Overview of Future Accelerators

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Chios, Greece

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Outline

- **Accelerators – why?**
- **Accelerators**
  - **in Science**
    - **Particle & Nuclear Physics**
    - **Physical and Life Sciences**
  - **in Industry**
  - **in Medicine**
- **Summary**

WHY?

Why do we need accelerators?

4 reasons:

1. As super-microscopes: $\lambda = h/p$
2. To create very high energies
3. To build nano-scale structures
4. As a source of radiation

Science

(particle & nuclear physics, physical, life and environmental sciences)

Society

(industry and medicine)

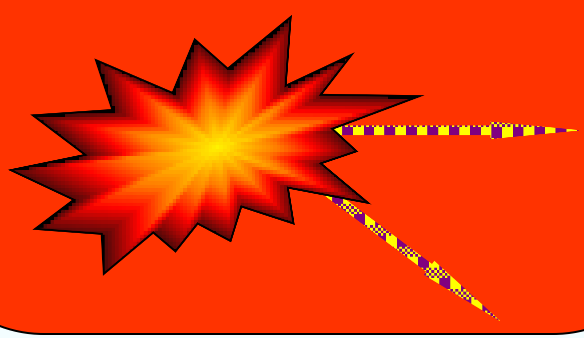
Accelerators for particle physics

What is needed, and why

2 routes to new knowledge about the fundamental structure of the matter

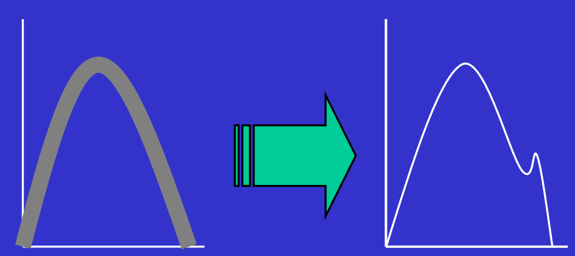
High Energy Frontier

New phenomena (new particles) created when the "usable" energy > mc^2 [×2]



High Precision Frontier

Known phenomena studied with high precision *may* show inconsistencies with theory

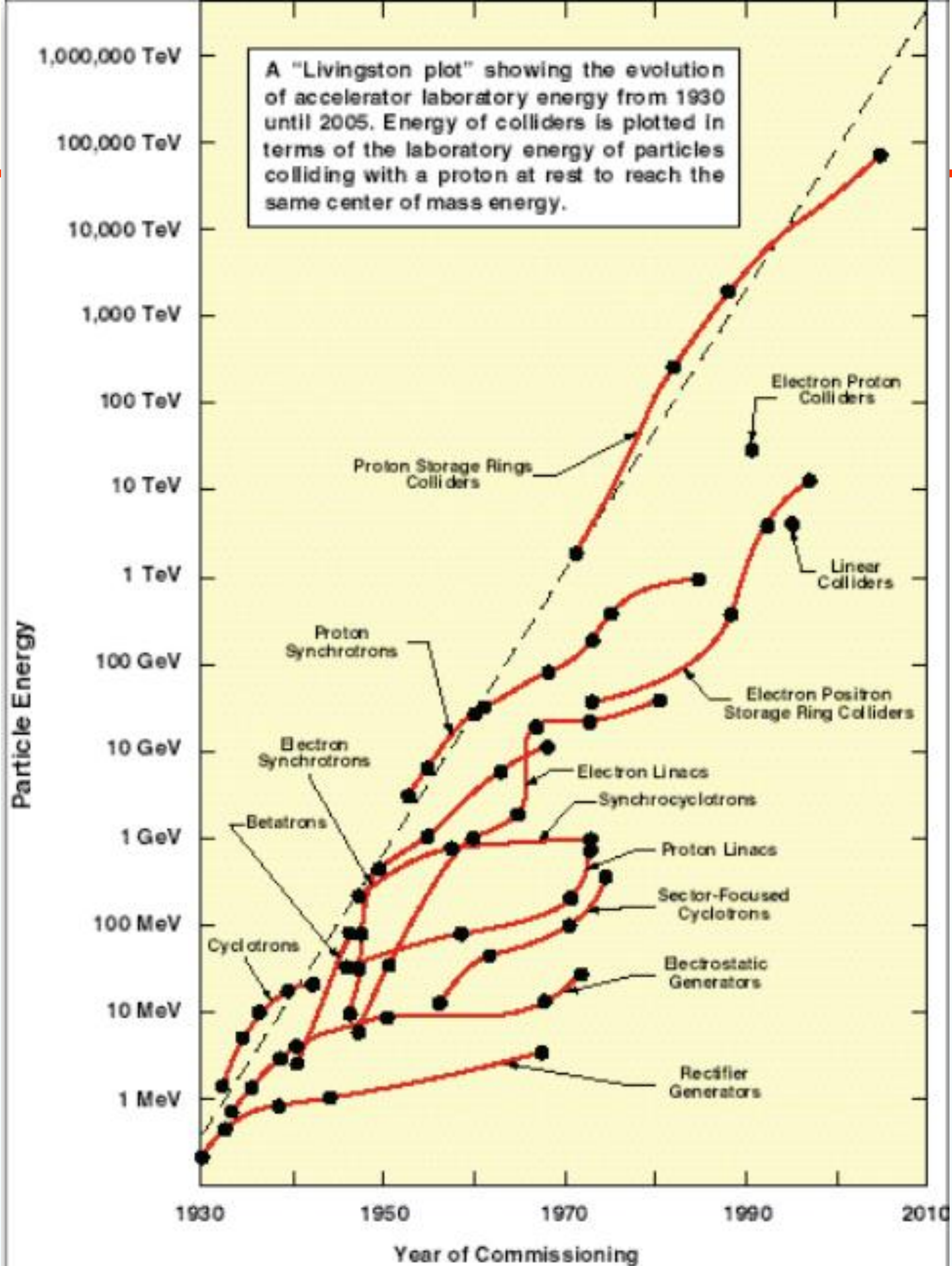


What to accelerate

- **We can accelerate *stable* particles**
  - ***"Stable"* means "with a lifetime long enough to capture and accelerate them**
    - **in practice, > ~μ–second**

- **Hadrons**
  - **p, d, t, α, … nuclei (up to Pb) & antiprotons**
    - **Hadrons contain "partons" (quarks, gluons…)**
- **Leptons**
  - **$e^{\pm}$, $\mu^{\pm}$**
    - **Leptons are "point-like"**
      - **(at our present energy scales)**

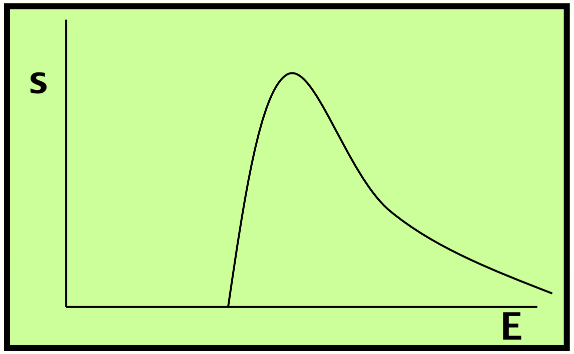
Livingston plot



The Evolution of Particle Accelerators & Colliders
by W. K. H. Panofsky

Energy and luminosity

- ***Energy*** **must be sufficient**
  - **Above the threshold**



- ***Luminosity*** **must be sufficient**
  - **enough events in a “reasonable” time**
    - **a few years**
      - **“lifetime” of a graduate student**

$N_{ev} = L \times s \times t$

t ~ 10^7 s/year

s ~ pb (10^{-36} cm^2)

For 1000 events in 1 year requires

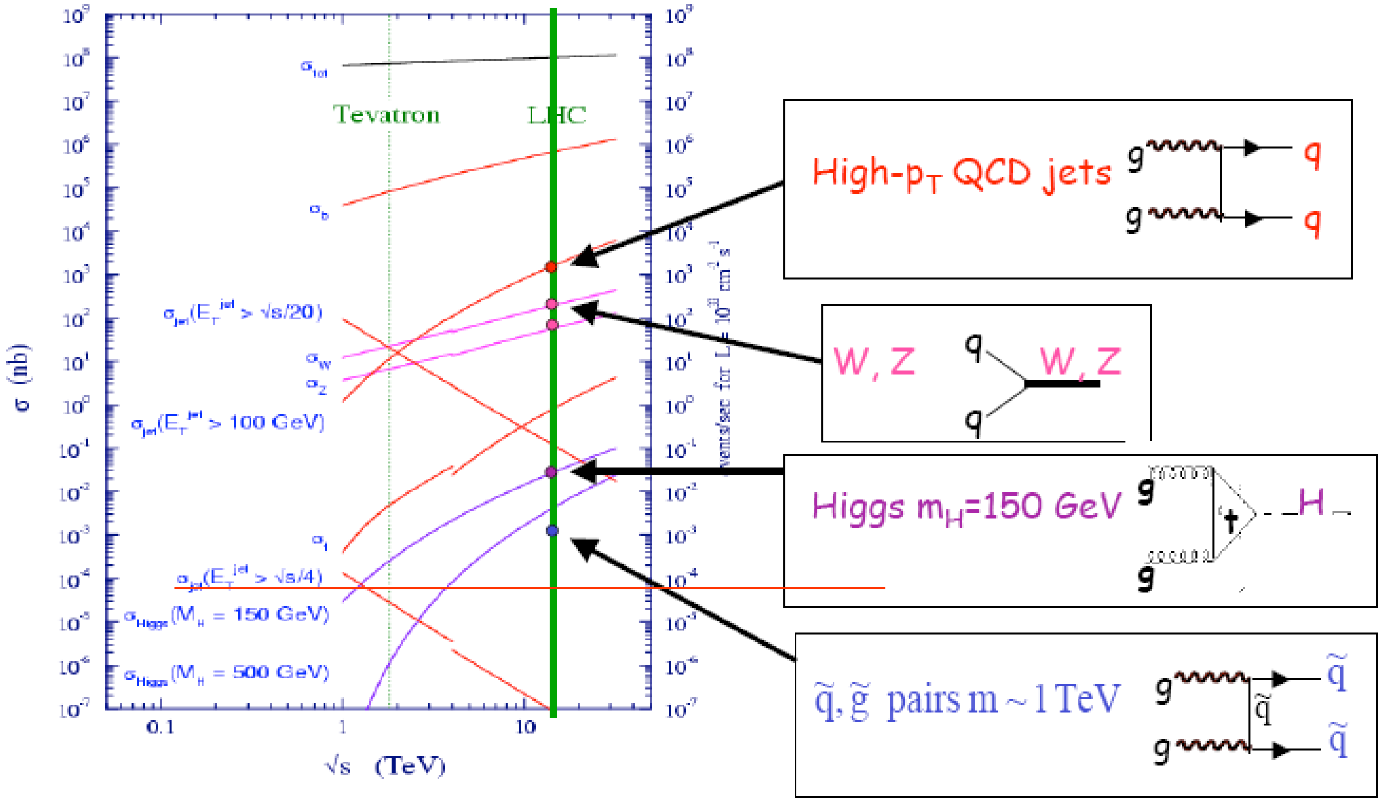
L ~ 10^{32} $cm^{2}s^{-1}$

For fixed target (esp. neutrino experiments) the equivalent parameter is

Beam Power or Protons on Target (POT)

An example – the LHC

❸ Huge (QCD) backgrounds (consequence of high energy ..)



- No hope to observe light objects (W, Z, H ?) in fully-hadronic final states → rely on l, γ
- Fully-hadronic final states (e.g. $q^* \rightarrow qg$) can be extracted from backgrounds only with hard O(100 GeV) p_T cuts → works only for heavy objects
- Mass resolutions of ~ 1% (10%) needed for l, γ (jets) to extract tiny signals from backgrounds
- Excellent particle identification: e.g. e/jet separation

Gianotti, LP05

- **Needs high Energy & high Luminosity**

Future Accelerators for Particle Physics

Large Hadron Collider

Linear (e^+e^-) Collider

Muon Collider

Neutrino Factory

EURISOL and Beta Beams

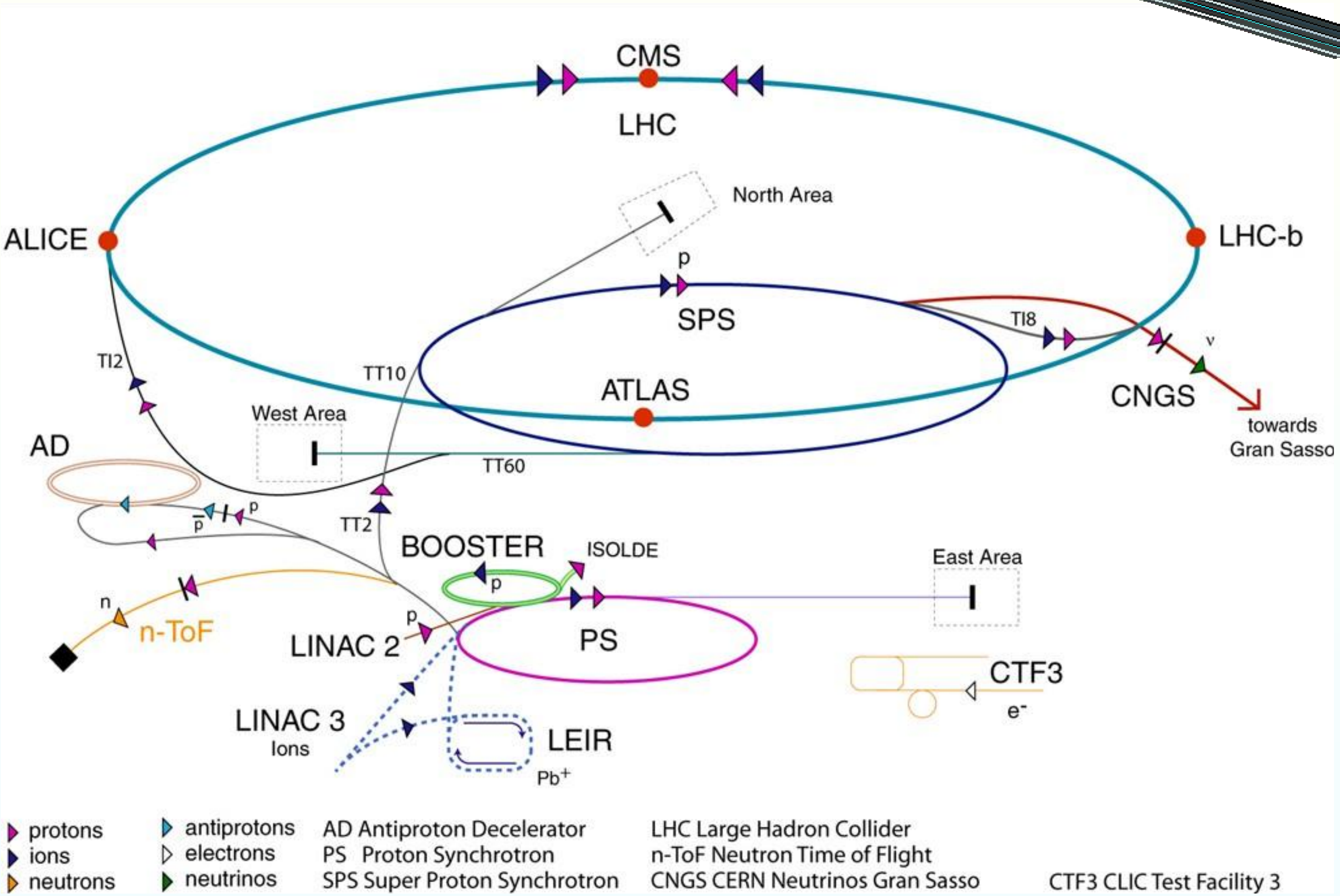
"Factories" (ϕ, τ, c, b)

LARGE HADRON COLLIDER

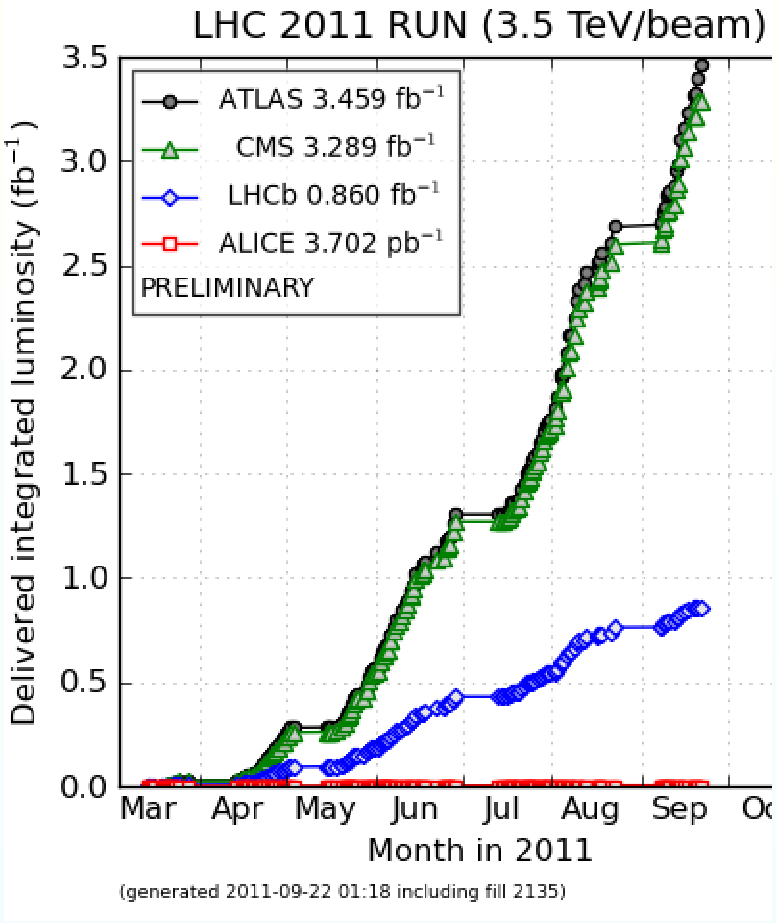
The Large Hadron Collider

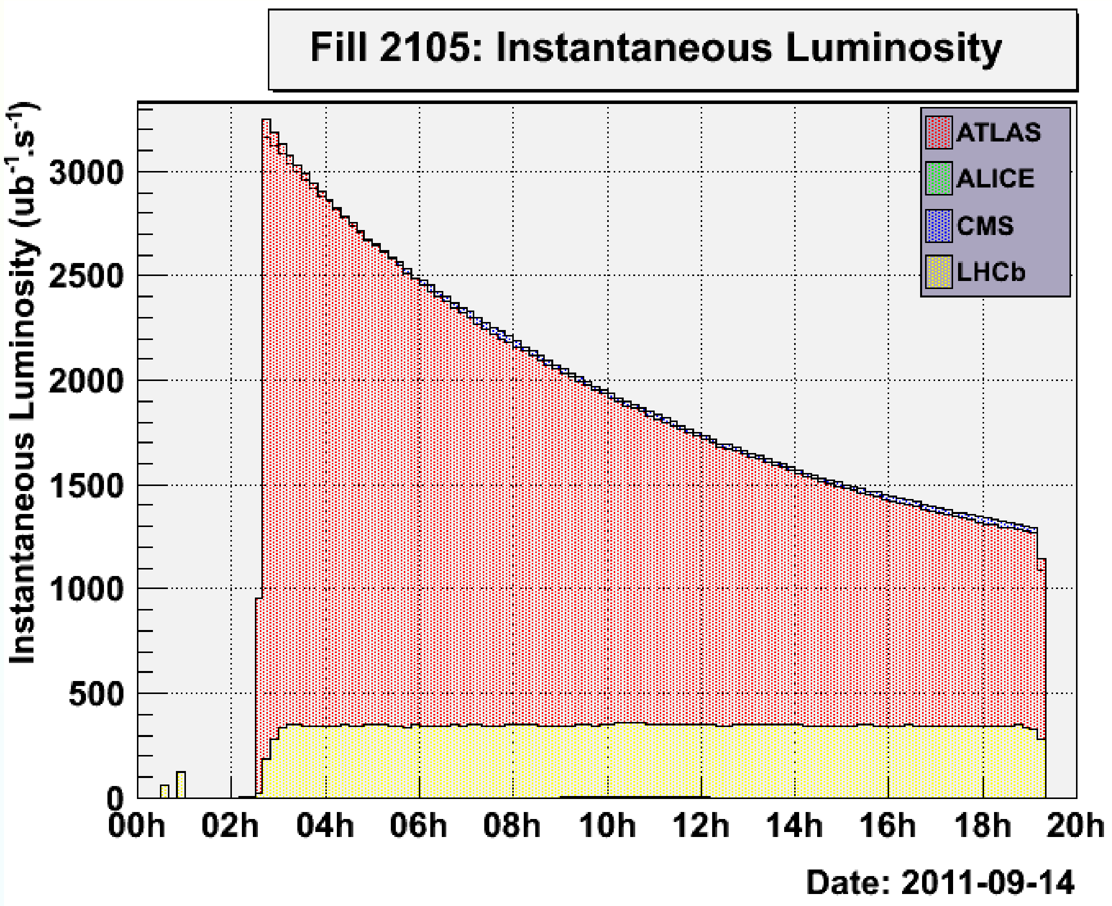
- **The two main goals are:**
  - **Find the Higgs**
    - ***If it exists!!!***
  - **Find the new physics**
    - ***If it exists!!!***
- **We know ~ the energy scales**
  - **M_H <250GeV ; E_{NP} < 1TeV** ??????????
- **pp collisions at high energy**
  - **Collision energy ~10% of total energy**
    - **Need a total collision energy >10TeV**
  - **Can calculate the cross-sections**
    - **Need a luminosity > $10^{33}cm^2/s$**
- **The Large Hadron Collider (LHC) @ CERN**
  - **E ~ 14TeV ; L ~ $10^{34}cm^2/s$**

The CERN Accelerator Complex

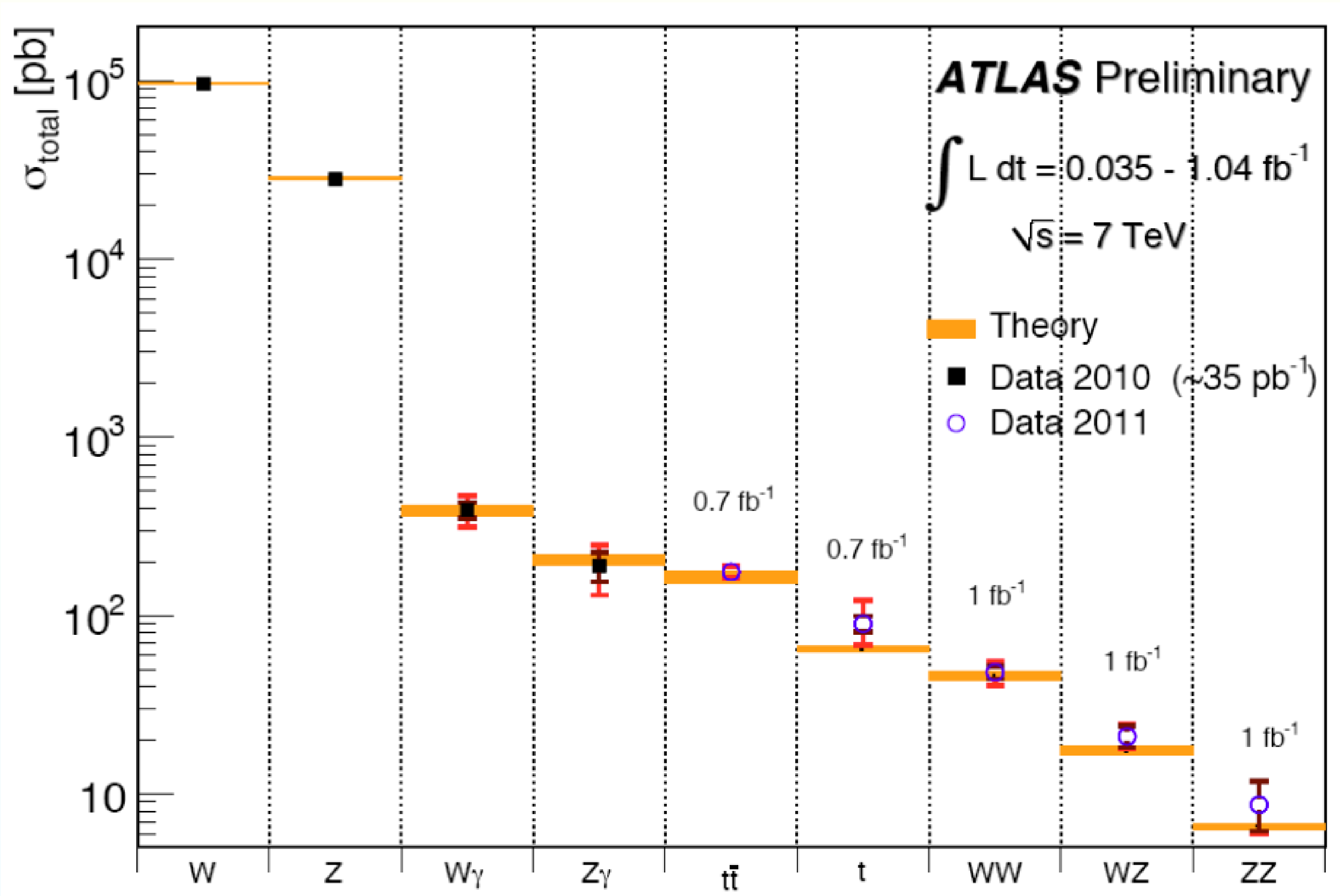


Integrated Luminosity



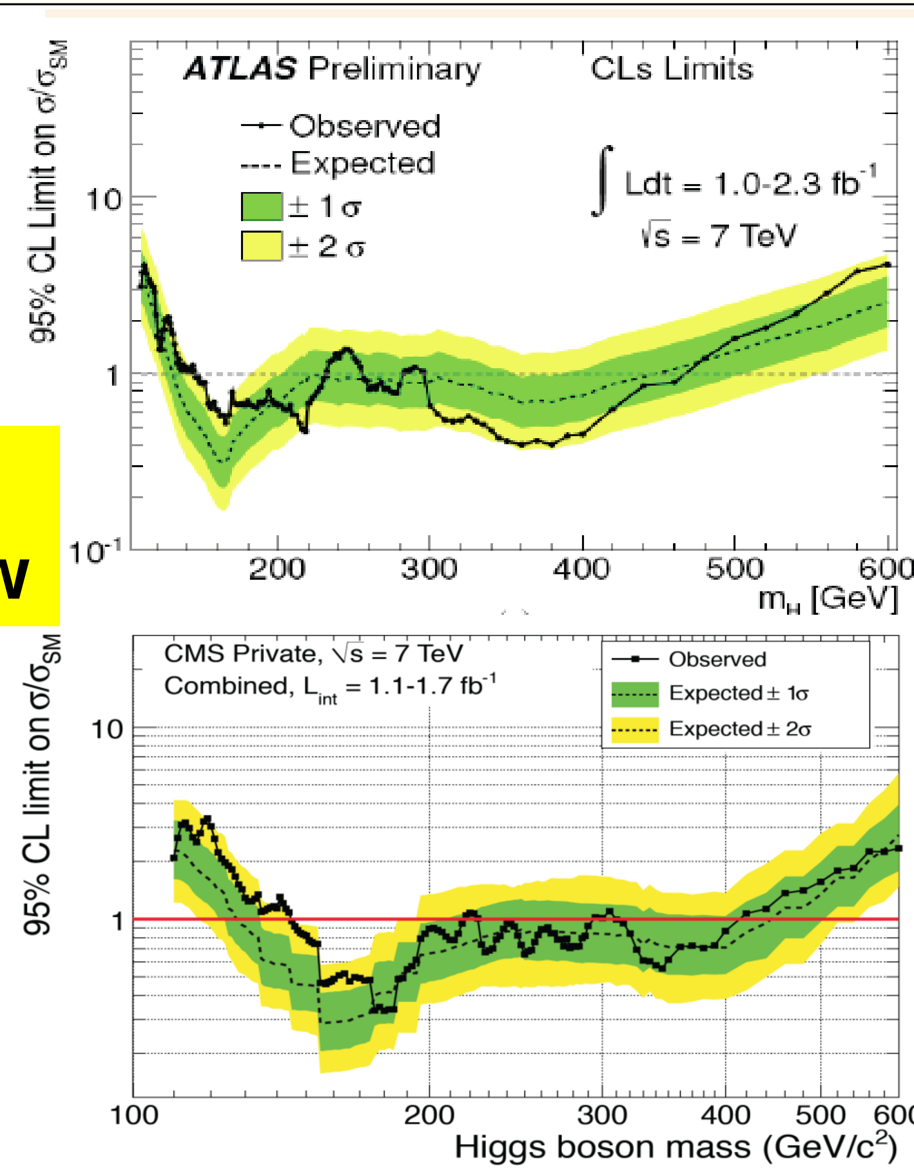


Do we know what we are doing?

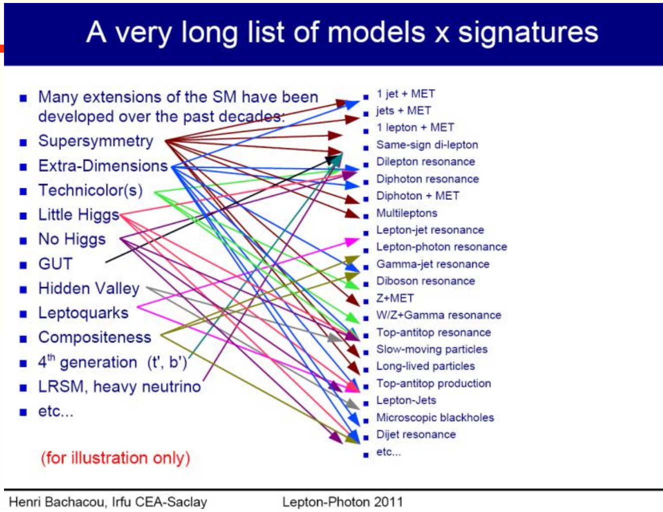


Where is Higgs?

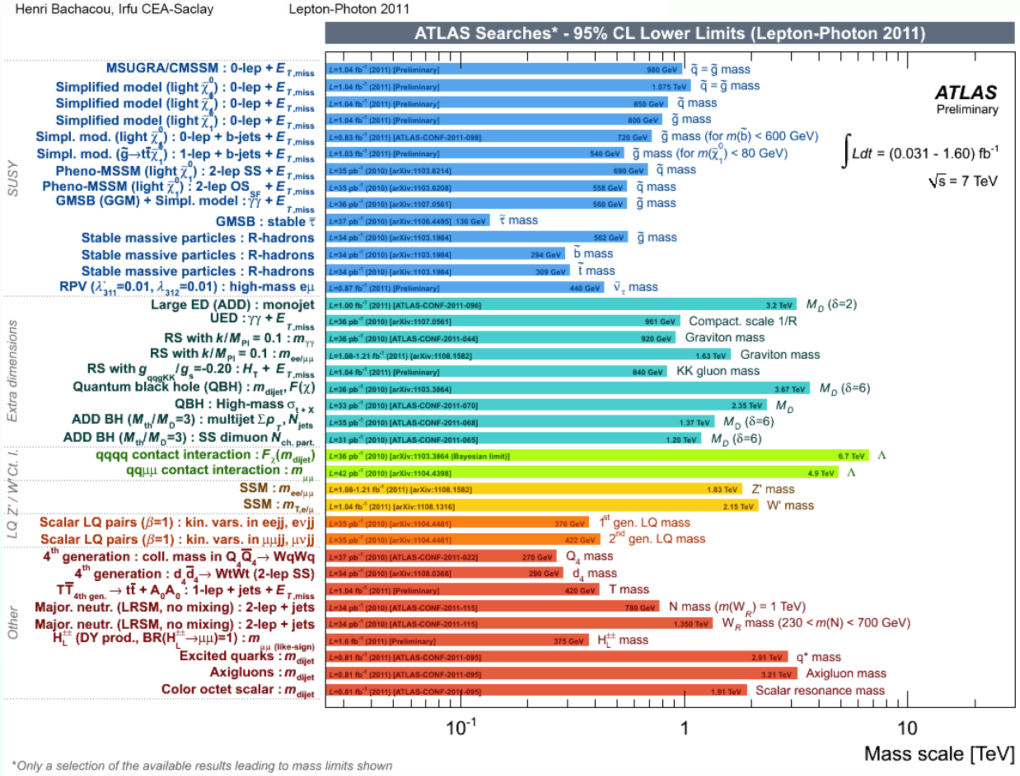
What we know now

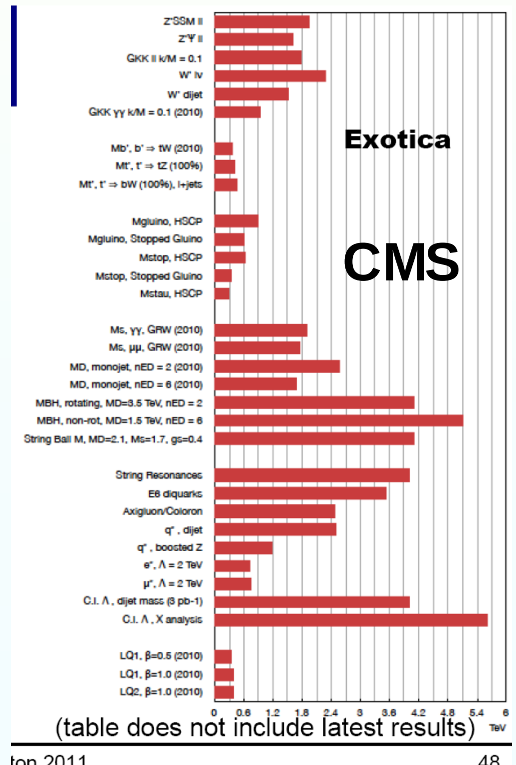


… and anything else?



- **Caution:**
  - **new physics may different!**





What Next?

