Alpha DTL beta

INFN-ACC 2 Marzo 2023

Abstract

Alpha-DTL is a **high perfomance linac for radioisotope** production.

The approach of using alpha particles beams may allow to yield radionuclides hard to be obtained with more traditional nuclear reactors or by proton accelerators, by exploiting new reaction routes. This approach may lead to better radionuclide impurity profiles, simplifying the radiochemical separation and purification process.

From the accelerator point of view, the use of cyclotron for α particles has an intensity limitation (mainly related to the extraction system): the IBA cyclotron at Arronax is for example limited to 35 microA .

The key idea of the alpha-DTL is to use **a high duty cycle linac (ECRIS, RFQ, DTL),** able to accelerate an **average current of 0.5 mA** alpha beam from few to 40 MeV, to cover the cross sections of many interesting reactions for radionuclides. **The energy at the exit of the DTL will be regulated** by a particular use of the stabilization system (Post couplers) of the DTL cavity.

The goal of the present experiment “alpha-DTL_beta” is to address the **R&D activities recognized as critical** during the evaluation of the “alpha-DTL” call and solve the feasibility of the accelerator for a future design report of the complete facility.

A full description of the scientific case can be found in the alpha-DTL call documentation, listed in the references and available to the referees, while in the next pages we will recall just for convenience the main accelerator aspects, then we will describe the project organization and the risk analysis.

This experiment will benefit from experiences and well-developed tools of the previous high intensity linac projects realized by the participants (ESS, TRASCO, IFMIF EVEDA).

Outline

- Scientific Proposal
  - Accelerator reference design
  - The DTL energy regulation
- Organization of the Project
  - WP1 Post Coupler R&D program
  - WP2 RF system R&D
  - WP 3 ION SOURCE
- Risk analysis
- Components of the group
- Budget
- References

Alpha beams for radionuclides

Interesting cases are e.g., the alternative supply of 99mTc through the 96Zr(α,n)99Mo reaction route, or the very important theranostic 67Cu (under the spotlight at international level) by using the 64Ni (α,p) route. Other interesting products are based upon the reaction routes 209Bi(α,2n)211At., or ^{nat}Mo(α x)97Ru.

Fig. 4 Estimation of ^{99}Mo production yields versus target thickness, by considering experimental [16] and theoretical [19] cross sections of the ^{96}Zr(α,n)^{99}Mo nuclear reaction and 100 % enriched target material ($\rho = 6.82$ g cm^{-3})

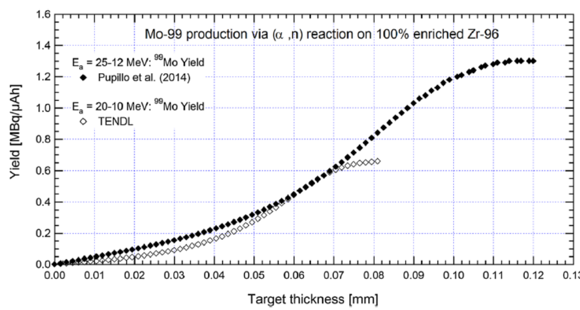


Table 1 Summary of estimated ^{99}Mo yields for fully enriched targets

	Cross section	Energy range (MeV)	Yield (MBq µA^{-1} h^{-1})	Target thickness (µm)
^{100}Mo(p,x)^{99}Mo	Experimental [18]	70–10	360	6550
	Theoretical [19]		380	
	Experimental [18]	40–10	120	2330
	Theoretical [19]		120	
^{96}Zr(α,n)^{99}Mo	Experimental [16]	25–12	1.26	115
	Theoretical [19]	20–10	0.65	80

Table 1: Radionuclides commonly produced using the α-particle beam.

