Modelling of superconducting magnets using QLASA

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Outline:

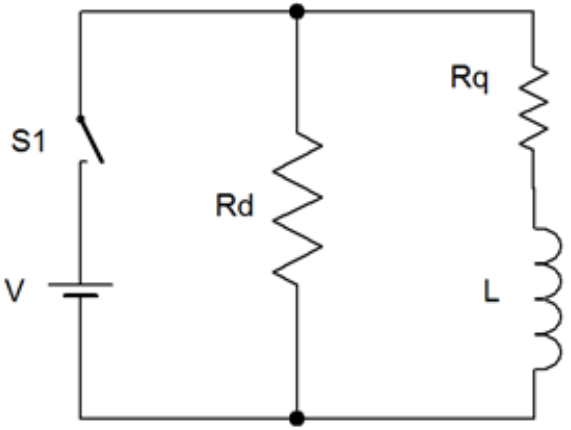
1. Introduction to QLASA
2. Input file
3. Main outputs
4. Example: modelling of a quadrupole
5. Conclusions

1.1 Introduction to QLASA

QLASA is a quench simulation software written at LASA (Milan University-INFN)

QLASA has been originally written for solenoids

- Can be adapted to any kind of magnet



QLASA is pseudo-analytical

- Quench propagation velocities are analytical formules (according to Wilson model)
- Thermal calculation is numeric (adiabatic approximation).
- The resistive zone is a 3D ellipse with the three axes growing according to propagation velocities.
- The coil is a homogenous material
- Numeric solution for the circuit
- Material properties from MATPRO, dependence on temperature, magnetic field, RRR.

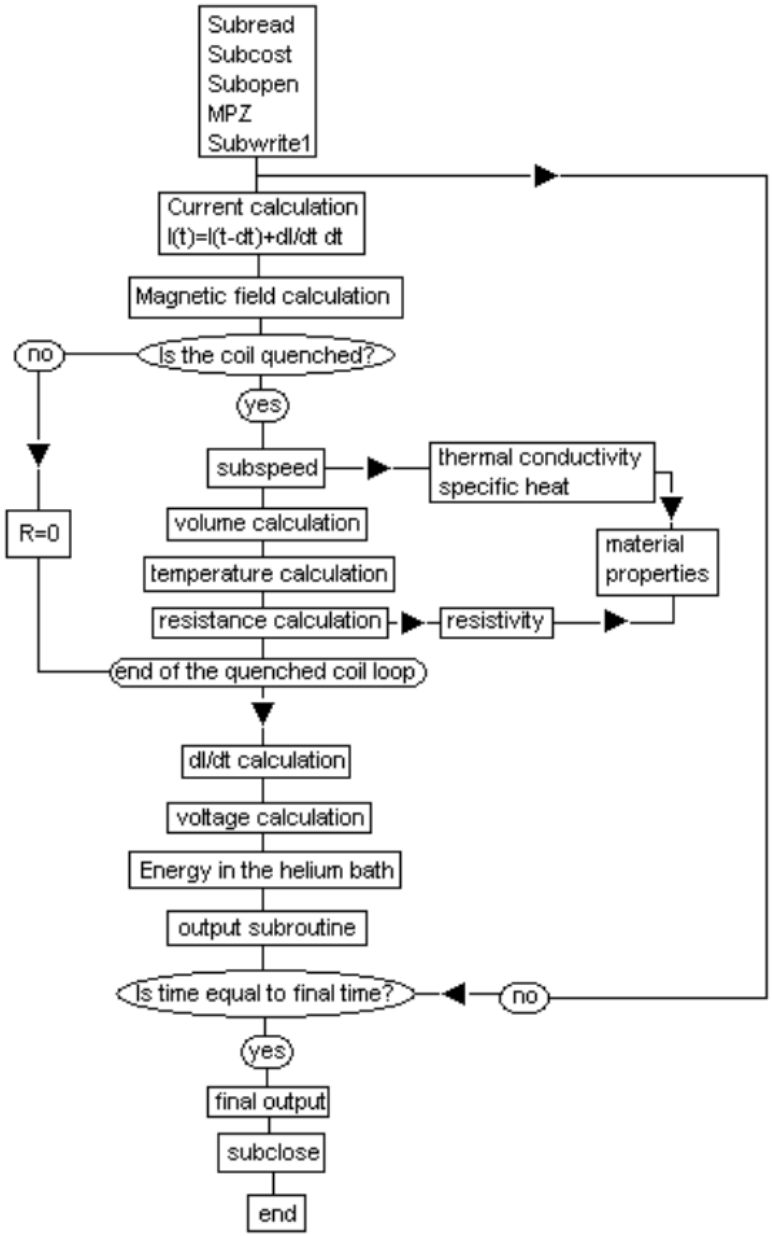
Advantages:

- Very fast (10 -100 s per run)
- 3D quench

Disadvantages:

- All main quantities are input (magnetic field, inductance, etc…)

1.2 Introduction to QLASA



At each time step the code computes:

- the current using the current derivative
- the magnetic field
- the temperature of the ellipse-sheets in the quenched coils
- the resistance of the quenched coils
- the new current derivative
- the new quenched volumes

2.1 Input file

The input file is a tabular text file

- Extension .inp

The input file describes the geometry and the electromagnetic features of maximum 10 solenoids, and the features of the protection circuit

