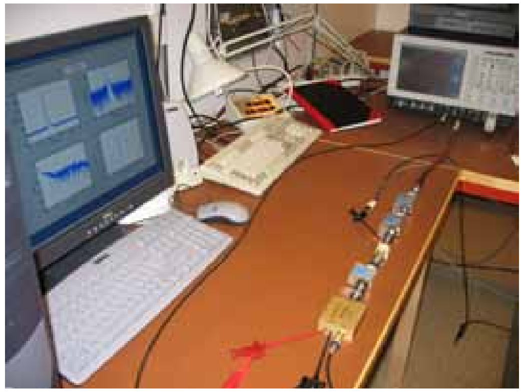
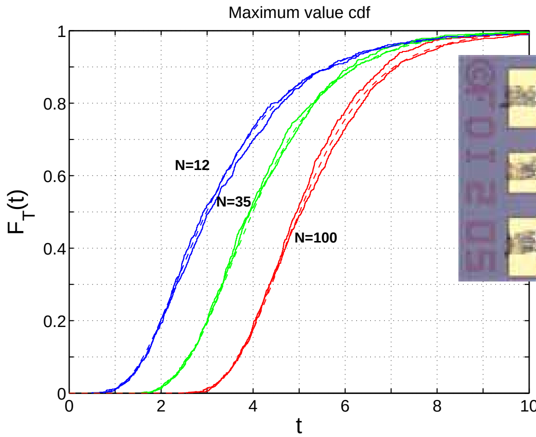
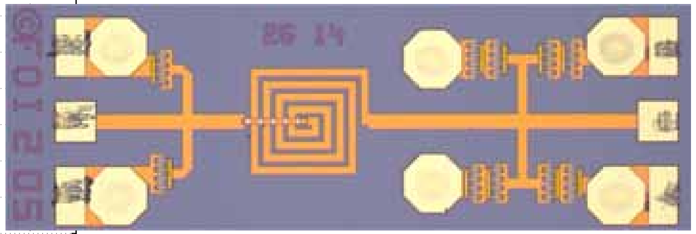
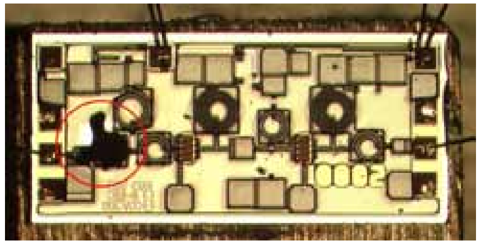
Final report:
HPM - skyddsmetoder för NBF

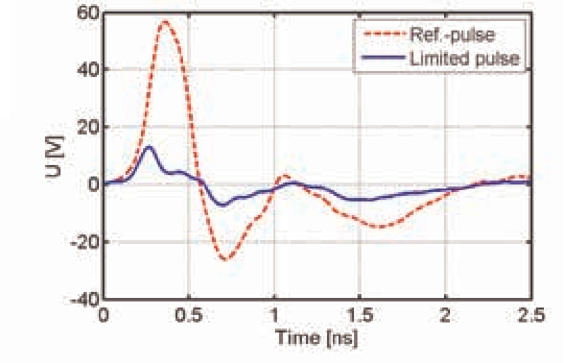
MAGNUS HÖIJER, MATS BÄCKSTRÖM, ROLF JONSSON,
TONY NILSSON, OLOF LUNDÉN, QAMAR UL WAHAB











FOI-R--2127--SE
ISSN 1650-1942

Technical Report
February 2007

Sensor Technology

FOI, Swedish Defence Research Agency, is a mainly assignment-funded agency under the Ministry of Defence. The core activities are research, method and technology development, as well as studies conducted in the interests of Swedish defence and the safety and security of society. The organisation employs approximately 1250 personnel of whom about 900 are scientists. This makes FOI Sweden's largest research institute. FOI gives its customers access to leading-edge expertise in a large number of fields such as security policy studies, defence and security related analyses, the assessment of various types of threat, systems for control and management of crises, protection against and management of hazardous substances, IT security and the potential offered by new sensors.

FOI
Swedish Defence Research Agency
Sensor Technology
P.O. Box 1165
SE-581 11 Linköping

Phone: +46 13 37 80 00
Fax: +46 13 37 81 00

www.foi.se

Magnus Höijer, Mats Bäckström, Rolf Jonsson, Tony Nilsson, Olof Lundén, Qamar ul Wahab

Final report:

HPM - skyddsmetoder för NBF

FOI-R--2127--SE Technical report Sensor Technology
ISSN 1650-1942 February 2007

Issuing organization FOI – Swedish Defence Research Agency Sensor Technology P.O. Box 1165 SE-581 11 Linköping	**Report number, ISRN** FOI-R--2127--SE
	Report type Technical report
	Research area code 6. Electronic Warfare and deceptive measures
	Month year February 2007
	Project no. E 3031
	Sub area code 61 Electronic Warfare including Electromagnetic Weapons and Protection
	Sub area code 2
Author/s (editor/s) Magnus Höijer Mats Bäckström Rolf Jonsson Tony Nilsson Olof Lundén Qamar ul Wahab	**Project manager** Magnus Höijer
	Approved by
	Sponsoring agency
	Scientifically and technically responsible

Report title

Final report: HPM - skyddsmetoder för NBF

Abstract

High Power Microwaves (HPM) is a brutal form of electronic warfare. It relies on that an electromagnetic source can generate enough electromagnetic energy to penetrate into electronic circuits in equipment to disturb or destroy the electronics.

This report highlights important results, knowledge and experiences which have been gained during the three year long project “HPM-skyddsmetoder för NBF”. The report does also contain a list of the written documentation, and information of how competence has been transferred to other parts of the society, mainly authorities and industry.

A general model of how electromagnetic energy hits electronics has been developed. When HPM penetrates through antennas typically a low noise amplifier is destroyed. The susceptibility of these has been investigated. Protection circuits have been developed and investigated.

Unintentional penetration through backdoors is hard to characterize. An essential tool in doing so is to use the Reverberation Chamber. Understanding and methods to use the Reverberation Chamber has been developed.

Keywords

High Power Microwaves, Frontdoor coupling, Backdoor coupling, Low Noise Amplifiers, Limiters, Reverberation Chamber

Further bibliographic information	**Language** English
ISSN 1650-1942	**Pages** 31 p.
	Price acc. to pricelist

<table>
<tr><td rowspan="5">Utgivare
FOI - Totalförsvarets forskningsinstitut
Sensorteknik
Box 1165
581 11 Linköping</td><td>Rapportnummer, ISRN
FOI-R--2127--SE</td><td>Klassificering
Teknisk rapport</td></tr>
<tr><td colspan="2">Forskningsområde
6. Telekrig och vilseledning</td></tr>
<tr><td>Månad, år
Februari 2007</td><td>Projektnummer
E 3031</td></tr>
<tr><td colspan="2">Delområde
61 Telekrigföring med EM-vapen och skydd</td></tr>
<tr><td colspan="2">Delområde 2</td></tr>
<tr><td rowspan="4">Författare/redaktör
Magnus Höijer
Mats Bäckström
Rolf Jonsson
Tony Nilsson
Olof Lundén
Qamar ul Wahab</td><td colspan="2">Projektledare
Magnus Höijer</td></tr>
<tr><td colspan="2">Godkänd av</td></tr>
<tr><td colspan="2">Uppdragsgivare/kundbeteckning</td></tr>
<tr><td colspan="2">Tekniskt och/eller vetenskapligt ansvarig</td></tr>
<tr><td colspan="3">Rapportens titel
Slutrapport: HPM - skyddsmetoder för NBF</td></tr>
<tr><td colspan="3">Sammanfattning

HPM är en grov form av elektronisk krigföring. Den utnyttjar att en elektromagnetisk källa kan generera tillräckligt mycket energi för att penetrera in i elektronikkretsar och störa eller förstöra dessa.

Denna rapport belyser viktiga resultat samt viktig kunskap och erfarenhet som har erhållits inom det treåriga projektet “HPM-skyddsmetoder för NBF” . Rapporten innehåller även en förteckning över samtliga skriftliga publikationer inom projekttiden. Dessutom beskrivs hur information har överförts till övriga samhället, huvudsakligen myndigheter och industri.

En generell modell för hur elektromagnetisk energi förstör/stör elektronik har utvecklats. När HPM tas emot av en antenn förstörs typiskt en lågbrusförstärkare. Sårbarheten hos dessa har undersökts. Skyddskretsar har utvecklats och undersökts.

Oavsiktig bakdörrsinträngning är mycket komplex. Ett viktigt verktyg för att kvantifiera bakvägsinkoppling är den Modväxlande kammaren. Förståelse och metoder för att använda den Modväxlande kammaren har utvecklats.</td></tr>
<tr><td colspan="3">Nyckelord
HPM, framvägskoppling, bakvägskoppling, lågbrusförstärkare, limiter, Modväxlande kammare</td></tr>
<tr><td>Övriga bibliografiska uppgifter</td><td colspan="2">Språk Engelska</td></tr>
<tr><td>ISSN 1650-1942</td><td colspan="2">Antal sidor: 31 s.</td></tr>
<tr><td>Distribution enligt missiv</td><td colspan="2">Pris: Enligt prislista</td></tr>
</table>

Table of Content

Introduction

High Power Microwaves (HPM) is a brutal form of electronic warfare. It relies on that an electromagnetic source can generate enough electromagnetic energy to penetrate into electronic circuits in equipment to disturb or destroy the electronics. Traditionally the coupling to electronics is divided into two forms, frontdoor and backdoor coupling, see Fig. 1. In frontdoor coupling the electromagnetic energy enters the equipment through an electromagnetic sensor. As the sensor is manufactured with the purpose of receiving electromagnetic radiation, large quantities of electromagnetic energy may potentially be received that way. On the other hand, as we have assumed that the electromagnetic energy enters the equipment through the sensor, the protection needs can easily be diagnosed. It is relatively easy to test whether the sensor and the nearby components can withstand a certain threat. If not we know that a protection circuit is to be placed at the sensor.

