Goodbye RD50

21 years of very successful R&D on semiconductor detectors for High Energy Physics applications

HOW DID WE MANAGE TO DO IT?

Michael Moll
CERN EP-DT, Geneva, Switzerland
Outline

A historical (quite statistical) look back into 21 years of RD50 *(in 20+ minutes)* complementing the presentation of Mara on the RD50 early days

- RD50 collaboration
- RD50 organization and interaction with the LHCC/Research Board
- RD50 workshops
  - .... many wonderful events and stories to remember (see special talk by Gregor)
- RD50 common projects
- RD50 achievements & impact on HEP instrumentation
  - .... just a teaser, as we will have a series of very nice talks on this:
    - Frank: HL-LHC upgrade & RD50, Gian: p-type sensors; Maurizio: 3D sensors, Giulio: LGAD, Marcos: instrumentation; Ioana: Fundamentals of radiation damage; Joern/Marco: Simulations; Eva: CMOS
- RD50: Mission accomplished? Yes!
21 years of R&D
How did we manage?

- **R&D on silicon detectors for HEP applications**
  - 1990-1994 RD2 on silicon detectors & electronics
  - 1995-2000 RD48 (ROSE) radiation hard silicon detectors
  - 23-24.10.2000 6th (and last) ROSE Workshop
    - First discussions on how to continue start …..

- **2001/2002: The RD50 story begins:**
  - 28-31 Nov. 2001 “1st Workshop on Radiation Hard Semiconductor Devices for Very High Luminosity Colliders” (~100 participants)
    - Proposal driving/writing: C.Da Via, M.Moll, C.Joram
    - Spokesperson search: “3 wise men” W.de Boer, E.Heijne, P.Weilhammer
    - 45 institutes and 2 industrial partners
    - Spokespersons: Mara Bruzzi (Florence) and Claude Leroy (Montreal)
    - Collaboration Board Chair: Eckhart Fretwurst (Hamburg)
  - 14/15 March 2002: Discussion of Proposal in LHCC closed session
  - 15/16 May 2002: Proposal presented to LHCC (open session)
  - 30 May 2002: Proposal approved by Research Board as RD50

- …followed by 21 years of RD50 research work (2002-2023)

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The ROSE Collaboration
CERN - RD48

ROSE

Research and development
On Silicon for future Experiments

RD58 Spokespersons:
Dr. Francois Lemeilleur
Prof. Dr. Dr. hc. Gunnar Lindstrom
Prof. Dr. Stephen J. Watts

ROSE representative at CERN:
Dr. Michael Moll

About ROSE

Three co-spokespersons (Fotos: 1999/2000)

Stephen J. Watts
Gunnar Lindstroem
Francois Lemeilleur

28 November 2023
Michael Moll - Goodbye RD50 - 21 years of RD50
The main mission of RD50 was the development of radiation hard detectors for “HL-LHC”

Did we manage? Yes! - We fulfilled this mission with bravura and can be proud about the output/impact!

How did we manage?
The RD50 Collaboration

“Individually, we are one drop. Together, we are an ocean.”
Ryunosuke Satoro
The RD50 Collaboration – 2002/2003

Proposal 2002 (45 institutes)

R&D Proposal

DEVELOPMENT OF RADIATION HARD SEMICONDUCTOR DEVICES FOR VERY HIGH LUMINOSITY COLLIDERS

signed by 45 institutes (231 members)

The proposed program covers the following research fields:

- Radiation damage basic studies, defect modeling and device simulation
- Oxygenated silicon and oxygen dimered silicon
- 3D and thin devices
- Forward bias operation
- Other detector materials, like SiC

First report to LHCC in 2003 (55 Institutes)

RD50 - Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

280 Members from 55 Institutes

Main Objective

Development of ultra-radiation hard semiconductor detectors, able to withstand fast hadron fluences and doses as expected for luminosity upgrade of the LHC to $10^{38}$ cm$^{-2}$s$^{-1}$.

47 European and Asian institutes (34 west, 11 east)
Belgium (Louvain), Czech Republic (Prague 2x), Finland (Helsinki 2x, Oulu), Germany (Berlin, Dortmund, Erlfurt, Halle, Hamburg, Karlsruhe), Greece (Athens), Italy (Bari, Bologna, Florence, Milano, Modena, Padova, Perugia, Pisa, Trento, Trieste, Turin), Lithuania (Vilnius), Norway (Oslo 2x), Poland (Warsaw), Romania (Bucharest 2x), Russia (Moscow 2x, St.Petersburg), Slovenia (Ljubljana), Spain (Barcelona, Valencia), Sweden (Lund) Switzerland (CERN, PSI), Ukraine (Kiev), United Kingdom (Exeter, Glasgow, Lancaster, Liverpool, London, Sheffield, University of Surrey)

7 North American institutes
Canada (Montreal), USA (Fermilab, Purdue University, Rutgers University, Syracuse University, BNL, University of New Mexico)

1 Middle East institute
Israel (Tel Aviv)

Detailed member list: http://www.cern.ch/rd50

Michael Moll - Goodbye RD50 - 21 years of RD50
The RD50 Collaboration : 2002-2023

Evolution of number of participating institutes

- Overall, a very stable participation in RD50 with some increase in recent years (from 2016)
- 2002: several institutes joining after approval
- 2005-10: slow decrease mainly due to solid state physics groups leaving and decreasing interest in non-silicon materials
- 2016-20: increase with re-focus on non-silicon materials, more interest in CMOS and Chinese groups joining
The RD50 Collaboration – November 2023

• RD50: 65 institutes and 440 members

51 European institutes
Austria (HEPHY), Belarus (Minsk), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), France (Marseille, Paris, Orsay), Germany (Bonn, Dortmund, Freiburg, Göttingen, Hamburg (Uni & DESY), Karlsruhe, Munich (MPI & MPG HLL)), Greece (Demokritos), Italy (Bari, Perugia, Pisa, Trento, Torino), Croatia (Zagreb), Lithuania (Vilnius), Montenegro (Montenegro), Netherlands (NIKHEF), Poland (Krakow), Romania (Bucharest), Russia (Moscow, St. Petersburg), Slovenia (Ljubljana), Spain (Barcelona(2x), Santander, Sevilla (2x), Valencia), Switzerland (CERN, PSI, Zurich), United Kingdom (Birmingham, Glasgow, Lancaster, Liverpool, Oxford, Manchester, RAL)

8 North-American institutes
Canada (Ottawa), USA (BNL, Brown Uni, Fermilab, LBNL, New Mexico, Santa Cruz, Syracuse)

7 Asian institutes
China (Beijing-IHEP, Dalian, Hefei, Jilin, Shanghai), India (Delhi), Israel (Tel Aviv)

Full member list: www.cern.ch/rd50
The RD50 Research Work Organization

“Leadership is the art of giving people a platform for spreading ideas that work.” Seth Godin
RD50 – Organization of research work

- RD50 is headed by a **Spokesperson** & **Deputy Spokesperson** (2002-2004) and from 2005 onwards by a team of two **Co-spokesperson** (≥ 2005).
- The work is organized in **Research Lines**, which are led by **Research Line Conveners**.
- The number of Research Lines is flexible and changes over time as needed by the R50 Research Program.

