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14. ABSTRACT

This final report covers the research and assessments conducted by Spectrum Lab at Montana State University (MSU) to advance the goals of the Quantum Information Science and Technology. The specific research and assessments are: 1) A study of heating in ion traps and possible abatement techniques, 2) Assessment of the diverse approaches to quantum information processing, and 3) Assessment of the requirements for stabilized lasers for difference approaches to quantum information processing.

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Report Title

Final Report on Quantum Information Science Research and Technical Assessment Project

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List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Number of Papers published in peer-reviewed journals: 0.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations:

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Number of Manuscripts:

Patents Submitted

Patents Awarded

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
William Randall Babbitt	0.08	No
Recep Avci	0.06	No
FTE Equivalent:	**0.14**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:......	0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED	
Krishna Rupavatharam, Senior Resea	0.22	No
Ken Kress, Senior Research Scientist	0.31	No
Charles Thiel, Research Scientist	0.33	No
Sue Martin, Operation Manager	0.10	No
Norm Williams, Shop Supervisor	0.08	No
FTE Equivalent:	**1.04**	
Total Number:	**5**	

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Inventions (DD882)

Final Report on
Quantum Information Science Research and Technical Assessment Project

SCIENTIFIC PROGRESS AND ACCOMPLISHMENTS

Foreword

This technical section of the final report for ARO grant number W911NF0710013 entitled "Quantum Information Science (QIS) Research and Technical Assessment" covers the scientific progress and accomplishment made between November 1, 2006 and March 31, 2010 on the different task areas of the grant.

1) Ion Heating Abatement Research
2) Quantum Information Science Technology (QIST) Assessment
3) Stable Laser assessment for QIST

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Statement of the Problem Studied

Statement of work

The proposed statement of work was stated as:

Task 1: Investigate the applicability of laser cleaning techniques to reduce heating effects in ion traps.

Task 2: Research and assess current and new approaches to QIS technologies.

Task 3: Assess the laser stabilization needs of different QIS research approaches and the feasibility of meeting these needs by using lasers that are frequency stabilized by locking them to spectral holes.

The analytic research on tasks 1 and 3 were funded only during the first and last reporting periods of the project. Task 2 was carried out continuously throughout the project.

Summary of Most Important Results

The results the three tasks listed in the statement of work are reported separately.

Summary of Results on Task 1: Laser Cleaning of Ion Traps

We studied the new approach of in-situ laser treatment of the ion trap electrodes as a potential practical technique for reducing ion heating effects. Laser technology has the advantage of being highly directional for detailed treatment, spectrally variable for contaminant specific applications, and applied in well-controlled pulses allowing in-situ cleaning to by synchronized with trap operation. It is anticipated that most surface contaminants can be removed with low energy (possibly resonant) bursts of light pulses. Higher energy or lower wavelength pulses can be used to achieve controlled surface melting and re-crystallization to smooth electrode surfaces. Under this grand, the need for ion trap cleaning was assess and a proof of concept demonstration of surfaces similar to those found in ion traps was performed. The goal of the project was to develop a research path that would eventually lead to a recommendation of a technique that can be implemented by an experimental quantum computing with trapped ion group, such as Dr. David Wineland's group at NIST, Boulder, Colorado, with micro ion-traps, such as those produced at Sandia National Laboratories. We report here the successful initial experimental studies of removing applicable contaminants on metal surfaces.

Heating in ion traps

Trapped ions are one of the top five leading candidate technologies for achieving multiple qubit processing in quantum information science applications [1]. One of the most attractive features of trapped ions is long quantum coherence times, on the order of seconds, orders of magnitude beyond most other qubit technologies. Current designs are exploring multiple ion trapping regions that improves functionality and minimizes ion movements. Compact trap designs with ten micron or less electrode separation, such as multi-zoned planar ion RF traps, are in development [[2]].

While trapped ions coherence times have been observed to be on the order of seconds under ideal conditions, in practice the coherence time in ions traps is currently limited by unexplained "heating" effects thought to be associated with non-uniform electromagnetic fields caused by non-uniform trap electrodes.[[3]] Several groups have investigated the effects of the smaller relative trap depth and planar surface on ion loading, ion motion, and ion heating [[4],[5]]. Surface electrode ion traps, while promising for large-scale quantum computation, have long been challenged by ion heating rates that increase rapidly as trap length scales are reduced. Existing research shows that ion heating rates are surprisingly sensitive to electrode material and morphology. Experiments have measured the heating rate to vary with trap size scale, r, as strongly as r^{-4}. This increase may be attributed to patch potentials due to the presence of contaminants on the trap electrodes. Often this contaminant material is deposited by the atom sources used to load ion traps [[6]].

As an example, the design, fabrication, and preliminary testing of a 150 zone ion trap array built in a 'surface-electrode' geometry microfabricated on a single substrate, using the gold-on-quartz structures, was carried out. The authors demonstrated the transport of atomic ions between the legs of a 'Y'-type junction and measured the characteristic parameter of an ion trap, i.e. the *in situ* heating rate of the ions due to fluctuating electric fields at the ion location [7]. A typical heating rate for a single ion was observed to be 87 x 10^3 phonon/s at a 3.5 MHz axial frequency and a 38 μm ion-to-surface distance, using the re-cooling method [8],which is considered to be in the average range of heating rates for its size scale [7]. This heating rate still two orders of magnitude higher than the desired limit on heating rates, less than 10^3 quanta/s [9]. It is not expected that special fabrication or pre-cleaning techniques will provide a sufficient decrease in heating rates in order to allow for high fidelity quantum information processing operations [10].

These anomalous heating effects limit the fidelity of qubit gates. Understanding and improving ion heating rates, especially for compact traps, is essential for building planar trap quantum simulators, repeaters, or computers. This heating must be reduced to a level that allows smaller traps thereby increased gate speed, which in turn facilitates ion separation in multiplexed trap schemes. The importance of ion heating in the design of the planar ion trap and the need to mitigate ion heating effects and improve coherence is a persistent problem, having been identified as such in the Quantum Information Processing and Quantum Computation - QUIST 2004 Roadmap [11] and still being one of the top challenges in achieving trapped ion quantum information processing [**Error! Bookmark not defined.**].

Prior work on reducing ion heating

Attempts to reduce the ion heating effects in conventional ion traps have included electrode surface cleaning methods, such as electro-polishing, acid wash, and abrasive polishing [12]. However, these conventional cleaning methods, have not been reliably repeatable, tend to be only effective for a short time during trap operation, and are not in situ, requiring considerable down time to implement in a practical trap. In addition, since it has been observed that electrode contaminants are deposited during trap loading by the atom sources used to load ion traps [13], pre-cleaning is not a practical solution to devices that must operate continuously, with multiple reloading of the traps. *These conventional cleaning methods thus do not meet the quantum computation roadmap requirements*.