- **Reach the full specification**
  - **14 TeV**
  - **10^{35} cm^{2}s^{-1} (Actually $\int d\mathcal{L} = 3000\ fb^{-1}$)**

- **then**
  - **Upgrade the luminosity (S-LHC)**

    ~10^{36} cm^{2}s^{-1}
  - **or the energy (D-LHC)**

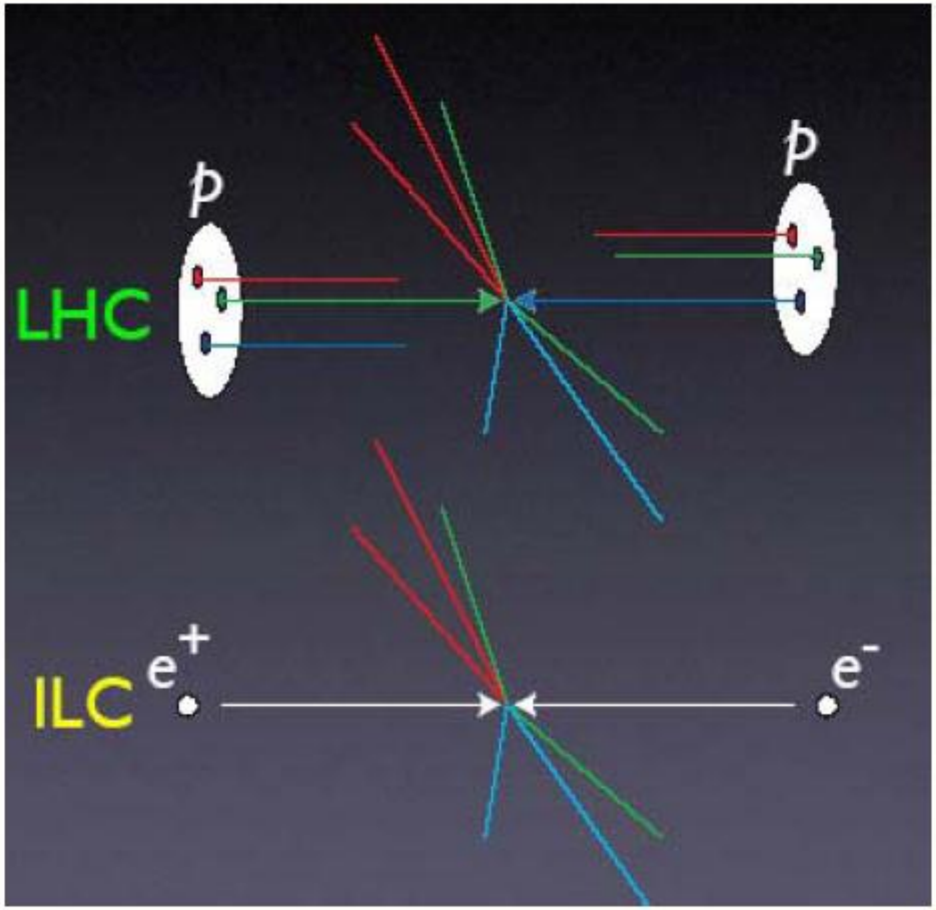
    >28 TeV

depending upon physics and technology

LINEAR e^+e^- COLLIDER

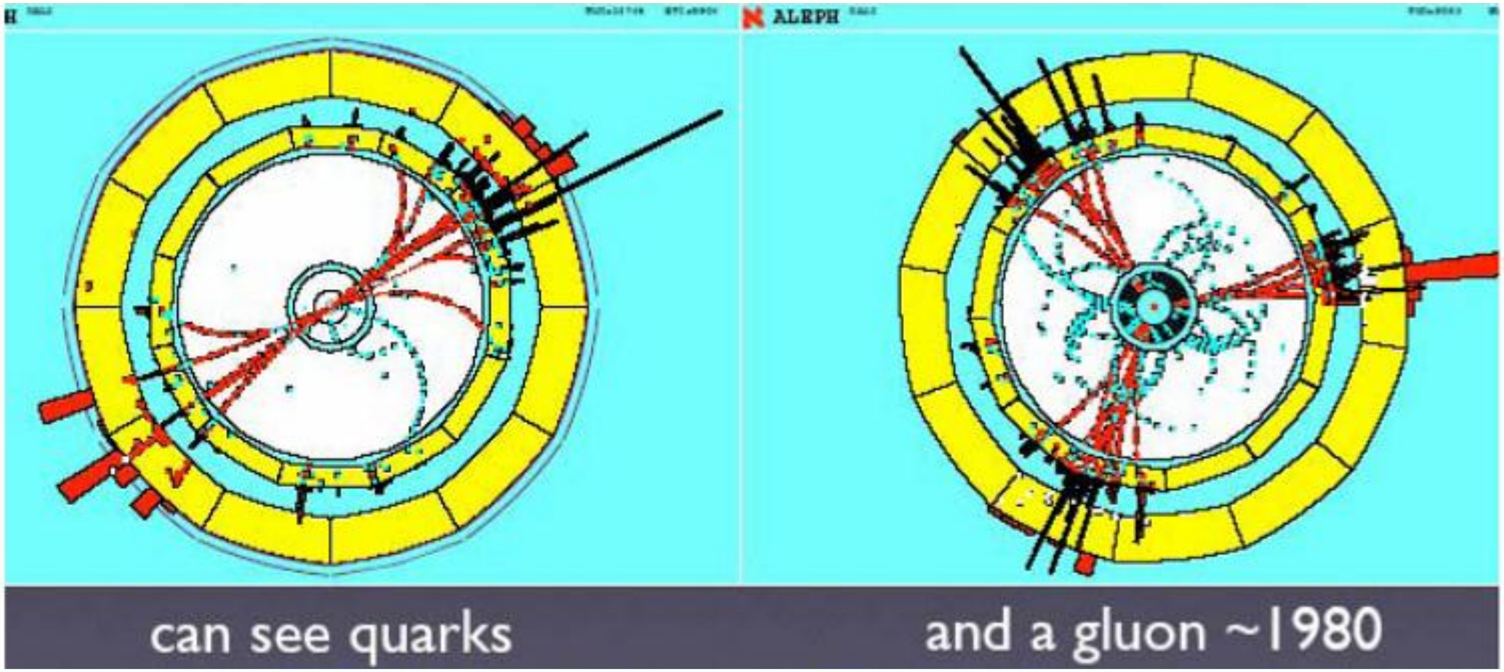
Why an e+e- collider?

- elementary particles
- well-defined
  - energy,
  - angular momentum
- uses full COM energy
- produces particles democratically
- can mostly fully reconstruct events



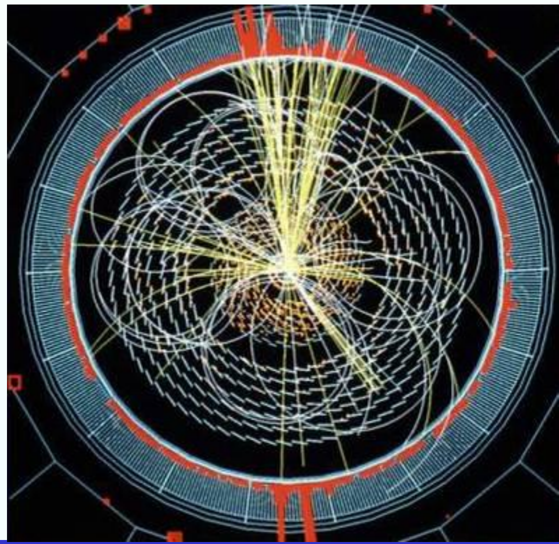
After Barry Barish

Why an e+e- collider?



← LEP

LHC →



After Barry Barish

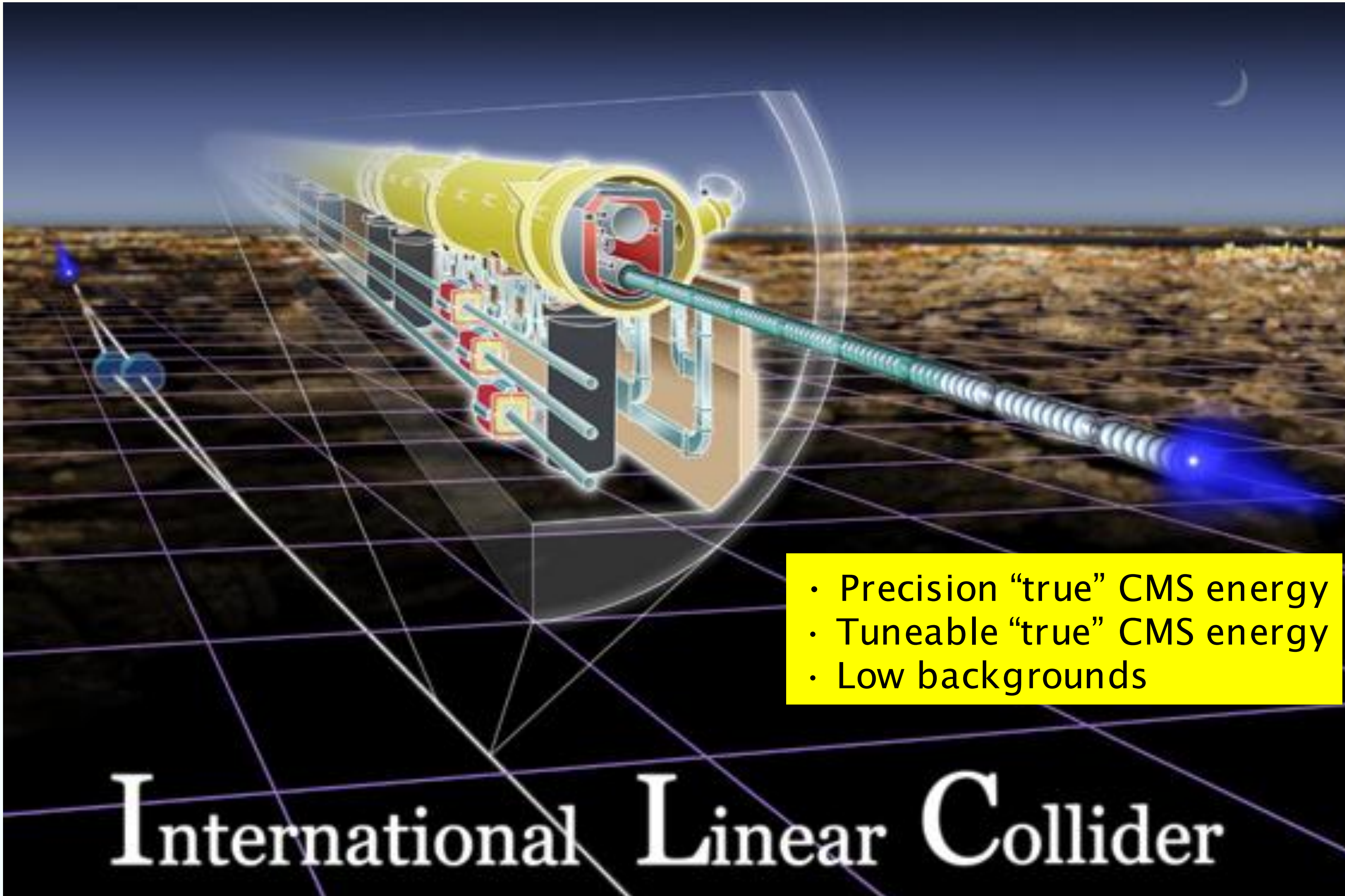
Why a *linear* e+e- collider?

Synchrotron Radiation!

or rather

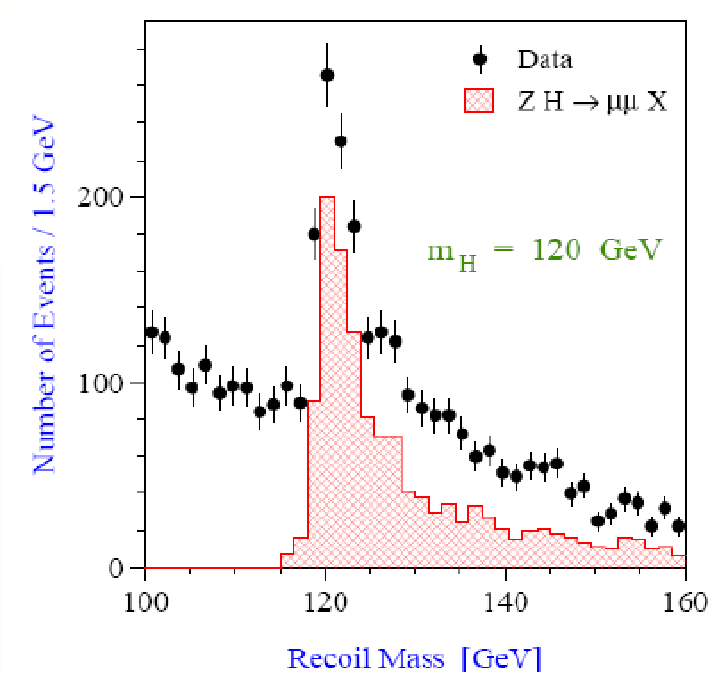
the lack of it in a linear machine

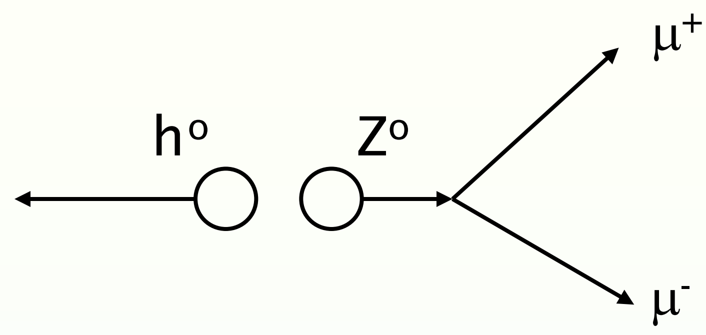
Key ILC Properties



- Precision "true" CMS energy
- Tuneable "true" CMS energy
- Low backgrounds

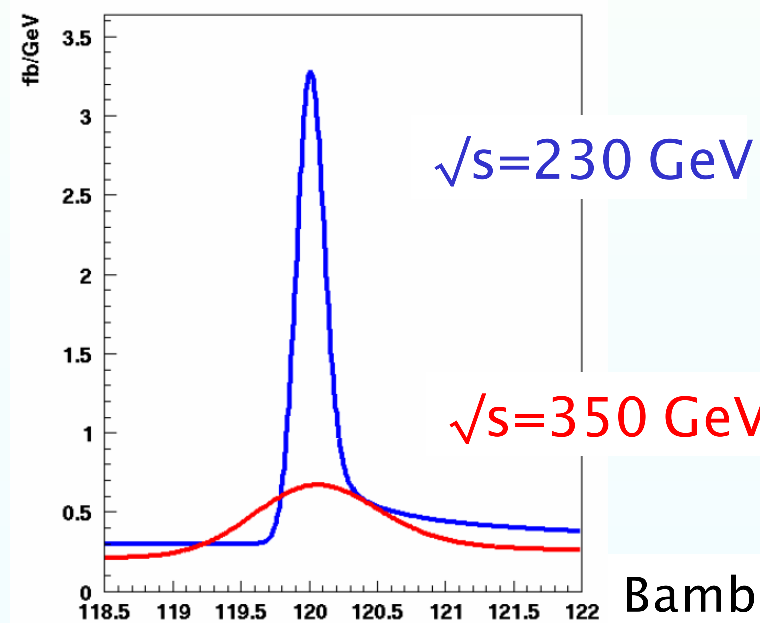
Invisible Higgs?





Measure recoil against Z^0

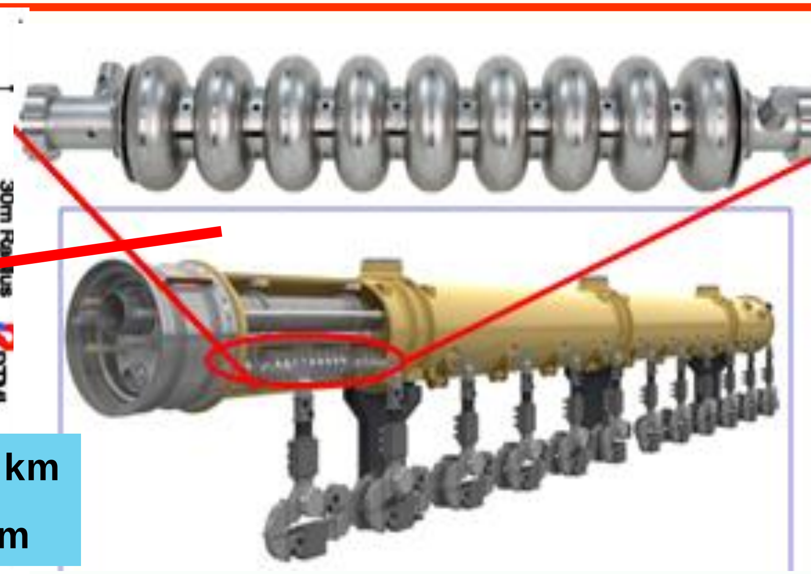
120 GeV Higgs:
Advantages of running at lower than top threshold:



Bambade et al.

Linear Collider layouts

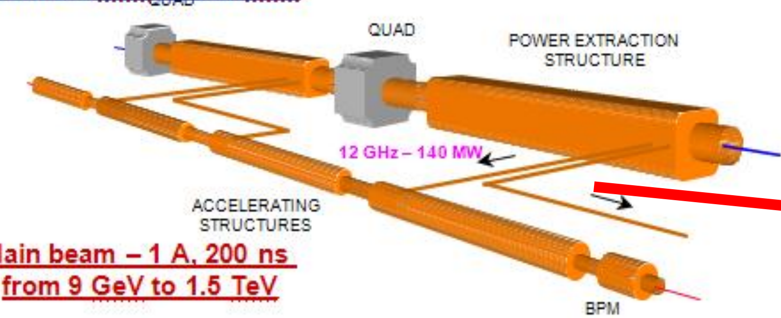
http://www.linearcollider.org/cms   http://clic-study.web.cern.ch/CLIC-Study/



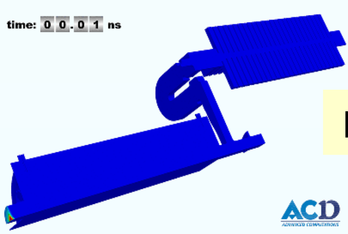
ILC 0.5 TeV – 30 km

ILC 1 TeV – 50 km

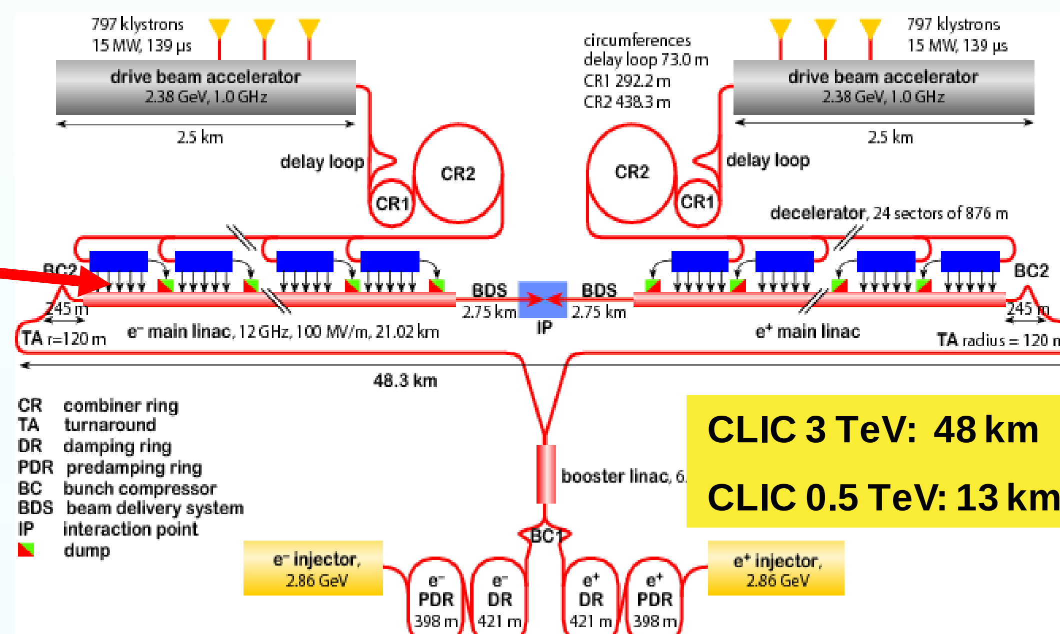
Drive beam - 95 A, 300 ns
from 2.4 GeV to 240 MeV



Main beam – 1 A, 200 ns
from 9 GeV to 1.5 TeV



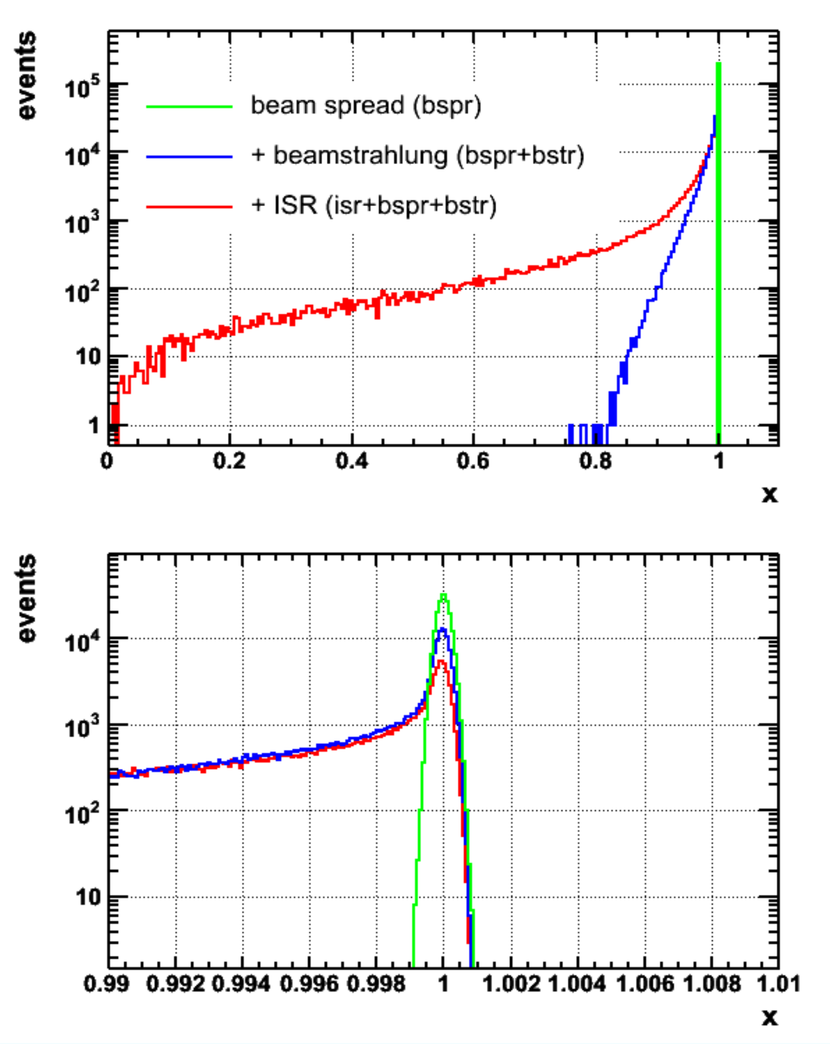
Delahaye, ICHEP10

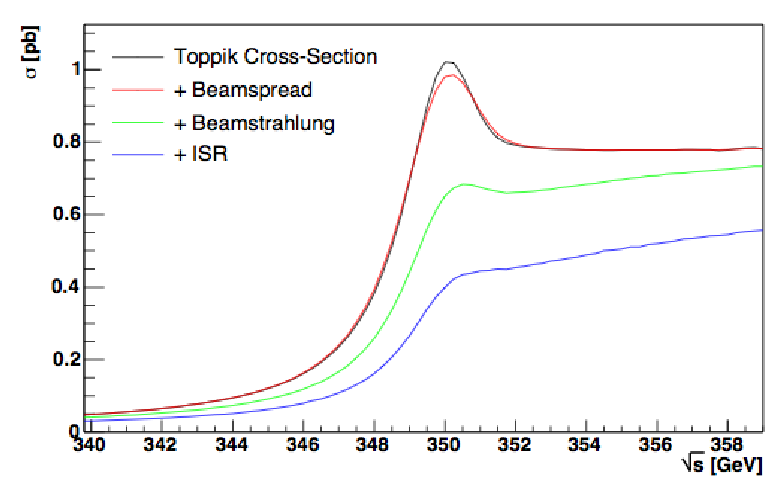


CLIC 3 TeV: 48 km

CLIC 0.5 TeV: 13 km

Energy spectrum; impacts physics output





Need for:

- Energy measurement accuracy 10^{-4}
- Stability and ease of operation
- Minimal impact on physics data taking

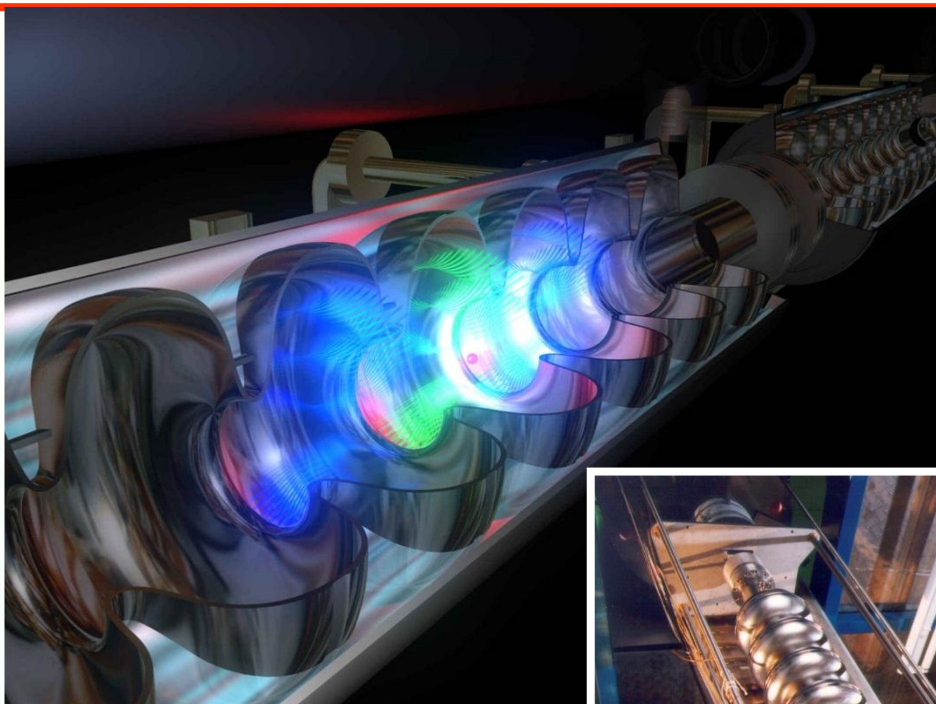
After Blair

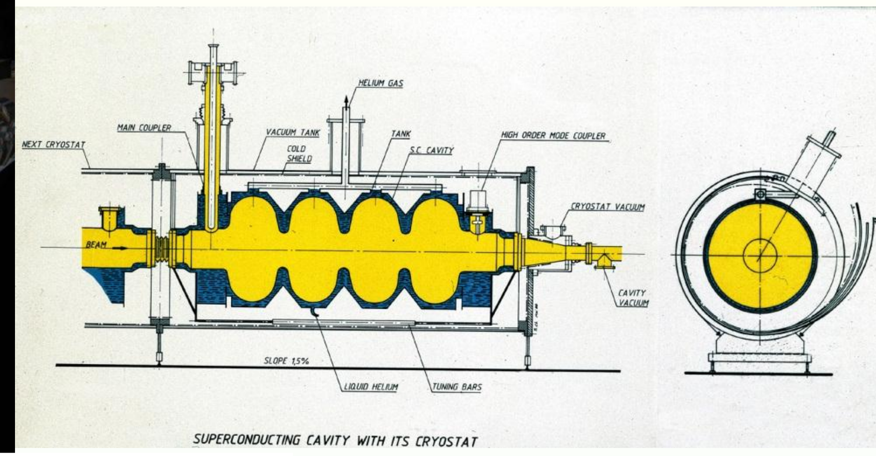
Linear Collider main parameters

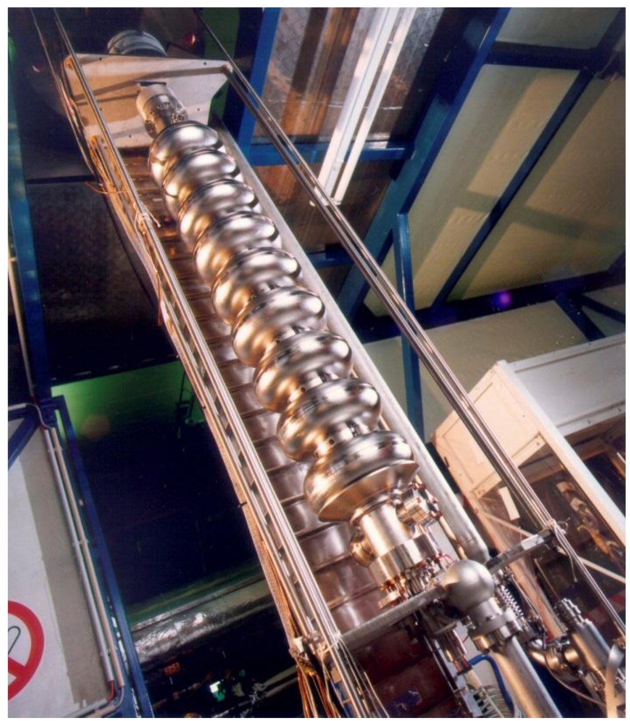
Delahaye, ICHEP10

Technology	ILC	CLIC	
Centre-of-mass energy (GeV)	500	500	3000
Total (Peak 1%) luminosity (10^{34})	2.0(1.5)	2.3(1.4)	5.9(2.0)
Total site length (km)	31	13.0	48.3
Loaded accel. gradient (MV/m)	31.5	80	100
Main linac RF frequency (GHz)	1.3 (Super Cond.)	12 (Normal Conducting)	
Beam power/beam (MW)	20	4.9	14
Bunch charge (10^9 e+/-)	20	6.8	3.72
Bunch separation (ns)	176	0.5	
Beam pulse duration (ns)	1000	177	156
Repetition rate (Hz)	5	50	
Hor./vert. norm. emitt ($10^{-6}/10^{-9}$)	10/40	4.8/25	0.66/20
Hor./vert. IP beam size (nm)	640/5.7	202 / 2.3	40 / 1
Hadronic events/crossing at IP	0.12	0.19	2.7
Coherent pairs at IP	10	100	$3.8\ 10^8$
Wall plug to beam transfer eff	9.4%	7.5%	6.8%
Total power consumption (MW)	216	129.4	415

The heart of the ILC







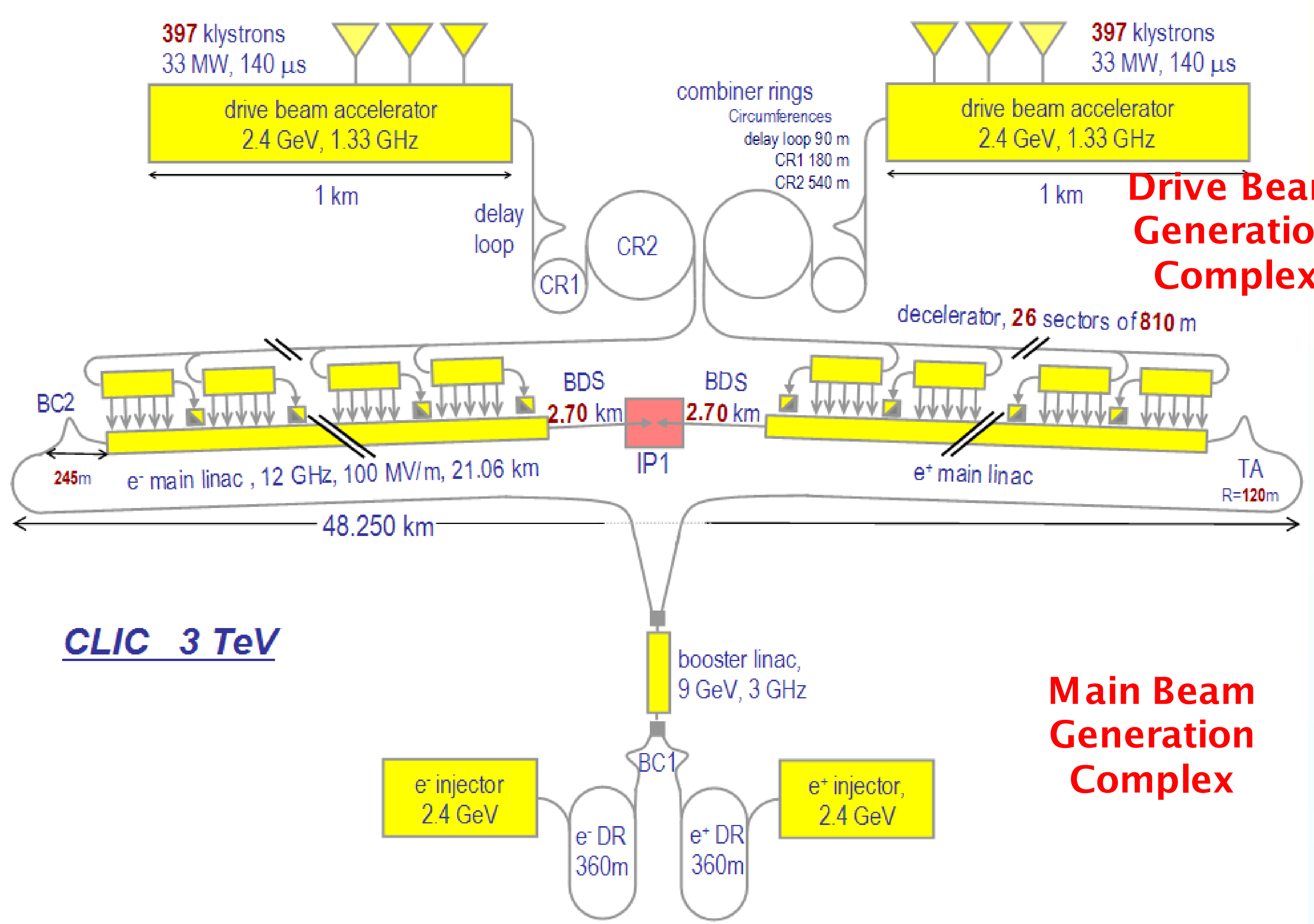
CLIC

Compact

LInear

Collider

CLIC – overall layout



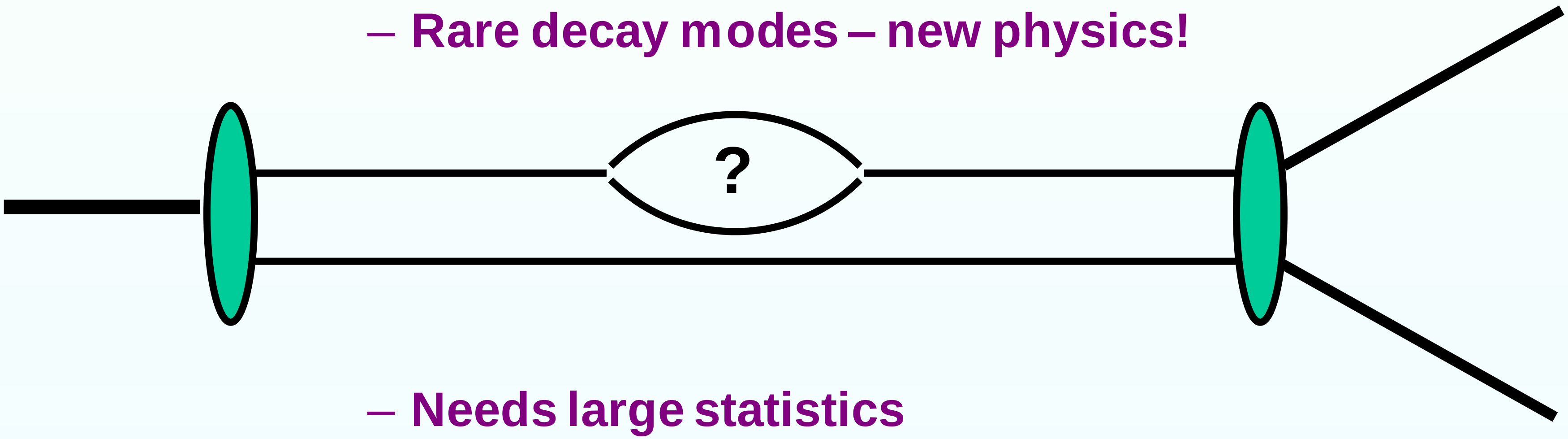
Decision point for the LC

- **2½ key facts are needed**
  1. **Is there a light (<200 GeV/c^2) Higgs?**
  2. **Is there New Physics (below 1 TeV)?**
     - ½ **If yes, what is the energy range?**
- **Note:**
  - **It does not matter much from the point of view of defining the *decision point* what the answers to these questions are – only that we know them!**
  - **The 1st question may be answered by end 2012**
  - **The 2nd question may be answered by end 2011**
    - **The ½ question may not be clear for some time**
  - **We need to define criteria for making a "fact"**
    - **Is 3σ enough for evidence?**
    - **Is 98% enough to exclude?**
  - **Do we need the answers to both to proceed?**
    - **(KJP) yes (politically)**
- **Reach of LC wrt HE-LHC or HL-LHC?**

THE HIGH LUMINOSITY FRONTIER

When is luminosity more important than energy?

