Fermilab's 50th Anniversary

50th Anniversary Scientific Symposium

June 7

Celebrating first 50 years and looking ahead to Fermilab's future

50th Fermilab Users Meeting

June 8

Current research enabled by Fermilab facilities

Fermilab's 50th Birthday

June 15

Celebrate lab's 1st day of operations online & on social media

Science & Innovation Open House

Sept. 23

University, lab and corporate partners invited to participate in community event

Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Accelerator Technologies and Beam Physics:

Challenges and Perspectives for the High Energy Physics Frontiers

Vladimir SHILTSEV (Fermilab*, USA)

University of Illinois Urbana-Champaign – Physics Colloquium

October 5, 2016

* Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy

Content :

- Great Accelerators Near You
  - Advanced Photon Source at Argonne - *BES*
  - Tevatron Collider – *Energy Frontier HEP*
  - Main Injector at Fermilab – *Neutrino Research*
- How They Work
  - LHC mechanics
  - Technologies are the key: magnets, RF, etc
- What’s Next ?
  - Economics of post-LHC machines
  - Focus on accelerator research
  - Opportunities for you

Advanced Photon Source @ ANL

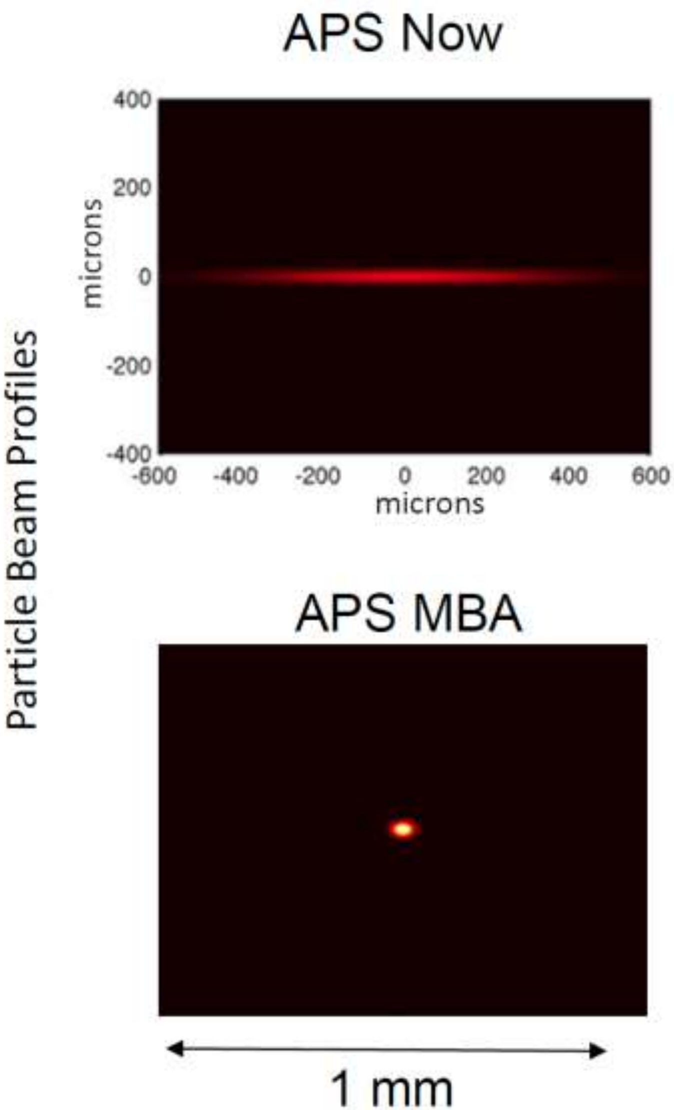
C=1100 m, e- E=7 GeV

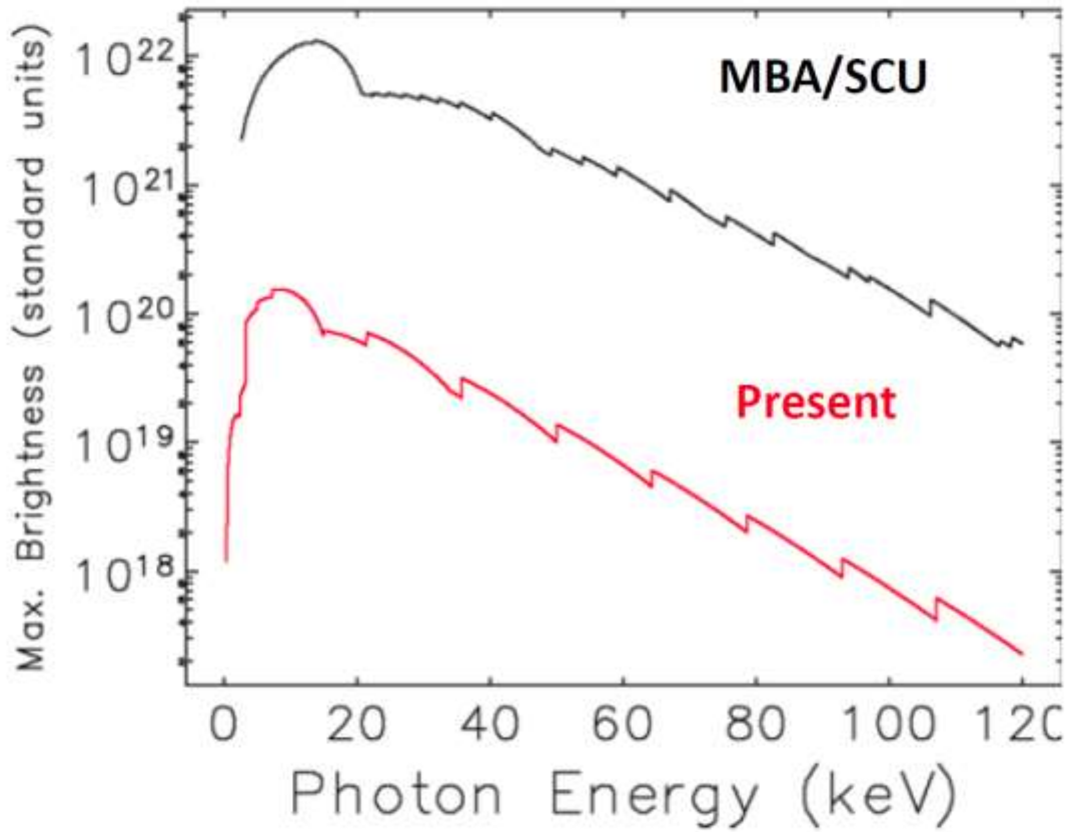
Serves community of >5,000 unique users per year

World's brightest storage ring light source w.photon energy > 4 keV

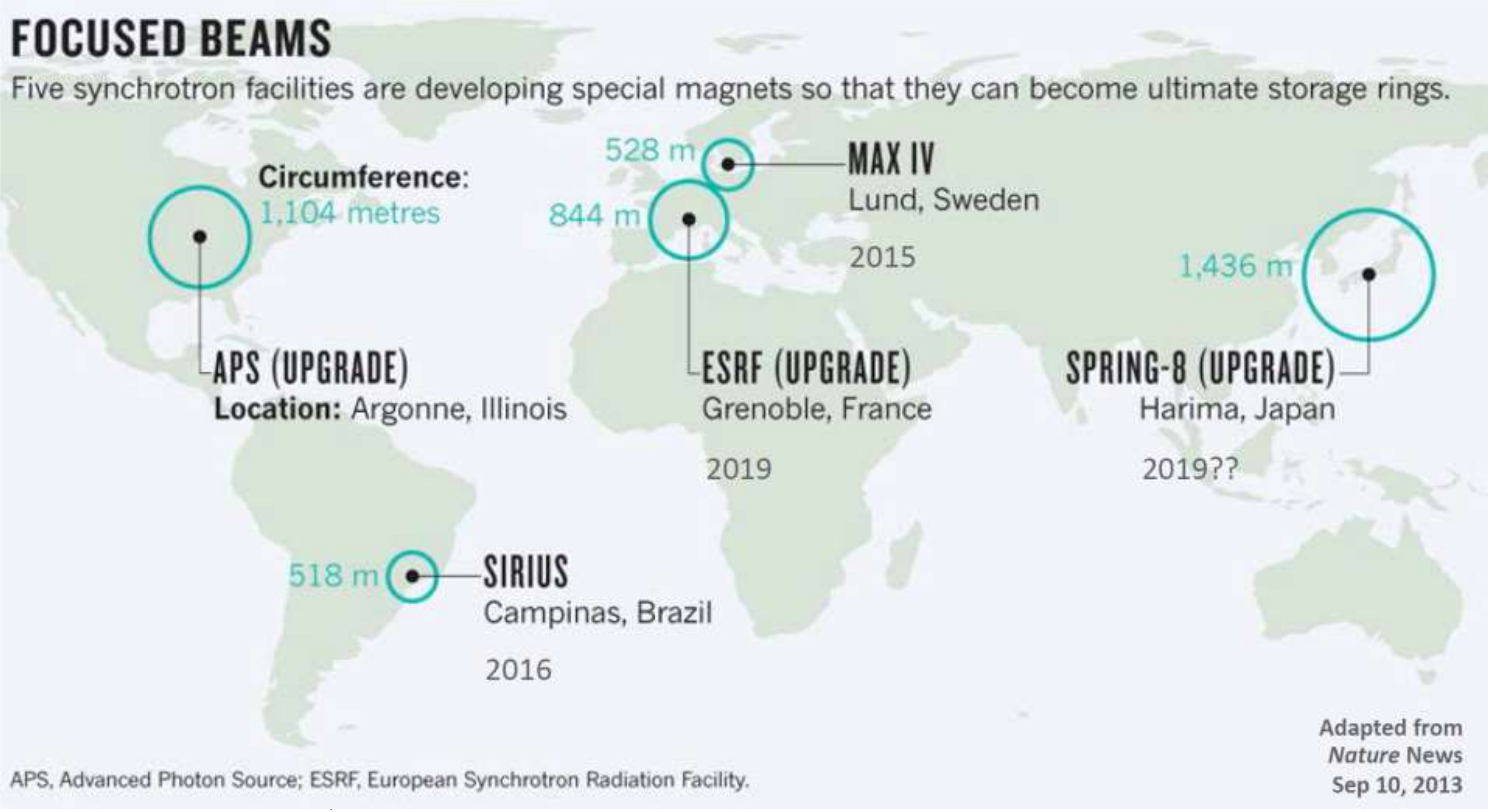
Started 734M$ upgrade, by 2024

APS Upgrade: 2-3 orders in Brightness



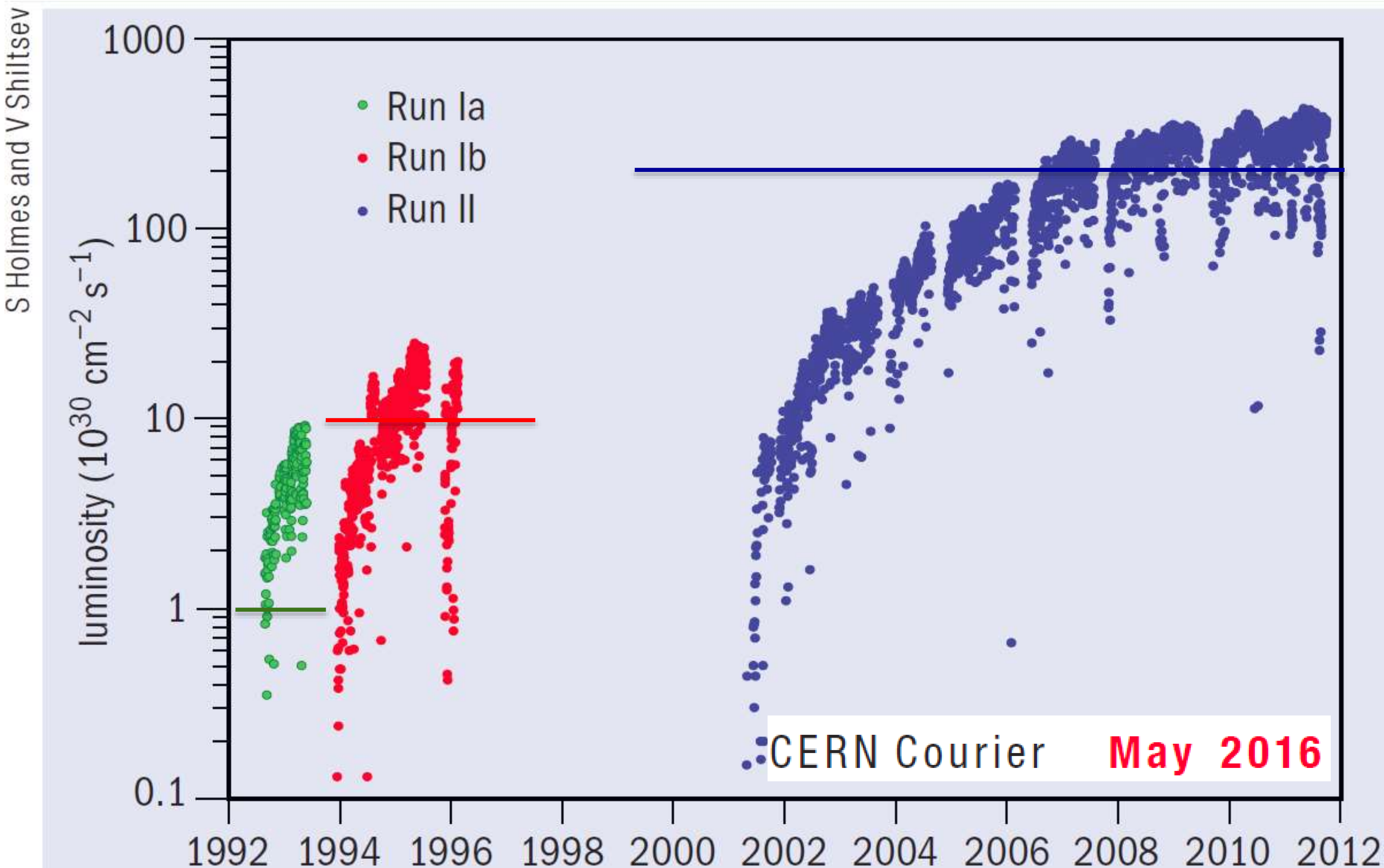


APS will maintain US leadership in Photon Science

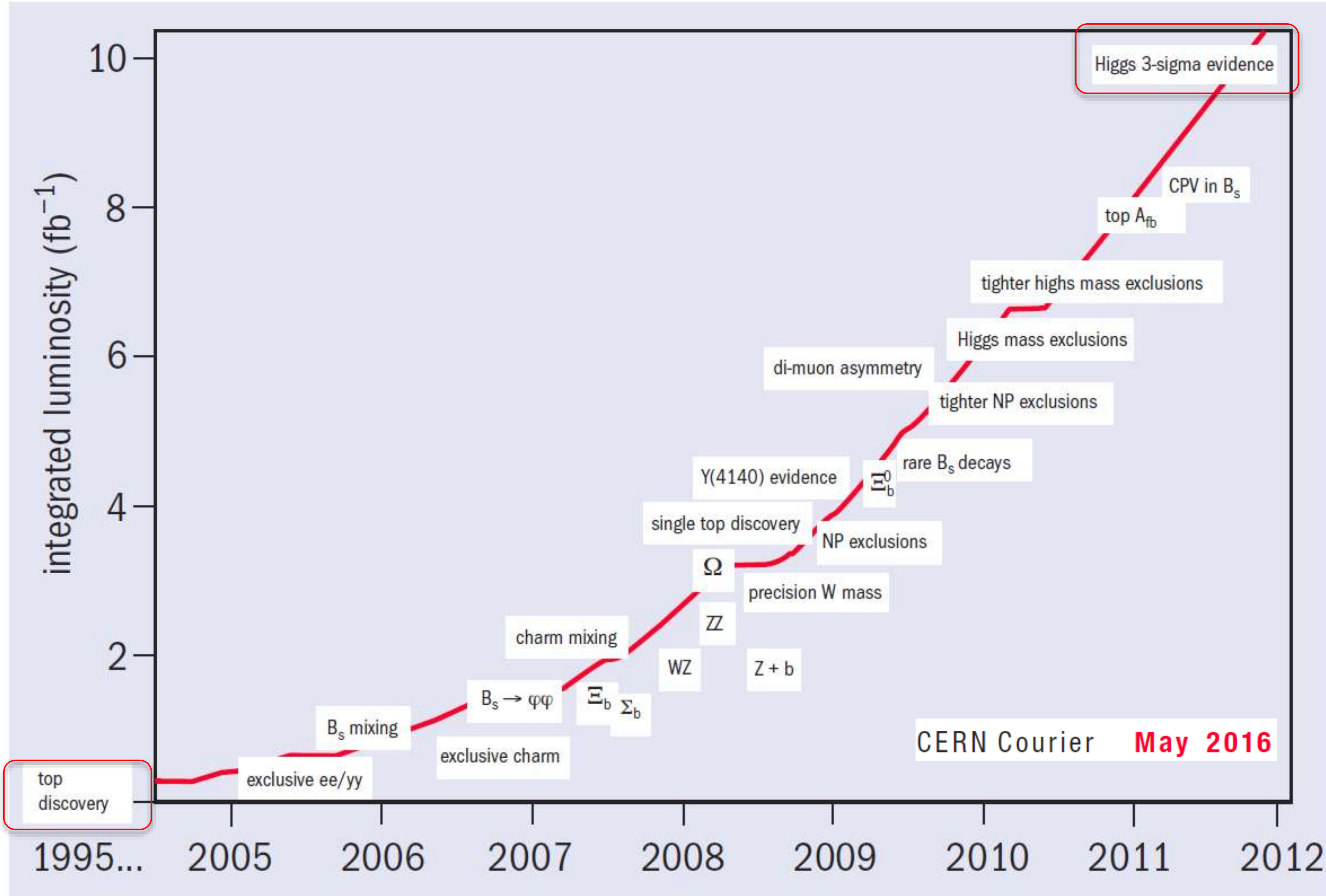


Fermilab Complex : 16 km of accelerators and beamlines, two high power targets, several low power target stations…

Tevatron Collider: 1985-2011



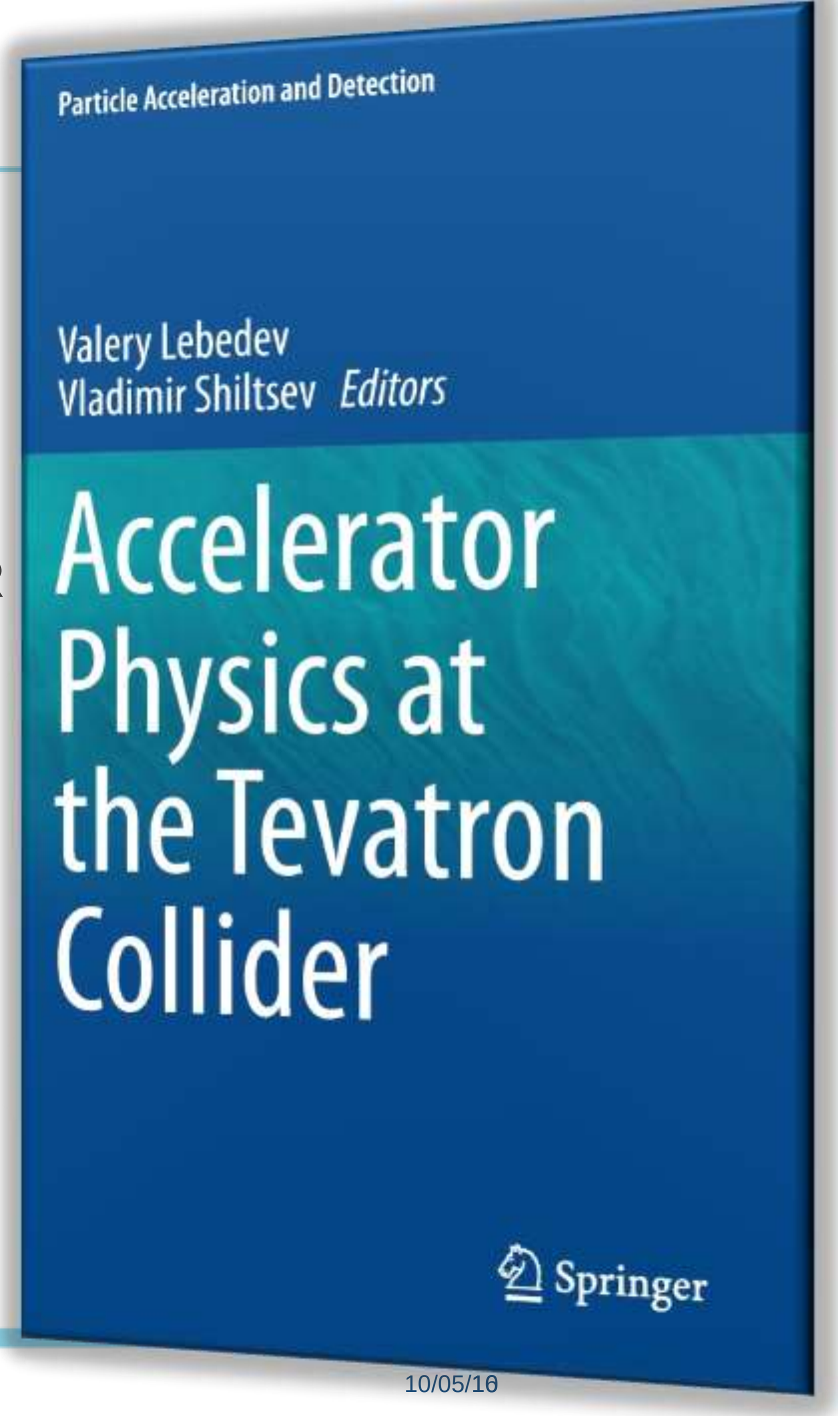
Good Physics Out of the Tevatron



Beam Physics out of Tevatron:

- 1st ever superconding magnet collider
- World's record antiproton production rate
- 1st ever permanent magnet ring 8 GeV RR
- High(est) energy electron cooling of antiprotons
- 1st ever electron lenses for collimation and beam-beam compensation
- Slip-stacking and barrier bucket RF manipulations

see in ***Accelerator Physics at the Tevatron Collider*** - by V.Lebedev and V.Shiltsev, (*Springer,* 2014)



Fermilab Accelerators Now: Fixed Targets/~2300 Users

- Proton Source (**400 MeV** Linac and 8 **GeV** Booster ring):
  - **8 GeV** Booster *Neutrino* Beam (BNB)
    - ANNIE
    - MicroBooNE
    - MiniBooNE
    - MITPC
    - SciBath
    - ICARUS (future)
    - SBND (future)

    } 8 GeV proton program expanding
  - Mucool Test Area (MTA, **400 MeV** beam test facility)
- **120 GeV** Main Injector / **8 GeV** Recycler:
  - NuMI: MINOS+, MINERvA, NOvA
  - LBNF/DUNE (future)

    } Neutrino experiments
  - Fixed Target: SeaQuest, LArIAT, Test Beam Facility
  - Muon: g-2, Mu2e (future)

Accelerators for Neutrino Research

300+ kW **JPARC (Japan)** 30 GeV

400+ kW **CNGS (CERN)** 400 GeV

630 kW **Fermilab's Main Injector (2016)** 120 GeV

EVOLUTION OF INTENSITY FRONTIER ACCELERATORS

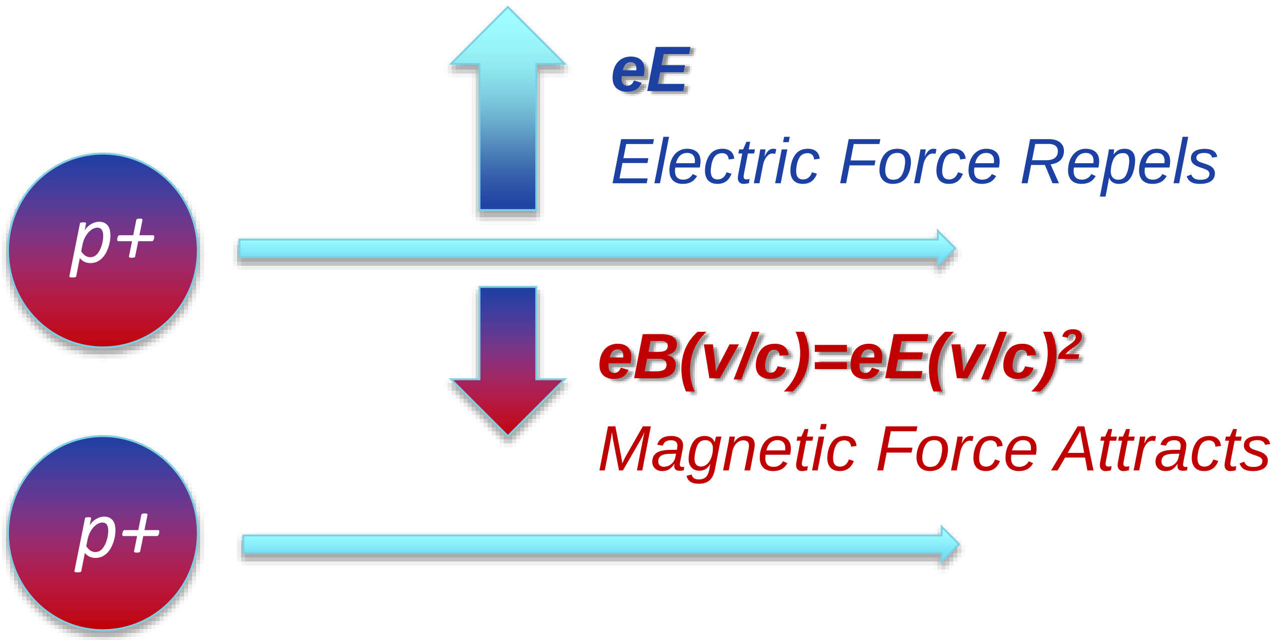
700+ kW Proton Improvement Plan (PIP, 2017)

1.2+ MW Proton Improvement Plan-II (ca 2025)

2.5 MW **5 MW?**

Plan for multi-MW Upgrade (under study)

Intense Beams : Forces and Losses (1)

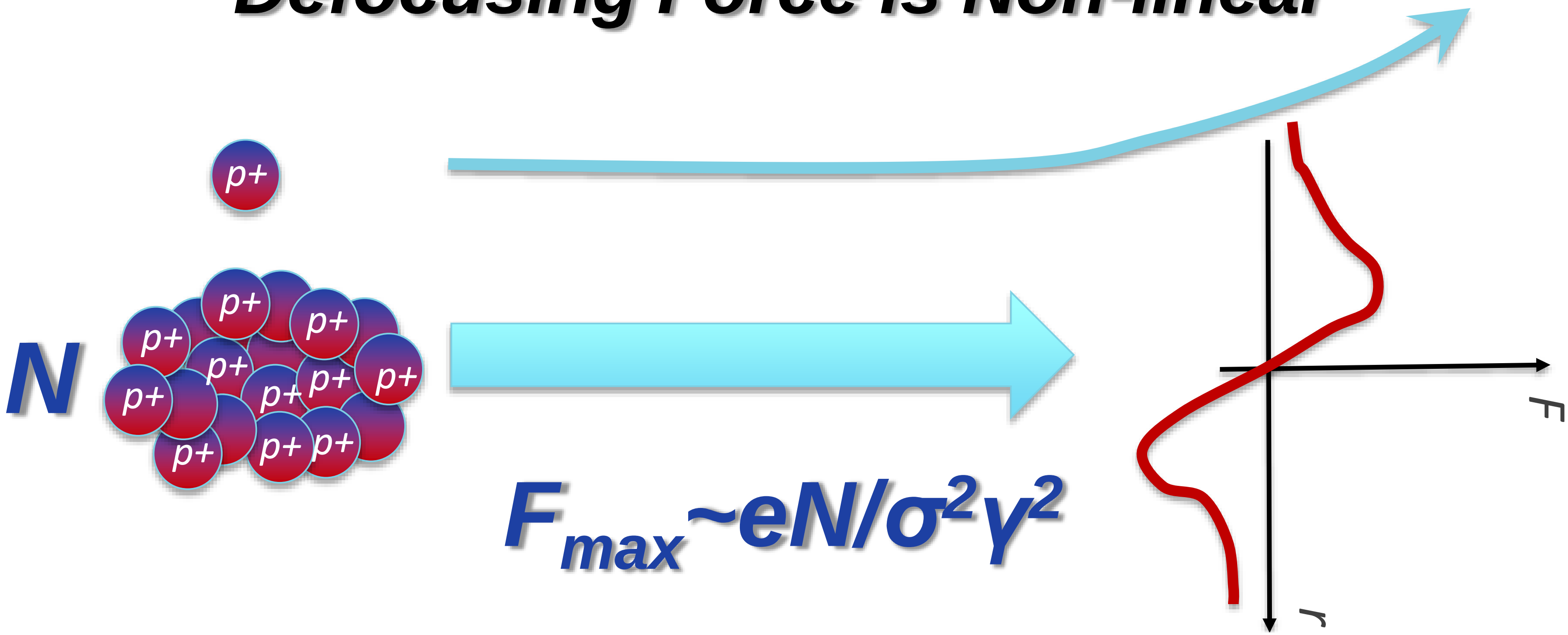


Net Force: Repels

$$eE - eE(v/c)^2 = eE\,(1-\beta^2) = eE/\gamma^2$$

Intense Beams : Forces and Losses (2)

Defocusing Force is Non-linear



$$F_{max} \sim eN/\sigma^2\gamma^2$$

Space-charge effect (emittance growth, losses):

a) proportional to current (N) – and we need that!

