

NPL REPORT

DEM-TQD 001

**A Roadmap for
Quantum Metrology**

Jeff Flowers

NOT RESTRICTED

March 2005

A Roadmap for Quantum Metrology

Jeff Flowers
DEM

ABSTRACT

This document presents a number of roadmaps for key metrology areas. These were developed within the Quantum Programme of the UK Department of Trade and Industry National Measurement System Policy Unit. We describe how these roadmaps were produced and discuss how the process can be carried forward to produce an international roadmap for quantum metrology.

© Crown copyright 2005
Reproduced with the permission of the Controller of HMSO
and Queen's Printer for Scotland

ISSN 1744-0491

National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

No extracts from this report may be reproduced without the prior written consent of the Managing Director, National Physical Laboratory; if consent is given the source must be acknowledged and the extracts may not be used out of context.

Approved on behalf of the Managing Director, NPL
by Dr J-T Janssen, Knowledge Leader *Time and Quantum Detection Team*

CONTENTS

1	Introduction.....	1
2	Status and application of this document	1
3	Initial production of roadmaps.....	1
4	Draft Quantum Roadmaps.....	2
4.1	Time and Frequency	3
4.2	Electrical.....	7
4.3	Mass.....	11
4.4	Temperature	15
5	Experience gained from developing the roadmaps.....	18
5.1	Initial development	18
5.2	Presentation	18
5.3	Process	19
5.4	Examples of cross-roadmap links	19
6	Future steps and recommendations	19
6.1	NPL Internal	19
6.2	International.....	20
7	References.....	20
	Appendix A Original accompanying notes to the roadmaps presented to the NMS quantum metrology working group	21

1 Introduction

Roadmapping is an established technique for developing a strategy and presenting it in perspective. It is widely used internally by companies and more recently has been used across industries and government agencies in diverse science and technology areas. These range from the well known semiconductor industry roadmap[1] to the quantum information science and technology roadmap[2]; with many other industries and science agencies also producing roadmaps.

This document presents draft roadmaps produced as the result of an evaluation of the UK National Measurement System (NMS) quantum programme areas of interest. Considering activities, generally funded by the Department of Trade and Industry (DTI) and taking place within the National Physical Laboratory, UK (NPL), and those in related science and technology areas taking place outside NPL, mainly in other national metrology institutes.

The objectives of this process are to initiate planning and analysis both internal to NPL and within the wider community of experts and to present this in a form suitable for decision making. It is our intention that the process of roadmapping should advise the direction of metrological research and highlight the opportunities for collaboration and co-operation in the international metrology community.

2 Status and application of this document

Roadmapping is an exploratory and iterative process of which we are only at the start. This document contains the results of our initial one-day roadmapping workshop plus additional refinement of the outputs. At this stage it is a consultation document; it is our aim that there will be revision to the roadmaps presented here and that the subject areas that we have not developed as part of this exercise will need to be addressed in future.

The topic areas discussed were based on the DTI NMS Quantum Metrology Programme[3], which covers most of the areas usually referred to as ‘quantum metrology’ along with some less traditional topic areas. The Quantum Metrology Programme is described in detail on the NPL website. The Quantum Metrology Programme has a strong underpinning research character so the roadmap is expected to cover metrological need in the longer term, as opposed to current needs. Current needs in metrology have been reviewed by the BIPM[4]. Metrology is a wide discipline and of course, there are areas of metrology that we have not explored; here we hope that others can contribute towards an international roadmap. It is hoped that the process can be taken up, perhaps through the consultative committees of the BIPM, to develop a detailed, comprehensive roadmap for metrology with the backing of the international metrology community, and that our experience can provide direction to that process.

3 Initial production of roadmaps

At the initial meetings between NPL scientists, members of the DTI NMS Policy Unit and roadmapping consultants, it was realised that a single diagrammatic roadmap of the graphical form initially envisioned, covering all the areas of metrology potentially to be included in the quantum programme, would be unfeasibly complex. To limit the scale of the exercise, a number of subject areas based on the present QMP and NPL strategic research areas were proposed and agreed upon. Groups of three or four experts in the subject area were assigned the task of producing a roadmap diagram for that specific area. The subject areas were not a complete set of all areas of metrology but were considered representative of important areas of the quantum programme. It will be necessary to review the coverage of science areas and the completeness of the roadmaps within a science area as part of the follow up to this exercise.

Seven groups produced all of the initial set of roadmap diagrams during a one-day long exercise. More details of the groups, subject areas and process are in the accompanying notes for the draft roadmaps reproduced here in Appendix A. The task of each group was to produce a single graphical representation based on a template, to show the expected progress in their subject area over a 15-20 year timescale. This is the timescale on which a typical DTI Quantum Programme project is expected to deliver. It is also based on a metrologist's analogue of Moore's Law that suggests a factor of ten improvement in measurement accuracy occurs typically over a fifteen year period, but as expected this varies with area of metrology. A number of the expert groups chose an accuracy scale as representative of the achievements of the improvements in technology they roadmapped.

Discussion during the day was very productive, and we feel that going through the process itself brings about one of the great benefits of roadmapping. Bringing together a group of experts, along with others such as project managers, who then discuss the future direction of their topic, with both other experts in their field and peers from other areas of metrology, brings about sharing of information, helps in producing a consensus view on direction and increases awareness across subject areas.

The roadmaps were given a limited peer review on the day by each group presenting their maps to the whole expert group, however there was limited time to make any changes following this review. In order to address this, the lead author of each roadmap reviewed the roadmap with this author following circulation of the set of roadmaps collated by the consultants. In some cases the roadmaps were nearly complete and this was a relatively easy process but in others there was no clear convergence. As time was limited, the focus was placed onto a subset of the roadmaps that both covered an important metrology area and had an encouraging initial development. As part of the review of these roadmaps it was felt that they could not stand alone especially if presented to those not specialists in the topic, and the roadmaps required some explanatory text and in some cases a glossary.

The NMS Quantum Programme Working Group reviewed the selected roadmaps. They endorsed the idea that the programme should be roadmapped and that this would be helpful in future programme formulation processes. However, they felt that as presented some of the roadmaps were too densely packed with information and suggested that less restrictive principles should be followed based on a white paper by the Centre for Technology Management, University of Cambridge[5] Therefore simplified roadmaps for each of the areas considered were also produced to incorporate these suggestions.

For comparison, note that the UK micro- and nanotechnology (MNT) network has produced a metrology roadmap[6]. They used a similar methodology of having an expert group brought together for a day but using different methods for arriving at an agreed position and produced their output in a different graphical format.

4 Draft Quantum Roadmaps

This section presents roadmaps for four of the chosen topic areas in both their original and a simplified form. The simplified form of the roadmaps was produced to address a number of issues. Because the roadmaps in each topic area were produced independently there was insufficient consistency in the degree of complexity presented, and some roadmaps were considered overloaded with detail. To address this issue, we have presented them in a two-tier way, an overview for presenting the general direction, and a more detailed view from which a project plan may be generated. These correspond to an unedited output of the roadmapping day and a modified and simplified version produced by this author. A short accompanying background text is also included with each roadmap, because, as stated above, it was agreed at the review stage that the roadmaps were hard to interpret without background knowledge. The cited roadmaps show that it is common practice for a technical roadmap to have extensive accompanying text[1,2,7,8]; however at the time our original roadmaps were developed that was not our intention. This led initially to some authors attempting to present too much content on the diagram tending to overload them with detail. This is remedied by a simplified roadmap with short accompanying text.

