Status of the Polarized Atomic Hydrogen Target at MAMI & MESA

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THE LOW-ENERGY FRONTIER
OF THE STANDARD MODEL

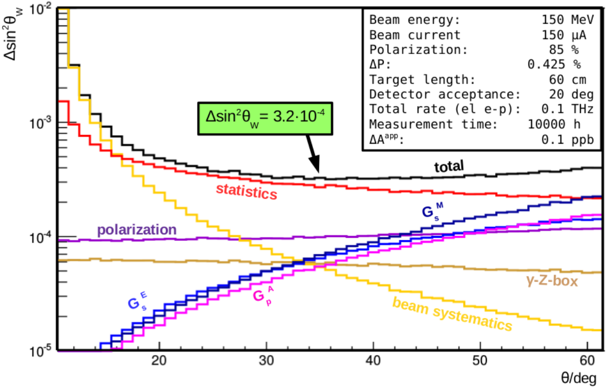
Contents

MESA

- The P2 Experiment - A future high-precision measurement of the electroweak mixing angle at low momentum transfer.
- Aim is to measure the weak mixing angle $\sin^2\theta_w$ in electron proton scattering to precision 0.14%
- CW spin polarized electron beam, polarization $\sim 85\,\%$
- Beam current $\sim 150\,\mu\mathrm{A}$, beam energy $\sim 150\,\mathrm{MeV}$

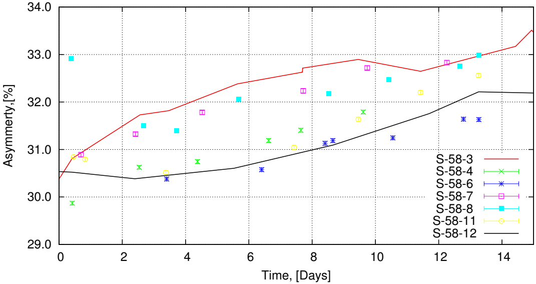
Reference: arXiv:1802.04759

P2 Experiment at MESA



- Beam polarization significantly contributes in precision

MAMI and MESA Photo cathodes



- $I_{\text{MAMI}} \sim 100.0\,\mu\text{A}$
- $E_{\text{MAMI}} \sim 180.0 - 1500.0\,\text{MeV}$,
- $P_{\text{MAMI}} \sim 85\,\%$
- 7 days/24 hours

- MAMI & MESA use super lattice photo cathodes SVT Associates
- Beam polarization could vary up to 10% during run
- Red line - a new photo cathode
- Black line - a good used cathode

Polarimeters chain at MESA

- Double Mott polarimeter at $100.0\,\mathrm{keV}$
- Mott polarimeter at $5.0\,\mathrm{MeV}$
- Møller polarimeter at $50.0 - 150.0\,\mathrm{MeV}$ with Polarised Atomic Hydrogen Target. Proposed in 2004 and revised in 2012 Dr. E. Chudakov (JLAB) and Dr. V. Luppov (Janis Res. Co.)
- The goals at MESA $P_{\text{Mott, double}} = P_{\text{Mott, 5.0 MeV}} = P_{\text{Møller, H}}$
- Accuracy $\Delta P < 0.5\%$
- Online measurements

The main idea of Polarized Atomic Hydrogen Target

Møller scattering of electron beam

$$\left(\frac{d\sigma}{d\Omega}\right)_{CM} = \left(\frac{d\sigma^0}{d\Omega}\right)_{CM} \times \left(1 + \sum_{i,j=x,y,z} a_{ij} P_i^B P_j^T\right) \quad (1)$$

where: P_j^T , P_i^B target and beam polarizations,
z - beam direction, x, y - scattering directions

$$A_{exp} = \frac{N^{\uparrow\uparrow} - N^{\uparrow\downarrow}}{N^{\uparrow\uparrow} + N^{\uparrow\downarrow}} = a_{zz} P^B P^T. \quad (2)$$

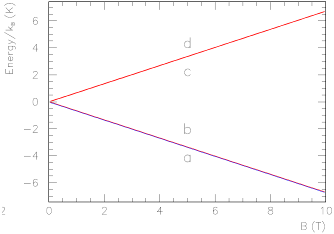
it would be more convenient with: $a_{zz}^{max} = -\frac{7}{9}$, $P^T = 1.00$

$$A_{exp} = -\frac{7}{9}\, P^B \quad (3)$$

Complication from hyperfine splitting

Molecular hydrogen H_2 opposite electron spin

Atomic hydrogen H_1 : $\vec{\mu} \approx \vec{\mu}_e$ in magnetic field



Low energy:

