"CPT Theorem" for Accelerators

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Abstract: In this paper we attempt to reveal common features in evolution of various colliders' luminosity over commissioning periods. A simplified formula, "CPT theorem" or *CP=T* is proposed which relates the time needed for commissioning *T*, the complexity of the machine *C* and performance increase goal *P*.

Evolution of Luminosity: CESR Example, Idealistic Model, and Complexity

Evolution of high energy colliders' luminosity is a subject of great importance for many parties: for accelerator physicists working with the machine they designed and built – because it's matter of self respect to deliver the promised performance and prove by fact that their scientific and technical decisions taken years ago were correct; for the experimental high energy physicists – because they build their schedules, plan their life and foresee possible upgrades on a basis of the luminosity promised and delivered by a corresponding collider; and for lab management and funding agencies – because running modern accelerators requires significant financial supplies and overall luminosity progress with that or other type of the colliders is used as an input to decide on future facilities and projects.
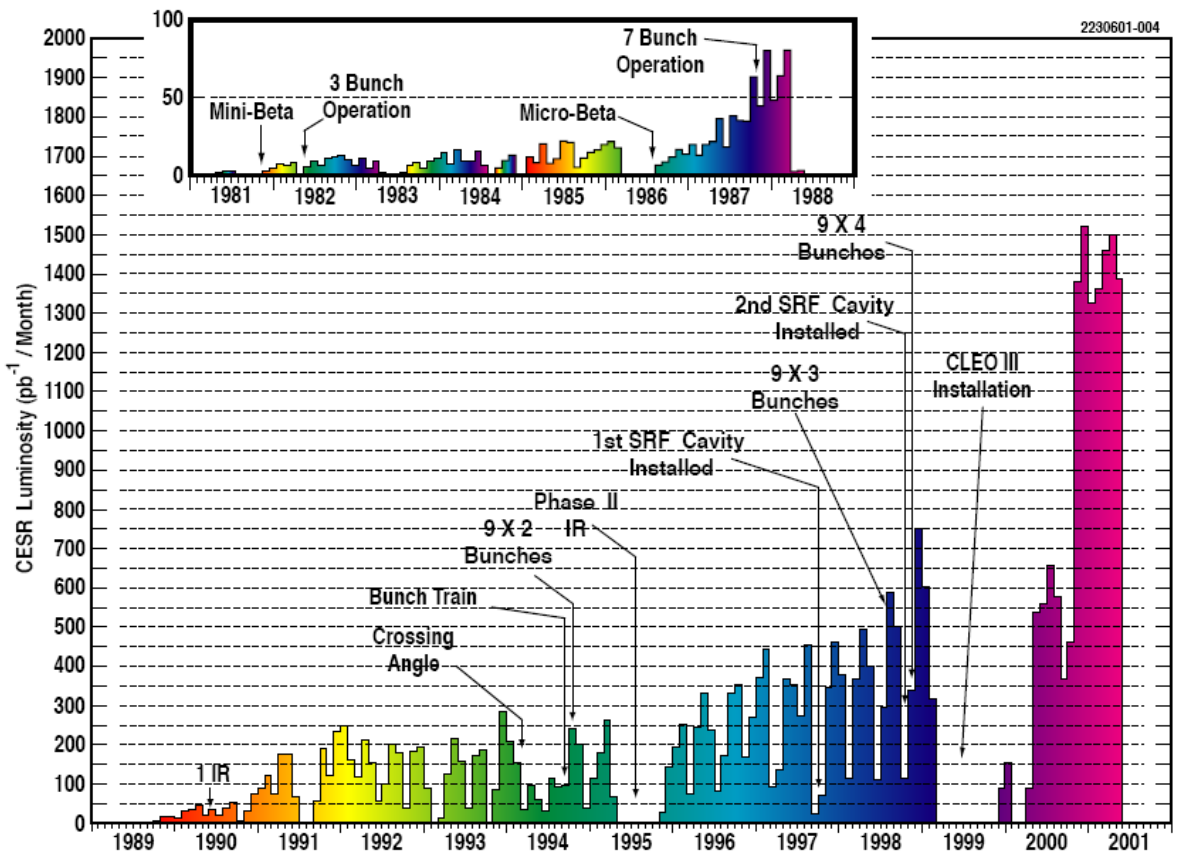

Fig.1: Luminosity of CESR e+e- collider since 1981; 1pb-1 corresponds to average luminosity of approximately 1e30 cm-2s-1 over 280 hrs of operation per month.

