UPGRADE PLANS FOR THE CERN ACCELERATOR COMPLEX

OUTLINE

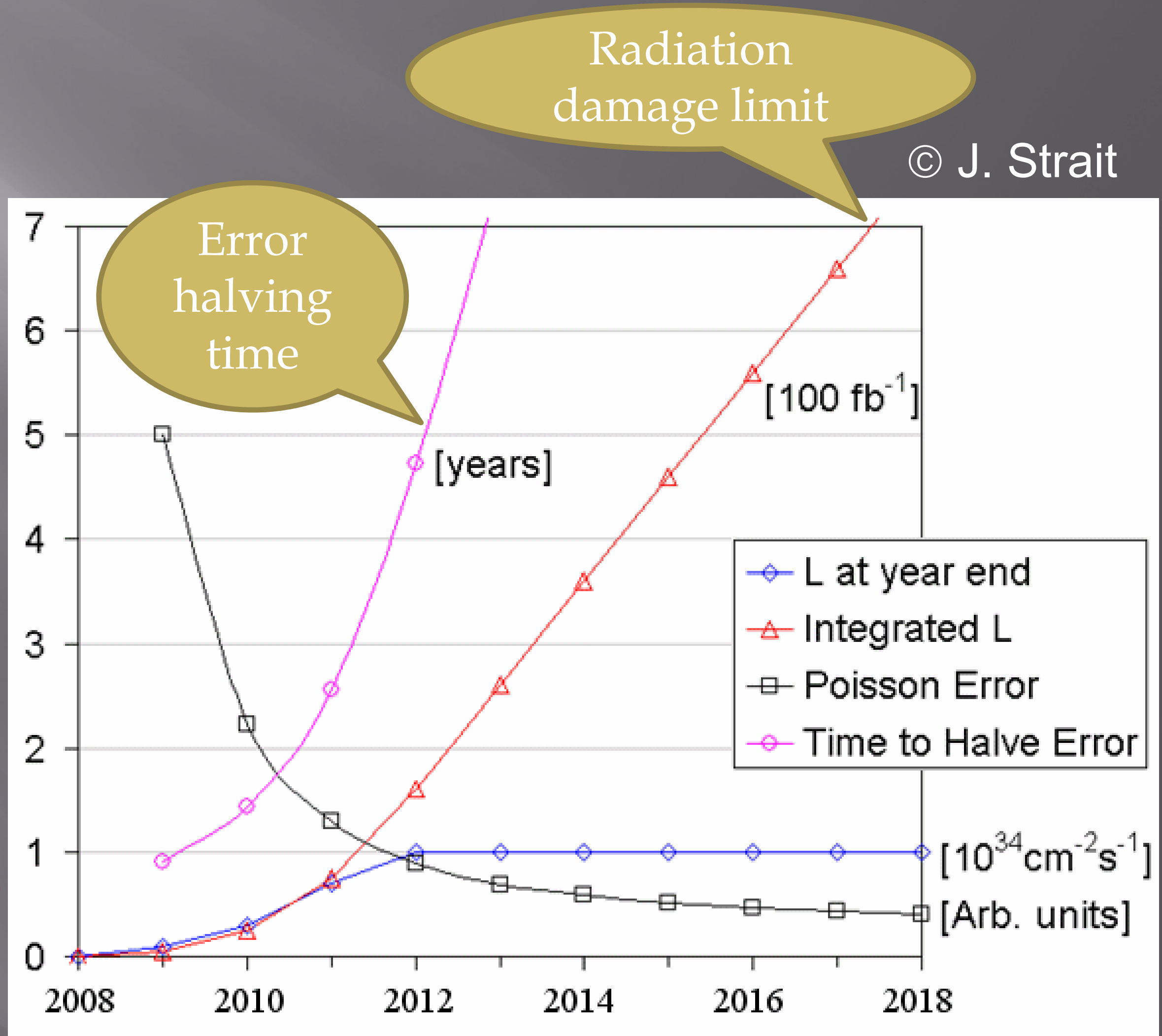
- **Why upgrade ? When ?**
- **Injectors**
- **LHC**
- **Preliminary expectations**

R. Garoby

Why upgrade the LHC ?

- Hardware ageing
- Foreseeable luminosity evolution

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



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**

INJECTORS

Upgrade procedure

Main performance limitation:

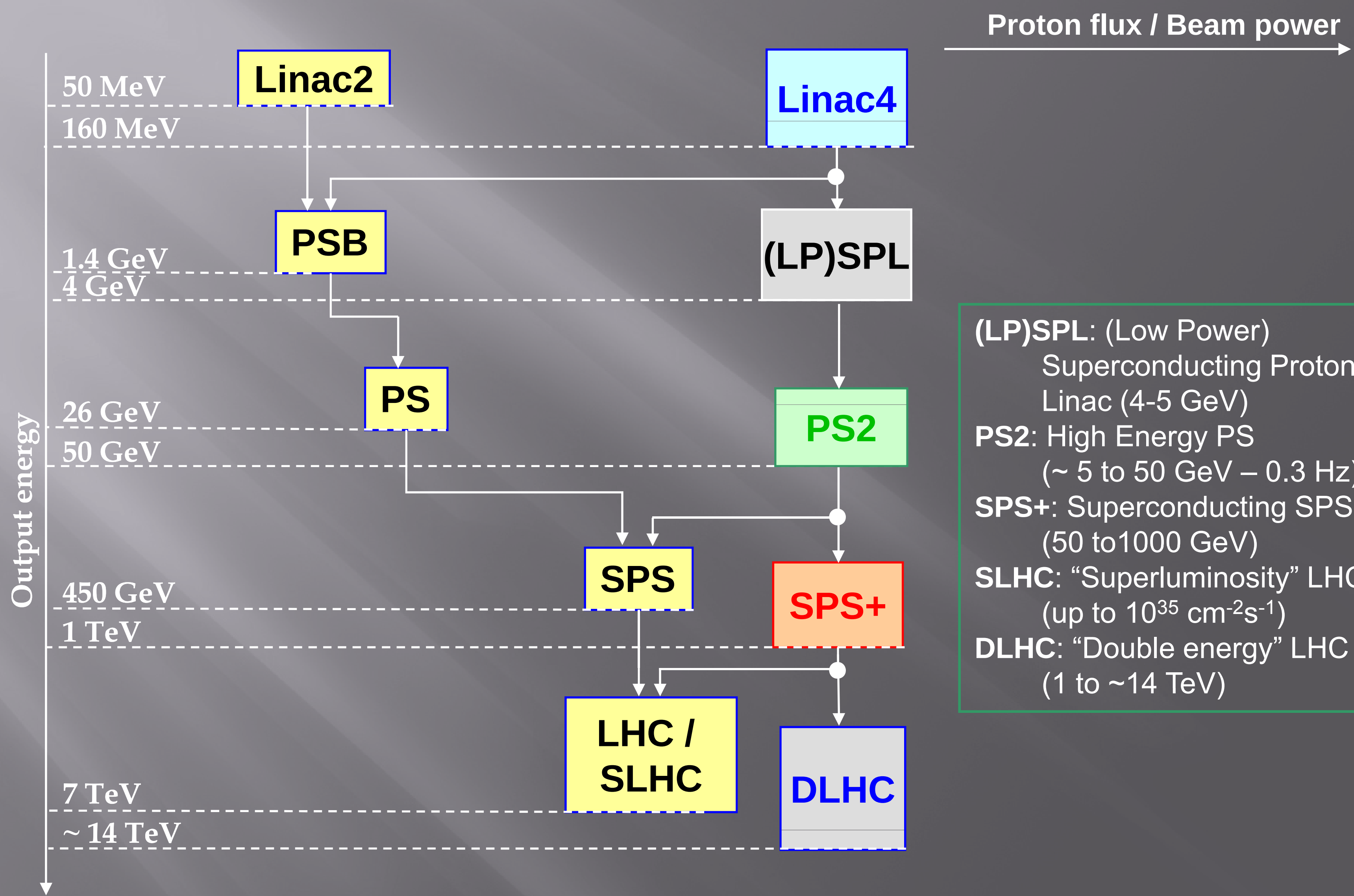
Incoherent space charge tune spreads ΔQ_{SC} at injection in the PSB (50 MeV) and PS (1.4 GeV) because of the required beam brightness N/ε^*.

