“Synergy and impact of the FCC magnet technology R&D with NMR, MRI and high-field magnet science”

2015 FCC Week , Washington D.C.

Antoine DAËL
CEA-Saclay
For the CERN-CEA Working Group:
G.KIRBY,D.MAZUR,C.PORCHERAY & T.SCHILD

The steering committee of the CERN-CEA collaboration agreement on magnets has decided to create an ad hoc Working Group on Future Superconducting Magnet Technology

The composition of the WG is:
A. Daël (CEA Saclay) - Chairman
T. Schild (CEA Saclay)
C. Porcheray (CEA Saclay)
G. Kirby (CERN)
D. Mazur (CERN)

The mandate of the WG is of two years,
starting from the 25th of November 2014.
The WG is open to additional expertise

MANDATE of the ad-hoc Working Group (WG) on Future Superconducting Magnet Technology.

Considering the high impact potential of the technology R&D within the efforts on HL-LHC and FCC, the mandate of the ad-hoc WG is:

1) to examine the synergies between on the one hand the **industrial areas of MRI, NMR as well as other relevant applications** and on the other hand the **FCC investments in the technology domains of superconducting magnets**;

2) to demonstrate the benefits of these investments to society;

3) to develop relationships with the European industries concerned;

4) to propose practical joint R&D actions to be implemented before the end of the decade.

A Nick Name for the ad hoc WG

FuSuMaTech

Ad hoc Working Group on Future Superconducting Magnet Technology

In Japanese traditional architecture , *fusuma* (襖) are vertical rectangular panels which can slide from side to side and act as doors.

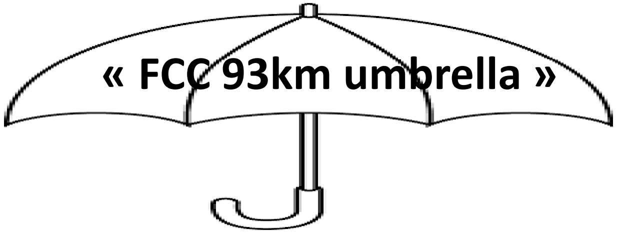
So let’s open the doors and have the communities working together!

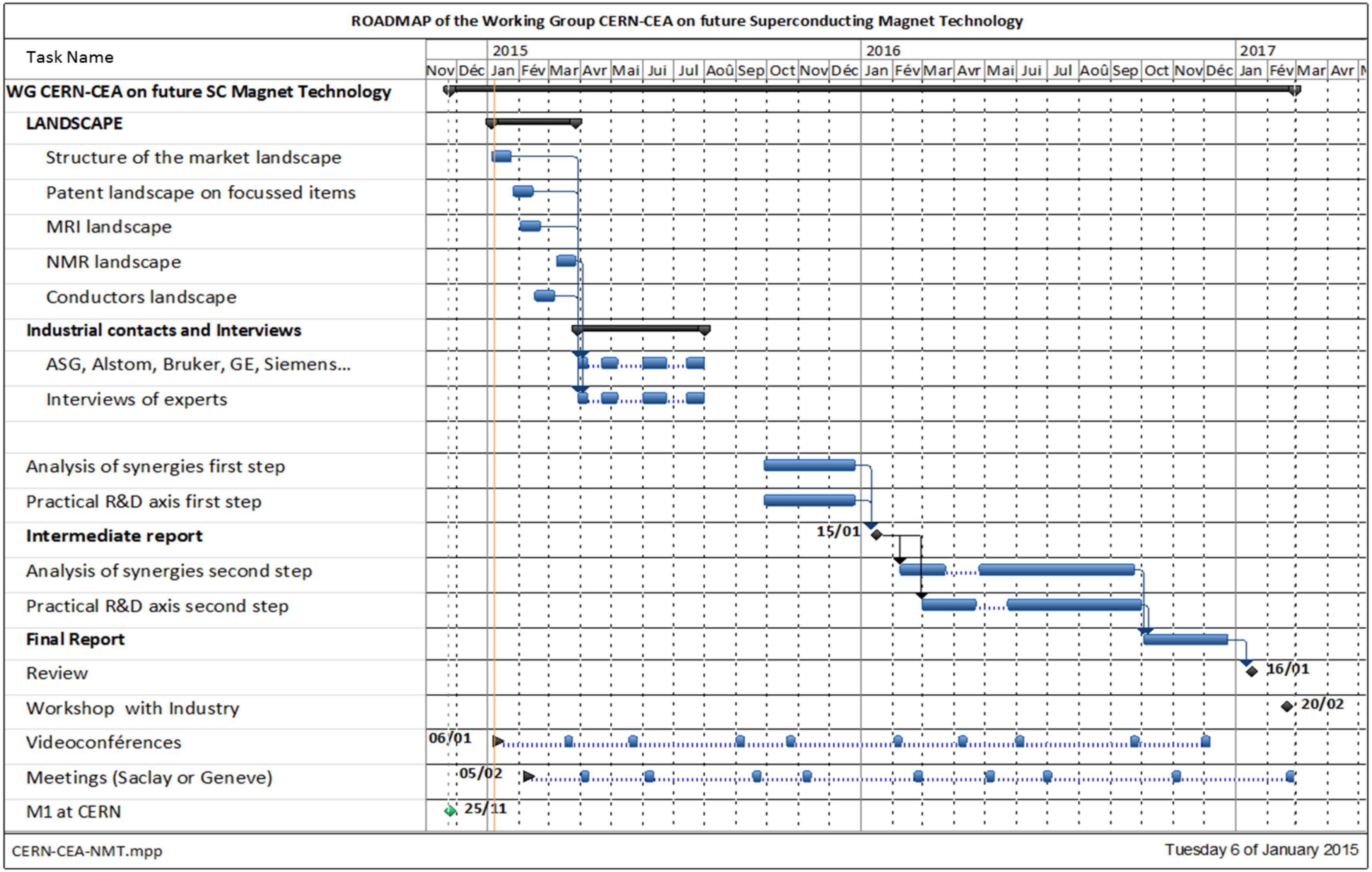
Thanks to Pierre Védrine and Akira Yamamoto

Methodology of the FuSuMaTech ad hoc WG

1. LOOK at the outside LANDSCAPES :
   - Patent landscape
   - MRI market landscape
   - NMR landscape
   - Conductor landscape
2. HAVE Industrial contacts and expert interviews
3. DEFINE a set of realistic R&D common actions
4. FIND the funding of these R&D common actions under the

We are just starting !





ROADMAP of the Working Group CERN-CEA on future Superconducting Magnet Technology

Task Name

WG CERN-CEA on future SC Magnet Technology

LANDSCAPE

- Structure of the market landscape
- Patent landscape on focussed items
- MRI landscape
- NMR landscape
- Conductors landscape

Industrial contacts and Interviews

- ASG, Alstom, Bruker, GE, Siemens...
- Interviews of experts

Analysis of synergies first step

Practical R&D axis first step

Intermediate report

Analysis of synergies second step

Practical R&D axis second step

Final Report

Review

Workshop with Industry

Videoconférences

Meetings (Saclay or Geneve)

M1 at CERN

CERN-CEA-NMT.mpp

Tuesday 6 of January 2015

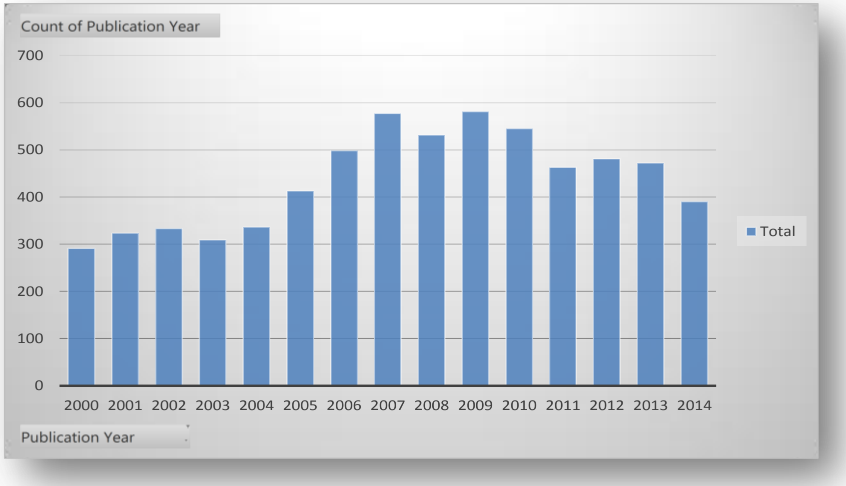
Patent landscape

- The patent landscape is a tool for market study, a tool for understanding R&D directions and to identify areas with freedom for innovation.
- Initial patent landscapes have been made for the technology domain of superconducting magnets with specific statistics for HTS (BSCCO / YBCO), and for the application domains of High-Field MRI and NMR.
- Whereas the number of patent filings in the technology domain is stable, the number of patent applications in the field of high-field MRI and NMR has grown over the last 10 years. The data will be further analyzed regarding R&D axis and geography (companies from member states).
- The IP is strongly protected and therefore poses a barrier to entry by new parties by the means of crossed patents.