Thus, it seems to be useful to perform an analysis of regularities in collider commissioning.

Let's start with luminosity of Cornell Electron Storage Ring which operated as a e+e- collider since 1981 – one of the longest living machines ever. Fig.1 from [1] shows its monthly integrated luminosity over 20 years period and reveals some features which we will repeatedly see in many other machines in further analysis. Namely, it's obvious that the Collider went through a number of various upgrades, some of them required significant downtime (shutdown). After each "re-incarnation", the luminosity starts at very low level, most probably because new and old hardware require some time to become fully operational and support decent machine uptime. But that does not last long as luminosity quickly goes up to a level which is comparable with previous running period. Basically, it just reflects the fact that the team operating the machine has enough professional knowledge to do comparatively quick "recovery" to pre-shutdown (or predecessor machine) level. After the recovery, the luminosity starts to exceed previous levels because the operating team introduces one or several improvements which lead better and better performance. More innovative ideas the better, as luminosity grows as "N% over M%", i.e. in principle, if the influx of helpful ideas for improvements is constant, and each of them give about the same increase, the luminosity would grow *exponentially*. As one can see, such periods of nonlinear growth occurred at CESR several times – in 1981-82, 1986-1988, 1989-1991, 1996-1998 and in 2001. After such periods, the possibilities for luminosity improvements without major operational interruptions are exhausted, the luminosity flattens, the machine either runs for some time with stable luminosity or prepares and goes into next major shutdown to make changes necessary for the next breakthrough.

Thus, one can summarize the "cycle of life" of a collider as follows: I. construction or major shutdown → II. short startup to commission new and old hardware → III. fast progress toward already explored luminosity levels (either from previous running period or to the level of a predecessor machine) → IV. a period of nonlinear ("exponential"?) luminosity growth over which new possible improvements are introduced → V. period of leveled luminosity → all over again. Schematically, the cycle is presented in Fig.2 a and 2b (in linear and logarithmic scale). It's obvious – e.g., from Fig.1 – that periods IV and V take most of the time. Though, there is a significant difference between them – length of the period V (stable operation, no growth) is determined by will of the people running the machine and performing HEP experiments at it, while duration of the period IV (commissioning, "exponential growth") can not be easily defined.
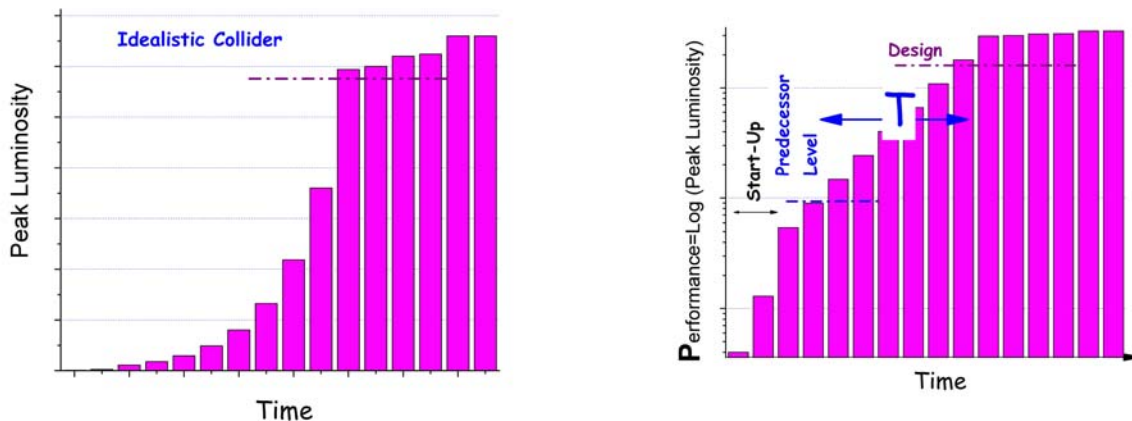

Fig.2: Schematic representation of colliders' "cycle of life" – a) linear scale, b) log scale.

Purpose of this work is to investigate objectives of collider luminosity growth times.

CPT Hypothesis and " Complexity" of Machine.

As it was mentioned above, growth of the luminosity beyond predecessor's level depends on realization of successful improvements. As an example, below we list improvements incorporated in operation of the Tevatron proton-antiproton collider after startup of Run II in March 2001 [2]. In the third column, an approximate gain in the peak Tevatron luminosity is given in %.

