Quench calculations for the Super-FRS quadrupoles

- Studied magnets: short and long quadrupoles designed by CIEMAT (22 Jan. 2009)
- Brief presentation of the magnets (stored energy, estimated resistive voltage)

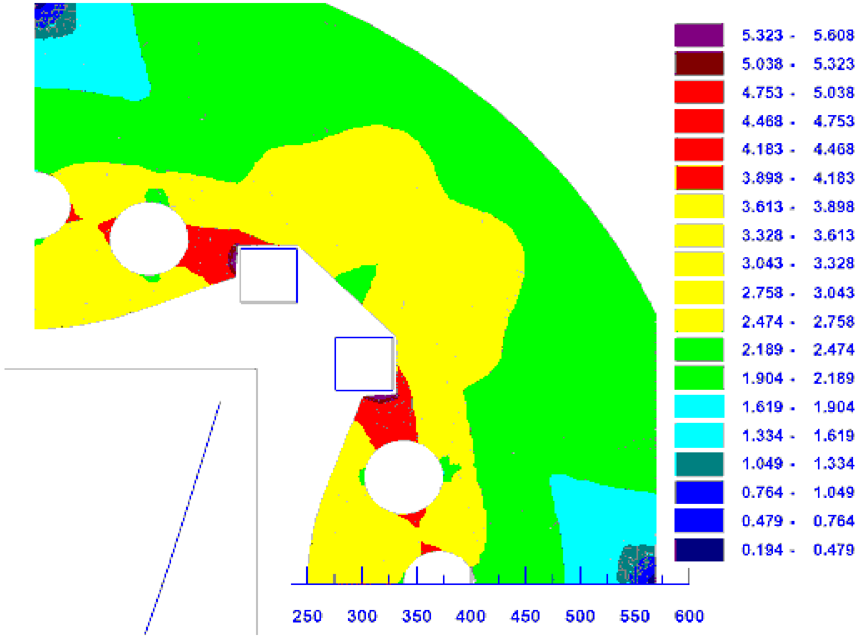
- Limits for the hotspot temperature and maximum coil to ground voltage

- Use of the M. Wilson's quench program
- Estimation of longitudinal and transverse propagation velocities based on measurements
- Validation of the quench program on 2 real magnets

- Quench calculations for the short quadrupole (without and with dump resistor)
- Quench calculations for the long quadrupole (without and with dump resistor)

- Conclusions

Super-FRS quadrupole (CIEMAT design, January 2009)



Bare conductor with (mm)	1.88
Bare conductor tickness (mm)	1.18
Bare Conductor size (mm*mm)	1.18x1.88
Conductor insulation thickness (mm)	0.04
insulation thickness between layers (mm)	0.1
Cu/Sc	2.4
RRR	> 70
Ic(4.2K,5T)_min (A)	1600
Ic(4.2K,4T)_min (A)	1900
I0/Ic(4.2K,Max)	**0.27**
Tcs-4.2 (K)	**3.06**

n° of layers	38
n° of turns per layer	27
total n° of turns	1026
L(450A) (H/m)	11.9
I0 (A)	450
Bmax (T)	4.85

Stored Energy

Superferric magnet	CIEMAT short quad	CIEMAT long quad	Toshiba long quad	Super-FRS dipole	big-Ribs Q500	MSU quad QE	MSU quad QD
magnetic effective length (m)	0.8	1.2	1.2	2.1	0.54	0.71	0.503
average turn length (m)	2.74	3.54	3.5	6.576	1.68	1.64	1.68
I (A)	450	450	292	224	142	110.9	404.5
L_I0 (H)	9.52	14.28	21.2	16.74	6.95	30.6513	4.5416
E (kJ)	**964**	**1446**	**904**	**420**	70	189	**372**
V=L*I0/120 (V)	36	54	52	31			
Coil cross section=wa*wr (mm*mm)	52.92*51.68	52.92*51.69	46.8*50.74	50*55	35*55	2716	2395
V1pole (m3)	0.00749	0.00968	0.009625	0.015618	0.00399	0.004454	0.004024
E/V1pole (MJ/m3)	**129**	**149**	**94**	27	18	42	**92**
E/length (kJ/m)	**1205**	**1205**	**753**	200	130	266	**744**

The Super-FRS quadrupole has an energy per unit length (J/m) and a "pole" energy density (J/m3) which is 60 % higher than the biggest MSU quadrupole.

"Quench" specification

- The quench protection scheme is designed so that the hotspot temperature (T_m) and the maximum coil to ground voltage (V_{cgm}) stay below secure limits.

- For a potted magnet with a fiber glass and resin insulation, most of the magnet designers choose $T_m < 300$ K.

- The European law for AC applications states that $V_{test} = 2*V_{max}+500$ V.
- The initial intention for the Super-FRS was to keep $V_{max} = 2*V_{cgm} = 750$ V so that the coil to ground insulation is tested at 2000 V at 4 and 300 K. (this values was applied for the design of the Super-FRS dipole)

. One can imagine extend V_{test} up to 2500 or 3000 V in order to allow V_{cgm} up to 1000 or 1250 V.

Spefication	T_m (K)	V_{cgm} (V)	$V_{test\_4 \text{ and } 300K}$ (V)	use of dump resistor for protection
initial and actual	300	750	2000	no
possible extention	300	1000	2500	yes
possible extention	300	1250	3000	yes

Orders of magnitude

- When the magnetic stored energy is used to heat up one pole homogenously, the corresponding temperature is T_{av}
- The hotspot temperature T_m will be higher than T_{av}
- The maximum quench resistance will be close to $R_{1pole}(T_{av})$
- The maximum resistive voltage will be of the order of $R_{1pole}(T_{av})/2*I_0/2$

Super-FRS magnets	short quad	long quad	dipole
Tav (K)	126	154	73
Rq(RRR=100, Tav,B=0) (ohm) (will be close to Rqmax)	10.0	17.6	8.1
(Rq(t)*I)max close to Rq(Tav)/2*I0/2 (V)	1145	2002	411

In the long quadrupole, we can already expect a resistive voltage
2* higher than in the short quadrupole
5 * higher than in the dipole

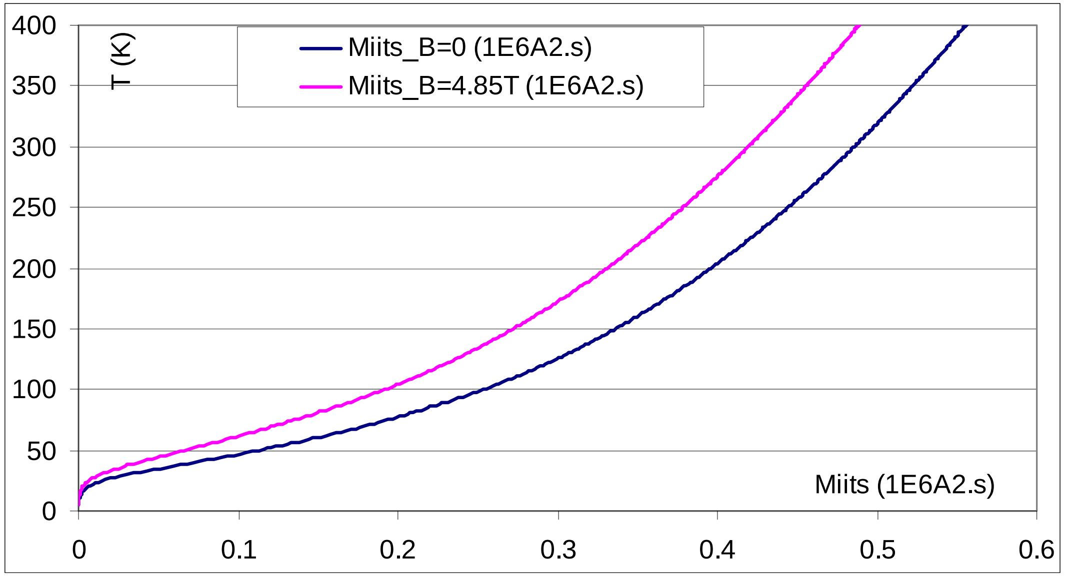
Use of M. Wilson quench program

One version of M. Wilson quench program was given to GSI by B. Hassenzahl

We introduced the following modifications:

- ρ(RRR, B, T) instead of ρ(RRR=60, T)
- T_m computed with B_m and R_q computed with $B_{av} = B_m/2$

Miits curves for the Super-FRS quadrupole conductor



- The original program of M. wilson does not take into account the magneto-resistance
- For the Super-FRS quadrupole (with Bm = 4.85 T), forgetting it would lead to underestimate by 100 K the hotspot temperature in case Miits = 0.49E6 A2.s

M. Wilson's longitudinal propagationvelocities

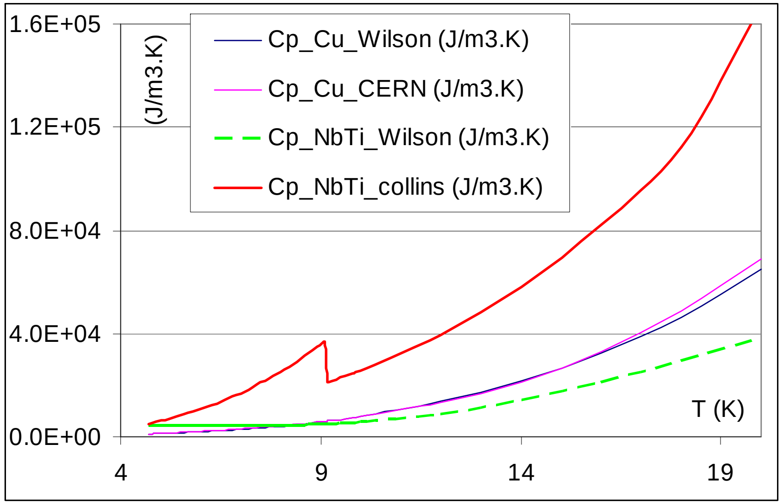
- The program uses as input parameters the longitudinal (V_{pfl}) and transverse (V_{pfa}, V_{pfr}) quench propagation velocities
- The program can either computes these velocities itself or the user chooses them

