CERN Plans for High Intensity Proton Linacs

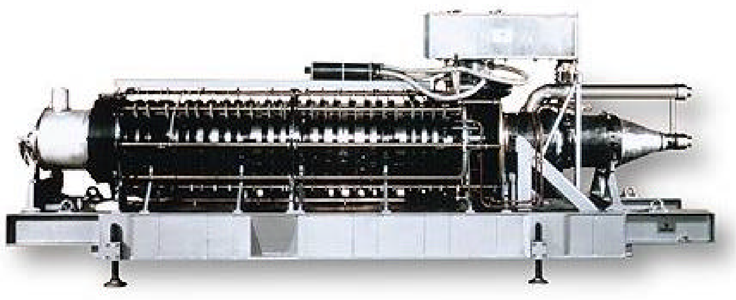
Maurizio Vretenar, CERN AB/RF

OUTLINE

- Motivations
- Baseline Scenario (SPL, Linac4)
- R&D Programme
- Roadmap

Motivations – The LEP RF

- The LEP Collider at CERN was decommissioned in 2000
- The 352 MHz RF equipment (SC cavities, cryostats, klystrons, waveguides, circulators, etc.) is now available for future projects (46 1-MW klystrons, 288 SC cavities, 6-km of waveguides, etc.)
- 352 MHz is an almost ideal frequency for a linear accelerator…



The LEP klystron

Storage of the LEP cavities in the ISR tunnel

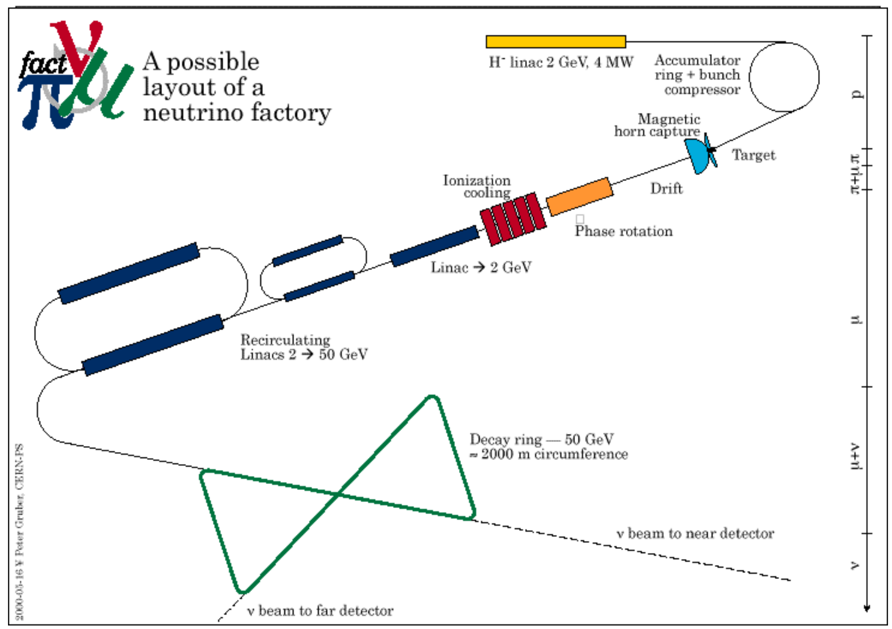
Motivations – Demands for higher intensity

- already with the present approved programme, CERN will lack protons from the year 2007: LHC, CNGS (Neutrinos), ISOLDE (Radioactive Ions).
- CERN users have already ambitious upgrade plans that are calling for even higher intensities (LHC upgrade, Neutrino Superbeam, EURISOL).
- an upgrade of the injectors is the only way to provide more proton intensity, preparing at the same time an interesting future for CERN after the LHC.
- a high-energy linac is the favorite candidate to achieve higher intensities *(no instabilities, long pulses, high repetition rates, simple to operate, ...)*

Example – The 3 neutrino roads

1. "conventional" way from pion decay: Accelerator, target and decay channel at CERN ? 400 kt detector in the Frejus tunnel (130 km)

2. from muon decay after muon acceleration ? Neutrino Factory (far detector)



The 3rd neutrino road

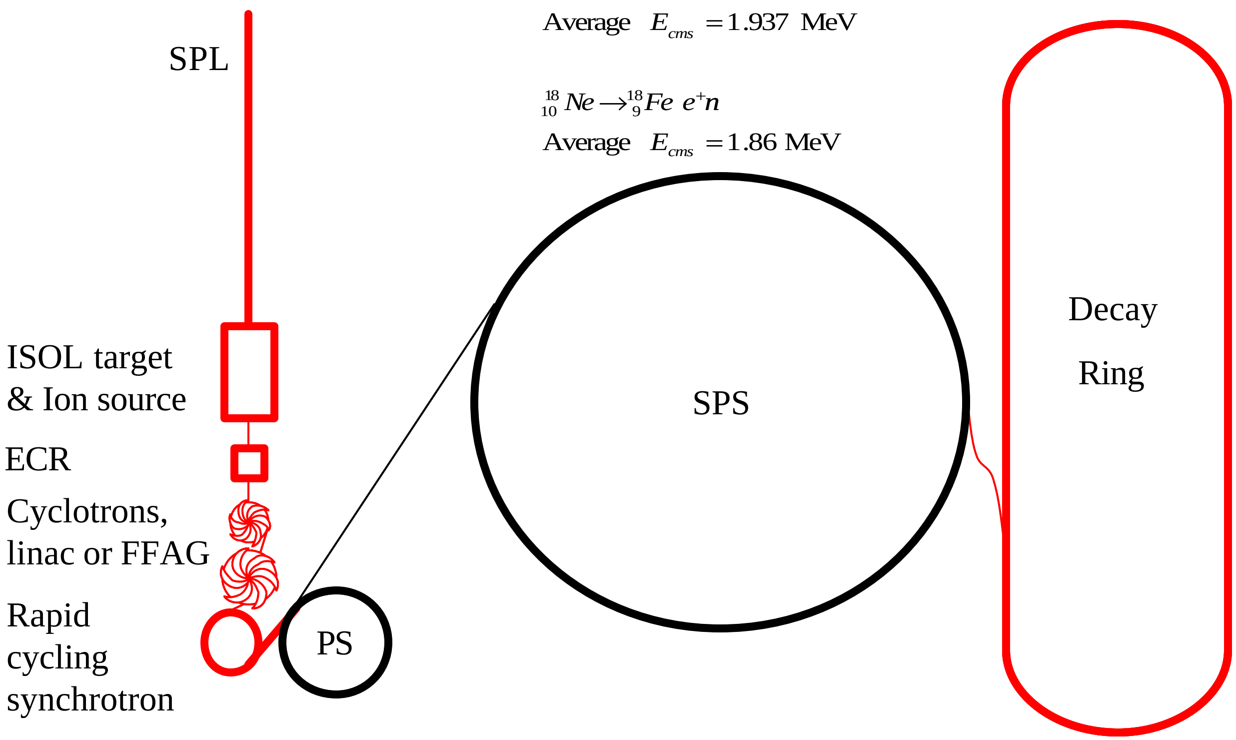
3. From beta-decay of radioactive ions (after production and acceleration) ?
to far detector (BETA-BEAMS)

$^{6}_{2}He \longrightarrow ^{6}_{3}Li\ e^{-}\bar{n}$

Average $E_{cms} = 1.937$ MeV

$^{18}_{10}Ne \longrightarrow ^{18}_{9}Fe\ e^{+}n$

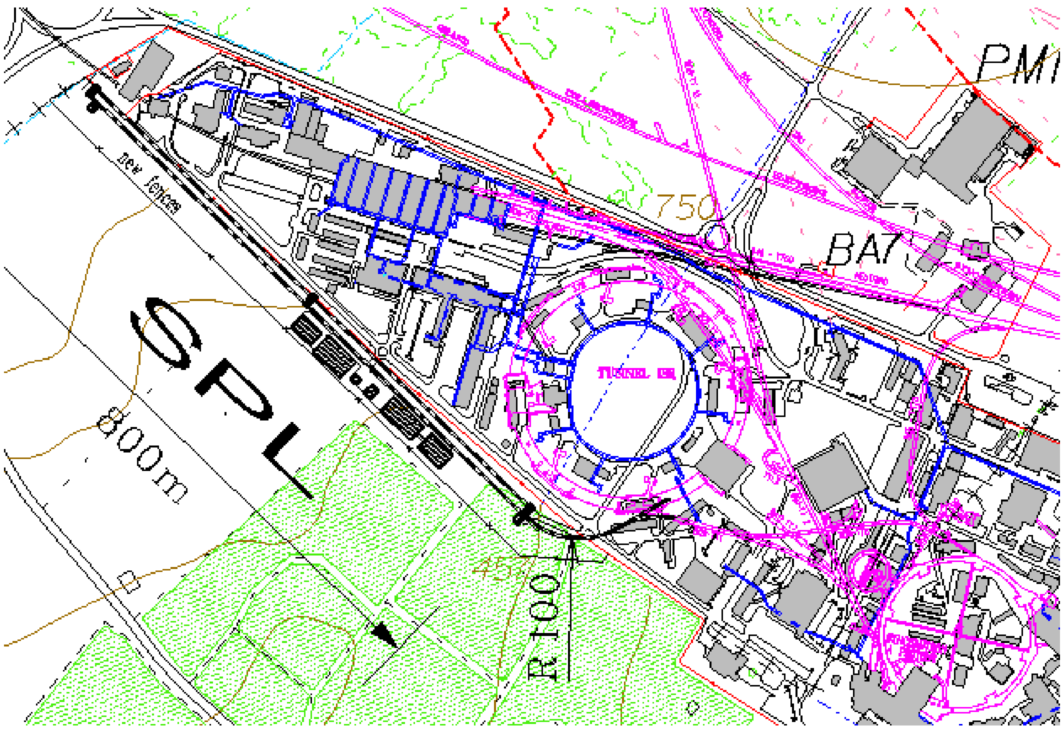
Average $E_{cms} = 1.86$ MeV



Baseline Design - The SPL

*** SPL = Superconducting Proton Linac**

A concept for improving the performance of the proton beams at CERN, ultimately based on a high-energy Superconducting Linear Accelerator



Baseline Design:

2.2 GeV, H-, 50 Hz,

4 MW on target

2 main users:

-high brightness beam to LHC through the PS

– high intensity beam to neutrino-RIB physics via accumulator/compressor rings in the ISR tunnel

The SPL Working Group

B. Autin, A. Blondel, **K. Bongardt**[1], O. Brunner, R. Cappi, **F. Caspers**, E. Cennini, E. Chiaveri, S. Claudet, **H. Frischholz**, R. Garoby, **F. Gerigk**[4], **K. Hanke**, H. Haseroth, C. Hill, N. Hilleret, I. Hoffman[2], J. Inigo-Golfin, M. Jimenez, A. Krusche, **D. Kuchler**, M. Lindroos, **A. Lombardi**, R. Nunes, **R. Losito**, **M. Paoluzzi**, J. Pedersen, **M. Poehler**, H. Ravn, **A. Rohlev**[3], R.D. Ryne[3], M. Sanmarti, H. Schönauer, **M. Silari**, **J. Tuckmantel**, H. Vinckle, A. Vital, **C. Vollinger**, **M. Vretenar**

[1] **KFZ Juelich, Germany**
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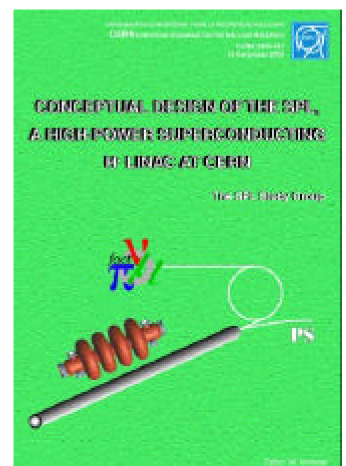
[3] **LANL - Los Alamos National Laboratory, USA**
[4] **RAL , Oxford, England**
others are from CERN, Switzerland

COLLABORATIONS

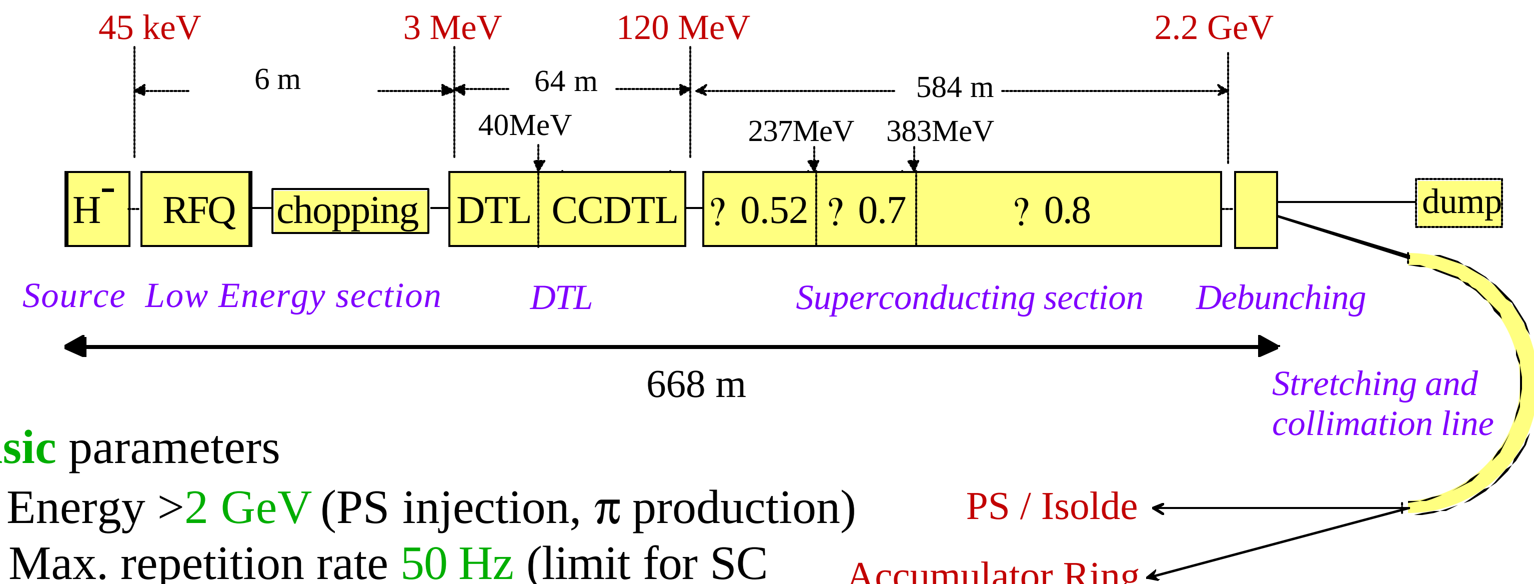
CEA (DSM/DAPNIA @ Saclay) + CNRS (IN2P3 @ Orsay & Grenoble): RFQ + DTL (IPHI)
INFN (Legnaro): RFQ

REFERENCES

- Conceptual Design of the SPL, a High Power Superconducting Proton Linac at CERN Ed. M. Vretenar, CERN 2000-012
- K. Bongardt et al., Progress in the Design of the SPL, EPAC 2002
- SPL web site: *http://ps-div.web.cern.ch/ps-div/SPL_SG/*



SPL Design - Basics



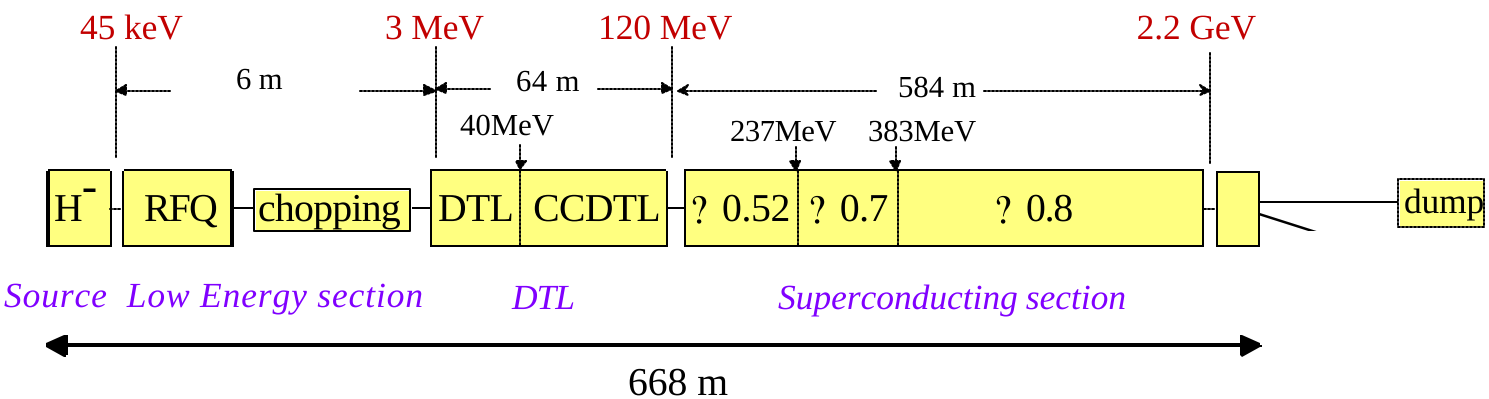
Basic parameters

- Energy >2 GeV (PS injection, π production)
- Max. repetition rate 50 Hz (limit for SC cavities)
- Beam power 4 MW (limit of target technology)

Design principles:

- 352 MHz frequency (LEP) for all the linac (standard RF, easy long. matching)
- start room-temperature, go to SC as soon as possible
- trade-off between current and pulse length (best compromise SC/RT)

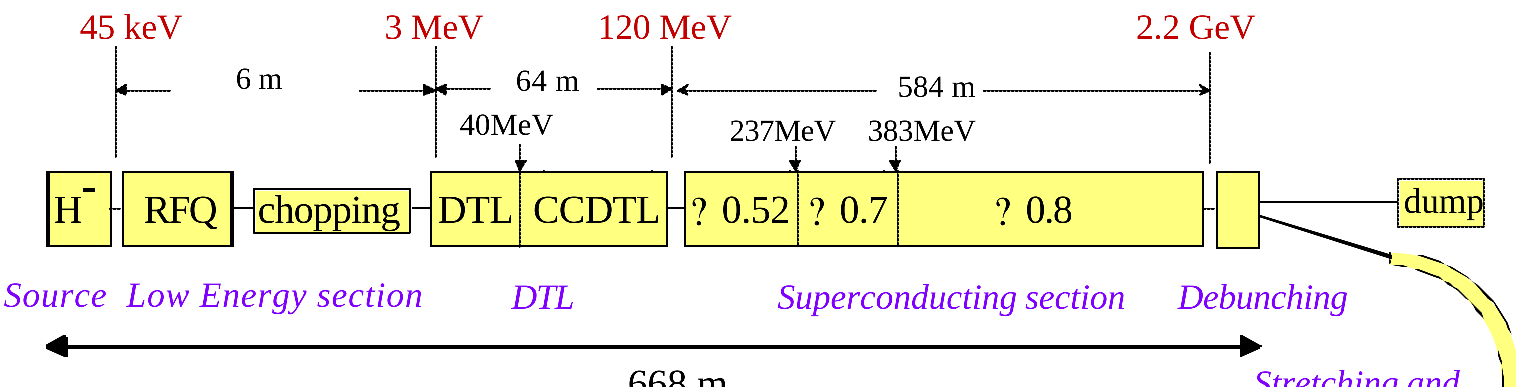
SPL Design - Parameters



Ion species	H-	
Kinetic energy	2.2	GeV
Mean current during the pulse	13	mA
Duty cycle	14.0	%
Mean beam power	4	MW
Pulse frequency	50	Hz
Pulse duration	2.80	ms
Duty cycle during the beam pulse	61.6	%
Maximum bunch current	22.7	mA
Bunch length (total)	0.5	ns
Energy spread (total)	0.5	MeV
Normalised rms horizontal emittance	0.4	p mm mrad
Normalised rms vertical emittance	0.4	p mm mrad
Longitudinal rms emittance (352 MHz)	0.3	p deg MeV