- First 9 months   Mar-Nov'01
- Optics AA->MI lines fixed   Dec'01   25%
- Quenches on abort fixed by TEL-1   Feb'02   0%, reliability
- Pbar loss in Sequence 13 fixed   Apr'02   40%
- "New-new" injection helix   May'02   15%
- Shot lattice, AA cooling reduces IBS   July'02   40%
- Tev BLT helps at injection   Sep'02   10%
- Pbar coalescing improved in MI   Oct'02   5%
- C0 Lambertsons Removed   Feb'03   15%
- S6 cuircuit tuned/SEMs removed   June'03   10%
- "5 star" helix on ramp   Aug'03   2%
- Reshimming/Alignment   Dec'03   10%
- MI dampers/Longer Stores   Feb'04   30%
- 2.5MHz AA → MI transfer/Cool shots   April'04   8%
- Reduction of beta^* to 35 cm   May'04   20%
- Antiprotons shots from both RR and AA   July'04   8%

One can see that over the last 32 months of operation, there were some 15 improvements performed in the Tevatron itself and various accelerators in the injector chain. An average gain in luminosity obtained after each step is about 16%, while the total resulting increase is $1.16^{15}=9.2$ (from 10e30 to 92 e30 cm-2s-1). An exponential growth of the luminosity is a good approximation of the Tevatron luminosity progress in average. Therefore, a following relation can be used to summarize evolution of the collider performance:

$$C \cdot P = T \qquad (1)$$

where the factor *P=ln(luminosity)* can be called a "performance"), *T* is the time needed to achieve the performance goal, and *C* is a coefficient equal to average time needed to increase the luminosity by *e=2.71...* times, or boost the performance *P* by 1 unit. Both, *T* and *C* have dimension of time, and below we will quote them in units of years. Note, that for non-colliding accelerator facilities, the performance goals are set in the units, other than luminosity, e.g. beam intensity or brilliance or something else, so that should be appropriately used in the CPT-analysis.

In the next section, we will consider a number of accelerators and estimate their complexities. Before I had done that analysis, my personal feeling was that in general, the complexity depends on how well understood is physics and technology of this or that machine. From that point of view, the best understood and performing machines are those with just one ring and one beam, so quite minimal time is needed to commission them.

Thus, their complexity should be the lowest, namely, close to *C=0*. Facilities with colliding electron and positron beams are in general more complex, but because many issues are simplified by presence of fast damping due to synchrotron radiation (SR) and can be (and are) well studied in computer simulations and beam studies (e.g., instabilities and beam-beam interaction effects), they can not be *very* complex. Thus, their complexity is expected to be about *C =1*. Hadron colliders do not have such an advantage as SR, so they should come next with *C* of about 2. And, finally, completely novel accelerator types, exploring never tried before technologies should have been at *C=3* or above.

CPT Analysis of the Past and Present Accelerators.

Let's start with single beam facilities. Two of the most recent examples are 7 GeV ANL APS ring and 150 GeV Fermilab Main Injector. Both accelerators were very challenging technically, cost significant money (some 400M$ and over 200M$, correspondingly), but were commissioned upto design beam parameters in significvantlt less than a year – 9 month in the case of the APS [3], and in some 6 months – for MI [4]. So, as expected, their "complexity" in the sense of previous section is close to zero.

