Future of the M2 beam at CERN in the Physics Beyond Colliders Context

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Impressions of the M2 beam line

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Agenda

• The “Physics Beyond Colliders” Initiative
• North Area Consolidation
• The M2 Beam and Future Options
• 2018 Test Beams in EHN2
• Summary and Outlook

http://pbc.web.cern.ch/
Physics Beyond Colliders – Introduction

• Extrapolatory study aiming at exploiting the full scientific potential of CERN's accelerator complex and its scientific infrastructure through projects complementary to the LHC, HL-LHC and other possible future colliders

• Projects targeting fundamental physics questions that are similar in spirit to those addressed by high-energy colliders, but that require different types of beams and experiments

• Initiated by CERN director-general and coordinated by J. Jaeckel, M. Lamont and C. Vallee (chair)

• Kick-off workshop (September 2016) identified a number of areas of interest, revisited at Annual Workshop (November 2017)

• Working groups in full-swing to pursue studies in these areas

• PBC study remains open to further ideas for new projects
Physics Beyond Colliders – Physics

Physics Groups

• **BSM subgroup**: SHIP; NA64++; NA62++; KLEVER; IAXO; LSW; EDM; REDTOP

• **QCD subgroup**: COMPASS++; μ-on-e; LHC FT (gas target + crystal extraction); DIRAC++; NA60++; NA61++

Deliverables:

• Evaluation of the physics case in the worldwide context

• Possible further detector optimization

• For new projects: investigation of the uniqueness of the CERN accelerator complex for their realization
Accelerator Working Group

BSM physics working group

QCD physics working group

PBC-AF committee

BDF working group

EDM working group

Conventional beam working group

Technology working group

LHC FT working group

Proton production study

NuSTORM study

AWAKE++ study

Gamma Factory study
Conventional Beams – Projects

Under consideration at present:

• NA62: Proposal to operate in beam-dump mode (HNL, axions)
• NA64++: High intensity electron, muon and hadron beams for dark sector searches (A’)
• K_{L}EVER: High intensity K_{L} beam (high flux, pencil beam, new target) for rare decays, in particular K_{L} \rightarrow \pi \nu \nu
• COMPASS++: RF separated beams for hadron structure and spectroscopy; proton radius measurement with muon beam
• $\mu$-on-e: 150 GeV muon beams for high precision measurement of hadron vacuum polarisation for g-2 of the muon
• DIRAC++: DIRAC@SPS for high statistics of mesonic atoms
• NA60++: Heavy ion beams for di-muon physics and open-charm
• NA61++: Higher intensity ion beam for open-charm studies
Conventional Beams – Structure

CONVENTIONAL BEAMS WORKING GROUP
Conveners: L. Gatignon, M. Brugger
Members: Experiments, H. Wilkens, G. Lanfranchi, T. Spadaro,
EA physicists, HSE, RP, EL, CV, RF, STI

CBWG-ECN3
Convener: L. Gatignon
• K_leeVER
• NA62 Dump
• NA60
• DIRAC

CBWG-EHN2
Convener: J. Bernhard
• COMPASS
  (μ, RF-separated and low energy pbar beams)
• μ-on-e
• NA64-μ
• CEDAR project

CBWG-EHN1
Convener: N. Charitonidis
• NA61
• NA64 hadrons

Main deliverable: Conceptual Design Report by end of 2018
EHN2 Working Group

- Work Breakdown Structure (top level)
  - WP1: Muon beams post 2020
  - WP2: Hadron and Electron beams post 2020
  - WP3: RF-separated beams
  - WP4: Beam Particle Identification (dedicated meetings, WP leader S.Mathot/EN-MME)
- One project associate (full-time) and since March 2018 one fellow (part-time) for studies plus additional resources for WP4
- User presentations for technical details and plans completed, user requirements document prepared
- Several studies launched
- Track progress by continuous reporting, about one WG meeting per month
EHN2 Working Group – WP4

• CEDAR thermal housing completed (main deliverable WP4)
• Duct works being finalised and system being commissioned
• System ready for 2018 physics run
North Area Consolidation – Safety

**EHN1**
- Flammable gas detection (2018 & LS2)
- Fixed ODH & CO2 detection (2018 & LS2)
- SUSI for underground galleries (LS2)
- ZORA for underground galleries (post-LS2)

**ECN3**
- Flammable gas detection (update tbc)
- Fixed ODH detection (update tbc)
- RP buffer zone (2018)

**EHN2**
- SUSI to access building (YETS)
- Flammable gas and ODH detection (LS2)
- ZORA for underground galleries (post-LS2)
- RP buffer zone (2018)

