LUMINOSITY CONSIDERATIONS FOR INTERNAL AND EXTERNAL EXPERIMENTS AT COSY

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Abstract

The future physics program at the Cooler-Synchrotron COSY [1,2] in Jülich requires intense beams to provide high luminosities up to $10^{32} cm^{-2}s^{-1}$ for internal and external experiments [3]. In 2003 the number of unpolarized protons could be significantly increased. This was achieved by careful study and adjustment of all subsystems in the accelerator chain of COSY. The intensity for polarized beams in COSY is typically one order of magnitude lower compared to the one for unpolarized beams. In this paper, luminosity considerations for polarized and unpolarized beams at COSY are presented taking different machine cycles and operation modes for internal and external experiments into account.

INTRODUCTION

The COSY beam is produced in (un-) polarized H^- and D^- sources, pre-accelerated in a cyclotron to 45MeV (H^-) and 70MeV (D^-) and injected via stripping injection into COSY. Depending on the experimental requirements, COSY can be operated in different modes. After single injection the beam can be accelerated directly or electron-cooled before acceleration to improve the beam quality. In addition, the beam can be multi injected utilizing electron cooling in combination with the technique of phase space stacking [4]. This method is in particular beneficial for low intensity polarized beams.

ACHIEVED BEAM INTENSITIES

At the present time, the maximum number of unpolarized protons accelerated at COSY is $1.5 \cdot 10^{11}$. This intensity was reached by single injection of $3 \cdot 10^{11}$ protons without electron cooling. Since the injection energy is pretty low at COSY, the theoretical direct space charge limit is in the range between $1 \cdot 10^{11}$ and $4 \cdot 10^{11}$ assuming a ‘Laslett’ tune shift of 0.025 to 0.1 for protons. In Table 1 the achieved intensities for different operation modes in COSY are summarized. Some operation modes for deuterons are missing, since the deuteron operation at COSY started in 2000 and there was no experimental request for these modes so far. The extraction efficiency utilizing slow extraction is routinely greater than 80% at COSY [2], with extraction time in the range from tens of seconds up to half an hour.

Table 1: Achieved beam intensities (best values) after acceleration in COSY for different operation modes and particle species. The beam accumulation time is written in brackets.

Operation mode	Accelerated Particles
Unpolarized protons:	
Single injection	$1.5 \cdot 10^{11}$
Single injection with electron cooling	$1.4 \cdot 10^{10}$ (10s)
Multiple injection with electron cooling and stacking	$5.0 \cdot 10^{10}$ (1-5min)
Polarized protons:	
Single injection	$1.0 \cdot 10^{10}$
Single injection with electron cooling	$5.0 \cdot 10^{9}$ (10s)
Multiple injection with electron cooling and stacking	$1.2 \cdot 10^{10}$ (15min)
Unpolarized deuterons:	
Single injection	$1.3 \cdot 10^{11}$
Single injection with electron cooling	$4.0 \cdot 10^{10}$ (10s)
Polarized deuterons:	
Single injection	$6.0 \cdot 10^{9}$

PEAK LUMINOSITY

To get acceptable beam lifetimes, internal targets have to be very thin or powerful beam cooling has to be applied. External targets are thicker by orders of magnitudes. In Table 2 the effective target thickness typically reached in internal and external experiments at COSY are shown.

Table 2: Effective target thickness of internal and external experiments at COSY.

Type of target (internal)	Thickness [atoms/cm^2]
Atomic beam	10^{12}
Atomic beam with storage cell	10^{14}
Cluster	10^{14}-10^{15}
Pellet	10^{15}-10^{16}
Solid	10^{16}-10^{18}
Type of target (external)	**Thickness [atoms/cm^2]**
Solid	$>5 \cdot 10^{19}$
Liquid hydrogen or Solid polarized (3.2mm)	$2 \cdot 10^{22}$