Let's consider colliders. The CESR luminosity has been already discussed above and presented in Fig.1, data on PEP-II and KEK-B [5], LEP [6], SLC [7], HERA[8] are presented in Fig. 3. The CERN ISR [9] and SppS [10], and Tevatron Run II and Run Ia,Ib,II luminosity plots [2] are shown in Fig.4.
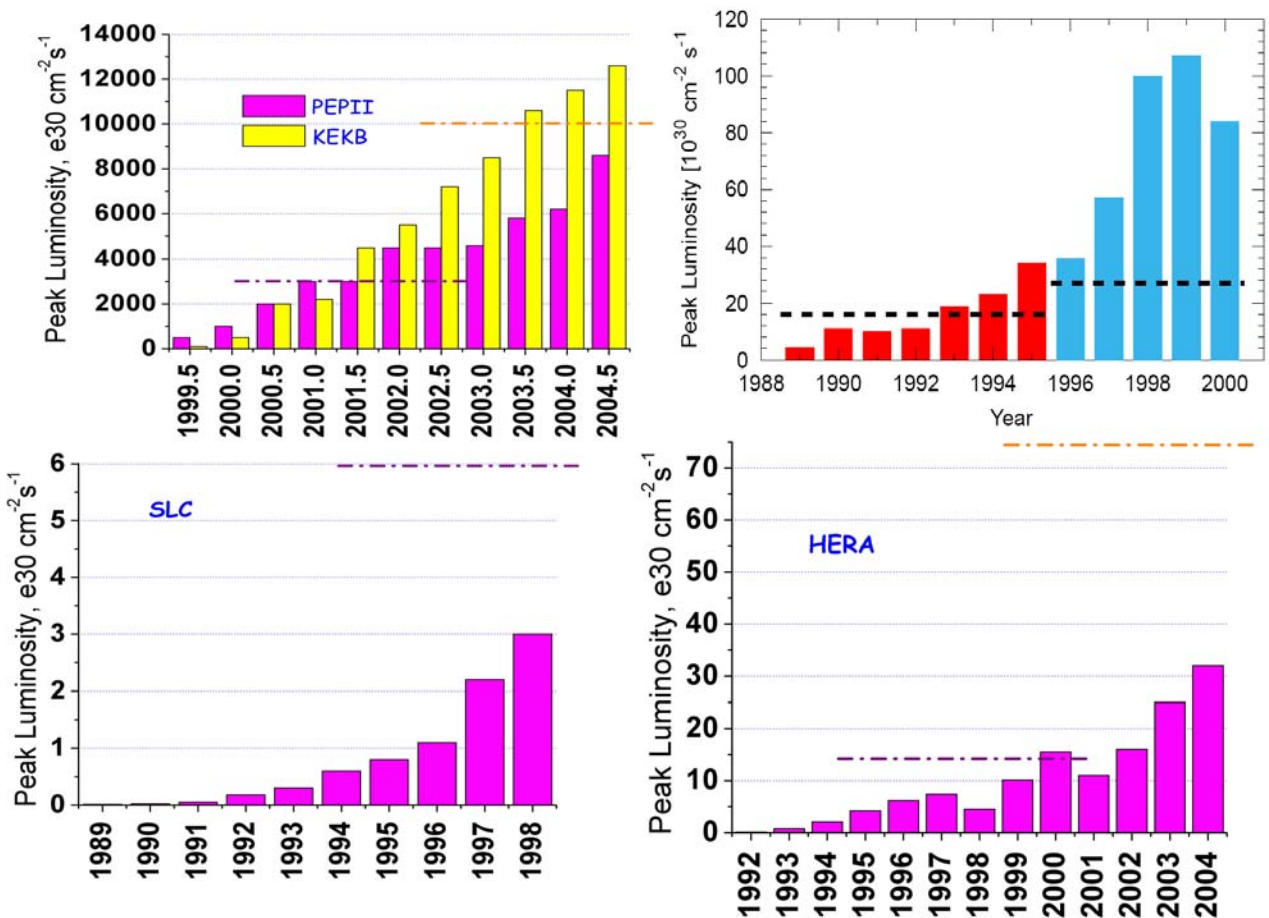

