# Status of the Polarized Atomic Hydrogen Target at MAMI & MESA

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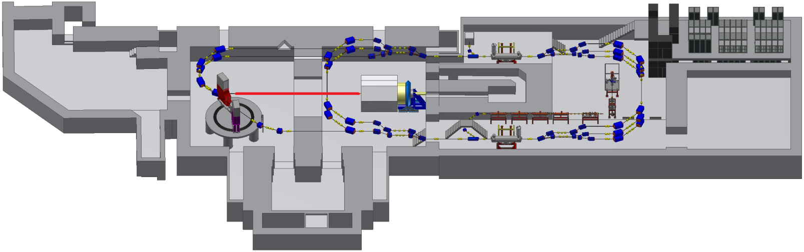
SFB 1044
THE LOW-ENERGY FRONTIER
OF THE STANDARD MODEL

PRISMA

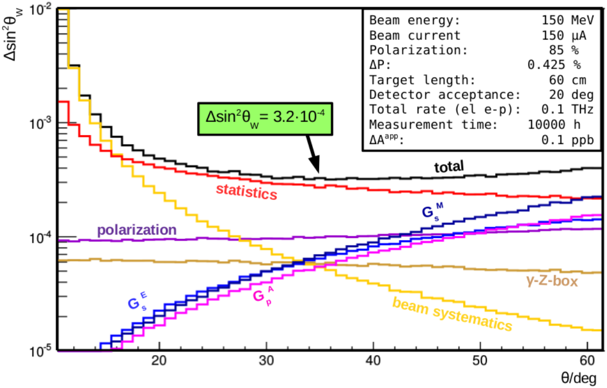
# Contents

# MESA



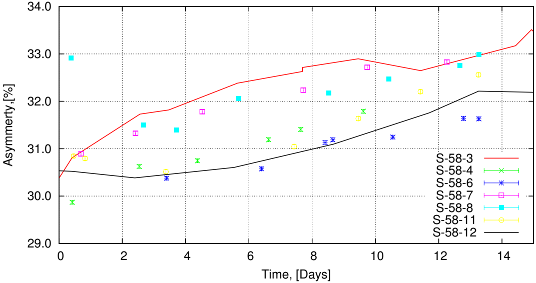
- The P2 Experiment - A future high-precision measurement of the electroweak mixing angle at low momentum transfer: arXiv:1802.04759
- Accelerator physics: multi-turn, superconducting ERL
- New technique for nuclear and particle physics PIT
- CW spin polarized electron beam
- Beam current $\sim 150 - 1000\,\mu\mathrm{A}$, beam energy $\sim 155\,\mathrm{MeV}$

# P2 Experiment at MESA. arXiv:1802.04759



- Aim is to measure the weak mixing angle $\sin^2\theta_w$ in electron proton scattering to precision 0.14%
- Beam polarization significantly contributes in precision

# MAMI and MESA Photo cathodes



- $I_{\mathrm{MAMI}} \sim 100.0\,\mu\mathrm{A}$
- $E_{\mathrm{MAMI}} \sim 180.0 - 1500.0\,\mathrm{MeV}$,
- $P_{\mathrm{MAMI}} \sim 0.85$
- 7 days/24 hours

- MAMI & MESA 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 MAMI and MESA

- Mott polarimeter at 3.5 $\mathrm{MeV}$ and at 5.0 $\mathrm{MeV}$
- Double Mott polarimeter at 100.0 $\mathrm{keV}$
- Møller polarimeter with Iron Target at $180.0 - 1600.0\,\mathrm{MeV}$
- Møller polarimeter with Polarised Atomic Hydrogen Target at $50.0 - 1600.0\,\mathrm{MeV}$. Proposed in 2004 and revised in 2012 E. Chudakov (JLAB) and V. Luppov (Janis Research Co.)
- The goals at MAMI $P_{\text{Mott, 3.5 MeV}} = P_{\text{Møller, Fe}}$
- The goals at MESA $P_{\text{Mott, 5.0 MeV}} = P_{\text{Mott, double}} = P_{\text{Møller, H}}$
- Accuracy $\Delta P < 0.5\%$
- Online measurements

