Fermilab

Tevatron Run II: Lessons from Commissioning and Operation + Comparisons with other Colliders

Vladimir Shiltsev

Fermilab

Hardware Lessons

- “Healthy bones” is a must for Hadron Collider (magnets, RF, vacuum, injectors, etc)
- Magnets should be built, understood and controlled to 1e-4 level
- things tend to “drift away” - enthropy increases - and continuous monitoring and control is needed (alignment, for example)
- “Pay attention to details” – unfortunately, there is only **one** denominator for so many systems, subsystems and factors - luminosity

Maintenance Lessons

- In the beginning of Collider (1980's) we ran until the wheels fell off then fixed them.
- Later we built in maintenance periods and often broke the machine in the process.
- Now we follow what is referred to by industry as: Reliability-Centered Maintenance (RCM)
  - The objective of maintenance is to preserve the item's function(s).
  - RCM focuses on the end system (accelerator - for us)
  - Reliability is the basis for decisions.

Beam Diagnostics Lessons

- Due to peculiarities of SC synchrotron operation, non-invasive beam diagnostic instruments should be preferred, effects of intrinsically invasive ones minimized (FW 33→7um)
- Having two or more instruments for same beam parameter measurements (makes life more complicated to bring them together but) makes the data more trustworthy
- Fast data collection rate (at least 1 sec for all channels) is a must – at all stages, for all bunches, all the time – and saved for years (for postmortem)
- Detectors have tons of beam diagnostics, so good communication channels with them are important

Beam Diagnostics Lessons (2)

- Accept help/ideas from other groups/labs – many of them have invaluable expertise:
- An instrument development is fast, compared to time needed to make it "fully operational" and satisfactory for operators and physicists – a lot of efforts went into that →
- Team up diagnostics developers and users from the very beginning till commissioning of the instruments (and even beyond that – in operation)

Beam Physics Lessons

- When all hardware problems resolved and machines run - solving a deep beam physics problem is often the only way to push collider performance further
- Some beam physics issues can be solved with existing tools:
  - "shot lattice", helices, slip-stacking, new WPs

  While others require new developments:
  - electron cooling, electron lenses
- It takes a great deal of patience to go thru R&D, beam studies and implementation in Collider operation
- Though collider improvements more obvious, progress in the injector chain propagates thru, too

Five Other Lessons

Colliders Do Work!

"Never, never, never give up!"

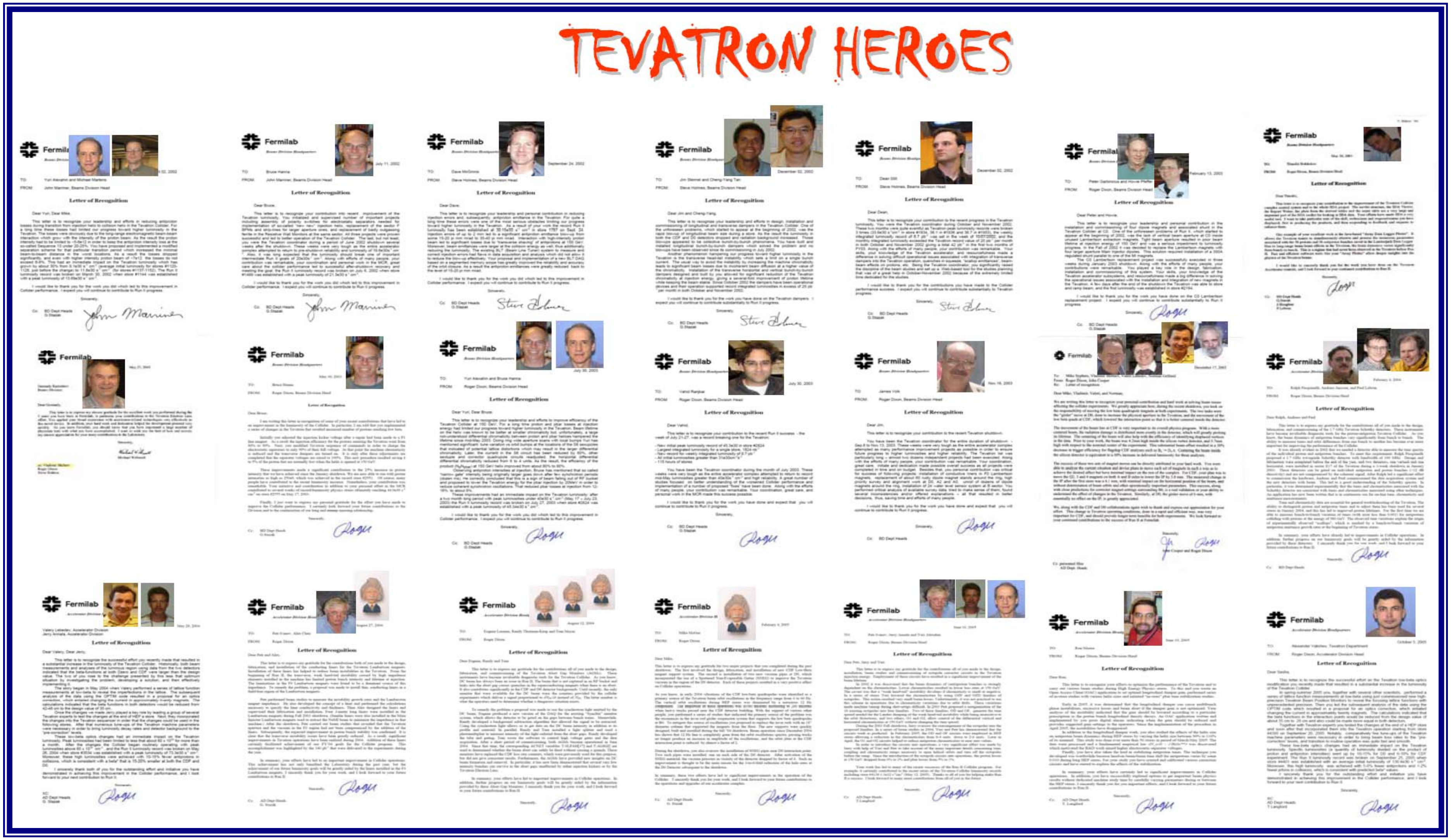
Winston Churchill

Keep team morale high

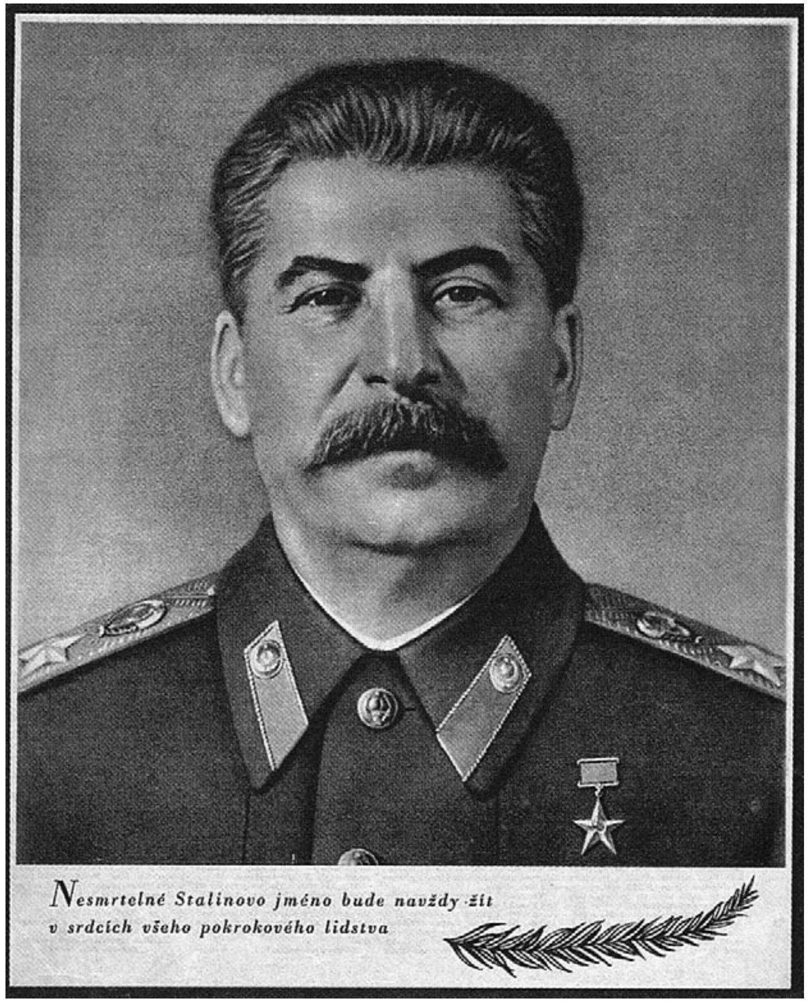
"Usually, it's soldiers who win battles and generals who get the credit…"

Napoleon Bonaparte

E.g. Such a Wall Poster



No scapegoats! We're all in the same boat!!



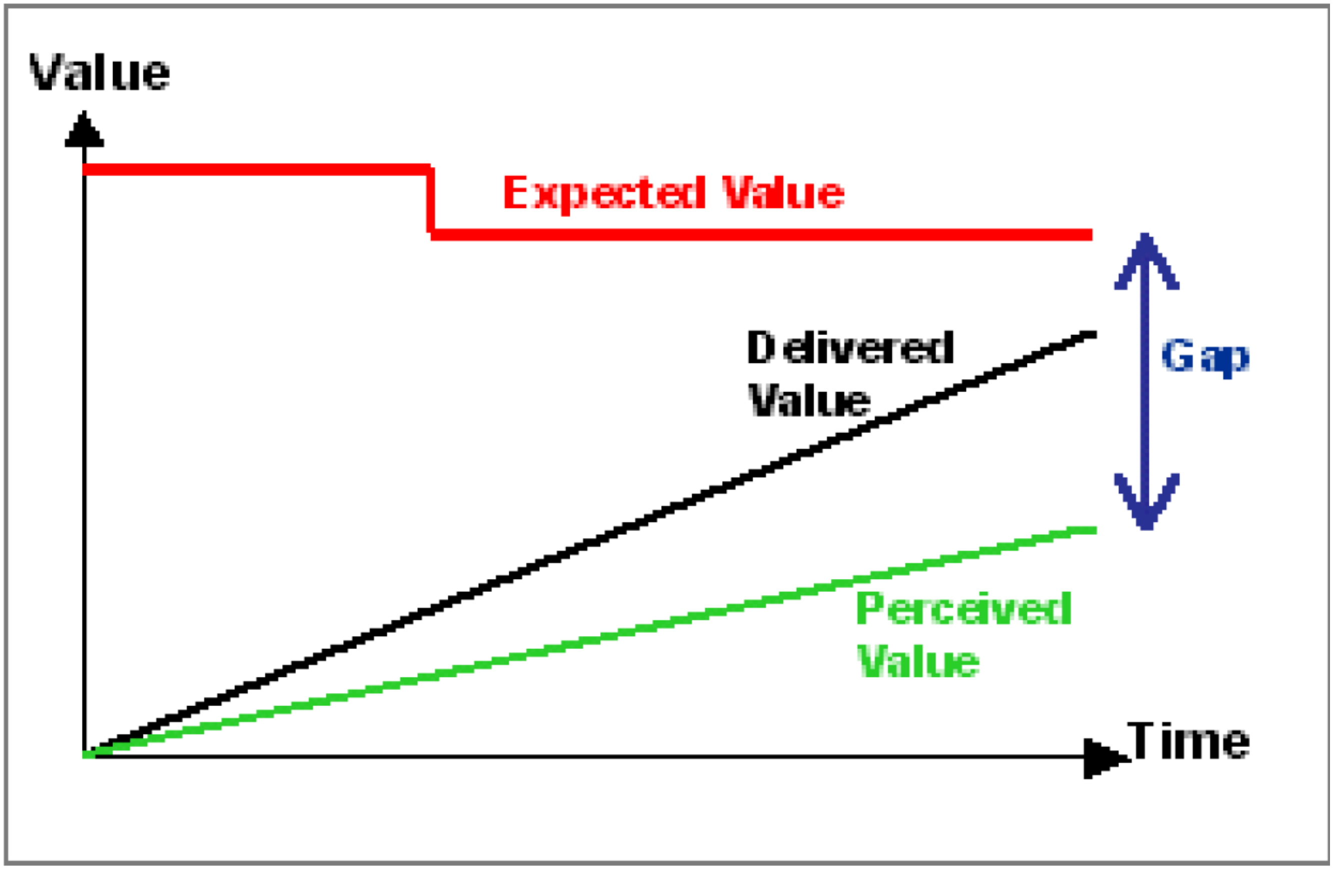
"That's the only writers I have, there are no other writers…"
Joseph Stalin when asked whether Soviet writers deserve to be punished

Colliders Are Complex: Prepare for Unexpected

"In principle, war is
simple business...
but fighting is tricky"

Carl von Clausewitz "On a War"

Manage Expectations (Yours and Others)



" Expectations are a primary measure of your success"

Any management textbook

The talk on "the art of collider commissioning" is over...