$|a\rangle$ $|\uparrow\Downarrow\rangle \cos(\theta) - |\downarrow\Uparrow\rangle \sin(\theta)$

$|b\rangle$ $|\downarrow\Downarrow\rangle$

High energy:

$|c\rangle$ $|\downarrow\Uparrow\rangle \cos(\theta) + |\uparrow\Downarrow\rangle \sin(\theta)$

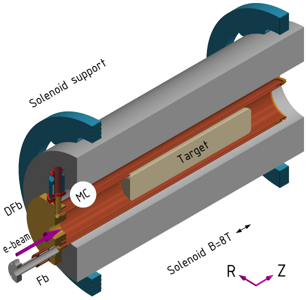
$|d\rangle$ $|\uparrow\Uparrow\rangle$

0

Target Polarization $P^T \sim (1 - 10^{-5}) \sim 0.99999$

- $H + H \to H_2$ recombination energy $4.45\,\mathrm{eV}$ high rate at low T
- gas: parallel electron spins 2-body kinematic suppression
- gas: 3-body density suppression
- surface: strong unless coated $\sim 50\,\mathrm{nm}$ film of superfluid ^{4}He

How to keep the target in Z and R-directions



On figure:
R and Z - coordinates
Fb - film burner
MC - mixing chamber

.

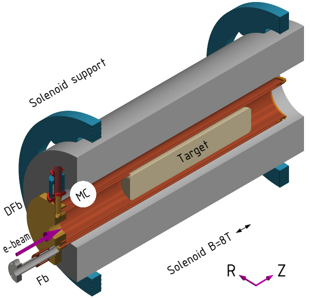
Trapping in Z-direction

- Superconducting magnet $B = 8.0\,\mathrm{T}$
- force in the field gradient $-\vec{\nabla}\left(\vec{\mu}_H \times \vec{B}\right)$
- $|a\rangle$ and $|b\rangle$ are pulled into strong field
- $|c\rangle$ and $|d\rangle$ are repelled out of field

Trapping in R-direction

- Wall of storage cell is coated $\sim 50\,\mathrm{nm}$ film of superfluid ^{4}He
- $T_{\text{wall}} = 0.25 - 0.30\,\mathrm{K}$

Storage cell, established



- $L_H = 0.20\,\mathrm{m}$,
- $D_H = 0.02\,\mathrm{m}$,
- $\rho_H = 3.0 \times 10^{15}\,\mathrm{cm}^{-3}$
- $\rho_H \times L_H = 6.0 \times 10^{16}\,\mathrm{cm}^{-2}$
- Gas lifetime $\sim 1.0\,\mathrm{hour}$

Nobody has put the target in a high power beam

I. F. Silvera and J. T. M. Walraven. Phys. Rev. Lett. V.44, N.3 (1980), M. Mertig et al. Rev. Sci. Inst. 62.1 (1991), E. Chudakov Nuovo Cim, V. C35, N.4 (2012)

Requirements to cryostat: heat load, cooling power

- Super fluid ^{4}He film coated wall at $T_{\text{wall}} = 0.25 - 0.30\,\text{K}$
- $P_{rec} = 10.0\,\text{mW}$, – H-pair recombination energy, depends on feed rate of atomic hydrogen
- P_{fb}=$10.0\,\text{mW}$, – film burners and transition unit
- P_{bb}=$25.0\,\text{mW}$, – estimated black body radiation to mixing chamber from warm parts of beam line.
- $P_{cooling}$=$P_{rec} + P_{fb} + P_{bb} = 45.0\,\text{mW}$
- $P_{cooling} \sim 45.0\,\text{mW}$ at $T_{mc} = 0.25\,\text{K}$ and $\dot{n}_{He3} = 16.5\,\frac{\text{mmol}}{\text{s}}$ in ideal case
- $P_{cooling} \sim 60.0\,\text{mW}$ at $T_{mc} = 0.25\,\text{K}$ and $\dot{n}_{He3} = 40.0\,\frac{\text{mmol}}{\text{s}}$ in real case

