RF Separated Beam Project for M2 Beam Line

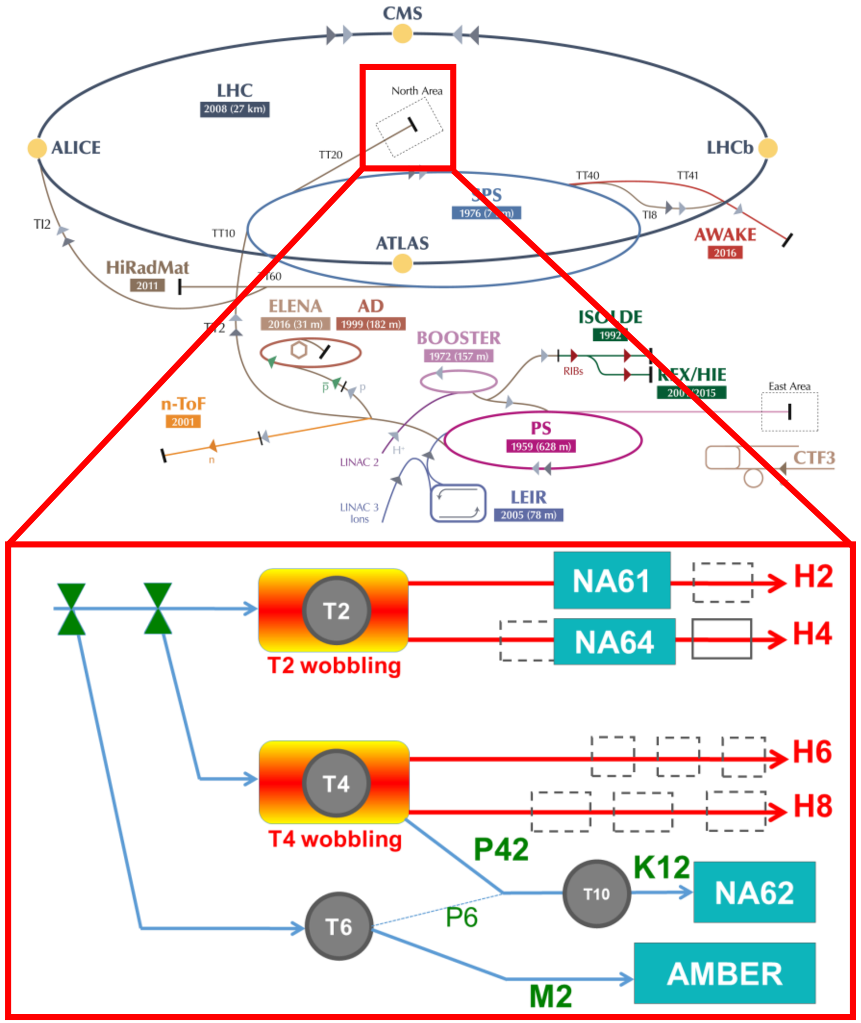
10 May 2022

A. Gerbershagen on behalf of RF separated beam study team
(Dipanwita Banerjee, Johannes Bernhard, Lau Gatignon, Fabian Metzger, Silvia Schuh-Erhard)

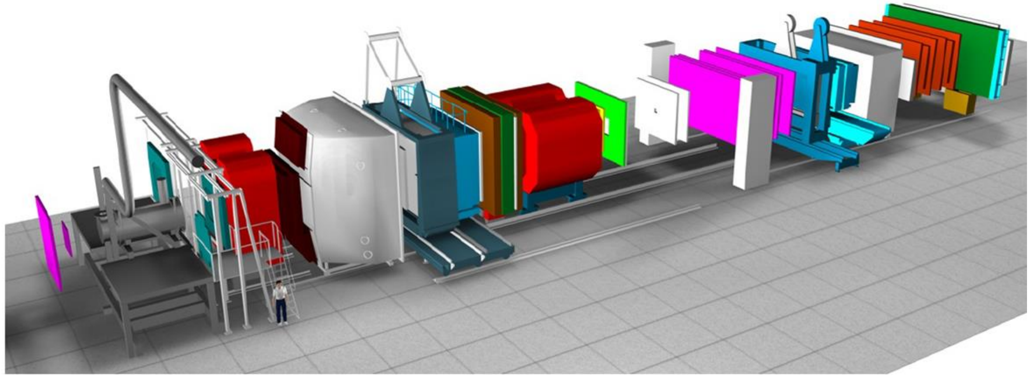
CERN · EA · Physics Beyond Colliders

M2 Beam Line and AMBER

COMPASS and AMBER



Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware additions
Drell-Yan (RF)	Kaon PDFs & Nucleon TMDs	$\sim$100	10^8	25-50	$K^\pm$, $\bar{p}$	$NH_3^\uparrow$, C/W	2026 2-3 years	"active absorber", vertex detector
Primakoff (RF)	Kaon polarisa-bility & pion life time	$\sim$100	$5 \cdot 10^6$	> 10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5 \cdot 10^6$	10-100	$K^\pm$ $\pi^\pm$	LH2, Ni	non-exclusive 2026 1-2 years	hodoscope
K-induced Spectroscopy (RF)	High-precision strange-meson spectrum	50-100	$5 \cdot 10^6$	25	K^-	LH2	2026 1 year	recoil TOF, forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5 \cdot 10^6$	10-100	$K^\pm, \pi^\pm$	from H to Pb	2026 1 year	



