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Do we need to modify the booster fast extraction kicker for Top-Off operation?

Input Data:

Extraction Energy:	E	1.95[GeV]
Beam stiffness at 1.95GeV	B_s	6.5 [Tm]
Required deflection angle-	θ	4 [mRad]
Effective length of the kicker (4 units)	l_{eff}	1.07[m]

Required Induction in the kicker air gap:

$$B_{Air} = \frac{B_s \cdot q}{l_{eff}} = 0.024[T] = 240[Gs] \qquad [1]$$

The cross-section of the ALS kicker is shown in Fig.1

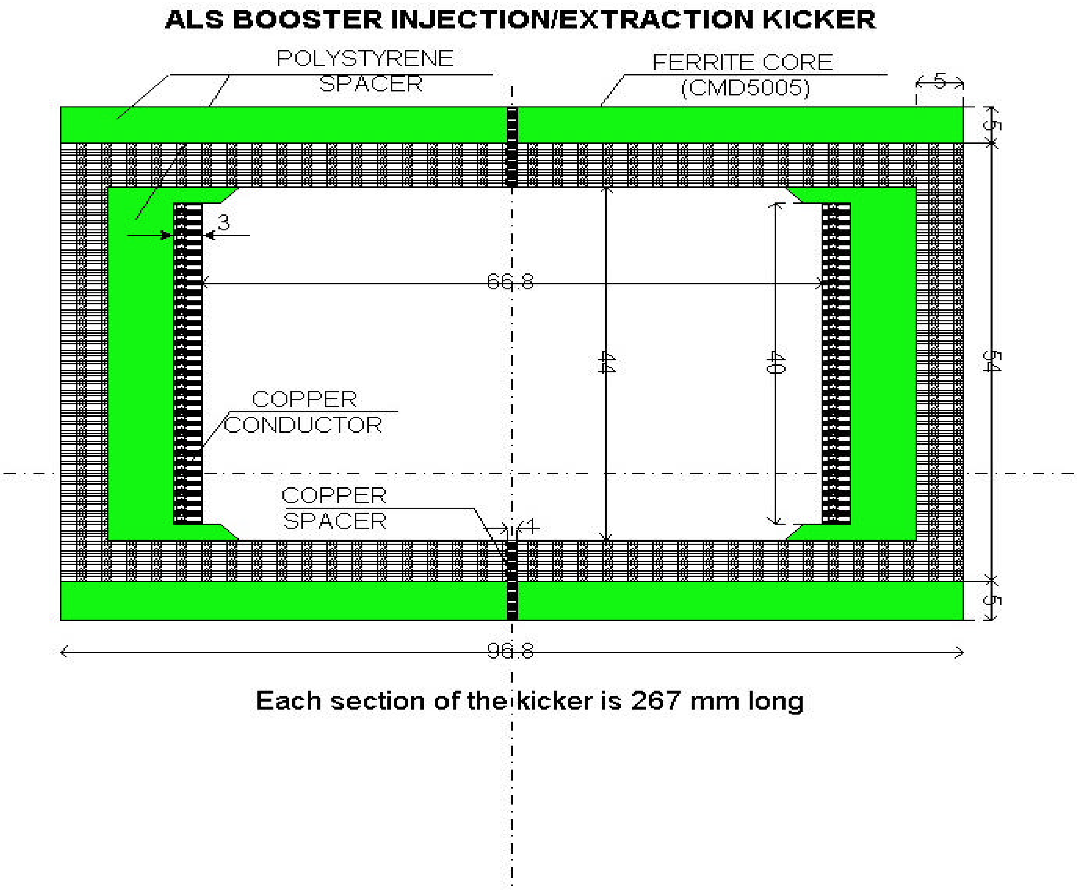


Fig.1

Since the magnetic flux is the same in the air gap and the ferrite core the average magnetic induction in the ferrite core equals:

$$B_{Ferr} = B_{Air} \cdot \frac{S_{Air}}{S_{Ferr}} = 1603[Gs] \qquad [2]$$

The maximum value of the magnetic induction in the ferrite core was calculated using INSOFT software and the results are given in Fig.2

