What will LP-SPL & PS2 provide for the LHC

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- LP-SPL & PS2 main parameters and LHC beam performance
- Implementation in accelerator complex and commissioning
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- Operation aspects
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Motivation for LP-SPL & PS2 upgrade

- **Improve reliability of injector chain for LHC era**
  - **Ageing accelerators, operating far beyond initial parameters and stretched to their limits to reach ultimate performance.**
  - **Complex operation requiring manpower intense tuning and very special expert knowledge and hardware**
  - **Efficient exploitation of high energy machines requires injector complex with sufficient performance margin**
    - **Need for new accelerators designed for the needs of (s)LHC**

- **Remove main performance limitation**
  - **Excessive incoherent space charge tune spreads ΔQ_{SC} at injection in the (50 MeV) and PS (1.4 GeV) because high required beam brightness N/ε*.**
    - **Need to increase the injection energy in the synchrotrons**

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

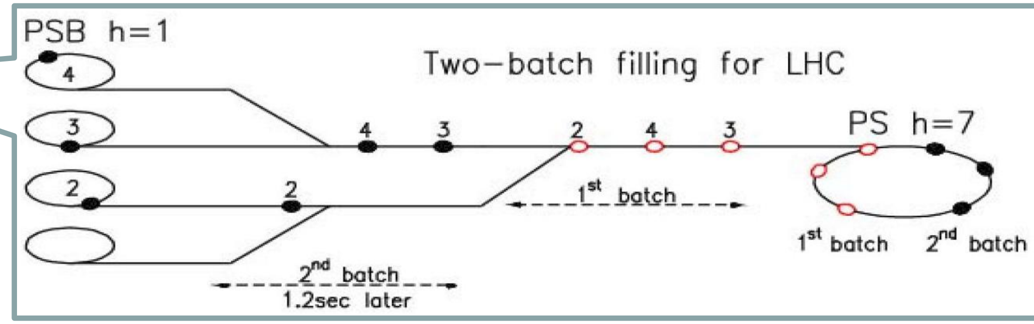
with N_b : number of protons/bunch

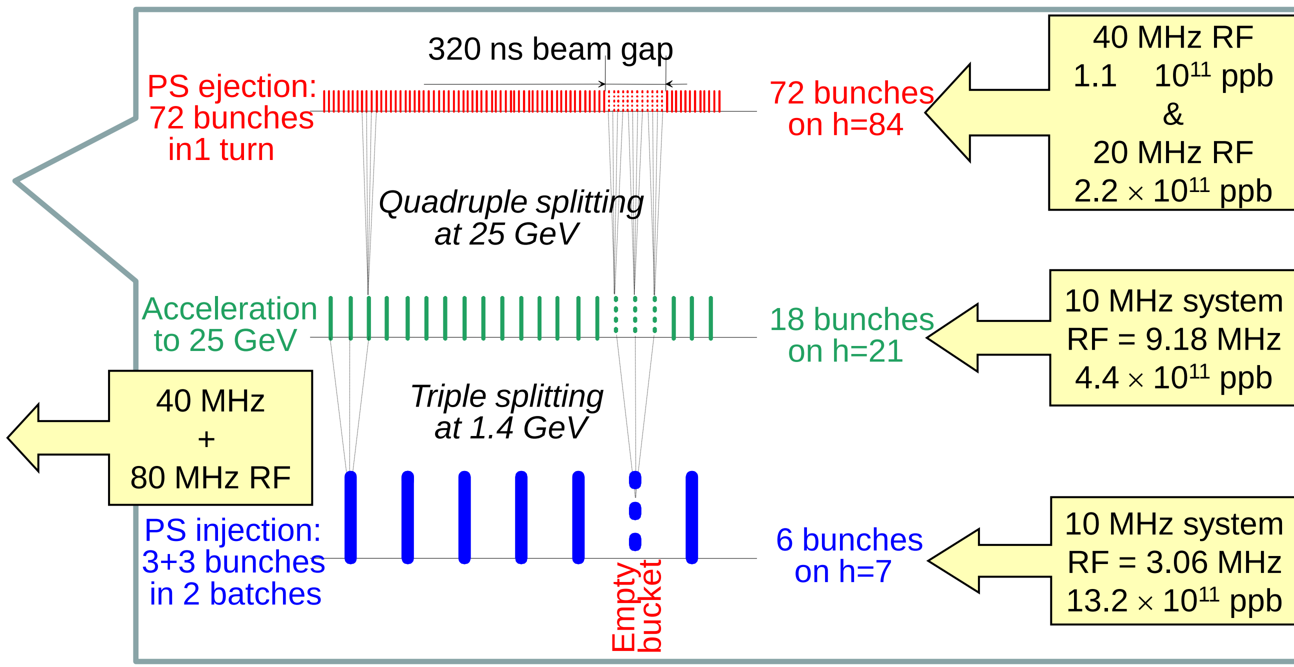
$\varepsilon_{X,Y}$: norm. transverse emittances

R : mean radius of the accelerator

Complication in operation: 25 ns bunch train production in PS complex

1. Division by 2 of the intensity in the PSB (one bunch per ring and double batch filling of the PS)
2. Increase of the injection energy in the PS (from 1 to 1.4 GeV)
3. Quasi-adiabatically splitting of each bunch 12 times in the PS to generate a train of bunches spaced by 25 ns
4. Compression of bunches to ~4ns length for bunch to bucket transfer to the SPS
5. Stacking of 3-4 PS batches in the SPS and acceleration to 450 GeV



