Chasing Parasitic Magnetic Fields Around the LHC

presented by
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Preamble (1/2)

- There is a long history of unforeseen and/or underestimated magnetic effects impeding machine commissioning
  - stray fields from the Main Ring located on top of the Tevatron ring during Tevatron commissioning (early 1980’s),
  - permanent magnetization of the Ni layer electro-deposited on LEP Al beam pipe during LEP commissioning (1989),
  - stray fields from the Main Injector located underneath the Recycler Ring at the beginning of Collider Run II at Fermilab (late 1990’s).
- Following up on issues raised during the Jan. 05 Magnet Test Review at CERN, the Field Quality Working Group launched in Febr. 05 an effort aimed at inventorying potential sources of parasitic magnetic fields and at evaluating their impacts on beam dynamics.

Preamble (2/2)

- The effort is ongoing and involves many contributors from various Groups who have done the hard work and who have been kind enough to share their results with me (I will try to give rightful credits as I go along).
- At present, three issues have been or are being investigated
  - beam screen effects,
  - superconducting-to-resistive transition of PbSb shields in connection cryostats,
  - stray fields generated by bus bars in magnet interconnects.
- The above list is not exhaustive and will be completed.

Contents

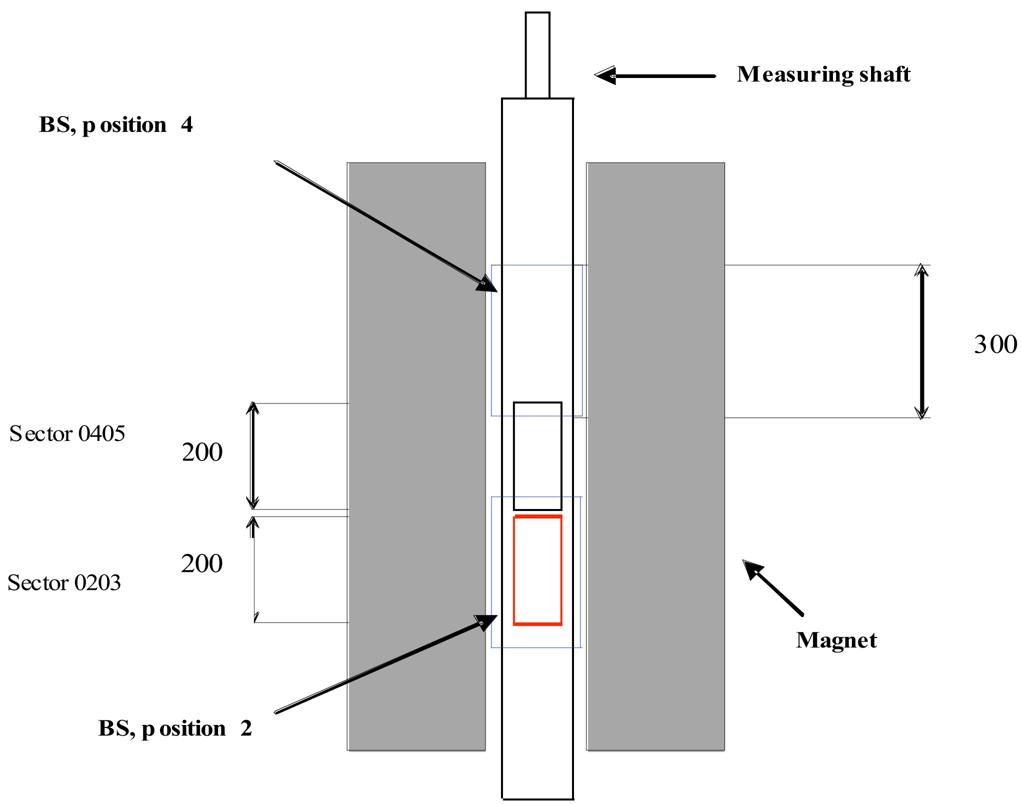
- **Beam screen effects**
- PbSb shields in connection cryostats
- Busbars in magnet interconnects

Contributors

- N. Kos (AT/VAC)
- B. Auchmann, S. Russenschuck, R. Wolf (AT/MEL)
- W. Venturini-Delsolaro (AT/MTM)
- E. Todesco (AT/MAS)

Measurement Setup

- A new set of magnetic measurements has been carried out in June 05, with and w/o beam screen, in one aperture of the MFISC model magnet.

