Potential future proton beam performance at CERN for HIE ISOLDE, n_TOF phase 2 and EURISOL

Michael Benedikt
AB Department, CERN

Outline

- Introduction
- Performance estimate for 2006-2010
- Upgrades
  - Shorter basic period length (900 ms) - upgrade via repetition rate.
  - Linac 4 - upgrade via intensity increase.
  - SPL - upgrade via duty factor.
  - Performance of upgrades.
- Conclusions

Introduction

- Aims of this analysis
  - Estimate availability of proton beams for n_TOF and ISOLDE 2006 – 2010.
  - Detection of eventual shortfalls in beam availability.
  - Quantify future upgrade and improvement possibilities.

- Large part of the work was made in the framework of the "High Intensity Proton Working Group" of the AB Department.

- "Report of the High Intensity Proton Working Group", CERN-AB-2004-022 OP/RF

"Top – down" performance estimate

- Strategy (rules) for the performance estimate:
  - Estimate the yearly time available for physics operation on all machines.
  - Calculate the time (number of cycles) required to fulfil each user request (based on present performance in routine operation, e.g. intensity…).
  - Assign time slots (cycles) to different users, respecting eventual supercycle constraints.

- "Top-down" – start with SPS since this is the slowest cycling machine:
  - Fulfil LHC beam request → fixes time left for SPS physics (CNGS + FT).
  - Fulfil CNGS request → fixes time left for SPS FT.
  - All SPS requirements known and also the corresponding PS / PSB cycles. → fixes remaining time for PS and PSB physics.
  - Fulfil PS EAST and nTOF requests → fixes PSB time for ISOLDE.

- NOTE: The distribution used for the analysis is by no means a definition of priorities for future operation!

Schedule 2006, assumptions 2007 - 2010

- 2006: total running time 5000 h (PS complex) and 4200 h (SPS complex).
- 2007 – 2010: total running time 6000 h (PS complex) and 5500 h (SPS).
  - Reduced by start-up, setting-up time and dedicated MDs.
  - Correction for machine availability; experience: 90% (PS), 80% (SPS).
  - Gives effective time for physics operation.

		2006		2007 - 2010			
		PSB/PS complex	SPS complex	PSB/PS complex	SPS complex		LHC
					2007*	2008-10	
Total running time with beam	[h]	**5000**	4200	**6000**	5500	5500	5000
Setup and dedicated MD	[h]	**500/1200**	1200	**600**	1000	800	-
Physics operation	[h]	**4500/3800**	3000	**5400**	4500	4700	-
Effective physics hours	[h]	**4050/3420**	2400	**4860**	3600	3760	-

- 2006: more time needed for PS and SPS start-up after 18 months shut-down.
- LHC is assumed to run during 5000 h / year.
- 2007* : Ions for LHC commissioning in SPS requires ~200 h operation time.

n_TOF and PS East Area performance

- Beam requests and standard operation conditions:
  - n_TOF: 1.5E19 protons on target per year (~1.3E19/y for 2002-2004).
    7E12 pot for dedicated operation and 4E12 pot for parasitic.
    20 GeV/c beam momentum, 1.2 s cycle length.
  - East Area: 1.3E6 spills (2006), 2.3E6 spills (from 2007) for DIRAC.
    Spill length of ~450 ms per cycle of 2.4 s.
    24 GeV/c beam momentum.

Year	PS physics operation [hours]	Spills to East Area	East Area request	Protons for nTOF	nTOF request
2006	3800	1.3×10^{6}	1.3×10^{6}	**1.3×10^{19}**	**1.5×10^{19}**
2007	5400	2.4×10^{6}	2.3×10^{6}	**1.6×10^{19}**	**1.5×10^{19}**
2010	5400	2.3×10^{6}	2.3×10^{6}	**1.6×10^{19}**	**1.5×10^{19}**

- PS physics requests can be fulfilled 2007 – 2010 (AD physics included).
  - Still PS cycle time available for additional physics / test beams.

ISOLDE performance

- Beam request and standard operation conditions:
  - ISOLDE: 50% of yearly PSB cycles (1350 cycles/hour on average).
    Beam energy 1.4 GeV (or 1 GeV).
    Up to 3.2E13 pot per cycle.
    Translates into an average current of 1.9 μA.

Year	PSB physics operation [hours]	PSB cycles to ISOLDE [%]	[cycles/h]	[μA]	PSB cycles requested [%]	[cycles/h]	[μA]
2006	4500	**50 %**	**1350**	**1.9**	50%	1350	1.9
2007	5400	**44 %**	**1185**	**1.7**	50%	1350	1.9
2010	5400	**47 %**	**1260**	**1.8**	50%	1350	1.9

- 2006 performance ok.
- Isolde performance estimated to ~10% below request for 2007-2010.

