CERN Accelerator School

Superconductivity for Accelerators

Case study introduction

Paolo Ferracin
paolo.ferracin@cern.ch
CERN, Geneva

Claire Antoine
claire.antoine@cea.fr
CEA, Saclay

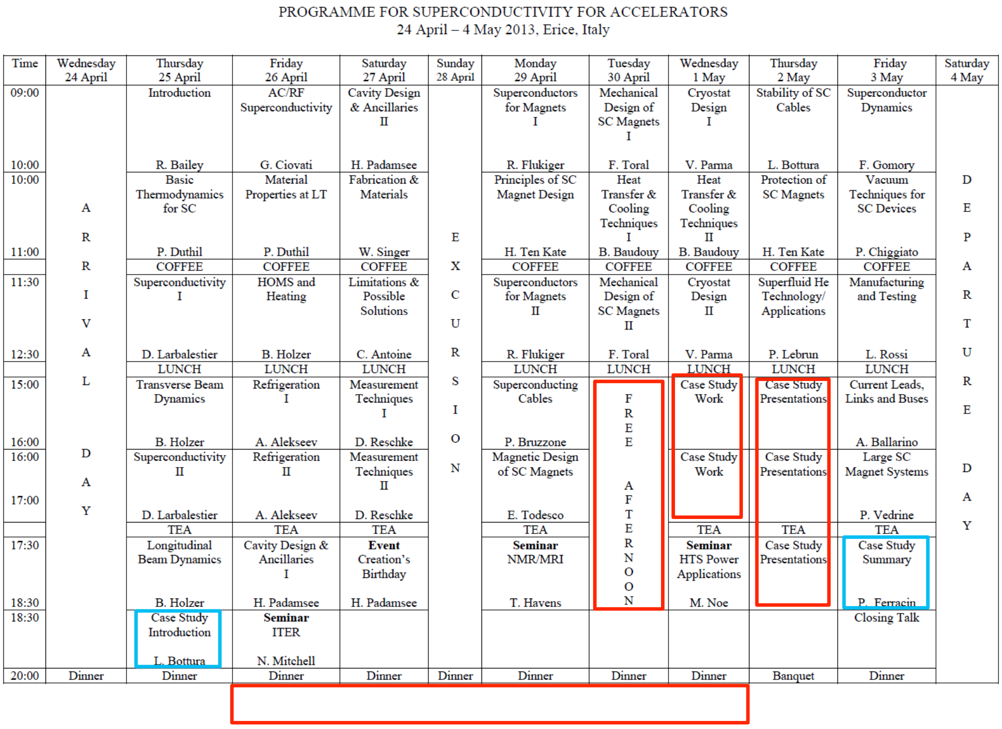
Goal of the case studies

- Apply the theory explained during the various lectures to practical cases
- Solve the case study using analytical formulas, plots, data, etc. provided during the presentations
  - Feel free to ask questions to the lecturers during case study work hours (and also later…)
- Compare the conceptual design with real cases
  - Understand reasoning behind previous designs
- Discuss and evaluate different design options

Case study overview

- 6 case study topics
  - 4 on superconducting magnets
  - 2 on RF cavities
- 18 working groups
  - 5-6 students per group
    - Different backgrounds and expertise
- Same topic covered by 3 groups
- Each group should prepare a 10 min presentation (not more than 6-7 slides) with a summary of the work.

Schedule



PROGRAMME FOR SUPERCONDUCTIVITY FOR ACCELERATORS
24 April – 4 May 2013, Erice, Italy

Time	Wednesday 24 April	Thursday 25 April	Friday 26 April	Saturday 27 April	Sunday 28 April	Monday 29 April	Tuesday 30 April	Wednesday 1 May	Thursday 2 May	Friday 3 May	Saturday 4 May
09:00 10:00	ARRIVAL DAY	Introduction R. Bailey	AC/RF Superconductivity G. Ciovati	Cavity Design & Ancillaries II H. Padamsee	EXCURSION	Superconductors for Magnets I R. Flukiger	Mechanical Design of SC Magnets I F. Toral	Cryostat Design I V. Parma	Stability of SC Cables L. Bottura	Superconductor Dynamics F. Gomory	DEPARTURE DAY
10:00 11:00		Basic Thermodynamics for SC P. Duthil	Material Properties at LT P. Duthil	Fabrication & Materials W. Singer		Principles of SC Magnet Design H. Ten Kate	Heat Transfer & Cooling Techniques I B. Baudouy	Heat Transfer & Cooling Techniques II B. Baudouy	Protection of SC Magnets H. Ten Kate	Vacuum Techniques for SC Devices P. Chiggiato	
		COFFEE	COFFEE	COFFEE		COFFEE	COFFEE	COFFEE	COFFEE	COFFEE	
11:30 12:30		Superconductivity I D. Larbalestier	HOMS and Heating B. Holzer	Limitations & Possible Solutions C. Antoine		Superconductors for Magnets II R. Flukiger	Mechanical Design of SC Magnets II F. Toral	Cryostat Design II V. Parma	Superfluid He Technology/ Applications P. Lebrun	Manufacturing and Testing L. Rossi	
		LUNCH	LUNCH	LUNCH		LUNCH	LUNCH	LUNCH	LUNCH	LUNCH	
15:00 16:00		Transverse Beam Dynamics B. Holzer	Refrigeration I A. Alekseev	Measurement Techniques I D. Reschke		Superconducting Cables P. Bruzzone	FREE AFTERNOON	Case Study Work	Case Study Presentations	Current Leads, Links and Buses A. Ballarino	
16:00 17:00		Superconductivity II D. Larbalestier	Refrigeration II A. Alekseev	Measurement Techniques II D. Reschke		Magnetic Design of SC Magnets E. Todesco		Case Study Work	Case Study Presentations	Large SC Magnet Systems P. Vedrine	
		TEA	TEA	TEA		TEA		TEA	TEA	TEA	
17:30 18:30		Longitudinal Beam Dynamics B. Holzer	Cavity Design & Ancillaries I H. Padamsee	**Event** Creation's Birthday H. Padamsee		**Seminar** NMR/MRI T. Havens		**Seminar** HTS Power Applications M. Noe	Case Study Presentations	Case Study Summary P. Ferracin	
18:30		Case Study Introduction L. Bottura	**Seminar** ITER N. Mitchell							Closing Talk	
20:00	Dinner	Dinner	Dinner	Dinner	Dinner	Dinner	Dinner	Dinner	Banquet	Dinner	

