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The ORNL Multicharged Ion Research Facility Upgrade project

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Abstract

A new 250 kV high voltage platform has been installed at the ORNL Multicharged Ion Research Facility (MIRF) to extend the energy range of multicharged ions available for experimental investigations of their collisional interactions with electrons, atoms, molecules, and solid surfaces. For the production of the multiply charged ions, a new all-permanent magnet Electron Cyclotron Resonance (ECR) ion source, designed and fabricated at CEA/Grenoble, is being used. After a brief summary of the project background and the expanded research program made possible upon its completion, design details of the new platform, associated beam transport, and control system are presented, together with information on the design and performance of the new ion source.

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Introduction

While developed initially as an injector for high-energy accelerators, in recent years the Electron Cyclotron Resonance (ECR) ion source has become an indispensable tool in the field of multicharged ion (MCI) collision physics. In fact, the availability of low energy, intense, high charge state, high duty factor, ion beams from ECR sources has opened many areas of MCI research that have previously been inaccessible. Examples include investigations of low energy collisions involving bare ions of Z>5, merged-beams experiments, studies of electron-ion collisions, and investigations of MCI-surface interactions [1]. Due to their great utility in atomic physics research, the number of ECR sources available, at least part time, for use in the study of MCI collisions has grown dramatically over the past 10-15 years.

At Oak Ridge, the ECR-source-based ORNL Multicharged Ion Research Facility (MIRF) has been in existence since 1984. The original ORNL ECR source, locally designed and built, was the first such source completely dedicated for use in atomic physics studies, and was able to provide fully stripped low-Z ions up to Ne of sufficient intensity to enable among the first collision studies with such ions. With the installation of a 10-GHz CAPRICE ECR ion source in 1992, carried out as part of a DOE-funded upgrade project to take advantage of ECR source developments that had occurred since the commissioning of the first generation ORNL ECR source, significant increases in ion beam intensities and attainable charge states were realized.

The MIRF Upgrade project

In FY 1997, a capital equipment project was initiated for a major facility upgrade. The upgrade project consists of two parts. The first entails the installation of a 250-kV high-voltage platform, for use in conjunction with a new all-permanent magnet ECR ion source. In addition to expanding the capabilities of present on-line experiments, higher energy MCI beams will allow new classes of experiments. The second part entails relocation of the present CAPRICE ECR ion source with the standard 25-kV isolation, to extend the availability of very low energy MCI beams. By using a floating beamline approach, keV-energy beams will be transported with high efficiency and then decelerated to a few eV x q (where q is the charge state of the ion of interest) upon entry into various experimental chambers at ground potential, using efficient ion optics already developed for the MIRF floating ion-surface interaction experiment. With these two sources, an energy range of almost five orders of magnitude will be available to the various experiments, a significant improvement over the 1-25 keV/q energy range capability of the present MIRF source configuration. The number of user ports available for non-dedicated experiments will be expanded as well. The layout of the upgraded facility is shown in Fig. 1.

Expanded Research Capabilities

The energy range between 25 – 250 x q keV is at present virtually inaccessible for highly charged ion collision experiments requiring beam intensities in the particle-µA range. The maximum energy with the present CAPRICE ECR ion source is 25 x q keV, typical of most ground-based ECR and Electron Beam Ion sources. Conventional accelerators cannot produce highly charged ion beams with sufficient intensity at energies below a few hundred keV per charge, due to the inefficiency of gas or foil stripping at lower energies.

Upon completion of the MIRF upgrade, a broad range of new experiments involving high charge state ions will be possible. In this energy range, the behavior of MCI collision systems evolves from the low-energy "molecular" to the intermediate-energy "atomic" regime, and experimental data are essential for benchmarking calculations in this theoretically challenging transition range. The near-threshold behaviors of, e.g. heavy-particle collisional ionization, inner shell excitation, and vacancy transfer processes are still not fully elucidated and require additional experimental data to validate progress in theoretical understanding.

In addition, all the online experiments at MIRF will benefit greatly from the higher energy beam capability developed by this project. For example, the merged electron-ion beams energy loss (MEIBEL) experiment will be able to investigate processes with much lower-energy thresholds, such as fine-structure transitions, using the present electron gun, owing to the higher available center of mass ion velocities. The higher ion energies available with the upgrade should also more than double the range above threshold open to measurement with this experiment; at present, the energy range is severely limited by electron backscattering in the ion frame. This will make possible the experimental study of many more of the interesting dielectronic resonance structures predicted to lie further above threshold in the electron-impact excitation cross section of many systems. The higher ion energies also result in increased energy resolution in the center-of-mass (c.m.) frame, important for mapping out dielectronic resonance structures and thus providing strict benchmarks for theoretical methods. In addition to the improved measurements on the excitation of atomic ions, the higher ion energies attainable with the platform will make possible investigations of dissociative recombination for heavy molecular ion species that are difficult for present magnetic storage rings. In a merged beams configuration, higher ion energies translate into higher laboratory frame electron energies for a given interaction (c.m.) energy. Since dissociative recombination peaks at very low energies, higher ion energies thus permit utilization of higher-energy laboratory frame electron beams, with corresponding improvements in beam intensities and qualities. The increased ion energies will also permit energy- and position-sensitive detection of the product neutral fragments with solid-state detectors, enabling a more complete picture of the dissociation process to be obtained.