- **Suppose we *know* a particle exists**
  - **What are its properties?**
    - **Charge is easy**
    - **Mass – depends upon the precision**
    - **Spin & parity – need statistics**
    - **Decay modes and dynamics**
      - **Common decay modes – spin-parity analysis**
      - **Rare decay modes – new physics!**

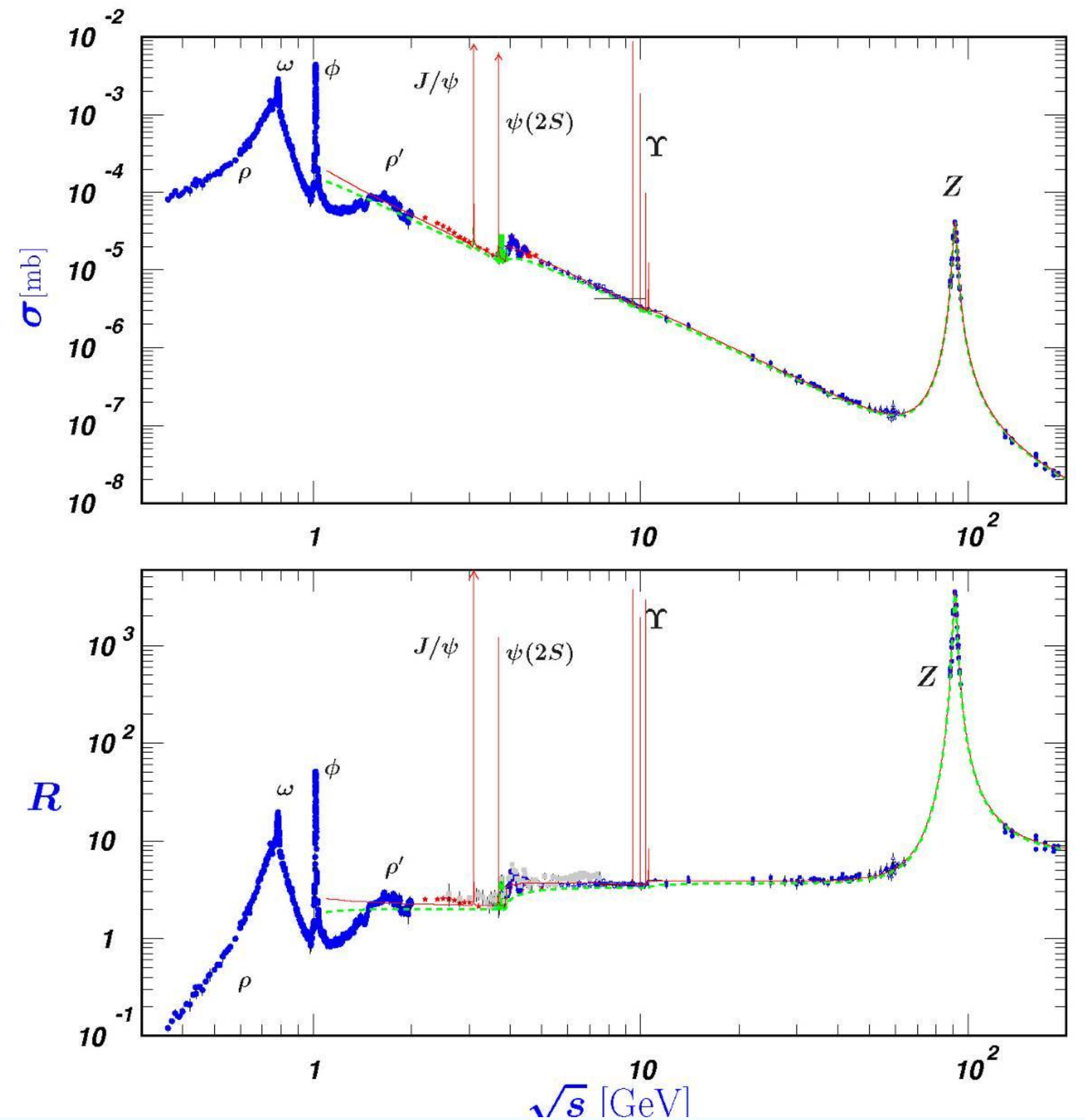


- **Needs large statistics**
- **High luminosity**

"Factories"

- **Several particle factories built**
  - **"b-factories" (KEKB and PEPII)**
    - **High statistics studies of B_d decays**
  - **"(tau-)charm factories" BEPC**
    - **High statistics studies of J/ψ, ψ' & τ decays**
  - **"Phi-factory" (Frascati)**
    - **High statistics studies of ϕ decays**
      - **(Actually, $\phi \rightarrow K_1 K_2$, which is the real interest)**
      - **(Also, $e^+e^- \rightarrow \pi^+\pi^-$ & other final states below 3 GeV for $(g-2)_\mu$ corrections)**
- **Future? Neutrino Factory?**

R = σ(e⁺e⁻→hadrons)/σ(e⁺e⁻→μ⁺μ⁻)



- **Large cross-sections in e⁺e⁻ when a "new quark" is discovered …**
  - **s (φ)**
    - → **KK**
  - **c (J/ψ, ψ', ψ(2S))**
    - → **DD**
  - **b (Υ…Υ(4S), Υ(5S))**
    - → **B̄B**

with low continuum backgrounds

Charm factories

- **Originally SPEAR @ SLAC in Palo Alto**
- **Then BEPC @ IHEP in Beijing**
- **Then CLEO-c @ Cornell**
- **Then BEPC-II @ IHEP in Beijing**

  – **Not discussed – impact of physics on the design between the ϕ-factory and the (symmetric) Υ-factory (CLEO-I & CLEO-II)**

Example: $\phi \rightarrow K_S K_L$

Kaons at KLOE

The φ decays at rest allow us to select monochromatic (p ~ 110 MeV/c) pure beams of Kaons:

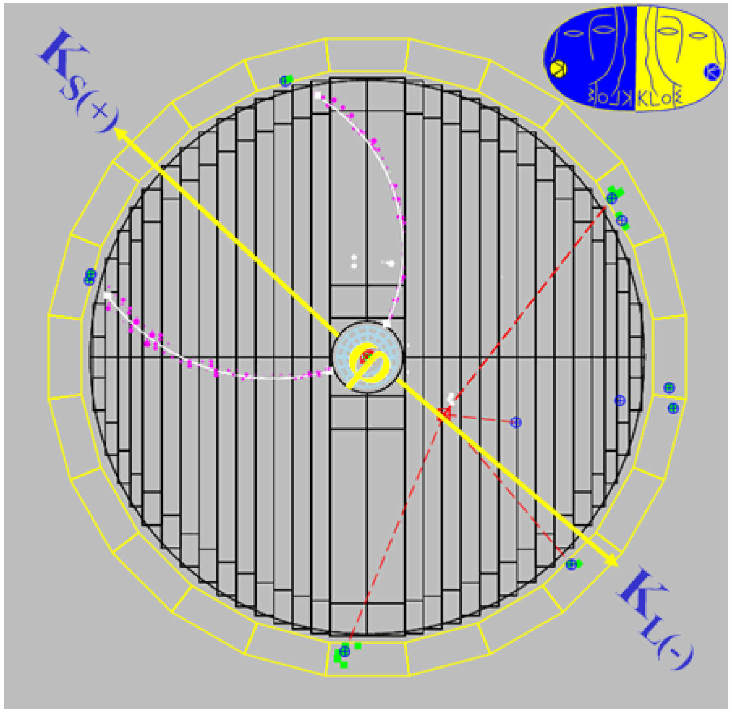
1. K rare decays.
2. Absolute branching ratios:

$$BR = \frac{N^{found}}{N^{tag}} \times \frac{1}{\varepsilon}$$

3. K life times:

$$\frac{\lambda_L}{L} \approx 2 \quad \frac{\lambda_\pm}{L} << 1 \quad \beta \approx 0.2$$

The variety of K decay channels and the possibility for a complete closure of the kinematics allow the selection of many samples for measuring the efficiencies directly from data.



$\lambda_L \sim 340$ cm $\quad \lambda_S \sim 0.6$ cm

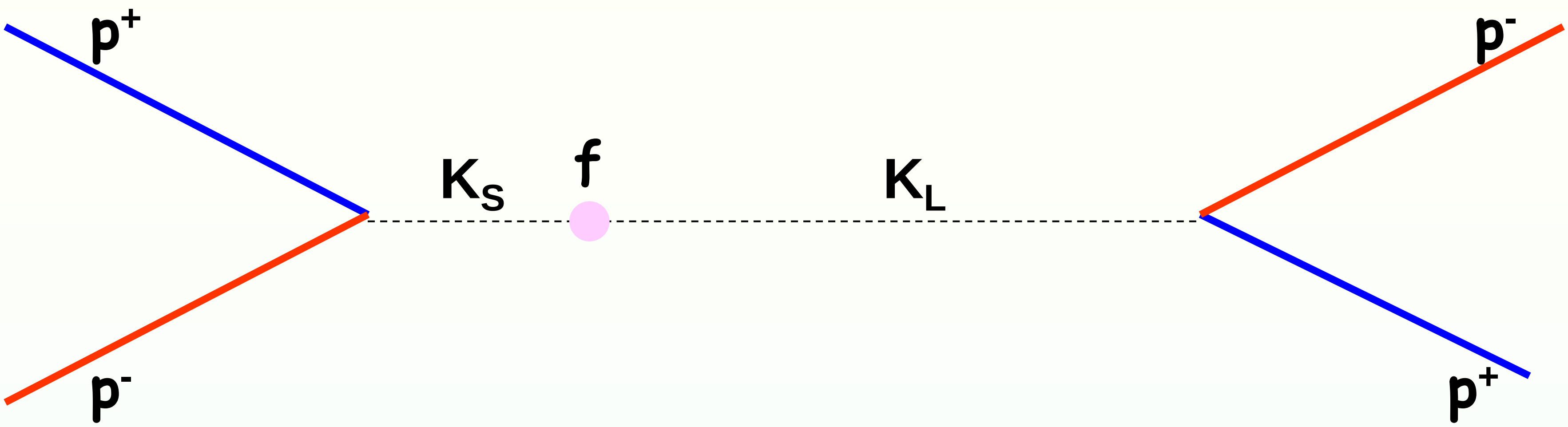
$\lambda_\pm \sim 95$ cm

K^+K^- $\quad 1.5 \times 10^6/pb^{-1}$

$K_L K_S$ $\quad 10^6/pb^{-1}$

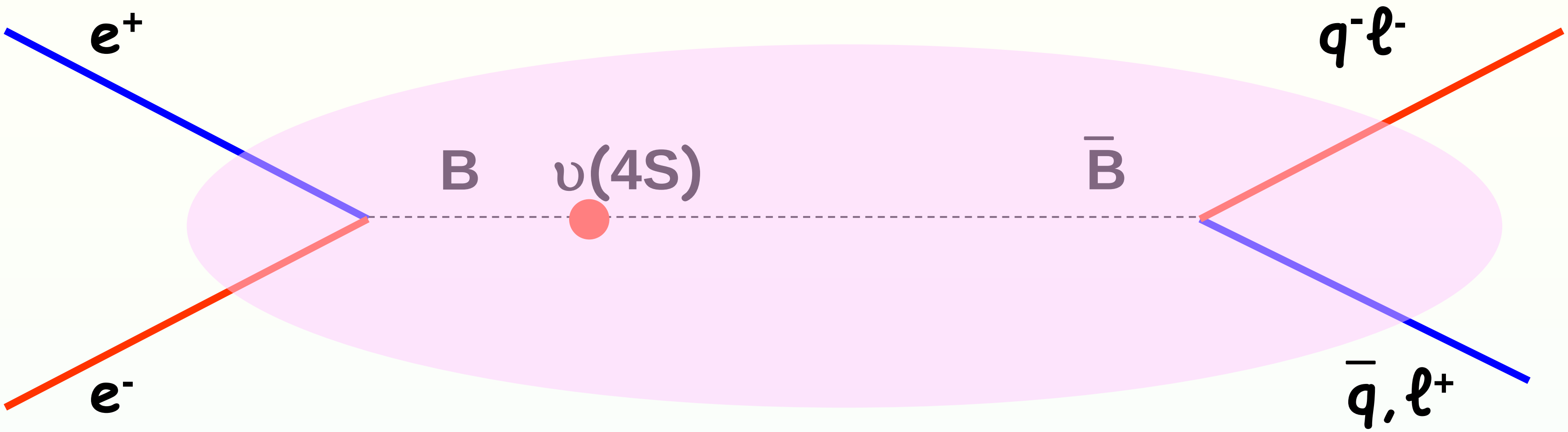

LNF-INFN
Frascati
INFN
Istituto Nazionale
di Fisica Nucleare
Laboratori Nazionali di Frascati

Why a ϕ factory?



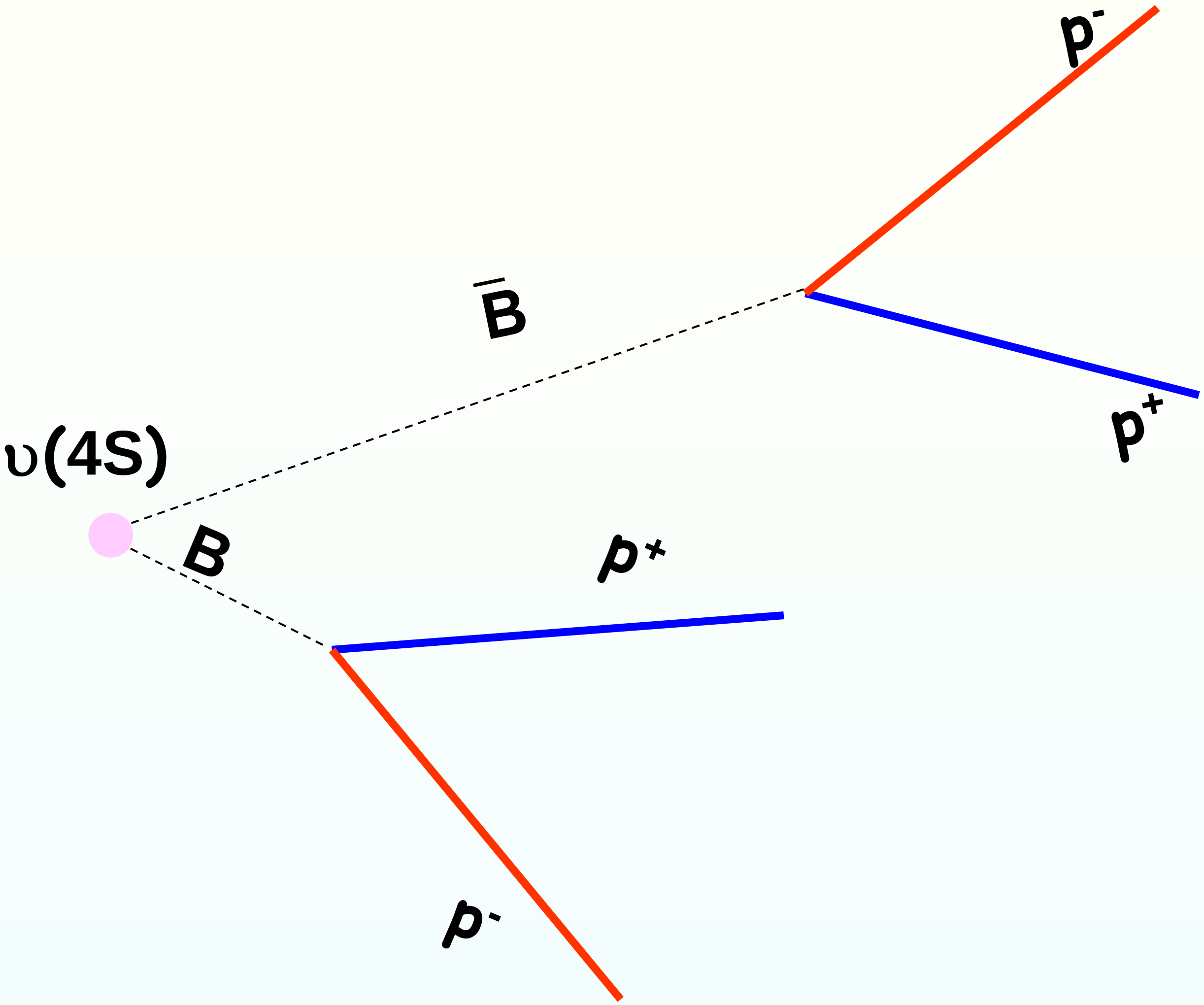
- **Observing the K_S decay (left) produces a pure K_L beam (right)**
  - **Study (rare) K_L physics**
- **Observing the K_L decay (right) produces a pure K_S beam (right)**
  - **Study (rare) K_S physics**
- **Observing the K_S decay (left) and a K_L decay (right)**
  - **Study (EPR) quantum interference**

Why a B factory?



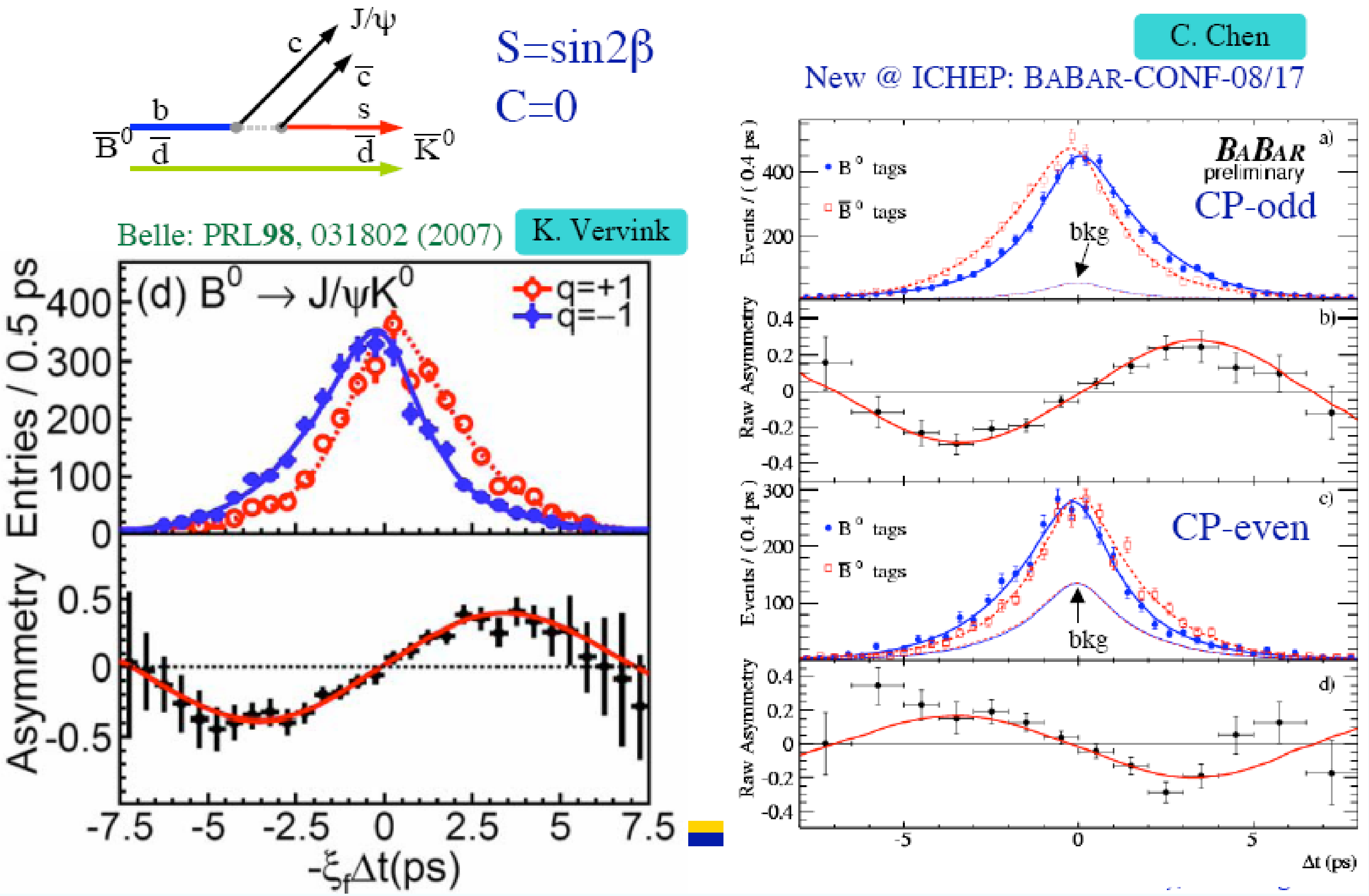
- **Exactly as in the Kaon system**
  - **… but $c\tau$(K) = 2.68cm (S) and 15.34m (L)**
  - **and $c\tau$(b) = 0.44μm (t~1.64ps)**
    - **impossible to measure the flight path and separate the two sides …**
  - **Beam spot size >> decay length**
    - **Can measure $\bar{\tau}+\tau$ but not $\bar{\tau}-\tau$, which contains the CP-violation information**

Why an *asymmetric* B factory?

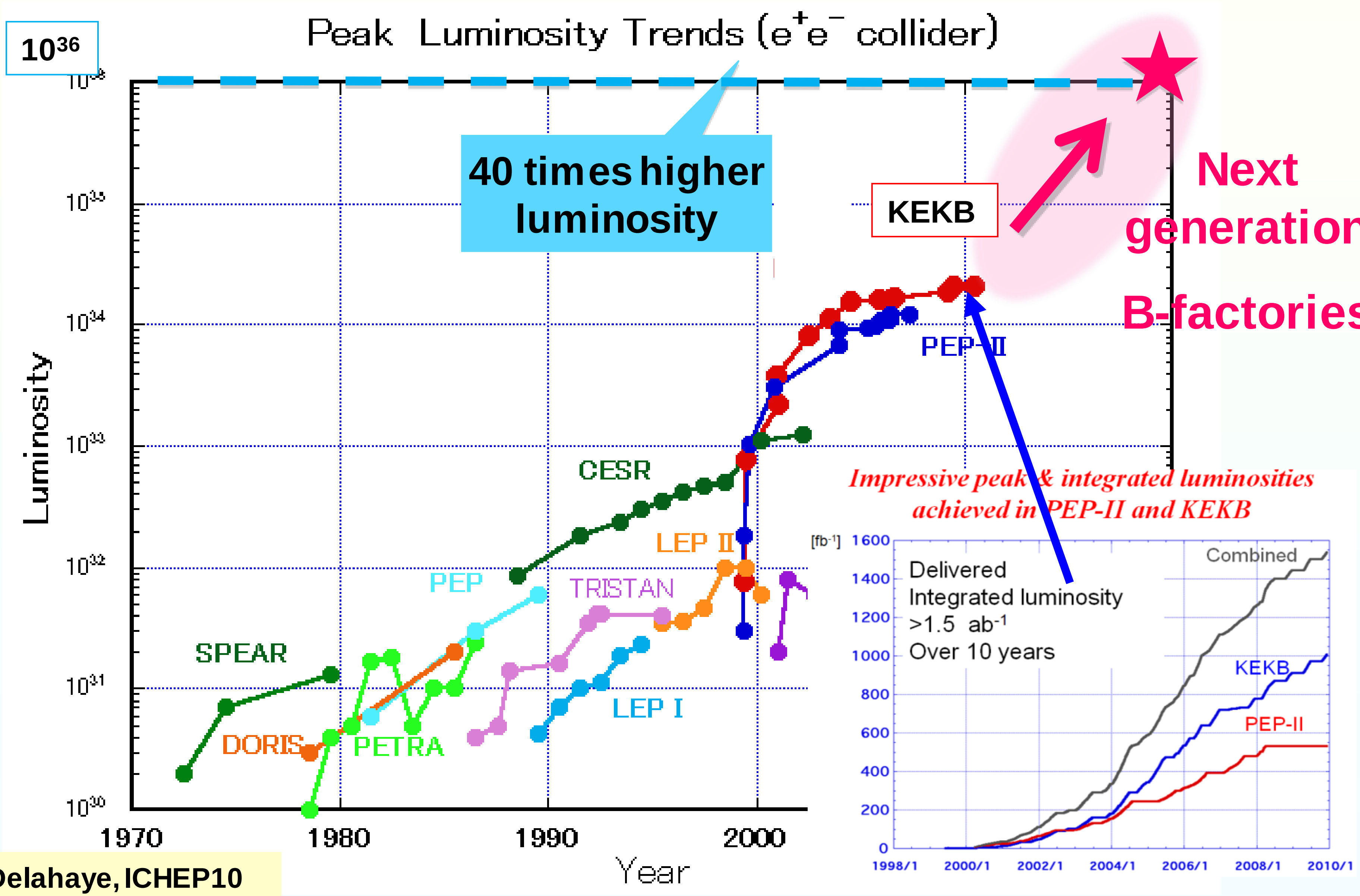


- **Say e⁺=3 GeV, e⁻=9 GeV; ➔ √s=10.4 GeV**

"Golden Channel" - $\bar{B}^0 B^0 \rightarrow K_S J/\Psi$

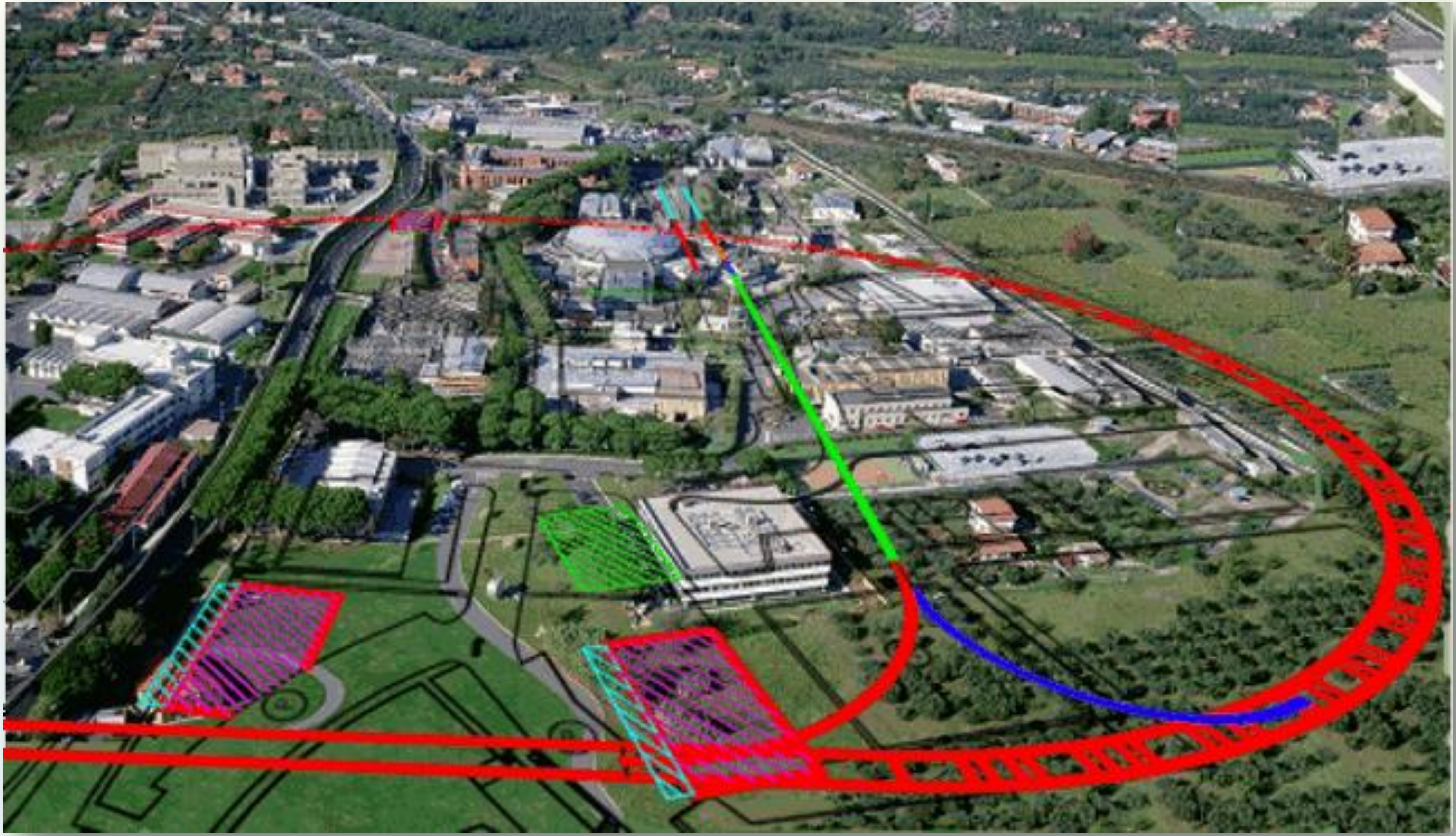


B Factories (PEPII&KEKB) to SuperB and SuperKEKB @ high luminosity frontier

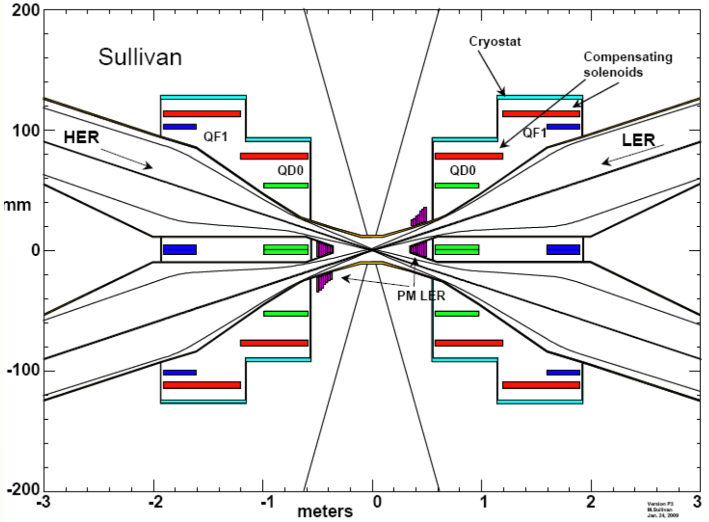


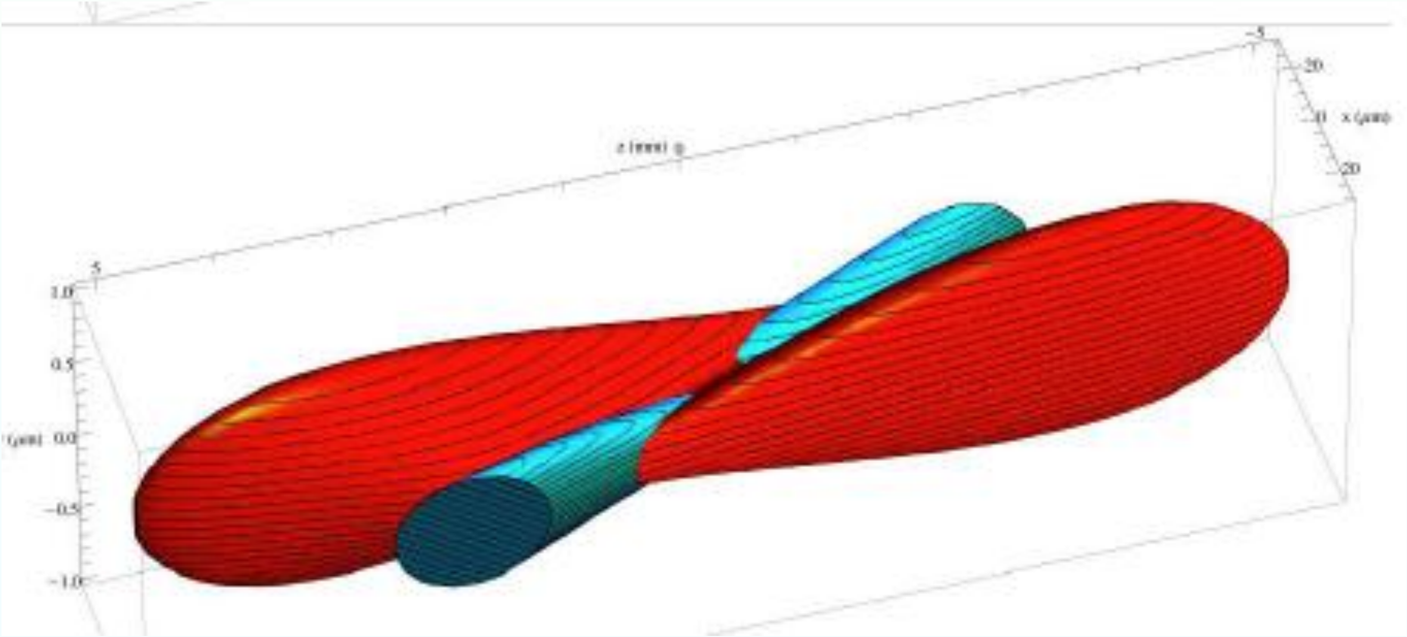
Delahaye, ICHEP10

The SuperB Factory



The SuperB factory





Major parameters B Factories

		SuperB (Baseline)		SuperKEKB	
Parameter	units	HER (e+)	LER (e-)	HER (e-)	LER (e+)
Circumference	m	1258.4		3016.3	
Energy	GeV	6.7	4.18	7	4
X angle (full)	mrad	66		83	
β_x at IP	cm	2.6	3.2	2.4	3.2
β_y at IP	cm	0.0252	0.0206	0.041	0.027
ε_x	nm	2.0	2.41	2.4	3.1
Emittance ratio	%	0.25	0.25	0.35	0.40
σ_z (full)	mm	5	5	5	6
I	mA	1892	2410	2620	3600
σ_x at IP	µm	7.211	8.782	7.75	10.2
σ_y at IP	µm	0.035	0.035	0.059	0.059
ξ_x		0.0021	0.0033	0.0028	0.0028
ξ_y		0.0978	0.0978	0.0875	0.09
Luminosity	$cm^{-2}\ s^{-1}$	1×10^{36}		0.8×10^{36}	

Next Generation B-factories IPAC10

Delahaye, ICHEP10

4

Precision Summary

- **Precision Frontier machine require**
  - **Very high luminosity**
    - **Peak and integrated**
  - **Highly tuned beams**
    - **Energy, spot size, [purity]**
  - **High reliability**
    - **Down time costs integrated luminosity**
  - **Limited flexibility**
    - **Modest changes in energy**
  - **Low machine backgrounds**
    - **Otherise background limits luminosity**

NEUTRINO BEAMS & FACTORIES

(see also seminar by Ken Long)

Neutrino Physics

- **1950's and early 60's**
  - Nature (and existence) of the neutrino
    - (Reines & Cowan, Lederman, Schwartz and Steinberger)
- **Late 1960s, 1970s, 1980s**
  - Structure of the nucleon
    - F_2, xF_3 etc
  - Structure of the weak current
    - Neutral currents, $sin_2\theta_w$ etc
- **Now, and future**
  - Nature of the neutrino
    - Neutrino Mass and Neutrino Oscillations
    - Standard Model assumption of massless neutrinos is *wrong!*
      - Note: difficult to add neutrino mass to SM *a la Higgs*
      - Lack of Charge → additional mass-like (Majorana) terms

New facilities allow old physics to be done much better

What to Measure?

