Hollow Electron Lens

Quench Protection Design and Analysis
status update

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EN-MME (HEL Design):
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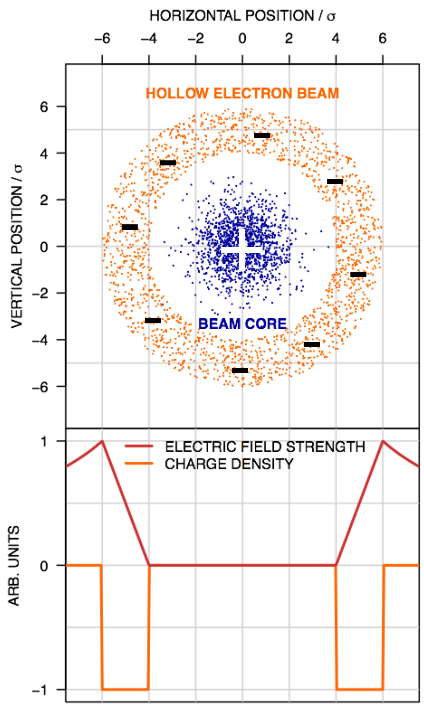
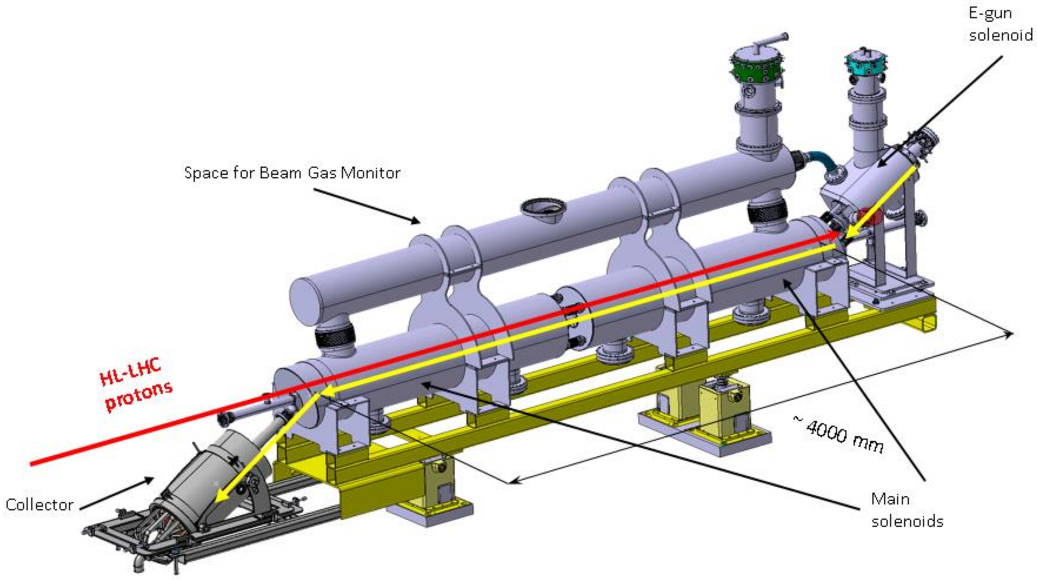
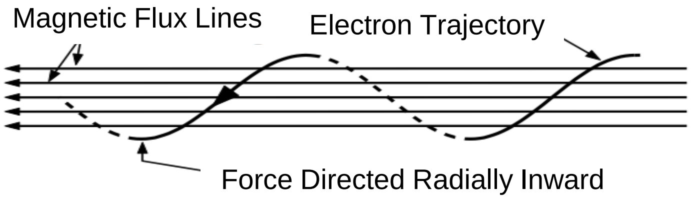
The HEL System – SC Magnets

Operating Principle (Collimator)*







The Hollow Electron Lens system consists of multiple superconducting magnets for

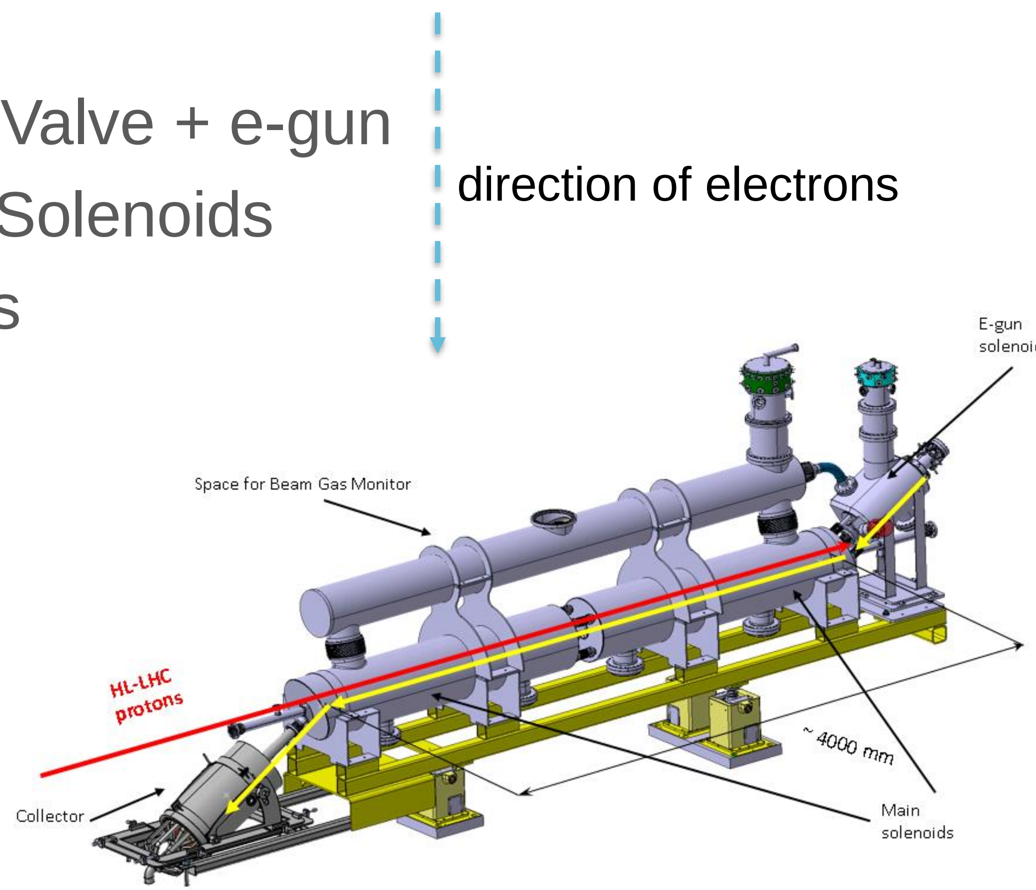
1. Guiding the hollow beam of electrons:
   a. (main solenoid, bending solenoid, solenoid after valve, e-gun, CCT)
2. Correcting the field imperfections and fine tune the beam position:
   a. (4 for the main solenoid, 4 for the main bending, 2 for the e-gun)

