Synergies ...

OUTLINE

1. Plans for future LHC injectors
2. Potential extensions for neutrinos
   - with the future LHC injectors:
     - "Conventional" ν beams
   - with the "High Power" SPL:
     - Neutrino Factory
     - Low energy ν "Super-beam"
     - β beams
3. Synergy with EURISOL
4. Final words

PLANS FOR FUTURE LHC INJECTORS

Motivation

Plans for future LHC injectors

1. Reliability ↑

The present accelerators are getting old (PS is 48 years old !) and they operate far beyond their initial design parameters

⇒ need for new accelerators designed for the needs of SLHC

2. Performance ↑

Brightness N/ε^* of the beam in LHC must be increased beyond the capability of the present injectors to allow for phase 2 of the LHC upgrade. [Excessive incoherent space charge tune spreads ΔQ_{SC} at injection in the PSB and PS].

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

with N_b : number of protons/bunch

$\varepsilon_{X,Y}$: normalized transverse emittances

R : mean radius of the accelerator

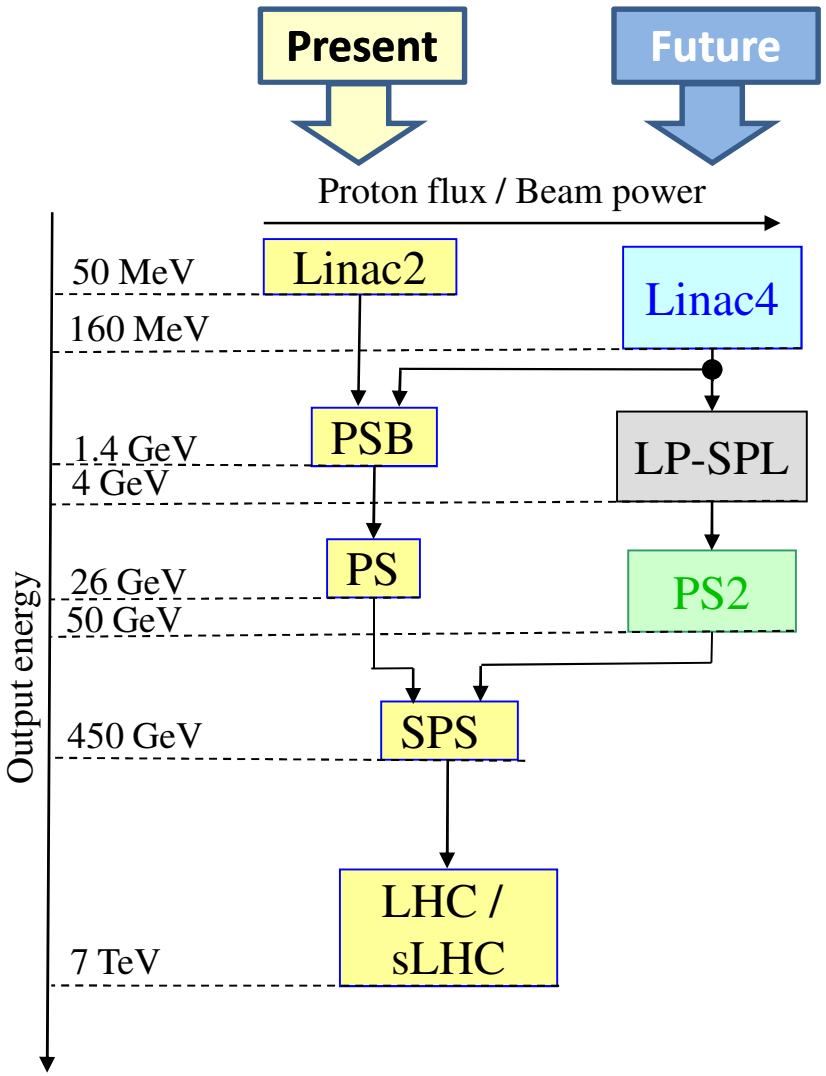
$\beta\gamma$: classical relativistic parameters

⇒ need to increase the injection energy in the synchrotrons

- **Increased injection energy in the PSB from 50 to 160 MeV kinetic**
- **Need for 4 GeV injection energy in PS2 (PS successor) to allow for 2.2 times the ultimate beam brightness in sLHC**
- **Increased injection energy in the SPS from 25 to 50 GeV kinetic (partly because of space charge, but mostly to inject further from transition energy and to displace TMCI threshold)**

Description

Plans for future LHC injectors



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

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

sLHC:
"Super-luminosity" LHC (up to 10^{35} $cm^{-2}s^{-1}$)

PS2 parameters

Plans for future LHC injectors

PS2 goals:

- to provide the beam brightness required by all sLHC options
- to improve SPS operation in fixed target mode

Reason	Physical parameter	Value
Space charge PS2	Injection energy (kinetic)	**4 GeV**
SPS improvement	Ejection energy (kinetic)	**50 GeV**
LHC	Transverse normalized 1 sigma emittances at ejection for LHC	**3 π mm.mrad**
LHC	Longitudinal emittance/bunch with 25 ns bunch spacing at ejection	**0.35 eVs**
2.2 × ultimate brightness for LHC (includes 10% loss)	Nb of protons / bunch with 25 ns bunch spacing at ejection for LHC (total 168 bunches)	**4×10^{11} (6.7×10^{13})**
Flux for SPS / PS2 fixed target physics	Nb of protons / bunch with 25 ns bunch spacing (total)	**6×10^{11} ($\sim1\times10^{14}$)**
Possible bunch spacings in LHC (25, 50 & 75 ns)	Size (ratio PS2/SPS)	**15/77**
	Circumference	**1346.4 m**
	h_{RF} for 25 ns (resp. 50 or 75 ns) bunch spacing	**180 (resp. 90 or 60)**
Flux for SPS / PS2 fixed target + LHC filling time	Cycling period to 50 GeV (case of no injection flat porch)	**2.4 s**

PS2 injector

Requirements of PS2 on its injector:

Plans for future LHC injectors

Reason	Physical parameter	Value
Space charge	Injection energy (kinetic)	**4 GeV**
Twice the ultimate brightness + 20 % margin for beam loss	Nb of protons per PS2 cycle for LHC	**6.7×10^{13}**
SPS / PS2 fixed target physics	Nb of protons per PS2 cycle for PS2 / SPS fixed target physics	**1.1×10^{14}**