Neutrinos

ν_e disappearance

$\nu_e \rightarrow \nu_\mu$ appearance

$\nu_e \rightarrow \nu_\tau$ appearance

ν_μ disappearance

$\nu_\mu \rightarrow \nu_e$ appearance

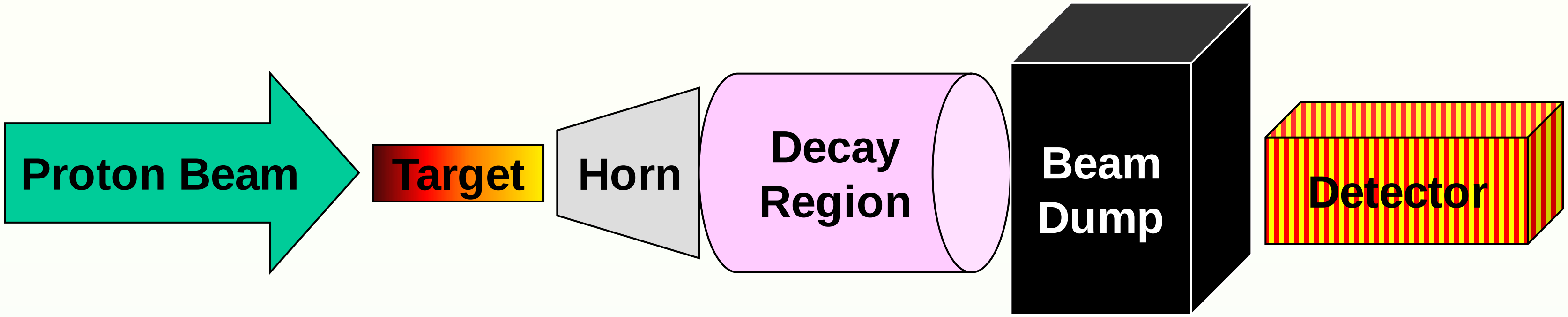
$\nu_\mu \rightarrow \nu_\tau$ appearance

… and the corresponding antineutrino interactions

Note: the beam requirements for these experiments are:

high intensity	**known flux**
known spectrum	**known composition**
	(preferably no background)

Conventional Neutrino Beams



- **Main components**
  - **Proton Beam**
    - **Energy, Intensity, frequency**
  - **Target**
  - **Horn (focussing)**
  - **Decay Region**
  - **Beam Dump**
  - **Detector**

Note

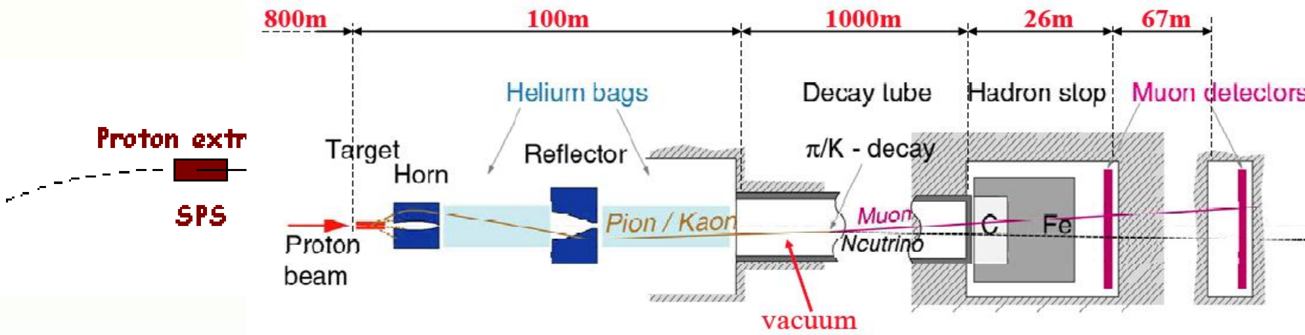
For any (class of) experiment

$$N_{ev} \propto P \times M \; (\times E_\nu)$$

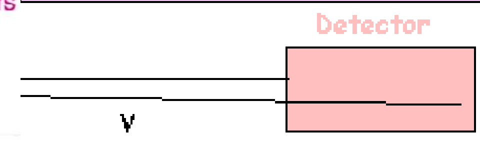
Beam Power	**Target Mass**	**Neutrino Energy**

Example of a Neutrino Beam

CERN Neutrinos to Gran Sasso at CERN SPS



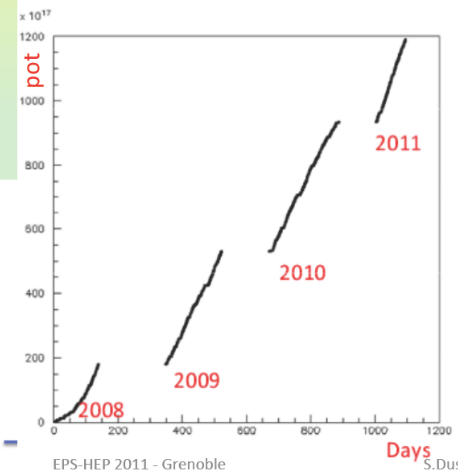
Why Change?



CNGS beam performance

Year	Beam days	Protons on target	SPS Eff.	Events in the bricks
2008	123	1.78×10^{19}	61%	1698
2009	155	3.52×10^{19}	70%	3693
2010	187	4.04×10^{19}	81%	4248
2011	Ongoing	2.86×10^{19}	79%	2858

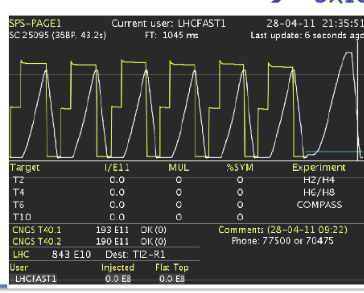
As 4/07/2011



In 2011 in dedicated mode (no other fixed target exp.) from March 18th to June 7th

Expected to run for 223 days

→ ≈5×10^{19} pot



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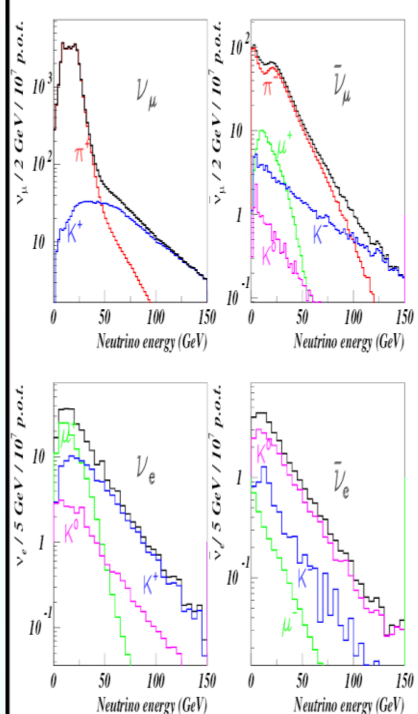

	Flux $(\nu/\mathrm{cm}^2/10^{19}\mathrm{pot})$	$<E_\nu>$ $[GeV]$	ν_i/ν_μ (%)	ν_i/ν_μ-CC (%)
ν_μ	$7.4\cdot10^6$	17.9		
$\bar{\nu}_\mu$	$2.9\cdot10^5$	21.8	3.9	2.40
ν_e	$4.7\cdot10^4$	24.5	0.65	0.89
$\bar{\nu}_e$	$6.0\cdot10^3$	24.4	0.08	0.06

expected event rate: 2800 ν CC/kt/y-low ν_i/ν_μ

last ν-parent

- ν_μ: from π^+ (97 %), K^+ (3 %)
- $\bar{\nu}_\mu$: from π^- (85 %), μ^+ (8 %), K^- (6 %)+ ...
- ν_e: from μ^+ (47 %), K^+ (39 %), K^0 (10 %) + ...
- $\bar{\nu}_e$: from K^0 (70 %), K^- (22 %) μ^- (8 %)

Another neutrino mystery

theguardian

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Faster than light particles found, claim scientists

Particle physicists detect neutrinos travelling faster than light, a feat forbidden by Einstein's theory of special relativity

Ian Sample, science correspondent
guardian.co.uk, Thursday 22 September 2011 23.32 BST
Article history

The New York Times — Science

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Tiny Neutrinos May Have Broken Cosmic Speed Limit

By DENNIS OVERBYE
Published: September 22, 2011

RECOMMEND

Roll over, Einstein?

Frankfurter Allgemeine FAZ.NET

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Neutrinos schneller als Licht?

Einstein muss zittern

Eine Konstante für die Ewigkeit: die Lichtgeschwindigkeit. Einsteins Relativitätstheorie baut darauf, unser ganzes Weltbild sogar. Physiker haben jetzt neu gemessen und festgestellt: Es geht auch schneller - mit Neutrinos. Eine unerklärliche Anomalie?

Von Manfred Lindinger

23. September 2011 Die Nachricht kam in der Nacht von Donnerstag auf Freitag in die Welt und schlug ein wie eine Bombe. Eine europäische Forschergruppe habe im italienischen Untergrundlabor Gran Sasso in der Nähe von Rom gemessen, dass Neutrinos eine Strecke von 730 Kilometern schneller zurückgelegt hätten als Licht.

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Gaffe della Gelmini più veloce del neutrino

24/09/2011, 22:02

Tam tam satirico sul web per la nota, subito rettificata, in cui "spunta" un tunnel tra Cern e Gran Sasso. Viale Trastevere: polemica strumentale.

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Challenging Einstein usually a losing venture

By Seth Borenstein, Associated Press

Comment 240 | Tweet 323

GENEVA – Betting against Einstein and his theory of relativity is a way to go broke.

For more than a century, everyone from physicists to the Nazi Party— which encouraged the publication of the tract "One Hundred Authors Against Einstein" — has tried to find cracks in his work. And all have failed.

On Thursday, the world's biggest physics lab unveiled a shocking finding: that one type of subatomic particle was clocked going faster than the speed of light. If true — a big if, even the scientists there concede — it could

Νετρίνα φημολογείται ότι μπορεί να έσπασαν το κοσμικό όριο της ταχύτητας στο CERN

Posted on 23 Σεπτεμβρίου, 2011 4:42 μμ by Σκληρο-Πυρηνικός Φυσικός — 56

Ο κόσμος των φυσικών αναστατώθηκε από μια ανακοίνωση ότι εντόπισαν νετρίνα, που φαίνεται να σπάνε το κοσμικό όριο της ταχύτητας στον κόσμο, ταξιδεύοντας ταχύτερα και από το φως.
Αν αυτό επιβεβαιωθεί – γιατί προς το παρόν υπάρχουν επιφυλάξεις- τότε απειλείται όχι μόνο η θεωρία του Άλμπερτ Αϊνστάιν, αλλά και όλο ο τρόπος της σύγχρονης Φυσικής. Ακόμα και ο τρόπος που βλέπουμε τον κόσμο, ενώ μπορεί να ανοίξει ο δρόμος για ταξίδια στον χρόνο, ακόμα και στο παρελθόν.
Η θεωρία της ειδικής σχετικότητας από το 1905 – ένας από τους ακρογωνιαίους λίθους της Φυσικής – απαγορεύει οπίδήποτε να κινηθεί πιο γρήγορα από την ταχύτητα των 299.792.458 μέτρων ανά δευτερόλεπτο του φωτός. Μέχρι τώρα καμία έρευνα δεν είχε βρει το παραμικρό σώμα είτε μεγάλο είτε μικροσκοπικό να κινείται πιο γρήγορα από το φως.

CERN to Gran Sasso Neutrino Beam

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Des particules mesurées à une vitesse dépassant celle de la lumière

Le Monde | 22.09.11 | 21h35 • Mis à jour le 24.09.11 | 14h57

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Light-speed results baffle Cern

Written by Online Journalist
Friday, 23 September 2011 09:03

The neutrinos are fired deep under the Italian Apennines

Puzzling results from Cern, home of the LHC, have confounded physicists - because it appears subatomic particles have exceeded the speed of light.

Neutrinos sent through the ground from Cern toward the Gran Sasso laboratory 732km away seemed to show up a tiny fraction of a second early.

The result - which threatens to upend a century of physics - will be put online for scrutiny by other scientists.

In the meantime, the group says it is being very cautious about its claims.

What was the fuss about?

Measurement of the neutrino velocity with the OPERA detector in the CNGS beam

T. Adam[a], N. Agafonova[b], A. Aleksandrov[c,1], O. Altinok[d], P. Alvarez Sanchez[e], S. Aoki[f], A. Ariga[g], T. Ariga[g], D. Autiero[h], A. Badertscher[i], A. Ben Dhahbi[g], A. Bertolin[j], C. Bozza[k], T. Brugière[h], F. Brunet[l], G. Brunetti[h,m,3], S. Buontempo[c], F. Cavanna[n], A. Cazes[h], L. Chaussard[h], M. Chernyavskiy[o], V. Chiarella[p], A. Chukanov[q], G. Colosimo[r], M. Crespi[r], N. D'Ambrosio[s], Y. Déclais[h], P. del Amo Sanchez[l], G. De Lellis[t,c], M. De Serio[u], F. Di Capua[c], F. Cavanna[n], A. Di Crescenzo[t,c], D. Di Ferdinando[v], N. Di Marco[s], S. Dmitrievsky[q], M. Dracos[a], D. Duchesneau[l], S. Dusini[j], J. Ebert[w], I. Eftimiopolous[e], O. Egorov[x], A. Ereditato[g], L.S. Esposito[i], J. Favier[l], T. Ferber[w], R.A. Fini[u], T. Fukuda[y], A. Garfagnini[z,j], G. Giacomelli[m,v], C. Girerd[h], M. Giorgini[m,v,3], M. Giovannozzi[e], J. Goldberg[aa], C. Göllnitz[w], L. Goncharova[o], Y. Gornushkin[q], G. Grella[k], F. Grianti[ab,p], E. Gschewentner[e], C. Guerin[h], A.M. Guler[d], C. Gustavino[ac], K. Hamada[ad], T. Hara[f], M. Hierholzer[w], A. Hollnagel[w], M. Ieva[u], H. Ishida[y], K. Ishiguro[ad], K. Jakovcic[ae], C. Jollet[a], M. Jones[e], F. Juget[g], M. Kamiscioglu[d], J. Kawada[g], S.H. Kim[af,4], M. Kimura[y], N. Kitagawa[ad], B. Klicek[ae], J. Knuesel[g], K. Kodama[ag], M. Komatsu[ad], U. Kose[j], I. Kreslo[g], C. Lazzaro[i], J. Lenkeit[w], A. Ljubicic[ae], A. Longhin[p], A. Malgin[b], G. Mandrioli[v], J. Marteau[h], T. Matsuo[y], N. Mauri[p], A. Mazzoni[r], E. Medinaceli[z,j], F. Meisel[g], A. Meregaglia[a], P. Migliozzi[c], S. Mikado[y], D. Missiaen[e], K. Morishima[ad], U. Moser[g], M.T. Muciaccia[ah,u], N. Naganawa[ad], T. Naka[ad], M. Nakamura[ad], T. Nakano[ad], Y. Nakatsuka[ad], D. Naumov[q], V. Nikitina[ai], S. Ogawa[y], N. Okateva[o], A. Olchevsky[q], O. Palamara[s], A. Paoloni[p], B.D. Park[af,5], I.G. Park[af], A. Pastore[ah,u], L. Patrizii[v], E. Pennacchio[h], H. Pessard[l], C. Pistillo[g], N. Polukhina[o], M. Pozzato[m,v], K. Pretzl[g], F. Pupilli[s], R. Rescigno[k], T. Roganova[ai], H. Rokujo[f], G. Rosa[aj,ac], I. Rostovtseva[x], A. Rubbia[i], A. Russo[c], O. Sato[ad], Y. Sato[ak], A. Schembri[s], J. Schuler[a], L. Scotto Lavina[g,6], J. Serrano[e], A. Sheshukov[q], H. Shibuya[y], G. Shoziyoev[ai], S. Simone[ah,u], M. Sioli[m,v], C. Sirignano[s], G. Sirri[v], J.S. Song[af], M. Spinetti[p], N. Starkov[o], M. Stellacci[k], M. Stipcevic[ae], T. Strauss[g], P. Strolin[t,c], S. Takahashi[f], M. Tenti[m,v,h], F. Terranova[p], I. Tezuka[ak], V. Tioukov[c], P. Tolun[d], T. Tran[h], S. Tufanli[g], P. Vilain[al], M. Vladimirov[o], L. Votano[p], J.-L. Vuilleumier[g], G. Wilquet[al], B. Wonsak[w], J. Wurtz[a], C.S. Yoon[af], J. Yoshida[ad], Y. Zaitsev[x], S. Zemskova[q], A. Zghiche[l]

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5 Now at Asian Medical Center, 388-1 Pungnap-2 Dong, Songpa-Gu, Seoul 138-736, Republic of Korea
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[d] METU-Middle East Technical University, TR-06532 Ankara, Turkey
[e] European Organization for Nuclear Research (CERN), Geneva, Switzerland
[f] Kobe University, J-657-8501 Kobe, Japan

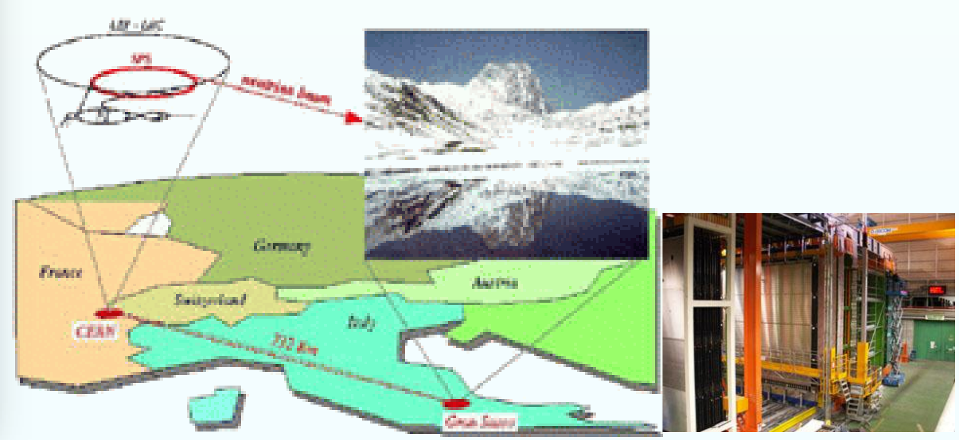
Abstract

The OPERA neutrino experiment at the underground Gran Sasso Laboratory has measured the velocity of neutrinos from the CERN CNGS beam over a baseline of about 730 km with much higher accuracy than previous studies conducted with accelerator neutrinos. The measurement is based on high-statistics data taken by OPERA in the years 2009, 2010 and 2011. Dedicated upgrades of the CNGS timing system and of the OPERA detector, as well as a high precision geodesy campaign for the measurement of the neutrino baseline, allowed reaching comparable systematic and statistical accuracies. An early arrival time of CNGS muon neutrinos with respect to the one computed assuming the speed of light in vacuum of (60.7 ± 6.9 (stat.) ± 7.4 (sys.)) ns was measured. This anomaly corresponds to a relative difference of the muon neutrino velocity with respect to the speed of light (v-c)/c = (2.48 ± 0.28 (stat.) ± 0.30 (sys.)) $\times 10^{-5}$.

This anomaly corresponds to a relative difference of the muon neutrino velocity with respect to the speed of light

$$\frac{(v-c)}{c} = (2.48 \pm 0.28\,(stat) \pm 0.30\,(syst)) \times 10^{-5}.$$

CERN to Gran Sasso Neutrino Beam

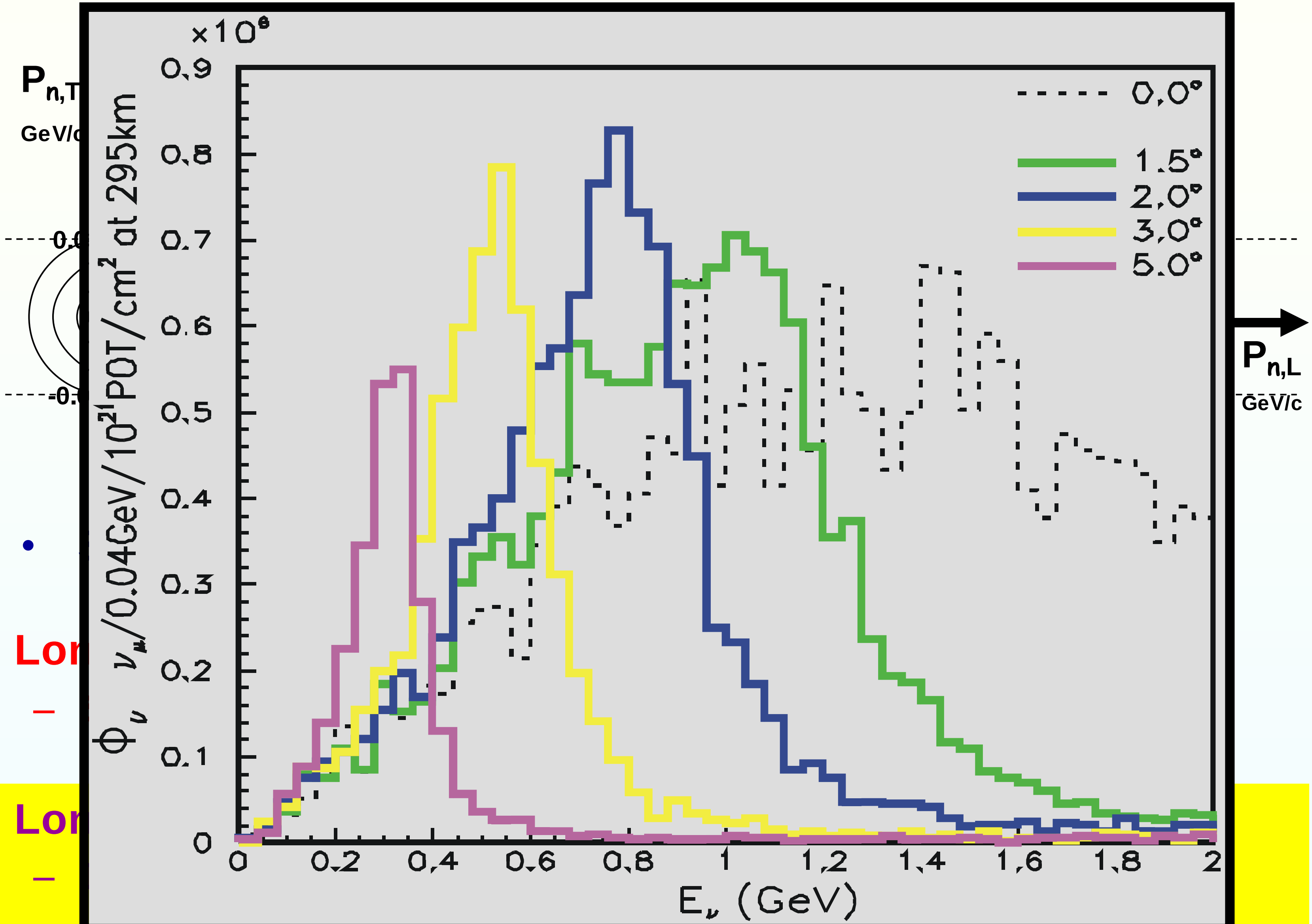


Is it true?

- (sadly) probably not
  - The experiment may not be "wrong"
    but may be less exciting than proving
    "Einstein was wrong"
    and might nevertheless be
    "interesting physics"

- "Good science" means
  - Observing
  - Reporting
  - Speculating
  - Experimenting
  - Repeating
  - Explaining

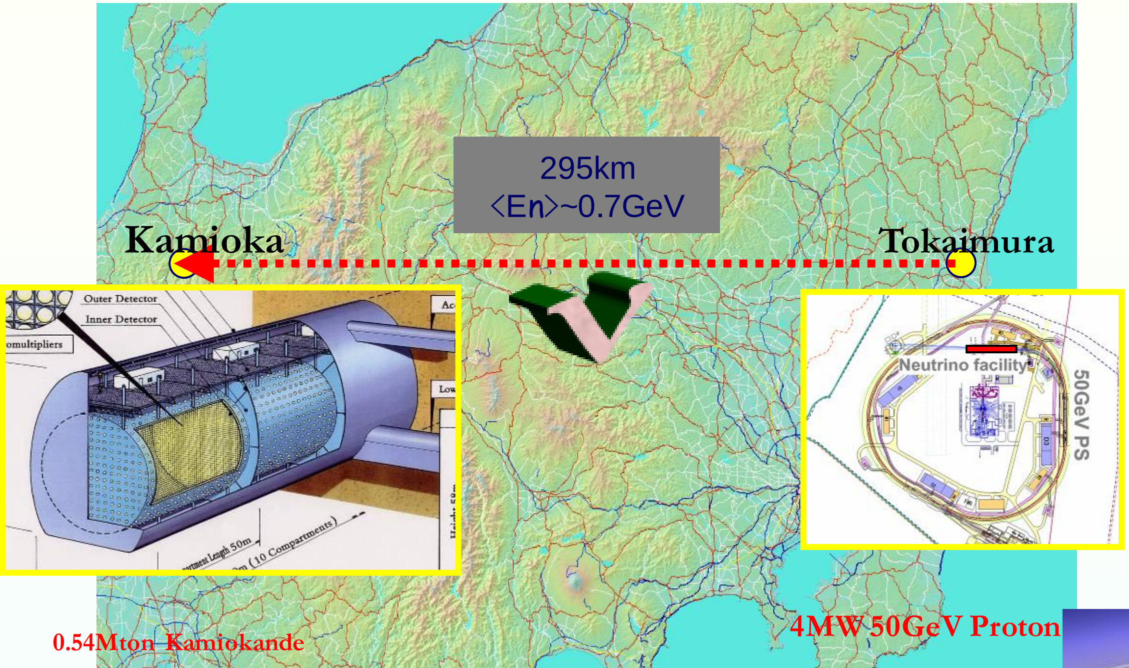
The “Off Axis” trick



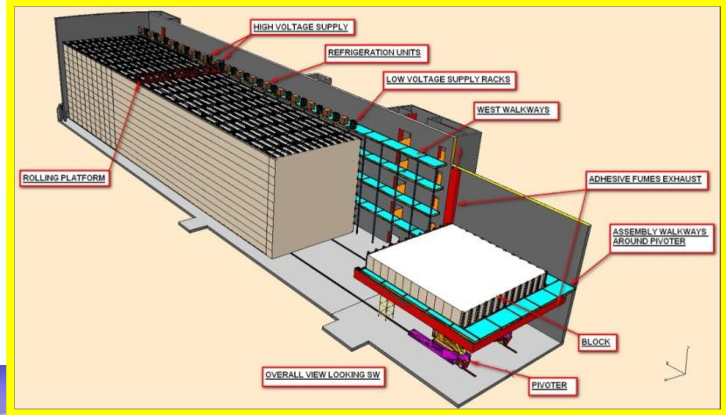
- Lon
  –
- Lon
  –

D. Beavis et al., “Long Baseline Neutrino Oscillation Experiment, E889, Physics Design Report,” BNL-52459, (1995)

T2K & Nova



295km
<En>~0.7GeV
Kamioka
Tokaimura
Outer Detector
Inner Detector
Neutrino facility
50GeV PS
0.54Mton Kamiokande
4MW 50GeV Proton



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REFRIGERATION UNITS
LOW VOLTAGE SUPPLY RACKS
WEST WALKWAYS
ROLLING PLATFORM
ADHESIVE FUMES EXHAUST
ASSEMBLY WALKWAYS AROUND PIVOTER
BLOCK
OVERALL VIEW LOOKING SW
PIVOTER

Ash River
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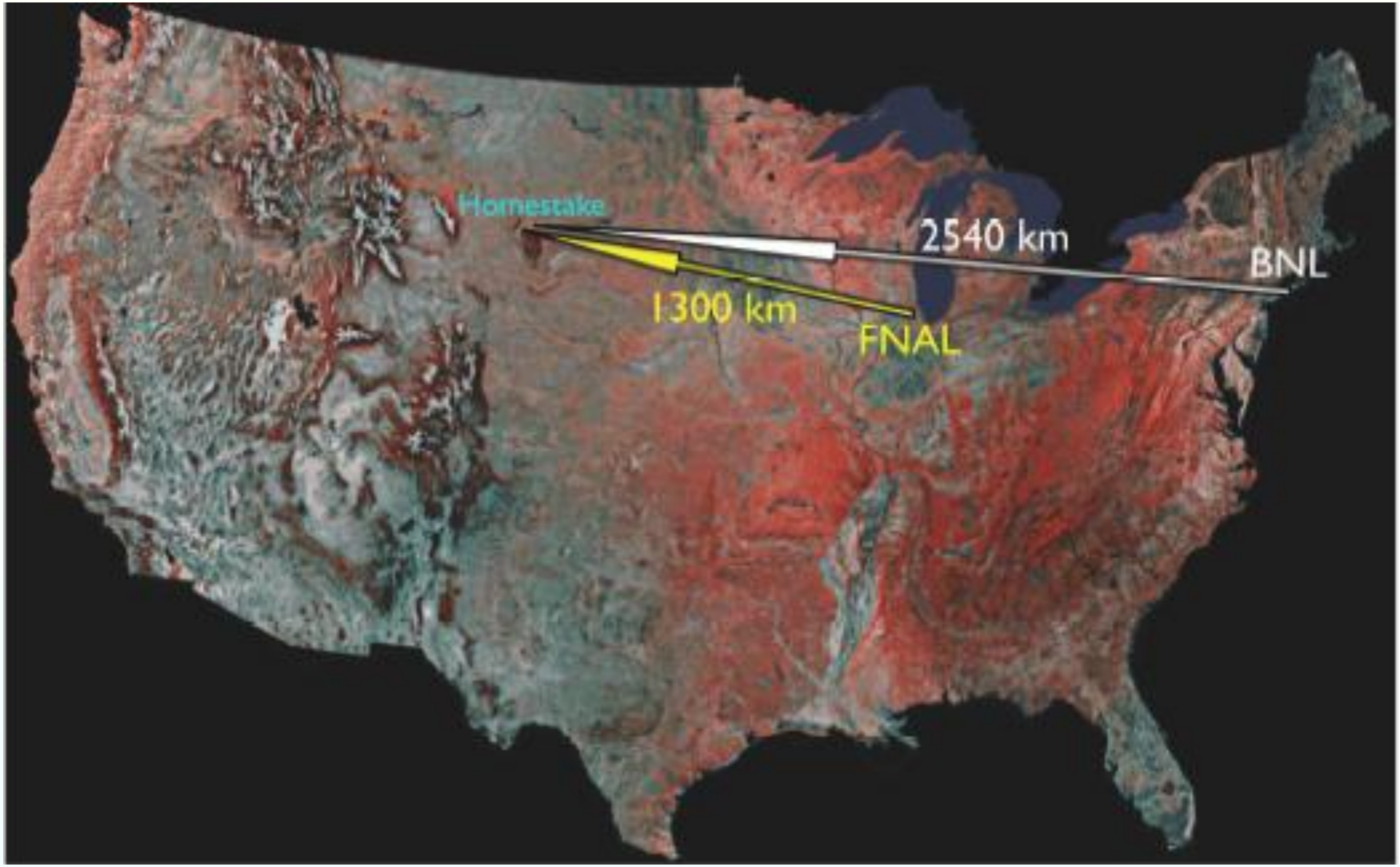
Chicago
Google

