Fermi National Accelerator Laboratory

FN-519

Main Injector - Coherent Instability Limits

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September 1989

Operated by Universities Research Association, Inc., under contract with the United States Department of Energy

MAIN INJECTOR – COHERENT INSTABILITY LIMITS

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ABSTRACT

This note summarizes briefly intensity limits of the proposed Main Injector set by various coherent instabilities. The study of effective impedances constructed for particular longitudinal and transverse beam spectra corresponding to specific instabilities allows us to select potentially offending instabilities relevant to specific operational scenarios. Here we consider beam injection and adiabatic debunching for slow extraction. Finally, a numerical study of the intensity thresholds (or the characteristic growth-times) is carried out for a set of tentatively selected instabilities.

OPERATIONAL MODES AND INSTABILITIES

Intensity thresholds of many coherent instabilities scale linearly with energy, due to increasing kinematic "stiffness" of the beam at higher energies. Therefore, we will study beam stability at injection. The beam at injection to the Main Injector is characterized by the following parameters:

$$E = 8.9 \text{ GeV} \qquad N = 8\times10^{10} \text{ ppb}$$
$$\varepsilon_N = 4\pi\times10^{-6} \text{ m rad (rms)} \qquad \varepsilon = 0.5 \text{ eV sec}$$

Another potentially unstable manipulation is an adiabatic debunching for slow extraction. The longitudinal phase-space of the beam is uniformly spread in the azimuthal direction, which yields extremely small values of $\Delta p/p$. This in turn, may substantially decrease the microwave instability threshold. Some parameters relevant to the adiabatic debunching are collected below

$$E = 150 \text{ GeV} \qquad N = 8\times10^{10} \text{ ppb}$$
$$\Delta p/p = 2\times10^{-4}$$

The list of potentially dangerous instabilities was tentatively selected on the basis of their occurrences in presently operating high intensity synchrotrons. They are listed below together with relevant operational modes:

- microwave instability (L) – injection, adiabatic debunching
- slow head-tail instability (T) – injection
- resistive wall coupled bunch instability (T) – injection
- coupled bunch instability (L) – a whole ramping cycle

Here.(L) stands for longitudinal and (T) for transverse instability respectively

COUPLING IMPEDANCE

Here we present a summary of the longitudinal and transverse coupling impedance of the Main Injector. We tentatively identified five dominant sources of the coupling impedance. These potentially offending vacuum structures are listed as follows:

(a) bellows

(b) kicker magnets

(c) beam position monitors

(d) resistive wall and Lambertson magnet laminations

(e) coherent space-charge impedance

All five contributions to both the longitudinal and transverse impedance are summarized by the net impedances illustrated in Fig.1. One can notice that the longitudinal impedance is virtually dominated by the broad-band contribution (bellows). Similarly, bellows contribute substantially to the broad-band part of the transverse impedance, together with the kicker magnets, which significantly raise the reactive component of the impedance spectrum. Finally, the low frequency region of the transverse impedance is dominated by the singular resistive wall contribution.

INSTABILITY THRESHOLDS

1. Longitudinal Stability

♦ The *microwave instability* at injection (8.9 GeV) is virtually dominated by the space-charge effects (capacitive longitudinal coupling impedance dominates the broad-band contribution). Our calculation based on the generalized Boussard criterion shows that the instability is quite safe below intensities of 10^{12} ppb. Going to higher energies the broad-band impedance induced by the bellows (TBCI simulation) dominates and the space charge contribution becomes negligible. Assuming small $\Delta p/p$ region ($\Delta p/p = 2\times10^{-4}$) specific for the adiabatic debunching process (uniform azimuthal distribution around the ring) the instability sets the intensity threshold at at 8×10^{11} ppb. The above results are illustrated in Fig.2.

♦ The *coupled bunch instability* can possibly be induced by high-Q parasitic resonances of the rf cavities, with Q's high enough to induce long lasting wake fields, which would couple synchrotron motion of individual bunches. Assuming exaggerated values of $Q \sim 10^3$ and shunt impedance $Z_s \sim 10^6$ Ohm a simple calculation shows that the instability does not develop for intensities below 10^{11} ppb. This instability should be considered safe providing that the beam is being ramped fast (the parasitic resonance is crossed fast on the scale of one synchrotron period), so that the parasitic resonance sweeps fast enough through the given mode to keep the integrated growth-rate below its threshold value.