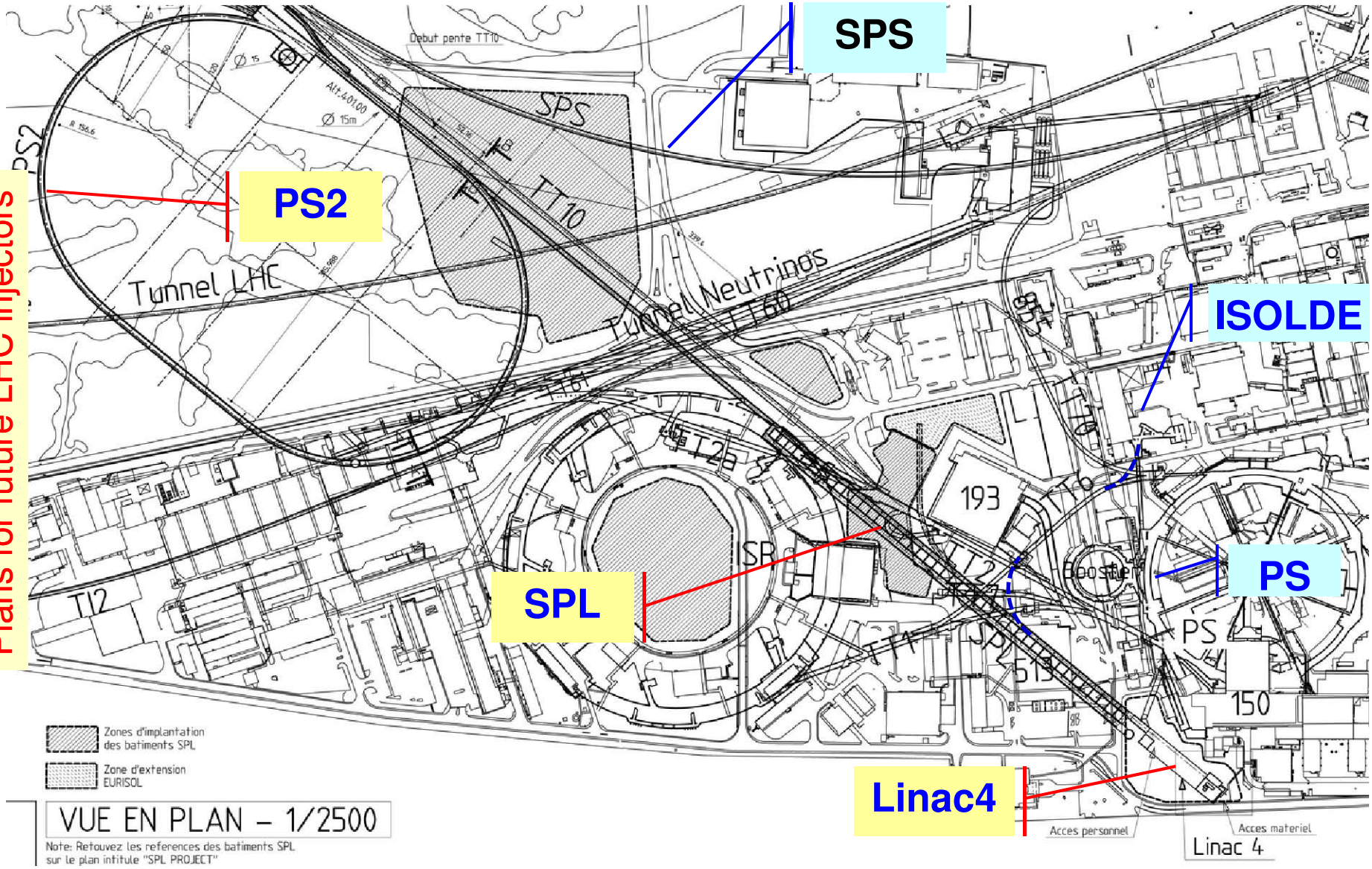
Why an SPL as PS2 injector?

CERN-AB-2007-14 (PAF)

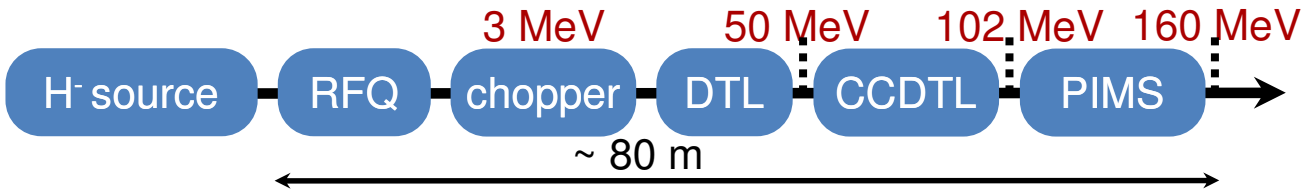
Plans for future LHC injectors

- H^- linac with charge exchange injection in the following synchrotron = proven solution for reliably reaching high beam performance,
- Superconducting accelerating structures allow for reaching 4 GeV with a single accelerator (minimum beam loss/irradiation + maximum reliability),
- An SPL provides a large potential of extension to adapt to future needs. Among the identified possibilities:
  - Radioactive ion beam facility (4 MW at ~ 2.5 GeV)
  - Proton driver for a neutrino factory (4 MW at 5 GeV) [design available]
  - e+/e- acceleration to ~20 GeV (using recirculation in the β=1 part of the SPL) for LHeC [preliminary study in progress]
- Extensive synergy with other projects (ESS, EURISOL, SNS, ADS + XFEL, ILC …) giving access to a large support base for R & D.

Site layout


Plans for future LHC injectors
SPS
PS2
ISOLDE
PS
SPL
Linac4
Tunnel LHC
Tunnel Neutrinos
TT10
TT60
SPS
SR
Booster
PS
193
150
T12
Zones d'implantation des batiments SPL
Zone d'extension EURISOL
VUE EN PLAN – 1/2500
Note: Retouvez les references des batiments SPL sur le plan intitule "SPL PROJECT"
Acces personnel
Acces materiel
Linac 4

Implementation stage 1: LINAC4



Plans for future LHC injectors

Ion species	**H^-**	
Output Energy	**160**	**MeV**
Bunch Frequency	**352.2**	**MHz**
Max. Rep. Rate	**2**	**Hz**
Max. Beam Pulse Length	**1.2**	**ms**
Max. Beam Duty Cycle	**0.24**	**%**
Chopper Beam-on Factor	**65**	**%**
Chopping scheme:		
222 transmitted /133 empty buckets		
Source current	**80**	**mA**
RFQ output current	**70**	**mA**
Linac pulse current	**40**	**mA**
N. particles per pulse	**1.0**	**$\times 10^{14}$**
Transverse emittance	**0.4**	**π mm mrad**

Max. rep. rate for accelerating structures: 50 Hz

H^- ⇒ charge exchange injection and painting in PSB

160/50 MeV ⇒ factor 2 in $\beta\gamma^2$) → same tune shift with twice the intensity.

Re-use of LEP RF components: klystrons, waveguides, circulators.

Chopping at low energy to reduce beam loss in PSB.

- Structures and klystrons dimensioned for 50 Hz
- Power supplies and electronics dimensioned for 2 Hz, 1.2 ms pulse.

Linac4 construction site - 5.5.2009

from M. Vretenar

Linac4 tunnel ("cut and cover" excavation) seen from high-energy side.

Final concrete works starting at low-energy side, excavation proceeding at high energy side.

Tunnel level -12 m, length 100 m.

Delivery of tunnel and surface equipment building end of 2010.