The aim of this work is to study the protectability of the superconducting circuits.

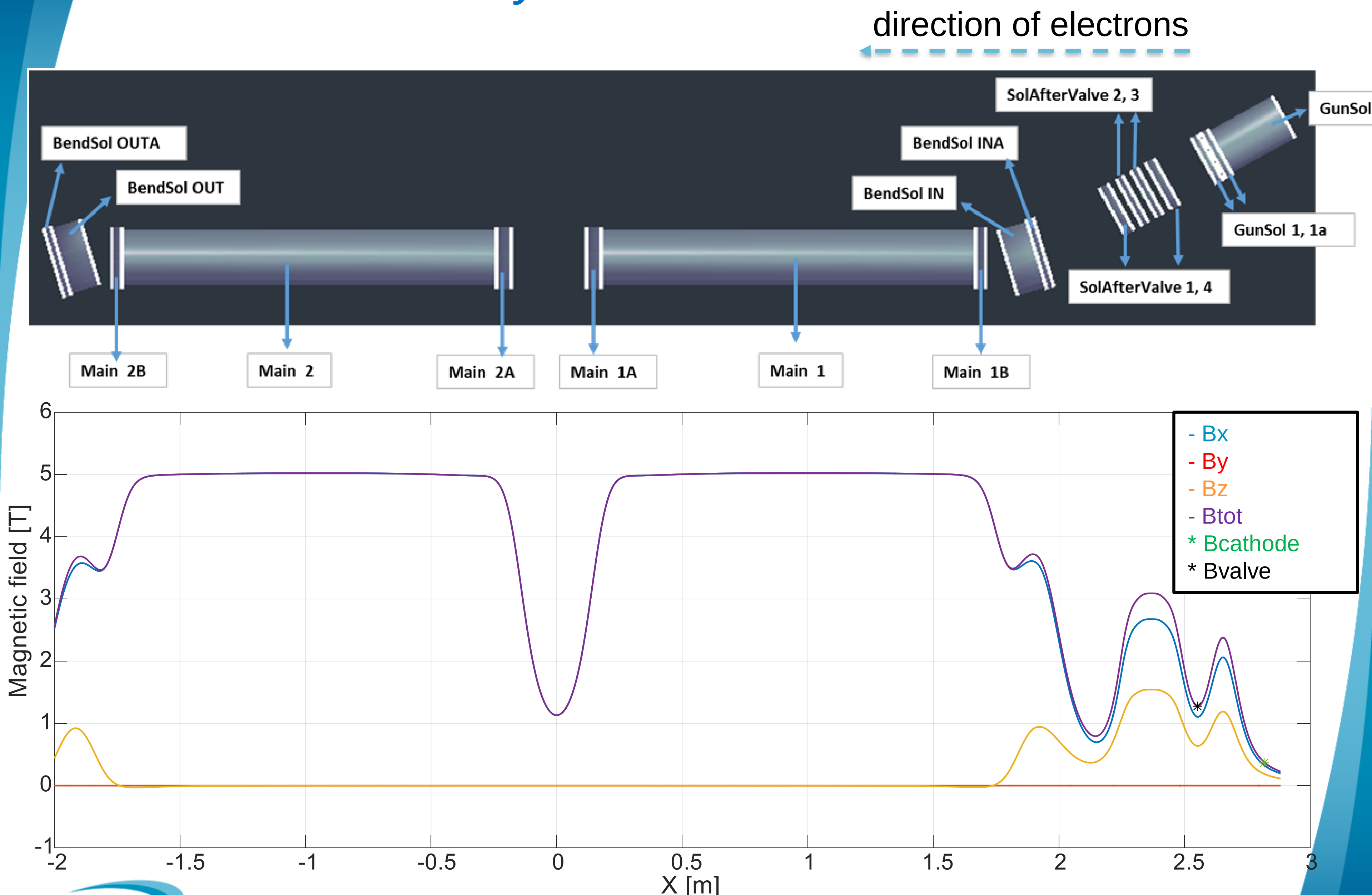
HL-MCF Meeting # 46: Conceptual Design of IFS, CLIQ and K-MOD Feeders+ Quench Study for MCBXF Magnets + Status on HEL Circuits, https://indico.cern.ch/event/794680/ D. Perini: Status Report on HEL Circuits
*A. Bertarelli, et al. Hollow Electron Lens Update, Collimation Upgrade Specification Meeting #56

Outline

1. System Overview
2. Quench Protection Design
   A. E-gun cathode
   B. Solenoid After Valve + e-gun
   C. Main Bending Solenoids
   D. Main Solenoids
3. Summary

