CLIC Pre-Damping and Damping Ring Kickers: Stability Requirements

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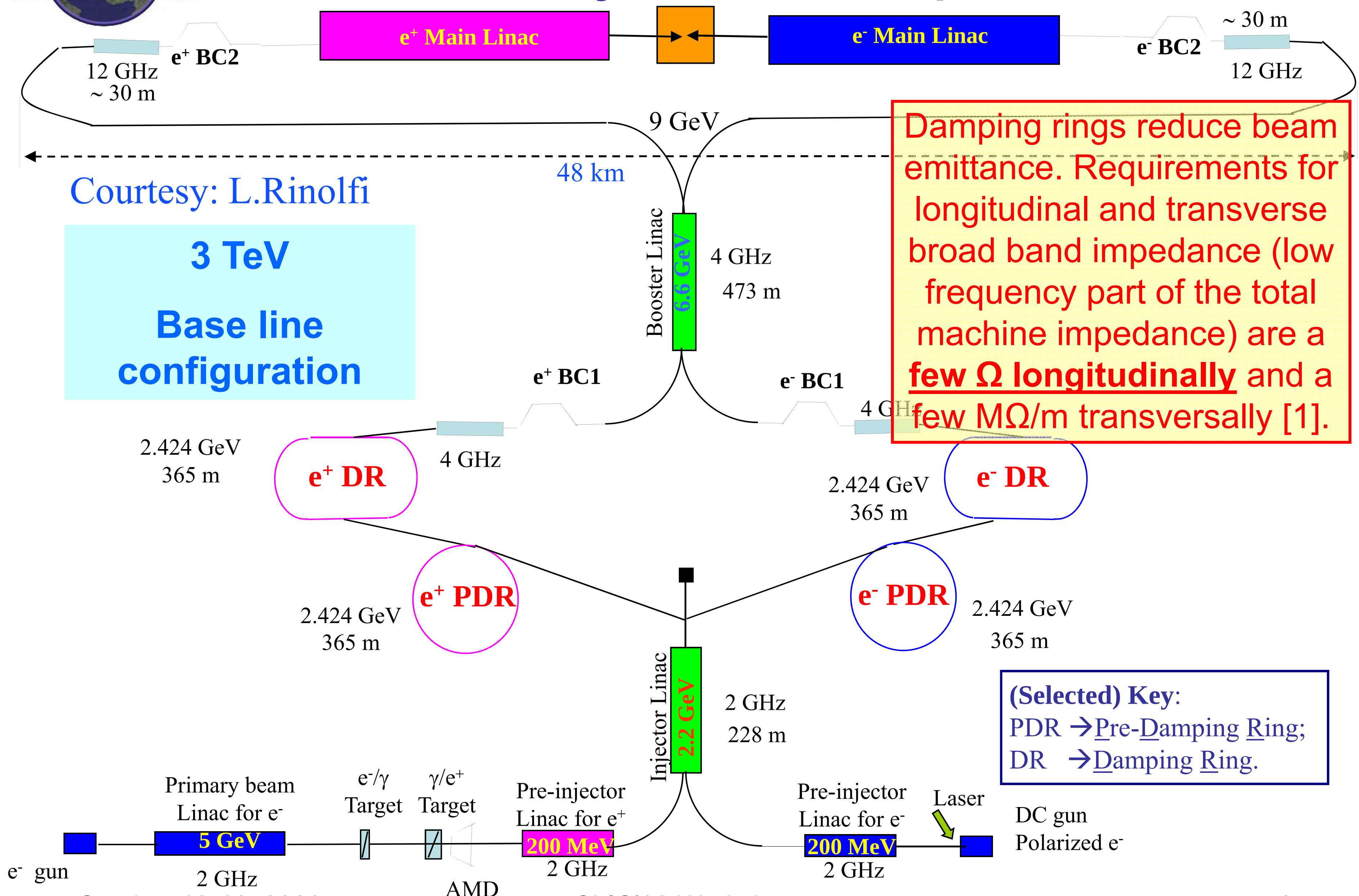
OVERVIEW

- Review specifications for CLIC pre-damping and damping rings & comparison of CLIC, ILC & DAΦNE specifications;
- Briefly discuss concept of double kicker system to reduce required field stability with respect to a single kicker system;
- Show that striplines are necessary to achieve low longitudinal beam-coupling impedance;
- Ideas for achieving low droop of pulsed field;
- Summary of main challenges of specifications for CLIC pre-damping and damping rings.

The CLIC Injector Complex in 2008



Damping rings reduce beam emittance. Requirements for longitudinal and transverse broad band impedance (low frequency part of the total machine impedance) are a **few Ω longitudinally** and a few MΩ/m transversally [1].

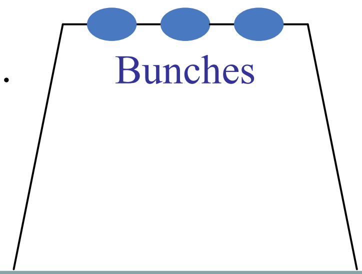
Selected CLIC, ILC & DAΦNE Parameters

	CLIC Damping Ring [2]	CLIC Pre-Damping Ring [2]	CTF3 Tail-Clipper	ILC [3,4]	DAΦNE [5]
Beam energy (GeV)	2.424	2.424	0.2	5	0.51
Total kick deflection angle (mrad)	3	3	1.2	0.7	5
Aperture (mm)	20	~55	40	24[4] (tapered)	54.8 (tapered)
Effective length (m)	**2**	**3*1.7**	4*0.295	20*0.32=~6.4	~0.9
Field rise time [definition ??] (ns)	1000	700	≤5	3	~5
Field fall time [definition ??] (ns)	1000	700	NA	3	~5
Pulse flattop duration (ns)	~160	~160	Up to 140	NA	NA
Input pulse duration (ns)				5.9	5.3
Flat-top reproducibility	$1x10^{-4}$	$1x10^{-4}$	NA	$1x10^{-3}$	??
Flat-top stability [inc. droop], per Kicker **SYSTEM** (Inj.) (Ext.)	$1.4x10^{-3}$ $1.5x10^{-4}$	$\sim 3x10^{-3}$ $\sim 7x10^{-4}$	NA	$1x10^{-4}$ $1x10^{-4}$	?? ??
Field homogeneity (%)	±??	±??	±18	±??	±3 (x=±27mm @y=0) ±10 (y=±10mm @x=0
Repetition rate (Hz)	50	50	50	5 (3M burst)	50
Stripline PFN voltage (kV)	**~±37**	**~±40**	±5.6		
Stripline Pulse voltage (kV)	**±18.2**	**±19.6**	±2.65	±5	±45
Stripline pulse current [50 Ω load] (A)	**±364**	**±392**	±53	±100	±900
Transmission line kicker pulse current (A)	**193**	**194**	NA	NA	NA

