The MESA project

The **M**ainz **E**nergy Recovering **S**uperconducting **A**ccelerator –a suggestion for a versatile experimental arrangement based on a compact accelerator

JLAB. June, 20, 2011
Kurt Aulenbacher for the
B1,B2 and A4 collaborations
at IKP Mainz

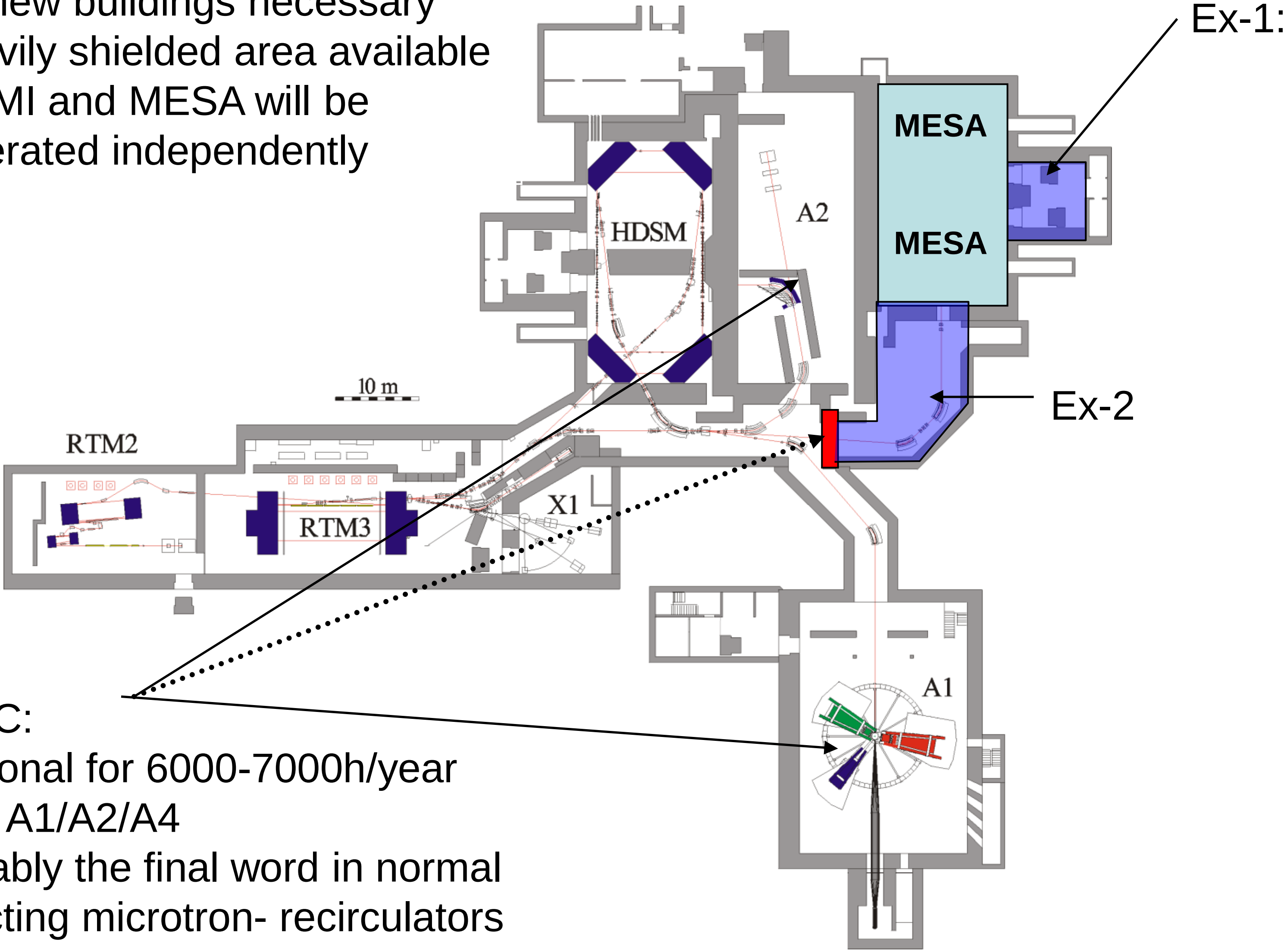
Outline

- MESA as research ‘engine’
- Accelerator physics issues at MESA
- Polarimetry for MESA-PV

….the eight-fold way to achieve $\Delta P/P < 0.5\%$?

MESA surroundings

- no new buildings necessary
- heavily shielded area available
- MAMI and MESA will be operated independently



MAMI-C:
operational for 6000-7000h/year
for exp A1/A2/A4
...probably the final word in normal conducting microtron- recirculators

MESA accelerator project rationale

- Experiments require a new & innovative accelerator
- low energy (100-200MeV) → therefore accelerator ‘affordable’
- MAMI acc. team competence represents basis for development
- Project will be attractive for young students and researchers

Make use of innovations in SRF accelerator science:

1. Energy recovery linac (ERL)
2. Improvements on high gradient-c.w.-SRF

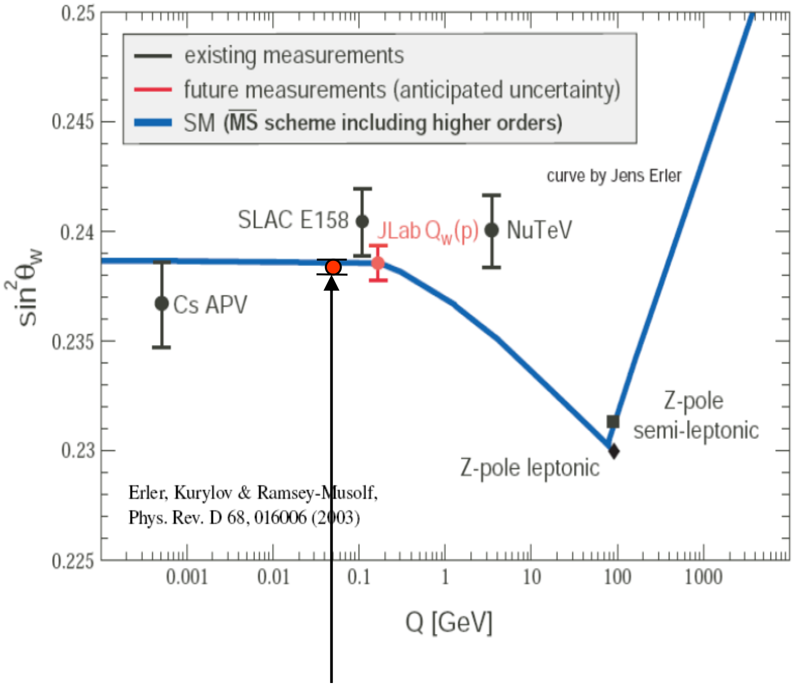
Beam parameter goals in two **different** modes of operation:

1.) EB-mode External spin-polarized c.w. beam (EB-mode) at 137 MeV (Q^2=0.005GeV/c at 30 degree). L>10^{39} $cm^{-2}s^{-1}$

2.) ERL-mode: 10mA at 100 MeV with L~10^{35} $cm^{-2}s^{-1}$

MESA-experiments:

1.) Parity violating elastic electron scattering



MESA-PV

- Measurement of PV asymmetry at low Q^2 is sensitive to 'new physics'
- JLAB runs 'Q_{weak}' at Q^2=0.02(GeV/c) E_{beam}=1.2GeV
- Exp. Asymmetry A_{exp}~ (1-4$\sin^2(\Theta_W)$)~140ppb (!)
- 3% Accuracy in A_{exp} → 0.5% in $\sin^2(\Theta_W)$
- model dependent corrections ~E_0

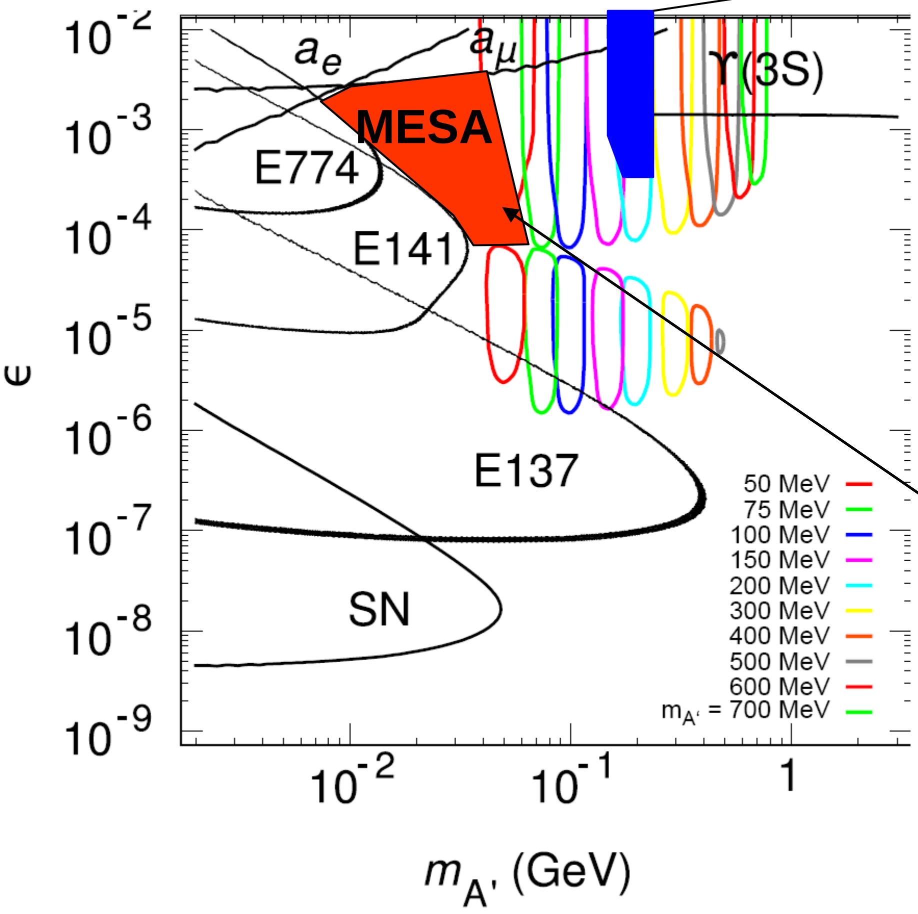
Improved parity experiment:

- low energy E_0 (small theory uncertainty)
- and even lower Q^2 (0.005$(GeV/c)^2$)
- optimized for control of systematic contributions to A_{exp}
- exclusive machine access and low running costs

→ MESA' workhorse' experiment
better statistics AND systematics:
1% Accuracy in A_{exp} → 0.15% in $\sin^2(\Theta_W)$

MESA-experiments-2- Search for Dark photon at MAMI/MESA

H. Merkel et al. (A1 collab. at MAMI): suggest to measure e+/e- pair invariant mass with double spectrometer set up at MAMI.



