Nanosecond Pulse Power Systems for TEM Kickers at SLAC

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TID/RFARED

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

Nanosecond pulse power systems for TEM kickers at SLAC are presented.

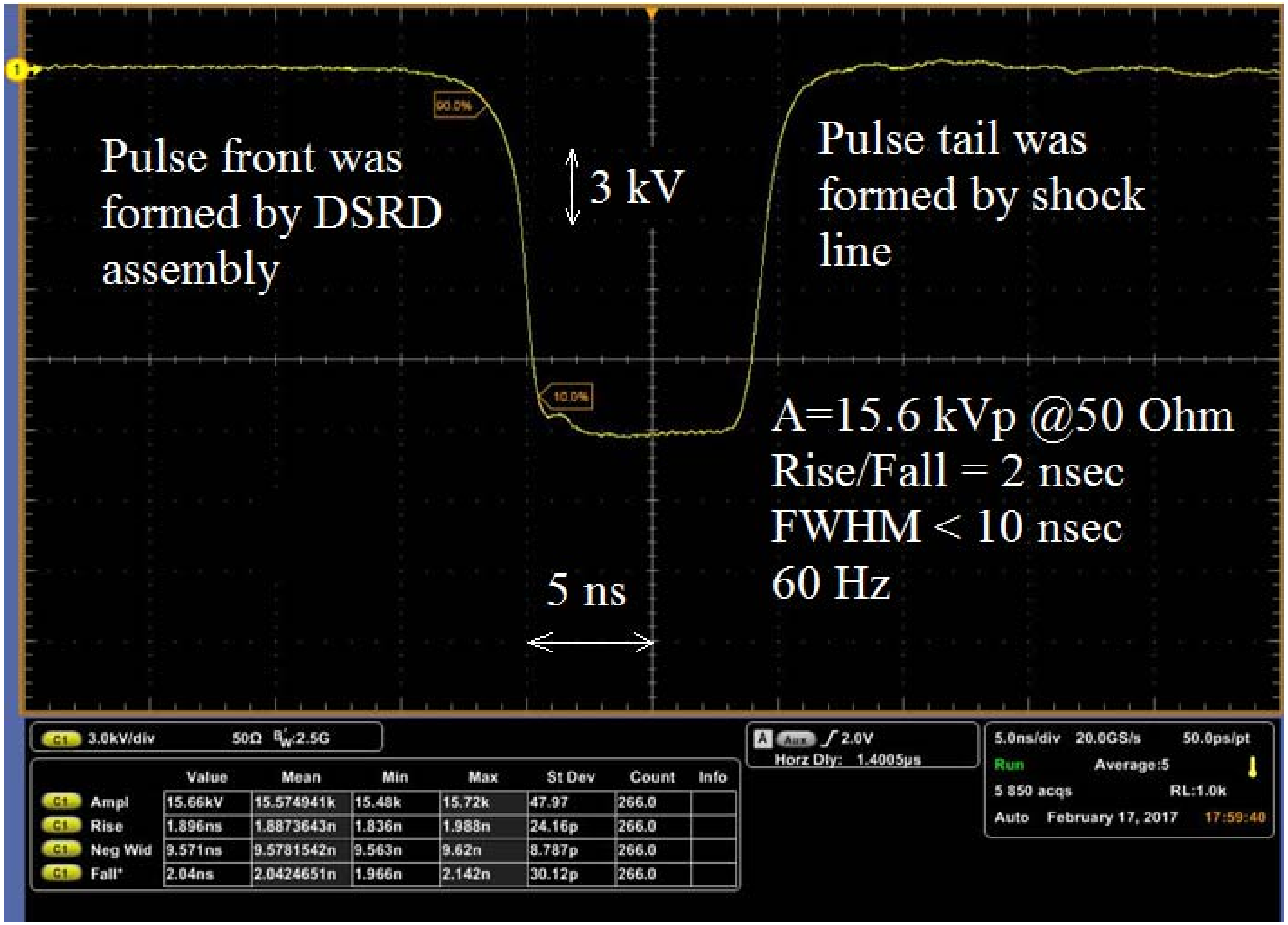
A nanosecond pulsers for injection/extraction kickers with a 3 MeV transverse kick.

LCLS-1 with transverse kicker structures and nanosecond pulsers.

LCLS-II ultra-fast kicker system and its nanosecond power supplies.

A 1.28 MHz kicker system for the camshaft bunch in storage rings and the nanosecond pulsers with a 256 kHz repetition rate.

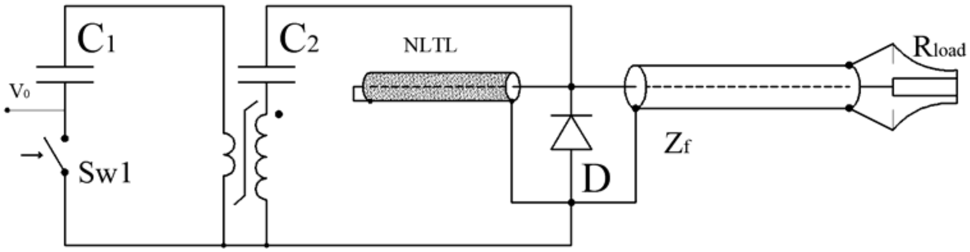
A Nanosecond Pulser for Injection/Extraction Kicker with a 3 MeV transverse kick

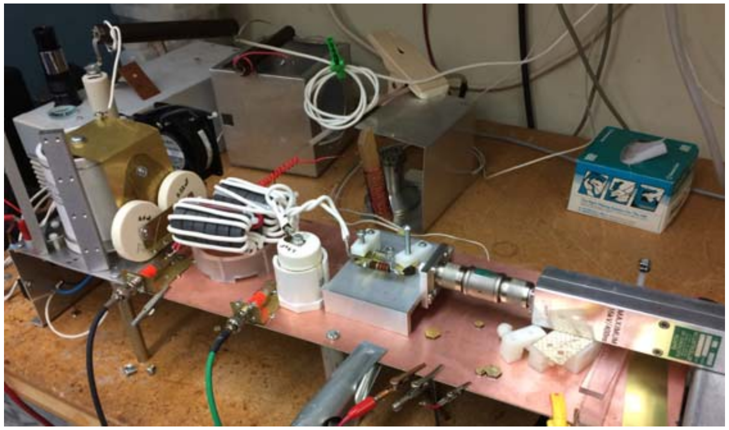


These pulse parameters meet spec for the injection/extraction kickers.

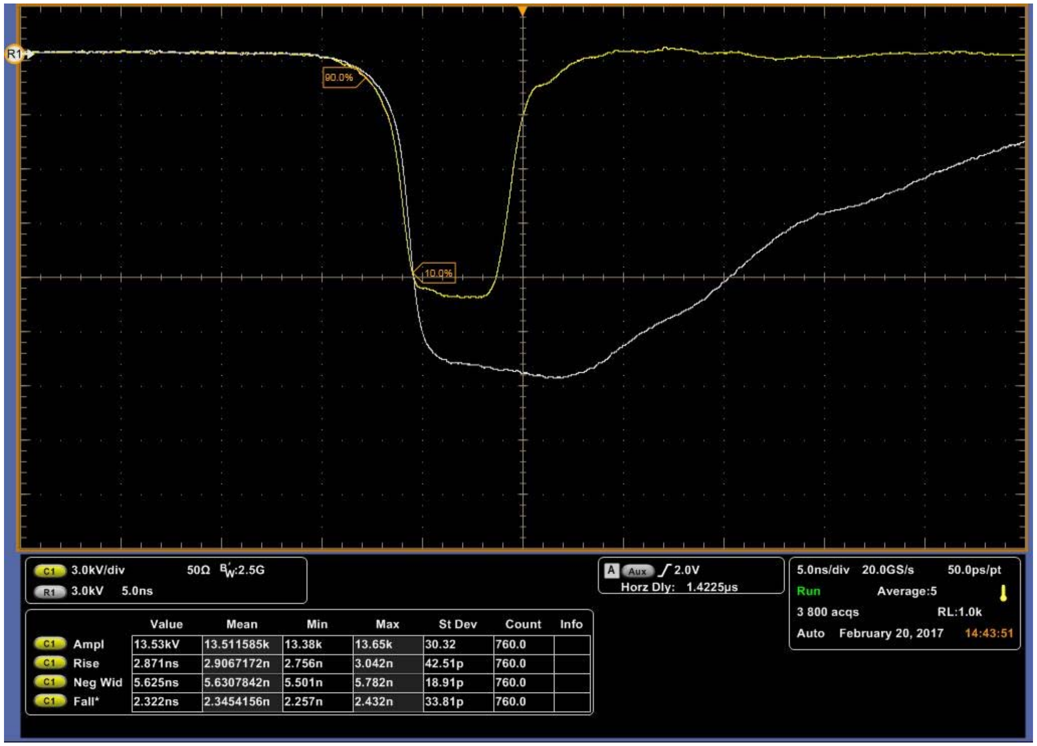
Kicker aperture: 30 mm
Length: 1200 mm
Kicker filling time: 4 ns
Transvers kick: 2.6 MeV

Pulser Prototype Details





HY3189, C1=16 nF, C2=1.7 nF
x-fmr: w1=2, w2=7, 6 ea. NiZn, OD=1.4”



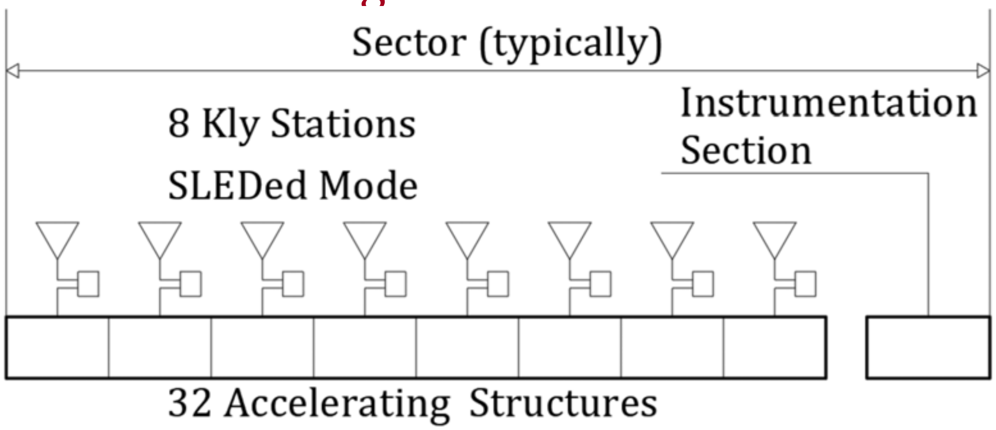
No NLTL case:
A=24.7 kV (I=494A)
NLTL cores: OD=0.16”, ID=0.088”

