Development of an Ultra Fast RF Kicker for an ERL-based Electron Cooler

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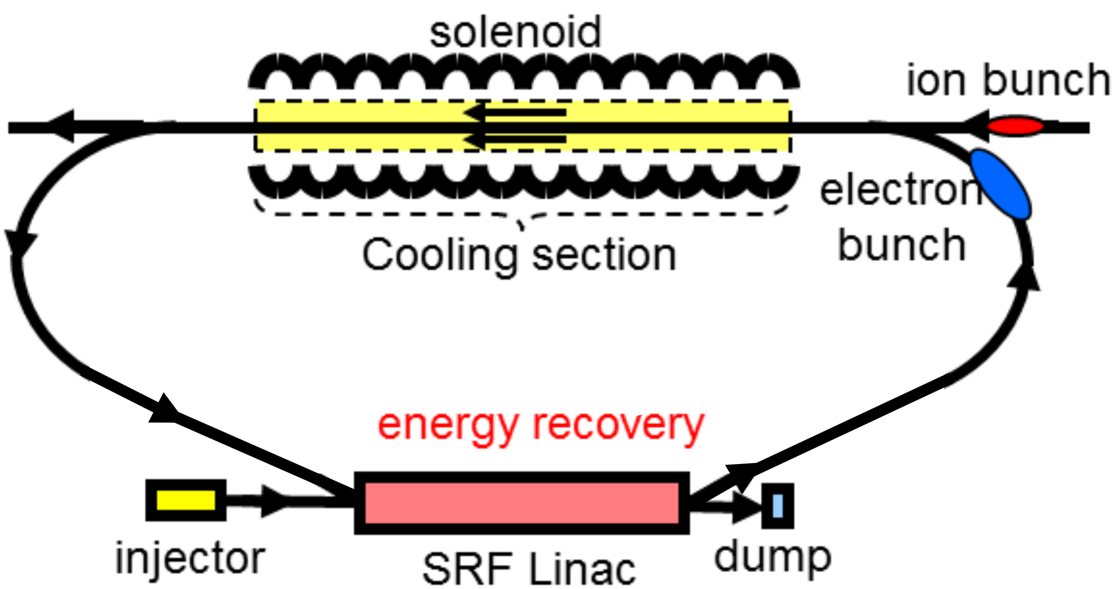
Fast kicker requirements for the JLab MEIC

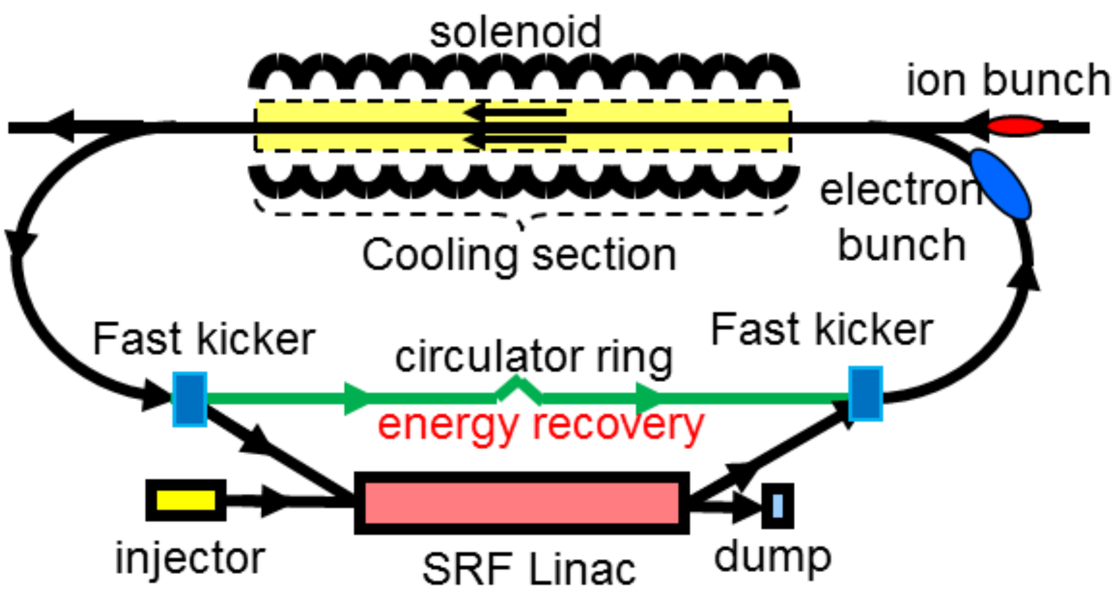
- The **Jefferson Lab Medium Energy Electron-Ion Collider (MEIC)** utilizes electron cooling of ions for reduced emittance, high luminosity
  - Staged approach to electron cooling employs **bunched beam cooling** in ion collider ring for suppressing IBS-induced emittance growth, maintaining design emittances
  - Single-pass ERL to accelerate/decelerate high current, high power bunches



  - Luminosity upgrade requires higher current for more intense electron cooling
  - **ERL with full circulator ring**

Fast kicker requirements for the JLab MEIC

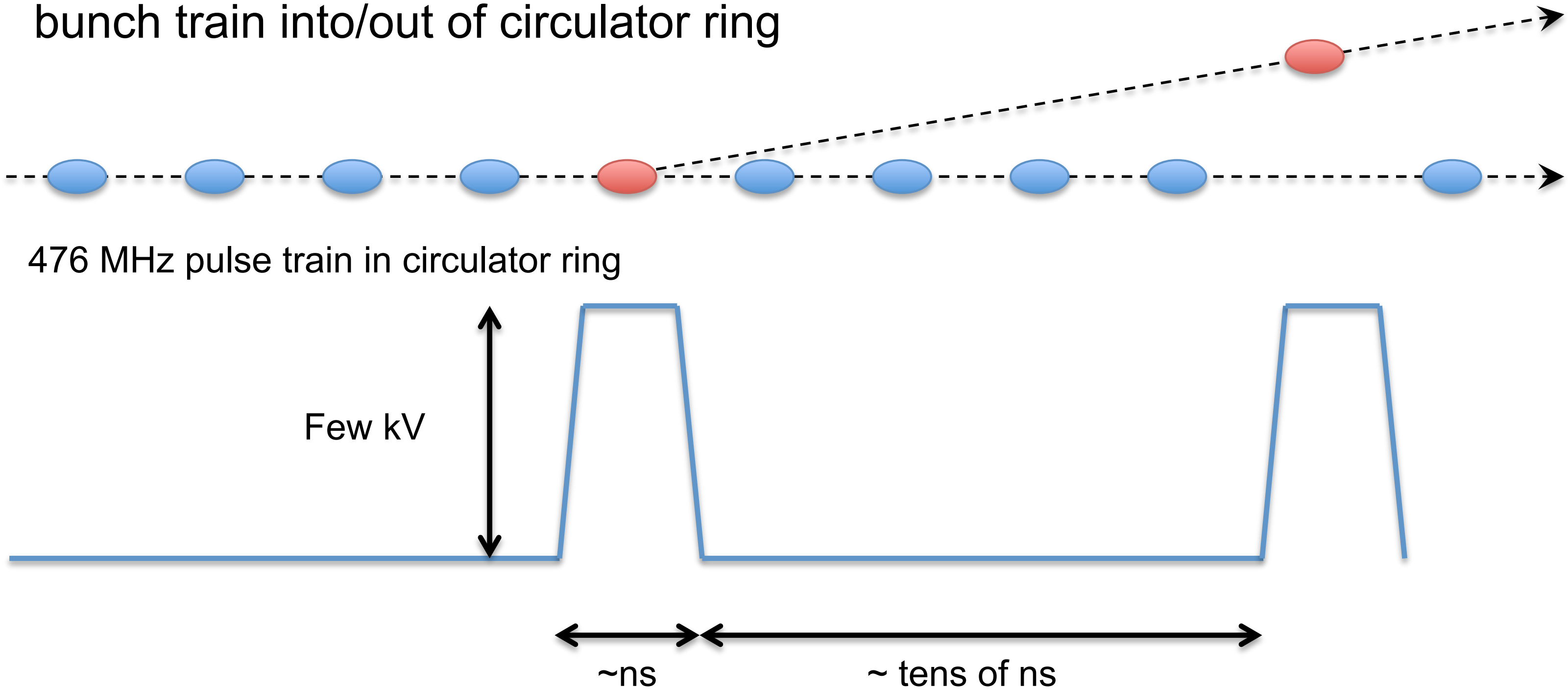
- An **ERL with full circulator ring** relaxes the current requirement from the injector
- At top energy with 3 nC electron bunches at 476 MHz
  - Single-pass: 1.5 A from source, 3 MW at dump
  - Multi-pass in ring: 60 mA from source, 120 kW at dump for 25 turns