Demonstration experiment at MAMI $100\mu A$/855MeV on 0.4% rad. length Tantal
(2 weeks runtime)
(accepted for pub by PRL)

Limits:

- Low energy regime (background)
- other decay modes of A' ?
- runtime (several years ???)

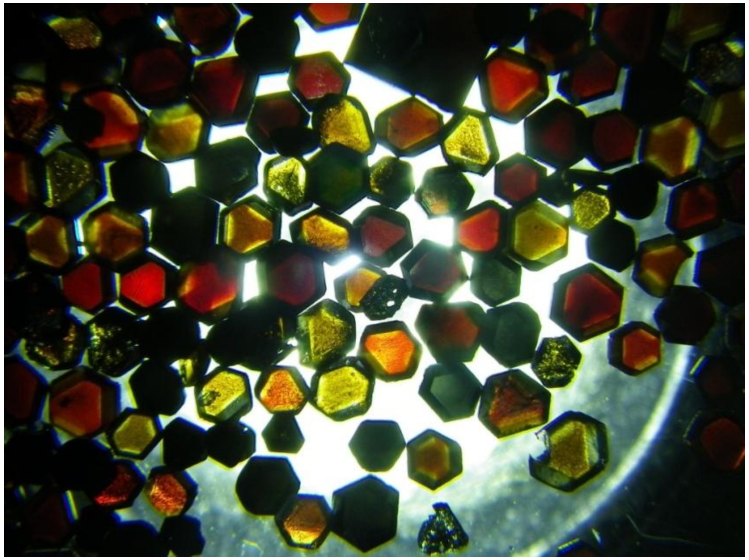
MESA's corner is adjacent to most of the a_μ region (interesting because of 3σ deviation of a_μ from SM)

MESA: Dedicated machine for $m_{A'}$ <100MeV with optimized background

MESA-experiments-3: Applied physics

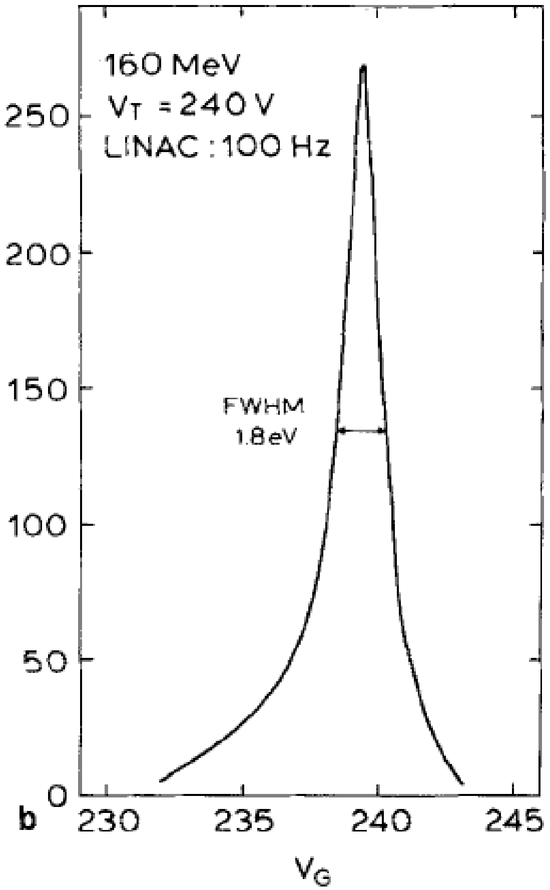
High beam power electron beam may be used for:

- ERL-mode: Production of NV-nanodiamonds (e.g. medical markers)
- EB-mode: High brightness source of cold (polarized) positrons



Color: NV-centers introduced in Diamond.
Irradiated at MAMI
for 3 days, 50µA at 14MeV

(J. Tisler et al. ACS NANO 3,7 p.1959 (2009))

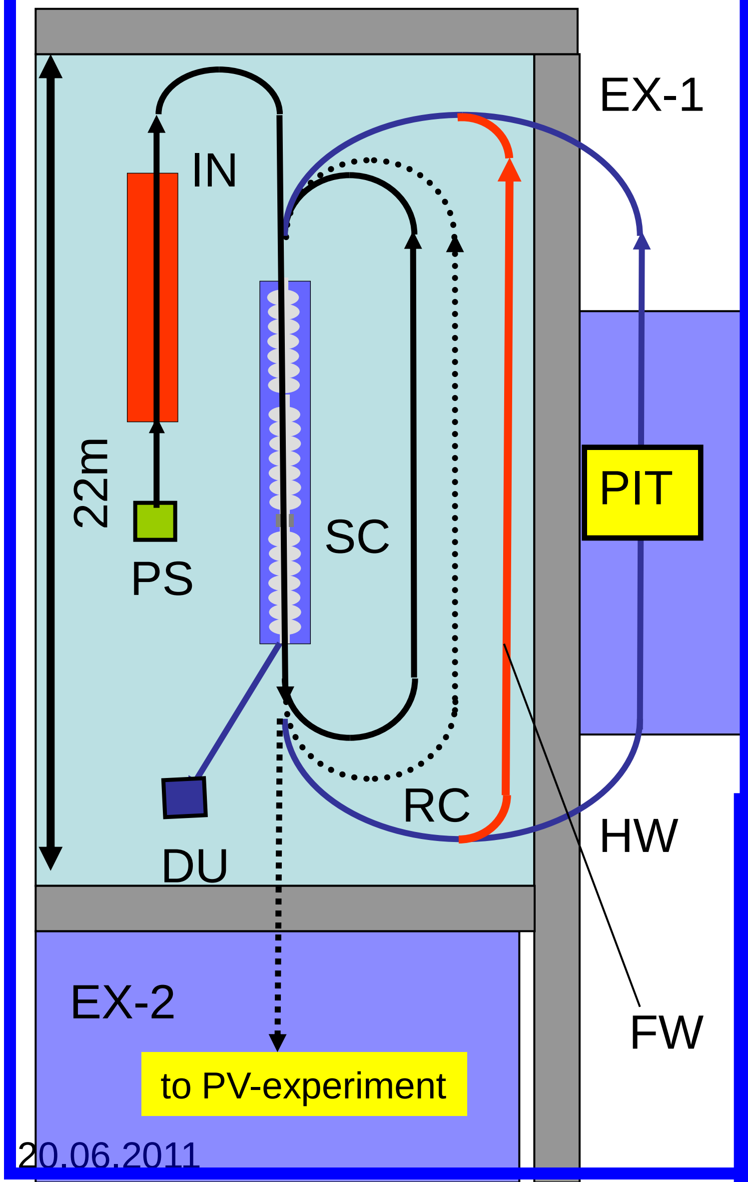


G. Werth et al. :
Appl. Phys. A 33
59 (1984)

→MESA
can produce
~10^9 positrons/s
in a beam of <1cm
diameter at 120eV
→surface science:
magnetic structure
→positronium
production

MESA-Layout

MESA-LAYOUT



KEY:

PS: Photosource (polarized or unpolarized beam)
IN: 2.5-5 MeV – NC injector
SC: 3 Superconducting cavities, @ 13 MV/m.
Energy gain 34 MeV per pass.
RC: Beam recirculation 3 times
HW: Third recirculation option ‘half wave’:
Energy Recovery Linac (ERL-) Mode
FW: Third recirculation option: ‘full wave’
External Beam (EB-) mode
PIT: Pseudo Internal target (ERL mode)
PV: Parity violation experiment (EB-mode)
DU: 2.5 MeV beam dump in ERL-mode
EX: Experimental areas 1 and 2

▨ Existing walls: 2-3m thick shielding

EXPERIMENTAL BEAM PARAMETERS:

1.3 GHz c.w.

EB-mode: 150 µA, 137 MeV polarized beam (liquid Hydrogen target L~10^{39})

ERL-mode: 10mA, 104 MeV unpolarized beam (Pseudo-Internal Hydrogen Gas target, L~10^{35})

MESA-beam parameters in comparison

Project/Purpose (status)	Av. Beam current (mA)	# of Recirc.	Norm. emit. (μm)	Bunch charge (pC)	Time structure
MESA/ particle physics (under design)	10	2-3	1-10	7.7	1300 MHz c.w.
JLAB/ light source (achieved)	10	1	7	135	75 MHz, c.w.
BERLinPro/light source demonstrator (under design, funded)	100	1	1	77	1300 Mhz, c.w.
eRHIC/particle physics (under design)	50	6			

