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Ultimate Colliders for Particle Physics : Limits and Possibilities

V. D. Shiltsev*

Fermi National Accelerator Laboratory, MS 312,
Batavia, IL 60510, USA
**E-mail: shiltsev@fnal.gov*

The future of the world-wide HEP community critically depends on the feasibility of the concepts for the post-LHC Higgs factories and energy frontier future colliders. Here we overview the accelerator options based on traditional technologies and consider the need for plasma colliders, particularly, muon crystal circular colliders. We briefly address the ultimate energy reach of such accelerators, their advantages, disadvantages and limits in the view of perspectives for the far future of the accelerator-based particle physics and outline possible directions of R&D to address the most critical issues.

Keywords: Colliders; accelerators; plasma accelerators; muons, crystals.

1. Current landscape of accelerator-based particle physics

Colliding beam facilities which produce high-energy collisions (interactions) between particles of approximately oppositely directed beams have been on the forefront of particle physics for more than half a century and. In total, 31 colliders ever reached operational stage and six of them are operational now[1],[2],[3],[4]. These facilities essentially shaped the modern particle physics as their energy has been on average increasing by an order of magnitude every decade until about the mid-1990s. Since then, following the demands of high energy physics (HEP), the paths of the colliders diverged: to reach record high energies in the particle reaction the Large Hadron Collider was built at CERN, while record high luminosity e^+e^- colliders called particle factories were focused on detailed exploration of phenomena at much lower energies. Currently, the HEP landscape is dominated by the LHC. The next generation of colliders is expected to lead the exploration of the smallest dimensions beyond the current Standard Model.

Given the cost, complexity and long construction time of the collider facilities, the international HEP community regularly goes through extensive planning exercises. For example, in the recent past and at present we have the European Strategy planning (2012-2013), the US US Snowmass and P5 plan (2013-2014), the European Strategy Update (2018-2020), under consideration now is the ILC250 project in Japan (decision by Spring 2020) and potential CepC project in China, the next US Snowmass and P5 process is set for 2019-2022. Discussions at the most recent 2019 European Particle Physics Strategy Update symposium (EPPSU, May 2019, Granada, Spain)[5] were focused on two types of the longer term (20-50 yrs) HEP facilities: Higgs Factories(HF) and the Energy Frontier (50-100 TeV pp or 6-15 TeV lepton). There are four possible concepts fof these machines: linear e^+e^- colliders,

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Table 1. Main parameters of proposed colliders for high energy particle physics research[6].

Project	**Type**	**Energy** TeV, c.m.e.	**Int.Lumi./ Oper.Time.**	**Power** years	**Cost** B(unit)
ILC	e^+e^-	0.25	2 ab^{-1} / 11yrs.	129	5.3ILCU
		0.5	4 ab^{-1} / 10 yrs.	163(204)	7.8ILCU
		1		300	?
CLIC	e^+e^-	0.38	1 ab^{-1} / 8yrs.	168	5.9CHF
		1.5	2.5 ab^{-1} / 7 yrs.	370	+5.1CHF
		3	5ab^{-1} / 8 yrs.	590	+7.3CHF
CEPC	e^+e^-	0.091	16 ab^{-1} / 4 yrs.	149	5 $
		0.24	5.6 ab^{-1} / 7yrs.	266	+?
FCC-ee	e^+e^-	0.091	150 ab^{-1}/ 4 yrs.	259	10.5CHF
		0.24	5 ab^{-1} / 3 yrs.	282	
		0.365	1.5 ab^{-1} / 4 yrs.	340	+1.1 CHF
LHeC	ep	0.06/7	1 ab^{-1} / 12 yrs.	(+100)	1.75 CHF
HE-LHC	pp	27	20 ab^{-1} / 20 yrs.	220	7.2 CHF
FCC-hh	pp	100	30 ab^{-1} / 25 yrs.	580	24 CHF
$\mu\mu$**Coll.**	$\mu\mu$	14	50 ab^{-1} / 15 yrs.	230	10.7* CHF

circular e^+e^- colliders, pp/ep colliders, and muon colliders. (Table 1 summarizes main parameters of the future facilities, paramters of the muon collider are given according to[7].) They all have limitations in the energy, luminosity, AC power consuption, and cost which in turn mostly depend on five basic underlying accelerator technologies: normal-conducting (NC) magnets, superconducting (SC) magnets, NC RF, SC RF and plasma. The technologies are at different level of performance and readiness, cost efficiency and required R&D[6].

