Linear Accelerator Designs for the Upgrade of the CERN Proton Injector Complex (Linac4, SPL)

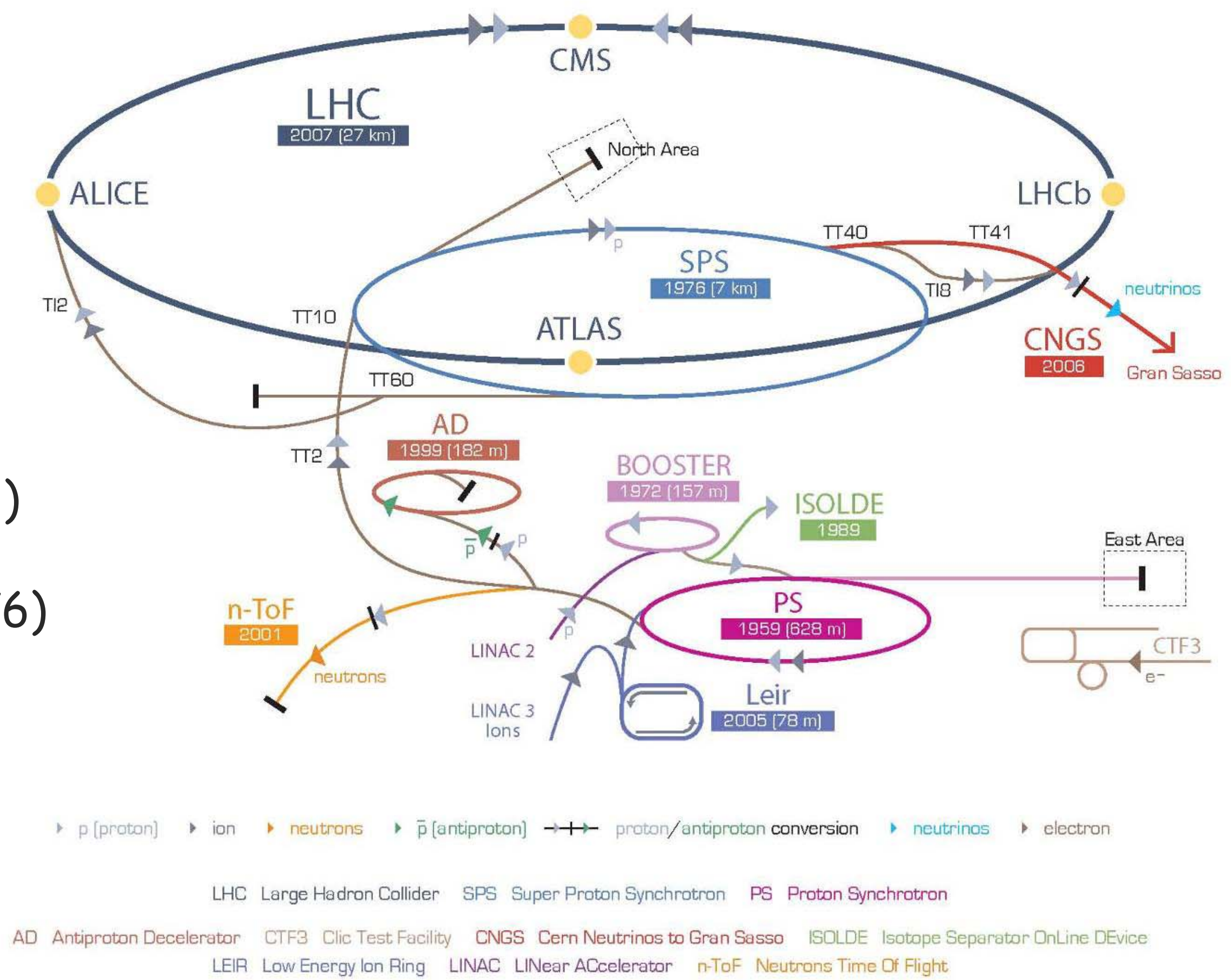
M. Vretenar for the Linac4-SPL Study Group

- The LHC Injector chain: performance and limitations
- A roadmap for the upgrade of the injectors
- Linac4 as first step towards the future: design and technical features
- SPL (Superconducting Proton Linac) as further option: basic design

The LHC Injector Chain

LHC Injectors

-Linac2 (p, 50 MeV, 1978)
-PSB (1.4 GeV, 1972)
-PS (28 GeV, 1959)
-SPS (450 GeV, 1976)

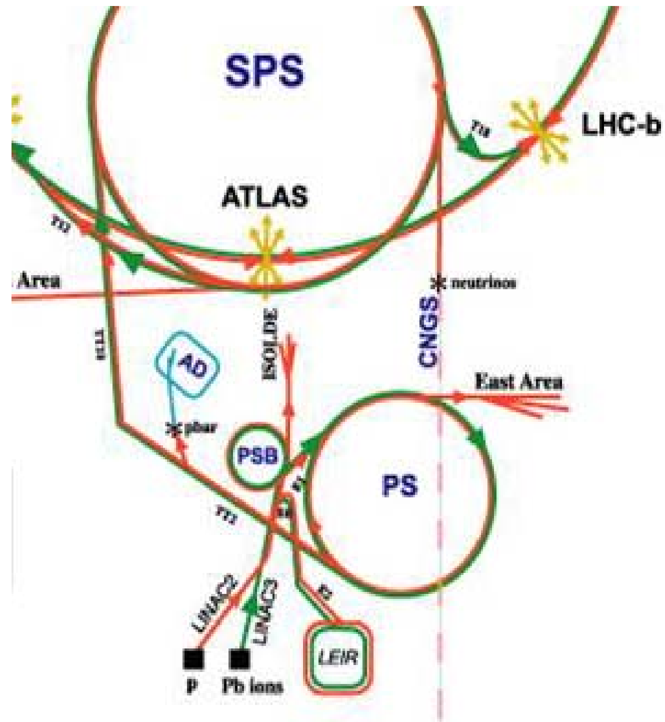


Performance of the LHC Injectors

The injectors have been upgraded in 1995-2000 to provide a high brightness (N_b/ε) beam for the LHC.

However, 2 concerns remain:

1. Limit performance: LHC nominal luminosity can be achieved, but ultimate (beam-beam limit) luminosity requires higher brightness, which can not be achieved with the present injectors.
2. Reliability: recurrent problems in last years on old accelerators: radiation damage PS magnets, water leaks SPS magnets, main PS power supply, linac vacuum, …



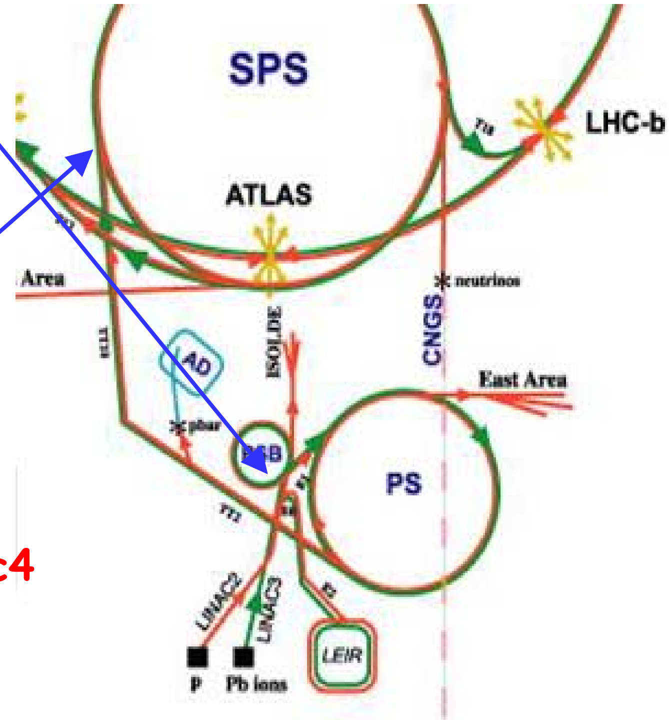
	LHC Luminosity	Intensity (in ε_n=3.75μm)
Nominal	1 x 10^{34} $cm^{-2}s^{-1}$	1.15 x 10^{11} ppb
Ultimate	2.5 x 10^{34} $cm^{-2}s^{-1}$	1.7 x 10^{11} ppb

Max. expected intensity with present injectors 1.2 x 10^{11} ppb

Increasing brightness for LHC

The first and most evident bottleneck for higher brightness is at the injection into the PSB:
At 50 MeV injection, incoherent space charge tune shift dominates injection process.