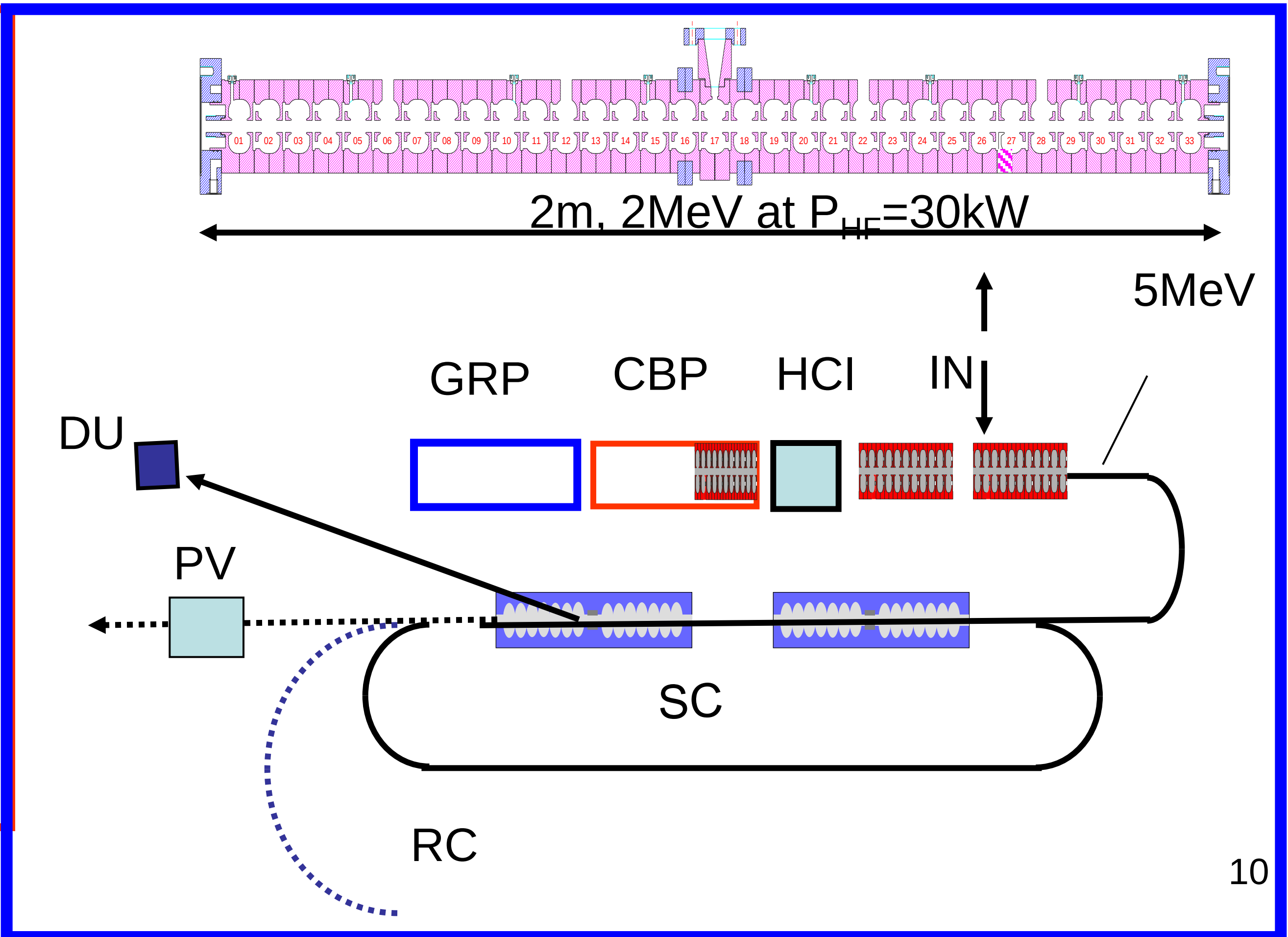
- MESA will **not** have to provide extreme bunch parameters (....is not a light source)
- New issue: **multi-turn recirculation** → MESA may be useful as a test-bench for LHeC, eRhic, or others….
- A **challenge** is compliance between ERL and EB operation
- costs,costs,costs! (minimize investment for cryogenics!)

Injector issues

Pro‘s for normal conducting injector:

- considerably lower cost, established design
- budget for cryogenics can be minimized
- RF/beam-power: ~ 3 at 10mA/5MV (300kW wallplug)
- compatibility between EB/ERL probably achievable

GRP: Gun/rotator/
polarimeter (EB-mode)
CBP: Chopper/buncher
Preacc. (g-beta)
HCI: 511keV high bunch
charge injection
(ERL-mode)
SC: three (four) cavities
33 (50) MeV/pass
13 (15)MeV/m
3 (2) recirculations
RC Recirculations
DU 5 MeV dump



Spin rotation

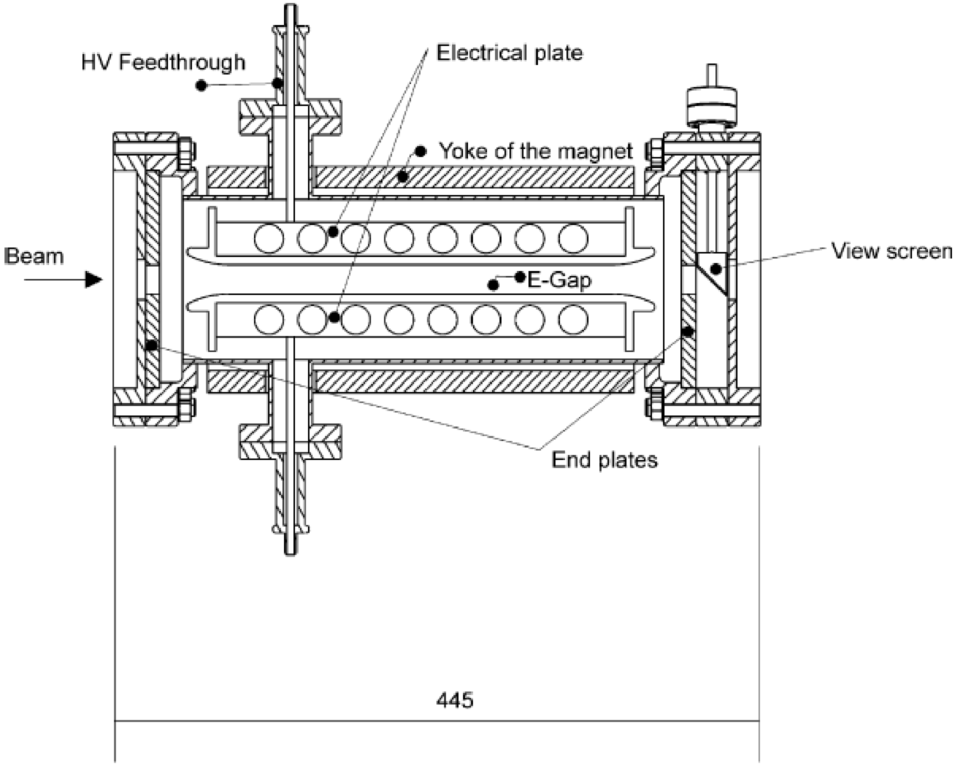


Fig. 1. Wien-filter cross-section, length is in mm.

V. Tioukine, K.A. NIM **A 568** 537 (2006)

$$\varphi_{Spin} = \frac{1}{m_e}\frac{1}{\gamma^2}EL$$

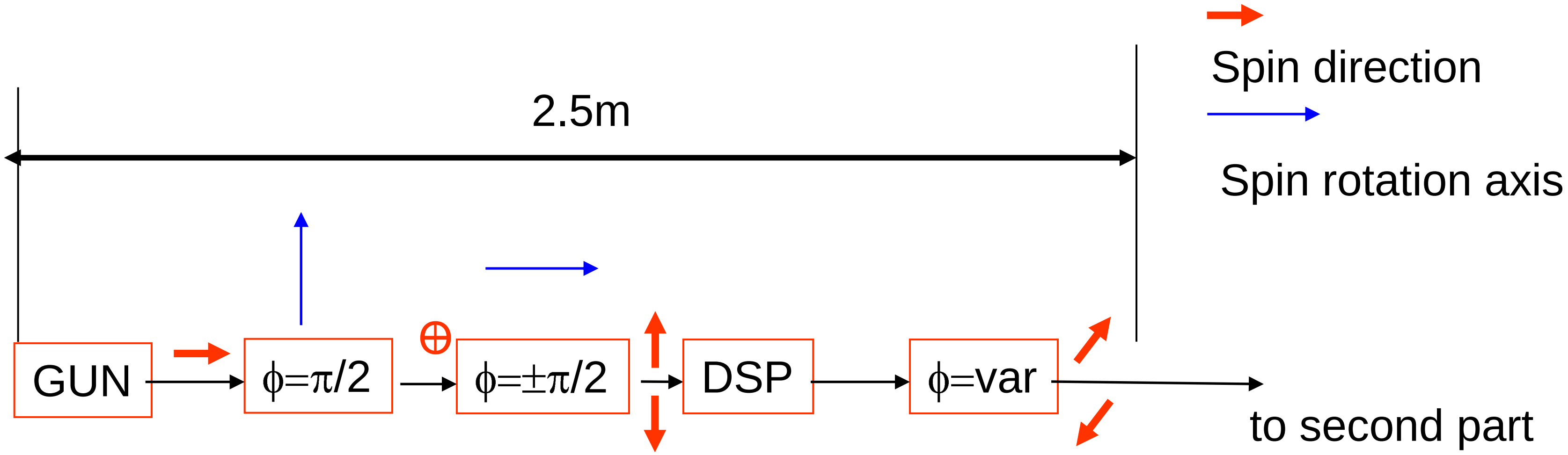
$$T_{21} = \frac{\varphi_{Spin}}{L}\gamma\sin(\gamma\varphi_{Spin}) \Rightarrow 0 < T_{21} < \frac{\pi\gamma}{2L}$$

