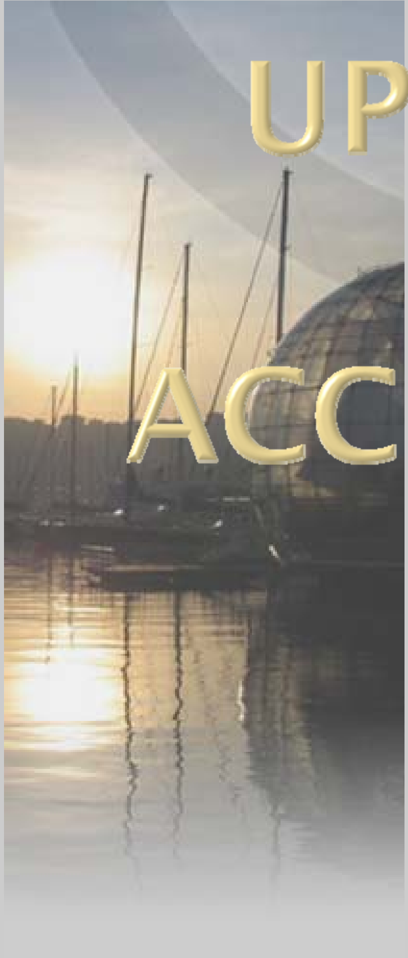


UPGRADE ISSUES FOR THE CERN ACCELERATOR COMPLEX

OUTLINE

- Introduction
- LHC
- Injector complex
- Conclusion

R. Garoby

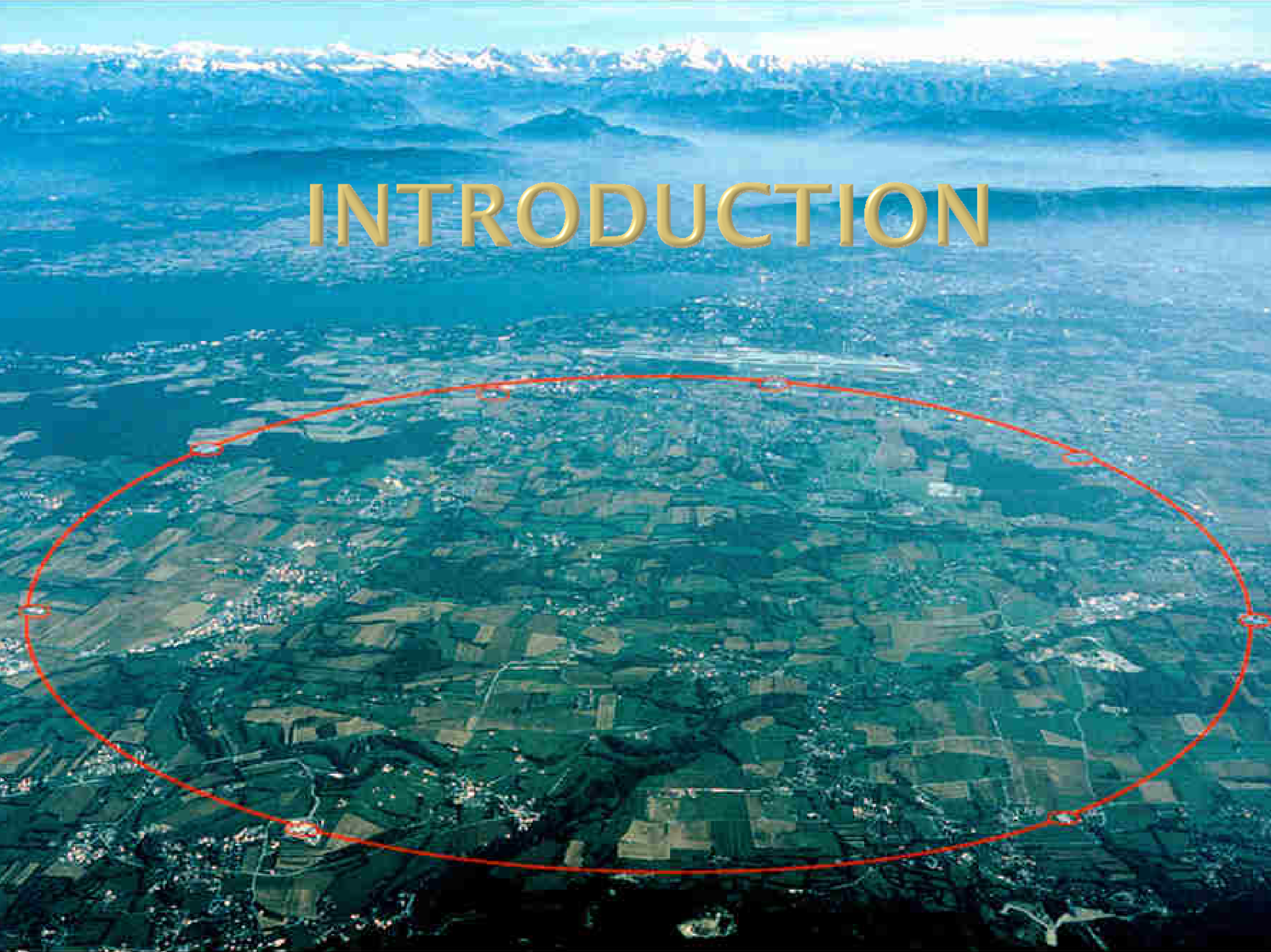
Credits

Many contributors outside and inside CERN in multiple working groups:

- On LHC itself: F. Ruggiero et al. mostly in the context of CARE – HHH network (with support of the EU-FP6) with contribution from US-LARP (with support of DOE).
- On the future of proton accelerators at CERN: POFPA and PAF
- On the injectors: design teams on Linac4, SPL, PS2, SPS improvements...

and invaluable help by numerous enlightening discussions during workshops & conferences…

INTRODUCTION



Objectives

- **TOPIC:**

Upgrades of proton (heavy ion) accelerators at CERN

~~LHC status~~

~~Lepton Hadron collider ("LHeC")~~

~~Higher Energy Collider ("DLHC")~~

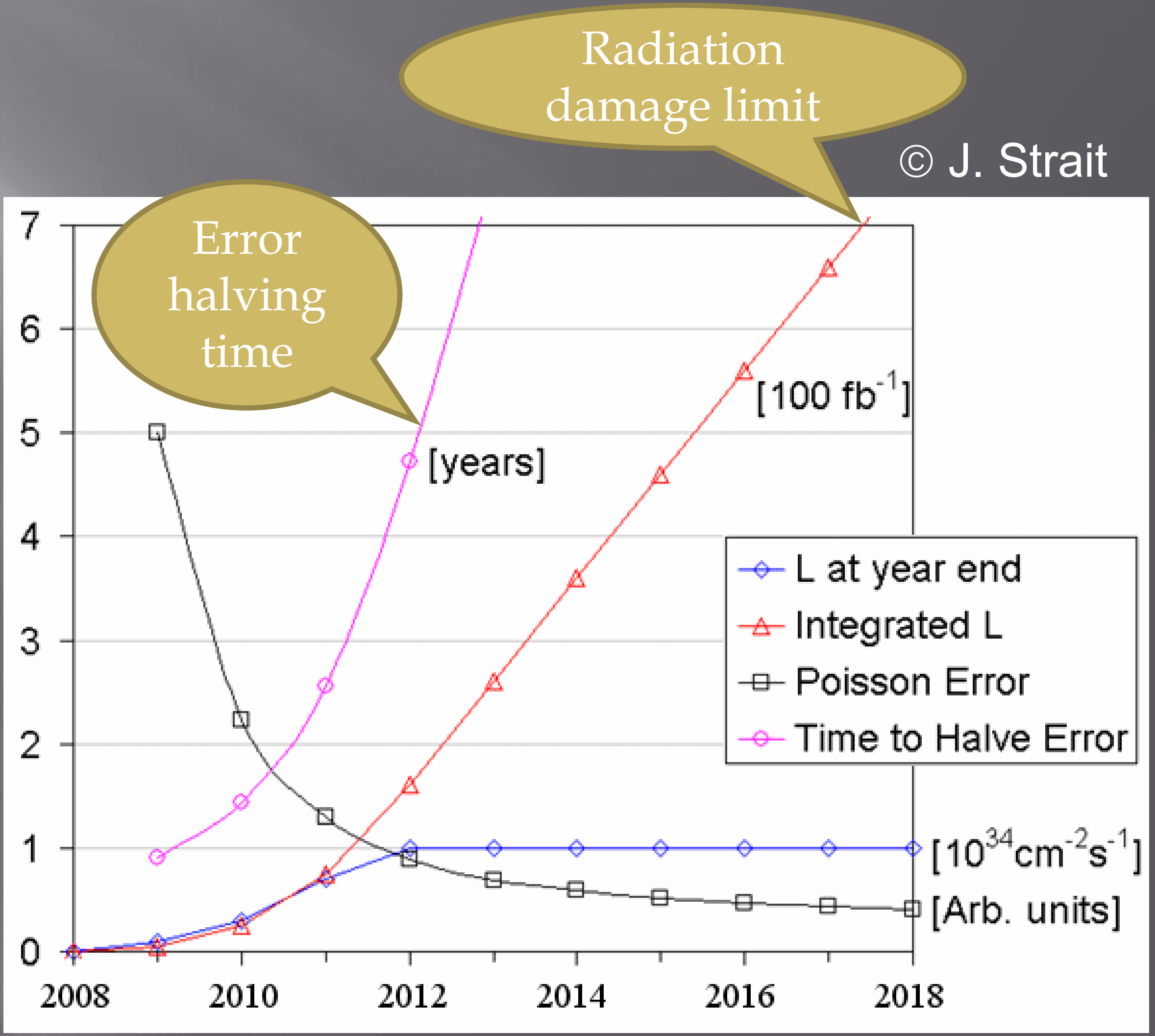
~~Lepton-Lepton Collider ("CLIC or ILC")~~

- **QUESTIONS:**
  - Why upgrade?
  - When?
  - Which upgrades?

Why upgrade the LHC ?

- Hardware ageing
- Foreseeable luminosity evolution

⇒ Need for a major luminosity upgrade in ~2017 (SLHC)



© J. Strait

Why upgrade the injectors ?

- Need for reliability:
  - Accelerators are old [Linac2: 1978, PSB: 1975, PS: 1959, SPS: 1976]
  - They operate far from their design parameters and close to hardware limits
  - The infrastructure has suffered from the concentration of resources on LHC during the past 10 years
- Need for better beam characteristics

When ?

Start of SLHC: **~2017**

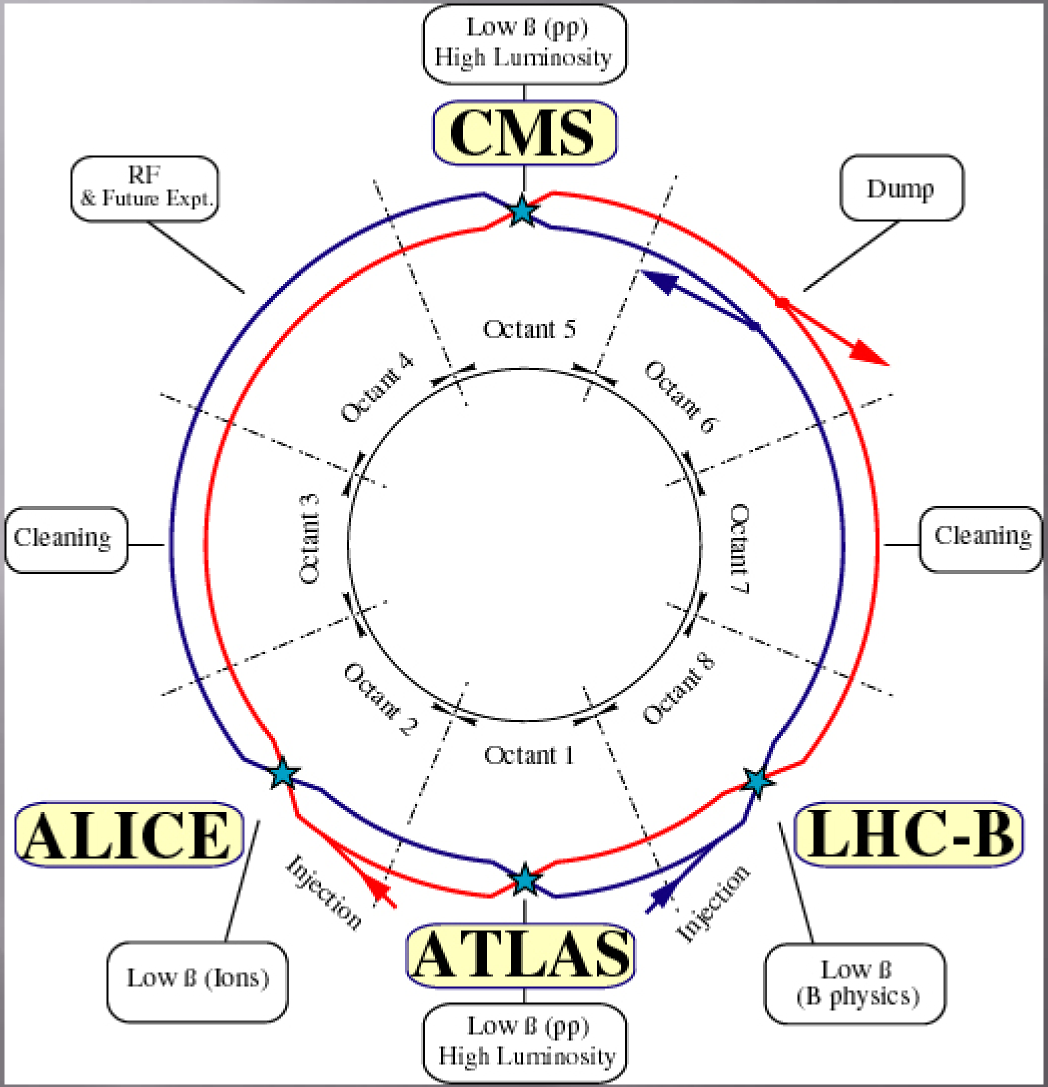
⇒ start of construction (New IR hardware and new injectors): **~2012**

