New LHC quench calculations and the luminosity limit for heavy-ion collisions

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Outline

- Background and introduction: Bound Free Pair Production
- Tracking: Distribution at the IP and at impact
- FLUKA simulation of shower in magnet
- Thermal network simulation (Dariusz)
  - Thermodynamics of magnet structure
  - Network model
  - Validation of the model
  - Steady state beam loss heat load simulation
- Comparison between optics version
- Simulation uncertainties
- Summary

Motivation (1)

The LHC will run ~1 month/year with heavy ions. Nominal parameters:

	$^{208}\mathrm{Pb}^{82+}$ ions	Protons
Energy per nucleon	2.76 TeV	7 TeV
Number of bunches	592	2808
Particles per bunch	7×10^{7}	1.15×10^{11}
Bunch spacing	100 ns	25 ns
Peak luminosity	10^{27} cm^{-2} s^{-1}	10^{34} cm^{-2} s^{-1}
Stored energy per beam	3.81 MJ	350 MJ

- **Although the stored energy in the Pb^{82+} beam is much lower than in the proton beam, beam loss mechanisms peculiar to ions may limit luminosity. Most serious are:**
  - **Collimation inefficiency**
  - **Bound free pair production (BFPP)**

Motivation (2)

- Important to predict the quench limit as accurately as possible to estimate the impact of these beam losses. Same holds true for proton losses.

- Earlier estimates of quench limit make simplifying assumptions about the distribution of beam losses or the thermal behaviour of magnets

- To make more accurate estimates, these factors need to be accounted for

- Here we calculate the quench limit for a specific beam loss mechanism – BFPP – combining tracking, FLUKA shower simulations and a thermal network simulation of the heat flow in a magnet

Bound free pair production

- **During Pb^{82+} operation in the LHC, electromagnetic interactions between colliding beams take place at IP:**

  - **Bound Free Pair production (BFPP):**

$$^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{81+} + \mathrm{e}^{+}$$

Cross section for Bound-Free Pair Production (BFPP) (several authors)

$$Z_1 + Z_2 \rightarrow \left(Z_1 + \mathrm{e}^-\right)_{1s_{1/2},\ldots} + \mathrm{e}^+ + Z_2$$

has very different dependence on ion charges (and energy)

$$\sigma_{\mathrm{PP}} \propto Z_1^{\,5} Z_2^{\,2}\left[A\log\gamma_{CM} + B\right]$$

$$\propto Z^7\left[A\log\gamma_{CM} + B\right] \text{ for } Z_1 = Z_2$$

$$\approx \begin{cases} 0.2 \text{ b for Cu-Cu RHIC} \\ 114 \text{ b for Au-Au RHIC} \\ 281 \text{ b for Pb-Pb LHC} \end{cases}$$

We use BFPP values from Meier et al, Phys. Rev. A, 63, 032713 (2001), includes detailed calculations for Pb-Pb at LHC energy

Compare: σ_{hadr}=8 barn

Magnetic rigidity change

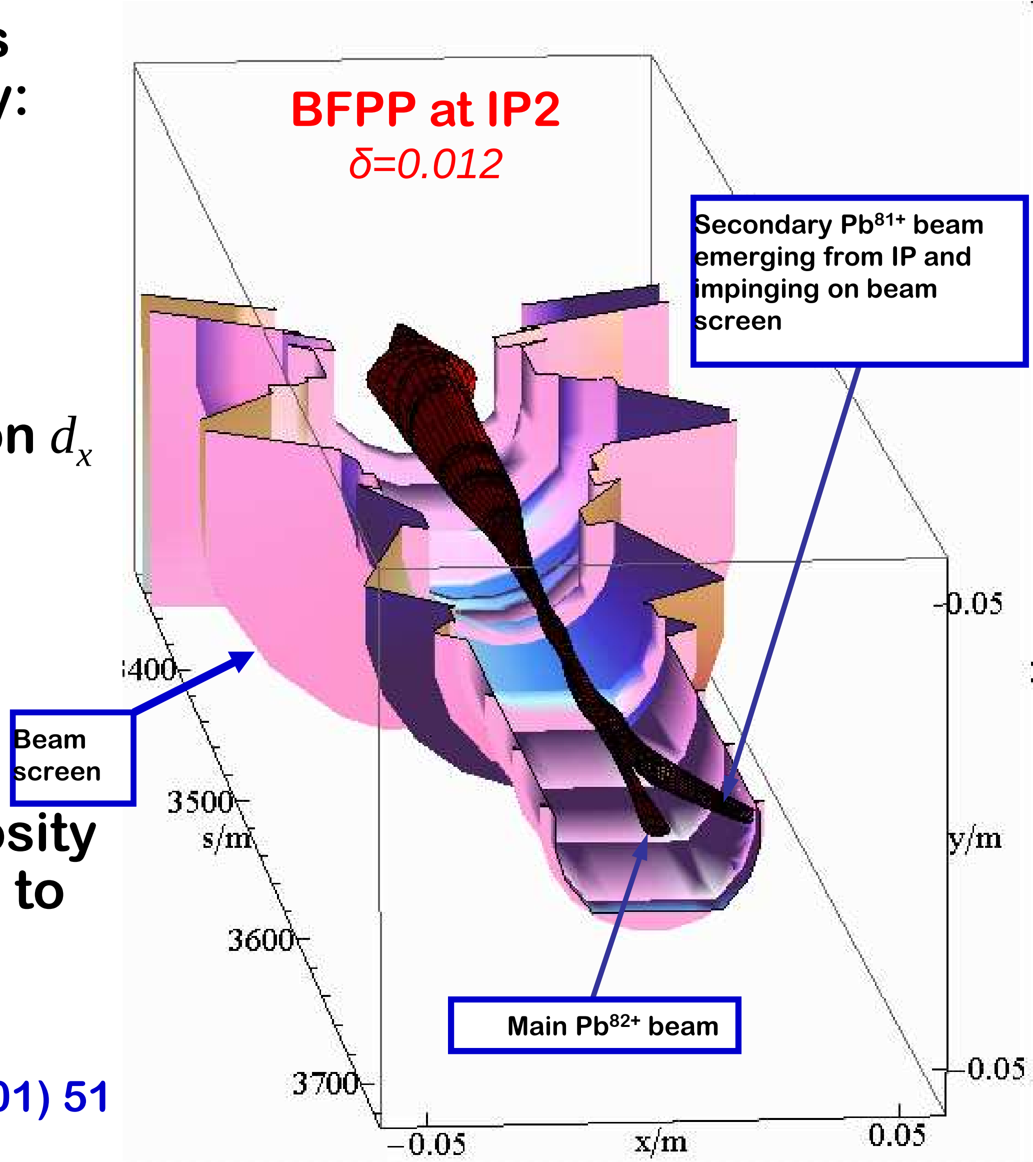
- **BFPP creates 1-electron ions with altered magnetic rigidity:**

$$\delta = \frac{Z_0}{A_0}\frac{A}{Z}(1+\delta_{\mathrm{kin}}) - 1$$

- **These ions follow locally generated dispersion function d_x from IP**
- **Lost in localized spot where aperture A_x and δ satisfy**

$$\delta\, d_x = A_x$$

- **Apart from significant luminosity decay, induced heating risks to quench superconducting magnets**



S. Klein, NIM A 459 (2001) 51

BFPP tracking

- Distribution leaving IP does not correspond to the bunch distribution, but to the distribution of collision points

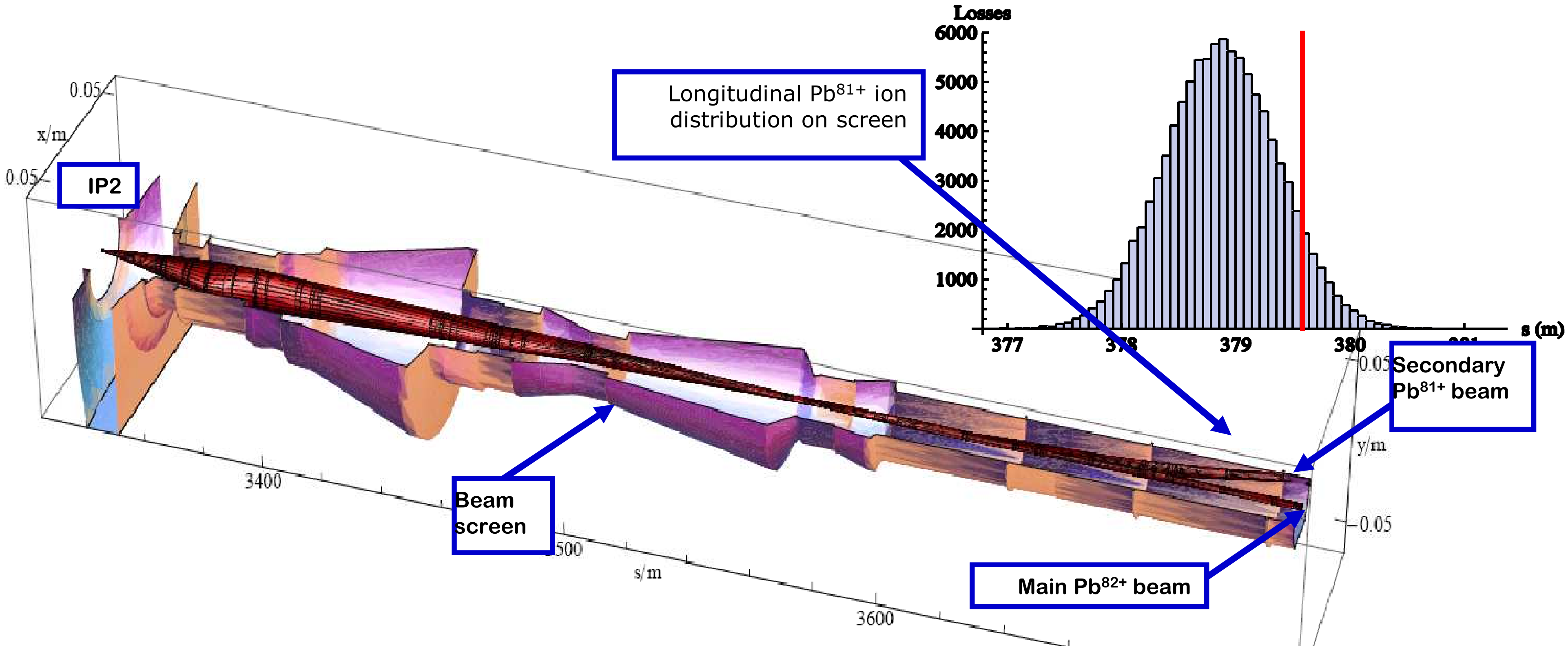
$$P_{\mathrm{col}}(x,x') = \frac{\beta_x}{\sqrt{2}\pi\sigma_x^2}\exp\left(-\frac{2x^2 + (\alpha_x x + \beta_x x')^2}{2\sigma_x^2}\right)$$

- Spatial distribution in each plane is narrow $\sqrt{2}$ by a factor
- As it propagates through the lattice, the distribution changes, in the same way as an unmatched beam at injection
- Beam size at a later point

$$\sigma_{\mathrm{col}}(s_1) = \sqrt{\frac{1+\sin^2(\Delta\mu_{\mathrm{off}})}{2}\beta_{\mathrm{off}}(s_1)\epsilon_x + d_{\mathrm{off}}^2(s_1) < \delta_p^2 >}$$

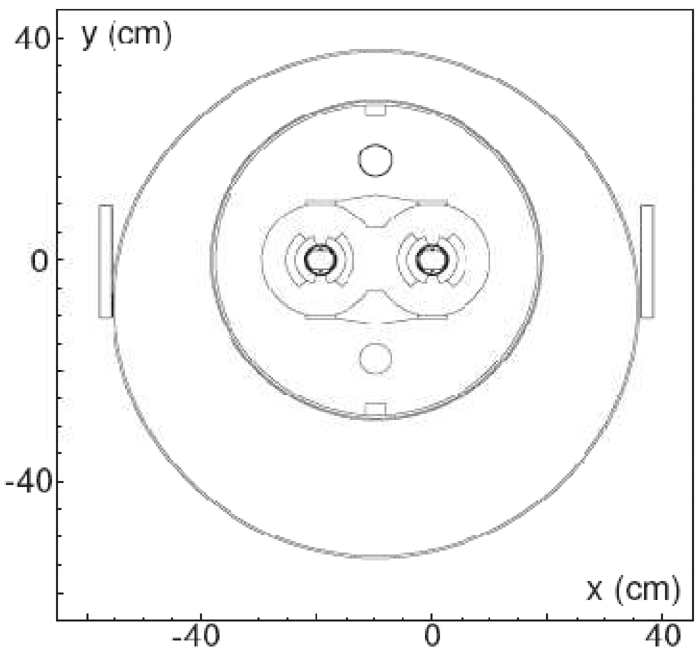
Tracking

- Tracking with matrix formalism, off-momentum optics calculated by MAD-X, analytical algorithm finds impact in MB.B10R2
- LHC optics 6.500 as reference case, comparison with 6.503 later
- At IP2: losses at s=378.9 m downstream in end of dispersion suppressor dipole, spot size around 0.5 m
- IP1 and IP5: losses in connection cryostat in missing dipole, less critical. Will focus on IP2.

