Proton Driver based on the SPL design

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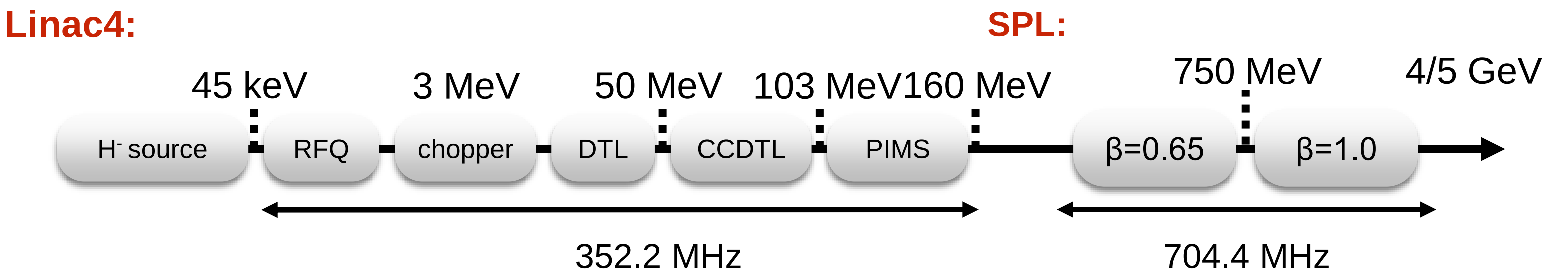
Content

- SPL layout and history
- Parameters for a muon proton driver
- Technical challenges
- Summary

The SPL layout for a 4-5 GeV, 4 MW proton driver



First ideas were to re-use LEP RF equipment (cavities and klystrons) to build a SC proton linac. It then evolved towards bulk Nb cavities and was designed as proton driver for i) neutrino super beam, ii) neutrino factory proton driver, iii) high-power radioactive ion beam facility, iv) replacement of the PSB in the LHC injector chain in combination with new PS..

- Conceptual Design of the Low-Power SPL: A Superconducting H- Linac at CERN (CERN-2014-007)
- Conceptual design of the SPL II: A high-power superconducting H- linac at CERN (CERN-2006-006)
- Conceptual design of the SPL, a high-power superconducting H- linac at CERN (CERN-2000-012)

Parameters adapted to a muon proton driver

Last conceptual design report

	Linac4	SPL
E [MeV]	160	5000
P_{av} [kW]	5	4000
I_{pulse} [mA]	40	20/40
I_{bunch} [mA]	64	32/64
I_{source} [mA]	80	40/80
Chopping	62%	62%
f_{rep} [Hz]	2	50
t_{pulse} [ms]	0.4	0.8/0.4

Never achieved

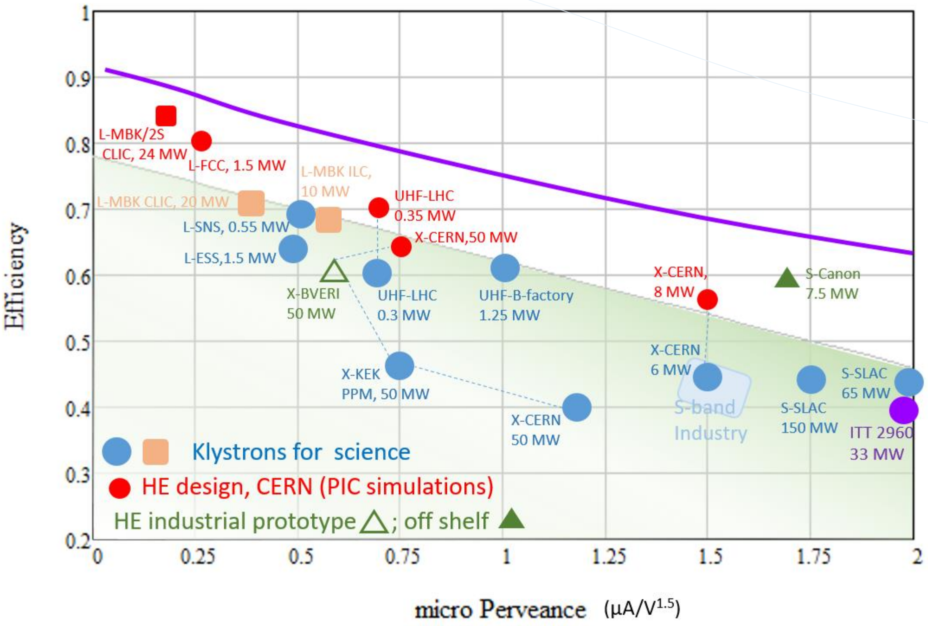
Muon proton driver

	Linac4	SPL
E [MeV]	160	5000
P_{av} [kW]	99.2	3100
I_{pulse} [mA]	40	40
I_{bunch} [mA]	64	64
I_{source} [mA]	80	80
Chopping	62%	62%
f_{rep} [Hz]	5	5
t_{pulse} [ms]	3.1	3.1

All Linac4 cavities are designed to work at the SPL duty cycle. Today's klystrons need a larger collector and the power converters need to be replaced to do this.