M. Wilson formulation

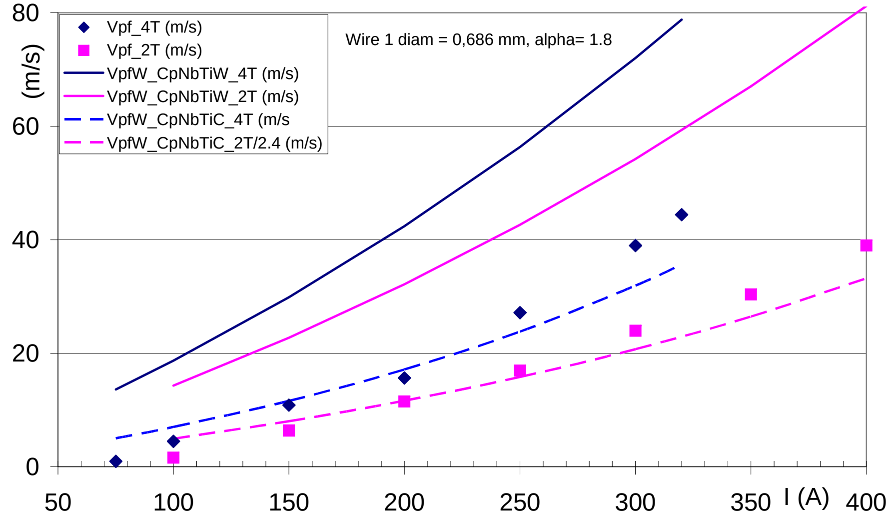
$$V_{pfW\_strands}(t) = \frac{I(t)}{A_{strands}} \cdot \frac{1}{Cp_{strands}(T_{share})} \sqrt{\frac{L \cdot T_{share}}{T_{share} - T_{He}}}$$

$$T_{share} = (T_{cs}(I,B) + Tc)/2$$

Volumetric specific heat



Use of CpNbTiW (Wilson) or CpNbTiC (Collins)



- Better fit of experimental values with CpNbTi Collins
- Computed velocities may give the good order of magnitude and should not be taken as "accurate" computations
- Propagation velocities must be measured

Estimation of quench propagation velocities (V_{pf})

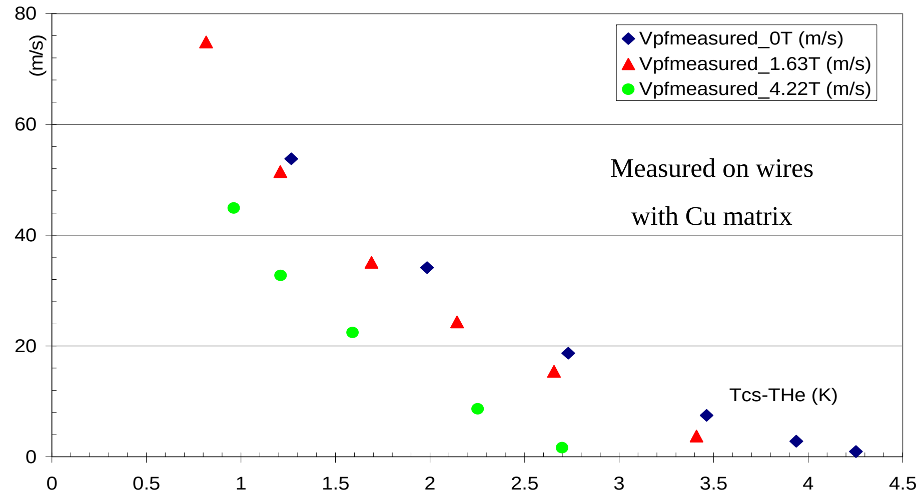
V_{pf} influenced by dT/dt at the normal front and T_{cs}-T_{He}.

$$\frac{dT}{dt} = \frac{\rho_{Cu} \cdot (RRR, B, T)}{\frac{\alpha}{\alpha+1} \cdot Cp_{Cu} + \frac{1}{\alpha+1} \cdot Cp_{NbTi}} \cdot \frac{I^2}{A_{Cu} \cdot (A_{Cu} + A_{NbTi})}$$

$$\text{with} \quad \alpha = A_{Cu} / A_{NbTi}$$

V_{pf} influenced by:

B, $I^2/(A_{Cu}*(A_{Cu}+A_{NbTi})$ and T_{cs}-T_{He}.



"	LHC_outer	LHC_outer	measurements published in litterature on Cu wire at 4.2K				
T_{He} (K)	1.9	1.9	4.2	4.2	4.2	4.2	4.2
B (T)	6.7	7.8	4.22	4.22	6	6	4
$I^2/(A_{Cu}*(A_{Cu}+A_{NbTi}))$ (A^2/mm^4)	5.6E+05	7.7E+05	1.7E+05	6.8E+05	2.0E+05	3.8E+05	8.2E+05
Tcs-T_{He} (K)	2.3	1.2	2.3	1.2	1.4	1.20	1.3
Vpf (m/s)	13	26	8.7	33	9.3	12	16

Considering measurements made on other Cu wires at 4 K:

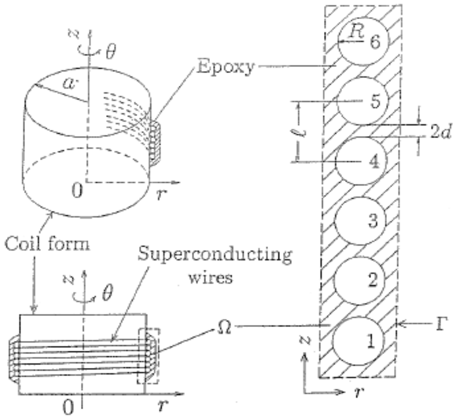
- we could estimate: 10 < Vpf < 30 m/s for the LHC outer cable
- which fits with measurements: 13 < Vpf < 26 m/s

Estimation method validated on one example

Estimation of transverse quench velocities (V_{pft})

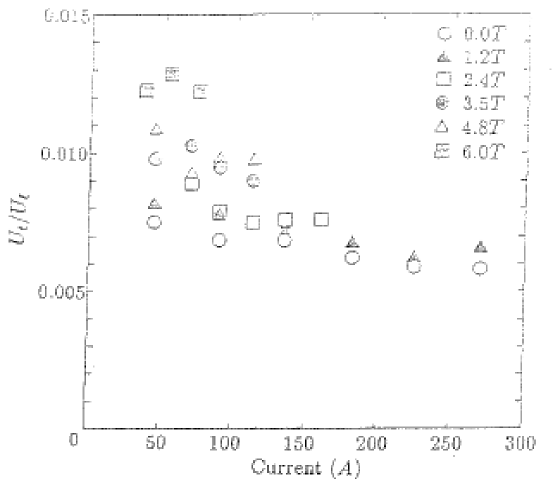
Experimental work done on single layer solenoids

where V_{pfl} and V_{pft} were measured

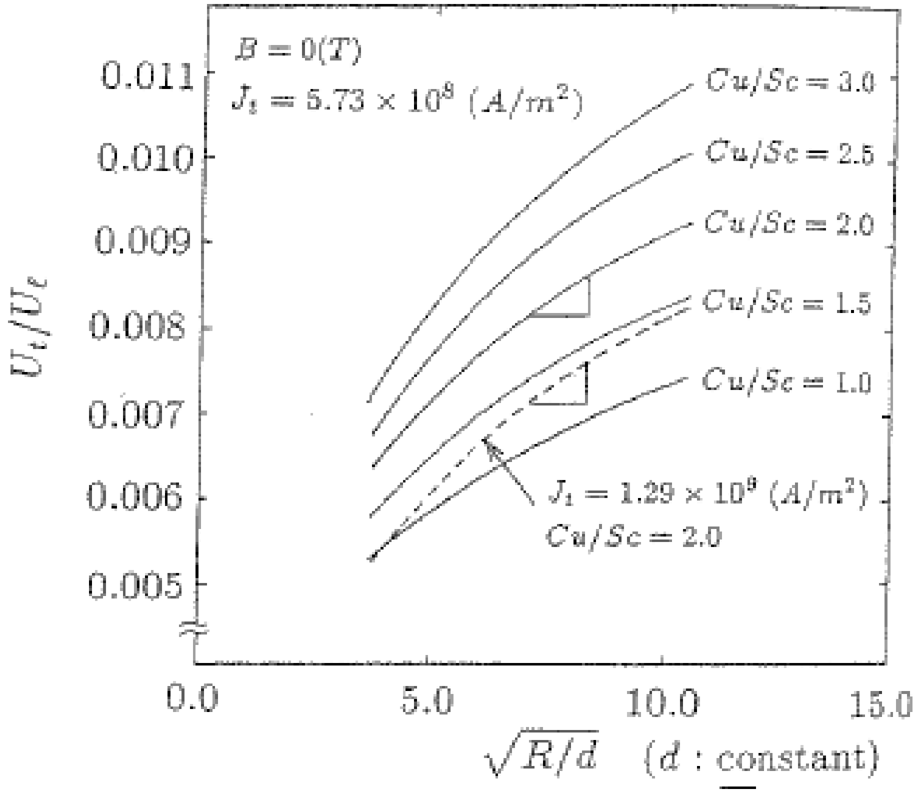


Measured on one solenoid

(in a background field)



