UPGRADE PLANS FOR THE LHC INJECTOR COMPLEX

OUTLINE

- **Why upgrade ?**
- **When?**
- **How?**
- **Summary**

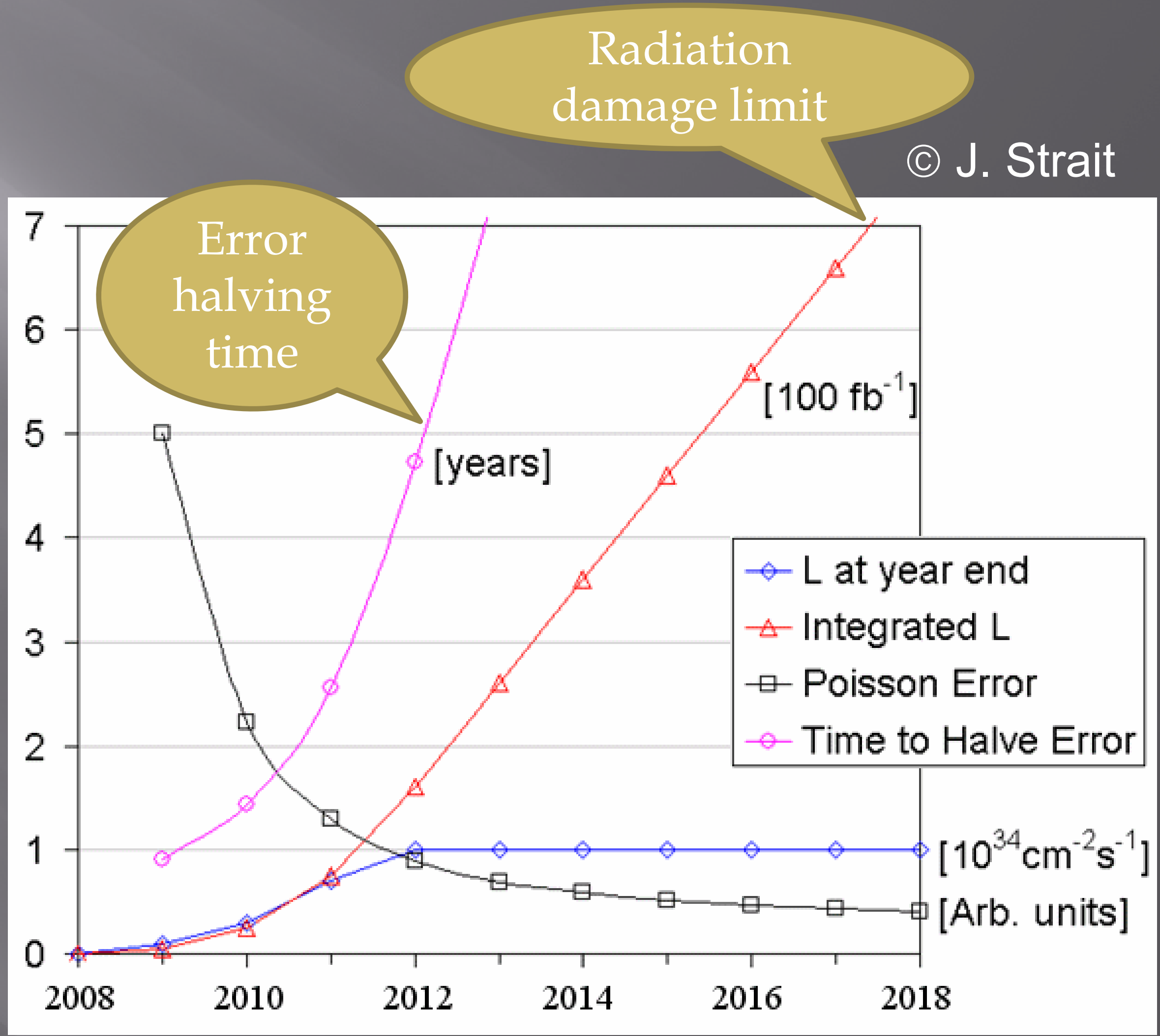
R. Garoby

Why upgrade?

Why upgrade the LHC performance?

- Hardware ageing
- Foreseeable luminosity evolution

⇒ **Need for a first upgrade in ~ 2013 and a major one 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?

Timetable

	PHASE 1	PHASE 2
2008	Start construction of Linac4 + IR upgrade – phase 1 + Collimation upgrade	Start design of SPL/PS2/SPS upgrade/LHC upgrade
Mid-2011		Detailed project proposals (TDR + cost estimates)
2012		Start of construction of new injectors
2013-14	Commissioning of LHC upgrade phase 1	
2018		Commissioning of LHC upgrade phase 2

How?

Upgrade procedure

Main performance limitation:

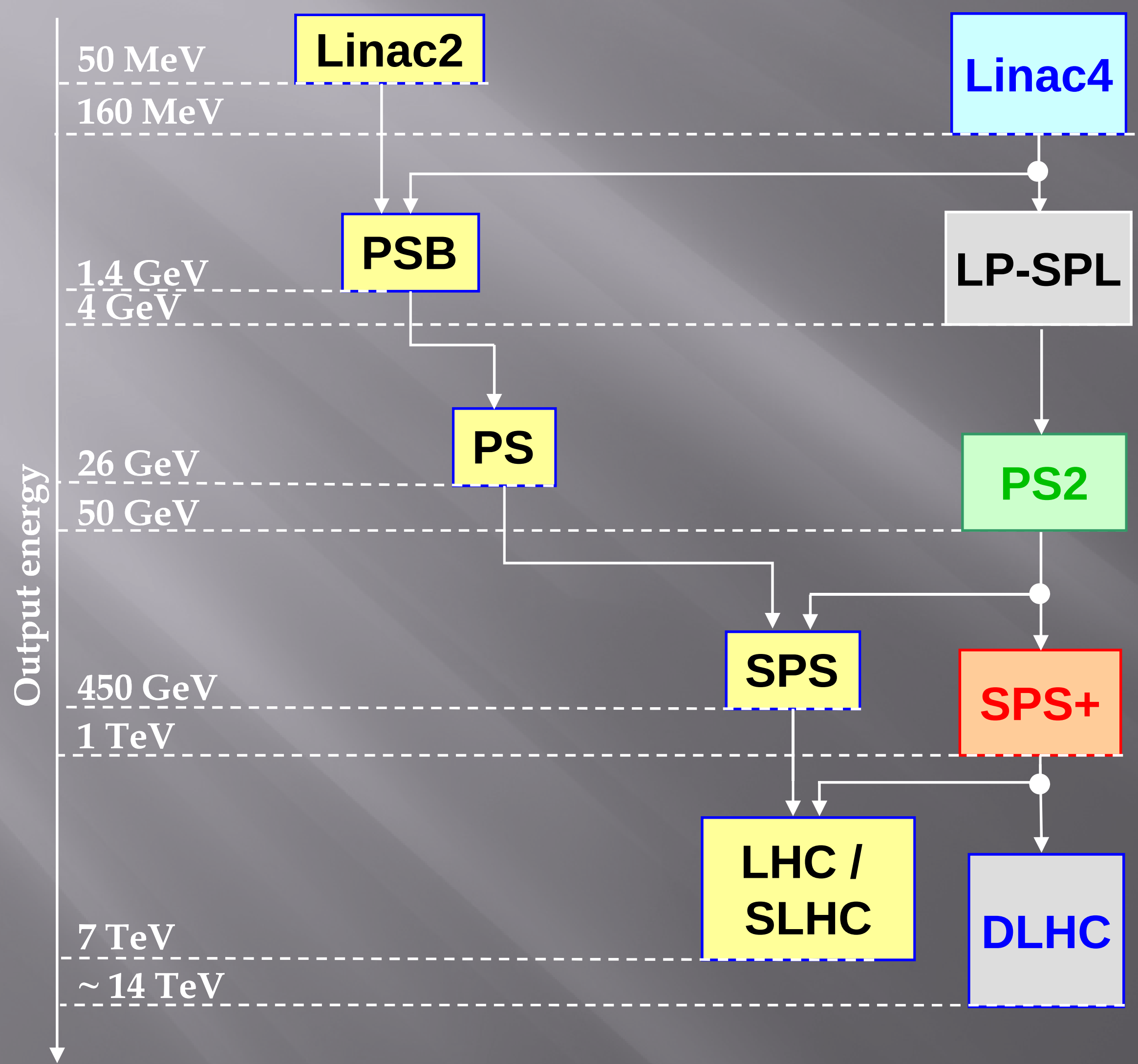
Incoherent space charge tune spreads ΔQ_{SC} at injection in the PSB (50 MeV) and PS (1.4 GeV) because of the required beam brightness N/ε^*.

