A Very Large Lepton Collider in a VLHC tunnel

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- Design strategy
- Intensity Limitations
- RF and Optics parameters: Arc, IR
- Lifetime
- Scaling the beam-beam parameter
- Luminosity, Energy reach
- Parameters of a 233 km ring, $\mathcal{L} = 10^{33}$cm^{-2}sec^{-1}, E = 185 GeV
- Low energy design at Z0 mass $E_{cm} = 90$GeV
- Accelerator Physics Challenges

Design Strategy

- Use the maximum RF power available
- Operate at the beam-beam limit

Synchrotron radiation power lost by *both beams*,

$$P_T = 2C_\gamma \frac{E^4 I}{e\rho} \tag{1}$$

$C_\gamma = (4\pi/3)(r_e/(m_e c^2)^3) = 8.86 \times 10^{-5}$ [m/GeV^3].

Luminosity

$$\mathcal{L} = \frac{f_{rev}}{4\pi}\frac{M_b N_b^2}{\sigma_x^* \sigma_y^*} \tag{2}$$

Vertical beam-beam tune shift

$$\xi_y = \frac{r_e}{2\pi}\frac{N_b \beta_y^*}{\gamma \sigma_x^* \sigma_y^*}, \qquad \sigma_y^* \ll \sigma_x^* \tag{3}$$

Replacing one power of bunch intensity,

$$\mathcal{L} = \frac{1}{2er_e}\frac{\xi_y}{\beta_y^*}\gamma I \tag{4}$$

or

$$\boxed{\mathcal{L}\gamma^3 = \frac{3}{16\pi r_e^2 (m_e c^2)}\frac{\xi_y P_T}{\beta_y^*}\rho} \tag{5}$$

Interpretations

- At fixed $\mathcal{L}$, P_T and ξ_y

  $$E \propto \rho^{1/3}$$

  This determines the maximum allowable energy at these parameters.
- At fixed bend radius or circumference C , P_T and ξ_y

  $$\mathcal{L} \propto \gamma^{-3}$$

- At constant luminosity, the maximum energy E *increases* if C, P_T, ξ_y *increase* and β_y^* *decrease*.
- ...

Intensity Limitations

Bunch intensity limitations

- At top energy, the limit is set by the beam-beam interactions.

  Limits from the desired collisions are included in the design, there may be additional limits from parasitic collisions.

- At injection energy, the transverse mode coupling instability sets the limit. At the threshold the $m = 0$ and $m = -1$ modes of the betatron modes $\omega_\beta + m\omega_s$ become degenerate. Threshold bunch current

  $$I_b^{TMCI} \simeq \frac{8 f_{rev} \nu_s E}{e \sum_i \beta_i k_{\perp\ i}(\sigma_s)} \tag{6}$$

  $k_{\perp\ i}$ is a bunch length dependent transverse mode loss factor. At LEP TMCI limits the bunch current to below 1mA. I assume that similar bunch intensities as in LEP will be stable in the large ring but this may be optimistic ...

Beam intensity limitations

- This is primarily determined by the available RF power.
- Cryogenic cooling power.

  The dynamic heat load on the cavities includes a contribution from the beam

  $$P_{dynamic}^{beam} = 2R_m(\sigma_s) I_b I_e \tag{7}$$

- HOM power in cavities.

Basic Parameters

- Choose β_x^*, β_y^* (limitations determined by IR optics, bunch length)
- Determine the maximum energy E from $\mathcal{L}$, β_y^*, P_T and ξ_y (choice of ξ_y has to be self-consistent with the energy) for a given circumference.
- Bunch intensity N_b is set by TMCI limitations
- Choose a coupling ratio (determined by β_y^*/β_x^*)

$$\kappa = \frac{\epsilon_y}{\epsilon_x} \tag{8}$$

- Equilibrium emittance is found from

$$\epsilon_x = \frac{N_b}{\gamma \xi_y} \left(\frac{r_e}{2\pi} \sqrt{\frac{\beta_y^*}{\kappa \beta_x^*}} \right) \tag{9}$$

  where factors within () are assumed to stay constant.

- Choose a phase advance per cell μ_C (upper limit usually determined by chromaticity sextupoles).
- The cell length L_C is determined by the equilibrium emittance

$$\epsilon_x \approx \left(\frac{C_q}{J_x} \frac{R}{\rho} [\frac{L_c}{\mu_c}]^3 \right) \frac{\gamma^2}{R^3} \tag{10}$$

  $C_q = 55\hbar c/(32\sqrt{3}(m_e c^2)) = 3.83 \times 10^{-13}$ [m]

- Filling factors f_1 and f_2

$$R = f_1 \frac{C}{2\pi} \ , \quad \text{and} \quad \rho = f_2 R \ , \qquad f_1, f_2 < 1 \tag{11}$$

  R is the arc radius, ρ is the bend radius. Typically $1 < R/\rho \leq 1.25$.

- Maximum number of bunches is determined by the beam power P_T

$$M_b^{max} = (\frac{P_T}{2C_\gamma}) \frac{\rho}{f_{rev} N_b E^4} \tag{12}$$

RF parameters

Requirements

- The RF must replenish the energy lost per turn.
- The RF must provide an acceptable quantum lifetime.

Energy Gain

$$eV_{RF}\sin\phi_s = U = C_\gamma \frac{E^4}{\rho} \tag{13}$$

The longitudinal quantum lifetime is determined by the energy headroom $N_{QL} = \Delta E_{RF}/\sigma_E$ as

$$\tau_{quant;s} = \frac{\tau_s}{N_{QL}^2}\exp[\frac{1}{2}N_{QL}^2] \tag{14}$$

$$\sqrt{\frac{1}{\pi h\eta_{slip}}eV_{RF}EG(\phi_s)} = N_{QL}\sqrt{\frac{C_q}{J_s\rho}\frac{E^2}{m_ec^2}} \tag{15}$$

where

$$G(\phi_s) = 2\cos\phi_s - (\pi - 2\phi_s)\sin\phi_s \tag{16}$$

Typically $N_{QL} \sim 10$. The two requirements determine the equation for the synchronous phase ϕ_s and the RF voltage V_{RF}.

RF frequency

- The RF acceptance $(\Delta E/E)_{accep} \propto 1/\sqrt{h}$ so lower RF frequencies increase the acceptance.
- However high power klystrons are cheaper above frequencies of 300MHz.

LEP operates with 352MHz. For this design we chose an RF frequency of 400MHz.

Arc parameters: phase advance and cell length

Equilibrium emittance

- The emittance *decreases* as the phase advance *increases*, reaching a minimum at 135°. In a lattice with FODO cells,

$$\epsilon_x(\mu_x^C) = 4\frac{C_q\gamma^2}{J_x}\theta^3\frac{1-\frac{3}{4}\sin^2(\mu_x^C/2)+\frac{1}{60}\sin^4(\mu_x^C/2)}{\sin^2(\mu_x^C/2)\sin\mu_x^C}. \tag{17}$$

  but

- Stronger focusing increases the chromaticity and the strength of the chromaticity sextupoles which can limit the dynamic aperture.

Typically

$$60^\circ \le \mu_c < 120^\circ$$

For example, LEP has operated with $(60^\circ, 60^\circ)$ at 45GeV, and since then $(90^\circ, 60^\circ)$, $(90^\circ, 90^\circ)$ and $(102^\circ, 90^\circ)$ at higher energies.

TMCI threshold

$$I_{thresh}^{TMCI} \propto \frac{\nu_s}{\langle\beta\rangle} \propto \frac{1}{L_c}\cos(\frac{\mu_c}{2}) \tag{18}$$

The TMCI threshold *increases* if the cell length L_C and phase advance per cell μ_C *decrease*.