Radio-nuclide	$T_{1/2}$	Radiation emitted (%)	Nuclear reaction	Energy range (MeV)	Yield[a)] (MBq/µAh)	Purity (%)	References to production	Other investigated reactions[e)] [Reference]
^{28}Mg	21.1 h	β^- (100)	^{27}Al(α,3p)^{28}Mg	140 → 30	1.5	> 99	[56, 57]	^{26}Mg(t,p)^{28}Mg (cf. [56, 57])
^{30}P	2.5 min	β^+ (100)	^{27}Al(α,n)^{30}P	24 → 10	ca. 1000[b)]	> 99.9	[60, 61]	^{32}S(n,t)^{30}P [61]
^{38}K	7.6 min	β^+ (100)	^{35}Cl(α,n)^{38}K	22 → 7	ca. 400[b)]	> 99.8	[62–67]	^{38}Ar(p,n)^{38}K [68] ^{40}Ar(p,3n)^{38}K [69, 70]
^{43}K	22.2 h	β^- (100)	^{40}Ar(α,p)^{43}K	21 → 10	7.0	97.5	[74–76]	^{44}Ca(γ,p)^{43}K [77, 78] ^{43}Ca(n,p)^{43}K [79]
^{77}Br	57.0 h	EC (99.3) β^+ (0.7)	^{75}As(α,2n)^{77}Br	28 → 16	16.6	> 99.9	[84–87]	^{77}Se(p,n)^{77}Br [88, 89] ^{78}Se(p,2n)^{77}Br [89, 90] ^{79}Br(p,3n)^{77}Kr → ^{77}Br [91, 92] ^{79}Br(d,4n)^{77}Kr → ^{77}Br [93]
^{95}Ru	1.65 h	EC (85.0) β^+ (15.0)	^{92}Mo(α,n)^{95}Ru	28 → 14	240[c)]	> 99	[97, 98]	^{nat}Mo(^{3}He,xn)^{95}Ru [97, 98]
^{97}Ru	2.9 d	EC (100)	^{nat}Mo(α,xn)^{97}Ru	28 → 16	1.8[d)]	> 99.8	[97–99]	^{nat}Mo(^{3}He,xn)^{97}Ru [97, 98]
^{147}Gd	38.1 h	EC (99.7) β^+ (0.3)	^{144}Sm(α,n) ^{147}Gd	27 → 12	4.8	> 99.8	[100, 101]	^{147}Sm(^{3}He,3n)^{147}Gd [100, 101]
^{211}At	7.3 h	EC (58) α (42)	^{209}Bi(α,2n)^{211}At	28 → 10	17.5	> 99	[81, 104–110]	^{232}Th,^{238}U(p,spall)^{211}At [112] ^{209}Bi(^{6,7}Li,xn)^{211}Rn → ^{211}At [113, 114]

a) Calculated from excitation function.
b) This is saturation yield.
c) Value extrapolated to 100% enrichment of ^{92}Mo.
d) At 15 h after EOB.
e) For comments on these reactions, see text.

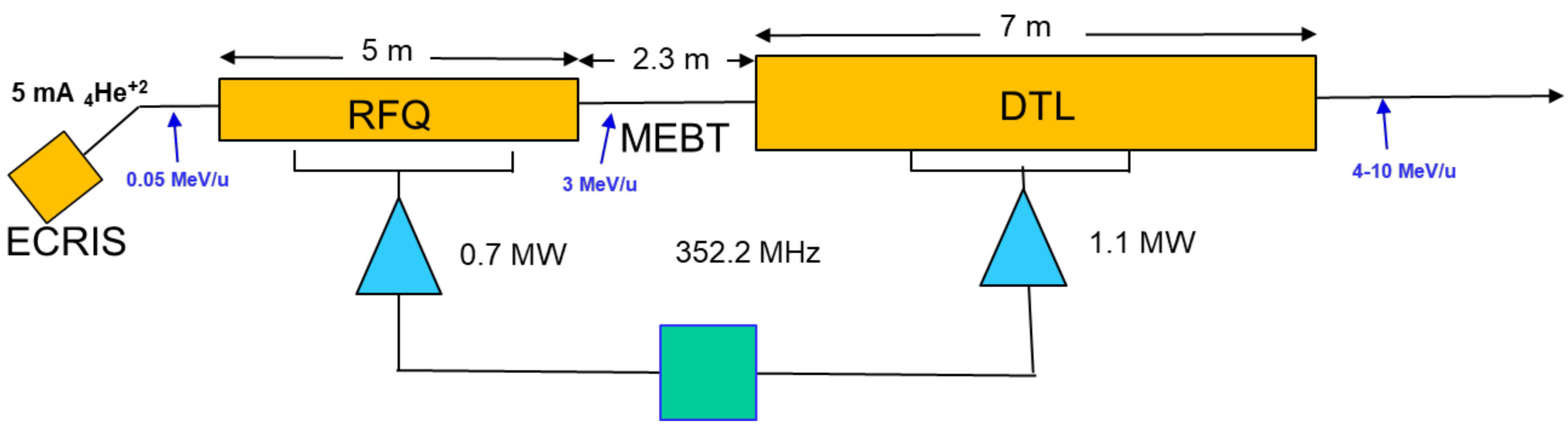
Ref.
Qaim et al. “Uses of alpha particles, especially in nuclear reaction studies and medical radionuclide production”
Pupillo, Esposito et al. “Accelerator-based production of 99Mo: a comparison between 100Mo(p,x) and 96Zr(α,x) reactions.»

