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Accelerator Considerations of Large Circular Colliders

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As we consider the tremendous physics reaches of the big future circular electron-positron and proton-proton colliders, it might be advisable to keep a close track of what accelerator challenges they face. Good progresses are being made, and yet it is reported here that substantial investments in funding, manpower, as well as a long sustained time to the R&D efforts will be required in preparation to realize these dream colliders.

1. Introduction

Several collider options are presently being considered today as potential candidates to provide the energy frontier facilities beyond the LHC. With a widely varying degrees of maturity, one quickly comes up with a list that at least include:

- e^+e^- linear collider: (a) superconducting, (b) normal conducting, (c) plasma-laser
- e^+e^- circular collider
- pp circular collider
- $\mu^+\mu^-$ circular collider
- $\gamma\gamma$ collider

It is too early to discuss which options should prevail at this point. For now, to limit the scope, let us consider only two of the options above, namely the circular e^+e^- and pp colliders. Furthermore, let us for now focus on their technical challenges — some of them are not simple extrapolations from what we have today or even tomorrow. As we consider the tremendous physics reaches of these powerful colliders, their induced technical challenges, and therefore the required R&D investments to make them realities are something we want to keep a close track of.

For this purpose, I will try to mention some of the main technical challenges for the big circular e^+e^- and pp colliders as presently envisioned, particularly the CEPC effort in China[1] and the FCC effort at CERN.[2] Clearly only the few high level challenges can be mentioned here. For discussion purposes, I choose to use the pre-CDR CEPC parameters when discussing the e^+e^- collider, and the FCC-hh parameters when discussing the pp collider. No programmatic or budgetary discussions are intended.

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2. e^+e^- circular collider issues in a nutshell

The pre-CDR design of CEPC is a single purpose Higgs factory with a circumference of 54 km. As such, its center-of-mass energy $E_{\mathrm{cm}} = 240$ GeV is considered given. In contrast, the FCC-ee aims for a wider physics goals with a higher energy and a larger ∼100 km circumference. As their technical issues are similar, we choose to apply the CEPC parameters for our discussions.

At this high energy, synchrotron radiation becomes an immediate challenge. To put it under control, we must have large circumference C. However, the synchrotron radiation power $P \propto E^4/C$, so we are using the first power of C to fight the fourth power of the beam energy E.

Let us try to scale from LEP on how to optimize the choice of C. There are two ways to do this:

(1) The first way is to minimize the total cost. The total cost contains two terms, one is proportional to the circumference, the other is proportional to the total synchrotron radiation power, i.e. we have $\$ = C + E^4/C$. It follows from this expression that the total cost is minimum when $C = E^2$, and the minimum cost is $\$_{\min} = 2E^2$. Since LEP-I was designed to minimize the total cost, we can use this result to scale from LEP-I ($E_{\mathrm{cm}} = 110$ GeV, $C = 27$ km) to obtain the Higgs factory parameters. By this scaling, we obtain $C = 128$ km when $E_{\mathrm{cm}} = 240$ GeV. We can also scale the total cost this way, but as promised, I will not venture in that direction.

(2) If minimum total cost is not the issue but the total synchrotron radiation power is, then we should scale by holding the total synchrotron radiation power fixed, i.e. the scaling is $C \propto E^4$. Since LEP-II was designed with synchrotron radiation power as the limit, we now scale from LEP-II ($E_{\mathrm{cm}} = 209$ GeV, $C = 27$ km). The result is for the Higgs factory, $E_{\mathrm{cm}} = 240$ GeV, $C = 47$ km.

The pre-CDR CEPC design $C = 54$ km is closer to case (2). Cost optimization was understandably not yet a consideration.