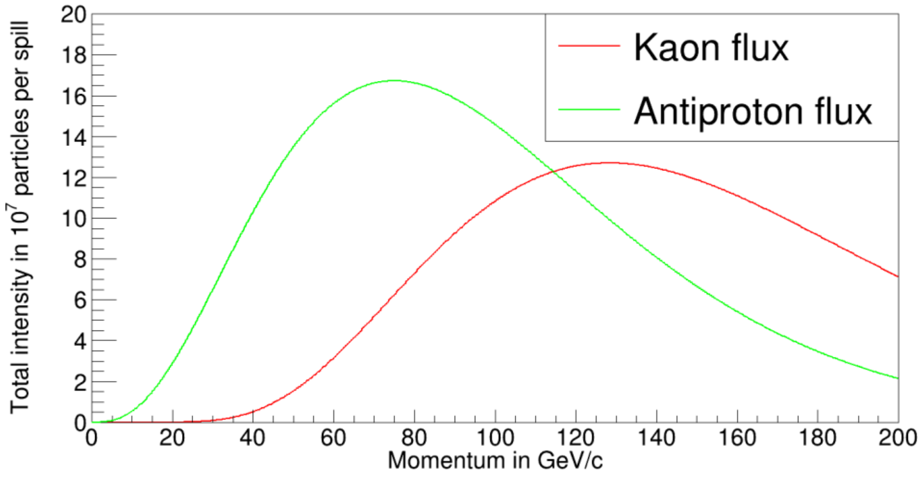
K^- and $\bar{p}$ vs momentum at AMBER target

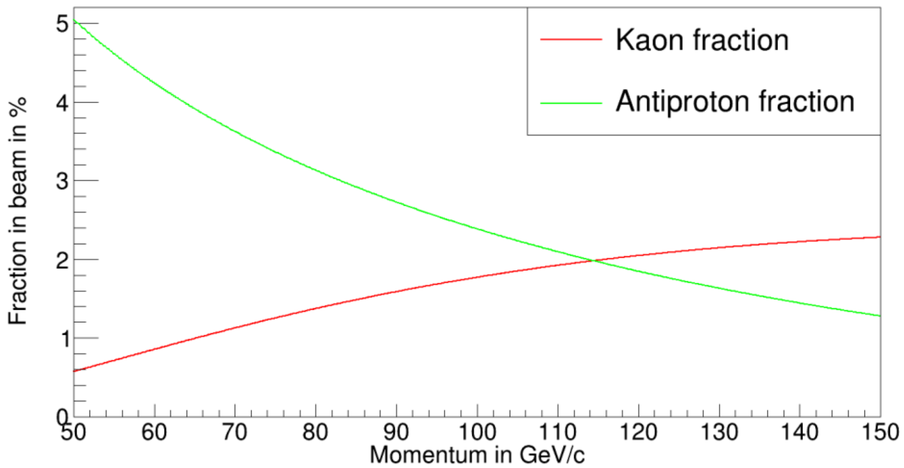
Atherton formula (parametrisation of measured particle production data from NA20) with following assumptions:

- No particle enrichment (e.g. RF separation)
- $\Delta p/p$ = 1% RMS
- Angular acceptance = 17.6 μsterad
- 1.5 x 10^{13} ppp on T6
- 500 mm BE target
- Distance T6 to Amber target: 1138 m
- Electrons are not considered

Current RP Limitation: $4{\cdot}10^8$ particles per spill

* See presentation by D. Banerjee regarding possible increases

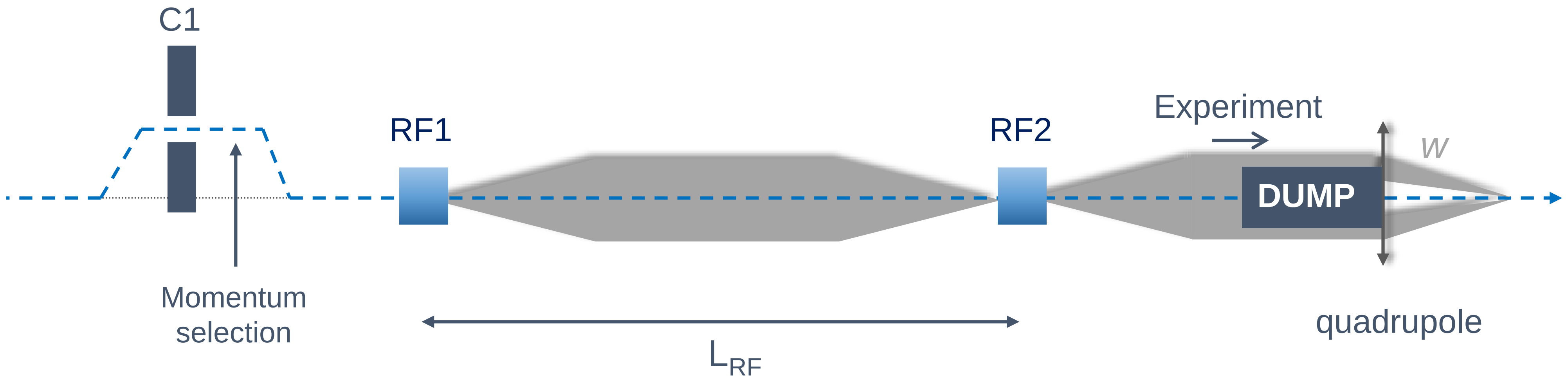




RF Separated Beam Principle

The RF-separated beams

- Particle species discrimination: same momentum but different velocities
  - For M2: Interest in K^- and antiproton beams
- Time-dependent transverse kick by RF cavities in dipole mode
- RF1 kick compensated or amplified by RF2 depending on velocity, i.e. particle species
- Studies to evaluate the feasibility for physics have started