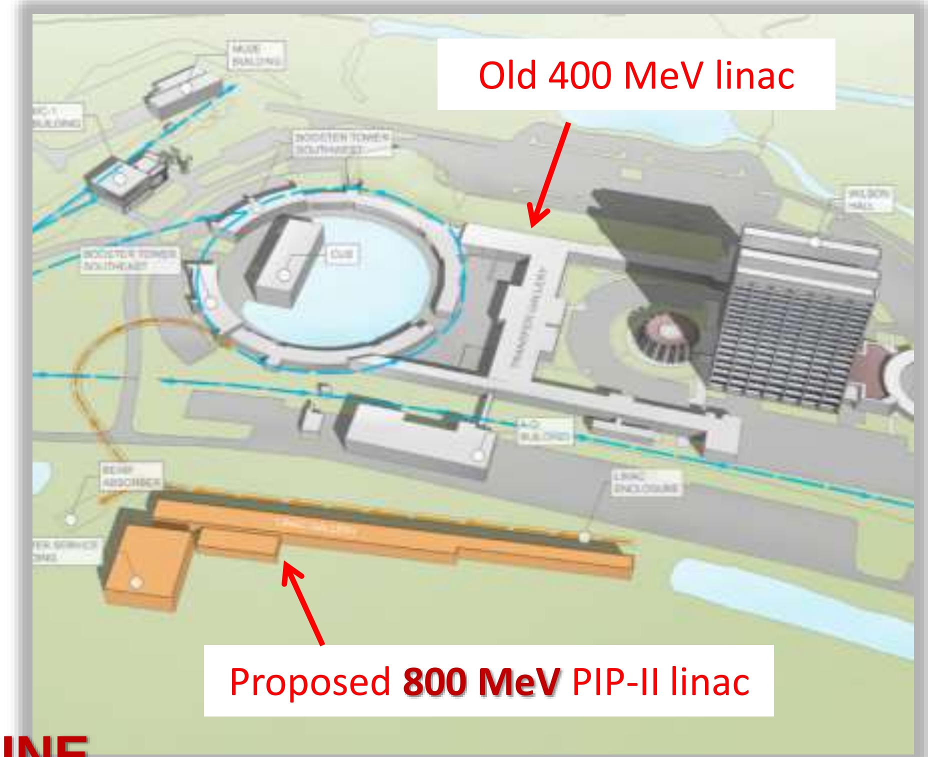
b) scales inversely with beam size (σ)

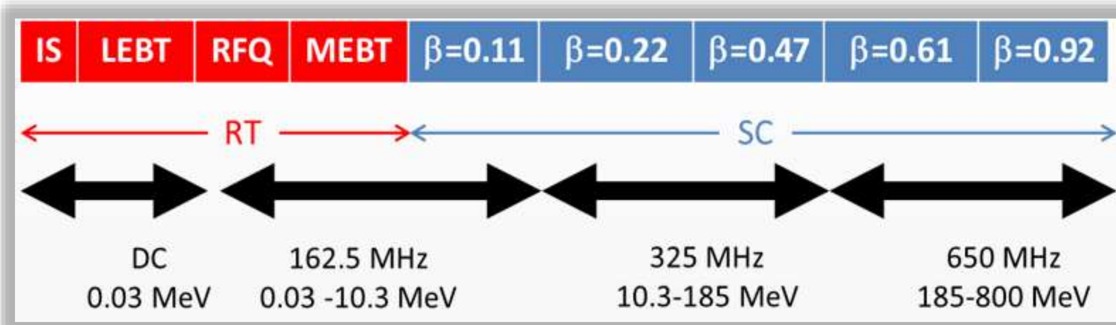
c) scales with time at low energies (γ)

Linacs 5-20 MeV/m
Rings 2-10 MeV/**km**

Proton Improvement Plan-II (PIP-II)

- **Key elements:**
  - Replace existing 400 MeV linac with an 800 MeV linac capable of CW operation.
    - Higher energy + painting = more beam in Booster
  - Increase Booster rate to 20 Hz
  - "Modest" improvements to Recycler and MI
  - Significant contributions from India
- **Goals:**
  - **1.2 MW @ 120 GeV for LBNF/DUNE**
  - Additional power:
    - 82 kW @ 8 GeV
      - Neutrinos (and kaons?)
    - ~100 kW @ 800 MeV
      - Arbitrary bunch structure
      - Muons (*mu2e**)





Fermilab

Large Hadron Collider at CERN

- 26 658.883 m
- 6.5 TeV x 2

LHC Accelerator Operations

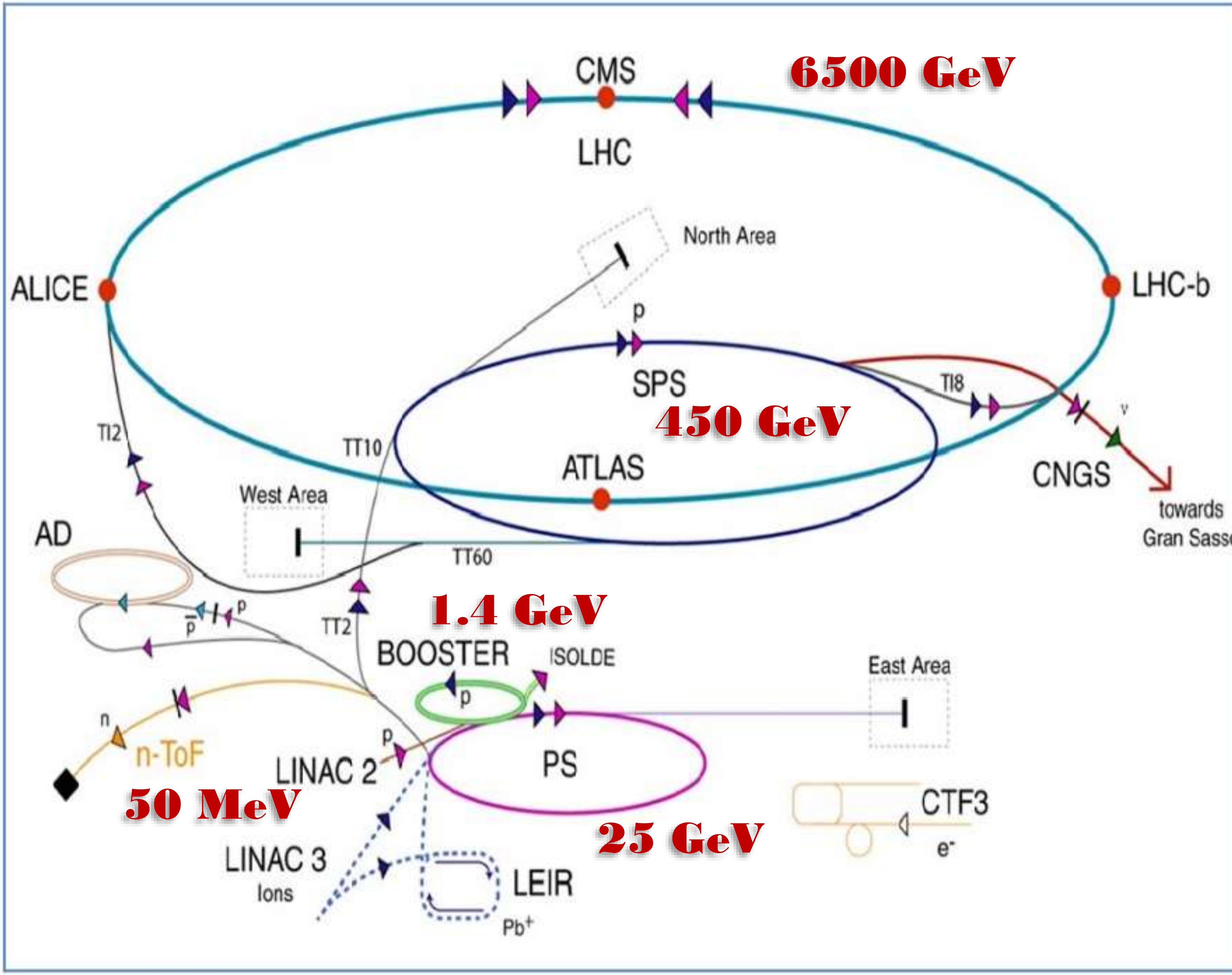
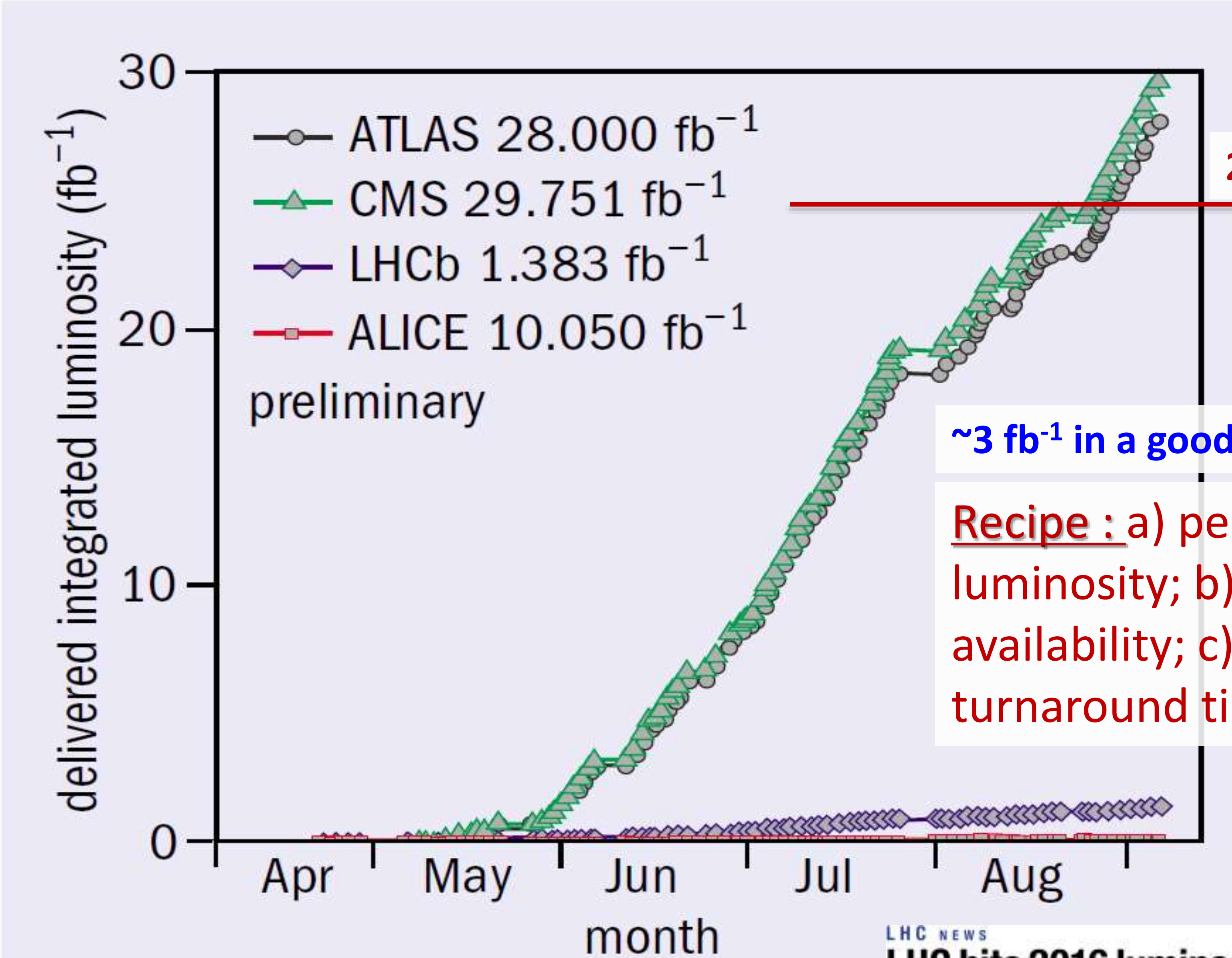

6500 GeV
CMS
LHC
North Area
ALICE
LHC-b
p
SPS
TI8
450 GeV
TI2
TT10
ATLAS
CNGS
ν
West Area
towards
Gran Sasso
AD
TT60
p̄
p
TT2
1.4 GeV
BOOSTER
ISOLDE
East Area
p
n
n-ToF
p
LINAC 2
PS
50 MeV
CTF3
e⁻
25 GeV
LINAC 3
Ions
LEIR
Pb⁺

Figure of Merit: Integrated Luminosity



2016 goal

~3 fb^{-1} in a good week

<u>Recipe :</u> a) peak luminosity; b) max availability; c) short turnaround time

LHC NEWS

LHC hits 2016 luminosity target

LHC Peak Luminosity

Rate → $R = L\sigma$ ← Cross-section ("physics"); L ← "Luminosity"

The relationship of the beam to the rate of observed physics processes is given by the "Luminosity"

Unit of Luminosity is cm^{-2}s^{-1}

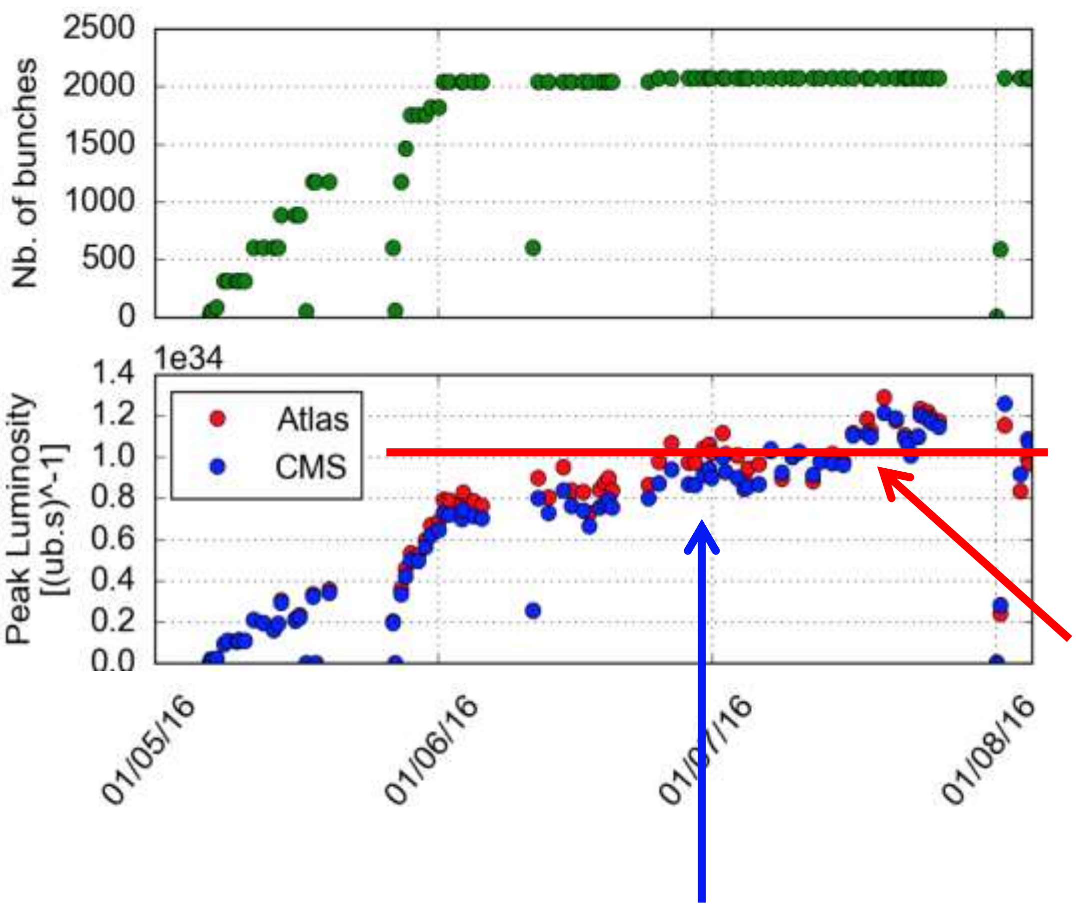
Colliding Gaussian beams

$$L = f_0 N_b \frac{N_p^2}{4\pi\sigma^2} R$$

- $f_0 N_b$: Collision frequency — *Number of bunches x f_rev*
- N_p: Particles in a bunch
- σ: Transverse beam size (RMS)
- R: Geometrical factor $O(1)$:
  - crossing angle
  - hourglass effect

Record *e+e-* Luminosity (KEK-B):	21000 $\times 10^{30}$ cm^{-2}s^{-1}
Record *p-pbar* Luminosity (Tevatron):	430 $\times 10^{30}$ cm^{-2}s^{-1}
Record *p-p* Luminosity (LHC):	14000 $\times 10^{30}$ cm^{-2}s^{-1}
Record *e-p* Luminosity (HERA):	75 $\times 10^{30}$ cm^{-2}s^{-1}

LHC Peak luminosity: design 10^{34} cm^{-2} s^{-1} reached!



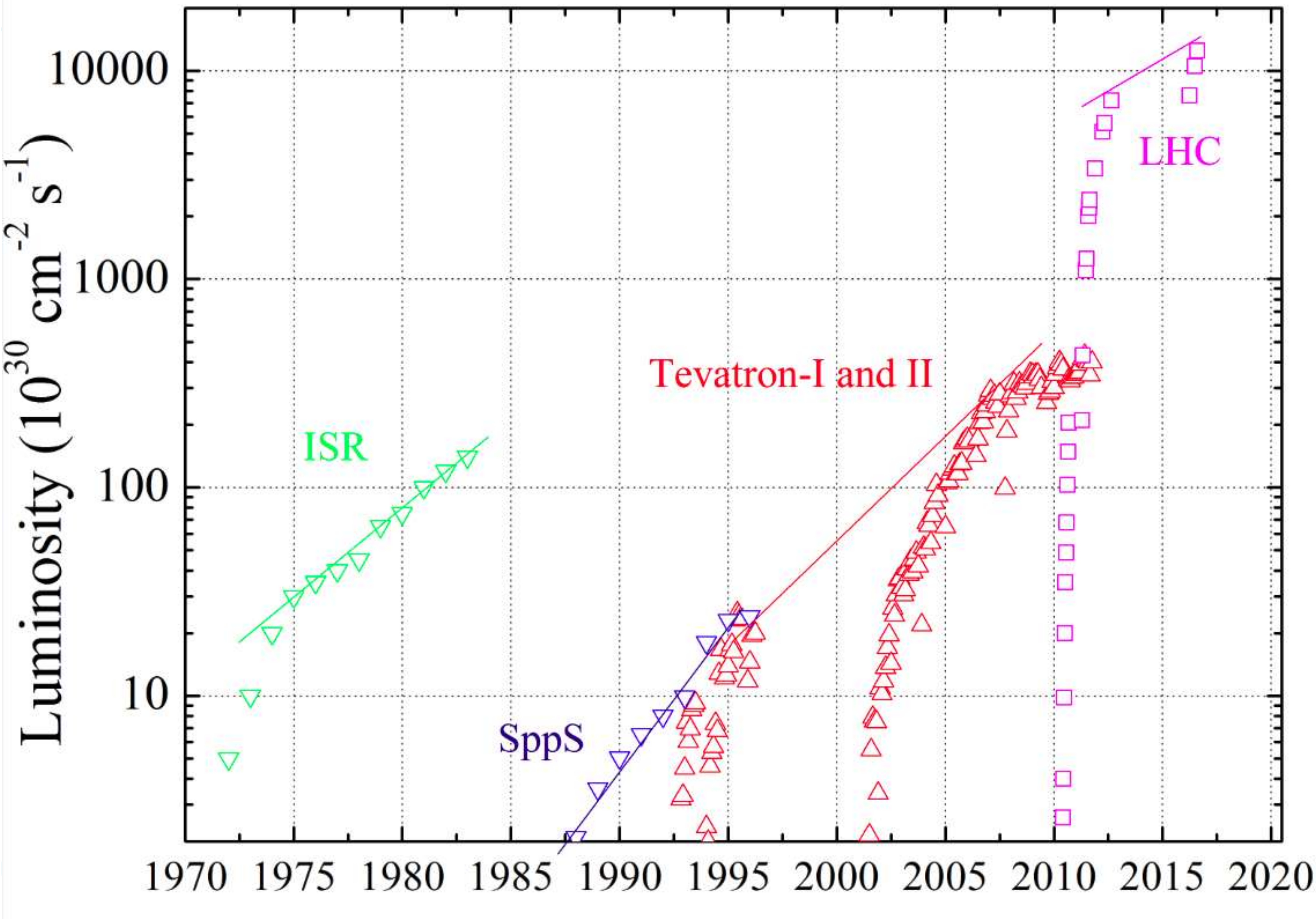
(8 yrs after start up, 6 yrs after 1st lumi)

- No of bunches ~2100 due to SPS beam dump
- 6.5TeV -8% off design
- 25 ns beam - nominal bunches ~1.2e11 p/bunch

- **But: Lower emittance from injectors (2.9 vs 3.5 um)**
- **Squeeze harder in ATLAS and CMS**
  - beta* = 40 cm
  - cf. 80 cm in 2015, 55 cm design

LHCb and ALICE: levelled operation at ~$3x10^{32}$ and ~$2x10^{30}$ cm^{-2}s^{-1} respectively

Luminosity evolution of hadron colliders



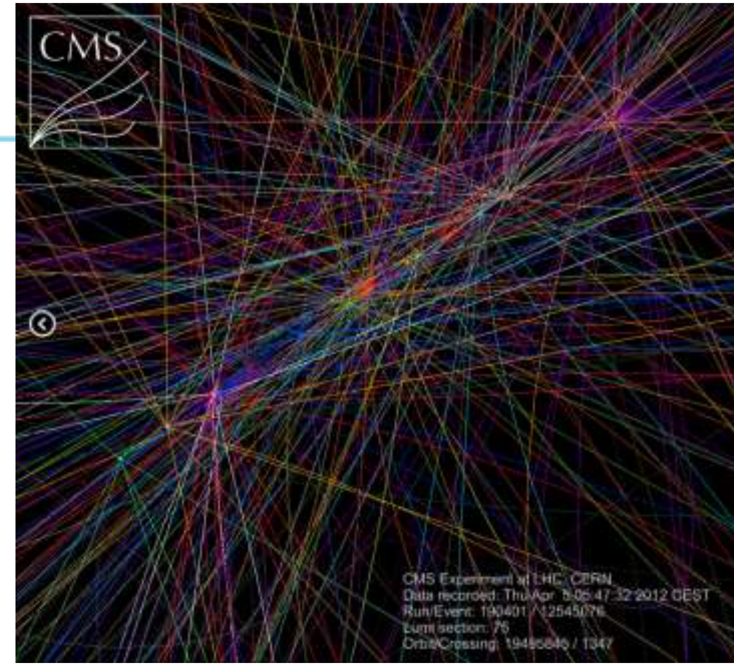
Proton's Death in LHC

$$R = L\sigma$$

"Luminosity" → L

Cross-section ("physics") → σ

1 barn= 10^{-24} cm^2



<u>Example:</u> total *p-p* inelastic+elastic cross section at 13 TeV cme is ~110 mbarn (58 inel+ 12 ssd+40 el not seen)→ ~30 interactions per crossing (NB: pile up is only ~20!) x 40,000,000 collision/sec= *1.1B protons leave each beam every second*

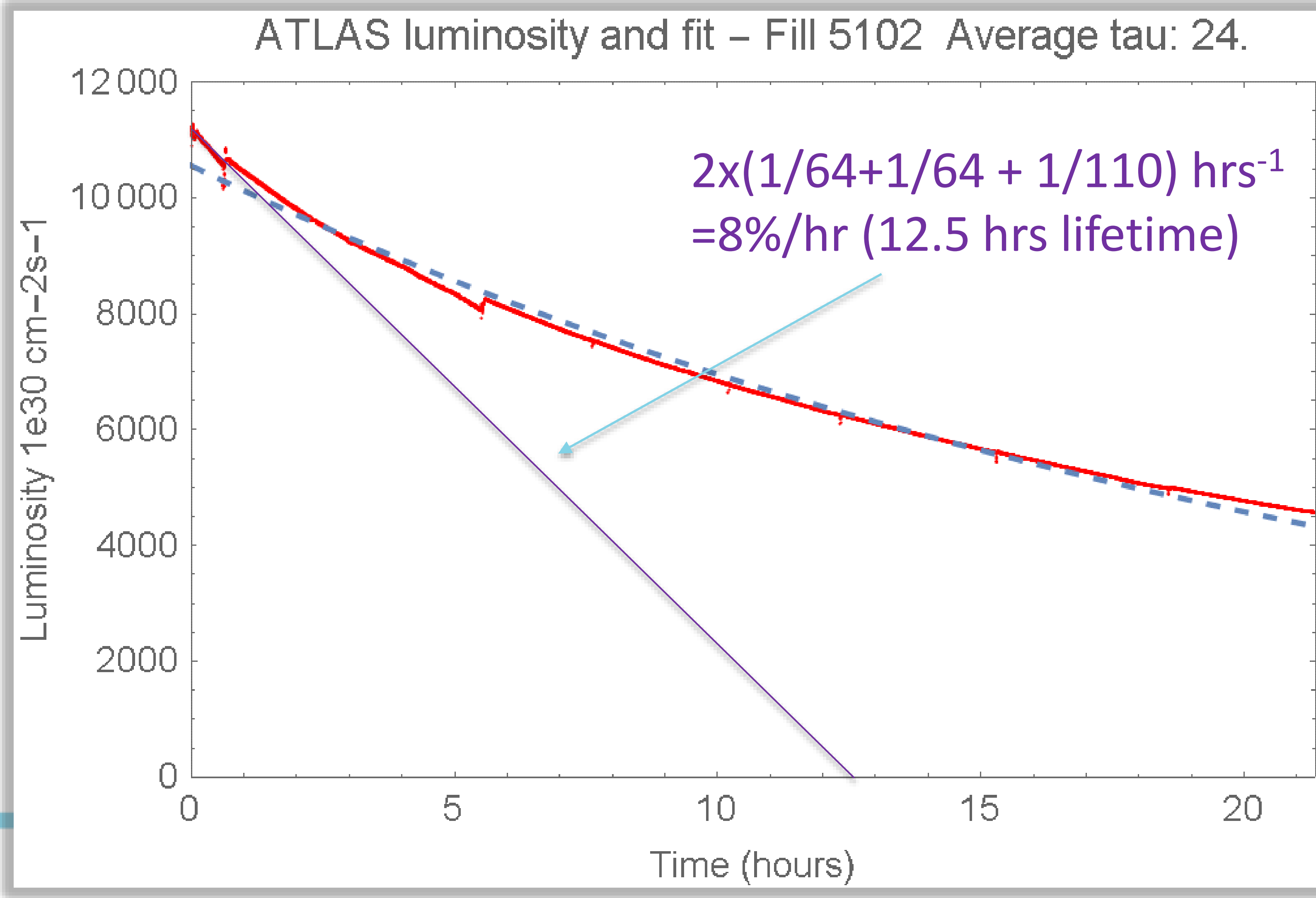
Beam lifetime due to such "Burn up" *T=N/(dN/dt)=*