The roadmap layout is essentially the same for both roadmaps. The horizontal axis is a timeline chosen to correspond to the 15-20 year timescale and corresponds to the typical timeframe for a quantum metrology project. The vertical axis in the original template moved from “Generic/underpinning technologies” at the bottom to “Products/product categories” (i.e. increasing integration). At the top of the vertical axis is a section which shows the triggers and targets for that roadmap. In the terminology of the roadmap triggers are external events that cause us to initiate activities and targets are the goals that we set ourselves. During the exercise it was found that the original labels were inappropriate to describe metrological research. Therefore in the overview roadmaps we have changed the labels on the vertical axis, however the intention is the same to show an increasing integration from the basic science and technology that underpins the metrological experiment to a metrological experiment itself.

4.1 Time and Frequency

4.1.1 Background

Atomic clocks based on caesium have been the basis of the timescale and the definition of the second since the 1960's. During this time there has been significant development of the technology and their accuracy has improved by an astounding factor of 10^5 . Nowadays a number of cold atom caesium fountains are among the clocks contributing to the global timescale, with uncertainties approaching one part in 10^{15} .

Recent advances have been made in optical frequency standards using single trapped ions or alternatively neutral atoms in an optical lattice. It has also become possible to compare these new optical frequency standards to microwave standards such as caesium fountains, which provide the present definition of the second. This link can be done using femtosecond frequency combs without loss of accuracy.

This roadmap charts the future development of time and frequency metrology, based initially on improvements to microwave frequency standards, but with optical frequency standards replacing them as the ultimate frequency references during the time under consideration. Optical standards have the potential to reach a part in 10^{18} in stability. However, in order to achieve and make use of this remarkable stability other technologies such as local oscillators and frequency combs must be commensurately improved. In particular, in order to establish a timescale at enhanced accuracy, the techniques that will allow time transfer at these improved accuracies must be developed using quantum information processing techniques. The timescale will have to take account of the gravitational redshift, which shifts a clock's frequency by about a part in 10^{16} for each metre of height, so improved mapping of the gravitational field will be required. The definition of the second is based on the microwave caesium transition so a new definition would be required to take the realisation of the second to accuracies achievable with optical clocks.

The improved frequency metrology infrastructure will enable improvements in a wide range of science and technology applications such as satellite navigation, high-speed communications, secure communications, fundamental physics and fundamental constant evaluations