Other weak points are the low injection energy into the SPS and resonances in the SPS.



First and more immediate (~low cost) solution →
Construction of a new linac injecting into PSB, **Linac4**

- at higher energy ($\Delta Q \propto 1 / \beta\gamma^2$)
- allowing for H^- charge exchange injection
- easing operation (LHC beam in PSB with single instead of double batch)

→ Factor 2 in intensity, i.e. factor 2 in $\beta\gamma^2$ → **160 MeV**
Proposed as medium-term solution for improving performance and reliability

Guidelines for the injectors upgrade

☞ On the long term, a more radical reconstruction of the proton injector complex has to be considered: the repairs on the PS are only temporary, and an LHC upgrade should be foreseen ~2015.

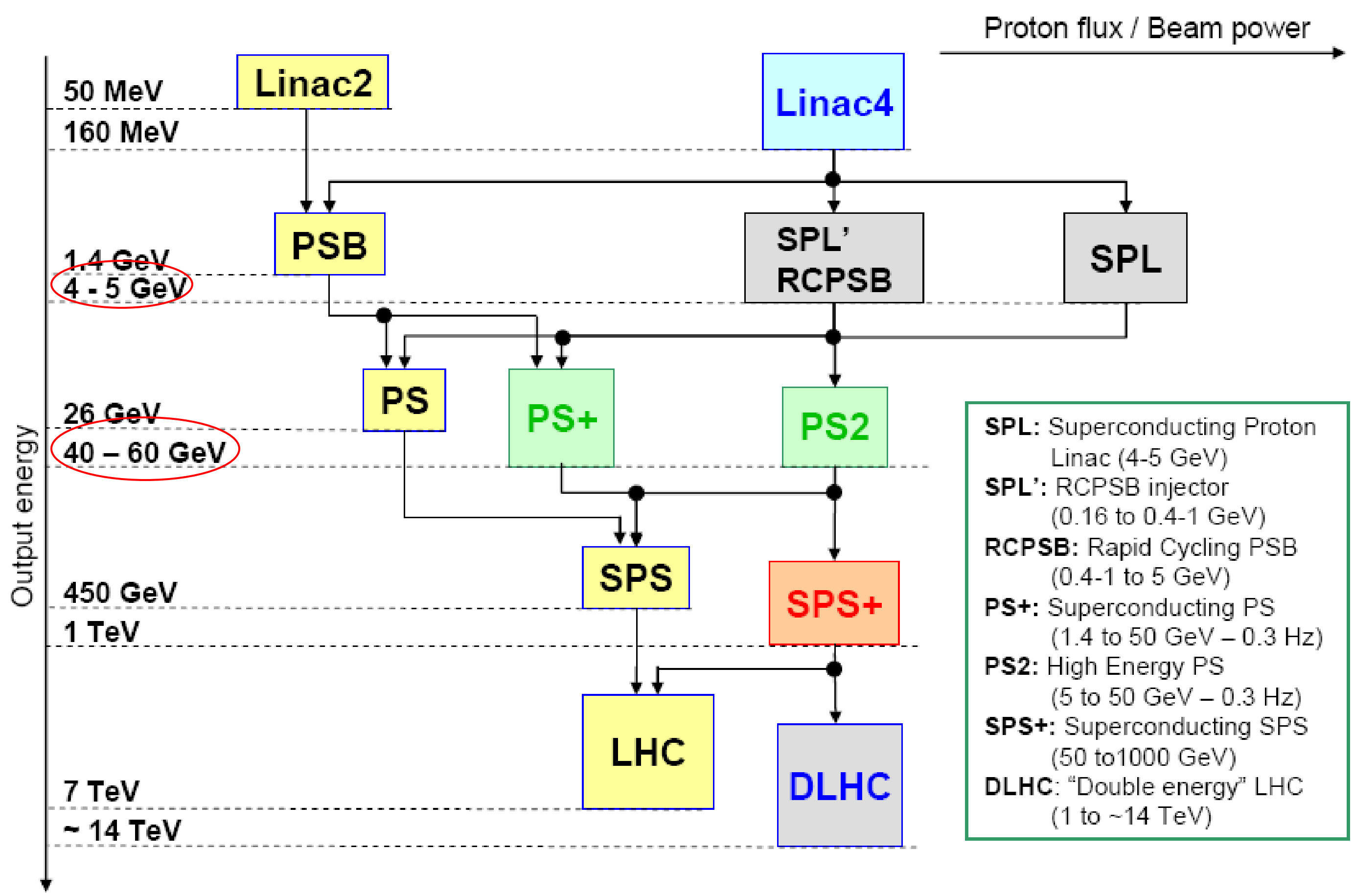
Long-term guidelines:

1. Prepare for the LHC luminosity upgrade, foreseen for >2015, which will require higher brightness from the injector chain.
2. Improve integrated LHC luminosity by increasing availability of the injector chain → replace or improve old accelerators (PS, SPS).
3. Simplify operation by optimising transfer energies and batch structure, reduce radiation produced by the old machines.
4. Make the new machines compatible with a future upgrade towards higher intensity, for the needs of neutrino physics (Superbeam, Beta-beams, Neutrino Factory) and/or Radioactive Ion Beam physics.

Strategy for the injectors upgrade

Roadmap from PAF (=Proton Accelerators for the Future) study group, focused on the goal of maximising LHC integrated luminosity, leaves open the option of producing high-intensity beams.

1. Replacement of Linac2 with Linac4
2. Replacement of PSB-PS with a new medium energy accelerator (SPL?) and a new PS2
3. SPS renovation



Revised CERN Medium Term Plan

As a consequence of this strategy, CERN is presently asking for the funding of an additional plan for the period 2008-2010, which includes some measures to improve performance and reliability of the LHC and a preliminary approach for the injector upgrade:

1. Construction of Linac4
2. Detailed design of a Superconducting Proton Linac (SPL) and of PS2

Preparation of Linac4 has started, a decision on the funding of the rest of the project is expected at mid-2007.

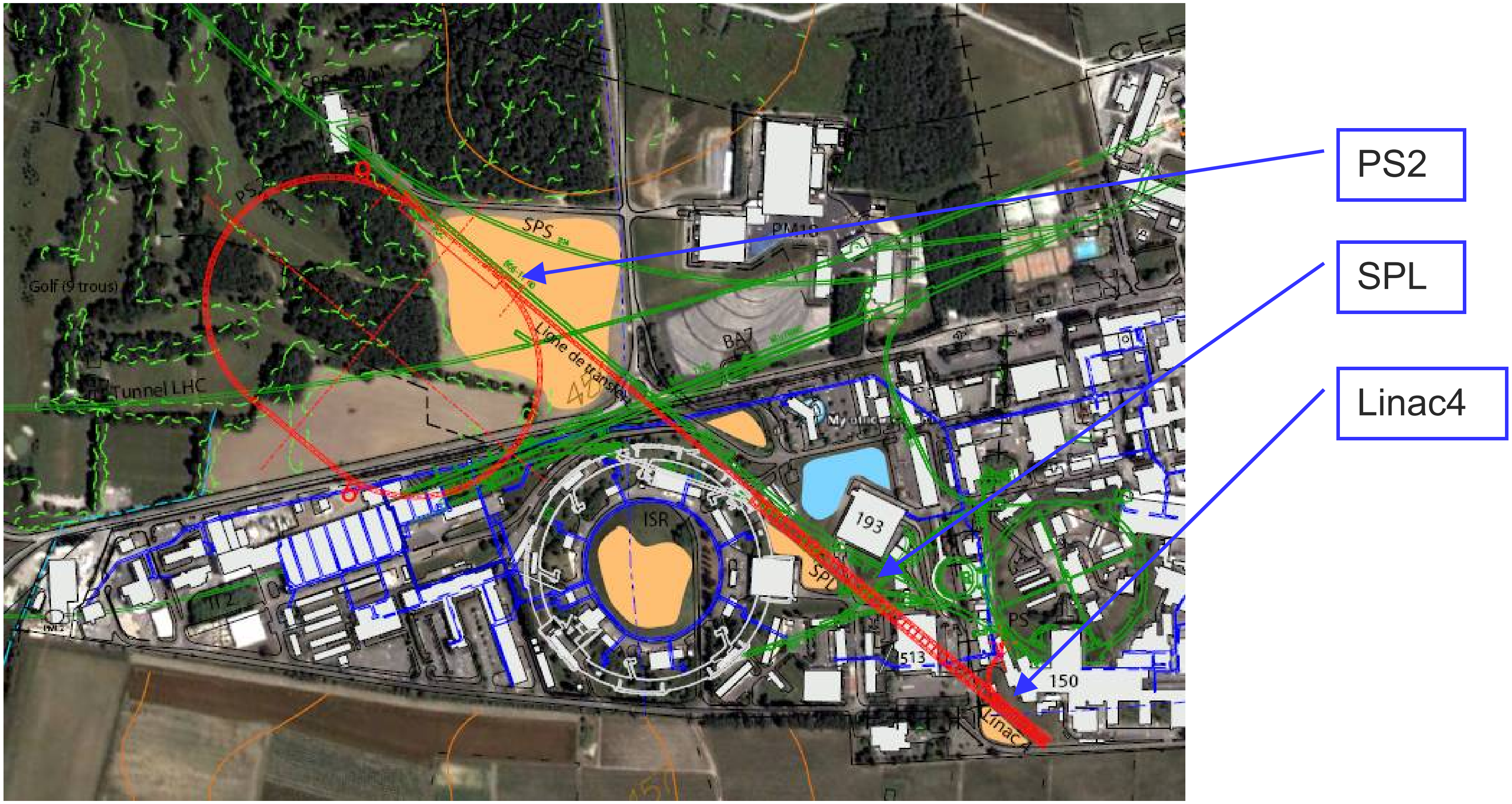
SPL or RCS as intermediate-energy accelerator?