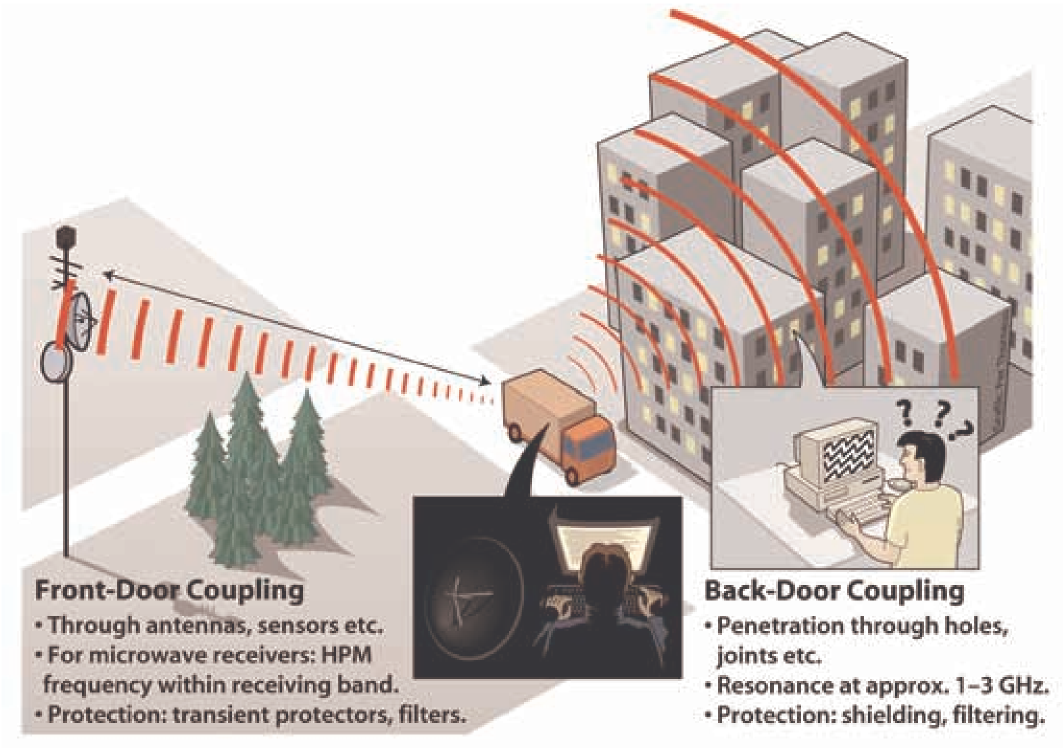


Figure 1: *An electromagnetic source, placed in a lorry, irradiates electromagnetic energy. Through frontdoor and backdoor coupling, electromagnetic energy penetrates into the electronics, causing disturbances in or destruction of the equipment.*

Backdoor coupling is more complex. Electronic circuitry act as unintentional antennas, and does hence receive electromagnetic energy. As the electronic circuitry is not a manufactured antenna, the receiving of electromagnetic energy is often not so efficient. On the other hand, the circuit may receive electromagnetic energy almost everywhere in the circuit and as we can not place protection circuits everywhere in the electronics, backdoor coupling is much more difficult to handle. A metal shield around the electronic circuitry is a sufficient protection. In practice however, the electronic circuitry cannot be completely screened from the rest of the world, so there is need for holes in that shield, and through every hole, electromagnetic energy can, and will, leak through in a complex manner.

In practice, the classification into frontdoor and backdoor coupling is not as clear as daylight. In a typical frontdoor coupling, the entrance is an antenna manufactured for exactly the same frequency as the frequency of the incident HPM. Given a certain incident threat, we know exactly how much power the antenna receives, and as the antenna itself normally is not vulnerable, we know how much power the input electronics behind the antenna has to be able to withstand. In practice, the frequency of the incident HPM might not be within the pass band of the receiving antenna. Then the entrance antenna work more like the backdoor case as an unintentional antenna. The entrance antenna may however still be the main entrance port for electromagnetic irradiation to the electronics.

The electromagnetic entrance sensor may also be an optical sensor. Some preliminary results does here show that the optical sensors themselves do not receive HPM and are also not sensitive to HPM. The sensor does here only work as a hole, were HPM leaks through. Hence, we have backdoor coupling.

This report summarises the results, experiences and progress which have been done within the three year project “HPM - skyddsmetoder för NBF”. The report does also include some highlights of the results. It includes some typical frontdoor cases, where testing has been performed on components sitting behind an entrance antenna, methods do tackle the complex backdoor coupling and testing of whole systems.

Research Aim and Direction

The project “HPM - skyddsmetoder för NBF” has aimed to estimate, evaluate and respond to the HPM-threat.

Research questions and goals

- To create the foundation for evaluation of the HPM-threat toward defence materiel and the infra structure
- Evaluate and develop protection methods for frontdoor coupling
- Maintenance and development of the expertise within the area of analysis of susceptibility and verification of susceptibility of systems

Benefit for the defence

The research within protection methods against HPM gives

- Knowledge of susceptibility of defence materiel
- Knowledge of how to test the susceptibility of materiel
- Knowledge of some protection methods
- Knowledge of optimal parameter choice for a HPM-source

Transfer of competence

The knowledge and competence which has been built up within the project has been reported to the Swedish Armed Forces, FMV, public authorities and industry through:

- Written documentation
- Study groups
- SAMHPM
- Lectures & Talks
- Industry Contacts
- Personal Communication

Written Documentation

A list of 59 reports and articles can be found at the end of this report. It includes

- 1 FOI Scientific Report [215],
- 7 FOI Technical Reports [169, 174, 188, 209, 212, 226, 227]
- 3 FOI Memo [189, 190, 191].
- 6 Journal Articles [183, 184, 192, 210, 214, 225]
- 35 Articles in Symposium Proceedings
- 2 Invited Workshop Presentations [221, 222]
- 1 University report [173]

Further FOI Memos have been written but within connecting FMV projects.

Study Groups

Magnus Höijer and Mats Bäckström has participated as technical experts in the study groups "Telekrig i urban miljö" and "Telekrig i breddad hotbild", respectively. The work is reported in:

- Lars Berglund, Jan Arnsby, Magnus Höijer, Nils-Uno Jonsson, Peter Klum, Gustaf Olsson, Lars Sjöquist and Åsa Waern, "Förstudie Telekrig I Urban Miljö" , FOI User Report, FOI-R--1386--SE, November 2004, Swedish Defence Research Agency FOI, Sensor Technology, P.O. Box 1165, SE-581 11 Linköping, Sweden.

- Roland Heickerö, Per Hyberg, Mats Bäckström, Gustaf Olsson, Ingemar Renhorn, Tobias Jonason, Fredrik Eklöf Hamrin, "Telekrig i en breddad hotbild" , FOI User Report, FOI-R--1370--SE, December 2004, Swedish Defence Research Agency FOI, Sensor Technology, P.O. Box 1165, SE-581 11 Linköping, Sweden.

SAMHPM

Participation in SAMHPM meetings and Mats Bäckström was the chairman for the last period.

Lectures & Talks

Several talks and lectures have been given by Magnus Höijer and Mats Bäckström. Those include but are not limited too:

- HPM-days at the headquarters
- Higher Course Electronic Warfare
- Police authorities
- Swedish Emergency Management Agency
- University Hospital

Industry contacts

The project team has actively participated in the

- Technical reference group for DEMO RF

Co-operation concerning limiters and low noise amplifiers with

- Saab Microwave Systems

Co-operation concerning Reverberation Chamber with

- Saab Bofors Dynamics

The project team has contributed with important knowledge of which the key parameters are and quantitative values on them.

International Co-operation

The project team has a co-operation with our Nordic neighbours

- Forsvarets Forskningsinstitut, Norway
- Forsvarets Forskningstjenste, Denmark
- PvTT, Finland

The co-operation has 2006 been formalised within NORDAC. Juhani Hämäläinen, PvTT, has been a guest researcher in our project.

The project team has participated in the FMV-lead co-operation with Germany, and participated in several co-operation meetings. A two week long measurement campaign on the generic missile GENEC was performed between Sweden and Germany in the autumn 2005.

The project team has participated in meetings with France and United Kingdom.

Groups from several countries have visited us at FOI in Linköping.

Personal scientific and technical contacts with colleagues inside and outside of Europe. E.g. Magnus Höijer recently started a co-operation on comparing electromagnetic fields with Dr. Luk Arnaut, NPL, London and Dr. Hans Georg Krauthäuser, Uni Magdeburg.

Symposium & Organisations

Much knowledge has been gained by participating in international and national symposiums as well as being member of engineering and scientific organisations. Our own written contribution can be found in the publication list at the end of this report.

Project members have been member of the IEEE EMC, URSI/SNRV and IEC/SEK.

Project members have also had commission of trust:

- Chairman, together with Daniel Nitsch, for the HPEM part of EuroEM2004 in Magdeburg (Mats Bäckström)
- Several session chairs (Mats Bäckström)
- Several reviews of journal articles and symposium articles (Mats Bäckström, Magnus Höijer, Olof Lundén and Niklas Wellander)
- Several invited speaker (Mats Bäckström)
- Invited workshop speaker (Magnus Höijer and Olof Lundén)
- Co-chairman of the Swedish URSI committee (Mats Bäckström)
- Chairman of the Swedish URSI Commission E (Electromagnetic noise and Interference) (Mats Bäckström)
- Swedish delegate to URSI commission E (Mats Bäckström)
- Chairman of the Swedish URSI Commission A (Electromagnetic metrology) (Olof Lundén)
- Co-chairman of the URSI working group on Intentional EMI (Mats Bäckström)
- Active in IEC working groups on Reverberation chambers, Intentional EMI and IEMI test facilities. (Magnus Höijer and Mats Bäckström)

University Contacts

Experimental work concerning testing of commercial products susceptibility has been performed together with Uppsala University. Formal contacts:

- Assistant tutor for Magnus Otterskog, Örebro University and Daniel Månsson, Uppsala University (Mats Bäckström)
- Opponent Urban Lundgren, Luleå University of Technology (Mats Bäckström)
- Discussion leader Ulf Carlberg, Chalmers University of Technology (Magnus Höijer)
- Several Grade committees (Mats Bäckström)

Highlights of Results

General description

A general antenna model of how electromagnetic radiation couples to electronics have been developed, see [188]. Fig. 2 shows the principal behaviour, the test object act as antenna receiving the electromagnetic radiation and through conductive parts in the antenna, the electromagnetic energy is conducted toward the most susceptible component. Thereby the most susceptible component is disturbed or destroyed.