2.5e14 protons/(1.1e9/s) *=63 hours*

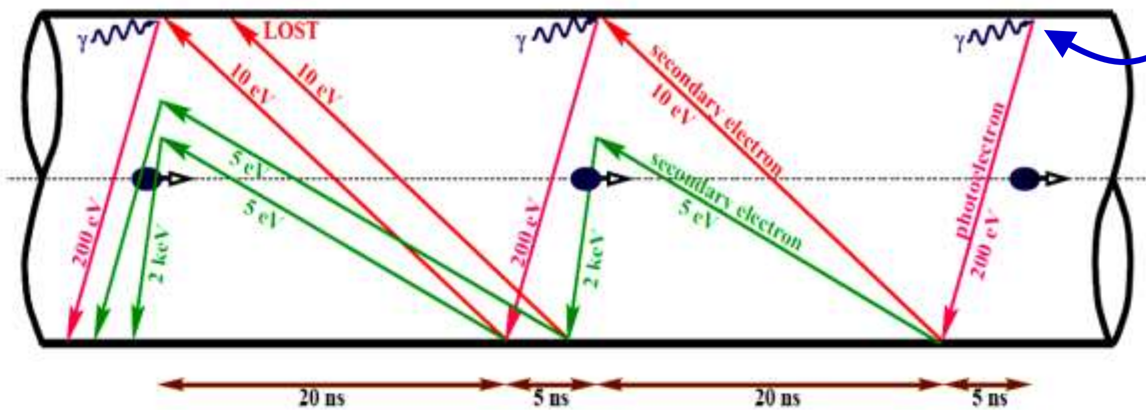
LHC : Luminosity Lifetime

Take into account two IPs (ATLAS, CMS and 3% LHCb) 1/64+1/64 hrs^{-1}

Take into account beam gas 1/110hrs^{-1} and that $Lumi \sim N \wedge 2$ → x2



LHC : Electron Cloud & Need of Scrubbing



The critical energy of the photons at 7 TeV ~ 44 eV

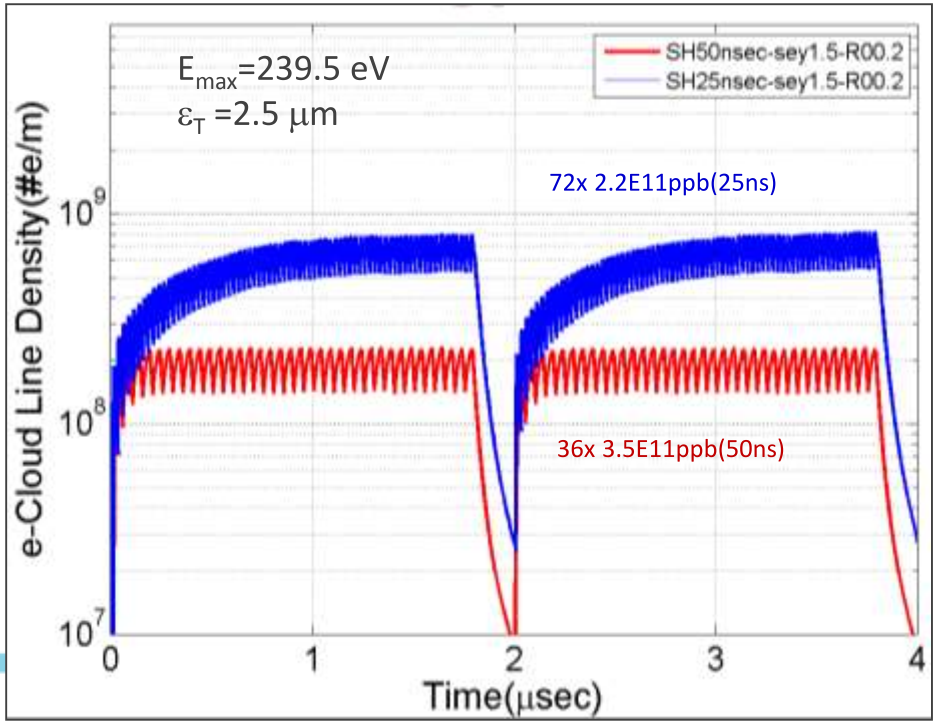
(LHC Beampipe !)

- Primary sources of electrons in the LHC
  - At Injection (450 GeV): gas ionization
  - At 7 TeV: Synchrotron Radiation

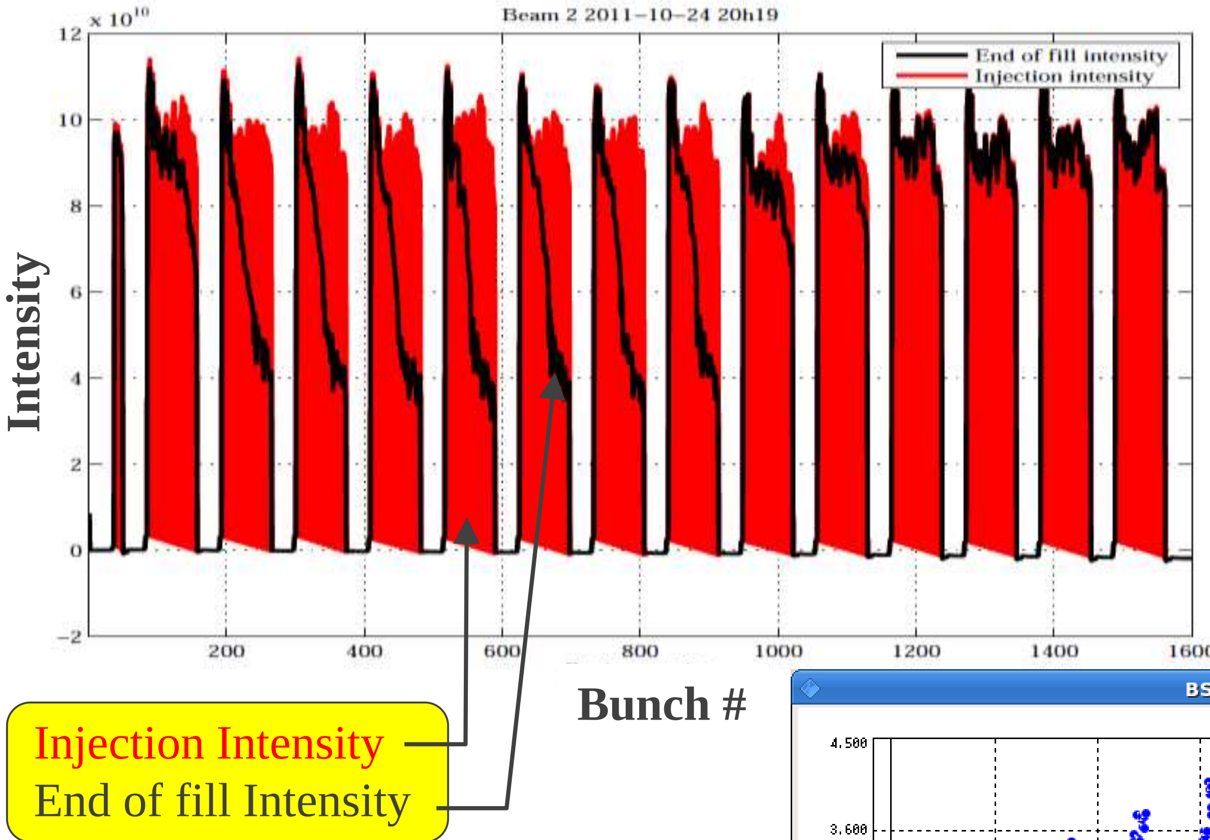
Consequences:

- instabilities, emittance growth, desorption ←bad vacuum, beam loss

- excessive energy deposition in the cold sectors



What e-cloud can do to the Beam?



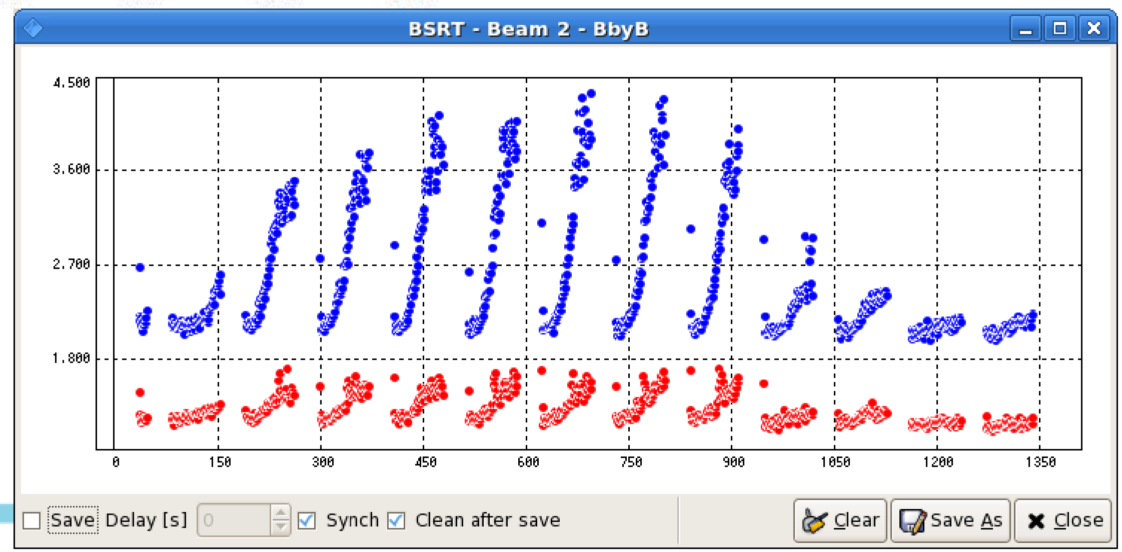
- Fill: 2249 (2011)
  25 ns Bunch Spacing
- Energy = 450 GeV
- Time between Injection to End ~10 min
- Dumped by BPM
- 1020 Bunches

Measured Emittance Growth

~33% Horizontal

~110% Vertical

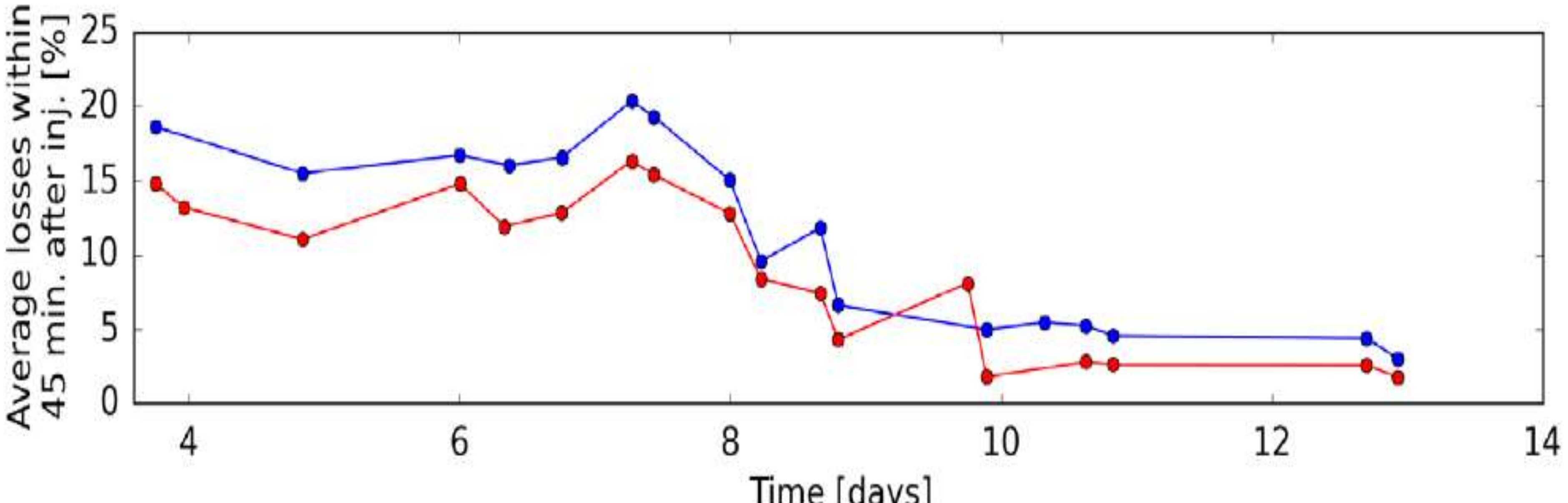
Associated beam loss



Scrubbing @ 25 ns bunch spacing

So far it is the only cure in the LHC….Takes time to clean the surface and reduce SEY (secondary electron yield) from ~2.2 to ~1.5

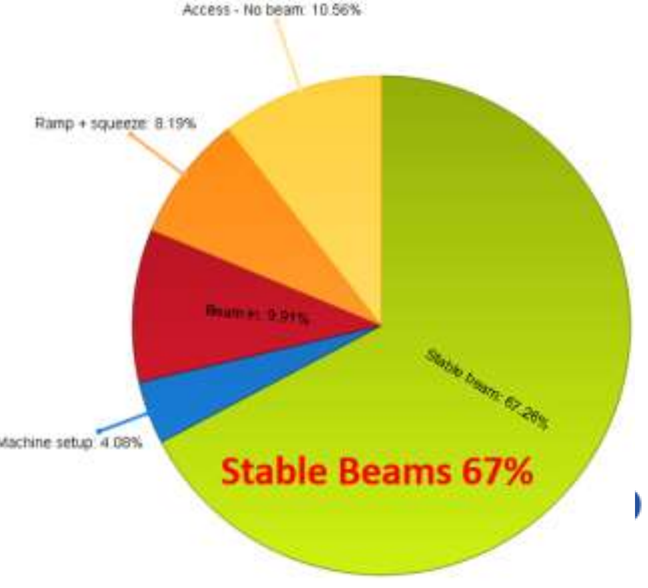
Scrubbing "memory" kept while running with 25 ns beams - **deconditioning** was observed after few weeks of low e-cloud operation



Other remarkable achievements :

- “Accident” Sep 19, 2009
  - Bad “splices”, QPS and He release
  - Damage 1 km of LHC
  - Quick fix and run at 3.5-4 TeV/ beam
  - “real fix” and run at 6.5 TeV/beam

- Machine “uptime”
  - Many trips, short stores
  - UFOs, cryogenics trips
  - Unbelievable progress: time in collisions went from 33% in 2015 to 67% in 2016 !!!



(see more in backup slides)

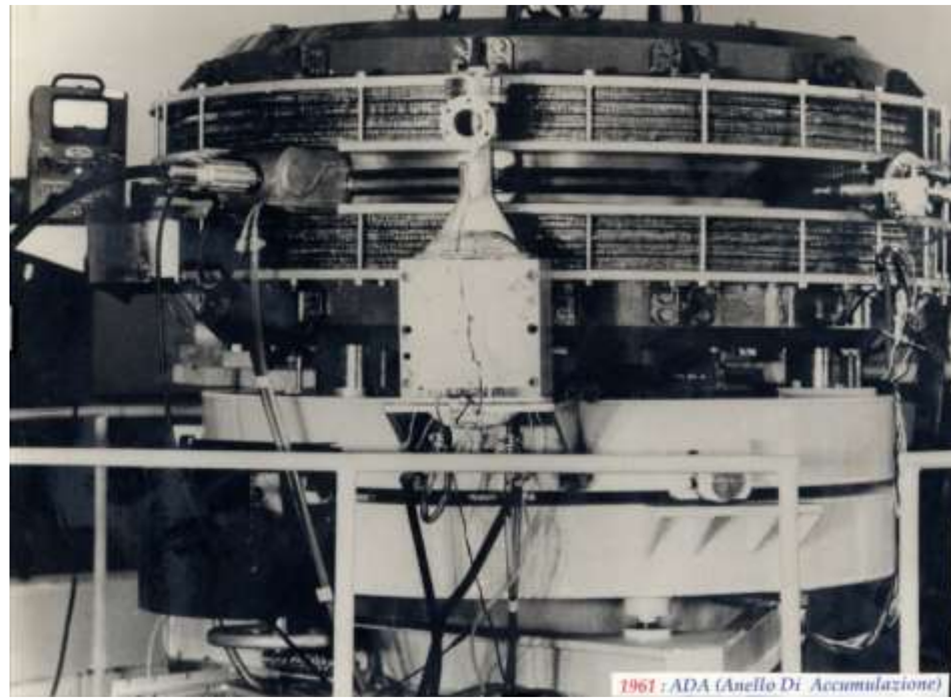
Colliders : 1964

It's easier to collide e+ / e-, because synchrotron radiation naturally "cools" the beam to smaller size.

- VEP-1 (*Встречные Электронные Пучки*) at Novosibirsk, USSR
  - 130 MeV e^- x 130 MeV e^-

  - 1963: Construction Finished
  - May 19, 1964: Luminosity

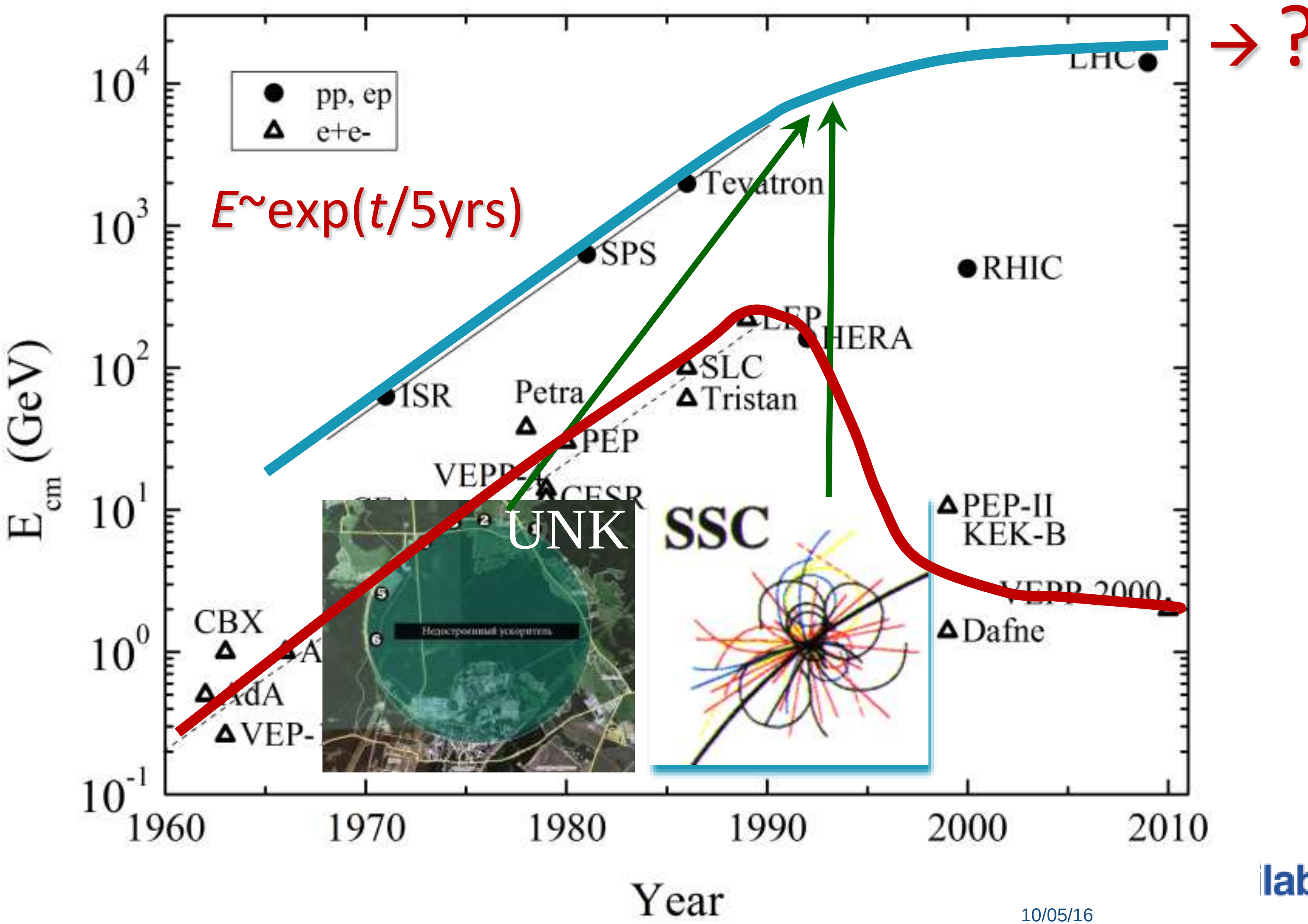
- ADA (*Anello Di Accumulazione*) at INFN, Frascati, Italy
  - 250 MeV e^+ x 250 MeV e^-



  - 1961 : Construction Finished
  - ~ May-June 1964: Luminosity Detected

Colliders: 29 Built… 7 in Operation

Colliders: Glorious Past

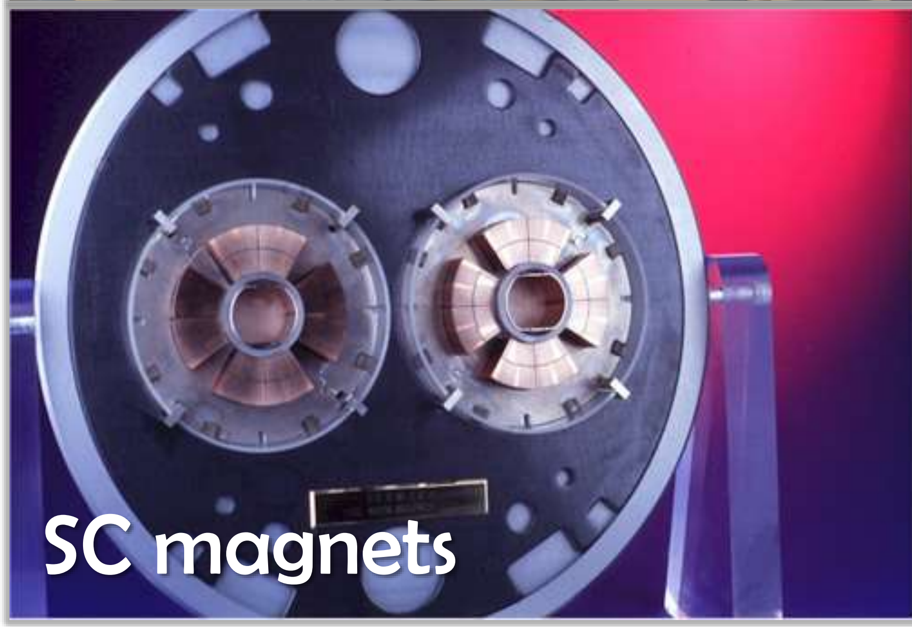


Will There Be Energy Frontier Colliders After LHC?

(***Yes*** or ***No***) = (*Physics* × Feasibility)

- **PHYSICS** case of post-LHC high energy physics machine depends on the LHC discoveries:
  - it might call for a collider (if signals are clear)
  - otherwise, search for signs of new physics in the neutrino/rare decays (*Intensity Frontier*) or astrophysics
- **FEASIBILITY** of an accelerator is actually complex:
  - Feasibility of **ENERGY**
    - Is it possible to reach the *E* of interest / what's needed ?
  - Feasibility of **PERFORMANCE**
    - Will we get enough physics out there / luminosity ?
  - Feasibility of **COST**
    - Is it affordable to build and operate ?
- **What can we learn/take from the past/present?**

Four “Feasible” Technologies



… in addition to “traditional” technologies of tunneling, electric power and site infrastructures, etc …

Analysis:

2014 JINST 9 T07002

17 "Data Points" - Costs of Big Accelerators:

- Actually built:
  - RHIC, MI, SNS, LHC
- Under construction:
  - XFEL, FAIR, ESS
- Not built but costed:
  - SSC, VLHC, NLC
  - ILC, TESLA, CLIC, Project-X, Beta-Beam, SPL, ν-Factory

Wide range :

- 4 orders in *E*nergy, >1 order in *P*ower, >2 orders in *L*ength
- Almost 2 orders in cost
  - (normalized to US TPC)

	Cost (B$) Year	Energy (TeV)	Accelerator technology	Comments	Length (km)	Site power (MW)	TPC range (Y14 B$)
SSC	11.8 B$ (1993)	40	SC Mag	Estimates changed many times [6–8]	87	~ 100	19–25
FNAL MI	260M$ (1994)	0.12	NC Mag	"old rules", no OH, existing injector [9]	3.3	~ 20	0.4–0.54
RHIC	660M$ (1999)	0.5	SC Mag	Tunnel, some infrastructure, injector re-used [10]	3.8	~ 40	0.8–1.2
TESLA	3.14 B€ (2000)	0.5	SC RF	"European accounting" [11]	39	~ 130	11–14
VLHC-I	4.1 B$ (2001)	40	SC Mag	"European accounting", existing injector [12]	233	~ 60	10–18
NLC	~ 7.5 B$ (2001)	1	NC RF	~ 6 B$ for 0.5 TeV collider, [13]	30	250	9–15
SNS	1.4 B$ (2006)	0.001	SC RF	[14]	0.4	20	1.6–1.7
LHC	6.5 BCHF (2009)	14	SC Mag	collider only — existing injector, tunnel & infrstr., no OH, R&D [15]	27	~ 40	7–11
CLIC	7.4–8.3B CHF(2012)	0.5	NC RF	"European accounting" [16]	18	250	12–18
Project X	1.5 B$ (2009)	0.008	SC RF	[17]	0.4	37	1.2–1.8
XFEL	1.2 B€ (2012)	0.014	SC RF	in 2005 prices, "European accounting" [18]	3.4	~ 10	2.9–4.0
NuFactory	4.7–6.5 B€ (2012)	0.012	NC RF	Mixed accounting, w. contingency [19]	6	~ 90	7–11
Beta-Beam	1.4–2.3 B€ (2012)	0.1	SC RF	Mixed accounting, w. contingency [19]	9.5	~ 30	3.7–5.4
SPL	1.2–1.6 B€ (2012)	0.005	SC RF	Mixed accounting, w. contingency [19]	0.6	~ 70	2.6–4.6
FAIR	1.2 B€ (2012)	0.003-.08	SC Mag	"European accounting" [20], 6 rings, existing injector	~ 3	~ 30	1.8–3.0
ILC	7.8 B$ (2013)	0.5	SC RF	"European accounting" [21]	34	230	13–19
ESS	1.84 B€ (2013)	0.0025	SC RF	"European accounting" [22, 23]	0.4	37	2.5–3.8

V.Shiltsev, A phenomenological cost model for high energy particle accelerators

! WARNING !

