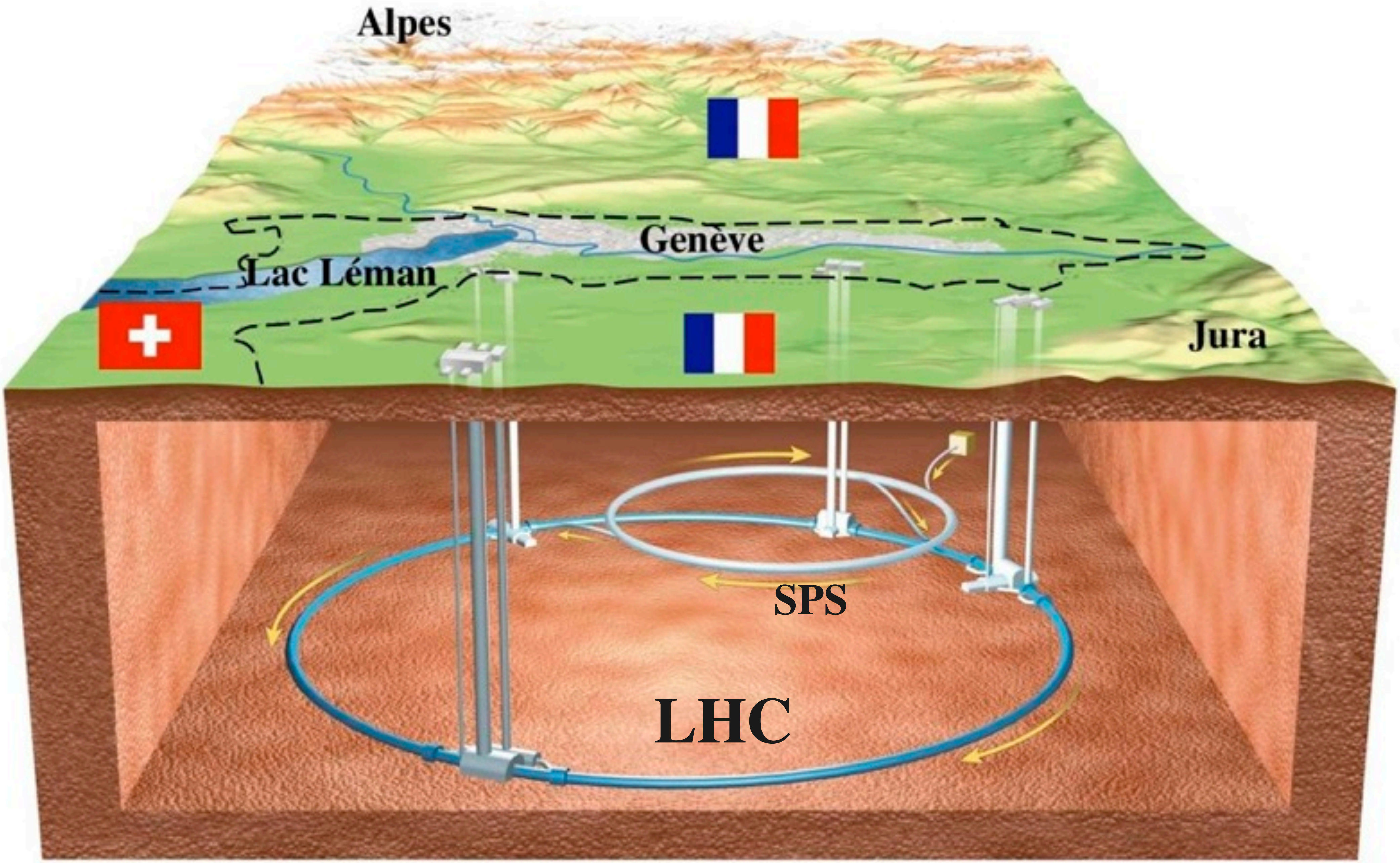
Teilchenbeschleuniger

die grössten wissenschaftlichen Instrumente

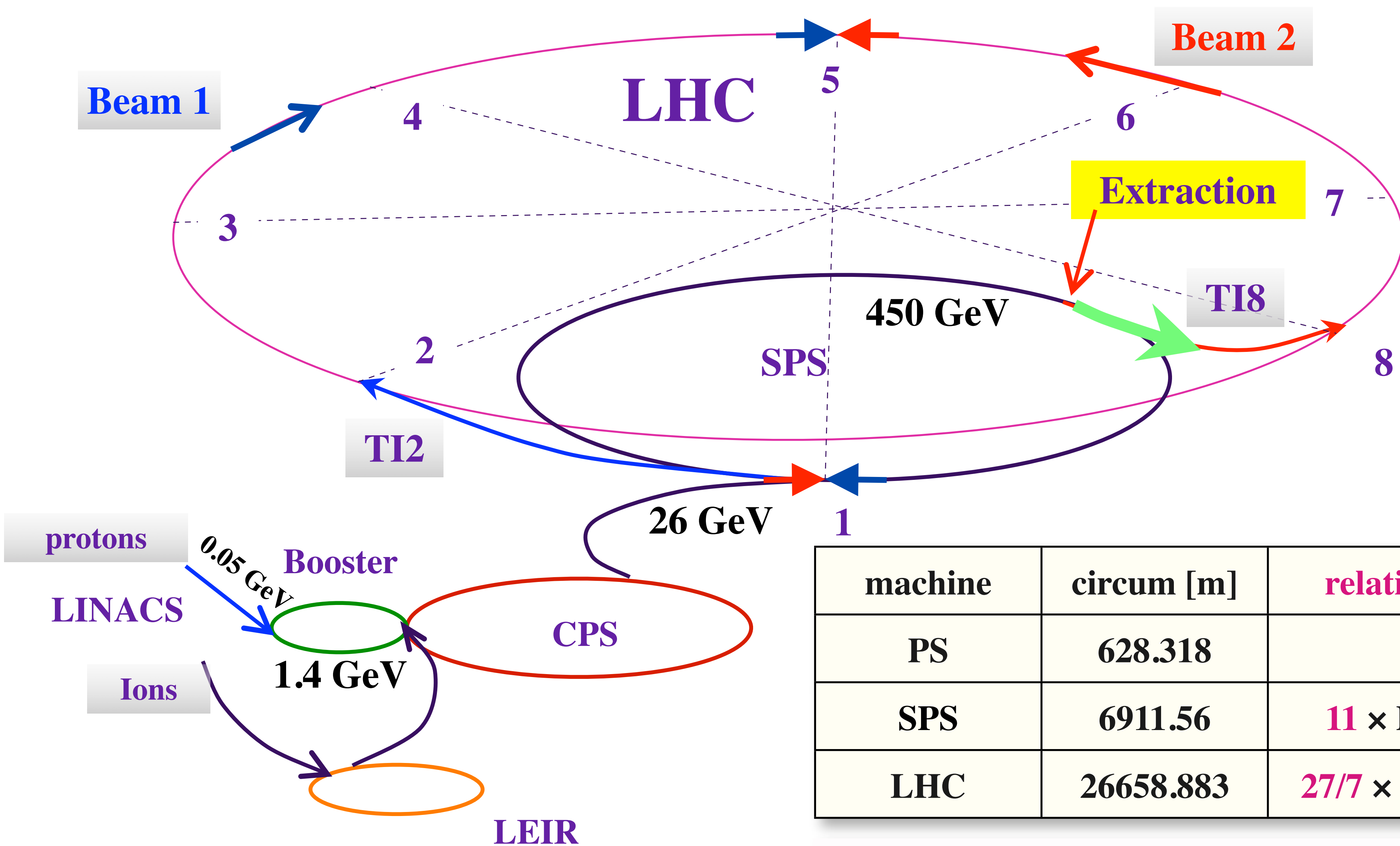
Helmut Burkhardt, CERN

German Teachers Programme 1-2/09/2014

Examples from CERN with the LHC



The CERN accelerator complex : injectors and transfer



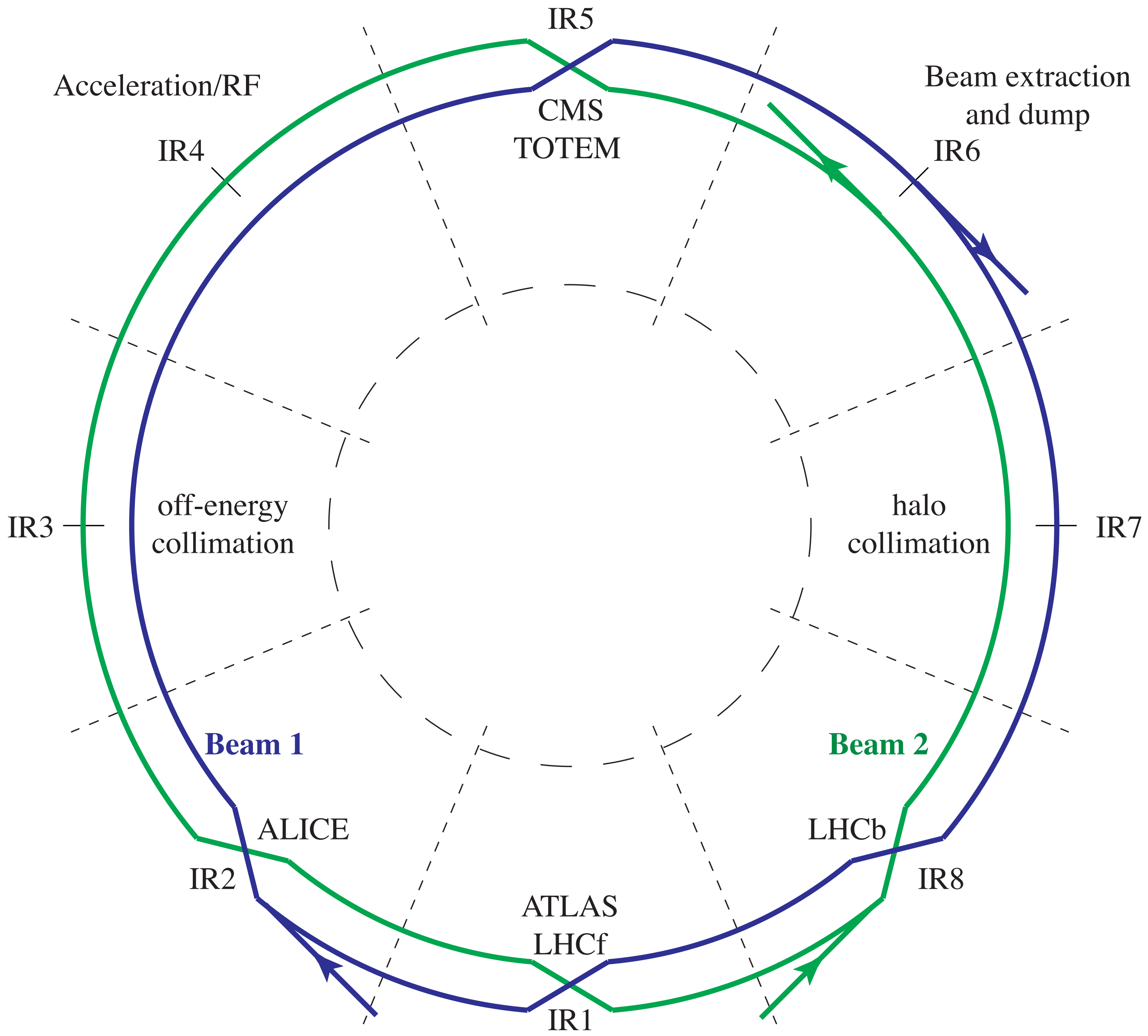
machine	circum [m]	relative
PS	628.318	
SPS	6911.56	11 × PS
LHC	26658.883	27/7 × SPS

simple rational fractions for synchronization based on a single frequency generator at injection

