ESS sc linac design overview

20th ICFA Advanced Beam Dynamics Workshop

High Intensity High Brightness Hadron Beams

Fermilab

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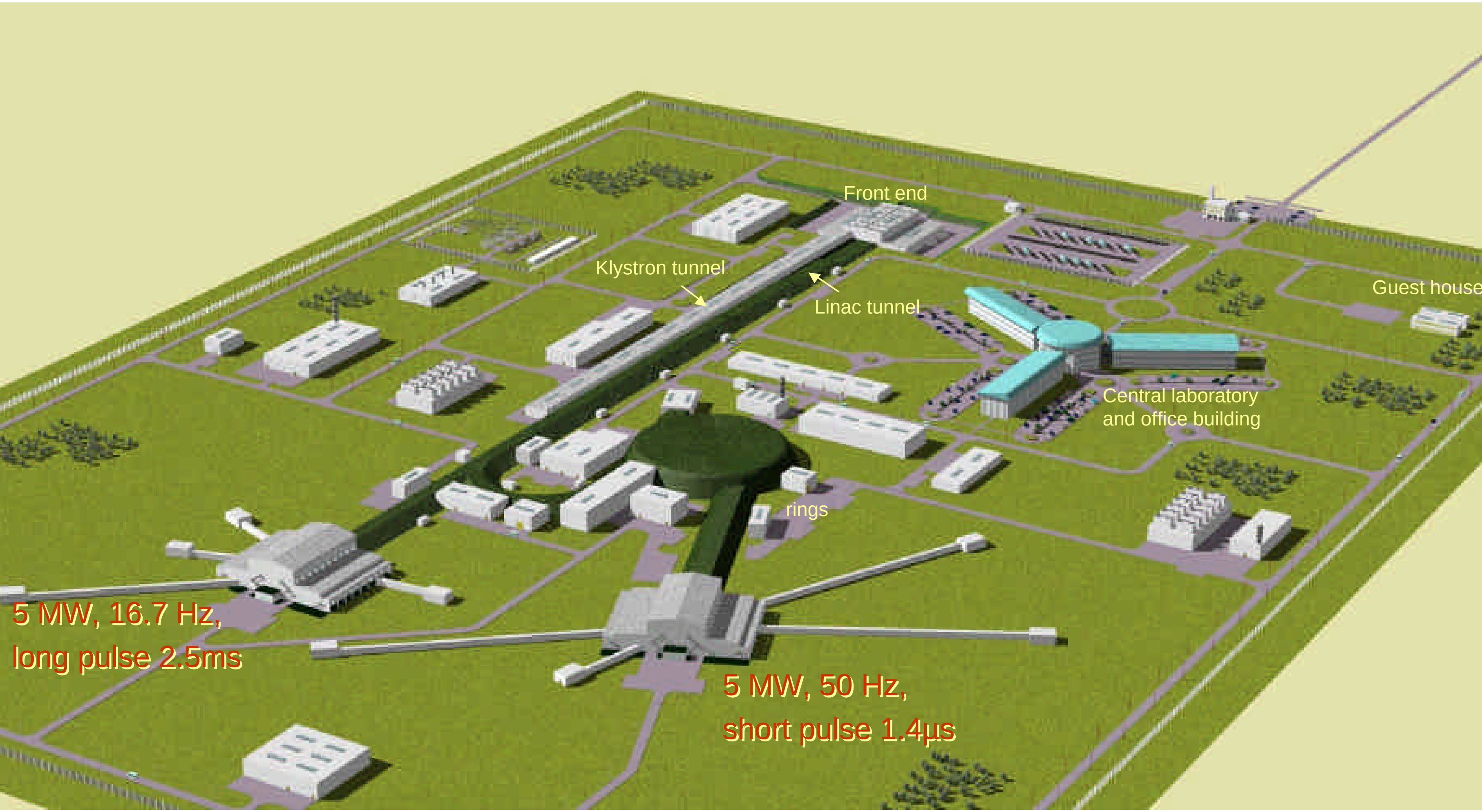
ESS requirements

- 10 MW beam power: 5 MW at 50 Hz plus 5 MW at 50/3 Hz, Short pulse and Long pulse
- Consider the most efficient and reliable option
- Maintenance and repair require that high-energy beam losses be kept below 1 nA/m

	SP	***LP***	
PRF (pulses per second)	50	50/3	
Beam pulse width, 1 ring (ms)	2×0.50	2.5	
Beam duty factor	5.0%	4.2%	
Non-chopped beam current (mA)	114	114	
Chopping factor	2/3	2/3	100%
Final energy (MeV)	1334	1334	
Peak beam power (MW)	101	101	152
Mean beam power (MW)	5.07	4.22	6.34
Pulse gaps, ring separation (ms)	0.10		