After choosing a large circumference, strong synchrotron radiation still severely limits the beam current:

$$P = IE^4/C$$

The beam current I must be kept low compared with colliders without synchrotron radiation power limit. To illustrate this point, one can compare the KEKB beam current of 2.6 A with the 18 mA beam current envisioned for CEPC. Now with a limited total beam current, the only way to push up the luminosity is to lump more particles into fewer bunches and to have very small bunch size. This consideration leads to the following comparison:

KEKB:	5000 bunches,	3×10^{10} particles/bunch
pre-CDR CEPC:	50 bunches,	4×10^{11} particles/bunch

It then follows that in a Higgs factory, each beam-beam collision is necessarily very violent and the beam-beam perturbation to the particle motion is very strong. The conventional beam-beam limit (Coulomb force between the colliding beam bunches) becomes substantially more severe.
But the beam-beam limit due to the conventional Coulomb interaction is not yet the main problem. What becomes critical is another effect called beamstrahlung (synchrotron radiation induced at the beam-beam collisions),[3] which has never been a problem before but becomes serious at 240 GeV. Beamstrahlung pushes the beam collision optimization and the interaction region design to unprecedented level of sophistication.
In a nutshell, the issues for the big e^+e^- collider are synchrotron radiation in the bending arcs, plus synchrotron radiation at the beam-beam collisions.

3. *pp* circular collider issues in a nutshell

By far the biggest technical challenge is superconducting magnets. This is a well recognized issue but let me restate the obvious here:

- The superconducting magnets are the most costly item in the big *pp* collider.
- There is presently no technological solution on the table.
- 15-20 years of sustained R&D is needed to develop a solution.

Next to the superconducting magnets, synchrotron radiation is again a culprit of technical challenges for the big *pp* collider. It is of course true that synchrotron radiation power in the *pp* collider is lower than e^+e^- case. First, it scales with E^4 and becomes smaller by the factor (50 TeV/120 GeV)^4 = 0.002. Second, it also scales linearly with beam current I and becomes larger by the factor (1 A/0.018 A) = 50. Overall, the synchrotron radiation power is lower by a factor of 10. However, this power is now to be removed cryogenically, and the Carnot efficiency is 230 if the power is to be removed at 4.5 K as is done at LHC with an insertion of a screen inside the 2 K chamber. The required cryogenic power is therefore $0.002\times50\times230 = 23$ times larger.
More quantitatively, the synchrotron radiation power is 2.4 MW/beam for the FCC-hh *pp* collider. This means the cryogenic power for the synchrotron radiation heat removal is 2×2.4 MW×230 = 1 GW if it is to be removed at 4.5 K. So other than the magnets, synchrotron radiation stands as another challenge for the *pp* collider. This time the burden is not on the RF system, but on the cryogenics. As will be mentioned later, the proposed solution is to raise the temperature of the screen to 50-100 K.
The critical photon energy of the synchrotron radiation is 4.3 keV. Some of the synchrotron radiation photons therefore have energies high enough to penetrate the vacuum chamber. Effects of these high energy photons also need to be evaluated.

Several other secondary technical issues can most likely be resolved by extrapolations from LHC and HL-LHC, so are not discussed in this report. Examples include the very large stored energies in the proton beams and in the superconducting magnets, collimation of the beam tails, and beam-beam effects. In all these case, experiences gained at LHC and to be gained at HL-LHC are/will be invaluable.
In a nutshell, the *pp* collider issues are synchrotron radiation in the cryogenic environment, plus the overwhelming technological issue of the high field magnets.

4. e^+e^- collider challenges

Beam collisions are violent To obtain high luminosity with limited total beam current, we introduce two requirements:

(1) The beam size must be strongly focused by the interaction region optics,

$$\begin{aligned} \sigma_x \times \sigma_y = 0.5 \text{ mm} \times 0.03 \text{ mm} \qquad & \text{in the regular ring arcs} \\ \rightarrow \quad 70\ \mu\text{m} \times 0.15\ \mu\text{m} \qquad & \text{at the IP} \end{aligned}$$

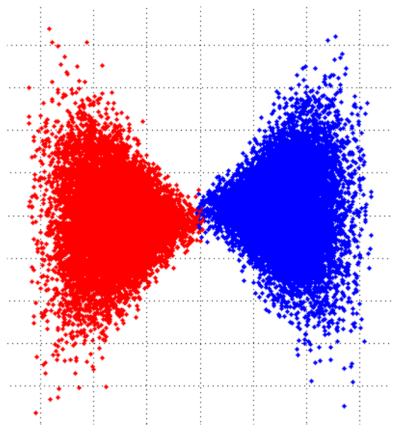
(2) As mentioned earlier, the beams are forced to be as lumpy as possible, i.e. a small filling factor with few bunches (50 bunches per beam, with bunch spacing ~1 km), each with an intense population (4×10^{11} particles/bunch).