Higher available ion beam energies will make possible velocity matching of intermediate mass multicharged ions with few keV neutral H or D beams, a necessary condition for carrying out very low velocity electron capture cross section measurements using the ion-atom merged beams experiment. For example, while the lowest energy attainable in the ion-atom merged beams experiment for the Mo^{q+} + H system with the present ECR source is a few 100 eV/amu, this limit will be reduced by at least two orders of magnitude with the higher-energy beams available after the platform upgrade.

In the ion-surface interactions investigations, significant insights into the effects of projectile charge state on ion-surface interaction dynamics can be obtained by comparing results for multicharged incident projectiles to those obtained for singly charged ions at identical energies. Extending the available energy range for singly charged ions will greatly facilitate such comparisons for processes active in the tens of keV energy range. Further, new investigations of grazing incidence resonant coherent excitation (RCE) and molecular dissociation processes will require access to energies significantly higher than could be provided by the present CAPRICE ECR ion source.

Regarding the floating beamline injected by the relocated CAPRICE source, the enhanced low-energy capability will make possible investigations of many new low-energy heavy particle interactions. These include single, multiple, and dissociative low energy electron capture, lifetime studies of metastable electronically excited MCI's, measurements of X-ray emission and surface modification in low energy MCI-surface interactions [2], and investigations of plasma wall interactions of relevance to present and future fusion plasma experiments.

All major fabrication and installation tasks of the HV platform part of the MIRF upgrade project have now been completed. The ECR source, as well as the platform- and ground-potential beamlines, are under vacuum of ~ 10^{-7} Torr. Testing of the various components is nearing completion, and the first experiment is planned for February, 2005. In the following sections, some design aspects of the major components of this phase of the project are presented.

ECR Ion Source

The ECR ion source was designed and built at CEA Grenoble. Design of its magnetic field structure, achieved by compact NdFeB permanent magnet assemblies for the radial hexapolar and axial solenoidal fields, was based on previous studies of optimum magnetic confinement [3,4]. The source features a 1 T radial magnetic field at the plasma chamber wall, an axial magnetic field maximum of 0.9 T on the extraction side, a minimum axial field of about 0.4

T, and a 1.3 T magnetic field maximum at the injection side. The latter was achieved by use of an iron plug inserted from the rear into the plasma chamber, which has penetrations for microwave injection, biased disk support, gas feed, and a mini-oven for ion beam production from solids. The plasma chamber has an inner diameter of 50 mm and is double walled to permit coolant circulation for protection of the immediately adjacent permanent magnet assemblies. Beam formation is achieved using a two electrode extraction system, the first of which can be biased at up to – 5kV, with the second at ground potential, as shown in Fig. 2. The injected microwave power is provided by a 700 W traveling wave tube (TWT) amplifier, whose output can be varied in the frequency range 12.75 – 14.5 GHz. The HV isolation of the source is sufficient to operate at more than +25kV relative to the platform potential. A more detailed description is presented in [5]. Intensities of extracted beams obtained immediately after magnetic analysis during initial testing at CEA Grenoble are summarized in Table I. The performances summarized in the table exceed those of the facility's present 10 GHz CAPRICE source, by up to factors of 2-3 in the case of the highest charge state Xe ions.

Beam transport system

The design energy range of the high voltage platform is 20 – 270 x q keV. To achieve this wide energy range with maximum beam transmission a number of specific features were incorporated into the design of the beam transport system. All effective optic element apertures on the platform (including the usable analyzing magnet gap) and up to, and including, the first 65 degree spherical deflector beam switcher were designed for 100% beam transport for beams having an unnormalized emittance of 160 π·mm·mrad at 20 x q keV. This large acceptance could only be achieved for the electrostatic beam switcher by the use of two interchangeable sets of deflection electrodes, the first with a 2.5 inch gap to handle beams up to about 150 x q keV, and the second set with a 1.5 inch gap to handle the lower divergence-angle beams at energies beyond this value. Exchange of the two sets of electrodes requires opening of the deflector vacuum chamber. In addition, two einzel lenses were added on either side of the acceleration column to permit refocusing of the beam at the entrance waist of the tandem quadrupole triplet section at ground for low platform voltages where the focusing of the acceleration column itself is weak or non-existent. Finally, large 2 inch. acceptance quadrupole lenses were used in a tandem configuration before the first beam switcher to achieve both high transmission at low energies and sufficient focusing power with ± 20 kV electrode potentials at high energies.

