Superconducting Proton Driver Accelerator extended capabilities

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Summary

- General constraints of the EURISOL driver
- Options considered
- New baseline design
- Cost estimate for different options
- Conclusions

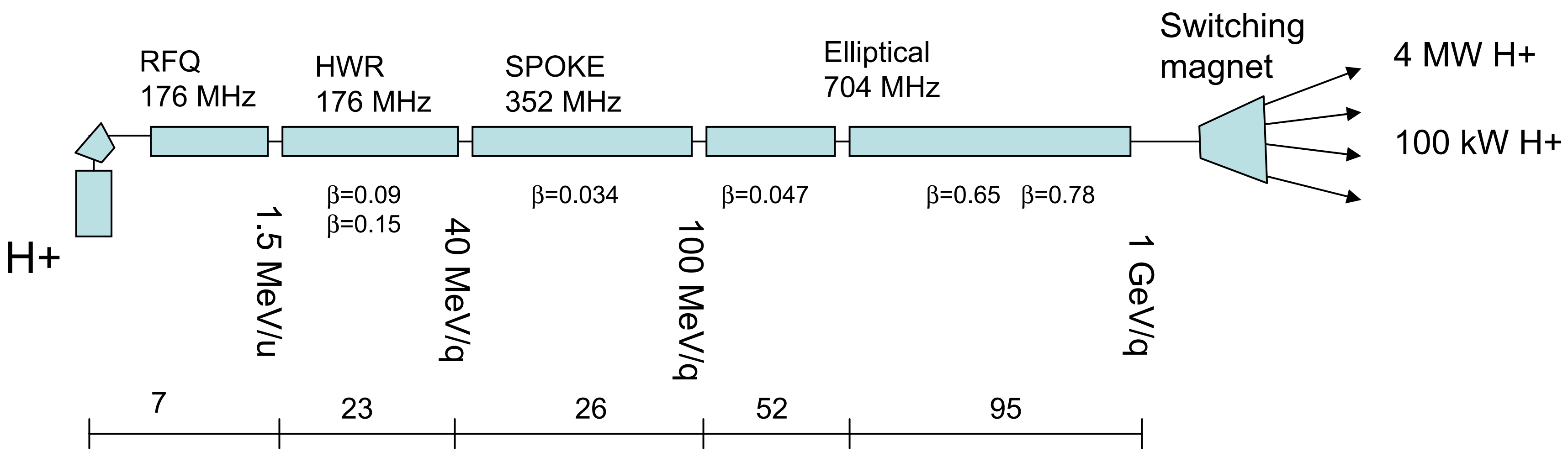
EURISOL driver general constraints

blue = required
green = desirable

- **Operation mode**
  - **CW (preferable), or pulsed, min 50 Hz, min. pulse length 1 ms**
  - **continuously adjustable beam current**
  - **Multi-user operation**
- **beams**
  - **P, 1 GeV, 5 mA**
  - **D (1≤A/q≤2), 200 MeV, 5 mA**
  - **^{3}He, 2 GeV, 2.5 mA**
- **extraction lines**
  - **@1 GeV:**
    - **1×4 MW**
    - **3 × 100 kW**
  - **@ 200 MeV: 1×1 MW**
  - **@ 2 GeV: 1×4 MW**
- **beam size at the target**
    - **σ< 1 cm n converter**
    - **σ< 3 cm direct target**
- **Maximum losses: 1 W/m**

Old baseline scheme

- 1 GeV, 5mA proton beam
- 1 injection line
- 4 extraction lines at 1 GeV (1 line 4 MW + 3 lines 100 kW)
- Multiple beam extraction partially achieved with pulsed beam



Options considered

- We have examined the possible layouts for the different linac sections
- We have chosen the most suitable technology for each section of the reference design
- We have integrated the different sections and made a preliminary optimization of different schemes

Linac Section I $1.5 \div \sim 60$ MeV/q

Low-β

Suitable schemes:

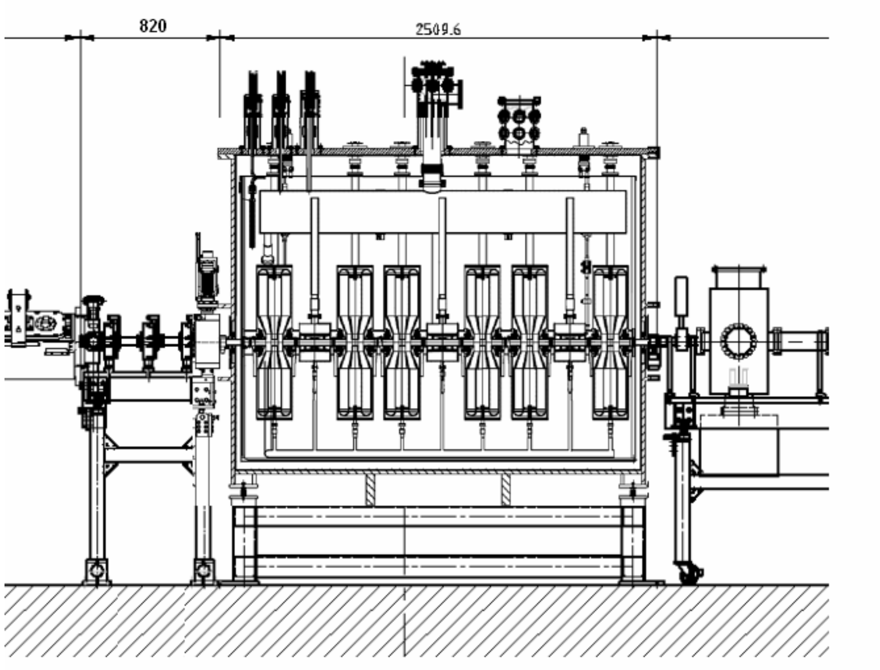
1. 352 MHz, SPES and IPNO scheme
2. 176 MHz, SARAF scheme
3. 88 MHz, SPIRAL-II scheme

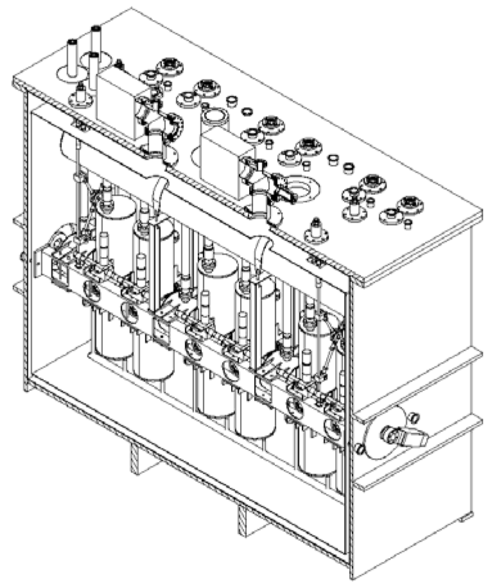
We have chosen the **SARAF scheme** because:

1. The 176 MHz RFQ and linac allows acceleration of both P and D
2. the solution is very compact and cost-effective
3. The frequency jump from 176 MHz to 352 is relatively easy
4. most components have already demonstrated their performance and a similar linac is under construction

Low-β linac

- Modified SARAF type (modified for symmetric cryostats)
- superconducting 176 MHz HWR with β=0.09 and β=0.15
- superconducting solenoids in cryostat

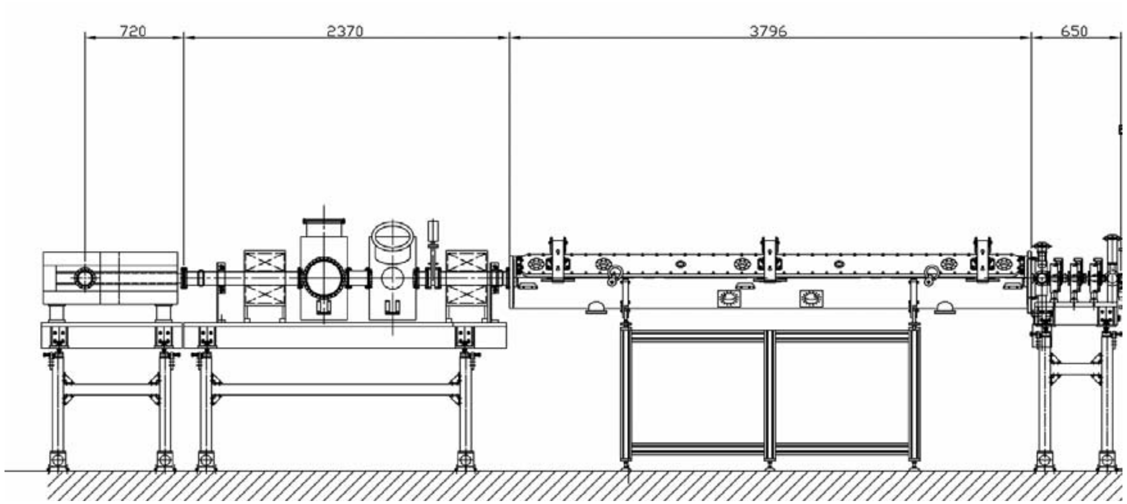




SARAF-ACCEL cryostat

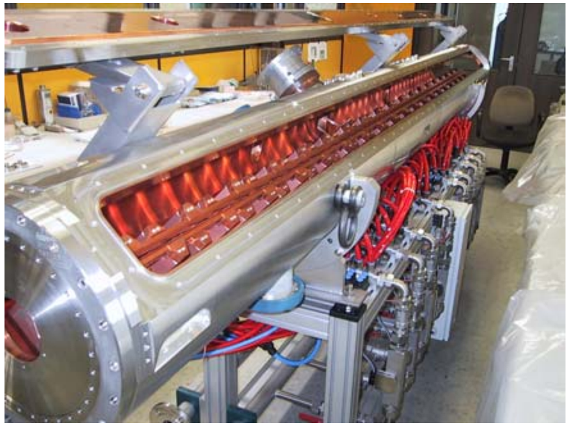
RFQ

- Most suitable candidate at present:
  - SARAF-NTG 176 MHz RFQ
- E_{in}= 20 keV/u, E_{out}=1.5 MeV/u
- 5 mA
- Moreover: **1≤A/q≤2**



