Penning discharge in the KATRIN pre-spectrometer

F. Glück, KIT IKP,
for the KATRIN collaboration

Strong Penning discharge
(large pressure and leakage current increase, electric breakdown, lot of information in literature)

Weak Penning discharge
(observable only by detector, little information in literature)

KATRIN Karlsruhe Tritium Neutrino Experiment

bmb+f - Förderschwerpunkt Astroteilchenphysik Großgeräte der physikalischen Grundlagenforschung

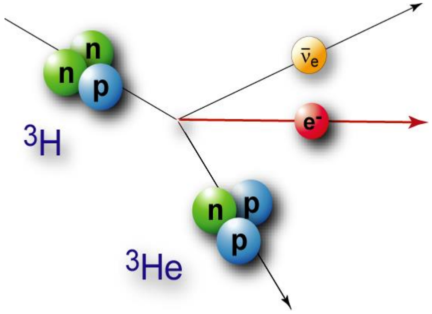
KIT Karlsruhe Institute of Technology

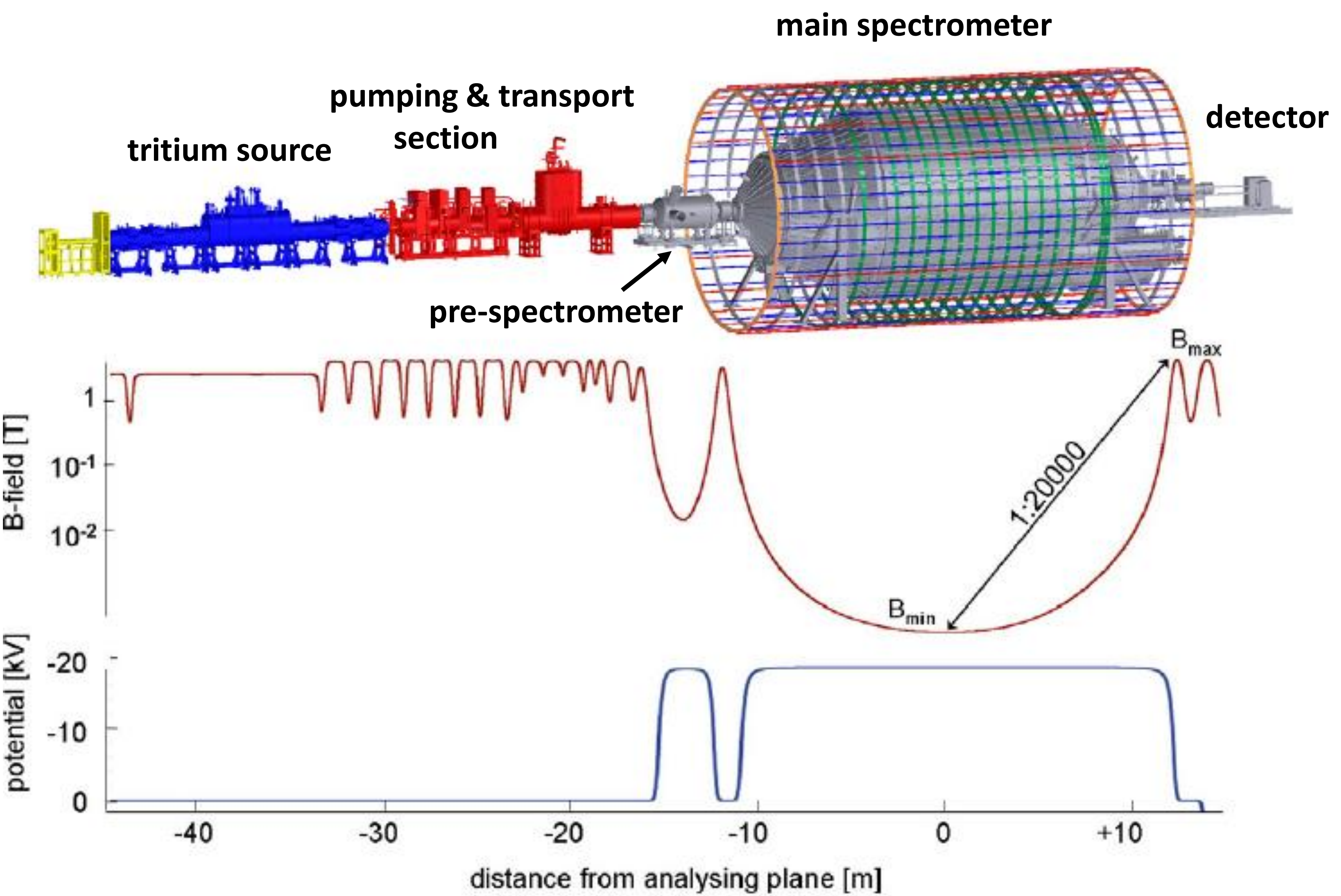
KATRIN experiment

Absolute neutrino mass scale determination down to 0.2 eV, with small model dependence.

Integral electron energy spectrum measurement (MAC-E filter method), close to endpoint of molecular tritium beta decay.

^{3}H: super-allowed	
E_0	18.6 keV
$t_{1/2}$	12.3 y

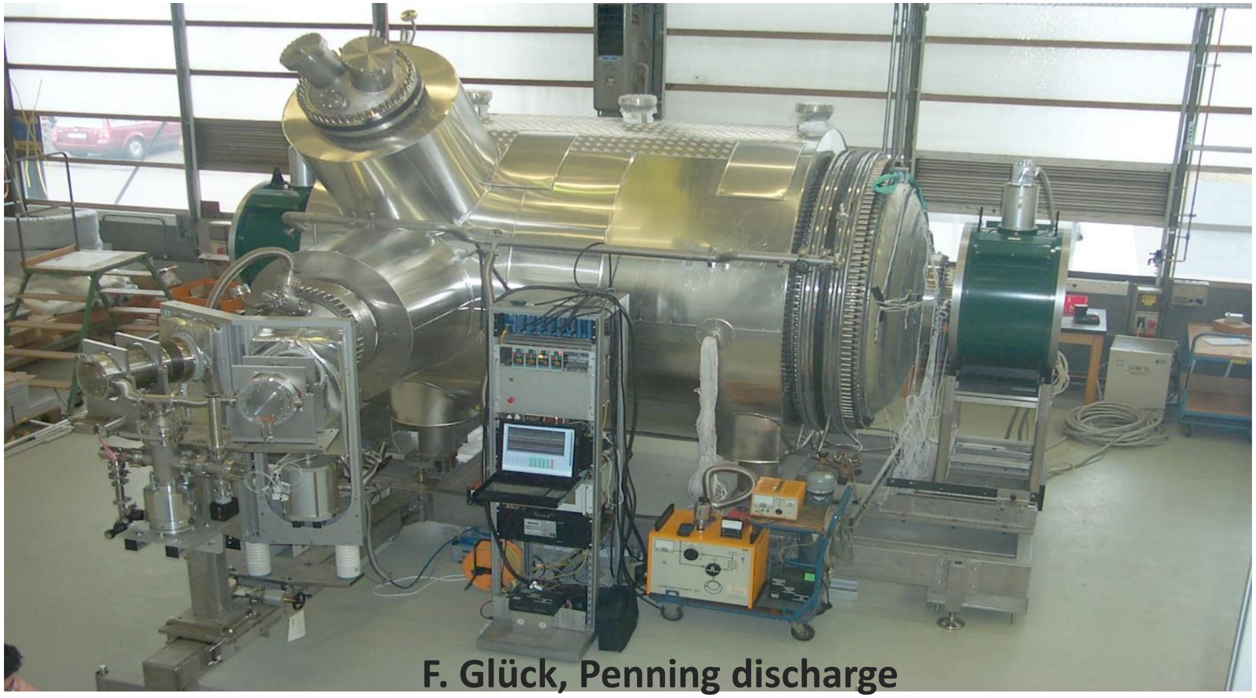


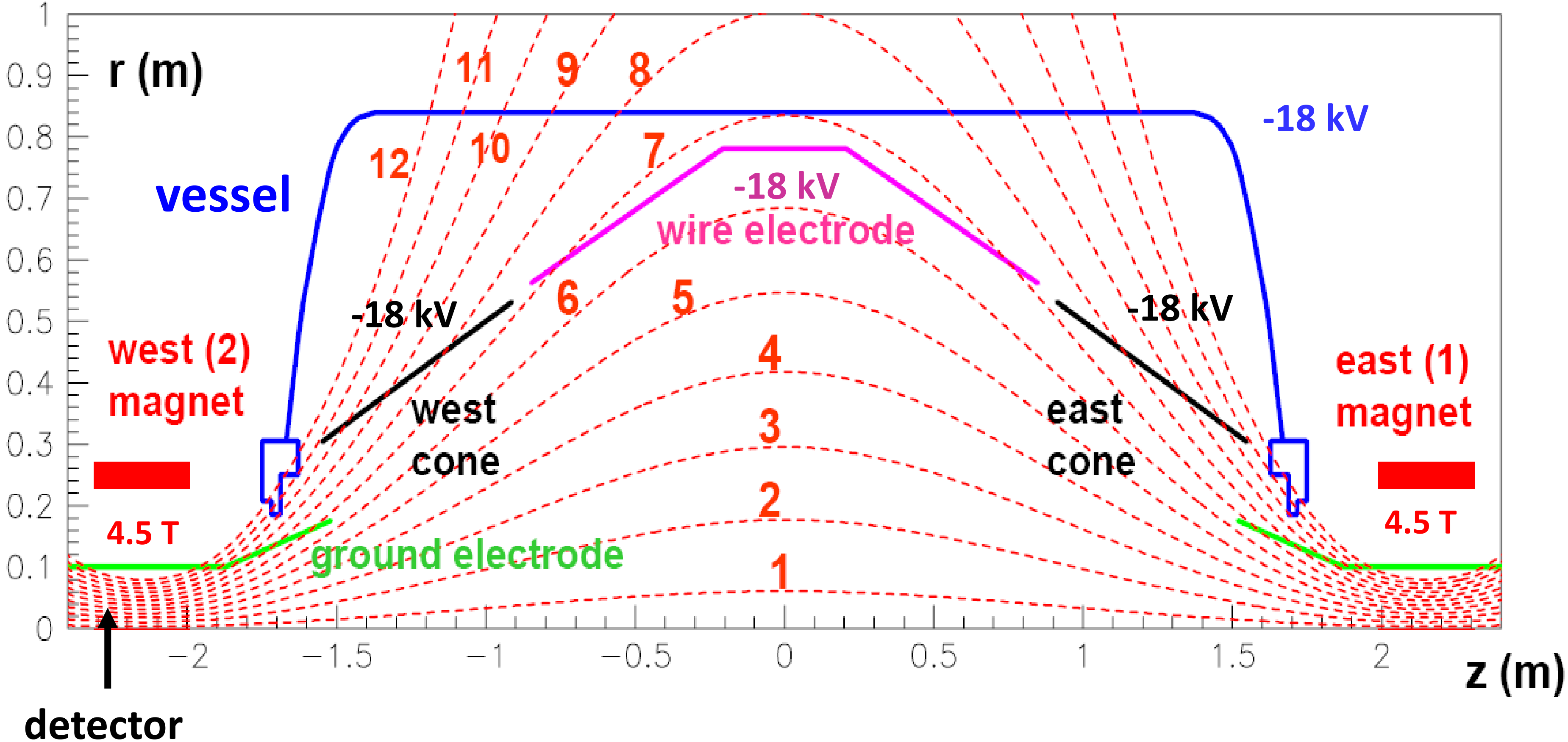

main spectrometer
pumping & transport section
tritium source
detector
pre-spectrometer
B-field [T]
1
10-1
10-2
Bmax
Bmin
1:20000
potential [kV]
-20
-10
0
-40
-30
-20
-10
0
+10
distance from analysing plane [m]

KATRIN pre-spectrometer

- **to reduce background due to positive ions created by many beta electrons at the entrance of the main spectrometer**
- **tritium pumping**
- **to get a lot of information that is useful for the main spectrometer design and operation**

Delivered to FZK in Autumn 2003;
Length: 3.4 m, diameter: 1.5 m





Electromagnetic design of KATRIN pre-spectrometer, with magnetic field lines. Electrodes before Sept 2007

First test experiments at KATRIN pre-spectrometer (end of 2006):

Vessel and electrodes at -18 kV, increase of magnetic field; at 0.15 T* field :

- increase of vacuum pressure from 10^{-9} mbar to 10^{-6} mbar (due to sputtering by positive ions)

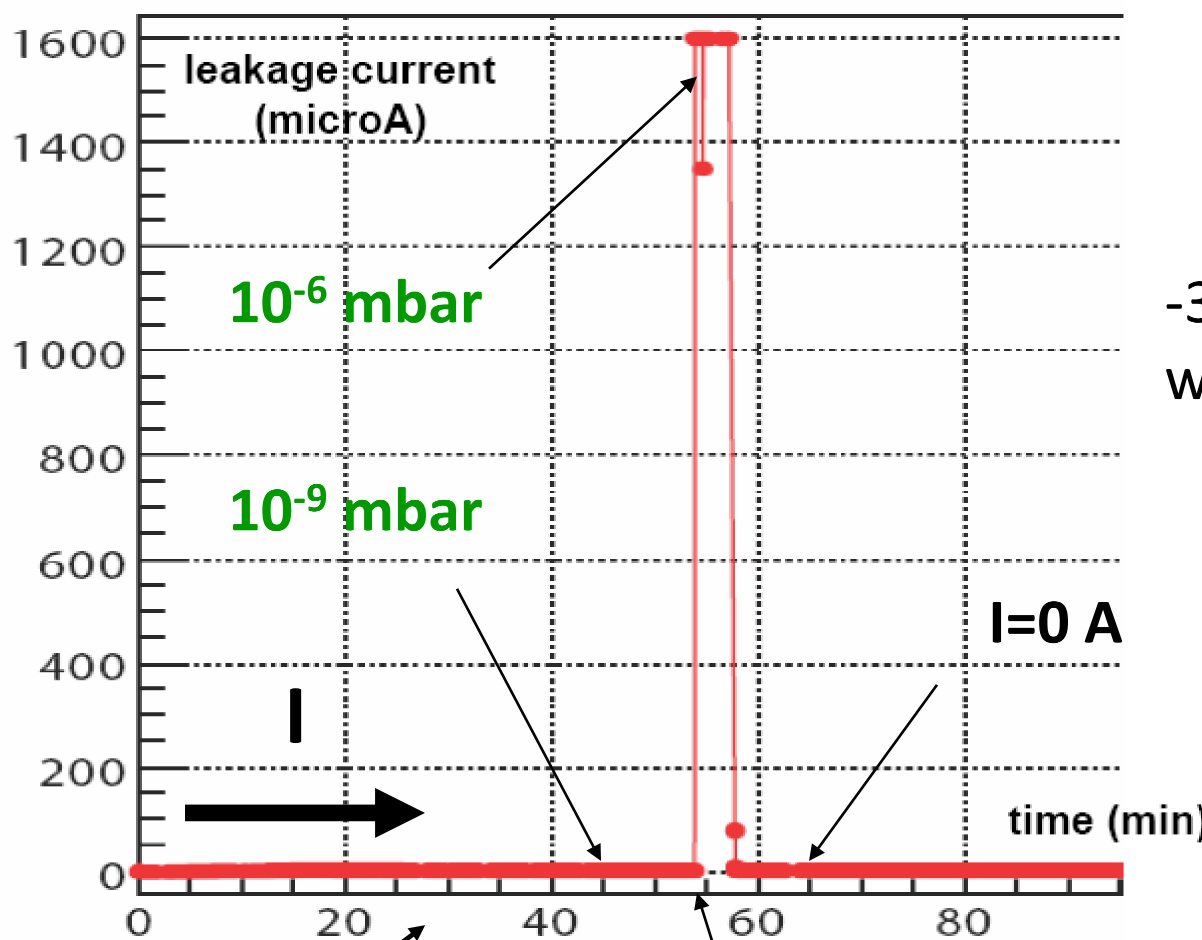
- increase of leakage current from 0.2 μA to mA (small resistance of vacuum with discharge)

