“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.

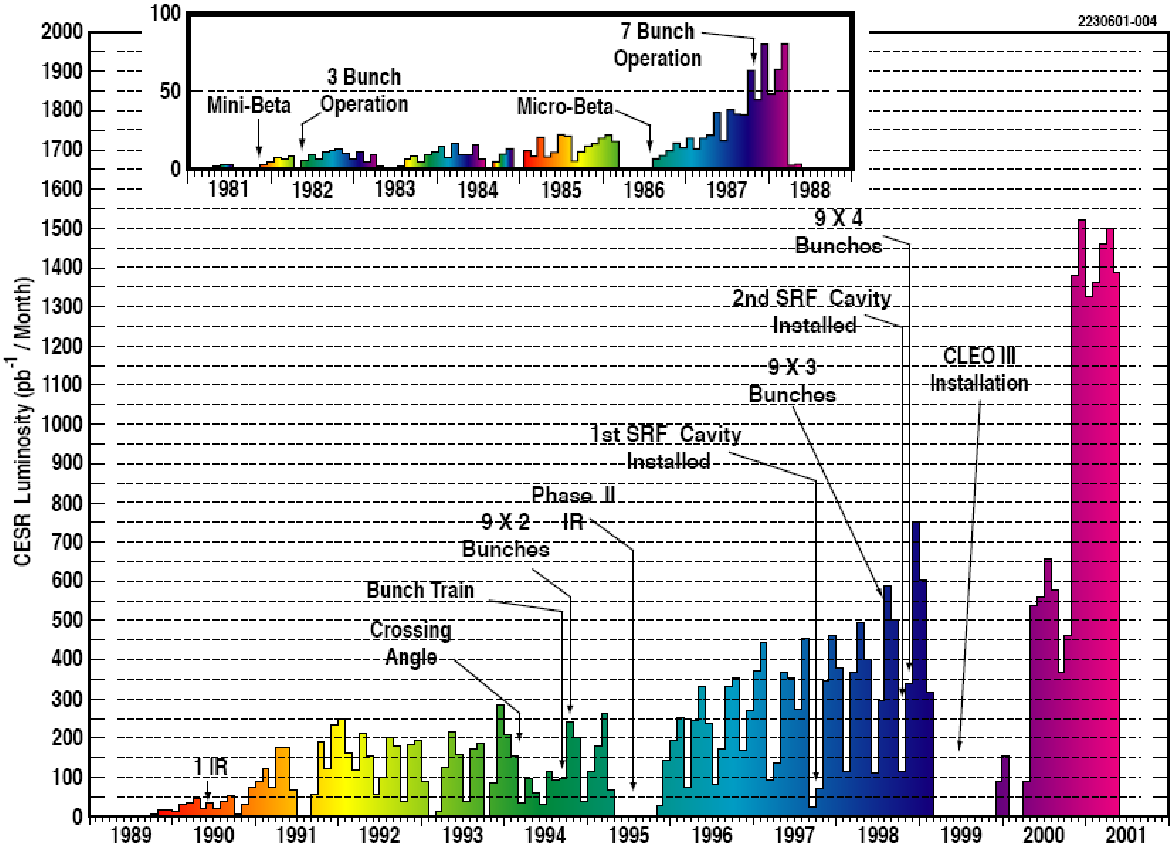

Fig.1: Luminosity of CESR e+e- collider since 1981; 1pb-1 corresponds to average luminosity of approximately 1e30 cm-2s-1 over 280 hrs of operation per month.

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.