Discussion on performance 2007 - 2010

- n_TOF and East Area requests can be fulfilled 2007 to 2010.
  - Even some more PS time available as reserve or upgrade →OK.

- ISOLDE performance estimated ~10% below request for 2007 to 2010.
  - …may be not too dramatic at first sight but looking in more detail to the PS:
    - No cycles for East Area test beams taken into account (time available).
    - Any additional PS programme will take away PSB cycles from ISOLDE and lead to a further performance degradation.
  - …and looking in more detail to the SPS:
    - Performance analysis on SPS revealed shortfall of SPS time for CNGS and COMPASS operation (2006-2010). One possibility for improvement:
    - Significant increase of intensity per SPS CNGS cycle.
    - Major ingredient is "double batch injection" from PSB to PS which means that 4 instead of 2 PSB cycles are required per SPS CNGS cycle.
    - Would significantly decrease ISOLDE performance.

Upgrades and requirements

- There are clearly arguments to look at an accelerator complex upgrade at the level of the PS-Booster. Such an upgrade could be basis for:
  - ISOLDE upgrade.
  - Full use of the available operation time on the PS (upgrades or add. physics).
  - Improvements for physics on SPS without negative impact on ISOLDE.
- Two directions to follow:
  - Increasing the repetition rate (improved duty cycle: pulse length/cycle).
  - Increasing the intensity.
- Upgrades at PSB level:
  - Faster cycling of complex: 900 ms instead 1200 ms → repetition rate.
  - Linac 4 as new PSB injector: → increasing the intensity.
- Upgrade with Superconducting Proton Linac (SPL):
  - SPL replacing Linac & PS Booster: large gain via duty factor (50 Hz).

Aims for upgrades

- For “standard” ISOLDE operation:
  - More than 50% of PSB cycles (some reserve) or ≥ 2 μA average current.
  - Corresponds to ≥ 2.8 kW beam power at 1.4 GeV.

- HIE ISOLDE:
  - Factor 5 higher average current than presently available ~10 μA current.
  - Corresponds to ~14 kW beam power at 1.4 GeV.

- EURISOL:
  - 5 MW beam power for neutron converter target (at few GeV).
  - Few 100 kW beam power for direct targets (1 to 2 GeV)

Upgrade 1: 900 ms basic period operation

- AIM increase the number of proton cycles available from the PS Booster
  - Presently Linac 2 and PSB cycles are repeated every 1.2 s
  - PS and SPS cycles are integer multiples of the 1.2 s basic period.
- Basic period of 900 ms means 33% more PSB cycles available (1.2/0.9).
- Consequences for accelerator operation
  - Cycles on all machines integer multiples of 900 ms
  - Linac2 and PSB pulsing at 900 ms.
  - PS: most cycles can be adapted to 900 ms basic period (not n_TOF).
  - SPS: long cycles, relatively unaffected.
- ISOLDE: basic beam parameters unchanged
  - PSB cycle 0.9 s instead of 1.2 s. Beam energy as present 1.4 (1.0) GeV.
- n_TOF: two scenarios with different proton energies
  - PS cycle 1.8 s instead of 1.2 s. Proton beam energy up to 24 GeV/c.
  - PS cycle 0.9 s instead of 1.2 s. Proton beam energy reduction to 15.3 GeV/c.

Summary of 900 ms test in 2005

- Full scale test over 4 weeks in 2005 (Linac2 – PSB – ISOLDE, Linac3)
  - Change of machine timing and control system to 900 ms basic period.
  - "Routine" operation for ISOLDE physics and tests of all physics beams.
- Test results Linac2-PSB
  - No evidence for technical problems on Linac2, PSB and transfer lines.
  - Nominal PSB performance for all physics beams (ISOLDE, PS, SPS beams).
  - Radiation increase proportional to flux increase, overall beam loss pattern similar to 1.2 s operation. Close to limits when max. intensity on all cycles!
- ISOLDE high intensity tests towards HRS
  - Using all cycles, a performance of ½ HIE ISOLDE was reached.
  - 3E13 pot per 0.9 s gives 5.3 μA or 7.5 kW that were delivered to HRS.
  - Main problems were radiation related. Radiation protection is a major issue.
- Open issues
  - Tests of 900ms compatible cycles on PS, SPS (esp. CNGS cycle in PS).

Upgrade 2: Linac4

- Aim is increase of PSB intensity per shot by increasing the transverse density of the beam (beam brightness, N/ε).

