MIX

The Multipole Ion-beam Experiment

Alexander Klein
www.beamfusion.org

Abstract & Background

The MIX device is an IEC experiment incorporating a powerful electromagnet which served also as cathode and ion accelerator. The magnetic field is of the multi-pole variety (truncated cube geometry). Included in the design are computer controlled ion-focusing electrodes, electron-suppression electrodes, electron guns, and low ion energy recovery electrodes. Although mothballed, the MIX device incorporates several types of ion sources, a suite of ambitious and novel diagnostics, and many other features that make it interesting as a 'state of the art' IEC system.

The MIX experiment was one of the very few privately funded fusion energy projects in recent history, and although modest in scale relative to magnetic confinement schemes, the resources used to construct the MIX device in 2010 exceeded the sum total of all other global IEC funding. This poster describes the experimental apparatus, associated hardware/software, and diagnostics.

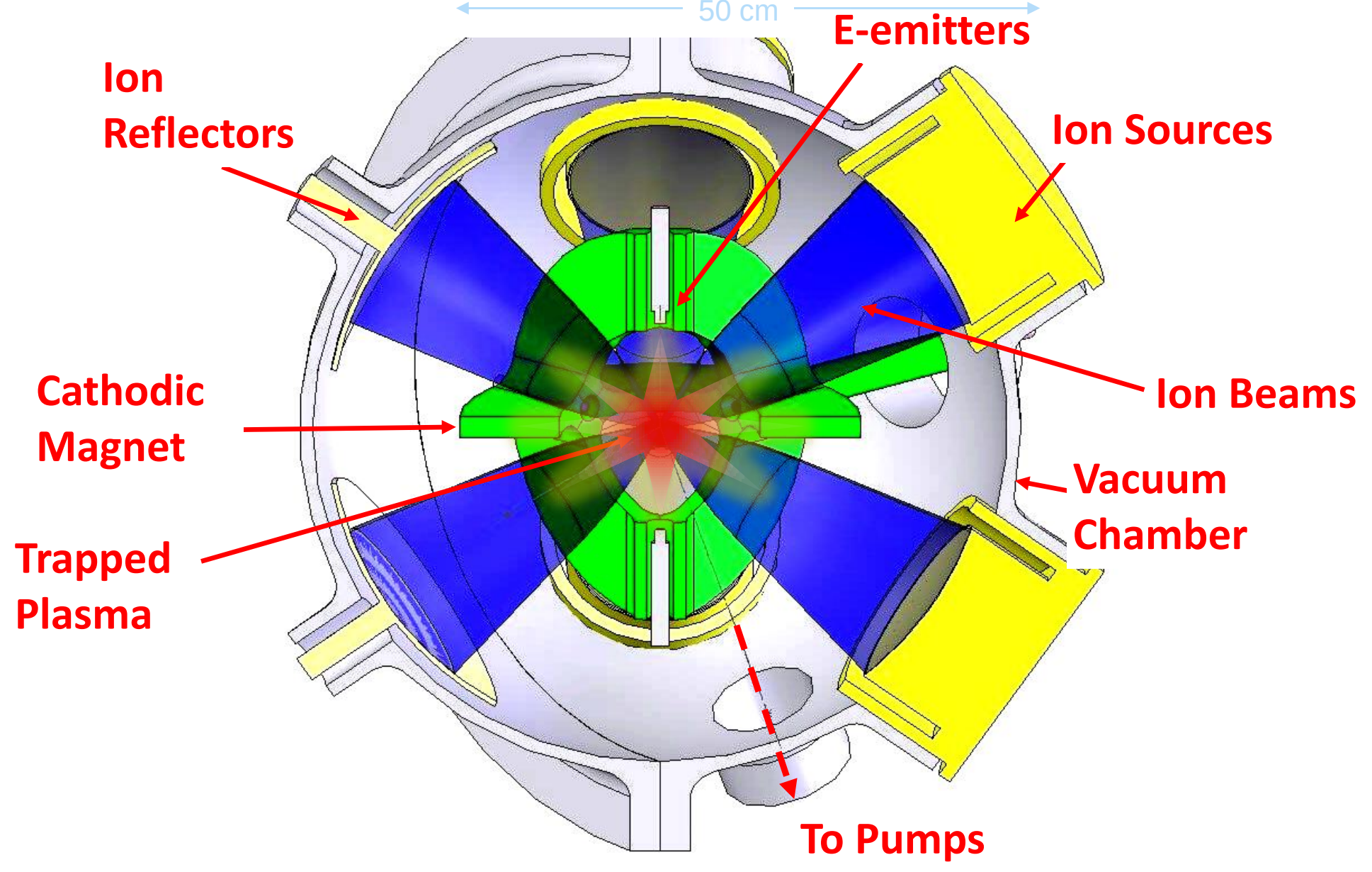

Fig. 1: Schematic of original MIX design (octahedral) showing essential components

MIX Overview

The MIX experiment was constructed nearly exclusively from custom parts and components, as this turned out to be the least expensive route.