**Overall NA buildings**
(TDC2, TCC2, TCC8, TT’s, EHN1&2, ECN3)
- Fire Detection Sectorisation Survey (YETS 2017/18)
- RP monitoring upgrade (LS2)
- Renovation of the Fire Detection & Evacuation Alarm (post –LS2)
- Renovation of the Beam Imminent Warning & Evacuation Alarm (post LS2)

Courtesy: Y. Kadi, F. Gautheron
North Area Consolidation

**EHN2**
- SM2 power converter upgrade (completed)
- Chilled water consolidation (pipework) => 2018, LS2 + post-LS2
- Roof renovation for water tightness => LS2
- BA’s sectional & personal doors => LS2

**Beam Instrumentation**
- XBPF beam profile monitors (SciFis)

**Further Works**
- Gas Network renovation (2018 + LS2)
- Cranes and lifts renovation (LS2 + post-LS2)
- Consolidation of TCC2/TCC8 target => YETS
- Thermal/FEM studies of primary target and TAX => 2018 & LS2
- Cooling Tower 2 works (2018+YETS)

Courtesy: Y. Kadi, F. Gautheron
The M2 Beam

Three main operation modes:

- High-energy, high-intensity muon beam. Normally for muon momenta up to 200 GeV/c. Higher momenta up to 280 GeV/c are possible, but the flux drops very rapidly with beam momentum.
- High-intensity secondary hadron beam for momenta up to 280 GeV/c with radiation protection constraints.
- Low-energy, low-intensity (and low-quality) in-situ electron calibration beam.

<table>
<thead>
<tr>
<th>Beam Mode</th>
<th>Momentum (GeV/c)</th>
<th>Max. Flux (ppp / 4.8s)</th>
<th>Typical Δp/p (%)</th>
<th>Typical RMS spot at target</th>
<th>Polarisation</th>
<th>Absorber (9.9 m Be)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muons</td>
<td>+208/190, +172/160</td>
<td>~10^8, 2.5 10^8</td>
<td>3%</td>
<td>8 x 8 mm</td>
<td>80%</td>
<td>IN</td>
</tr>
<tr>
<td>Hadrons</td>
<td>+190, -190</td>
<td>10^8 (RP), 4 10^8 (with dedicated dump)</td>
<td>_</td>
<td>5 x 5 mm</td>
<td>_</td>
<td>OUT</td>
</tr>
<tr>
<td>Electrons</td>
<td>-10 to -40</td>
<td>&lt; 2 10^4</td>
<td>_</td>
<td>&gt; 10 x 10 mm</td>
<td>_</td>
<td>OUT</td>
</tr>
</tbody>
</table>
The M2 Beam – Parameters and Principle

<table>
<thead>
<tr>
<th>Beam Parameters for COMPASS</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam momentum $p_\mu/p_\pi$</td>
<td>$160 / 172$ GeV/c</td>
</tr>
<tr>
<td>Proton flux on T6 per SPS cycle</td>
<td>$1.5 \times 10^{13}$</td>
</tr>
<tr>
<td>Muon flux at COMPASS per SPS cycle</td>
<td>$2.5 \times 10^8$</td>
</tr>
<tr>
<td>Beam polarisation</td>
<td>$-80% \pm 4%$</td>
</tr>
<tr>
<td>Spot size at COMPASS target $(\sigma_x \times \sigma_y)$</td>
<td>$8\text{mm} \times 8\text{mm}$</td>
</tr>
<tr>
<td>Divergence at COMPASS target $(\sigma_{dx} \times \sigma_{dy})$</td>
<td>$0.4\text{mrad} \times 0.8\text{mrad}$</td>
</tr>
<tr>
<td>Muon halo within 50mm from beam axis</td>
<td>$16%$</td>
</tr>
<tr>
<td>Halo in experiment $(6 \times 4\text{m}^2)$ at $</td>
<td>x,y</td>
</tr>
</tbody>
</table>

(172 ± 17) GeV/c

600 m

Hadron Decay Section

(160 ± 6) GeV/c

400 m

Muon Cleaning Section

J. Bernhard

Future of M2 within PBC
RF-separated Beams

Reminder: Panofsky-Schnell-System with two cavities (CERN 68-29)

- Particle species have same momenta but different velocities
- Time-dependent transverse kick by RF cavities in dipole mode
- RF₁ kick compensated or amplified by RF₂
- Selection of particle species by selection of phase difference
  \[ \Delta \Phi = 2\pi \left( \frac{L f}{c} \right) (\beta₁^{-1} - \beta₂^{-1}) \]
- For large momenta: \[ \beta₁^{-1} - \beta₂^{-1} = \frac{(m₁^2-m₂^2)}{2p^2} \]
RF-separated Beams - Phases

For $K^\pm$ beams: $\Delta \Phi_{\pi p} = 360^\circ$ and $\Phi_{RF2}$ such that both $\pi$ and $p$ go straight i.e. dumped