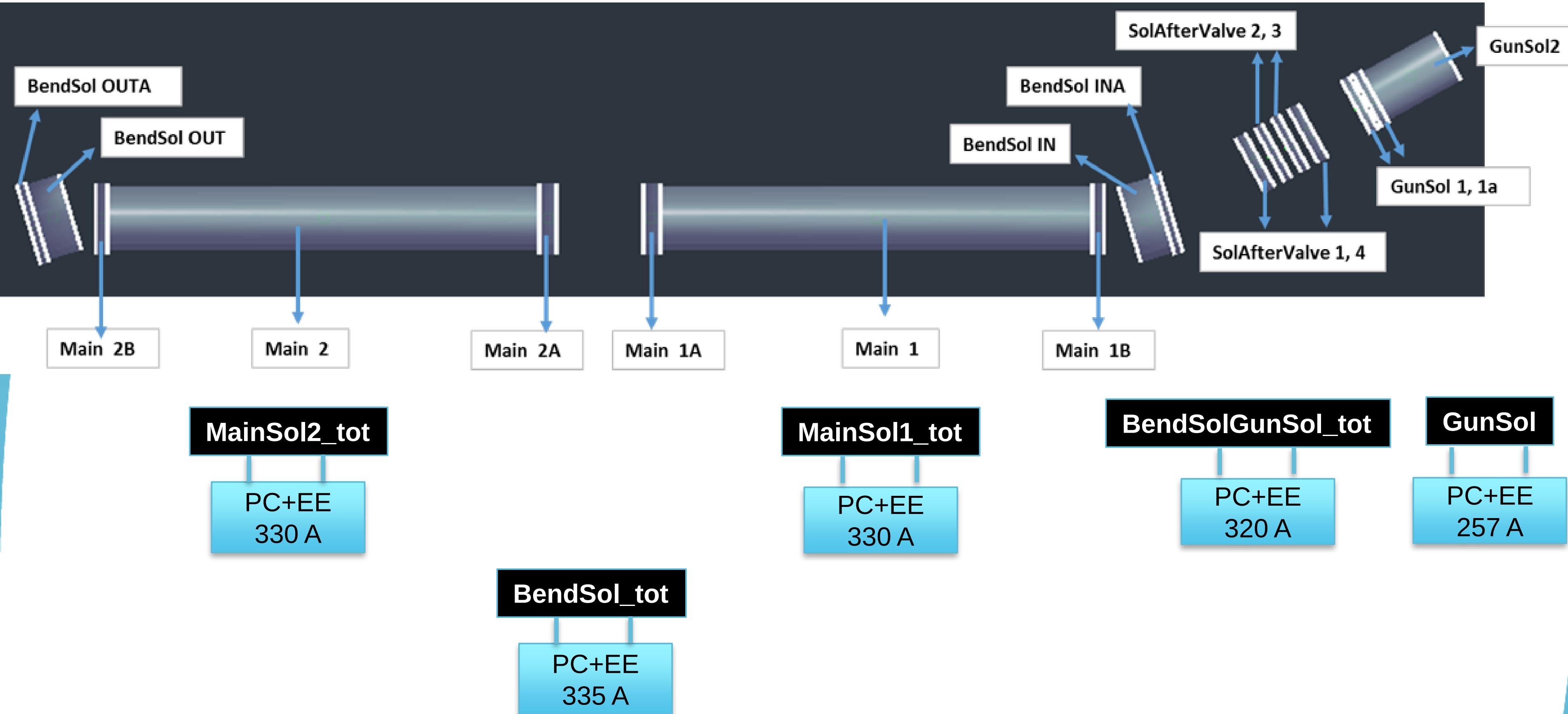


1. System Overview*



*G. Gobbi, D, Perini: Main parameters of HEL electrical circuits, EDMS [2036694]

2. Solenoids – Powering Scheme



Differential Inductance [mH]

	GunSol	BendSolGunSol_tot	BendSol_tot	MainSol1_tot	MainSol2_tot
GunSol	834.18	100.79	1.63	1.92	0.19
BendSolGunSol_tot	100.79	806.74	13.24	7.29	0.34
BendSol_tot	1.63	13.24	2146.47	130.35	130.35
MainSol1_tot	1.92	7.29	130.35	8877.46	49.91
MainSol2_tot	0.19	0.34	130.35	49.91	8877.46

Stored Energy [kJ]

GunSol	32
BendSolGunSol_tot	47
BendSol_tot	135
MainSol1_tot	494
MainSol2_tot	493

BendSolGunSol_tot = SolAftValve1…4 + GunSol1 + GunSol1a; **GunSol** = GunSol2
MainSol1_tot = Main1 + Main1A + Main1B; **MainSol2_tot** = Main2+Main2A + Main2B
BendSol_tot = BendSolIN + BendSolINA + BendSolIN + BendSolINA

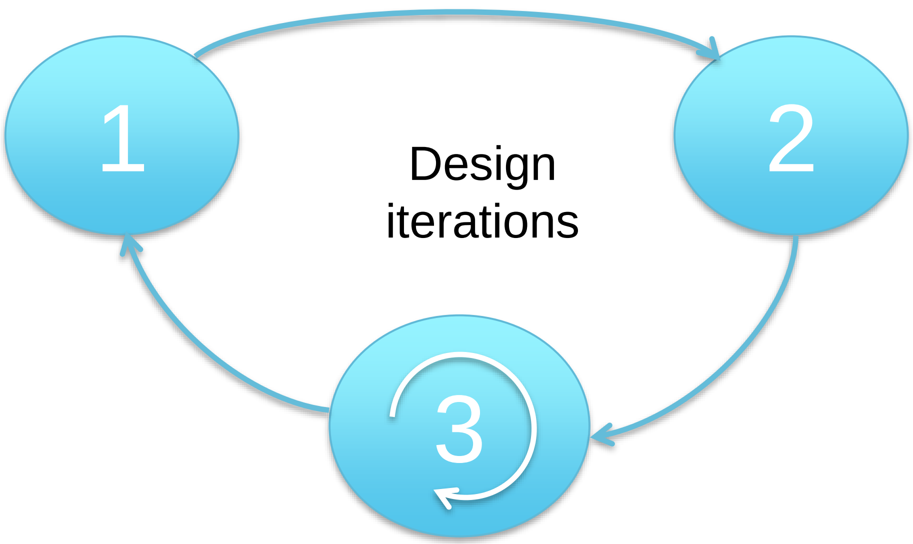
2. Strategy for Quench Protection Analysis