chopping

SPL Design - Layout



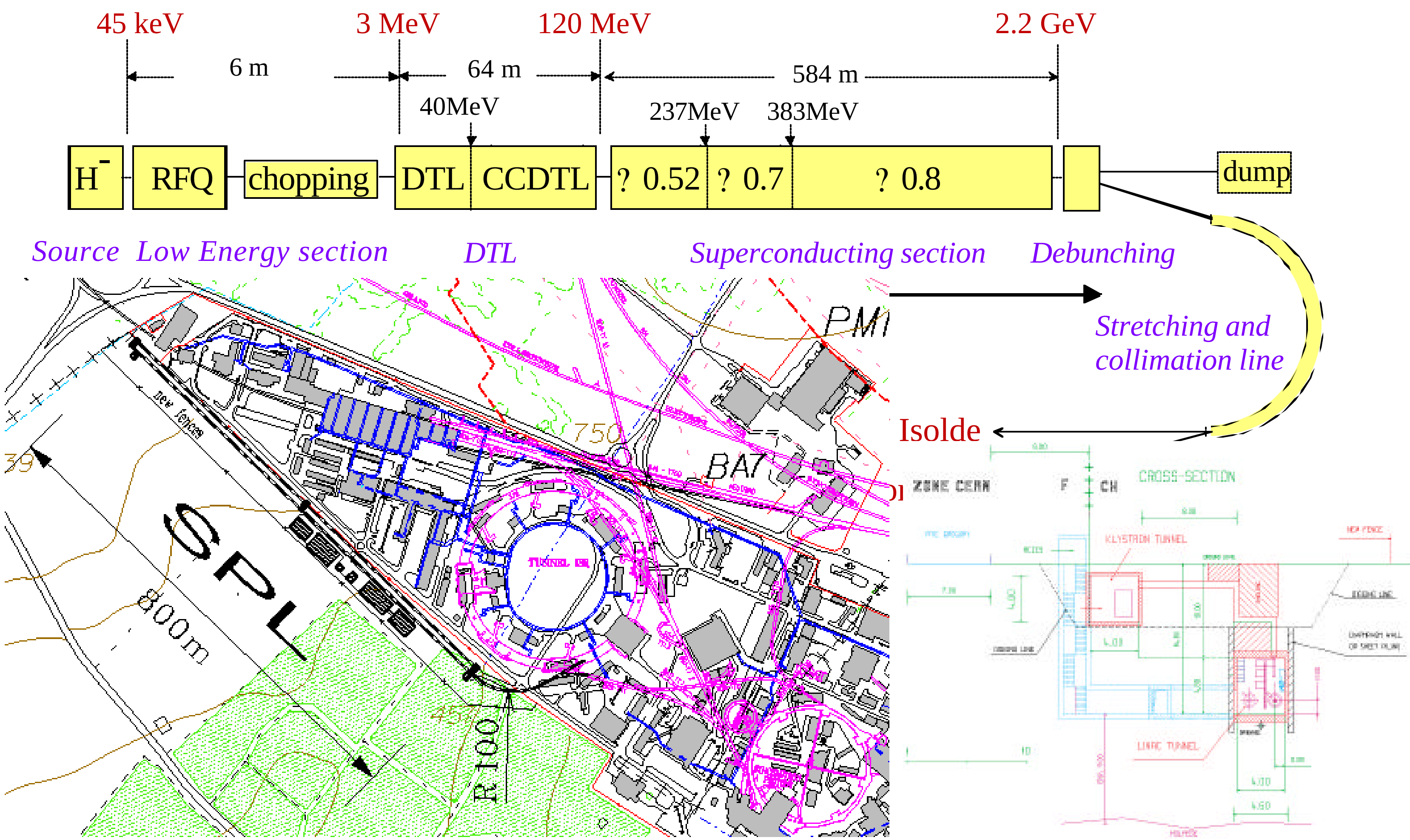
Section	Input energy (MeV)	Output energy (MeV)	No. of cavities	Peak RF power (MW)	No. of klystrons	No. of tetrodes	No. of Quads	Length (m)
Source, LEBT	-	0.095	-	-	-	-	-	2
RFQ	0.095	3	1	0.9	1	-	-	6
Chopper line	3	3	3	0.1	-	3	6	3.7
DTL	7	120	13	11.8	15	-	160	64
β=0.52	120	236	42	1.5	-	42	28	101
β=0.7	236	383	32	1.9	-	32	16	80
β=0.8 I	383	1111	52	9.5	13	-	26	166
β=0.8 II	1111	2235	76	14.6	19	-	19	237
Debunching	2235	2235	4	-	1	-	2	13
Total			223	40.3	49	77	257	672.7

55 cryostats, 33 from LEP, 22 using components (68 total available)

49 klystrons (44 used in LEP)

Note:
no more unmodified LEP cavities are used in the SPL design, for a 87 m shorter linac

SPL Design – Layout on site



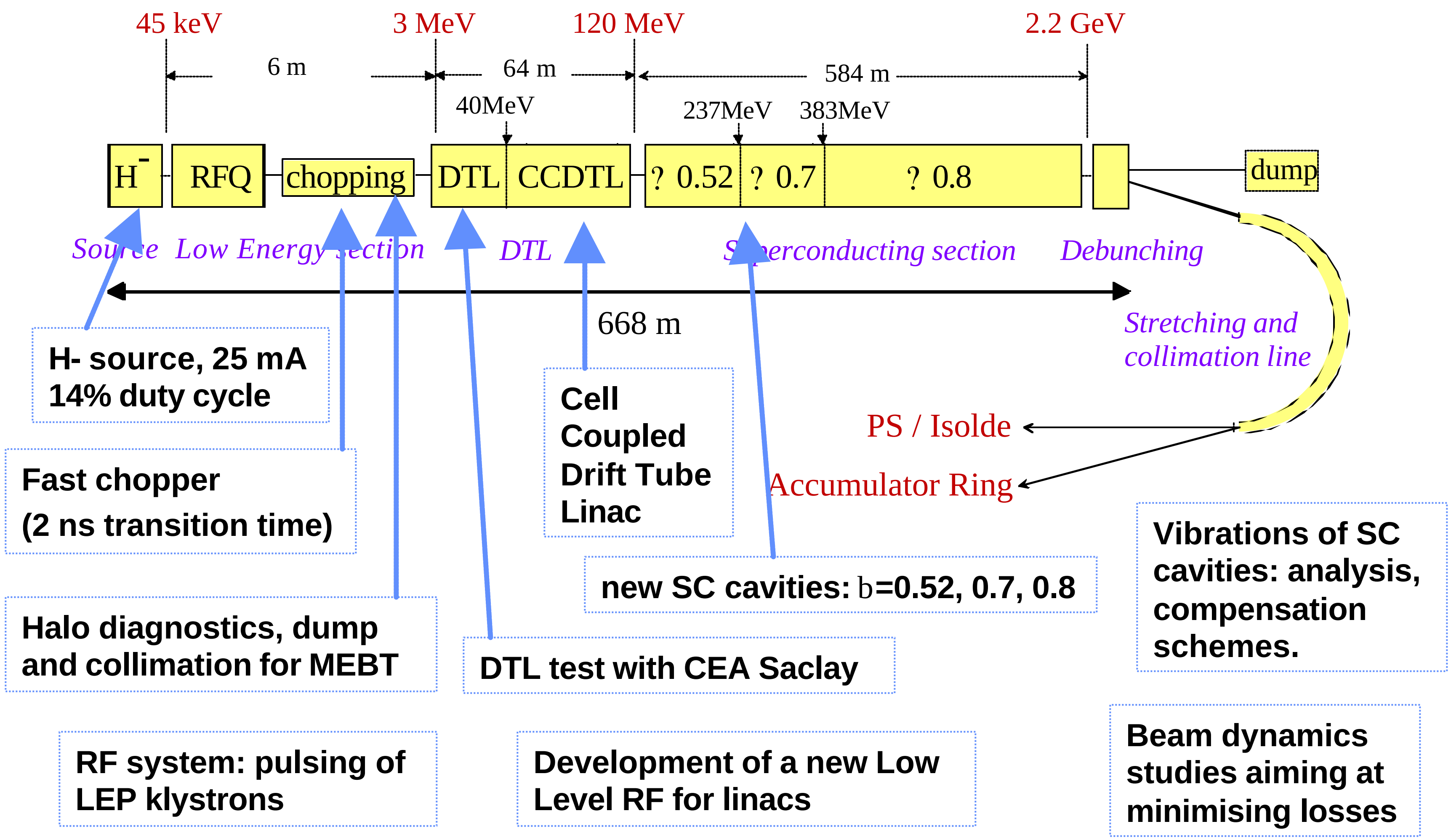
SPL R&D guidelines

The SPL R&D programme is funded inside the CERN R&D plan (2001-2008)

The goal is to concentrate effort on strategic items (with associated priorities):

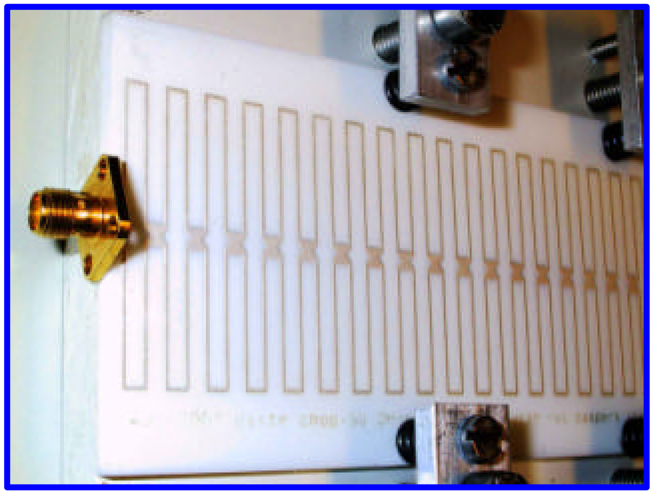
1. Requiring limited resources (inside SPL R&D budget)
2. Essential / critical to the project
3. Where CERN competence/experience is particularly valuable
4. With a maximum of collaboration/exchanges with other labs
5. Useful for any upgrade of the CERN injectors ? priority to the low-energy part.