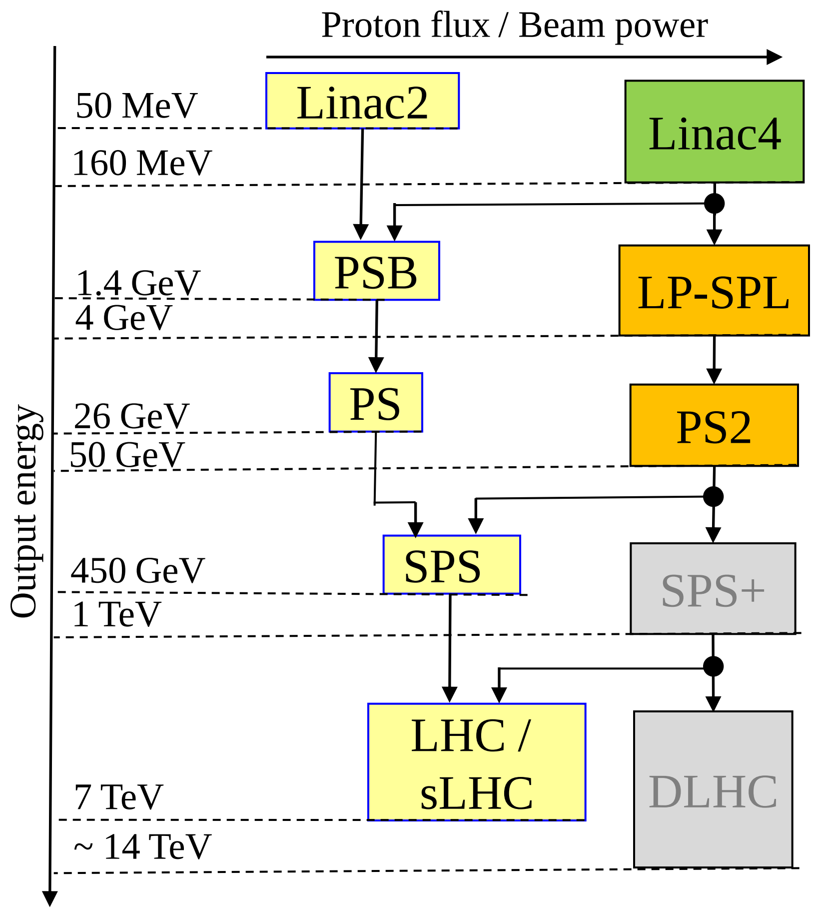


LP-SPL & PS2 design goals

- **For LHC operation**
  - **Significantly increased beam brightness**
  - **Flexibility for generating various bunch spacings and bunch patterns**
  - **Reduction of SPS injection plateau and LHC filling time**

- **General design goals**
  - **High reliability and availability**
  - **Simplification of operation schemes for complete complex**
  - **Reduced beam losses in operation for complete complex**
  - **Potential for future upgrades of the accelerator complex and future p+ (non-LHC) physics programmes**