# The main idea of Polarized Atomic Hydrogen Target

Møller scattering of electron beam

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

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

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

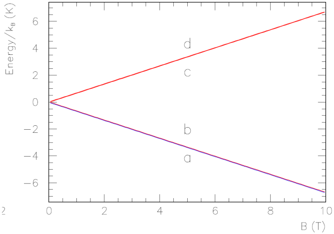
it would be more convenient with: $a_{zz}^{max} = -\frac{7}{9}$, $P^T = 1.00$

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

# 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:

$|a\rangle \; |{\uparrow}{\not\downarrow}\rangle \cos(\theta) - |{\downarrow}{\not\uparrow}\rangle \sin(\theta)$

$|b\rangle \; |{\downarrow}{\not\downarrow}\rangle$

High energy:

$|c\rangle \; |{\downarrow}{\not\uparrow}\rangle \cos(\theta) + |{\uparrow}{\not\downarrow}\rangle \sin(\theta)$

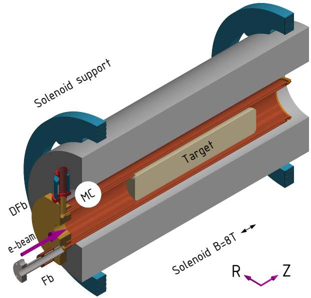
$|d\rangle \; |{\uparrow}{\not\uparrow}\rangle$

Mixture $\sim 53\%$ of $|a\rangle$ and $\sim 47\%$ of $|b\rangle$

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

- $H + H \rightarrow H_2$ 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

.

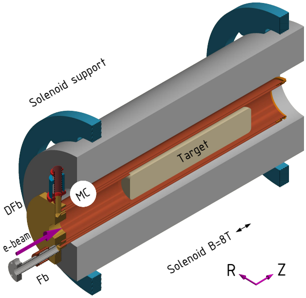
Trapping in Z-direction

- 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



- $L_H = 0.20\,\mathrm{m}$,
- $D_H = 0.02\,\mathrm{m}$,
- $\rho_H = 3.0 \times 10^{15}\,\mathrm{cm}^{-3}$
- Gas lifetime $\sim 1.0\,\mathrm{hour}$
- M. Mertig et al.
  Rev. of Sci. Inst. 62.1 (1991)
- I. F. Silvera and J. T. M. Walraven.
  Phys. Rev. Lett. V.44, N.3 (1980)
- E. Chudakov
  Nuovo Cim, V. C35, N.4 (2012)

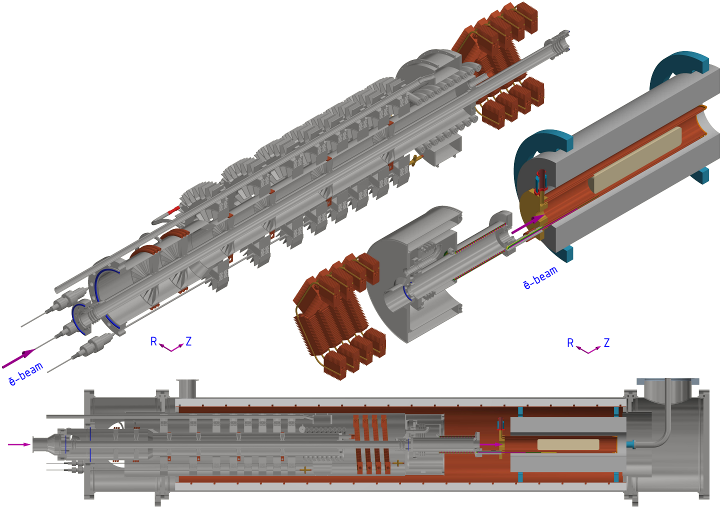
**Nobody has put the target in the high power beam**