Very Long Baseline Neutrino Oscillations



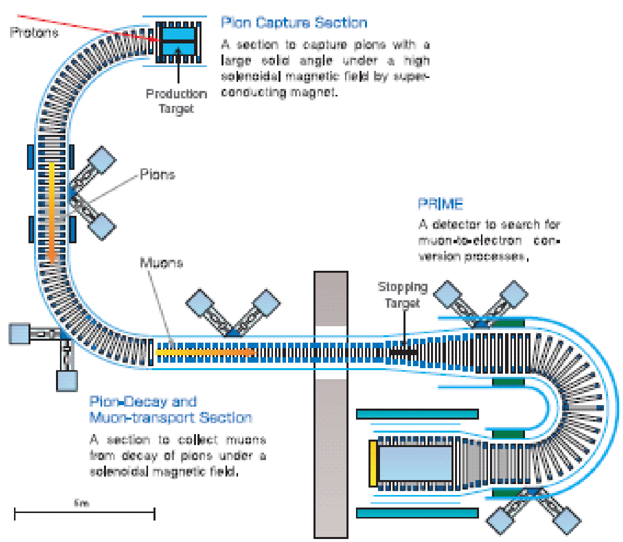
Accelerating muons – $(g\text{-}2)_\mu$

$\mu \rightarrow e$ conversion

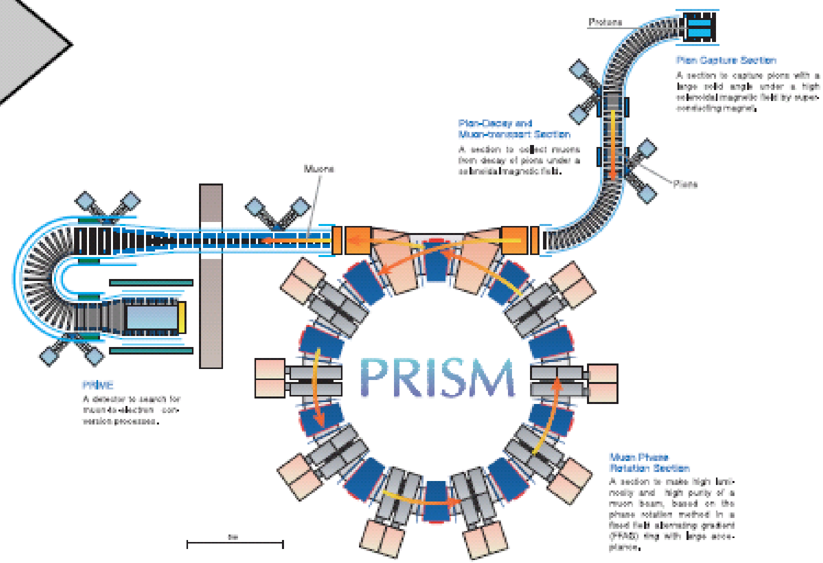
COMET and PRISM in Japan

(Yoshi Kuno)

COMET



PRISM



Br(μ^- + Al → e^- + Al) < 10^{-16}

- without a muon storage ring.
- with a slowly-extracted pulsed proton beam.
- doable at the J-PARC NP Hall.
- regarded as the first phase / MECO type
- Early realization

Br(μ^- + Ti → e^- + Ti) < 10^{-18}

- with a muon storage ring.
- with a fast-extracted pulsed proton beam.
- need a new beamline and experimental hall.
- regarded as the second phase.
- Ultimate search

MUON COLLIDER

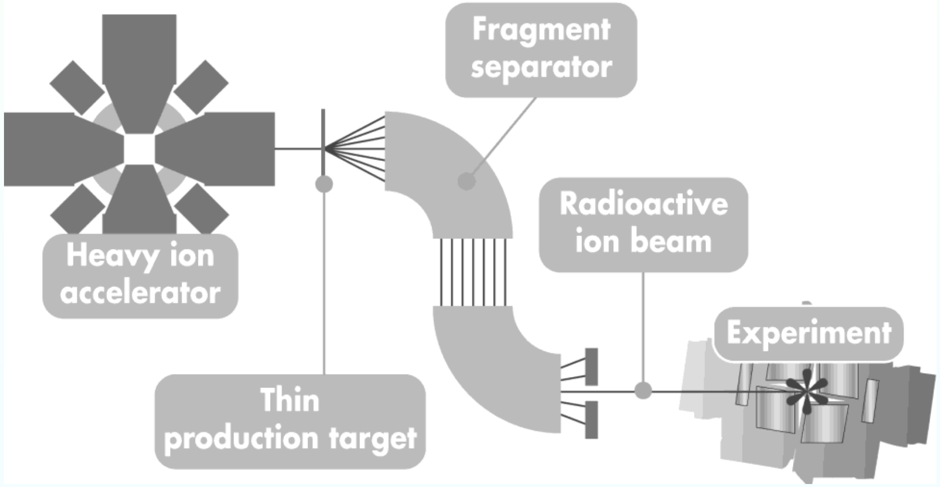
See Ken Long's seminar

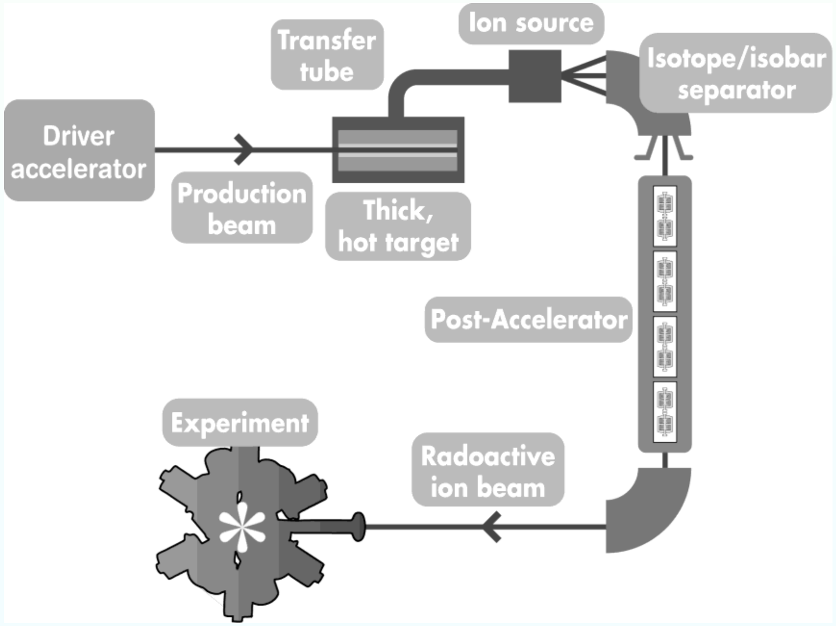
NUCLEAR PHYSICS

Accelerated heavy ions

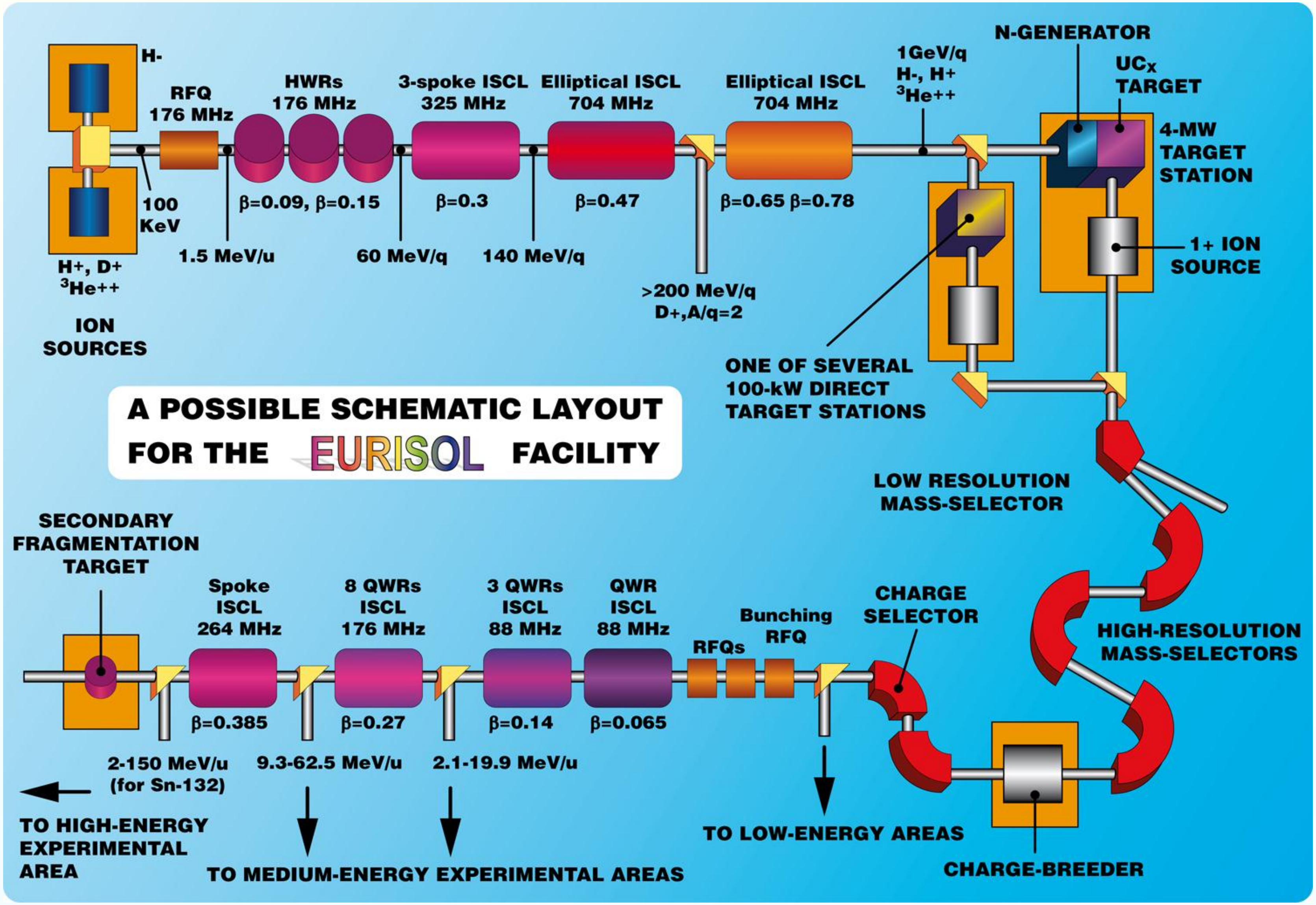
- **Studies of nuclear properties**
  - New superheavy (> uranium) elements
  - Nuclear structure
  - Two techniques

Isotope separation **"in-flight"**

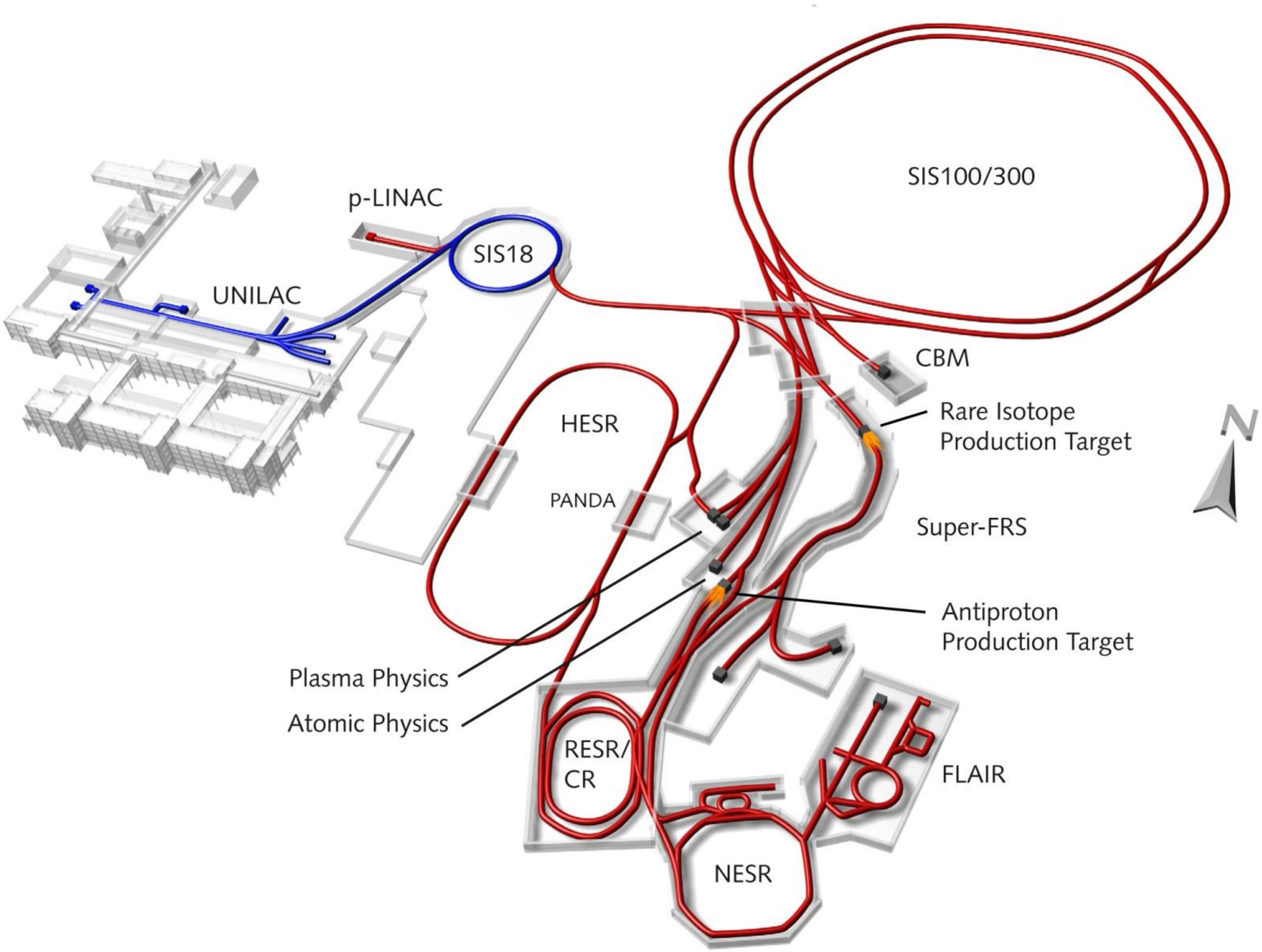




EURISOL

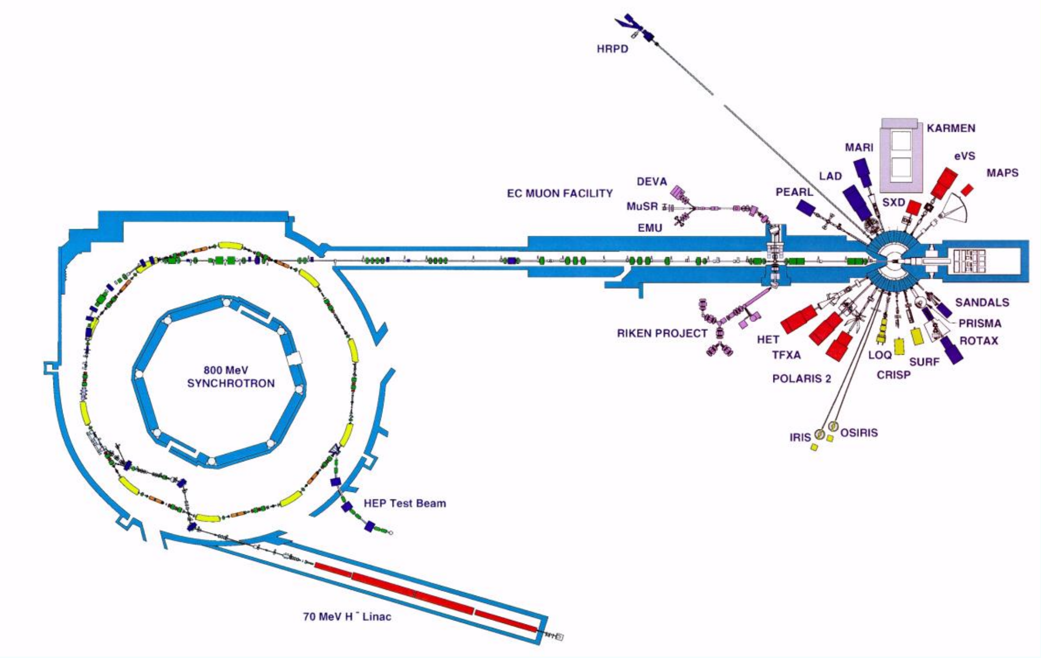

H-
RFQ
176 MHz
HWRs
176 MHz
3-spoke ISCL
325 MHz
Elliptical ISCL
704 MHz
Elliptical ISCL
704 MHz
1GeV/q
H-, H+
^{3}He++
N-GENERATOR
UCx
TARGET
4-MW
TARGET
STATION
100
KeV
β=0.09, β=0.15
β=0.3
β=0.47
β=0.65 β=0.78
1.5 MeV/u
60 MeV/q
140 MeV/q
1+ ION
SOURCE
H+, D+
^{3}He++
>200 MeV/q
D+,A/q=2
ION
SOURCES
ONE OF SEVERAL
100-kW DIRECT
TARGET STATIONS
A POSSIBLE SCHEMATIC LAYOUT
FOR THE EURISOL FACILITY
LOW RESOLUTION
MASS-SELECTOR
SECONDARY
FRAGMENTATION
TARGET
Spoke
ISCL
264 MHz
8 QWRs
ISCL
176 MHz
3 QWRs
ISCL
88 MHz
QWR
ISCL
88 MHz
Bunching
RFQ
RFQs
CHARGE
SELECTOR
HIGH-RESOLUTION
MASS-SELECTORS
β=0.385
β=0.27
β=0.14
β=0.065
2-150 MeV/u
(for Sn-132)
9.3-62.5 MeV/u
2.1-19.9 MeV/u
TO HIGH-ENERGY
EXPERIMENTAL
AREA
TO MEDIUM-ENERGY EXPERIMENTAL AREAS
TO LOW-ENERGY AREAS
CHARGE-BREEDER

FAIR (Darmstadt)



OTHER SCIENCE APPLICATIONS

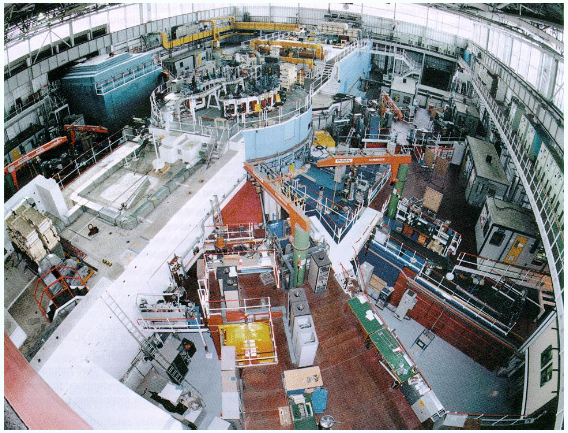
ISIS - Neutron Beams



600 Experiments/year

1200 Users/year

235 UK Groups



Neutron Facilities

Demand for growth in capability and capacity

Declining number available world-wide

The Spallation Sources

The China Spallation Neutron Source

Project Phase	I	II	II’
Beam power on target [kW]	120	240	500
Proton energy on target [GeV]	1.6	1.6	1.6
Average beam current [μA]	76	151	315
Pulse repetition rate [Hz]	25	25	25
Proton per pulse on target [10^{13}]	1.9	3.8	7.8
Pulse length on target [ns]	<400	<400	<400
Linac output energy [MeV]	81	134	230
Ion source/linac length [m]	50	76	86
Linac RF frequency [MHz]	324	324	324
Macropulse ave. current [mA]	15	30	40
Macropulse duty factor [%]	1.1	1.1	1.7
LRBT length [m]	142	116	106
Synchrotron circumference [m]	230.8	230.8	230.8
Ring filling time [ms]	0.42	0.42	0.68
Ring RF frequency [MHz]	1.0-2.4	1.3-2.4	1.6-2.4
Max. uncontr. beam loss [W/m]	1	1	1
Target material	tungsten		
Moderators	H_2O, CH_4, H_2		
Number of spectrometers	5	18	>18

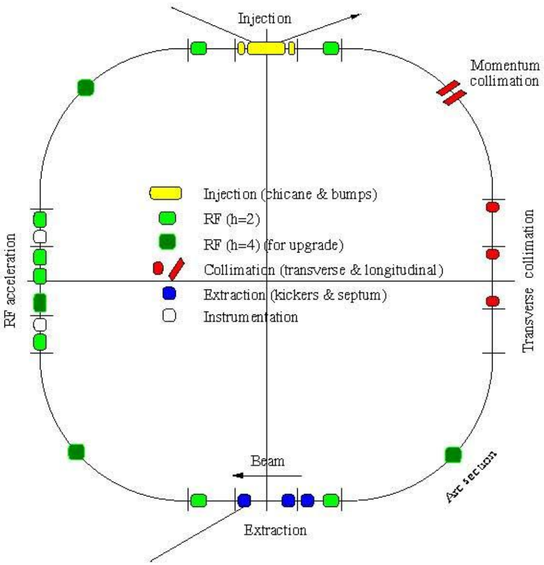
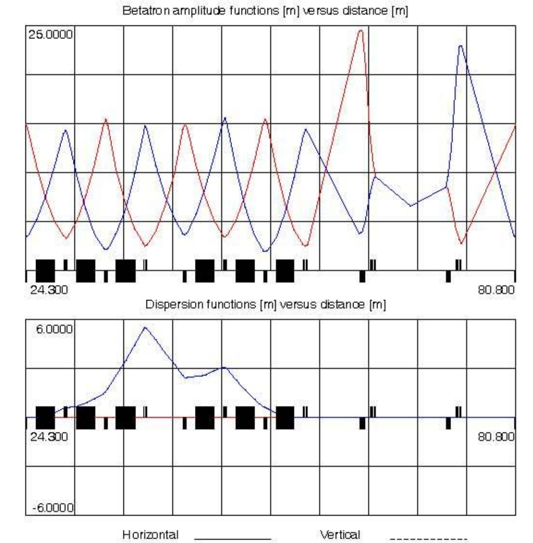
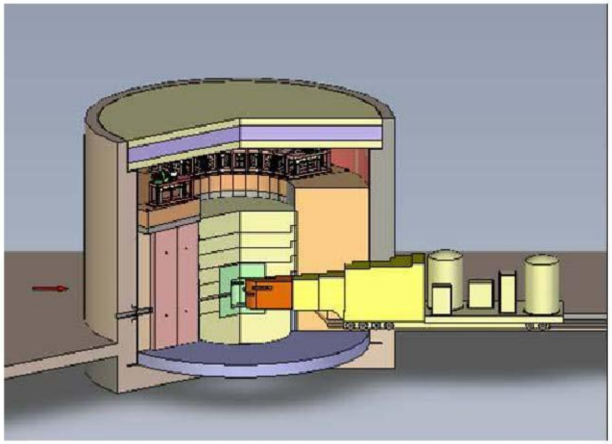
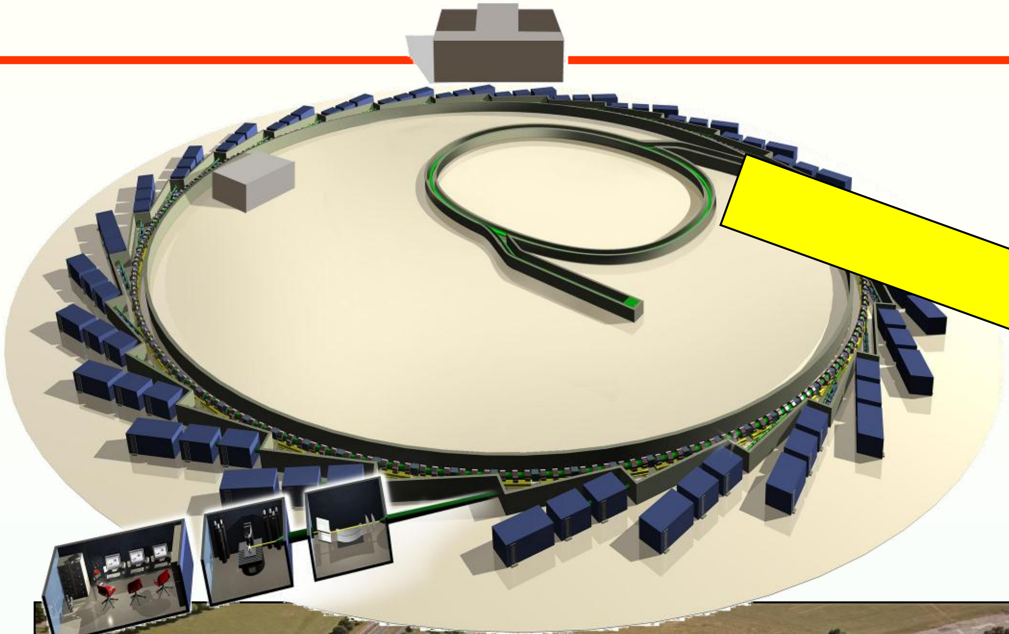


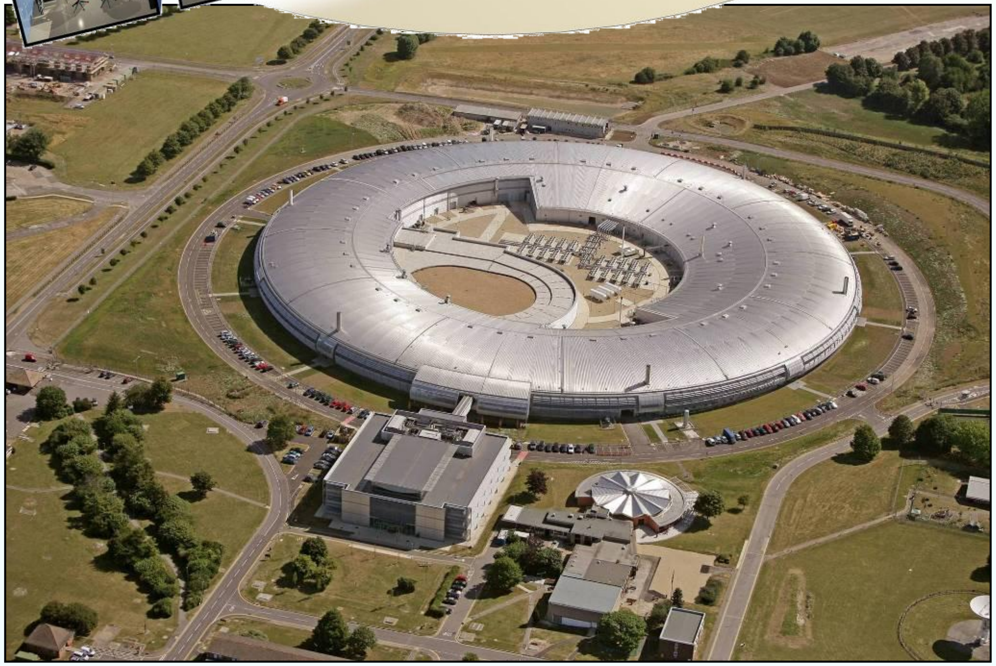
Figure 4: Functional layout of the CSNS RCS ring.



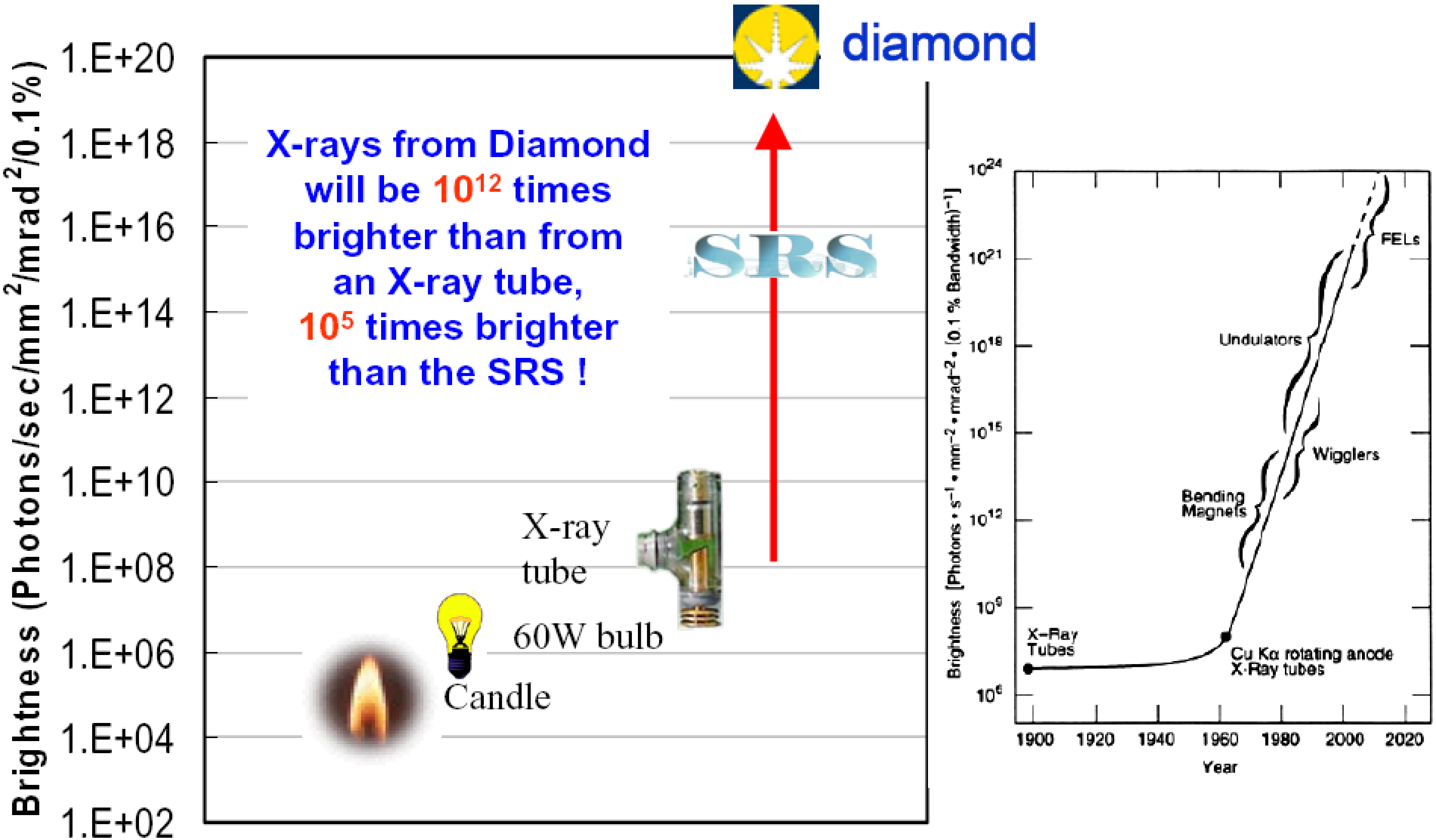


The Diamond Synchrotron





Progress in light sources!



After Bartolini

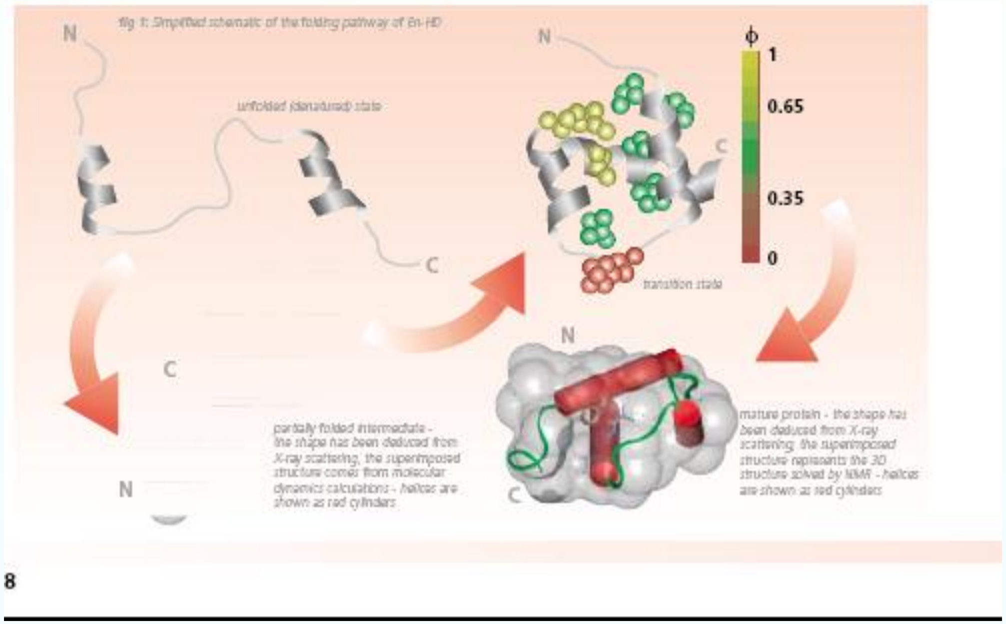
Examples of use of Synchrotron Radiation

Characterisation of the metallurgical properties of a 7th cBC Corinthian-type Greek bronze helmet

'First Aias son of Telamon, bulwark of the Achaians, brake a battalion of the Trojans and brought his comrades salvation, smiting a warrior that was chiefest among the Thracians, Eussoros' son Akamas the goodly and great. Him first he smote upon his thick-crested helmet ridge and drave into his forehead, so that the point of bronze pierced into the bone; and darkness shrouded his eyes'. **Homer, Iliad VI 5-11.** (translation by Andrew Lang, Walter Leaf and Ernest Myers, Macmillan 1912).