Technical Challenges

RF efficiency



Courtesy: Igor Syratchev

High efficiency klystron program

- Active development at CERN for 400 MHz up to X-band.
- Replacement for LHC klystrons expected within 3-5 years. FCC/ILC developments ongoing (400 MHz, 600 MHz 800 MHz, 1.3 GHz).

For a muon collider

- **No showstopper, HE-klystrons already being developed at CERN. Needs continued effort and should enable sizeable plug-power savings.**
- **Long pulses are better for power efficiency because less power is "wasted" for "filling" and "emptying" the cavities.**

Klystron power converters

Courtesy: ESS

ESS power converter

- for 2.86 ms beam pulses, 14 Hz, 115 kV, 4x1.4 MW klystrons.
- Made to present a constant load to the electrical grid.
- ~10 years of development.

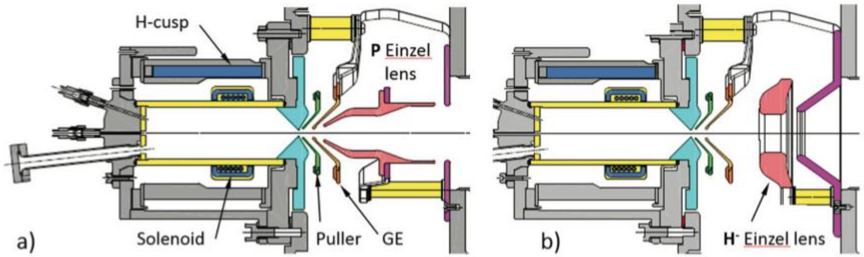
For a muon collider

- we assume high-efficiency klystrons with reduced voltage, which simplifies a lot the power converter (e.g. no oil bath, simpler components, etc.)

→ **No showstopper, HE-klystrons already being developed at CERN.**

H- ion sources

	ISIS	SNS	BNL	SPL
E [keV]	17-35	65	35,40	45
t_{pulse} [ms]	0.5	1	0.8	3.1
f_{rep} [Hz]	50	60	6.6	5
I [mA]	35	60	65,100	80
H^- prod.	Cs arc	Cs surf	Cs surf	CS surf
E_{rms} [mm mrad]	0.2	0.25	0.4,0.56	0.25
Cs [mg/day]	100	<1	12	?
Operation [MTBM]	5 w	6 w	36 w	> 12



From: J. Lettry et al., DOI: 10.1063/1.4995722

Linac4 H- source

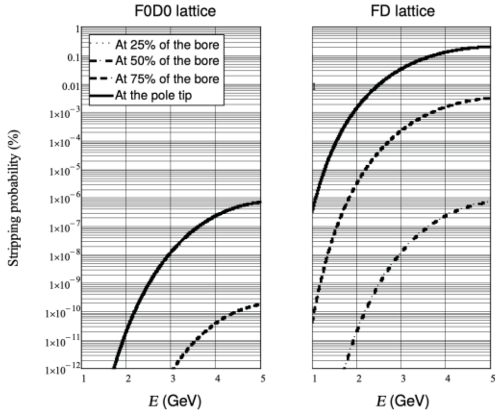
- The goal was to achieve 80 mA with an emittance of 0.25 mm mrad. Achieved are 25 mA within the target emittance, or 36 mA w/o losses in the LEBT.
- ~10 years of development but then stopped as the above performance was sufficient for Linac4 as PSB injector

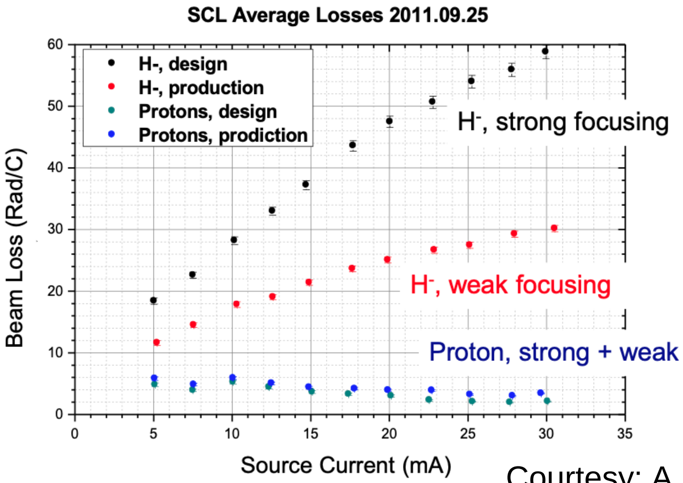
For a muon collider

- Using even longer pulses with lower current will make accumulation and compression more difficult.