Summary of measurements



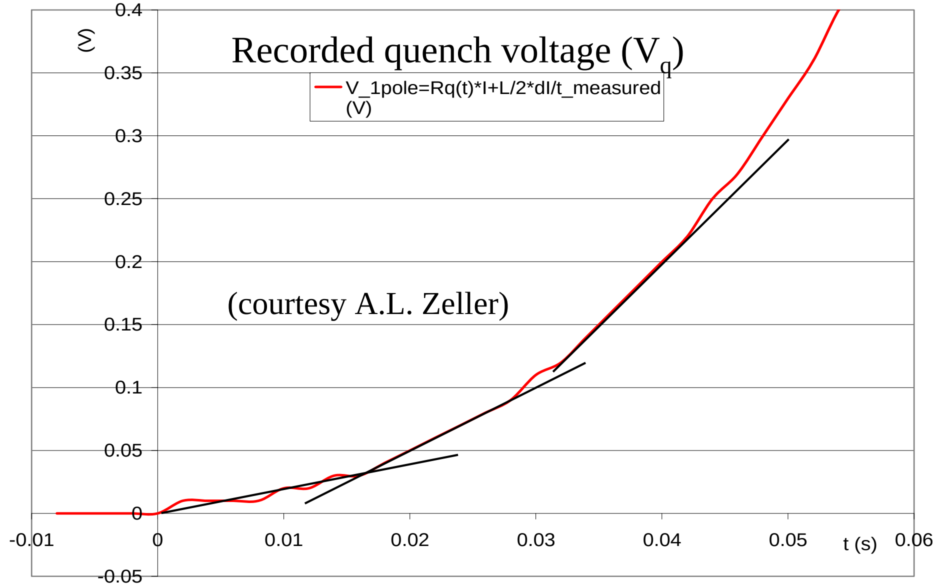
V_{pf} and V_{pft} for the ctd 6 kJ dipole (MSU)

L (H)	4.82	bare diameter (mm)	0.445
I (A)	50	Insulated diameter (mm)	0.48
E (kJ)	6.02	Cu ratio	7
B (T)	3	A_{NbTi} (%)	6.6
n° of turns	2200	A_{Cu}(%)	46.4
		A_{FRP} (%)	47.0

	ctd dipole	Measured in literature		
B (T)	3	2.4	4.22	4
$I^2/(A_{Cu}*(A_{Cu}+A_{NbTi}))$ (A^4/mm^4)	1.2E+05	7.2E+4	6.8E+5	8.9E+5
T_{cs}-T_0 (K)	1.2	3.5	1.2	1.2
$V_{pf\ measured}$ (m/s)	?	10	33	35

From measurements in literature, we can estimate:

$10 < V_{pf} < 35$ m/s

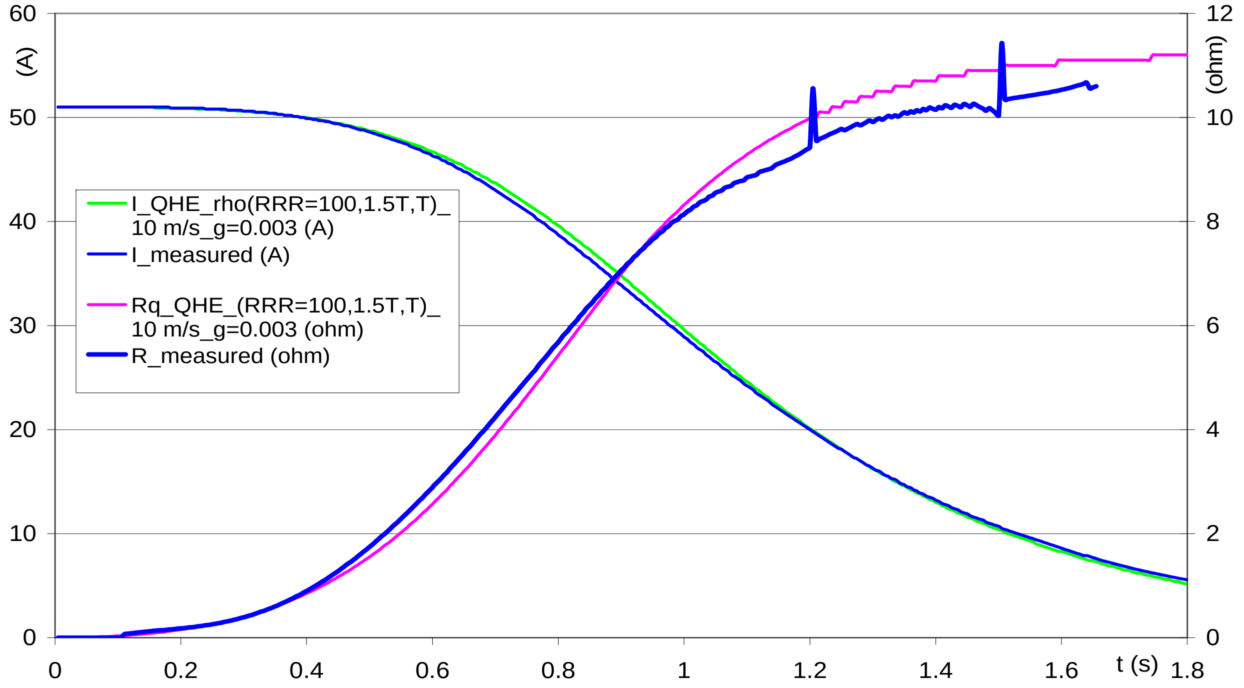


$$\frac{dV}{dt} = \frac{\rho(RRR, B, 10K)}{A_{Cu}} \cdot n_q \cdot 2 \cdot V_{pf} \cdot I$$

n_q : n° of quench initiating points

	dV/dt (V/s)	nq	V_{pf_3T} (m/s)	Δt_{qt} (ms)	V_{pft} (mm/s)
from 0 to 18 ms	2.2	1	9.3	18	27
from 18 to 28 ms	5.0	2	10.5	10	48
from 28 to 32 ms	7.5	3	10.5	14	34
from 32 to 42 ms	10.0	4	10.5		

Quench calculations on the ctd 6 kJ dipole



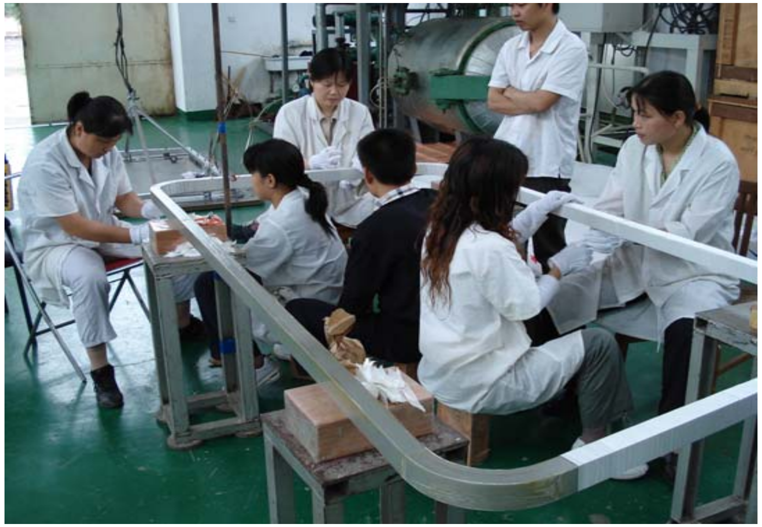
	measured	used in program
V_{pf} (m/s)	9.3 < < 10.5	10
V_{pft} (mm/s)	27 < < 48	30

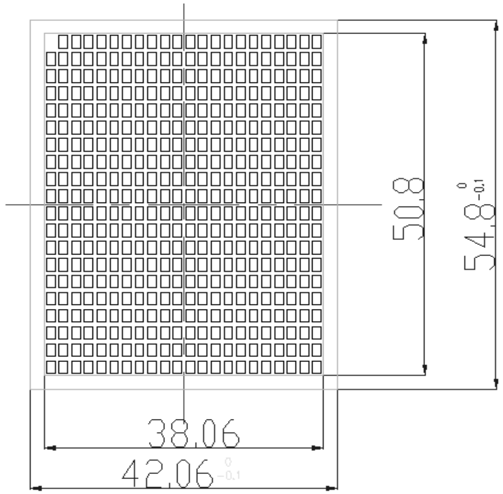
The quench program was validated on a 6 kJ dipole

when using measured quench propagation velocities

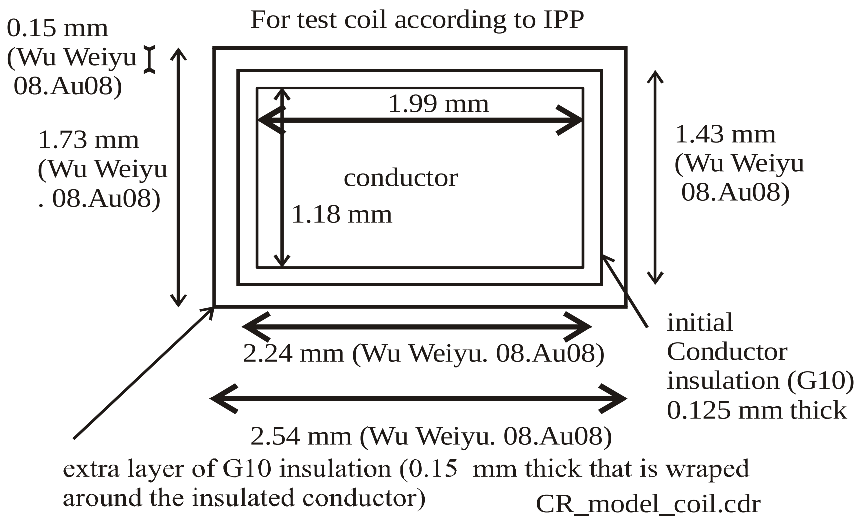
Super-FRS dipole test coil

Wrapping the G10 ground insulation (Spring 2007)