Double Kicker System for Extraction [6-8]: Basic Concept

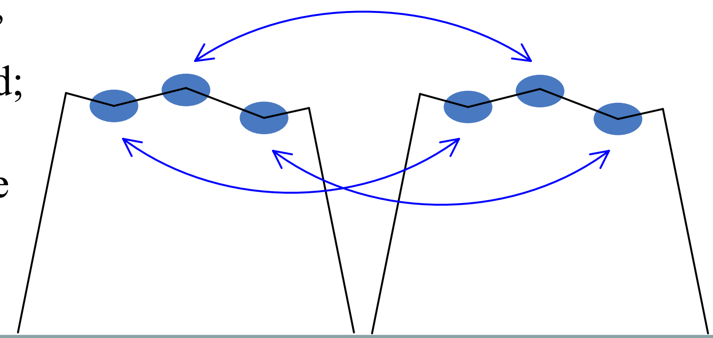
Extraction with **one** kicker magnet:

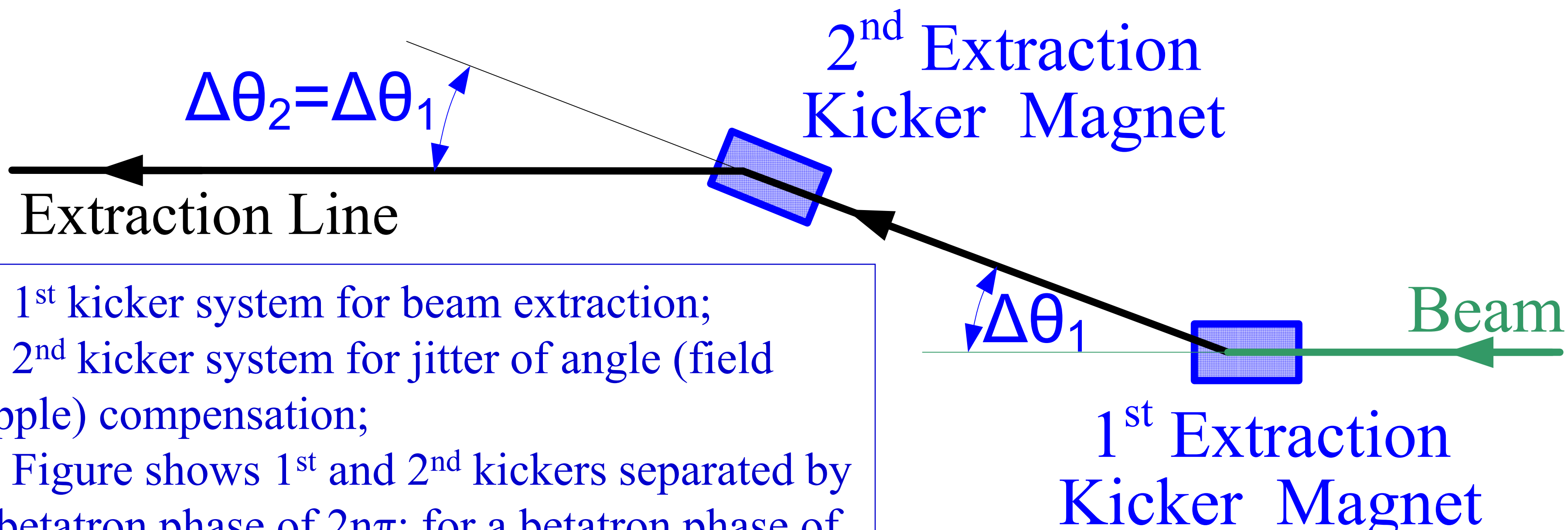
- Requires a uniform and stable magnetic field pulse.



Extraction with **two** kicker magnets:

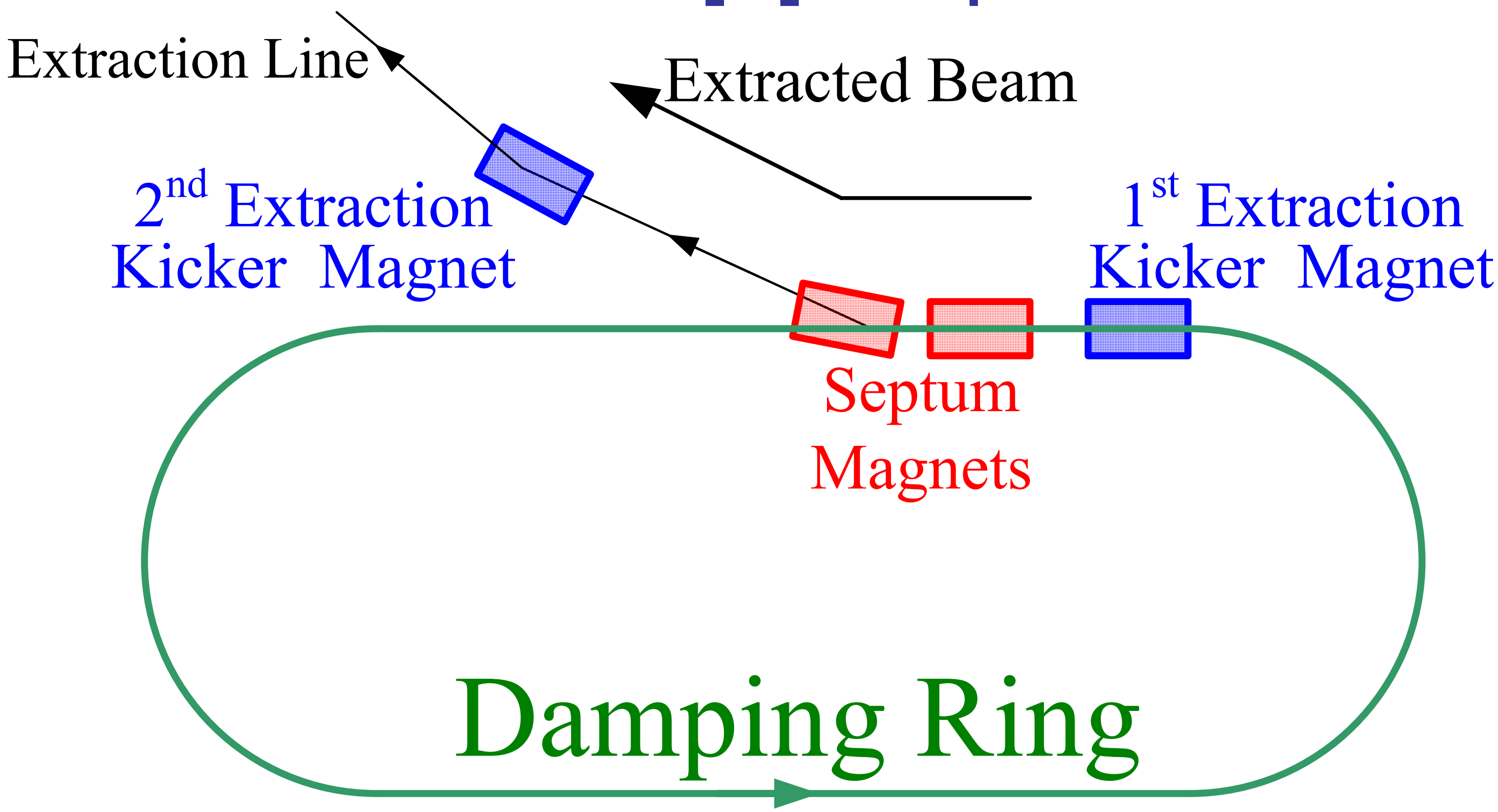
- Two “identical” pulses are required;
- One power supply sends pulse to 2 “identical” kickers.