Patent Landscape – Initial findings

Technology domain

Superconducting magnets



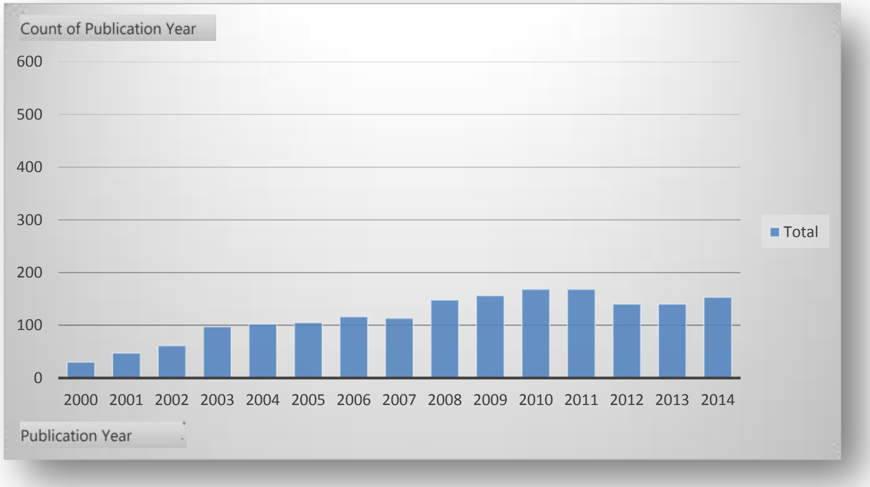
HTS – Peak in patenting activity (2007-2010)

Overall relatively stable volume of patenting

Next steps: identify main technologies protected

Application domains

High-field MRI and NMR



Emerging field in terms of patenting

Growth from 20 to 150 applications/year

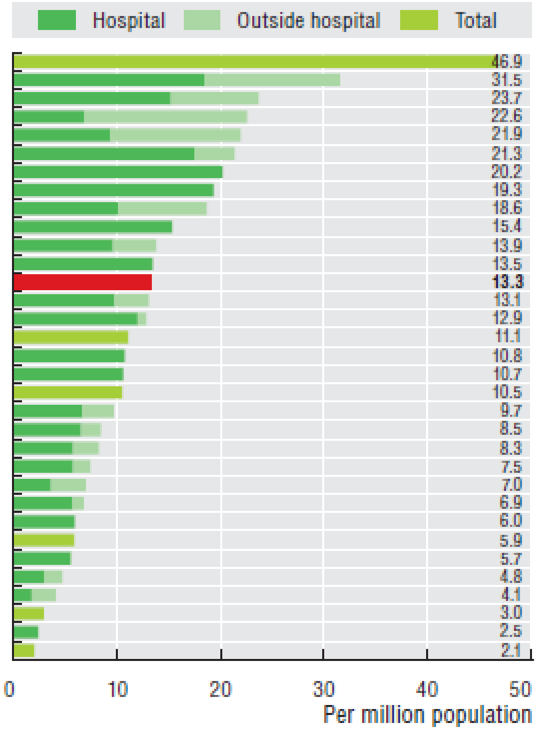
Next steps: identify main drivers behind growth

Intellectual Property Landscape

- With the objective of proposing R&D axis to industry, it is important to perform an analysis of the IP landscape :
- Which technologies are patented ? Who owns them ? Which R&D axis are already covered by many patents, and which are not ?
- Even though most applications are filed by large multinationals, the application domain is also covered by smaller companies and start-ups.
- In a next step, the detailed analysis of the patent landscape will take place and results published.
- This is also seen as an important part of the documentation when applying for EU funding.
- The innovation cycles are long (5 years) and new innovations are driven by the end-user.

Number of MRI in the world (mostly 1.5 tesla)

4.2.1. MRI units, 2011 (or nearest year)

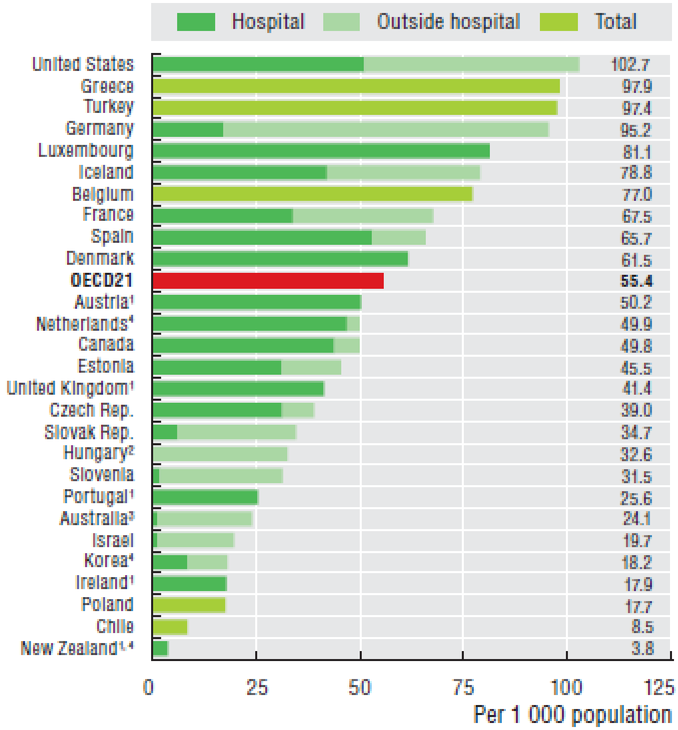


1. Equipement outside hospital not included.
2. Only equipment eligible for public reimbursement.

Source: OECD Health Statistics 2013, *http://dx.doi.org/10.1787/health-data-en.*

StatLink *http://dx.doi.org/10.1787/888932917256*

4.2.3. MRI exams, 2011 (or nearest year)



1. Exams outside hospital not included.
2. Exams in hospital not included.
3. Exams on public patients not included.
4. Exams privately-funded not included.

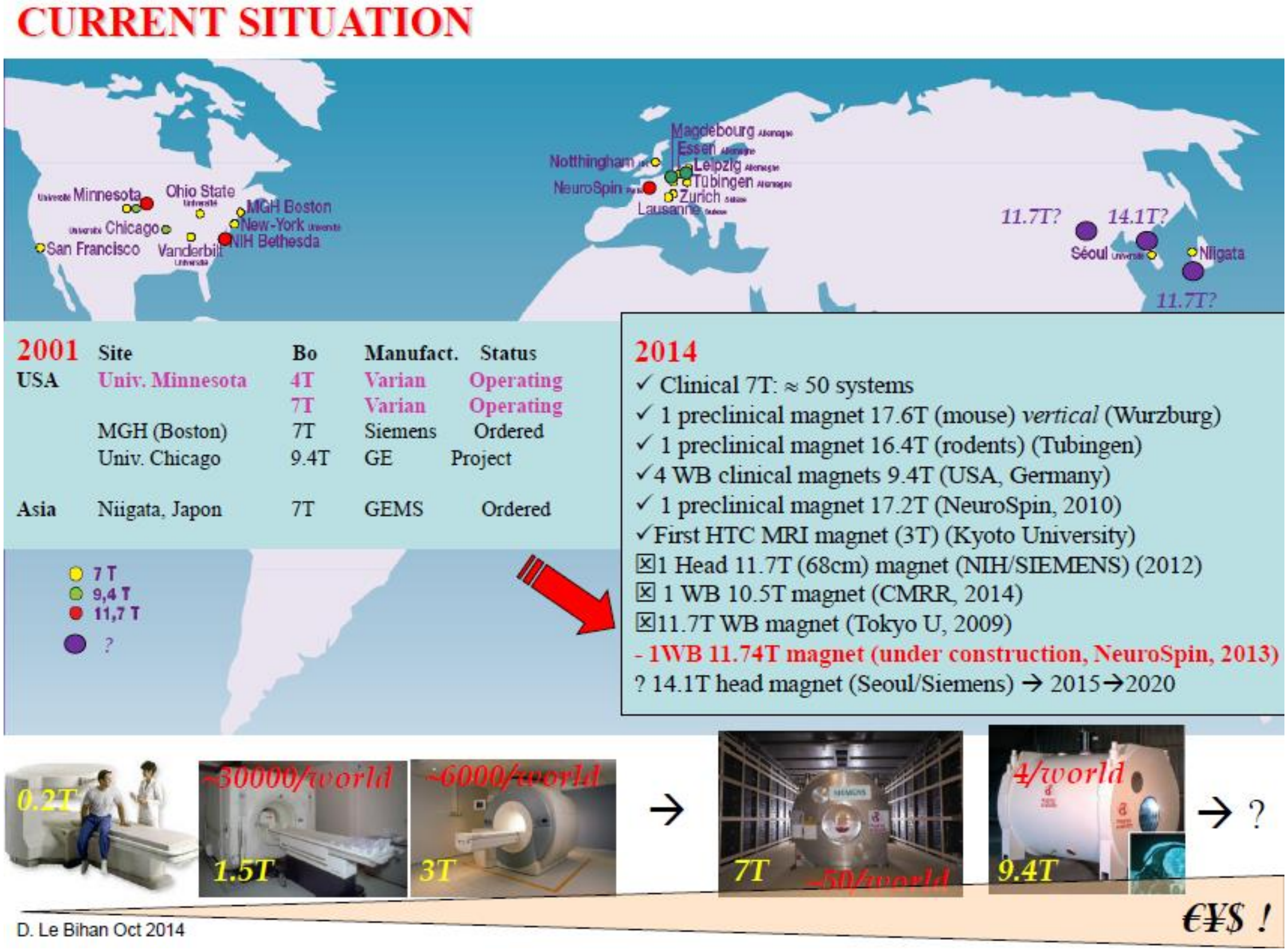
Source: OECD Health Statistics 2013, *http://dx.doi.org/10.1787/health-data-en.*

