SLAC-WP-096

Analysis of Approaches for a Design of APS-U Fast Injection System

For Mini Kicker Work Shop in ANL

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10/25/2013

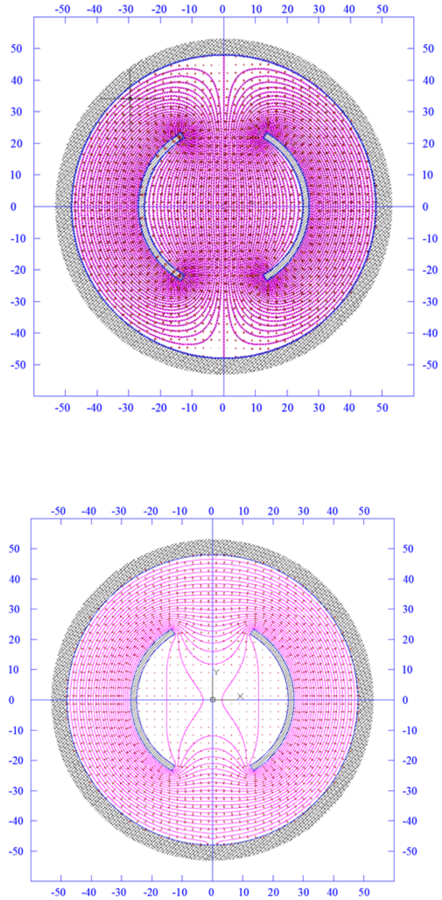
Work supported by US Department of Energy contract DE-AC02-76SF00515 and BES.

Outline

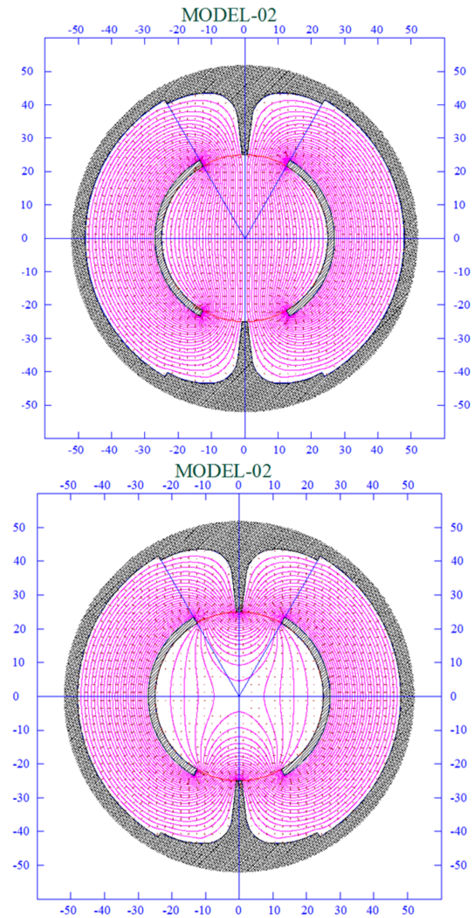
- Approaches for Broadband Kicker Structures
  - Even and Odd TEM-modes
  - Kicker directivity
  - Kicker end effects
  - Kicker components (feedthrough, electrodes, etc.)
- Analysis for Kicker Drivers
  - Thyratron (or Pseudo-Spark) based approaches
  - Shock wave transmission lines as an assist of fast pulsers
  - MOSFET based pulser concepts
  - DSRD as an assist for fast pulsers

Some additional details related to this issue could be found in SLAC-WP-077, SLAC-WP-078, SLAC-WP where the ILC DR fast TEM-mode kicker problems and other issues of a HP nsec technology had been discussed.

TEM-mode Even and Odd Kicker Impedances



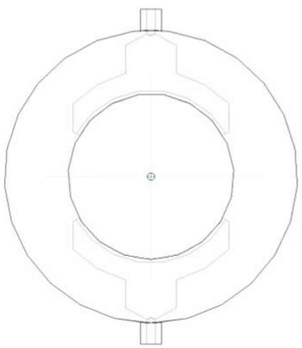
Zodd = 50 Ohms
Zeven = 64 Ohms

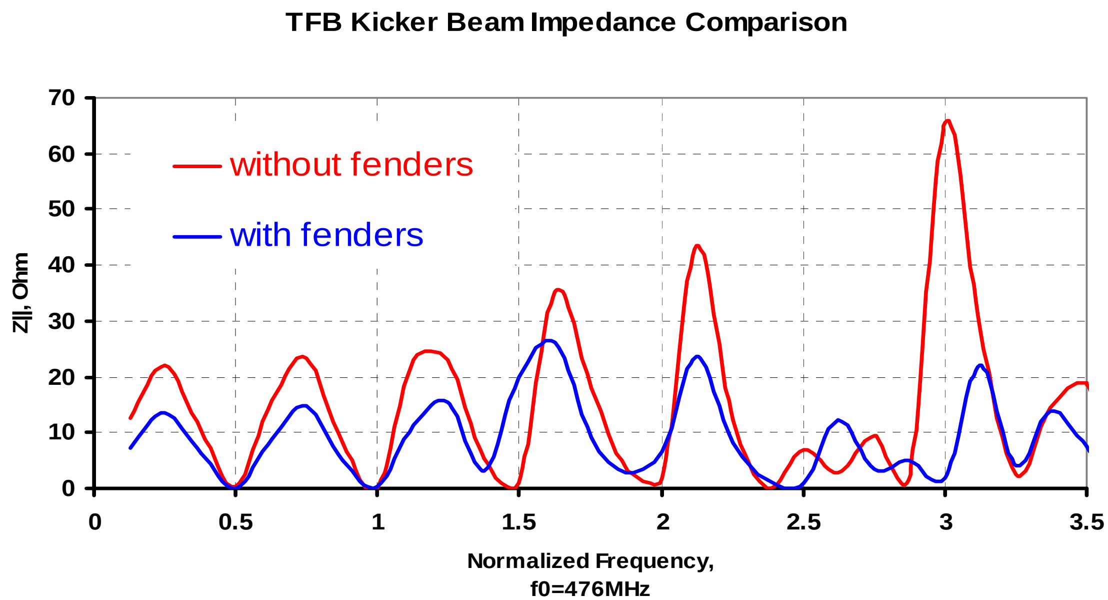


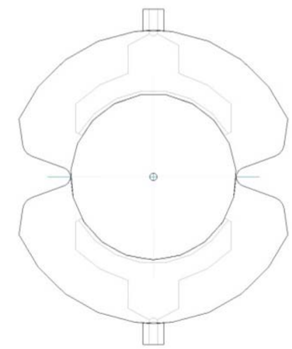
Zodd = 49 Ohms
Zeven = 55 Ohms

- Pulsers produce a transvers kick. The odd TEM mode is excided.
- The bunch pusses a kicker structure without offset. The even TEM mode is generated in the kicker structure.
- The field patterns for modes are dissimilar. As a result the impedances are different.
- Matching both impedances is possible by the introduction of the ground fenders.
- Additional fenders will reduce the beam impedance and will help the SR beam dynamics.

Kicker Electrodynamics: Ground Fenders







Beam Impedance Ratio for the (59.5-1725.5) MHz range is ~1.6.
This ratio is reduced for the higher frequencies (in 3.6-5 normalized frequency range). Geometry of the kicker ends (geometry of paddles and absence of tapering on the electrode ends, i.e. the absence of transient region) are dependable for a reduction of Beam Impedance Ratio.

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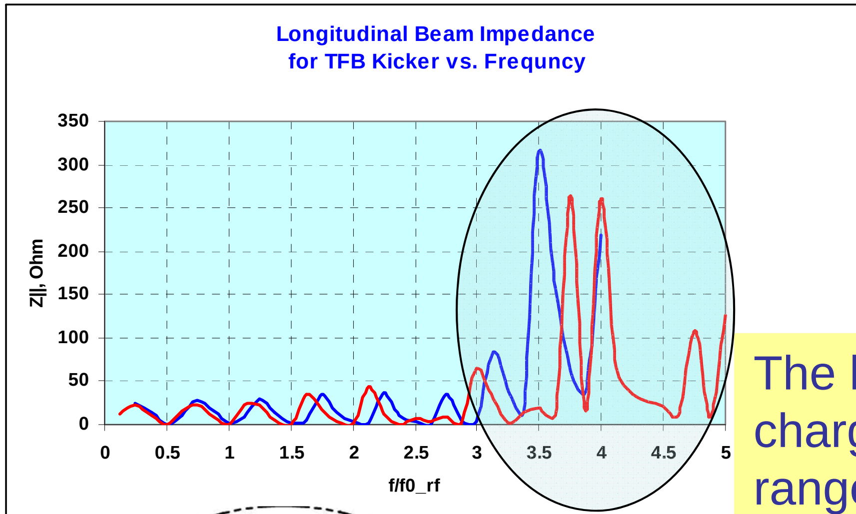
Lesson Learned (LER X-TFB TEM-Kicker)