RF-frequency calculations

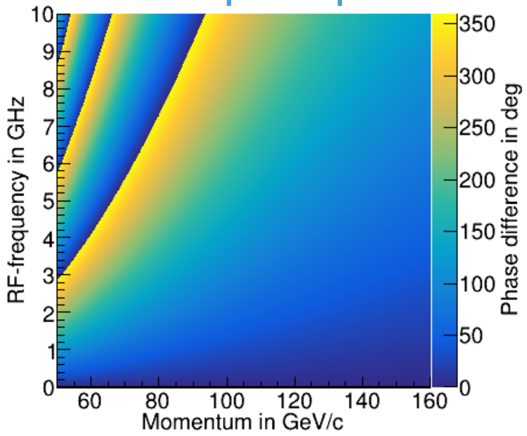
- L is the distance between the cavities
  - First version of beam optics reached $L \approx 830\mathrm{m}$
- Phase difference between two particles given by

$$\Delta\varphi = 2\pi f \Delta t = \frac{2\pi f L}{c} \cdot \frac{E_\mathrm{w} - E_\mathrm{u}}{pc} \approx \frac{\pi f L}{c} \cdot \frac{(m_\mathrm{w}^2 - m_\mathrm{u}^2)c^2}{p^2}$$

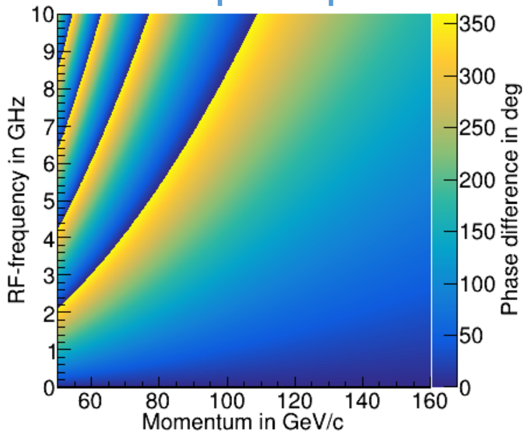
- Frequency to separate the two species by $\Delta\varphi$

$$f = \frac{\Delta\varphi c}{2\pi L} \cdot \frac{pc}{E_\mathrm{w} - E_\mathrm{u}} \approx \frac{\Delta\varphi c}{\pi L} \cdot \frac{p^2}{(m_\mathrm{w}^2 - m_\mathrm{u}^2)c^2}$$