Groups

	1	2	3	4	5	6
A	ROBERTS, W.	VOGT, J.	KARIO, A.	TULU, E.	MARTINELLO, M.	MIKULAS, S.
	MURANAKA, T.	VALLCORBA, R.	ZICKLER, T.	BETEMPS, R.	MIERAU, A.	MARTINEZ DE ALVARO, T.
	PORHIEL, A.	PRINCIPE, R.	KAR, S.	SUBLET, A.	TAN, J.	CHECCHIN, M.
	MAEDER, J.	BAYER, C.	PASQUET, R.	ZHANG, P.	PEREZ BERMEJO, J.	EOZENOU, F.
	GIANNELLI, S.	VALUCH, D.	DALLOCCHIO, A.	SUGANO, S.	BEDNAREK, M.	STECKERT, T.
	ALBERTY, L.	DASSA, L.	MONDINO, I.	BROWN, M.		
B	SPINA, T.	JECKLIN, N.	BAYLISS, V.	AULL, S.	PRIEBE, A.	IZQUIERDO BERMUDEZ, S.
	ARIMOTO, Y.	YUE, W.	JENSEN, E.	TRUBLET, T.	DZITKO, H.	DARVE, C.
	SHORNIKOV, A.	FERRAND, G.	ELEFANT, F.	HAGEN, P.	SEGAL, C.	PAPKE, K.
	GADE, P.V.	WEGNER, R.	IIO, M.	ALTINKOK, A.	BERTUCCI, M.	PURUSHOTAMAN, S.
	BRODZINSKI, K.	SANTIAGO KERN, R.	JUCHNO, M.	DEVAUX, M.	TERENZIANI, G.	NIU, X.
C	BONOMI, R.	MAIANO, C.	NAVARRO-TAPIA, M.	BAGRETS, N.	TAN, F.	GEITHNER, O.
	KLEINDIENST, R.	SAPINSKI, M.	XU, M.	HE, S.	STODEL, M.	ZHENG, S.
	MUNILLA LOPEZ, J.	YUREVICH, S.	GILLEY, G.	LACKNER, F.	GLOWA, N.	ARNAU IZQUIERDO, G.
	CHAIBI, M.	ROGER, V.	INGLESE, V.	CORNACCHINI, A.	LOZANO BENITO, M.	BAJAS, H.
	ROGEZ, E.	LOUVET, M.	DOBOS, D.	FERNANDES, M.	GABOURIN, S.	FURCI, H.

Group assignments

Case study 1 **Case study 2** **Case study 3** **Case study 4** **Case study 5** **Case study 6**

	1	2	3	4	5	6
A	ROBERTS, W.	VOGT, J.	KARIO, A.	TULU, E.	MARTINELLO, M.	MIKULAS, S.
	MURANAKA, T.	VALLCORBA, R.	ZICKLER, T.	BETEMPS, R.	MIERAU, A.	MARTINEZ DE ALVARO, T.
	PORHIEL, A.	PRINCIPE, R.	KAR, S.	SUBLET, A.	TAN, J.	CHECCHIN, M.
	MAEDER, J.	BAYER, C.	PASQUET, R.	ZHANG, P.	PEREZ BERMEJO, J.	EOZENOU, F.
	GIANNELLI, S.	VALUCH, D.	DALLOCCHIO, A.	SUGANO, S.	BEDNAREK, M.	STECKERT, T.
	ALBERTY, L.	DASSA, L.	MONDINO, I.	BROWN, M.		

