

**Dark matter research at
the MESA facility**
(**MESA=M**ainz **E**nergy recovering
Superconducting **A**ccelerator)

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Dark forces workshop

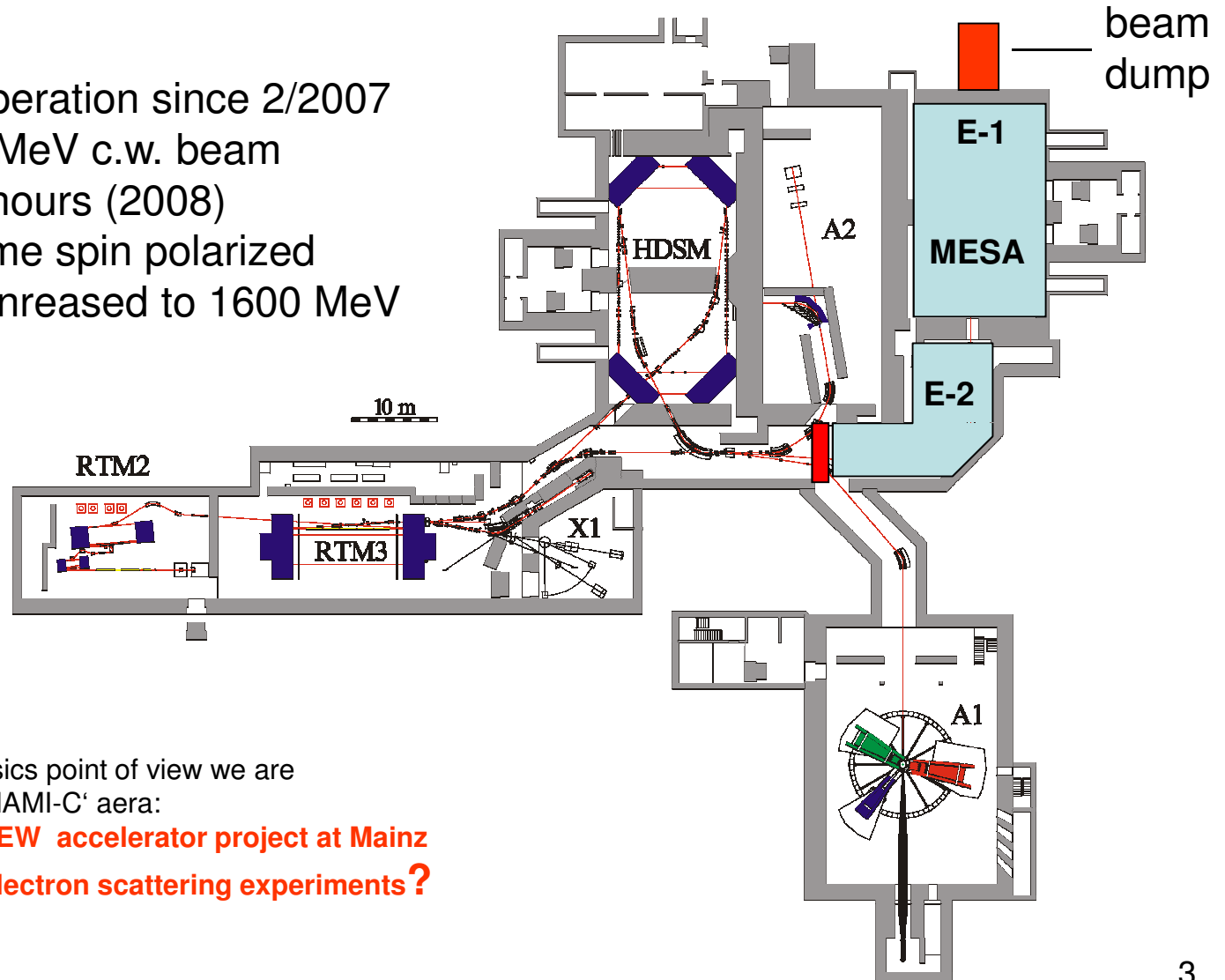
SLAC, 26.09.2009

Outline

- Introducing the MESA accelerator
- Experiments at MESA
- Dark matter experiment(s) at MESA

Experiments at MAMI-C

- MAMI-C: In Operation since 2/2007
- $100\mu\text{A}$, 1508 MeV c.w. beam
- op-time: 7000 hours (2008)
- 2/3 of beam time spin polarized
- beam energy increased to 1600 MeV



From Accelerator physics point of view we are (almost) in the 'Post MAMI-C' era:

Can one think of a NEW accelerator project at Mainz being dedicated to electron scattering experiments?

The Paradigma

MESA must allow to perform electron scattering experiments which are:

- not feasible at MAMI-C
- have an important physics impact
- are competitive

....but must be realized within the given constraints
→ ‚precision‘ frontier → new experimental regime

21th centuries innovations for c.w. electron accelerators

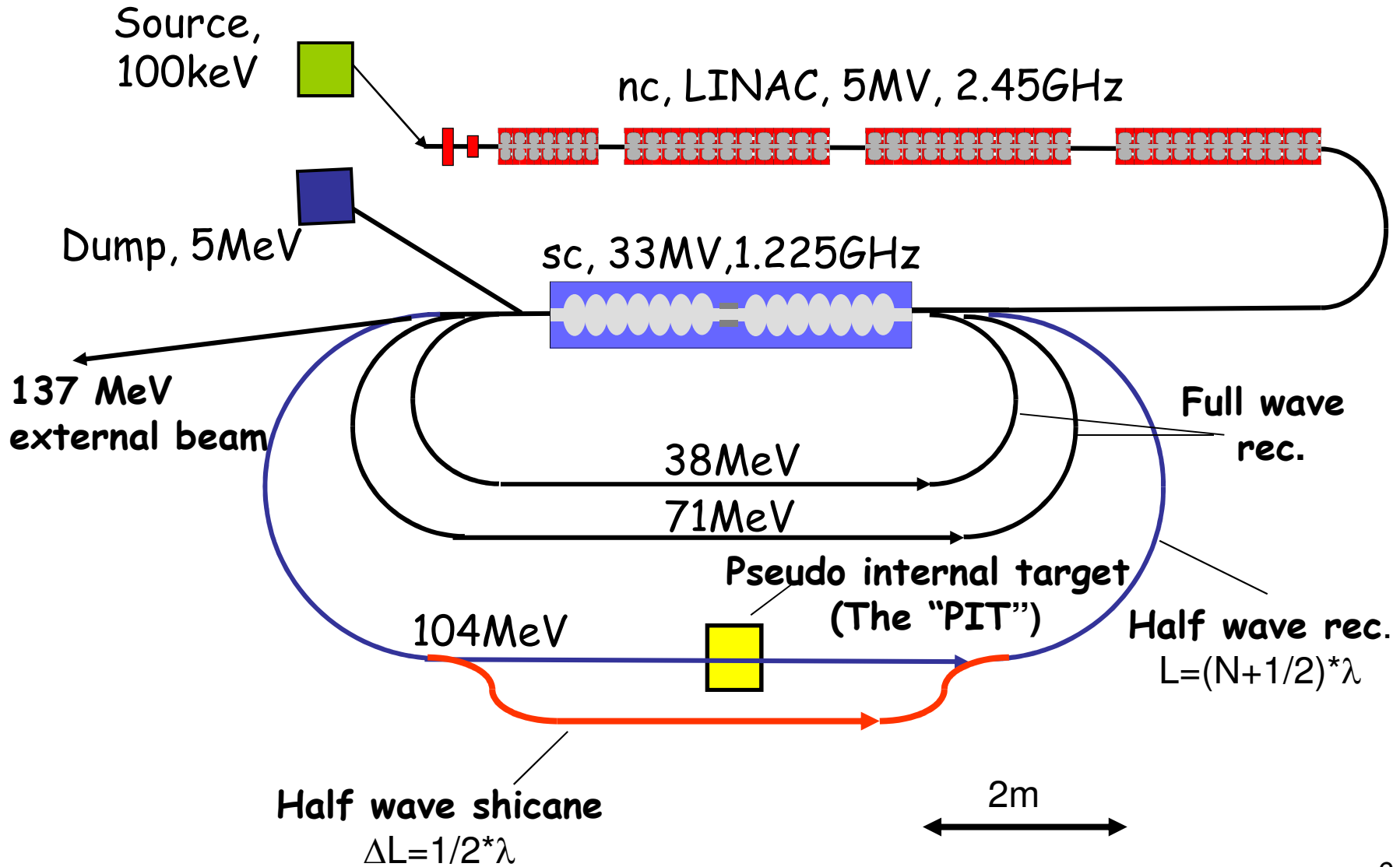
1. Energy recovery linac (ERL)
(5mA c.w. beamcurrent, JLAB-ERL, 2004)
2. Improvements on high gradient-SC-c.w. op:
(e.g. 20 MeV/m BESSY 2007)