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

$\Rightarrow$ **need to increase the injection energy in the synchrotrons**

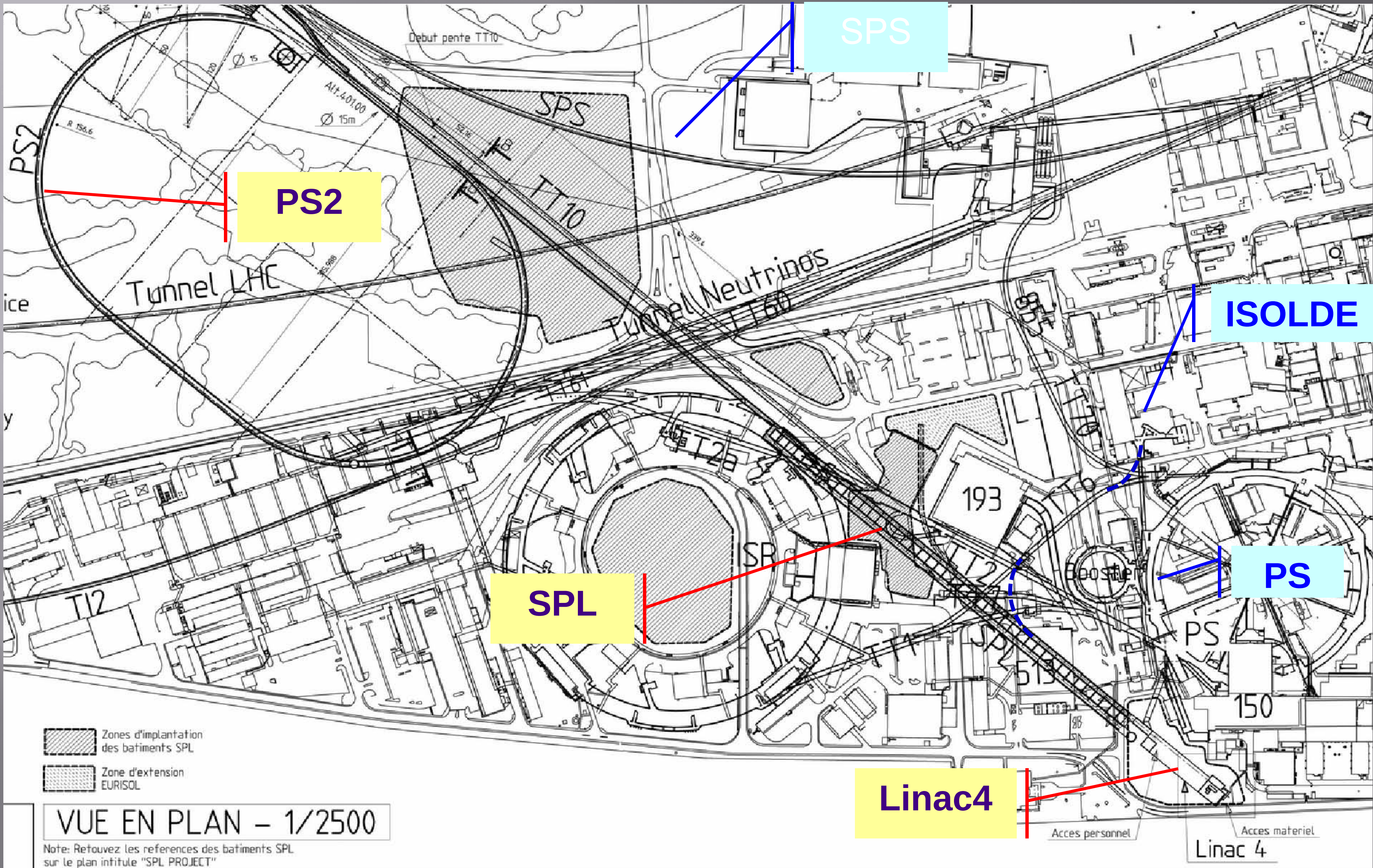
- Increase injection energy in the PSB from 50 to 160 MeV kinetic
- Increase injection energy in the SPS from 25 to 50 GeV kinetic
- Design the PS successor (PS2) with an acceptable space charge effect for the maximum beam envisaged for SLHC: => injection energy of 4 GeV

Present and future injectors

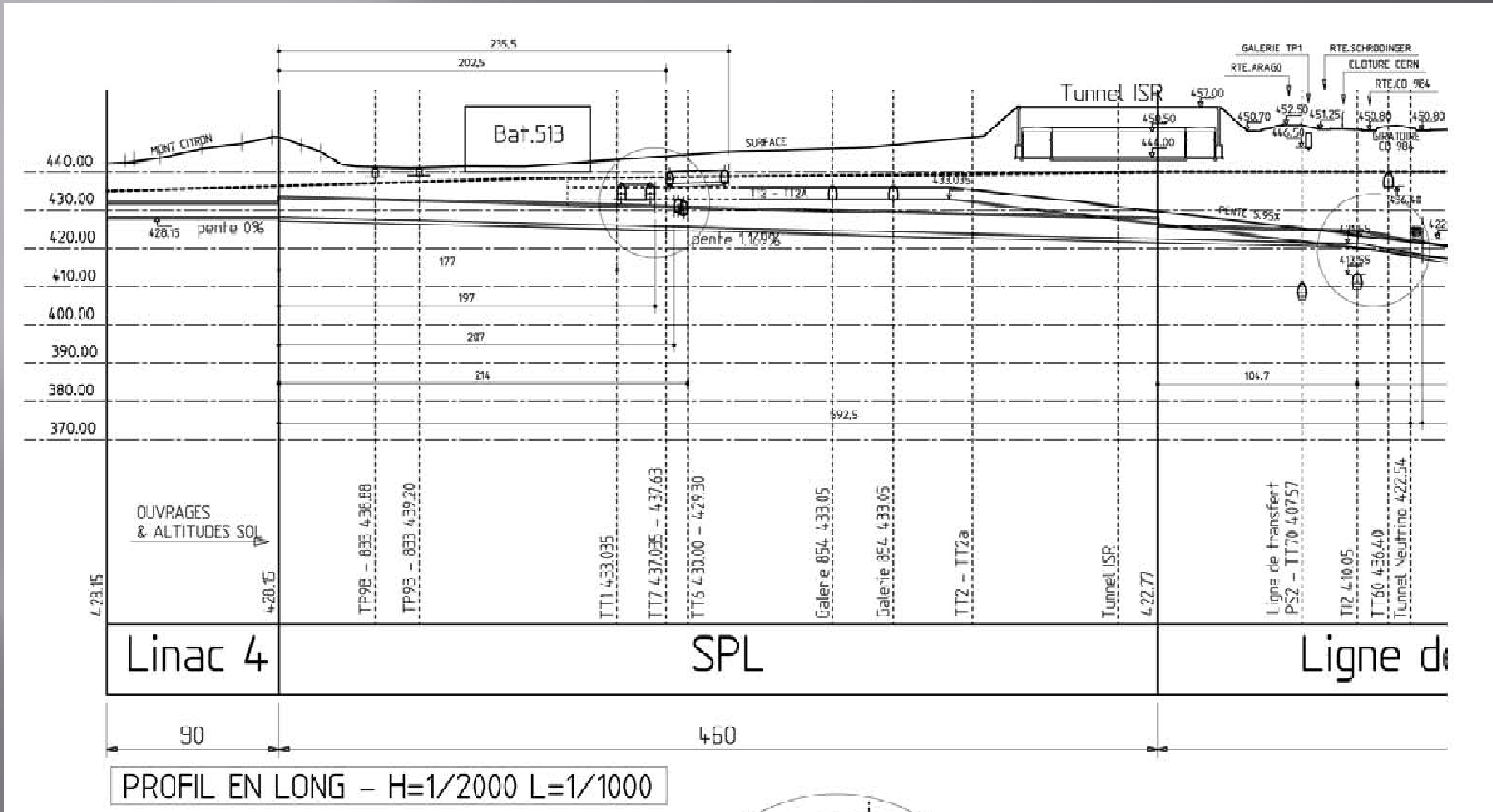


(LP)SPL: (Low Power) Superconducting Proton Linac (4-5 GeV)
PS2: High Energy PS (~ 5 to 50 GeV – 0.3 Hz)
SPS+: Superconducting SPS (50 to1000 GeV)
SLHC: "Superluminosity" LHC (up to 10^{35} $cm^{-2}s^{-1}$)
DLHC: "Double energy" LHC (1 to ~14 TeV)