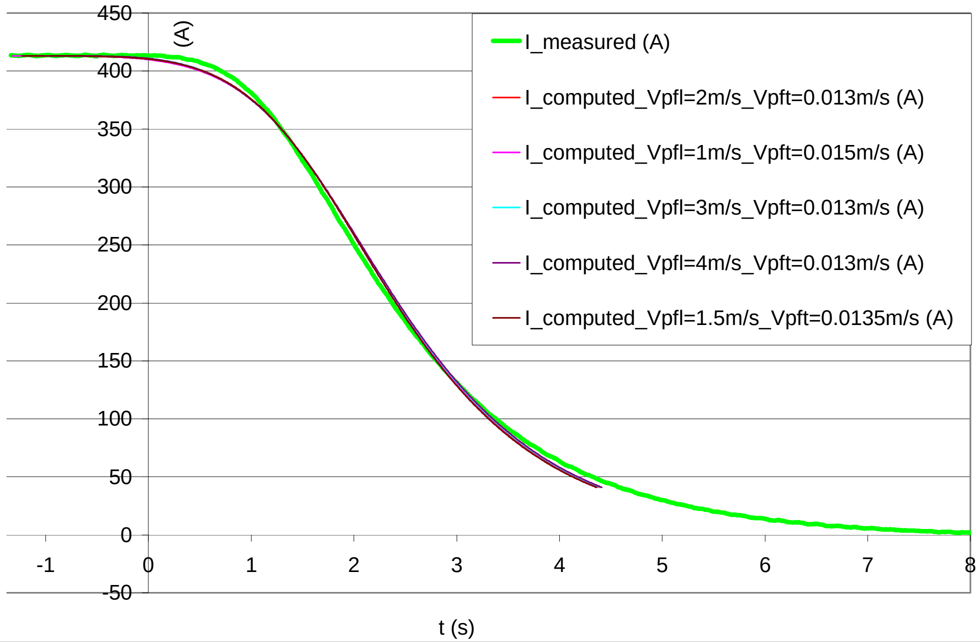




	test coil	Prototype coil
turn length (m)	6.515	6.576
n° of layers	22	28
turns/layer	20	20
I (A)	413	224
E (kJ)	54.9	420 (dipole with iron)
$B_{max\_conductor}$ (T\`)	1.6	1.29



Quench measurement for the Super-FRS dipole test coil

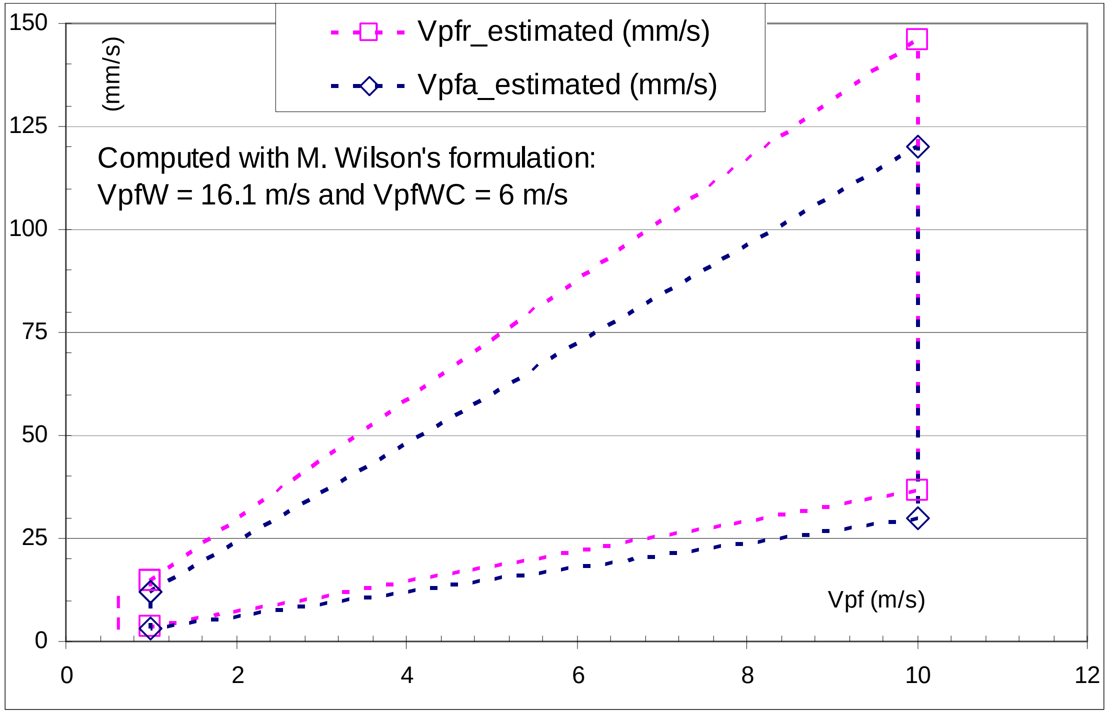


Vpf computed with Wilson's formulation and Collins specific heat= VpfWc (m/s)	8.3
Vpf estimated from measurements in literature (m/s)	3 < < 8.3
Vpf = deduced from temperature sensor placed on coil (m/s)	> 1.4
Vpf used by the quench progarm to fit the experimental curve (m/s)	1 < < 4
Vpfa/Vpf= Vpfr/Vpf deduced from literature	0.0115
Vpfa=Vpfr deduced from literature (mm/s)	34.5 < < 95.5
Vpfa = Vpfr deduced from temperature sensor placed on coil (mm/s)	> 25
Vpfa=Vpfr used by the quench progarm to fit the experimental curve (mm/s)	13 < < 15

Estimated quench velocities for the Super-FRS quadrupole

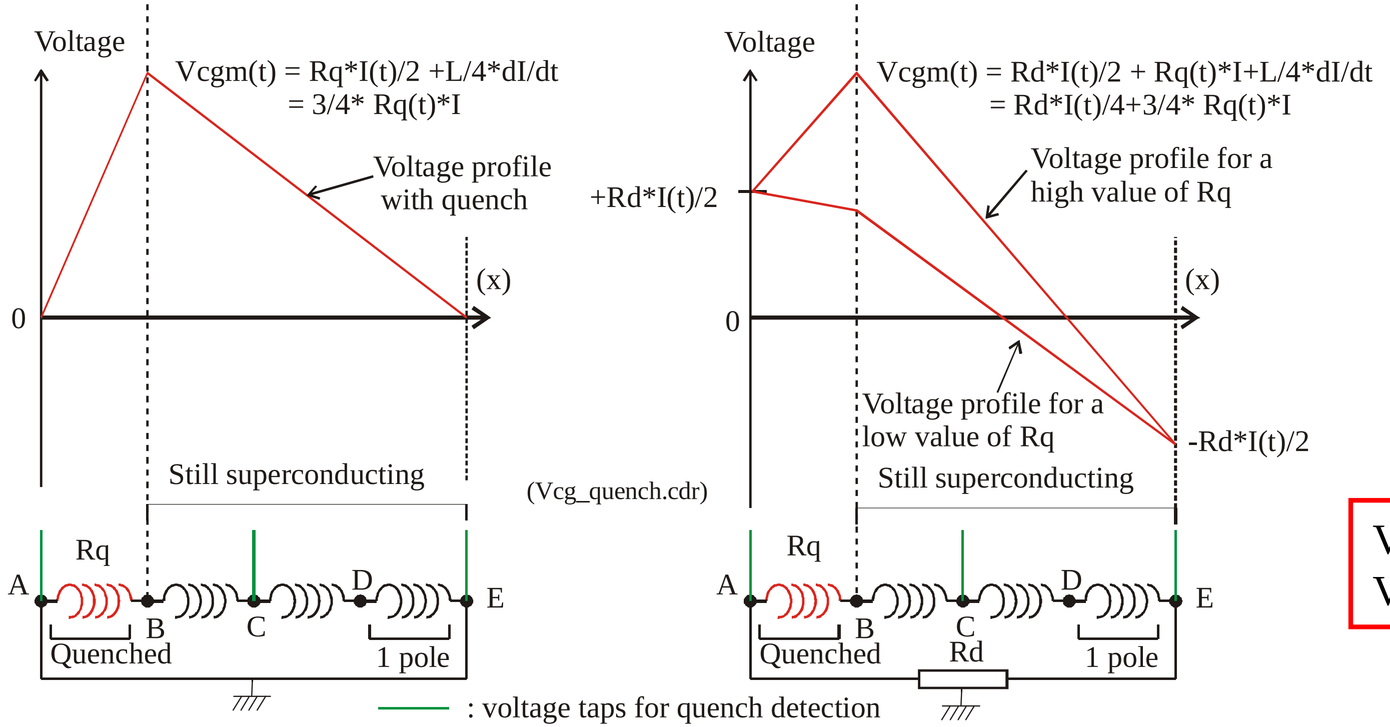
Estimated velocities from measurement in the literature

V_{pf} (m/s)	1 < < 10
V_{pfa}/V_{pfr}	1.22
V_{pfa}/V_{pf}	0.00365< <0.0144
V_{pfr}/V_{pf}	0.003< <0.012
(V_{pfa},V_{pfr},V_{pf}) (m/s, mm/s, mm/s)	(1, 3.6, 3) < < (10, 144, 120)