For high-intensity applications, a high energy (3 - 5 GeV) linac is the ideal machine. In case only low-intensity beams are considered, a Rapid Cycling Synchrotron (RCS) is a valid alternative.

The SPL will be designed for low-duty (only LHC needs), with the option of a future upgrade to high-intensity.

A modern high-energy linac is considered as competitive in cost with a RCS.

Possible layout on the CERN site



One of the options presently under study: Linac4 in an underground building, connected to the present system of accelerators.

SPL and PS2 to be built in underground tunnels, connected to SPS

Linac4

Technical Design Report (December 2006)

CERN-AB-2006-084, http://cdsweb.cern.ch/record/1004186

L. Arnaudon, P. Baudrenghien, M. Baylac, G. Bellodi, Y. Body, J. Borburgh, P. Bourquin, J. Broere, O.Brunner, L. Bruno, C. Carli, F. Caspers, S.; Cousineau, Y. Cuvet, C. De Almeida Martins, T. Dobers, T. Fowler, R. Garoby, F. Gerigk, B. Goddard, K. Hanke, M. Hori, M. Jones, K. Kahle, W. Kalbreier, T. Kroyer, D. Küchler, A.M Lombardi, L.A López-Hernandez, M. Magistris, M. Martini, S. Maury, E.Page, M. Paoluzzi, M. Pasini, U. Raich, C. Rossi, J.P Royer, E. Sargsyan, J. Serrano, R. Scrivens, M. Silari, M. Timmins, W.Venturini-Delsolaro, M. Vretenar, R. Wegner, W. Weterings, T. Zickler

Linac4 parameters

Ion species	H−	
Output Energy	160	MeV
Bunch Frequency	352.2	MHz
Max. Rep. Rate	2	Hz
Beam Pulse Length	400	μs
Max. Beam Duty Cycle	0.08	%
Chopper Beam-on Factor	62	%
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

Will re-use 352 MHz LEP RF components: klystrons, waveguides, circulators.

2 operating modes: low duty for PS Booster (PSB) injection in the first phase, high duty for the SPL in a second phase.

- Structures and klystrons dimensioned for 50 Hz
- Power supplies and electronics dimensioned for 2 Hz.

Linac4 basic design

95keV → RFQ, 3MeV → CHOPPER, 3MeV → DTL, 40MeV → CCDTL, 90MeV → SCL, 160MeV

H-	RFQ	CHOPPER	DTL	CCDTL	SCL
RF volume source (DESY) 35 kV Extrac. +60kV Postacc.	Radio Frequency Quadrupole (IPHI) 352 MHz 6 m 1 Klystron 1 MW	Chopper 352 MHz 3.6 m 11 EMquad 3 rf cavity	Drift Tube Linac 352 MHz 13.4 m 3 tanks 5 klystrons 4 MW 82 PMQuad	Cell-Coupled Drift Tube Linac 352 MHz 25.3 m 24 tanks 8 klystrons 6.5 MW 24 EMQuads	Side Coupled Linac 704 MHz 28 m 20 tanks 4 klystrons 12.5 MW 20 EMQuads

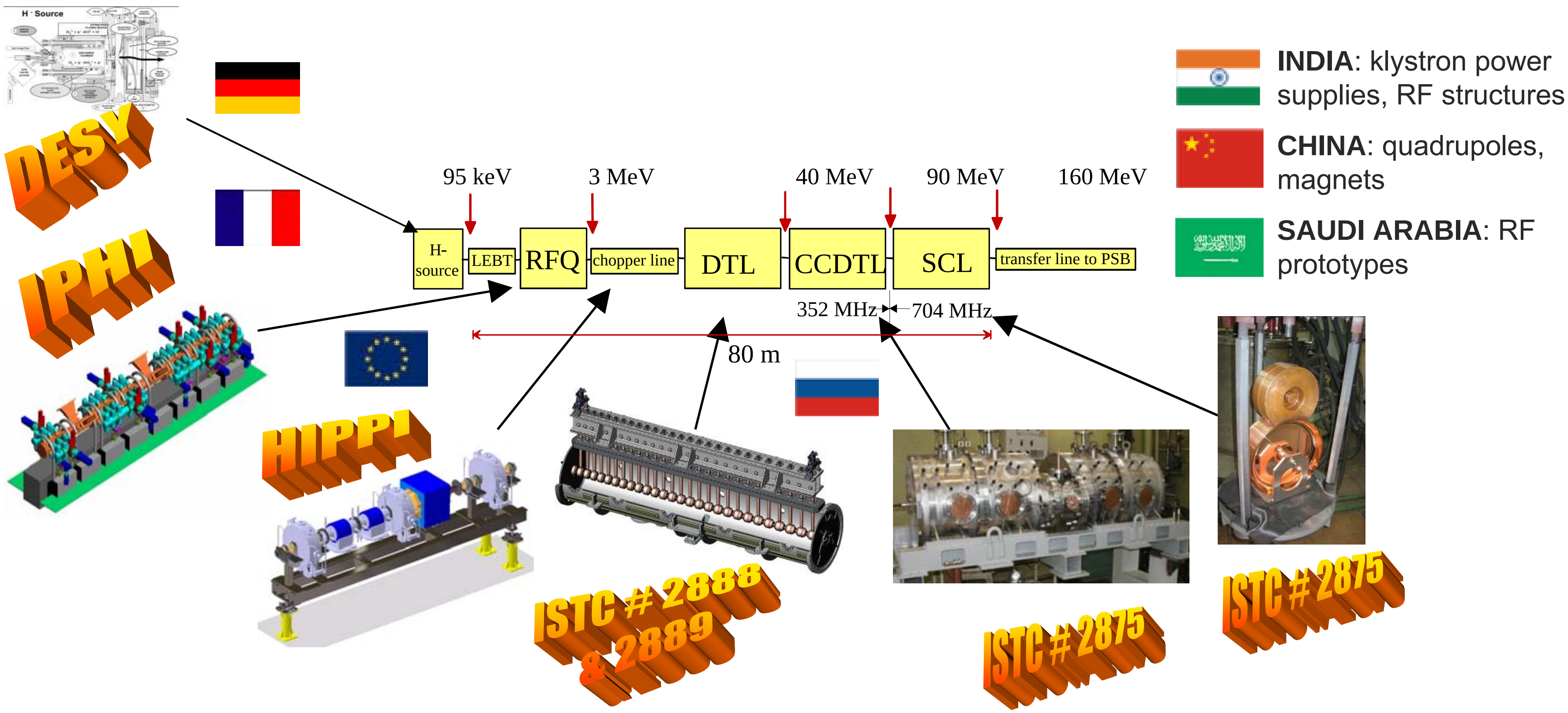
Total Linac4:
80 m,
18 klystrons

RF Duty cycle:
0.1% phase 1 (Linac4)
3-4% phase 2 (SPL)
(design: 15%)