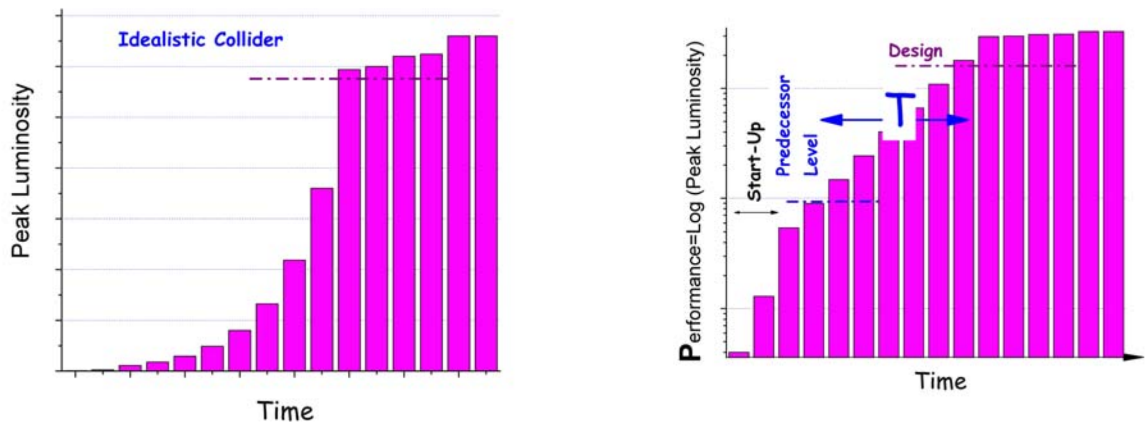

Fig.2: Schematic representation of colliders’ “cycle of life” – a) linear scale, b) log scale.

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:

$$C \cdot P = T \tag{1}$$

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. Below we will address the coefficient *C* as “complexity” while its exact meaning will be discussed later. 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) studied in depth in simulations and beam studies (e.g., instabilities and beam-beam interaction effects), they can not be *very* complex. Thus, their complexity was expected to be about *C =1*. Hadron colliders do not enjoy advantages of the SR, so they should come next with *C* of about 2. And, finally, completely novel accelerator types which exploit 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 apparent "complexity" is close to zero.

Next, we consider colliding beam facilities. The CESR luminosity has been already discussed above and presented in Fig.1. Fig.3 presents performance evolution of e+e- colliders, namely, KEK-B and PEP-II B-factories [5], DAFNE [6], SLC [7], and LEP [8]. Luminosity plots of hadron colliders of CERN ISR [9] and SppS [10], RHIC[11], e-p collider HERA [12], Tevatron Run II and Run I [2] are shown in Fig.4.