Let's talk about "Science" of collider commissionig

Slide from Lecture 1: What we thought in '96

Recycler TDR
FNAL TM-1991

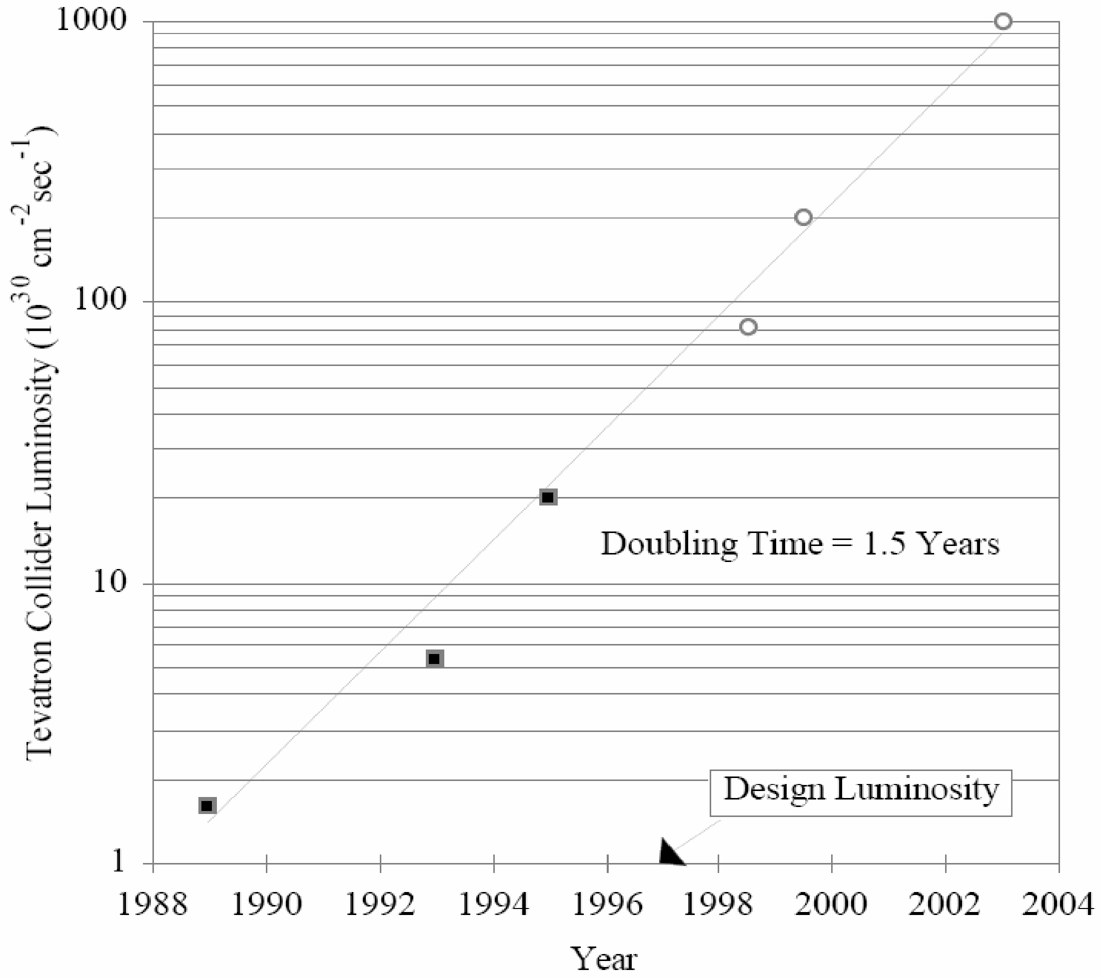
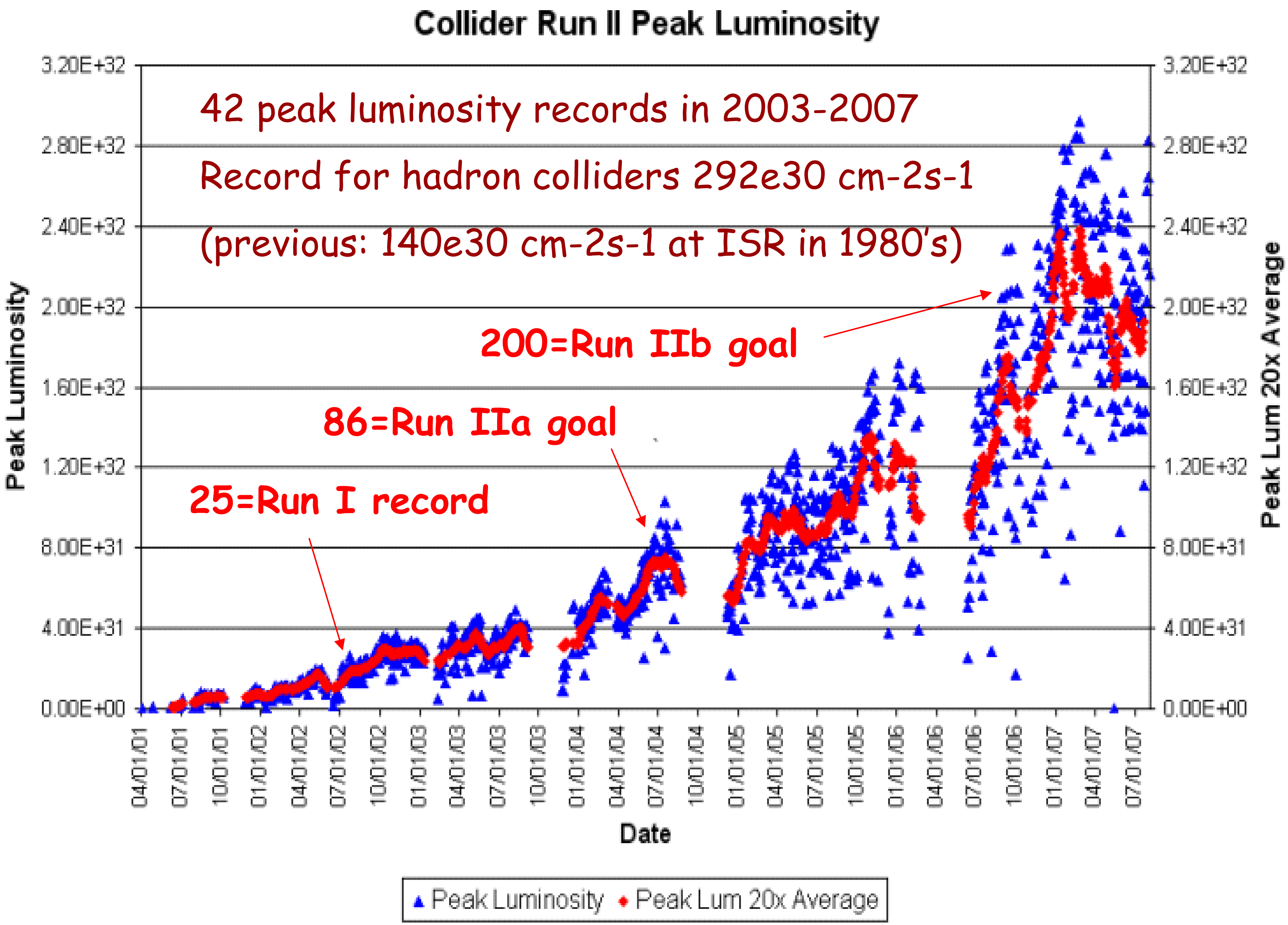


Figure 1.1: Tevatron Collider luminosity as a function of time. The filled circles are measured "best typical" peak luminosities, the line is an exponential fit to the data, and the open points represent goals for the future.



Collider Run II Peak Luminosity
42 peak luminosity records in 2003-2007
Record for hadron colliders 292e30 cm-2s-1
(previous: 140e30 cm-2s-1 at ISR in 1980's)
200=Run IIb goal
86=Run IIa goal
25=Run I record
Peak Luminosity
Peak Lum 20x Average
Date
3.20E+32
2.80E+32
2.40E+32
2.00E+32
1.60E+32
1.20E+32
8.00E+31
4.00E+31
0.00E+00
04/01/01
07/01/01
10/01/01
01/01/02
04/01/02
07/01/02
10/01/02
01/01/03
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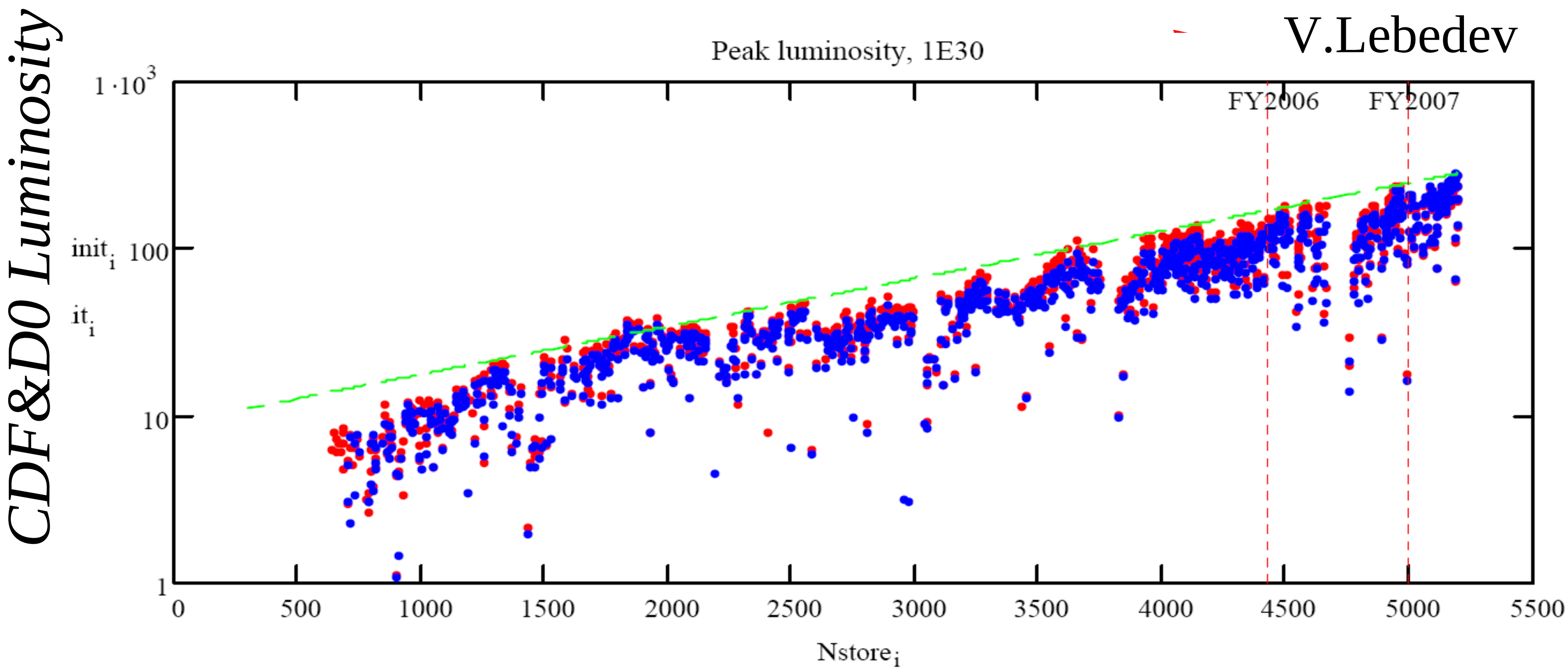
10/01/06
01/01/07
04/01/07
07/01/07
Peak Luminosity
Peak Lum 20x Average

Tevatron Luminosity Growth *log-lin*

Luminosity doubles every 1050 stores (~1 year and 4 month)

e-growth time ~ 2 years



Luminosity Progress Steps

1.	Optics AA->MI lines fixed	Dec'01	~25 %
2.	DC beam cleaned by TEL-1	Feb'02	uptime
3.	New LB squeeze helix	Mar'02	~40 %
4.	"New-new" injection helix	May'02	~15 %
5.	AA Shot lattice vs IBS	July'02	~40 %
6.	Tev BLT/inst.dampers at injection	Sep'02	~10 %
7.	Pbar coalescing improved in MI	Oct'02	~5 %
8.	C0 Lambertsons Removed	Feb'03	~15 %
9.	S6 cuircuit tuned/SEMs removed	June'03	~10 %
10.	"5 star" helix on ramp	Aug'03	~2 %
11.	Reshimming/Alignment	Nov'03	~12 %
12.	Longer Stores/ MI dampers	Feb'04	~19 %
13.	2.5MHz AA→MI trnsf/Cool shots	April'04	~8 %
14.	Reduction of beta* to 35 cm	May'04	~26 %
15.	Shots from Recycler	July'04	~18%

Luminosity Progress: More Steps

16. Slip Stacking in MI	Mar'05	~20%
17. Tev Octupoles at 150 GeV	April'05	~5%
18. Reduction of beta* to 28 cm	Sep'05	~10 %
19. RR Electron Cooling operational	2006	~30%
20. Pbar production task force	Feb'06	~10 %
21. Tev 150 GeV helix→ more p's	June'06	~10 %
22. Tev collision helix → lifetime	July'06	~15 %
23. New RR WP →emittances	Sep'06	~25 %
24. Fast AA→RR trsfers (60→15min)	End'06	~15%
25. New Pbar target/higher gradient	Jan'07	~10%
26. Accumulator stack-tail gain correct	Spring'07	~12%
27. Tevatron sextupoles for new WP	(ongoing)	~10?%

Tevatron Lesson (Yet Another):

#1: there was no "silver bullet" which would bring to the goal

#2: 27 steps resulted in ~30-fold increase in luminosity

#3: that makes an average ~12.5% increase per step

$$Gain\ after\ 8\ steps\ (1+0.125)^8 \approx e$$

$$Gain\ after\ 16\ steps\ (1+0.125)^{16} \approx e^2$$

$$Gain\ after\ N\ steps\ (1+0.125)^N \approx e^{N/8}$$

Some Conclusions:

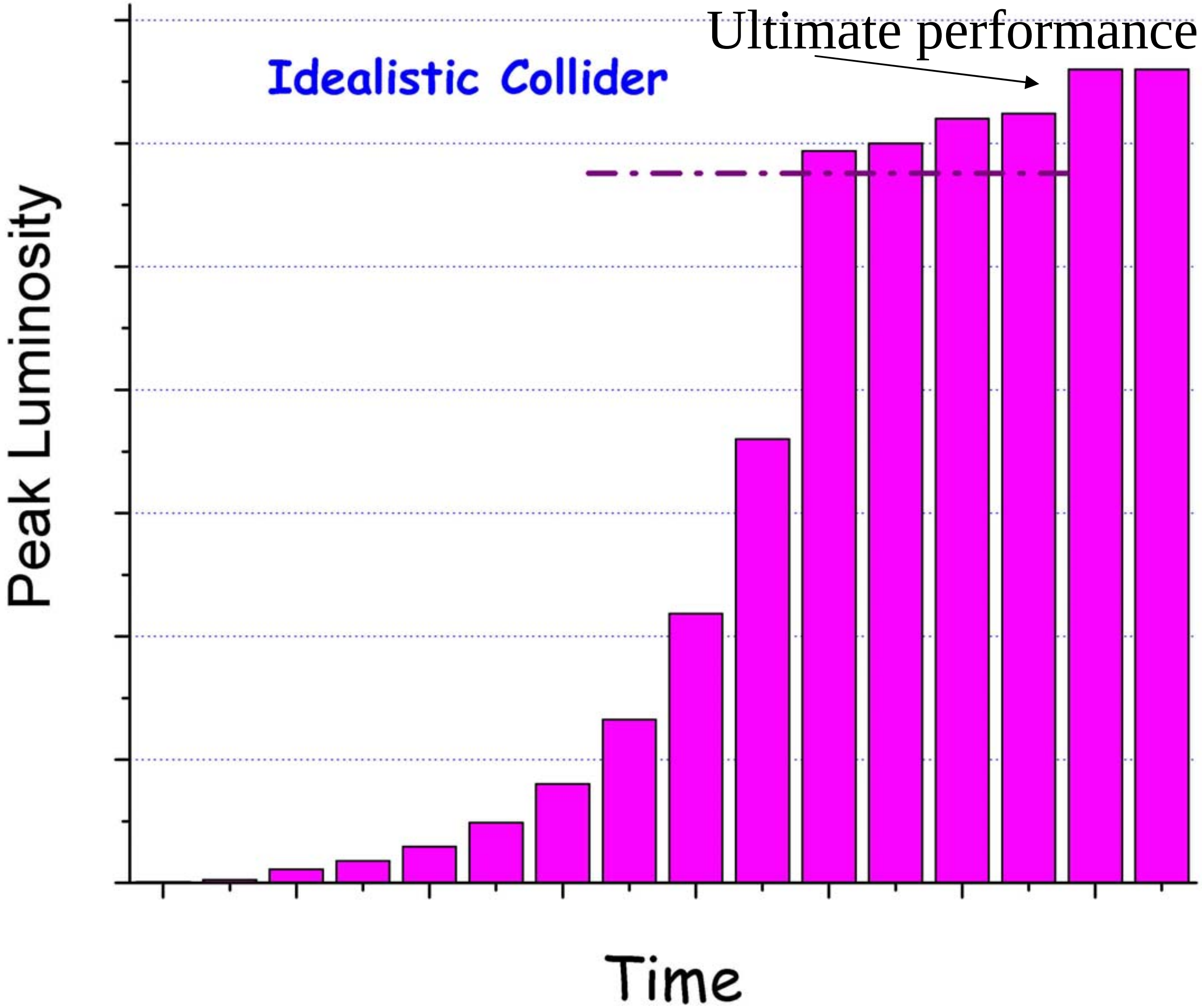
a) Larger steps (12.5%) the better

b) More possibilities (N) addressed the better

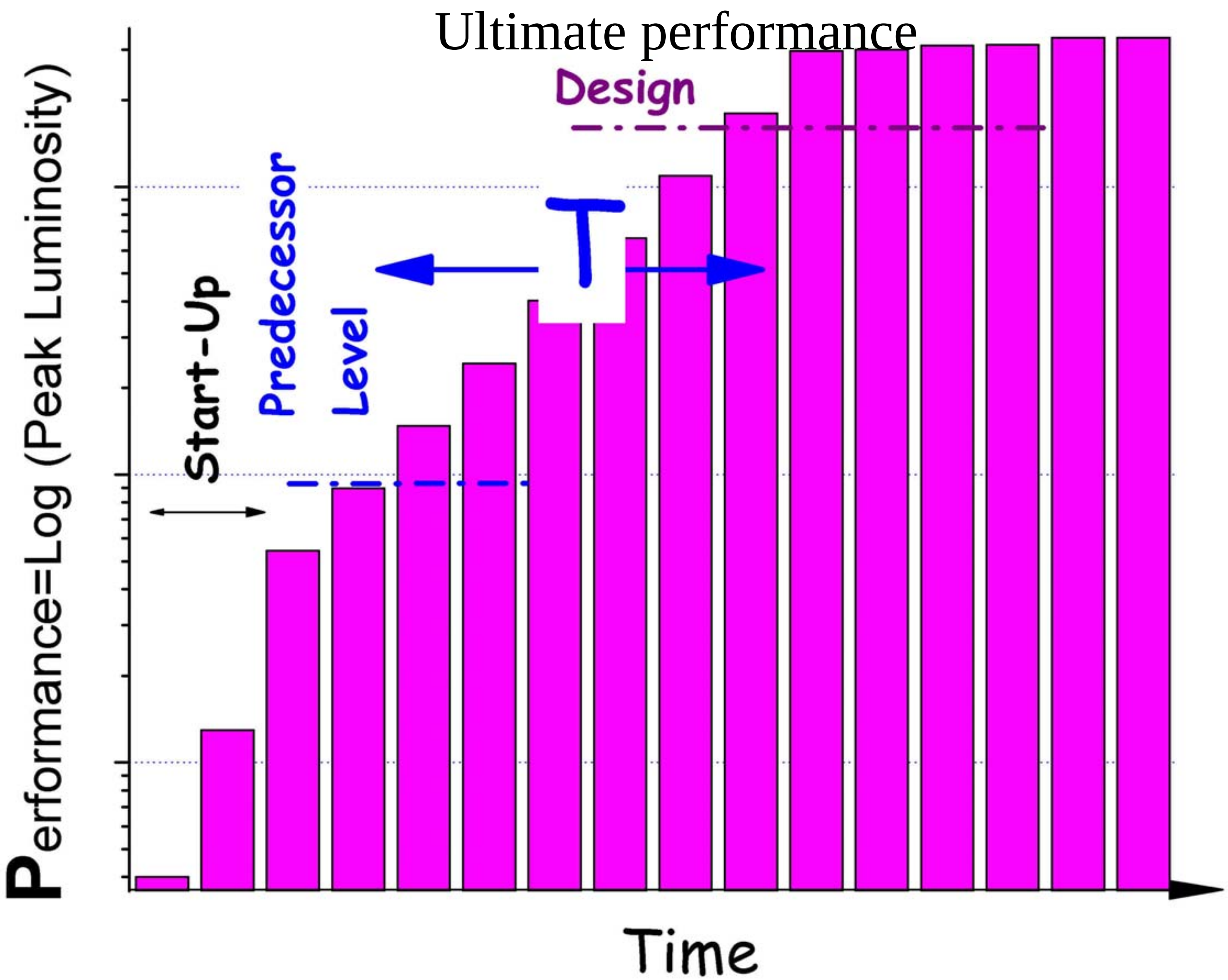
c) Faster the team addresses them the better

d) a) and b) depend on complexity of the machine and quality of the team which runs it

Idealized Case of "Small Steps" Evolution



Luminosity - Idealized Case



CPT Theorem for Accelerators

$$C \times P = T$$

C = Complexity of the machine

P = Performance (or Challenge)

= Ln(*Lumi Increase Ratio*)

T = Time to reach *P*

CPT Luminosity Evolution

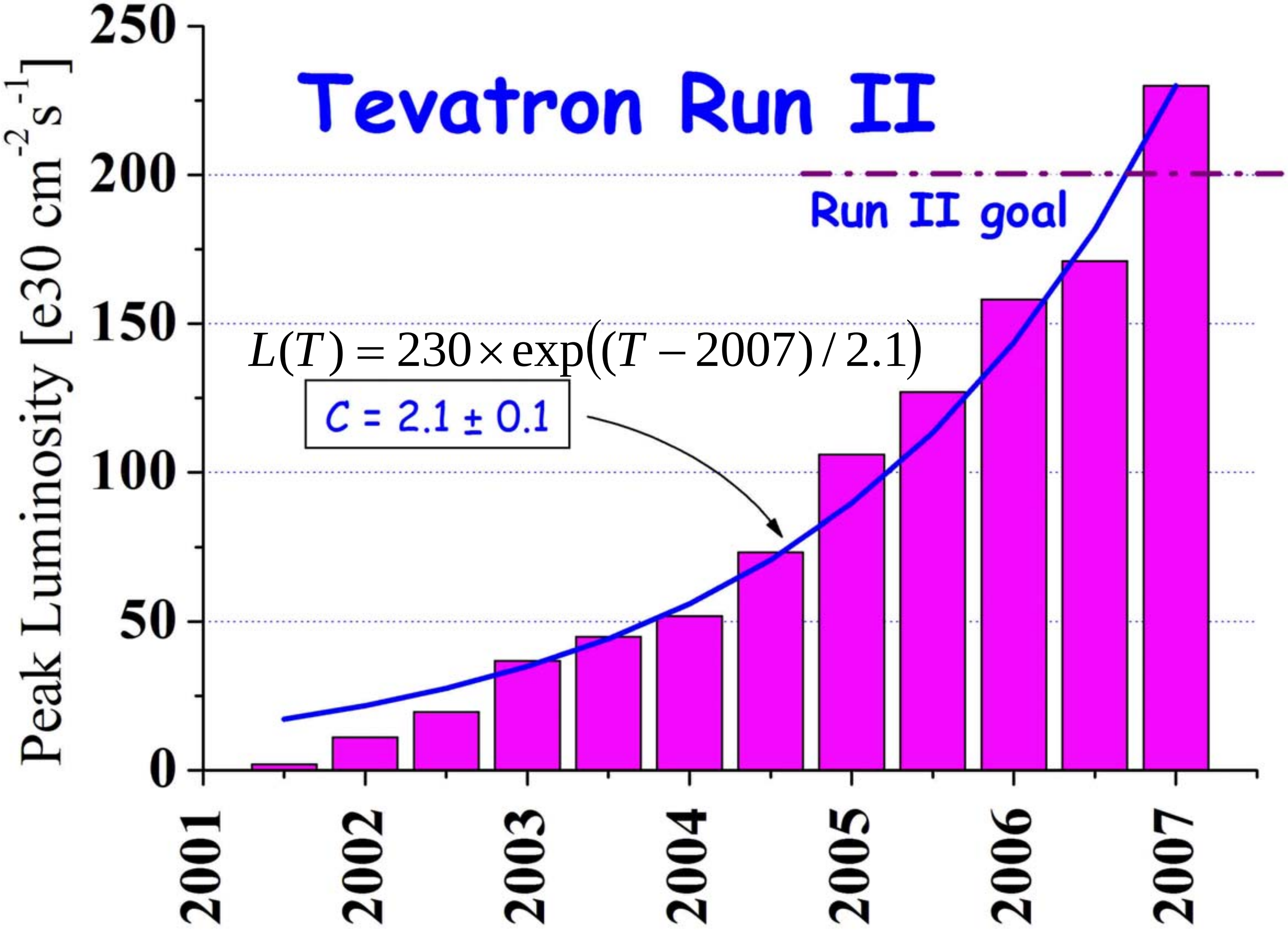
$$L = \gamma f_0 \frac{N_b N_p^2}{4\pi\beta^* \varepsilon_n} \times F(geometry)$$

..so, one starts with some initial luminosity L_0, improves all the factors (Np, Nb, beta*, F(…), emittance) in small steps and – over years of progress - gets:

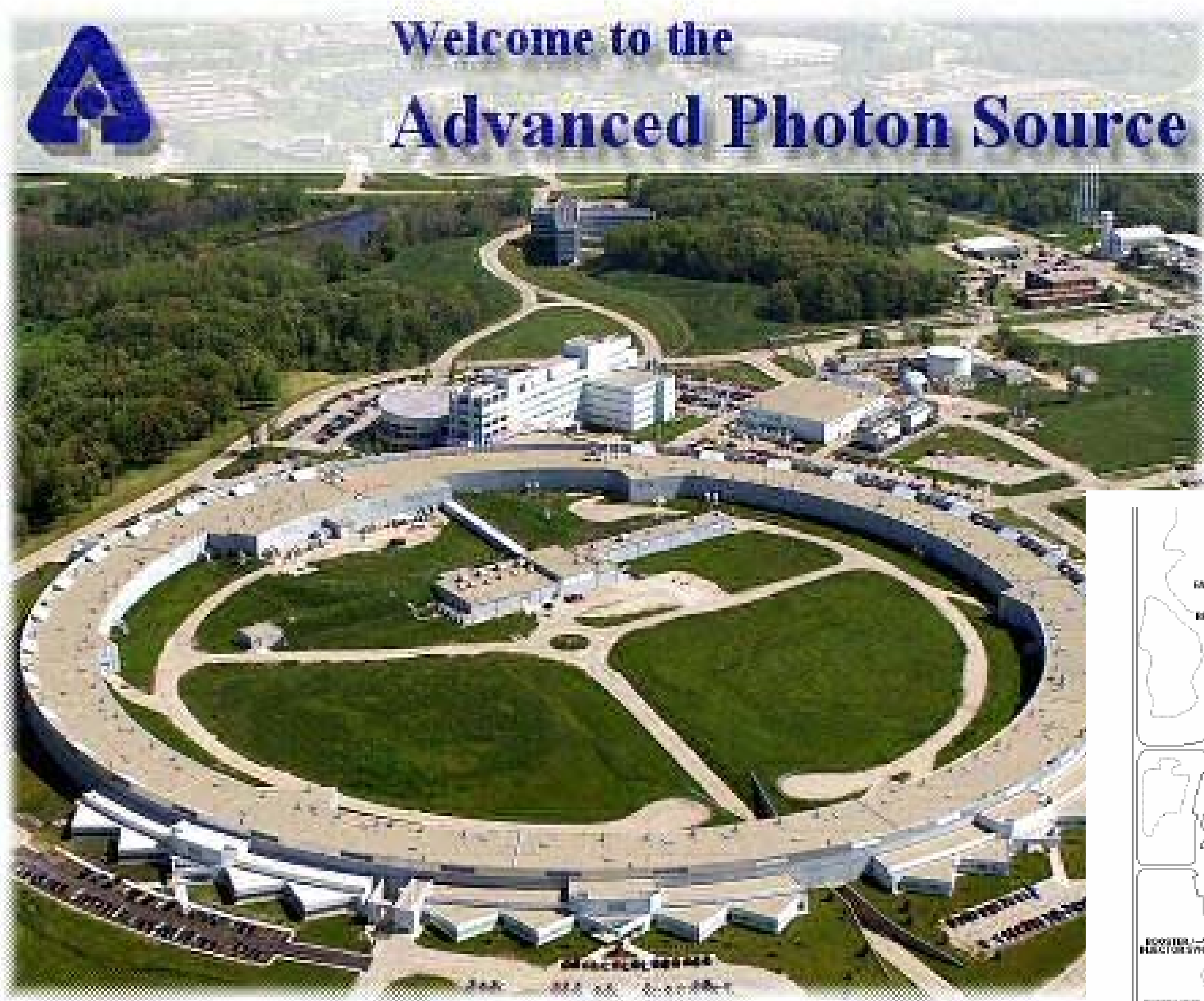
$$L(after\ \ time\, T) = L_0 \times \exp(T / C)$$

C (Complexity)=Time[years] to *e*-fold

Tevatron Run II Luminosity Evolution



"Not Very Complex Machine"



Complexity=low (0-0.5)

Constructed ahead of schedule and within budget (400M$)

<u>9 mos</u> of commissioning

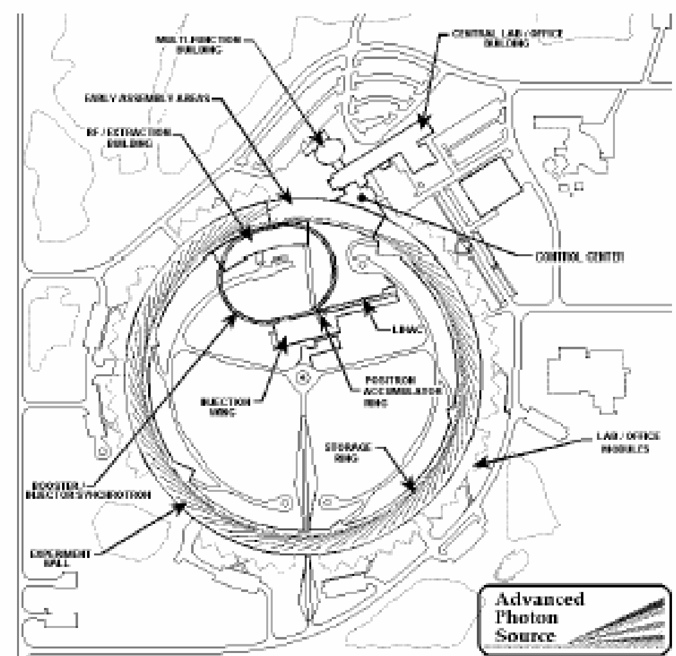


Figure 1: APS Site.