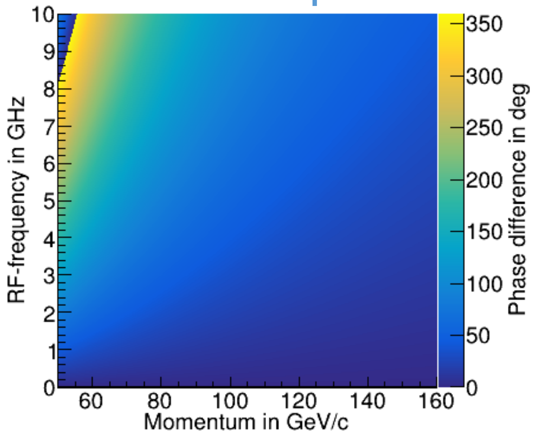
Kaon-antiproton phase



Pion-antiproton phase



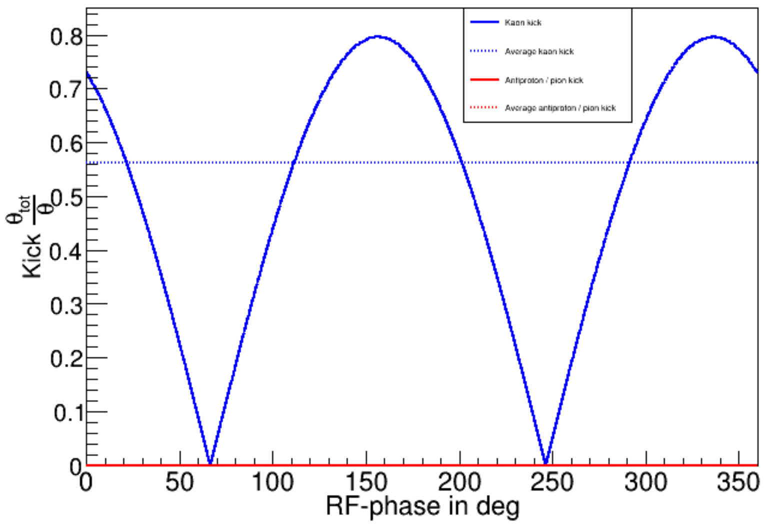
Pion-kaon phase



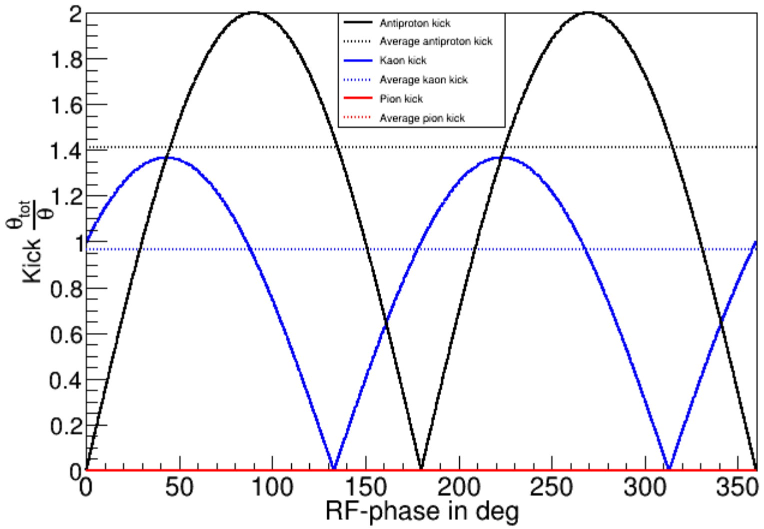
Kick of the cavities

- $\theta_{\text{tot}} = \theta\left(\sin(\varphi(t)) + \sin(\varphi(t) + \alpha)\right) = 2\theta\sin\left(\varphi(t) + \frac{\alpha}{2}\right)\cos\left(\frac{\alpha}{2}\right)$
- $\bar{\theta} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi}\theta_{\text{tot}}^2(\varphi)\,d\varphi} = \sqrt{2}\theta\cos\left(\frac{\alpha}{2}\right)$
- Kaon beams with $\Delta\varphi_{\text{pion}}^{\text{antiproton}} = 2\pi$. For $p = 75\ \text{GeV}/c$ one gets $f \approx 4.72\ \text{GHz}$
- Antiproton beams with $\Delta\varphi_{\text{pion}}^{\text{antiproton}} = \pi$. For $p = 105\ \text{GeV}/c$ one gets $f \approx 4.63\ \text{GHz}$

Kaon beams ($\mathbf{75\ GeV/}\boldsymbol{c}$)



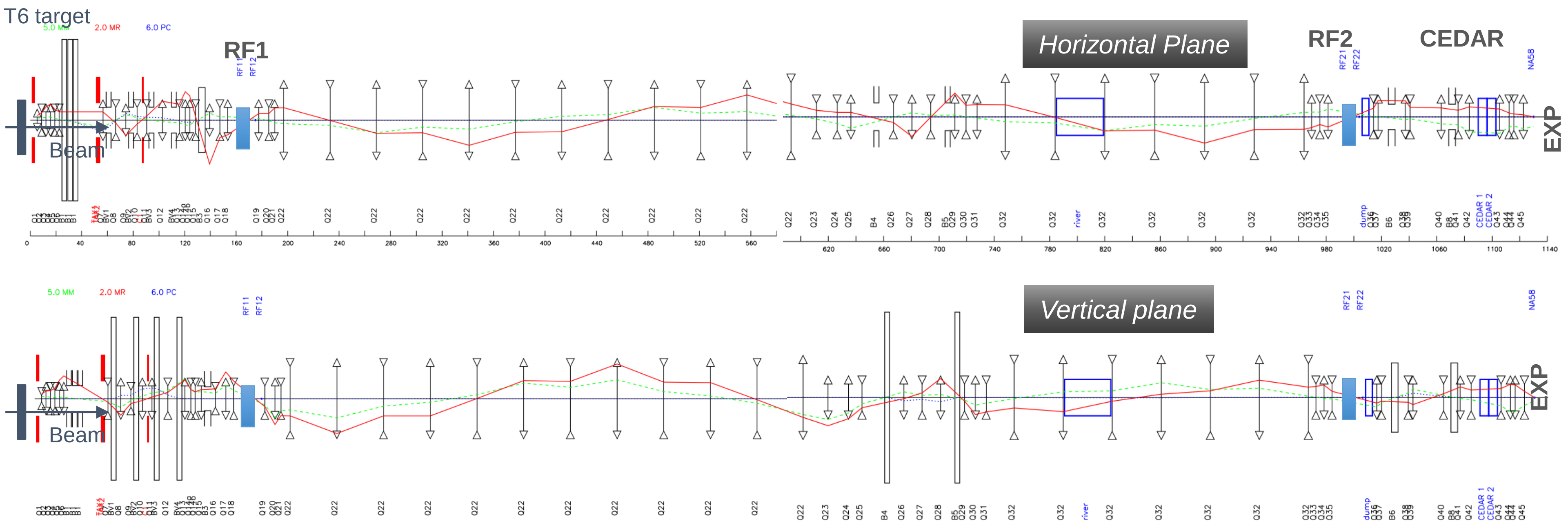
Antiproton beams ($\mathbf{105\ GeV/}\boldsymbol{c}$)