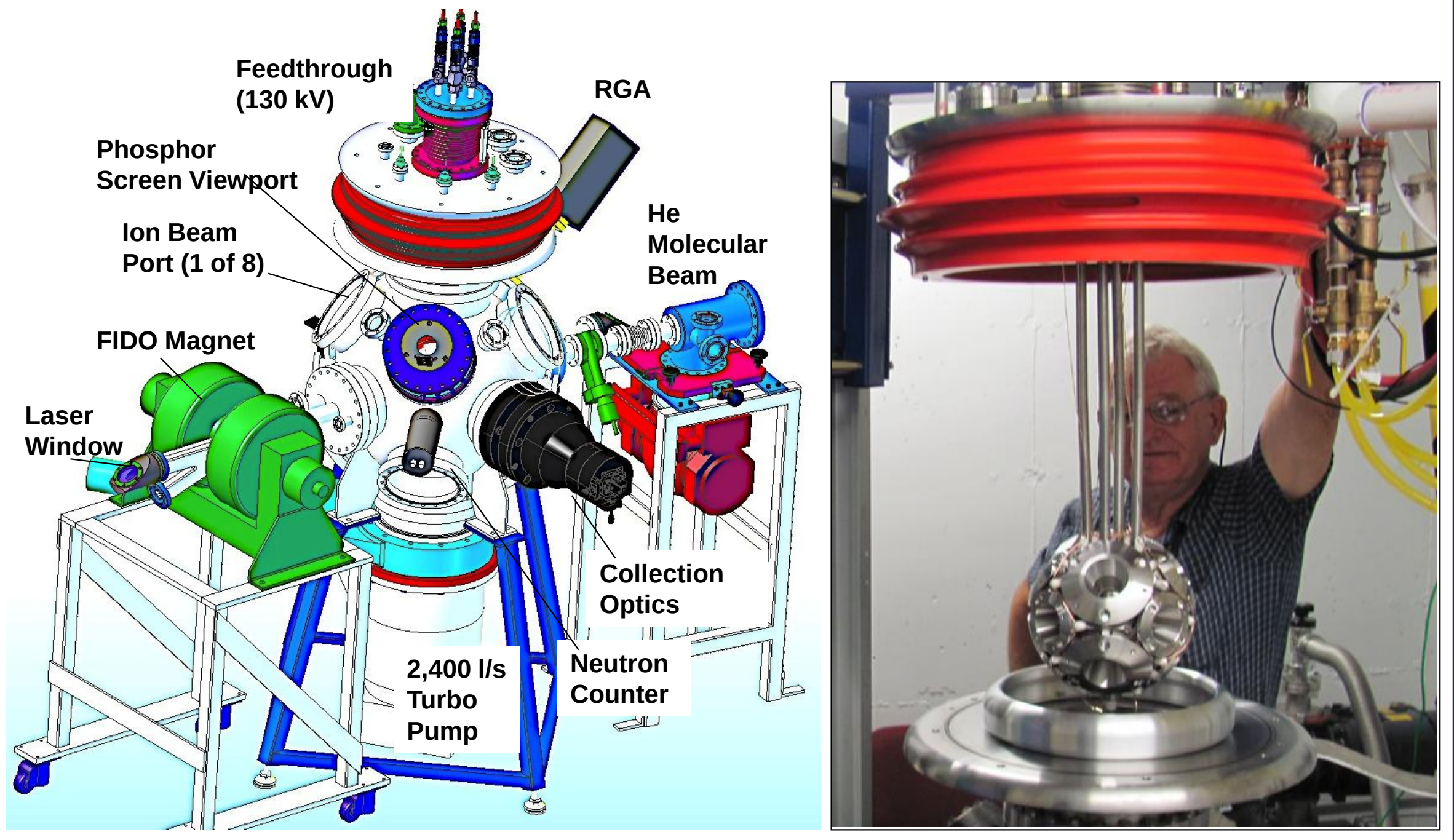

Fig. 2: Left: Engineering drawing of MIX chamber and peripheral diagnostics systems. Right: MIX magnet and HV electrical connections can easily be lifted out of chamber using hand activated crane. Plastic insulator, O-ring sealed to chamber, is the only non-metal seal but, well-shadowed from any energetic particles.

The device was situated inside a specially built concrete "bunker", designed to attenuate neutron flux by factor of 5000. Special HV conduit was built into the ceiling of the structure, all HV equipment housed on top of bunker in special HV rack (surfaces smooth and rounded, resulting in complete lack of corona or arcing problems even at 100 kV). The HV equipment (e-gun power supplies, magnet supply, repeller supplies) was powered via a large isolation transformer (10kVA, 150 kV), and controlled via fiber optic link.

A well-designed grounding scheme resulted in minimal ground loop problems, and very short return paths for any HV arcs or sparks.
The ultimate IEC facility!

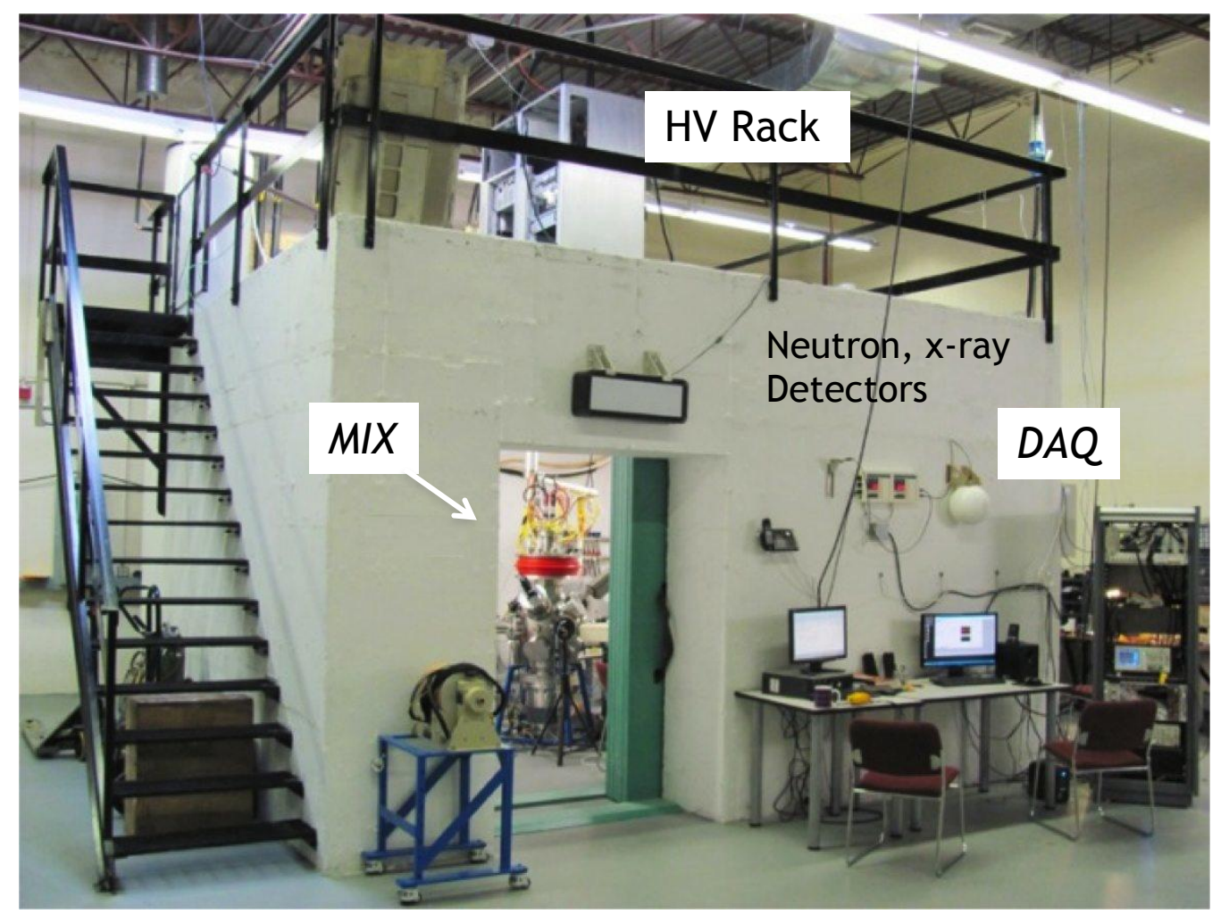

Fig. 3: Radiation bunker containing the experiment. Safety interlocks abound. No line of sight to the outside world, using angled feedthroughs for power and signal cables.

