Fermi National Accelerator Laboratory

FERMILAB-Conf-96/111

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V. Shiltsev

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

May 1996

To be presented at the *EPAC (European Particle Accelerator Conference),*
Sitges, Barcelona, Spain, July 10-14, 1996

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

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Beam Dynamic Issues in TESLA Damping Ring *

Vladimir SHILTSEV
FNAL †, M.S.345, P.O.Box 500, Batavia, IL 60510, USA

Abstract

In this paper we study general requirements on impedances of the linear collider TESLA damping ring design. Quantitative consideration is performed for 17-km long "dog-bone" ring. Beam dynamics in alternative options of 6.3 and 2.3-km long damping rings is briefly discussed.

1 INTRODUCTION

The TESLA linear collider design [1] intends to use damping rings (DRs) for great reduction of phase space volumes of the beams before injection in the main linac at the energy of 3.3 GeV. The positron beam is produced on a target with large emittance and the damping ring appears to be the only solution for the needed decrease of the emittance within the linac cycle time of T_c=200 ms, while a RF gun source to achieve the design emittance of the electron beam could be a possible alternative, which would allow to save one of two damping rings.

Large circumference of the ring is conditioned by injection/ejection. The TESLA design intends a bunch train duration of about 800 μs (or about 240 km length) in the main linac. The train of some 1100 bunches must be compressed in a storage ring and then expanded when extracted out of it. Thus, the injection and ejection of every bunch has to be done individually. If the kicker rise/fall time is τ, then the circumference of the ring is about $C[km] \simeq \tau[ns]/3$. The "dog-bone" proposal for the damping ring assumes ultimate conventional kickers with $\tau \sim 50$ ns, and therefore, $C \simeq 17$ km [2]. The "dog-bone" ring consists of two long (about 8 km each) straight sections which share the tunnel of the main linac and a pair of end-rings.

The RF frequency in the DR is chosen to be equal to f_{RF} = 433.33 MHz, that is one third of the TESLA linac RF frequency of 1.3 GHz. The heat dissipation in the walls of 30 normal conducting cavities is about 1.8 MW at design cavity shunt impedance of $4M\Omega$, cavity voltage is V_1=700 kV.

* Work partially supported by DESY(Hamburg)
† Operated by the Universities Research Association Inc., under contract with the U.S. Department of Energy

Table 1: Main Parameters of the TESLA Damping Ring

Energy	E	3.3	GeV
Circumference	C	17	km
Rev. frequency	f_0	17.65	kHz
Beam current	I_B	0.117	A
Cycle time	T_c	200	ms
No. of bunches	N_b	1116	
Particles/bunch	N_e	$3.6{\cdot}10^{10}$	
Energy spread	σ_E	$1{\cdot}10^{-3}$	
Bunch length	σ_s	$\simeq 1$	cm
Bunch spacing	τ_b	50.7	ns
Synchrotron tune	ν_s	0.074	
Betatron tune	$\nu_\perp$	$\simeq$40	
Mom.comp.factor	α	$2.7{\cdot}10^{-4}$	
Mom. acceptance	$\Delta p/p$	$1.4{\cdot}10^{-2}$	
Norm. emittances			
at injection	$\epsilon_x^0/\epsilon_y^0$	$10^4/10^4$	μm
at ejection	ϵ_x/ϵ_y	10/0.2	μm
Damping times	$\tau_s/\tau_{x,y}$	18/35	ms
Energy loss/turn	U_0	10.2	MeV
RF voltage	V_{RF}	20.4	MeV
RF frequency	f_{RF}	433.33	MHz
Wiggler field	B_0	1.5	T
Wiggler length	L_w	350	m

Natural beam energy spread of about $1.04 \cdot 10^{-3}$ is determined mostly by quantum fluctuations of synchrotron radiation in the 350 m long magnetic wiggler with piecewise constant magnetic field of 1.5 T which has to be installed in order to obtain 37 ms transverse radiative damping time.

Numerical estimations in further sections are made under conditions: 1) β-function is about 10 m in the wiggler sections, the arcs and the RF cavities; 2) $\beta \simeq 120$ m in the straight sections of the "dog-bone" and at the kickers; 3) total length of the arcs in the "dog-bone" ring is about 0.8 km; 4) the mean radius of the aluminum beam pipe is about 3 cm in the arcs, about 5 cm in the straight sections and about 1 cm (half aperture) in the wiggler.