Special thanks N. Borisov JINR, Dr. T. Niinikoski CERN

Storage cell: Operating with atomic hydrogen

Working sequence

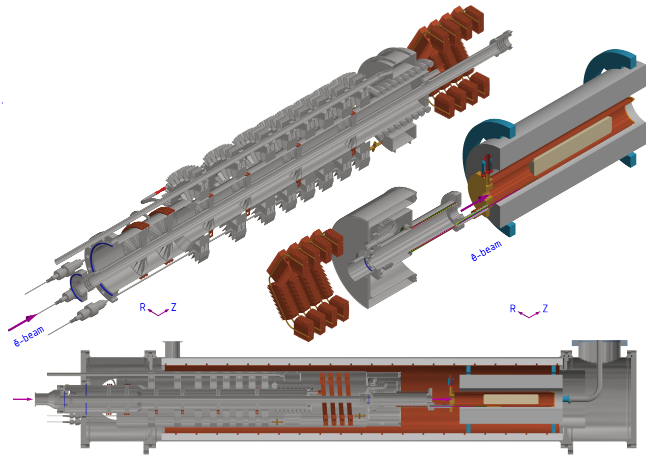
- Filling time $\sim 1\,\mathrm{hours}$
- Work time $\sim 1\,\mathrm{hours}$
- Baffles of feed system blocked due to frozen hydrogen
- Warm up $\sim 25\,\mathrm{K}$
- Not available continuously on line
- Losses $\sim 1.0 \times 10^{14}\,\frac{\mathrm{atom}}{\mathrm{s}}$

Proposed and discussed FZ Jülich, Germany

- Suppress flux of H_2 and H_1 in states $|c\rangle$ and $|d\rangle$
- Inlet only H_1 in states $|a\rangle$ and $|b\rangle$
- It seems continuous operation possible

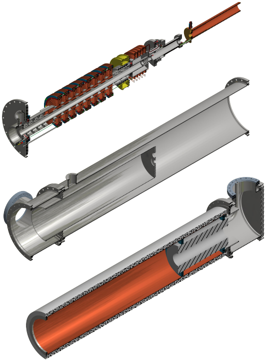
Thanks Dr. F. Rathmann, Dr. Ralf W. Engels, FZ Jülich

Horizontal cryostat and solenoid



Thanks: N. Borisov, Yu. Usov (JINR), Ch. Keith, M. Lowry, E. Chudakov (JLAB), T. Niinikoski (CERN)

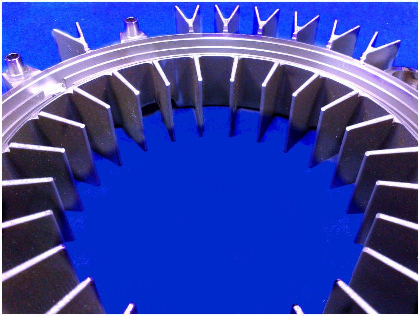
Polarimeter components = Dilution cryostat + Storage cell + Møller Detector



- Horizontal oriented dilution cryostat – mixing ^{3}He in ^{4}He
- Cryostat insert (up)
- Cryostat housing (middle)
- Superconductive magnet, thermal shield and atomic hydrogen feed system (down)
- Detector of Møller polarimeter (not shown) → JLAB, W&M
- Dimensions: $L \sim 2.5 + 2.0\,\mathrm{m}$, $D \sim 0.50\,\mathrm{m}$
- Funding applied
- Under construction: JGU Mainz