StatLink *http://dx.doi.org/10.1787/888932917294*

Technological issues with MRI magnets

- Cryogenics: remove helium from the system
- Today the gold standard is the zero boil off magnet using GM cold head.
- Conductor: all manufacturer (GE, Siemens) try to develop MgB2 magnets
- Improve magnet stability by increasing the temperature margin
- Ease the design of cryogen free
- Decrease the conductor cost

High Field MRI (>7T)is a tool for research



CURRENT SITUATION

2001	Site	Bo	Manufact.	Status
USA	Univ. Minnesota	4T	Varian	Operating
		7T	Varian	Operating
	MGH (Boston)	7T	Siemens	Ordered
	Univ. Chicago	9.4T	GE	Project
Asia	Niigata, Japon	7T	GEMS	Ordered

2014

✓ Clinical 7T: ≈ 50 systems
✓ 1 preclinical magnet 17.6T (mouse) *vertical* (Wurzburg)
✓ 1 preclinical magnet 16.4T (rodents) (Tubingen)
✓4 WB clinical magnets 9.4T (USA, Germany)
✓ 1 preclinical magnet 17.2T (NeuroSpin, 2010)
✓First HTC MRI magnet (3T) (Kyoto University)
☒1 Head 11.7T (68cm) magnet (NIH/SIEMENS) (2012)
☒ 1 WB 10.5T magnet (CMRR, 2014)
☒11.7T WB magnet (Tokyo U, 2009)
- 1WB 11.74T magnet (under construction, NeuroSpin, 2013)
? 14.1T head magnet (Seoul/Siemens) → 2015→2020

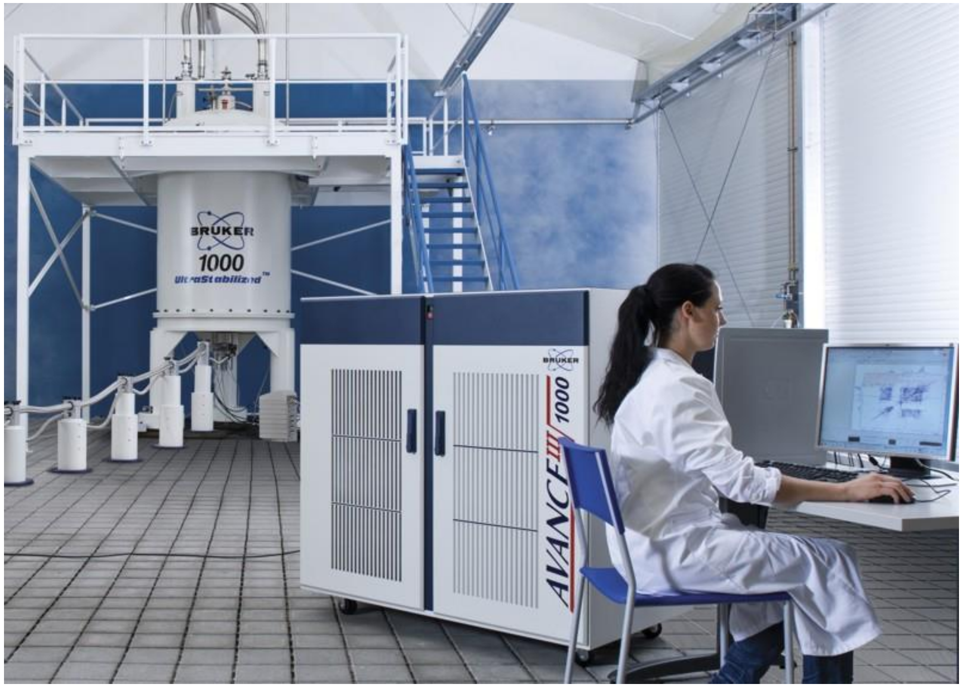
D. Le Bihan Oct 2014

Technological issues of high field MRI

- Quench protection: on high field MRI magnet, the risk that a magnet quench induce a damage is very high
  - 17,2T(NeuroSpin), 11,7T(NIH- Agilent)
  - Protection is based on multiple coils protected with diodes, in case of quench unbalance currents can induced high stress especially on external coils
- Cryogeny: high field MRI, starting 11,7T, may require a subatmospheric pressure bath to work around 2K in order to avoid the use of Nb3Sn.
- Gradient/Magnet coupling: gradient pulsed induced Eddy current in metallic inner tubes (vacuum vessel, thermal shield, helium vessel): noise, heat load on helium vessel, field distorsion. It requires very complex multiphysics modeling.

High field NMR beyond 1GHz

Worlds first, standard high homogeneity 1GHz NMR magnet installed in Lyon 2009 by BRUKER
We will propose an open discussion to Bruker on possible synergies

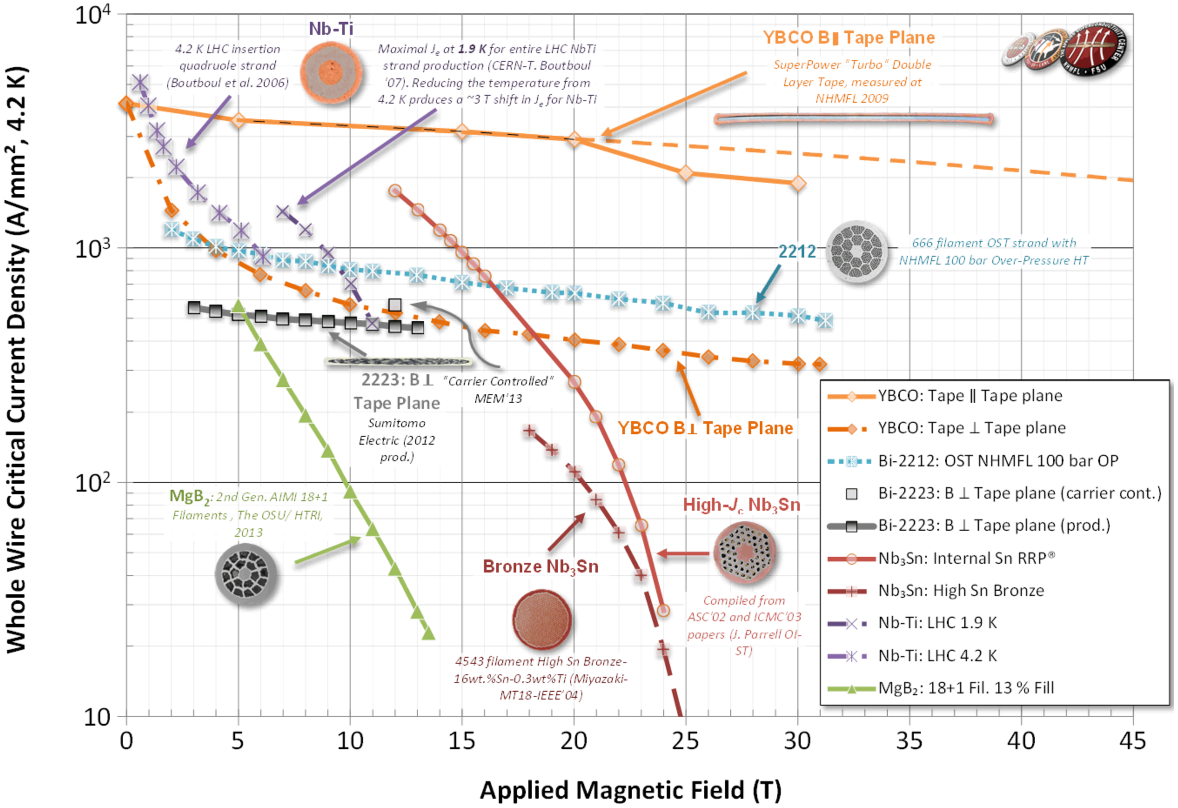


Courtesy of Bruker

HTS tape :