2 SINGLE BUNCH EFFECTS

2.1 Longitudinal Impedance

The mean single bunch current in the TESLA DR is equal to $I_s = I_B/N_b = 0.1$ mA. The microwave longitudinal instability sets the first constraint on the effective broadband impedance (averaged with the bunch spectrum):

$$\left(\frac{Z}{n}\right)^{thr} = \frac{\sqrt{2\pi}\alpha(E/e)\sigma_E^2\sigma_s}{I_s R} = 86\, m\Omega. \qquad (1)$$

As the requirements on the impedance are rather tight, some special efforts must be done for "smoothing" the beam pipe (shielding of bellows, tapering of all shape transitions, screening of vacuum pumps and ports, etc.).

The impedance budget consideration gives following estimates of major sources of the impedance (in $m\Omega$) [3]:

RF cavities	$(1+i)\cdot 2.8$
Resistive wall	$(1-i)\cdot 5.1$
Bellows, BPMs, kickers, etc.	$-i \cdot 17.4$

Purely inductive impedance $-i\omega_0 L$ of about 17 $m\Omega$ does not lead to the microwave instability, but cause about 10%bunch lengthening due to distortion of the RF potential well.

Real part of impedance leads to energy losses of the beam. The estimate of the total longitudinal loss factor $k_l \approx 43\, V/pC$ (major contributors are RF cavities and resistive walls) gives the power deposited in the beam pipe by a train of N_b bunches $P = N_b k_l (eN_e)^2 f_0 \approx 30\, kW$.

2.2 Transverse Impedance

The transverse mode-coupling (TMC, or "strong head-tail") instability leads to fast beam break-up, and, therefore, sets strong constraint on transverse broad-band impedance $\mathtt{Im} < Z_\perp \beta_\perp >^{thr} = \frac{16\sqrt{\pi}(E/e)\sigma_s\nu_s}{3I_sR} \simeq 82\, M\Omega$ – here brackets $< .... >$ mean averaging with the beta-function at the locations of the impedance sources. Using the approximate relation between the longitudinal and transverse impedances $Z_\perp \simeq \frac{2R}{b^2}\left(\frac{Z}{n}\right)$, R is the mean radius of the ring, b is the vacuum chamber radius, then we estimate the major contributions to the $\mathtt{Im} < Z_\perp \beta_\perp >$ (in $M\Omega$):

RF Cavities	0.05
Resistive wall	1.9
Bellows, BPMs, kickers, etc.	7.4
Total:	≃9.3

Therefore, the TESLA DR design current is some 9 times less than the estimation on the TMC threshold.

3 MULTI-BUNCH EFFECTS

Long range wakefields in a storage ring cause different bunches to interact. For certain values of relative phase between bunches, the coupled-bunch motion can be unstable, that leads to the beam loss. The beam remains stable if damping times due to radiation (about 18 ms and 37 ms for longitudinal and transverse oscillations, respectively) or due to a feedback system are smaller than the instability growth times.

3.1 Longitudinal Instability

The resonant frequencies for the longitudinal case are $\omega_{pk} = \omega_0(pN_b + k + \nu_s)$. If the effective ring impedance $Z(\omega)$ is not zero at these frequencies, then the growth rate (increment) of longitudinal instability at the mode number $k = 0, 1, 2...N_b - 1$ is equal to

$$\frac{1}{\tau_\parallel^k} = \frac{\alpha I_B f_0}{2(E/e)\nu_s} \sum_{p=-\infty}^{+\infty} \frac{\omega_{pk}}{\omega_0} \cdot \mathtt{Re} Z(\omega_{pk}), \qquad (2)$$

here I_B is the total beam dc current.

Resistive Wall longitudinal instability growth rate was found several orders of magnitude less then the synchrotron radiation decrement.

Instability due to Accelerating Mode. In storage rings, the cavity tuning is usually set to compensate the reactive part of the beam loading and to minimize the required RF power. Without this detuning, large amount of the RF power is reflected from the cavity. The optimum detuning is 3.4 kHz for the "dog-bone" TESLA DR (or about 1/5 of the revolution frequency). This shift leads to unequal impedances of the upper and the lower synchrotron sidebands, that gives the instability increment of about 36 s^{-1} for the design parameters of I_B=0.117 A, $(R/Q) = 100$ Ohms, $R_s = 4$ MΩ, $Q_L = 5000$, $V_1 = 0.7$ MV, other values – accordingly to the Table 1.

HOMs in RF Cavities Growth time of instability due to higher order modes in the RF cavities (at frequencies 0.5–2 GHz, characteristic $(R/Q) \approx 60\,\Omega$) can be estimated as $\frac{1}{\tau_\parallel}\, [s^{-1}] = \frac{1.35 N_{cav}}{C^2[km]} Q_L$. Recent R&D on HOMs damping allows us to hope that the damped value of HOM's quality factors can be as small as $Q_L \simeq 100$. With 30 cavities, the expected growth rate in the TESLA DR is $14\, s^{-1}$.

