Particle Accelerators –

Fusion of Science, Technology & Art

… but - ***Do They Have Future?***

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PART I:

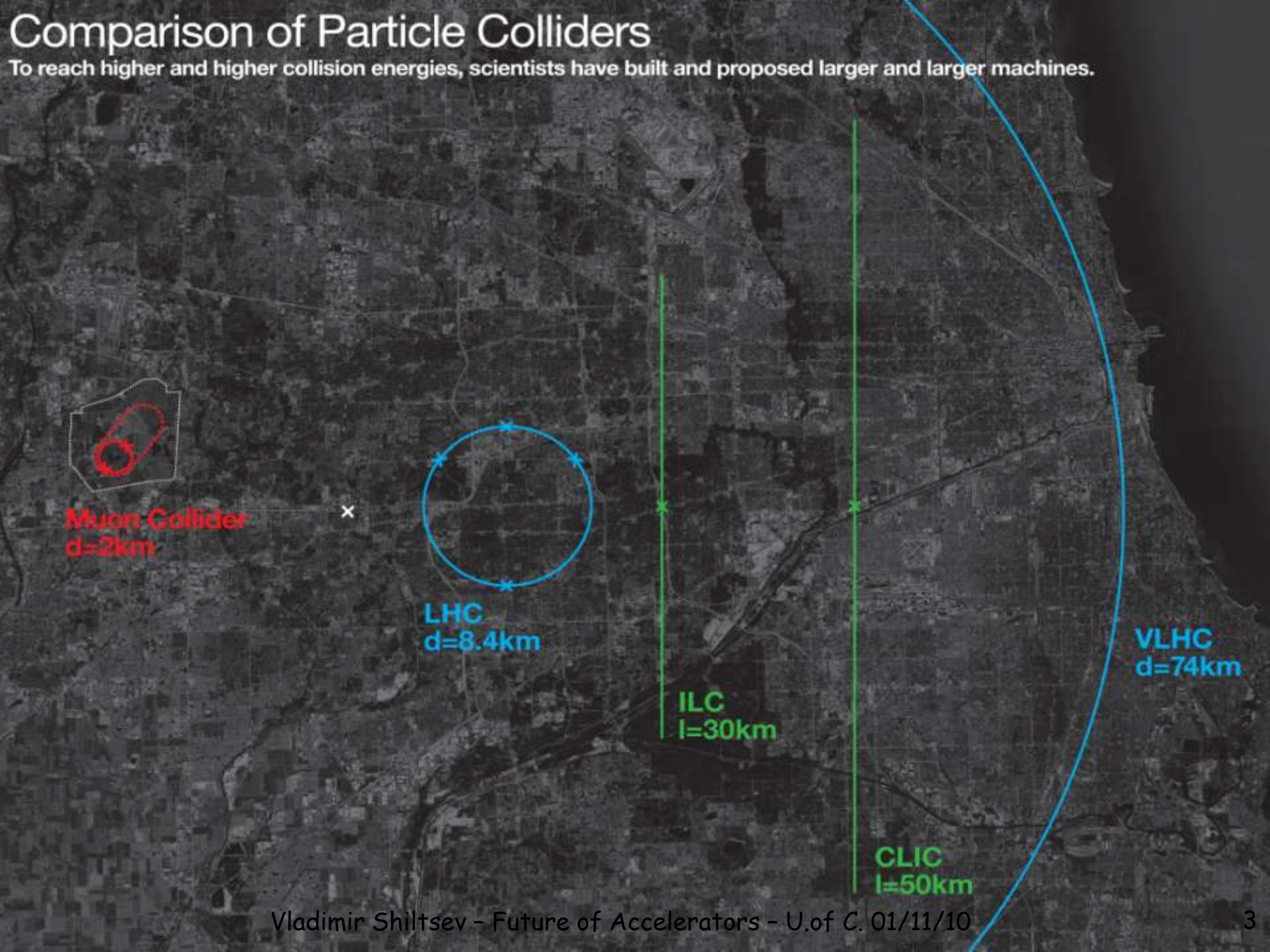
Complexity of Accelerators,

"CPT Theorem"

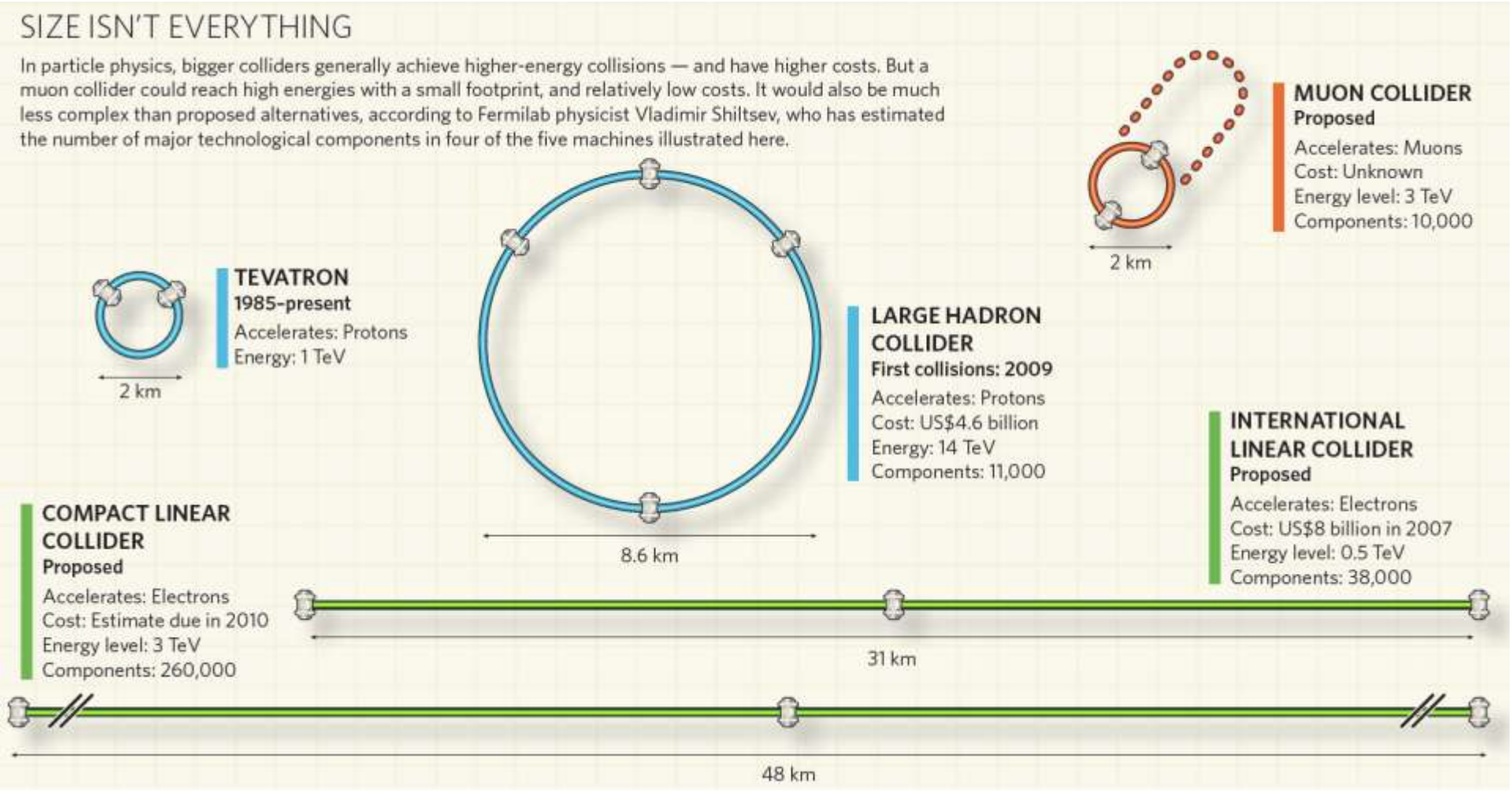
LHC Luminosity Outlook

Comparison of Particle Colliders

To reach higher and higher collision energies, scientists have built and proposed larger and larger machines.



Size, Cost and Complexity

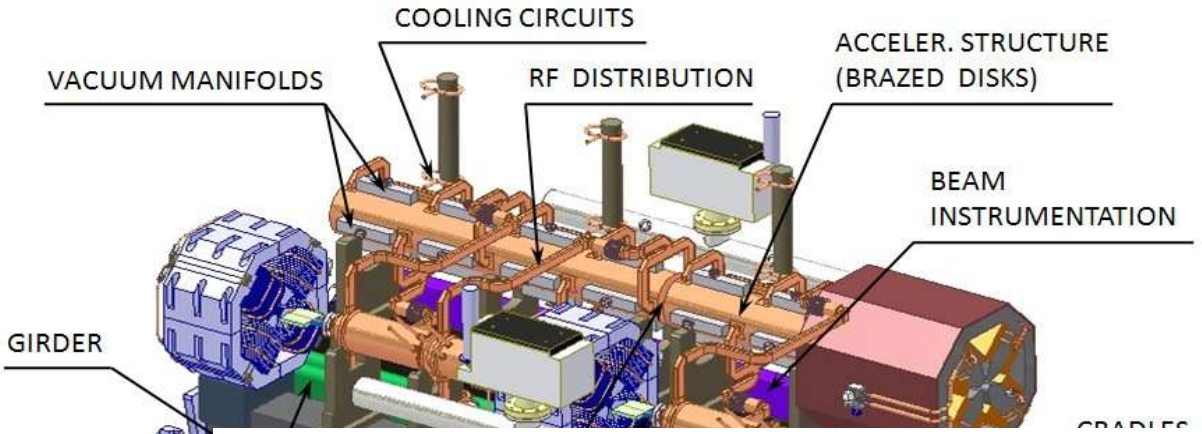


Nature 462, 260-261 (2009)

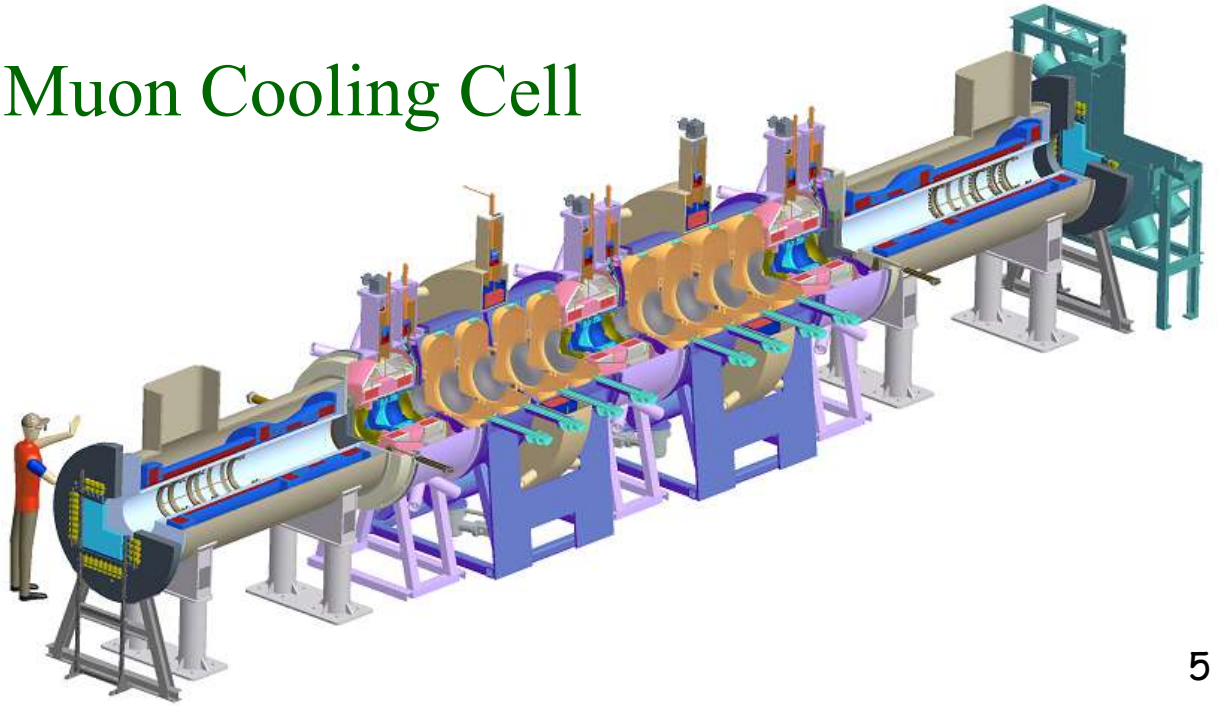
Accelerator Elements: “near” Future

ILC Cryomodul

CLIC Two-beams module

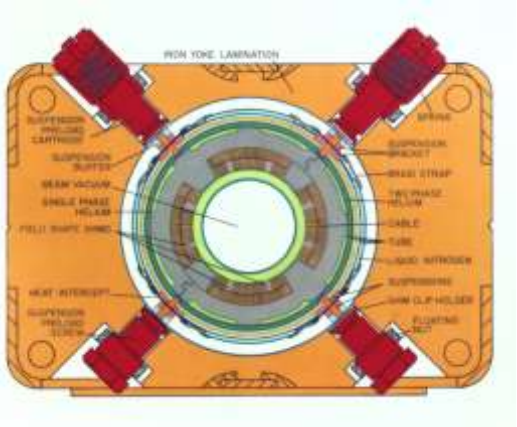


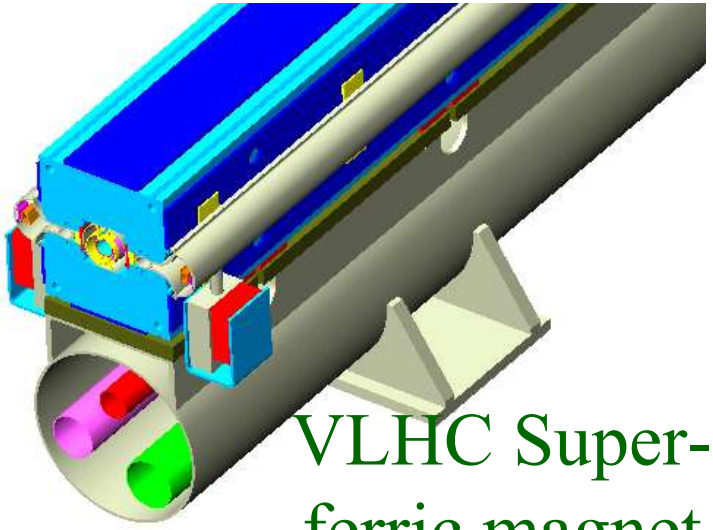
Muon Cooling Cell



Accelerator Elements : Present

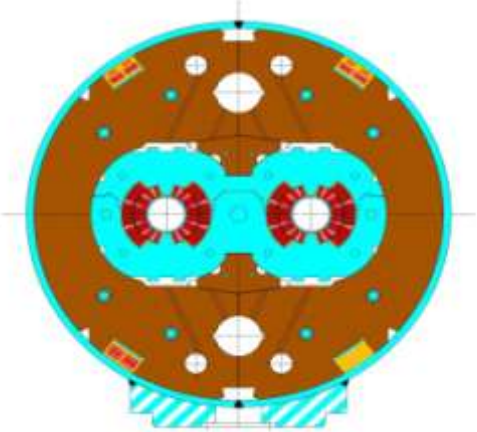
Tevatron
SC magnet

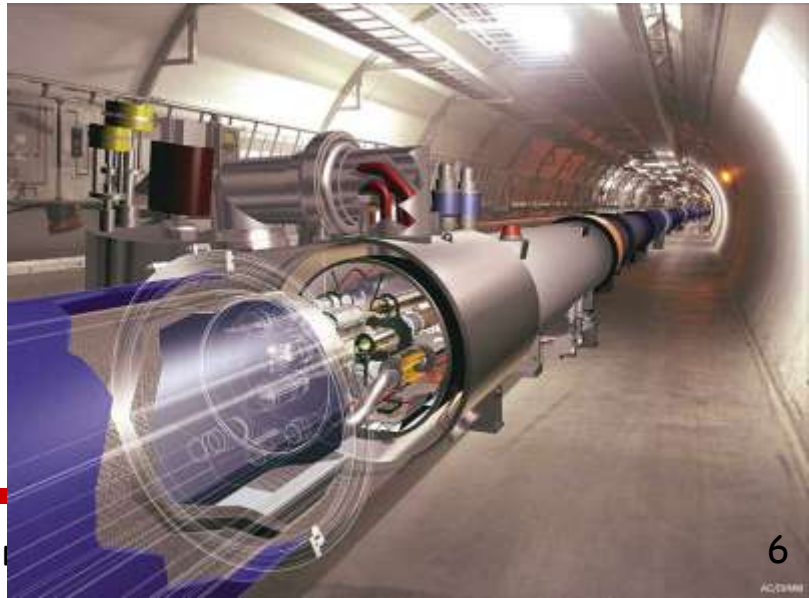




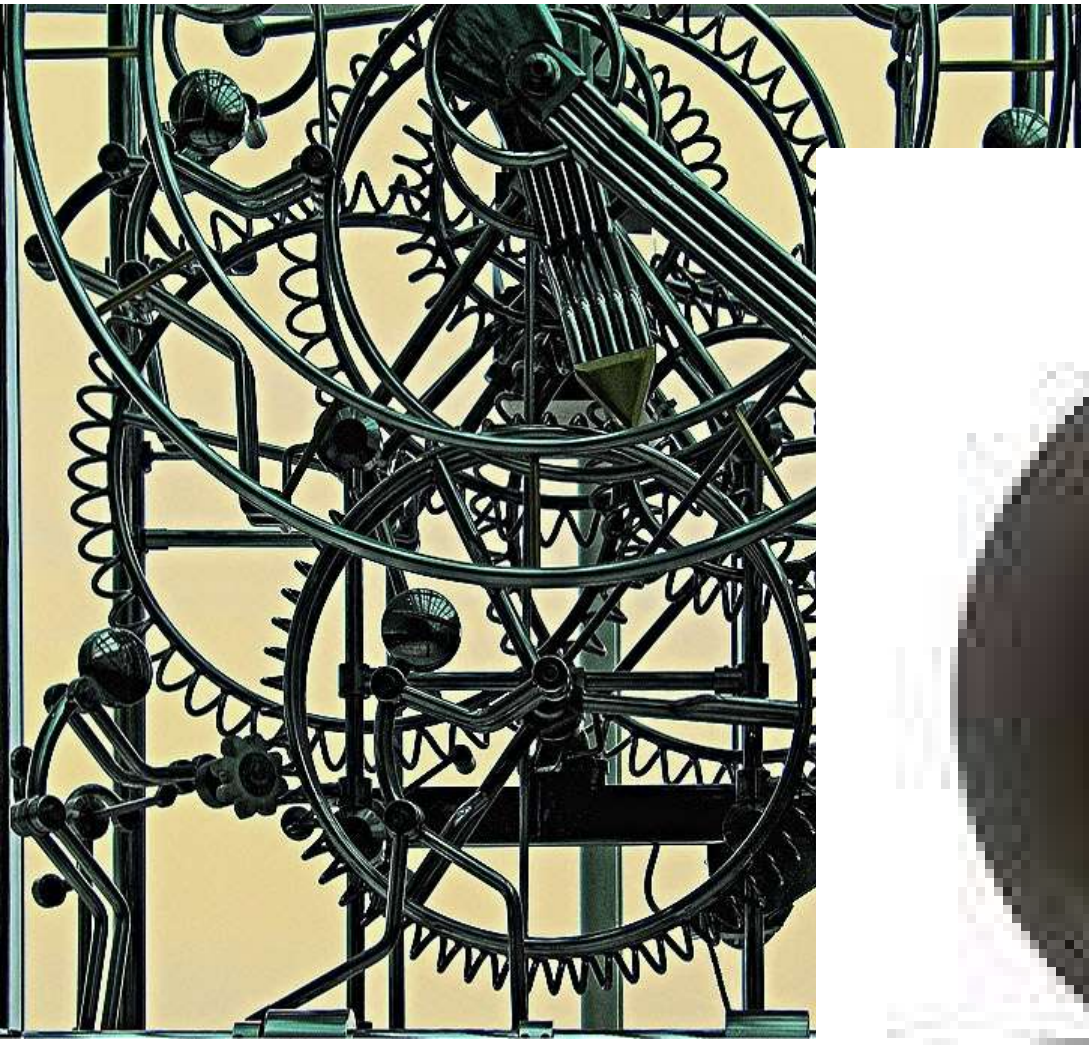
VLHC Super-
ferric magnet

LHC SC magnets





Complexity and Simplicity



Complexity is not just Number of Elements

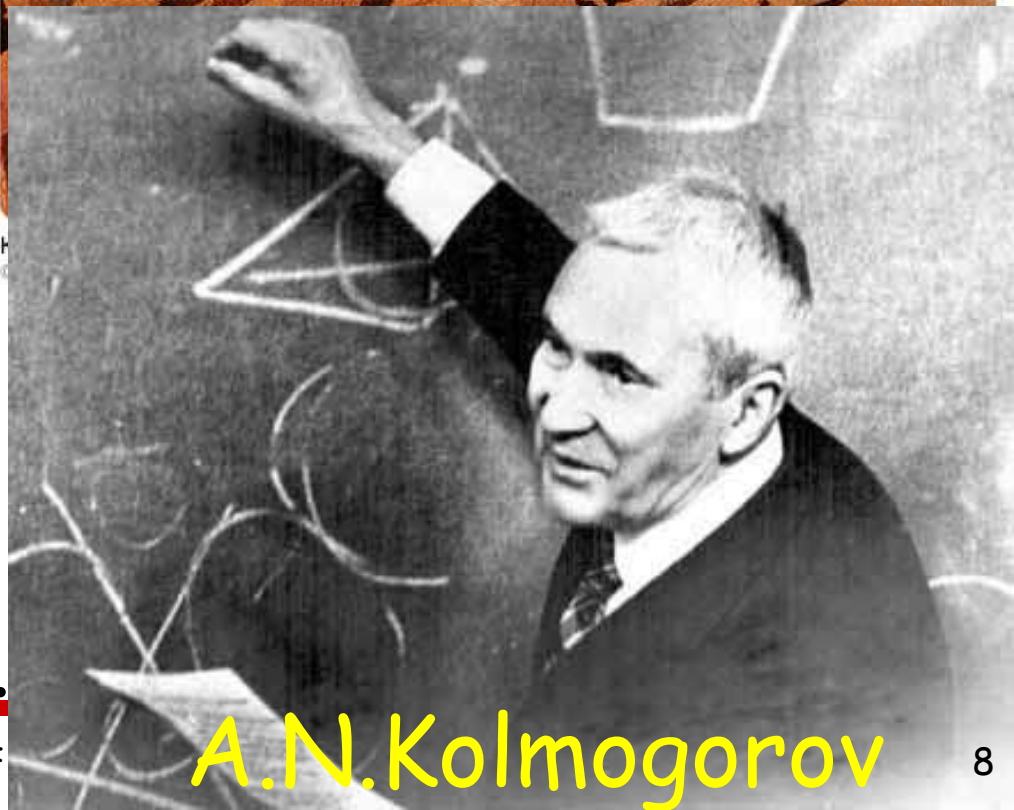
Kolmogorov's Complexity:

0101010101010....

110110110110110....