SPL Design – R&D topics



R&D topics: the chopper structure and driver

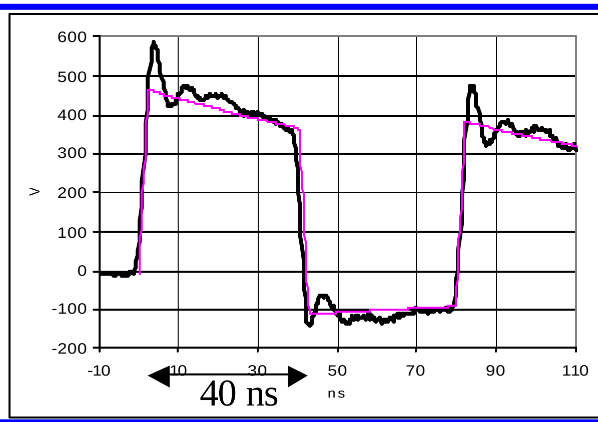
Chopper: Travelling-wave RF deflector (meander line) at 3 MeV

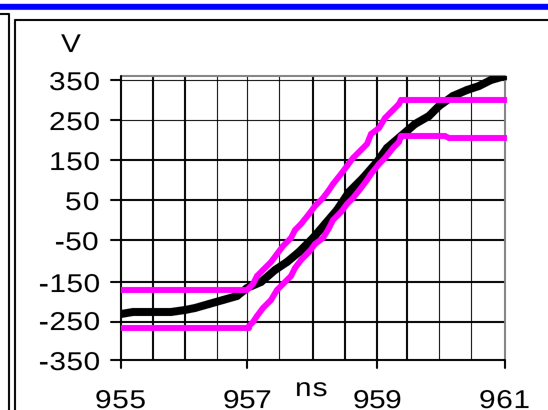


Only 1 fast chopper (2 ns rise/fall time)
Placed inside quadrupoles
Double 100Ω meander

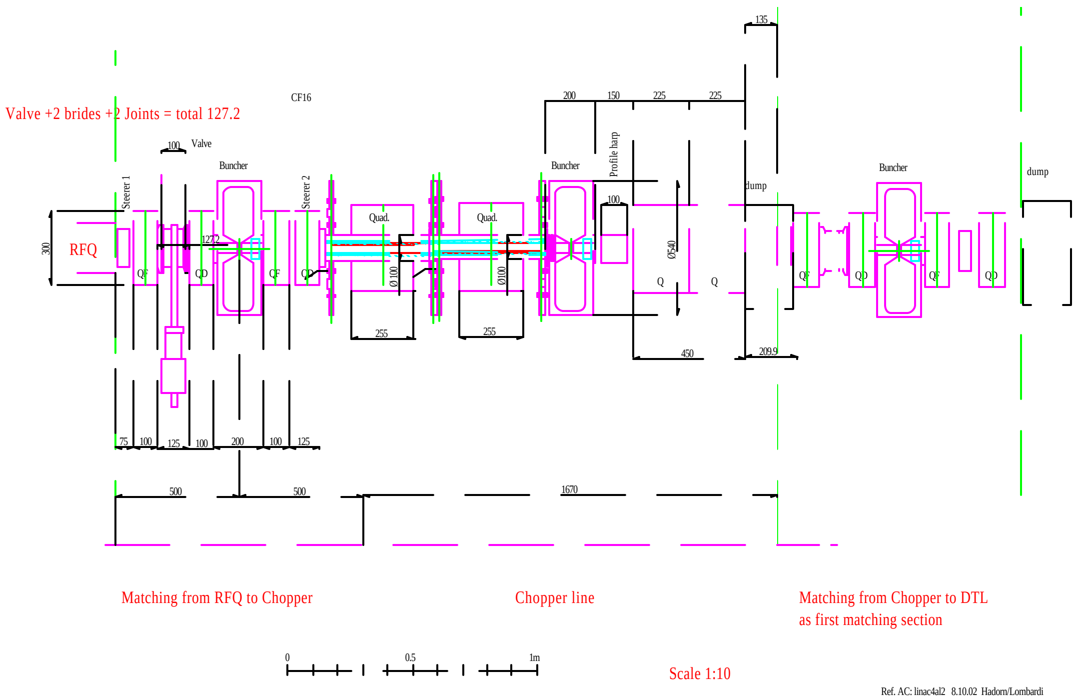
CERN Chopper structure *(F. Caspers)* **:**
Alumina substrate, reduced width
Prototypes tested (attenuation and dispersion)
Can stand beam losses

Driver amplifier
(HF prototype):
• 2.2 ns rise-fall time achieved (10%-90%)
• ± 500 V
(M. Paoluzzi)





The MEBT (chopper line)



MEBT (chopper line) at 3MeV
under construction at CERN

a. 2 chopper plates inside quadrupoles
b. 3 bunch rotating cavities
c. Valves, diagnostics, collimation, halo measurement device
- all in 3.6 m
- minimising emittance growth (~25%)

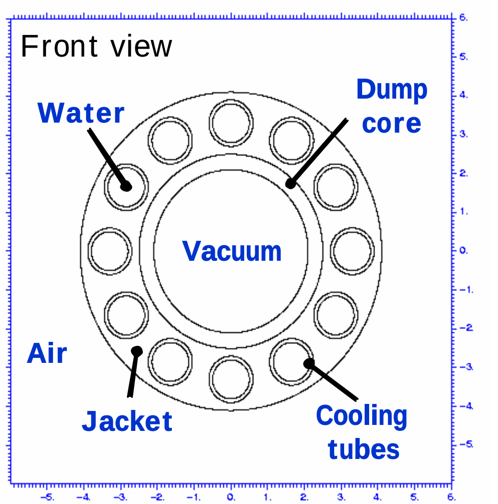
Status (5/2003):
quads recuperated from old CERN lines, bunchers at execution drawings, chopper 1 (prototype) in construction, dump and diagnostics being designed.

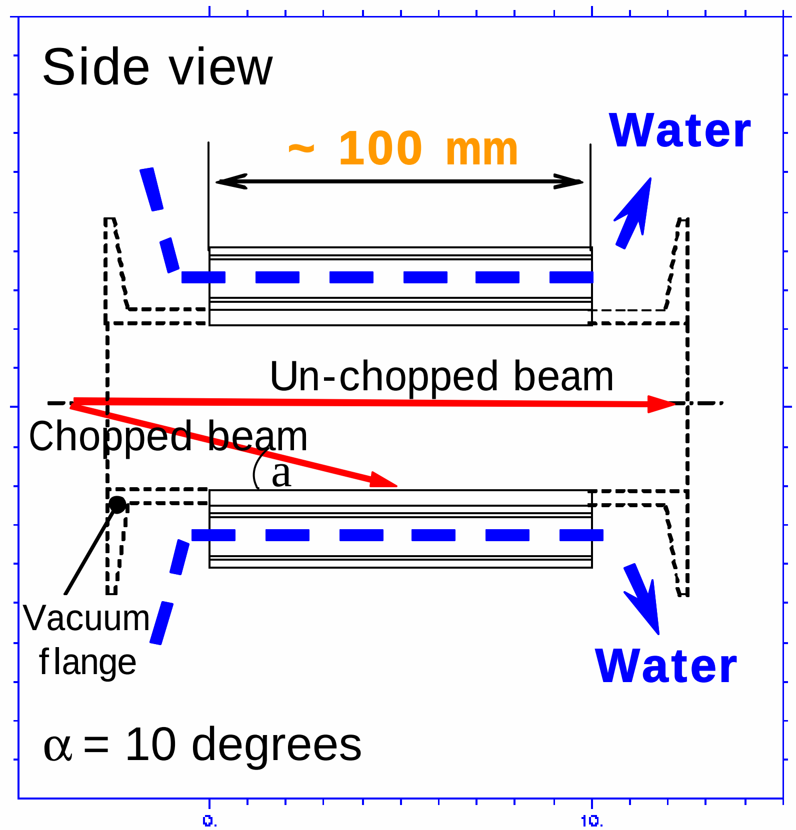
Chopper Dump

The chopper dump (target)

(L. Bruno)

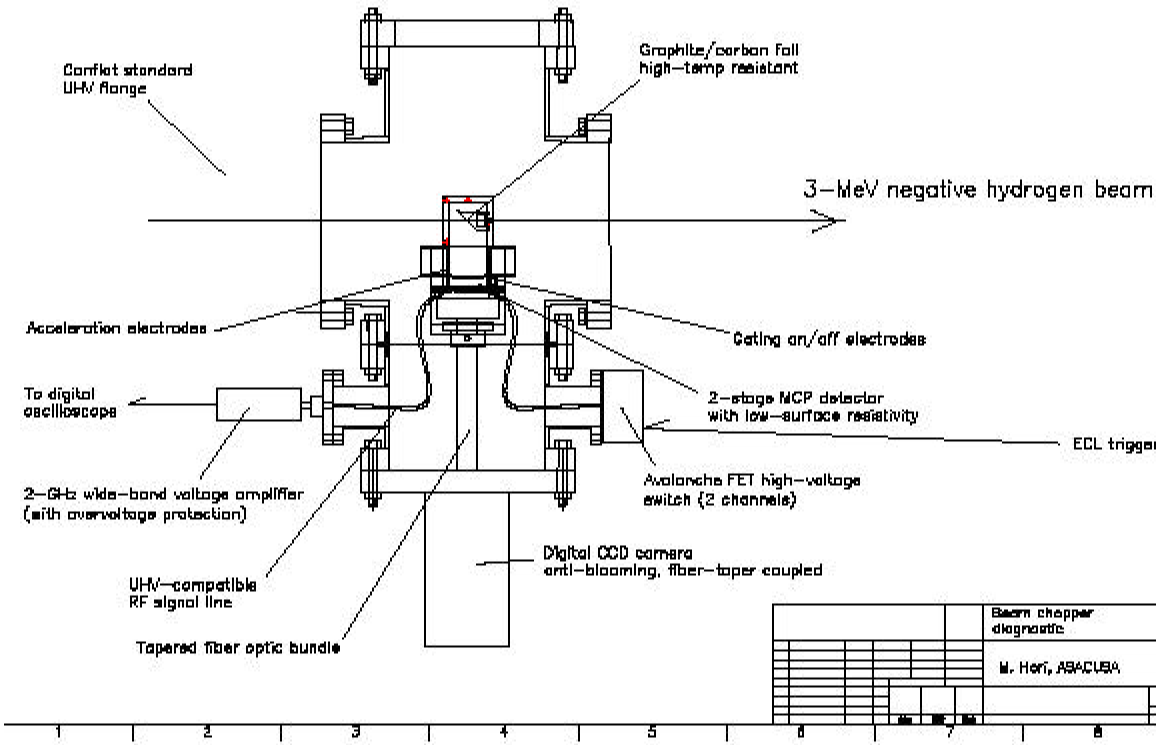
- designed for 14% duty (3.3 kW)
- copper core shrink-fit into a water-cooled Cu/Al_2O_3 jacket
- can be rotated (if needed)
- makes a good collimator
- not expensive