Beam size of protons decreases with energy : area $\sigma^2 \propto 1 / E$

Beam size largest at injection, using the full aperture

Layout of the LHC

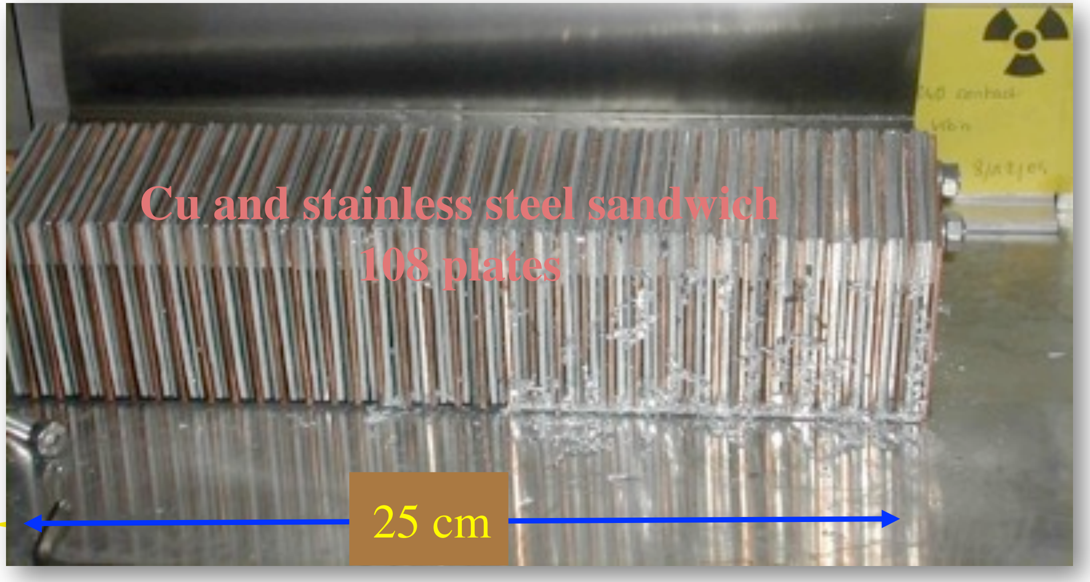


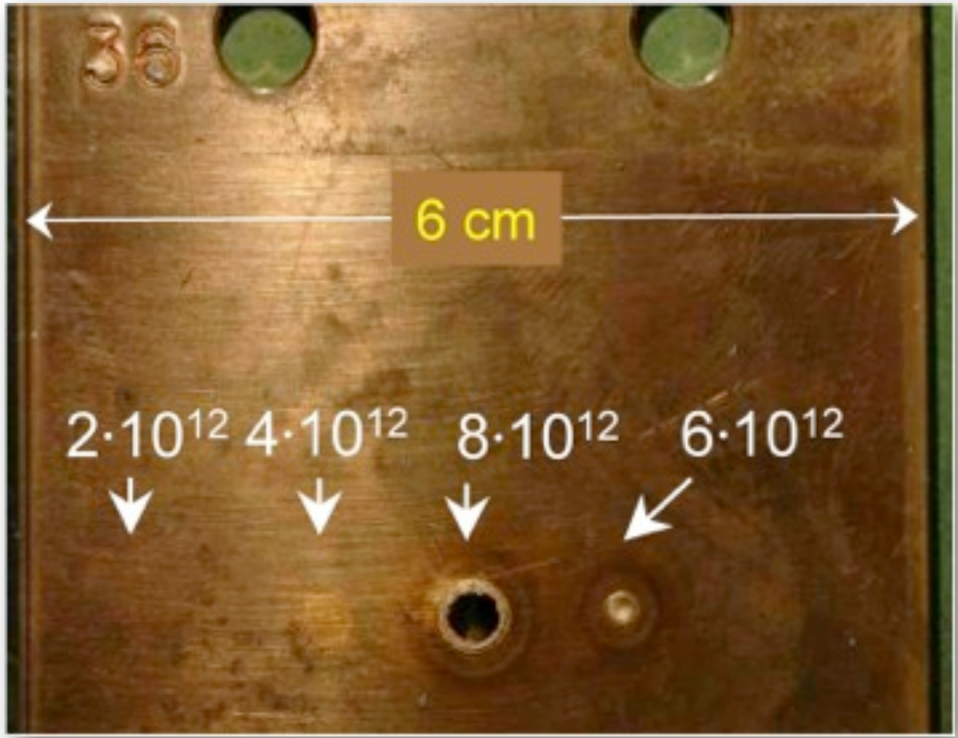
Damage potential : confirmed in controlled SPS experiment

controlled experiment with beam extracted from SPS at 450 GeV in a single turn, with perpendicular impact on Cu + stainless steel target

450 GeV protons →

r.m.s. beam sizes $\sigma_{x/y} \approx 1$ mm





SPS results confirmed :