- Beam kicker to deflect bunches into and out of circulator ring needs rise and fall times ~ 1 ns at MHz repetition rates
  - **Beyond current driver technology**

Kicker waveform generation

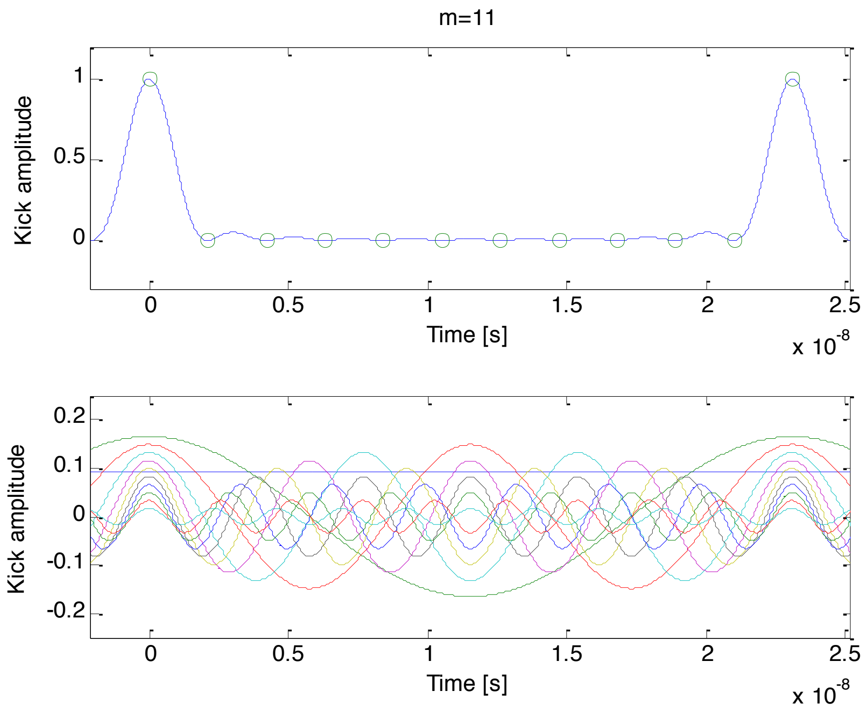
- For n turns in the circulator ring, kicker needs to deflect every n-th bunch in bunch train into/out of circulator ring



- ~ Periodic delta function with frequency f_{eff} = 476/n MHz
  - Use this approximation to generate a suitable waveform

Kicker waveform generation

- **Subharmonics of the electron bunch frequency*** summed to generate a continuous waveform with peaks at the effective frequency f_{eff} = 476/n MHz
- Relative phases and amplitudes of subharmonics manipulated to shape waveform according to desired characteristics



- Rise and fall times == bunch spacing
- Magnitude of kicking pulse == zero for non-kicked bunches that continue in circulator ring
- Gradient of kicking pulse == zero for non-kicked bunches

*[A. Hutton, B. Terzic]

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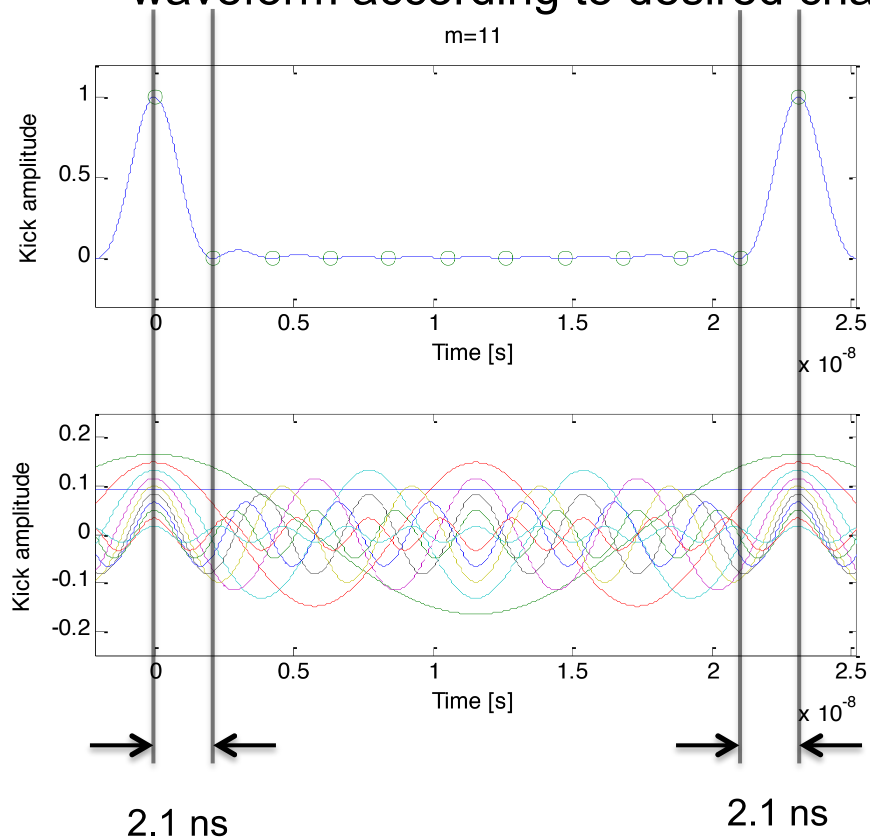

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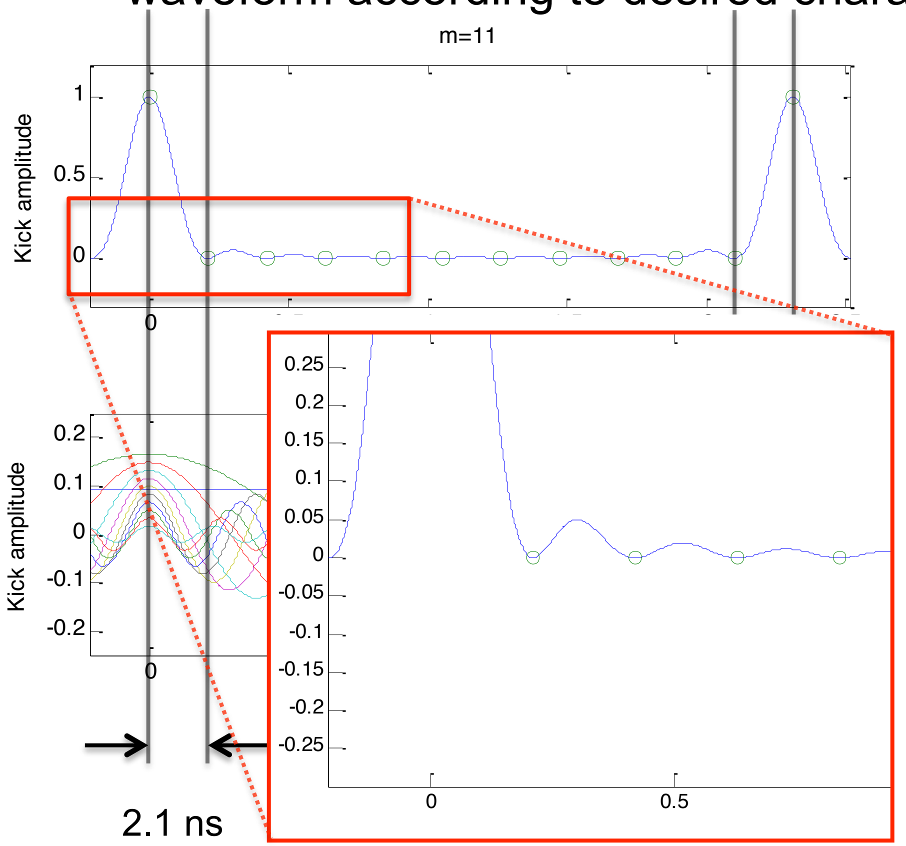