Inventions were prompted by desire for
FEL's or other light sources

Our plan:

- Combine both achievements,
- use accelerator for hadron or particle physics (**no light source!**)
- make use of existing technology & know how
- take advantage from lower demands towards source brightness

MESA-Layout



MESA-Opmodes:

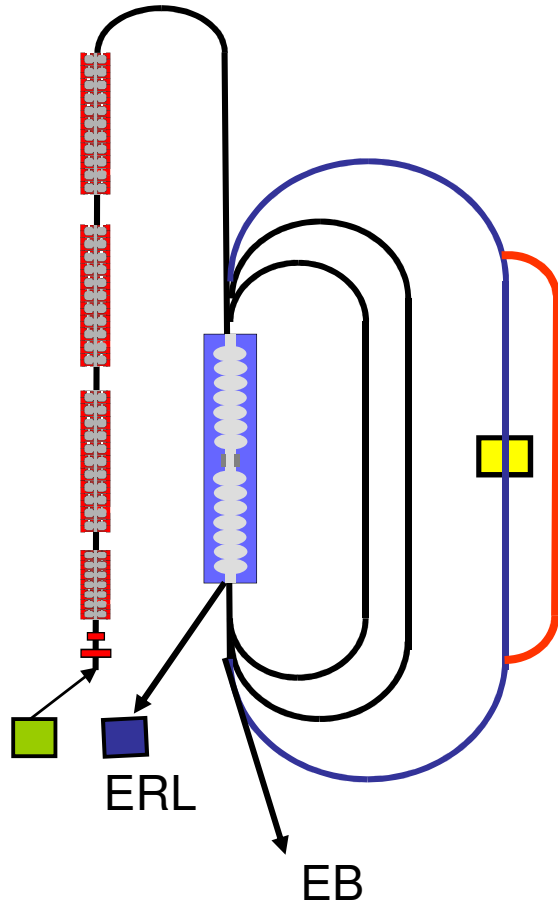
Beam Time Structure:

1.2245 GHz, c.w.

Beam operation modes:

Energy recovery (ERL): 10mA, 104 MeV, unpolarized

Ext. Beam (EB): 0.15mA, 137 MeV, polarized, $P=0.85$



Investment Cost of machine: ~10 M\$
+ Investment for experiments

→ Physics 'Portfolio' required to justify investment

MESA: Potential Experiments (Status: March 2009)

ERL-Mode:

1 'dark matter' $p(e, e'p)U$
(Particle physics)

EB-modus:

2 PV: weak charge
3 PV: strange magnetic form factor
(hadron physics)

} 'workhorse
experiment'

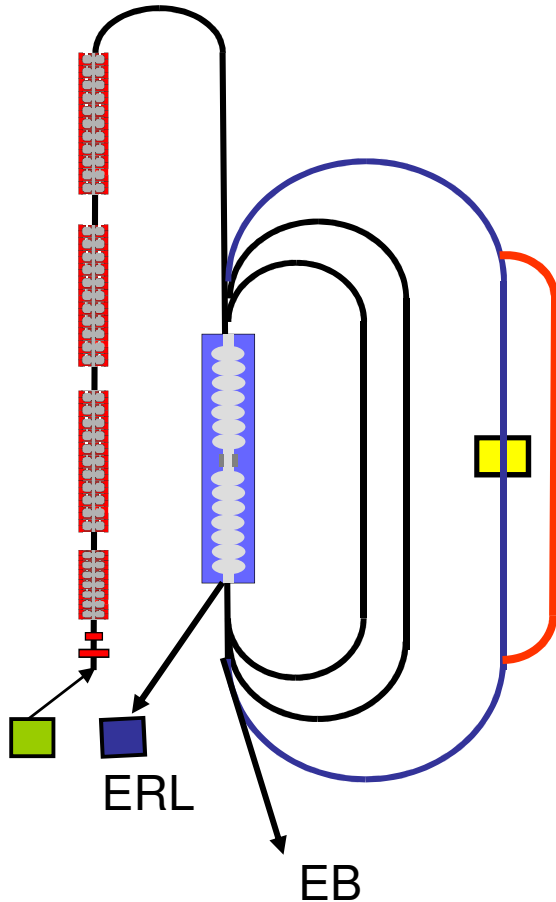
Other, 'interesting' experiments/applications

4 (ERL-mode) $^{16}O(e, e' \alpha)^{12}C$
(Nuclear-stellar-astrophysics)

5 (EB-mode) cold positrons to MAMI:
channelling radiation from e^+ ;

but ' 2γ ' hadron physics 'impossible' (!!)

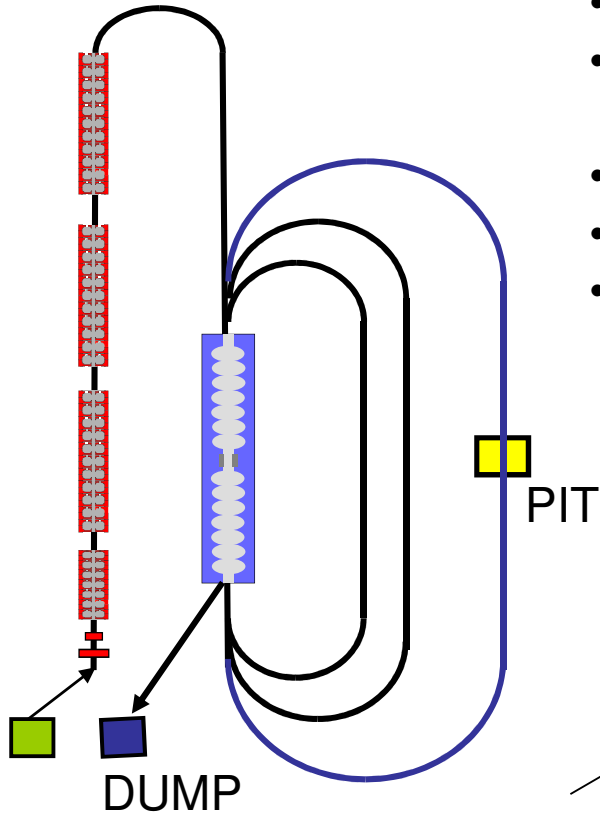
6 (ERL-mode, parasitic) Nanodiamonds (medical,
spintronics, ...) cold polarized positrons for mat. res.