4.1.2 Glossary

Cs – Caesium

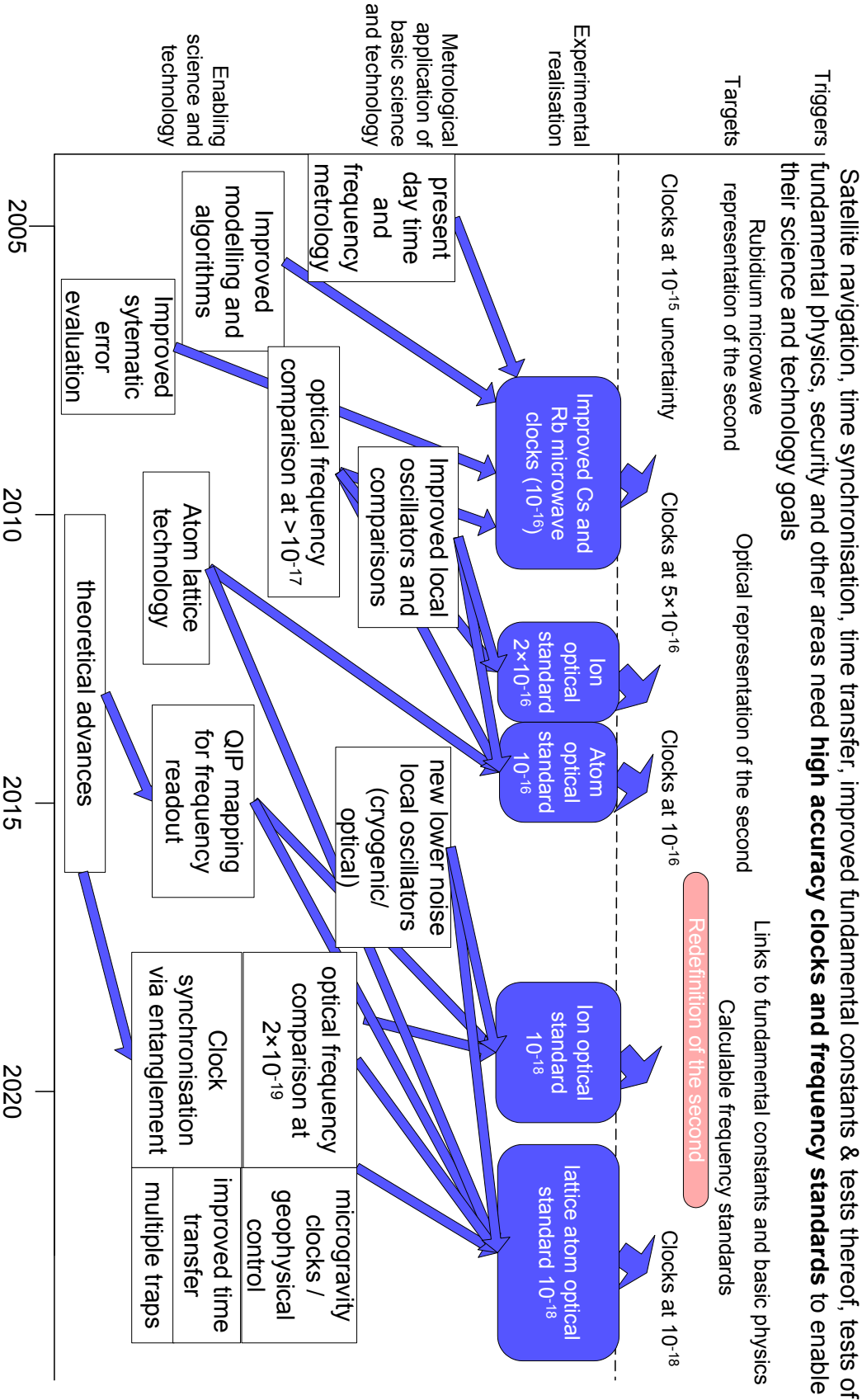
LO – Local Oscillator

QIP – Quantum Information Processing

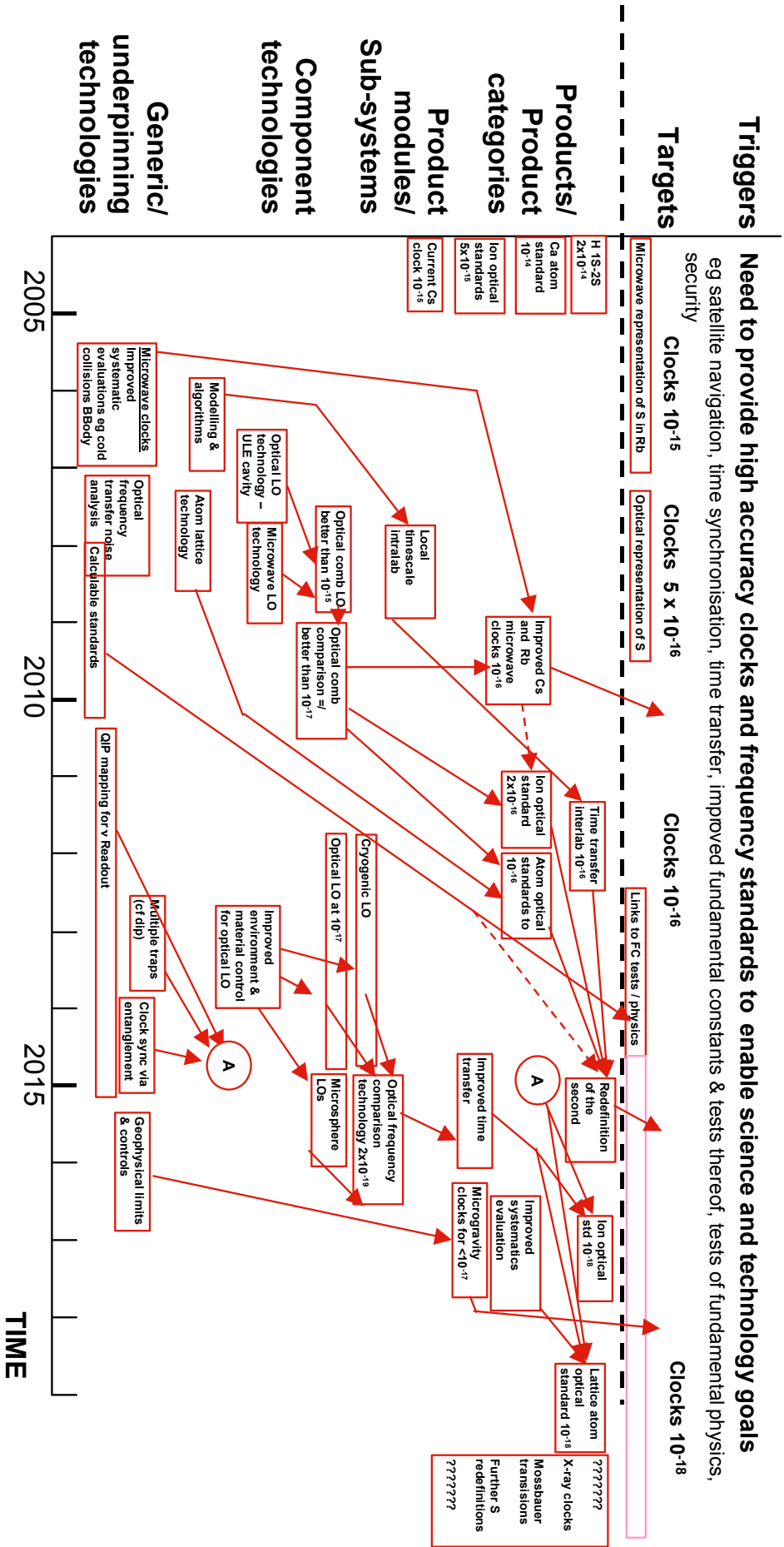
Rb – Rubidium

ULE – Ultra Low Expansion (glass)

Time and Frequency: better clocks

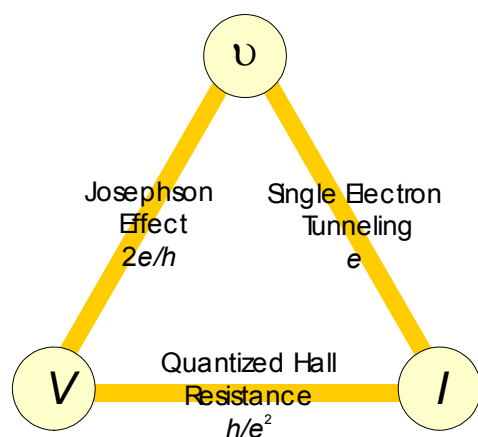


Roadmap: T&F – Better clocks



4.2 Electrical

4.2.1 Background



Representation of the metrological triangle. The sides represent three quantum effects and the points the quantities related by each

Since 1990 the volt and ohm have been maintained using quantum effects, the Josephson and quantum Hall effects respectively. Two constants are introduced the Josephson constant K_J and the von Klitzing constant R_K . These constants are predicted by theory to have the following relationships to the Planck constant h and the electron charge e :

$$K_J = 2e/h \text{ and } R_K = h/e^2.$$

Experiments to date have yielded results consistent with the above relations. For the purpose of uniformity of electrical standards based on quantum effects, these two constants were given assigned exact values K_{J-90} and R_{K-90} which were chosen to be as close to the SI values as possible. This gives the volt and ohm to a much greater stability than accuracy (in the SI system).

A long-standing goal of electrical metrology is to test whether the above relations are indeed identities. One approach to this is to test the consistency of these relationships using the 'metrological triangle'. The

experiment is to compare the voltage produced by a quantised current (controlled passage of counted electrons) passing through a quantum Hall effect resistor with a Josephson voltage. To do this at a meaningful level will require a quantum standard of current accurate at about one part in 10^8 whereas the current state of the art is approaching one part in 10^7 . This roadmap explores the route for closing the metrological triangle, which would greatly enhance confidence in these quantum standards, which support voltage and resistance measurements at the highest level. It encompasses the development of a quantum current standard, which combined with other experiments, would improve knowledge of the value of the electron charge.