αβγ - Cost Estimate Model:

$$\mathrm{Cost(TPC)} = \alpha\, L^{1/2} + \beta\, E^{1/2} + \gamma\, P^{1/2}$$

a) **±33% estimate, for a "green field" accelerators**

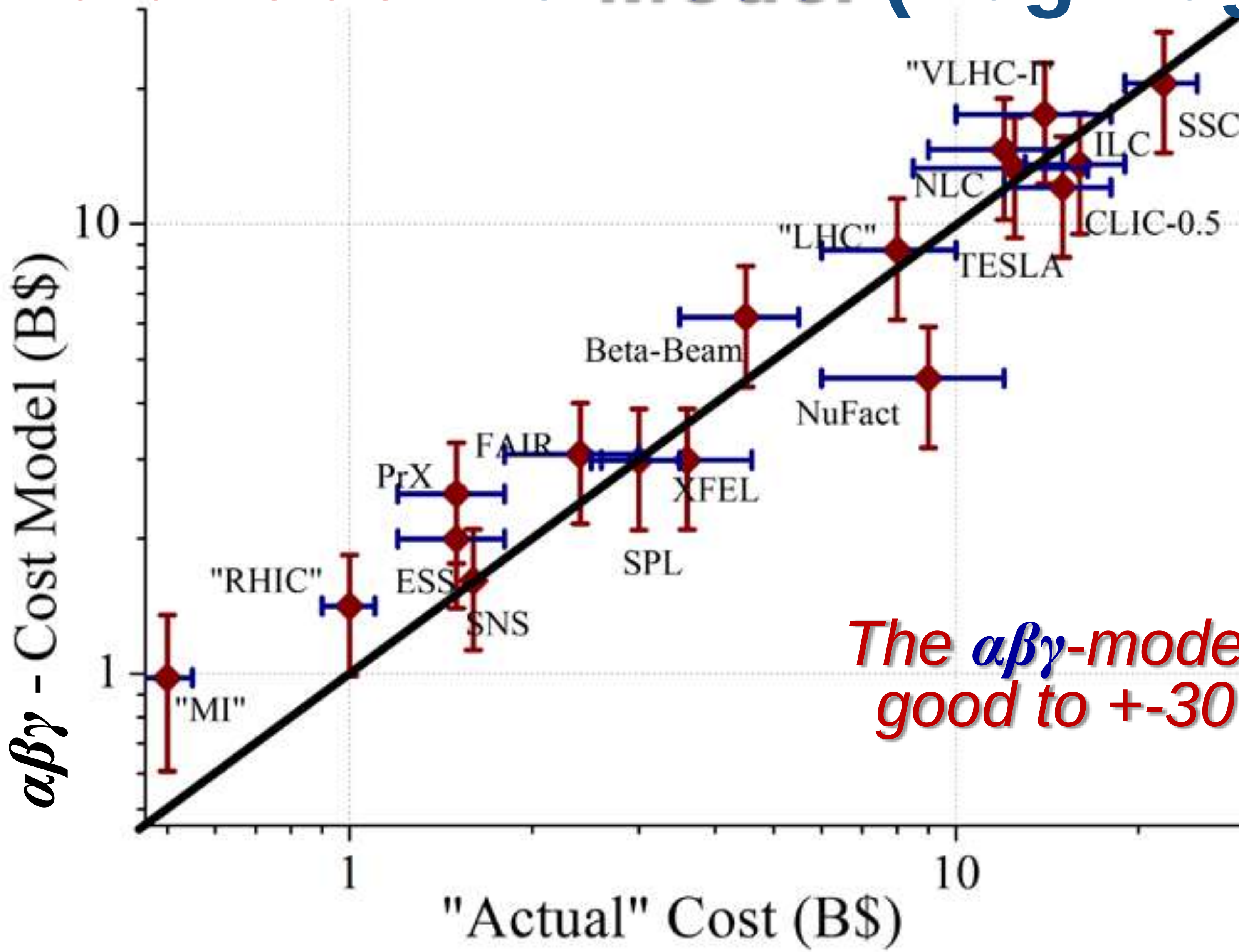
b) **"US-Accounting" = TPC !** (~ 2 × *European Accounting*)

c) **Coefficients** (units: 10 km for *L*, 1 TeV for *E*, 100 MW for *P*)

- **$\alpha \approx$ 2B$/sqrt(*L*/10 km)**
- **$\beta \approx$ 10B$/sqrt(*E*/TeV)** for SC/NC RF
- **$\beta \approx$ 2B$ /sqrt(*E*/TeV)** for SC magnets
- **$\beta \approx$ 1B$ /sqrt(*E*/TeV)** for NC magnets
- **$\gamma \approx$ 2B$/sqrt(*P*/100 MW)**

USE AT YOUR OWN RISK!

Total Cost **vs** ***Model*** **(Log-Log)**

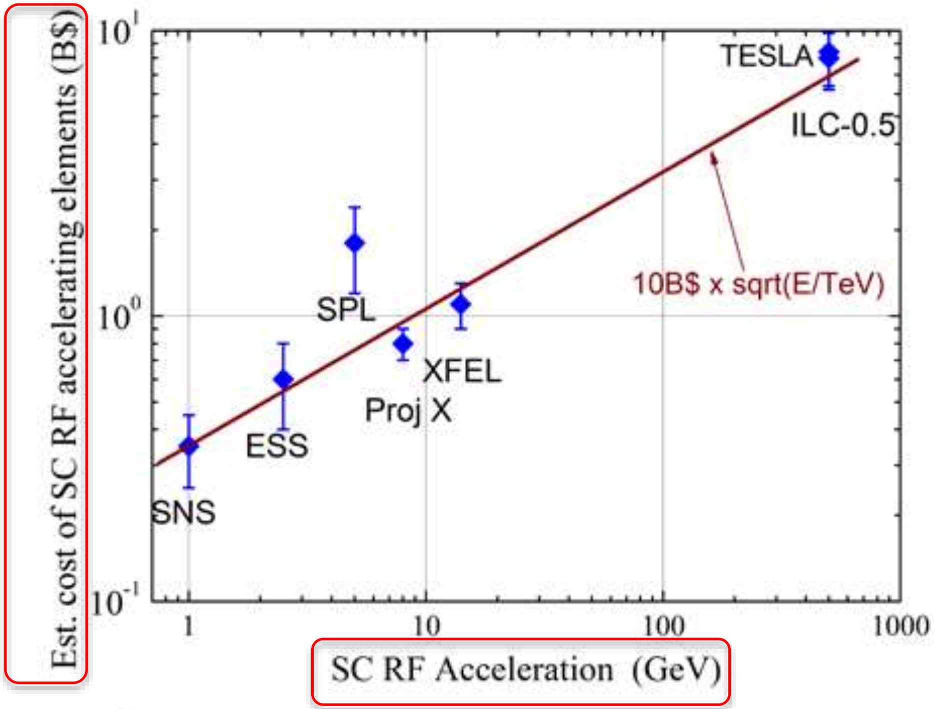


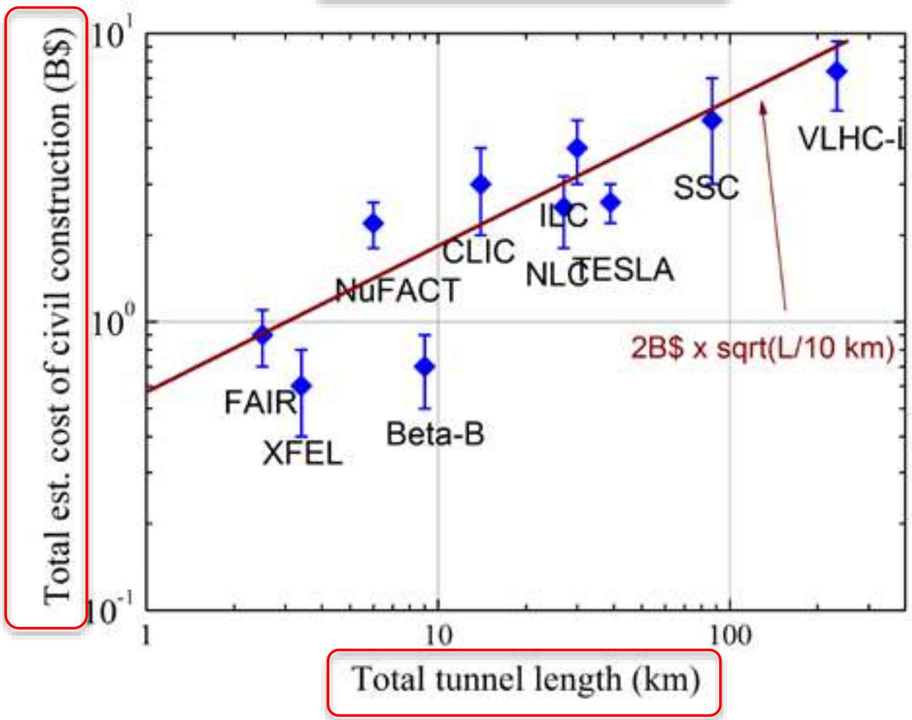
The ***αβγ****-model is good to +-30%*

Illustrations

Comment:

Sqrt-functions are quite accurate over wide range because such dependence well approximates the ***"initial cost" – effect*** :





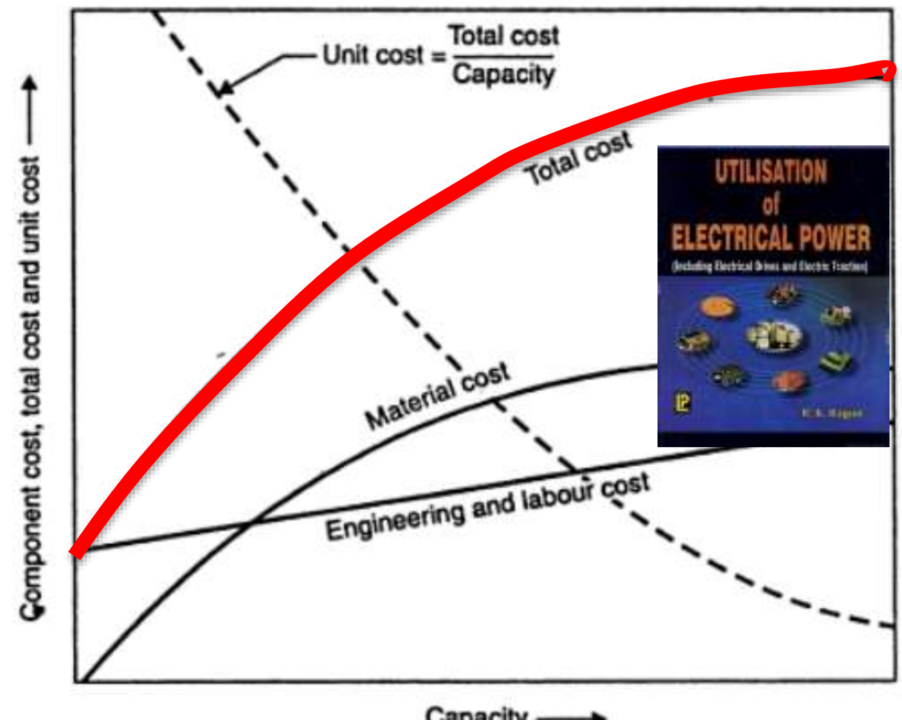


Fig. 9.5. Variation of costs of power plant *versus* its capacity.

Take LHC as an Example:

- ***αβγ* – Model:**
  - 40 km of tunnels
  - 14 TeV c.o.m SC magnets
  - ~150 MW of site power

$$2\sqrt{40/10} = 4$$

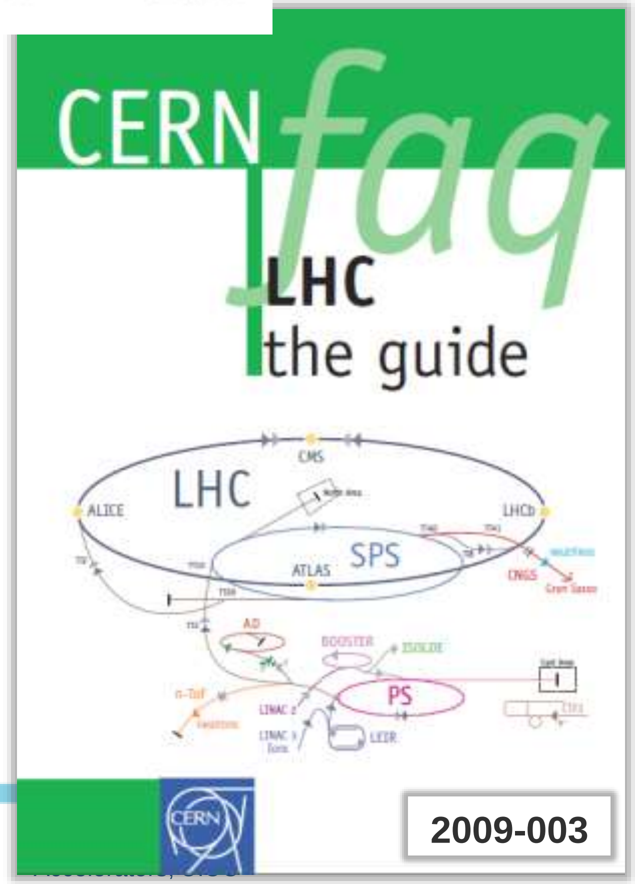
$$2\sqrt{14} = 7.5$$

$$2\sqrt{150/100} = 2.5$$

TOTAL PROJECT COST : **14B$ ± 4.5B$**

- **CERN LHC Factbook (2009):**
  - 6.5 BCHF, incl. **5 BCHF** for accelerator
    (European Accounting)
  - x 2 to US TPC → **10 BCHF=10B$**
  - Cost of existing injector complex ~30-40% **3-4 B$**

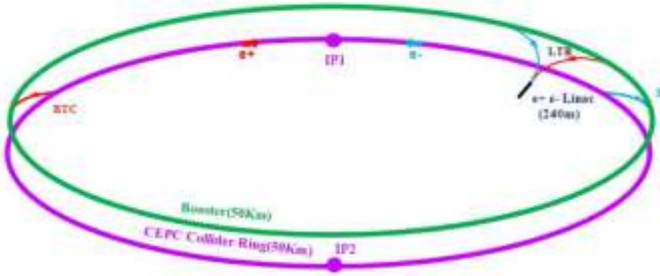
TPC : ~**13-14B$**



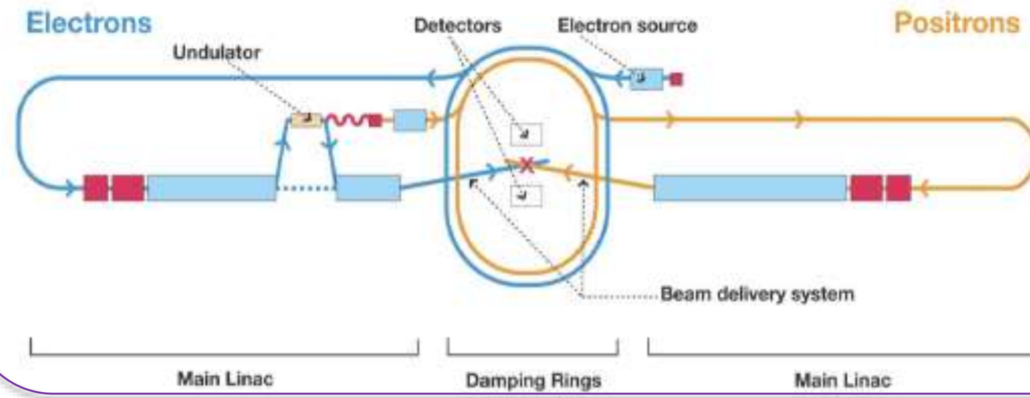
Possible Future Lepton Colliders

- ***CepC/FCC-ee*** 250GeV cm

C=52/100 km *SCRF* *NC Mag*



- ***ILC*** 30 km long, 250 + 250 GeV e^+e^- - *SCRF*

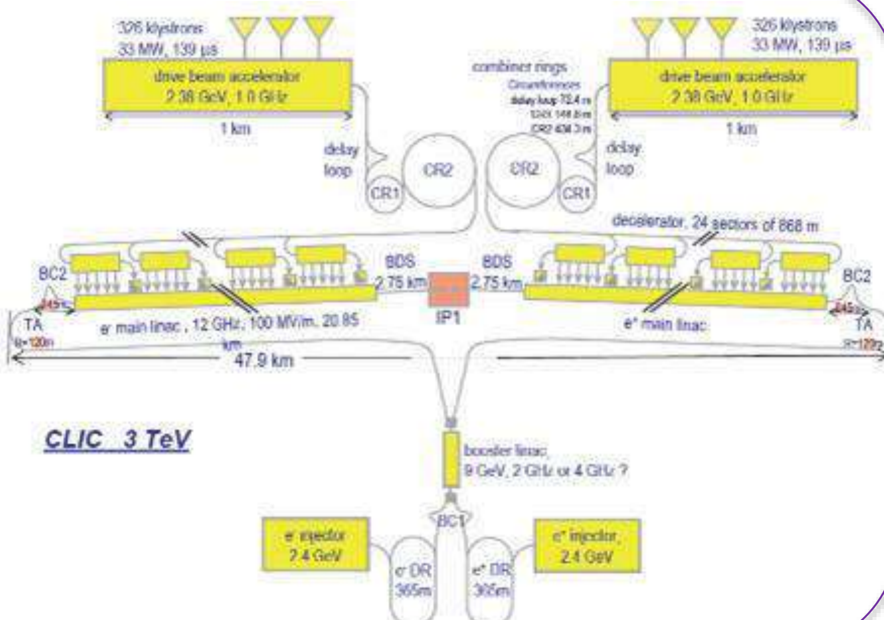


- ***CLIC***

e^+e^- 50km

1.5 + 1.5 TeV

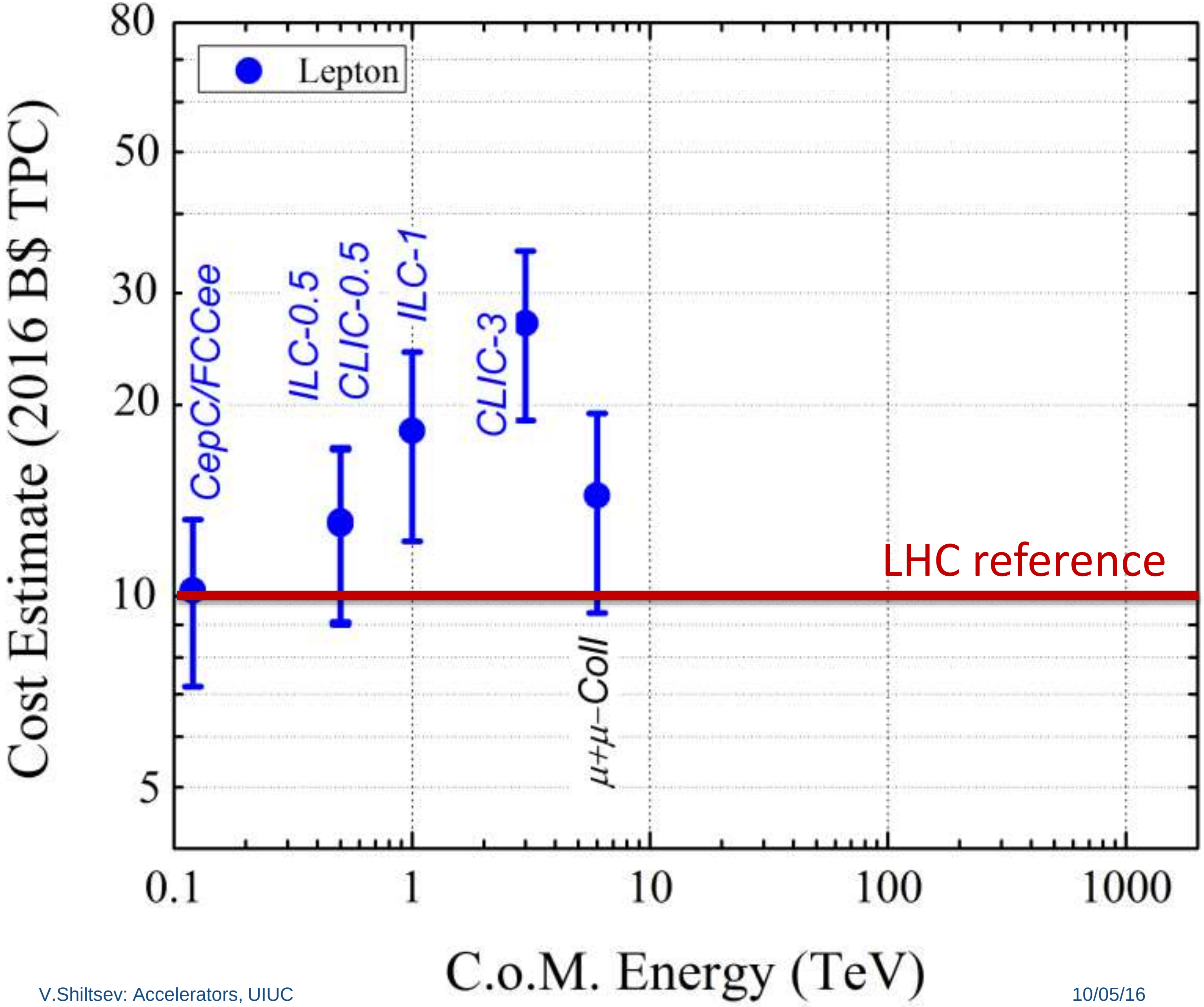
- *NC RF*
- *Two beam acceleration*



- ***Muon Collider***

~15km *μ-μ+* 3+3TeV

NC RF+SC Magn+Muon produc'n; cooling; accel'n


Lepton
CepC/FCCee
ILC-0.5
CLIC-0.5
ILC-1
CLIC-3
μ+μ−Coll
LHC reference
80
50
30
20
10
5
0.1
1
10
100
1000
Cost Estimate (2016 B$ TPC)
C.o.M. Energy (TeV)

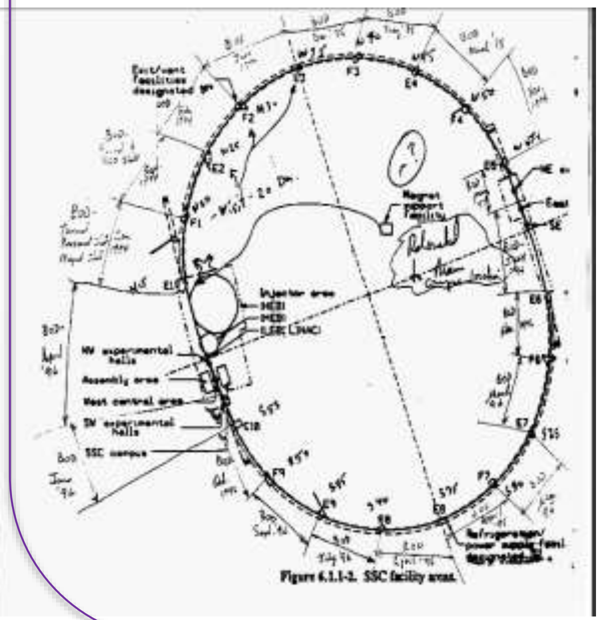
Possible Future Hadron Colliders

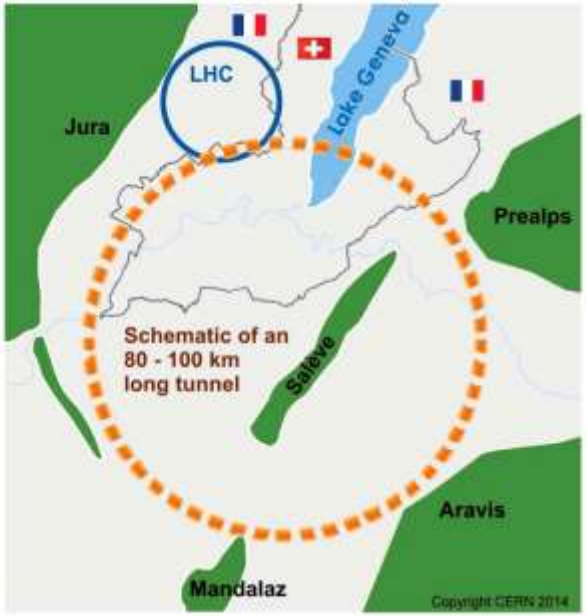
- ***HE-LHC*** same tunnel, **25-30 TeV** cm *pp* *16T SC magnets*

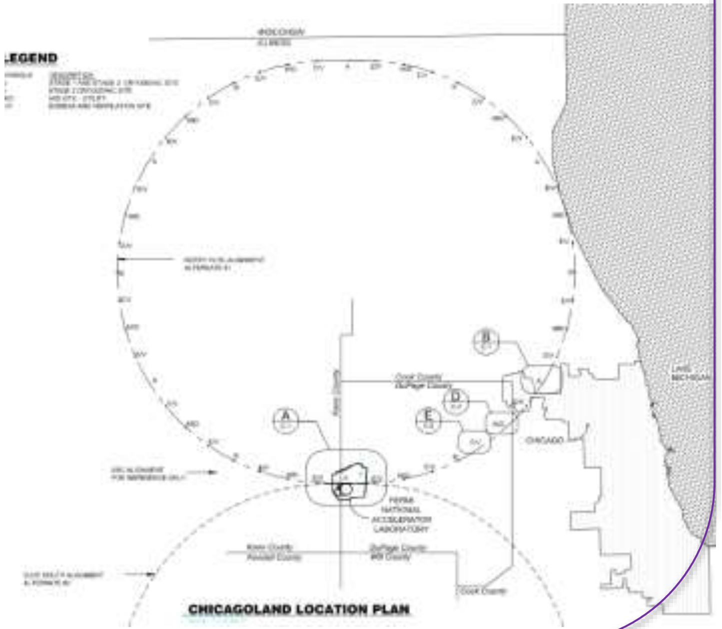
- ***SSC*** 87km
  40cme=20+20TeV
  - *6.6T SC Magnets*