⇒ Detailed project proposal (TDR + cost estimates): **mid-2011**

⇒ R & D for new IR hardware and new injectors: **2008-2011**

LHC

LHC Interaction Regions



proton-proton collider

c.m. energy 14 TeV
(7x Tevatron)

Design luminosity
10^{34} cm^{-2}s^{-1}
(~100x Tevatron)

Start of
beam commissioning
in 2008

LHC baseline luminosity was pushed in competition with SSC

Preliminary improvements

Enabled by additional resources for "New Initiatives" + Support of EU-FP7 & US-LARP

Known limitations of LHC "as built"

- Collimation phase 1:

  Limit at ~40% of nominal intensity

- Initial IR triplets:
  - gradient : 205 T/m
  - aperture:
    - Coil 70 mm
    - Beam screen 60 mm ⇒ minimum $\beta^* = 0.55$ m

      maximum $L = 10^{34}$ cm^{-2}s^{-1}
  - Power in triplet ~ 200 W at 1.9 K

Preliminary improvements

Enabled by additional resources for “New Initiatives” + Support of EU-FP7 & US-LARP

Collimation phase 2

- Goal: 10 × better in cleaning efficiency / impedance / set-up time (accuracy?), much more robust against radiation and better for radiation handling.
- Means:
  - Cleaning efficiency: add. metallic collim. + cryogenics collim. inside sc dispersion suppressor + # material for primary collim.
  - Impedance: investigate new ideas (!) + beam feedback + use less collimators + increased triplet aperture (IR upgrade phase 1)
  - Set-up time (accuracy ?): BPM inside collimator jaws
- Planning:
  - Conceptual design review by end 2008
  - Hardware test with & without beam in 2009/2010
  - Operational in 2011/2012

Preliminary improvements

Enabled by additional resources for “New Initiatives” + Support of EC-FP7 & US-LARP

IR upgrade phase 1

- Goal: Enable focusing of the beams to $\beta^*=0.25$ m in IP1 and IP5, and reliable operation of the LHC at 2×10^{34} cm^{-2}s^{-1}.
- Scope:
  - Upgrade of ATLAS and CMS IRs.
  - Replace present triplets with wide aperture quadrupoles based on LHC dipole cables (Nb-Ti) cooled at 1.9 K.
  - Upgrade D1 separation dipole, TAS and other beam-line equipment so as to be compatible with the inner triplet aperture.
  - Modify matching sections (D2-Q4, Q5, Q6) to improve optics flexibility. Introduction of other equipment to the extent of available resources.
- Planning: operational for physics in 2013

Instantaneous luminosity

For operation at the beam-beam limit with alternating planes of crossing at two IPs:

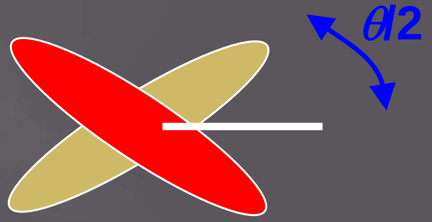
$$\boxed{L = \frac{f_{rev}\gamma}{2r_p} n_b \frac{1}{\beta^*} N_b(\Delta Q_{bb}) F_{profile} F_{hg}}$$

where (ΔQ_{bb}) = total beam-beam tune shift

$$\boxed{\Delta Q_{bb} \cong -\frac{N_b}{\varepsilon_N} \frac{r_p}{2\pi\sqrt{1+\phi^2}}}$$

with ϕ = Piwinski angle

$$\boxed{\phi = \theta\sigma_Z/(2\sigma^*)}$$



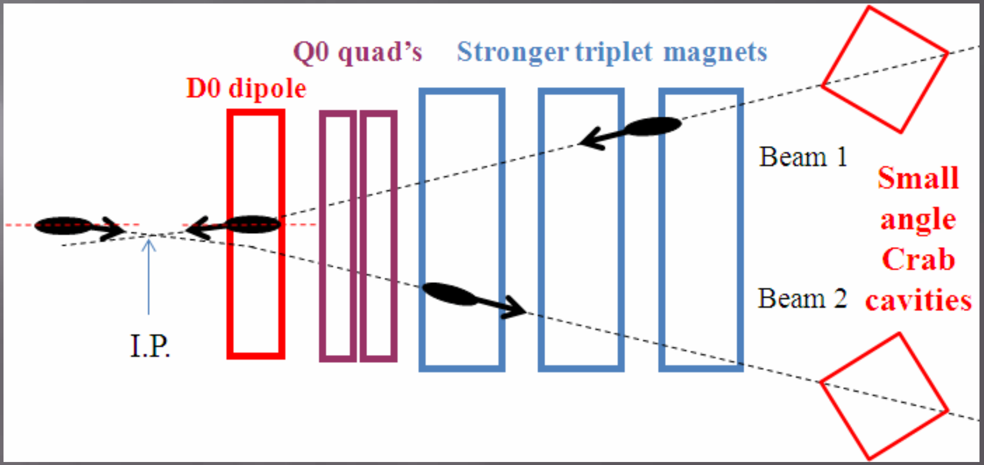
effective beam size

$$\sigma \to \sigma\sqrt{1+\phi^2}$$

“Early Separation” scheme

Main ingredients:	Factor wrt ultimate
Ultimate beam	1
D0 dipole close to IP ⇒ bunches quasi-aligned at collision ($\phi \sim 0$) ⇒ larger ΔQ_{bb}	1.3
Very small β^*(8 cm)	6
Hour-glass effect	0.86
Total	6.7

J.-P. Koutchouk



- ultimate beam ($1.7x10^{11}$ protons/bunch, 25 spacing), β^* ~10 cm
- early-separation dipoles in side detectors , crab cavities

→ hardware inside ATLAS & CMS detectors, first hadron crab cavities; off-δ β

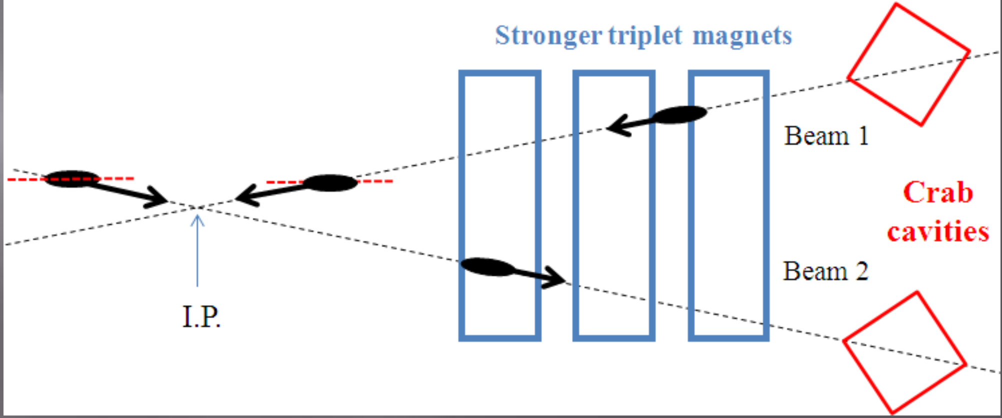
"Full Crab Crossing" scheme

Factor wrt ultimate

L. Evans,
W. Scandale,
F. Zimmermann

Main ingredients:

▣ Ultimate beam	1
▣ Crab cavities ⇒ bunches quasi-aligned at collision ($\phi \sim 0$) ⇒ larger ΔQ_{bb}	1.3
▣ Very small β^*(8 cm)	6
▣ Hour-glass effect	0.86
Total	6.7



- ultimate LHC beam (1.7×10^{11} protons/bunch, 25 spacing)
- β* ~10 cm
- crab cavities with 60% higher voltage

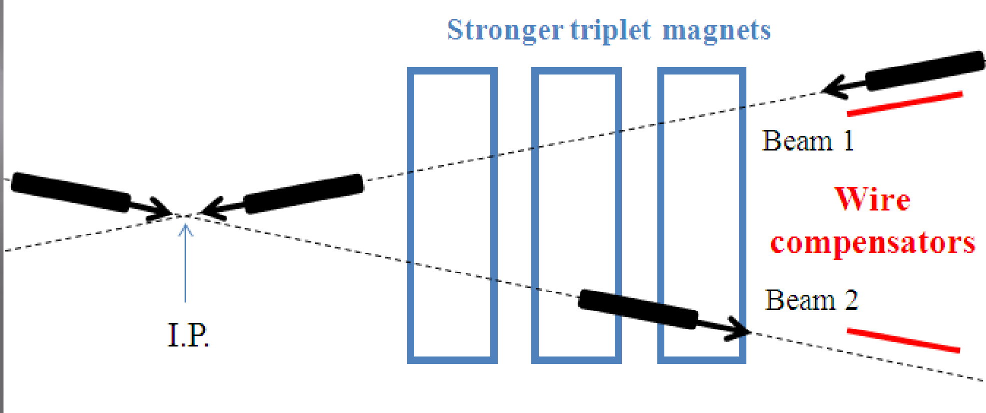
→ **first hadron crab cavities, off-δ β-beat**

“Large Piwinski angle” scheme

F. Ruggiero,
W. Scandale.
F. Zimmermann

Main ingredients:

	Factor wrt ultimate
▣ Larger beam current	1.45
▣ Large Piwinski angle and 3× intensity per bunch($\phi \sim 2$) ⇒ larger ΔQ_{bb}	1.3
▣ Reduced β^*(25 cm)	2
▣ Longit. profile	1.4
Total	5.3



- 50 ns spacing, longer & more intense bunches (5×10^{11} protons/bunch)
- $\beta^* \sim 25$ cm, no elements inside detectors
- long-range beam-beam wire compensation

→ novel operating regime for hadron colliders

Schemes comparison

© F. Zimmermann

Parameter	**Symbol**	**Nominal**	**Ultimate**	**EA**	**FCC**	**LPA**
transverse emittance	ε [μm]	3.75	3.75	**3.75**	**3.75**	**3.75**
protons per bunch	N_b [10^{11}]	1.15	1.7	**1.7**	**1.7**	**4.9**
bunch spacing	Δt [ns]	25	25	**25**	**25**	**50**
beam current	I [A]	0.58	0.86	**0.86**	**0.86**	**1.22**
longitudinal profile		Gauss	Gauss	**Gauss**	**Gauss**	**Flat**
rms bunch length	σ_z [cm]	7.55	7.55	**7.55**	**7.55**	**11.8**
beta* at IP1&5	β* [m]	0.55	0.5	**0.08**	**0.08**	**0.25**
full crossing angle	θ_c [μrad]	285	315	**0**	**673**	**381**
Piwinski parameter	$\phi=\theta_c\sigma_z/(2^*\sigma_x^*)$	0.64	0.75	**0**	**0**	**2.0**
hourglass reduction		1	1	**0.86**	**0.86**	**0.99**
peak luminosity	L [10^{34} cm^{-2}s^{-1}]	1	2.3	**15.5**	**15.5**	**10.7**
peak events per #ing		19	44	**294**	**294**	**403**
initial lumi lifetime	τ_L [h]	22	14	**2.2**	**2.2**	**4.5**
effective luminosity ($T_{turnaround}$=10 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	0.46	0.91	**2.4**	**2.4**	**2.5**
	$T_{run,opt}$ [h]	21.2	17.0	**6.6**	**6.6**	**9.5**
effective luminosity ($T_{turnaround}$=5 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	0.56	1.15	**3.6**	**3.6**	**3.5**
	$T_{run,opt}$ [h]	15.0	12.0	**4.6**	**4.6**	**6.7**
e-c heat SEY=1.4(1.3)	P [W/m]	1.07 (0.44)	1.04 (0.59)	**1.04 (0.59)**	**1.04 (0.59)**	**0.36 (0.1)**
SR heat load 4.6-20 K	P_{SR} [W/m]	0.17	0.25	**0.25**	**0.25**	**0.36**
image current heat	P_{IC} [W/m]	0.15	0.33	**0.33**	**0.33**	**0.78**