100kV Filter, L=0.3m
operated at 23kV over 2cm gap

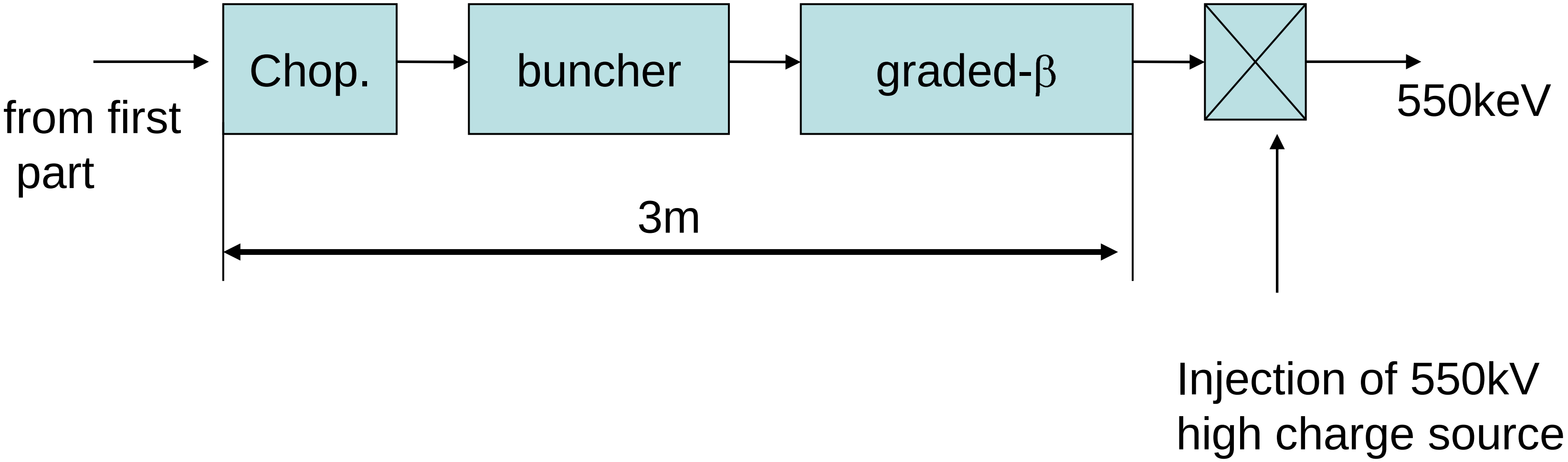
→not practical to handle filter at 500keV (γ=2), difficult at 200

For PV helicity switch (independent from fast optical switch) is desirable
→ realized at JLAB by double Wien (3-axis Spin roator for QWEAK)

Polarized injection layout



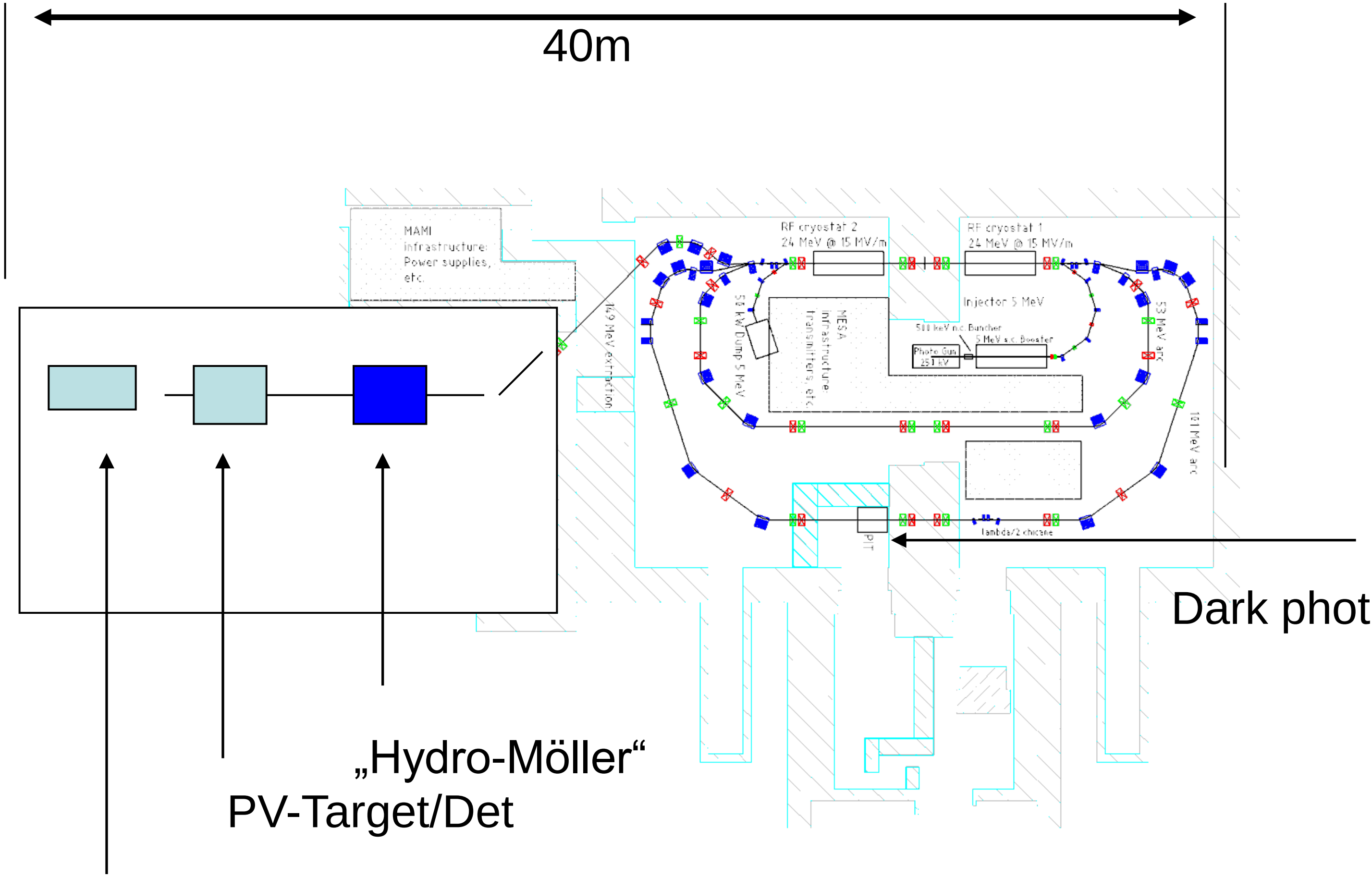
First part of pol. 100keV injector with spin rotator similar to JLAB/QWEAK



second part of pol. injector identical to MAMI

Recirculator challenges

- 10 mA in 2-3 fold SRF-recirculating system calls for specific HOM-control
- space & budget restrictions!
- So far no SRF infrastructure in house (but clean room & HPR… etc will be available)



40m

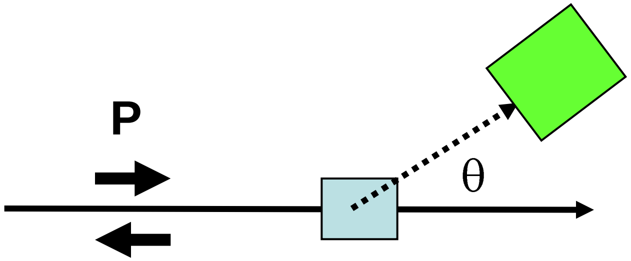
Dark photon-exp.

„Hydro-Möller“

PV-Target/Det

150MeV/20-100kW-Dump

PV is a simple experiment



$A_{exp}=(N\uparrow-N\downarrow)/(N\uparrow+N\downarrow)$

For elastic scattering on Hydrogen

$$A_{\exp} = P\left(\underbrace{(1-4\sin^2(\vartheta_W))Q^2}_{A_{PV}} * \underbrace{Korr + F(G^{E,M}_{P,N}(Q^2),Q^2,E_0\vartheta)}_{\text{minimize syst. errors by low } Q^2 \text{ and } E_0} \right) + A_{FALSE}$$

$$Korr(\gamma Z) \propto (1 + k(\gamma Z)E_0) \quad ;$$

$$\text{k}(\gamma Z) \text{ is not very well known !}$$

Penalty for choosing low Q^2: A_{PV} becomes very small (roughly 50 ppb)

→ Even at $L>10^{39}$ the experiment will need about 10000 hours BOT: Experiment cannot be done at MAMI without strong interference with ongoing program.

→ A_{False} must be controlled to <0.4 ppb: Improve established techniques from PVA4 by about an order of magnitude

→ $\Delta A_{PV}/A_{PV}=1\%$ → $\Delta P/P < 0.7\%$, better <0.5%.