- drop of high voltage from -18 kV down to -3 kV (current limit of power supply: 1.6 mA)

* maximal planned field at centre of pre-spectrometer magnets: 4.5 T

Fixed potential, increasing magnetic field: sharp transition to electric breakdown

(equal vessel-wire-cone potential)



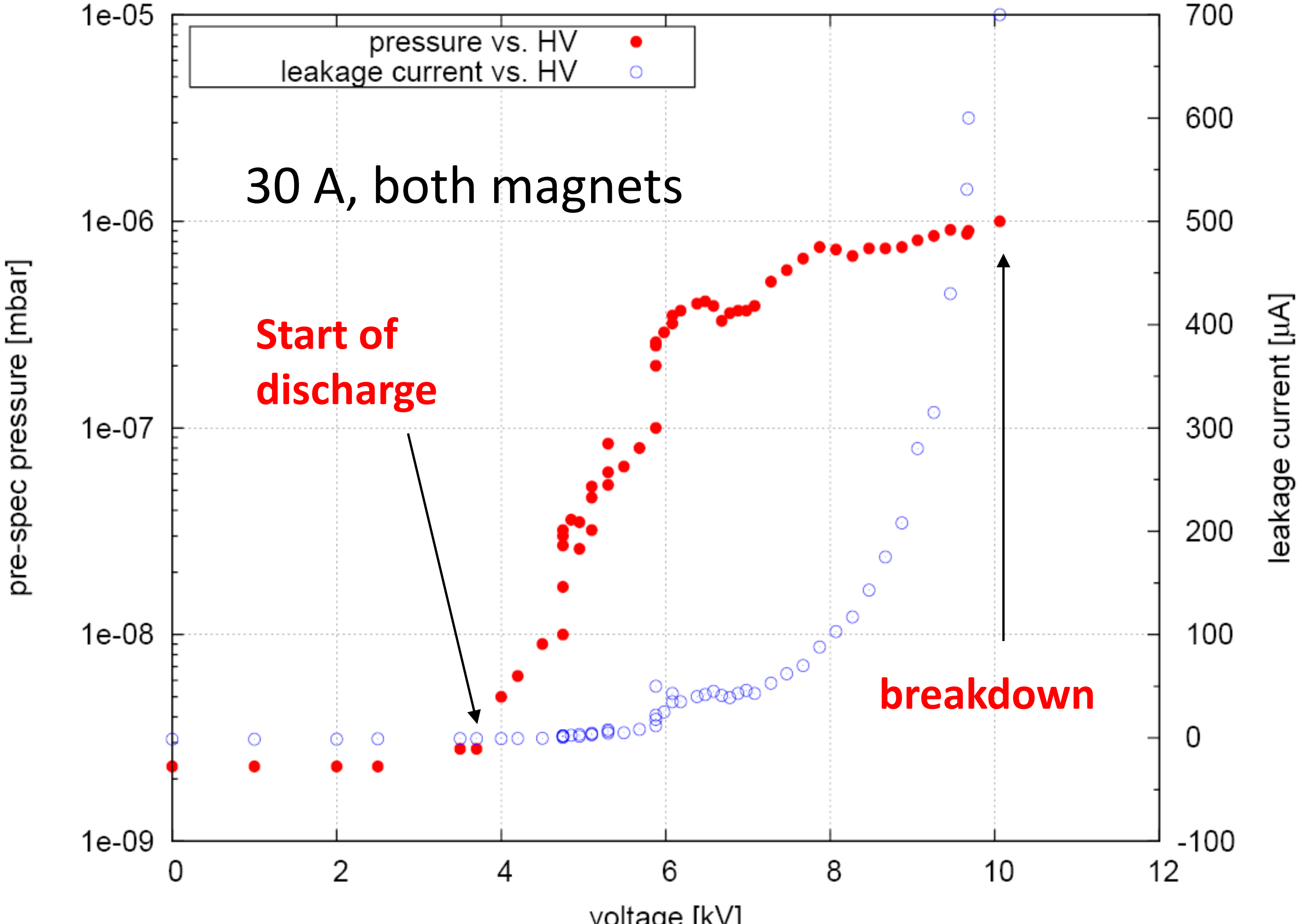
-30 kV,
west magnet

no pressure and leakage current increase until breakdown

B=0.15 T (breakdown)

Fixed magnetic field, increasing potential: continuous transition to electric breakdown

(equal vessel-wire-cone potential)



F. Glück, Penning discharge

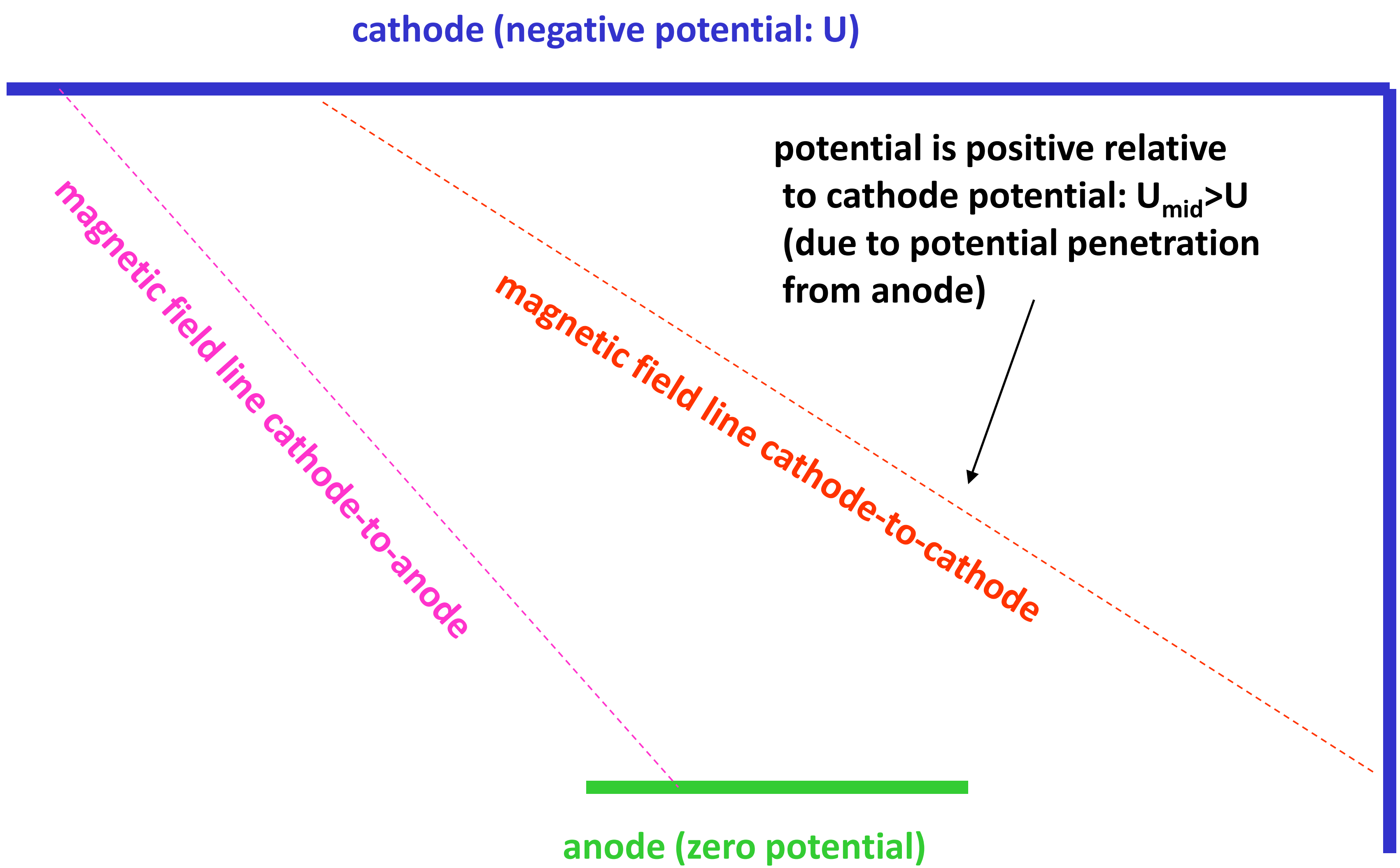
Strong discharge with crossed electric and magnetic field in good vacuum:

Penning discharge

Experience from the literature: Strutt 1913, Penning 1936, Haefer 1952, Tyurykanov et al. 1978, Knauer 1962, Harcombe et al. 1963, Redhead 1958, Smirnitskaya 1969, Arsh et al. 1985, Hara et al. 1989; Byrne 1974, Mainz and Troitsk neutrino mass experiments. Cold cathode vacuum gauges; cold cathode ion sources; ion sputtering; UV lamps

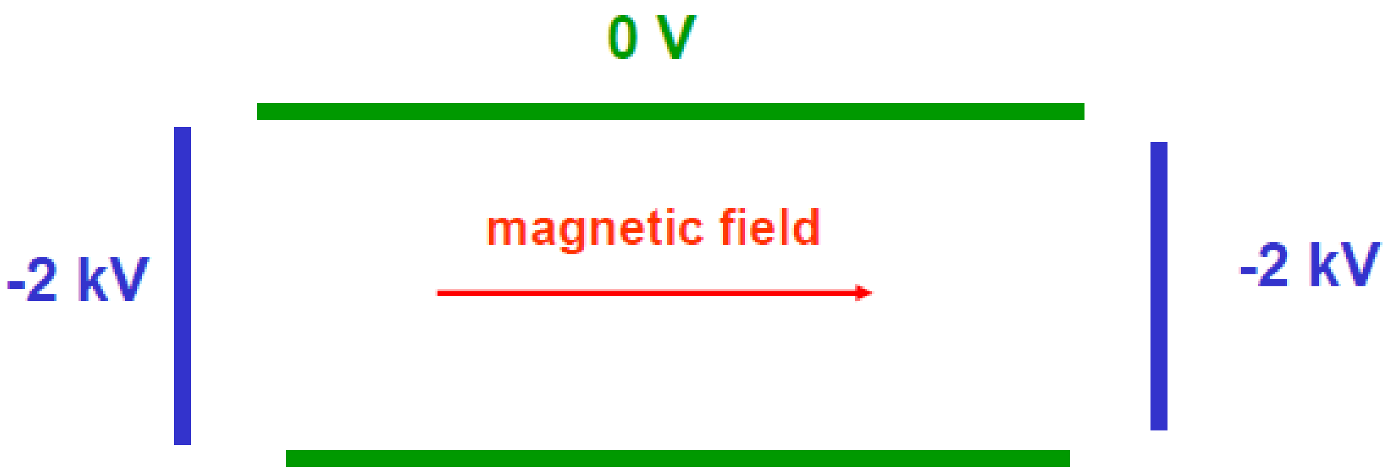
Discharge is caused by Penning traps for electrons !

What is a Penning trap?

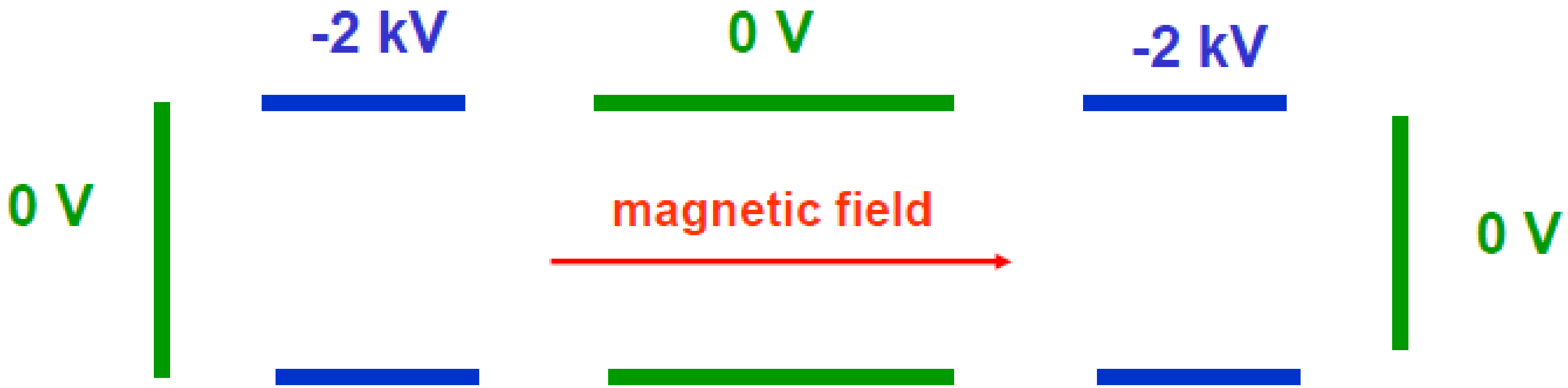


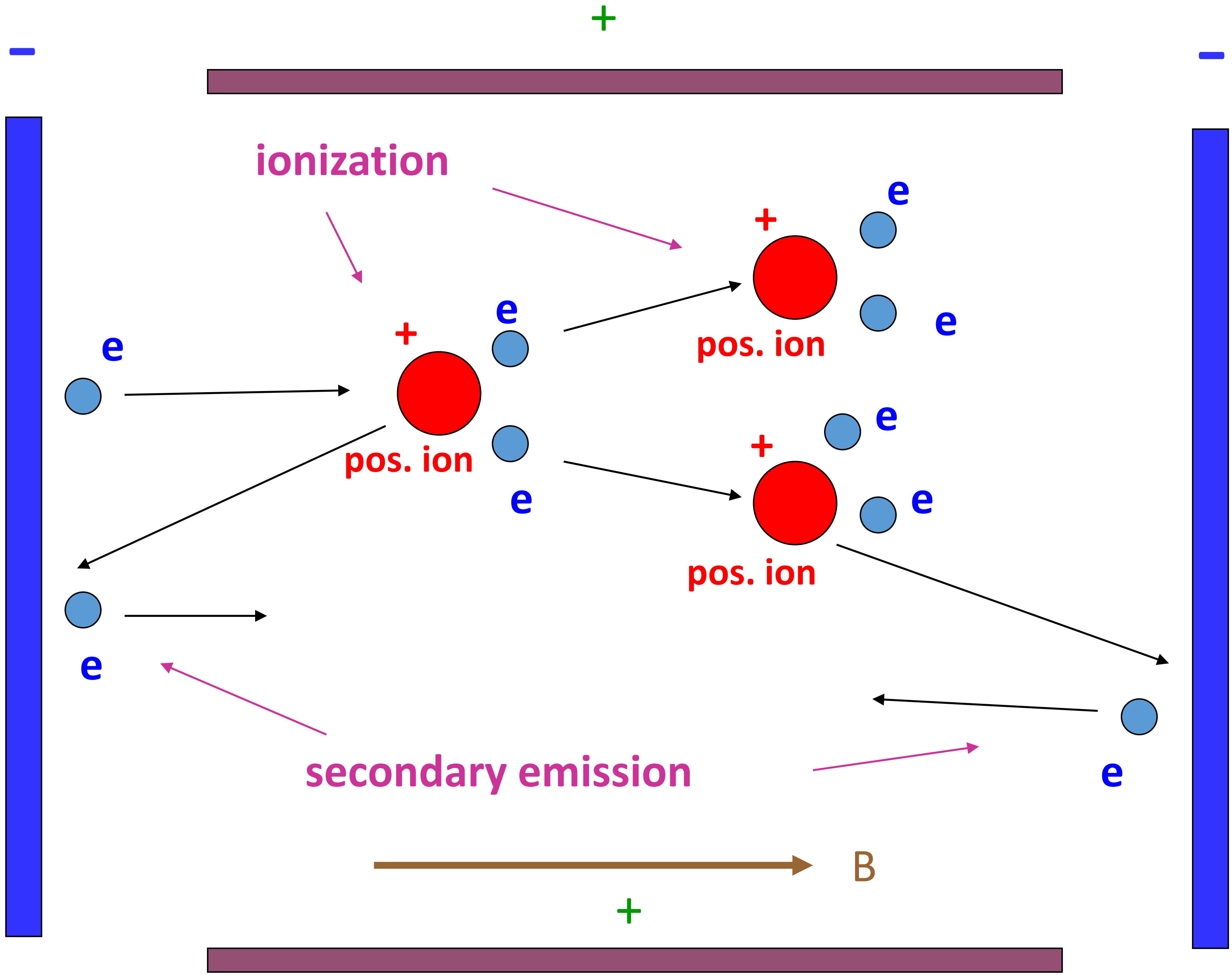
Penning discharge is caused by Penning traps for electrons !