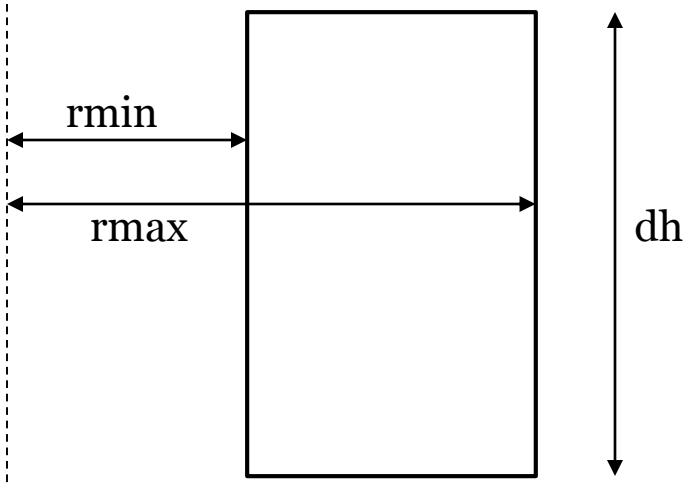
- Since all electromagnetic features are input, one can describe as a solenoid each kind of magnet.

We are going to examine the main parts of the input file

L. Rossi and M. Sorbi, "QLASA: A computer code for quench simulation in adiabatic multicoil superconducting windings," Nat. Inst. of Nucl. Phys. (INFN), Rome, Italy, Tech. Rep. TC-04-13,2004.

2.2 Input file - geometry

```
MQXF
drv             !mode
7       1               !ncoil  !necoil
5.338386088     5.356826088     0.01089         !rmin, rmax, dh
5.338386088     5.356826088     0.01452         !rmin, rmax, dh
5.338386088     5.356826088     0.01452         !rmin, rmax, dh
16.03359826     16.05203826     0.019965        !rmin, rmax, dh
16.03359826     16.05203826     0.019965        !rmin, rmax, dh
21.38120435     21.39964435     0.02541         !rmin, rmax, dh
21.38120435     21.39964435     0.02541         !rmin, rmax, dh
```



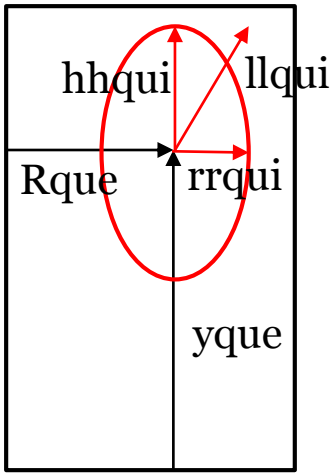
Other kind of magnets (dipole, etc…) can be described using a geometrical transformation which preserves the volume and the lenght.

2.3 Input file – quench in the coils

```
0.0005  5.338386088   0.005445    0   0           0           !timq, Rque, yque, rrqui, hhqui, llqui
0.035   5.338386088   0.00726     0   0.00726     0.0125      !timq, Rque, yque, rrqui, hhqui, llqui
0.036   5.338386088   0.00726     0   0.0045375   0.0125      !timq, Rque, yque, rrqui, hhqui, llqui
0.035   16.03359826   0.0099825   0   0.0081675   0.0125      !timq, Rque, yque, rrqui, hhqui, llqui
0.036   16.03359826   0.0099825   0   0.00726     0.0125      !timq, Rque, yque, rrqui, hhqui, llqui
2.037   21.38120435   0.012705    0   0.01        0.02        !timq, Rque, yque, rrqui, hhqui, llqui
0.041   21.38120435   0.012705    0   0.01        0.02        !timq, Rque, yque, rrqui, hhqui, llqui
```

Per each coil one can set:

- Time of the quench beginning
- Position of the quench inside the coil (ellipse center)
- Initial dimensions of the quench (ellipse semi-axes)



Important: in each coil only one quench can begin!

2.4 Input file – voltage taps

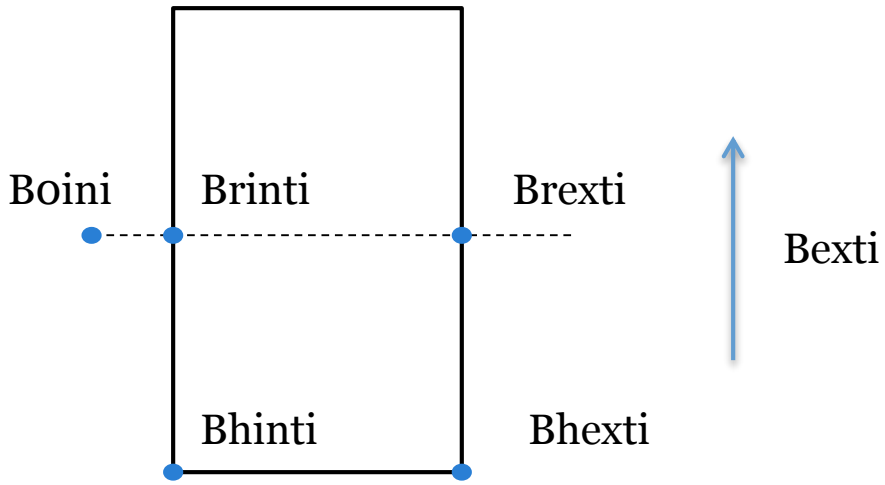
```
1                !nzon
1                !nzon
1                !nzon
1                !nzon
1                !nzon
1                !nzon
1                !nzon
1                !nzonh
1                !nzonh
1                !nzonh
1                !nzonh
1                !nzonh
1                !nzonh
1                !nzonh
5.338386088      5.356826088              !R(ncoil, nzon)
5.338386088      5.356826088              !R(ncoil, nzon)
5.338386088      5.356826088              !R(ncoil, nzon)
16.03359826      16.05203826              !R(ncoil, nzon)
16.03359826      16.05203826              !R(ncoil, nzon)
21.38120435      21.39964435              !R(ncoil, nzon)
21.38120435      21.39964435              !R(ncoil, nzon)
0        0.01089          !d(ncoil, nzonh)
0        0.01452          !d(ncoil, nzonh)
0        0.01452          !d(ncoil, nzonh)
0        0.019965         !d(ncoil, nzonh)
0        0.019965         !d(ncoil, nzonh)
0        0.02541          !d(ncoil, nzonh)
0        0.02541          !d(ncoil, nzonh)
```