→ **Low rep-rate, long-pulse and high-current H-source will need significant R&D effort.**

H- stripping





Courtesy: A. Shishlo (SNS)

Magnetic stripping of H-

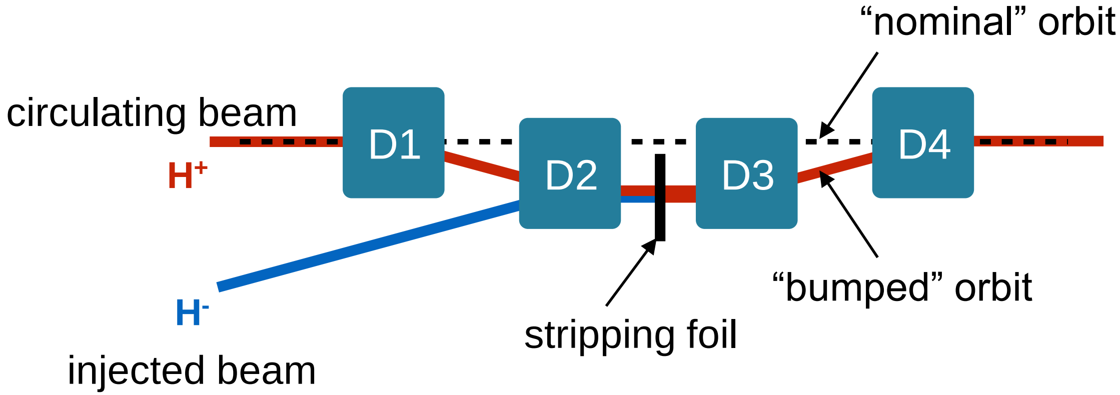
- defined by Jason/Hudgings/van Dyck, IEEE Trans. Nucl. Sci. 28 (1981),
- Translates into max B-fields as a function of energy to limit losses. **Understood.**

Intrabeam stripping of H-

- First observed at CERN: Chanel et al., Phys. Lett. B **192** (3-4) (1987) 475.
- Became a problem at SNS and was then understood and explained by Lebedev: PRL **108**, 114801 (2012)

→ **No showstopper, phenomenon understood.**

H- injection



Foil stripping

- Passing MW of beam through a um thick foil is highly challenging. SNS made excellent progress and needs 1-2 foils per 2500 h.
- SNS also predicts a power limit of 5 MW.

Laser stripping

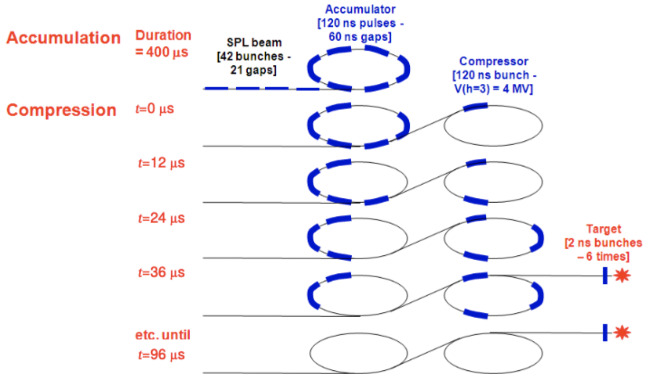
- Very promising but needs high level of energy stability from the linac.

→ **No showstopper for H- injection**, but needs some effort.

Accumulator - compressor rings

Table 2.4: Main parameters of the accumulator and compressor rings

Ring	Parameter	Units	6 bunches	3 bunches
Accumulator	Circumference	m	318.5	185.8
	Accumulation turns		690	1180
	Type of magnets		NC	SC
Compressor	Circumference	m	314.2	200
	Compression turns		36	86
	RF voltage at $h = 3$	MV	4	1.7
	Transition gamma		2.3	2.83
	Type of magnets		SC	NC
	Interval between bunches	μs	12	30



SPL set-up for a neutrino factory

- Assumed a accumulator ring and compressor ring to transform the 50 Hz linac pulses into 3 or 6 high-intensity bunches at 50 Hz.
- Simulation work stopped over 10 years ago and was difficult because of high space charge and large number of turns.

For a muon collider

→ **R&D needed!** A crucial part of the proton driver set-up that must be studied in detail.

→ Corresponding HW (magnets and RF) to be defined and tested.

Other items that deserve effort

- **Fundamental Power couplers:** Today we assume 1 MW peak power in pulsed operation per coupler. This is feasible but far from trivial. Continued R&D effort needed at CERN.
- **SC cavities for protons:** are used at SNS, ESS. Assumed gradient at SPL was 25 MV/m max (corresponding to 1 MW power couplers at 40 mA average pulse current). Still seems reasonable for stable operation.
- **High-Q cavities:** Can give significant savings in cryogenic power. Mostly pursued at FNAL, very few studies at < 1.3 GHz so far. Deserves attention.
- **Compact klystrons and modulators:** The equipment gallery is much larger than the accelerator tunnel, assuming that the gallery is above ground and the tunnel underground but that creates losses in long waveguide ducts. Optimisation needed.
- **Fast and "clean" beam chopper:** SPL assumed 5 bunches and 3 empty ones for injection into accumulator. To be re-assessed and studied.

Summary

- There are no fundamental show stoppers on the proton driver side.
- The technologies and the power ramp-up are challenging but can be solved by continued commissioning effort and gradual improvements (e.g. as done at SNS to ramp up the power, you should count 5-10 years to get to nominal)
- H- sources and the accumulator - compressor rings are the most critical items that need an immediate and prolonged R&D effort.

International
MUON Collider
Collaboration

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Thank you for attention