PSB and SPL connection area - 5.5.2009

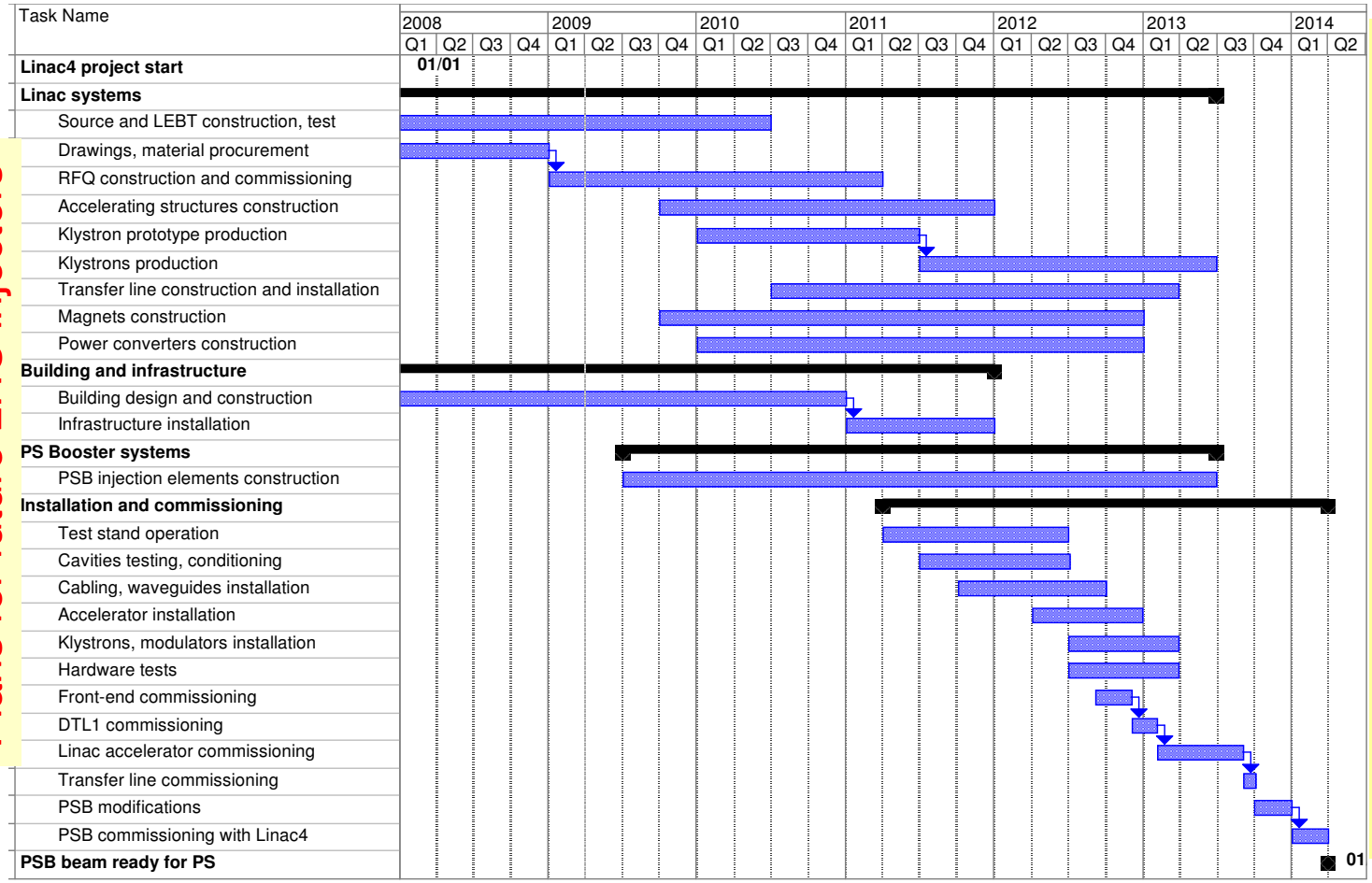
Plans for future LHC injectors

from M. Vretenar

High-energy side of Linac4 tunnel, with beam dump chamber and connecting tunnel to the end of Linac2.

Implementation stage 1: **Planning**

Plans for future LHC injectors

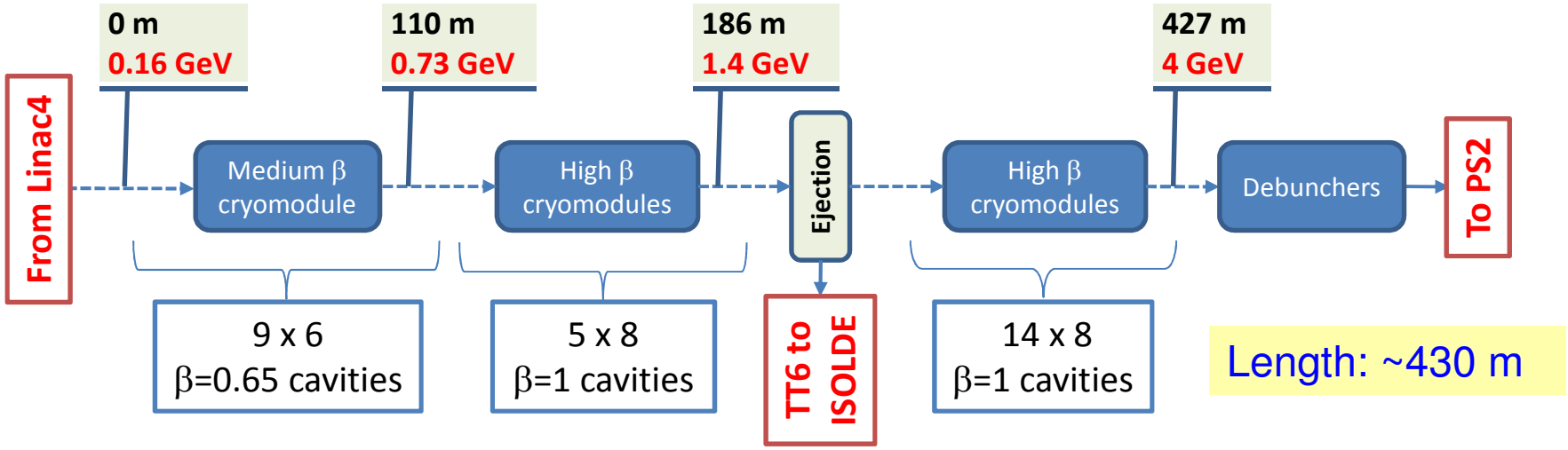


project duration: ~ 6 years

Milestones

- End CE works: December 2010
- Infrastructure: 2011
- Installation: 2011-2012
- Commissioning: 2012-2013
- Modifications PSB: shut-down 2013/14
- **Operation: 1st of April 2014**

Implementation stage 2: LP-SPL



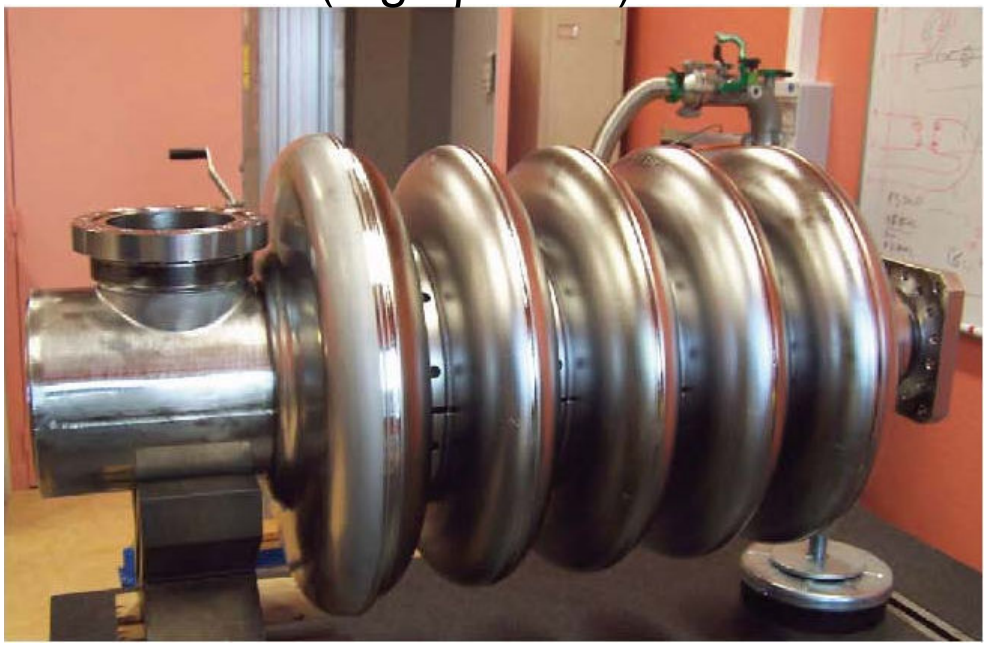
Plans for future LHC injectors

Ion species	H^-	
Output Energy	4	GeV
Bunch Frequency	352.2	MHz
Max. Rep. Rate	2	Hz
Max. Beam Pulse Length	0.9	ms
Linac pulse current	20	mA
Number of ions per pulse	1.1	$\times 10^{14}$
RF frequency	704.4	MHz
Cooling temperature	2	K
Max. rep. rate for acc. structures & klystrons:	50	Hz

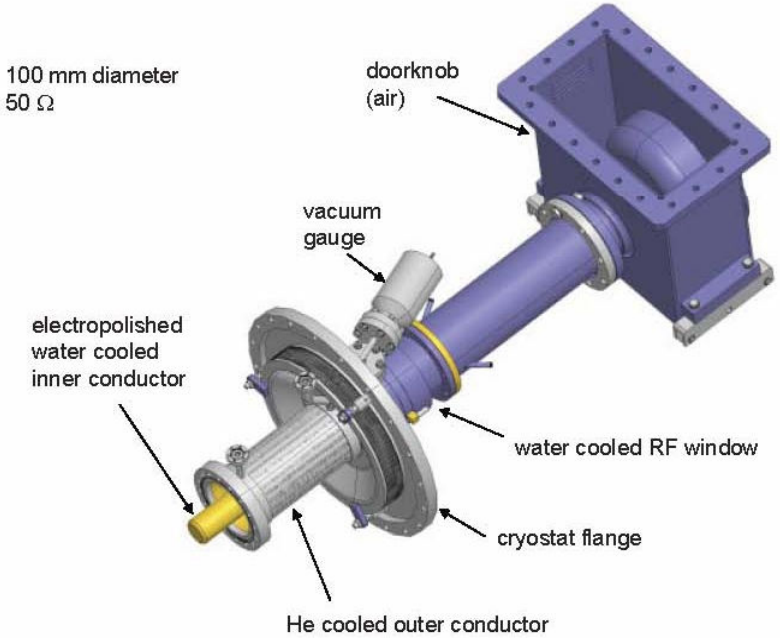
Examples of SPL developments [from HIPPI inside CARE (EU FP6)]

Plans for future LHC injectors

Elliptical 5 cell bulk Niobium cavities (e.g.: β=0.47)



Auxiliary equipment (e.g.: 1 MW RF coupler)



from G. Devanz (CEA) – HIPPI meeting Nov. 2007)

Goal of the SPL study (2008-2012)

from Note on 31/03/2009 (EDMS Id 993472)

The goal of the SPL study is to submit to the CERN Council in mid-2012 a detailed Conceptual Design Report and a cost estimate.