Cathode-to-cathode Penning trap:



Vacuum-to-vacuum Penning trap:





F. Glück, Penning discharge

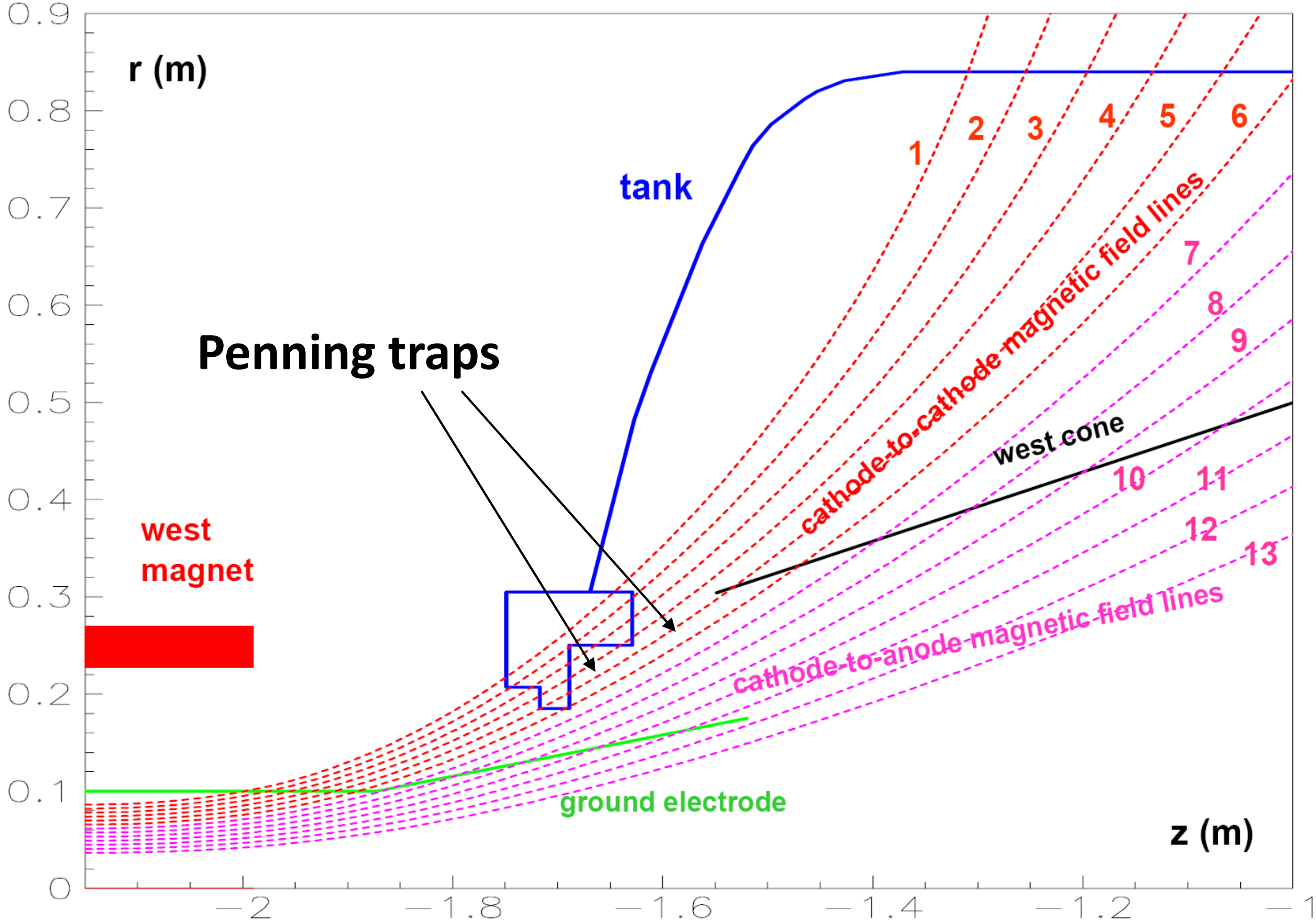
Mechanism of Penning discharge:

- electrons from cathode go into Penning trap; they gain kinetic energy by the more positive potential
- trapped electrons make ionization collisions with residual gas molecules (if they have enough energy)
- secondary electrons are also trapped, they make further ionizations
- positive ions created by ionizations go to cathode, where they create additional electrons by secondary emission (and remove also neutral molecules: sputtering)

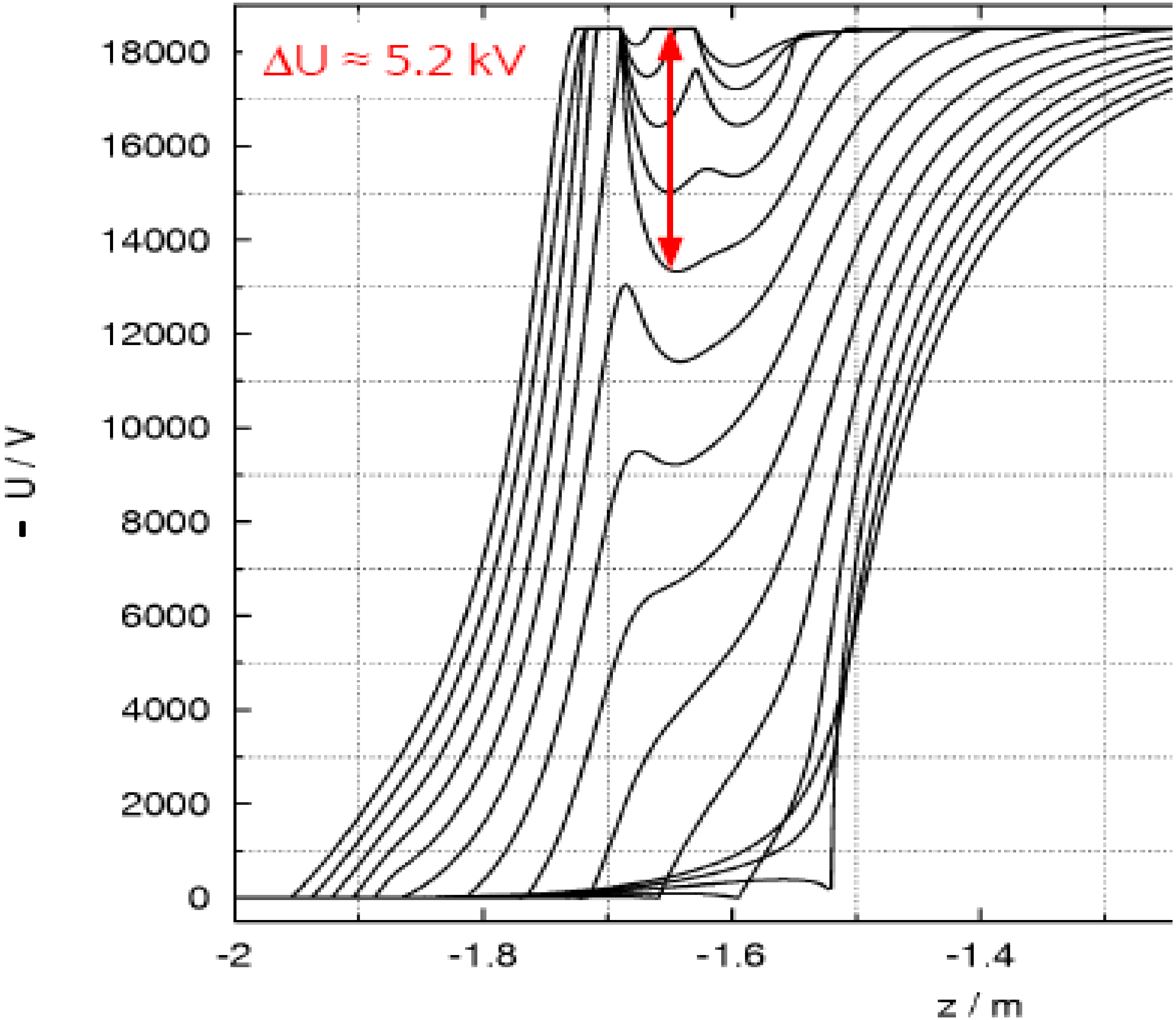
Deep and stable trap:

Effective amplification mechanism, dense electron plasma is created in the trap, large current flows between cathode and anode

$\longrightarrow$ electric breakdown (discharge)



KATRIN pre-spectrometer: cathode-to-cathode magnetic field lines, potential penetration from anode (ground electrode)



Electric potential on various magnetic field lines at the entrance of pre-spectrometer (with -18.6 kV)

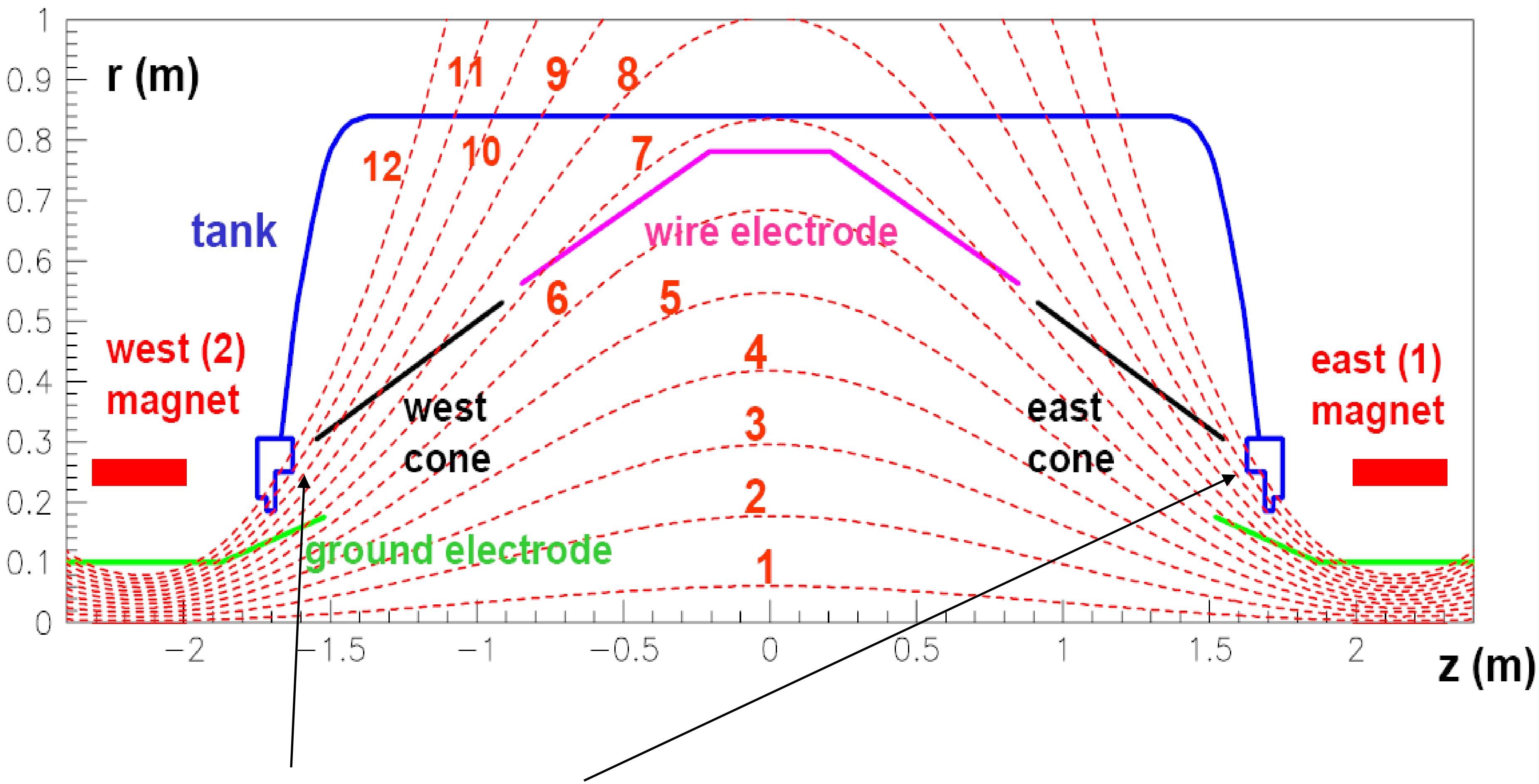
From Dec. 2006 many experiments with different configurations have been made, in order to understand the properties of the discharge with magnetic field in the pre-spectrometer, and to verify the Penning trap hypothesis of the strong discharge phenomena.

