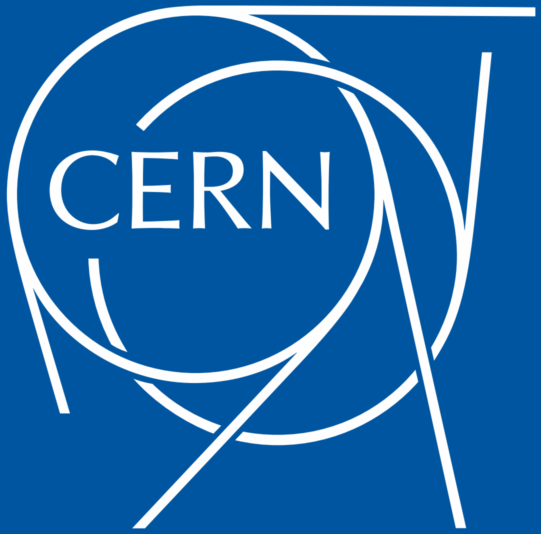
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PSpice and Opera-2d modelling: a very brief review

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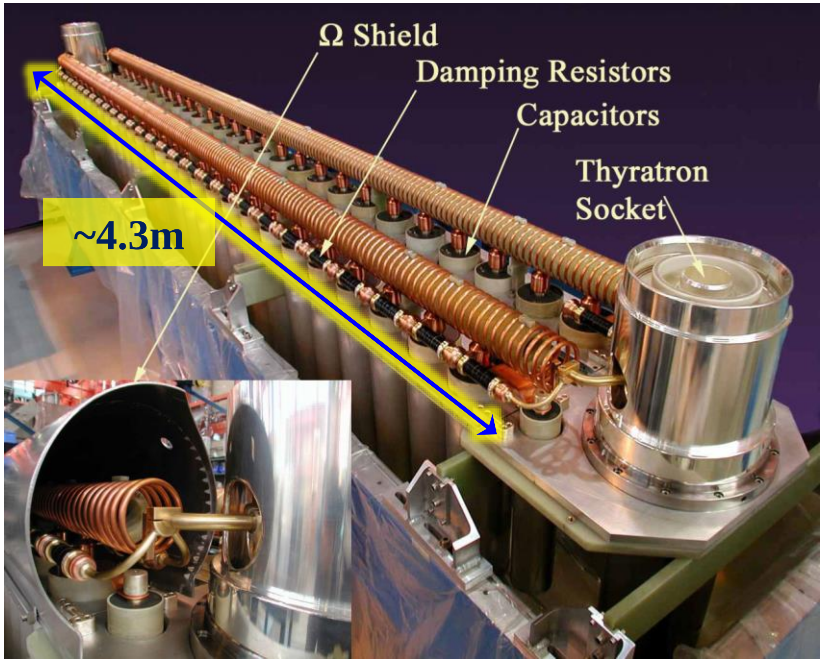
Acknowledgements:
L. Ducimetiere and L. Sermeus

Outline

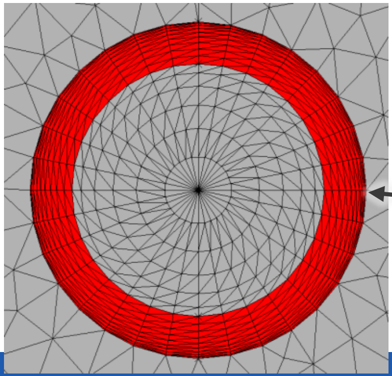
- PSpice simulation of skin and proximity effect:
  - Derivation and modelling of frequency dependence of resistance and inductance – for use in, e.g. PSpice AC and transient simulations
- PSpice simulation of thyratron turn-on:
  - Non-linear switching for use in transient simulations

Skin and proximity effect – example application

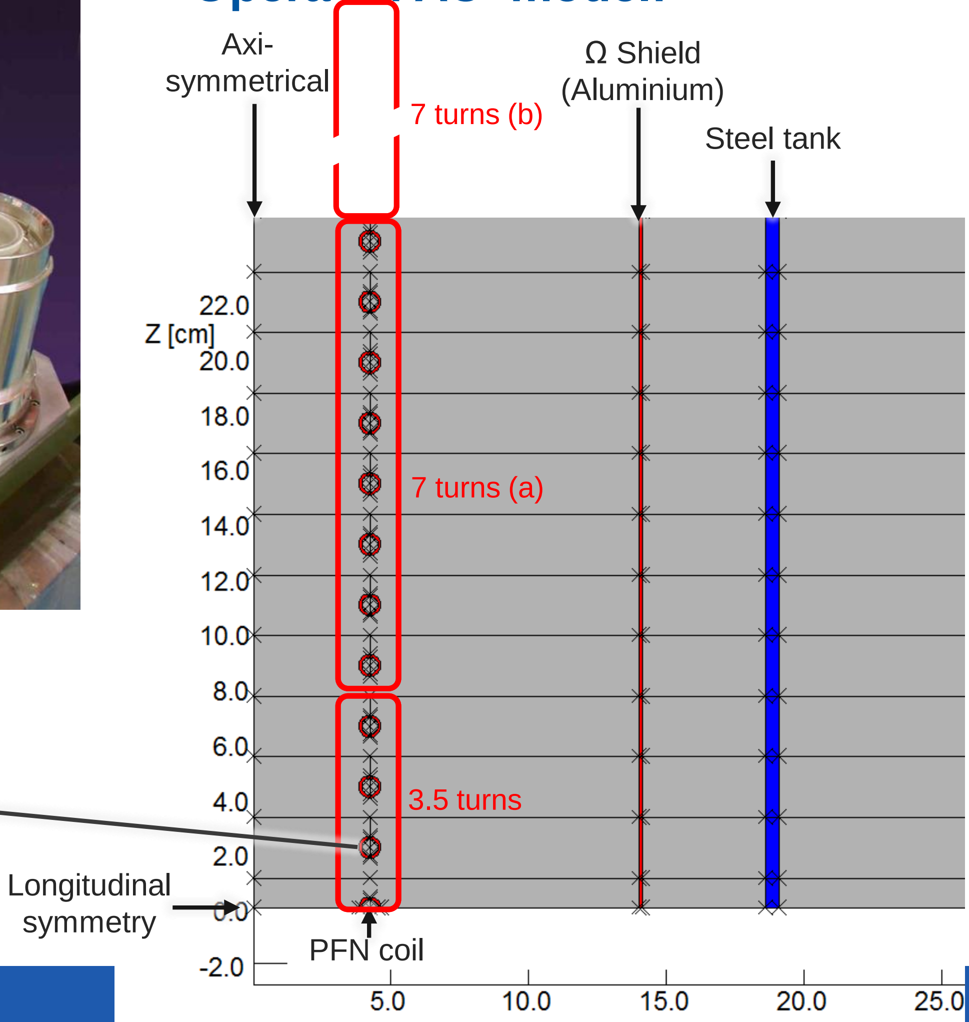
Frequency dependence of resistance and inductance has important effects on the performance of many circuits. For example, for the LHC Injection PFN:



Suitably fine mesh in conductors (biased towards the outer surface)

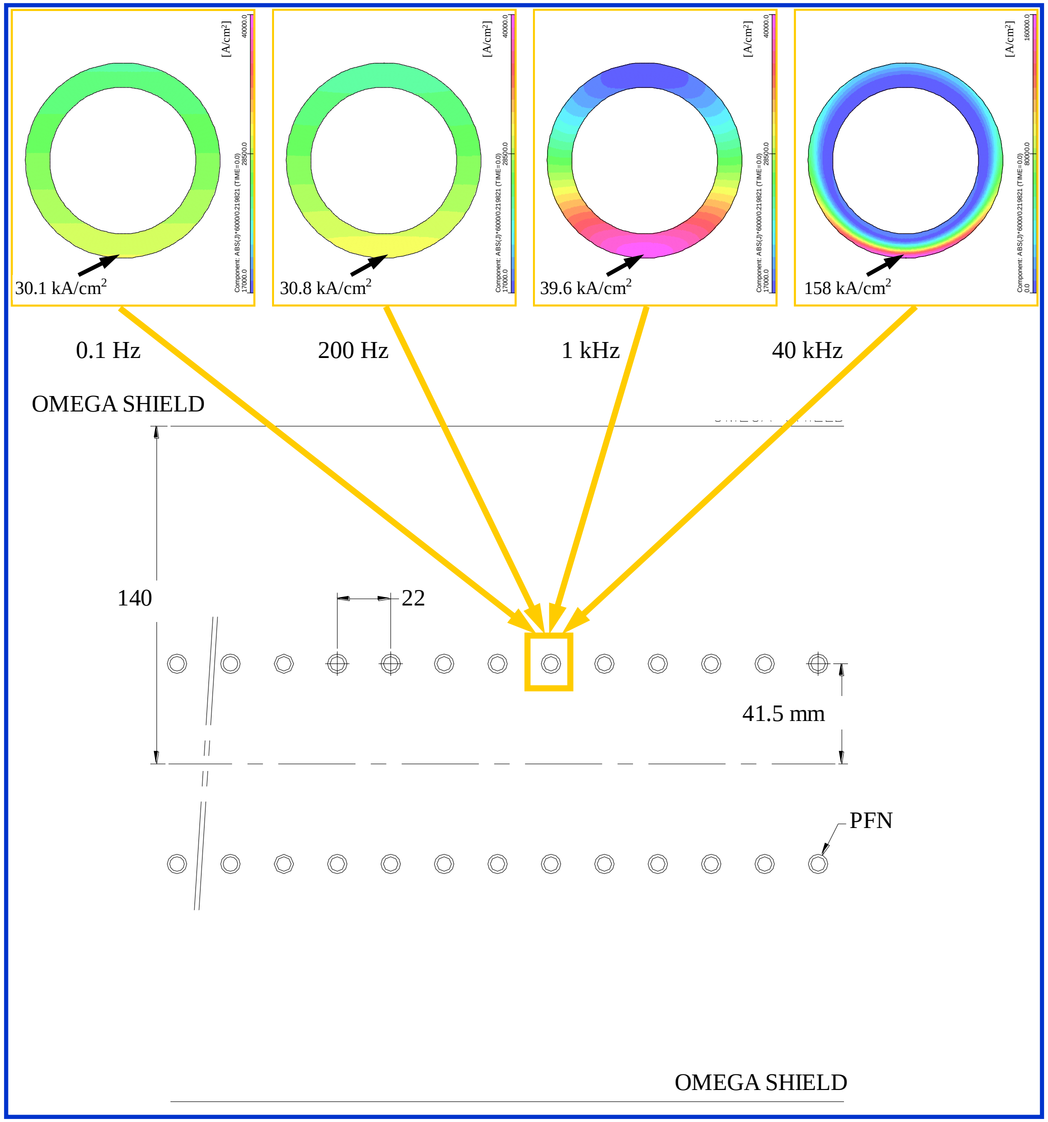


Opera-2d AC model:



Skin and proximity effect – example application (2)

Opera-2d AC predictions:



<u>Inductance derivation*</u> (from stored energy, per unit length) ⇨ inductance per unit length :

1) Current in only 3.5 turns ⇨ self-inductance of one-cell (7-turns);
2) Current in only 7 turns (a) ⇨ self-inductance of two-cells + Mutual13;
3) Current in 3.5 turns + 7 turns (a) ⇨ self-inductance of three-cells + Mutual13 + 2·Mutual12.