Injector complex upgrade – proton operation

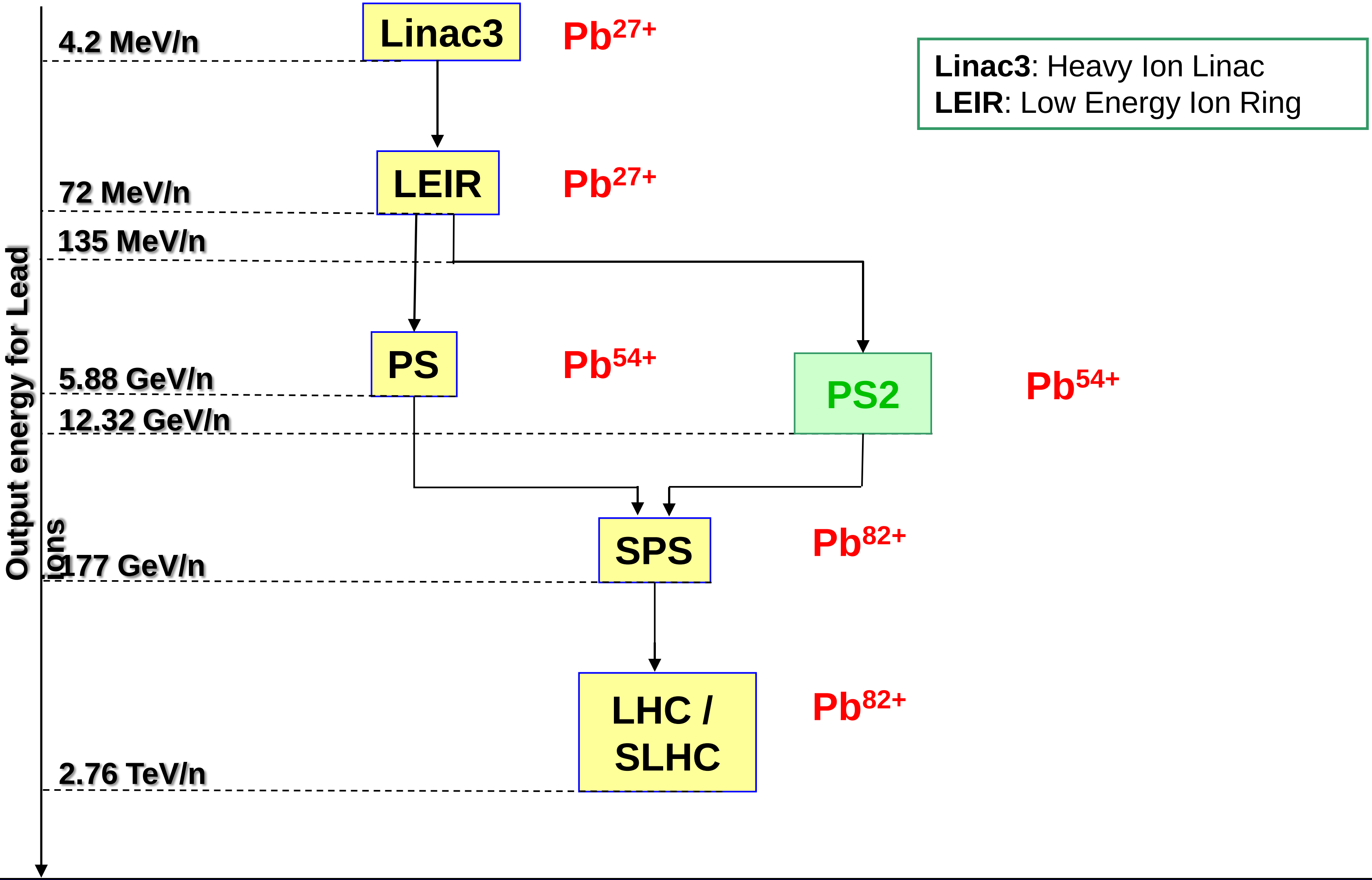


Linac4: H- Linac
(160 MeV)
LP-SPL: Low Power- Superconducting Proton Linac (4 GeV)
PS2: High Energy PS
(4 to 50 GeV – 0.3 Hz)
SPS+: Superconducting SPS
(50 to1000 GeV)
sLHC: "Superluminosity" LHC
(up to 10^{35} $cm^{-2}s^{-1}$peak)
DLHC: "Double energy" LHC
(1 to ~14 TeV)

Stage 1: Linac4
- construction 2008 – 2014

Stage 2: PS2 and LP-SPL: preparation of Conceptual Design Reports for
- **project approval mid 2012**
- start of construction begin 2013

Injector complex upgrade – ion operation



Performance requirements and parameters

- **Starting point for the design is brightness (N/ε_n) for LHC beams**
  - **Design goal: Twice higher brightness than "ultimate" 25ns beam with 20% intensity reserve for transfer losses**
    - **4.0×10^{11}ppb = $2 \times 1.7\times10^{11} \times 1.2$ in transverse emittances of 3μm**
- **Transfer energy LP-SPL – PS2**
  - **Determined by the beam brightness of the LHC beam**
  - **Limiting the incoherent space charge tune spread at injection to below 0.2 requires**
    - **4 GeV injection energy**
- **PS2 Extraction energy**
  - **Injection into SPS well above transition energy to reduce space charge effects and TMCI**
  - **Higher energy gives smaller transverse emittances and beam sizes and therefore reduced injection losses**
  - **Potential for long-term SPS replacement with higher energy**
    - **~50 GeV extraction energy**

LHC beams from SPL & PS2 (i)

- **Nominal bunch train at PS2 extraction**
  - h=180 (40 MHz) with bunch shortening to fit SPS 200 MHz.
  - 168 buckets filled leaving a kicker gap of ~ 300 ns (50 GeV!)
    - Achieved by direct painting into PS2 40 MHz buckets using SPL chopper.
    - No sophisticated RF gymnastics required.

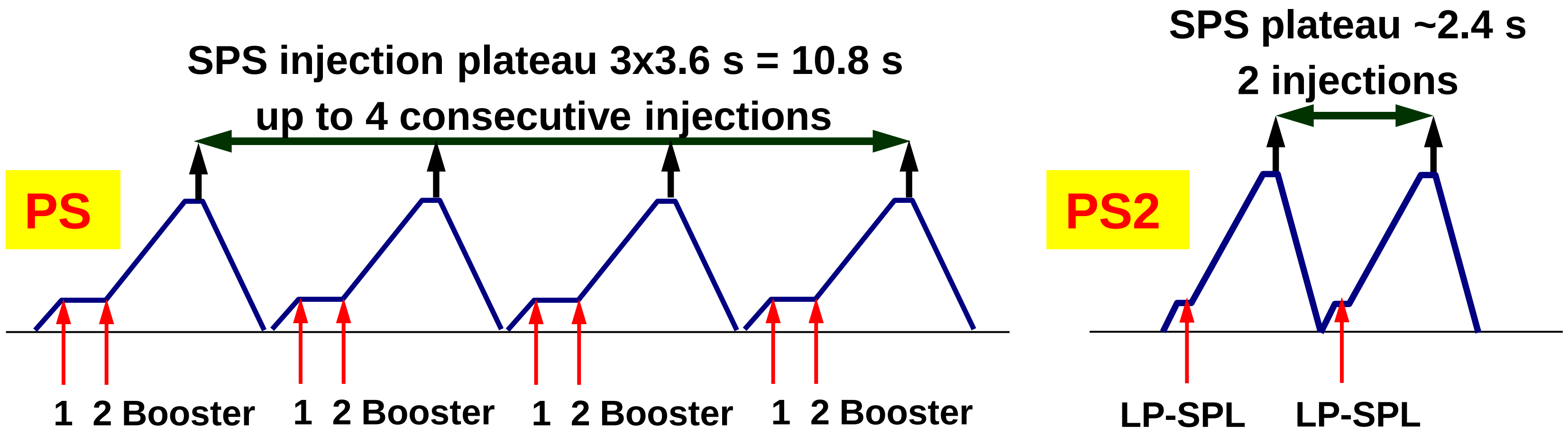
- **Beam parameters**
  - Extraction energy: 50 GeV
  - Maximum bunch intensity: 4E11 / protons per LHC bunch (25 ns)
  - Bunch length rms: 1 ns (identical to PS)
  - Transverse emittances norm. rms: 3 μm (identical to PS)
  - Alternatively "low-emittance" beams e.g. 1.7×10^{11} in ~1.5μm