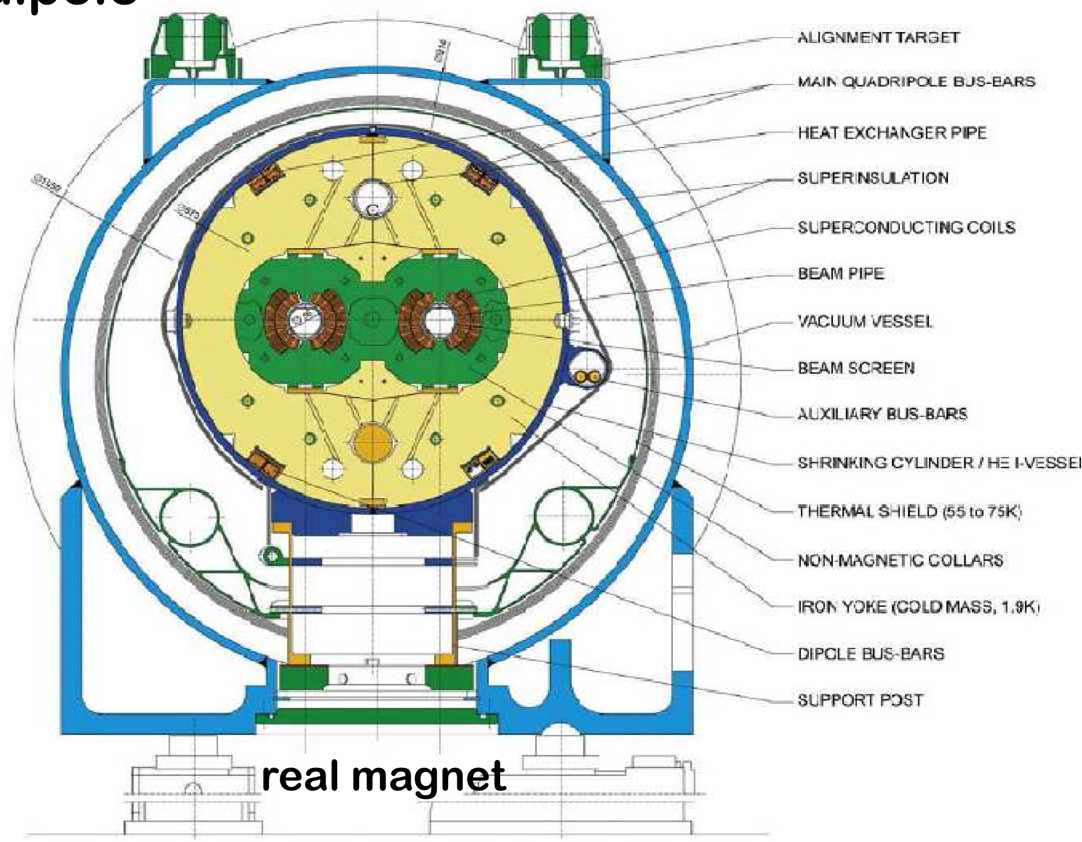


FLUKA shower simulation

- **FLUKA simulation to estimate the heat load in the dispersion suppressor dipole at IP2**
- **impact coordinates of lost BFPP particles from tracking fed as starting conditions to FLUKA**
- **3D model of LHC main dipole**



FLUKA model



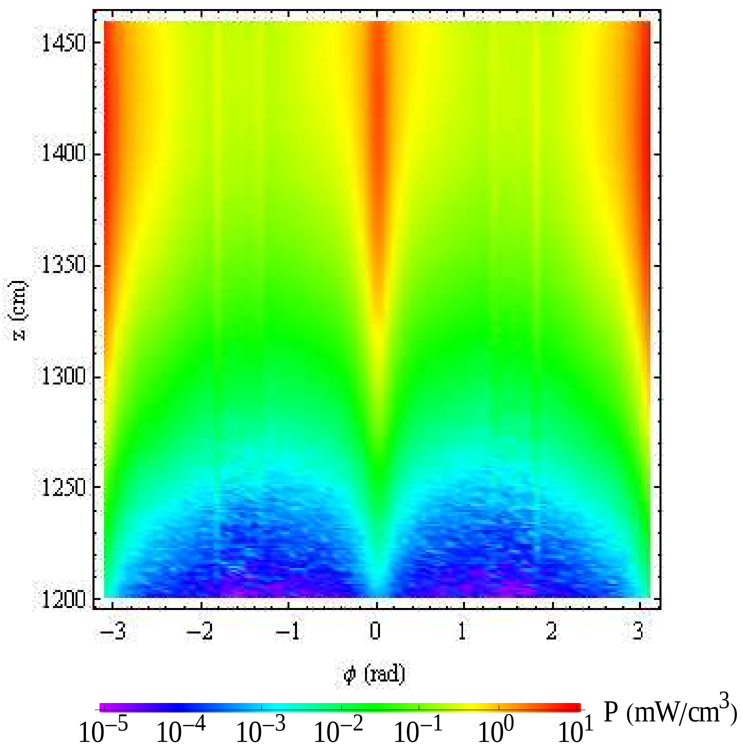
real magnet

Simulated power deposition

Power deposition from FLUKA in the inner coil layer, averaged over width of coil,

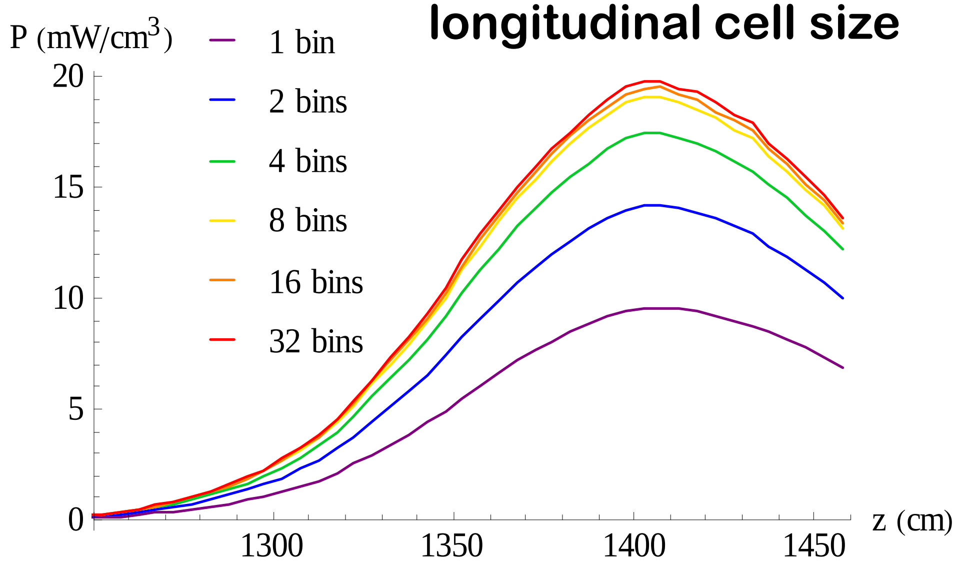
normalized with BFPP cross section and luminosity:

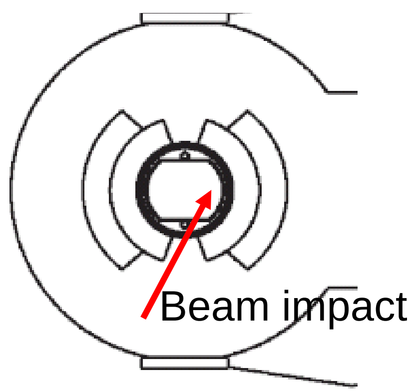
$$P_{tot} = \sigma_{BFPP}\, \mathcal{L}\, E_{particle}$$



Energy deposition longitudinally in hottest bin, different radial binnings.

88 bins in φ (cable), 5 cm longitudinal cell size



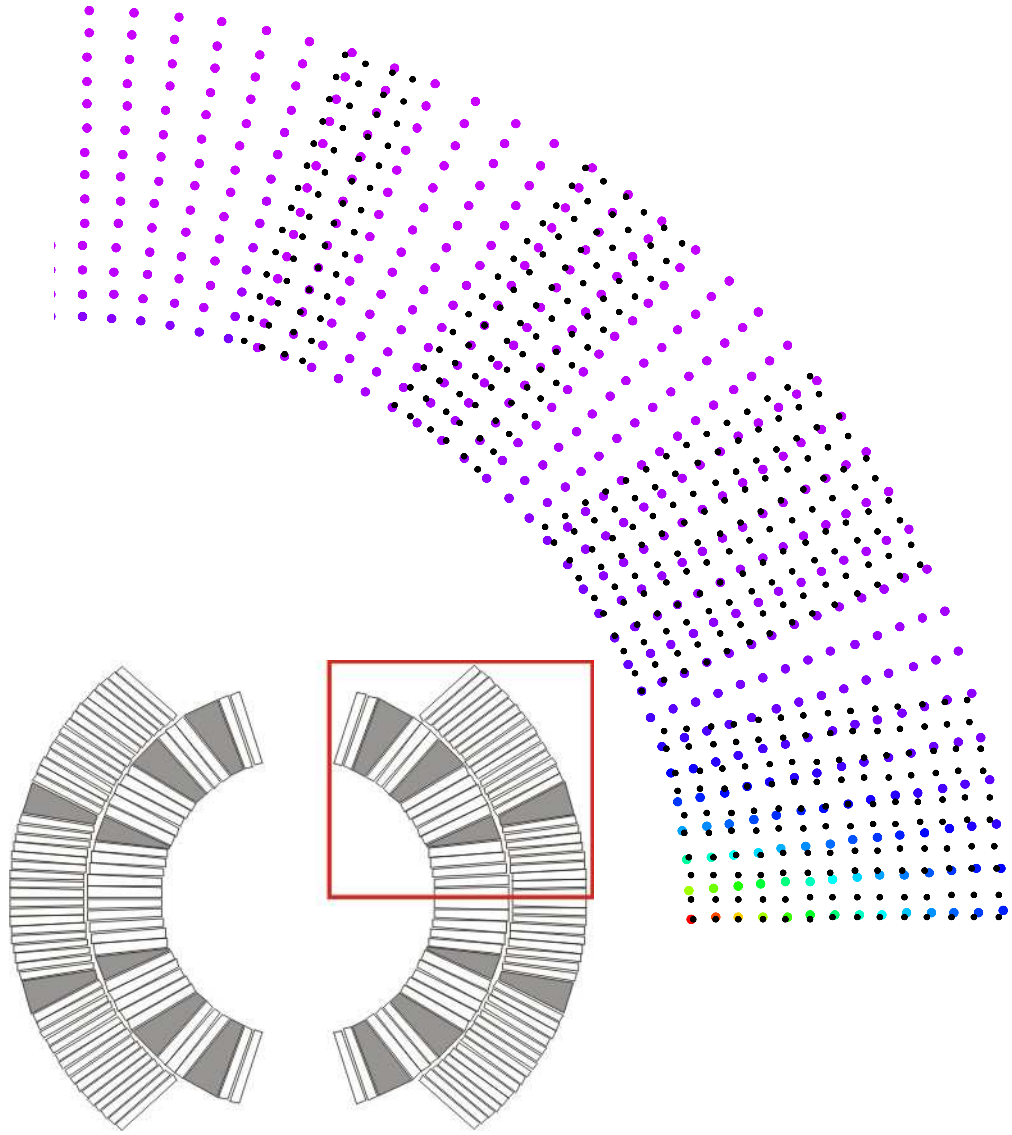


in LHC design report:

Quench limit= 4.5 mW/cm³

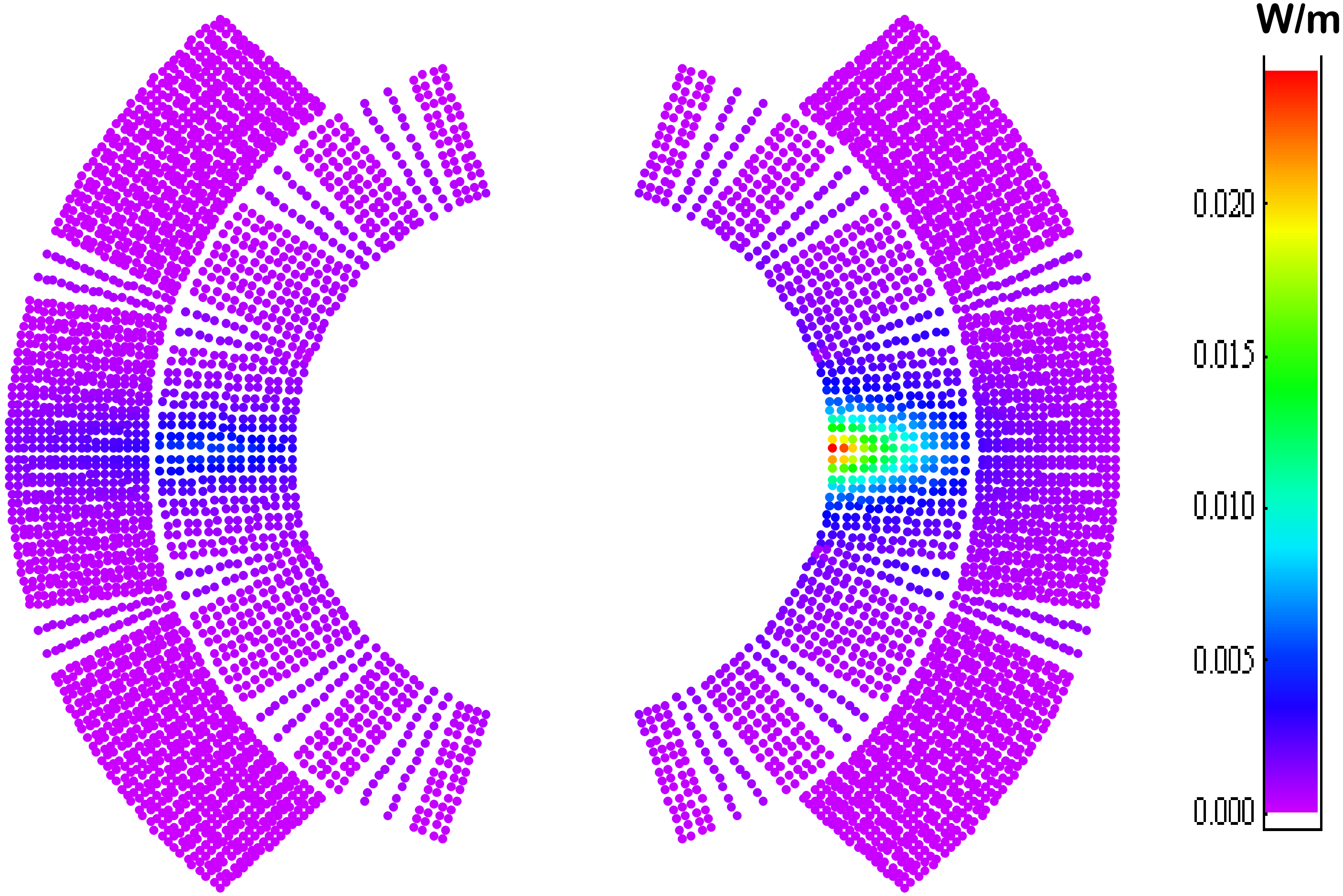
Interpolation of power deposition

- However, now more accurate methods to estimate the quench limit exists – thermal network model (see later slides)
- Detailed map of power deposition in the coil needed
- Strand positions not compatible with R-φ mesh used in FLUKA
- Interpolating the "best possible" FLUKA mesh
- Applying global scaling factor to compensate for insulation, helium space in cables etc.
- Mathematica program automatically generates network input from FLUKA output



