

Fermilab

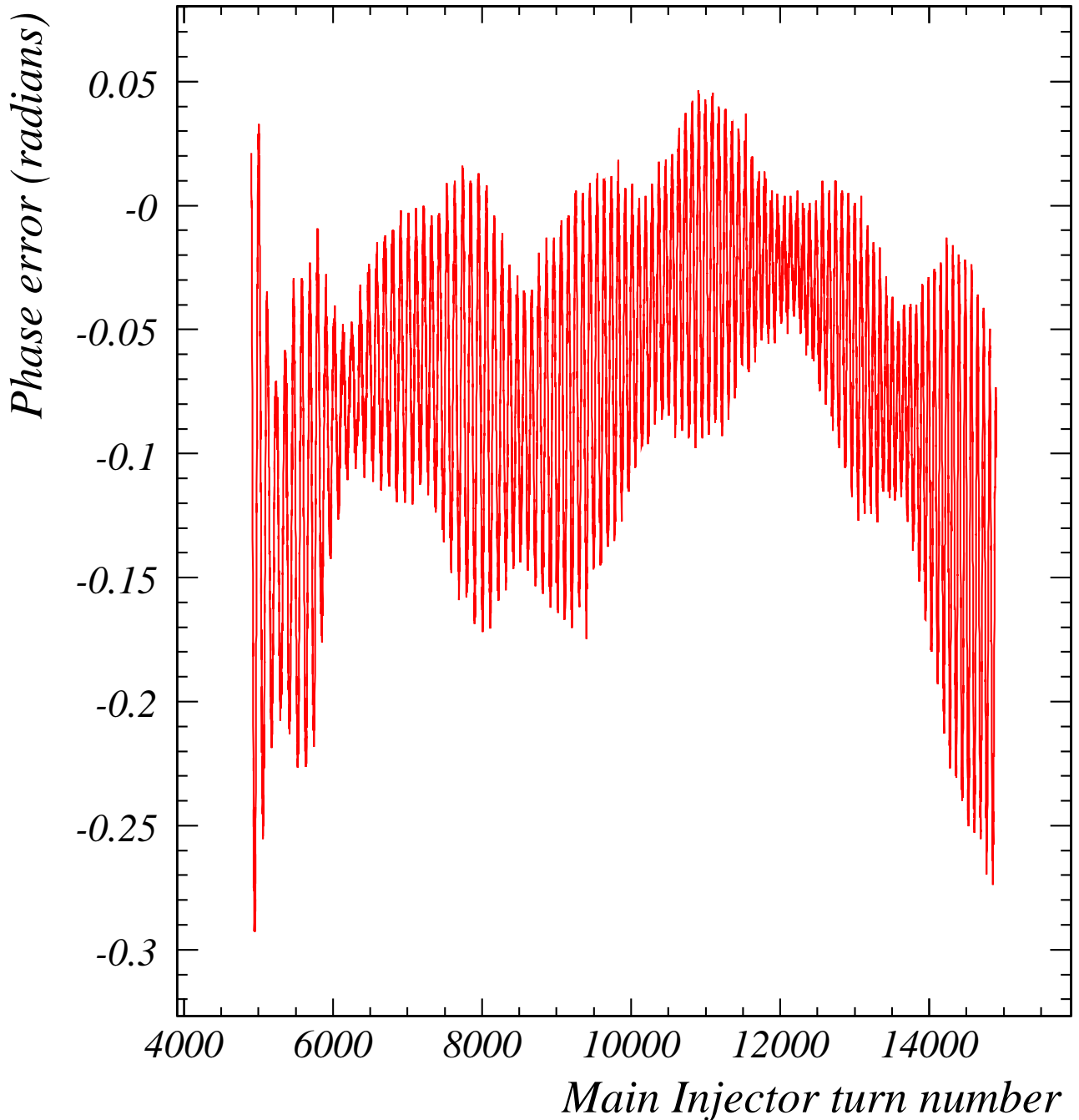
J. MacLachlan, Fermilab, AD/PS

Thursday 21 Oct. 04

Charge-Dependent Increase in Coherence of Synchrotron Oscillation at Injection

- Observation in Fermilab Main Injector (FMI)
- Coherence predicted by single particle EOM
- Coherence at or near nominal FMI parameters
- Qualitative understanding
- Expected performance of 2 kV FMI longitudinal damper
- Coherence maintained at very high intensity