Luminosity lifetime

$$\boxed{\tau = \frac{1}{2}\frac{N_b}{\dot{N}_b} = \frac{n_b N_b}{L\sigma}}$$

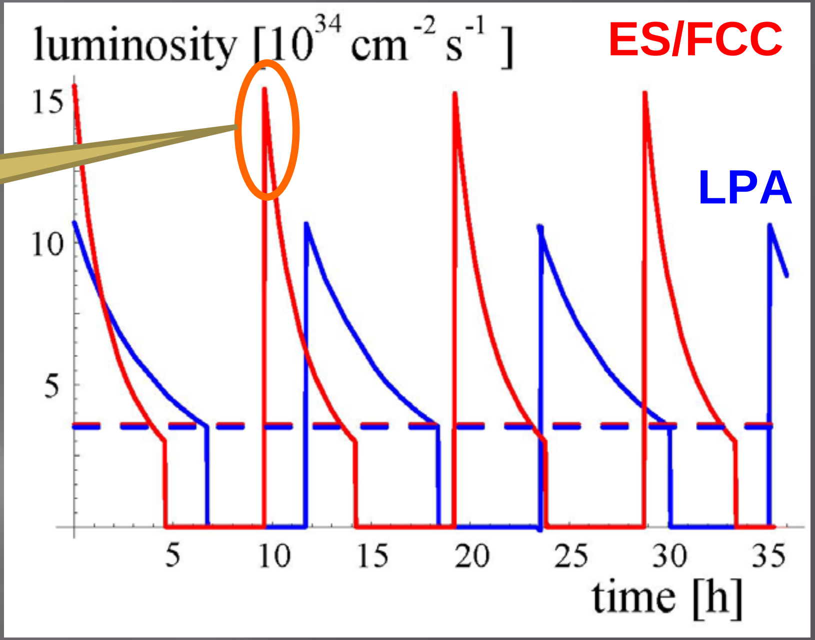
Increased luminosity ⇒ reduced life time

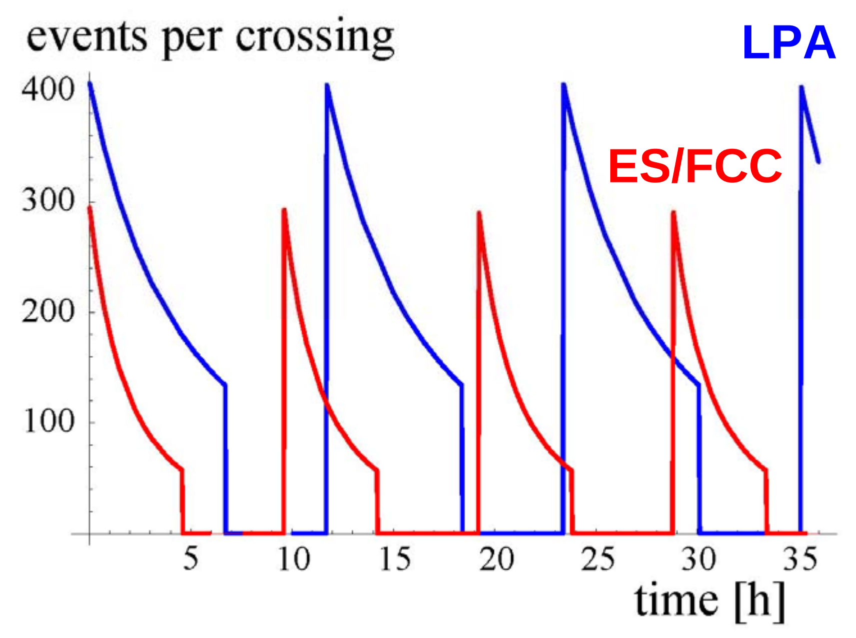
- Compensation measures ⇒ **increased total intensity**:
  - either more bunches (n_b ↑) : abandoned because of heat load to the beam screen and electron clouds effects
  - or higher intensity per bunch (N_b ↑): "soft" limit used in the LPA scheme
- Possible additional action: **luminosity leveling**

Luminosity evolution

- Luminosity decays faster with ES/FCC schemes

Initial peak luminosity may not be useful for physics





- But LPA always gives more events per crossing…

Luminosity leveling

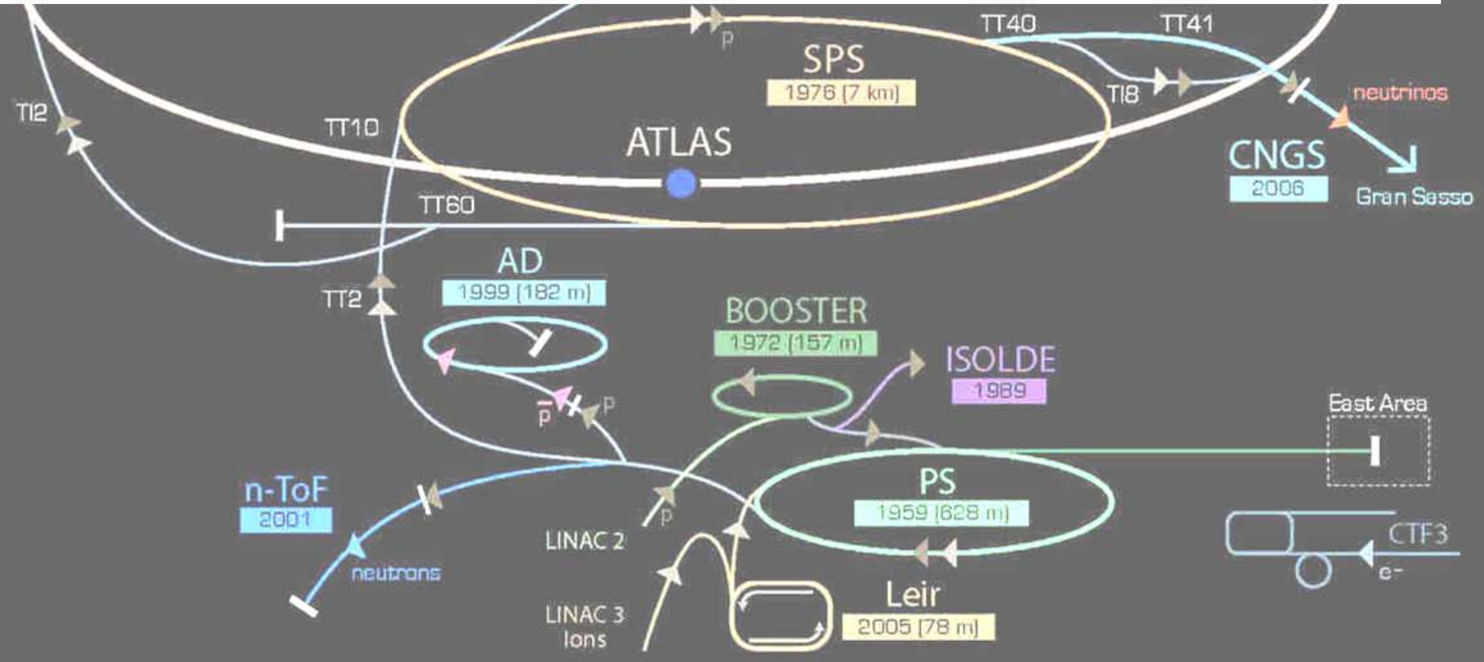
Experiments prefer more constant luminosity, with less pile up at the start of the run and higher luminosity at the end.

⇒ **Interest for luminosity leveling**

How?

- ES/FCC schemes: variable β^* and/or θ (either the effective crossing angle at the IP or the field in the crab cavities)
- LPA scheme: variable β^* and/or σ_Z

INJECTOR COMPLEX



▸ p (proton) ▸ ion ▸ neutrons ▸ p̄ (antiproton) —+—+— proton/antiproton conversion ▸ neutrinos ▸ electron

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice

LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

Upgrade procedure

Main performance limitation:

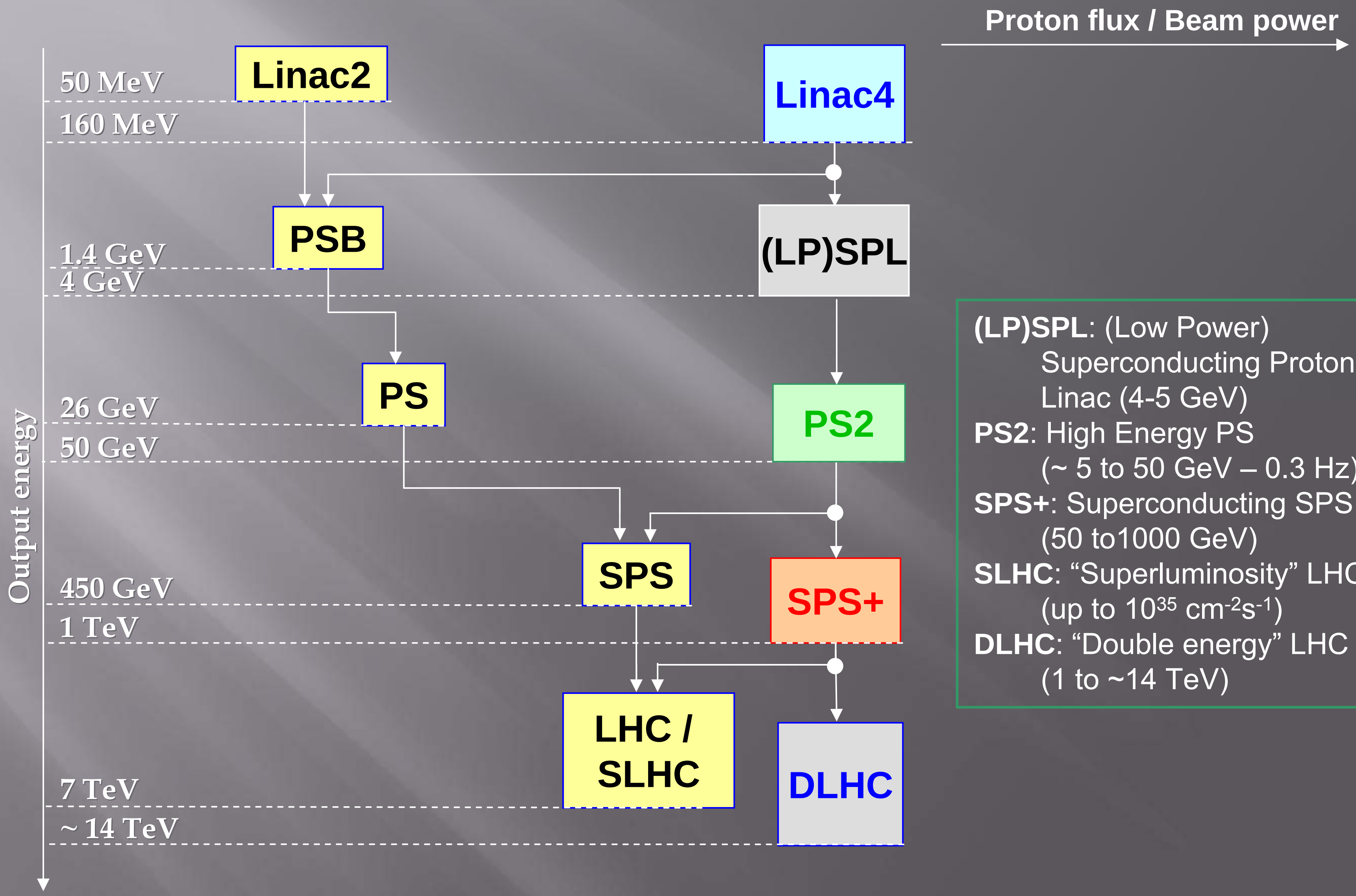
Incoherent space charge tune spreads ΔQ_{SC} at injection in the PSB (50 MeV) and PS (1.4 GeV) because of the required beam brightness N/ε^*.

$$\Delta Q_{SC} \propto \frac{N_b}{\varepsilon_{X,Y}} \cdot \frac{R}{\beta\gamma^2}$$

⇒ need to increase the injection energy in the synchrotrons

- Increase injection energy in the PSB from 50 to 160 MeV kinetic
- Increase injection energy in the SPS from 25 to 50 GeV kinetic
- Design the PS successor (PS2) with an acceptable space charge effect for the maximum beam envisaged for SLHC: => injection energy of 4 GeV

Present and future injectors



(LP)SPL: (Low Power) Superconducting Proton Linac (4-5 GeV)