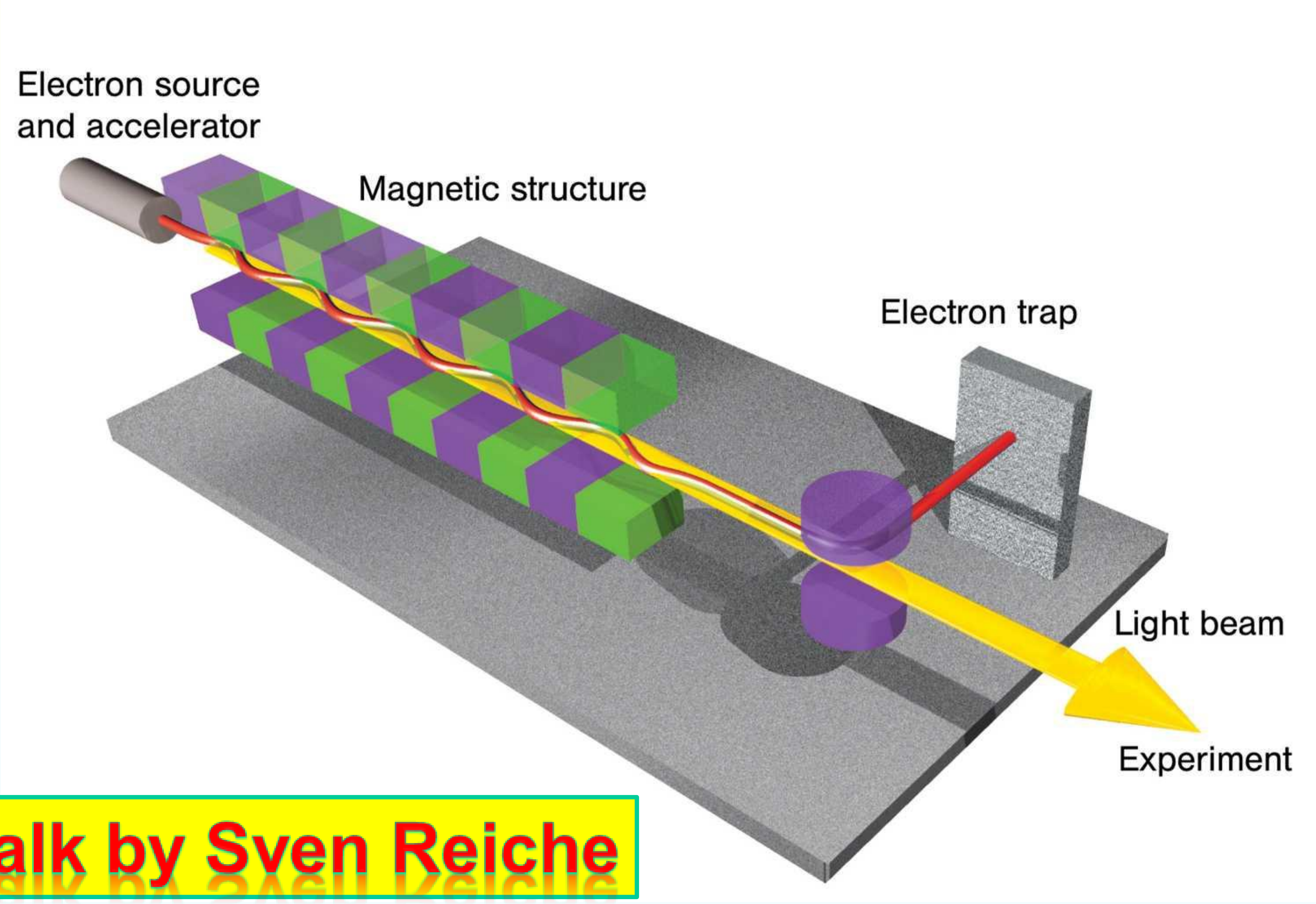
Straightening out protein folding of a small three-helix bundle protein

Recent discoveries show that apparently unrelated diseases such as Alzheimer's, cystic fibrosis or BSE/CJD result from protein folding gone wrong. Understanding how proteins fold and create the three-dimensional shapes crucial to their function is therefore more than a scientific challenge.



CCLRC/SRD annual report

The X-ray Free Electron Laser



See talk by Sven Reiche

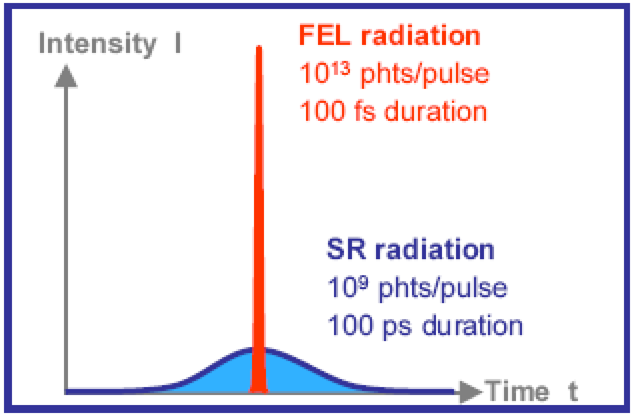
The X-ray Free Electron Laser

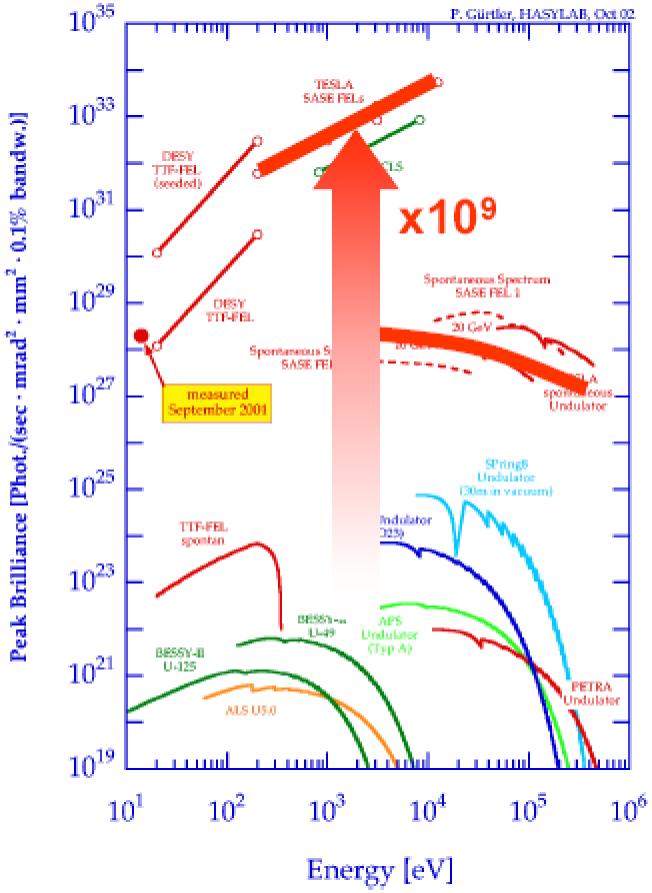
X-ray FEL radiation (0.2 - 14.4 keV)

- ultrashort pulse duration 100 fs
- extreme pulse intensities 10^{12}-10^{14} ph
- coherent radiation $x10^9$
- average brilliance $x10^4$

Spontaneous radiation (20-200 keV)

- ultrashort pulse duration <200 fs
- high brilliance





LASER-PLASMA ACCELERATORS

Plasma accelerators driven by TW lasers

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

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

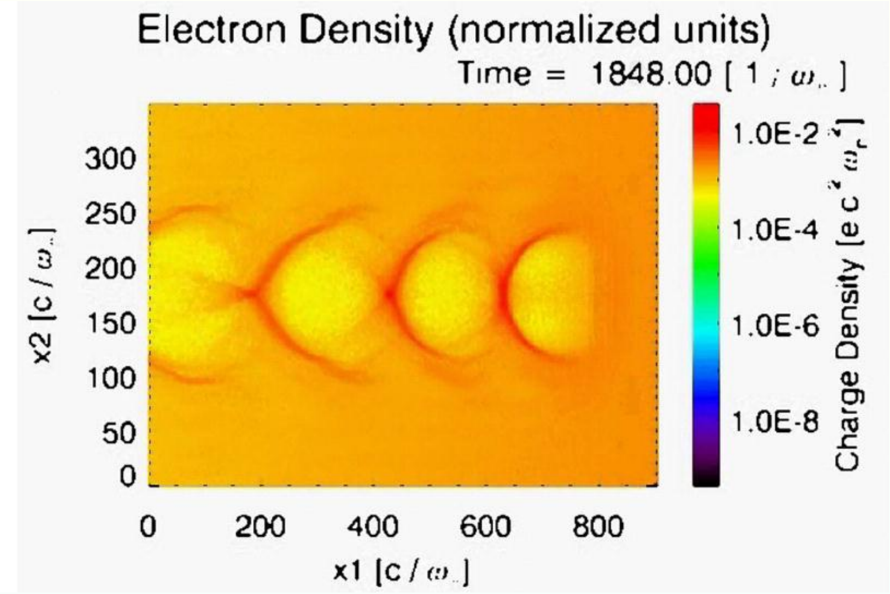
T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024

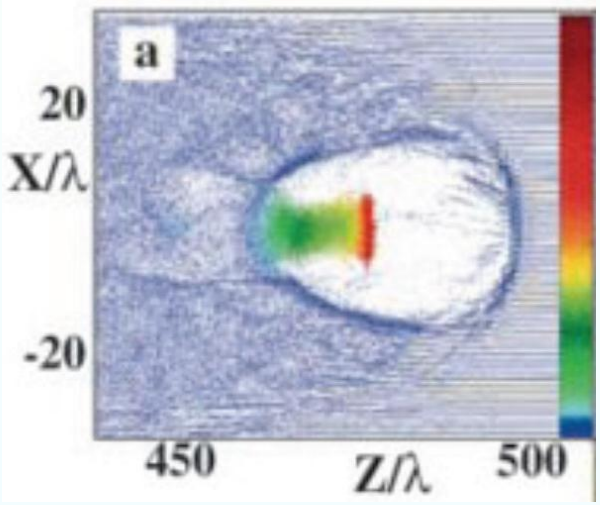
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

Hooker, Oxford

Nonlinear plasma waves





- Plasma frequency decreases with intensity.
- Wavefronts of plasma wave become curved.
- At very high intensities reach the "blow-out" or "bubble" regime.

Pukhov *et al.* Appl. Phys. Lett. **74** 355 (2002)

Hooker, Oxford

Generation of quasi-monoenergetic beams

– Three milestone results

(Nature at end of 2004)

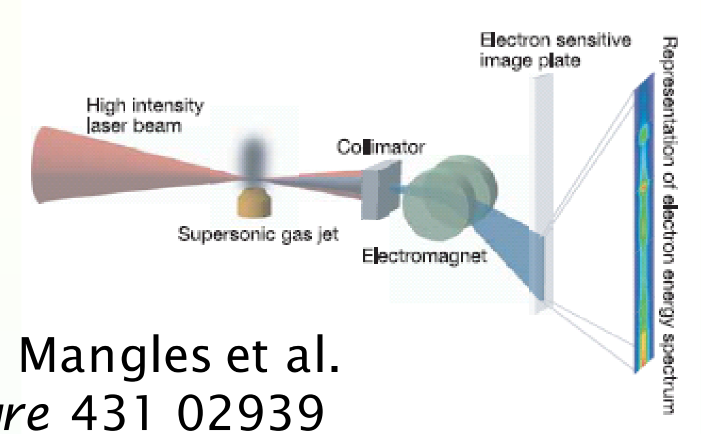
- **Karl Krushelnick (Imperial College, UK)**
- **Victor Malka (LOA, France)**
- **Wim Leemans (Lawrence Berkeley, USA)**

1st evidence

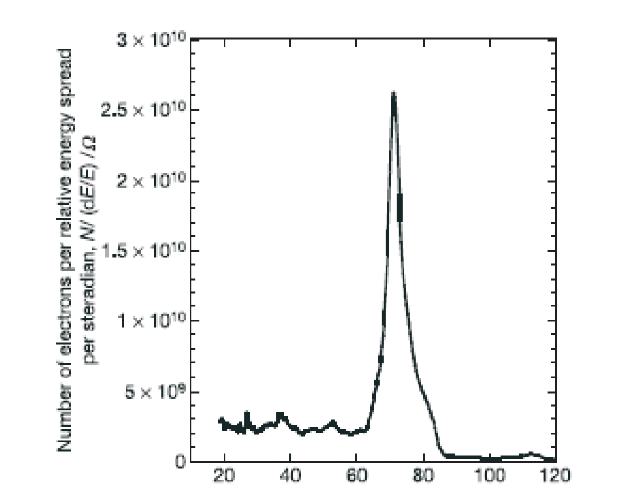
quasi-monoenergetic electron beams

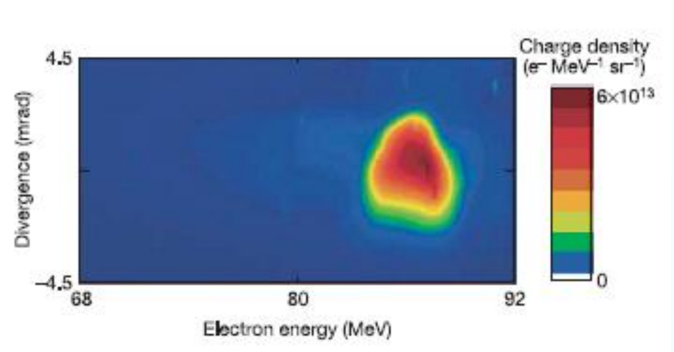
Hooker, Oxford

Generation of quasi-monoenergetic beams

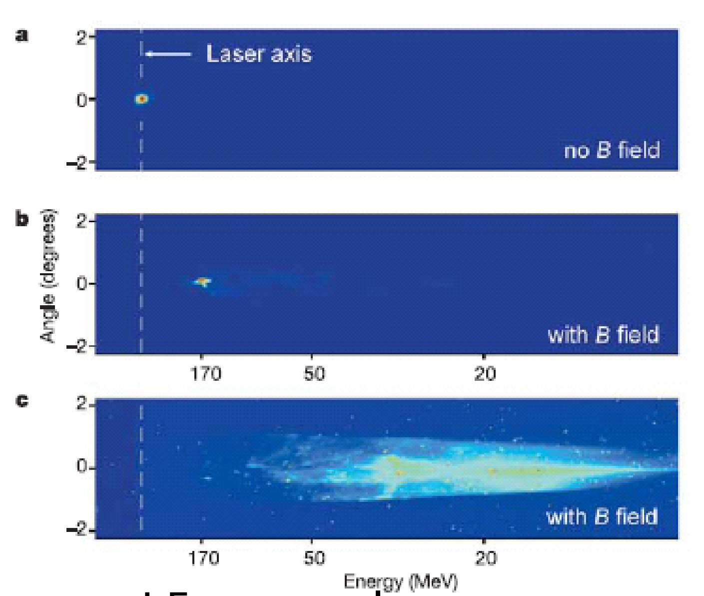


S. D. Mangles et al.
Nature 431 02939 (2004)





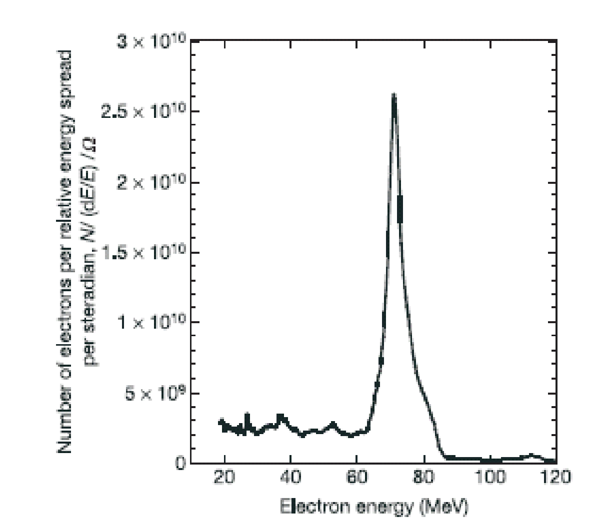
C. G. R. Geddes et al.
Nature 431 02900 (2004)

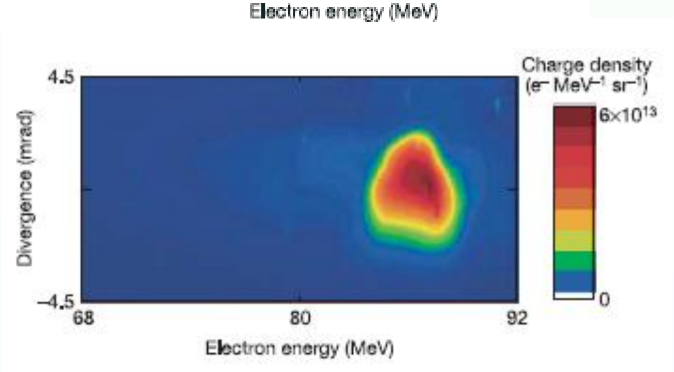


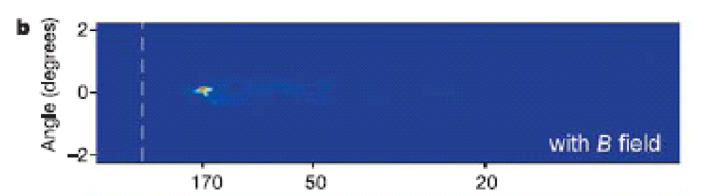
J Faure et al.
Nature 431 02963 (2004)

Hooker, Oxford

Generation of quasi-monoenergetic beams





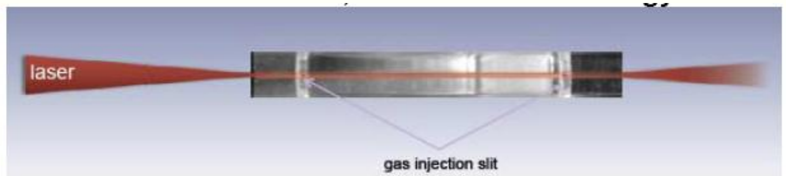


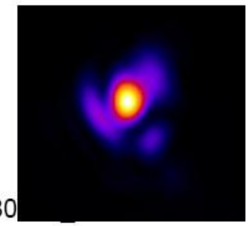
– Typical output parameters:

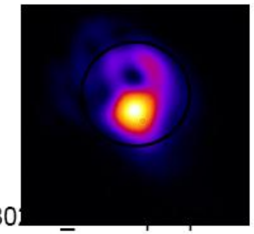
- **Output energy: 100 - 170 MeV**
- **Energy spread: 2.5 - 8%**
- **Bunch charge: 20 - 500 pC**
- **Normalized emittance: 1-2 π mm mrad**

Hooker, Oxford

Laser-Driven FELs

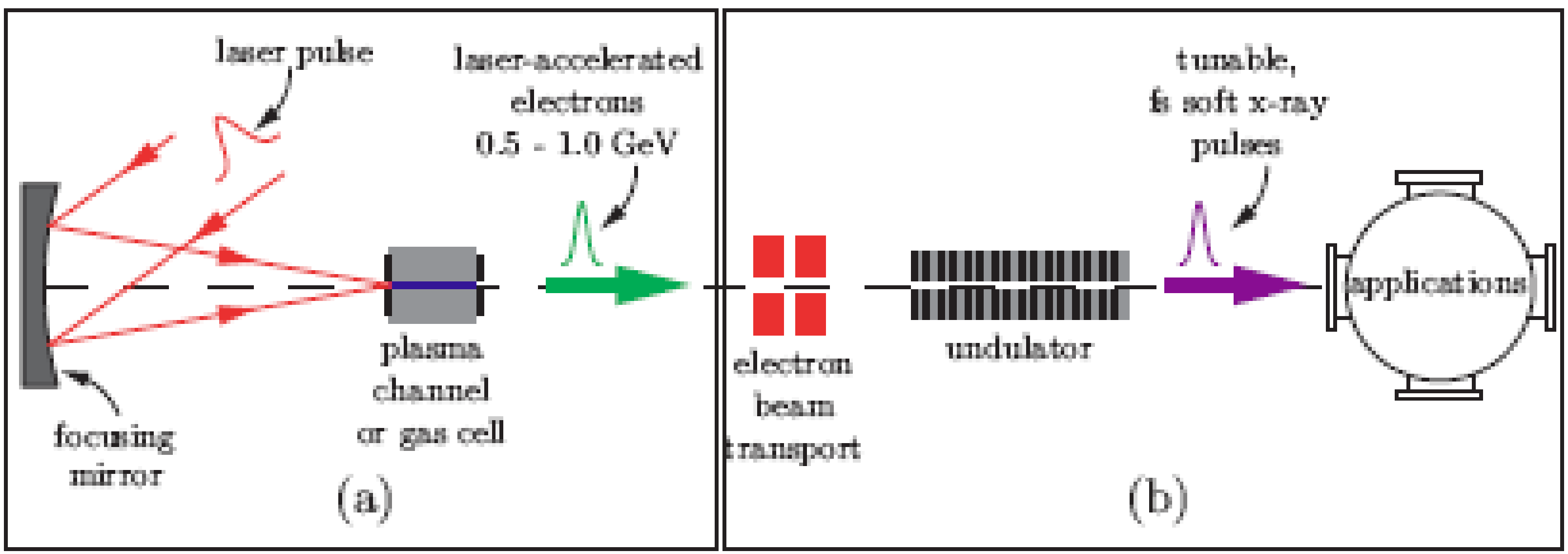




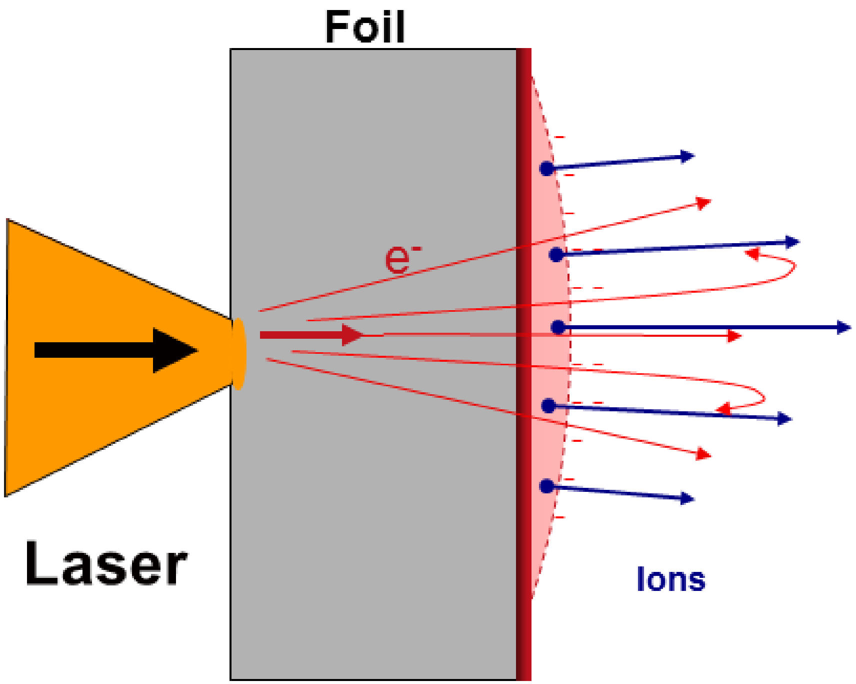


Incident power 24TW,
(37 fs, 0.9J)
Intensity 9 10^{17}W cm^{-2}
vaccuum

Capillary output
L = 81.7mm, 2r = 150μm
Intensity 1.6 10^{18}W cm^{-2}
30 mbar H2



Laser Driven Plasma Ion Acceleration



- Extreme laminarity
- Short duration source: ~ 1 ps *($\Delta E \Delta t$ < 10^{-6} eV-s)*
- High brightness: 10^{11} –10^{13} protons/ions in a single shot (> 5 MeV)
- High current (if stripped of electrons): kA range

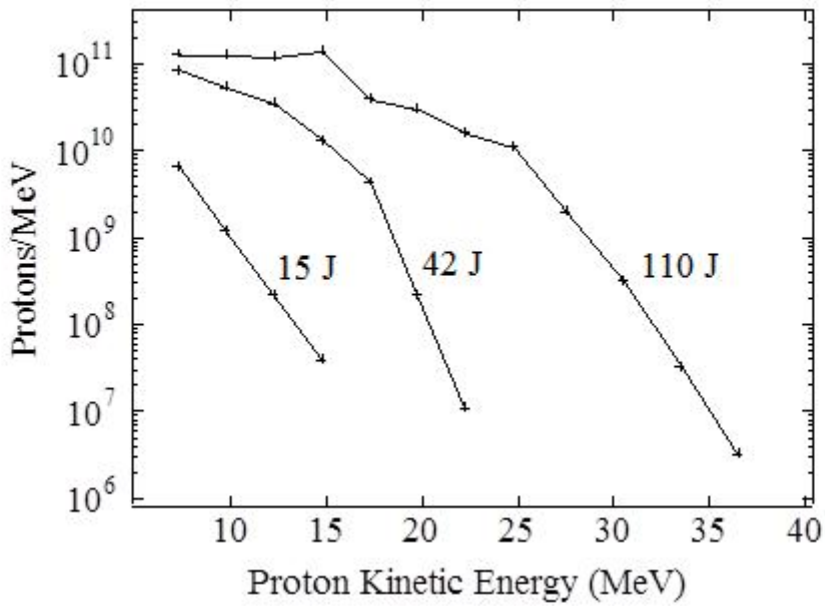
Target Normal Sheath Acceleration (TNSA)
(acceleration driven by hot electron pressure)

Protons are always observed regardless of target material, although bulk ions can be accelerated

- **Divergent** (~ 10s degrees)
- **Broad spectrum**

After Borghesi/QUB

Typical results (Vulcan)

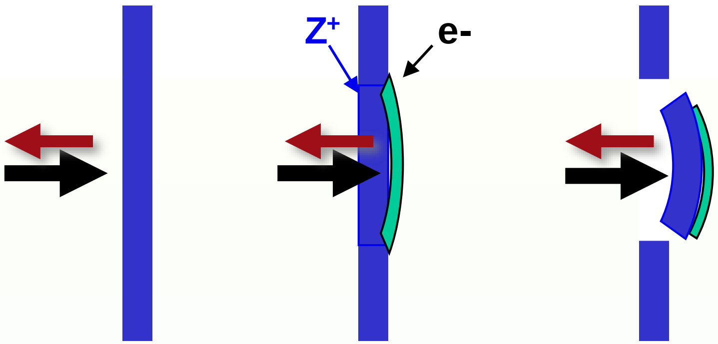


- Target: 10μm Al
- Temperature
  ~ 1.8 MeV for 12 J
  ~ 5 MeV for 85J
- Energy conversion
  $\eta \sim 2\ 10^{-3}$ for 12 J
  $\eta \sim 5\ 10^{-2}$ for 85 J
  $\eta \sim 1\ 10^{-1}$ for 400 J
- Efficiency at 30-35 MeV
  $\eta_{hot} \sim 10^{-5}$-10^{-4}

Typical divergence:
20-40°

After Borghesi/QUB

New mechanism - Radiation Pressure Acceleration (RPA)



In ultrathin foils the laser push on electrons may lead to the detachment of a portion of the foil (light sail)

Acceleration by Radiation Pressure:

$$F_R = (1+R)A\frac{I_L}{c}$$

$$\Rightarrow v_i = \frac{(1+R)\tau}{m_i n_i d}\frac{I_L}{c}$$

W ~ I²

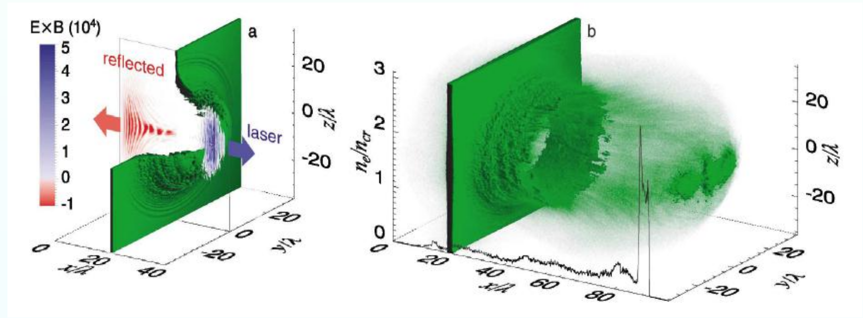
- Cyclical re-acceleration of ions
- Narrow-band spectrum (whole-foil acceleration)
- Energy transfer more efficient as ions approach relativistic regime
- Issues : Stability of acceleration

  Electron heating:

  Competition with TNSA

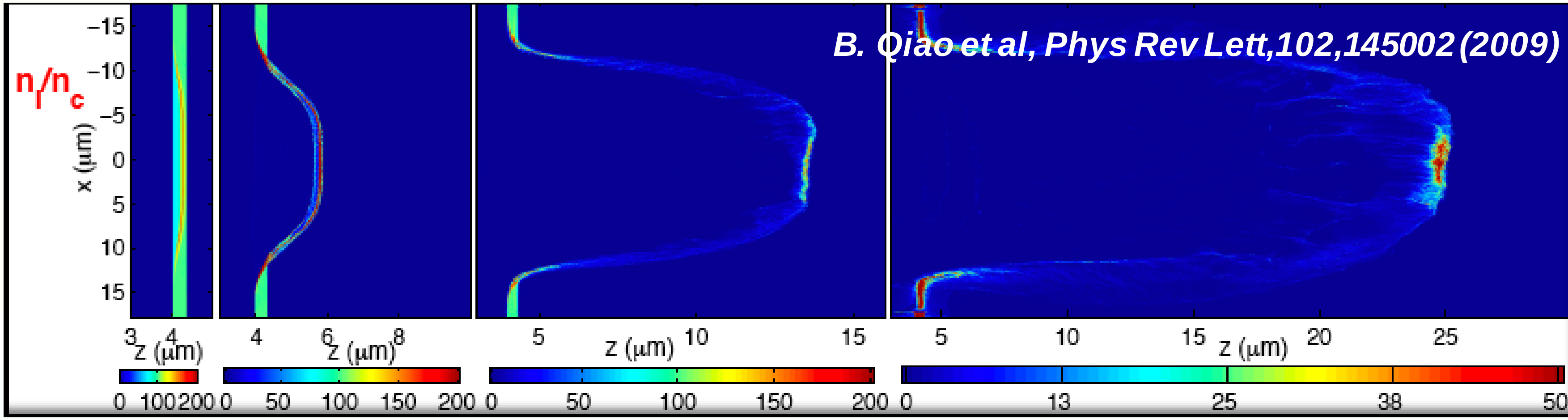
  Target disassembly
- Dominant mechanism at I~ 10^{23} W/cm²

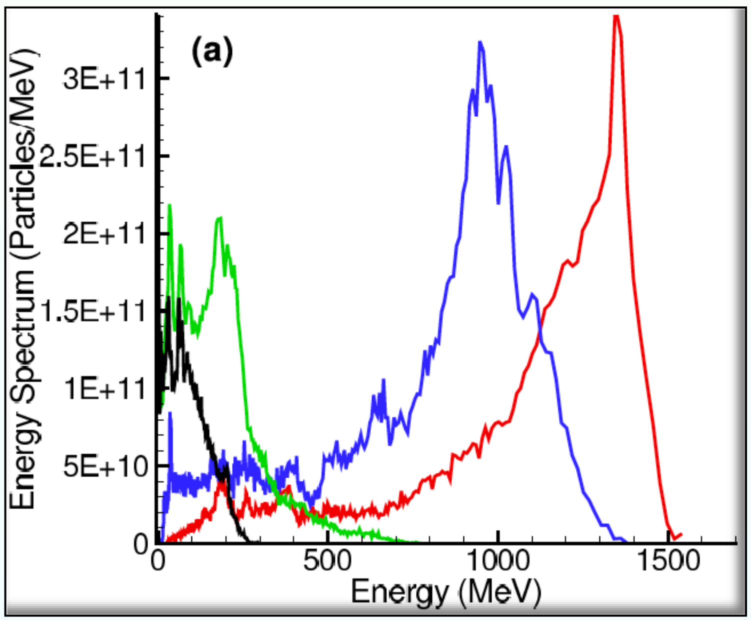
  GeV acceleration in a single laser cycle!!