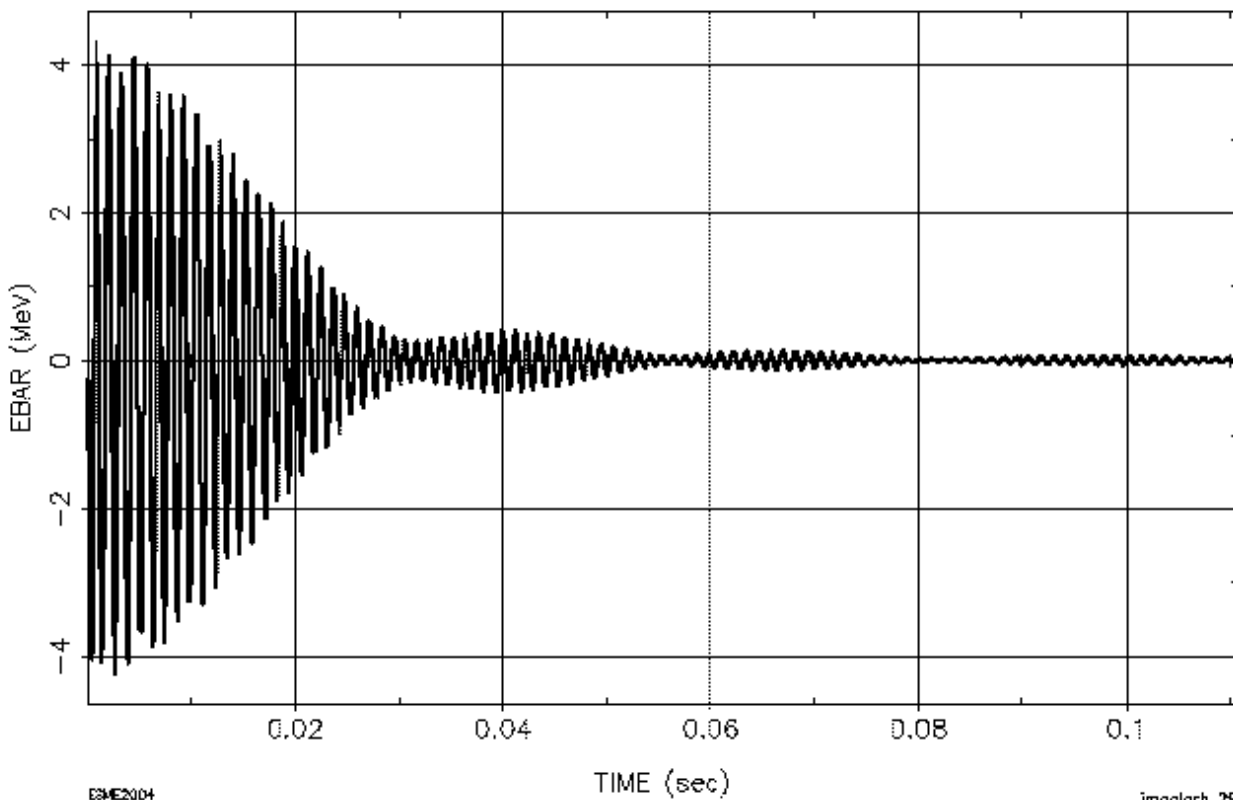
Longitudinal dampers off



Single bunch phase seen in damper error signal. (Thanks to Phil Adamson) Ignore wander arising from radial position loop. The amplitude is generally $\pm \sim 10^\circ$ of 53 MHz (the rf frequency) phase.

Expectations from Single Particle EOM

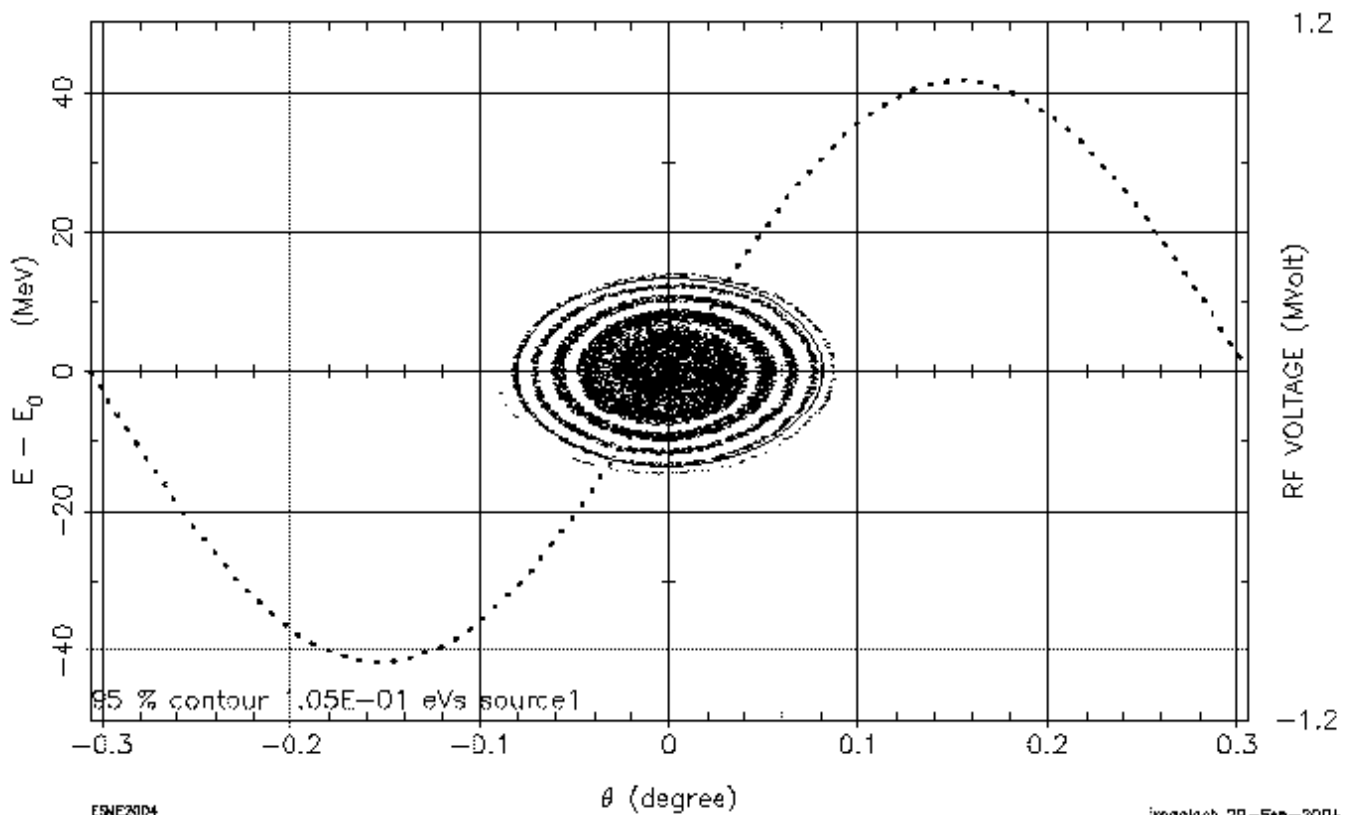
- filamenting of bunch depends on nonlinearity of potential
- the larger the injection error, the larger the nonlinearity
- the larger the bunch, the greater the spread in synchrotron frequencies
- bunch should eventually fill centered contour passing through extreme action of initial bunch