- **Any other bunch train pattern down to 25 ns spacing**
  - Straightforward with SPL 40 MHz chopping and PS2 40 MHz system
    - Again without sophisticated RF gymnastics

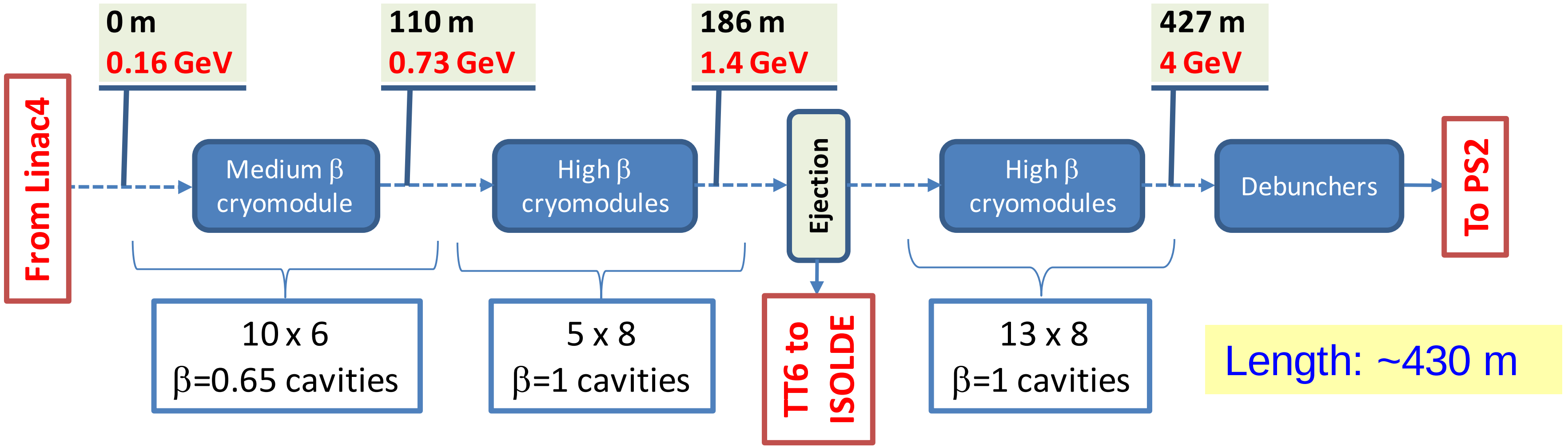
LHC beam from PS2 (ii)

- **Example 25 ns beam from LP-SPL – PS2:**
  - **PS2 will provide "twice ultimate" LHC bunches with 25 ns spacing**
  - **Bunch train for SPS twice as long as from PS**
  - **Only 2 injections (instead of 4) from PS to fill SPS for LHC**
  - **PS2 cycle length 2.4 s instead of 3.6 s for PS**
    - Reduces SPS LHC cycle length by **8.4 of 21.6 s** (3x3.6 – 1x2.4)

- **Reduced LHC filling time**



LP-SPL – block diagram & beam parameters



LP-SPL beam characteristics

Kinetic energy (GeV)	4
Beam power at 4 GeV (MW)	0.12
Rep. period (s)	0.6
Protons/pulse (x 10^{14})	1.1
Average pulse current (mA)	20
Pulse duration (ms)	0.9