Three ways counterflow HX from stainless steel

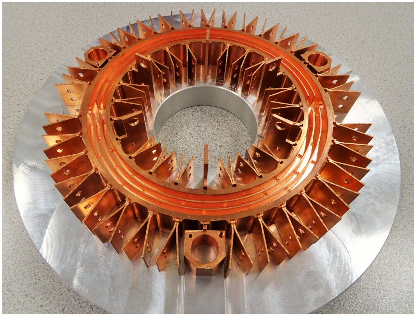
HT-HX from SS
complete welding system



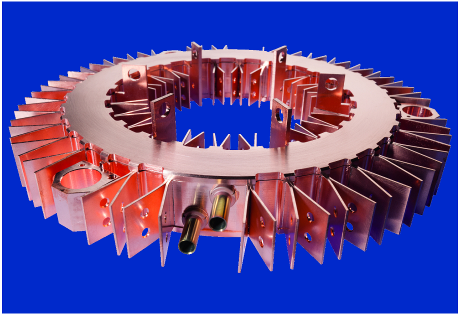
HT-HX from SS
before welding

Heat transfer between cold ^3He,^4He and warm ^3He

Three ways counterflow HX from copper



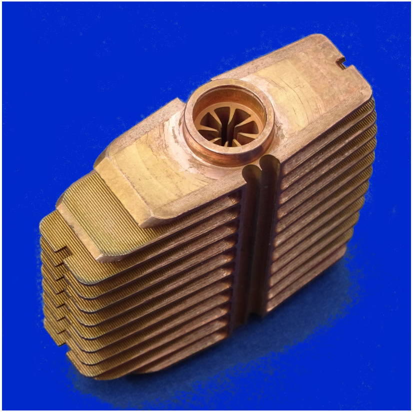
HT-HX plate before soldering



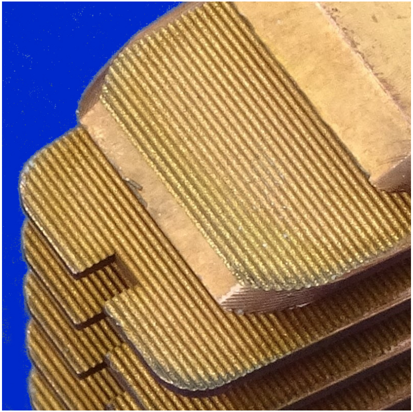
HT-HX from OFHC-Cu

Heat transfer between cold ^{3}He, ^{4}He and warm ^{3}He

Four ways counterflow HX LT from copper



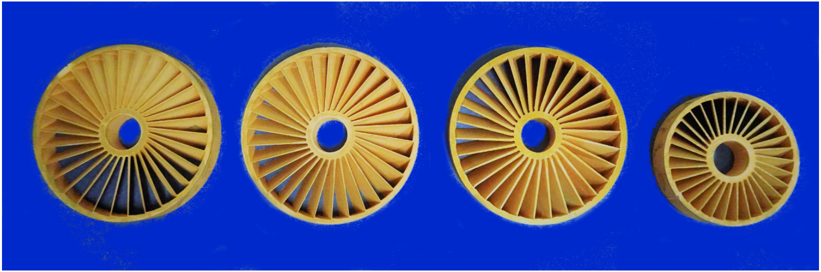
LT-HX element



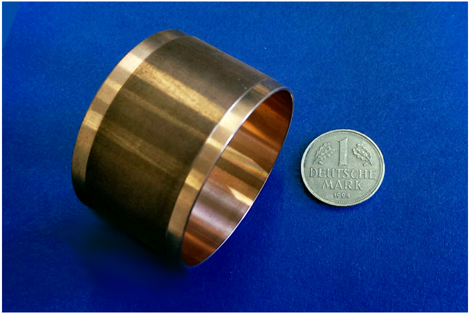
fine structure $\sim 0.3\,\mathrm{mm}$

Heat transfer between cold ^{3}He,^{4}He and "warm" ^{3}He,^{4}He

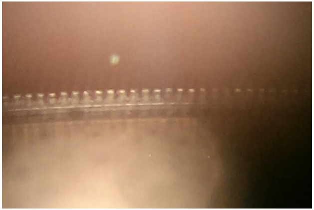
Pumping line elements from copper



Laser technology for mixing chamber

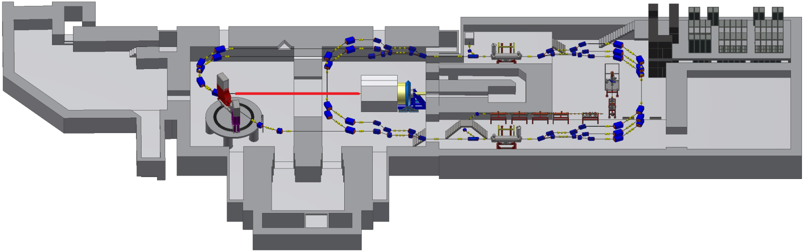


Instead of sintering MC



Fine grooves 200x100 μm
OFHC Copper

Position at MESA



Position of Møller polarimeter at MESA - red line

Summary

- The Møller polarimeter for MESA
- Collaboration or technology transfer necessary
  - Experience with superfluid helium films
  - Møller detector - looking for collaboration
  - Some technological efforts
  - Some design issues still have to be solved (e.g. FX-HX, Target "clearing")
- Hardware in fabrication
- Cooling down in 2019

Thank you for attention

Thank you for your attention!