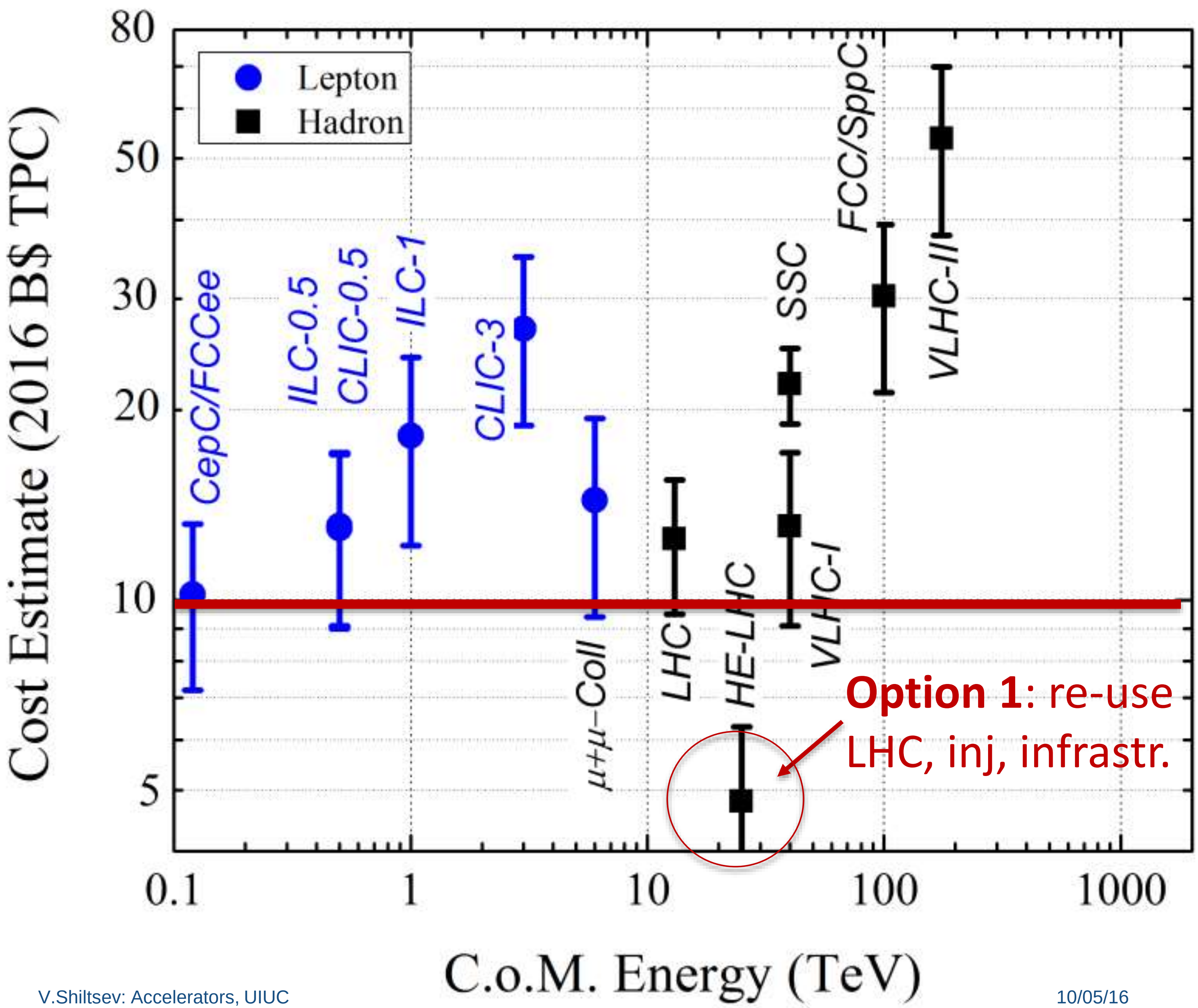
- ***FCC/SppC***
  80-100/54 km
  100/70 TeV cme
  - *16-20T SC Magn*

- ***VLHC***
  233 km
  175 TeV cme
  - *9.8T SC Magnets*



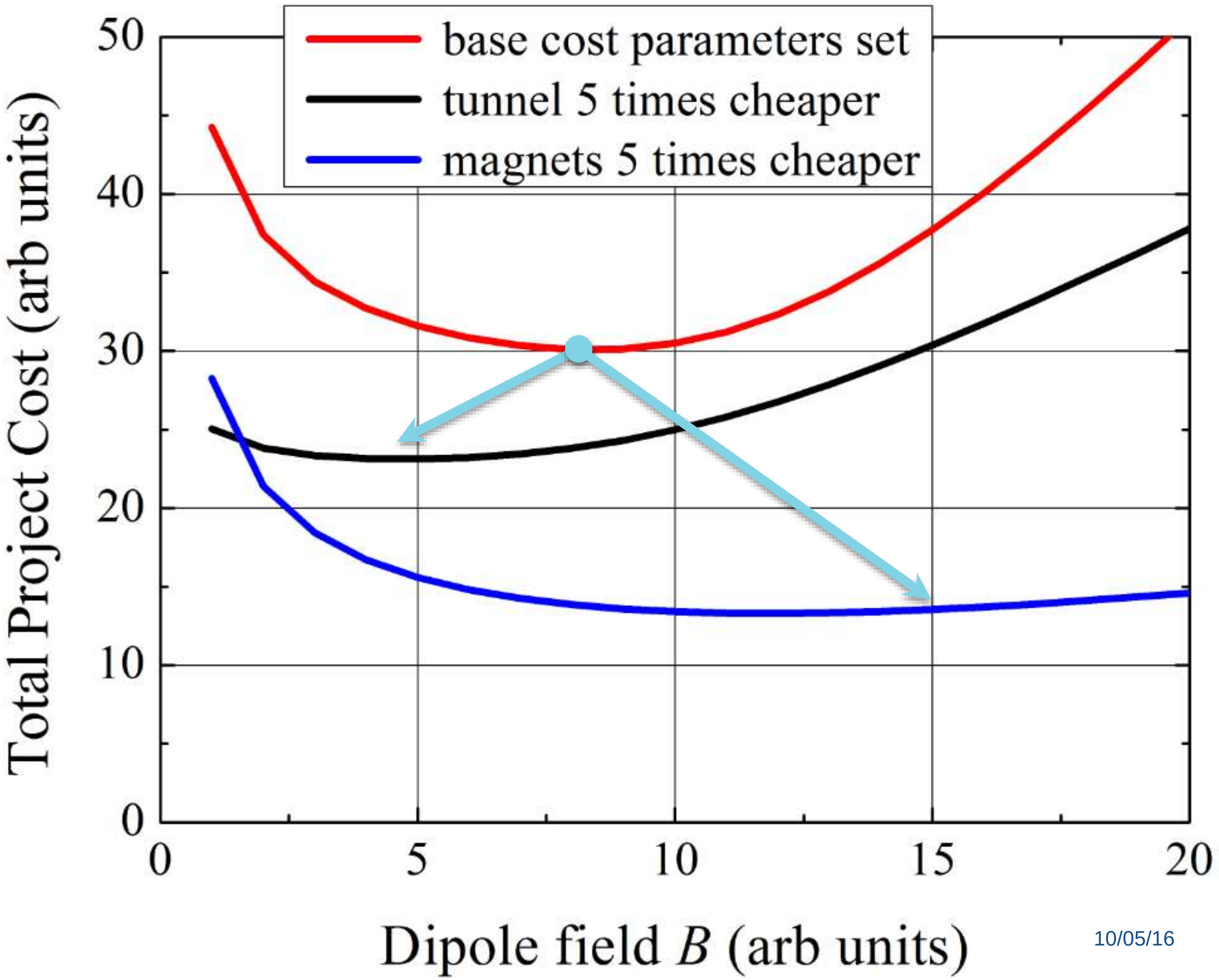





Cost Estimate (2016 B$ TPC)
80
50
30
20
10
5
Lepton
Hadron
CepC/FCCee
ILC-0.5
CLIC-0.5
ILC-1
CLIC-3
μ+μ−Coll
LHC
HE-LHC
SSC
VLHC-I
FCC/SppC
VLHC-II
Option 1: re-use
LHC, inj, infrastr.
0.1
1
10
100
1000
C.o.M. Energy (TeV)

Option 2 : Develop Technology to Lower Cost

100 TeV *pp* : Qualitative Cost Dependencies



* for illustration purposes only

State of the Art SC Magnets: 3 Decades

4.5T

Tevatron,
6 m, 76 mm
774 dipoles

4.5 K He, NbTi
+ warm iron
small He-plant

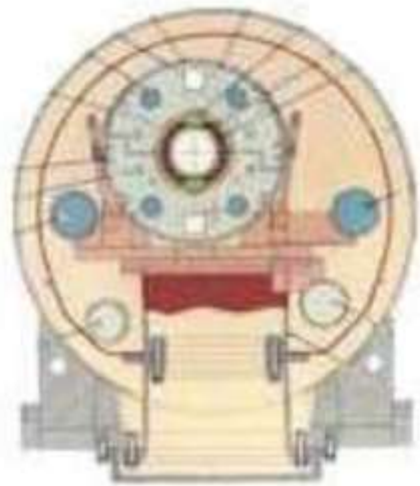
5.3T

HERA,
9 m, 75 mm
416 dipoles

NbTi cable
cold iron
Al collar

3.5T

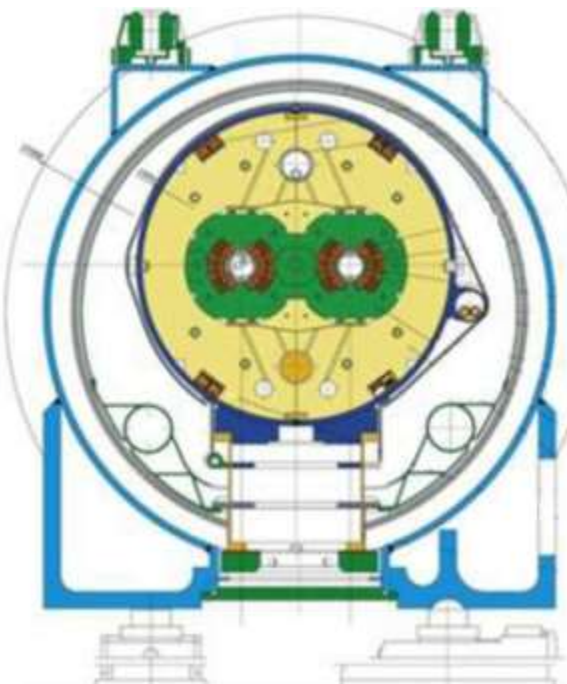
RHIC,
9 m, 80 mm
264 dipoles



NbTi cable
simple &
cheap

8.3T

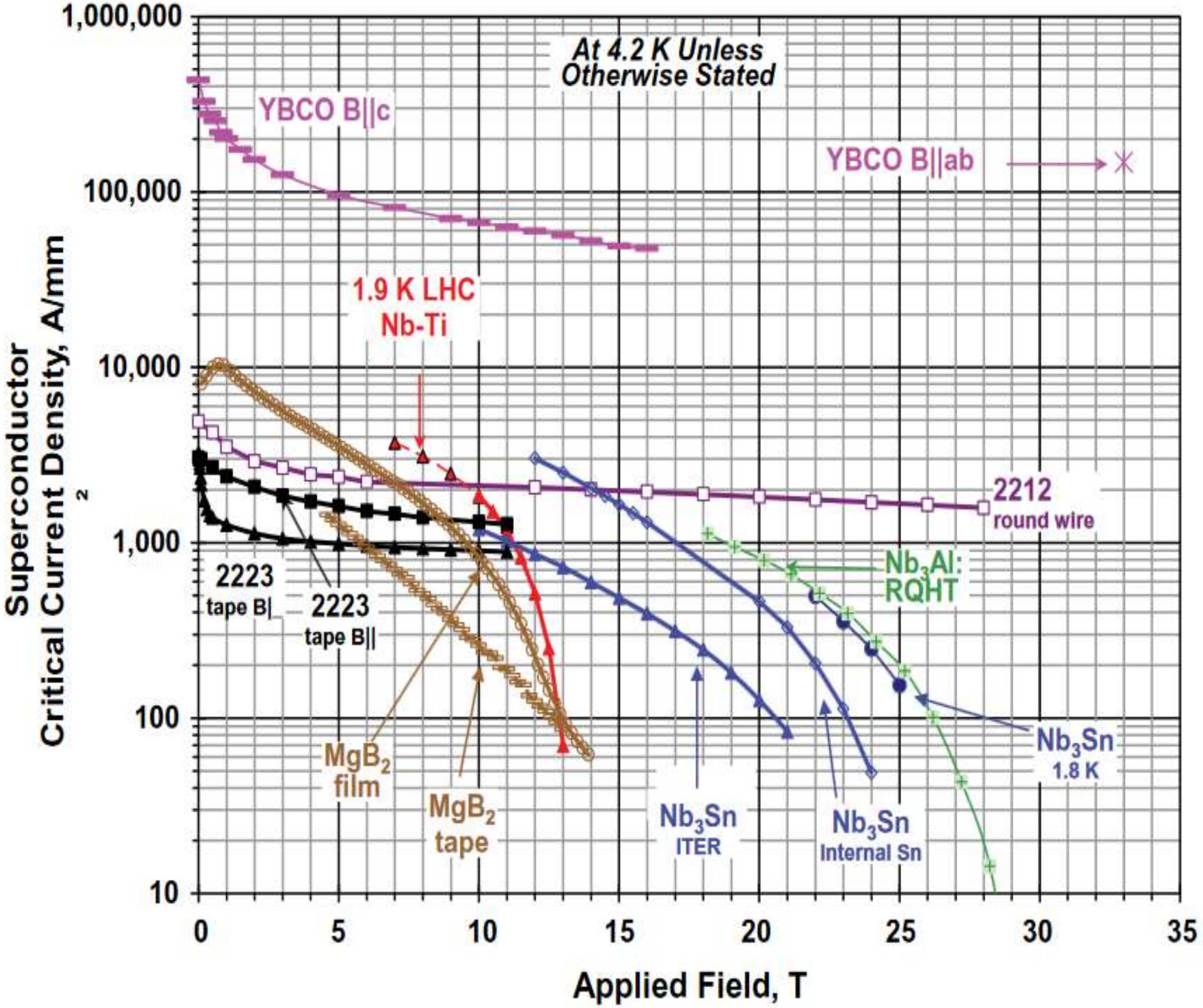
LHC,
15 m, 56 mm
1276 dipoles



NbTi cable
2K He
two bores

(Tev magnet, NbTi cable, Cu bus, HTS tape)

On SC Magnet Technology



Driven by SC cable technology

- *NbTi – upto 10 T*
- *Nb_3Sn – upto 16 T*
- *HTS – 20+T*

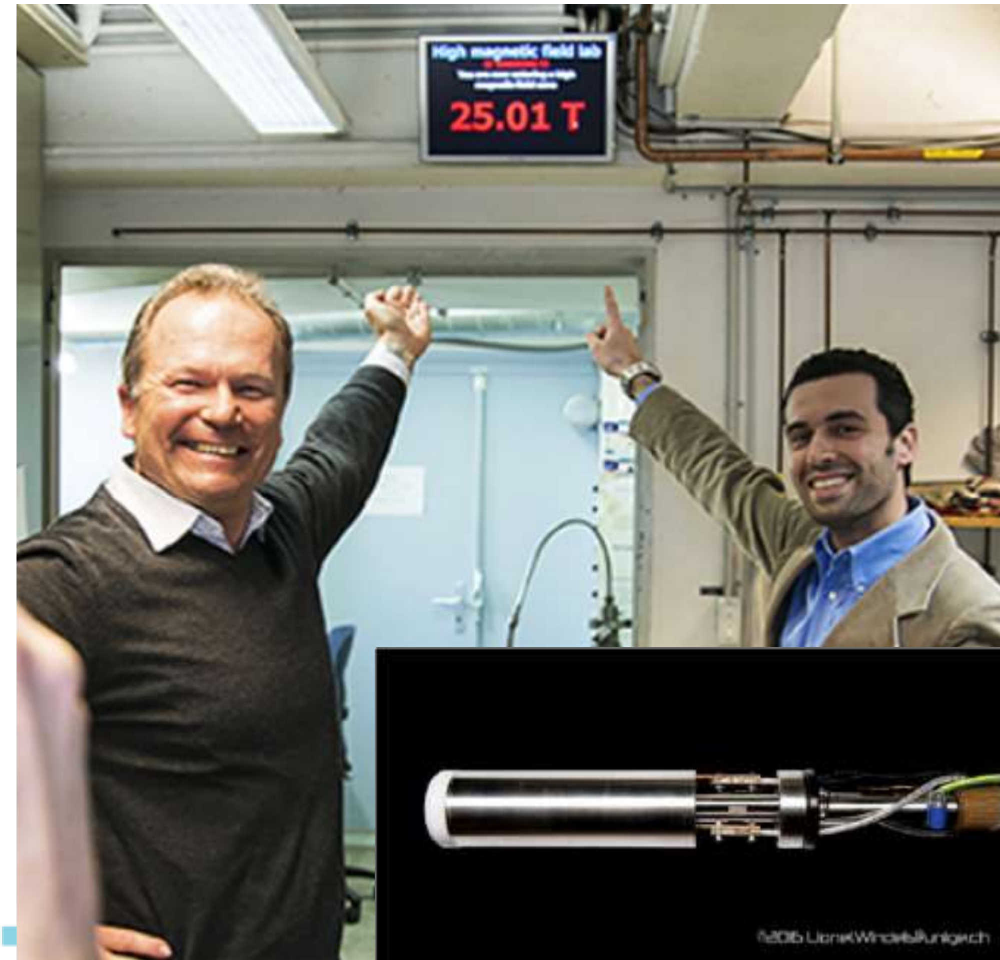
Cost of SC conductor

- *NbTi –* $$
- *Nb_3Sn –* $$ x 5
- *HTS –* $$ x 25

High Temperature Superconductors (HTS)

REBa2Cu3O7-x (REBCO, RE = rare earth) coated conductors **Geneva, 2016**

Achieved **25 T = 21T LTS +4T HTS** insert



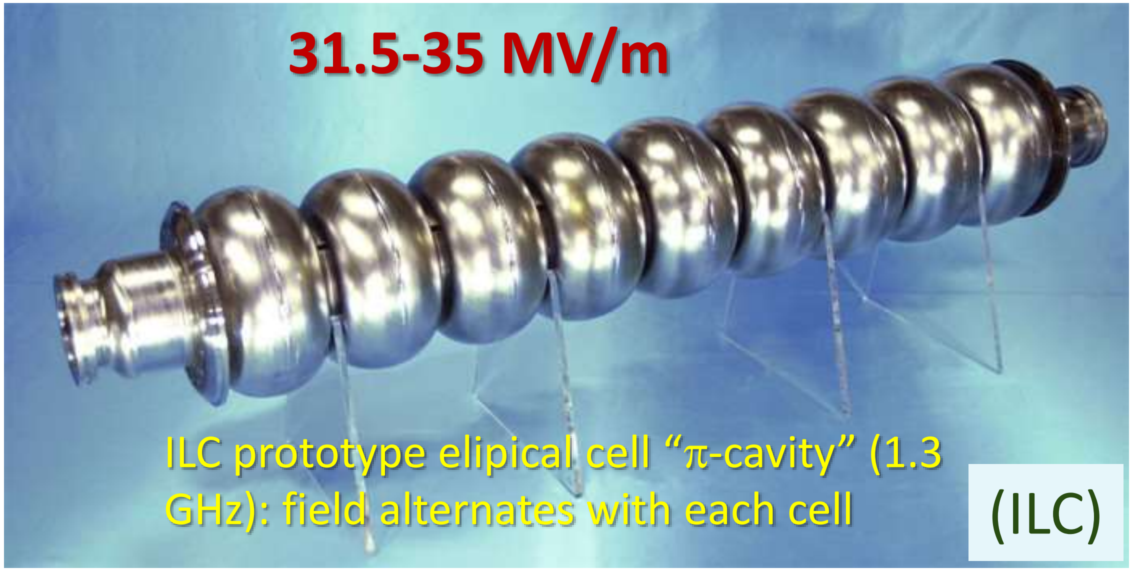
Details of the innovative superconducting coil, conceived and manufactured by researchers from UNIGE and Bruker BioSpin. (Image: © L. Windels, UNIGE)

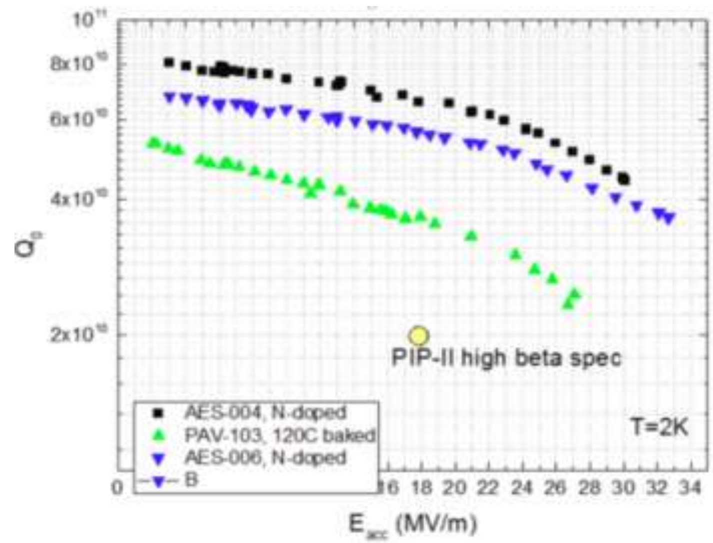
NHMFL (Talahassie)

YBCO coil test (2015)

27 T = 18T LTS +9T HTS insert

R&D On Cost-Effective SRF Structures





New materials (Nb3Sn) –

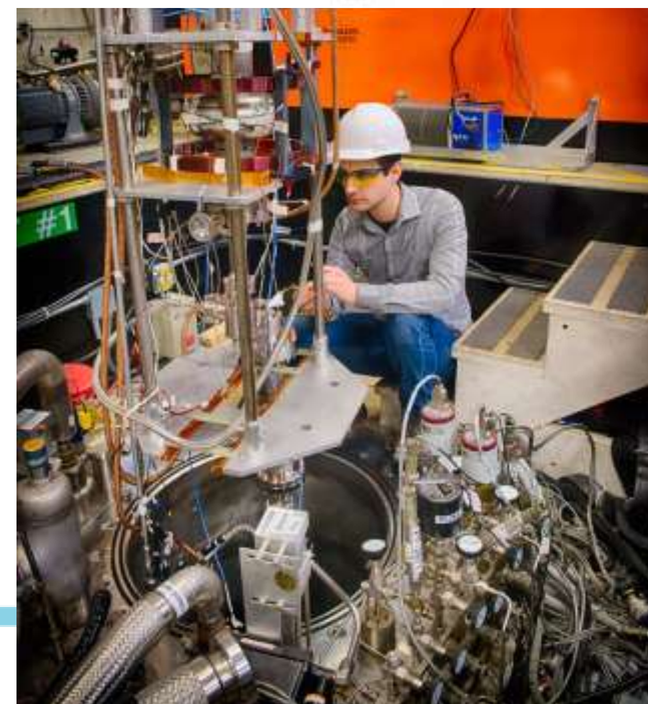
higher gradients

New techniques (Nb on Cu) –

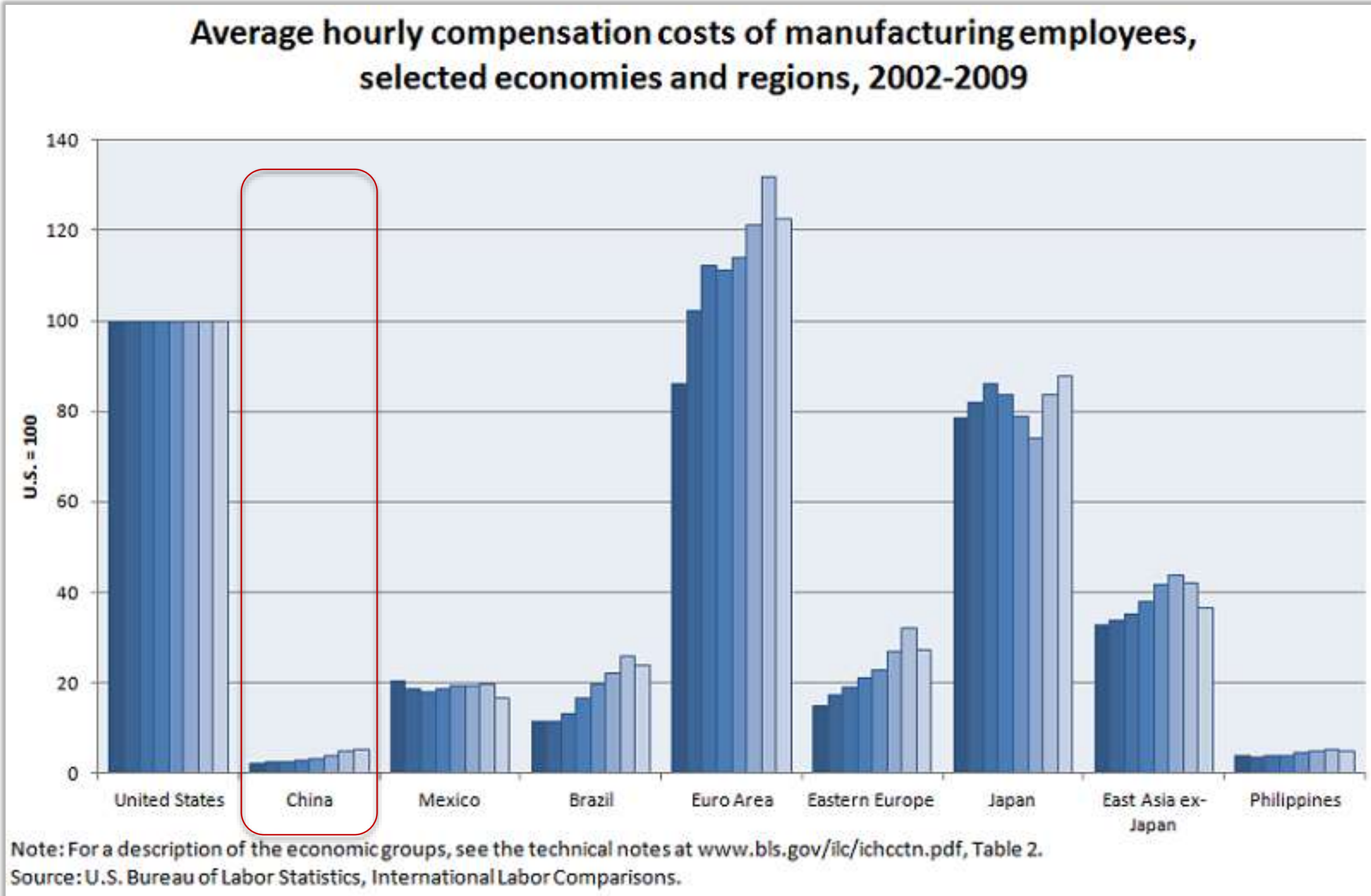
lower cost

Surface treatment (N2 doping) –

higher Q0 and lower operation cost



Option 3: *"Move to China !"*

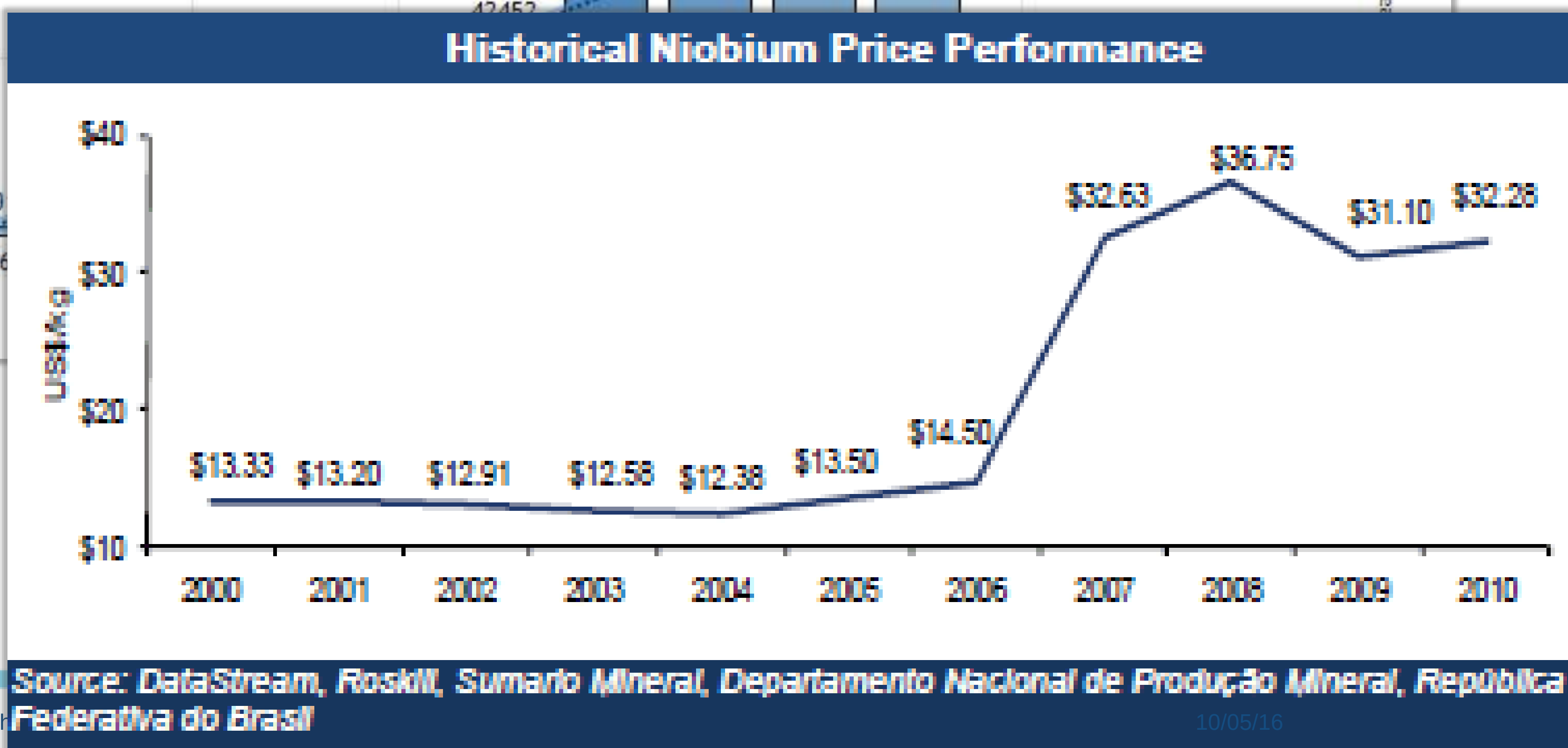


SSRF	Spring-8	Diamond	NSLSII
China	*Japan*	*UK*	*USA*
			
• 432 m	**• 1436 m**	**• 562 m**	**• 792 m**
• 3.5 GeV	**• 8 GeV**	**• 3 GeV**	**• 3 GeV**
• 1.2B RMB	**• 11 BY**	**• 383 M £**	**• 912 M$**
2007	1997	2007	2015