- Achievable beam brightness is limited by space charge of the beam.
  - Defocusing effect of space charge leads to a tune spread ΔQ in the beam.
  - Once ΔQ becomes too big, parts of the beam cannot be controlled anymore.

$$\Delta Q \propto -\frac{1}{\beta\gamma^2} \cdot \frac{N_b}{\varepsilon_n}$$

- Keep ΔQ constant, act on relativistic parameters to increase N_b.
  - Most important at low energy → therefore increase injection energy.
  - Linac4 injection energy 160 MeV instead of 50 MeV gives factor 2.

- Expect factor 2 increase in max. intensity from PSB → ISOLDE, (high int.)
- Expect factor 2 increase in density, important for small beam like LHC.

Linac4 – parameters and status

- Location: PS South Hall and extension
- Technical Design report in preparation (publication mid-2006)
- Possible planning:
  - Authorization: December 2006
  - Construction: 2007-2010
  - Setting-up & commissioning: 2010
  - Availability (replacing Linac2): 2011

Linac4 - characteristics

Ion species	H^-	
Kinetic energy	160	MeV
Mean current during pulse	40	mA
Pulse duration	≤ 0.4	ms
Particles per pulse	≤ 10^{14}	
Pulse repetition rate	≤ 2	Hz
Beam power (160 MeV)	≤ 5	kW
Bunch frequency	352.2	MHz

- 3 MeV test place construction (front end for Linac4)
  - Ongoing project supported by HIPPI (FP6) + IPHI (CEA+IN2P3+CERN).
  - Location: PS South Hall extension (future location in Linac4).
  - Test with beam : 2007-2008.

Performance for Linac4

- ISOLDE
  - Around twice the presently obtained max. current (~6.4E13 pot/cycle).
  - For the target, the peak power will be also twice the present value.
  - 3.8 μA (5.3 kW) for 1.2 s operation with 50% PSB cycles and 90% efficiency.
  - 5.1 μA (7.1 kW) for 0.9 s operation with 50% PSB cycles and 90% efficiency.
- Linac4 with 900 ms reaches ~half the desired HIE ISOLDE performance.

- n_TOF
  - Linac4 reduces space charge at PS-Booster injection but does not change space charge limits at PS injection.
  - Transverse and longitudinal limitations in the PS remain identical to now.
  - Detailed investigations needed to quantify potential gain.

Performance for 1.2s, 0.9s and Linac4

2006 Accelerator complex performance					
	Request	**1200 ms**	**900 ms**	***Linac4***	***Linac4 + 900 ms***
ISOLDE [pulses/hour] Average current [μA]	1350 (50%) 1.9	1350 (50%) 1.9	***2150 (60%)*** *3.1*	*1350 (50%)* ***3.8***	***2150 (60%)*** ***6.2***
nTOF [$\times 10^{19}$ pot/year]	1.5	**1.3**	*1.6*	***1.3***	*1.6*
East Area [$\times 10^{6}$ spills/year]	1.3	1.3	*1.3*	*1.3*	*1.3*
2007 Accelerator complex performance					
	Request	**1200 ms**	**900 ms**	***Linac4***	***Linac4 + 900 ms***
ISOLDE [pulses/hour] Average current [μA]	1350 (50%) 1.9	**1185 (44%)** **1.7**	**2060 (57%)** 2.9	*1210 (45%)* ***3.5***	***2160 (60%)*** ***6.2***
nTOF [$\times 10^{19}$ pot/year]	1.5	1.5	1.6	*1.6*	*1.6*
East Area [$\times 10^{6}$ spills/year]	2.3	2.4	2.4	*2.4*	*2.4*
2010 Accelerator complex performance					
	Request	**1200 ms**	**900 ms**	**Linac4**	**Linac4 + 900 ms**
ISOLDE [pulses/hour] Average current [μA]	1350 (50%) 1.9	**1260 (47%)** **1.8**	**2140 (59%)** 3.0	1260 (47%) **3.6**	**2160 (60%)** **6.2**
nTOF [$\times 10^{19}$ pot/year]	1.5	1.5	1.6	1.6	1.6
East Area [$\times 10^{6}$ spills/year]	1.3	2.3	2.4	2.4	2.4