T.Esirkepov *et al*, PRL, 92, 175004 (2004)

Radiation Pressure Acceleration





Circularly polarized pulses

suppress hot electron production

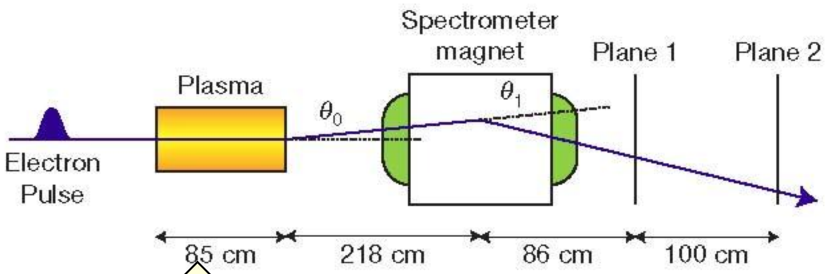
suppress TNSA

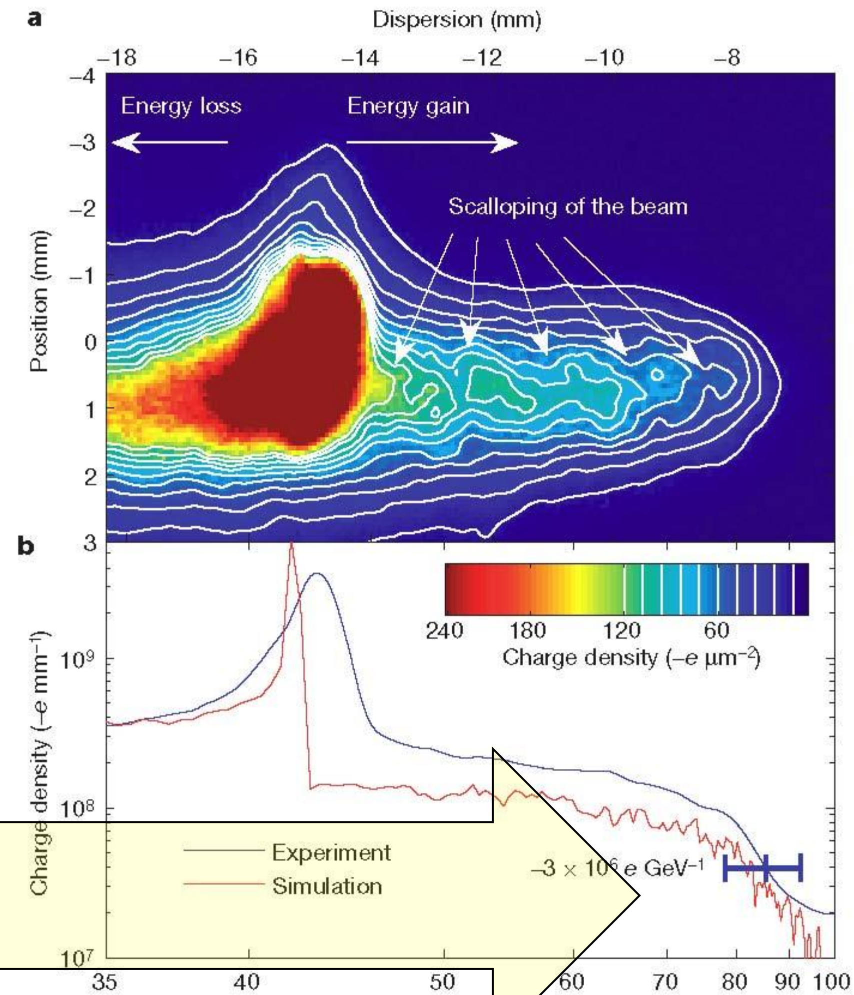
limit target disassembly

+ *ultra-thin target* @ 10^{21}-10^{22} W/cm^2

promising for 0.1-1GeV acceleration

electron driven plasma acceleration





85 cm!

Energy doubled!

Blumenfeld et al, SLAC-PUB-12363

Prospects for laser-plasma accelerators

- **Laser-plasma accelerators: enormous progress:**
  - **Electrons**
    - **Demonstration of quasi-mononergetic beams**
    - **Increase of output energy to 1 GeV**
    - **Demonstration of controlled injection**
  - **Protons & ions**
    - **Similar dramatic progress**
  - **Many groups, many plans**
- **Beam-driven plasma accelerators**
  - **"Energy doubling" @SLAC (electrons)**
  - **Protons-excited plasmas**
  - **FACET @ SLAC, something @ CERN**

INDUSTRIAL ACCELERATORS

Industrial uses

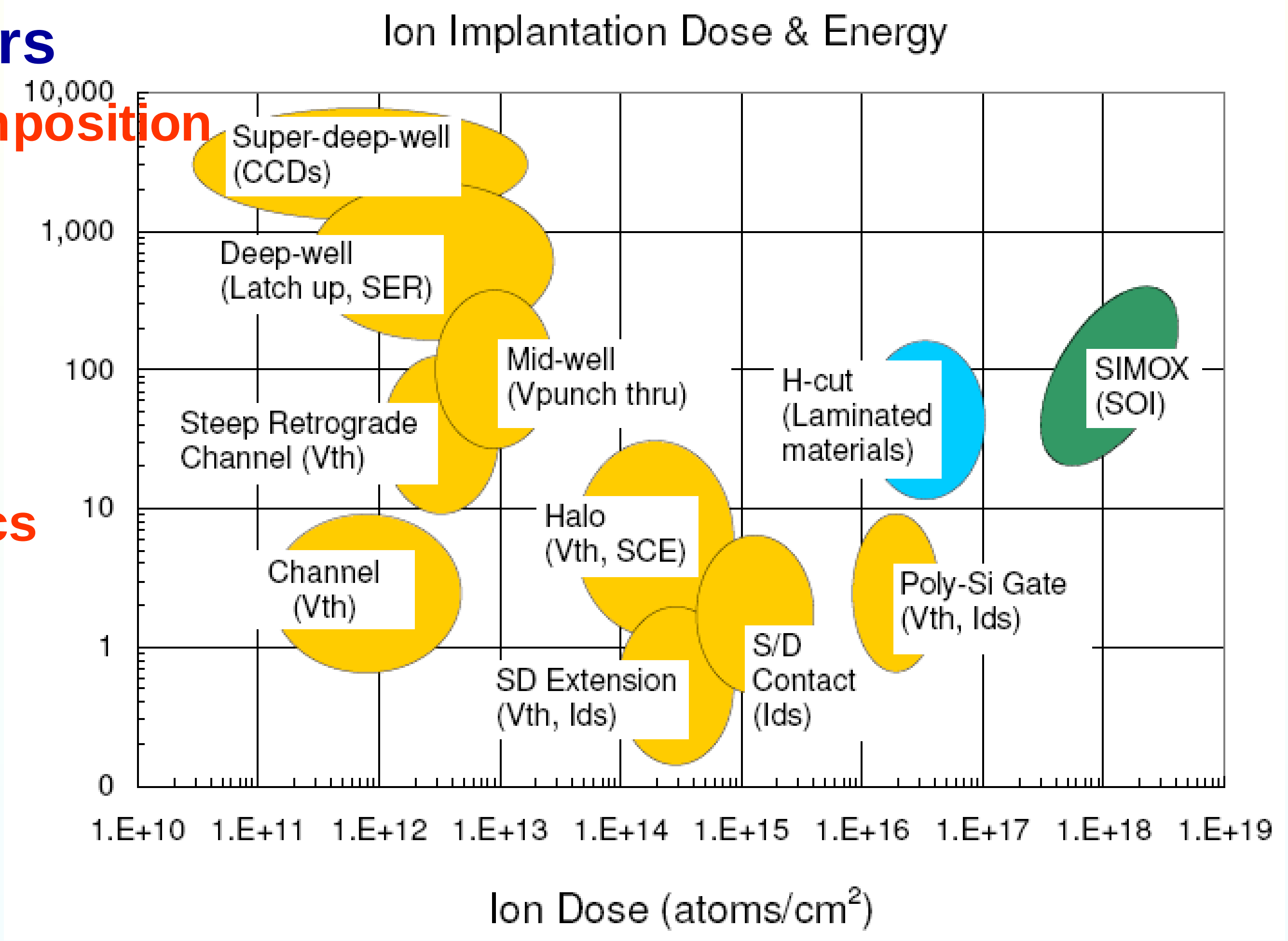
1. **Cyclotrons for radio-isotope production**
2. **Ion implantation (electrostatic, linear)**
3. **Sterilisation**
4. **Fusion reactors**
5. **(coming?) security applications**
6. **ADSR?**

Industrial Accelerators

- Direct Voltage
  - Van de Graaf, Cockcroft Walton …
    - Protons, ions to a few MeV (~5)
- Linacs
  - Electron beam
    - Up to 16 MeV
  - Ion beam
    - Up to ~70 MeV
- Rings
  - Cyclotrons
    - Ions up to ~70+ MeV
  - Betatrons
    - Electrons up to a few 10s of MeV
  - Synchrotrons
    - Up to several GeV

Ion Implantation

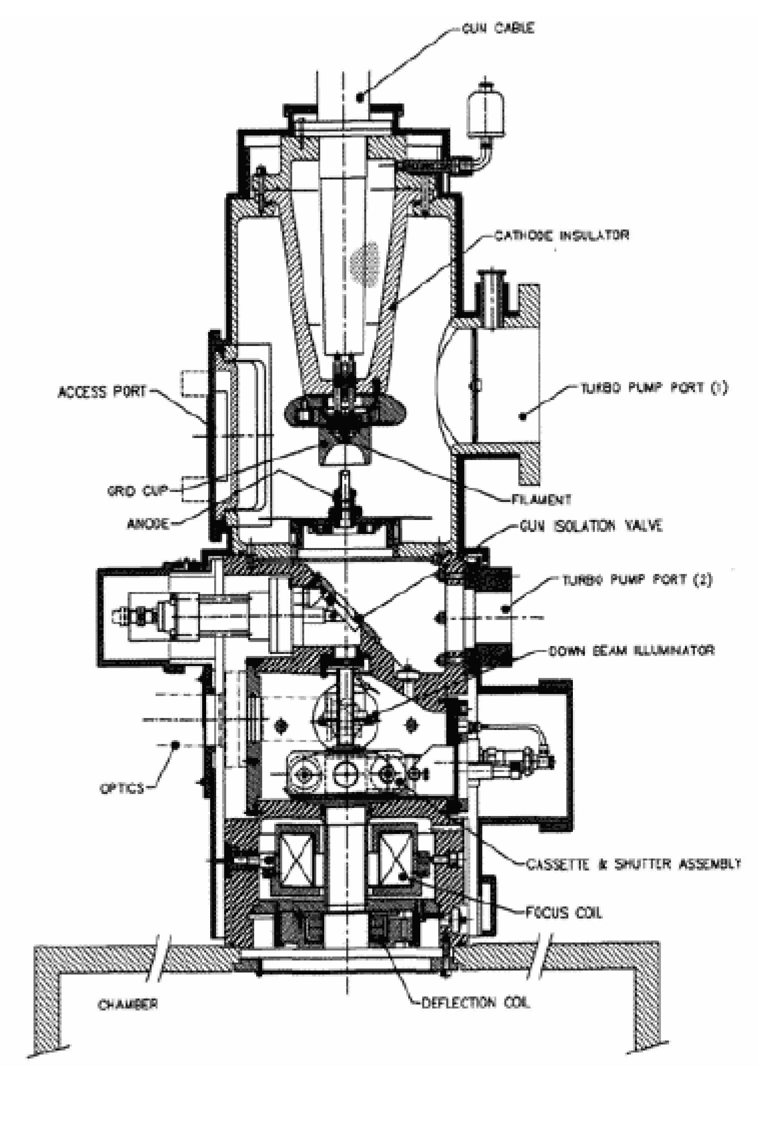
- **Semiconductors**
  - Precision composition
- **Metals**
  - hardening
- **Glass**
  - Hardening
  - Modified optics



- **Note: All digital electronics depends upon ion implantation**

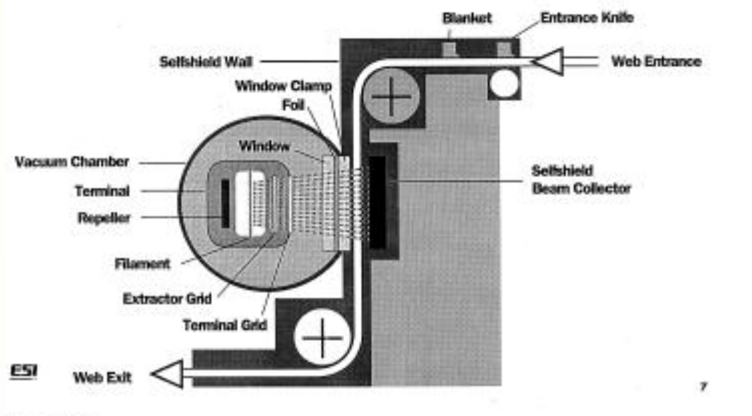
Electron Beam Materials Processing

- **Usually low energy**
  - **Few hundred keV**
  - **Precision engineering (cutting, welding)**



Electron Beam Irradiators

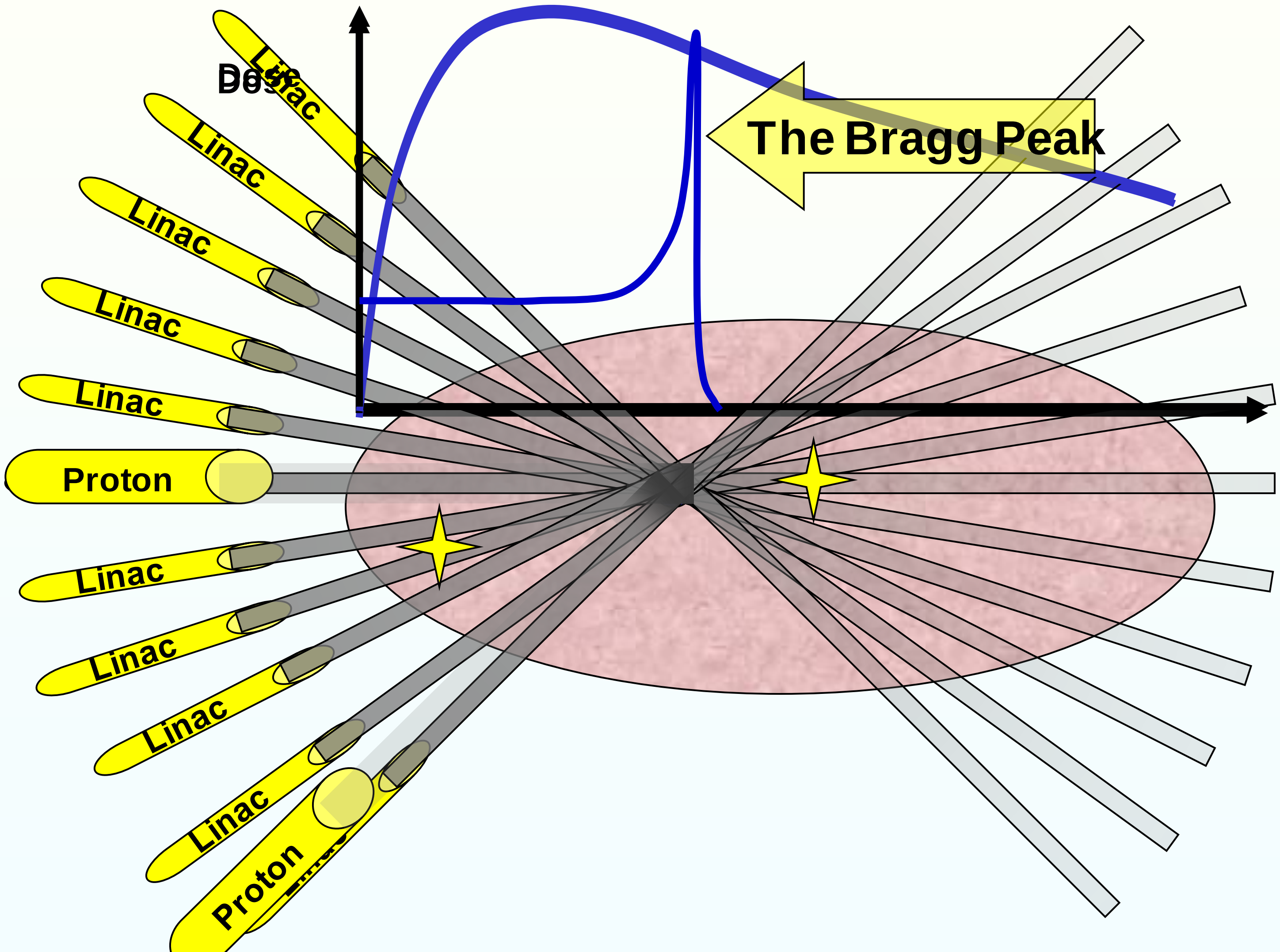
- **Low energy (<300 keV)**
  - **Curing, laminating**
- **– up to 1 MeV**
  - **Also polymerisation**
- **Medium energy (<5 MeV)**
  - **Polimerisation**
  - **Sterilisation (medical)**
- **High Energy (~10 MeV)**
  - **Food irradiation**
  - **Waste water treatment**
  - **Gemstone colour enhanceme**



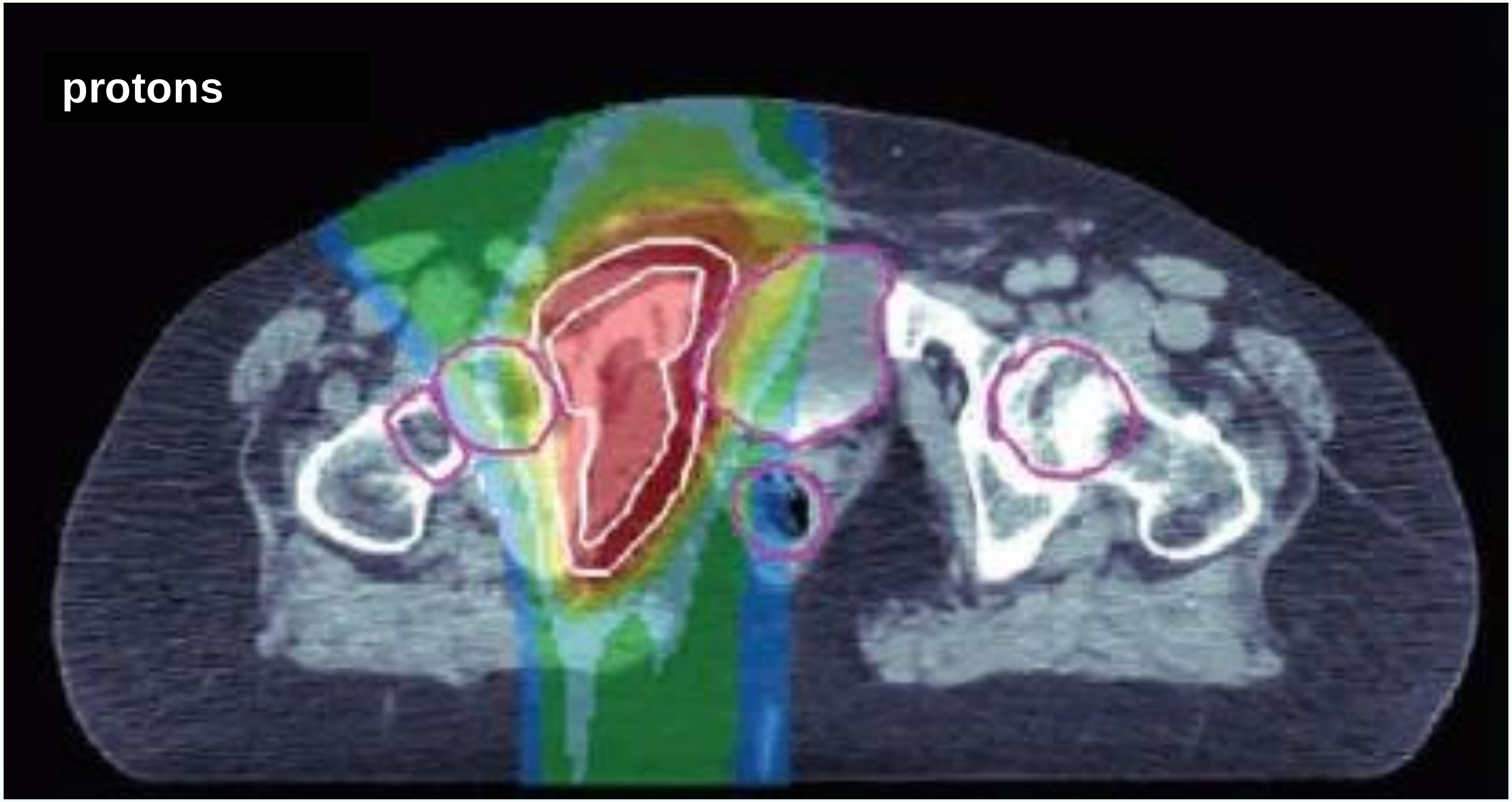
MEDICAL – CANCER THERAPY

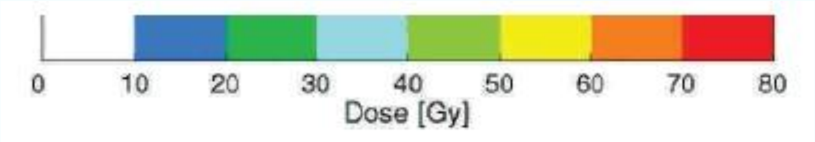
Radiotherapy – photons and protons

- Charged particle therapy uses protons to destroy cancer cells

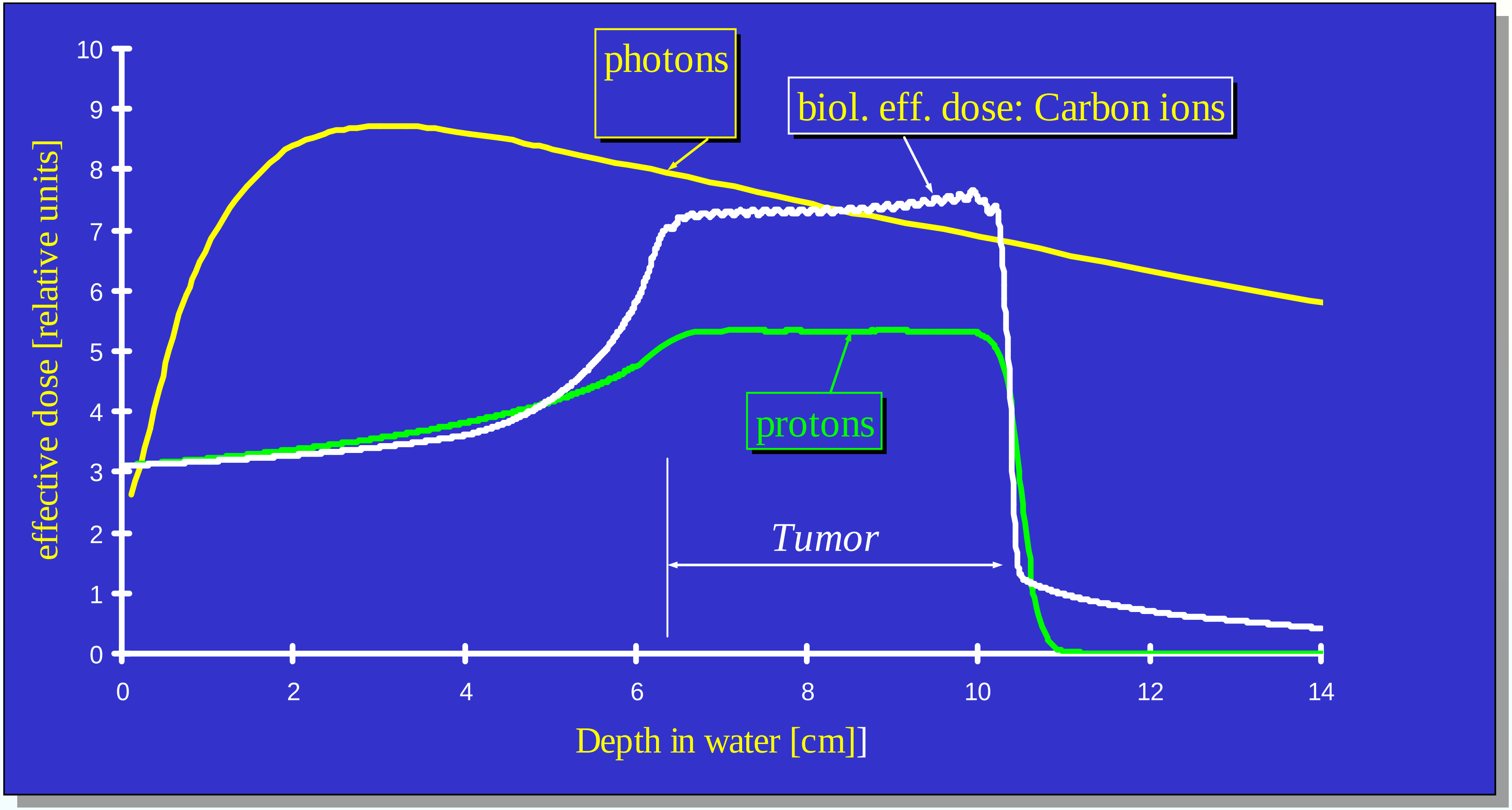


X-rays compared with protons

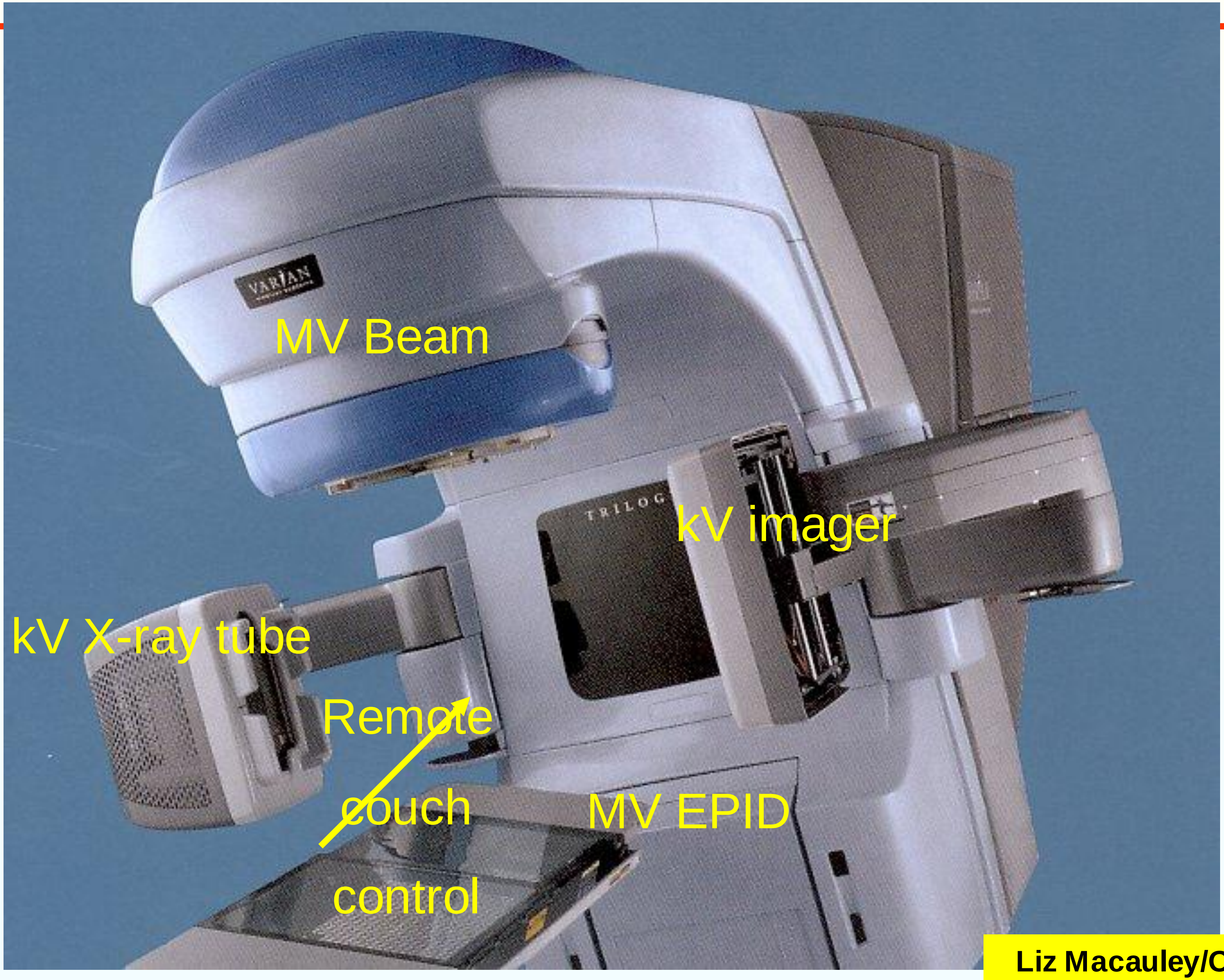




Photons, Protons and Carbon



Linacs with on-Board Imaging



Liz Macauley/ORHT

Inside …

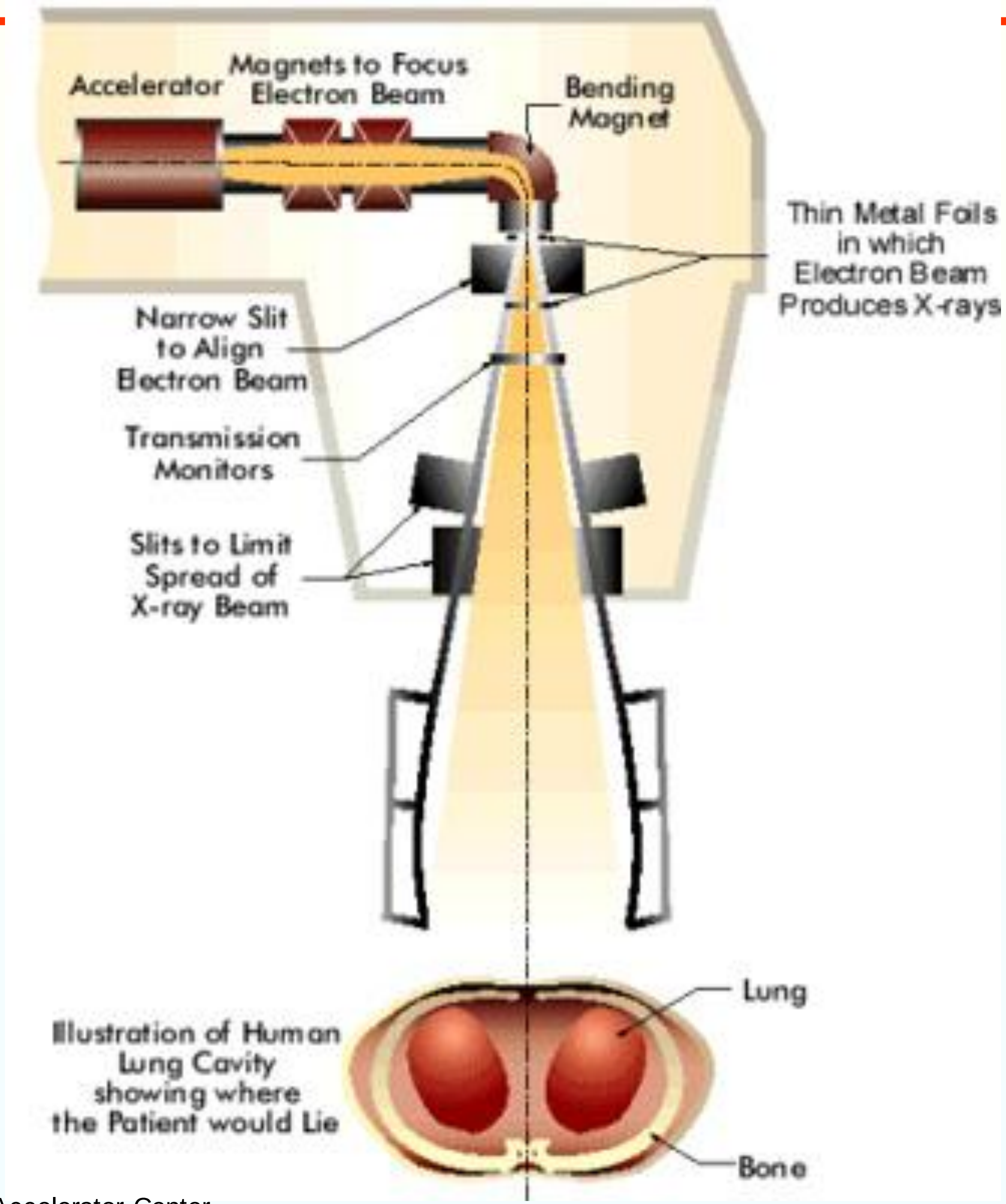
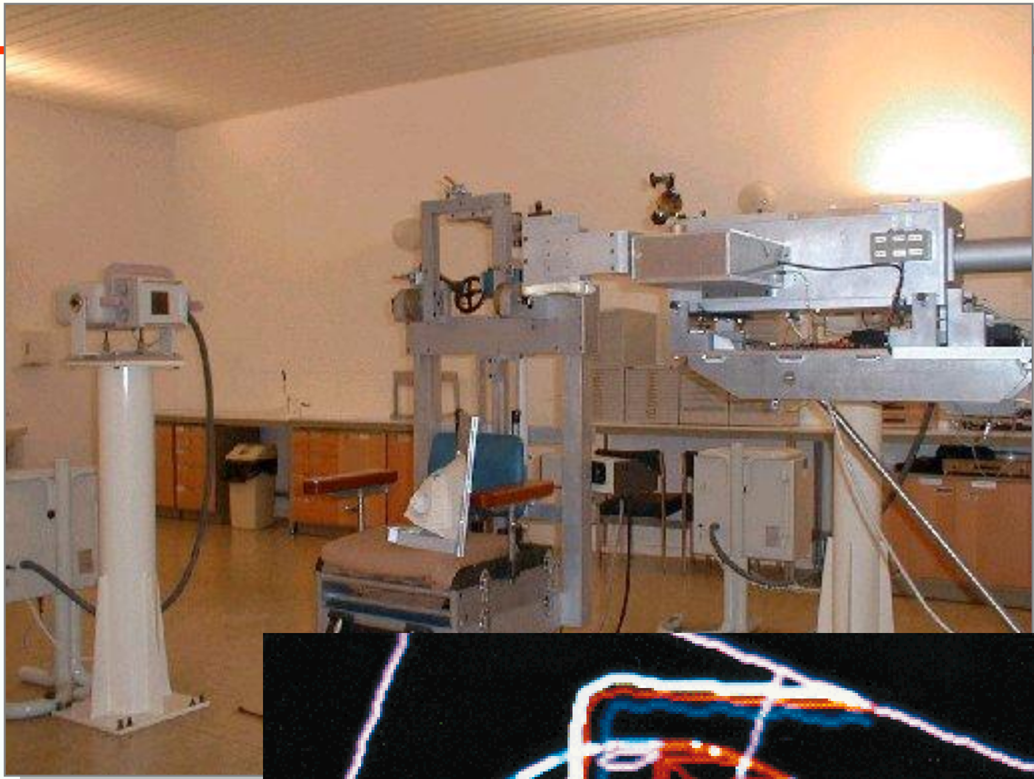
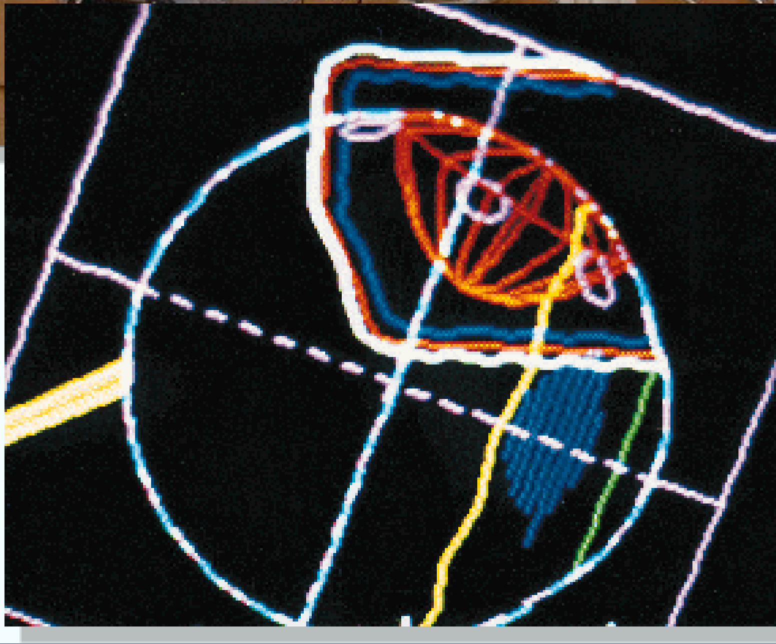