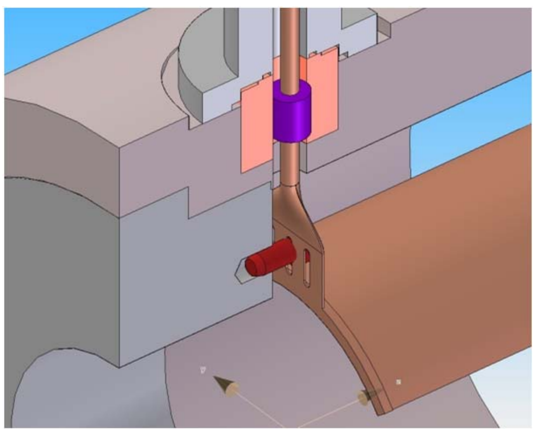


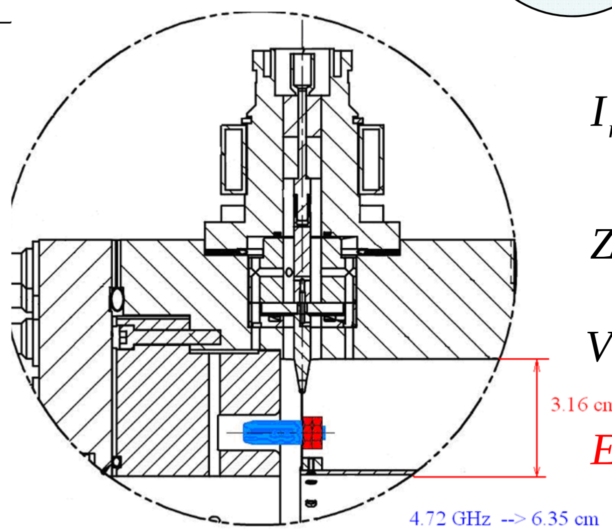
$$Z_{\parallel}^{av} \cong 34 \ \ Ohm$$

$$P_k \cong 306W \quad @3A$$

$$V_g^{av} \cong 102V$$

The kicker ends are in charge for this freq. range





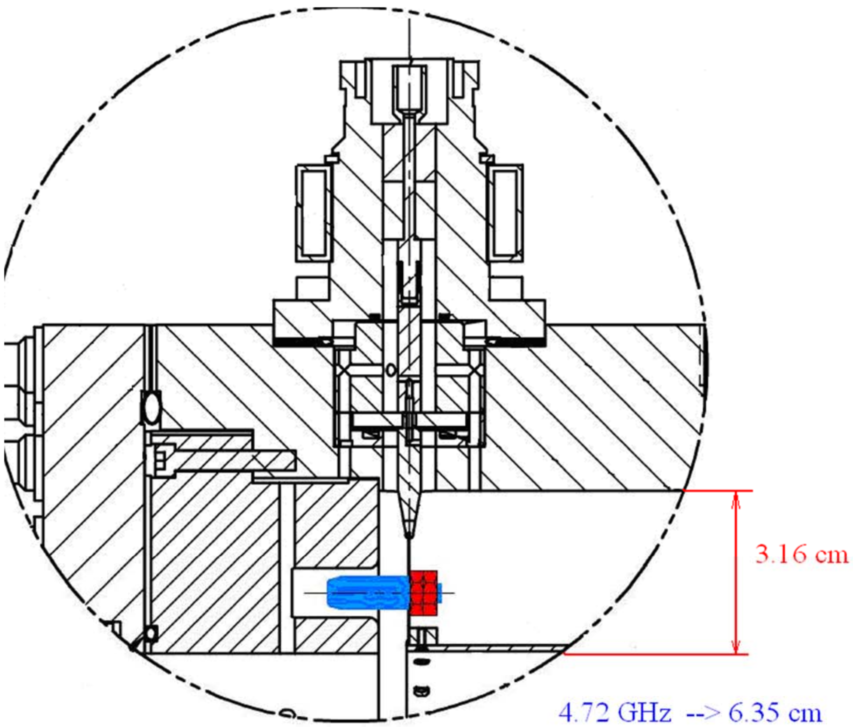
$$I_m = i_{av} \cdot \frac{T}{5\sigma_t} \cong 10^{-3} \cdot \frac{7.4 \cdot 10^{-6}}{5 \cdot 40 \cdot 10^{-12}} \cong 40A$$

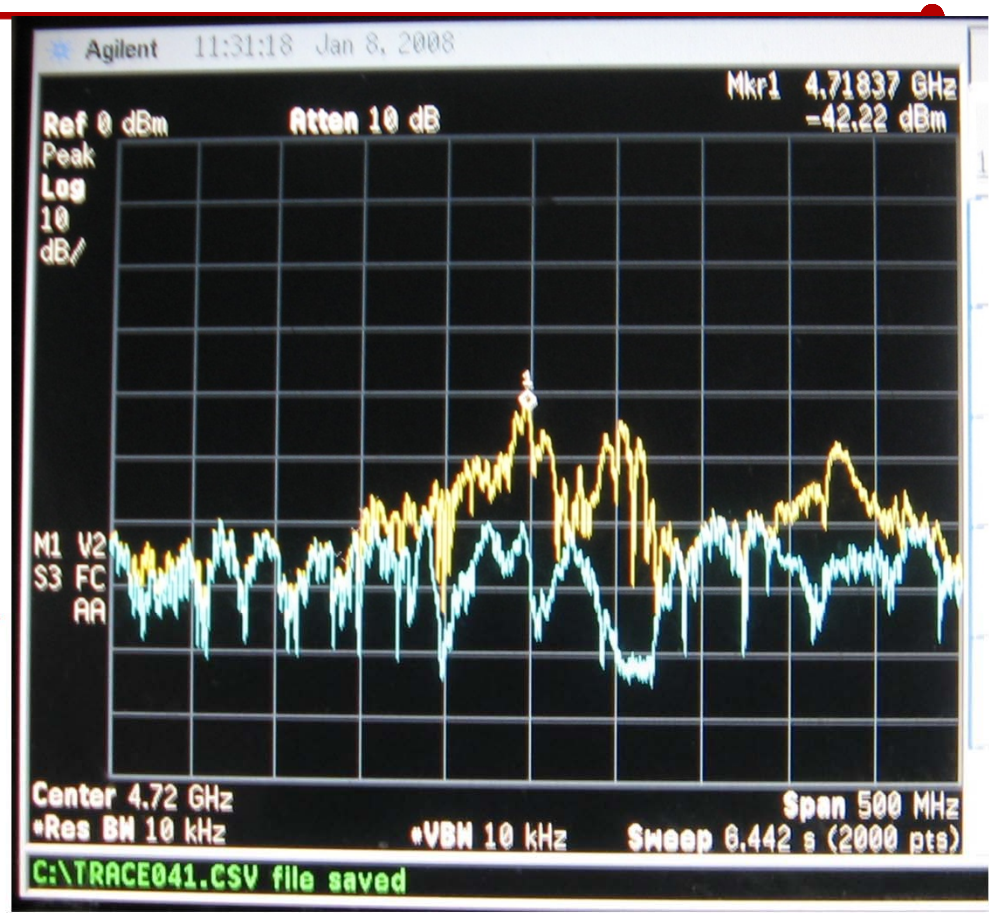
$$Z_{\parallel}^{peak} \cong 250 \ \ Ohm$$

$$V_p \cong Z_{\parallel} \cdot I_m = 10 \ \ kV$$

$$E_{surf} \cong 20 \ \ \frac{kV}{cm} > E_{\lim}$$

Lesson Learned (LER X-TFB TEM-Kicker)





A tapered ends are needed

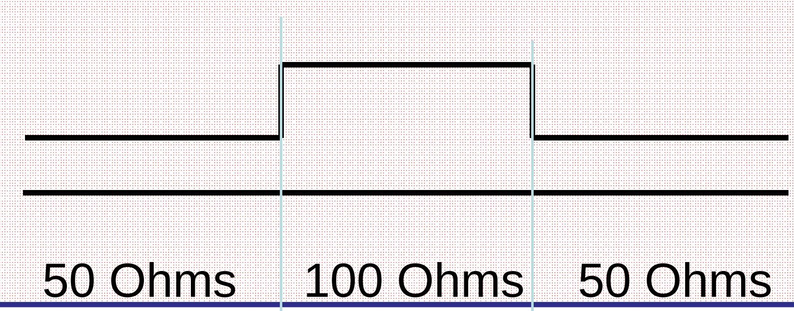
Does mismatch be allowed?

- Bunch pattern:
  - High single-bunch charge 48-singlet
  - 324-singlet
- Total space for kickers: 3 m
- Beam energy: 6 GeV
- Total kick angle: 3 mrad
- Length of each kicker: 0.6 m
- Number of kickers: 5
- Kick angle per kicker: 0.6 mrad
- Kicker type: two-blade horizontal stripline
- Body geometry: Elliptical + Circles
- Blade geometry: Elliptical + tapered ends
- Gap between blades: 9 and 12 mm
- Differential impedance: 2x 50±0.5 Ω
- Common mode impedance: 50±5 Ω
- Design work is under way.

Quantity	Symbol	Range	Units
Total current	I	200	mA
Number of bunches	N_b	48-324	
Bunch rate	f_b	13-88	MHz
Rms bunch duration	σ_t	70-18	ps

A broadband kicker structure will be needed!

There will be an impedance mismatch



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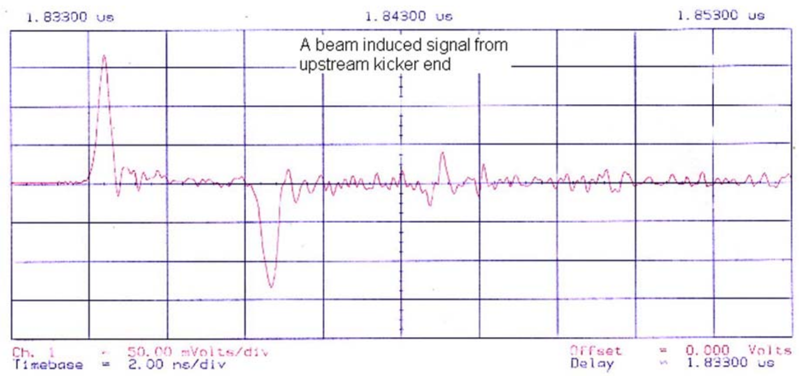
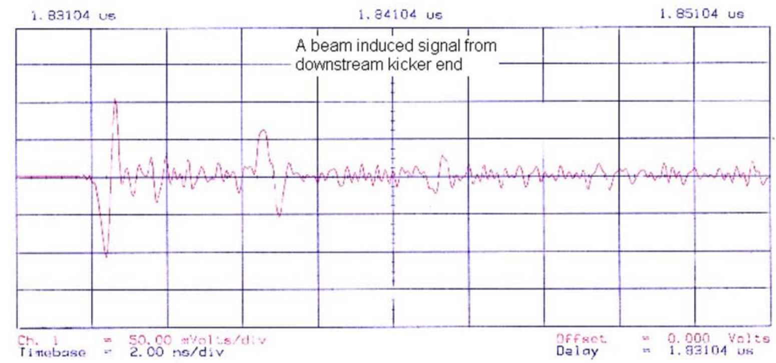
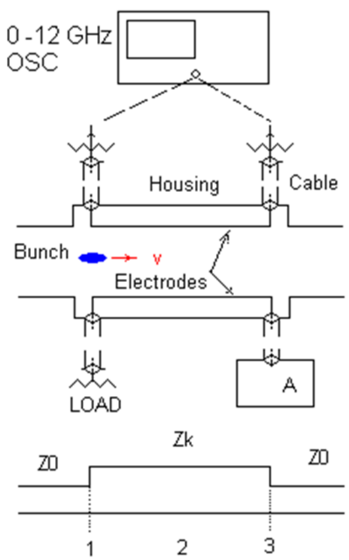
Directivity: Kicker End Effects