Fig. 3 shows calculated beam envelopes up to the waist produced by the first 65 degree deflector for the two extremes of the beam energy range to illustrate the action of the tandem einzel lenses at low energies, and the stronger focusing action of the acceleration column at the higher energies. The envelope calculations are to first order, using the Trace 3-D Module with Electrostatic Palette in PBO Lab v2.1 [6]. Ray tracing and electrostatic field modeling were done with the SIMION trajectory simulation software [7]. Effective lengths for the quadrupole elements were calculated from SIMION radial field gradients: $L_{eff} = \int(dE/dz)]/(dE/dz)_0\, dz$, where the integral range is between the zero-gradient points and $(dE/dz)_0$ is the gradient at the mid-point of the electrode. Because of the large bore-to-length ratio (particularly for the outer elements), the effective lengths were not independent of off-axis distance, and limited the usable aperture radius having sufficiently low aberrations to about 2 cm.

The 65^o spherical sector electrostatic deflector ion optics were designed using SIMION as well. Special care was taken with the design and placement of the entrance and exit field termination slits, because of their importance in defining the virtual field boundary of the sector, which in turn significantly affect trajectory offsets and other focal properties. The electrodes were machined from aluminum blanks and then gold plated for optimum vacuum and HV compatibility. They, together with the slit assemblies, are mounted on a turntable supported by a ceramic ball bearing race . The turntable can be externally rotated about a vertical axis to one of three positions: the first two direct beam either into the left or right beamline, by a rotation of

115^{o} that reverses entrance and exit planes of the deflector, and the “straight-thru” position allows the beam to pass undeflected through the chamber past the outside of the “outer” electrode structure (in this case grounded, of course), which has a milled slot to accommodate up to 1 in. diameter beams. The deflector schematic and electrode/slit turntable assembly is shown in Fig. 4.

Control System

Most elements of the HV platform as well as the beamlines leading to the various endstations are controlled and monitored via Allen-Bradley ControlLogix programmable logic controllers (PLC's). Several devices employ serial protocols over RS-232 or GPIB communication channels. All devices are integrated into a Linux-hosted, EPICS [8]-based distributed control system which provides device independent, uniform access to all hardware via a distributed real-time database. Standard EPICS extensions include display management, alarm processing, data archiving, and diagnostic monitoring. Custom applications, e.g. mass or charge state scans and beam tuning parameter recall are easily implemented using EPICS Channel Access. This approach is compatible with that used at the ORNL Spallation Neutron Source, and serves as a testbed for the control system being developed for the HV platform being constructed as part of the new High Power Target Lab (HPTL) at the ORNL Holifield Radioactive Ion Beam Facility (HRIBF). Three separate PLC chassis, at source HV, platform HV, and ground potentials, are linked by ethernet-bridge-driven fiber-optic cables and controlled by a single Logix5555 processor in the ground potential chassis. Fig. 5 shows a schematic of the control system communication topology.

Platform Cooling

The three components on the platform requiring active cooling are the ECR source, the analyzing magnet, and the traveling wave tube (TWT) microwave amplifier. The TWT is cooled by 250 CFM of forced air flow. Sufficient cooling of the ECR source to permit operation at injected microwave power levels up to750 W is critical in order to avoid irreversible de-magnetization of the NdFeB permanent magnet structures. It is achieved using a NESLAB recirculating chiller with deionizer, operating at platform (not source) potential. The resistive losses in the analyzing magnet coils approach 10 kW when transporting beams with maximum magnetic rigidity. This heat load is dissipated by closed-loop circulation of cooling water through a finned-coil radiator with forced air flow of 1500 CFM. The water circulation is achieved by a centrifugal water pump capable of providing a 2 GPM flow rate at 80 psi head pressure, and the necessary air flow is achieved using a directly driven ducted fan. For optimum space utilization, the heat exchange/fan assembly was installed above the analyzing magnet. The compact platform layout is shown in Figure 6.

Platform Electrical Power

Electrical power to the platform is supplied by an efficient 250 kV mineral-oil-filled isolation transformer capable of providing up to 30 kW of three-phase 208V power, fabricated by Guth Hochspannungsgeräte GmbH [9]. This power is distributed to the various platform and source potential electrical components via a balanced single and three phase distribution network fed from the isolated transformer Y-connection with loadable midpoint (N) at the end of an oil-filled nylon pylon extending across the 29 inch gap between ground enclosure and HV platform. Total power required by platform components in the present configuration is a little over 20 kW, leaving almost 10 kW available for future expansion.

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Acknowledgements

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Figure Captions

Figure 1 - The layout of the upgraded MIRF.

Figure 2 - Schematic diagram of the platform ECR ion source.

Figure 3 – Horizontal (upper traces) and vertical (lower traces) beam envelopes from ECR source to the exit waist of the 65 degree deflector at the two energy extremes: a) for a 270 x q keV beam, and b) for a 20 x q keV beam. The transverse distance scales are 60 mm, total longitudinal distance is about 9 m.

Figure 4 – Schematic diagram and photograph of the 65^{o} spherical sector electrostatic deflector.