Account infl'n, convert to USD and scale to sqrt(1 km):

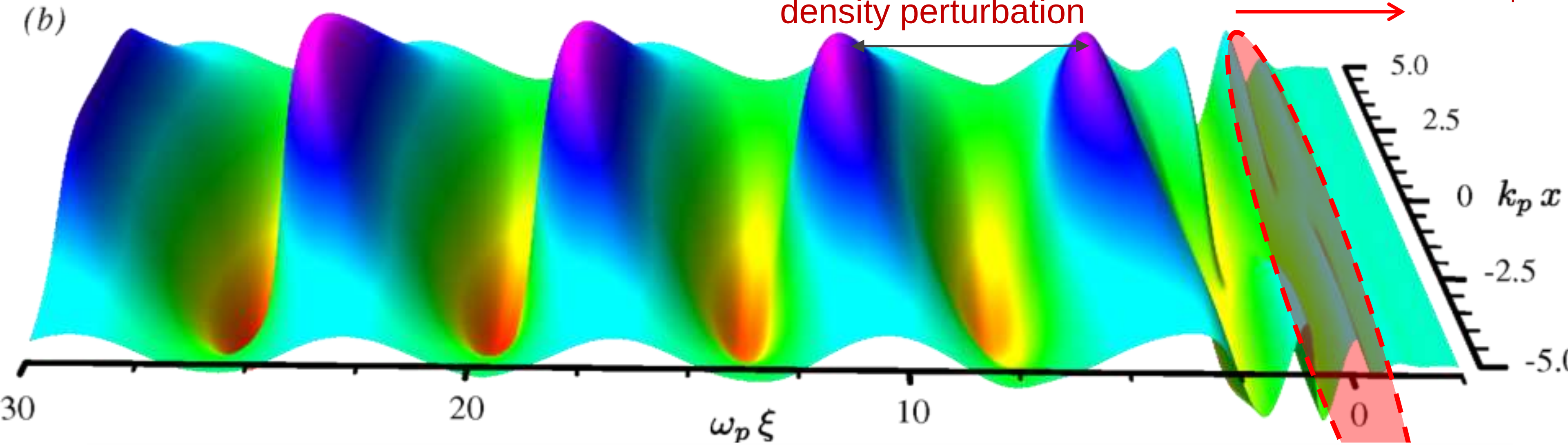
350 M$	***772 M$***	***1040 M$***	***1024 M$***

“Move to China !” - Caveats



Option 4: New Technology- Plasma

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



$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

Option A:

Short intense e-/e+/p bunch

Few 10^{16}cm^{-3}, **~5 GV/m** over 1.3m

Option B:

Short intense laser pulse

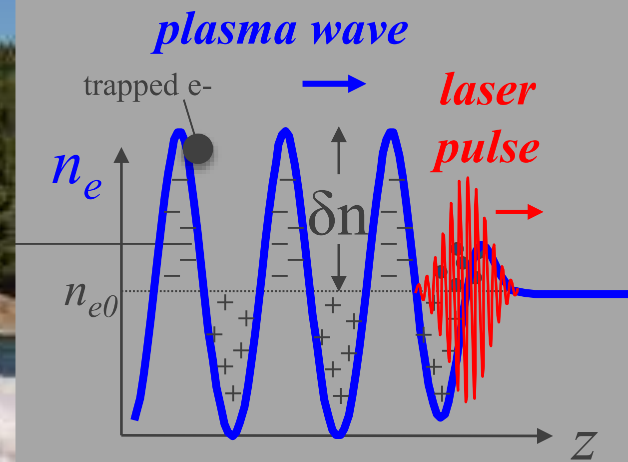
~10^{18}cm^{-3}, **50 GV/m** over 0.1m

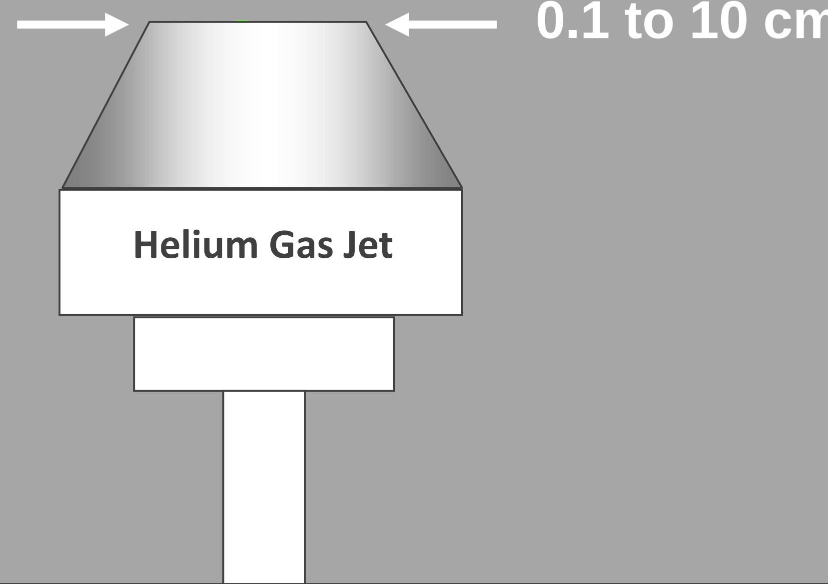
Electrons Surfing on a Laser-Driven Plasma Wave

Tajima & Dawson, Phys. Rev. Lett. ***43,*** *267 (1979)*

Ta

Dawson



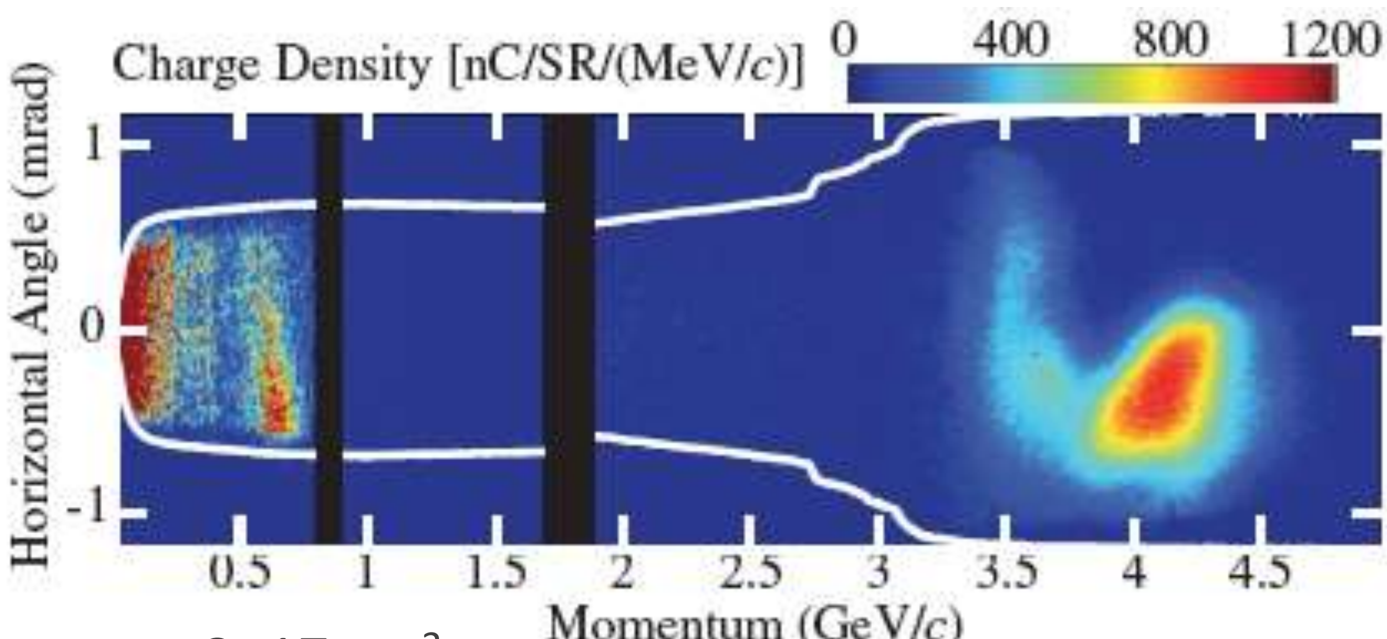


PRL 113, 245002 (2014) PHYSICAL REVIEW LETTERS

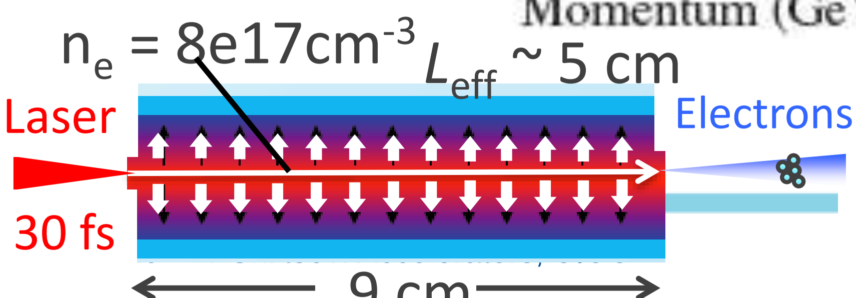
2014

Multi-GeV Electron Beams from Capillary-Discharge-Guided Subpetawatt Laser Pulses in the Self-Trapping Regime

W. P. Leemans,[1,2,*] A. J. Gonsalves,[1] H.-S. Mao,[1] K. Nakamura,[1] C. Benedetti,[1] C. B. Schroeder,[1] Cs. Tóth,[1] J. Daniels,[1] D. E. Mittelberger,[2,1] S. S. Bulanov,[2,1] J.-L. Vay,[1] C. G. R. Geddes,[1] and E. Esarey[1]
[1]Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
[2]Department of Physics, University of California, Berkeley, California 94720, USA



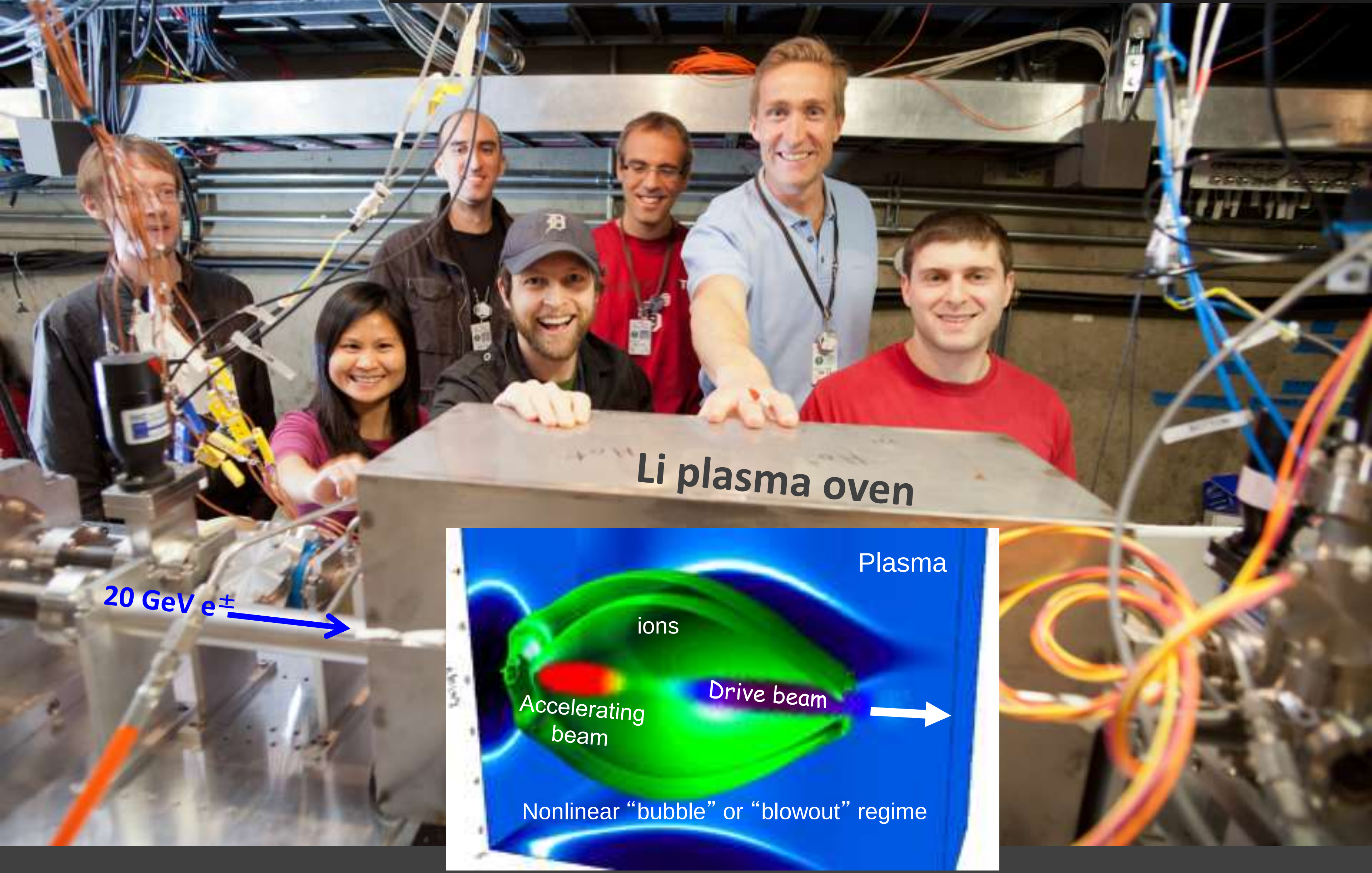
energy gain
4.3 GeV
over 9 cm



Q = 6 pC
ΔE/E = .06
Δθ = 0.3 mrad

16 J (laser) → .024 J (e^-):
0.15% **efficiency**

linac delivers synchronized 20 GeV $e^{\pm}$ drive & witness bunches to a 1m plasma



2014

Nature **515**, 92 (2014)

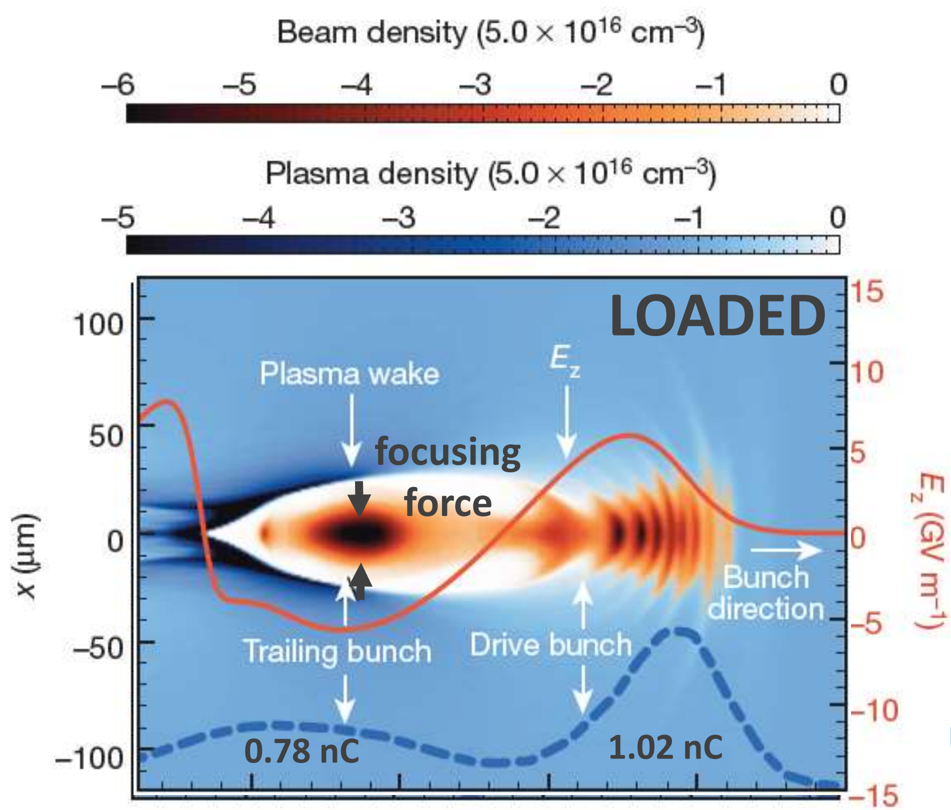
doi:10.1038/nature13882

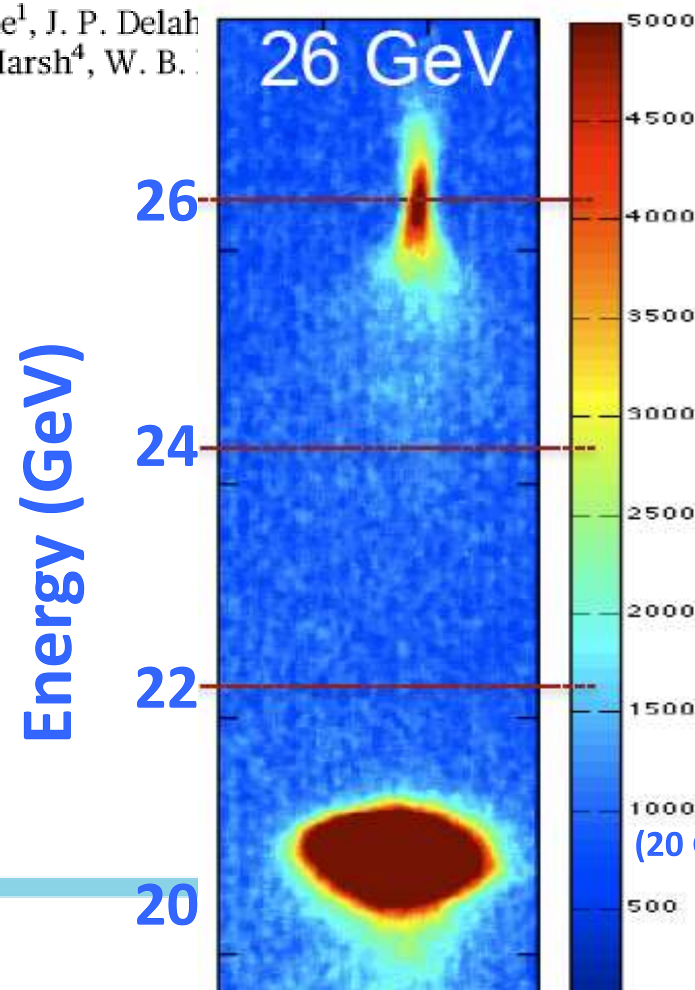
High-efficiency acceleration of an electron beam in a plasma wakefield accelerator

energy gain 1.6GeV over 36cm

5.0GeV over 1.3m

M. Litos[1], E. Adli[1,2], W. An[3], C. I. Clarke[1], C. E. Clayton[4], S. Corde[1], J. P. Delah… J. Frederico[1], S. Gessner[1], S. Z. Green[1], M. J. Hogan[1], C. Joshi[4], W. Lu[5], K. A. Marsh[4], W. B. … …badi[4], D. Walz[1], G. White[1], Z. Wu[1], V. Yakimenko[1] & G. Yocky[1]





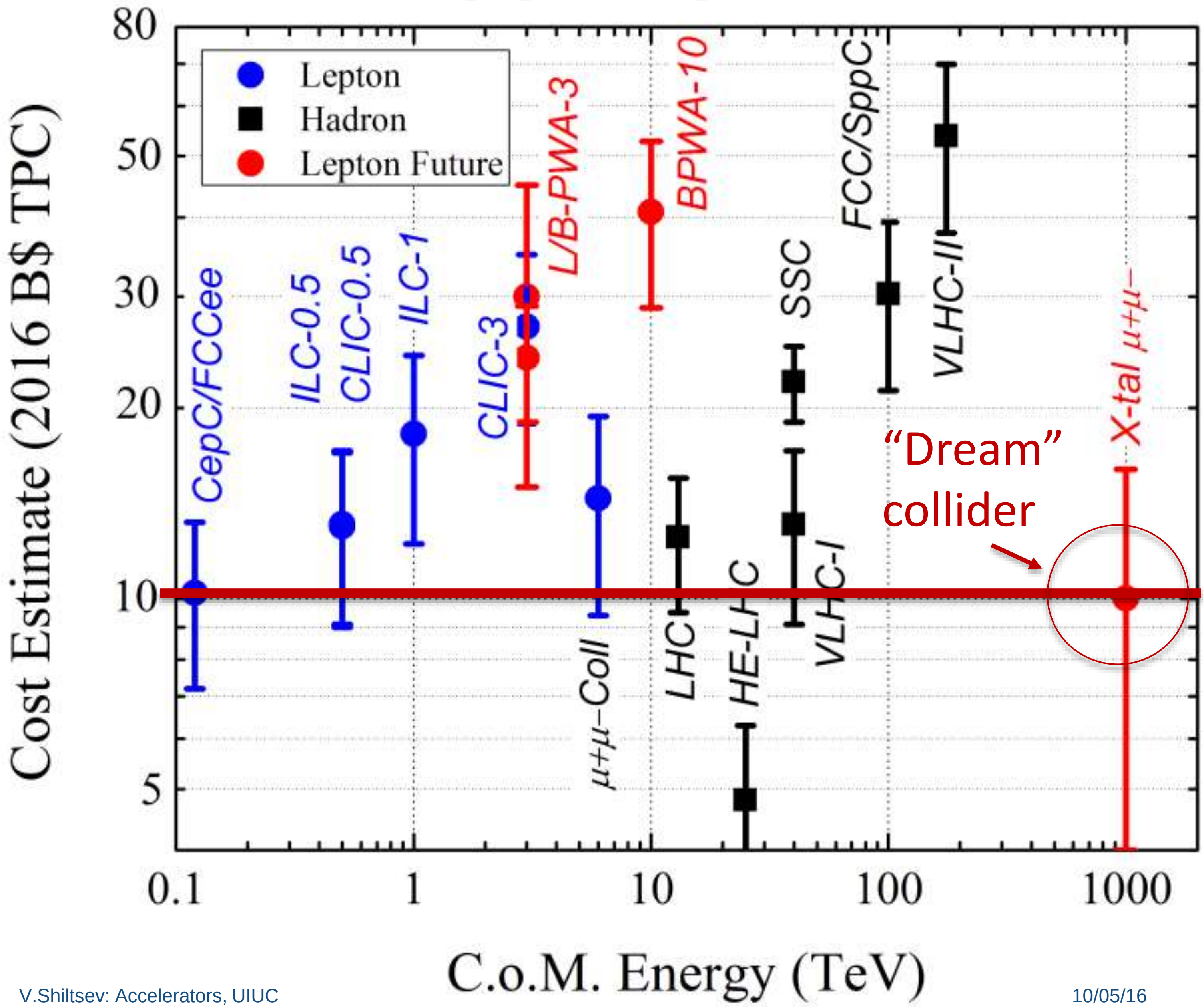
Accelerated trailing e⁻ bunch (~80 pC)

Drive e⁻ Bunch (20 GeV, 1 nC, 83 fs)

Fermilab

NB: now “Plasma-Colliders” do not work even on paper

can not accelerate *e+* , staging kills the gradient <*E*>~2 GV/m, *ε*, efficiencies



"Dream" Collider: Choices

- Far Future "Energy Frontier" assumes
  - 300-1000 TeV (*20-100 × LHC*)
  - "decent luminosity" (TBD)
- Surely we know:

1. For the same reason there is no circular ***e+e-*** collider above Higgs-F there will be no circular ***pp*** colliders beyond 100 TeV → **LINEAR**

circular collider

$$L \propto \frac{\eta P_{wall}}{E^3} \frac{\xi_y}{\beta_y}$$

2. Electrons radiate 100% *beam-strahlung* (<3 TeV) and in focusing channel (<10 TeV) → ***μ+μ-*** or ***pp***

linear collider

$$L \propto \frac{\eta_{\mathrm{linac}} P_{wall}}{E} \frac{N_\gamma}{\sigma_y}$$

“Phase-Space” is Further Limited

- **“Cost Feasibility”:** for 20-100 × LHC
  - < 10 B$
  - < 10 km
  - < 10 MW (beam power, ~100MW total)

→New technology should provide >30 GeV/m @ total component cost <1M$/m (~NC magnets now)

SC magnets equiv. ~ 0.5 GeV per meter (LHC)