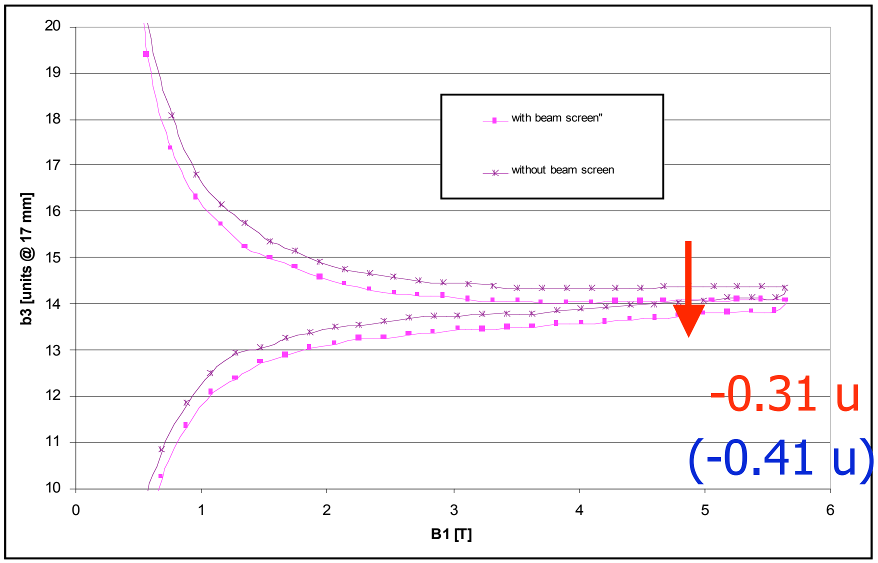


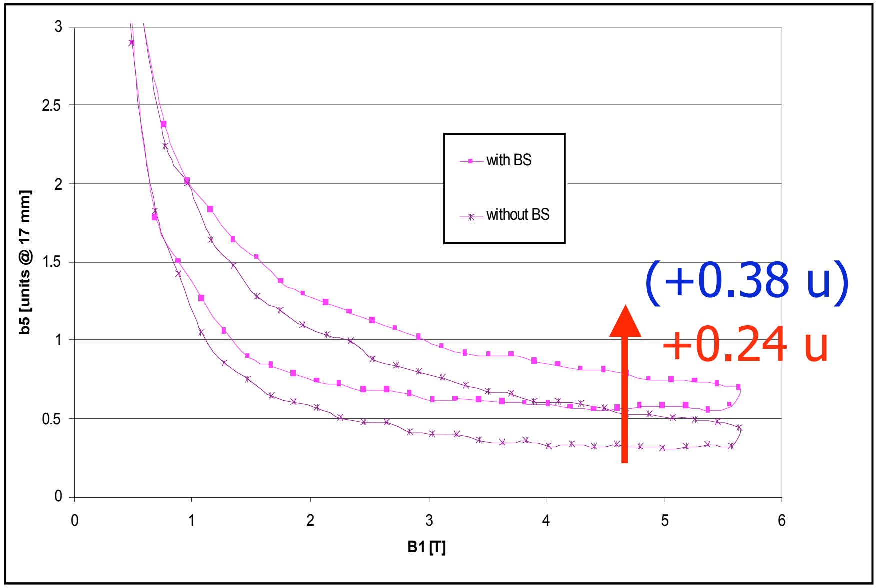
(Courtesy W. Venturini)

- The beam screen sample was 300 mm long, while the rotating coil was 200 mm long.
- Due to large interstrand coupling currents in the MFISC coils, the measurements were taken “on the fly” (at 10 A/s).

Measurement Results (1/2)

- There appear systematic shifts of the allowed multipole coefficients, but the measured offsets are about 2/3rd of the computed ones.



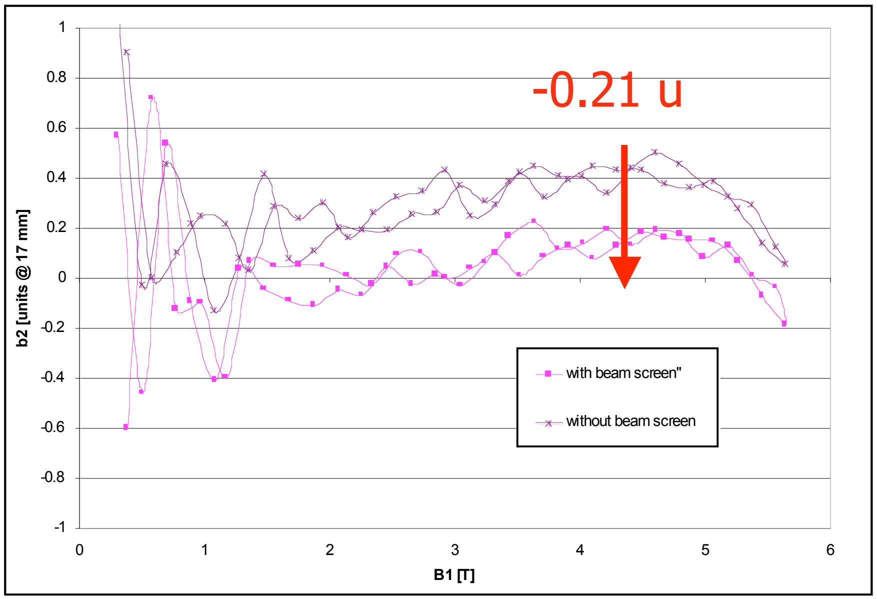


Measured hystereses of allowed multipole coefficients
(Courtesy W. Venturini)

- Such effect can be explained by an horizontal misalignment of the beam screen of ~1 mm.

Measurement Results (2/2)

- There also appear systematic shifts of some un-allowed multipole coefficients, such as a_2 and b_2.



Measured normal quadrupole coefficient (Courtesy W. Venturini)

- Given the amplitude of b_3 (14 u), a ~0.1-mm error in the centering correction feeds down quadrupole terms of ~0.16 u.
- Such an error could result from the 22-pole perturbation introduced by the beam screen

$$\Delta x + i\Delta y \approx \frac{R_{\mathrm{ref}}}{10} \frac{b_{10} + ia_{10}}{b_{11,\mathrm{magnet}} + b_{11,\mathrm{beam\ screen}}}$$

~1 u ~0.2 u

Future Work & Preliminary Conclusions

- A preliminary re-processing of the data (with elimination of the centering correction) already shows a large reduction in the shifts of the quadrupole coefficients.
- A more thorough re-analysis is required to confirm the proposed explanations for the discrepancies between measured and computed effects, but we seem on the right track.
- The present data enable us to verify that the eddy currents generated in the chamber are negligible (as foreseen from computations).
- Let us note the sensitivity to transverse alignment: in practice, the beam screen positioning is controlled within +/- 0.5 mm and this can reduce the expected b_3-, b_5- and b_7- shifts by up to ~0.05 units.