Figure 5 – Control system communication topology for the three PLC chassis at different potentials. Serial to ethernet interfacing is achieved using B&B DE-304 4 port Ethernet to RS-232 hubs, the GPIB to Ethernet interface uses an Agilent E5810A LAN?GPIB gateway, the fiber optics links use Allied Telesyn AT-MC101XL-10 fiber converters, and the Ethernet switches used are Netgear FS605 5 port or FS608 8 port 10/100 Fast Ethernet Switches.

Figure 6 – Platform layout, including the new all permanent magnet ECR ion source, the analyzing magnet and associated forced air heat exchanger.

Table I – Typical extracted beam currents of the new all permanent magnet ECR ion source, for 25 kV source high voltage.

Species	Charge state	Beam current (μA)
Argon	8+	510
	9+	310
	11+	90
Xenon	20+	52
	23+	31
	26+	24
	27+	18
	28+	6
	29+	3
	30+	1
Oxygen	1+	700
	2+	700
	3+	700
	5+	600
	6+	650
	7+	90

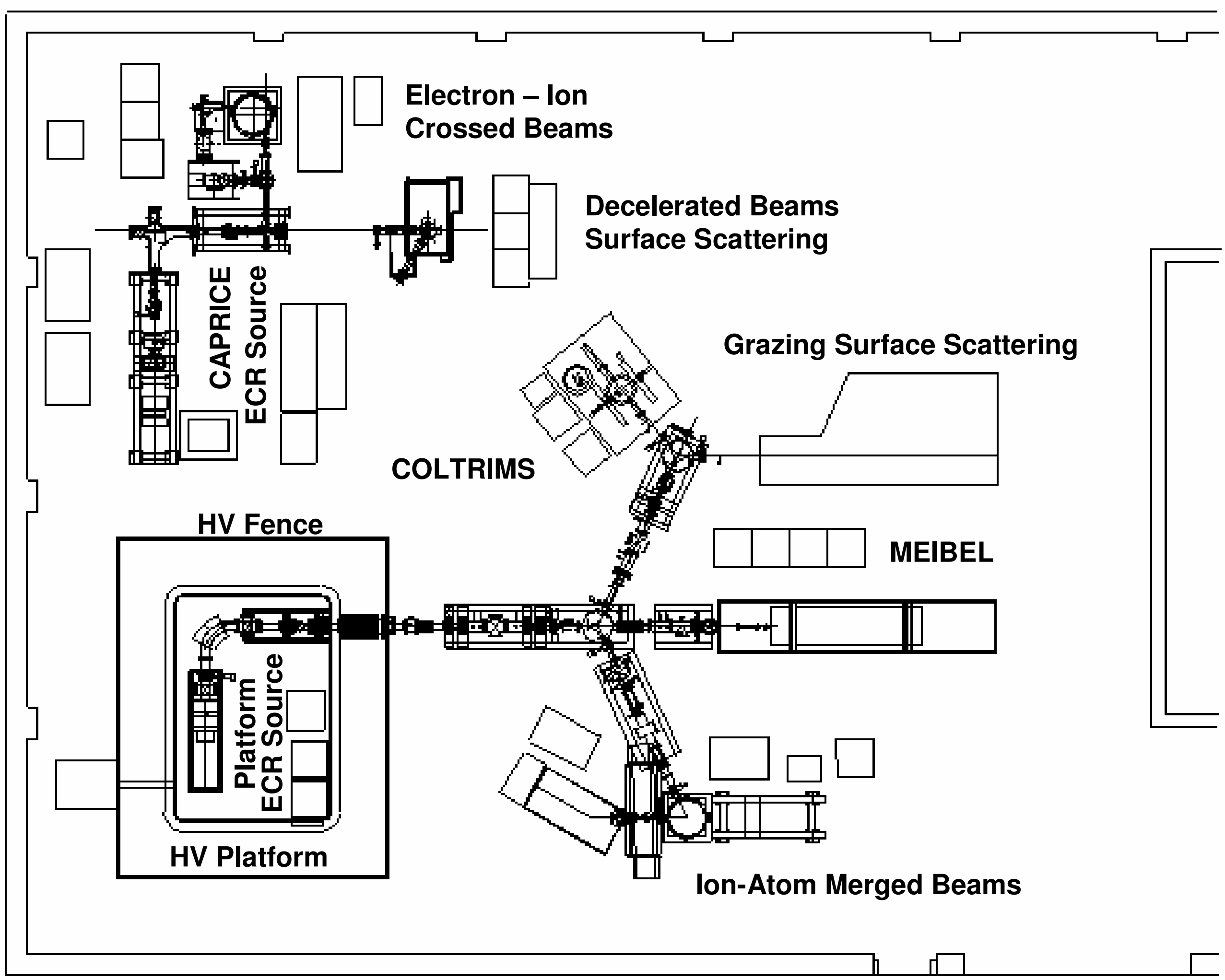
Electron – Ion
Crossed Beams
Decelerated Beams
Surface Scattering
CAPRICE
ECR Source
Grazing Surface Scattering
COLTRIMS
HV Fence
MEIBEL
Platform
ECR Source
HV Platform
Ion-Atom Merged Beams