Another technique for reducing ion heating effects is cryogenic cooling. The heating effects of patch potentials in cryogenically cooled surface-electrode traps, with characteristic sizes in the 75 to 150 μm range were characterized. [14] It was established that the heating rates can be significantly suppressed by cooling of the trap electrodes. For instance, upon cooling to 6 K, the measured rates are suppressed by 7 orders of magnitude from that of the room temperature, The heating rates out of the motional quantum ground state of a single Sr+ ion in an aluminum ion trap operated at cryogenic temperatures have been studied [15]. Aluminum oxidizes rapidly to form a tough, resistant, surface oxide (alumina), that protects it from further oxidation. Aluminum ion traps are more difficult to compensate compared to others, and often have short ion lifetimes, which may be due to this nanometer-thick alumina layer. A series of aluminum traps with different and controlled alumina layer thickness were fabricated and investigated. The ion heating rate versus the oxide layer thickness study indicated a sensitive dependence on electrode material and surface morphology even at cryogenic temperatures.

Moreover cryogenic cooling is a costly overhead for a practical device and imposes complications on the electronic and optical access to the ion traps. Also, as electrodes of ion traps evolve from macro to micro sizes to improve gate speeds, the orders of magnitude improvement that cryogenic cooling provides may be insufficient to overcome the r^4 dependence of ion heating effects.

In summary, while cryogenic cooling has been demonstrated to greatly reduce ion heating effects in current traps, it may not be sufficient or practical to rely on cryogenic cooling to reduce ion heating to acceptable levels in future micro ion traps. *To achieve high fidelity quantum information processing operations, cryogenic cooling will likely have to be combined with other techniques for abating ion heating effects.*

Generation of Thin Metallic Films and Controlled Levels of Contamination

One key aspect of this project is the ability produce controlled amounts of surface contamination on a range of metallic films of varying thickness and composition. To achieve this, we designed and constructed a basic physical vapor deposition (PVD) system based on thermal evaporation of source elements. This flexible system allows us to produce both metallic films and low levels of surface contamination under controlled, clean conditions, enabling a systematic exploration over a wide range of parameter space. This system incorporates heaters, deposition monitors, temperature sensors, and adjustable substrate holders and masks under high-vacuum conditions (pressures of ~1×10^{-6} Torr). This system was employed to produce all samples used in this project.

Construction of physical vapor deposition system

A physical vapor deposition system was designed and constructed to meet the requirements of the project goals. A block diagram outlining the components of this system is presented in Figure 1. The system operates with a base pressure of ~1 x 10^{-6} Torr and the substrates may be heated to temperatures greater than 200°C under vacuum before or during the deposition process. The evaporation sources can accommodate coil, basket, or boat sources of the usual refractory materials, including tungsten, tantalum, and molybdenum. This system allows us to deposit metal films of Au, Al, and Ag up to ~10 μm thick on a variety of target substrates, including SiO_2, stainless steel, silicon, and glass. Contamination of these surfaces is possible at thickness down to sub-monolayers using a variety of materials of interest, including Mg, Ca, and Sr. Samples are removed from the system and transported to the Imaging and Chemical Analysis Laboratory for cleaning and testing under an inert atmosphere of argon gas to minimize any potential detrimental effects of ambient conditions on the sample surface.

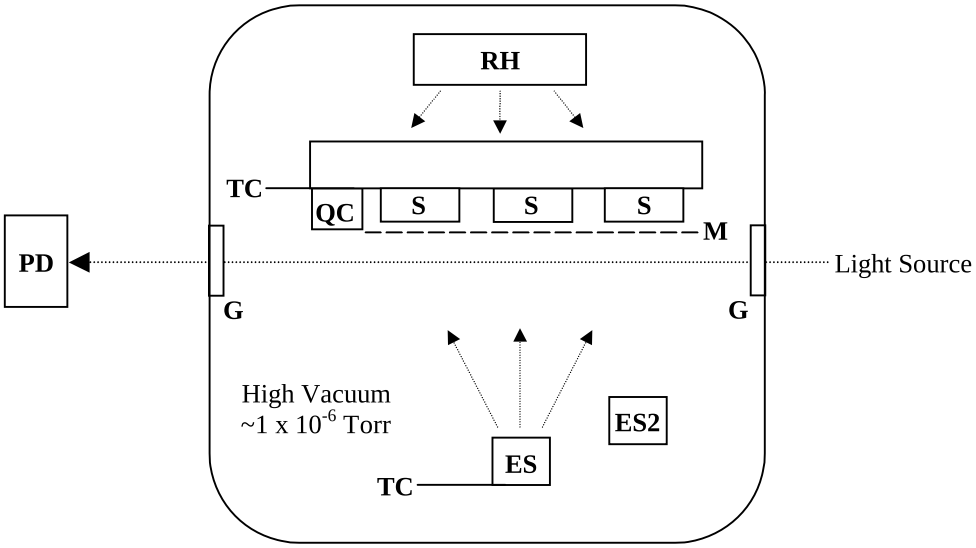

Figure 1. Block diagram of physical vapor deposition system constructed to produce metallic films and controlled levels of contamination. Film thickness is monitored during deposition using both a quartz crystal microbalance and optical transmission of a light source through the films. Key components are labeled: ES = primary thermal evaporation source (boat or basket); ES2 = secondary evaporation source; S = sample deposition substrates; M = optional substrate mask; RH = radiant heater for substrate temperatures up to > 200°C; QC = quartz crystal microbalance thickness monitor; G = glass surfaces for transmission measurements; PD = photodiode; TC = thermocouple temperature sensors.

Substrate Preparation

To evaluate the effects of surface conditions on adhesion and cleaning, several techniques were employed to prepare the substrates for either deposition of the metal films or contamination. The most basic approach was to simply employ the common method of washing with the usual series of organic solvents. As a more robust cleaning procedure, we also tested techniques of light acid etching and alkaline washing. Another technique that we employed was UV irradiation and ozone cleaning followed by vacuum desiccation. These initial efforts suggested that surface preparation does have an impact on surface adhesion, with ozone cleaning producing the best adhesion. This study indicates that surface treatment is an important factor that can influence surface adhesion and potential contamination rates (through surface sticking coefficients) and therefore merits further investigation.

Measurement and Calibration of Deposition Process

In this project, it was essential to accurately control the deposition process over a very wide range of materials and film thickness varying from sub-monolayer up to 10 μm. To achieve this in our system, we employed a combination of three techniques.

The primary technique that we employed to monitor the deposition process was to monitor the shift in resonance frequency of a quartz crystal due to the mass of material deposited on the crystal. By adjusting the distance of the sensor relative to the source and employing the $\sim 1/R^2$ dependence of vapor density on distance, the sensitivity of this "quartz crystal microbalance" (QCM) may be adjusted to monitor deposition on the target substrates down to sub-monolayer levels in real time during the deposition process.

We also employed a secondary optical technique where the transmission of the deposited thin films was monitored. By adjusting the relative distances of the reference surface and target substrates from the vapor source, the sensitivity of this approach may be controlled just as with the QCM method. This method provides a useful complement to the QCM approach since the optical method is directly sensitive to the thickness of the deposited material while the QCM method is sensitive to the mass of the deposited material.

The third method employed was the classic gravimetric technique, which provides an absolute quantitative determination of deposited mass. In this method, a large-area reference target is weighed before and after deposition, with the deposited film resulting in a measurable difference in mass. From the measured change in mass of the target, the number of atoms deposited on the surface per unit area may be determined. For thick films, the known density of the deposited material may be used to also calculate thickness. By using sensitive scales with 0.01 mg precision, this method allowed us to determine the absolute calibration of our more sensitive optical and QCM monitoring techniques.