- very high critical current @ B > 23.5T
- long length > 1000m
- high mechanical strength
- state of the art quality control

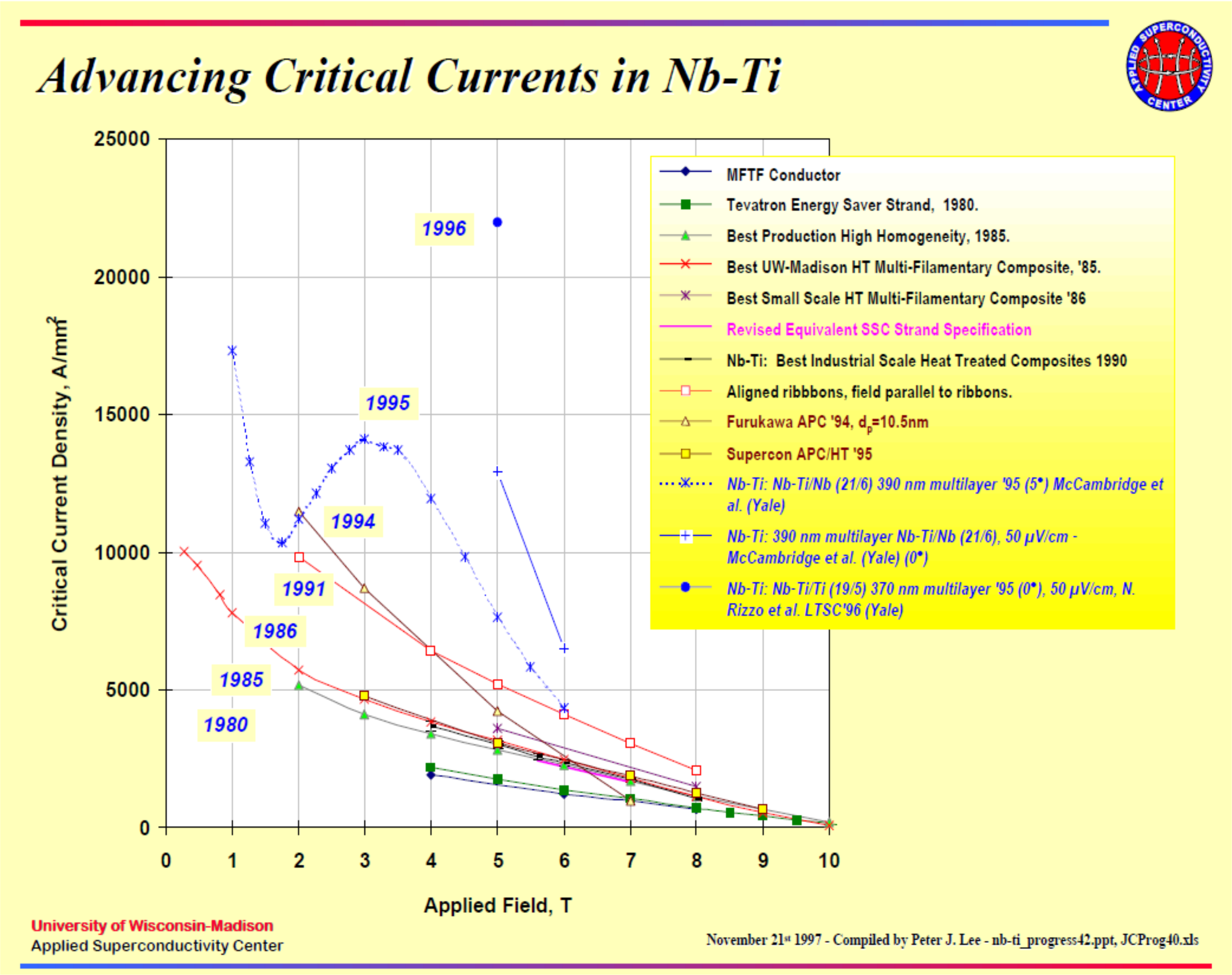
Conductor Landscape



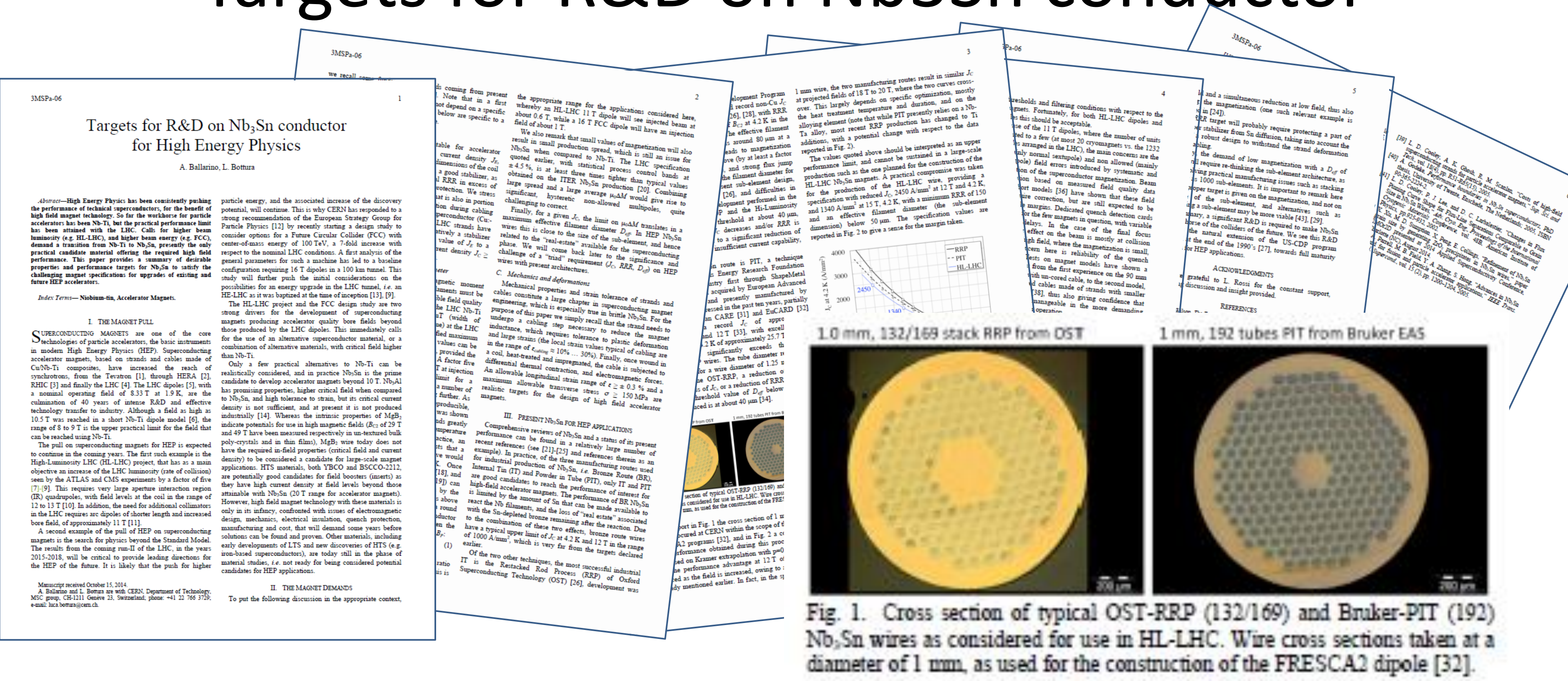
An analysis has been made at CERN of the different type of conductors, in particular with regard to the Whole Critical Current Density v.s .Applied Magnetic Field. (Peter Lee's Plot from NHMFL Florida State University webpage thanks)

A well known conductor :Nb-Ti

- No significant improvement during the past two decades! 10T
- Nb-Ti revisiting the optimisation of Niobium Titanium to achieve high Jc at desired fields! Why Not ?



