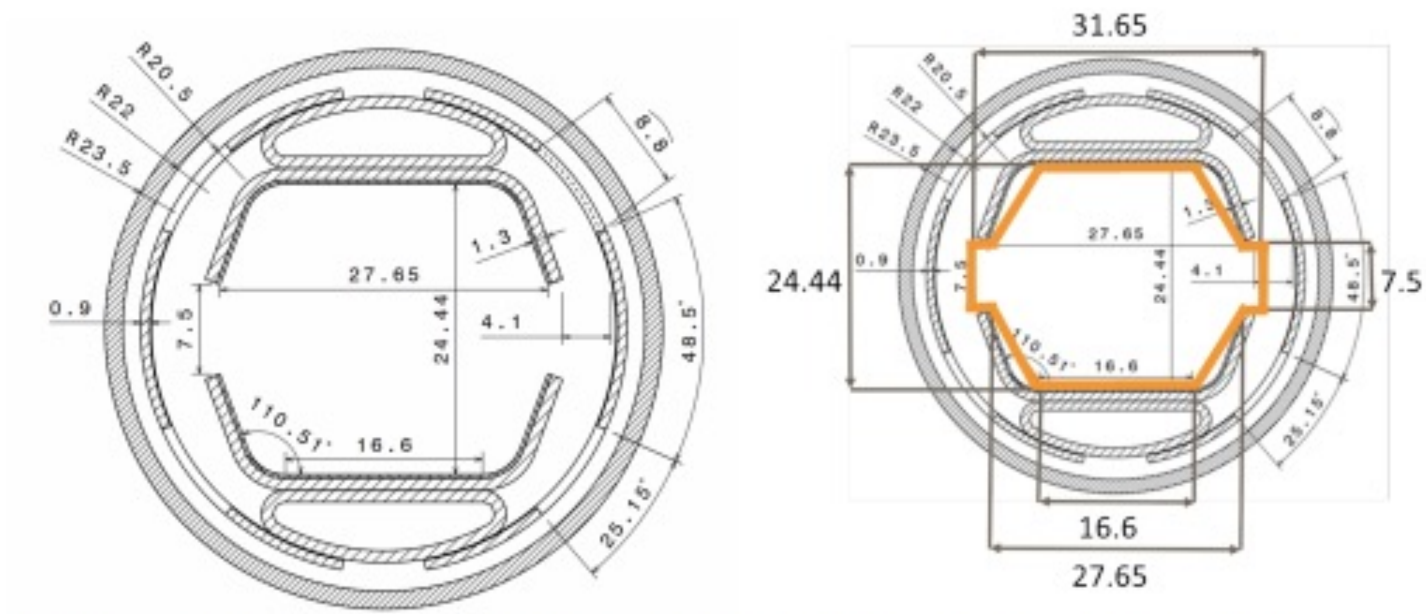


Figure 2.1: Beamscreen proposed for FCC-hh and HE-LHC [31] (left); and the approximation used for aperture calculation [32] (orange line, right).

e-p Collider ?