Backup slides

Backup

Abstract

One aim for the new electron accelerator MESA is to measure the weak mixing angle in electron proton scattering to a precision of 0.14%. The beam polarization significantly contributes to this measurement. The Møller polarimeter proposed by V. Luppov and E. Chudakov opens the way to reach a sufficiently accurate determination of polarization. At the moment the polarized atomic hydrogen target is under construction. The current status is presented.

NR	Main view	Flow diagram	Stage	Offer, €
1	Port flange			3500, Vacom
2	Cross			3500, Vacom
3	Connector flange cryostat			5000, Vacom
4	Housing			7500, Pink, Vacom
5	High temperature HX	HT-HX		10000 + 20000 + 5000
6	Intermediate temperature HX	IM-HX		4000, brazing
7	Low temperature HX	LT-HX		7500 + 15000 + 5000
8	Final HX	FN-HX		
9	One-sided film burner			
10	Double-sided film burner			
11	Super conducting solenoid			
12	Connector flange solenoid			2500, Pink
13	Tees			
14	Output flange			
15	He4 - connections			
16	Mixing chamber	MC		
17	Thermally insulated mounting			
18	Still	Still		
19	Evaporator	Evaporator		2500 + Reuter
20	Needle valves	V1...V5		2500
21	Separator	Separator		2500
22	77 K shield	Shield 77K-20K		5000
23	Multi layer insulation			12000
24	Evaporator pump line			20000 Reuter, Pink
25	Condenser HX	CND1, CND2		5000

Contaminations and depolarization of the target gas

Ideally, the trapped gas polarization is nearly 100 % ($\sim 10^{-5}$ contamination).

No Beam

- Hydrogen molecules $\sim 10^{-5}$
- Upper states $|c\rangle$ and $|d\rangle < 10^{-5}$
- Excited states $< 10^{-5}$
- Helium and residual gas $< 0.1\%$ - measurable with the beam

At $100.0\,\mu\mathrm{A}$ e-beam

- Depolarization by beam RF $< 2 \times 10^{-4}$
- Ion, electron contamination $< 10^{-5}$
- Excited states $< 10^{-5}$
- Ionization heating $< 10^{-10}$
- Expected depolarization $< 2 \times 10^{-4}$

Gas properties

- Atom velocity $\approx 80\,\frac{\mathrm{m}}{\mathrm{s}}$
- Atomic collisions $\approx 1.4 \times 10^5\,\mathrm{s}^{-1}$
- Mean free path $\lambda \approx 0.6\,\mathrm{mm}$
- Wall collision time $t_R \approx 2.0\,\mathrm{ms}$
- Escape (10 cm drift) $t_{es} \approx 1.4\,\mathrm{s}$

Beam impacts on the target - RF influence

For example at $100.0\,\mu\mathrm{A}$ beam current

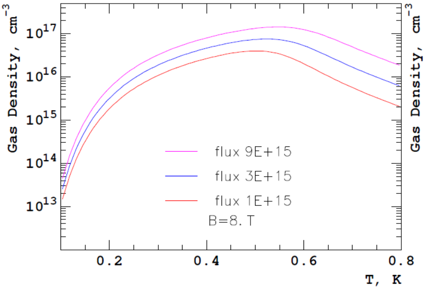
- $|a\rangle \rightarrow |d\rangle$ and $|b\rangle \rightarrow |c\rangle \sim 200\,\mathrm{GHz}$
- Checked for CEBAF. RF spectrum is flat $< 300\,\mathrm{GHz}$
- $\sim 10^{-4}\,\mathrm{s}^{-1}$ conversions (all atoms)
- $\sim 6\,\%$ conversions (beam area)
- Diffusion: contamination
- $\sim 1.5 \times 10^{-4}$ in the beam areas
- Solution: solenoid tune to avoid resonances
- For MAMI and MESA to be checked.

Beam impacts on the target - gas ionization

- $\sim 10^{-5}\,\mathrm{s}^{-1}$ of all atoms
- $\sim 20\,\%$ in the beam area
- Problems:
  No transverse diffusion (charged)
  Recombination suppressed
  Contamination 40 % in beam
- Solution: electric feld $\sim 1.0\,\frac{\mathrm{V}}{\mathrm{cm}}$ Cleaning time $\sim 20\,\mu\mathrm{S}$
  Contamination $< 10^{-5}$

See more details in backup

Stable gas density



Dependence of the stable gas density on temperature (at $8\,\mathrm{T}$) and the magnetic field (at $0.300\,\mathrm{K}$) for different incoming fluxes of hydrogen. The incoming flux has to balance the losses due to surface recombination and the thermal escape through the field gradient. The latter component dominates at $T > 0.55$ K.