Targets for R&D on Nb3Sn conductor



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Targets for R&D on Nb_3Sn conductor for High Energy Physics

A. Ballarino, L. Bottura

Abstract—**High Energy Physics has been consistently pushing the performance of technical superconductors, for the benefit of high field magnet technology. So far the workhorse for particle accelerators has been Nb-Ti, but the practical performance limit has been attained with the LHC. Calls for higher beam luminosity (e.g. HL-LHC), and higher beam energy (e.g. FCC), demand a transition from Nb-Ti to Nb_3Sn, presently the only practical candidate material offering the required high field performance. This paper provides a summary of desirable properties and performance targets for Nb_3Sn to satisfy the challenging magnet specifications for upgrades of existing and future HEP accelerators.**

Index Terms— **Niobium-tin, Accelerator Magnets.**

I. THE MAGNET PULL

SUPERCONDUCTING MAGNETS are one of the core technologies of particle accelerators, the basic instruments in modern High Energy Physics (HEP). Superconducting accelerator magnets, based on strands and cables made of Cu/Nb-Ti composites, have increased the reach of synchrotrons, from the Tevatron [1], through HERA [2], RHIC [3] and finally the LHC [4]. The LHC dipoles [5], with a nominal operating field of 8.33 T at 1.9 K, are the culmination of 40 years of intense R&D and effective technology transfer to industry. Although a field as high as 10.5 T was reached in a short Nb-Ti dipole model [6], the range of 8 to 9 T is the upper practical limit for the field that can be reached using Nb-Ti.

The pull on superconducting magnets for HEP is expected to continue in the coming years. The first such example is the High-Luminosity LHC (HL-LHC) project, that has as a main objective an increase of the LHC luminosity (rate of collision) seen by the ATLAS and CMS experiments by a factor of five [7]-[9]. This requires very large aperture interaction region (IR) quadrupoles, with field levels at the coil in the range of 12 to 13 T [10]. In addition, the need for additional collimators in the LHC requires arc dipoles of shorter length and increased bore field, of approximately 11 T [11].

A second example of the pull of HEP on superconducting magnets is the search for physics beyond the Standard Model. The results from the coming run-II of the LHC, in the years 2015-2018, will be critical to provide leading directions for the HEP of the future. It is likely that the push for higher particle energy, and the associated increase of the discovery potential, will continue. This is why CERN has responded to a strong recommendation of the European Strategy Group for Particle Physics [12] by recently starting a design study to consider options for a Future Circular Collider (FCC) with center-of-mass energy of 100 TeV, a 7-fold increase with respect to the nominal LHC conditions. A first analysis of the general parameters for such a machine has led to a baseline configuration requiring 16 T dipoles in a 100 km tunnel. This study will further push the initial considerations on the possibilities for an energy upgrade in the LHC tunnel, *i.e.* an HE-LHC as it was baptized at the time of inception [13], [9].

The HL-LHC project and the FCC design study are two strong drivers for the development of superconducting magnets producing accelerator quality bore fields beyond those produced by the LHC dipoles. This immediately calls for the use of an alternative superconductor material, or a combination of alternative materials, with critical field higher than Nb-Ti.

Only a few practical alternatives to Nb-Ti can be realistically considered, and in practice Nb_3Sn is the prime candidate to develop accelerator magnets beyond 10 T. Nb_3Al has promising properties, higher critical field when compared to Nb_3Sn, and high tolerance to strain, but its critical current density is not sufficient, and at present it is not produced industrially [14]. Whereas the intrinsic properties of MgB_2 indicate potentials for use in high magnetic fields (B_{C2} of 29 T and 49 T have been measured respectively in un-textured bulk poly-crystals and in thin films), MgB_2 wire today does not have the required in-field properties (critical field and current density) to be considered a candidate for large-scale magnet applications. HTS materials, both YBCO and BSCCO-2212, are potentially good candidates for field boosters (inserts) as they have high current density at field levels beyond those attainable with Nb_3Sn (20 T range for accelerator magnets). However, high field magnet technology with these materials is only in its infancy, confronted with issues of electromagnetic design, mechanics, electrical insulation, quench protection, manufacturing and cost, that will demand some years before solutions can be found and proven. Other materials, including early developments of LTS and new discoveries of HTS (e.g. iron-based superconductors), are today still in the phase of material studies, *i.e.* not ready for being considered potential candidates for HEP applications.

II. THE MAGNET DEMANDS

To put the following discussion in the appropriate context,

Manuscript received October 15, 2014.

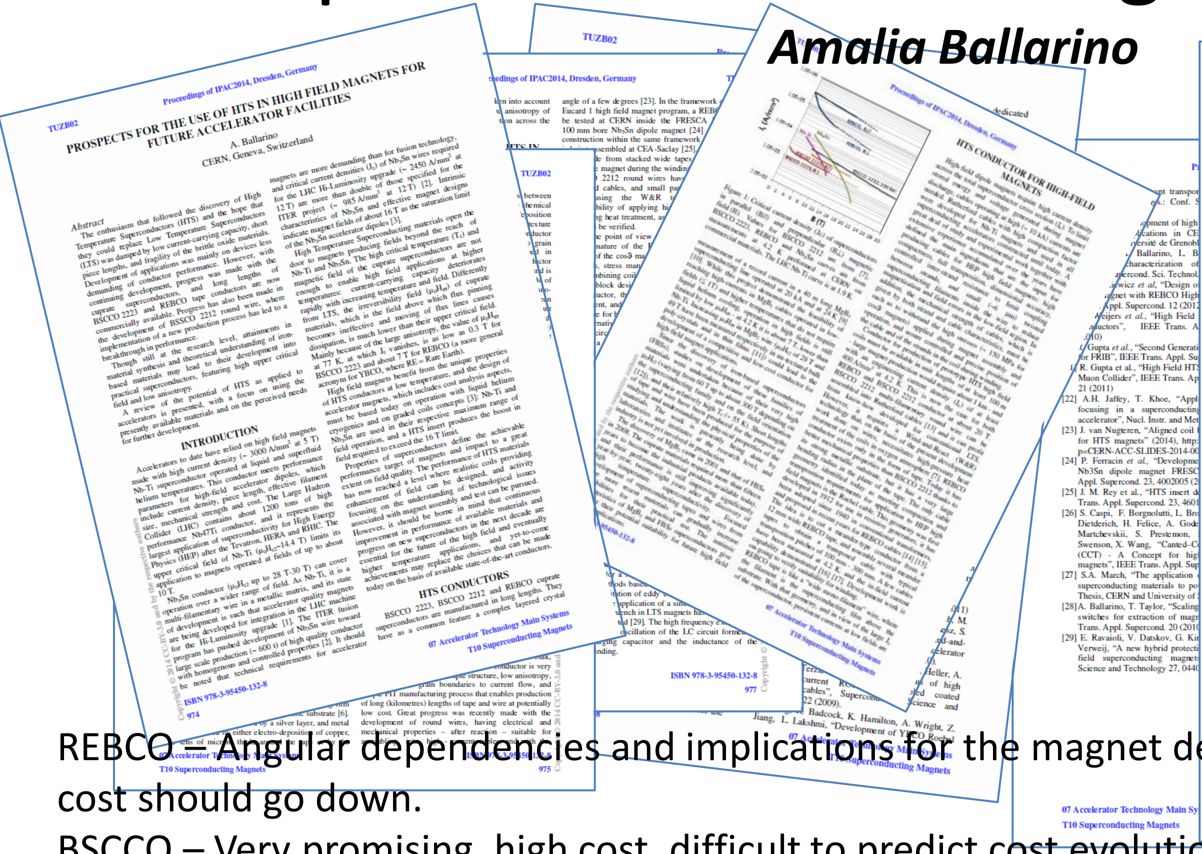
A. Ballarino and L. Bottura are with CERN, Department of Technology, MSC group, CH-1211 Genève 23, Switzerland; phone: +41 22 766 3729; e-mail: luca.bottura@cern.ch.

Fig. 1. Cross section of typical OST-RRP (132/169) and Bruker-PIT (192) Nb_3Sn wires as considered for use in HL-LHC. Wire cross sections taken at a diameter of 1 mm, as used for the construction of the FRESCA2 dipole [32].

Nb3Sn and corresponding magnet geometries. No major improvement factor to be expected. For Nb3Sn, PIT and RRP are competing. PIT is improving. Nb3Sn, Target for the upcoming high luminosity LHC is 2500 A/mm2 at 12 T.