Various experimental configurations :

- **using both magnets, or only 1, with various coil current values**
- **positive or negative potential**
- **various vessel, wire, east cone, west cone potentials**
- **measurements without or with detector (MCP)**

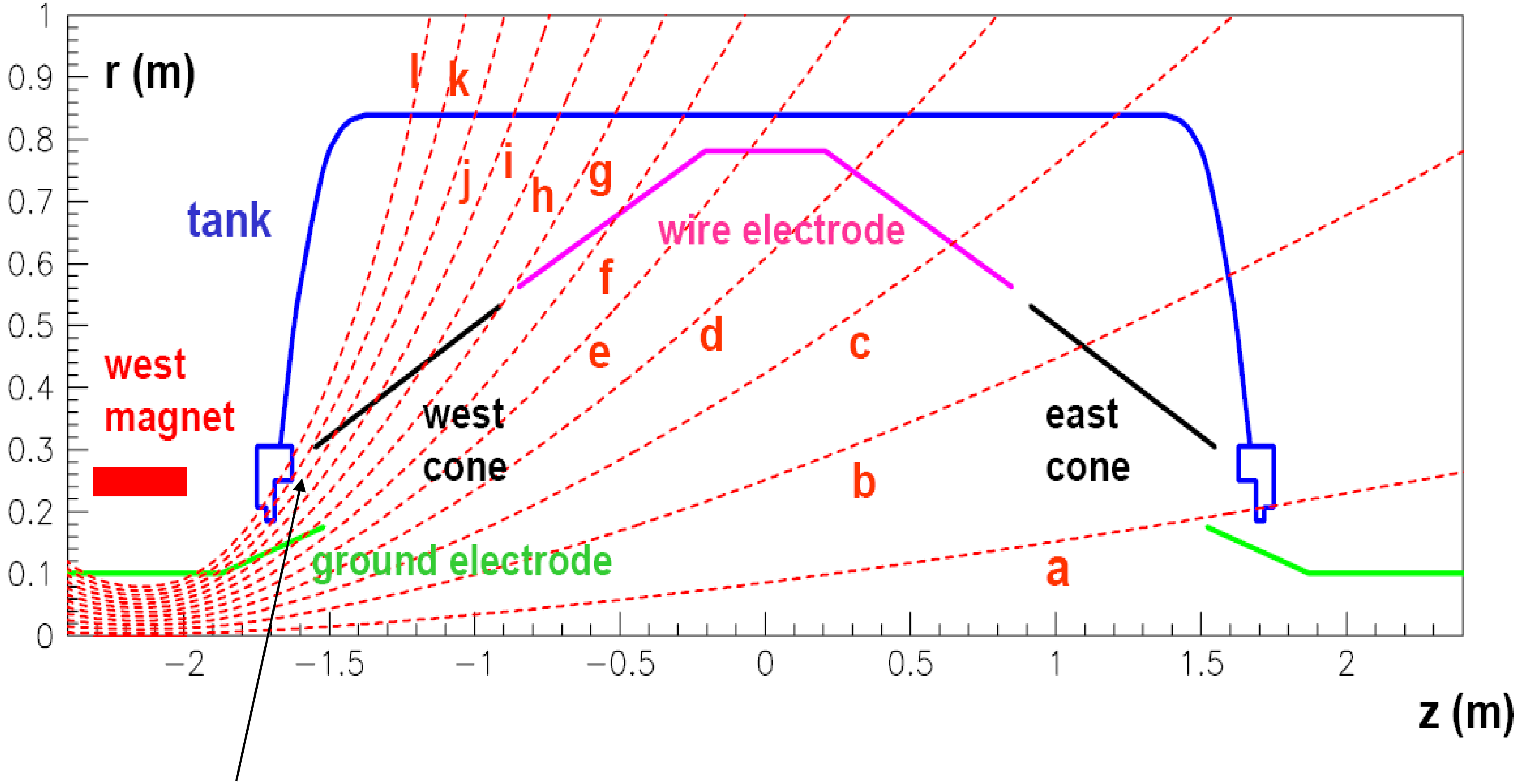
Diagnostics of discharge without detectors: increase of pressure and leakage current (f.e.: stronger discharge = larger pressure and leakage current)

Using both magnets



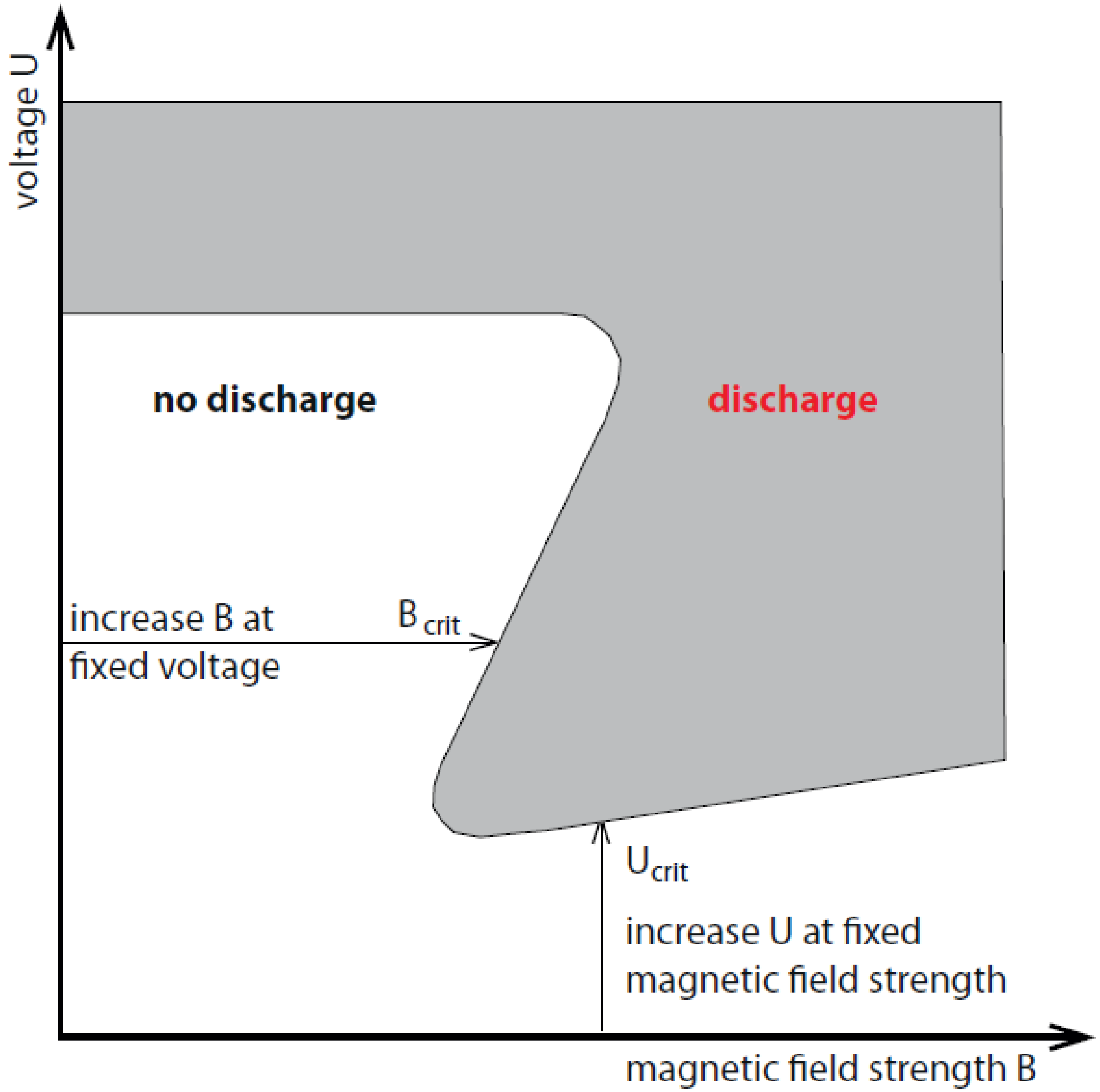
2 Penning traps (west and east)