Beam impacts on the target - gas ionization

At $I_{beam} = 150.0\,\mu\mathrm{A}$, $E_{beam} = 150.0\,\mathrm{MeV}$, $d_{beam} = 0.1\,\mathrm{cm}$

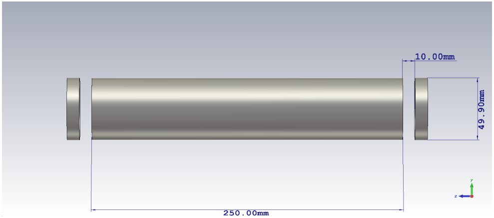
$$N_{ion} = \frac{\partial E}{\partial z}\,\rho\,L_H \times \frac{I_{beam}}{q_e} \times \frac{1}{E_i} \sim 3.6 \times 10^{13}\,\mathrm{s}^{-1}$$

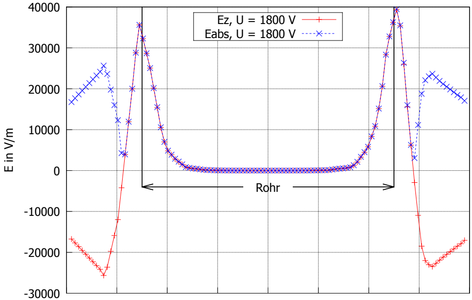
$$N_{beam\ area} = n\,\frac{\pi}{4} d_{beam}^2\,L_H \sim 1.9 \times 10^{15}$$

$$\frac{N_{ion}}{N_{beam\ area}} \sim 0.075$$

where: $\rho = n_H m_p = 5.0 \times 10^{-9}\,\frac{\mathrm{g}}{\mathrm{cm}^3}$– gas density,
$n_H = 3.0 \times 10^{15}\,\mathrm{cm}^{-3}$ – gas concentration, m_p – mass of proton,
$\frac{\partial E}{\partial z} = 7.35\,\frac{\mathrm{MeV}\times\mathrm{cm}^2}{\mathrm{g}}$ –total stopping power at $150\,\mathrm{MeV}$
$E_i = 19.2\,\mathrm{eV}$ – ionization energy, q_e – electron charge

Beam impacts on the target - gas ionization





- Two electrodes
- $\pm 1800\,\mathrm{V}$

CMC simulation S. Friedrich

Dynamic Equilibrium and Proton Polarization

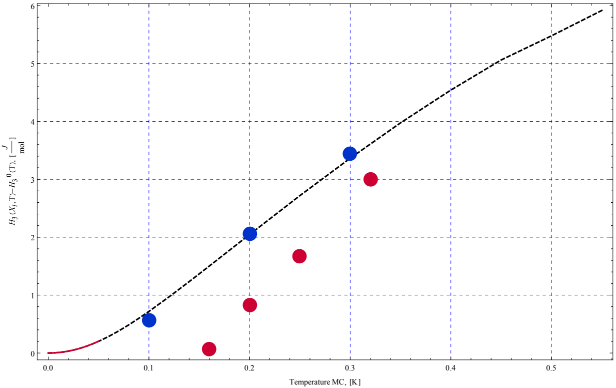
Proton polarization builds up, because of recombination of states with opposite electron spins: $|a\rangle$ $|\uparrow\downharpoonright\rangle \cos(\theta) - |\downarrow\upharpoonright\rangle \sin(\theta)$ and $|b\rangle$ $|\downarrow\downharpoonright\rangle$

As a result, $|a\rangle$ dies out and only $|b\rangle$ is left!

