Simulations of ionisation vacuum gauges

Measurements of ultra- and extreme-high vacua

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Going towards extreme high vacuum, we need better gauges

10^{-8} mbar to 10^{-12} mbar	In ultra-high vacuum range only ionisation gauges can be used, like SVT
below 10^{-12} mbar	In extreme-high vacuum region we need another gauge

Simulations of ionisation vacuum gauges

Outline

Ionisation gauges measure density of molecules which is proportional to pressure

$P \sim \frac{NT}{V}$
$N \sim I_+$

- Pressure is proportional to density of molecules

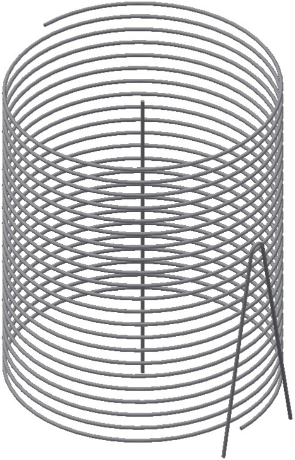
$P \sim I_+$

- Molecules are ionised and collected — flow of ions, *current* is measured

OPERA 3D with SCALA module enables us to simulate ionisation gauges

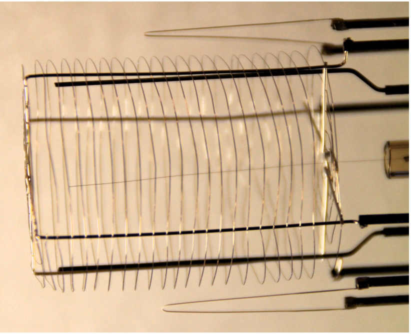
- We can input complex geometry
  Such as small parts of gauge geometry
- We can trace charged particles
  And hence calculate currents
- We can see space charge effects
  This has not been done before

Hot cathode ionisation gauge stems from triode geometry



- Hot filament is external to grid
  Emits electrons, 50 V
- Helical grid accelerates electrons
  They ionise gas, 150 V
- Central ion collector is very thin
  Collects ionised molecules, 0 V

When testing a real gauge, we measure currents



- Emission current
- Collector current
- Current flowing to grid

Electrostatic space charge simulation requires numerous steps

1. First, geometry must form union and be meshed because OPERA uses finite element method
2. Second, electric potential is calculated using boundaries; in all nodes of the mesh
3. Third, trajectories are calculated and ionised particles emitted
4. Fourth, space charge is calculated and if necessary we go back to step 2

Ionisation cross section depends on electron energy, it determines ionisation probability

Ionisation cross section σ is different for various gases, that is why sensitivity depends on gas.

$N_{+} \sim I_{+} \sim \sigma(E_{el})$

Simulation runs for fixed pressure but ionisation cross section is implemented.

Cross section was implemented in two ways:

- Approach 1: H2, N2 Theoretical model for cross section was used
- Approach 2: Ar Experimental data of cross section was analytically fitted

Sensitivity and ion collection efficiency depend on gauge's geometry

Sensitivity tells us how many ions will be collected for given emission current and pressure

$$I_c = SI_eP$$

Inversely, knowing sensitivity and ion collector current, one can calculate pressure.

Ion collection efficiency tells us, how many ions, from all ions produced, will be collected:

$$\eta = \frac{I_c}{I_+}$$

Residual pressure (current) is caused by limiting processes

X-ray and ESD ions are produced when electrons hit the grid.

Soft X-ray:
grid
↓
x-ray
↓
collector
↓
photoelectrons
positive current

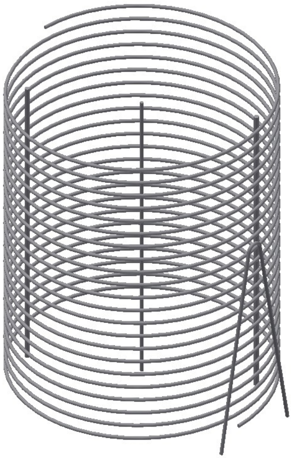
Three sources of residual current:

- Soft x-ray
- Reverse x-ray
- Electron-stimulated-desorption ions

They limit the lowest measurable pressure.
They are not simulated in this work.