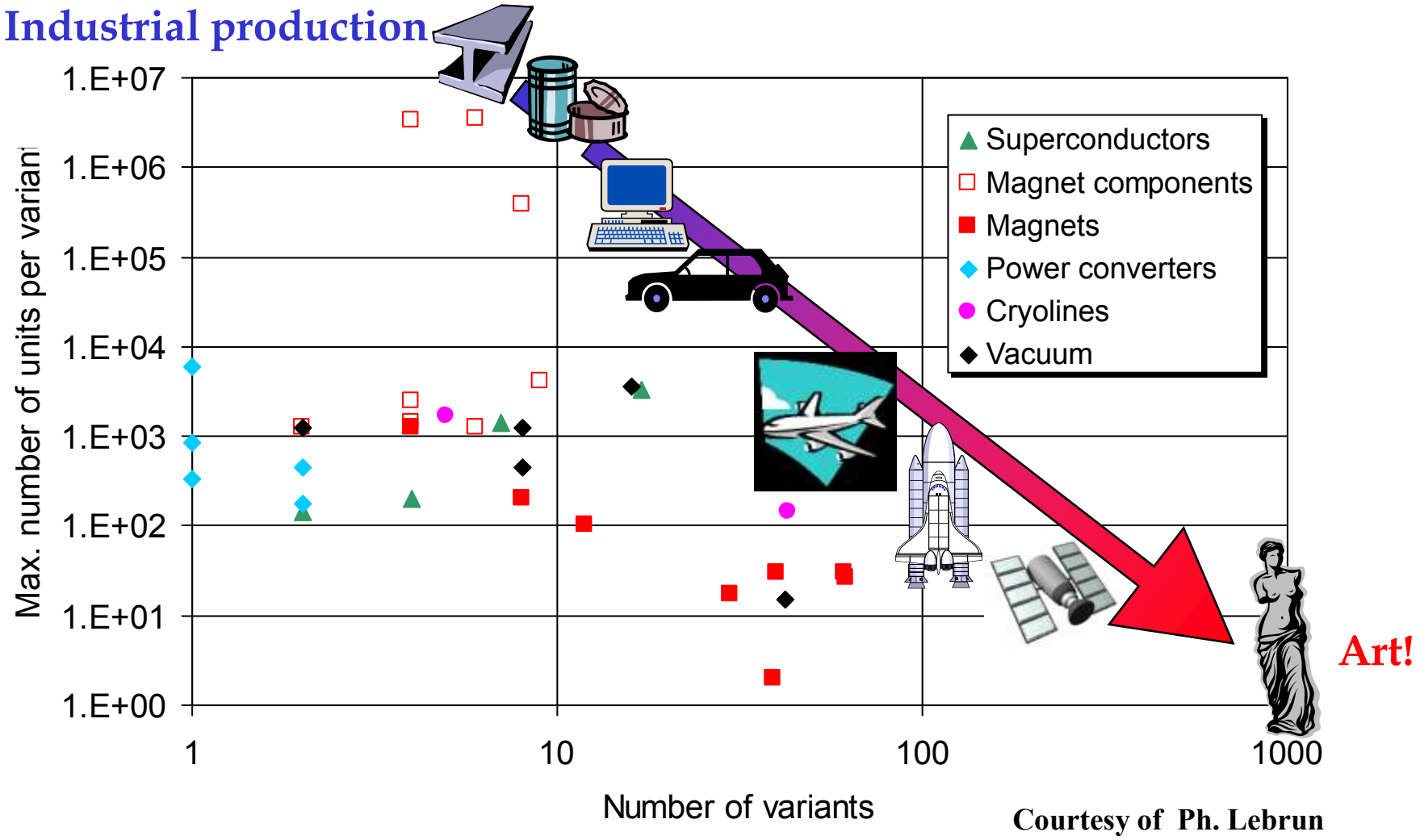
010010001000001.....

0100010111010101 1...



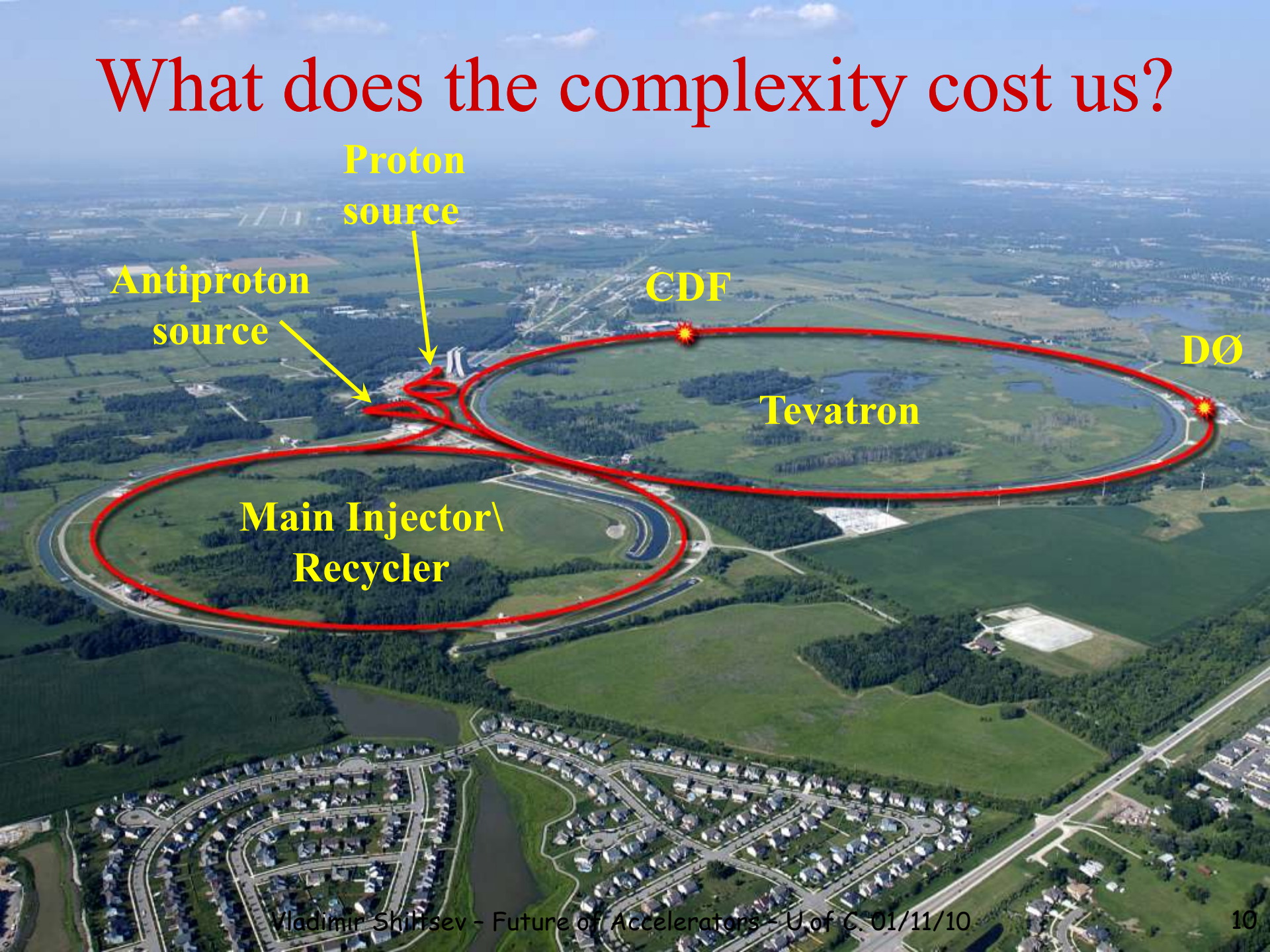
A.N.Kolmogorov

LHC components & industrial products



Courtesy of Ph. Lebrun

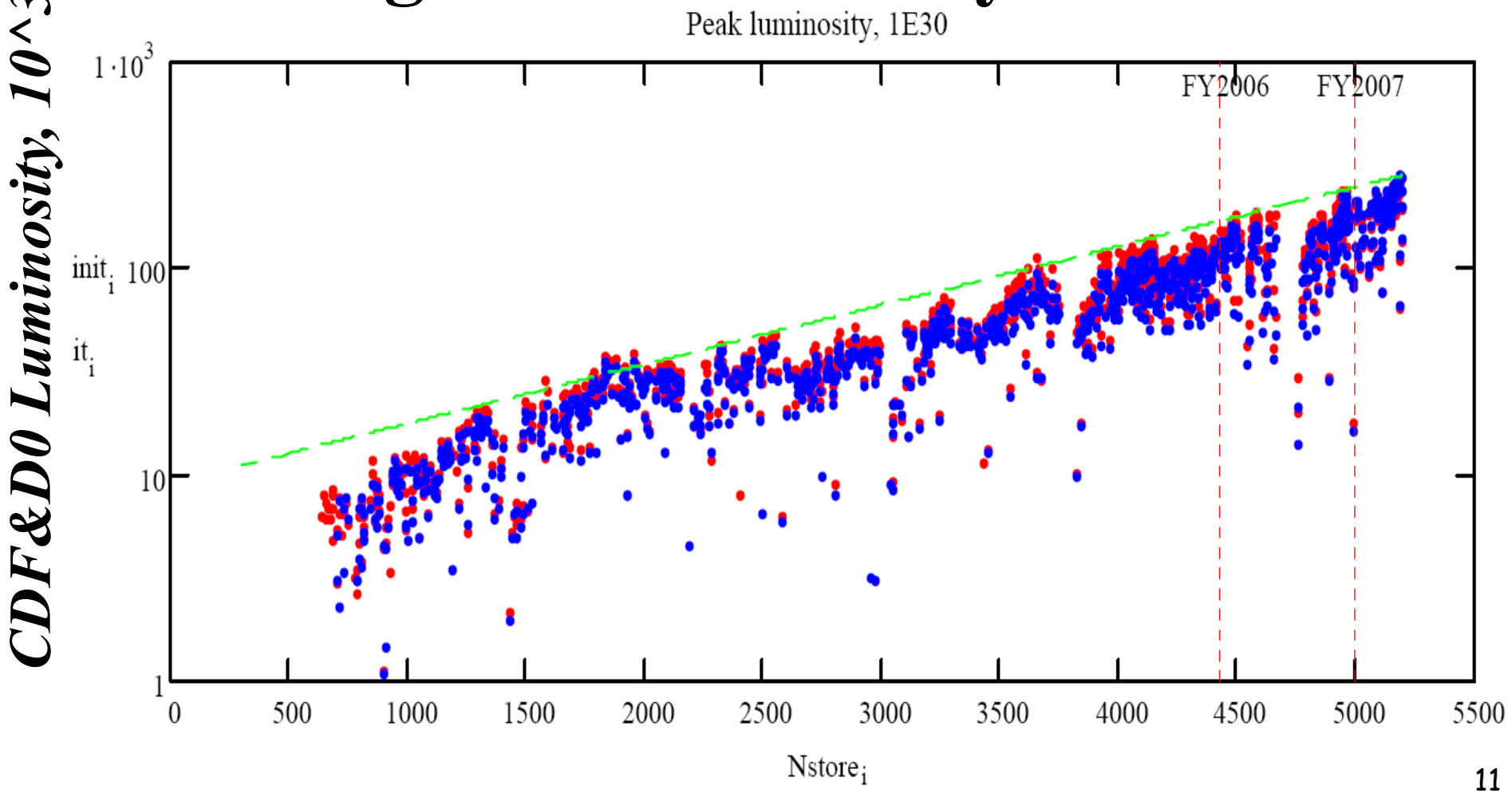
What does the complexity cost us?



Tevatron Luminosity Growth *log-lin*

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

e-growth time ~ 2 years



Tev Luminosity Improvements 2002-05

1.	Optics AA->MI lines fixed	Dec'01	~25 %
2.	New LB squeeze helix, TEL-1 abort	Mar'02	~40 %
3.	"New-new" injection helix	May'02	~15 %
4.	AA Shot lattice vs IBS	July'02	~40 %
5.	Tev BLT/inst.dampers at injection	Sep'02	~10 %
6.	Pbar coalescing improved in MI	Oct'02	~5 %
7.	C0 Lambertsons Removed	Feb'03	~15 %
8.	S6 cuircuit tuned/SEMs removed	June'03	~10 %
9.	"5 star" helix on ramp	Aug'03	~2 %
10.	Reshimming/Alignment	Nov'03	~12 %
11.	Longer Stores/ MI dampers	Feb'04	~19 %
12.	2.5MHz AA → MI trnsf/Cool shots	April'04	~8 %
13.	Reduction of beta* to 35 cm	May'04	~26 %
14.	Shots from Recycler	July'04	~20% (?)
15.	RR e-cooling operation	Jan-Jul'05	~25% (?)
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 %

2006-09 improvements

19. Pbar production task force	Feb'06	~10 %
20. Tevatron 150 GeV helix→ more p's	June'06	~10 %
21. Tev collision helix → lifetime	July'06	~15 %
22. New RR WP →emittances	Sep'06	~25 %
23. Fast AA→RR transfers (60→15min)	End'06	~15%
24. New Pbar target/higher gradient	Jan'07	~10%
25. Tevatron sextupoles for new WP	2007	~10(?)%
26. Tevatron optics Q"=0	2008	~5%?
27. Shot-setup time reduction/multi-p	2008-09	~5%?
28. Scraping protons in MI	2008-09	~3-4%?
29. Pbar emittance dilution/B0 aperture	2008-09	~2-4%?
30. MI Collim and Booster Correctors	2009	~3-5%?

Tevatron Experience - Lessons

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

#2: 30 steps resulted in ~36-fold increase in luminosity

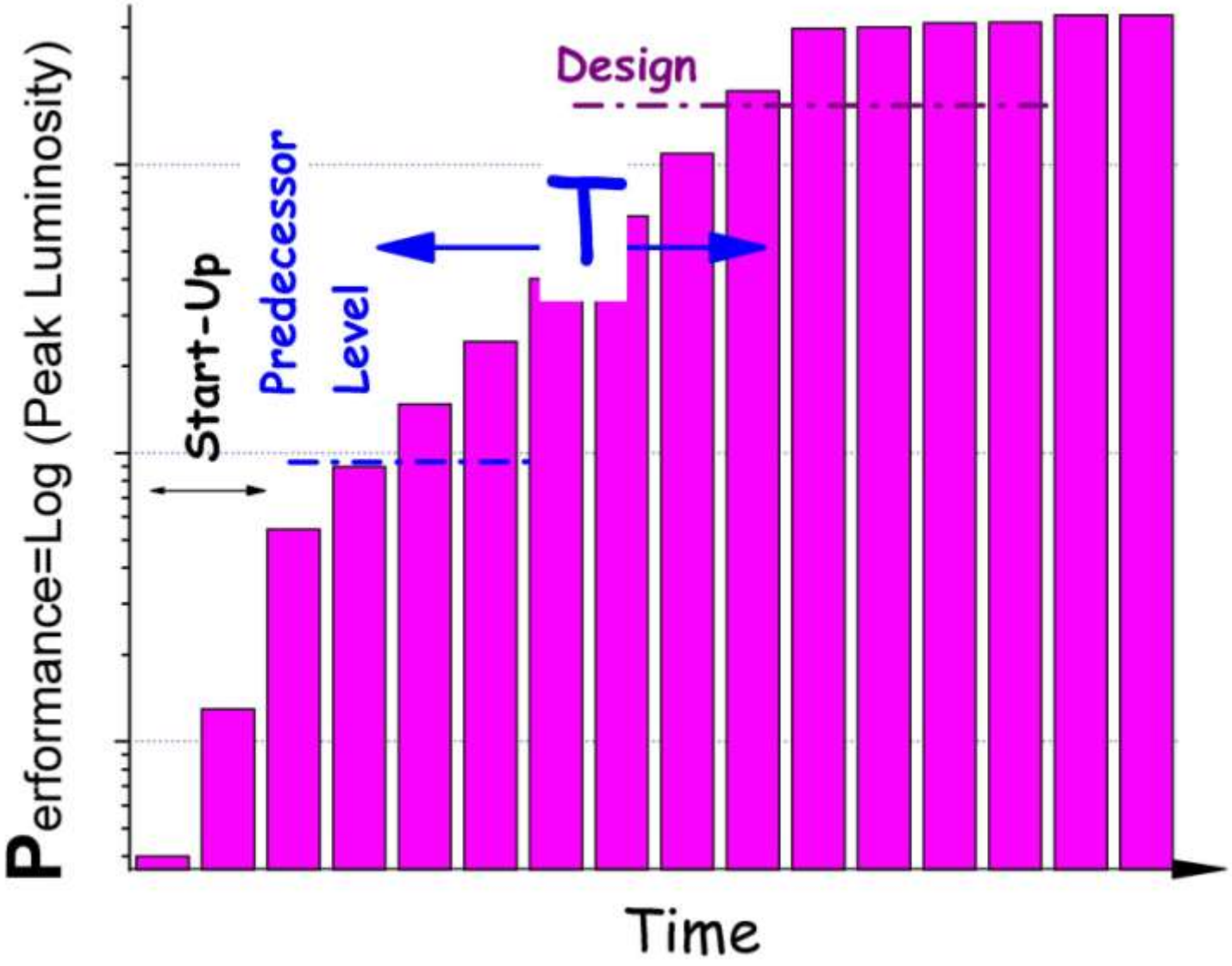
#3: that makes on average ~12.5% increase per step

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

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

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

Luminosity: "δ-Steps" Evolution



CPT Theorem for Accelerators

$$C \times P = T$$

C = Complexity

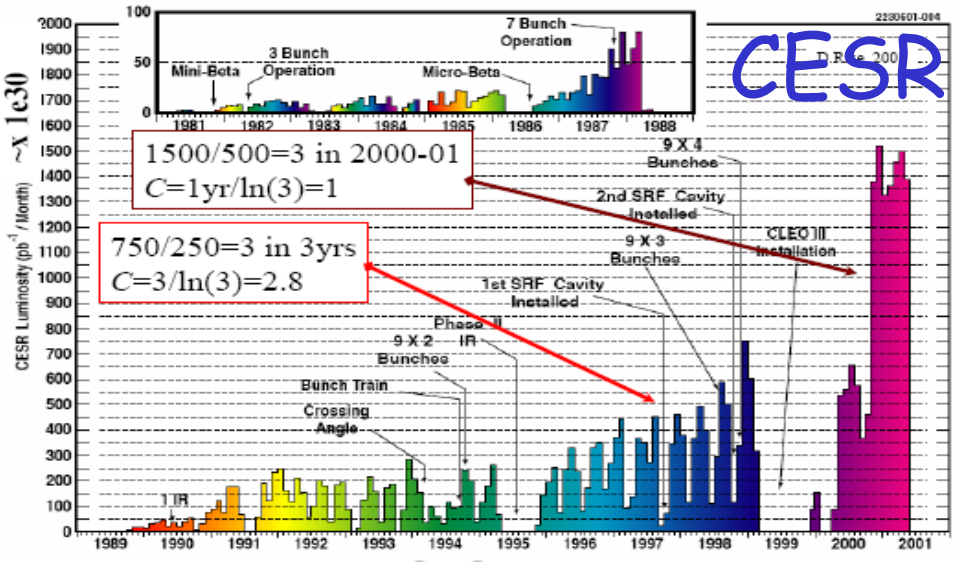
P = Performance

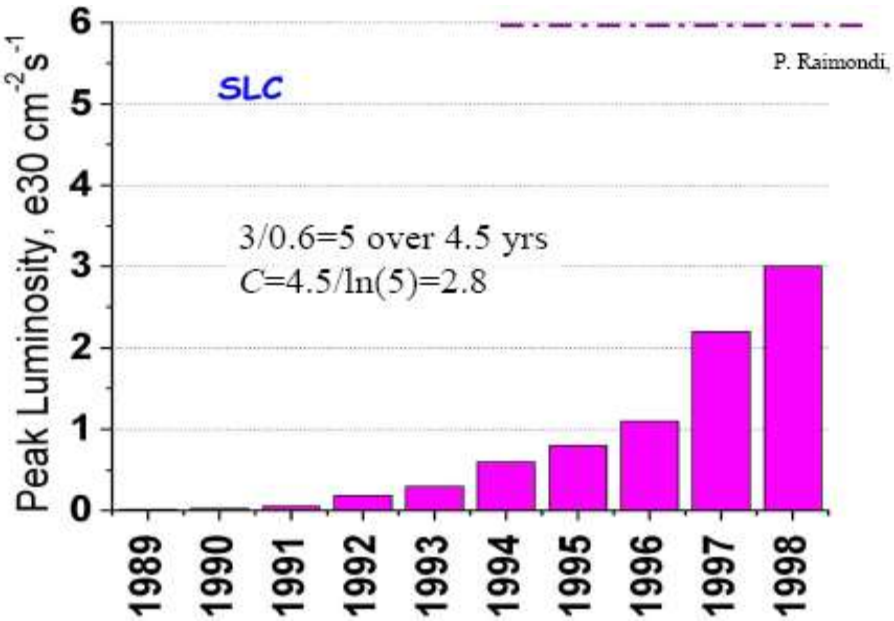
or Challenge = Ln(*Lumi*)

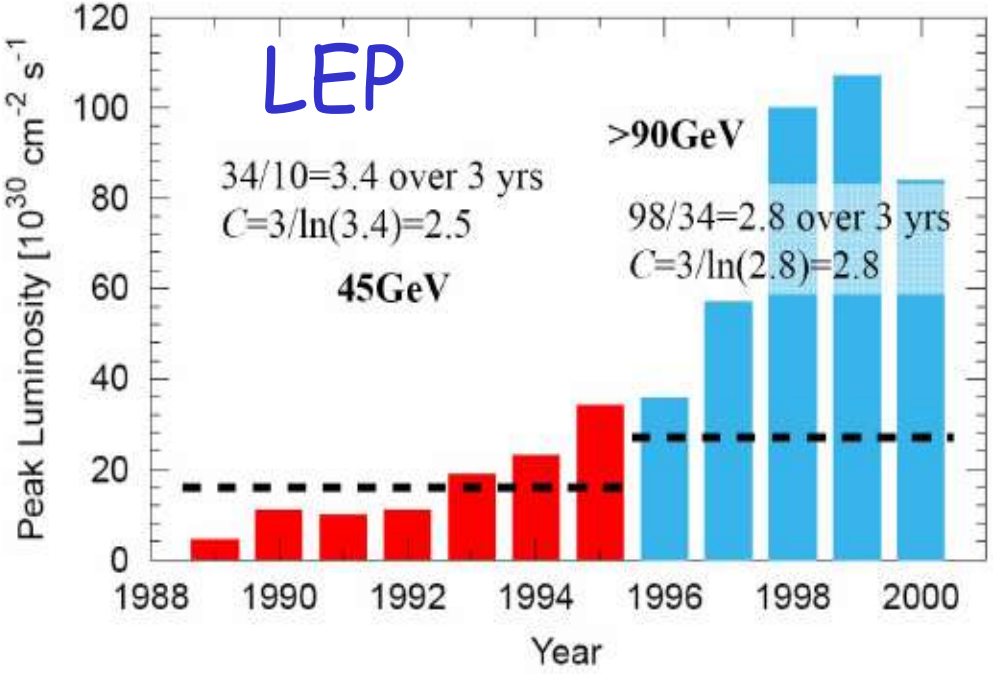
T = Time to reach P

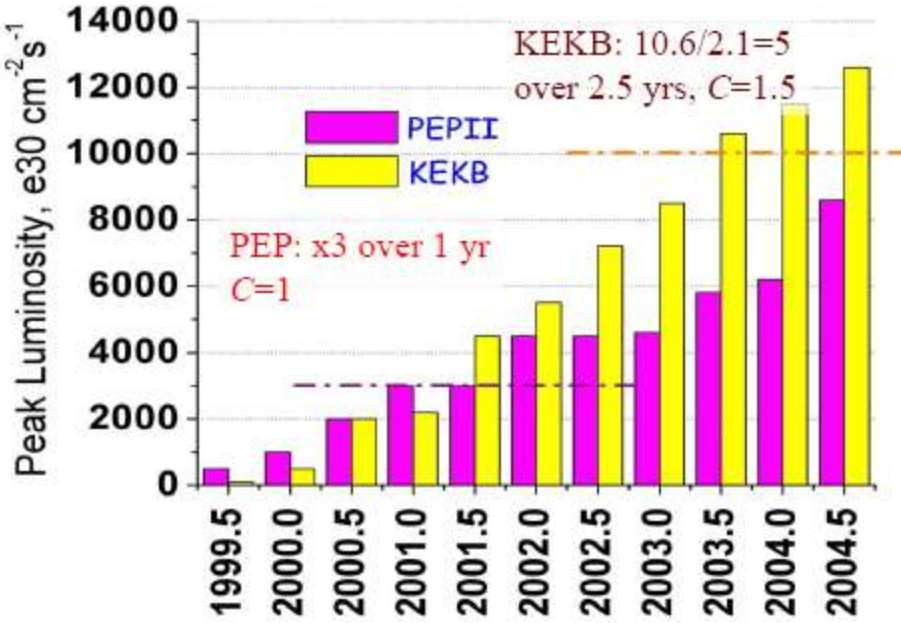
$$L(after\ time\ T) = L_0 \times \exp(T / C)$$