Layout of the new injectors

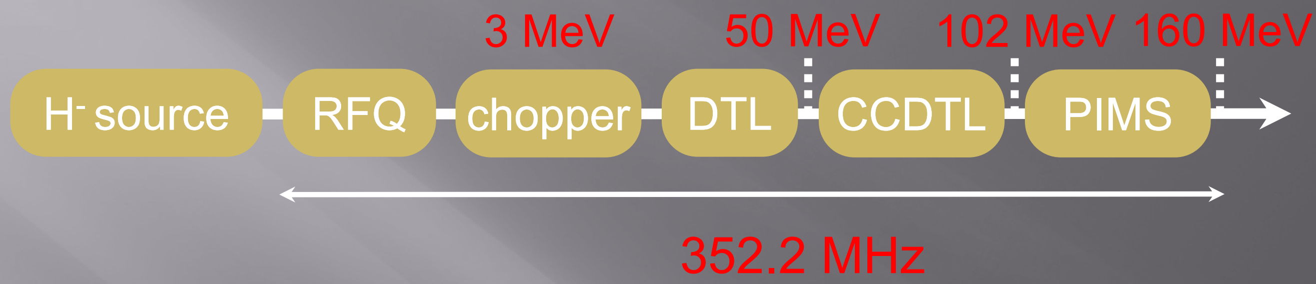


Layout of the new injectors



Stage 1: Linac4

Enabled by additional resources for “New Initiatives”

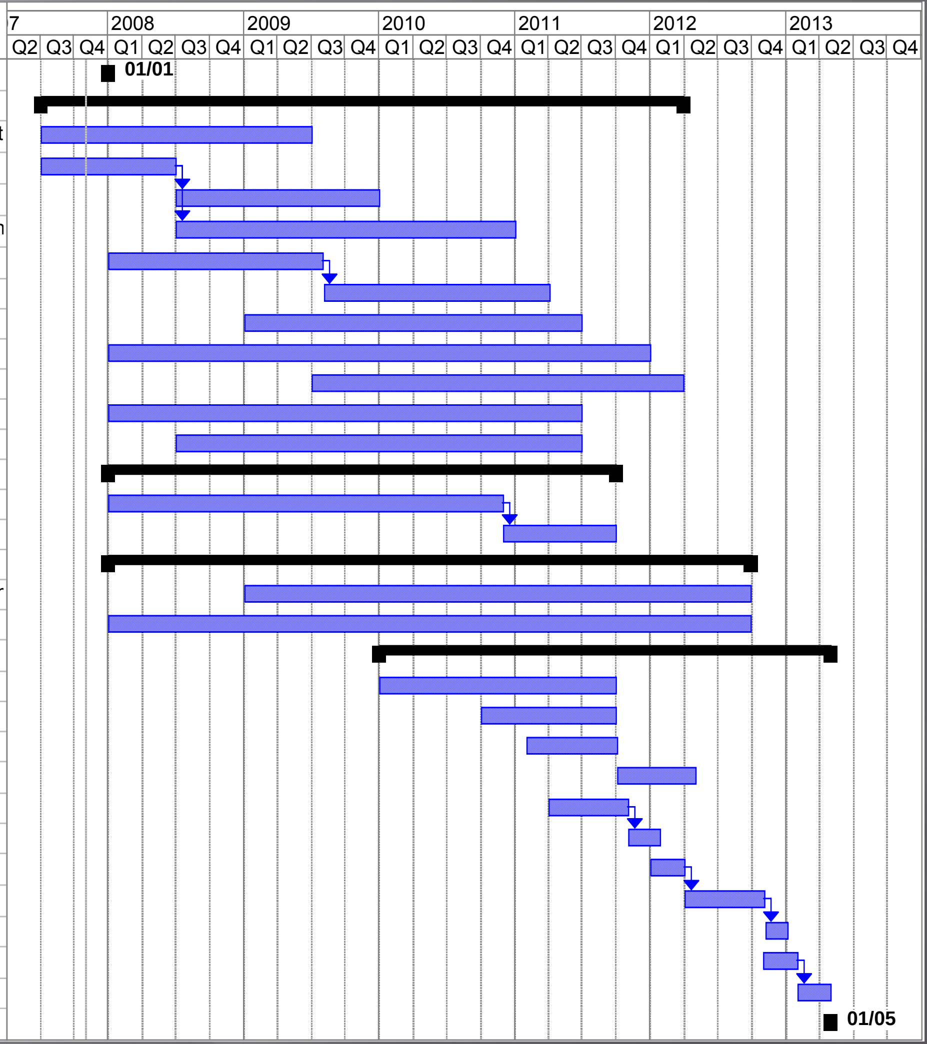


Linac4 beam characteristics

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)

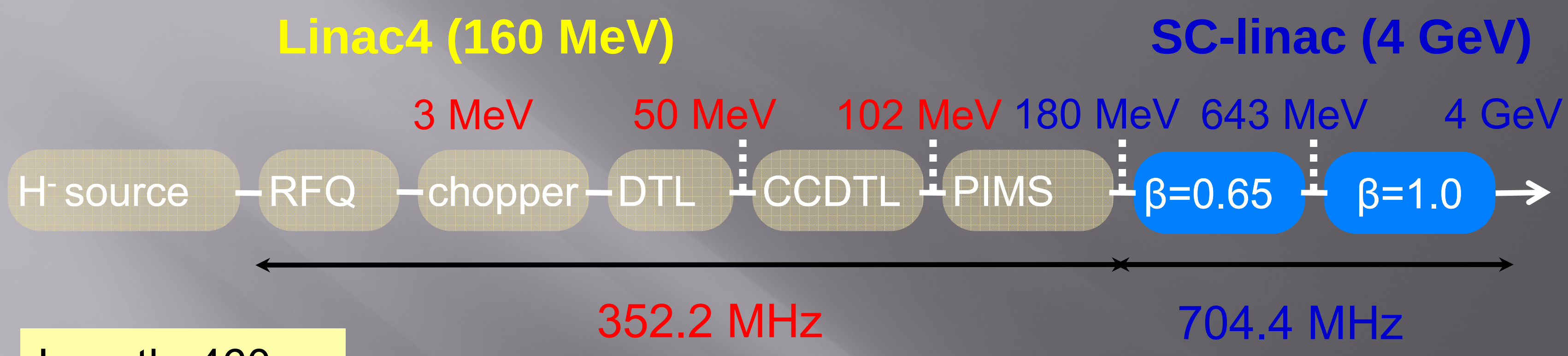
Higher performance for the PSB:

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



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

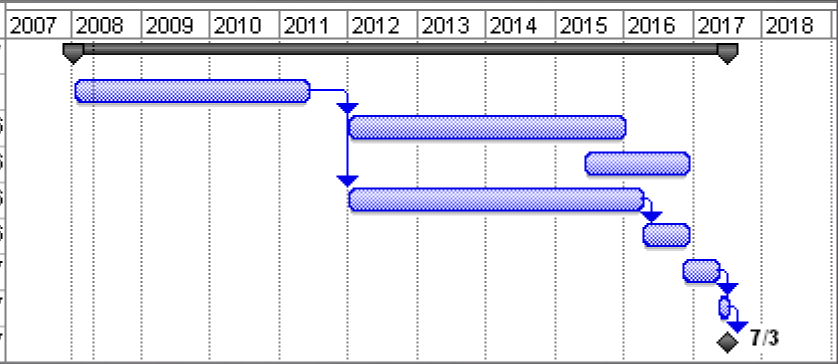
	PS2	PS
Injection energy kinetic (GeV)	4.0	1.4
Extraction energy kinetic (GeV)	~ 50	13/25
Circumference (m)	1346	628
Maximum intensity LHC (25ns) (p/b)	4.0×10^{11}	$\sim 1.7 \times 10^{11}$
Maximum intensity for fixed target physics (p/p)	1.2×10^{14}	3.3×10^{13}
Maximum energy per beam pulse (kJ)	1000	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

LHC

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 β^*=0.25 m in IP1 and IP5, and reliable operation of the LHC at $2 - 3 \times 10^{34}$ 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 <u>at two IPs:</u>