4 different structures,
(RFQ, DTL, CCDTL, SCL)
2 frequencies

current: 40 mA (avg. in pulse), 65 mA (bunch)

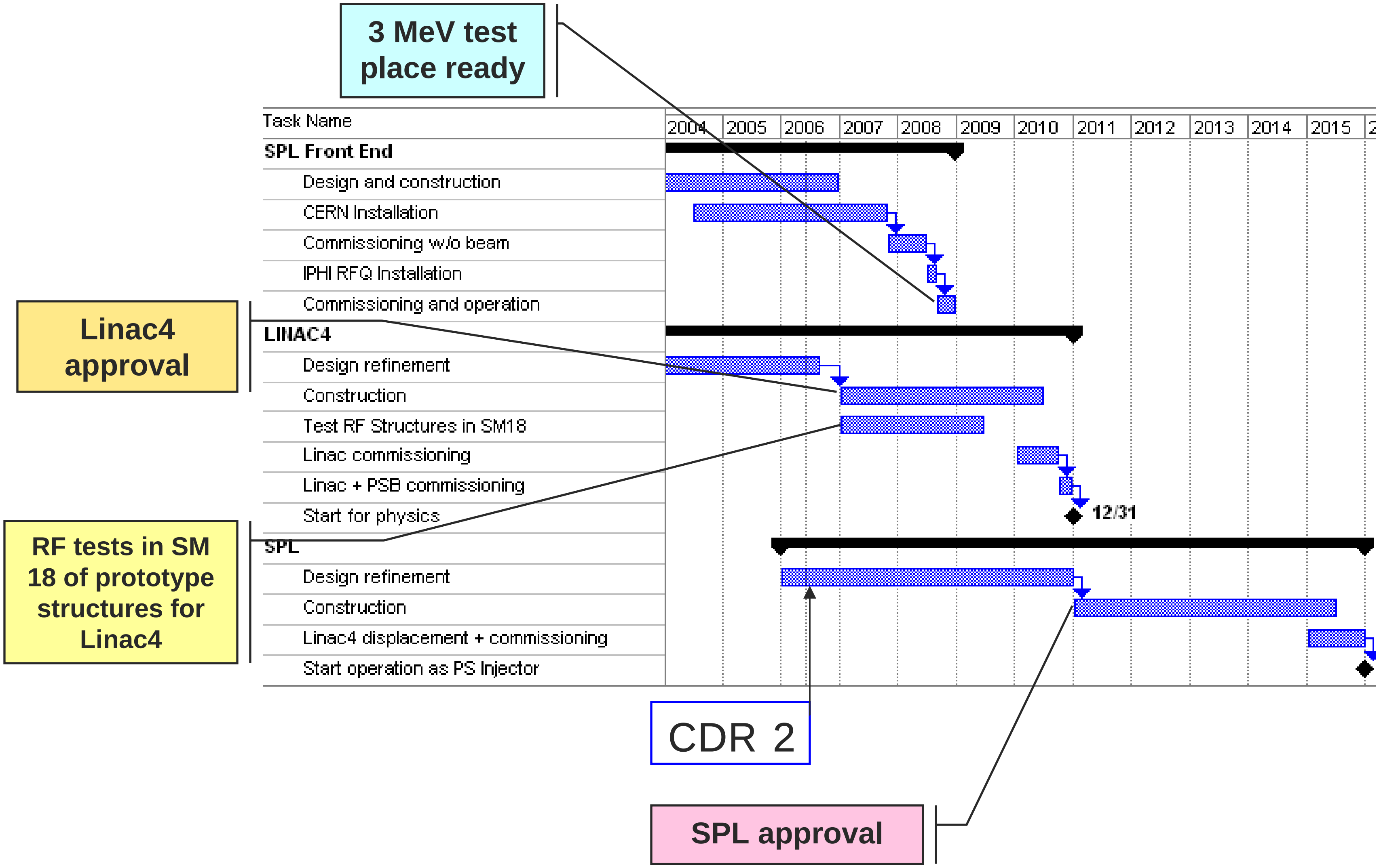
Linac4 collaborations



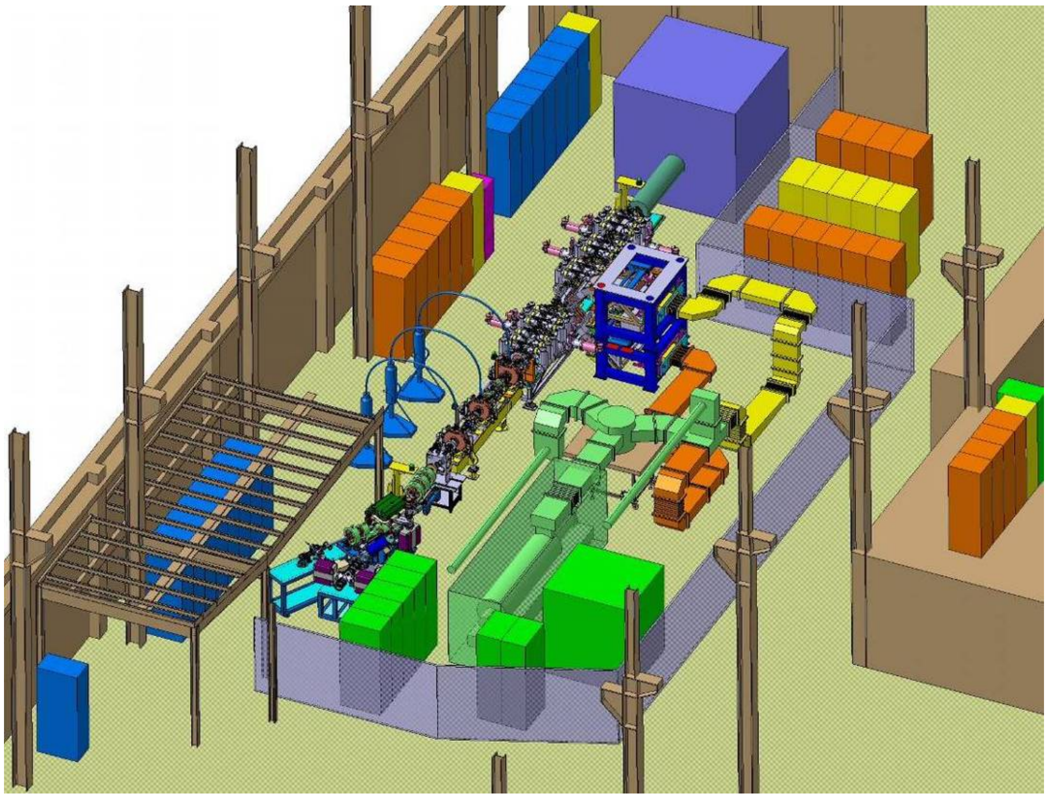
Network of collaborations for the R&D phase, via EU-FP6, CERN-CEA/IN2P3, ISTC (CERN-Russia), CERN-India and CERN-China agreements.

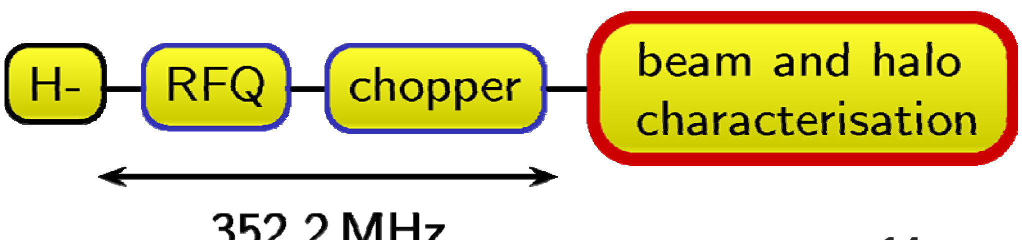
Preparation in view of future international participation to the construction of Linac4