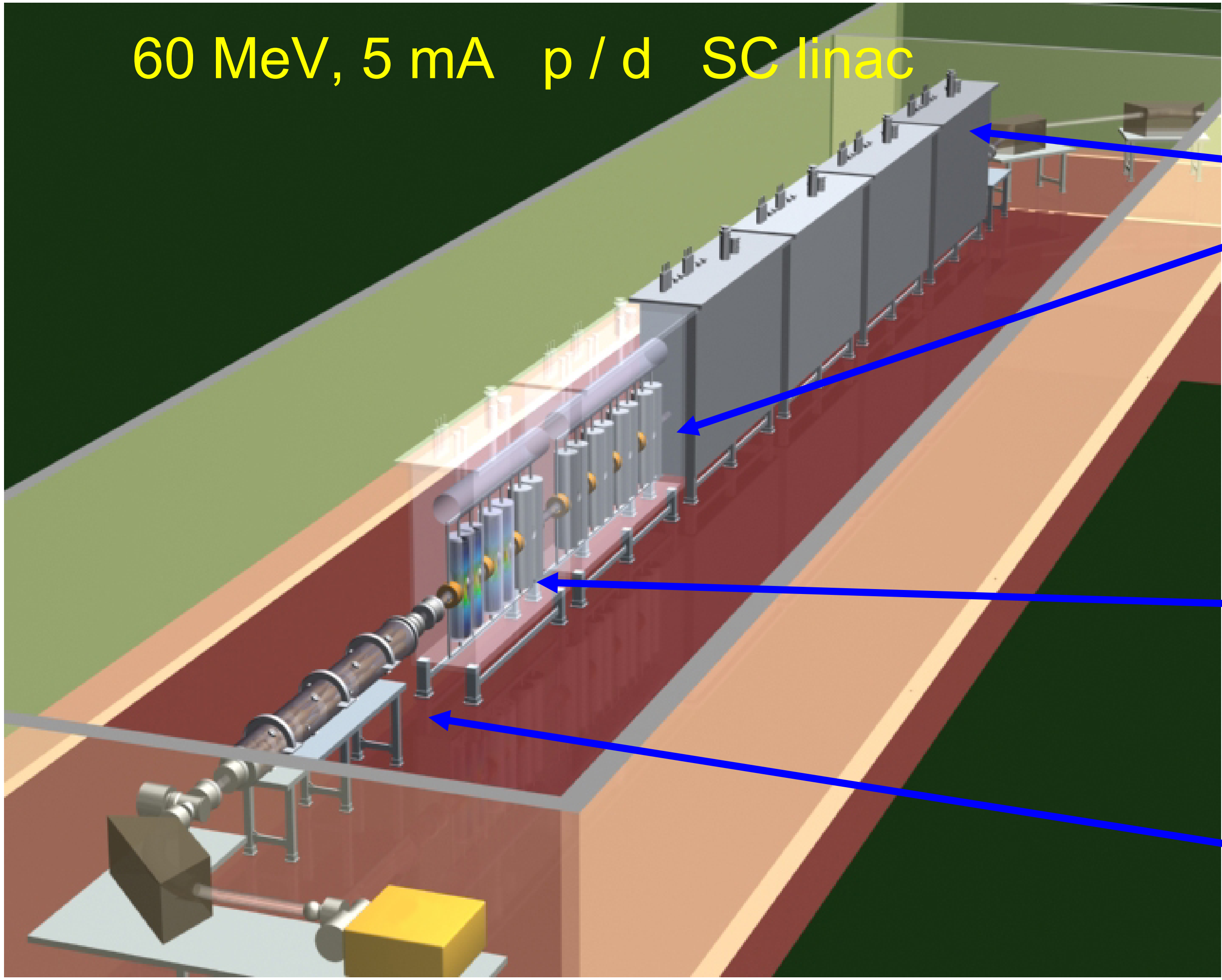
EIS + LEBT RFQ MEBT

The SARAF injector



Example: the SARAF-NTG 176 MHz rfq

0÷60 MeV/q, *1≤A/q≤2*



Linac Length: ~32 m

3[nd]– 9[th] cryostats

7×8 SC HWR

β_0=0.15

1[st], 2[nd]cryostat

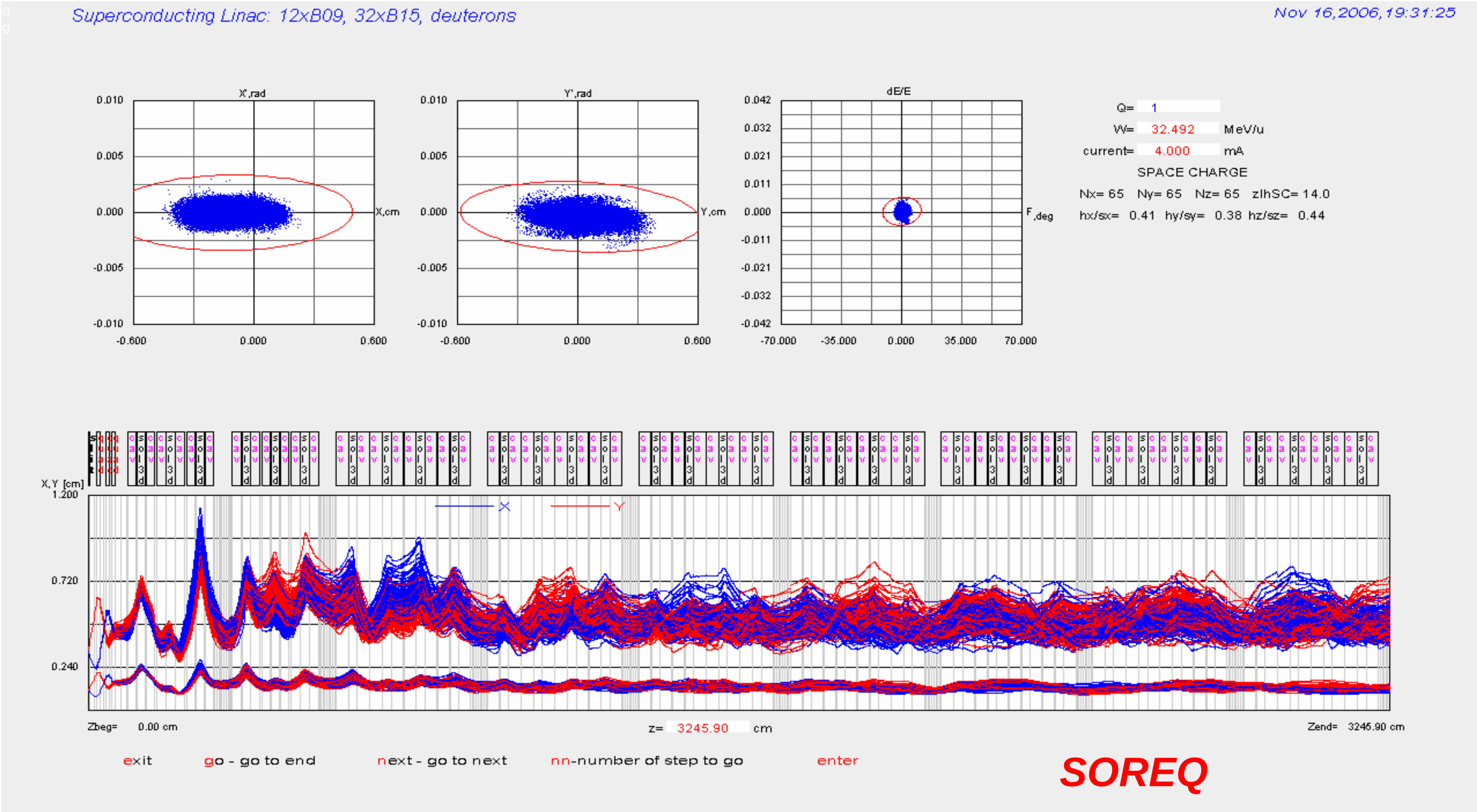
2×6 SC HWR, β_0=0.09

176 MHz RFQ

1.5 MeV/u A/q=2

3.8 m

Error analysis - TRACK simulation deuteron beam



Linac Section II ~60÷140 MeV/q

Medium-low β

Suitable schemes:

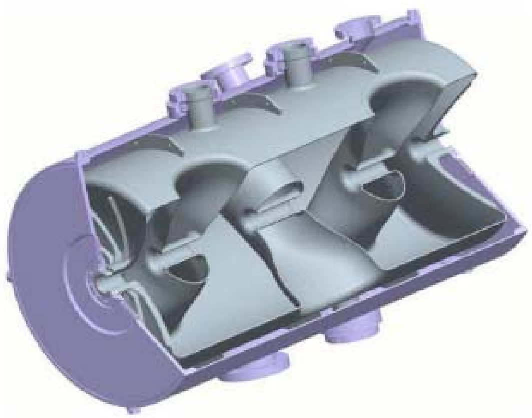
1. SPES 352 MHz, with β=0.31 coaxial HWRs
2. IPNO 352 MHz, with β=0.36 SPOKE cavities
3. IPNO 352 MHz, with β=0.3 TRIPLE-SPOKE cavities

The choice is not straightforward, because:

- Both SPOKE and HWR cavities have been developed and tested off-line, but none of them was used in a beam line yet
- Multi–SPOKE have been developed at Argonne (USA) with excellent results, but only for higher β.
- The cryostat and other components for SPOKE and HWR cavities are under development in the TASK 8 framework; the HWRs could already fit in the same SARAF type cryostat used in the Low-β section

TRIPLE-SPOKE is our best choice, because:

1. This resonator is the most efficient for our needs according to calculations in the 60-140 MeV section
2. According to our experience and to the worldwide results on prototypes, we believe that a β=0.3 TRIPLE-SPOKE fitting our requirements is reliably feasible in Task 8 within the EURISOL time schedule
3. Good backup solutions exist anyhow, with β=0.31 coaxial HWRs and single spoke



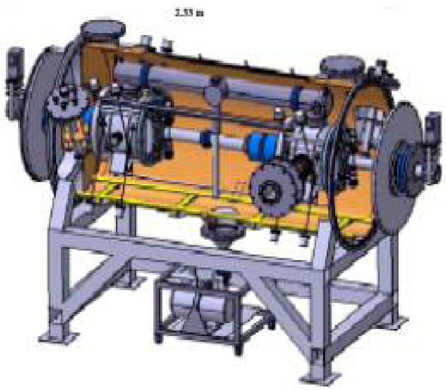
3D view of a 3-spoke prototype developed by ANL.

