Fermilab

"CPT Theorem", Complexity of Accelerators and Outlook for LHC Evolution

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on basis of presentation at Alvin's Symposium (06/04) and FNAL-Conf-04-126 (2004)

FERMILAB-CONF-04-126 (Aug 2004)

"CPT Theorem" for Accelerators

What people thought in 1996

Recycler TDR
FNAL TM-1991

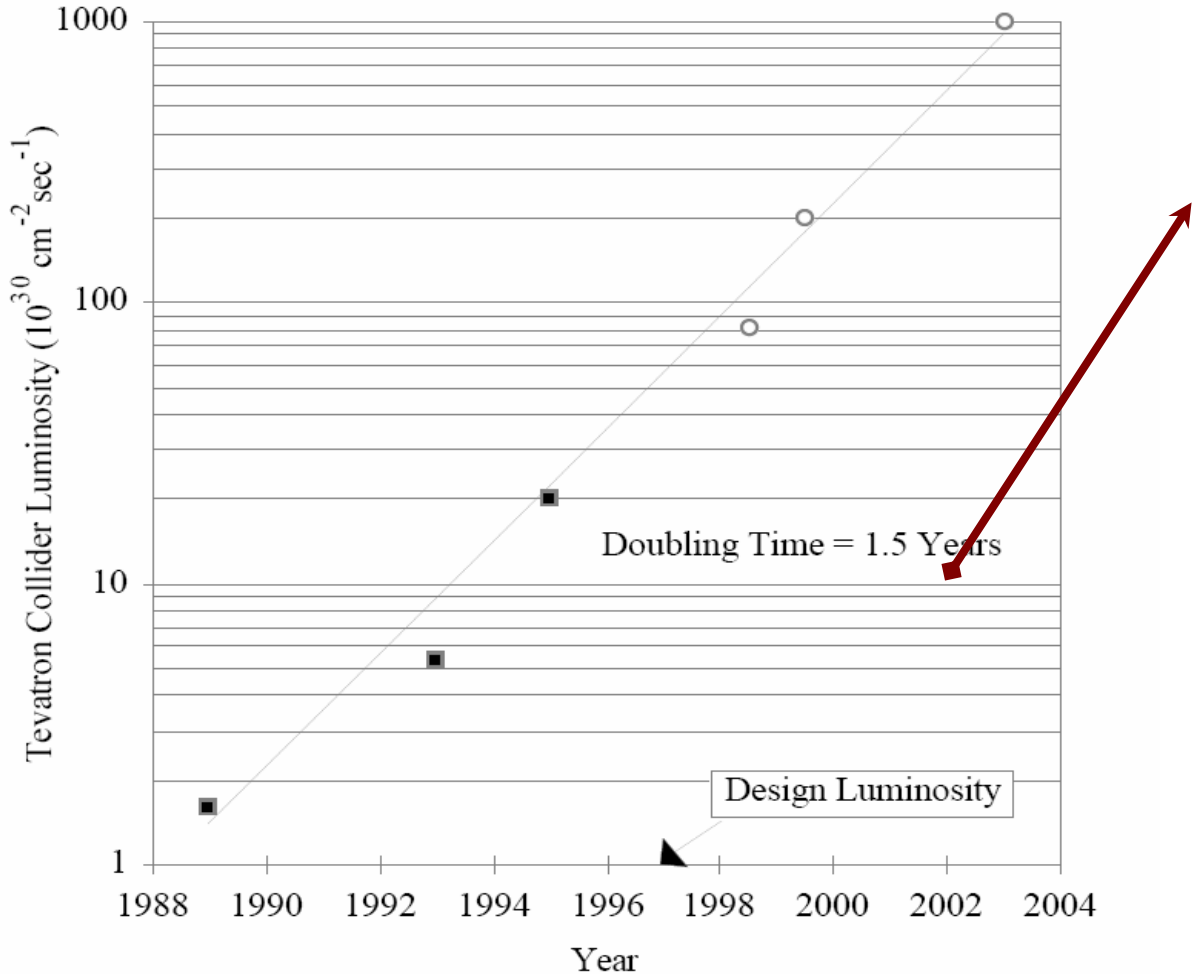
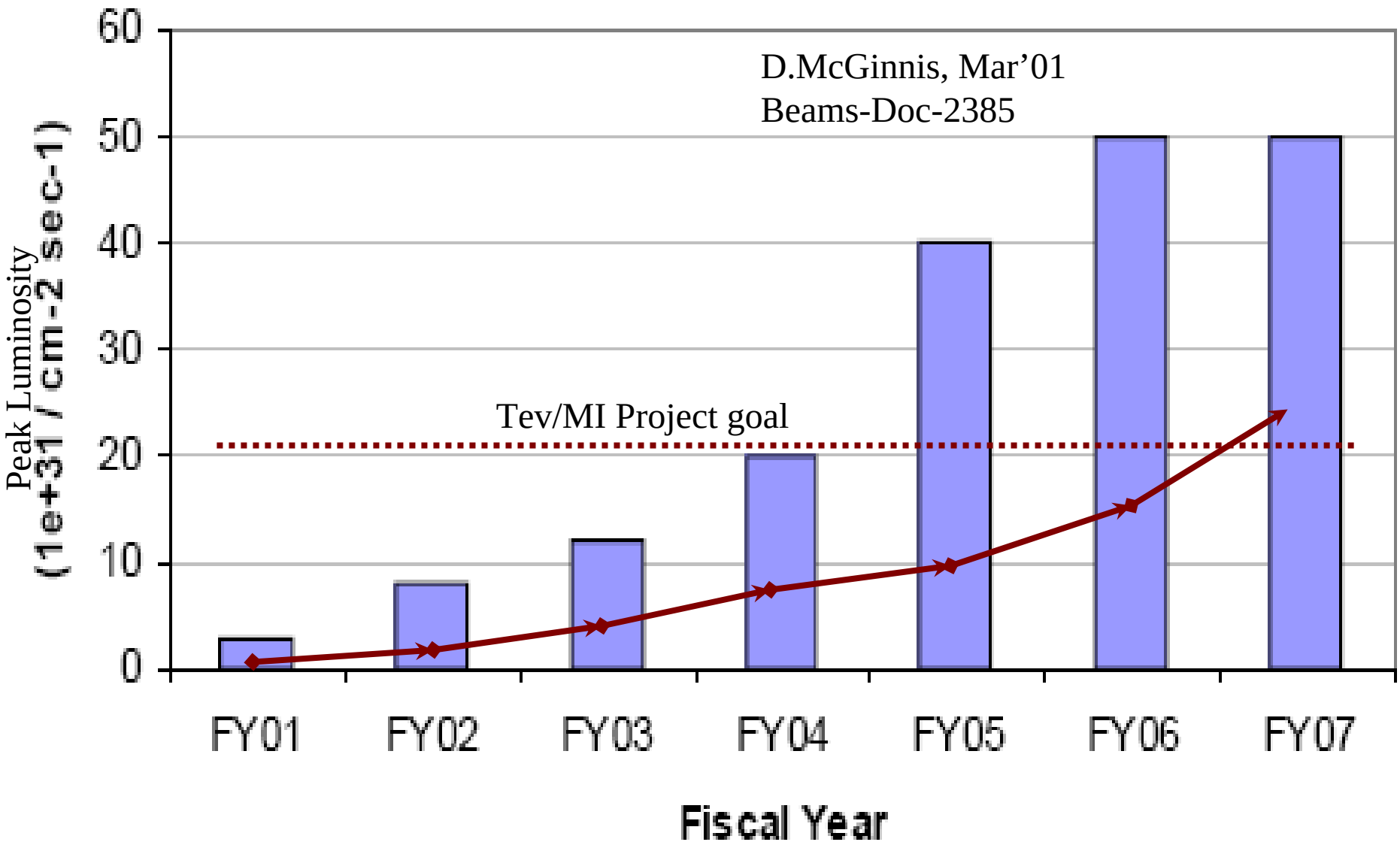


Figure 1.1: Tevatron Collider luminosity as a function of time. The filled circles are measured "best typical" peak luminosities, the line is an exponential fit to the data, and the open points represent goals for the future.

What we thought in 2001 vs Reality



21 Luminosity Steps Up in '02-'06 → x23

Optics AA->MI lines fixed	Dec'01	~25 %
New LB squeeze helix, TEL-1 abort	Mar'02	~40 %
"New-new" injection helix	May'02	~15 %
AA Shot lattice vs IBS	July'02	~40 %
Tev BLT/inst.dampers 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	Nov'03	~12 %
Longer Stores/ MI dampers	Feb'04	~19 %
2.5MHz AA → MI trnsf/Cool shots	April'04	~8 %
Reduction of beta* to 35 cm	May'04	~26 %
Shots from Recycler	July'04	~20%
Slip Stacking in MI	Mar'05	~20%
Tev Octupoles at 150 GeV	April'05	~5%
Reduction of beta* to 28 cm	Sep'05	~8 %
Pbar production task force	Feb'06	~10 %
Tevatron 150 GeV helix→ more p	June'06	~10 %
Tev collision helix → lifetime	July'06	~15 %
New RR WP → emittances, loss	Sep'06	~25 %

Tevatron Lessons:

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

#2: 21 steps resulted in 23-fold increase in luminosity

#3: that makes an average 16% increase per step

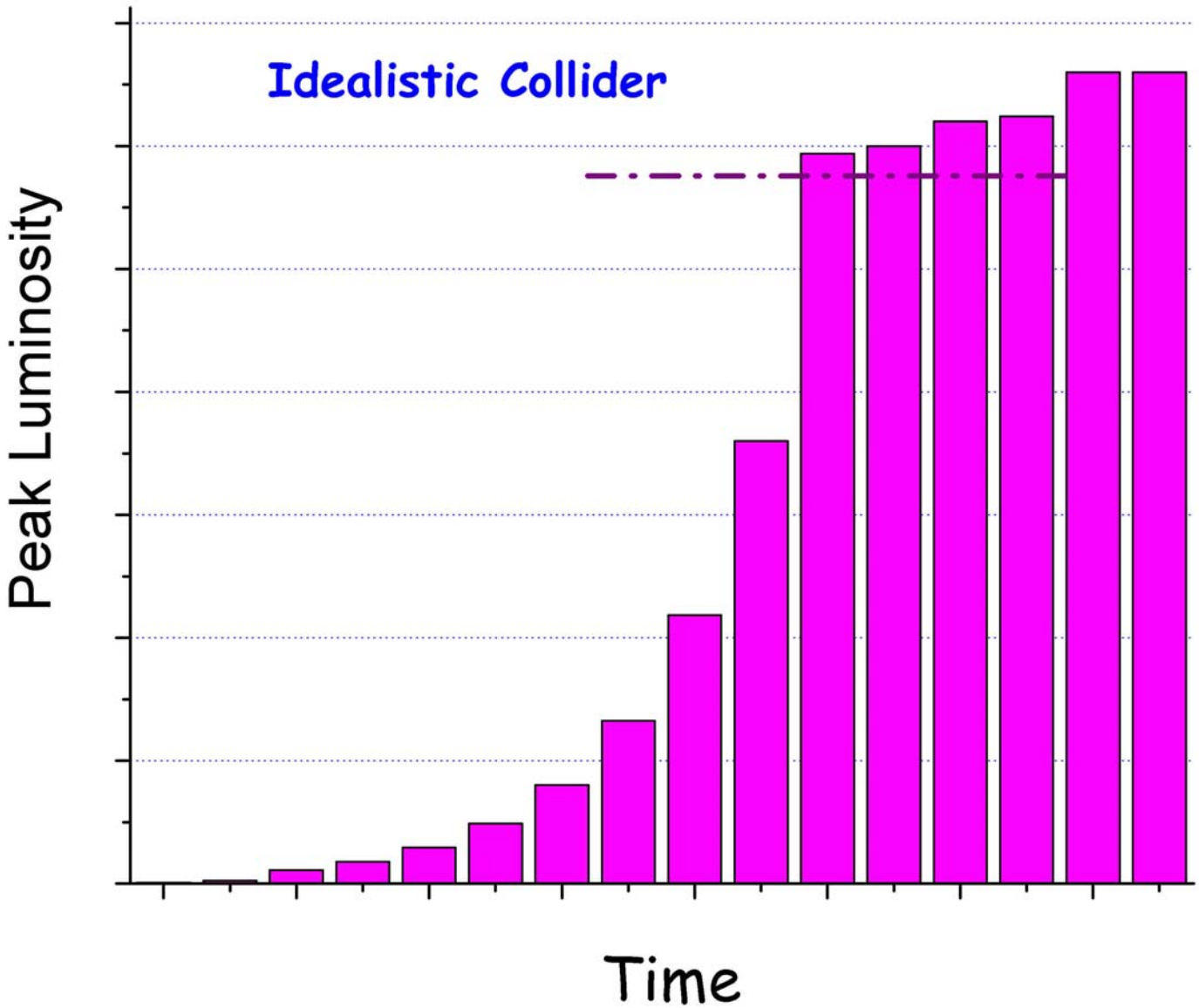
Conclusions:

a) More possibilities addressed the better

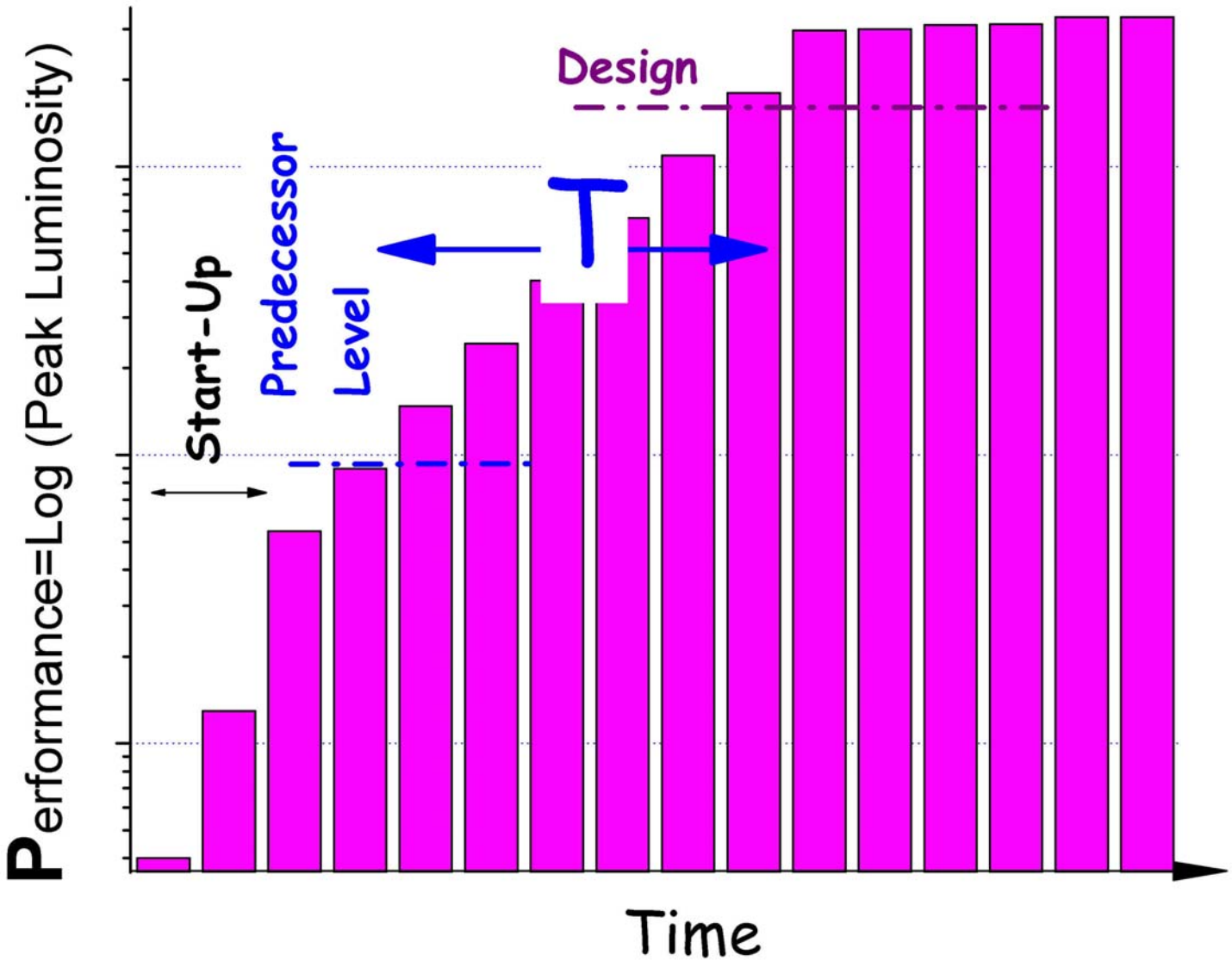
b) Faster the team addresses them the better

c) a) and b) depend on <u>complexity of the machine</u> and <u>quality of the team</u> running it

Luminosity: Idealized Case of "Small Steps" Evolution



Luminosity - Idealized Case



CPT Theorem for Accelerators

$$C \times P = T$$

C = Complexity

P = Performance

or Challenge = Ln($Lumi$)