MV, 15/05/2003, ORNL

Beam Shape & Halo Monitor



BSHM:

(M. Hori, K. Hanke)

Gated time-resolved beam profile monitor

- empty buckets
- halo characterisation

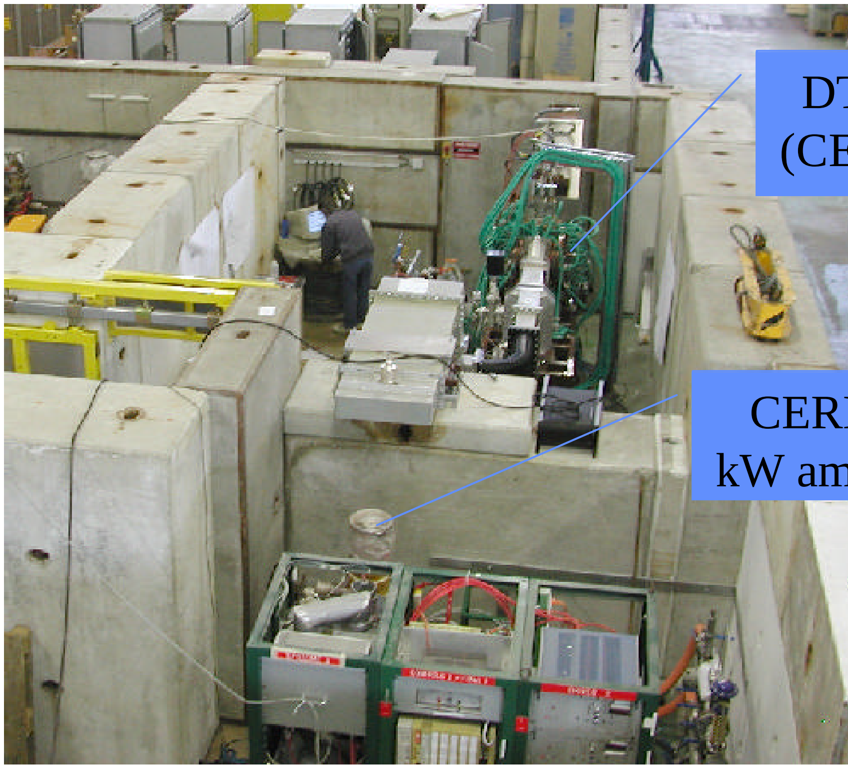
Secondary e- emission from a carbon foil

Phosphor screen with optical fibres

Gated photomultiplier for high sensitivity

Integration on a CCD camera for profile

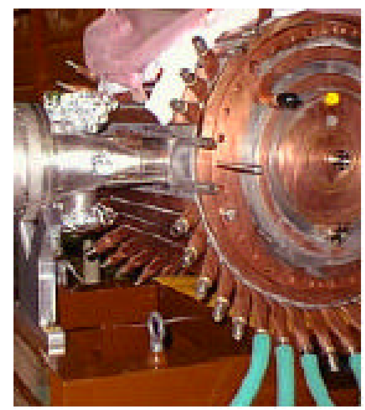
R&D : the DTL test stand



DTL model
(CEA-Saclay)

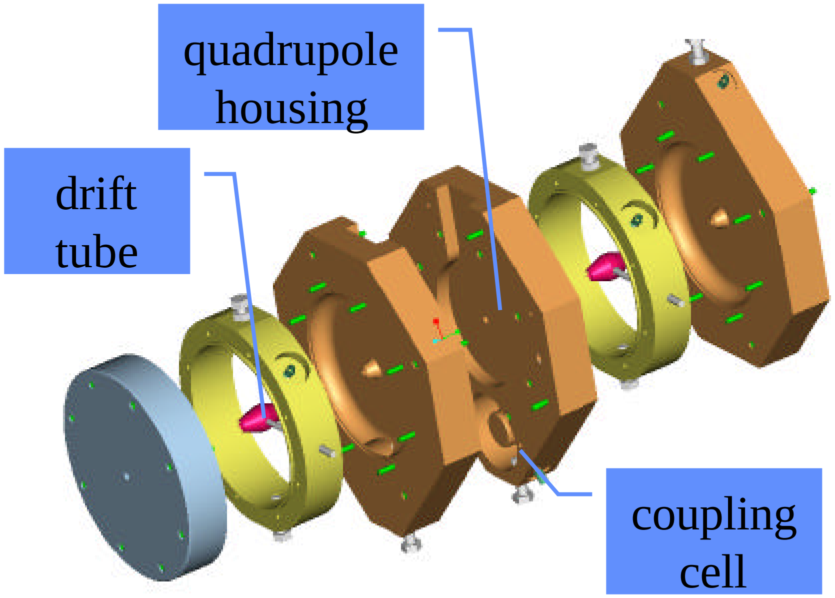
CERN 50
kW amplifier

Test stand in
for 352 MHz linac
structures
50 kW CW, 100 kW pulse



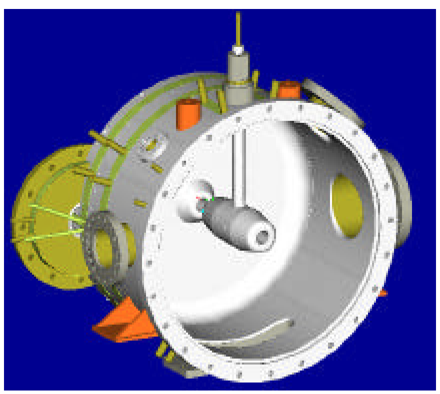
2002: tested the IPHI DTL model
(3 drift tubes, 5 MeV, CW, electromagnets)
mech. design close to CERN Linac2

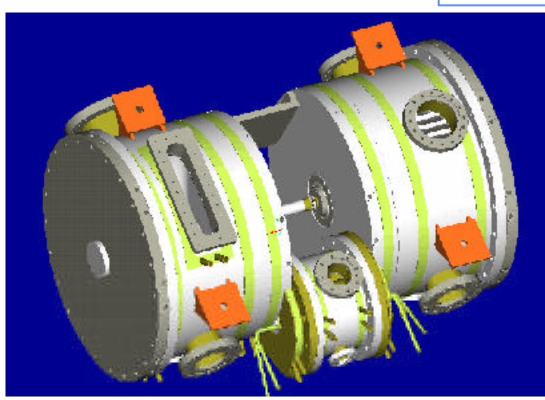
R&D topics – the CCDTL



From 40 MeV (up to 120 MeV) the Alvarez can be replaced by a *Cell-Coupled Drift Tube Linac:*

1. Quadrupoles outside drift tubes: simpler cooling, access/replacement, alignment
2. Less expensive structure than DTL
3. Same real estate shunt impedance
4. Continuous focusing lattice
5. Stabilised structure (π/2 mode)
6. One resonator/klystron





Full scale CCDTL prototype
(2 half cells + 1 coupling cell, cooled)
in construction at CERN,
RF power tests in April 2004.

R&D topics – low b SC cavities

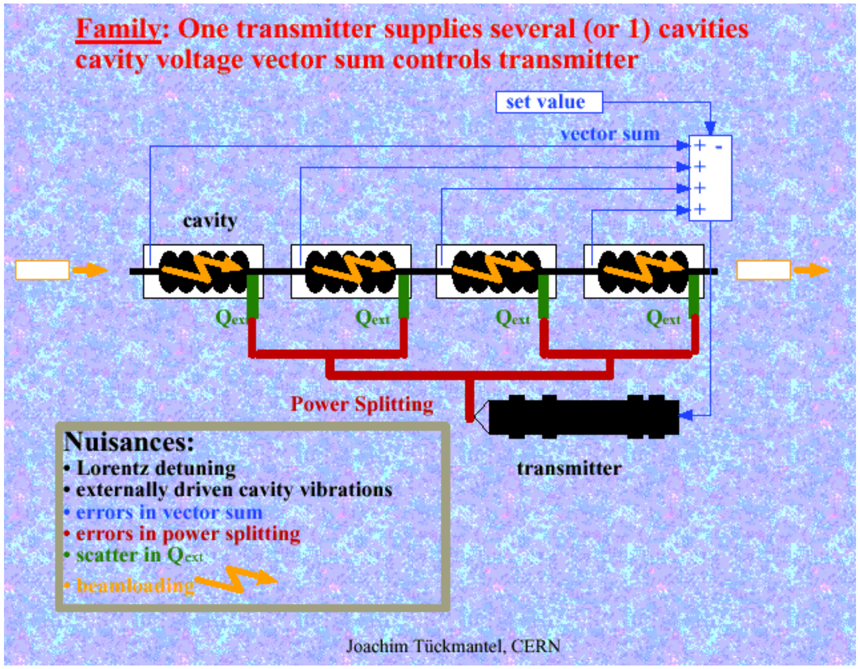
The β=0.7 4-cell prototype

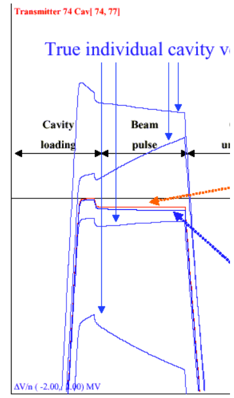
☆ CERN technique of Nb/Cu sputtering
⇨ excellent thermal and mechanical stability (important for pulsed systems)
⇨ lower material cost, large apertures, released tolerances, 4.5 °K operation with Q = 10^9

☆ Bulk Nb or mixed technique for β=0.52 (one 100 kW tetrode per cavity)

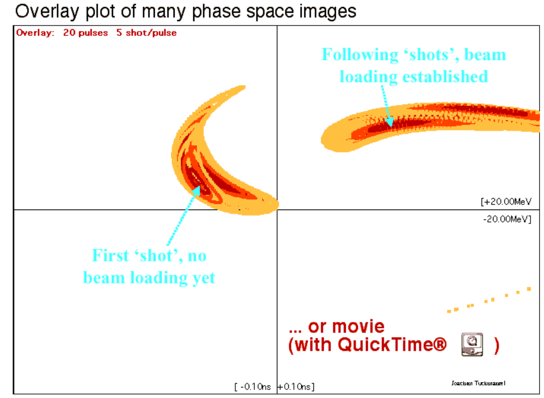
(E. Chiaveri, R. Losito)