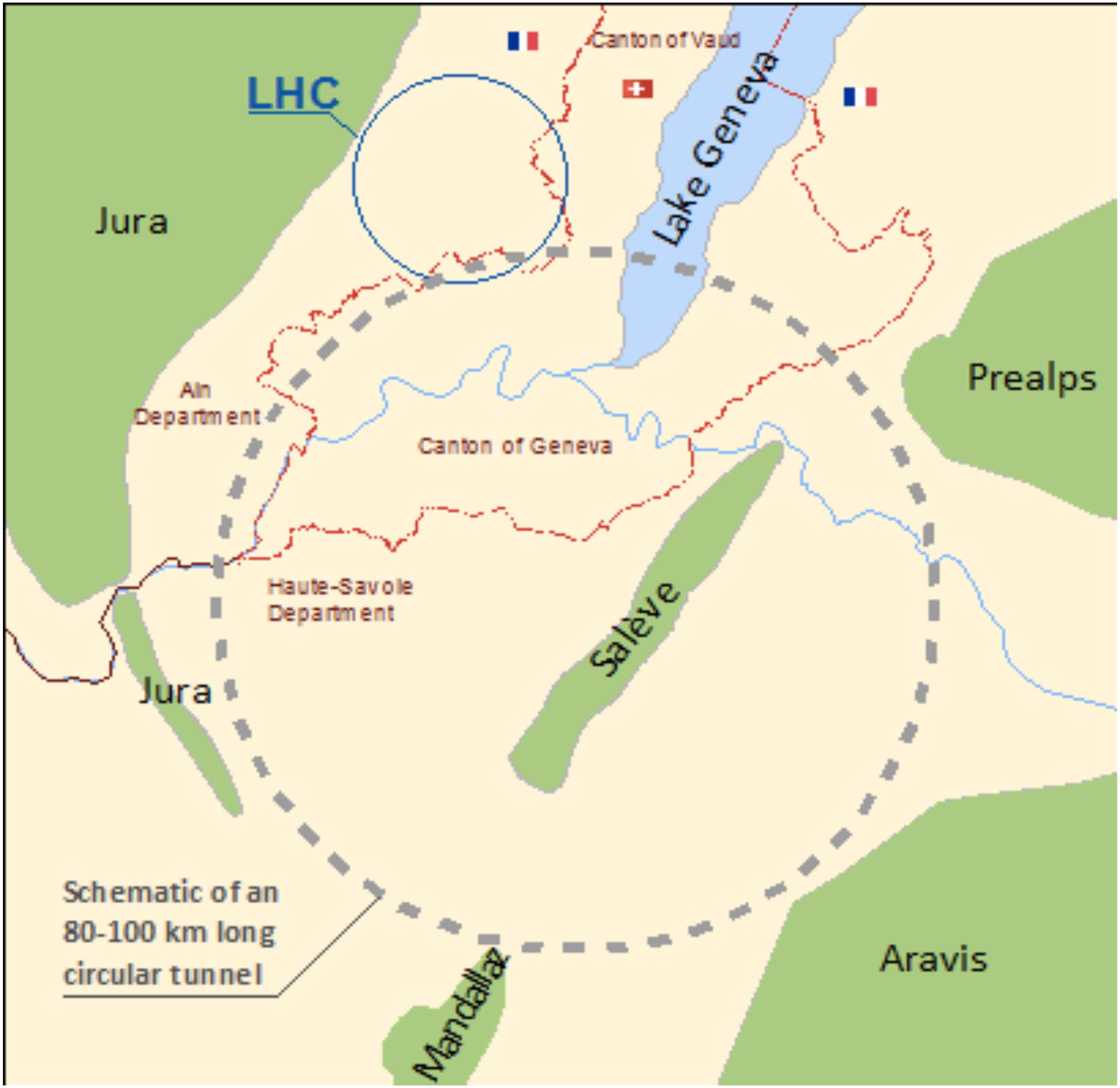
able 2.13: Baseline parameters and estimated peak luminosities of future ep collider configuratior ased on an electron ERL, esp. HE-LHeC, when used in concurrent ep and pp operation mode [110].

Parameter [unit]	**LHeC CDR**	**ep at HL-LHC**	**ep at HE-LHC**	**FCC-he**
E_p [TeV]	7	7	13.5	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

Table 7.1: Key values relating the detector challenges at the different accelerators.

Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
Circumference	km	26.7	26.7	26.7	97.8
Peak $\mathcal{L}$, nominal (ultimate)	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1 (2)	5 (7.5)	16	30
Bunch spacing	ns	25	25	25	25
Number of bunches		2,808	2,760	2,808	10,600
Goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel} [244]	mb	80	80	86	103
σ_{tot} [244]	mb	108	108	120	150
BC rate	MHz	31.6	31.0	31.6	32.5
Peak pp collision rate	GHz	0.8	4	14	31
Peak av. PU events/BC, nominal (ultimate)		25 (50)	130 (200)	435	950
RMS luminous region σ_z	mm	45	57	57	49
Line PU density	mm^{-1}	0.2	1.0	3.2	8.1
Time PU density	ps^{-1}	0.1	0.29	0.97	2.43
$dN_{ch}/d\eta\vert_{\eta=0}$ [244]		6.0	6.0	7.2	10.2
Charged tracks per collision N_{ch} [244]		70	70	85	122
Rate of charged tracks	GHz	59	297	1,234	3,942
$< p_T >$ [244]	GeV/c	0.56	0.56	0.6	0.7
Bending radius for $< p_T >$ at B=4 T	cm	47	47	49	59
Total number of pp collisions	10^{16}	2.6	26	91	324
Charged part. flux at 2.5 cm, est.(FLUKA)	$\mathrm{GHz\,cm}^{-2}$	0.1	0.7	2.7	8.4 (10)
1 MeV-neq fluence at 2.5 cm, est.(FLUKA)	$10^{16}\,\mathrm{cm}^{-2}$	0.4	3.9	16.8	84.3 (60)
Total ionising dose at 2.5 cm, est.(FLUKA)	MGy	1.3	13	54	270 (300)
$dE/d\eta\vert_{\eta=5}$ [244]	GeV	316	316	427	765
$dP/d\eta\vert_{\eta=5}$	kW	0.04	0.2	1.0	4.0