Proof of Concept Demonstration of laser cleaning of contaminated surfaces

We investigated the effect of laser ablation on typical electrode surfaces using surface analysis based on Time-of-Flight Secondary Ion Mass Spectroscopy (ToF SIMS) techniques. The ToF SIMS technique uses a pulsed ion beam (microfocused Ga) to remove a small amount of material from the outermost surface of the sample for analysis. The particles removed from the surface by ion beam bombardment are accelerated into a "flight tube" and their mass is determined by measuring the exact time at which they reach the detector. The ToF SIMS can detect trace elements and image the chemical distribution on surfaces with x-y spatial resolution on the order of 0.5 μm. For our demonstration, we used ToF SIMS to analyze the metal surfaces before, during, and after laser treatment.

Figure 1 shows the setup for laser treatment and the operational principle that was employed to analyze metal ion contaminations on surfaces. In our proof-of-concept experiment, we employed a Vibrant OPO pulsed laser that is tunable over the full transmission range of the fused quartz windows, 260 nm to above 2 μm. The ICAL setup included a well-calibrated fluence measurement and laser beam profile imaging capability. With the current setup, the effect of laser irradiation at preselected wavelengths could be studied to observe ion-surface dependent resonance effects. The rate of removal as a function of the appropriate fluence and suitable number of laser pulses could also be studied.

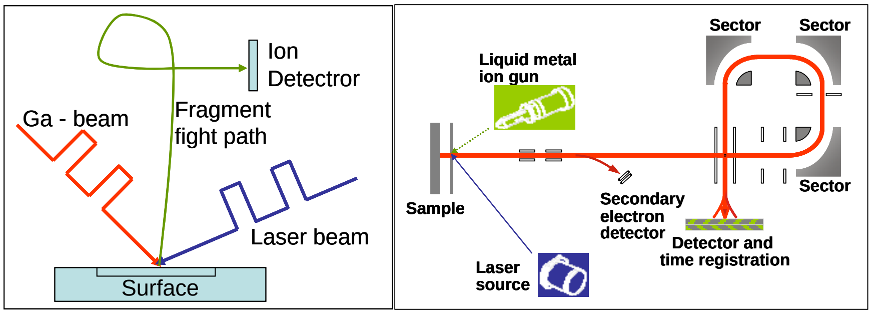

Figure 2 Left: Illustrative representation of laser treatment and surface analysis. The short laser cleaning pulse preceded the primary ion beam (Ga+) used in analyzing the effectiveness of the laser pulse. Right: Detailed schematic of the laser treatment and ToF-SIMS set up used for surface analysis.

To prepare the samples to be studied, a custom-built vapor deposition system that could be adapted to multiple sources was utilized. To emulate ion trap electrodes, Gold (*Au*) and Aluminum (*Al*) films of thickness in the 0.1-2 μm range, were deposited on substrates such as *Si*, SiO_2, and *stainless steel* and then purposely contaminated. Magnesium (*Mg*) was the chosen contaminant for the initial studies and a contaminant coating 1-2 nm thick was deposited onto both and Au and Al metal films in a controlled environment. The contaminated films were transported to the ToF SIMS setup for laser treatment and surface analysis. The laser was set to 5 ns pulses at 370 nm with a pulse energy ~ 17 μJ. TOF-SIMS spectra were taken with a *Ga* ion source. The results for the Mg contaminated Au films deposited on SiO_2 are shown in Figure 3.

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Figure 3 Images from the video microscope: area of analysis - 65 μm x 65 μm (256 x 256 pixels). Left: Prior to exposure. Center: After 5 shots. Right: After 100 shots. The focused laser treatment spot size is ~ 20 x 60 μm with higher intensity (hot spots) at the ends.

We first tried conventionally cleaning (washing with a mixture of base/acid mixture) the surfaces of Au films contaminated with Mg and found (using ToF SIMS analysis) that this method is ineffective in removing Mg contamination. We then used *in situ* laser treatment to remove Mg contamination from Au films. Figure 4 shows the results of the ToF SIMS analysis of the laser treated surfaces. The decrease in the occurrence of Mg counts in the region exposed to the laser pulse can be seen. At the same time, the *Au* counts are seen to be increasing, establishing the successful removal of *Mg* contamination from gold surface.

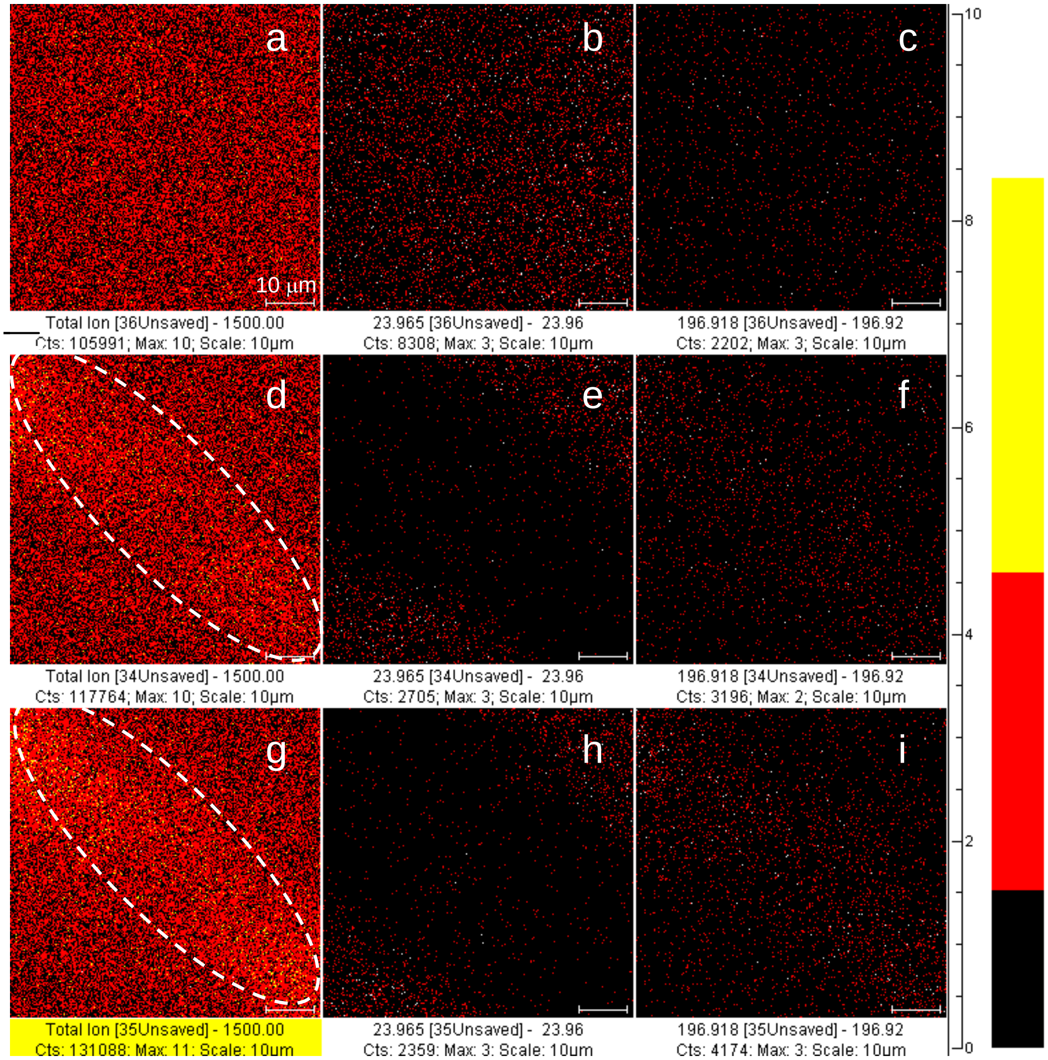
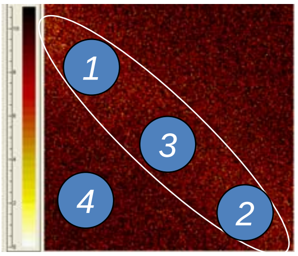