Each coil can be divided in axial and radial direction in order to obtain the voltage within the windings.

Remember that the coil is a homogeneous material!

2.5 Input file – magnetic field

```
0       11.60763006     10.9416185      9.99017341      7.611560694     0               !BOini, Brinti, Brexti, Bhinti, Bhexti, Bexti
0       9.99017341      7.611560694     9.038728324     4.757225434     0               !BOini, Brinti, Brexti, Bhinti, Bhexti, Bexti
0       9.038728324     4.757225434     8.56300578      2.378612717     0               !BOini, Brinti, Brexti, Bhinti, Bhexti, Bexti
0       11.60763006     10.9416185      9.038728324     5.70867052      0               !BOini, Brinti, Brexti, Bhinti, Bhexti, Bexti
0       9.038728324     5.70867052      8.56300578      2.378612717     0               !BOini, Brinti, Brexti, Bhinti, Bhexti, Bexti
0       10.9416185      8.56300578      6.660115607     6.184393064     0               !BOini, Brinti, Brexti, Bhinti, Bhexti, Bexti
0       6.660115607     6.184393064     2.378612717     5.232947977     0               !BOini, Brinti, Brexti, Bhinti, Bhexti, Bexti
```



- The final magnetic field within the coil is a linear interpolation of the four points given in input
- The field is symmetric respect to the mid-plane
- The field scales linearly with the current during the quench
- One can describe any kind of magnetic field, but with a certain approximation

2.5 Input file – critical current

```
18.3    22      0.55            !themax, Bmax, xlub (MECO values for Nb3Sn)
18.3    22      0.55            !themax, Bmax, xlub (MECO values for Nb3Sn)
18.3    22      0.55            !themax, Bmax, xlub (MECO values for Nb3Sn)
18.3    22      0.55            !themax, Bmax, xlub (MECO values for Nb3Sn)
18.3    22      0.55            !themax, Bmax, xlub (MECO values for Nb3Sn)
18.3    22      0.55            !themax, Bmax, xlub (MECO values for Nb3Sn)
18.3    22      0.55            !themax, Bmax, xlub (MECO values for Nb3Sn)
3       0.5     0.25    4.2             !num(Ic & B), alfa, beta, thecc
28400   12              !(Ic & B)
40807   10              !(Ic & B)
100116  5               !(Ic & B)
3       0.5     0.25    4.2             !num(Ic & B), alfa, beta, thecc
28400   12              !(Ic & B)
40807   10              !(Ic & B)
100116  5               !(Ic & B)
3       0.5     0.25    4.2             !num(Ic & B), alfa, beta, thecc
28400   12              !(Ic & B)
40807   10              !(Ic & B)
100116  5               !(Ic & B)
3       0.5     0.25    4.2             !num(Ic & B), alfa, beta, thecc
28400   12              !(Ic & B)
40807   10              !(Ic & B)
100116  5               !(Ic & B)
3       0.5     0.25    4.2             !num(Ic & B), alfa, beta, thecc
28400   12              !(Ic & B)
40807   10              !(Ic & B)
100116  5               !(Ic & B)
3       0.5     0.25    4.2             !num(Ic & B), alfa, beta, thecc
28400   12              !(Ic & B)
40807   10              !(Ic & B)
100116  5               !(Ic & B)
```

- The critical current is obtained from the Summers fit
- Per each coil, one has to set the fit parameters, and to give at least three points (current in Amps and field) of the critical curve