**2002 – The first RD50 Organigram**

- **Spokesperson**
  - *Mara Buzzi*
  - INFN and University of Florence

- **Deputy-Spokesperson**
  - *Claude Leroy*
  - INFN and University of Florence

**Defect / Material Characterization**
- Bregt Swerts (OOS University)
- Defect formation, defect annealing, energy states, ... 
- Post-irradiation TSC, DUS, DPM, PICTS...

**Defect Engineering**
- Eckhart Frevert (Hamburg University)
- Oxygenation
- Dimerization
- Other impurities H, N, C, ...
- Thermal donors
- Pre-irradiation procedures

**New Materials**
- Aneta V. Fuchs (Viita University)
- SC
- CTe
- other materials

**Macroscopic Effects**
- Simon Proctor (Rutgers University)
- Test structure characterization
- Cost effective solutions
- 3D detectors
- Thin detectors
- Pre-irradiation
- Device modeling
- Operational conditions

**New Structures**
- Mohsinur Rahman (Glaz Universität)
- NIEL

**Full Detector Systems**
- Convenor to be nominated
- LHC-like tests
- Links to HEP
- Links to R&D of electronics
- Comparison: pad-mmt-full detectors

**2003 – RD50 Organigram**

- **Spokesperson**
  - *Mara Buzzi*
  - INFN and University of Florence

- **Deputy-Spokesperson**
  - *Michael Moll*
  - CERN

**Defect / Material Characterization**
- Bregt Swerts (OOS University)
- Characterization of microscopic properties of standards, defect engineered and new materials pre- and post-irradiation
- DETS Calibration (R.Swerts)

**Defect Engineering**
- Eckhart Frevert (Hamburg University)
- Development and testing of new materials with promising radiation hard properties
- De-pitching
- 3D detectors
- Pre-irradiation
- Oxygen Dimer (M. Moll)

**New Materials**
- Aneta V. Fuchs (Viita University)
- NIEL
- other materials

**Pad Detector Characterization**
- Jaakko Hiltunen (Helsinki HIF)
- Characterization of microscopic properties of heavily irradiated single pad detectors in different operational conditions
- Common irradiation
- Standardization of microscopic measurements (A. Chilingarova)
- Systematic channel of segmented microstrip pixels LHC-like detectors. Links with LHC experiments
- Comparison of detectors made by different producers

**New Structures**
- Mohsinur Rahman (Glaz Universität)

**Full Detector Systems**
- Gianluigi Cossutti (Geneva University)

2003: project leaders added
• 2006: RD50 concludes that SiC and GaN are not relevant for Hi-Lumi LHC
• The New Materials Research Line is suppressed; work on WBG materials continued with lower priority
RD50 – Organization of research work

- 2022: The organizational structure was about to change (but the end of RD50 was announced)
  - “WBG & New Materials” and “CMOS Monolithic sensors” deserve their own research lines
  - Radiation Hardness no longer the main goal of the collaboration; Precision timing, spacial resolution, low cost, low mass, low power were since long getting more and more emphasis in the research program.

2023 – RD50 Organigram

Co-Spokespersons
Gianluigi Casse (Liverpool University, UK) and Michael Moll (CERN EP-DT)

Defect / Material Characterization
Ioana Pintilie (NIMP Bucharest)
- Characterization of microscopic properties of standard-.defect engineered and new materials; pre- and post- irradiation
- DLTS, TSC, ...
- SIMS, SR, ...
- NIEL (calculations)
- Cluster and point defects
- Boron related defects
- SiC/GaN based detectors

Detector Characterization
Eckhart Freyward (Hamburg University)
- Characterization of test structures (IV, CV, CCE, TCT,)
- Development and testing of defect engineered devices
- EPI, MCZ and other materials
- NIEL (experimental)
- Device modeling
- Operational conditions
- Common irradiations
- Very high radiation fluences
- Water procurement (M.Moll)
- Acceptor removal (Kramberger)
- TCAD modeling (U.Schwandt)

New Structures
Giulio Pellegrini (CNM Barcelona)
- 3D detectors
- Thin detectors
- Cost effective solutions
- Other new structures
- Detectors with internal gain
- LGAD: Low Gain Avalanche Det.
- Deep Depleted Avalanche Det.
- Slim Edges
- HCMOS
- LGAD (S.Hidalgo)
- HCMOS (E. Villegas)

Full Detector Systems
Gregor Kramberger (Ljubljana University)
- LHC-like tests
- Links to HEP (LHC P2, FCC)
- Links electronics R&D
- Low no strips
- Sensor readout (Canbou, Albaipa)
- Comparison:
  - pad-mini full detectors
  - different producers
- Radiation Damage in HEP detectors
- Timing detectors
- Test beams
  (M.Bombe & G.Casse)

Covering all fields of semiconductor detectors exposed to radiation

Targeting new solid-state detector technologies including high precision 4D detectors

RD50 work program and key achievements documented in a 5yrs work plan
2018-2023 (70 milestones)
[LHCC-SR-007]
Roles within RD50 today [2023]

• Spokespersons
  • Gianluigi Casse (Liverpool University)
  • Michael Moll (CERN EP-DT)

• Research Line Conveners
  • Ioana Pintilie (NIMP, Bucharest)
  • Eckhart Fretwurst (Hamburg Uni)
  • Giulio Pellegrini (IMB-CNMI, Barcelona)
  • Gregor Kramberger (JSI Ljubljana)