Plans for future LHC injectors

For that purpose:

- cavities must be built and tested for a reliable assessment of the achievable gradient,
- a full size prototype cryomodule must be designed and assembled,
- the SM18 test place at CERN must be upgraded to allow for exercising multiple cavities in the prototype cryomodule at the nominal RF power,
- Civil Engineering and Integration must be studied, including safety and environment concerns.

Multiple partners are already collaborating or are planning to collaborate:

- Member states institutions [CEA, IN2P3, DESY, Rostock & Frankfurt Universities, STFC-DL, ASTEC-RHUL, Cockcroft Institute, Soltan Institute, ESS (Lund, Bilbao,...), ...] often with the support of the E.U., in the context of its FP7 programme ("sLHC" CNI-PP + "EuCARD" IA)
- Non-member states institutions [TRIUMF, Stony Brook/BNL, FNAL, SNS]

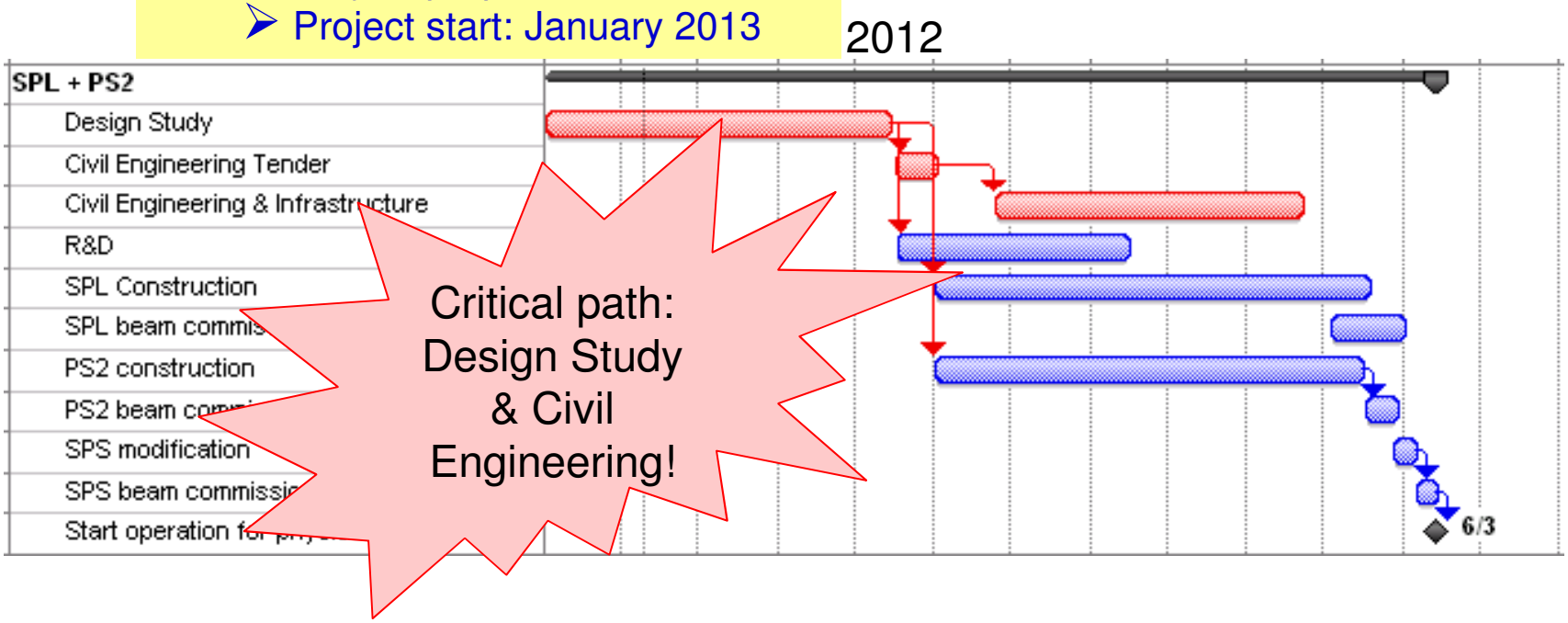
and more are in discussion (USA, China, India, Turkey, Hungary,...)

Implementation stage 2: Planning

Plans for future LHC injectors

First milestones

- Project proposal: 2011- 2012
- Project start: January 2013



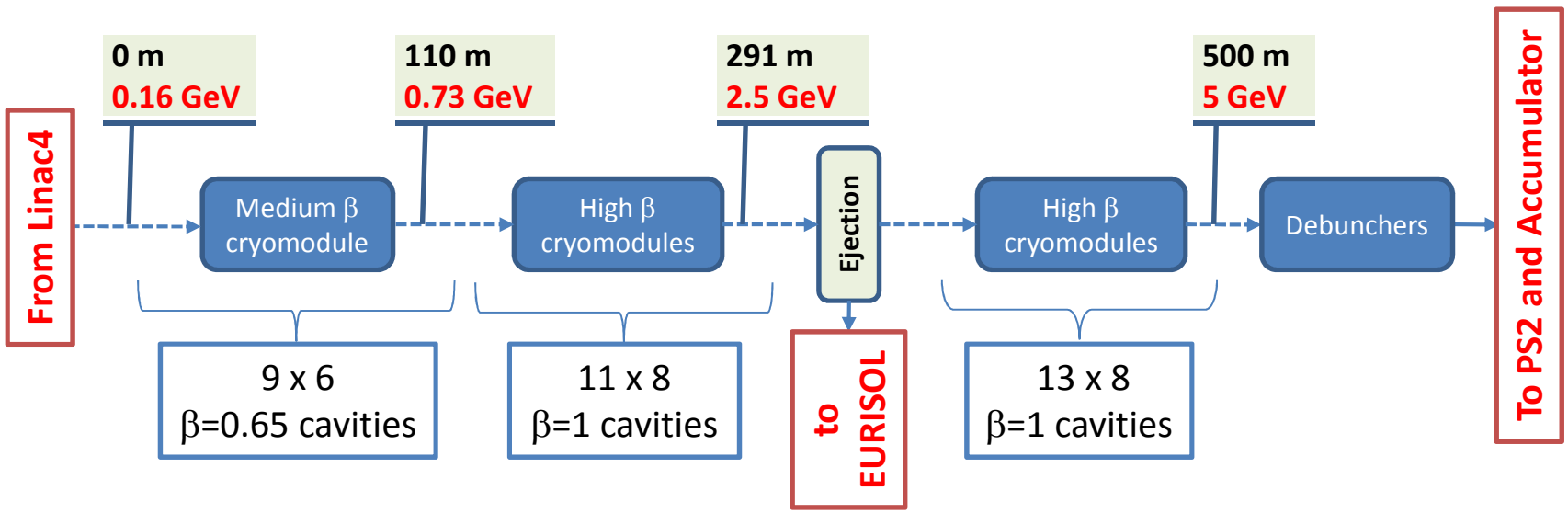
Construction of LP-SPL and PS2 will not interfere with the regular operation of Linac4 + PSB for physics. Similarly, beam commissioning of LP-SPL and PS2 will take place without interference with physics.