$\Delta \Phi_{pK} = 94^\circ$, i.e. a good fraction of $K$ outside the dump, depending on phase at 1$^{st}$ cavity

For $p\bar{p}$ beams: $\Delta \Phi_{\pi p} = 180^\circ$ and then $\Delta \Phi_{pe} = 184^\circ$, $\Delta \Phi_{pK} = 133^\circ$

with phase of RF2 such that pions go straight, antiprotons get reasonable deflection, electrons are dumped effectively and $K$ reduced
RF-separated Beams

\[ \Delta \Phi = 2\pi \left( L \frac{f}{c} \right) (\beta_1^{-1} - \beta_2^{-1}) \]

For large momenta: \[ \beta_1^{-1} - \beta_2^{-1} = \frac{(m_1^2 - m_2^2)}{2p^2} \]

Example: input from CKM studies
- Kick: 15 MeV/c
- \( f = 3.9 \) GHz
- \( \frac{dp}{p} = 2\% \)
- \( \Delta \phi_{\pi p} = \pi \) (pbar selection) / \( \Delta \phi_{\pi p} = 2\pi \) (K selection)
CKM-based Example

$$\Delta \Phi = 2\pi \left( \frac{L}{c} \frac{f}{c} \right) (\beta_1^{-1} - \beta_2^{-1})$$

For large momenta: $\beta_1^{-1} - \beta_2^{-1} = \frac{(m_1^2 - m_2^2)}{2p^2}$
Crab Cavities Example

Currently available technology at CERN: Crab Cavities for LIU SPS upgrade (400 MHz superconducting dipole cavities)

Assume availability of $L=800 \text{ m}$:

<table>
<thead>
<tr>
<th>RF frequency</th>
<th>Limit $p(K)$</th>
<th>Limit $p(p\bar{p})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>400 MHz</td>
<td>20 GeV/c</td>
<td>30 GeV/c</td>
</tr>
<tr>
<td>1.3 GHz</td>
<td>37 GeV/c</td>
<td>55 GeV/c</td>
</tr>
</tbody>
</table>

Conclusion: crab cavity design so far not compatible with user requirements, new developments necessary
RF-separated Beams – Hadron Section M2

Front-end

• Hadron section optimised for large acceptance
• About 100m necessary for front-end and momentum selection with goal to keep it for compatibility
RF-separated Beams – Absorber Region

Dispersion challenge
• To make use of the full length of the M2 tunnel, the beam needs to be adjusted vertically to the second slope with BENDs 4+5
• This introduces a new source of dispersion and thus needs to be compensated before the second cavity
Radiation Protection Considerations

• Intensity limitations: What can be gained with additional (roof) shielding for the beam line and/or a part of experimental set-up?
• To be studied (Summer Student project, new fellow)
Future Options for Experiments in EHN2

- Historically, EHN2 has already housed more than one muon beam experiment / set-up (e.g. NA2 + NA4, SMC + polarimeter)
- Most important WP1 challenge: Will we be able to run µ-on-e or NA64 together with COMPASS?
- Main questions
  - Are the physics requirements compatible enough (e.g. beam momentum)?
  - Are the required intensities comparable?
  - Is there enough space?
  - Need to study this from scratch

L. Gatignon, N. Doble et al., NIM A 343 (1994) 351-362
Optics – Muon Section M2

- Focussing on targets non-trivial as the beam is not produced from a point-like source and has a relatively large $\Delta p/p$
- Important to know user requirements such as needed divergence and beam spot size to re-design the final focus
Future Options for $\mu$-on-e in EHN2

- Entrance Area of EHN2
  - **Pro:** no interference with COMPASS spectrometer, enough space for full set-up
  - **Con:** needs many weeks change-over time, no installation of CEDARs possible, $\mu$-on-e targets introduce multiple scattering
  - Compatibility with proton radius measurement depends on required beam quality and characteristics (energy, intensity, divergence)
Future Options for $\mu$-on-e in EHN2

• Entrance Area of EHN2
Future Options for $\mu$-on-e/NA64 in EHN2

- Downstream Area of EHN2
  - Pro: compatible with COMPASS running at the same time (able to use full COMPASS set-up)
  - Con: safety aspects (lock ABS in, no hadron beams), limited space, energy loss of muons in COMPASS could imply to re-measure momentum (i.e. another spectrometer magnet), re-/de-focusing of muons would imply 2-3 quadrupoles plus compensation of SM1+SM2 kick, thus an extension of the building
Future Options for NA64 in EHN2

- Installation inside SM2
  - Pro: compatible with COMPASS (able to use full COMPASS set-up)
  - Con: limited space, energy loss of muons within COMPASS, NA64 would need to invest in new non-magnetic calorimeter modules, change-over time
2018 Test Beams