Using only the west magnet

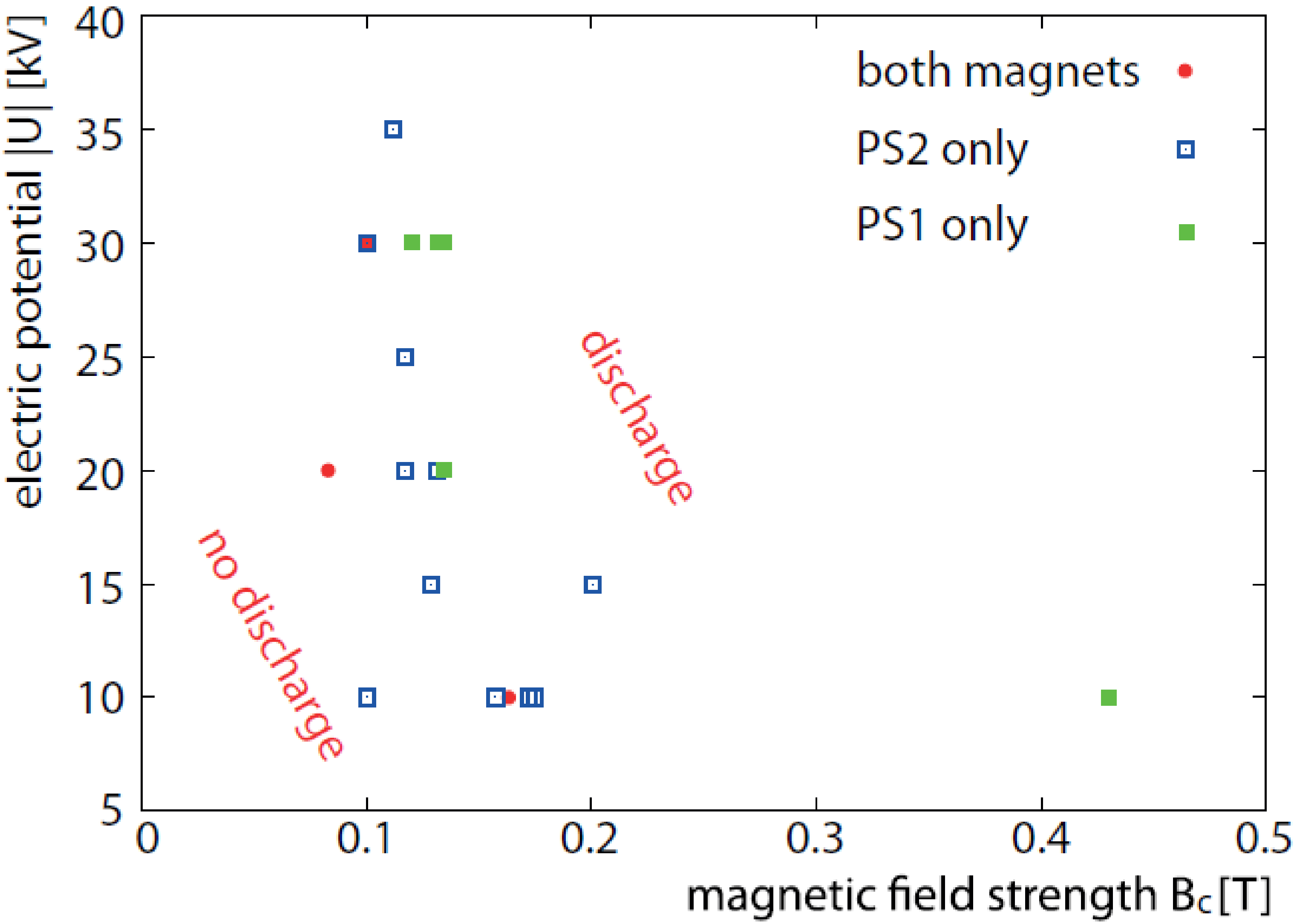


Only the west side Penning trap is active

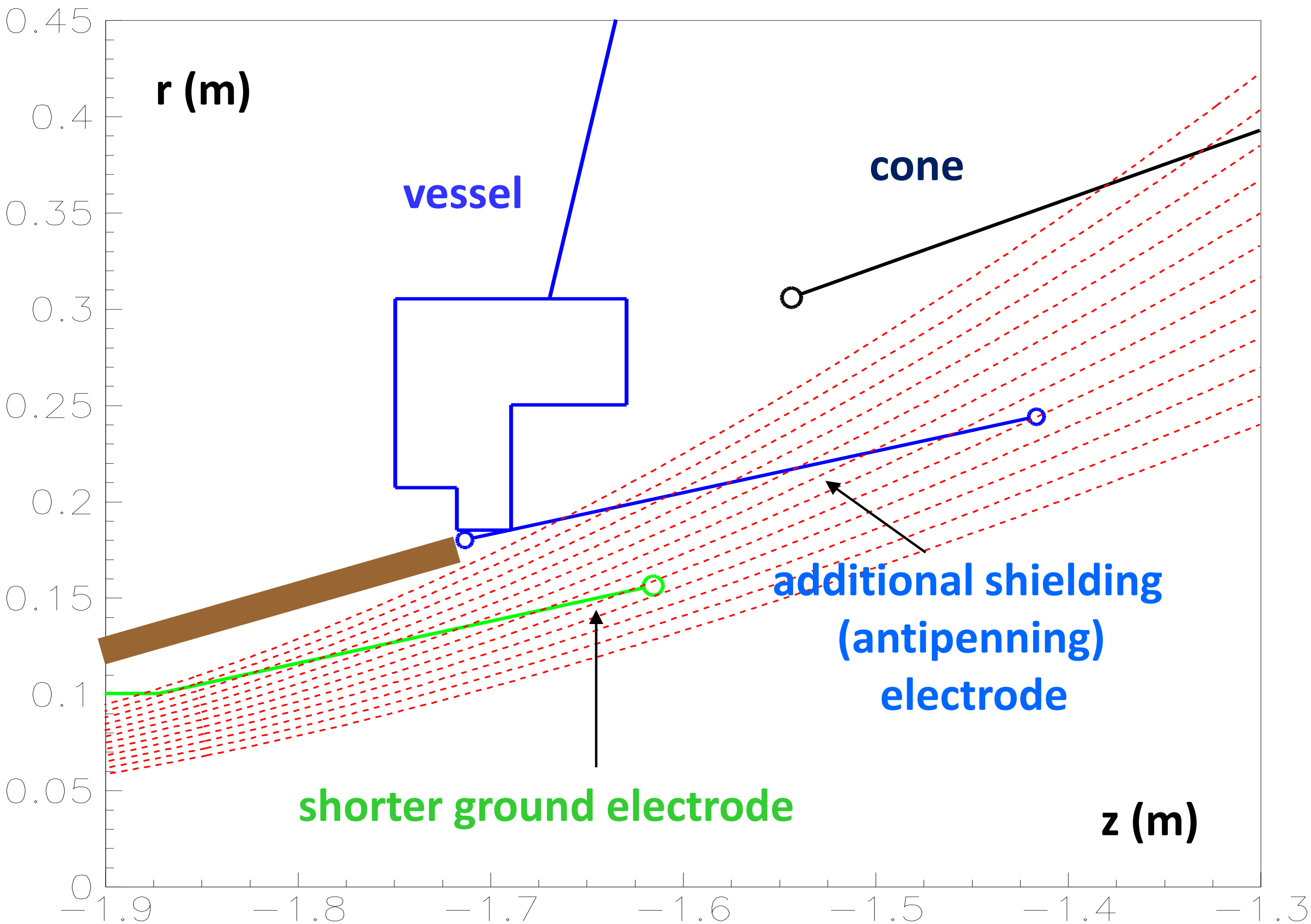
Penning discharge ignition curve



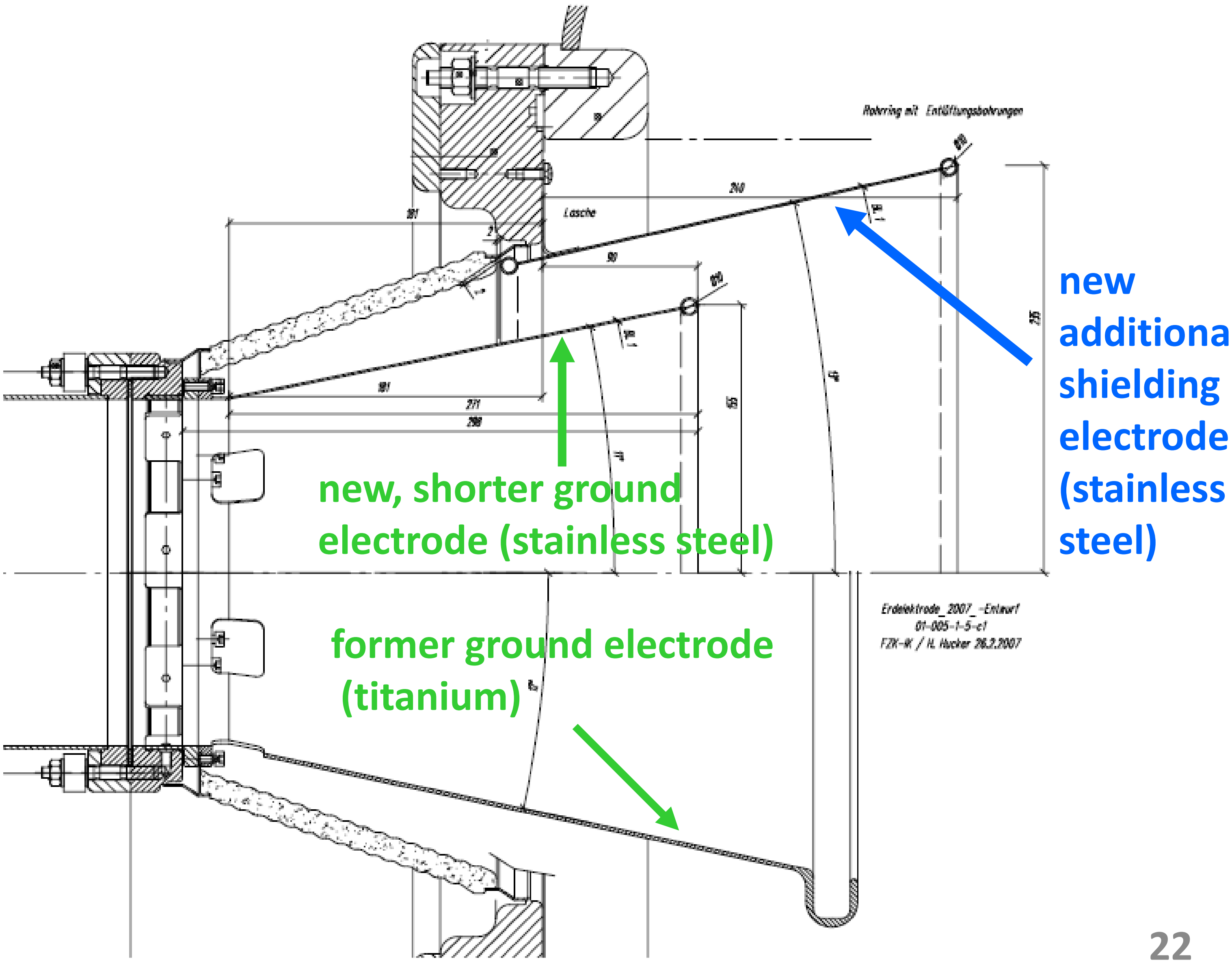
Penning discharge ignition in KATRIN pre-spectrometer

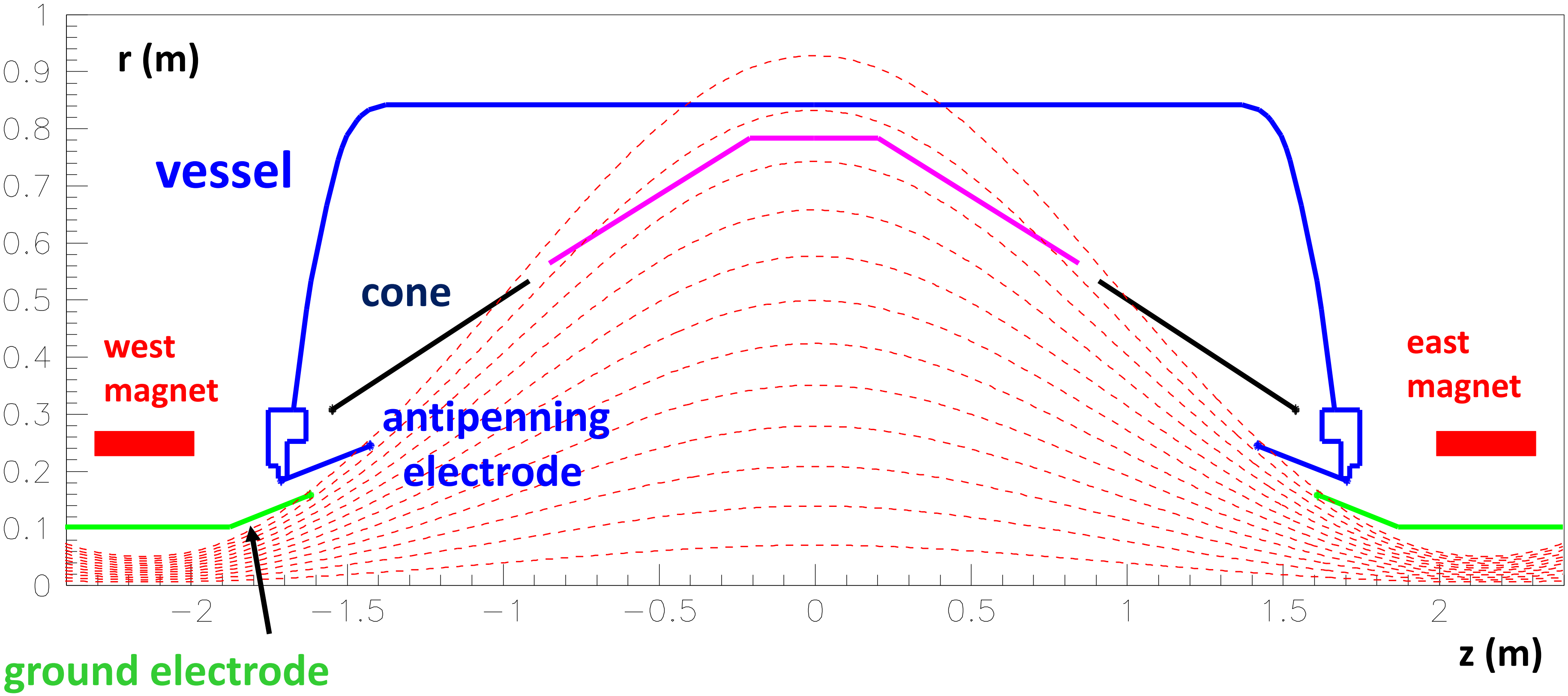


by shielding the Penning trap region against potential penetration from the anode by an additional electrode



Technical drawing:

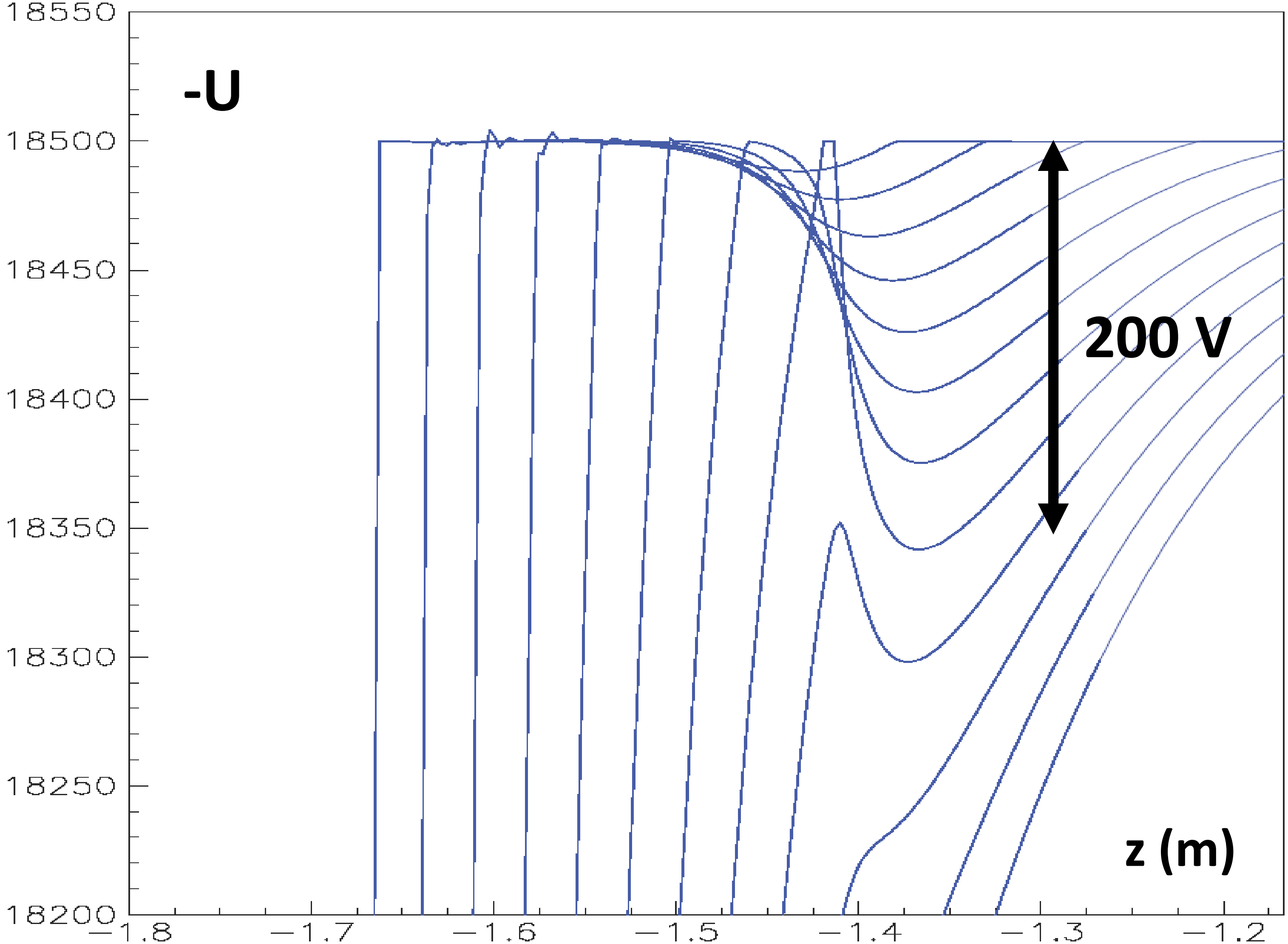




Electromagnetic design of the KATRIN pre-spectrometer, with the new electrodes

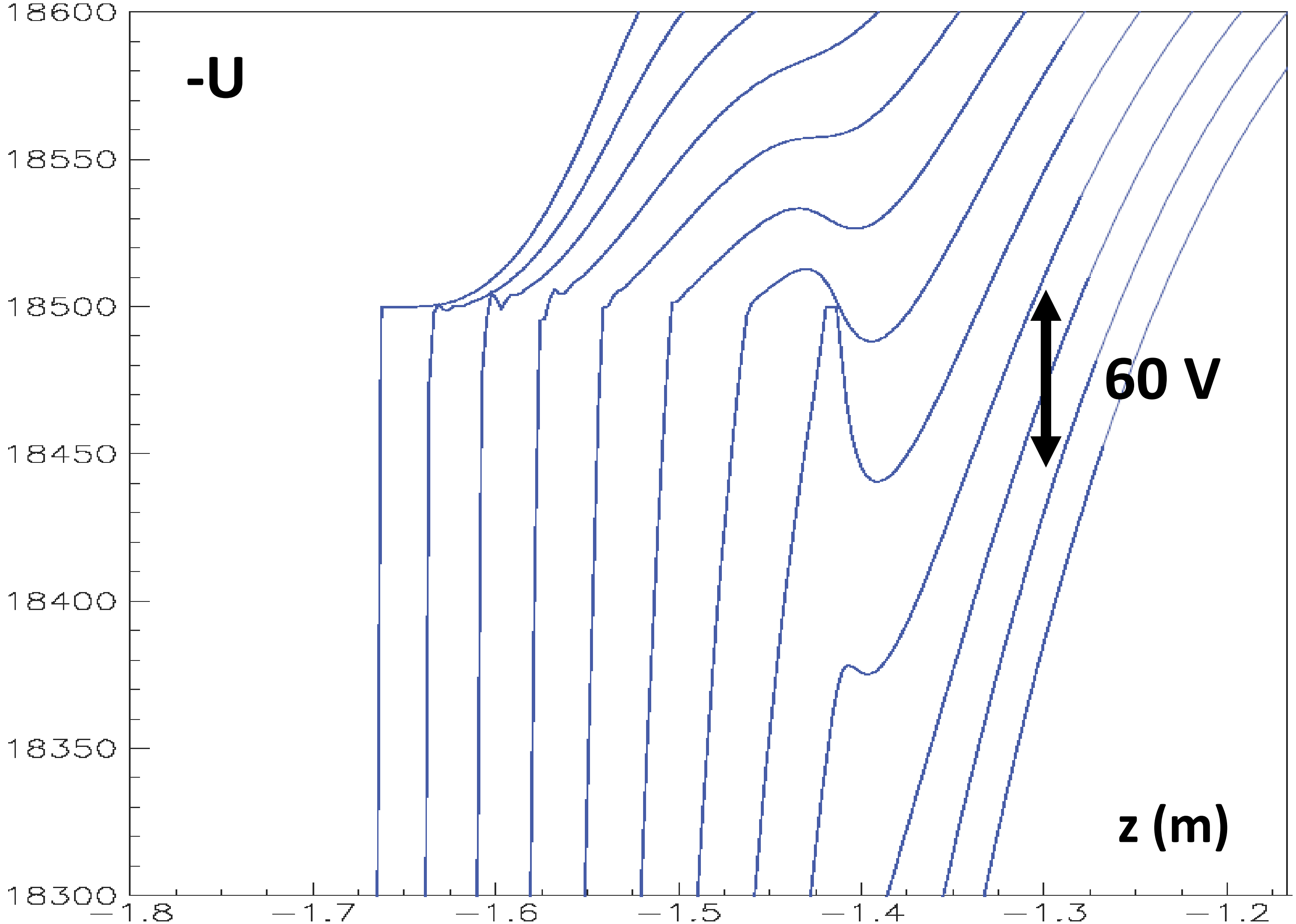
Penning traps with shielding electrode and shorter ground electrode

U_{vessel}=U_{cone}=-18.5 kV



Penning traps with shielding electrode and shorter ground electrode

U_{tank}=-18.5kV, U_{cone}=-18.7 kV



After installation of the new electrodes (Sept 2007):

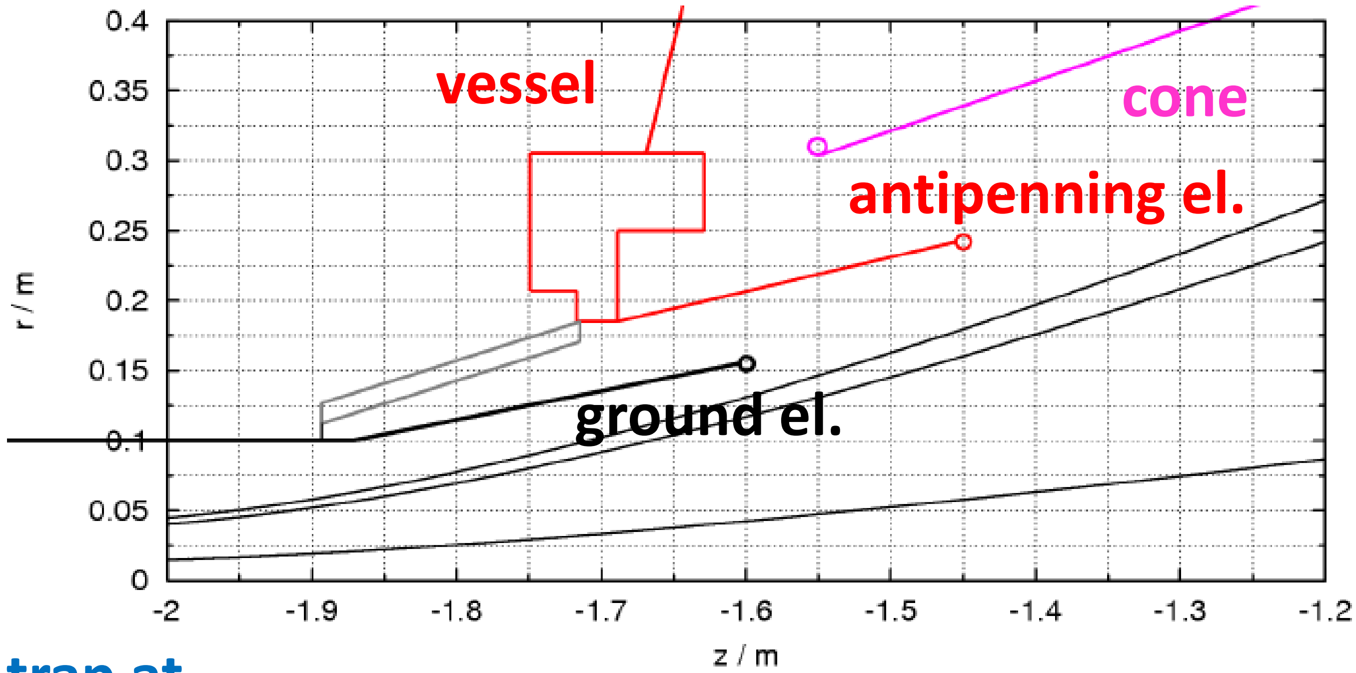
No pressure and leakage current increase, no electric breakdown (up to -30 kV, 4.5 T)

→ large Penning discharge disappeared !