Input to network simulation

- **Combining detailed simulated energy deposition from “real beam loss” with thermal network model of magnet**
- **input to network model:**



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Modelling of quench levels induced by steady state beam loss heat load

- Thermodynamics of magnet structure
- Network Model
- Validation of the model
- Steady state beam loss heat load simulation

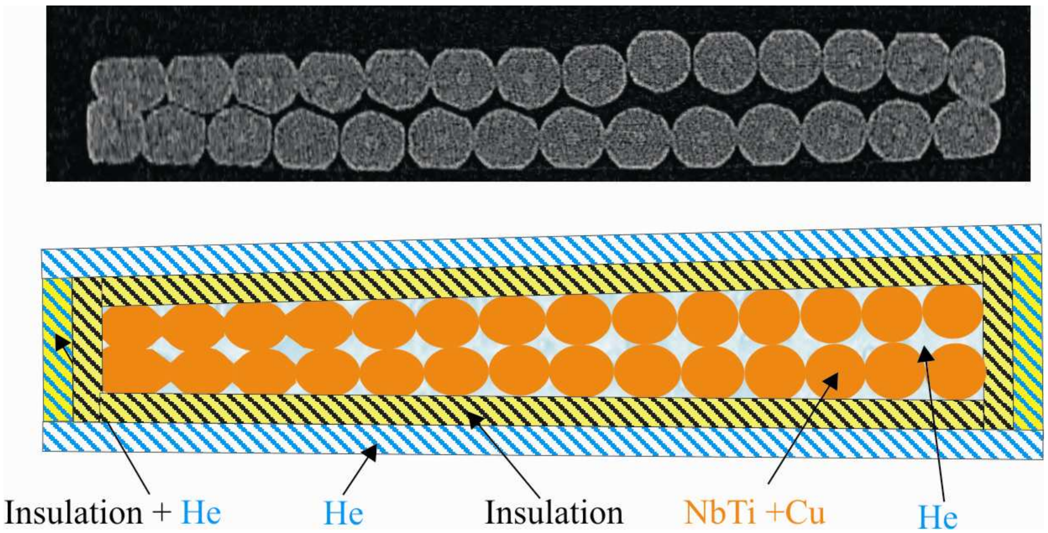
More details:

D. Bocian, B. Dehning, A. Siemko, *Modeling of Quench Limit for Steady State Heat Deposits in LHC Magnets*, IEEE Transactions on Applied Superconductivity, vol. 18, Issue 2, June 2008 Page(s):112 – 115; CERN-AB-2008-006, 2008;

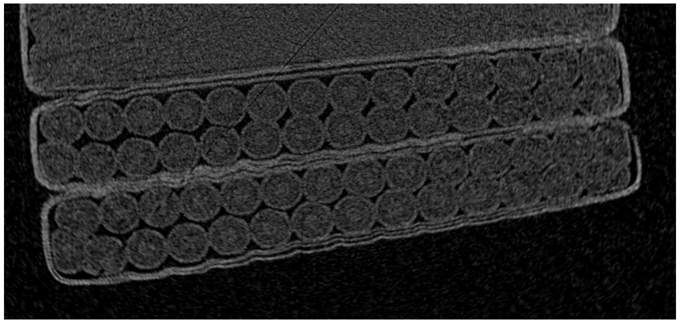
D. Bocian, B. Dehning, A. Siemko, *Quench Limit Model and Measurements for Steady State Heat Deposits in LHC Magnets,* accepted for publication in IEEE Transactions on Applied Superconductivity, 2009

Heat transport in the cable

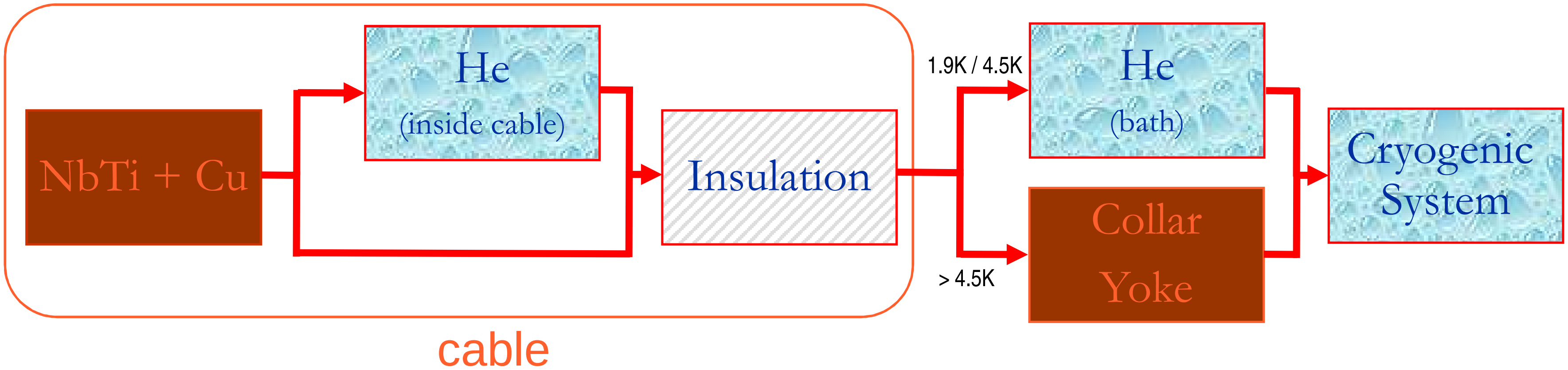
Rutheford type cable



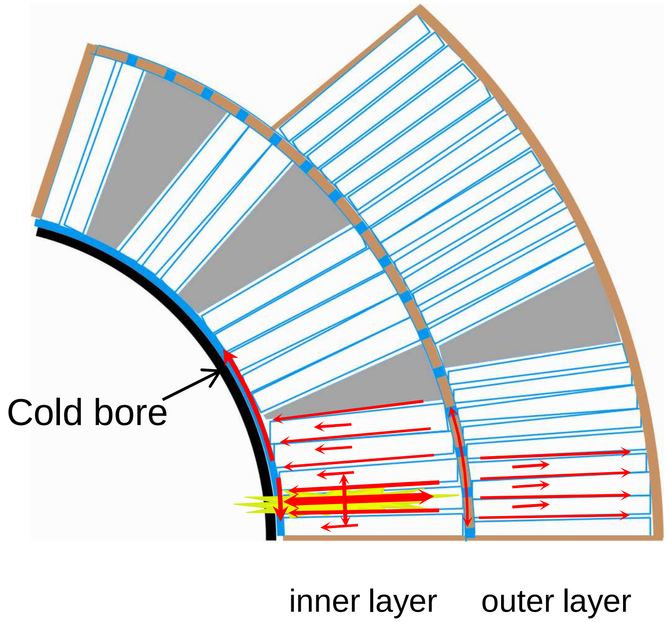
MB magnet – inner layer

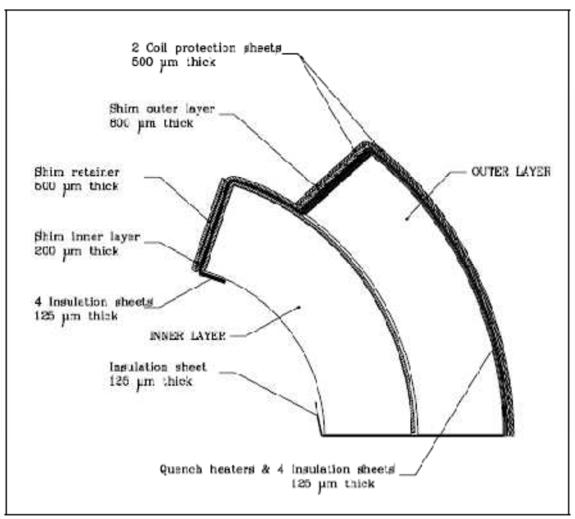


Courtesy C. Scheuerlein

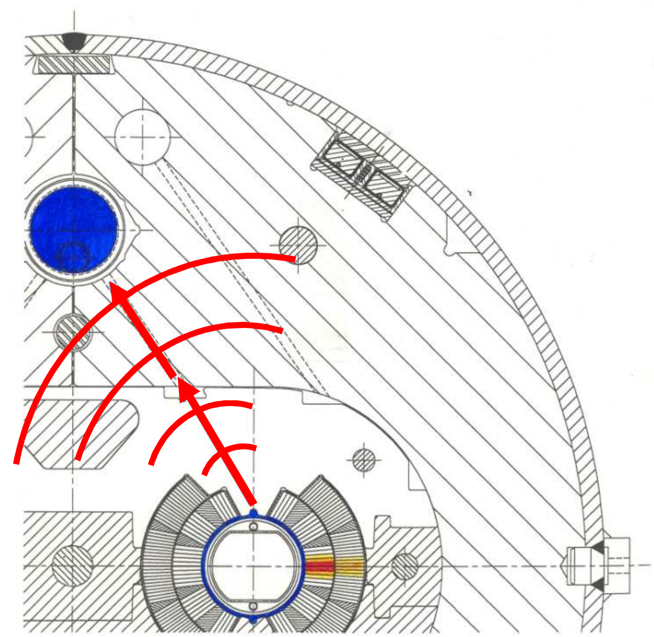


Thermodynamics of magnet structure
Heat transport in the coil at 1.9K



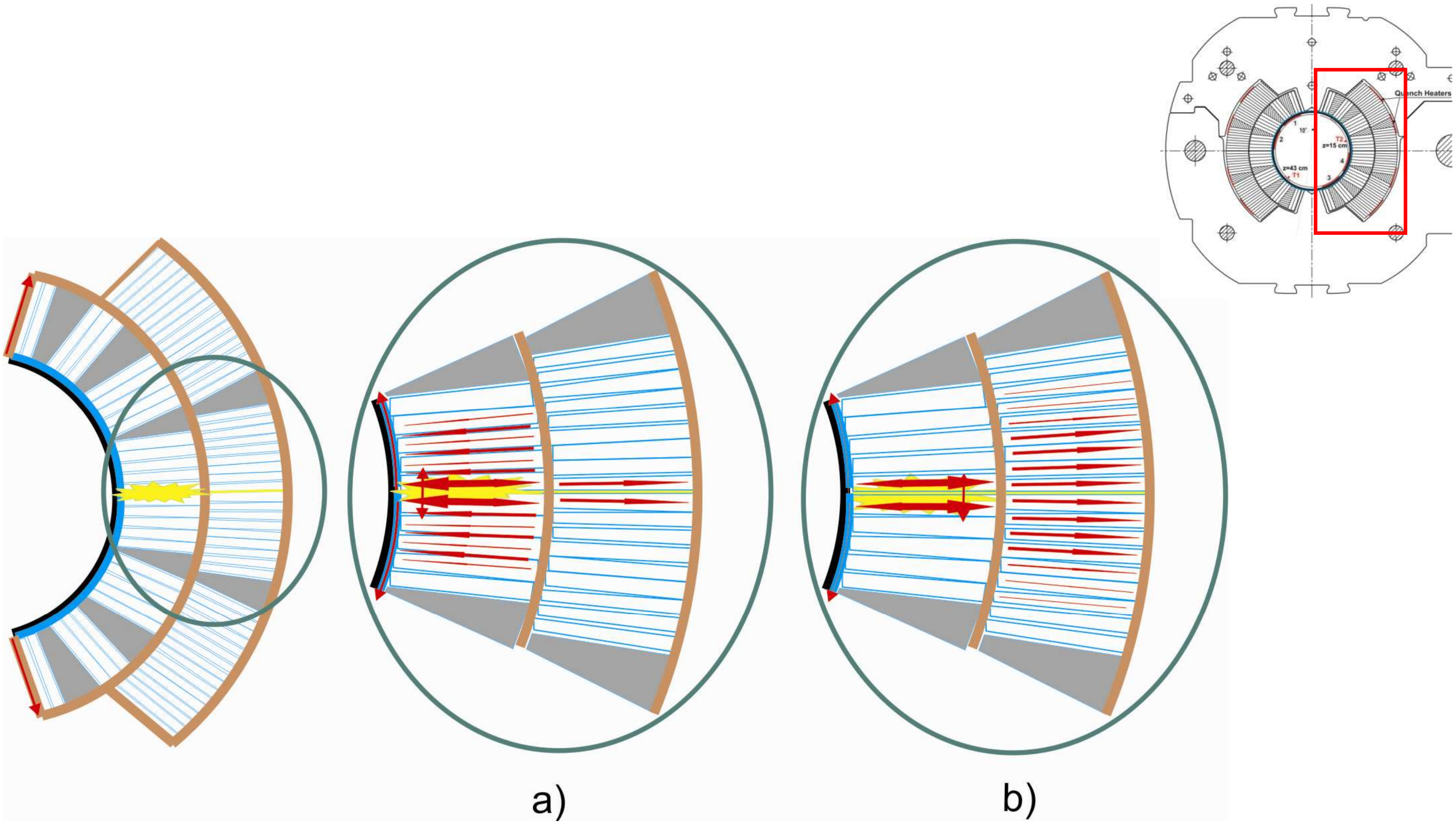


A heat transfer in the main dipole



Electrical insulation is the largest thermal barrier at 1.9 K against cooling

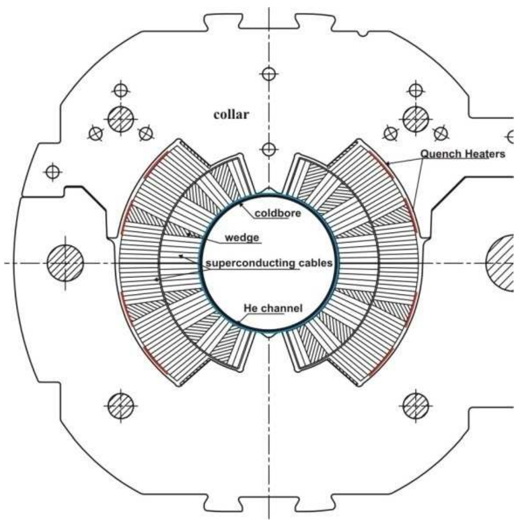
Thermodynamics of magnet structure
Heat transfer in the magnet coil