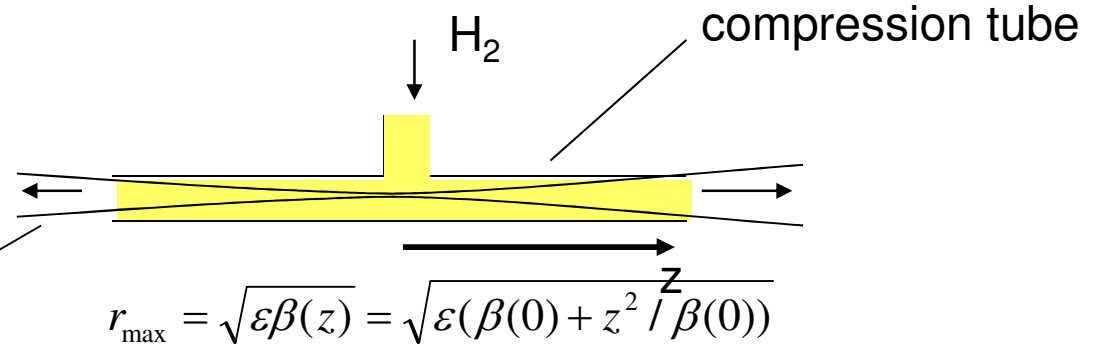
(!!) see Proposal of Bogdan Wojtsekowski
to investigate $e^+e^- \rightarrow \gamma + U$

MESA-ERL as ultra low background electron scattering machine

- windowless gas target
- low target density compensated by high (10mA) beam current: $L \sim 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$
- High beampower (1MW) feasible due to energy recovery
- Electron energy at dump 5MV \rightarrow minimized background
- $< 50\text{nm}$ beam emittance allows for $> 10 \sigma$ beam clearance in target



Beam envelope:



Parameters: $\beta(0) \sim 1\text{m}$; $z_{\max} = 1\text{m}$; $\varepsilon = 10^{-7} \text{ m}$

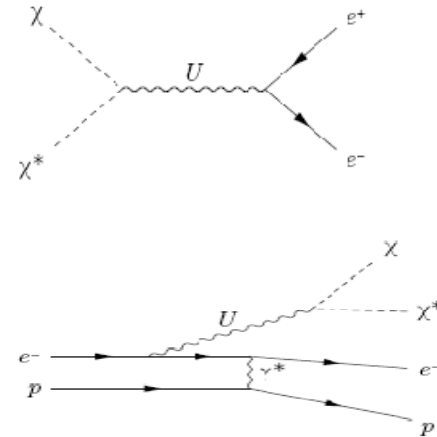
$$r_{\max} = 0.44\text{mm}$$

Dark matter signature: in e,p 'elastic'

Hypothetical WIMPS “ χ, χ^* ” and “U-Boson”,
may explain 511 keV γ -flux from galactic center

(C. Boehm et al.:Nucl. Phys. B683 (2004) 219)

e.g. Heinemeyer et al: arXiv:0705.4056v2 (2007)
Proposes to test hypothesis at accelerator
by detecting U-Boson-radiation in e,p-scattering



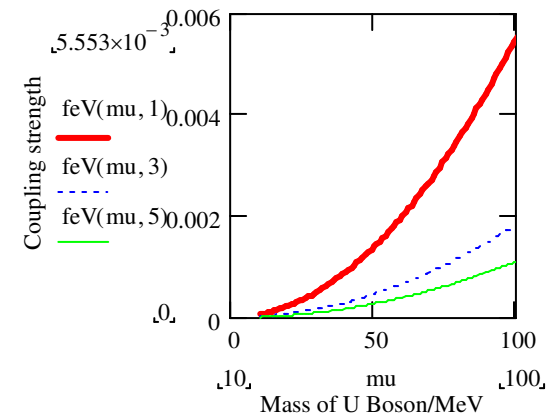
Production rate depends on several unknown parameters

P. Fayet, arXiv:hep-ph/0607094

$$C_\chi \sqrt{(f_{e,V}^2 + f_{e,A}^2)} \approx 10^{-6} \frac{|m_U^2 - 4m_\chi^2|}{1.8 \text{ MeV} \cdot m_\chi} \sqrt{B_{ann}^{ee}}$$

Example: $C_\chi=1$, $f_{e,A}=0$, $m_U=10\dots 100$, $m_\chi=5$, $B=1$

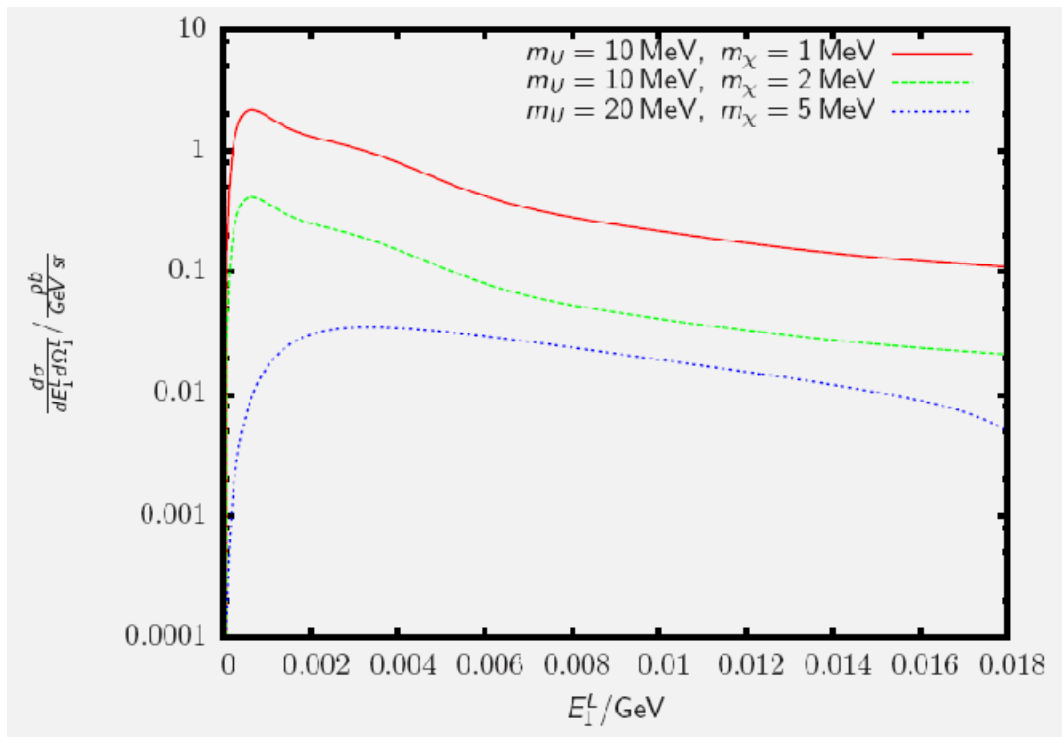
Fayet: Limit to $f_{e,V}$ from $g_{e-2} < 1.3 \cdot 10^{-4} \cdot \mu[\text{MeV}]$



Calculation of cross section

First estimations by: Heinemeyer et al: arXiv:0705.4056v2 (2007)

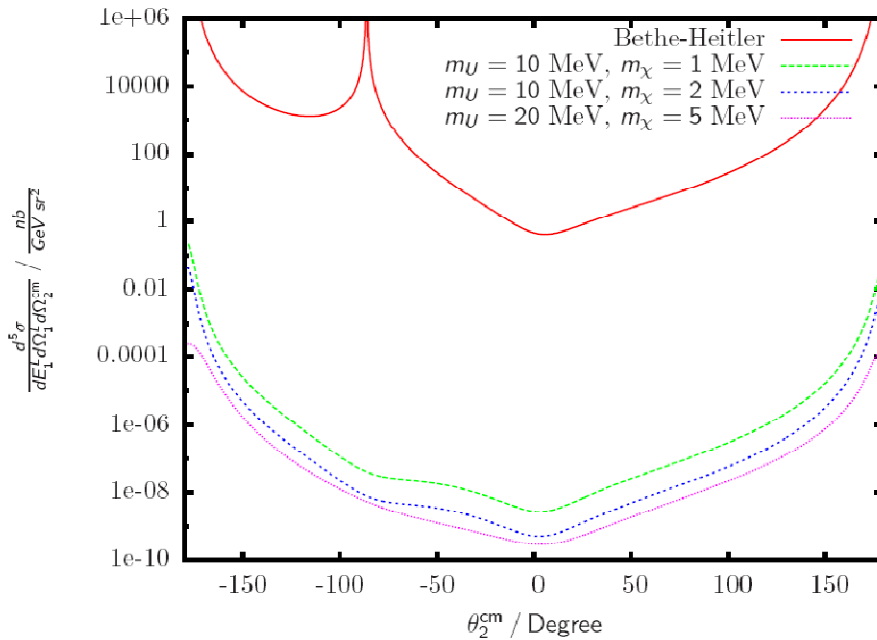
New calculations by T. Beranek (Mainz): $C_\chi=1$, 40 MeV beam energy, 90 degree lab scattering angle: 10-1000 fb/(sr*GeV)



500msr Elektron Detektor
5-15 MeV bin with average
cross section 0.4pb/(sr*GeV)
→2femtoBarn at $L=10^{35}$
yields 17 events per day.