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

⇒ **need to increase the injection energy in the synchrotrons**

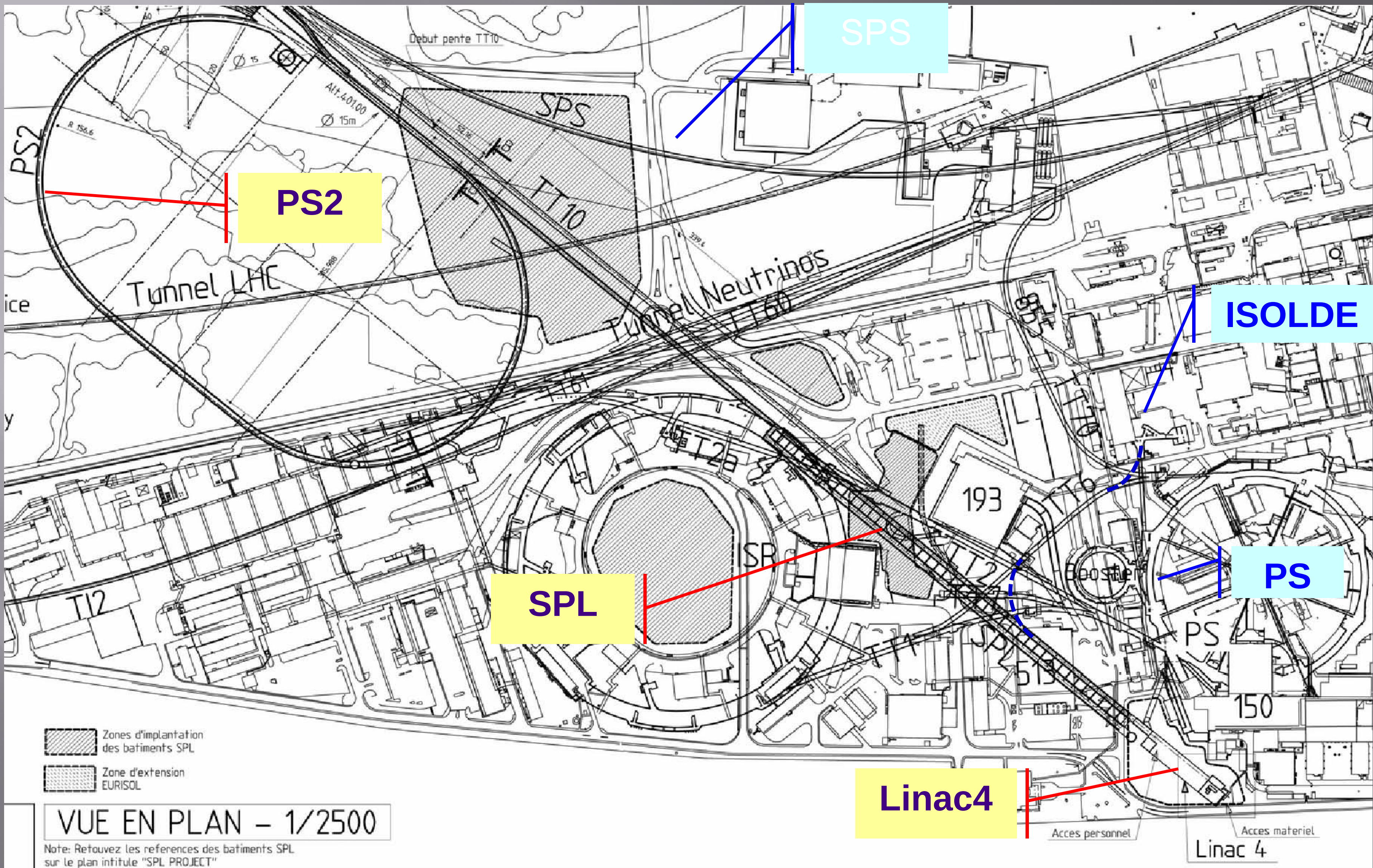
- **Increase injection energy in the PSB from 50 to 160 MeV kinetic**
- **Increase injection energy in the SPS from 25 to 50 GeV kinetic**
- **Design the PS successor (PS2) with an acceptable space charge effect for the maximum beam envisaged for SLHC: => injection energy of 4 GeV**

Present and future injectors

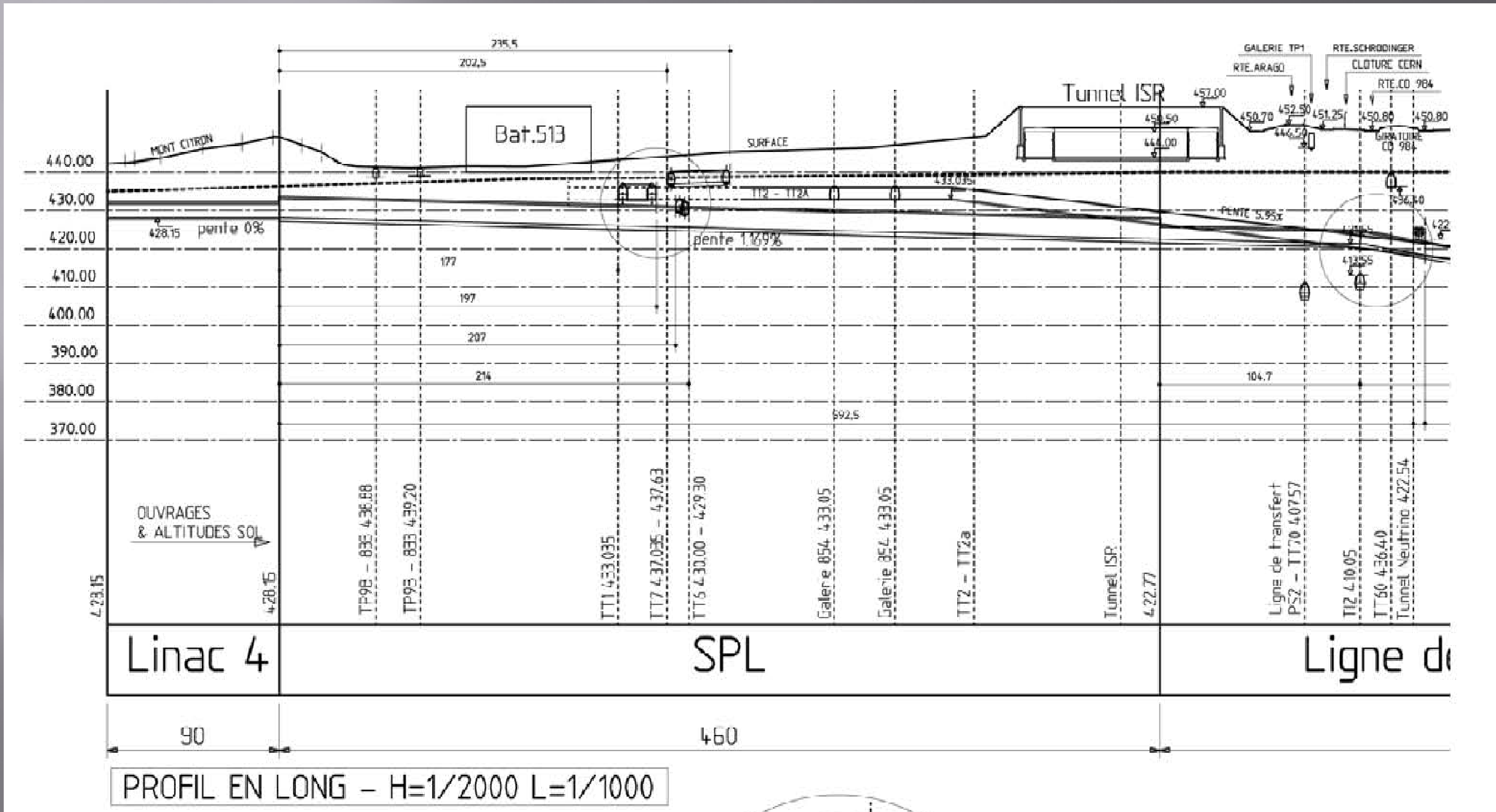


- **LP-SPL**: Low Power - Superconducting Proton Linac (4-5 GeV)
- **PS2**: High Energy PS (~ 5 to 50 GeV – 0.3 Hz)
- **SPS+**: Superconducting SPS (50 to1000 GeV)
- **SLHC**: "Superluminosity" LHC (up to 10^{35} $cm^{-2}s^{-1}$)
- **DLHC**: "Double energy" LHC (1 to ~14 TeV)