Prospects for of HTS in high field magnets

Amalia Ballarino



TUZB02

Proceedings of IPAC2014, Dresden, Germany

PROSPECTS FOR THE USE OF HTS IN HIGH FIELD MAGNETS FOR FUTURE ACCELERATOR FACILITIES

A. Ballarino

CERN, Geneva, Switzerland

HTS CONDUCTOR FOR HIGH-FIELD MAGNETS

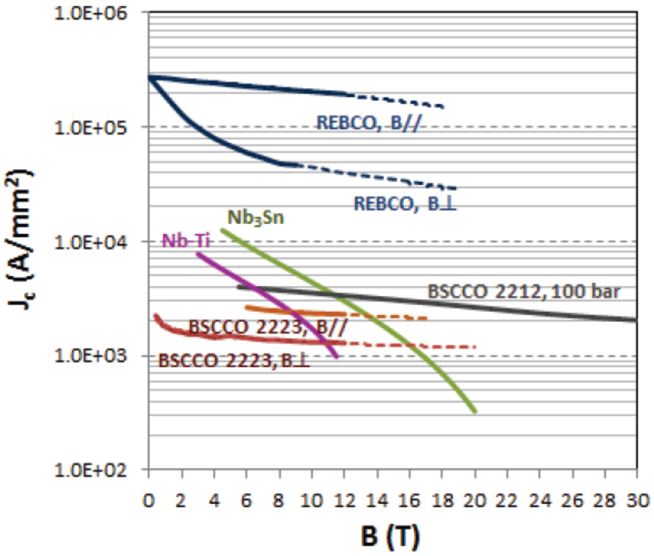


Figure 1: Critical current density (Jc) of superconductors in parallel (B//) and perpendicular (B⊥) magnetic field (B). Values for BSCCO 2212 are from [7], BSCCO2223, REBCO and Nb3Sn curves are from measurements at 4.2 K performed at CERN on commercial materials. The LHC Nb-Ti curve is at 1.9 K.

REBCO – Angular dependencies and implications for the magnet design. Major improvements expected, cost should go down.

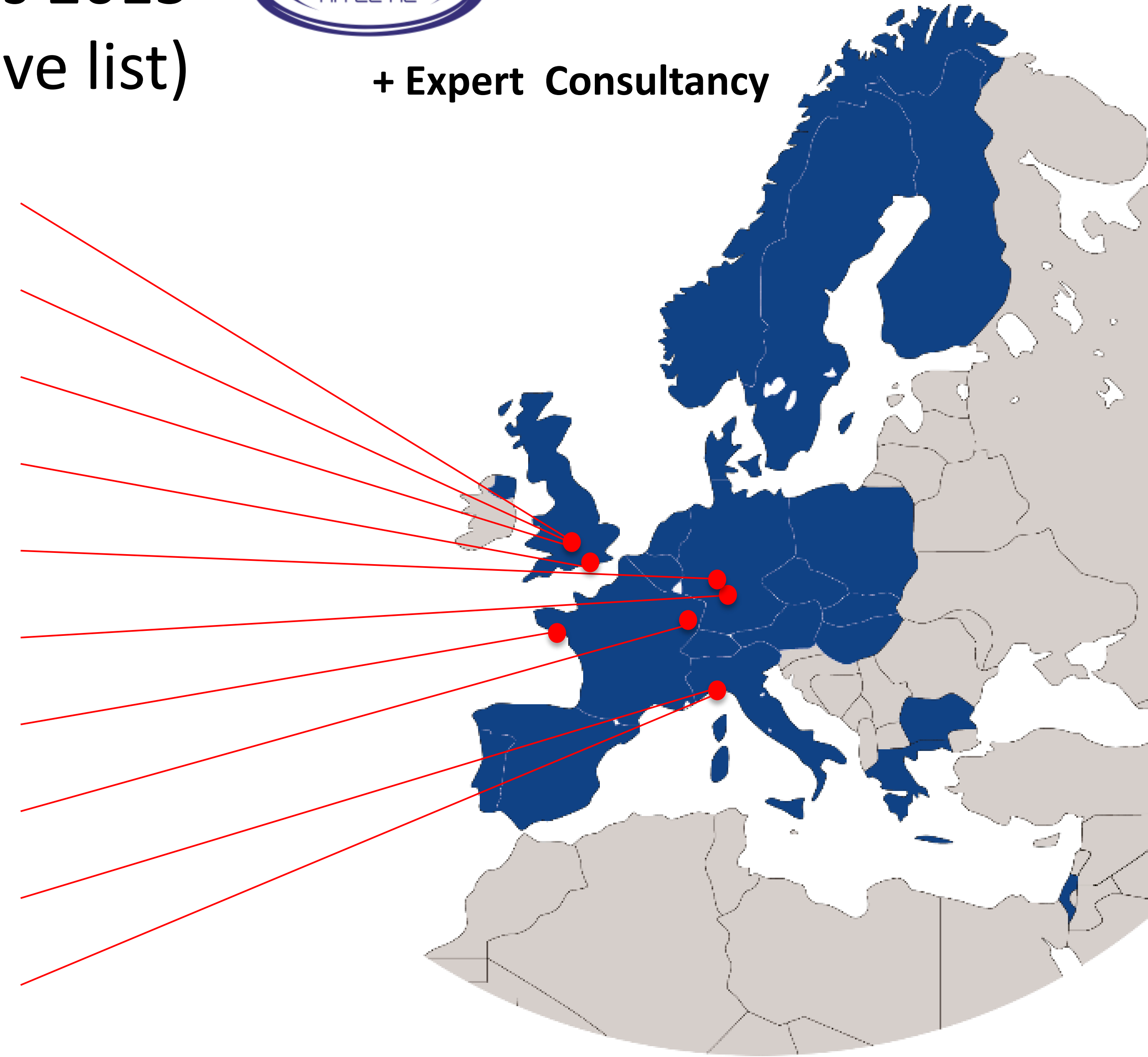
BSCCO – Very promising, high cost, difficult to predict cost evolution (new process).

The prospects for HTS paper by Amalia and Luca. With REBCO due to angular dependence and self-field the cosθ performance is presently compromised by a factor 2.3 in conductor volume due to the angular dependence.

The BSCCO conductor canted Cosine theta concept could be envisaged but needs development.

Company visits 2015 (Non-exhaustive list)

+ Expert Consultancy

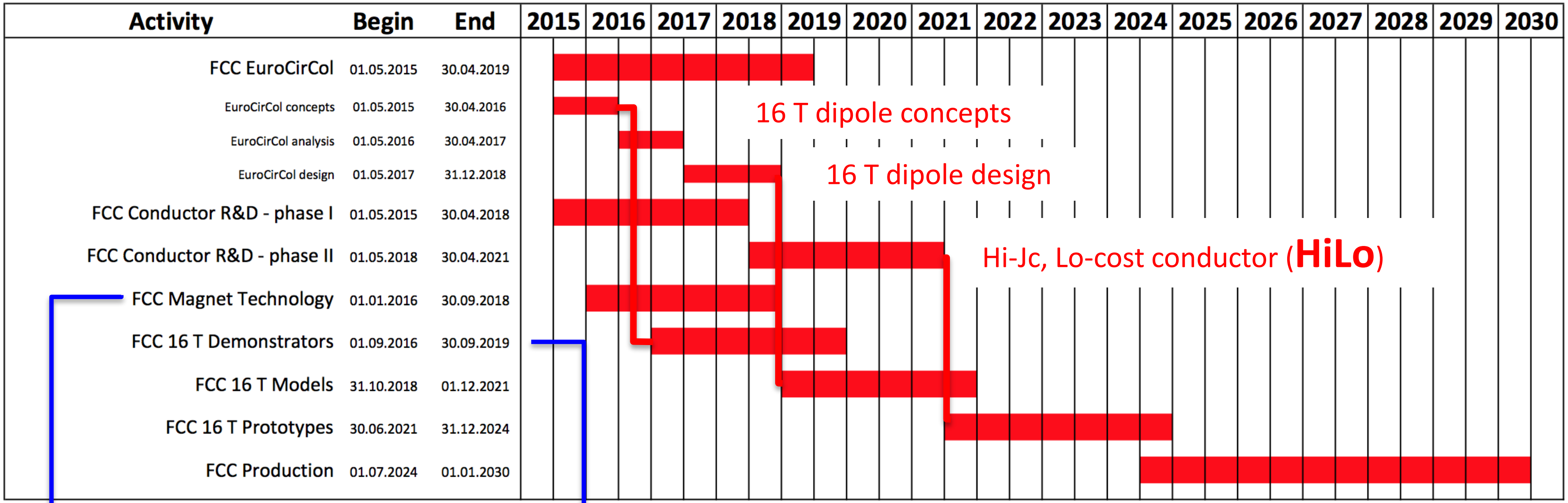


- Oxford Instruments
- SMT Siemens
- Scientific Magnetics
- Tesla
- Bruker
- Babcock Noell
- SigmaPhi
- Alstom
- Columbus
- ASG

Open to EoI

FCC ACCELERATOR ROADMAP: A plan for discussion 1/2

- Focus on the main course: LTS 16 T MB and conductor R&D

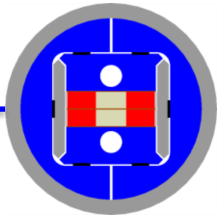


Activity	Begin	End
FCC EuroCirCol	01.05.2015	30.04.2019
EuroCirCol concepts	01.05.2015	30.04.2016
EuroCirCol analysis	01.05.2016	30.04.2017
EuroCirCol design	01.05.2017	31.12.2018
FCC Conductor R&D - phase I	01.05.2015	30.04.2018
FCC Conductor R&D - phase II	01.05.2018	30.04.2021
FCC Magnet Technology	01.01.2016	30.09.2018
FCC 16 T Demonstrators	01.09.2016	30.09.2019
FCC 16 T Models	31.10.2018	01.12.2021
FCC 16 T Prototypes	30.06.2021	31.12.2024
FCC Production	01.07.2024	01.01.2030