Another "Not Very Complex Machine"…

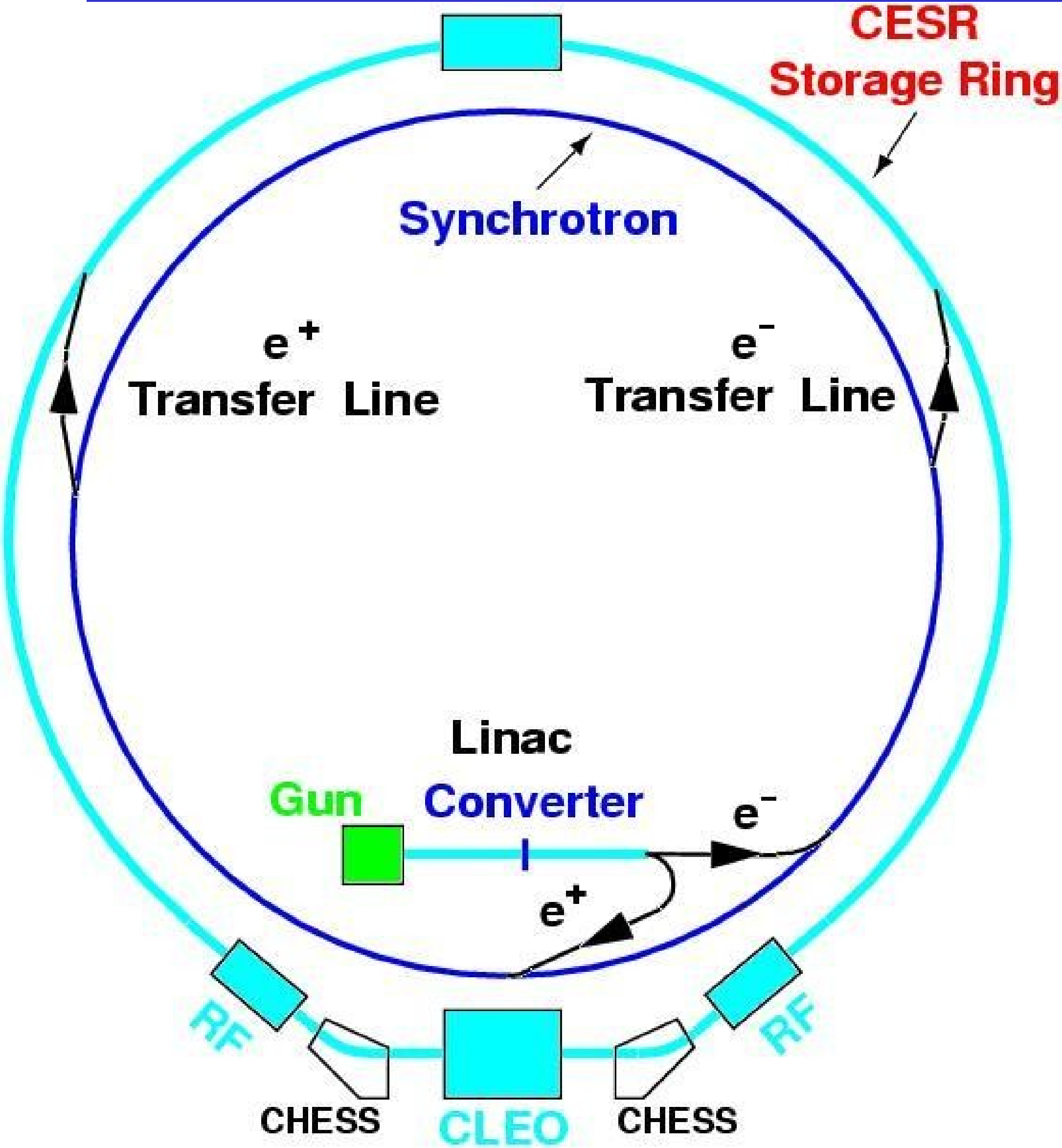
Fermilab Main Injector

Complexity=low (0-0.5)

Constructied on schedule within budget (200M$)

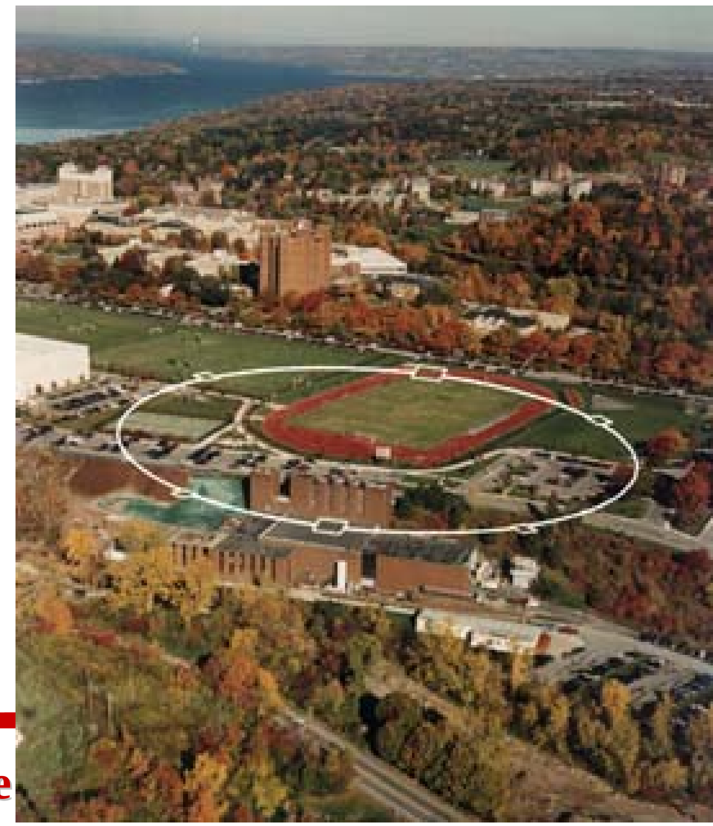
<u>6 months</u> of commissioning

Cornell Electron Storage Ring

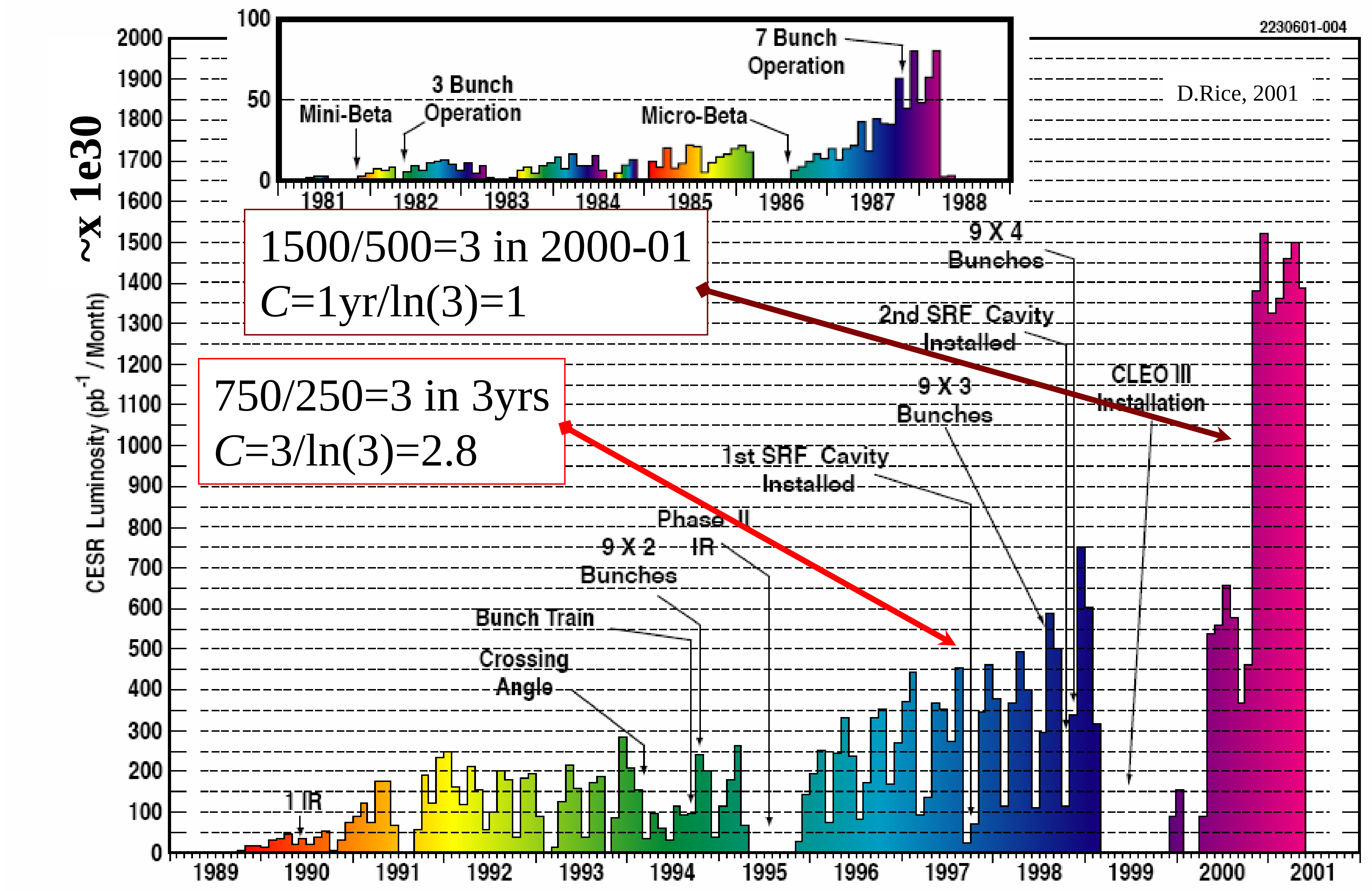


3.5-12 GeV com e+e- collider

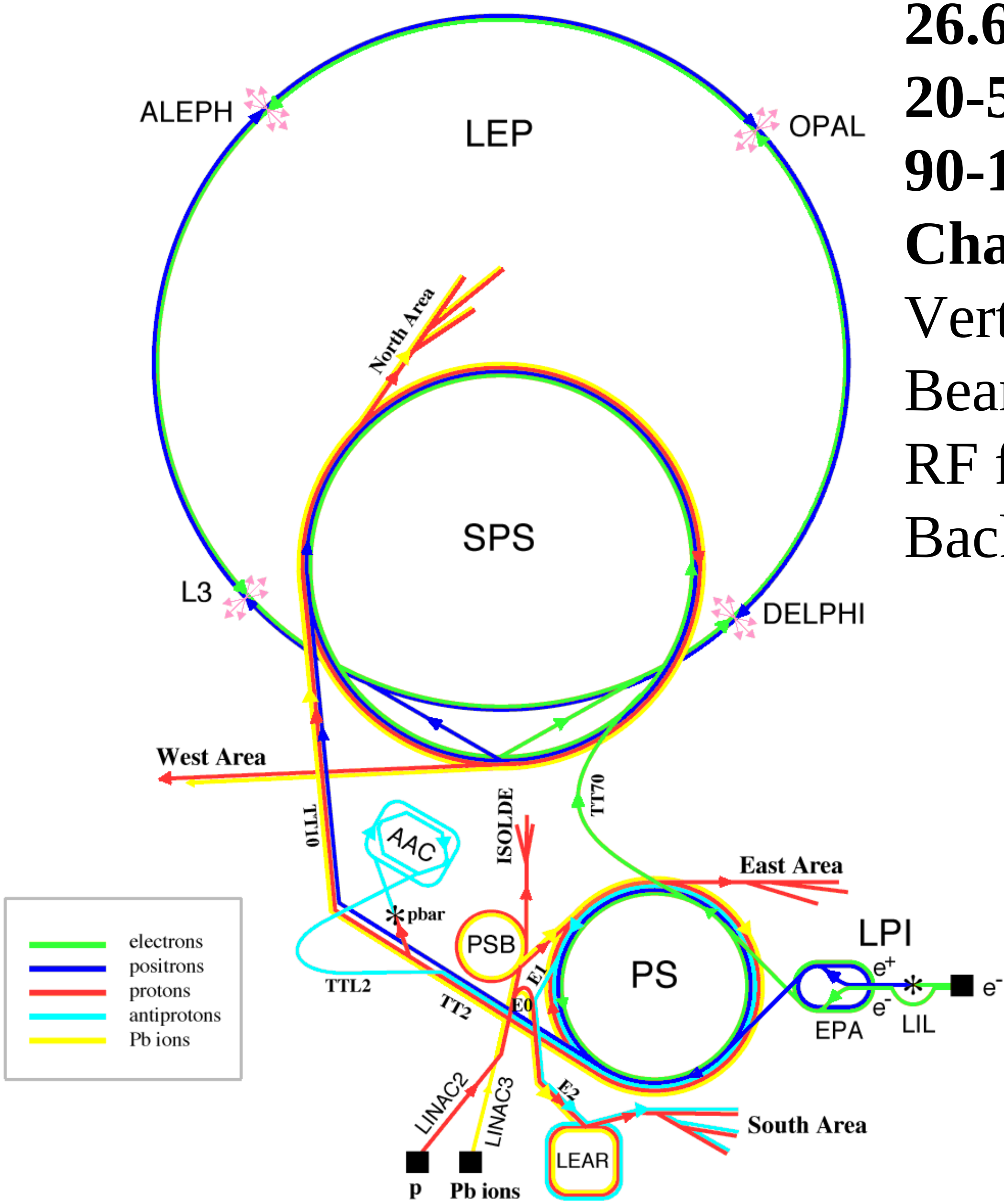
Challenge: e+ e- collider where a lot of new ideas were tested to keep up with the race for luminosity