2.6 Input file – material fractions

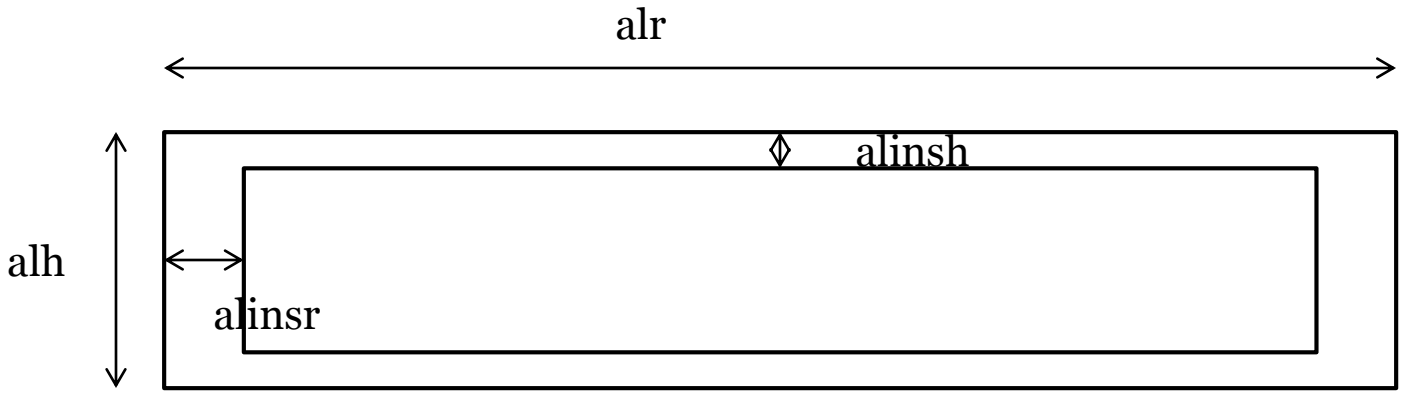
```
4       4       4       4       4       4       4               !nmat
'COPPER'        0.351853678     150     2               !mat, frac, RRR, mattype
'NB3SN'         0.195474265     1       3               !mat, frac, RRR, mattype
'G10'           0.354934924     1       1               !mat, frac, RRR, mattype
'BRONZE'        0.097737133     1       2               !mat, frac, RRR, mattype
'COPPER'        0.351853678     150     2               !mat, frac, RRR, mattype
'NB3SN'         0.195474265     1       3               !mat, frac, RRR, mattype
'G10'           0.354934924     1       1               !mat, frac, RRR, mattype
'BRONZE'        0.097737133     1       2               !mat, frac, RRR, mattype
'COPPER'        0.351853678     150     2               !mat, frac, RRR, mattype
'NB3SN'         0.195474265     1       3               !mat, frac, RRR, mattype
'G10'           0.354934924     1       1               !mat, frac, RRR, mattype
'BRONZE'        0.097737133     1       2               !mat, frac, RRR, mattype
'COPPER'        0.351853678     150     2               !mat, frac, RRR, mattype
'NB3SN'         0.195474265     1       3               !mat, frac, RRR, mattype
'G10'           0.354934924     1       1               !mat, frac, RRR, mattype
'BRONZE'        0.097737133     1       2               !mat, frac, RRR, mattype
'COPPER'        0.351853678     150     2               !mat, frac, RRR, mattype
'NB3SN'         0.195474265     1       3               !mat, frac, RRR, mattype
'G10'           0.354934924     1       1               !mat, frac, RRR, mattype
'BRONZE'        0.097737133     1       2               !mat, frac, RRR, mattype
'COPPER'        0.351853678     150     2               !mat, frac, RRR, mattype
'NB3SN'         0.195474265     1       3               !mat, frac, RRR, mattype
'BRONZE'        0.097737133     1       2               !mat, frac, RRR, mattype
'G10'           0.354934924     1       1               !mat, frac, RRR, mattype
'COPPER'        0.351853678     150     2               !mat, frac, RRR, mattype
'NB3SN'         0.195474265     1       3               !mat, frac, RRR, mattype
'BRONZE'        0.097737133     1       2               !mat, frac, RRR, mattype
'G10'           0.354934924     1       1               !mat, frac, RRR, mattype
```

- Per each coil, one has to set the number of materials, the type of the material, and the fraction respect to the conductor area.
- The fractions can be computed using strand Cu/NCu and void in the conductor

2.7 Input file – unitary cell

```
0.01844 0.001815        0.000145        0.000145        !alr, alh, alinsr, alinsh
0.01844 0.001815        0.000145        0.000145        !alr, alh, alinsr, alinsh
0.01844 0.001815        0.000145        0.000145        !alr, alh, alinsr, alinsh
0.01844 0.001815        0.000145        0.000145        !alr, alh, alinsr, alinsh
0.01844 0.001815        0.000145        0.000145        !alr, alh, alinsr, alinsh
0.01844 0.001815        0.000145        0.000145        !alr, alh, alinsr, alinsh
0.01844 0.001815        0.000145        0.000145        !alr, alh, alinsr, alinsh
```

