RF separated beam and other beam issues

Lau Gatignon, COMPASS workshop, 22 March 2016
Outline

• First thought on a RF separated beam

• Other remarks on future beam options
Particle production at 0 mrad (i.e. like in M2)

Apply ‘Atherton formula’ for 0 mrad (only approximation for \( p \leq 60 \) GeV/c).
Obtain number of particles per steradian per GeV/c and per \( 10^{12} \) interacting protons:

![Graphs showing particle production rate vs. momentum for different particles at 0 mrad](image-url)
Pbar production according to ‘Atherton formula’
(for 0 mrad production angle)

Best case for flux: 80 GeV/c

0.77 pbar / interacting proton / steradian / GeV

Pbar are 3.2% of the total negative hadron flux

However: many e⁻ at lower energies !!
Electron Monte Carlo: $\pi^0 = (\pi^+ + \pi^-)/2$, $\pi^0 \rightarrow \gamma\gamma$, $x = E_e/E_\gamma$ using $f(x) = x^2 + (1-x)^2 + 2x(1-x)/3$

Parametrisation of Electron production MC data at 0 mrad

$$d^2N/dp d\Omega = A \cdot (B/p_o) \cdot e^{-Bp/p_o} \cdot (2Cp_o^2/2\pi) \cdot e^{-C(p\theta)^2}$$

$A = 0.0023$, $B = 10$, $C = 9$

From West Area experience:
electrons are about 8% of beam at -120 GeV/c (0 mrad)

Can reduce electron fraction with Pb sheet using Bremsstrahlung, but thick sheets will affect parallelism at Cedar ……

Try to keep $e^-$ not too much higher than $K^+$ i.e. do calculation for 100 GeV/c

<table>
<thead>
<tr>
<th>Momentum [GeV/c]</th>
<th>e- fraction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>100</td>
<td>8</td>
</tr>
<tr>
<td>200</td>
<td>0.7</td>
</tr>
</tbody>
</table>
At -100 GeV/c one may expect the following beam composition (in %):

<table>
<thead>
<tr>
<th>Particle type</th>
<th>Fraction at T6</th>
<th>Fraction at COMPASS</th>
</tr>
</thead>
<tbody>
<tr>
<td>p\bar{}</td>
<td>1.7</td>
<td>2.1</td>
</tr>
<tr>
<td>K^-</td>
<td>5.8</td>
<td>1.6</td>
</tr>
<tr>
<td>π^-</td>
<td>84.5</td>
<td>86.3</td>
</tr>
<tr>
<td>e^-</td>
<td>8.0</td>
<td>10.0</td>
</tr>
</tbody>
</table>

In present M2 hadron beam \leq 2 \times 10^6 p\bar{}

(due to \(10^8\) limit on total beam flux for RP)
What about a RF separated beam?

First and very preliminary thoughts, guided by

- initial studies for P326
- CKM studies by J. Doornbos/TRIUMF, e.g.
  http://trshare.triumf.ca/~trjd/rfbeam.ps.gz

E.g. a system with two cavities:

\[
\Delta \Phi = 2\pi \left( \frac{L f}{c} \right) \left( \beta_1^{-1} - \beta_2^{-1} \right) \quad \text{with} \quad \beta_1^{-1} - \beta_2^{-1} = \frac{(m_1^2 - m_2^2)}{2p^2}
\]
How to choose phases?

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

$\Delta \Phi_{\pi K} = 94^\circ$, therefore a good fraction of the kaons go outside the dump (depending on phase at 1st cavity).

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

Choose the phase of RF2 such that pions go straight, then antiprotons get reasonable deflection, electrons are dumped quite effectively and kaons are reduced.

However, the $p\bar{b}$ar may arrive at any phase w.r.t. the RF signal $\rightarrow$ Losses!
\[ \Delta \varphi = \frac{2\pi}{c} L f \frac{m_1^2 - m_2^2}{p^2} \]

\[ \Delta \phi_{\pi p} = \pi \quad \rightarrow \quad L f = 1.74 \times 10^{12} \text{ m/s} \]

For \( f = 3.9 \text{ GHz} \) \( \rightarrow \) \( L \approx 450 \text{ metres} \)

Phase shifts depend on square of momentum – separation over limited range !

Avoid phase changes of more than a few degrees \( \rightarrow \) \( \Delta p/p \leq 1\% \)
Coherence length of cavity

At 6 GHz the RF wavelength is $\lambda = c/f = 3 \times 10^{10} \text{ cm s}^{-1} / 6 \times 10^9 \text{ s}^{-1} = 5 \text{ cm}$

The ‘coherence length (over which the phase is sufficiently preserved)’ corresponds to something of the order of $\Delta \phi \approx \pi/10$, hence

$$L_{\text{coh}} \approx \lambda \cdot (\pi/10) / (2\pi) \approx 3 \text{ mm}$$

The beam spot has thus to remain within 2, i.e. ±1 mm throughout the cavity!

**Can be improved to 9 mm with X-Band technology at 3.9 GHz(???)**

The $p_t$-kick of the cavity is of the order of 15 MeV/c (see CKM system), corresponding to about 0.3 mrad at 50 GeV.

The beam divergence must be a lot smaller than this, say ± 0.15 mrad, at least in the bending plane.

In the other plane the beam must stay sufficiently small, but a somewhat larger divergence may be acceptable, e.g. ± 0.5 mrad.