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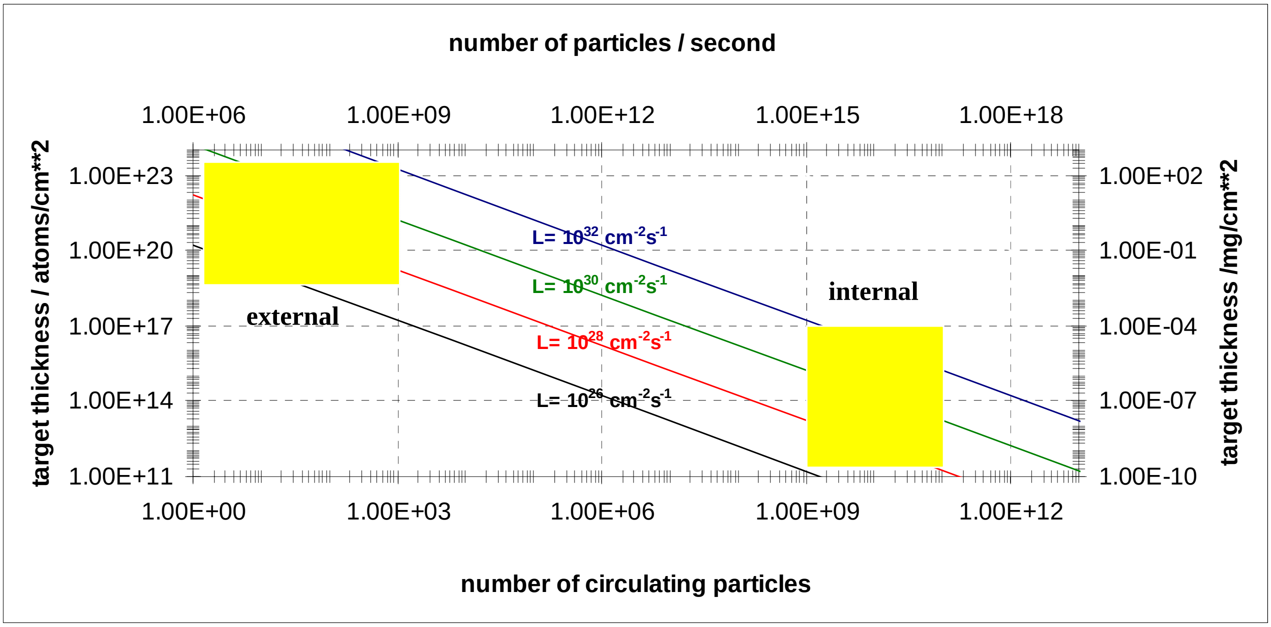

Fig. 1: Peak luminosity of internal (area indicated right) and external (area indicated left) experiments for different effective target thickness at COSY. The luminosity is calculated for a typical range of circulating particles (10^9 to 10^{11}) in COSY with a particle revolution frequency of 1MHz. For external experiments an extraction time of 100s is assumed.

In Figure 1 the internal and external peak luminosity is plotted applying the numbers for effective target thickness from Table 2. For the number of circulating particles a typical range from 10^9 to 10^{11} was chosen. The peak luminosity is between 10^{26} and 10^{32}cm^{-2}s^{-1} at COSY, depending on the target thickness and number of circulating or extracted particles per second. To reach high peak luminosities the beam target overlap should be large. Common beam sizes at internal targets are in the range of 3 to 6mm (FWHM) for protons and up to 15mm (FWHM) for deuterons. Externally the beam can be focussed on target much easier, leading to beam sizes of less than 1mm (FWHM).

AVERAGE LUMINOSITY

To calculate the average luminosity, machine cycles and beam preparation times have to be specified. In Table 3 typical values for COSY are listed.

Table 3: Beam preparation time for different machine cycles.

Type of beam preparation	**Time**
Beam injection and accumulation	200ms
Acceleration	2 to 3s
Beam preparation for experiments	up to 3s
Magnet down ramp	2 to 3s
Distance between two cycles	1s
Cooling and single injection	10s
Cooling and stacking injection	1 to 15min

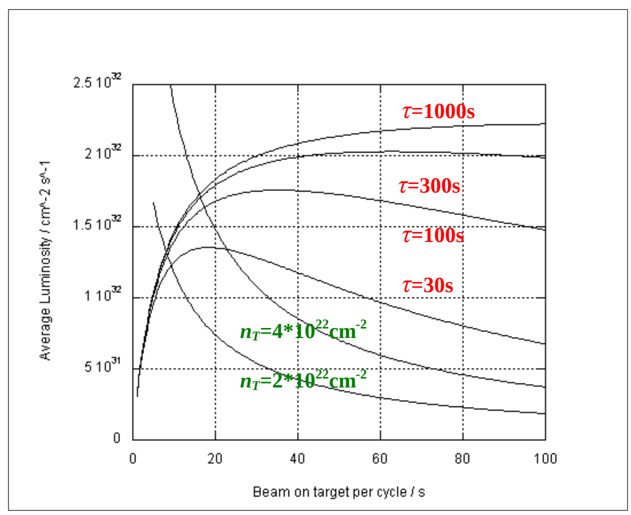

Fig. 2: Average luminosity for internal experiments with different beam lifetimes τ (upper curves) assuming a target thickness of $2.5\cdot10^{15}$cm^{-2}, and for external experiments with a different target thickness n_T (lower curves) plotted versus beam on target time per cycle. 10^{11} circulating particles at 1MHz and a preparation time 7s were taken for this calculation.

The average internal and external luminosity as function of the experimental (beam on target) time is given by:

$$\bar{L}_{\text{int}} = N_C\, n_T\, f\, \frac{\tau[1-e^{-\frac{t_{exp}}{\tau}}]}{t_{exp}+t_{prep}},\quad \bar{L}_{ext} = N_E\, n_T\, \frac{1}{t_{\exp}+t_{prep}},$$

where N_C is the number of circulating particles, N_E the number of extracted particles, n_T the target thickness, f the particles' revolution frequency of the beam, τ the beam lifetime, t_{exp} the beam on target time per cycle and t_{prep} the beam preparation time.