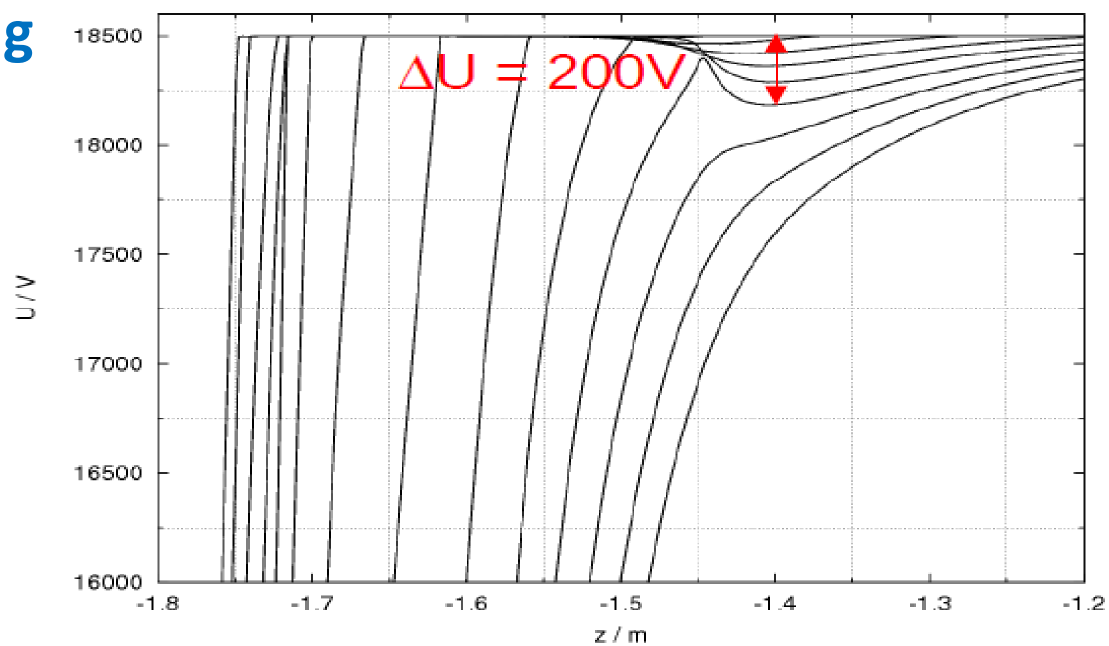
It was then possible to start background measurements with the segmented PIN-diode detector.

More information in:

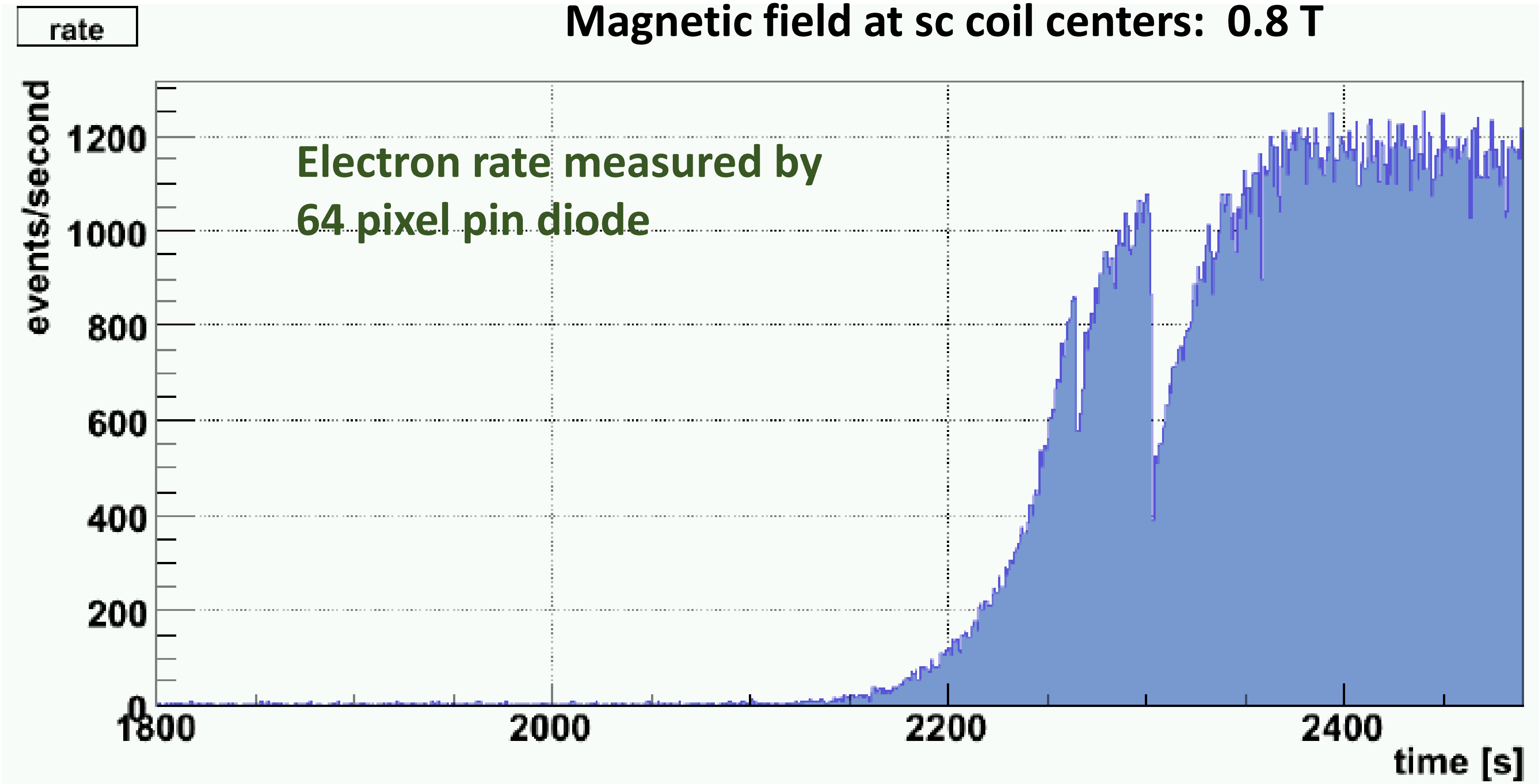
F. Fränkle et al., Penning discharge in the KATRIN pre-spectrometer, JINST 9, P07028
http://dx.doi.org/10.1088/1748-0221/9/07/P07028



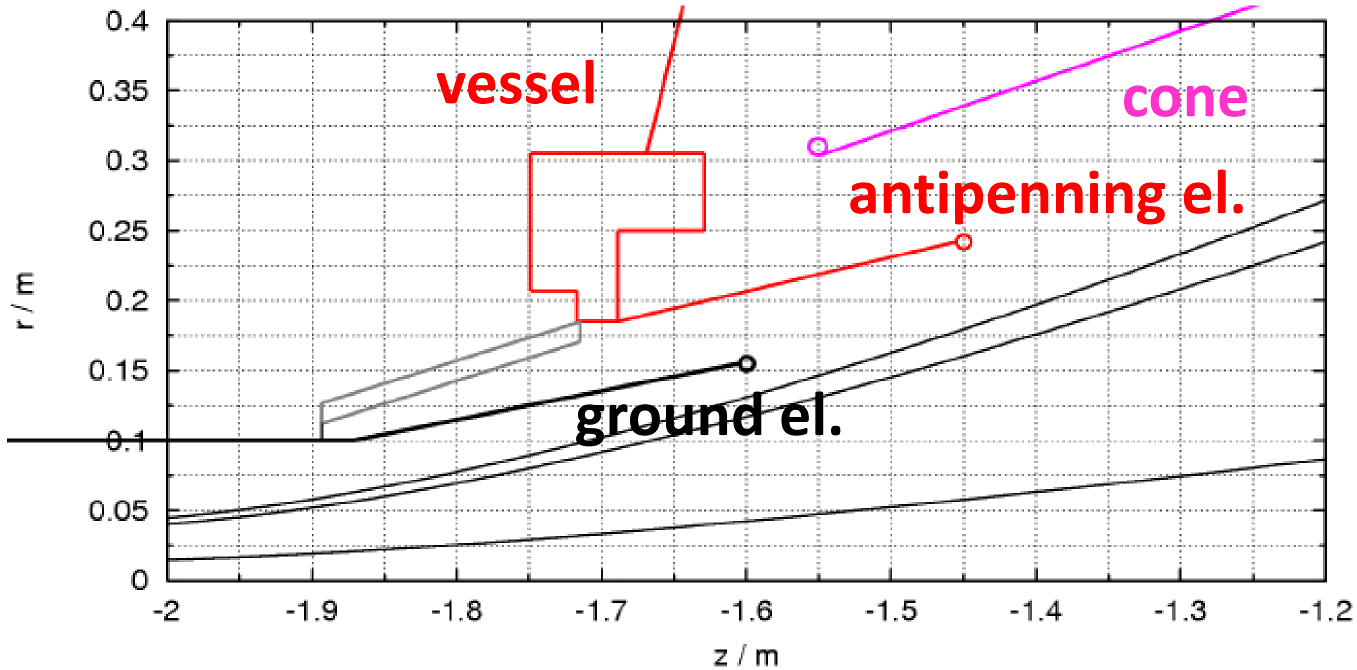
Penning trap at end of antipenning electrode (200 V deep with vessel and and cone at -18 kV)



Weak Penning discharge ignition when vessel and electrodes at different power supplies



Penning discharge does not ignite when vessel and electrodes at same power supply !

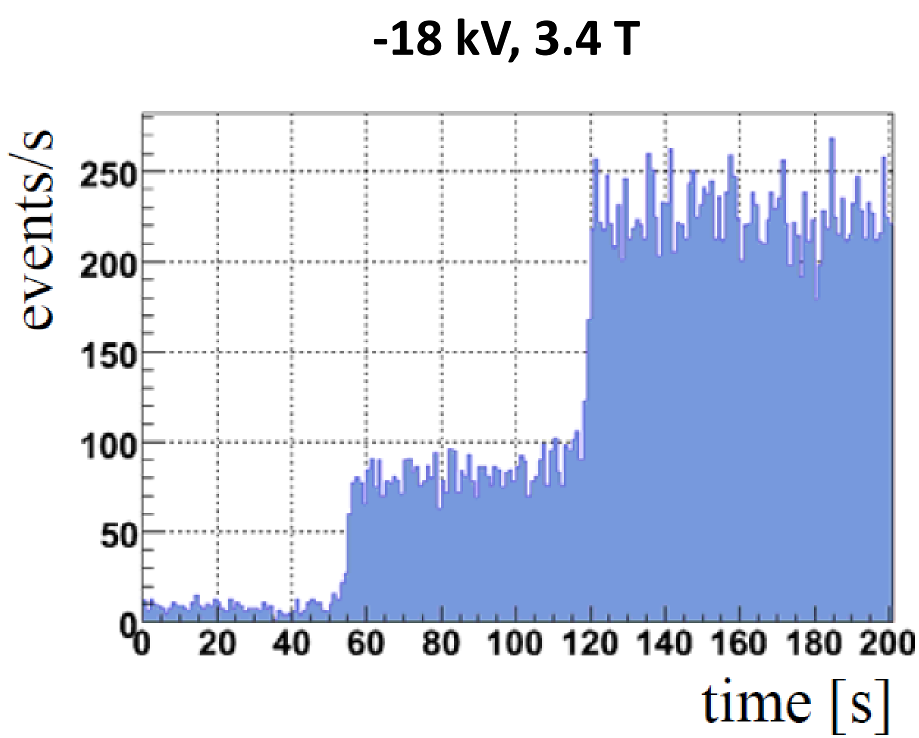


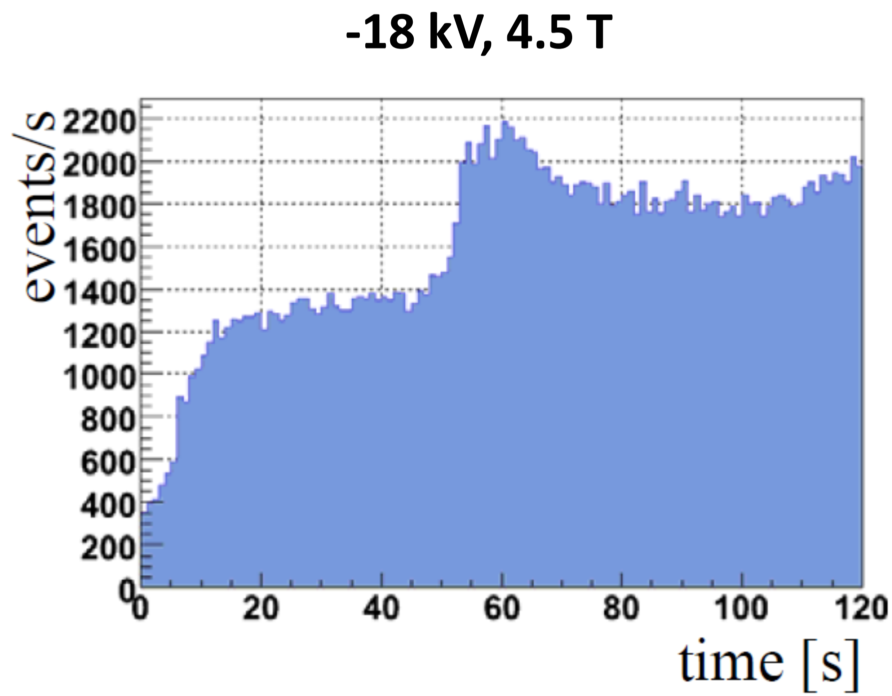
$U_{antipenning}=U_{vessel}$

Vessel at -18 kV, cone electrode at -18.5 kV:
no Penning trap at end of antipenning electrode (from simulations)