T = Time to reach P

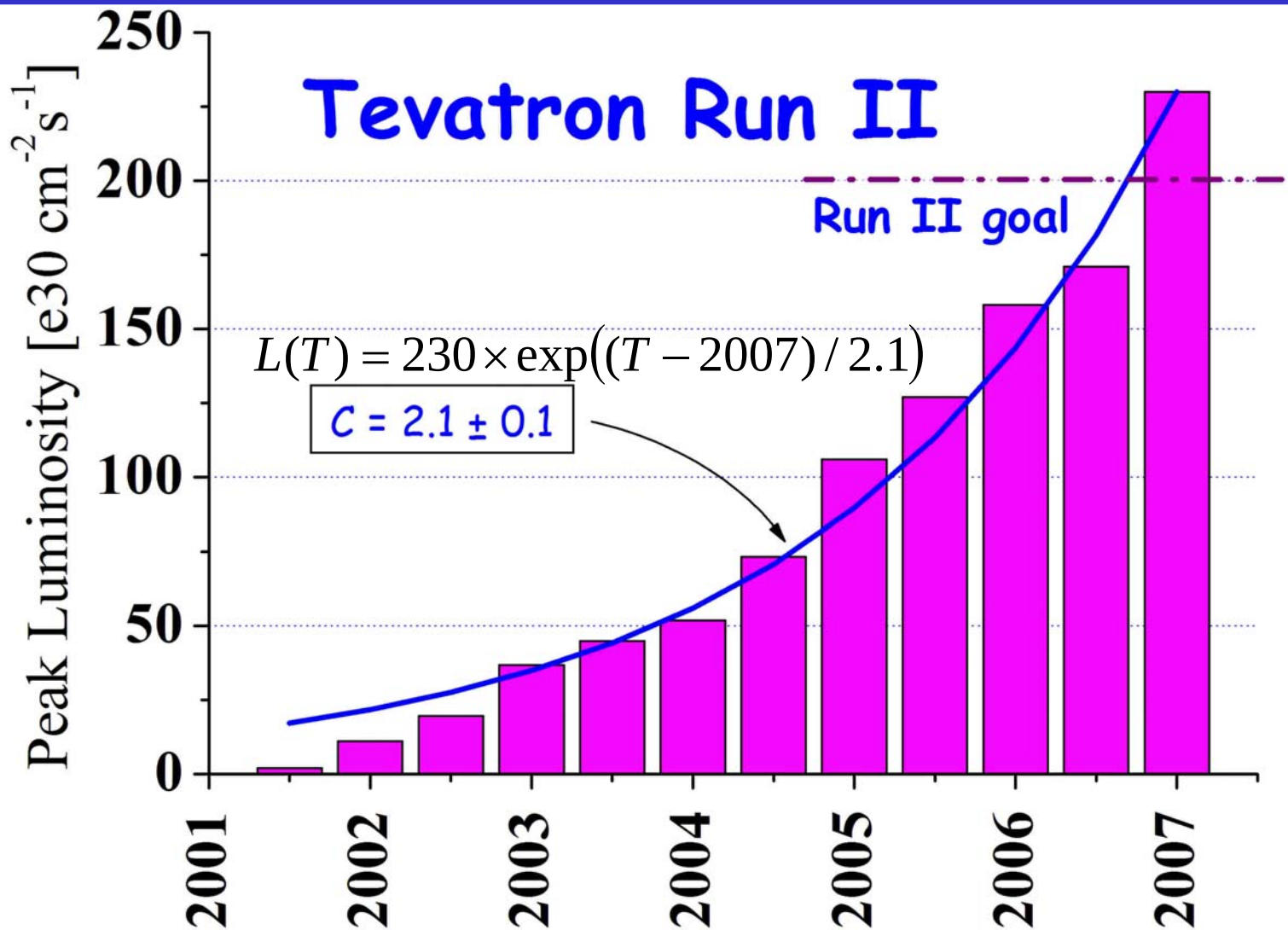
CPT Luminosity Evolution

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

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

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

Tevatron Run II Luminosity Evolution



Complexity of Accelerators – Naive Approach

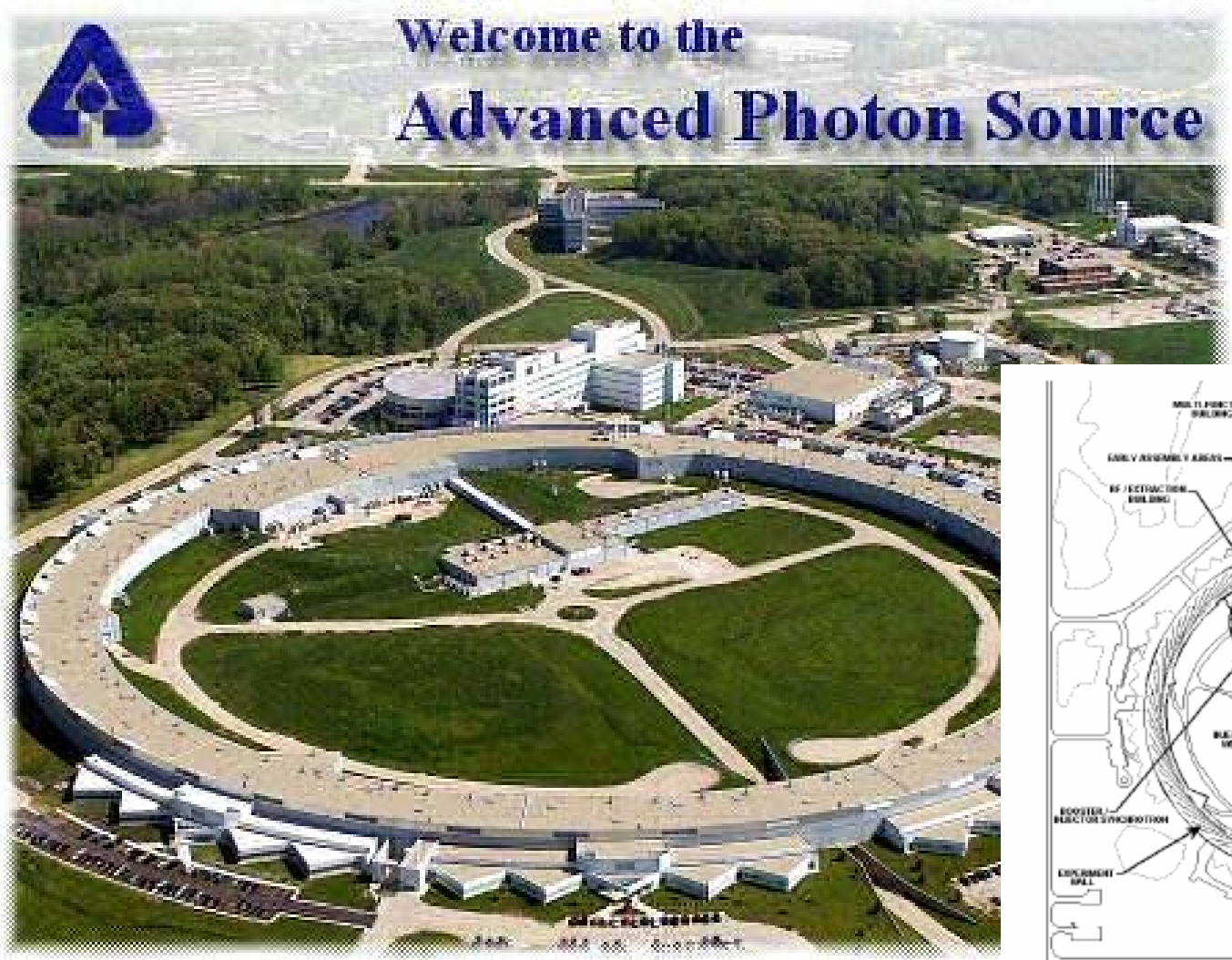
C = 0 Single Beam Machines

C = 1 e+e- Colliders

C = 2 Hadron Colliders (esp. SC)

C = 3 New Technology Machines (e.g. LC)

"Not Very Complex Machine"



Complexity=0

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

<u>9 months</u> of commissioning

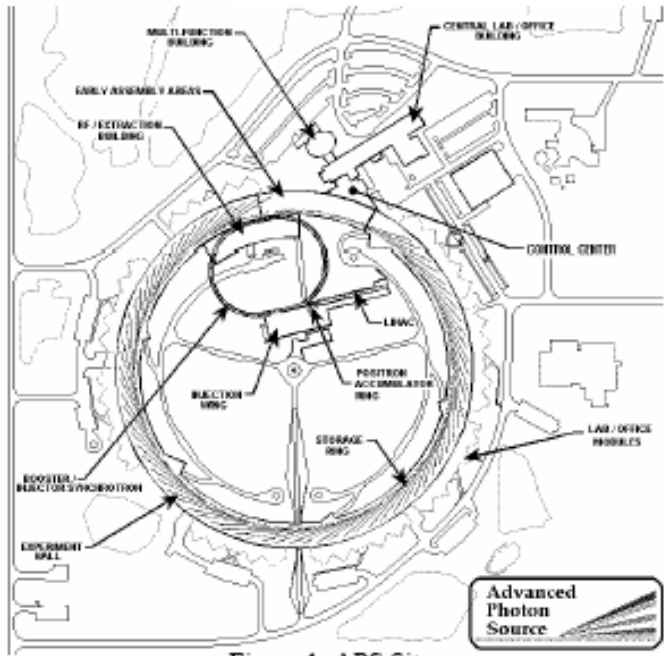


Figure 1: APS Site.

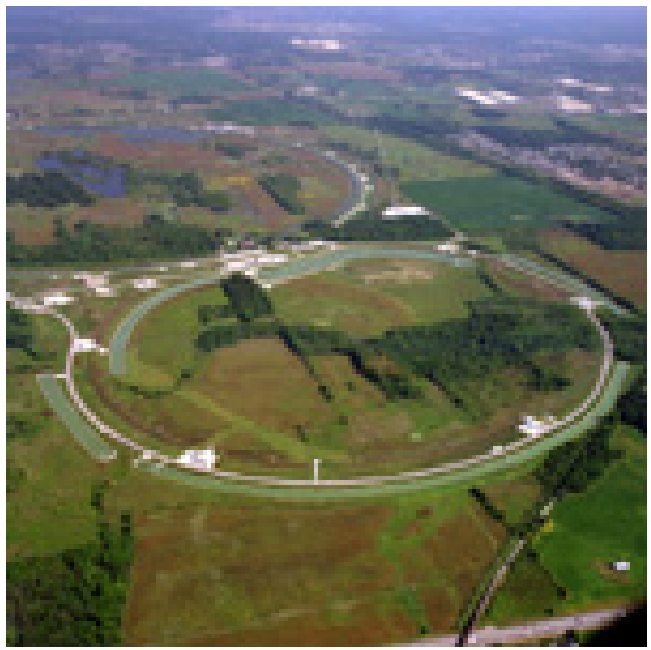
Another "Not Very Complex Machine"…

Fermilab Main Injector

Complexity=0

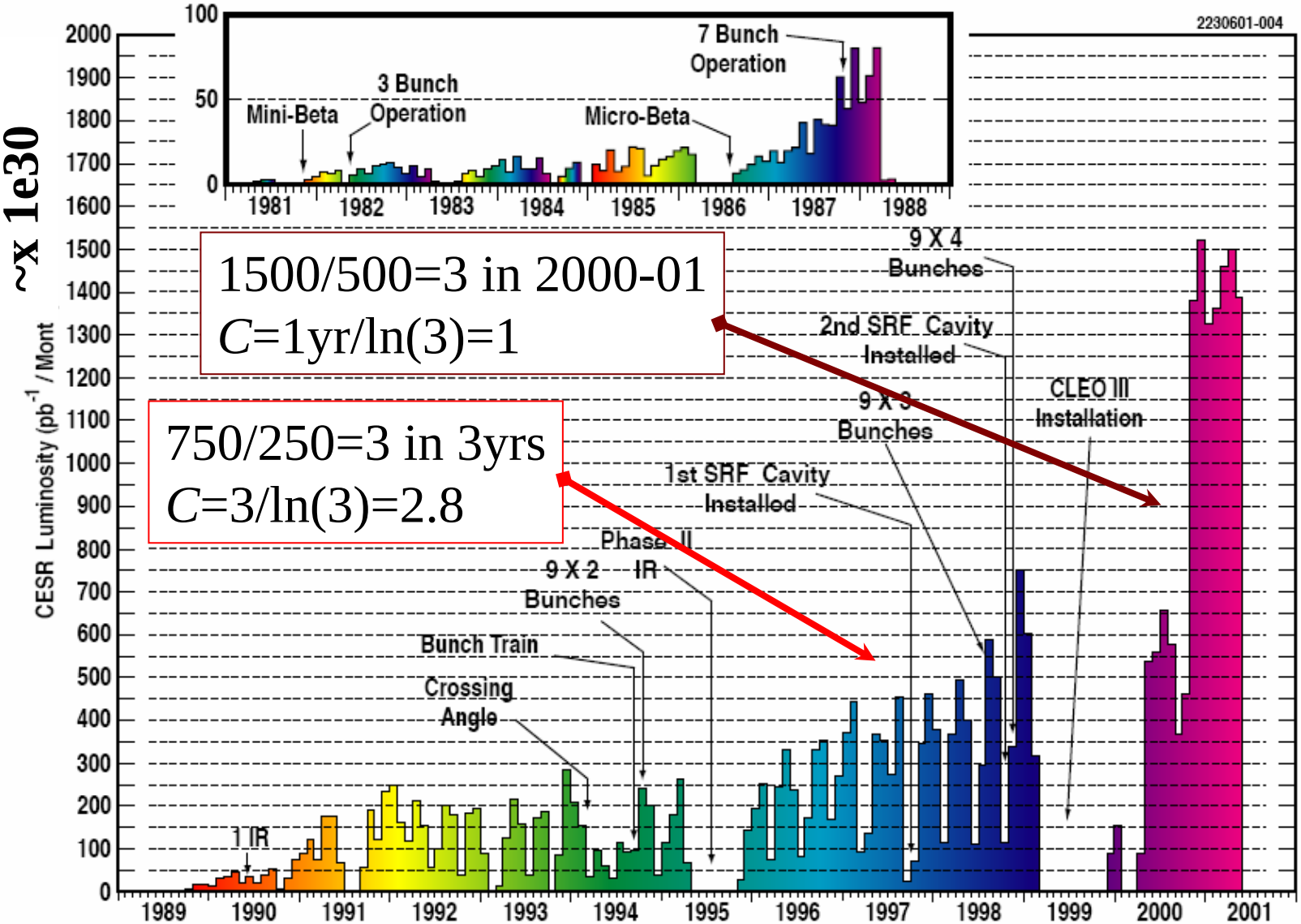
Constructied on schedule within budget (200M$)