Luminosity - CESR



LEP: Large Electron Positron e+e- collider



26.67 km

20-50GeV (LEP1)

90-105GeV (LEP2)

Challenges:

Vert.emittance (steering, drifts)

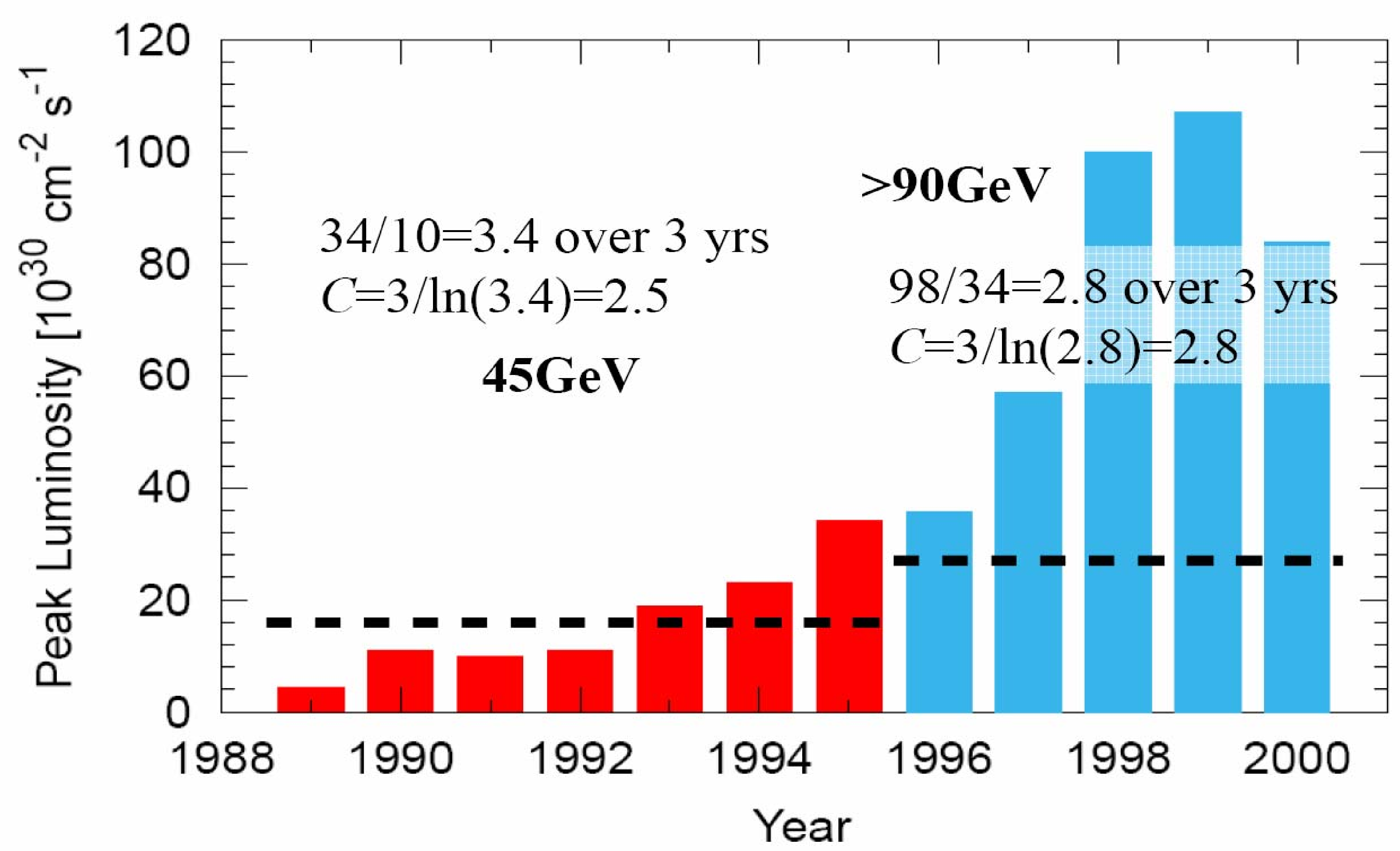
Beam-beam effects

RF for high Energy

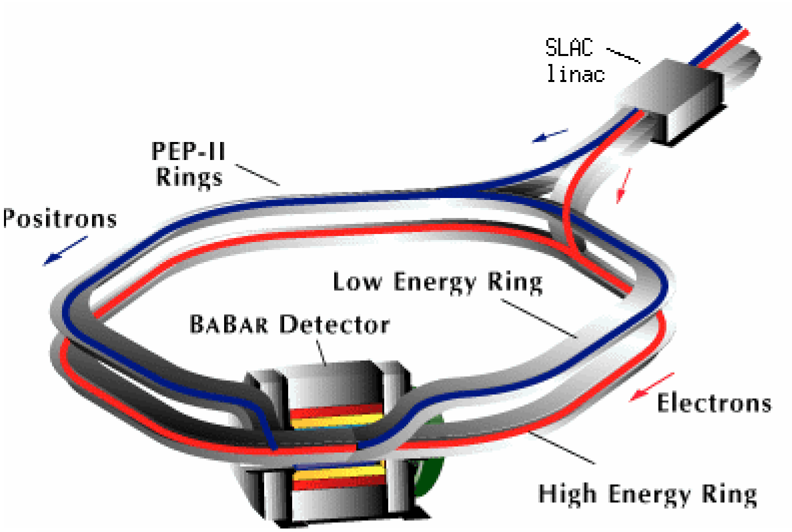
Background

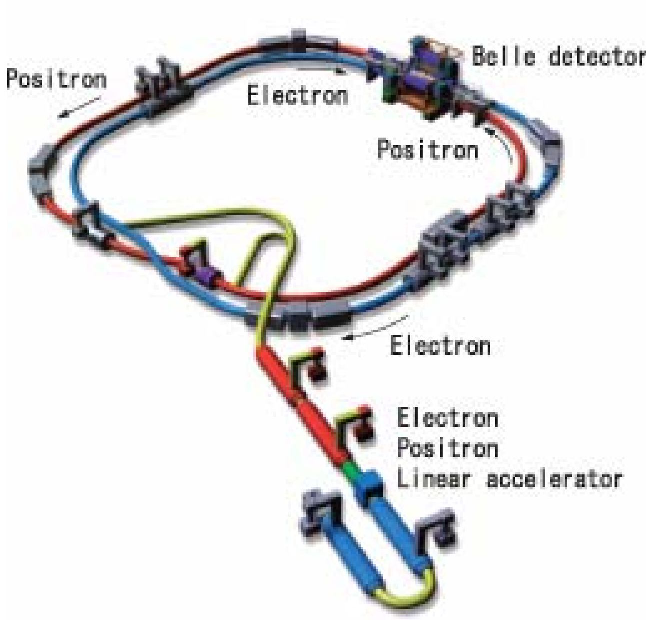
Luminosity – LEP: design 16/27e30

R.Assmann, APAC'2001



e+e- Colliders: B-factories





2.2 km

9GeV(e-)+3.1GeV(e+) (PEP-II)

8GeV(e-)+3.5GeV(e+) (KEK-B)

Challenges:

Asymmetric colliders

Electron ion instability

Electron cloud instability

Vert.emittance (steering, drifts)