# Requirements to cryostat: heat load, cooling power

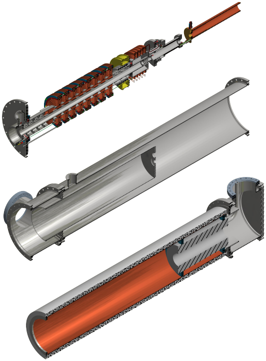
- Super fluid $^4$He film coated wall at $T_{\text{wall}} = 0.25 - 0.30\,\mathrm{K}$
- $P_{rec} = \frac{1}{2}\ \dot{n}_H\ E_{rec}\ q = 10.0\,\mathrm{mW}$, – where $\dot{n}_H = 3.0 \times 10^{16}\,\mathrm{s}^{-1}$ feed rate of atomic hydrogen , q-electron charge,
  $E_{rec} = 4.45\,\mathrm{eV}$ - H-pair recombination energy
- $P_{fb}$=$10.0\,\mathrm{mW}$, – film burners and transition unit
- $P_{bb}$=$25.0\,\mathrm{mW}$, – estimated black body radiation to mixing chamber from warm parts of beam line.
- $P_{cooling}$=$P_{rec} + P_{fb} + P_{bb} = 45.0\,\mathrm{mW}$
- $P_{cooling} \sim 45.0\,\mathrm{mW}$ at $T_{mc} = 0.25\,\mathrm{K}$ and $\dot{n}_{He3} = 16.5\,\frac{\mathrm{mmol}}{\mathrm{s}}$ in ideal case
- $P_{precooling} \sim \dot{n}_{He3} \times C_p \times (T_{room} - T_{mc}) \sim 250.0\,\mathrm{W}$
- $P_{cooling} \sim 60.0\,\mathrm{mW}$ at $T_{mc} = 0.25\,\mathrm{K}$ and $\dot{n}_{He3} = 40.0\,\frac{\mathrm{mmol}}{\mathrm{s}}$ in real case

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

# Horizontal cryostat

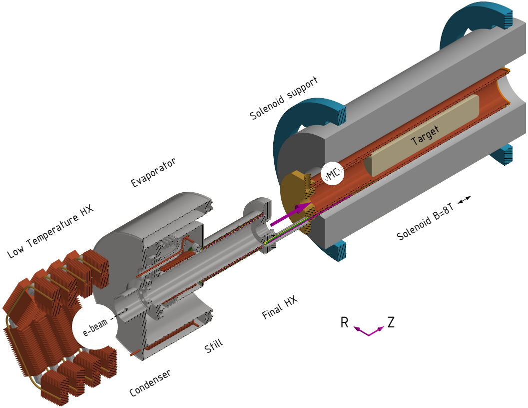


# Polarimeter components = Dilution cryostat + Storage cell + Møller Detector



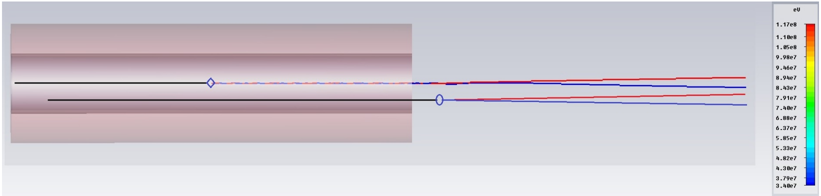
- Horizontal oriented dilution cryostat – mixing $^{3}$He in $^{4}$He
- Cryostat insert (up)
- Cryostat housing (middle)
- Superconductive magnet, thermal shield and atomic hydrogen feed system (down)
- Detector of Møller polarimeter (not shown) → JLAB, W&M
- Dimensions: $L \sim 2.5 + 2.0\,\mathrm{m}$, $D \sim 0.50\,\mathrm{m}$
- Funding applied ∼ 1 M €
- Under construction: JGU Mainz