- 1st kicker system for beam extraction;
- 2nd kicker system for jitter of angle (field ripple) compensation;
- Figure shows 1st and 2nd kickers separated by a betatron phase of $2n\pi$: for a betatron phase of $(2n-1)\pi$ the 2nd kick is in the other direction.

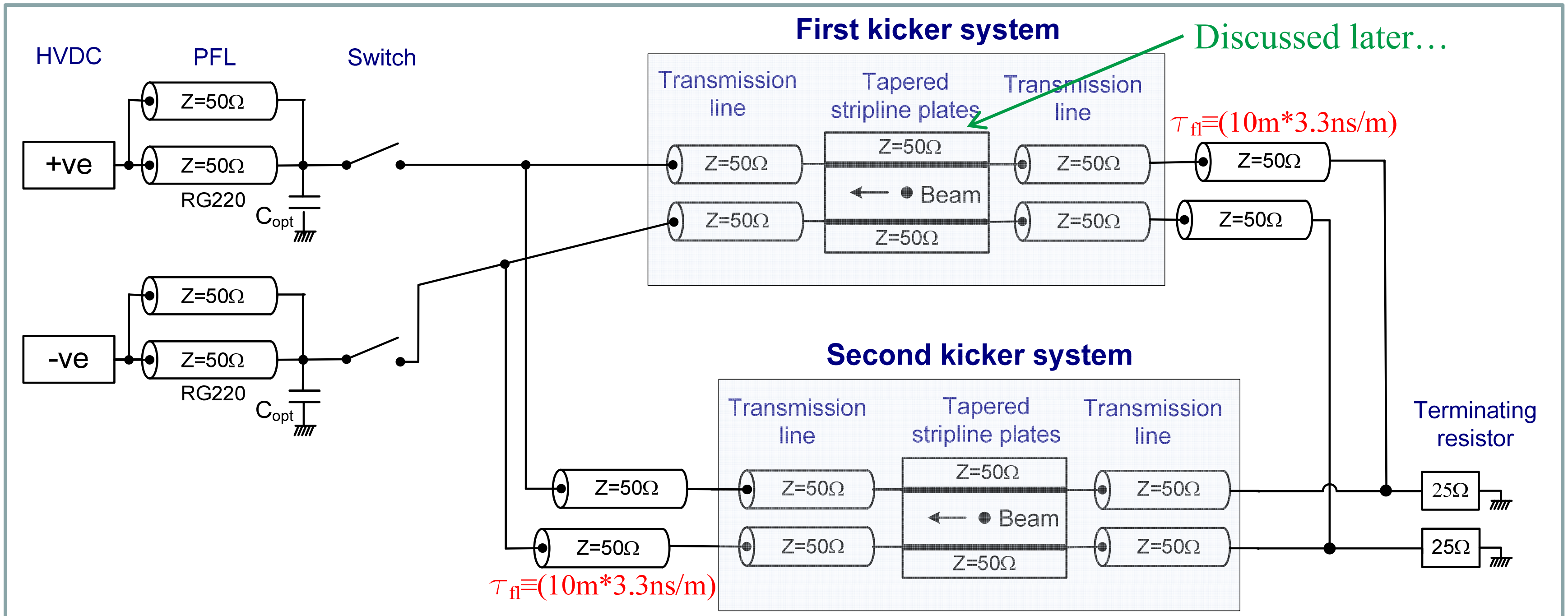
Double Kicker System for Extraction [8]: Implementation



- 1st kicker system (in damping ring) for beam extraction;
- 2nd kicker system (in extraction line), for jitter compensation, separated by a betatron phase of π from 1st kicker.

Ref [9] shows *a factor of ~3.3 reduction in kick jitter angle*, w.r.t. a single kicker, with a double kicker system: the fact that the improvement was not even greater is attributed to errors in the optics and errors in estimating horizontal displacement (due to insufficient position resolution of the BPMs).

Example of Double Kicker System for DR Extraction



- 1st kicker system (in damping ring) for beam extraction;
- 2nd kicker system (in extraction line) for jitter compensation.