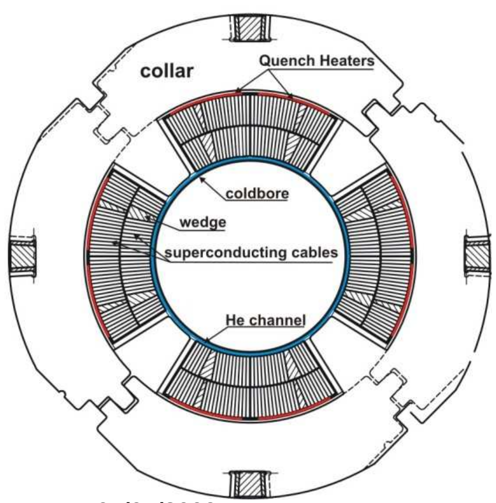
A sketch of the heat transfer in the magnet at nominal operation (a) and at quench limit (b).

Thermodynamics of magnet structure
Heat flow limits

MB – arc magnet, T_b=1.9 K



MQM – LSS magnet, T_b=1.9/4.5 K



HEAT FLOW LIMITS

- heat flow barriers

- cable insulation
- interlayer insulation (MQM)
- ground insulation
- helium channel around cold bore (for temperatures above 2.16 K)

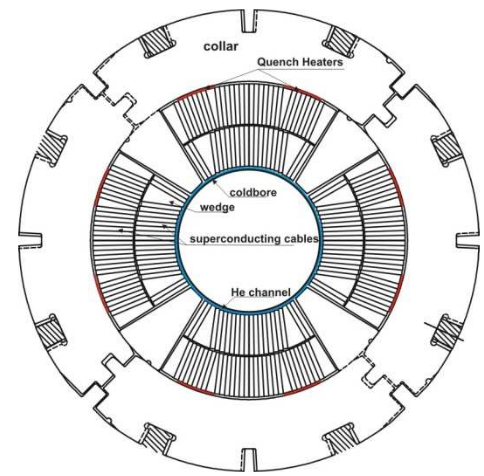
- bath temperature 1.9 K

- Transition HeII $\rightarrow$ HeI: helium channels are blocked = less effective heat evacuation due to the changing of heat evacuation path

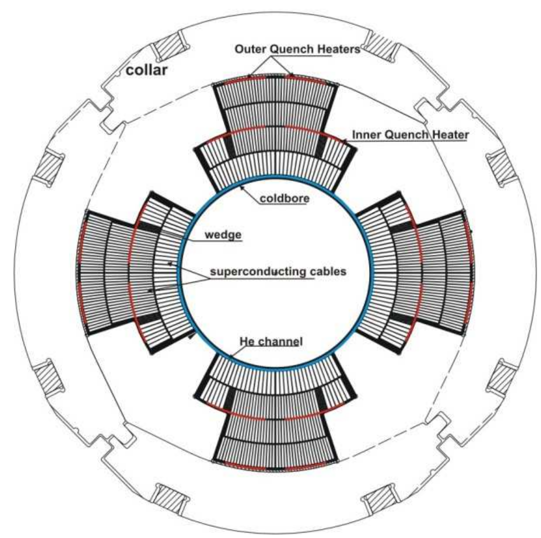
- bath temperature 4.5K

- lower temperature margin (worst case: MQM 0.45K)
- Helium channels does not play dominating role (heat conduction of He I and polyimide is the same order)

MQ – arc magnet, T_b=1.9 K



MQY – LSS magnet, T_b=4.5 K



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    - Model construction
    - Model of the superconducting cable and coils
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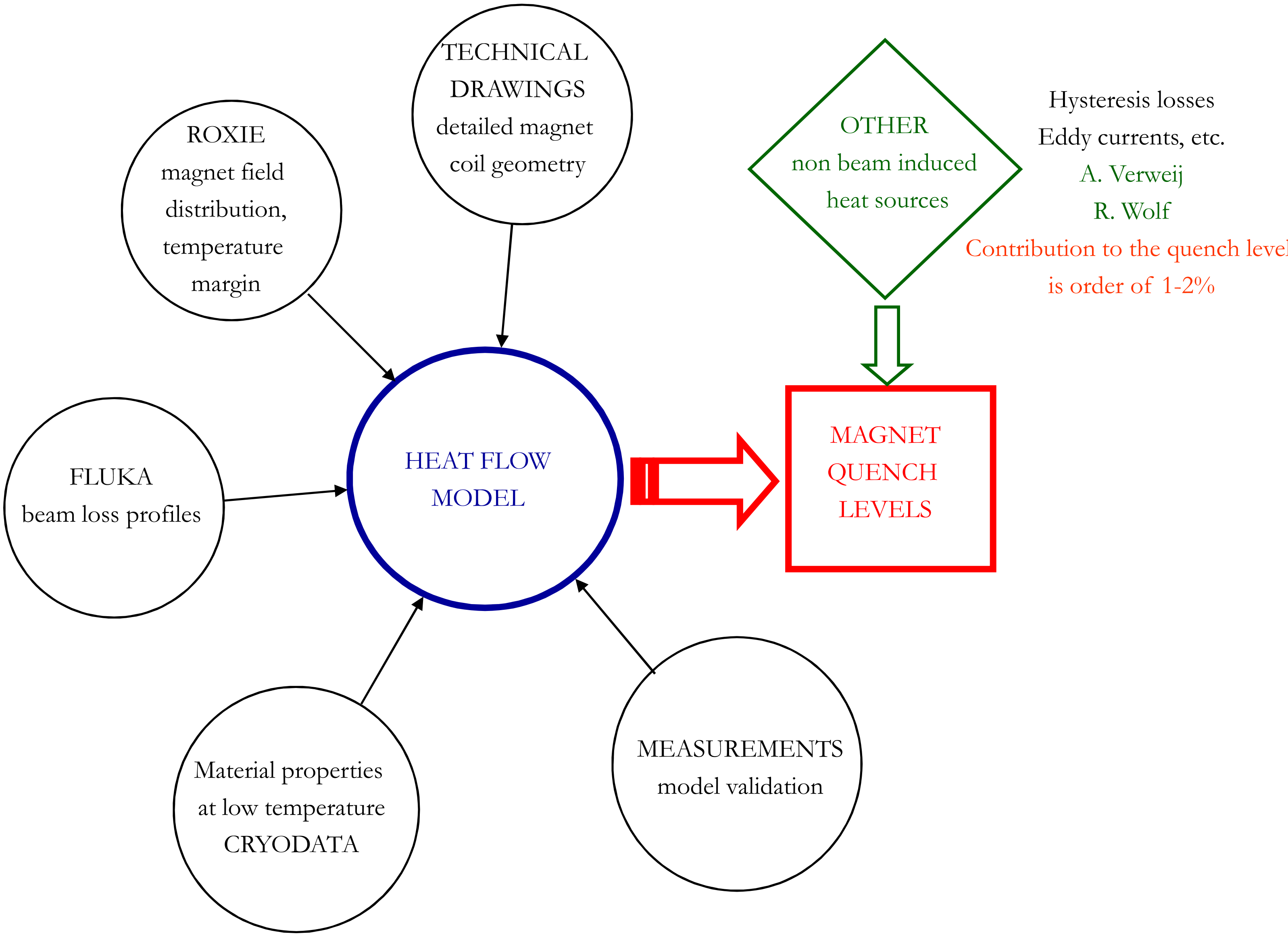
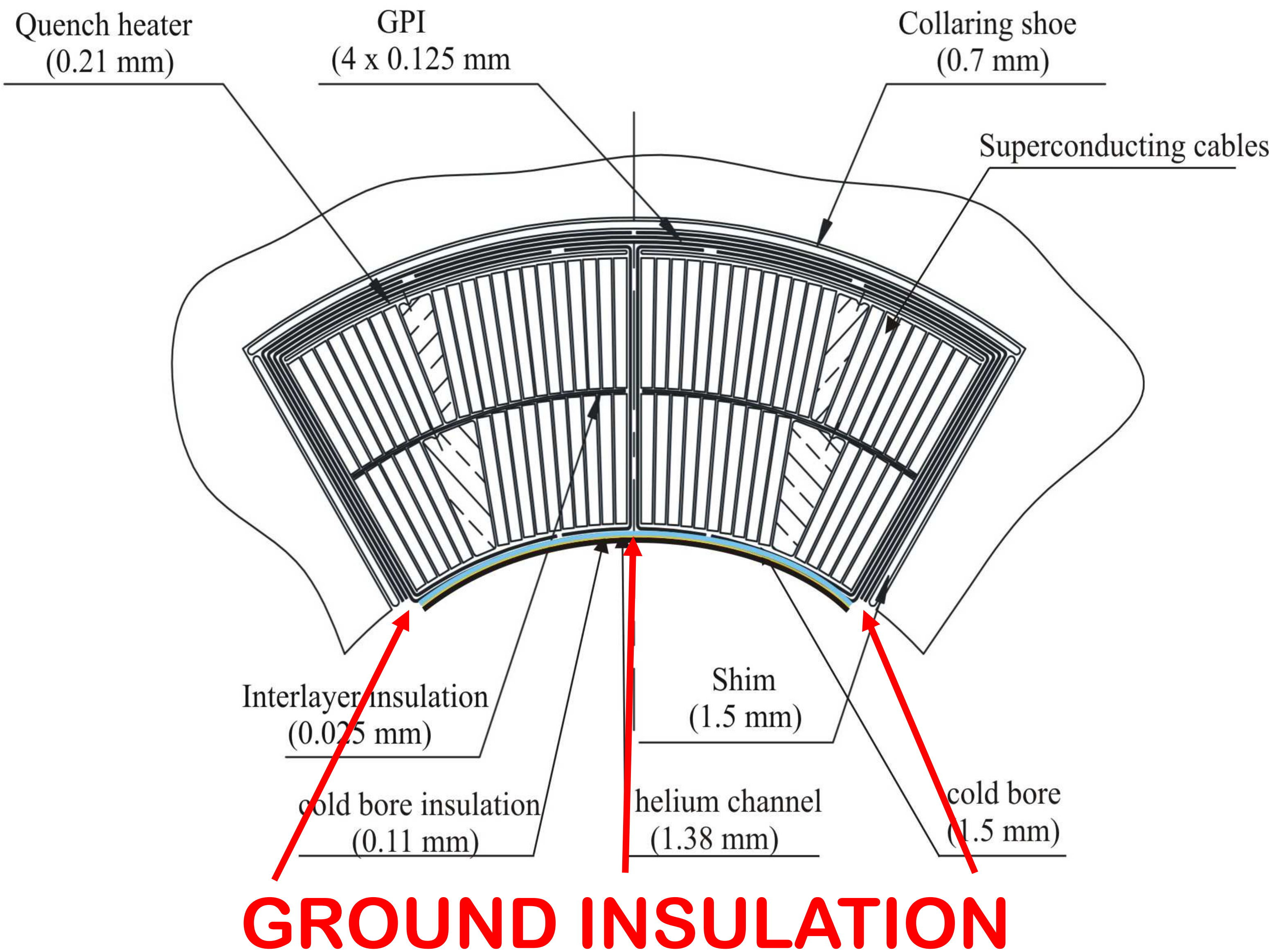
Network Model