Modulation allows determining residual pressure

Modulated BAG

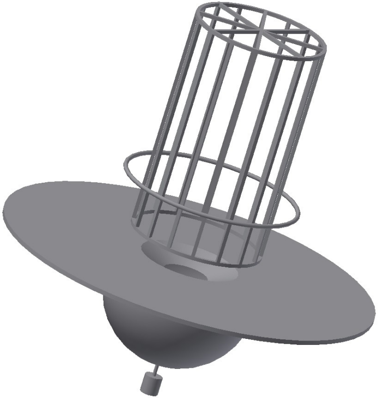


Modulators are two rods inside the grid, which can be at 0 V or 150 V potential.

- In normal operation (150 V) they are almost invisible.
- In modulation mode (0 V) they collect ions.
- Modulation factor $K = 1 - \frac{I_c^M}{I_c}$ allows determination of residual. It describes proportion between collector current in two modes.

Hiding collector reduces X-ray current

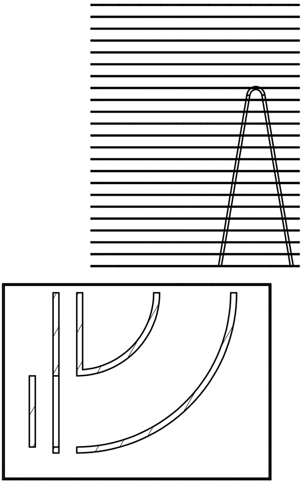
Extractor gauge



- Shielding plate is grounded
- Spherical reflector is at ground potential
- ion collector is hidden below the plate

Bent-beam gauges are most promising extreme-high vacuum gauges

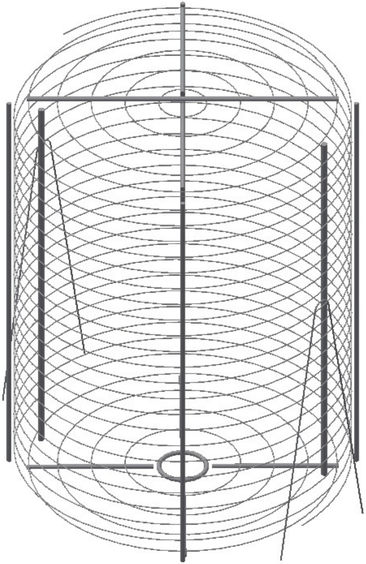
Helmer gauge



- Upper part resembles BAG
- Extracts and bends ion beam
- Reduced residual pressure

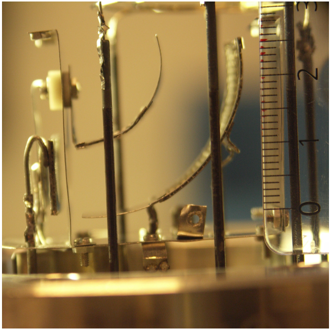
Outline

Technical documentation of SVT enabled me to build a precise model of the gauge



- Grid supports are built
- Grid is a helix
- All tiny dimensions are exact

To build the model of the Helmer gauge, dimensions were taken from photographs



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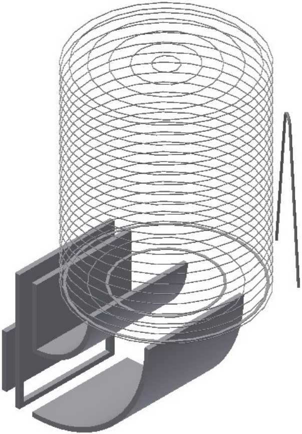
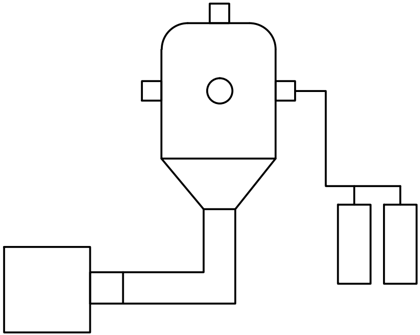


Extreme-high vacuum stand was designed in order to test gauges



4 gauges can be tested

We inject gases dynamically

NEG strips in the dome

Ultimate pressure:
1×10^{-12} mbar
Pressure reading: Leybold extractor gauge

Outline

Complete series of SVT simulation comprises. . .