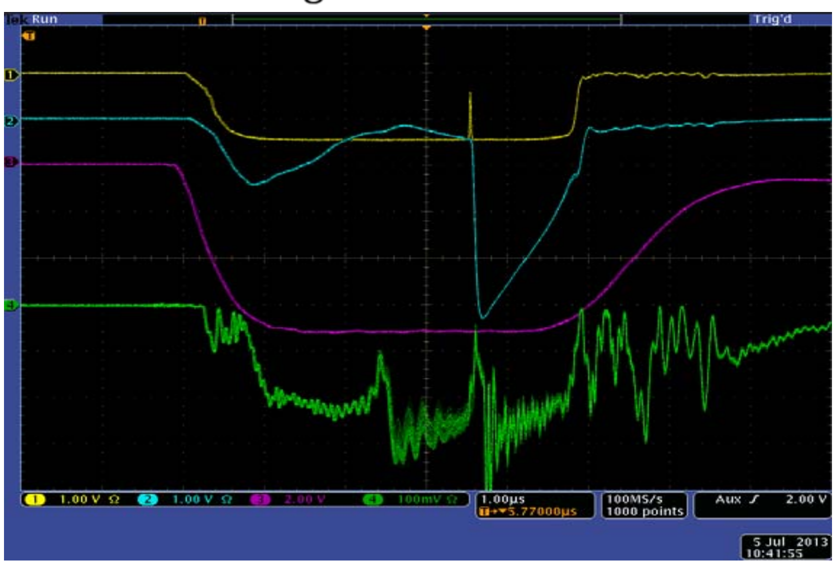
With NLTL:
H_{FWD}~124 A/cm, H_{sw}~55 A/cm

H_{RE} ~240 A/cm
S_{sw}~0.66 uC/cm
$t_{sw}= S_{sw}/ H_{RE}$ ~2.7 nsec

A LCLS-I Layout with the TEM Kickers

A nanosecond multi-bunch mode in LCLS-I extends the FEL capabilities. There are several critical components to be added to the LCLS-I baseline for the multi bunch mode of operation. One of the component is the system that properly control the individual bunch orbit. The individual bunch orbit control based on the RF amplitude and phase modulation is limited by the bandwidth. Powerful and fast solid-state switches driving TEM kickers are needed to breakthrough these limitations.



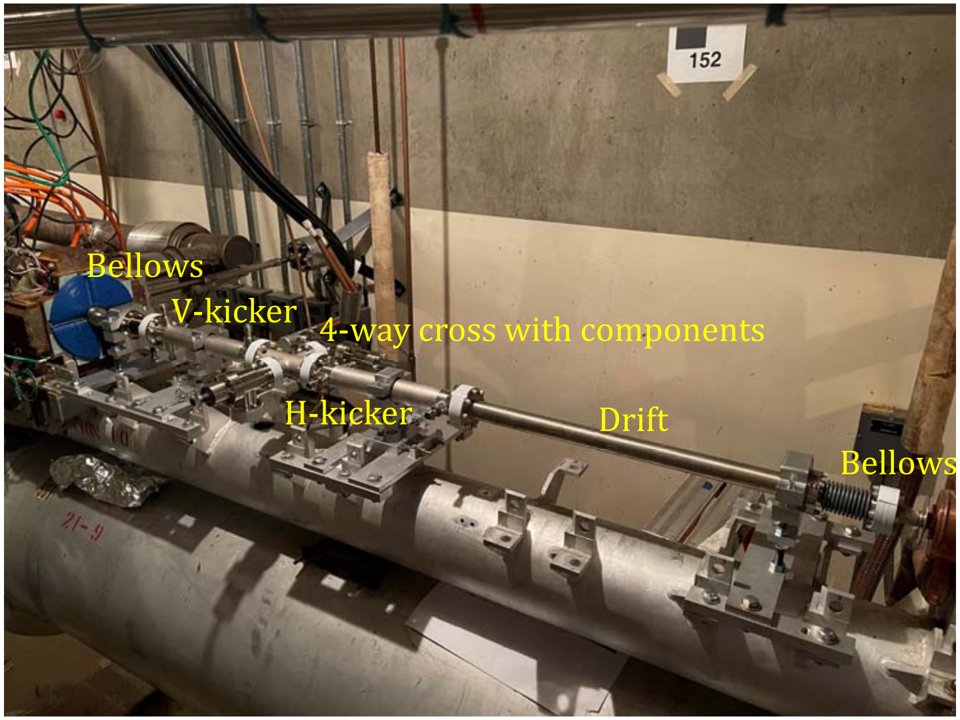


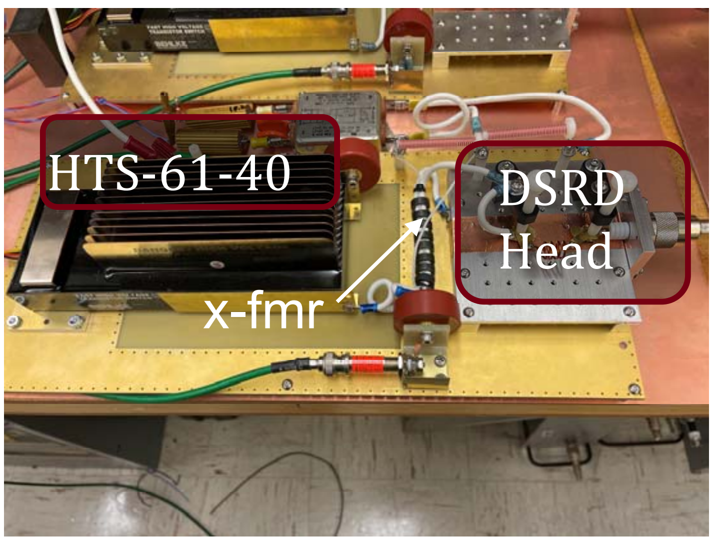
LCLS-I: 10 sectors with the instrumentation sections.

Potentially, two (V- and H-) TEM kicker structures could be placed on each instrumental section to correct the orbits of the individual bunches.

So, the orbits of 10 bunches could be corrected.

A Layout of the 21-9 Instrumentation Section with V- and H- Kickers

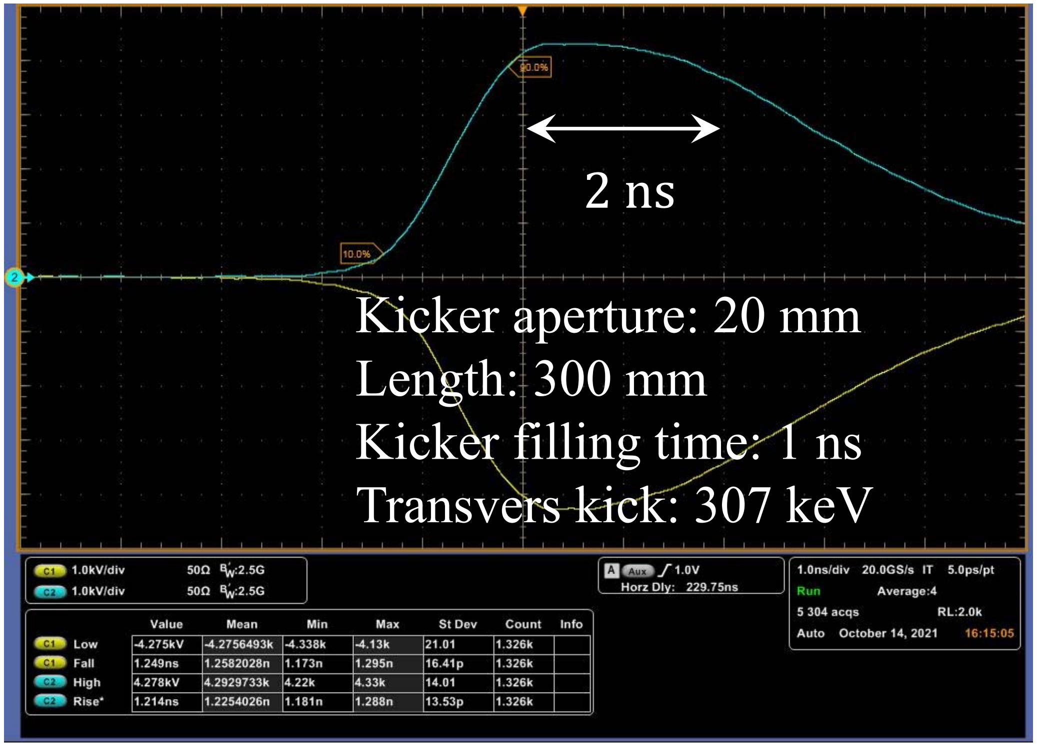




Pulser: PS=2.2 kVDC, C0=3.2 nF, x-fmr (w1=1, w2=1), C1= 3.2 nF, two DSRD cells, 2 ea. per cell.
Output pulser amplitude is 4.3 kV peak at 50 Ohm.
Rep rate: 120 Hz.

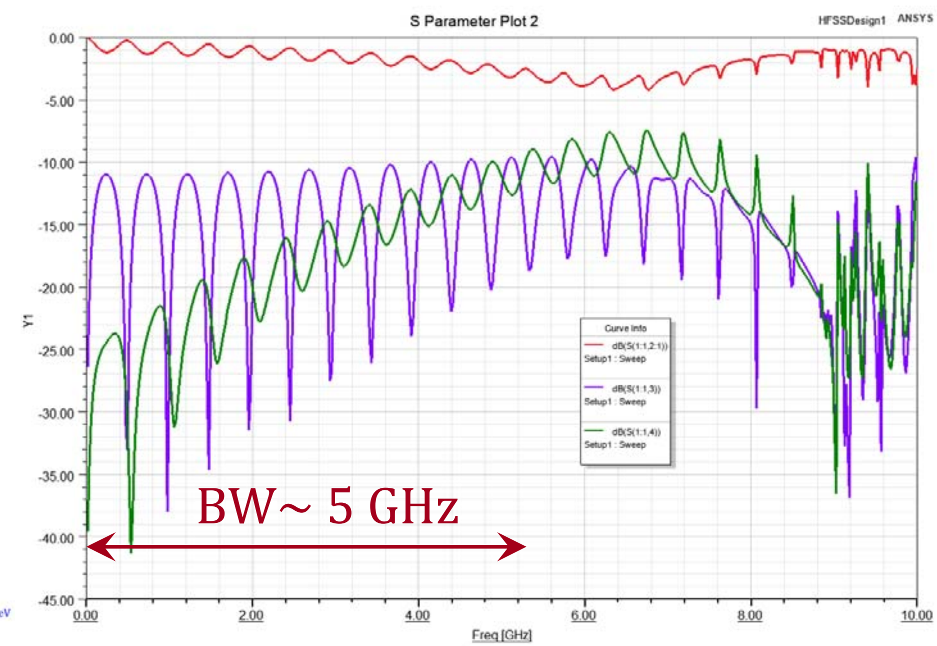
Pulser circuit layout is based on the simplified circuit diagram “D” shown in SLAC-PUB-17099.