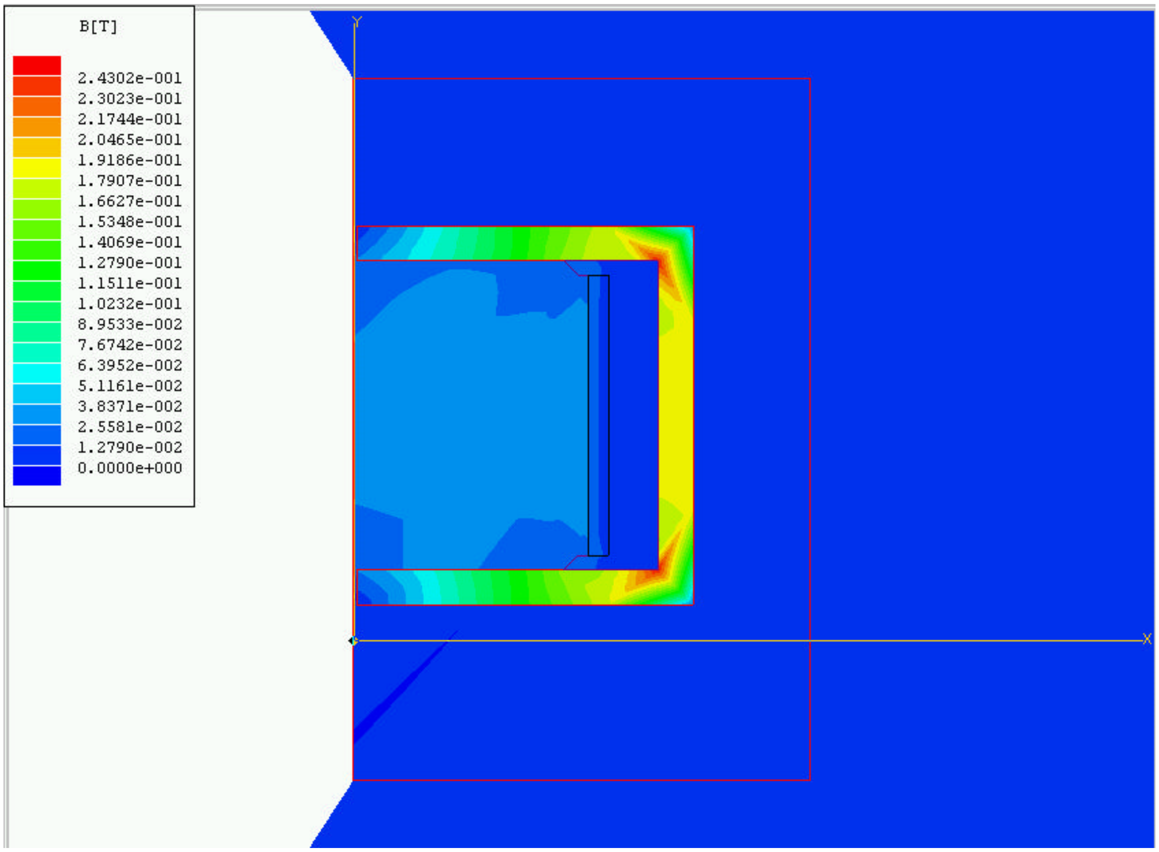


Fig.2

The maximum B-field in the corners of the ferrite core reaches the value of 2400[Gs] What is still well below the saturation value for CMD 5005 ferrite (3200[Gs]). Kicker is powered in push-pull mode so the currents in both conductors are flowing in opposite directions forcing magnetic fluxes through the air gap inside the yoke.