4.2.2 Glossary

QHR – Quantum Hall Resistor / Resistance

CCC – Cryogenic Current Comparator

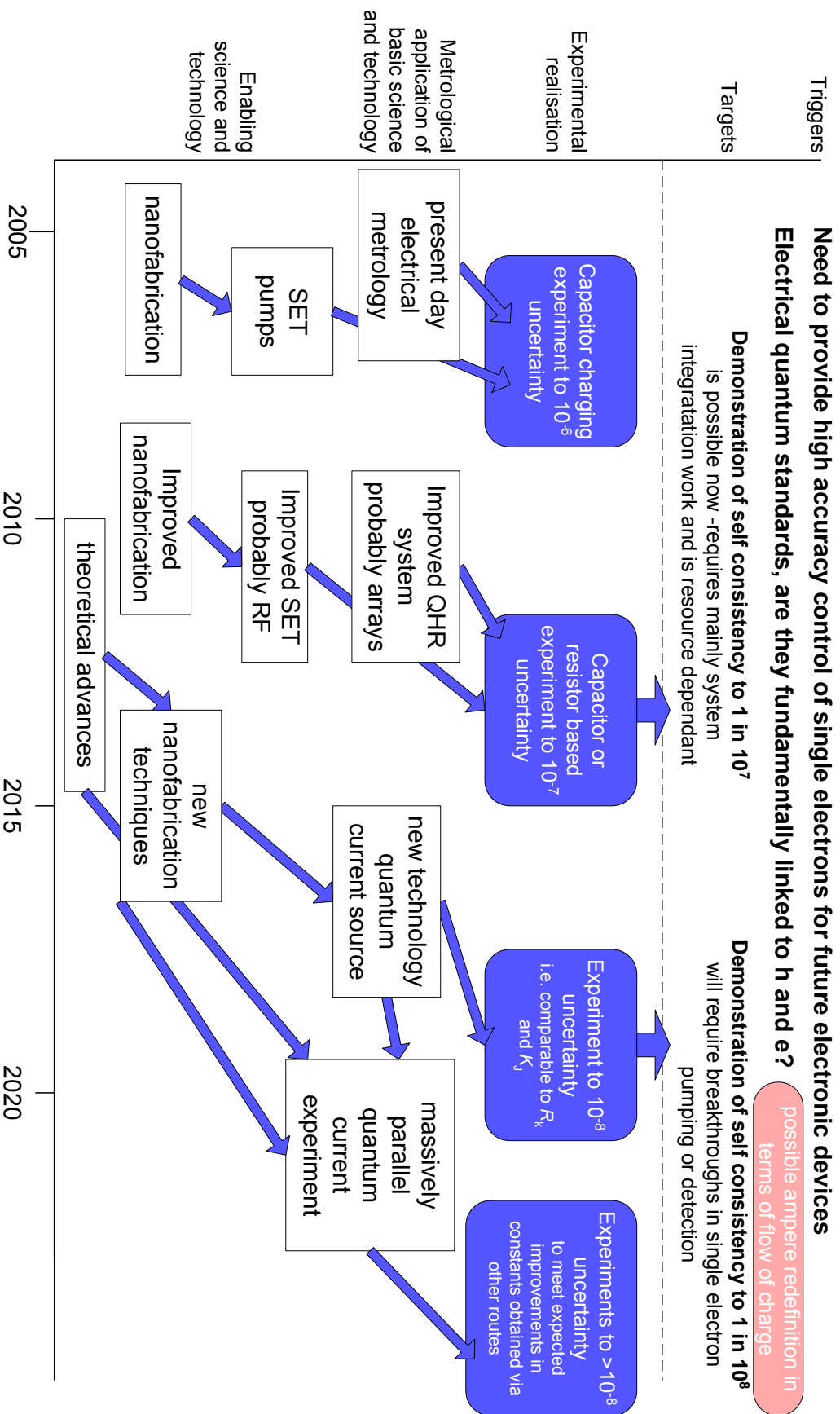
SET – Single Electron Tunnelling / Transistor