- We study protection of busbars, magnets, and circuits.
- We assume that if one of the main circuits quenches, all circuits are discharged.
- For coils, we consider 100 mV threshold for quench detection and 10 ms validation.

In order to explore the parameter space, the following strategy was applied:

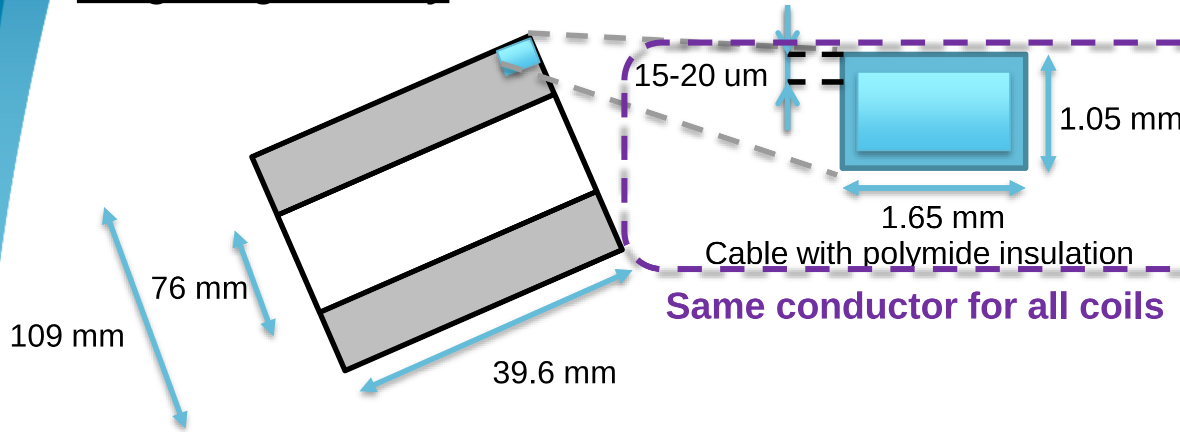
1. Quench propagation to calculate the quench detection time – 1D **STEAM-BBQ** model
2. Calculation of the maximum hot-spot temperature
   A. Quench integral curves with 1D **STEAM-BBQ** model
3. Calculation of minimum quench integral for a given maximum voltage to ground – **Excel**
   - Neglecting internal magnet resistance growth and assuming constant inductance
   - Constant energy extraction resistance

Iterate 3. varying energy extraction resistance until to conditions (can be adjusted) are met
$T_{hot\text{-}spot}$ **< 200 K** - to limit the thermal load on the conductor as well as the cryogenic system
$V_{ground,max}$ **< 500 V** - to limit the power converter common mode voltage and the insulation testing voltage



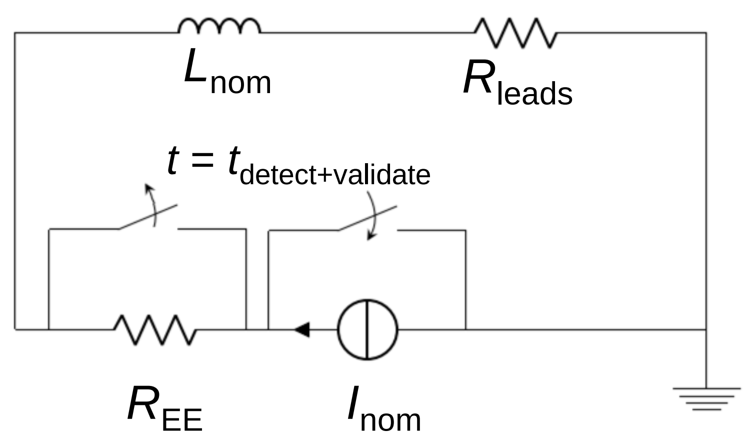
2.A. E-gun Cathode - Parameters

Magnet geometry

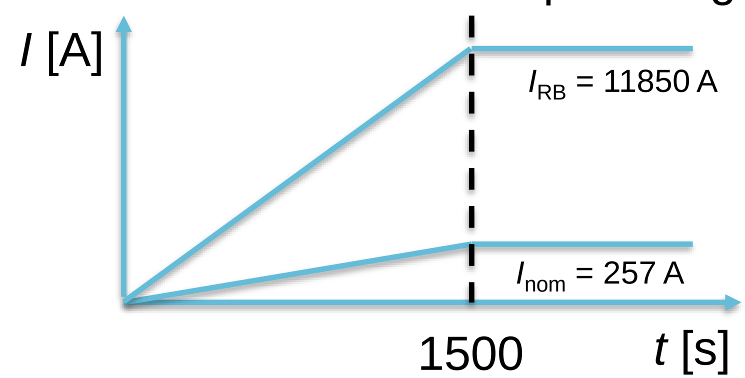


Parameter	Value
Cu/Nb-Ti	4:1
I_c(5 T, 4.2 K)	>= 750 A
RRR	>=100*
I_{nom}	257 A
J_{nom}	149 A/mm^2
L_{nom}	0.83 H
$B_{nom,max}$	3.7 T
V_{Rleads} @ I_{nom}	1 V