Contents

- Beam screen effects
- **PbSb shields in connection cryostats**
- Busbars in magnet interconnects

Contributors

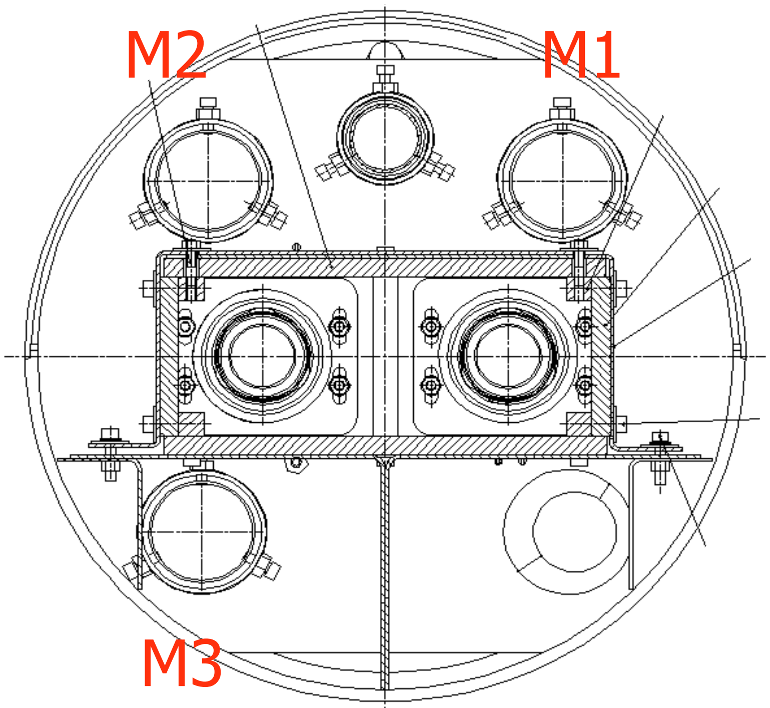
- T. Colombet, A. Poncet, S. Marque (AT/CRI)
- B. Auchmann, R. Wolf (AT/MEL)
- L. Oberli, Z. Charifoulline, J.P. Koutchouk (AT/MAS)
- P. Lebrun (AT)
- M. Jewell (University of Wisconsin at Madison)

+ MTM staff who performed cold test of first connection cryostat at SM18 in Aug. 05.

Connection Cryostat Overview (1/4)

- The connection cryostats fill the gaps near Q11 at the extremities of the Dispersion Suppressors; they come in two lengths (11.7 m and 12.6 m) and are 16 in total.
- They do not house any magnet but are traversed by the two beam pipes and by the superconducting bus bars supplying the dipole, quadrupole and corrector magnets of the arcs.

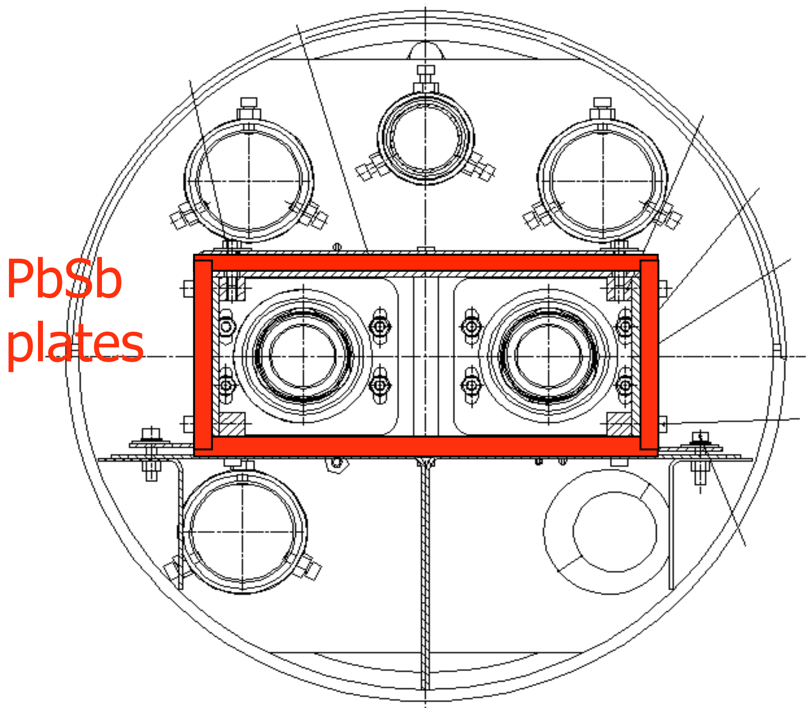
Connection Cryostat Overview (2/4)



Cross-sectional view
of connection cryostat
(Courtesy T. Colombet)

- The bus bars are implemented in the M1, M2 and M3 cryogenics lines and are cooled down to 1.9 K.
- The cold mass is completed by a welded, stainless steel, outer shell similar to the one implemented in the arc dipole magnets, that is thermally linked by a braid to the M2 line.

Connection Cryostat Overview (3/4)



Cross-sectional view
of connection cryostat
(Courtesy T. Colombet)