SQUID – Superconducting Quantum Interference Device

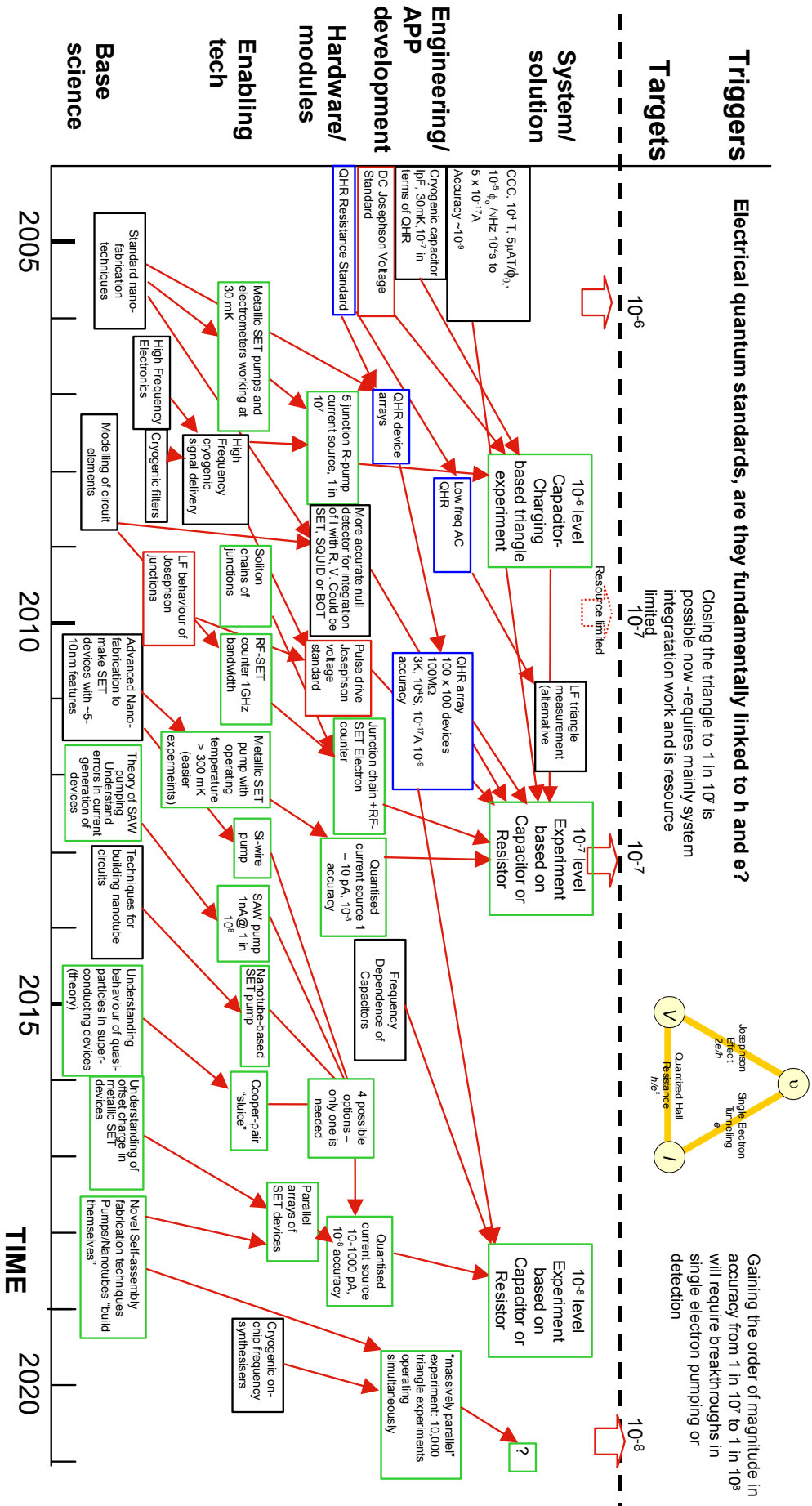
BOT – Bloch Oscillating Transistor

SAW – Surface Acoustic Wave

Quantum electrical standards



Roadmap: Electrical – Quantum Electrical Standards



4.3 Mass

4.3.1 Background

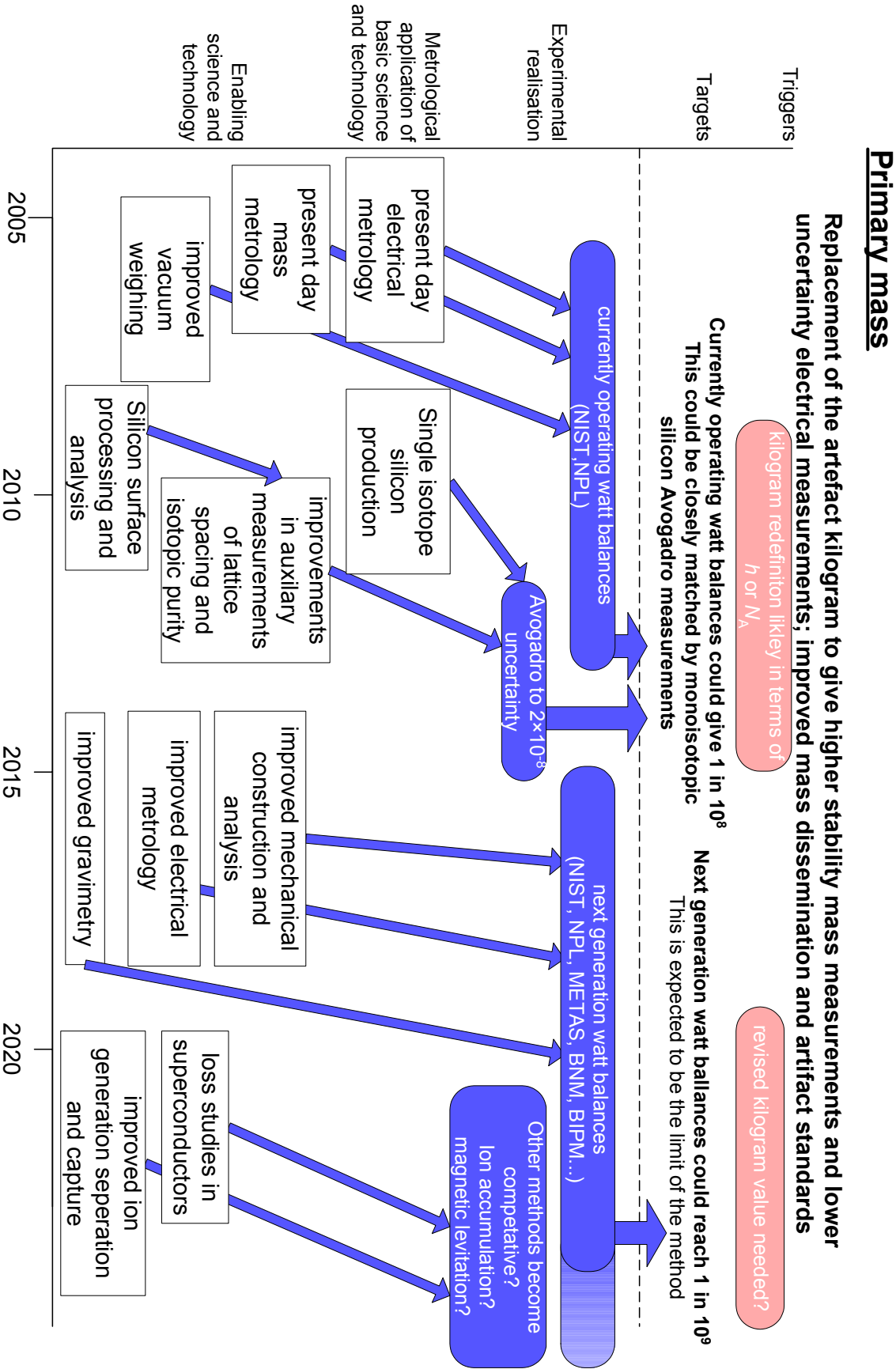
The replacement of the artefact prototype kilogram is a long-standing goal of quantum metrology. This would replace the last base unit of the SI system to be based on an artefact standard, eliminating concerns over the stability of the prototype kilogram. A new method would have to provide mass measurements with an uncertainty of better than a part in 10^8 before it could be considered and improvement on the present status.

Of the methods likely to enable replacement of the kilogram, the most developed is the watt balance. This works by comparing the mechanical power of a moving mass with electrical power provided by electrical standards of voltage and resistance, which have a high stability. The apparatus is a mechanical balance. It compares the force produced by a current flowing through a coil with the weight of a kilogram mass. Measurement of the voltage produced by moving the coil in the same magnetic field then allows the geometry of the coil and the magnetic flux density to be cancelled out. Precision electrical measurements, mechanical alignment and gravity measurements are needed as well as time stability of the apparatus.

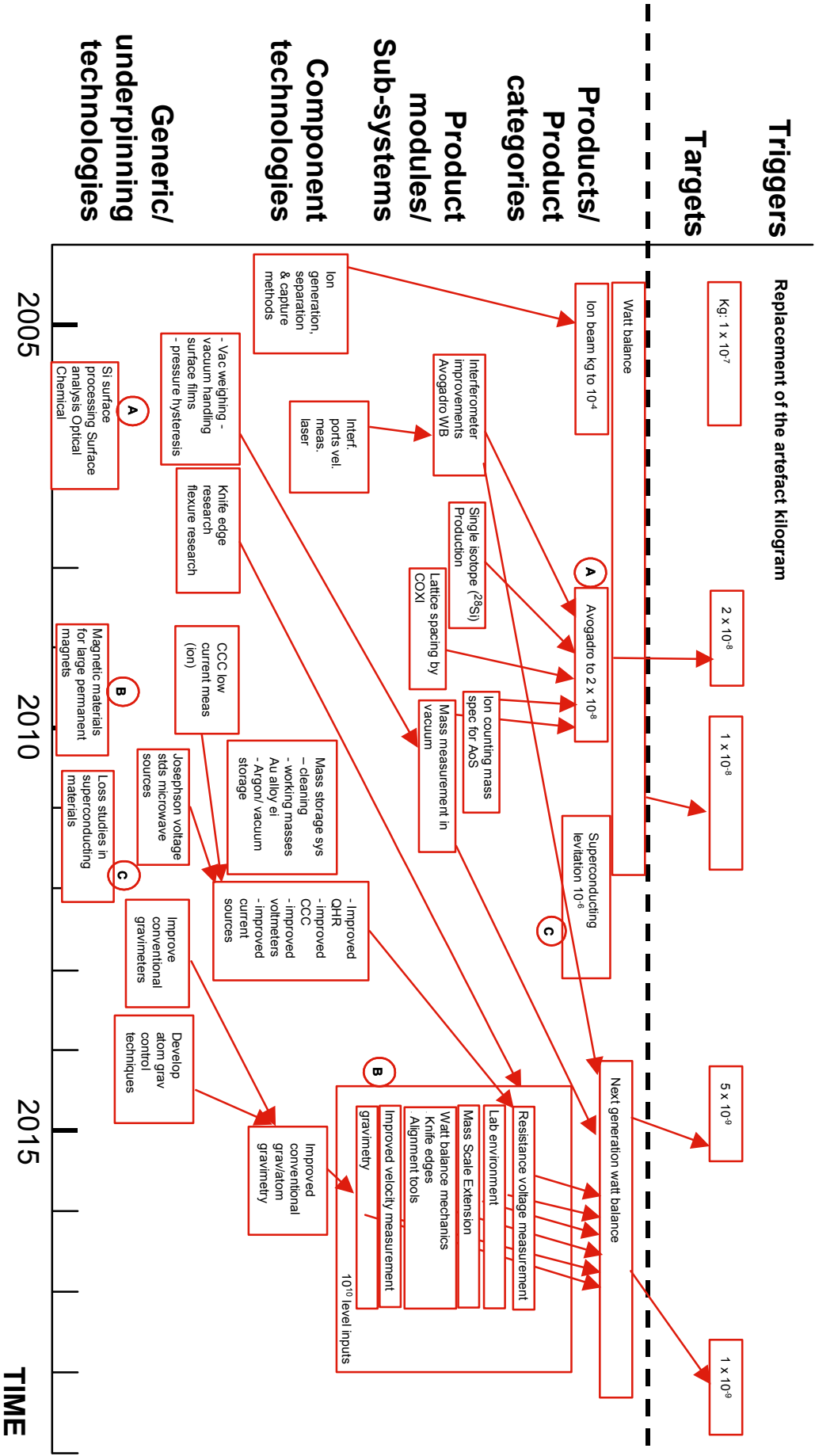
An alternative approach to a new mass standard is counting atoms. In the Avogadro method the number of atoms in a single crystal sphere of silicon is determined from its volume and the measured spacing of silicon atoms in a crystal lattice. Hence the mass is determined in terms of the atomic mass. This method has run into problems due to the unknown isotopic makeup of the silicon and so the collaboration is pursuing the preparation of a crystal of pure silicon 28.