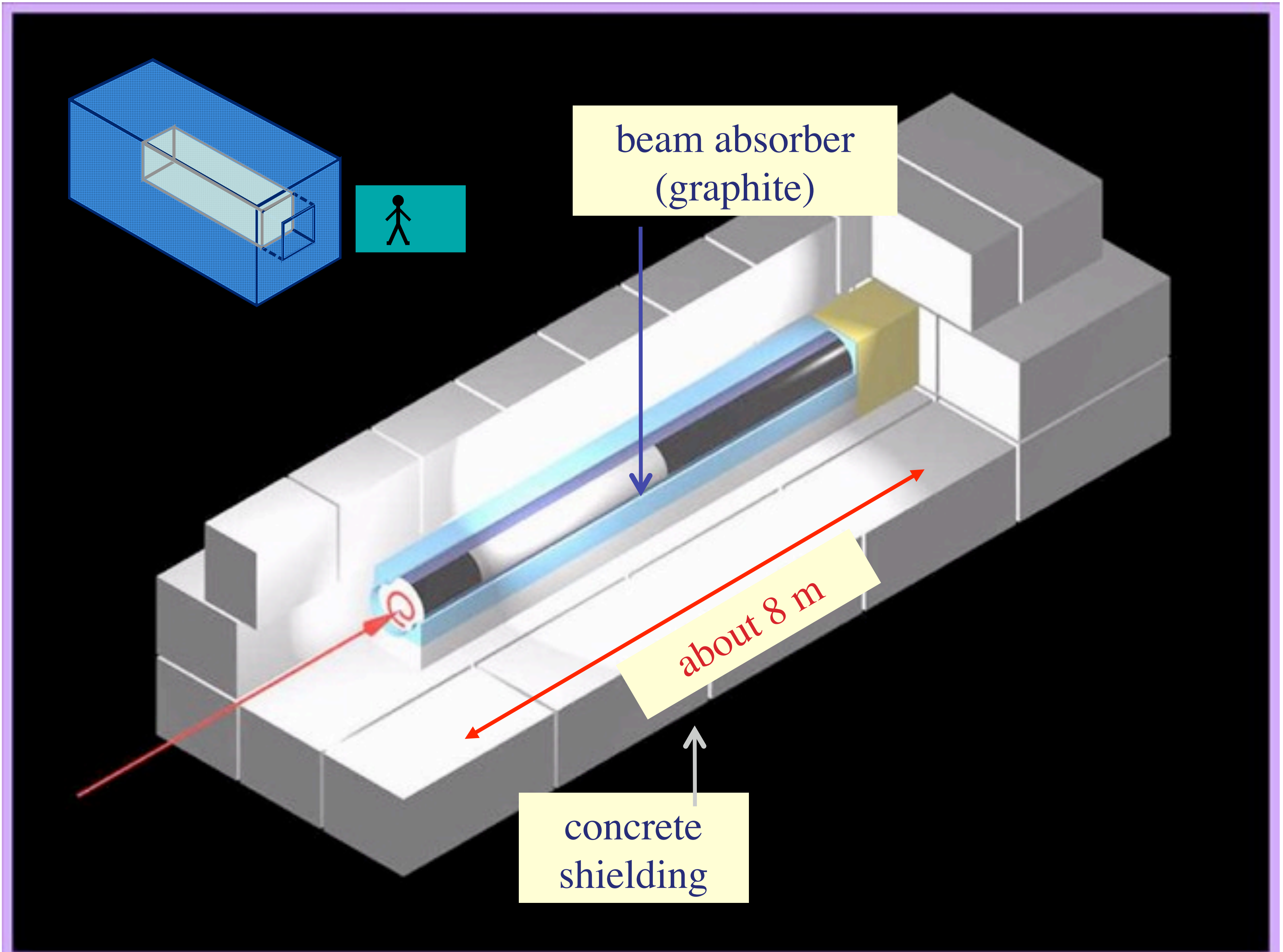
8×10^{12} clear damage

2×10^{12} below damage limit

for details see V. Kain et al., PAC 2005 RPPE018

For comparison, the LHC nominal at 7 TeV :
$2808 \times 1.15\times10^{11} = 3.2\times10^{14}$ p/beam
at $< \sigma_{x/y} > \approx 0.2$ mm
over 3 orders of magnitude above damage level for perpendicular impact

Dumping the LHC beam

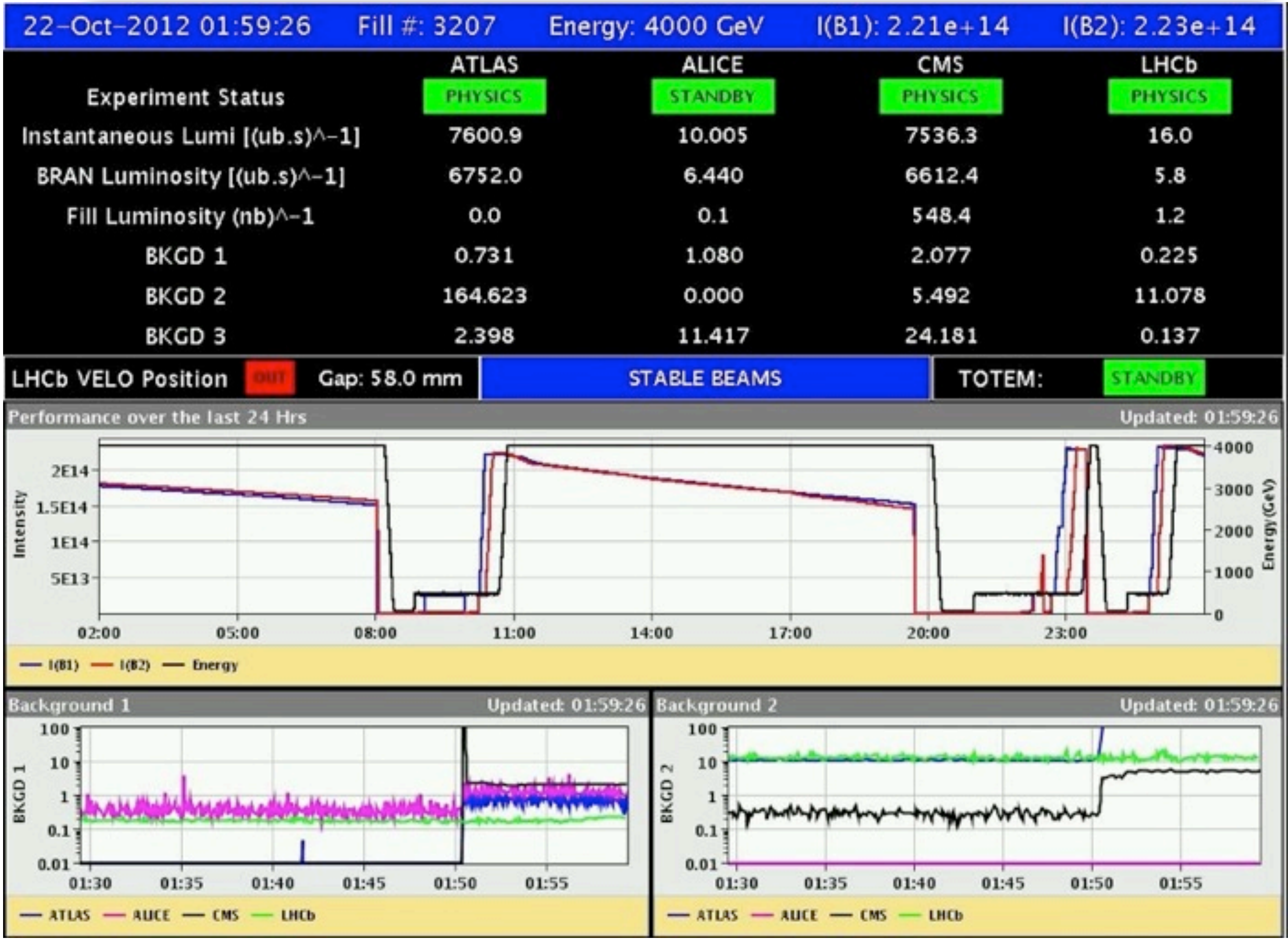


10 September 2008

10:30	**beam 1**	**3 turns**
15:00	**beam 2**	**3 turns**
22:00	**beam 2**	**several 100 turns**