E3ME2004

jmaclach 29-Sep-2004 10:03

Phase of bunch centroid during 111 ms after injection according to single particle EOM. The 0.07 eVs bunch was injected into the FMI with a 15° phase error.



The phase space distribution of the bunch 111 ms after injection according to single particle EOM. The 0.07 eVs bunch was injected into the FMI with a 15° phase error.

Accelerator and beam parameters for injection into the FMI

Parameter	Symbol	Value	Units
injection energy (total)	E_s	8938	MeV
momentum aperture		$\approx \pm 8 \cdot 10^{-3}$	
longitudinal emittance	ϵ_ℓ	0.07	eVs
max. phase error	$\Delta\phi$	30	degree
max. kicker voltage	V_d	2	kV
circulation period	τ	11.14	μs
synchrotron period	τ_s	1.166	ms
slip factor	η	-0.008616	
rf voltage	V_{rf}	1	MV
rf frequency	f_{rf}	52.785	MHz
rf harmonic number	h	588	

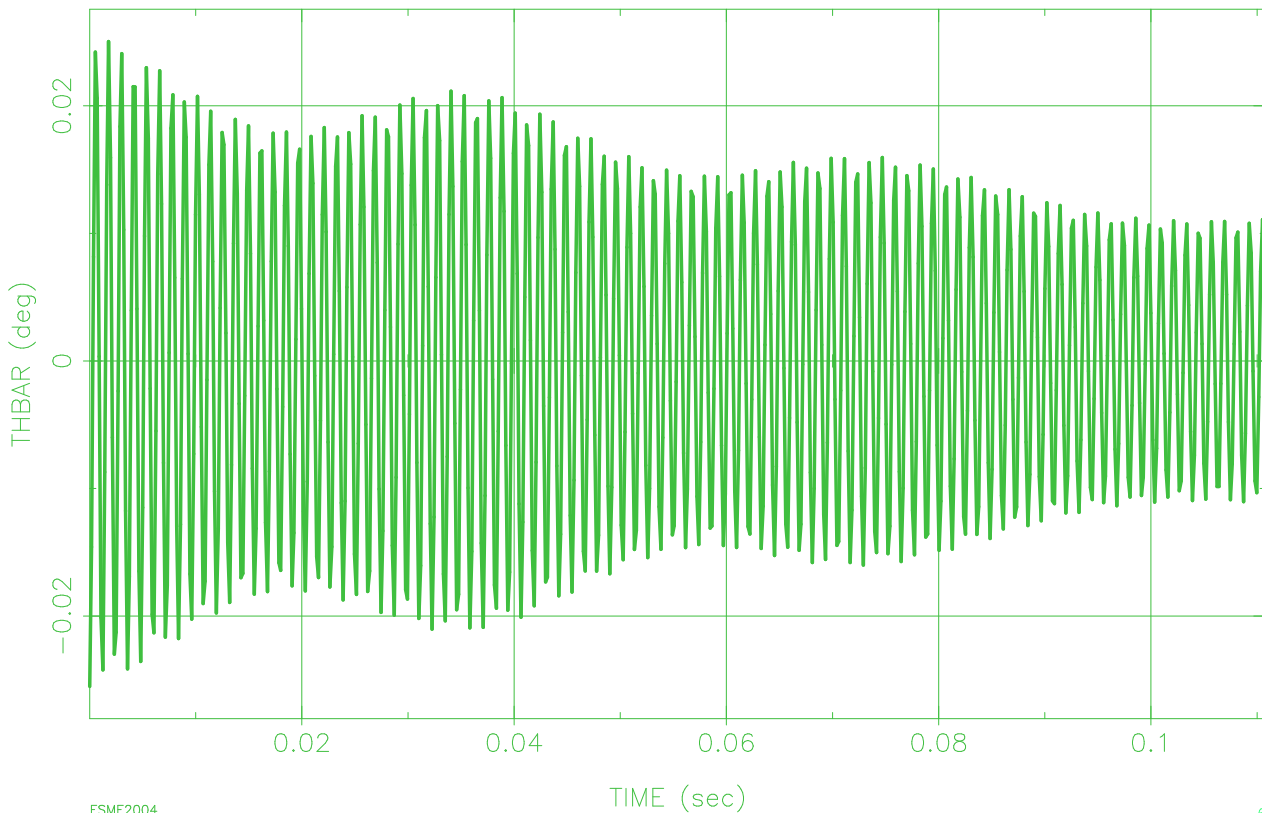
Coherence At or Near Nominal FMI Parameters