# View of 1K stage



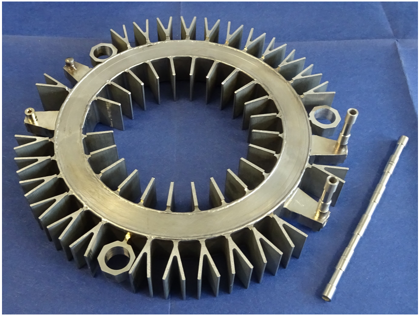
- Commissioning of dilution stage is still required
- Special thanks for advices and support JLAB, CERN, JINR staff

# Storage cell and detector

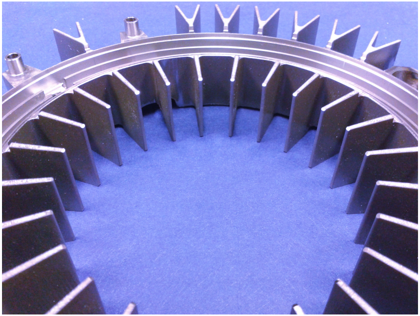


- Upper lines - scattering on hydrogen atom
- Down lines - scattering on residual gases atom
- $e^- + e^- \rightarrow e^- + e^-$, $150.0 + 0.0 \rightarrow 116.0 + 34.0$ in MeV
- Vertex reconstruction in Møller detector is necessary, R&D
- Target "cleaning" because beam impacts on the target - gas ionization