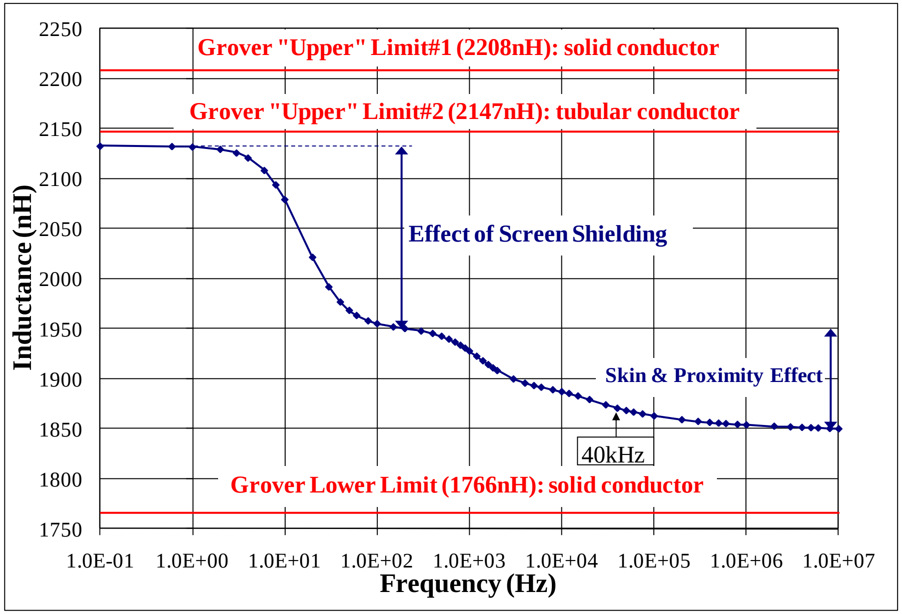
<u>Resistance derivation*</u> (from power, per unit length) ⇨ resistance per unit length:

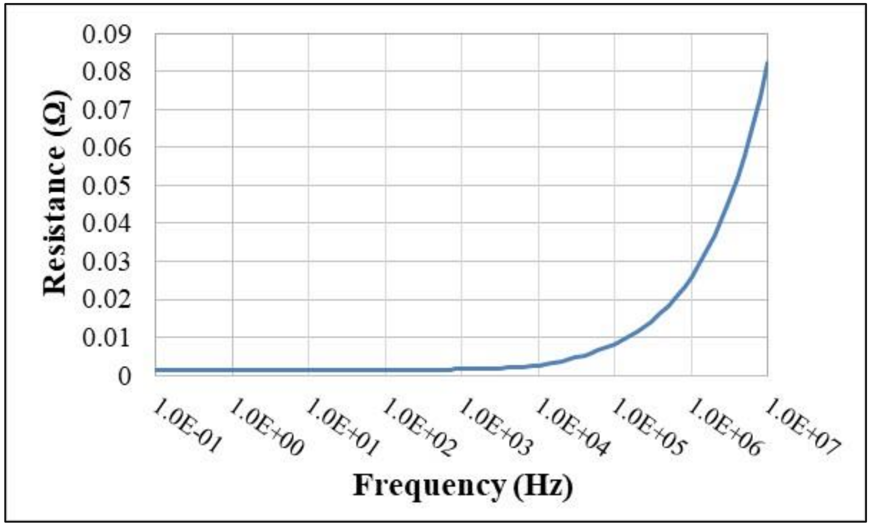
1) Current in only 3.5 turns ⇨ resistance of one-cell (7-turns).

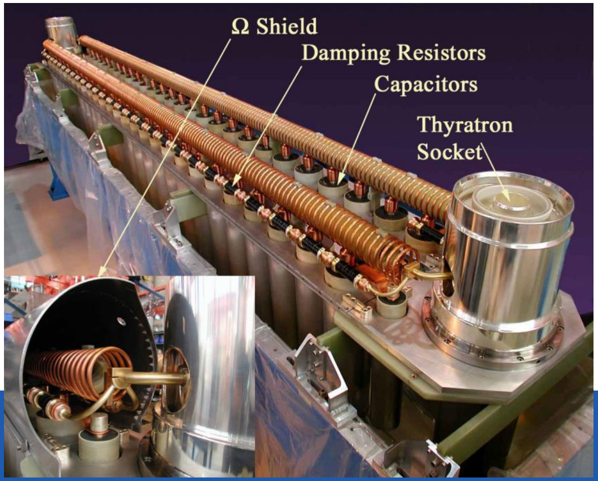
*: be careful of geometry, i.e. stored energy/power is in “visible geometry”.

Skin and proximity effect – example values

From Opera-2d AC simulations inductance (self and mutual) and resistance are derived, for the PFN, at each frequency (for a 7-turn cell):







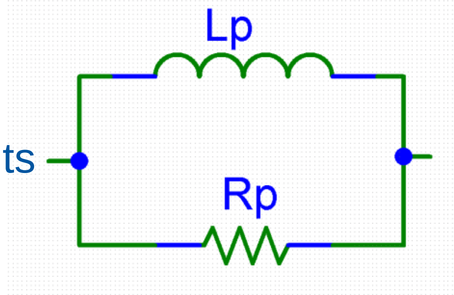
Methods of modelling frequency dependency

Various approaches could be used to simulate frequency dependent inductance and resistance:

1) E.g. Laplace transforms:
   - ☹ Not straightforward to *“fit” a* Laplace transform to data;
   - ☹ PSpice needs to carry out an “impulse response” of (each) Laplace transform before the transient analysis – frequency resolution and maximum frequency are not easily controllable (e.g. only by 1/Tstop and RELTOL)
2) Passive components:
   - ☺ Relatively straightforward to *“fit”* component values to reproduce Opera data over a limited frequency range;
   - ☺ Applicable in both frequency and time domain, provided *“fit”* covers complete frequency range of interest (e.g. Max. frequency ≥ 10MHz for 30ns rise time) -- PSpice does not need to carry out an “impulse response” before the transient analysis.