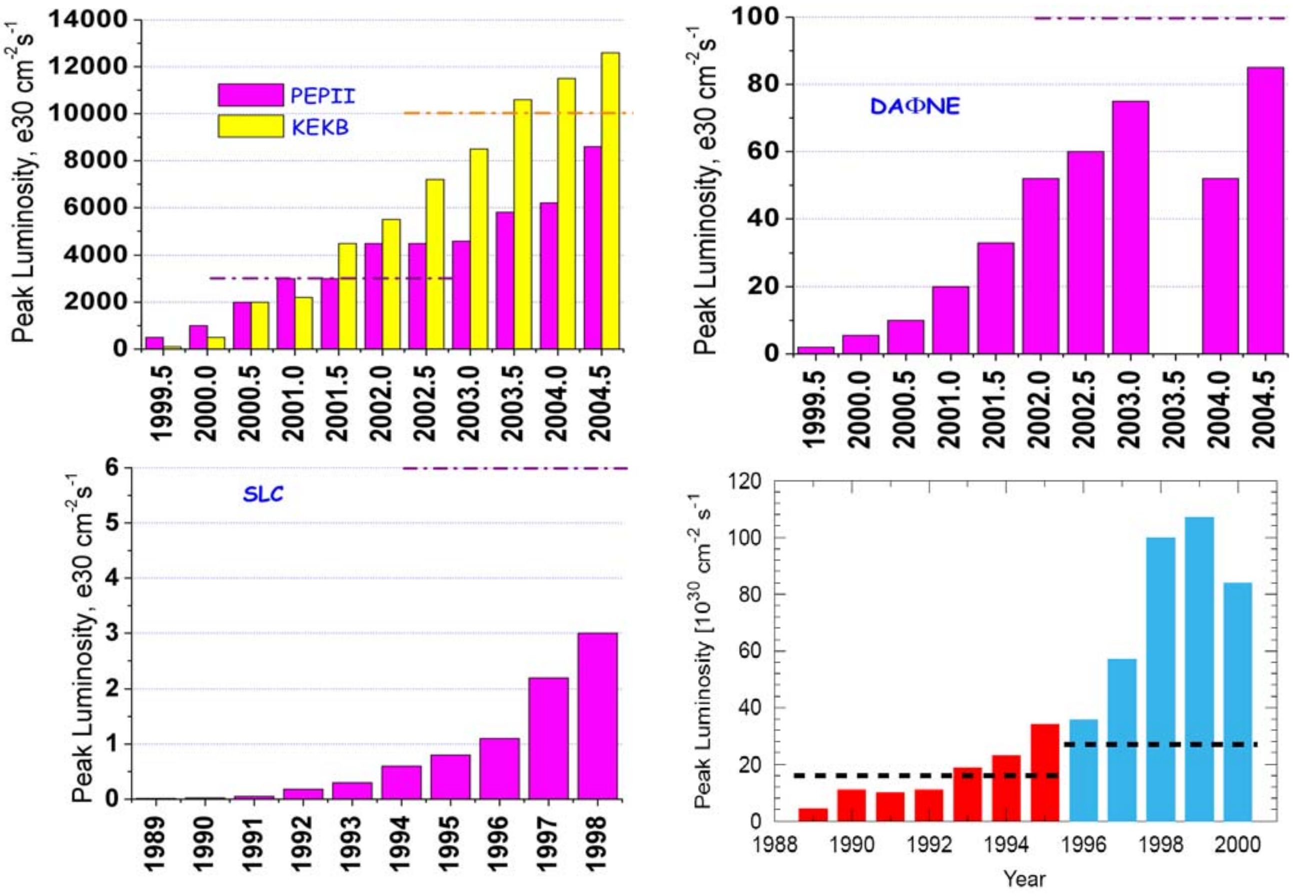

Fig.3: Luminosity of e+e- colliders: PEP-II and KEK-B, DAFNE, SLC and LEP.