Circuit topology



HEL circuits follow LHC powering cycle



Inductive voltage during ramp-up

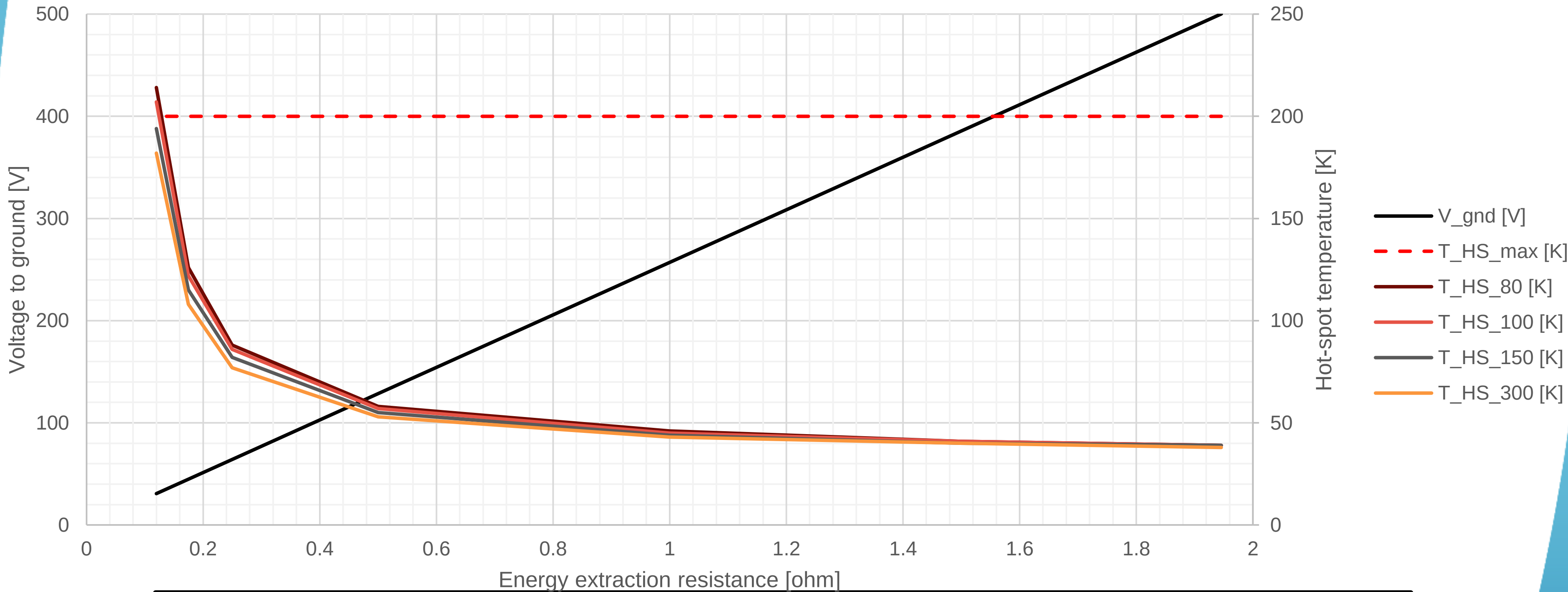
$$L_{nom}\frac{dI}{dt} = 0.83\ H\ \frac{257A}{1500\ s} = 0.14\ V$$

2.A. E-gun – Energy Extraction Resistance Sweep

Quench detection and validation time

RRR	80	100	150	300
$t_{detect+validate}$ [ms]	160	190	220	270

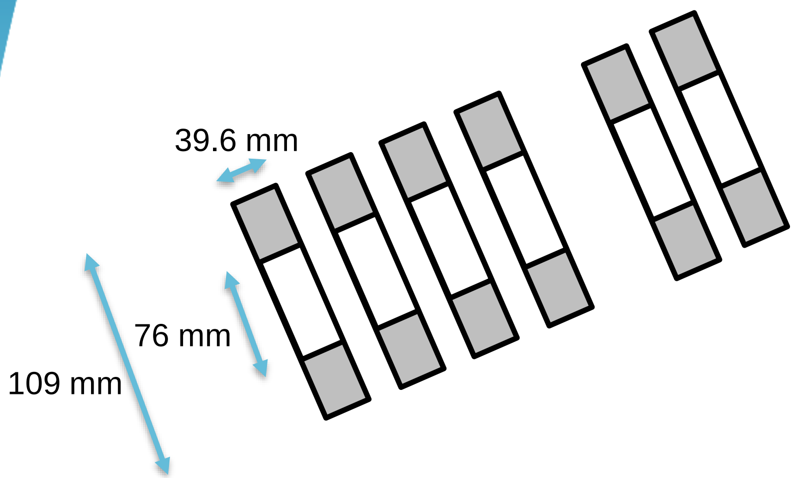
Voltage to ground and hot-spot temperature as a function of energy extraction resistance.
Energy extraction grounded at the input terminal.



With the maximum temperature (**200 K**) and voltage to ground (**500 V**) the permissible energy extraction resistance values span from **0.12** to **1.9** Ω.