One geometric model

Two modes of operation
- Normal operation and modulation

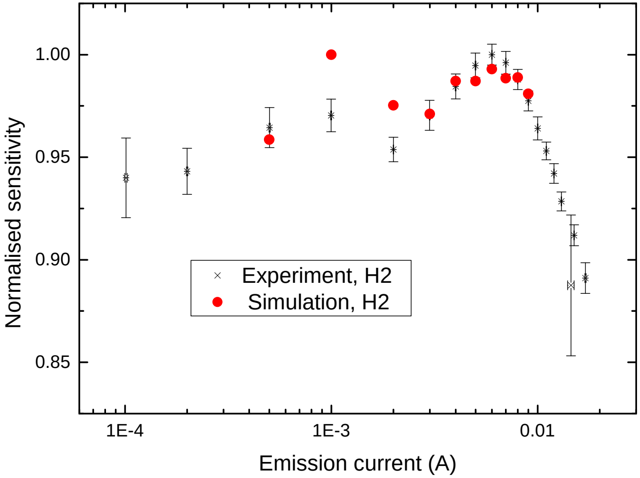
Three gases
- Hydrogen, nitrogen and argon

Compared to data from calibration, simulation gives similar (a bit higher) results

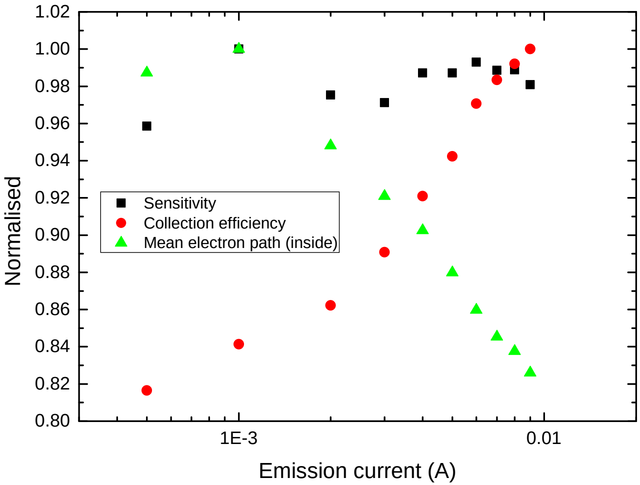
H_2	[11.5, 15.5]	$15.5\,\text{mbar}^{-1}$
N_2	[26, 34]	$38\,\text{mbar}^{-1}$
Ar	[36, 44]	$45\,\text{mbar}^{-1}$

All modulation factors are within experimental range, typically [0.85, 0.90], simulated 0.85.

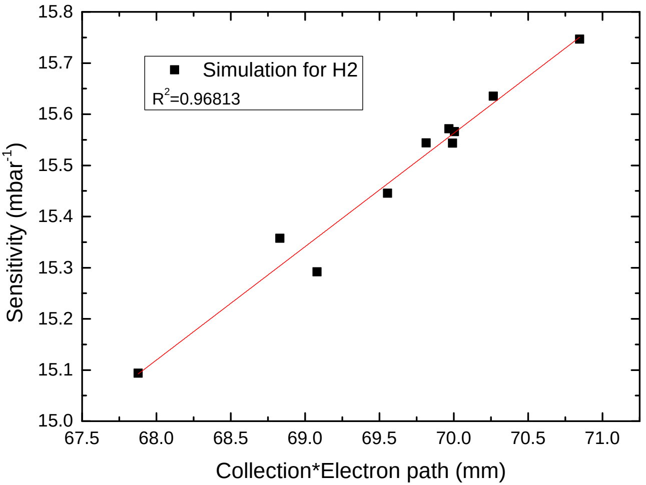
Simulated sensitivity profile matches experimental curve