- First refinement to single particle EOM is to incorporate bunch self field and perfectly conducting vacuum chamber.
 - well known & understood
 - rather straightforward
 - sufficient to establish consistency with observation
- Experimented with other known (or expected) sources of coupling impedance.
 - small quantitative effects found
 - Perfectly conducting wall is basic cause of persistent coherence observed.
- Bunch charge in normal operating range is helpful in preserving emittance of bunches injected off synchronous energy and/or phase.
- 2 kV of damper voltage are not sufficient to remove 15° error in 111 ms. Following model results are for 8 kV (still insufficient but close).
- The longitudinal emittance is well preserved.

Following are two so called animations which cover 111 ms of injection oscillation without damping for a single bunch using parameters of the preceding table *except that* the first is according to the single particle EOM, *i. e.*, no self field, while the second is calculated for a normal $6 \cdot 10^{10}$ proton charges.

What a difference a little detail makes!

-15 deg offset, Q=6E10, 8 kV damping
THBAR VS TIME

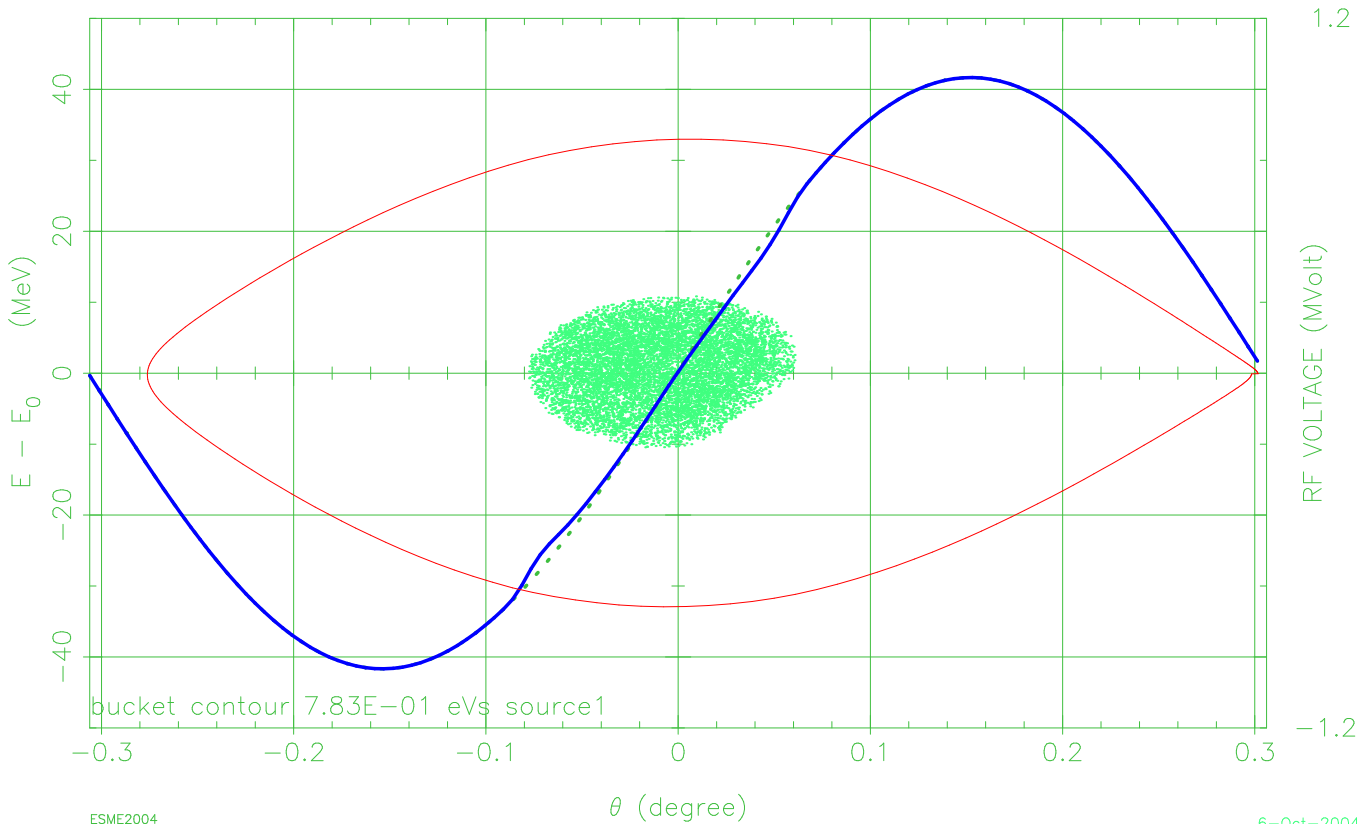


The phase of the centroid of a bunch of $6 \cdot 10^{10}$ protons during 111 ms after injection. The 0.07 eVs bunch was injected into the FMI with a 15° phase error. The oscillation was damped with 8 kV on the broadband kicker.

-15 deg offset, Q=6E10, 8 kV damping

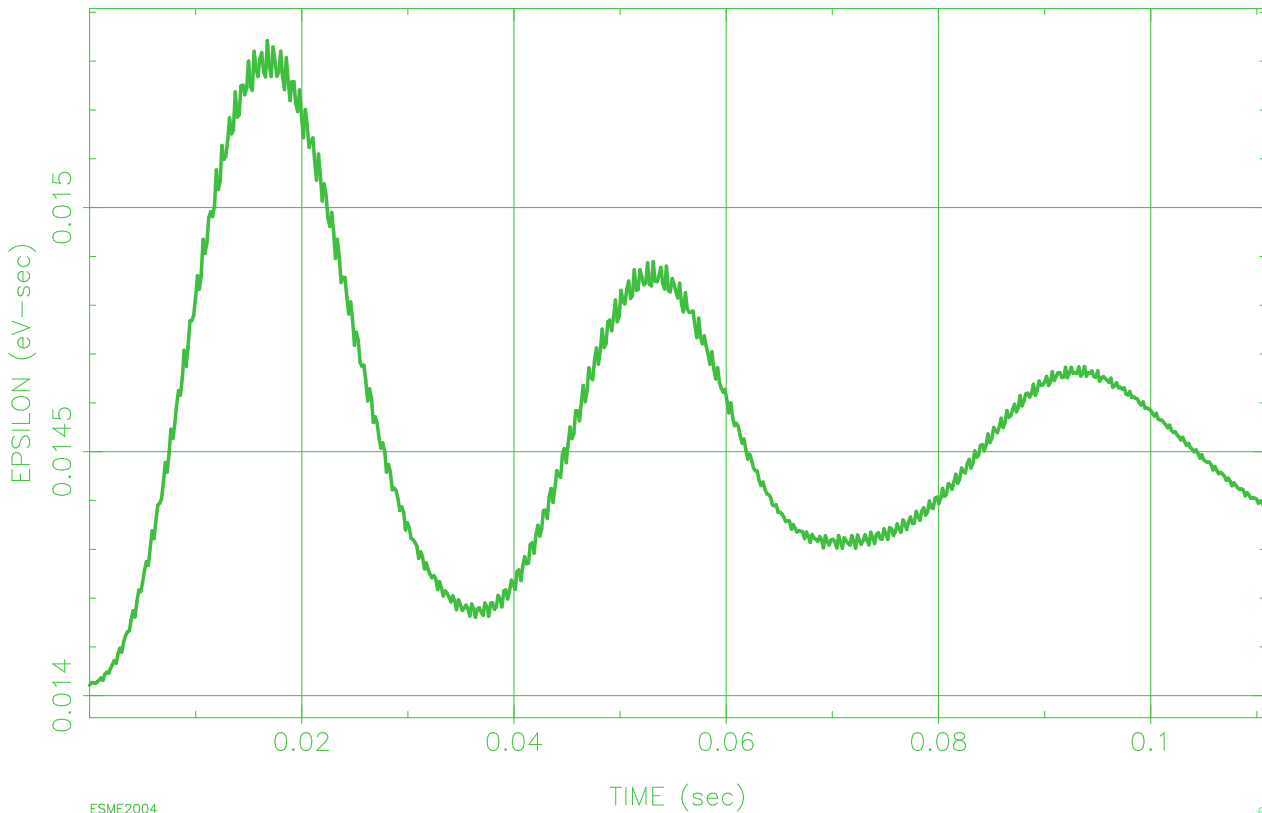
Iter 9965 1.110E-01 sec

H_B (MeV)	S_B (eV s)	E_S (MeV)	h	V (MV)	ψ (deg)
3.2949E+01	7.8268E-01	8.9382E+03	588	1.000E+00	4.584E-01
ν_S (turn ⁻¹)	pdot (MeV s ⁻¹)	η			
9.5507E-03	7.2799E+02	-8.6165E-03			
τ (s)	S_b (eV s)	N			
1.1140E-05	1.4390E-02	640000			



The phase space distribution of the bunch of $6 \cdot 10^{10}$ protons 111 ms after injection. The 0.07 eVs bunch was injected into the FMI with a 15° phase error. The oscillation was damped with 8 kV on the broadband kicker.