Voltages of importance and location

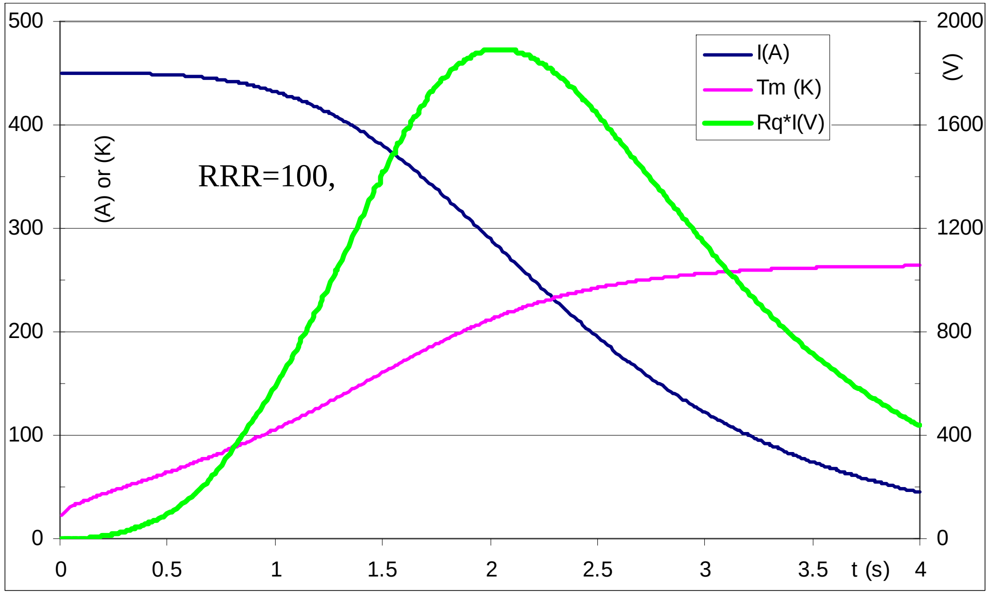
- V_{qm} = max(R_q*I): the maximum quench voltage (R_q is the quench resistance),
- V_{cgm} the maximum coil to ground voltage (determines the necessary thickness of the ground insulation)
- V_{ttm}: maximum turn to turn voltage within one layer (related to the conductor insulation thickness)
- V_{llm}: maximum layer to layer voltage (related to the corresponding conductor and interlayer insulation thickness)
- V_{vtm}: maximum voltage seen by one of the 3 voltage taps connected to the quadrupole (determines the insulation level of the quench electronics)

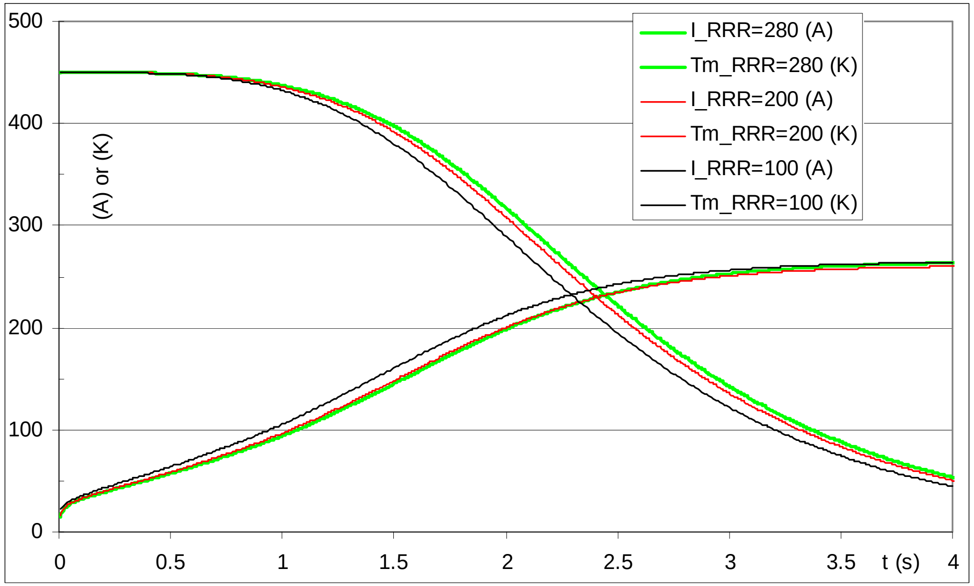


V_{cgm} will be see at point A or B
V_{vtm} will be seen at point A or C

Short quadrupole without dump resistor (Rd= 0)

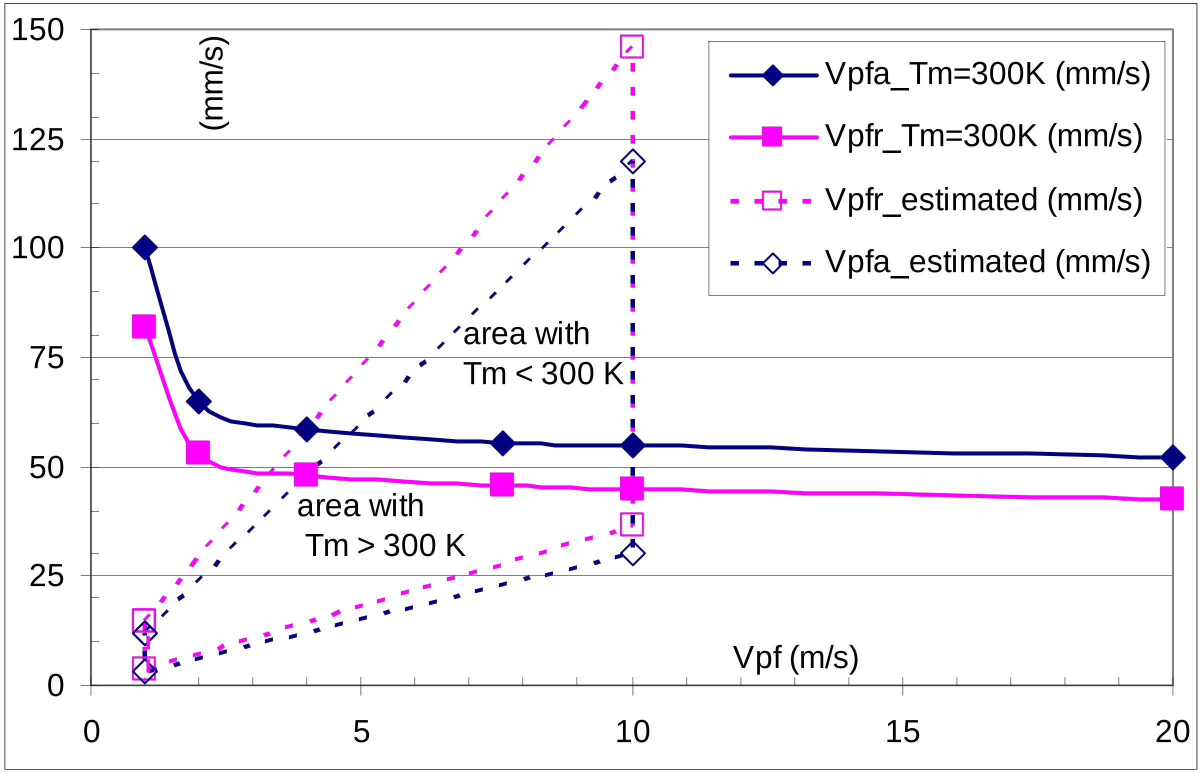
Vpf =10 m/s, Vpfa =73 mm/s, Vpfr = 60 mm/s (average transverse velocities), Rd=0





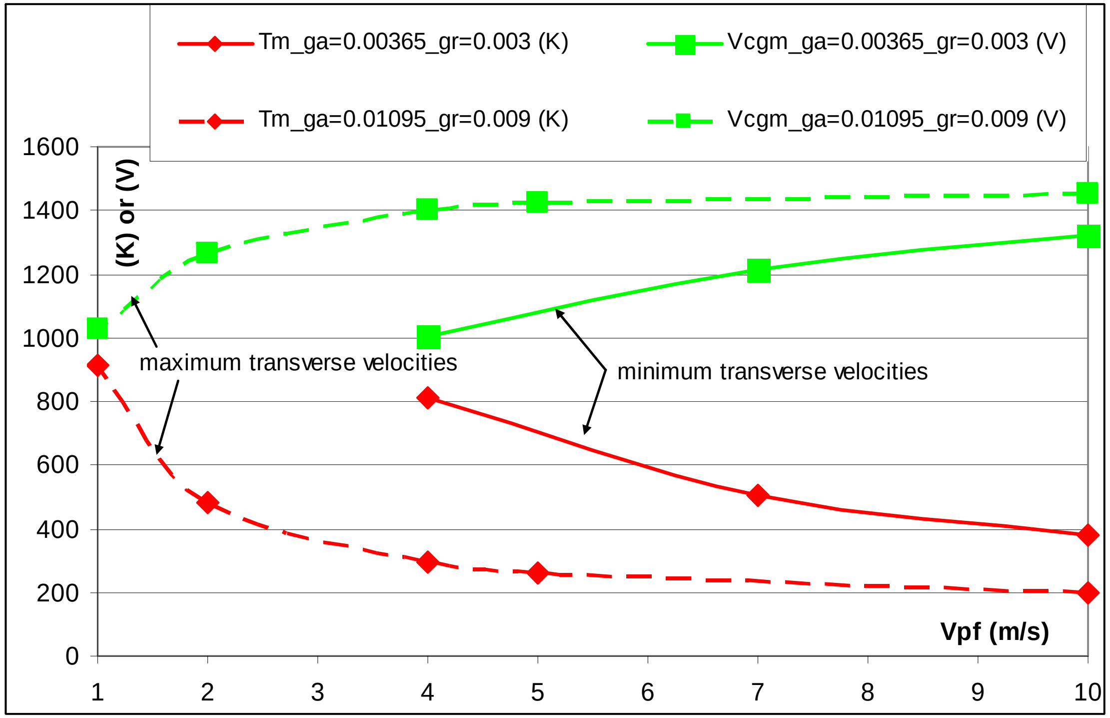
The RRR has a little influence on T_m
We will take for all the other calculations RRR = 100