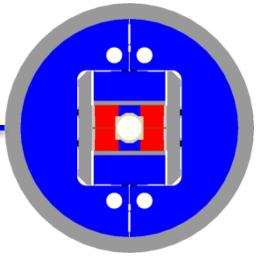
16 T dipole concepts

16 T dipole design

Hi-Jc, Lo-cost conductor (**HiLo**)



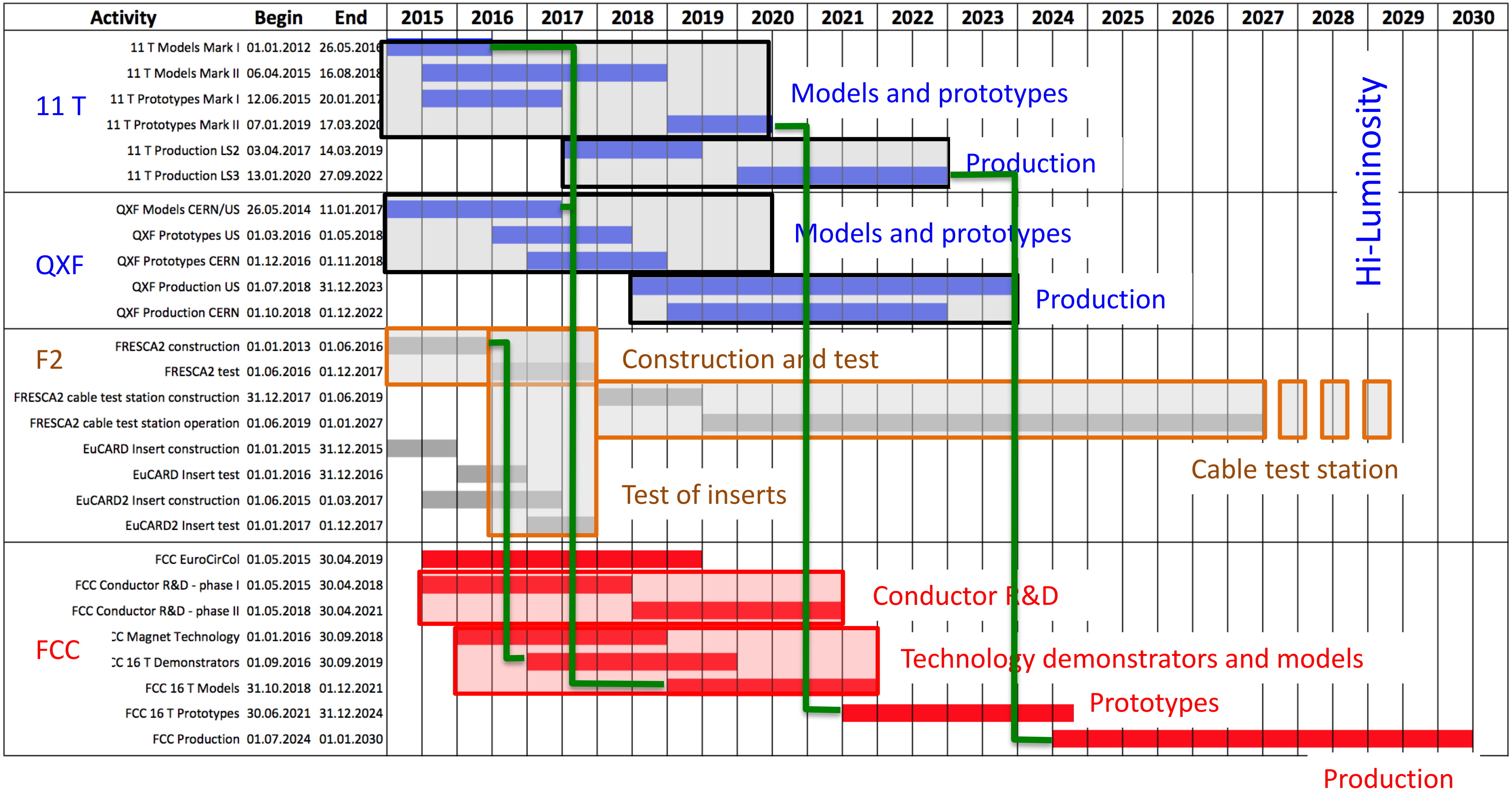
Technology: SC, SMC/RMC



Demonstrator: HD, *DMC*

My warm Thanks to Luca

FCC ACCELERATOR ROADMAP: A plan for discussion – 2/2



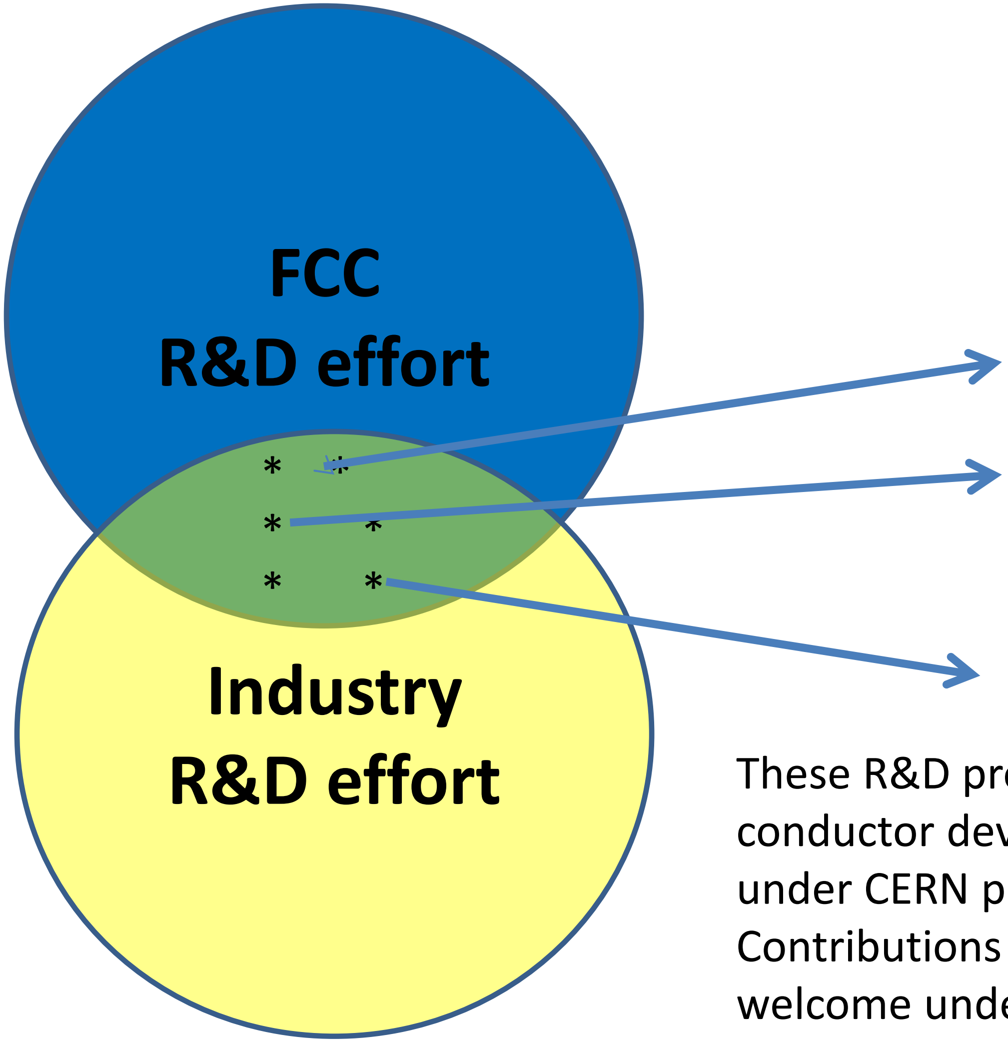
Activity	Begin	End
11 T Models Mark I	01.01.2012	26.05.2016
11 T Models Mark II	06.04.2015	16.08.2018
11 T Prototypes Mark I	12.06.2015	20.01.2017
11 T Prototypes Mark II	07.01.2019	17.03.2020
11 T Production LS2	03.04.2017	14.03.2019
11 T Production LS3	13.01.2020	27.09.2022
QXF Models CERN/US	26.05.2014	11.01.2017
QXF Prototypes US	01.03.2016	01.05.2018
QXF Prototypes CERN	01.12.2016	01.11.2018
QXF Production US	01.07.2018	31.12.2023
QXF Production CERN	01.10.2018	01.12.2022
FRESCA2 construction	01.01.2013	01.06.2016
FRESCA2 test	01.06.2016	01.12.2017
FRESCA2 cable test station construction	31.12.2017	01.06.2019
FRESCA2 cable test station operation	01.06.2019	01.01.2027
EuCARD Insert construction	01.01.2015	31.12.2015
EuCARD Insert test	01.01.2016	31.12.2016
EuCARD2 Insert construction	01.06.2015	01.03.2017
EuCARD2 Insert test	01.01.2017	01.12.2017
FCC EuroCirCol	01.05.2015	30.04.2019
FCC Conductor R&D - phase I	01.05.2015	30.04.2018
FCC Conductor R&D - phase II	01.05.2018	30.04.2021
C Magnet Technology	01.01.2016	30.09.2018
C 16 T Demonstrators	01.09.2016	30.09.2019
FCC 16 T Models	31.10.2018	01.12.2021
FCC 16 T Prototypes	30.06.2021	31.12.2024
FCC Production	01.07.2024	01.01.2030