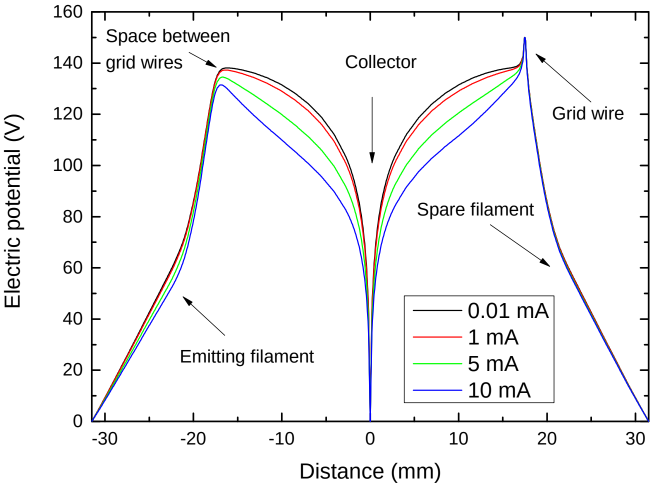
Sensitivity is fairly constant below 10 mA but this is complex phenomena



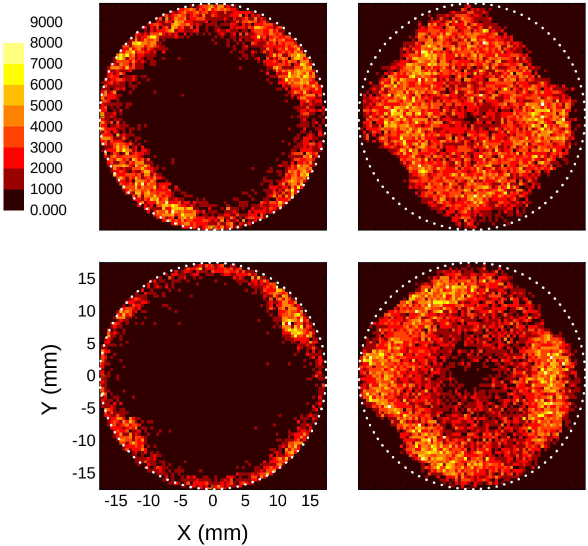
Product of collection efficiency mean path of electrons correlates with sensitivity



Space charge enhances collection efficiency by reducing electric potential



Lost ions are created in the region of higher potential

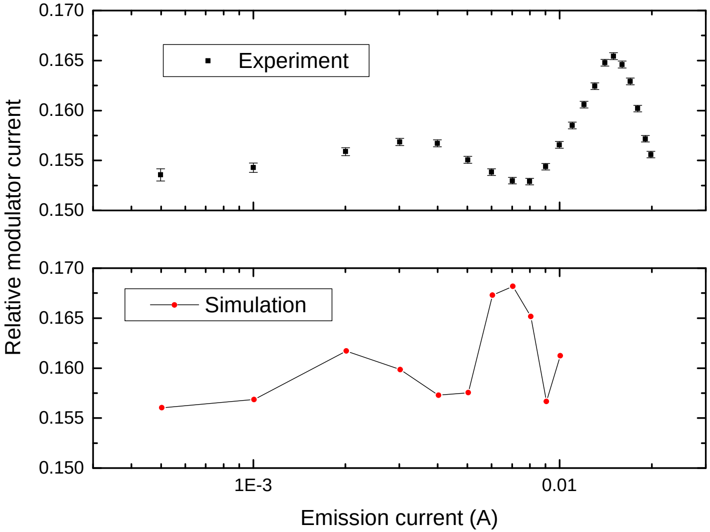


Oscillations of ions contribute to long computation time

Path length of particles has exponential distribution.

- Electrons make on average 4 turns
  - Before they impinge on the grid
  - Their average path is about 150 mm
  - Only path inside the grid is useful.
- Ions oscillate more than electrons
  - About 50 turns — above 1 m
  - Collected ions oscillate more than repelled.
  - In modulation mode path is much shorter.

About 16% of emitted electrons impinge on modulators in normal mode; simulation can trace such fine effects



Simulation provides tools for analysing different aspects of the gauge

- Gauge can be easily improved by changing modulator potential (and filament position).
- Space charge affects operation from about 4 mA.
  Gauge operation is not stable — should be avoided.
- Good coherence has been found but some effects are distorted or gauge dependent.