♦ The *longitudinal emittance* of an intense proton beam extracted from the Main Injector may be limited by a phase-space dilution effects caused by the possible presence of a single coupled bunch mode driven by a sharp parasitic resonance of the rf cavities. A longitudinal phase-space simulation (ESME) of the net emittance blow-up due to a single coupled bunch mode is carried out for various beam intensities (6×10^9 ppb, 6×10^{10} ppb, 4×10^{11} ppb and 6×10^{11} ppb). The resulting plot, Fig.3, (final emittance vs bunch intensity) reveals exponential emittance growth with intensity.

2. Transverse Stability

- The *resistive wall instability* driven by the wake fields due to the Lambertson magnet lamination and resistive vacuum chamber walls dominates the coherent betatron motion in the low frequency region. For the fixed target mode (injection of 8×10^{10} ppb @ 8.9 GeV) the characteristic growth-time of the instability is $\tau = 10\times10^{-3}$ sec. The injection energy is low enough so that the incoherent space-charge force produces enough betatron tune spread (Laslett effect) to suppress the instability through Landau damping. Above the cross over energy some other decohering mechanism is required. This last condition is relevant to the collider mode when 5 consecutive bunches of intensity 8×10^{10} ppb are being coalesced @ 150 GeV. We showed that the resistive wall coupling results in coherent betatron motion of consecutive bunches with the characteristic growth-time of $\tau = 30\times10^{-3}$ sec. Simple stability diagram calculation shows that the incoherent space-charge tune spread itself is not able to suppress the instability. However the same formalism reveals that some additional tune spread necessary to stabilize the beam can be easily achieved by applying a small octupole field component. In terms of the normalized octupole strength, S_{oct}, defined as follows

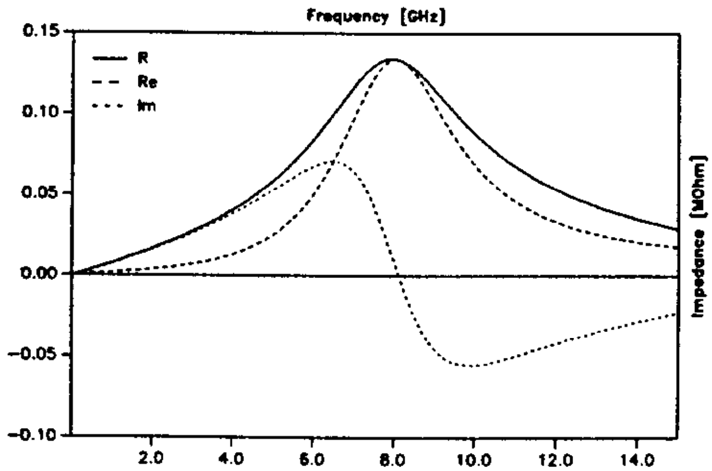
$$S_{oct} = \frac{1}{B\rho} B_o \int b_3 \, ds \ ,$$

values of $S_{oct} \sim 10^{-4}$ are sufficient to suppress the instability. The above results are summarized in Fig.4.

- The *slow head-tail instability* driven by the wake fields induced by the kicker magnets dominates the coherent betatron motion in the high frequency region. The transverse impedance (previously calculated) allows us for a simple estimate of the characteristic instability growth-time for various modes as a function of chromaticity (Sacherer's model). For the intensity of 8×10^{10} ppb the offending $\ell = 3$ mode is characterized by a very short growth-time $\tau = 30\times10^{-3}$ sec. Further study will show whether the octupole field component provides enough betatron tune spread to suppress the instability through Landau damping (using more realistic models e.g the hollow beam "air bag" model*). Illustration of the above results is presented in Fig.5.