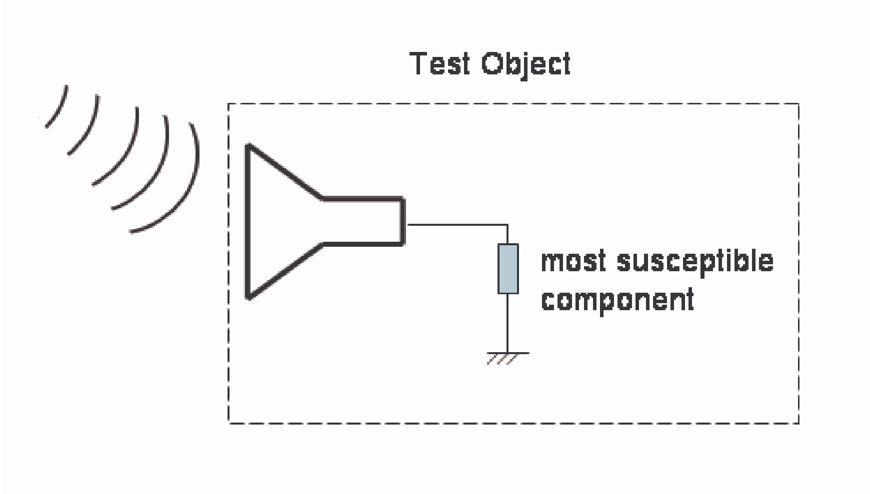


Figure 2: *All objects do, intentionally or unintentionally, act as antennas receiving electromagnetic radiation. Through conductive parts in the antenna, the electromagnetic energy is conducted toward the most susceptible component. Thereby the most susceptible component is disturbed or destroyed.*

In the case of frontdoor coupling, we have an intentional receiving antenna with known properties. Hence we can, outgoing from the incident electromagnetic field, easily calculate the electromagnetic energy stressed onto the first component after the receiving antenna. Fig. 3 shows an example of how the incident electromagnetic pulse is received in the antenna and a pulse is conducted toward the first component. A typical first component is a low noise amplifier (LNA). In Fig. 3 a limiter has been mounted before the LNA to protect the LNA against damage. The limiter stops too large pulses from coming through and thereby the LNA is protected.

The main focus in frontdoor coupling protection is to characterise the susceptibility of typical components like the LNA, as well as to develop and characterise limiters. As the receiving antenna properties are well known, no focus has to be put onto that part. Hence, the characterising can be done by direct injection of electromagnetic energy into the components. The testing procedure is thereby substantially simplified.

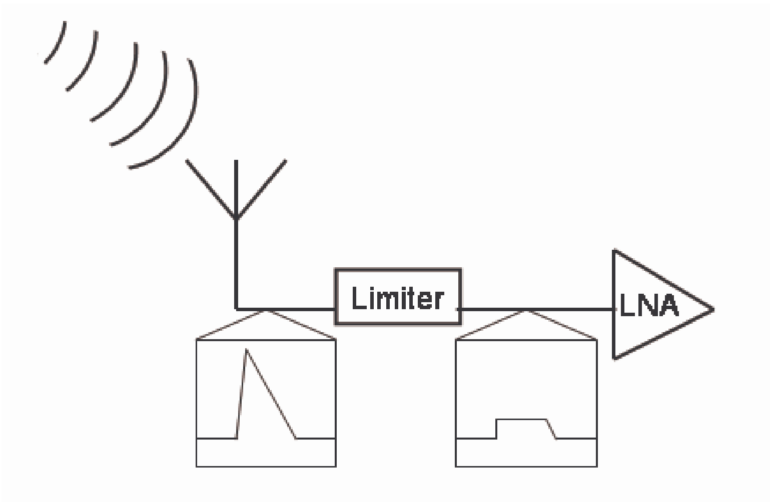


Figure 3: *A typical frontdoor coupling. An electromagnetic pulse enters the electronic circuitry through an antenna. By introducing a limiter as the first component, the subsequent components are protected against damage. The figure shows how a limiter limits a too large pulse.*

Backdoor coupling is by far more complicated. There are so many ways for the electromagnetic energy to reach the electronic circuitry that the incident electromagnetic energy may in principal hit components in almost every part of the equipment. Added to that, in the backdoor case, the receiving properties of the antenna in fig. 2 are much unknown[1]. The amount of received electromagnetic energy is strongly affected by from which direction the antenna is irradiated as well as the orientation of the test object. There is also probably some form of, intentional or unintentional, shielding in the form that energy is reflected or absorbed in not fragile parts of the test object.

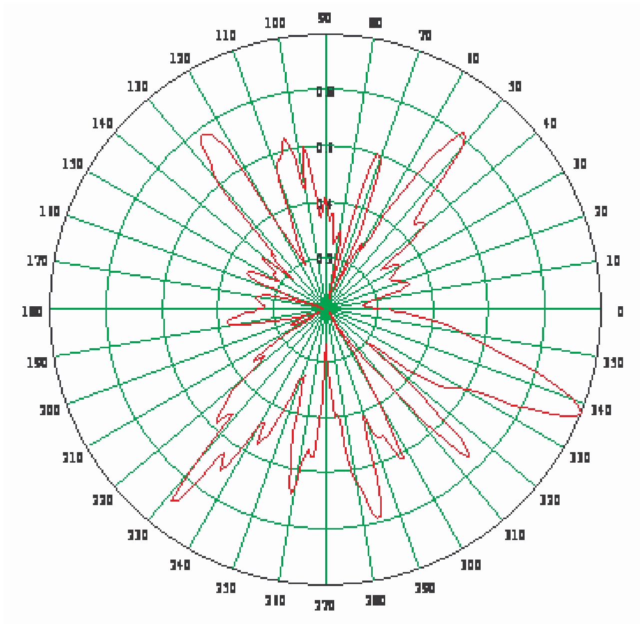


Figure 4: *The amount of energy received in a critical component in the test object depends strongly on from which direction the test object is irradiated. This figure shows one example from one object being tested at FOI in Linköping.*

[1] It is important to see the difference between backdoor coupling and frontdoor coupling. In the ideal frontdoor case, the receiving properties of the antenna are well known, but in the backdoor case the receiving properties of the receiving antenna are unknown.

Fig. 4 shows one typical example of how the amount of received electromagnetic energy varies with from which direction the test object is irradiated. Such a complex pattern is impossible to predict in advance. The pattern does also changes very fast as function of frequency.

This implies that equipment may be tested by irradiation from one direction and found to pass the requirements. Later in a live situation the same equipment may be irradiated from another direction where it is very susceptible. Not surprising the equipment breaks down. This is a problem which has not yet been solved. To perform testing by irradiation from all possible direction is today seen as too expensive and too time consuming. **It is again to be stressed that this is a problem. Much of the testing of equipment which has been performed can be questioned.** A materiel might have been found more vulnerable than another. In reality the truth might be the opposite, the reason being that one materiel was hit from a very vulnerable direction and the other from a less vulnerable direction when the testing was performed.

One possible way to address this problem is to use the reverberation chamber (RC) as test facility. The advantage of the reverberation chamber is that it gives a more unequivocal result.

Frontdoor coupling

We have tested the susceptibility of low noise amplifiers (LNA). That is because a LNA is typically the first component in a sensor. Its task is to amplify the week input signal and at the same time add as little noise as possible. A particular example is phased array antennas, which often have many LNA:s as the first component. Phased arrays are researched in other projects at the department and by studying LNA:s we can obtain a synergy with those projects. Fig. 5 shows a test set-up where narrow band pulses, of different pulse lengths, are injected onto the component and Fig. 6 shows a test set-up where short pulses are injected onto the components.