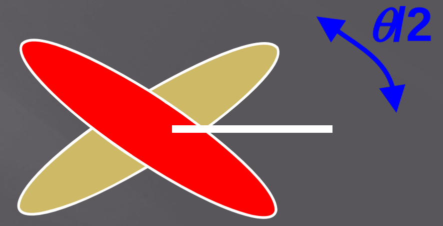
$$[illegible]$$

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

$$[illegible]$$

with ϕ = Piwinski angle

$$[illegible]$$



effective beam emittance

$$[illegible]$$

Schemes comparison

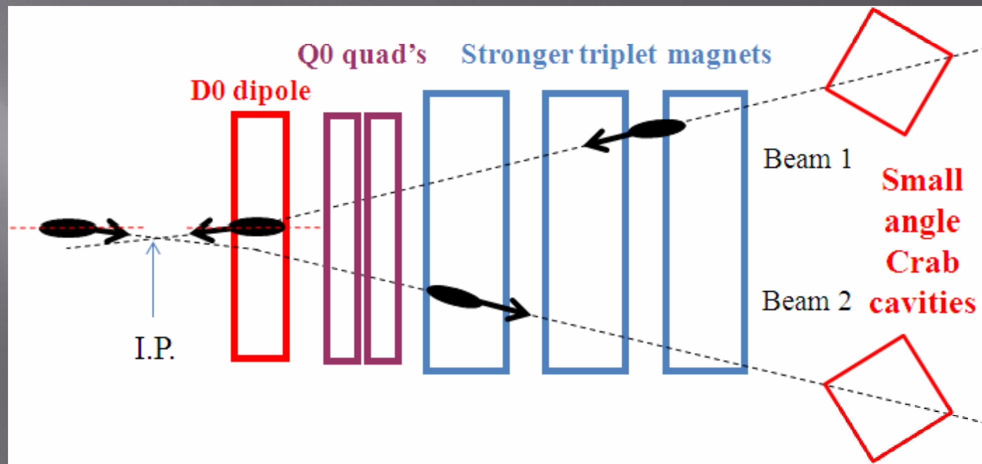
© F. Zimmermann

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

"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

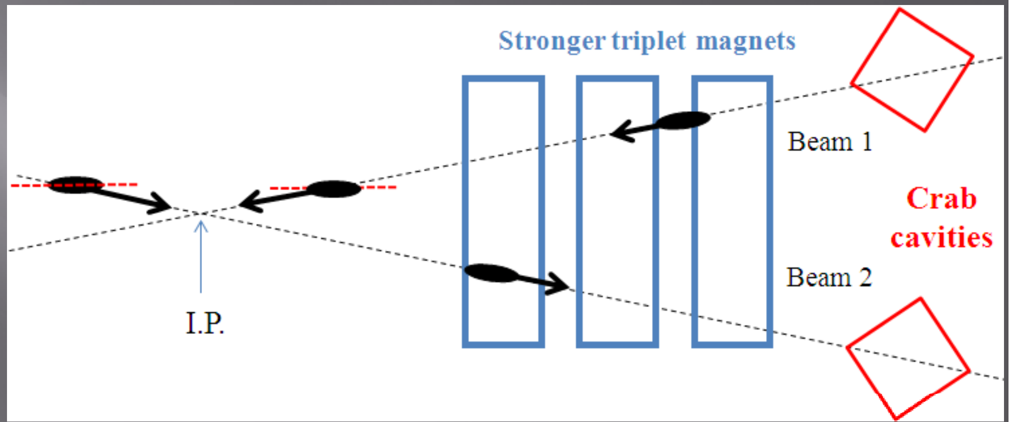
"Full Crab Crossing" scheme

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 (1.7x10^{11} protons/bunch, 25 spacing)
- β* ~10 cm
- crab cavities with 60% higher voltage

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

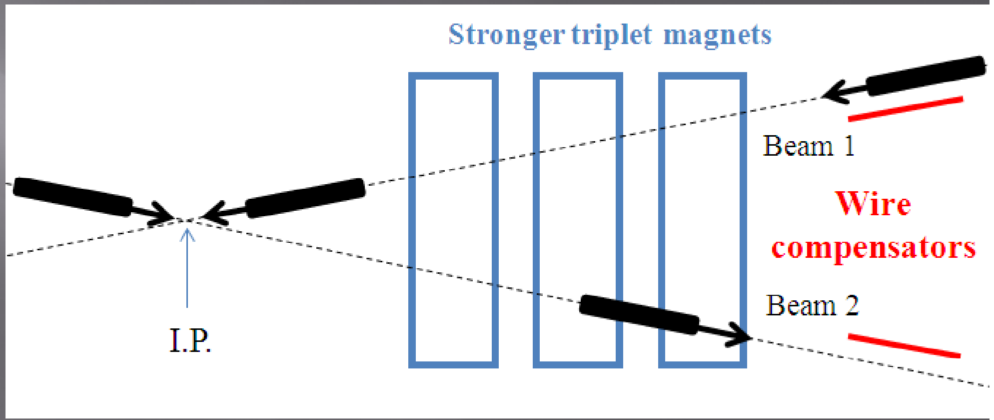
"Large Piwinski angle" scheme

Factor wrt ultimate

F. Ruggiero,
W. Scandale.
F. Zimmermann

Main ingredients:

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

Luminosity lifetime

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

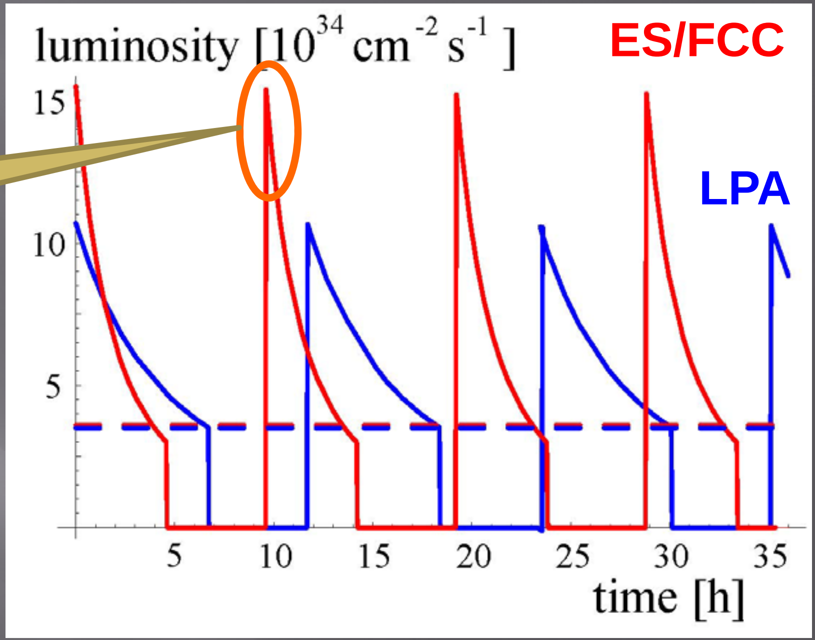
Increased luminosity ⇒ reduced life time

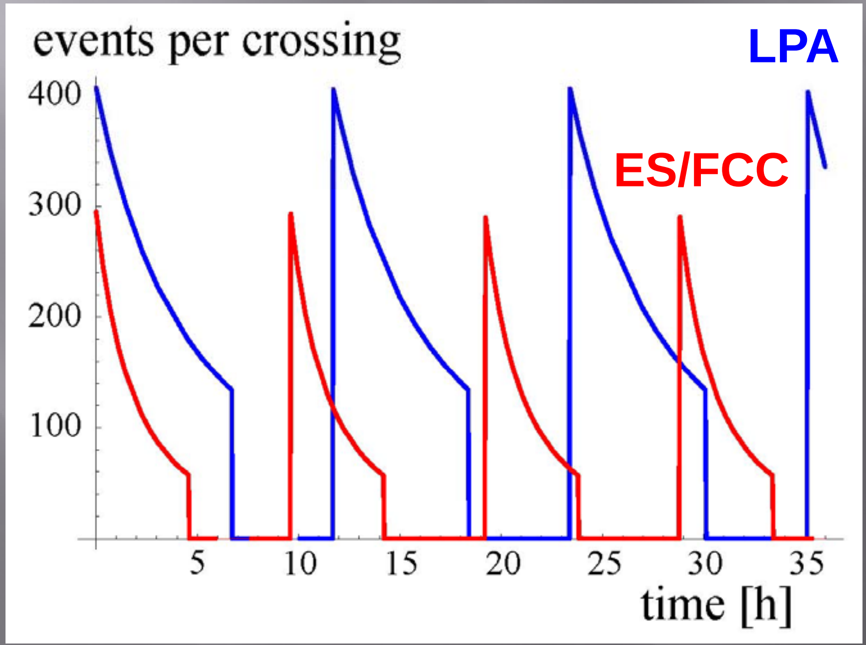
- **Compensation measures ⇒ increased total intensity:**
  - **either more bunches (n_b ↑) : abandoned because of heat load to the beam screen and electron clouds effects**
  - **or higher intensity per bunch (N_b ↑): "soft" limit used in the LPA scheme**
- **Possible additional action: luminosity leveling**

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.