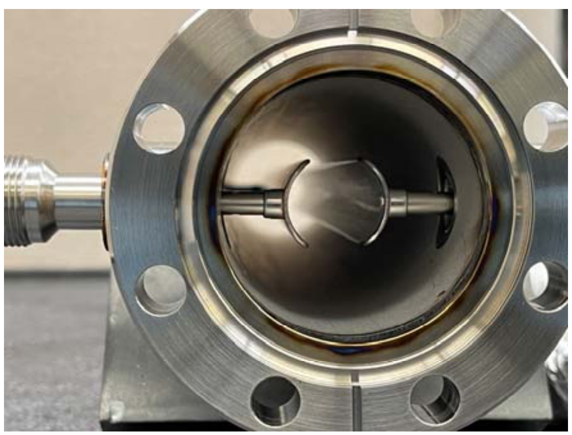
TEM Kickers for LCLS-1

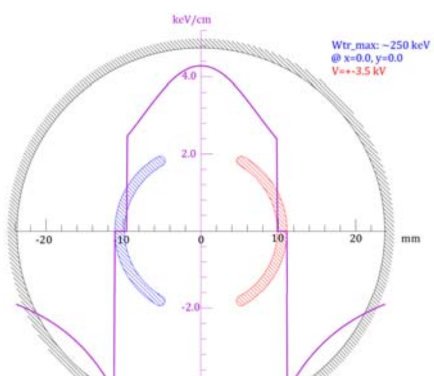


$$W_{tr} = 4.3[kV] \cdot 2.38\left[\frac{1}{cm}\right] \cdot 30[cm] \cong 307[keV]$$

LCLS-1: Multi-bunch mode operation with SLEDed linac,
Transverse orbit correction of the selected bunch.



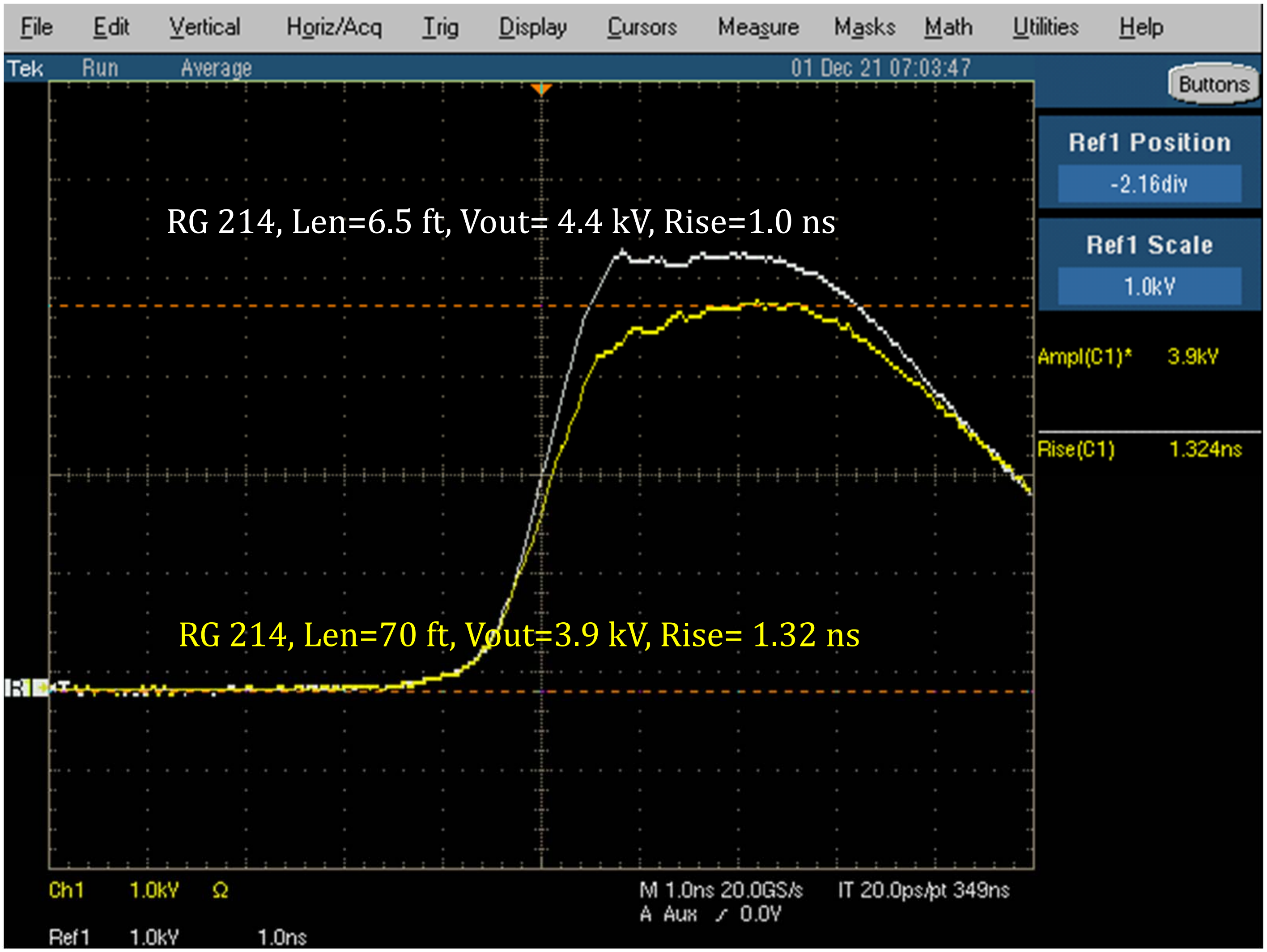




Electrodes and housing are made from standard pipes (a cost-effective solution).

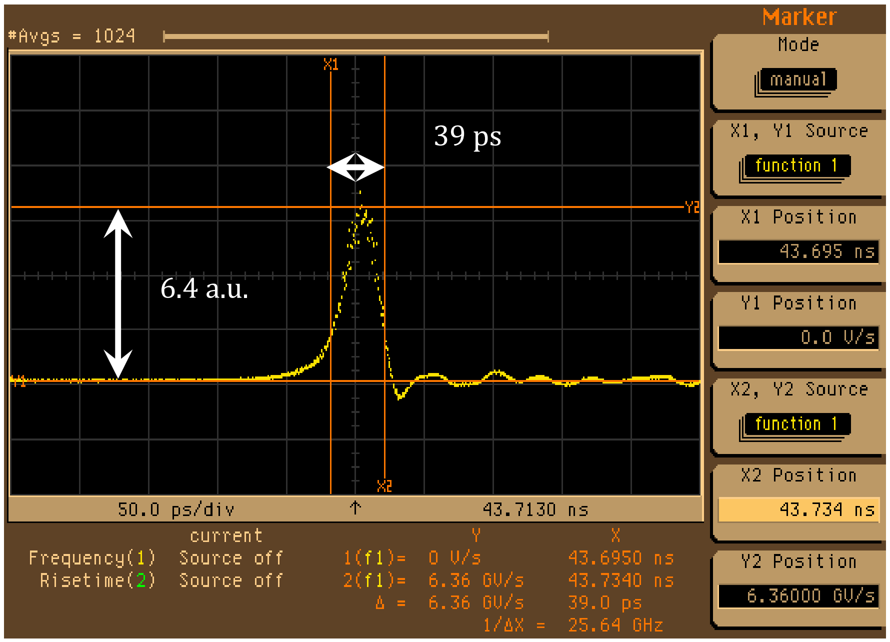
Two kickers have been installed on Cu linac.
See our articles in IPAC21 and on
https://iopscience.iop.org/article/10.1088/1748-0221/17/11/P11031

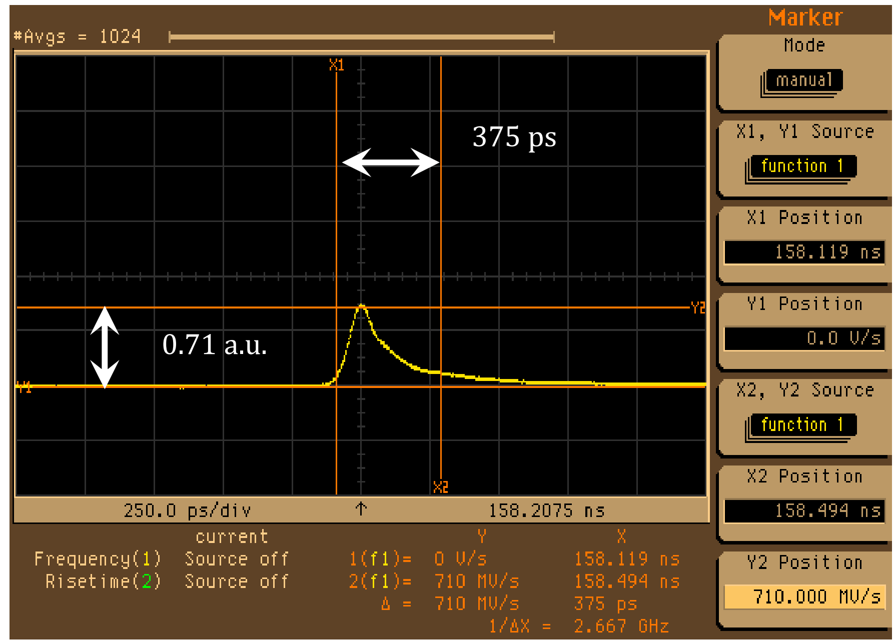
Pulse Distortion in the 70FT Long RG 214 Coax