Emittance control by changing the RF frequency.

$$\frac{dJ_x}{d\delta} = -\frac{dJ_s}{d\delta} = -4\frac{L_D}{L_Q}\left[\frac{2+\frac{1}{2}\sin^2\mu_C/2}{\sin^2\mu_C/2}\right] \tag{19}$$

L_D: length of dipoles in a half cell, L_Q: length of a quadrupole.

Required RF frequency shift is related to the momentum deviation δ by

$$\frac{\Delta f_{RF}}{f_{RF}} = -\frac{\Delta R}{R} = -\alpha_C\delta \tag{20}$$

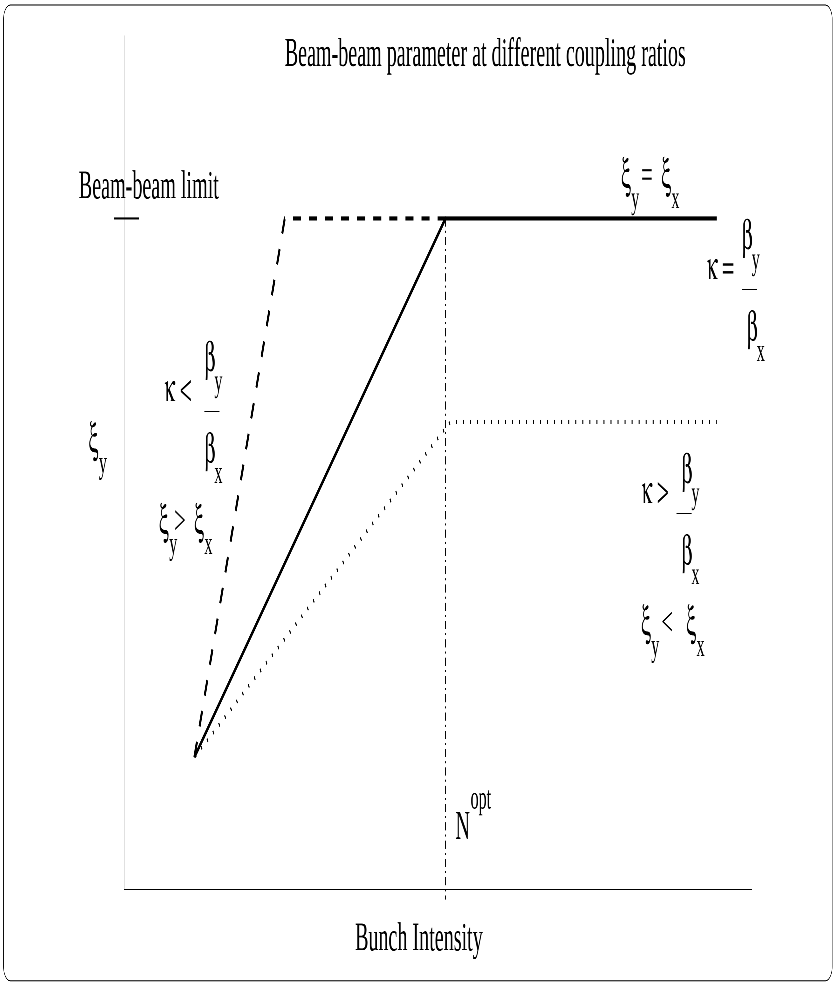
Important to keep ΔR small to minimize loss in physical aperture and transverse quantum lifetime, i.e. design $\Delta J_x/\Delta R$ to be large. This requires lower μ_C and L_Q/L_D to be small i.e. *weaker focusing*.

Example: $C = 228$km, $L_D = 103.7$m, $L_Q = 4.1$m, $\mu_C = 90^\circ$, $\alpha_C = 0.28\times10^{-4}$,

$$\frac{\Delta J_x}{\Delta R} = 0.54\ /[\mathrm{mm}]$$

This is large enough to be useful.

Beam-beam limit



IR Parameters

Lower limits on β^*

- Set by the tolerable beam size in the IR quadrupoles and the chromaticity of these quadrupoles. With $\beta_y^* \ll \beta_x^*$, aperture and chromaticity limitations will first arise in the vertical plane.
- $\beta_y^* \gg \sigma_s$ to prevent the luminosity loss due to the hourglass effect.

β^*, coupling and the beam-beam limit

Beyond the beam-beam limit, $\epsilon_x \propto I$, $\xi_x, \xi_y \sim \mathrm{const.}$ and $\mathcal{L} \propto I$.

$$\xi_x = \left[\sqrt{\frac{\kappa}{\beta_y^*/\beta_x^*}}\right]\xi_y, \quad \mathcal{L} \propto \xi_y \tag{21}$$

If $\kappa > \beta_y^*/\beta_x^*$, then $\xi_x > \xi_y$, the beam-beam limit is reached first in the horizontal plane. ξ_y never reaches its maximum value and since $\mathcal{L} \propto \xi_y$ the maximum luminosity is not obtained. So require $\kappa \leq \beta_y^*/\beta_x^*$ or $\xi_y \geq \xi_x$.

Optimal coupling: $\kappa = \beta_y^*/\beta_x^*$ and $\xi_x = \xi_y$.

$$N^{opt} = \frac{2\pi\gamma\epsilon_x}{r_e}\xi_y \tag{22}$$

If $\kappa < \beta_y^*/\beta_x^*$, the limit is reached at intensity

$$N^{limit} = \frac{2\pi\gamma\epsilon_x}{r_e}\sqrt{\frac{\kappa}{\beta_y^*/\beta_x^*}}\xi_y < N^{opt} \tag{23}$$

Beam Lifetime

- Radiative Bhabha scattering process $e^+e^- \rightarrow e^+e^-\gamma$.

$$\begin{aligned} \tau_L &= \frac{1}{N_{IP}} \frac{M_b N_b}{\mathcal{L}\sigma_{e^+e^-}} \\ &= \left[\frac{2r_e}{N_{IP}} \frac{\beta_y^*}{\xi_y} \frac{1}{\sigma_{e^+e^-}} \right] \frac{1}{\gamma f_{rev}} \\ &\propto \frac{1}{\gamma \xi_y} \end{aligned} \tag{24}$$

  The cross-section $\sigma_{e^+e^-}$ depends on the energy acceptance and has a weak logarithmic dependence on energy. In the energy range from 175 - 200 GeV per beam, $\sigma_{e^+e^-} \sim 0.36$ mbarns assuming an RF acceptance of 1%.

- Beam-gas scattering.

