General abstract:

This paper presents the development of a new instrument, an intense collimated photon source for use with dynamically-polarized solid-state polarized targets. In the first section we formulate the motivation, the requirements, and perspectives for high-energy photo-production experiments. In the second section we review the prior state-of-the-art of photon source design. The third section presents the ideas of the concept of such a new Compact Photon Source (CPS). The fourth section briefly analyzes the methods to distribute the power of heat and radiation load over the area of the polarized material. The next section then describes the implementation of a CPS at Jefferson Lab in support of several experiments. In the sixth section, we present the radiation analysis based on several methods including Fluka and Geant4. Finally, we conclude with the initial engineering plan for the CPS.

Plan on CPS paper(s)

a. collection of the papers on prior art

b. physics with photon beams

c. motivations for compact photon beam and options

d. unpolarized and polarized target needs

e. radiation effect in polarized target â€œold storyâ€□ from CERN, T20 â€¦

f. why and how to distribute the heat and radiation load

g. CPS concept and realization option

h. physics experiments under discussion with CPS at JLab

Physics Motivation for a Compact and High-Intensity Photon Source

Traditionally, knowledge has been gathered on the structure of protons and neutrons from studies of their static properties (mass and spin, polarizabilities, form factors) and the one-dimensional quark and gluon momentum distributions underlying them. Yet despite decades of research, our knowledge of the microcosm of proton structure has remained elusive.

Just as the earth orbits around the Sun while simultaneously spinning about its own axis, the quarks and gluons in a proton could have linear motion, orbital motion, and spin – the latter two responsible for the overall proton spin that is exploited daily in thousands of MRI images worldwide. But, well beyond this classical analogy in the proton's quantum mechanical microcosm quark and gluon constituents are dynamic, they can appear and disappear (that is, beyond a very few ever-prevalent "valence" quarks that define the proton's identity), and all strongly interact. In fact, unlike with the more familiar atomic and molecular matter, interactions and structures in nuclear matter are inextricably mixed up, and the observed properties of nucleons and nuclei, such as mass & spin, emerge out of this complex system.

Realization has grown that the true study of the proton dynamical structure has to come from more exclusive reactions, processes in which the deep inside of the proton is studied with a highly-energetic photon or electron probe but such that the reaction leads to a completely-measured set of only a few particles. Even though the scattering probability of such reactions is minuscule – it is much easier for the highly energetic electron probe to use its energy to break the proton apart – realization has dawned that such more exclusive "designer" reactions have a much closer connection to imaging and understanding the elusive 3D proton substructure. Indeed, there have been increasingly sophisticated theoretical effort to exploit the richness of exclusive reactions at moderate resolution scales (or momentum transfer). This mimics progress in other fields of science, where imaging the physical systems under study has been key to gaining new understanding, with as prominent examples the progress in understanding since advent of X-ray diffraction in the 1920's or the advent of large-scale cosmological surveys in the 2000's.

Even if much progress to image proton structure can be made with electron-scattering reactions alone, experiments using high-energy photon beams will play a unique science role. But, to measure the small scattering probabilities related to exclusive reactions needs high-intensive photon beams. Further, our basic understanding will be much strengthened by imaging longitudinally-polarized (along the photon beam direction) and transversely-polarized (transverse to this) protons. It is for this combination that our proposal is so unique – with a new-developed Compact Photon Source and a dynamically-nuclear polarized target system, we gain a factor of 30 in the Figure-Of-Merit (as defined by the photon intensity and the average target polarization over the experiment). This gain is further doubled by a novel magnet system to polarize targets with much larger particle detection acceptance than previously possible. The net gain opens the window on the minuscule scattering probabilities associated with a new suite of high-energy photon scattering experiments to image and understand the dynamical proton structure. We should add here that the basic technique to establish the Compact Photon Source also enables other science, such as the creation of, by conversion of an intense photon source, a beam of neutral kaons.