Short quad., hotspot temperature (T_m) versus quench velocities



For half of the estimated volume (V_{pf}, V_{pfa}, V_{pfr}), we have $T_m > 300$ K which would require the use of a dump resistor

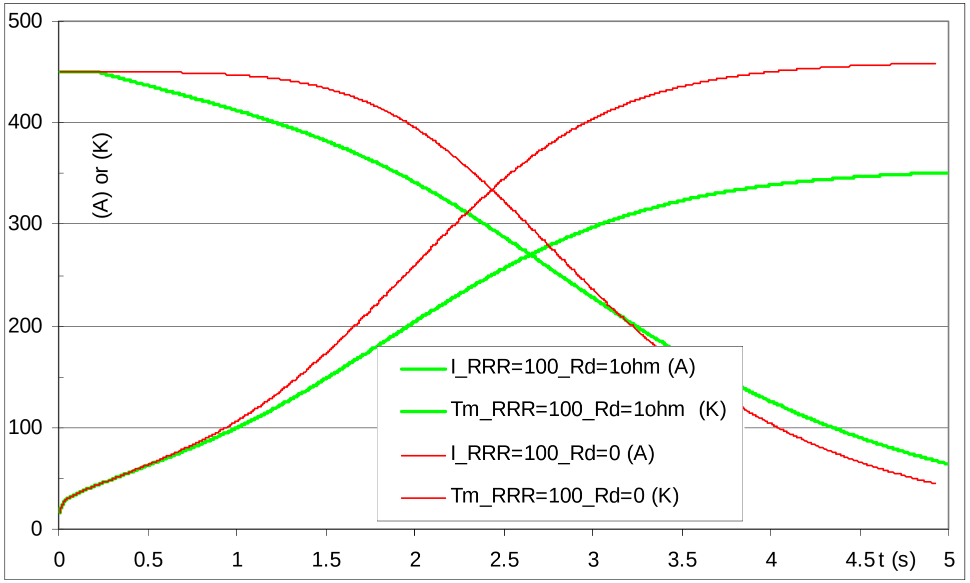
Short quad., maximum coil to ground voltage (V_{cgm}) versus quench velocities

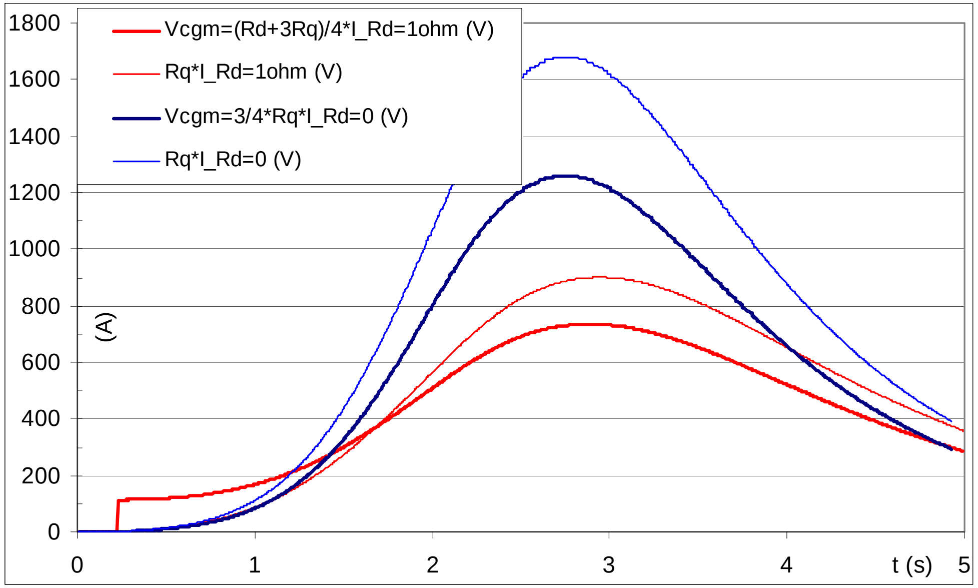


- For more than half of the (V_{pf}, V_{pfa}, V_{pfr}) volume, we have $1000 < V_{cgm} < 1400$ V
- There is no (V_{pf}, V_{pfa}, V_{pfr}) triplet giving $T_m < 300$ K and $V_{cgm} < 1000$ V
- To get $T_m < 300$ K and $V_{cgm} < 750$ or 1000 V, a dump resistor is needed

Short quad., use of a dump resistor (R_d)

RRR=100, t_{Rd} = 230 ms, V_{pf} = 4 m/s, V_{pfa} = 29.2 mm/s, V_{pfr} = 24 mm/s (average transverse velocities)

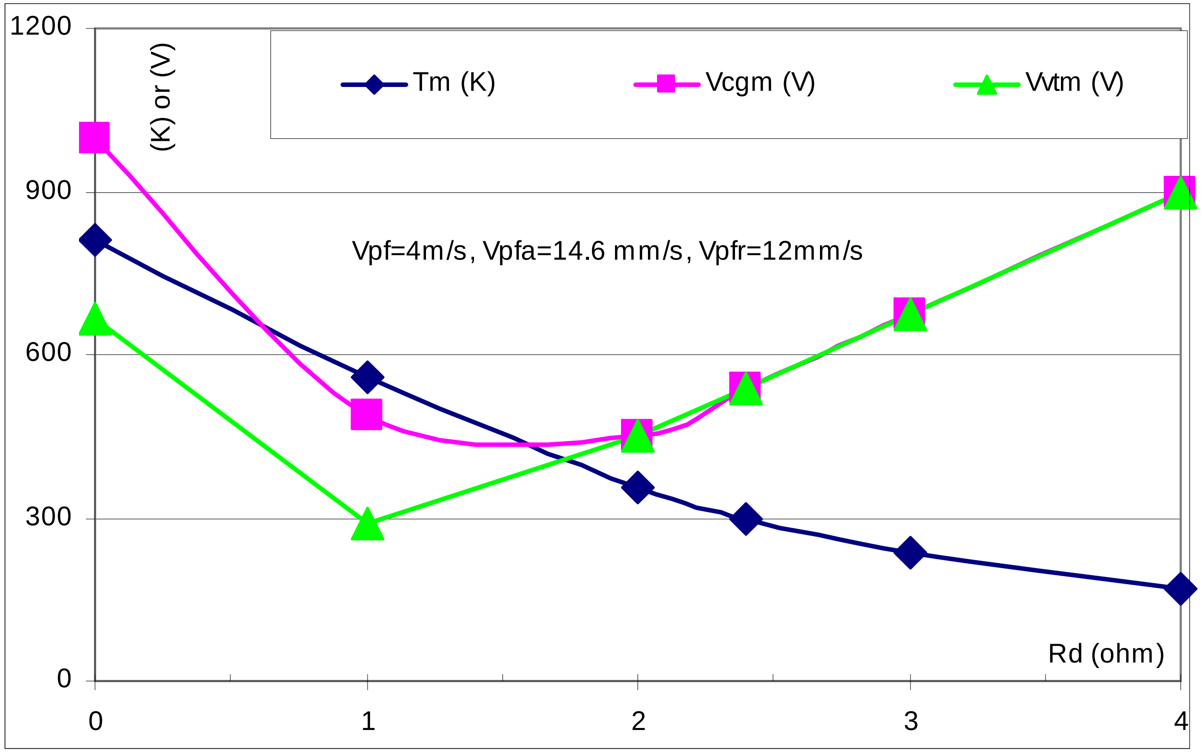




In that particular case, using R_d= 1 Ω enables to reduce T_m from 458 to 351 K and V_{cgm} from1260 to 736 V.

Short quad., used of a dump resistor (R_d)

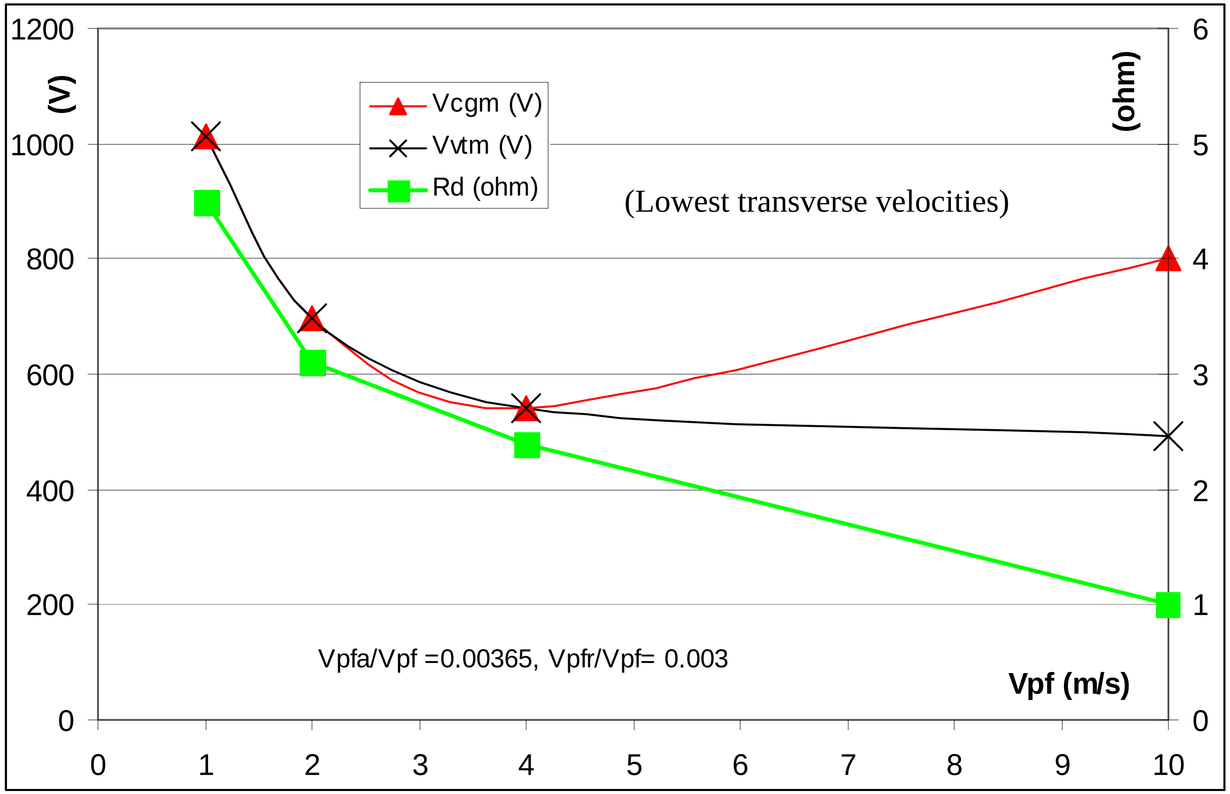
(Lowest transverse velocities)