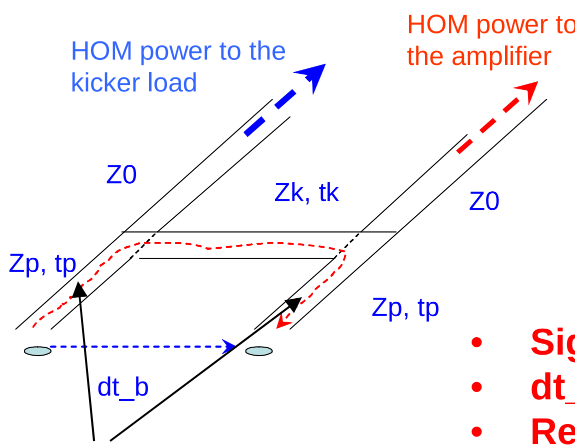
Example is based on experimental results from PEP-II



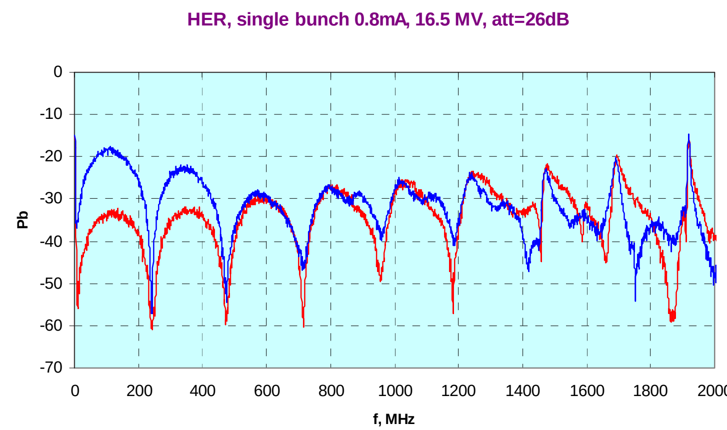




Beam induced power is
in both feeders !!!

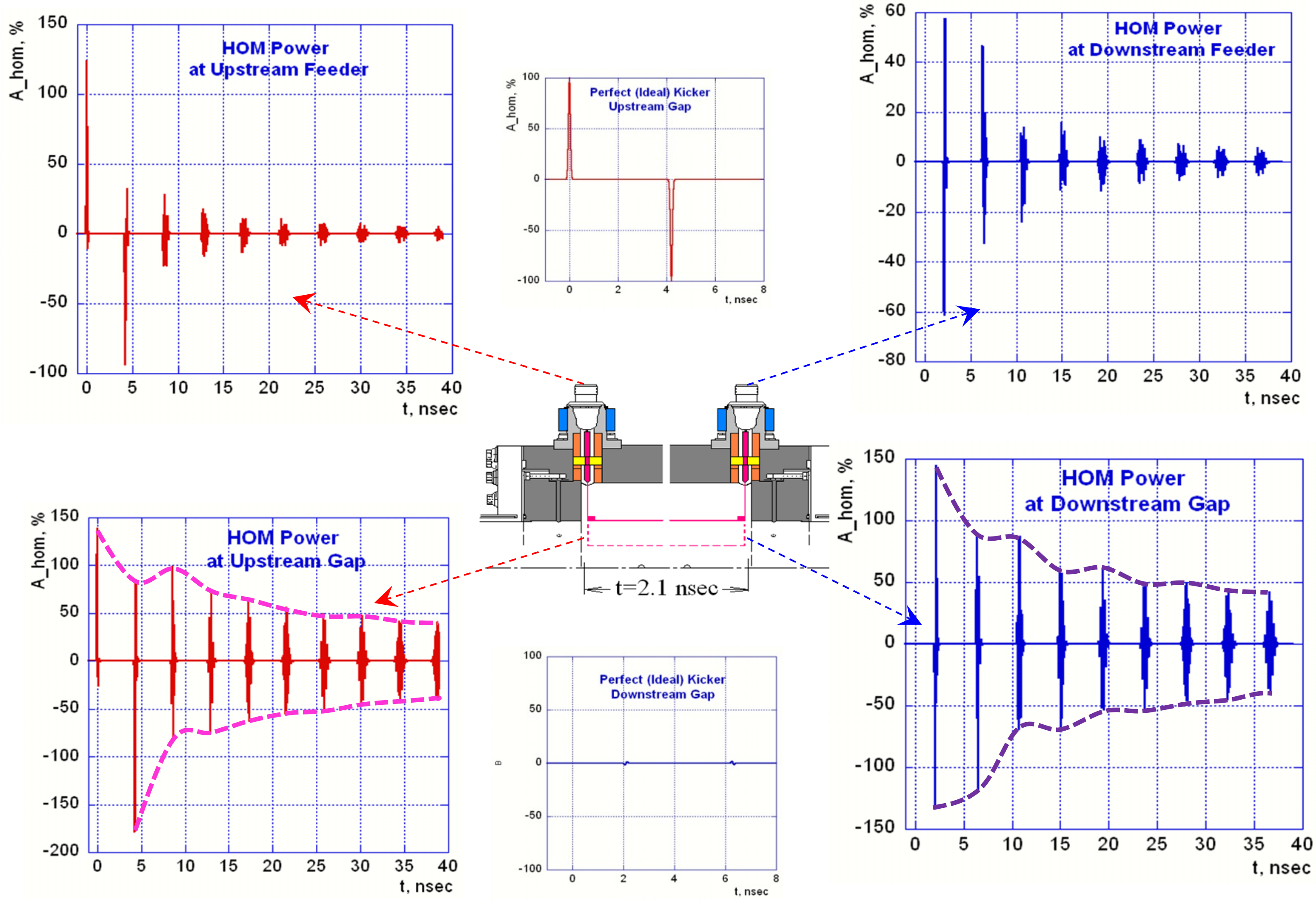


Paddles regions



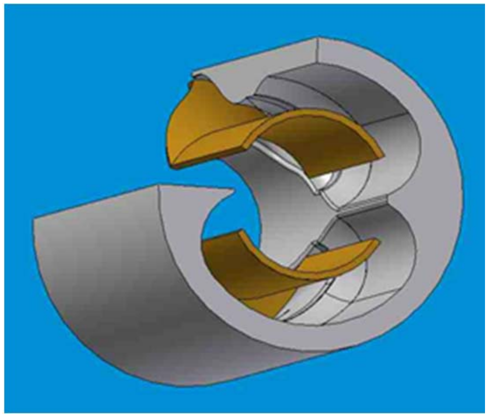
- **Sigma_beam < dR (a condition)**
- **dt_b < 2tp + tk (a root of problem)**
- **Reflection on the (Z0, Zp, Zk) nodes (a result)**
- **Dissipation in kicker electrodes (an effect)**

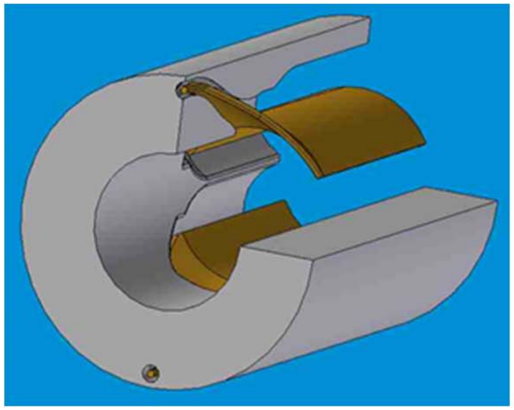
Loss of Directivity: HOM Simulations (single bunch)

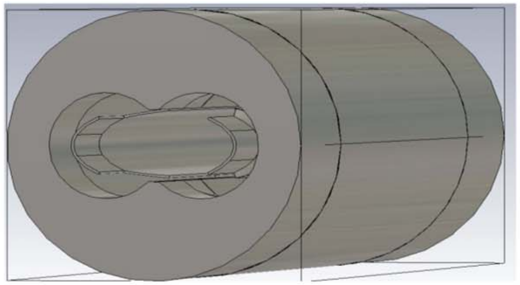


Decay and disperse

Advanced kicker structure

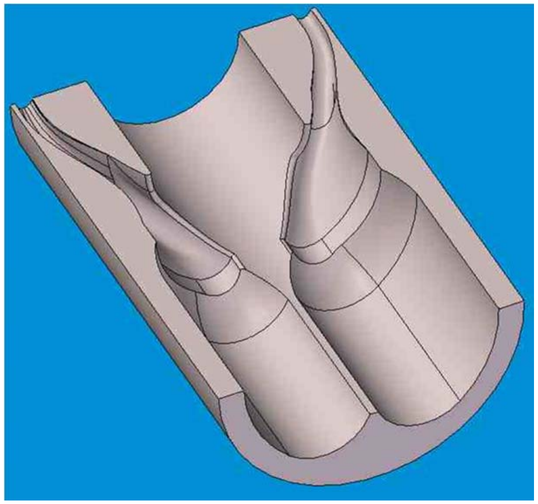


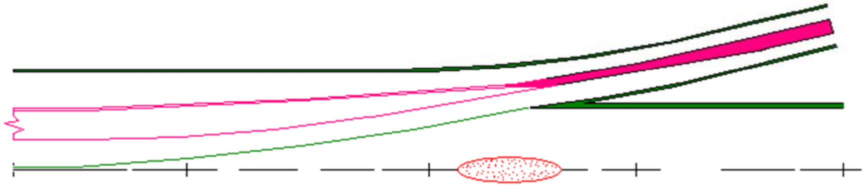


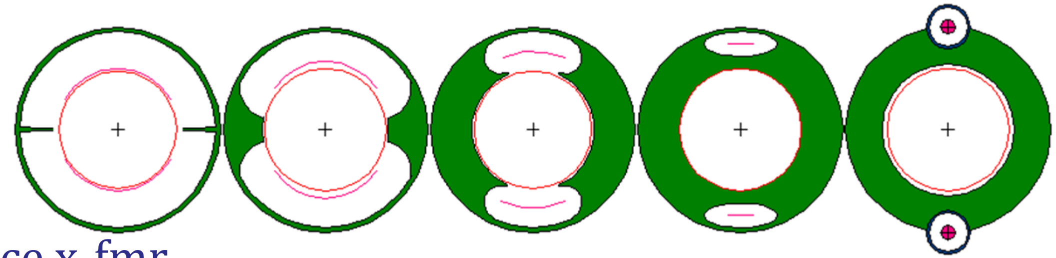


The blade inner surfaces are flush with connecting vacuum chamber for reduction of impedance seen by the beam.
Tapered ends are necessary for connection to the feedthroughs.
A clip is used to connect the end of blades to the inner conductor of the feedthroughs. Geometry of the clip is optimized for impedance matching.