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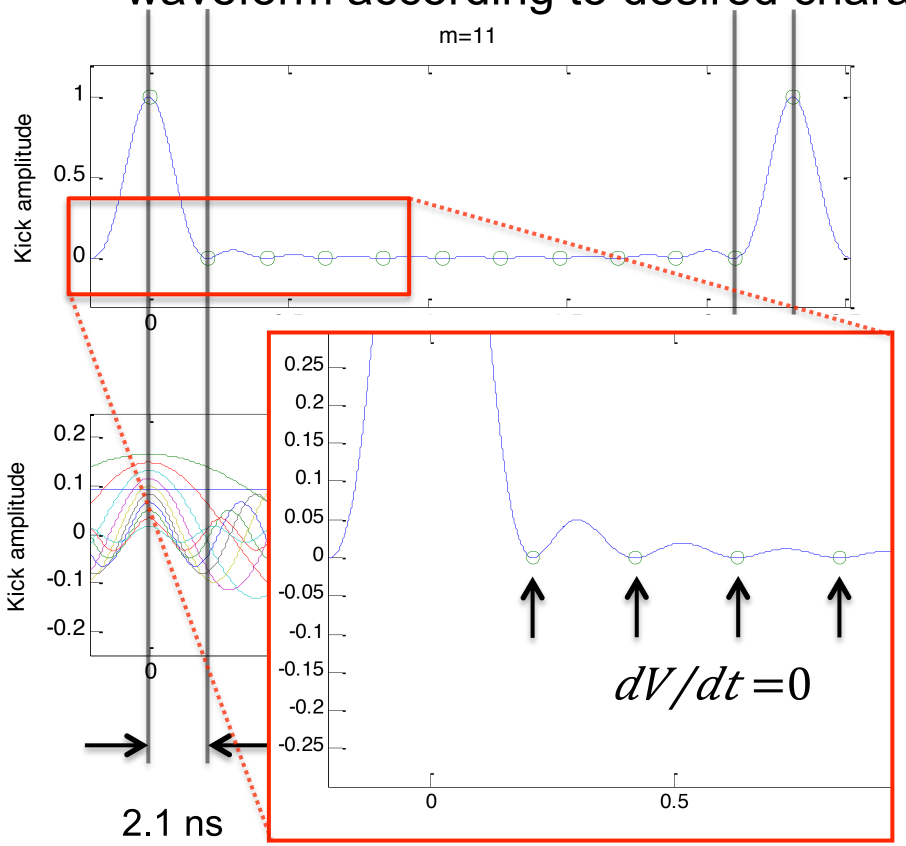

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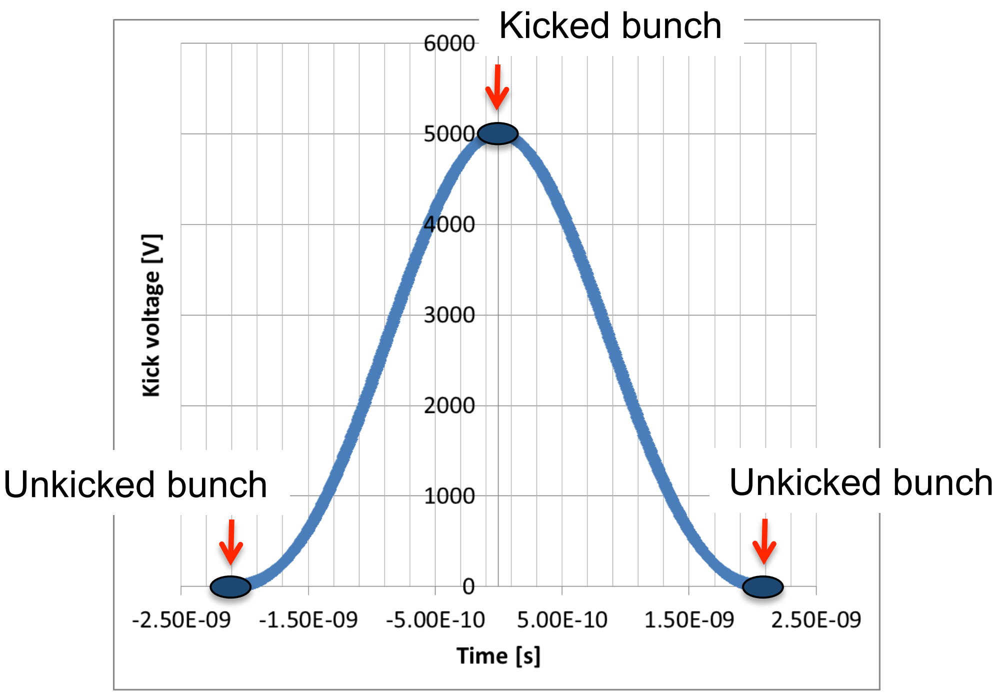
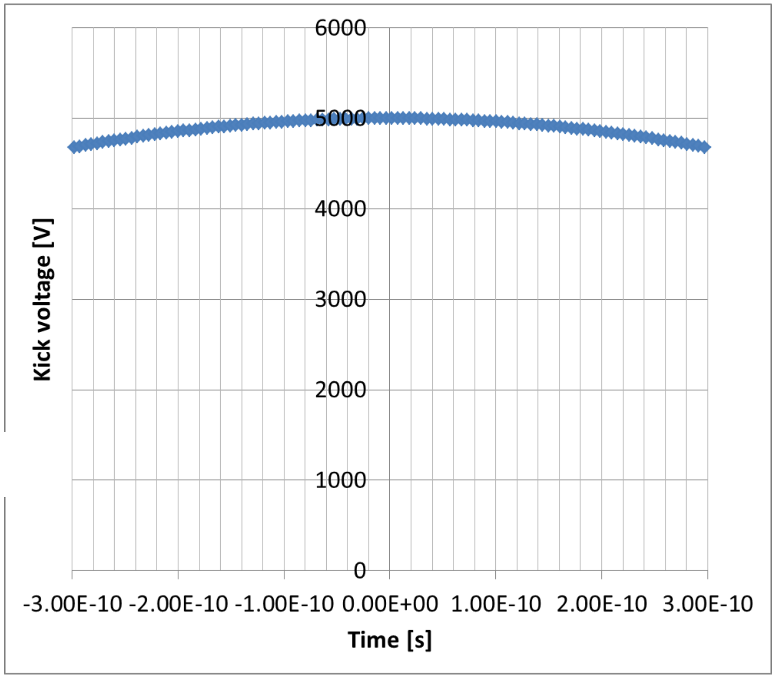
Non-uniformity of kicking pulse