Feasibility of the future colliders depends on their energy reach, luminosity, cost, length and power efficiency. So far, the most advanced of the proposals for the energy frontier collidsers call for acceleration by wakefields in plasma which can be excited by: lasers (demonstrated electron energy gain of about 8 GeV over 20 cm of plasma with density $3{\cdot}10^{17}$ cm^{-3} at the BELLA facility in LBNL); very short electron bunches (9 GeV gain over 1.3m of $\sim 10^{17}$ cm^{-3} plasma at FACET facility in SLAC) and by proton bunches (some 2 GeV gain over 10 m of 10^{15} cm^{-3} plasma at the AWAKE experiment at CERN). In principle, the plasma wake field acceleration (PWFA) is thought to make possible multi-TeV e^+e^- colliders. There is a number of critical issues to resolve along that path, though, such as the power efficiency of the laser/beam PWFA schemes; acceleration of positrons (which are defocused when accelerated in plasma); efficiency of staging (beam transfer and matching from one short plasma accelerator cell to another); beam emittance control in scattering media; the beamstrahlung effect that leads to the rms energy spread at IP of about 30% for 10 TeV machines and 80% for 30 TeV collider.

An attempt to assess options for ultimate future energy frontier collider facility with c.o.m. energies of 300-1000 TeV (20-100 times the LHC) was made in[8]. There it was argued that for the same reason the circular e^+e^- collider energies do not extend beyond the Higgs factory range (~ 0.25 TeV), there will be no circular proton-proton colliders beyond 100 TeV because of unacceptable synchrotron radiation power therefore, the colliders will have to be linear. Moreover, electrons and positrons even in linear accelerators become impractical above about 3 TeV due to beam-strahlung (radiation due to interaction) at the IPs and beyond about 10 TeV due to the radiation in the focusing channel. That leaves only $\mu^+\mu^-$ or pp options for the far future colliders. If one goes further and requests such a flagship machine not to exceed ~10 km in length then an accelerator technology is needed to provide average accelerating gradient of over 30 GeV/m (to be compared with ~0.5 GeV per meter in the LHC). There is only one such option known now: super-dense plasma as in, e.g., crystals[9], but that excludes protons because of nuclear interactions and leaves us with muons as the particles of choice. Acceleration of muons (instead of electrons or hadrons) in crystals or carbon nanotubes with charge carrier density $\sim 10^{22}$ cm^{-3} has the promise of the maximum theoretical accelerating gradients of 1-10 TeV/m allowing to envision a compact 1 PeV linear crystal muon collider[1]. High luminosity can not be expected for such a facility if the beam power P is limited (e.g., to keep the total facility site power to some affordable level of $P \sim$100MW). In that case, the beam current will have to go down with the particle energy as $I = P/E_p$, and, consequently, the luminosity will need to go down with energy E_p. Therefore, there is a need in the paradigm shift for the particle colliders which in the past expected the luminosity to scale as $L \propto E_p^2$.

2. Acceleration in Crystals and Nanostructures

The very first proposal to accelerate muons in crystals[9] assumed excitation of solid plasmas by short intense X-ray pulses. The density of charge carriers (conduction electrons) in solids $n_0 \sim 10^{22-24}$cm^{-3} is significantly higher than that in gaseous plasma, and correspondingly, the longitudinal accelerating fields of upto 100-1000 GeV/cm (10-100 TV/m) are possible according to