Beam polarimetry is a simple experiment

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{0.\,proc} \cdot \left(1 + \sum_{i=x,y,z} S_i(\vartheta)\cdot P_i^{Beam} + \sum_{i,j=x,y,z} S_{i,j}(\vartheta)\cdot P_i^{Beam} P_j^{T}\right)$$

Processexamples: Elastic Electron(Mott-)scattering: S_y

Möller- or Compton - Backscattering : S_{zz}

$$\mathrm{A}_{\mathrm{Mott}} = P_y^{BEAM} \underbrace{S_y(\vartheta, E...)}_{\text{to be determined.}} \;\; ; \;\; \mathrm{A}_{\mathrm{Möller}} = P_z^{BEAM} \underbrace{P_z^{\mathrm{Target}} S_{zz}(\vartheta, E...)}_{\text{to be determined.}}$$

Desired::

1.) Online operation at experimental beam conditions,

2.)ΔP/P <0.5%,

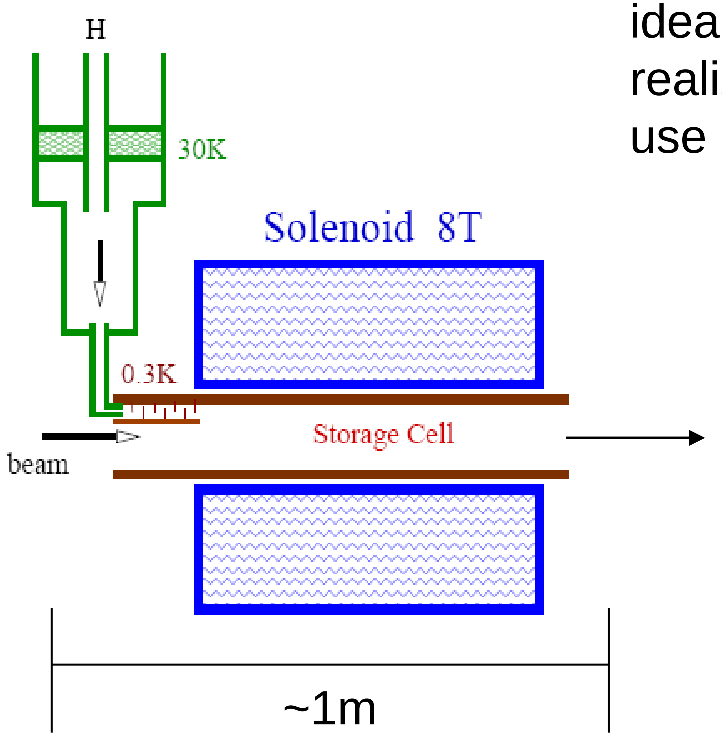
3.) fast polarization monitoring.

Probably the best approach: The “Hydro-Möller”-Polarimeter

- Online operation possible
- low Levchuk effect (Z=1 vs Z=26 conventional)
- very high $P_T S_{zz}$→ good efficiency in spite of low count rate statistics to 0.5% within about 30min
- P^{Target}=1-ε→ small Target polarization error (ε~10^{-5})
- Problem: Not realized yet→how does it work?

Principle of Hydro-Möller

Proposed by Chudakov&Luppov, Proceedings IEEE Trans. Nucl. Sc. 51 (2004)…



idea:
realize Hydro-Möller at MESA,
use it later for JLAB-Möller exp.

exp.

Solenoid traps pure H↑ which has a long lifetime due to He-coating of storage cell. All other species are removed quickly from the trap.

→1-ε Polarization can be reasonably well estimated, but not measured.

→Check these results by a different principle NOT based on estimation of an ‚effective analyzing power' S_{eff}

A different aproach

$$A_{\exp} = P_{beam}\underbrace{Corr P_T S_0}_{S_{eff}} \qquad \text{Corr} = \text{exp. motivated Correction}$$

How to avoid the systematic errors caused by individual factors?
Apparent attractiveness of Mott-scattering:

$$A_{\exp} = P_{beam}\underbrace{Corr S^{y}{}_0}_{S_{eff}} \quad \Rightarrow \text{No } \mathrm{P_T}\,!$$

In **double** elastic scattering S_{eff} can be measured directly!

After scattering of unpolarized beam

$$\mathrm{P_{sc}} = S_{eff}$$

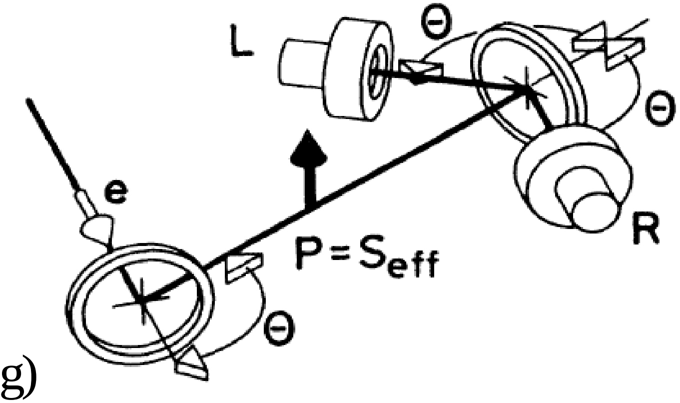
(Equality of polarizing and Analyzing Power :)

After second "identical" scattering process

$$A_{\exp} = S^2{}_{eff}$$

(sounds simple but extremly difficult to elliminate apparative asymmetries and to provide 'identical' scattering)

Claimed accuracy in $\mathrm{S_{eff}} < 0.3\%$!



A. Gellrich and J.Kessler
PRA 43 204 (1991)

More elaborated double scattering

1.) measurement : Pol beam on second target

$$A_1 = S_{eff} P_0$$

2.) with 'auxiliary target': $S_T; +P_0$

$$A_2 = P_T S_{eff} = \frac{S_T + \alpha P_0}{1 + S_T P_0} S_{eff}$$

α = Depolarization factor for first Target

3.with 'auxiliary target': $S_T; -P_0$

$$A_3 = P_T S_{eff} = \frac{S_T - \alpha P_0}{1 - S_T P_0} S_{eff}$$

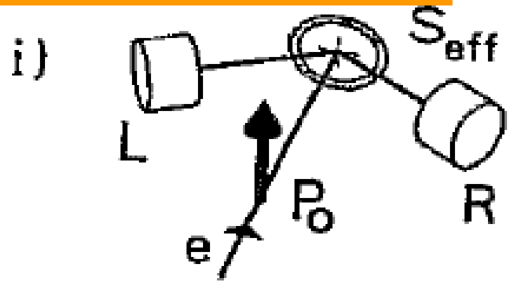
4. unpolarized beam on aux. target

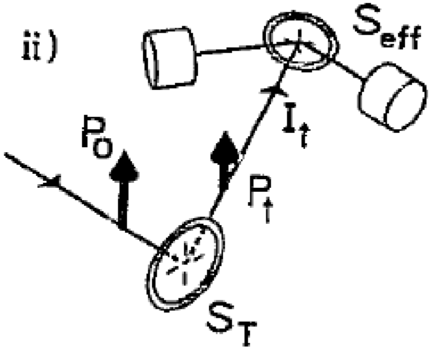
$$A_4 = S_T S_{eff}$$

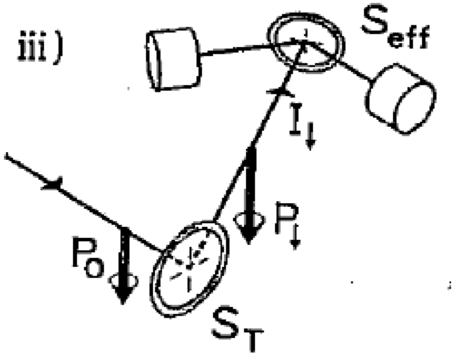
5. Scattering asymmetry from auxiliary target

$$A_5 = P_0 S_T$$

5 equations with four unknowns→
consistency check for apparative asymmetries!