Magnet Design and Construction

Modular design: the MIX magnet is composed of two stainless steel hemispheres, each containing four water cooled coils connected in series. The coils can be individually replaced, and are sealed with recessed O-rings into their respective locations. Total (ohmic) heat load at full power: 6 kW, producing 1 kG of field at the magnetic mirror tops.

- 8 coils in individual O-ring sealed high-pressure compartments, high vacuum seals, with forced water cooling
- Magnet heat load (ohmic): 6 kW, heat exchanger on roof of building
- Cooling liquid: D.I. water (magnet potential up to 130 kV without problems)
- Included: electron gun (thermionic emitter, focusing and suppression electrodes)
- Incorporates electron-repeller electrodes, preventing electron leakage

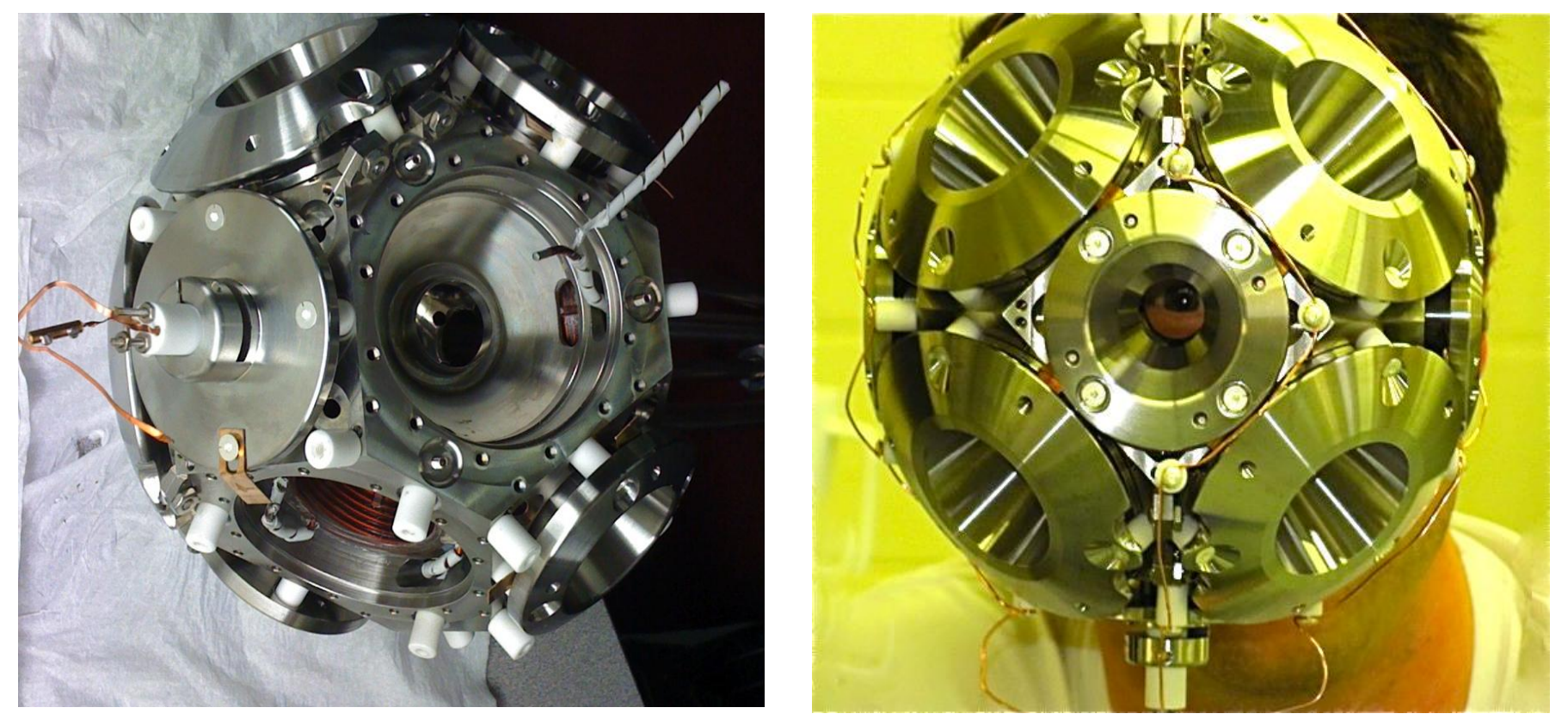

Fig. 4: MIX magnet, partially assembled, showing coil seat. Right: Fully assembled