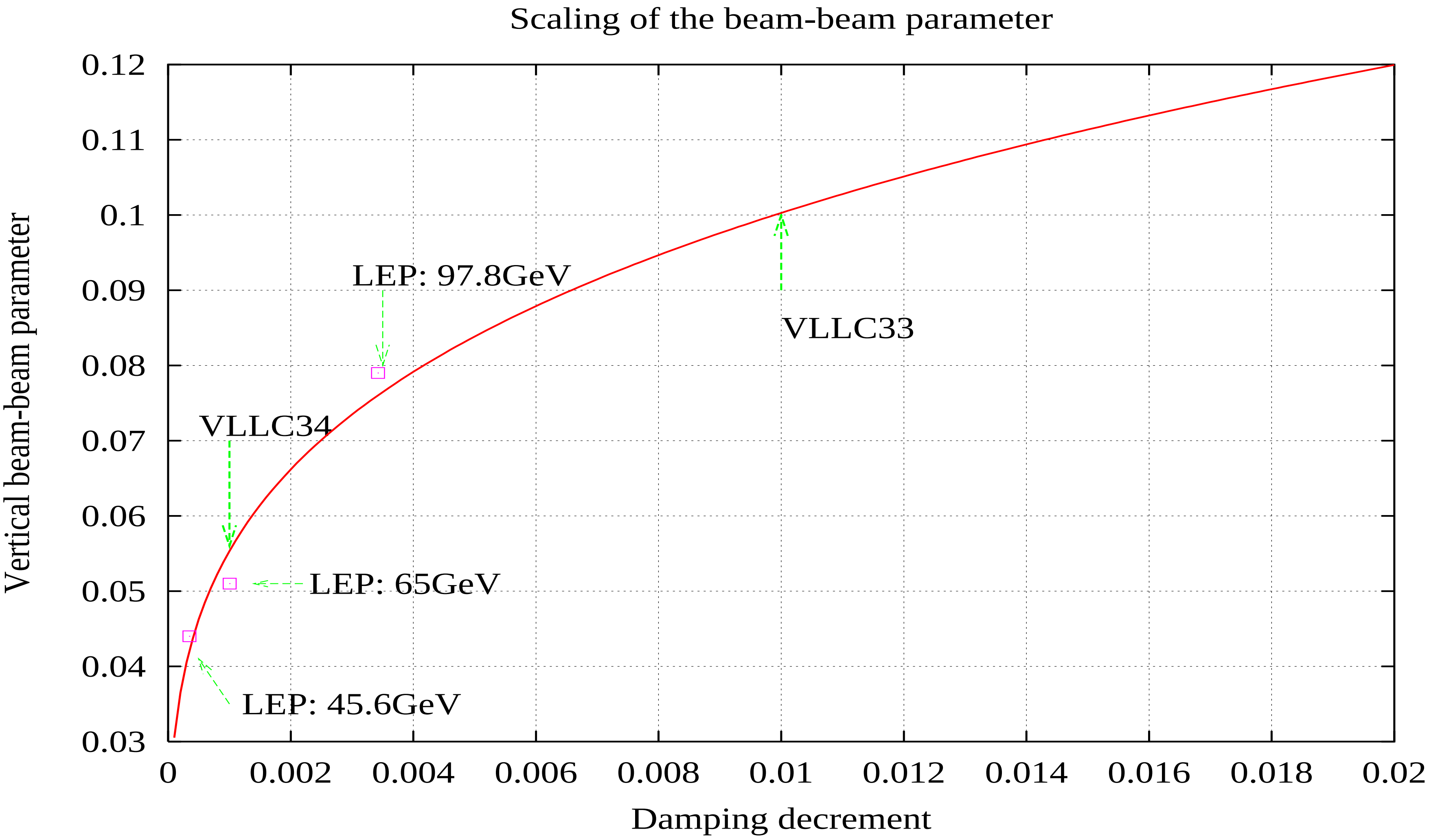
- Compton scattering off thermal photons.

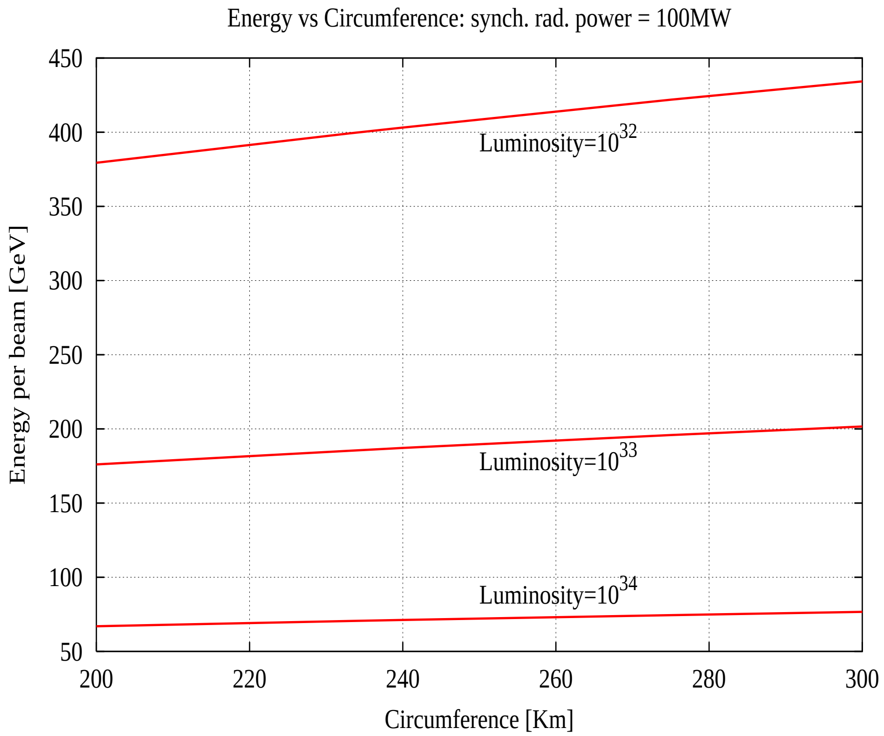
Total lifetime

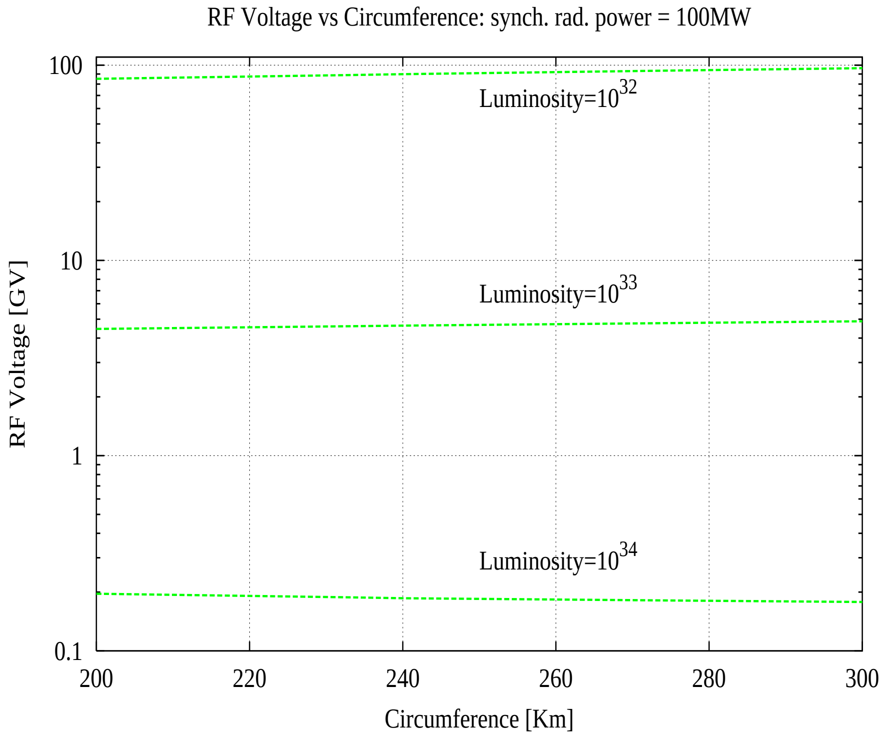
$$\frac{1}{\tau} = \sum_i \frac{1}{\tau_i} \tag{25}$$