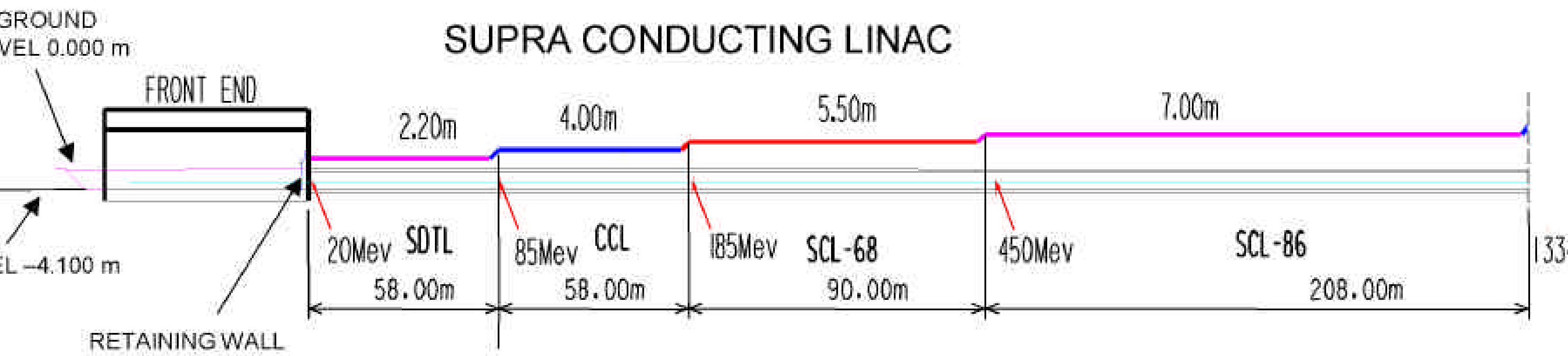
ESS layout

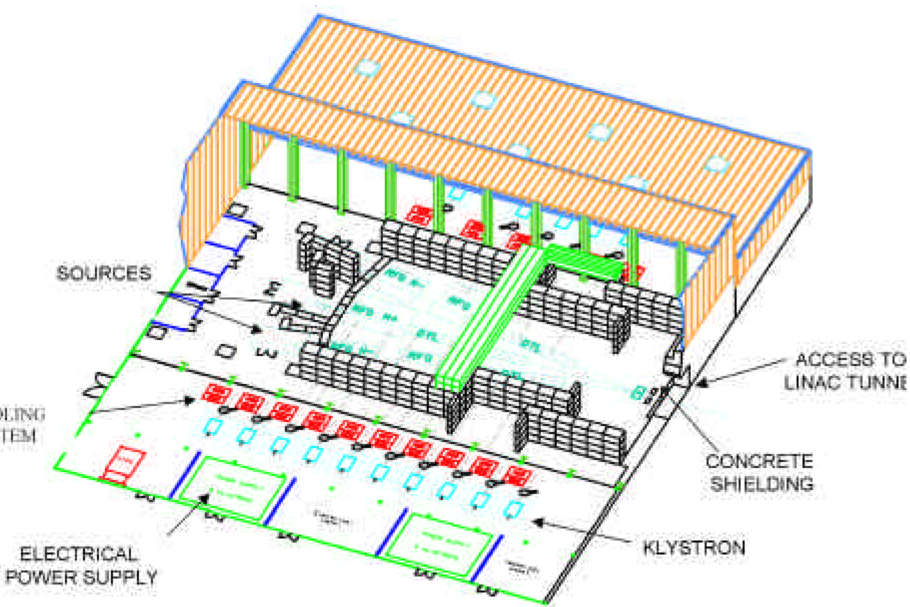


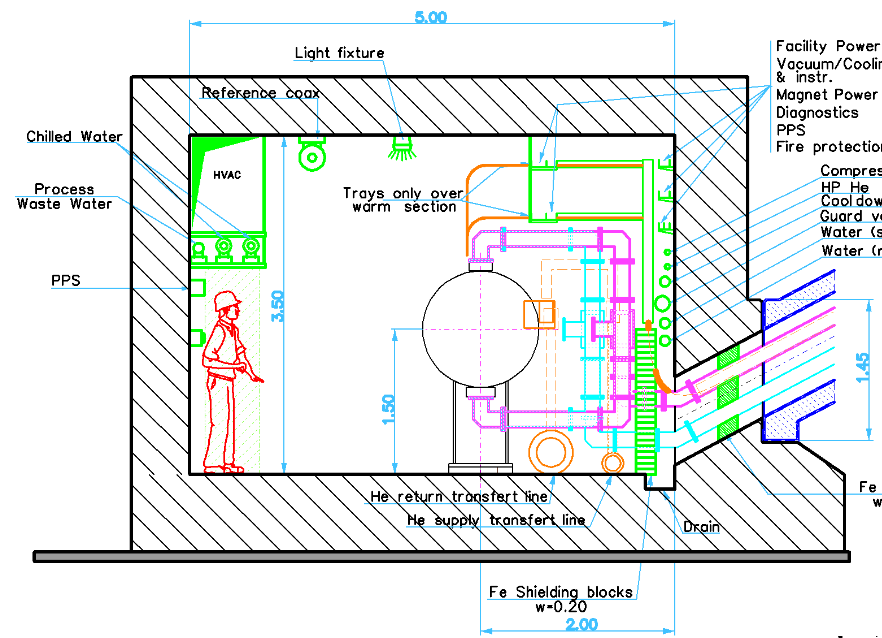
Front end
Klystron tunnel
Linac tunnel
Guest house
Central laboratory
and office building
rings
5 MW, 16.7 Hz,
long pulse 2.5ms
5 MW, 50 Hz,
short pulse 1.4µs

Cross section and earth thickness

DOSE RATE : less than 0.5 µSv/h on the top of the earth covering material





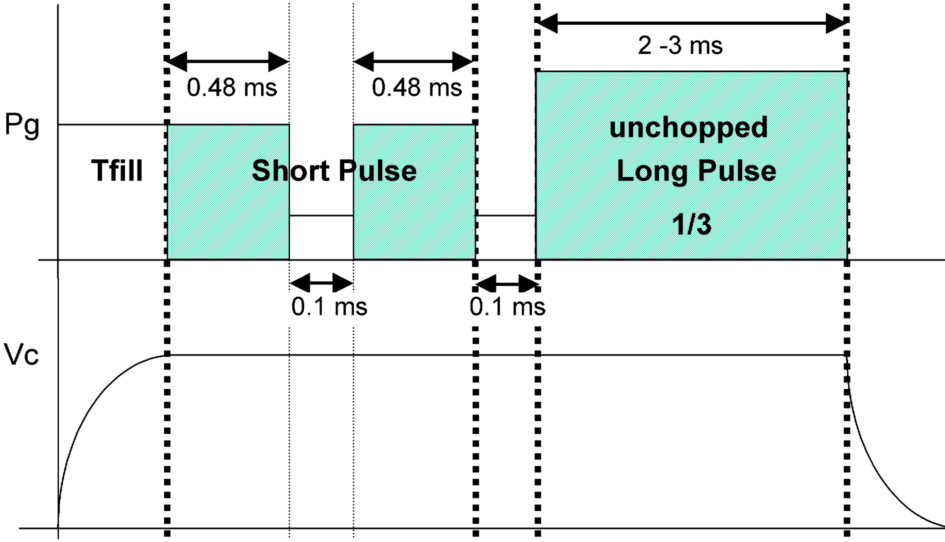


Superconducting option overview

- Higher frequency preferred for the SC cavities: 352.2/704.4 MHz
- Total linac length is 428.4m for H^- and 431.1m for H^+

	SP H^-	LP H^-	LP H^+
unch frequency (MHz)	704.4	704.4	352.2
ulse length (ms)	0.48	2.0	2.5
b pulses per cycle	2	1/3	1/3
eam chopping factor (%)	70	100	100
unch charge (nC)	0.162	0.162	0.256
eak current (mA)	114	114	90
ulse current (mA)	79.8	114	90
lean current (mA)	3.83	3.75	3.75
lax beam power (MW)	5.1	5.0	5.0