ESR method , van Yaperen et al 1983

Nuclear polarization $P \to 0.8$

Normalized cooling power

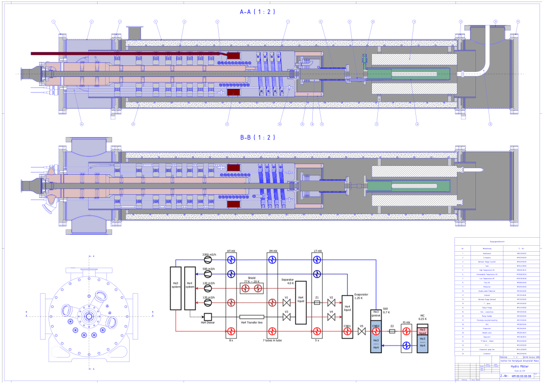


The dashed line shows the ideal performance, i.e. $T_{ex} = T_{mc}$ and $Q_{leak} = 0$, red line - $82 \times T^2$, red circles - MARK-II, degradation, blue circles - JLAB Frozen spin target.
Exsample: $\mu_4 = const$, $T_{still} = 0.9\,\mathrm{K}$, $T_{mc} = 0.3\,\mathrm{K}$, $X_{still} = 0.035$, $X_{vapor} = 0.95$

Atomic hydrogen feed system

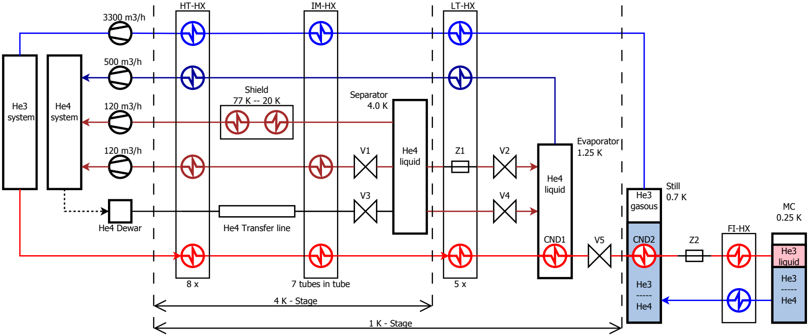
The cell is filled with atomic hydrogen from an RF dissociator. Hydrogen passes through a Teflon pipe to a nozzle, entering at 30 K a system of helium coated baffles, where it is cooled down to 0.3 K. At 30 K no recombination occurs because of the high temperature, while at 0.3 K it is suppressed by helium coating. In the input flow, the atoms and molecules are mixed in comparable amounts, but most of the molecules are frozen out in the baffles and do not enter the cell.
The gas arrives to the area of a strong field gradient which separates at this moment the lower and higher atomic energy states, therefore a constant feeding of the cell does not affect the average electron polarization.

Cryostat unit and storage cell

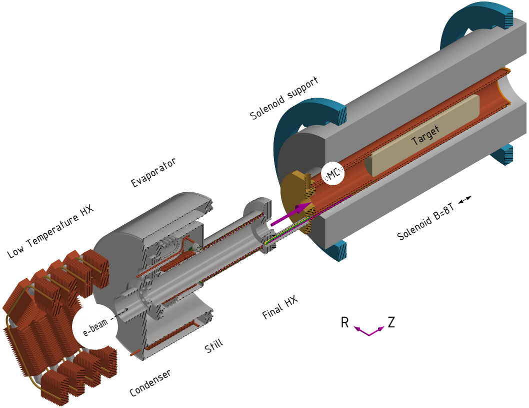


- Cryostat insert
- Housing
- Storage cell
- Dimensions:
  $L \sim 2.5\,\mathrm{m}, D \sim 0.50\,\mathrm{m}$
- Under construction: Uni Mainz, Reuter Tech. GmbH, Witzenmann GmbH.