Group assignments

	Case study 1	Case study 2	Case study 5	Case study 3	Case study 4	Case study 6
B	SPINA, T.	JECKLIN, N.	BAYLISS, V.	AULL, S.	PRIEBE, A.	IZQUIERDO BERMUDEZ, S.
	ARIMOTO, Y.	YUE, W.	JENSEN, E.	TRUBLET, T.	DZITKO, H.	DARVE, C.
	SHORNIKOV, A.	FERRAND, G.	ELEFANT, F.	HAGEN, P.	SEGAL, C.	PAPKE, K.
	GADE, P.V.	WEGNER, R.	IIO, M.	ALTINKOK, A.	BERTUCCI, M.	PURUSHOTAMAN, S.
	BRODZINSKI, K.	SANTIAGO KERN, R.	JUCHNO, M.	DEVAUX, M.	TERENZIANI, G.	NIU, X.

Group assignments

	Case study 1	Case study 2	Case study 3	Case study 4	Case study 5	Case study 6
C	BONOMI, R.	MAIANO, C.	NAVARRO-TAPIA, M.	BAGRETS, N.	TAN, F.	GEITHNER, O.
	KLEINDIENST, R.	SAPINSKI, M.	XU, M.	HE, S.	STODEL, M.	ZHENG, S.
	MUNILLA LOPEZ, J.	YUREVICH, S.	GILLEY, G.	LACKNER, F.	GLOWA, N.	ARNAU IZQUIERDO, G.
	CHAIBI, M.	ROGER, V.	INGLESE, V.	CORNACCHINI, A.	LOZANO BENITO, M.	BAJAS, H.
	ROGEZ, E.	LOUVET, M.	DOBOS, D.	FERNANDES, M.	GABOURIN, S.	FURCI, H.

CASE STUDY 1

Case study 1

- Low-beta Nb_3Sn quadrupoles for the HL-LHC
  - **Introduction**
    - LARGE HADRON COLLIDER (LHC) it will run at 6.5-7 TeV, providing 300 fb^{-1} of integrated luminosity within the end of the decade.
    - After 2020, CERN is planning to have an upgrade of the LHC to obtain ten times more integrated luminosity, i.e., 3000 fb^{-1} .
    - Part of the upgrade relies on reducing the beam sizes in the Interaction Points (IPs), by increasing the aperture of the present triplets.
    - Currently, the LHC interaction regions feature NbTi quadrupole magnets with a 70 mm aperture and a gradient of 200 T/m.
  - **Goal**
    - Design a **Nb_3Sn** superconducting **quadrupole** with an **150 mm aperture** for the upgrade of the LHC interaction region operating at **1.9 K**

Case study 1

- Low-beta Nb_3Sn quadrupoles for the HL-LHC
  - **Questions**
    1. Determine maximum gradient and coil size (using sector coil scaling laws)
    2. Define strands and cable parameters
       1. Strand diameter and number of strands
       2. Cu to SC ratio and pitch angle
       3. Cable width, cable mid-thickness and insulation thickness
       4. Filling factor κ
    3. Determine load-line (no iron) and "short sample" conditions
       1. Compute j_{sc_ss}, j_{o_ss}, I_{ss}, G_{ss}, B_{peak_ss}
    4. Determine "operational" conditions (80% of I_{ss}) and margins
       1. Compute j_{sc_op}, j_{o_op}, I_{op}, G_{op}, B_{peak_op}
       2. Compute T, j_{sc}, B_{peak} margins
    5. Compare "short sample", "operational" conditions and margins if the same design uses Nb-Ti superconducting technology
    6. Define a possible coil lay-out to minimize field errors
    7. Determine e.m forces F_x and F_y and the accumulated stress on the coil mid-plane in the operational conditions (80% of I_{ss})
    8. Evaluate dimension iron yoke, collars and shrinking cylinder, assuming that the support structure is designed to reach 90% of I_{ss}

Case study 1

- Additional questions
  - Evaluate, compare, discuss, take a stand (… and justify it …) regarding the following issues
    - High temperature superconductor: YBCO vs. Bi2212
    - Superconducting coil design: block vs. cosϑ
    - Support structures: collar-based vs. shell-based
    - Assembly procedure: high pre-stress vs. low pre-stress

CASE STUDY 2

Case study 2

- Low-beta Nb-Ti quadrupoles for the HL-LHC
  - **Introduction**
    - LARGE HADRON COLLIDER (LHC) it will run at 6.5-7 TeV, providing 300 fb^{-1} of integrated luminosity within the end of the decade.
    - CERN is planning to have an upgrade of the LHC to obtain significantly higher integrated luminosity.
    - Part of the upgrade relies on reducing the beam sizes in the Interaction Points (IPs), by increasing the aperture of the present triplets.
    - Currently, the LHC interaction regions feature NbTi quadrupole magnets with a 70 mm aperture and a gradient of 200 T/m.
  - **Goal**
    - Design a **Nb-Ti** superconducting **quadrupole** with an **120 mm aperture** for the upgrade of the LHC interaction region operating at **1.9 K**