Table 1: RF performances at 4.2 K of the existing spoke cavities around the world.

Labs	Spoke –type	Geometrical /Optimal betas*	Eacc max @ 4.2 K [MV/m]	Epk [MV/m]	Bpk [mT]	Voltage gain [MV]	Limitation	Ref
IPN Orsay†	Single	0.15/0.20	4.77	32	69	0.81	Quench	[6]
	Single	0.35/0.36	8.15	38	104	2.49	Power	[7,8]
ANL‡	Single	0.29/0.29	8.46	40	106	2.21	Quench	[9,10]
	Single	0.40/0.40	7.57	46	123	2.63	Quench	[11,12, 13]
	Double	0.40/0.40	8.60	40	79	4.40	Quench	[14]
	Triple	0.50/0.50	7.65	28	88	6.65	Quench	[15]
	Triple	0.63/0.63	8.61	34	104	9.40	Quench	[16]
LANL§	Single	0.175/0.21	7.50	38	99	1.34	Quench	[17,18]

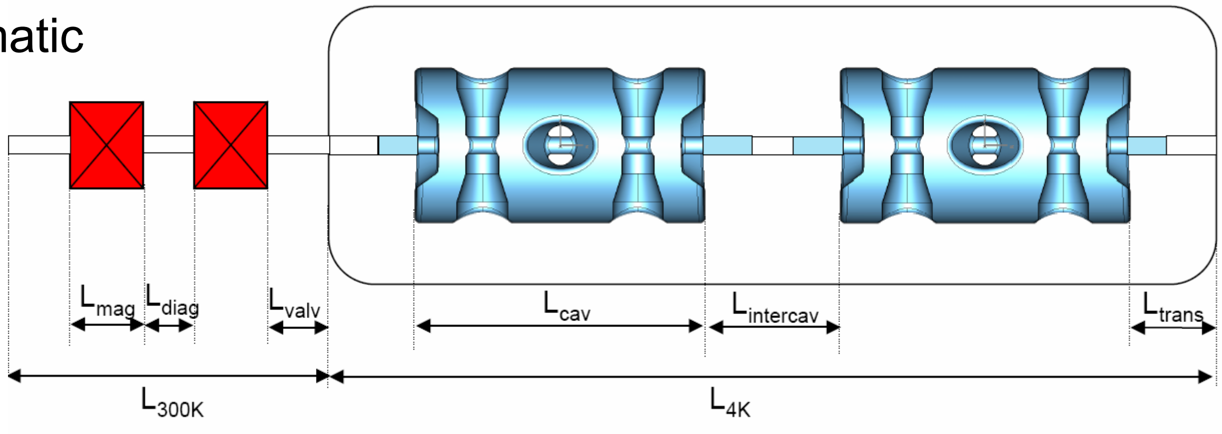
60÷140 MeV/q, $1 \leq A/q \leq 2$

- superconducting Triple-SPOKE cavities $\beta=0.3$
- E_{in}= 60 MeV/q
- E_{out}=140 MeV/q
- length ~30 m



IPNO cryostat design for SPOKE resonators

3-spoke cryomodule schematic



Linac Section III ~140÷~300 MeV/q

Medium-high β

Suitable schemes:

1. 704 MHz, 5-cell β=0.47 elliptical, CEA scheme
2. 352 MHz, 4-gap β=0.5 SPOKE, IPNO scheme

The **elliptical cavity scheme** was chosen, because:

1. The overall linac is shorter with elliptical cavities
2. The overall linac cost is lower
3. this solution preserves anyhow the possibility of accelerating A/q=2 up to ~250 MeV/q, and A/q=1.5 up to ~1 GeV/q

Linac Section IV ~300÷~1000 MeV/q

High-β

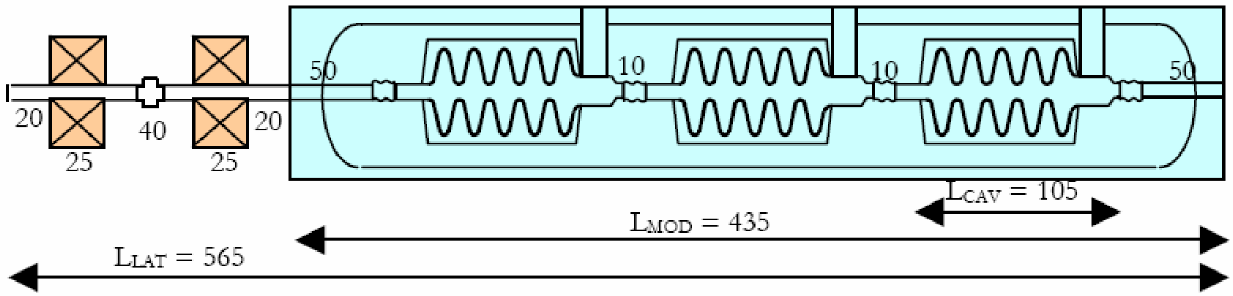
For the high-β section our best choice is again the scheme based on 5-cell elliptical cavities with β=0.65 and 0.78

1. Well established cryostat technology (SNS)
2. The resonators prototypes have been successfully developed by EURISOL DS participants
3. The only alternative (4-gap SPOKE) is more expensive, with no clear advantage for our application ($1 \leq A/q \leq 1.5$) in this energy range

140÷250 MeV/q, *1≤A/q≤2*
250÷1000 MeV/q, *1≤A/q≤1.5*

- superconducting elliptical cavities
- β=0.47, 0.65, 0.78
- E_{in}= 140 MeV/q
- E_{out}=1000 MeV/q
- section III+IV length ~160 m