CESR, SLC, LEP, PEP-II, KEK-B

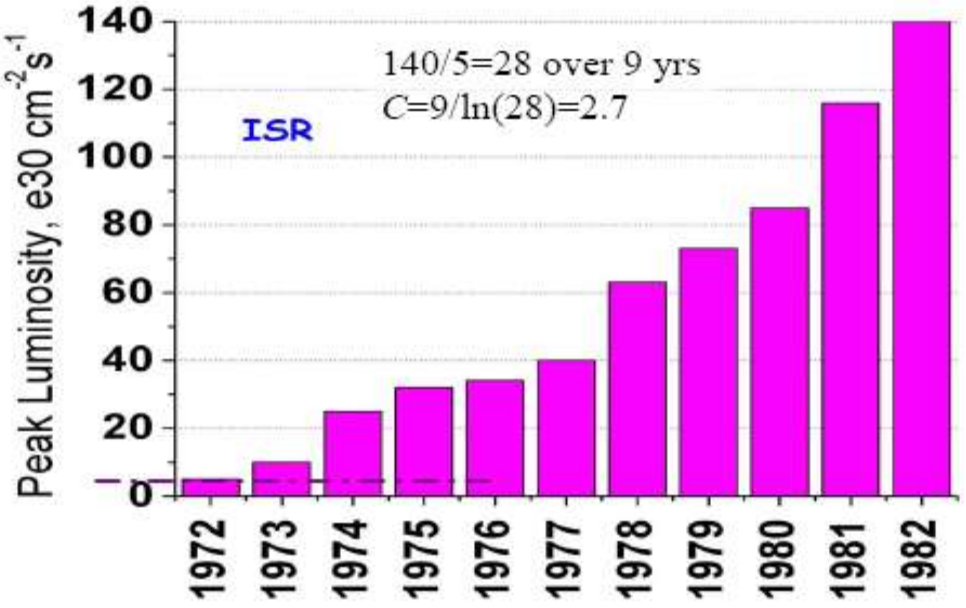


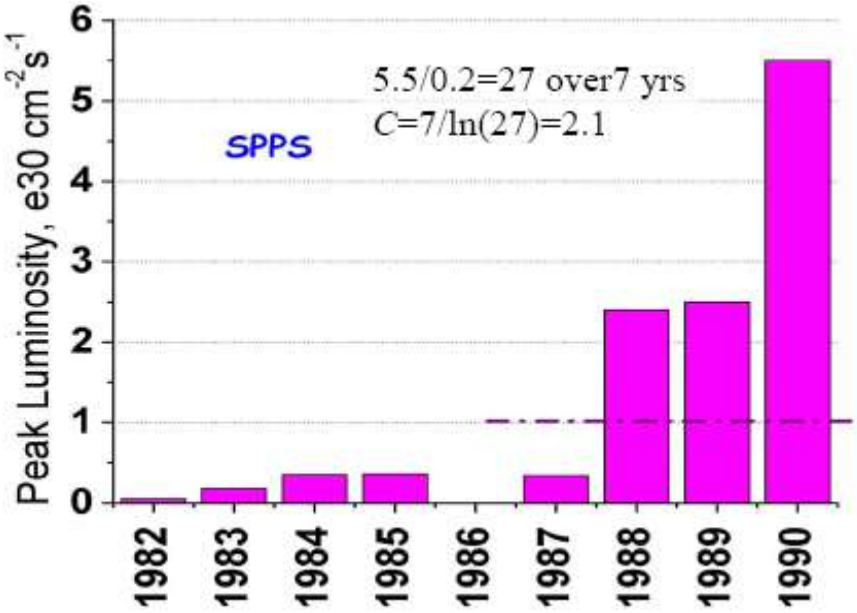


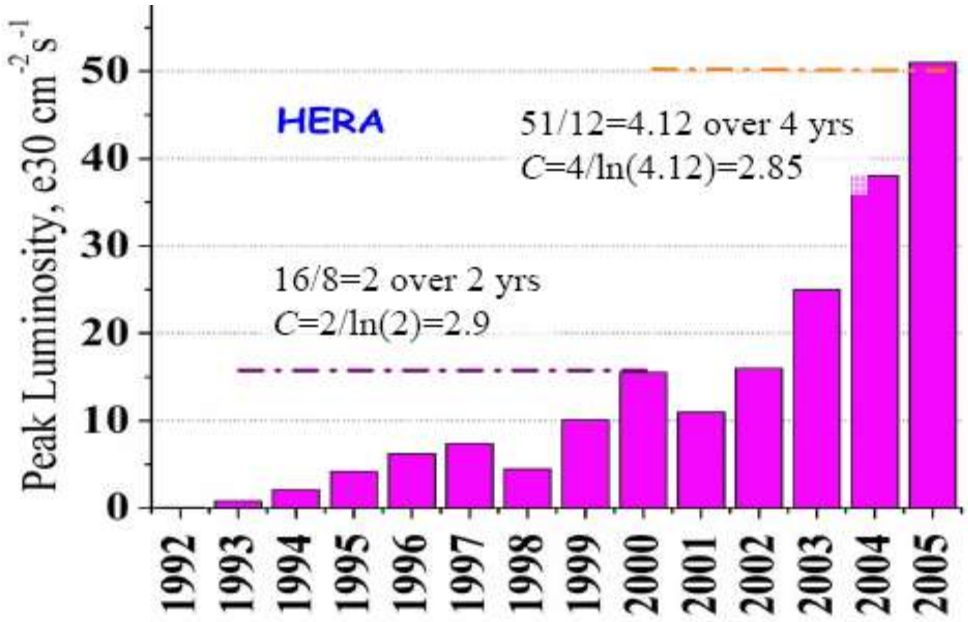


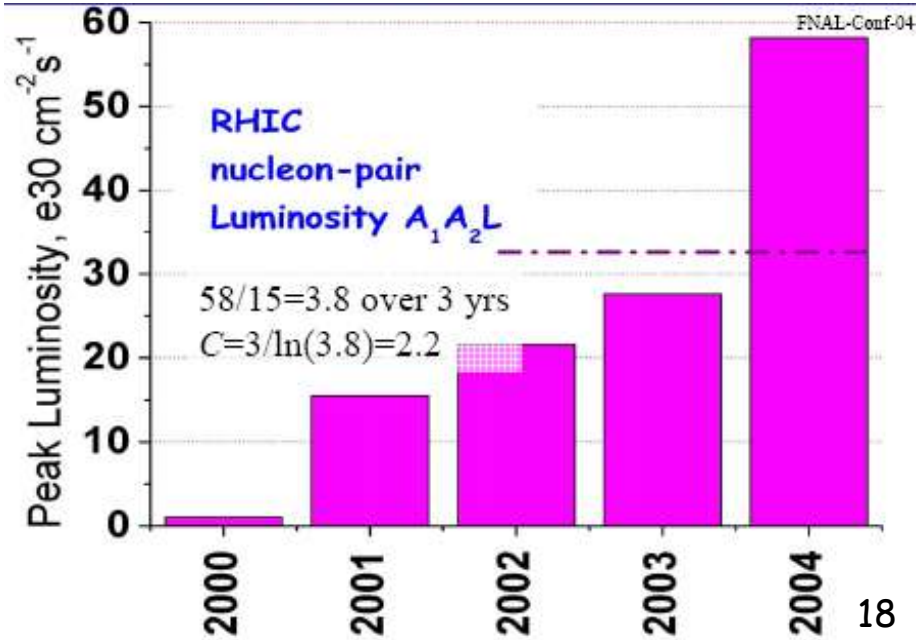


ISR, SppS, HERA, RHIC









The Art of Commissioning

It takes time to get to perfection…
~3-8 years for today's colliders

Leonardo worked on ***La Gioconda*** *from 1503 to 1508… and left it unfinished*

"Not Very Complex Machine"

Constructed on schedule and within 400M$ budget

9 months of commissioning

Complexity=0

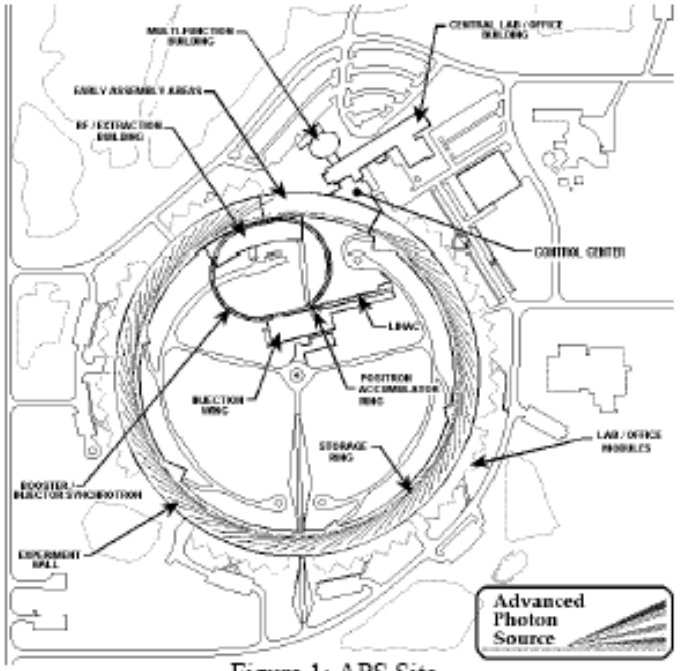


Figure 1: APS Site.

Another "Not Very Complex Machine"

Fermilab's Main Injector

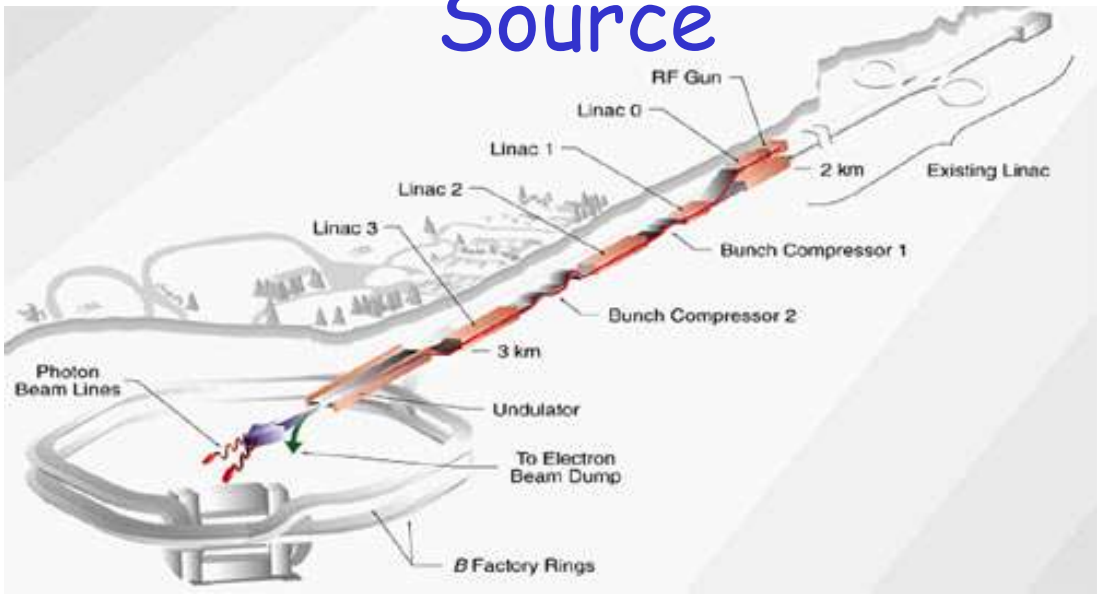
Constructed on schedule and within 200M$ budget

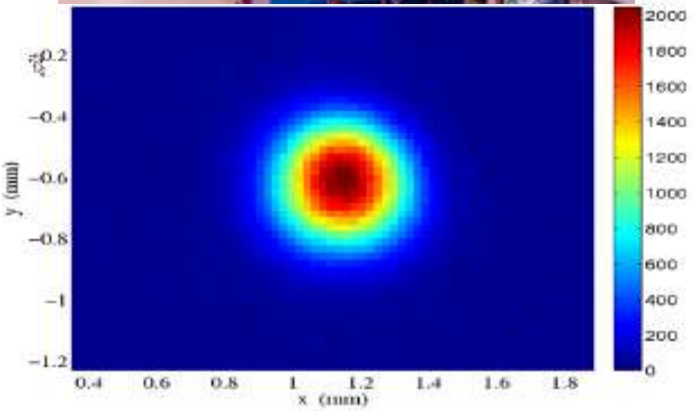
6 months of commissioning

Complexity=0

"Negative Complexity" - ???

SLAC Linac Coherent Light Source





"…This is the most difficult lightsource that has ever been turned on, " said LCLS Construction Project Director John Galayda. "It's on the boundary between the impossible and possible, and within two hours of start-up these guys had it right on…"

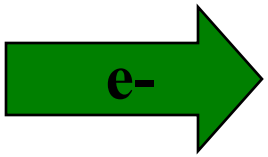
"…used only 12 of an eventual 33 undulators…" ***SLAC Press Release, April 28, 2009***

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

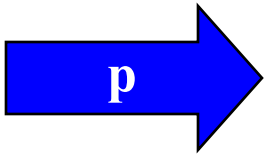
Complexity of Beams

Complexity 0-0.5



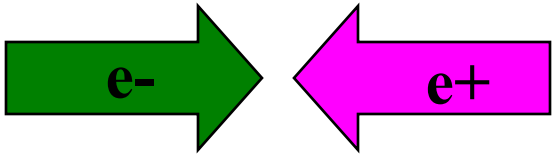
APS, LCLS

Complexity 0.5-1



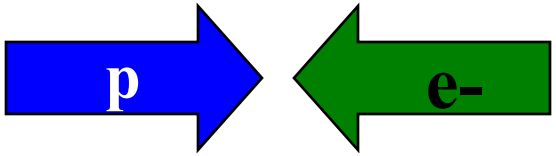
FNAL/MI

Complexity 1



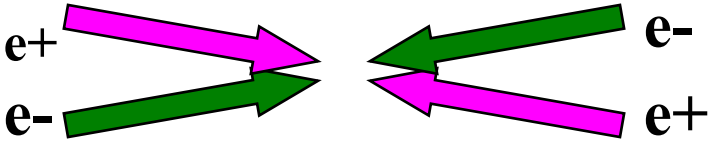
B-factories

Complexity 1.5



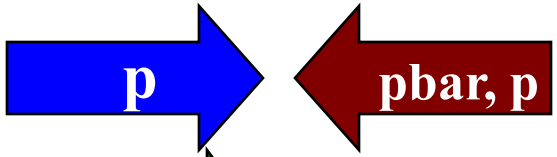
HERA

Complexity 2



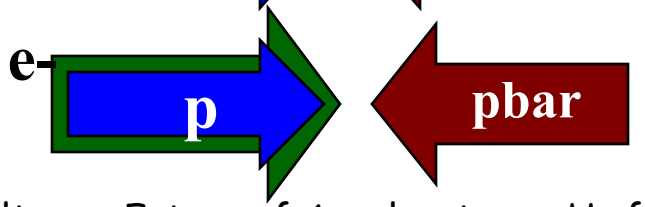
DCI/Orsay,80

Complexity 2



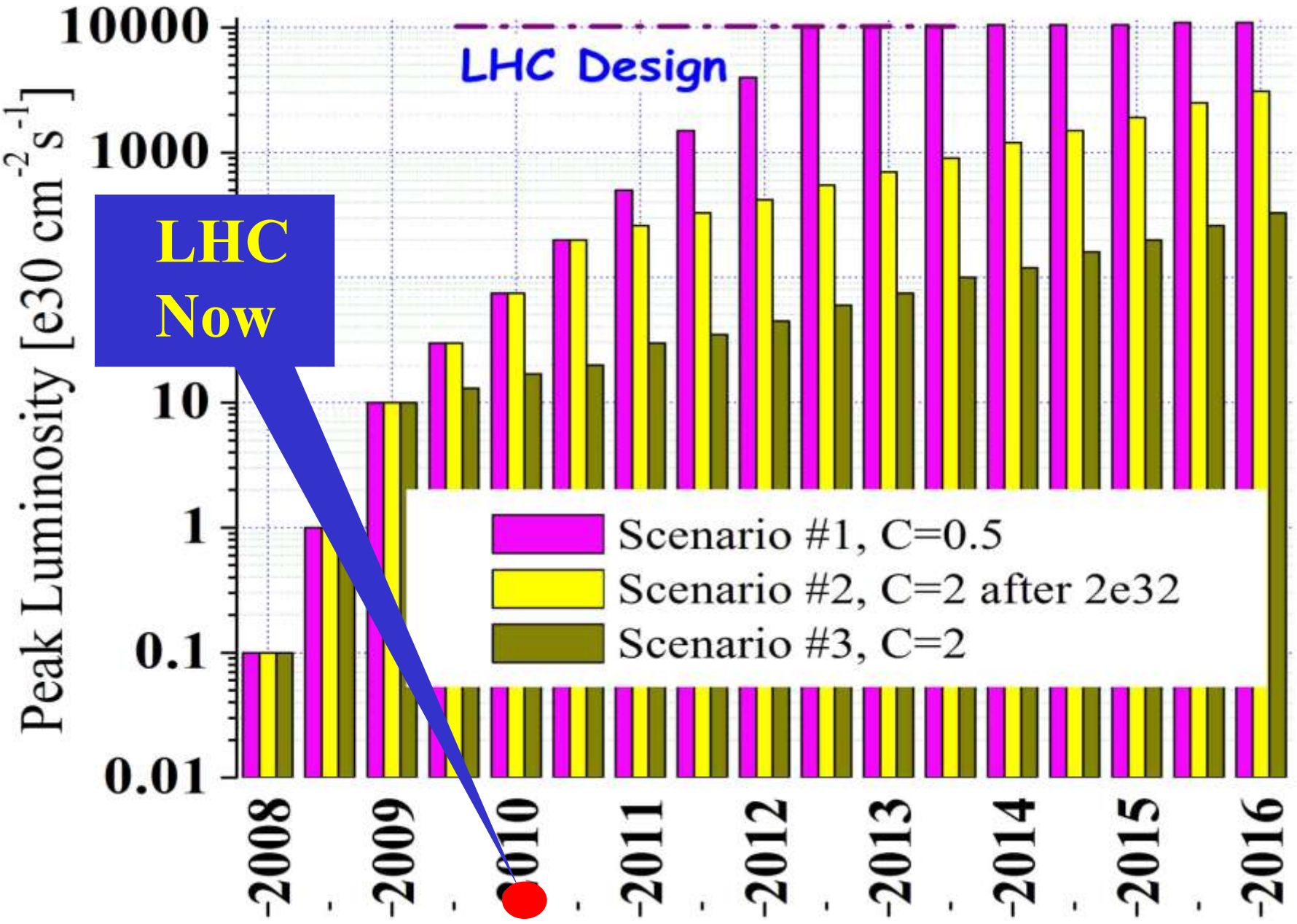
Tevatron,LHC

Complexity 2.5



B-B-Comps'n

Scenarios of LHC Luminosity ca'07



Three Points of Part I:

- **Accelerators are complex:**
  - "Complexity" depends on the type (# beams, type of particles) and size of the machine
  - Energy Frontier Colliders are the most complex
  - Small single beam accelerators are "simple", have numerous applications and built in dozens-to-hundreds
- **Don't hold your breath for very fast ramp of the LHC luminosity to design value** (CPT theorem)
- **Accelerators are really a conjunction of Technology, Art and Science:**
  - "state-of-the-art" magnet and/or RF technology
  - long battles for performance need "artistic" ingenuity
  - capitalized on many scientific breakthroughs.. more under study →

PART II:

Science of Accelerators

New Ideas, Crazy Ideas

New Paradigm for HEP

"Look Into Future" – 60 Years Ago

Major Advances since 1951:

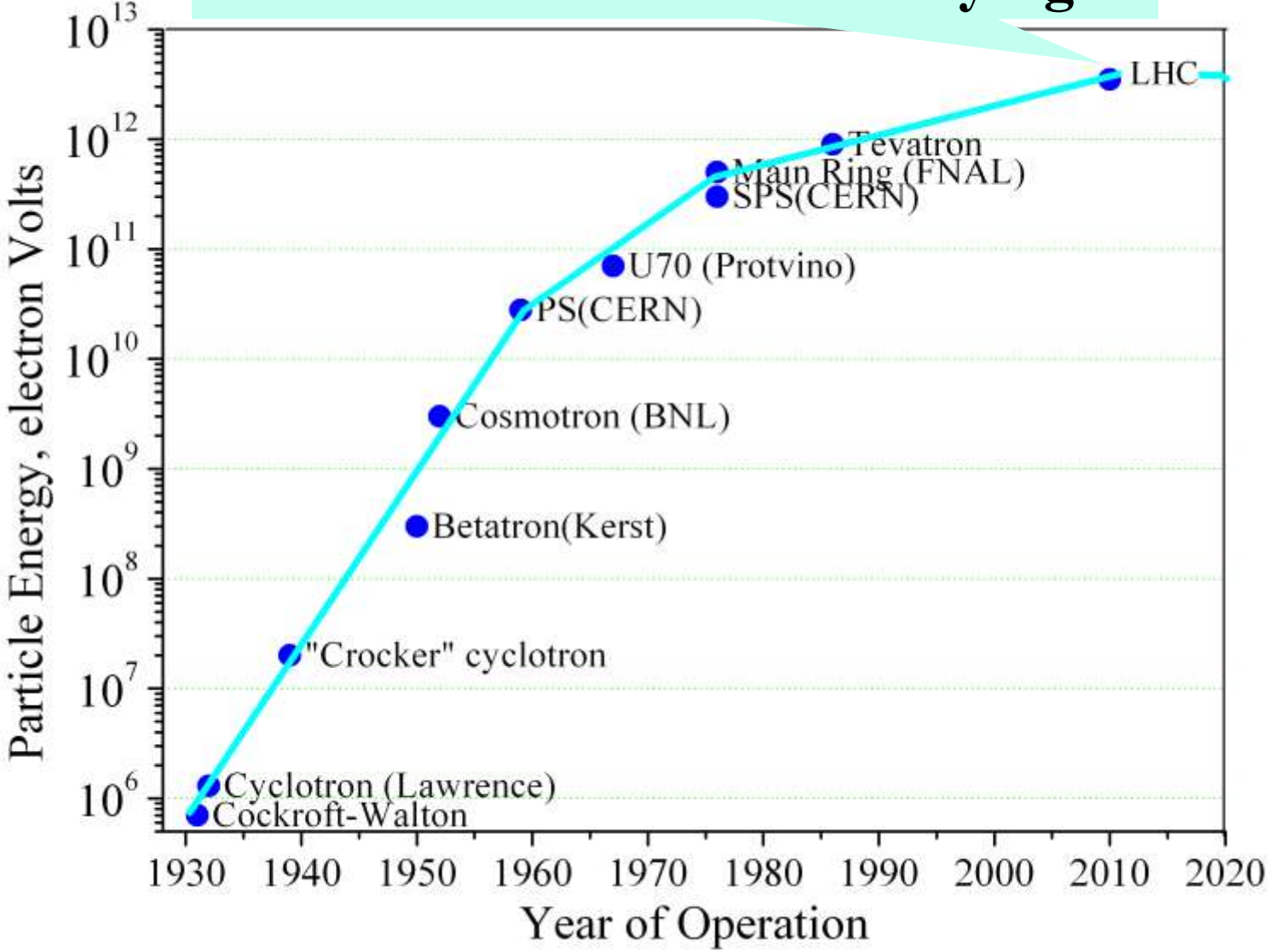
- Strong Focusing
- Colliding Beams
- Super-conducting Magnets
- Super-conducting RF

"…Looking to the future, it is difficult to see how particles of energy greater than 10,000 MeV can be produced economically by existing methods. Further progress may have to await the introduction of new ideas."