Experiment with 0.8 T:
no Penning discharge with this configuration

High B-field background (HBB)

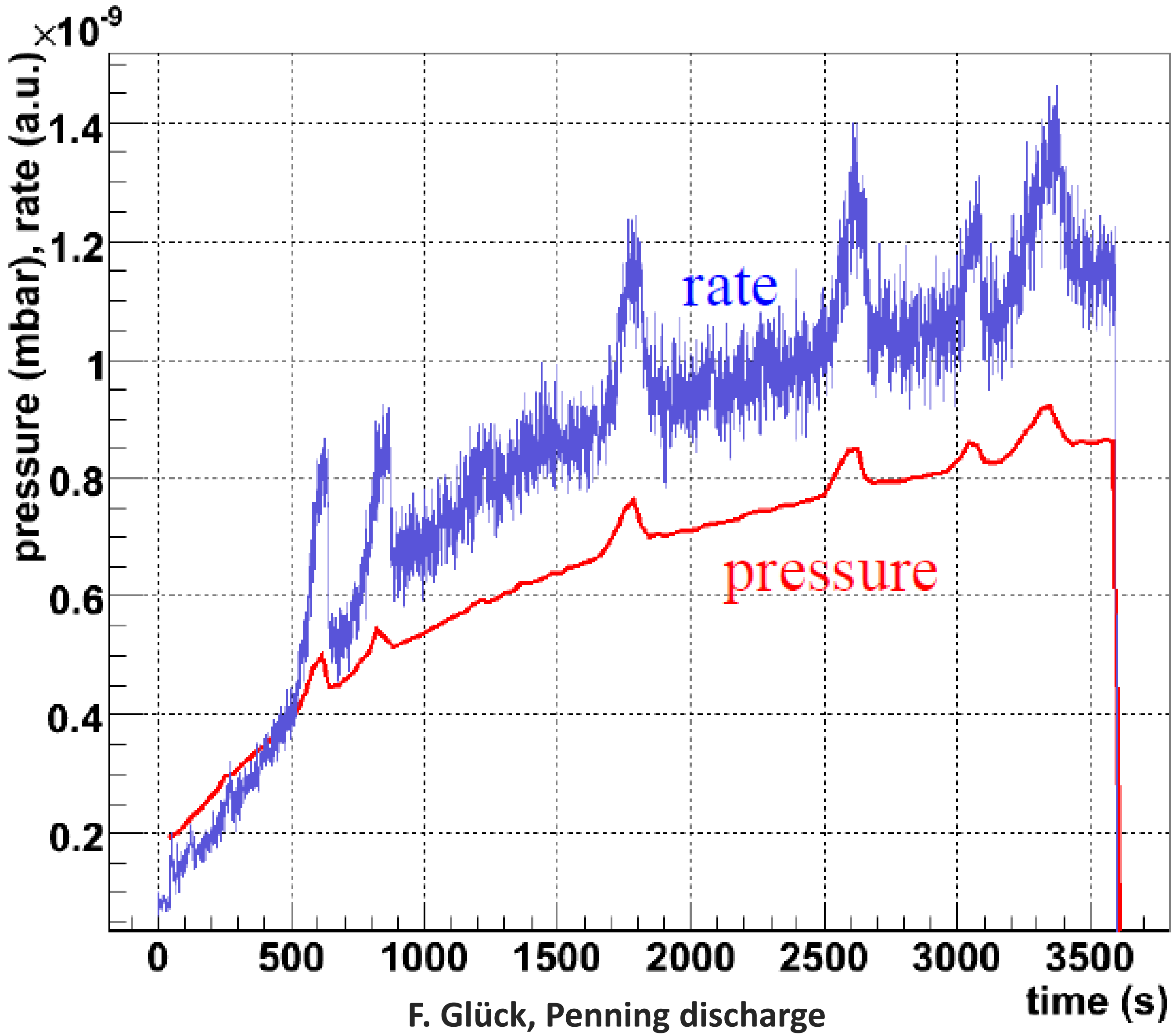




Time until first ignition for low pressures (10^{-10} mbar region):

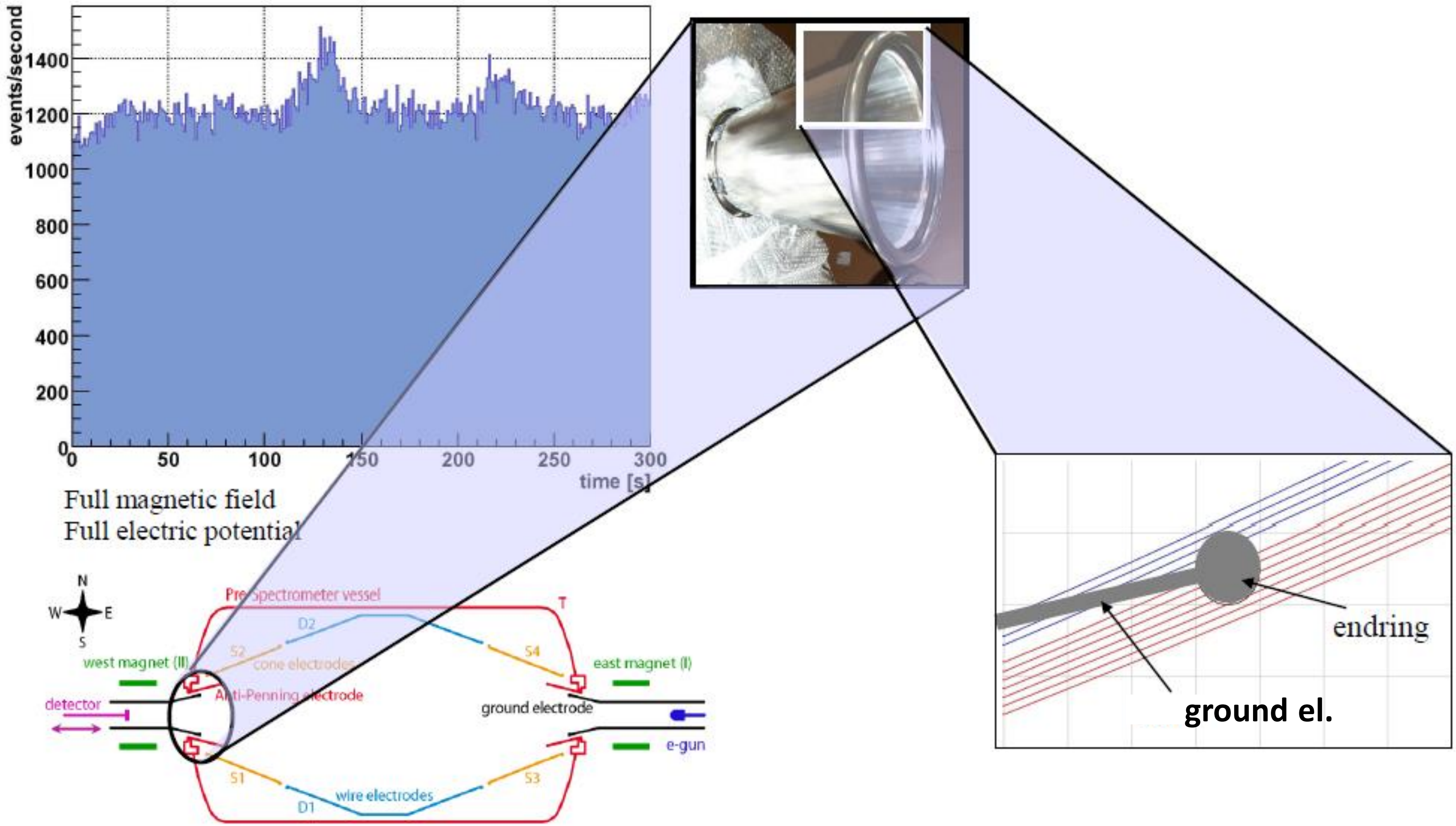
B [T]	4.5 / 0.016	3.4 / 0.012	2.6 / 0.009	1.7 / 0.006
Time	1 second	1 min	30 min	> 16 hours