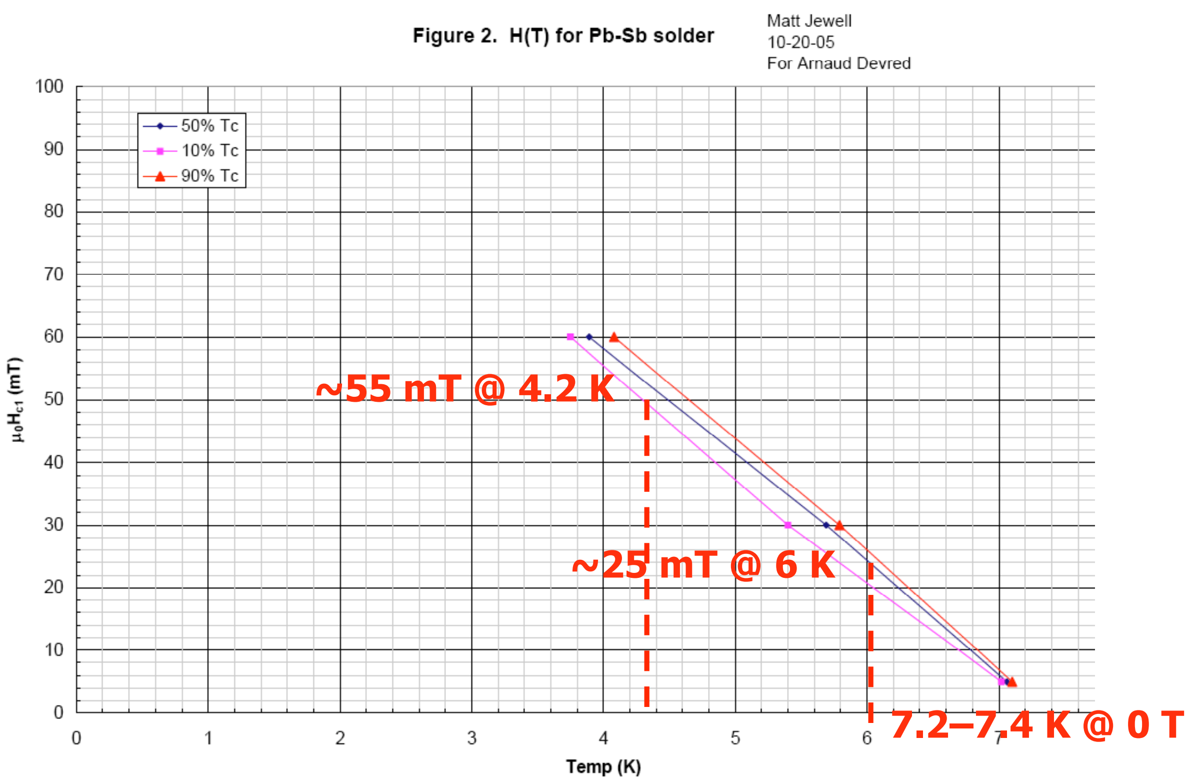
- Upon TIS request, radiation shields are implemented around the beam pipes.
- To minimize size and weight, the shields are made up of 15-mm-thick Pb–4wt%Sb plates assembled so as to form rectangular blocks, which are 1.2 m long and weigh 170 kg; there are up to 10 blocks in a cryostat.
- Each box is thermally connected to the shell (by its support) and is linked by a braid to the M2 line.

Connection Cryostat Overview (4/4)

- At present, eight pseudo cold masses have been completed and two of these cold masses have been cryostated.
- The first connection cryostat was tested at SM18 in August 05.
- The manufacturing has been put on hold since mid November 05.

Superconducting Properties of PbSb

- At the time of the first connection cryostat coldtest, A. Siemko (AT/MTM) recalled that the PbSb alloy used for the shielding might become superconducting at low temperatures.

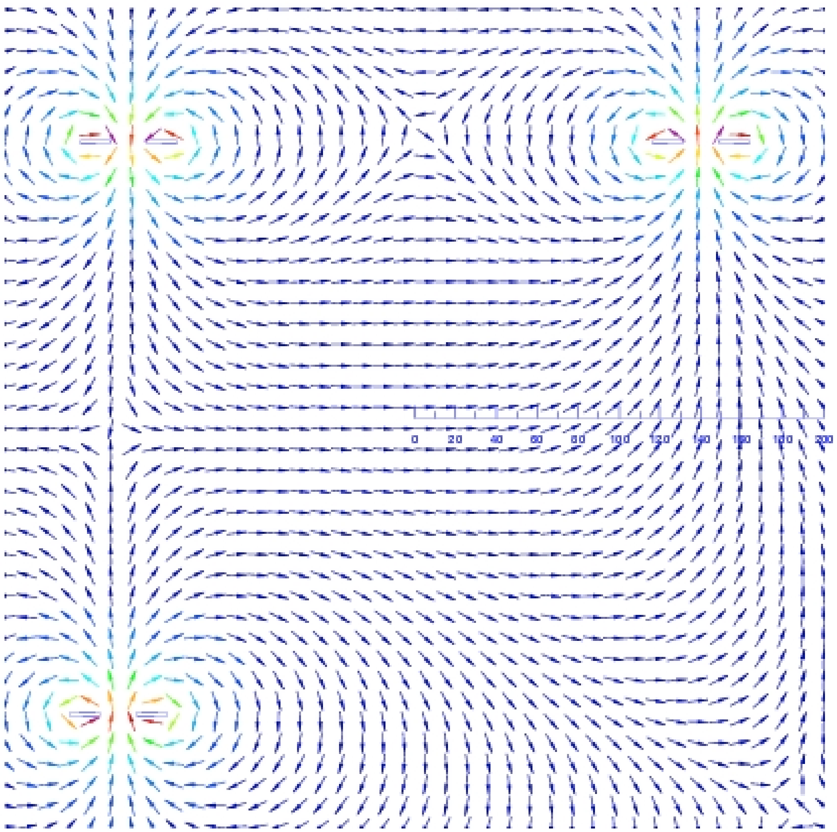


Results of SQUID magnetometer measurements
(Courtesy M. Jewell)

- This suspicion was soon after verified by Z. Charifoulline (AT/MAS) and PbSb samples were sent to M. Jewell (University of Wisconsin at Madison) for a more comprehensive characterization.

Influence of Bus Bars’ Stray Field

- Hence, if the thermalization temperature of the PbSb blocks is below 7.2-7-4 K, they are likely to be superconducting at the end of cooldown.



Map of stray field generated by bus bars
(Courtesy B. Auchmann)

- Then, the next question is: what happens when they are subjected to the stray field generated by the bus bars.
- According to a ROXIE computation, the maximum amplitude of the stray field on the PbSb blocks is

  ~1.6 mT at injection,

  ~25 mT at collision.

Possible Quench Scenario

- Given the ($\mu_0 H_{C2}$) vs. T_C data of PbSb, a stray field of 25 mT is likely to quench the PbSb blocks whenever their temperature exceeds ~6 K.
- As a result, a possible scenario could be
  - at the end of cooldown, the blocks achieve a temperature below the PbSb T_C at 0 T and become superconducting,
  - at the beginning of current ramping in the bus bars, the PbSb blocks remain superconducting and magnetically shield the beam pipes from the bus bars' stray field,
  - this magnetic shielding lasts until the stray field on the lead blocks exceeds their critical field at the given temperature and causes the blocks to quench,
  - at the time of quench, the stray field quasi-instantaneously penetrates in the beam pipe resulting in a sudden kick.