Case study 2

Low-beta Nb-Ti quadrupoles for the HL-LHC

- **Questions**
  1. Determine maximum gradient and coil size (using sector coil scaling laws)
  2. Define strands and cable parameters
     1. Strand diameter and number of strands
     2. Cu to SC ratio and pitch angle
     3. Cable width, cable mid-thickness and insulation thickness
     4. Filling factor κ
  3. Determine load-line (no iron) and "short sample" conditions
     1. Compute j_{sc_ss}, j_{o_ss}, I_{ss}, G_{ss} , B_{peak_ss}
  4. Determine "operational" conditions (80% of I_{ss}) and margins
     1. Compute j_{sc_op}, j_{o_op}, I_{op}, G_{op} , B_{peak_op}
     2. Compute T, j_{sc}, B_{peak} margins
  5. Compare "short sample", "operational" conditions and margins if the same design uses Nb_3Sn superconducting technology
  6. Define a possible coil lay-out to minimize field errors
  7. Determine e.m forces F_x and F_y and the accumulated stress on the coil mid-plane in the operational conditions (80% of I_{ss})
  8. Evaluate dimension iron yoke, collars and shrinking cylinder, assuming that the support structure is designed to reach 90% of I_{ss}

Case study 2

Additional questions

- Evaluate, compare, discuss, take a stand (… and justify it …) regarding the following issues

  - High temperature superconductor: YBCO vs. Bi2212
  - Superconducting coil design: block vs. cosϑ
  - Support structures: collar-based vs. shell-based
  - Assembly procedure: high pre-stress vs. low pre-stress

CASE STUDY 3

Case study 3

- High field - large aperture magnet for a cable test facility
  - **Introduction**
    - High field (B_{bore}>10 T) magnets are needed to upgrade existing accelerators in Europe and to prepare for new projects on a longer timescale.
    - Nb_3Sn is today the right candidate to meet those objectives, because of its superconducting properties and its industrial availability.
    - On the very long term, further upgrades could require dipole magnets with a field of around 20 Tesla (T): a possible solution is to combine an outer Nb_3Sn coil with an inner coil of High Critical Temperature (HTS) conductor, both contributing to the field.
    - In addition, an high-field dipole magnet with a large aperture could be used to upgrade the Fresca test facility at CERN, in the aim of meeting the strong need to qualify conductor at higher fields.
  - **Goal**
    - Design a superconducting **dipole** with an **100 mm aperture** and capable of reaching **15 T** at **1.9 K** (~90% of I_{ss}).

Case study 3

- High field - large aperture magnet for a cable test facility
  - **Questions**
    1. Determine maximum gradient and coil size (using sector coil scaling laws)
    2. Define strands and cable parameters
       1. Strand diameter and number of strands
       2. Cu to SC ratio and pitch angle
       3. Cable width, cable mid-thickness and insulation thickness
       4. Filling factor κ
    3. Determine load-line (no iron) and "short sample" conditions
       1. Compute j_{sc_ss}, j_{o_ss}, I_{ss}, G_{ss} , B_{peak_ss}
    4. Determine "operational" conditions (80% of I_{ss}) and margins
       1. Compute j_{sc_op}, j_{o_op}, I_{op}, G_{op} , B_{peak_op}
       2. Compute T, j_{sc}, B_{peak} margins
    5. Compare "short sample", "operational" conditions and margins if the same design uses Nb-Ti superconducting technology
    6. Define a possible coil lay-out to minimize field errors
    7. Determine e.m forces F_x and F_y and the accumulated stress on the coil mid-plane in the operational conditions (80% of I_{ss})
    8. Evaluate dimension iron yoke, collars and shrinking cylinder, assuming that the support structure is designed to reach 90% of I_{ss}

Case study 3

- Additional questions
  - Evaluate, compare, discuss, take a stand (… and justify it …) regarding the following issues
    - High temperature superconductor: YBCO vs. Bi2212
    - Superconducting coil design: block vs. cosϑ
    - Support structures: collar-based vs. shell-based
    - Assembly procedure: high pre-stress vs. low pre-stress

CASE STUDY 4

Case study 4

11 T Nb_3Sn dipole for the LHC collimation upgrade

- **Introduction**
  - The second phase of the LHC collimation upgrade will enable proton and ion beam operation at nominal and ultimate intensities.
  - To improve the collimation efficiency by a factor 15–90, additional collimators are foreseen in the room temperature insertions and in the dispersion suppression (DS) regions around points 2, 3, and 7.
  - To provide longitudinal space of about 3.5 m for additional collimators, a solution based on the substitution of a pair of 5.5-m-long 11 T dipoles for several 14.3-m-long 8.33 T LHC main dipoles (MB) is being considered.

- **Goal**
  - Design a **Nb_3Sn** superconducting **dipole** with an **60 mm aperture** and a operational field (80% of I_{ss}) at **1.9 K** of **11 T**.