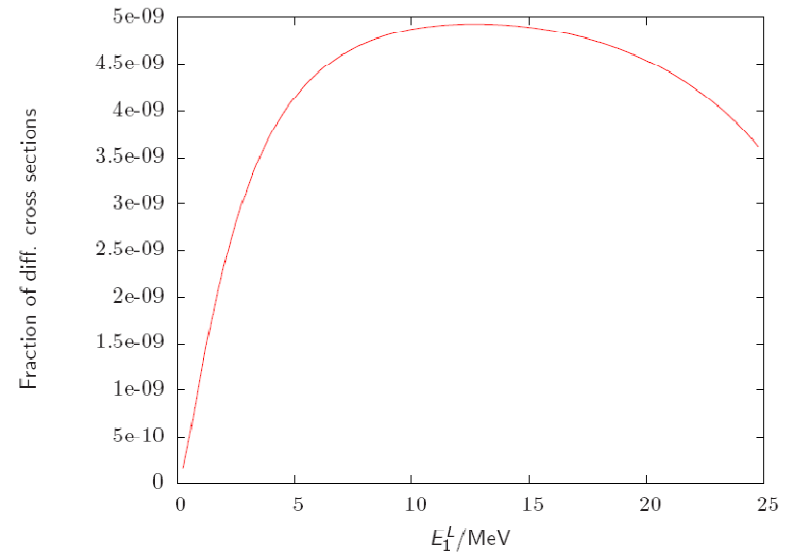
Background cross sections

Bethe Heitler Background
(5 times differential cross section)



$C_\chi=1$;
 $E_{\text{out}}(\text{electron})=1\text{ MeV}$
 $\theta_{\text{lab}}(\text{elektron})=\pi/2$

S/B Ratio Signal
for given kinematics

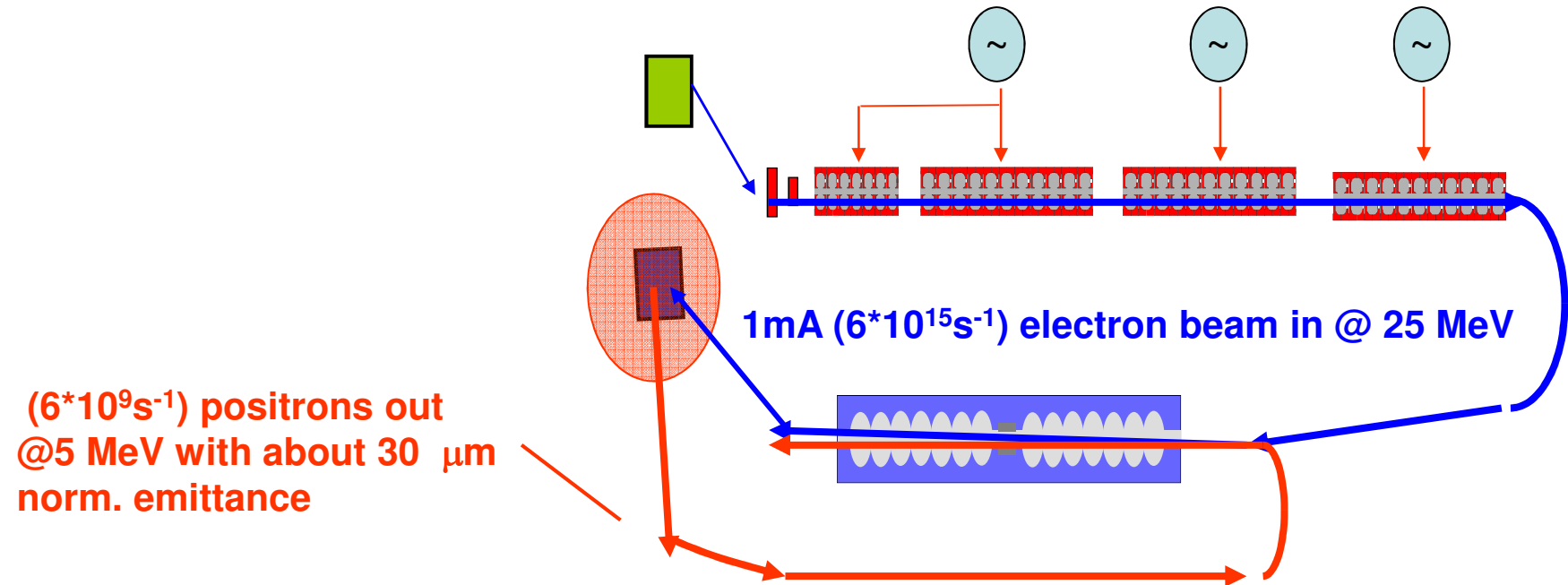


$C_\chi=1$;
 $\theta_{\text{CM}}(\text{Proton})=\pi/4$
 $\theta_{\text{lab}}(\text{Electron})=\pi/2$

BH can be eliminated, \rightarrow to which extend?? other backgrounds??

MESA as Positron generator for $e^+ + e^- \rightarrow \gamma + U$

(see talk by Bogdan Wojtsekhowski, yesterday!)



Positrons could be also injected into recirculator
→ c.w. positron beam (EB 1 nA, 137 MeV)

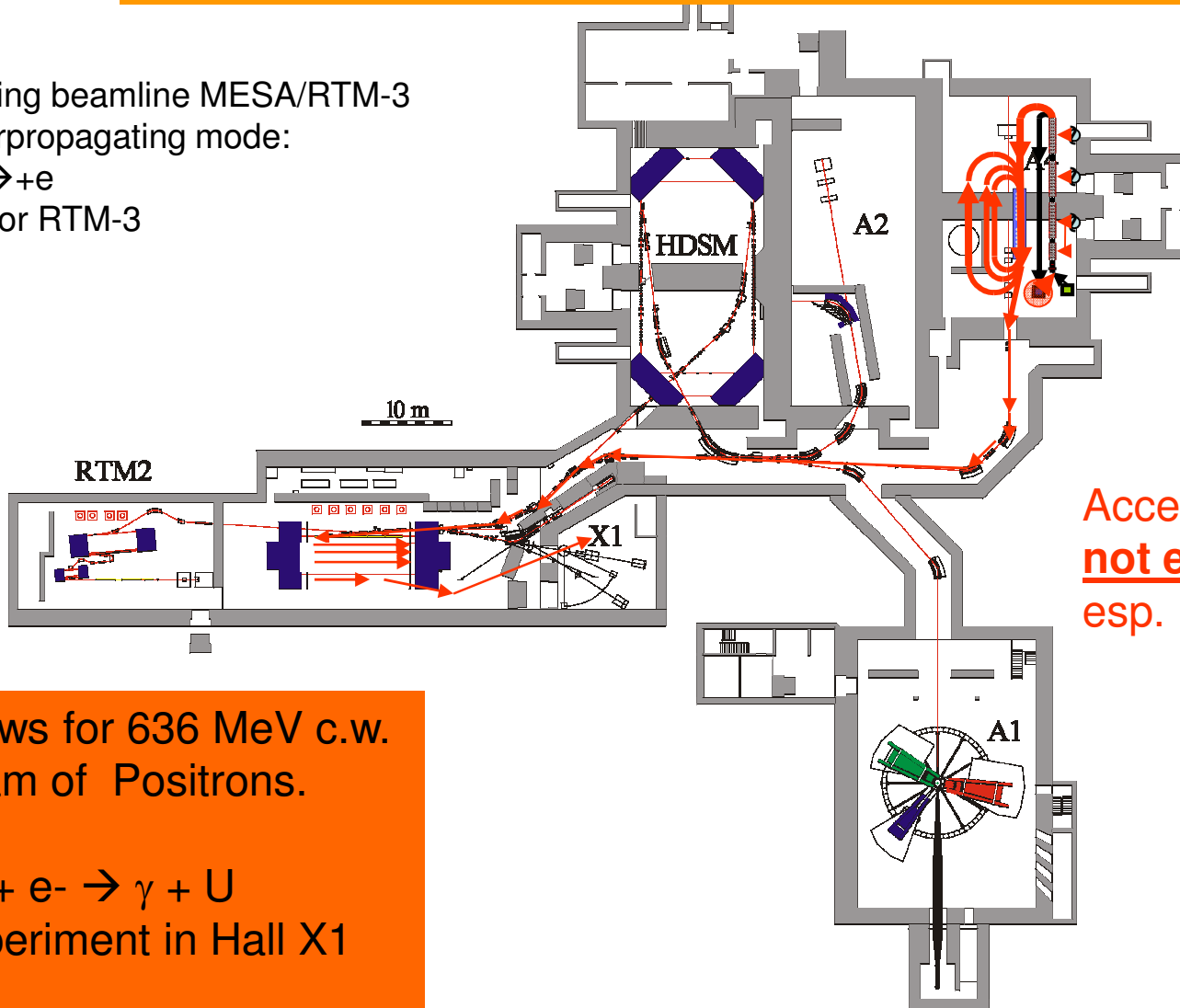
To be optimized/investigated:
r.f. power, cooling, emittance, halo, co-acceleration
(bunching), e^+ beam diagnostics → 10 nA??