Overall planning



The 3 MeV Test Stand





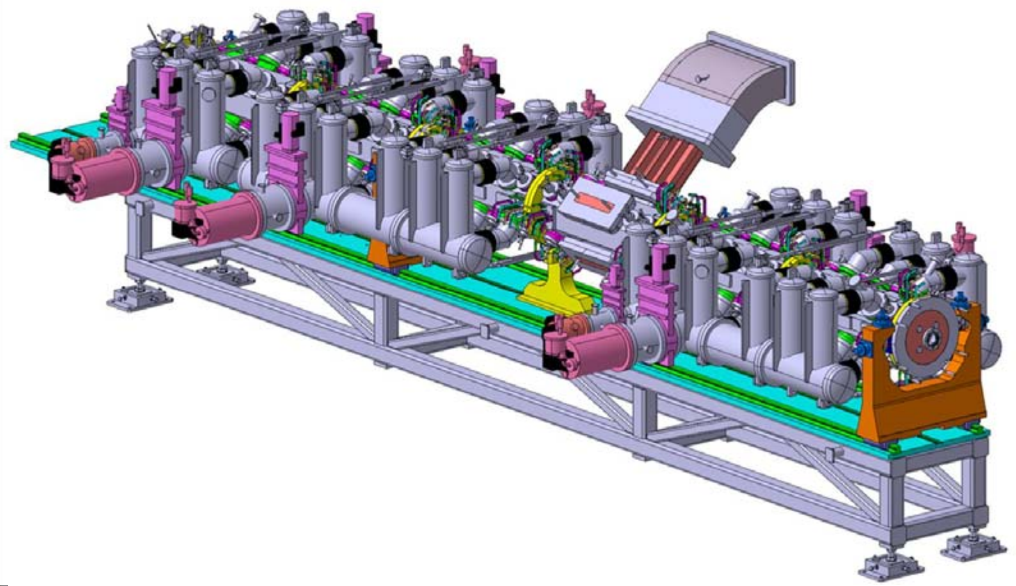
In construction, first beam foreseen in 2008.

- H- source (DESY type,
- LEBT (2 solenoid)
- IPHI RFQ
- Chopper line (from CERN)
- Diagnostics line (IPHI and CERN components)
- Infrastructure (1 LEP Klystron, pulsed power supply, etc.)

In the front end are concentrated some of the most challenging technologies in linacs, and this is where the beam quality is generated:

Early understanding and optimisation of front-end is fundamental for a modern linac project.

The IPHI RFQ

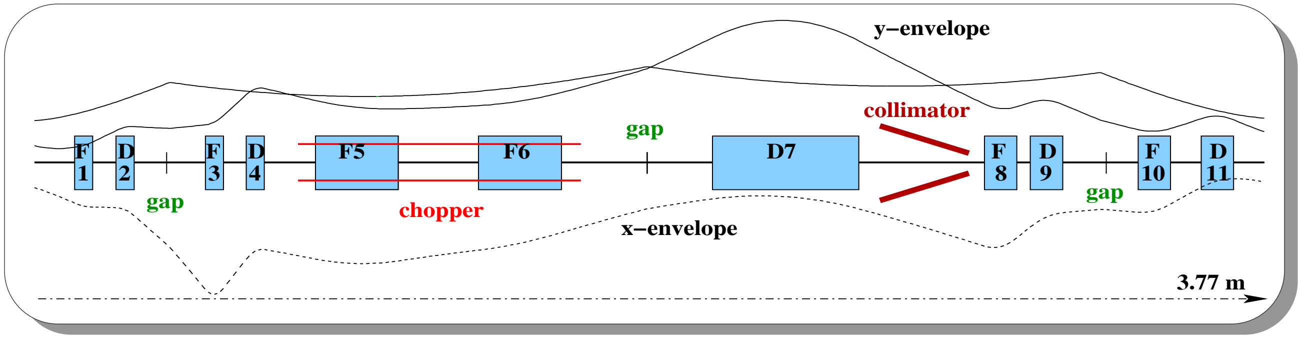


The 3 MeV Test Stand and Linac4 will use the RFQ being built by the French IPHI project.

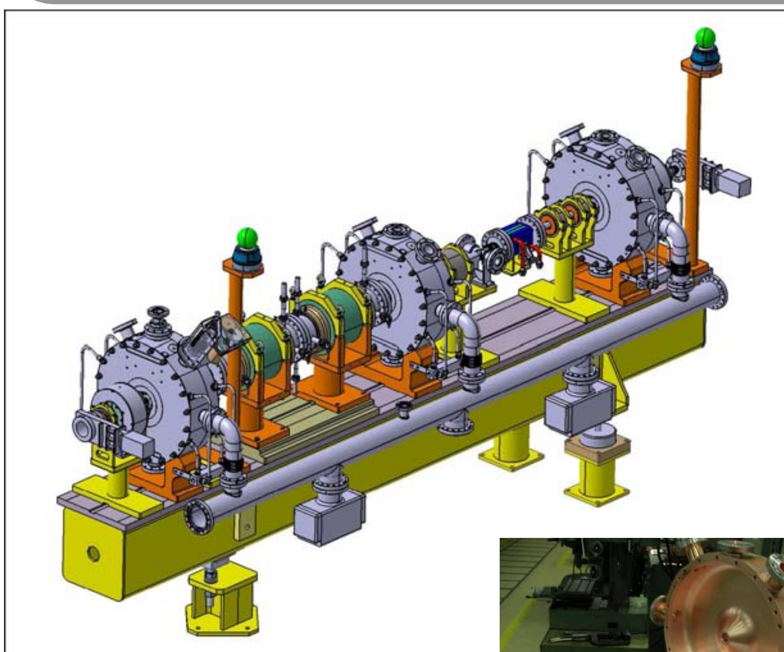
After first beam tests in France, the RFQ will be delivered to CERN (June 2008).

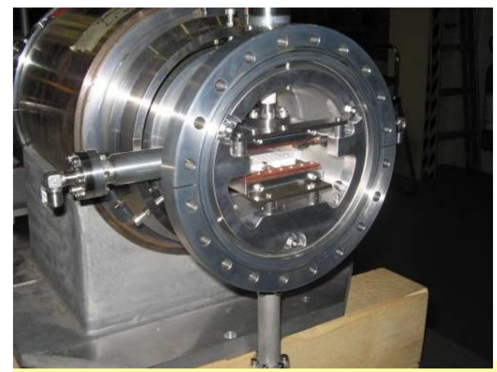
352 MHz, 95 keV – 3 MeV, 6 meters long
Brazing done at CERN

The 3 MeV chopper line

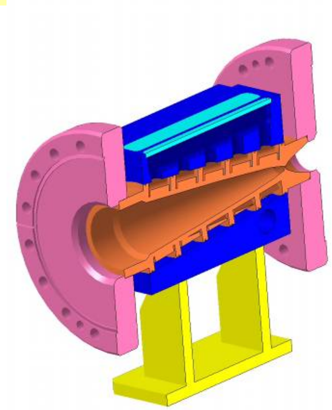


Compact design 3.7 m length
Dynamic range 20 – 60 mA
Small ε growth 4% long., 8% trans.
Tolerant to alignment errors





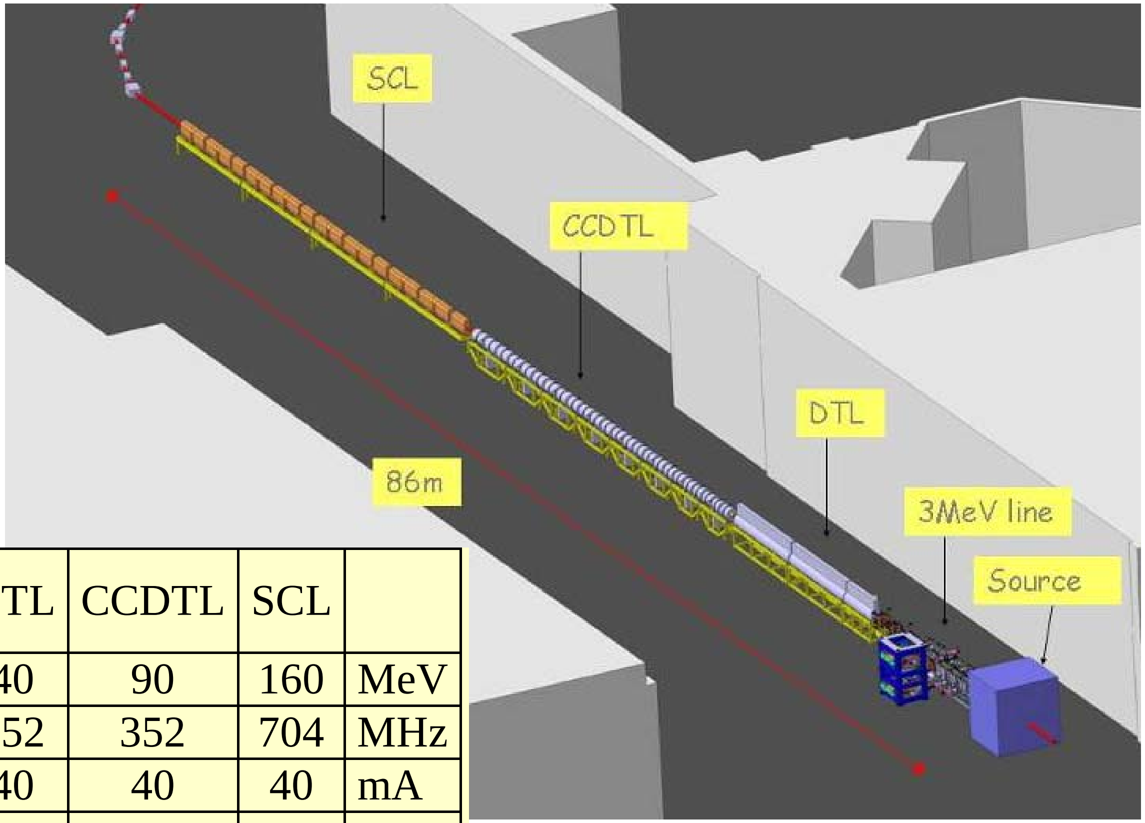
Dumping of chopped beam and collimation of unchopped beam in a conical dump structure