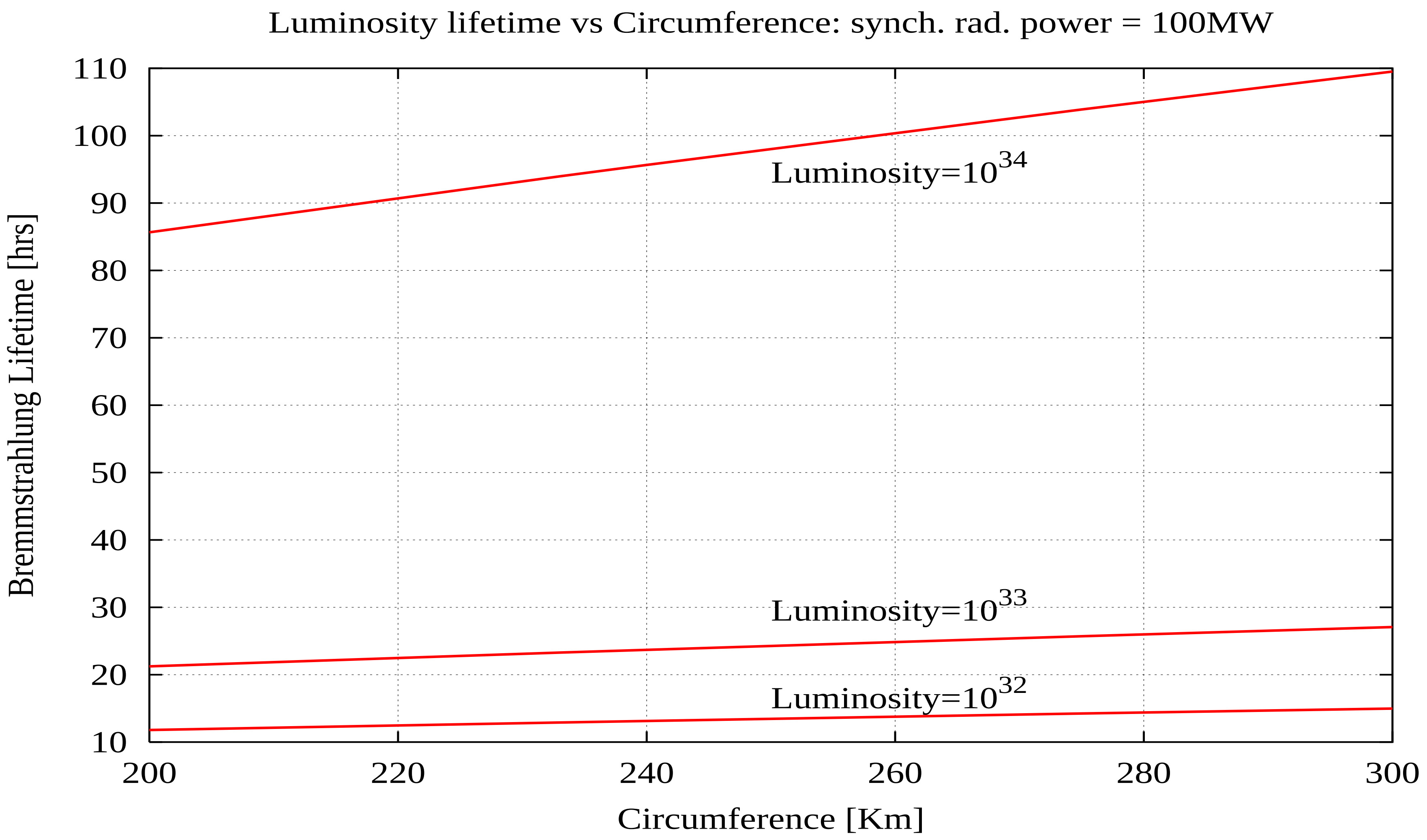
Example: LEP

Process	τ[hrs]
Radiative Bhabha scattering	5.8
Compton scattering	60
Beam-gas scattering (pressure=0.6 nTorr)	80
Total	5.0


Scaling of the beam-beam parameter
Vertical beam-beam parameter
Damping decrement
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
0.02
LEP: 97.8GeV
VLLC33
VLLC34
LEP: 65GeV
LEP: 45.6GeV


Energy vs Circumference: synch. rad. power = 100MW


RF Voltage vs Circumference: synch. rad. power = 100MW


Luminosity lifetime vs Circumference: synch. rad. power = 100MW
Bremmstrahlung Lifetime [hrs]
110
100
90
80
70
60
50
40
30
20
10
200
220
240
260
280
300
Circumference [Km]
Luminosity=10^{34}
Luminosity=10^{33}
Luminosity=10^{32}

$e^+ - e^-$ **Collider Parameters**

Energy [GeV]	**185.00**
Luminosity	1.00 $\times 10^{33}$
Synch. radiation power(both beams) [MW]	100.712
σ_x^*, σ_y^* [microns]	77.520, 3.876
Number of bunches	126
Bunch spacing [km]	1.8492
Particles per bunch	4.851 $\times 10^{11}$
Bunch current [mA]	0.100
Emittances [nano-m]	6.009, 0.300
Beam-beam parameter	0.10650
Damping decrement	0.01080
Single beam current [mA]	12.600
Brho [Tesla-m]	617.078
Arc tune	215.356
Phase advance per cell [deg]	90.000
Dipole field [T]	0.02376
Focal length of cell [m]	80.025
Quad gradient [T/m]	15.595
Quad field at $1\sigma_x^{max}$/dipole field	1.000
Cell: β^{max}, β^{min} [m]	386.395, 66.295
Cell: σ_x^{max}, σ_x^{min} [mm]	1.524, 0.631
Cell: σ_y^{max}, σ_y^{min} [mm]	0.341, 0.141
Max apertures required [cm]	2.524, 1.341
Max and min disp. [m]	1.117, 0.534
Momentum compaction	0.2226E-04
Energy loss per turn [GeV]	3.996
Damping time [turns]	46
RF Voltage [GV]	4.57254
Synchronous phase [deg]	60.930
Relative energy spread	0.9834E-03
RF acceptance	0.9822E-02
Synchrotron tune	0.11501
Bunch length [mm]	7.058
Longitudinal emittance [eV-sec]	0.01346
Bremm cros-section [barns]	0.36022
Bremm lifetime [hrs]	23.6
Polarization time [hrs]	2.215
Critical energy [keV]	452.611
Critical wavelength [A]	0.023
Number of photons/m/sec	0.115E+17
Gas load [torr-L/m-sec]	0.104E-07
Linear Power load(both beams) [kW/m]	0.517
specif press. rise [Torr/mA]	0.138E-12
specific current [mA]	7238.604
spec. current/beam current	574.49