Possible stage 3: High Power SPL

- Upgrade of infrastructure (cooling water, electricity, cryogenics etc.)
- Replacement of klystron power supplies,
- Addition of 5 high β cryomodules to accelerate up to 5 GeV (π production for ν Factory)?

Plans for future LHC injectors

SC-linac [160 MeV → 4 (5?) GeV] with ejection at intermediate energy



Length: ~500 m

Possible stage 3: High Power SPL

Plans for future LHC injectors

Faster rep. rate ⇒ new power supplies, more cooling etc.

Beam characteristics of the main options

	Option 1	Option 2
Energy (GeV)	2.5 or 5	2.5 and 5
Beam power (MW)	2.25 MW (2.5 GeV) or 4.5 MW (5 GeV)	5 MW (2.5 GeV) and 4 MW (5 GeV)
Rep. frequency (Hz)	50	50
Protons/pulse (x 10^{14})	1.1	2 (2.5 GeV) + 1 (5 GeV)
Av. Pulse current (mA)	20	40
Pulse duration (ms)	0.9	1 (2.5 GeV) + 0.4 (5 GeV)

2 × beam current ⇒ 2 × nb. of klystrons etc .

POTENTIAL FOR NEUTRINOS:
- WITH THE FUTURE LHC INJECTORS

Conventional ν beam from PS2

PS2 beam characteristics

Dimensioned for the LHC upgrade
Simple scaling to get the values for SPS in fixed target mode (with 5 turn ejection):

- $1 \cdot 10^{14}$ p/p at 50 GeV every 2.4 s (~330 kW)
- $\sim 4 \cdot 10^{20}$ pot/year (10^7 s)
- Beam pulse duration: 4.2 μs

⇒ **A new design is needed if a higher flux is required.**

Conventional ν beam from the SPS (1/3)

Neutrinos with the future LHC injectors

Nominal CNGS

- 732 km baseline from CERN to Gran Sasso (Italy) [Elevation of 5.9°]
- Far detectors: OPERA (1.21 kt), Icarus (600 t)
- Commissioned in 2006, operational since 2008
- **Proton beam characteristics:**
  - 2x 2.4 · 10^{13} p/p at 400 GeV every 6 s
  - 4.5· 10^{19} pot/year
  - 2 extractions separated by 50 ms
  - Beam pulse duration: 10.5 μs

Improvement with the new injectors?

Analysis of the maximum potential proton flux to CNGS

M. Meddahi and E. Shaposhnikova
CERN AB-2007-013 (PAF)

Conventional ν beam from the SPS (2/3)

Neutrinos with the future LHC injectors

Intensity limitation from the design values of the CNGS facility

Equipment	Protons per extraction	Protons per cycle	POT per year
Radiation Protection calculation and optimisation			Soil/concrete activation: **4.5 E19** Residual dose for intervention: **1.38 E20** Air/water activation: **7.6 E19**
Target	**3.5 E13** from dynamic stresses and assuming increased time between 2 extractions	**1.4 E14** from target cooling	**2 E20** from radiation damage
Horns	**3.5 E13** from powering system: maximum of 2 extractions	**7 E13** from water cooling system	**1.38 E20** from air cooling system and mechanical fatigue lifetime (2 E7 pulses)
Shielding, Decay Tube, Hadron stop design			**1.38 E20** from air/water cooling systems
Kicker system	**3.5 E13** from ferrite heating, with MKE equipped with shielding stripes (TBC) from powering system: maximum of 2 extractions	**1 E14** marginal, pending 2007 SPS beam measurements	
Instrumentation	**3.5 E13** from dynamic range – Electronics system		

Conventional ν beam from the SPS (3/3)

Neutrinos with the future LHC injectors

POT/year [10^{19}] for 200 days of operation with 80% machine efficiency

	SPS cycle length	6 s		4.8 s	
	Injection Energy	14 GeV		26 GeV	
	Beam sharing / Max SPS intensity @ 400GeV [x10^{13}]	0.45	0.85	0.45	0.85
Present injectors + machines' improvement	4.8	5	9.4		
	5.7	5.9	11.1		
Future injectors (>2018) + SPS RF upgrade	7			9	17.1
Future injectors + new SPS RF system + CNGS new equipment design	10			12.9	24.5

Performance range: 2 – 4 x flux for CNGS

POTENTIAL FOR NEUTRINOS:
- WITH THE “HIGH POWER” SPL

ν FACTORY: SPL-based proton driver (1/4)

Neutrinos with the "High power" SPL

Table 1: Requirements for the neutrino factory proton driver.
Taken from the summary of 3rd ISS [4].
* Maximum bunch spacing ~50/(Nb-1) for the number of bunches Nb >2.

Parameters	Values (basic/range)	Unit
Kinetic energy	10 / 5-15	GeV
Burst repetition rate	50 / -	Hz
Number of bunches per burst	4 / 1-6	
Bunch spacing	16 / 0.6-16 *	μs
Total duration of the burst	~50 / 40-60	μs
Bunch length	2 / 1-3	ns

SPL-based 5 GeV – 4 MW proton drivers have been designed [SPL + 2 fixed energy rings (accumulator & compressor)] which meet these requirements

References:

- **Feasibility Study of Accumulator and Compressor for the 6-bunches SPL-based Proton Driver** / M. Aiba, CERN-AB-2008-060
- **A first analysis of 3-bunches and 1-bunch scenario for the SPL-based Proton Driver** / M. Aiba, CERN-AB-Note-2008-048-BI
- **Beam Stability in the SPL Proton Driver Accumulator for a Neutrino Factory at CERN** / E. Benedetto, http://nufact09.iit.edu/wg3/wg3_benedetto-splstability.ppt, to be published
- **SPL-based Proton Driver for a Neutrino Factory at CERN,** M. Aiba, E. Benedetto, R. Garoby, M. Meddahi, **poster nb.25 (this workshop)**

ν FACTORY: SPL-based proton driver (2/4)