In that example R_d = 2.4 ohm gives T_m = 300 K
For each (V_{pf}, V_{pfa}, V_{pfr}) triplet, it is possible to find R_d so that T_m = 300 K

Short quad., used of a dump resistor (R_d)

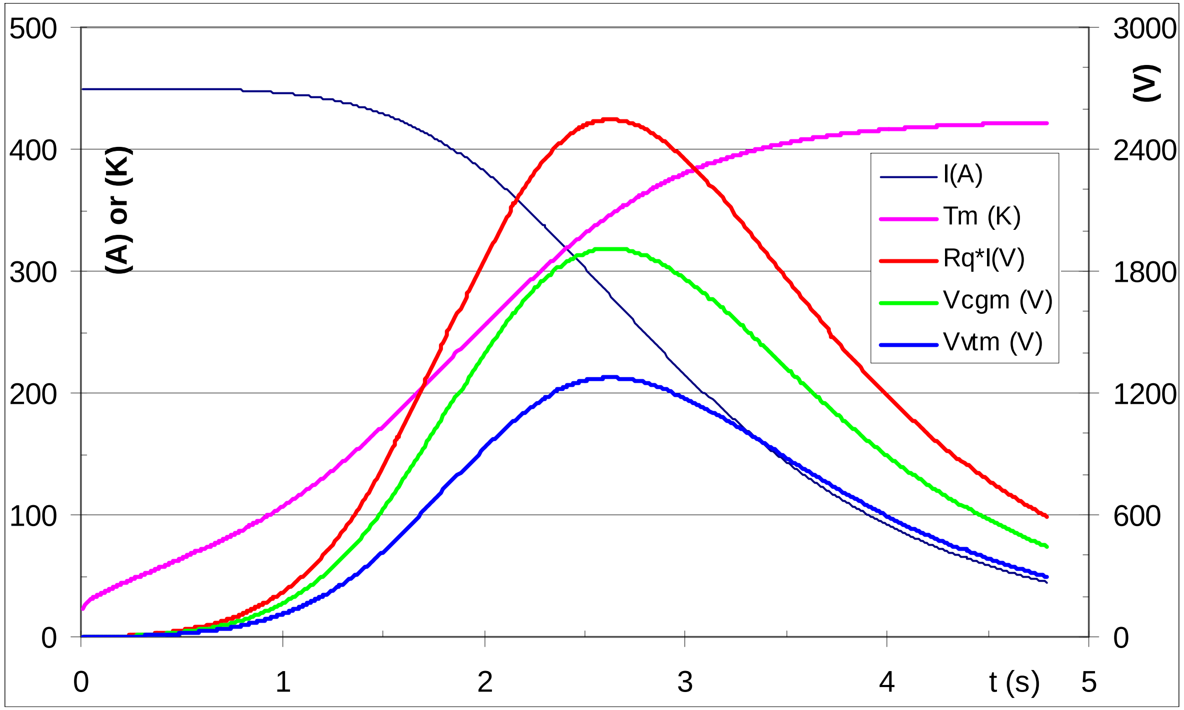
The following simulations give the value of R_d that corresponds to T_m = 300 K



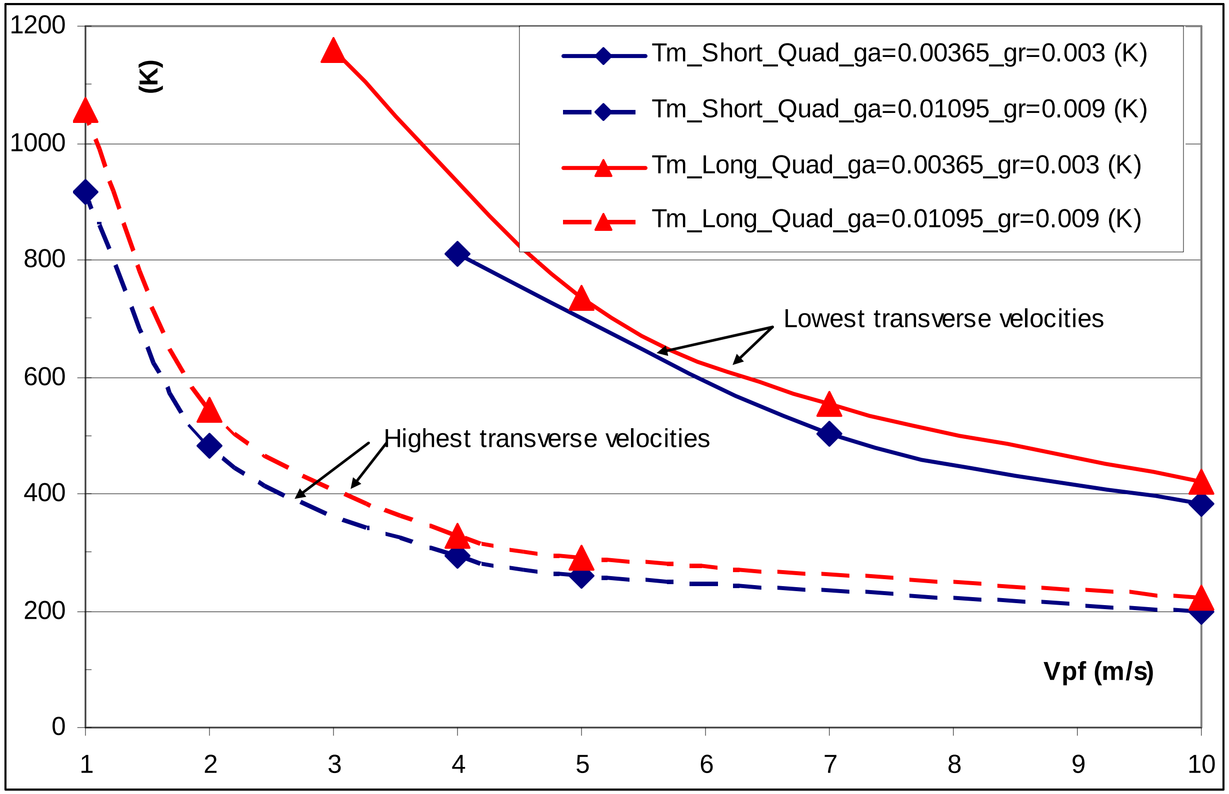
For the lowest transverse propagation velocities, it is possible to have:
T_m = 300 K and V_{cgm} < 1000 V
by properly choosing R_d between 1 and 4.5 ohm

Long quadrupole without dump resistor (Rd= 0)

RRR=100, Vpf = 10 m/s, Vpfa = 36.5 mm/s, Vpfr = 30 mm/s (lowest transverse velocities)

