Exploring confinement

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Abstract

This note is an extended version of the contribution to the CERN Council Open Symposium on European Strategy for Particle Physics. It discusses an experimental programme to explore the QCD confinement phenomena at CERN with a new electron-proton and electron-nucleus collider using the existing SPS beams (optionally also the future SPL and PS proton and ions beams) and the polarised electron beam in the range of 5 to 20 GeV from a newly built Energy Recovery Linac.
1 Introduction

While the elementary, point-like particles, carrying a unit electric charge (expressed in terms of the electron charge) can propagate freely in vacuum, those carrying fractional charges: quarks, cannot. They are confined, in the present day Universe, within fermi-size objects: nucleons.

The strong force which confines quarks, does not only allow to store their relict, early Universe, kinetic energies in the form of the mass of the nucleons but, in addition, provides the mechanism for a gradual, life-sustaining release of a small fraction of the stored energy. This mechanism is the process of formation of atomic nuclei taking place in the core of the stars.

Given the importance of the strong interactions it is hard to admit that, precisely 100 years after the discovery of atomic nucleus, the role of the quark degrees of freedom in the strong interactions phenomena involving nucleons and nuclei, remains still to be investigated experimentally and understood.

We hardly understand the mechanism which confines quarks in nucleons, nor the role of the quark degrees of freedom in forming atomic nuclei. We do not know if the gauge carriers of strong interaction forces: gluons, can propagate in atomic nucleus, or whether they are confined within nucleons. Moreover, we do not know if they can propagate within the nucleon volumes, or whether they are confined within the instanton or constituent quark distance scales.

We have still not fully understood the quark/gluon orbital momentum in hadrons and have no idea how the movements of quarks and gluons are correlated within nucleon/nucleus. We do not know how “rigid” the nucleon and nuclear matter is, i.e., how easy/difficult is to pull/push or rotate the nucleons, placed in the vacuum and in the nuclear matter, by pulling/pushing or spinning of one of its quarks or gluons.

It is fair to say that over the last 40 years the domain of our ignorance was partially reduced. A significant experimental and theoretical progress has been made in understanding the strong force at the distances sizeably smaller that the quark confinement distances, where it strength weakens. Quantum Chromodynamics (QCD) has been established to be an underlying theory of interactions of quarks and gluons. Its quantitative predictions based upon the perturbative calculation techniques passed successfully the experimental data scrutiny. More advanced computational techniques (lattice calculations) have been subsequently developed to extend the predictive power of QCD to static observables such as the masses of baryons and mesons.

Despite of all the above successes, the basic observables describing the quark and gluon dynamics at the confinement scale are beyond the jurisdiction of the present day calculation methods of QCD. For example: the partonic momentum distributions in the nucleus and in the nuclei at the fixed resolution scale cannot be
calculated/predicted, neither perturbatively nor using the lattice techniques. The fragmentation functions of quarks into hadrons both in the vacuum and in the hadronic matter are also beyond the reach of the available computational methods of the QCD.

The present day QCD status resembles that of the Quantum Electrodynamics (QED) in the first half of the 20th century: many intriguing observed phenomena could not have been derived from the QED Lagrangian alone. What is striking is a remarkable difference in the respective experimental programs: the lack of adequate QED theoretical tools did not stop, but rather accelerated or strengthen, the curiosity driven experimental investigation of the media composed of atoms in all its aspects including those which escaped the jurisdiction of the rigorous calculation methods. Such a curiosity driven research led to milestone discoveries which could have never been predicted by the theory. Superconductivity and superfluidity, both lying foundations for the construction of the present day particle accelerators, are the notable examples here.

On the contrary, the QCD confinement-focused experimental programme has hardly been addressed. Some of its aspects have been studied at the Jefferson Lab, BNL, CERN and DESY. However, to a large extent, the confinement phenomena have been considered more as a burden than as the research target. As a consequence the quest for understanding was often replaced by an efficient absorbing the lack of knowledge in terms of phenomenological models or parametrisations, with plethora of ad-hoc parameters having no link the underlying theory of strong interactions.

2 The past and the present context

2.1 DESY

A confinement-focused experimental programme has been proposed in 1996 [1], [2] as one of the three possible extensions of the HERA programme. The necessary upgrades of the DESY accelerator infrastructure, in particular the construction of the new proton and ion injectors jointly by GSI and DESY were discussed at the Seeheim workshop [3].

Unfortunately, this programme was proposed at the time when DESY was aiming to build TESLA, and since only one of these two above options could be pursued, the confinement project was abandoned, leaving a place for the TESLA project. The ”high” luminosity programme, the least interfering with TESLA, was chosen as an extension of the HERA programme at DESY.