H^+ bunch charge is $2\times95/114$ = 1.67 time bigger that the H^- bunch charge

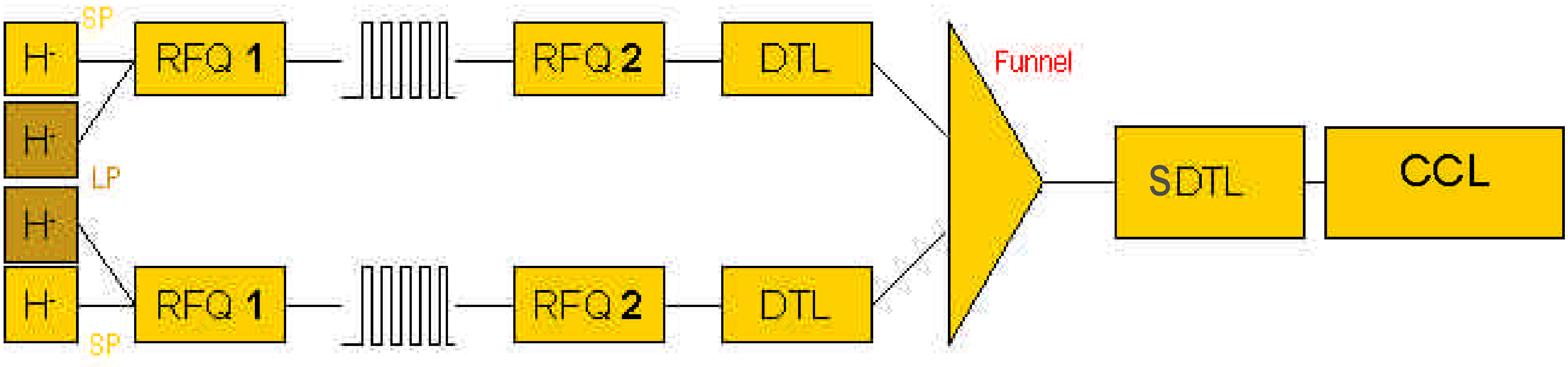


ESS sources

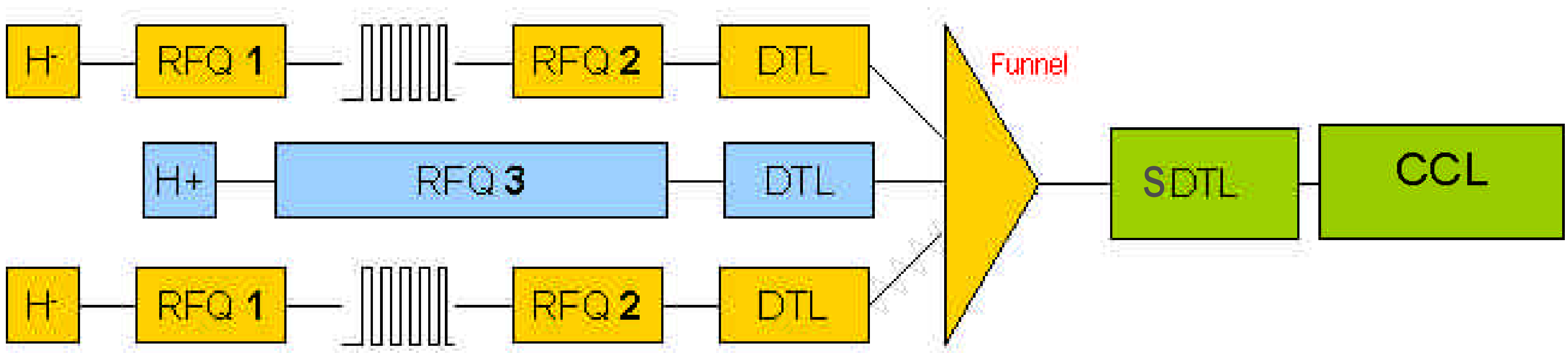
- Key element in the design of the ESS facility
- Call for 5 MW with a Short Pulse (SP) and 5 MW with a Long Pulse (LP) on Day 1
- SP requirements with a single ion source would need a considerable extrapolation from present H^- ion source performance
- For the ESS application, all the best performance levels achieved in the world are simultaneously required. This is considered to be very challenging.
- A double front end with a funnel is required

- LP (5MW) is as important as SP for the ESS project
- LP requirements were recognised as one step further than for the SP (different thermal regimes due to the pulse length). 2 solutions possible:
  - 2 sources, one for the SP and one for the LP, would be merged (total of 4 H^- sources)
  - No need for H^- particles for the LP, and proton sources have already fulfilled the ESS LP requirement

The 2 options of the LE RT linac



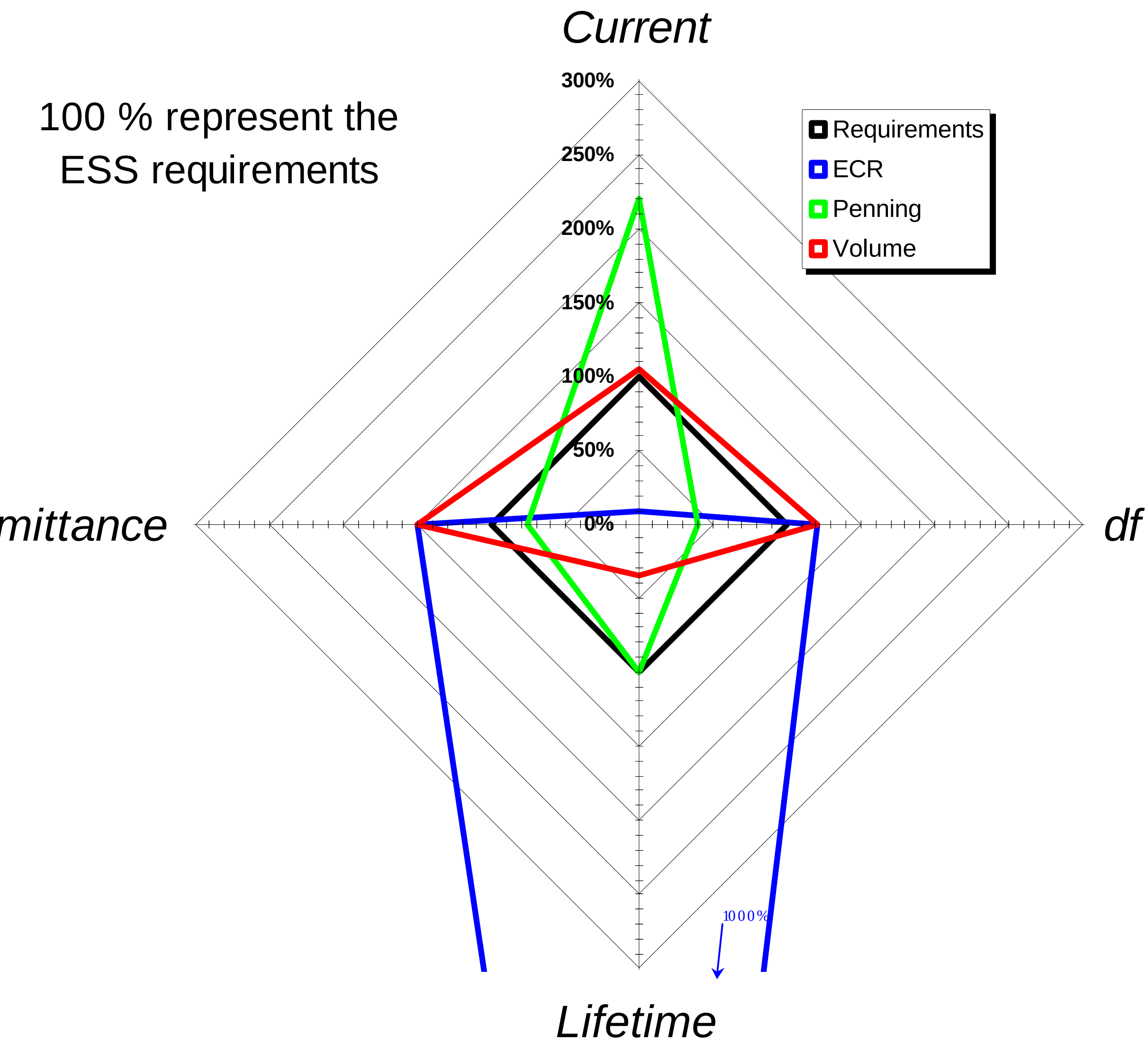
Reference design

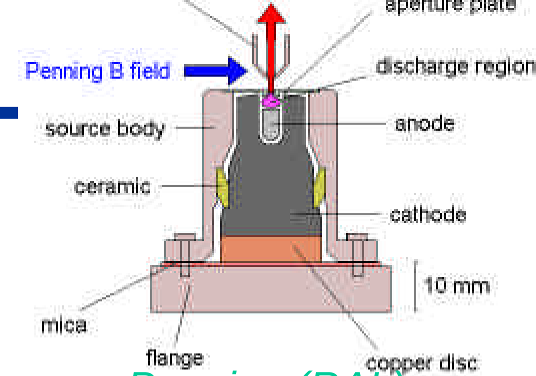


Fallback solution to ensure LP 5 MW on Day 1

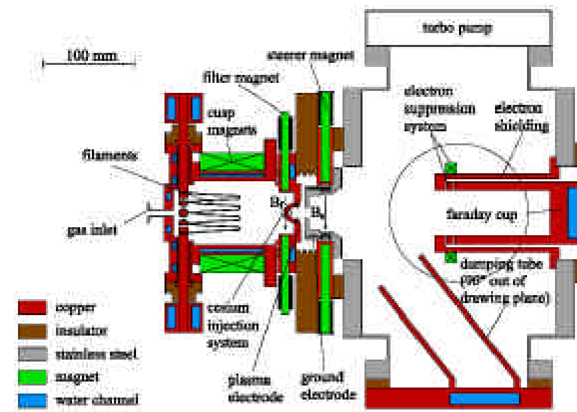
Different source type

100 % represent the ESS requirements

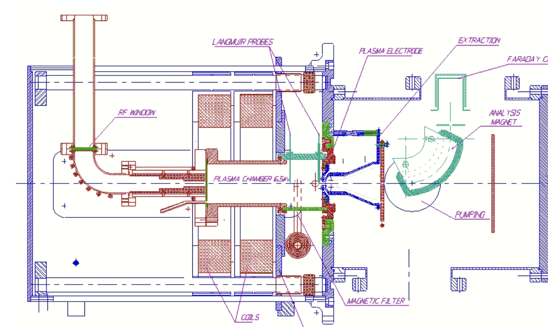




Penning (RAL)