- μ-on-e: Measure μ-e scattering on 2 target modules with Silicon instrumentation + 1 EM calorimeter. Total length 3m.
- Compass TPC: Measure μ-p scattering in high pressure TPC + Silicon telescope
2018 Test Beams

- Studies initialised due to parasitic nature of 2018 tests
- COMPASS has a physics program that uses the 190 GeV/c hadron beam mode with a dedicated hadron absorber
- Goal: Extrapolate muon beam through COMPASS set-up and assert widening of beam due to multiple scattering with HALO
2018 Test Beams

- Beam distribution at test location for muon beam configuration

- Beam momentum after passing hadron absorber
2018 Test Beams

• Beam divergence muon beam (after passing absorber)

- 160 GeV/c:
  - X' distribution
  - Y' distribution

- 190 GeV/c:
  - X' distribution
  - Y' distribution
2018 Test Beams

- Muon distribution at test location for 2018 190 GeV/c DY hadron beam

\[
\sigma_x \times \sigma_y = 100 \text{ mm} \times 84 \text{ mm}
\]

- Momentum \( \sim 186 \text{ GeV/c} \)

- Good news, still very useful for tests
- Flux for \( 10^{13} \text{ pot} \sim 10^5/\text{spill} \) (within 10cm x 10cm of beam axis)
2018 Test Beams

- Beam divergence of muons from DY hadron beam (after passing absorber)
2018 Test Beams

• A little extra output: Muon halo from for 2018 190 GeV/c DY hadron beam at the COMPASS target

Zoom to 15cm radius around target
Summary and Outlook

- The M2 beam at CERN continues to serve in its 40th year of operation.
- Future options of RF-separated beams, other beam configurations (µ, h, e) plus compatibility of proposed experiments and integration of the full set-ups is currently being studied within the conventional beams working group / EHN2 WG of Physics Beyond Colliders.
- More personnel available (project associate) for studies since 12/17, more from 03/18 (new fellow).
- North Area Consolidation Study established and first urgent consolidation works already completed.
- Optics studies for 2018 tests finalised, proposal: Check RP limit for µ flux with tests this year.
- Other news: Expect 10% increase of duty cycle in 2018 due to faster repetition of spills.

http://pbc.web.cern.ch/
Thank you!
Secondary Beams at CERN

High intensity secondary beams in a wide range of momenta with largely selectable particle species

- East Area / PS (24 GeV/c primary protons and ions for irradiation and 0.5 – 15 GeV/c secondary beams)
- North Area / SPS (400 GeV/c primary protons and up to 380 GeV/c secondary and ion beams)
Production Targets

<table>
<thead>
<tr>
<th>Position</th>
<th>Material</th>
<th>Length (mm)</th>
<th>Height (mm)</th>
<th>Width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Air/OUT</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>Be</td>
<td>500</td>
<td>2</td>
<td>160</td>
</tr>
<tr>
<td>2</td>
<td>Be</td>
<td>300</td>
<td>2</td>
<td>160</td>
</tr>
<tr>
<td>3</td>
<td>Be</td>
<td>180</td>
<td>2</td>
<td>160</td>
</tr>
<tr>
<td>4</td>
<td>Be</td>
<td>100</td>
<td>2</td>
<td>160</td>
</tr>
<tr>
<td>5</td>
<td>Be</td>
<td>40</td>
<td>2</td>
<td>160</td>
</tr>
</tbody>
</table>

5x plates, 40 mm inter-plate distance
Secondary Particle Production

Atherton parameterisation (CERN 80-07):

\[
\frac{d^2N}{dpd\Omega} = A \left[ \frac{B}{p_0} e^{-Bp/p_0} \right] \left[ \frac{2Cp^2}{2\pi} e^{-C(p\theta)^2} \right]
\]

with primary momentum \(p_0\) and production angle \(\theta\)

Flux per solid angle [steradian], per interacting proton, and per dp [GeV/c]
Secondary Particle Production

**Primary Target (Be)**
- **Primary beam**
  - 400 GeV/c $p$
  - Few $10^{12}$ ppp

**Secondary Target**
- **Secondary beam**
  - Mixed (e+h+μ)
  - Typically ~100 GeV/c
  - Flux ~ $10^7$ ppp

**Absorber (few mm Pb)**
- **Tertiary beam**
  - Typically 10-80 GeV/c
  - Flux up to $10^4$ ppp, e.g.
  - ~4 mm Pb: $1X_{o}$, $<<1 \lambda_{l}$: ‘pure’ electrons
  - ~40 cm Cu: $3 \lambda_{l}$, ~30 $X_{o}$: hadrons

**Nota bene:** Flux given for a typical EHN1 beam line, e.g. H8