• Budget Holder – Resource coordinators
  • Maurice Glaser (budget), in Brazil (retired)
  • Michael Moll (projects, official budget holder)
  • Veronique Wedlake (invoicing)

• RD50 common projects management
  • Michael Moll (CERN)
  • Ruddy Costanzi – support (CERN)

• GLIMOS
  • GLIMOS: Ruddy Costanzi (CERN EP-DT)
  • Deputy: Michael Moll (CERN)
  • LSSO: Marcos Fernandez Garcia (IFCA)

• CERN contact person
  • Michael Moll (CERN)

• Conference participation
  • Ulrich Parzefall (Freiburg University)

• Secretary at CERN
  • Veronique Wedlake (CERN)

• Web site, member database, mailing lists, computer accounts, ..... 
  • Michael Moll (CERN)

• Collaboration Board
  • Chairman: Gregor Kramberger (Ljubljana)
  • Deputy: Daniel Münstermann (Lancaster)

• RD50 Project Funding Committee
  • Conveners and spokespersons
  • Chair: Michael Moll (CERN)
RD50 – Outstanding Contributions Award

- For outstanding contributions in running the RD50 collaboration

Maurice Glaser
“RD50 budget holder”
continued working even so
Maurice is retired since many
years and living in Brazil!

Véronique Wedlake
RD50 secretariat
always ready to help
even if RD50 is only one item
on her very long task list as EP-DT secretary
RD50 Hall of Fame [2002-23]

• Spokespersons
  • Mara Bruzzi (2002-10)
  • Michael Moll (2005-23)
  • Gianluigi Casse (2010-23)
• Deputy Spokespersons
  • Claude Leroy (2002)
  • Michael Moll (2003-05)
• Collaboration Board Chairs
  • Eckhart Fretwurst (2002-11)
  • Gregor Kramberger (2011-23)
• Deputy CB Board Chairs
  • Gianluigi Casse (2002-10)
  • Juosaz Vaitkus (2010-21)
  • Daniel Münstermann (2021-23)
• Research Line Conveners
  • Richard Bates (2004-2011)
  • Mara Bruzzi (2010-2015)
  • Gianluigi Casse (2002-2010)
  • Eckhart Fretwurst (2002-2023)
  • Jaakko Härkönen (2003-2004)
  • Gregor Kramberger (2005-2023)
  • Giulio Pellegrini (2012-2023)
  • Ioana Pintilie (2015-2023)
  • Stanislav Pospisil (2002)
  • Bengt Svensson (2002-2009)
  • Juozas Vaitkus (2002-2004)
  • Elena Verbitskaya (2005-2006)
• Project leaders
  • Many collaboration members took commitment in leading common projects or other common activities
• CERN contact person
  • Michael Moll (2002-23)
• Budget holders
  • Christian Joram (2002-04)
  • Maurice Glaser (2004-16)
  • M.Moll/M.Glaser (2016-23)
• common projects handling
  • Christian Joram (2002-04)
  • Michael Moll (2004-23)
• secretariat
  • Veronique Wedlake
• conferences
  • Ulrich Parzefall
• website, member databases
  • Michael Moll (2002-23)
• safety officers
  • M.Glaser (EXSO)
  • R.Costanzi (EXSO)
  • M.Fernandes (LSSO)

RD50 management based on a small but long-term committed and efficient team operating in a lightweight organizational structure (only 22 different names in the lists above!). RD50 success is based on the RD50 members!

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RD50 Memorial

**Bengt Gunnar Svensson**
Oslo University
(1953-2018)

**Olaf Krasel**
Dortmund University
(1975-2010)

**Jaakko Härkönen**
Helsinki Institute of Physics
(1972-2021)

**Gino Bolla**
Fermilab
(1968-2016)

**Reiner Klingenberg**
Dortmund University
(1965-2017)

**Tuurė Tuuva**
Lappeenranta University
(1957-2021)

**Willem de Boer**
Karlsruhe University
(1948-2020)

**Aurimas Uleckas**
Vilnius University
(31.1.2013)
LHCC: Monitoring of RD50
RD50: Reporting to LHCC
Interaction with the LHCC

**CERN – Research Board**
- **Chairperson:** CERN Director-General

**LHCC – Large Hadron Collider Committee**

- Reporting to LHCC (yearly reports)
- Approval for continuation

**20 years of reporting to LHCC**

- **LHCC chairpersons**
  - Sergio Bertolucci (2004-2006)
  - Terry Wyatt (2007-2010)
  - Eckhart Elsen (2011-2014)
  - Francesco Forti (2015-2018)
  - Frank Simon (2019-2023)

- **LHCC referees for RD50**
  - Claude Vallée (2003-3004)
  - Rick Yoshida (2005-2008)
  - Andrei Nomerotski (2008-2012)
  - Katja Krüger (2018-2021)
  - Daniela Calvo (2022)

- **LHCC reporting for RD50**
  - Mara Bruzzi, Michael Moll (2002-10)
  - Gianluigi Casse, Michael Moll (2011-22)

**CERN DGs**
- 1999-2003 Luciano Maiani
- 2004-2008 Robert Aymar
- 2009-2015 Rolf-Dieter Heuer
- 2016-2025 Fabiola Gianotti

**LHCC chairpersons**
- Sergio Bertolucci (2004-2006)
- Terry Wyatt (2007-2010)
- Eckhart Elsen (2011-2014)
- Francesco Forti (2015-2018)
- Frank Simon (2019-2023)

**LHCC referees for RD50**
- Claude Vallée (2003-3004)
- Rick Yoshida (2005-2008)
- Andrei Nomerotski (2008-2012)
- Katja Krüger (2018-2021)
- Daniela Calvo (2022)

**LHCC reporting for RD50**
- Mara Bruzzi, Michael Moll (2002-10)
- Gianluigi Casse, Michael Moll (2011-22)
LHCC & Research Board feedback

- 20 years of positive experience in interaction with the LHCC
  - LHCC: constructive feedback and important leverage to communicate with management, FAs, CERN
  - LHCC: always very positive regarding RD50

The RD50 collaboration reported on their progress within their 5-year workplan approved by the CERN Research Board in June 2018. Many new results were shown in the open session, with most milestones achieved or in progress. RD50 is a very active collaboration serving as a central forum for experts from all experiments. Key topics continue to be the study of radiation damage in silicon, extreme timing applications, and more generally new structures for LGADs, 3D and CMOS, which are gaining in importance. The RD50 model of collaboration between institutes and industry works remarkably well even with minimal funding (2kCHF/year per institute).