* F. Sacherer, CERN/SI-BR/72-5 (1972), unpublished

A) LONGITUDINAL IMPEDANCE



B) TRANSVERSE IMPEDANCE

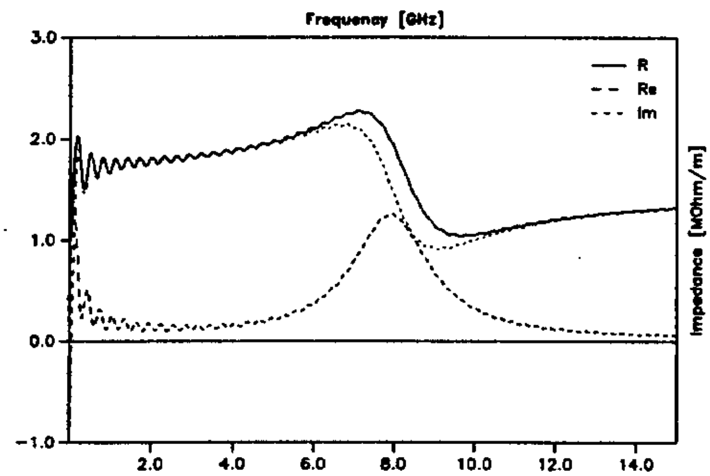


Fig.1

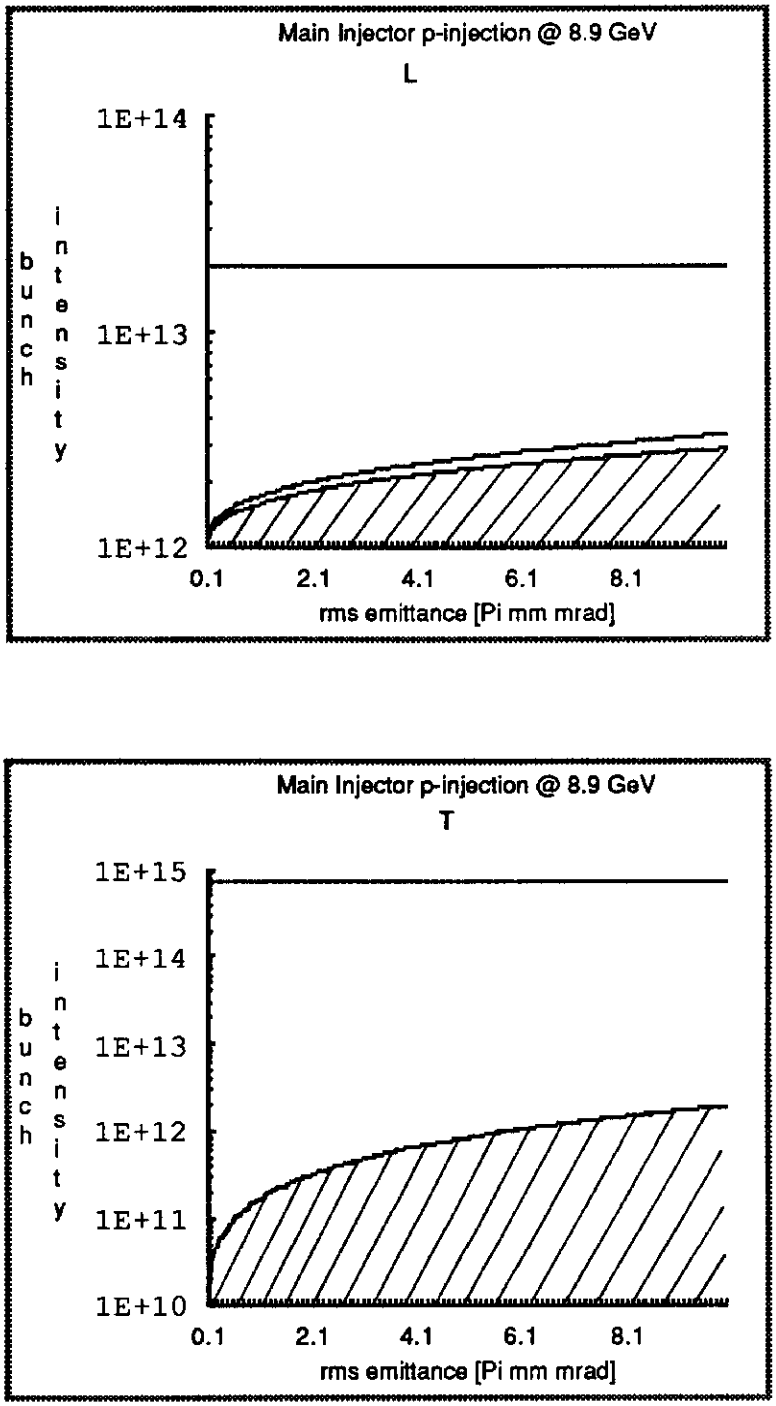

Main Injector p-injection @ 8.9 GeV
L
1E+14
1E+13
1E+12
bunch intensity
0.1
2.1
4.1
6.1
8.1
rms emittance [Pi mm mrad]
Main Injector p-injection @ 8.9 GeV
T
1E+15
1E+14
1E+13
1E+12
1E+11
1E+10
bunch intensity
0.1
2.1
4.1
6.1
8.1
rms emittance [Pi mm mrad]