MESA joins MAMI for $e^+ + e^- \rightarrow \gamma + U$

Use existing beamline MESA/RTM-3
in counterpropagating mode:

$\nu \rightarrow -\nu, -e \rightarrow +e$

...Same for RTM-3



Accelerator set up
not easy,
esp. Phasing,

allows for 636 MeV c.w.
beam of Positrons.

$e^+ + e^- \rightarrow \gamma + U$
Experiment in Hall X1

MESA summary

W.r.t. to DM three possibilities at Mainz:

A: Use existing Hall (+equipment ?) for beam dump experiment with 1.6 GeV beam from MAMI-C (until MESA will be buildt)

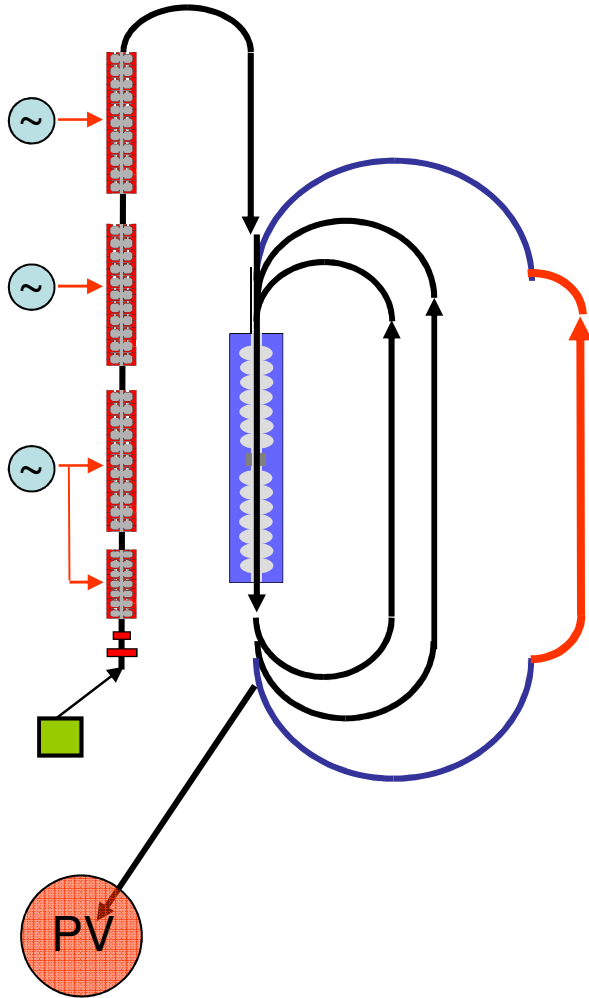
B: PIT experiment at MESA: $p, (e, e'p)U$ (see proposal by W. Fisher for JLAB ERL)

C: Positron experiment $e(e^+, \gamma)U$ (see proposal by B. Wojtsekhowski for JLAB ERL)

- MESA is a small scale machine, affordable for U Mainz
- innovative, explorative Experiments ('dark matter') require feasibility study
- collaborators would be greatly appreciated!
- Parity violation a possible 'workhorse' experiment
- several other options in applied science,
- high potential for effective education of post graduate students in accelerator physics + other fields!

follow: MESA-backups

PV @ MESA



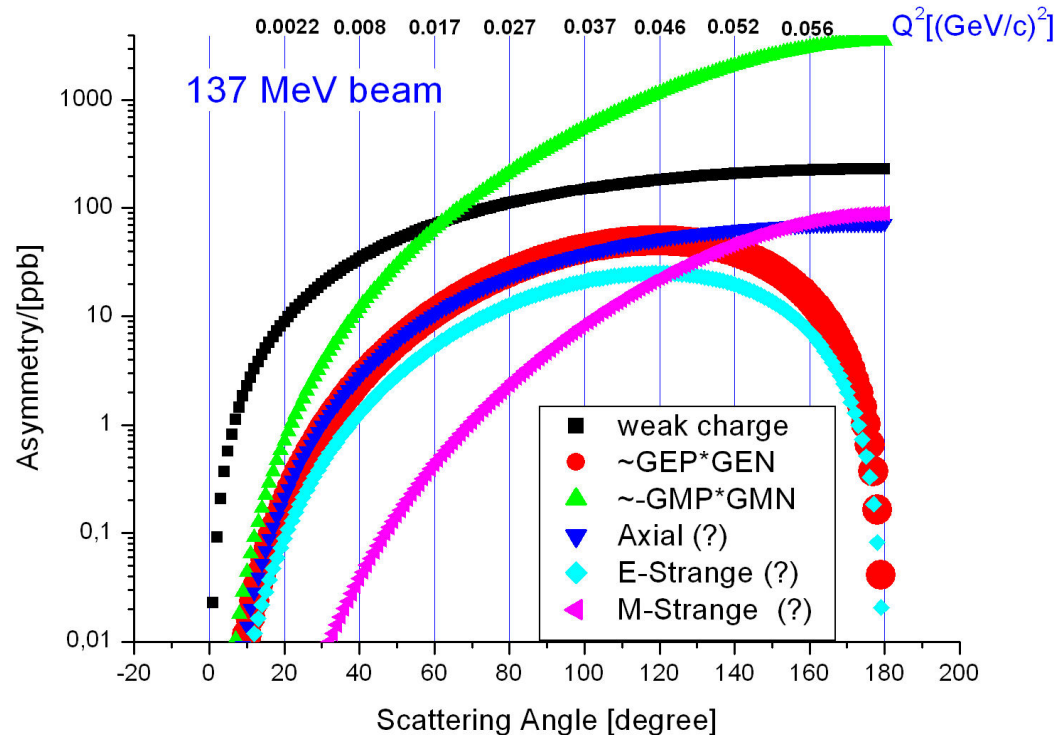
EB-mode,
0.15mA, 137MeV, $P=0.85$
Target: 20cm lq. H2
 $L=10^{39} \text{ cm}^{-2}\text{s}^{-1}$

Exp: Only small momentum transfer available!