Comments on Parameters

- $C(VLLC33)/C(LEP) \sim 8.5$, $P_T(VLLC)/P_T(LEP) \sim 7$
  $\Rightarrow \mathcal{L}(VLLC33)/\mathcal{L}(LEP) \sim 10$ at almost double the energy.
- The $e^+ - e^-$ bremmstrahlung lifetime in VLLC33 is significantly longer at 23 hours.
- The beam sizes in the two machines are comparable. Hence vacuum chamber dimensions in VLLC33 can be similar to those in LEP if a two-ring machine (long-range interactions in a single ring machinemay require a larger aperture).
- $B_{dip}(VLLC)/B_{dip}(LEP) \sim 1/5$. Warm iron magnets will suffice. But good shielding from stray magnetic fields will be more important.
- The quadrupole gradient is determined by requiring that synchrotron radiation in quadrupoles be small. Require $B_{quad}(r = 1\sigma)/B_{dip} = 1$ (E. Keil).
- The critical energy is smaller in VLLC33 so shielding against synchotron radiation as in LEP should be adequate for VLLC33. The photon flux per unit length is almost the same in the two machines.
- The RF voltage required for VLLC33 is higher at 4.7GV compared to 3.1GV for LEP.
- $f_1 = f_2 = 0.84$ was chosen to have the same ratio $\rho : C/(2\pi)$ as in LEP. A more aggressive choice of $2\pi\rho/C = 0.81$ yields e.g. maximum energy $E_{max} =$ 193GeV, RF voltage $V_{RF} = 4883$MV.
- We chose optimum coupling, i.e. $\epsilon_y/\epsilon_x = \beta_y^*/\beta_x^* 0.05$ which $\Rightarrow$ $\xi_x = \xi_y$. If we reduce it to $\epsilon_y/\epsilon_x = 0.025$, then $\xi_x = 0.071$, $\xi_y = 0.1$. Optics and beam size parameters change, e.g. $\epsilon_x = 11.8$nm, cell length=278m, $\beta^{max} = 475$m, $D_x^{max} = 1.72$m, $\sigma_x^{max} = 2.4$mm, $\nu_s = 0.156$, $\sigma_l = 8.1$mm. The RF voltage increases to 4780MV, most other parameters are relatively unaffected.
- We chose $N_{QL} = 10$ to ensure sufficient quantum lifetime. At LEP $N_{QL} = 6.6$. If we assume this value for the 228km ring, the RF voltage is lowered from 4.66GV to 4.43GV.

Comparison of parameters

Parameter	Bunch current $I_b = 0.1$mA			Bunch current $I_b = 0.05$mA	
	$\kappa = \beta_y^*/\beta_x^*$ $\xi_y = 0.1$	$\kappa = 0.5\beta_y^*/\beta_x^*$ $\xi_y = 0.1$	$\kappa = \beta_y^*/\beta_x^*$ $\xi_y = 0.08$	$\kappa = \beta_y^*/\beta_x^*$ $\xi_y = 0.1$	$\kappa = \beta_y^*/\beta_x^*$ $\xi_y = 0.08$
Energy [GeV]	185	185	172	185	172
Emittances ϵ_x, ϵ_y [nm]	6.1, 0.3	8.6, 0.21	8.1, 0.40	3.0, 0.15	4.1, 0.2
Number of bunches	123	123	167	246	332
τ_{bremm} [hrs]	23	23	31	23	31
Arc tune	215	191	186	271	234
Cell Length [m]	227	255	262	180	209
Arc $\sigma_x^{max}, \sigma_x^{min}$ [mm]	1.53, 0.63	1.93, 0.80	1.90, 0.79	0.96, 0.40	1.2, 0.5
Synchrotron tune ν_s	0.116	0.135	0.128	0.084	0.094

The luminosity is 10^{33} cm^{-2} sec^{-1} in each case. Ring circumference is 233 km and the synchrotron radiation power is fixed at 100 MW.

Low Energy Operation

At “low energies”, the ring is

- not limited by available power
- only constrained by the beam-beam tune shift

$$\begin{aligned}\mathcal{L} &= \frac{\pi}{r_e^2} M_B f_{rev} [\frac{\sigma_x^* \sigma_y^*}{(\beta_y^*)^2}] \gamma^2 \xi_y^2 \\ &= \frac{\pi}{r_e^2}\ M_B f_{rev}\ [\frac{\kappa \beta_x^*}{(\beta_y^*)^3}]^{1/2}\ \gamma^2 \xi_y^2\ \ \epsilon_x\end{aligned}$$

In this regime,

Luminosity increases with the emittance $\mathcal{L} \propto \epsilon_x$

This requires *filling the aperture* at these energies.

Sufficient physical aperture

$$\text{Aperture} \approx 10 * [\sigma_x^2 + (D_x \delta_p^2)]^{1/2} + 1\text{cm}(\text{c.o.d}) \tag{26}$$

The bunch intensity is low in order to limit the beam-beam tune shift. Number of bunches have to be increased to increase the luminosity.

What is the minimum bunch spacing at these intensities?

Assume (without justification) a minimum spacing of 5m.

Low Energy Design Strategy

- *Increase the emittance* by lowering the phase advance per cell μ_C.
- The emittance

$$\epsilon_x = (\frac{C_q}{J_x}\frac{R}{\rho})[\frac{L_C}{R\mu_C}]^3\gamma^2$$

- Find the smallest phase advance so that

$$10 * [\sigma_x^2 + (D_x^{max}\delta_p)^2]^{1/2} + 1\mathrm{cm} \leq \mathrm{Aperture}$$

- Find the bunch intensity from the beam-beam tune shift

$$N_b = (\frac{2\pi}{r_e}\sqrt{\frac{\kappa}{\beta_y^*/\beta_x^*}})\gamma\epsilon_x\,\xi_y$$