A 40 ps Pulse Attenuation in a 70 ft RG 214 Coax

An evaluation of the beam induced power on the kicker pulser output

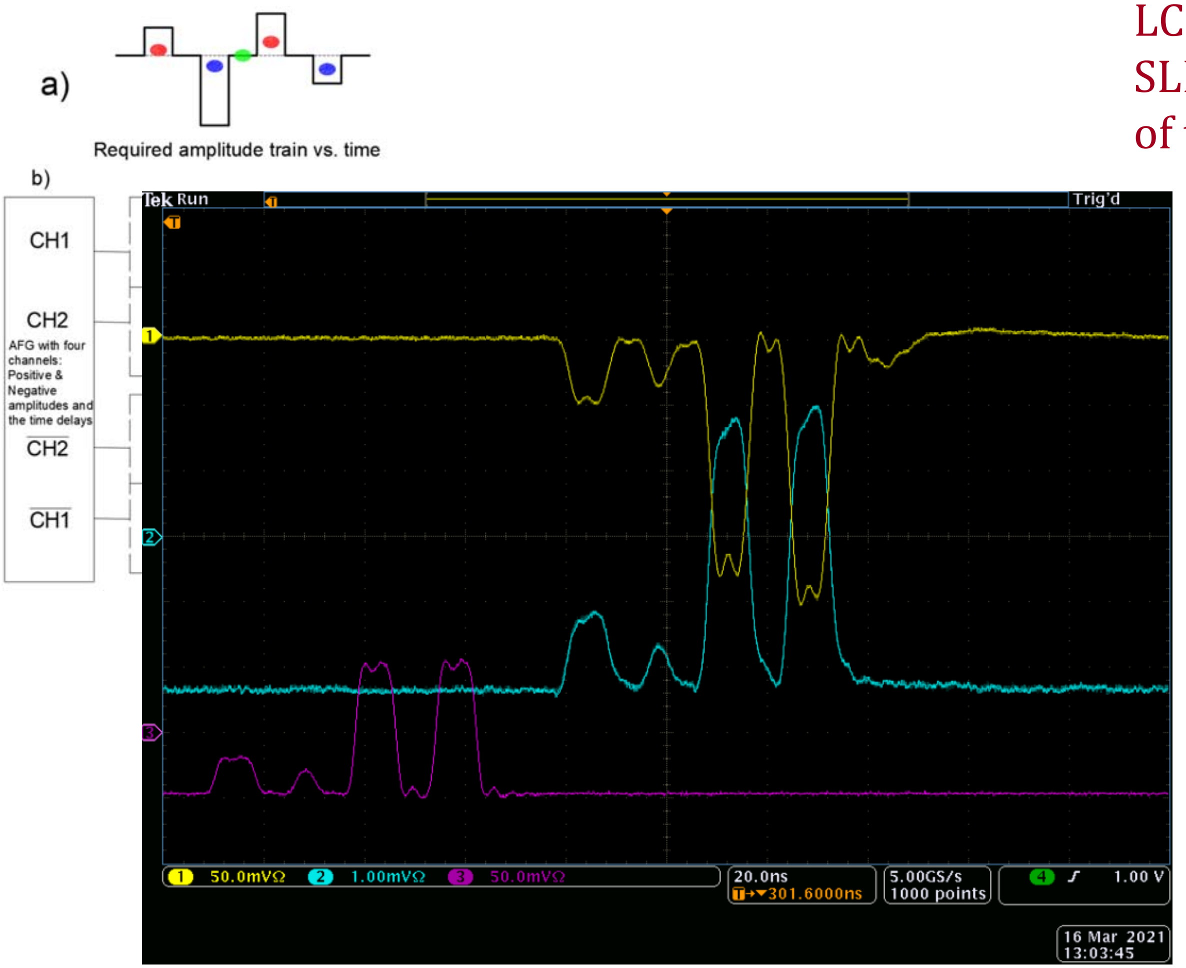




Experiment: $Att = \dfrac{6.24}{0.71} \cong 8.8\ (19\ dB\ @\ 12\ GHz)$

Calculation: A copper coax with the PTEE dielectric, OD=7.24 mm, ID=2.26 mm, Len=21 m will give a 19.7 dB composite loss. A cutoff frequency is ~14 GHz

TEM Kickers Driven by Broadband SS Amplifiers in the Nanosecond Pulse Mode



LCLS-1: Multi-bunch mode operation with SLEDed linac; Transverse orbit correction of the selected bunch; Feedback

Voltage $\leq 700\ V_p$

$(P_{peak}^{max} = 10\ kW_p$ @ 50 Ohm)

Kicker length: 30 cm

Kicker aperture: 20 cm

Max transvers kick: 50 kV

Pulse Train During <50 ns

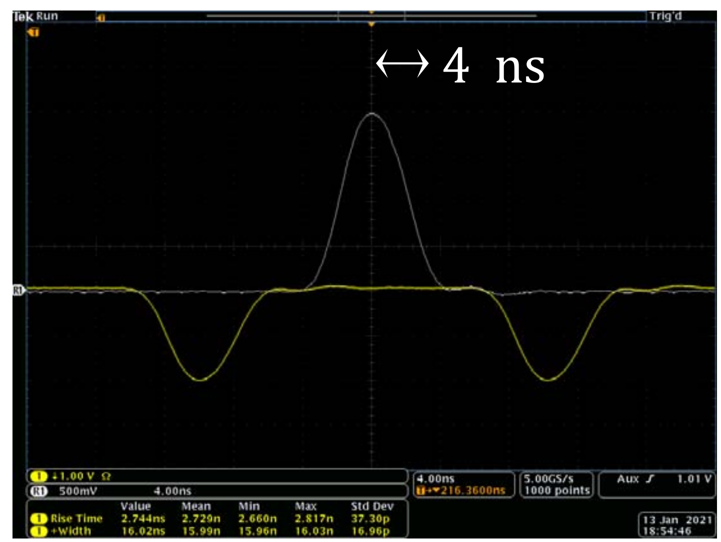
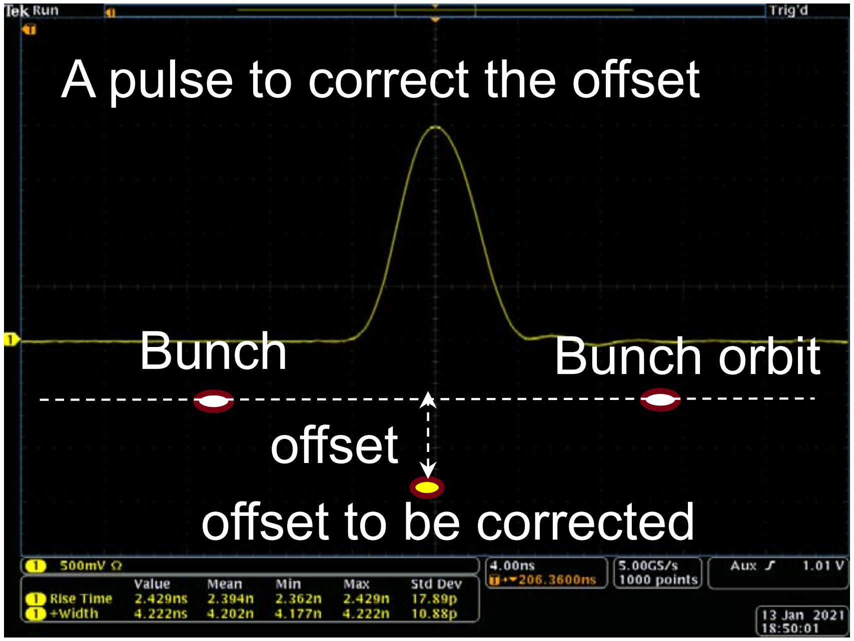
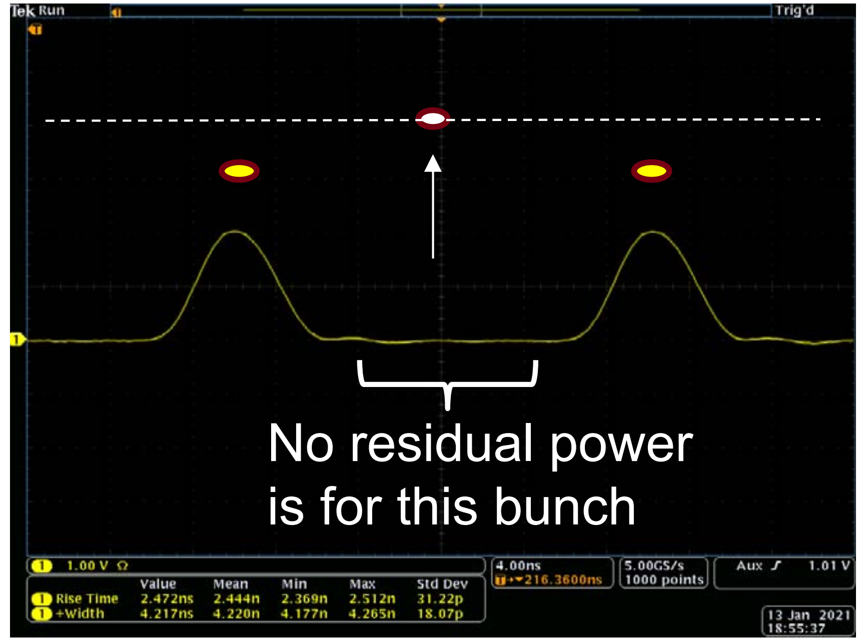
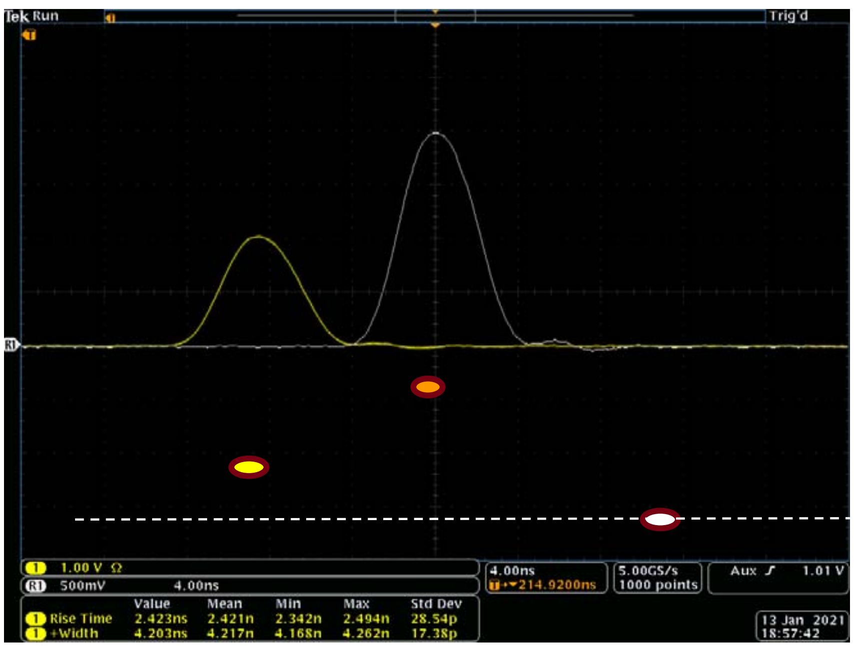
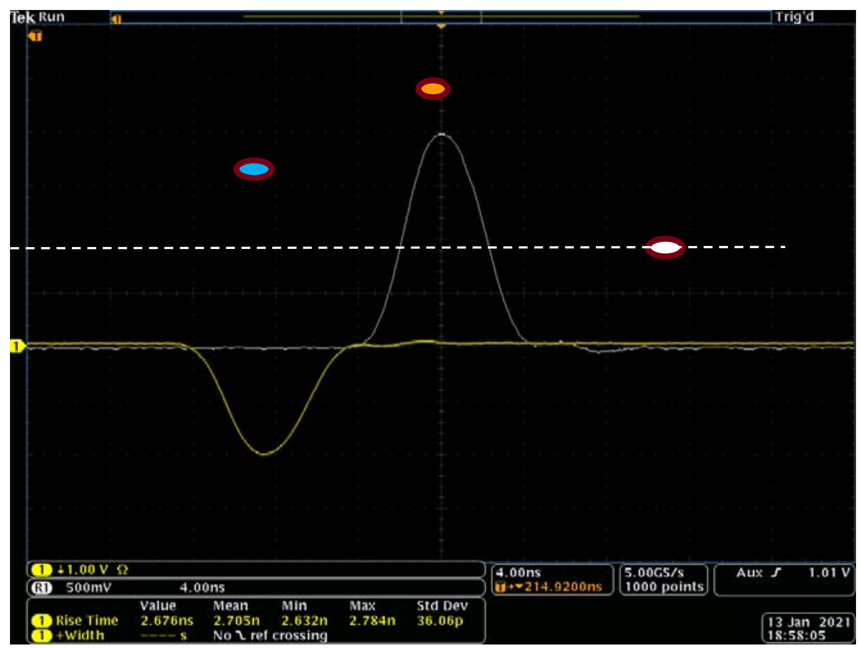