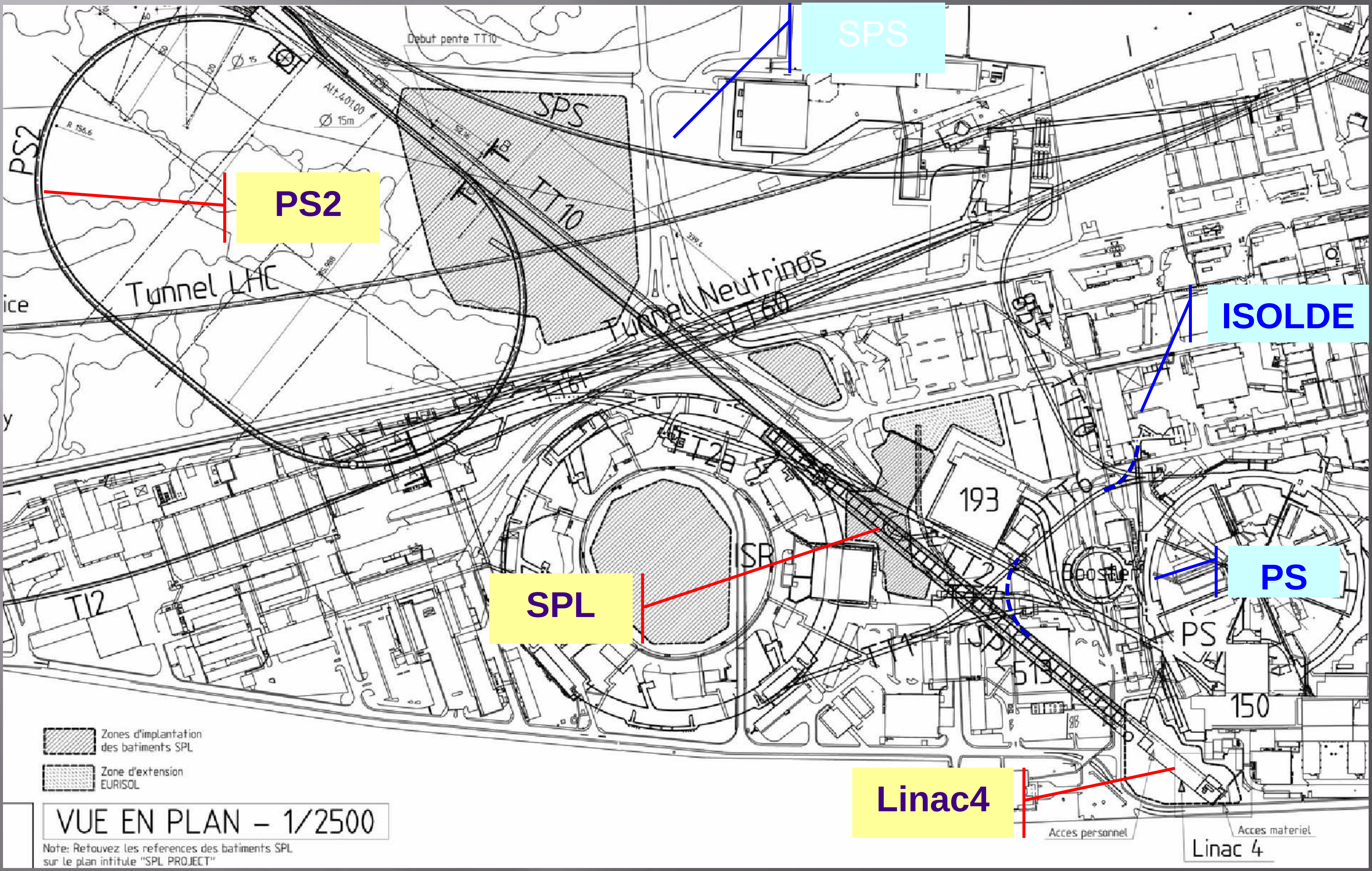
PS2: High Energy PS (~ 5 to 50 GeV – 0.3 Hz)

SPS+: Superconducting SPS (50 to1000 GeV)

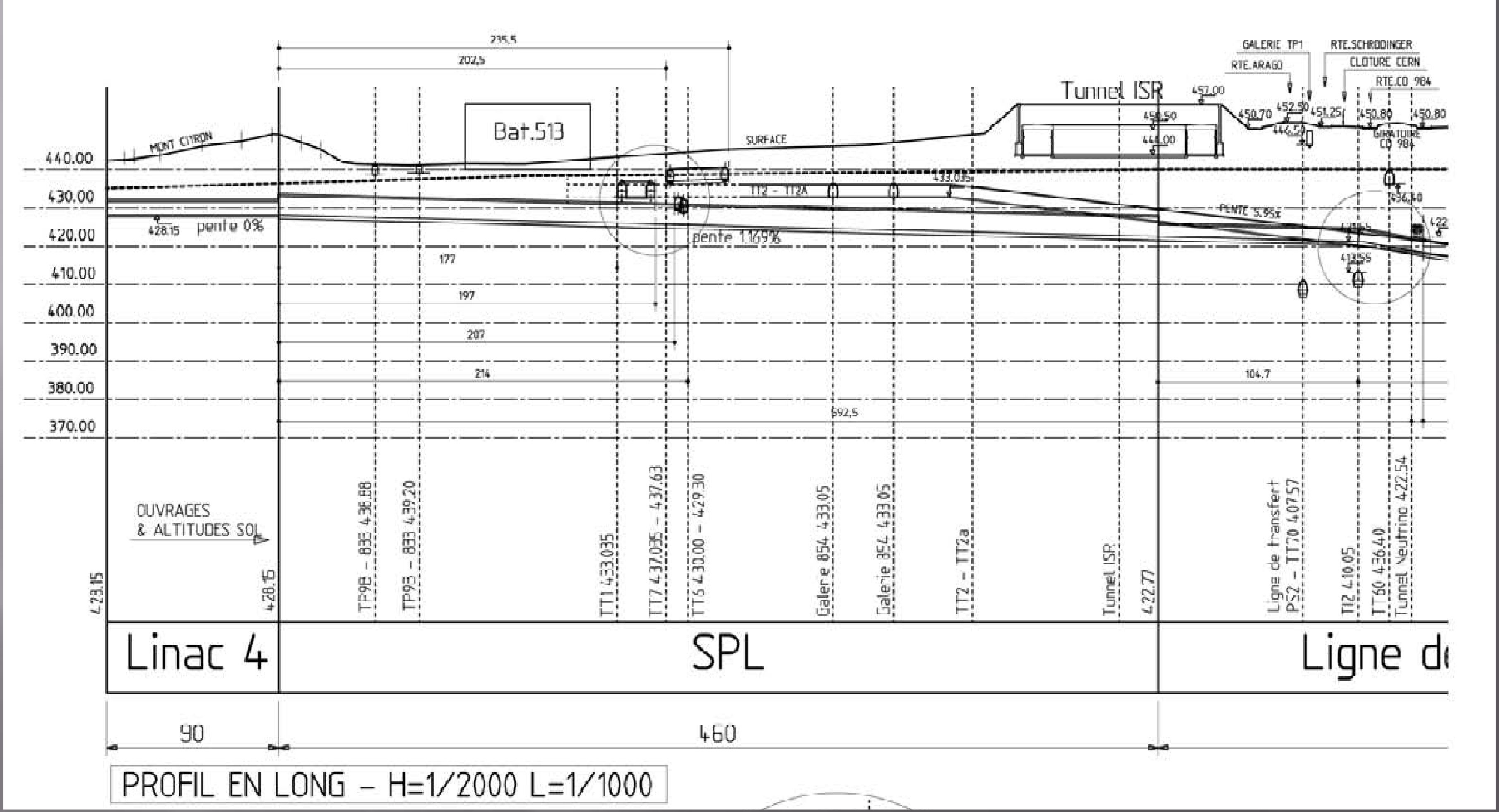
SLHC: “Superluminosity” LHC (up to 10^{35} cm^{-2}s^{-1})

DLHC: “Double energy” LHC (1 to ~14 TeV)

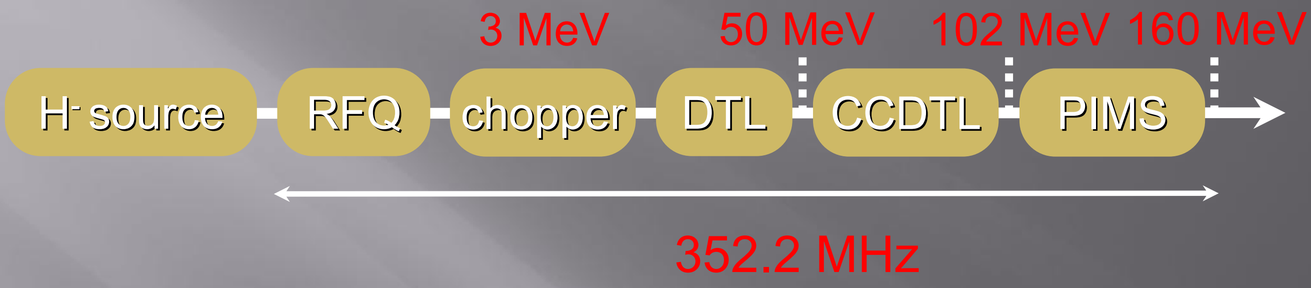
Layout of the new injectors



Layout of the new injectors



Stage 1: Linac4



3 MeV 50 MeV 102 MeV 160 MeV

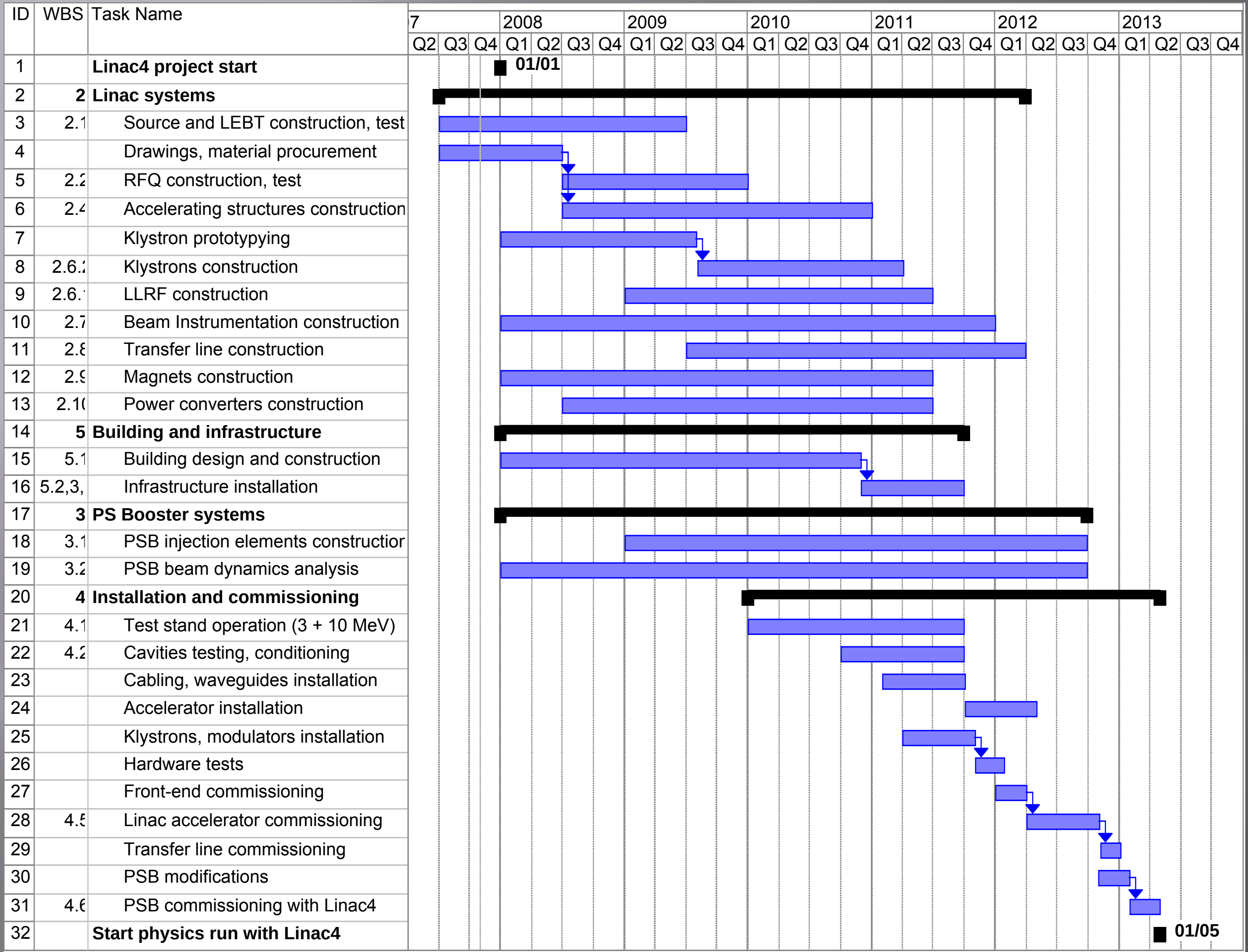
H^- source → RFQ → chopper → DTL → CCDTL → PIMS

352.2 MHz

Linac4 beam characteristics

Ion species	H^-
Output kinetic energy	160 MeV
Bunch frequency	352.2 MHz
Max. repetition rate	1.1 (2) Hz
Beam pulse duration	0.4 (1.2) ms
Chopping factor (beam on)	62%
Source current	80 mA
RFQ output current	70 mA
Linac current	64 mA
Average current during beam pulse	40 mA
Beam power	5.1 kW
Particles / pulse	$1.0\ 10^{14}$
Transverse emittance (source)	0.2 mm mrad
Transverse emittance (linac)	0.4 mm mrad