As a result, the beam-beam collisions are more violent than conventional e^+e^- colliders, including the high achievers of the B factories.
As is well known, the way to control the beam-beam perturbation is to make the β-functions at the IP, β_x^* and β_y^*, small,

$$\begin{aligned} \beta_x \approx \beta_y \approx 50 \text{ m} \qquad & \text{in the regular ring arcs} \\ \rightarrow \quad \beta_x^* = 0.8 \text{ m},\ \beta_y^* = 1.2 \text{ mm} \qquad & \text{at the IP} \end{aligned}$$

In addition, the beam at the IP is made to be extremely flat, with aspect ratio ~500, to help relieve the beam-beam issue. This is believed achievable in principle, with demanding requirements on various error tolerances.

Bunch length is too long The conventional "beam-beam tune shifts" exceed present records: $\xi_x = 0.12,\ \xi_y = 0.08$ — to be compared with 0.045 at LEP-I. These are demanding, but they alone are not the real challenges. A real challenge occurs when the bunch length is considered.
With the small β_x^* and β_y^*, the beam looks like an hourglass at the IP, as sketched below of two colliding bunches.

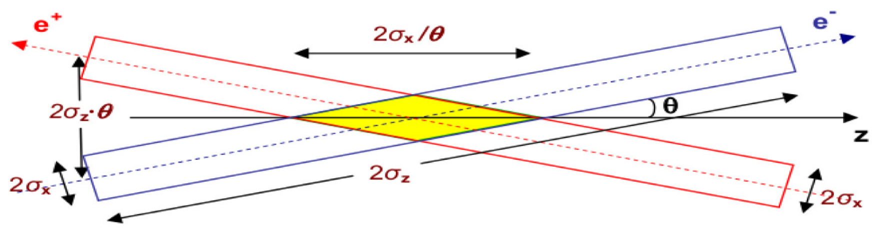


To achieve a high luminosity, we need to maintain a small beam size at the IP, but this small beam size is maintained only over a distance $\sim \beta_x^*$ and β_y^*. To maintain small beam size throughout the collision, bunch length must be short, i.e.

$$\sigma_z < \beta_x^* \text{ and } \beta_y^*$$

which means we need $\sigma_z < \beta_y^*$, i.e. $\sigma_z < 1.2$ mm.
The nominal way to shorten an electron bunch length is to apply higher RF voltage, but RF system is already over-burdened as is to fight synchrotron radiation, and this RF system as presently designed gives a bunch length of $\sigma_z = 2.2\ \beta_y^*$ which is too long.
Since σ_z scales as $V_{\mathrm{RF}}^{1/2}$, shortening the bunch length by a factor of 2.2 requires raising V_{RF} by a factor of 5, which is hardly the answer.

Crab waist is introduced The bunch length issue, however, has a ready ingenious solution called crab waist,[4] initially tested at DAΦNE, adopted by SUPERKEKB and FCC-ee. The pre-CDR CEPC did not resolve the bunch length issue but it is proposed to consider crab waist in its next effort.



Although the bunch length is long, with a large crossing angle θ, the beam-beam collision region (yellow region above) can be smaller than σ_z, i.e. $\sigma_x/\theta \ll \sigma_z$. With this configuration, β_y^* now only needs to be $< \sigma_x/\theta$ in order to control the hour-glass effect. The collisions in the yellow region are with fewer particle, so the

bunch intensity is raised to reach the beam-beam limit and to make up for the luminosity.
The crab waist requires:

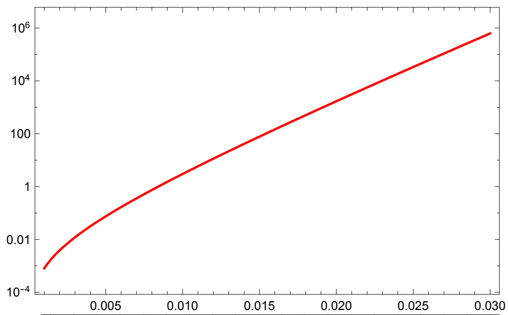
- a large crossing angle
- a two-ring configuration
- reoptimize the collision parameters, keeping beam-beam tune shift and total synchrotron radiation power fixed.
- a clever Interaction Region (IR) optics design with additional sextupoles to control the chromatic aberrations at the interaction point, while not hurting the dynamic aperture.