R&D topics - vibrations





Overlay plot of many phase space images



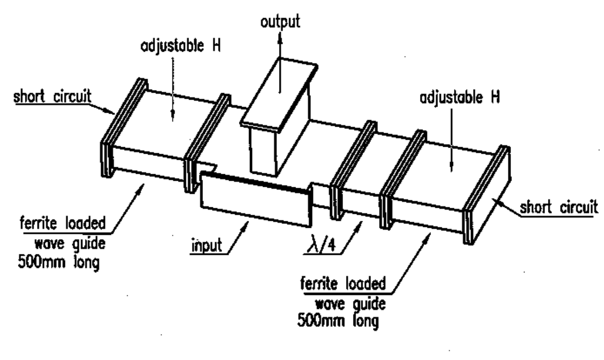
Effect on field regulation

Effect on the beam

+ possible chaotic effects *(J. Tückmantel)*

⇒ **vector sum feedback can compensate only for vibration amplitudes below 40 Hz**

⇒ **possible remedies: piezos and/or high power phase and amplitude modulators *(prototype ordered - H. Frischholz)***

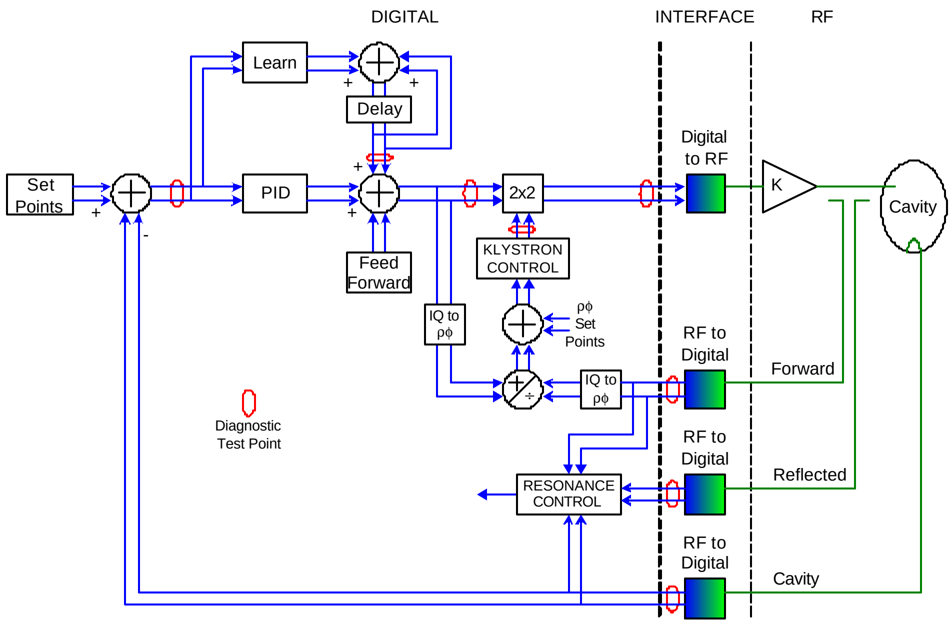


Phase /Amplitude Modulator Type B

R&D topics - Low Level RF

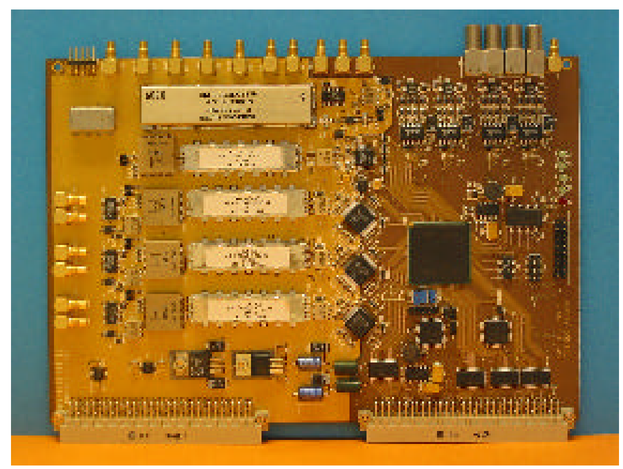
Need of a modern RF Low Level, to be tested on the CERN Linacs

Development of a prototype I/Q servo-system (T. Rohlev)



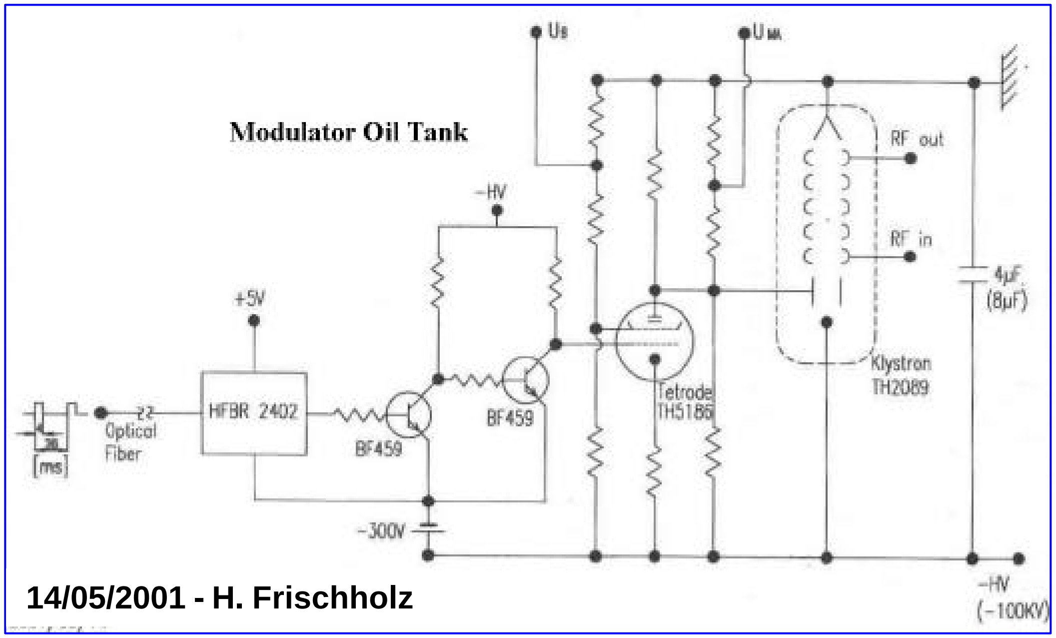
1. Built on a single VME card
2. All processing done in a single FPGA
3. Digital I/Q Modulator
4. 3 input / 1 output channels

The board is now finished and under test.

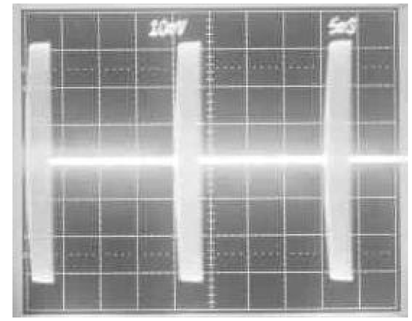


R&D topics – pulsing of LEP klystrons

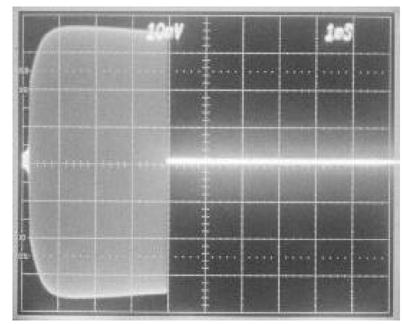
Mod anode driver



14/05/2001 - H. Frischholz



5 ms/div



1 ms/div

⇒ **LEP power supplies and klystrons are capable to operate in pulsed mode after minor modifications**

⇒ **up to 12 klystrons can be connected to one LEP power supply**

R&D topics – loss management

For *hands-on maintenance* loss < 1 W/m

For the *SPL*, 10 nA/m (10^{-6}/m) @ 100 MeV,
0.5 nA/m (10^{-7}/m) @ 2 GeV

Present Linac2 loss level (transfer line): ~ 25W/80m = 0.3 W/m
(but hot spots at > 1 W/m !)

Mechanism of beam loss in the SPL:

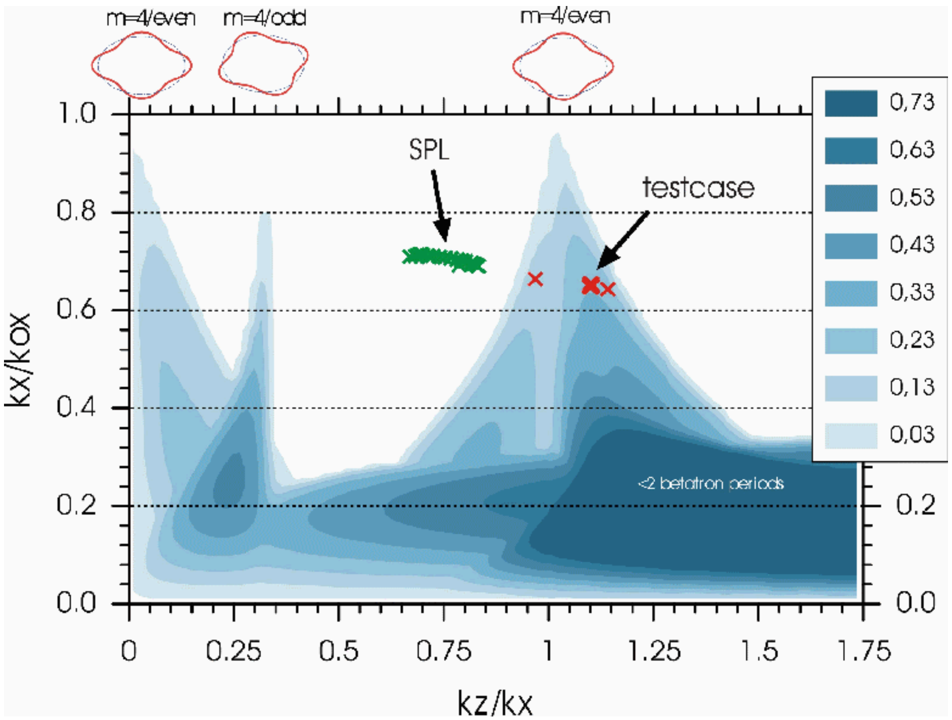
1. H- stripping Þ < 0.01 W/m in quads for an off-axis beam
2. Residual gas Þ < 0.03 W/m @ 10^{-8} mbar, 2 GeV (but 0.25 W/m @ 10^{-7})
3. Halo scraping Þ more delicate, requires:
   - ♥ large apertures (SC is good!)
   - ♥ careful beam dynamics design