- Sharp rise and fall times create a narrow pulse that is not uniform over the length of the electron bunch
- "Flat-top" kicking pulse formed by adjusting subharmonic amplitudes and phases appropriately
- For full beam size of 2 mm transverse, 600 ps longitudinal (+/- 3σ)
  - $V = 0.934\ V_{peak}$ for f=476 MHz





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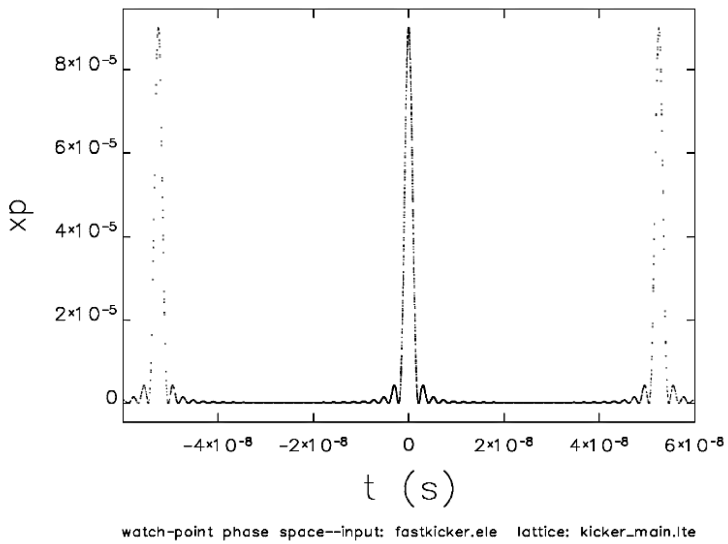
Simulations of transverse effects

- Transverse effects on kicked and unkicked bunches in a circulator ring simulated using ELEGANT
- Circulator ring approximated with 1 turn linear transfer matrix
- Kicker waveform generated using a series of zero-length RF deflectors with appropriate frequencies, phases, and amplitudes

Nominal parameters

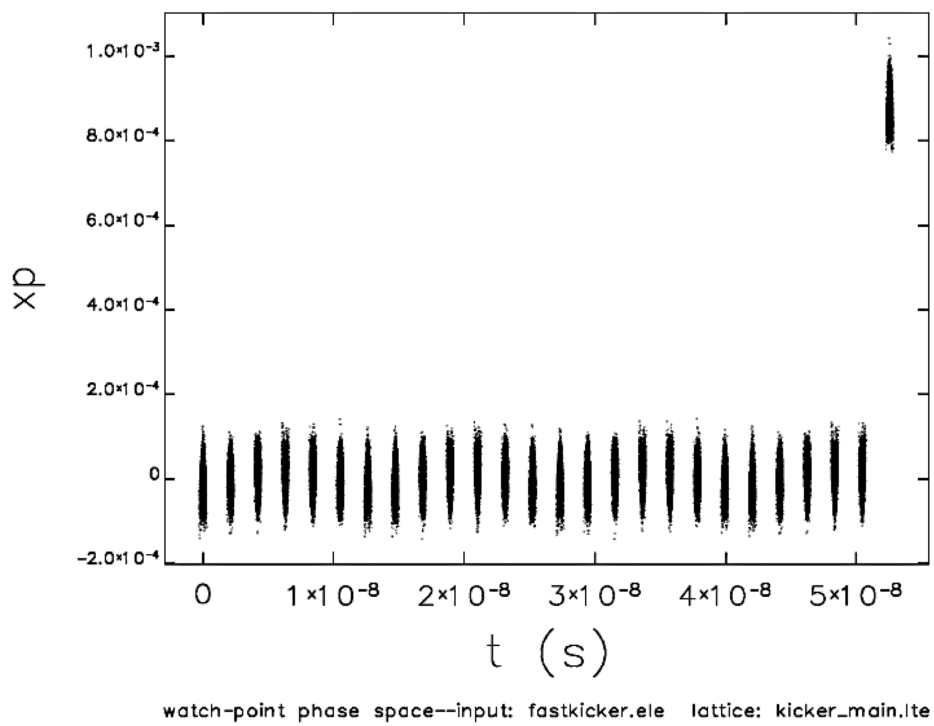
P [MeV/c]	55.5086
ε_x, ε_y [nm]	10
β_x, β_y [m]	10
σ_s [cm]	3
$\sigma_{\Delta p/p}$	3e-4
f [MHz]	476
n	25
V_{kick} [kV]	50



ELEGANT verification of kicker waveform generation

Transverse effects for zero-gradient pulse

- **Zero-gradient pulse**: V=0 and dV/dt=0 at bunch arrival times for any non-kicked bunch
  - No relative phase offset between subharmonics
  - Kicking pulse non-uniformity 6.6%



- At time t=0, bunch is kicked into ring
- With each turn, bunch sees different part of intermediate kicker waveform
- After 25th turn, bunch again sees kicking pulse and is kicked out of ring

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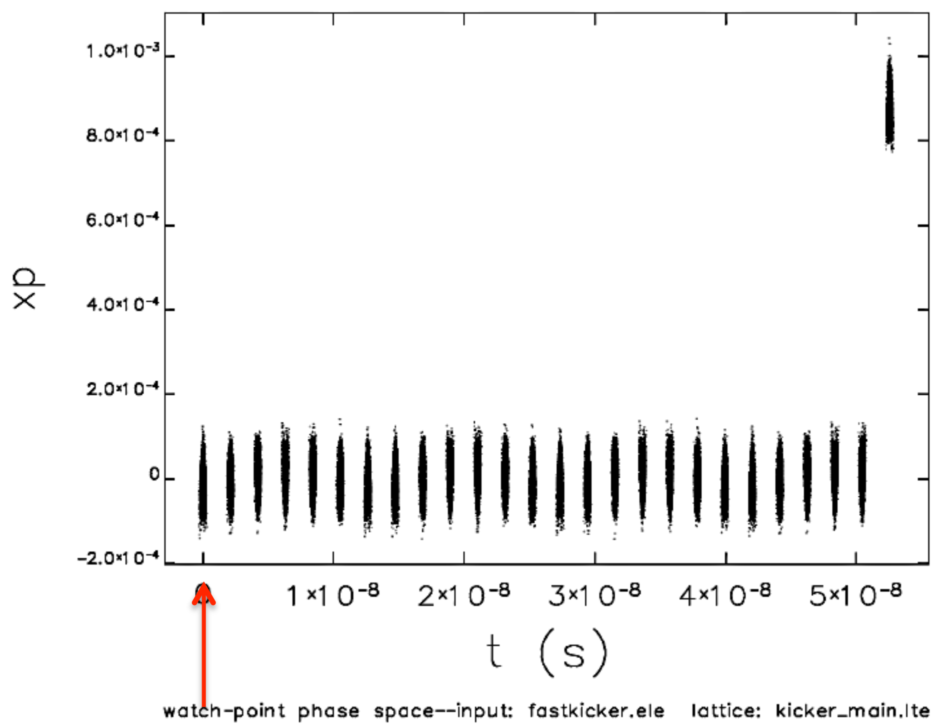