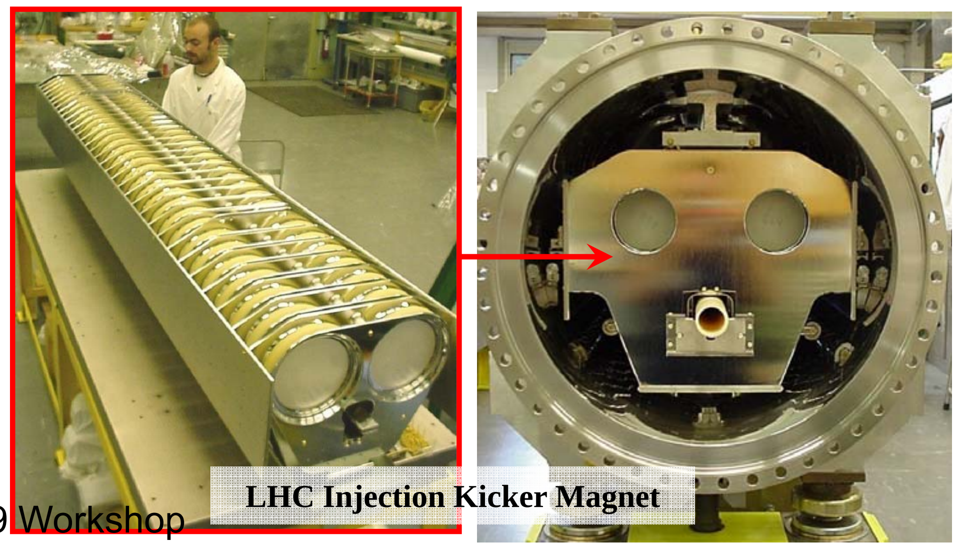
Assuming a 10m separation between the 1st and 2nd kickers (i.e. time of flight ~33.3ns for beam and ~50ns for kicker current pulse), the two kicker systems are in parallel. A series connection would require a ~16.7ns delay loop, for the beam, so that beam bunches and kicker field are synchronized in time at the 2nd kicker system!

KEK/ATF system used **ferrite loaded** kicker magnets to demonstrate the double kicker concept [9].

Comparison of CLIC Requirements with two CERN Ferrite Loaded Kicker Systems

	CLIC Damping Ring	CLIC Pre-Damping Ring	SPS Extraction (MKE4)	LHC Injection	
Transmission line kicker, total ∫B·dl	0.024	0.024	5*0.144	4*0.325	T·m
Field rise-time	1000	700	~1100	900	ns
Field flat top duration	160	160	10500	≤7860	ns
Field fall-time	1000	700	~1100	3000	ns
Flat-top stability (including ripple & droop)	±0.015 (Ext.)	±0.07 (Ext.)	±2	±0.5	%
Aperture "height"	20 / 36	55 / 71	2@32 & 3@35	54	mm
Magnet Length	2	3*1.7	5*1.7	4*2.65	m
System Impedance	50	50	10	5	Ω
Magnet Current	193 / 347	194 / 269	2500 & 2560	5400	A
PFN Voltage	19.3 / 34.7	19.4 / 26.9	50 & 51.2	54	kV

- Specified rise/fall similar for all 4 systems considered here ✓;
- Flat-top stability requirements significantly more stringent for CLIC than existing systems ***X***;
- PFN voltages less than for LHC injection ✓;



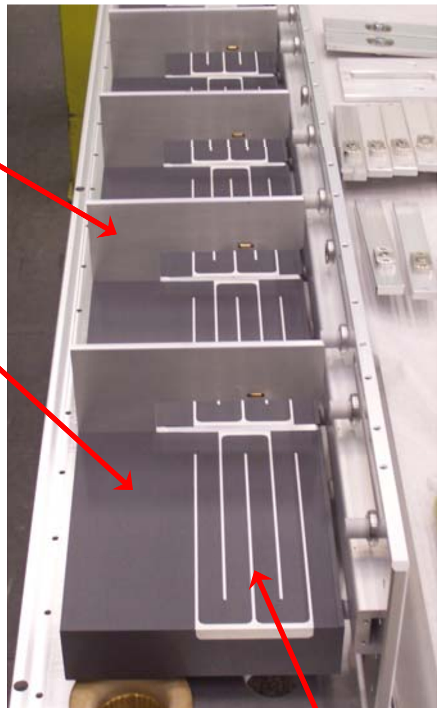
LHC Injection Kicker Magnet

Ferrite Loaded Transmission Line Kickers: Beam Coupling Impedance

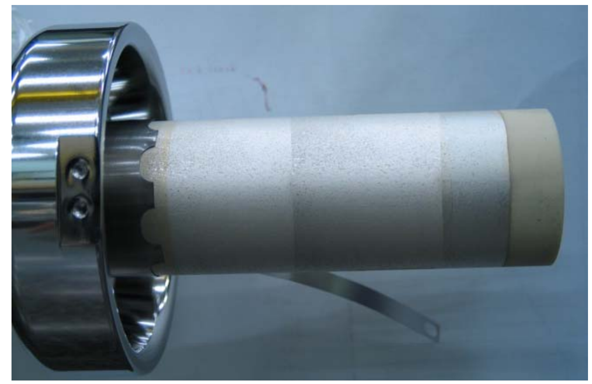
In order to reduce beam coupling impedance, in a transmission line kicker, the ferrite must be shielded from the beam by providing a path for beam image current. However the design must ensure that eddy-currents, induced by the fast rising field, do not unduly increase field rise-time.

HV Plate

Ferrite

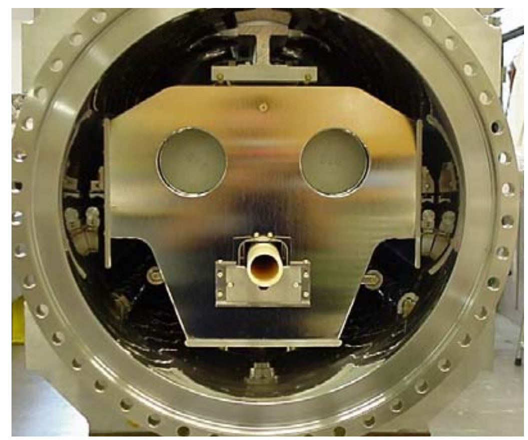


MKE Kicker: serigraphy on ferrite



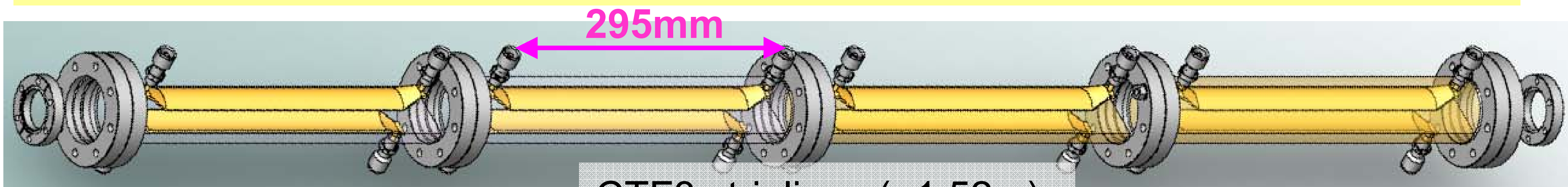
LHC Injection Kicker: ceramic tube with "beam-screen" conductors in slots