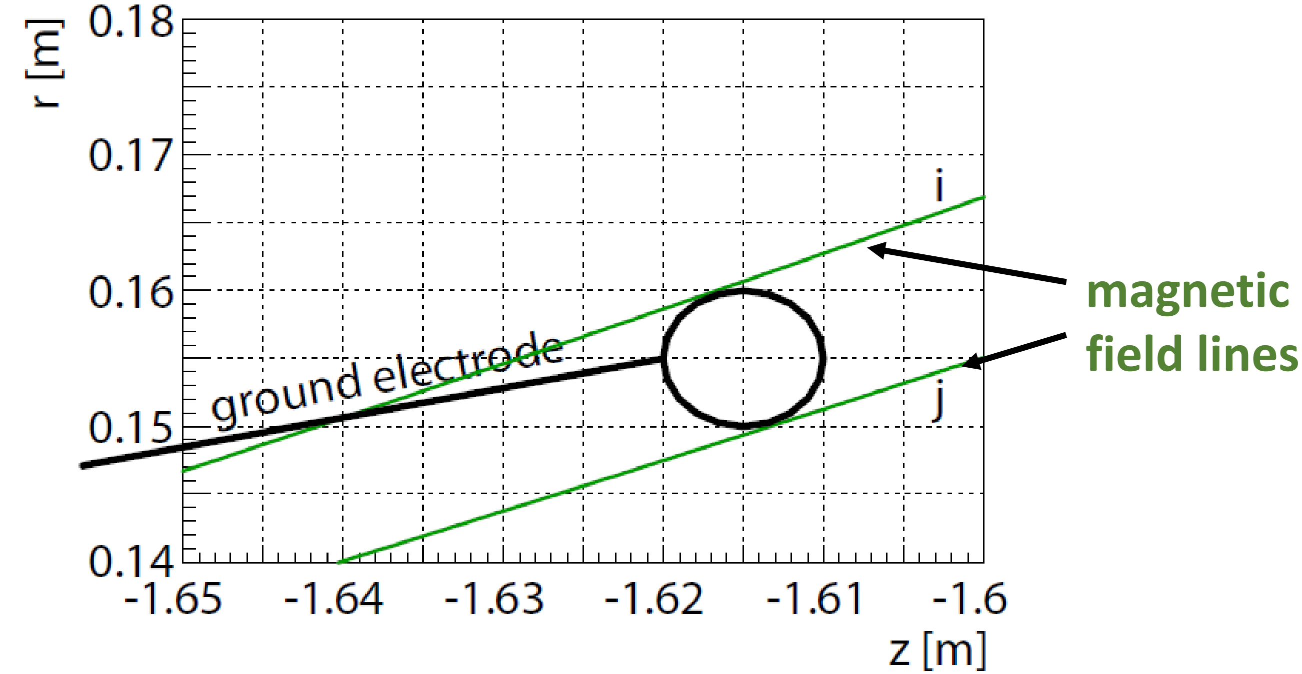
HBB increases with pressure



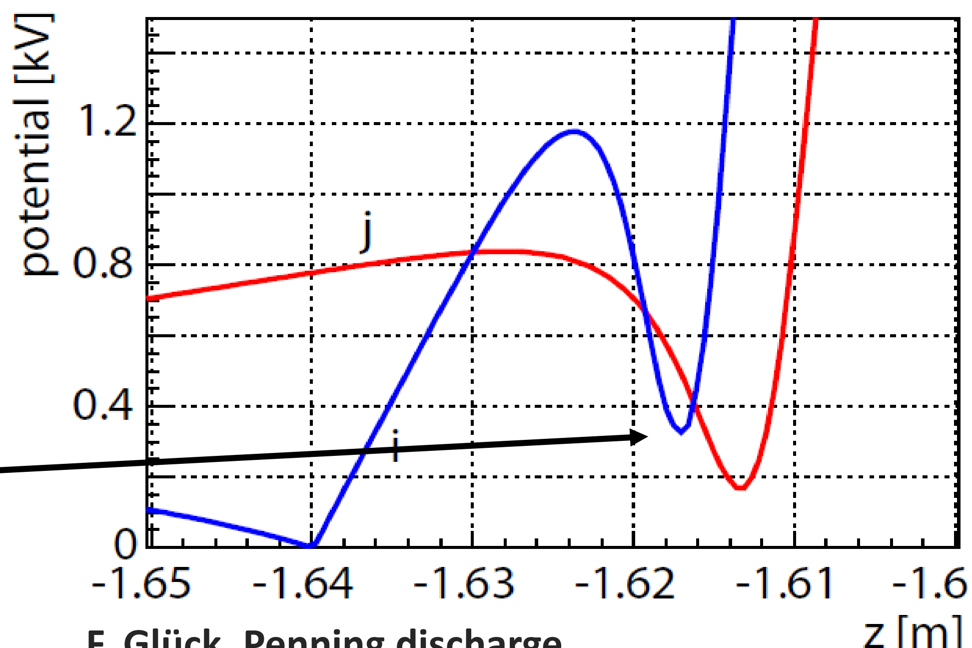
F. Glück, Penning discharge

Penning trap at ground electrode as main source of background

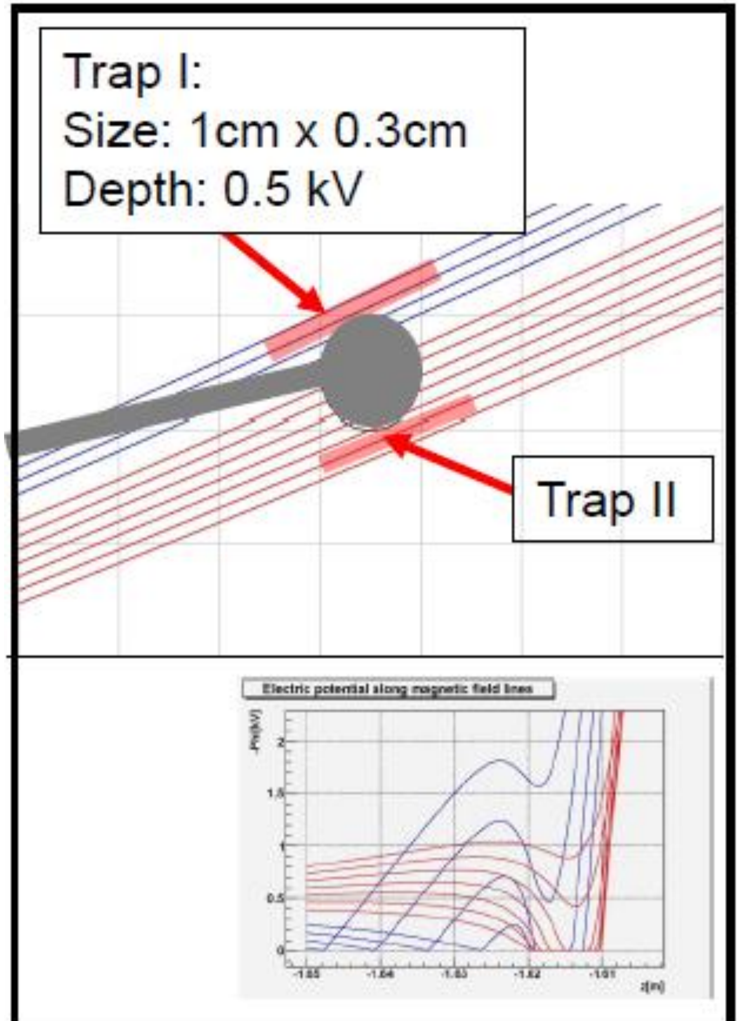




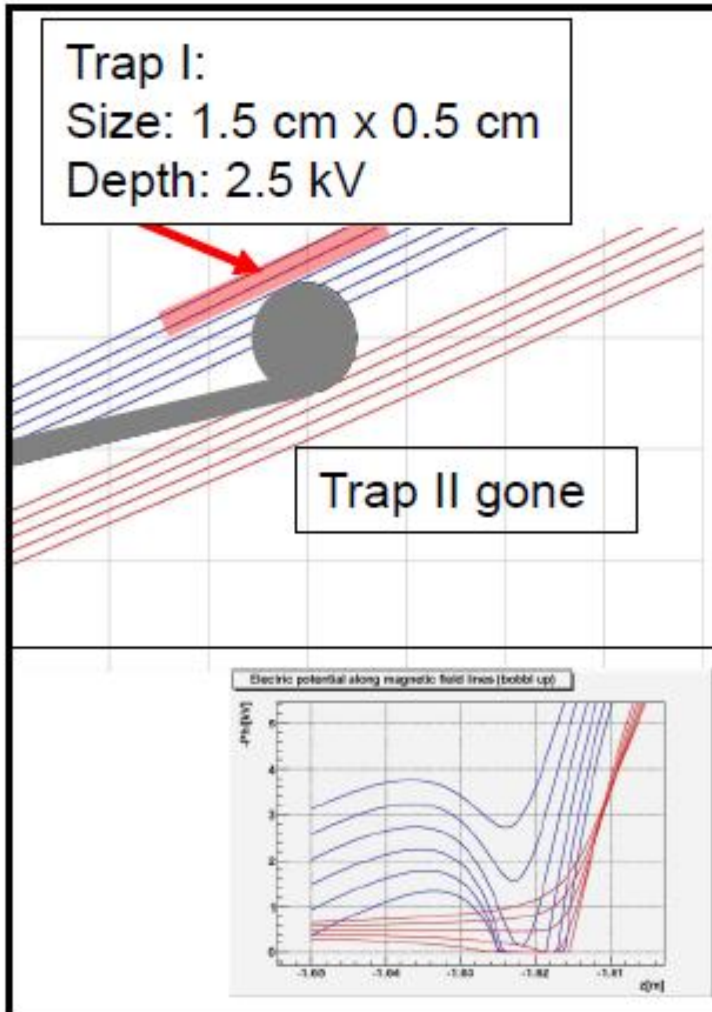
Vacuum-to-vacuum
Penning traps
for electrons.
Small size !



F. Glück, Penning discharge

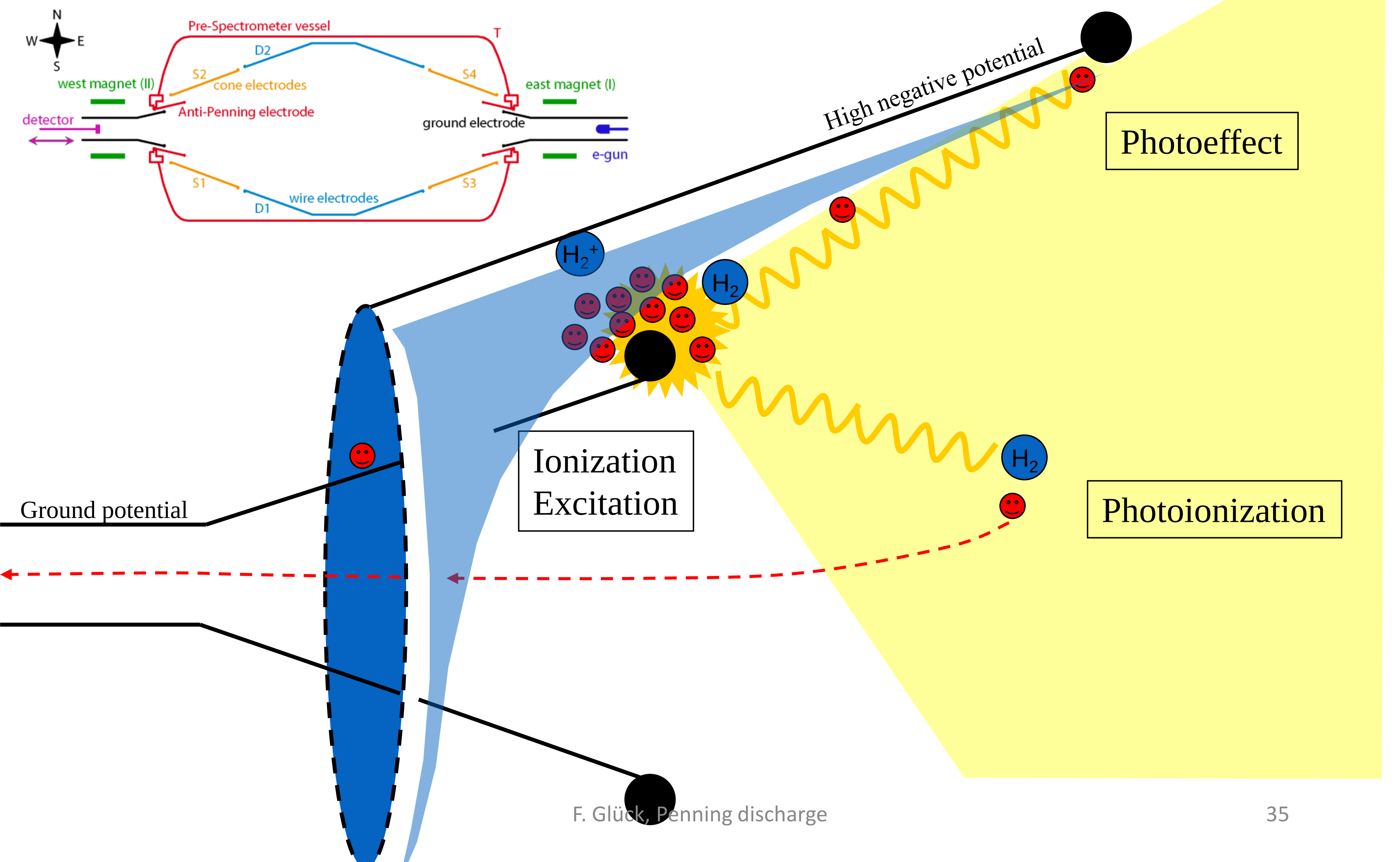


Large Background



Trap I larger and deeper:
Background larger !!!

Background production mechanism



Expected Countrate

Measured Background: 10^3 electrons/second

How many photons of this energy need to be emmited from penning trap?

Probability for photoionization of H_2 : 10^{-7}

(by a 20 eV photon, travelling 1m, at pressure 10^{-9} mbar)

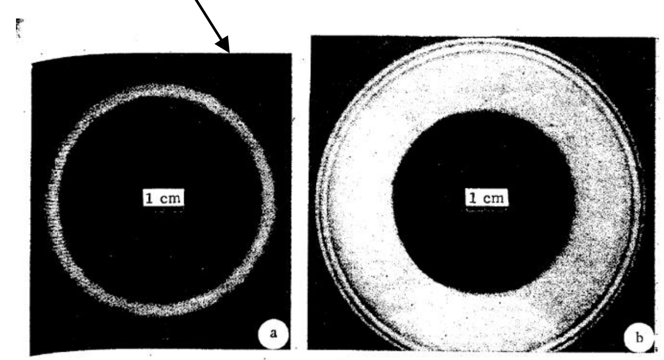
→ We need more than 10^{10} Photons/s

July 1977 / Vol. 16, No. 7 / APPLIED OPTICS

Zh. Tekh. Fiz. **48**, 1809–1814 (September 1978)

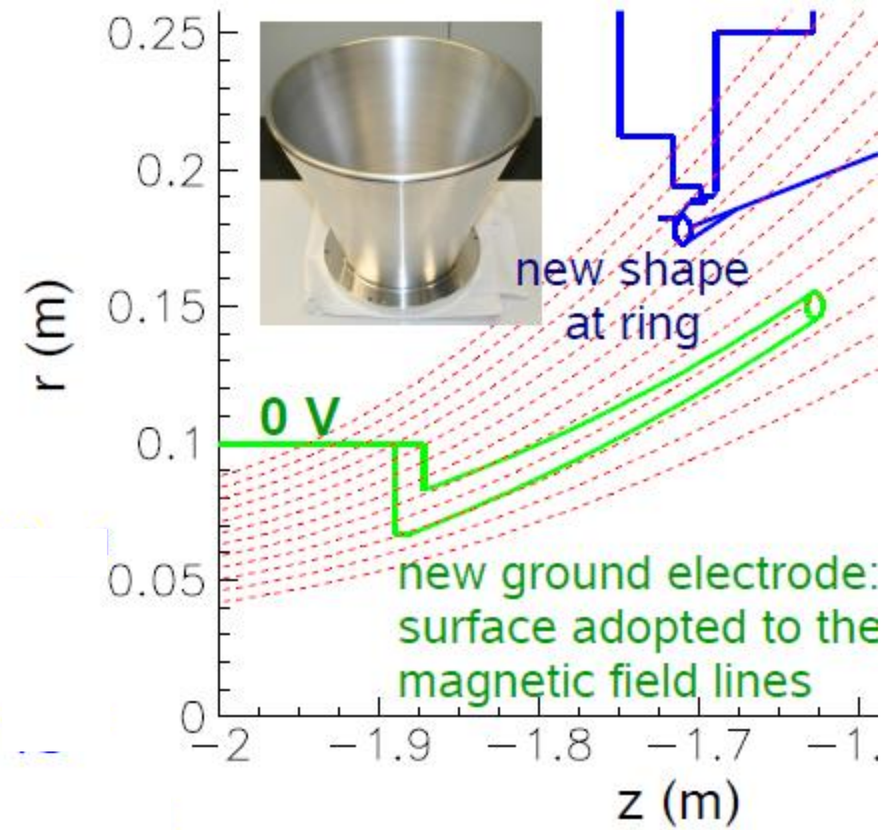
Papers about penning traps as UV light source

„(10^{15} photons/sec sr)“



Solution to HBB problem:

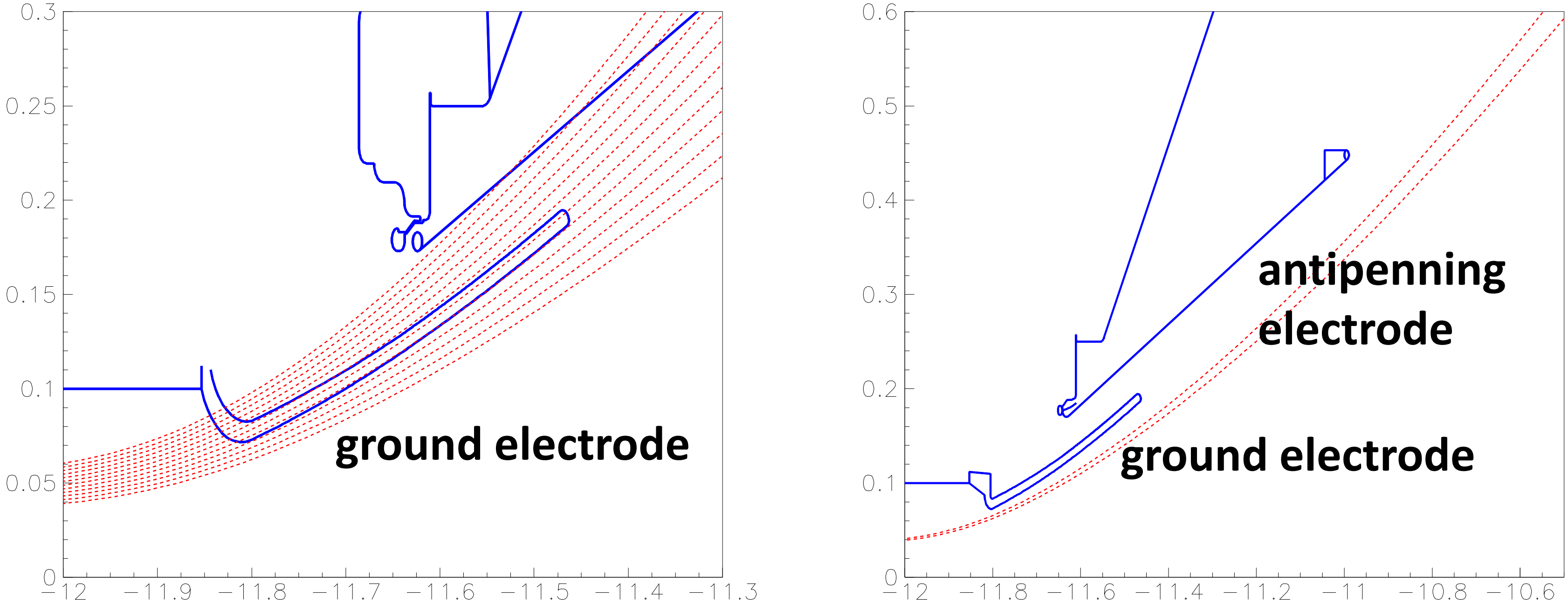
new ground electrode design, with detailed simulations, Penning traps eliminated



Using the new ground electrode (material: Al):

Background decreased from few 100 cps to few mcps

Background reduction factor of new ground electrode: 100000



KATRIN main spectrometer: similar (but larger) ground and antipenning electrodes.

No Penning discharge (neither strong nor weak) in main spec. observed !

More information about weak Penning discharge in KATRIN:

- **M. Zacher PhD thesis, Münster, 2014;**
- **F. Fränkle, PhD thesis, KIT, 2010;**
- **S. Mertens, PhD thesis, KIT, 2012.**

Summary

- Strong Penning discharge in KATRIN pre-spectrometer, caused by large and deep Penning traps for electrons
- Diagnostics: pressure and leakage current increase; electric breakdown
- Large Penning traps eliminated by antipenning electrodes → strong Penning discharge disappeared
- Weak Penning discharge from Penning trap at end of antipenning electrode
  → order of 1 kcps background at detector (pin diode)
  → disappeared by more negative cones: Penning traps eliminated
- Weak Penning discharge at high magnetic field (HBB)
  → order of 1 kcps background at detector (pin diode)
  → caused by small Penning traps at end of ground electrodes
  → disappeared by modified ground electrodes without Penning traps

General conclusions

- Penning discharge is caused always by Penning traps for electrons; Penning traps for positive ions do not cause Penning discharge.

- Penning discharges with different potential polarities: electron Penning traps can be present with both polarities; of course: different electron traps for negative and positive polarities.

- Large size traps: Penning discharge ignites already for small magnetic field; small size traps: high magnetic field needed for ignition.

- Stronger Penning discharge and smaller ignition time at higher potential, higher pressure and higher magnetic field.