Ernest T.S. WALTON, Nobel Lecture, Dec. 11, 1951

Energy Frontier History

Is the field of accelerators dying?



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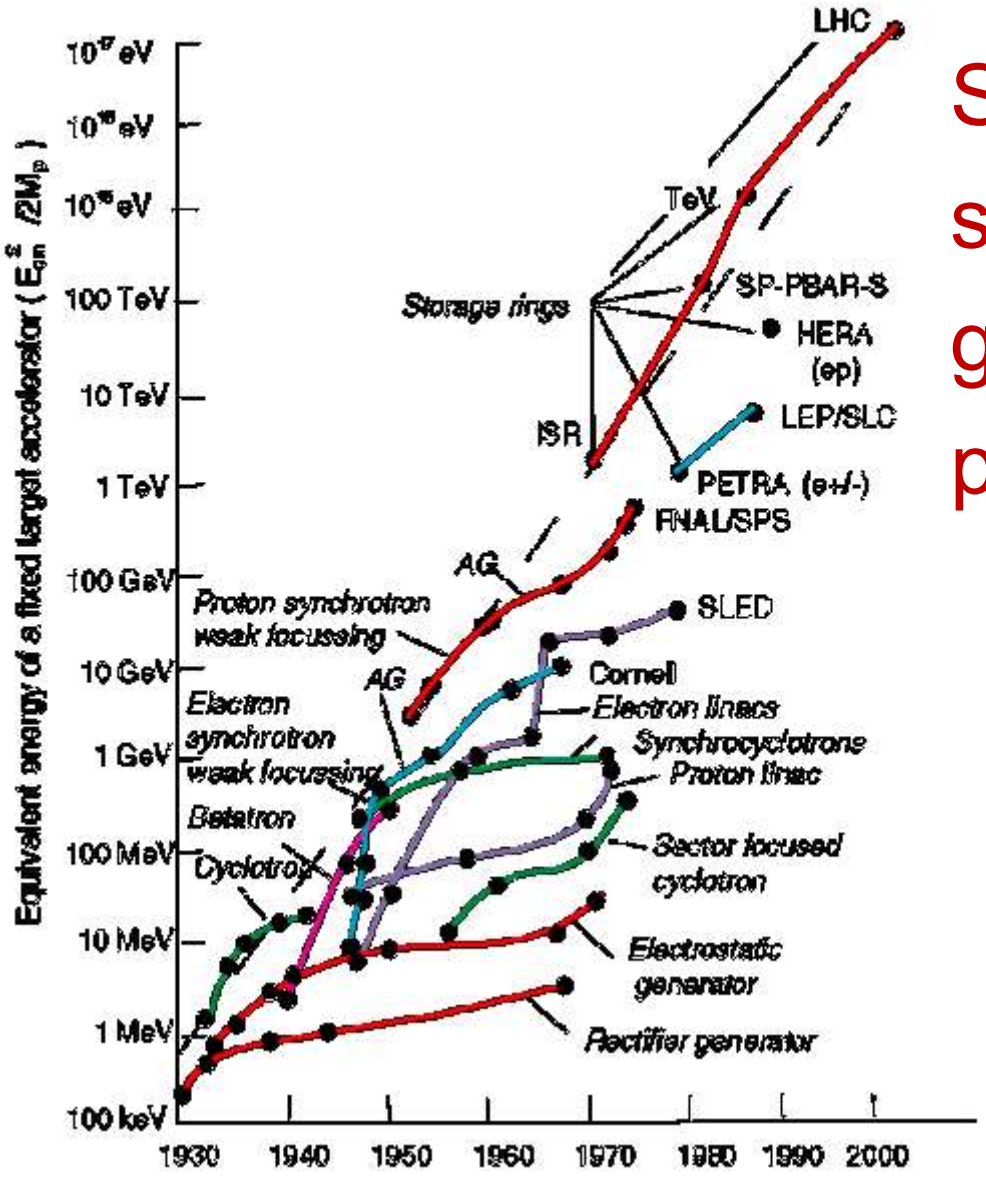
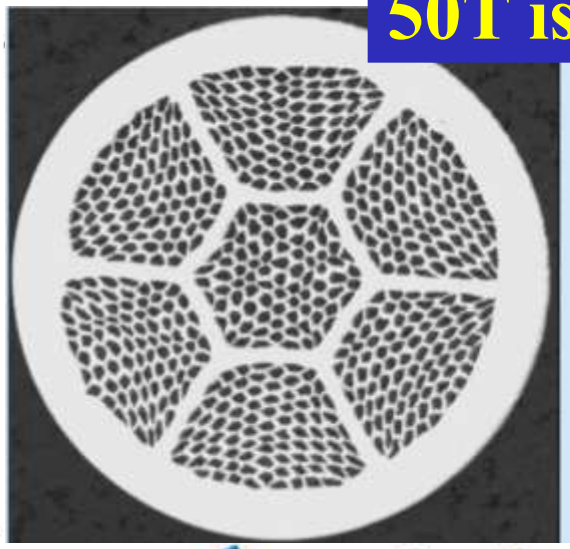


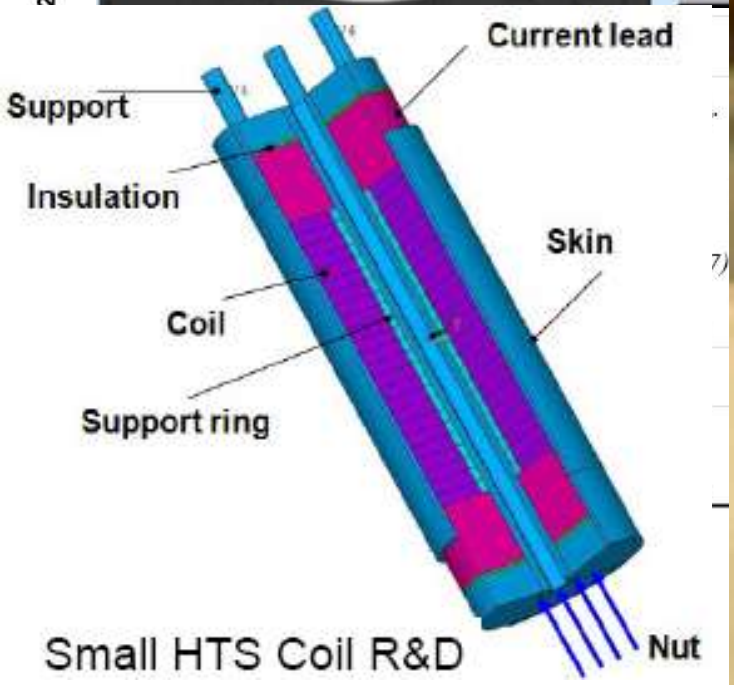
Situation looked similarly dim at any given moment, and the progress was due to:

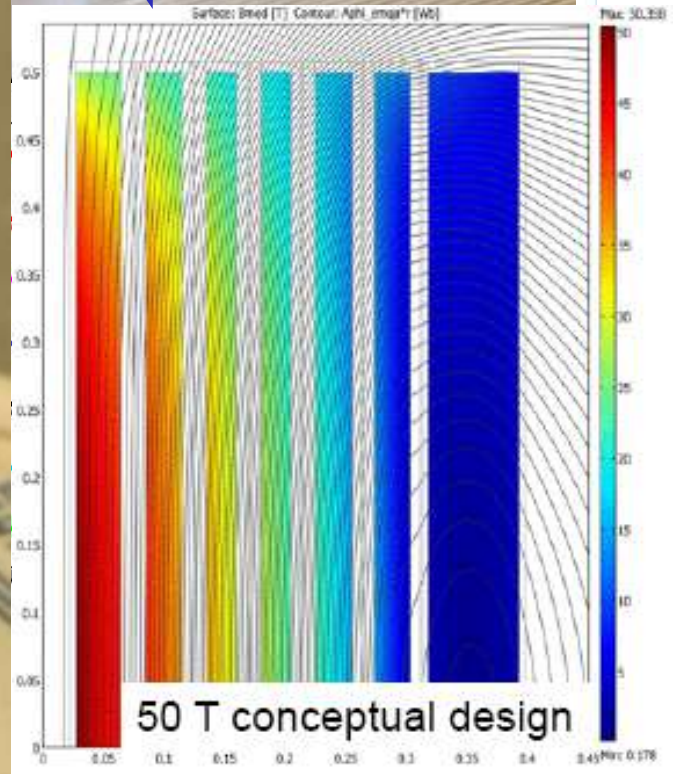
- push existing technologies
- improve beam handling
- develop new ideas
- think “out of box” (drop some requirements)

Advancing Technology - Magnets

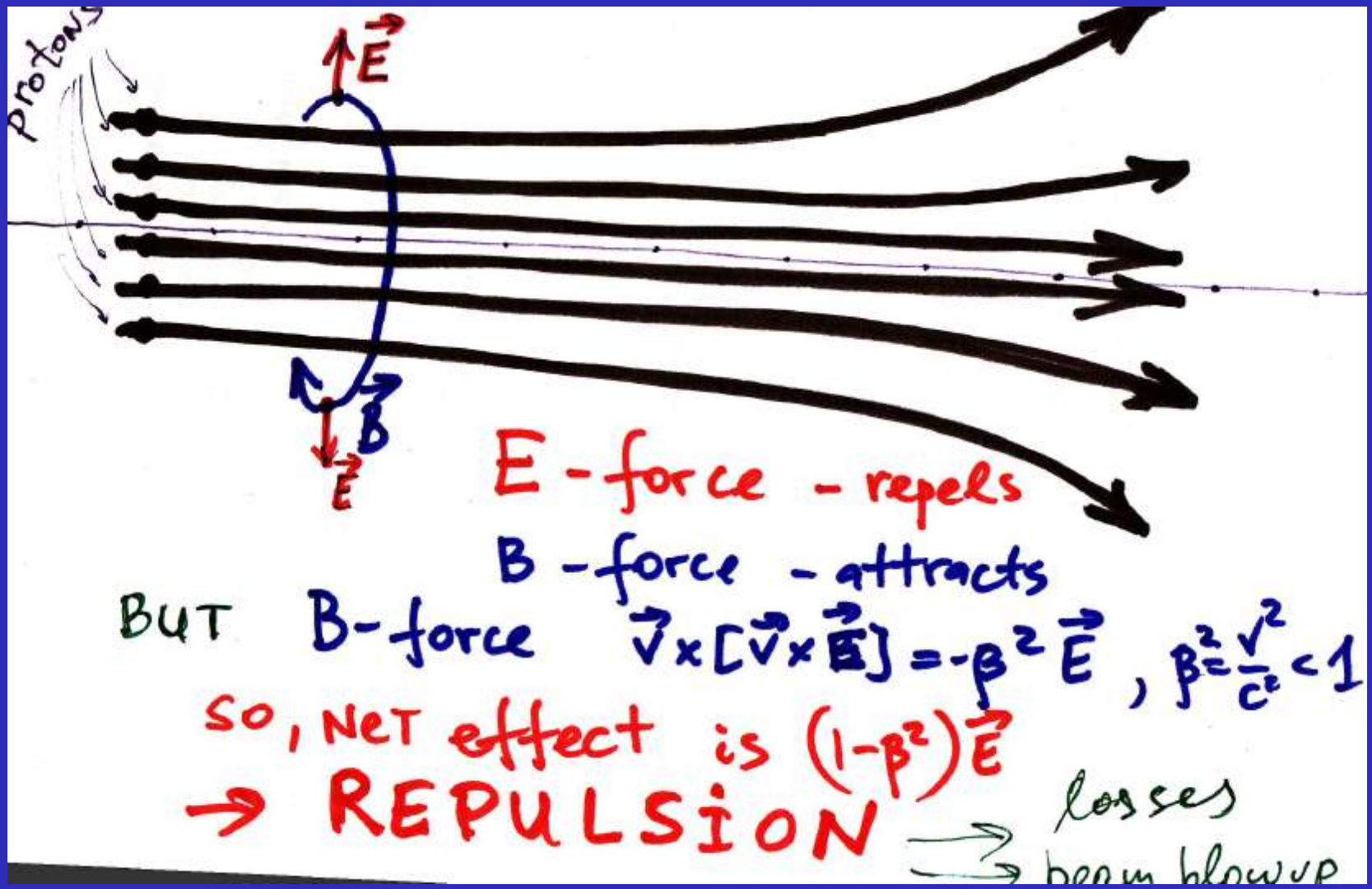
50T is 10x Tevatron and 5x LHC





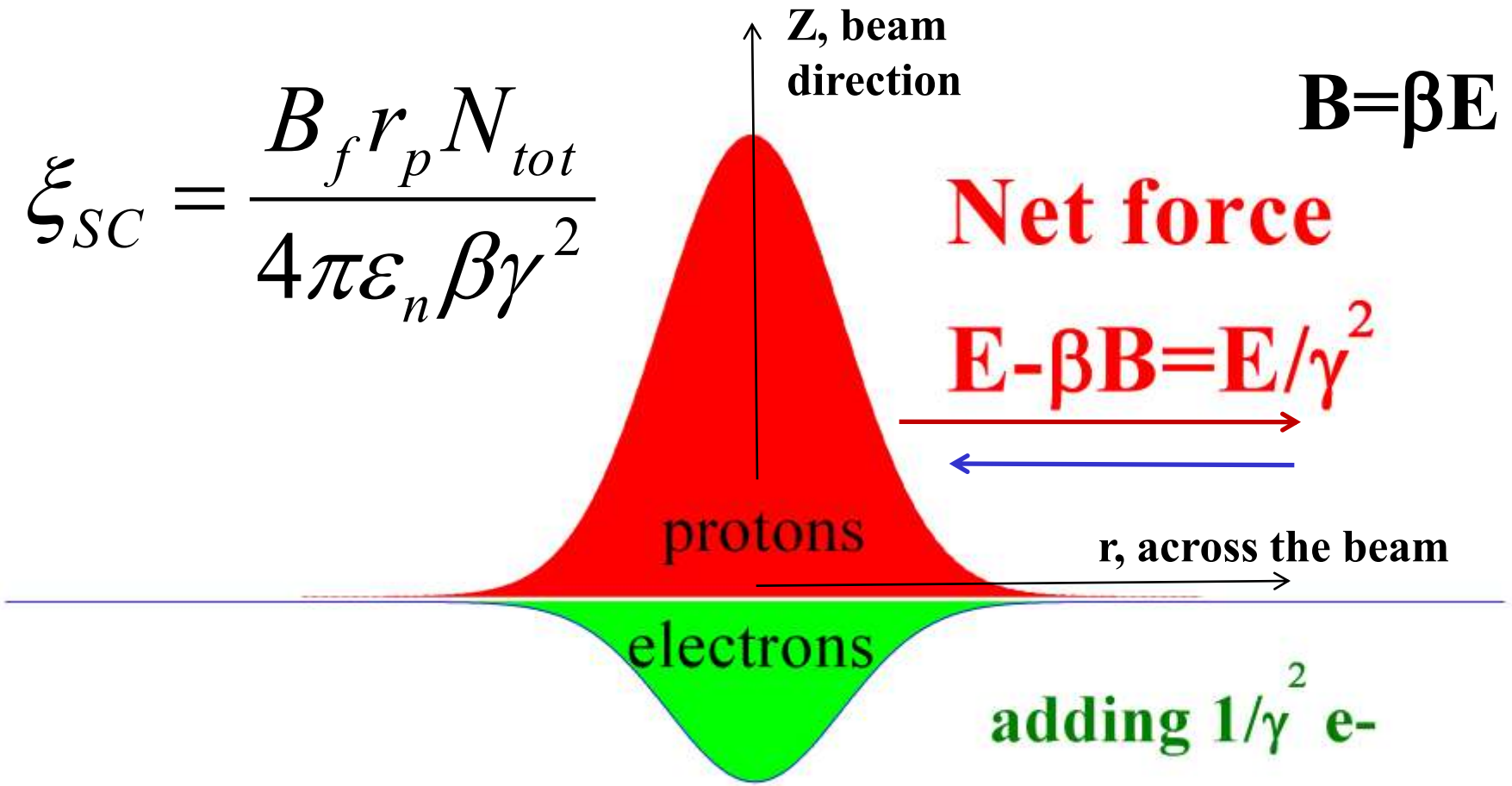


Better Beam Handling - Repulsion



Space Charge Neutralization

$$\xi_{SC} = \frac{B_f r_p N_{tot}}{4\pi\varepsilon_n \beta\gamma^2}$$



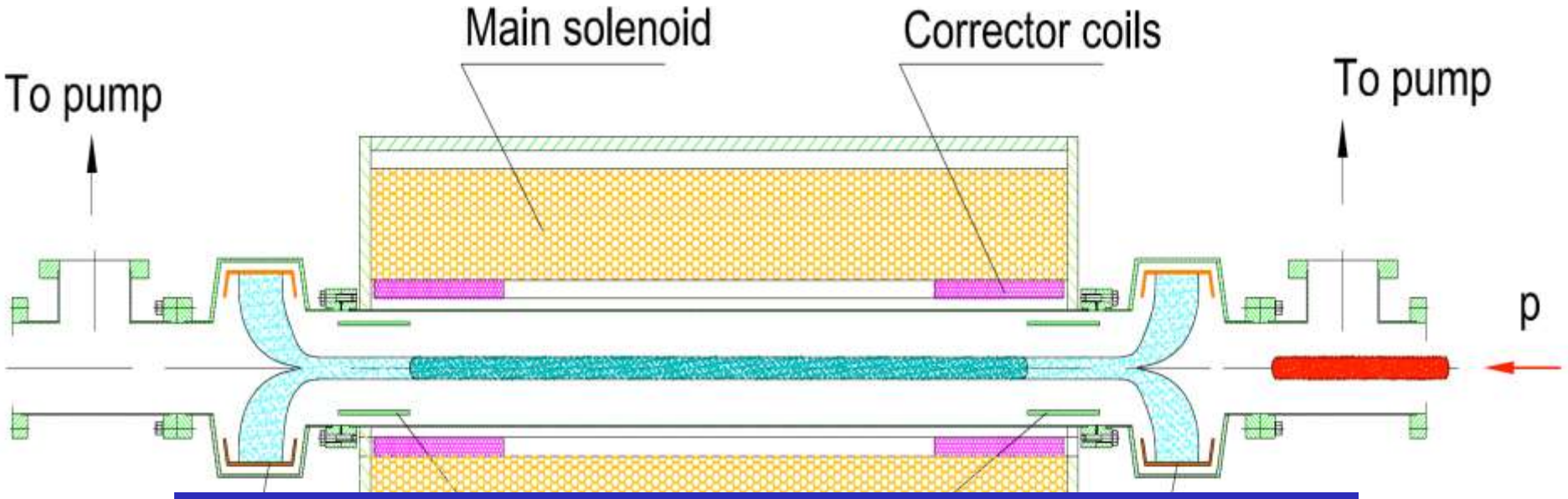
Budker , 1956 …. Studies, tests → not stable!