Skin and proximity effect – example steps

1) Create a frequency-dependent cell using, standard, Spice elements whose values are frequency-independent:



Effective series resistance (R_s) and series imaginary impedance (X_s) are given by:

$$R_s = \frac{R_p \cdot X_p^2}{R_p^2 + X_p^2} \qquad X_s = \frac{R_p^2 \cdot X_p}{R_p^2 + X_p^2}$$

Where: $X_p = 2 \cdot \pi \cdot f \cdot L_p$

2) To determine **approximate values** for the R_p and L_p, over an appropriate frequency range:

a) When inductance is reducing and series resistance is fairly constant (e.g. < 10 kHz):

$$R_p = \sqrt{\frac{X_{s2} \cdot X_{p2}^2}{X_{p2} - X_{s2}}} \quad \text{and} \quad L_p = \frac{X_{s1} \cdot X_{s2}\left(\omega_1^2 - \omega_2^2\right)}{X_{s1} \cdot \omega_1^2 \cdot \omega_2 - X_{s2} \cdot \omega_2^2 \cdot \omega_1}$$

Where: X_{s1} and X_{s2} are the values of the cell's imaginary impedance at the lower (f_1) and upper (f_2) values of frequency, respectively.

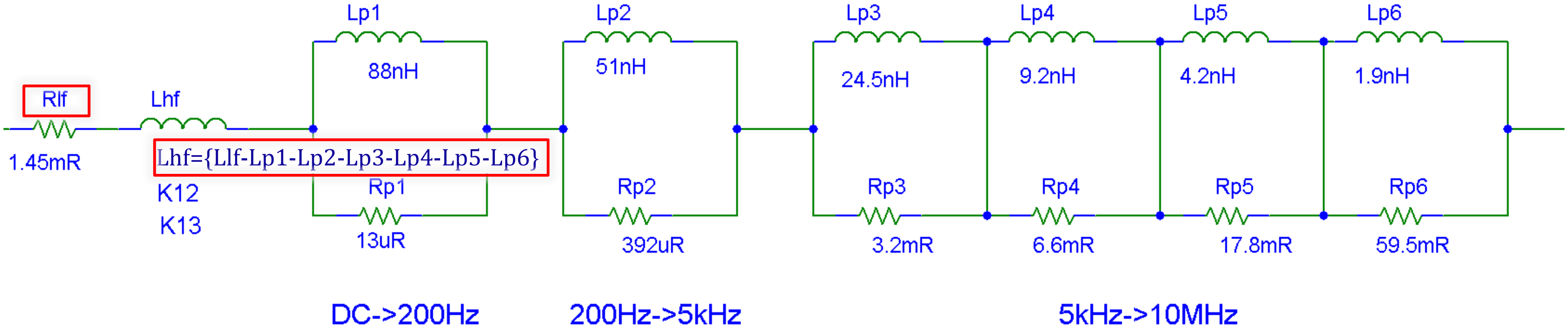
b) When series resistance is increasing (e.g. > 10 kHz) and inductance is fairly constant:

$$R_p = \frac{R_1 \cdot R_2\left(f_2^2 - f_1^2\right)}{R_1 \cdot f_2^2 - R_2 \cdot f_1^2} \quad \text{and} \quad L_p = \frac{1}{2 \cdot \pi \cdot f_2}\sqrt{\frac{R_2 \cdot R_p^2}{R_p - R_2}}$$

3) Use the PSpice Optimizer (Advanced Analysis Option) to find the best values of R_p and L_p to *"fit"* the curves of series resistance and series inductance, as a function of frequency:

a) Can weight curve-fit of, e.g., inductance more than resistance.

Equivalent L(f) and R(f) circuit for one PFN cell



Lhf (& coupling coefficients) represents the high-frequency inductance;
Rlf represents the low-frequency inductance.

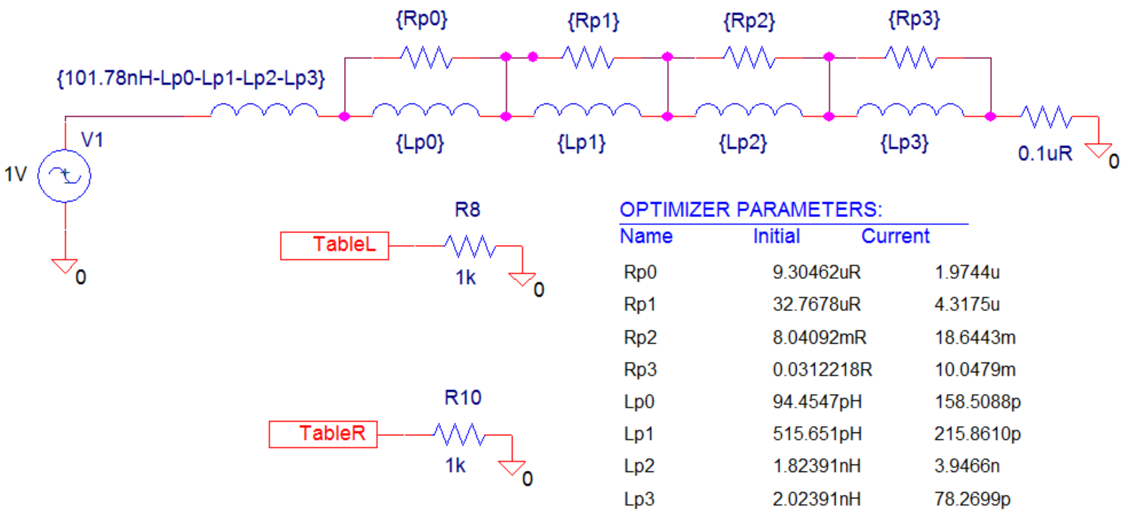
Notes:

1) At low frequency, current flows through the parallel inductors, bypassing all the parallel resistors: hence, the sum of the values of the parallel inductors and the series inductor must equal the low-frequency value of required inductance.
2) Each cell represents a variation of resistance and inductance with frequency and not the absolute values of resistance and inductance. Hence subtract the series resistance and inductance from the absolute values before using the equations; on the previous slide, to calculate Lp and Rp.
3) Also used to represent L(f) and R(f) of screen conductors in the aperture of a kicker magnet (see next slide).