Chopper structure: double meander strip line, 400mm length, metallized ceramic plate. 2 ns rise/fall time for bunch selectivity (352 MHz beam structure), ±500V between deflecting plates.

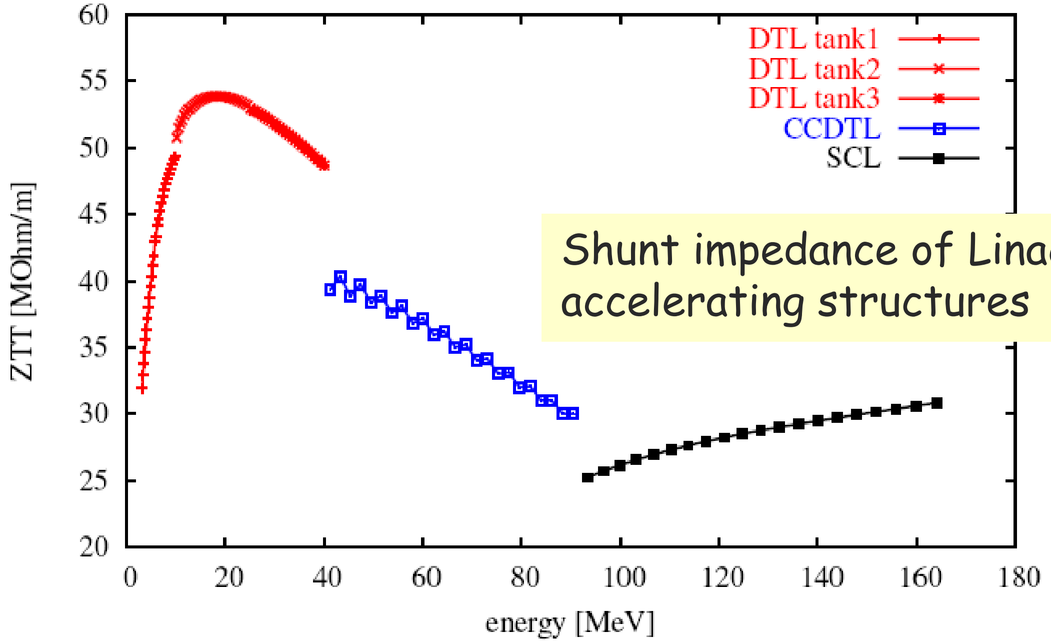
3 RF bunchers

Linac4 accelerating structures



	RFQ	Chopper line	DTL	CCDTL	SCL	
Energy	3.0	3.0	40	90	160	MeV
Frequency	352	352	352	352	704	MHz
Current	70	40	40	40	40	mA
RF Power	1.0	-	3.9	6.4	12.5	MW
Klystrons	1	-	5	8	4	-
No. tanks	1	-	3	24	20	-
Length	5.95	3.7	13.4	25.2	28.0	m

Accelerating structures design



Shunt impedance of Linac4 accelerating structures

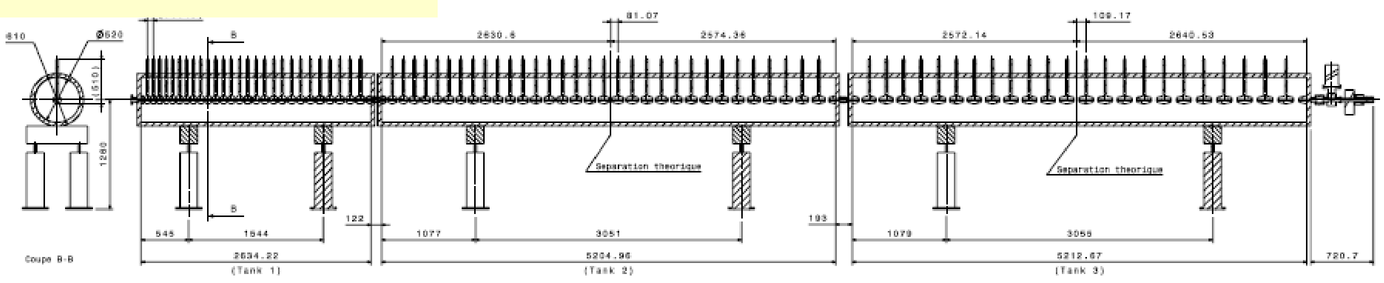
Traditional design (DTL-like + π mode), required for reliability and proper beam dynamics.

Accelerating gradients 3 – 4 MV/m, peak field <1.7K

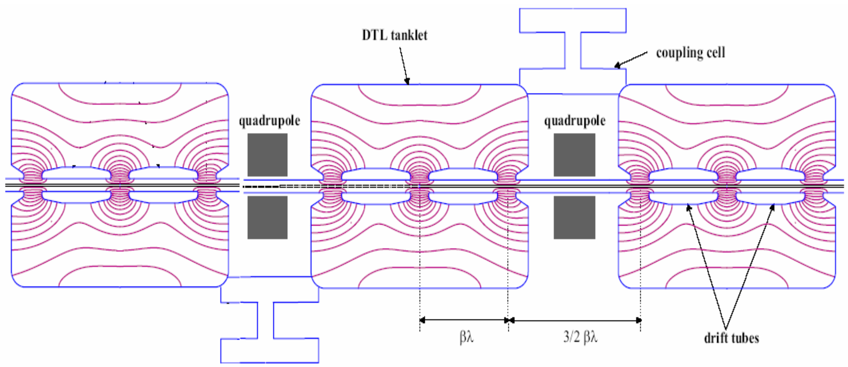
Apertures 20-32 mm

1. DTL with Permanent Magnets (40 MeV)
2. CCDTL (Cell-coupled) DTL with Electromagnets (90 MeV)
3. Side Coupled (SCL) at 704 MHz

DTL layout (3 tanks)



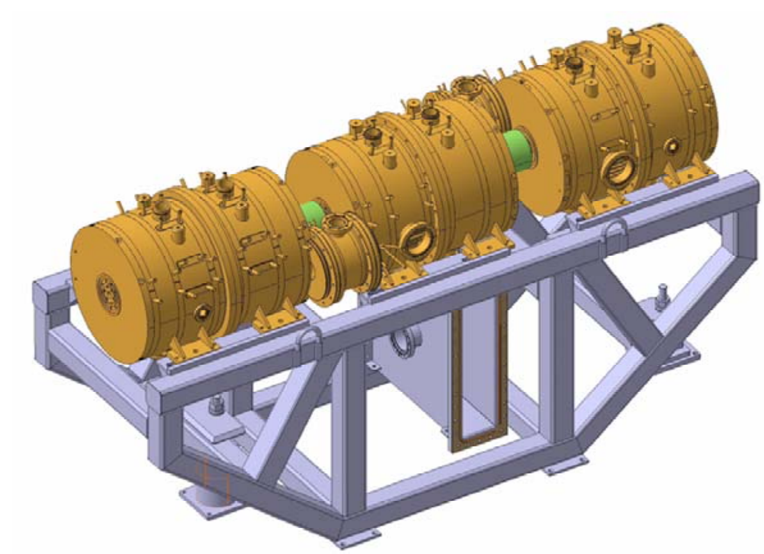
Cell Coupled DTL



High-power prototype tested at CERN (poster TUPMA088)