R&D topics – beam dynamics

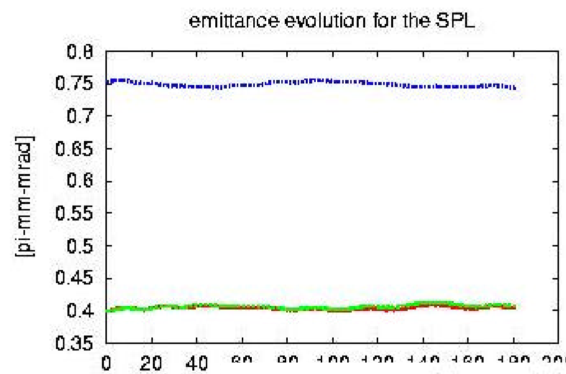
Þ Control *rms emittance growth* and *loss from the outer halo* by avoiding parametric resonances

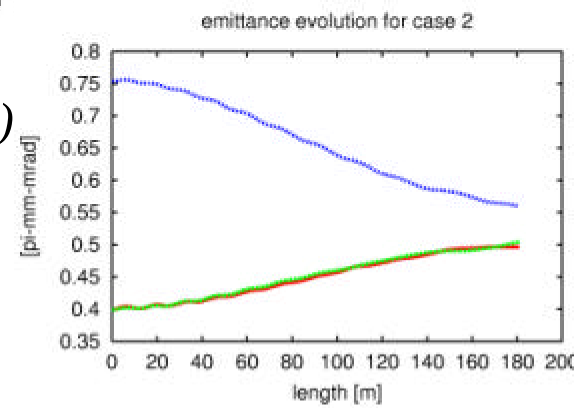
Þ Selection of the working point (phase advances) on the Hofmann's chart

\+ Careful matching (50Mpart simulations with IMPACT at NERSC, Berkeley)



(F. Gerigk)





R&D topics – after the linac…

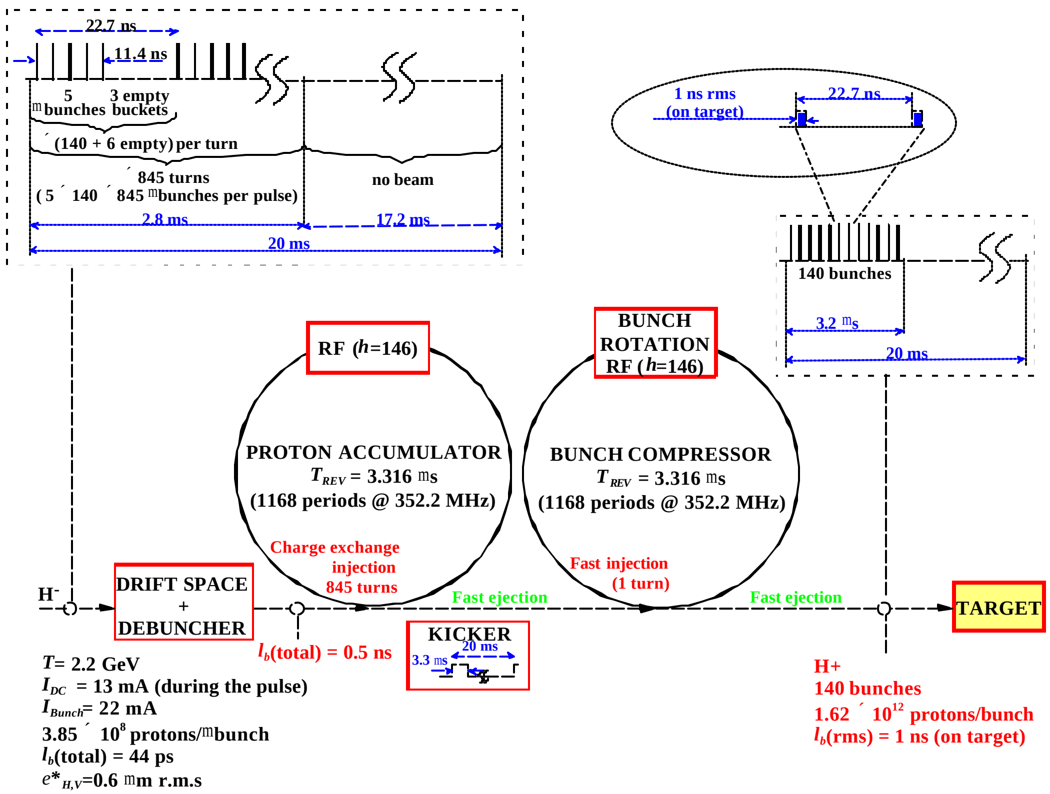
Transfer lines, collimation (= *scrape away halo particles before the accumulator*), etc.

Accumulator/Collector scheme *(PDAC study group)* for NuFact

Two Rings in the ISR Tunnel

Accumulator:
3.3 ms burst of 144 bunches at 44 MHz

Compressor:
Bunch length reduced to 3 ns



Roadmap

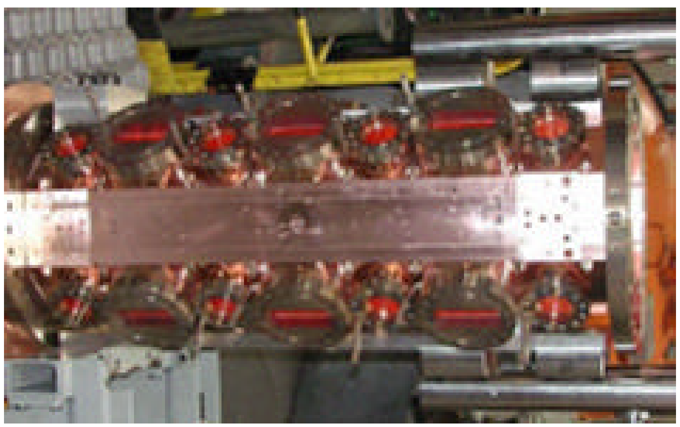
Build the front-end in collaboration with IPHI	2006	funded
Build the room-temperature part to inject at 150 MeV into the Booster (RF from LEP, hall and infrastructure available).	2008	
	2010	
	2012	
Build the complete SPL		
	2014	

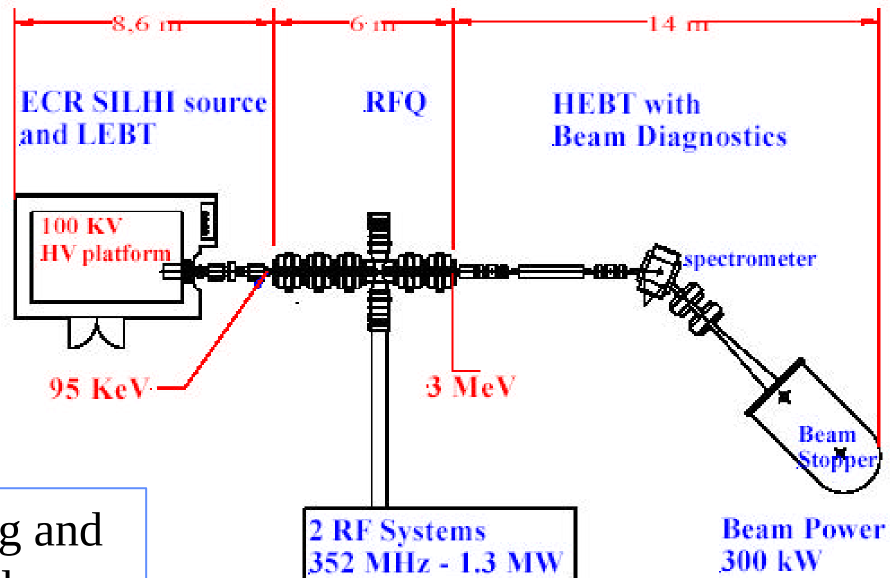
Stage 1: putting together the 3 MeV front-end

A 352 MHz CW RFQ at 3 MeV, 100 mA is in construction at CEA-Saclay
Formal agreement CERN/CEA-IN2P3:

1. 2005: test of the RFQ at Saclay (p, CW, 100 mA)
2. from 2006: installation of the RFQ at CERN (max. 14%, 40 mA, p&H-)

IPHI=Injecteur de Protons Haute Intensité (CEA+IN2P3)

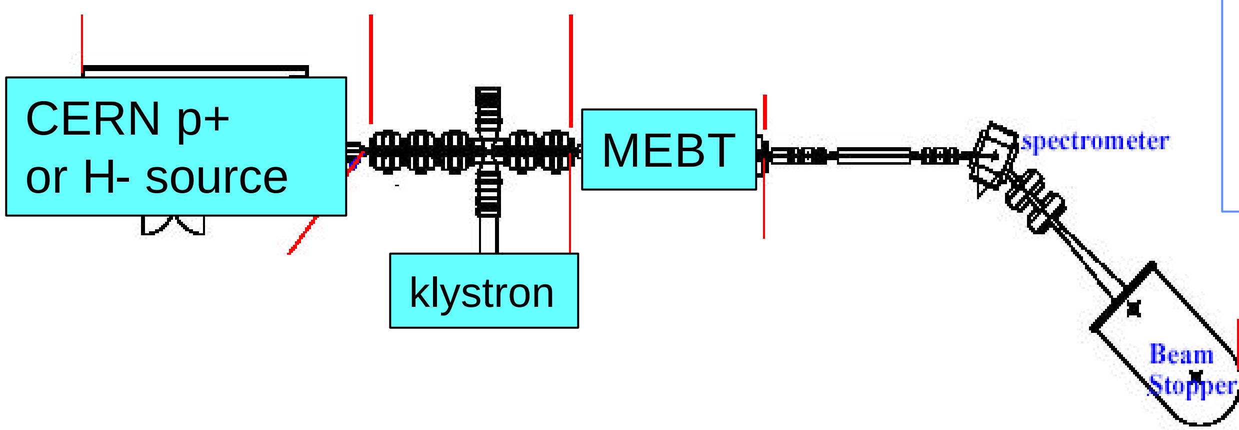




The 1st RFQ module (1m) after brazing and the layout of the Saclay test stand.