Crab waist is a critical path design aspect and involves subtle beam dynamics. Although basically validated, more operational experience at SUPERKEKB will play an important role to sharpen up the crab waist concept.

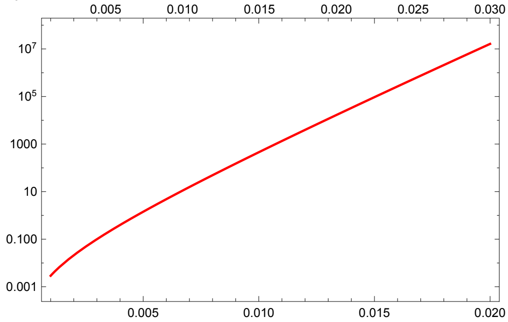
Beamstrahlung In case a beam-beam induced synchrotron radiation causes the emission of a photon too energetic, the emitting particle gets outside of the momentum aperture $\pm A_\delta$ of the storage ring and gets lost from the beam. Beamstrahlung beam lifetime:

$$\tau_{\rm bs}^{-1} = \frac{9\pi^2}{2\sqrt{2}} \frac{\gamma^{3/2} N^{5/2} r_e^4}{\alpha_F^{1/2} w^{5/2} A_\delta^{3/2} \ell^{3/2} T_0} \exp\left(-\frac{\alpha_F A_\delta \ell w}{3\pi N \gamma r_e^2}\right)$$

Taking the CEPC parameters, we obtain the beamstrahlung lifetime (in second) as a function of A_δ as shown below:



When $\sigma_z = 2.2\ \beta_y^*$, we require $A_\delta = 1.1\%$ to achieve 1 hr lifetime.



When $\sigma_z = \beta_y^*$, we require $A_\delta = 2.2\%$ to achieve 1 hr lifetime.

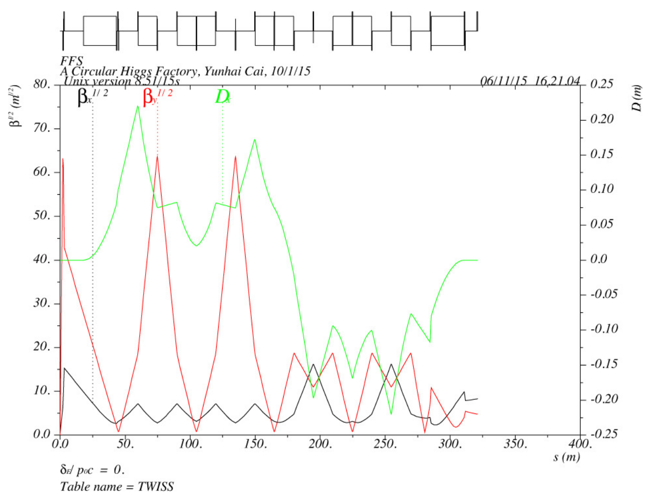
The demand of an acceptable beamstrahlung lifetime is transferred to a requirement on the storage ring's momentum stability aperture A_δ. A conventional electron storage ring has typically A_δ of 1%.

Interaction region optics The IR optics for the big e^+e^- collider requires heroic efforts and is one of the critical path accelerator physics issues. It requires:

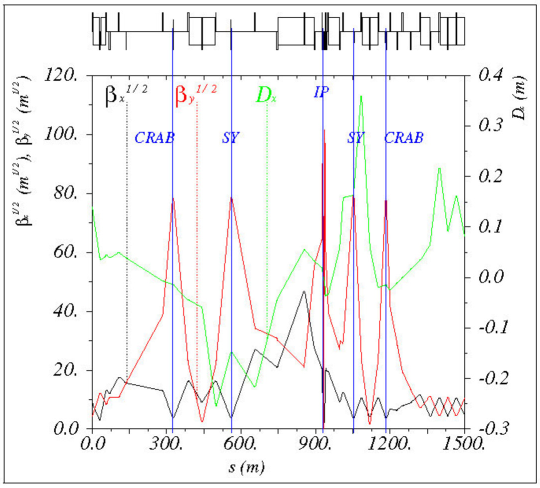
- a very small β^*, which means the IR optics is strongly nonlinear, and the dynamic stability aperture is a highly technical challenge.
- A crab waist optics is to be included.
- At the same time, a very large momentum aperture of $\pm 2.2\%$ is needed to handle beamstrahlung.