June 2013: LHCC minutes (CERN-LHCC-2013-012; LHCC-114)

The LHCC considers that the RD50 is an active, productive and diversified R&D Collaboration. The LHC experiments have profited from the work of RD50 and their work is vital for the upgrades of the LHC experiments and for other experiments as well.

September 2021: LHCC minutes (CERN-LHCC-2021-015; LHCC-147)

The LHCC recommends continuing the RD50 collaboration, including CERN support at the level currently provided. The LHCC notes that the CERN contribution to RD50 (access to facilities, person power) is crucial, and strongly encourages CERN to maintain its support of RD50. The LHCC congratulates RD50 for the progress made since the last report.

September 2020: LHCC minutes (CERN-LHCC-2020-006; LHCC-143)

The LHCC congratulates RD50 on its achievements over the last year and recommends continuing the support for RD50 for another year.

The LHCC recognizes the importance of the RD50 developments for the HL-LHC upgrades, and notes that in particular ATLAS and CMS have already significantly profited from RD50 developments.

The LHCC requests a plan to be developed for the next three years, with clearly identified and traceable milestones and goals.

May 2017: LHCC minutes (CERN-LHCC-2017-007; LHCC-130)

September 2022: LHCC minutes (CERN-LHCC-2022-014; LHCC-151)
The RD50 MoU

*Memorandum of Understanding*
The RD50 MoU (..as lightweight as possible)

• Jan. 2001: Christian Joram (supported by M. Moll) write the first version of the MoU
• Oct. 2002: RD50 Collaboration Board (CB) approves the first version of the MoU
  • The approval by the CB is deemed sufficient!
    • no signatures of Funding Agencies (FAs), institute directors or CERN directorate or FAs - unthinkable today!
• 2002-2005: smaller changes to MoU, always with approval of CB
  • Detailing of specific rules (e.g. for common projects) are documented in CB minutes
    • today they would require the formulation/update of an Annex to the MoU
• 2005-2019: no changes to MoU (at least I cannot remember)

• 2016: First requests to establish a “modern” MoU appear
  • Needed by some RD50 institutions to continue contributing to RD50
  • Requested by CERN to justify the existence of RD50 activities
  • 2018/19 MoU writing: Gregor, Ioana and Michael
    .... with a lot of discussions inside CERN and the RD50 institutes
• 2019: MoUs are signed starting from June 2019 ..... 
  • One Annex per Institute (or Funding Agency) signed by CERN and Institute (or Funding Agency)
• 2022: most recent signature of 2019 Collaboration members, … not all institutes signed

CERN-MoU-2019-023
The RD50 Logo
The RD50 Logo

- 2016: RD50 logo competition
- Logo selected by voting of all institutes

Winner Logo designed by:
Marco Milovanović

Many Thanks Marco!

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Michael Moll - Goodbye RD50 - 21 years of RD50
The RD50 Workshops

..where knowledge is shared, ideas are born, and the collaboration starts ..

"Coming together is a beginning. Keeping together is progress. Working together is success."

Henry Ford
RD50 workshops
43 workshops in 21 years!

• R&D Workshop, CERN, 28-30 November 2001
  • Followed by writing and submission of proposal, approval…
  • Formation of the Collaboration “Radiation hard semiconductor devices for very high luminosity colliders” (25.2.2002)
  • Approval as RD50 collaboration (June 2002)

• 1st RD50 Workshop, CERN, 2-4. October 2002
• ...
• ...
• ...

• 43rd RD50 Workshop, CERN, 28.November to 1.December 2023
  • “The last RD50 Workshop”

In 21 years
43 RD50 Workshops
with
≈ 1571 talks
≈ 215 discussion rounds
≈ 255 coffee breaks
2500 litres of coffee
40 Gala Dinners
43 RD50 Workshops

• Two RD50 workshops per year
  • One at CERN and one at an RD50 Institute
  • The two most important R&D events every year (for many of us)
    • Short presentations (20 min) with in-depth discussion sessions for each research line
    • Open discussions in friendly atmosphere
    • Opportunity for young researchers to get known and present their work to experts in the field
    • Events where new ideas are born and R&D plans are forged
  • Social contact (..from colleagues to friends)

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39 Workshops in Europe (21 at CERN)
3 online Workshops

1 Workshop in the USA
May 2004: 4th RD50 Workshop in Geneva

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Eugenius Gaubas
Michael Moll
Bengt Svensson
Pawel Kaminski
Sergey Korjenevski
Roman Kozlowski
Ralf Roeder
Alex Chilingarov
Paul Sellin
Giulio Pellegrini
Alexander Furgeri
Maurizio Boscardin
Andrea Candelori
Vladimir Eremin
Nicola Zorzi
Igor Mandic
Vladimir Cindro
Alison Bates

Daniela Bortoletto
Arie Ruzin
Giorgio Pignatel
Mara Bruzzi
Zheng Li
Donato Creanza
Manuel Lozano
Hartmut Sadrozinski
Claudio Piemonte
Gabriele Segneri
Gregor Kramberger
Eckhart Fretwurst

Nicola Zorzi
June 2006: 8th RD50 Workshop in Prague

RD50 budget holder at work
RD50 Workshops

June 2007 : Vilnius
10th RD50 Workshop

June 2008 : Ljubljana
12th RD50 Workshop

June 2012 : Bari
20th RD50 Workshop
RD50 Workshops

June 2009 : Freiburg
14th RD50 Workshop

June 2010 : Barcelona
16th RD50 Workshop

June 2022 : CERN

Freiburg 2009

October 2002 : CERN

June 2022 : CERN

Barcelona 2010

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31
RD50 Workshops

June 2005 : Helsinki
6th RD50 Workshop

May 2004 : CERN
4th RD50 Workshop

June 2017 : Krakow
30th RD50 Workshop

June 2015 : Santander
26th RD50 Workshop

28 November 2023
Michael Moll - Goodbye RD50 - 21 years of RD50
…impossible to cover all these nice workshops and ‘stories’ here

….more in Gregor’s presentation and during the RD50 farewell drink this evening
RD50 Workshop statistics

- RD50 Workshops (until 2019): <35 talks> <72 participants>
- RD50 Workshops (since 2020)*: <43 talks> <180 participants>

- 2002-23 RD50 Workshops
  - continuous high interest of collaboration members in the workshops: success!