→ let's immerse in magnetic field (e-column)

e-Column for FNAL Main Injector

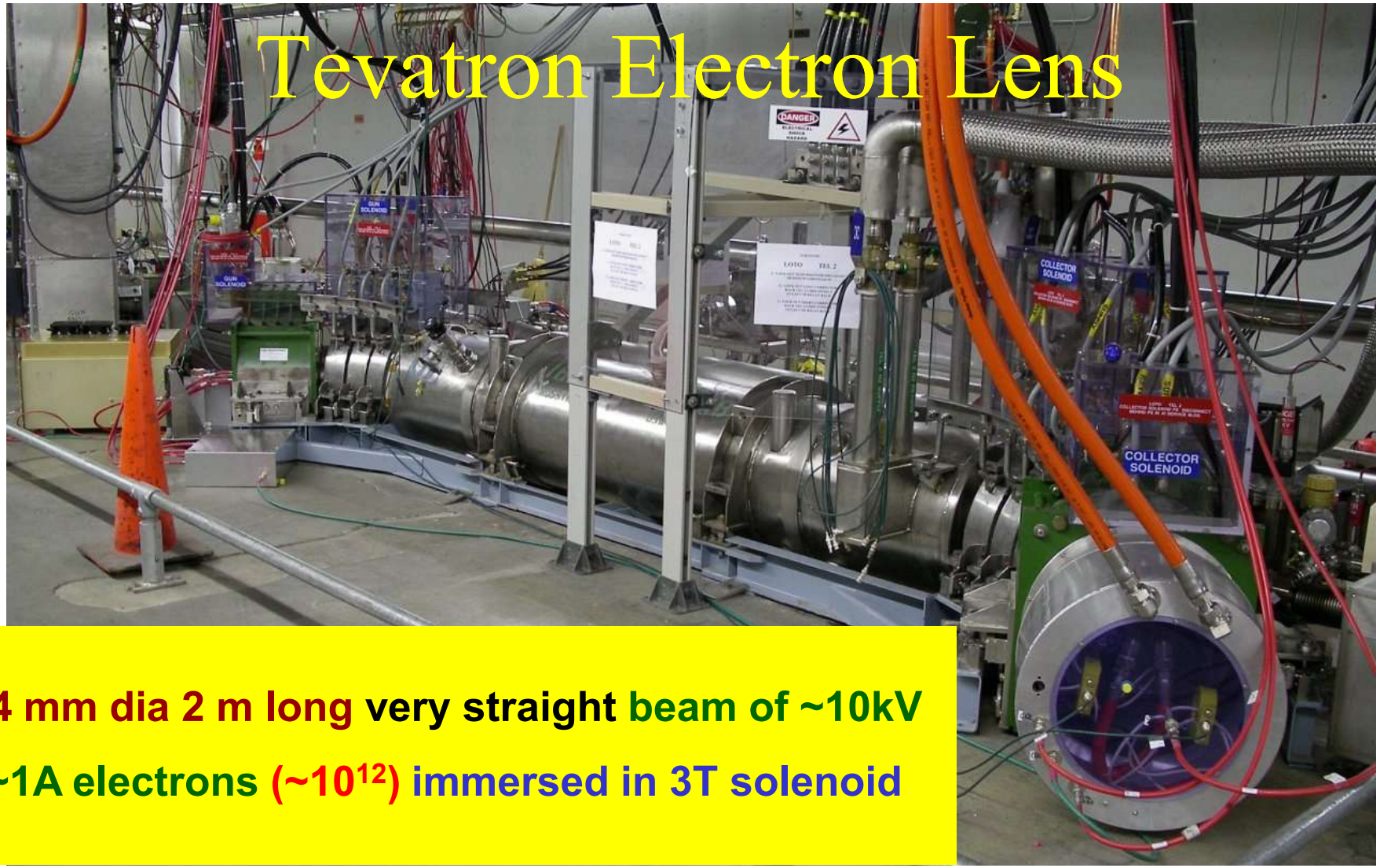
Ionization electrons stay on magnetic filed lines

Residual ions removed



The idea works well in simulations → tests needed

Similar Device Works in Tevatron



~4 mm dia 2 m long very straight beam of ~10kV

~1A electrons (~10^{12}) immersed in 3T solenoid

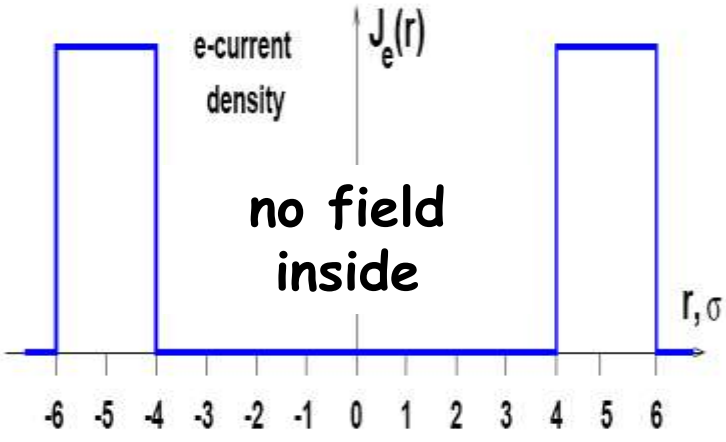
TEL helps bunches dying in collisions

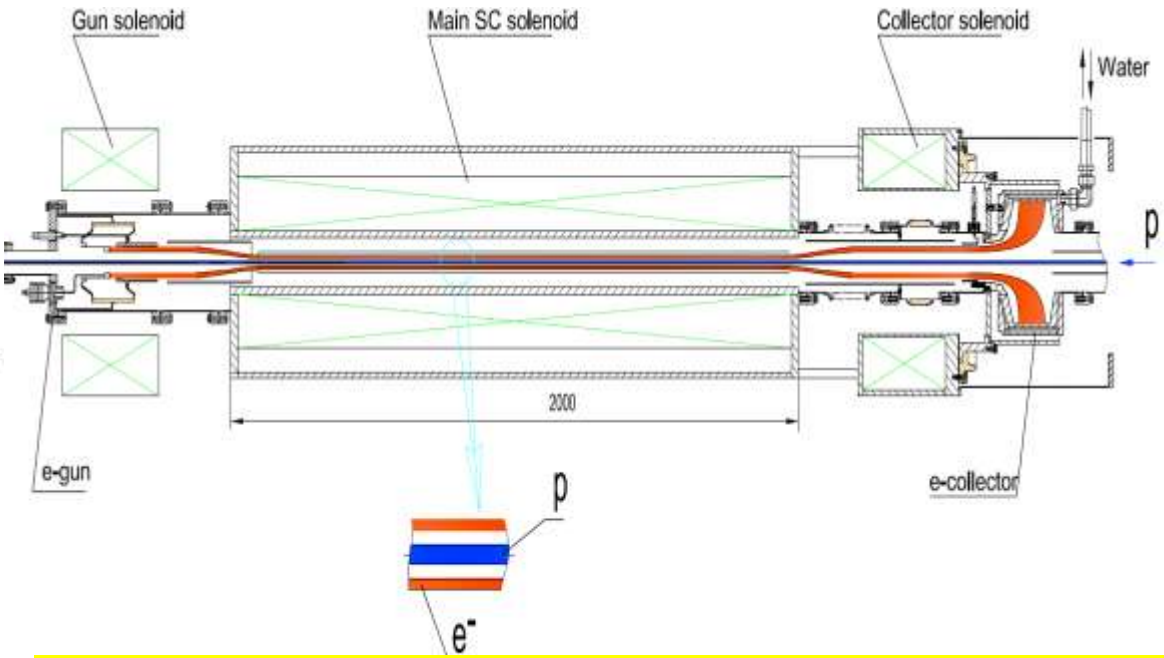
similar electron lens should greatly help LHC when/if it will get to design beam intensities

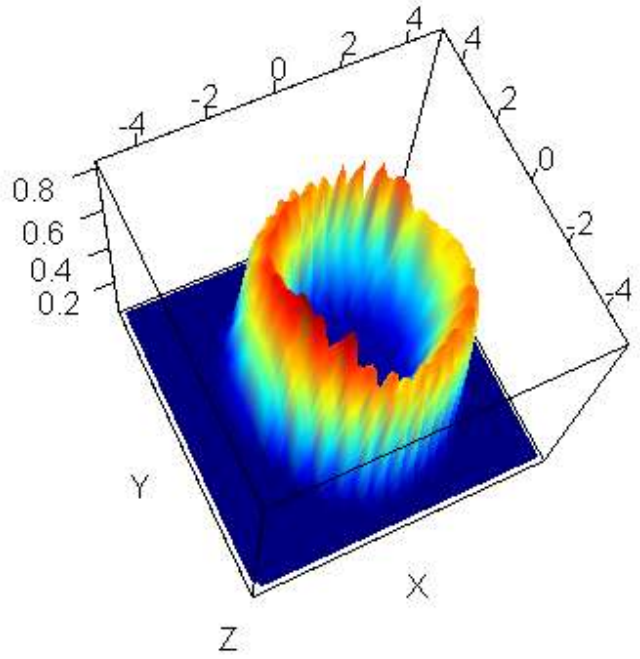
17.4 hrs vs 10.0 hr

ime in collisions (min)

Hollow Electron Beam Collimator



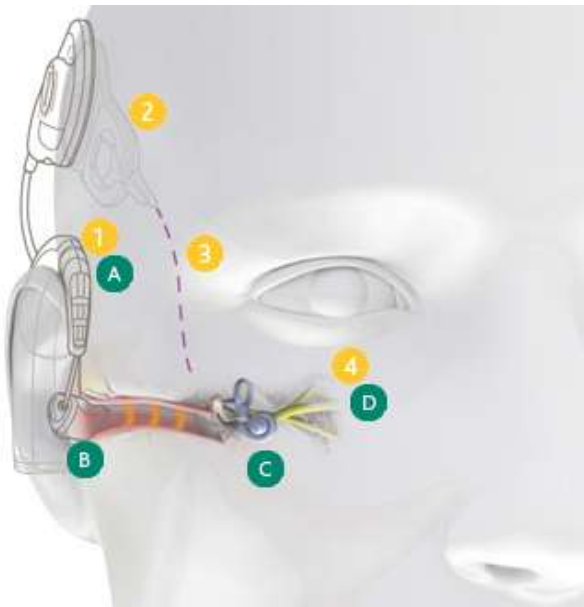




Collimator to control particle loss without any material (no matter)

- another "must have" for LHC

Example of Evolution: Music to Ears



Qualitative Advances

New Drivers/Power Sources:

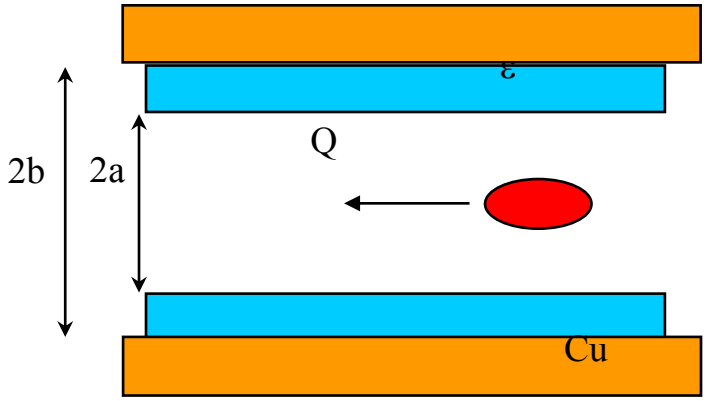
- another beam
- laser

New Accelerating Media:

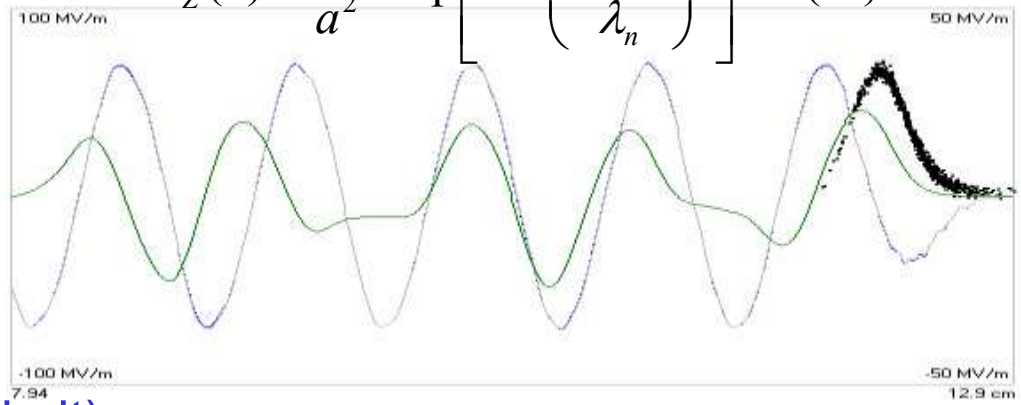
- plasma
- dielectrics
- microstructures
- crystals

Weird Schemes/Ideas

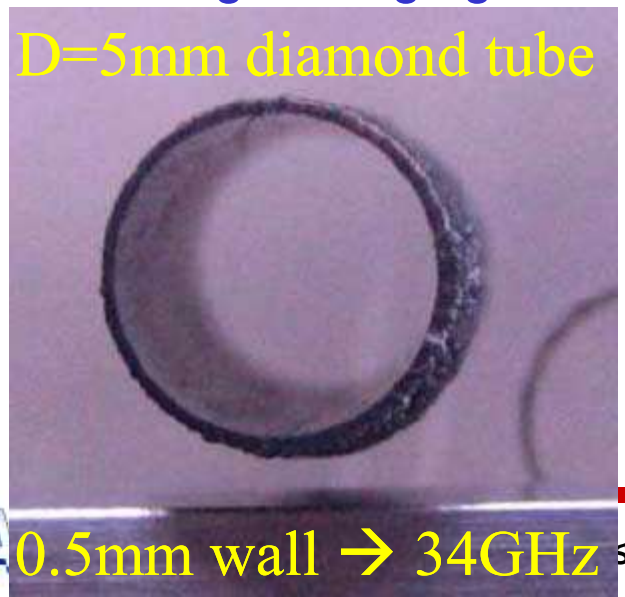
Wakefields In Dielectric Tube

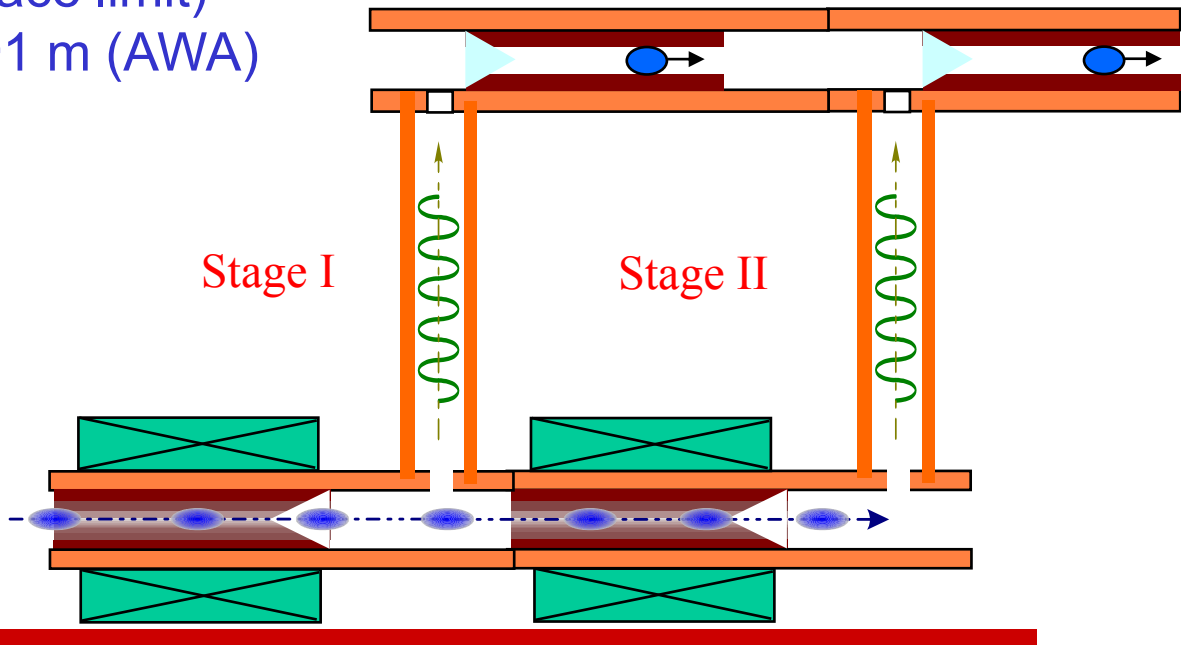


$$W_Z(z) \approx \frac{Q}{a^2} \exp\left[-2\left(\frac{\pi\,\sigma_z}{\lambda_n}\right)^2\right]\cos(kz)$$

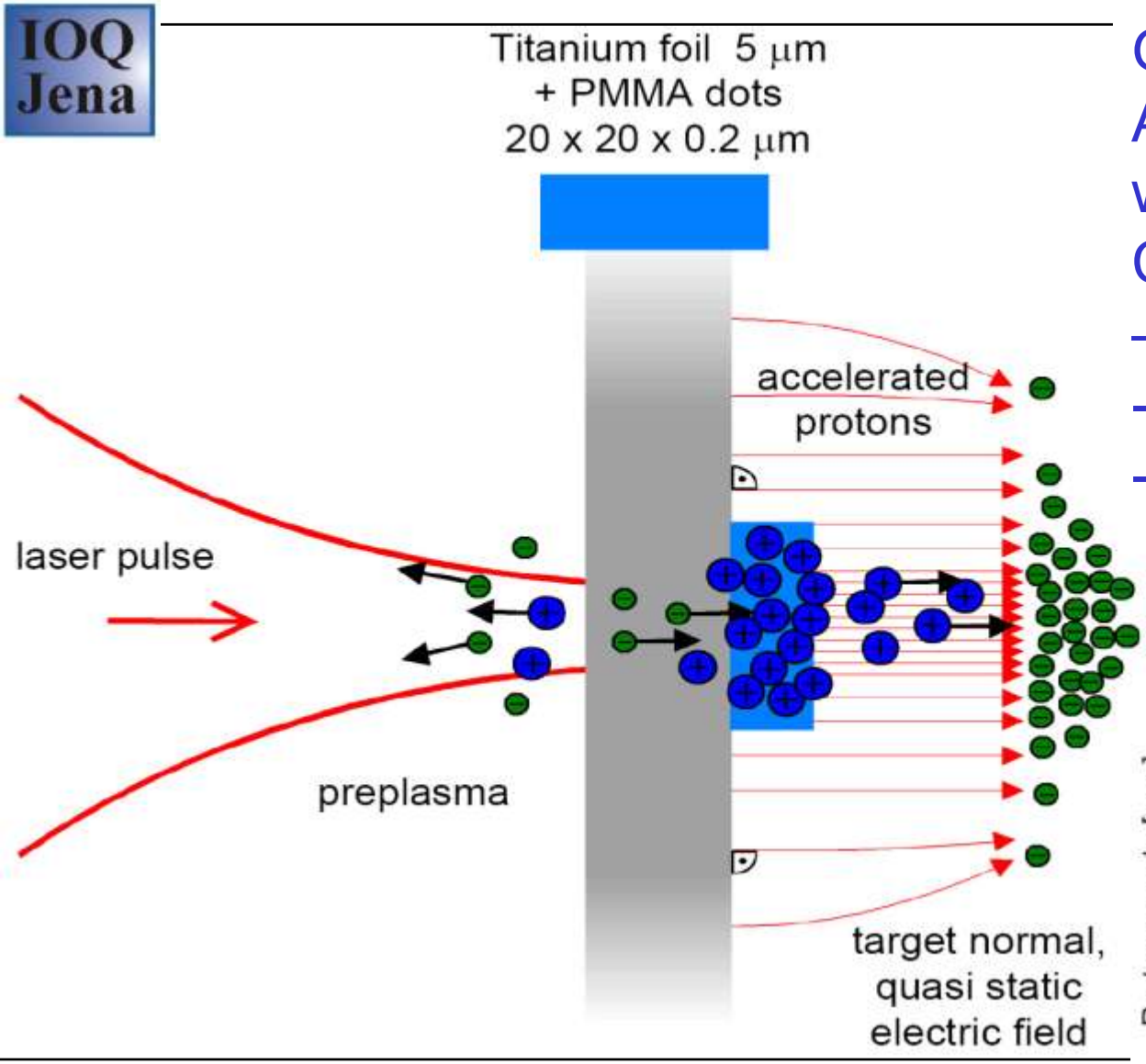


Goal ~1GV/m (diamond surface limit)
Achieved ~100 MV/m over ~1 m (AWA)
Challenge - staging

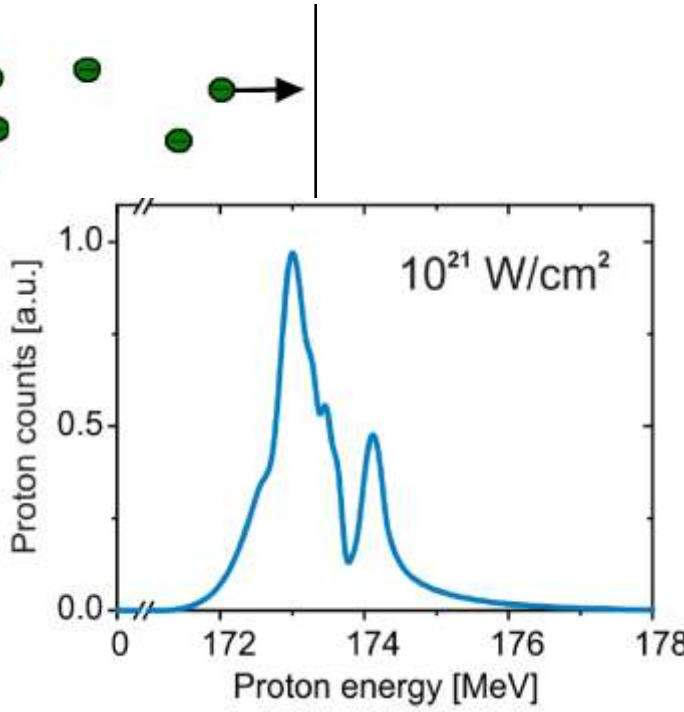




Monochromatic protons from laser jolt

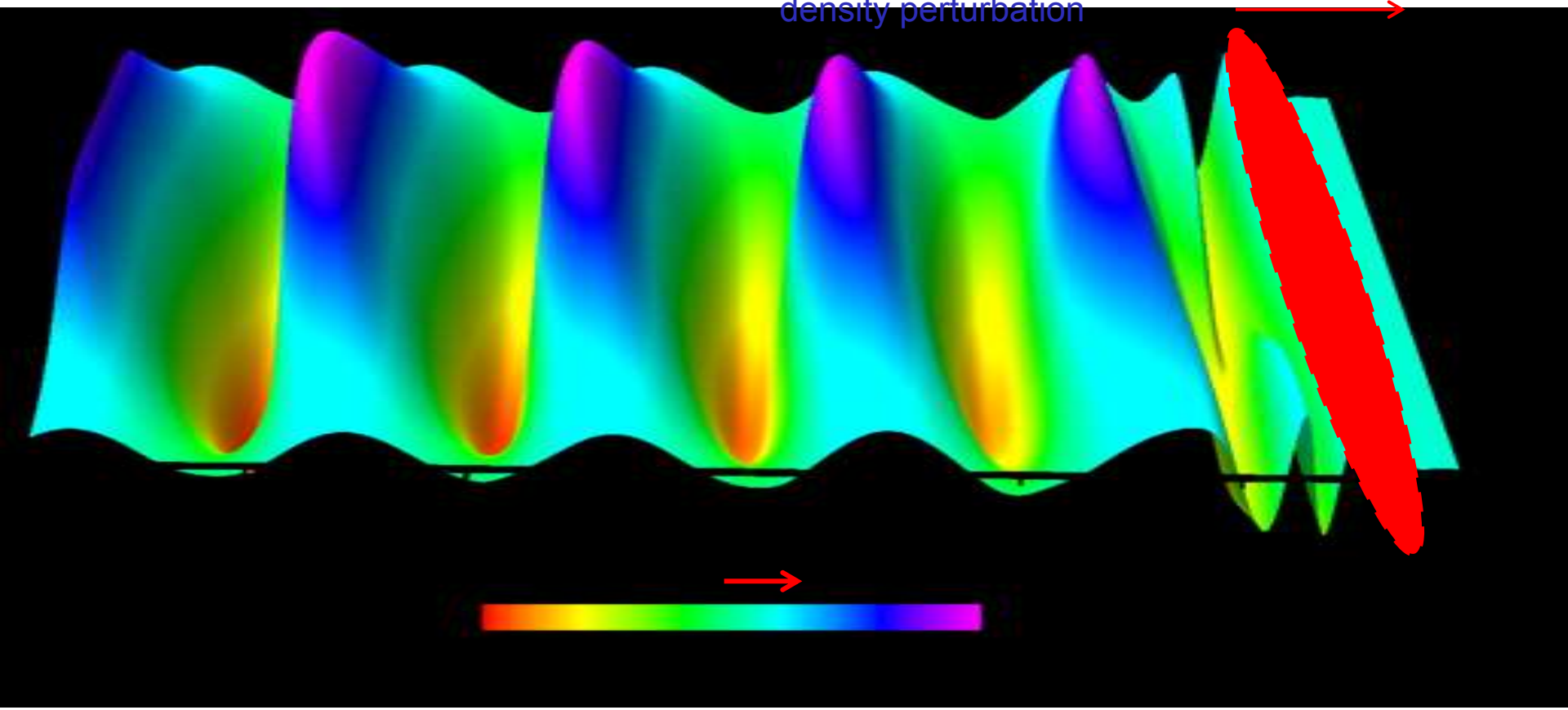


Goal ~1GeV
Achieved ~200 MeV
with dE/E<3%
Challenge s
– get high charge
-- small sizes
-- higher laser power