Fig. 2

Emittance Blow-up - Coupled Bunch Instability

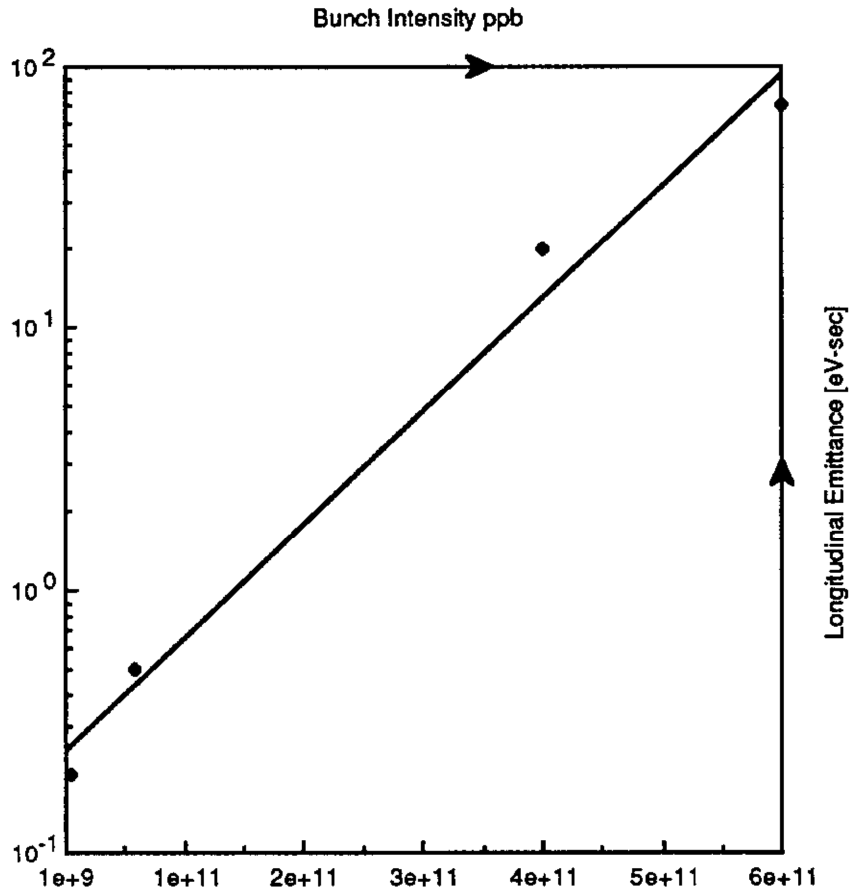


Fig.3

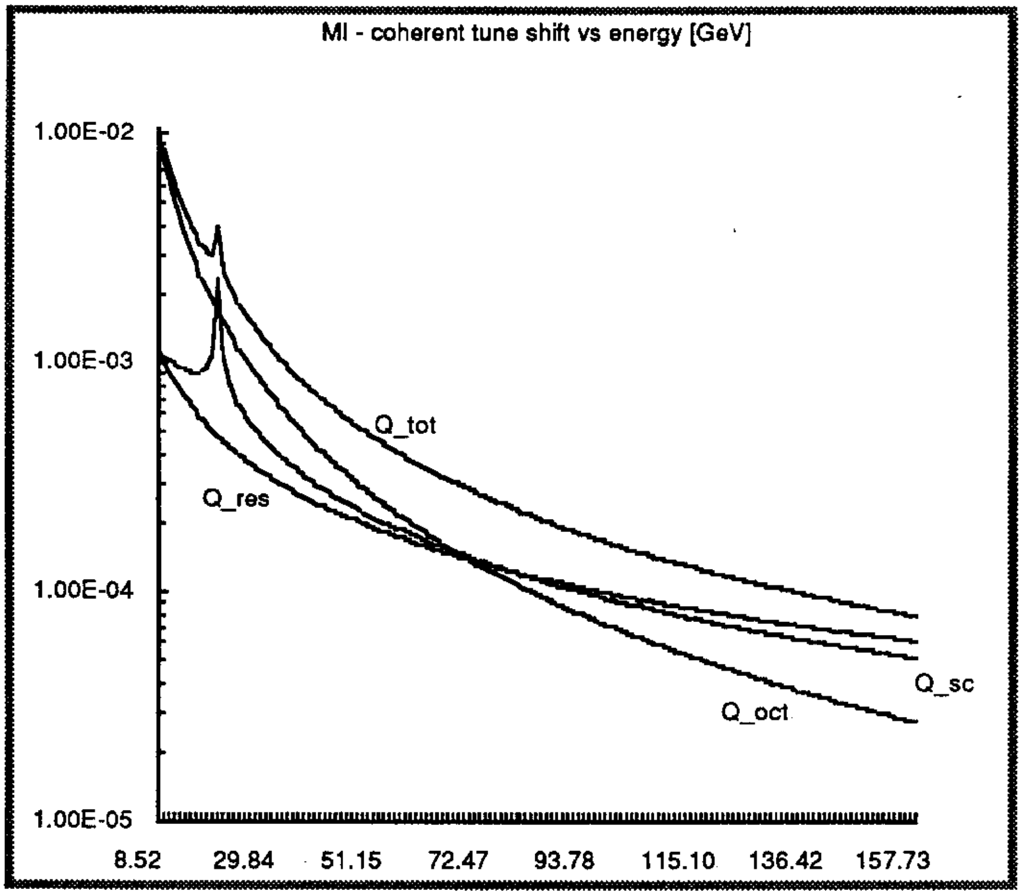

MI - coherent tune shift vs energy [GeV]
1.00E-02
1.00E-03
1.00E-04