β = 0.65, 704 MHz elliptical cavity



schematic of the β=0.47 cryomodule

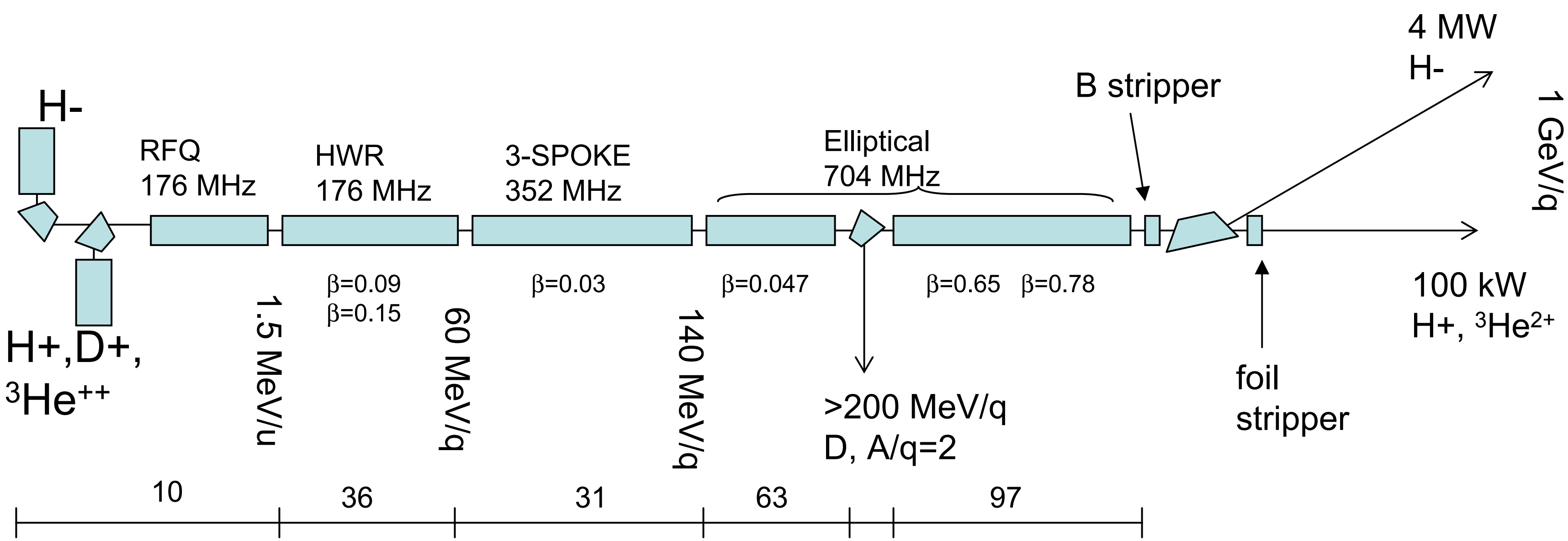
Extending capabilities of the original proton linac design

- The linac components that we have chosen allow some A/q flexibility
- By adding suitable ion sources we can accelerate deuterons, $^{3}He^{++}$ and other fully stripped light ions
- By using also negative ions H^{-}, we can produce CW parallel proton beams at 1 GeV by high energy beam splitters based on H^{-} stripping

  → *we don't need anymore beam chopping*

New baseline scheme

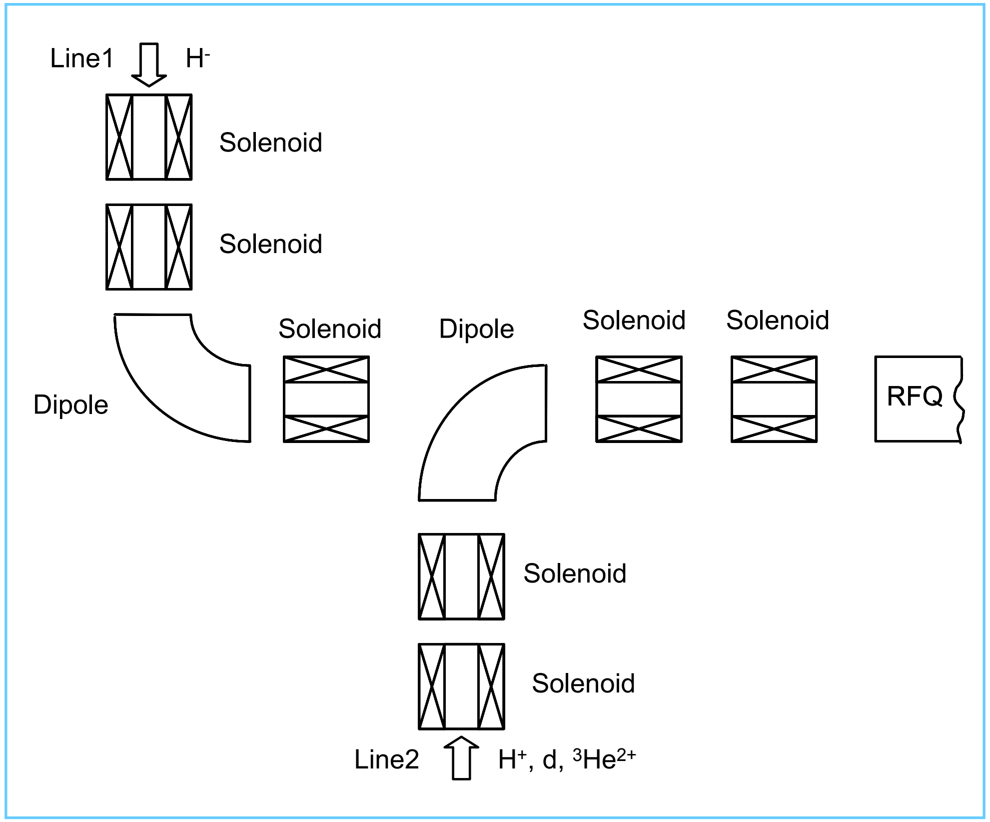
- 2 injection lines
- SARAF scheme up to 60 MeV/q
- IPNO scheme from 60 to 140 MeV/q
- CEA scheme from 140 to 1000 MeV/u
- cw beam splitting at 1 GeV (1 line 4 MW + 3 lines 100 kW)
- Total length of the linac: ~240 m



Ion sources

- The required ion sources for the new proposed baseline design are presently available
- Commercial sources available for 5 mA CW beams of H^+, D^+ and 1 mA CW $^3He^{++}$
- 2 mA CW $^3He^{++}$ seems achievable with no major difficulties
- TRIUMF multicusp source allows for 5 mA CW, H^- beams
- Recently developed sources can produce fully stripped O (~50 μA), Ar (~1 μA) and others
- Future projects for ion sources aim to tens of μA of fully stripped ions up to Calcium

LEBT modifications



Schematic of the modified SARAF injector

- Modified SARAF-type scheme, with confluence of 2 lines
- source 1
  - H- 5 mA 20keV
- source 2
  - H+ 5 mA 20 keV
  - D+ 5 mA 20 keV/u
  - 3He(2+) 2 mA 20 keV/u

New baseline design components

Additional performance:

1≤A/q≤ 2 up to ~250 MeV

1≤ A/q≤1.5 up to ~ 1 GeV/q

Additional equipment to the original baseline proton linac:

+41 cavities, mainly at low-β

+31 m length

+2 new extraction lines

	f(MHz)	n. cells	n. cav	n. cryo	L(m)	BetaG	Wout(MeV) PROTONS	Wout(MeV) DEUTERONS	Wout(MeV) $^3He^{2+}$
INJ+RFQ	176		1		7		1.5	3	4.5
HWR1	176	2	6	2	6	0.09	4	5	11.5
HWR2	176	2	56	7	30	0.15	60	60	120
3-Spoke	352	4	22	11	31	0.30	130	140	285
ELL1	704	5	45	15	63	0.47	310	280	590
ELL2	704	5	40	10	61	0.65	720		1510
ELL3	704	5	24	4	36	0.76	1060		2230

Comparison of possible scenarios

#1 1 GeV proton only
#2 1GeV proton and 100 MeV deuterons
#3a 1GeV proton and >200 MeV deuterons
#3b 1GeV proton and 2 GeV ^{3}He
#4 1GeV proton, >200 MeV deuterons and 2 GeV ^{3}He
#5 as above + multi-user for 1 GeV protons

- The cost calculations are based on facilities that are either existing or under construction (SNS, SARAF,SPIRAL, ALPI-PIAVE,…).
- Resulting from parametric calculations, the absolute values are only approximate. The cost comparison of different linacs, however, should be reasonably precise.
- The cost calculations include:
  - Injector, linac, Rf system, cryogenics, controls, building and infrastructures, man power
- The cost calculations do not include extraction lines and contingency.

Cost comparison

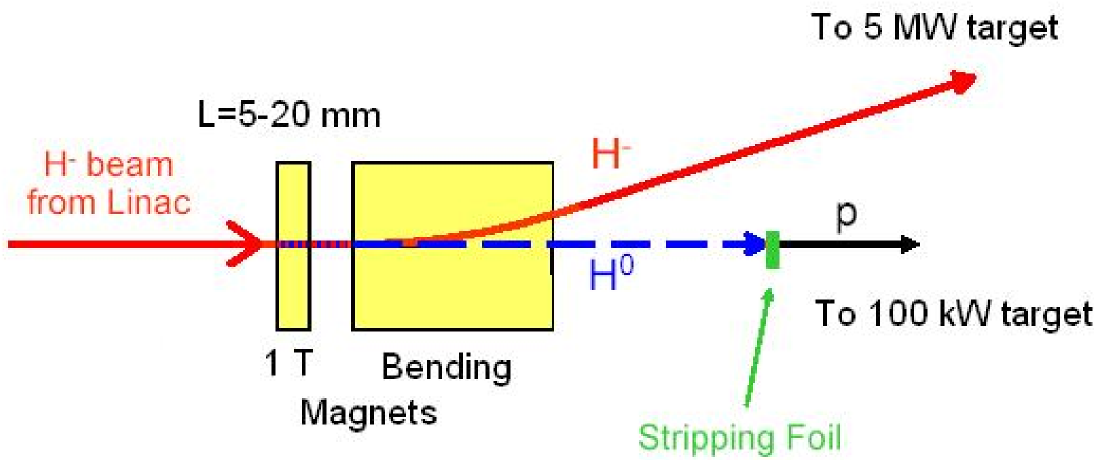
Option	beams in operation	length, m	extras required	**cost M€**	Δcost
#1 proton only	1 GeV **p**, 4 MW **or** 100 kW	203		**199**	+0 %
#2 *p* + 100 MeV *d*	1 GeV **p**, 4 MW **or** 100 kW **or** 100 MeV **d**, 50 kW	203	176 MHz RFQ instead of 352	**199**	+0 %
#3a *p* + 250 MeV *d*	1 GeV **p**, 4 MW **or** 100 kW **or** 200 MeV **d**, 125 kW	218	as #2 + low-β to 140 MeV	**211**	+6 %
#3b *p*+ ^{3}He	1 GeV **p**, 4 MW **or** 100 kW **or** 2 GeV **$^3He^{++}$** , 4 MW	223	as #2 + more β=0.47 cavities	**220**	+11 %
#4 *p*+ ^{3}He+*d*	1 GeV **p**, 4 MW **or** 100 kW **or** 200 MeV **d** , 100 kW **or** 2 GeV **$^3He^{++}$** , 2 MW	231	as #3a + #3b	**230**	+16 %
#5 *p*+ ^{3}He+*d* + multi-user *p*	1 GeV **p**, 1× 4 MW **and** 3×100 kW **or** 200 MeV **d** 125 kW **or** 2 GeV **$^3He^{++}$** , 2 MW	231	H- injector+ 4 stripping stations	**+3%**	+19 %

New extraction scheme

- **1 GeV/q**
  - 1 line | 0÷4 MW | H^-
  - 3 lines | 0÷100 kW | H^+
    - **Possibility of simultaneous operation of the lines with H^- and H^+ beams by using high energy beam splitters**
  - 1 line | 0÷4 MW | $^3He^{2+}$
- **250 MeV/q**
  - 1 line | 0÷125 kW | deuterons and all achievable A/q=2 beams

High energy beam splitters

- magnetic stripping at 1 GeV of a small part of the H^- beam to H^0
- bending of H^- with a magnetic dipole
- stripping of H^0 to H^+ by means of a stripper foil
- H^- to target 1 and H^+ to target 2(3,4).
- The spilled beam intensity can be controlled by adjusting the field strength of the magnetic stripper.