Atom counting is also being attempted by a method of ion accumulation. Here ions in a beam of known current are captured and weighed. The known current means that if all the ions can be captured and neutralised a known mass of material is produced. The method is limited at present by the small mass produced and the difficulty of collecting all the ions in the beam with high reliability. This method is at a much less developed stage than the watt balance or Avogadro method.

The uncertainties across the top of this roadmap indicate the ability to monitor the stability of a prototype kilogram at the appropriate level. The redefinition of mass is a political process, which would require approval through a number of committees of the BIPM



Roadmap: Mass



4.4 Temperature

4.4.1 Background

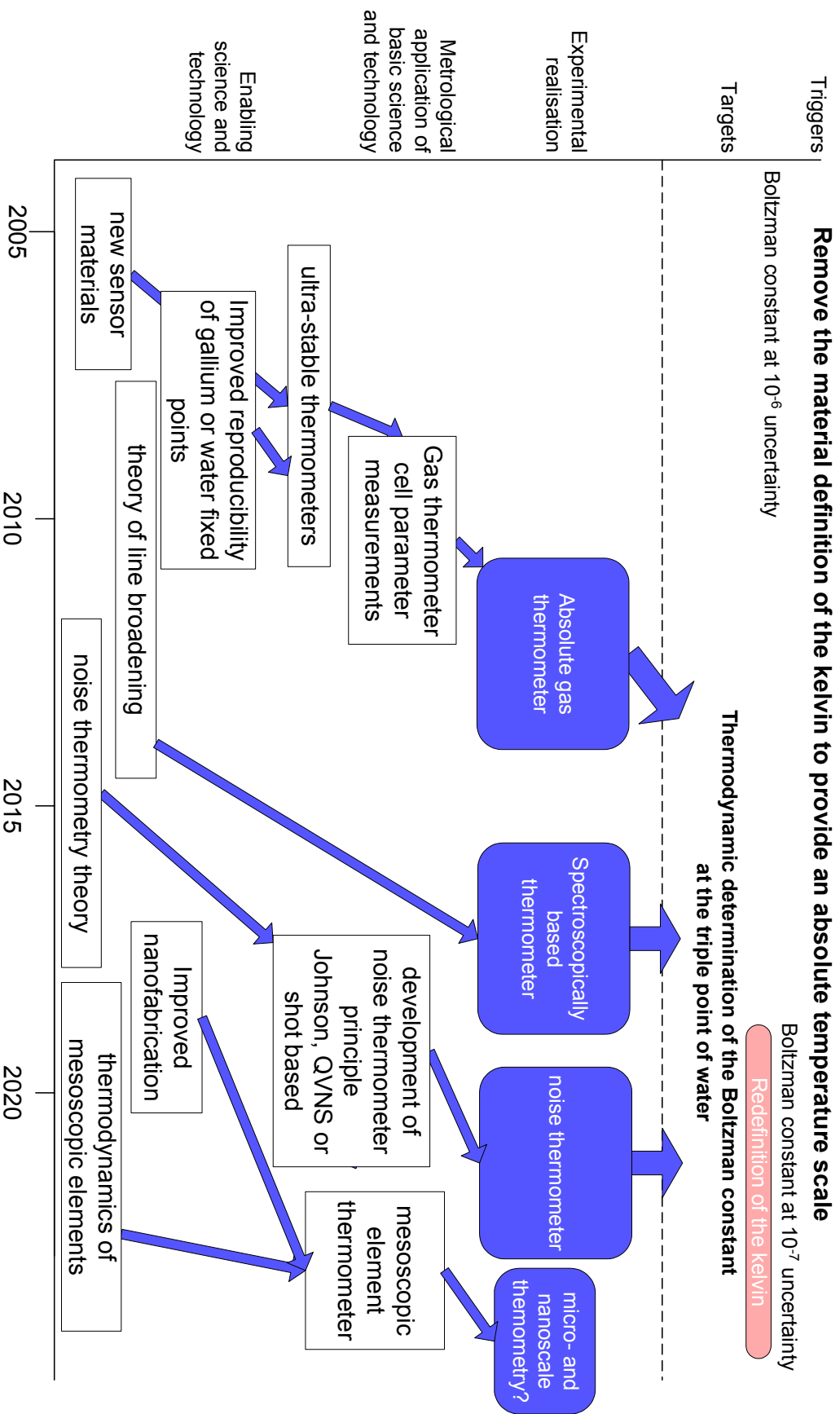
The current definition of the kelvin in terms of the triple point of water is ultimately limited by the properties of a material substance. The limiting uncertainty is likely to be in the region of 10^{-7} due to isotopic and impurity effects. It has become interesting to consider whether it is possible to determine the value of the Boltzmann constant k , consistent with the unit as currently defined, with this accuracy. If so, the unit could be defined by fixing the value of k without any noticeable discontinuity from the previous definition, freeing it from any particular temperature value or state of matter or measurement method.

Since T always enters physics (in this context, thermodynamics and statistical mechanics) as the product kT , any experiment can in principle be used, if it is based on a fundamental law governing the statistical properties of an ensemble of particles at equilibrium, or on an equivalent time series measurement. Candidates are atoms in a gas, electrons in metals, photons in a cavity and ions in excited states, all of which have already been exploited in thermometry. Plausible ideas for harnessing more exotic particles have not yet been advanced. This roadmap attempts to place the possibilities for reaching accuracies of 10^{-7} on a time-scale and identifies some of the known landmarks on the way.