Assuming perfect symmetry in the magnet geometry we can make calculations for the half of the problem:
From Ampere Law:

$$\Theta = \oint_{l} H_l \cdot dl = I \cdot n \quad ; \qquad H = \frac{B}{m} = \frac{\Phi}{m \cdot S} = \frac{\Phi}{m_0 \cdot m_r \cdot S} = \Phi \cdot R_M \qquad [3]$$

$$n \cdot I = \Phi \cdot R_{Mgap} + \Phi \cdot R_{Mfer1} + \Phi \cdot R_{Mfer2} = \Phi \cdot \sum R_M \qquad [4]$$

$$R_{Mgap} = \frac{l_{gap}}{m_0 \cdot S_{gap}} = \frac{0.044}{1.257e^{-6} \cdot 0.267 \cdot 0.0334} = 3.93 \cdot 10^6 [\frac{1}{H}] \qquad [5]$$

$R_{Mfer1}=2.69*10^4[1/H]$; $R_{Mfer1}=2.38*10^4[1/H]$;

where:

H-magnetic field strength -	[A/m]	
B-magnetic induction -	[T]	$1[T]=1[Vs/m^2]$
Φ -magnetic flux -	[Wb]	1[Wb]=1[Vs]
μ_0-free space permeability =	$4\pi 10^{-7}$[H/m]	
μ_r – relative magnetic permeability		
R_M-magetic reluctance	[1/Hm]	
n-number of turns		
I- electric current	[A]	

The linear ramp with the rise time Δt-100ns correspond to the equivalent sine wave with the frequency ω≅1/Δt=1e7[1/s]. Since the flat top part of the pulse has similar length as the initial ramp ($t_{flattop}$=150ns) for simplicity sake we will follow our analysis with an assumption that the magnetization current has an shape of half of sinusoid with the frequency of 1.59MHz. From the CMD5005 ferrite data sheet:

for f=1.59MHz: μ_r=1200

For required magnetic induction in the air gap B=240[Gs]

$$\Phi = B_{gap} \cdot S_{gap} = 2.14 \cdot 10^{-4} [Wb] \qquad [6]$$

Required kicker current:

$$I = \Phi \cdot \sum R_M = 2.14 \cdot 10^{-4} \cdot 3.98 \cdot 10^6 = 852[A] \qquad [7]$$

From the second Kirchoff law for the magnetic circuits the self inductance of the kicker:

$$L = \frac{\Phi}{I} = \frac{1}{\sum R_M} = 251[nH] \qquad [8]$$

The effective capacitance of the kicker was calculated using INSOFT electrostatic finite element code (58pF) and measured (65pF).

$$I = I_M \cdot \sin(w \cdot t) \Rightarrow \frac{dI}{dt} = I_M \cdot w \cdot \cos(w \cdot t)$$

taking into account that for the linear ramp the slope $\frac{dI}{dt} \cong \frac{I_M}{\Delta t}$;

equivalent frequency of the sine-wave with the same slope as the linear ramp: $w \cong \frac{1}{\Delta t}$

Required 100ns ramp time and 150ns “flat-top” make the kicker pulse shape similar to the half of the sine-wave with the frequency of 1.59MHz.

The effective resistance of the kicker copper conductors at 1.59MHz could be calculated from the following formula:

$$R_L = k \cdot \frac{2.61e^{-7} \cdot h_{cond}\sqrt{f}}{l_{cond}} = 0.002[\Omega] \qquad [9]$$

where:

l_{cond}-perimeter of the kicker copper conductor(86mm)

h_{cond}-kicker length.

k-fudge factor (since the current density at the “air gap side” of the kicker is by order of magnitude higher than at the “ferrite side”(Fig.3) and also taking into account the resistant of the current return path we set k value in the equation [9] to be equal 2).