PS2 main parameters

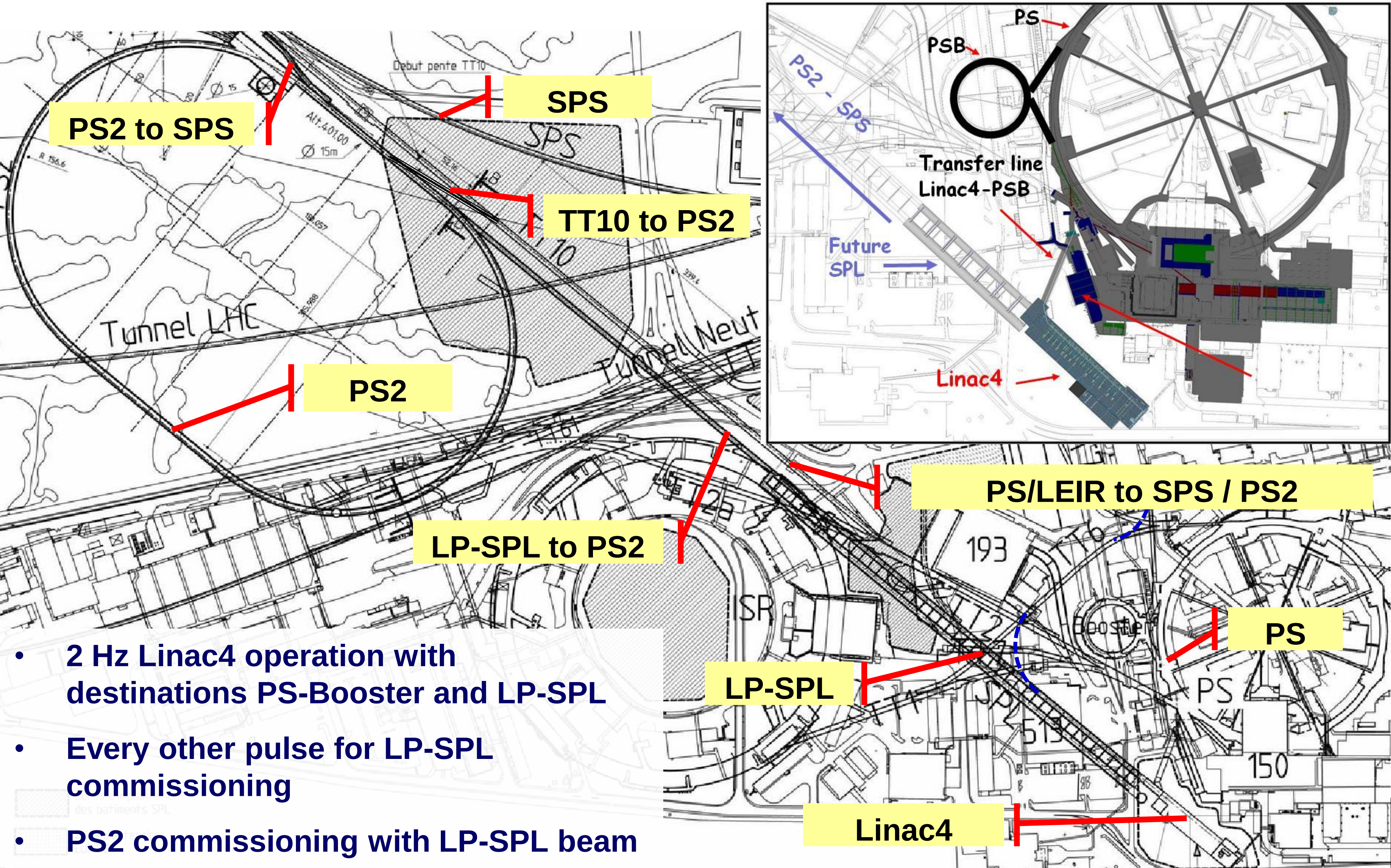
Parameter	unit	PS2	PS
Injection energy kinetic	GeV	4.0	1.4
Extraction energy kinetic	GeV	20 - 50	13 - 25
Circumference	m	1346	628
Max. bunch intensity LHC (25ns)	ppb	4.0×10^{11}	1.7×10^{11}
Max. pulse intensity LHC (25ns)	ppp	6.7×10^{13}	1.2×10^{13}
Max. pulse intensity FT	ppp	1.0×10^{14}	3.3×10^{13}
Linear ramp rate	T/s	1.5	2.2
Repetition time (50 GeV)	s	~ 2.4	1.2/2.4
Max. stored energy	kJ	800	70
Max. effective beam power	kW	350	60

In comparison with PS: line density x 2, circumference x 2, energy x 2

Implementation and commissioning

1. **Staged CE work (cf. SPS – TT40)**
   - **Excavation and CE work *in parallel to operation* for SPL tunnel, LP-SPL to PS2 TL, PS2 ring and injection/extraction cavern**
   - **CE connection between TT10 and PS2 cavern *during shutdown (~ 4 months)* for ion injection line and extraction channel of all beams towards SPS**
     - **Dismantling/protection of ~100 m of TT10 equipment in the 2 regions concerned**
     - **Physical tunnel connection & CE work**
     - **Installation of removable (RP) shielding in tunnel connection**
     - **Reinstallation of (old) TT10 equipment**
2. **Commissioning of LP-SPL & PS2 in parallel to physics with PS complex**
   - **LP-SPL commissioning from Linac4 with every 2nd pulse (2 Hz operation)**
   - **PS2 commissioning with H- from LP-SPL**
   - **Alternatively low int. PS2 commissioning with p from PS complex via TT10**
     - **Requires earlier installation of new TL from TT10 to PS2 *(can be accommodated in normal shutdown)***
     - **Would allow also commissioning with ions from LEIR/PS via TT10**

Implementation and commissioning



- **2 Hz Linac4 operation with destinations PS-Booster and LP-SPL**
- **Every other pulse for LP-SPL commissioning**
- **PS2 commissioning with LP-SPL beam**

Putting SPL & PS2 in operation for physics (i)

- **Assumptions**
  - **Most SPS upgrades have taken place independently of the construction and setting up of LP-SPL & PS2 (*see SPS Upgrade Working Group*)**
    - **e-cloud mitigation**
    - **possibly new RF system, internal dump, etc.**
  - **LP-SPL & PS2 have reached performance identical to top-performance of the Linac4 – PSB – PS injector complex in stand-alone commissioning**