Bunch kicked in

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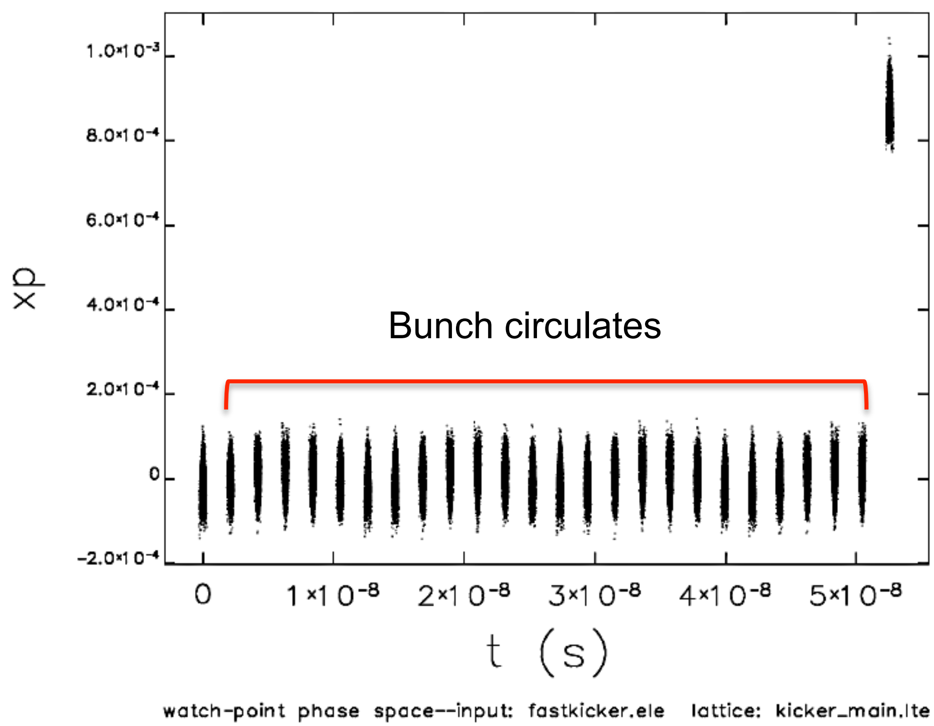

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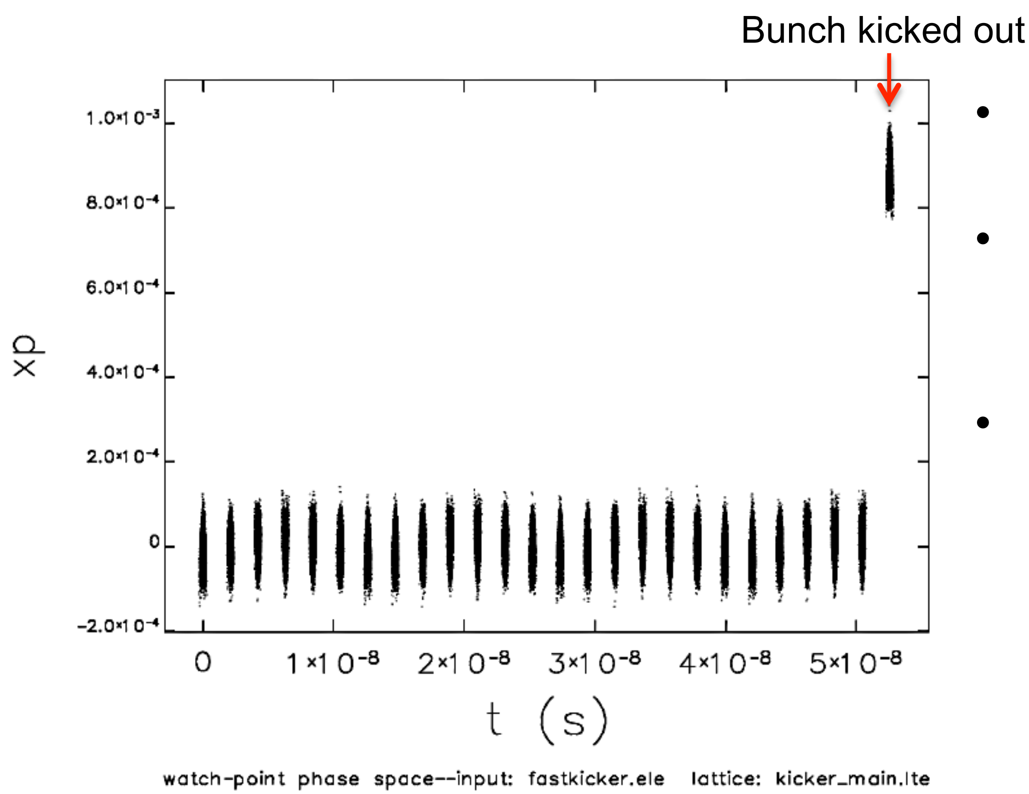

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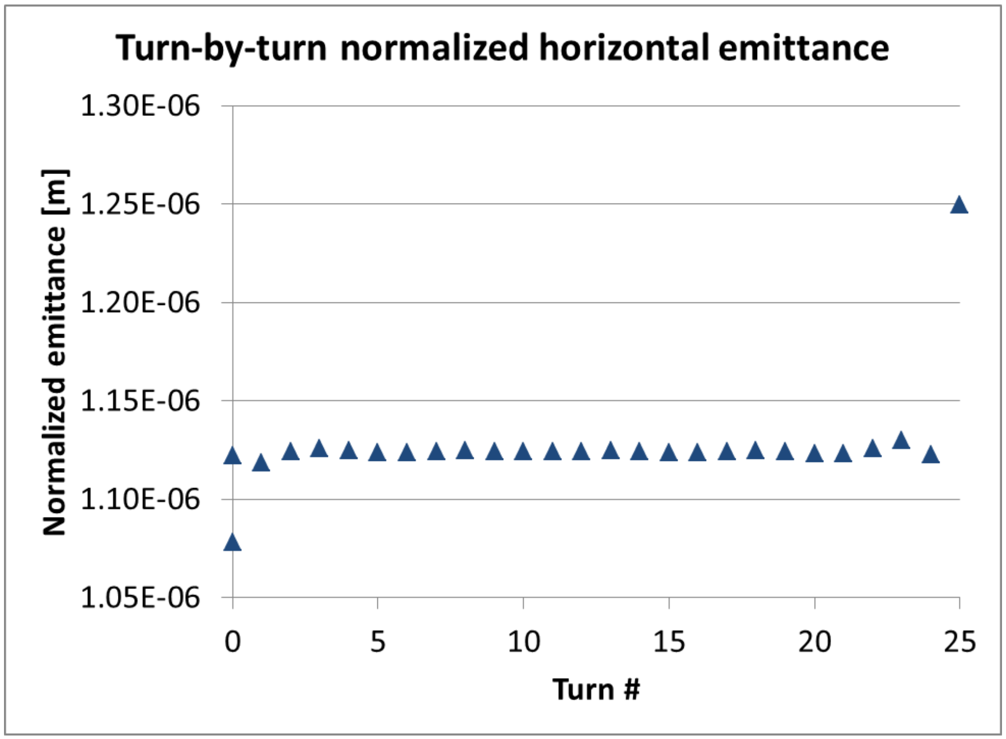
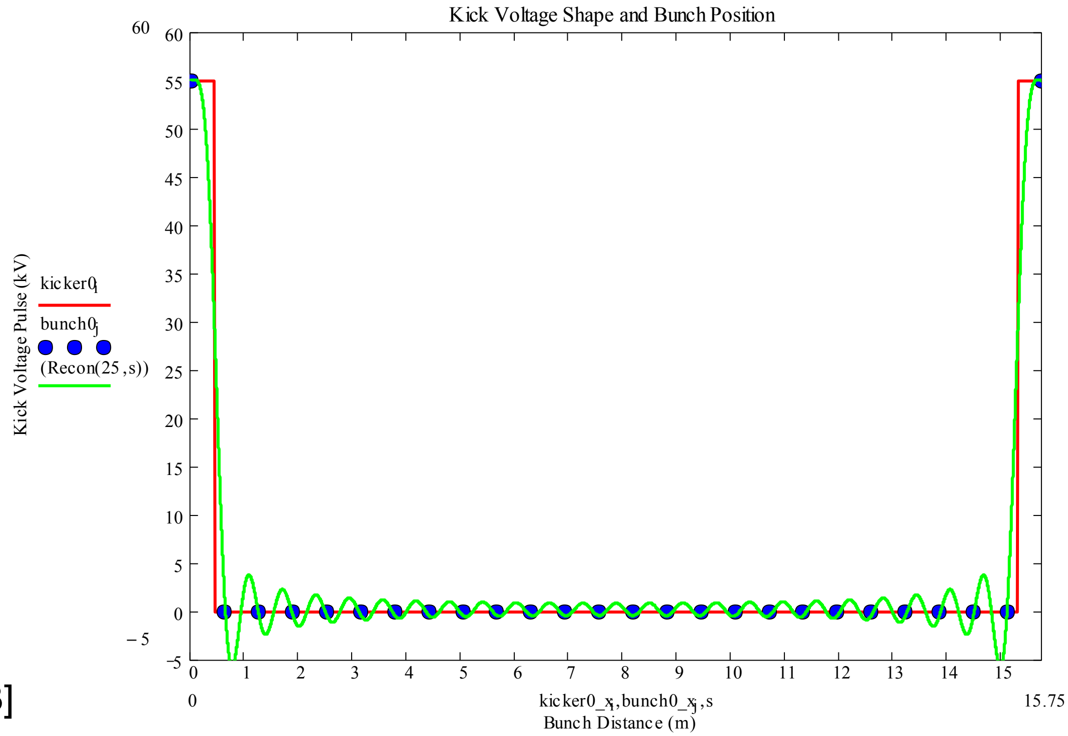