**Therefore the presence of a RF system also limits the transverse emittance of the beam**
Acceptance values for RF separated $K^+$ beam  
(rough estimate, based on extrap from J.Doornbos)

<table>
<thead>
<tr>
<th></th>
<th>CKM $K^+$ beam</th>
<th>pbar beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam momentum [GeV/c]</td>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>Momentum spread [%]</td>
<td>$\pm 2$</td>
<td>$\pm 1$</td>
</tr>
<tr>
<td>Angular emittance H, V [mrad]</td>
<td>$\pm 3.5$, $\pm 2.5$</td>
<td>$\pm 3.5$, $\pm 2.5$</td>
</tr>
<tr>
<td>Solid angle [$\mu$sterad]</td>
<td>10-12 $\pi$</td>
<td>10-12 $\pi$</td>
</tr>
<tr>
<td>% wanted particles lost on stopper</td>
<td>37</td>
<td>20</td>
</tr>
</tbody>
</table>

As the pbar kick is more favorable than for $K^+$, I assume that 80% of p bar pass beyond the beam stopper.

Acceptance $10\pi$ $\mu$sterad, 2 GeV/c
Very preliminary conclusion

- H.W. Atherton formula tells us: \(0.42 \text{ pbar} / \text{int.proton} / \text{GeV}\)

- Assume target efficiency of 40% 
  Then for \(10^{13}\) ppp on target one obtains:

  \[0.4 \times 10^{13} \times 0.42 \times \pi \times 10^{-5} \times 2 \times 0.8 \text{ pbar} = 8 \times 10^7 \text{ pbar/pulse}\]

for a total intensity probably not exceeding \(10^{13}\) ppp, knowing that \(e^-\) and \(\pi\) are well filtered, but \(K^+\) only partly.

- If \(10^8\) limit on total flux, max antiproton flux remains limited by purity (probably about 50%).
  Hence \(\approx 5 \times 10^7 \text{ pbar per pulse}\)

- For \(K^+\), rate is smaller: by factor \(1.6 / 2.1 \approx 0.75\) (see before)
Other beam issues

- From recent SHiP studies the limit of $4 \times 10^{13}$ ppp total was reconfirmed and due to recent radiation issues in and around TCC2 even $2 \times 10^{13}$ ppp is questioned at least for the coming years…..
- The existing T6 target has a limit of $1.3 \times 10^{13}$ for a 4.8 s flat top. Many other limits come at the same level
- Muon beams at surface halls are limited by muon halo and by the muon beam leaving the hall. COMPASS is at the extreme limit.
- Hadron beams require complete roof shielding above $\sim 5 \times 10^8$ ppp. Even then there are limits due to muon halo, air activation and so forth.
- Many of these issues get much easier in underground caverns (e.g. NA62 runs at $> 2 \times 10^9$ ppp).
- The SHiP proposal assumes several pulses of $4 \times 10^{13}$ ppp per supercycle. This will be very challenging and expensive.
- The SPS will not go higher in energy in the foreseeable future. Linac4 will not significantly improve the performance for fixed target. Neither the 2 GeV injection for the Booster. PS/2 is abandoned.
- The DG will set up a WG for fixed target physics at the injectors and at the LHC.
Outlook

• Higher energies may require underground areas

• Radiation protection limits will only get tighter…

• RF separated beams will increase the beam content of the wanted particle type and thus reduce the required overall beam intensity, hence the radiation issues

• However, they are complex, expensive and need detailed study. COMPASS would have to provide some justification to launch such a study.
## Estimates for 2017 and 2018

Intensities per spill with 4.8 s flat top:

<table>
<thead>
<tr>
<th>Target</th>
<th>Intensity driver</th>
<th>Request for 2016</th>
<th>‘Normal’ intensity</th>
<th>Request for 2017</th>
<th>Request for 2018</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2</td>
<td>NA61, P348</td>
<td>$2 \times 10^{12}$</td>
<td>$4 \times 10^{12}$</td>
<td>$2 \times 10^{12}$</td>
<td>$3 \times 10^{12}$</td>
<td>Neutrino platform in 2018</td>
</tr>
<tr>
<td>T4</td>
<td>NA62*)</td>
<td>$4 \times 10^{12}$</td>
<td>$8 \times 10^{12}$</td>
<td>$8 \times 10^{12}$</td>
<td>$8 \times 10^{12}$</td>
<td></td>
</tr>
<tr>
<td>T6</td>
<td>COMPASS</td>
<td>$1.5 \times 10^{13}$</td>
<td>$1.5 \times 10^{13}$</td>
<td>$1.5 \times 10^{13}$</td>
<td>$1.2 \times 10^{13}$</td>
<td>Hadrons in 2018, but better shielding</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>$2.1 \times 10^{13}$</td>
<td>$2.7 \times 10^{13}$</td>
<td>$2.5 \times 10^{13}$</td>
<td>$2.3 \times 10^{13}$</td>
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</tbody>
</table>
Final remarks

- For most of 2016, a total T2+T4+T6 of 2.1 $10^{13}$ ppp should be ok. For limited periods, higher intensities will be requested (NA62, P348).
- The total intensity extracted must be somewhat higher (splitter losses, etc).
- The nominal requests of the big approved experiments are in some cases higher than this and they will come in the future (NA62).
- The dose rates are higher than in the CNGS period, due to higher repetition rate, but should (ideally) not be higher than before CNGS.
- There are indications that there is an increased dose per proton extracted, at extraction and possibly still further downstream. A lot of good work has been done in 2015. Even better understanding would be useful.
- Most of the experiments were approved before the problems started and the corresponding intensities were mentioned on many occasions at IEFC meetings and workshops.
- In 2018 the total request is slightly higher.