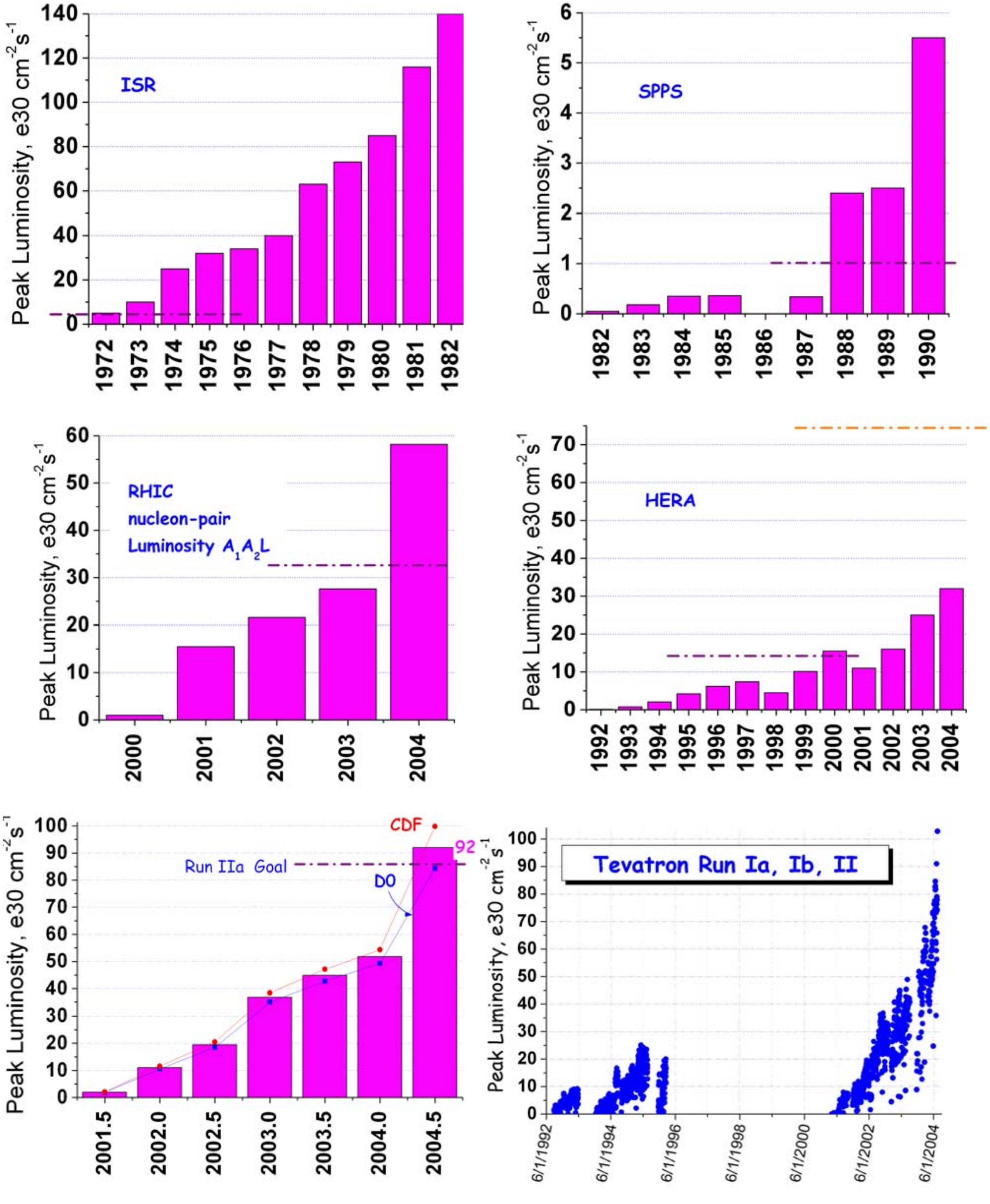

Fig.4:Luminosity of hadron colliders: CERN ISR and SppS, RHIC, HERA (e-p collider), record luminosity of the Tevatron in Run IIa and initial store luminosities in Tevatron Run Ia, Ib and IIa.

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
DAFNE	100	01/2003	3	75	5	**1.1**	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	32	5	**1.6**	3
ISR II		1982	6	140	35	**4.3**	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
RHIC	32, n-pair	2004	3	58	15	**2.2**	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. For RHIC, the nucleon- pair luminosity is cited which relates to commonly used luminosity as $A_1 A_2 L$, where A is number of nucleons per ion, e.g. A=179 for Au.

Discussion, CPT Predictions for Future Accelerators, Other CPT-like Observations

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 8 lines in the Table) of the ISR, SppS, Tevatron, HERA and RHIC is $<C>=2.4$ 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 $L \sim \gamma \frac{N_1 N_2}{\varepsilon_n}$

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.