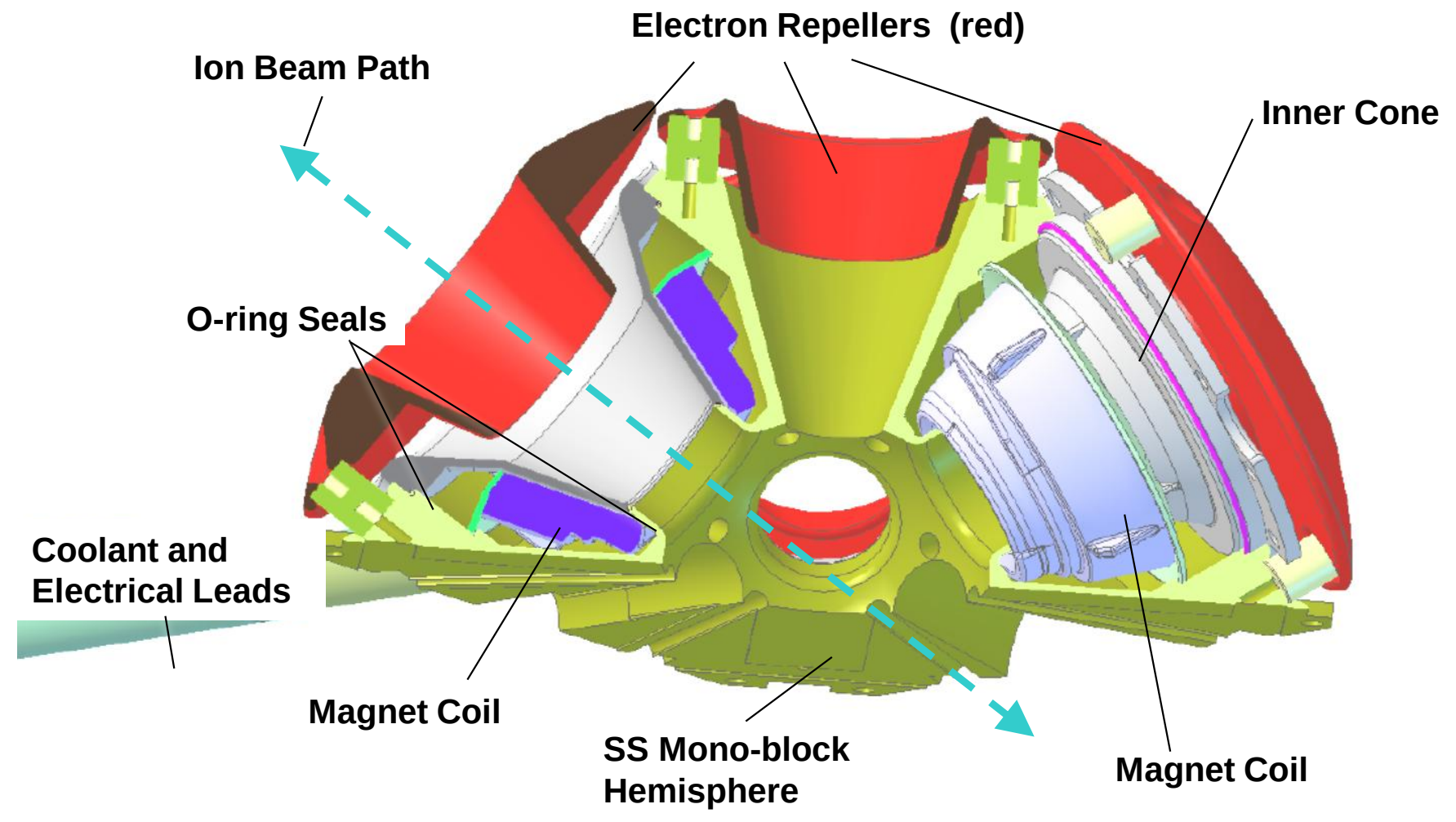

Fig. 5: Cross-sectional engineering drawing of MIX magnet

MIX Magnetic Field

The MIX magnetic field is a multipole topology known as "truncated cube". It results from placing coils on the faces of a cube, or, alternatively, on the corners of a cube. The latter configuration is how the magnet was constructed, it allows round (conical) coils which produce magnetic mirrors with roughly equal strength in all directions (there are 14 mirrors, and 12 "cusps". A cusp in a multipole is a line along which the field strength is 0).

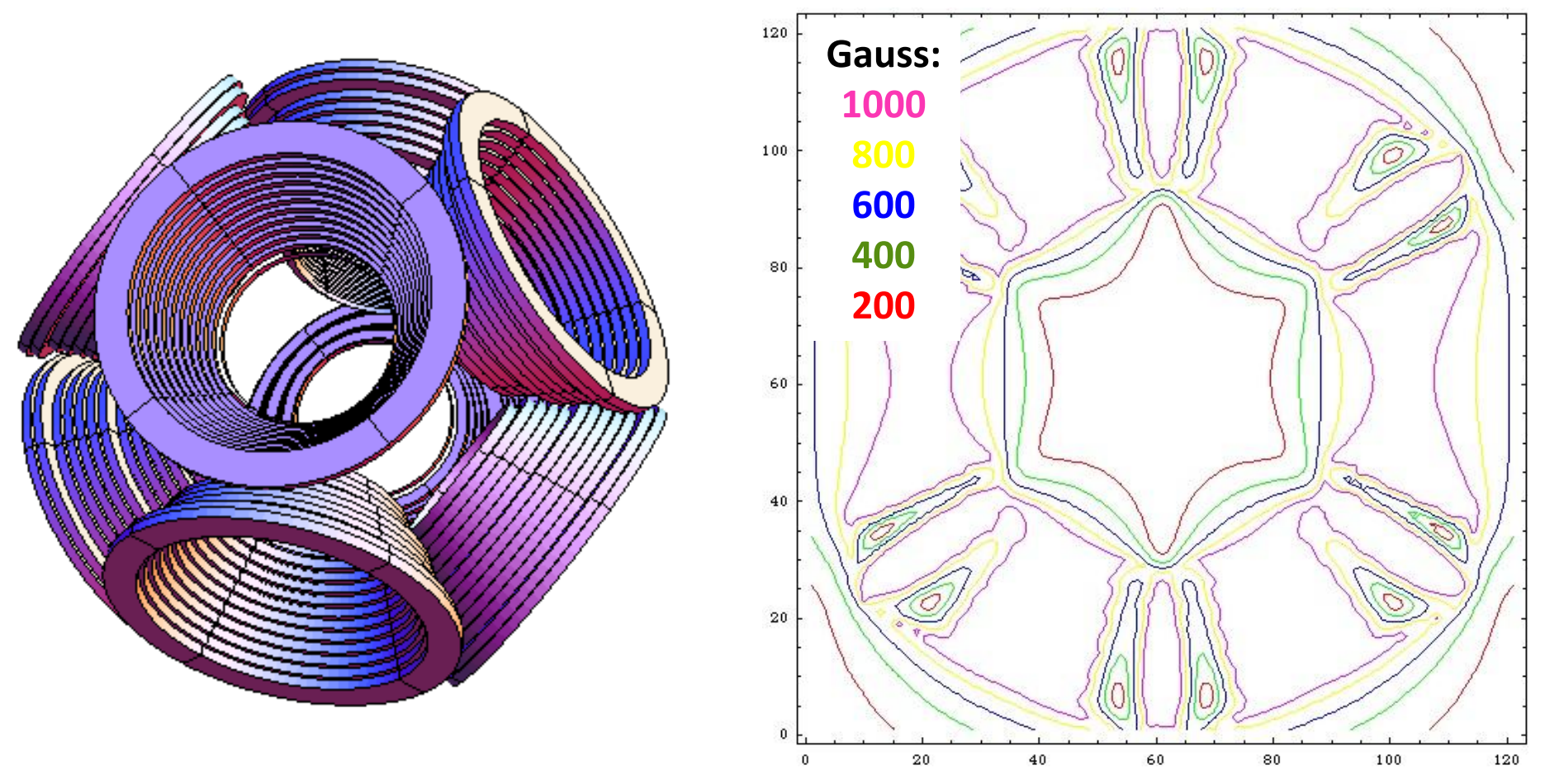

Fig. 6: Left: Arrangement of MIX coils (all coils same polarity). Right: B-mod surfaces on cross-section containing plane of ion beam

The temperature in each hemisphere was implicitly monitored via the total resistance in each half of the magnet; any deviation from expected values resulted in shut down and alert. At full power and in steady state, MIX magnet operated near the limits of safety (insulation temp > 100° C).