Layout of the new injectors

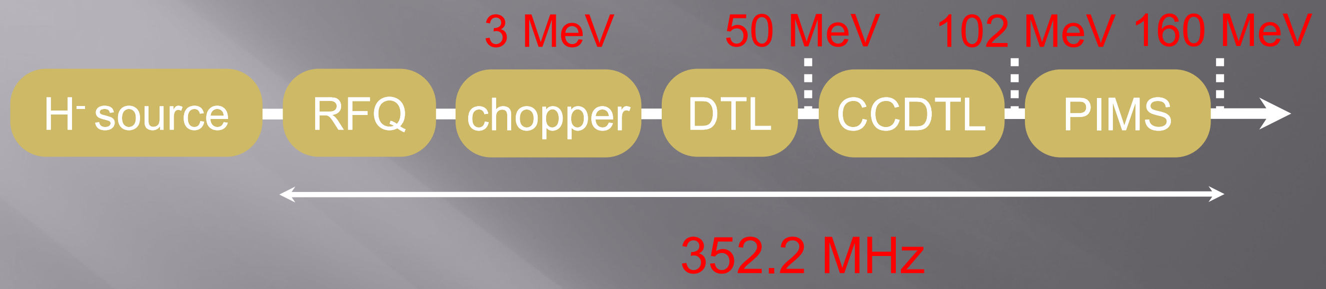


Layout of the new injectors



Stage 1: Linac4

Enabled by additional resources for “New Initiatives”

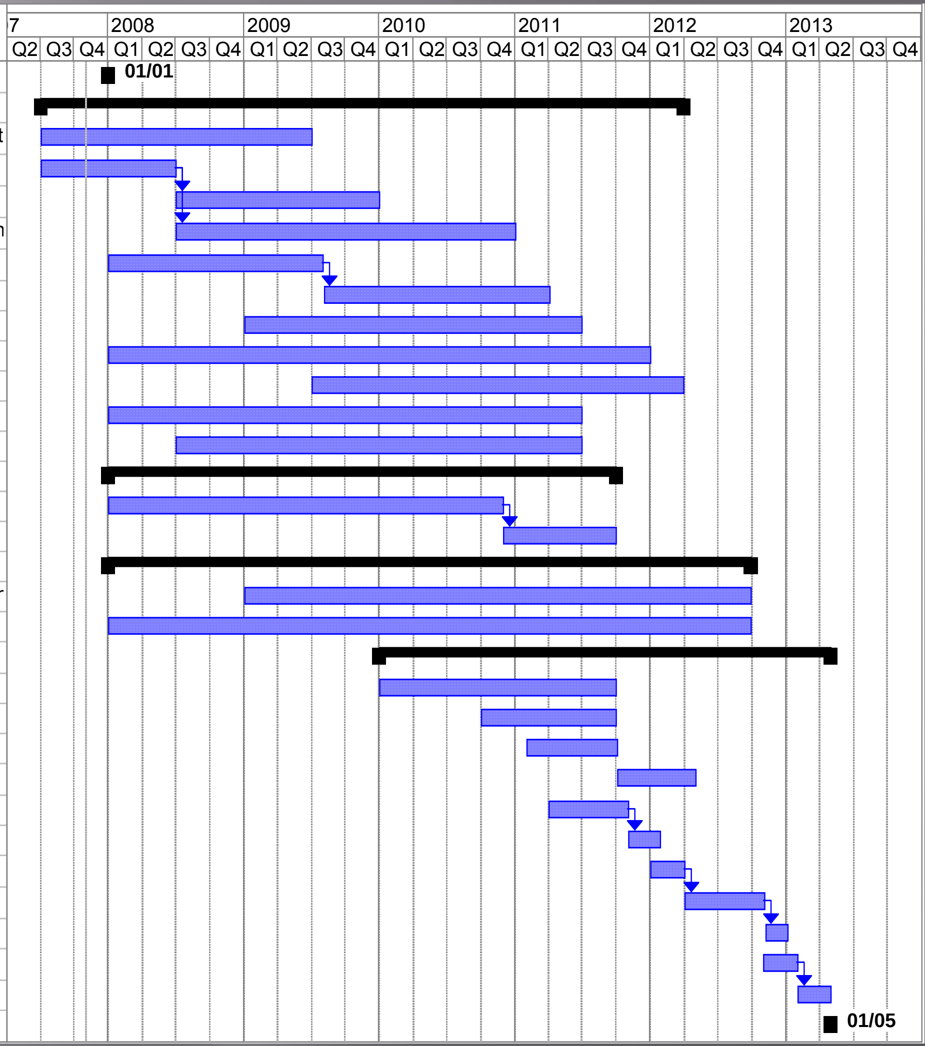


Linac4 beam characteristics

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 construction
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: mid-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

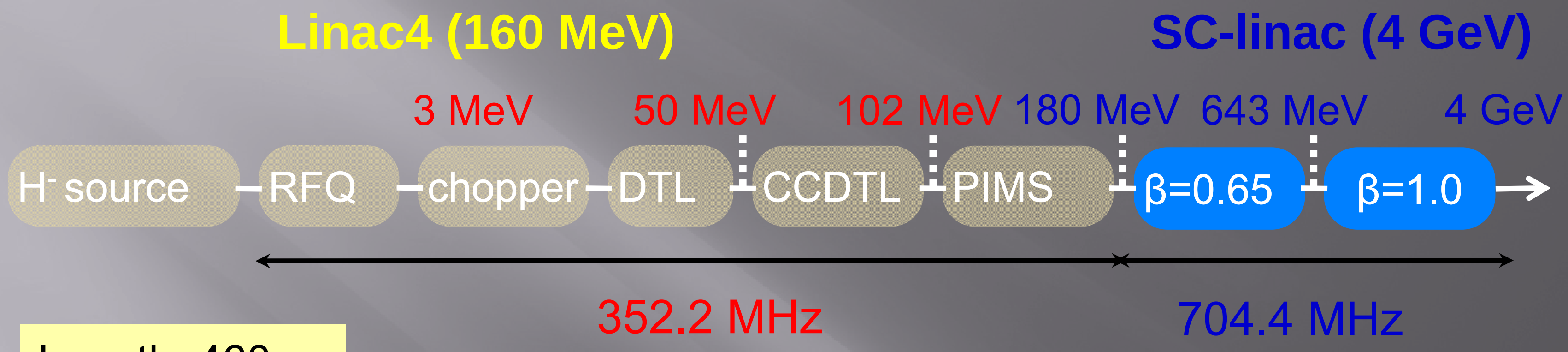
  ⇒ potential to double the beam brightness and fill the PS with the LHC beam in a single pulse: no more long flat bottom at PS injection + shorter flat bottom at SPS injection: easier/ more reliable operation / potential for ultimate beam from the PS

  ⇒ 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 LP-SPL + 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: SPS upgrade

To be able to transmit the higher quality beam provided by PS2, the SPS must be upgraded. The following subjects are identified:

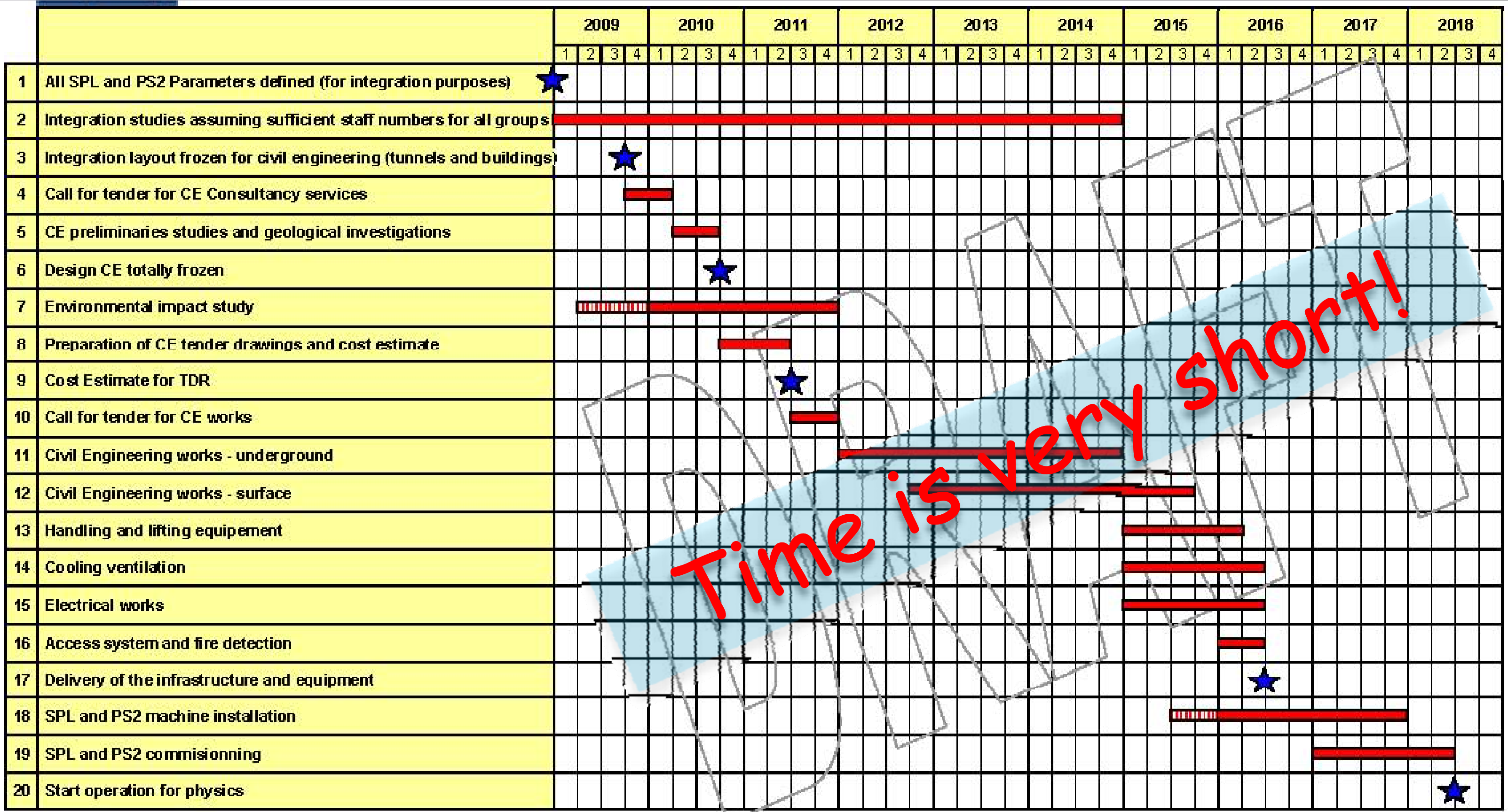
- Injection kickers have to be replaced (50 GeV),
- Impedance (heating) of ejection kickers must be reduced*
- Electron-cloud effects due to SEY of vacuum chambers must be reduced*

Machine Developments with beam will extensively be used during the next years to identify other potential limitations and explore cures.

* Effects impacting on SPS performance already today

Stage 2: Planning

Construction of LP-SPL and PS2 will not interfere with the regular operation for physics. Similarly, beam commissioning of LP-SPL and PS2 will take place without disturbing users.



Notes : The 3 years between the first item, "all parameters defined", and the starting of the CE Works is extremely challenging
The planning for EL, CV, HE, ... works needs to be approved by various TS corresponding Groups
The planning for items 19 to 20 results from preliminary discussions with R. Garoby and F. Gerigk
Except new FTE, the first financial commitment for either project will be item 5 (~1 MCHF). We will try to present the financial commitment planning before end 2008

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:

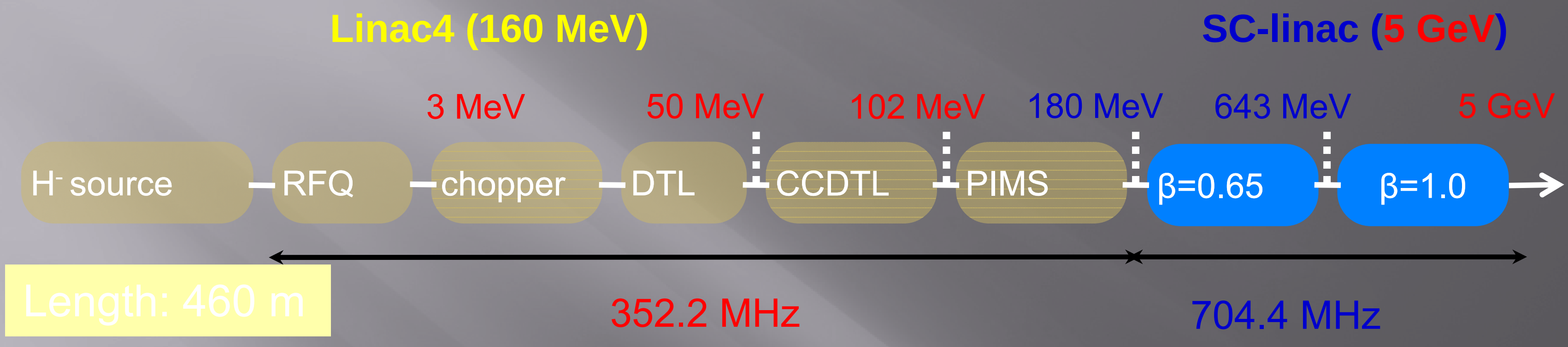
- Capability to deliver 2.2× the ultimate beam for LHC to the SPS

  ⇒ 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 LP-SPL and PS2
  - More than 50 % of the LP-SPL 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 3a: SPL (High Power)



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) <u>or</u> 6 MW (5 GeV)	4 MW (2.5 GeV) <u>and</u> 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 (mA)	20	40
Pulse duration (ms)	1.2	0.8 (2.5 GeV) + 0.4 (5 GeV)

Stage 3b: LHeC …

Additional option initiated in September 2008 (LHeC workshop in Divonne): use the β=1 part of the SPL for multi-pass acceleration of e+/e- for LHeC…

In any case, any upgrade beyond stage 2 (LP-SPL):

- will depend upon the approval of major new physics programmes [Radioactive Ion beams (EURISOL-type facility) / Neutrino factory / LHeC].
- will be mostly implemented during a series of ordinary shutdowns
- **is unlikely to be in operation before 2020**

Summary

Impact of the new injectors

The replacement of the SPS injectors and the SPS upgrade are essential ingredients for maximizing the physics reach of the LHC:

- The reliability of the injectors is key to reducing the turn-around time between physics data-taking, which is necessary to maximize the integrated luminosity.
- The improved beam characteristics (higher brightness, potential for smaller emittances) are essential ingredients of the scenarios envisaged to increase the integrated luminosity by a factor of 10.

The LHC injector chain will be used by the collider only during a limited percentage of the time. The proposed accelerators try to address as much as possible the perceived needs of physicists and to include the flexibility to later evolve and fulfill future requirements.