(aperture: 38mm→54mm)



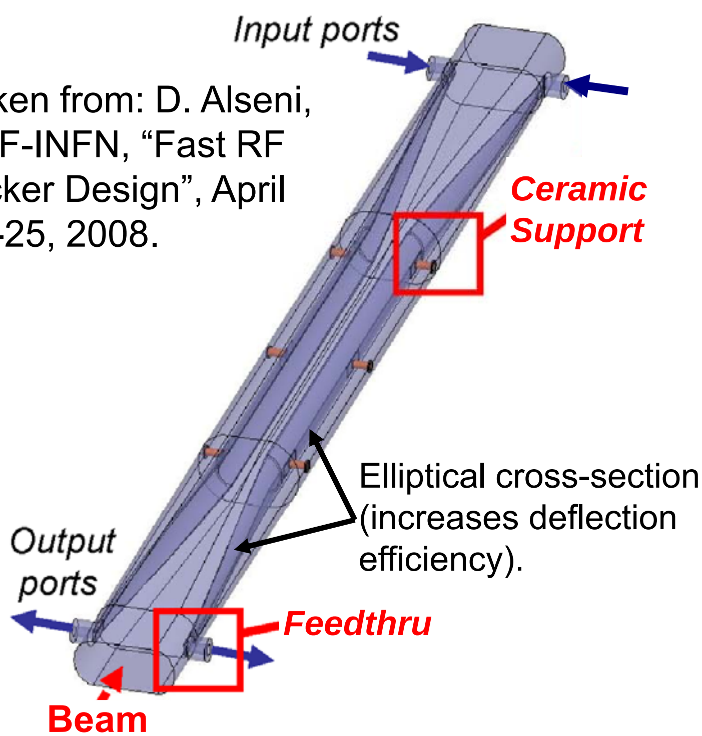
Striplines - 1

• CTF3 Tail-Clipper, ILC & DAΦNE prototype damping ring kickers employ tapered striplines



CTF3 striplines (~1.52m)

Taken from: D. Alseni, LNF-INFN, "Fast RF Kicker Design", April 23-25, 2008.



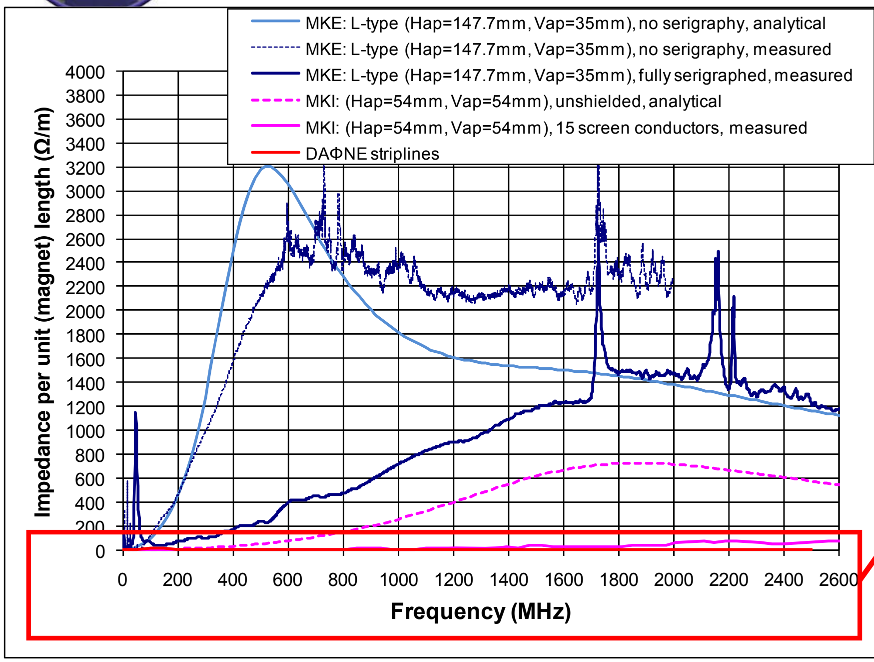
DAΦNE Stripline (~0.94m)

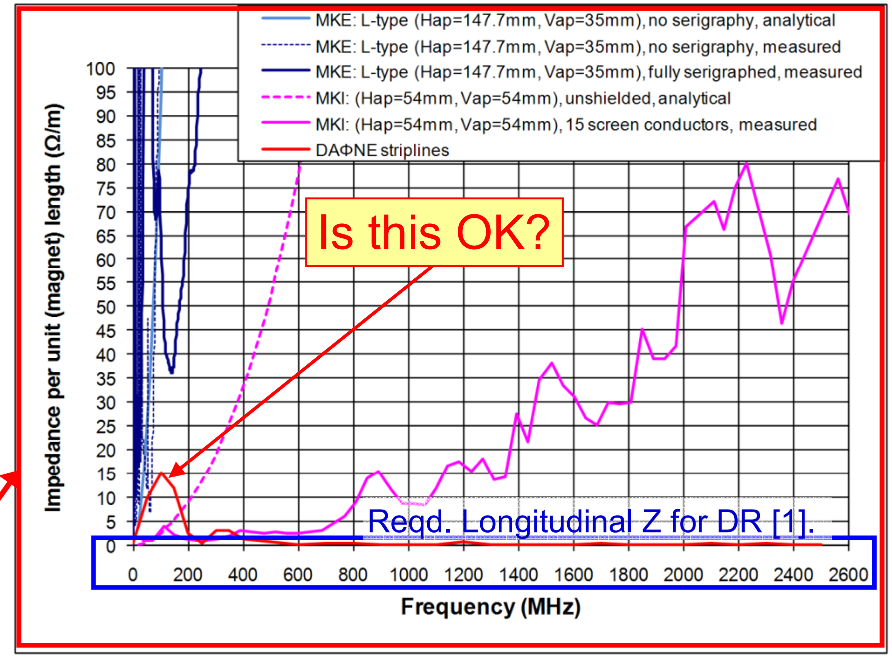
Much research has been carried out, for ILC & DAΦNE, into tapered, elliptical cross-section, striplines and wide-band feedthrus [10]. By tapering the transition between the kicker structure and the adjacent beam pipe it is possible to minimize [10]:

- the non uniformity of transverse deflection as a function of the transverse position;
- the contribution of the kicker to the machine impedance;
- the reflection coefficient at high frequency (short pulses for ILC).