Case study 4

- 11 T Nb_3Sn dipole for the LHC collimation upgrade
  - **Questions**
    1. Determine maximum gradient and coil size (using sector coil scaling laws)
    2. Define strands and cable parameters
       1. Strand diameter and number of strands
       2. Cu to SC ratio and pitch angle
       3. Cable width, cable mid-thickness and insulation thickness
       4. Filling factor κ
    3. Determine load-line (no iron) and "short sample" conditions
       1. Compute j_{sc_ss}, j_{o_ss}, I_{ss}, G_{ss}, B_{peak_ss}
    4. Determine "operational" conditions (80% of I_{ss}) and margins
       1. Compute j_{sc_op}, j_{o_op}, I_{op}, G_{op}, B_{peak_op}
       2. Compute T, j_{sc}, B_{peak} margins
    5. Compare "short sample", "operational" conditions and margins if the same design uses Nb-Ti superconducting technology
    6. Define a possible coil lay-out to minimize field errors
    7. Determine e.m forces F_x and F_y and the accumulated stress on the coil mid-plane in the operational conditions (80% of I_{ss})
    8. Evaluate dimension iron yoke, collars and shrinking cylinder, assuming that the support structure is designed to reach 90% of I_{ss}

Case study 4

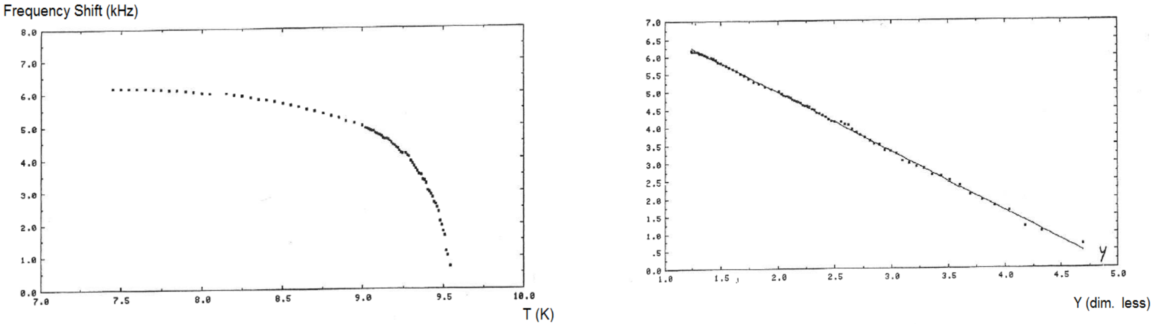
- Additional questions
  - Evaluate, compare, discuss, take a stand (… and justify it …) regarding the following issues
    - High temperature superconductor: YBCO vs. Bi2212
    - Superconducting coil design: block vs. $\cos\vartheta$
    - Support structures: collar-based vs. shell-based
    - Assembly procedure: high pre-stress vs. low pre-stress

CASE STUDY 5

Courtesies: M. Desmon, P. Bosland, J. Plouin, S. Calatroni

Case study 5
RF cavities: superconductivity and thin films, local defect…

Thin Film Niobium: penetration depth



Frequency shift during cooldown. Linear representation is given in function of Y, where $Y = (1-(T/T_C)^4)^{-1/2}$

Q1 : What can explain the variation of frequency observed ?

Q2 : Calculate the penetration depths of the film. Make the comparison with bulk value. How can you explain the difference?

The calculation can be done considering the frequency variation within the perturbation limit with the Slater formula:

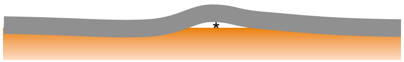
$$\frac{\Delta F}{F} = \frac{\pi \mu_0 \ F_0}{G} \Delta\lambda$$

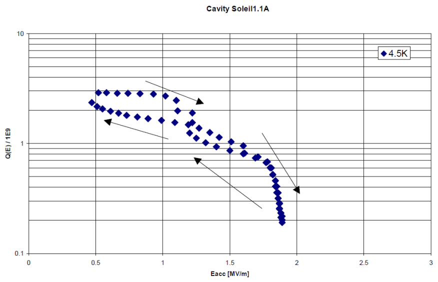
where W is the power inside the cavity, l figures the penetration depth in the Pippard limit.

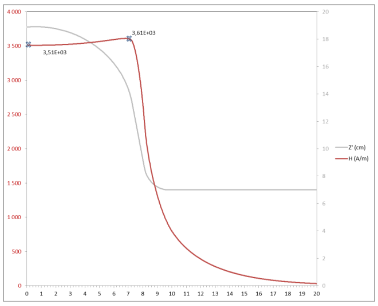
For the courageous : explain how we reach this approximation *(H. Safa. "Surface resistance of a superconductor". SRF 91)*

Case study 5
RF cavities: superconductivity and thin films, local defect…

Thin Film Niobium: local defect







Q3 : explain qualitatively the experimental observations.

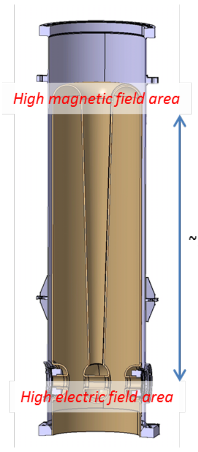
Q4 : deduce the surface of the defect. (For simplicity, one will take the field repartition and dimension from the cavity shown on the right. Note the actual field B_{peak} is proportional to $_{Eacc}$ (B_{peak}/E_{acc}~2))

Q5: If the hot spot had been observed 7.3 cm from the equator, what conclusion could you draw from the experimental data ?