Illustration of Potential Modes Operations



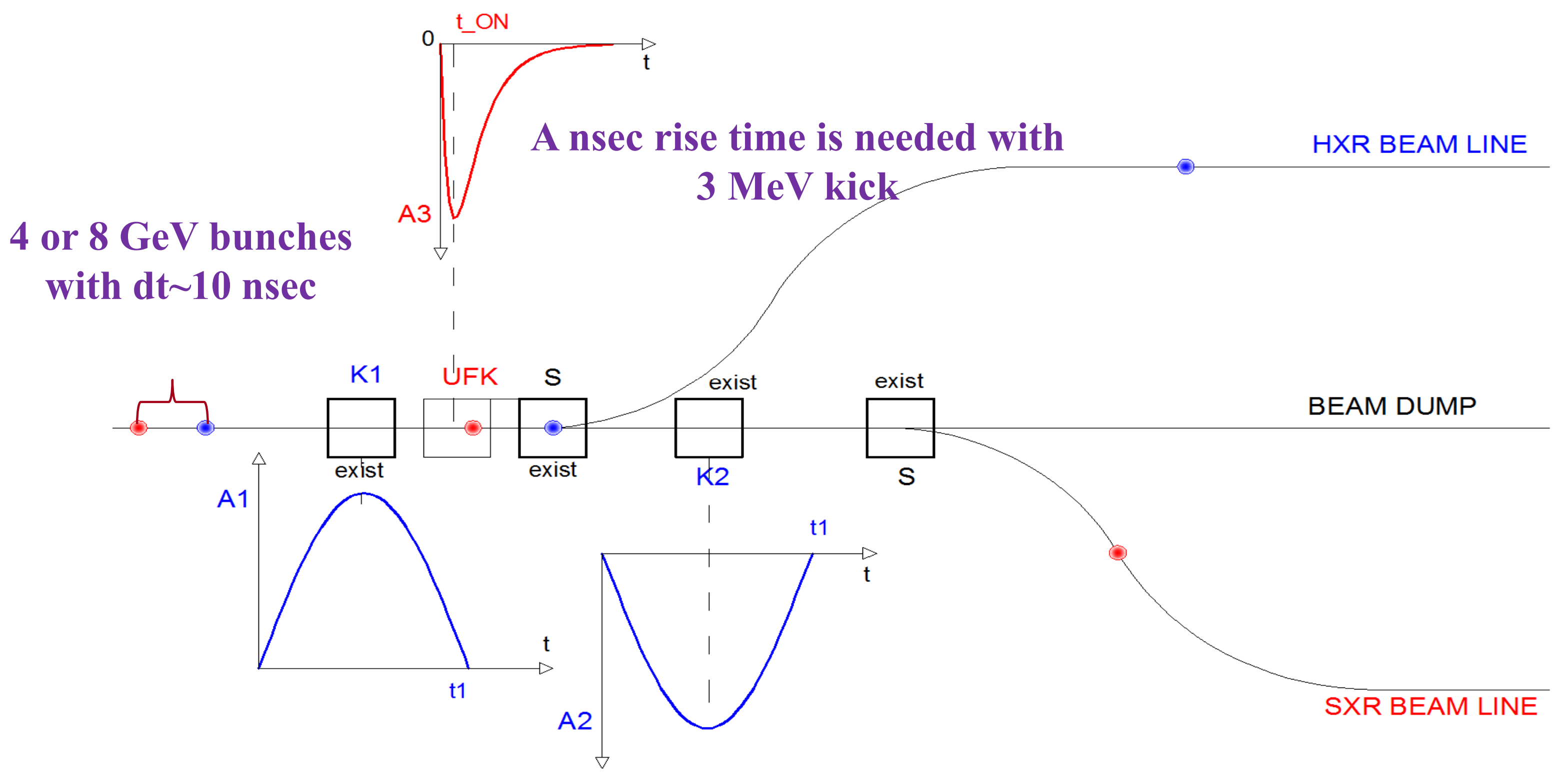






LCLS-II Pump-Probe Experiments

LCLS-II Beamline with a 14 RF Bucket Bunch Separation



One bunch would go to the SXR undulator and the other to the HXR undulator. The resulting x-rays, of different color, would be recombined for pump-probe experiments.

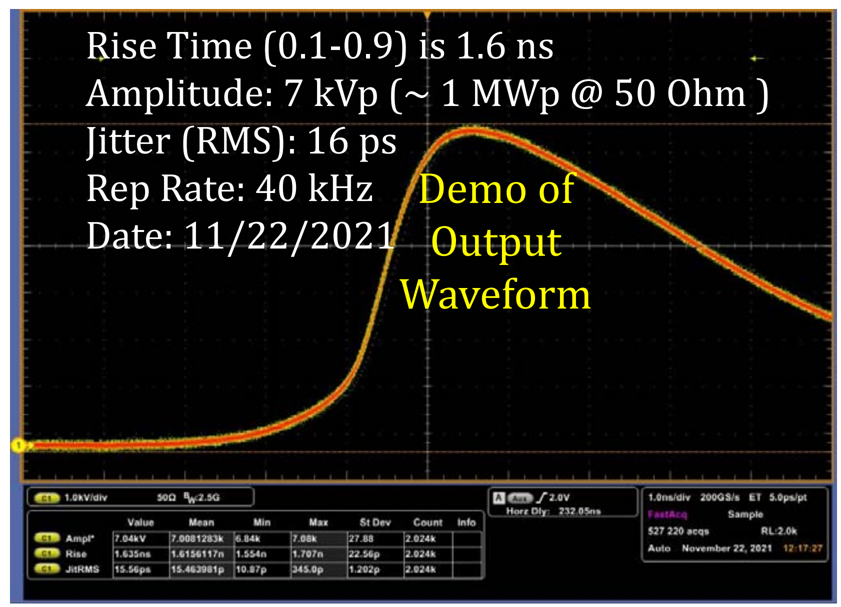
Add ultrafast kickers to the existing spreader kicker system to allow separation of two closely spaced bunches for two color experiments.

See our presentation on 38th FEL conference

TEM Kickers for the LCLS-II Two Color Experiments

The initial spec of the pulser rep rate was 1 kHz. A target of the rep rate spec is lifted (several tens of kHz).

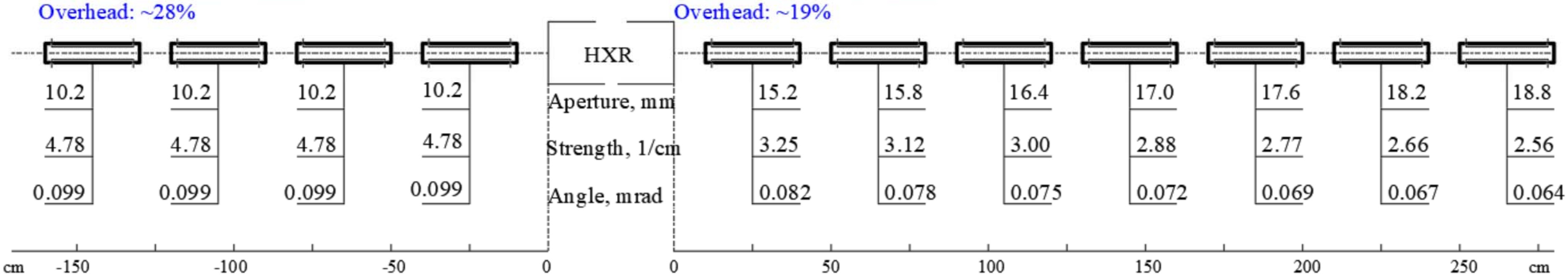
- A benchmark demo: 1 kW power supply to feed the kicker pulser is used.
- The pulser circuit layout is the like the LCLS-I kicker pulser.
- The pulser charging circuit is upgraded accordingly for a kHz repetition rate.



An Ultra-fast Kicker Layout at an 8 GeV Beam

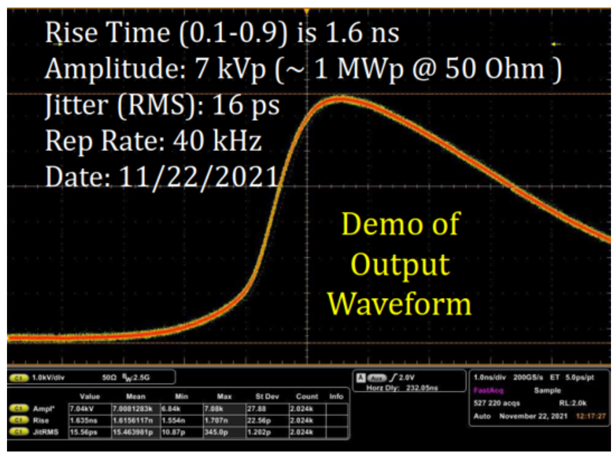
A 8 GeV beam, TEM kickers before the HXR kickers
Layout Pattern: V=+_5.5 kVp, Len=30 cm, gap=10 cm
Total angle: 0.396 mrad
Required angle: 0.3097 mrad
Overhead: ~28%

A 8 GeV beam, TEM kickers after the HXR kickers
Layout Pattern: V=+_6.7 kVp, Len=30 cm, gap=10 cm
Total angle: 0.508 mrad
Required angle: 0.434 mrad
Overhead: ~19%



$$W_{tr}^{require} = 8 \cdot 10^{9} \cdot 0.31 \cdot 10^{-3} \cong 2.48\ MeV$$

$$W_{tr}^{demo} = 7 \cdot 10^{3} \cdot 4.8 \cdot 30 \cdot 4 \cong 4\ MeV$$



$$W_{tr}^{require} = 8 \cdot 10^{9} \cdot 0.434 \cdot 10^{-3} \cong 3.47\ MeV$$

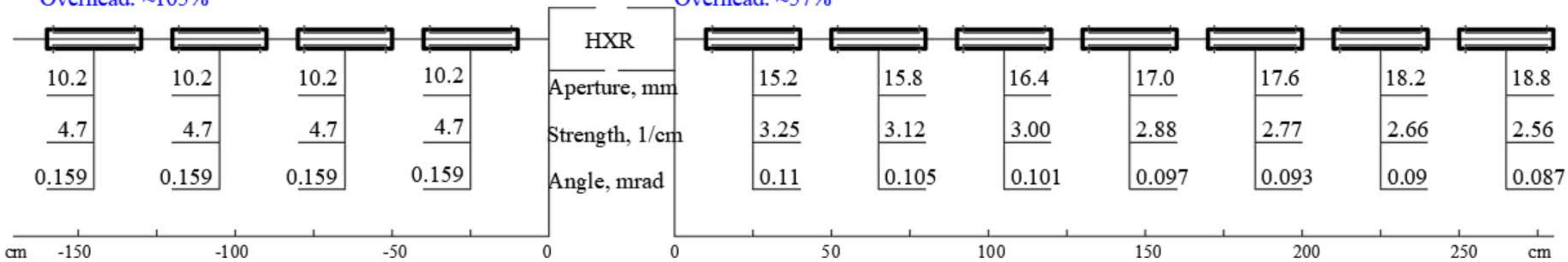
$$W_{tr}^{demo} = 7 \cdot 10^{3} \cdot < 2.9 > \cdot 30 \cdot 7 \cong 4.26\ MeV$$

The ultra-fast kicker system can deliver the required transverse kick for an 8 GeV beam at a 40 kHz repetition rate.