Example: kicker magnet cell inductance

Alumina tube

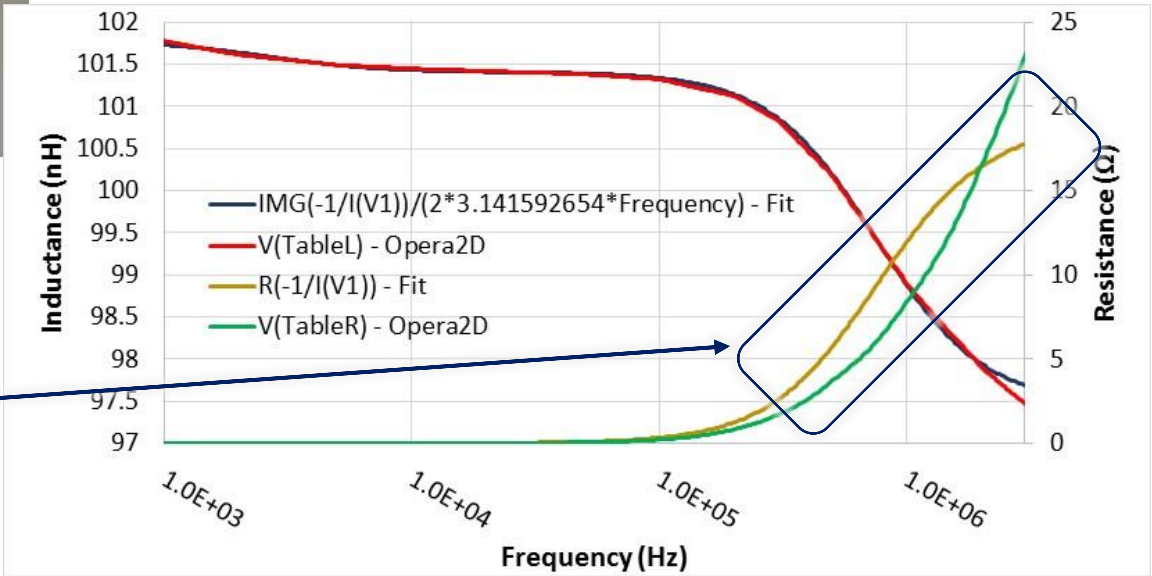
Screen conductors.



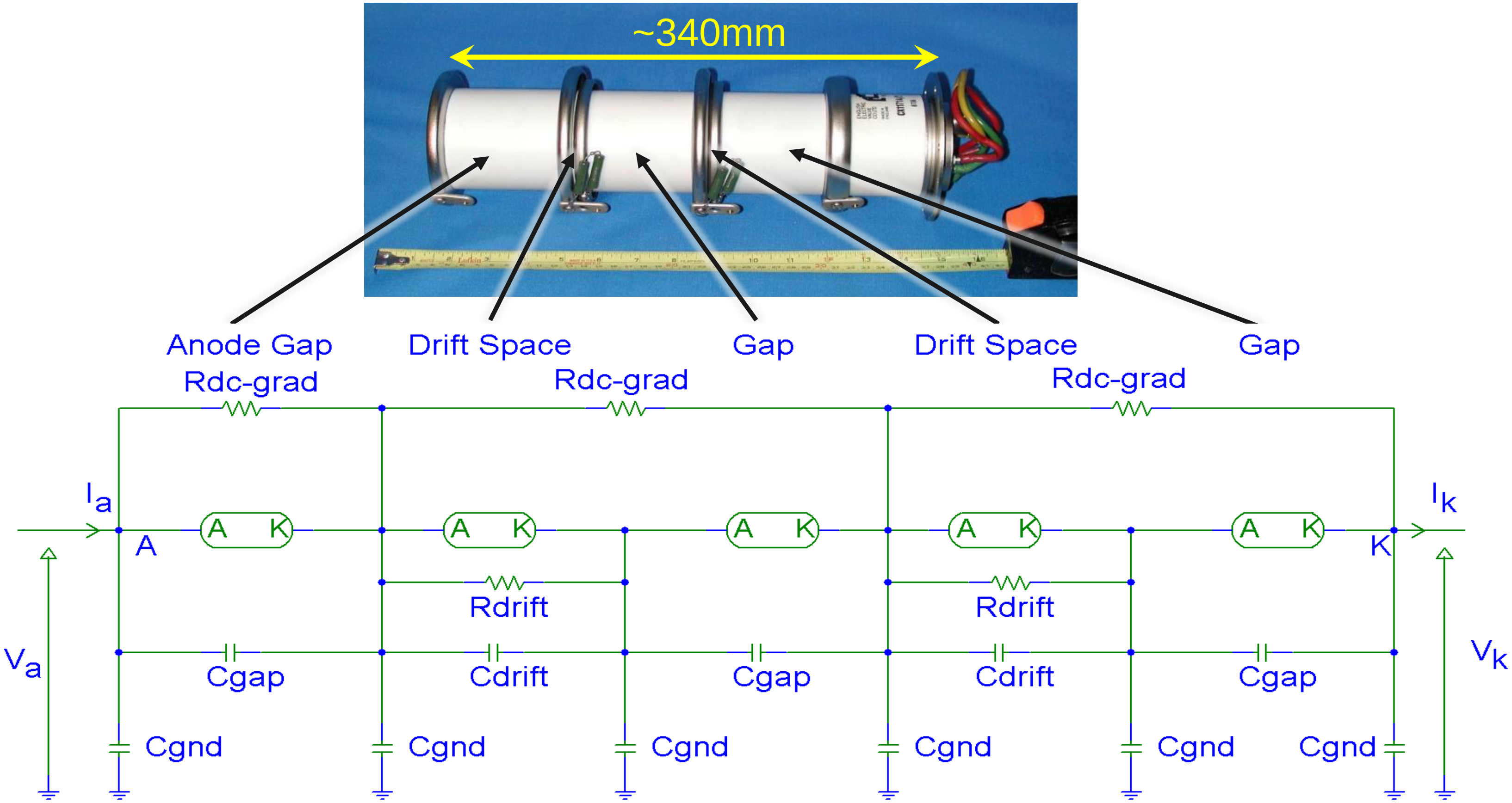
OPTIMIZER PARAMETERS:

Name	Initial	Current
Rp0	9.30462uR	1.9744u
Rp1	32.7678uR	4.3175u
Rp2	8.04092mR	18.6443m
Rp3	0.0312218R	10.0479m
Lp0	94.4547pH	158.5088p
Lp1	515.651pH	215.8610p
Lp2	1.82391nH	3.9466n
Lp3	2.02391nH	78.2699p

A better "fit" to resistance could likely be obtained with more cells.