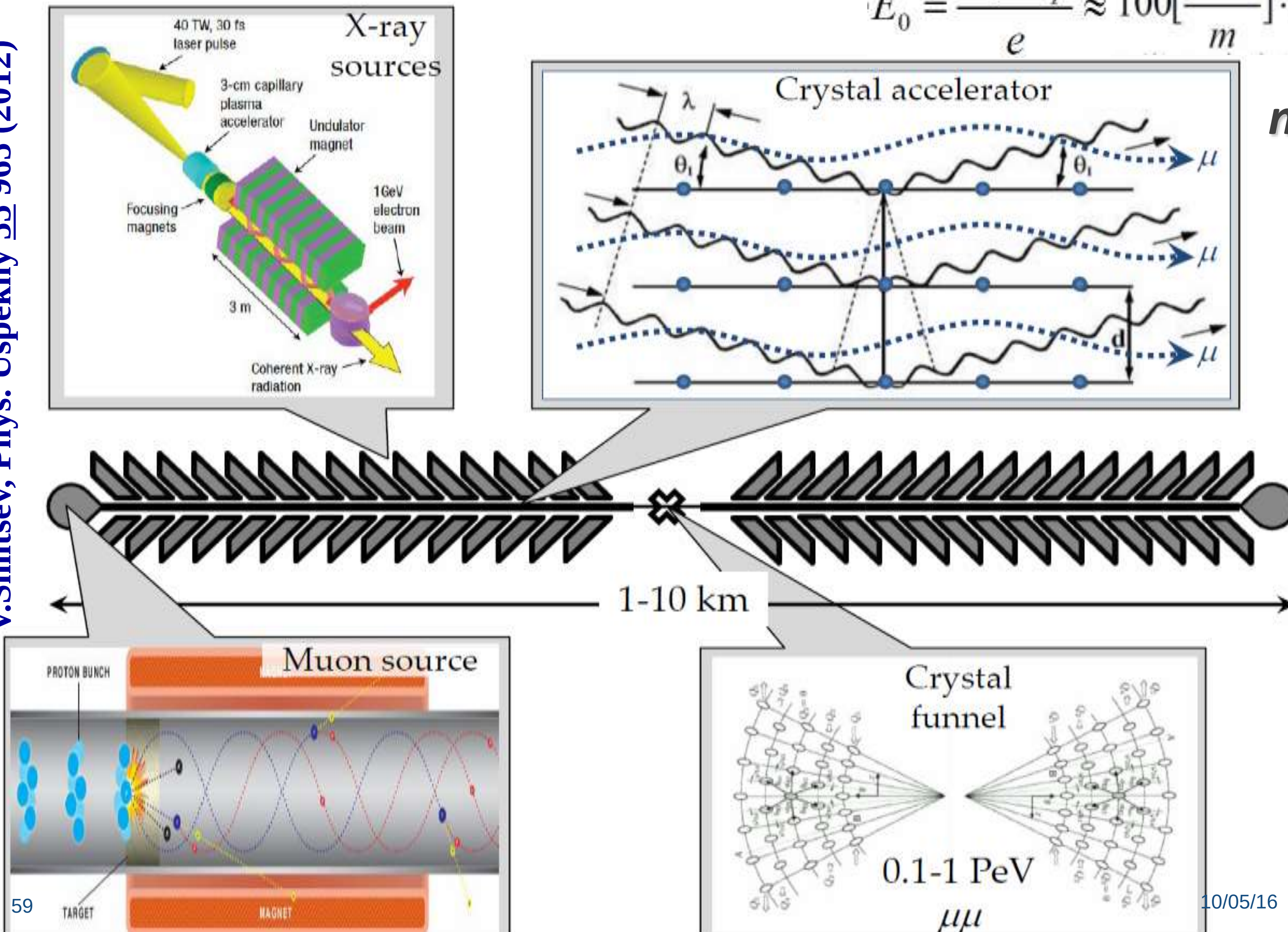
3. Only one option for >30 GeV/m known now:
dense plasma→ that excludes *protons*→ only *muons*

(Xtal model)

"Dream" Collider = Muons + Acceleration in Crystals + Continuous Focusing (Channeling)

V.Shiltsev, Phys. Uspekhy 55 965 (2012)

$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$



***n*~10²² cm⁻³,**

10 TeV/m

→

1 PeV = 1000 TeV

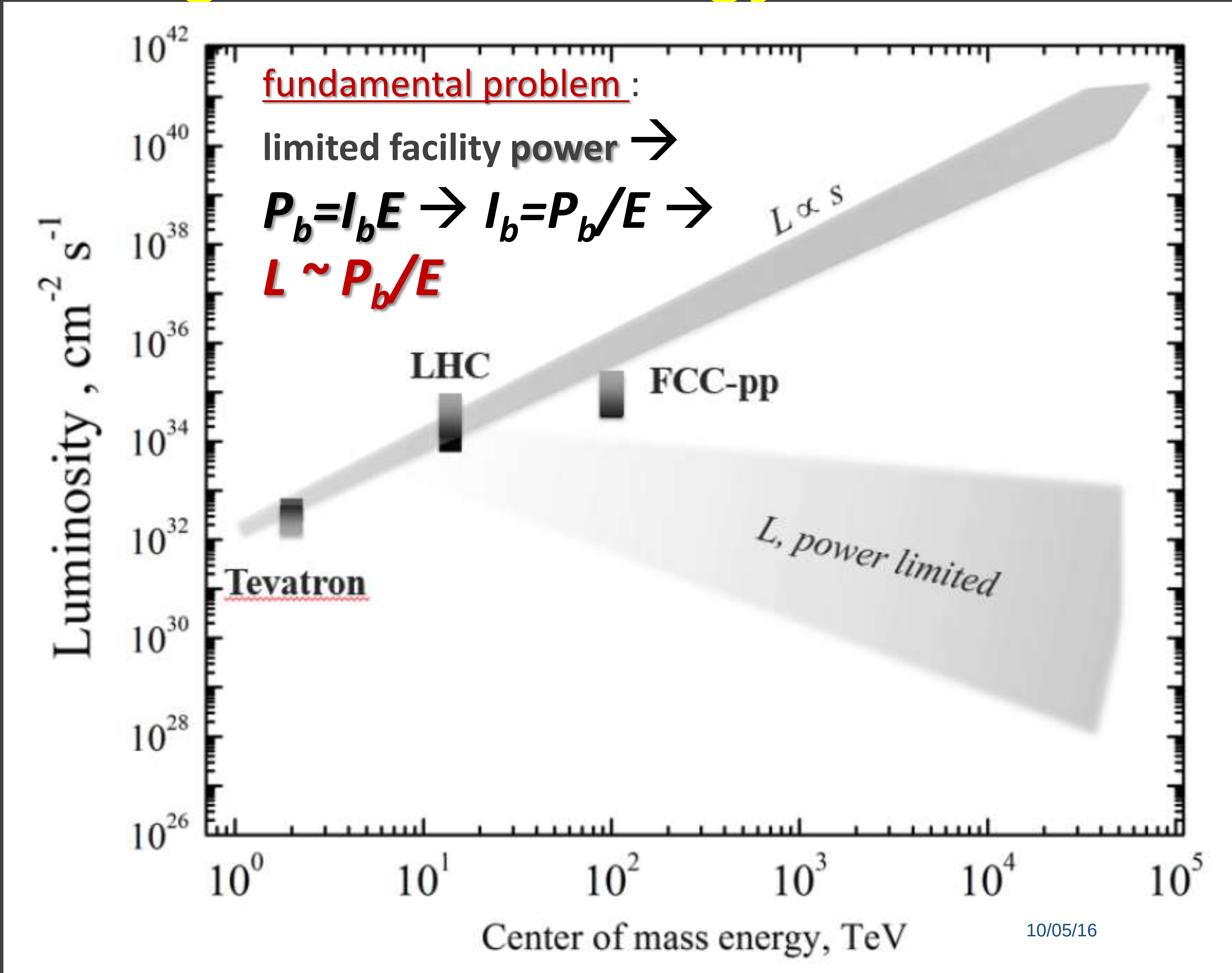
n_μ ~1000

n_B ~100

f_{rep} ~10^6

L ~$10^{30\text{-}32}$

Paradigm Shift : *Energy* vs *Luminosity*



HEP's "Far" Future

- **Good News**
  - options **EXIST**
    - 300-1000 TeV muons in plasma/crystals
- **Bad News**
  - It will be

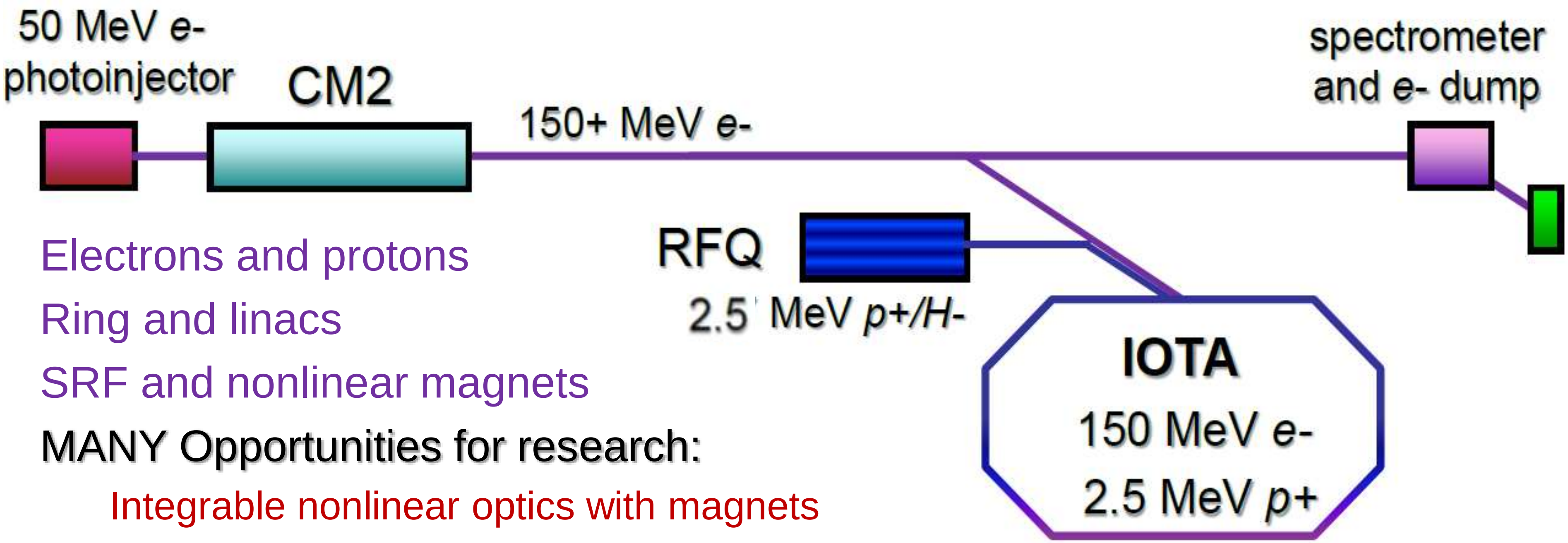
High

Energy

Low

Luminosity

Unique Accel. R&D Facility IOTA at Fermilab



Electrons and protons

Ring and linacs

SRF and nonlinear magnets

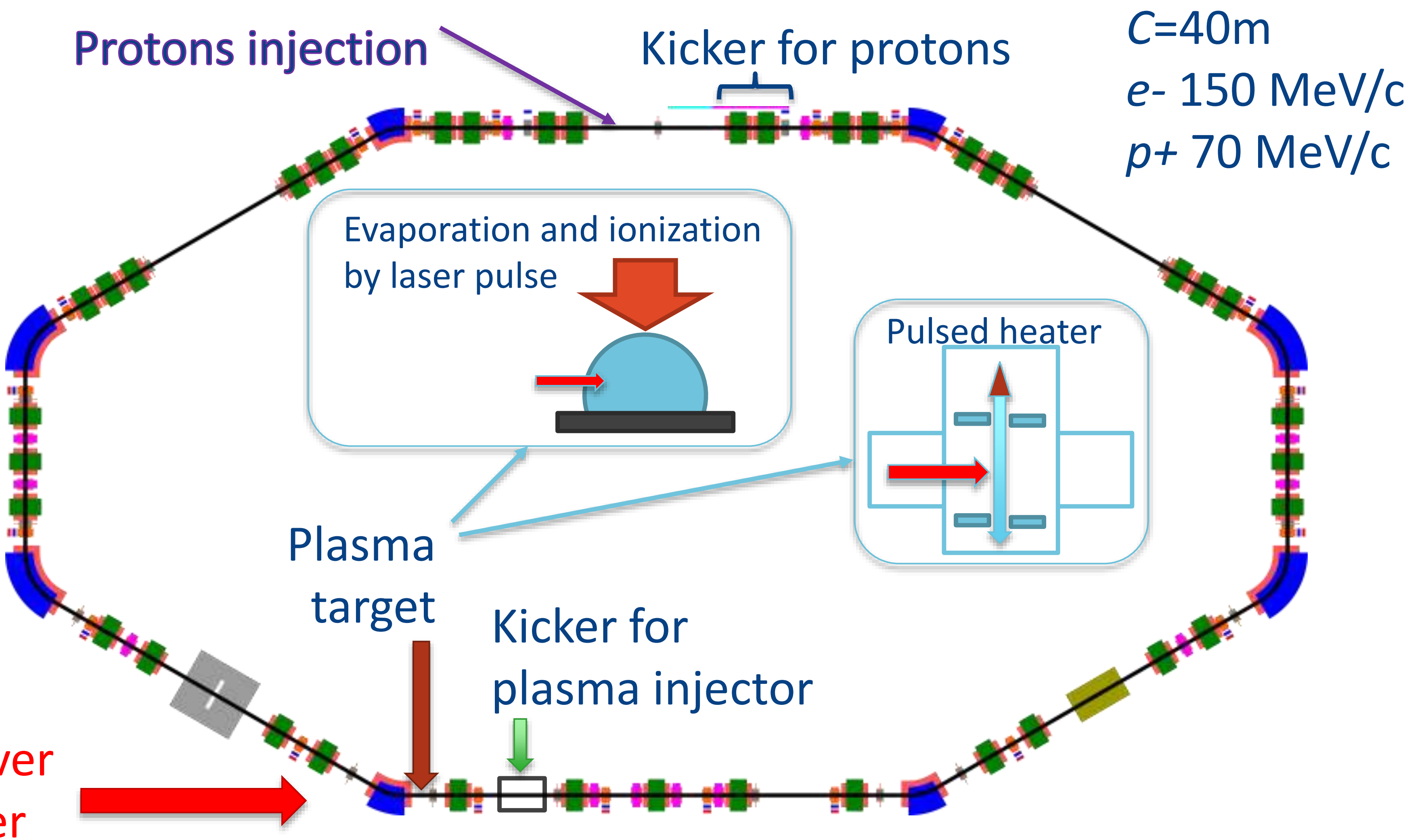
MANY Opportunities for research:

- Integrable nonlinear optics with magnets
- Space-charge compensation with electron lenses and electron columns
- Optical stochastic cooling
- Laser plasma wakefield injector
- Acceleration in carbon nanotubes and crystals, etc etc

IOTA/FAST supported by:

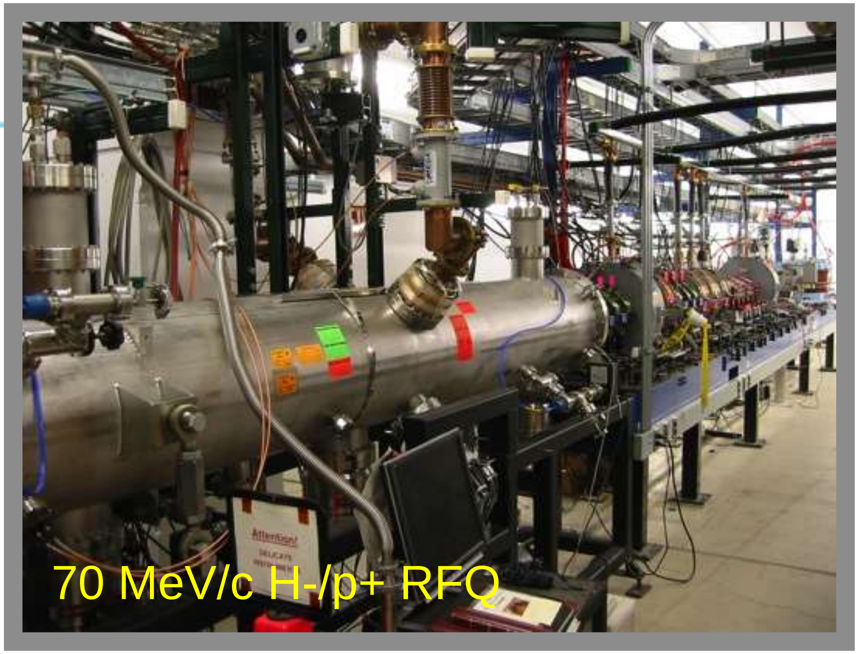
- DOE Office of HEP: construction, installation, research, operations
- Collaborators (25): components, research

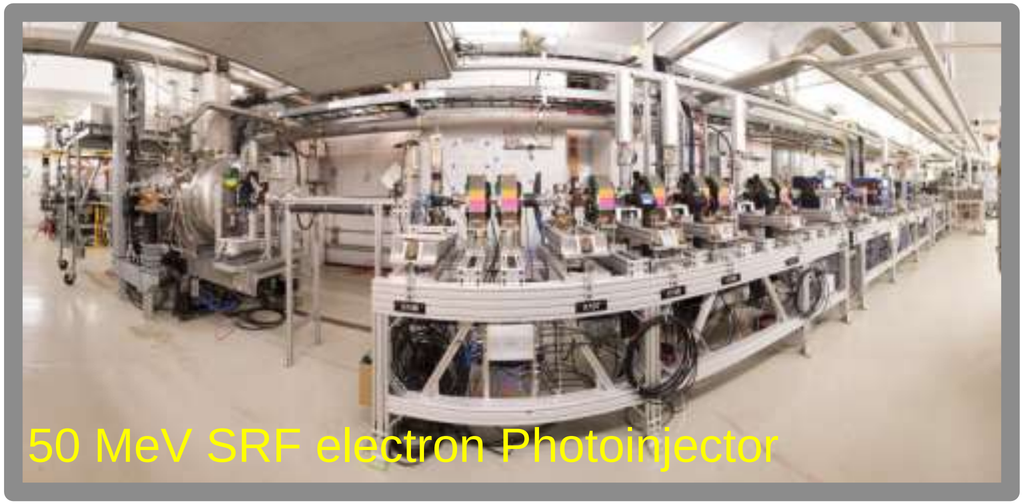
IOTA (Integrable Optics Test Accelerator) Ring at FNAL



"Electron injection into a cyclic accelerator using laser wakefield acceleration", Ya. V. Getmanov, O. A. Shevchenko, N. Vinokurov
"Laser wakefield acceleration using a laser produced aluminum plasma", J. Kim, Y. Hwangbo, S.-G. Jeon , W. J. Ryu, K. N. Kim, S. H. Park, N. Vinokurov

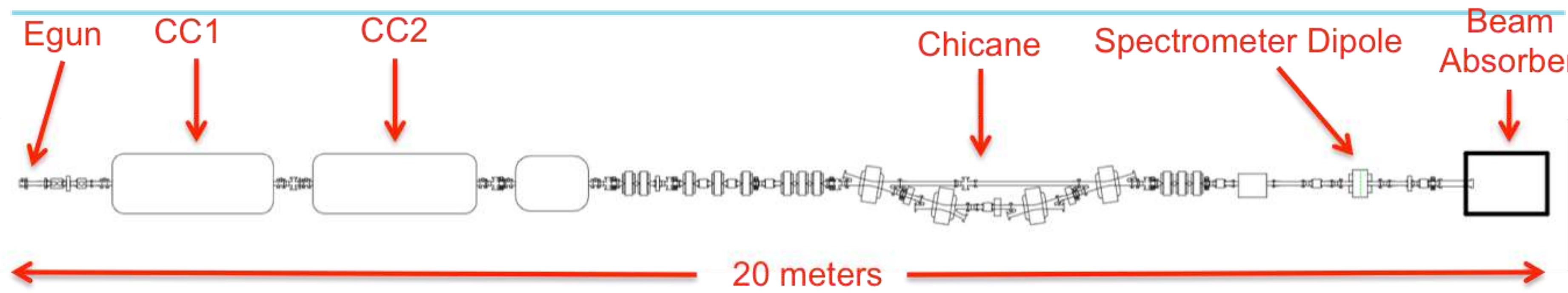

record gradient 31.5 MV/m
achieved in CM2
1.3 GHz SRF Cryomodule


70 MeV/c H-/p+ RFQ


50 MeV SRF electron Photoinjector

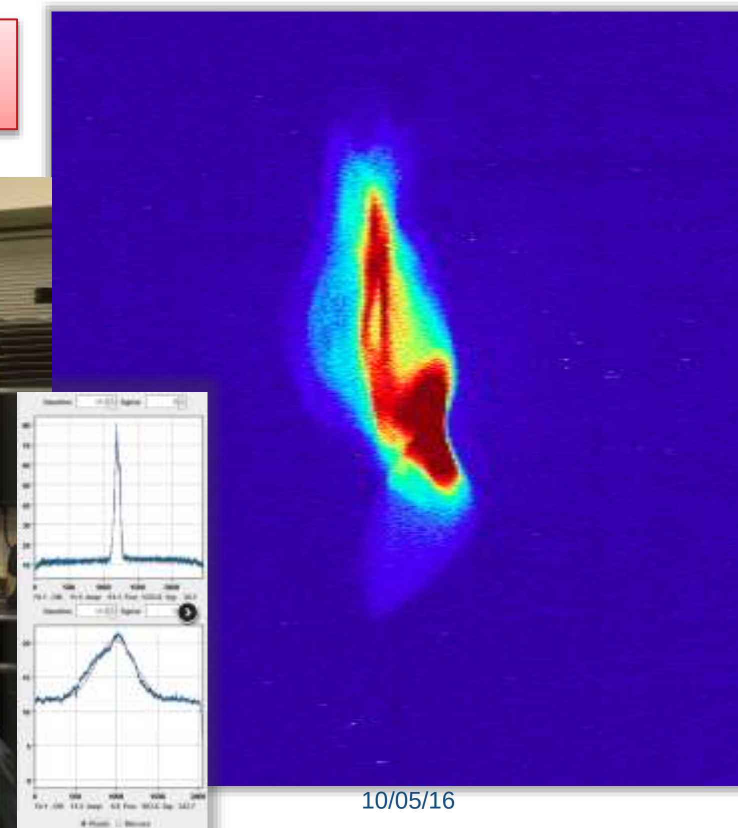

IOTA Ring Hall

May 2016 : IOTA Electron Injector 50 MeV

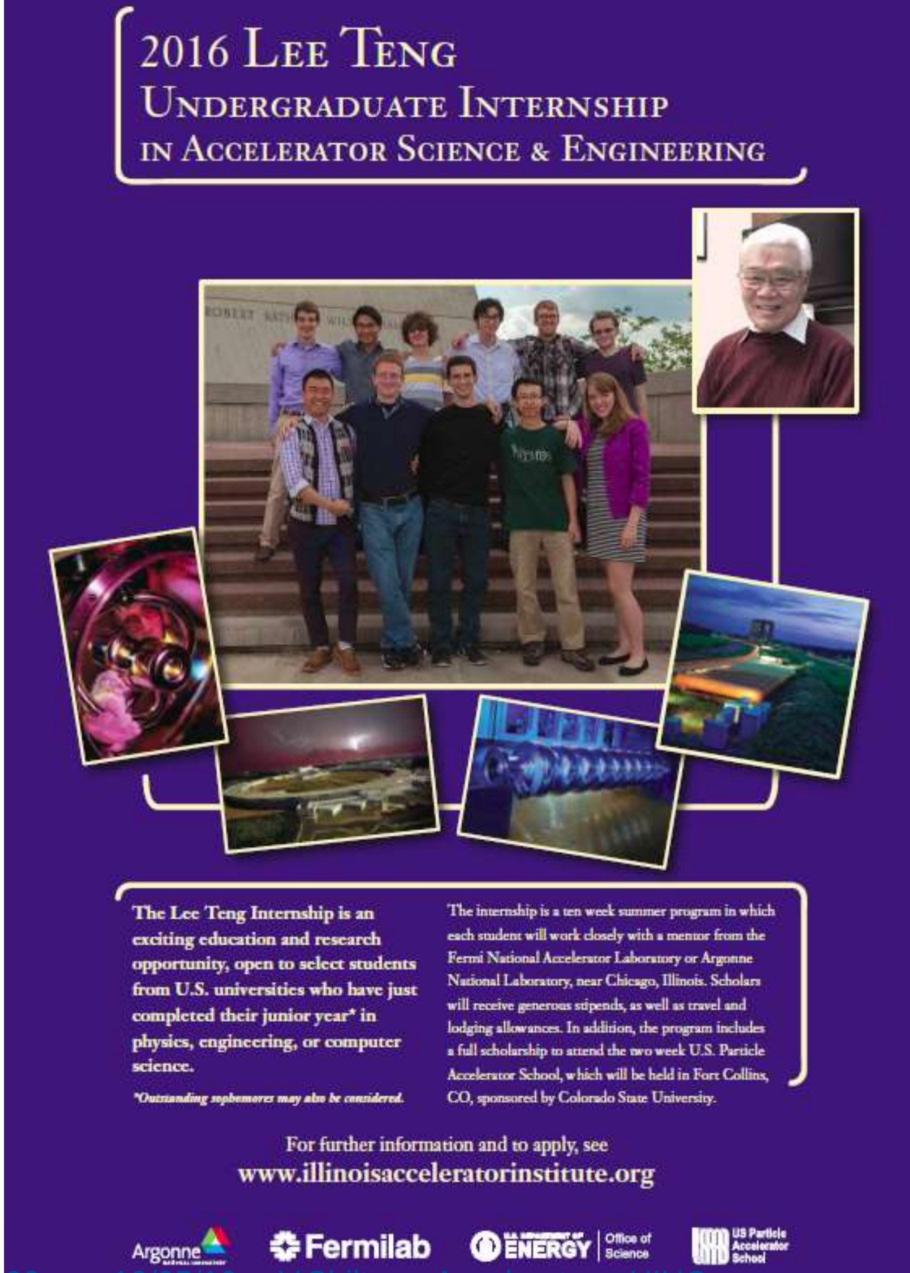


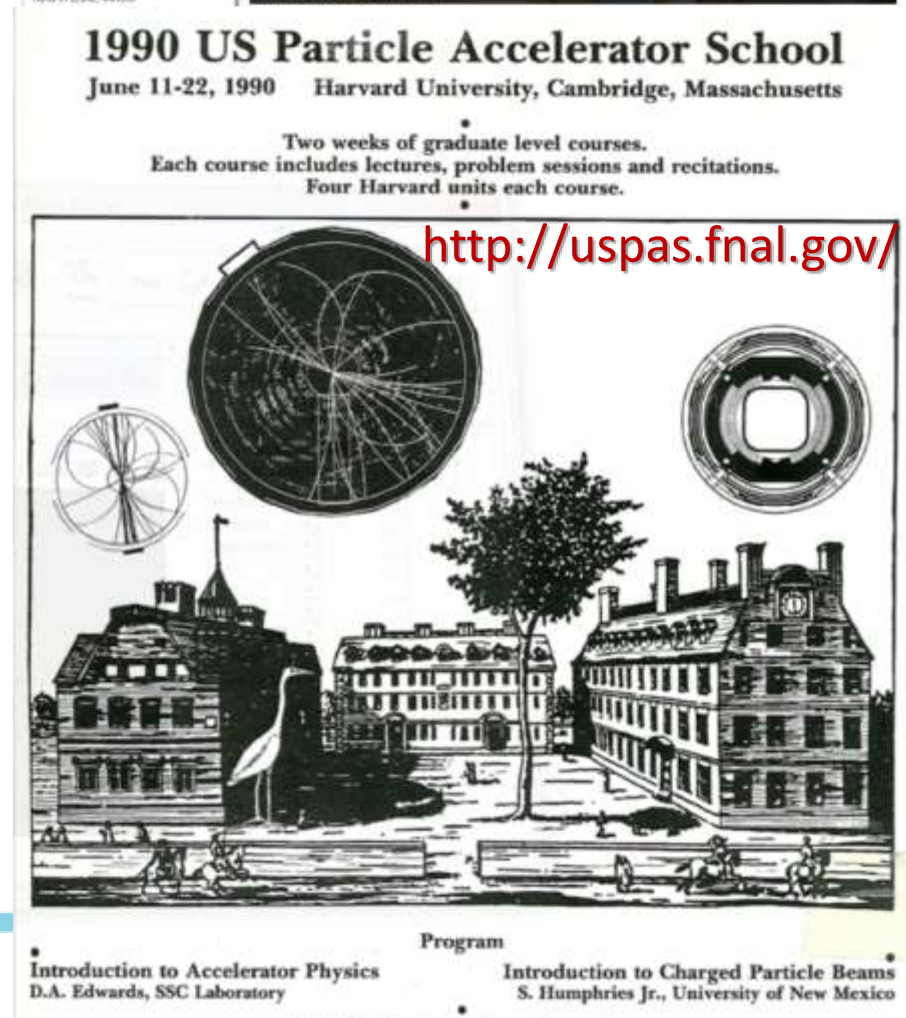
52.5 MeV e^- beam through IOTA/FAST injector !