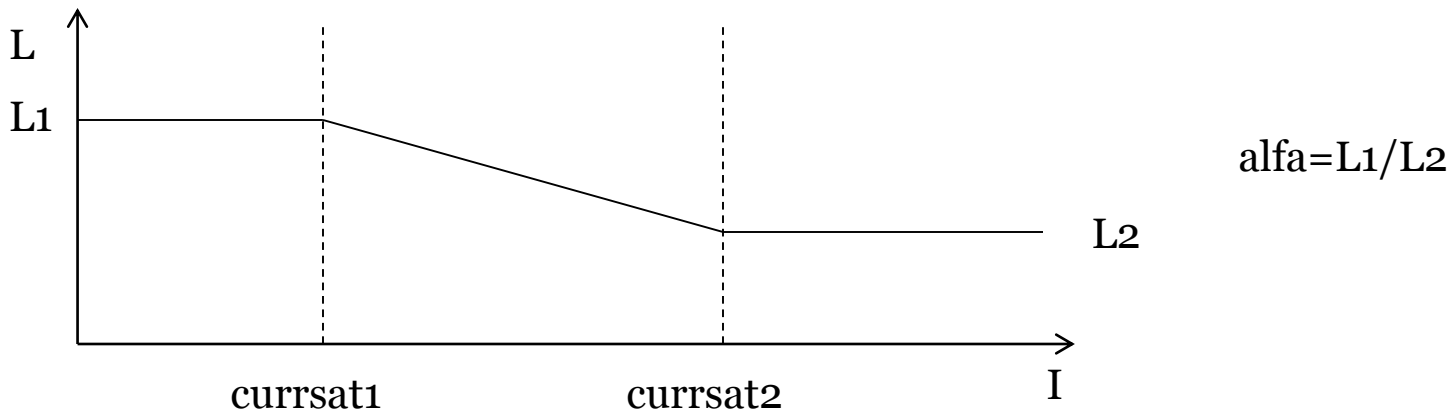
- Per each coil, one has to set the unitary cell
- The shape is a rectangle, the dimensions are given considering the insulation
- The material properties are averaged over the unitary cell



2.8 Input file – inductance

```
0.019704        0       0       0       0       0       0       !hmuts
0       0.019704        0       0       0       0       0
0       0       0.019704        0       0       0       0
0       0       0       0.019704        0       0       0
0       0       0       0       0.019704        0       0
0       0       0       0       0       0.019704        0
0       0       0       0       0       0       0.019704
2000    16000   0.86                                    !currsat1, currsat2, alfa
```

- The inductance is given as a matrix (put the values at zero current)
- On the diagonal, the self-inductances are reported, elsewhere the mutual inductances are reported
- According to the number of circuits, the inductances are automatically and properly combined
- The inductance depends on the current (for example, iron saturation can be simulated)



2.9 Input file – inductance

```
0.075   0.11188 16.8          !rin, rout, lenght
0.03                          !taueddy
0.7                           !fillingfactor
200                           !nspire
1                             !ondyn
```

- For costheta dipoles and quadrupoles, the inductance can be corrected with AC effects due to inter-filament coupling currents
- The reduction is computed completely analytically (using energetic considerations), therefore some magnet parameters have to be put in the input
- The option is only for inductance reduction, and not for quench back and AC losses
- The option can be disabled

2.10 Input file – circuit and protection

```
0.1                !vqds
0.1                !vqds
0.1                !vqds
0.1                !vqds
0.1                !vqds
0.1                !vqds
0.1                !vqds
16470    0.05      2        2                !amp01, rdump1 ,ind1, ivt1
0.001    0.015               !timarc1, deltim1
1                  !nswi
5                  !vmax1a
6                  !vmax2a
0.05               !tau1
7                  !nacc
```

- Per each coil, the voltage threshold can be set for the detection
- Per each circuit, the initial current has to be set, and a dump resistor can be set
- The switch delay time and the arch time can be set
- The power supply parameters has to be set
- The number of coil per circuit has to be set (nacc)

2.11 Input file – propagation correctors

```
15      15      0.5     0.5     1               !corvri, corvre, corvhu,corvhd,corvel
15      15      1       1       258.72          !corvri, corvre, corvhu,corvhd,corvel
15      15      1       1       258.72          !corvri, corvre, corvhu,corvhd,corvel
15      15      1       1       776.16          !corvri, corvre, corvhu,corvhd,corvel
15      15      1       1       776.16          !corvri, corvre, corvhu,corvhd,corvel
15      15      1       1       833.28          !corvri, corvre, corvhu,corvhd,corvel
15      15      1       1       833.28          !corvri, corvre, corvhu,corvhd,corvel
```

- The quench propagation velocities computed analytically can be corrected with some scaling factor in the three directions (radial right and left, axial up and down, and longitudinal)
- These factors are important to model conductors for accelerator magnets and quench protection system in the right way

3.1 Main outputs – normal zone size

NORMAL ZONE VOLUM, Z-SEMI-AXIS AND QUENCH POSITION

time	Volum(m^3)	Z-semi-axis(deg.)	Rqi(m)	Rqe(m)	Hqu(m)	Hqd(m)
0.001	0.70919E-08	0.0581	0.0000	0.0056	0.0001	0.0001
0.001	0.56717E-07	0.1162	0.0000	0.0111	0.0002	0.0002
0.002	0.19103E-06	0.1743	0.0000	0.0165	0.0003	0.0003
0.002	0.43281E-06	0.2324	0.0000	0.0184	0.0005	0.0005
0.003	0.74779E-06	0.2905	0.0000	0.0184	0.0006	0.0006
0.003	0.11330E-05	0.3487	0.0000	0.0184	0.0007	0.0007
0.004	0.15877E-05	0.4068	0.0000	0.0184	0.0008	0.0008
0.004	0.21116E-05	0.4649	0.0000	0.0184	0.0009	0.0009
0.005	0.27019E-05	0.5230	0.0000	0.0184	0.0010	0.0010
0.005	0.33630E-05	0.5811	0.0000	0.0184	0.0011	0.0011
0.006	0.40897E-05	0.6392	0.0000	0.0184	0.0012	0.0012
0.006	0.48842E-05	0.6973	0.0000	0.0184	0.0013	0.0013
0.007	0.57481E-05	0.7554	0.0000	0.0184	0.0014	0.0014
0.007	0.66744E-05	0.8135	0.0000	0.0184	0.0015	0.0015
0.008	0.76697E-05	0.8716	0.0000	0.0184	0.0017	0.0017