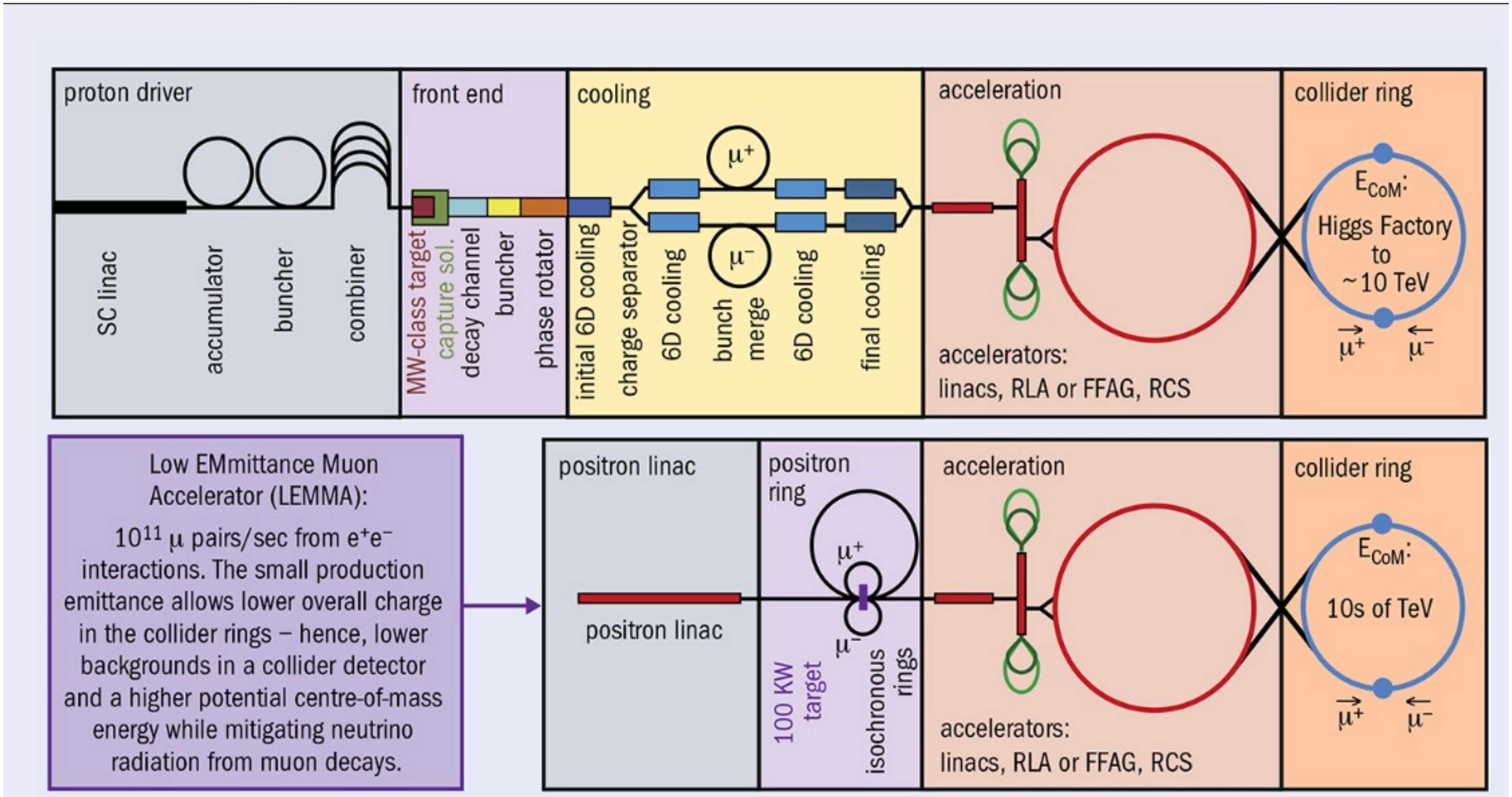
		LHC	HL-LHC	HE-LHC	FHC
90% $b\bar{b}$ $p_T^b > 30$ GeV/c [245]	$\|\eta\| <$	3	3	3.3	4.5
VBF jet peak [245]	$\|\eta\|$	3.4	3.4	3.7	4.4
90% VBF jets [245]	$\|\eta\| <$	4.5	4.5	5.0	6.0
90% $H \to 4l$ [245]	$\|\eta\| <$	3.8	3.8	4.1	4.8
$b\bar{b}$ cross-section	mb	0.5	0.5	1	2.5
$b\bar{b}$ rate	MHz	5	25	250	750
$b\bar{b}$ $p_T^b > 30$ GeV/c cross-section	μb	1.6	1.6	4.3	28
$b\bar{b}$ $p_T^b > 30$ GeV/c rate	MHz	0.02	0.08	1	8
Jets $p_T^{jet} > 50$ GeV/c cross-section [244]	μb	21	21	56	300
Jets $p_T^{jet} > 50$ GeV/c rate	MHz	0.2	1.1	14	90
$W^+ + W^-$ cross-section [246]	μb	0.2	0.2	0.4	1.3
$W^+ + W^-$ rate	kHz	2	10	100	390
$W^+ \to l + \nu$ cross-section [246]	nb	12	12	23	77
$W^+ \to l + \nu$ rate	kHz	0.12	0.6	5.8	23
$W^- \to l + \nu$ cross-section [246]	nb	9	9	18	63
$W^- \to l + \nu$ rate	kHz	0.1	0.5	4.5	19
Z cross-section [246]	nb	60	60	100	400
Z rate	kHz	0.6	3	25	120
$Z \to ll$ cross-section [246]	nb	2	2	4	14
$Z \to ll$ rate	kHz	0.02	0.1	1	4.2
$t\bar{t}$ cross-section [246]	nb	1	1	4	35
$t\bar{t}$ rate	kHz	0.01	0.05	1	11


LHC
Canton of Vaud
Lake Geneva
Jura
Ain Department
Canton of Geneva
Prealps
Haute-Savoie Department
Salève
Jura
Schematic of an 80-100 km long circular tunnel
Mandallaz
Aravis

Muon Collider

- Muons (like electrons) are point-like projectiles
  - All energy available in collisions → new particles
  - Bending radiation $\gamma^4 \sim 200^4$ smaller than electrons
- Their rest lifetime is only 2 us
  - Accelerate them to near *v~c* they survive for $\gamma\tau$
  - Long enough to make collisions
- Muon beam halo difficult for detectors

Schematic of a Muon Collider



Muon Beam halo backgrounds