An elliptical cross section minimizes the variation of the vertical dimension of the beam pipe between the injection region and the adjacent dipole region and increases the deflection efficiency.

Longitudinal Beam Coupling Impedance



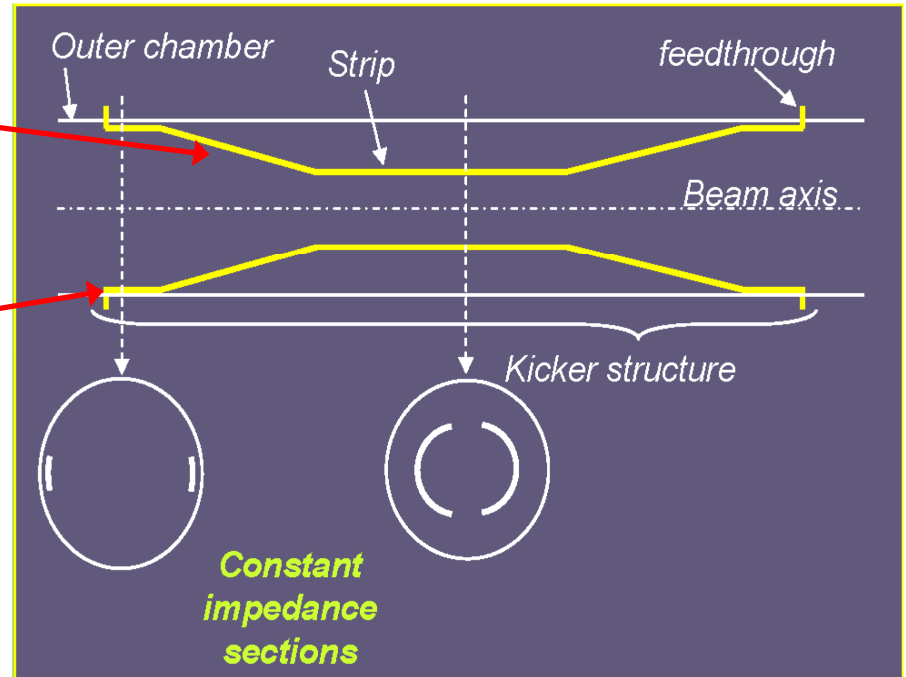


- Longitudinal beam coupling impedance of DAΦNE striplines is higher than that of a screened MKI kicker below 200MHz;
- Longitudinal beam coupling impedance of DAΦNE striplines is significantly less than that of a screened MKI kicker above 400MHz;
- Requirements for longitudinal broad band impedance (low frequency part of the total machine impedance) is a few Ω [1] – external circuit is also important to contribution [11];
- Bunch spacing in CLIC DR=0.5ns. BUT, 160ns pulse per 1.2µs ring length: expected frequency lines of DR & PDR are ~820kHz spaced;
- Also remember that screening/shielding requires ferrite aperture to be increased !

Conclusion: striplines are required to achieve adequately low longitudinal beam coupling impedance.

Striplines - 2

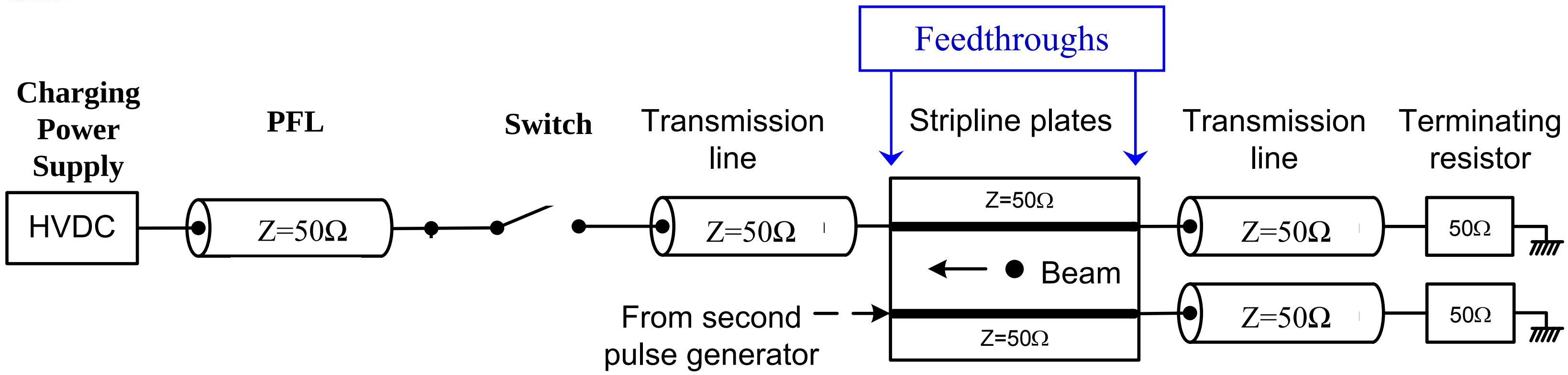
- Tapering of ILC striplines reduces effective length, in comparison with central (untapered) section, to ~90% (~90% for DAΦNE too: this should be a relatively small effect for CLIC, i.e. ~95% [c.f. 2m length of striplines]);
- When HV is applied, the possibility of discharges is higher in the end-sections of the kicker electrodes, where the stripline is closer to the vacuum tube [10]. NOTE: CLIC pulse is significantly longer than DAΦNE pulse;
- HV 50 Ohm (wide band) commercial feedthroughs do not exist and LNF, Frascati, has developed & tested one. Wide band feedthroughs are important to keep low beam impedance for the kicker even well beyond the frequencies content of the input pulse [10].