Sasha's proposal



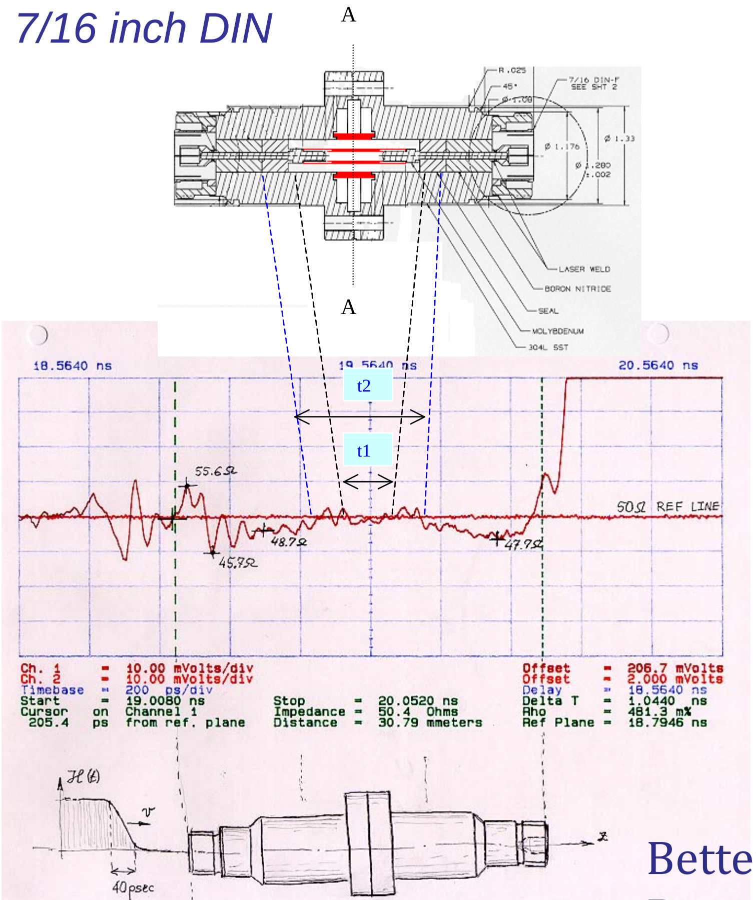




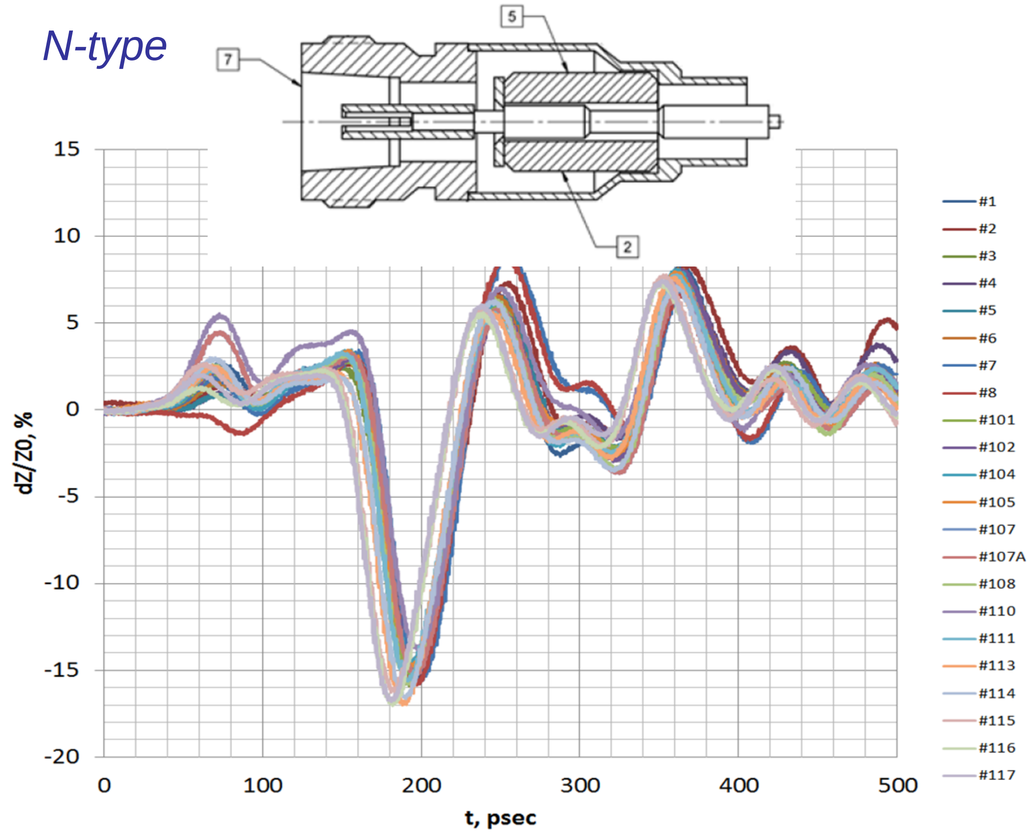
Similar to a balun-type impedance x-fmr

Feedthrough Performances

7/16 inch DIN



N-type



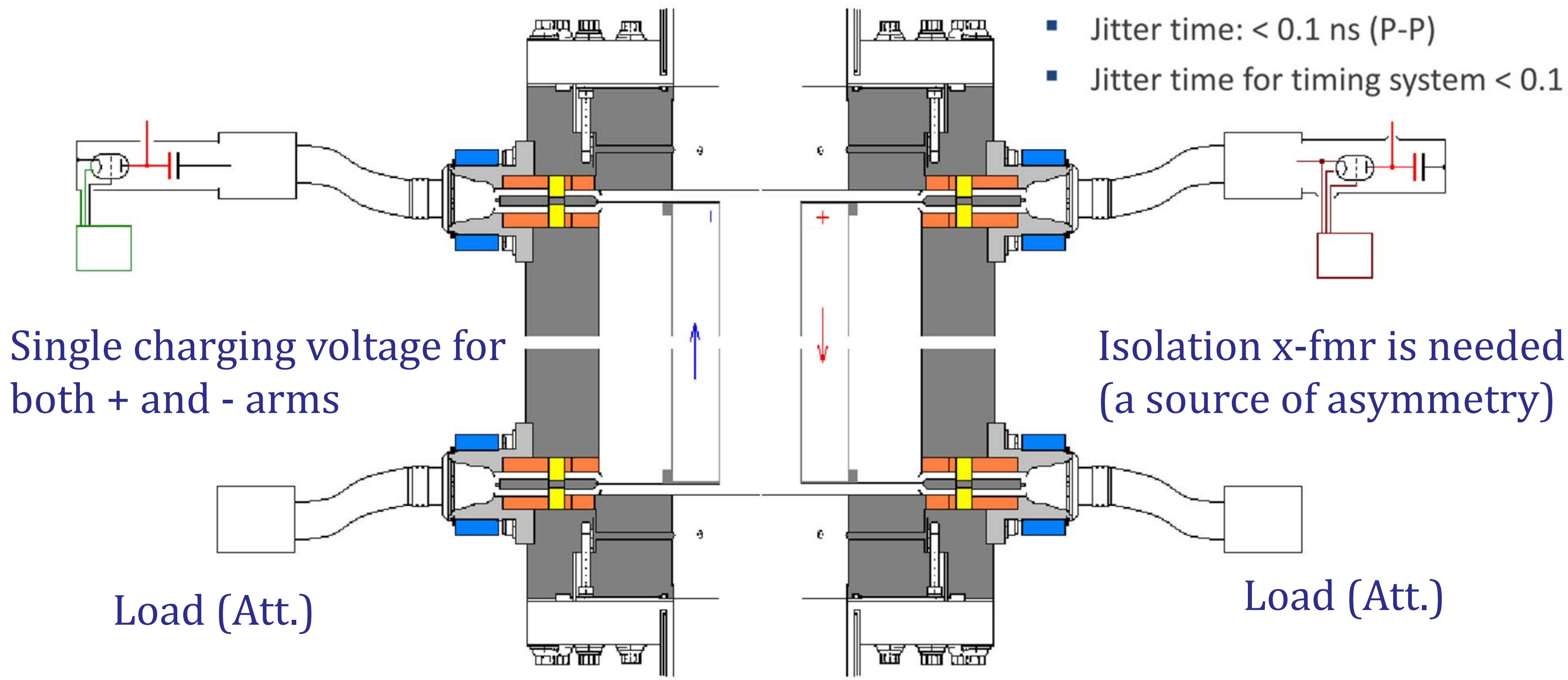
Better feedthroughs are needed:
Broadband, HV, vacuum tight, bake able, identical

May a topic be for SBIR?