<u>6 months</u> of commissioning



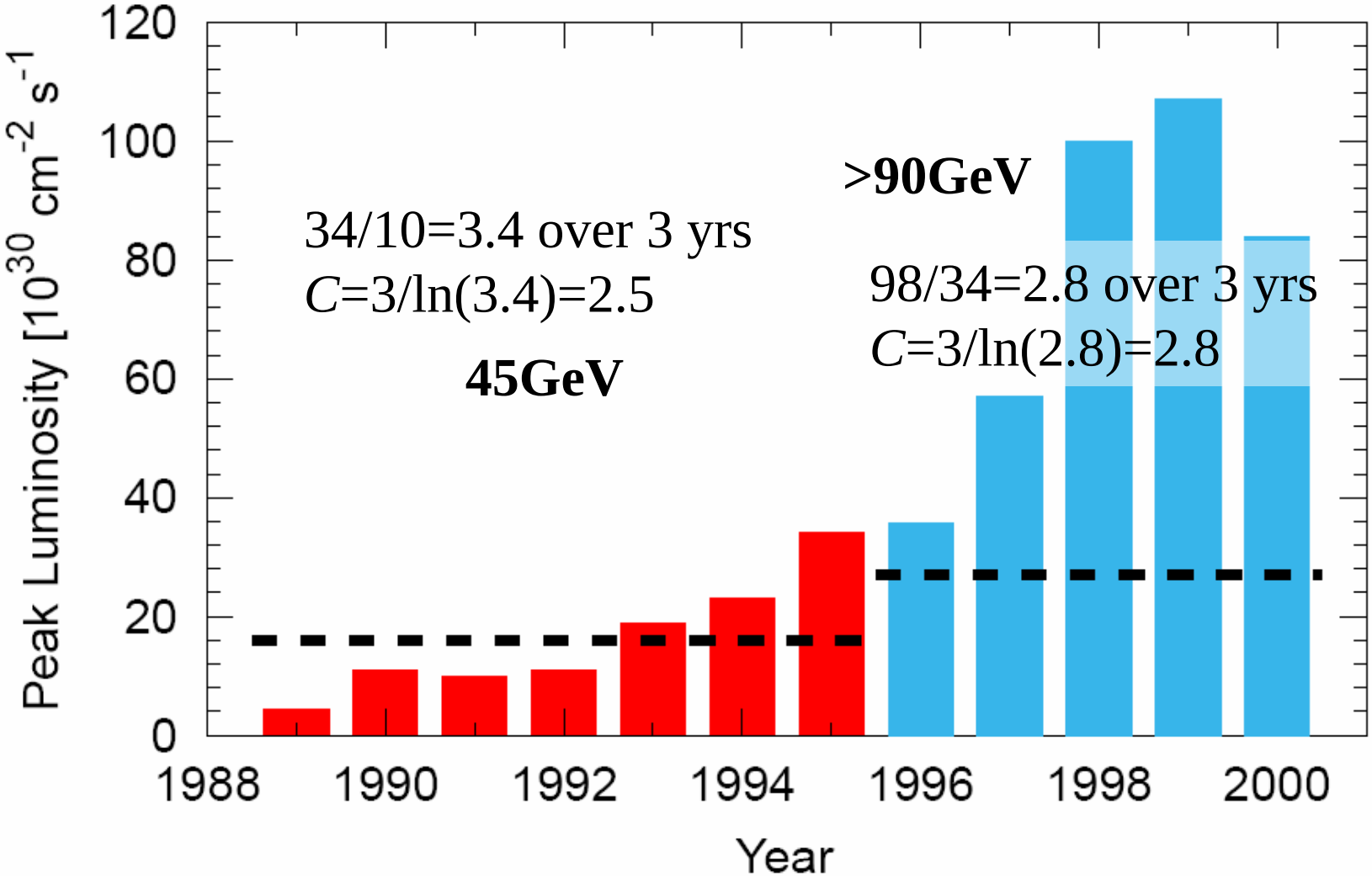
Luminosity - CESR

D.Rice, 2001



Luminosity – LEP: design 16/27e30

R.Assmann, APAC'2001

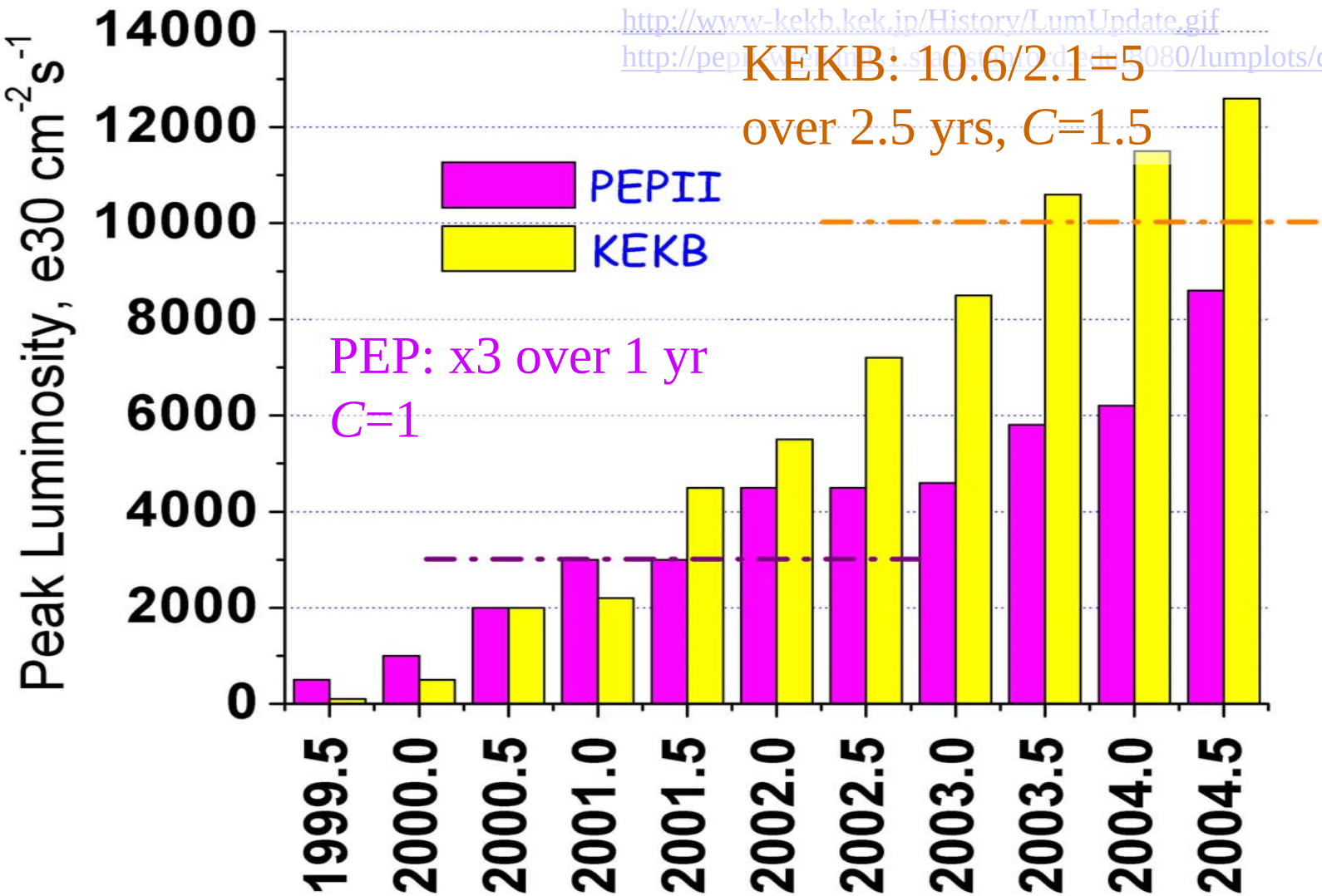


Luminosity – PEP-II/KEK-B: design 3/10e33

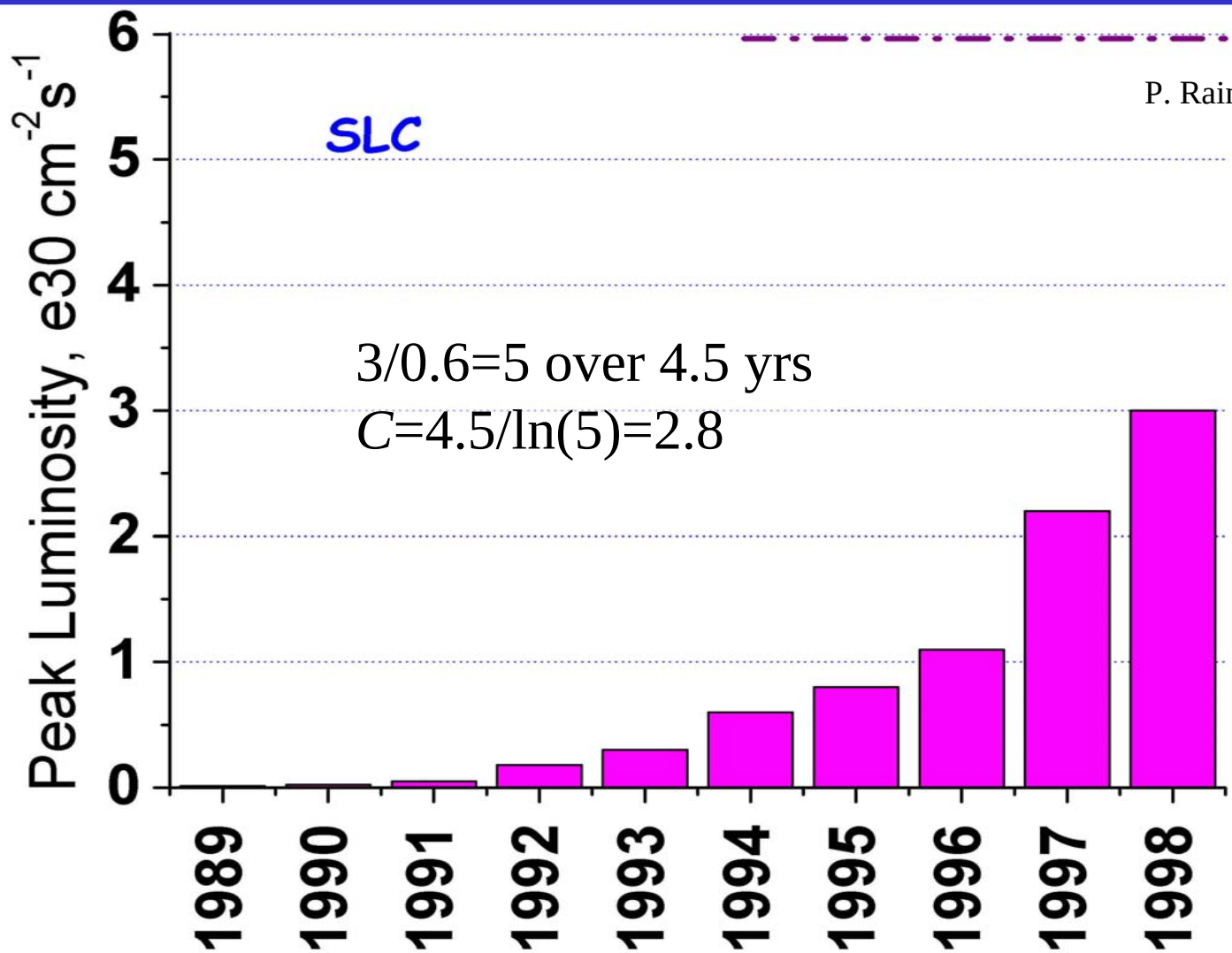
K.Oide, EPAC'2002

http://www-kekb.kek.jp/History/LumUpdate.gif

http://pep[illegible]080/lumplots/daily/



Luminosity – SLC: design 6e30

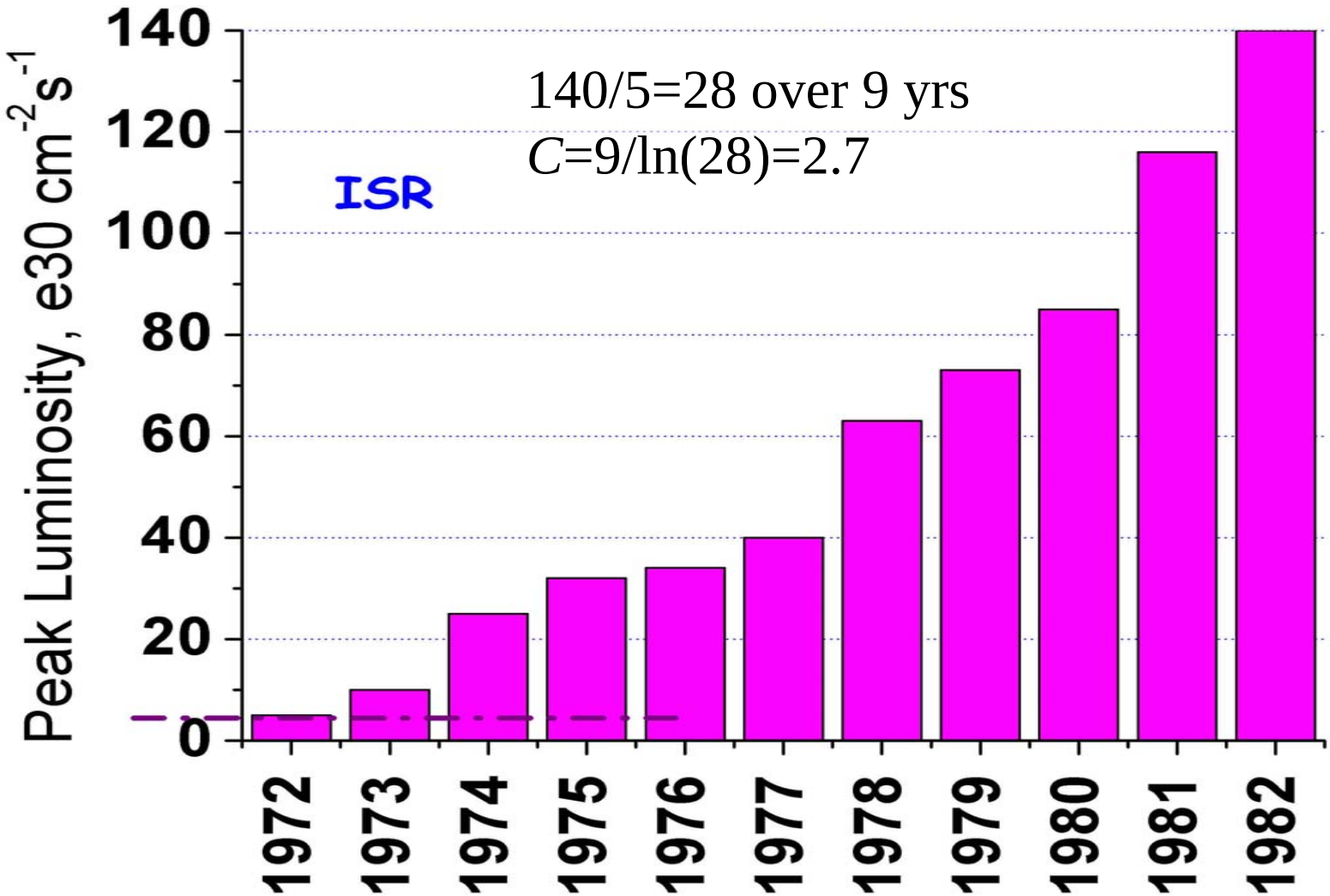