2.B. Solenoids After Valve + e-gun - Parameters

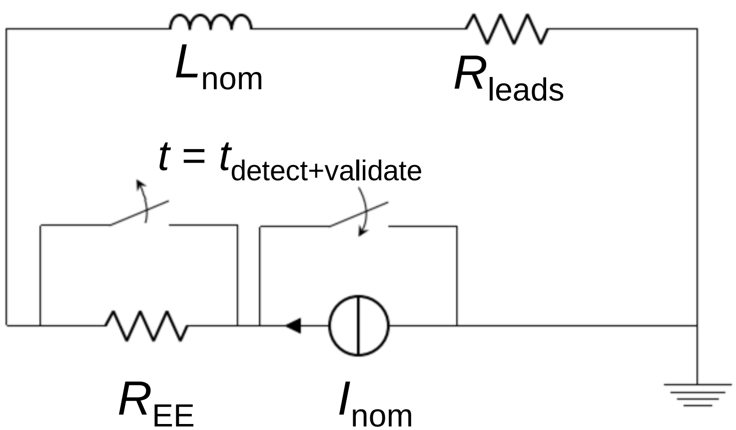
Magnet geometry



Same conductor as in the e-gun solenoid

Parameter	Value
I_{nom}	320 A
J_{nom}	185 A/mm^2
L_{nom}	0.81 H
$B_{nom,max}$	3.1 T

Circuit topology



Inductive voltage during ramp-up

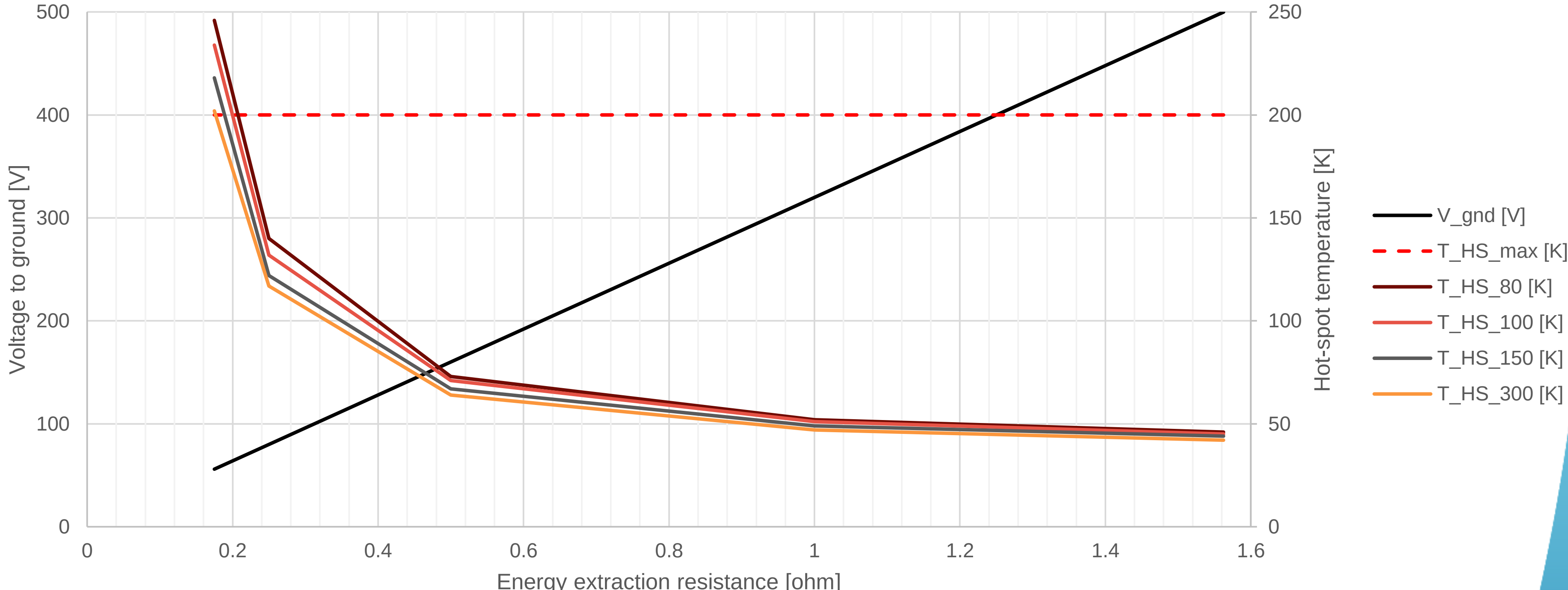
$$L_{\text{nom}} \frac{dI}{dt} = 0.81\ H \frac{320\ A}{1500\ s} = 0.17\ V$$

2.B. Solenoid after Valve + e-gun – Energy Extraction Resistance Sweep

Quench detection and validation time

RRR	80	100	150	300
$t_{detect+validate}$ [ms]	105	115	125	165

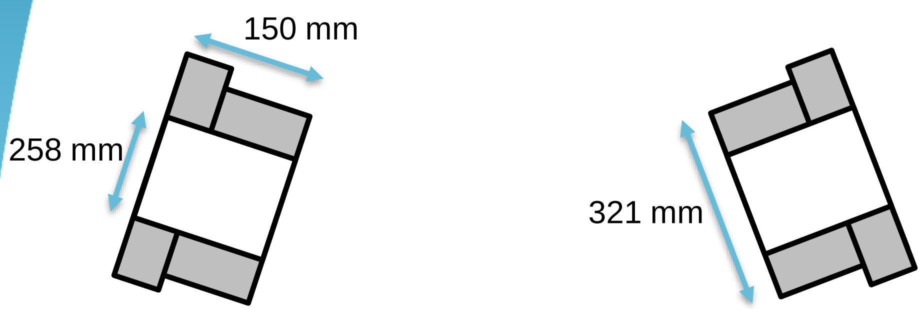
Voltage to ground and hot-spot temperature as a function of energy extraction resistance. Energy extraction grounded at the input terminal.



With the maximum temperature (**200 K**) and voltage to ground (**500 V**) the permissible energy extraction resistance values span from **0.2** to **1.56** Ω.