Figure 4 Images from ToF SIMS under various conditions of laser treatment. Images *a-c*: The SIMS images prior to exposure of the contaminated film to laser treatment. Images *d-f and g-i*: SIMS images after 5 and 100 laser shots, respectively. The dashed line marks the laser spot. The left images (*a,d,g*) are of the total integrated spectra over elements up to 1500 atomic mass units (AMU). The middle images (*b,e, h*) show counts for the contaminant Mg (AMU 24) and right images *(c, f, i)* show the counts for Au (AMU 197) from the Au film. The removal of Mg from the area of the laser spot can be seen in images *e* and *h*. Also note that the counts of Au go up after laser treatment.

A detailed analysis of the surface composition before and after laser treatment is shown in Figure 5. The reduction in the integrated spectral counts for Mg conclusively show removal from the treated regions, ROI (1-3), and simultaneously the Au counts show corresponding increases. The counts after treatment are similar to the uncontaminated sample and result from very low levels of intrinsic Mg impurities in the metal film, demonstrating the well-known high sensitivity of the ToF SIMS method. The counts in the untreated region ROI 4 remain unchanged as expected. As mentioned earlier, the intensity of the laser beam in ROI (1 & 2) is greater than ROI 3 and thus the contamination removal is observed to be nominally better in ROI 1 & 2.



	Mg Counts			Au Counts		
	Before Exposure	*After 5 shots*	*After 100 shots*	*Before Exposure*	*After 5 shots*	*After 100 shots*
Uncontaminated (ROI 2)	21	-	-	284	-	-
Mg Contamination						
Total	8307	2705	2359	2173	3110	4088
ROI 1	292	23	33	90	184	269
ROI 2	381	14	14	116	162	282
ROI 3	339	41	54	82	132	162
ROI 4	208	256	226	92	73	100

Figure 5 Detailed analysis of the SIMS images is carried out at four different regions of interest (ROI), three ROIs in the region of laser treated and one outside the treated surface. The table shows the integrated spectral counts for Mg and Au at the different ROIs before and after exposure. Significant Mg removal from the treated regions (1-3) is verified by the reduction in the counts in these regions, while ROI 4 counts for Mg remain significantly unchanged. The Au counts show corresponding significant increases in ROIs 1-3, demonstrating the Mg at the surface has been removed.

For laser cleaning treatment to be successful, it was not effect the flatness of the surfaces being cleaned. The conditions to remove the contaminant metal cations from the surface without ablating or damaging the surface itself or leading to surface irregularities (which could, in principle, increase the patch potentials) was also studied qualitatively by adjusting exposure, wavelength, and peak power. Under the conditions used studies above, no laser damage was observed. Laser damage of surfaces was observed under conditions of higher pulse energy and shorter wavelengths. The results are shown in Figure 6. Further quantitative studies are needed to determine the damage threshold for different film and substrate compositions using AFM and SEM techniques to characterize surfaces to nanometer scale. The conditions for surface melting and recrystallization also need to be studied.

Figure 6 Video microscope images of thin Au films with less than 300 nm thickness. Left: Before laser exposure. Right: Laser induced surface damage was observed with high peak power pulses and at shorter laser wavelengths.

To laser clean ion traps, the laser must be scanned over the surface of the electrodes to be cleaned. A preliminary treatment of a large surface area by rastering the laser spot across the surface was demonstrated. The laser spot was scanned across the film through an external mirror positioner. The results are shown in Figure 7.

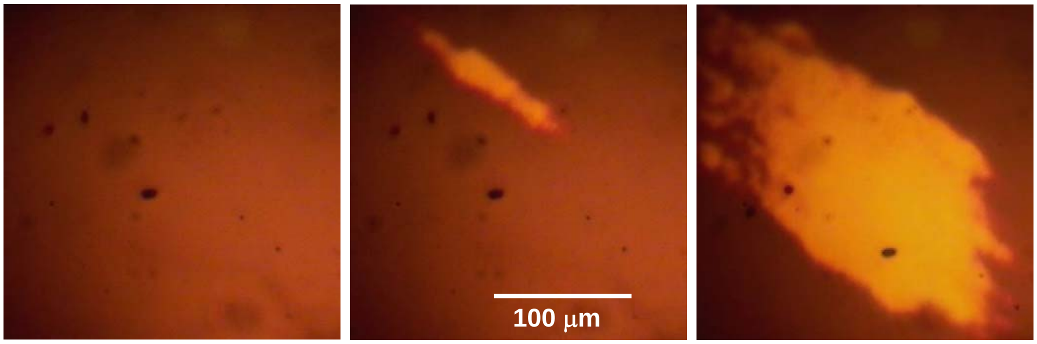


Figure 7 Rastering of laser spot across surface can effectively clean large areas of the contaminated surface rapidly and in a controlled manner. Left: Untreated Mg on Au film. Middle: After exposure to 1 laser shot. Right: Raster scan over 200 x .200 μm area on the metal surface.

Summary of Results on Task 2: QIS Science Technology Assessment

This work under task 2 is best separated into the work done during each reporting period of the grant.

Results from 11/1/06 – 7/31/07

As a major activity, Dr. Ken Kress reviewed technical proposals received by the Disruptive Technology Office (DTO, within the Office of Director of National Intelligence) in response to a broad area announcement for FY07 funding. With advisory authority, the proposals were reviewed, compared with requirements and ranked. These ranking were provided to Dr. Karl Roenigk, the government procurement authority, for consideration in his funding decisions and authorization. Proposals included research on trapped ions, neutral atoms, superconductors, optical qubits and quantum communications, entangled photon bright light sources and high quantum efficiency and photon resolving detectors.

Additional efforts included advisement to DTO on technical quantum information science and technology program strategy derived from attendance at technical conferences and workshops, discussions with researchers, review of relevant literature as well as related government programs at the National Science Foundation, Army Research Office and other relevant elements of the federal research community.