Flow diagram

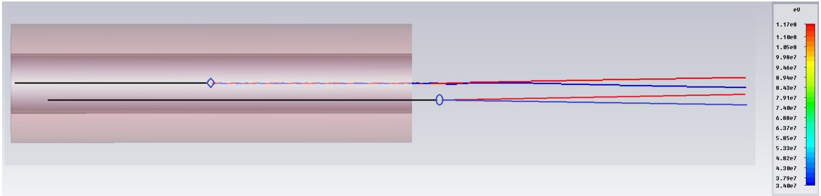


View of 1K stage



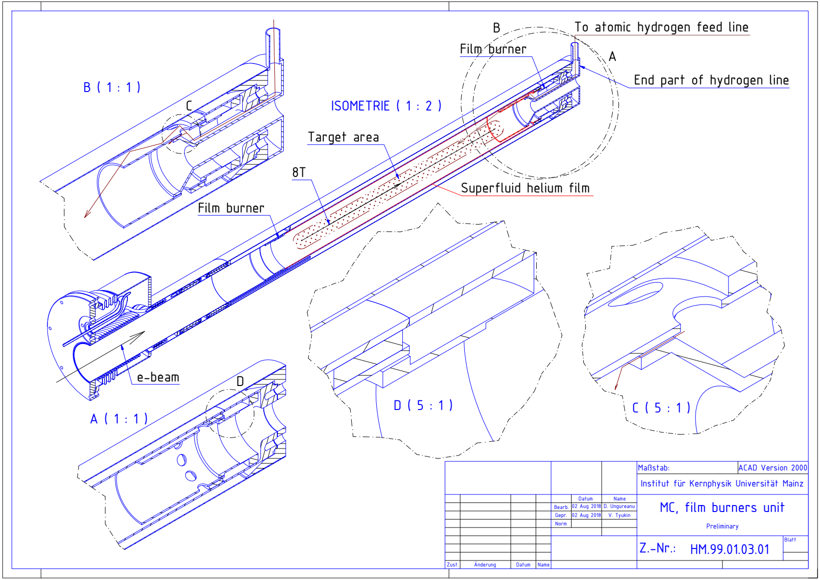
- Commissioning of dilution stage is still required
- Special thanks for advices and support JLAB, CERN, JINR staff

Storage cell and detector

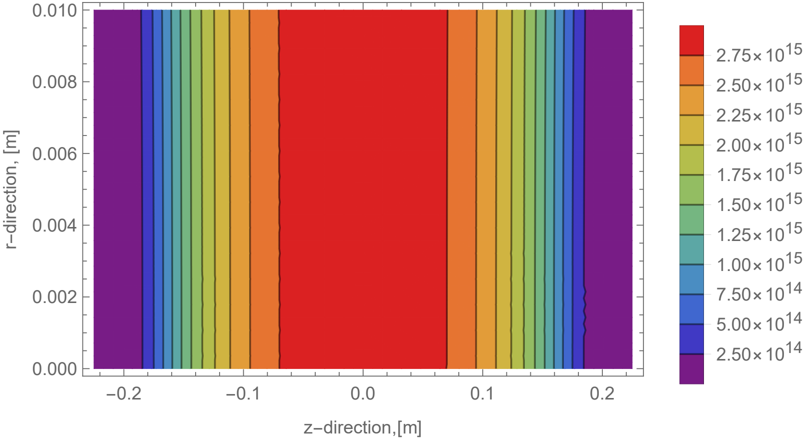


- Upper lines - scattering on hydrogen atom
- Down lines - scattering on residual gases atom
- $e^- + e^- \rightarrow e^- + e^-$, $150.0 + 0.0 \rightarrow 116.0 + 34.0$ in MeV
- Vertex reconstruction in Møller detector is necessary, R&D
- Target "cleaning" because beam impacts on the target - gas ionization

Some technological problem and efforts

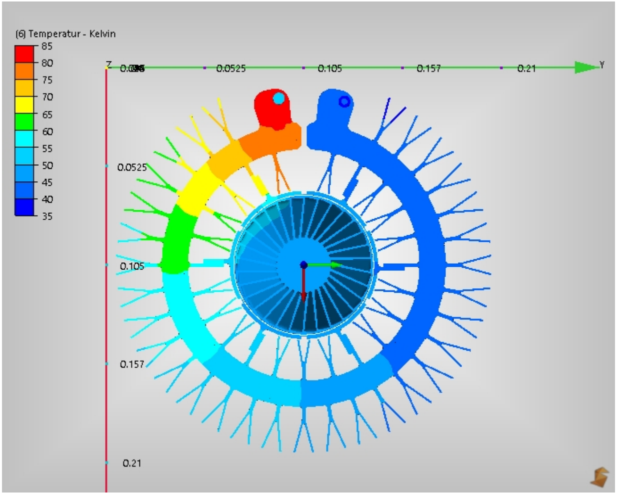


Density inside of solenoid (scaled)



(Z/ρ-scale not proportional)

Thermal simulation using CFD 2015 of HT-HX



Film burners: UMI weekly jet report 8/21-8/25/89[1]

- The results with this new film burner were very encouraging
- $p_{vac} = 2.5 \times 10^{-6}\,\mathrm{torr}$ at $3.0\,\mathrm{mW}$ heating power, $T_{burner} = 0.700\,\mathrm{K}$
- $p_{vac} = 2.0 \times 10^{-6}\,\mathrm{torr}$ without film
- It was possible to build up a thick film

[1] Uni Michigan H-Jet Collaboration. *Computation Book 1-6*. 1988-1991.