Volume (IAP-Frankfurt)



ECR (CEA-Saclay)

RFQs

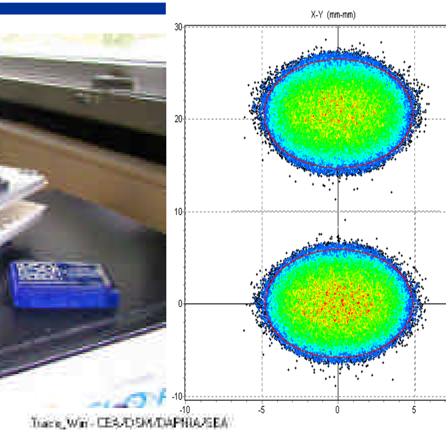
- 3 different RFQs:
  - 2x RFQ1 for H^- branches for 60keV to 2MeV
    - Insertion of the chopper line
    - 2MeV= avoid activation in RFQ1
  - 2x RFQ2 from 2MeV to 5MeV
  - 1x RFQ3 from 95keV to 5MeV for the H^+ branch
- 352 MHz, Already demonstrated (LEDA, IPHI)
- RFQ1 minimize transverse emittance growth, with large acceptance (0.3 π.mm.mrad) and max transmission

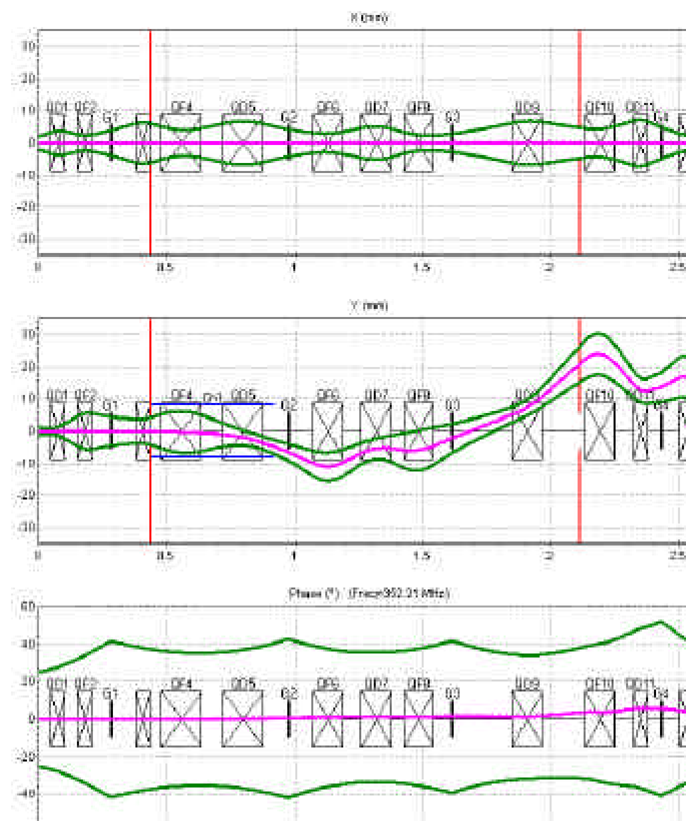
IPHI RFQ after brazing step (RFQ3)

- RFQ2 reshape the beam, minimize emittance growth, give same zero current phase advance at exit as RFQ3, 100% transmission
- RFQ3 minimize losses over 2.16MeV, bunching and acceleration process kept as adiabatic as possible. Same as IPHI RFQ, 100mA, trs=99.5%

Chopper section

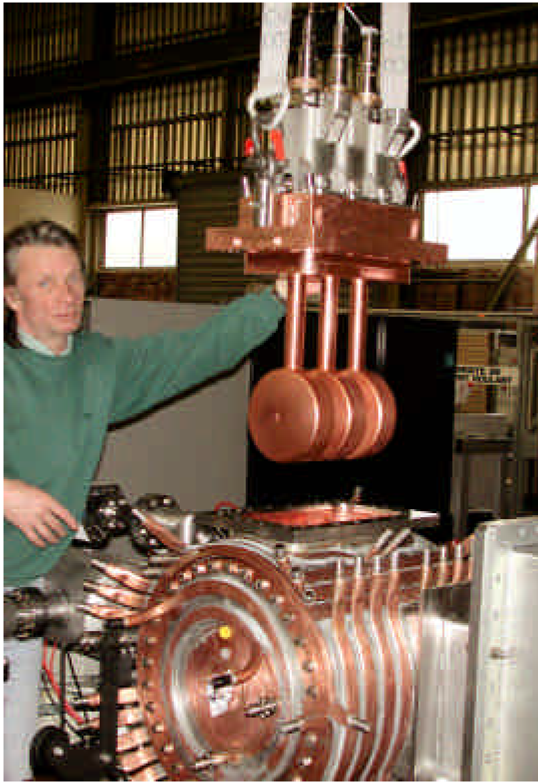
- Fast chopper (2ns) at 2MeV
- Meander strip line
- Drive with sinusoidal shape instead of pulse shape
  - Frequency = half the bunch bandwidth from 600MHz down to 300MHz
  - 2 beam stop = easier to cool down
  - Higher voltage (1.4kV)
- Distance between chopped and un chopped beam = 8.5 beam rms size at the beam stop location
- Emittance growth < 3%, transmission = 96.3%





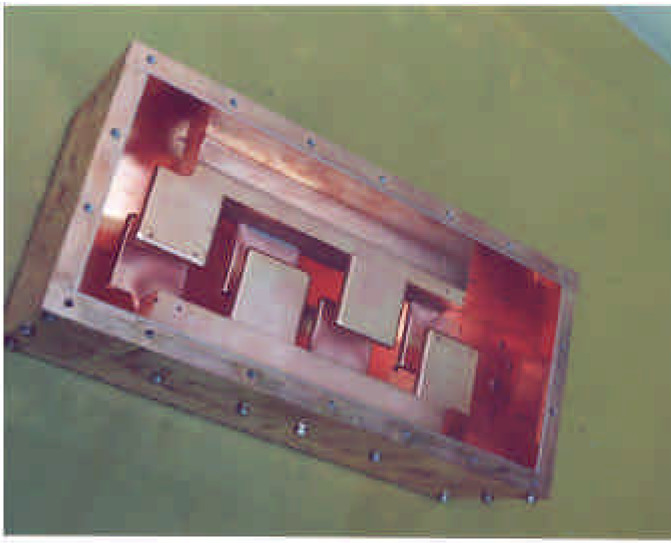
DTLs From 5 MeV to 21.9MeV

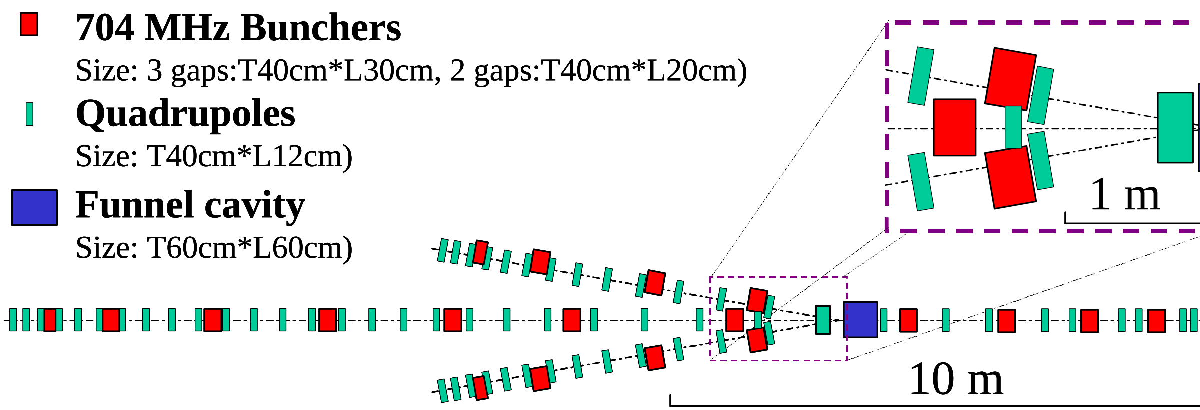
- From 5 MeV to 21.89 MeV, the funnel energy
- Based on IPHI R&D, use of conventional EM quadrupoles (tuning → restrict halo development)
- 1MW per tank, FD focusing scheme (period of 2 $\beta\lambda$)
- Continuity of the phase advance per meter
- H^- peak beam current = 57mA, H^+ peak beam current = 90mA
- 2 tanks for the H^- lines, 3 tanks for the H^+ line