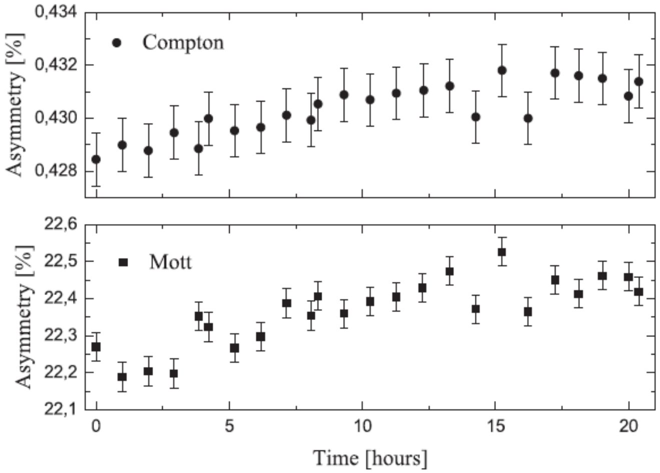




S. Mayer et al
Rev. Sci. Instrum. 64 952 (1993)

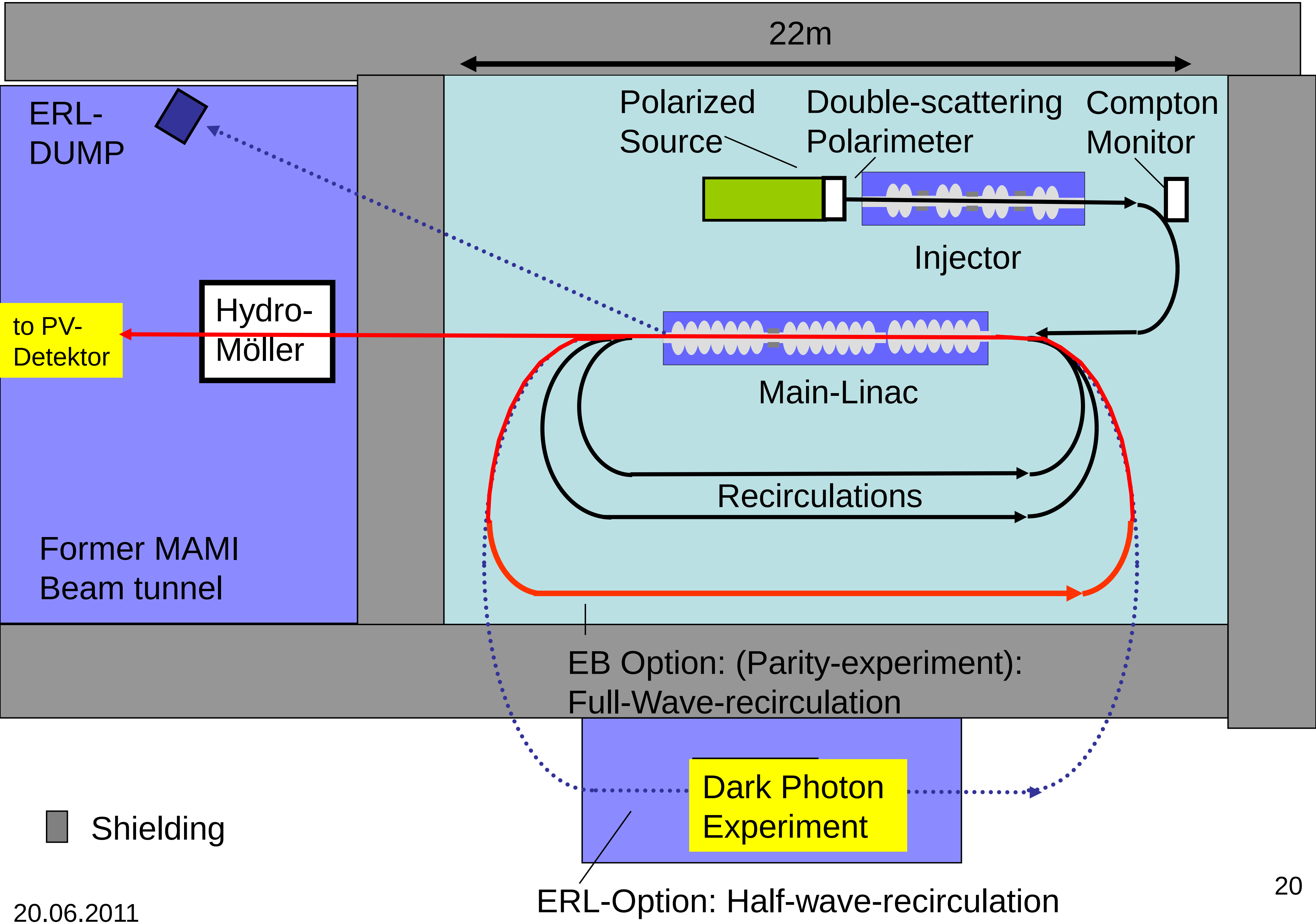
The MESA Spin chain
(‘The eightfold way’)

- DSP measures polarization at 100kV
- tuning of spin angle at Hydro-Möller (and PV) by second Wien rotator.
- Depolarization in MESA <<10^{-3}. (low energy!, no resonances)
- Monitoring, stability and cross calibration can be supported by extremely precise&fast 5 MeV Mott/Compton combination.
- In general, 8 polarization measurements required



R. Barday et al. Proc PESP2010

Polarization Drift consistently observed
in transvere AND longitudinal observable
at the <0.5% level.
Both polarimeters can be used over wide
range covering operational regime
of Hydro-Möller


22m
ERL-DUMP
Polarized Source
Double-scattering Polarimeter
Compton Monitor
Injector
Hydro-Möller
to PV-Detektor
Main-Linac
Recirculations
Former MAMI Beam tunnel
EB Option: (Parity-experiment):
Full-Wave-recirculation
Dark Photon Experiment
▨ Shielding
ERL-Option: Half-wave-recirculation

Conclusion

- MESA operates in EB-mode for PV and in ERL-mode for Dark Photon experiment.
- Main cost factor – building - eliminated, other one –SRF- reduced by multi-turn recirculation.
- PV requires extreme beam parameter stability
- …and accurate polarization measurement by a polarimeter chain
- In ERL mode, the new issue is multi-turn recirculation

Back-ups

Emittance requiments

An emittance of ≤10μm is the key for successful operation of DM-experment
With $t_{bunch} << t_{accel}$ we have a lower limit for emittance at the cathode

$$\varepsilon_{\min} = \sqrt{\frac{q_{bunch}(E_{\gamma} - W)}{6\pi\varepsilon_0 E_{cath} mc^2}} \sim< 0.2\mu m @ 7.7\,pC @ 1MV/m$$

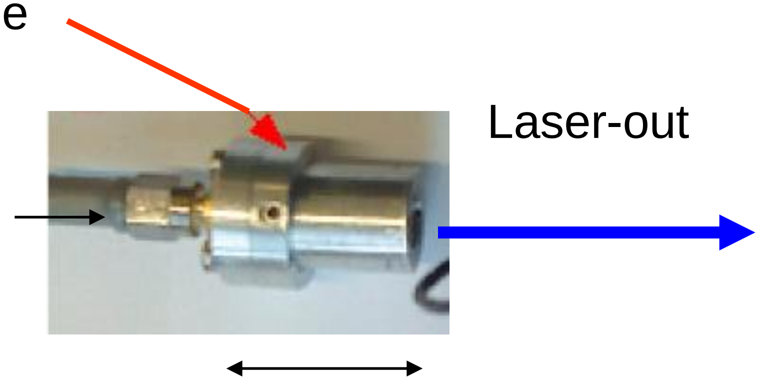
$$(E_{\gamma} - W) \sim 0.4eV\ (\mathrm{KCsSb}),\ 0.1eV(\mathrm{NEA\text{-}GaAs})$$

But: vacuum space charge destroys beam emittance by nonlinearity of forces!

Countermeasures:
1.) accelerate with high field to relativistic velocities because $F_q \sim 1/\gamma^2$.
ERL-d.c guns ~6MV/m to 0.25-0.5 MeV
SRF gun with 15MV/m to ~ 5 MeV (FZD, future: BERLinPRO)
2.) Note: d.c. acceleration allows long bunches without any correlation between phase and energy &d.c acceleration allows for low longitudinal charge densi
Example MAMI-A (1979, with van de Graaf generator)
1.5MV/m to 2MeV (γ=5) at 40ps length with subsequent bunch compression to 4ps.
→MESA baseline: γ=2 electrostatic acceleration with E>1MV/m
Modern times: Laser will provide 40-100ps bunches, power supply (e.g. ICT, now available at 2MV with 20kW→HIM/FZJ ‚cooler'-collaboration) will replace van de Graaf

405nm Laser

- Advantage of 405 nm: KCsSb QE~30mA/Watt. Cost ~ 3k€/watt (d.c.);
- optimum beam quality: 1mm dia-spot at 1m only with collimation tube!
- electron gun current presently limited by power supply (<3mA)
- Diode is well suited for pulsing at GHz-frequencies , (<40ps at full power)
- Could provide ~1W (40ps, r.f. synchronized) for MESA (1 lifetime 'overhead')
  → five DVD-player diodes in parallel!