# Three way counter flow HX from SS

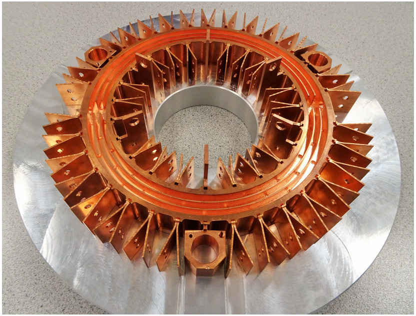


HT-HX from SS
complete welding system

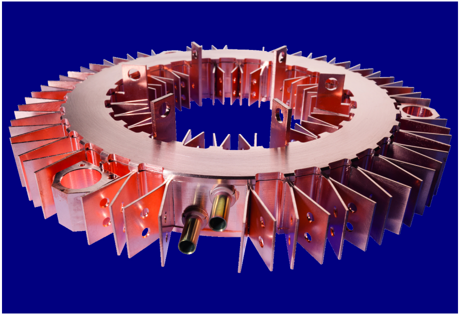


HT-HX from SS
before welding

# Three way counter flow HX from Cu

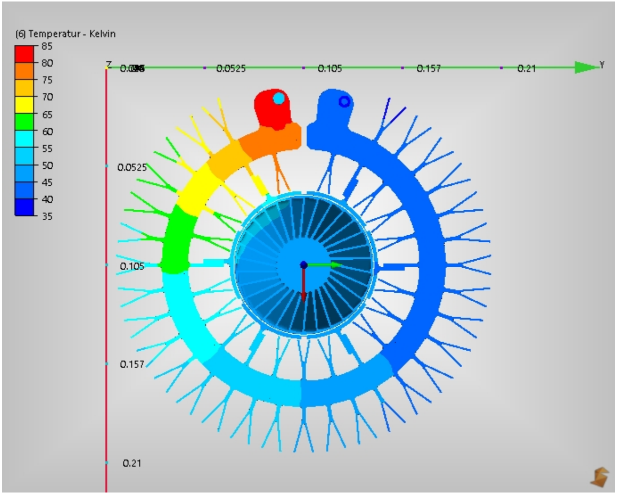


HT-HX plate before soldering

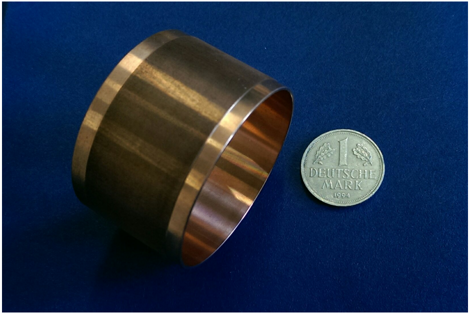


HT-HX from OFHC-Cu

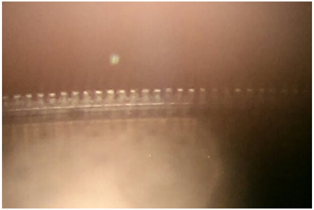
# Thermal simulation using CFD 2015 of HT-HX



# Laser technology for mixing chamber



Instead of sintering MC



Fine grooves 200x100 $\mu$m
OFHC Copper

# Film burners: UMI weekly jet report 8/21-8/25/89$^{\textbf{BNL-Book}}$

- 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

# 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 all time, when installed on beam line
- Need separate bypass electron beam line
- Warm up – cool down cycles – problem

Proposed and discussed FZ Julich

- The idea the preselect hydrogen molecules and atoms
- Suppress flux of $H_2$ and $H_1$ at $|c\rangle$ and $|d\rangle$
- Inlet only $H_1$ at $|a\rangle$ and $|b\rangle$
- Losses to be compensate $\sim 1.5 \times 10^{13}\,\frac{\mathrm{atom}}{\mathrm{s}}$
- It seems continuous operation possible

## Time table

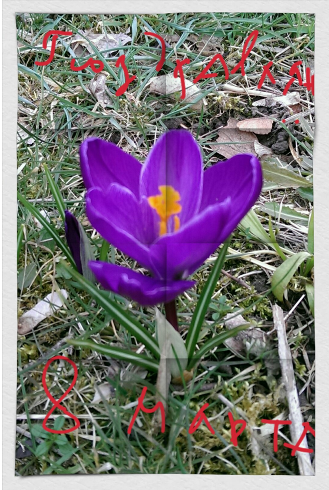
| Module | Ready | Status | Remarks & Problems |
|---|---|---|---|
| Cryostat housing | Oct-2018 | R&D<br>Construction<br>Depends on HE design | Using Super-MLI<br>Accurate positioning of solenoid |
| Stage 1.00 K | Oct-2018 | Development<br>Construction<br>Under production | HT–HX<br>IM–HX<br>LT–HX<br>Valves |
| Stage 0.25 K | Oct-2019 | R&D | FI–HX<br>Mixing Chamber<br>Film burners<br>Sintering technology<br>not yet under control<br>need about one year time |
| Hydrogen feed system | Oct-2019 | R&D | Literature references<br>Transition unit not ready |
| Super conducting solenoid | Oct-2019 | Test old or bay new | |
| Detection system | Apr-2020 | R&D | Collaboration ? |
| Pumping system | Oct-2019 | Not yet funded | $^{3}$He Still<br>$^{4}$He Evaporator<br>$^{4}$He Separator<br>$^{4}$He IM–HX |
| $^{3}$He - Filling | Oct-2019 | Not yet funded | Volume = $200\,\mathrm{l}$ STP |
| Target test | after 2020 | | |

# Summary

- The Møller polarimeter for MESA
- Collaboration or technology transfer necessary
    - The best channel configuration for concentrated and dilution phases
    - Experience with superfluid helium films
    - and more ???
- Møller detector - looking for collaboration
- Some technological efforts
- Some design issues still have to be solved (e.g. FX-HX, Target "clearing")

# Thank you for attention

Thank you for your attention!



Поздравляем с днем 8 марта!