Effect of a PbSb Blocks' Quench

- In the previous scenario, the kick generated by a quenching of a connection cryostat while the main bus bars are supplied by I is

$$\theta_{\text{kick}} = \frac{\left|0 - B_{\text{busbars}}(I)\right| L_{\text{cryostat}}}{B_{\text{dip}}(I)\ \rho_{\text{LHC}}} \approx 2.5\ \mu\text{rad}$$

- The resulting orbit deviation in an arc quadrupole is

$$x_1 = \sqrt{\beta_{\text{max,quad}}}\sqrt{\beta_{\text{av,cryostat}}}\ \theta_{\text{kick}} \approx\ 0.4\ \text{mm per cryostat}$$

- Assuming a quadratic sum of the perturbations among the 16 cryostats, the global trajectory deviation is

$$\hat{x} = \sqrt{16}\ x_1 \approx\ 1.6\ \text{mm} \approx 1.3\ \sigma$$

which is not acceptable compared to the collimation requirement of 0.25 σ (at nominal beam current).

Other Scenarios

- More unfavorable scenarios have been envisioned.

- For instance, let us start from a state where the PbSb blocks are normal and let us assume that they are cooled down to the superconducting state while still under a high stray field.

- Then, this stray field may get trapped and remain trapped until a subsequent quench (caused either by external heating or by flux jump).

- The worst-case scenario is when the field trapping occurs at $I_{\text{collision}}$ and the cleansing quench occurs at $I_{\text{injection}}$; then

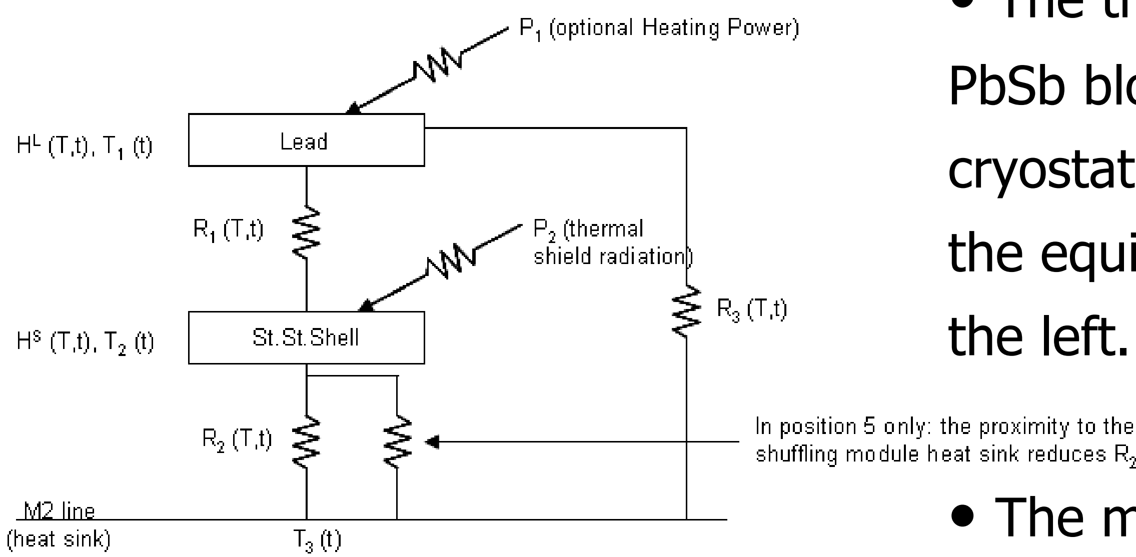
$$\theta_{\text{kick,worst case}} = \frac{\left| B_{\text{busbars}}(I_{\text{injection}}) - B_{\text{busbars}}(I_{\text{collision}}) \right| L_{\text{cryostat}}}{B_{\text{dip}}\left(I_{\text{injection}}\right) \rho_{\text{LHC}}} \approx 35\ \mu\text{rad}$$

and

$$\hat{x}_{\text{worst case}} \approx 21\ \text{mm} \approx 17\ \sigma$$

Thermal Model

- The next question is: what is the thermalization temperature achieved by the blocks at the end of cooldown and is it or not below the PbSb T_C at 0 T?



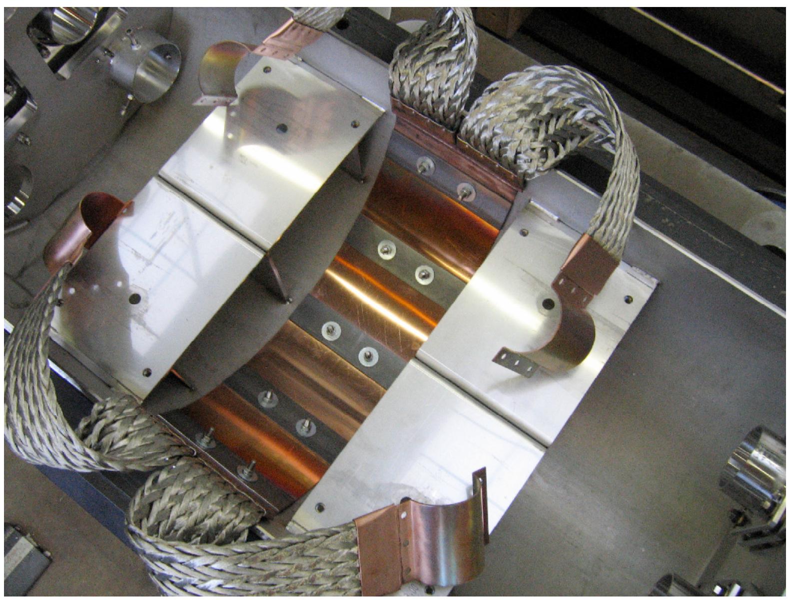
Equivalent thermal circuit of PbSb blocks in connection cryostats (Courtesy A. Poncet, *et al.*)

- The thermal environment of a PbSb block in a connection cryostat can be represented by the equivalent circuit shown on the left.