Neutrinos with the "High power" SPL

Accumulation Duration = 400 μs

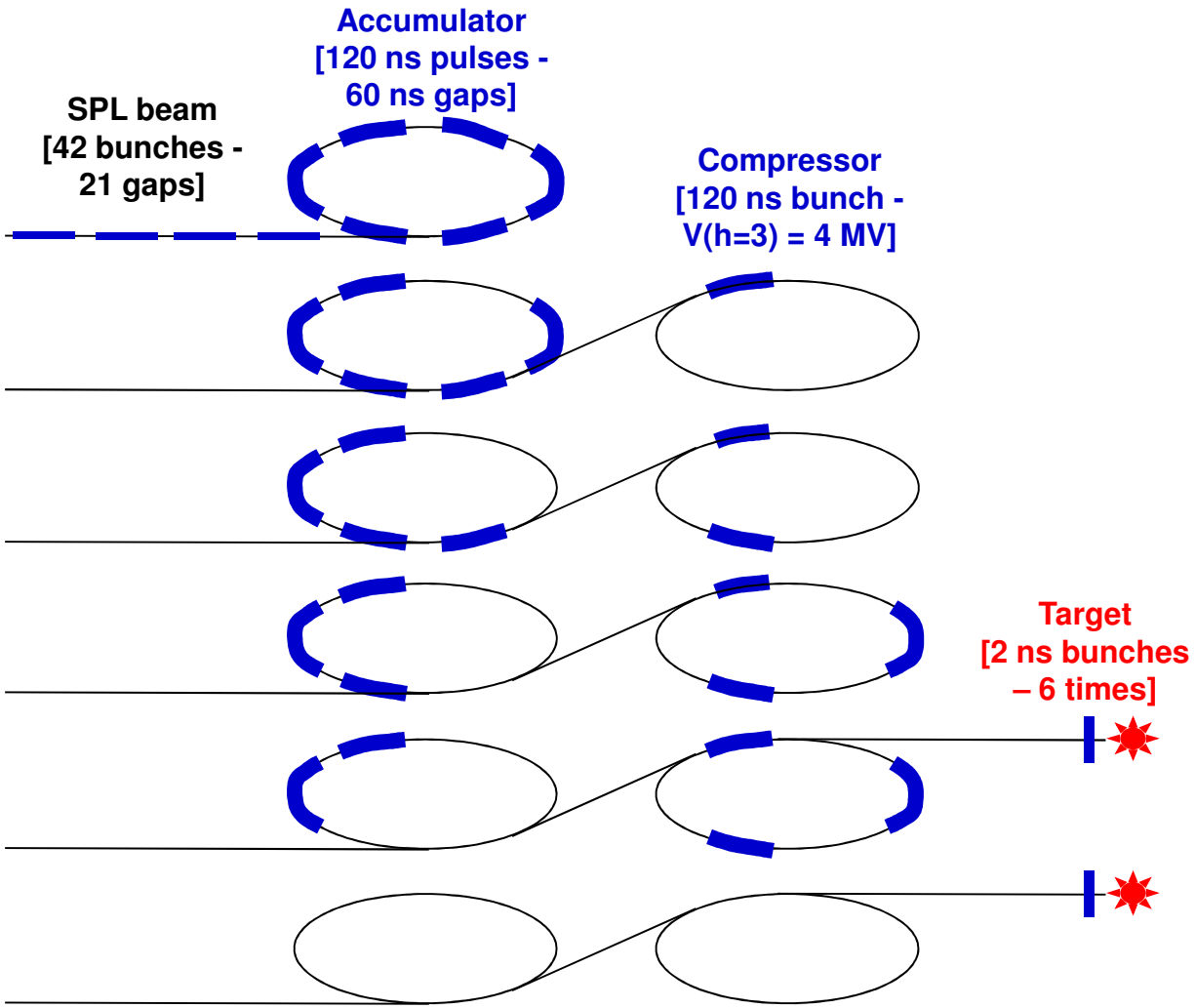
Compression t = 0 μs

t = 12 μs

t = 24 μs

t = 36 μs

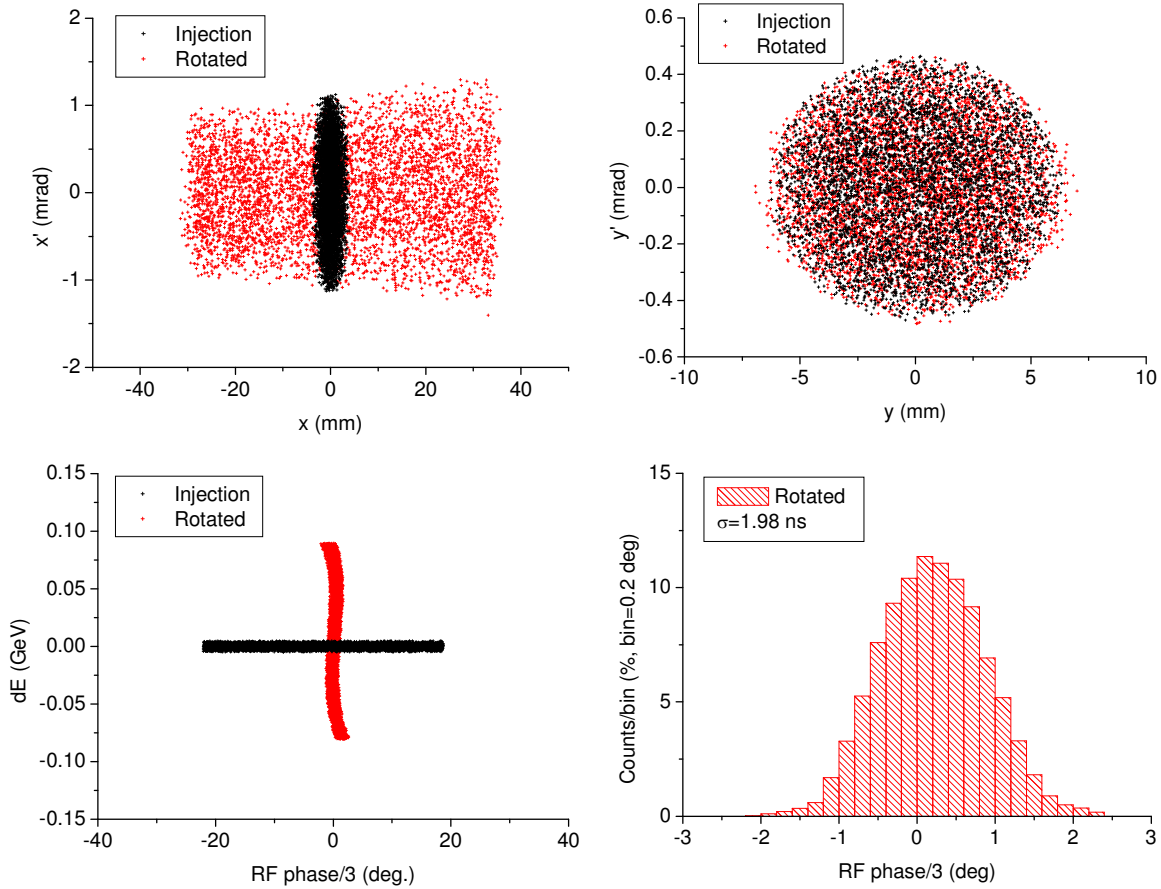
etc. until t = 96 μs



ν FACTORY: SPL-based proton driver (3/4)

from M. Aiba

Neutrinos with the "High power" SPL



ν FACTORY: SPL-based proton driver (4/4)