Other activities included:

- Advised on the effective management of research of Quantum Information Science.
- Developed security constraints respecting community sensitivities.
- In concert with the NSA-LPS, developed parameters and agenda for a Superconducting Qubit Workshop in 2007 to make a critical assessment of decoherence and preferred qubit instantiations.
- Coordinated mutual interests with DARPA in Quantum Information Science and served on panels to review proposed research as a representative to DTO.
- Coordinated relations and provided advisement to IC Post-doc candidates who are selected by the community to conduct research across a wide landscape.
- Maintained current awareness and advised the DTO Team of world developments in QIS.

These activities we coordinated with Dr. Karl Roenigk, Quantum Information Science and Technology Program Manager of DTO, who has assessed the progress in these activities and concurs on their satisfactory completion.

Results from 8/1/07 – 7/31/08

The major activities were to give technical and management advice as well as program planning support for the Quantum Information Science (QIS) Program managed by the Intelligence Advanced Research Projects Activity (IARPA). Parts of these activities contain procurement and other restricted information not fully discussed in this report. The concurrence of Dr. Kress' government supervisor in his annual report to MSU attests to this work fully meeting expectations and otherwise satisfactory performance of the restriction and other activities as delineated below.

Additional activities included advising on technical QIS program strategy derived from attendance at technical conferences and workshops, discussion with key researchers, review of relevant literature as well as related government programs at National Science Foundation, Army Research Office (ARO), Defense Advanced Projects Agency, National Reconnaissance Office and other relevant elements of the federal research community.

Specific activities included:

- For ARO reviewed and commented on proposals in superconducting qubits and quantum networks based on cavity produced "flying qubits."
- Published a weekly summary of selected QIS-relevant events and alerts as they appear on Internet.
- In concert with NSA-LPS, developed an agenda for a Superconducting Qubit Workshop that made a critical assessment of superconductor de-coherence issues.
- Participated in grant reviews at Harvard, MIT, Georgia Tech, National Institute of Science and Technology and the comprehensive annual QIS Program review in conjunction with the related Laboratory for Physical Sciences/NSA Program.
- Advised IARPA on worldwide developments in quantum information science.
- Reviewed and commented on other IARPA/QIS grants and contracts.

Results from 8/1/08-7/31/09

The major activities were to give technical analysis and associated activities supporting the Intelligence Advanced Research Projects Activity (IARPA), with particular focus is the Quantum Information Science (QIS) Program. Parts of these activities contain procurement and other restricted information not fully discussed in this report. Dr. Kress continues to work closely with his government supervisor to meet expectations and satisfactory perform his duties in aiding IARPA management.

Specific activities included, but were not limited to:

- Attended Annual Joint IARPA & for the National Security Agency's Laboratory Physical Sciences (LPS) Program Review and provided comments to the caucus of program managers that aided in procurement decisions such as continuation, modification or termination of each project.
- Attended Gordon Conference on QIST at Big Sky Montana and provided report.
- Participated in a review of the MIT grant that is studying the issue of anomalous heating of trapped ions.
- Participated in a review of the NIST/Boulder contract related to trapped ions.
- Participated in review of the micro trap chip foundry at Sandia as part of an IARPA team lead by the program manager, Dr. M. Mandelberg
- Participated in review of the micro trap chip foundry at Georgia Tech Research Institute.

- Helped prepare for the program's new strategic direction by assembling current performance metrics for solid state qubits, reviewing similar analysis by other technical consultants, and providing comments and suggestions for the new strategic to the Program Manager
- Developed and presented a briefing on new concepts for nuclear gamma ray and neutron detectors to senior IARPA management.

Results from 8/1/2009- 12/31/2009

The IARPA's Quantum Information Science Technology program developed a new strategy, created a Broad Area Announcement and received/evaluated responsive proposals during the summer and fall of 2009. Dr. Kress contributed to all aspects of this new program development.

Specific activities include:

- supported the new strategy of a goal-oriented program opposed to a science-based program
- helped select multi-qubit interactions as the main goal of the new program
- helped develop a program technology threshold that the existence of well-defined single qubit and two qubit interactions is a minimum threshold for funding a proposal by program
- with in-depth interactions among quantum scientists, the program manager and his support staff that included Dr. Kress, a five-year program with three phases was developed with many metrics such as the development of at least a three qubit interaction within a two-year period; more details are found on http://www.iarpa.gov/
- a proposers Day was held during the summer 2009 and Dr. Kress ran one of the sessions
- a BAA was approved and released in the fall 2009
- late in November a select group of government quantum information science experts was convened to evaluate the proposals with the help of the technical support staff that included Dr. Kress
- by the end of this reporting period proposals have been evaluated ranked and were being readied for briefing to the IARPA office director for final decision

Summary of Results on Task 3: Stable Laser assessment for QIST

Quantum information processing and the ability to experimentally manipulate quantum systems has evolved significantly over the past decade, and the search for new and potentially scalable qubit systems is ongoing. Under the grant, we are investigating and assessing the laser stabilization needs of various quantum information processing platforms, and evaluating the applicability to these platforms of laser stabilized to spectral hole. The technique of locking a laser's frequency to a spectral hole burned in an inhomogeneously broadened absorber was developed mostly to meet the needs of traditional classical optical signal processing and storage devices, particularly holeburning related devices, but it is also being used for laser stabilization for QIP in rare-earth doped materials. Stabilization via spectral holes may have broader applicability in the Quantum Information Processing (QIP) community, which is one of the subjects of this research project.

MSU researchers have extensive experience in the development of laser stabilization utilizing the coherence and storage properties of rare earth doped spectral holeburning materials [16-19], which has the potential of meeting the needs of some of the leading groups in Quantum Information Science (QIS). We have been either in correspondence or visiting with various QIS groups, in particular those utilizing spectral hole burning materials and stable laser sources such as Matthew Sellars at ANU in Australia and Stefan Kroll at Lund Institute of Technology in Sweden, to determine the requirements for stable lasers that can be helpful to advancing these QIS technologies. We have also corresponded with major QIS research group, including ion trap researchers such as Dave Wineland at NIST Boulder, and surveyed the research from groups headed by Andrew Steane in Oxford, Chris Monroe in Michigan, and Rainer Blatt in Innsbruck, the neutral atoms researchers such as Bill Phillips at NIST Gaithersburg and Mark Saffman at U. Wisconsin, Madison, as well as groups working on optical, cavity QED, and quantum dot approaches, with particular focus on the stable laser requirements for quantum state operations.

The following sections summarize the results of our investigations into the laser stabilization requirements of QIS groups. The results are divided into two sections: one that deals with the stable laser requirements for the spectral holeburning (SHB) based approaches and one that deals with the requirements for non-holeburning approaches.

Stable Laser requirement assessment for SHB approaches

In this section, we report on the efforts of QIS research groups around the world, utilizing spectral hole burning materials and stable laser sources to perform Quantum Information Processing.