When a photon probe is used to study the proton, with in the final state one energetic photon and the proton remaining, the process is called Real Compton Scattering (RCS). This is a fundamental and basic process, yet its mechanism in the center-of-mass energy regime of $\sqrt{s}$ = 5-10 GeV remains poorly understood. Measurements show that these data cannot be described by perturbative calculations involving the scattering of three valence quarks, but that the dominant mechanism could be the so-called “handbag model” where the photon scatters of a single quark, convoluted with a coupling of this struck quark to the spectator system described by so-called Generalized Parton Distributions (GPDs). It is this latter conceptual mechanism that lies at the root of the worldwide efforts of 3D (spatial) imaging of the proton’s quark-gluon substructure, as the GPDs contain information about the transverse spatial distribution of quarks and their longitudinal momenta inside the proton. A measurement of the spin asymmetry in RCS with the proton target longitudinally polarized can further disentangle the existing handbag mechanisms. If consistent with the measurement of the spin transfer from the photon to the scattered proton, the asymmetry can indeed be surprisingly large and stable with respect to the photon center-of-mass scattering angle. Such investigations into the mechanisms behind RCS will provide crucial insight into the nature of exclusive reactions and proton structure and are ideally suited for the facilities provided by the Jefferson Lab 12-GeV upgrade, a $340M US/DOE investment.

When a real photon is scattered off a quark of the proton and a high-mass (virtual) photon is emitted, then decays into a lepton pair, the process is called Timelike Compton Scattering (TCS). Using a transversely polarized proton target and a real circularly polarized photon beam, we can access several independent observables directly sensitive to the GPDs, and in particular the GPD E which is poorly constrained and of great interest due to its relation with the orbital momentum of the quarks. We plan to measure the unpolarized scattering probabilities or cross section, the cross section using circularly polarized photon beam, and the cross sections using transversely-polarized protons. This together also provides a first fundamental test of the universality of the GPDs, as the GPDs extracted from TCS should be comparable with those that will be extracted from the analogous spacelike (electron) scattering process - Deeply Virtual Compton Scattering, a flagship program of the 12-GeV Jefferson Lab Upgrade.

Compact Photon Source Concept and Implementation in JLab Experiments

A traditional source of high-energy photons comes from an electron beam hitting a radiator, most common Cu, producing a cone of bremsstrahlung photons accompanying the electron beam (see Fig. 1a). The photon and ongoing electron beam spread is dominated by electron multiple scattering, and for electron beam energies of a few GeV is typically less than 1 mrad. Accompanying this mixed photon and electron beam is a much larger angular distribution of secondary particles produced in the electron-nuclei shower. For example, the cone of secondary particles that survive filtering through a heavy absorber material of one nuclear interaction length ($\approx$140-190 g/cm^2 or $\approx$15 cm) has an angular spread of 100-1000 mrad. Even if this method can produce the largest flux of photons, drawbacks are that the beam is a mix of photons and electrons, that the photon beam energy is not a priori known, and that the method is accompanied with large radiation background doses due to the large spread of secondary particles produced.

An alternate method to produce a (pure) photon beam includes a radiator, a deflection magnet and a beam dump for the undeflected electrons, augmented for energy-tagged photon beams with a set of focal plane detectors covering a modest to large momentum acceptance (see Fig. 1b). Such a configuration requires significant space along the beam direction and heavy shielding around the magnet and the beam dump, which have large openings due to the large angular and energy spread of the electrons after interaction with the radiator. In addition, without tight collimation the traditional scheme leads to a large size of the photon beam at the target due to divergence of the photon beam and the long path from the radiator to the target. This can be an issue as the beam spot size contributes to the angular and momentum reconstruction resolution of the resultant reaction products due to uncertainty in the transverse vertex position. As an example, to obtain the needed reconstruction resolution of the scattered photon in RCS the photon spot size at the target must be equal or less than 2 mm. This would require the target to be at a distance of 2 meters from the radiator, which is often practically impossible. The advantage of this method is that one has a pure photon beam, and if augmented with a set of focal-plane tagging detectors the exact photon energies can be determined. Drawback is that to accomplish this the flux of incident electrons, and thus the photon flux, has to be drastically reduced, especially when the tagging method is used. Similar, this scheme also comes with appreciable radiation doses, especially with increased photon fluxes, as particles are allowed to propagate over short distances before mitigation of radiation by containment starts to be effective.