2.C. Bending Solenoids - Parameters

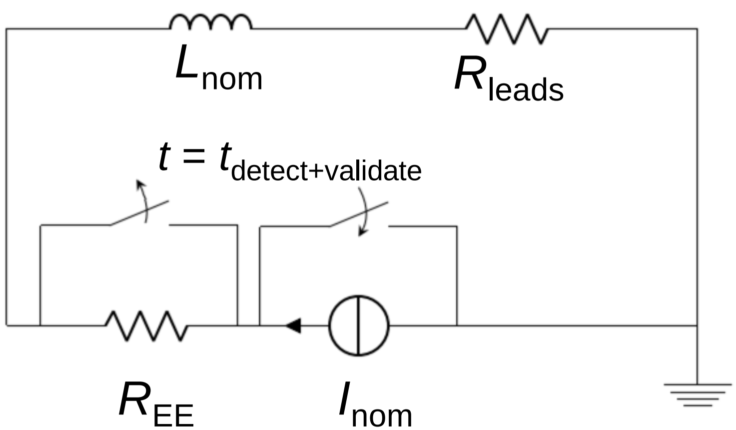
Magnet geometry



Same conductor as in the e-gun solenoid

Parameter	Value
I_{nom}	335 A
J_{nom}	193 A/mm^2
L_{nom}	2.147 H
$B_{nom,max}$	3.5 T

Circuit topology



Inductive voltage during ramp-up

$$L_{\mathrm{nom}} \frac{dI}{dt} = 2.147\ H \frac{335\ A}{1500\ s} = 0.48\ V$$

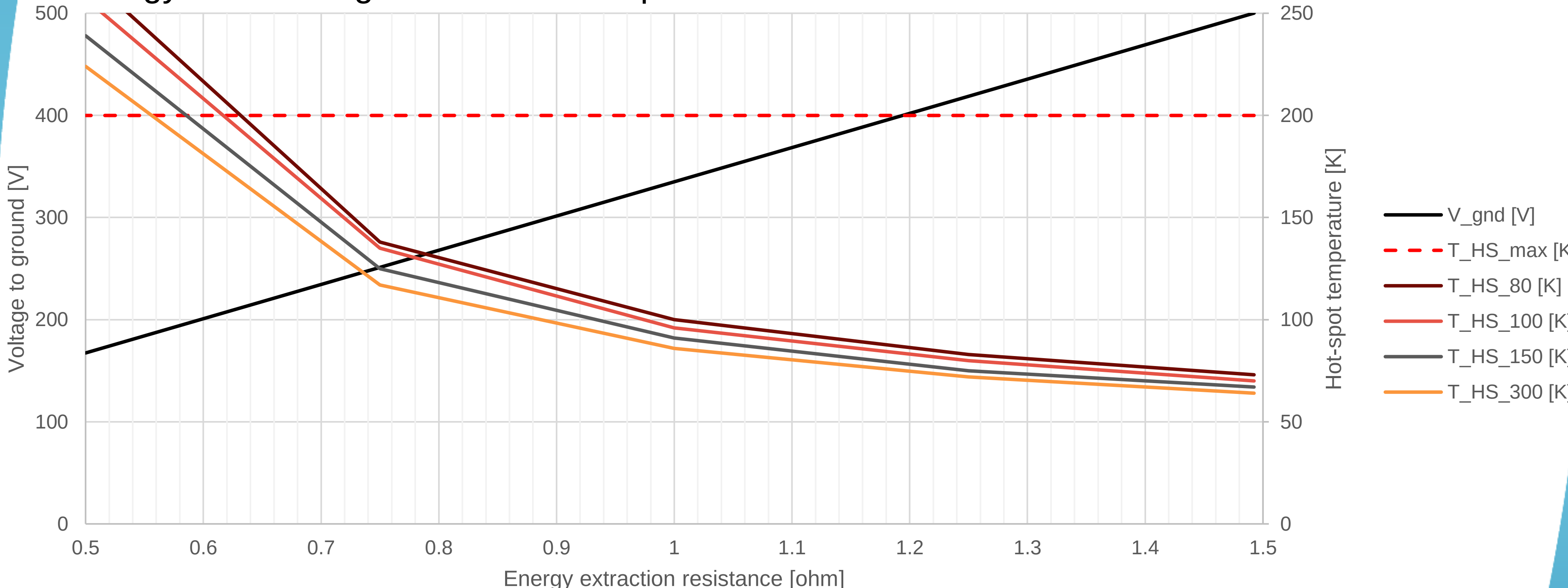
CCT temporarily removed from the circuit.

2.C. Bending Solenoids - Energy Extraction Resistance Sweep

Quench detection and validation time

RRR	80	100	150	300
$t_{detect+validate}$ [ms]	105	115	125	165

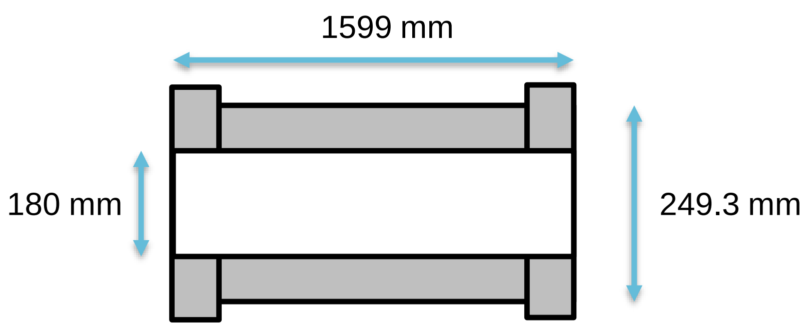
Voltage to ground and hot-spot temperature as a function of energy extraction resistance.
Energy extraction grounded at the input terminal.



With the maximum temperature (**200 K**) and voltage to ground (**500 V**)
the permissible energy extraction resistance values span from **0.65** to **1.5** Ω.
To stay below the limits, the maximum allowed inductance for the CCT is 8 H.

