Fourier series damping ring kicker for TESLA

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Introduction

Linac beam (TESLA TDR):
• 2820 bunches, 337 nsec spacing (~300 kilometers)
• Cool an entire pulse in the damping rings before linac injection

Damping ring beam (TESLA TDR):
• 2820 bunches, ~20 nsec spacing (~17 kilometers)
• Eject every $n^{th}$ bunch into linac (leave adjacent bunches undisturbed)

Kicker speed determines minimum damping ring circumference.

We are investigating a “Fourier series kicker”: use a series of rf cavities to create a kicking function with periodic zeroes and an occasional spike. Perhaps closer bunches/smaller damping ring will be possible?
Participants

This project is part of the US university-based Linear Collider R&D effort (LCRD/UCLC)

**Fermilab**
- Leo Bellantoni
- David Finley
- Chris Jensen
- George Krafczyk
- Shekhar Mishra
- François Ostiguy
- Vladimir Shiltsev

**University of Illinois**
- Guy Bresler
- Keri Dixon
- George Gollin
- Mike Haney
- Tom Junk

**Cornell University**
- Gerry Dugan
- Joe Rogers
- Dave Rubin
TESLA damping ring kicker à la TDR

TDR design: bunch “collides” with electromagnetic pulses traveling in the opposite direction inside a series of traveling wave structures. Hard to turn on/off fast enough.

Fast kicker specs (à la TDR):
- $\int Bdl = 100$ Gauss-meter $= 3$ MeV/c (= 30 MeV/m $\times$ 10 cm)
- stability/ripple/precision $\sim .07$ Gauss-meter $= 0.07\%$
A different idea: “Fourier series kicker”

Kicker would be a series of $N$ “rf cavities” oscillating at harmonics of the linac bunch frequency $1/(337 \text{ nsec}) \approx 3 \text{ MHz}$:

$$p_T = A \left[ \sum_{j=0}^{j=N_{\text{cavities}}-1} A_j \cos \left[ (\omega_{\text{high}} + j\omega_{\text{low}}) t \right] \right]; \quad \omega_{\text{low}} = \frac{2\pi}{337 \text{ ns}}$$
Run transverse kicking cavities at 3 MHz, 6 MHz, 9 MHz,… in phase with equal amplitudes. Unkicked bunches traverse kicker when field integral sums to zero.

Problems with this:

- slope at zero-crossings might induce head-tail differences
- LOTS of different cavity designs (one per frequency)
Damping ring operation with an FS kicker

Fourier series kicker would be located in a bypass section.

While damping, beam follows the upper path.

During injection/extraction, deflectors route beam through bypass section. Bunches are kicked onto/off orbit by kicker.

SCRF and transverse kick minimize beam-induced fields in cavities.
Better idea: permits one (tunable) cavity design

Run transverse kicking cavities at much higher frequency; split the individual cavity frequencies by 3 MHz. (V. Shiltsev)

Kicked bunches are here

...undisturbed bunches are here (call these “major zeroes”)

Still a problem: finite slope at zero-crossings.
We’d like the slopes of the $p_T$ curves when not-to-be-kicked bunches pass through the kicker to be as small as possible so that the head, center, and tail of a (20 ps rms) bunch will experience about the same field integral.

$p_T$ in the vicinity of two zeroes

1 nsec

1% of kick
More dramatic $dp_T/dt$ reduction…

…is possible with different amplitudes $A_j$ in each of the cavities.

We (in particular Guy Bresler) figured this out last summer

Bresler’s algorithm finds sets of amplitudes which have $dp_T/dt = 0$ at evenly-spaced “major zeroes” in $p_T$.

There are lots of different possible sets of amplitudes which will work.
More dramatic $dp_T/dt$ reduction…

Here’s one set for a 29-cavity system (which makes 28 zeroes in $p_T$ and $dp_T/dt$ in between kicks), with 300 MHz, 303 MHz,…:
Kick corresponding to those amplitudes

The “major zeroes” aren’t quite at the obvious symmetry points.

Note that zeroes also satisfy \( dpT/dt = 0 \).
How well do we do with these amplitudes?

Old, equal-amplitudes scheme (head-to-tail, one orbit):

New, intelligently-selected-amplitudes scheme (head-to-tail, one orbit):
Multiple passes through the kicker

Previous plots were for a single pass through the kicker.
Most bunches make multiple passes through the kicker.
Modeling of effects associated with multiple passes must take into account damping ring’s

• synchrotron tune (0.10 in TESLA TDR)
• horizontal tune (72.28 in TESLA TDR)

We (in particular, Keri Dixon) worked on this last summer.
Good news…
Multiple passes through the kicker

…selecting amplitudes to zero out $p_T$ slopes fixes the problem! Here’s a worst-case plot for 300 MHz,… (assumes tune effects always work against us).
Is there an even better way to do this?