-15 deg offset, Q=6E10, 8 kV damping
EPSILON VS TIME



The statistical (rms) emittance of the bunch of $6 \cdot 10^{10}$ protons during 111 ms after injection. The 0.07 eVs bunch was injected into the FMI with a 15° phase error. The oscillation was damped with 8 kV on the broadband kicker.

Qualitative Understanding

- The tail of bunch contributes a steep positive gradient to total potential.
- Steepened potential must exist over sufficient phase extent to contain bunch.
- \implies Since bunch oscillates (practically) without change of form, collective force MUST serve to locally linearize the total potential.
- If bunch charge is too weak, oscillation carries tail particles onto the nonlinear rf potential and smearing occurs.
- Satisfactory analysis will incorporate, at least, emittance, bunch charge, magnitude of injection error.
- Phenomenon much like that described by Blaskiewicz [PRST-AB 7 044402 (2004)], but analysis in reference not entirely apposite.

Expected Performance of the 2 kV FMI Longitudinal Damper*

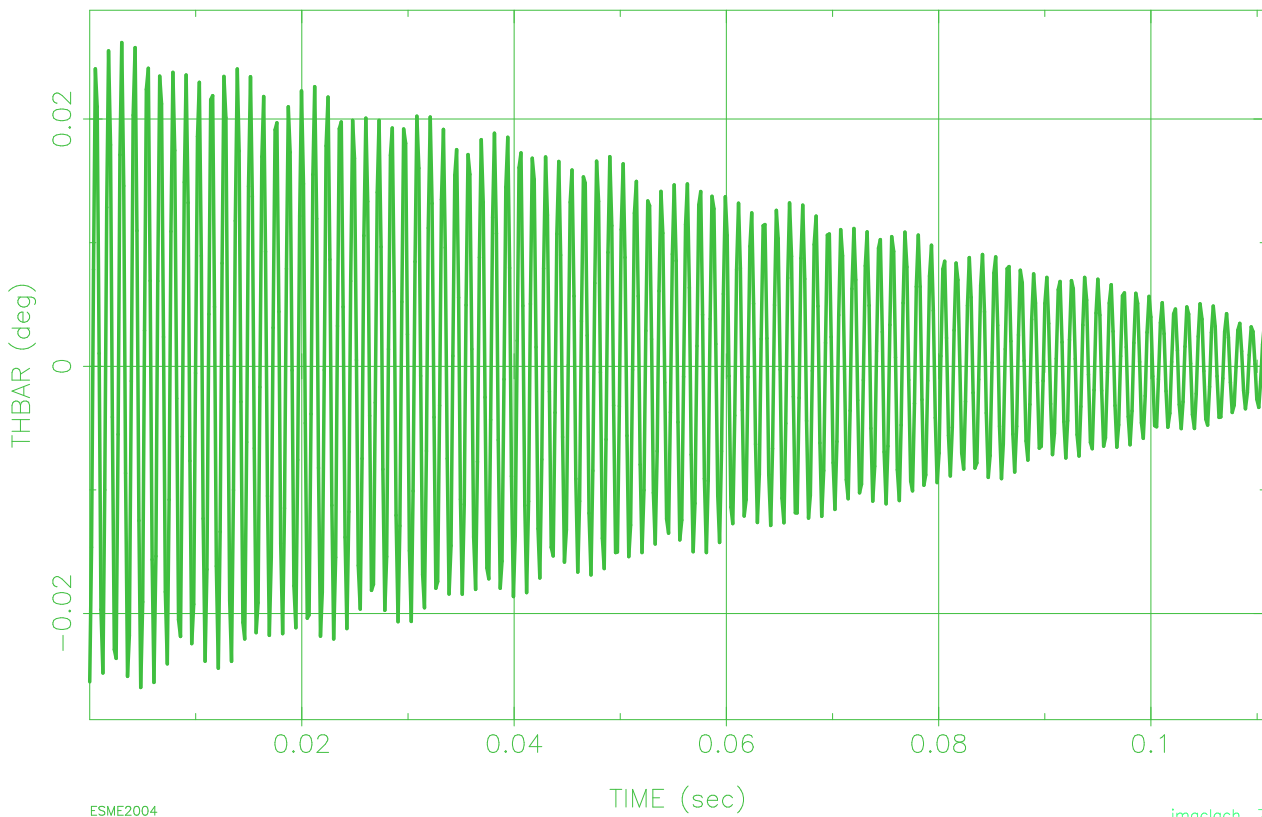
* G. William Foster *et al.*, US Accelerator Conf. PAC03, <http://accelconf.web.cern.ch/accelconf/p03/PAPERS/TOPD003.PDF>