Per each coil, one can obtain the normal zone volume, and the position of the three ellipse axes, as a function of the time

3.2 Main outputs – quench

TIME	CURR(A)	TEMP(K)	DVol(m3)	RES(Ohm)	VOLT(V)	DTMAX(K)
0.0005	16470.00	9.88	.7092E-08	.1080E-07	0.0002	7.88
0.0010	16470.00	14.65	.4963E-07	.8595E-07	0.0012	12.65
0.0015	16470.00	18.35	.1343E-06	.2882E-06	0.0041	16.35
0.0020	16470.00	20.80	.2418E-06	.6499E-06	0.0092	18.80
0.0025	16470.00	22.68	.3150E-06	.1120E-05	0.0158	20.68
0.0030	16470.00	24.25	.3852E-06	.1696E-05	0.0239	22.25
0.0035	16470.00	25.64	.4548E-06	.2375E-05	0.0335	23.64
0.0040	16470.00	26.87	.5239E-06	.3158E-05	0.0446	24.87
0.0045	16470.00	28.00	.5903E-06	.4039E-05	0.0570	26.00
0.0050	16470.00	29.03	.6610E-06	.5027E-05	0.0710	27.03
0.0055	16470.00	30.01	.7268E-06	.6115E-05	0.0863	28.01
0.0060	16470.00	30.92	.7944E-06	.7305E-05	0.1031	28.92

Per each coil, one can obtain as a function of the time:

- The current
- The maximum temperature
- The total resistance
- The total voltage across the coil
- The maximum temperature difference

If foreseen, also voltage across voltage taps is reported

3.3 Main outputs – propagation velocities

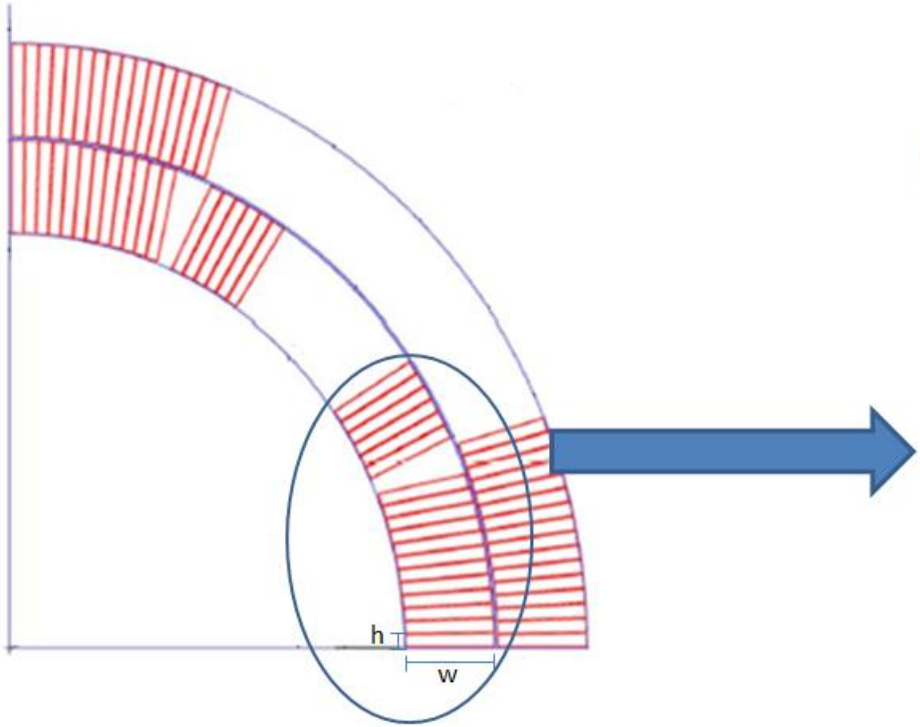
VELOCITY OF QUENCH (m/s)