Beam Optics for RF Separated Beam

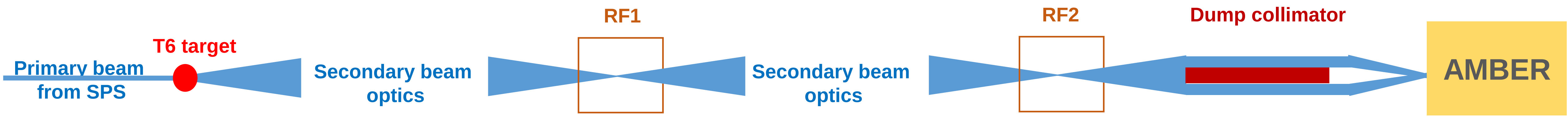
The RF-separated beam optics in M2

- First optics up to the AMBER target position done
  - Aim for momentum resolution ≤1%, if ok for RF
  - Beam spot size in the two RF cavities optimized and distance between the cavities maximized ($L \approx 830\text{m}$)
  - Implementation of two RF-deflectors
  - 5 m of space reserved for dump system
  - Beam as parallel as possible at CEDAR location



Beam in the cavities

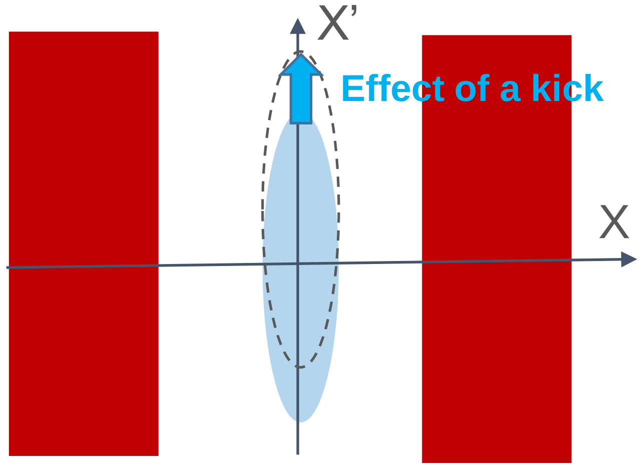
Focused optics: Minimize beam size in the cavities



Parallel optics: Minimize beam divergence in the cavities

Focused and parallel beams

Focused beam

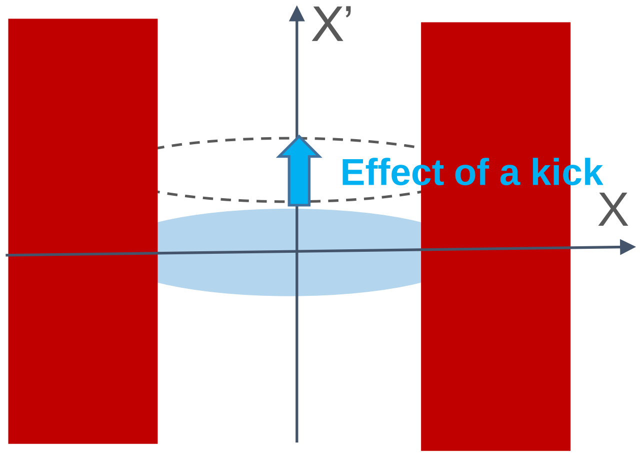


Beam large in X', small in X

⇒ Relative kick is small

⇒ Beam fits well through **apertures**

Parallel beam



Beam small in X', large in X

⇒ Relative kick is large

  ⇒ Better separation

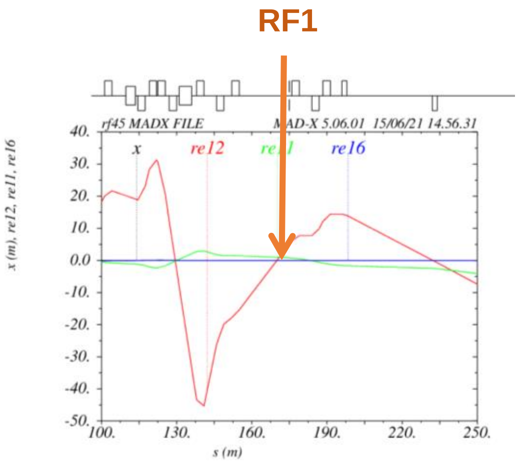
⇒ Beam is limited by **apertures**

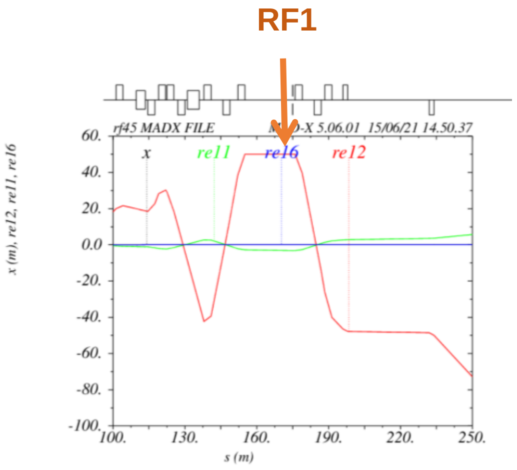
  ⇒ Beam size determined by beamline angular acceptance and R_{12} optical function