  Check that $N_b \leq N_b^{TMCI}$

- Find the number of bunches M_B from the minimum bunch spacing

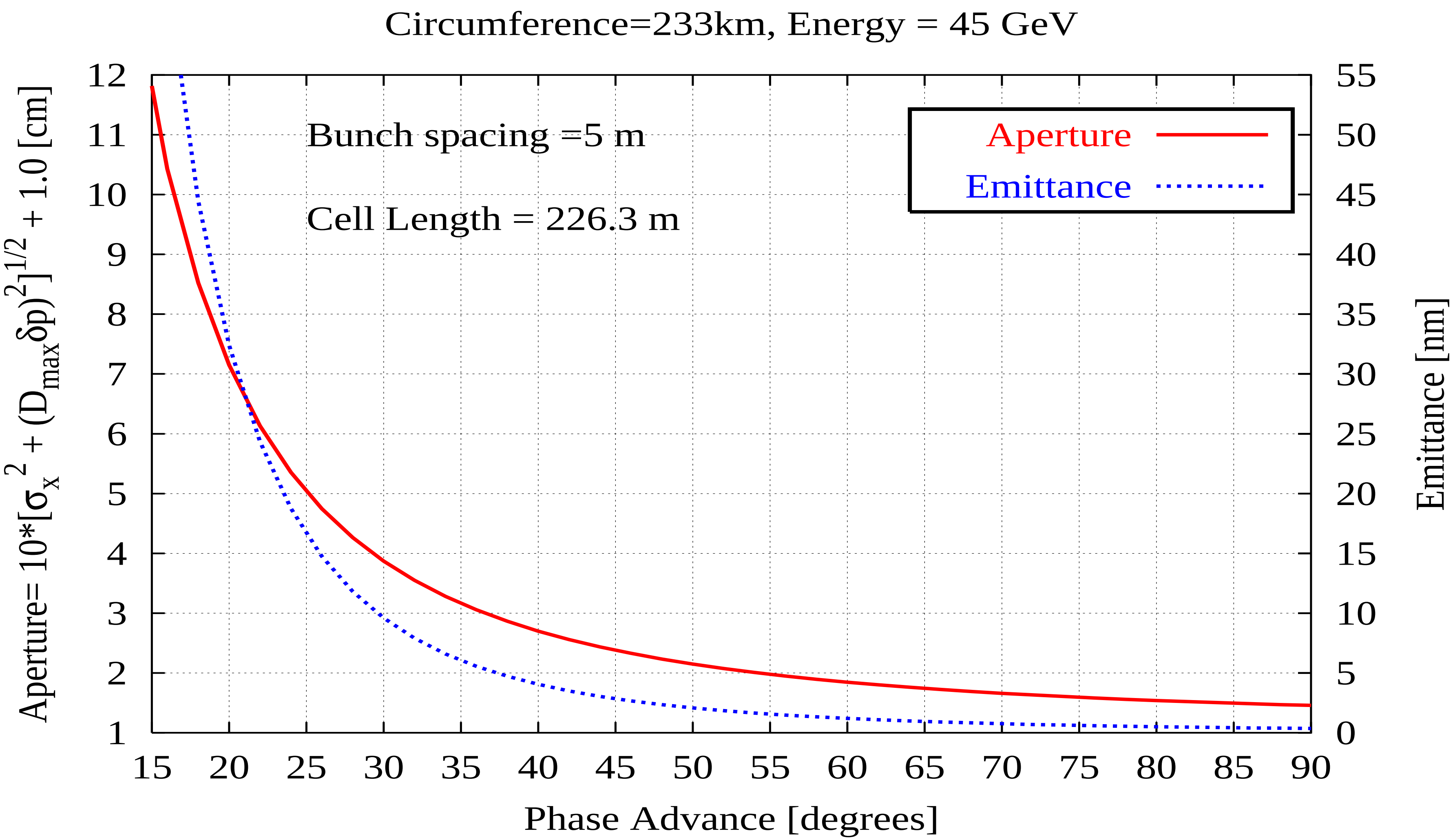
$$M_B f_{rev} = \frac{c}{S_B}$$

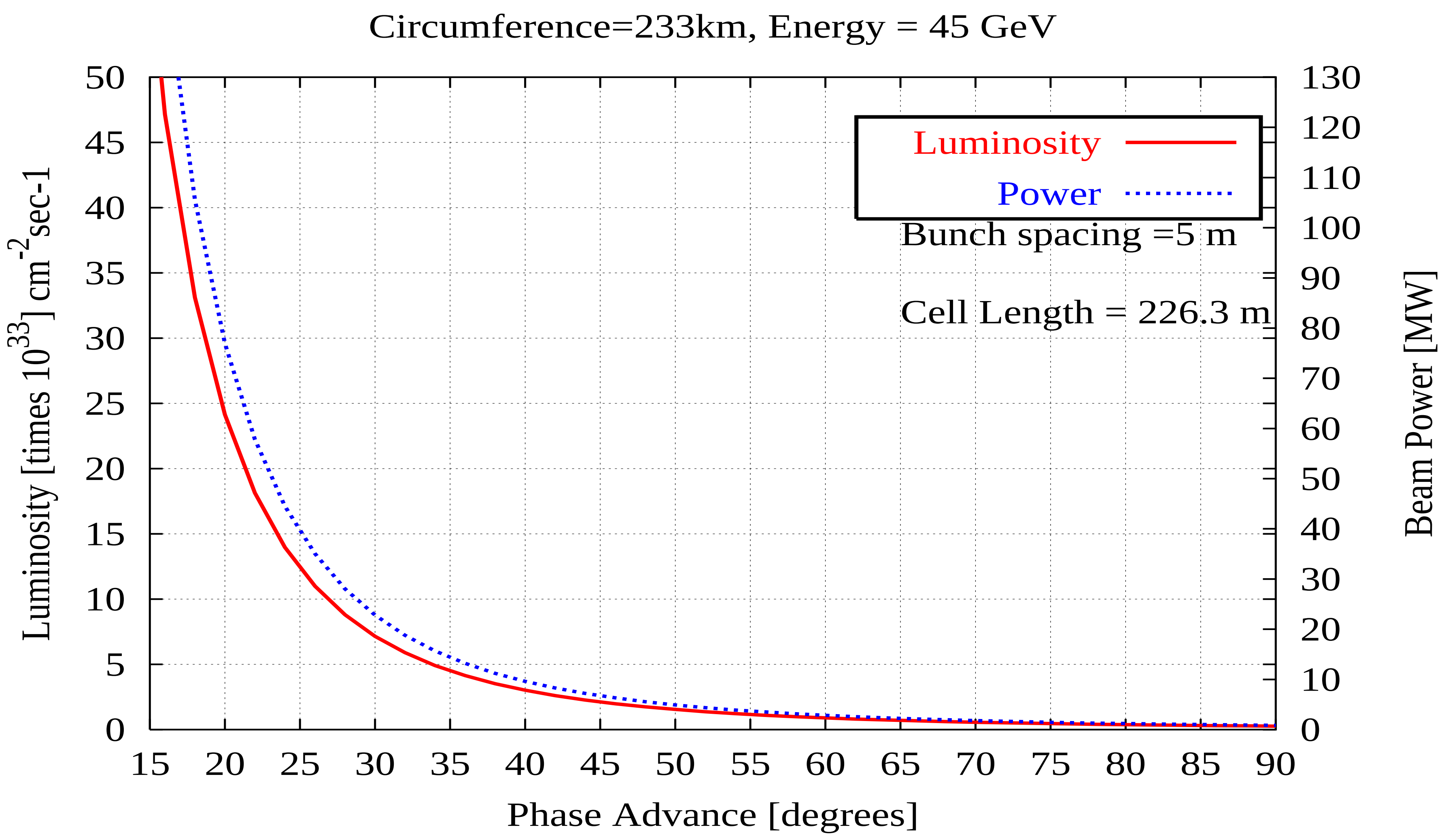
- Luminosity

$$\mathcal{L} = \frac{\pi}{r_e^2}M_B f_{rev}[\frac{\kappa\beta_x^*}{(\beta_y^*)^3}]^{1/2}\gamma^2\xi_y^2\ \ \epsilon_x$$

- Alternative strategy of increasing the emittance:

  Double the cell length by turning off half the quadrupoles.


Circumference=233km, Energy = 45 GeV
Bunch spacing =5 m
Cell Length = 226.3 m
Aperture
Emittance
Aperture= 10*[$\sigma_x^2 + (D_{max}\delta p)^2]^{1/2}$ + 1.0 [cm]
Emittance [nm]
Phase Advance [degrees]
1
2
3
4
5
6
7
8
9
10
11
12
0
5
10
15
20
25
30
35
40
45
50
55
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90