Stage 1: Planning



ID	WBS	Task Name
1		**Linac4 project start**
2	**2**	**Linac systems**
3	2.1	Source and LEBT construction, test
4		Drawings, material procurement
5	2.2	RFQ construction, test
6	2.4	Accelerating structures construction
7		Klystron prototyping
8	2.6.2	Klystrons construction
9	2.6.1	LLRF construction
10	2.7	Beam Instrumentation construction
11	2.8	Transfer line construction
12	2.9	Magnets construction
13	2.10	Power converters construction
14	**5**	**Building and infrastructure**
15	5.1	Building design and construction
16	5.2,3,	Infrastructure installation
17	**3**	**PS Booster systems**
18	3.1	PSB injection elements constructior
19	3.2	PSB beam dynamics analysis
20	**4**	**Installation and commissioning**
21	4.1	Test stand operation (3 + 10 MeV)
22	4.2	Cavities testing, conditioning
23		Cabling, waveguides installation
24		Accelerator installation
25		Klystrons, modulators installation
26		Hardware tests
27		Front-end commissioning
28	4.5	Linac accelerator commissioning
29		Transfer line commissioning
30		PSB modifications
31	4.6	PSB commissioning with Linac4
32		**Start physics run with Linac4**

Milestones

- End CE works: December 2010
- Installation: 2011
- Linac commissioning: 2012
- Modifications PSB: shut-down 2012/13 (6 months)
- Beam from PSB: 1rst of May 2013

Stage 1: Benefits

Stop of Linac2:

- End of recurrent problems with Linac2 (vacuum leaks, etc.)
- End of use of obsolete RF triodes (hard to get + expensive)

Higher performance for the PSB:

- Space charge decreased by a factor of 2 in the PSB

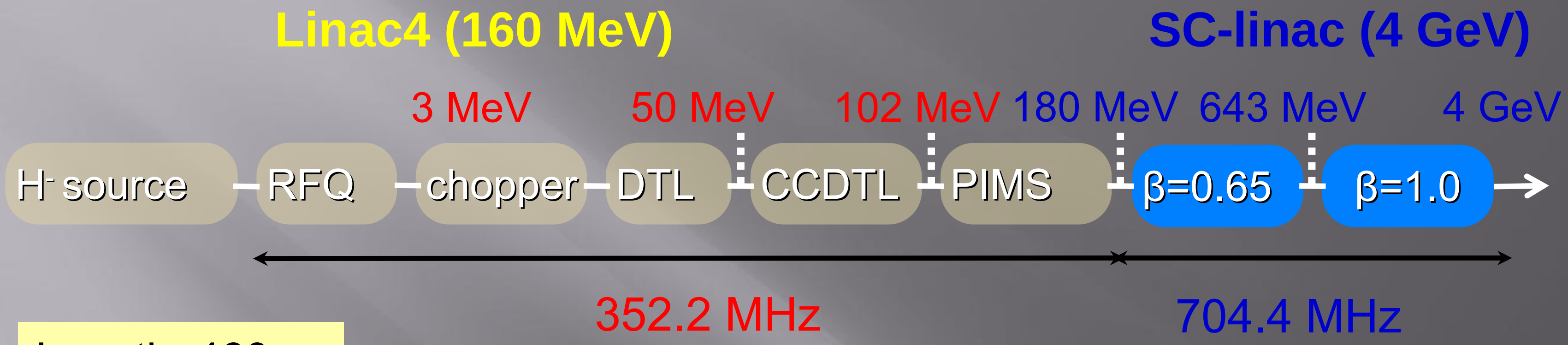
  ⇒ potential to double the beam brightness and fill the PS with the LHC beam in a single pulse: no more long flat bottom at PS injection + shorter flat bottom at SPS injection: easier/ more reliable operation / potential for ultimate beam from the PS

  ⇒ easier handling of high intensity.
- Low loss injection process (Charge exchange instead of betatron stacking)
- High flexibility for painting in the transverse and longitudinal planes (high speed chopper at 3 MeV in Linac4)
- More intensity per pulse available for PSB beam users (ISOLDE) – up to 2×
- More PSB cycles available for other uses than LHC

First step towards the SPL:

- Linac4 will provide beam for commissioning LPSPL + PS2 without disturbing physics

Stage 2: LP-SPL



Linac4 (160 MeV)

SC-linac (4 GeV)

3 MeV 50 MeV 102 MeV 180 MeV 643 MeV 4 GeV

H⁻ source – RFQ – chopper – DTL – CCDTL – PIMS – β=0.65 – β=1.0 →

352.2 MHz

704.4 MHz

Length: 460 m

LP-SPL beam characteristics

Kinetic energy (GeV)	**4**
Beam power at 4 GeV (MW)	**0.16**
Rep. period (s)	**0.6**
Protons/pulse (x 10^{14})	**1.5**
Average pulse current (mA)	**20**
Pulse duration (ms)	**1.2**

Stage 2: PS2

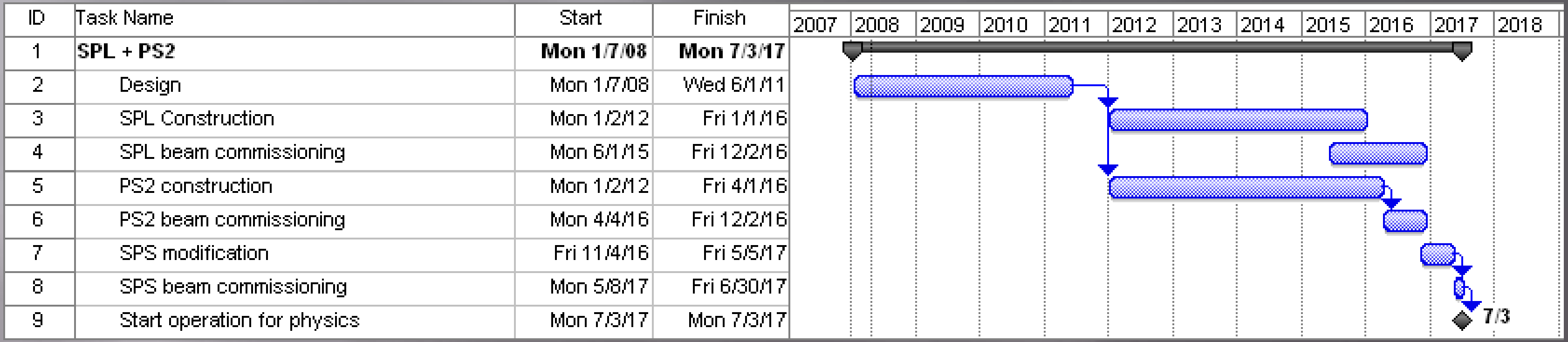
PS2 main characteristics
compared to the present PS

	PS2	PS
Injection energy kinetic (GeV)	4.0	1.4
Extraction energy kinetic (GeV)	~ 50	13/25
Circumference (m)	1346	628
Maximum intensity LHC (25ns) (p/b)	4.0×10^{11}	$\sim 1.7 \times 10^{11}$
Maximum intensity for fixed target physics (p/p)	1.2×10^{14}	3.3×10^{13}
Maximum energy per beam pulse (kJ)	1000	70
Max ramp rate (T/s)	1.5	2.2
Cycle time at 50 GeV (s)	2.4	1.2/2.4
Max. effective beam power (kW)	400	60

Stage 2: Planning

Construction of LP-SPL and PS2 will not interfere with the regular operation of Linac4 + PSB for physics.

Similarly, beam commissioning of LP-SPL and PS2 will take place without interference with physics.



ID	Task Name	Start	Finish
1	**SPL + PS2**	**Mon 1/7/08**	**Mon 7/3/17**
2	Design	Mon 1/7/08	Wed 6/1/11
3	SPL Construction	Mon 1/2/12	Fri 1/1/16
4	SPL beam commissioning	Mon 6/1/15	Fri 12/2/16
5	PS2 construction	Mon 1/2/12	Fri 4/1/16
6	PS2 beam commissioning	Mon 4/4/16	Fri 12/2/16
7	SPS modification	Fri 11/4/16	Fri 5/5/17
8	SPS beam commissioning	Mon 5/8/17	Fri 6/30/17
9	Start operation for physics	Mon 7/3/17	Mon 7/3/17

Milestones

- Project proposal: June 2011
- Project start: January 2012
- LP-SPL commissioning: mid-2015
- PS2 commissioning: mid-2016
- SPS commissioning: May 2017
- Beam for physics: July 2017

Stage 2: Benefits

Stop of PSB and PS:

- End of recurrent problems (damaged magnets in the PS, etc.)
- End of operation of old accelerators at their maximum capability
- Safer operation at higher proton flux (adequate shielding and collimation)

Higher performance:

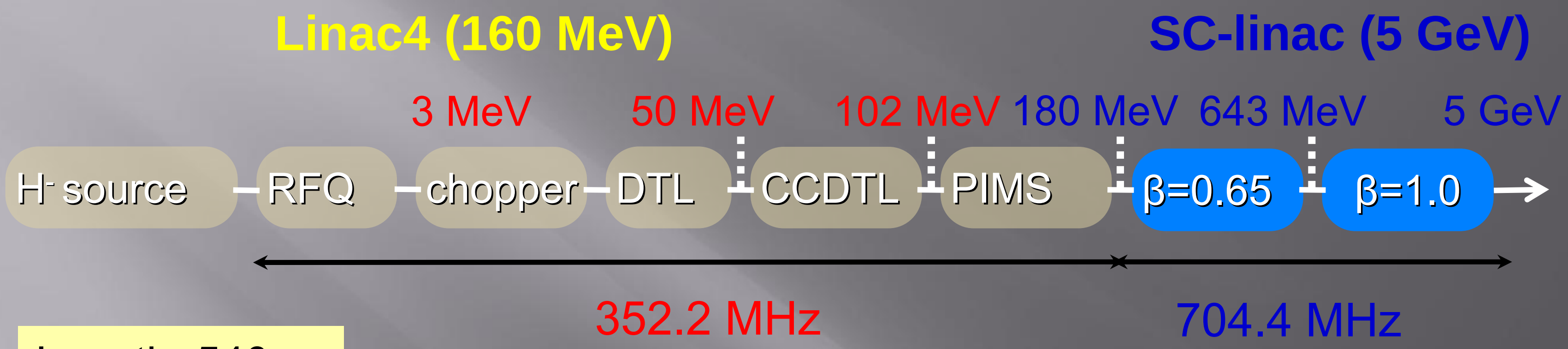
- Capability to deliver 2.2× the ultimate beam for LHC to the SPS

  ⇒ potential to prepare the SPS for supplying the beam required for the SLHC,
- Higher injection energy in the SPS + higher intensity and brightness

  ⇒ easier handling of high intensity. Potential to increase the intensity per pulse.
- Benefits for users of the LPSPL and PS2
  - More than 50 % of the LPSPL pulses will be available (not needed by PS2)

    ⇒ New nuclear physics experiments – extension of ISOLDE (if no EURISOL)…
  - Upgraded characteristics of the PS2 beam wrt the PS (energy and flux)
  - Potential for a higher proton flux from the SPS

Stage 3: HP-SPL



Length: 540 m

HP-SPL beam characteristics

	Option 1	Option 2
Energy (GeV)	2.5 or 5	2.5 and 5
Beam power (MW)	3 MW (2.5 GeV) or 6 MW (5 GeV)	4 MW (2.5 GeV) and 4 MW (5 GeV)
Rep. frequency (Hz)	50	50
Protons/pulse (x 10^{14})	1.5	2 (2.5 GeV) + 1 (5 GeV)
Av. Pulse current	20	40
Pulse duration (ms)	1.2	0.8 (2.5 GeV) + 0.4 (5 GeV)

Stage 3: Benefits

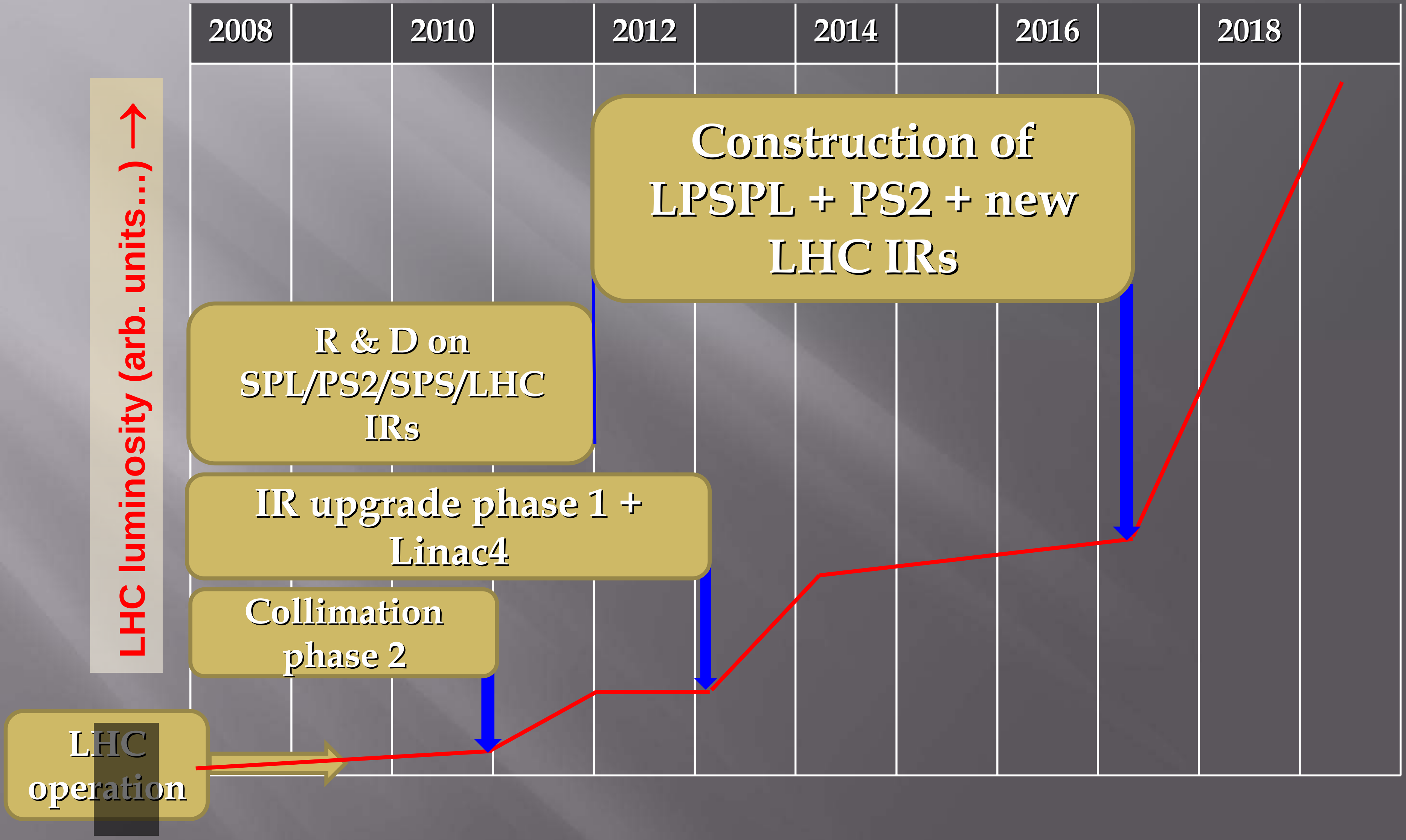
Possibility of (a) new experimental facilities(y) using a very high beam power:

- For neutrinos (e.g. Neutrino Factory), adding an accumulator and a compressor ring (300 circumference) + muon facility with storage ring(s) at 20-50 GeV

- For Radioactive Ion Beams (ISOL-like), adding beam switchyard with targets and experimental hall

SUMMARY

Roadmap for LHC



Construction of LPSPL + PS2 + new LHC IRs

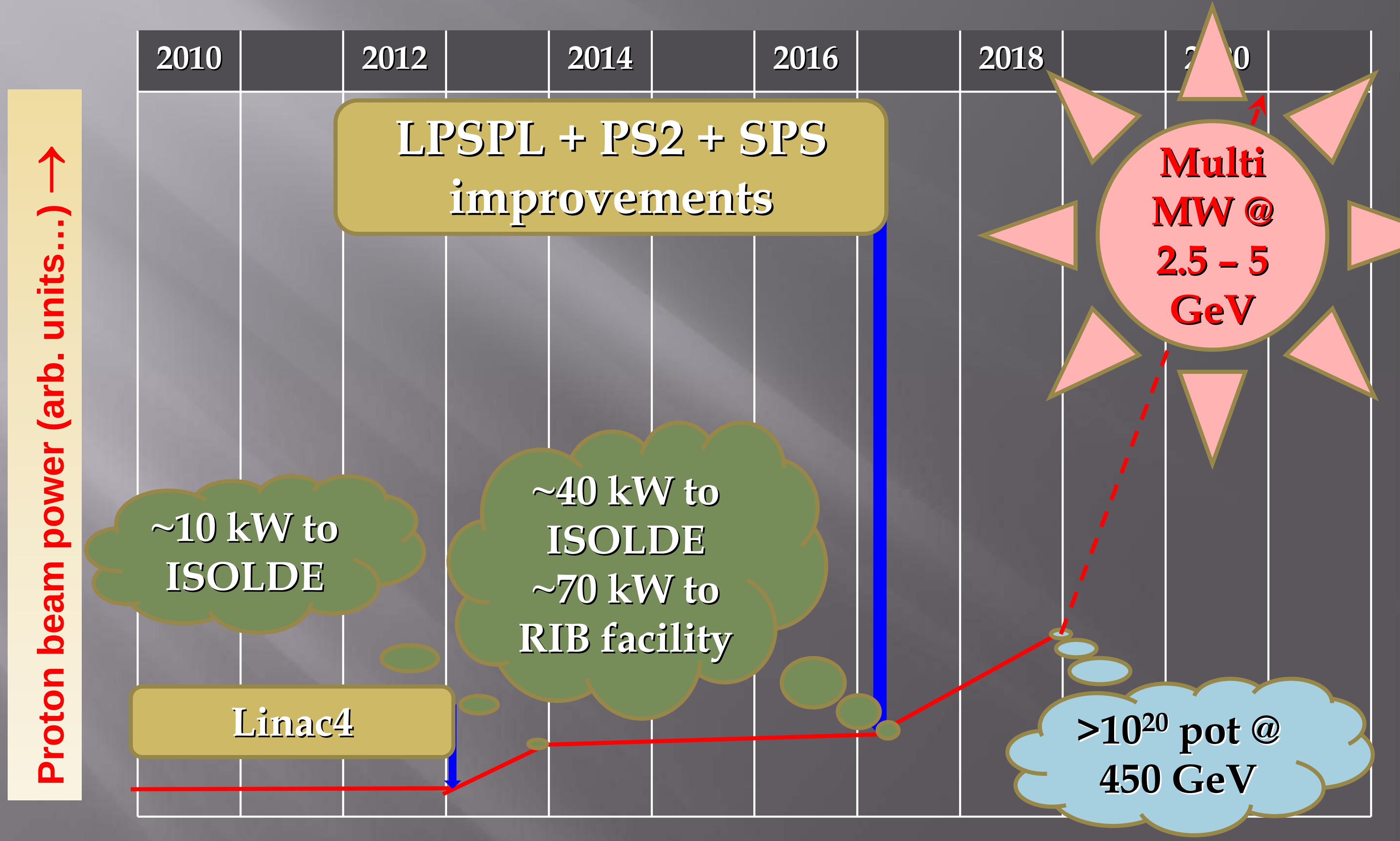
R & D on SPL/PS2/SPS/LHC IRs

IR upgrade phase 1 + Linac4

Collimation phase 2

LHC operation

Potential for other users



LPSPL + PS2 + SPS improvements

Multi MW @ 2.5 – 5 GeV

~10 kW to ISOLDE

~40 kW to ISOLDE
~70 kW to RIB facility

Linac4

>10^{20} pot @ 450 GeV

THANK YOU FOR YOUR ATTENTION!

REFERENCES
- Linac4-

Linac4 accelerating structures

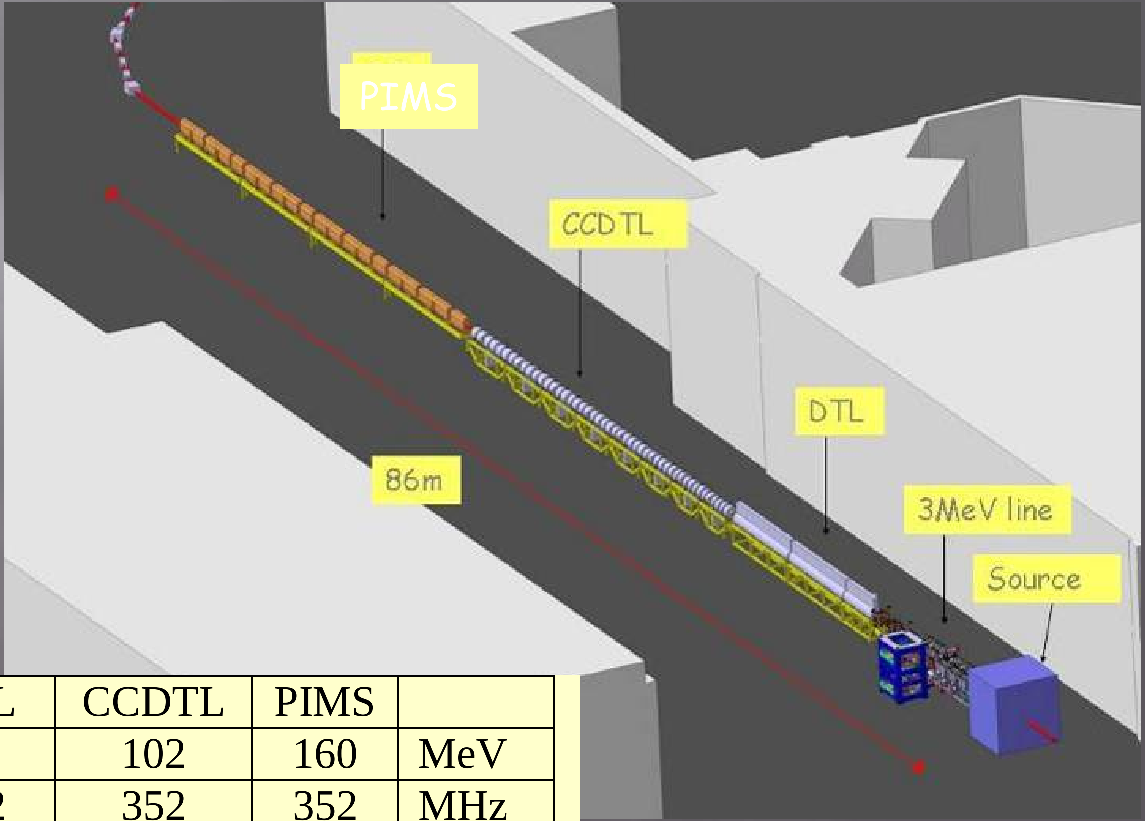
Linac4 accelerates H- ions up to 160 MeV energy:

☐ in about 80 m length

☐ using 4 different accelerating structures, all at 352 MHz

☐ the Radio-Frequency power is produced by 19 klystrons

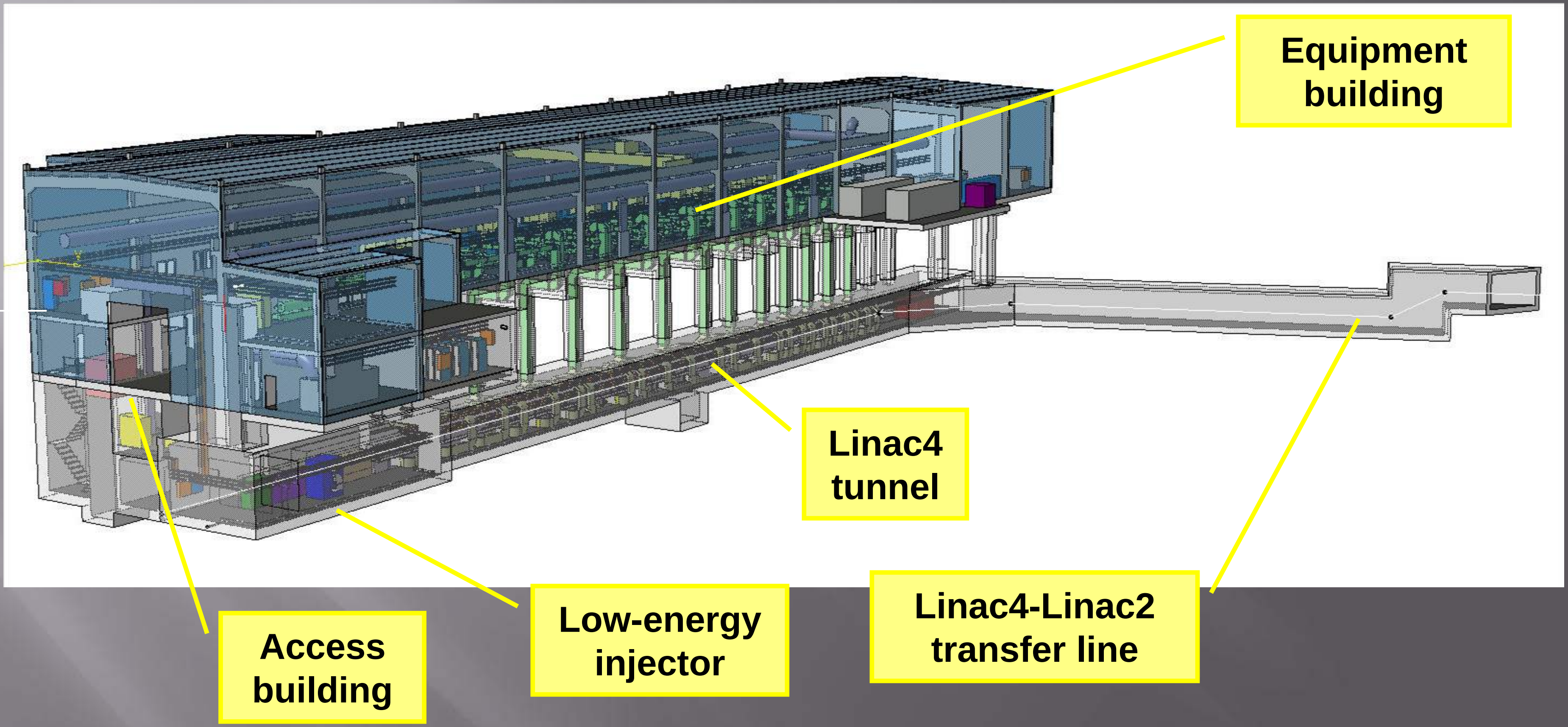
☐ focusing of the beam is provided by 111 Permanent Magnet Quadrupoles and 33 Electromagnetic Quadrupoles