Model Construction



Network Model

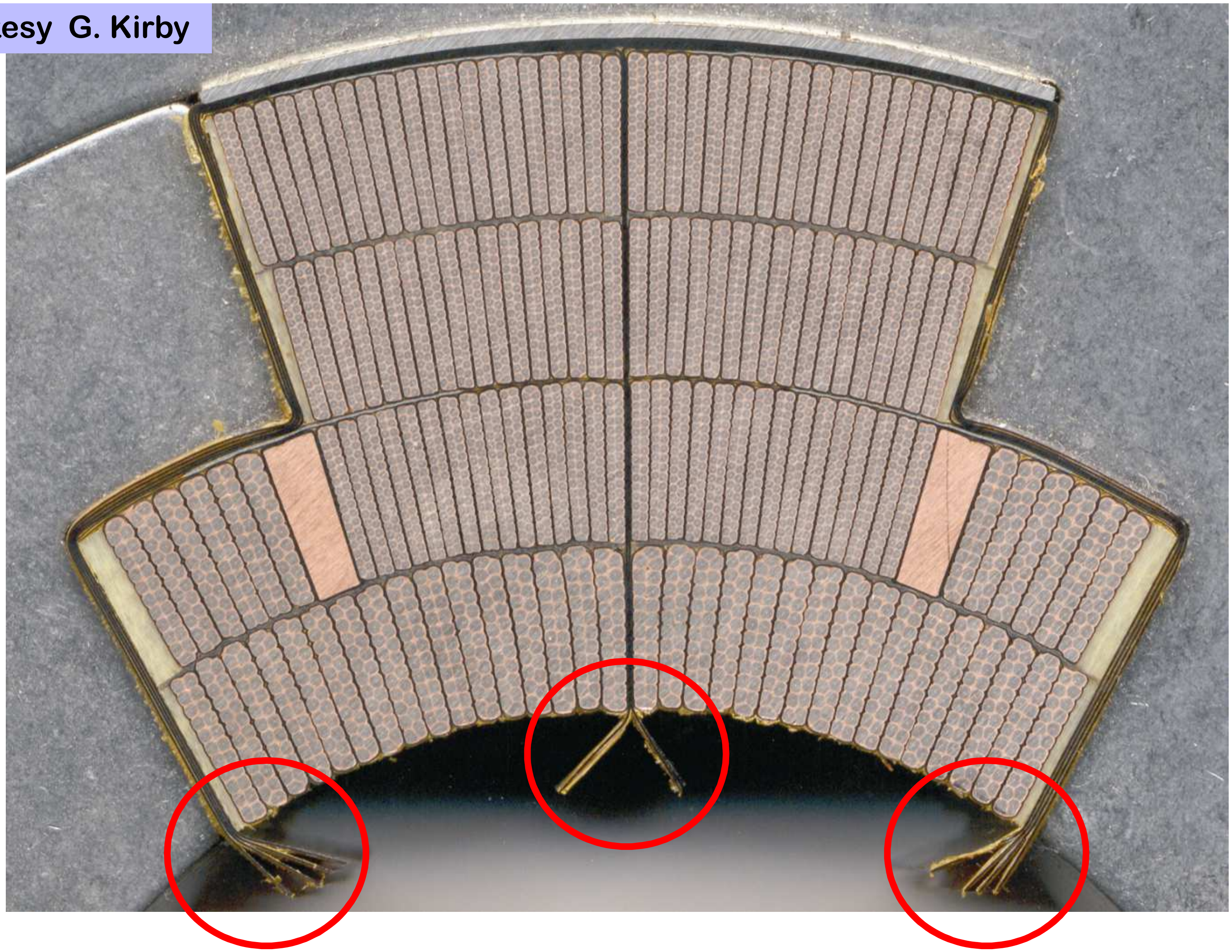
Model Construction



Network Model

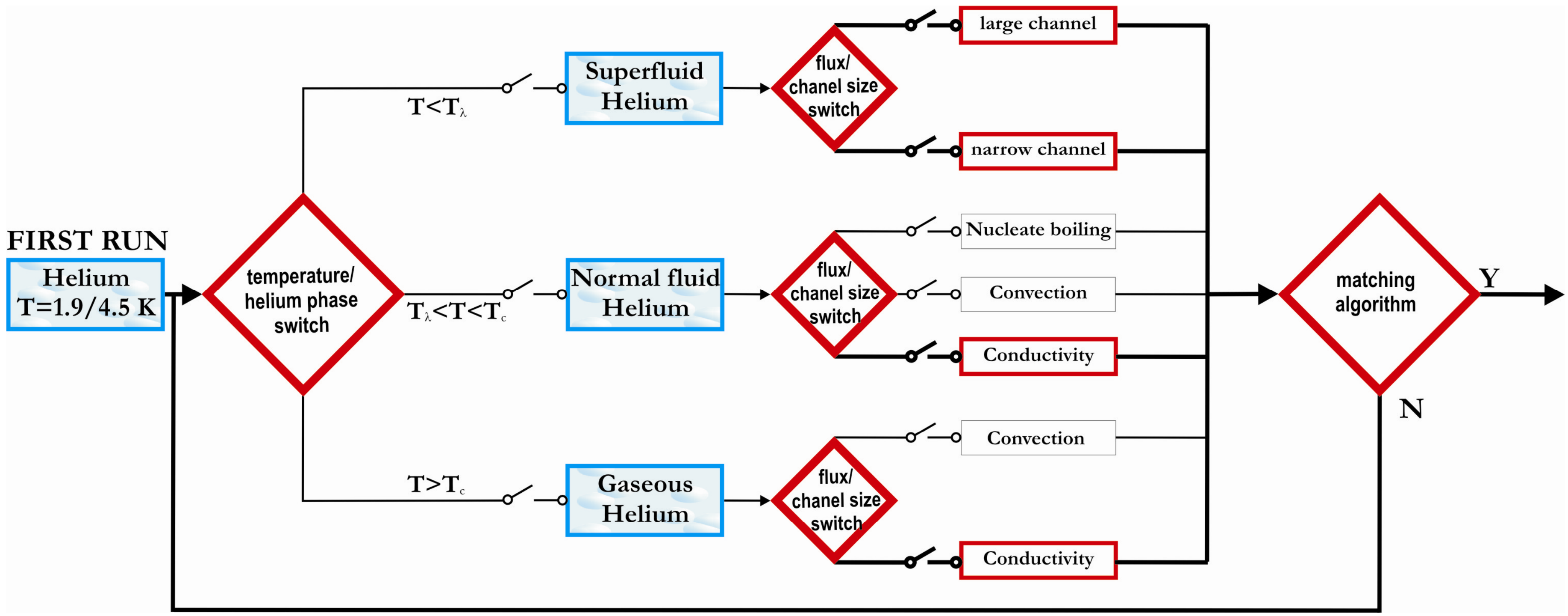
Model Construction

Courtesy G. Kirby



Network Model

Helium in the Network Model



The volumes occupied by helium in the magnet are considered as:

-the narrow channels,

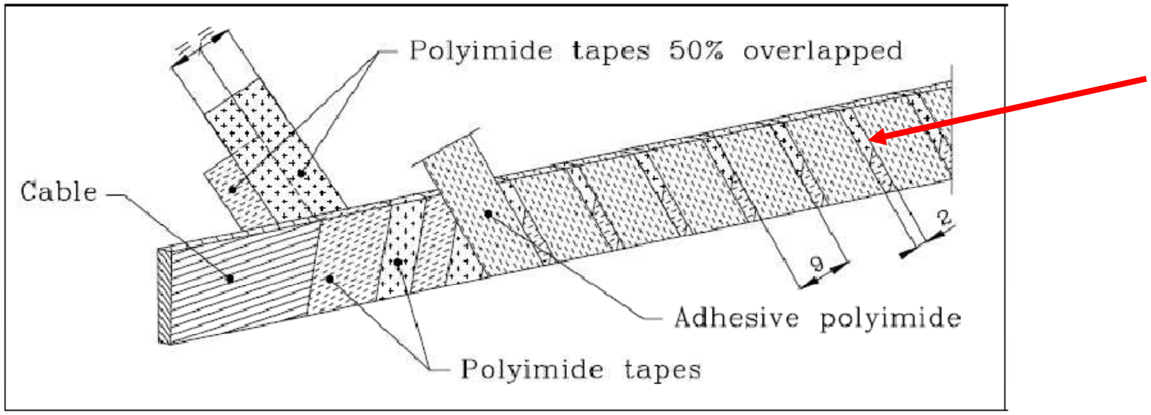
-semi-closed volumes = inefficient inlet of fresh helium.

The steady heat load, heat up the helium in the semi- closed volumes:

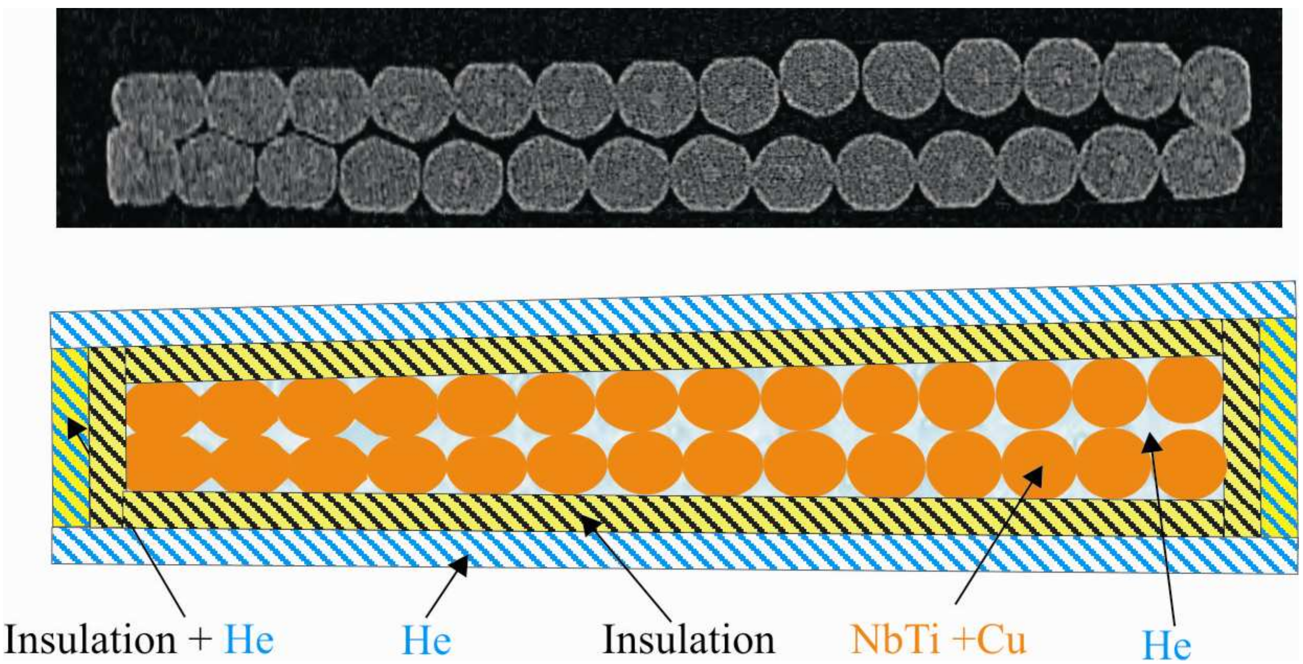
-Helium temperature well above critical temperature at T_b=4.5K