Circumference=233km, Energy = 45 GeV
Luminosity
Power
Bunch spacing =5 m
Cell Length = 226.3 m
Luminosity [times 10^{33}] cm^{-2}sec-1
Beam Power [MW]
Phase Advance [degrees]
0
5
10
15
20
25
30
35
40
45
50
0
10
20
30
40
50
60
70
80
90
100
110
120
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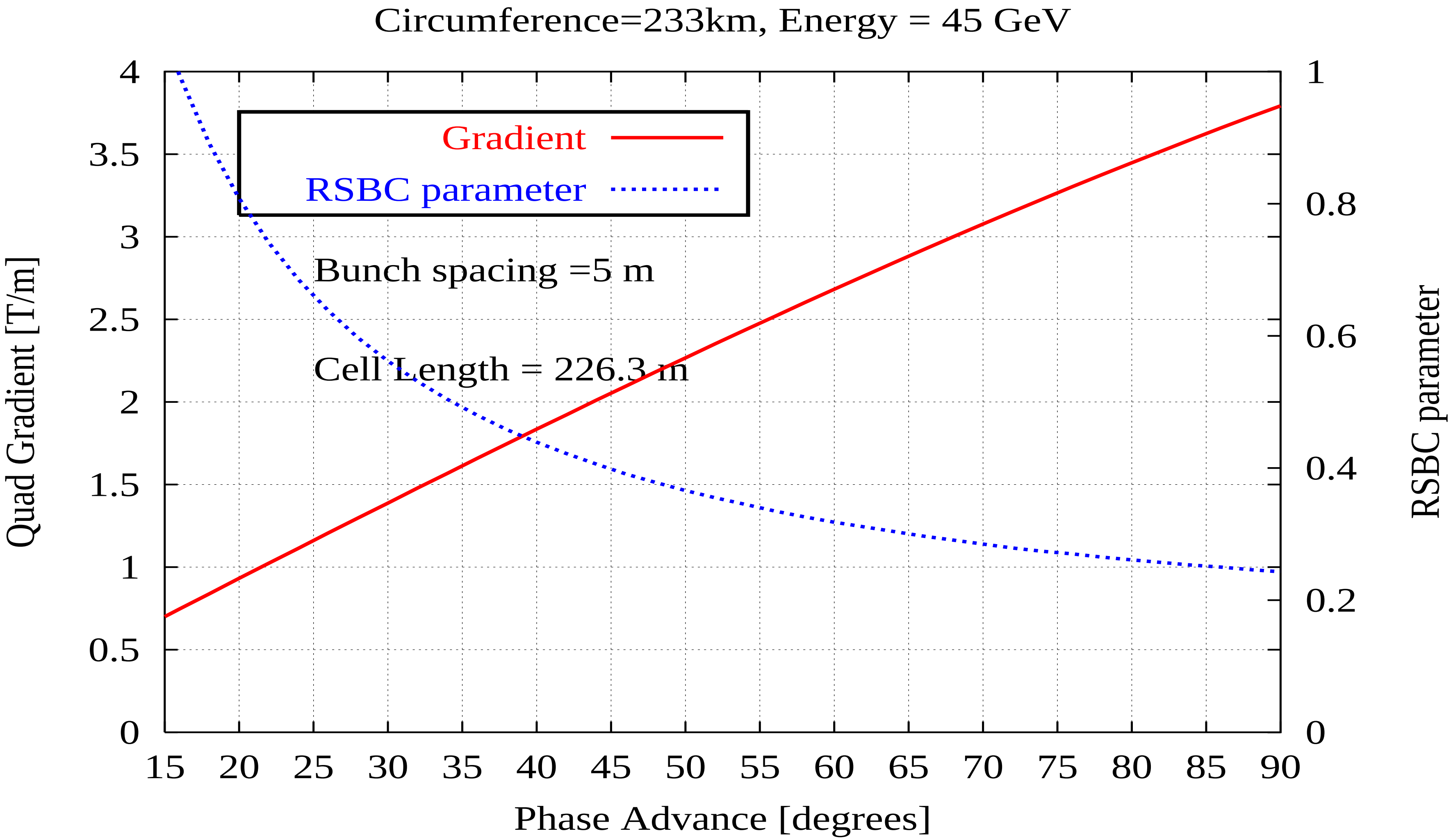
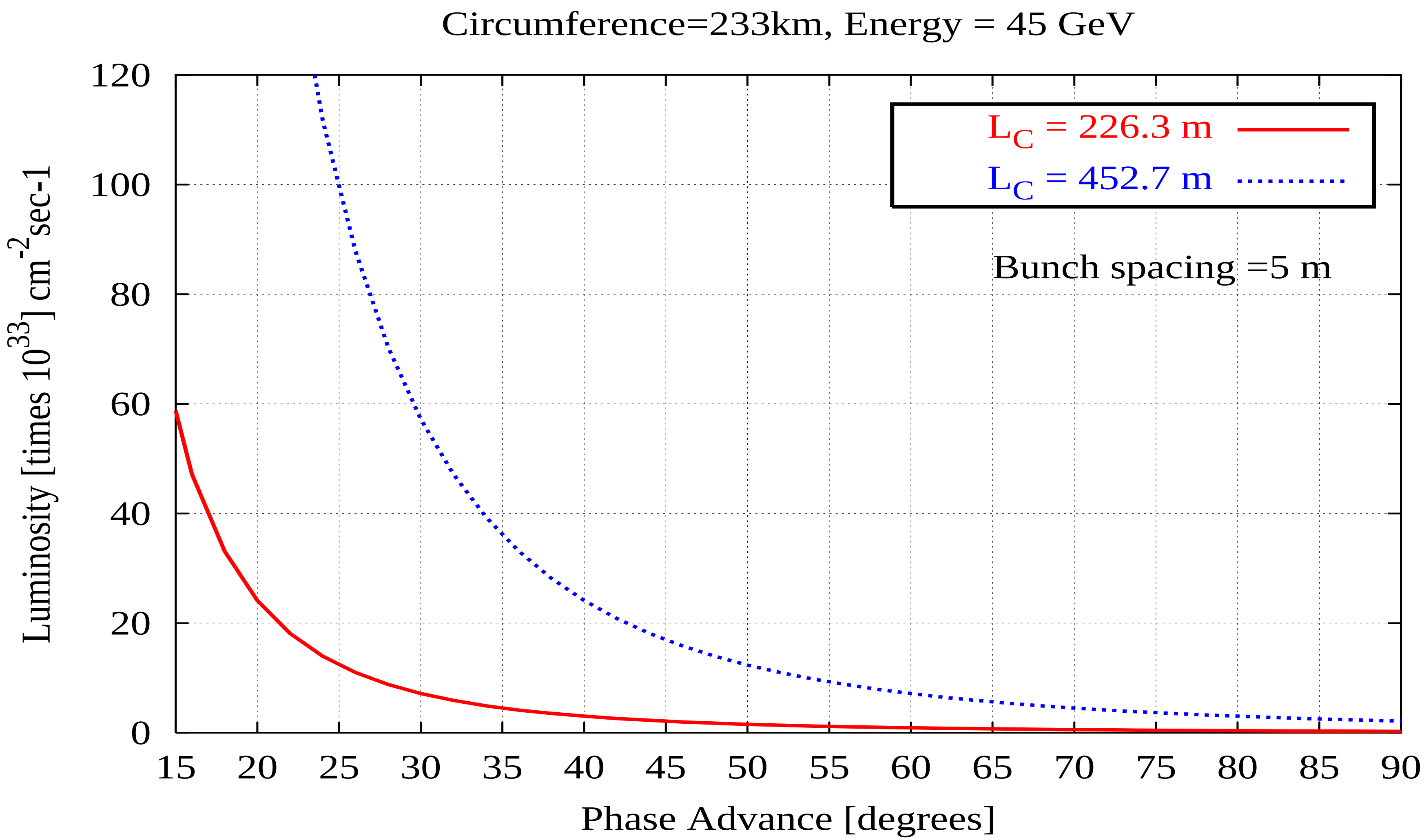
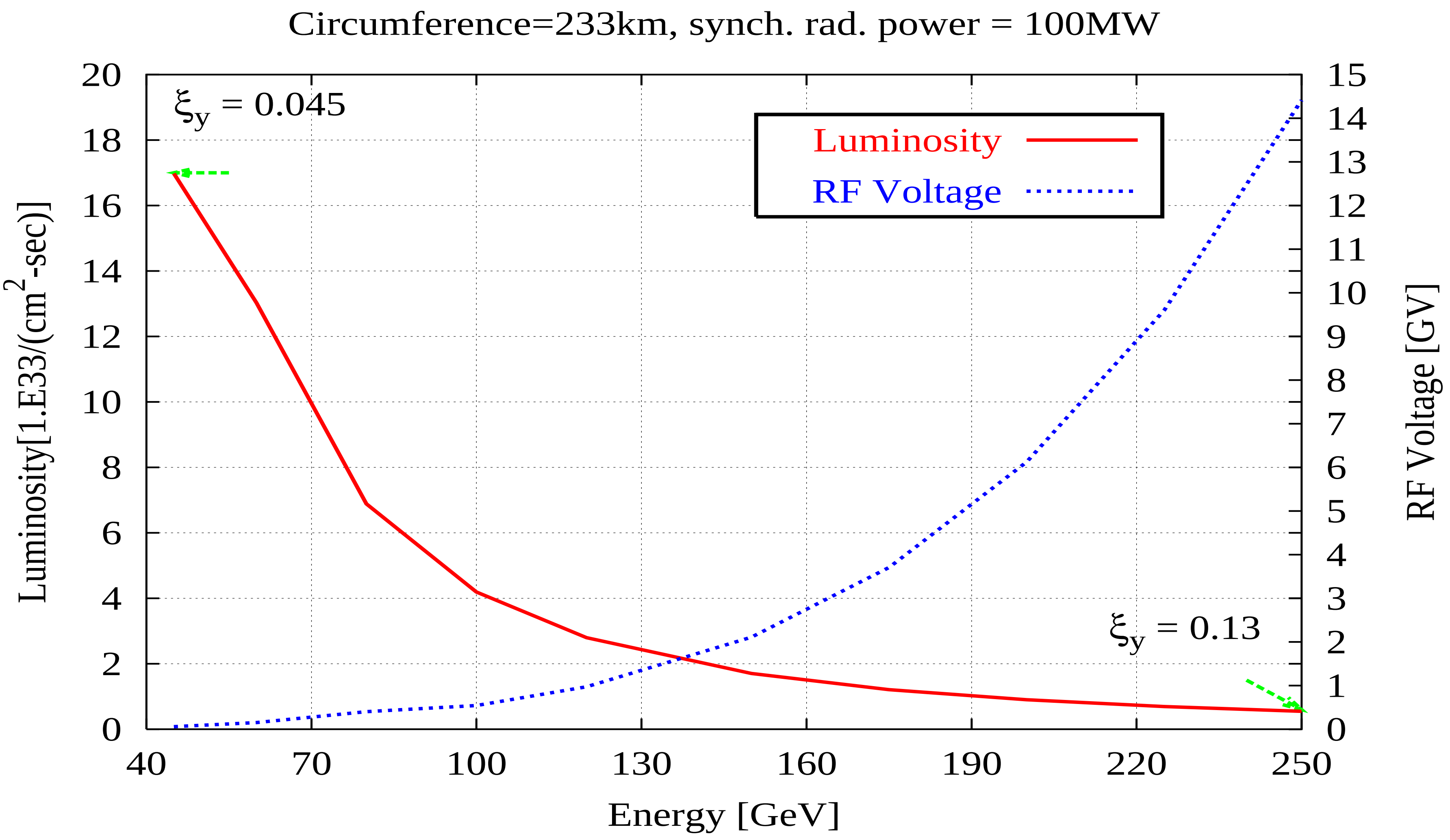
60
65
70
75
80
85
90