Lorentz force stripping

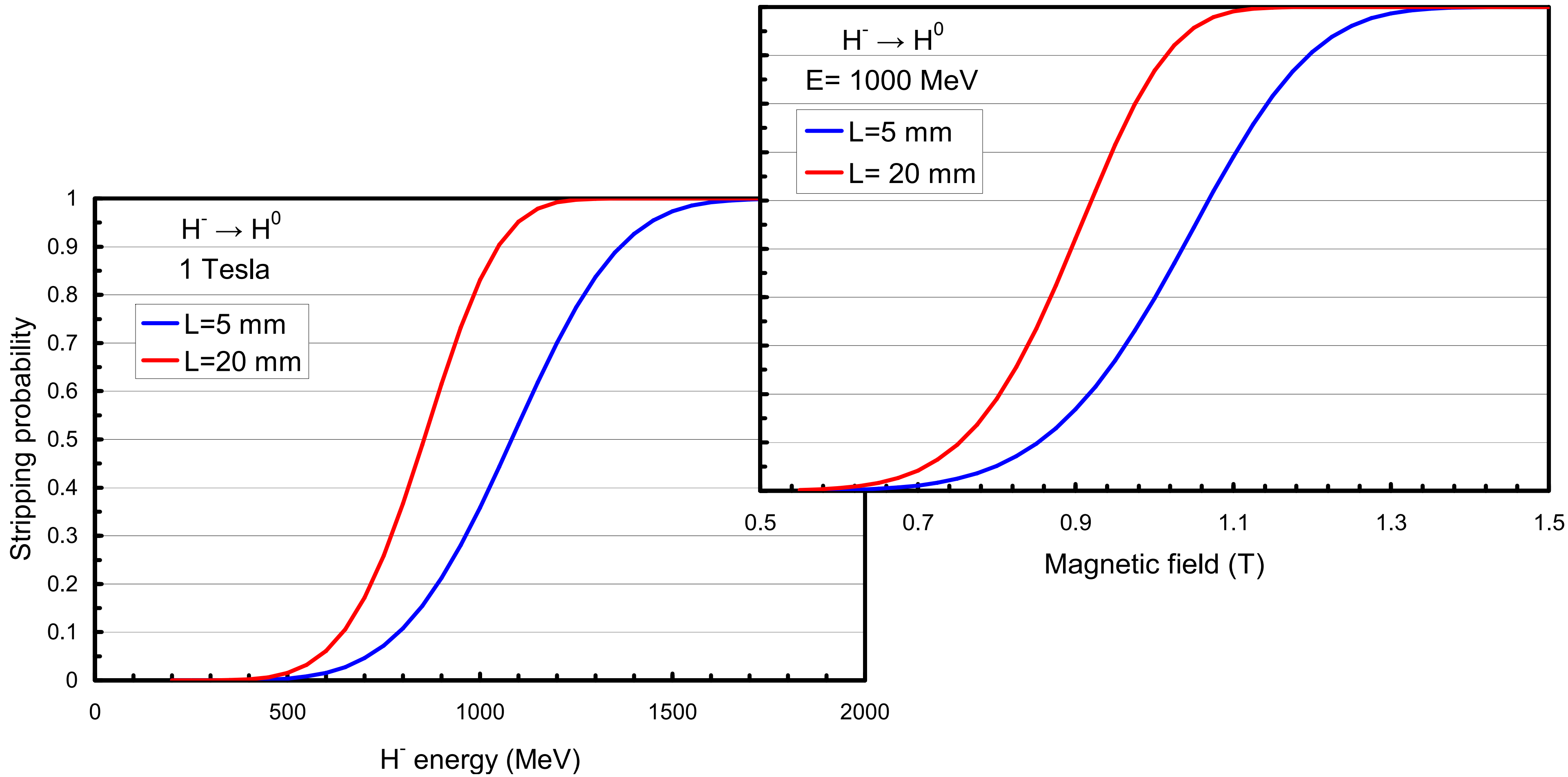
•It allows neutralization of H^- into H^0 with a small magnet
•it can be used with high power beam
•the neutralization rate is easily adjustable by varying the the field
•if the H^0 current is not too high, it can be stripped to H^+ by means of a thick carbon foil with nearly 100% efficiency

World wide Lorentz stripping

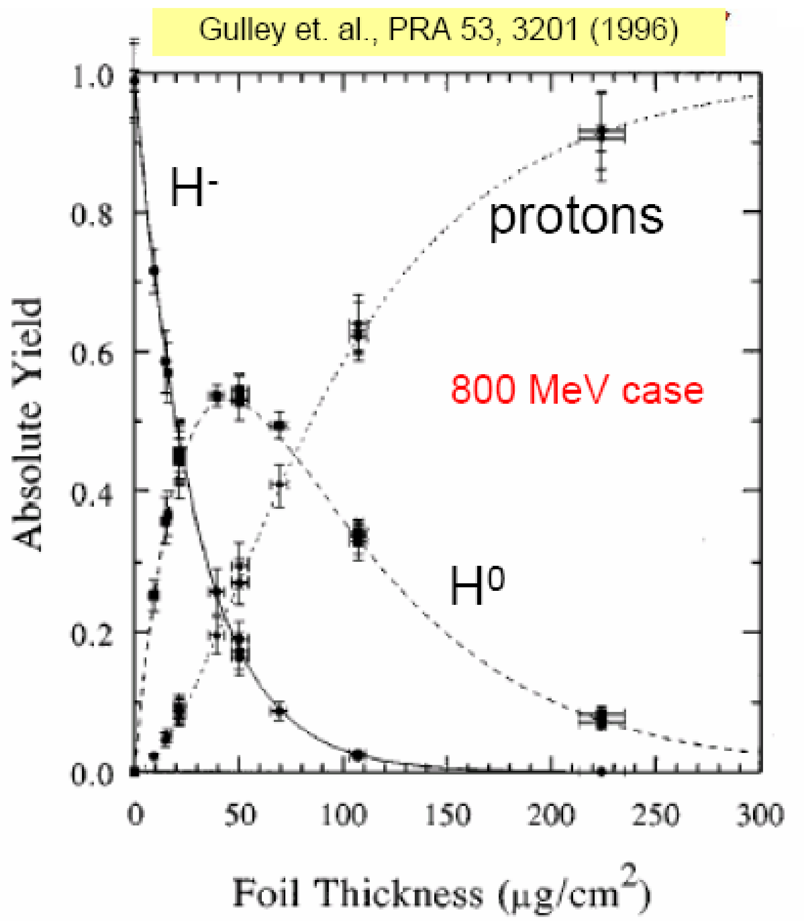
•Exists at LANCE PSR at 800 MeV.
•Suggested for injection of H^- beams into a proton ring at the JAERI neutron source driver using H^- beam at 1.5 GeV [i], for the neutrino factory–muon collider facility at 2 GeV [ii] and for SNS at 1 GeV [iii].

[i] Isao Yamane, PHYS. REV. ST-AB, 1(1998)053501.
[ii] U. Gastaldi and M. Placentino, NIM A 451(2000)318.
[iii] V. Danilov et al. PHYS. REV. ST-AB, 6(2003)053501.

Magnetic stripping probability



beam losses at the splitters



Missing beam from
1. stripping efficiency
2. H^0 excited states+magnetic field

SNS 1° carbon foil:
- 300 μg/cm^2
- 97% efficiency
- 1.4 MW beam

SNS 2° carbon foil:
- 10 mg/cm^2
- ~100% efficiency
- ~ 70 kW beam

EURISOL:
- ~ 100 kW beam
- similar to SNS 2° foil: ~100% efficiency
- little beam loss expected from H^0
- dipole magnet + beam dump (low power) in the splitting stations could be needed

angular spread of H^0

- the primary H^- beam is not affected
- the H^0 angular spread induced by the magnetic neutralization can be made comparable to the primary beam angular spread
- additional spread is introduced by the foil stripper to H^+
- only beam transfer lines from the stripper to the RIB sources: some emittance growth is acceptable