Group of Applied Physics (GAP) at Geneva University, Switzerland

MSU and S2 Corporation (who has licensed MSU's stabilization technology) are in discussion with Professor Nicolas Gisin's group in Geneva, Switzerland about the Gisin group's plans to use lasers that are frequency stabilized by locking to spectral holes to address their quantum memory systems. Their research involves long-lived sub-state population storage in Zeeman states of Erbium. In particular, they are investigating Er-doped fibers and Er^{3+}:$LiNbO_3$ for a quantum memory using the 'flying qubits' approach [20,21] based on controlled reversible inhomogeneous broadening (CRIB). The goal is to create a narrow, isolated absorption peak within the inhomogeneous broadening by optically pumping away ions and storing them in a metastable ground state level. The isolated peak is then inhomogeneously broadened by an external electric field gradient, after which the light pulse is absorbed by this structure. By reversing the inhomogeneous broadening (i.e., switching the polarity of the E-field, also known as CRIB, controlled reversal of inhomogeneous broadening) a photon echo is created, which potentially could be much more efficient than a standard photon echo, potentially close to 100% efficient. In addition to quantum cryptography, they propose application of CRIB memory to produce single photons on demand and as a repeater.

There are several factors that need careful consideration in this approach. First of all, the isolated peak should be narrow since the inverse of its spectral width determines the effective optical coherence time during storage. In order to extend the storage time beyond this, one could imagine transferring the excited state population to a metastable ground state, like in E-field induced transparency (EIT) for instance, which could have longer coherence time. In such a case, the inverse of the width of the isolated peak limits the time during which the light pulses are absorbed. They are aiming to store pulses less than 100 ns. Their approach is to create ion ensembles isolated in a spectral bin of the order of 10 kHz and then inhomogeneously broaden the prepared peak by a factor of 1000, to about 10 MHz. From this perspective, they analyzed that the laser coherence requirement is on the order of 10 kHz, if not better.

Another important consideration is the need to access ions at different frequencies in order to create the wide spectral hole and the narrow anti-hole within this structure. Since the Zeeman states of the materials under their consideration could be separated by more than 1 GHz, the acousto-optic modulator approach used by many other groups including those in Sweden and Australia to create laser beams at necessary frequencies is not practical. Depending on the number of ions groups needed, the bandwidth over which different sets of ions would be locked could be several hundred gigahertz. It has been suggested that several lasers would be needed to manipulate the ions and these should then have their long-term frequency locked to each other in order to implement this with good phase and frequency control. The expertise of MSU and S2 Corporation in setting absolute frequency references using S2 materials can provide solutions to either locking the absolute frequency of several lasers independently or to stabilizing them relative to each other using techniques such as locking to sidebands of an electro-optic modulator. The relative merits, cost-effectiveness, and complexity of the different approaches are yet to be fully analyzed.

Quantum Coherence Group, ANU, Canberra, Australia

The Quantum Coherence Group at ANU, Canberra, Australia, led by Dr. M. Sellars, is engaged in Rare Earth Quantum Computing, involving two qubit gate operations in materials with extended coherence times. Apart from Europium and Praseodymium doped crystals [22-24], the ANU group has also pioneered the use of Nitrogen-Vacancy color center in Diamond as a potential QIP system. They have carried out high resolution solid state optical spectroscopy to measure coherence times of these materials and used these materials to perform several quantum memory related demonstrations, such as slow light and storage of non-classical light.

In the experimental implementation of QIP schemes using rare earth ion doped crystals, Eu:YSO was used extensively, since the homogeneous linewidths of the optical transitions for this material are extremely narrow. The quantum computing and memory schemes being pursued typically rely on the ability to prepare sharp absorptive features in a controlled homogeneous environment. Two methods have been used to prepare sharp absorptive features to which accurate pulses for quantum state transformations can be applied: (i) Quantum state preparation using zero area pulses, where zero area pulses are repeatedly applied and the ions that are close to resonance with the laser, but not exactly on resonance, are burnt away and (ii) preparation using the burn back of ions, where a broadband hole is burned with a swept frequency beam, followed by the application of a different frequency, determined by the hyperfine splittings, which causes an anti-hole to be burnt back in the middle of the trench.

To make full use of the long coherence times of the materials and since both approaches involve long preparation times, a laser that is phase stable for at least comparable timescales is required. This is a very strict criterion and considerable time and effort was put into developing a laser stabilization system as described in [25]. A modified Coherent 699 ring dye laser was used. An investigation of the frequency noise of this laser showed significant frequency jitter over timescales much faster than the 2 kHz bandwidth of the commercial frequency stabilization system that proved detrimental. The stabilization system bandwidth was improved by modifying the servo electronics. When optimized, the resulting stability was better than 200 Hz over timescales of 0.2 s [25]. The apparatus used for this stabilization is large and complex.

Mingzhen Tian from MSU visited the group (February 2006, prior to grant) and has participated in fruitful discussions on the implementation of the scheme and analyzed the effect of jitter on the fidelity of quantum state reconstruction prior to and during this grant. The analysis indicates that the interaction strength for the burning process is not only limited by the homogeneous line width of the optical transitions but also sensitive to laser jitter. For these experiments, the frequency jitter of the laser was on the order of 200 Hz. A more stable laser (~100 Hz frequency stability) would allow smaller interaction strengths to be selected by using appropriately longer pulse sequences, which would in turn reduce the spatial ion density required. As a result, the spectral width of the control anti-hole is reduced allowing more accurate single qubit operations to be applied to the control anti-hole resulting in higher two-qubit fidelities. Thus, this is an area where laser stabilization via spectral holeburning is well suited, as it could provide better performance with a simpler set-up.

Quantum Information Group, Atomfysik, LTH, Lund, Sweden

At Lund Institute of Technology, Sweden, the group headed by Prof Stefan Kroll, investigates quantum computing and memory schemes that employ rare-earth-ion-doped crystals such as $Pr^{3+}:Y_2SiO_5$ [16,17] and $Eu^{3+}:Y_2SiO_5$ [22] because of their good coherence properties. In their schemes, qubits are constituted in the hyperfine levels (|0> and |1>) of the rare earth ions and they are manipulated using optical transitions to the excited level |e>. Their analysis indicated that this optical manipulation requires very stable lasers to obtain high-fidelity gate operations. In order not to be limited by laser performance, the laser must remain phase coherent on a timescale comparable to the optical coherence time, T2, of the atomic material. Their current experimental focus is on $Pr^{3+}:Y_2SiO_5$, which has an optical transition at 605.977 nm with coherence time as long as $T_2 = 152$ μs [17]. This wavelength is typically accessible with dye lasers. The narrow optical transitions are hidden inside a much broader inhomogeneous profile, but they can be isolated by optical pumping methods, taking advantage of the very long hyperfine level lifetime. For example the lifetimes in $Pr^{3+}:Y_2SiO_5$ can be ≈100 seconds and longer in a moderate magnetic field. The experimental approach utilizes spectral holeburning to isolate strongly interacting qubits, as described in [26,27]. These initialization techniques employ several cycles of population transfer with subsequent relaxation and may last for times of the order of several hundreds of milliseconds, which impose some long term stability requirements on the laser performance. The qubit structures will typically have a spectral width of ≈ 200 kHz and can be prepared by several hundred cycles of optical pumping. The entire preparation process may take hundreds of milliseconds. It is important that the laser drift is much less than 200 kHz during the preparation time. A second consideration is the phase fluctuation on the fidelity of reconstruction of the qubit. Their analysis indicates that the phase fluctuations play no role if the initial state is in either of the basis states, |0> or |1>. However, the impact is maximal if the initial state is an even superposition with $|\alpha|^2 = |\beta|^2 = 1/2$. In this case, for a phase error with a standard deviation as high as 10 degrees, the fidelity is 98.5%.