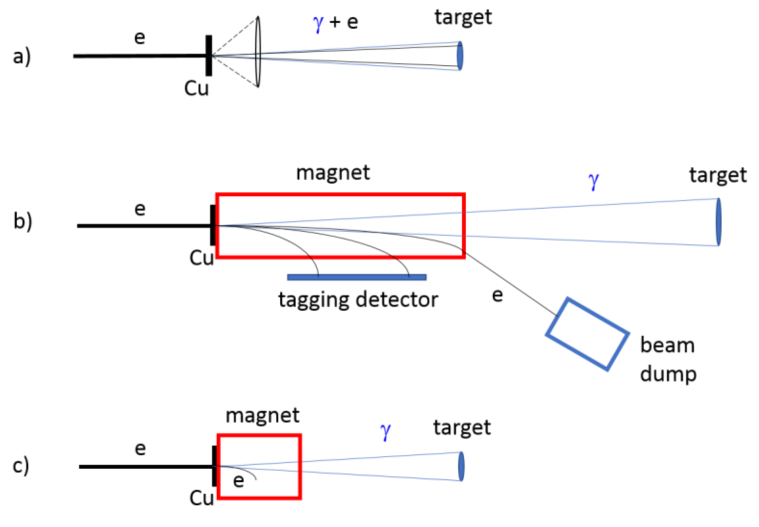

Fig. 1: Different schemes to produce high-energy photon beams. Scheme a) is the traditional bremsstrahlung technique where a Cu radiator is placed in an electron beam to render a mixed photon and electron beam. In scheme b) a deflection magnet and beam dump are used to peel off the electrons and produce a photon-only beam. Scheme c) is the new Compact Photon Source technique, with a compact combined magnet-electron dump and a narrow photon-only beam.

A new solution, see Fig. 1c, that addresses the shortcomings of these two traditional techniques is a high-intensity Compact Photon Source (CPS) and is presented here. The concept of the CPS takes advantage of the narrowness of the photon beam relative to the angular distribution of the secondary particles produced in the electron-nuclei shower. The CPS combines in a single shielded assembly all elements necessary for the production of the intense photon beam and ensures that the operational radiation dose rates around it are acceptable. Much of this is achieved by keeping the overall dimensions of the setup limited, and by careful choice and ordering of materials. The CPS design features a magnet, a central copper absorber to handle the power deposition, and tungsten powder and borated plastic to hermetically shield the induced radiation doses as close to the source as possible. The magnet acts as dump for the electrons with a cone of photons escaping through a small collimator without loss of intensity. The size of the collimator can be as narrow as the photon beam size with natural divergence plus the size of the beam raster. The combined magnet-dump thus allows for dramatically reducing the magnet aperture and length, as well as the weight of the radiation shield, due to the compactness of the source and minimization of openings, thus reducing radiation leakage. This opens a practical way forward with management of both the radiation environment in the magnet and the power deposition density in the copper absorber.

Compared to the more traditional bremsstrahlung photon sources (Figs. 1a and 1b), the proposed solution offers several advantages, including an intense and narrow photon-only beam and much lower radiation levels, both prompt and post-operational due to the beam line elements radio-activation. The drawbacks are a somewhat reduced photon flux as compared to the scheme of Fig. 1a, and not having with a focal plane detection option the ability to directly measure the photon energy as in the scheme of Fig. 1b.

The primary gain of the CPS is for experiments using Dynamically Nuclear Polarized (DNP) Targets, with an estimated gain in figure-of-merit of a factor of 30. Such polarized targets have to provide high and sustained proton polarization and beam intensity. Conventional target cells have diameters much larger than the desirable beam spot size, and one is faced to minimize rapid degradation of the target polarization by the beam, induced by either heat deposition or ionizing radiation, at one location at the target. The traditional solution of minimizing such localized polarization degradation is fast movement of the beam spot, which allows avoiding overheating of the material and equalizing of the degradation over the target volume. A beam raster magnet, which moves the beam with a frequency of several Hz, was used in past experiments at Hall C. However, this does not work for very small apertures, e.g. a few mm by a few mm collimation cone, limiting possible beam motion. The CPS solution for the beam-target raster thus includes a combination of the target rotation around the horizontal axis and ±10 mm vertical motion of the target ladder. Such a raster method effectively moves the motion complexity out of the high radiation area of the absorber. The same effect can be achieved by vertical displacement of the beam spot, i.e. by a small variation of the vertical incident angle of the electron beam at the radiator. With a ±5 mrad vertical angle variation and 200 cm distance between the radiator and the target, the displacement of the beam spot is equal to ±1 cm, about the size of the conventional target cells. Traditionally, such photon beam experiments have been performed using the scheme indicated in Fig. 1a. This limits the electron beam current to less than 100 nA to prevent rapid target polarization damage. With the CPS scheme, we anticipate use of an electron beam current of up to 2.7 muA to provide the photon flux for an equivalent heat load in the DNP target. Hence, we gain a factor of about 30. The history of the figure-of-merit of bremsstrahlung photon beam experiments with DNP targets is further illustrated in Fig. 2.