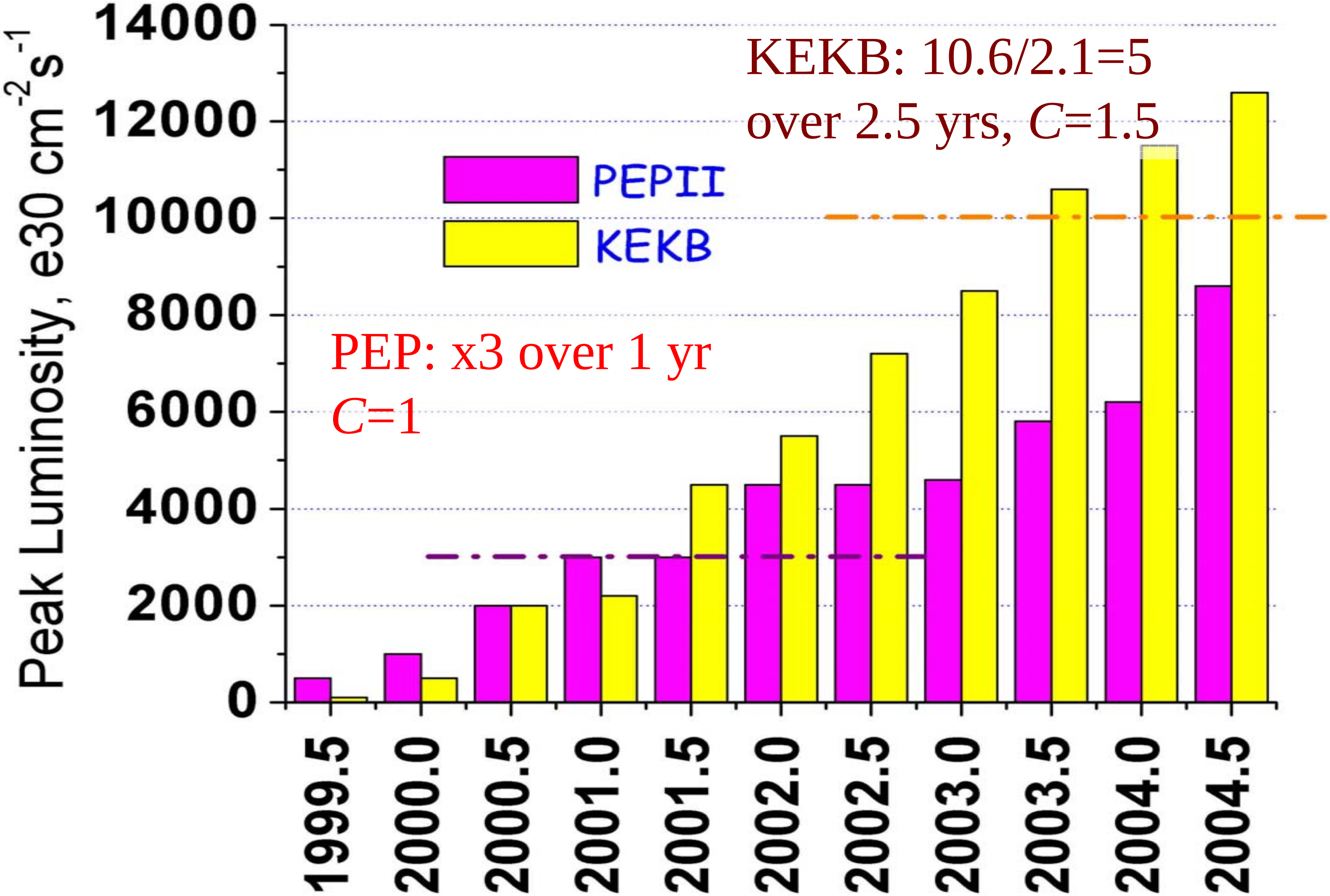
Beam-beam effects

Crossing angle

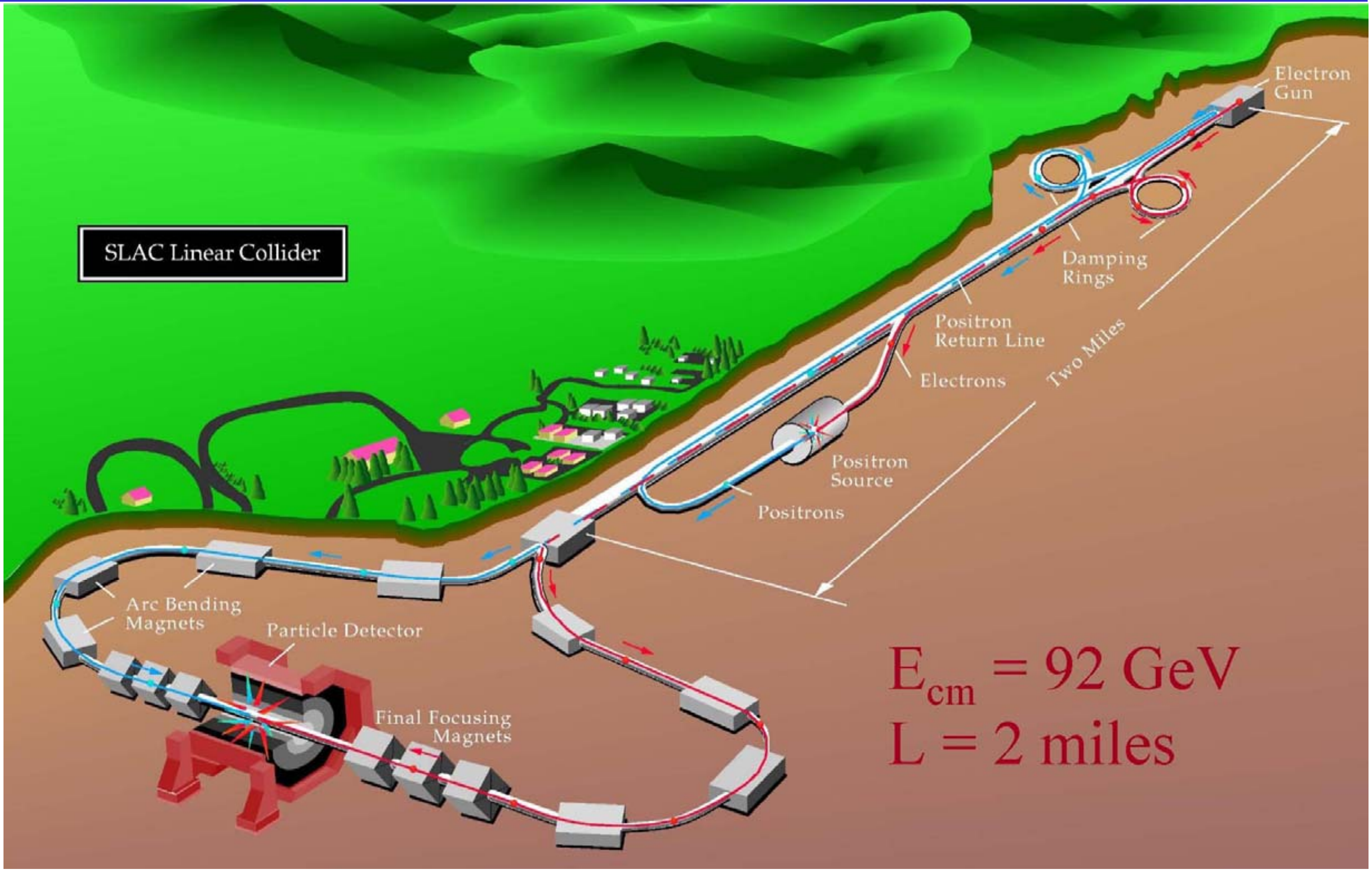
Crab-cavities

Background in detectors

PEP-II/KEK-B: design 3/10e33

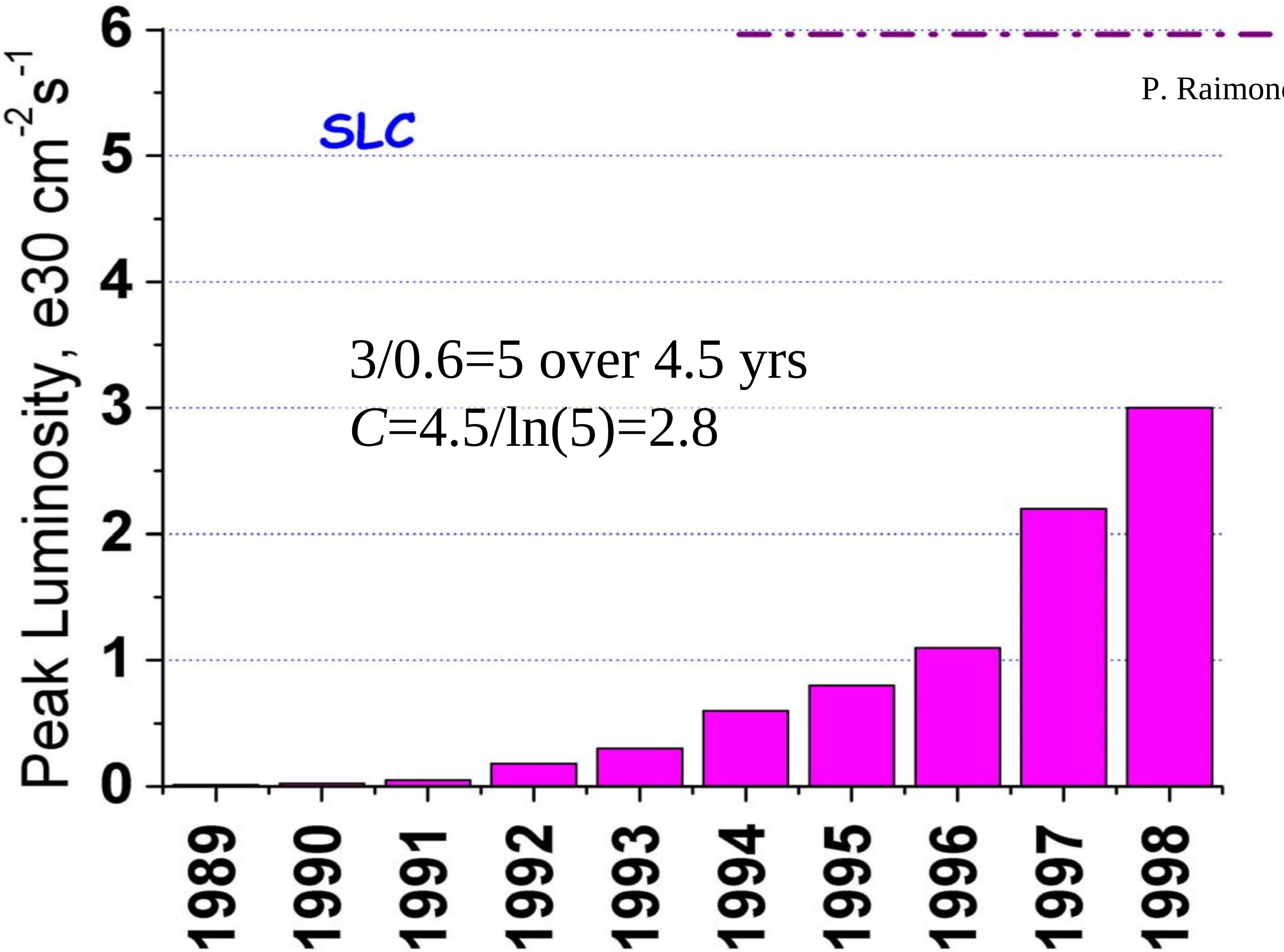


SLAC Linear Collider



Challenges: First in class, vert.emittance, arcs, FF, etc

Luminosity – SLC: design 6e30

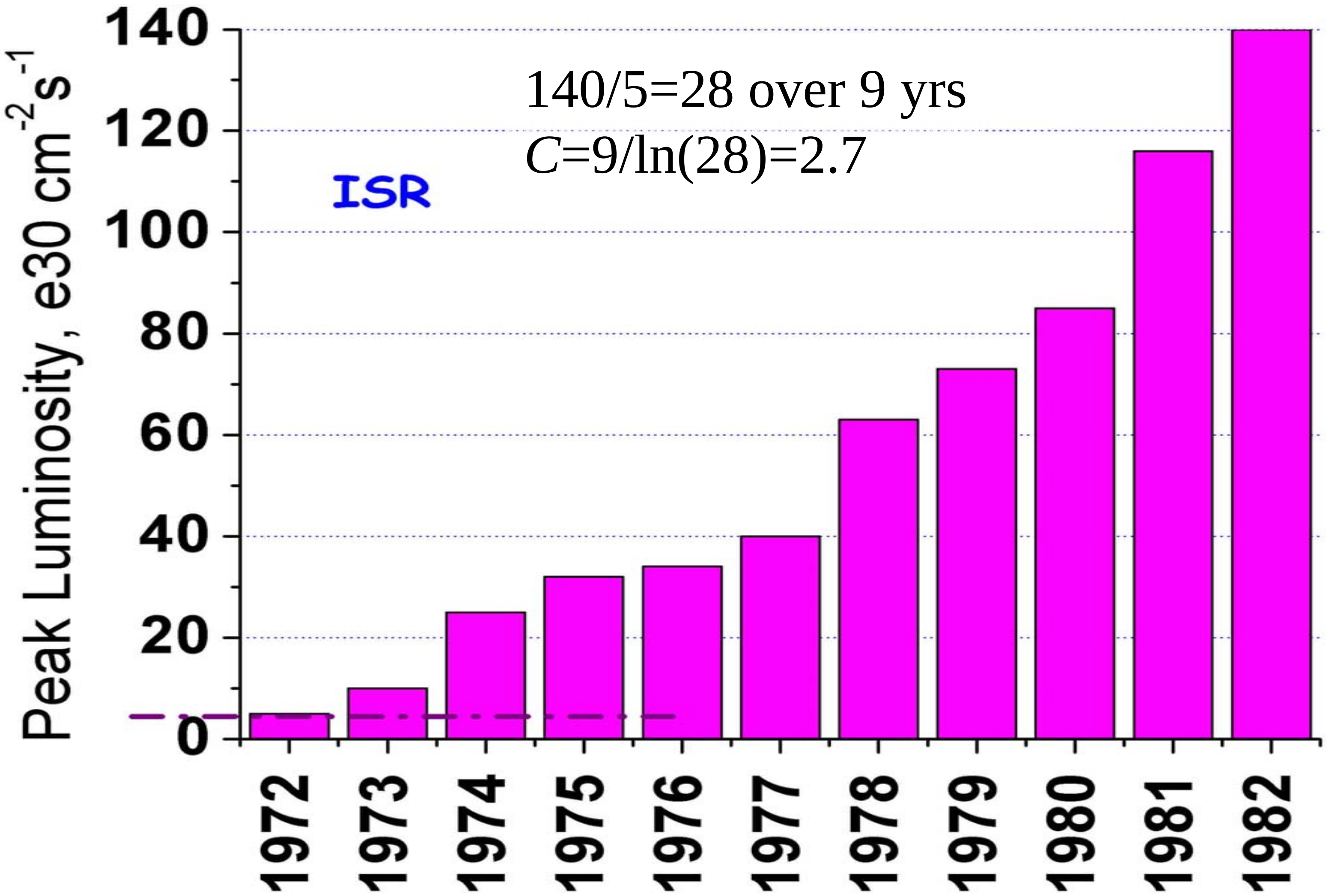


P. Raimondi, PAC'1999

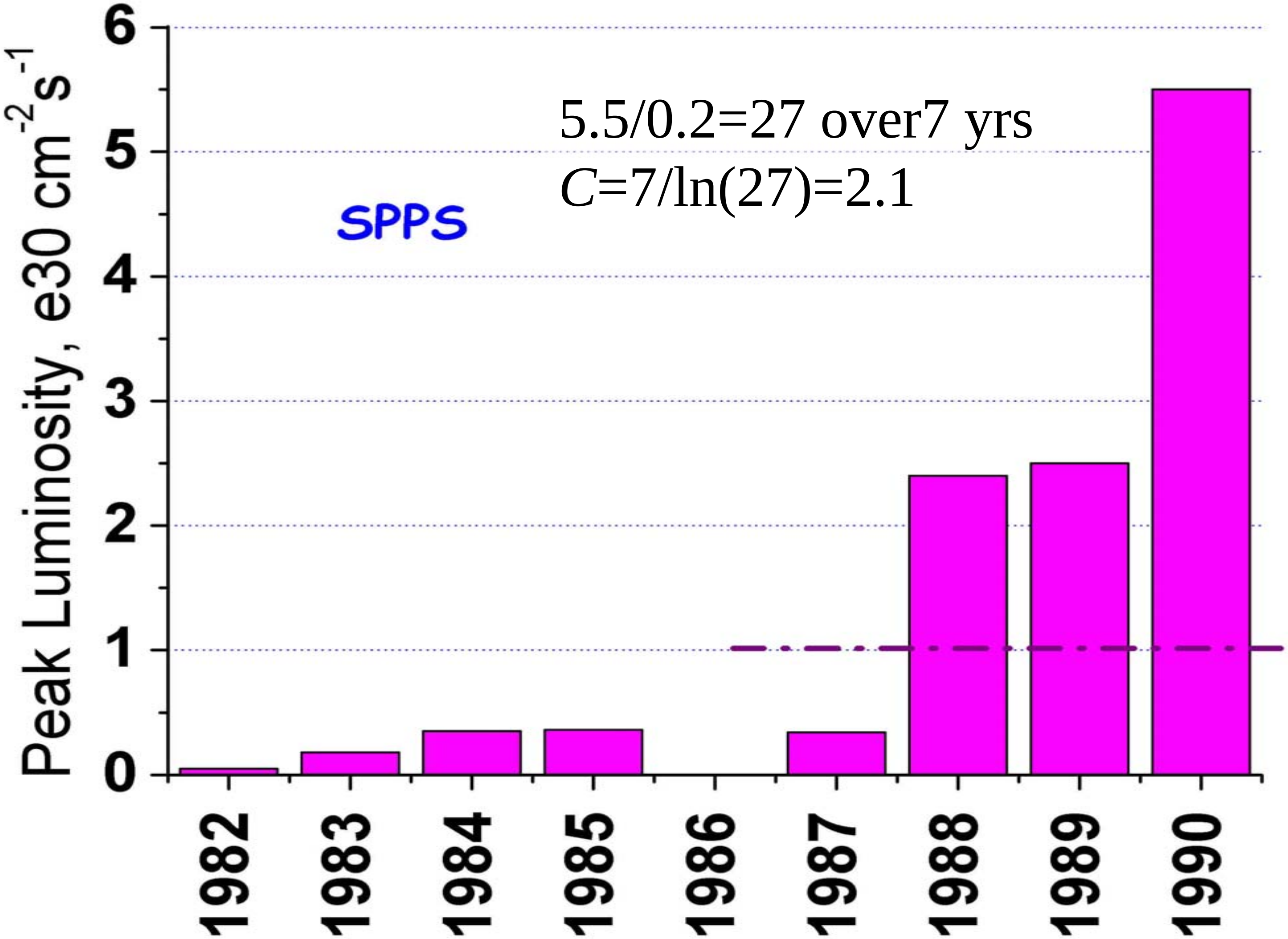
3/0.6=5 over 4.5 yrs

C=4.5/ln(5)=2.8

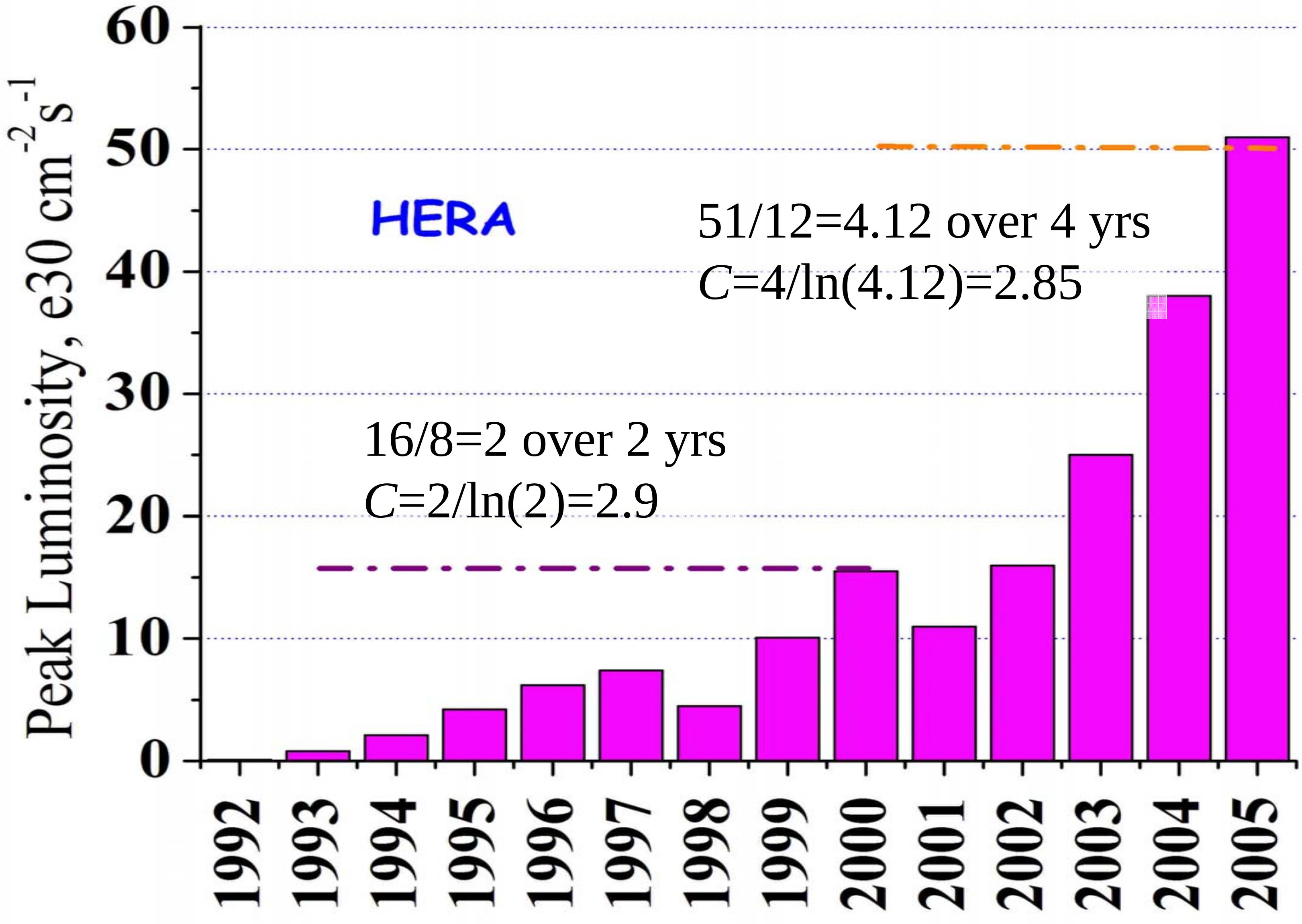
Luminosity – ISR: design 5e30



Luminosity - SppS: design 1e30



Luminosity – HERA: design 15e30 →50

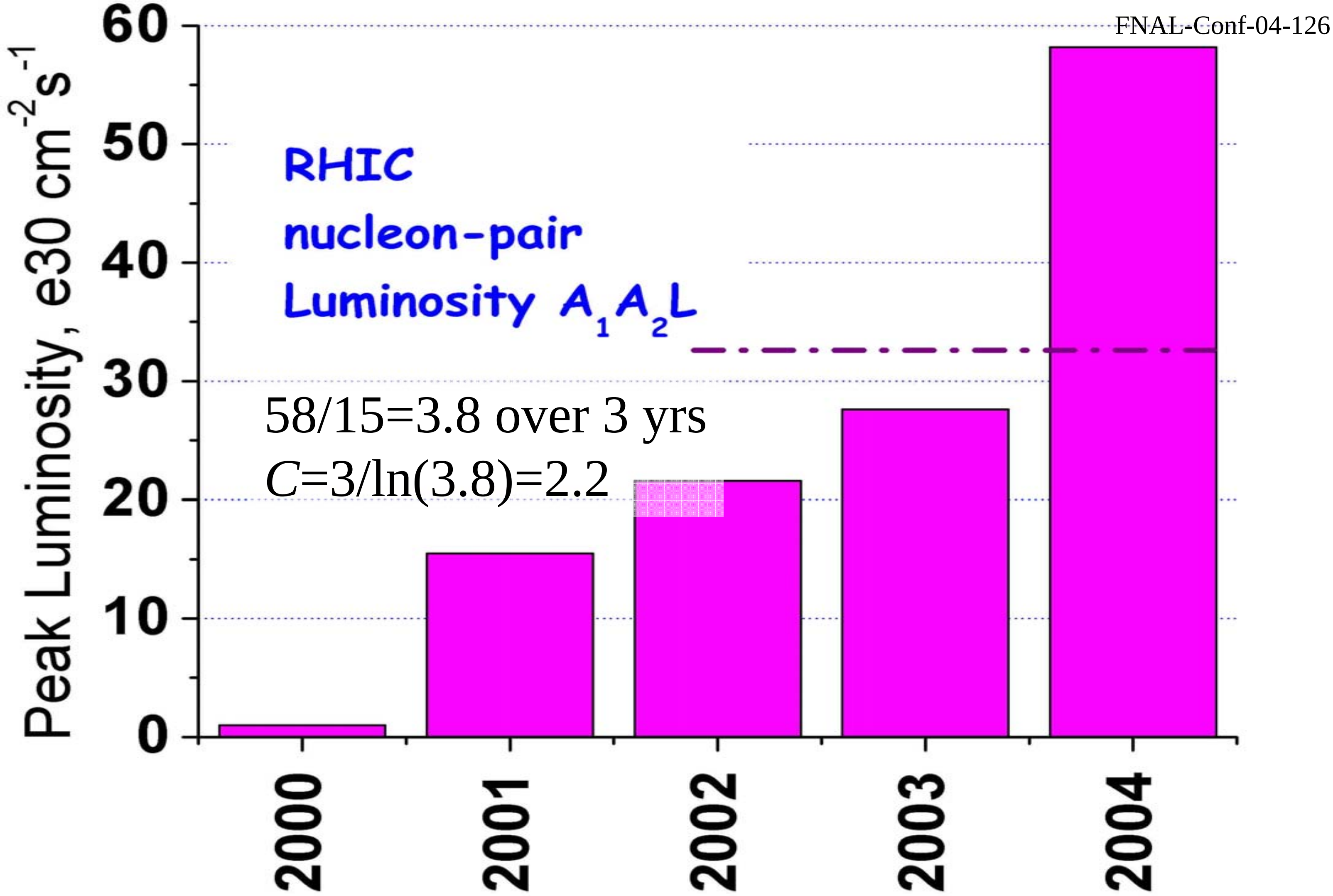


Relativistic Heavy Ion Collider

- 2 superconducting rings
- 3.8 km length
- operation since 2000
- 5 experiments so far

- only operating ion collider
  (up to gold 100 GeV/nucleon)