	RFQ	DTL	CCDTL	PIMS	
Output energy	3	50	102	160	MeV
Frequency	352	352	352	352	MHz
No. of resonators	1	3	7	12	
Gradient E_0	-	3.2	2.8-3.9	4.0	MV/m
Max. field	1.95	1.6	1.7	1.8	Kilp.
RF power	0.5	4.7	6.4	11.9	MW
No. of klystrons	1	1+2	7	4+4	
Length	6	18.7	25.2	21.5	m

A 70 m long transfer line connects to the existing line Linac2 - PS Booster

Linac4 civil engineering



Equipment building

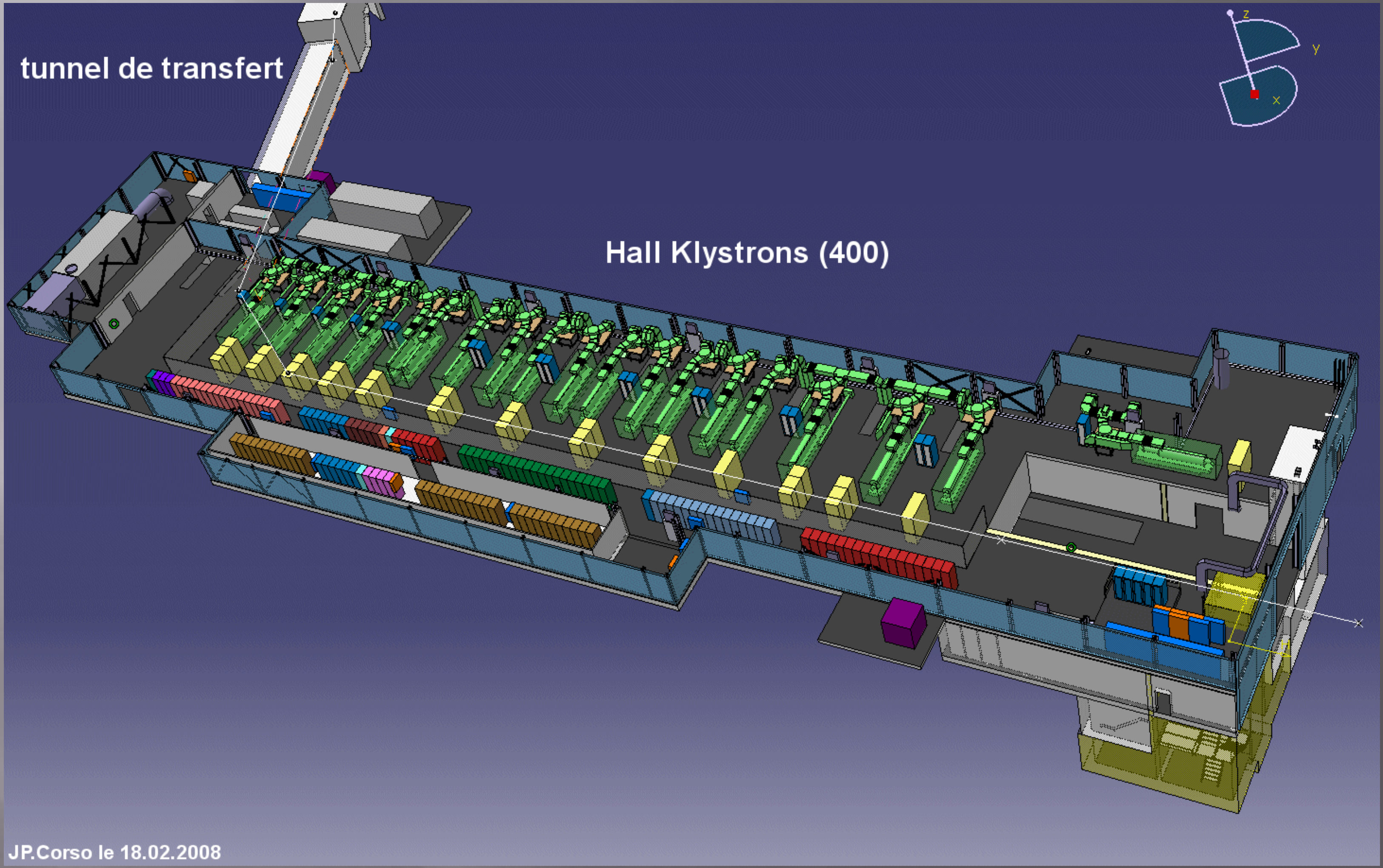
Linac4 tunnel

Linac4-Linac2 transfer line

Access building

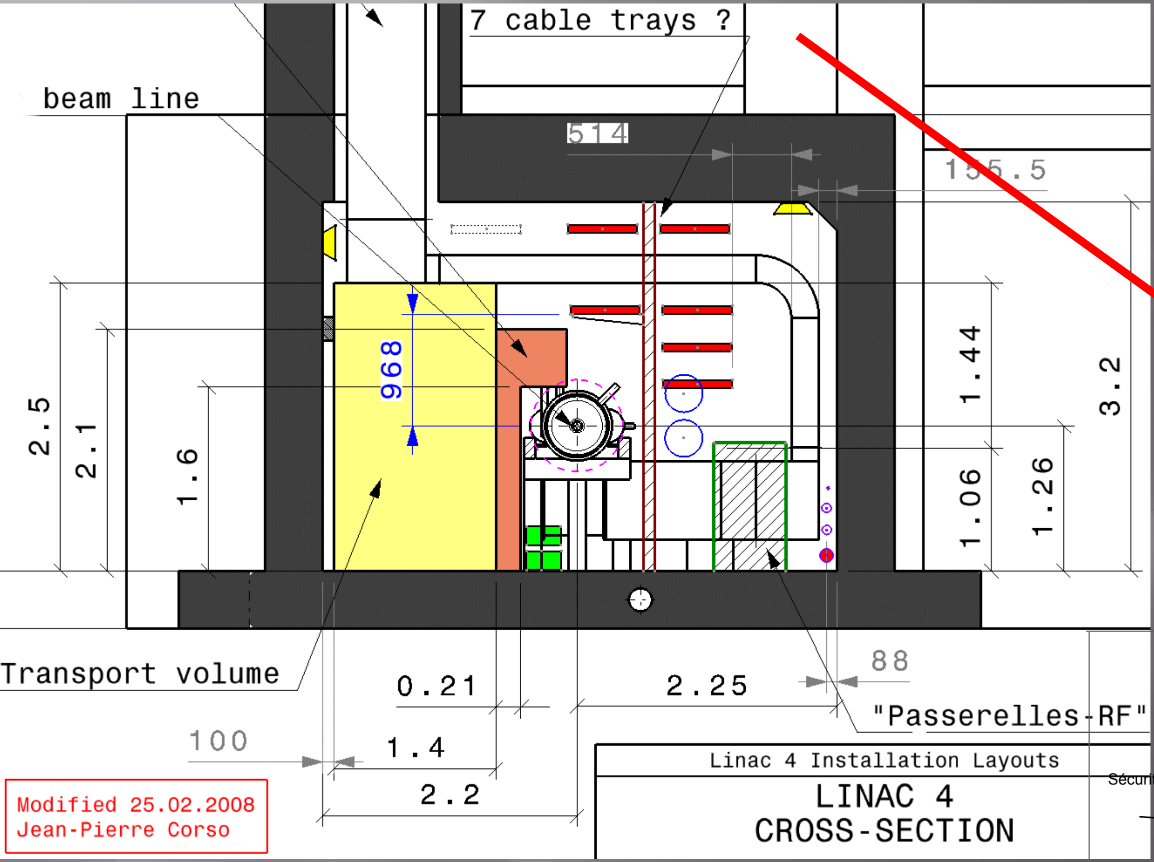
Low-energy injector

Equipment Hall (Bld. 400)

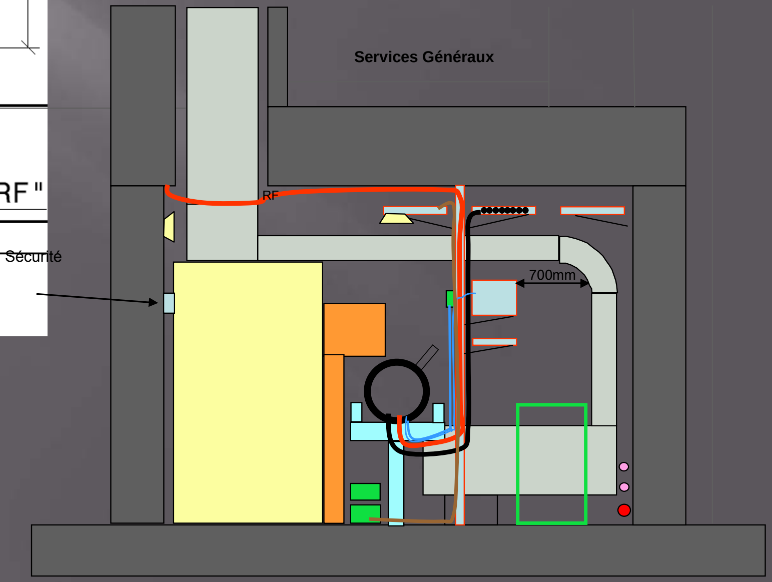


False floor 500mm (all along equipment hall)

Tunnel cross-section



Final position of cable trays:



REFERENCES
- SPL -

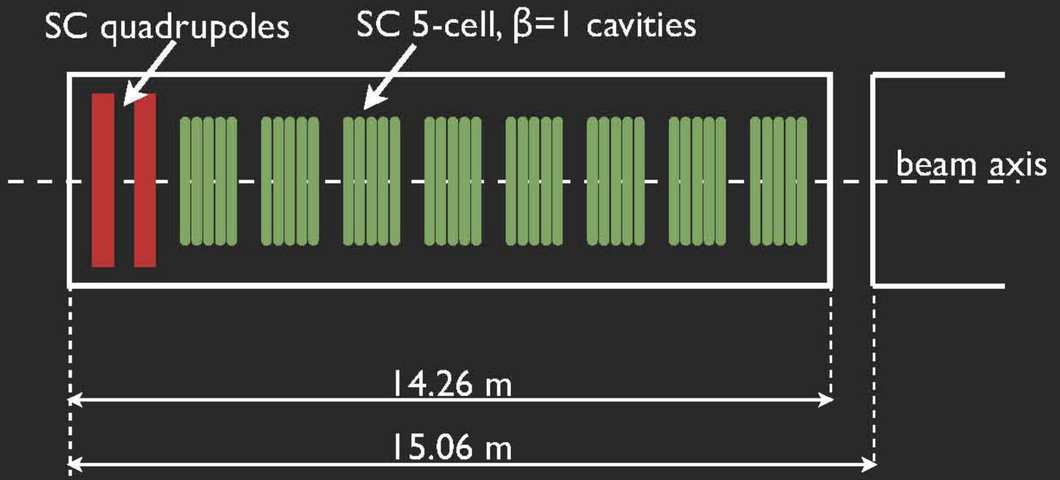
SPL architecture

SPL type	nominal improved	~~option I~~	~~I b~~
frequency [MHz]	704.4	~~1408.8~~	~~352.2/1408.8~~
beta families	0.65/0.92	~~0.6/0.76/0.94~~	~~0.67/0.8/0.94~~
cells/cavity	5/5	~~7/9/9~~	~~4/5/9~~
trans. energies [MeV]	160/589	~~160/358/876~~	~~tbs~~
output energy [MeV]	5137	~~4992~~	~~tbs~~
gradients [MV/m]	19/25	~~19/20/28~~	~~tbs~~
cavities p. module	6/8	~~4/4/8~~	~~1/1/8~~
cavities p. period	3/8	~~2/4/8~~	~~tbs~~
cavities p. family	39/192	~~32/48/176~~	~~tbs~~
cavities in total	**231**	~~**256**~~	~~**tbs**~~
length [m]	**425**	~~**466**~~	~~**tbs**~~

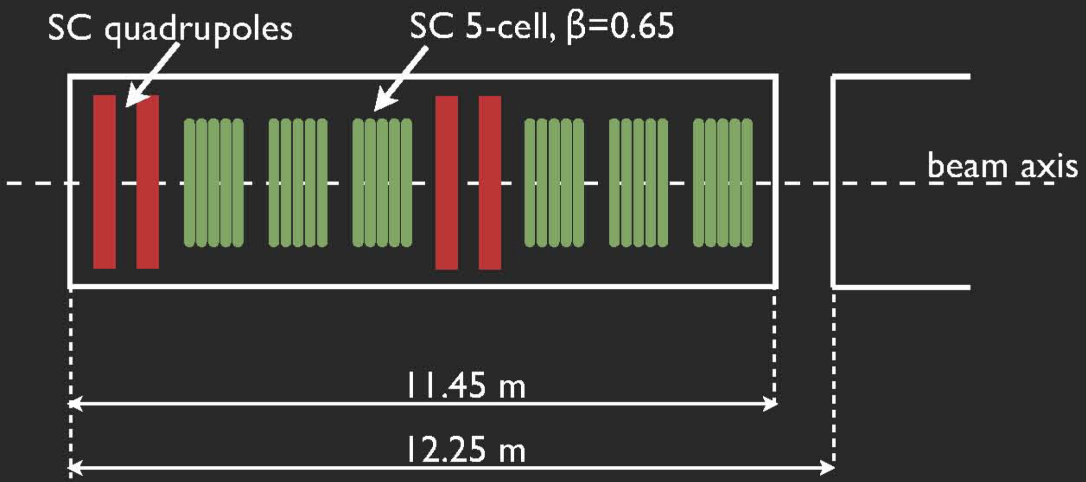
“Potential SPL architectures”, SPL review, 30 April 2008, F. Gerigk, M. Eshraqi