DAΦNE Striplines [7].
(54.8mm d at center; 78mm d at ends)

- KEK has also developed an HV coaxial connector, designed using HFSS, which provides much improved impedance matching in comparison with their original connectors [8].

Contributors to instability/ripple & droop

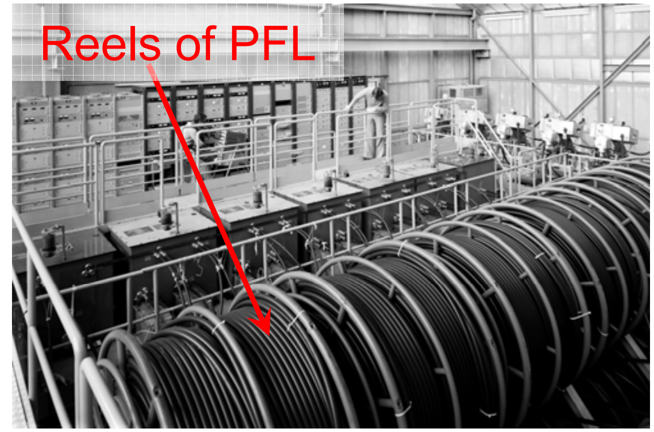


Schematic of one possible stripline kicker system

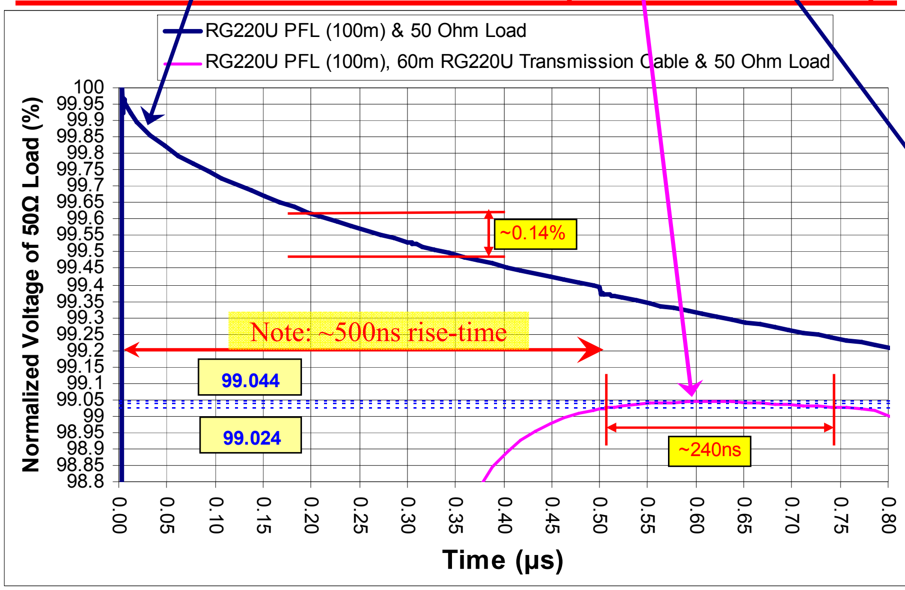
- Charging power supply (not expected to be significant contributor for "slow" charging of PFL);
- Pulse Forming Line (PFL) and transmission lines;
- Switch (dynamic characteristic and temperature effects);
- Feedthroughs;
- Mechanical stability of striplines;
- Terminator (frequency dependence of value and temperature effects);
- Impedance matching of system;
- Temperature effects (during a pulse);
- Long-term temperature effects (e.g. switches for LHC kicker dump generators ⇨ 0.2%/˚C ambient).

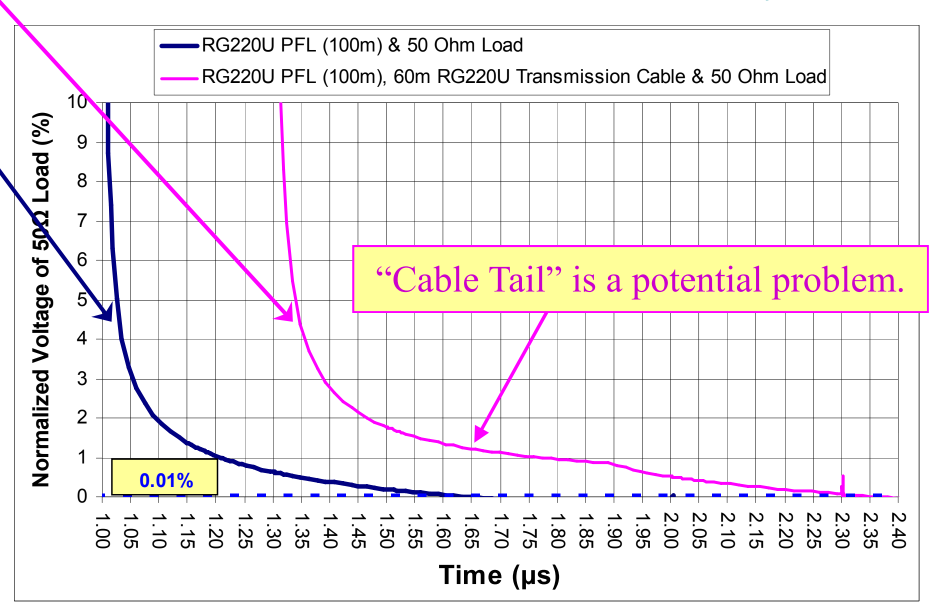
Compensation of droop due to PFL (1)

- One of several problems, for stability, is PFL droop.
- PFL (cable) gives low ripple pulses, but low attenuation is essential (especially with longer pulses) to control droop and "cable tail";
- Frequency dependent attenuation, of <u>transmission cable</u>, might be usable to compensate for <u>PFL droop</u>, but increased cable tail is a potential problem.