Modelling a Turn-on of a Multi-Gap Thyratron

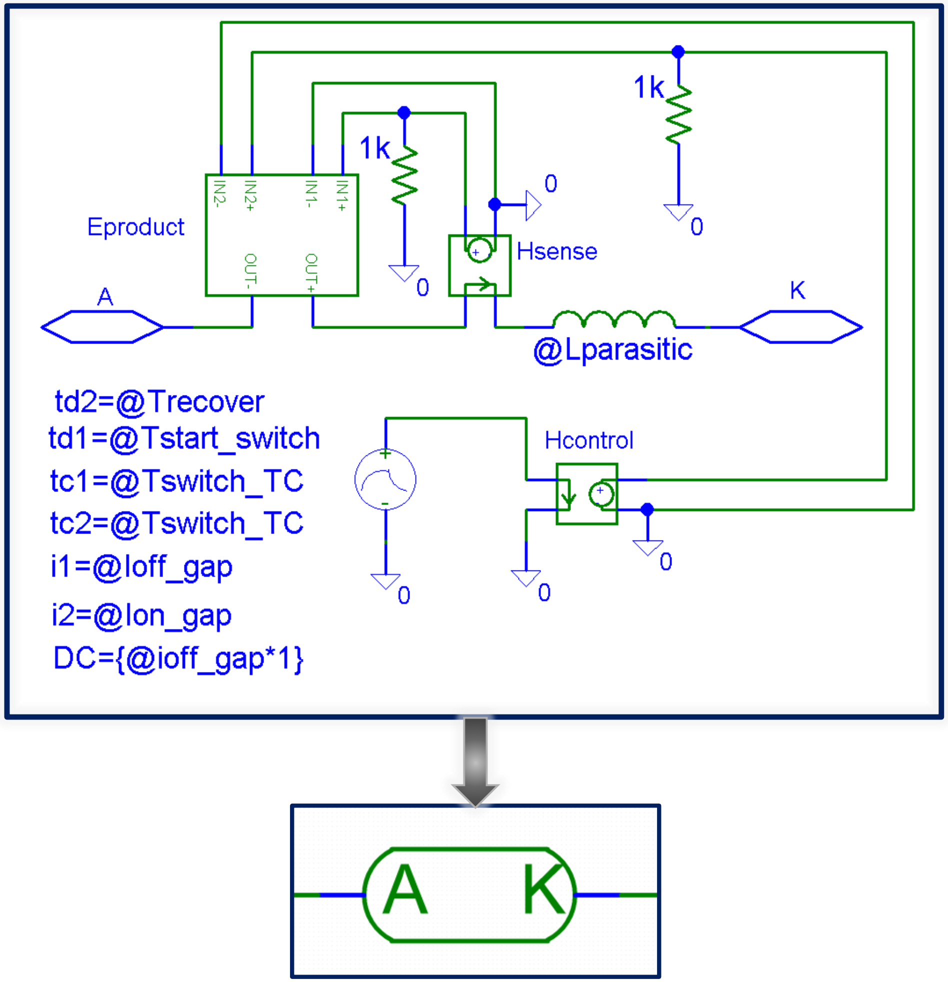


Example values for CX1171A in a CERN coaxial housing:

- Total parasitic inductance: ~80 nH
- Cgap (inter-electrode capacitance of each of each gap): 15 pF to 20 pF;
- Cdrift (drift space capacitance): 25 pF to 30 pF;
- Cgnd (parasitic capacitance from the grading ring to ground): ~11 pF.

Modelling Thyratron Turn-on

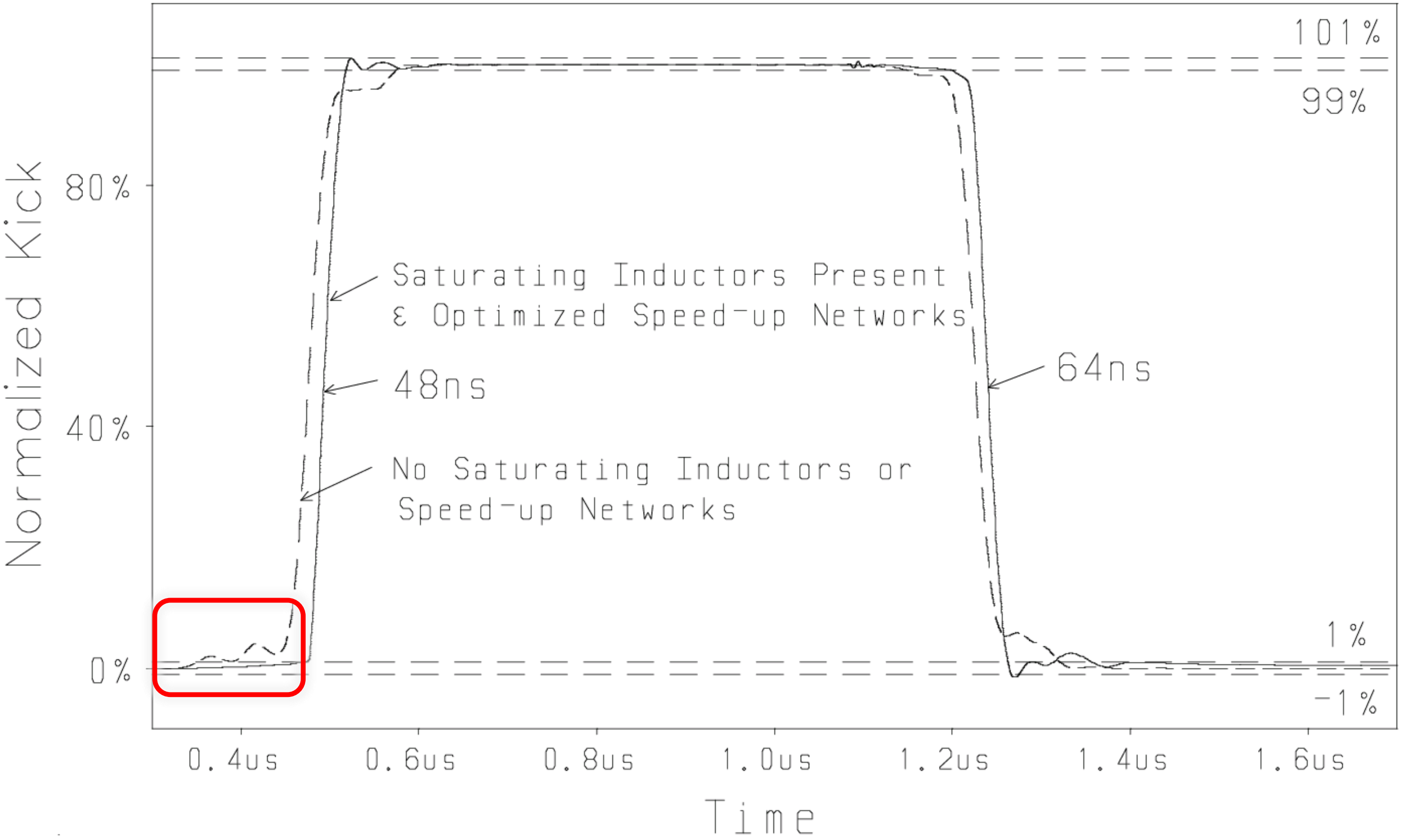
A non-linear turn-on switching characteristic for a thyratron may be represented using the following equivalent circuit.