- 4% emittance growth due to non-uniformity of kick
- Negligible emittance growth due to residual voltages seen as bunch circulates
- Larger growth seen after bunch receives second kick
  - Less significant as bunch heads toward energy recovery

Transverse effects for flat-top pulse

- Immediate 4% emittance growth due to non-uniformity of zero-gradient pulse
- **Flat-top pulse***: adjust relative phase offsets, amplitudes of subharmonics while maintaining V=0 at bunch arrival times for non-kicked bunches
  - dV/dt≠0
  - Kicking pulse non-uniformity 0.1%



*[Y. Huang, MOPF13]

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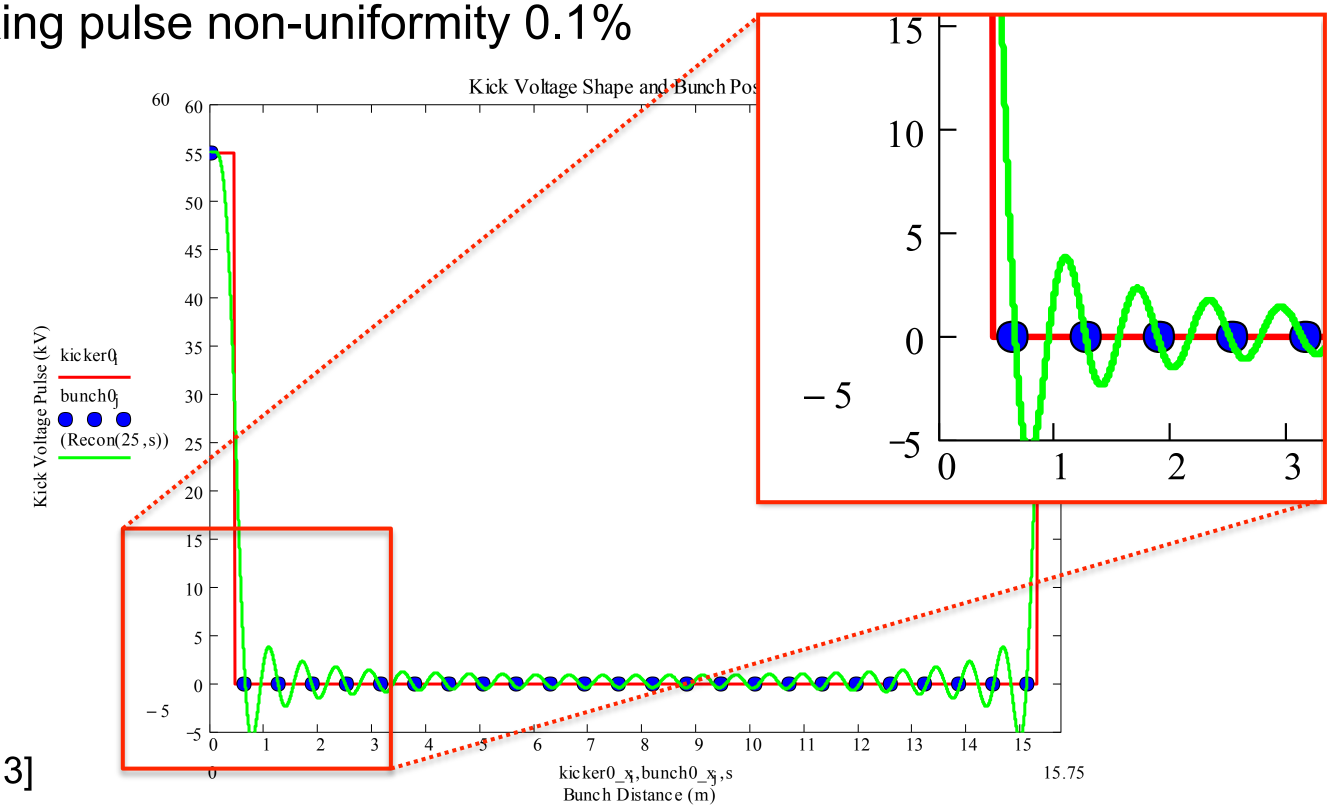

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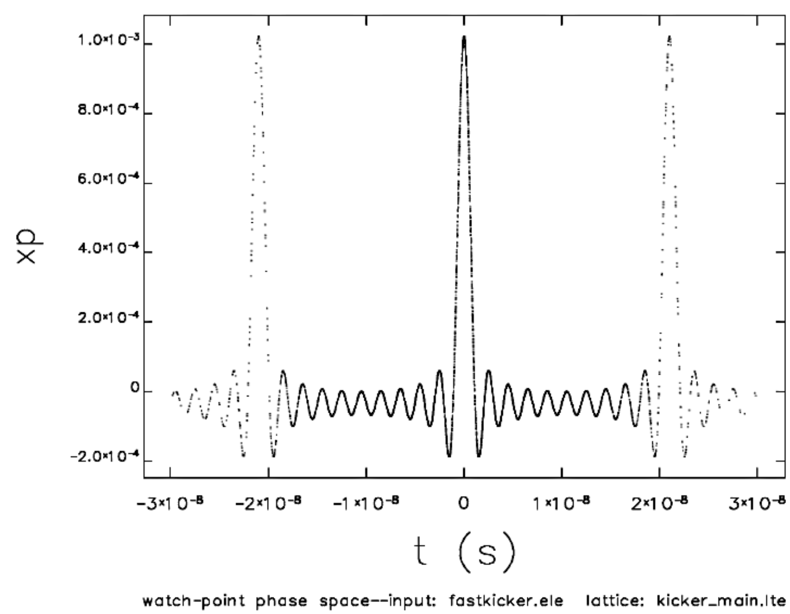
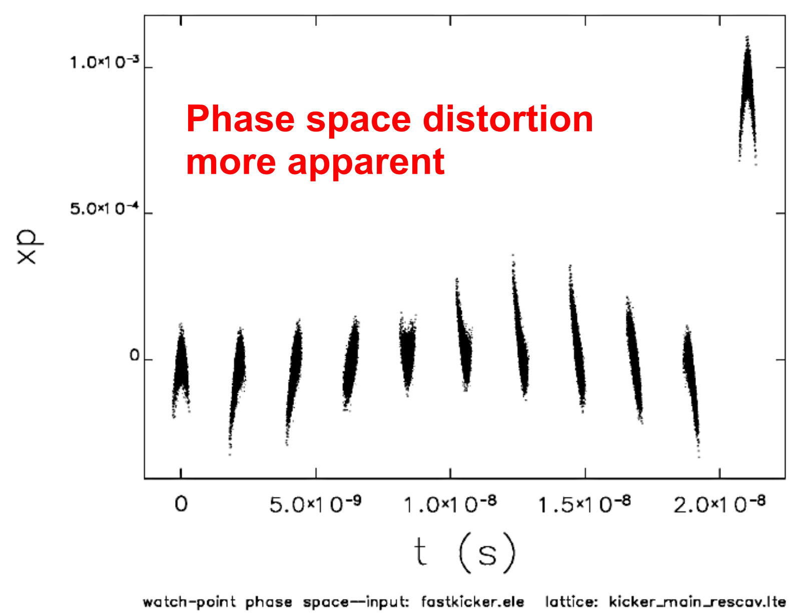
n=11 for illustration only