- Critical helium temperature reached already below the calculated quench limit

Network Model
Cable modelling



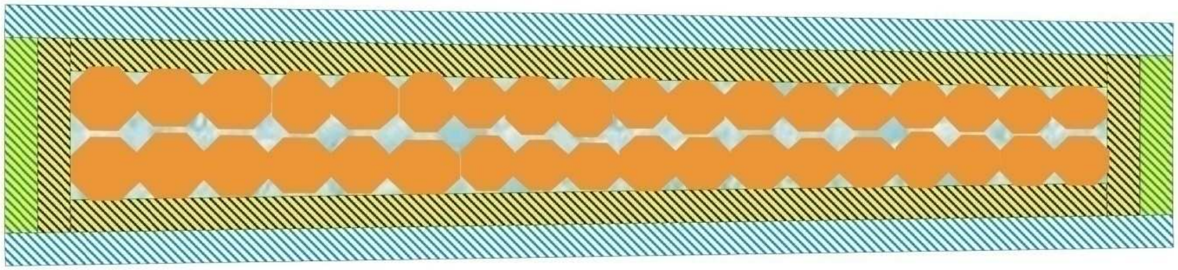
μ-channel

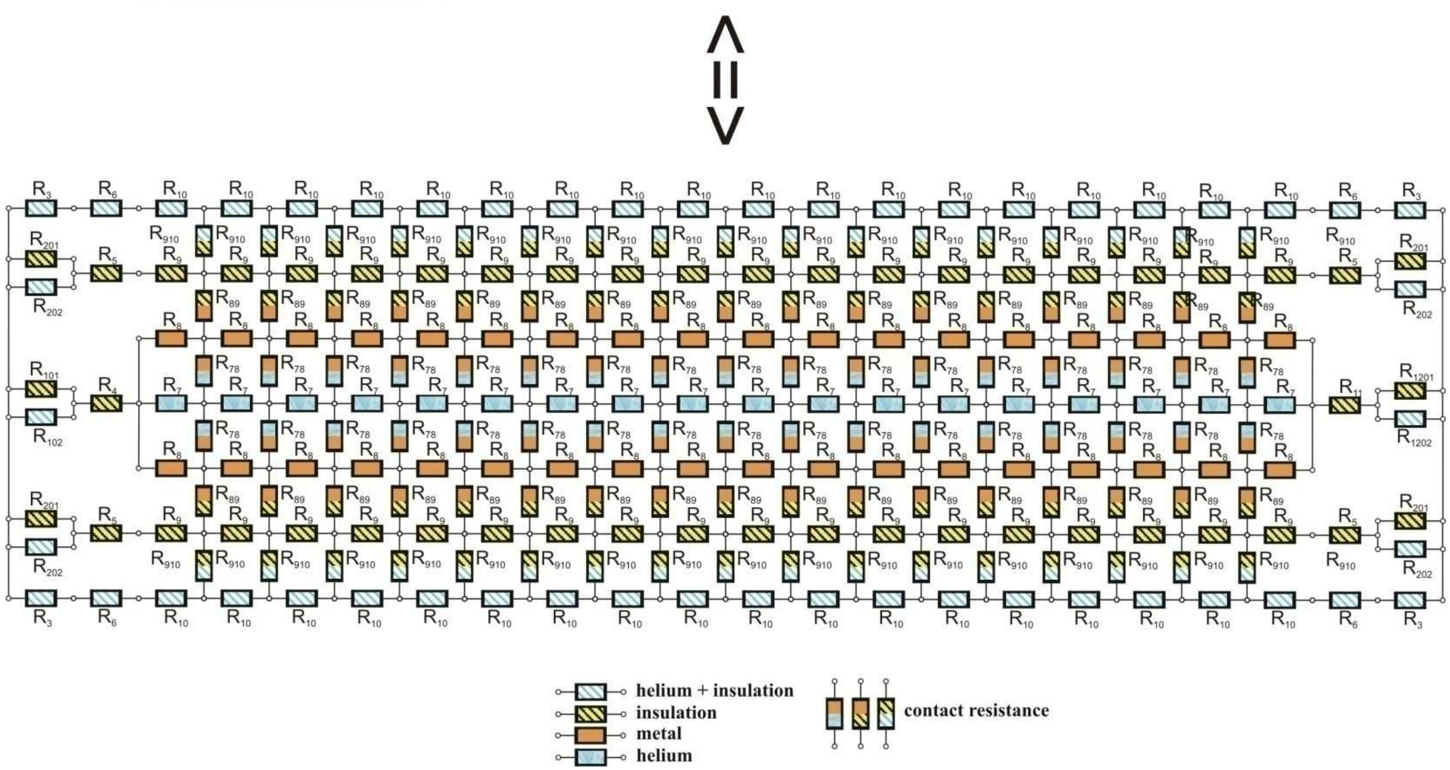


Network Model

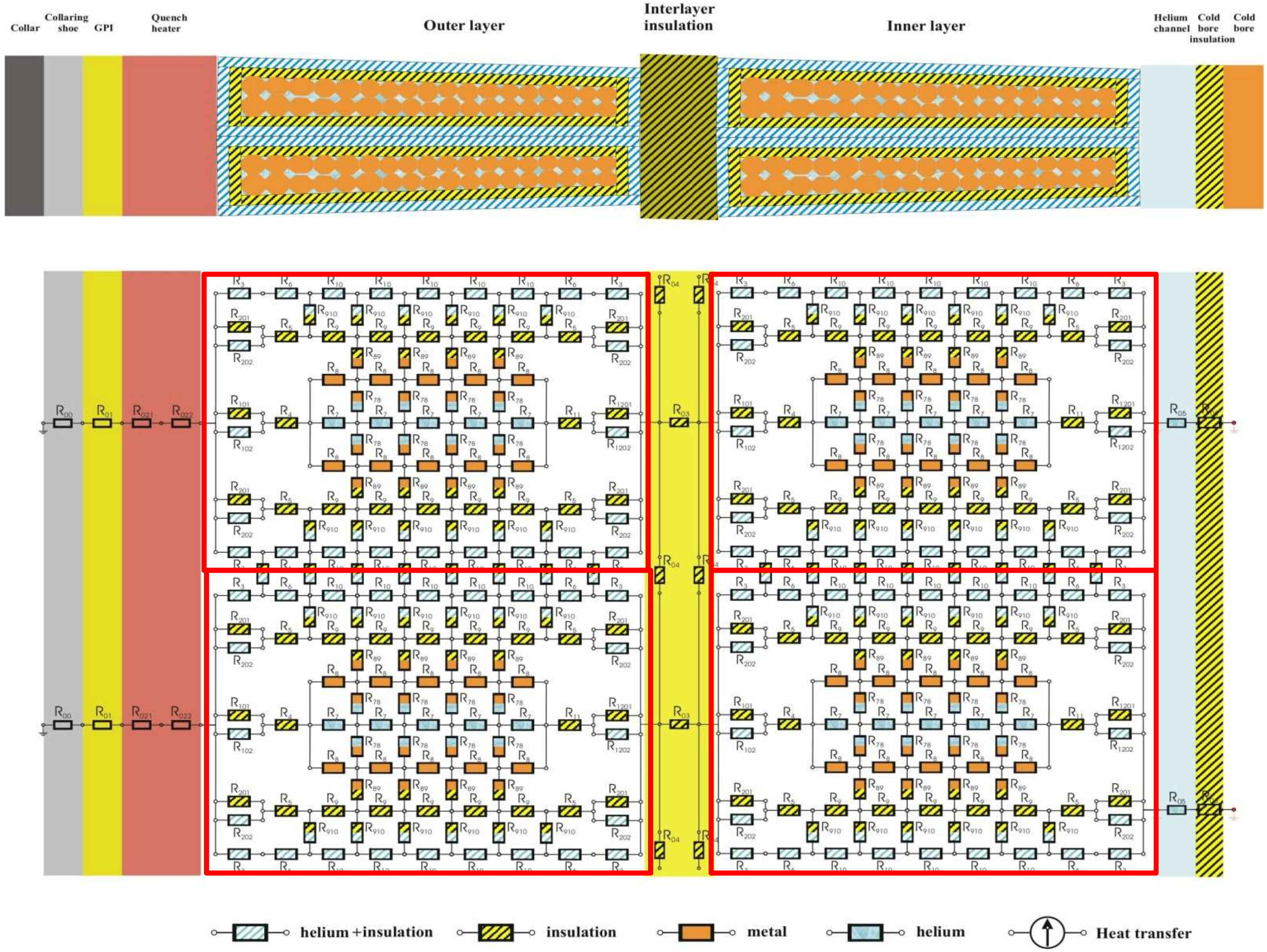
Cable modelling

Network model of the superconducting cable





Network Model
Coil modelling



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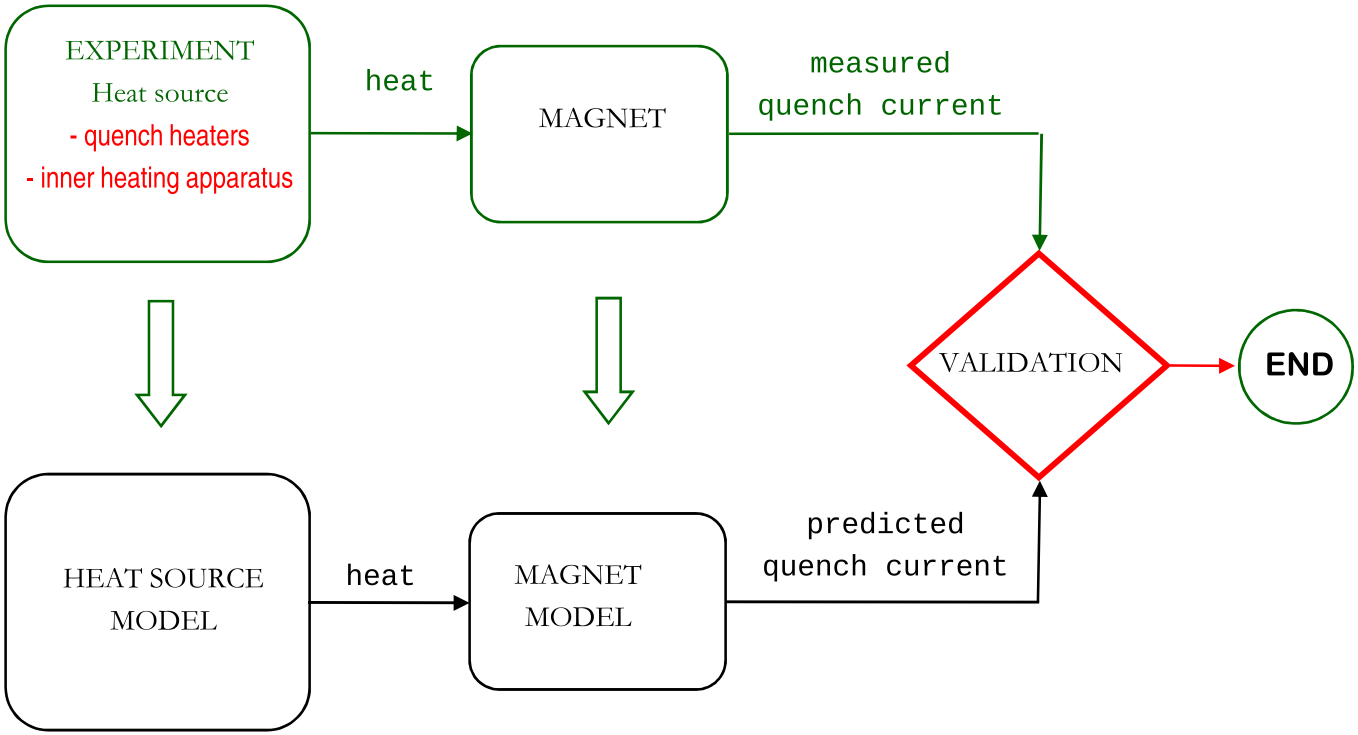
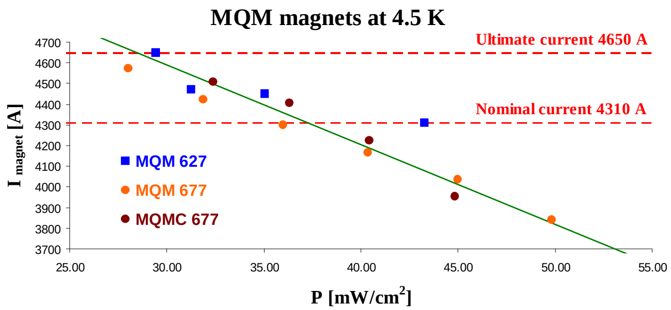
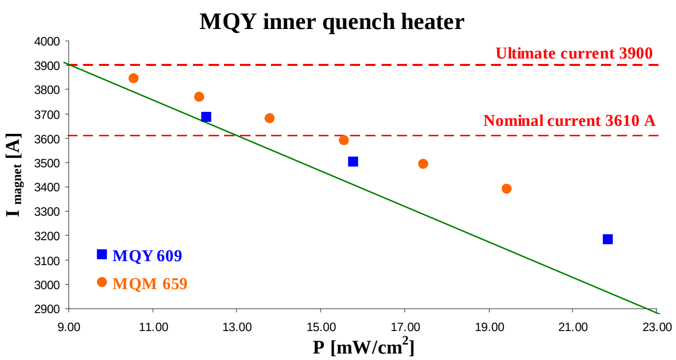
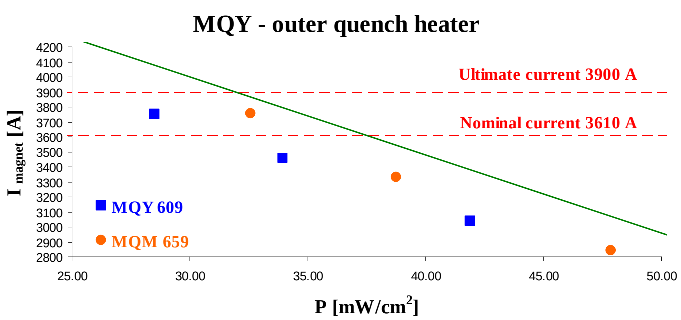
Validation of the Network Model