P. Raimondi, PAC'1999

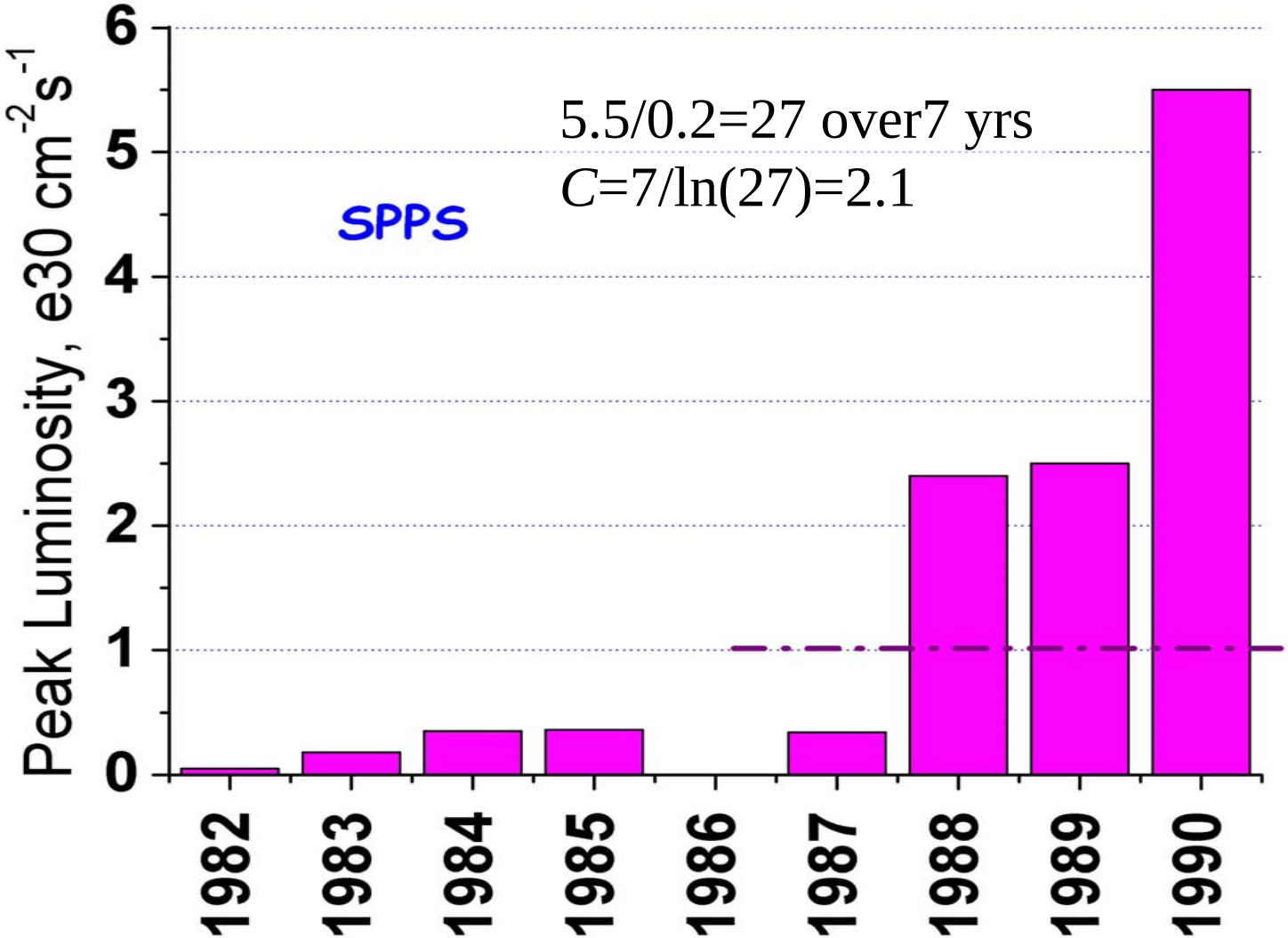
3/0.6=5 over 4.5 yrs

C=4.5/ln(5)=2.8

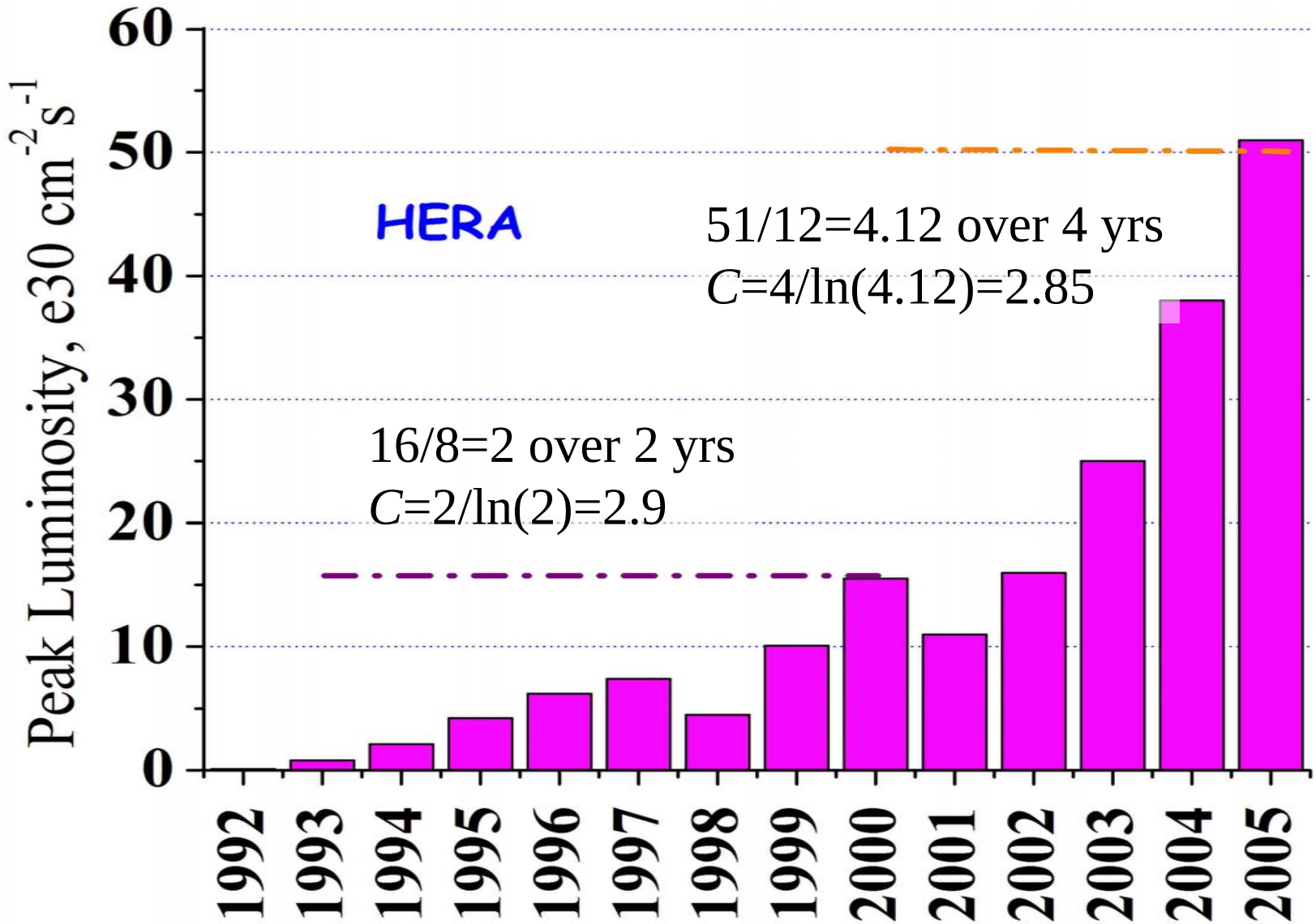
Luminosity – ISR: design 5e30



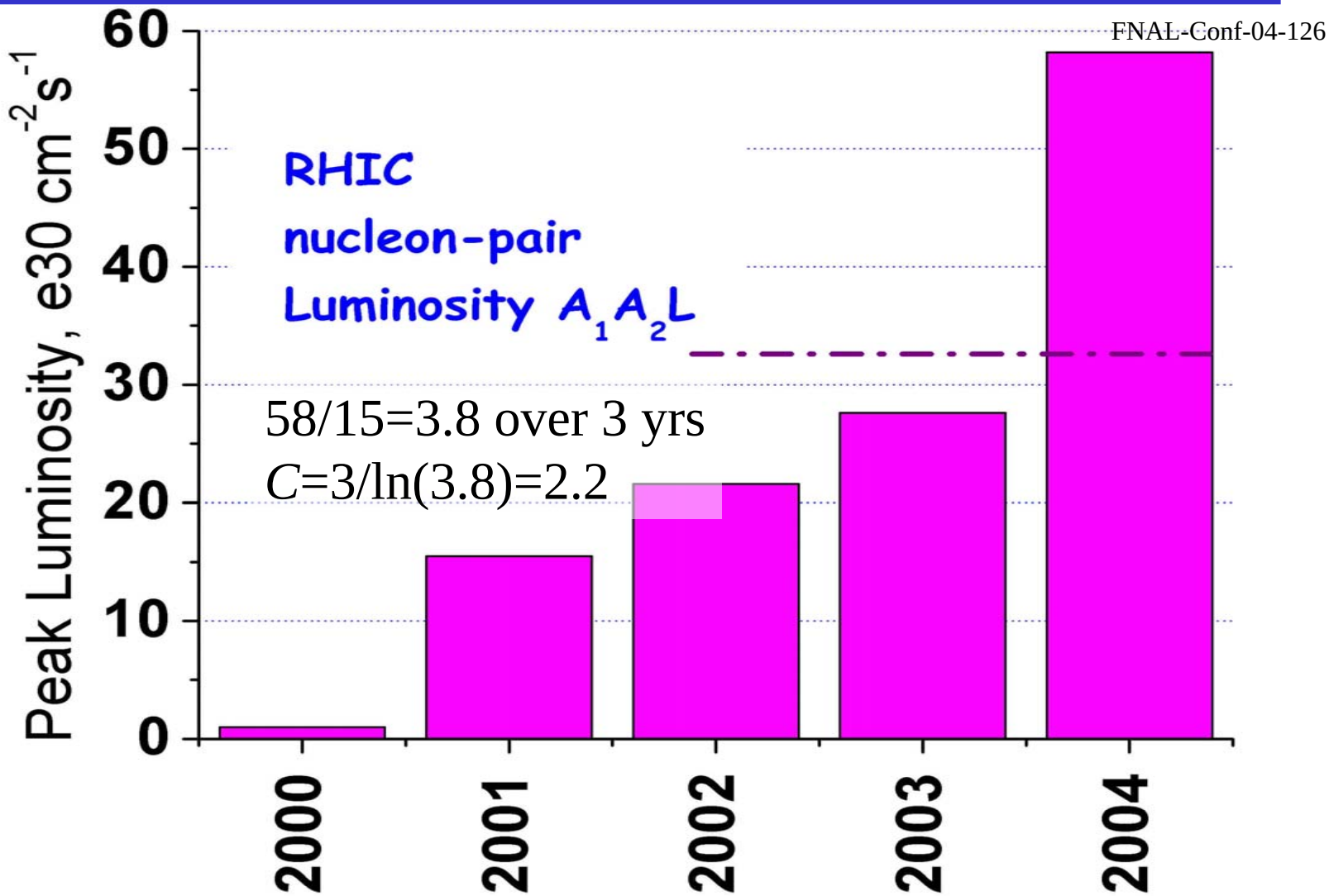
Luminosity – SppS: design 1e30



Luminosity – HERA: design 15e30 →50



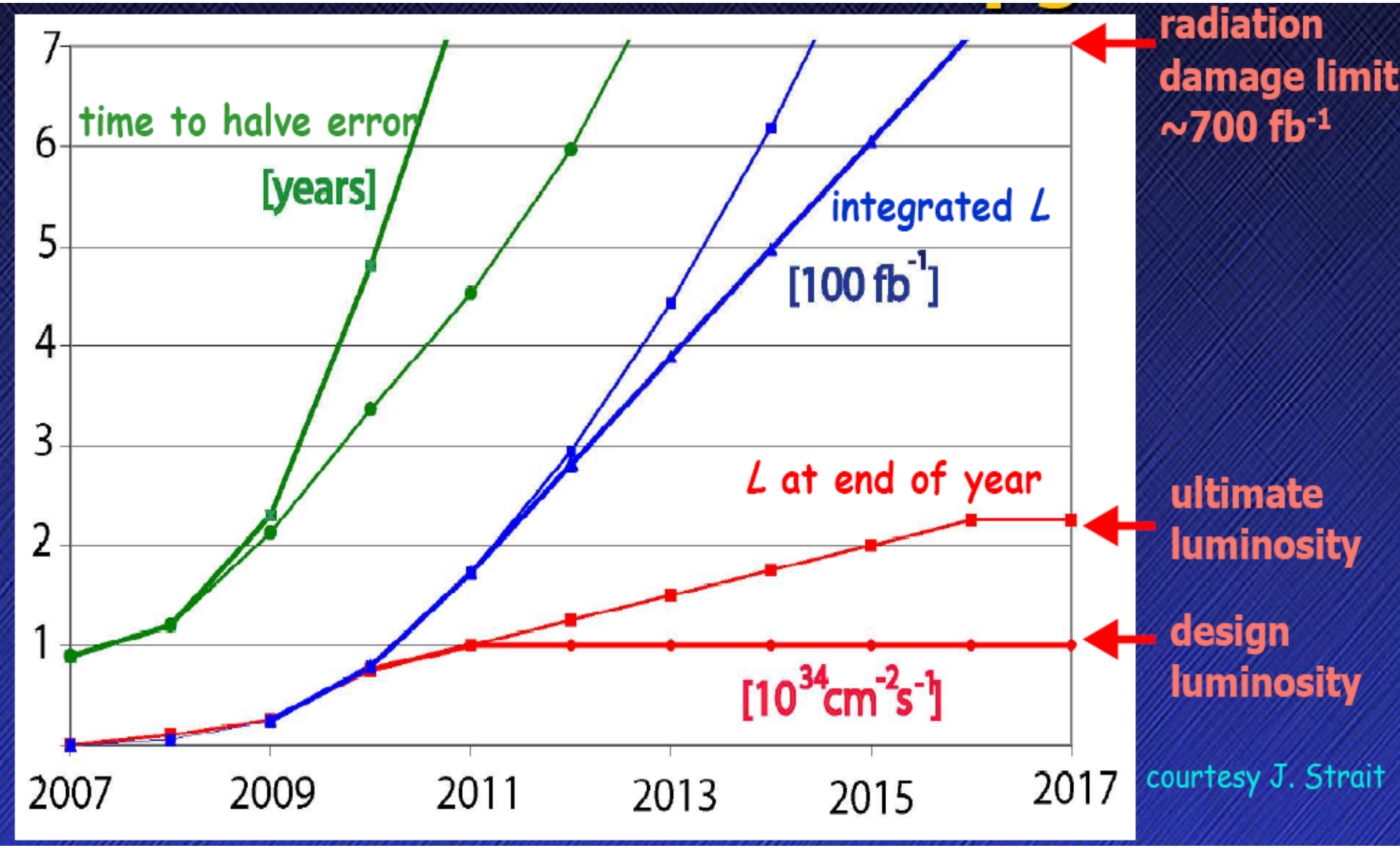
Luminosity – RHIC: design 33e30



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

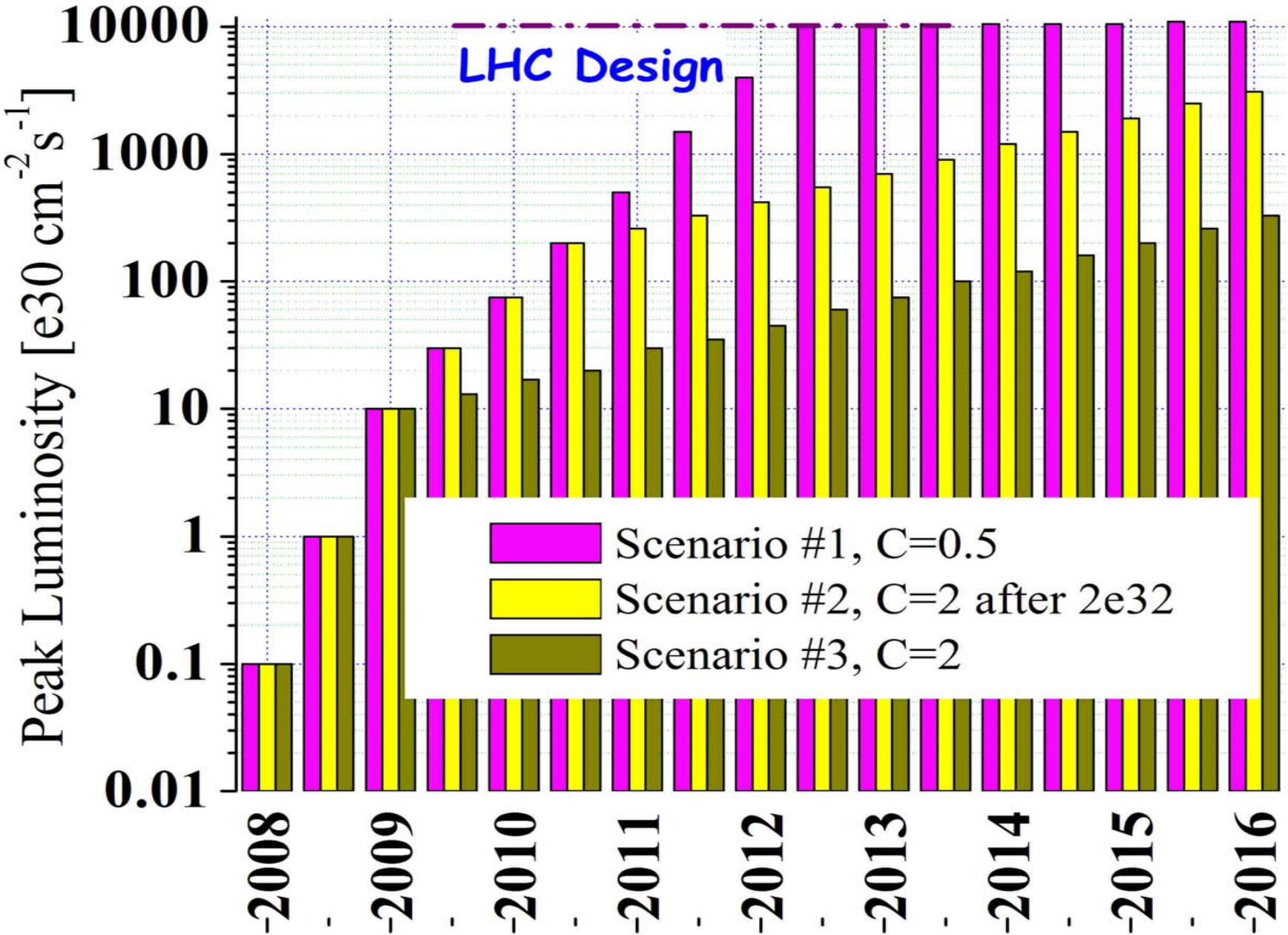
LHC Luminosity Outlook: "Current Vision"