Fig.3: Evolution of luminosity of PEP-II and KEK-B, LEP, SLC and HERA colliders.
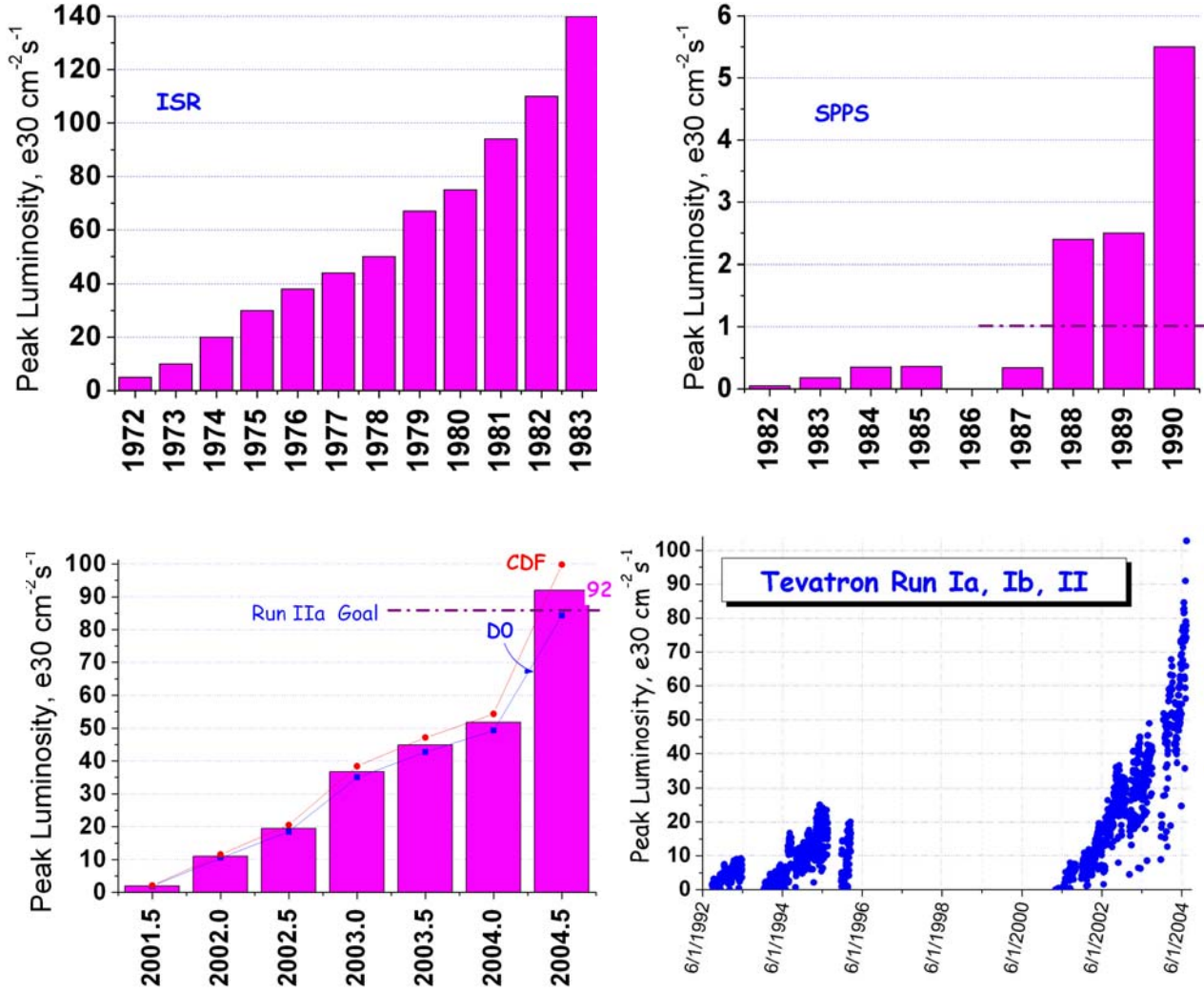
Fig.4: Tevatron Run II record luminosity vs time, and Run Ia,Ib, II luminosity in stores.

In accordance with discussion in previous section, we will calculate the complexity as $C = dT / ln(L_f/L_i)$, where L_f is either the luminosity level at which collider performance stabilized or final luminosity at the end of the running period while L_i is either the level achieved in previous run or the level at which the luminosity started to grow nonlinearly (exponentially), $dT = T_f - T_i$ is the length of the evolution period between L_i and L_f. For example, the Tevatron collider luminosity in Run Ib exceeded its predecessor, Run Ia, luminosity of $L_i = 10e30$ on 07/23/1994 1994 and reached its maximum luminosity of $L_f = 25e30$ on 05/10/1995, that gives us $dT = 0.8$ year and $C = dT / ln(L_f/L_i) = 0.9$. For the Tevatron Run II, naturally, the predecessor is Run Ib, so, $L_i = 25e30$ (that level was established on 7/26/2002) and with luminosity record $L_f = 92e30$ set on 7/6/2004 one gets $C = 2$yr $/ ln(L_f/L_i) = 1.5$. Table below summarizes such analysis for several machines.