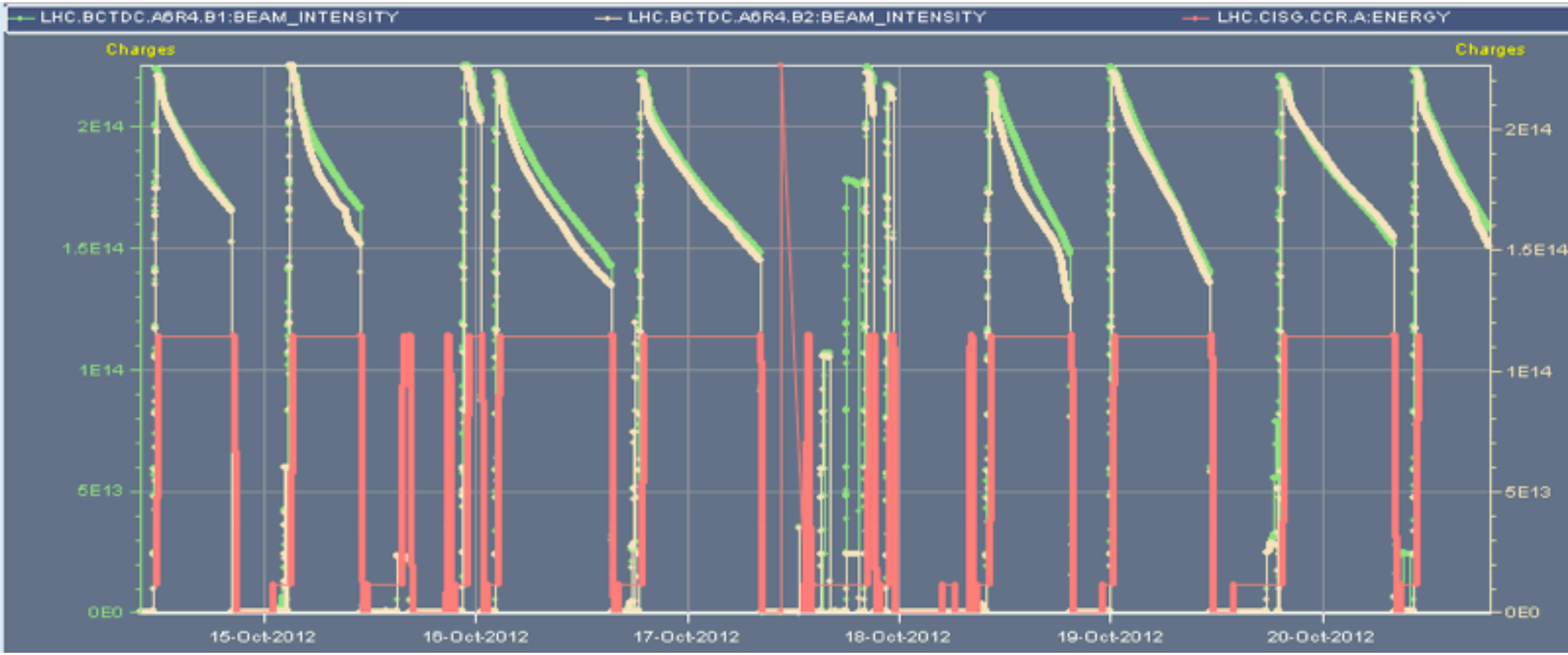
First high energy 3.5TeV+3.5TeV collisions, 30 March 2010

LHC running very well



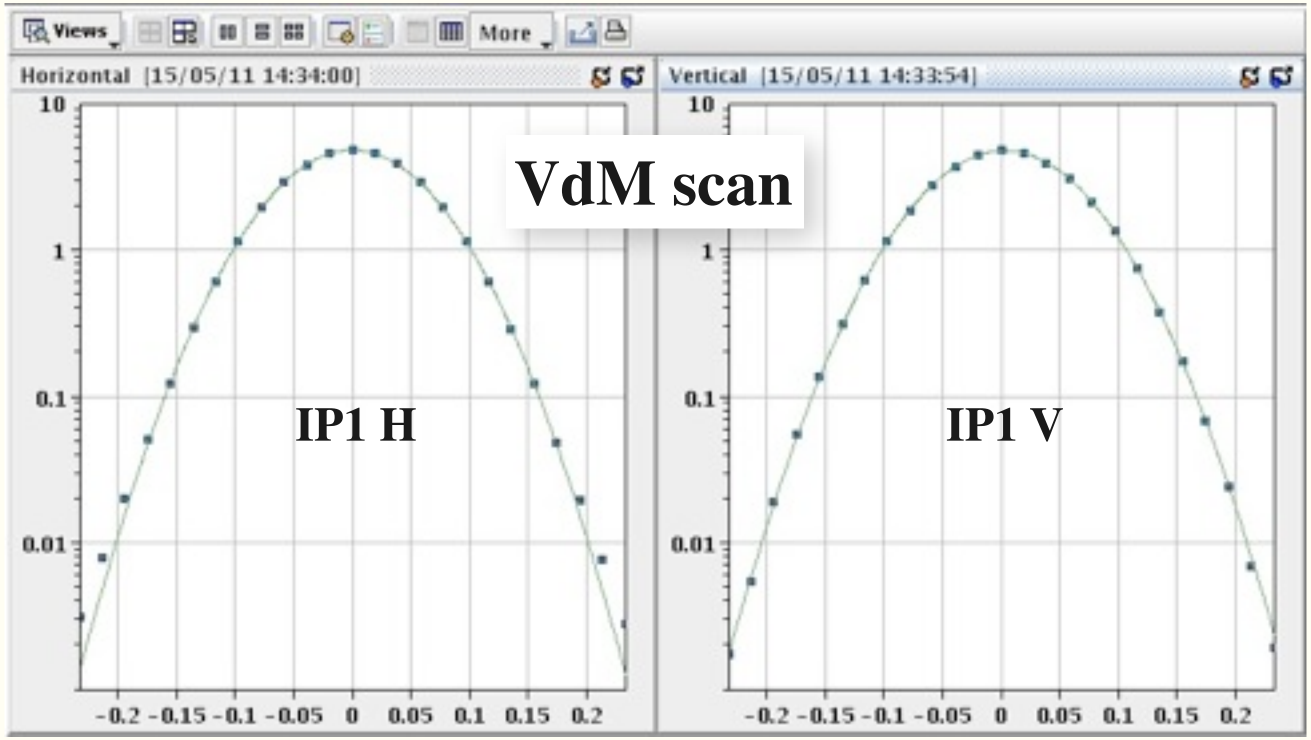
peak Luminosity 7.8 $\times 10^{33} cm^{-2} s^{-1}$

LHC typical week, Oct. '12, 1.2 pb-1



Precision front - high quality of LHC beams

- absolute luminosity normalization
- low, well understood backgrounds
- precision optics for ATLAS-ALFA and TOTEM
  β* = 1000 m, Oct.'12



precise measurement of the luminous region + beam intensity --> absolute luminosity and cross section calibration

currently ~ 3 % level (Tevatron had ~ 15 %)

LHC Run1 2009-2013

- **main LHC challenge : damage potential --- increase safely (slowly) the intensity**
- **enormous stored energy :** nominal is 10 GJ in magnets, 362 MJ in beam; 0.7 MJ melts 1kg Cu
- currently 3.3 GJ in magnets, 130 MJ in beam

LHC :

2009 first collisions, mostly at injection energy 2x450 GeV

2010 2x3.5 TeV, β^*= 3.5 m, $L_{peak} = 0.2\times10^{33}\ cm^{-2}s^{-1}$ $\int L\,dt = 0.044\ fb^{-1}$ 368 bunches

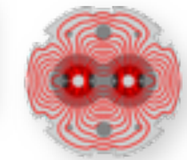
2011 2×3.5 TeV, β^*= 1.0 m, $L_{peak} = 3.5\times10^{33}\ cm^{-2}s^{-1}$ $\int L\,dt = 6.1\ fb^{-1}$ 1380 bunches

2012 2×4.0 TeV, β^*= 0.6 m, $L_{peak} = 7.7\times10^{33}\ cm^{-2}s^{-1}$ $\int L\,dt = 23.3\ fb^{-1}$ 1380 bunches

2013 Pb-p run, shutdown, magnet interconnects, restart in 2015 at **2×6.5 TeV,** increase #bunches

	LHC design	achieved
Momentum at collision, TeV/c	**7**	**4**
Luminosity, $cm^{-2}s^{-1}$	**1.0E+34**	**7.7E+33**
Dipole field at top energy, T	**8.33**	**4.8**
Number of bunches, each beam	**2808**	**1380**
Particles / bunch	**1.15E+11**	**1.70E+11**
Typical beam size in ring, µm	**200 – 300**	**~300**
Beam size at IP, µm	**17**	**20**