Therefore, the total increment of longitudinal multibunch instabilities is about $50 s^{-1}$, that is somewhat less than the radiative damping decrement of 55 s^{-1}.

3.2 Transverse Instability

The resonant frequencies in transverse case are $\omega_{pk} = \omega_0(pN_b + k + \nu_\perp)$ where $\nu_\perp$ is the betatron tune (vertical or horizontal). Increment of the transverse coupled-bunch instability in the TESLA DR can be estimated as

$$\frac{1}{\tau_\perp^k} = \frac{I_B f_0}{(E/e)} \sum_{p=-\infty}^{+\infty} \beta_\perp \mathtt{Re} Z_\perp(\omega_{pk}) \qquad (3)$$

Resistive Wall impedance of the Al chamber of the ring is $\beta \mathtt{Re} Z_\perp[M\Omega] \approx \frac{800}{\sqrt{\Delta\nu_\perp}}$ (with about 90 % contribution from the straight sections). With fractal part of the transverse tune of $\Delta\nu_\perp = 0.17$, we get $\frac{1}{\tau_\perp} \approx 1200\ s^{-1}$ for the "dog-bone" ring.

HOMs We expect to have the damped transverse impedance of the HOMs of the order of $Z_\perp \simeq 4 \cdot Q_L$ kΩ/m, and, therefore, with $Q_L \sim 100$ the increment of transverse oscillations to be about 80 s^{-1} ($\beta_\perp \sim 10$ m at each of 30 the RF cavities).

Slow Photoelectrons Instability is caused by secondary electrons which are born on the surface of the vacuum chamber under the synchrotron radiation bombardment. With use of theory [4]and the KEK Photon Factory data we calculated the growth rate of 720 s^{-1} in the TESLA DR [3]. Nevertheless the issue of this instability is unclear because it does not take place in high-current multibunch positron rings of PETRA and HERA-e.

4 DISCUSSION

Two other concepts of the TESLA DR are based on some novel approaches to solve injection/ejection issues (see Table 2). Under assumption of an injection/ejection scheme with several RF deflectors the ring with circumference of about 6.3 km (DR#2 in Table 2) in the existing HERA tunnel was discussed in Ref.[5]. Another alternative damping ring option intends to use fast traveling wave kicker with $\tau \simeq$7 ns (R&D of such a kicker is now under way in DESY). Consequently, an option for a low-cost damping ring in the existing tunnel of the PETRA ring with $C \approx 2.3$ km (DR#3) has been considered in Ref.[3].

In the Table 2 we compare several circumference-dependent parameters of these options with the "dog-bone" ring – DR#1 (the parameter notations are the same as in Table 1, $(Z/n)^{thr}$ denotes threshold value of broadband longitudinal impedance, $< Z_\perp \beta >^{thr}$ is threshold impedance of TMC instability, $1/\tau_{s,\perp}$ is for multibunch instabilities growth rates. Other parameters are as in Table 1.

Comparing the three options, one can see that hopefully single bunch collective effects will not affect performances of all three DRs. The estimation of the inductive impedance allows to predict for all options some 10% bunch lengthening due to potential RF well distortion which is still acceptable.

Table 2: Options of the TESLA Damping Ring

	DR#1	DR#2	DR#3
E, GeV	3.3	4.0	3.3
C, km	17	6.3	2.3
τ_b, ns	50	19	7
U_0. MeV	10.2	4.6	1.4
I_B, A	0.117	0.31	0.86
ν_s	.074	0.042	0.022
$\alpha \times 10^4$	2.7	3.3	6.1
$(\frac{\Delta p}{p})_{max}$	0.014	0.022	0.019
V_{RF}, MV	20.4	15	5.5
N_{cav}	30	20	8
$(Z/n)^{thr}$, Ω	0.09	0.14	0.2
$< Z_\perp \beta >^{thr}, M\Omega$	82	41	18
$1/\tau_s$, s^{-1}	50	540	4000
$1/\tau_\perp$, s^{-1}	1300	~1000	2000

The growth time of longitudinal multibunch instability (driven mostly by main accelerating mode of the detuned RF system) is much smaller than the damping time in the case of DR#2 and DR#3 due to large mean current. To stabilize this instability one should either use superconducting RF cavities or introduce a local RF cavity feedback which can effectively counteract the effect.

To cancel transverse instability due to resistive wall and HOMs (even damped down to $Q \sim 100$), a bunch-by-bunch feedback system with about 0.5–1 ms damping time will be necessary for all the options.

Larger bunch spacing in the longer ring is beneficial from the point of view of the slow photoelectron instability in the positron ring or ion-induced instability in the electron ring.

I acknowledge valuable comments by R.Brinkmann.

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