- only operating polarized
  proton collider

Luminosity – RHIC: design 33e30

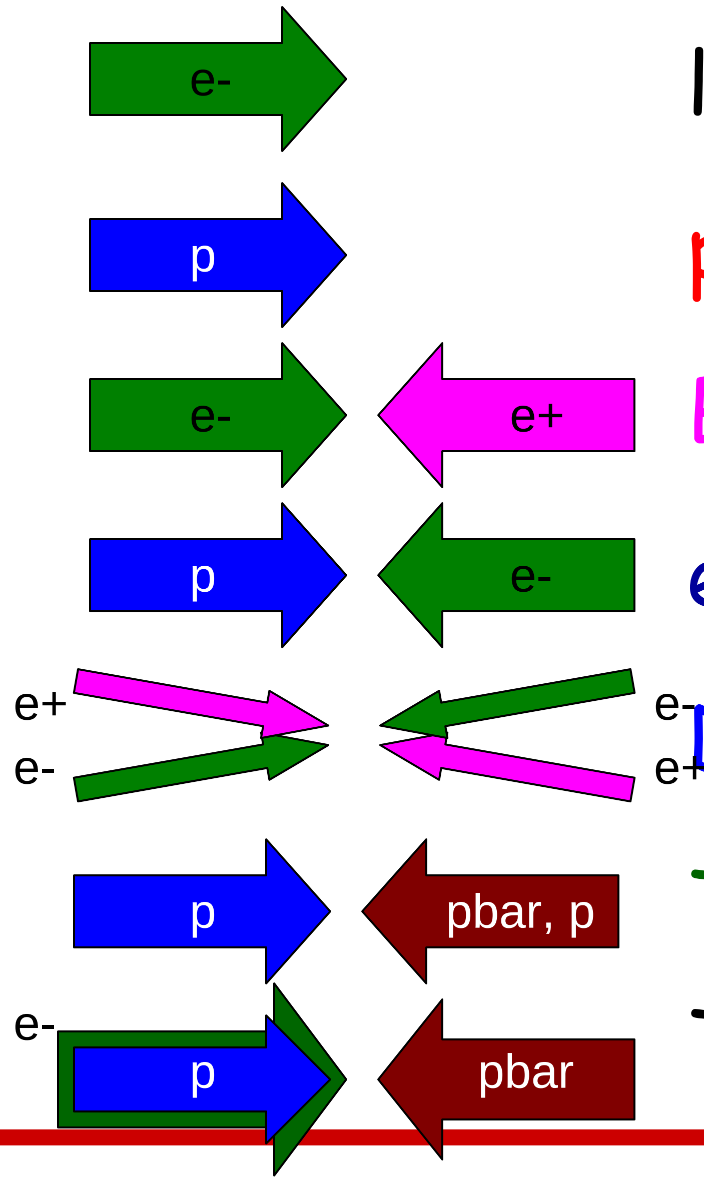


Machine Complexity Table

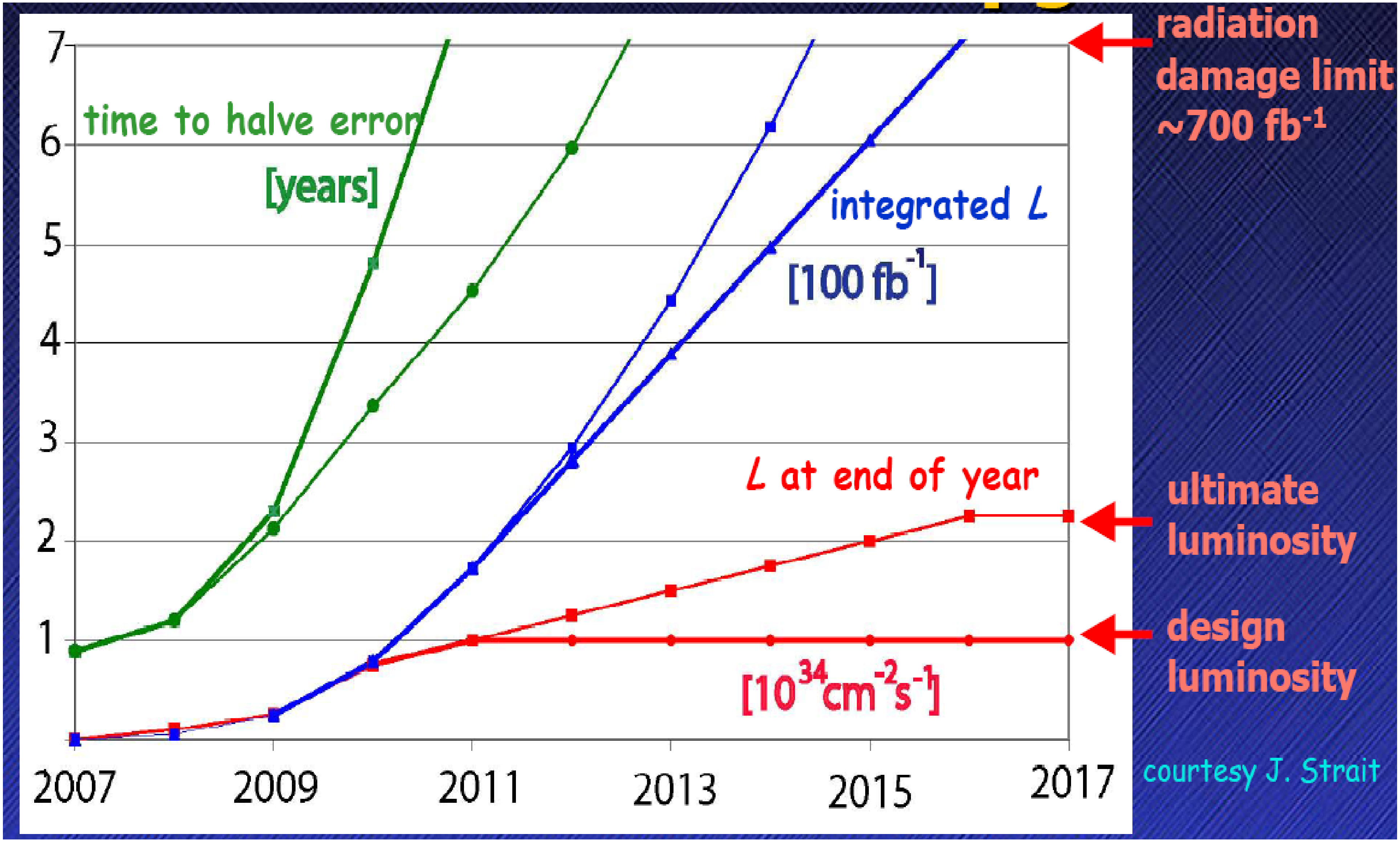
Machine	Design L	T_f	dT, yr	L_f	L_i	C	Ce
APS (ANL)			0.5			0	0
MI (FNAL)			0.6			0	0
CESR, 1986-88 Run		01/1988	1	83	20	0.7	1
1990-92 Run		03/1992	1.33	250	50	0.8	1
1996-99 Run		02/1999	3	750	250	2.7	1
2000-01 Run		06/2001	1	1500	550	1.0	1
PEP-II 1999-2001	3000	01/2001	1.5	300	3000	0.7	1
2002-04	3000	06/2004	1.5	8200	4400	2.4	1
KEK-B	10000	06/2003	2.5	10400	2000	1.5	1
DAFNE	100	01/2005	5	143	5	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	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	07/2005	4.5	51	11	2.9	2
Tevatron Run Ib	15	09/1995	0.8	25	10	0.9	2
Run IIa	200	11/2006	4.0	232	25	2.1	2
RHIC	32, n-pair	2004	3	58	15	2.2	2