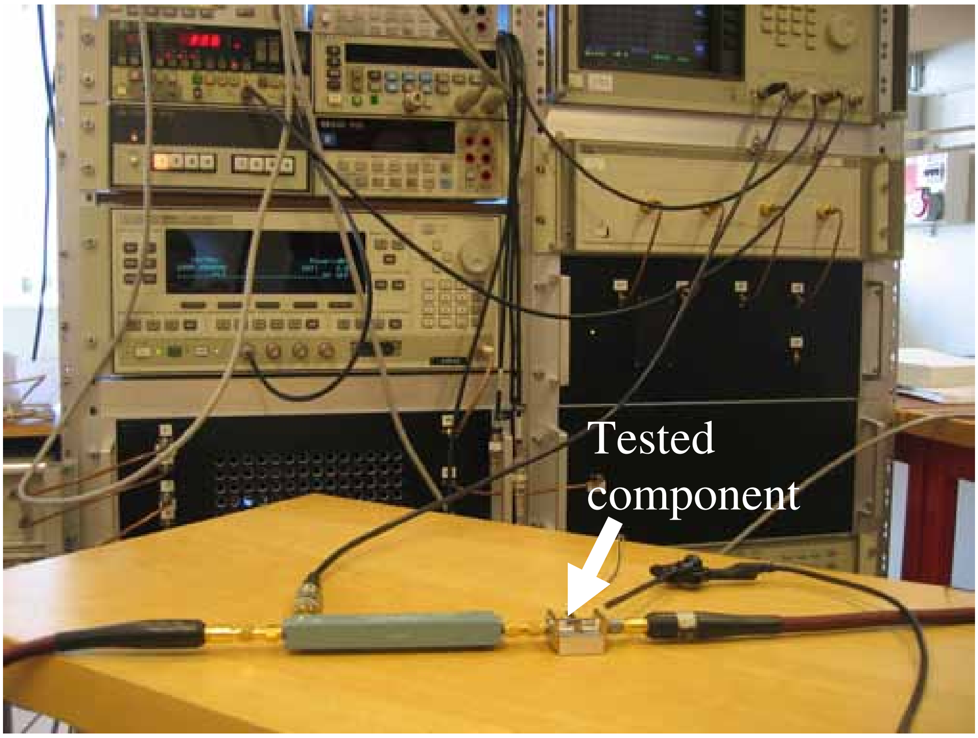


Figure 5: *Narrow band HPM-pulses are injected on the component under test.*

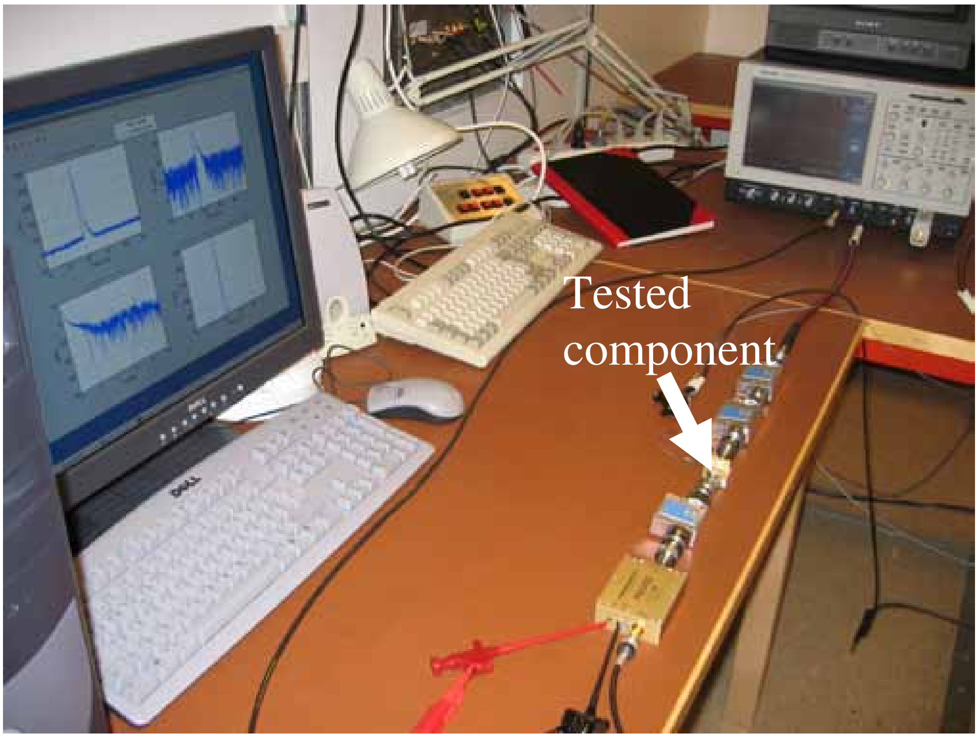


Figure 6: *Short HPM-pulses are injected on the component under test.*

Low Noise Amplifiers

In Fig. 7 the effect of injecting a HPM-pulse on the LNA can be seen. Its properties as an amplifier have also been investigated. In Fig. 8 it can be seen that after the HPM-pulse the amplifier does not longer work as an amplifier. For further results, see [189].

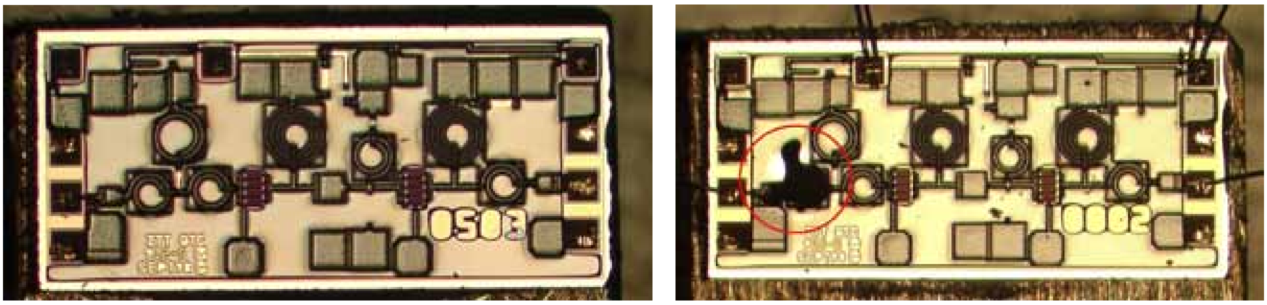


Figure 7: *A Low Noise Amplifier (LNA) before the injection of a narrow band HPM-pulse (left), and after the injection of a narrow band HPM-pulse (right). The red circle shows the damage to the component.*

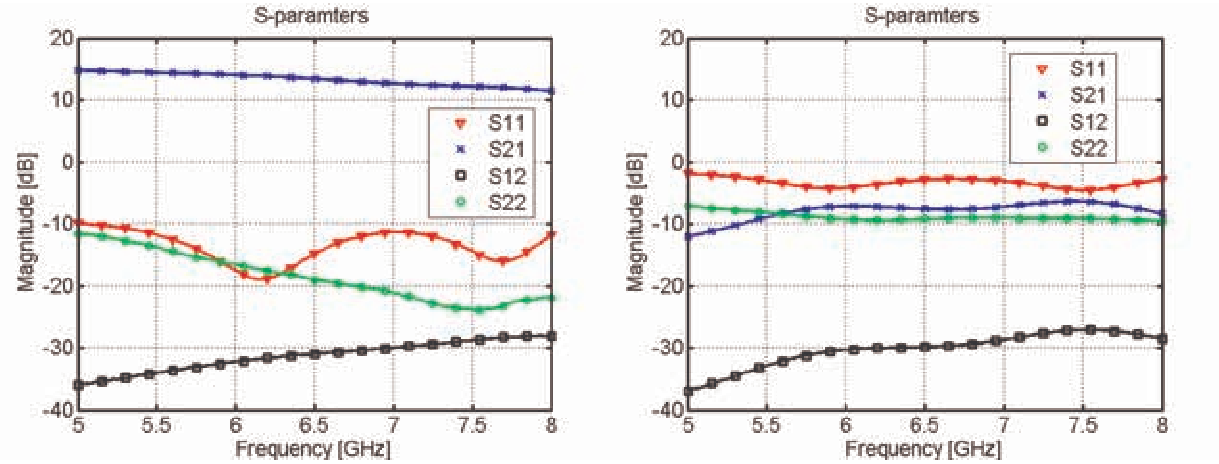
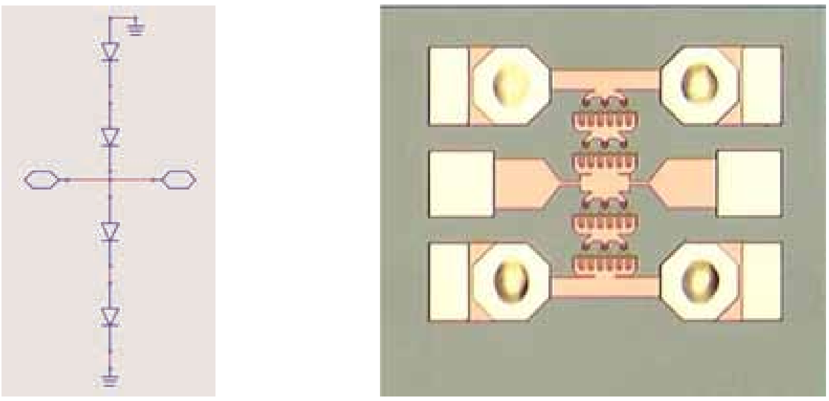


Figure 8: *The electrical small signal properties of the LNA before (left) and after (right) a narrow band HPM-pulse has been injected. The most important curve is the blue one (S21), showing that before the HPM-pulse the LNA amplifies the input signal by 10-15 dB. After the HPM-pulse the LNA does no longer work, instead of amplifying the input signal, the broken LNA attenuates the signal by around 10 dB.*

Limiters

As shown in Fig. 3 the LNA can be protected by putting a limiter before the LNA. At FOI we have designed Schottky-diode limiters. They have been fabricated in the OMMIC ED02AH monolithic microwave integrated circuit (MMIC) process, see Fig. 9. Fig. 10 shows how a short input signal is limited by the limiter.



(a) **(b)**

Figure 9: *FOI Schottky-diode limiter schematic (a) and photograph (b).*

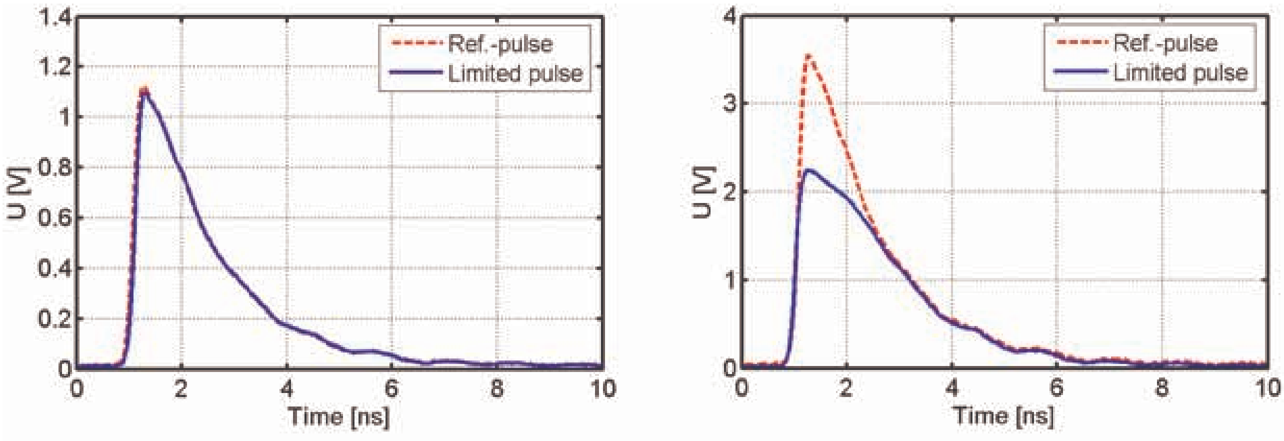


Figure 10: *The red dashed input pulse is limited by the FOI Schottky-diode limiter. The blue solid line shows the output signal from the FOI Schottky-diode limiter. For small input signals (left) there is almost no limitation of the signal.*

Outgoing from the experience, a second attempt to make better limiters were done, see Fig. 11 and Fig. 12.