May 16, 2016: Beam accelerated by two 1.3GHz SRF Capture Cavities #1 and #2: 4.5 MeV (gun)+28MeV+20MeV



http://www.illinoisacceleratorinstitute.org/





http://uspas.fnal.gov/

Summary

- Accelerators progressed immensely
  - now set up landscape of photon science, neutrino research and HEP colliders (success of LHC)
- Post-LHC colliders are *possible but* :
  - *Dependent on the LHC results (motivation)*
  - *if based on current technologies (SRF, SCMag, etc) only HE-LHC is cost feasible (<LHC), some are close (CepC/FCCee, ILC, Muon Coll, VLHC-I), others need significant R&D (FCC)…or in China (?)*
  - *hopeful technology of plasma acceleration*

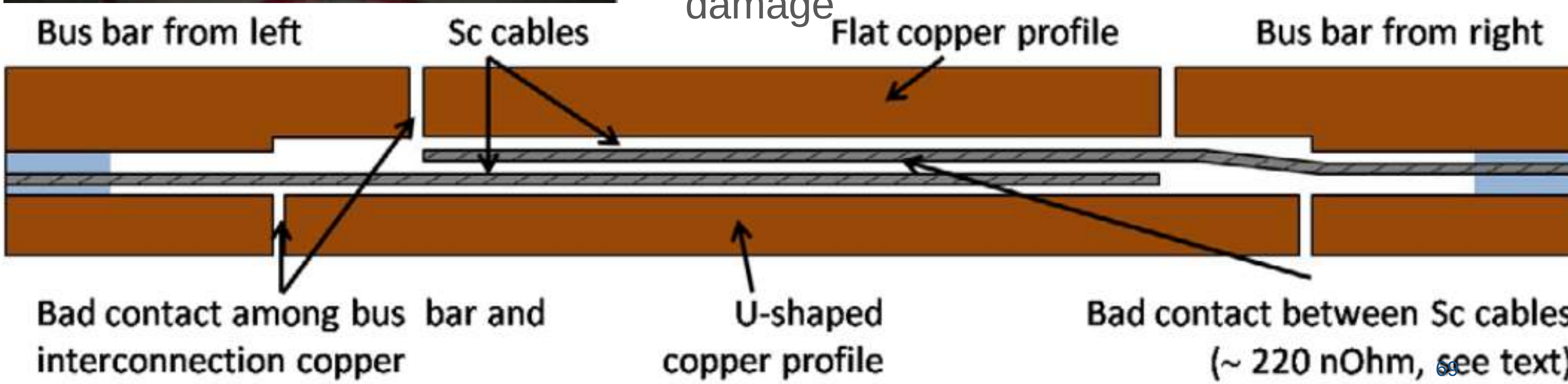
  is very expensive now, need ~3 decades of R&D; "dream" 1PeV Xtal μμ will be a H.E.L.L. collider

We need you – please join!

Thank You for Your Attention!

Splices… all began Sept 19 2008

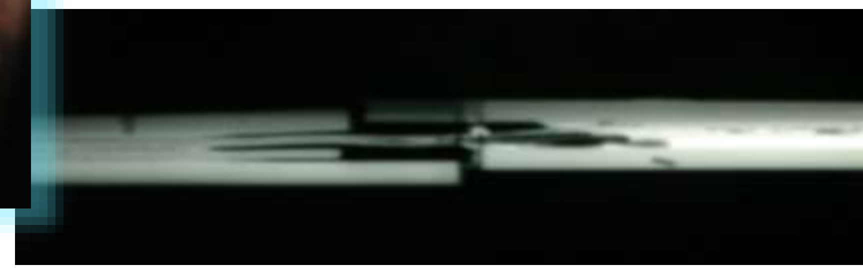
- A splice with bad thermal and electrical contact between the superconductor and the copper produced sufficient resistive heating to lead to thermal runaway.
- This provoked the melting of the material surro-unding the splice, and subsequently an electric arc developed between two exposed cable ends.
- This arc melted through the helium line in which the cable travels, releasing Helium into the insulation vacuum of the interconnect.
- The rapid and voluminous expansion of the Helium caused a pressure wave that propagated along the insulation vacuum causing extensive damage



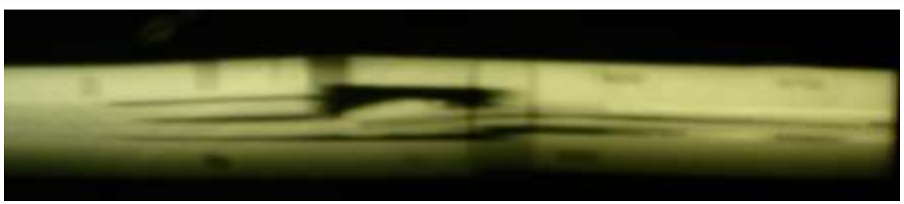
LHC = “big and long vessel”

Sample Joint X-Rays

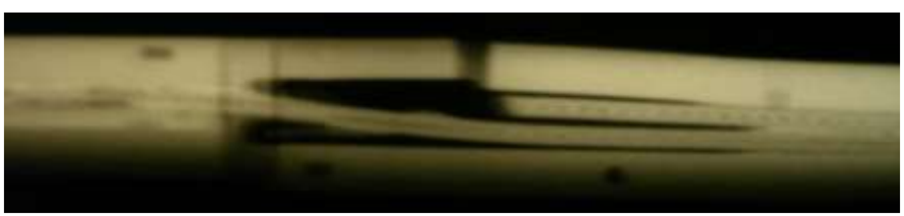
Sample 3A left (26 μΩ)



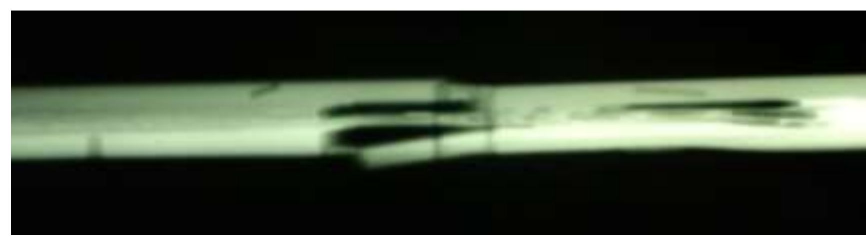
Sample 3A right (43 μΩ)



Sample 2A right (43 μΩ)



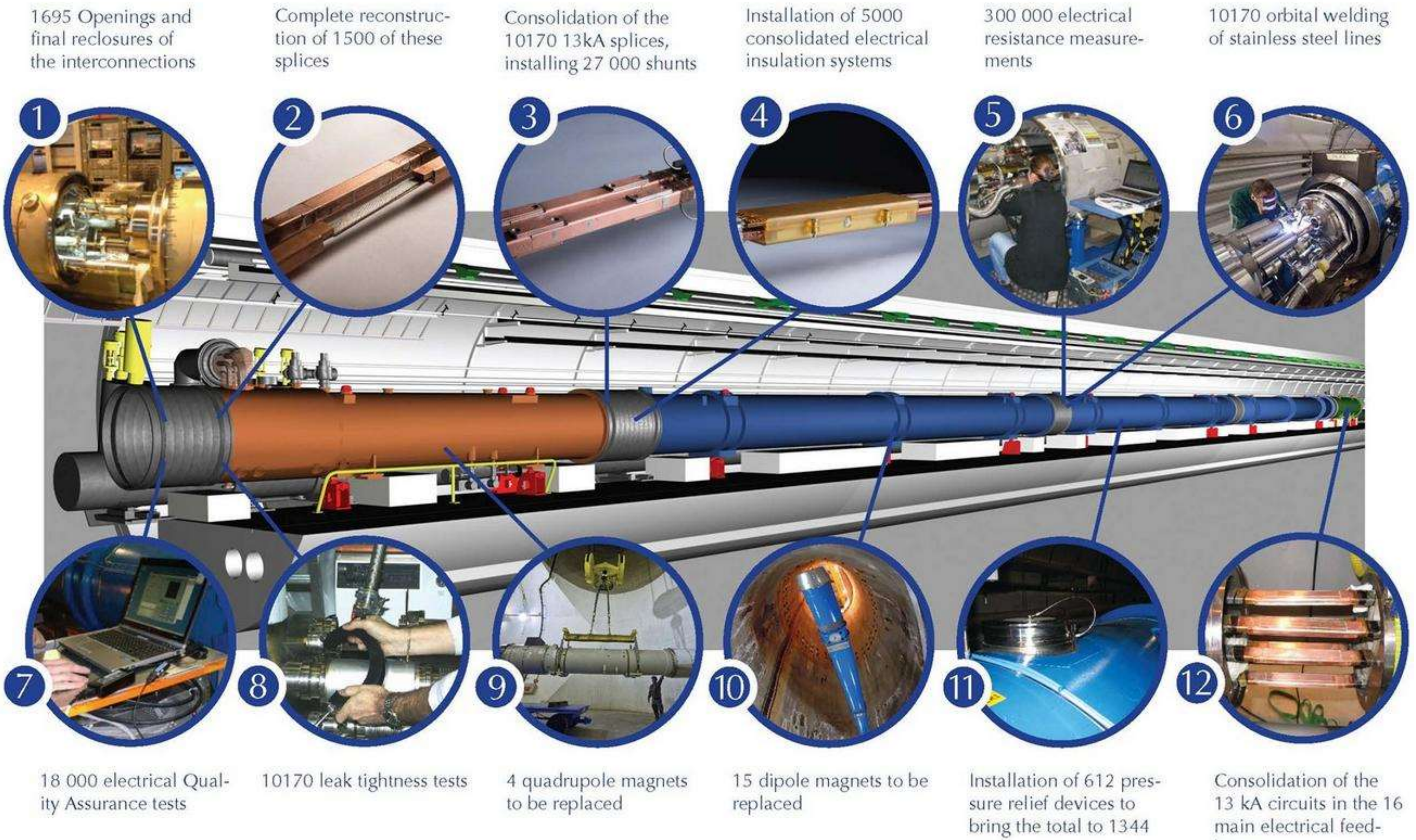
Sample 2B (42 μΩ)



Sample 3B (21 μΩ)

Pictures by J.-M. Dalin

The main 2013-14 LHC consolidations



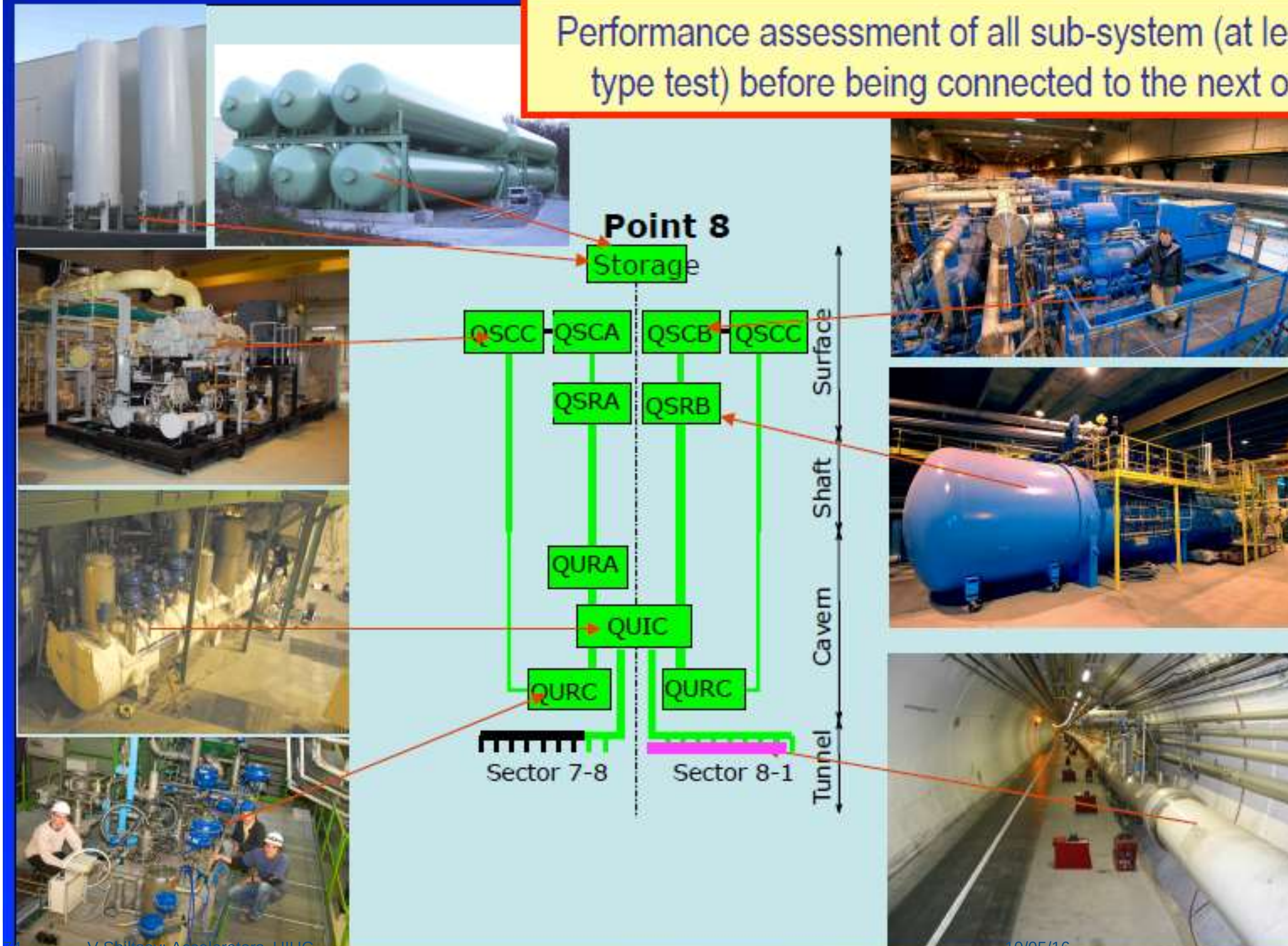
A 13kA splice has a resistance of about 300 pΩ, which can be measured with a precision ~20pΩ. The acceptance criteria is 10 nΩ. Any splice does not meet this criteria is replaced/repaired. The resistance acceptance criteria at the Cu - superconducting splice joints was 5 μΩ. Any joint does not meet this criteria is replaced or repaired.

LHC : Cryogenics , Trips

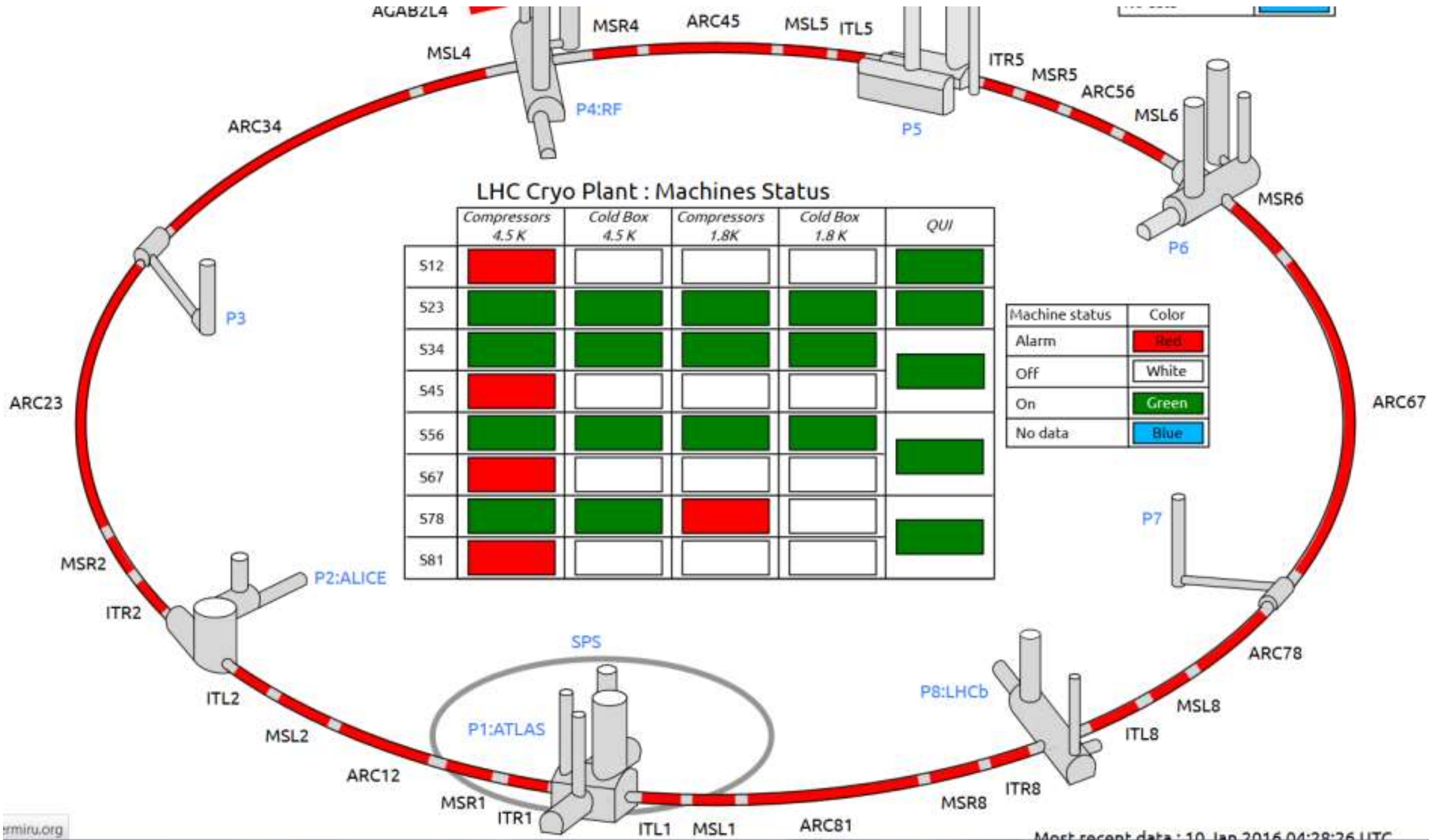
- LHC: 8 cryoplants total 35 MW wall plug; 130 tons of LHe to keep 36,000 tons at 1.9K
- Efficiency ~250 W wall plug power per Watt at 4.5 K
  - CERN cryocapacity of 150 kW @4.5K and 20kW at 1.9K
- Three Temperatures:
  - 50-70 T-shield
  - 4.6 K Heat Intercept
  - 4.6-20 K Beam Screen
  - 1.9K cold mass
- Safety factor 1.6 (design)
- Reality: ~none (1.1?)

Temp. level	Heat load source		LHC nominal
TS	Heat inleaks	[W/m]	7.7
	Total TS	[W/m]	**7.7**
HI	Heat inleaks	[W/m]	0.23
	Total HI	[W/m]	**0.23**
BS	Heat inleaks	[W/m]	0
	Synchrotron radiation	[W/m]	0.33
	Image current	[W/m]	0.36
	Photo-electron cloud	[W/m]	0.90
	Total BS	**[W/m]**	**1.82**
CM	Heat inleaks	[W/m]	0.21
	Resistive heating	[W/m]	0.10
	Beam-gas scattering	[W/m]	0.05
	Total CM	**[W/m]**	**0.36**

Performance assessment of all sub-system (at lea
type test) before being connected to the next on

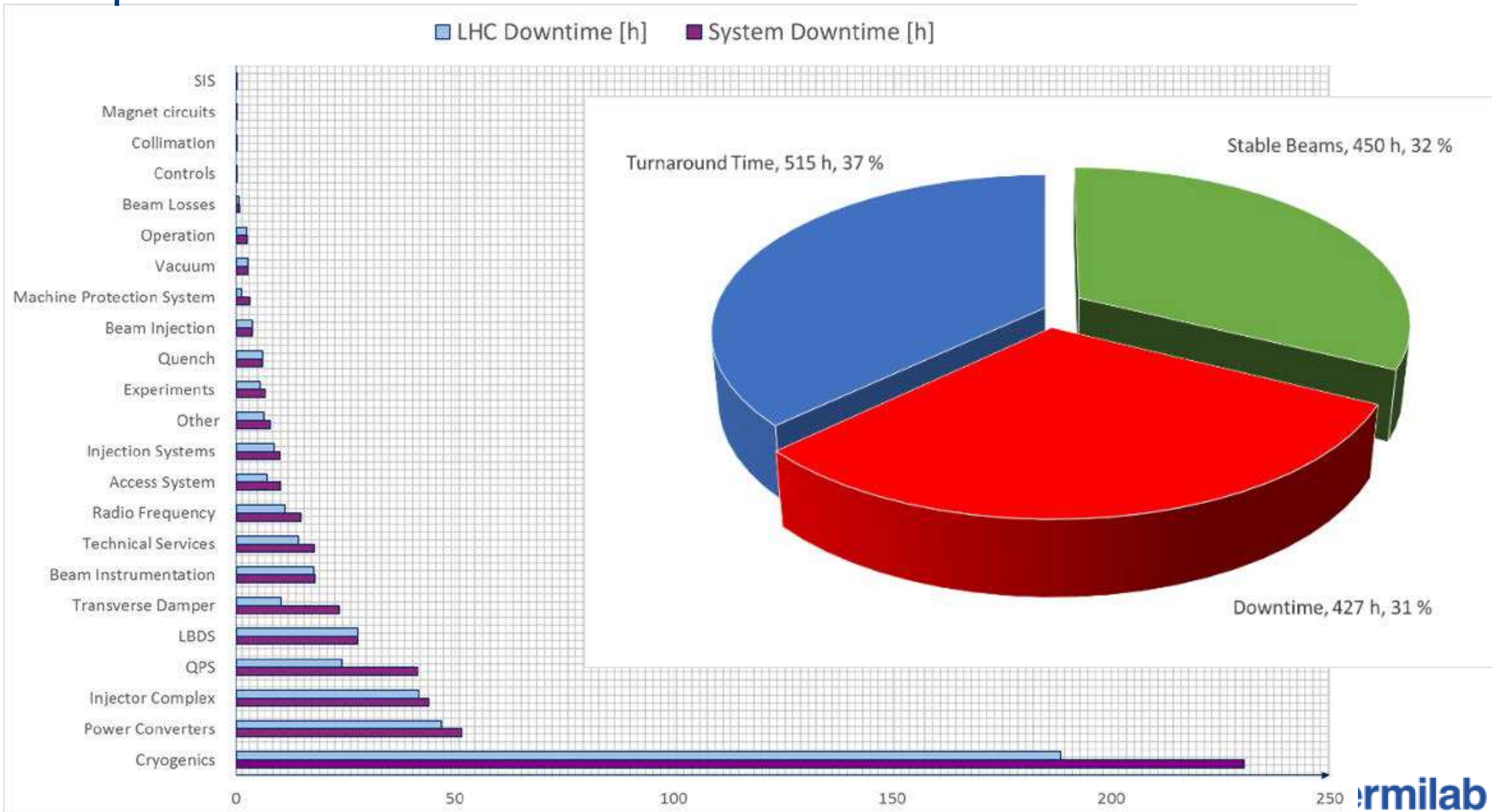


Cryo: Complex and Large Machinery



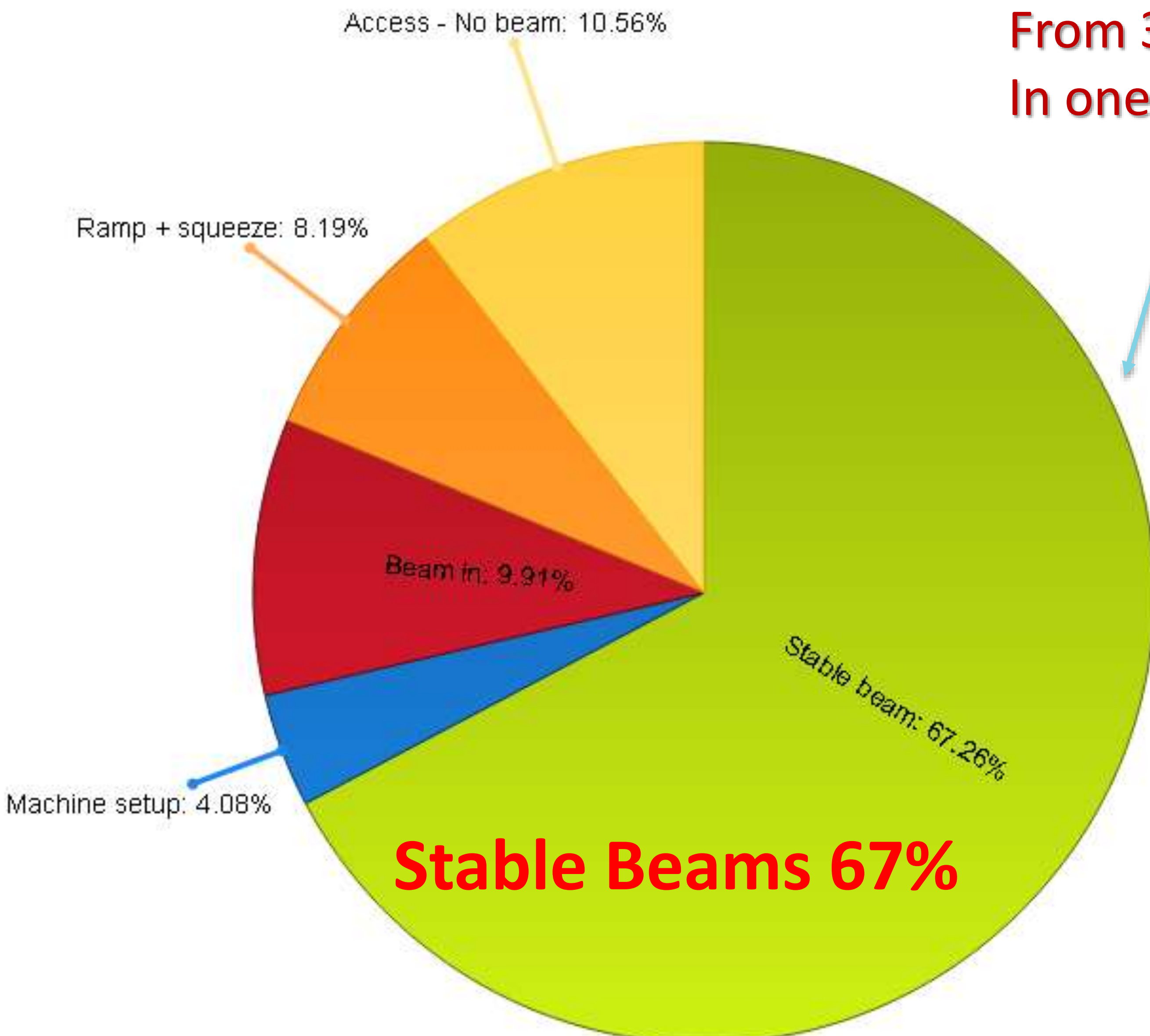
2015 LHC Machine availability

Statistics for 25 ns run from
September 7 to November 3



2016 LHC Availability: 11th June – 23rd July

From 32% to 67%
In one year !!!



Will There Be Energy Frontier Colliders After LHC?

"Any headline that ends in a question mark can be answered by the word ***NO****."*

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Betteridge's law of headlines

Ian Betteridge, a British technology journalist

Hinchliffe's rule

particle physicist Ian Hinchliffe

Davis' law

(who’s Davis ?)