- **Remaining SPS and TT10 modifications**
  - **Removal of shielding in the two TLs between PS2 and TT10**
  - **TT10 beam line rearrangement and installation of new elements from/to PS2**
  - **Replacement of SPS injection system with new 50 GeV injection system**
    - **Kickers and septa**
    - **Cabling and services**
    - **PFNs and converters**
  - ***Normal shutdown of > 4 months is considered compatible with these modifications (preparation in preceding shutdowns)***

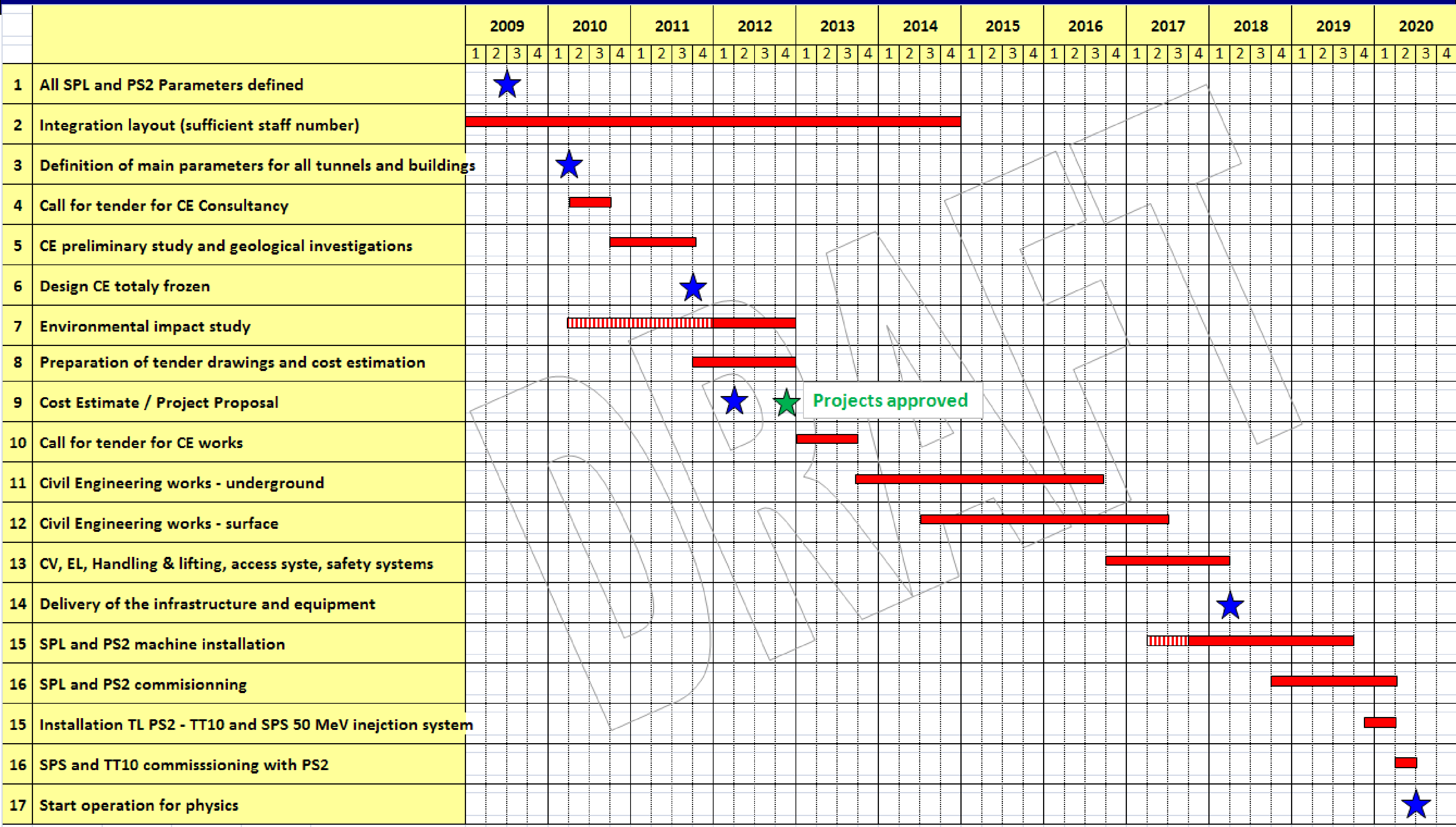
Putting SPL & PS2 in operation for physics (ii)

- **SPS injection and TT10 commissioning**
  - **New TL PS2 – SPS, TT10 modifications and SPS 50 GeV injection system**
  - **Short duration expected since only TL modification and new injection system.**
  - **Ion injection line & PS2 fast injection commissioning can be done with ions/protons from PS (possibly already earlier if TL is installed)**

- **Further increase of LP-SPL , PS2 and SPS performance to its final level will take place in parasitic mode in parallel to physics operation.**

- **All construction, integration beam commissioning and switch to operation of the chain LP-SPL & PS2 can be done in parallel to physics operation, using "normal-length" shutdowns.**
  - **No specific requirements on LHC planning and injector chain availability for LHC operation.**

LP-SPL & PS2 Prelminary Project Schedule



Nota : The planning of EL, CV, CSE and ... works needs to be approved by the different TS correspondingGroups