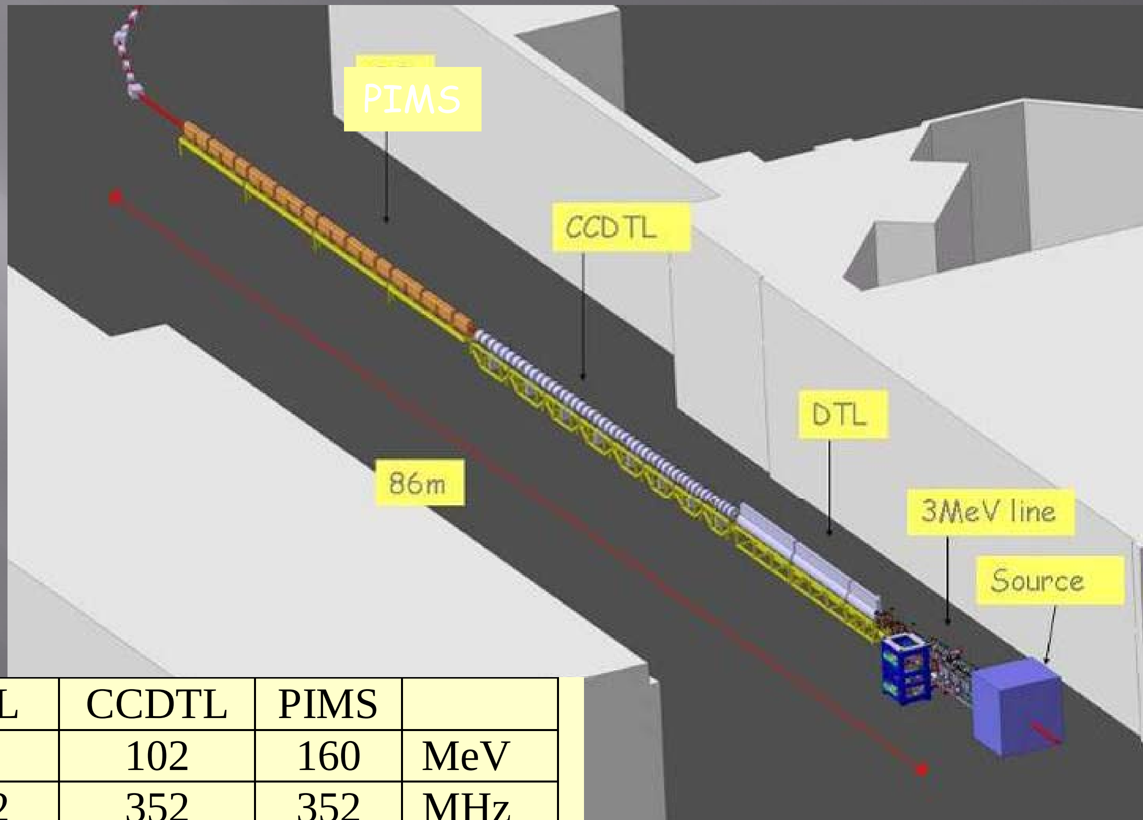
THANK YOU!

REFERENCES
- Linac4-

Linac4 accelerating structures

Linac4 accelerates H- ions up to 160 MeV energy:

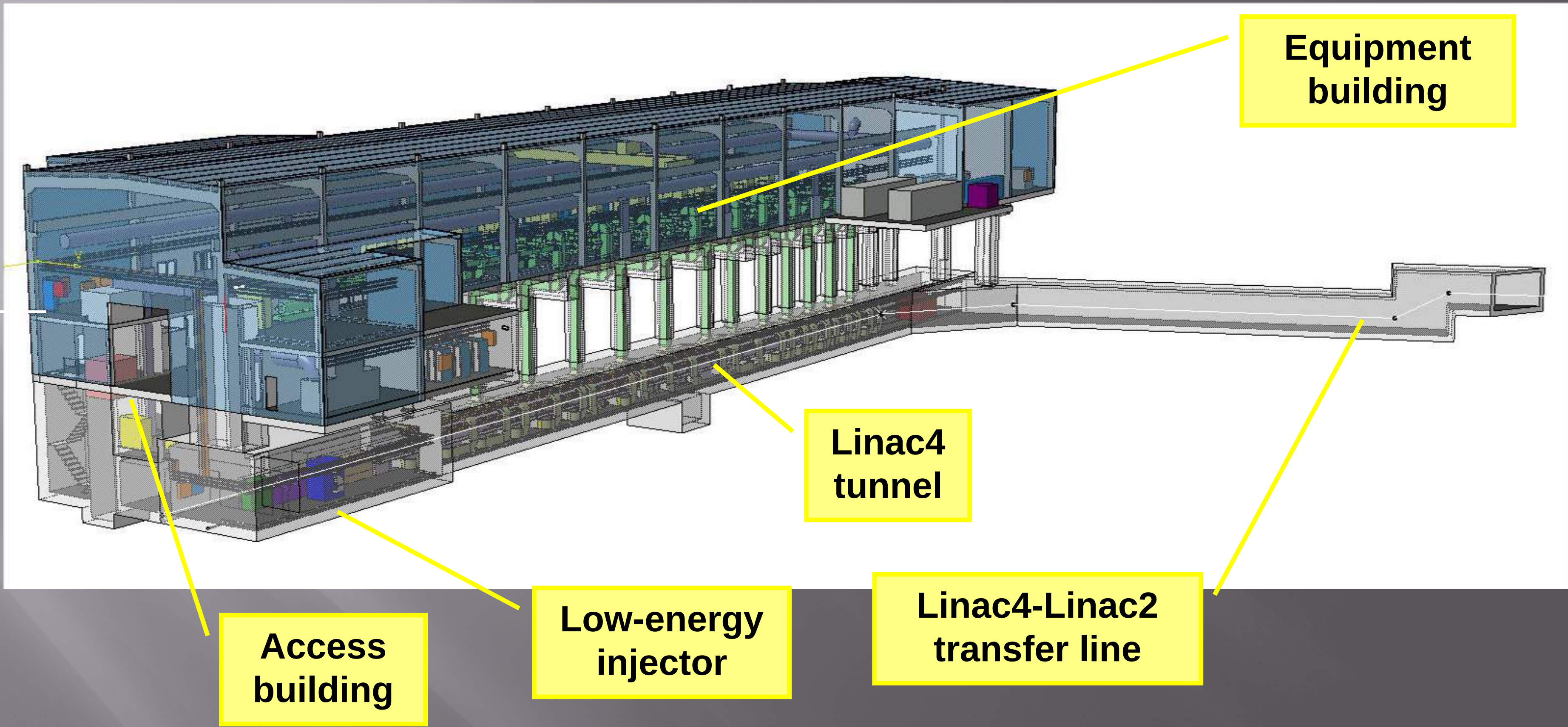
- in about 80 m length
- using 4 different accelerating structures, all at 352 MHz
- the Radio-Frequency power is produced by 19 klystrons
- focusing of the beam is provided by 111 Permanent Magnet Quadrupoles and 33 Electromagnetic Quadrupoles