An Ultra-fast Kicker Layout at a 4 GeV Beam

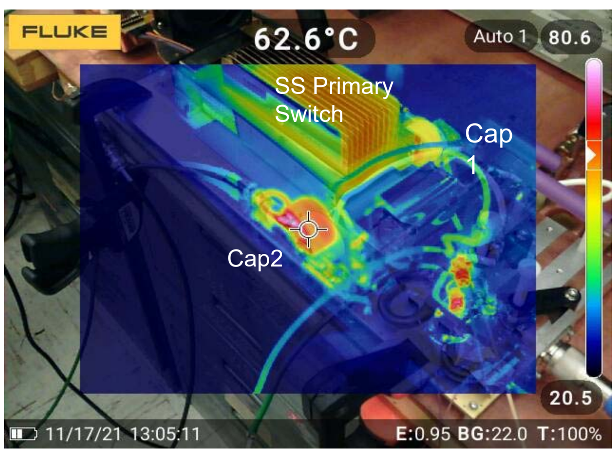
4 GeV beam, TEM kickers before the HXR kickers
Layout Pattern: V=+_4.5 kVp, Len=30 cm, gap=10 cm
Total angle: 0.635 mrad
Required angle: 0.3097 mrad
Overhead: ~105%

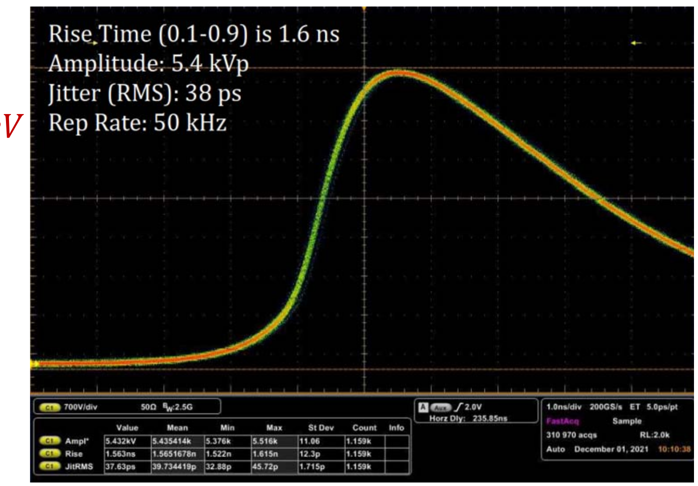
4 GeV beam, TEM kickers after the HXR kickers
Layout Pattern: V=+_4.5 kVp, Len=30 cm, gap=10 cm
Total angle: 0.683 mrad
Required angle: 0.434 mrad
Overhead: ~57%



$$W_{tr}^{require} = 4 \cdot 10^9 \cdot 0.31 \cdot 10^{-3} \cong 1.24\ MeV$$

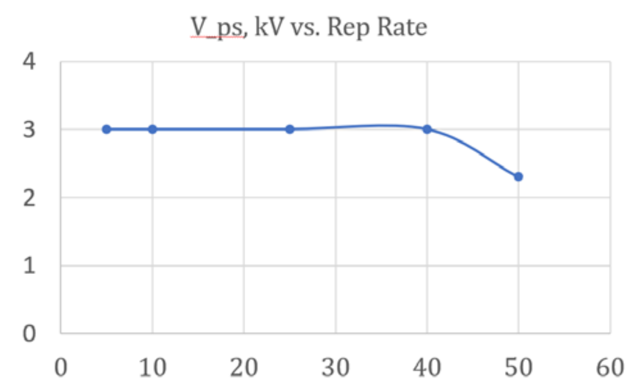
$$W_{tr}^{demo} = 5.4 \cdot 10^3 \cdot 4.7 \cdot 30 \cdot 4 \cong 3\ MeV$$



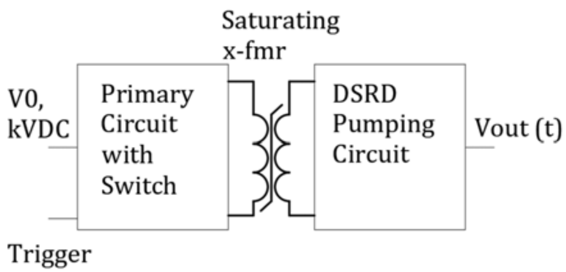


$$W_{tr}^{require} = 4 \cdot 10^9 \cdot 0.434 \cdot 10^{-3} \cong 1.74\ MeV$$

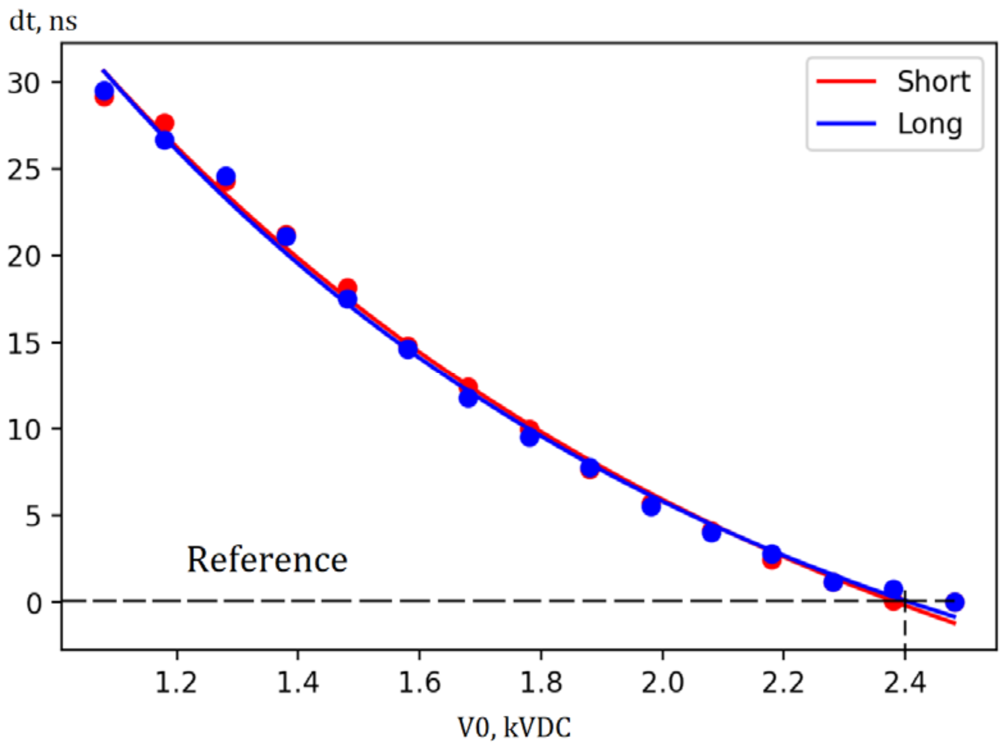
$$W_{tr}^{demo} = 5.4 \cdot 10^3 \cdot < 2.9 > \cdot 30 \cdot 7 \cong 3.2\ MeV$$



The ultra-fast kicker system can deliver the required transverse kick for a 4 GeV beam at a 50 kHz repetition rate.



A circuit with the saturating core transformer is a one simple way to form the DSRD mode operation. It allows easily to build the pulser with the positive and negative polarities. One drawback to employ this circuit topology is a fact that there is a strong time dependence of the output pulse vs. the charging voltage.



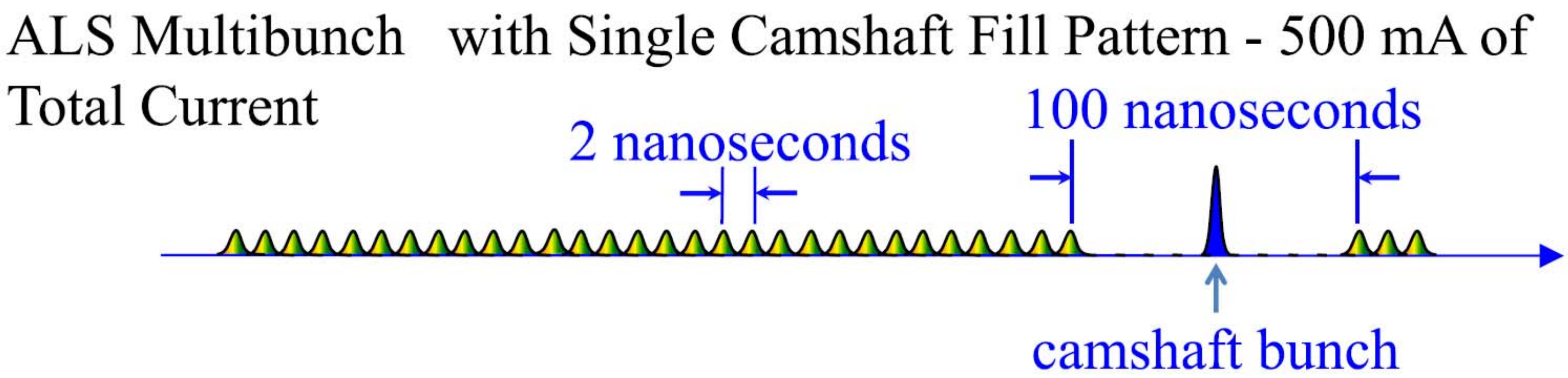
A synchronization with the bunch must be corrected accordingly to a value of the output pulser voltage (the transfer kick).

The delay function was fit with a polynomial function and pre-compensated automatically in the process of machine tuning in LCLS-I case.

There are DSRD pumping circuits without the saturating x-fmrs, which will be discussed in the next slides.