Figure 1

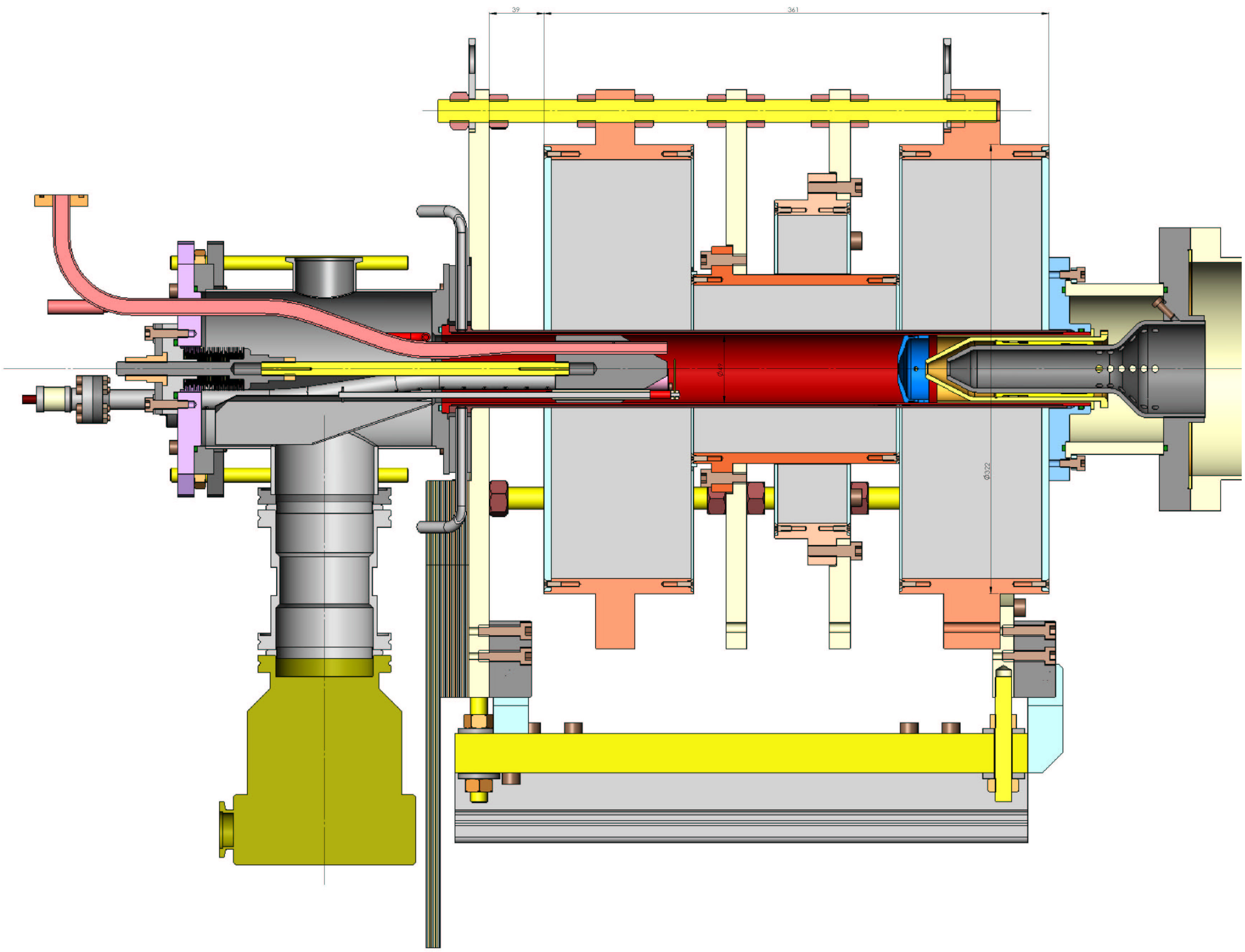

Figure 2

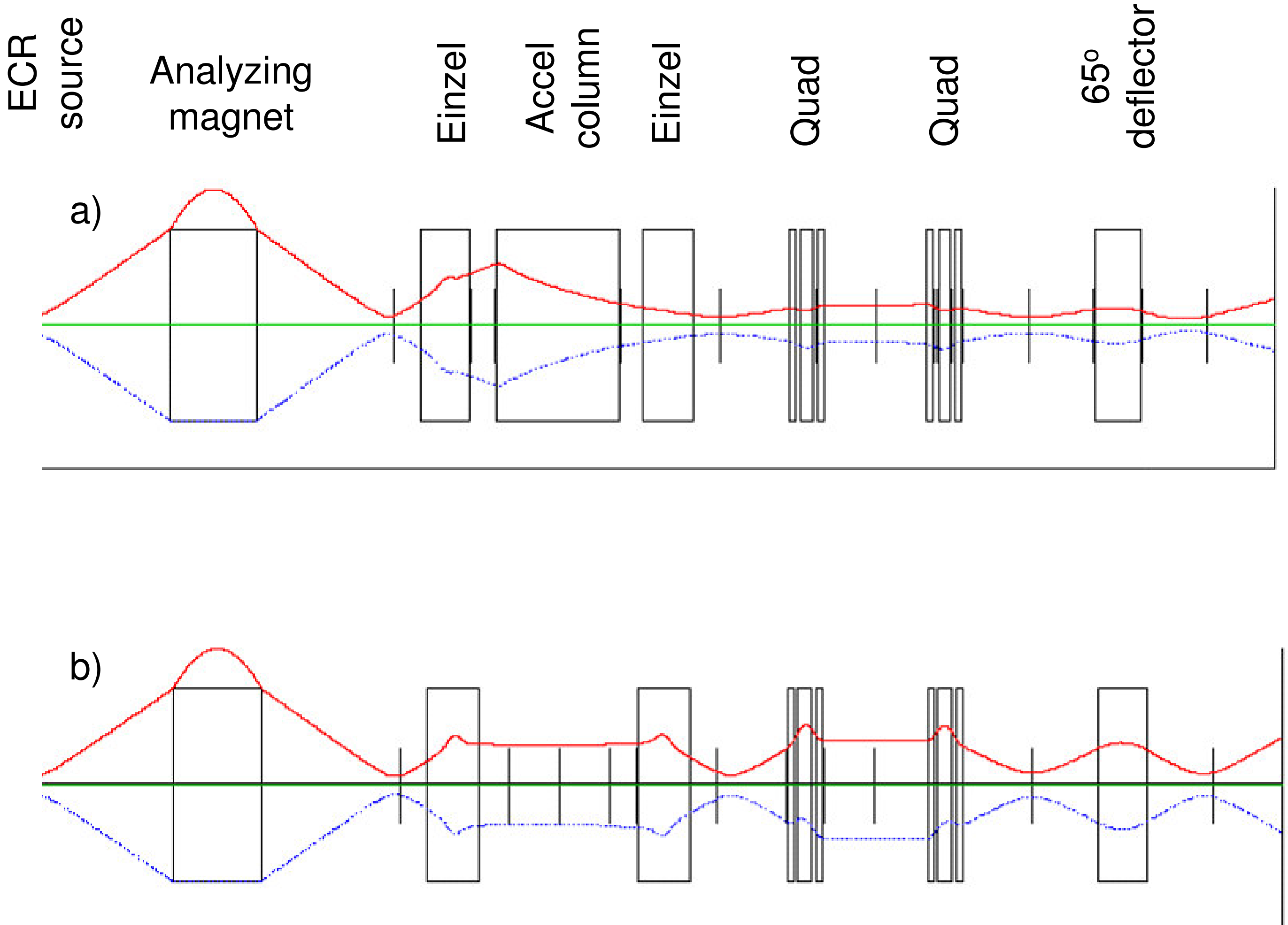
ECR source
Analyzing magnet
Einzel
Accel column
Einzel
Quad
Quad
65o deflector
a)
b)