Image courtesy of the Stanford Linear Accelerator Center

The Clatterbridge Centre for Oncology

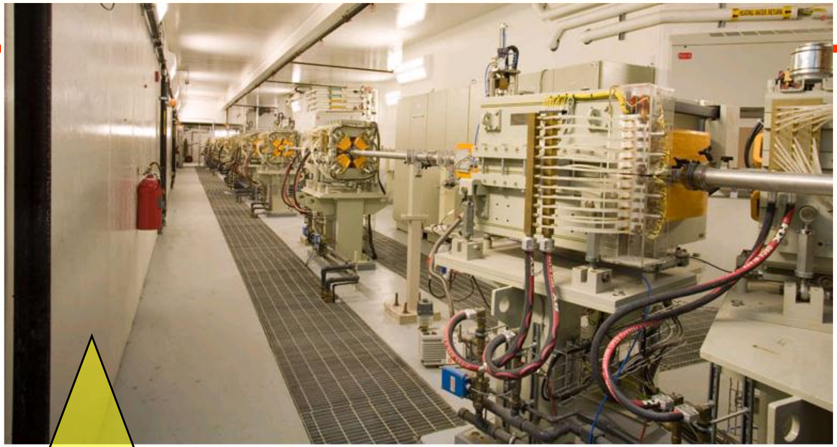


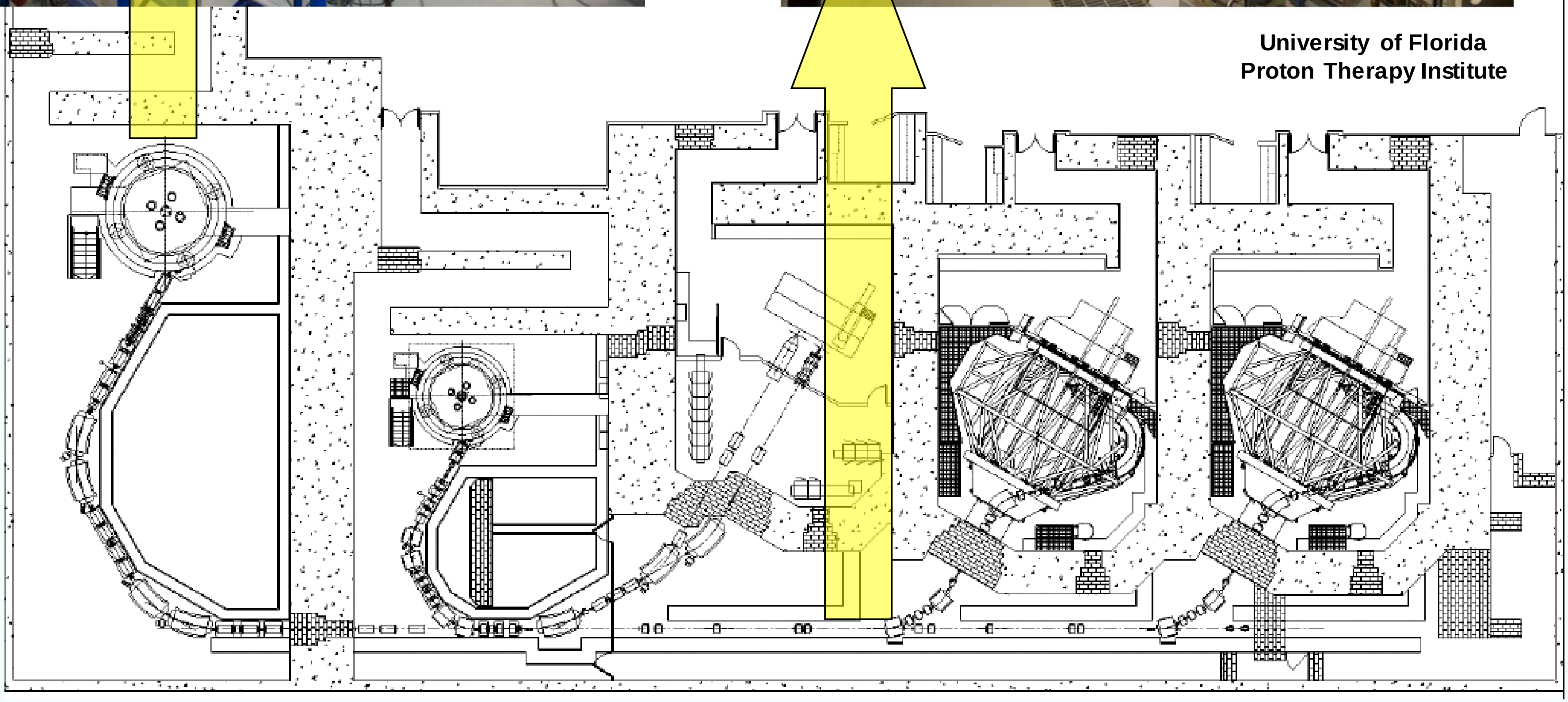
- **Established 1989**
  - **Douglas 62 MeV cyclotron**
  - **First hospital based proton therapy**
  - **>1700 patients with ocular melanoma**
  - **First example of 3D computer treatment planning in UK;**
    - **eye gaze direction used to obtain best approach angle to eye.**



After Bleddyn Jones
Courtesy Clatterbridge

The IBA solution





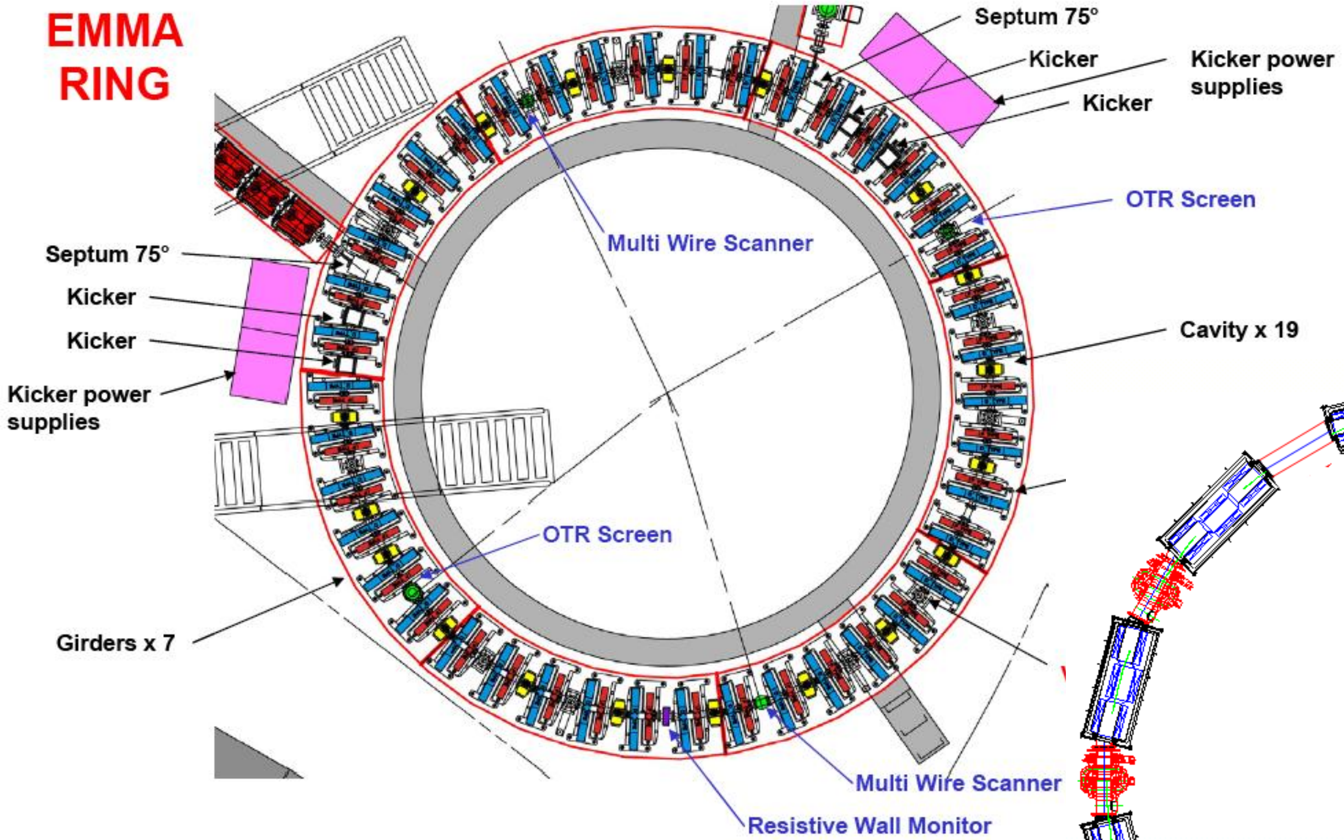
IBA

What the patient sees

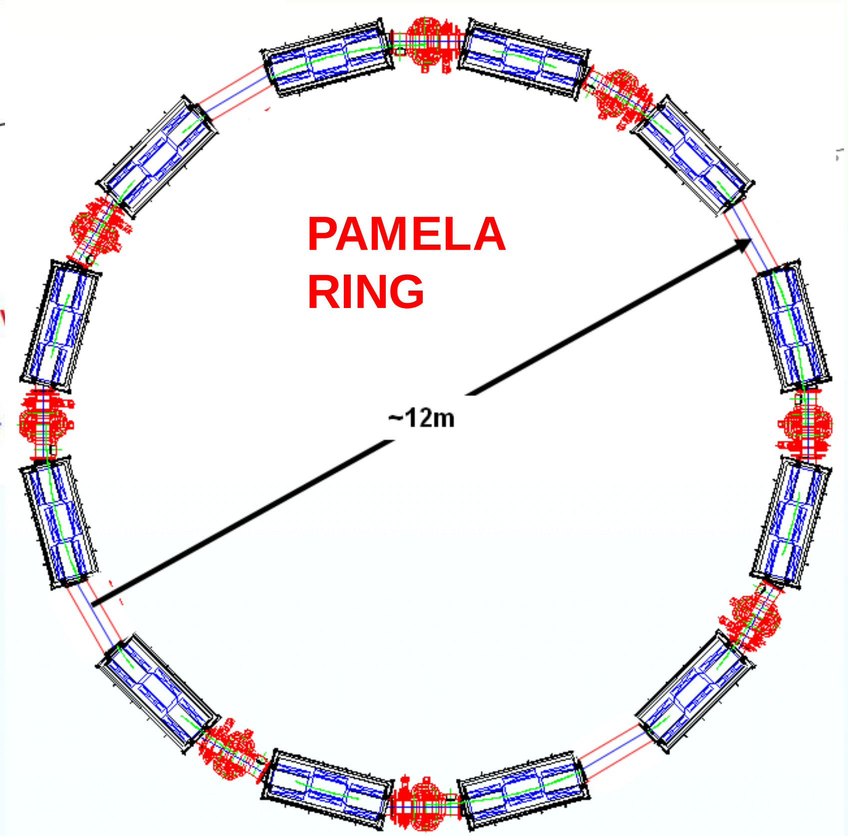
non-scaling FFAGs

- **Fixed Field Alternating Gradient**
  - **See Ken Long**
    - **EMMA – Electron Model with Many Applications**
      - **“Proof of Principle”**
      - **Relativistic – fixed frequency**
- **Does a linear EMMA-like machine work**
  - **For protons?**
    - **Relativistic – yes**
    - **Non-relativistic - no**
      - **Too dense a lattice**

EMMA & PAMELA

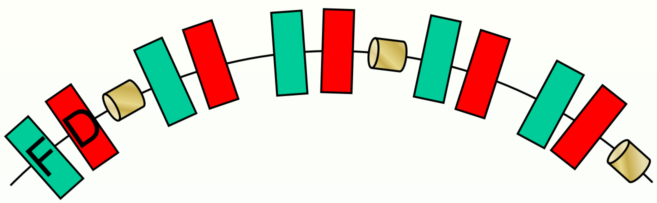


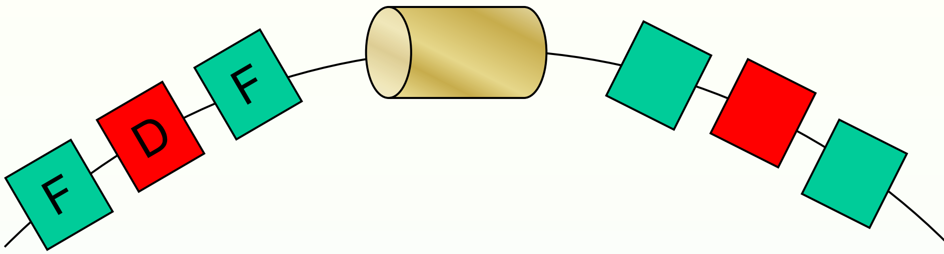
EMMA
RING
Septum 75°
Kicker
Kicker power
supplies
Kicker
OTR Screen
Multi Wire Scanner
Septum 75°
Kicker
Kicker
Kicker power
supplies
Cavity x 19
OTR Screen
Girders x 7
Multi Wire Scanner
Resistive Wall Monitor



PAMELA
RING
~12m

From EMMA to PAMELA





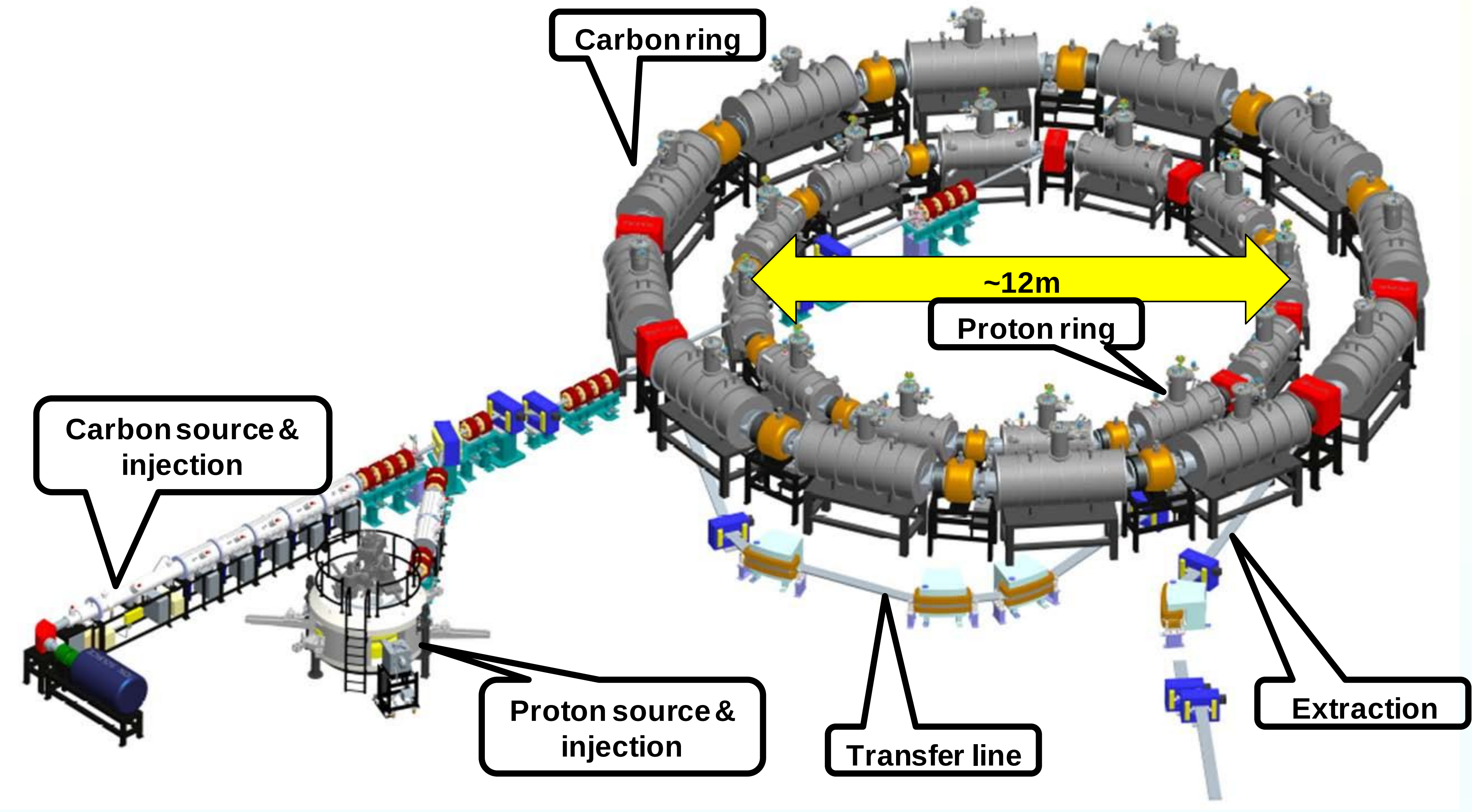
The EMMA lattice

- **Doublet structure**
  - **Focus and Defocus**
- **Dense lattice**
  - **Little space between magnets**
- **Lots of RF Acceleration**
  - **Almost every other cell**

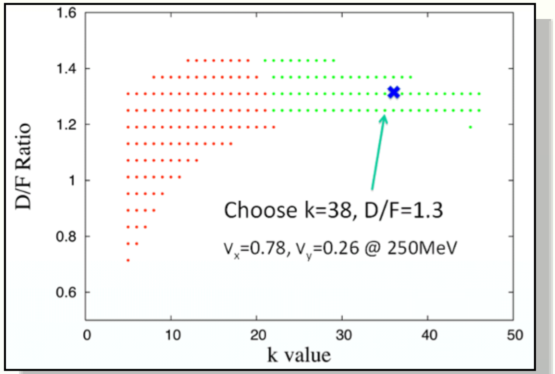
The PAMELA lattice

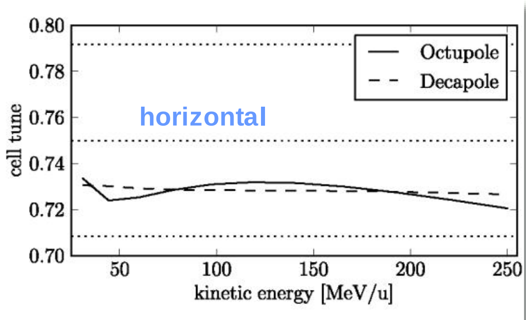
- **Triplet structure**
  - **Focus, Defocus, Focus**
- **Less Dense lattice**
  - **Long straight sections**
- **Less of RF Acceleration**
  - **Larger cavities**
  - **Lower frequencies**
- **Larger radius**

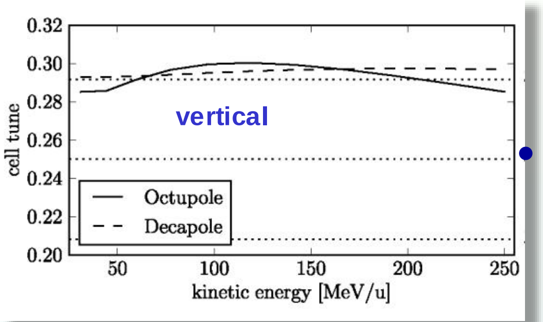
PAMELA Layout

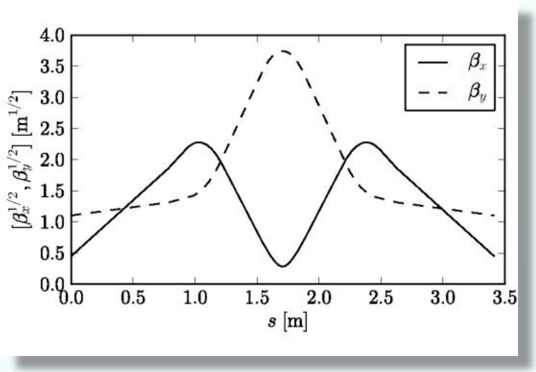


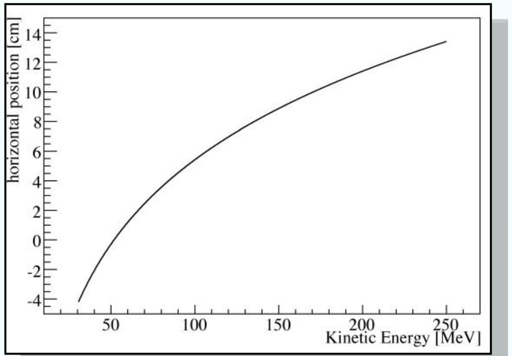
Working Point and Tunes









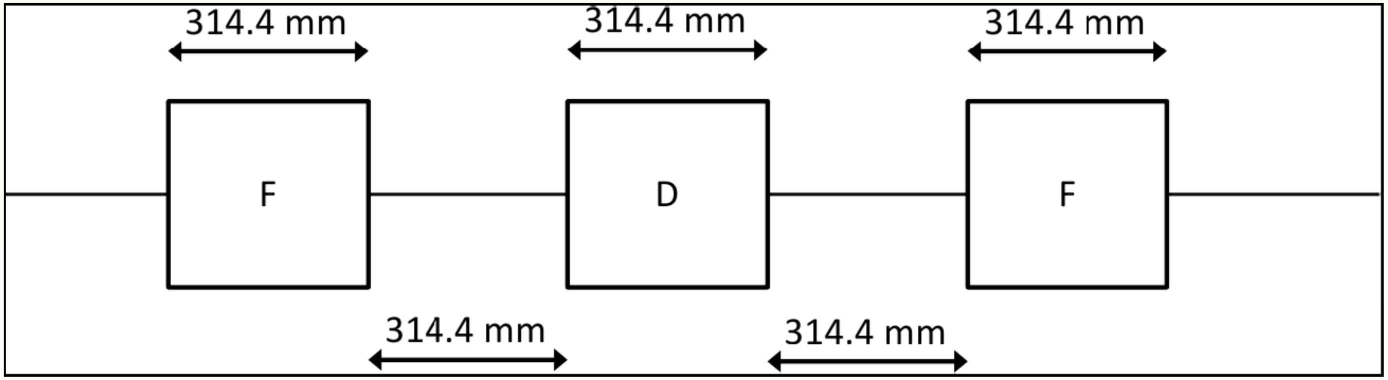


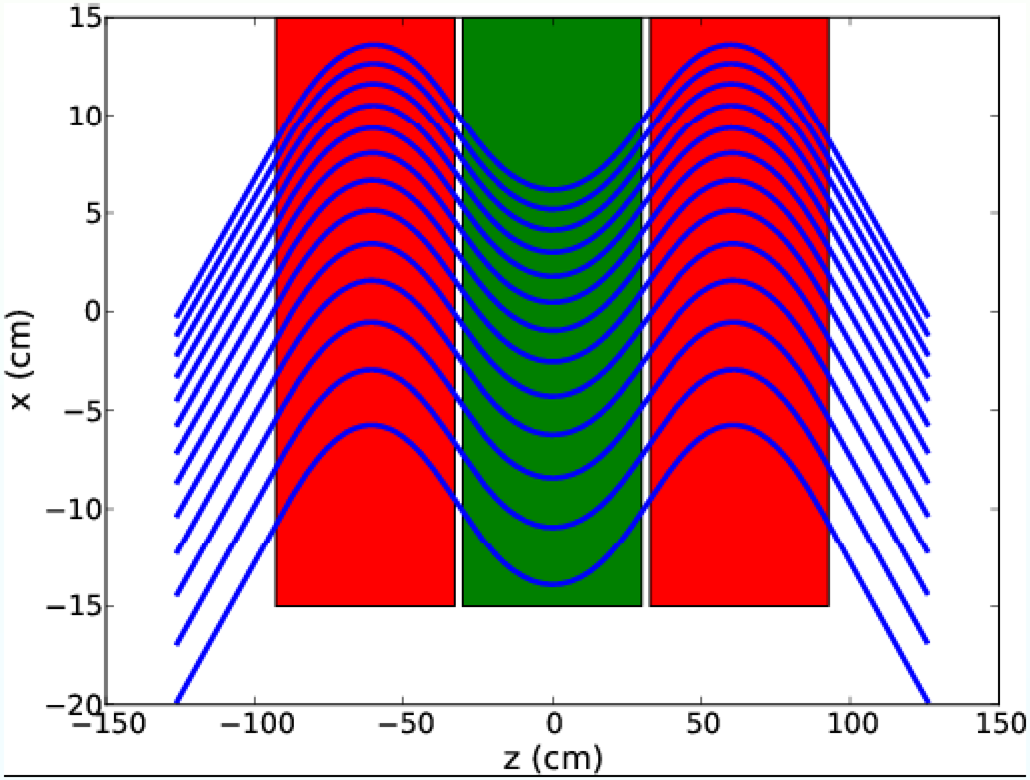
- **Working point**
  - **High k (38)**
    - **minimize orbit excursion**
- **Machine tune variation (cell tune variation*12): [decapole]**
  - **v_x within 0.0476**
  - **v_y within 0.0528**
  - **Well within an integer!**
- **Beam sensitivity**
  - **Amplification factor 5.8 (h)**
  - **9.5 (v)**

(A = orbit distortion [mm] / 1σ alignment error [mm])

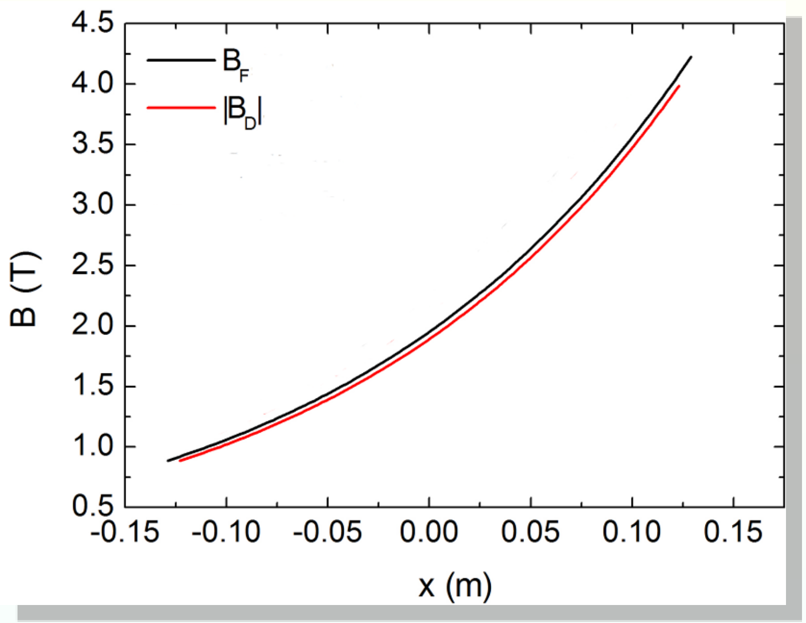
Proton Ring

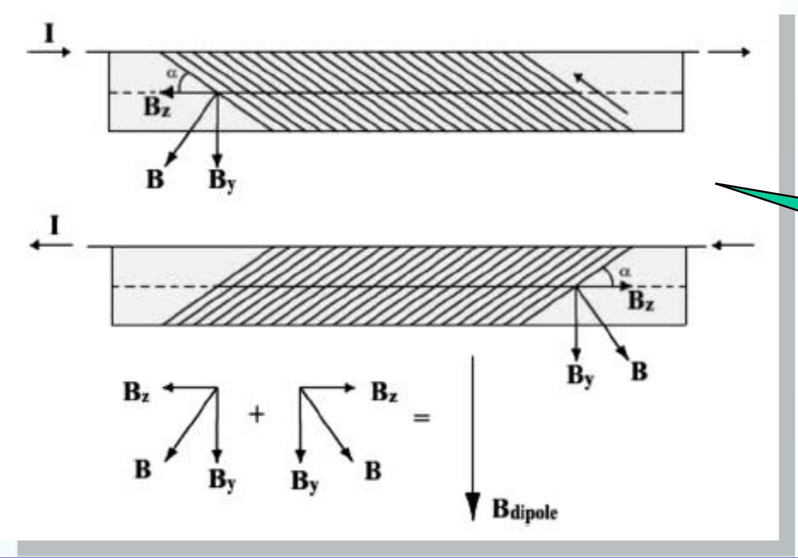
Magnetic Lattice





Magnet Requirements



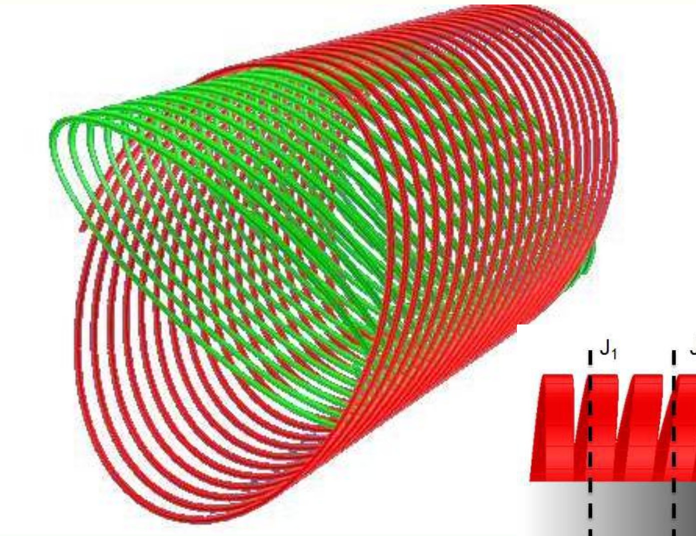


- **Non-scaling, non-linear FFAG**
  - **Multipoles up to decapole**
- **Challenges**
  - **Maximum field (4.25T)**
  - **Length restriction (314 mm)**
  - **Required bore (>250 mm)**
- **Magnet options**
  - **n/c Iron cored magnets**
  - **Superferric coils**
  - **S/C cos(θ) magnets**
  - **S/C Double-helix coils**

Choose: Double-helix coils

Double-Helix Principle

Current density:



Helix 1

$$x: \quad \frac{Jx}{J_0} = -R\sin(\Theta)$$

$$y: \quad \frac{Jy}{J_0} = R\cos(\Theta)$$

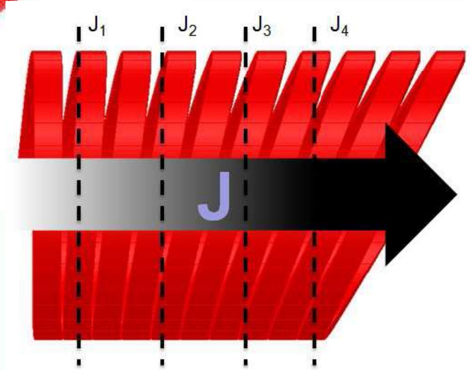
$$z: \quad \frac{Jz}{J_0} = \frac{nR}{\tan\alpha}\cos(n\Theta)$$

Helix 2

$$\frac{Jx}{J_0} = R\sin(\Theta)$$

$$\frac{Jy}{J_0} = -R\cos(\Theta)$$

$$\frac{Jz}{J_0} = -\frac{nR}{\tan(-\alpha)}\cos(n\Theta)$$

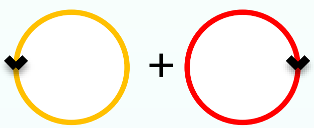


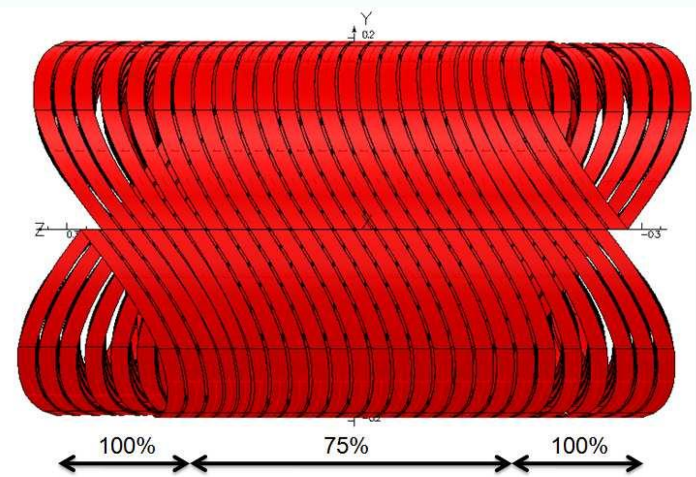
Double-Helix

$$Jx = 0$$

$$Jy = 0$$

$$Jz = const\cos(n\Theta)$$





Double-helix coil:

Smart way of creating a cosine-theta magnet

Main advantage for PAMELA: **No coil end problem**

Conclusion

- **Accelerators have an exciting future**
  - **in particle physics**
    - **LHC, LC, CLIC, NF, factories …**
  - **in other sciences**
    - **Light sources, FELs, spallation sources…**
  - **in society**
    - **Industry**
    - **Medical accelerators (isotopes, hadron-therapy…)**
- **And they are *fun too!***