When TESLA project was finally abandoned, GSI had already embarked on the development of the FAIR project. The opportunity for DESY to become the leading world laboratory for the studies of confinement phenomena in terms of the quark and gluon degrees of freedom had been lost.
2.2 BNL

A reincarnation attempt of the confinement-focused experimental programme, tailored to the BNL accelerator infrastructure, was made in the years 1999-2001. The first ideas for the BNL based experimental facility for confinement studies were presented at the Moriond meeting in March 1999 [4]. It was followed by the first design of the eRHIC collider [5] and by the first design of the full acceptance detector specialised in the confinement research programme [6].

At the 2001 Snowmass workshop, devoted to the “Future of the High Energy Physics”, the role of intermediate energy electron-proton and electron-ion colliders for the confinement studies was discussed. The optimisation of the collider and detector parameters to address the confinement programme was summarised in [7] and [8].

The initial momentum of the BNL-based confinement project has been significantly reduced in 2002 by the decision of the NSAC long range planning committee to put the Rare Isotope Accelerator (RIA), presently called the Facility for Rare Isotope Beams (FRIB), as the first priority project on the list of the Nuclear Physics large infrastructure projects in the USA. Nevertheless, the eRHIC collider design has been, since then, refined [9]. In addition the ELIC project at TJNAF have been proposed [10]. These two accelerator projects are presently competing to be endorsed by the NSAC as the highest priority project after a completion of the JLAB 12 GeV upgrade and after a completion of FRIB.

2.3 CERN

Recently, a project of colliding the LHC proton and ion beams with the beam of electrons was resurrected at CERN and the design report of the LHeC collider has been presented [11].

This initiative, even if driven by different research targets, shares the common interest with the programme discussed in this note in creating at CERN the high intensity polarised electron beams.

3 The experimental programme

The research target of the confinement programme is to investigate experimentally quark and gluon dynamics at the confinement distance scale by studying the response of the variable colour-charge configuration QCD media – vacuum, nucleons and nuclei – to experimentally well resolved and theoretically well controlled electromagnetic perturbations. As in the previous high energy lepton scattering experiments at SLAC, CERN and HERA the initial perturbation of quark and gluon degrees of freedom is controlled experimentally by a high resolution measurement
of the outgoing lepton momentum and theoretically, in the restricted domain of the four momentum transfer to the coloured medium, by the perturbative QED. However, the lepton scattering process is used as the surgery tool rather than the research target.

The confinement programme extends the past QCD research in the following aspects:

1. The adjustable focal length of the lepton probe would allow, for the first time in a single experiment, to cover the full dynamical range required for studies of confinement phenomena: the distances of 0.01 - 10 fermi in the direction transverse to the colliding particle axis, and the distances of 0.01 -100 fermi in the longitudinal direction. The low “calibration”, limit assures applicability of the leading twist QCD perturbative techniques to control the response of the strongly interacting matter to the EM perturbation. The upper limit assures that all the relevant strong interaction length scales are covered (constituent quark size, nucleon size, nuclear size).

2. On top of the proton beams, a broad range on ion beams are foreseen – both the isoscalar beams, such as deuterium, helium, oxygen and calcium ions and the large atomic number beams, such as the lead ion beams.

3. The nuclei would no longer play only the role of passive targets (as in the previous fixed target DIS experiments) but also the role of femto-detectors to study the space-time dependent aspects of the strong interactions at the confinement distance scale.

4. The confinement programme would make a full profit from the tagged momentum photon beams both for the studies of photon initiated nucleus disintegration processes, but also for the creation of strongly interacting matter in photon-photon collisions.

5. It could provide the necessary input measurements for the LHC experimental programme to either significantly improve the LHC measurement precision (e.g. to measure the sea/valence structure of the proton for high precision measurements of the electroweak parameters at the LHC) or to avoid the interpretation ambiguities of the LHC results (e.g. resolving the initial and the final state interactions in the hard AA collisions).

4 The research facility

The facility to conduct the confinement programme is a specialised lepton-proton and lepton-ion collider. Two complementary detectors are needed in these studies:
(1) a large $\beta^*$ beam crossing detector capable to detect all the particles produced in the collisions and to resolve the nuclear fermi-motion scale momenta of all the nucleons and nuclear fragments, and (2) a small $\beta^*$ detector optimised to achieve the highest statistical precision of selected observables, in particular for the studies of rigidity of hadronic matter, for investigation of the spin and orbital momentum of nucleon constituents and for the studies of quark and gluon momentum and angular momentum correlations.

5 The collider parameters

5.1 The centre-of-mass energies

This programme requires a broad range of the collision centre-of-mass energies. The optimal energy range is specified by the following boundary conditions: $10\ \text{GeV} \leq \sqrt{s} \leq 200\ \text{GeV}$ \cite{7}. The low limit allows for a significant overlap with the TJNF high luminosity fixed-target measurements. The upper limit assures an overlap with the HERA measurements. The proposed range covers the requisite EM-probe resolution range of the longitudinal and transverse distances and allows to separate the processes of absorption of the transversely and longitudinally polarised virtual photons in hadronic matter.