from M. Aiba

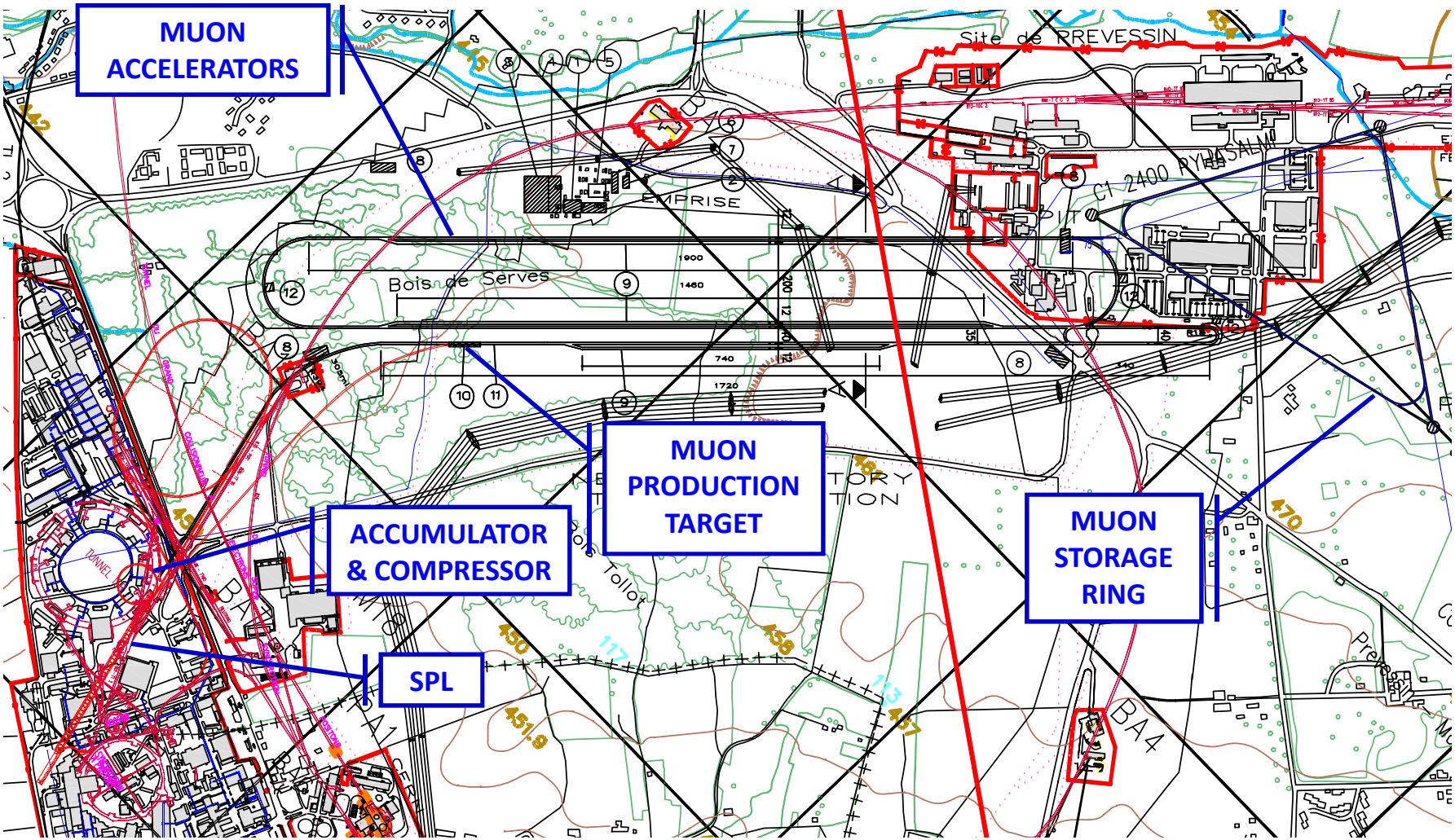
Neutrinos with the "High power" SPL

SPL for proton driver		**Output beam**	
Parameters	Values	Parameters	Values
Kinetic beam energy	5 GeV	Kinetic beam energy	5 GeV
Repetition rate	50 Hz	Repetition rate	50 Hz
Average current during the burst	40 mA	No. of bunches per cycle	6
Beam power	4 MW	Bunch length (r.m.s.)	~2 ns
		Bunch spacing	~12 μs
		Transverse emittance (r.m.s., physical)	3 πmm-mrad
Accumulator		**Compressor**	
Parameters	Values	Parameters	Values
Circumference	318.5 m	Circumference	314.2 m
Transition gamma	6.33	Transition gamma	2.3
RF voltage	-	RF voltage	4 MV
Harmonics number	-	Harmonic number	3
No. of arc cells	24	No. of arc cells	6
Super periodicity	2	Super periodicity	2
Nominal transverse tune	7.77/ 7.67	Nominal transverse tune	10.79/5.77
No. of turns for accum.	400	No. of turns for comp.	36
Maximum no. of bunches	6	Maximum no. of bunches	3
Main quadrupole		Main quadrupole	
Bore radius	56 mm	Bore radius	148 mm
Field gradient	5.5 T/m	Field gradient	7.1 T/m
Magnetic length	1.2 m	Magnetic length	1.9 m
Main bending		Main bending	
Full gap	103 mm	Full gap	125 mm
Full width	162 mm	Full width	379 mm
Field stength	1.7 T	Field strength	5.1 T
Magnetic length	1.5 m	Magnetic length	3 m

Neutrino Factory at CERN

"Proof of principle" [obsolete ν Factory design]

Neutrinos with the "High power" SPL



SPL-based Proton Driver for a Low Energy ν Superbeam

Neutrinos with the "High power" SPL

SPL for proton driver		**Output beam**	
Parameters	Values	Parameters	Values
Kinetic beam energy	5 GeV	Kinetic bea	
Repetition rate	50 Hz	Repeti	
Average current during the burst	40 mA		
Beam power	4 MW	Bu	
		B	
		Transv	
		(r.m.s., physical)	

Only the accumulator is needed for a low energy ν superbeam

Accumulator		**Compressor**	
Parameters	Values	Parameters	Values
Circumference	318.5 m	Circumference	314.2 m
Transition gamma	6.33	Transition gamma	2.3
RF voltage	-	RF voltage	4 MV
Harmonics number	-	Harmonic number	3
No. of arc cells	24	No. of arc cells	6
Super periodicity	2	Super periodicity	2
Nominal transverse tune	7.77/ 7.67	Nominal transverse tune	10.79/5.77
No. of turns for accum.	400	No. of turns for comp	36
Maximum no. of bunches	6	Maximum no. of bunches	3
Main quadrupole		Main quadrupole	
Bore radius	56 mm	Bore radius	148 mm
Field gradient	5.5 T/m	Field gradient	7.1 T/m
Magnetic length	1.2 m	Magnetic length	1.9 m
Main bending		Main bending	
Full gap	103 mm	Full gap	125 mm
Full width	162 mm	Full width	379 mm
Field stength	1.7 T	Field strength	5.1 T
Magnetic length	1.5 m	Magnetic length	3 m

SPL-based Proton Driver for a β Beam Facility

ISOL production method at 1-2 GeV (200 kW)

[Studied within EURISOL Design Study (FP6)]

Close to LP-SPL capability

Neutrinos with the "High power" SPL

Data from E. Wildner's and T. Stora's talks

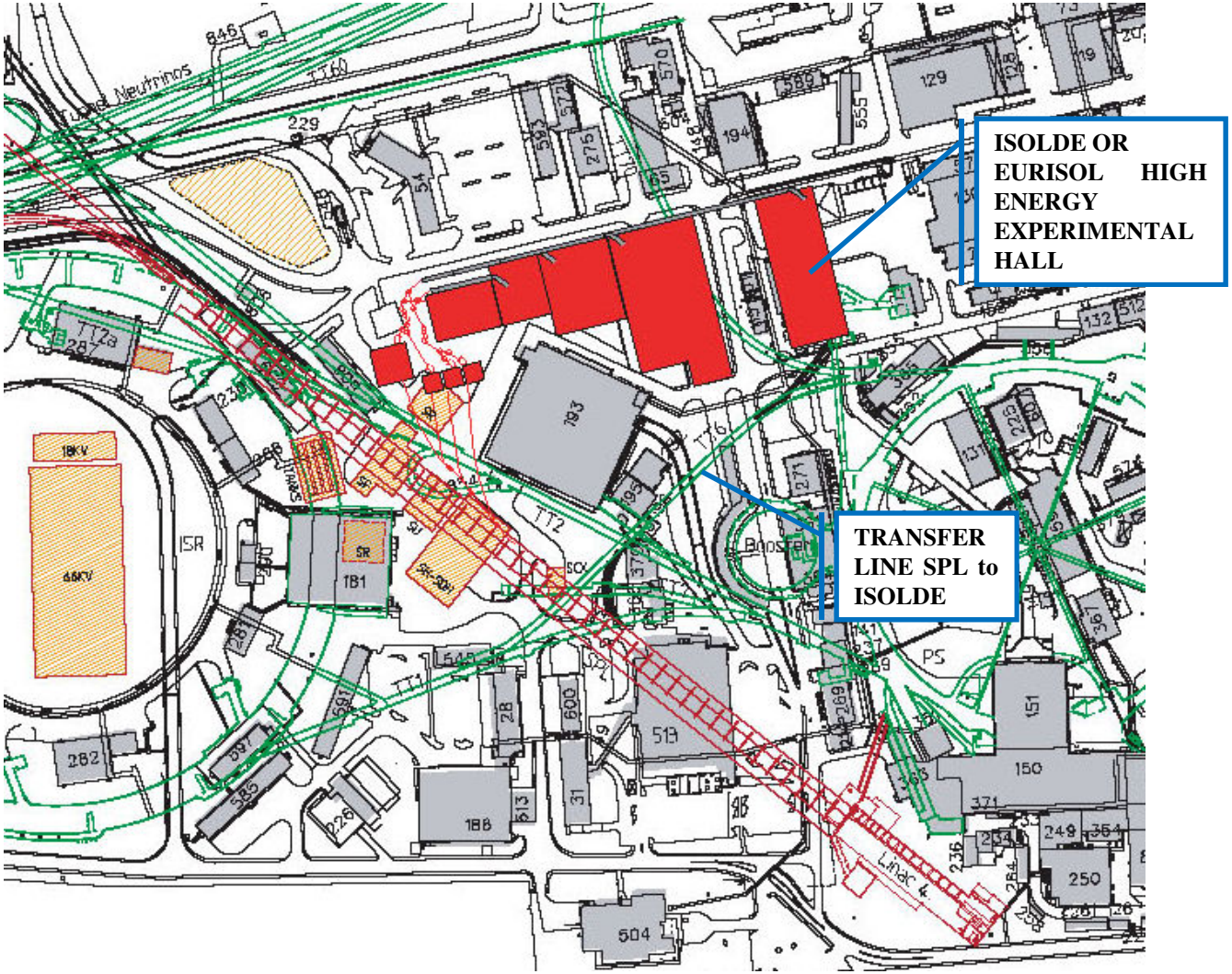
Ion	Production rate (estimate)	Production scheme	Missing factor
^{6}He	2-3×10^{13} /s	1-2 GeV proton @ 200 kW - with converter	OK
^{18}Ne	< 8×10^{11} /s	1-2 GeV proton @ 200 kW - without converter	>20