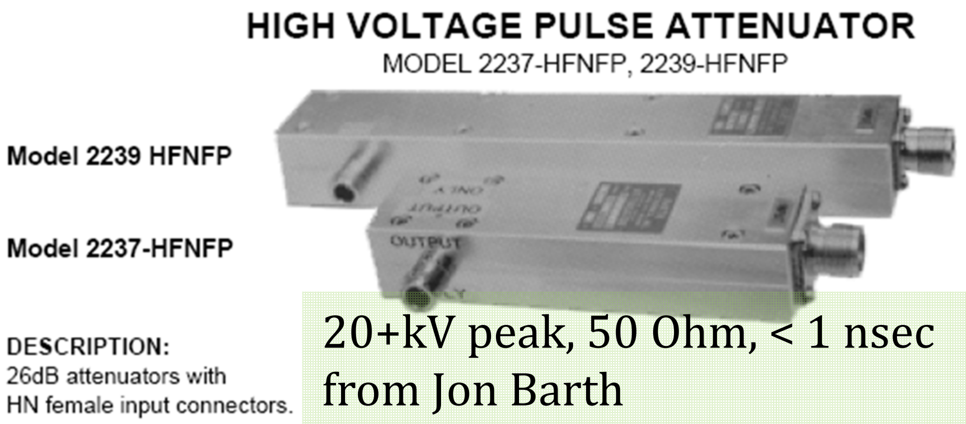
TEM-mode Kicker System

- Kicker housing with plates
- Feedthroughs with feeders
- ➢ Loads
- ➢ Neg. and Pos. pulse generators

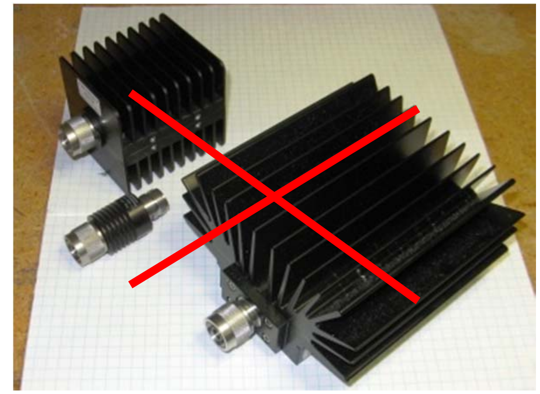
- Drive pulse shape: flat top
- Peak blade voltage: ± 15kV to ±22kV.
- Total pulse width: 18.7 ns
- Flat-top width: 4 ns*
- Maximum rise / fall time: 7.3 ns*
- Maximum repetition rate: 2Hz
- Jitter time: < 0.1 ns (P-P)
- Jitter time for timing system < 0.1 ns (P-P)



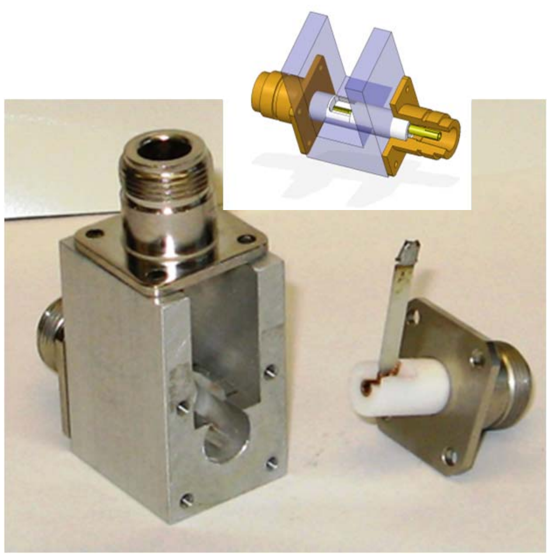
HV Broadband Loads and Attenuators

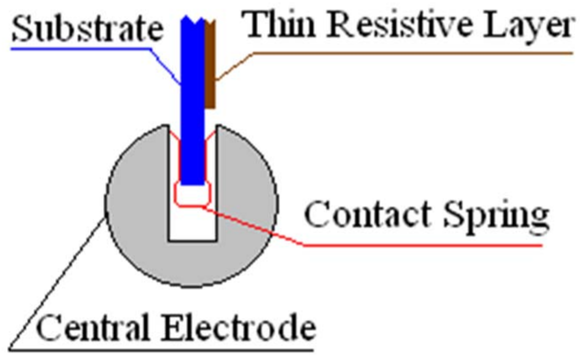


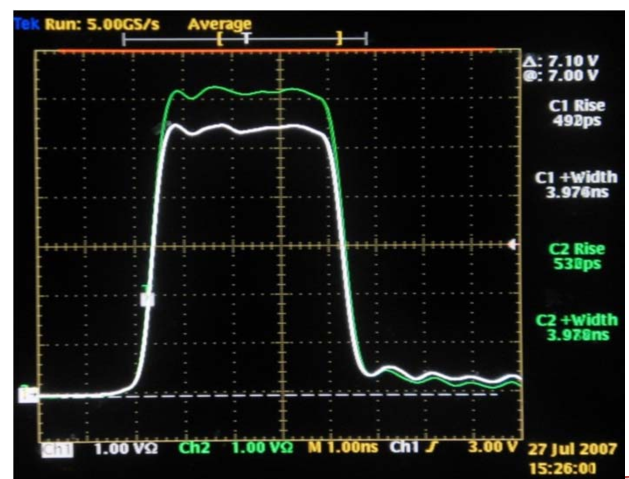
20+kV peak, 50 Ohm, < 1 nsec
from Jon Barth



Home Made HV Attenuators

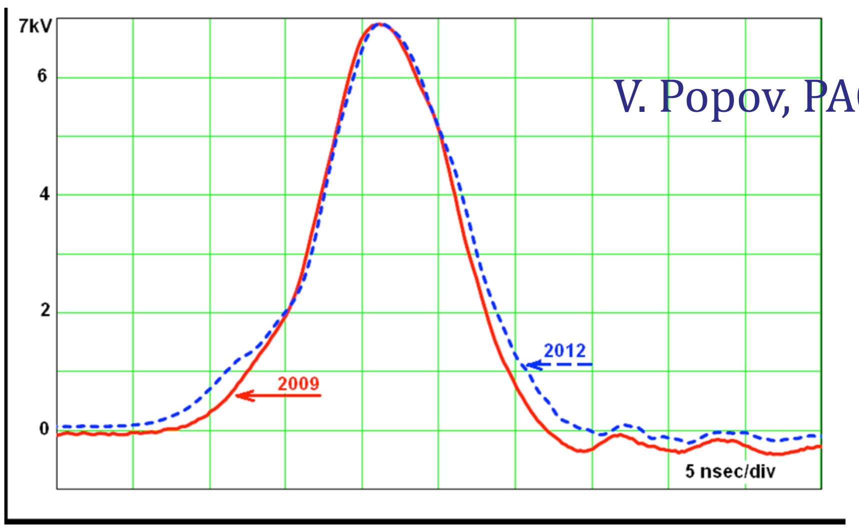






Fast Kicker Drivers: Thyratrons and Pseudo-Spark Switches

High power handling (50+kV, kA)
Marginal di/dt, dV/dt (~10E12 A/sec)
Recovery time too long
Life time may be limited and operation costly (to keep the optimal pressure)



V. Popov, PAC09, TU6RFP080

Thyratron based approaches may need in a shock wave (SW) transmission line (TL) assistance

Approach would be recommended for an evaluation of shorter and better shape pulses

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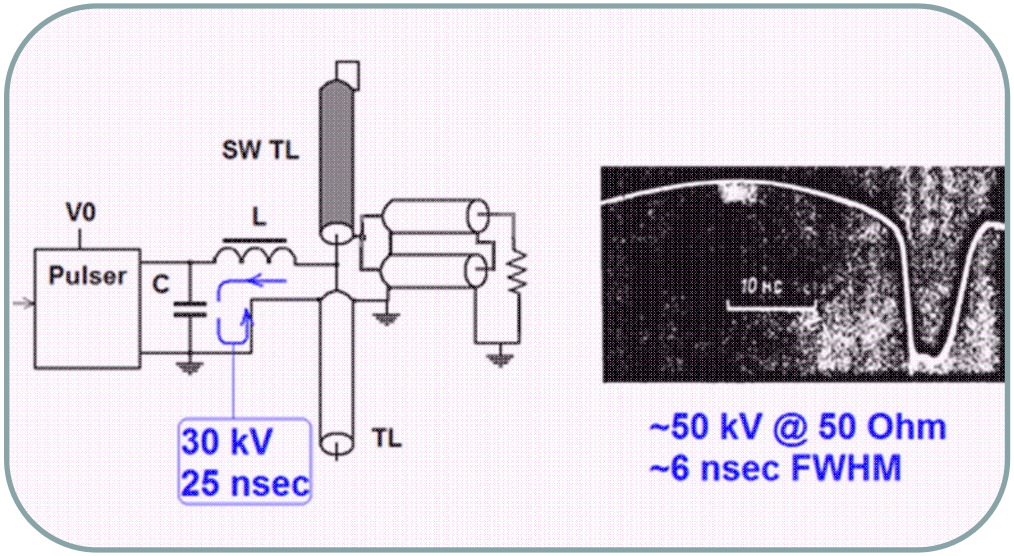
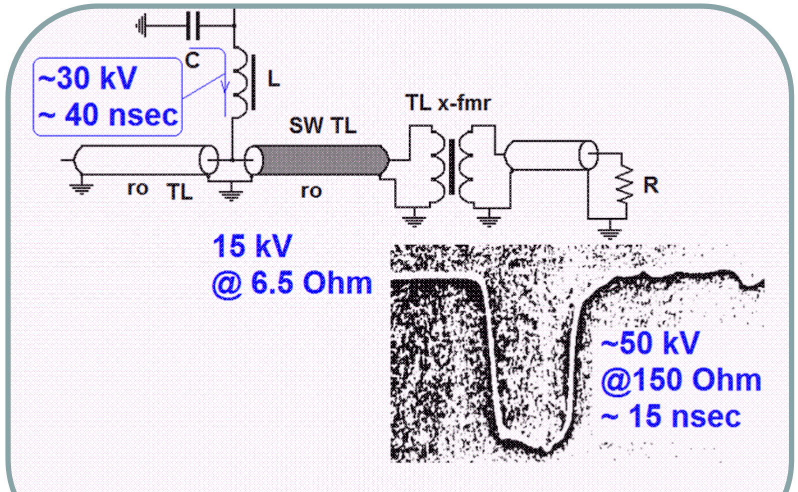
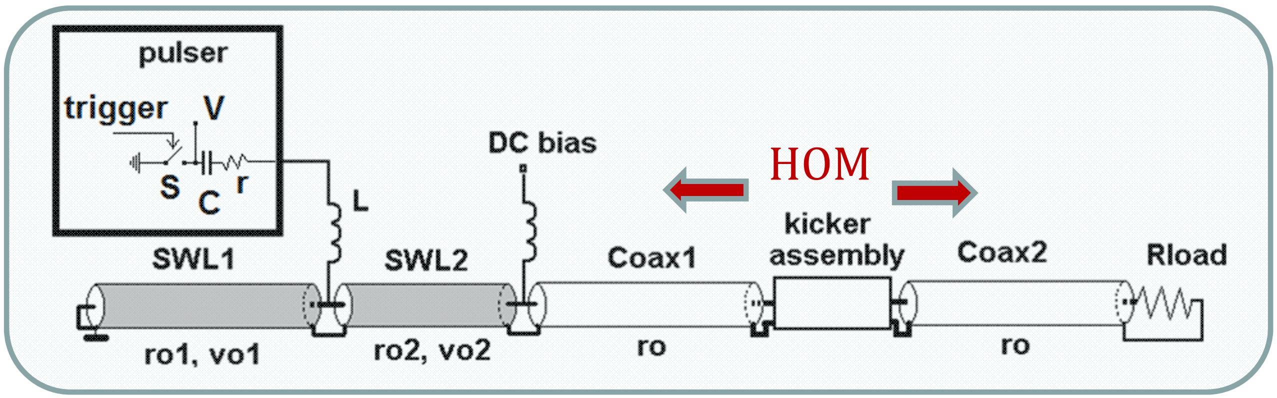
Potential Fast Kicker Diver Concepts