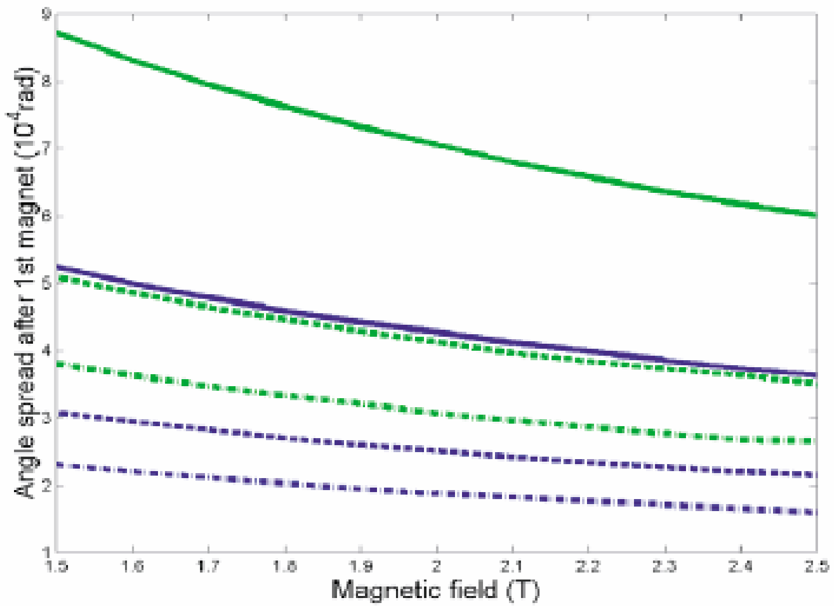


FIG. 1. (Color) Angular spread vs field for 1 GeV (solid lines), 1.3 GeV (dashed lines), and 1.5 GeV (dash-dotted lines) H^- beam energies for the magnet gap 2 cm (blue lines) and 4 cm (green lines).

from V. Danilov et al., PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS,VOLUME **6**, 053501 (2003)

Summary of Lorentz + foil stripper for the EURISOL beam splitter

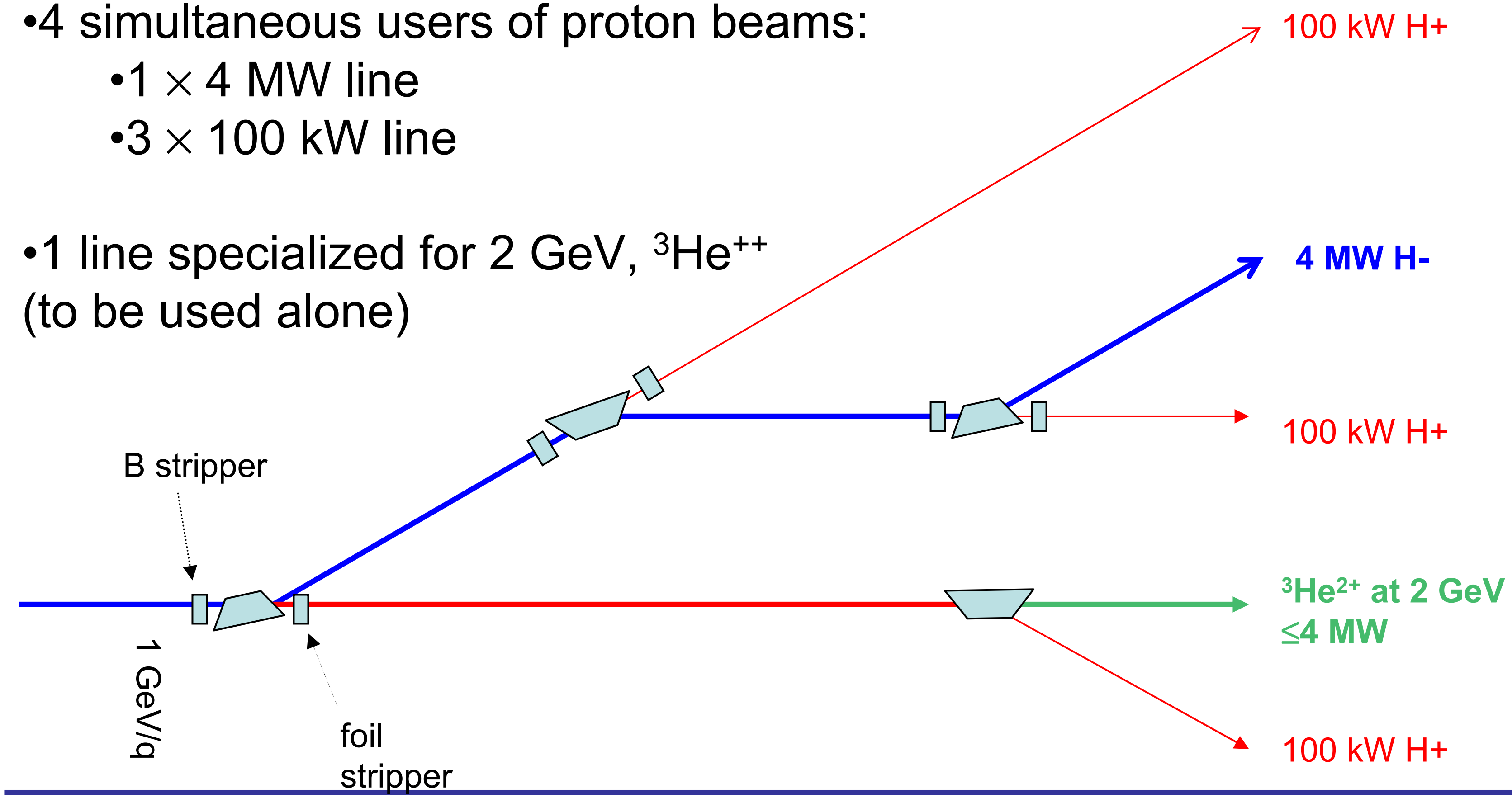
- **Advantages**
  - Existing
  - CW – no thermal shocks
  - Simple to control
  - No disposable parts

- **Drawbacks**
  - (Low intensity spilled beam)
  - H^+ emittance growth

1 GeV Extraction possible scheme

- 3 splitting stations
- 4 simultaneous users of proton beams:
  - 1 × 4 MW line
  - 3 × 100 kW line

- 1 line specialized for 2 GeV, $^3He^{++}$ (to be used alone)



Conclusions

- We have compared different scenarios for the EURISOL Driver, and checked feasibility, performance and cost
- We found that the approximate length of a 5 mA cw, 1 GeV proton linac would be ~200 m and its approximate cost ~200 M€
- We found also that including: 280 MeV A/q=2 and 2 GeV ^{3}He beams would increase length and cost of the driver by only ~16% , without major modifications of the linac structure
- The possibility of using the 1GeV proton beam in 2 or more extraction lines in parallel appears to be feasible with an extra cost of about 3 %
- **The new baseline design includes all the "desirable" features**