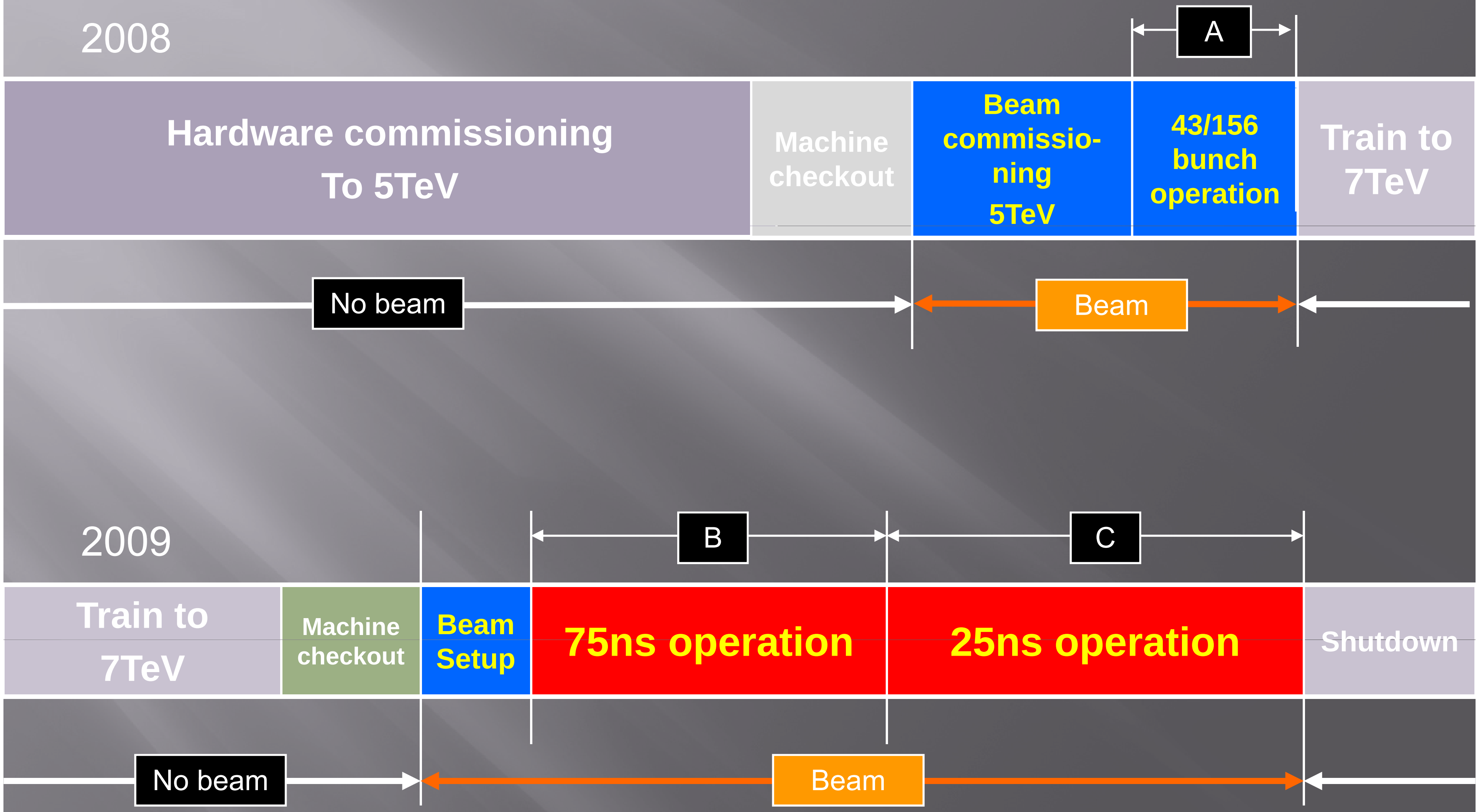
⇒ Interest for luminosity leveling

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

PRELIMINARY EXPECTATIONS

Strategy for 2008 and 2009



Courtesy R. Bailey

Parameter evolution and rates

$$L = \frac{N^2 k_b f \gamma}{4\pi \varepsilon_n \beta^*} F$$

$$Eventrate / Cross = \frac{L \sigma_{TOT}}{k_b f}$$

All values for nominal emittance, 10m β* in points 2 and 8

All values for 936 or 2808 bunches colliding in 2 and 8 (not quite right)

	Parameters			Beam levels		Rates in 1 and 5		Rates in 2 and 8	
	k_b	N	β* 1,5 (m)	I_{beam} proton	E_{beam} (MJ)	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing
5 TeV	43	$4\ 10^{10}$	11	$1.7\ 10^{12}$	1.4	$8.0\ 10^{29}$	<< 1	Depend on the configuration of collision pattern	
5 TeV	43	$4\ 10^{10}$	3	$1.7\ 10^{12}$	1.4	$2.9\ 10^{30}$	0.36		
5 TeV	156	$4\ 10^{10}$	3	$6.2\ 10^{12}$	5	$1.0\ 10^{31}$	0.36		
5 TeV	156	$9\ 10^{10}$	3	$1.4\ 10^{13}$	11	$5.4\ 10^{31}$	1.8		
7 TeV	936	$4\ 10^{10}$	11	$3.7\ 10^{13}$	42	$2.4\ 10^{31}$	<< 1	$2.6\ 10^{31}$	0.15
7 TeV	936	$4\ 10^{10}$	2	$3.7\ 10^{13}$	42	$1.3\ 10^{32}$	0.73	$2.6\ 10^{31}$	0.15
7 TeV	936	$6\ 10^{10}$	2	$5.6\ 10^{13}$	63	$2.9\ 10^{32}$	1.6	$6.0\ 10^{31}$	0.34
7 TeV	936	$9\ 10^{10}$	1	$8.4\ 10^{13}$	94	$1.2\ 10^{33}$	7	$1.3\ 10^{32}$	0.76
7 TeV	2808	$4\ 10^{10}$	11	$1.1\ 10^{14}$	126	$7.2\ 10^{31}$	<< 1	$7.9\ 10^{31}$	0.15
7 TeV	2808	$4\ 10^{10}$	2	$1.1\ 10^{14}$	126	$3.8\ 10^{32}$	0.72	$7.9\ 10^{31}$	0.15
7 TeV	2808	$5\ 10^{10}$	1	$1.4\ 10^{14}$	157	$1.1\ 10^{33}$	2.1	$1.2\ 10^{32}$	0.24
7 TeV	2808	$5\ 10^{10}$	0.55	$1.4\ 10^{14}$	157	$1.9\ 10^{33}$	3.6	$1.2\ 10^{32}$	0.24

Basic expectations

	Normal Ramp			No phase II		
Year	Peak Lumi ($\times 10^{34}$)	Annual Integrated (fb^{-1})	Total Integrated (fb^{-1})	Peak Lumi ($\times 10^{34}$)	Annual Integrated (fb^{-1})	Total Integrated (fb^{-1})
2009	0.1	6	6	0.1	6	6
2010	0.2	12	18	0.2	12	18
2011	0.5	30	48	0.5	30	48
2012	1	60	108	1	60	108
2013	1.5	90	198	1.5	90	198
2014	2	120	318	2	120	318
2015	2.5	150	468	2.5	150	468
2016	3	180	648	3	180	648
2017	3	0	648	3	0	648
2018	5	300	948	3	180	828
2019	8	420	1428	3	180	1008
2020	10	540	2028	3	180	1188
2021	10	600	2628	3	180	1368
2022	10	600	3228	3	180	1548
2023	10	600	3828	3	180	1728
2024	10	600	4428	3	180	1908
2025	10	600	5028	3	180	2088