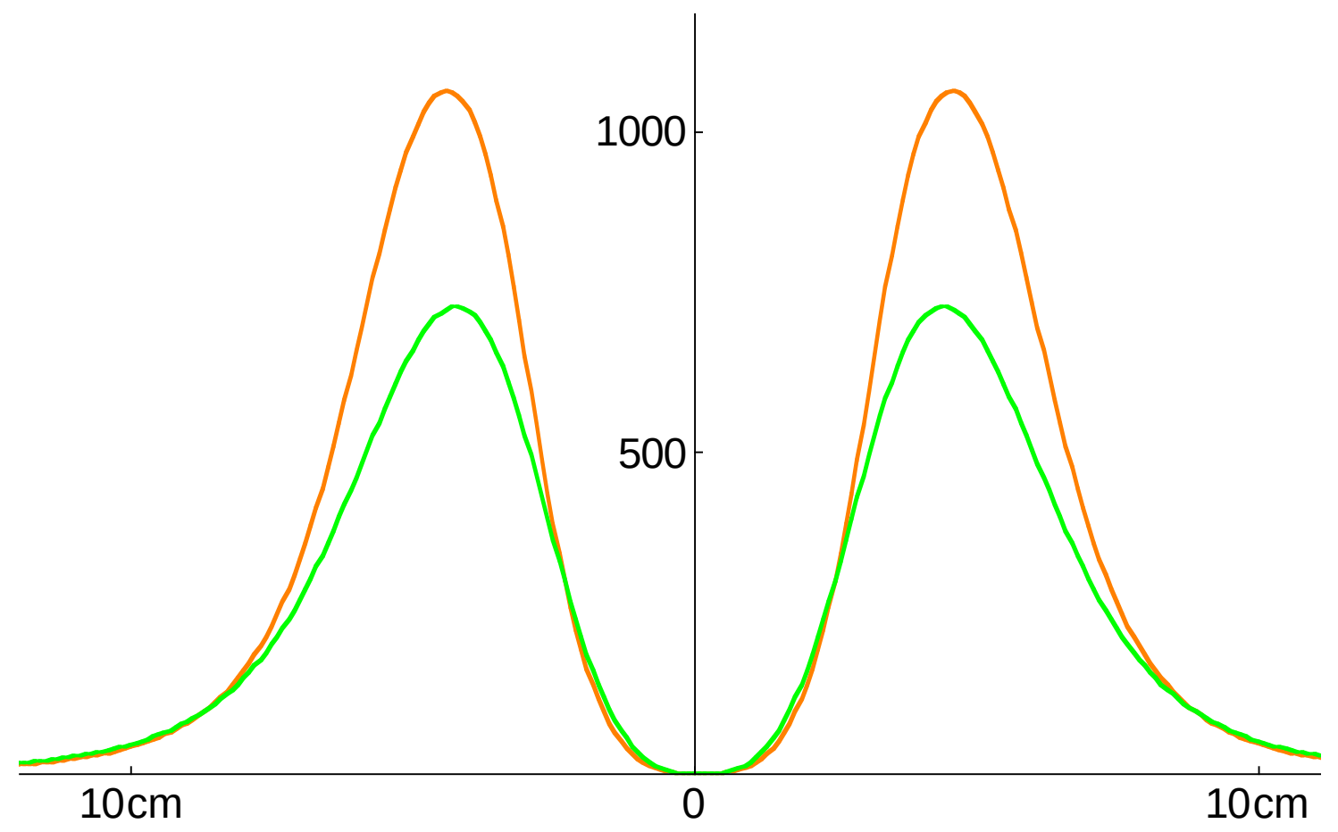

Fig. 7: Magnetic field strength along ion beam axis (red) and diagnostics axis

Ion Sources

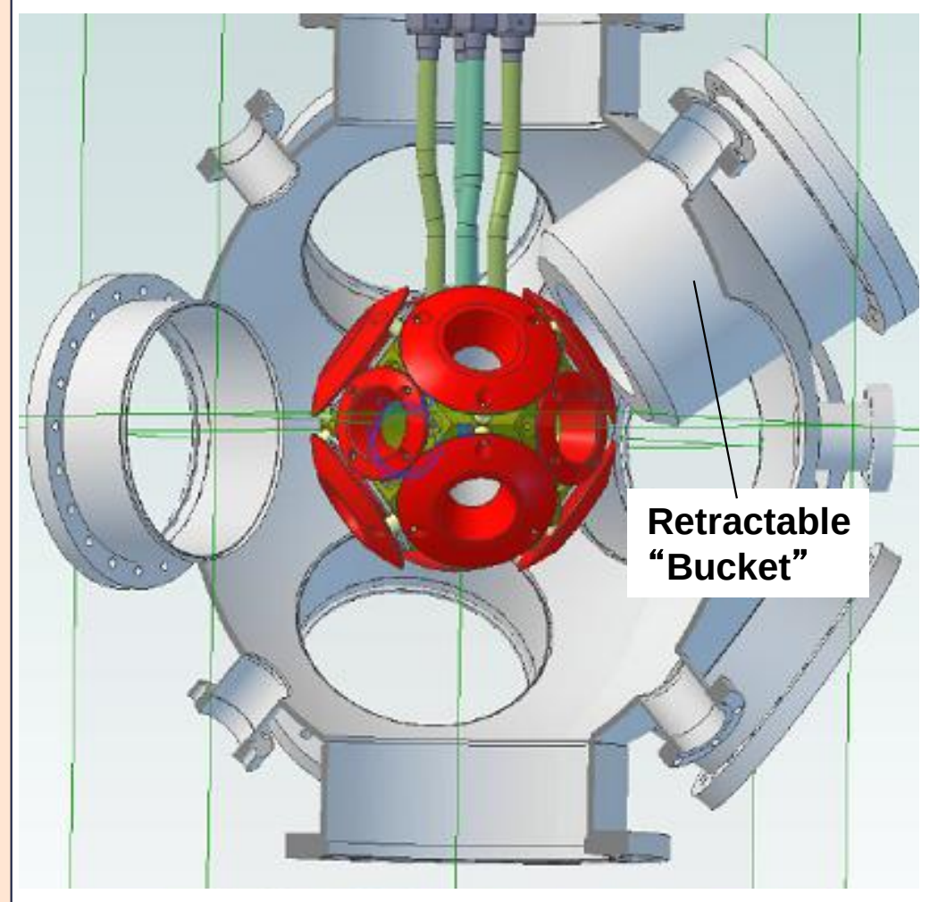

Fig. 8: Adjustable ion source design

The choice of ion source and the details of the electrodes near the ion turning points turned out to be the most crucial aspect to the MIX experiment, and the source of most of the difficulties encountered.

The MIX chamber incorporated moveable "buckets", which allowed adjustments to the ion source and reflector positions and distances with respect to the magnet.

Such a design presented problems when we discovered that precise alignment of all electrode components was crucial, irrespective of the type of source used.