Figure 3

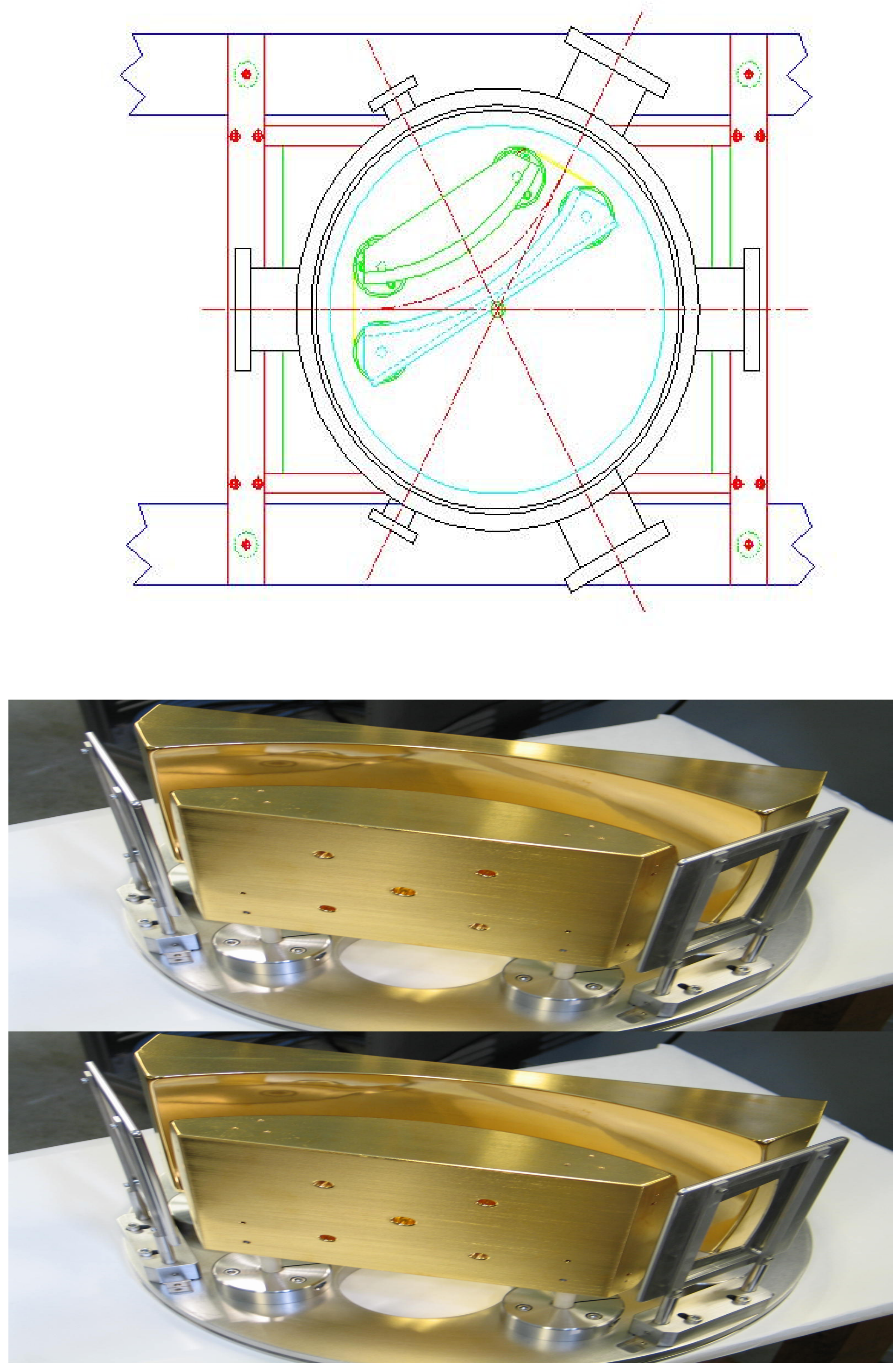

Figure 4

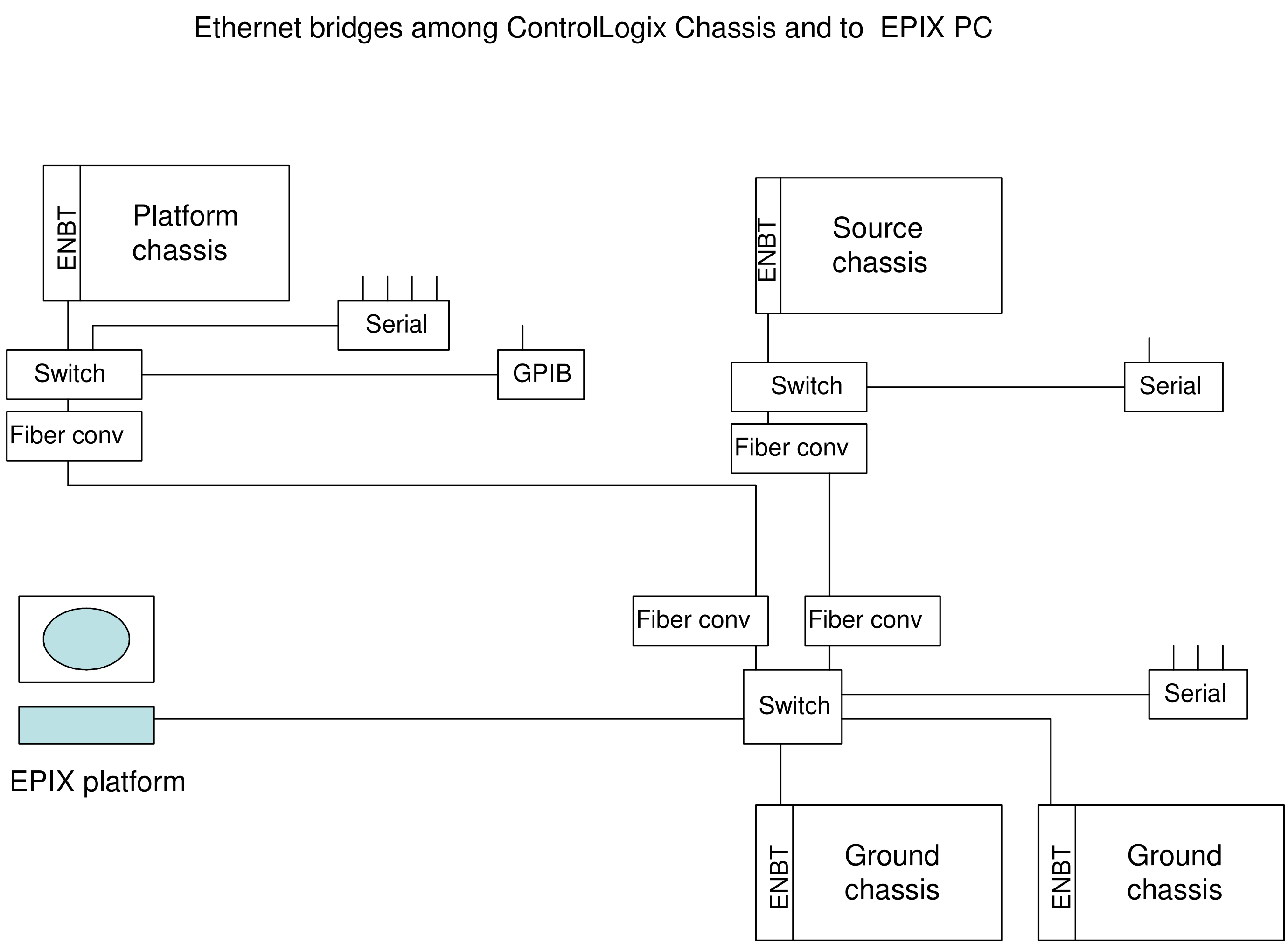
Ethernet bridges among ControlLogix Chassis and to EPIX PC
ENBT
Platform chassis
Serial
Switch
GPIB
Fiber conv
ENBT
Source chassis
Switch
Serial
Fiber conv
Fiber conv
Fiber conv
Switch
Serial
EPIX platform
ENBT
Ground chassis
ENBT
Ground chassis