There are presently proposed ingenious and sophisticated solutions, yielding $\pm 2\%$ apertures.[5–7] Some of the salient features include:

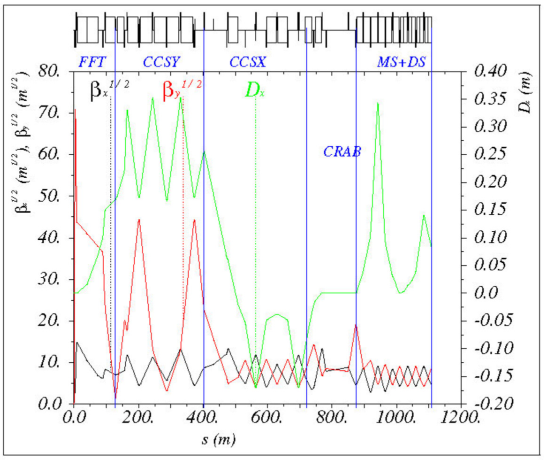
- The optics is asymmetric upstream-downstream to accommodate synchrotron radiation without hitting the detector.
- Some ideas were borrowed from linear collider designs. (Linacs are single pass devices, circular colliders are repetitive passage devices. One can not simply insert a final focus of a linear collider into a circular collider, but some ideas can be borrowed.)
- Some of the more subtle features will require experimental confirmation. Computer simulations help but do not suffice.
- Machine-detector interface is critical but can be done later.
- It is unlikely to have longitudinal polarization even in a future upgrade. IR optics has been already over-burdened as is. Strong physics motivation is required to initiate this effort if at all.



Y. Cai, symmetric design, total length 0.7 km, IP at $s = 0$.



K. Oide, et al., asymmetric design, total length 1.5 km, IP at $s \approx 900$ m.

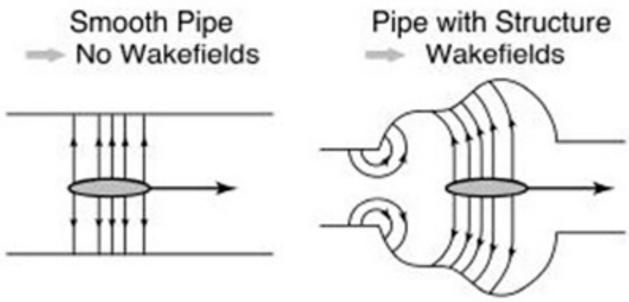


A. Bogomyagkov/E. Levichev, asymmetric design, total length 1.5 km, IP at $s = 0$.

Superconducting RF system For 120 GeV beams and with a 54-km circumference, RF system is the dominant cost item. Dipole magnets filling factor is pushed to 70% to lower as much as possible the dipole magnetic field and therefore the synchrotron radiation power. Basically all remaining conceivable spaces, including the interaction region straight sections, are filled with RF to spread out RF burden. Due to the distributed energy gains at the RFs and energy losses at the dipoles, there is a beam-energy sawtooth behavior around the circumference, generating a severe optics issue with the one-ring scenario adopted by CEPC pre-CDR.

RF is the pumping heart of the e^+e^- collider system. The total RF voltage is 7 GV, which is about 6% of the nominal electron energy. The total wall plug power is designed to be 500 MW for the collider facility, with 230 MW allocated for synchrotron radiation. Because of the high power involved, the cavities are required to have high Q-value at high voltage. The input coupler has to sustain high power. The RF power conversion efficiency and the cryogenic system efficiency need to be high. By pushing the known technologies to their limits, these are considered within reach given dedicated and sustained efforts. One potential exception that stands out from these items concerns the handling of the higher order modes (HOMs) in the RF cavities.