LP-SPL Cost estimate

Item	Cost (MCHF)	
RF equipment (80 klystrons for 160 b=1 cavities + 66 IOTs for 66 b=0.65 cavities + power supplies, waveguides, LLRF, interlocks & controls, etc.) and 2 test places for cryomodules.	219	45.6 %
Civil Engineering (underground & surface buildings) + cooling/ventilation & electrical infrastructure	113	23.5 %
Cryomodules (20 cryomodules with 8 b=1 cavities + 11 cryomodules with 6 b=0.65 cavities + 226 tuners & couplers + 80 quadrupoles + 30 BPMs)	79	16.4 %
Cryogenics (6.4 kW at 4.5 K + distribution)	17	3.5 %
Dumps (~1.4 and 4 GeV) and ejection system to ISOLDE (20 ms rise/fall time deflection system + stripping foil and H0 dump)	15	3.1 %
Beam instrumentation (transformers, beam loss monitors, laser wire profile monitors, screens…)	15	3.1 %
Controls (including machine interlocks)	10	2.1 %
Accelerator vacuum (including isolation vacuum in cryomodules)	8.5	1.8 %
Safety & access (monitors, alarms, access doors with control system)	3	0.6 %
Magnets (normal conducting in the transfer line + power supplies)	1.3	0.3 %
TOTAL	**480.8**	**100 %**

PS2 Cost estimate

Item	Cost (MCHF)	
Civil Engineering (underground work PS2 & related TLs & surface buildings, environment shaping)	90	22.0 %
Main magnets (main dipoles, 4 types of main quadrupole magnets, dipole correctors, quadrupole correctors, skew quadrupoles, chromaticity and resonance sextupoles, octopoles)	70	17.1 %
RF equipment (18.5-40 MHz tuneable system: cavities + power supplies, waveguides, LLRF, interlocks & controls, etc., transverse dumper system)	58	14.1 %
Injection and extraction elements, tune kickers, dump kickers and dump lines, PFNs for fast kickers and bumpers, electronics and controls, cabling	45	10.9 %
Technical infrastructure (electrical distribution, cabling, cooling and ventilation, piping, plants, access control, safety, heavy handling)	43	10.5 %
Transfer lines (SPL to PS2 (H-), existing TT10 to PS2 (ions from LEIR), PS2 to SPS and PS2 to and injection dump); all equipment included (scaled from CNGS transfer line) without CE.	36	8.8 %
Power converters (main converters, auxiliary correction magnets converters, septa converters)	29	7.1 %
Vacuum system (coated vacuum chambers, ion and NEG pumps, cabling, bakeout equipment)	13	3.2 %
Beam instrumentation (110 beam position monitors, 250 fast beam loss monitors, wire scanner, dc and fast BCTs, wall current monitors, tune measurement, controls and electronics, cabling.	10	2.4 %
Control system (control HW and software, racks, interlock system, timing system, cabling)	10	2.4 %
Collimation and machine protection (primary and secondary collimators & masks for TLs and PS2)	6	1.5 %
TOTAL	**410**	**100 %**

Cost estimate summary

- **Cost comparison LP-SPL with SNS Linac:**
  - **A comparison of the estimates for RF, cryomodules and cryogenics has been made with the corresponding figures from SNS:**
    - **LP SPL: 304 MCHF (63% of total LP SPL *material* cost)**
    - **SNS: 378 MCHF (includes *manpower* cost)**
  - **SNS number is 20% larger than the CERN estimate, but it includes manpower and it assumes an RF system capable of 6% duty factor instead of 0.04%**
    - **The LP-SPL estimate is credible!**