5.2 Luminosity

The luminosity range: $10^{30}\ \text{cm}^{-2}\text{s}^{-1} \leq \mathcal{L} \leq 10^{33}\ \text{cm}^{-2}\text{s}^{-1}$ is optimal for the experimental programme discussed in this note. While the low luminosity runs are sufficient for precise studies of the nucleus disintegration processes, the highest ones are necessary to measure the polarisation asymmetries and multidimensional quark fragmentation functions in vacuum and in nuclear media with a high statistical precision. A possible running scheme is to use the low emittance beams and to tune the value of the $\beta^*$ for the optimal trade-off of the luminosity and measurement precision performance.

5.3 Flavour, charge, and polarisation of the lepton beam

The main reason to chose the electron beam instead of the muon beam is to reach the luminosity targets specified above. The price to pay is a more sophisticated insertion of the beam and the final focussing in the Interaction Point (IP) to handle the photon radiation in the beam collisions zone (this can be partially circumvented by choosing highly asymmetric energies for the nucleon and for the electron beam, as discussed later in this section).
Electron and positron beams are equivalent for the proposed programme. Polarisation of the electron/positron beam is important, however not critical.

5.4 The choice of ions
The highest atomic number A ions and the light isoscalar ions are of comparable importance. While for the e-Pb collisions the main emphasis would be on maximising the medium effects, the isoscalar beams such as He, O or Ca would be beneficial for the high-precision relative measurements – in particular, if the maximum momentum spread of the stored ions of 0.25% of the nominal value can be tolerated and the He, O and Ca ion bunch trains could collide simultaneously.

A special emphasis would be on the runs with D beam.

5.5 The ratio of the proton(ion) and electron beam energies
There are several reasons to choose a highly asymmetric, $E_{\text{nuc}} \gg E_e$, collision scheme:

- better angular separation of the scattered quark associated particles and nuclear fragments,
- better resolution power of the electromagnetic probe,
- easier recognition of diffractive events,
- decoupling of the electron and the ion IP beam optics,
- detection, identification and measurement of all products of nuclear fragmentation.

The upper limit of the maximal energy of the nucleon is specified by the requirement of detecting of all the nuclear fragments: evaporated nucleons, wounded nucleons, and nuclear de-excitation gammas. Studies presented at the 2001 Snowmass workshop showed that above the energy of $\approx 200 \text{ GeV/nucleon}$ the design of the IR beam insertion and focusing optics was in conflict with the requirement to identify nuclear fragments and to measure their momenta with the requisite precision. The lowest nucleon energy for which the atomic number of the detected nuclear fragment can be unambiguously identified using the measurement of the deposited energy in the calorimeter is $\approx 4 \text{ GeV}$.

For the electron beam momentum smaller than $\approx 5 \text{ GeV}$ the identification issues of the scattered electron in highly inelastic events become critical. This defines the lower limit of the electron beam energy. The upper limit is constrained by the radiation power and the critical energy value in the IP zone. Note that a small-bend
electron insertion is incompatible with a full acceptance capacity of the detector. All the above constraints provide a rather sharp upper limit of the maximum electron beam energy of $\approx 20$ GeV [8].

6 The confinement project at CERN

The eRHIC project [5] which adds to the existing BNL RHIC ring the Energy-Recovery-Linac (ERL) fulfils most of the requirements discussed in the previous section. However, the eRHIC project was proposed already more than 10 years ago and as the time passes it becomes more and more unlikely that it will ever be realised at the BNL site. In addition, its target physics programme drifted away from the initial confinement project towards a mere continuation of the HERA programme at the higher luminosity machine. The status of the lower energy TJNAF ELIC project [10] is similar to that of the eRHIC project. If ever constructed it will come late, certainly after the TJNAF 12 GeV upgrade.

The proposal presented here is to implement the confinement research programme at CERN in synergy with the planned upgrade of the LHC injectors: SPL and PS and with the ongoing LHC physics programme. The basic idea is to construct, at the CERN site, an Energy Recovery Linac (ERL) to accelerate polarised electrons to the top energies in the range of 5-20 GeV and to collide the ERL beam with the proton and ion beams stored in the SPS (in the equivalent proton energy range of 170 - 400 GeV). In addition, delivering the future SPL proton beam and the PS proton and ion beams at their top energies to the electron-proton and electron-ion collision interaction point(s) IPs would be highly beneficial for the proposed physics programme. The ERL design could e.g. follow that of the eRHIC collider based on the 4 pass energy recuperation scheme an providing electron beams of the energies of 5, 10, 15 and 20 GeV.