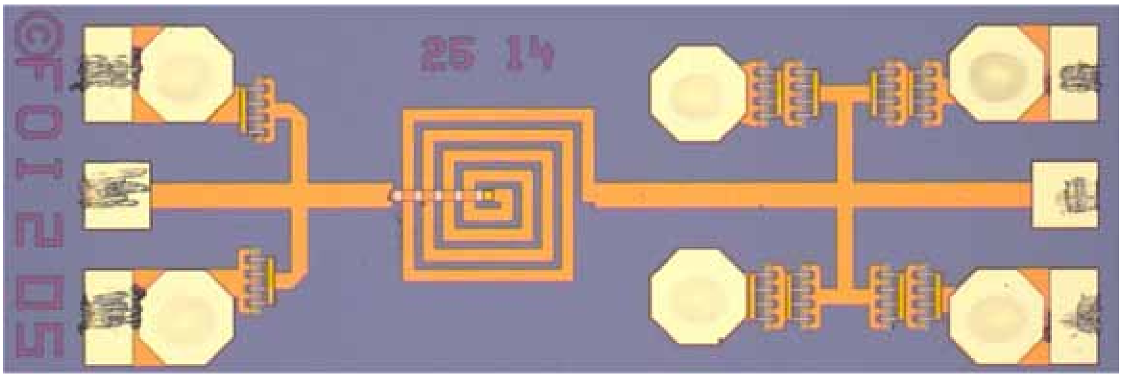


Figure 11: *Photo of the GaAs MMIC limiter chip with FOI Schottky-diode limiters.*

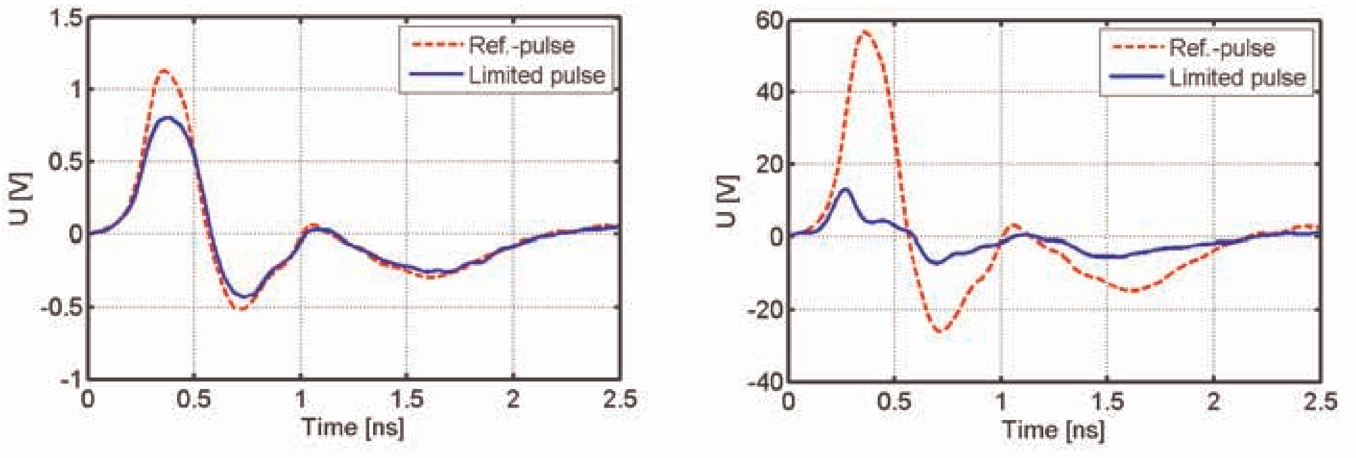


Figure 12: *Performance of the FOI Schottky-diode limiter in Fig. 11. The red dashed input pulse is limited by the FOI Schottky-diode limiter. The blue solid line shows the output signal from the FOI Schottky-diode limiter. For small input signals (left) there is only a small limitation of the signal.*

Though the results look good, there are still substantial problems. The main problem is the parasitic resistance of the diodes that increase the off-state small signal loss of the circuit, limiting both bandwidth and the use of larger diodes that would allow better isolation in the on-state [226].

Commercial limiters have been investigated. One of the best, is the TGL2201 from Triquint (USA) based on VPIN-diodes, see Fig. 13. Fig. 14 shows how it limits a short input pulse. For further results, see [212].

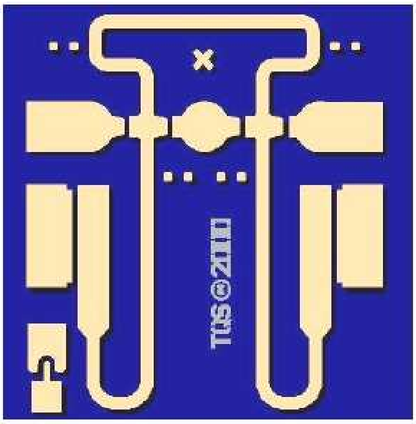


Figure 13: *Picture of the Triquint TGL2201-EPU limiter MMIC chip.*

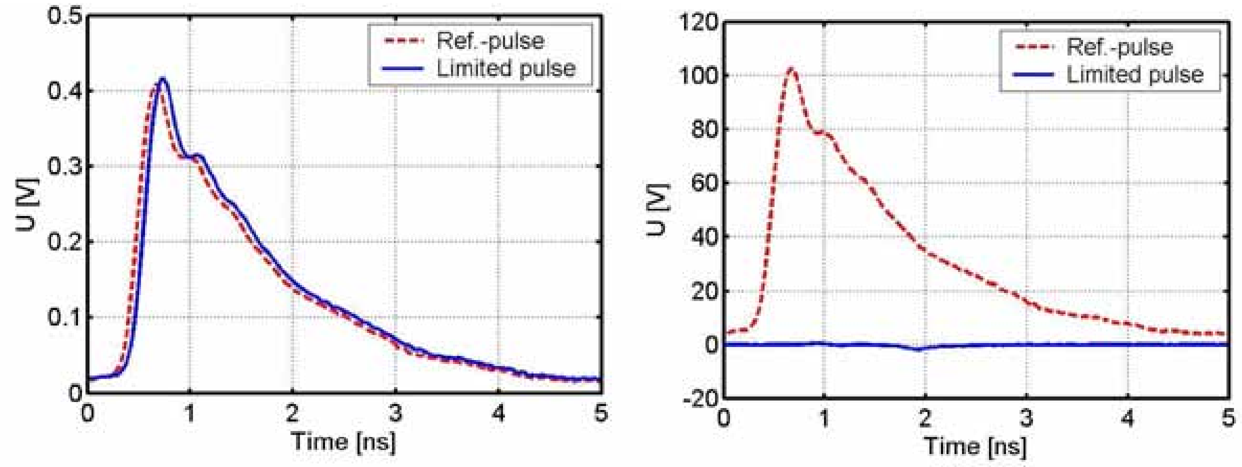


Figure 14: *To the left the incoming and transmitted pulse at low signal level are shown, the TGL2201 is not limiting the short pulse. To the right the corresponding pulses at high signal level are shown. The TGL2201 is now limiting the short pulse very efficiently.*

New materials

A simulation comparison of Si, GaAs and 4H-SiC PIN diodes for microwave protection circuits against high power microwave (HPM) pulses was conducted. The on-resistance and junction capacitance is similar to that of Si diodes but the thermal conductivity is higher, this should enable better power performance for the same size diodes or better small signal performance with the same power rating. For further results, see [201].

Backdoor coupling

As pointed out above the backdoor coupling case is much more complicated than the frontdoor coupling case. We have managed to describe the complexity. There are two important parameters describing the case, the *directivity* and the *polarisation efficiency*. The directivity describes how susceptible the test object is for a specific irradiation direction compared to the average taken over all irradiation directions. The polarisation efficiency describes how well the polarisation of the incident HPM pulse couples to the receiving polarisation of the test object. Both parameters vary rapidly with irradiation direction (Fig. 4) and the frequency in use. The strength of the variations is also very large; it can be a factor of 1000 or even more.

Consequently, if we have tested our object for a few irradiation directions we do not know much. Have we tested our object for directions were it is very susceptible it is good, but perhaps we have tested our object for directions were it is very durable? In the later case we have to add a margin of a 1000 or more. The problem is that we do not know if we have to add this margin of a thousand or more. There is a huge unwanted uncertainty.

Reverberation Chamber

One way to tackle that problem is to use the reverberation chamber (RC). We have shown that when a susceptibility test is performed in the RC, the directivity and receiving polarisation of the test object does not affect the result [215]. They are replaced by their average values, 1 and 0.5, respectively. Hence we get an unequivocal value, and the large uncertainty is gone.

The price to pay is that substantial knowledge of electromagnetic statistics much be gained. The RC is a room (chamber) with metallic walls, see Fig. 15. The test object is to be placed somewhere in the middle of the chamber, exact position does not matter. Electromagnetic power is pumped into the chamber and the object is stressed for some different positions of the rotating stirrers. The strength of the stress is measured by a separate reference antenna. The average received power in the reference antenna is a measure of the total energy in the chamber. The stress onto the test object differs from stirrer position to stirrer position, but we are interested in the maximum stress onto the object. The random environment implies that there is an uncertainty in the maximum power stressed onto the test object. We have developed distribution functions to quantitatively describe this uncertainty [215].