- The main unknowns are the thermal resistances R_1 (PbSb block supports) and R_2 and R_3 (thermalization braids).

Estimation of Thermal Resistances (1/2)

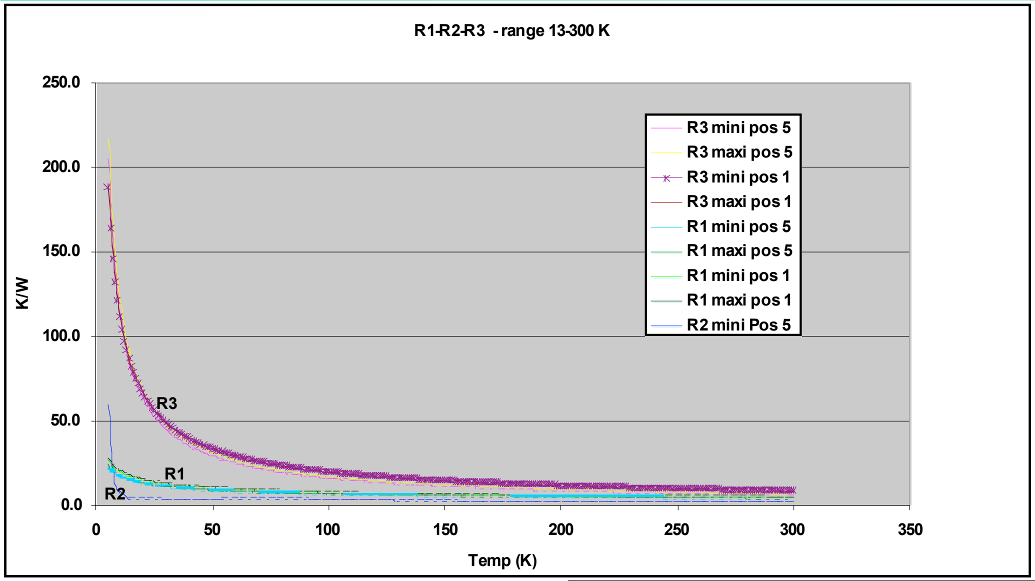
- Each thermal resistance in the circuit can broken down into two terms: a conduction term (*e.g.*, along the braids) and a contact term (*e.g.,* at the interface between the braid terminals and the blocks or the shell on one side and the M2 line on the other side).



View of the components making up resistance R_2
(Courtesy T. Colombet)

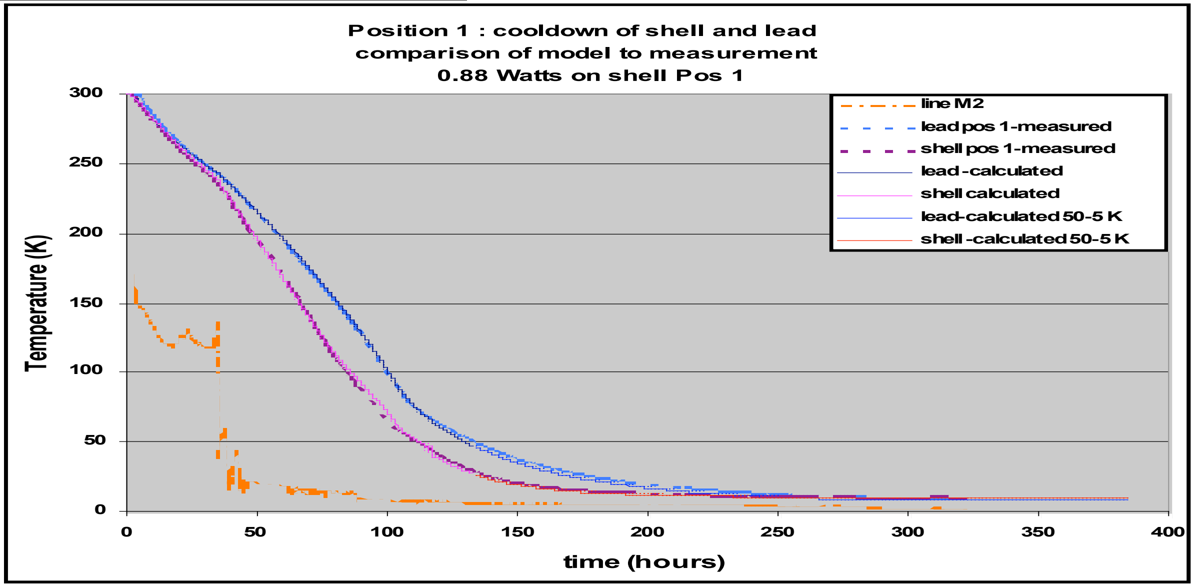
- The conduction terms can be derived from known material properties.
- The contact terms can be derived to best-fit the experimental data recorded during the SM18 test of the first connection cryostat.

Estimation of Thermal Resistances (2/2)



Estimation of thermal resistances derived from first connection cryostat test data at SM18 (Courtesy A. Poncet, *et al.*)

Consistency check of thermal model applied to cooldown of first connection cryostat at SM18 (Courtesy A. Poncet, *et al.*)



Thermalization Temperatures

- Having a working thermal model, it can now be used to estimate the thermalization temperatures achieved by the PbSb blocks and the shell at the end of machine cooldown under static nominal conditions.
- In the absence of beam, no additional power is deposited onto the PbSb blocks ($P_1 = 0$) and the additional power, P_2, deposited onto the shell is due to radiation from the 60-65 K thermal shield (estimated to 60 mW/m^2).
- Then, the model yields