LS1 : LHC 2013 - 2014 shutdown - consolidation



LHC schedule beyond LS1

Only EYETS (19 weeks) (no Linac4 connection during Run2)

LS2 starting in 2018 (July) 18 months + 3months BC (Beam Commissioning)

LS3 LHC: starting in 2023 => 30 months + 3 BC

injectors: in 2024 => 13 months + 3 BC

LHC
300 fb-1
to LS3

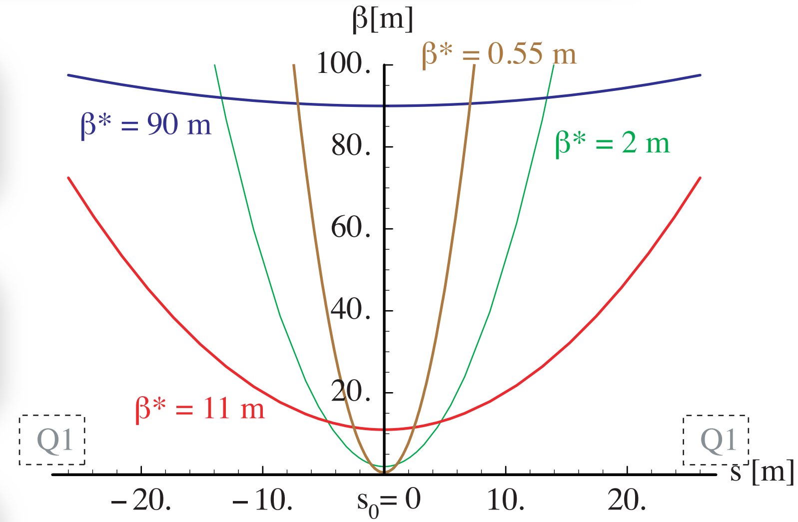
HL-LHC
3000 fb-1

LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators
Monday 2nd December 2013

Low β insertion ; LHC

the β-function in a field free region has a form of a parabola with

$$\beta(s) = \beta^* + \frac{(s - s_0)^2}{\beta^*}$$

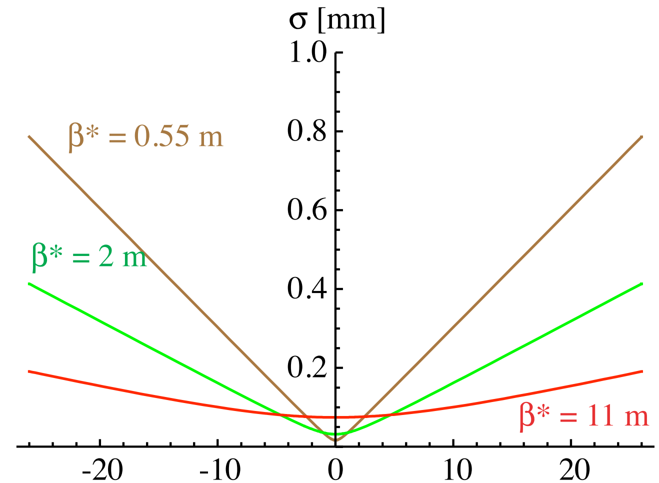


the beam size of a beam of emittance ε in a dispersion free region is

$$\sigma = \sqrt{\beta\,\varepsilon}$$

and the angular beam size divergence

$$\sigma' = \sqrt{\frac{\varepsilon}{\beta}}$$



the beam size increases about linearly from the IP to the first quadrupole, by a factor s / β* (for s >> β*)

--> aperture limit for low β*

LHC triplet aperture currently 70 mm (50 mm with screen)

upgrade studies --> 130 mm aperture, NbTi

for the nominal emittance

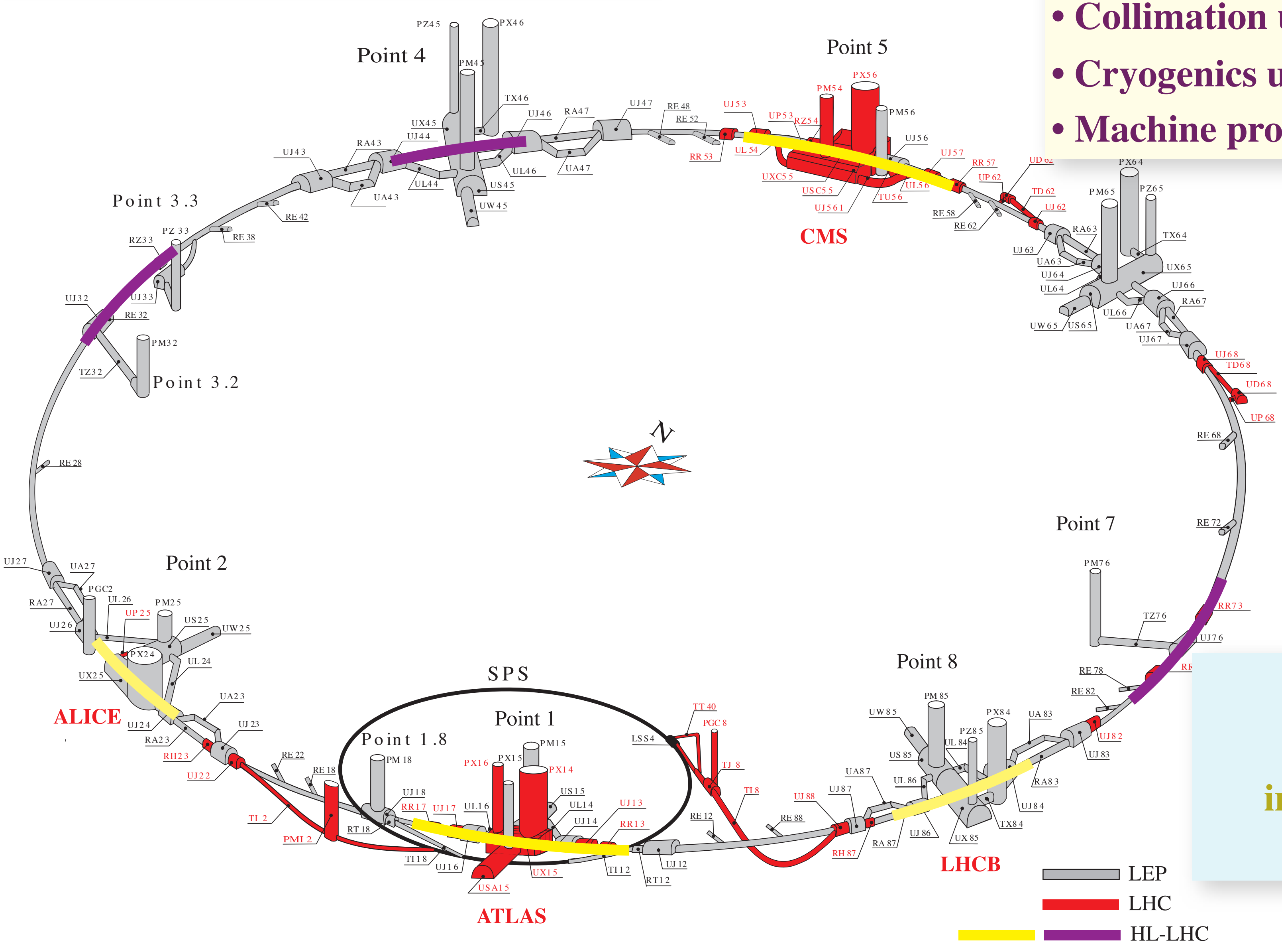
$\varepsilon_N = 3.75\ \mu m$, $\varepsilon_N = \varepsilon\,\beta\,\gamma$

$\varepsilon = 0.503$ nm at 7 TeV

HighLuminosity-LHC, major upgrade over ~ 1.2 km

- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles

- Crab Cavities
- Harmonic RF, 200 or 800 MHz
- Cold powering
- Collimation upgrade
- Cryogenics upgrade
- Machine protection, ...