In Figure 2 the average luminosity for internal and external experiments is plotted versus beam on target time per cycle. In general, the extraction time should be short to get high external luminosity. Utilizing the slow extraction system of COSY, the spill structure contains higher frequency components due to the higher power necessary for shorter extraction times. The internal luminosity strongly depends on the beam lifetime. Typical beam lifetimes of circulating beams passing through different internal targets are shown in Table 4.

Table 4: Typical beam lifetimes of the circulating COSY beam for different targets.

Internal target type	**Typical beam lifetime**
Solid	ms to s
Cluster	below 1h
Cluster with stochastic cooling	order of hours
Atomic beam	10 to 100h
Without target	10 to 100 h

A pellet target is not implemented in the COSY ring yet, but the implementation is foreseen for the next years [3]. The beam lifetime of the circulating COSY beam interacting with a pellet target was calculated [5]. The used simulation program is based on random number generators, applying Landau's theory for thin targets to describe energy loss straggling in the longitudinal plane. For thicker targets other distributions (Vavilov, Gauss) can be implemented in the code. In the transverse phase space the beam-target interaction is described by single scattering processes of the circulating particles in the Coulomb potential of the target nuclei including atomic screening. The cross section becomes finite and a mean free path can be given. The individual free path and scattering angles follow from random numbers.
With a pellet target in COSY and without beam cooling the calculated beam lifetime is in the range of minutes (45s up to 80s) for a target thickness of 10^{16}atoms/cm^2, depending on beam momentum [5]. The simulation shows that the beam lifetime can be increased significantly with bunched beams to compensate for the mean energy loss of the beam by almost a factor of three, assuming a momentum acceptance $\Delta p/p=2\cdot 10^{-3}$.

CONCLUSION

For internal experiments with unpolarized beams and targets at COSY, average luminosities above 10^{32}cm^{-2}s^{-1} can be reached. The average luminosity for external experiments strongly depends on the extraction time. Only rather short extraction times in the range of 5 to 20 seconds can provide the desired luminosities. For polarized beams the average luminosity is typically one order of magnitude lower, due the lower intensity of polarized beam delivered by the COSY injector system. Performing internal experiments with polarized beams and a polarized atomic beam target, an average luminosity of 10^{28}cm^{-2}s^{-1} is feasible. A luminosity of 10^{30}cm^{-2}s^{-1} can be reached if the polarized atomic beam is utilized in combination with a storage cell [6,7]. For external polarized experiments with a solid polarized target the average luminosity depends on the number of particles that can be put on target per time unit without affecting too much the polarization in the target. The limit depends on the strength of the magnetic field in the polarized target.

REFERENCES

[1] R. Maier, Cooler Synchrotron COSY - performance and perspectives, NIM A 390 (1997) 1-8.
[2] H. Stockhorst, U. Bechstedt, J. Dietrich, R. Gebel, K. Henn, A. Lehrach, B. Lorentz, R. Maier, D. Prasuhn, A. Schnase, H. Schneider, R. Stassen, H.J. Stein, R. Tölle, Progress and Developments at The Cooler Synchrotron COSY, Proceedings of the 8th European Particle Accelerator Conference (EPAC).
[3] Advanced Electromagnetic Calorimetry and its Applications: Physics with a 4π Detector at COSY (FINUPHY Workshop FEMC04), 26.-29. Januar 2004, Forschungszentrum Jülich.
[4] V. Kamerdzhiev, Untersuchung und Verbesserung des Stabilitätsverhaltens eines intensiven elektronengekühlten Teilchenstrahles in COSY, Dissertation Universität Dortmund (2003), Jül-4114, Februar 2004.
[5] Calculations for pellet target in COSY by H.R. Koch (IKP, FZ Jülich), see also H.R. Koch, Luminosities in the ANKE experiments with heavy nuclear targets, IKP Annual Report 2001, Bericht des FZ Jülich, Jül-3978.
[6] O. Felden, R. Gebel, M. Glende, A. Lehrach, R. Maier, D. Prasuhn, P. von Rossen, J. Bisplinghoff, P.D. Eversheim, F. Hinterberger, The storage cell for the TRI-experiment at COSY-Jülich, Proceedings of the 9th International Workshop on Polarized Sources and Targets (PST2001), Nashville, IN, 2001, published in edited by V. P. Derenchuk and B. von Przewoski (World Scientific, Singapore, 2002), p. 73.
[7] F. Rathmann, COSY Polarized Gas Targets, to be published in the Proceedings of the 10th International Workshop on Polarized Sources and Targets (PST2003), Novosibirsk, Russia, 2003.