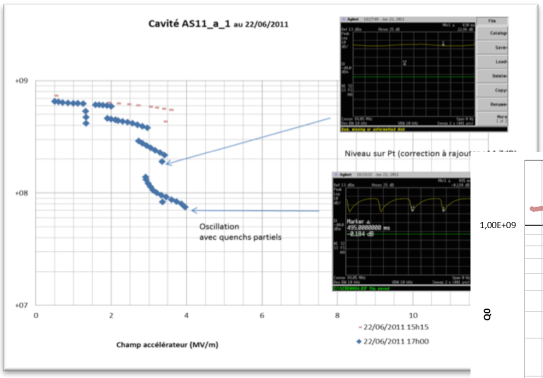
Case study 5
RF cavities: superconductivity and thin films, local defect…

Q-switches can also be observed in bulk Nb cavities

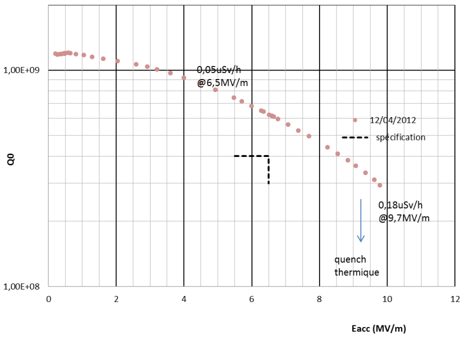
Bulk Niobium: local defects



After 40 µm etching



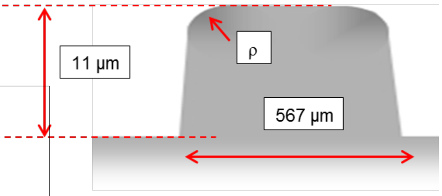
After 150 µm etching

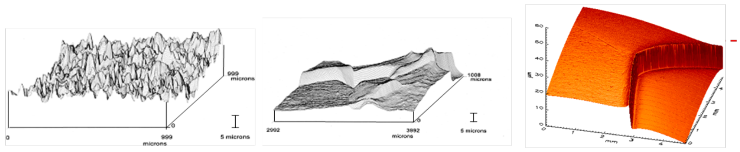


Q6 : regarding the previous questions, and the field distribution in these cavities, how can you explain the multiple observed Q-switches ?

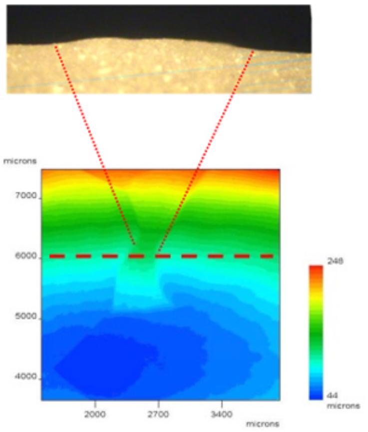
Case study 5
RF cavities: superconductivity and thin films, local defect…

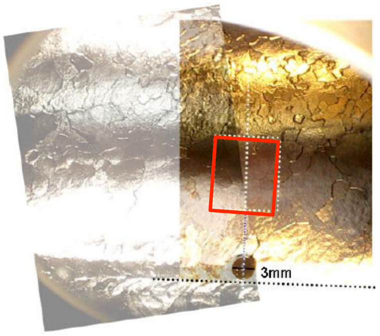
Bulk Niobium: local defects: steps @ GB

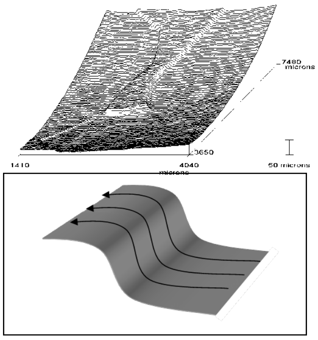




⇑ Non annealed (small grain) Annealed (medium grains) ⇑ / Ingot slice (large grains) ⇑



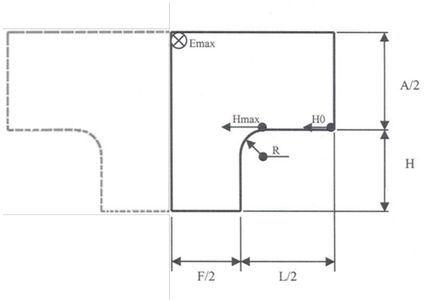




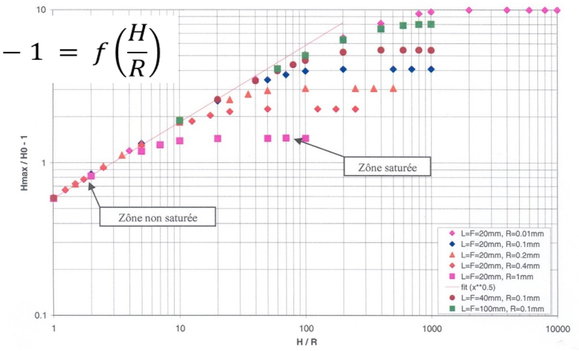
Case study 5
RF cavities: superconductivity and thin films, local defect…