A Pulser for the Camshaft Bunch in Storage Ring

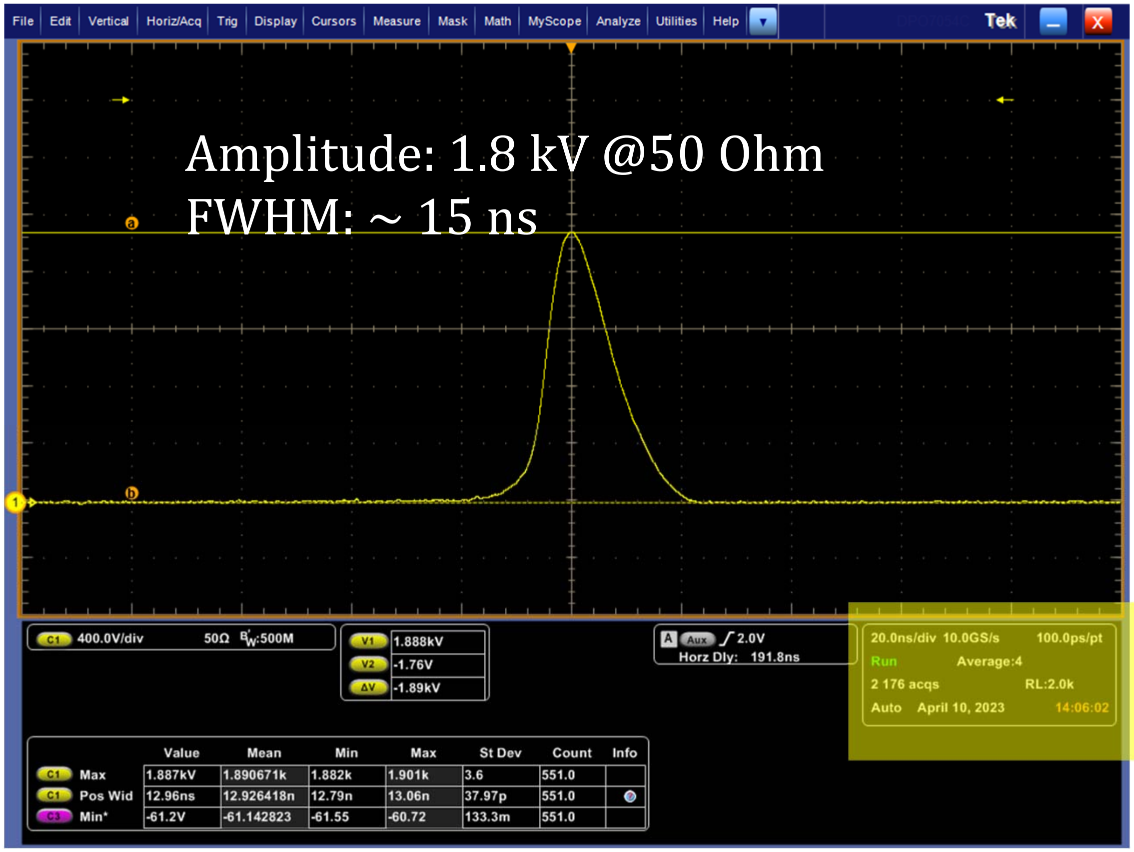
A specialized bunch pattern are used in many existing synchrotron rings. The fill pattern consists the ion-cleaning gap and multiple uniform bunch train with mini-gaps between them. There are a user request to place a single high current bunch ("camshaft bunch") that located in the middle of the ion-clearing gap (see, for example, fill patterns in ALS, NSLS, MAX IV. BESSY. etc.).

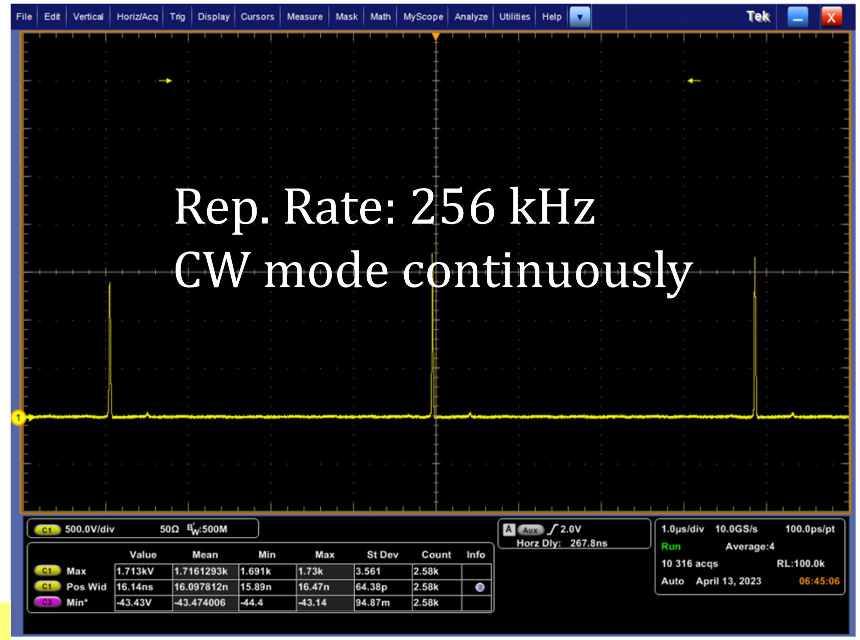


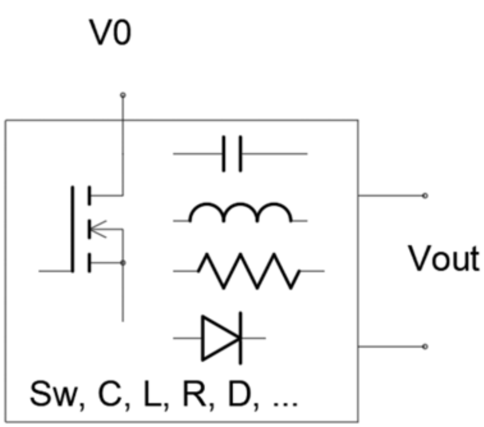
Courteously C. Sun, LBNL, Physical Review Letters, 2012

To control the camshaft bunch orbit, a nanosecond range kick is needed with a revolution frequency repetition rate. The revolution rate is in MHz range.

A 256 kHz Pulser for the Camshaft Bunch in Storage Ring as an Example







Pulser: V0=350 VDC, ~0.9A

Circuit Layout: Transformerless, unidirectional cycle *)

Storage Capacitor: 5.1 nF (mica)

Inductor: 15 turns, OD=0.35", d=0.051"

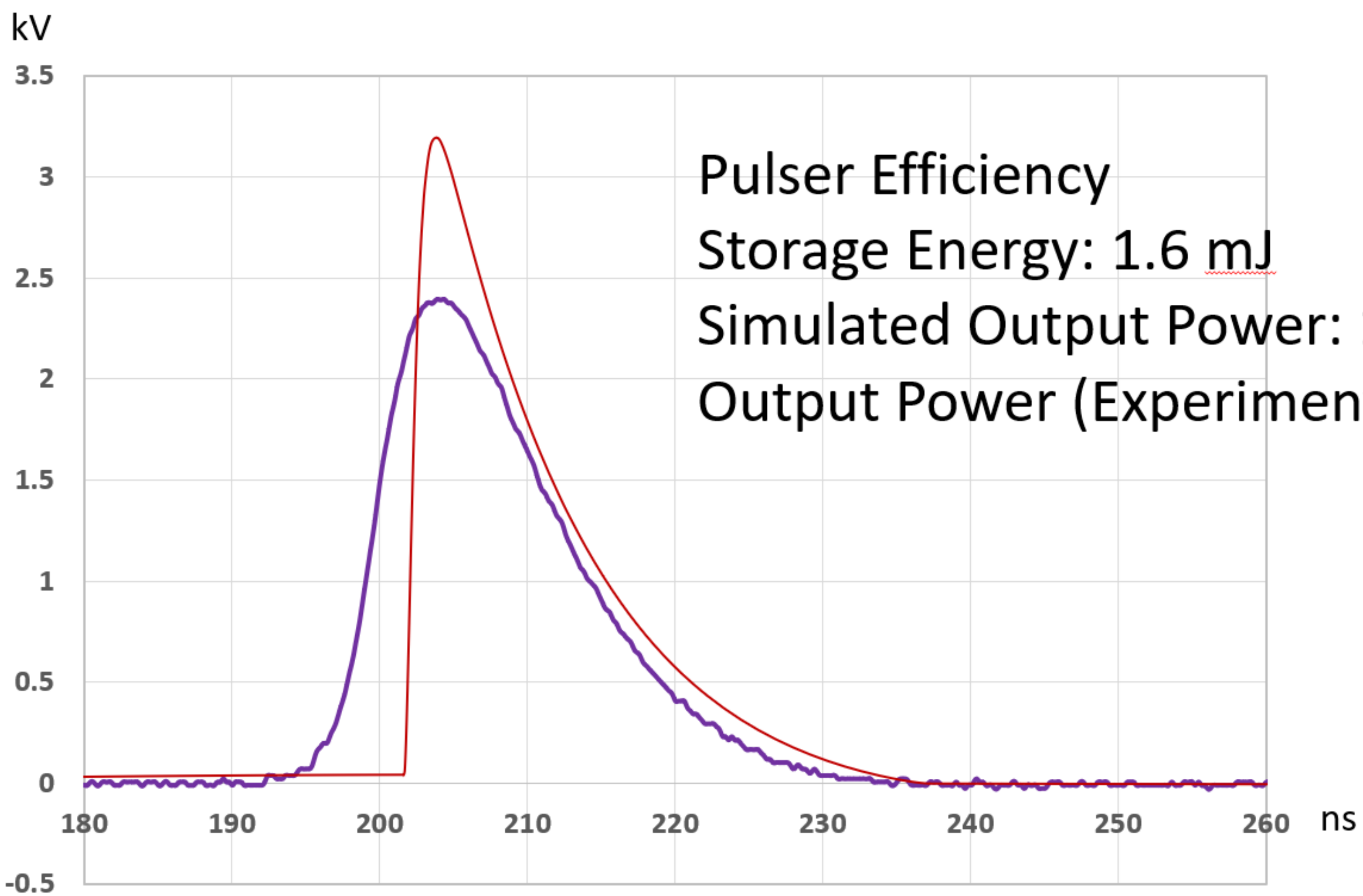
Primary Switch: Two MSC080SMA330B4 SiC MOSFETs

Output: one DSRD cell

Pulser Efficiency: ~70%

*) A circuit layout is like the W. Melville's cascade-discharge-circuit which was published in 1950th.