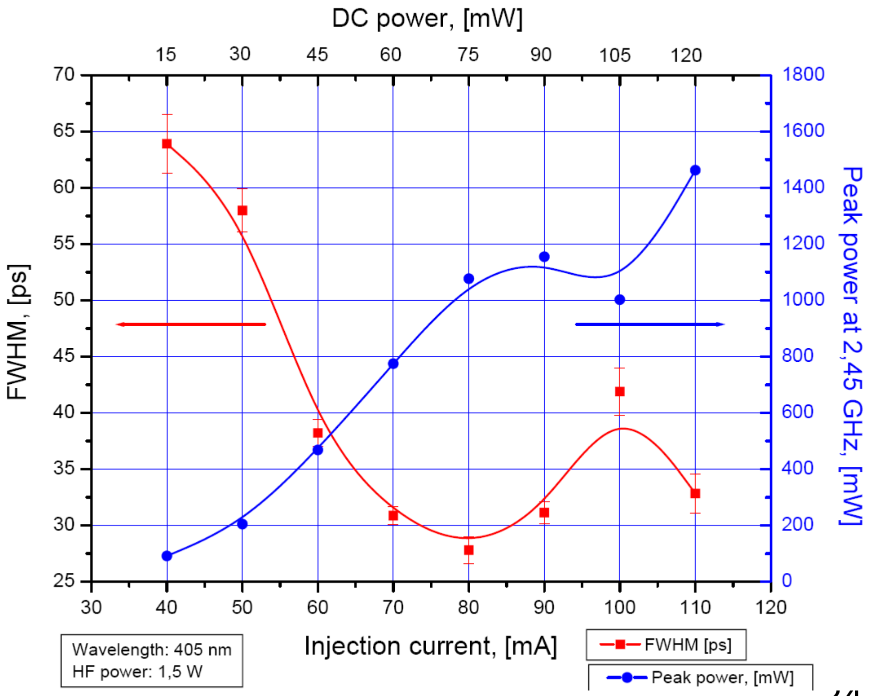
collimation tube

d.c or R.f

Laser-out

2cm

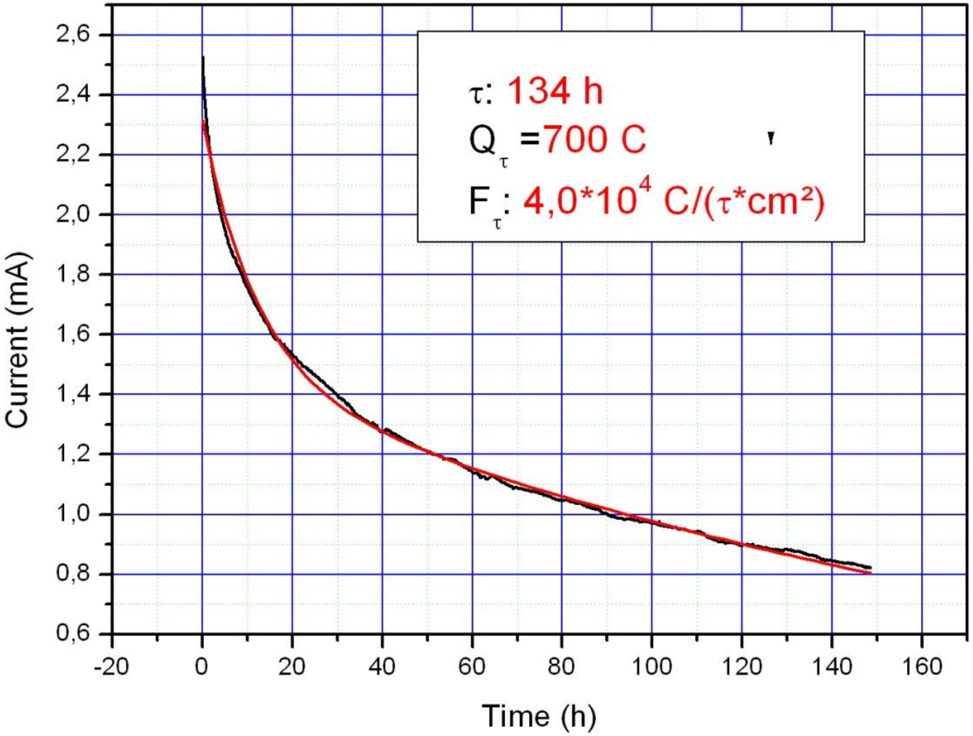
€100 purchase from eBay



Diploma thesis I. Alexander

Lifetime issue

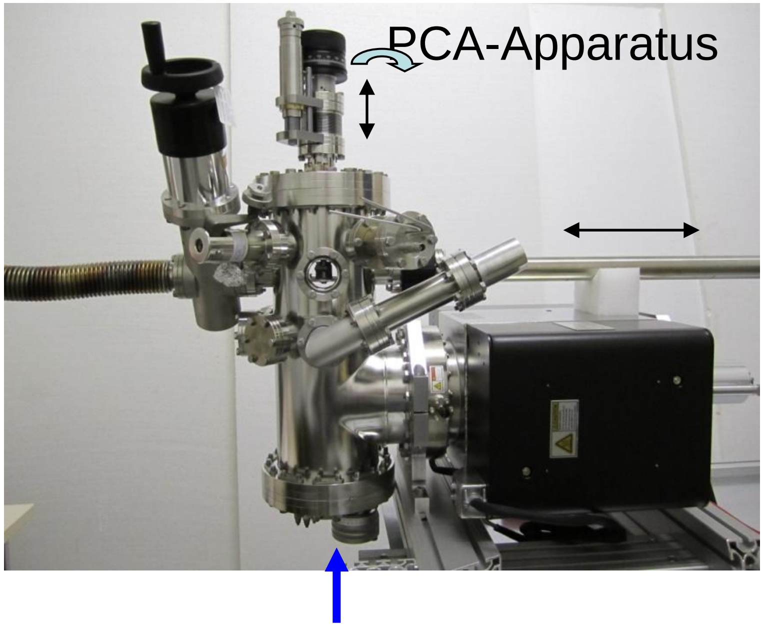
Milliampere- test experiment with NEA-GaAs

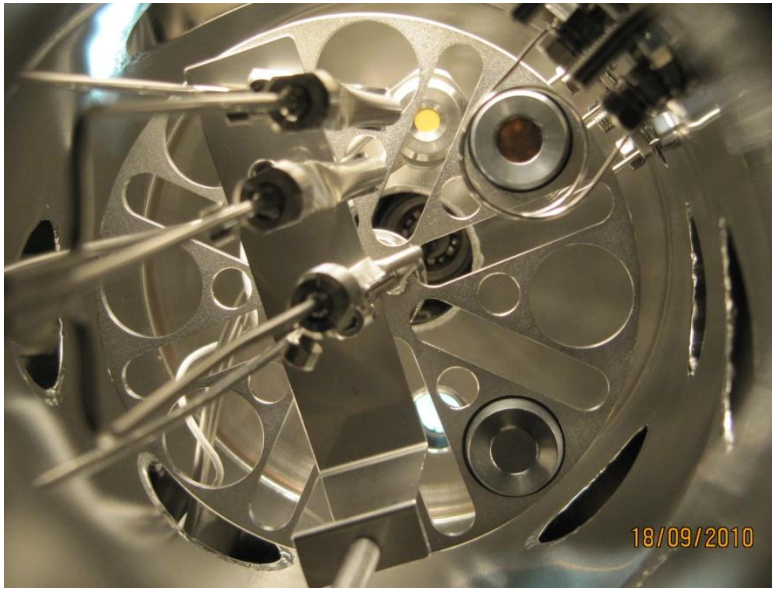


GaAs operation would be possible, but inconvenient

- long lifetime required → KCsSb (unpolarized) photocathode

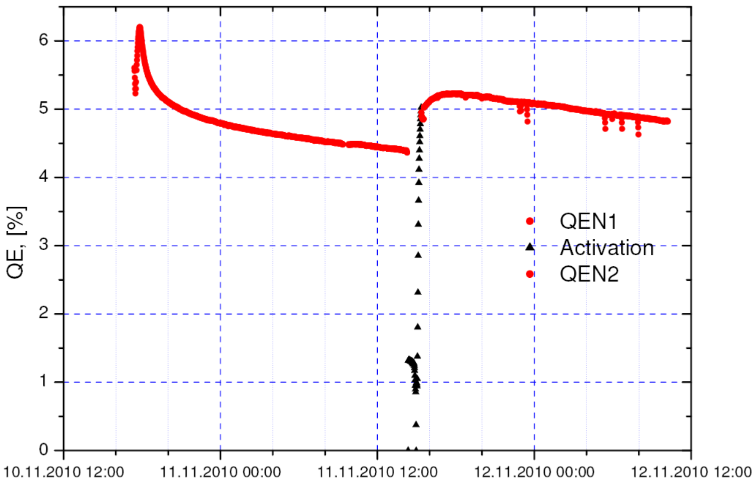
PCA fabrication chamber at Mainz-HIM



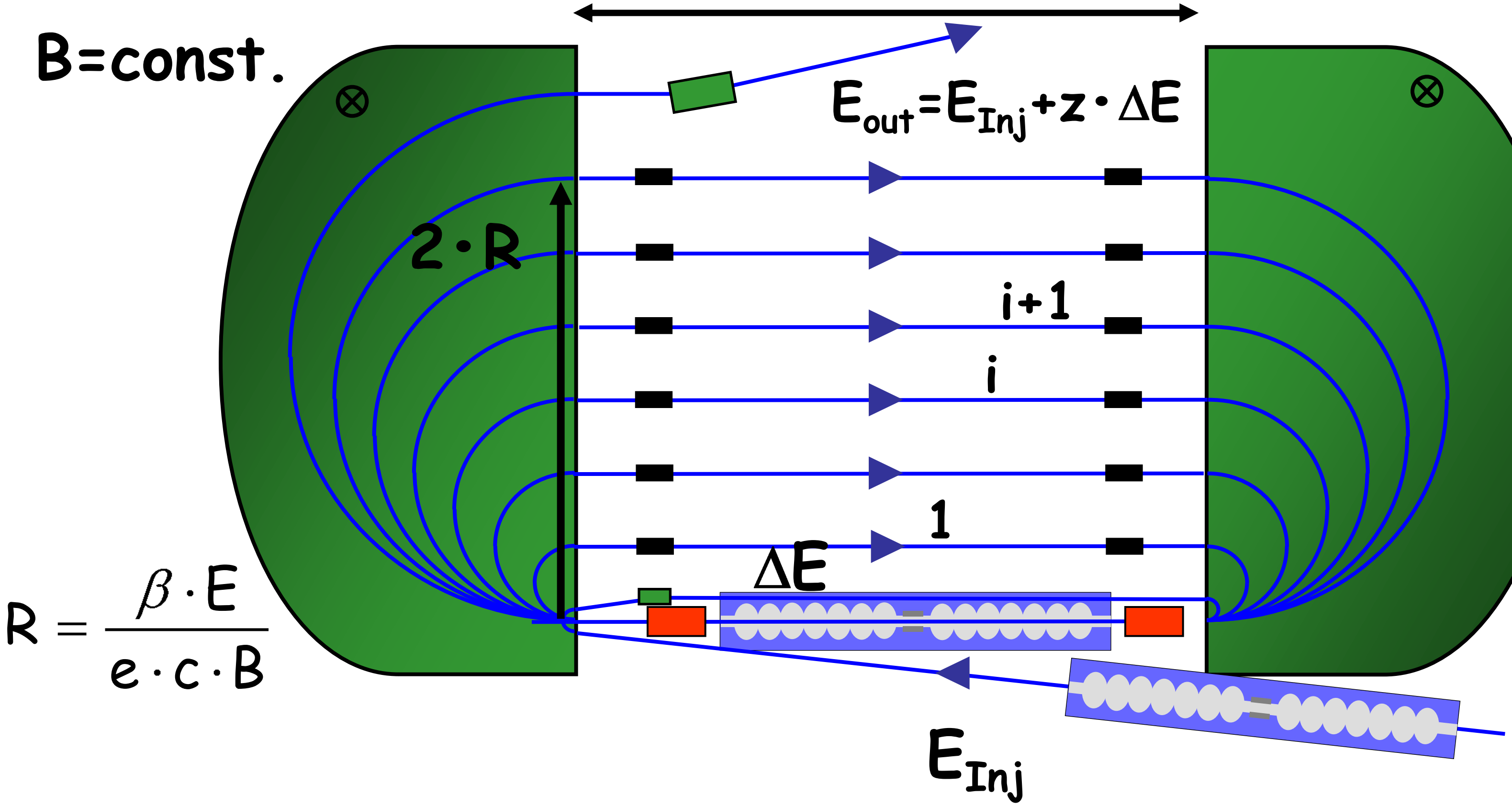


- KCsSb technology available at Mainz
- good results >30mA/Watt (>10% Q.E)
- evidence for *100 stability increase with respect to GaAs (2000 hours at 10mA?)