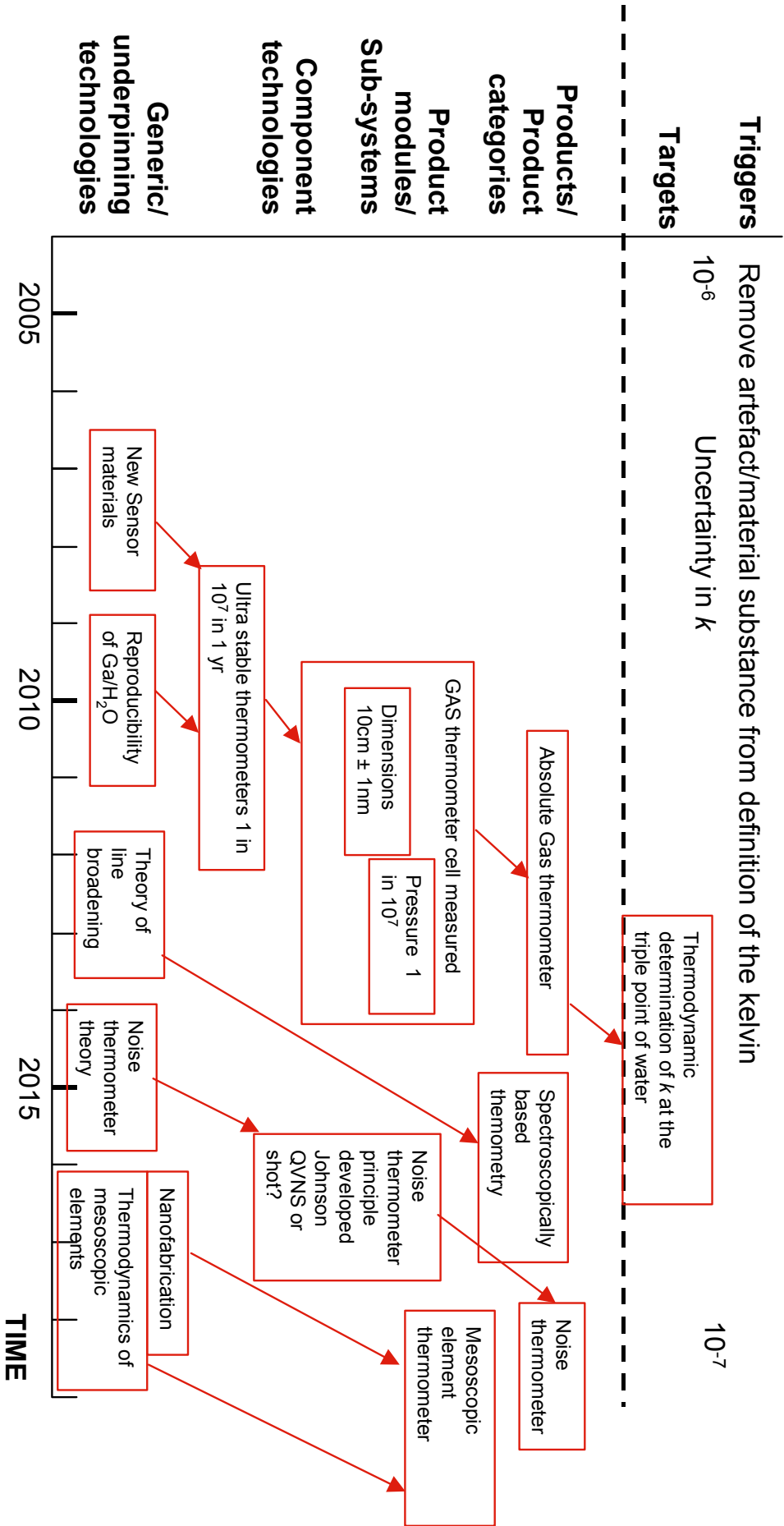
4.4.2 Glossary

QVNS – quantum(quantized) voltage noise source

Temperature: definition of the kelvin



Roadmap: Temperature - Definition of Kelvin



5 Experience gained from developing the roadmaps

5.1 Initial development

The consultant emphasised that each process roadmapped must have a clear ‘goal’ and these were surprisingly difficult to define. It is clear that the research in the Quantum Metrology Programme at NPL is not driven by specific product requirements in the way that is usual for a corporate technology roadmap. Thus further consideration must be given to presenting metrology roadmaps in a way appropriate for a science area and its degree of maturity.

Therefore in interpreting the roadmaps it must be borne in mind that they are ‘only’ a representation. They give an overview of the expected route but it is important not to try and extract too much detail from the graphical presentation.

The degree of consistency between the original roadmaps was disappointing even though there were people moving between groups during the roadmapping event to try and bring consistency between the outputs of the different groups. It is expected that a more iterative process can address this, for example by having more discussion and pre-agreement on the form of the output followed by further roadmapping. Of course this would require significant resources to be devoted to the roadmapping process. We hope this document will provide a basis for discussion on what form an international metrology roadmap will take.

5.2 Presentation

The roadmaps were developed with the intention that they would be single page stand-alone diagrams, but this led to a number of difficulties. The groups producing the roadmaps tended to fill them with detail to ensure that nothing was excluded. They also used technical terms and acronyms to label the boxes to save space. As a result of the process it has become clear that the roadmaps cannot be stand-alone and that considerable accompanying text is needed, depending on the intended audience. In many comparable roadmap documents, those cited earlier and many others consulted, the textual content forms the bulk of the document and the diagrams are illustrative.

The expert groups found the original labels on the vertical axis of the consultant’s template roadmap not to be meaningful in the context of metrological science. Thus there was immediate difficulty and a lack of ‘ownership’ of the maps. Clearly it is beneficial from a presentational point of view that a uniform presentation is adopted and as result alternative labels were proposed on the abbreviated form roadmaps.

There was some ambiguity to the meaning of the arrows and our advice is that the arrow is to be read as ‘is a prerequisite of’. Thus the roadmap clearly shows that some developments require the success of others to make them possible.

Representing timing of progress caused another difficulty in the presentation of the roadmaps. Many metrology activities are a process of gradual refinement over a long term and it could be argued that the box to represent them should go from the start to the end of the timeline, as it represents an activity of continual improvement in a particular method, science or technology. This is not helpful in presenting their relationship to other activities so they are drawn at a time where they are expected to be required to impact on other work or make significant progress. This choice is somewhat arbitrary. Thus some of the boxes that are towards the end of the timeline represent activities that are being worked on now, perhaps in an exploratory way. The box shows the time of expected delivery of useful input to the subject of the roadmap. A more sophisticated presentation or more detailed roadmap may solve this dilemma by presenting the ongoing activity in terms of multiple sub-tasks. Again, it is important not to read too much from the roadmaps and reiterates the case for significant accompanying text.

There are several software packages specifically designed for the production maintenance and presentation of roadmaps. These could, for instance, store the information in a database and then present various levels of detail in an interactive way. This would show links more clearly while remaining uncluttered, in a way that is not possible in a paper presentation.

5.3 Process

Perhaps the most useful output so far has been the activity. Bringing the expert groups together and giving them a day to brainstorm the direction in which their scientific endeavour should be heading and what outputs can be expected. This should be repeated, perhaps as a stand-alone roadmapping exercise, or as part of strategy development, or part of programme formulation.

A roadmap should be an output from a foresight process and strategy development. Our most successful roadmaps were those where a pre-existing process had taken place in the community at large. For the kilogram replacement and the metrological triangle in particular there has been debate internal and external to NPL over many years on the goals and methods involved. Novel topic areas that do not have this history to fall back on will require much more effort to produce a detailed and robust roadmap.

5.4 Examples of cross-roadmap links

There are a number of limitations to what can be shown graphically. One area that is not brought out by the collection of individual roadmaps is the myriad of links between different areas of metrology, both in relationships between the measured quantities and in related technology used across measurement area. Two examples from the roadmaps in section 4 are expanded on in this section.