For given Q^2
large $\Delta\Omega$ Detektor must
compensate for $\sim E^2/Q^4$
cross section behavior in
ep elastic

Experimental challenges for the source

Black und magenta curve contain interesting observables, others are t.s.e. 'background'



- High statistics → extreme Luminosity+ extended runtime (several thousand hours)
- Control of false Asymmetries at the few ppb level
- 1% absolute beam polarization measurement

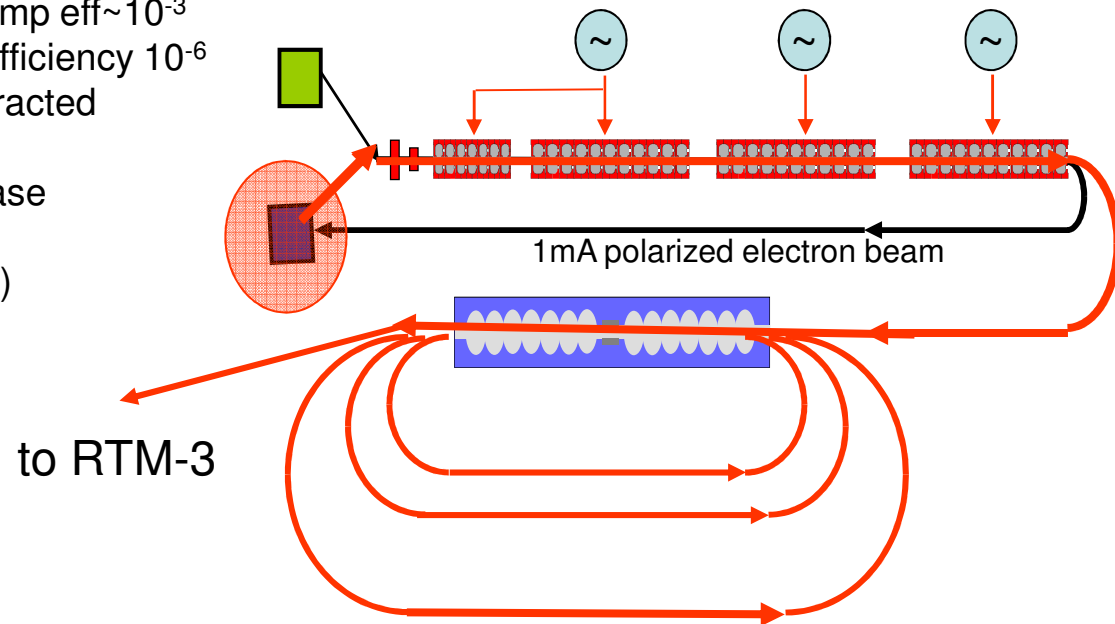
Advantages of MESA approach for PV-experiment

.....with respect to competing experiments:

- Weak radiative corrections much smaller than at GeV energy
- Backgrounds reduced since operating below pion threshold
- First Accelerator with “Parity integrated design”: optimized for HCA-control, stability, diagnostic & feedback equipment.
- More economic approach
- Exclusive access to machine for at least 4000h/year.

The MESA PHYSICS repertory: Polarized Positrons

1. Polarized Positron generation in beamdump $\text{eff} \sim 10^{-3}$
2. Moderation of positrons: $\text{eff} \sim 10^{-3} \rightarrow$ total efficiency 10^{-6}
3. Cold polarized positrons ($P > 0.5$) are extracted
4. Norm emittance of positrons $< 30 \mu\text{m}$.
5. Co-Acceleration in ILAC on 180 deg. Phase
6. separation of e^+/e^- after ILAC,
7. (Accelerate with rev. Recirculator polarity)



Creates a third mode of operation:
EB- e^+ : 1 nA, $\text{Pol} \geq 0.5$, $E = 137 \text{ MeV}$,
(100 nA unpol.)

Injector: Using existing technology for predictable behaviour

Beam operation modes:

ERL: 10mA 104 MeV, unpolarized

External Beam (EB): 0.15mA, 137 MeV, polarized

Source:

100keV, Photosource (MAMI-standard)

Norm. emittance, ERL mode: $\epsilon=10\mu\text{m}$ EB: $\epsilon=0.2$

bunchlength: 150ps

Cathodes:

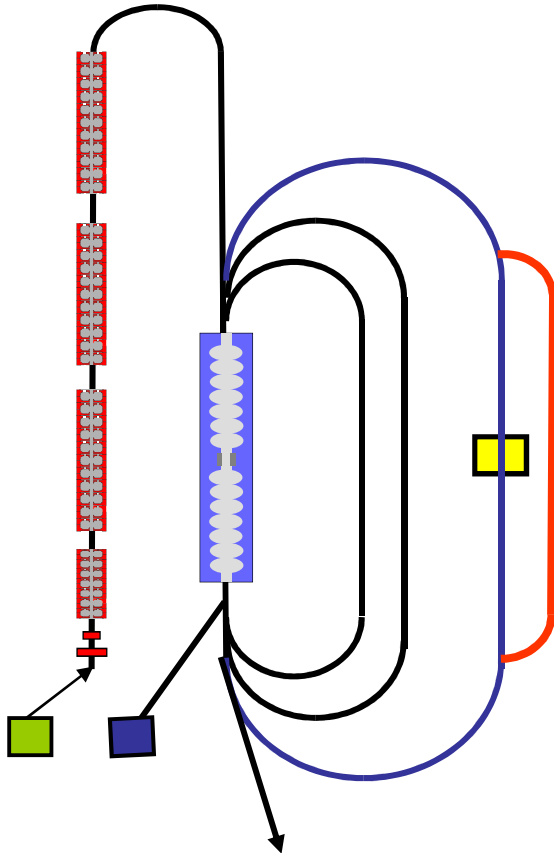
ERL-mode: bulk GaAs (later: CsK2Sb)

EB-mode: GaAs/GaAsP-superlattice

Lasers:

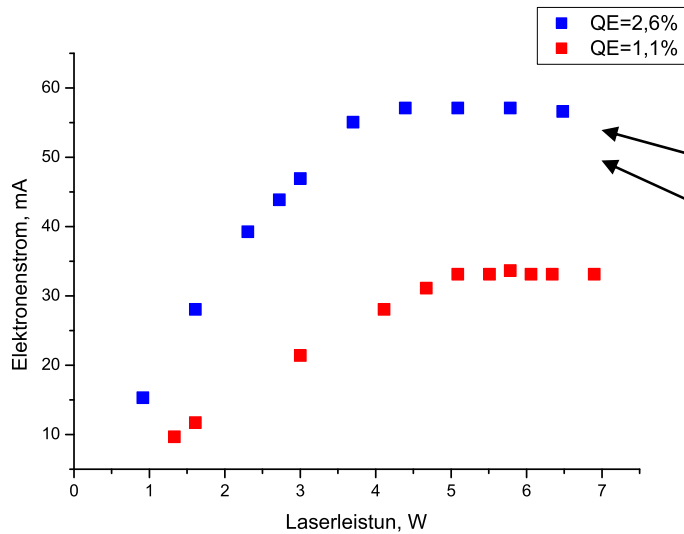
2 Frequency doubled Fiber-Synchro-MOPAs (775nm/530nm),

$P_{\text{av}}=1$ Watt.



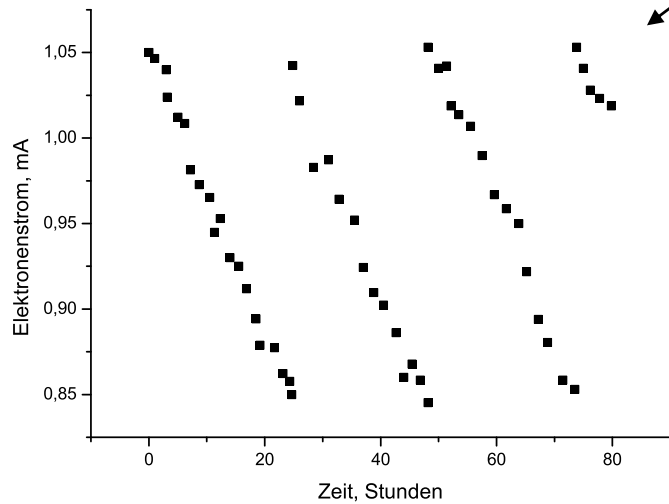
Green Laser will allow for average current of 70mA from bulk GaAs,
IR-Laser for 2mA highly polarized beam

Beam & Source: Achieved results



GaAs-Photocathode

- 50mA current possible from 2 mm diameter cathode emission site
- Beam transport over 3 Meter demonstrated
- 300 Coulomb lifetime
→ ~10 hours operation at 20mA possible
→ GaAs cathode is a good starting point for unpolarized ERL-mode



→but commisioning of more stable cathode (CsKSb) is desirable!