- June/Nov. 2020 and June 2021
  - COVID forces us into online workshops
  - record high participation (up to > 50% of collaboration members participate!)
  - ‘COVID lessons’ learned for workshops:
    - Hybrid workshops enlarge the reach within the collaboration (travel limitations)
    - Social contacts are essential! (we need to know each other)

- from November 2021 onwards
  - shifting from 3 to 4 days workshops to cope with the increasing interest in the RD50 workshops and the increasing number of RD50 members

* 43rd RD50 Workshop (last RD50) only preliminary data
28.11-1.12.23 not included in statistics
The RD50 Work Plan

“A goal without a plan is just a wish”
Antoine de Saint-Exupéry
RD50 – 5 Year Work Plan

- 5 year work program submitted in May 2018
  - Approved by CERN Research Board in June 2018

- Workplan [70 milestones]
  - Defect and Material Characterization [16 MS]
    - p-type silicon [7 MS]
    - Cluster defects [4 MS]
    - Theory of defects [5 MS]
  - Device Characterization & Device Simulation [21 MS]
    - Silicon materials [5 MS]
    - Extreme fluences [5 MS]
    - Experimental techniques [3 MS]
    - Surface damage [1 MS]
    - TCAD simulations [7 MS]
  - New structures [21 MS]
    - 3D sensors [6 MS] ; LGAD [4 MS]
    - CMOS [6 MS] ; New Materials [5 MS]
  - Full Detector Systems [12 MS]
    - LHC [7 MS] ; HL-LHC [3 MS]
    - FCC [2 MS]

Covering RD50 activities until 31.12.2023


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The RD50 Common Projects

..where innovation and brilliant ideas are turned into reality (or proved not to work)..

"In the world of ideas, to think is not enough. You must act."

Johann Wolfgang von Goethe
RD50 Common Projects

Common Fund (CF) contributions
2000 CHF/institute yearly contribution

Common Project Proposal
several RD50 institutes come together and propose a ‘common project’

RD50 common project
co-funded (usually 50/50) by RD50 CF & participating institutes
+ regular reporting to RD50 collaboration
+ publications by participating institutes with acknowledgement to RD50

participating institutes
~50%
~50%
Common Projects in the MoU

2002: proposal

• **Common Fund**
  It is planned to set up a low volume Common Fund to which each institute contributes every year a minimum amount. The Common Fund may be used for the organization of collaboration workshops, rental costs (electronics pool), or other specific activities of common interest. For project related investments, like processing of common test structures or purchasing of special equipment, additional contributions may be requested from the institutes participating in the concerned project.

2002: The first MoU

VII. COMMON COLLABORATION FUND (CCF)

• A common collaboration fund is set up to be used for activities of common interests (Workshop and meetings of the collaboration, training and mobility, support to research projects). Every institute of the collaboration contributes to the CCF. The CB decides on the regular annual contribution. The CB can grant a reduced contribution to very small research groups or groups from economically weak institutes. The CB can accept in-kind contributions. For specific project funding (the scientific activity within projects, e.g. material acquisition, processing costs) additional contribution could be asked to participating institutes.
• The Spokesperson and the Research Project Conveners propose the annual budget (main investments and other expenditures), which is endorsed by the CB.
• The CB approves the annual economical report of the budget holder.

2005: Common projects enter the MoU

VII. COMMON COLLABORATION FUND (CCF)

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• The funding requests will be reviewed by a committee composed by the spokesperson, deputy and project conveners.
• The recommendations of the committee will be made available on the intranet.

• **Common Projects are introduced in the RD50 collaboration in 2003**
  *(rules are documented in CB minutes)*

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Common Projects in the MoU

Common Projects included in 2019 RD50 MoU
(i.e. first RD50 MoU signed by all funding agencies)

Annex 6 Contributions to the Common Fund and Common Project Funding

Funding of common projects

The projects proposed by collaborating institutes can benefit from CCF, where the following rules should be respected for each common project:

- A project is eligible for CCF contribution if proposed by a minimum of three member institutes excluding observers and industrial partners.
- A maximum contribution from CCF is limited to 5000 CHF per participating member.
- A maximum of 50% of the total project cost can be covered by CCF. In-kind contributions can be part of the total project budget.
- With approval of the CB up to 70% can be funded from the CCF.

Any project considered for CCF participation should be submitted to the spokesperson(s). The project is reviewed by the Spokesperson(s) and research line conveners. Upon positive review it is accepted for funding and the CB chair is informed. The project is presented at the CB meeting following the approval to the CB. The projects funded from CCF have to report on their progress at collaboration meetings and shall at the end of the project present the list of publications/conference contributions/technical reports that arose from it.
Example of project requests

- Written project requests are submitted to the RD50 funding committee
  - scope, project, cost, resource commitment and responsibility by institute, milestones, deliverables

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RD50 Common Projects

• Nice concept
  ... but
  ... did we get projects?
  ...and were there successful projects?

....let's take a look
### RD50 common projects [1]


  - 2003-01: Semi-3D sensors *(Zheng Li, BNL)*
  - 2003-02: Pad detector Mask *(J.Haerkoenen, HIP)*
  - 2004-01: Oxygen dimer formation *(Michael Moll, CERN)*
  - 2004-02: Strip sensor processing at CNM *(Gianluigi Casse, Liverpool, UK)*
  - 2004-03: SiC sensors *(Andrea Scorzoni, INFN Perugia)*
  - 2005-01: Surface related effects in the interstrip gap - ISTRA *(Elena Verbitskaya, St.Petersburg)*
  - 2005-02: Radiation hardness of SiC-films *(A.Lebedev)*
  - 2005-03: Commercial production of prototype silicon 6” wafers *(H.Sadrozinski, SCIPP)*
  - 2005-04: Comparison of thin and standard p-type devices *(G.Casse, Liverpool)*
  - 2005-05: Silicon Sensors *(D.Creanza, Bari)*
  - 2005-06: First industrial scale production of 3D detectors *(Richard Bates, Glasgow)*
  - 2005-07: Optimization of radiation hard epitaxial silicon detectors *(E.Fretwurst, Hamburg University)*
  - 2005-08: Common purchase of MCz wafers *(Michael Moll, CERN)*
  - 2007-01: Common FZ wafer order *(Michael Moll, CERN)*
  - 2007-02: WODEAN project sensors *(G.Lindstroem, Hamburg Uni)*
RD50 common projects [2]