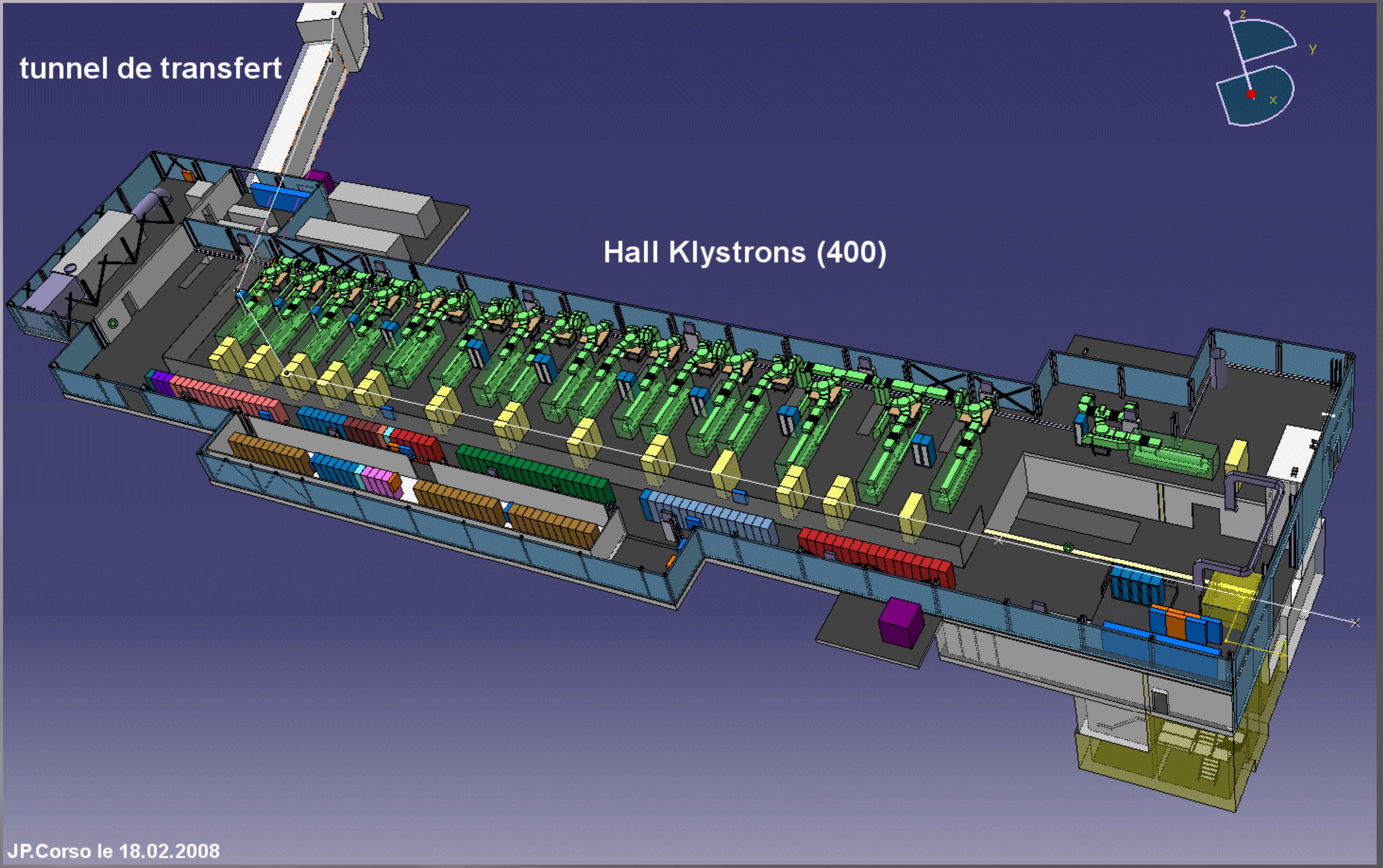
	RFQ	DTL	CCDTL	PIMS	
Output energy	3	50	102	160	MeV
Frequency	352	352	352	352	MHz
No. of resonators	1	3	7	12	
Gradient E_0	-	3.2	2.8-3.9	4.0	MV/m
Max. field	1.95	1.6	1.7	1.8	Kilp.
RF power	0.5	4.7	6.4	11.9	MW
No. of klystrons	1	1+2	7	4+4	
Length	6	18.7	25.2	21.5	m

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

Linac4 civil engineering

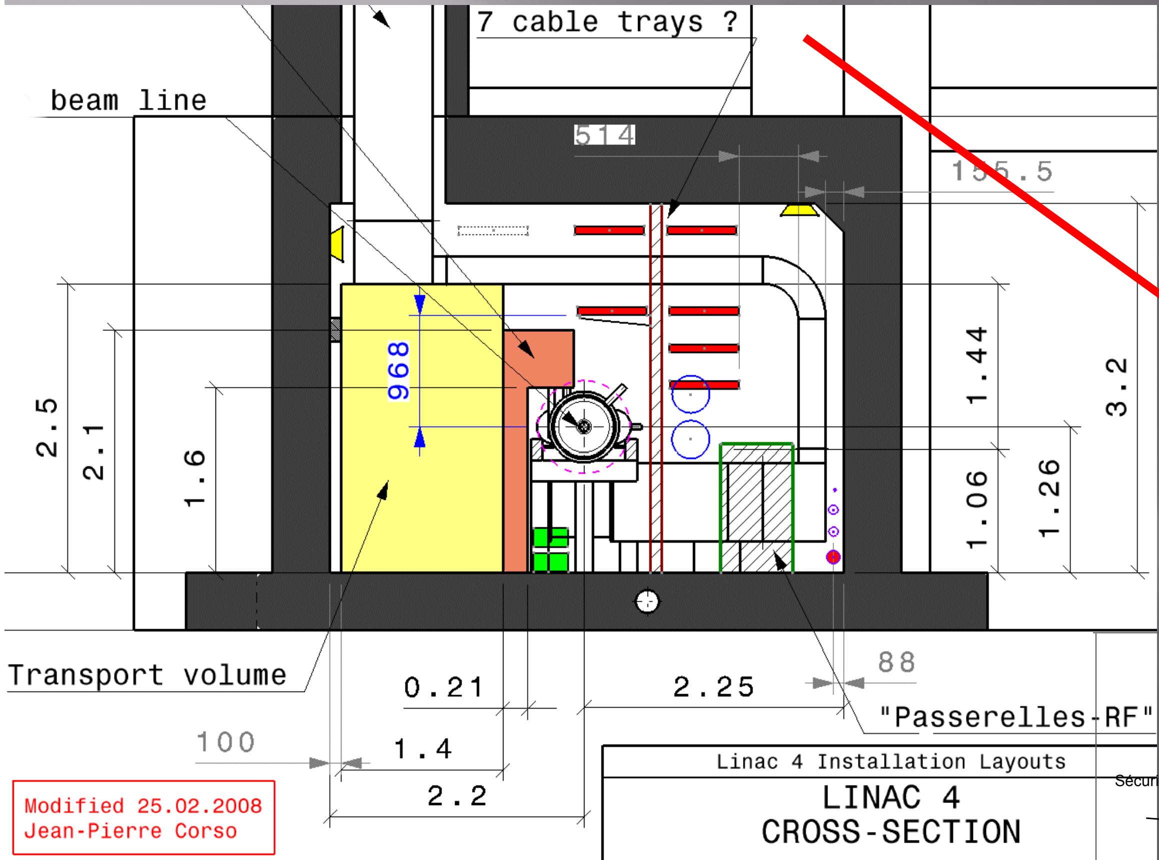


Equipment Hall (Bld. 400)

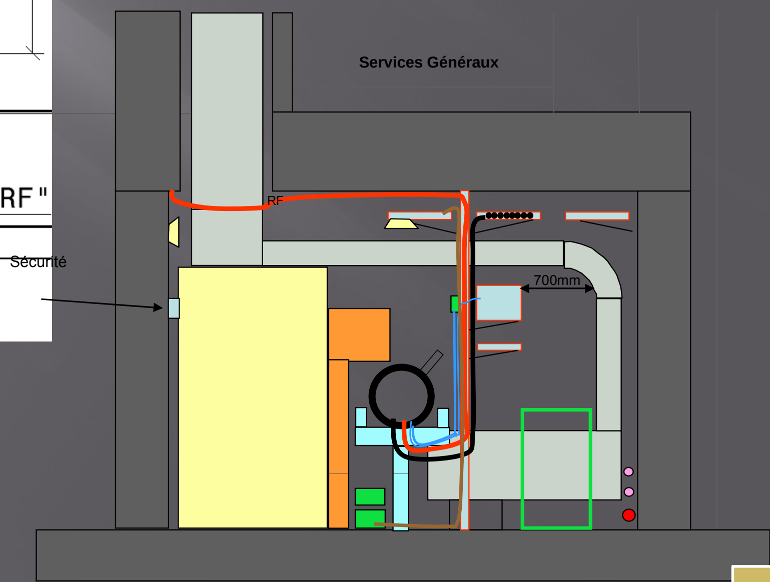


False floor 500mm (all along equipment hall)

Tunnel cross-section



Final position of cable trays:



REFERENCES
- SPL -

SPL architecture

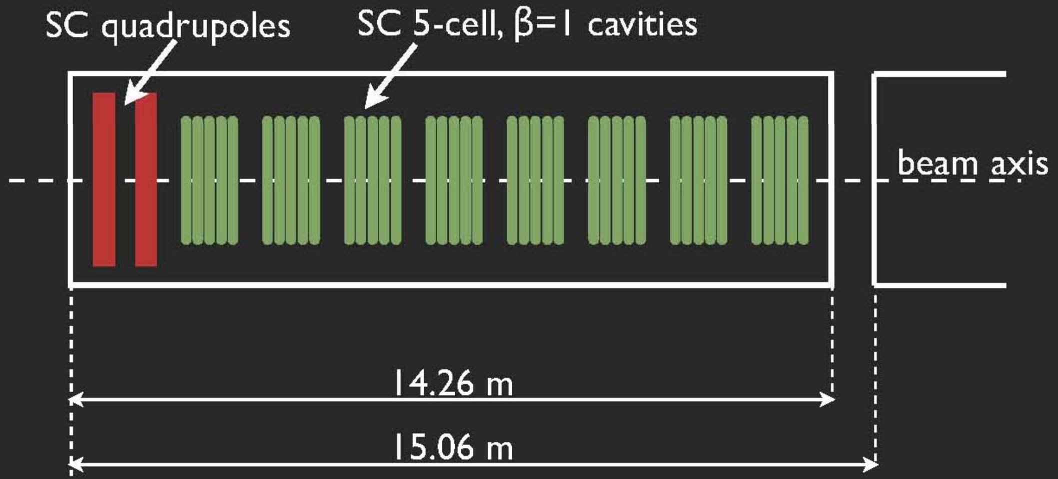
SPL type	nominal improved	option I	I b
frequency [MHz]	704.4	1408.8	352.2/1408.8
beta families	0.65/0.92	0.6/0.76/0.94	0.67/0.8/0.94
cells/cavity	5/5	7/9/9	4/5/9
trans. energies [MeV]	160/589	160/358/876	tbs
output energy [MeV]	5137	4992	tbs
gradients [MV/m]	19/25	19/20/28	tbs
cavities p. module	6/8	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

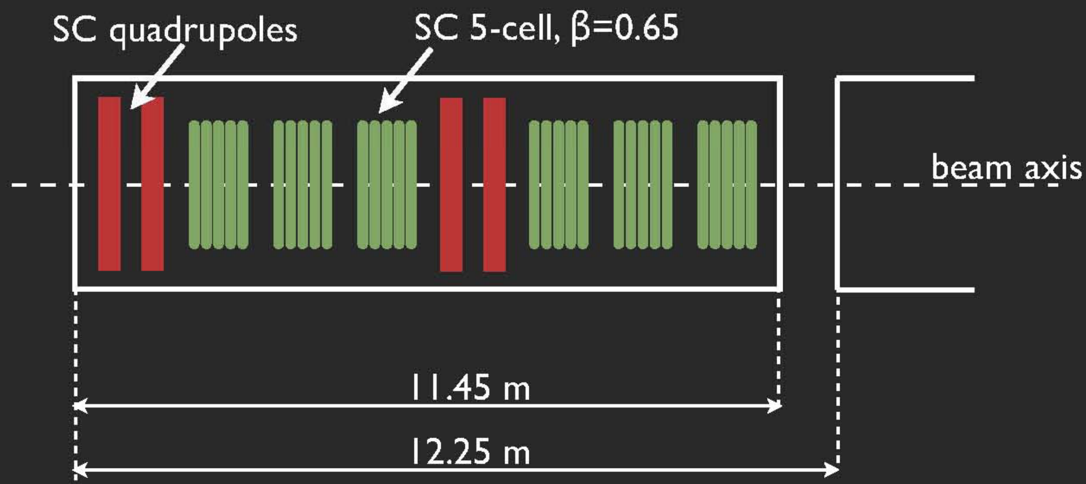
high-beta section:

- 704.4 MHz, 25 MV/m,
- 668 - 5094 MeV,
- 25 periods, 200 cavities,
- 377 m



low-beta section:

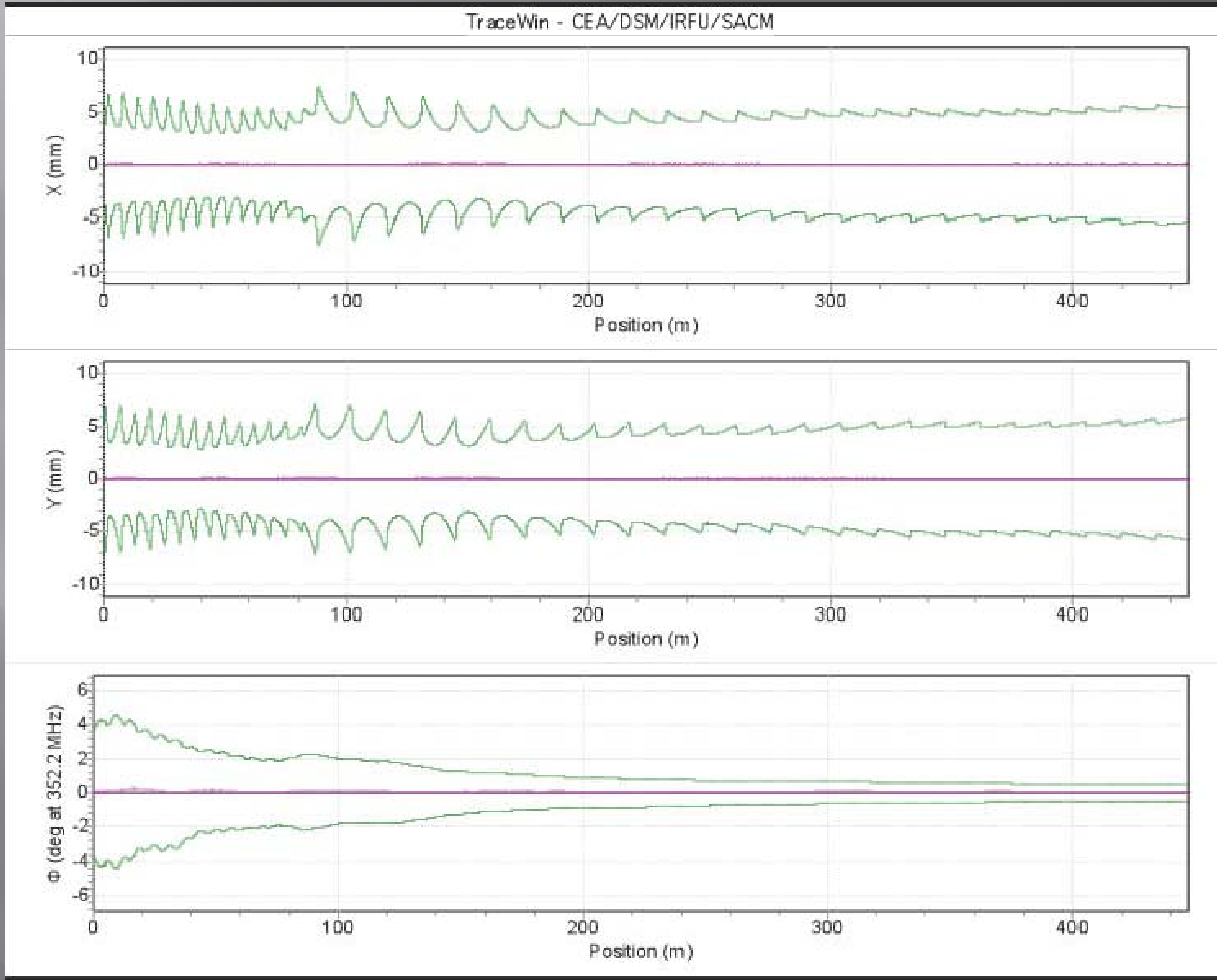
- 704.4 MHz, 19 MV/m,
- 180 - 668 MeV,
- 14 periods, 42 cavities,
- 86 m



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)



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

REFERENCES
- SPS upgrade -

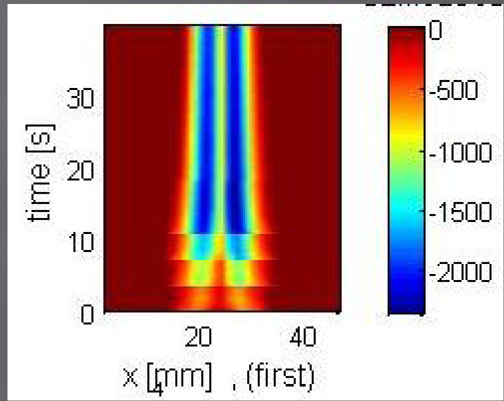
SPS upgrade (1/2)