$$E[\mathrm{GV/m}] \approx 100\sqrt{n_0[10^{18}\mathrm{cm}^{-3}]}. \tag{1}$$

The are several critical phenomena in the solid plasma due to intense energy radiation in high fields and increased scattering rates which result in fast pitch-angle diffusion over distances of l_d[m]$\sim E_p$[TeV]. The latter leads to particles escaping from the driving field; thus, it was suggested that particles(muons) have to be accelerated in solids along major crystallographic directions, which provide a channeling effect in combination with low emittance determined by an Angstrom-scale aperture of the atomic tubes[10,11]. Channeling in the nanotubes was later brought up as a promising option[12–14]. Positively charged particles are channeled more robustly, as they are repelled from ions and thus experience weaker scattering. Radiation emission due to the betatron oscillations between the atomic planes is thought to be the major source of energy dissipation, and the maximum beam energies are limited to about 0.3 TeV for positrons, 10^4 TeV for muons and 10^6 TeV for protons[10]. For energies of 1 to 10 PeV, muons offer much more attraction because they are point-like particles and, contrary to protons, do not carry an intrinsic energy spread of elementary constituents; and they can much easier propagate in solid plasma than protons which will extinct due to nuclear interactions. The muon decay becomes practically irrelevant in the proposed very fast acceleration scheme as the muon lifetime quickly grows with energy as $2.2\mu\text{s} \times\gamma$. Very high gradient crystal accelerators have to be disposable if the externally excited fields exceed the ionization thresholds and destroy the periodic atomic structure of the crystal (so acceleration will take place only in a short time before full dissociation of the lattice). For the fields of about 1 GV/cm=0.1 TV/m or less, reusable crystal accelerators can probably be built which can survive multiple pulses. Possible conceptual scheme of a crystal lin-

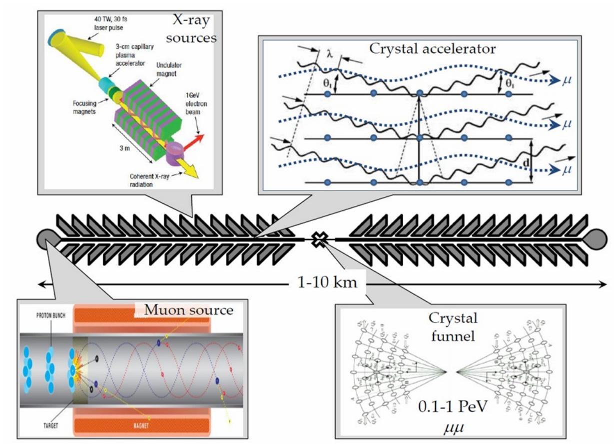

Fig. 1. Concept of a linear X-ray crystal muon collider (adapted from [1]).

ear muon collider - see - includes two high brightness muon sources, two continuous crystal linacs of a total length of 1 to 10 km driven by numerous X-ray sources (or other type of drivers) to reach 1-10 PeV c.m.e. at the interaction point with a crystal funnel [1]. Initial luminosity analysis of such machine assumes the minimal overlap area of the colliding beams to the crystal lattice cell size $A \sim 1$ $\mathring{A}^2$=10^{-16}cm^{-2} and that the crystals in each collider arm are aligned channel to channel. The number of muons per bunch N also can not be made arbitrary high due to the beam loading effect and should be $N{\sim}10^3$. Excitation many parallel atomic channels n_{ch} can increase the luminosity $L{=}fn_{ch}\ N^2/A{=}f{\cdot}10^{16}{\cdot}10^6{\cdot}n_{ch}$[cm^{-2}s^{-1}] which can reach 10^{30}cm^{-2}s^{-1} at, e.g., $f{=}10^6$ Hz and $n_{ch}{\sim}100$. Exceeding the value of the product fn_{ch} beyond 10^8 Hz can be very costly as the total beam power $P{=}\ fn_{ch}NE_p$ will get beyond a practical limit of $\sim$10 MW. Instead, using some kind of *crystal funnel* to bring microbeams from many channels into one can increase the luminosity by a factor of n_{ch} to some 10^{32}cm^{-2}s^{-1}.