Circumference=233km, Energy = 45 GeV
Gradient
RSBC parameter
Bunch spacing =5 m
Cell Length = 226.3 m
Quad Gradient [T/m]
RSBC parameter
Phase Advance [degrees]
0
0.5
1
1.5
2
2.5
3
3.5
4
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
0
0.2
0.4
0.6
0.8
1


Circumference=233km, Energy = 45 GeV
Luminosity [times 10^33] cm^-2 sec-1
Phase Advance [degrees]
120
100
80
60
40
20
0
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
L_C = 226.3 m
L_C = 452.7 m
Bunch spacing =5 m

Energy [GeV]	**45.00**
Luminosity	16.98 $\times 10^{33}$
Synch. radiation power(both beams) [MW]	54.046
σ_x^*, σ_y^* [microns]	150.849, 7.542
Number of bunches	46599
Bunch spacing [km]	0.0050
Particles per bunch	2.011 $\times 10^{11}$
Bunch current [mA]	0.04145
Emittances [nano-m]	22.755, 1.138
Beam-beam parameter	0.04500
Damping decrement	0.00016
Single beam current [mA]	1931.485
Brho [Tesla-m]	150.100
Arc tune	53.839
Phase advance per cell [deg]	22.500
Dipole field [T]	0.00578
Focal length of cell [m]	290.051
Quad gradient [T/m]	1.047
Quad field at $1\sigma_x^{max}$/dipole field	0.726
Cell: β^{max}, β^{min} [m]	706.857, 476.078
Cell: σ_x^{max}, σ_x^{min} [mm]	4.011, 3.291
Cell: σ_y^{max}, σ_y^{min} [mm]	0.897, 0.736
Max apertures required [cm]	5.011, 1.897
Max and min disp. [m]	11.902, 9.786
Momentum compaction	0.2924E-03
Energy loss per turn [GeV]	0.0140
Damping time [turns]	3216
RF Voltage [GV]	0.05729
Synchronous phase [deg]	14.136
Relative energy spread	0.2392E-03
RF acceptance	0.2400E-02
Synchrotron tune	0.13365
Bunch length [mm]	19.409
Longitudinal emittance [eV-sec]	0.00219
Bremm cros-section [barns]	0.45368
Bremm lifetime [hrs]	168.9
Polarization time [hrs]	2600.792
Critical energy [keV]	6.514
Critical wavelength [A]	1.593
Number of photons/m/sec	0.430E+18
Gas load [torr-L/m-sec]	0.387E-06
Linear Power load(both beams) [kW/m]	0.277
specif press. rise [Torr/mA]	0.336E-13
specific current [mA]	29758.71
spec. current/beam current	15.41


Circumference=233km, synch. rad. power = 100MW
ξ_y = 0.045
ξ_y = 0.13
Luminosity
RF Voltage
Luminosity[1.E33/(cm^2-sec)]
RF Voltage [GV]
Energy [GeV]
0
2
4
6
8
10
12
14
16
18
20
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
40
70
100
130
160
190
220
250

Stored Energy, Site Power

Stored energy per beam

- LEP (E=98GeV, I=2.88mA, frev=11.25kHz)
  Stored energy $\sim$ 25kJ
- VLLC (E=185GeV, I=12.4mA, frev=1.315kH)
  Stored energy $\sim$ 1.74MJ
- VLHC (E=7TeV, I=0.53A , frev=11.25kHz)
  Stored energy $\sim$ 334MJ

Stored energy is not large in comparison to hadron colliders.

Site Power requirements

- Beam power 100MW. Assuming a klystron efficiency of 50%, this requires a wall plug power of 200MW.
- Cryogenic cooling power $\sim$ 100 MW (?).
- 100 MW of heat has to be extracted by cooling water. Some fraction of this power will be required to pump the water.

Power requirements are significant.

Accelerator Physics Challenges

- Combating TMCI

  The transverse impedance of the beam pipe alone is close to the threshold impedance. Other major contributions to the impedance from cavities, bellows, ... will likely increase the impedance to beyond threshold.

  Possible solutions

  - Coalescing bunches at top energy
  - Feedback system
  - Raising the injection energy
  - Increasing the bunch length and the synchrotron tune.
  - ...
- If a single ring machine, then long-range beam-beam interactions with many bunches will limit the beam stability. Will likely affect the required physical aperture.
- With many bunches, multi-bunch instabilities may be an issue.
- Avoiding synchro-betatron resonances e.g. those driven by dispersion in the cavities.
- The beam-beam limit may not increase with damping decrement as hoped for. In that case, achievable luminosities will be lower.
- At low energy (45 GeV), the beam current is high ($\sim$ 2 A) and the number of bunches is very large (about 47000). Operation in a single ring machine at these parameters will be extremely difficult if not impossible and will be challenging even in a two ring machine of this circumference.
- ...