Upgrade 3: Superconducting Proton Linac

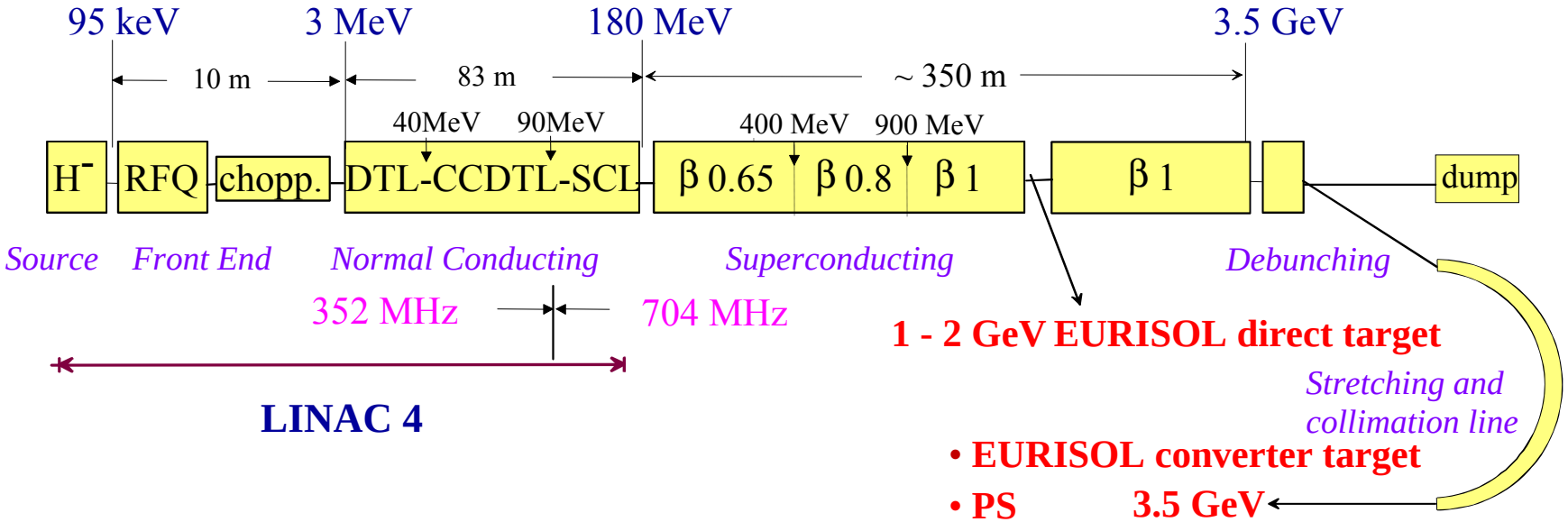
- Large scale upgrade of the complex. SPL replaces the PS-Booster and uses Linac4 as front end.
- 5 MW machine, the high power is achieved via an enormously improved duty factor and higher energy:
  - 50 Hz (20 ms) operation in comparison to 1200 or 900 ms repetition time.
  - 5 MW available at 3.5 GeV.

Ion species	H^-	
Kinetic energy	3.5	GeV
Mean current during the pulse	50	mA
Mean beam power	5	MW
Pulse repetition rate	50	Hz
Pulse duration	0.57	ms
Duty factor	2.82	%

- Due to high duty factor relatively low peak power on target.
- Mean current in pulse of 50 mA compared to 5 A at present.

SPL beam sharing

- Simultaneous operation of direct target (~100 kW at around 1 GeV) and converter target (≤5 MW at 3.5 GeV) or MMW (super beam, ν-factory).
  - In shared operation reduced power (100kW @ 1GeV → 350kW @ 3.5 GeV).
  - Gap in each 50 Hz pulse is created at low energy (3MeV). At the sharing energy a section with a fast deflector is inserted. Sharing energy is fixed.



SPL CDR2 Preliminary Layout 15.3.2005

Work in progress

Performance for SPL

- EURISOL
  - Up to 5 MW on converter target at 3.5 GeV proton energy.
  - Few 100 kW at ~1 GeV (up to 1.4 MW available).
  - For the targets: peak power in pulse significantly reduced in comparison to present situation (much higher duty cycle and lower current).
- n_TOF
  - SPL injection into PS at 3.5 GeV reduces space charge (factor 3.85 in $\beta\gamma^2$).
  - Transverse situation is improved and should allow for higher brightness.
  - Longitudinal limitations in the PS remain identical to now.
  - Overall performance increase needs to be studied.
- Other high-power users (periods without EURISOL converter operation)
  - multi-MW operation for Superbeam / ν-factory.
- Various other benefits for the different operations (brightness LHC, etc.).

Conclusions

- All approved and anticipated requests for physics on PS can be fulfilled from 2007 – 2010. ISOLDE performance is estimated at around 10% below request.
- 900 ms operation is a short term upgrade that could quickly bring a significant performance increase (~50%) for ISOLDE and flexibility for improvements for PS or SPS physics at relatively low cost.
- Linac4 is a medium term upgrade (factor 2) for ISOLDE with several improvements for other physics programmes. Also a first step towards SPL. Brings ~60% of HIE goal when combined with 900 ms.
- SPL is a a longer term upgrade for ~2015 if decided by ~2010. Multi-MW machine with many potential applications.