The 3 MeV line at CERN

At CERN, the IPHI RFQ will be used at lower current (? only 1 klystron) and tested with the CERN-made chopper line (MEBT) from 2006.
Tests will start with protons, and then with H- from the ECR source under development (or from another source)



First test with proton,
then with H- source
+ IPHI RFQ
+ CERN chopper line
+ Diagnostics line

Stage 2 – The Linac4

Build in a preliminary stage the room temperature section (120/150 MeV) of the SPL as new injector for the CERN Booster.
? Increase of Booster intensity (p/pulse) by a factor ~2 as compared to present proton injection at 50 MeV + increased brightness.

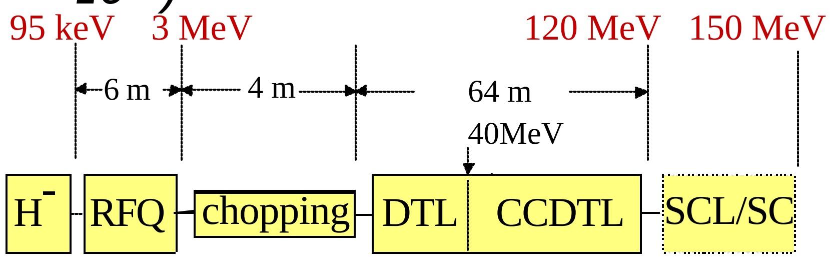
4th linac built at CERN ? Linac4

- *Relaxed parameters*
- *Space and infrastructure available in the PS South Hall*
- *RF from LEP (klystrons, waveguides, etc. - already stored).*

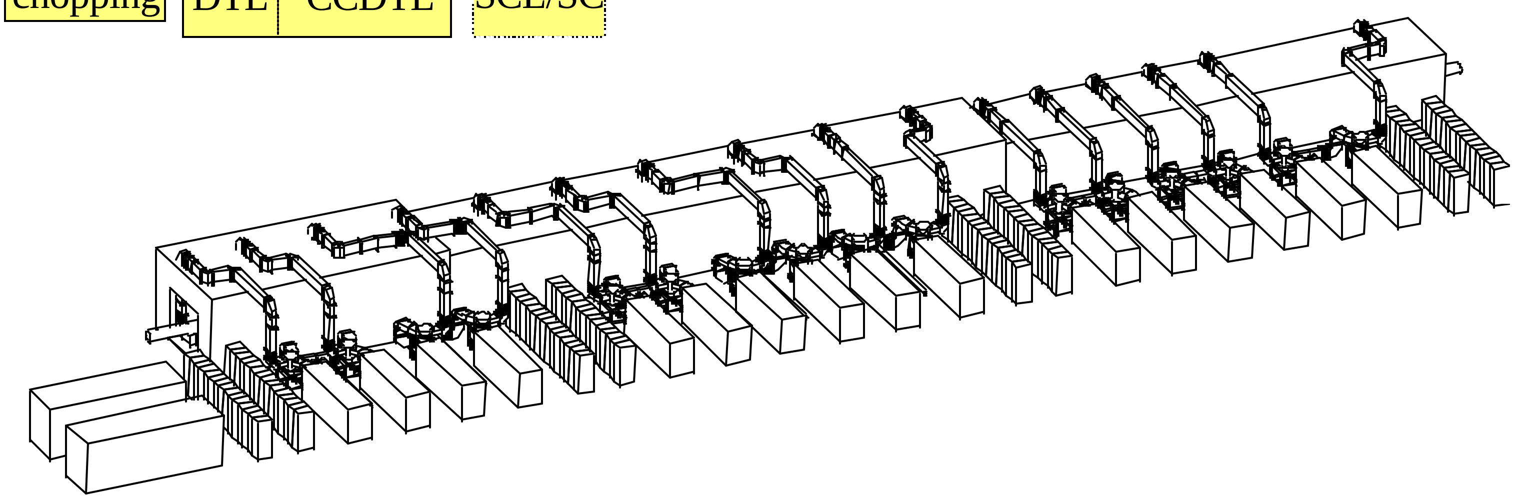
PARAMETERS	**Phase 1 (PSB)**	Phase 2 (SPL)	
Maximum repetition rate	**2**	50	Hz
Source current *	**50**	30	mA
RFQ current *	**40**	21	mA
Chopper beam-on factor	**75**	62	%
Current after chopper *	**30**	13	mA
Pulse length (max.)	**0.5**	2.8	ms
Average current	**15**	1820	µA
Max. beam duty cycle	**0.1**	14	%
Max. number of particles per pulse	**0.9**	2.3	$\cdot 10^{14}$
Transverse norm. emittance (rms)	**0.25**	0.25	π mm mrad
Longitudinal emittance (rms)	**0.3**	0.3	π deg MeV
Maximum design current	**30**		µA

Linac4

Take only the room temperature part of the SPL (120 MeV)
and install it in the PS South Hall, to inject H- into the PS Booster
⇨ *> twice the number of protons/pulse in the PSB (5 10^{13})*

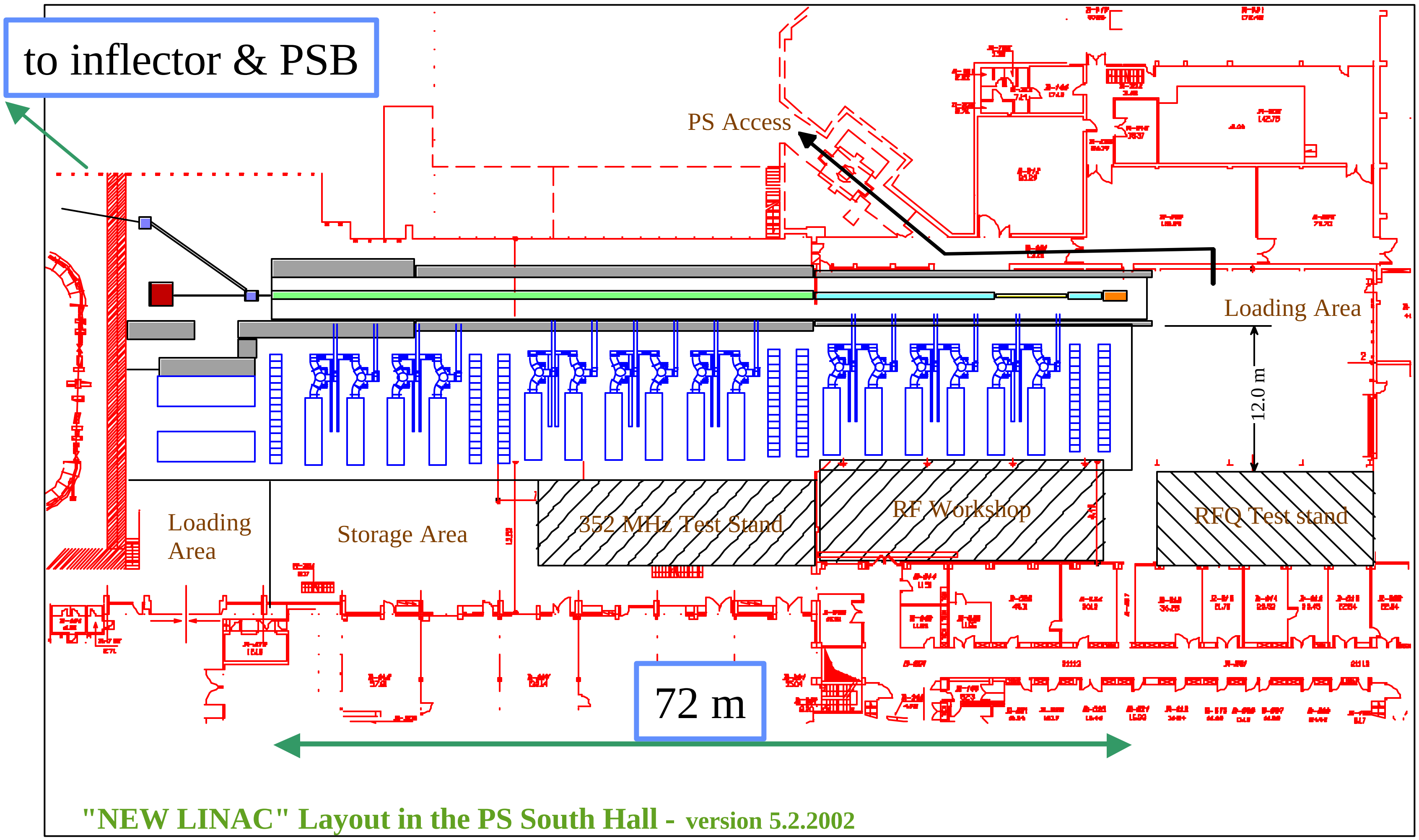


120 MeV, 80m, 16 LEP klystrons



MV, 15/05/2003, ORNL

Linac4 in the PS Hall



European Integration

- Some funding for accelerator research can come from the European Union, but the condition is to integrate programmes between EU laboratories.
- Established (2003) the HIPPI Joint Research Activity (HIPPI=High Intensity Pulsed Proton Injectors)
- Bid to EU in the 6th FW Programme, inside CARE (Coordinated Accelerator Research in Europe)
- HIPPI = 8 laboratories (CEA, CERN, FZJ, GSI, IAP-FU, INFN-Mi, IN2P3, RAL) joining efforts in the R&D for pulsed linacs 3-200 MeV (RT and SC), for the design of new injectors for 3 laboratories: CERN, GSI, RAL.
- An answer to the bid is expected for June-September 03.

CONCLUSIONS

More than a project, the SPL (Superconducting Proton Linac) is a roadmap for an evolution of the CERN complex towards higher proton intensity and brightness, as a viable alternative for the future after the LHC and for an LHC upgrade.

☞ But of course first of all we have to work hard to finish the LHC !

And without forgetting that the SPL (and CLIC) are the seeds of the CERN future !