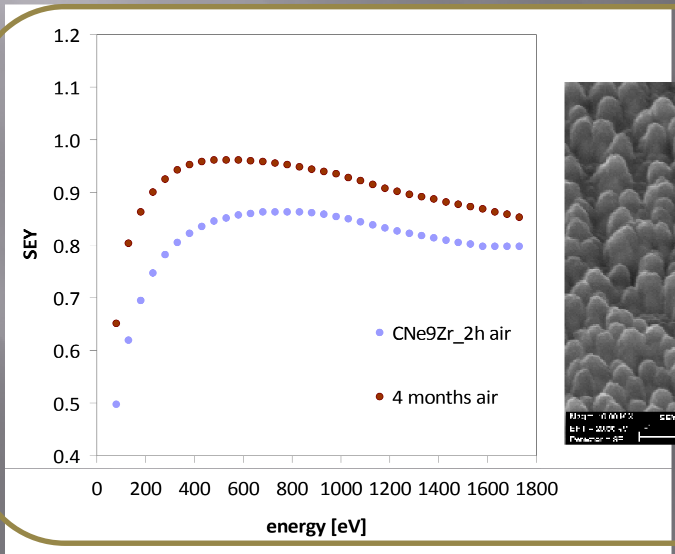
from E. Shaposhnikova

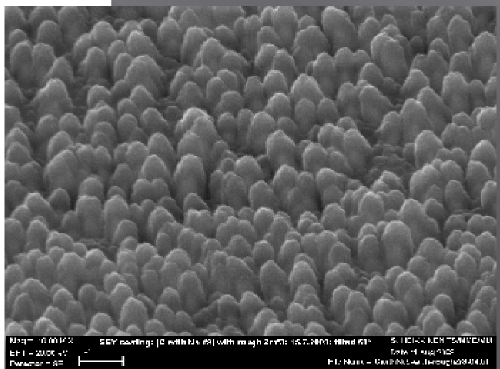
Possible techniques for electron cloud mitigation:

- surface treatment: in-situ, no aperture reduction, no re-activation
  - carbon based composites, SEY<1 obtained, - ageing problem (with venting)
  - rough surfaces – 2 layers
- active damping system in V-plan
  (in collaboration with US-LARP)
- grooves - 35% SEY reduction in lab – but also aperture reduction
- cleaning (enamel) electrodes

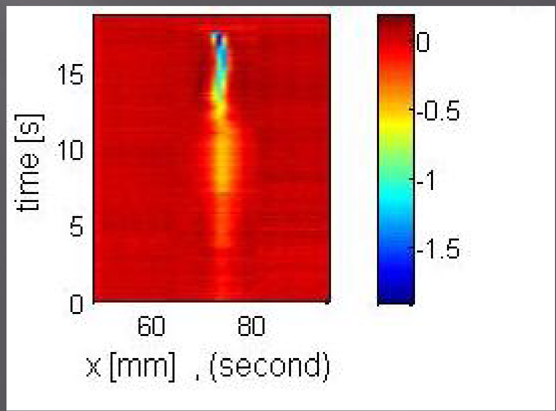
"Typical" Stainless Steel





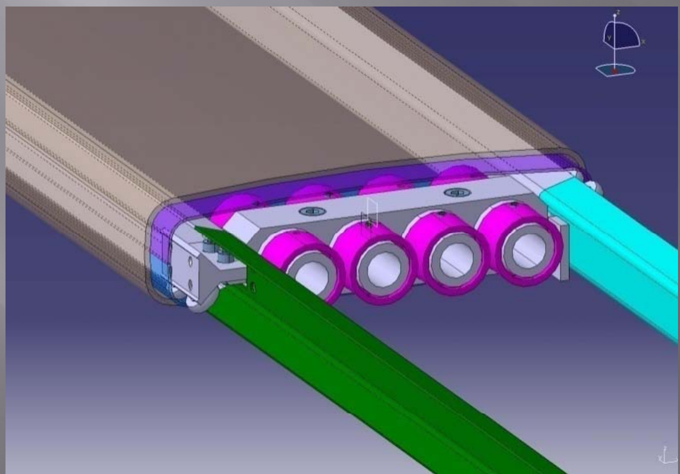


Amorphous Carbon C-8



SPS upgrade (2/2)

from E. Shaposhnikova



Implementation in the SPS tunnel

• Experience from installation of RF shields (1999-2001) and ongoing refurbishing of the cooling circuits of dipoles (2007-2009)

• Infrastructure: ECX5 cavern – ø20 m

• 750 dipoles can be coated in 120 days → 2 shutdowns (48 h/chamber, 6/day) with 2 Dumont machines and 2 coating benches

Plans for 2009

• **Large size test of carbon coating in accelerator context** (installation of coated chambers in 3 MBB magnets in the SPS test area with **microwave and vacuum diagnostics)**

• **Continuation of experimentation with different coating techniques**

REFERENCES
- Low emittances -

Instantaneous luminosity

The new injectors are designed to provide beam with much higher brightness.

$\Downarrow$

How much could the LHC characteristics be improved with lower transverse emittances?

BASIC FORMULAE

Luminosity is given by:

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

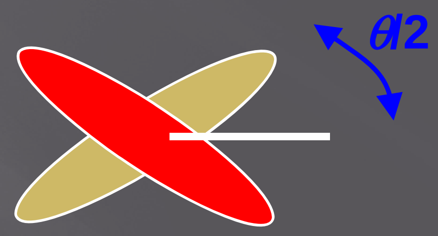
where ΔQ_{bb} = total beam-beam tune shift

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

with a tight constraint on its maximum value

and ϕ = Piwinski angle

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



Effective beam emittance

"Low Emittances" schemes (1/3)

- **Nominal beam intensity per bunch**
- **25 ns bunch spacing**
- **Phase-1 upgrade (IR + Linac4)**

Maximum luminosity with ε*=3.75 mm.mrad: 1.47 x 10^{34} $cm^{-2}s^{-1}$

	Nominal	Nominal with IR phase 1	Nominal with IR phase 1 and reduced emittance
N_b (x 10^{11})	1.15	1.15	1.15
ε (μm)	3.75	3.75	**2.54**
β*	0.55	0.25	0.25
σ* (μm)	16.58	11.18	9.20
Crossing angle (mrad)	0.290	0.440	**0.360**
σ_z (mm)	75.50	75.50	75.50
ϕ (Piwinski angle)	0.66	1.49	**1.48**
ΔQ_{bb} head-on	1.00	0.67	**0.99**
Luminosity	1.00	**1.47**	**2.18**
Luminosity lifetime (h)	22.00	14.95	**10.08**

N_b/ε is at the level assumed with Linac4

Maximum luminosity with ε*=2.54 mm.mrad: 2.18 x 10^{34} $cm^{-2}s^{-1}$

"Low Emittances" schemes (2/3)

- Intensity per bunch: ultimate and 1.4 x ultimate
- 25 ns bunch spacing
- Phase-2 upgrade (IR + new injectors)

	Ultimate with β^*=0.25 m	Ultimate with β^*=0.25 m and reduced emittance	> Ultimate with β^*=0.15 m and reduced emittance
N_b (x 10^{11})	1.70	1.70	2.36
ε (μm)	3.75	**2.60**	**2.60**
β^*	0.25	0.25	0.15
σ^* (μm)	11.18	9.31	7.21
Crossing angle (mrad)	0.440	**0.365**	**0.474**
σ_z (mm)	75.50	75.50	75.50
ϕ (Piwinski angle)	1.49	**1.48**	**2.48**
ΔQ_{bb} head-on	0.99	**1.43**	**1.33**
Luminosity	3.22	**4.65**	**9.98**
Luminosity lifetime (h)	10.11	**6.99**	**4.52**

N_b/ε is at the level assumed with the new injectors

Maximum luminosity with ε^*=2.6 mm.mrad: 10^{35} $cm^{-2}s^{-1}$

"Low Emittances" schemes (3/3)

Additional comments:

- 25 ns bunch spacing,
- no D0 inside the detector,
- the ratio N/ε in the case of the phase-1 upgrade is the one foreseen with Linac4,
- the ratio N/ε in the case of the phase-2 upgrade is the one foreseen with the new injectors,
- the intensity assumed in the case of the phase-2 upgrade is the one foreseen in the "LPA" scenario.

⇓

The new injectors are at the design stage.
It is still time to refine their specifications and maximize their impact on LHC performance!