Excitation of Plasma Waves

Idea- Tajima & Dawson, Phys. Rev. Lett. (1979)

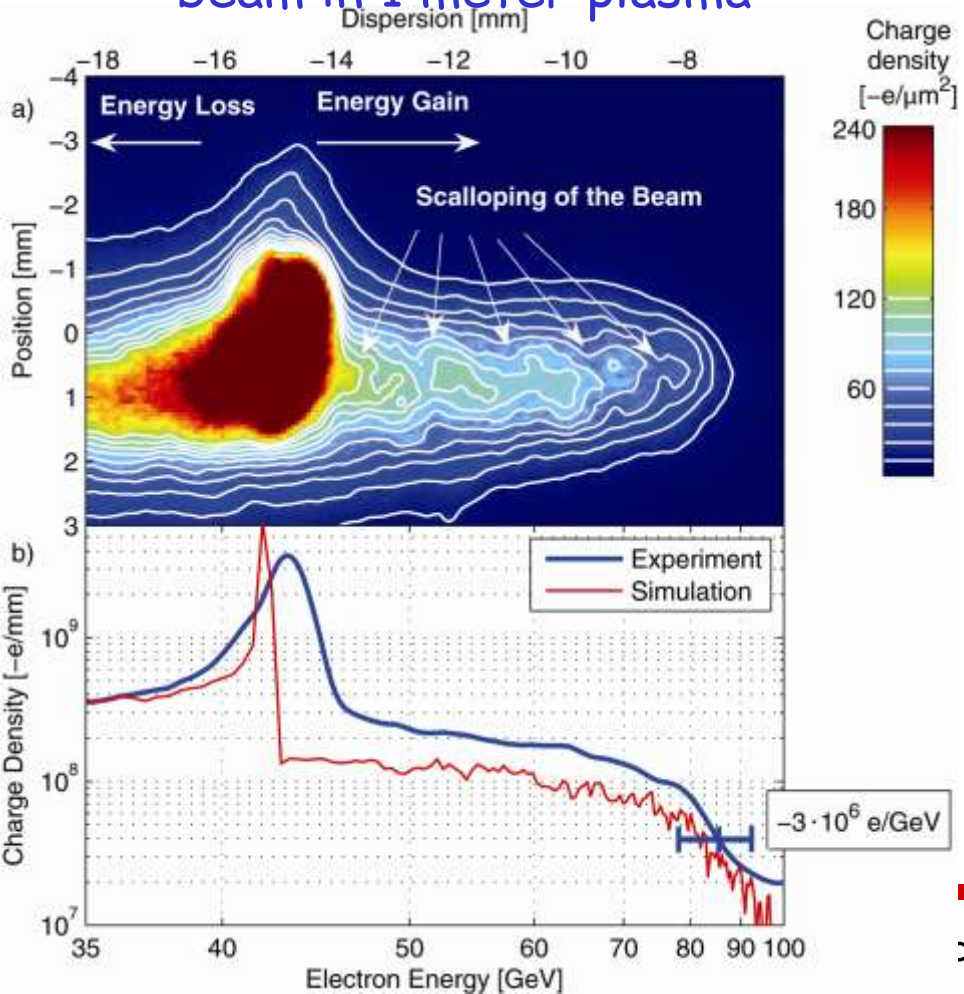


Option #1:
Short intense e-/e+/p bunch

Option #2:
Short intense laser pulse

Beam Excites Plasma

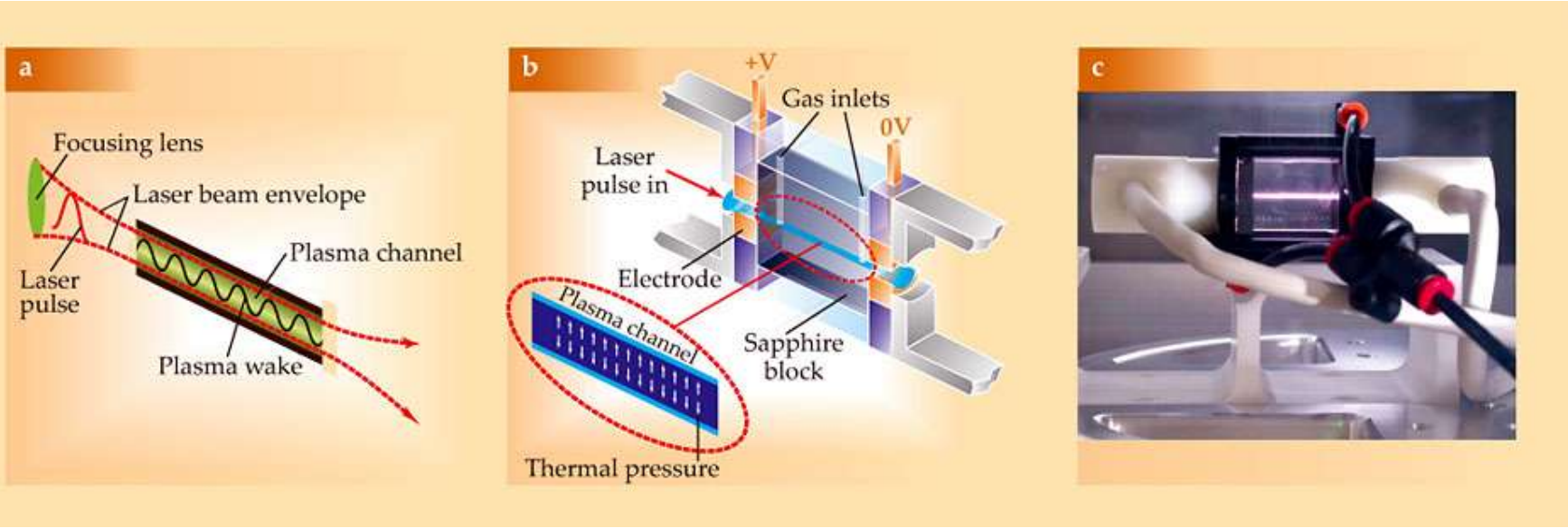
- Acceleration gradients of ~50 GV/m (3000 x SLAC)
  - Doubled energy of 45 GeV beam in 1 meter plasma

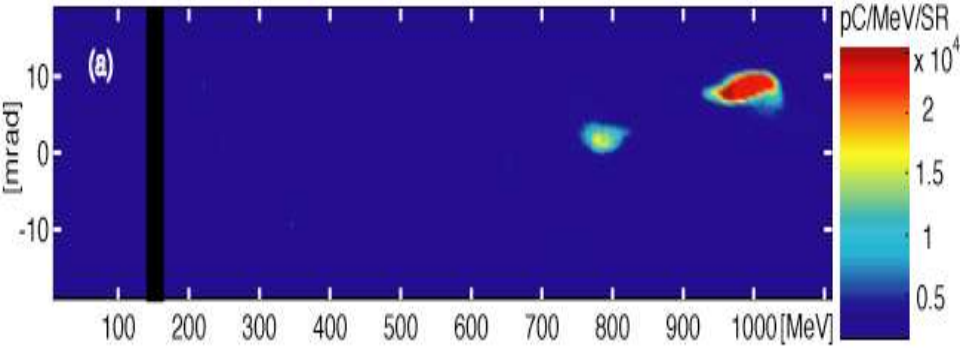


Challenges/Issues:

- small (dE/E, size) beam still to be achieved
- (FACET experiment at SLAC underway)
- needs unique drive beam
- defocuses positrons
- hard to preserve ultra small beam emittances
- thinking of using protons as a drive (even harder)

Laser Excites Plasma



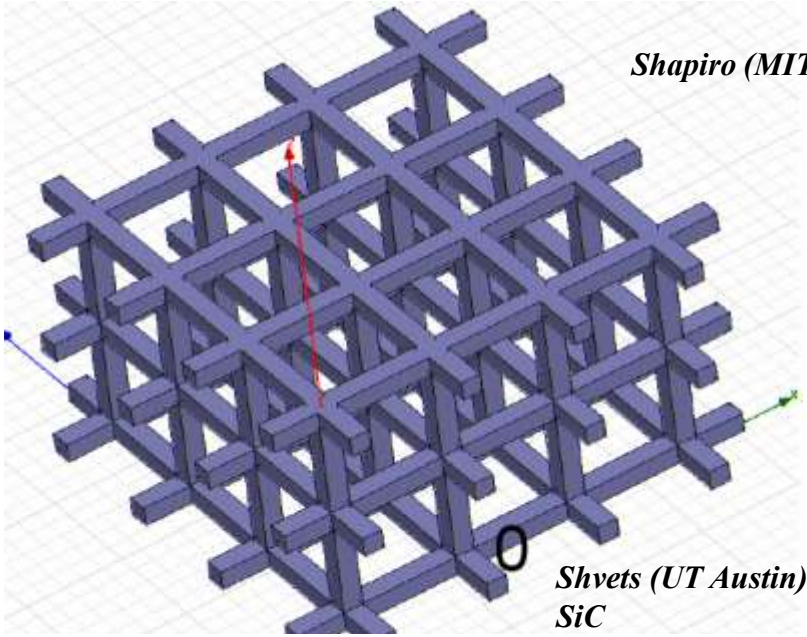


- Achieved ~30 GV/m (Berkeley)
  - 1 GeV over 3 cm
  - 40 TW laser

Challenges/Issues:

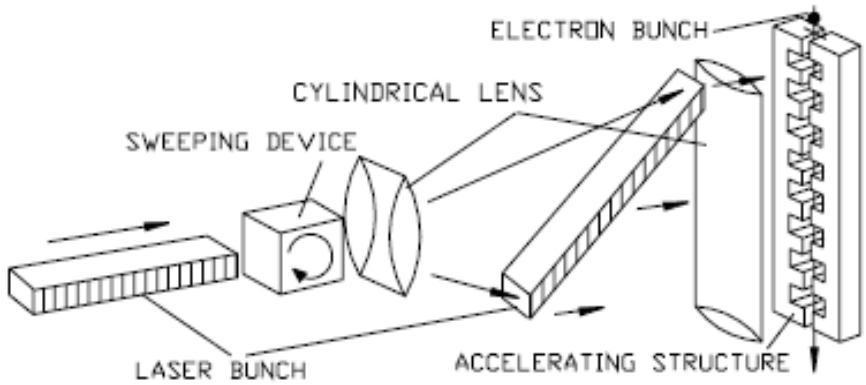
- speed of light in plasma always <c
- need many stages - hard
- BELLA experiment at LBNL with Petawatt laser (not table top!)
- low rep rate, efficiencies
- hard to preserve ultra small beams

SiC, diamond, metamaterials, etc



Shapiro (MIT)

Shvets (UT Austin)
SiC

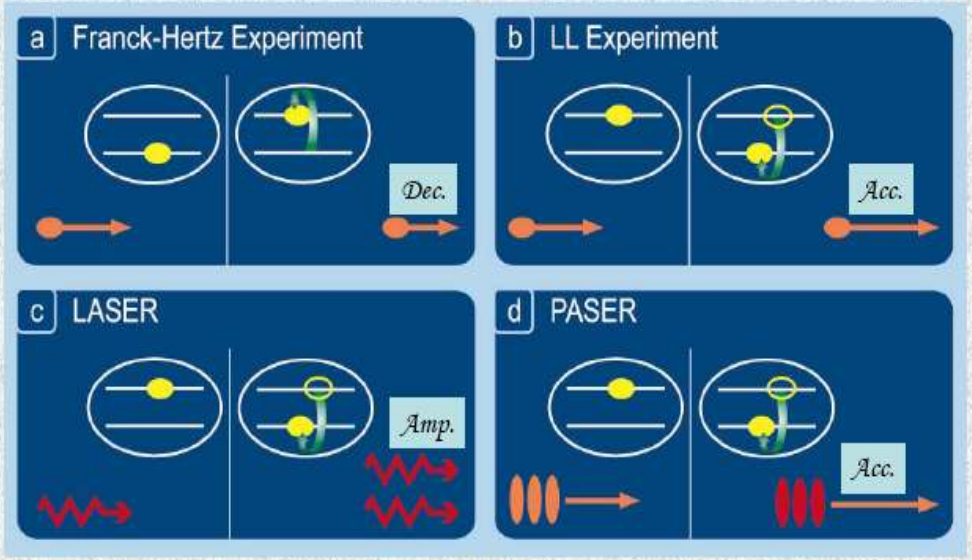


Travelling Laser Focus across Resonant Microsytructures
Mikhailichenko (Cornell)

Metamaterials

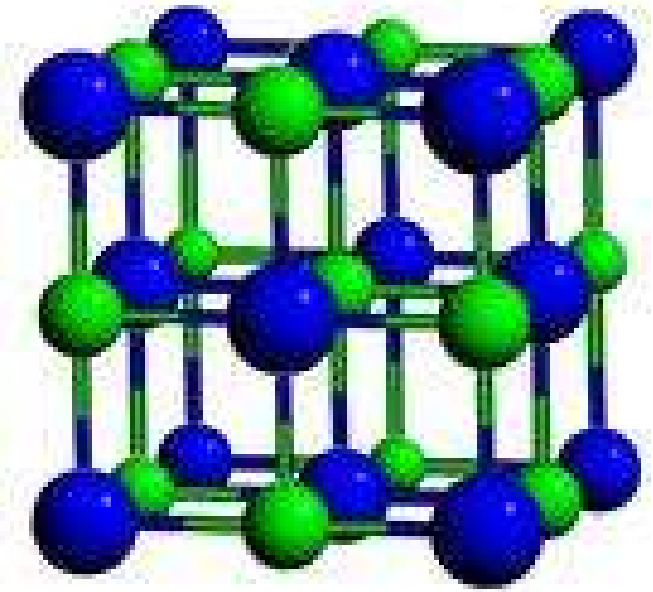
Antipov (ANL)

Essence of the PASER (micro)

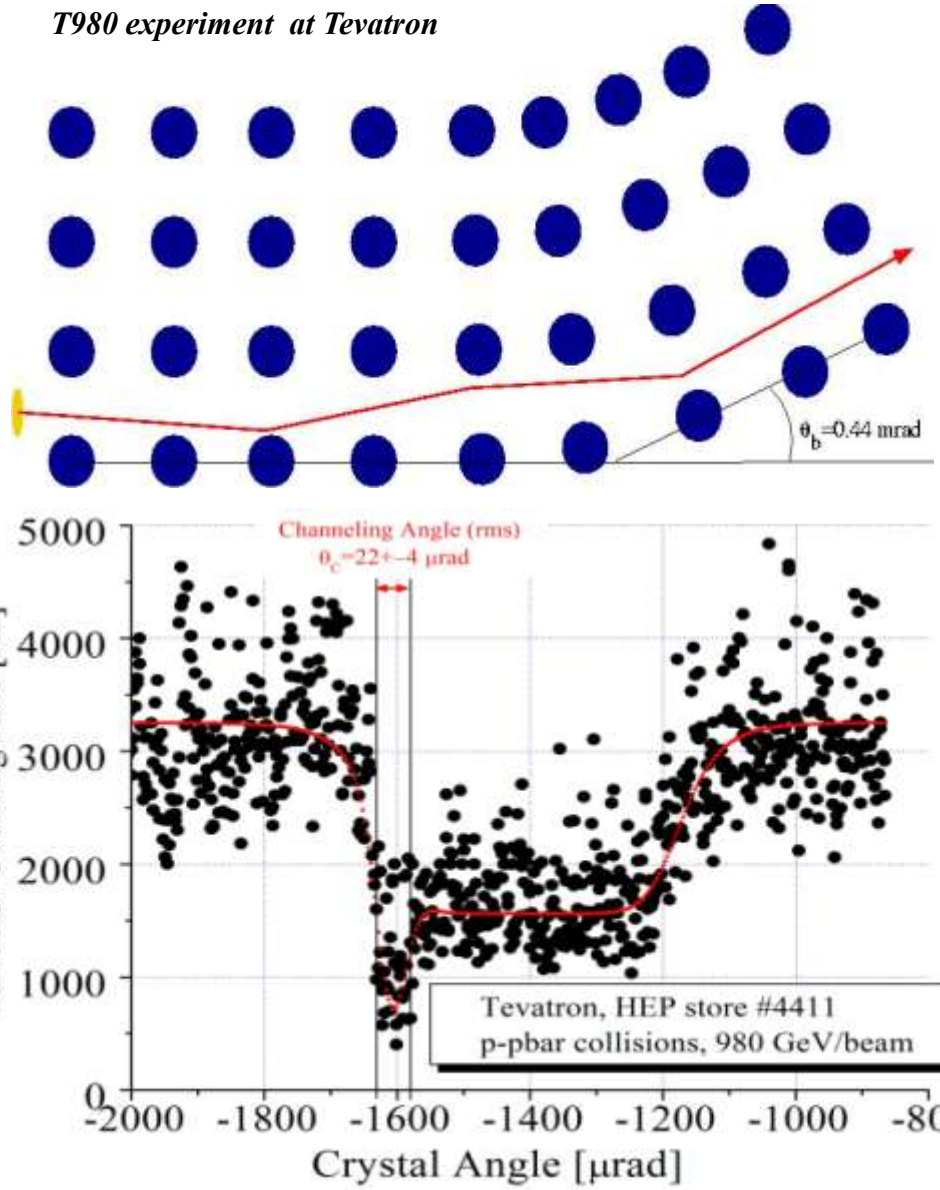


L. Schächter, Phys. Lett. A ., **205**, p. 355-358(1995).

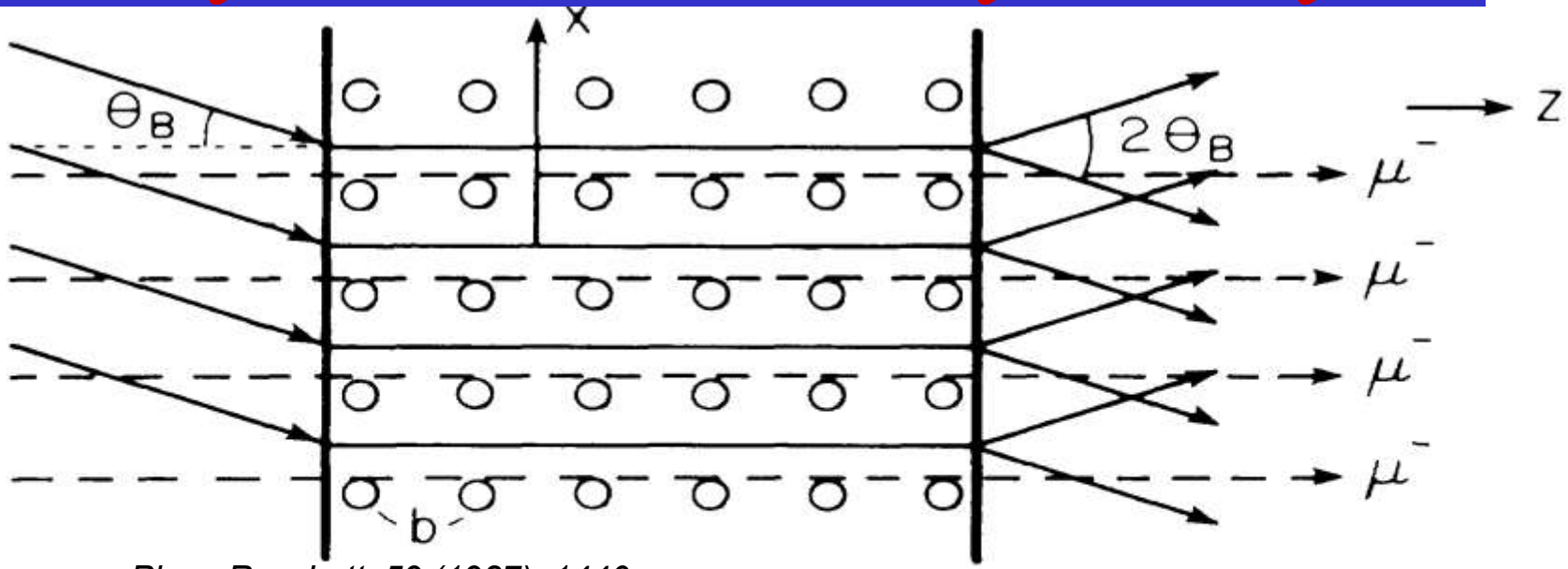
My Favorite "Theme" - Crystals



- Strong inter-planar electric fields ~10V/A=1GV/cm
- Very stable, can be used for
  - deflection/bending (*works*)
  - focusing (*works*)
  - acceleration (*if excited*)



Crystal Excitation by X-Rays

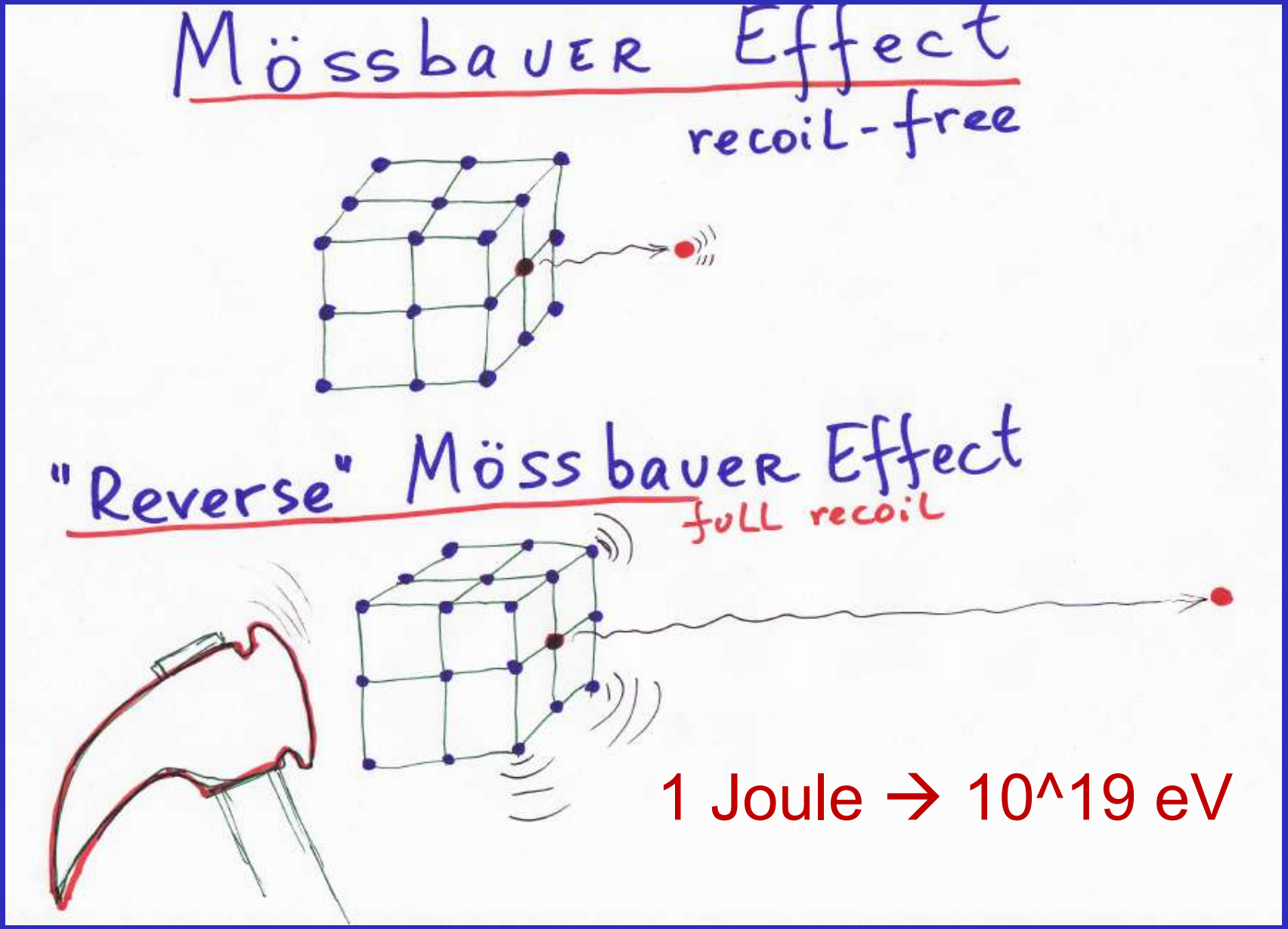


Tajima,Cavenago, Phys. Rev. Lett. 59 (1987), 1440

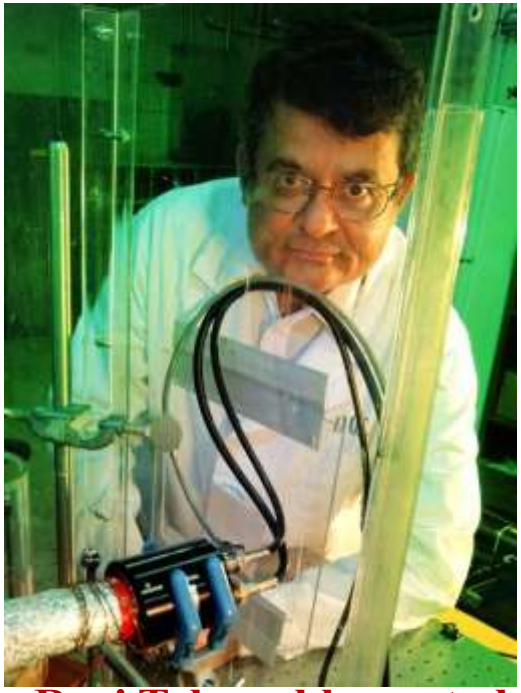
FIG. 1. Bormann anomalous transmission. When the x rays are injected at the Bragg angle, the Bormann effect takes place. Particle beams are injected along the crystal axis.