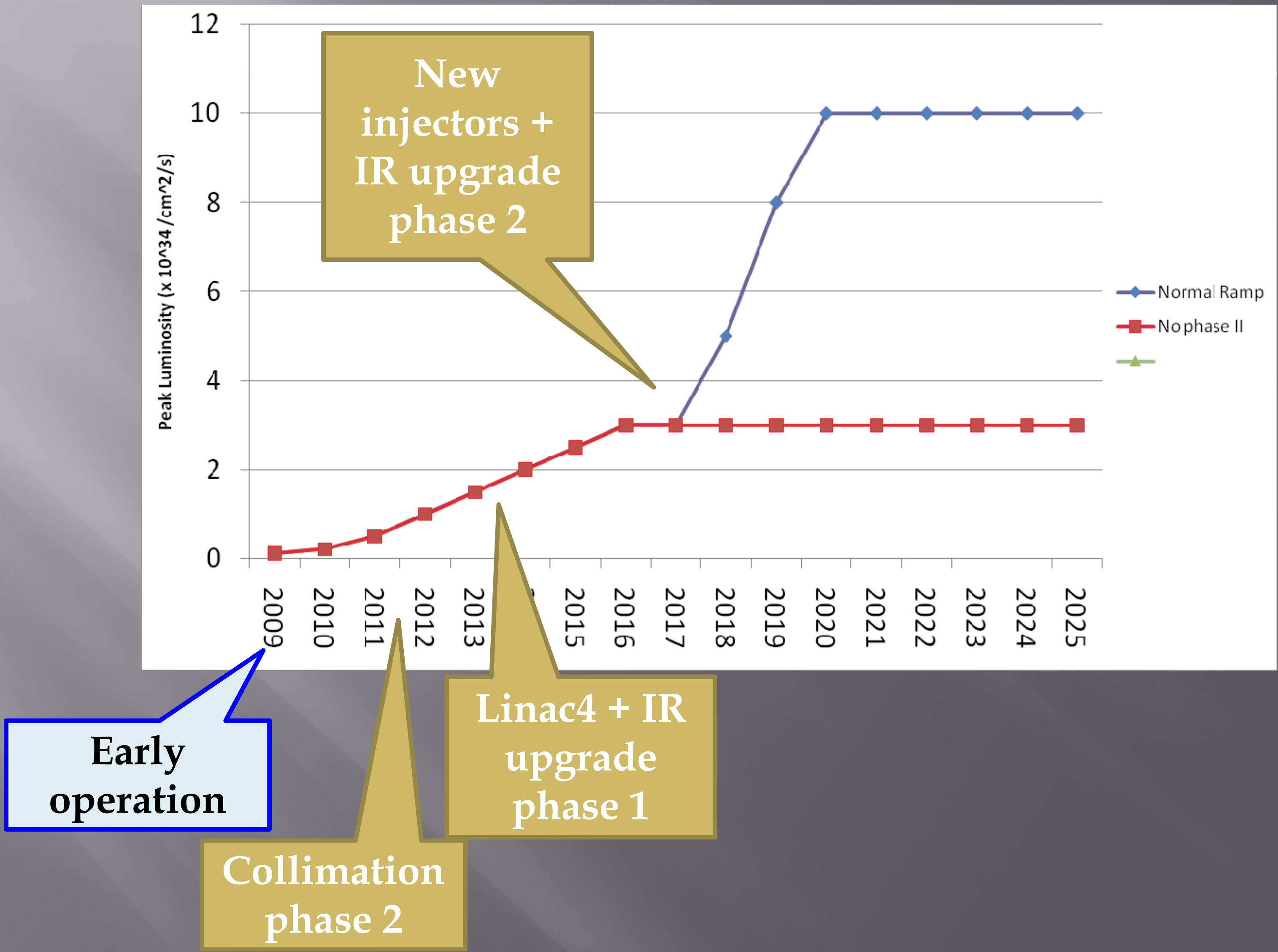
Collimation phase 2 (2011)

Linac4 + IR upgrade phase 1 (2013)

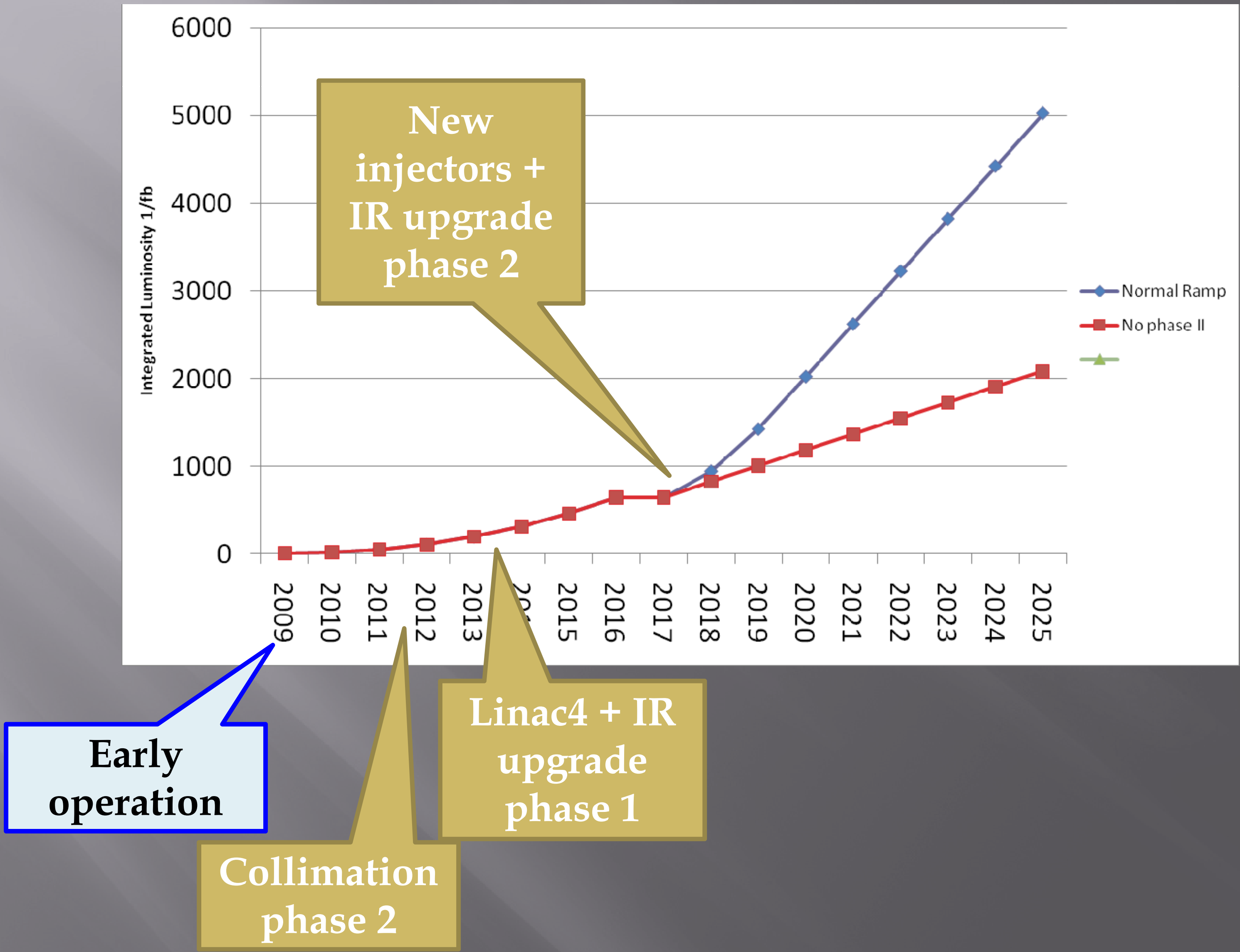
New injectors + IR upgrade phase 2 (2018)

Radiation damage limit ??? (2022–2025)

Peak luminosity…



Integrated luminosity…

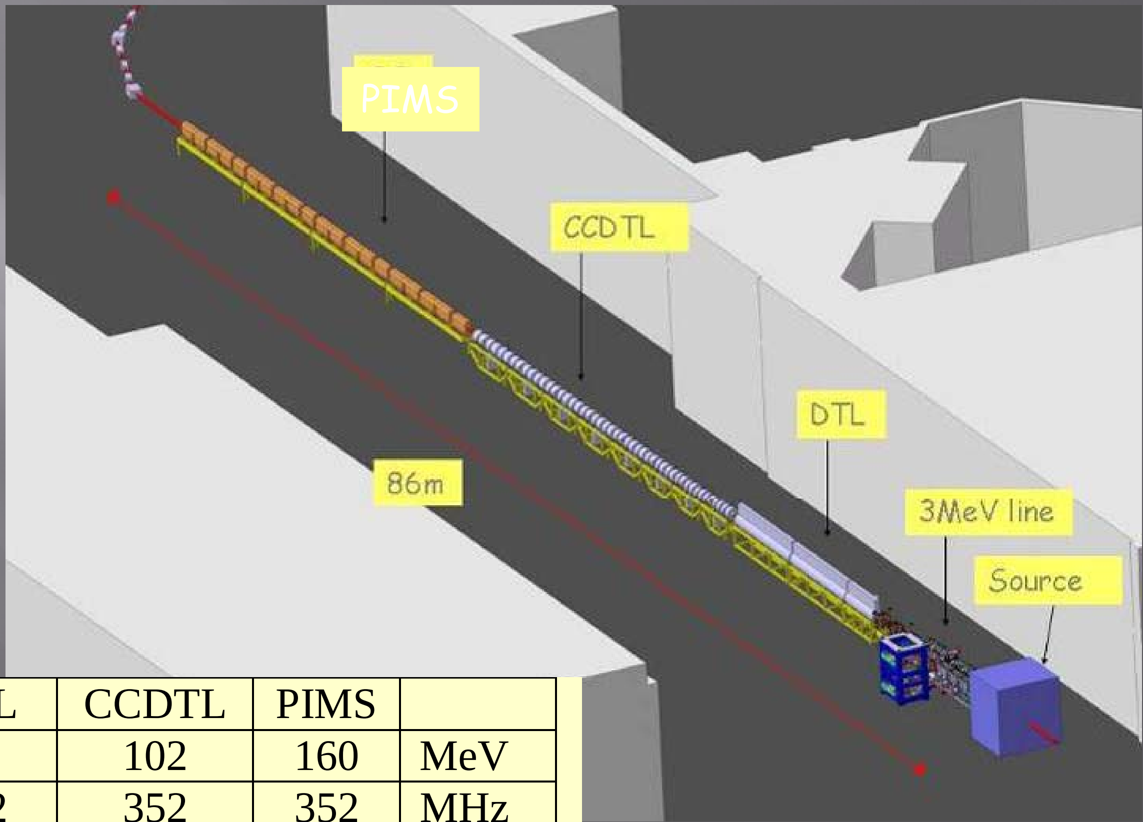


REFERENCES
- Linac4-

Linac4 accelerating structures

Linac4 accelerates H- ions up to 160 MeV energy:

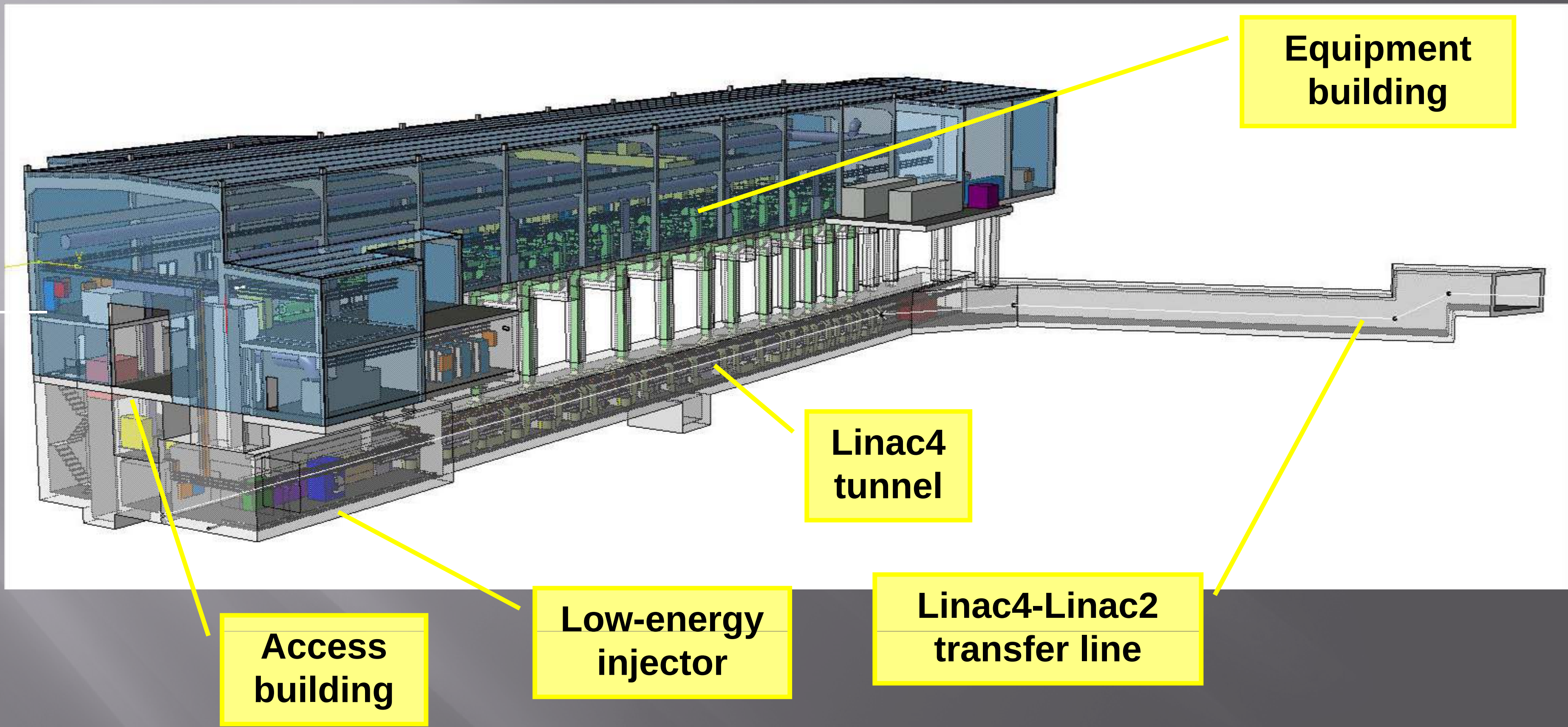
- ❑ in about 80 m length
- ❑ using 4 different accelerating structures, all at 352 MHz
- ❑ the Radio-Frequency power is produced by 19 klystrons
- ❑ focusing of the beam is provided by 111 Permanent Magnet Quadrupoles and 33 Electromagnetic Quadrupoles



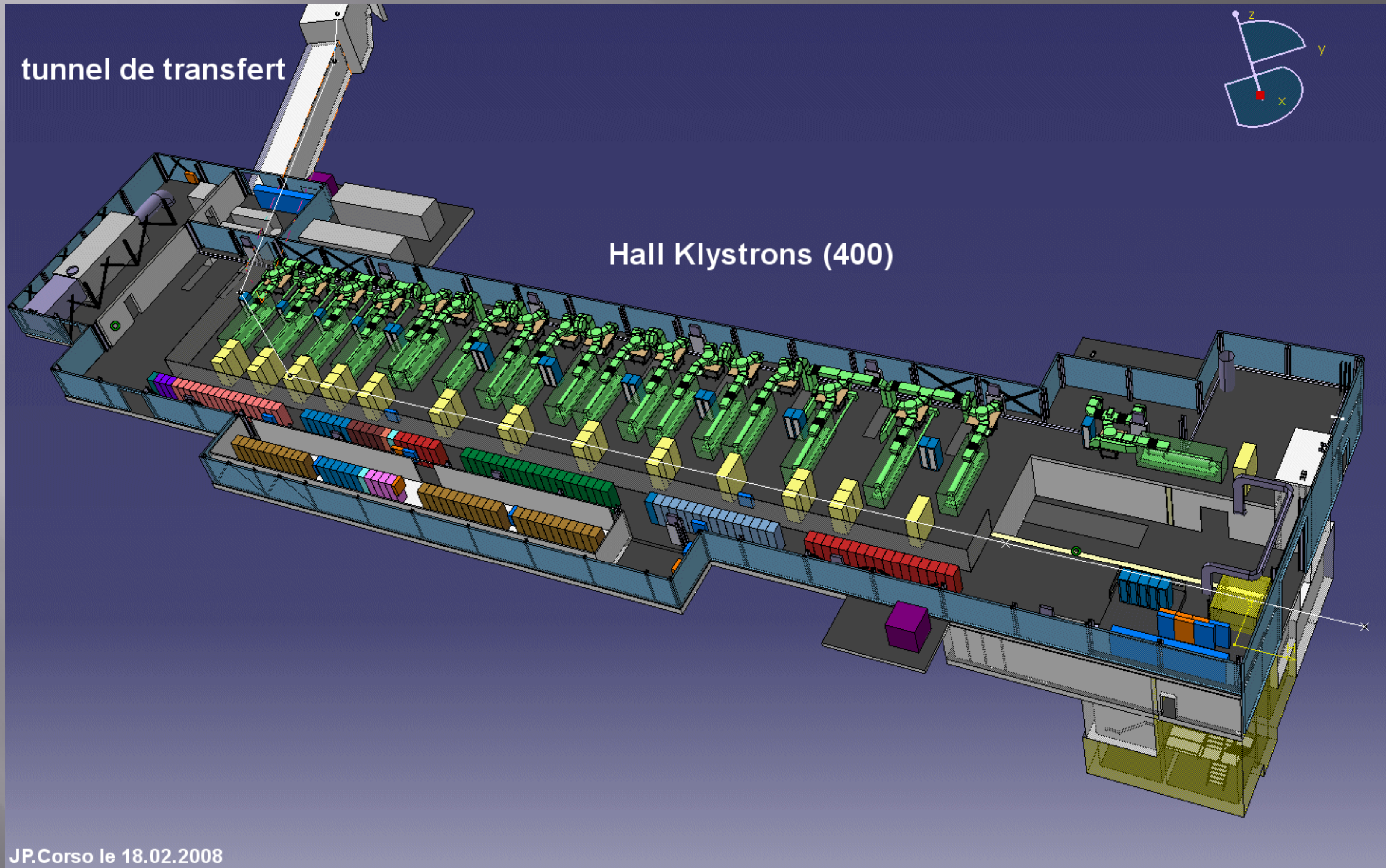
	RFQ	DTL	CCDTL	PIMS	
Output energy	3	50	102	160	MeV
Frequency	352	352	352	352	MHz
No. of resonators	1	3	7	12	
Gradient E_0	-	3.2	2.8-3.9	4.0	MV/m
Max. field	1.95	1.6	1.7	1.8	Kilp.
RF power	0.5	4.7	6.4	11.9	MW
No. of klystrons	1	1+2	7	4+4	
Length	6	18.7	25.2	21.5	m