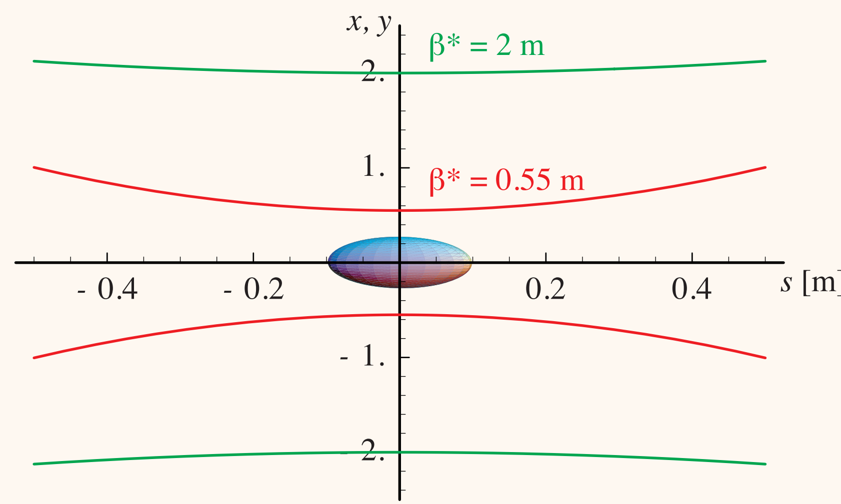
IP1, 5
new large aperture triplet crab-cavities

IP2, 8
ALICE, LHCb improved TDI and shielding IP8

Hourglass and crab-crossing

Hourglass effect. Relevent when β^* is decreased close to the bunch length σ_z. Define $r = \beta^* / \sigma_z$. Luminosity gets reduced. For round beams the factor is

$$H(r) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{e^{-s^2}}{1 + s^2/r^2}\, ds = \sqrt{\pi}\, r\, e^{r^2}\, \mathrm{Erfc}(r)$$



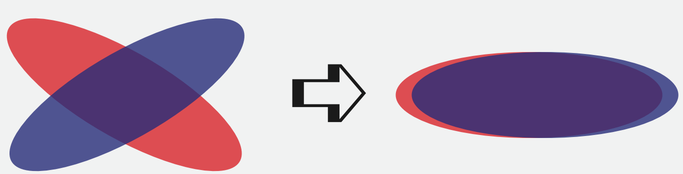
LHC values

$\sigma_z = 7.55$ cm

β^*	r	$H(r)$
10.	132.	0.999972
2.	26.5	0.999289
1.	13.2	0.997174
0.55	7.28	0.990833

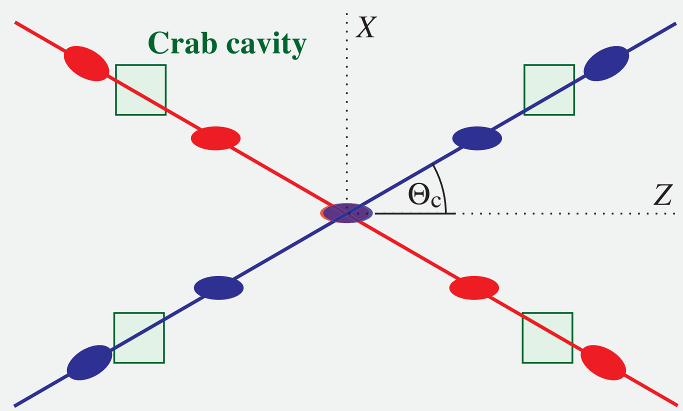
Crab crossing : relevant for large crossing angle θ_c or more precisely large Piwinski angles Φ

Use rf-cavities to rotate bunches by θ_c to get better overlap (higher lumi)



$$R_\theta = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

$R_\theta = 0.84$ or 20 % loss for nominal LHC



and less resonance excitation.

Tested at KEKB ; main option for LHC upgrade

Piwinski angle $\Phi = \frac{\sigma_z}{\sigma_x} \tan \theta c$

Options for future high energy machines beyond LHC

- **Linear collider CLIC**

- **FCC Future circular colliders from 27 km to ~ 100 km ring**
- **FCC-hh hadron hadron (pp, ions - very high energy LHC), 100 TeV**
- **FCC-ee e+e- collider options, ~ 350 GeV, precision + Higgs factory**

- **electron hadron options in LHC or FCC tunnel, LHeC, FCC eh**

other ideas, not discussed here :

Neutrino factories, based on

very high intensity (conventional) accelerators

beta beams

or muon colliders

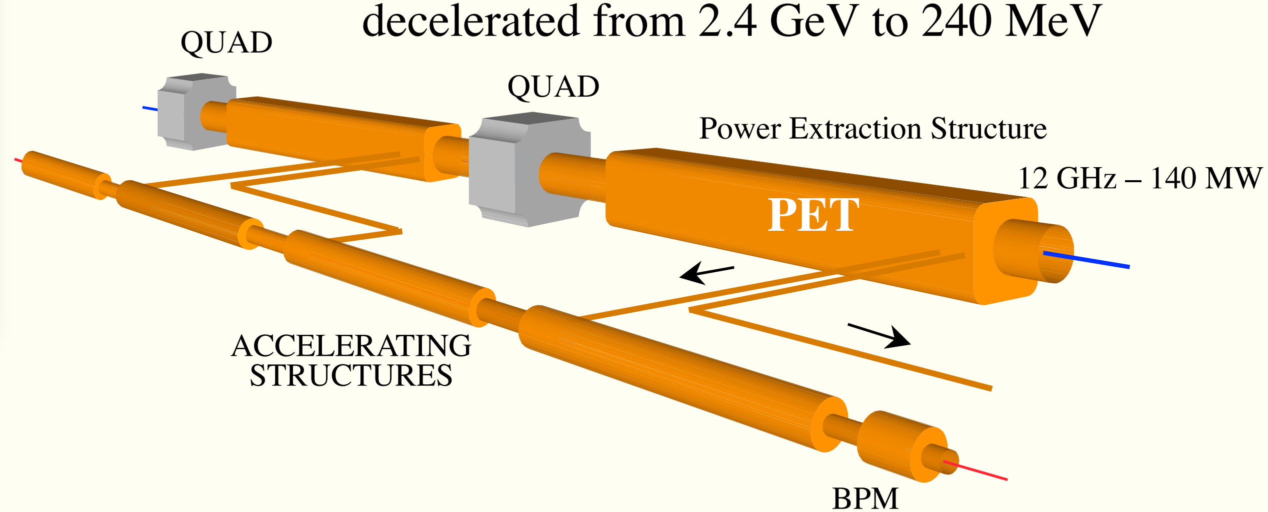
Two Beam Scheme

Drive Beam supplies RF power

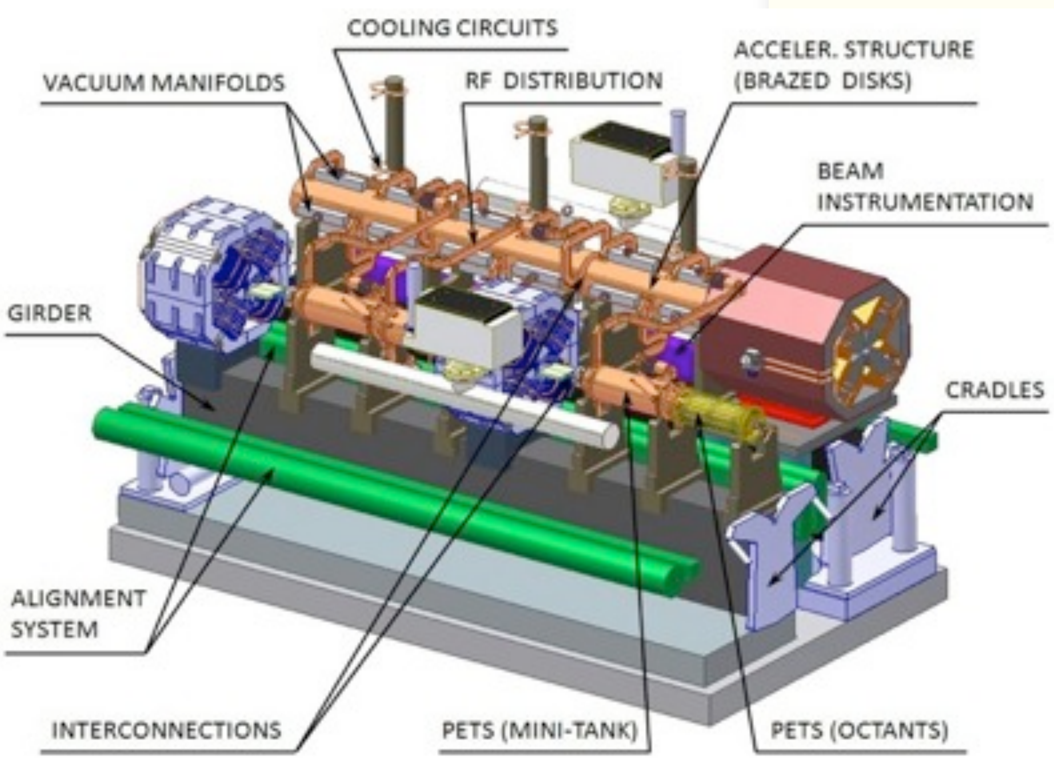
- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