Funnel line

- Funnel cavity give about ±5° deflection angle
- Multicell cavity type (Y. Senichev), no dipole magnet needed
- Allow insertion of the H^+ line
- ±10.9° obtained with Quadrupoles
- 10% emittance growth (1% due to space-charge, 2% due to line non-chromaticity, rest due to phase-dependent particle transverse deflection
- non-chromaticity effect seems marginal





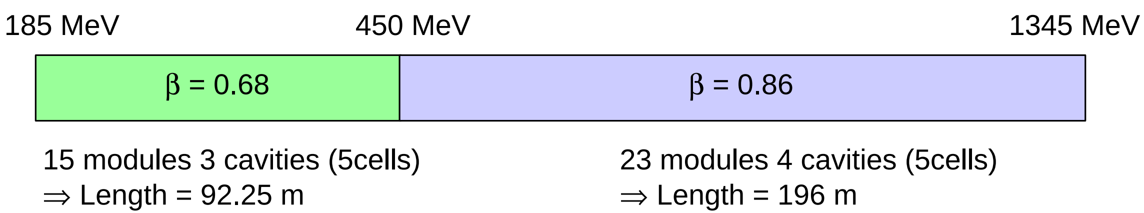
SDTL to 90.5MeV CCL to 185MeV

- Frequency now equal 704MHz
- SDTL = doublet period = very convenient for matching with CCL and SCL. Less matching compared to DTL. Less complex compared to CCDTL.
- Maximize shunt impedance but same nose shape (reduce cost)

- Above 100MeV shunt impedance decrease → CCL
- SDTL, CCL and SCL use doublet lattice period

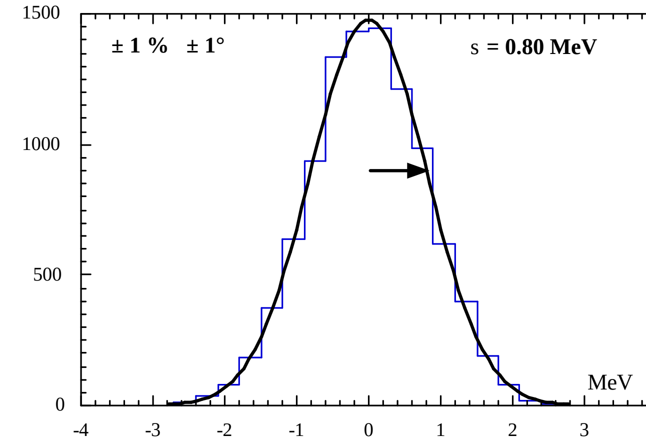
SCL from 184.5MeV to 1348MeV

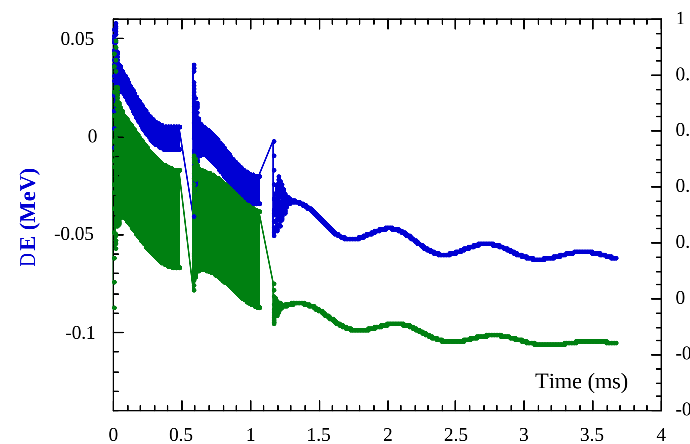
- Two 5-cell cavity families, geometric β of 0.66 and 0.85
- Length = 290m
- B_p = 50 mT (about Ep = 27.5 MV/m, 2 times lower than TESLA)
- 2x800 kW rf power coupler per cavity



Field control and energy stability

- Random errors of uniform distribution, simultaneous cavity field errors (1% amplitude, 1° phase) lead to an rms energy fluctuation of 0.8 MeV and phase fluctuation of 1.2° at linac exit (10000 simulations)
- “one klystron per cavity” scheme
  - each cavity has its own feedback/feedforward RF control system
  - simplest operating procedure
  - greatest flexibility (if failure)
- Lorentz force was carefully studied (welding rings between cells) → *K* lower than 2 Hz / [MV/m]^2
- With additional perturbations, such as microphonics, maximum jitter remain small (± 0.2 MeV and ± 0.5°)



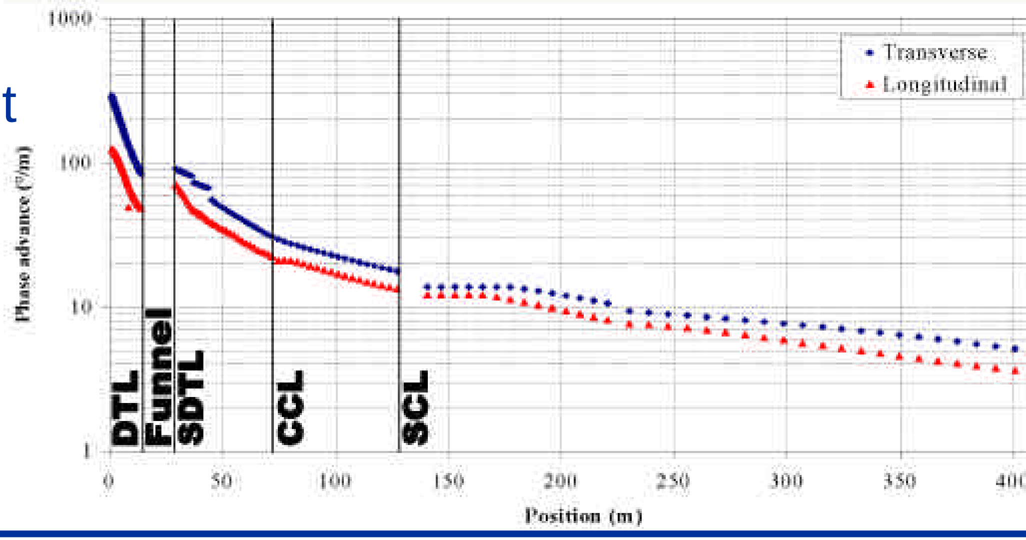


Energy and phase deviations (mu
pulse beam at the linac exit at
steady-state with computed
mechanical modes)