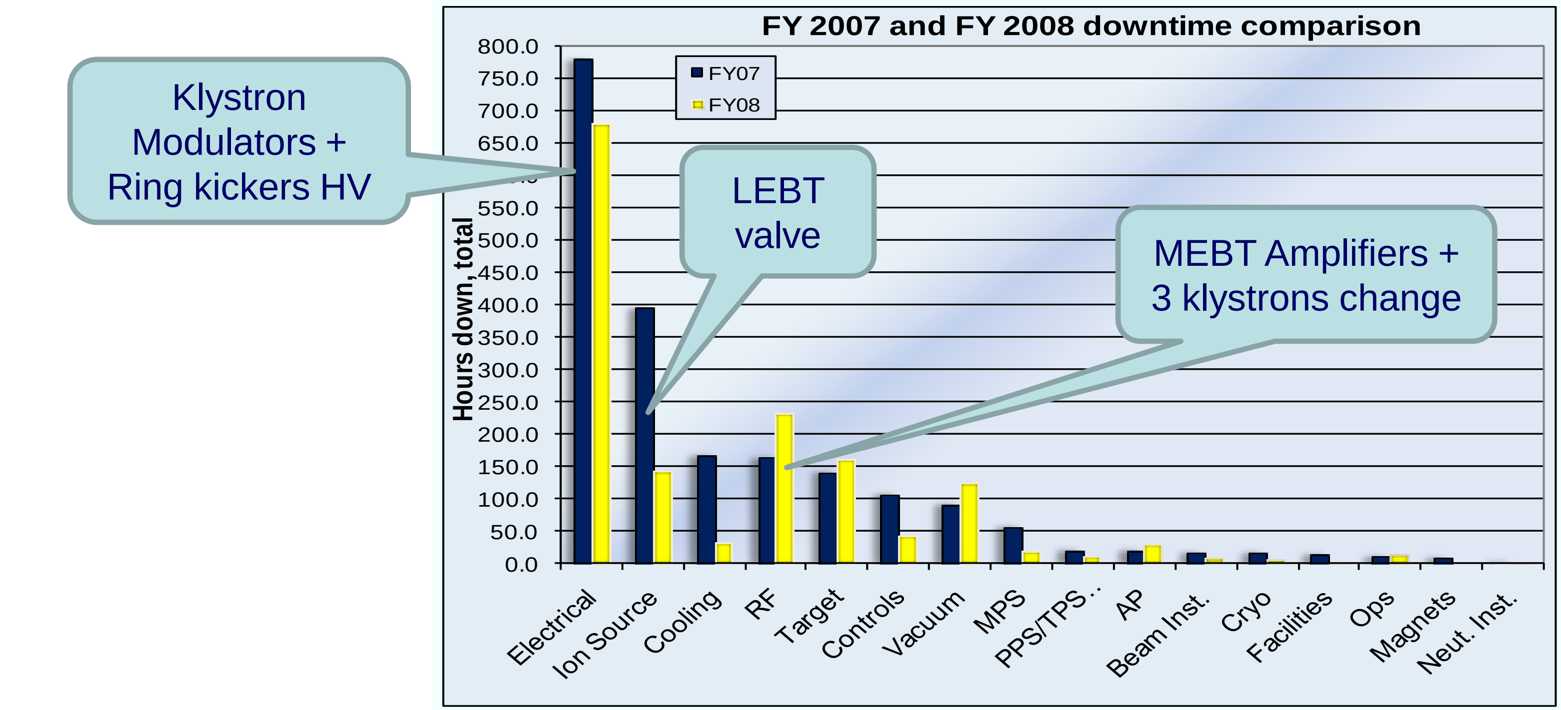
- **Total material cost estimate for LP-SPL, PS2 and SPS upgrade (~65 MCHF, see SPSU WG) is around 1000 MCHF (incl. FSU, consultancy).**

- **Manpower resources:**
  - **Estimated manpower for PS2 construction: ~ 700 FTE (~110 MCHF, 585 k/my or 400 k/my without CE+TI)**
  - **Assuming similar ratio M/P for LP-SPL and SPS gives: ~ 900 FTE (~140 MCHF)**

- **Total cost for LP-SPL, PS2 and SPS upgrade (P&M) is around 1250 MCHF.**

Operation aspects (1/2)
SPL reliability: lessons from SNS

Failures 2007-2008 (first 2 years) **[Stuart Henderson (SNS), SNS AAC, Feb. 24, 2009 ORNL]**



- **Apart from conventional causes, the main sources of problems are with HV systems and RF, linked to high duty cycle, stressing the equipment (HV, modulators, RF)**
  - **The LP-SPL will be easier/better than SNS because of the low duty factor**
- **The SC cavities and the cryogenics system do not contribute noticeably**
  - **High availability can be expected from LP-SPL**

Operation aspects (ii) - PS2 and summary

- **PS2 operation aspects**
  - Important simplification of many operational aspects compared to PS
    - No transition crossing with NMC
    - Direct painting of LHC bunch structures – no complex RF manipulations
  - Strong impact on requirements on equipment, tuning, expert know-how, beam losses, beam availability, etc.

- **General aspects**
  - The present injector complex operates close to (or at) its limits for LHC
  - LP-SPL and PS2 will allow simpler operation, provide sufficient margin and flexibility to fully exploit LHC
    - Simpler tuning and easier maintenance of beam quality, better availability
    - Reduced (manpower) requirements on operation and expert teams
  - One circular machine & injection/extraction/transfer systems less in the chain
  - Machines will be built with new equipment, using state-of the art technology, operating well below limits, with high multiplicity and well documented.
    - Positive impact on component and machine availability.
    - Reduced (manpower) requirements for maintenance and HW teams
    - Simplified spare part management

Conclusions

- **LP-SPL & PS2 upgrade has been designed to provide *large flexibility* and *operational margin for full exploitation* of the LHC with *large potential for upgrades*.**
- **Total material cost ~1000 MCHF, total manpower cost ~250 MCHF**
- **Integration and commissioning can be done *without impact on LHC operation using "normal" shutdowns.***
- **Reliable and state-of the art equipment with high multiplicity for efficient *maintenance and spare policy and manpower resources***
- ***Significant simplification of operation processes* minimizing *breakdowns, beam quality fluctuations and operator intervention and tuning needs*.**
- **The new injector complex will be a solid basis for future proton operation and upgrades at CERN offering large potential and flexibility for LHC and other applications.**

Reserve slide
High intensity physics beam for SPS

- **SPL & PS2 provides up to twice line density of PS high-intensity beam**
- **Twice circumference gives up to~4 times more intensity in total**
  - ~1.0E14 per PS2 cycle (~8E13 with a longer kicker gap)
- **Five-turn extraction will fill SPS with single shot instead of two from PS**
  - Twice more intensity in SPS via twice higher line density.
  - No injection flat bottom in the SPS (two shot filling from PS presently)
- **Clean bunch to bucket transfer PS2 40 MHz to SPS 200 MHz (cf. LHC)**
  - ~6E11 protons per PS2 40 MHz bucket → 1.2E11 in every fifths SPS 200 MHz bucket (extraction kicker gap by leaving buckets unfilled at PS2 injection)

PS2 = 15/7PS = 15/77 SPS