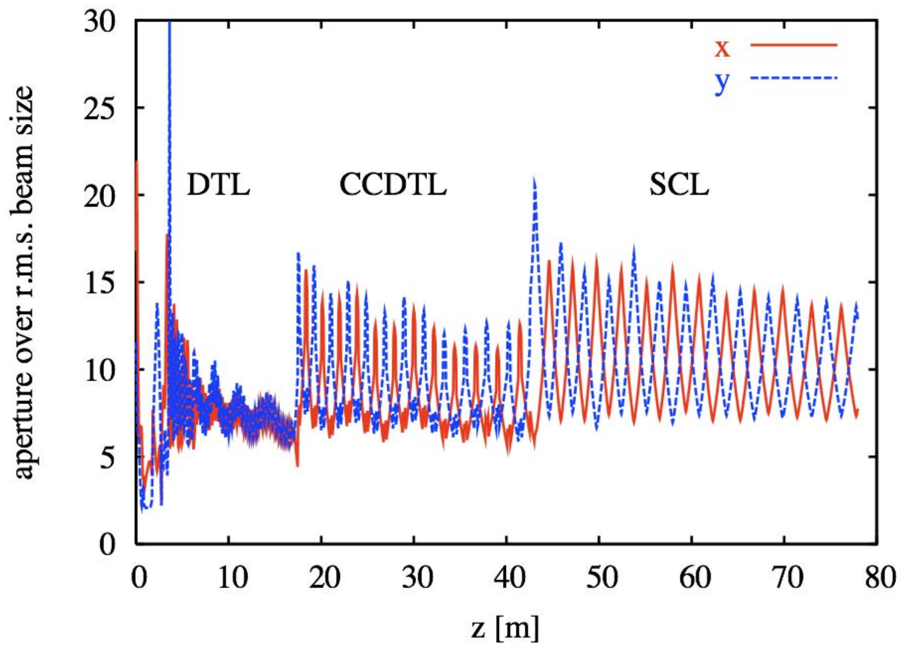
Used above 40 MeV:

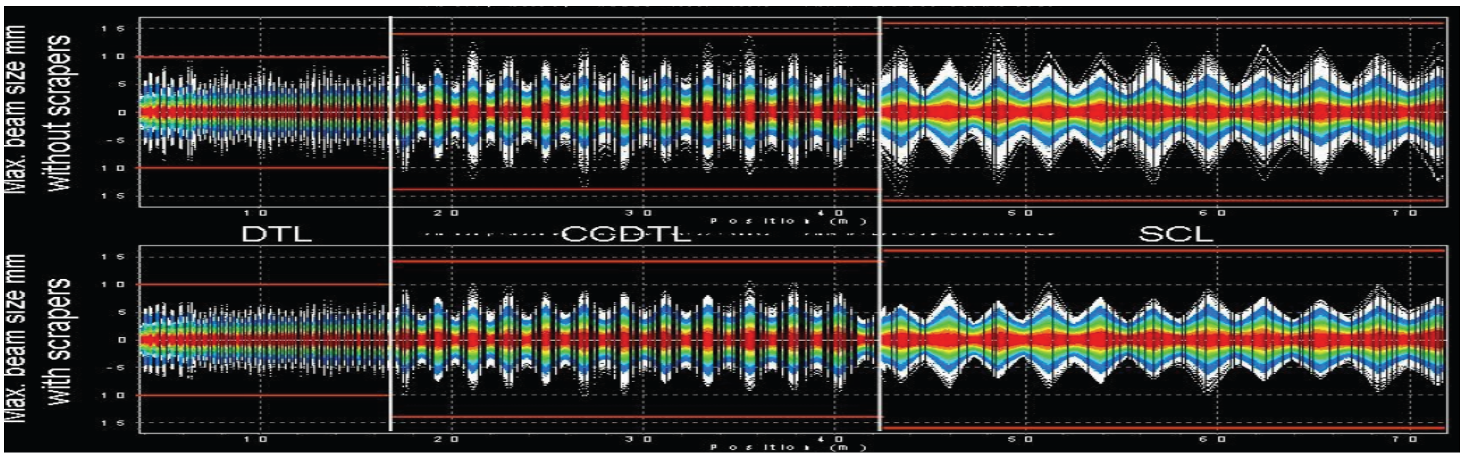
- focusing periods can be longer → structure with external quadrupoles, placed between short DTL-like tanks
- With respect to DTL: can use electro-magnets, easy access and cooling, easier machining and alignment, simpler and more economic construction
- Modules of 3 tanks connected by coupling cells, 2 drift tubes per tank



Beam dynamics, aperture and beam size

Large apertures (>5 times rms beam size) to minimise losses.
Scraping foreseen to reduce maximum beam size in presence of errors.





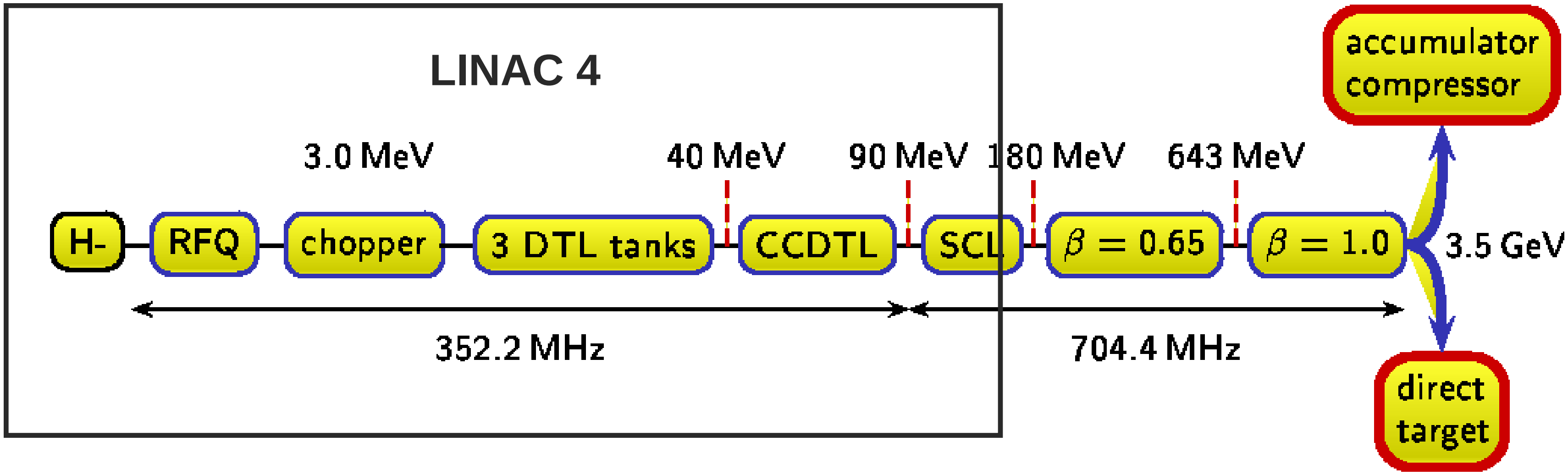
SPL

Conceptual Design Report (July 2006)

CERN-2006-006, http://cdsweb.cern.ch/record/975366

Baylac, M; (LPSC Grenoble) Gerigk, F (ed.); Benedico-Mora, E; Caspers, F; Chel, S (CEA Saclay) ; Deconto, J M (LPSC Grenoble) ; Duperrier, R (CEA Saclay) ; Froidefond, E (LPSC Grenoble) ; Garoby, R; Hanke, K; Hill, C; Hori, M (CERN and Tokyo Univ.) ; Inigo-Golfin, J; Kahle, K; Kroyer, T; Küchler, D; Lallement, J B; Lindroos, M; Lombardi, A M; López Hernández, A; Magistris, M; Meinschad, T K; Millich, Antonio; Noah-Messomo, E; Pagani, C (INFN Milan) ; Palladino, V (INFN Naples) ; Paoluzzi, M; Pasini, M; Pierini, P (INFN Milan) ; Rossi, C; Royer, J P; Sanmartí, M; Sargsyan, E; Scrivens, R; Silari, M; Steiner, T; Tückmantel, Joachim; Uriot, D (CEA Saclay) ; Vretenar, M;

SPL New Layout (CDR2, 2006)



New SPL Design (CDR2, CERN Yellow Report 2006-006):

SPL is made of Linac4 (extended to 180 MeV) + 2 superconducting sections based on 5-cell elliptical cavities at 704 MHz (INFN/CEA).