- Need 40keV high peak power x-rays
  - now available from SASE FELs like LCLS
- Gradients >1GV/cm
- Muons preferred
  - bremstrahlung
- μ+ rad length 10^9 cm
  - total energy~10^9 GeV

Even Better Way (…but – Fantastic)



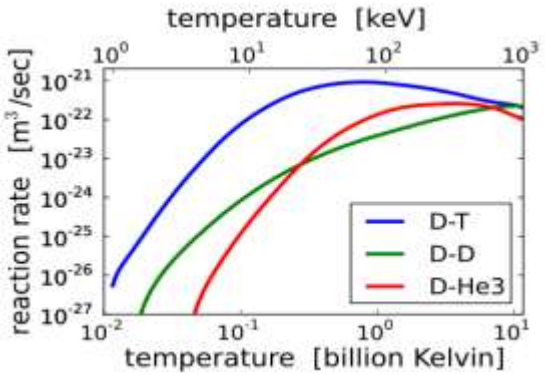
Bubble fusion: 2002→2007… RIP?

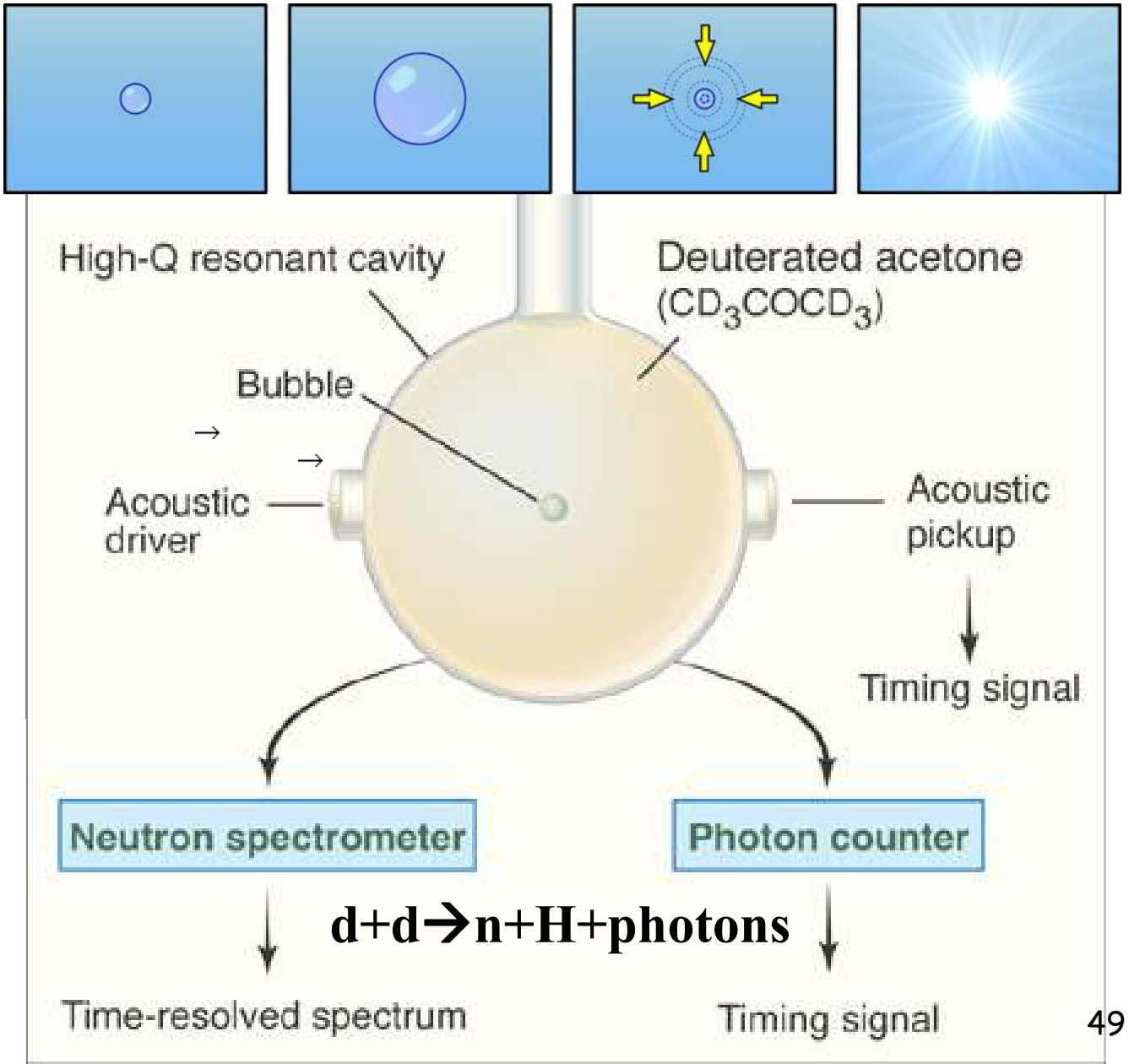


Rusi Taleyarkhan, et al

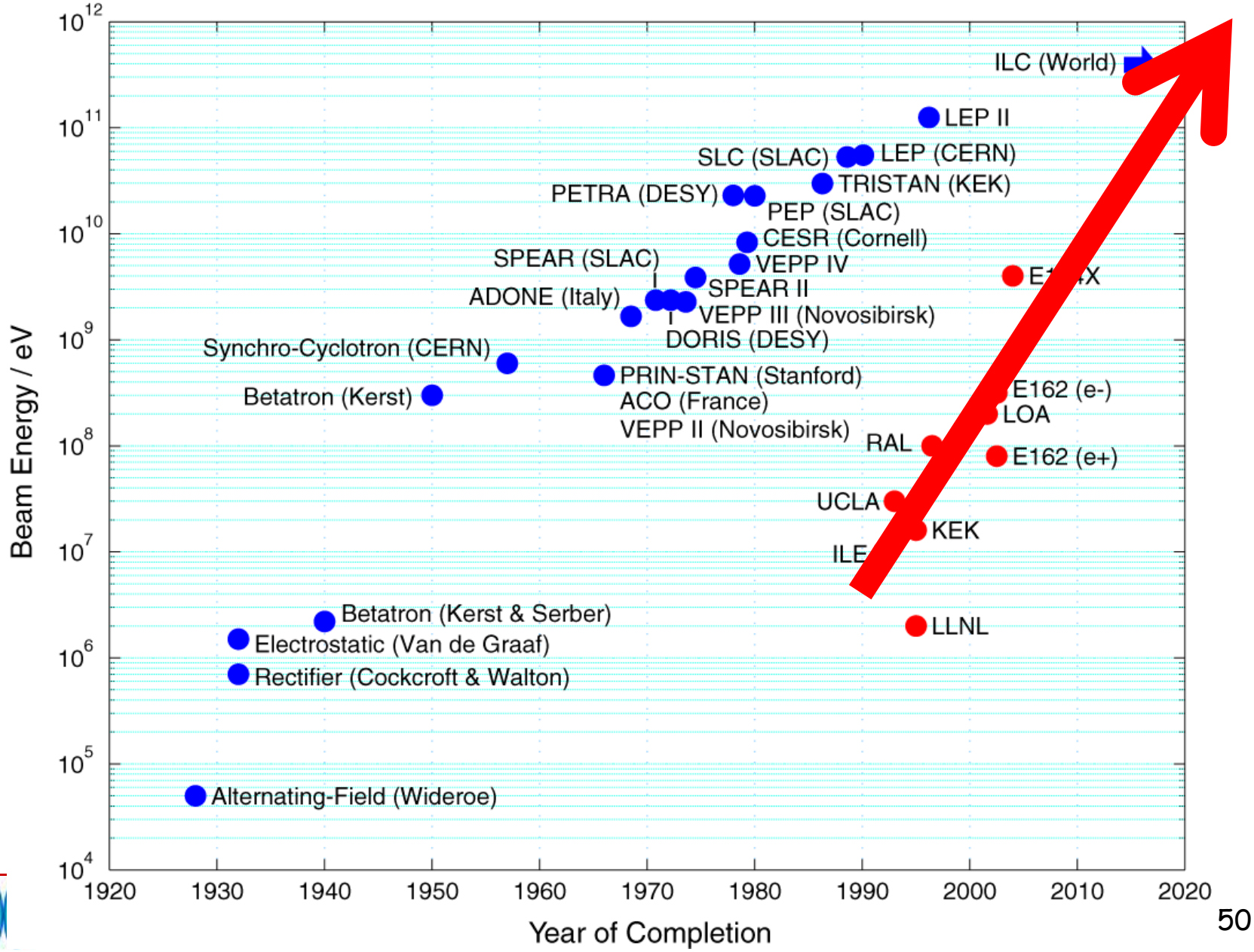
Evidence for Nuclear Emissions During Acoustic Cavitation

Science, v.295, p.1850 (2002)





Progress Feeds Dreams



Plasma-Accelerator-Based Linear Collider

Leemans & Esarey, Physics Today (March 2009)

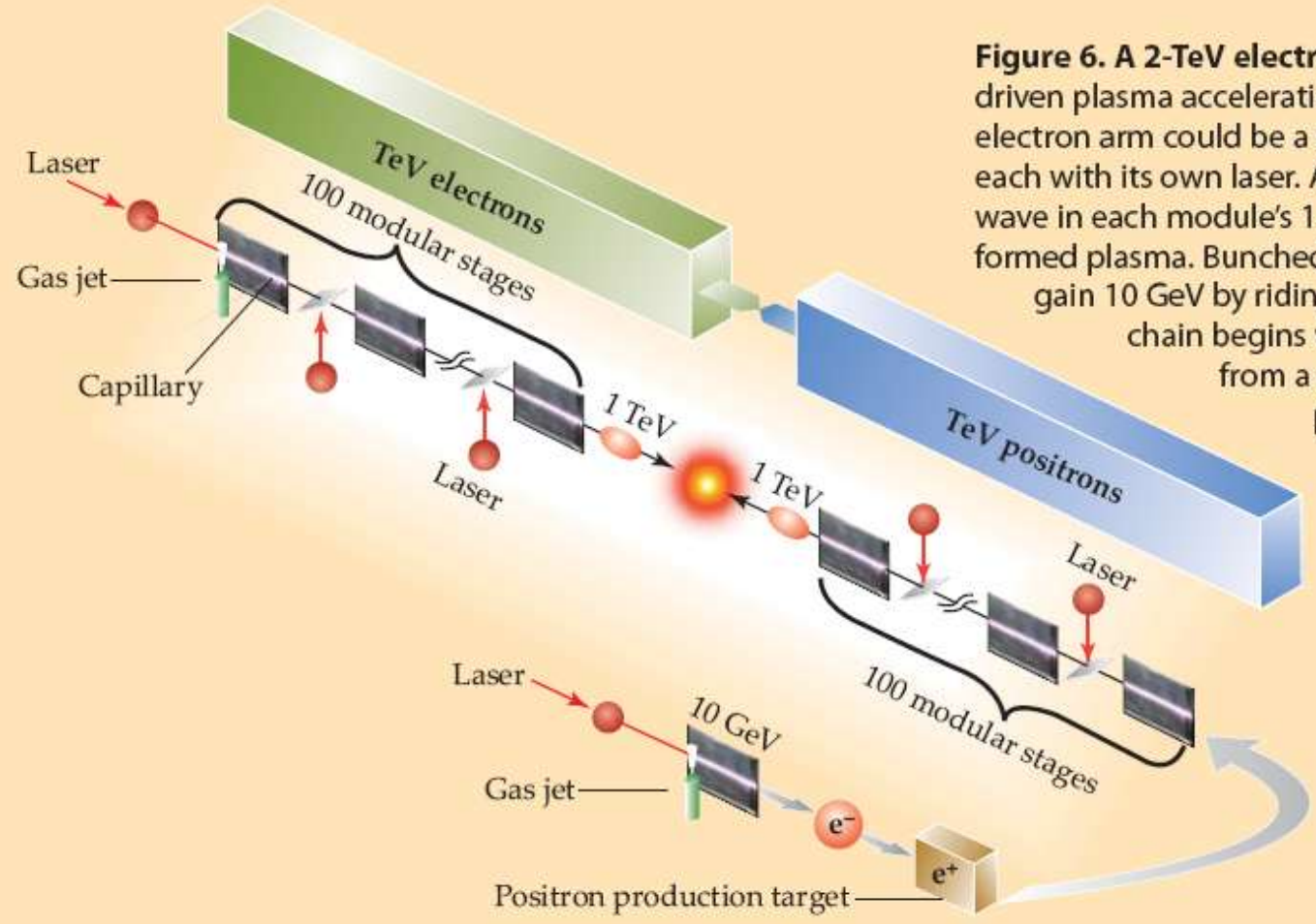


Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

Scientia Potentia Est

F.Bacon

"Knowledge ∝ Power"

"Power ∝ Money"…

literally so for accelerators:

Tevatron (2TeV)	20 MW
LHC (7+ TeV)	120 MW
μμ Collider(4TeV)	140 MW
ILC(0.5TeV)	230 MW
CLIC(3TeV)	420 MW
LaserPlasma *x*TeV	?? GW

Desires vs Possibilities

What do HEP folks want?

$\sigma_{QED} = \frac{90fb}{s} \rightarrow \mathcal{L} \propto E_{cm}^2$

$1\,TeV \rightarrow 10^{32}$

$10^3\,TeV \rightarrow 10^{38}$

What Accelerator geniuses can (suggest)?

$\times$

MANY

$$\mathcal{L} = \frac{f_{rep} \cdot N_{bunches} \cdot N_p^2}{4\pi\sigma^2} = \frac{[\gamma f_{rep} \cdot N_p \cdot N_b]}{4\pi\beta^*} \left[\frac{N_p}{\varepsilon}\right]$$

Beam power — Brightness

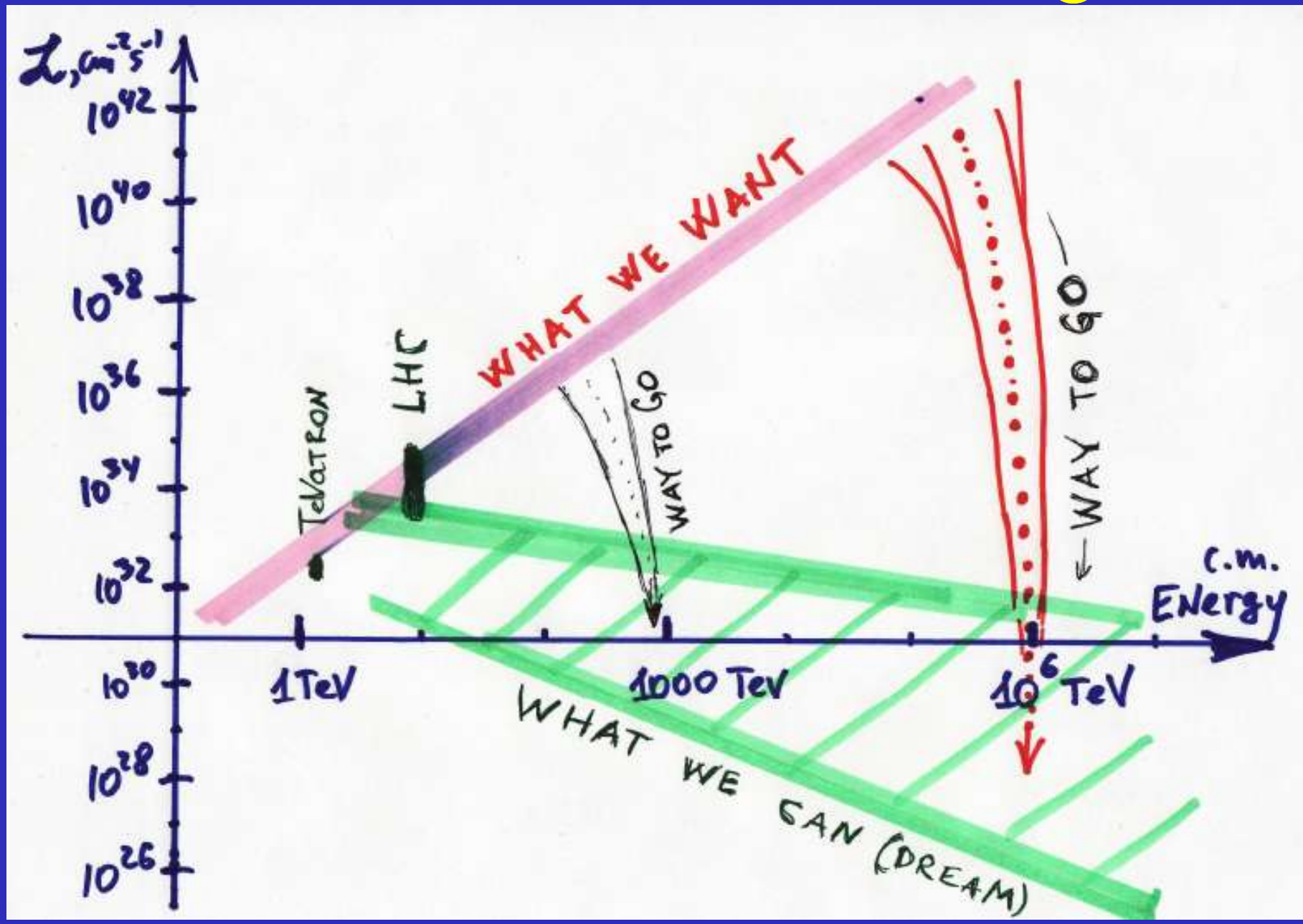
$P_{power} = \eta \cdot P_{WALL}$

$\rightarrow P_{WALL} \leq (MAX)$, $\eta \propto E_{cm}^{-1/3 \ldots -1/5}$

$\rightarrow$ [Brightness] ~ CONST

Best case $\mathcal{L} = 1\,Hz \cdot \frac{(10^5\,particles)^2}{(1\,\text{Å})^2} = 10^{27}\,cm^{-2}s^{-1}$

That Leads to New Paradigm



New Paradigm for HEP

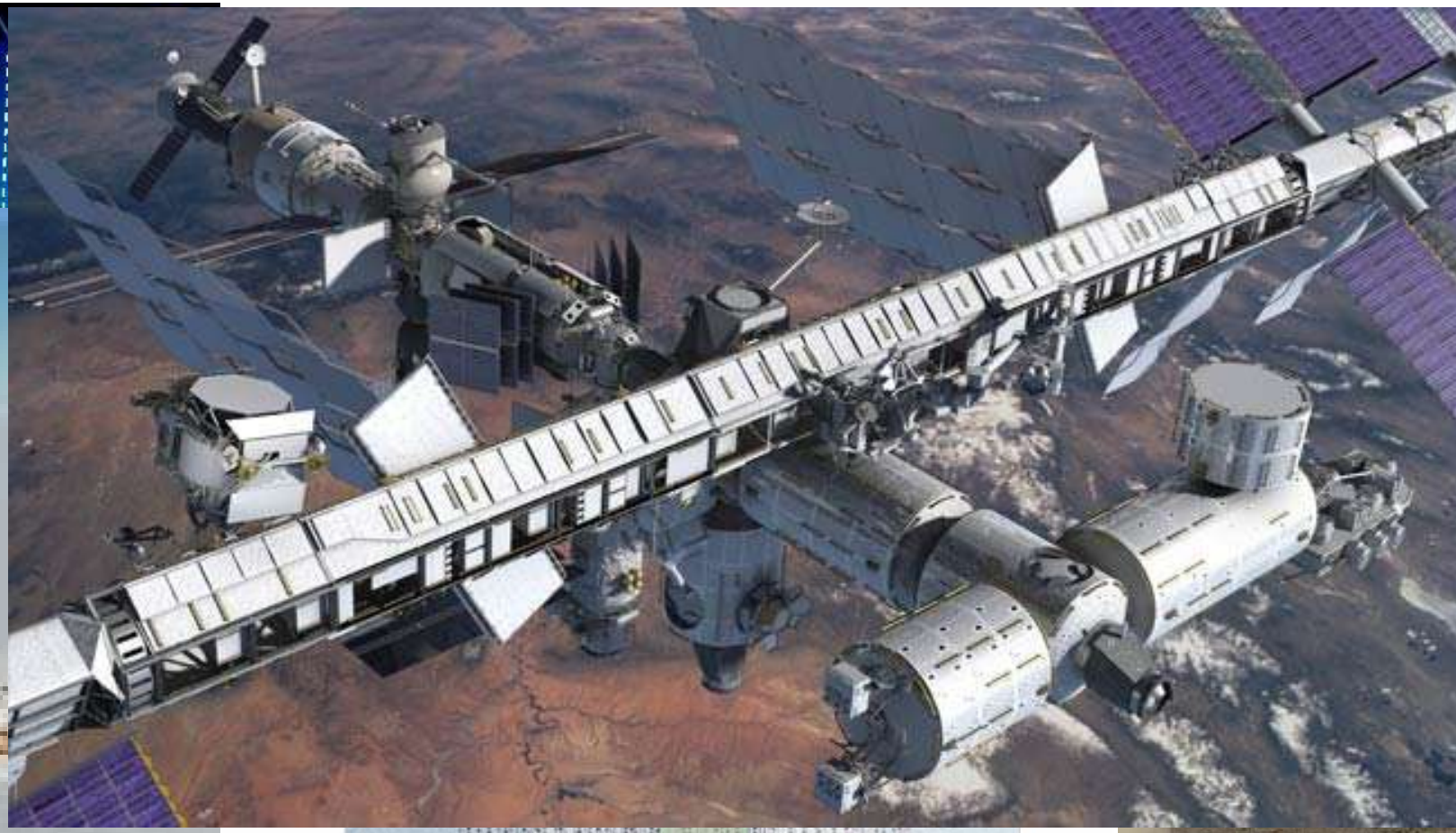
Go After The Highest Possible Energy

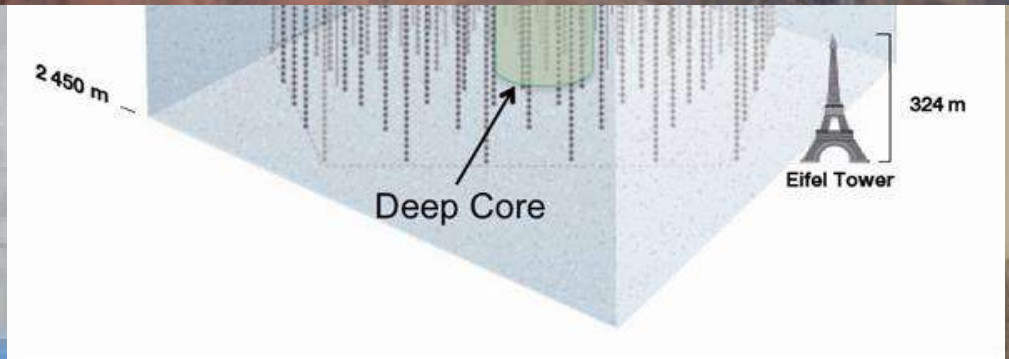
Frequent and very predictable collisions but VERY low luminosity

Develop New Classes of Detectors

[Small Accelerators+Large Detectors]?