2.D. Main Solenoid - Parameters

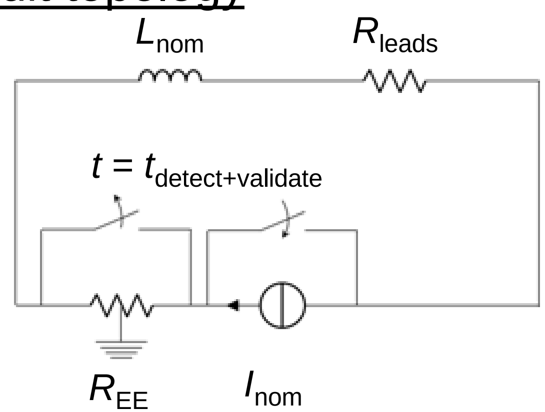
Magnet geometry



Same conductor as in the e-gun solenoid

Parameter	Value
I_{nom}	330 A
J_{nom}	191 A/mm^2
L_{nom}	8.877 H
$B_{nom,max}$	5 T

Circuit topology



Inductive voltage during ramp-up

$$L_{\mathrm{nom}} \frac{dI}{dt} = 8.877\ H \frac{330\ A}{1500\ s} = 1.95\ V$$

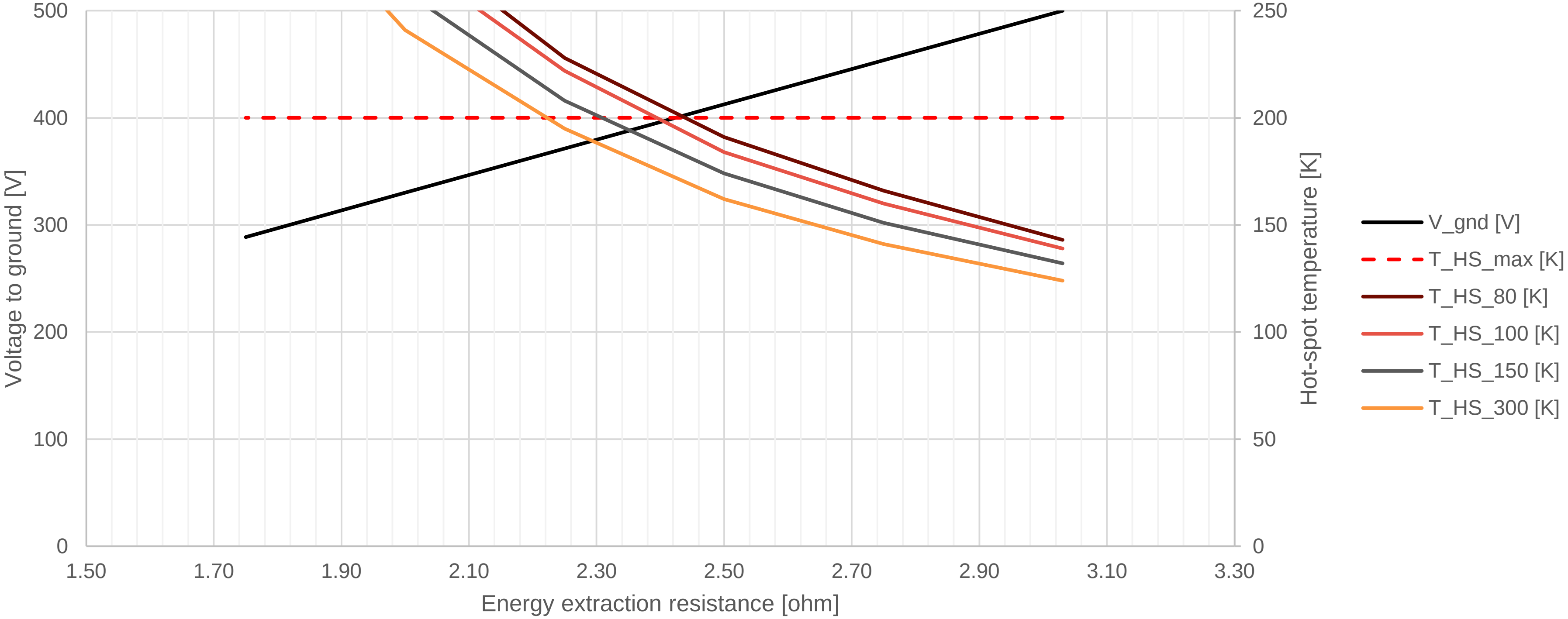
Feasibility of application of 600 A LHC power converter with EE grounded in the middle for this circuit (**maximum voltage, stored energy, inductance**) has to be studied by TE-EPC.

2.D. Main Solenoid - Energy Extraction Resistance Sweep

Quench detection and validation time

RRR	80	100	150	300
$t_{detect+validate}$ [ms]	65	75	85	95

Voltage to ground and hot-spot temperature as a function of energy extraction resistance.
Energy extraction grounded in the middle.
500 V during standard operation, up to 1 kV under earth fault on current lead.



With the maximum temperature (**200 K**) and voltage to ground (**500 V**) the permissible energy extraction resistance values span from **2.46** to **3** Ω.

3. Conclusion

1. The HEL superconducting magnets and circuits are still under design work
    1. Very good contact with colleagues at EN-MME.
    2. Changes are still expected and the study will undertake iterations (mostly correctors).
2. We study the main superconducting circuits
    1. The circuits can be protected with energy extraction systems
        1. All circuits except the main solenoid are protectable with a regular EE system.
        2. To limit the voltage to ground in the main solenoid circuit, for the main solenoid we assume that the energy extractor is grounded in the middle.
           However, this option needs further study in cooperation with TE-EPC to ensure that this is compatible with the power converter.
        3. The choice of the final EE resistance is a trade-off between the peak voltage and temperature (the peak values might need to be adjusted).
    2. **Design* of the corrector magnets to be confirmed with beam dynamics analysis.**

*G. Gobbi, D. Perin: Main parameters of HEL electrical circuits, EDMS **2036694**