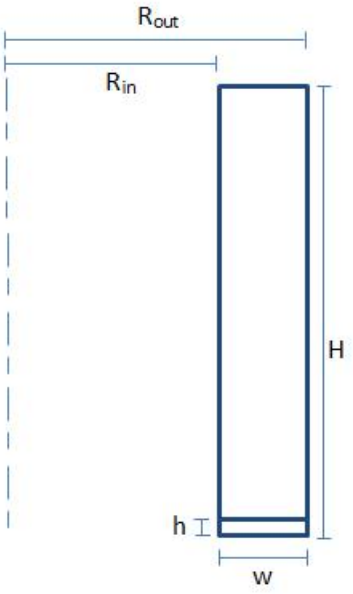
time	Vr_i	Vr_e	Vh_u	Vh_d	Vl_q	Vl_Ri	Vl_Re	Vl_Hu	Vl_Hd
0.0005	0.111E+02	0.111E+02	0.227E+00	0.227E+00	0.108E+02	0.108E+02	0.108E+02	0.108E+02	0.108E+02
0.0010	0.111E+02	0.110E+02	0.225E+00	0.225E+00	0.108E+02	0.108E+02	0.106E+02	0.108E+02	0.108E+02
0.0015	0.111E+02	0.109E+02	0.225E+00	0.225E+00	0.108E+02	0.108E+02	0.104E+02	0.107E+02	0.107E+02
0.0020	0.111E+02	0.107E+02	0.224E+00	0.224E+00	0.108E+02	0.108E+02	0.102E+02	0.107E+02	0.107E+02
0.0025	0.111E+02	0.107E+02	0.223E+00	0.223E+00	0.108E+02	0.108E+02	0.101E+02	0.107E+02	0.107E+02
0.0030	0.111E+02	0.107E+02	0.222E+00	0.222E+00	0.108E+02	0.108E+02	0.101E+02	0.106E+02	0.106E+02
0.0035	0.111E+02	0.107E+02	0.222E+00	0.222E+00	0.108E+02	0.108E+02	0.101E+02	0.106E+02	0.106E+02
0.0040	0.111E+02	0.107E+02	0.221E+00	0.221E+00	0.108E+02	0.108E+02	0.101E+02	0.106E+02	0.106E+02
0.0045	0.111E+02	0.107E+02	0.220E+00	0.220E+00	0.108E+02	0.108E+02	0.101E+02	0.105E+02	0.105E+02
0.0050	0.111E+02	0.107E+02	0.219E+00	0.219E+00	0.108E+02	0.108E+02	0.101E+02	0.105E+02	0.105E+02
0.0055	0.111E+02	0.107E+02	0.219E+00	0.219E+00	0.108E+02	0.108E+02	0.101E+02	0.105E+02	0.105E+02
0.0060	0.111E+02	0.107E+02	0.218E+00	0.218E+00	0.108E+02	0.108E+02	0.101E+02	0.104E+02	0.104E+02
0.0065	0.111E+02	0.107E+02	0.217E+00	0.217E+00	0.108E+02	0.108E+02	0.101E+02	0.104E+02	0.104E+02

- Per each coil, one can obtain the propagation velocities on the three axes, in both the directions
- These velocities are reported already scaled with the correcting factors

4.1 Example – double layer cosθ quadrupole Geometry

- Each coil can be represented as a solenoid
- It is important to preserve the volume in order to simulate the right resistance





Quadrupole length

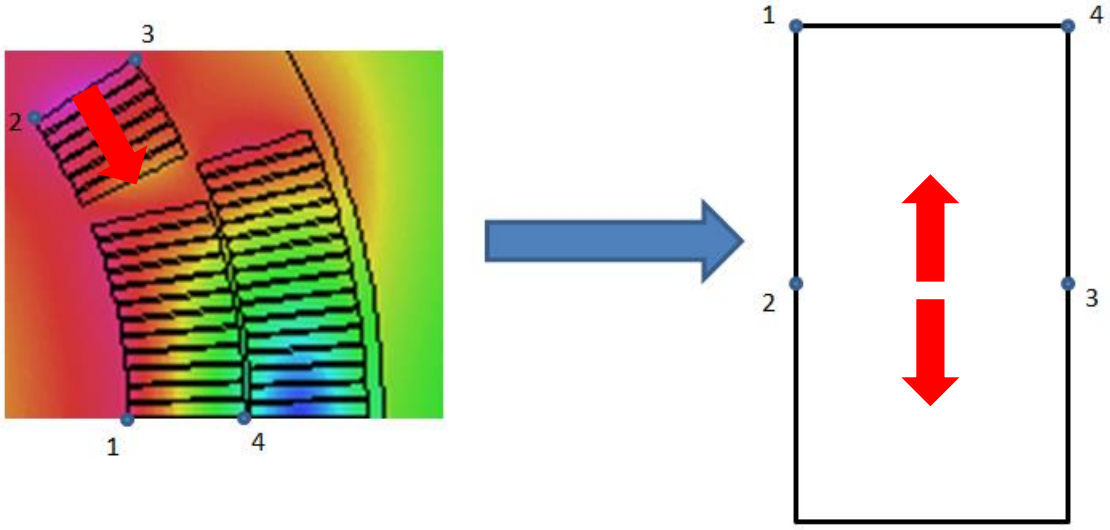
$$R_{in} = \frac{L}{\pi} - \frac{w}{2}$$

$$R_{out} = R_{in} + \frac{w}{2}$$

$$H = Nh$$

4.2 Example – double layer cosθ quadrupole Magnetic field

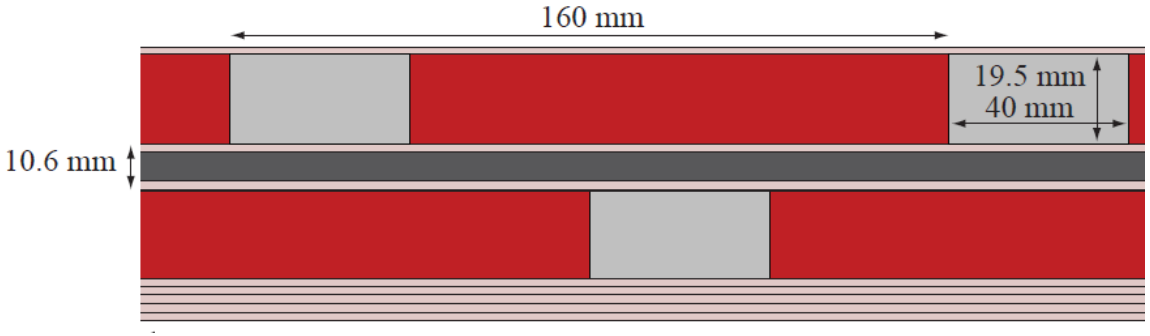
- Probably, weakest point of QLASA
- We have symmetry on the mid-plane, and linear interpolation
- The best solution could be to put the high-field region in the middle, and begin the eventual quench there, correcting the transversal velocity with a 0.5 factor