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

Linac4 civil engineering

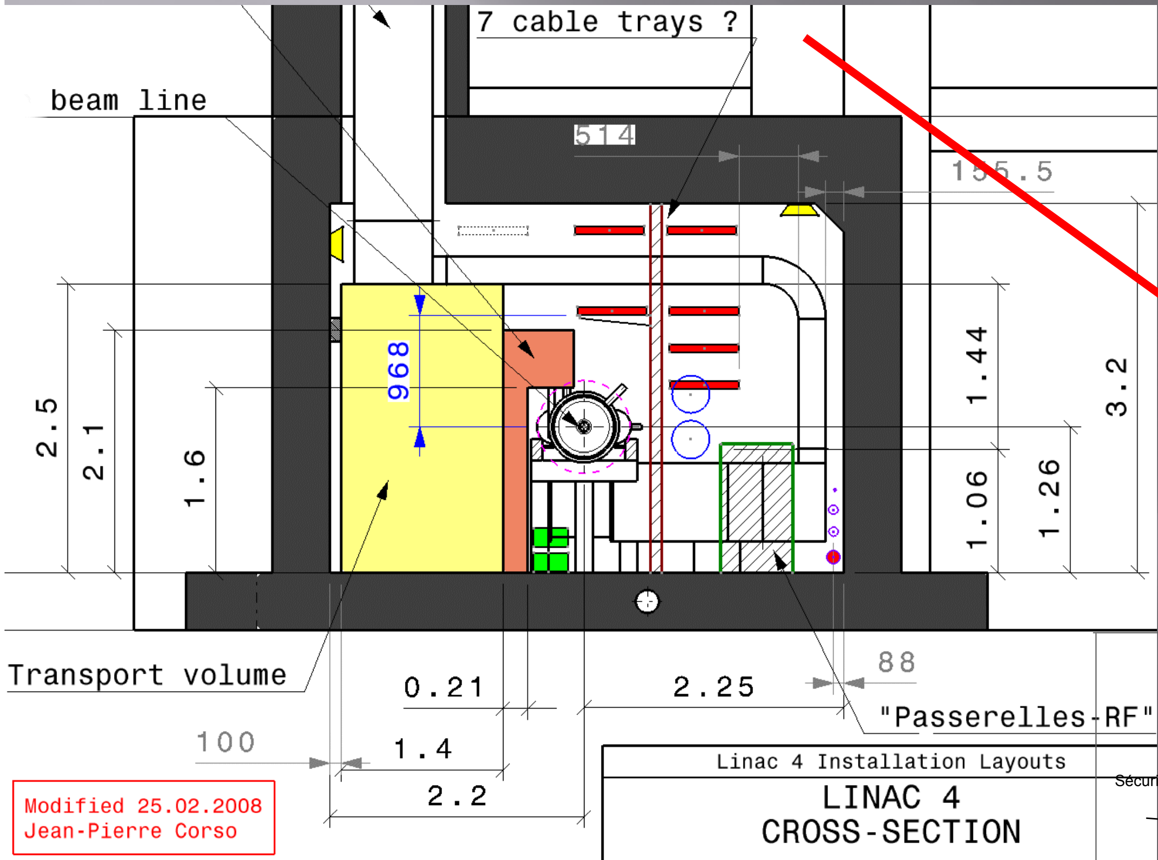


Equipment Hall (Bld. 400)

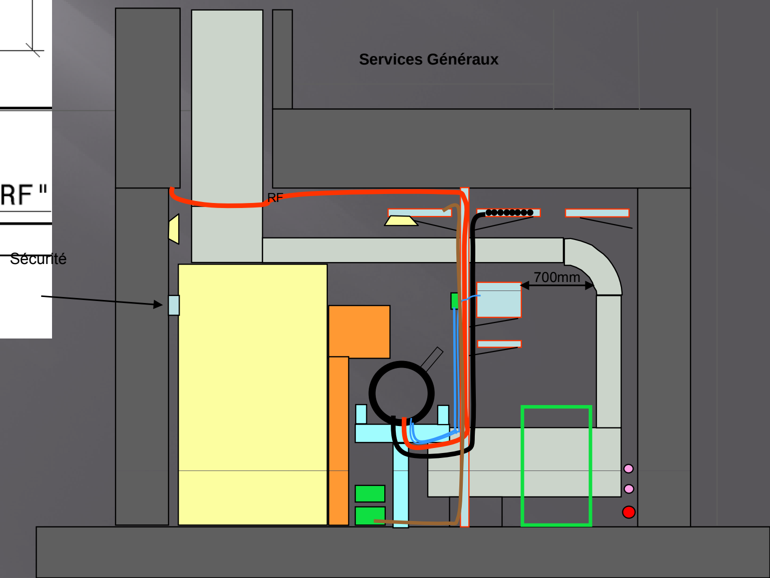


False floor 500mm (all along equipment hall)

Tunnel cross-section



Final position of cable trays:



REFERENCES
- SPL -

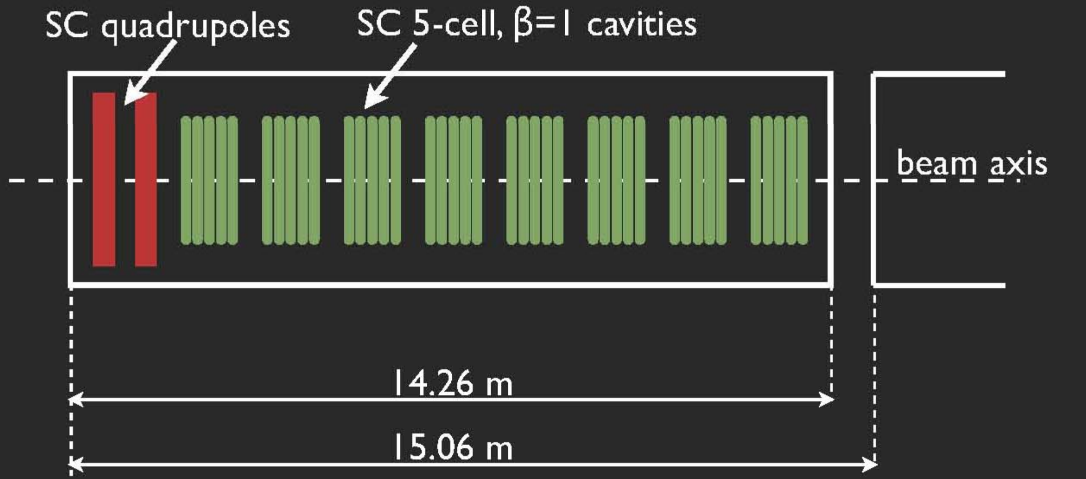
SPL architecture

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**

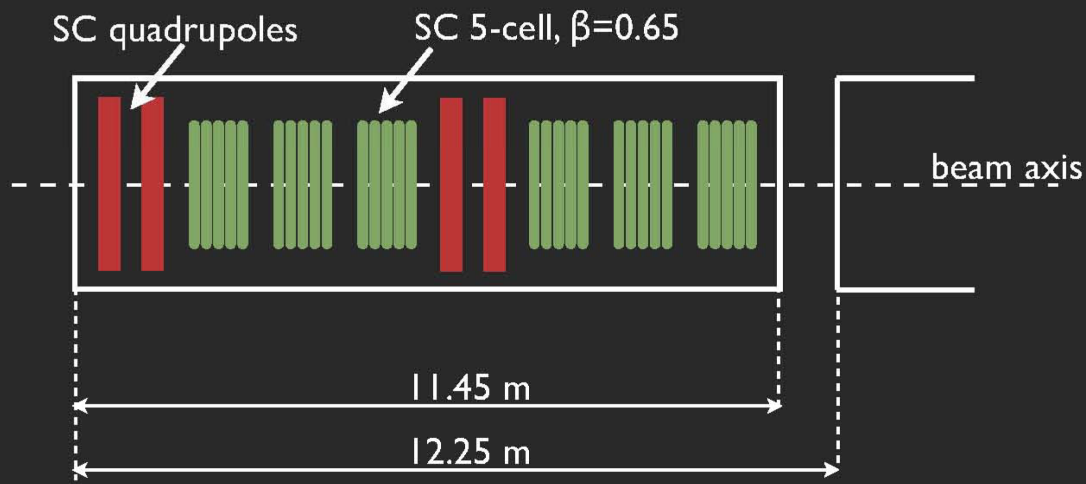
"Potential SPL architectures", SPL review, 30 April 2008, F. Gerigk, M. Eshraqi

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)