  - 2007-03: H.G.Moser
  - 2007-04: R.Bates
  - 2008-01: H.Sadrozinski
  - 2009-01: Project on CIS Sensors
  - 2009-03: Micron wafers for avalanche study *(Gianluigi Casse, Liverpool)*
  - 2009-04: MCZ silicon sensors *(Michael Moll, CERN)*
  - 2010-01: 4 inch wafers with Micron for ministrip sensors *(Gianluigi Casse, Liverpool)*
  - 2010-02: n-in-n pixel sensors with CIS *(Daniel Muenstermann, Dortmund)*
  - 2010-03: CNM- P-type sensors with trench *(Giulio Pellegrini, CNM)*
  - 2011-01: Silicon Wafers from TOPSIL *(Michael Moll, CERN)*
  - 2011-02: Bump bonding of ATLAS Pixel Sensors *(D.Muenstermann, CERN)*
  - 2011-03: Slim Edges - Hartmut Sadrozinski
  - 2011-04: Thin p-type pixel from CIS *(MPI, Anna Macchiolo)*
  - 2011-05: Low resistance strip sensors *(Miguel Ullan, IMB-CNMT, CSIC)*
  - 2012-01: p-type planar pixel sensors and diodes at CIS *(Anna Macciolo and Mara Bruzzi)*
RD50 common projects [3]

• Common Projects (2013 – 2016) [reference, title, lead scientist]
  
  • 2013-01: Fabrication of p-type pixel detectors with enhanced multiplication (Giulio Pellegrini, CNM)
  • 2013-02: Fabrication of 3D p-type pixel detectors with enhanced multiplication on SOI wafers (Giulio Pellegrini, CNM)
  • 2013-03: Radiation induced defects in Silicon, O17 enriched silicon, EPR, HRTEM (G. Lindstroem and I. Pintilie)
  • 2014-01: UBM at IZM for Avalanche Detectors (Giulio Pellegrini, CNM)
  • 2014-02: Fabrication of 200 um p- an n-type pad detectors with enhanced multiplication (Giulio Pellegrini, CNM)
  • 2014-03: Production of thin active edge pixel sensors at ADVACAM (Anna Macchiolo)
  • 2014-05: Thin LGAD devices (Nicolo Cartiglia, Torino)
  • 2015-01: HVCMOS developments towards engineering run (G. Casse, Liverpool)
  • 2015-02: 3D sensors for HL-LHC (Marcos Fernandez Garcia, Santander)
  • 2015-03: Evaluation of TPA for sensor characterization (Ivan Vila, Santander)
  • 2015-04: Doping profiling of LGAD and other devices, SIMS (Hartmut Sadrozinski, SCIPP, USA)
  • 2016-01: NITROSIL project: Nitrogen doped silicon (Alexander Dierlamm, Karlsruhe, Germany)
  • 2016-02: Gallium doping (David Fores, CNM, Barcelona)
  • 2016-03: Acceptor Removal in boron doped silicon wafers (Giulio Pellegrini, CNM)
  • 2016-04: TPA-TCT in Bilbao laser facility on pad like diodes (Ivan Vila, Santander)

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RD50 common projects [4]

- Common Projects (2017 – 2020) [reference, title, lead scientist]
  - 2017-01: LGAD based on EPI wafers (G. Pellegini, CNM, Barcelona)
  - 2017-02: TPA TCT on CMOS sensors (I. Vila, Santander)
  - 2017-03: LGAD fabricated with epitaxial layer (G. Pellegini, CNM, Barcelona)
  - 2017-04: RD50 CMOS submission (Gianluigi Casse, Liverpool, UK / Vitaliy Fadeyev, SCIPP, USA)
  - 2017-05: 50 µm thin LGAD fabricated with Ga multiplication layer (Joern Lange, IFAE Barcelona)
  - 2017-06: Thin LGADs characterization using IBIC and time-resolved IBIC at CAN (Carmen Jiménez-Ramos, Sevilla)
  - 2017-07: MPW run with LFoundry (Eva Vilella, Liverpool)
  - 2017-08: 50 µm thin AC-LGAD (Mar Carulla, CNM Barcelona)
  - 2018-01: Development of Segmented LGAD with small pixels and high Fill-Factor (Giovanni Paternoster, FBK)
  - 2019-01: RD50-MPW2 (Eva Vilella, Liverpool)
  - 2019-02: Proof of concept of 3D detectors fabricated in Silicon Carbide (SiC) semiconductor layers (Sofia Otero-Ugobono, CNM Barcelona)
  - 2019-03: Schottky diodes on Epitaxial Silicon for Radiation Damage Characterization of CMOS MAPS (Giulio Villani, STFC Rutherford Appleton Laboratory)
  - 2020-01: 3D detectors optimized for timing applications (Gregor Kramberger, JSI, Ljubljana)
  - 2020-02: Proof-of-concept and radiation tolerance assessment of thin pixelated Inverse Low Gain Avalanche Detectors (ILGAD) (Ivan Vila, UC-CSIC, Santander)
RD50 common projects [5]

- Common Projects (2021-23) [reference, title, lead scientist]
  - 2021-01: Production of Caribou CaR boards for RD50 DMAPS developments; (Dominik Dannheim, CERN)
  - 2021-02: Characterisation of GaN Based Materials, Electronics, and Sensors, Subject to Large Radiation Doses (Tomas Koffas, Carleton)
  - 2021-03: Defect engineering for sensors with intrinsic gain (Gkougkousis Evangelos, CERN)
  - 2021-04: RD50-MPW3 (Eva Vilella, Liverpool)
  - 2022-01: Defect engineering in PAD diodes mimicking the gain layer in LGADs (Ioana Pintilie, NIMP)
  - 2023-01: SiC-LGAD, (Thomas Bergauer, HEPHY Vienna)
  - 2023-02: RD50-MPW4, (Eva Vilella, Liverpool)
  - 2023-03: DeepJunction-LGAD and adaptive gain layer, (Simone M.Mazza, SCIPP, UC Santa Cruz)
  - 2023-04: “RD50-DAQ” for MPW4 based on Caribou DAQ system (Rogelio Palomo Pinto, Seville)
  - 2023-05: Partial Activation of Boron (PAB) to enhance radiation tolerance (Valentina Sola, Torino)
  - 2023-06: Impact ionization parameterization at extreme fluences (Gregor Kramberger, Ljubljana)
  - 2023-07: PIN sensors for dosimetry and NIEL studies (Michael Moll, CERN)

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RD50 Common Projects

• Nice concept
  … but
  … did we get projects?
  … and were there successful projects?