End to End simulations 1/4

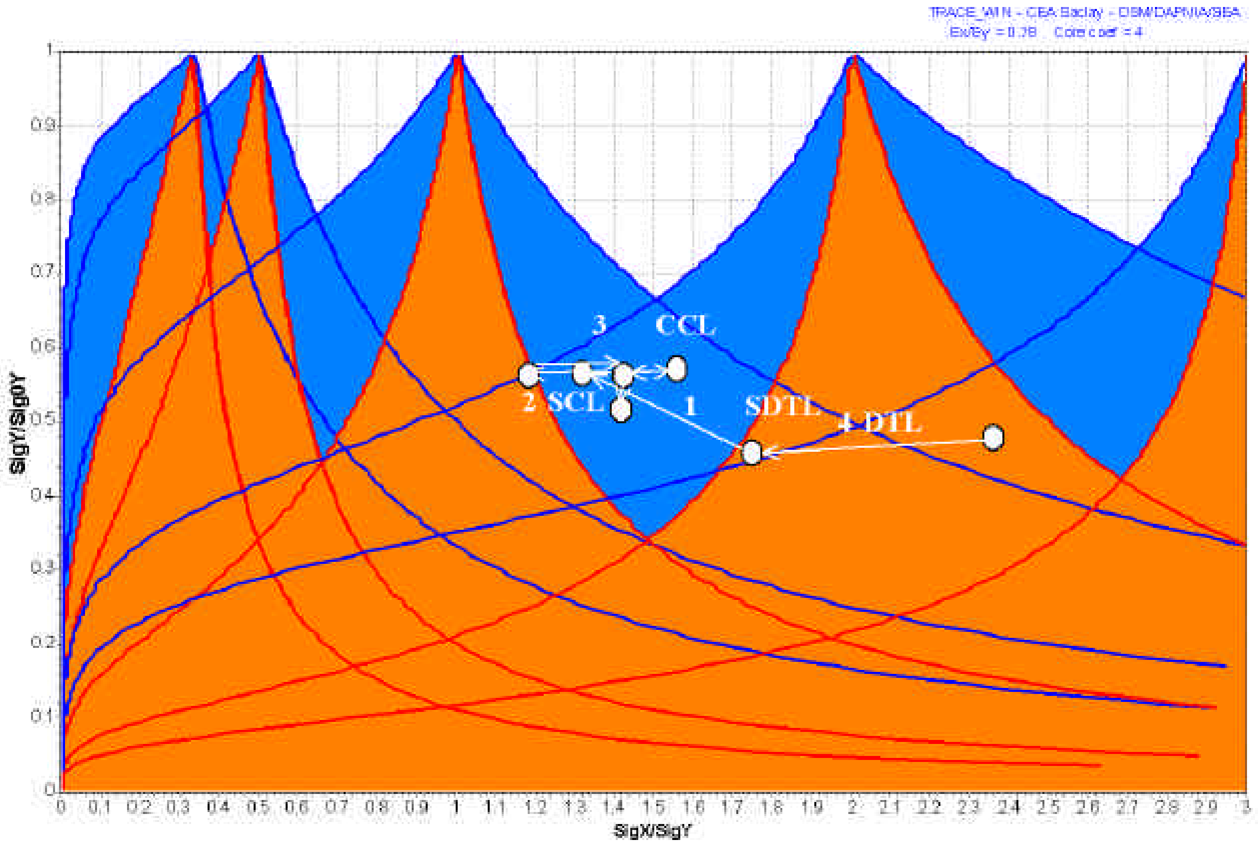
- keep the average phase advance per meter (average beam confinement) as smooth as possible,
- keep the focusing lattice scheme as continuous as possible,
- match the rms beam parameters at the transitions,
- avoid zero current phase-advance per lattice higher than 90°,
- avoid the same transverse and longitudinal phase advances in order to stay away from emittance exchanges,
- keep the tune depression as high as possible.

- 4-D waterbag at the RFQ input
- Emit = 0.3 π.mm.mrad (rms, norm)
- 100 000 particles
- TOUTATIS, TRACEWIN, PARTRAN, 3D space charge

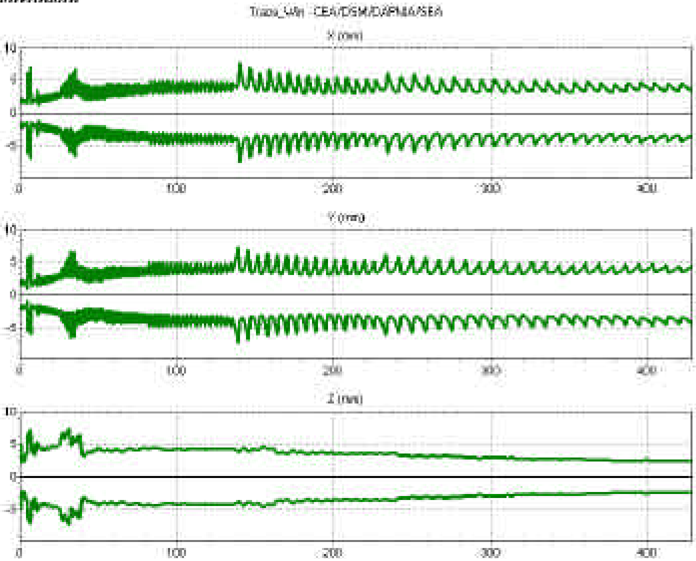


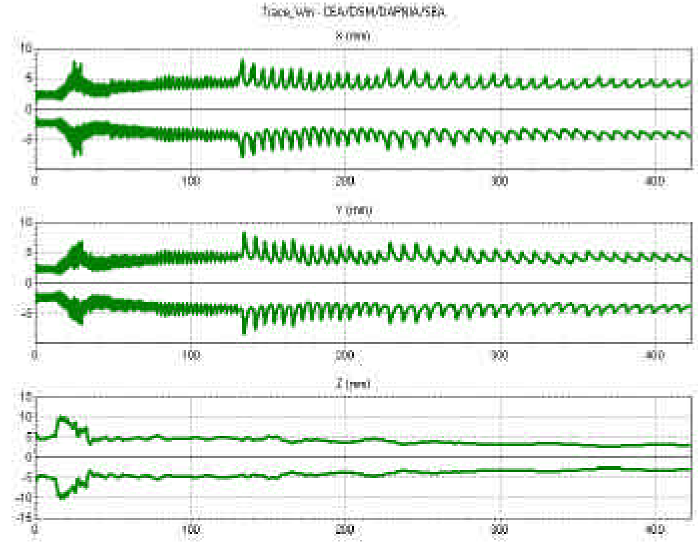
Working point evolution

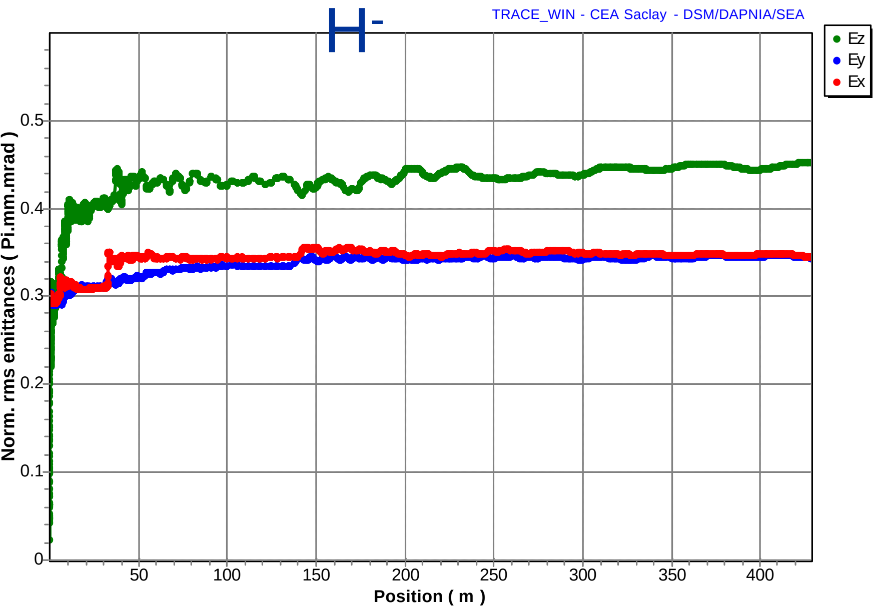
- Coupling resonance chart (Hofmann-Lagniel chart)