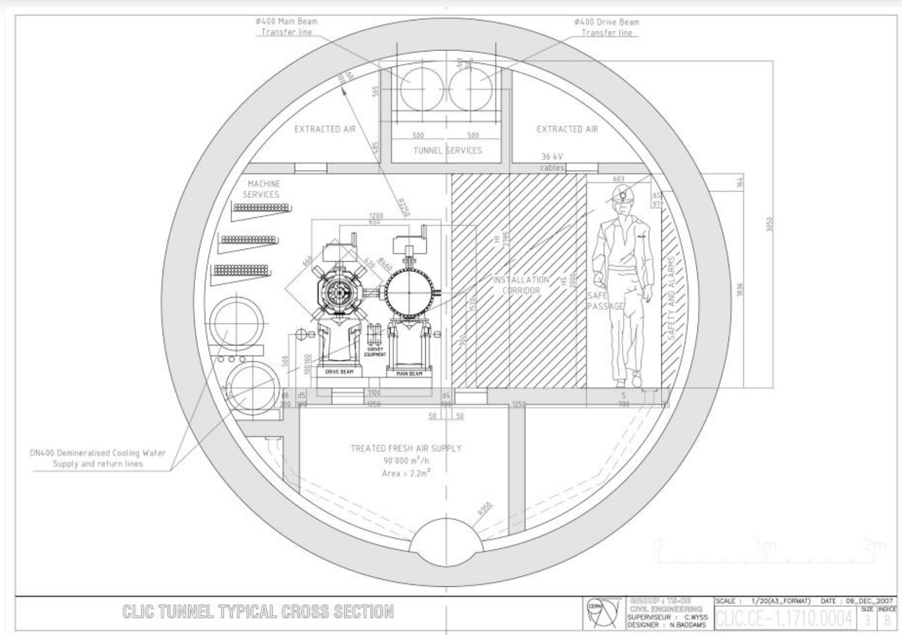
warm (not superconducting) RF

Drive beam - 100 A, 240 ns
decelerated from 2.4 GeV to 240 MeV

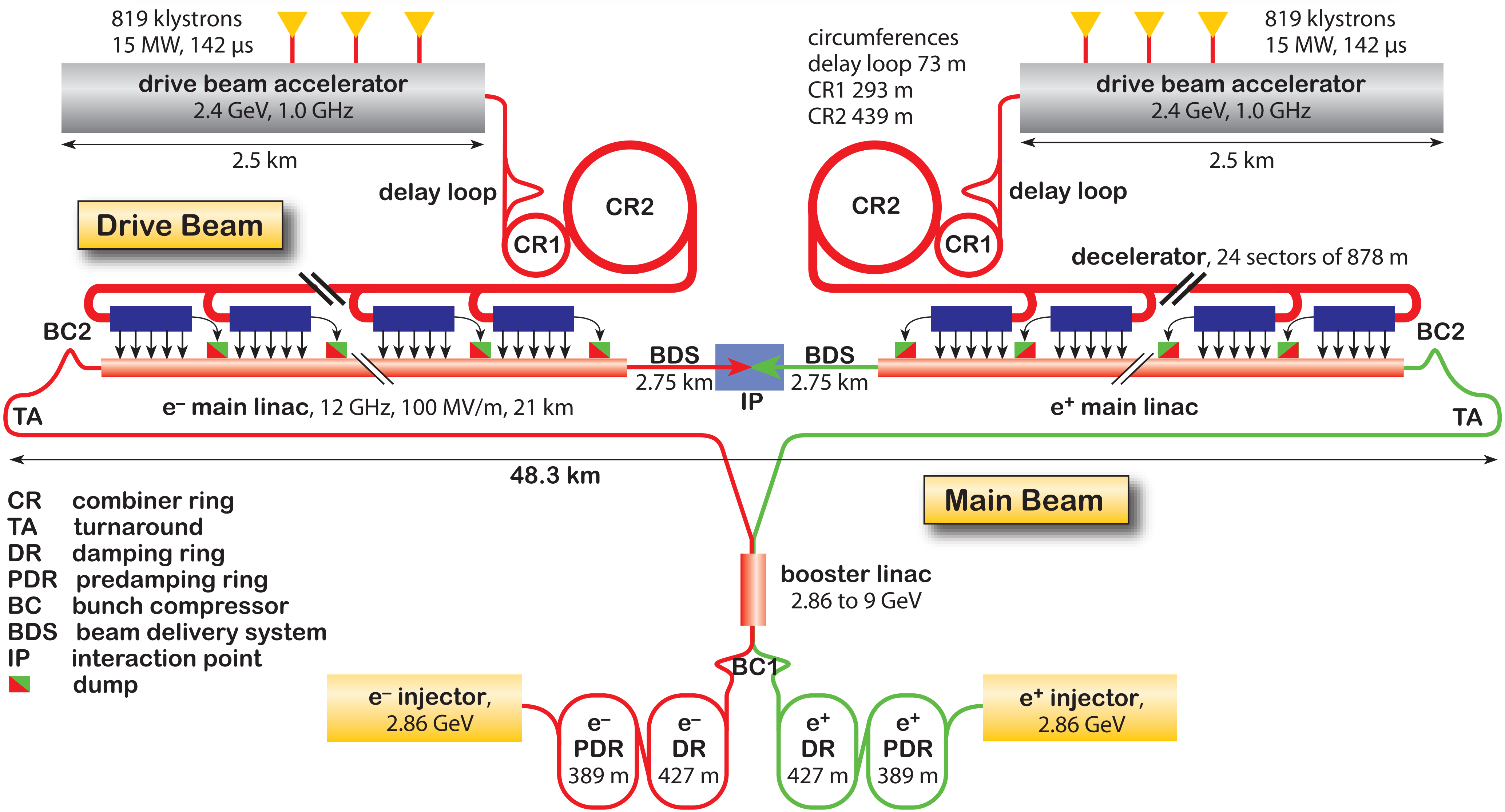


Main beam - 1.2 A, 156 ns bunch trains
accelerated from 9 GeV to 1.5 TeV





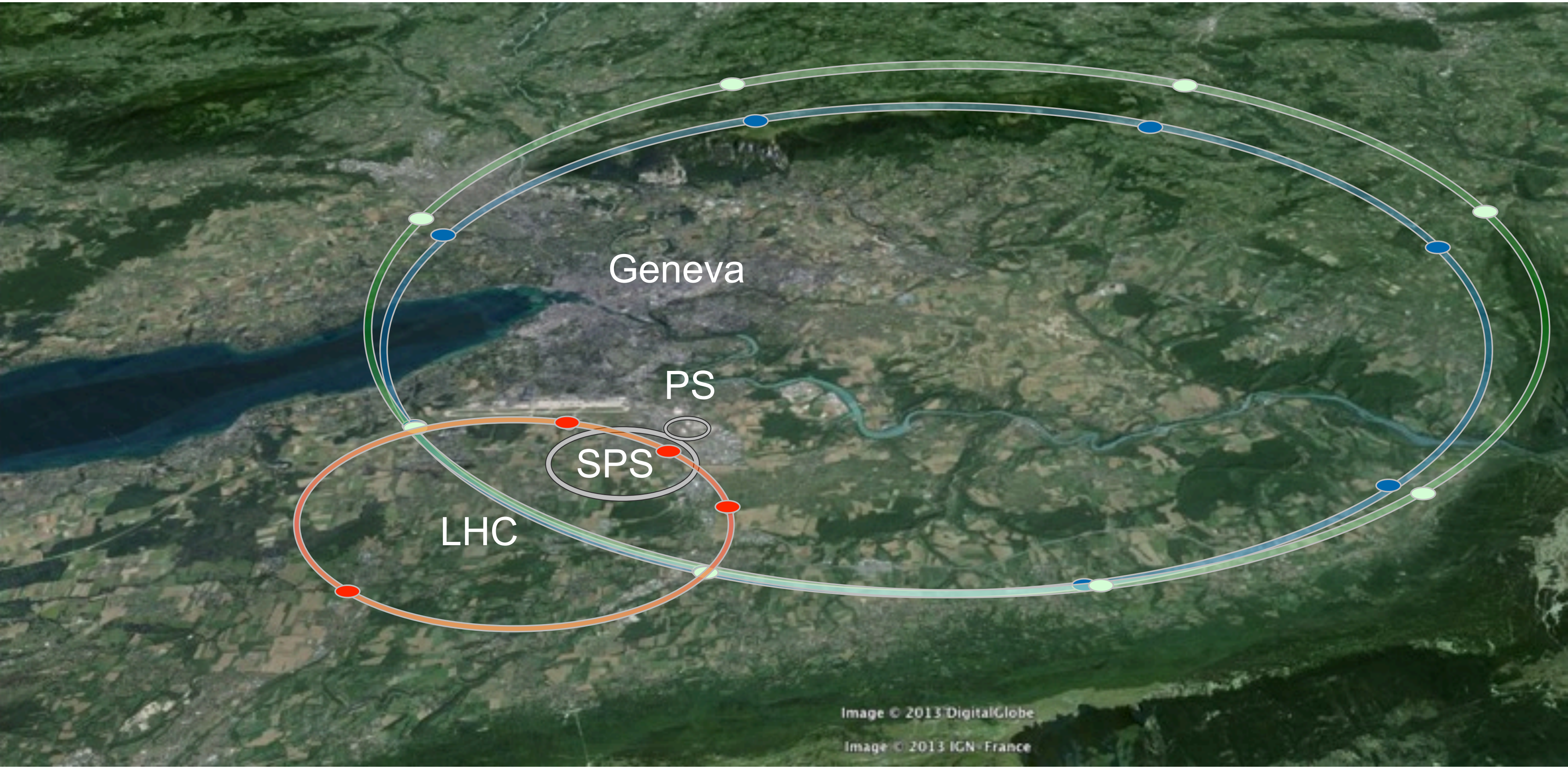
CLIC



Overview of the CLIC layout at $\sqrt{s} = 3$ TeV

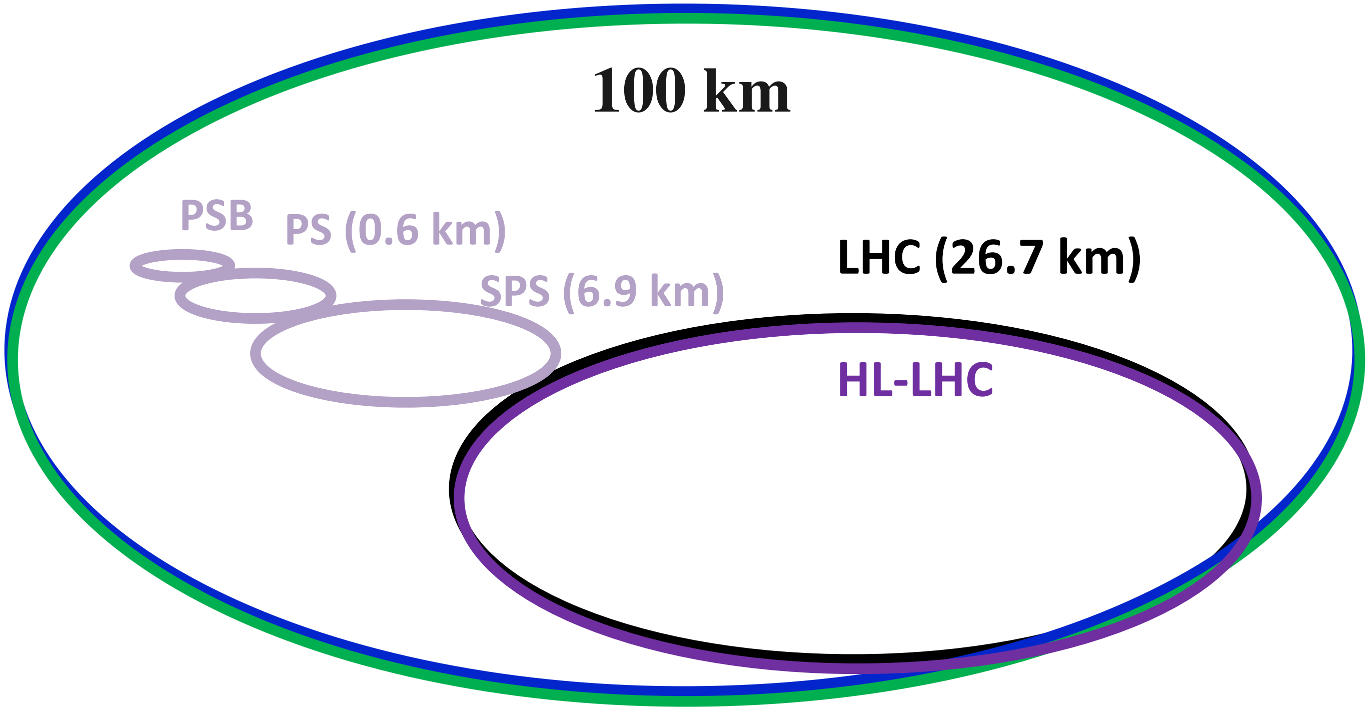
The machine requires only one drive beam complex for stages 1 and 2.

FCC-hh: 100 TeV pp collider



LHC	"HE-LHC"	FCC-hh (alternative)	FCC-hh (baseline)
27 km, 8.33 T	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV (c.m.)	33 TeV (c.m.)	100 TeV (c.m.)	100 TeV (c.m.)

FCC tunnel, many options : pp, ee, heavy ions, ep, eIon



FCC-hh
pp
100 TeV c.m.
& Heavy ion

FCC-ee e^+e^- collider
Higgs, top .. up to 350 GeV c.m.

≥50 years *pp*, *e^+e^-*, *$e^\pm p$/ion* physics at highest energies

parameter	LEP2	FCC-ee					CepC
		Z	Z (c.w.)	W	H	t	H
E_{beam} [GeV]	104	45	45	80	120	175	120
circumference [km]	26.7	100	100	100	100	100	54
current [mA]	3.0	1450	1431	152	30	6.6	16.6
$P_{SR,tot}$ [MW]	22	100	100	100	100	100	100
no. bunches	4	16700	29791	4490	1360	98	50
N_b [10^{11}]	4.2	1.8	1.0	0.7	0.46	1.4	3.7
ε_x [nm]	22	29	0.14	3.3	0.94	2	6.8
ε_y [pm]	250	60	1	1	2	2	20
β^*_x [m]	1.2	0.5	0.5	0.5	0.5	1.0	0.8
β^*_y [mm]	50	1	1	1	1	1	1.2