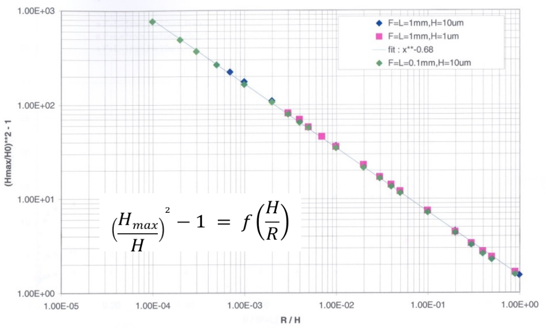
Bulk Niobium: steps @ GB

2D RF model



$$\frac{H_{max}}{H} - 1 = f\left(\frac{H}{R}\right)$$





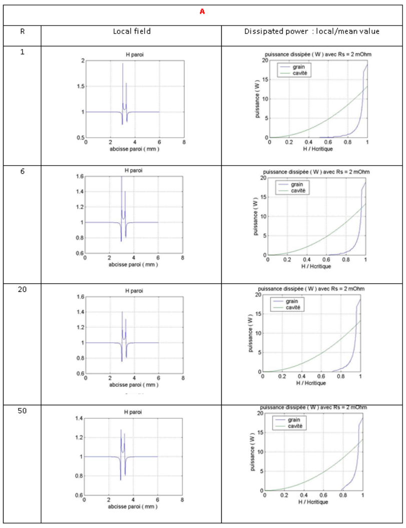
$$\left(\frac{H_{max}}{H}\right)^2 - 1 = f\left(\frac{H}{R}\right)$$

Q7. What conclusion can we draw about:
- The influence of the lateral dimensions of the defect? Its height ?
- The influence of the curvature radius?
- The behavior at high field?
- What happens if the defect is a hole instead of bump (F<<L) ?

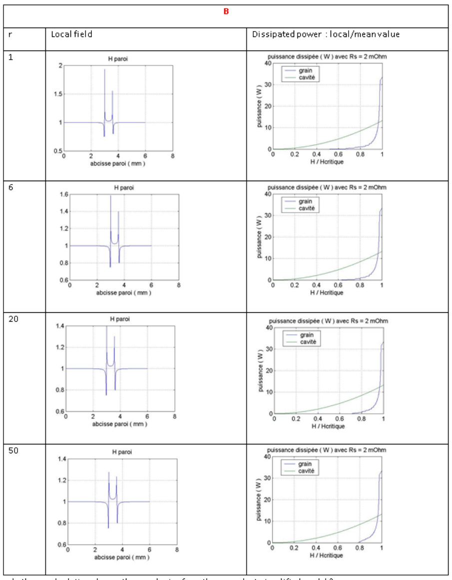
Case study 5
RF cavities: superconductivity and thin films, local defect…

Steps @ GB w. realistic dimension

RF only



A		
R	Local field	Dissipated power : local/mean value
1	H paroi	puissance dissipée (W) avec Rs = 2 mOhm
6	H paroi	puissance dissipée (W) avec Rs = 2 mOhm
20	H paroi	puissance dissipée (W) avec Rs = 2 mOhm
50	H paroi	puissance dissipée (W) avec Rs = 2 mOhm



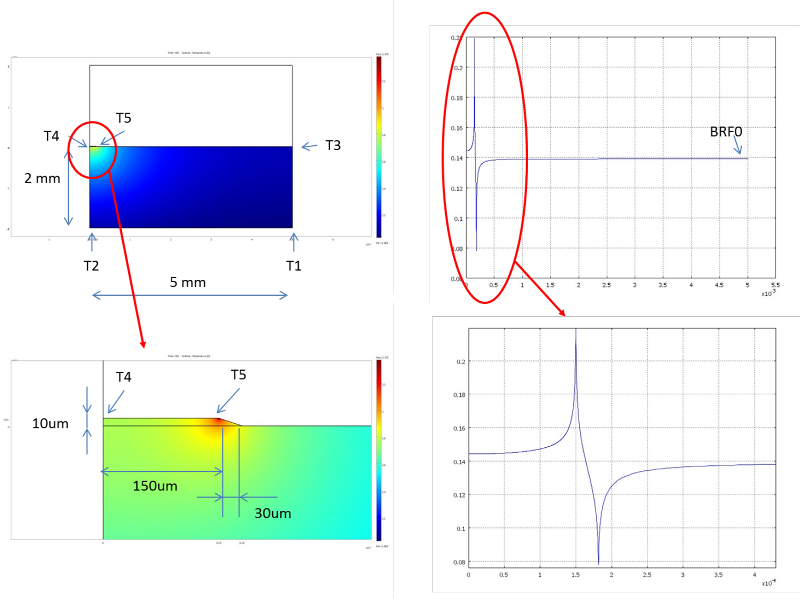
B		
r	Local field	Dissipated power : local/mean value
1	H paroi	puissance dissipée (W) avec Rs = 2 mOhm
6	H paroi	puissance dissipée (W) avec Rs = 2 mOhm
20	H paroi	puissance dissipée (W) avec Rs = 2 mOhm
50	H paroi	puissance dissipée (W) avec Rs = 2 mOhm

Q8.- do these calculation change the conclusion from the precedent simplified model ?
- what prediction can be done about the thermal breakdown of the cavity?
- why is this model underestimating the field enhancement factor and overestimating the thermal dissipations?