Three different ion sources were tried with the MIX device:

A) Duoplasmatron: this type of source is a very old design yet remains somewhat of a black art. When operated at design points, the source produces intense ion beam which must be matched to the environment, i.e. the acceleration stage. The source is not very controllable (either "on" or "off"), and returning ions are faced with a turning potential surface which is substantially different from vacuum, and not at all uniform due to the brightness of the source. Therefore, we found this source to be unsuitable to serve as an external ion source in IEC devices.

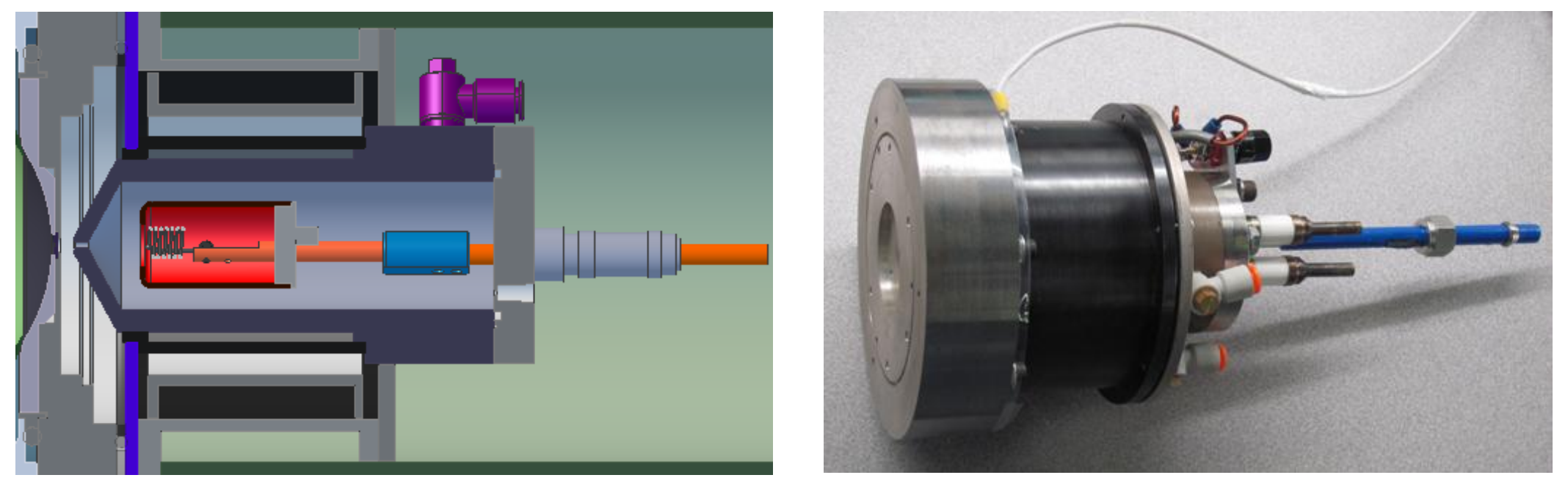

Fig. 9: Duoplasmatron engineering drawing and on the bench

B) ECR ion source: a microwave ion source presents a large area peppered with apertures, providing an array of ion beamlets. It is very robust (being filamentless) and controllable, the ion current is reproducibly determined by the combination of pressure in the source and microwave power. The ionization efficiency is not as impressive as that of the duoplasmatron, so that for increased ion current the chamber neutral pressure is raised. We were able to produce 0.2 mA of ion current while keeping the neutral pressure in the recirculation regime ($P<10^{-5}$ Torr). However, the ECR source also failed to facilitate measurable recirculations - due to the fact that it creates ions that lie outside of the trapping phase space.

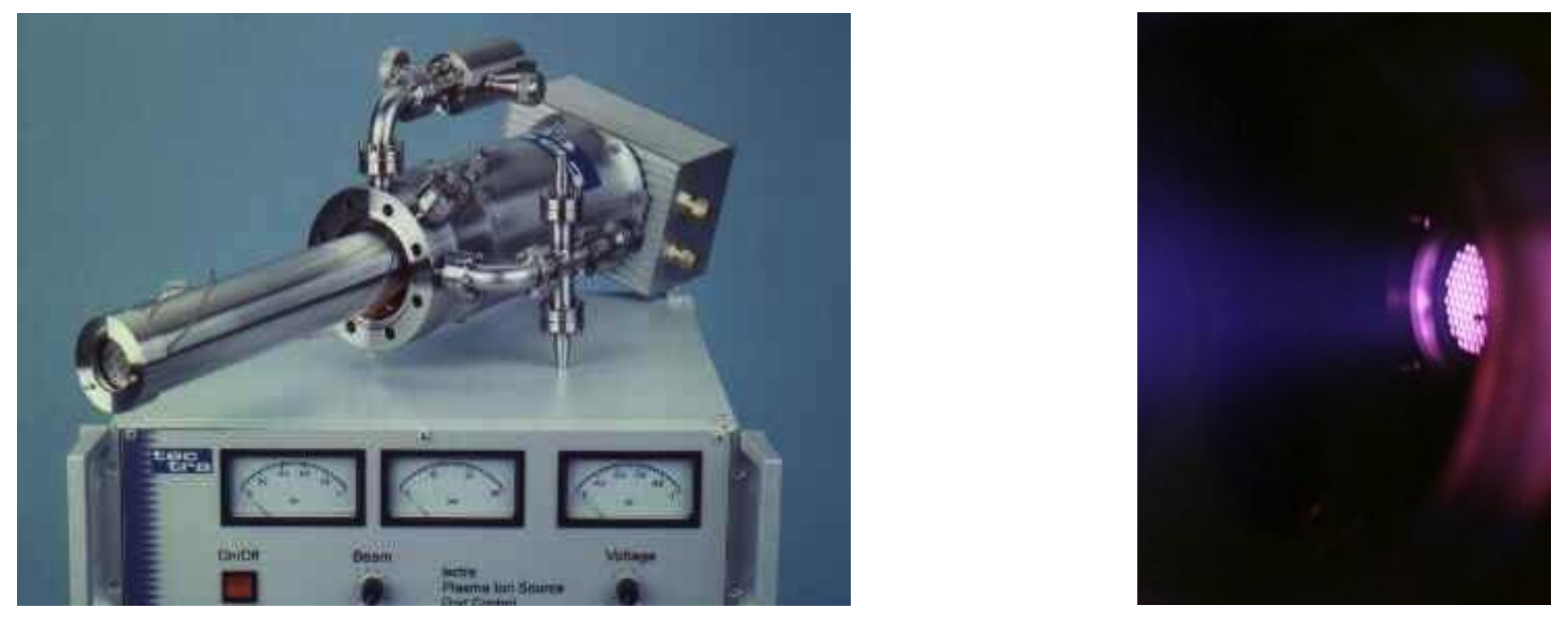

Fig. 10: Left: ECR ion source and power supply on bench. Right: Front end of ion source during operation

C) Integrated PIG source: this source was incorporated into the MIX ion trap by creating an ionization region within the trapping phase space (ion turning points were located in the source). This is the only way to achieve recirculating ion currents, but the drawback is that substantial neutral gas densities in the beam paths are required to achieve macroscopic ionization rates.