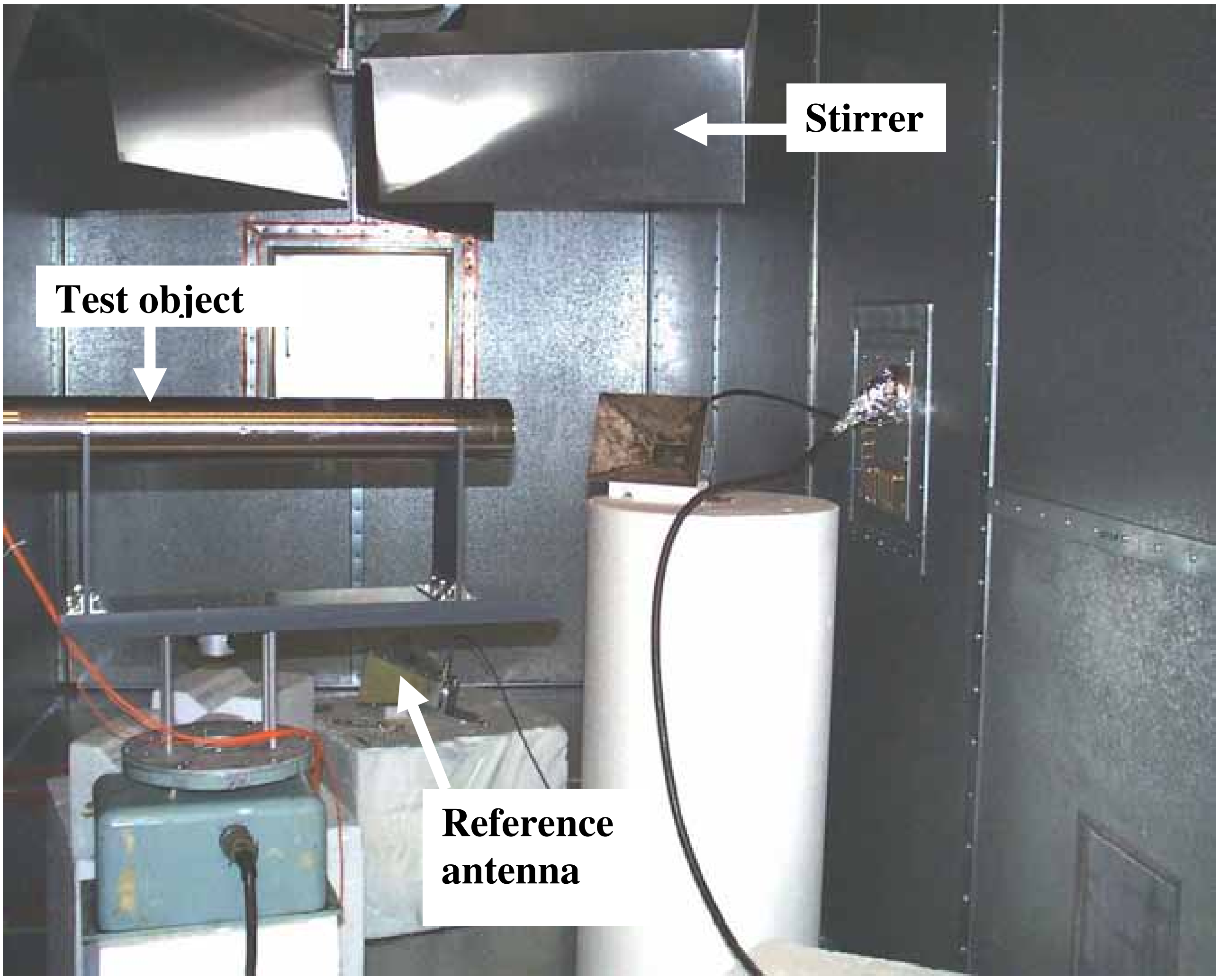


Figure 15: *Electromagnetic power is pumped into the reverberation chamber, and thereby stressing the test object. The strength of the stress is measured in the reference antenna.*

The most important distribution is the T-distribution describing the distribution of the maximum power stressed onto the test object compared to the average power measured in the reference antenna. The dashed curves in Fig. 16 show the cumulative distribution for T. The T-distribution does depend on the number of stirrer positions, and in Fig. 16 the cumulative distribution for T is shown for 12, 35 and 100 stirrer positions. Not surprising the maximum stress onto the test object tends to be higher when it is stressed for more stirrer positions. If e.g. 100 stirrer positions are used we can with almost 100 % confidence say that the maximum stress onto the test object is at least 3 times as high as the average power measured in our reference antenna.

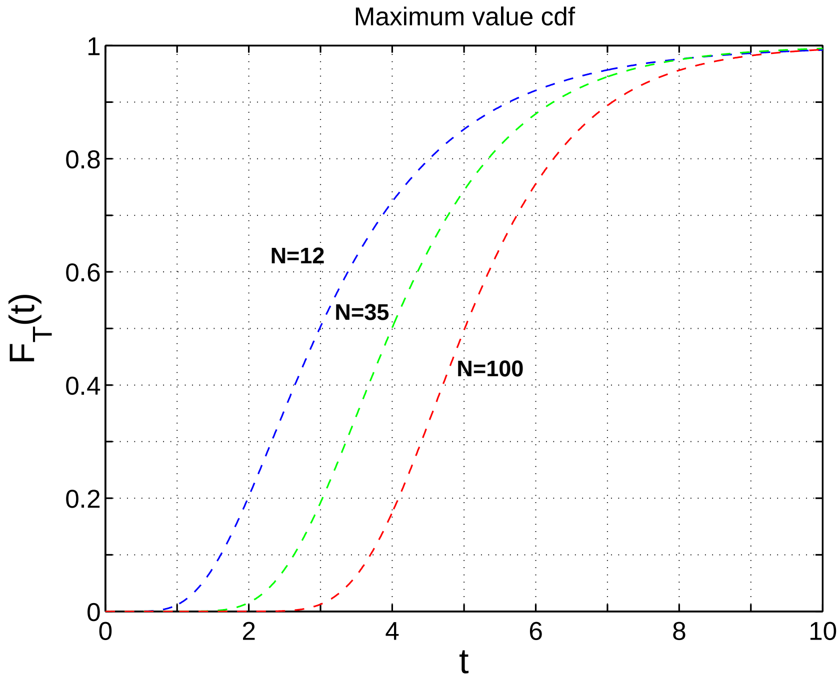


Figure 16: *The cumulative distribution or T. T is the maximum power stressed onto our test object compared to average power measured in our reference antenna. The distribution of T depends on the number of stirrers in use. In this graph the cumulative distribution is plotted for 12, 35 and 100 stirrer positions.*

We have performed measurements to verify the theoretical distribution. The solid lines in Fig. 17 are the results of two different measurements of the T-distribution. The agreement between theory and experiment is so excellent that we can feel confidence in using the T-distribution.

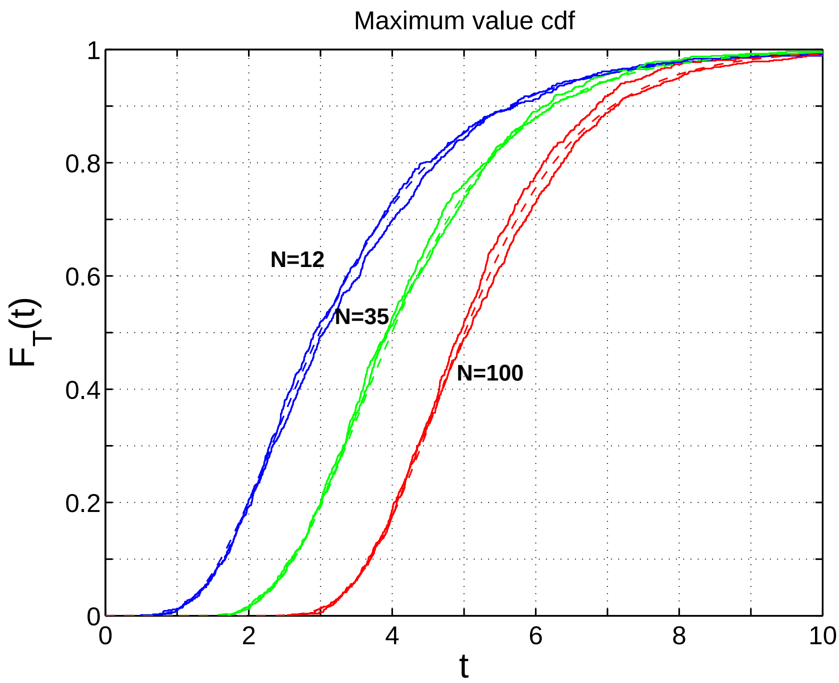


Figure 17: *The theoretical distribution in Fig. 16 is here compared to measurements. The measurements are presented as solid curves and the theory as dashed curves. Two different measurements were performed for all three different number of stirrer positions. The agreement among the two measurements curves and the theoretical curve is so excellent that we can feel confidence in using the T-distribution.*

Efficient Stirrers in Reverberation Chambers.

In an effort to gain better understanding of the stirrer behavior in reverberation chambers an extensive experimental study has been conducted [224]. The background was that the national physical laboratory (NPL) in UK made measurements in a newly constructed chamber and found that the performance achieved was only half of what was reported in our study [FOA-R--99-01139-612--SE May 1999]. A common view at that time was that size and shape was of some importance i.e. the stirrer should occupy the major part of at least one dimension of the chamber [IEC 61000-4-21]. Most current stirrers have a small diameter to height ratio. We measured the efficiency of the stirrer, in two chambers with volumes 27.1 respectively 36.7 m^3, in terms of the lowest possible frequency for which it gives a certain number of uncorrelated samples. Two different kinds of stirring were tested, the common rotational stirring and horizontal translation, see Fig. 18.

Figure 18: *Rotating stirrer (left) and translating stirrer (right).*

The stirrers were assembled of aluminum panels of different widths. The tested diameters were 0.72, 1.15, 1.55, 1.95 and 2.40 m which each were made in eight different heights 0.28, 0.40, 0.53, 0.80, 1.2, 1.6, 2.0 and 2.4 m.

Mathematical modeling of the design parameters was based on dimensionless quantities which were fitted to the experimental data. When evaluating the stirrer parameters influence on the efficiency we assumed that the lowest frequency yielding uncorrelated samples to have a power dependence with respect to the design parameters i.e. diameter, height and volume. It turned out that for 200 uncorrelated stirrer positions we got the expression:

$$f_{200} = \exp(6.8)\frac{V_{ch}^{0.2}}{h^{0.38}d^{1.2}}$$

where f_{200} is the frequency in MHz, V is the chamber volume, h and d the stirrer height and diameter. The impact of changing the stirrer diameter is approximately cubic compared to a change in stirrer height. Fig. 19 shows the lowest usable frequency as function of stirrer height and diameter. The efficiency of stirrers that are translated is proportional to the stepping increment and to the square root of the area of the projection of the stirrer on a plane orthogonal to the direction of the translation.

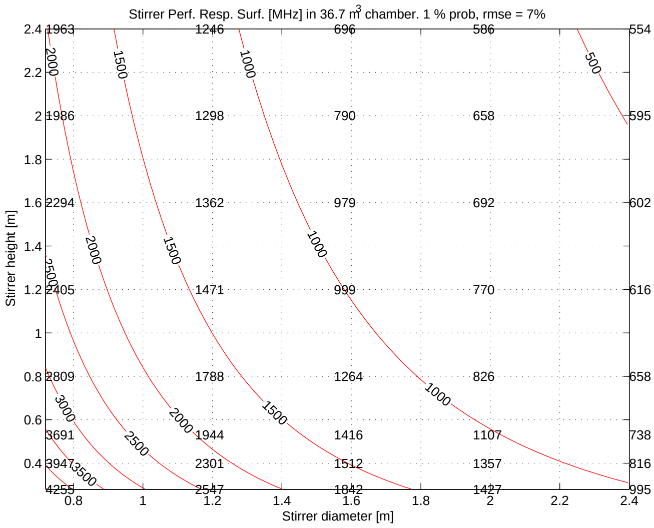


Figure 19: *The curves are isolines of the lowest frequency yielding 200 uncorrelated samples for the rotating principle. The numbers in the grid are the corresponding frequencies obtained from measurements.*

Non-linear Effects and Degradation of EMC Joints Irradiated by HPM

Determination of shielding effectiveness is a vital part in the analysis of an electronic systems capability to withstand HPM. It is usually assumed that the shielding effectiveness, determined at low field levels, is also valid at HPM threat levels. This assumption might be refuted by the presence of non-linear effects, e.g. due to electrical discharge or metal-insulator-metal junctions caused by corrosion (the "rusty bolt effect"). Irradiation at threat level may also result in damage and degradation of the shielding joint. Both these aspects have been studied [174].