# Backup slades

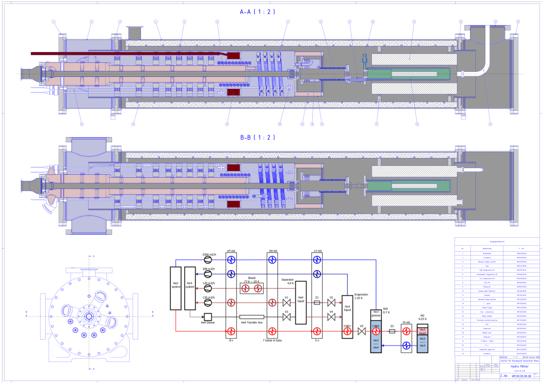
Backup

# Abstract

One aim for the new electron accelerator MESA is to measure the weak mixing angle in electron proton scattering to a precision of 0.13%. 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.

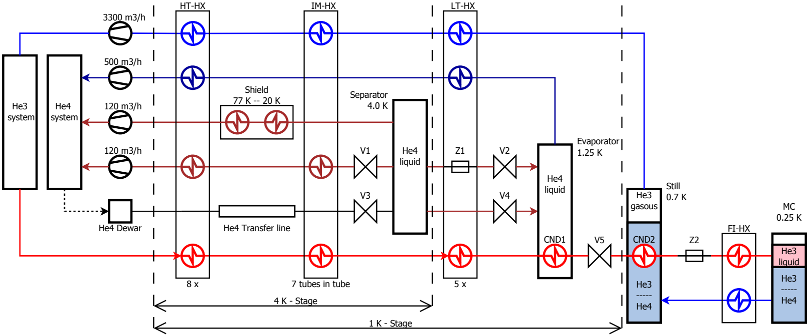
| NR | Main view | Flow diagram | Stage | Offer, € |
|---|---|---|---|---|
| 1 | Port flange |  | 🟦 | 3500, Vacom |
| 2 | Cross |  | 🟦 | 3500, Vacom |
| 3 | Connector flange cryostat |  | 🟦 | 5000, Vacom |
| 4 | Housing |  | 🟦 | 7500, Pink, Vacom |
| 5 | High temperature HX | HT-HX | 🟦 | 10000 + 20000 + 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 |

# Cryostat unit and storage cell



- Cryostat insert
- Housing
- Storage cell
- Dimensions: $L \sim 2.5\,\mathrm{m}$, $D \sim 0.50\,\mathrm{m}$
- Funding applied ~ 1 M €
- Under construction: Uni Mainz, Reuter Tech. GmbH, Witzenmann GmbH.

# Flow diagram



# Beam impacts on the target - gas ionization

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

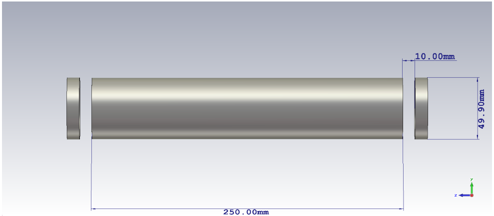
$$N_{ion} = \frac{\partial E}{\partial z}\,\rho\,L_H \;\times \frac{I_{beam}}{q_e} \times \frac{1}{E_i} \sim 3.6 \times 10^{13}\,\mathrm{s}^{-1}$$

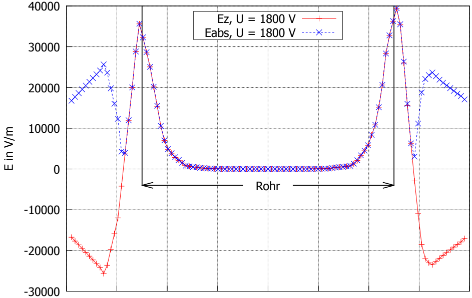
$$N_{beam\ area} = n\,\frac{\pi}{4} d^2_{beam}\,L_H \sim 1.9 \times 10^{15}$$