FCC DETECTOR MAGNET ROADMAP

(Courtesy of Herman Ten Kate)

- The CDR must be ready in 3 years from now.
- Technology roadmap for conductor includes:
  - Micro alloying to reinforce the Aluminum jacket
  - Development of Cable in Conduit , close to fusion
  - Development of HTS Cable in Conduit , close to fusion DEMO !
  - NMR Aluminum stabilized conductor ?
- Technology roadmap needs careful analysis of the modularity as far as the coils are huge.

Outcome of the Fusuma Tech ad hoc WG



Around 5 R&D common projects on magnet technology to be implemented over 3 or 5 years together with industry and academics

These R&D projects may not be devoted to conductor development which is already under CERN perfect control.
Contributions of non european countries is welcome under the FCC coordination umbrella

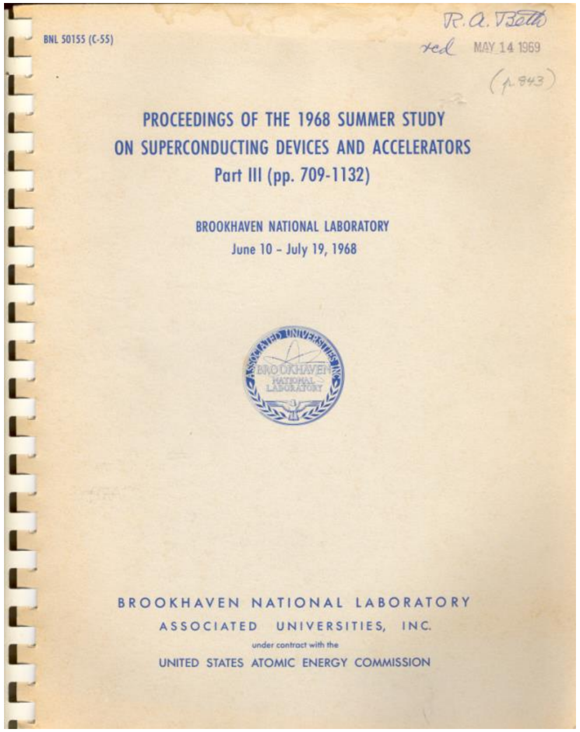
R&D shopping list : a first proposal

- Quench analysis new approach based on new computing capabilities and based on multiphysics
- Large material properties database
- Cold wireless instrumentation
- Quench detection and quench management
- Smart diagnostics
- Heat extraction
- Conductor R&D is mastered by companies under CERN leadership

Historical « love story » of HEP and Superconducting Magnet technology

Bruce Strauss , Feb 2013
FCC Design Study, Geneva,

To day we are at the beginning of a new big push and it's time for the old lovers to start a new romance and make babies !



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R.A. Beth
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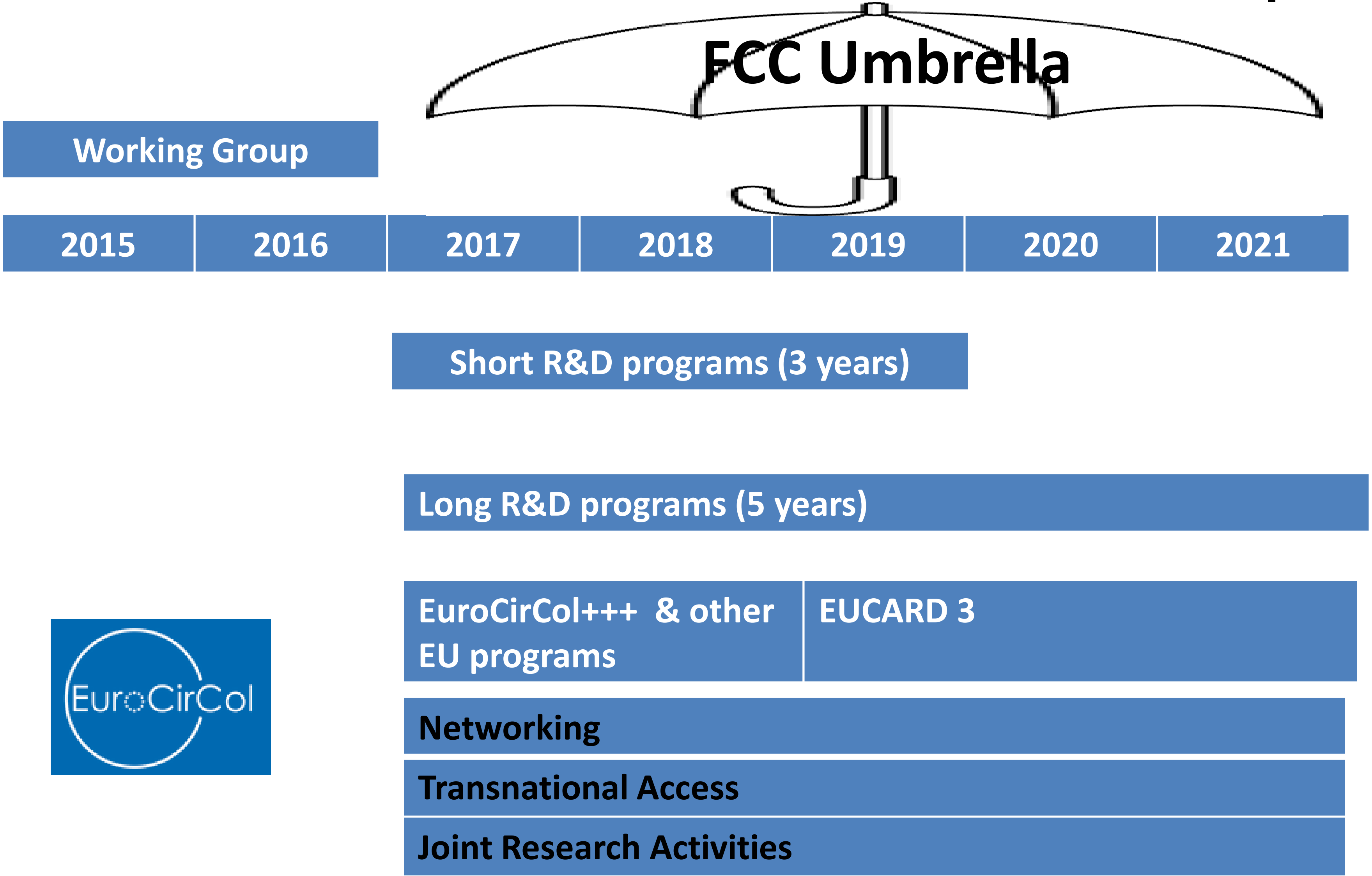
(p. 843)

PROCEEDINGS OF THE 1968 SUMMER STUDY
ON SUPERCONDUCTING DEVICES AND ACCELERATORS
Part III (pp. 709-1132)

BROOKHAVEN NATIONAL LABORATORY
June 10 – July 19, 1968

BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.
under contract with the
UNITED STATES ATOMIC ENERGY COMMISSION

« FuSuMaTech » Overall roadmap



Best practices of European Language

- **Networking:**Ways for horizontal interaction with the company at expert level (technical contacts, newsletters, document servers, technical/scientific events, etc.)
- **Transnational Access: «** CERN and also laboratories will support a wide access to existing infrastructures for Industry » (Lucio ROSSI)
- **Joint Research Activities:** Real prototypes. « FCC will be built by industry » (Lucio Rossi)

“The future is just around the corner”
Rolf HEUER , CERN DG

- CERN as worlwide HEP Lab is leading a huge effort for HL-LHC Project and for FCC study.
- The teams are working at the frontier edge
- Industry is also working at the frontier edge in superconducting magnet technology
- There is an endless list of technology challenges
- We are volunteers to share R&D on technology blocks in a win-win strategy with industrial companies interested in applications.
- So please come on board and join us !