  ⇒ Emittance is constant (Liouville's theorem), hence higher parallelism means larger beam size and hence larger aperture losses

Parameters of Beam Optics

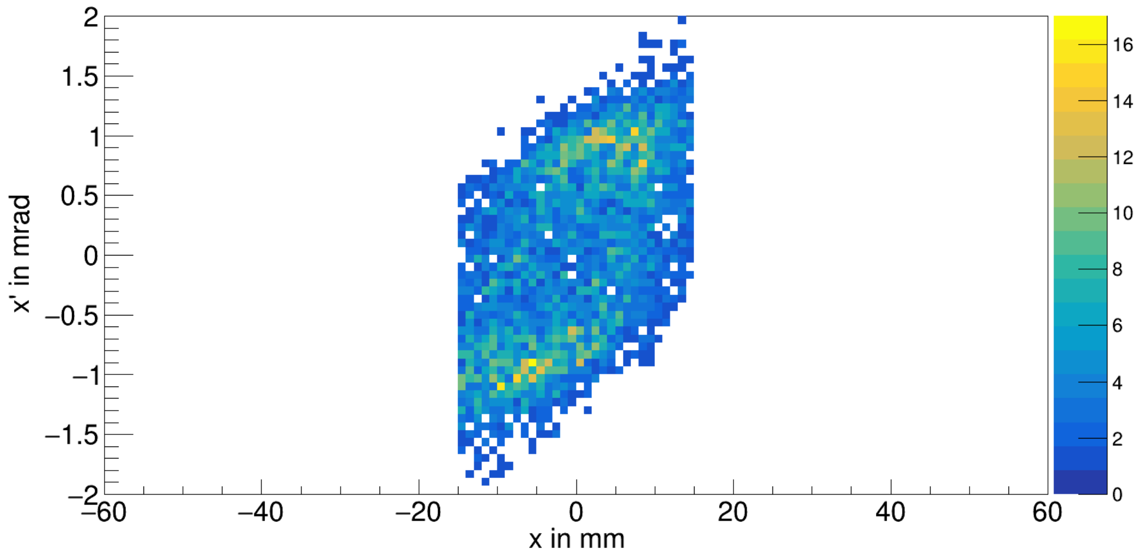
- Several versions of the optics:
  - Focused beam
  - Parallel beam with R_{12} = 50, R_{12} = 5, and R_{12} = 7.5
- Separation and transmission depend on many parameters, like
  - Beam initial distribution in X, Y and momentum (impacts time of flight)
  - Cavity type
    - Assumptions based on the design of the crab cavities for ILC
      - RF frequency 3.9 GHz
      - Iris size d=30 mm (consider impact on effective iris aperture due to beam deflection)
      - Kick of 5 MV/m * 10 m