71 common projects funded and executed (or in progress) over last 20 years!
RD50 Success Stories
..as seen through the reporting to LHCC

“Creativity is thinking up new things. Innovation is doing new things.” Theodore Levitt

..just a flashy teaser of some RD50 success stories
see following talks for more
RD50 success stories: p-type sensors

- **2002:** n-in-p segmented sensors: not mentioned in proposal
- **LHCC 2004:** First “very encouraging” results on p-type strip sensors presented

Today:

All HL-LHC silicon detector upgrades are based on p-type sensors: Pixel, Tracker, Calorimeter, Timing

see talks:

Gianluigi, Frank
RD50 success stories: 3D sensors

May 2014 – ATLAS IBL installed
...3D detectors are operating in the LHC

Today – 3D sensors
HL-LHC ATLAS/CMS inner pixel layers

see talks: Maurizio, Frank
RD50 success stories: Characterization Tools

- Several characterization tools and methods developed by RD50, examples:

**LHCC :2011**
Edge TCT

- Edge-TCT, luminescent sensor
- Transverse detector thickness
- Measures charge and induced current as function of depth
- Reconstructs electric field

**LHCC :2015**
TPA TCT

- TPA - Two Photon Absorption
- Investigation on a new technique for sensor characterization (TPA – TCT)
- Deposition of charge at specific position on detector
- Laser: λ ~ 1300 nm, P = 20-200µJ, Δt ~ 240 fs
- Proof of principle achieved

**LHCC :2019**

- Table-top TPA-TCT system
  - Seed funding: CERN KT-Fund grant
  - Development of a commercialized laser (150W), 80X with external cooling
  - Laser operational at CERN since August 2019
  - Proof of concept achieved

- Control and DAQ software under development
- System development ongoing (mechanics, automation, cooling,...)

..spin offs

see talk: Marcos
RD50 success stories: LGADs

• Born out of RD50 “charge multiplication studies”

2013: first time presented to LHCC

2010-2018: more than 30 production runs

LHCC 2018: Development in full swing

LHCC 2018: Radiation hardening

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2010: LGAD activities started with CERN project

2012: First 4 inch wafer, 300 μm thick, LGAD

2014: First 200 μm thick LGAD, First Gallium Process

2015: First 50 μm thick LGAD for Timing applications (ATLAS HGMT and CMS CT-PPS, SOT and SOL, 4 inch wafer), Gallium and Carbon Processes

2017: First LGAD on 6 inch wafers

25 Fabrication processes, 200 Wafers processed at CNM

Today: CNM Spain, First production run 2017 (processed, being characterized)

Today – LGAD sensors

HL-LHC ATLAS/CMS timing detectors

see talks: Giulio, Frank
RD50 success stories: Defect Characterization

...and many more success stories on CMOS (see Eva talk), simulations (see Joern/Marco talk), models, sensors, designs, work with experiments, .....

1999

WODEAN

LHCC :2008

• WODEAN project (started in 2000, 10 RD50 institutes, guided by G.Lindstrom, Hamburg)
  • Aim: Identify defects responsible for Trapping, Leakage Current, Change of N_eff
  • Method: Defect Analysis on identical samples performed with the various tools available inside the RD50 network:
    - C-DLTS (Capacitance Deep Level Transition Spectroscopy)
    - A-DLTS (Current Deep Level Transition Spectroscopy)
    - TSC (Thermally Stimulated Currents)
    - PITS (Photo Induced Transient Spectroscopy)
    - FTIR (Fourier Transform Infrared Spectroscopy)
    - DL (Dye Laser Measurements)
    - PCD (Photo Conductivity Measurements)
    - EPR (Electron Paramagnetic Resonance)
    - TC (Transport Charge Technique)
    - CV (Capacitance-Voltage)

  - 240 samples irradiated with protons and neutrons
  - First results presented at 2007 RD50 Workshops, further analysis in 2008 and publication of most important results in Applied Physics Letters
  - significant impact of RD50 on silicon solid state physics – defect identification

Example: TSC measurement on defects (acceptors) responsible for the reverse annealing

LHCC :2013

• Some identified defects:
  - Phosphorus: shallow dopant (positive charge)
  - Positive charge: high electric field
  - Positive charge: high electric field

Summary on defects with strong impact on device performance after irradiation

LHCC :2022

Characterization of the B_2O_3 defect...

Observation: level at E = 0.25 eV related to boron, electron trap, strong Poole Frankel effect hinting to donor level, annealing at 180°C gives negative space charge level is matching an assignment as B_2O_3.

...and...
RD50 links with LHC Experiments

• Very close links to the LHC experiments collaborations:
  • Only few RD50 groups are not involved in either ATLAS, CMS or LHCb upgrade activities (natural close contact, same people).
  • Common projects with experiments: detector developments and detector characterization, irradiation campaigns, test beams, ....
  • Close collaboration with LHC experiments on radiation damage issues of present detectors.
  • It was/is often not distinguishable if a development was going on in RD50 or in the LHC experiments or parallel in both (see talk of Frank).

   Perfect synergy!
Example: Radiation Effects in LHC Experiments

  - Common Workshop: (ALICE), ATLAS, CMS, LHCb, RD50
  - Sensor Measurements
  - Electronics/Optoelectronics
  - Radiation Simulation and Monitoring
  - Sensor Simulation

- Outcome and follow-up:
  - Generally good agreement between RD50 damage prediction models (e.g. “Hamburg model”) and radiation damage observed by the LHC experiments.
  - More coherent approach in data analyses agreed and documented.
  - Modelling will have to be refined in some areas for run 3!