Courtesy I. Kataev & I. Meshkov

$$t_r \propto \frac{1}{H_{sw}}$$



Limitation of SW TL Assistant

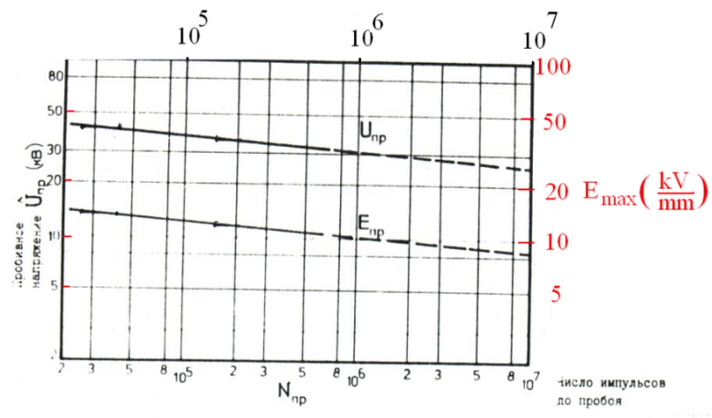
Transmission line with ferromagnetic medium needs a high current.

$$t_r \approx \frac{2.5 \cdot 10^{-5}}{H_{sw}}$$

More current will be produced by a higher applied voltage.

High electric fields may produce the ionization in ferromagnetic media. Plasma formation and breakdown are a killer of shock wave formation.

E_ferrite ~ 10 kV/cm, (for long life time: E ~ 5 kV/cm is acting electric field) → gives the rise/fall times ~1 nsec



"Кривая жизни" для ферритов 600НН.

JINR preprint 9-12448, 1979

Small size NiZn toroid cores are preferable. A needed length of the oil filled coax depends on an initial rise time and magnetic core parameters. A design of SW TL would require conducting the R&D.

May a topic be for SBIR?

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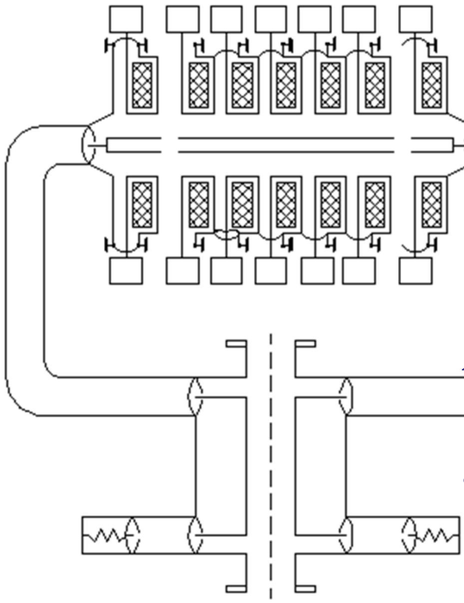
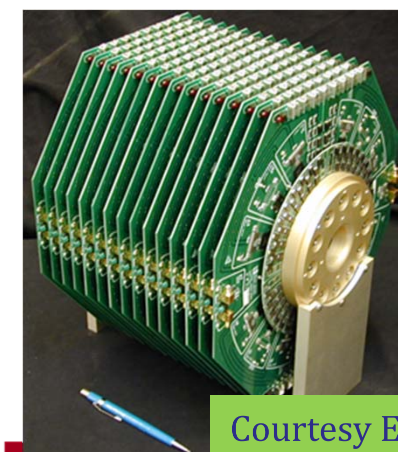
Kicker Drivers: MOSFET based Approaches

A single MOSFET voltage hold off is less than 2 kV, switching current is <100 A, and a rise time ~5 nsec @ high impedance load. DE and APT are leaders in the fast MOSFET industry.

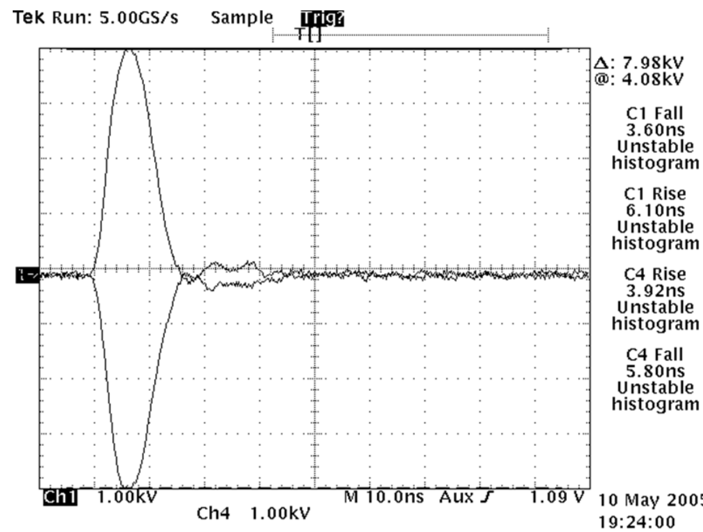


A nsec switching sub kA currents will employ the array of MOSFETs



Courtesy Ed Cook

+_4 kV @ 50 Ohm Loads, ~200 ea. APT MOSFETs



A higher output voltage will require more cells. A rise time will degrade. For example, DARHT-II kicker, +_20 kV @ 50 Ohm loads, rise time is ~10 nsec

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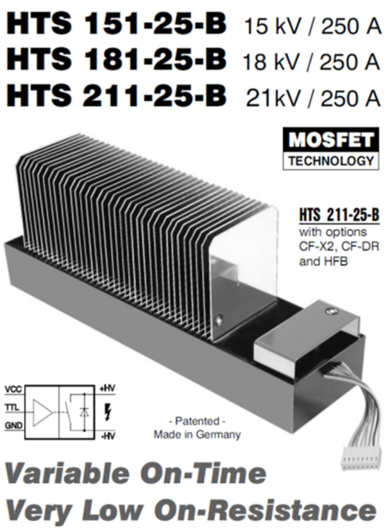
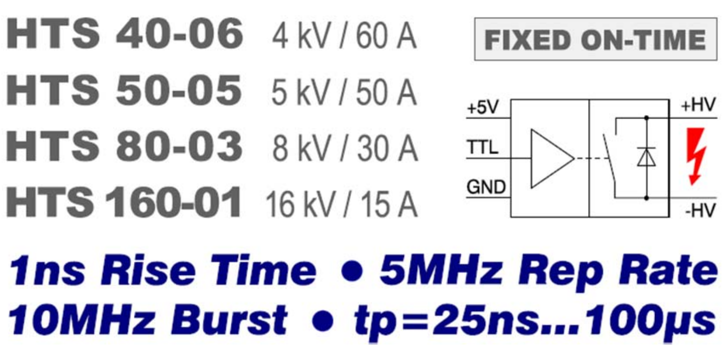
MOSFET based Approaches (cont.)



Behlke HV switches (array of stacked MOSFETs)

- Technical Data (for example): 0.8 x 21 kV ~17 kV @ 250A
  on rise time ~40 nsec

Best guess: 5 each of them (an effective impedance is ~15 Ohm), + SW TLs, and TL-based x-fmr → 20+kVp @15 nsec

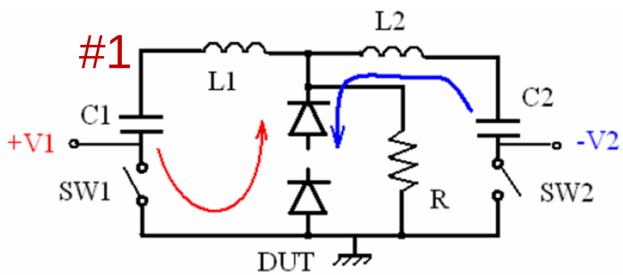


Just buy bunch of them and combine the TLs with TL-based x-fmrs to get the required voltage on resistive load.

Apparently home made TLs are will be needed (a rise time is realized on rather high resistive loads)

Fast Pulsers with a DSRD Assist

- A DSRD is a fast solid state device that can improve the switching performance of industrial high power switches (thyratrons, MOSGETs, etc.).
- All mentioned above kicker drivers are based on turn ON switches (SW relates also to this class). DSRD mode operation is based on a turn OFF mode. DSRD is a device with two electrodes (anode and cathode). A special circuit (a pumping circuit of the DSRD) is needed to realize the fast opening mode. The pumping circuit has to provide a current flow through the DSRDiode in forward and reverse directions. There are several electronic circuits to create such current flow.