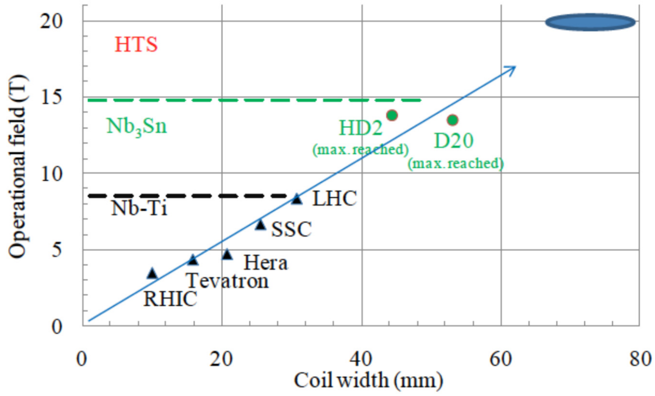
Higher order mode damping HOM are higher order modes excited in the RF structures when the beam bunches pass by. We intentionally excite only the fundamental mode, but the beam excites all modes if beam intensity is high and if bunch length is short. HOMs are the worst kind of losses because it is energy extracted directly from the beam and deposited directly onto the cryogenics as heat. Once generated, there is no mechanism to couple the HOMs out of the envisioned 5-cell structures.



The HOM heat load is estimated to be 2 kW per cavity. This leads to a required cooling power for HOM to be added to synchrotron radiation by the amount 2 kW×384×(Carnot efficiency 460 at 2K) = 320 MW. This HOM heating breaks the power budget. This estimate is when the bunch length is $\sigma = 2.2\ \beta_y^*$. If the bunch length needs to be shortened to $\sigma_z = \beta_y^*$ (to avoid the complication of a crab waist), the HOM heat load would scale with σ_z^{-3}. The HOM heating is a key issue to be resolved. Some reconfiguration and reoptimization will at least be needed.

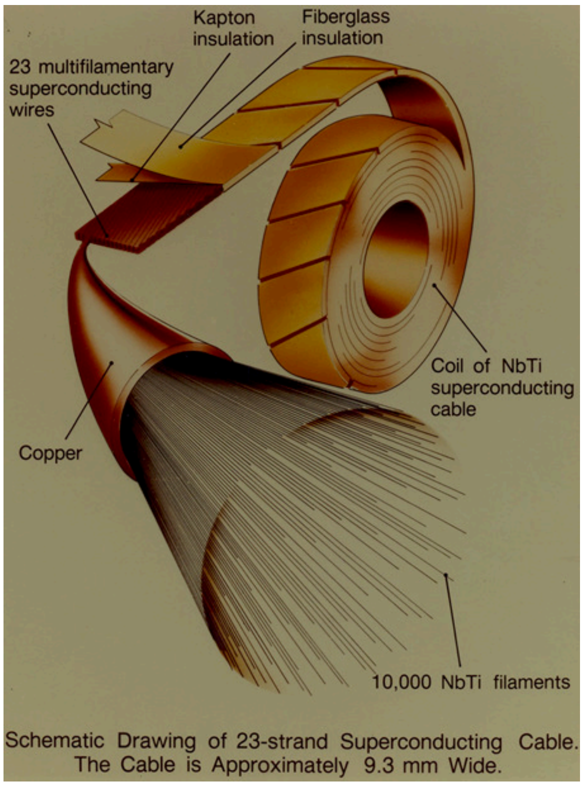
5. *pp* collider challenges

Superconducting magnet Superconducting magnets are the critical path item. The present state of the art is reached at the LHC after ∼40 years of R&D. New R&D is on-going for (Nb_3Tn) technology. Technology for (Nb_3Tn + HTSC) is further down the path. Evolution of superconducting technology is well summarized by the CERN web site:[8]



(NbTi)
ISA
RHIC
Tevatron
HERA
SSC
LHC
(Nb_3Tn)
HL-LHC
(Nb_3Tn + HTSC)
FCC-hh

Design and construction of high-field superconducting magnets is a highly evolved process. Victims along the long learning process included a few large science projects. Instead of reviewing the present round of R&D of superconducting technology, it is perhaps constructive to review the evolution of the past, particularly the path that led to the present NbTi designs.