- CERN Yellow Report written and edited by a team from RD50 & all LHC experiments has been published (154 pages, Radiation effects in the LHC experiments https://cds.cern.ch/record/2764325) summarizing observations, comparing results from different experiments against each other, listing open questions and outlining further work towards Run 3.
Phase 2 upgrades – High Lumi LHC

### ATLAS Phase-2 upgrade

- Upgraded Trigger and Data Acquisition system
  - Level-0 Trigger at 1 MHz
  - Improved High-Low Trigger (150 MHz full scan tracking)
- Electronics Upgrade
  - On-detector and off-detector electronics upgrades of LAr Calorimeter
  - Tile Calorimeter
  - Muon Detectors
- High Granularity Timing Detector (HGTDC)
  - Forward region
  - Precision time rec. (30 ps) with Low Gain Avalanche Detectors (LGAD)

### CMS Phase-2 upgrade

- L1-Trigger
  - HLT/DAQ
  - [https://cds.cern.ch/record/2714892](https://cds.cern.ch/record/2714892)
  - [https://cds.cern.ch/record/2780072](https://cds.cern.ch/record/2780072)
  - Tracks in L1-Trigger at 40 MHz
  - PFlow selection 750 MHz L1 output
  - HLT output 7.5 kHz
  - 40 MHz data scouting
- Barrel Calorimeters
  - [https://cds.cern.ch/record/2283187](https://cds.cern.ch/record/2283187)
  - ECAL crystal granularity readout at 40 MHz
  - with precise timing for s/s at 35 GeV
  - ECAL and HCAL new Back-End boards
- Muon Systems
  - [https://cds.cern.ch/record/2283189](https://cds.cern.ch/record/2283189)
  - DT & CSC new FE/BE readout
  - RPC back-end electronics
  - New GEM/WPC 1.6 < η < 2.4
  - Extended coverage: to η = 3
- Calorimeter Endcap
  - [https://cds.cern.ch/record/2293646](https://cds.cern.ch/record/2293646)
  - 3D showers and precise timing
  - Si, Scint+SiPM in PbW-SS
- Tracker
  - [https://cds.cern.ch/record/2277226](https://cds.cern.ch/record/2277226)
  - Si-Strip and Pixels increased granularity
  - Design for tracking in L1-Trigger
  - Extended coverage to η = 3.8
- MIP Timing Detector
  - [https://cds.cern.ch/record/2267167](https://cds.cern.ch/record/2267167)
  - Precision timing with:
    - Barrel layer: Crystals + SiPMs
    - Endcap layer: Low Gain Avalanche Diodes

### About 800 m² of silicon sensors for Phase-2 upgrades of ATLAS & CMS (RUN 4 ≥ 2029)

RD50 contributed to the R&D of all used Silicon technologies – p-type strip/pixel, 3D, LGAD

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...also very close collaboration with LHCb!

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see talk: Frank Hartmann

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RD50 achievements (Highlights)

- The RD50 collaboration was formed in 2001, building on previous R&D (RD48, RD2) projects and is “the place” to discuss radiation effects and new sensor concepts for solid state tracking detectors.

- RD50 has given important contributions towards the LHC and LHC upgrade detectors:
  - p-type silicon (brought forward by RD50 community) is used for the ATLAS and CMS Strip Tracker upgrades.
  - MCZ and oxygenated silicon (introduced by RD50) can improve performance in mixed radiation fields.
  - Double column 3D detector technology (developed within RD50 with CNM and FBK) was picked up by ATLAS and further developed for ATLAS IBL needs, followed by AFP and TOTEM and now also within CMS/ATLAS upgrades.
  - RD50 results on highly irradiated planar segmented sensors demonstrated: planar devices are a feasible option for LHC upgrade.
  - RD50 data and damage models are essential input for operation scenarios of LHC experiments and sensor designs.
  - Precision timing sensors: LGAD (Low Gain Avalanche Detectors) were developed within the RD50 community.
  - New characterization techniques and simulation tools for the community:
    - Edge-TCT, Alivaba readout, TPA-TCT, … are now available through spin-off companies.

- In all these developments, RD50 keeps a very close links to the LHC experiments collaborations:
  - Only few RD50 groups are not involved in ATLAS, CMS and LHCb upgrade activities (natural close contact).
  - Common projects with experiments: detector developments and detector characterization, irradiation campaigns, test beams, ….
  - Close collaboration with LHC experiments on radiation damage issues of present detectors.
How did we manage? (my point of view)

RD50: A driver and discussion forum on detector R&D, but also the place where many creative ideas were put into first prototype sensors that eventually enabled the (Si-based) HL-LHC detectors in their present form and many other detectors to come…

- **R&D is passion:** We are scientists and driven by scientific curiosity.
  - What can be better than to do research work and share/discuss your results with others?

- **Continuity: R&D needs expertise, time and a sustained supportive environment**
  - Expertise, know-how and networks inherited from previous R&D efforts (RD48,RD2). We nurtured and expanded them over the years and are committed to sustain and extend these assets, ensuring they are passed on to the next generation.

- **Supportive, friendly and open environment**
  - RD50 managed to create a tolerant, open and innovative community that is highly integrative to newcomers;
  - For many students the first chance to present their work in front of renown experts with constructive feedback on their work
  - Competition only on the level of scientific achievements and (luckily) not on resources or ‘political’ interests

- **A balanced and fruitful combination of collaboration members – “a cross-disciplinary collaborative community”**
  - RD50: experts from several research fields: solid-state, electronics, radiation physics, detector and particle physicists,…
  - RD50: place where the LHC experiments communities met to exchange their latest technological challenges and advancements
  - RD50: place where “blue sky researchers” with somewhat unrealistic ideas meet hands-on “detector builders”:
    - *Spreading inspiration for new developments vs. bringing lofty ideas back down to the ground of reality*

- **Need for only little resources, high flexibility and lightweight organization**
  - We were in the lucky situation that many RD50 institutes could hook-up on resources for their LHC/HL-LHC activities
  - “Common projects” are an efficient means to gather experts and commitment to specific projects and validate new concepts
  - RD50 had very low operational overhead costs (only a small fraction of effort/resources were needed to keep it running)
  - Participation required for most RD50 members only a small fraction of their time; flexibility in time-sharing between R&D and other commitments

- **The main reason for success remains the community: The collaboration members, i.e. you!**

My advice: Keep as many as possible of these qualities for the new DRD concept and combine them with the wider scope and the strategic R&D
Goodbye RD50

… and welcome to DRD3