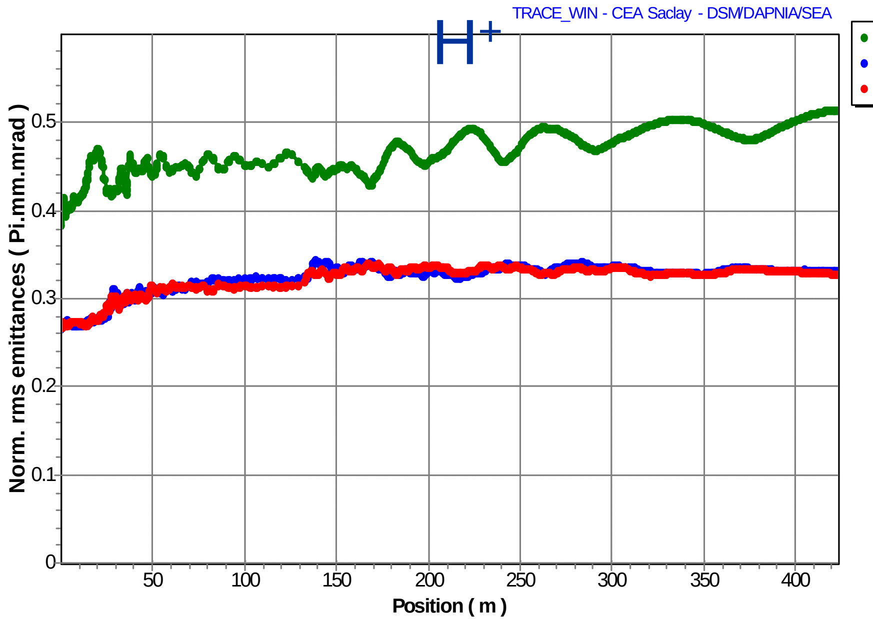


End to End simulations 2/4



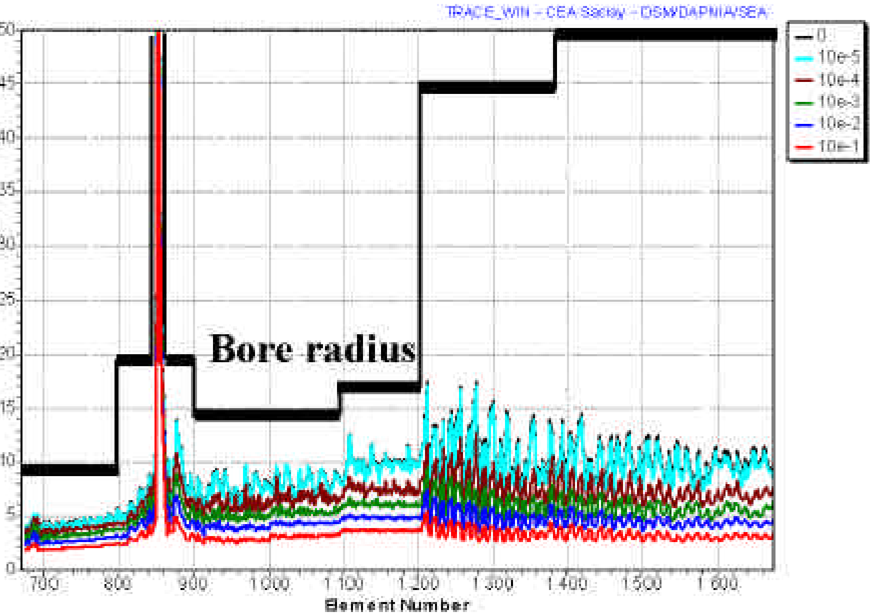




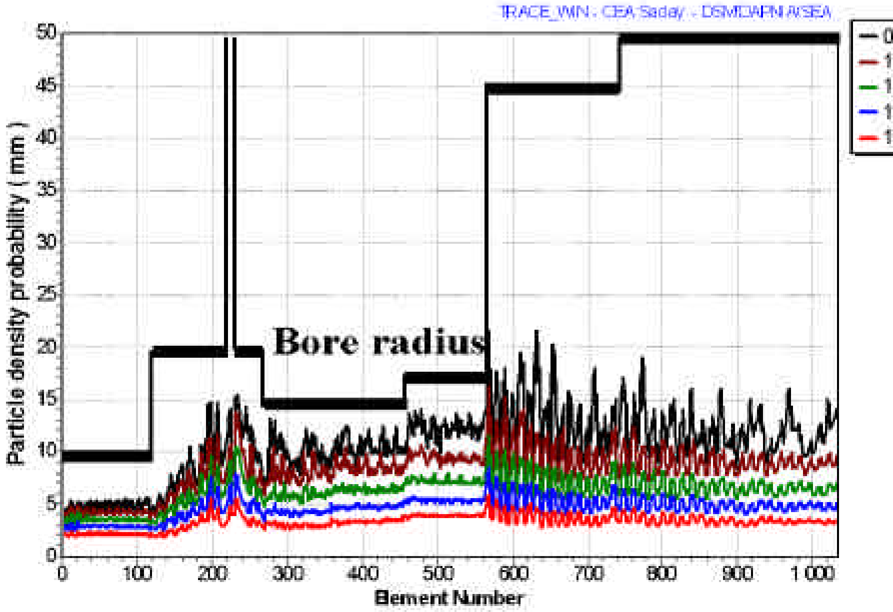


End to End simulations 3/4

H^-



H^+



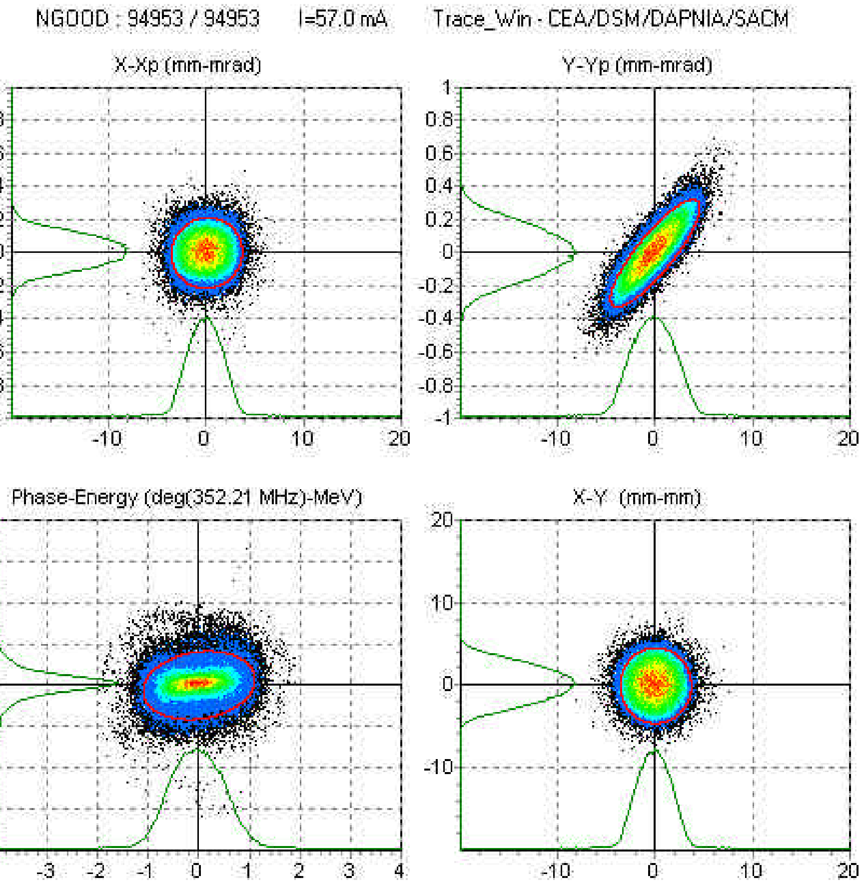
The minimum ratio between the bore radius and the 10^{-5} level is about:

- 1.45 in nc linac for H^-,
- 2.55 in sc linac for H^-,
- 1.15 in nc linac for protons,
- 2.1 in nc linac for protons.