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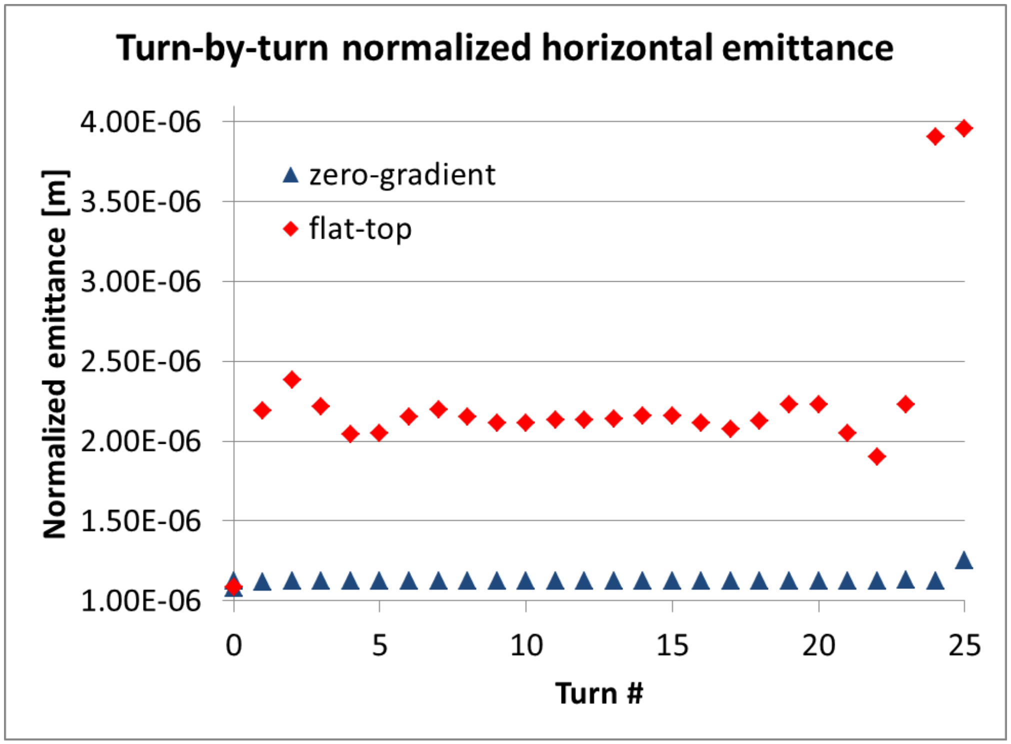
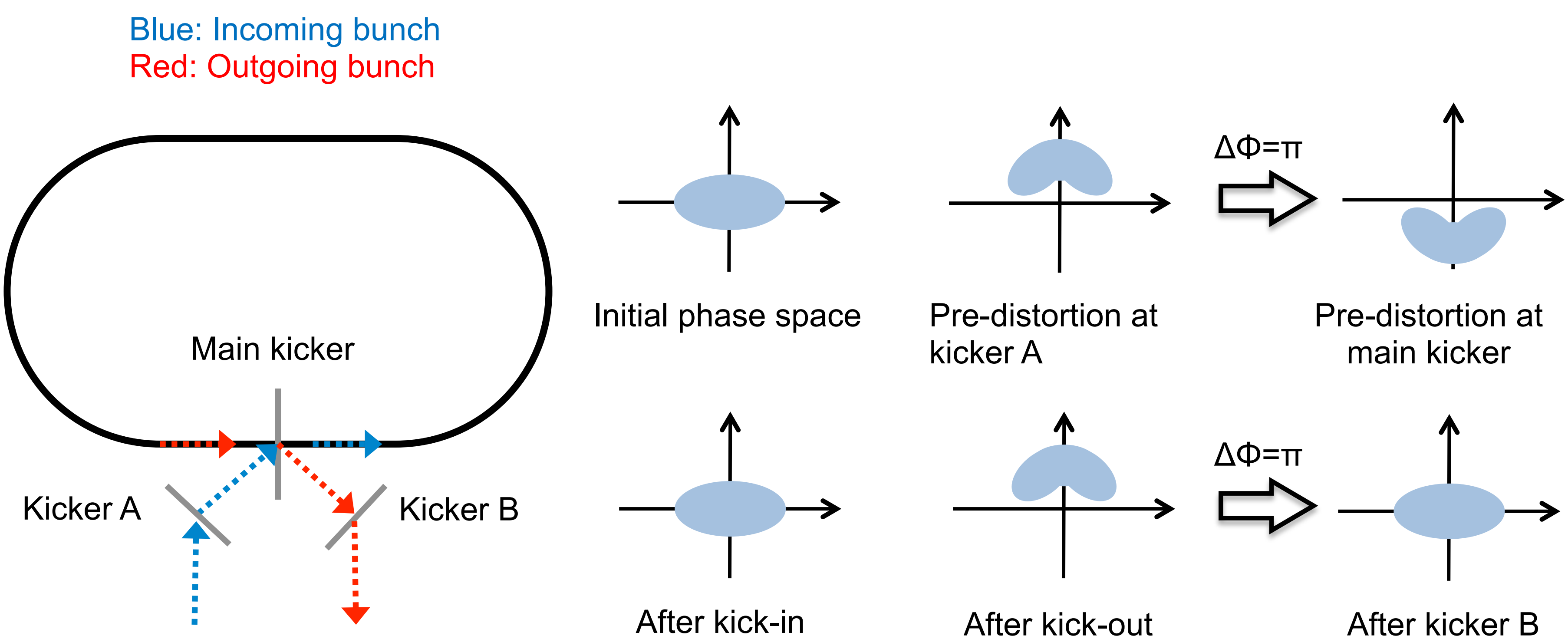


- 0.4% emittance growth due to non-uniformity of kick
- Large emittance growth due to large gradients seen by bunches during first few turns
  - Very large emittance growth as bunch prepares to exit ring
  - ~ 2x increase due to gradients on first turn, additional 2x increase due to gradients on $(n-1)^{th}$ turn

Compensation of phase space distortion

- For flat-top pulse, transverse phase space distortion is amplified by large gradients, resulting in large emittance growth that degrades cooling efficiency
- Phase space distortion is well-defined – we know our kicking pulse
- **Pre-distort** the distribution to send a matched bunch into the circulator ring