We Actually Have Started Already





Three Points of Part II:

- **Energy frontier evolution depends on scientific advances in the field of acceleration:**
  - yes, the progress has greatly slowed down
  - despite the fact the we push the technology envelopes and introduce new & improved methods regularly
- **The pace is expected to be changed by scientific breakthroughs, leading ideas include:**
  - two-beam acceleration, laser drive, plasma waves
  - new media (Meta-M) and crystals (+ even more advanced)
- **The c.m.energy increase will (most probably) NOT be accompanied by high luminosity:**
  - to make of use of such accelerators, the way we extract Physics out of such events should be modified (e.g. new paradigm of low event rate detectors)

PART III:

Directions

How To Contribute

Cheerful Ending

Where Will Accelerators Evolve?

- There is a threat that the community will decide in favor of applications of the (*low complexity – low risk*) accelerators, and will gradually abandon *more complex* accelerators as a tool to push the High Energy Frontier:
  - then – no accelerator-based HEP after ~2030??
  - new acceleration methods under development now will surely be in demand for low-*E* applications, too (small/cheap)

- High-*E* physicists have to take big part in the advancement of accelerators:
  - explore and develop new methods of acceleration
  - understand how to lower the luminosity requirements

University of Chicago Role

- UChicago has unique opportunity to contribute:
  - great minds, cover broad spectrum of physics
  - two Labs – ANL and FNAL - under the UC "umbrella"
- Raising bright scientists capable of pushing the accelerator frontier seems to be natural task for UC
- Possibilities:
  - full-time/part-time faculty, adjunct professors
  - Accelerator group/chair set at the Lab (Novosibirsk model: years 3&4 – 2-3 days a week at the Lab, special courses - lectures at the Lab, lecturers from the Lab & University, research – at the Lab, full scholarship support by UC-ANL-FNAL consortium)
- To our help:
  - IARC (see next slide)

Illinois Accelerator Research Center

About IARC

- IARC is funded via grant from Illinois Department of Commerce and Economic Opportunity.
- Basic goal is to make Northern Illinois a center for accelerator development and IARC was also sold as a mechanism to support training of scientists and engineers in accelerator physics and related technology via work with local universities.
- $ 20 M cash contribution from State of Illinois
  - Augmented by DOE OHEP contribution ~13M$
- Start in FY10, finish construction in FY12, start operation in FY12-13
- Argonne as a key partner

"Cheerful Ending"

Not convinced yet that there is future for the field of high energy particle accelerators?

Let me offer a "fully scientific" argument

Gott's Conception of *Copernican Principle*

R.Gott

Let L denote the lifetime of the phenomenon in question. We observe the phenomenon in progress, so

$$L = t_{past} + t_{future}$$

nature

Nature **363**, 315-319 (27 May 1993) | doi:10.1038/363315a0

Implications of the Copernican principle for our future prospects

J. Richard Gott, III

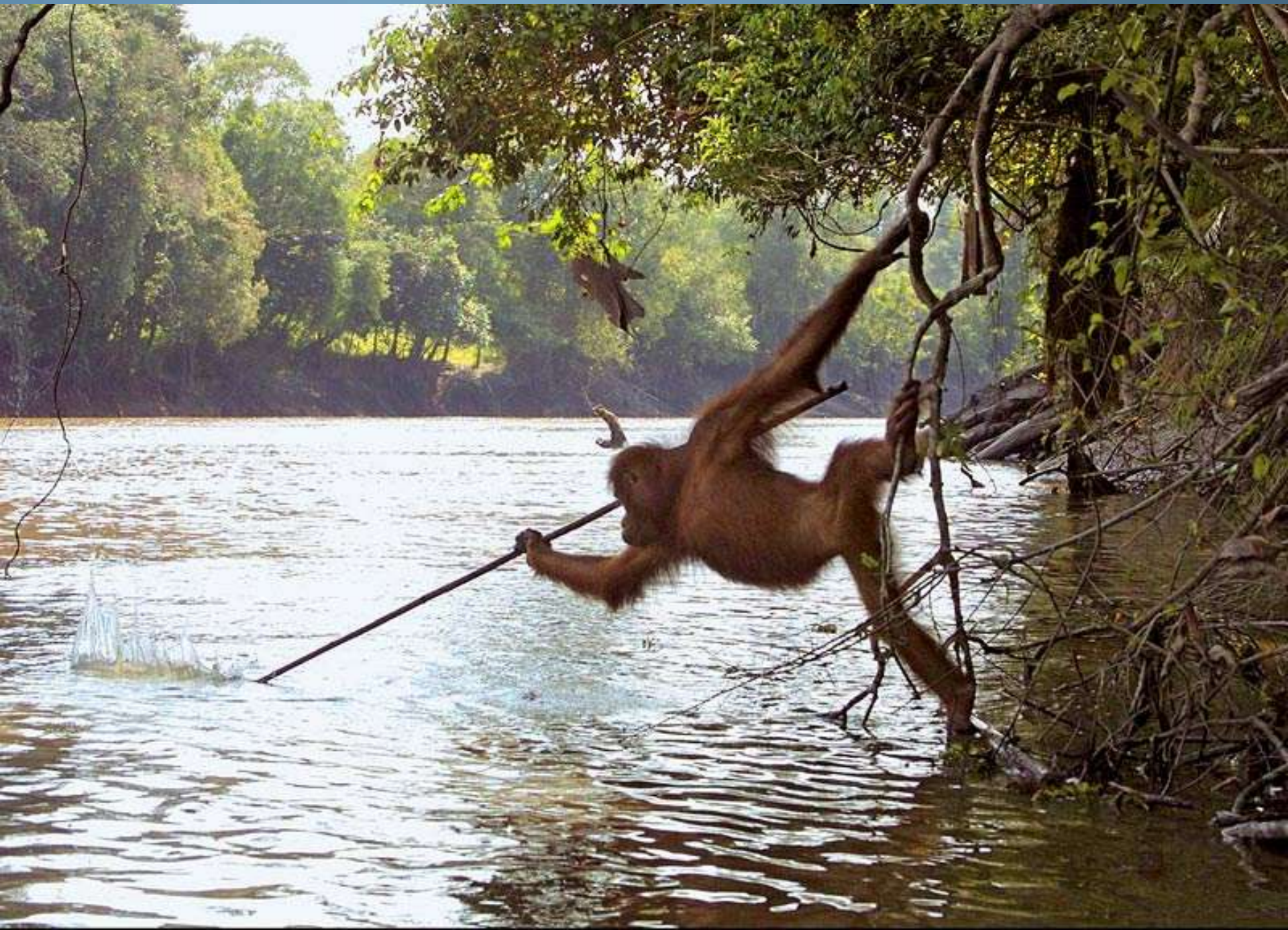
$$\frac{1}{3}t_{past} < t_{future} < 3t_{past}$$

(50% confidence level)

High Energy Particle accelerators exist for t_past = 90 years so with 50% confidence they will exists for another t_future=30 to 270 years

Thank You Very Much
For Inviting Me (*Ed*) and
For Your Attention!

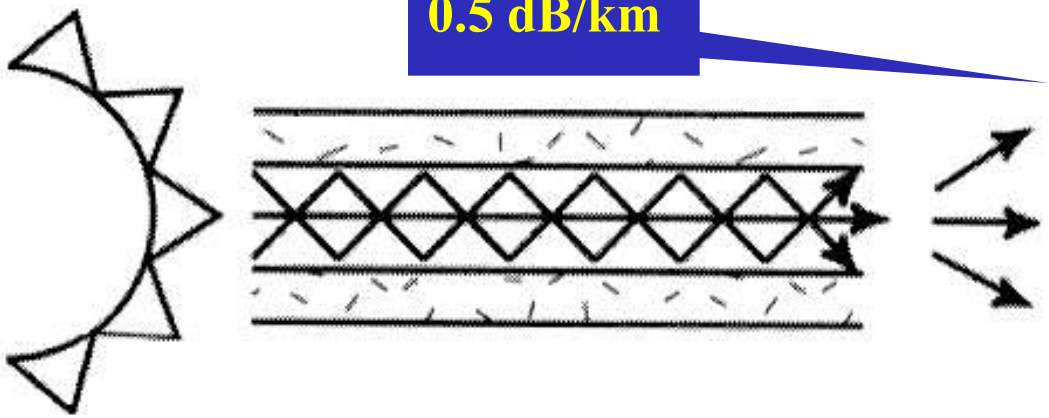
Hope you've got the main message that accelerators are far from dying but their future (say, >2030) is dependent on scientific breakthroughs [for us to do]

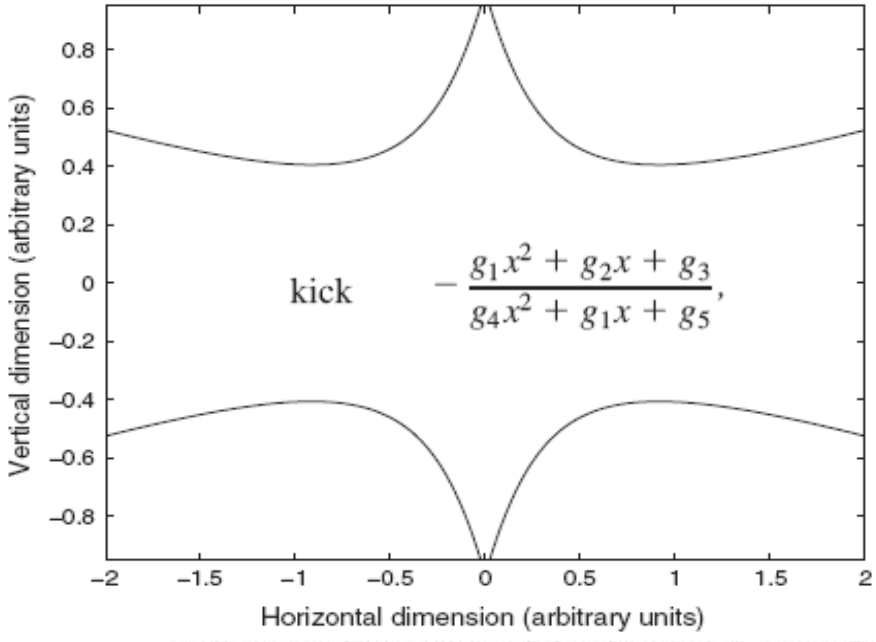


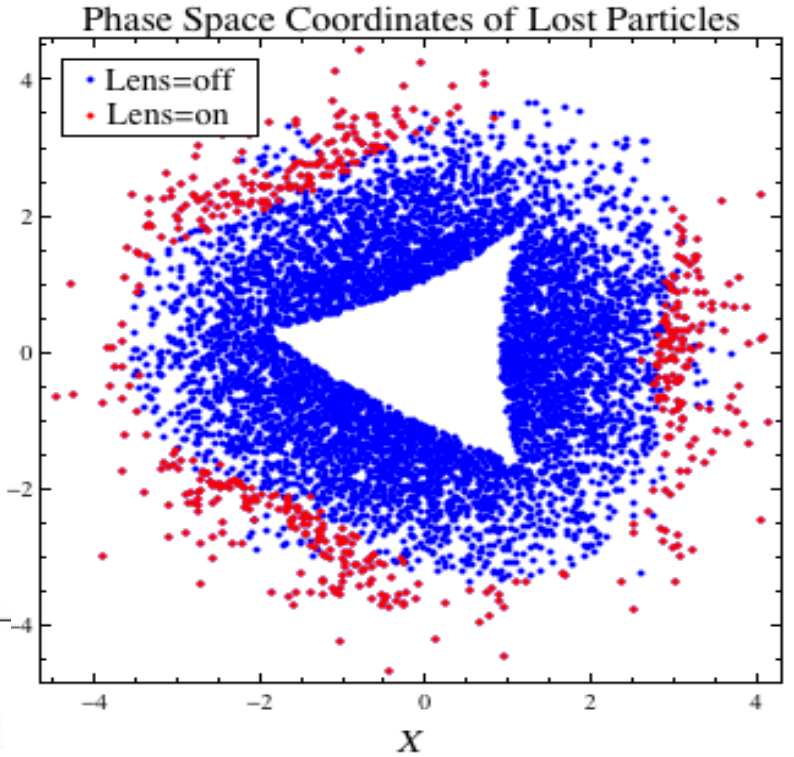
BACK UP

Another Neat Idea: Integrable Optics

0.5 dB/km







PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 11, 114001 (2008)

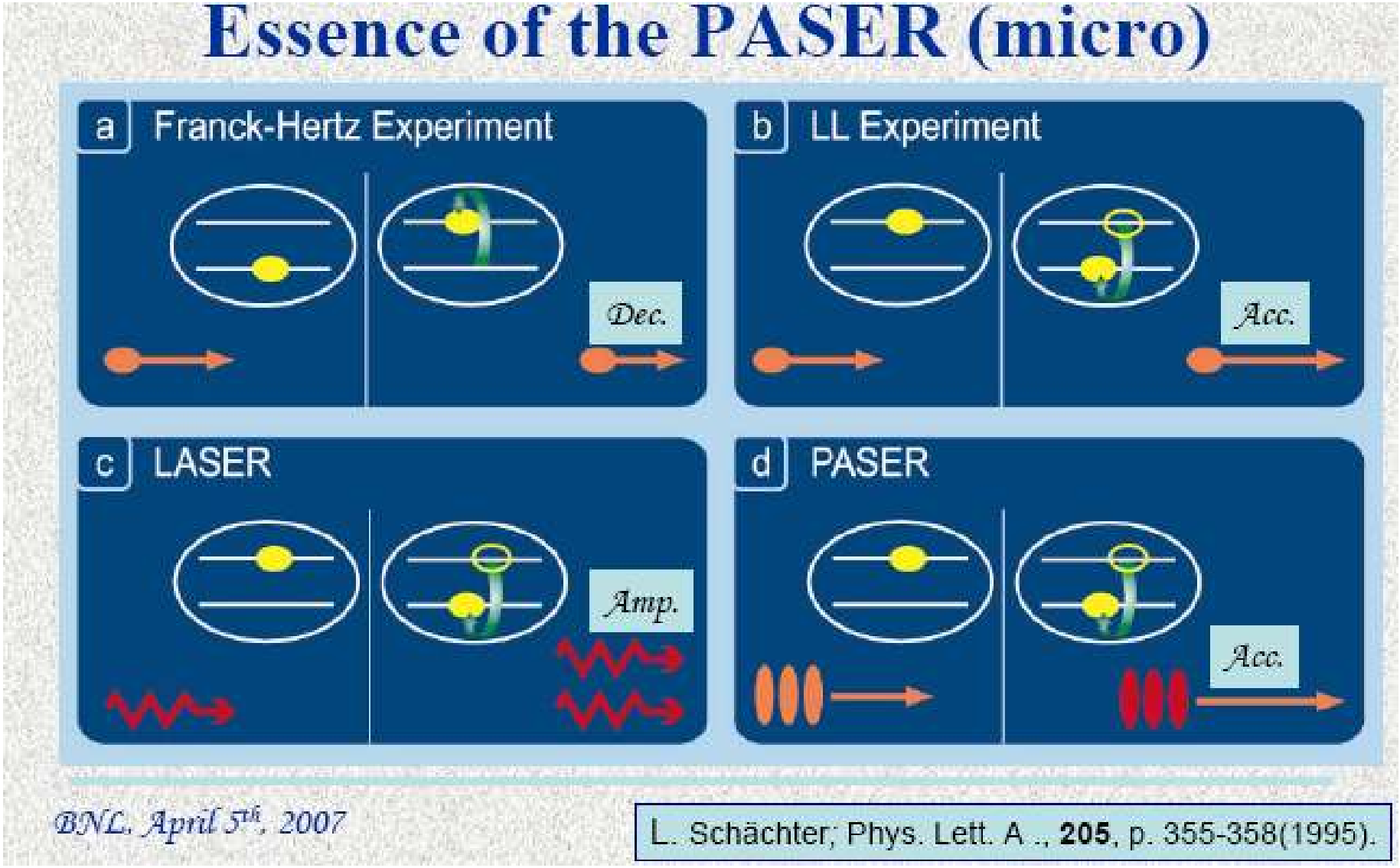
Practical solutions for nonlinear accelerator lattice with stable nearly regular motion

V. Danilov

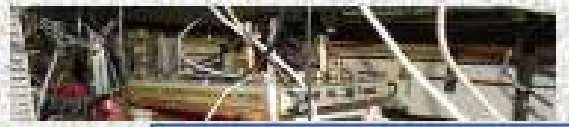
Spallation Neutron Source Project, Oak Ridge National Laboratory, Building 8600, Oak Ridge, Tennessee 37830, USA

(Received 21 August 2008; published 20 November 2008)

Beam in Active(Excited) Media



MC vs CLIC: M&S+Labor

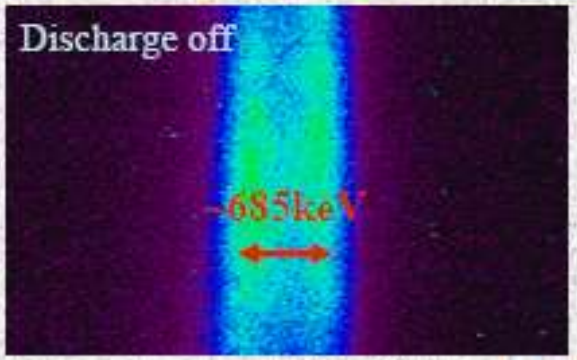


Experiment

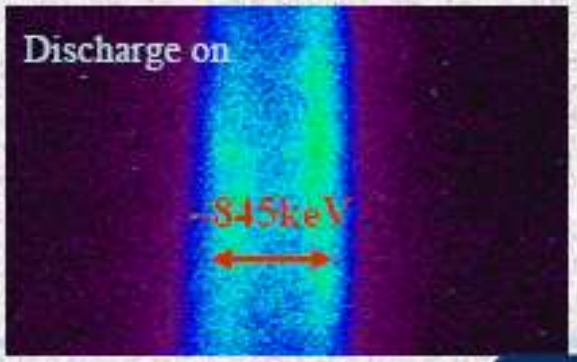
Experiment

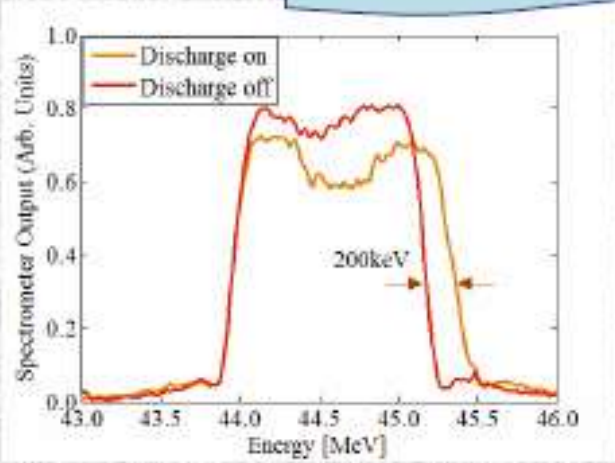
2,000,000 collisions !!

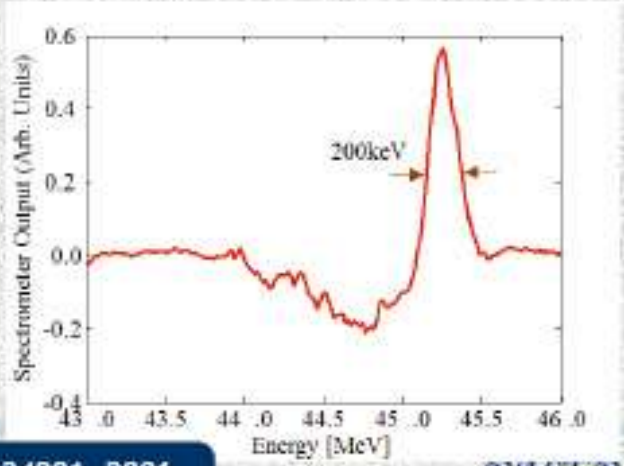
1.5% peak-to-peak energy modulation



Direction of increasing energy







Banna et al., PRL 97, 134801, 2006