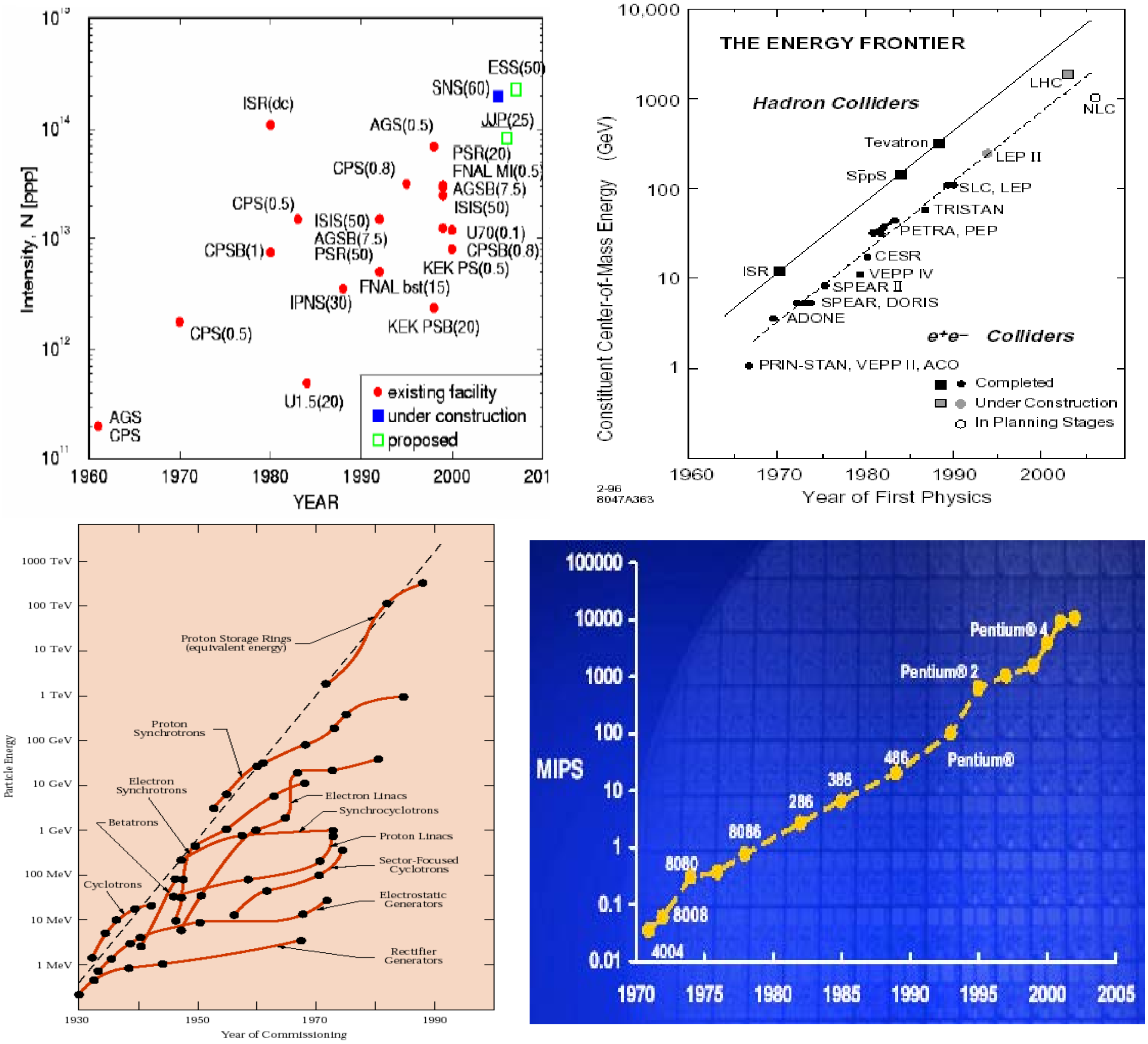

Fig.5: Exponential growth of pulse intensity in multi-GeV proton accelerators, progress in the CM energy of frontier hadron and e+e- colliders, Livingston plot (the maximum energy of different types of particle accelerators versus the year in which they reached that energy), and evolution of processor performance.

Exponential growth is characteristic to advances in other areas of science and technology. There the *CPT* analysis can be used for complexity evaluation simply by replacing luminosity as performance goal by some other parameter. That can be number of protons per pulse in high-intensity proton accelerators [13], in that case $P=ln(N_{PPP})$ – see Fig.5 (a) – and straight red line represents *CPT* with *C*=5.4. Energy evolution of energy frontier colliders [14] also demonstrated tradition of exponential growth with *C*= 5.8 (see fit lines in Fig. 5 (b)) if one takes center-of-mass energy as performance parameter $P=ln(E_{CM})$. The development of particle accelerators is another example, and complexity coefficient of that growth – presented in so-called “Livingston plot” [15], Fig.5(c) - is *C*=2.6. Note, that the Livingston plot depicts “equivalent beam energy” for colliders, which is equal to $E^2_{CM}/\ 2M_pc^2$, thus, in units of center-of-mass energy “ the Livingston plot complexity is *C*=2.6x2=5.2, i.e. not very different from those of the colliders only. One can also note, that in accordance with ideas presented above, the evolution of colliders and other accelerator technologies is exponential only up to a certain level, and beyond that the progress slows down significantly. E.g. the LHC and

NLC data points in Fig. 5(b) are significantly below the straight fit lines for existing colliders. Finally, Fig. 5 (d) illustrates the "Moore's Law" [16] of exponential growth of modern microprocessor speed and putting *P=ln(MIPS)* one gets C=2.4 (i.e., the speed doubles every 20 months).

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. It was shown that evolution curves of accelerator and microprocessor technologies demonstrate *CPT*-like dynamics as well.

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