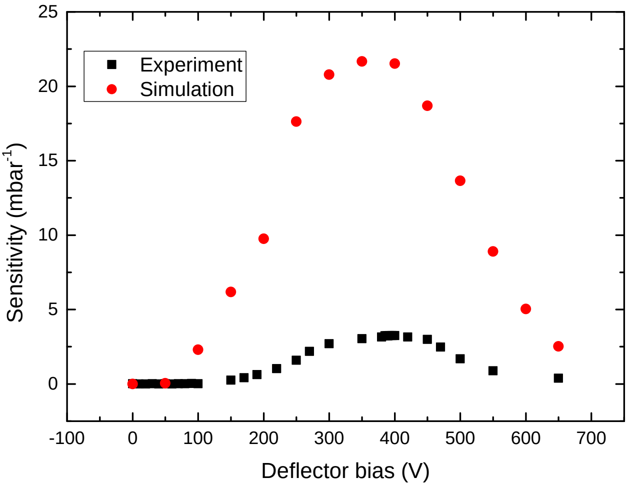
Roadmap for the Helmer optimisation

Clear goal: optimise improved Helmer gauge mentioned in Benvenuti's paper.

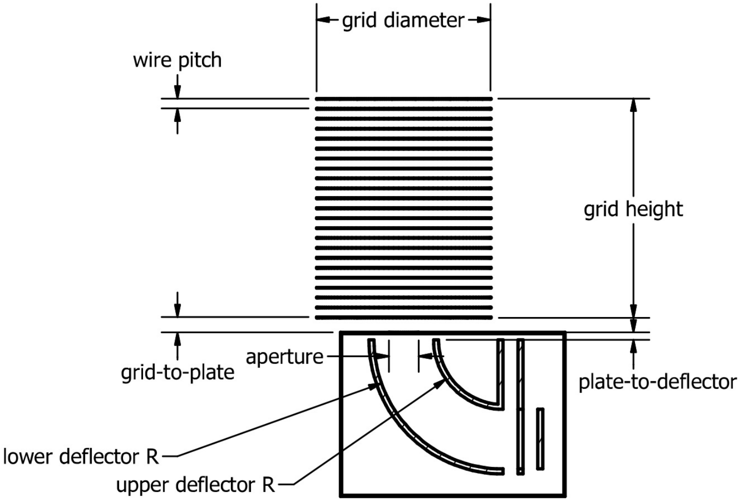
Starting point: 2 Helmer gauge prototypes, technical drawings, and the article. Archived technical note.

Result: two proposed designs, one resembling initial gauge, one suggesting fusion with extractor.

Model is valid: sensitivity profiles are coherent when changing deflector bias



If we simulated all combinations, 5 dimensions each, we would get $5^8 = 390625$ simulations. It needs to be simplified



Boundaries for geometry are crucial for design

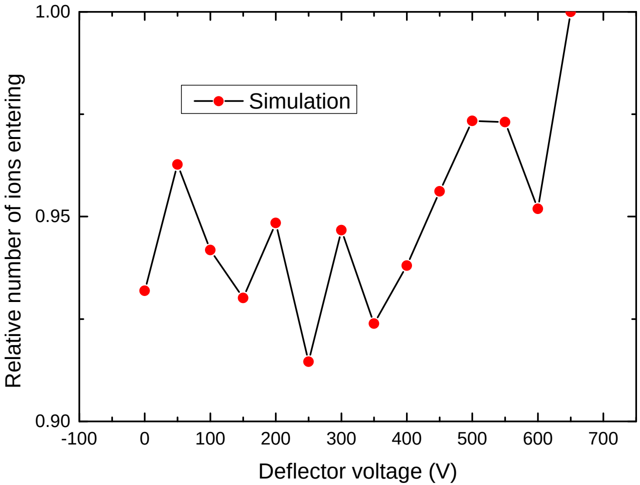
Gauge mounting geometry: 63 mm diameter
  This is a technical limit