- Lparasitic ⇨ parasitic inductance of a gap and/or drift space;
- Hsense and Hcontrol ⇨ both current-controlled voltage sources with unity gain, which are used for controlling voltage source Eproduct: the potential difference across the output terminals of Eproduct ⇨ product of the current through Hsense and Hcontrol.
- ISA is a current source whose current decays exponentially, with time-constant *tc1*, from a high-current (e.g. 50kA) to a low current (e.g. 20mA). The low current value is chosen to give a representative conduction voltage drop at the required load current.
- 7ns for *tc1* ⇨ predicted 10% to 90% current rise-time of ~32ns.

Predicted current from a multi-gap thyratron model

Pre-pulse displacement current, resulting from turn-on of the individual gaps and drift spaces, can be predicted using the multi-gap thyratron model:



Thank you for your attention !

Questions, comments, etc …

References

- Cobham, Opera-2d, http://www.cobham.com/communications-and-connectivity/antenna-systems/specialist-technical-services-and-software/design-simulation-software/opera/opera-2d/
- Grover, FW, “Inductance Calculations: Working Formulas and Tables”, Special edition prepared for Instrument Society of America, 1973. Originally published by Van Nostrand (New York), 1946.
- M.J. Barnes, G.D. Wait, L. Ducimetière, “Inductance Calculations and Measurements for the CERN LHC Injection Pulse Forming Network”, proc. of 7th European Particle Accelerator Conf. (EPAC’00), Vienna, Austria, June 26-30, 2000, pp2355-2357.
- M.J. Barnes, G.D. Wait, “A Mathematical Model of a Three-Gap Thyratron Simulating Turn-On”, proc. of 9th International Pulse Power Conf., Albuquerque, USA, June 21-23, 1993, pp293-296.
- D. Fiander, K. Metzmacher and P. Pearce, Kickers and Septa at the PS
- Complex, CERN. Proc. of the KAON PDS Magnet Design Workshop, October 1988, pp 71-79.
- L. Ducimetière, D.C. Fiander, “Commutation Losses of a Multigap High Voltage Thyratron". IEEE Conf. Record of the 1990 19th Power Modulator Symposium, June 26-28, 1990, San Diego, pp248-253.
- R.L. Cassel, T.S. Mattison, “Kicker Prepulse Canceller". IEEE Conf. Record of the 1991 Particle Accelerator Conference, May 6-9, 1991, pp3162-3164.
- E2V Technologies, Hydrogen Thyratrons Preamble, available at https://www.tayloredge.com/reference/Electronics/VacuumTube/thyratron_preamble.pdf.
- M.J. Barnes, G.D. Wait, “Effect of Saturating Ferrites for the 30Ω Resistively Terminated, Prototype Kicker Magnet". TRI-DN-91-K192.