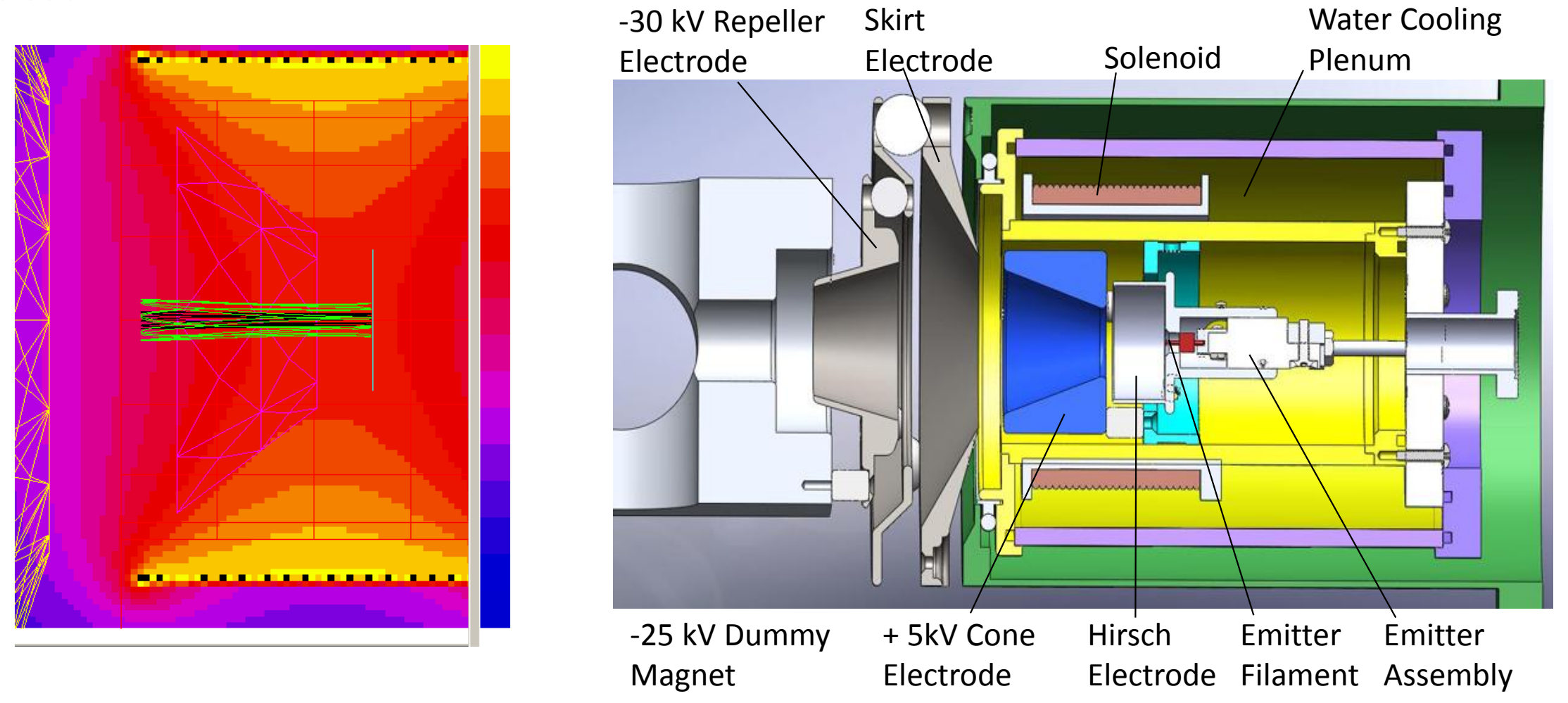

Fig. 11: Left: Electron orbit modeling for ionization design in PIG source. Right: Engineering drawing. Beam ion turning points lie within the source

Diagnostics

A highly ambitious suite of diagnostics was planned for the MIX experiment. Many of these systems were not used before the experiment shut down, but the majority of them were built and assembled. The design of the major diagnostics systems is presented here for edification.