Thus, these considerations have necessitated the development of a laser stabilization system based on holeburning. Researchers in the two groups at MSU and Sweden have had frequent exchanges of communications and visits to develop the laser stabilization system. Krishna Rupavatharam visited Kroll lab (July 2006, prior to grant) and participated in the analysis of the scheme and discussions on the stabilization implementation during the grant period. The stabilization system, in addition to the typical feedback and control loops, utilizes a novel RF holeburning/filling technique described in [28]. The current system has typical drift rates of 1 kHz/s that fulfilled the stability requirement of the QIP scheme.

Laboratoire Aime Cotton, Orsay, France

The research group in France works on quantum information exchange between light and atomic ensembles, with emphasis on thulium (Tm) doped solids. Their focus is on storing optically carried quantum information into an atomic ensemble entangled state. Their approach is guided by the thought that a spin wave in the electronic ground state is not subject to decoherence by spontaneous emission and can therefore be a reliable and long-lived storage unit for quantum information. This superposition state can be optically created and manipulated in a three-level Λ system, where two ground spin levels are coupled by optical transitions to a common excited level. In this scheme, the spin coherence lifetime is of paramount importance since it determines the storage time.

Long coherence time sources are needed in order to take advantage of the long optical coherence lifetimes in rare-earth ions, such as Pr^{3+}: YSO and Eu^{3+}: YSO are, respectively, operated at 606nm and 580 nm. However, only dye lasers are available at these wavelengths as is evident from the research at Sweden and Australia. Due to the high frequency noise generated by the dye jet in these lasers, it is a challenging task to reach sub-kHz linewidth and jitter and an intense effort was necessary to achieve this level of stability. Thulium, on the other hand, is another non-Kramers rare-earth ion and its 793nm absorption wavelength falls within reach of the more tractable lasers, especially semi-conductor lasers. In addition, thulium has a very simple level structure when compared to other rare-earth ions. In particular, thulium-doped $Y_3Al_5O_{12}$ (YAG) presents interesting features. It has been widely studied in the field of laser stabilization and coherent transient-based signal processing schemes at both Orsay, France, and MSU.

The research at France involved the characterization of Tm:YAG system and the evaluation of its viability as a suitable candidate for quantum hardware [29,30,31]. Krishna Rupavatharam had the opportunity to meet F. Bretenaker and F. Goldfarb from this group (December 2006) and discuss the stabilization techniques using regenerative spectral hole burning developed at MSU and laser stability requirements for Tm:YAG based quantum systems. It was generally agreed that one of the most important considerations to use Tm:YAG system, in addition to those listed above, is the development of laser stabilization techniques to stabilize commercially available compact, inexpensive external cavity diode lasers (ECDL) at these wavelengths.

Recent evidence is that Tm:YAG may not have all the required properties needed for performing the desired quantum manipulations and that a new material, Tm:LiNbO3, developed at MSU, may be the more desirable Tm doped crystal structure. The French group and the Canadian group of Wolfgang Tittel are currently in discussion with MSU on collaborations on the spectroscopy of these crystals and their use in QIS demonstrations. MSU has also done preliminary development of laser locking to spectral holes in Tm:LiNbO3.

Montana State University (MSU), Bozeman, USA

At MSU, the research group previously led by Mingzhen Tian (now at George Mason University) and now led by Prof. Wm. Randall Babbitt, is engaged in investigating a QIP scheme that involves universal single qubit quantum operations by pure geometric manipulation of two-level and three-level atoms with laser pulses. The two level system chosen as the building block for quantum computation is Tm3+ doped in yttrium aluminum garnet (YAG) crystal, where the two necessary universal operations (i) accurately controllable arbitrary unitary operations on a single qubit and (ii) a controlled-NOT operation involving two qubits have been shown to be possible. It was realized that the whole set of universal quantum operations can be accomplished purely through geometric effects on the wave functions of the qubits that are imparted by the external controls, such as laser pulses and magnetic fields [32,33]. The states of Tm:YAG can be split by a magnetic field to create three-level lambda systems.

If a Hamiltonian drives a Bloch vector going through a cyclic path, the tip of the Bloch vector traces out a circuit on the Bloch sphere and returns to its initial position. This evolution makes the wave function associated with the Bloch vector gain a geometric phase besides the dynamic phase. The geometric phase solely depends on the amount of the solid angle enclosed by the evolution path. It does not depend on the details of the path, the time spent, the driving Hamiltonian, or the initial and final states of the evolution. Therefore, it is expected that the geometric operations are relatively robust compared to the dynamic ones and are resilient to errors caused by certain types of noises in the driving Hamiltonian.

The current research at MSU involves designing and implementing a scheme for universal single qubit operations, on two-level atoms in Tm:YAG, composed purely of laser-controlled geometric phase changes [34]. In a proof-of-concept experiment, they demonstrated the laser-pulse controlled Bloch vector rotation, on the two-level Tm:YAG crystal [32,33]. The resulting quantum states of the ions were measured using photon echoes. Since the rephasing process of the photon echo cancels the dynamic phase differences for atoms at different frequencies, it allowed for the observation of pure geometric phase change of an ensemble of inhomogeneously detuned two-level systems. The investigation was carried out with a cw Ti:Sapphire, laser, frequency stabilized to submegahertz using the spectral hole burning technique, developed at MSU. The investigation revealed that the rotation accuracy was limited by the laser frequency jitter. The phase measurement technique also demonstrated that it could be used to evaluate the operation fidelity when various noises are present on the control pulses, such as frequency jitter and amplitude fluctuations. The analysis of the phase rotation accuracy indicated that the precision critically depends on the laser stability. The current efforts at MSU involve studying the lambda system (three level) in Tm:YAG, with qubit in the nuclear Zeeman split ground state. These investigations are being pursued with an external cavity diode laser (ECDL) stabilized to spectral holes, with ~10 kHz linewidth and good stability.

Mingzhen Tian has recently joined George Mason University. Her work at MSU is now being led by Prof. W. Randall Babbitt. As discussed in previous, the Tm QIS work may be better done in a new material developed at MSU, Tm:LiNbO3. MSU is in the process of characterizing the suitability of these materials for QIS studies and has developed laser stabilization techniques that would allow locking to spectral holes in Tm:LiNbO3.

Stable Laser needs for non-holeburning based approaches

There are a large number of non-holeburning approaches for physical implementation of quantum computing being pursued by various groups all around the world. Some of techniques listed in the Quantum Computation Roadmap [35] with a high probability of success are ion trap, neutral atom trap, optical, cavity QED, and quantum dot approach based quantum systems. According the roadmap document, several factors need to be addressed in the near future for these approaches to be viable and satisfy the quantum hardware criteria. Since lasers are used in a majority of the systems for state preparation, quantum operations, and even state reconstruction, considerable effort has been placed on developing lasers with exceptional phase and amplitude stability. We have corresponded with major QIS researchers, including ion trap researchers such as Dave Wineland at NIST Boulder, and surveyed the research from groups in different parts of the world as well as the Eurovision document that details the efforts of the groups in Europe. This section of the report deals with an assessment of the needs for laser frequency stabilization for several of these approaches.