Cage aperture should be 6 mm or lower
  To push down X-ray limit

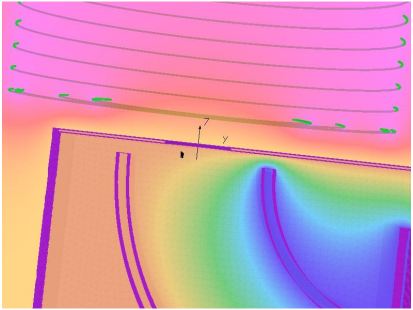
Deflectors should be co-cylindrical and 90° arcs

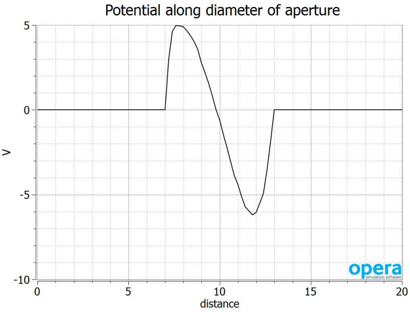
All shapes should be maintained
  For simplicity of manufacturing

Deflector potential does not affect number of ions entering the cage

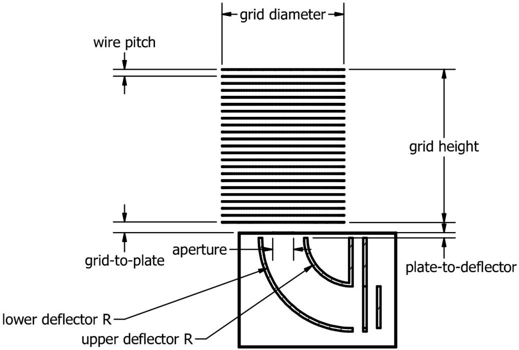


And the potential at the aperture can be approximated with cage potential:
a solid plate can be used instead!





Each part was optimised in relation to initial optimisation

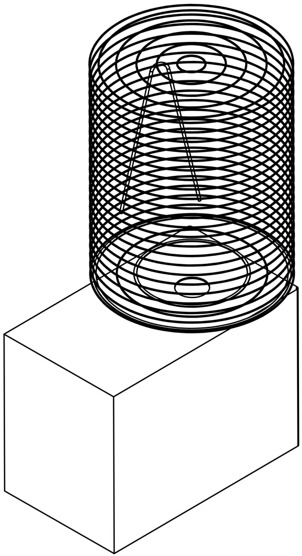


First, I changed deflectors dimensions.

Tested gauge seems to be optimal but deflectors.

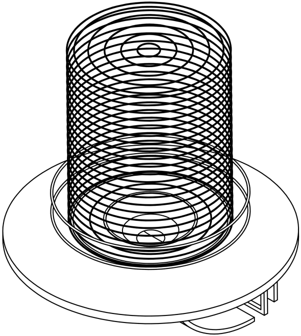
Design stems from optimised SVT design.

Improved model performs much better



- Sensitivity: 28 mbar^{-1} Ar compared to prototype: 22 mbar^{-1}
- 25 % of entering ions impinge on deflectors they can be improved
- Worse than in paper: suppressor is not simulated

If we can change shape of parts, we gain much more



- Sensitivity: $41.5\,\text{mbar}^{-1}$ Ar Only about 15 percent of extracted ions are lost
- Further fusion of extractor-type geometry with Helmer geometry is very promising.

Further research on the Helmer gauge should be done: both experimental and using simulations

If boundaries for design are clearly defined

A more precise simulation can be set up

Experimental study of limiting effects can result

Helmer gauge is not the only (and maybe not the best) XHV gauge. Other gauges may be of interest, too, like: (1) other types of bend beam gauges and (2) modern-technology gauges (laser-based).

Estimating simulation errors is almost impossible

Geometry cannot be reproduced accurately

Results of simulation depend on mesh size

This we cannot decrease infinitely

We use finite number of trajectories

We can successfully simulate vacuum gauges with OPERA, but it is not our dream-tool

Two approaches are especially relevant:

- building an accurate model and studying it extensively
  It requires lot of patience and computational power
- Simplifying model as far as possible
  It allows to modify model easily but errors are significant

Based on *finite element method*, OPERA is not fully suitable for simulations of vacuum gauges but it is best available solution.

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