The main advantages of the ERL based electron-proton and electron-ion collider scheme are:

- large luminosity (the electron bunch interacts only once),
- an easy variation of the electron bunch frequency adjusted to the proton/ion bunch frequency at variable proton/ion energies (note, that ions and protons in the large fraction of the proposed energy range are not fully relativistic),
- very long “free” straight section in the vicinity of the IP allowing to design a $4\pi$ detector capable to measure the products of the nucleus disintegration (the femto-detector signals),
- high (80 %) electron beam polarisation at each of the electron beam energies,
• a low emittance electron beam

The three LHC injectors: SPL, PS and SPS, together with the ERL could provide the full range of the optimal electron and hadron beam energies for the confinement research programme.

To implement such a programme at CERN an R&D at the present technology frontier on: ERLs, polarised electron guns, and advanced cooling techniques of the ion beams would be required. The R&D in this domain could be useful not only for the confinement project but also for the future high energy project at CERN: the CLIC project. As far as the accelerator technological challenges are concerned, the confinement project is equivalent to the LHeC project. But the analogy ends here. In all the other aspects the confinement project targets differ from those of the LHeC programme.

7 The LHeC and the confinement programme

7.1 The physics

The confinement programme cannot be conducted at the LHeC. The physics goals of the LHeC and of the confinement proposals are distinct.

The LHeC can be considered as the continuation of the HERA scientific programme at the high energy frontier and its merits should be judged in comparison with the other high energy frontier projects. The comparison of the LHeC with LHC is particularly straightforward. It can be extrapolated from the relative merits of the HERA and the Tevatron projects because: (1) HERA and Tevatron were operating at similar proton beam energy (as in the case of the LHeC and LHC), (2) the ratio of the HERA electron beam energy to the proton beam energy is similar as in the LHeC case, and (3) the ratio of collected luminosities at HERA and at the Tevatron are similar to the ratio of the design values of luminosities collected by the LHeC and the LHC.

It is rather obvious that HERA hardly improved our knowledge of the electroweak (EW) sector of the Standard Model. In the QCD sector, it provided a very important initial input to the LHC programme by measuring some combination of the quark parton distribution functions (PDFs) and by deriving the gluon PDF from the scaling violation of the DIS structure functions. However, the precision achieved at HERA turned out to be inferior with respect to the one required for improving the present precision EW measurements at the LHC [13] (mostly due to large statistical errors of the charged current and heavy quark cross section measurements). The requisite precision target can certainly be reached at the LHeC. Unfortunately such an improvement would come out of phase with the LHC programme - it is unlikely that the LHC results will be reanalysed.
The confinement programme discussed here would be focussed on asking new questions and exploring new territories rather than on continuing the measurements of canonical observables in the new energy regime. It would be complementary to the QCD research programs at TJNAF and at the future FAIR facility at Darmstadt. It could provide also a necessary input data for: (1) increasing the precision of the LHC EW measurements (precision input information for understanding of the W and Z boson polarisation at the LHC) and (2) experimental resolving of the final and initial state state effects in the hard AA collisions – both in phase with the ongoing LHC experimental programme.

7.2 The cost

The cost of the confinement project represents a small fraction of the LHeC project due to two important factors: (1) the requisite maximal energy of the electron beam is smaller by factor of 3-10 than in the LHeC case; (2) the electron ring could be placed in the SPS tunnel (as foreseen already in the year 1976 in the design of the CHEEP project [12]). This would significantly reduce the civil engineering work on the transfer lines.

7.3 Synergies

The proposed project optimises the duty cycle of the LHC injectors. As soon as the LHC is filled the proton/ion bunches, the SPS could be used for collisions with the electron beam. The interference of the confinement programme with the the LHC pp and AA collision programme would thus be minimal. The construction of the ERL could be, to a large extent, decoupled from the ongoing LHC operation. The CERN confinement project could attract the eRHIC and ELIC communities. CERN could thus become not only the leading world laboratory for the electroweak interaction studies at the high energy frontier but also in the domain of strong interactions at the exploratory frontier.

8 Conclusions

New collider projects addressing the high energy frontier of particle physics have certainly the highest potential in discovering new phenomena. However they require costly investments. Given the present financial crisis in Europe, it may be worthwhile to consider, at present, a relatively “low” cost accelerator project for CERN. Such a project could be realised in parallel to the ongoing LHC experimental programme, while waiting for a clear vision for the most optimal high energy frontier project which can be establish only following the completion of the high luminosity phase of the LHC scientific programme.
The confinement project could play such a role. It could be designed in synergy with the upgrade of the LHC injectors, executed in parallel with the LHC experimental programme, and could provide better understanding of the confinement phenomena. Moreover, the investment in the ERL technology inherent to this project, may be crucial in developing the next high energy frontier project at CERN.

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