Observables in PV-ep-elastic:

$$A_{PV} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{A_V + A_A + A_S}{\varepsilon(GE^p)^2 + \tau(GM^p)}$$

$$Q^2 < 0.0577 \text{ (GeV}^2/c^2\text{)}$$

$$\tau = \frac{Q^2}{4M_p}$$

$$\varepsilon = \left[(1 + (1 + \tau)(\tan(\theta/2))^2) \right]^{-1}$$

$$A_V = \underbrace{1 - 4\sin^2(\theta_w)}_{\text{"weak charge" } \sim 0.0448} (\varepsilon(GE^p)^2 + \tau(GM^p)) - \varepsilon GE^p GE^n + \tau GM^n GM^p$$

$$A_A = 1 - 4\sin^2(\theta_w) \sqrt{(1 - \varepsilon^2)} \sqrt{\tau(1 + \tau)} GM^p GA^{p,weak}$$

$$A_S = \varepsilon GE^p GSE + \tau GM^p GM^s$$

FF's in our momentum transfer range :

$$GE^p \approx 1; \quad GM^p \approx 2.79; \quad GM^n \approx -1.91$$

$$GE^n \approx 0.4Q^2; \quad GM^s \approx 0.7Q^2$$

assumption on exotic FF :

$$GE^s \approx 0 \quad GM^s \approx 0.04 \quad GA^{p,s} = 1.$$

Weak charge Term is dominant for forward scattering,

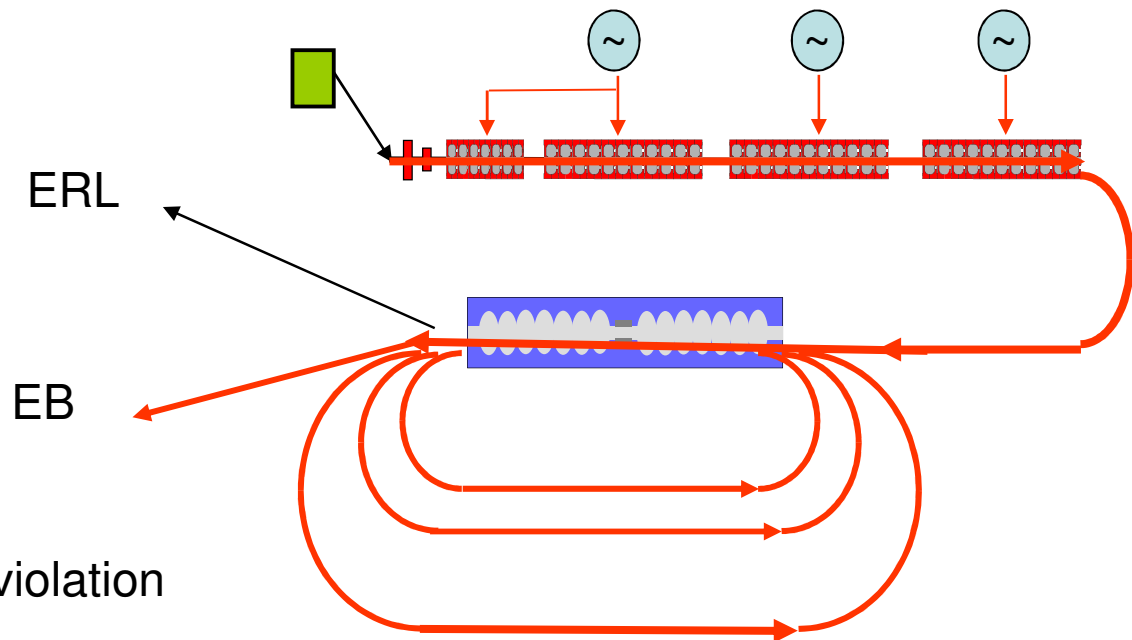
Magnetic Term is dominant for backward scattering

Backward Strange magnetic Term contribution few percent.

Important issues for feasibility study of the MESA-ACcelerator project

A) ERL-Beam dynamics

- 1.) Injector: source(s), space charge,....
- 2.) Recuperator Beam dynamics
- 3.) Photosource with robust cathode for ERL operation (+related issues)

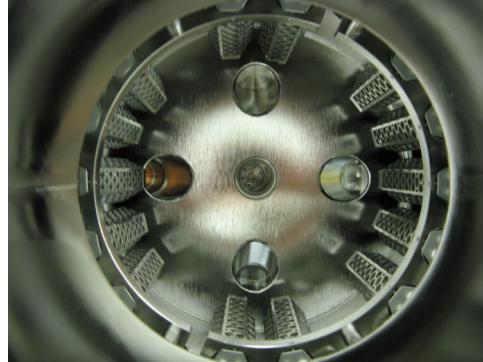


B) Integrated Design for Parity violation

- 4.) Optimized HCA-compensation +diagnostic set-up
- 5.) Polarimetry: “self calibrating” polarimeter + Möller Polarimeter
- 6.) Optimization of accelerator/beam transport lattice with respect to beam parameter stability

Was kann man von vorhandener GaAs-Quelle erwarten?

1. GaAs ist leicht beschaffbar, preiswert, extrem effizient ($S \geq 70 \text{ mA/Watt}$) @500nm
2. Synchro-Laser bei 1.3GHz einige 10 Watt bei 500nm demonstriert (Cornell)
3. bis 12mA d.c. (65mA Langpuls 100 μs) polarisiert erprobt, $\epsilon \sim 5\text{-}20 \mu\text{m}$. (norm)
4. 2mA Demo 500nm: $>4^*$ Stabiler als IR \rightarrow 300Coulomb pro τ aus $d=2,5 \text{ mm}$
5. Skalierung auf Fläche erwartet (J. Grames et al. Proc. PAC 2005, 2875 (??))
6. Erwartete Standzeit bei 10mA entspricht 1000C pro τ : $1 \cdot 10^5 \text{ s}$ ($>1 \text{ Tag}$).



7. Neue Quellenkammer (in Betrieb seit 1/2009) mit 10^* besserem S/O Verhältnis
8. Cs:KSb3 $> 50^*$ stabiler (D.H. Dowell et al. , NIM A 356 167 (1995)) : CAVEAT!! \rightarrow Tests
9. 2 Isolator-konzept überdimensioniert: Vorteil: 150kV Betrieb denkbar \rightarrow Tests

Was kann man von d.c.-GaAs-Quelle NICHT erwarten?

Emittanzskalierung:

$$\varepsilon_{x,y,norm} = \sigma_{x,y} \sqrt{\frac{kT_{eff}}{mc^2}}$$

0.25 μ m pro mm radius ?
 T_{eff} GaAs ~300-400K (IR)
 ~ 1200K (Blau)

I.V. Bazarov et al. Proc PAC 2007 1221

Brillanzskalierung:

$$\frac{I}{\varepsilon^2} \propto B \xrightarrow{\sigma \rightarrow 0} \infty \quad ???$$

$$B_{max} \propto \frac{E_{Kath}}{kT_{eff}}$$

Kurzpulslimit: $(q/A)_{max} = \varepsilon_0 E_{kath}$

Favorisiert eine R.f.-quelle

Ionenbackbombardment: -R.f.-Hochbrillanzquelle schwieriger. wg. $\sigma \sim 1$ mm
 +CsTe dafür toleranter (GaAs/IR *1000 ??)+Vakuumbgain
 +Ionenbombardment nur bis einige keV
 (BNL, E. Pozdeyev, Proc. PESP2008)
 +keine Cs-Verdampfung
 - Sputtering !?

→ Experimentelles Programm an MESA mit d.c. Quelle starten,
 und H.f.-Quellenentwicklung abwarten.