Measurements were performed on 31 corroded EMC joints. These objects represent selections taken from two studies headed by the Swedish Corrosion Institute (SCI). In the first study the influence of accelerated corrosion on the shielding properties of different material combinations used in joints was studied. Five objects were chosen from this study, see Fig. 20 and Fig. 21. In the second study 26 different combinations of gasket, frame and cover plate, exposed to one year outdoor environment in Stockholm, were studied.

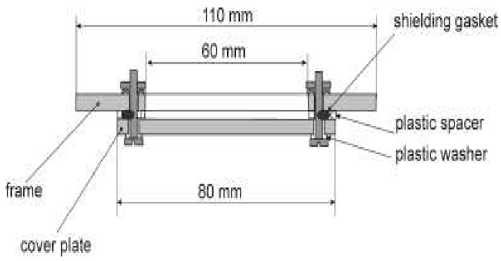


Figure 20: *Geometry of the EMC joints from first study.*

Figure 21: *Test object with clear chromated aluminum/tin plated contact fingers after exposure to accelerated corrosion test.*

Two different kinds of measurements were performed: determination of the transmission cross section of the EMC joints at low field levels and high level irradiation of the joints. The determination of the transmission cross section was made in a reverberation chamber before and after the high level HPM irradiation test in order to detect any degradation of the shielding properties of the objects. The irradiation at high levels was carried out, using a 3 GHz, 700 kW magnetron source, in order to find out if degradation would occur and if a spectral broadening occurs, the latter detected using a D-dot probe mounted behind the joint. The pulse length was 1 μs and the PRF was 70 Hz.

No major degradation of the 31 corroded test objects could be detected after HPM irradiation at high field levels. Also, most of the tested objects showed rather small changes of the time domain shape of the transmitted pulse. This indicates only a very limited effect due non-linear behavior. However, some objects show enhanced peaks at 6 GHz and also indicate a significant spectral content below and around 1 MHz.

Equipment testing

We have also performed high level testing on small complete equipment. That is no research work. It does not address questions like how equipment is destroyed, what parameters are important and how to protect and to validate protection. However, testing of complete equipment, give us the ability to verify that the knowledge which we develop is applicable also to complete equipment. Sometimes, we also discover new phenomena.

An example is a radiated susceptibility test which we performed on GPS receivers. Three different types were tested (GPS A, B and C), see Fig. 22. Both susceptibility tests with short pulses and long pulses were done. The short pulses were generated with a RADAN 303B source, incl. a sub slicer, and the long pulses 700 kW magnetron. In Fig. 23 the field levels to create a level 4 disturbance in the electronics can be seen. Level 4 implies that an operator manually has to restart the GPS to get it to work. One can clearly see that the disturbance levels vary between the different GPS, but one can also see that the irradiation direction does also affect the disturbance levels.

By performing the irradiation for only three different irradiation directions we are not even close to tell what is the difference in disturbance level between the most susceptible irradiation direction and the less susceptible irradiation direction, but we have verified that even on complete equipment there is an important directional dependence in the susceptibility. For further results, see [217].

Figure 22: *Photo of the three types of GPS A, B and C.*

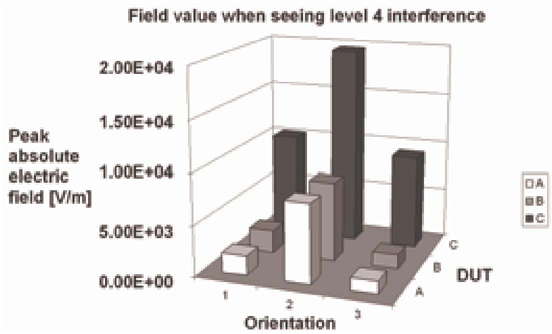


Figure 23: *Field levels which causes a level 4 disturbance in the electronics.* (*Level 4 disturbance implies that an operator manually has to restart the GPS to get it to work.*)

Suggestions to main focus of future work

- To find and quantify the important parameter to cause destruction in essential components, e.g. limiters and low noise amplifiers.
- Find reasonable simple ways to characterise the threat and susceptibility of components in the complex backdoor case.
- Equipment testing to verify gained knowledge

This work gives essential knowledge of the threat, how to protect own equipment and input on what the desired parameters of a HPM-source are. It gives knowledge on optimal parameters e.g. pulse length, pulse repetition frequency, frequency, polarisation, pulse form etc.

Publication List 2004-2006

The reports are ordered in chronological order. The numbering corresponds to reports published since the start of HPM-projects at FOI Sensor Technology.

169. V. Isovic, "Investigation of the Equivalence between Susceptibility Testing Performed with Many Angles of Incidence and Susceptibility Testing Performed with Many Frequencies", FOI-R—1179—SE, February 2004, Swedish Defence Research Agency FOI, Sensor Technology, P.O. Box 1165, SE-581 11 Linköping, Sweden.

170. M.Höijer, ”Parametervärden till RF-demo avseende materielsårbarhet", FOI Reg. Nr. 04-H 91,2004-03-19,

171. M. Höijer, ”Demo RF stridsdel etapp 1/FOI: Målobjekt till demonstration", FOI Reg. Nr. 04-H 92, 2204-05-19.

172. M. Höijer, ”Demo RF stridsdel etapp 1/FOI: Lägesrapport 2004-05-21", FOI Reg. Nr. 04-H 159, 2004-05-19.

173. U. Jordan, D. Andersson, A. Kim, M. Lisak, M. Bäckström, O. Lundén, ”Microwave Breakdown in Slots", Dep. of Electromagnetics, Chalmers University of Technology, Göteborg, Sweden, 2004.

174. M. Bäckström, O. Lundén, "Experimental Investigation of Degradation and Non-Linear Effects in Corroded EMC Joints Exposed to High Power Microwaves (HPM)", FOI-R—1246—SE, June 2004, Swedish Defence Research Agency FOI, Sensor Technology, P.O. Box 1165, SE-581 11 Linköpng, Sweden.

175. Ulf Jordan, Dan Andersson, Arkady Kim, Mitek Lisak, Mats Bäckström, Olof Lundén, ”Microwave Breakdown in Slots", Book of Abstracts, Euroem2004, 12 –16 July 2004, Magdeburg, Germany.

176. Juhani Hämäläinen, P Järviö, Torleif Martin, Mats Bäckström, ”Histogram Solution of the Maxwell Equations Inside Rectangular Enclosure which is not Electrically Large", Book of Abstracts, Euroem2004, 12 –16 July 2004, Magdeburg, Germany.

177. Stefan Silfverskiöld, Torbjörn Johannesson, Mats Bäckström, Sten E Nyholm, Karl Gunnar Lövstrand, " HPM - A Serious Threat to Vital Parts of the Net Centric Warfare Concept", Book of Abstracts, Euroem2004, 12 –16 July 2004, Magdeburg, Germany.

178. Stefan Silfverskiöld, Mats Bäckström, Jörgen Lorén, " Field Coupling to Printed-Circuit-Board Traces in Reverberation Chamber", Book of Abstracts, Euroem2004, 12 –16 July 2004, Magdeburg, Germany.

179. Olof Lundén, Niklas Wellander, Mats Bäckström, ”Evaluation of Stirrer Efficiency in Reverberation Chambers", Book of Abstracts, Euroem2004, 12 –16 July 2004, Magdeburg, Germany.

180. Magnus Höijer, ”Interchanging Frequency and Directional Dependencies in Susceptibility Testing", Book of Abstracts, Euroem2004, 12 –16 July 2004, Magdeburg, Germany.

181. Tony Nilsson, Rolf Jonsson, ”Investigation of Limiters for HPM Front Door Protection”, Book of Abstracts, Euroem2004, 12 –16 July 2004, Magdeburg, Germany.

182. Magnus Höijer and Vanesa Isovic, ” Frequency Resolved Susceptibility Testing as a Substitute for Angular Resolved Susceptibility Testing”, in Proceedings of *The 2004 International Symposium on Electromagnetic Compatibility (EMC)*, Santa Clara, USA, August 9 - 13, 2004.

183. Mats Bäckström, Karl Gunnar Lövstrand, ” Susceptibility of Electronic Systems to High-Power Microwaves: Summary of Test Experiences”, IEEE Transactions on Electromagnetic Compatibility, Vol. 46, No. 3, August 2004, pp. 396 – 403.

184. Frank Sabath, Mats Bäckström, Barbro Nordström, Dominique Sérafin, Arnhold Kaiser, Brian A, Kerr, Daniel Nitsch, ”Overview of Four European High-Power Microwave Narrow-Band Test Facilities”, IEEE Transactions on Electromagnetic Compatibility, Vol. 46, No. 3, August 2004, pp. 396 – 403.

185. Magnus Höijer, Vanesa Isovic, Mats Bäckström, ”A Heuristic statistical Method to Tackle that No Information of the Partial Directivity Properties of theEquipment Under Test is given from Testing in the Revereberation Chamber”, in Proceedings from EMC Europe 2004, 6 – 10 September, Eindhoven, the Netherlands.

186. Rolf Jonsson, Tony Nilsson, Mats Bäckström, ” Design and measurements of experimental MMIC limiters for HPM protection” , in Proceedings from EMC Europe 2004, 6 – 10 September, Eindhoven, the Netherlands.

187. Magnus Höijer, “Demo RF stridsdel etapp1/FOI: Lägesrapport 2004-11-26”, FOI Memo H235, Utgiven som hemlig handling 04-H353.

188. Magnus Höijer, Vanesa Isovic, Mats Bäckström, “Electromagnetic Transfer effectiveness of Complex Electronic Equipment”, FOI-R—1395—SE, December 2004, Swedish Defence Research Agency FOI, Sensor Technology, P.O. Box 1165, SE-581 11 Linköpng, Sweden.

189. Tony Nilsson, Mats Bäckström “HPM Measurements on Low Noise Amplifiers”, FOI Memo 1073, 2004-11-08. Swedish Defence Research Agency FOI, Sensor Technology, P.O. Box 1165, SE-581 11 Linköpng, Sweden.

190. Tony Nilsson, Rolf Jonsson, Ahsan Ullah Kashif, Mats Bäckström, “Limiter Characterisation”, FOI Memo 1072, 2004-12-02, Swedish Defence Research Agency FOI, Sensor Technology, P.O. Box 1165, SE-581 11 Linköpng, Sweden.