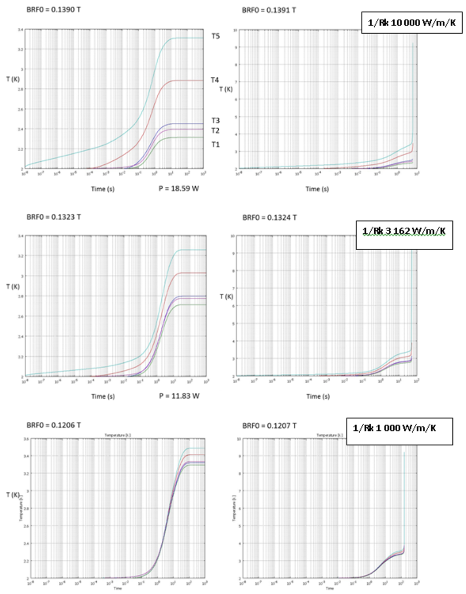
Case study 5
RF cavities: superconductivity and thin films, local defect…

Steps @ GB w. realistic dimension

RF + thermal



Case study 5
RF cavities: superconductivity and thin films, local defect…



Q9 Comment these figures.

- What will happen if we introduce thermal variation of κ.
- What happen if we increase the purity of Nb ?, why ?

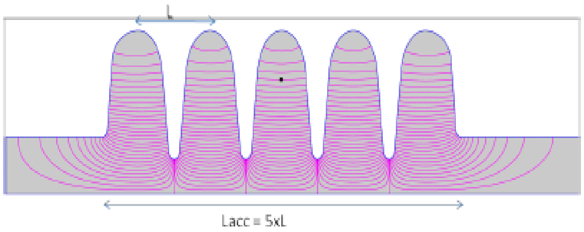
CASE STUDY 6

Courtesies: J. Plouin, D. Reschke

Case study 6

- RF test and properties of a superconducting cavity
- Basic parameters of a superconducting accelerator cavity for proton acceleration

Frequency [MHz]	704.4
E_{pk}/E_{acc}	3.36
B_{pk}/E_{acc} [mT/(MV/m)]	5.59
r/Q [Ω]	173
G [Ω]	161
Geometrical β (βg)	0.47



- The cavity is operated in its π-mode and has 5 cells.
  - What is the necessary energy of the protons for β = 0,47?
  - Please give the relation between β_g, λ and L. L is the distance between two neighboring cells (see sketch above)
  - Calculate the value of L and L_{acc}.
  - Is it necessary to know the material of the cavity in order to calculate the parameters given in the table? Please briefly explain your answer.

Case study 6

- The cavity is made of superconducting niobium. The operation temperature is 2K.
  - Please calculate the BCS component R_{BCS} of the surface resistance according to the approximated expression $Rbcs = 2 \cdot 10^{-4}\,\frac{1}{T}\left(\frac{f}{1.5}\right)^2 exp\left(-\frac{17{,}67}{T}\right)$
    with T: temperature in [K]
    and f: frequency in [GHz].
  - Please explain qualitatively why the operational temperature of 2K is preferable compared to operation at 4.3K.
  - Please explain, which parameters which will modify the above approximated expression.
- If R_{BCS} is the surface resistance, calculate the value of the quality factor Q_0 of this cavity.For real tested cavities there are more components of the surface resistance. Please give and describe these components.

Case study 6

- In operation a stored energy of 65 J was measured inside the cavity.
  - What is the corresponding accelerating gradient E_{acc}?
  - What is the dissipated power in the cavity walls (in cw operation)?
- If we take 190mT as the critical magnetic RF surface field at 2K, what is the maximum gradient, which can be achieved in this cavity?
  - At which surface area inside the cavity do you expect the magnetic quench (qualitatively)?
- Verify that the calculated gradient in question 6 is lower than in question 7.
  - Please explain qualitatively which phenomena can limit the experimental achieved gradient.

Case study 6

- Please remember that the loaded quality factor Q_L is related to Q_0 by:

$$\frac{1}{Q_L} = \frac{1}{Q_{ext}} + \frac{1}{Q_0}$$

  Q_{ext} describes the effect of the power coupler attached to the cavity $Q_{ext} = \omega \cdot W/P_{ext}$. W is the stored energy in the cavity; P_{ext} is the power exchanged with the coupler. In the cavity test the stored energy was 65J, the power exchanged with coupler was 100kW. Calculate the loaded quality factor Q_L and the frequency bandwidth of the cavity.
- Please explain which technique is used to keep the frequency of the cavity on its nominal value.
- Assume that some normal conducting material (e.g some piece of copper) is inside of the cavity.
  - What are the effects on gradient and Q-value? Please explain qualitatively
  - How can you calculate the effects?

Case study 6

- Additional questions
  - Evaluate, compare, discuss, take a stand (… and justify it …) regarding the following issues

    - High temperature superconductor: YBCO vs. Bi2212
    - Superconducting coil design: block vs. cosϑ
    - Support structures: collar-based vs. shell-based
    - Assembly procedure: high pre-stress vs. low pre-stress