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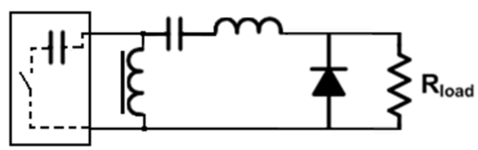

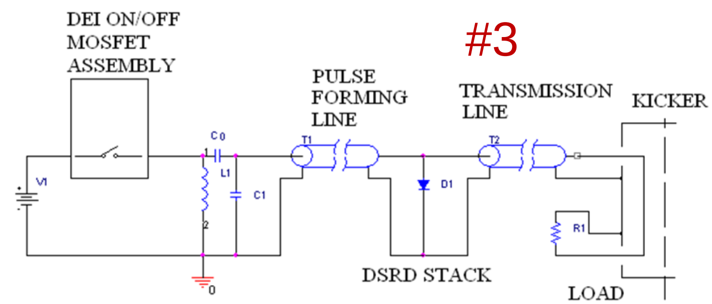

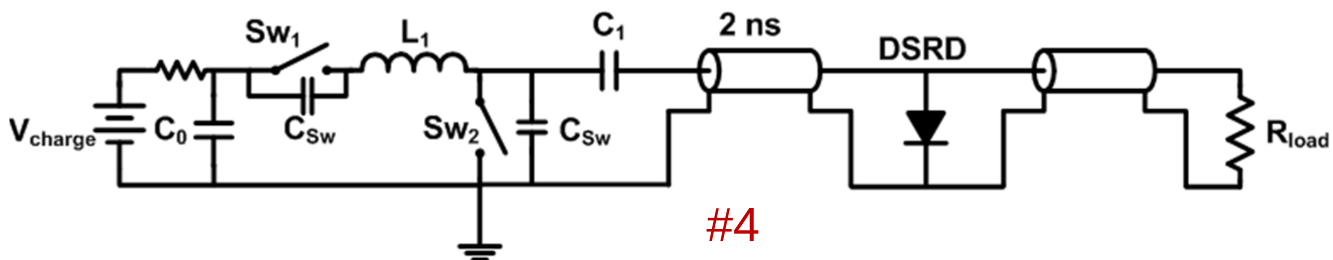

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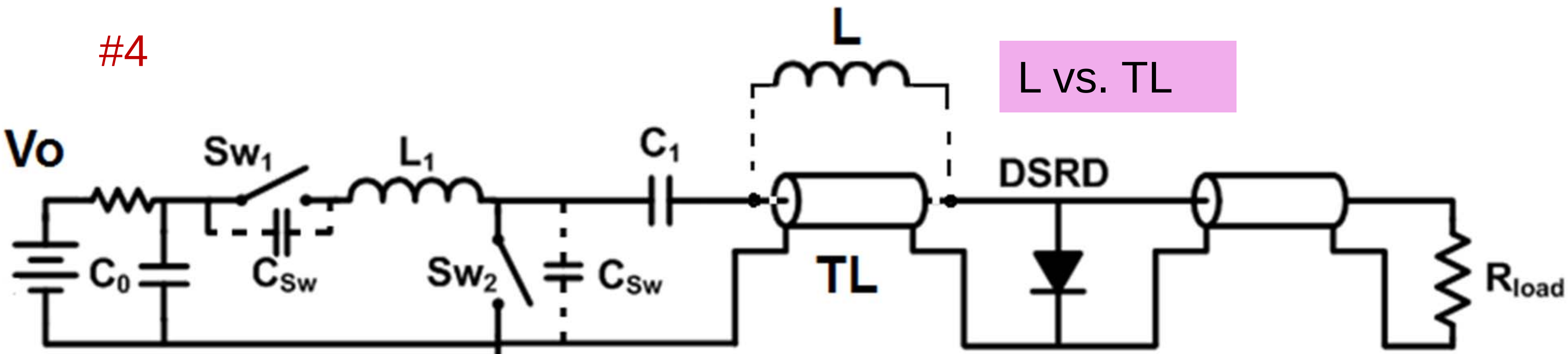
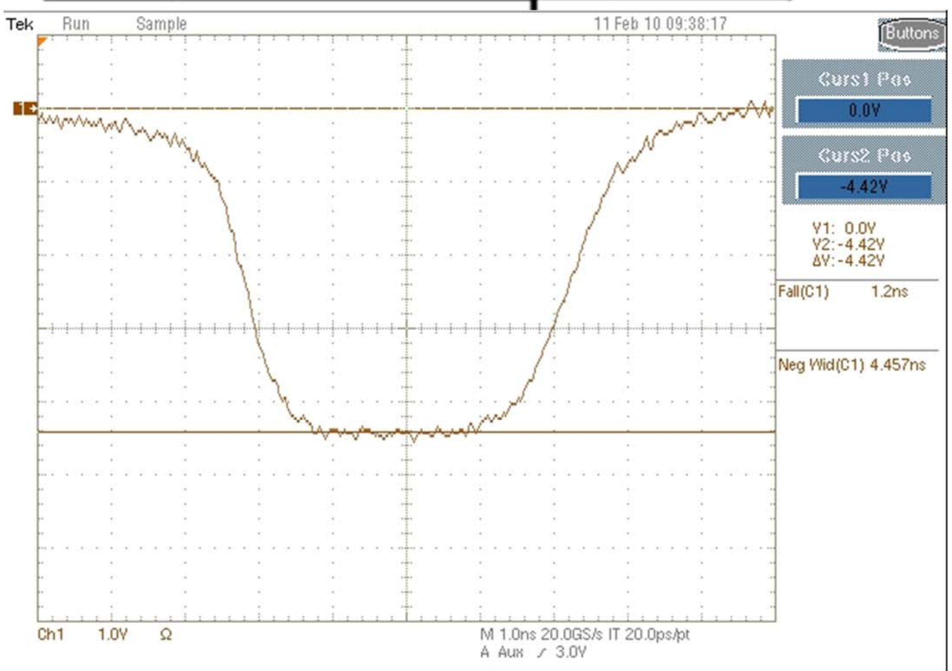
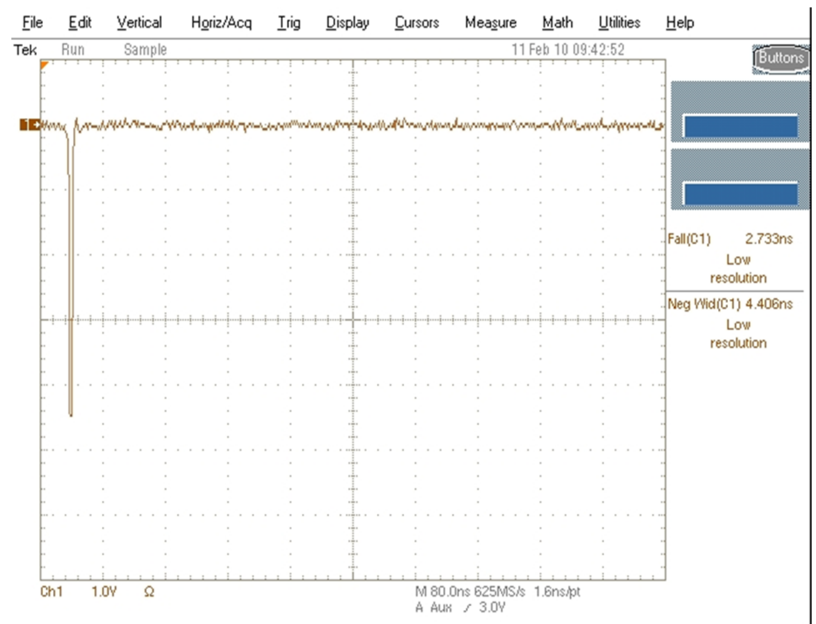
Pulsers with DSRD Assist (cont.)

#4

L vs. TL







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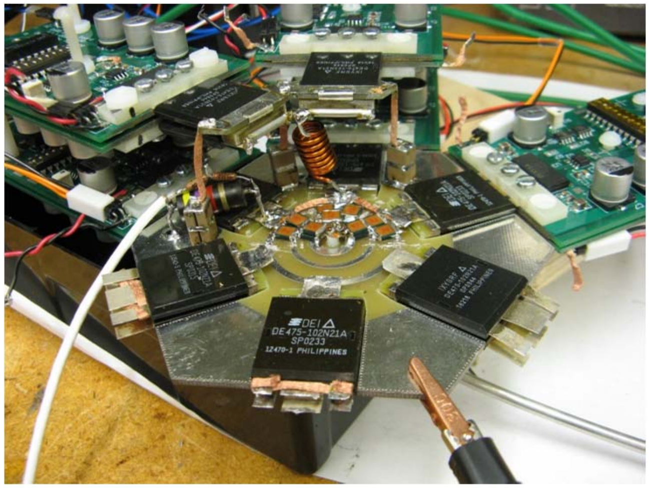
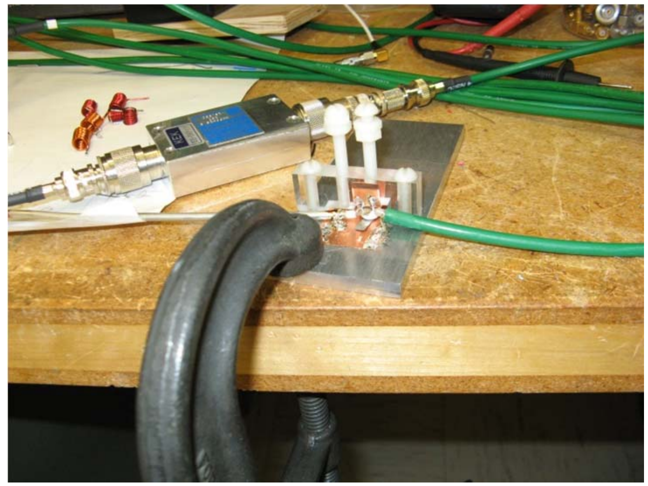
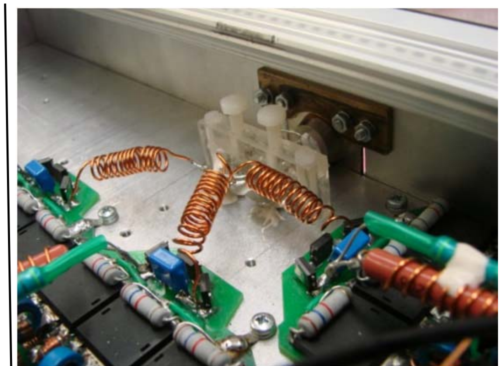
Overall Comments