3. Challenges and Open Questions

Until now, crystals were of interest for particle accelerators because of their strong inter-planar electric fields $\sim$10V/Å=1GV/cm [15]. Given their unique radiation hardness and stability, crystals were used even in the highest energy hadron colliders like the 2 TeV Tevatron and the 14 TeV LHC for particle focusing and/or for deflection (with efficiency notably growing with the energy, e.g. better than $\sim$95% in the Tevatron and over 99% in the LHC for some 4 mm bent crystals [16,17]).

Several methods can be envisioned for the wakefield excitation in the crystals [18] - see Fig.2. Historically first was the suggestion to use ultrashort and powerful 40 keV X-ray pulses injected in the crystal at a proper angle to achieve Bormann anamalous transmission over longer distances [9]. Extreme X-ray pulse power density $O(10^{23-24}\mathrm{W/cm}^2)$ can now be achieved at the SASE FELs like LCLS at SLAC, and the gradients of about 0.2[TV/m]$\cdot a_0^2$ are predicated in CNTs which can lead to 100s of MeV of acceleration in few micron long structures [13,14] (here $a_0 \sim O(1)$ is the normalized field intensity of a O(1nm) wavelength laser). Further opportunities to increase the laser intensities can be offered by recently proposed ICAN and thin film compression schemes.

Bunches of charged particles can excite plasma effectively if their transverse and longitudinal sizes are comparable or shorter than the plasma wavelength of $\lambda_p \sim 0.3$ μm for $n_0 = 10^{22}$ cm^{-3} and the total number of particles in that volume approaches the number of free electrons in the solid plasma $n_0\lambda_p^3$. Arguably the closest to such conditions are the electron bunches prepared for the FACET-II experiments at SLAC - at the initial stage of 3D compression they will by 8×7×2 μm that for the total charge of 2 nC results in $n_e = 6 \cdot 10^{18}$ cm^{-3}, while at the ultimate compression 2×2×0.4 μm the density will be about $n_e = 2 \cdot 10^{20}$ cm^{-3} (and corresponding peak current of about 300 kA).

Relativistic fully stripped heavy ions can offer yet another possibility for wakefields excitation in crystals or carbon nanotubes [18] as the fields they leave behind in the media are about the ionization loss gradient of

$$E_i \approx 2[\mathrm{MeV}/(\mathrm{g/cm}^2)] \times Z^2, \tag{2}$$

that gives $E_i \approx$2 TV/m for Z=70-80 in silicon. Naturally, one can envision these ions either channeling in crystals ahead of the accelerating particles (e.g., muons) or being well aligned with them so the latter are always kept in sync with accelerating wake. At present, the highest energy heavy ions are available at RHIC (100 GeV/u gold, Z=79) and LHC (2.5 TeV/u lead, Z=82) and the dephasing length $2\gamma_p^2\lambda_p$ can be as long as few cm - few meters.

Figs. 2d) and 2e) conceptually depict two other possibilities to excite structured solid plasmas by either pre-modulated high density bunches of charged particles or by initially unmodulated long bunches which get microbunched while propagating in the media due to self modulation instability (SMI). In both cases it is important that the drive beam density modulation is resonant to the plasma waves, i.e. occurs