Long cryomodules (LHC/TESLA-like, 12-14m), 6-8 cavities/module, cold quads in cryomodules

Overall length 430 m (for 3.5 GeV, was 690 m in previous version for 2.2 GeV)

	Medium β	*High* β
Cavity β	**0.65**	**1**
R/Q (Ohm)	**235**	**575**
Aperture (mm)	**85**	**90**
E_p/E_{acc}	**2.6**	**2.4**
E_{acc} (MV/m)	**19**	**25**

SPL Beam parameters

Design		CDR1 (2000)	CDR2 (2006)	CDR2+	SPL for LHC
Energy	GeV	2.2	3.5	5	4 – 5
Beam power	MW	4	4	4	0.064
Rep. frequency	Hz	75	50	50	2
Protons / pulse	10^{14}	1.5	1.4	1.0	0.5
Av. pulse current	mA	11	40	40	40
Chopping ratio	%	62	62	62	62
Pulse length	ms	2.2	0.57	0.4	0.2
Bunch frequency	MHz	352.2	352.2	352.2	352.2
Length	m	690	430	535	~ 500

4 different designs:

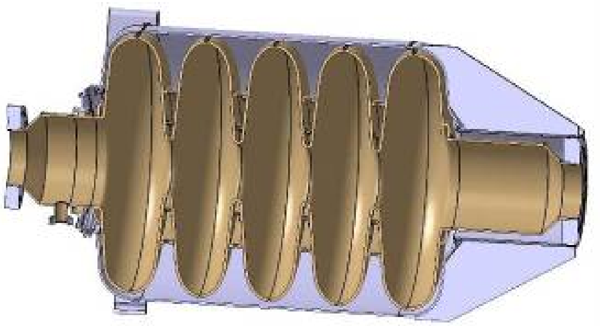
CDR1 (2000) based on LEP-type SC cavities (352 MHz)

CDR2 (2006) based on 700 MHz high-gradient cavities

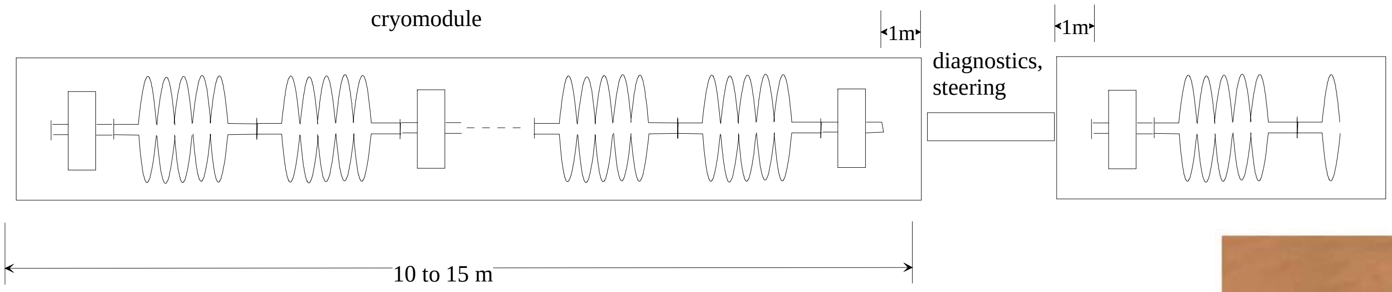
CDR2+ (2006) at higher energy, for the needs of neutrino machines

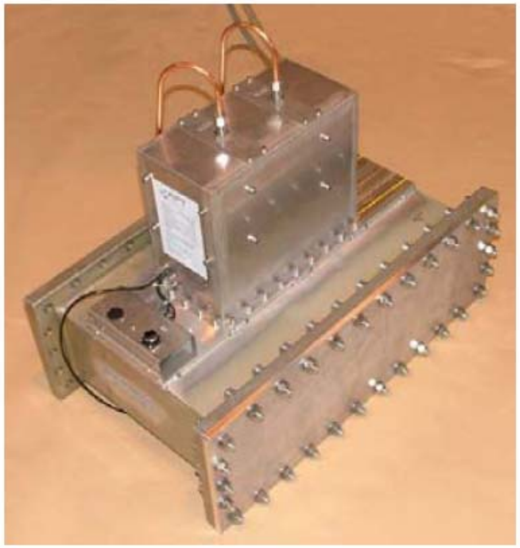
SPL for LHC (2007) at low beam power, for the needs of the LHC

SPL cavities: elliptical, 704 MHz



Elliptical cavities at β=0.5 (CEA, INFN) are giving promising results. Stiffened for pulse operation.
Length ~ 0.9m
Designed for 12 MV/m.



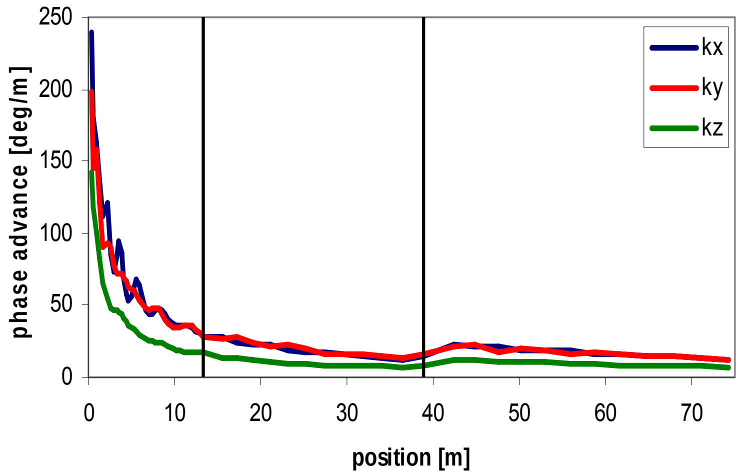


* Feed 4 to 6 cavities per klystron using high power phase and amplitude modulators developed at CERN

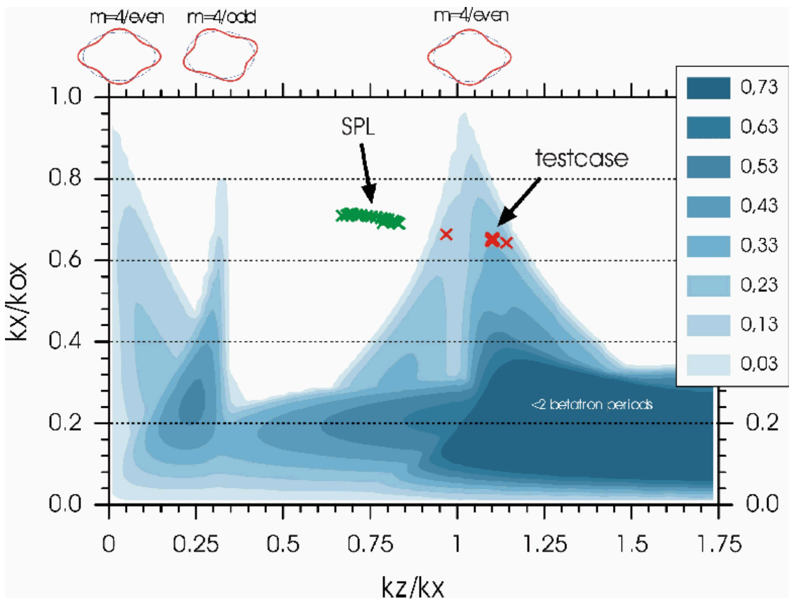
SPL Beam Dynamics

Control of losses, minimization of the emittance growth and halo development.

1) zero current phase advance always below 90 degrees, for stability;
2) longitudinal to transverse phase advance ratio (with current) between 0.5 and 0.8 in order to avoid resonances
3) smooth variation of the transverse and longitudinal phase advance per meter.



Smooth phase advance variation



Selection of the working point (phase advances) on the Hofmann's chart

Conclusions

The new linac designs (Linac4, SPL) open new perspectives for the future of the CERN accelerator complex.

While Linac4 is already at the starting phase, the decision on the continuation will depend on the LHC results and on the physics priorities on a global scale.