Figure 5

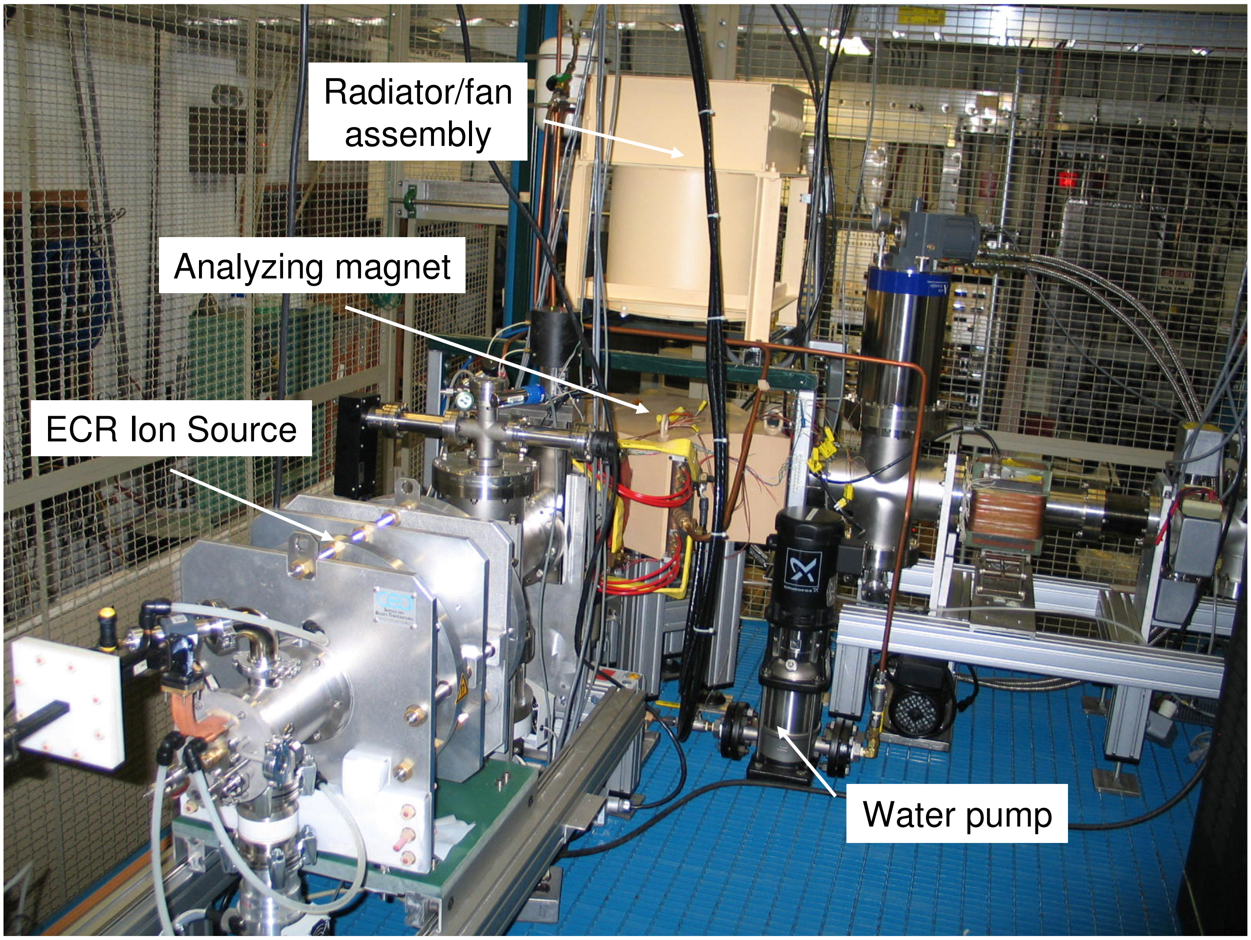
Radiator/fan assembly
Analyzing magnet
ECR Ion Source
Water pump

Figure 6