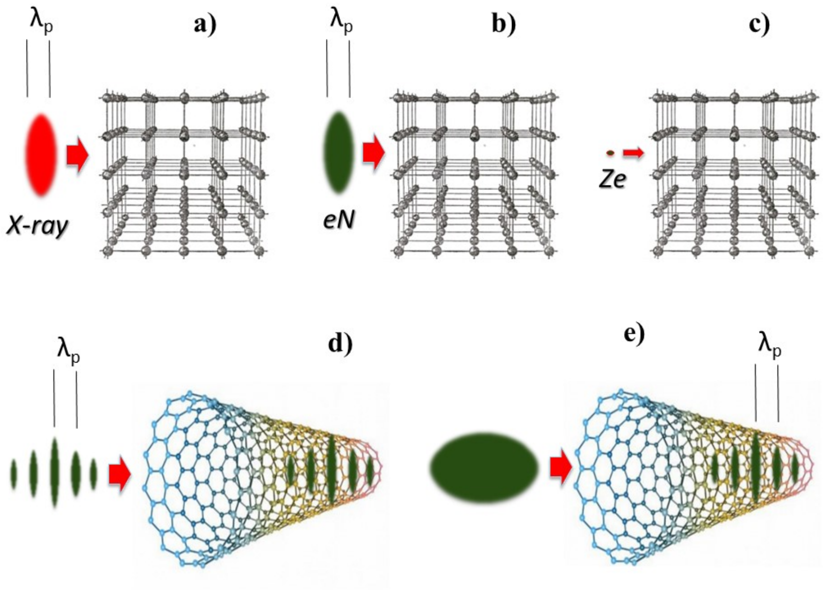

Fig. 2. Possible ways to excite plasma wakefields in crystals or/and nanostructures: a) by short X-ray laser pulses; b) by short high density bunches of charged particles; c) by heavy high-Z ions; d) by modulated high current beams; d) by longer bunches experiencing self modulation instability in the media.

at λ_p so the waves excited by individual microbunches add up coherently. The first of these methods can employ, e.g. either the nanomodulated bunches at the end of SASE (self amplified spontaneous emission) process in modern X-ray FELs or micromodulated beams obtained via slit-masking in chicanes as, e.g., it was proposed in[19]. The SMI in longer proton bunches traversing low density gaseous plasma has been demonstrated in the AWAKE experiment at CERN. Of course, in the solid plasma of crystals or CNTs the SMI will compete with other phenomena, such as the Weibel or filamentation instabilities and that issue requires detail study.

In general, there are many important topics for future research on acceleration in crystals and nanostructures, including: a) critical overview of the past and present theoretical developments toward crystal acceleration, exploration of the ultimate possibilities of the concept; b) further development of the concepts and most optimal schemes of PeV crystal colliders for HEP; c) theory, modeling and experiments on effective crystal wave drivers such as beams (including self-modulation instability), lasers , other schemes; d) particle and beam dynamics in crystal acceleration channels; e) instabilities in crystal acceleration channels, such as filamentation/Weibel instability, etc; f) acceleration in nanostructures (CNTs, alumna honeycomb holes, zeolites, others); g) high brightness muon sources for crystal acceleration; h) possible practical applications of crystal accelerators (X-ray sources, etc); i) comprehensive study of possible steps toward "proof-of-principle" experiment to demonstrate 1 GeV energy gain over 1 mm; j) preparation of possible crystal acceleration experiments at FACET-II, FAST, BELLA, AWAKE, AWA, RHIC, LHC or elsewhere (including addressing open theory questions, modeling and simulation, hardware and diagnostics development, etc).

4. Conclusions

The concept of beam acceleration in solid-state plasma of crystals or nanostructures like CNTs (or alumna honeycomb holes) has the promise of ultra-high accelerating gradients O(1-10) TeV/m, continuous focusing and small emittances of, e.g., muon beams and, thus, may be of interest for future high energy physics colliders. Recent advances in the acceleration in gaseous beam- or laser-driven plasma and muon production and cooling, progress in the intense X-ray pulse generation, production of short very high peak current bunches of charged particles, development of sophisticated high-performance PIC codes to model high density plasmas - all that paves the way for comprehensive studies of the theory, corresponding modeling, and eventually experiments on the wakefield excitation in solid plasmas, acceleration of particles in crystals or CNTs, muon production and detection, etc. Some schemes of the crystal/CNT excitation can be tested at the beam test facilities such FACET-II at SLAC, FAST at Fermilab, BELLA at LBNL and AWAKE at CERN. One can also explore opportunities for proof-of-principle experimental studies with either high energy high-Z ions available at RHIC or LHC or to exploit unique properties of the self-modulated electron beams in the SASE FEL facilities, like, e.g. the LCLS-I and -II at SLAC. Past experience with crystals in high energy particle accelerators as well as available hardware might very helpful for the initial studies.

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