  ~6.1 K for the PbSb blocks,

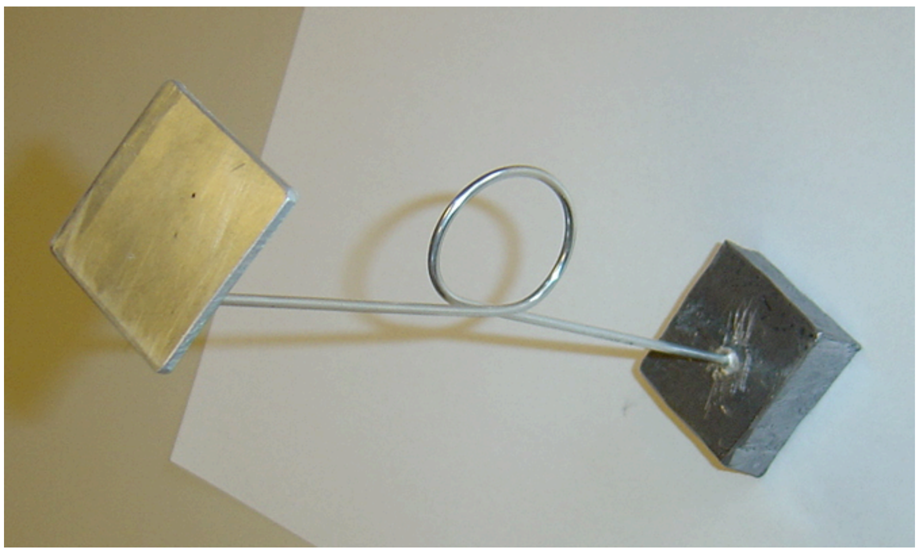
  ~6.4 K for the stainless steel shell,

with an estimated uncertainty of +/- 0.5 K.

- In any case, the PbSb ends up below its critical temperature at 0 T.

Proposed Corrective Action

• To eliminate any risk of quenching, the AT/CRI Group has proposed to add a thermal link between each PbSb block and the 60-65 K thermal shield ensuring that its temperature stays above 7.5 K at all time.



Sample of additional thermal links between PbSb blocks and 60-65 K shield (Courtesy A. Poncet, *et al.*)

• The links are dimensioned to bring an additional 0.2 to 0.3 W per PbSb block (thereby increasing the heat inleak on the 1.9 K system by 2 to 3 W per cryostat).

• The links can be implemented in the already-assembled cold masses without requiring to cut out their shells.

Contents

- Beam screen effects
- Lead shields in connection cryostats
- **Busbars in magnet interconnects**

Contributors

- V. Ferapontov, T. Sahner (TS/MME)
- Y Boncompagni (TS/CSE)
- B. Auchmann, J.L. Perinet-Marquet, S. Russenschuck (AT/MEL)
- J.P. Koutchouk, C. Vollinger (AT/MAS)

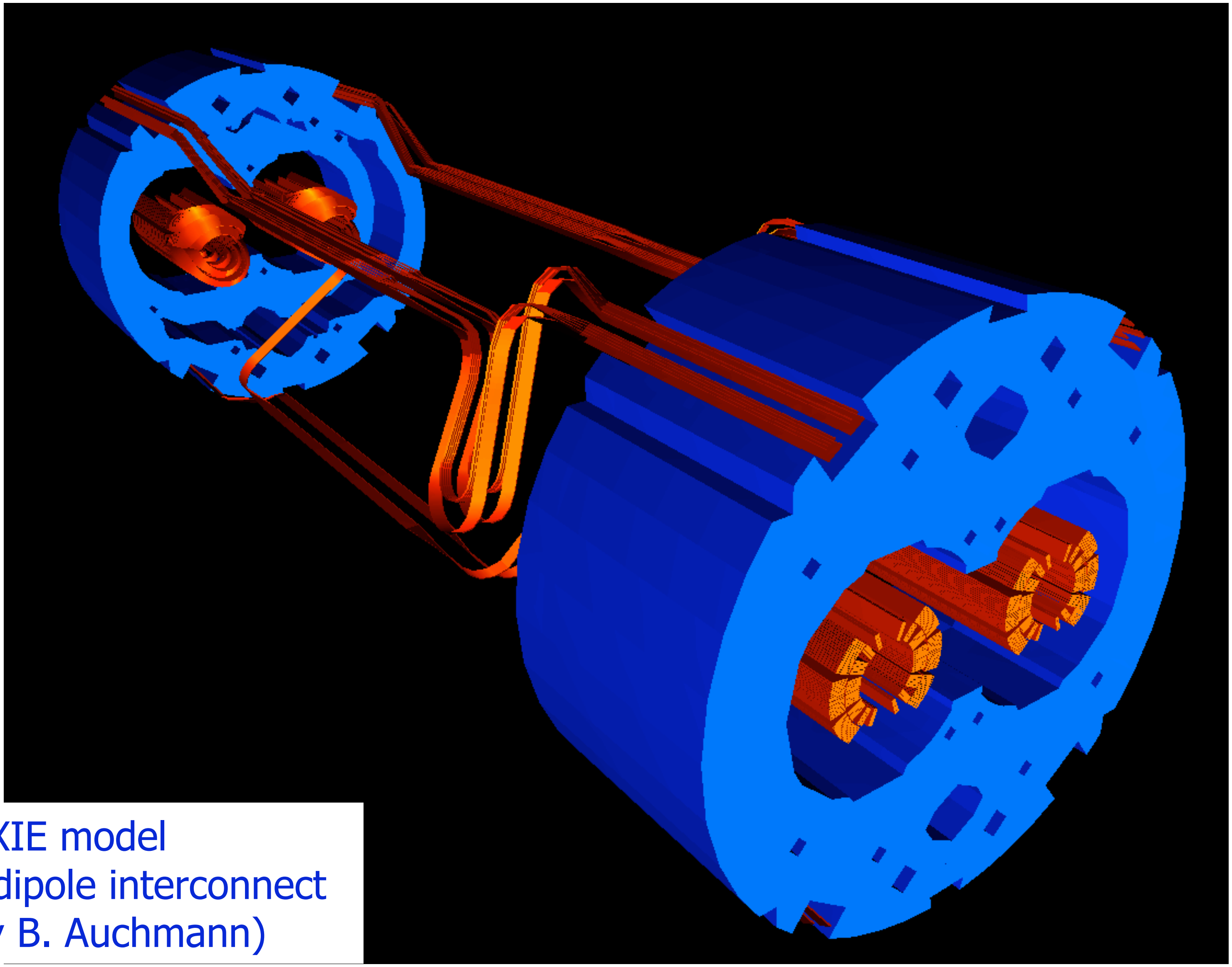
Introduction

- To the speaker knowledge, the stray fields generated by bus bars in the LHC magnet interconnects have never been thoroughly investigated.
- To get started, it was decided to consider the simple (and most numerous) case of the dipole-to-dipole interconnect and to develop a 3D ROXIE model.
- To have an accurate geometry (and with the hope of developing automated procedures), it was decided to build the ROXIE model from the EUCLID drawings.
- The interface EUCLID/ROXIE is not straightforward and requires extensive pre-processing on the EUCLID side.