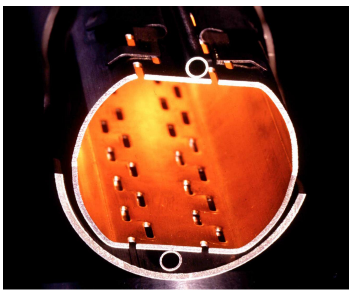


Perhaps we can use the superconducting cable as an illustration of the point. The superconducting cable that replaces the copper wire in a normal conducting magnet is not just a wire that conducts high current at low temperature but a highly evolved object (see the sketch above):

(1) The coil package is constructed from cables
(2) A cable is constructed from twisted strands
(3) Each strand is constructed of twisted superconducting filaments (a few microns diameter) imbedded in a copper matrix

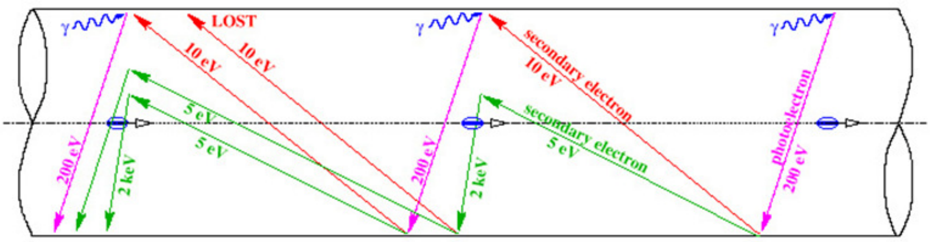
Each step described above had its hard-learned experiences of R&D. It took a long learning process to evolve just the coil package. A natural question to be addressed is what evolution steps will be needed when we change to another technology not based on NbTi?
Once the cables are available, they still need to be assembled into magnets. The magnitude of the technical challenge to be faced requires a mention of some of the issues involved here too. For example, the field quality required for the big collider is of the order of 10^{-4}. The superconducting coils must be placed accurately to the accuracy $\sim\mu$m. These coils experience strong Lorentz forces (10000 psi when powered), and yet any movement by $\sim\mu$m will release sufficient field energy to quench the magnet. The coil packages therefore must be mechanically confined by strong collars. The collars also are heavily pre-stressed to $\gg$ 10000 psi so that the coil packages do not become loose when not powered. Also, stresses increase quadratically with the magnetic field.
The most challenging problem to a large degree is not so much the high magnetic field, but also how to confine the coils so that the field constitutes a robust precision accelerator magnet. In other words, reaching a high magnetic field, say 20 T, is only a fraction of the journey.

Synchrotron radiation heat load Synchrotron radiation heat load to the cryogenic system, as mentioned earlier, is to be absorbed by a screen inside the vacuum chamber. A prototype of such a screen can be seen in the LHC vacuum chamber design (below), but the design for the big *pp* collider will have to be substantially changed.



The synchrotron radiation power in the big *pp* collider is estimated to be 2.4 MW per beam, which translates to about 28 W/m of heat load (to be compared with 0.22 W/m for LHC). If we allocate 100 MW power to be used to remove this heating, the screen needs to be maintained at a temperature of about 50-100K. Heat insulation between the screen and the 2 K chamber is an issue to be resolved. With 40 mm magnet aperture, and a room for the beam of 26 mm, the addition of a screen has implications on collective instabilities. Resistive wall (at 50 K) instability for example has a strength estimated to be about 100 times that of the LHC.

Electron cloud Electron cloud is a phenomenon that occurs in positron or proton rings.[9] Its effect depends sensitively on bunch spacing of 25 ns. Electron clouds can cause beam emittance growth which in turn causes loss of luminosity. Electron-cloud-induced collective instability is not expected to be critical, but its induced heating is estimated to be about 10 W/m if secondary electron yield of the surface coating is 1.4. If so, it contributes a heat load of 1 MW/beam to be added on top of the synchrotron radiation and HOMs to the required cryogenic power.



6. Summary

- Going from existing colliders to the big colliders, a few of the more critical technical issues are mentioned. Some of these challenges do not presently have a design and are waiting for conceptual decisions.
- The high energy physics goals are grand and wonderful. They provide powerful incentives for the big colliders.
- HL-LHC and SUPERKEKB are critical test beds for some of the required technologies.
- Much progress has been made in identifying the technical issues and challenges and in developing the accelerator technology towards these big colliders. Facing the challenges, however, more R&D efforts will be required to realize them. Investments to be prepared indicate the need of 100s M$ funding, 10^3 FTEs manpower, and 10s years sustained time period before a credible design can be made and construction can be launched.

- If it sounds alarming/exciting, join the accelerator R&D efforts. Without their successes, there will not be a dream collider.

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