Let's Apply CPT to LHC: Three Scenarios

1. Optimistic:
   - startup 2007
   - In 2008 machine is being tuned for running
   - L=1e31 achieved by Jan'09
   - … and then no problems, "easy", *C=0.5*
2. Modest:
   - Startup in 2007, 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 2007, tuneup in 2008, L=1e31 by 01/09
   - then progress as in all hadron machines, *C=2.0*

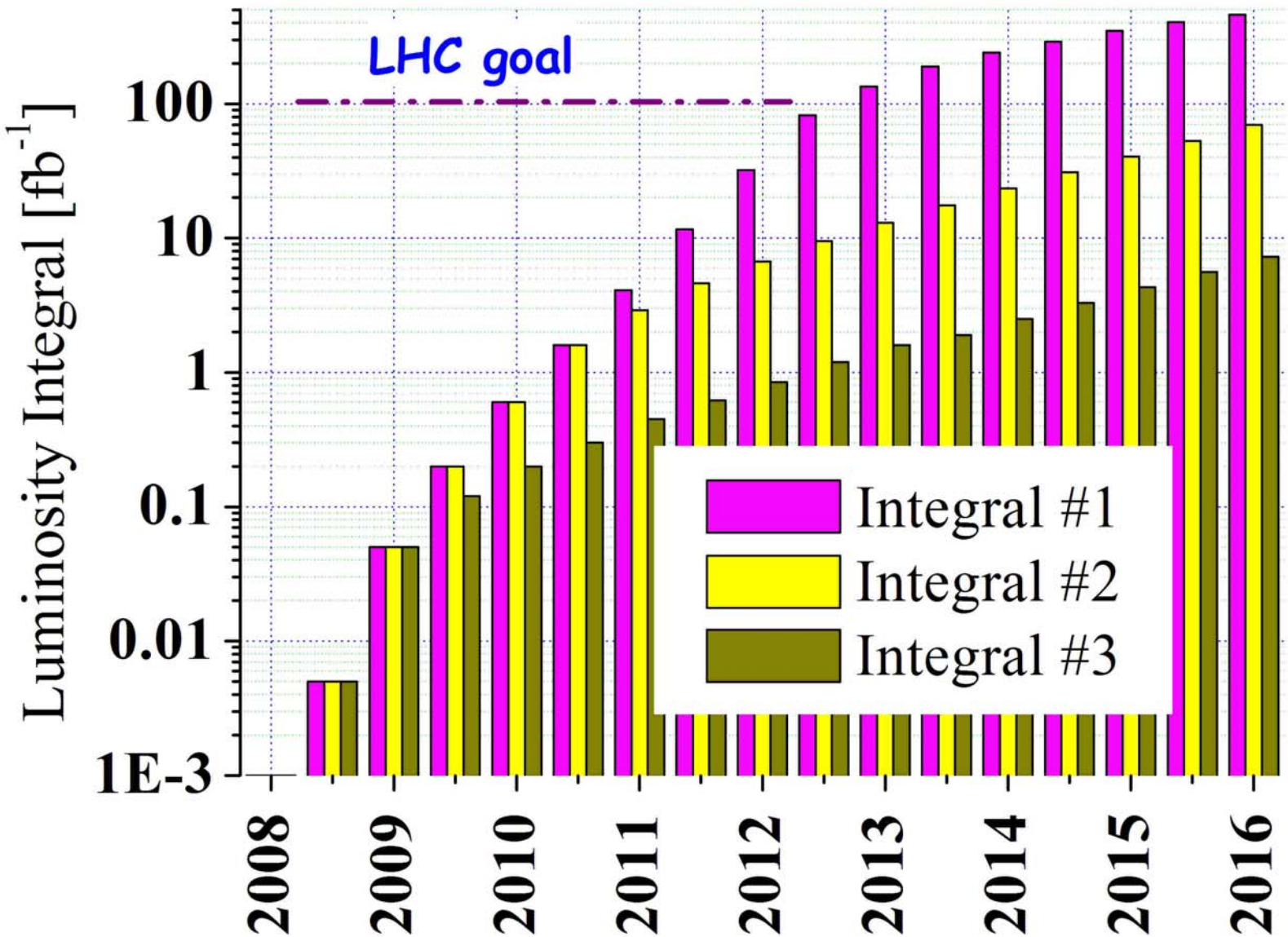
Three Scenarios of LHC Luminosity Evolution