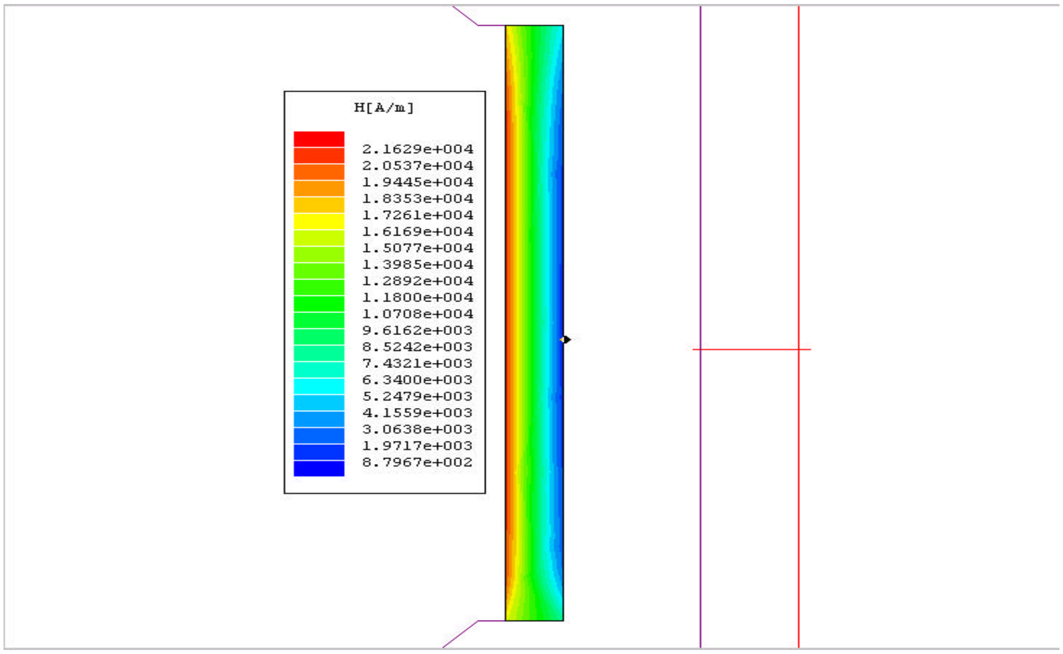


Fig.3

In the PSPICE model ALS injection/extraction kicker could be represented as a two-pieces of the transmission line with the characteristic impedance:

Zo=SQR(L/C)=62.1[Ω] and the electrical length: L=4.04[ns]

During our search for the alternative switching device we found new BEHLKE MOSFET solid state switches (HTS101-62-B) with extremely low internal resistance and fast switching time (<20ns). HTS101-62-B is controlled by 5V triggering pulse. By applying these devices to our extraction kickers would decrease the complexity of the triggering circuitry, increase the kicking pulse rise time (0-90% rise and fall time about 55ns) and eliminate pulse transformer. On the other hand we will need two solid-state switches per unit and additional 10kV dc power supply.
The PSICE model of the ALS kicker with ss switches (half of the problem) is shown in Fig.4 and the results of the simulations in the Fig.5

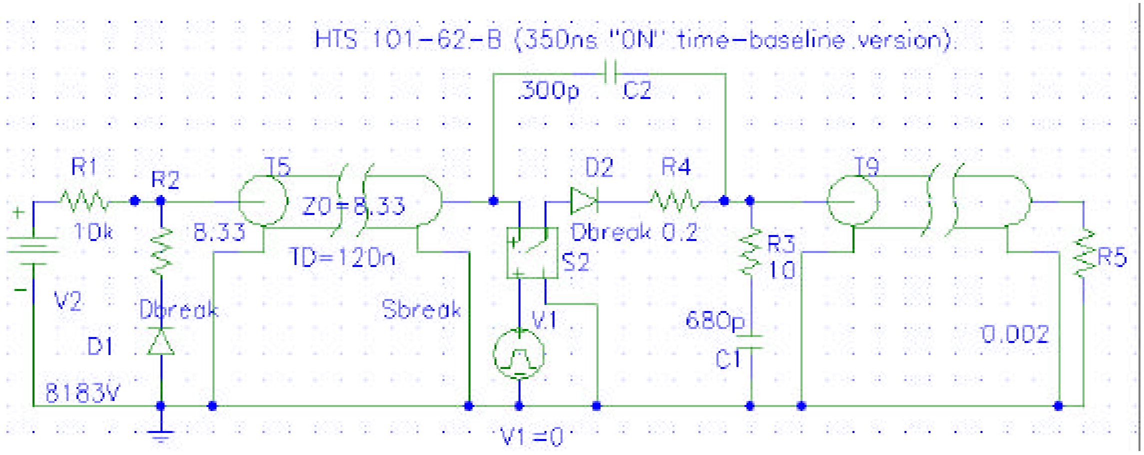


Fig.4

Fig.5

Pulse transformer issue.