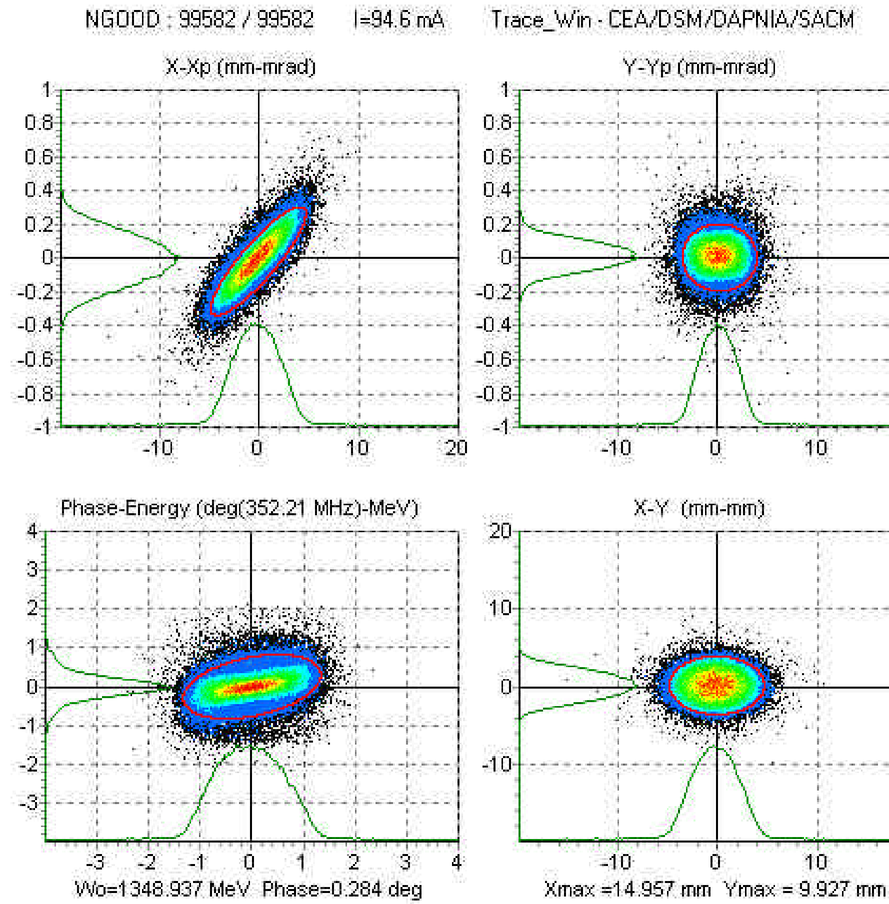
Superconducting linac has much more margin than normalconducting one.

Dynamic errors do not lead to significant beam radius increase

End to End simulations 4/4



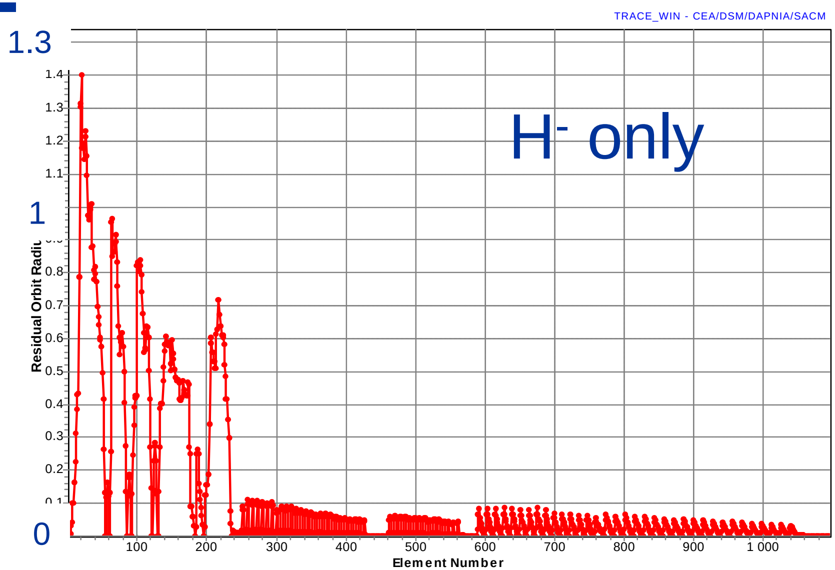
H$^-$



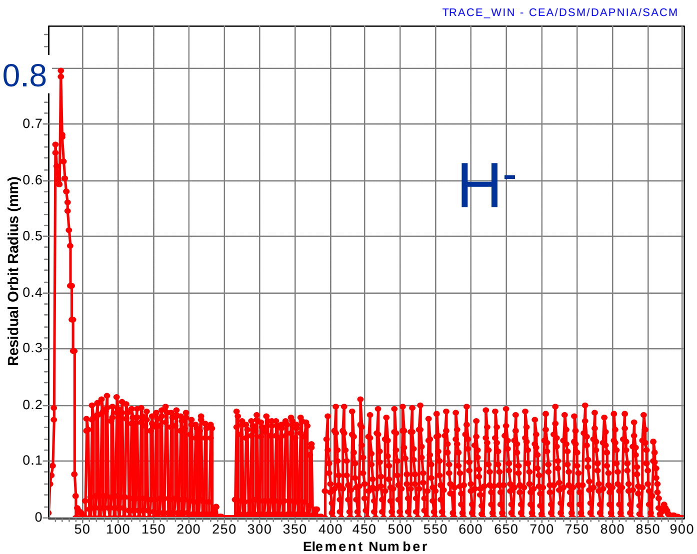
H$^+$

Linac output distributions

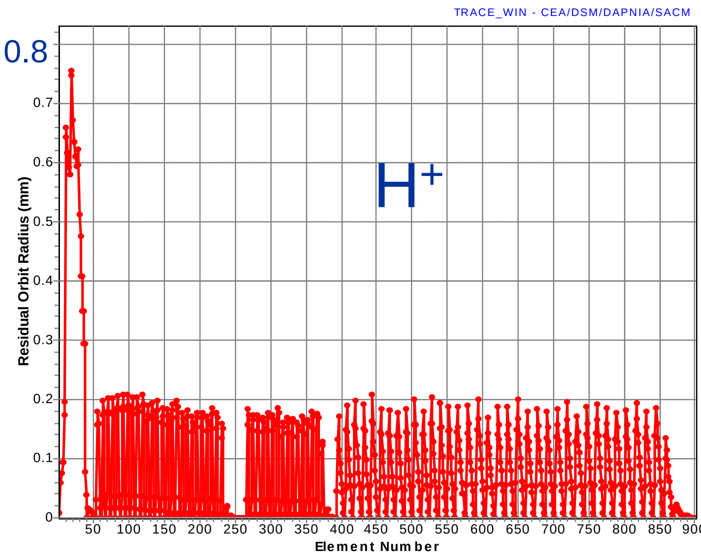
2 beams tuning



The correction scheme is very efficient after the funnel line (a few 100µm), but it is less efficient in the DTL (~1mm). This is due to the huge number of quadrupoles between the correctors and the diagnostics



and



Residual orbit RMS value along the linac with Quads and cavity static errors