- 2 kV is not sufficient for $> 4^\circ$ injection phase error because of time allowable, not because of loss of coherent error signal.
- About 8 kV could be OK; that much is within reason.
- The bunch-to-bunch waveform on the kicker is practically arbitrary because of the extremely broadband rf system.
- An upper limit on damping time is set by transition time because the focusing from self field fails above transition.
- Although not explored in detail, 10^4 turns (0.111 s) seems a good operational allowance for damping, because transition occurs at about 0.2 s.

Coherence Maintained at Very High Intensity

- Generally beam current complicates beam handling.
- For correction of errors in synchronous injection, bunch charge reduces the strength required of longitudinal kickers by maintaining emittance during a slow correction.
- The self-focusing effects of bunch charge are useful to intensity far above where negative effects of beam current dominate in other respects.

-15 deg offset, Q=6E11, 8 kV damping
THBAR VS TIME

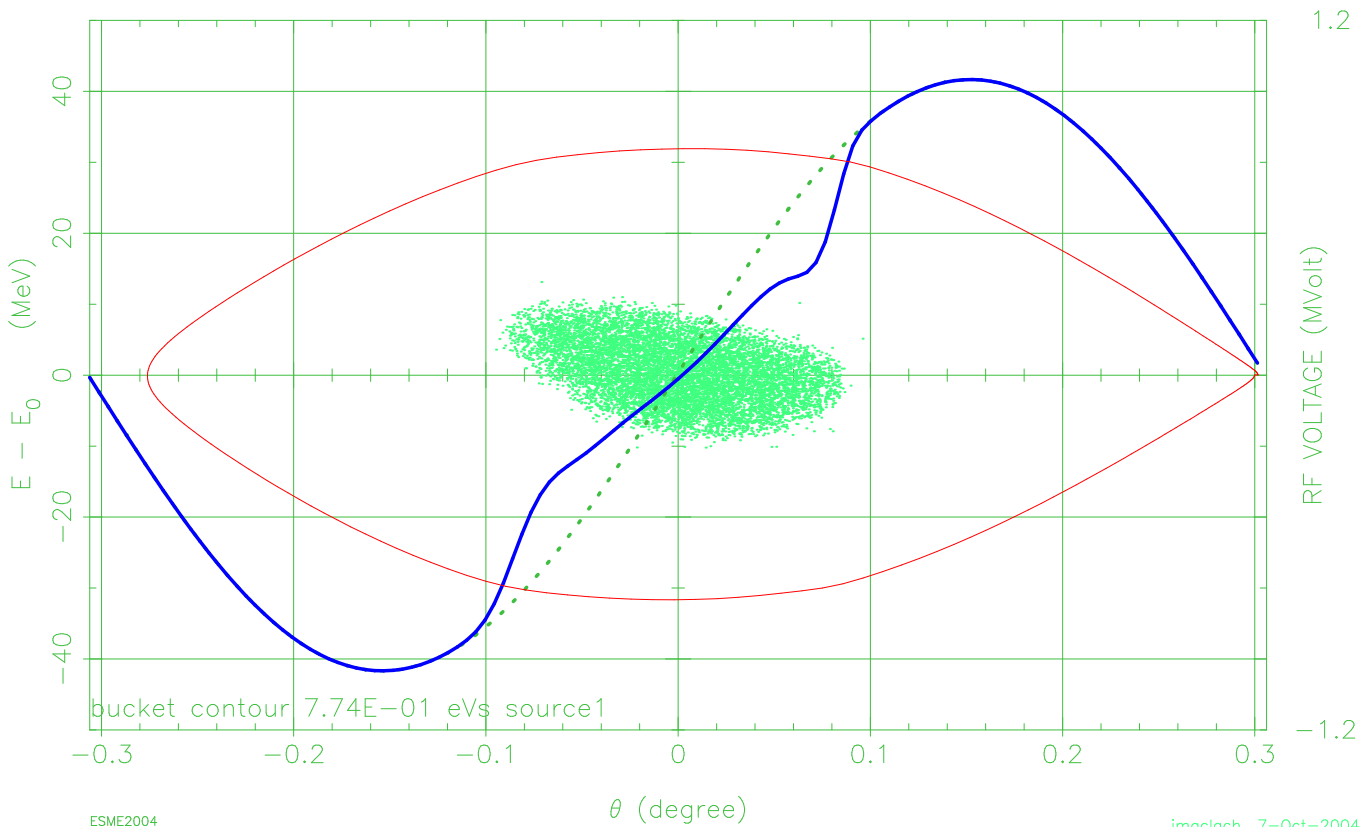


Phase of bunch centroid of a 0.07 eVs bunch of $6 \cdot 10^{11}$ protons during 111 ms after injection into the FMI with 8 kV of longitudinal damping