Cryomodules

high-beta section:
- 704.4 MHz, 25 MV/m,
- 668 - 5094 MeV,
- 25 periods, 200 cavities,
- 377 m



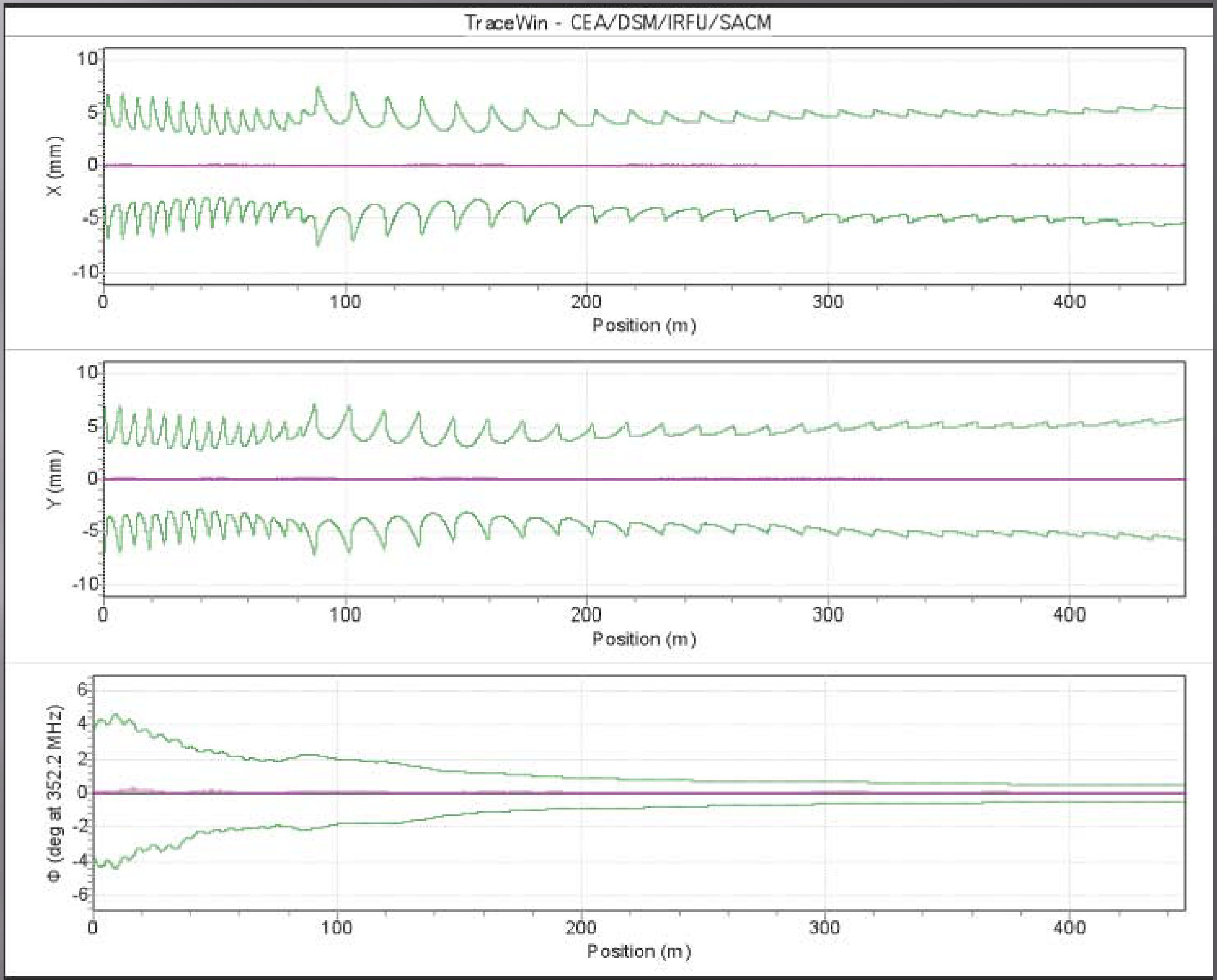
low-beta section:
- 704.4 MHz, 19 MV/m,
- 180 - 668 MeV,
- 14 periods, 42 cavities,
- 86 m



in total: 463 m, 242 cavities, 2 families, 704 MHz

"Potential SPL architectures", SPL review, 30 April 2008, F. Gerigk, M. Eshraqi

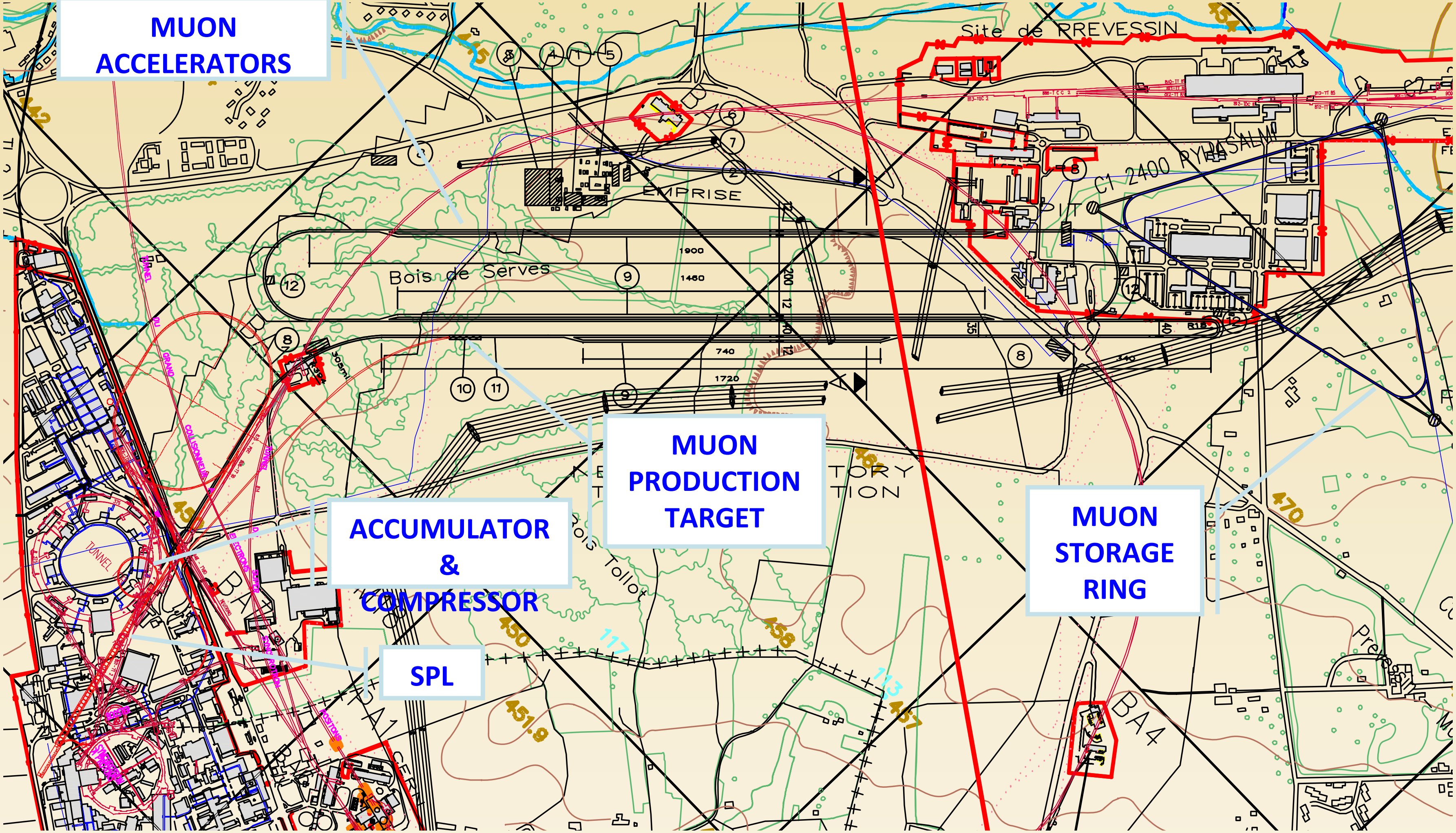
Beam envelopes (5 rms)



"Potential SPL architectures", SPL review, 30 April 2008, F. Gerigk, M. Eshraqi

REFERENCES
- ν Factory and RIB facility -

Neutrino Factory



MUON ACCELERATORS

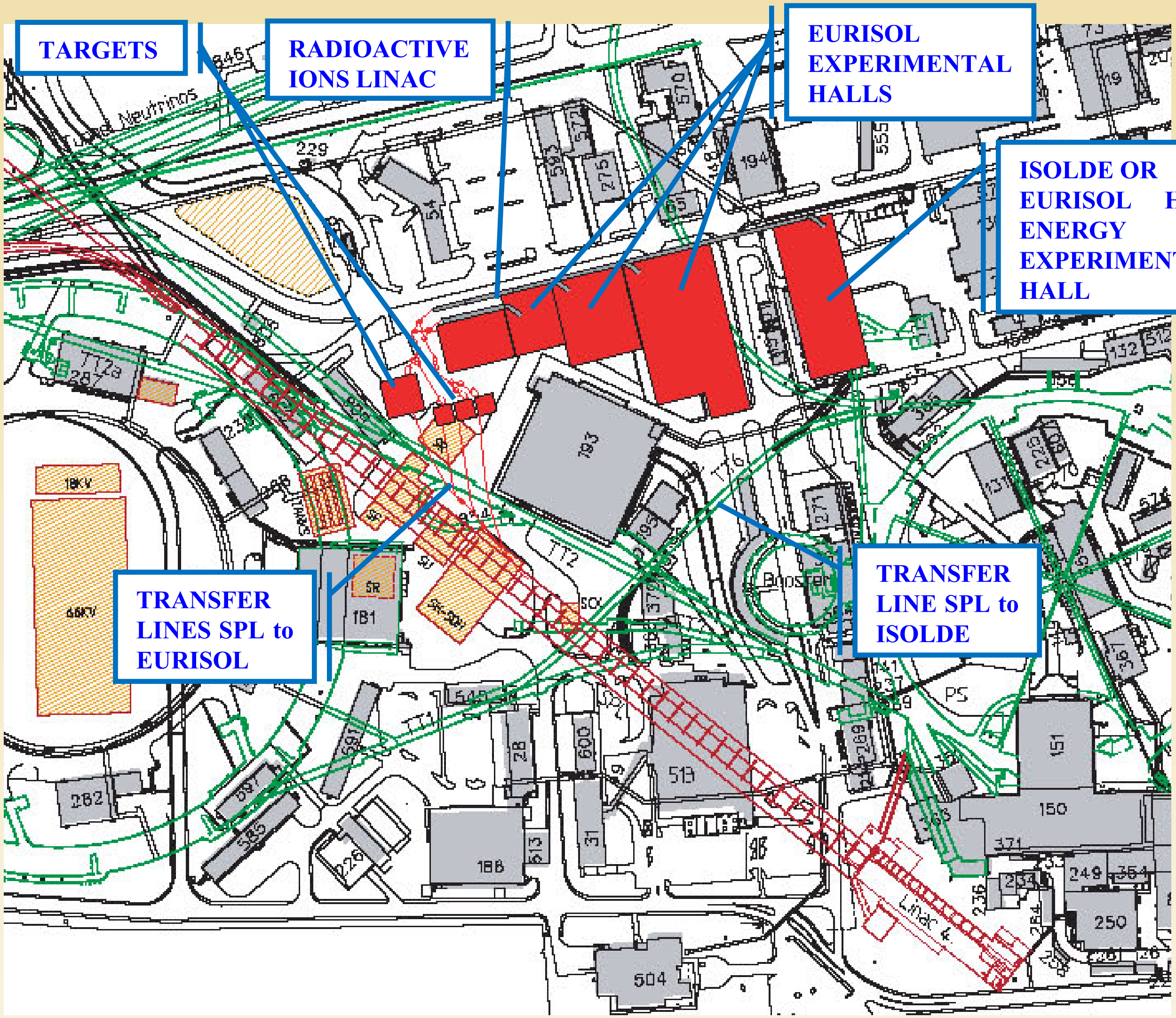
MUON PRODUCTION TARGET

ACCUMULATOR & COMPRESSOR

SPL

MUON STORAGE RING

RIB facility



TARGETS

RADIOACTIVE IONS LINAC

EURISOL EXPERIMENTAL HALLS

ISOLDE OR EURISOL HIGH ENERGY EXPERIMENTAL HALL

TRANSFER LINES SPL to EURISOL

TRANSFER LINE SPL to ISOLDE