191. Tony Nilsson, Mats Bäckström, “HPM Measurements on WLAN”, FOI Memo H212, 2004-12-07, Swedish Defence Research Agency FOI, Sensor Technology, P.O. Box 1165, SE-581 11 Linköpng, Sweden.

192. Ulf Jordan, Dan Anderson, Mats Bäckström, Arkady V. Kim, Mietek Lisak, and Olof Lundén, ” Microwave Breakdown in Slots”, IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 32, NO. 6, December 2004, pp.2250 – 2262.

193. Magnus Höijer, ”Reduction of the Uncertainty in Radiated susceptibility Testing by Introduction of the Compound Polarisation Efficiency”, in Proc. from 16th Int. Zurich Symp. on electromagnetic Compatibility, February 13-18 2005, Zurich Switzerland, pp. 475-478.

194. Niklas Wellander, Olof Lundén, Mats Bäckström, "Parameter estimates for the stirrer efficiency in reverberation chambers", in Proc. from 16th Int. Zurich Symp. on electromagnetic Compatibility, February 13-18 2005, Zurich Switzerland, pp. 35-38.

195. Lena Sjögren, Mats Bäckström, "Ageing of shielding joints. Shielding performance and corrosion", in Proc. from 16th Int. Zurich Symp. on electromagnetic Compatibility, February 13-18 2005, Zurich Switzerland, pp. 575-578.

196. Ulf Jordan, Dan Anderson, Arkady Kim, Mietek Lisak, Mats Bäckström, and Olof Lundén, "Microwave Breakdown in Slots", RVK05 (Radiovetenskap och Kommunikation), Linköping, 14 – 16 juni 2005.

197. Mats Bäckström and Olof Lundén, "Degradation an Non-Linear Effects in Corroded EMC Joints Exposed to High Power Microwaves (HPM)", RVK05 (Radiovetenskap och Kommunikation), Linköping, 14 – 16 juni 2005.

198. Juhani Hämäläinen, Torleif Martin, and Mats Bäckström, "Sensitivity of the shape of the electromagnetic field histograms inside rectangular enclosures", RVK05 (Radiovetenskap och Kommunikation), Linköping, 14 – 16 juni 2005.

199. Niklas Wellander, Olof Lundén and Mats Bäckström, "Design parameters for efficient stirring of reverberation chambers", RVK05 (Radiovetenskap och Kommunikation), Linköping, 14 – 16 juni 2005.

200. Magnus Höijer and Mats Bäckström, "Comparison of High Level Radiated Susceptibility Measurements in the Reverberation Chamber and at the Open Area Test Site", RVK05 (Radiovetenskap och Kommunikation), Linköping, 14 – 16 juni 2005.

201. A. U. Kashif, R. Jonsson, M. Bäckström and Q. Wahab, "4H-SiC PIN and Schottky Diodes for RF Limiter Circuit", RVK05 (Radiovetenskap och Kommunikation), Linköping, 14 – 16 juni 2005.

202. Rolf Jonsson, Tony Nilsson, and Mats Bäckström, " Design and Characterization of Limiters for HPM Front Door Protection", RVK05 (Radiovetenskap och Kommunikation), Linköping, 14 – 16 juni 2005.

203. Juhani Hämäläinen, Matias Aunola, Torleif Martin and Mats Bäckström, "Comparing and visualising statistical shielding effectiveness for rectangular enclosures with different inner structures", in Proceedings of *The 2005 International Symposium on Electromagnetic Compatibility (EMC)*, Chicago, USA, August 8 - 12, 2005.

204. William. A. Radasky, Mats Bäckström, "Overview of the Threat of Intentional EMI (IEMI) to Civil Wireless Systems", *EMC Europe Workshop, Electromagnetic Compatibility of Wireless Systems*, Rome, Italy, 19-21 September 2005.

205. Tony Nilsson, Olof Lundén and Mats Bäckström, " HPM Susceptibility Measurements on WLAN and GPS Systems", *EMC Europe Workshop, Electromagnetic Compatibility of Wireless Systems*, Rome, Italy, 19-21 September 2005.

206. Odd Harry Arnesen, Ernst Krogager, Mats Bäckström, Sigbjørn Bø-Sande, Jostein Godø, Seppo Härkönen, Karl G. Lövstrand, Mikko Moisio, Barbro Nordström, Jouni Peltonen and Ole-Magne Øystad, "High Power Microwave effects on civilian wireless

equipment", *EMC Europe Workshop, Electromagnetic Compatibility of Wireless Systems*, Rome, Italy, 19-21 September 2005.

207. Rajeev Thottappillil, Daniel Månsson, Nelson Theethayi, Mats Bäckström, Tony Nilsson, Göran Undén, Barbro Nordström, Per Bohlin, Per Anders Lindeberg, Ulf Hellström, Peter Lindeberg, Georg Bohlin, Mihael Zitnik, Lise Ekenberg, "Response of Civilian Facilities to Intentional Electromagnetic Interference (IEMI), with Emphasis on the Swedish Railway Network", *EMC Europe Workshop, Electromagnetic Compatibility of Wireless Systems*, Rome, Italy, 19-21 September 2005.

208. Rolf Jonsson, Ahsan U Kashif, Mats Bäckström, Qamar ul_Wahab, "Microwave limiters based on 4H-SiC", Conf. Int. SiC and related material conference, September 21-26, 2005, Pittsburg, USA, Proc. Trans Tech Pub.

209. Magnus Höijer, "Polarisation Efficiency in Radiated Susceptibility Testing", FOI Technical Report, FOI-R--1714--SE, September 2005, Swedish Defence Research Agency FOI, Sensor Technology, P.O. Box 1165, SE-581 11 Linköping, Sweden.

210. Lena Sjögren and Mats Bäckström, "Ageing of Shielding Joints. Shielding Performance and Corrosion. Part 1 – Measurement Methods: Transmission loss measurements in the near field and transmission cross-section measurements using a reverberation chamber", IEEE Society Newsletter, Issue No. 206, Summer 2005.

211. Odd Harry Arnesen, Ernst Krogager, Mats Bäckström et al., "HIGH POWER MICROWAVE EFFECTS ON CIVILIAN EQUIPMENT, Invited", URSI XXVIIIth General Assembly, New Delhi, India, October 23 – 29, 2005.

212. Tony Nilsson, Rolf Jonsson, "Investigation of HPM Front-door Protection Devices and Component Susceptibility", FOI Technical Report, FOI-R--1771--SE, November 2005, Swedish Defence Research Agency FOI, Sensor Technology, P.O. Box 1165, SE-581 11 Linköping, Sweden.

213. J. Delsing, J. Ekman, J. Johansson, S. Sundberg, M. Bäckström, T. Nilsson, "Susceptibility of Sensor Networks to Intentional Electromagnetic Interference", Proc. of *EMC - Zurich in Singapore 2006*, 27 February - 3 March 2006, pp.172 – 175.

214. M. Höijer, "Maximum Power Available to Stress Onto the Critical Component in the Equipment Under Test When Performing a Radiated Susceptibility Test in the Reverberation Chamber", IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY, VOL. 48, NO. 2, MAY 2006

215. Magnus Höijer, "Radiated Susceptibility Test in Reverberation Chamber", FOI Scientific Report, FOI-R—2007—SE, June 2006, Swedish Defence Research Agency FOI, Sensor Technology, P.O. Box 1165, SE-581 11 Linköping, Sweden.

216. M. Bäckström, O. Lundén, "NoN-Linear Effects and Degradation of EMC Joints Irradiated by HPM", 2006 IEEE AP-S/URSI/AMEREM Symposium, Albuquerque, USA, July 9 – July 14, 2006.

217. T. Nilsson, D. Månsson and M. Bäckström, "Investigation of HPM and UWB Susceptibility on GPS Receivers", 2006 IEEE AP-S/URSI/AMEREM Symposium, Albuquerque, USA, July 9 – July 14, 2006.

218. F. Sabath, M. Bäckström, “Intentional Electromagnetic Interference (IEMI) simulator Compendium”, 2006 IEEE AP-S/URSI/AMEREM Symposium, Albuquerque, USA, July 9 – July 14, 2006.

219. M. Höijer, “Inherent Uncertainties when Performing a Radiated Susceptibility Test in the Reverberation Chamber”, 2006 IEEE AP-S/URSI/AMEREM Symposium, Albuquerque, USA, July 9 – July 14, 2006.

220. T. Nilsson, R. Malmqvist and M. Bäckström, 2006, “Investigation of HPM Susceptibility Levels on Low Noise Amplifiers”, EMC Europe 2006, Barcelona, Spain, September 4-8, 2006.

221. Olof Lundén, ” Occasional Unstirred High Frequency Components and How to Avoid Them”, Workshop on Reverberation Chambers (no paper), EMC Europe 2006, Barcelona, Spain, September 4-8, 2006.

222. Magnus Höijer, The Distribution Function to use When Performing a Radiated Susceptibility Test in the Reverberation Chamber, Workshop on Reverberation Chambers (no paper), EMC Europe 2006, Barcelona, Spain, September 4-8, 2006.

223. M. Höijer, O. Lundén and M. Bäckström, Reverberation Chamber: the quest for the distribution of the maximum stress onto the equipment under test, EMC Europe 2006, Barcelona, Spain, September 4-8, 2006.

224. O Lundén, ” Design Parameters for Efficient Stirring of Reverberation Chambers”, *The 2006 International Symposium on Electromagnetic Compatibility (EMC)*, Portland, USA, August 14 - 18, 2006.

225. M. Höijer, L. Jansson and M. Bäckström, ”Question to the Authors of ”HIRF Penetration Into Simplified Fuselage Using a Reverberation Chamber””, IEEE Transactions on Electromagnetic Compatibility, Vol. 48, No. 4, November 2006, pp. 834 – 835.

226. Tony Nilsson, Rolf Jonsson, “Implementation of HPM front-door protections and component investigations” , FOI Technical Report, FOI-R--2126--SE, December 2006, Swedish Defence Research Agency FOI, Sensor Technology, P.O. Box 1165, SE-581 11 Linköping, Sweden.

227. Magnus Höijer, Mats Bäckström, Rolf Jonsson, Tony Nilsson, Olof Lundén and Qamar ul Wahab , “Final report: HPM-skyddsmetoder för NBF” , FOI Technical Report, FOI-R--2127--SE, February 2007, Swedish Defence Research Agency FOI, Sensor Technology, P.O. Box 1165, SE-581 11 Linköping, Sweden.