-15 deg offset, Q=6E11, 8 kV damping

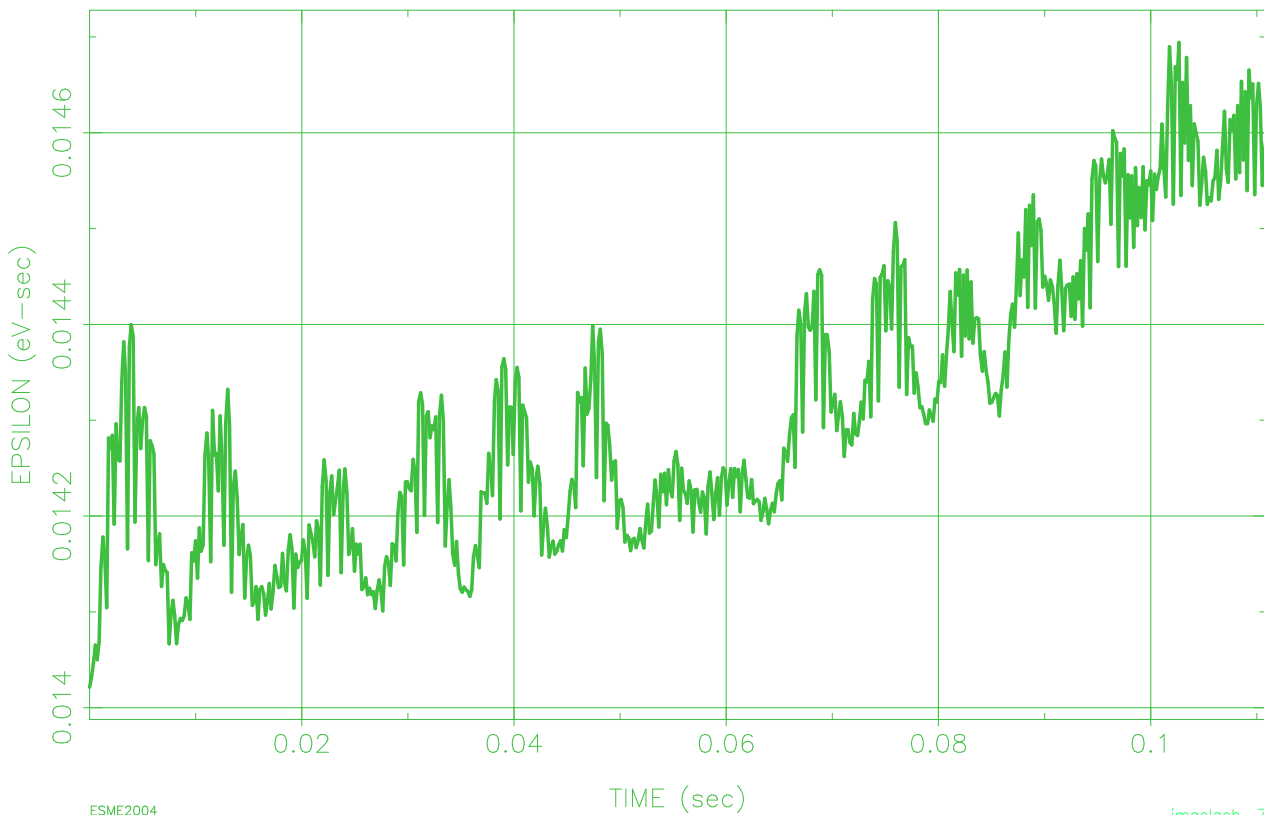
Iter 9965 1.110E-01 sec

H_B (MeV)	S_B (eV s)	E_S (MeV)	h	V (MV)	ψ (deg)
3.1788E+01	7.7433E-01	8.9383E+03	588	1.000E+00	4.584E-01
ν_S (turn ⁻¹)	pdot (MeV s ⁻¹)	η			
9.5505E-03	7.8413E+02	-8.6162E-03			
τ (s)	S_b (eV s)	N			
1.1140E-05	1.4618E-02	640000			



Phase space distribution of a 0.07 eVs bunch of $6 \cdot 10^{11}$ protons 111 ms after injection into the FMI with 8 kV of longitudinal damping

-15 deg offset, Q=6E11, 8 kV damping
EPSILON VS TIME



ESME2004

jmaclach 7-Oct-2004 14:34

The statistical (rms) emittance of a 0.07 eVs bunch of $6 \cdot 10^{11}$ protons during 111 ms after injection into the FMI with 8 kV of longitudinal damping

Comments or Conclusions

- Most of what has been presented can be described in terms of potential well distortion without further dynamics understanding.
- The most interesting feature dynamically seems to be the self field induced local linearization of the total potential.
- Analysis in the spirit of the initial part of the Blaskiewicz paper is likely to offer some fundamental grounding.
- In some contexts the phenomenon is too important practically to wait upon a satisfying analytical treatment before being included in operational or design considerations.