Alternative scheme with ~70 MeV protons to be studied (see contribution by T. Stora)

SYNERGY WITH EURISOL

EURISOL PRELIMINARY STAGE [ISOLDE AREA] (1/2)

Synergy with EURISOL



EURISOL PRELIMINARY STAGE [ISOLDE AREA] (2/2)

Synergy with EURISOL

Baseline solution

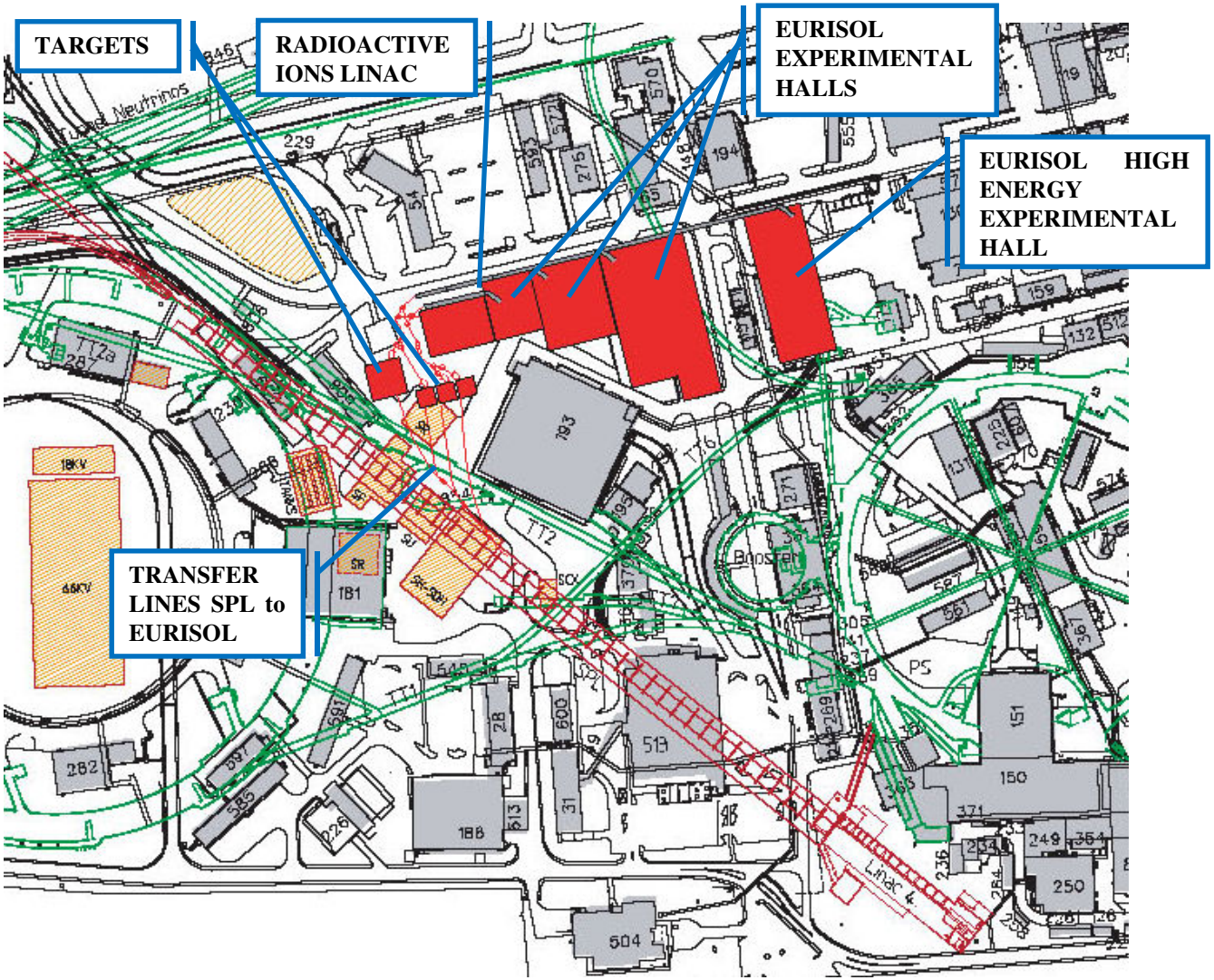
Unchanged modulator topology

Duty factor	Beam energy (GeV)	Max. pulse duration (ms)	Max. current pulse (mA)	Cycling rate* (Hz)	Max. protons /pulse ($x10^{13}$)	Max. beam power (kW)
LP-SPL	~1.4	0.9	20	1.25 (3 out of 4 pulses)	11	31
LP-SPL	~1	0.35	28	2.92 (7 out of 8 pulses)	6.1	29
3 x LP-SPL	~1	0.35	28	~ 10 (23 out of 24 pulses)	6.1	94

Need for wide range high power RF phase shifters or 1 amplifier /cavity

EURISOL (1/2)

Synergy with EURISOL



EURISOL (2/2)

Direct capability of the High Power SPL

Synergy with EURISOL

Option 1

Option 2: full EURISOL specs.

Duty factor	Beam energy (GeV)	Pulse duration (ms)	Current during pulse (mA)	Cycling rate* (Hz)	Protons /pulse ($x10^{13}$)	Beam power (MW)
4.5 %	~2.5	0.9	20	**50**	11	**2.25**
5 %	~2.5	1	**40**	**50**	**25**	**5**

FINAL WORDS

Concerning the future LHC injectors…

Final words

- **There has been significant progress during the past years in the definition of CERN future proton accelerators for the needs of LHC. Detailed project proposals will be ready by mid-2012.**
- **Superconducting RF is a key technology for many future accelerator projects. It makes sense for CERN to be active in that field. It helps SPL development and it will reduce cost.**
- **A High Power SPL is of interest as a Proton Driver for EURISOL as well as for different types of Neutrino Facilities. The possibility to upgrade to an HP-SPL has therefore been preserved until now.**

HOWEVER

- **Schedule has shifted (level of resources + better understanding of Civil Engineering needs…).**
- **Numerous issues deserve special investigation to prepare for multi-MW proton drivers (Beam dynamics and hardware design for the accelerators, Design of target and target area…).**
- **The possibility to upgrade to high beam power will have a cost: approval by the CERN Council cannot be taken as granted.**

Concerning ν's…

Final words

- Safety and environmental issues will be important ingredients for any future Neutrino Facility (as well as for any future high energy Lepton Collider…).
- CERN involvement in future Neutrino Facilities is very small since ~2001.
- Neutrino Factories:
  - CERN involvement is especially low:
    - Except for a significant investment in the low energy front end (Linac4), only a limited effort has been made in the basic design of a proton driver
    - ~ Nothing on muon cooling, acceleration and storage
    - ~ Nothing on hardware development.
  - It is still time to investigate new options => need joint effort of accelerator physicists in close relation with hardware designers.
- Beta-beams: the fruitful link established during the EURISOL DS between Nuclear and Particle Physics has a lot to do with the presence of ISOLDE at CERN.

Recommendations

Final words

Neutrinos

- **Need decision if CERN shall be involved in the study of future neutrino facilities.**
- **If "YES": need to study more subjects / more completely (e.g.: alternative options for muon front end in connection with hardware development, safety and environmental studies…) => need for a structured effort with more resources (especially if CERN is a potential host of a future facility).**
- **To save on resources: focus as soon as possible on the most promising type of facility.**

CERN future accelerators

- **Need for statement of interest in the study of the high power option.**
- **Prepare for the Council decision in 2012, where the cost of keeping the possibility of high beam power will be debated.**
- **It would be cheaper (and faster!) to build immediately for high beam power…**

THANK YOU
FOR YOUR ATTENTION!