Ion Traps

Majority of the trapped ion species used for quantum information processing (QIP) belong to alkaline-earth family (from Beryllium through Barium), most of which has been investigated so far. Other ion species not in the family, but with similar energy structure, such as Cd+ and Yb+ have also be investigated. Laser beams are usually needed to interact with the trapped ions through electronic transitions for cooling, loading, and observing the ions in the trap, also for precise temperature measurement, qubit operation, and quantum state measurement. The requirement for the laser frequency stability is mainly determined by the line width of the electronic transition of the trapped ion. The electronic transitions involved in ion trap QIP are S-P and S-D transitions. The transition wave lengths vary with the ion species. In general, S-P transitions are relatively broad (few MHz to tens of MHz) in UV to blue region. S-D transitions, on the other hand, are extremely narrow (sub Hz with lifetime >1s). The required wavelengths are usually in red to near infrared.

These two types of transition require different specification on laser frequency stability. The sub MHz line width is good enough for S-P transition while the frequency drift has to be kept with the transition bandwidth during the time of the experiment. This is usually realized by locking lasers to a stabilized cavity or an atomic transition. An example is locking a diode laser frequency to a Rubidium transition line (843nm) and use frequency-doubled light at 422 nm for cooling Strontium [36]. For the S-D transition, most of the experiments with trapped ions avoid the difficulty with the stringent requirement on laser line width through stimulated two-photon Raman process in a three-level system by including a P level in the process. However, some experiments have achieved direct excitation with stabilized lasers. Two examples provided here.

1. $^{40}Ca^+$ and $^{43}Ca^+$ S-D transitions at 729 nm with sub-Hertz transition bandwidth were used for sideband cooling, qubit operation, and state measurement. The requirements for the laser to access this transition includes,
    a. fast frequency tuning 100MHz over microsecond scale,
    b. slow tuning for 5.5GHz to bridge the resonance of $^{40}Ca^+$ and $^{43}Ca^+$, and
    c. frequency stabilized to line width 10Hz and frequency drift below 1Hz/s.

Currently, these are achieved with Ti: S laser locked to a high finesse cavity in Rainer Blatt's group at U. Innsbruck [37] and would be difficult achieve with laser locking to spectral holes.

2. Sr^+ S-D transitions at 674 nm was directly accessed by stabilized diode to 4 KHz at Los Alamos National Lab, [38]. The locking techniques is unknown, but is stated under improvement. There may be a role to play for lasers locked to spectral holes, though a wavelength shift to/from the 674nm from/to a holeburning transition would likely be needed.

Atom traps

Alkali atoms, especially rubidium and cesium are the most popular neutral atoms for atom trap based QIP. The electronic transitions involved in atom trapping, probing, and quantum gate operations are S-P transitions. Among these transitions are the strongest spectral lines, D1 and D2. The line width is typically on the order of MHz. This should be the upper limit of the laser line width and the long term drift. Current approaches of laser stabilization include locking laser frequency to stabilized high finesse cavity or atomic transition, as described below:

1) Locking to atomic transitions: When a frequency stabilized laser is needed to excite an electronic transition of the trap atom, it is a straight forward choice to lock the laser frequency to the electronic transition of the same atomic species in a vapor cell. In one example, an ECDL was locked to ^{87}Rb D2 line at 780nm. Frequency stability was measured to be less than $2x10^{-12}$ for integration time form 1 s up to 1 day [39]

2) Locking to high finesse cavity: Two sources at 780 nm and 980 nm are needed simultaneously for Raman excitation of Rydberg state to perform 2-qubit gates. Two diode lasers providing the wave lengths are locked to one stabilized cavity (Q=105). Line width of 5 kHz and long term frequency drift <<100 kHz at both wavelengths have been achieved by Saffman's group at University of Wisconsin, Madison [40].

Quantum dots

The quantum dot approach to QIP is based on spin qubit and exciton qubit and laser excitation is used for state initialization and manipulation either through direct excitation (exciton qubit) or two-photon Raman process (spin qubit). In GaAs quantum dot system, the transition wavelengths to manipulate Raman coherence for the electronic spin state is around 770 nm and bandwidth is relatively large on the order of sub THz due to the short lifetime of the exciton state (tens of ps). The spin coherence time was measured to be around 10 ns. In this case, short laser pulses from mode-locked Ti:S were used, which did not require frequency stabilization. However, frequency-locked cw lasers have been used for high resolution spectroscopic work on this system. The laser bandwidth was observed to be ~ MHz. [41]. In the case of exciton qubit, pulsed laser is required for quantum gate operations and the coherence time is limited to 50 ps to 1ns.

Optical (photon qubit) approach

The main obstacle to this approach is to realize reliable periodic single photon source and related problems. Frequency stabilized lasers do not seem to play an important role in this approach.

Cavity QED

Cavity QED approach utilizes the interaction of material qubits, usually ions or atoms with photon qubits in high finesse optical or micro-wave cavity. To achieve the strong coupling regime, the coherent Rabi frequency of the atom-field interaction has to be faster than the spontaneous emission rate of the ion/atom or the decay rate of the cavity. When a trapped ion or atoms discussed above are used in cavity QED, the lasers needed in the ion trap or atom trap approaches have to interact with ion/atom qubits in the high finesse cavity. Some of the laser beams (such as cooling laser beams) incident in the cavity's transverse direction do not need to match the cavity mode while some (state manipulation and probe beams) incident in the longitudinal direction have to match the cavity mode. It turns out that in strong coupling regime the cavity decay rate can be slightly faster than the ion/atomic decay rate. This means that the cavity line width is slightly broader than the electronic transitions, which should not, in principle, pose more stringent requirement on laser frequency stability than the regular ion/atom trap approaches, according to the QC roadmap [35].

QIP Eurovision Document

We have also examined the QIP Eurovision document [42] written by a consortium of quantum research groups in Europe. This article outlines the different approaches undertaken by various research groups in Europe and identifies the challenges and goals towards the realization of quantum computing systems. A key identification is that long coherence times are necessary to provide a robust quantum memory. Mechanisms such as spontaneous emission must be avoided by all means thereby necessitating the exploration of decoherence-free subspaces. A test case is the well studied ion-trap based system. Techniques to build large-scale ion trap quantum computers have been established. Moreover, the near-unity state detection and the availability and operability of a universal set of gate operations make it already a test-bed for small-scale quantum computation. On the downside, motional decoherence by stochastically fluctuating fields (originating from trap electrodes) is not completely understood and must be reduced. A glance at the short-term goals that have been suggested for the next 3-5 years shows that improving laser intensity stability and phase stability, so as to reach fault-tolerant limits, is deemed an important task. A significant recommendation is that current technical constraints, such as the availability of laser sources, their respective stability and purity need to be improved dramatically and is identified to be critical to the success and advancement of several approaches.

Additional Information

Wm. Randall Babbitt was a Program subcommittee member of Optical Processing and Analog Subsystems, OFC/NFOEC 2010, San Diego, CA, March 22-25, 2010 and attended the conference as well as the program committee meeting to select papers for the conference in December 2009.

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