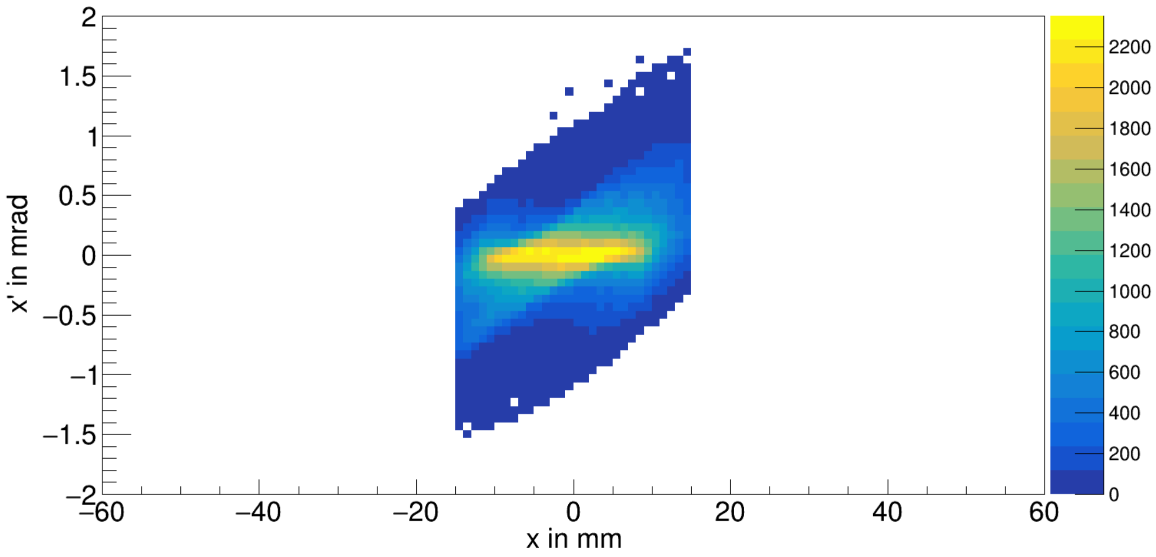


Phase space distribution after RF2

- K^- phase space

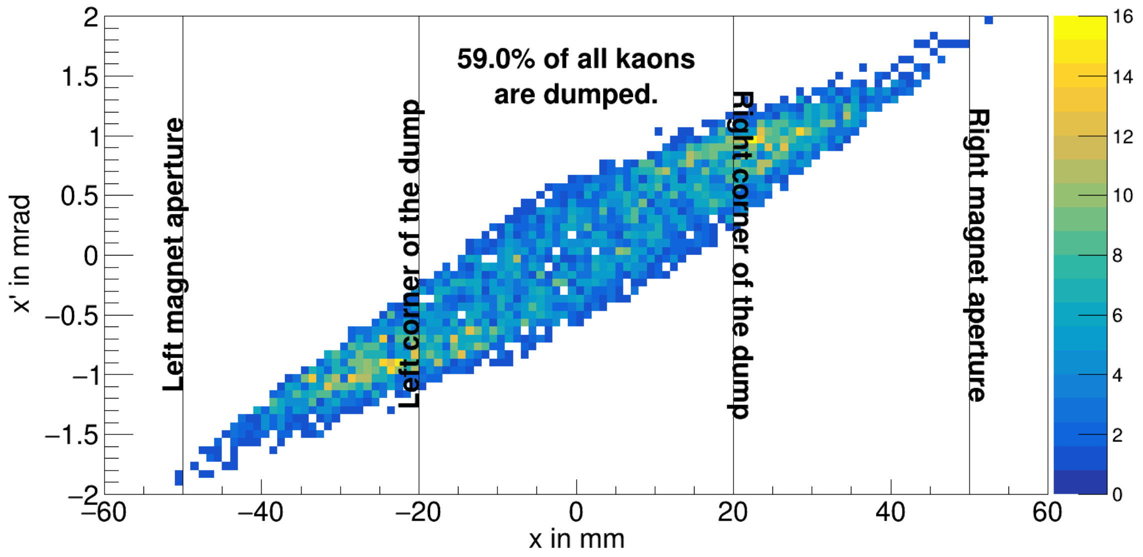


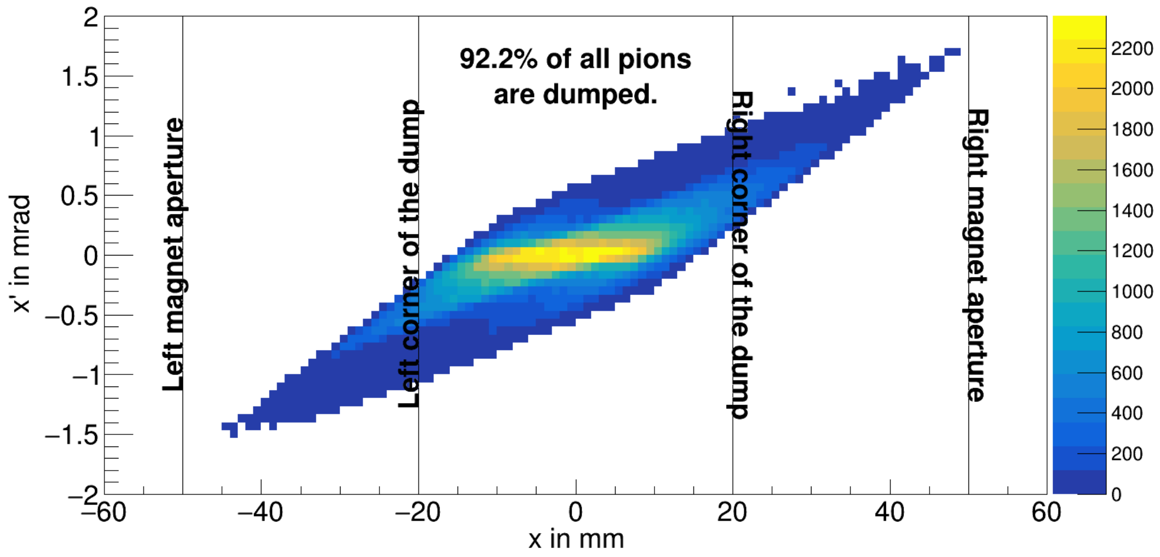
- π^- and antiproton phase space



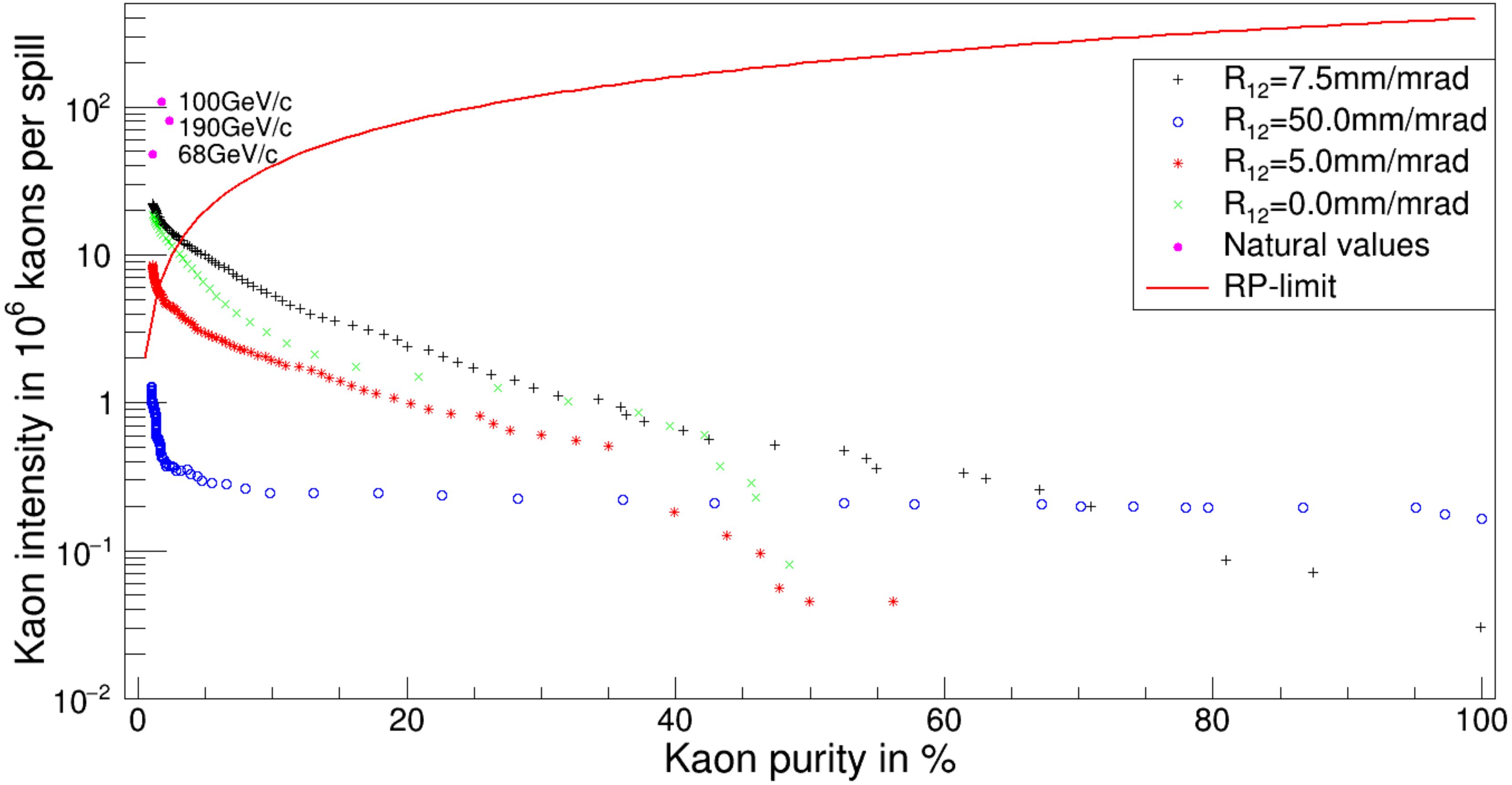
Phase space distribution before dump

- K^- phase space
- π^- and antiproton phase space





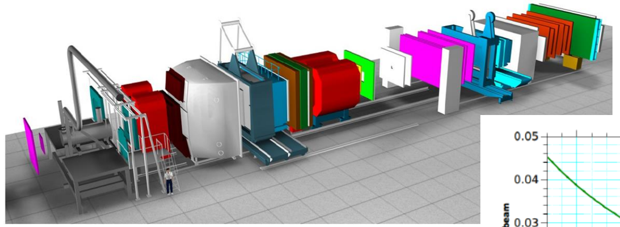
Separation power

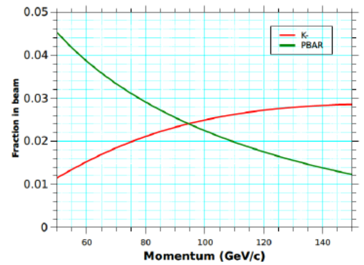


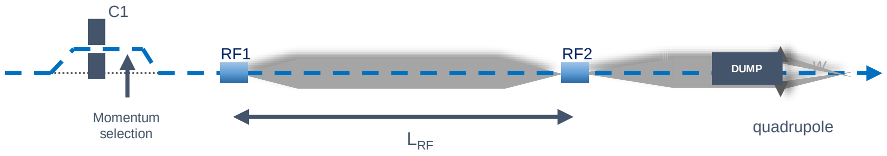
- Everything above red curve is forbidden by RP
- Trade-off between beam intensity and purity
- E.g. 5×10^5 kaons at 50% purity can be delivered

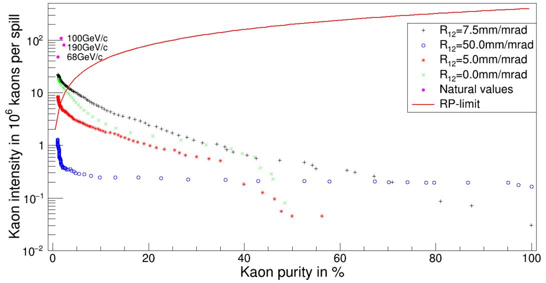
Summary

- AMBER Phase 2 requires higher intensity of kaon and antiproton beams
- The share of kaons and antiprotons in the beam is limited by their production share at the target and the kaon decay
- The overall intensity of the beam is limited by RP considerations in EHN2
- RF Separated beam technique is an option to increase the share of kaons/antiprotons in the M2 beam
- Current design is capable to deliver $5{\times}10^5$ kaons at 50% purity
- Studies on optimization and error sensitivity are ongoing









Thank you for your attention!