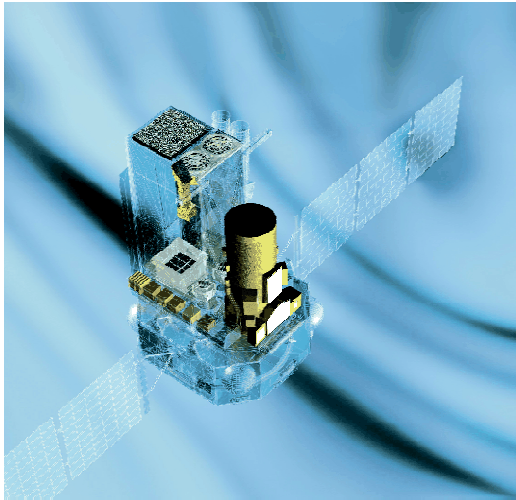
‘Dunkle Materie’ im Elektronenbeschleuniger

The emission. The data suggest that the emission follows an azimuthally symmetric galactic bulge of $\sim 9^\circ$ typical *FWHM*, yet the uncertainties on the width are still rather large ($6^\circ\text{--}18^\circ$, 2σ). The bulge seems centred on the galactic centre, yet a marginal displacement towards positive latitudes and negative longitudes may be indicated. Obviously, this displacement clearly needs confirmation by the analysis of a much larger set of data.

J. Knödelseder et al.
Astron, Astrophys.
411 (2003) L457

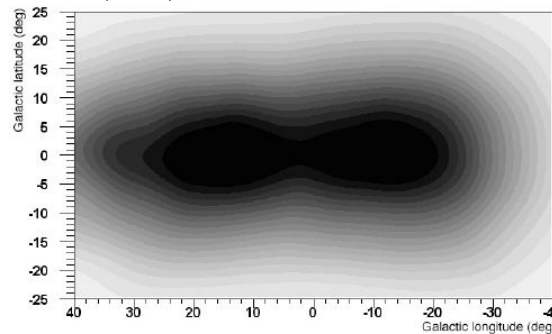
Dunkle Materie suchen ist spekulativ und das Thema kann leicht von heute auf morgen obsolet werden. → MESA braucht ‘Arbeitspferde’

MESA-PHYSIK 'Dunkle Materie':



"INTEGRAL"-Satellit:
 γ -Beobachtung des Himmels

J. Knödelseder et al.
Astron. Astrophys.
411 (2003) L457



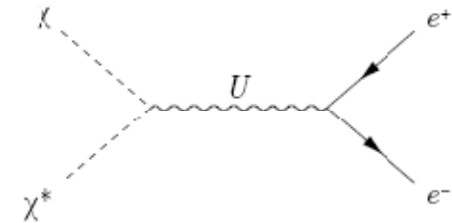
Intensität der 511keV- γ Linie
(Positronenvernichtung)
im galaktischen Zentrum

Erklärung des Signals mit
konventionellen Quellen
(z.B. radioaktive Substanzen
aus Supernovae) schwierig.

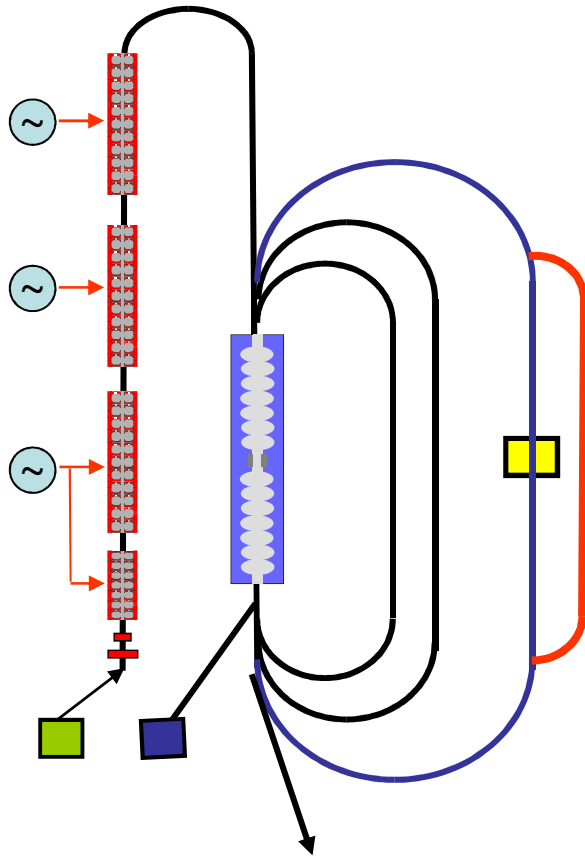
Unkonventionelle Erklärung:
Leichte Teilchen χ, χ^* , die nur
schwach Wechselwirken
(WIMPS, \rightarrow Dunkle Materie)

C. Boehm, P. Fayet
Nucl. Phys. B683 (2004) 219

Die Fermionen χ, χ^* erzeugen Electron Positron Paare,
 \rightarrow die so entstandenen Positronen erzeugen das
das Signal des INTEGRALSatelliten
 \rightarrow die Masse der χ, χ^* wäre etwa 3-20 MeV, die Masse
des U-Bosons < 100 MeV



MESA-Parameters: ILAC



ILAC-R.f.:

2.449 GHz, c.w., normal conducting
harmonic buncher

graded- β section (0.1-0.55 MeV)

discrete- β section (0.55-2 MeV)

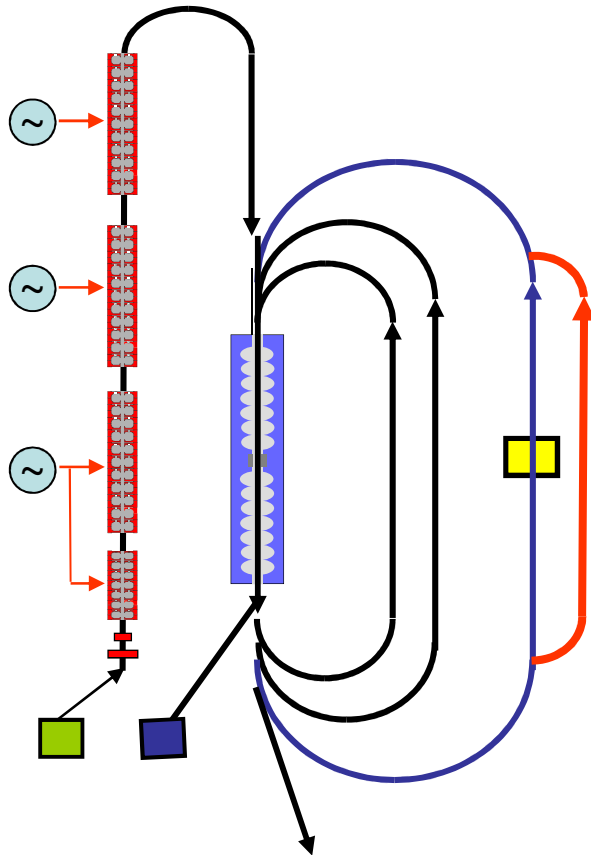
$2 \cdot \beta = 1$ section (2-5 MeV)

typ. Gradient 0.75MV/m

Rf-transmitters:

3* Thales TH2155, 50kW each
beam power/rf power 1/3

MESA-Parameters: s.c. accelerating module



R.f.:

1.2245 GHz c.w.

2*7 cell module

Gradient: 20MV/m

Beam loading <0.01 kW (ERL) 19.8 kW (EB)

Energy gain: 33MeV per pass.

Transmitter: 2*IOT + Combiner

Kryogenics:

T=1.8K

total Losses (dynamic+static): 80 Watt

Recirculation:

2* Full wave, (38, 71 MeV)

1* Full wave (EB) / Half wave(ERL) (137 MeV/5MeV)

Energy recovery to:

5MeV (50kW load to beam dump, ERL-Mode)

MESA-COST in k€

He liquifier, 4K (140l/h with N ₂ precooling)	1550
1.8K booster, cooling cap. 80 watt	1100
1 high. grad module (2 x 7cell, 1.2245GHz) (HoBiCat like)	1600
rf-station (30kW, 1.2245GHz)	500
Laser+nclLAC ,chopper/buncher, solenoids, graded- β , disc. β , klystron HVPS, vacuum, diagnostics...)	1100
Isochronous recirc. (dipoles, quads, sexts, vacuum, diagnostics, shicane...)	1300
infra-structure (He-distrib., cooling, construction)	800
misc. (control, beam dump, safety system)	300
Total:	8250