Quantum Efficiency of K_2SbCs cathode at Cu substrate



Stability issues



Longitudinal stability due to long. dispersion!

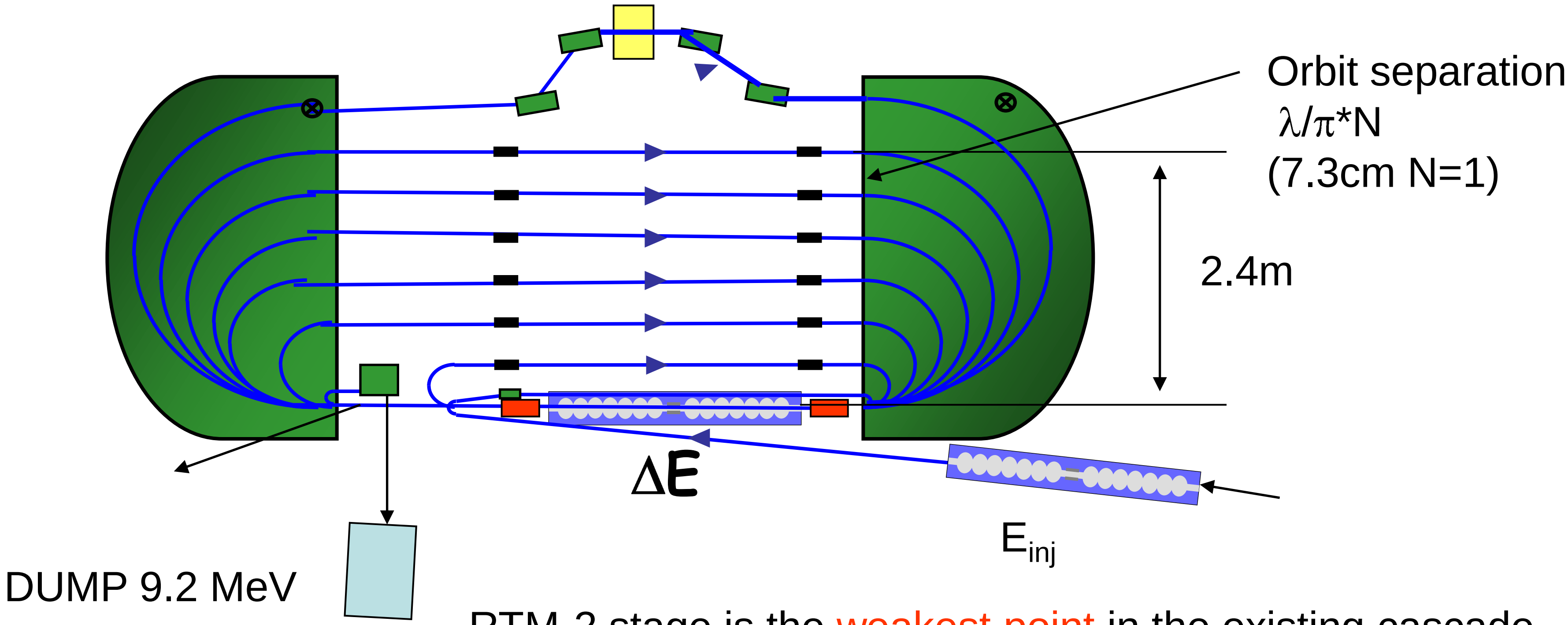
Transverse stability if ‘Herminghaus Criterion’ is followed $E_{inj}/E_{out}<10$

Practical criterion $E_{out}=(E_{INJ}+\Delta E)$* (diameter magnet/diameter first orbit)

→practical first orbit diameter > cryostat radius ~0.4m

→ analyze for our case.

Microtron based solution



RTM-2 stage is the weakest point in the existing cascade
→ high potential for GAIN in stability!

Purpose	B/T	N	ΔE MeV	E_{inj}+ΔE MeV	2*R0	Rez.	E_{out}	Power/ current
PV/high E	0.5	1	5.5	30	0.40	28	180	27kW/0.15
ERL	1.4	2	30.8	40	0.20	2	102	100/10

Conclusions

- Due to the non-extreme bunch parameters MESA does not require the same amount of investment as the light-source demonstrator machines
- Challenge is the compatibility between PV and ERL, but promising approaches exist.

DM: Focusing through the PIT

$$\varepsilon_{\mathrm{Norm}} = 10\mu m \,(\mathrm{or}\ 3.2\ \pi\ \mathrm{mm} * \mathrm{mrad} * \mathrm{m_e c})\quad (\mathrm{MESA\ goal})$$

$$\varepsilon_{\mathrm{Geo}} = \frac{\varepsilon_{\mathrm{Norm}}}{\sqrt{\gamma^2 - 1}} \quad \Rightarrow \varepsilon_{\mathrm{Geo}}(100\mathrm{MeV}) \sim 50\mathrm{nm.}$$

Beam diameter as a function of optical function β:

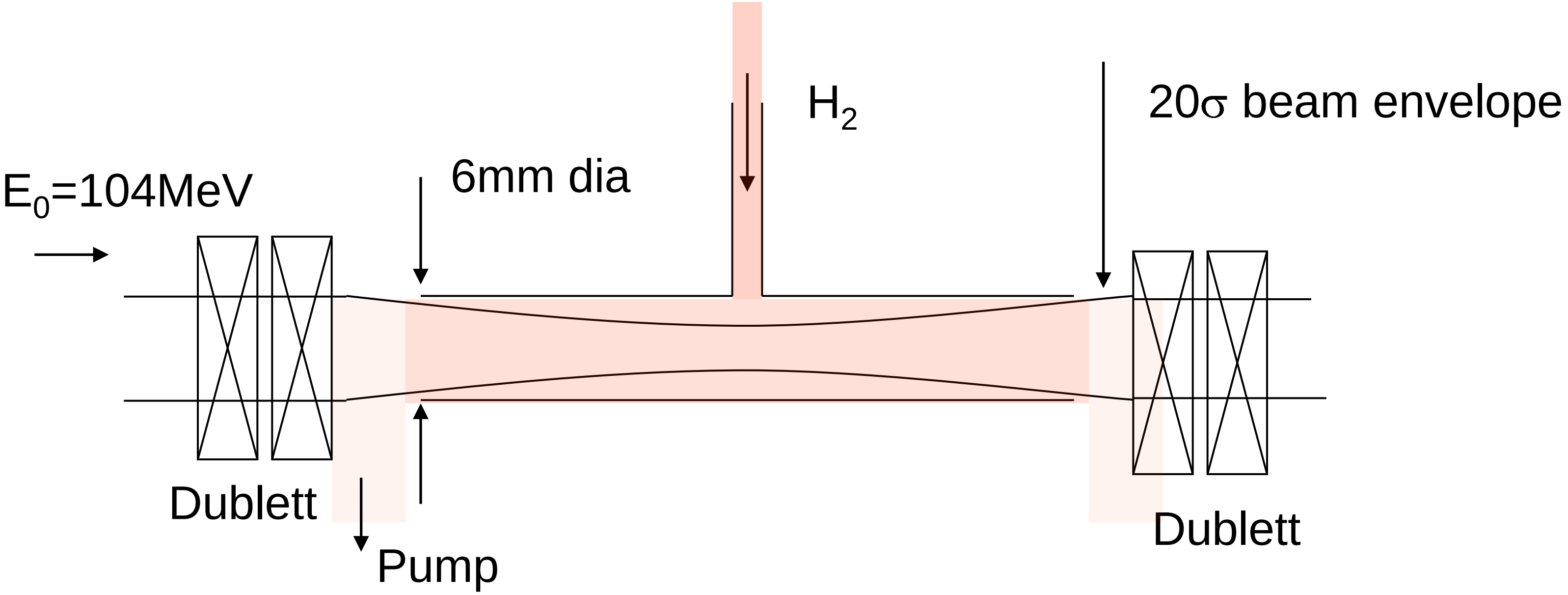
$$\mathrm{r}^2_{\mathrm{beam}}(z) = \varepsilon_{Geo} * \beta(z)$$

in the field free region around symmetry point $z^* = 0$

$$\beta(z) = \beta(z^*) + \frac{z^2}{\beta(z^*)} = \beta^*(1 + (z/\beta^*)^2)\ \mathrm{choose:}\ \beta^* = 1m$$

$\Rightarrow$ Maximum beam diameter ≤ 0.62mm over 2 Meters of length

DM: Focusing through the PIT



Assuming target density N=$2*10^{18}$ atoms/cm^{-2} (3.2 μg/cm^2, $5*10^{-8}$ X_0)
we have (at $I_0=10^{-2}$ A) luminosity of L= I_0/e*N=$1.2*10^{35}cm^{-2}s^{-1}$
→(average) ionization Energy loss: ~ 17eV
→ could allow to recuperate more energy than in conventional ERL (2.5MeV).
→RMS scattering-angle (multiple Coulomb scattering): 10μrad
→ single pass beam deterioration is acceptable Note: storage ring:
beam emittance lifetime ~ 10milliseconds (stationary vs. variable background…)
→ beam halo & long tails of distribution due to Coulomb scattering have to be studied