- Kicker structure is an efficient HOM power extractor
- Peak HOM voltage and average power at the feeder may be sufficient to act on the kicker pulser system if the kicker structure has been designed with a narrow bandwidth
- Feeder imperfections (real cables, feedthroughs, kicker electrodes, loads) are one source of residual energy between bunches. HOM spectrum is broad and imperfections could select and capture the "right mode". Common actions (HV peak and HOM) need to be careful evaluated and mitigated
- Best guess: thyratron/MOSFET pulser with an assistance of shock wave (or DSRD stack as option) is more attractive concept for the APS-U injection system
- A practical evaluation (R&D) of prototypes will be necessary to allow a optimal selection of injection system

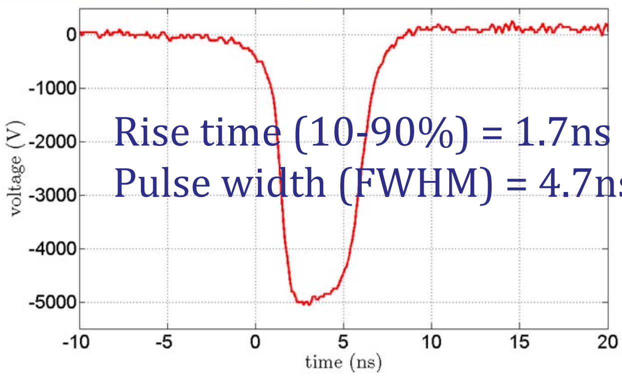
Backup Slides



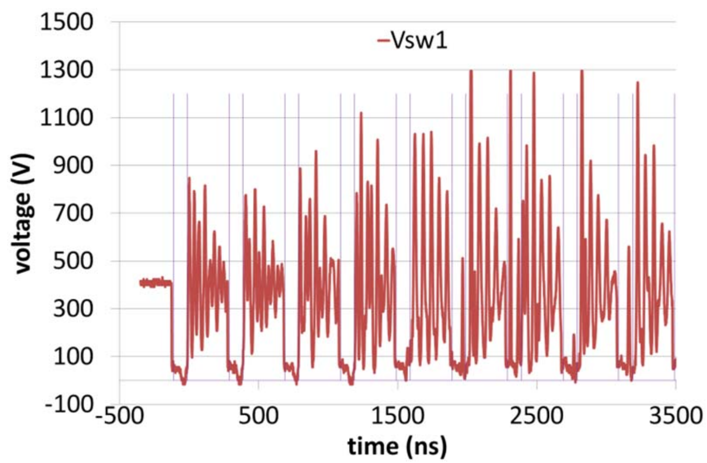


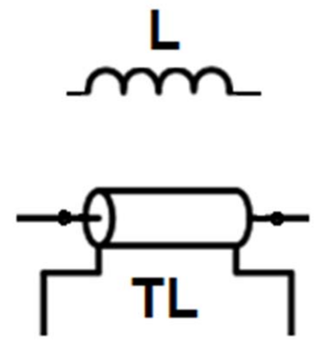


Courtesy FID Technology



Rise time (10-90%) = 1.7ns
Pulse width (FWHM) = 4.7ns

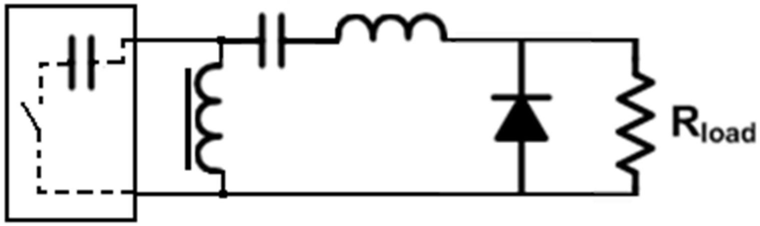


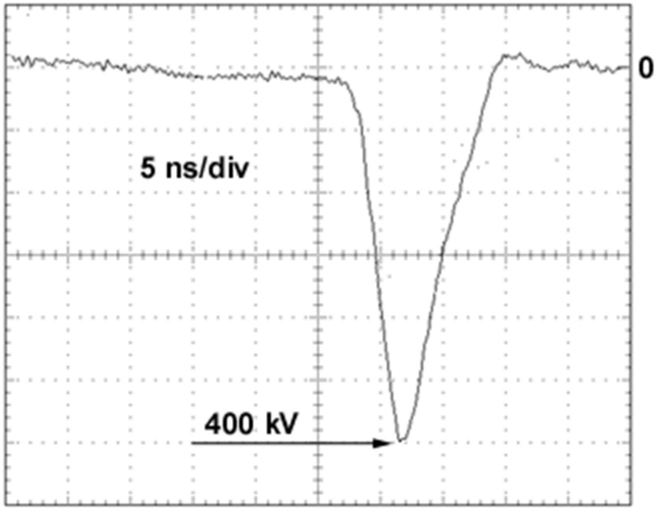


SLAC NATIONAL ACCELERATOR LABORATORY

Backup Slides

#2

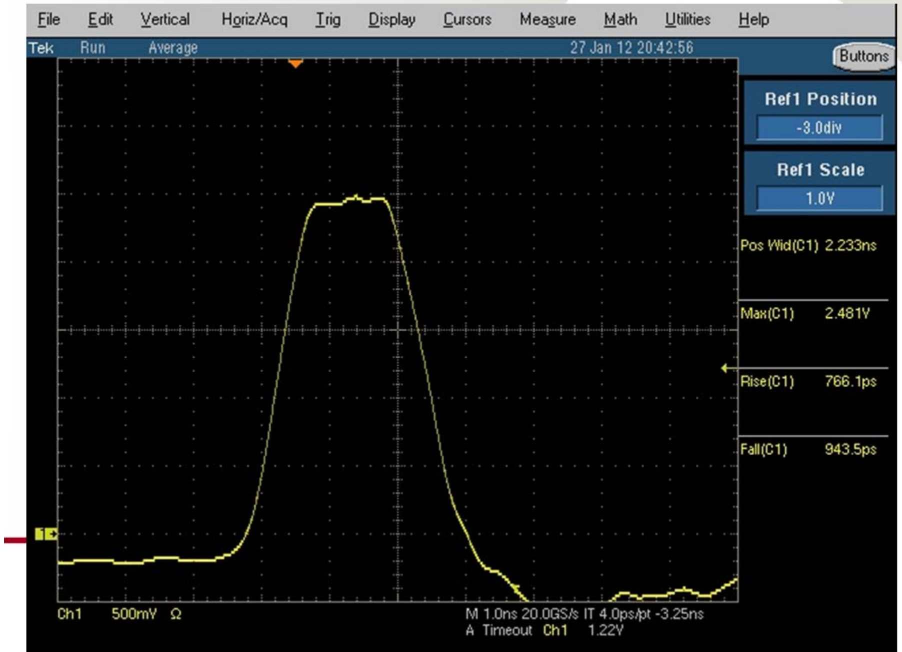


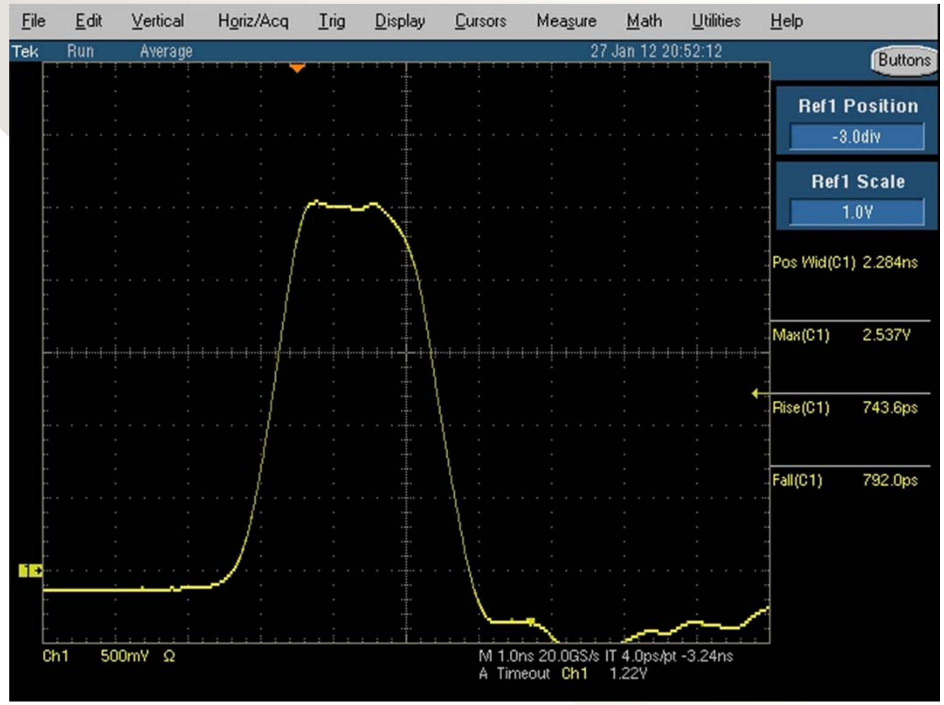


Courtesy G. Mesyats

Backup Slides

Wafer # R9-16a in DO-35 package





Crystal	Run	time	Horiz scale, nsec	Vp @50 Ohm, V	FWHM, nsec	Rise, nsec	Fall, nsec
R9-16	20120127	20:29:07	0.5	304	0.914	0.826	0.422
R9-16	20120127	20:29:53	5				
R9-16&R9-16	20120127	20:42:56	1	124	2.2	0.77	0.943
R9-16&R9-16	20120127	20:52:12	1	127	2.3	0.74	0.79