Three Scenarios: Peak Luminosity [e30] Table

Year	*#1*	*#2*	*#3*
2008	0.1	0.1	0.1
2008.5	1	1	1
2009	10	10	10
2009.5	30	30	13
2010	75	75	17
2010.5	200	200	20
2011	500	260	30
2011.5	1500	330	35
2012	4000	420	45
2012.5	10000	550	60
2013	10500	700	75
2013.5	10500	900	100
2014	10500	1200	120
2014.5	10500	1500	160
2015	10500	1900	200
2015.5	11000	2500	260
2016	11000	3100	330

LHC Integrated Luminosity



Three Scenarios: Luminosity Integral [fb-1] Table

Year	*#1*	*#2*	*#3*
2008	5E-4	5E-4	5E-4
2008.5	0.005	0.005	0.005
2009	0.05	0.05	0.05
2009.5	0.2	0.2	0.12
2010	0.6	0.6	0.2
2010.5	1.6	1.6	0.3
2011	4.1	2.9	0.45
2011.5	11.6	4.6	0.62
2012	32	6.7	0.85
2012.5	82	9.5	1.2
2013	135	13	1.6
2013.5	190	17.5	1.9
2014	240	23.5	2.5
2014.5	290	31	3.3
2015	350	40.5	4.3
2015.5	405	53	5.6
2016	460	70	7.3

Let's take a look into other accelerators for HEP

"*CPT* Theorem" Predictions - #1

<u>Tevatron Run II Upgrade</u> L → 300e30 :

$C \approx 2.1$

$\Delta P = \mathrm{Ln}\,(L_max/L_now) =$

$\mathrm{Ln}\,(300/230) = 0.3$

$C \times \Delta P = \Delta T = 8$ mos

Nov '06 + 8 mos = ***<u>July'07</u>***

Prediction #2

LHC L-Upgrade from L=5e33 to 5e34:

$C \approx 2$ – as Tevatron

$\Delta P = \mathrm{Ln}\,(L_max/L_lhc) =$

$\mathrm{Ln}\,(10) = 2.7$

$C \times \Delta P = \Delta T = 5.4$ yrs

2016 hardware startup + 1 yr to reach previous LHC luminosity ($\approx$ 5e33) + 5.4 years

= 2022

Prediction #2 a

LHC E-Upgrade 14+14 TeV L=5e34:

$C \approx 2$ – as Tevatron

$\Delta P = \mathrm{Ln}\,(L_max/L_lhc) = \mathrm{Ln}\,(10) = 2.7$

$C \times \Delta P = \Delta T = 5.4$ yrs

2019 hardware startup + 2 yr to reach previous LHC luminosity ($\approx$ 5e33) + 5.4 years

= 2026

Prediction #3

ILC	0.5+0.5 TeV	L=2e34
CLIC	1.5 +1.5 TeV	L=1e35

$C \approx 2.5$ – easier than SLC was

Consider getting to 5e32 in 2 yrs "easy"

$\Delta T = C \times \Delta P = 9$ yrs for ILC or CLIC

2019 startup + 2 yrs to reach 5e32 + 9 years = ***2030***

Prediction #3

Very Large Hadron Collider #1 20+20 TeV
L=1e34

$C \approx 2$ – as Tevatron and LHC(?)

L=3e33 (=LHC) is "easy"

$\Delta P = \mathrm{Ln}\,(L_vlhc/L_lhc) = \mathrm{Ln}\,(3) = 1$

$C \times \Delta P = \Delta T = 2$ yrs

2019 startup + 2-3 yr to reach equivalent LHC luminosity ($\approx$ 3e33) + 2 years = ***2024***

Prediction #4

Muon Collider 1+1 TeV
L=1e35

$C \approx 2.5$ – as SLC

L=3e33 is "easy" (?) – 2 years

$\Delta P = \mathrm{Ln}\,(L_mc/L_lhc) = \ln(30) = 3.4$

$C \times \Delta P = \Delta T = 7$ yrs

2019 startup + 2 yr to reach 3e33 + 7 years
= ***2028***

Summary of CPT Predictions

Collider	*C.M.E*	*LumiGoal*	*Achieved*
Tevatron Run II	2 TeV,	L=3e32	2008
LHC	14TeV,	L=3e33	2015
LHC L-Upgrade	14TeV,	L=5e34	2022
ILC	1 TeV,	L=2e34	2030
LHC E-upgrade	28TeV,	L=5e34	2026
Muon Collider	2 TeV,	L=1e35	2028
VLHC	40TeV,	L=1e34	2024

Summary

- Operational experience at many colliders tells us that:
  - It takes may steps before reaching ultimate/design Luminosity
  - Evolution of that work can be described by "CPT-theorem"
  - "Complexity" depends on the type of the machine
  - hadron colliders have/had <C>=2 (spread from 0.9 to 3.6)
- LHC luminosity evolution considered so far is ~2 years faster than a very optimistic "CPT-scenario"
- Three CPT scenarios for the LHC performance predict:
  - "optimistic": design luminosity by 2013
  - "modest": L=3e33 and 50 fb-1 by 2016
  - "pessimistic": LHC reaches Tevatron Luminosity 3e32 by 2015
- First few years of LHC operation will show how complex the Collider is and will set the time to start upgrades.
- CPT applied to HEP colliders favors some of them (MC, VLHC) and unfavors others (ILC)

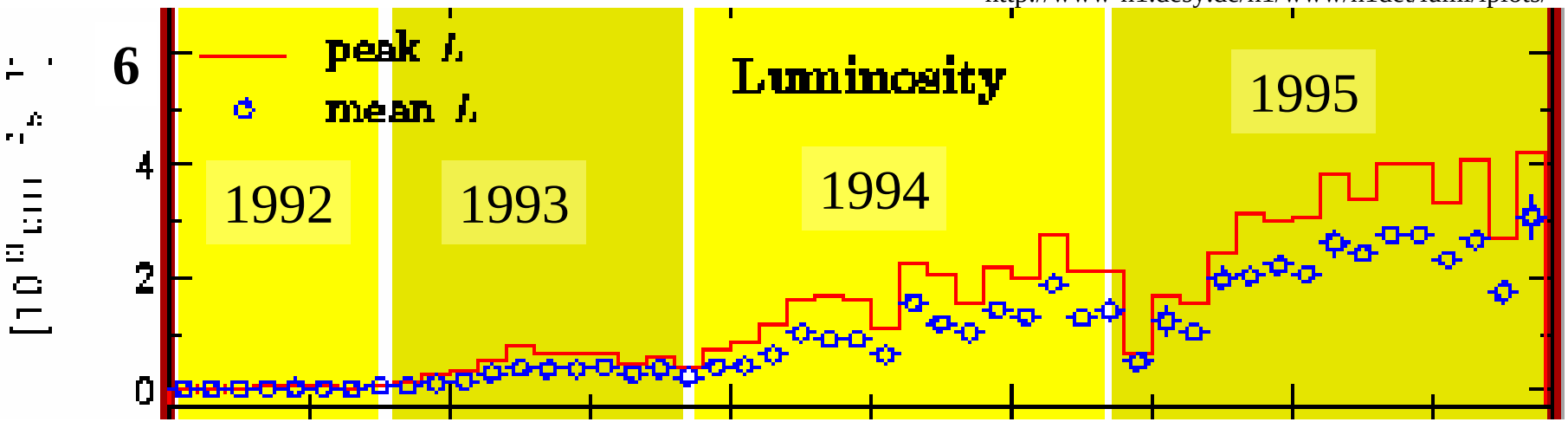
Back-up slides

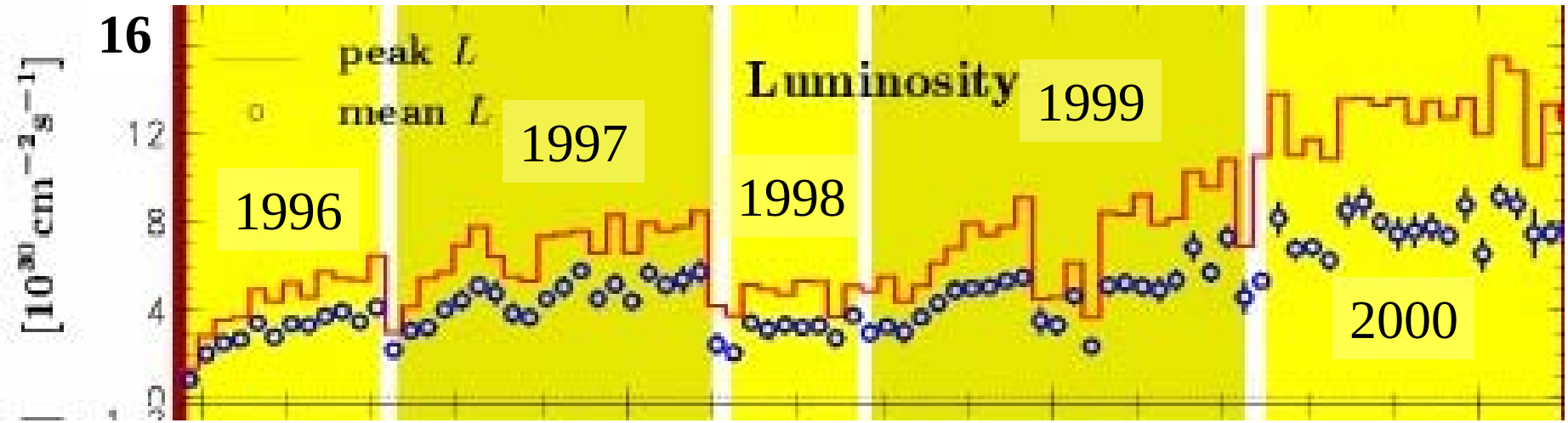
Factors

$$L = \mathcal{H} f_0 \frac{N_b N_p^2}{4\pi\beta^* \varepsilon_n}$$

Luminosity – HERA: design 15e30

http://www-h1.desy.de/h1/www/h1det/lumi/lplots/





Changes btw Run Ib and Run II

Main Injector instead of Main Ring

Pbar Source cooling upgrade

36x36 in Tevatron instead of 6x6

…

"Big Deal" ? – Tevatron Alone:

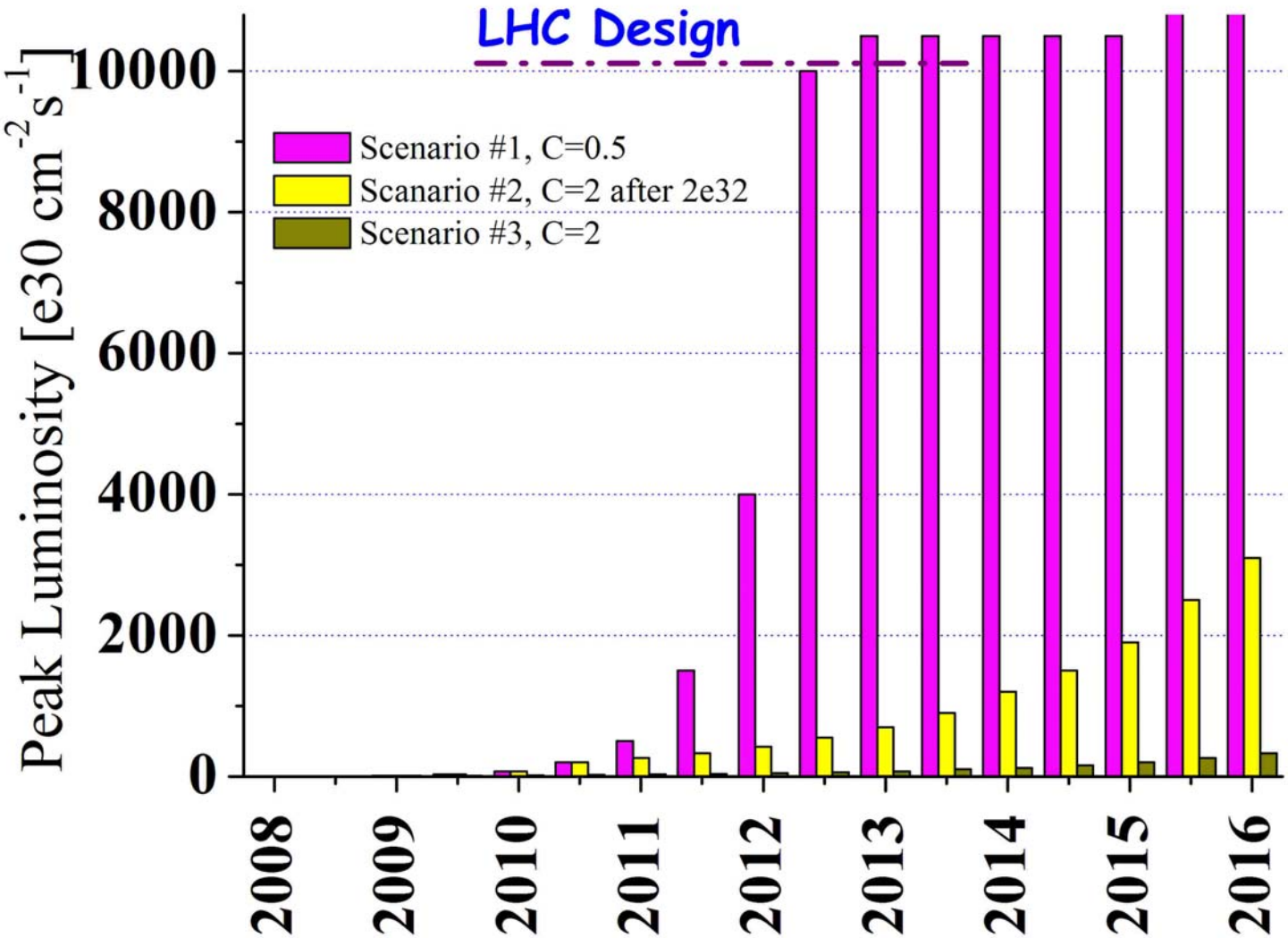
980 GeV =twice closer to SC limit than 900

6x total beam intensity → instabilities

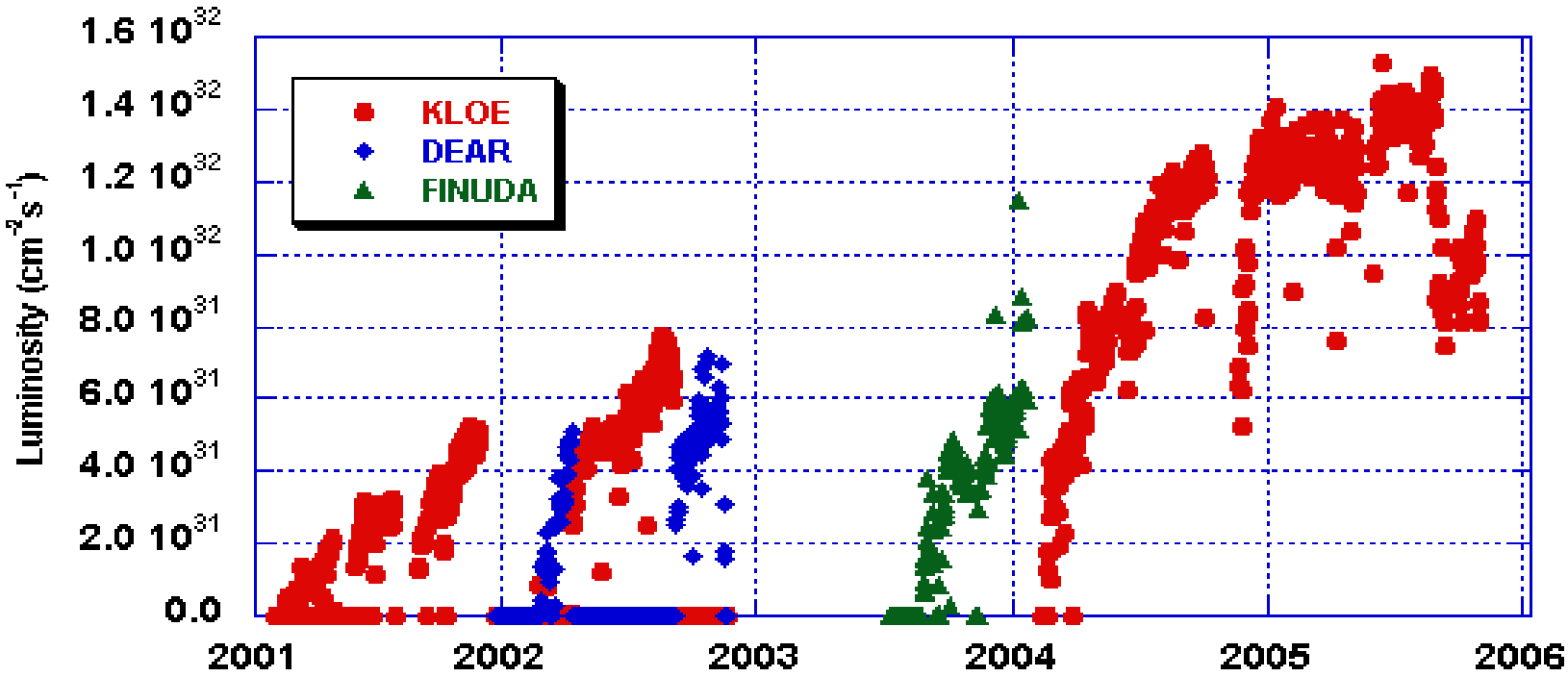
6x beam power → quenches, collimators

36x2-2=70 parasitic collisions instead of 10 →

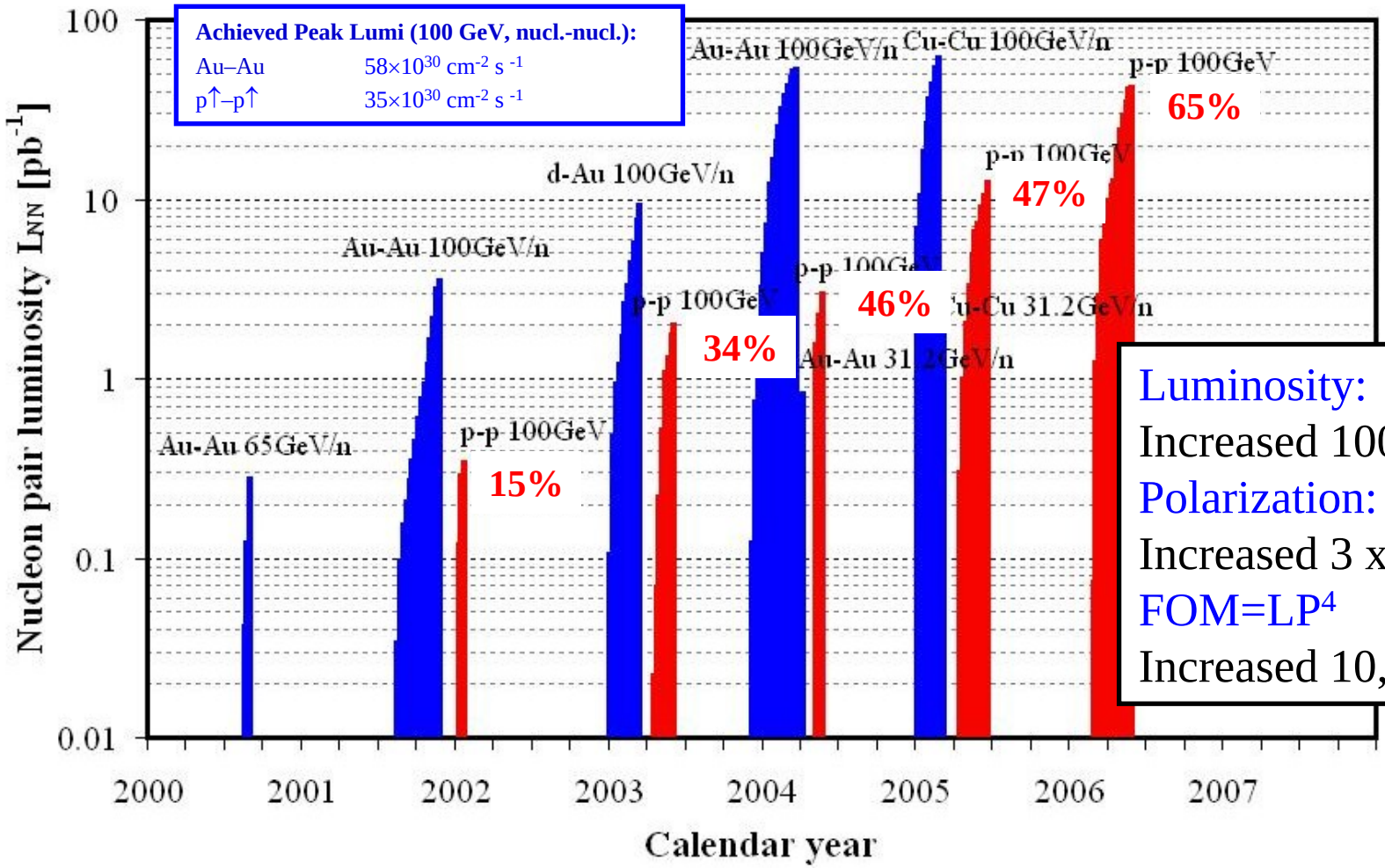
LHC Luminosity (Linear Scale)



DAFNE Luminosity Progress



RHIC Delivered luminosity and polarization 2000-2006



T.Roser
APEX'06

Luminosity:
Increased 100 x
Polarization:
Increased 3 x
FOM=LP^4
Increased 10,000 x

- **Major improvements: warm sections NEG coating, cold sections vacuum pumps, AGS Siberian snakes**