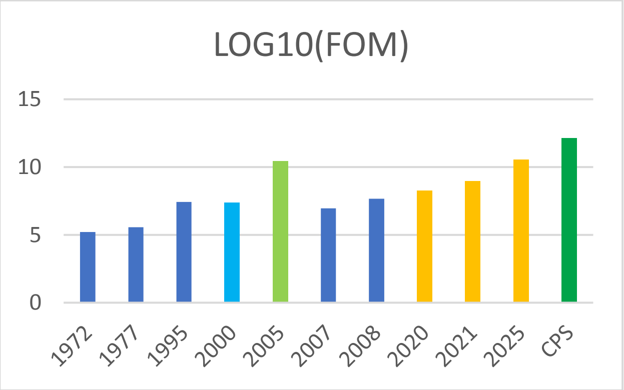

Fig. 2: The Figure-Of-Merit (FOM) of photon beam experiments with Dynamically Nuclear Polarized targets, defined as the logarithm of the effective photon beam intensity times the averaged target polarization squared, as a function of time. Note the large gain, over a factor of 30 as compared to any setup, enabled by the CPS. The indicated FOM in 1972, 1977, 1995, 2007 and 2008 are based on actual experiments at Daresbury, Bonn, Jefferson Lab and Mainz. The FOM noted in 2000 and 2005 are based upon proposed setups at SLAC and Jefferson Lab, with the latter closest in concept to the CPS. We also add the projected FOM of approved future experiments at HiGS/Duke and Jefferson Lab.

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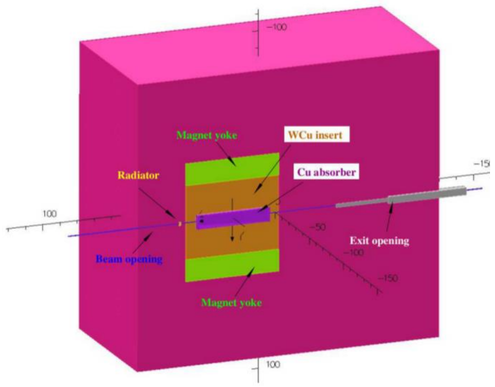

Fig. 3: The CPS cut-off view. Most of the deflected electrons strike a Cu absorber, surrounded by a WCu insert inside the magnet yoke. The outer rectangular region in this view is the tungsten-powder shield.

The CPS design features a magnet, a central copper absorber, and hermetic shielding consisting of tungsten powder and borated plastic. The magnet acts as dump for the electrons with a cone of photons escaping through a small collimator without loss of intensity. The size of the collimator can be as narrow as the photon beam size with natural divergence plus the size of the beam raster. The electron energy dumping starts on the side of the photon beam channel, so a shift of the electron trajectory by just 1-3 mm is already sufficient for the start of the shower. The trajectory deflection radius is about 10 m for 11 GeV electrons, the collimator size is 0.3 cm, and the raster size is 0.2 cm, so that the distance after traveling in the magnetic field has an average value of 17 cm with a spread of 12 cm. A total field integral of 1000 kG-cm is adequate, which requires a 50 cm long iron dominated magnet. The combined magnet-dump thus allows for dramatically reducing the magnet aperture and length, as well as the weight of the radiation shield, due to the compactness of the source and minimization of openings, thus reducing radiation leakage. This opens a practical way forward with management of both the radiation environment in the magnet and the power deposition density in the copper absorber.

The target polarization uncertainty is estimated to be maintained at less than 5% relative. This is achieved by keeping exposure to depolarizing sources as uniform as possible. For example, radiation damage caused by e+e- pair production will be non-uniform, with the downstream portion of the sample receiving more damage than that upstream. An advantage is provided by NMR sampling while rotating with a coil that has additional turns in the z-direction. Locating the beam spot with high precision on the target surface, having the rotation cover the entire face of the target, and paying close attention to the number of rotations and the rotation rate over each cycle then allows for insuring that the dose is distributed evenly. Another consideration is that polarized targets operate with strong 2.5-5 Tesla polarizing fields near the CPS magnet. Polarized target operation thus imposes strict requirements on the field quality at the polarized target location, where fields and gradients need to be compensated at the 10^-4 level.