Complexity of Beams in *log*-Scale (TV tube=0)

Complexity 0.5	light sources
Complexity 1	p-synchrotron
Complexity 1	B-factories
Complexity 1.5	eCool, HERA
Complexity 2	DCI-Orsay,'80
Complexity 2	Tevatron,LHC
Complexity 2.5	Tev+elens BBC



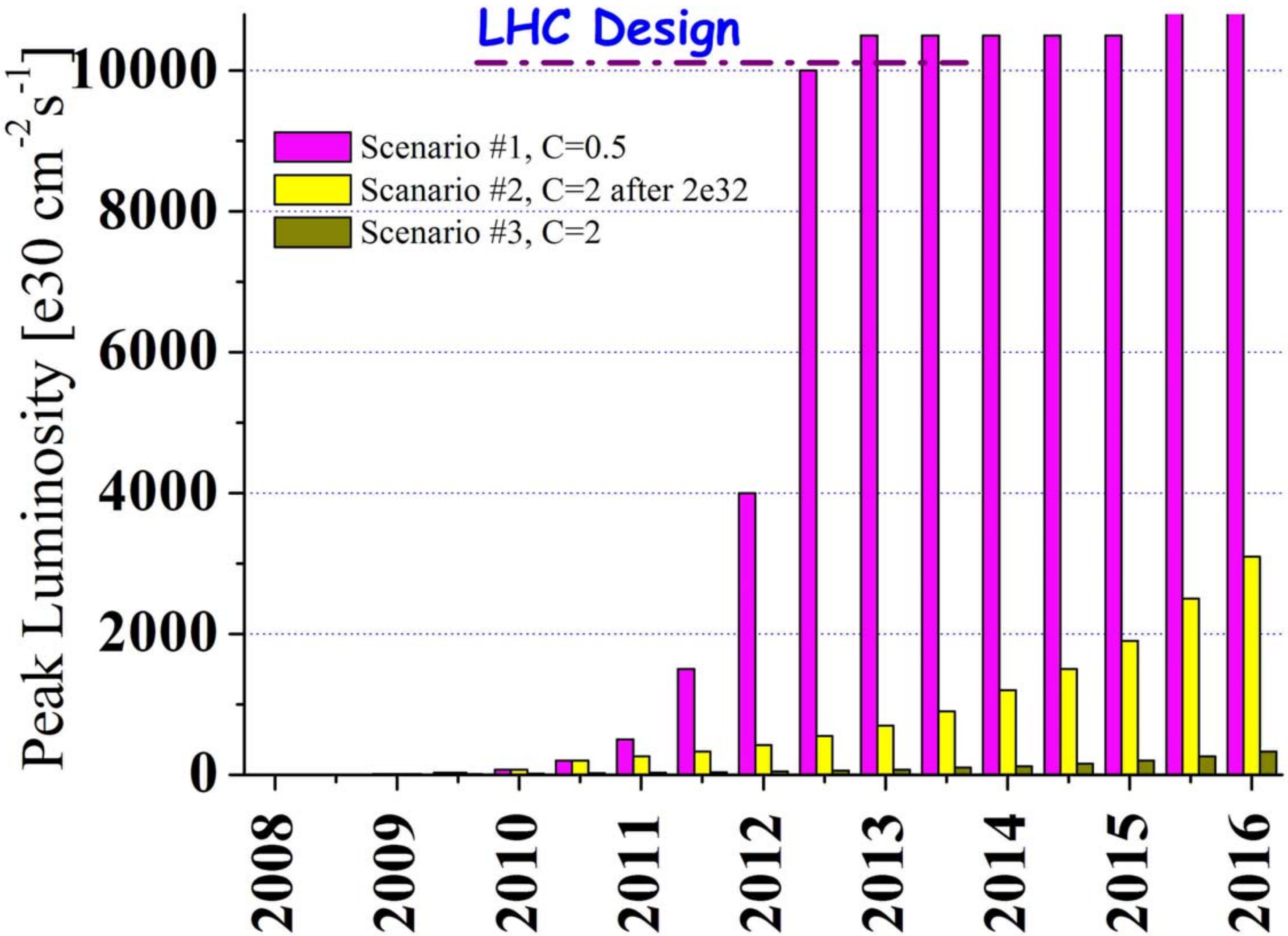
LHC Luminosity Outlook: 2003 Vision



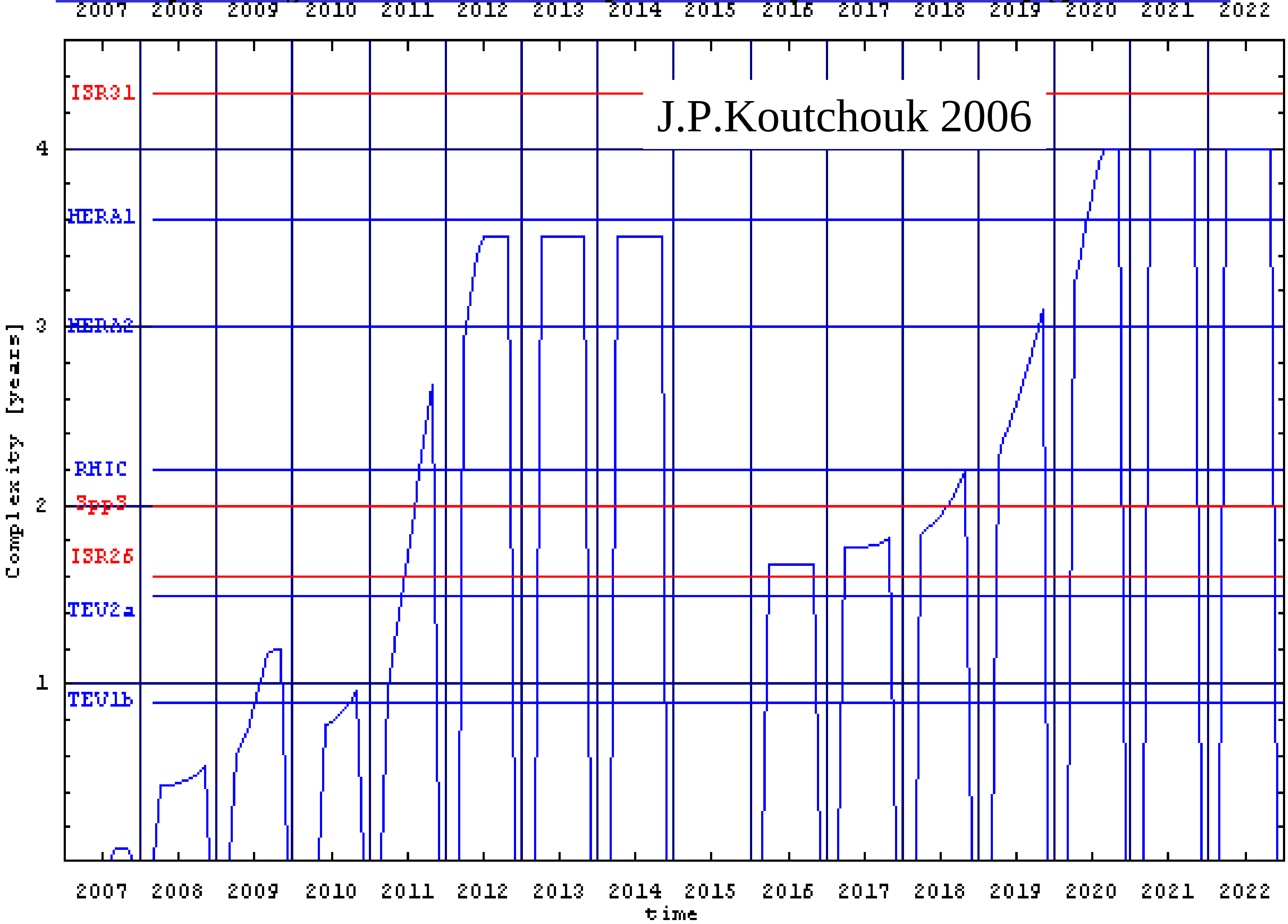
Let's Apply CPT to LHC: Three Scenarios

1. Optimistic:
   - startup 2008
   - In 2008-09 machine is being tuned for running
   - L=1e31 achieved by Jan'09
   - … and then no problems, "easy", ***C=0.5***
2. Modest:
   - Startup in 2008, tuneup in 2008, L=1e31 by 01/09
   - "easy", ***C=0.5***, until L=2e32 (2xTev beam intensity)
   - then progress somewhat slowed down, ***C=2.0***
3. Pessimistic
   - Startup in 2008, tuneup in 2009, L=1e31 by 01/09
   - then progress as in all hadron machines, ***C=2.0***

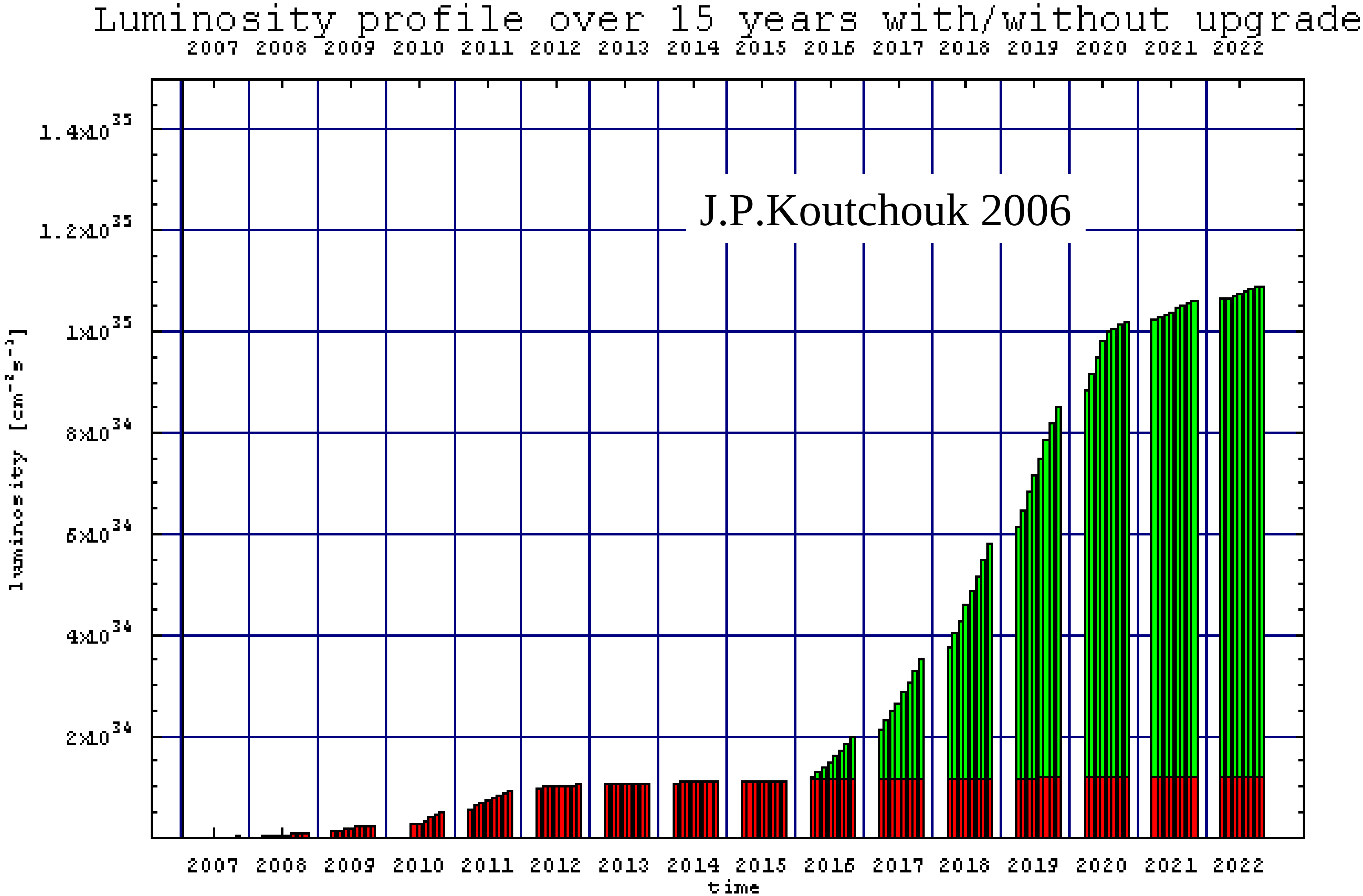
LHC Luminosity (Linear Scale)



Complexity in the case of the “reference” upgrade



Luminosity profile in the case of the "reference" upgrade



Aknowledgements

Work, Inputs, Slides, Contributions from:

J.Annala, C.Gattuso, B.Hanna, D.Still, S.Nagaitsev, D.McGinnis,
V.Lebedev, R.Dixon, V.Papadimitrou, V.Kamerdzhiev, Yu.Alexahin,
XL.Zhang, G.Kuznetsov, D.Wolff, J.Volk, S.Singatulin, P.Lebrun,
A.Shemyakin, J.Spalding, E,McCrory, R.Pasquinelli, A.Jansson,
V.Scarpine, N.Eddy, R.Keup, R.Webber, J.Steimel, CY.Tan, S.Pordes,
A.Valishev, A.Burov, A.Tollestrup, J.Estrada, M.Martens, V.Ranjbar,
D.Plant, T.Johnson, T.Anderson, J.Reid, G.Romanov, T.Khabibulin,
J.P.Koutchouk, P.Ivanov, F.Zimmermann, A.Chen, O.Bruning,
M.Syphers, J.Streit, D.Harding, I.Kourbanis, D.Capista, K.Seyia,
R.Flora, G.Saewert, R.Moore, K.Gollwitzer, E.Prebys, P.Derwent,
J.Marriner, L.Prost, P.Czarapata, A.Chandra, C.Bhat, P.Bhat,
S.Wolbers, V.Sajaev, E.Wendt, P.Bauer, L.Bottura, P.Ivanov

… and many others from Accelerator Division, Technical and Computing Divisions, CDF and D0 collaborations, other US and foreign labs

Thank you for attending these lectures!

Hope the lectures were useful…

Entertaining…

And Cheerful…

See you in the LHC Control Room!