Output Pulse (Result of Simulation vs Experiment)



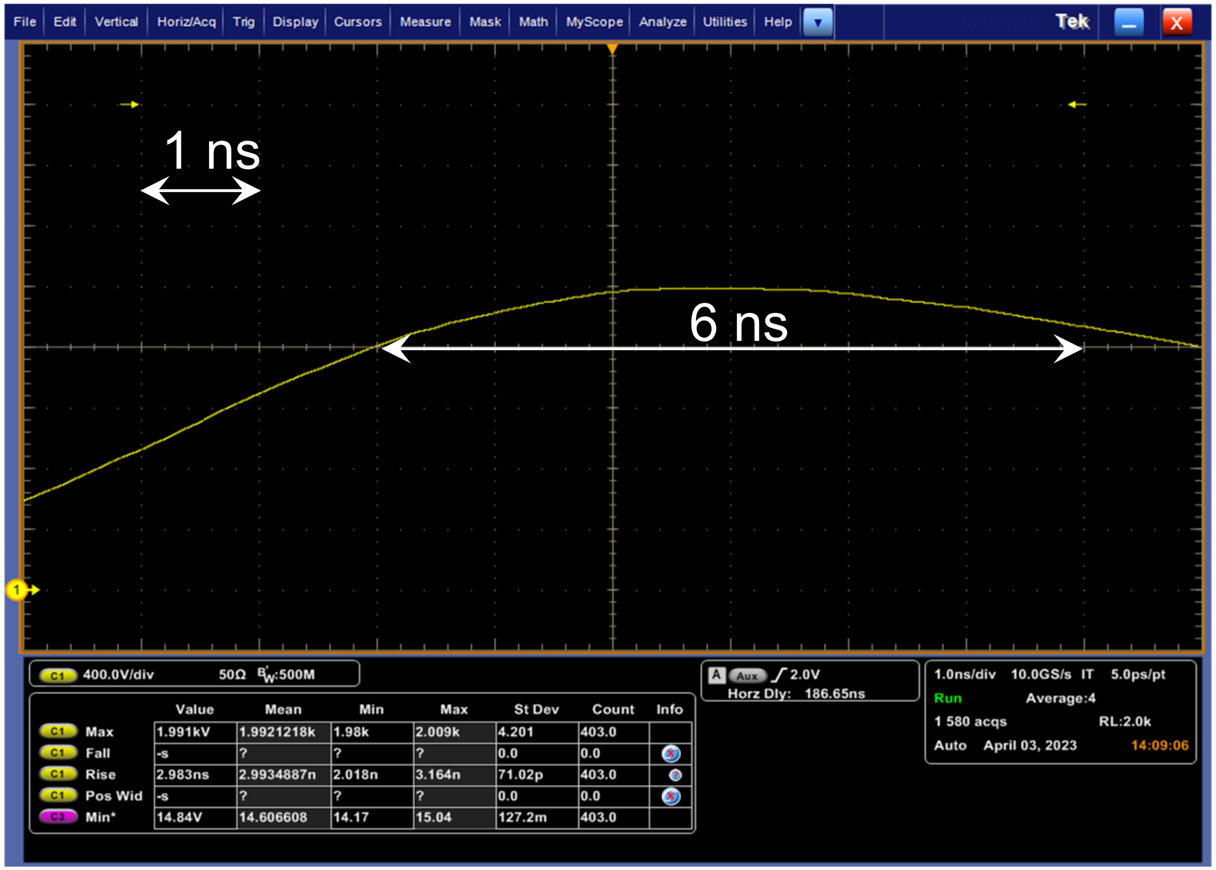
Pulser Efficiency

Storage Energy: 1.6 mJ

Simulated Output Power: 1.33 mJ (83%)

Output Power (Experiment): 1.15 mJ (72%)

A 1.28 MHz Kicker System for the Camshaft Bunch in Storage Ring



Speculation

Kicker Length: 900 mm

Kicker Aperture: 15 mm

Pulser Amplitude: 1.8 kV

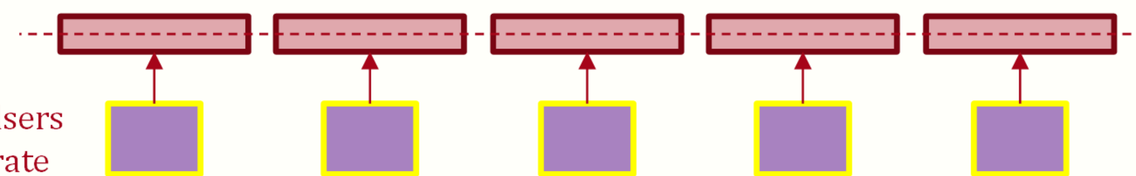
Transvers Kick: ~500 keV

A kick angle is 170 urad
for a 3 GeV storage ring.

For example,

~ 5 m

5 ea. kickers



10 ea. +_ polarity pulsers
with a 256 kHz rep. rate

$5 \cdot 256\ kHz = 1.28\ MHz$ => Revolution Period

A time trigger delay between the neighbor pulsers is equal to one revolution time.

Conclusion

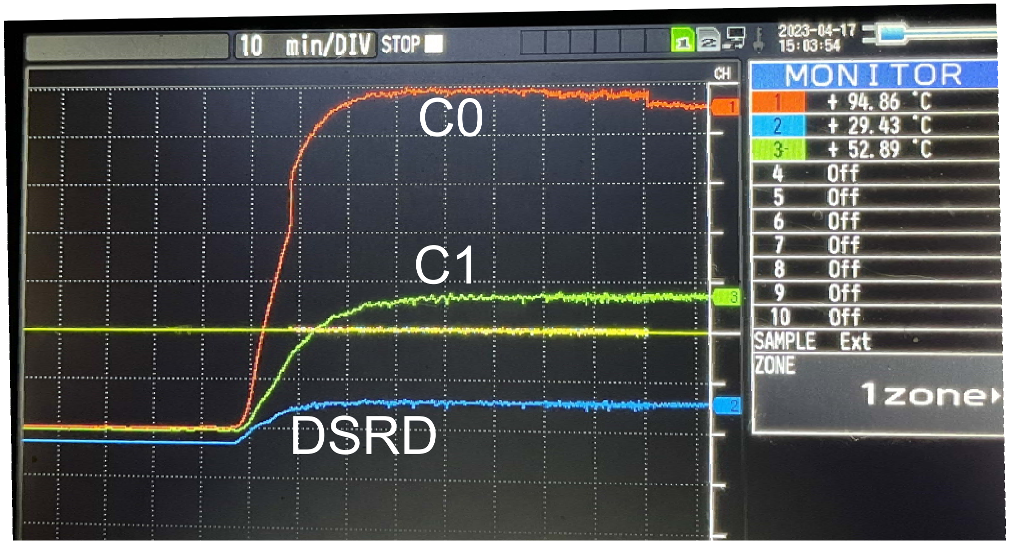
A cost-effective technical solutions for the TEM kicker structures and their power systems were discussed.

The LCLS-I arrangement with the kicker system was considered. Experiments with kickers, which were installed on the first instrument section of LCLS-I, demonstrated the growth of FEL capabilities in the multi-bunch mode.

The two-color LCLS-II beamline requires an ultra-fast kicker system capable of a stable operation at repetition rates in kHz. Our experiments show that the developed pulse generators can provide the required transverse kick for an 8 GeV beam at a repetition rate of 50 kHz with an RMS temporal jitter of 20 ps.

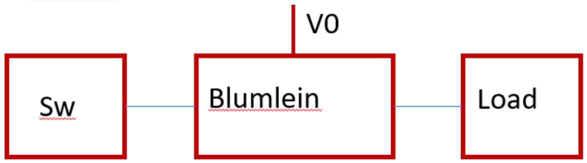
A MHz-rate kicker system for the camshaft bunch in storage rings is discussed. A potential 1.28 MHz kicker system is discussed as an example. A current proposal includes five kickers driven with a 256 MHz pulse repetition rate. A time trigger delay between the neighbor pulsers is equal to one revolution time. An experimental work on a further developing of the pulser for the camshaft bunch is continuing.

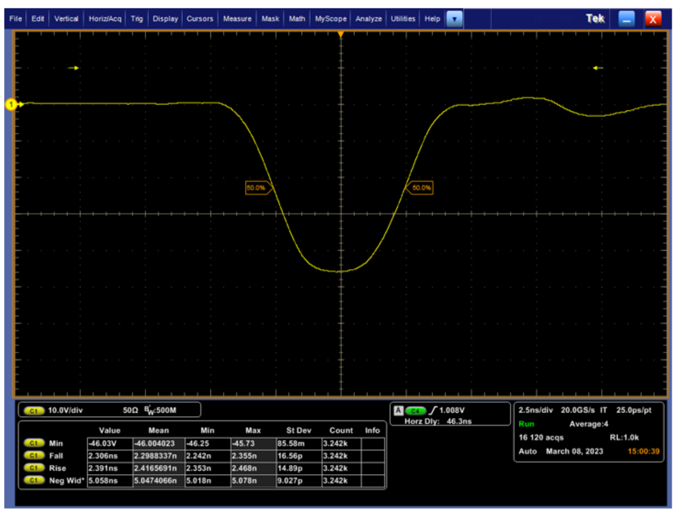
Work supported by US Department of Energy contract DE-AC02-76SF00515

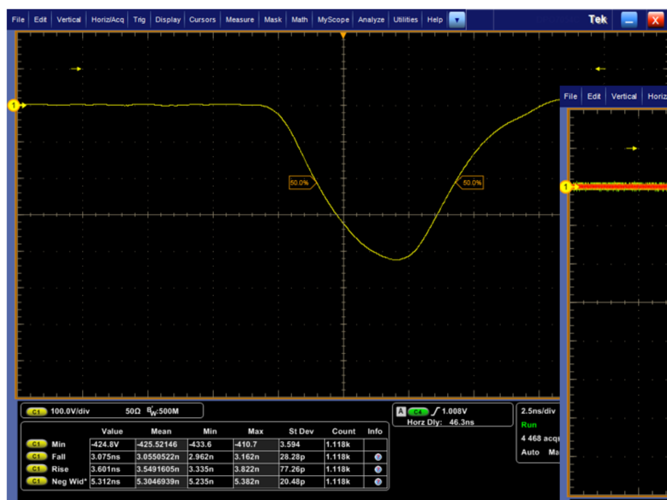


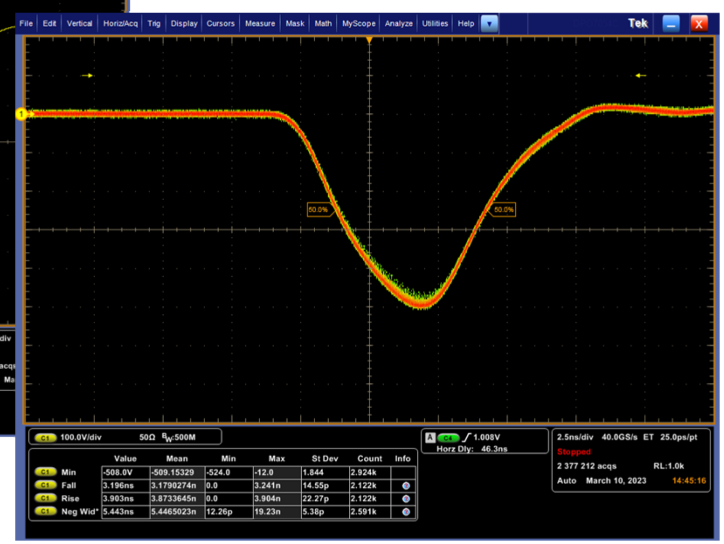
A Couple of Backup Pictures

Test of GaN GPIHV30SB5L at 100 kHz Rep Rate









V0

tf=2.3 ns

10*V0

tf is 35% higher