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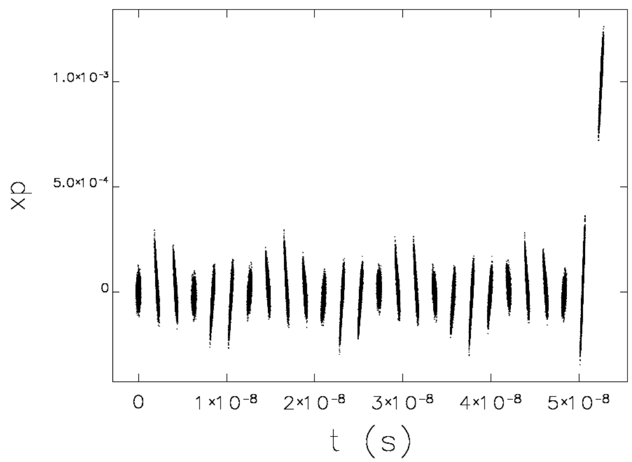
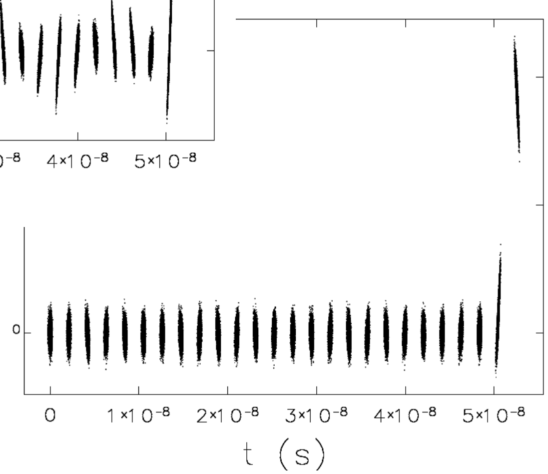
Compensation of phase space distortion

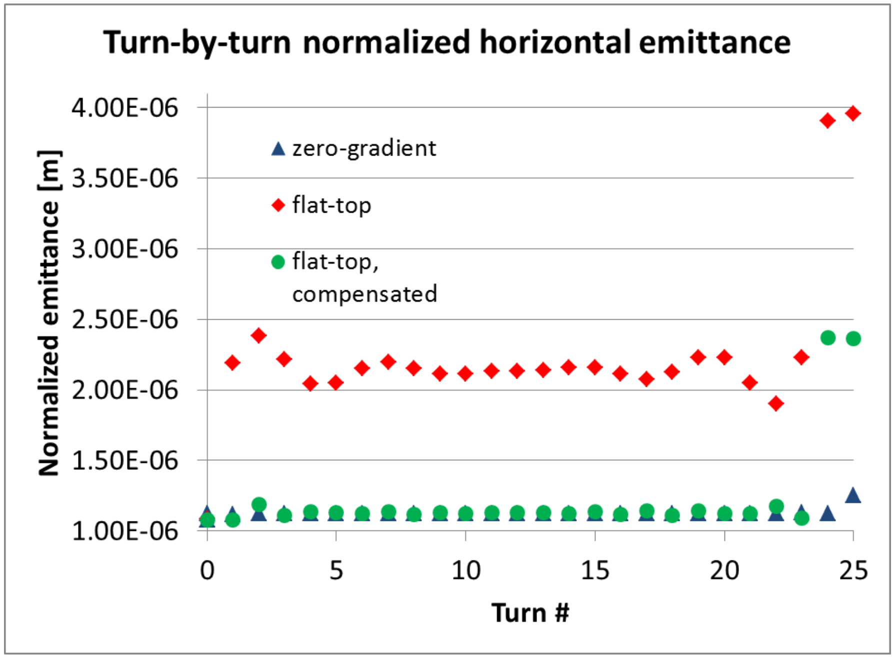
- Compensation of phase space distortion reduces emittance growth for the flat-top pulse to ~5%
  - Comparable to non-compensated zero-gradient pulse

Non-compensated flat-top pulse



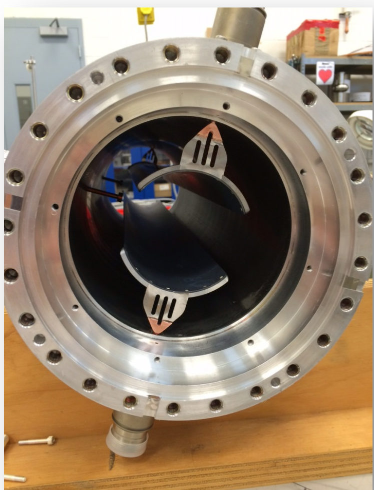


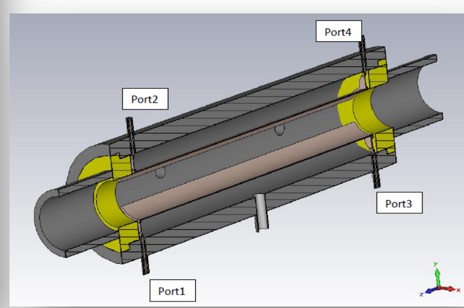
With pre-distortion



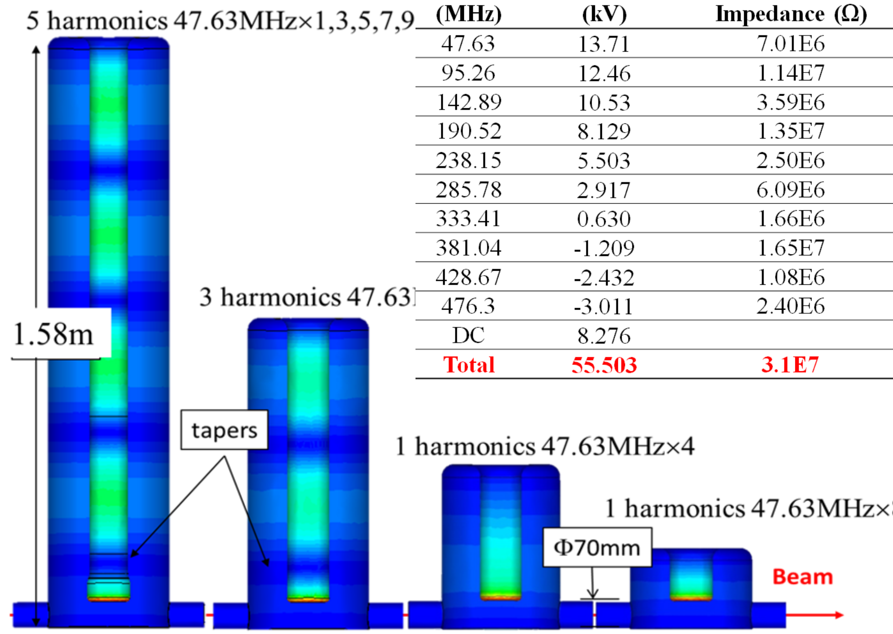
Possible cavity structures for fast kicker

- PEP-II fast feedback transverse kicker on loan from SLAC – strip line kicker designed for lower frequency
- Initial CST simulations (J. Guo, TUPF10) indicate high power consumption to drive the SLAC kicker with this type of kicker waveform (> 10 kW)
- Design and simulation of resonant cavity structure supporting the flat-top pulse with 100 W total power consumption





SLAC PEP-II fast feedback kicker



Mode (MHz)	Kick Voltage (kV)	Trans. Shunt Impedance (Ω)	Power (W)
47.63	13.71	7.01E6	26.8
95.26	12.46	1.14E7	13.6
142.89	10.53	3.59E6	30.9
190.52	8.129	1.35E7	4.89
238.15	5.503	2.50E6	12.1
285.78	2.917	6.09E6	1.40
333.41	0.630	1.66E6	0.24
381.04	-1.209	1.65E7	0.09
428.67	-2.432	1.08E6	5.48
476.3	-3.011	2.40E6	3.78
DC	8.276		
Total	**55.503**	**3.1E7**	**99.28**

Resonant cavity kicker

[Y. Huang, MOPF13]

Summary

- Bunched beam cooling is an integral component to attaining high luminosity in the JLab MEIC
- An ERL + circulator ring complex for possible luminosity upgrade requires fast RF kickers that are beyond current driver technology
- Simulations indicate that kicking waveform with ~ns rise and fall times and MHz repetition rates can successfully kick suitable electron bunches without major degradation of bunch quality
  - 4% transverse emittance growth due to kick
- Possible cavity structures and experimental measurements are being pursued
- We are optimistic about the prospects of an ultra fast RF kicker!