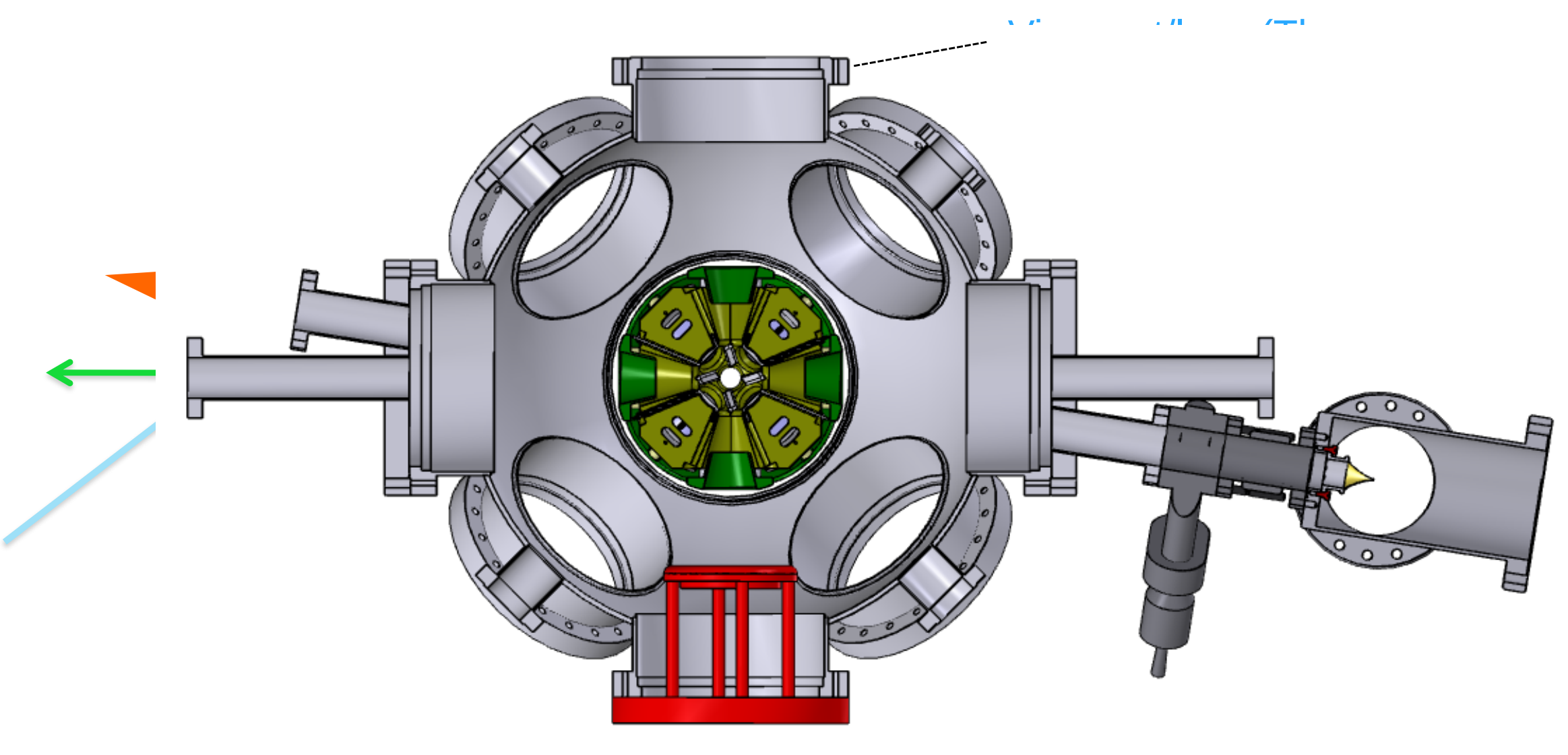

Fig. 12: Layout of major diagnostics systems on MIX device. Included: Multipoint Thomson Scattering, Charge Exchange Spectroscopy, Fusion Ion Doppler Analysis, Charged Particle phosphor screen detection, Recombination Spectroscopy.

Major Diagnostics:

A.Multipoint Thomson Scattering: a 600 mJ YAG (freq. doubled, 530 nm) laser fires 3 ns pulses through the core at 50 Hz. The core is imaged onto a large (⃠8", antireflection coated) collection lens, then onto 10 large diameter fiber optic cables. Each cable receives light from a 3x3 mm core region. High throughput (Holospec, f1.4) imaging spectrometer creates 2D image (wavelength vs. position), recorded by photon counting ICCD camera (Andor, 2nsec gate, integrating). With calibration, can measure local electron densities and temperatures in the MIX core. System was never used, components cost $100k.

B.Charge Exchange Spectrometer: Separate vacuum chamber holds fast gas puff valve (20 microsecond pulses, 50 Hz) and skimmer, to create collimated super-sonic helium gas plug flying through MIX core. The same optical and detection system as in (A) is used to look at doppler shifted emissions from fast (up to 100 kV) charge exchanged-deuterium. Measures temperature of ion beams, and with calibration also density of ion beams. System was never used, component cost $35k (without optics).

C.Conductive phosphor screens produce light when impacted by charged particles. Modulation of potential of special ion reflector (permeated with holes) reveals ion beam profiles. Modulation of special electron repeller reveals information about confined electron cloud in MIX.

D.Fusion ion energy analyzer (FIDO): identical to Madison's FIDO diagnostic, bends MeV charged particles emanating from the core into energy analyzer (silicon detector with MCA) with powerful electromagnet (1.2 Tesla). Allows measurement of ion densities indirectly from fusion rates, and distinguishes between beam-beam vs. beam-background fusion events. Also reveals ratio of core fusion rates vs. total fusion rate. System was never used, component cost $35k.

E.Visible light imaging camera: looking at the MIX core in the presence of small amounts of background gas, with an integrating CCD camera at maximum gain can reveal the ion beam profile as it traverses the core (looking for hollow beams, alignment issues, etc).

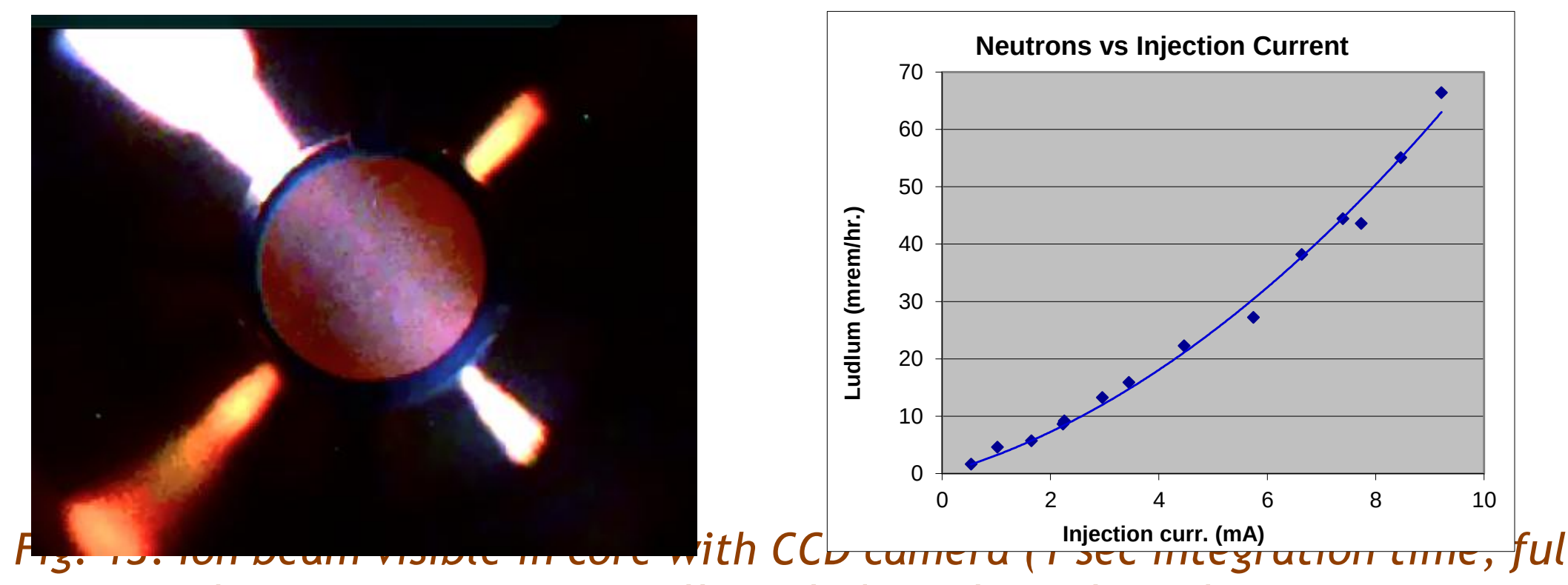

Fig. 13: Ion beam visible in core with CCD camera (1 sec integration time, full gain). Right: Neutron rates initially scaled non-linearly with injection current

Status

All components of the MIX experiment are neatly packed and en route to the University of Maryland, to the Lab of Prof. Raymond Sedwick.