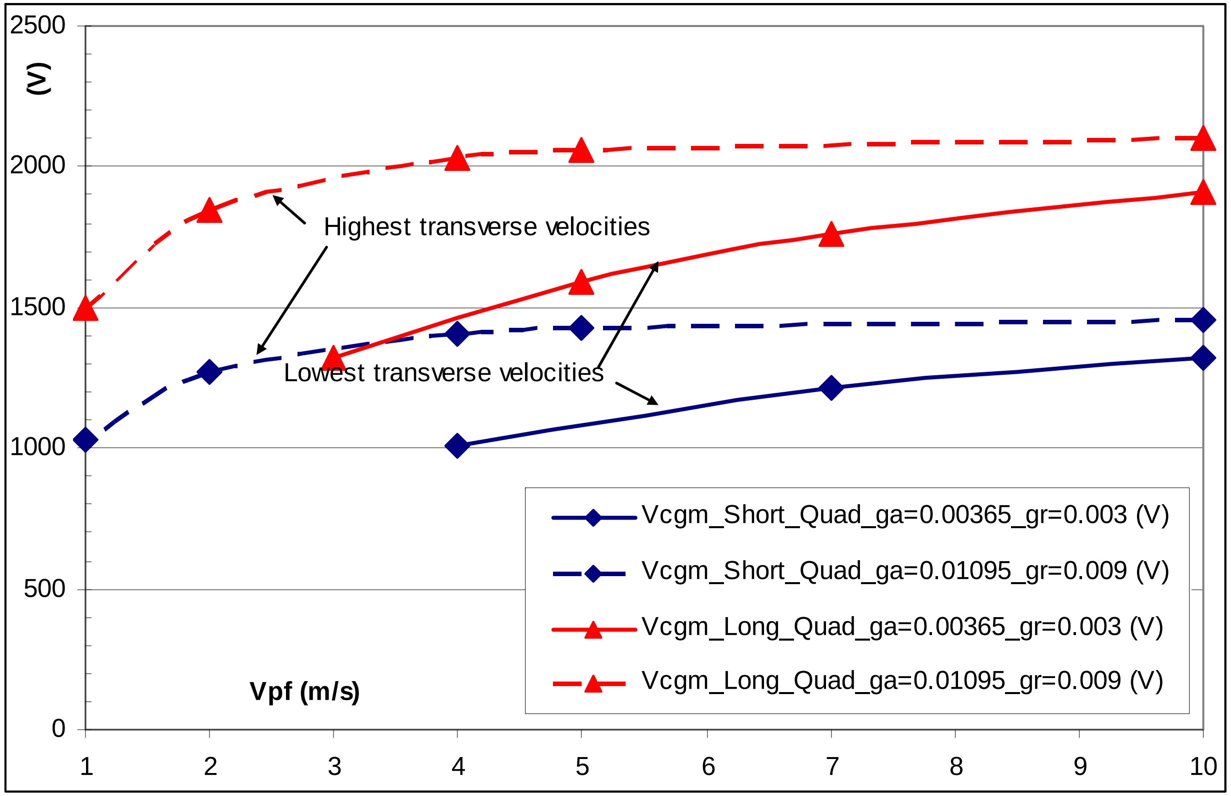


Short and long quadrupoles without dump resistor



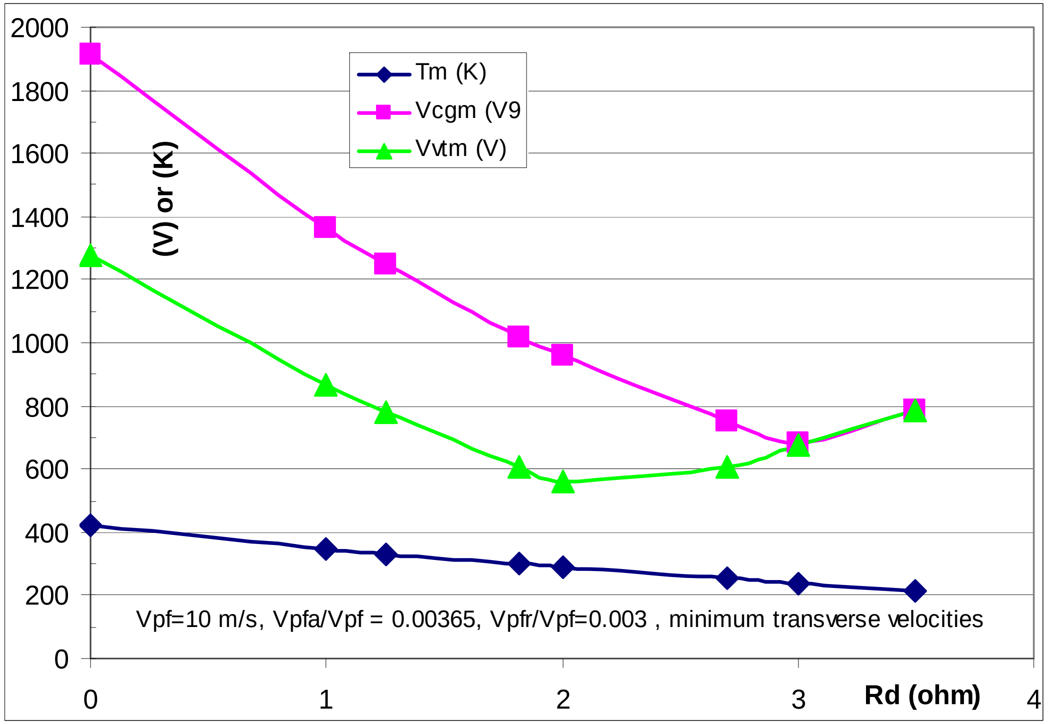
- T_m only increases from 25 to 140 K when we change from the short to the long quadrupole.
- This relatively small increase is due the fact that the half turn length is only increased by 0.4 m.
- With Vpf = 10 m/s, this 0.4 m induces a delay of 40 ms in the time needed to completely quench the coil. This delay is very low compared to the 5 s of the current decay and do not increase T_m much.

Short and long quadrupoles without dump resistor



- V_{cgm} =is from 450 to 650 V higher for the long quadrupole.
- As the short quadrupole, the long quadrupole also requires a dump resistor.

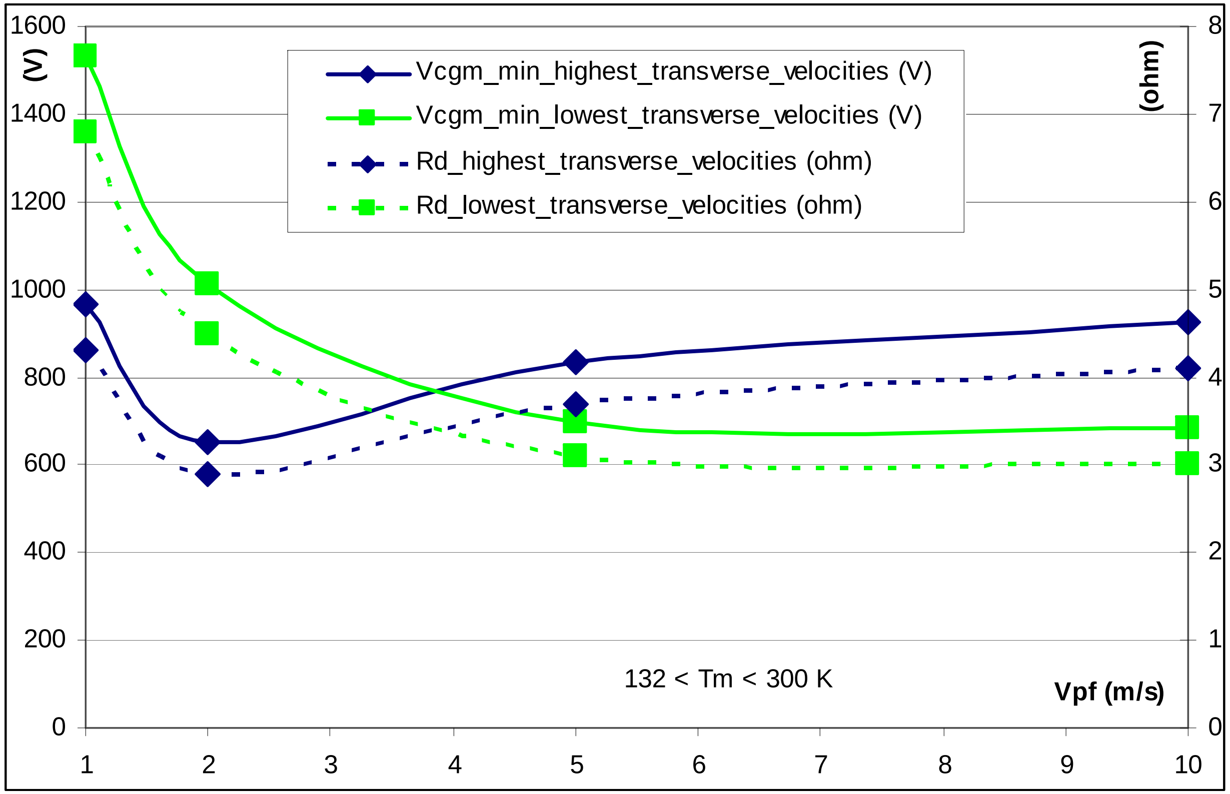
Long quadrupole with dump resistor



- Using R_d = 1.82 Ω enables to reduce T_m from 415 to 300 K and V_{cgm} from 1913 to 1020 V.
- Using R_d = 3 Ω, it is possible to bring V_{cgm} to a minimum value of 675 V (**let's call it Vcgm_min**)

Long quadrupole with dump resistor

By properly choosing R_d, it is possible to reach a minimum value of V_{cgm} and have T_m < 300 K



- For 2 < V_{pf} < 10 m/s, choosing Rd between 1.5 and 7 Ω enables to have V_{cgm} < 1000 V.
- For V_{pf} = 1m/s and the lowest transverse velocities, the time t_{rt} to reach 800 mV is 1020 ms for which T_m(1020s) = 109 K. In order to get 300 K, one has to use a big value of R_d (6.8Ω) which gives $V_{cgm} = R_d*I_0/2$= 1530 V.

Conclusions

- The Super-FRS (CIEMAT) long quad. has an energy density 60 % higher than the biggest MSU quad.
- The choice of the initial quench propagation velocities has a very strong influence on T_m and V_{cgm}
- Propagation velocities can be estimated from measurements on other wires or cables
- For the estimated velocities, there no possibility to have both $T_m < 300$ K and $V_{cgm} < 750$ V which leads to the necessity of using a dump resistor (R_d)
- Knowing the quench propagation velocities, it is possible to choose R_d so that $T_m < 300$ K and $V_{cgm} < 1000$ V This is achievable for the short quadrupole for all estimated velocities. For the long one, it requires $V_{pf} > 2$ m/s

- The CIEMAT design (for the estimated velocities) does not fulfill our initial specification: $T_m < 300$ K, $V_{cgm} < 750$ V, $R_d = 0$: self-protecting magnet (magnets tested at 2000 V)
- We could change our specification to: $T_m < 300$ K, $V_{cgm} < 1000$ V, use of R_d (magnets tested at 2500 V) Before doing so, an internal discussion and contacts with other experts are needed

- If our "quench" specification is changed:
    - turn to turn and layer to layer voltages must be tested on a coil mock-up before the fabrication of the 1st full size quad.
    - quench propagation must be measured before or during the fabrication of the 1st full size quad.
    - the 1st full size quad. should be equipped with a spot heater
    - the actual quench detection scheme (which uses a bridge) would not detect an symmetrical quench (due to beam losses). With an non-self protecting magnet, such a quench must be detected. This will require a more complex and costly quench electronics.