4.3 Example – double layer cosθ quadrupole Protection heaters

```
0.0005  5.338386088   0.005445    0   0          0          !timq, Rque, yque, rrqui, hhqui, llqui
0.035   5.338386088   0.00726     0   0.00726    0.0125     !timq, Rque, yque, rrqui, hhqui, llqui
0.036   5.338386088   0.00726     0   0.0045375  0.0125     !timq, Rque, yque, rrqui, hhqui, llqui
0.035   16.03359826   0.0099825   0   0.0081675  0.0125     !timq, Rque, yque, rrqui, hhqui, llqui
0.036   16.03359826   0.0099825   0   0.00726    0.0125     !timq, Rque, yque, rrqui, hhqui, llqui
2.037   21.38120435   0.012705    0   0.01       0.02       !timq, Rque, yque, rrqui, hhqui, llqui
0.041   21.38120435   0.012705    0   0.01       0.02       !timq, Rque, yque, rrqui, hhqui, llqui
```

- The heaters delay time cannot be simulated
- The quench heaters can be simulated as a quench with
  - Null radial dimension
  - Axial dimensions equal to the number of covered turns times the turn thickness
  - Longitudinal dimensions equal to the number of heating stations times the heating stations length



4.4 Example – double layer cosθ quadrupole
Heaters correcting factors

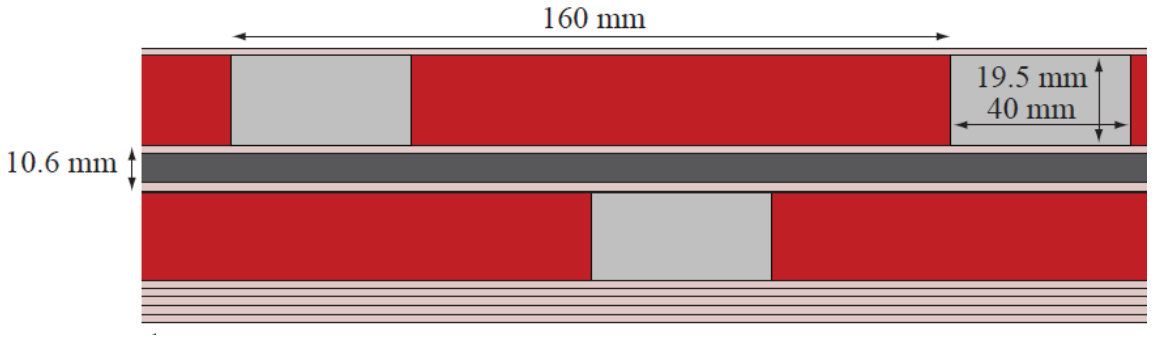
```
15      15      0.5     0.5     1               !corvri, corvre, corvhu,corvhd,corvel
15      15      1       1       258.72          !corvri, corvre, corvhu,corvhd,corvel
15      15      1       1       258.72          !corvri, corvre, corvhu,corvhd,corvel
15      15      1       1       776.16          !corvri, corvre, corvhu,corvhd,corvel
15      15      1       1       776.16          !corvri, corvre, corvhu,corvhd,corvel
15      15      1       1       833.28          !corvri, corvre, corvhu,corvhd,corvel
15      15      1       1       833.28          !corvri, corvre, corvhu,corvhd,corvel
```

- Remember that the solenoid is represented as a material with average properties!

- The radial propagation is dominated by copper in conductors for accelerator magnets, and it is almost instantaneous
  - ➢ It has to be increased in QLASA!

- The longitudinal propagation has to be increased of a factor equal to

$$2\frac{L_{magnet} - N_{HS}L_{HS}}{DIST_{HS}}$$



4.5 Example – double layer cosθ quadrupole Spontaneous quench

- Remember that in each solenoid just one quench can be began!
- This means that the coil where one wants to model a spontaneous quench cannot be covered by protection heaters.
- A possible solution is to split the considered solenoid in two solenoids, one with the spontaneous quench, one covered by heaters
  - Take care to take the solenoid with spontaneous quench small enough to have a good approximation for the heaters resistance, but large enough for the transversal propagation and the quench detection
- Remember that maximum 10 solenoids can be simulated

5.1 Conclusions

- QLASA is a quench simulation program
- It is pseudo-analytic, and therefore very fast
- It is for solenoids, but adaptable to any kind of magnet
- The input file is a text tabular file easy to generate starting from the magnet parameters
- The quench is 3D, and heating stations can be easily simulated
- The inductance is current dependent and AC effects dependent
- AC losses cannot be simulated
- Magnetic field is strongly approximated