In a Fourier series kicker, the beam sums the effects of the different (high-Q) cavities.

60 cavities would allow the damping ring to fit into the Tevatron (or HERA) tunnel.

That’s a lot of cavities to stabilize.

Is there a way to sum the different frequencies in a single cavity?

Yes, maybe…
Dumb, not so dumb, promising

Summing signals in a single cavity…

• dumb: build a 3MHz cavity and drive it so that multiple modes are populated. (cavity is huge, lots of modes to control…)

• not so dumb: use a high frequency cavity with low $Q$ (so that it can support a wider range of frequencies), drive it with some kind of broadband signal. (large peak power needed, and we’re back to the same problem)

• promising: launch different frequencies down a long (dispersive) waveguide to a low-Q cavity. Send the frequency with slowest group velocity first, fastest last. Signals arrive at cavity properly phased to make a short pulse.
Chirped waveform pulse compression kicker
(Joe Rogers, Cornell)

Dispersive wave guide compresses chirped RF signal.

Commercial broadcast RF amplifier ~100kW, but compression generates large peak power for kicking pulse in low-Q cavity.
Group velocity vs. frequency

Dispersive wave guide compresses chirped RF signal. 500 MHz signal travels more slowly than 1 GHz signal.
Chirped signal into the wave guide...

Wave guide input signal (not from actual measurements!): 340 ns
Signal at the far end of the wave guide…

Narrow!

10 ns
Chirped waveform pulse compression kicker

Unlike Fourier series kicker, in which bunches “sum” the effects of different frequencies, this design uses the cavity to form the sum.

System is linear, so low-power tests can be used to evaluate concept. (Fermilab is interested in pursuing this.)

Programmable function generator can be reprogrammed to compensate for drifts and amplifier aging.
Testing our kicker ideas

A0 photoinjector lab at Fermilab produces a relativistic (16 MeV now, 50 MeV in a few months), bunched low-emittance electron beam. (It’s rather like a TESLA injector.)

This should be an excellent facility for kicker studies!
Small Damping Ring Lattice

What might a damping ring, small enough to fit into the Tevatron or HERA or tunnels, look like?

We had a small workshop in March at Fermilab to think about this.

Participants: ANL, LBNL, SLAC, Cornell, DESY, FNAL…

6 kms, 6 straight sections, 25 wigglers.

this version: 16 March, 2004
## Comparison of the two designs

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<tr>
<th>Parameter</th>
<th>Small ring ((e^+/e^-))</th>
<th>Dogbone ((e^+/e^-))</th>
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<tr>
<td>Energy</td>
<td>5 GeV</td>
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<tr>
<td>Circumference</td>
<td>6.12 km</td>
<td>17 km</td>
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<td>Horizontal emittance (\gamma e_x)</td>
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<td>8 mm·mr</td>
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<tr>
<td>Vertical emittance (\gamma e_y)</td>
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<td>0.02 mm·mr</td>
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<tr>
<td>Transverse damping time (\tau_d)</td>
<td>28 ms / 44 ms</td>
<td>28 ms / 50 ms</td>
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<td>Current</td>
<td>443 mA</td>
<td>160 mA</td>
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<tr>
<td>Energy loss/turn</td>
<td>7.3 MeV / 4.7 MeV</td>
<td>21 MeV / 12 MeV</td>
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<td>Radiated power</td>
<td>3.25 MW / 2.1 MW</td>
<td>3.2 MW / 1.8 MW</td>
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<td>Tunes (Q_x, Q_y)</td>
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<td>72.28, 44.18</td>
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<tr>
<td>Chromaticities (\xi_x, \xi_y)</td>
<td>-112, -64</td>
<td>-125, -68</td>
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</table>

Comments about damping rings

It will be interesting to see how various optimizations turn out if it is possible to remove the 20 ns minimum bunch spacing requirement.

A small damping ring could be built and tested before linac construction was complete. (Independent tunnels) This is an appealing idea! It could allow beam to be injected into the linac as soon as the main linac was under construction.

Exploration of technical issues associated with damping rings is becoming a major focus of LC activity at Fermilab.
Summary/conclusions

It is possible that alternative TESLA damping ring kicker designs will allow the construction of smaller rings.

Simulations are encouraging; we will begin testing some of these ideas over the next few months at Fermilab. Stay tuned!