Task Sharing

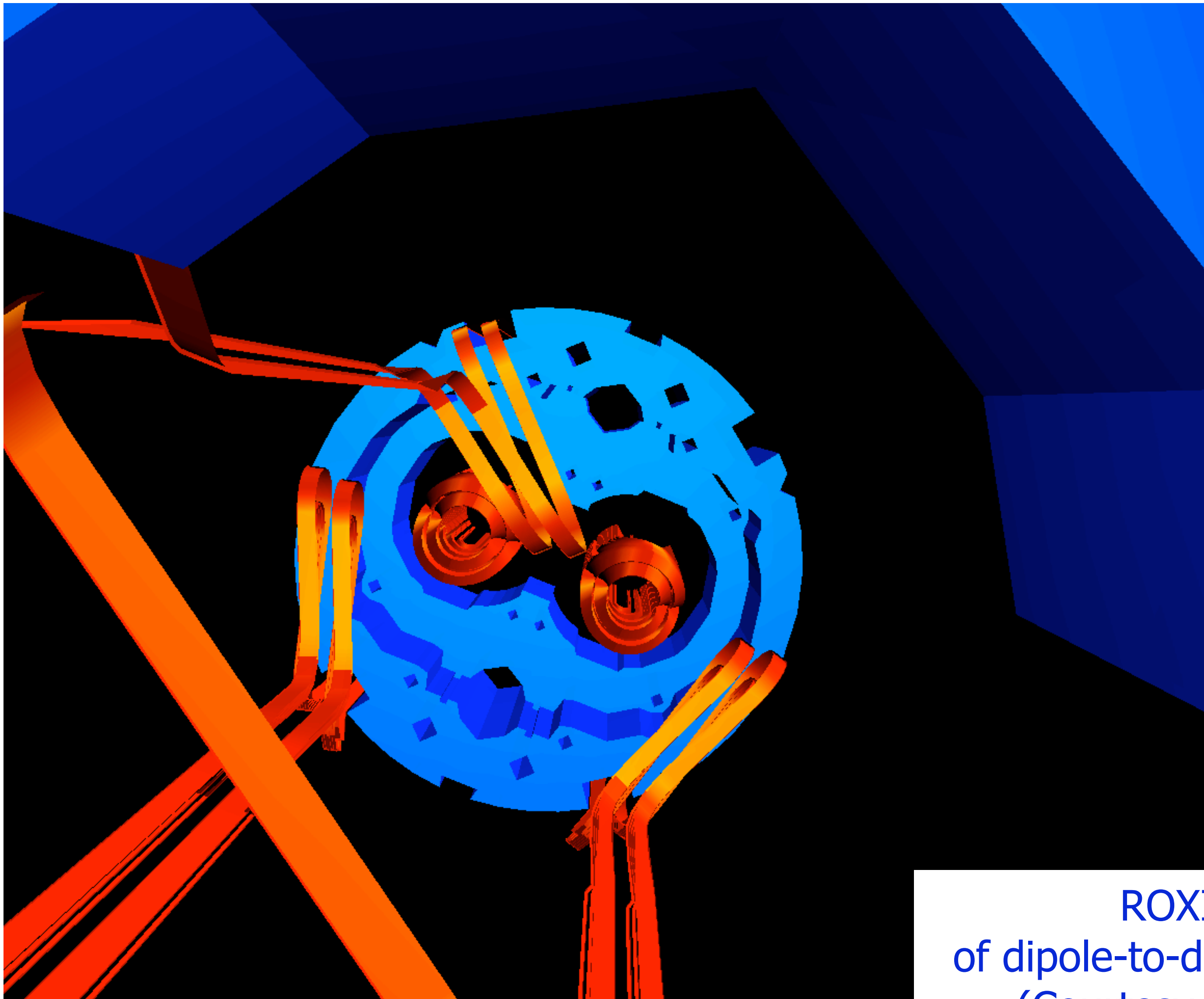
- The sharing of the work is as follows
  - – generation of a 3D EUCLID model relying on existing drawings (T. Sahner),
  - – retrieval of a coherent and ordered set of data point coordinates from the EUCLID model that can be used to define the brick elements forming the ROXIE model (Y. Boncompagni and V. Ferapontov),
  - – generation and validation of ROXIE model (B. Auchmann),
  - – field computations (C. Vollinger),
  - – estimation of effects on beam optics (J.P. Koutchouk).
- Tasks 1 to 3 are completed and the field computations were started in week 2 of 2006.

ROXIE Model (1/2)



ROXIE model
of dipole-to-dipole interconnect
(Courtesy B. Auchmann)

ROXIE Model (2/2)



ROXIE model
of dipole-to-dipole interconnect
(Courtesy B. Auchmann)

Future Work

- The next steps are
  - compute a sensitivity matrix of integral field coefficients along the interconnect versus bus bar types and determine the sign rules to be applied so as to compute the stray field at any dipole interconnect location around the ring,
  - draw up a comprehensive list of all types of magnet interconnects, and whenever appropriate, carry out similar computations.

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  - compute a sensitivity matrix of integral field coefficients along the interconnect versus bus bar types and determine the sign rules to be applied so as to compute the stray field at any dipole interconnect location around the ring,
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To be continued…

PS: Contact J.P. Koutchouk or myself if you have any suspicion about a potential parasitic field.