Photon Sources in the last 80 years

High-energy photons have been used in experimental nuclear physics for over 80 years especially since the seminal deuteron photo-disintegration experiment in 1935 by Chadwick and Goldhaber. That same year the electron bremsstrahlung process was calculated by Bethe-Heitler, and has since become the main tool for high-energy photon production with the further advent in the 1940s of high-energy and high-intensity electron accelerators. The only serious disadvantage of this type of source is a falling shape of the energy spectra, characterized by its inverse proportionality with photon energy. Hence, it is traditional to characterize the intensity of the photon beam in units of equivalent quanta per second, eq. γ/s, which equates to the photon intensity N_γ in an interval of photon energy dE_γ, times E_γ/dE_γ.

To further establish a monochromatic photon beam (i.e., a photon beam with a defined single energy) two methods of so-called end-point monochromatization were used. One was based on modulation of the electron beam energy, and the second on measurement of the momentum of the final-state particle (a pion or a photon). This latter endpoint method was used in a number of experiments at SLAC and JLab to study the deuteron two-body photo-disintegration, single meson production, and forward angle Compton scattering. At relatively low photon intensity, positron in-flight annihilation would allow a third and alternate method of characterization of the photon spectrum.

A dramatic improvement to establish a monochromatic photon beam was achieved by means of coherent scattering in an aligned crystal. This method, however, typically renders monochromatic photons at about 70\% or less of the primary electron energy, and at more modest intensity. Another somewhat similar development was realized at SLAC by using filtering of high energy photons through a block of carbon crystals. This has the advantage that it allowed preparation of transversely polarized photons with high degree of polarization.

In the 1970s, a new type of technique was developed to produce a high-energy photon source based on Compton back-scattering off the high-energy electron beams. With the advance of laser intensity and intra-cavity technology, this has by now provided well-focused photon beams with intensities of up to about 10^8 eq. γ/s and photon energy ranges roughly up to 3 GeV.

The pre-JLab era of photon beams effectively ended in 1979 and a major review was published by Bauer $\it et al \rm$~\cite{Ba1979}. The highest photon beam intensity achieved was about 10^{10} eq. γ\s by a Compton Scattering experiment at Cornell~\cite{SH1979} with an unpolarized hydrogen target. The experiment was repeated 25 years later at JLab, using a mixed electron/photon beam and advances in detector technology, which allowed to increase the photon beam intensity to 10^{13} eq. γ/s, in part due to the continuous-wave character of the CEBAF electron beam.

The prospects of the elegant and relatively simple Compton Scattering process as tool for modern studies of the sub-structure of protons and neutrons has seen a revived interest in recent years. To access the small cross section probabilities, such studies impose a similar high photon beam intensity, on the level of 10^{12} eq. γ/s and maximum photon energy, but now in conjunction with a versatile use of polarized targets. The photon beam intensity required for such Compton scattering experiments becomes so high, however, that it can reach the limit of the polarized target capabilities in terms of heat load and radiation damage. Hence, this requires a sophisticated novel photon beam approach – the Compact Photon Source.

\bibitem{JC1935} J.~Chadwick and M.~Goldhaber, Nature volume 134, 237 (18 August 1934); Proc. Roy. Soc., A, 151, 479 (1935).

\bibitem{S-1} G.Buschhorn \etal, Physics Letters, 33 B, 241 (1970).

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A compact transverse size of the photon beam realized in JLab experiment 2002 (1 mm x 1 mm) allowed accurate reconstruction of the final state missing momentum which is needed for suppression of the single pion photo-production background with a cross section about 50 times larger than RCS.

The photon production sources are based on electron beam bremsstrahlung and deals with dumping of the used electron beam. In many cases a radiator thickness of 5-10\% of radiation length was used. Here, the secondary beam has a wide energy spectrum with about 90-95\% of the primary beam power.

In a typical design the distance between the radiator and the experimental target is of twenty meters which used for deflection of secondary beam to the beam dump and large thickness of radiation shielding. Such structure of the photon source was used at SLAC~\cite{.}, DESY~\cite{.}, Cornell~\cite{.}, Daresbury~\cite{.}, Bonn~\cite{.}, CEA~\cite{.}, and several others facilities.

A large group of experiments require the photon energy to be determine accurately in event-by-event by means of tagging on a secondary electron. In that case the photon intensity is limited by the tagger rate capability of 10^7-10^8~Hz.