Redefinition of units such as the kilogram as shown in the mass roadmap requires inputs from other areas of metrology or physics. In particular the electrical units, as the route from the kilogram via the watt balance to the Planck constant, h , assumes the correctness of the Josephson and von Klitzing relations ($K_J = 2e/h$, $R_K = h/e^2$) these will be experimentally checked by closure of the metrological triangle. The redefinition of the kilogram using a fixed value of h can be used to move the uncertainty in the electrical units due to the kilogram realisation to the mechanical units. A redefinition of the ampere in terms of a counted electrical current flow could then make the as-maintained electrical units (Ω_{90} , V_{90} etc) be the SI values.

The second alternative being considered as the basis of a kilogram redefinition is the Avogadro constant. The relationship between the Avogadro constant and the Planck constants incorporates knowledge of the fine structure constant and the Rydberg. Only providing these other constants are well enough known can the alternative definitions be considered as equivalent. There are many other examples of links, often via fundamental constants, that ensure consistency of measurements from one area to another.

6 Future steps and recommendations

We have produced a starting point for discussion but there is still much work to be done to produce an International Metrology Road Map. We envisage this will incorporate an analysis of the work and plans of the major NMIs in areas relevant to quantum metrology.

6.1 NPL Internal

The subject area roadmaps produced in this phase of the project must be thoroughly critiqued and validated internally and then updated. The less developed roadmaps need reworking and accompanying text to be produced by some or all of the original authors. They can then be used as input to new programme formulation and be presented externally to NPL in a completed form.

This is not the end of the process; the development of these roadmaps is the initial stage in the process of integrating roadmapping in a beneficial way into strategy development and the planning, selection and implementation of projects.

6.2 International

Metrology is a research area with a high degree of international cooperation. We propose that a roadmap for the global metrology effort could be used, most likely through the BIPM, for the steering of global metrology effort. It will examine the degree of international alignment and the scope for collaboration. It will transcend the individual national metrology institutes and their programs in the way that the ITRS roadmap transcends individual manufacturers to give the whole industry a coherent direction.

We propose that the task of producing the global roadmap be co-ordinated by the BIPM combining local roadmaps produced within each area of metrology, co-ordinated by the appropriate consultative committee and perhaps undertaken or lead by a NMI or other laboratory with a strong interest in the subject area. We hope that the roadmaps presented here will be a stimulus to enable this wide-ranging roadmapping effort.

To produce a fully developed roadmap requires extensive consultation with scientists, managers, funding agencies and the public.

7 References

1. ITRS *International Technology Roadmap for Semiconductors* (2004) <http://public.itrs.net/>.
2. ARDA *A Quantum Information Science and Technology Roadmap* (2004) http://qist.lanl.gov/qcomp_map.shtml.
3. DTI *Quantum Programme* (2004) <http://www.npl.co.uk/quantum/quantum.pdf>.
4. CIPM *National and international needs relating to metrology* BIPM (1998).
5. Phaal, R., Farrukh, C. & Probert, D. *White Paper. Technology Roadmapping: linking technology resources to business objectives* Centre for Technology Management, University of Cambridge (2001).
6. Smith, A. *MNT Roadmap in Metrology* (2004) <http://mnt.globalwatchonline.com> (requires registration).
7. JPL *Fundamental physics in space roadmap* NASA (1998) <http://funphysics.jpl.nasa.gov/technical/library/roadmap.html>.
8. PPARC *The 2003 PPARC Roadmap* (2003) <http://www.pparc.ac.uk/Rs/Pp/Sp/Roadmap.asp>.

Appendix A Original accompanying notes to the roadmaps presented to the NMS Quantum Metrology Working Group

A kick off meeting was held at NPL between Petar Stojic (DTI), Duncan Westland, Nancy-Ann Bennett (PA knowledge) and Duncan Jarvis, Hugh Klein and Jeff Flowers (NPL). Duncan Westland presented the rationale and implementation of roadmapping and the roadmap presentation format developed by PA. There was agreement that the complexity of the quantum programme meant that it would require a number of roadmaps each covering a different subject area. The areas suggested with their targets were;

Optical definition of the second

The quantum candela

The quantum current standard

A non artefact mass standard

Definition of temperature in terms of Boltzmann constant

Measurement of a Q-bit.

On 6th July, a pilot half-day roadmapping session was held which addressed electrical metrology, the quantum current standard and the 'metrological triangle'. This exercise convinced us that an outline roadmap could be developed in half a day. However the 'metrological triangle' has been the subject of a number of studies and papers and so could be considered one of the less speculative subject areas, yet the roadmapping still required considerable effort and technical input. The roadmap has since been reworked twice, in the main roadmapping session and as part of the follow-up described below.

A one-day workshop session was held at NPL on 19 July 2004 with over twenty technical experts in attendance. The starting points developed from the suggested areas above, with their targets were;

Quantum electrical standards

Closing the electrical "metrological triangle" with reducing uncertainty (10^6 through 10^8)

Detection of a single Bohr Magnetron

Time & frequency

An optical redefinition of the second through increased stabilities and accuracies (1 part in 10^{15} down to 1 in 10^{18})

Mass

Monitor the stability of mass standards to 1 part in 10^8 to pave the way for a redefinition of the kilogram

Measure the acceleration due to gravity with an uncertainty less than 1 part in 10^9

Measure Planck's constant to 1 part in 10^7 through 1 in 10^9 (can also present this in terms of the Avogadro number)

Temperature

Redefinition of the kelvin through determination of the Boltzmann constant with decreasing uncertainty (1 in 10^6 through 3 in 10^7)

Amount of substance

Quantum candela

The SI base unit for optical radiation having a quantum basis with an uncertainty of 1 part in 10^4 through 1 in 10^8

Qbit

The realisation of enhanced measurements through the preparation, evolution and detection of individual quantum states.

The day started with a presentation by Duncan Westland repeating his presentation made at the kick off meeting and answering questions on the roadmapping process.

The roadmaps were developed over the day using PA's format by a number of groups of the technical experts. Each group typically had three to five members and was charged with producing a roadmap in one of the themes above. Some felt the need to splinter their theme subject area and produce multiple roadmaps. Towards the end of the day the spokesperson for each group presented their roadmap(s) to all.

The roadmaps that then consisted of notes stuck onto an A0 template of the PA format were taken away by PA and used to produce the draft workshop outputs powerpoint document.

PA's document was circulated, and further discussions were held within a group, to review each roadmap in the light of the others and further discussions between the group members. This was to include input that had come out of the question and answer session and other comments from members of other groups. It was generally felt that the roadmaps could not stand alone so a small introductory text to each is being written. The review process was also intended to produce more consistency between the roadmaps.

Concerns were frequently expressed that the roadmaps were an oversimplification. It was very difficult to prevent specialists from including technical details of many possible options. It is intended that these should be moved to the accompanying text

This revision process is not yet complete in all cases but this document contains draft roadmaps for the electrical, time, mass and temperature areas with the intention that the feedback received on these will be use to refine all the roadmaps. The full set of roadmaps being developed are entitled;

Amount of substance
Optical radiation – SI base unit
Optical radiation – Known photon source
Optical radiation – Stefan-Boltzmann
Optical radiation – Predictable quantum efficiency detector
Temperature - Definition of kelvin
Qbit – Entangled ion traps
Qbit – Quantum dissemination of standards
Qbit – Quantum communications
Mass
Nanoforce
T&F – Better clocks
Electrical - Magnetism
Electrical – Quantum electrical standards.