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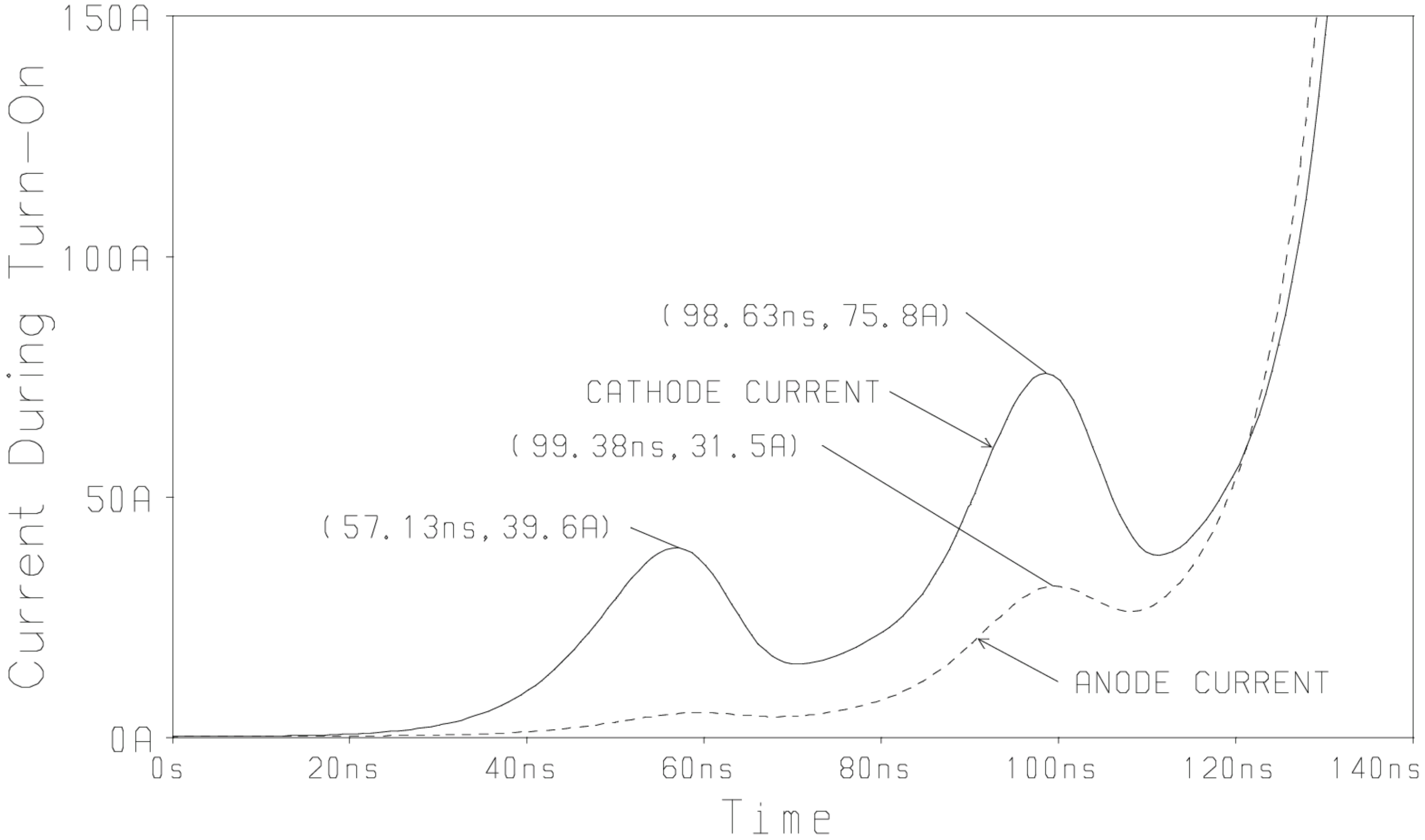
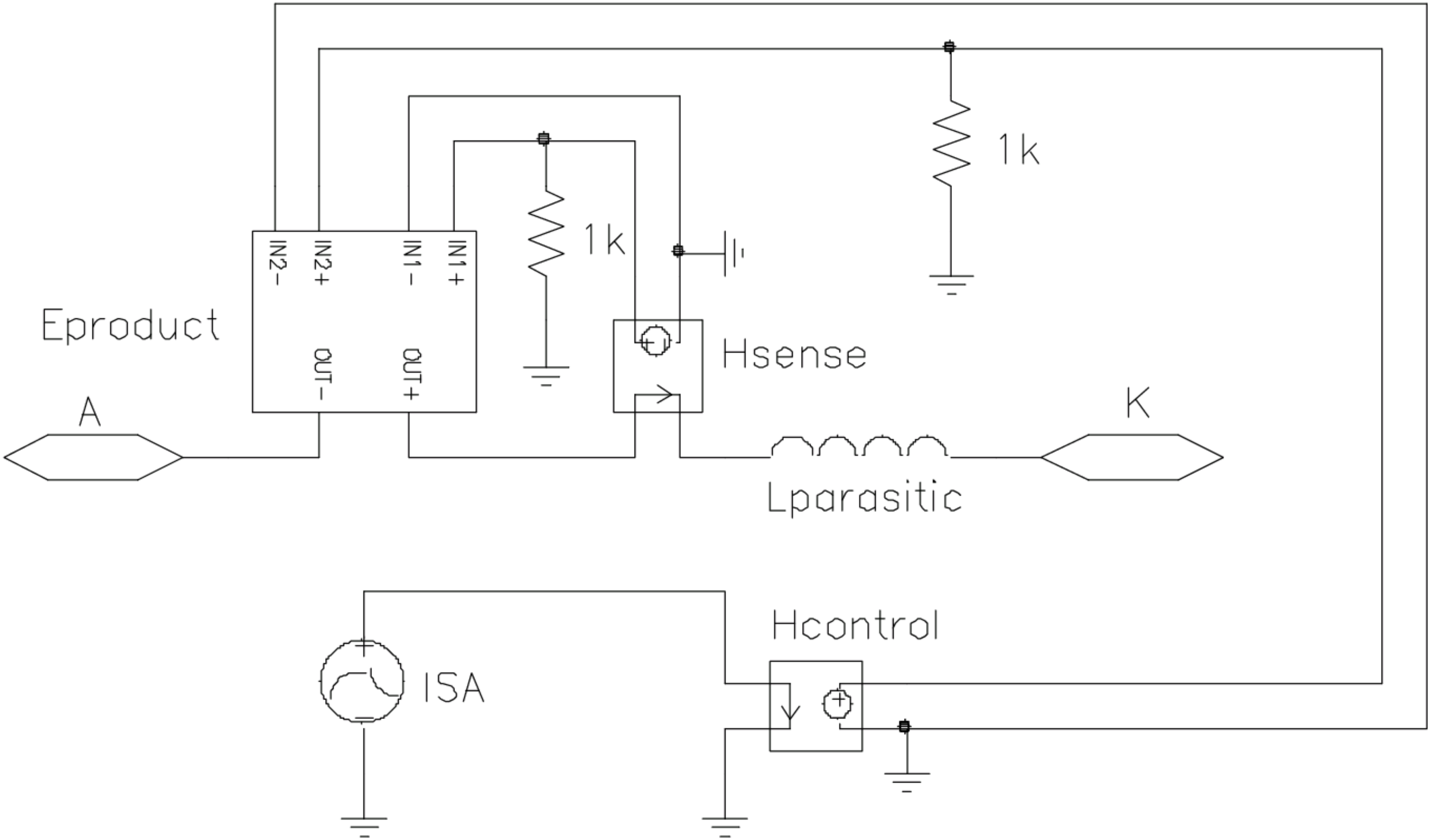
Spare Slides

Predicted pre-pulse displacement current from a multi-gap thyratron model

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