Theoretical simulations ("ideal" switch):





➢ RG220U PFL (without compensation): droop over 160ns ~0.14%;

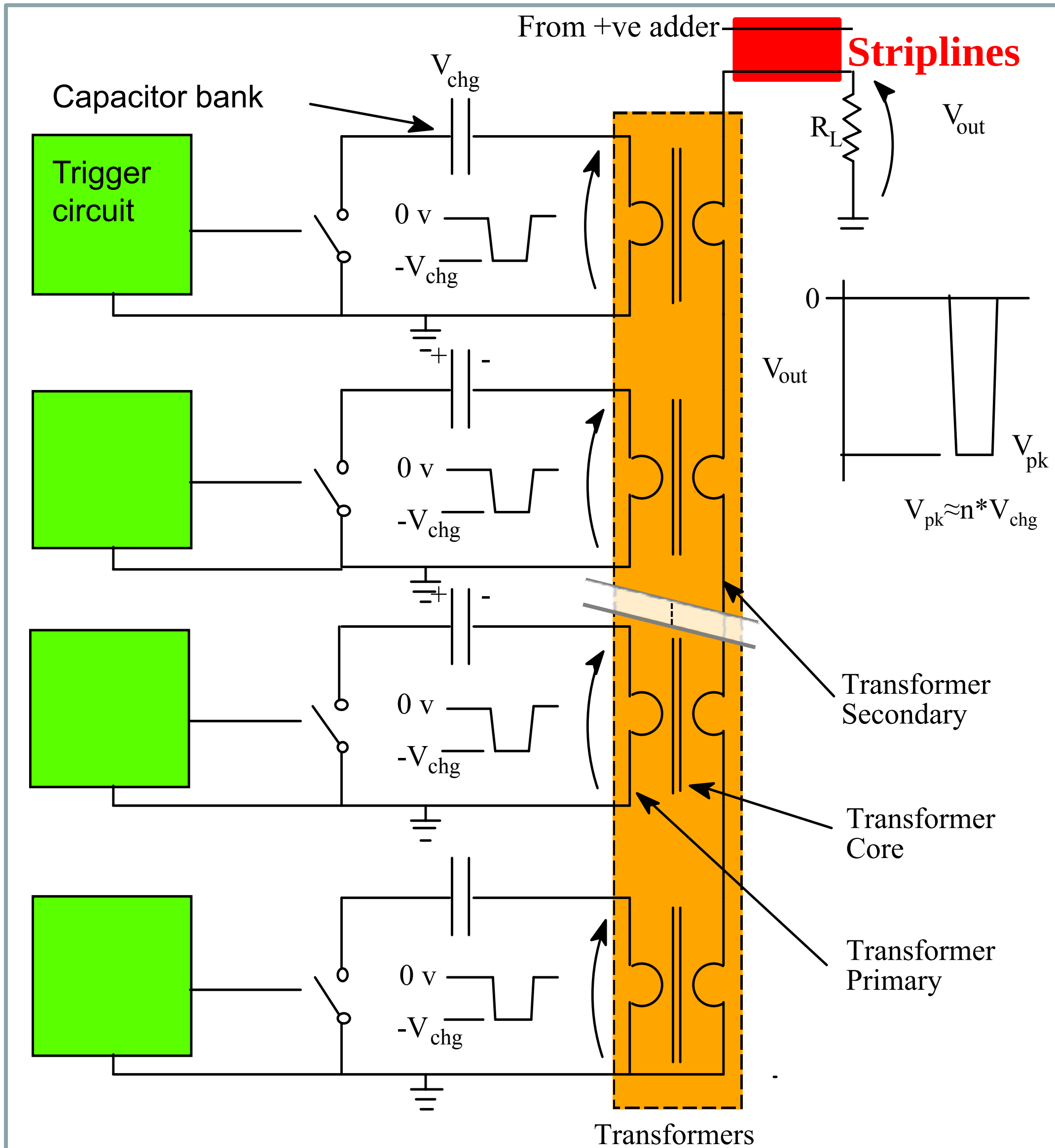
➢ With 60m transmission cable to 'compensate' for droop: ±0.01% over ~240ns. But 0.01% droop is significant c.f. required $1.5\text{x}10^{-4}$ stability for DR extraction!. (Note: ~500ns rise time).

Or….. an "n-Cell" Inductive Adder

An **Inductive Adder** [12] may be a promising means of compensating for losses in the PFL and transmission cables. The adder consists of:

- A multi-cell primary circuit;
- A single secondary winding;
- A fast pulse transformer with adequate voltage isolation.

Each primary circuit has a fast switch. The switches can be turned on and off **independently**, via trigger circuits, to provide some pulse shaping.



n-Cell Inductive Adder: adapted from [12]

Switch

- Thyratron or semiconductor switch (semiconductor switch preferred for repetition-rate, long-term reliability & low maintenance);

- For "non-inductive adder" semiconductor switch: MOSFETs (stacked in series) or a Fast Ionization Dynistor (FID) probably required (very high power IGBTs and IGCTs are relatively slow and may exhibit long switch-on tail) – R&D required;

- For an "inductive adder" semiconductor switch: MOSFETs or IGBTs – collaborate with ILC (also on design of pulse transformer);

- Switch should not be too fast, so as to avoid exciting oscillations with parasitic inductance and capacitances (maybe add series inductance to slow-down current rise time) – R&D required;

- Temperature rise of semiconductor switch, during current pulse, may be an issue, as this would effect the value of on-state resistance – R&D required.

Summary

1. Beam coupling impedance issues will require the use of striplines, rather than a ferrite loaded kicker magnet;
2. Short duration pulses (fast rise and fall) are advantageous for minimizing the total duration of the pulse. Hence a multi-cell inductive adder may be a good choice to:
   - Minimize dissipation in terminators (and therefore thermal effects);
   - Achieve reliable insulation, especially at ends of striplines, and adequately low beam coupling impedance of striplines – R&D required;
3. Stability of DR extraction kicker (0.015% reqd.) will be a significant challenge especially because of relatively long (160ns) pulse length. The following require R&D;
   - Power supply – probably OK for slow charging;
   - Choice between PFL & alternative (e.g. inductive adder);
   - Switch;
   - Transmission cable;
   - Feedthroughs;
   - Striplines;
   - Terminator.
4. A double kicker system relaxes the requirements for individual kickers, but this has never been tried at CERN. KEK-ATF achieved a factor of 3.3 reduction in kick jitter angle, w.r.t. a single kicker: the fact that the gain was not even greater is attributed to errors in the optics and errors in estimating horizontal displacement (due to insufficient position resolution of the BPMs) – can this be improved upon? – R&D required

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