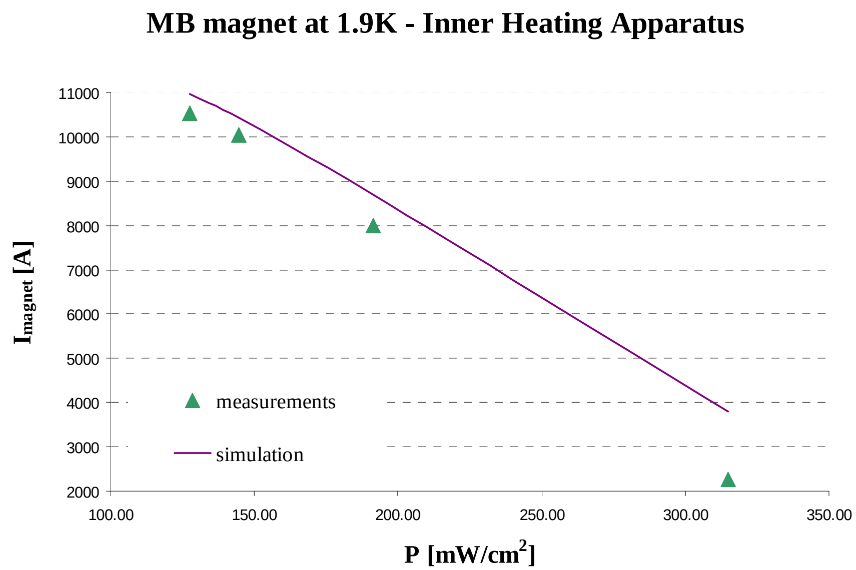


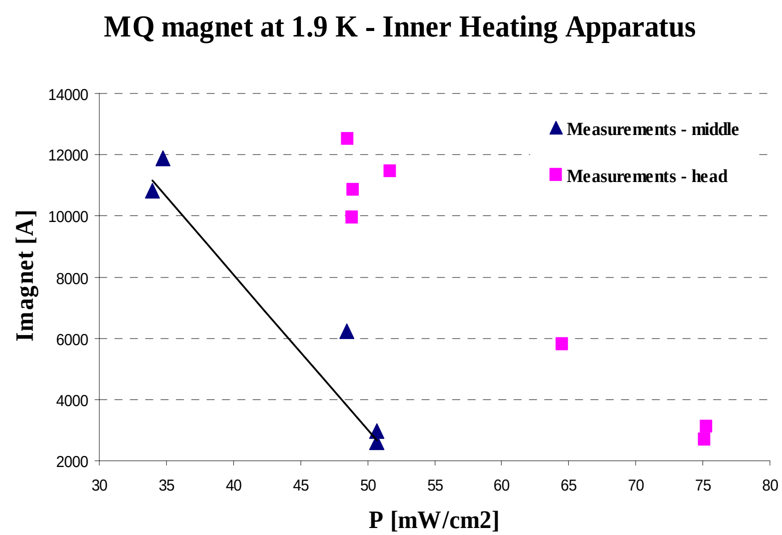
Validation of the model











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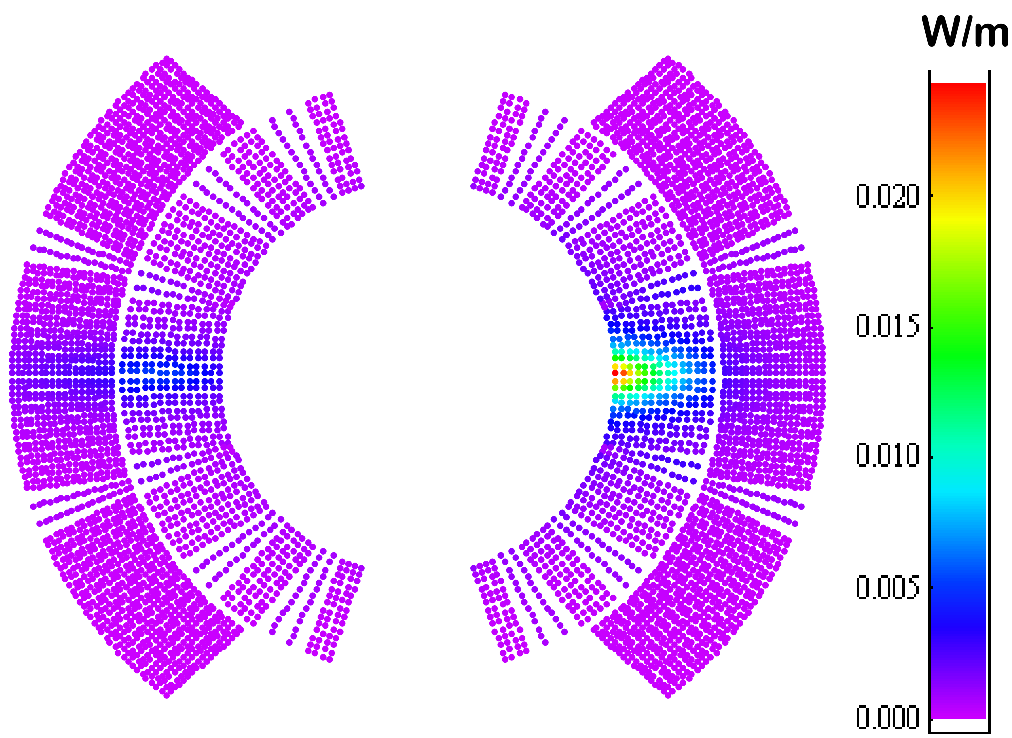
Quench limit simulations

- heat deposition map for nominal LHC ion beam intensity was created by interpolation of FLUKA data to the cable strand coordinates from ROXIE (Roderik)

- heat deposition map was implemented to Network Model

- the magnet current range from injection to ultimate values (761 A to 12840 A, nominal is 11850 A) was scanned by linear scaling of heat deposition map

Heat deposition map in the MB dipole magnet coil



Energy peak in the coil = 24.3 mW/m
Energy peak in the cold bore = 80.3 mW/m

ENERGY PEAK corresponds to the nominal LHC ion beam conditions (optics ver. 6.500)

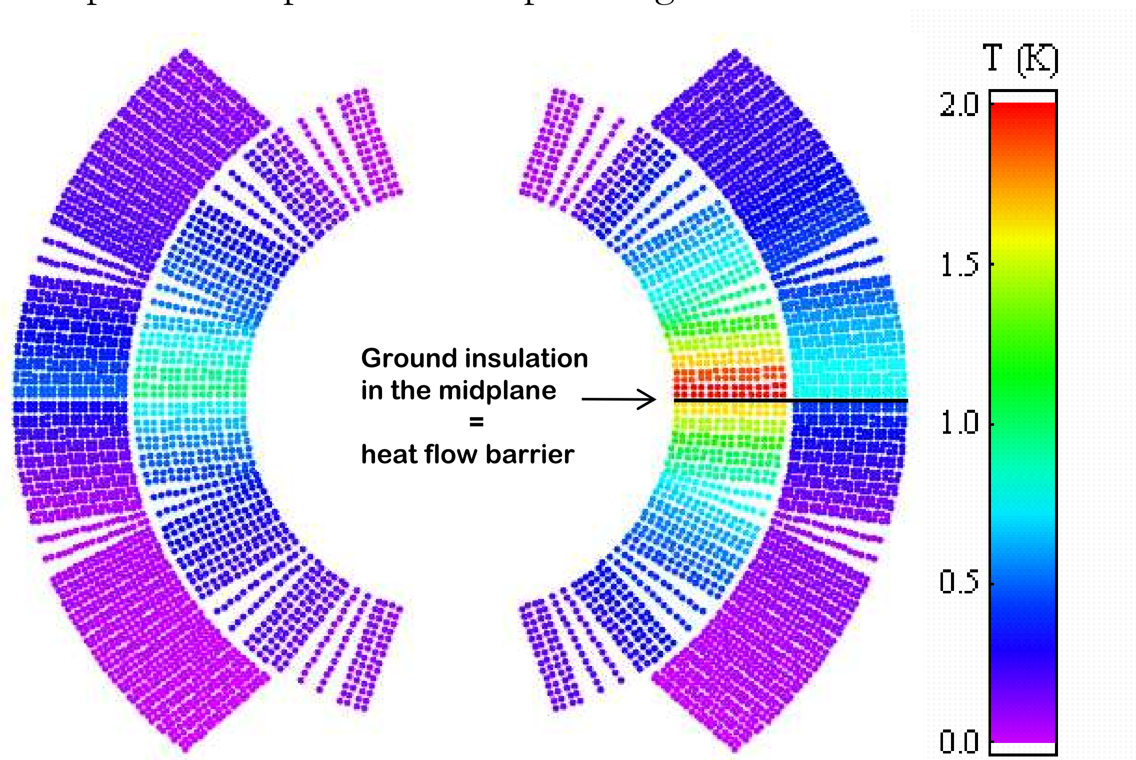
Quench limit simulations

- ➢ temperature distribution for nominal LHC ion beam conditions, corresponding to 95% of loss energy peak in the coil (23.1 mW/m) and 95% loss energy peak in the coldbore (76.3 mW/m)

- ➢ quenching cable is located at the coil mid-plane

- ➢this temperature map corresponds to nominal magnet current (11850 A)

Temperature map in the MB dipole magnet coil after heat load

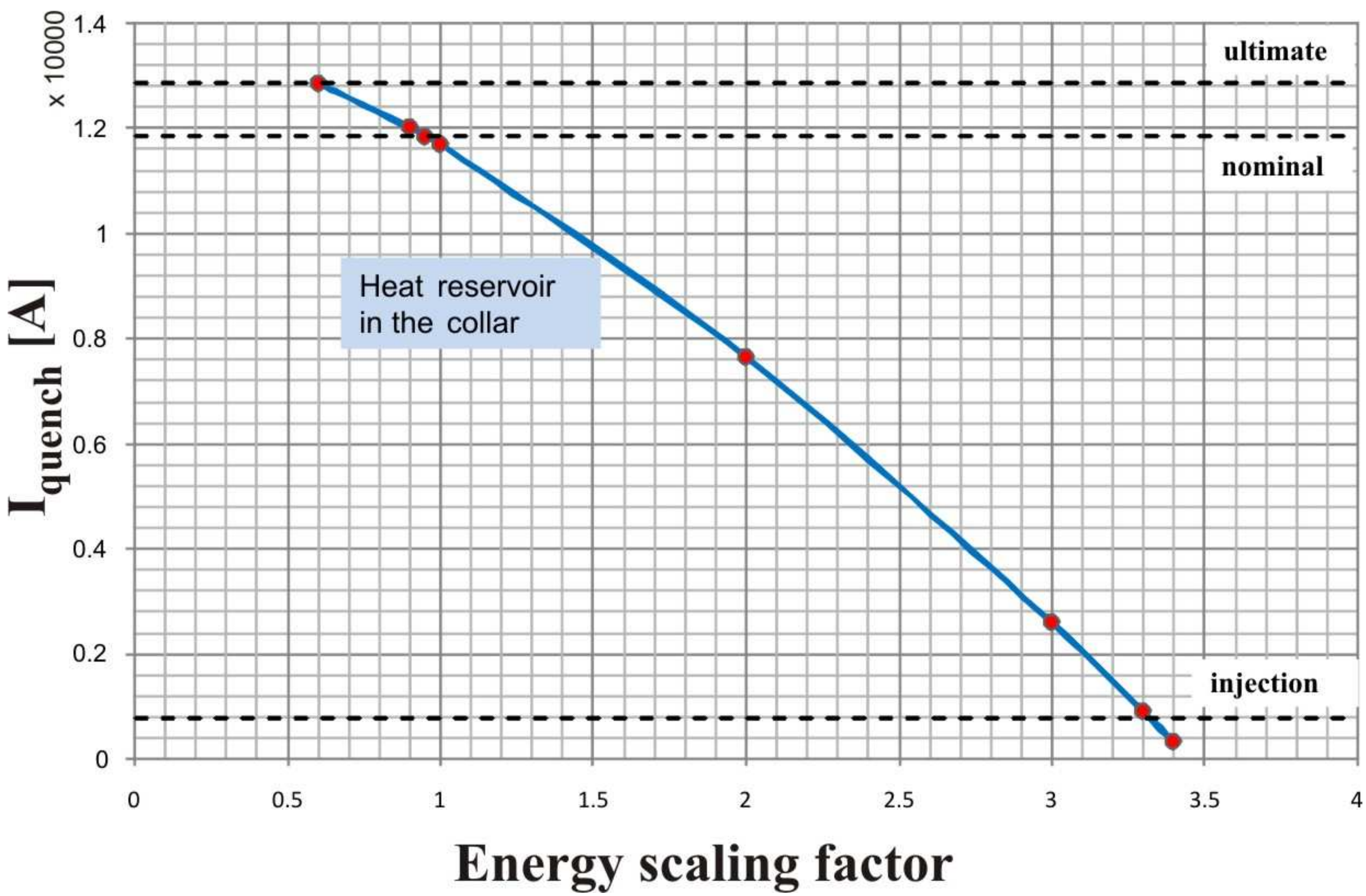


Peak temperature rise in the coil ΔT= 2.0 K
Peak temperature rise in the cold bore ΔT=1.4K

For nominal LHC ion beam conditions (beam optics ver. 6.500)

Quench limit simulations

Energy peak in the coil = 24.3 mW/m and in the cold bore = 80.3 mW/m
ENERGY PEAK corresponds to the nominal LHC ion beam conditions



R. Bruce, D. Bocian, AP Forum

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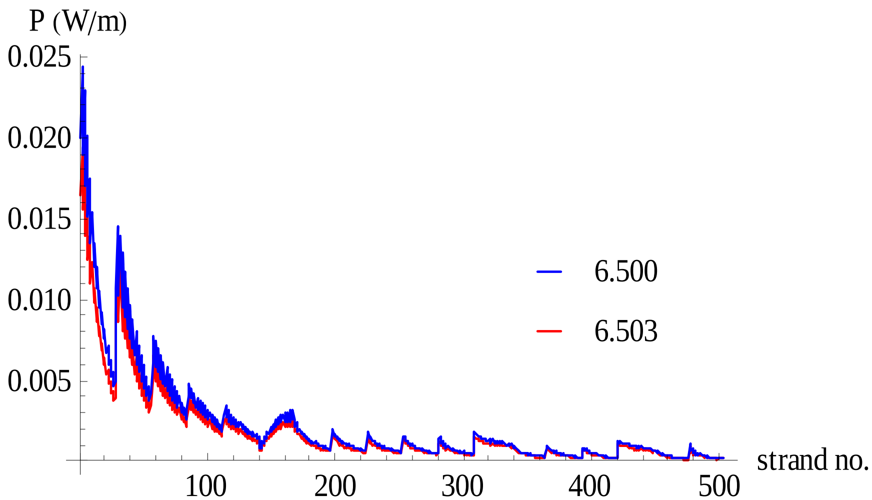
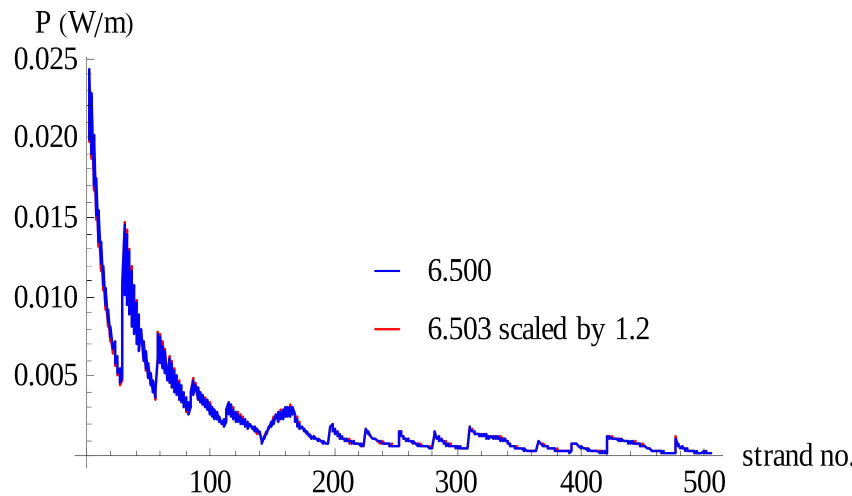
Extrapolation to other cases

- Redone tracking in v6.503, new FLUKA simulation
- Profile of power deposition in coil similar to v6.500 except global scaling factor. Scaling by integrated power:

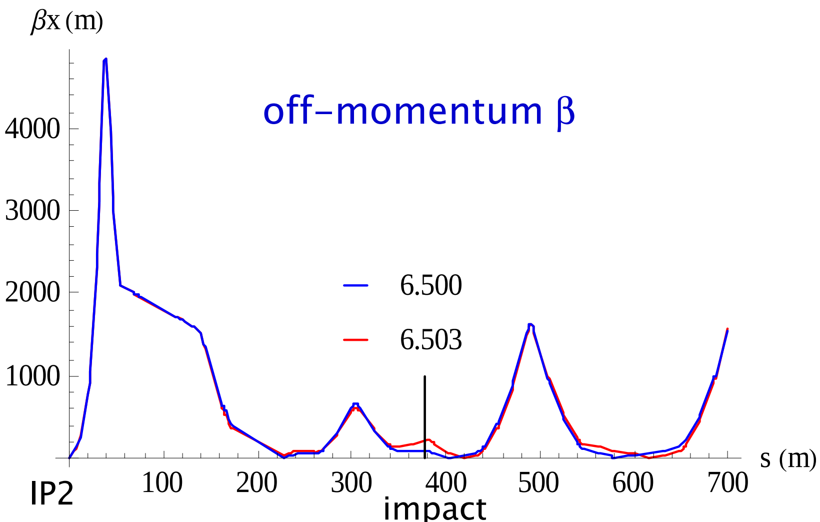


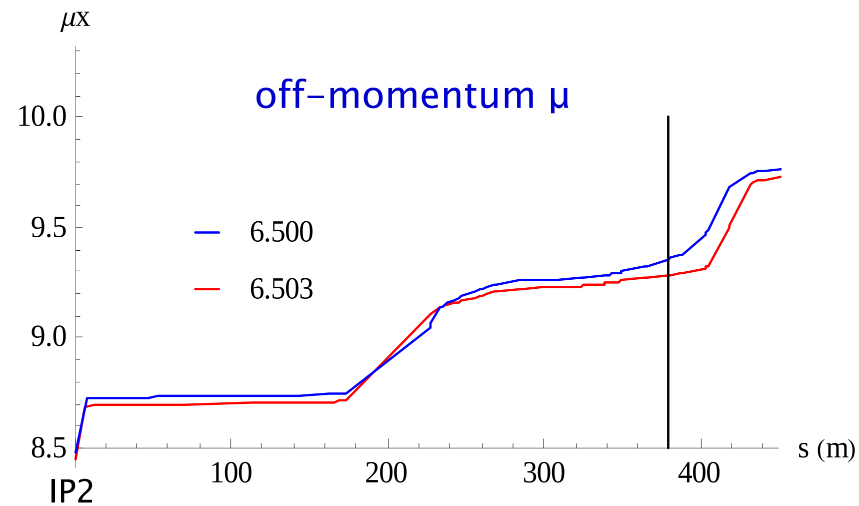


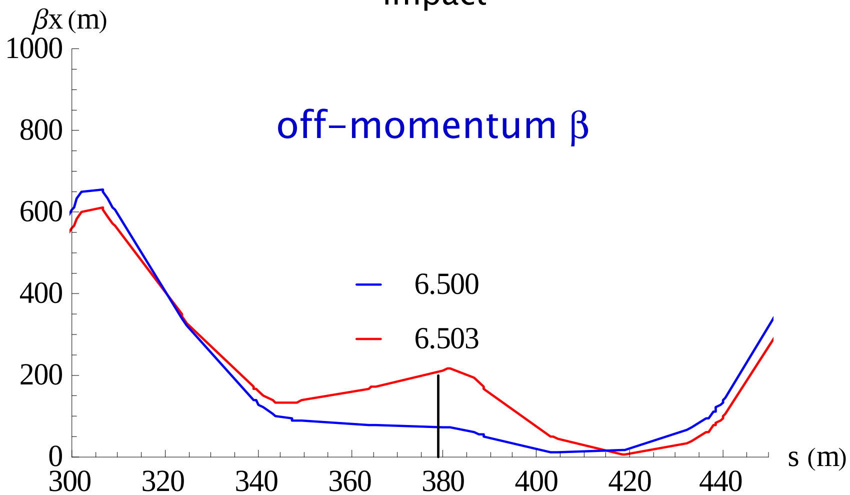
- Gives approximate margin of 15% to quench limit in v6.503
- Question: what has changed ?

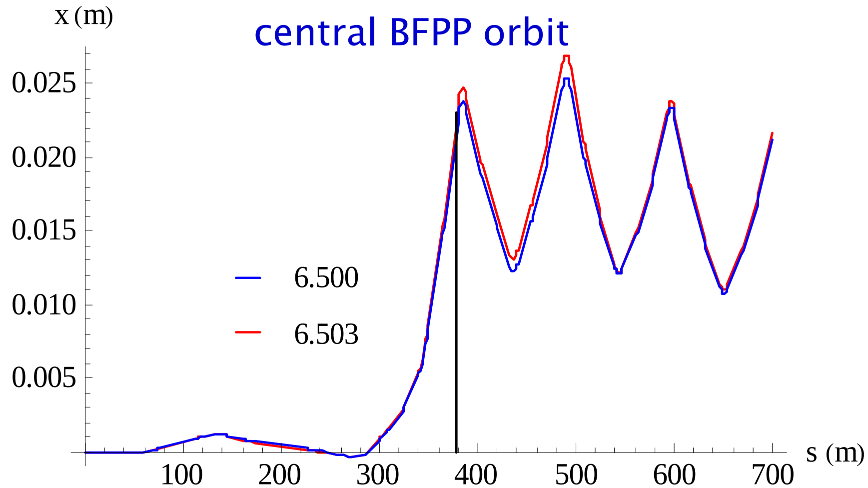
Difference in optics

- **Phase advance after IP2 changed from v6.500 to v6.503**
- **Spot size larger - dependent on off-momentum β (calculated from starting conditions at IP2)**



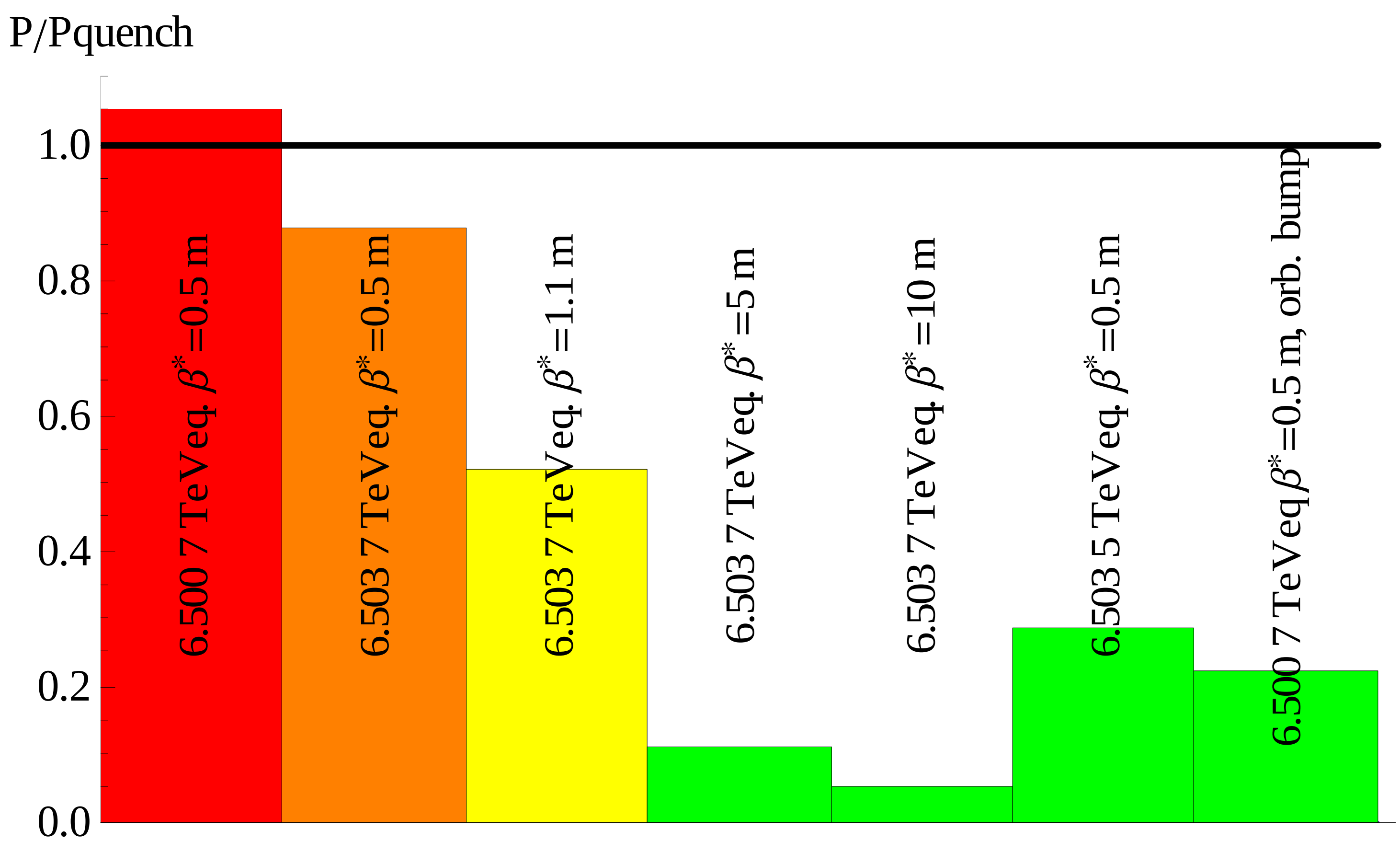






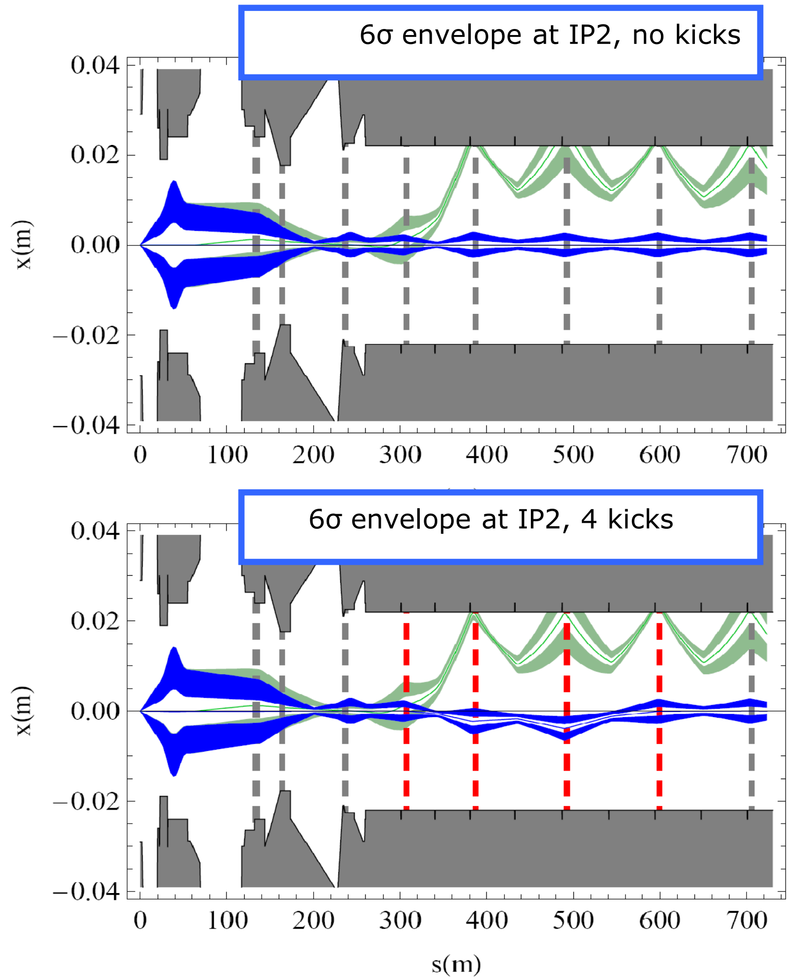
Squeeze, 5 TeV: preliminary result

- **Tracking + FLUKA simulation for different β* and 5 TeV**



Possible alleviation methods

- with orbit bump we could gain >factor 5:
  - possible to introduce orbit bump around BFPP impact
  - particles lost at second dispersion max, with larger off-momentum β
  - nominal orbit shifted by 2-3.8 mm depending on optics
- cold collimators *(R.W. Assmann et al)*:
  - could be installed at a later stage around IPs taking ion collisions
- at 5 TeV we gain a factor 3.5:
  - lower field gives higher quench limit
  - lower energy per BFPP particle
  - larger geometric emittance gives larger spot size
  - cross section only weakly energy dependent
- Increase of β*: not desired



Simulation uncertainties

- **BFPP cross section: ~20%**
- **Changes in the optics (e.g. beta beating) could change the spot size: ~10%**
- **Network model: ~ 30%.**
- **On top of this, uncertainty on the energy deposition from the FLUKA simulation, could in worst case be a factor 2. Dominating uncertainty for this specific beam loss but could be less in other cases.**

Outline

- Background and introduction: Bound Free Pair Production
- Tracking: Distribution at the IP and at impact
- FLUKA simulation of shower in magnet
- Thermal network simulation (Dariusz)
  - Thermodynamics of magnet structure
  - Network model
  - Validation of the model
  - Steady state beam loss heat load simulation
- Comparison between optics version
- Simulation uncertainties
- Summary

Summary

- To make a detailed calculation of the quench limit for a main dipole due to a specific beam loss mechanism (BFPP during LHC Pb^{82+} ion operation), we have combined
  - particle tracking,
  - a FLUKA shower simulation of the heat load in a single magnet and
  - a thermal network simulation of the heat flow in the magnet
- BFPP creates one-electron Pb^{81+} ions at the IP, which follow an off-momentum orbit and are lost in the dispersion suppressor in the case of IP2.
- At nominal performance, the estimated heat load is expected to be very close to, and possibly above, the quench limit.
- For this loss distribution, the quench limit is a factor ~2 higher than calculated in LHC report 44 and LHC design report
- Possible alleviation methods include orbit bumps and cold collimators

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