Each pulse transformer has one primary single turn and two single turn secondary windings. The results of the measured parameters of the transformers are given in Tab.1

Winding	No of turns	Self inductance (@ 1.59MHz other windings open)	Leakage inductance (@ 1.59MHz other windings closed	Self capacitance	Winding resistance (@1.59MHz)	Coupling coefficient $k = \sqrt{1 - \frac{L_{closed}}{L_{open}}}$
Primary	1	8uH	54nH	150pF	0.002Ω	$K_{p\text{-}s1}$=0.9966
Secondary 1	1	8uH	54nH	50pF	0.0025Ω	$K_{s1\text{-}s2}$=0.9966
Secondary 2	1	8uH	54nH	50pF	0.0025Ω	$K_{s2\text{-}p}$=0.9966

Windings cross-capacitance (primary-secondary is 120pF)

Tab.1

The magnetizing inductance is almost equal the inductance of the primary winding ($L=k^2Lp\cong 8uH$).

The simplify P-SPICE model of the present configuration of the ALS kicker with pulse transformer is shown in Fig.6 (in our model one secondary winding of the pulse transformer has been omitted and both lines of the kicker are connected in parallel).

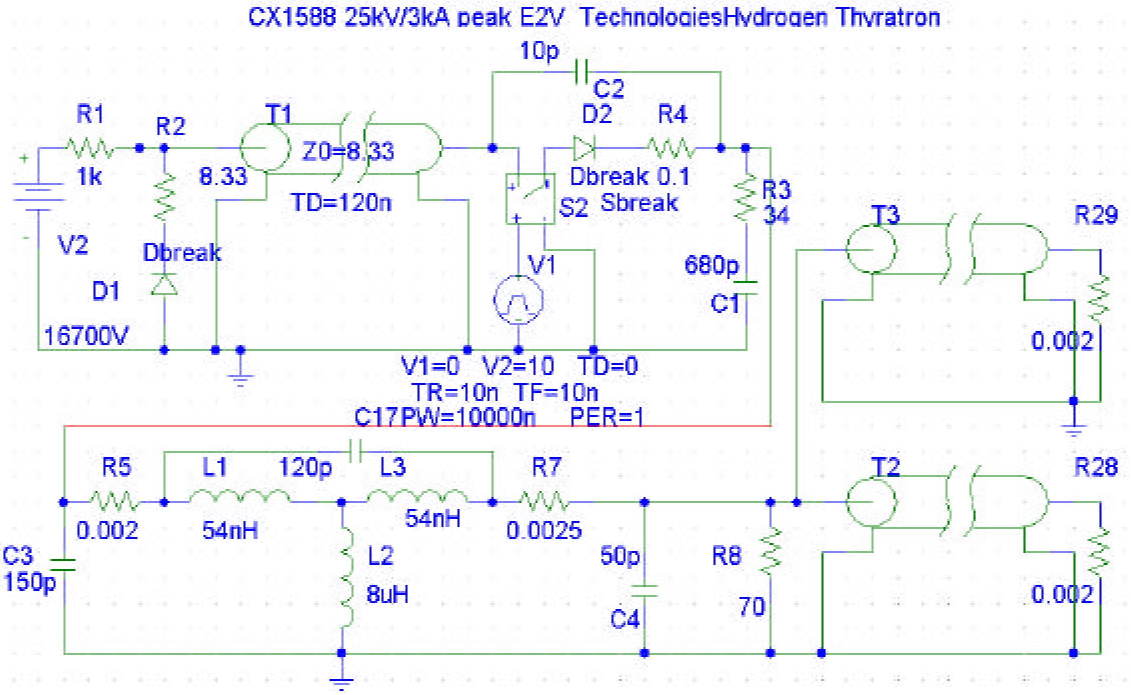
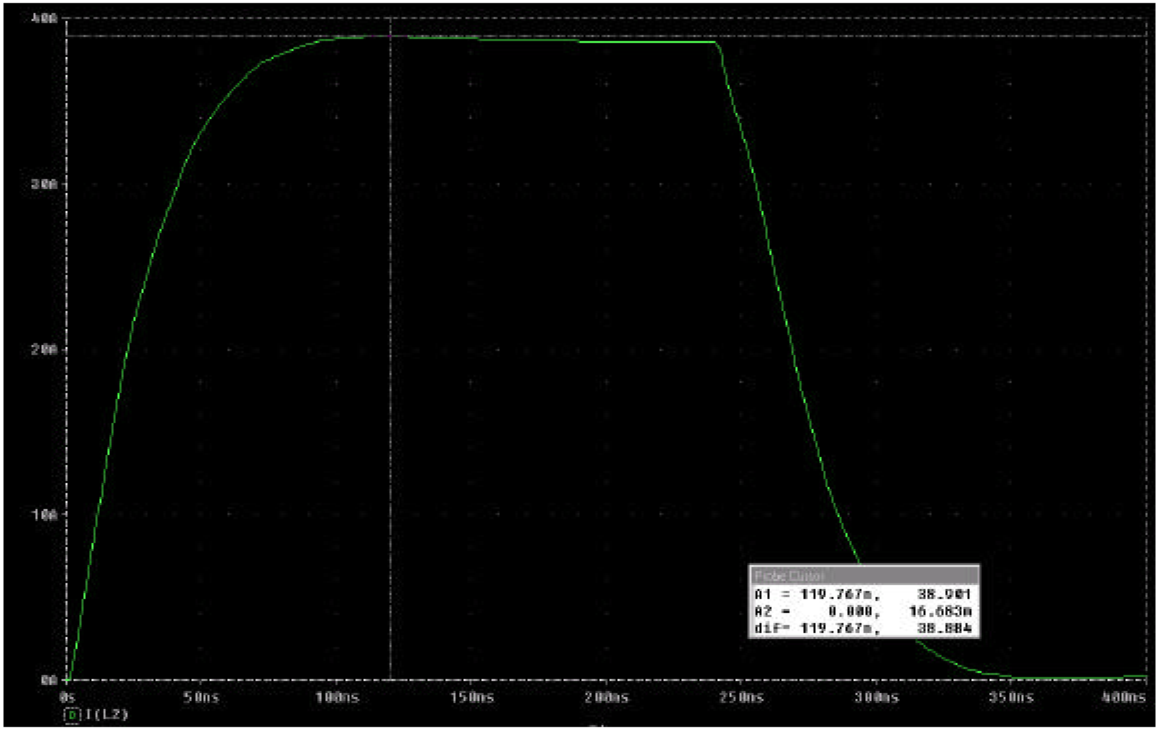


Fig.6

The calculated value of the magnetization current of the pulse transformer is shown in Fig.7.



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A1 = 119.767n,     38.901
A2 =     0.000,   16.683m
dif= 119.767n,     38.884
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Fig.7

From the P-Spice simulation and geometrical dimensions of the pulse transformer the magnetic induction in the transformer core could be determined from the second Kirchoff Law for the magnetic circuits:

$$B_{core} = \frac{L \cdot I_M}{S_{core}} = \frac{8e-6[H] \cdot 38.9[A]}{0.001066[m^2]} = 0.29[T] = 2900[Gs]$$

The saturation induction for CMD 5005 is 3200[Gs].

Conclusion:

Let’s replace the existing thyratron with CX1588 and test the ALS spare kicker at the power level required for the 1.95GeV beam. If it will survive the test let it fly.