Machine	Design L	T_f	dT, yr	L_f	L_i	C	Ce
APS (ANL)			0.5			**0**	0
MI (FNAL)			0.6			**0**	0
CESR, 1986-88 Run		01/1988	1	83	20	**0.7**	1
1990-92 Run		03/1992	1.33	250	50	**0.8**	1
1996-99 Run		02/1999	3	750	250	**2.7**	1

2000-01 Run		06/2001	1	1500	550	**1.0**	1
PEP-II 1999-2001	3000	01/2001	1.5	300	3000	**0.7**	1
2002-04	3000	06/2004	1.5	8200	4400	**2.4**	1
KEK-B	10000	06/2003	2.5	10400	2000	**1.5**	1
LEP 45 GeV	16	1995	3	33	11	**2.7**	1
90 GeV	27	1998	2	102	34	**1.8**	1
SLC	6	1998	5	3	0.3	**2.2**	3
ISR I		1975	3	30	5	**1.7**	3
ISR II		1983	8	140	3	**5.2**	2
SppS	1	1990	7	5.5	0.18	**2.0**	2
HERA I	16	06/2000	5	18	4	**3.6**	2
Upgrade	75	07/2004	2	35	18	**3.0**	2
Tevatron Run Ib	15	09/1995	0.8	25	10	**0.9**	2
Run IIa	86	07/2004	2.0	92	25	**1.5**	2

Here, luminosities are in units of 1e30cm-2s-1, the last column shows naïve "complexity" expectation Ce as discussed at the end of previous section.

Discussion, CPT Predictions for Future Accelerators

Let us first mention once again that the CPT formula (1) is, of coarse, a simplification of reality and can not pretend to describe it in detail: nonlinear luminosity growth is not necessarily the phase every machine goes through (though as we saw above, it's the case for many), real operation schedule is often interrupted by shorter or longer shutdowns after those, in many cases, accelerators to be re-commissioned again, also, it's not always clear at which moment the growth period ends and the "leveled luminosity" period starts, etc. Also, the performance factor P always requires to know an initial level to start from, that may inject another uncertainty into the analysis.

From the examples summarized in the Table above one can conclude that complexity is not something which characterize machine forever. Instead, complexity of the machine may go up or down after major shutdowns and upgrades and – CESR and Tevatron histories demonstrate that well. Also, comparing columns C and Ce one can see that though in each particular case the expectation can be quite far from reality, in general, hadron machines are more complex than electron-positron colliders: average complexity (if such a thing is thinkable at all, formally, average of the last 7 lines in the Table) of the ISR, SppS, Tevatron and HERA is $<C>=2.6$ is way above that of lepton colliders $<C>=1.5$.

Differences in machine complexities may be due to various reasons: a) first of all, beam physics issues are quite different not only between classes of machines (hadrons vs e+e-) but often between colliders from the same class – all that affects how fast and what kind of improvements can be implemented; b) accelerator reliability may affect the luminosity progress, especially for larger machines with greater number of potentially not-reliable elements; c) another factor is "team quality" – capability of the team running the machine to cope with challenges, generate ideas for improvements and implement them; d) and, of coarse, the latter depends on resources available for each team, often closely related to the priority, the laboratory or funding agency set for that.

Given all that, it'd be interesting to use the CPT relation for future accelerator facilities. The easiest example is Tevatron Upgrade project which aims for peak luminosities of about $L_f=270e30$ cm-2s-1. Comparing it with current performance of L_i

=92e30, one gets $\Delta P = ln(L_f/L_i)=1$ and for complexity parameter C=1.5(now)-2.3(average for hadron machines) one should expect to reach the goal by January-November 2006.

To make predictions for the LHC, which has no past, one can consider the Tevatron (with luminosity of 100-150e30) as natural predecessor but should take into account that due to energy difference only (7 times) equivalent startup luminosity should be proportionally higher because $L \sim \gamma \dfrac{N_1 N_2}{\varepsilon_n}$

Thus, for the LHC the increase from L_i =7x140e30=1e33cm-2s-1 to L_f=1e34 cm-2s-1 should take 3.5-5 years (again, the spread reflects C=1.5(Tevatron now)-2.3(average for hadron machines) . Therefore, possible schedule for the LHC may look like: 2007-hardware startup and first beam, full year of 2008 to get luminosity up to L_i =1e33, and the design luminosity to be achieved by 2012-2014.

Conclusions

A simplified *CPT* approximation is proposed to describe luminosity evolution of various colliders. The complexity coefficient *C* was found to be machine dependent but in average larger for hadron colliders. Primitive *CPT*-predictions are made for the time needed for the upgraded Tevatron and CERN LHC to reach their design goals.

This talk has been presented at Αλβιν Συμποσιον dedicated to Alvin Tollestrup's 80-th birthday. I am indebted to Alvin for that and many other occasions to discuss various aspects of life and science with him.

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