1.00E-05
Q_tot
Q_res
Q_sc
Q_oct
8.52
29.84
51.15
72.47
93.78
115.10
136.42
157.73

Fig.4

Main Injector (p-Injection @ 8.9 GeV) N = 8.E10 ppb

ε = 0.5 eV-sec

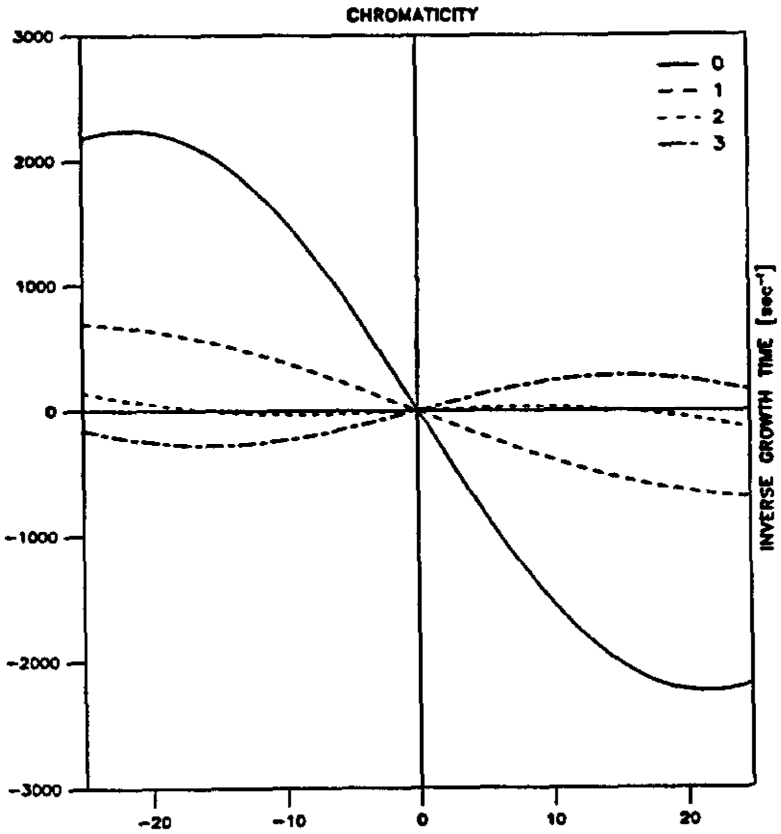


Fig.5