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

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





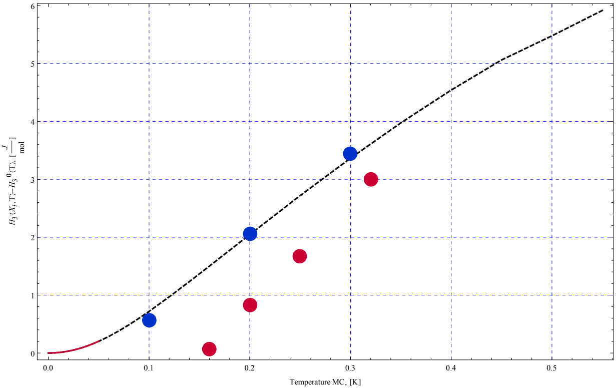
- Two electrodes
- $\pm 1800\,\mathrm{V}$

CMC simulation S. Friedrich

# Dynamic Equilibrium and Proton Polarization

Proton polarization builds up, because of recombination of states with opposite electron spins: $|a\rangle$ $|\uparrow\ddagger\rangle\cos(\theta) - |\downarrow\dagger\rangle\sin(\theta)$ and $|b\rangle$ $|\downarrow\ddagger\rangle$
As a result, $|a\rangle$ dies out and only $|b\rangle$ is left!
ESR method , van Yaperen et al 1983
Nuclear polarization $P \rightarrow 0.8$

# Normalized cooling power, degradation



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: $\mu_4 = const$, $T_{still} = 0.9\,\mathrm{K}$, $T_{mc} = 0.3\,\mathrm{K}$, $X_{still} = 0.035$, $X_{vapor} = 0.95$

# Contaminations and depolarization of the target gas

Ideally, the trapped gas polarization is nearly 100 % ($\sim 10^{-5}$ contamination). Good understanding of the gas properties (without beam).

Contamination and Depolarization 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

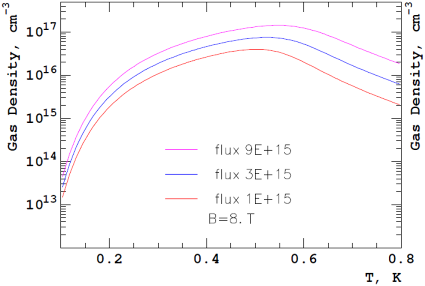
- $|a\rangle \rightarrow |d\rangle$ and $|b\rangle \rightarrow |c\rangle \sim 200\,\mathrm{GHz}$
- Checked for CEBAF. RF spectrum is flat $< 300\,\mathrm{GHz}$
- $\sim 10^{-4}\,\mathrm{s}^{-1}$ conversions (all atoms)
- $\sim 6\,\%$ conversions (beam area)
- Diffusion: contamination
- $\sim 1.5 \times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

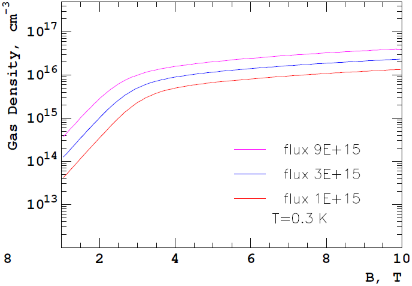
# Beam impacts on the target - gas ionization

- $\sim 10^{-5}\,\mathrm{s}^{-1}$ 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.

Back to proposal E. Chudakov and V. Luppov (original text)

# 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.

# 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 all time, when installed on beam line
- Need separate bypass electron beam line
- Warm up – cool down cycles – problem

Proposed and discussed FZ Julich

- The idea the preselect hydrogen molecules and atoms
- Suppress flux of $H_2$ and $H_1$ at $|c\rangle$ and $|d\rangle$
- Inlet only $H_1$ at $|a\rangle$ and $|b\rangle$
- Losses to be compensate $\sim 1.5 \times 10^{13}\,\frac{\mathrm{atom}}{\mathrm{s}}$
- It seems continuously operation possible