σ^*_y [nm]	3500	250	32	130	44	45	160
$\sigma_{z,SR}$ [mm]	11.5	1.64	2.7	1.01	0.81	1.16	2.3
$\sigma_{z,tot}$ [mm] (w beamstr.)	11.5	2.56	5.9	1.49	1.17	1.49	2.7
hourglass factor F_{hg}	0.99	0.64	0.94	0.79	0.80	0.73	0.61
L/IP [10^{34} cm^{-2}s^{-1}]	0.01	28	212	12	6	1.7	1.8
τ_{beam} [min]	300	287	39	72	30	23	40

Accelerator applications and R&D (last slide)

- **The largest flag-ship accelerator is the LHC here at CERN**
- **By now many more accelerators outside particle physics**
  #Accelerators in the world : O (30 000) mostly smaller for medical and industrial applications
  examples HIT Heidelberger Ionenstrahl-Therapiezentrum, MedAustron bei Wien

- **Broad range of particle accelerator types and applications**

Large research facilities for :
Synchrotron light, UV, X-Ray (electron accelerators)
High intensity proton accelerators + neutron spallation sources
condensed matter, material science and biology research,
accelerator driven subcritical fission (energy production & radioactive waste incineration)

Yearly international accelerator conferences IPAC, last in Dresden, next in Richmond / US

Some of the hot-subjects and keywords :

- **Free electrons lasers FEL, X-FEL, Laser induced coherent SR**
- **Advanced LINACS -- including recirculation and energy recovery ERL**
- **New acceleration techniques :**
  - **Dieletric, LASER, Plasma driven**