Linac general scheme

The key idea of the alpha-DTL is to use a high duty cycle linac (ECRIS, RFQ, DTL), able to accelerate an average current of 0.5 mA alpha beam from few to 40 MeV, to cover the cross sections of many interesting reactions for radionuclides. **The energy at the exit of the DTL will be regulated by a particular use of the stabilization system (Post couplers) of the DTL cavity**. An average of 0.5 mA of fully stripped He can be delivered to the target.

The starting points:

- ECRIS studies →AISHA source of LNS.
- RFQ→ TRASCO RFQ
- DTL→ ESS.
- RF system→ two klystrons-single modulator architecture is the same of ESS normal conducting section. To be used at ½ peak power and twice duty cycle.



Reference accelerator design

Table summarize the main parameters of the reference linac. The frequency is 352 MHz. The RFQ will end at 3 MeV/u, the DTL at 10 MeV/u. The total lengh of the linac will be around 15 m. It is important to highlight here that a criticality is **the demonstration of the starting beam parameters: the intensity goal of 5 mA within 0.2 mm.mrad normalized r.m.s. emittance is possible but challenging**.

Parameter	Symbol, unit	RFQ Value	DTL Value
Frequency	f [MHz]	352.21	352.21
Peak Current	I_p [mA]	5	5
Ion		$^4He^{2+}$	$^4He^{2+}$
Duty Cycle	D.C. [%]	10	10
Input / Output Energy	E_{in}/E_{out} [MeV/u]	0.05/3.0	3.0/10.125
Resonator length	L [m], λ	4.99, 5.874	6.8, 8.0
Maximum surface field	K_p	1.85	1.6
Transmission WB, Gaussian	[%]	92.5, 88.9	100, 100
Transverse Emittance in/out	$\varepsilon_{in,n,x,rms}/\varepsilon_{out,n,x,rms}$ [mm mrad]	0.2/0.17	0.24 /0.24
Longitudinal Emittance	$\varepsilon_{l,rms}$ [deg MeV/u]	0.129	0.15
Min and Max Voltage	V_{GB}, V_{acc} [kV]	68, 102.5	-
Average Acc. Field	E_0[MV/m]	-	2.6
Quadrupoles Gradient	G_{max}, G_{min} [T/m]	-	57.6, 41
Quadrupoles Length	PMQ length [mm]	-	50
Average Aperture	$R_{0,\,GB}$ $R_{0,\,ACC}$ [mm]	2.55, 4.13	-
Quadrupoles Bore	Rbore [mm]	-	10
dissipated Power and beam loading (peak)	Pd, Pb [kW]	672, 29.5	1020, 70

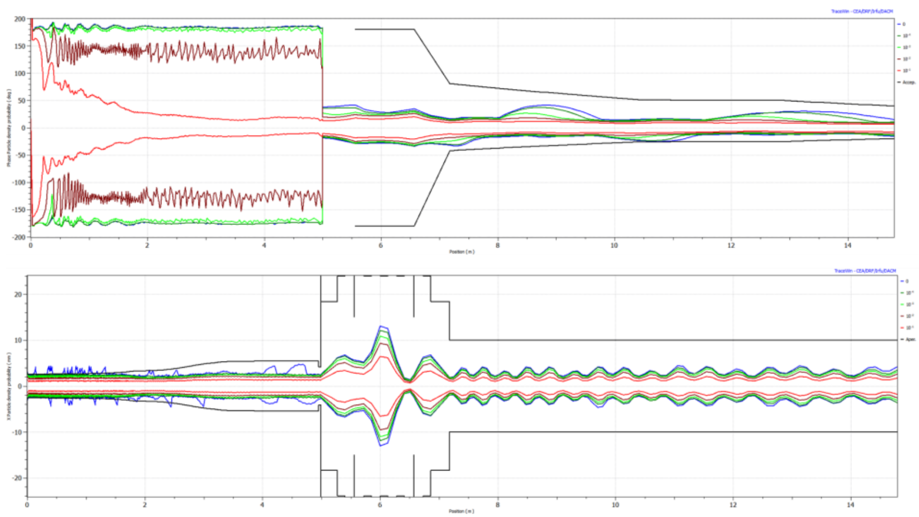
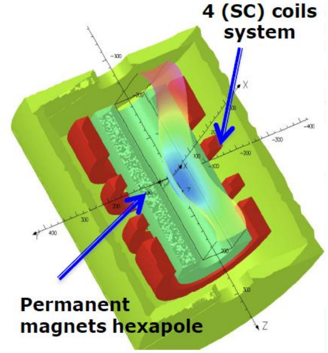


Fig. 5: Start to End simulation from the begin of RFQ to the end of DTL.

AISHA ECRIS

AISHA is a hybrid ECRIS: the radial confining field is obtained by means of a permanent magnet hexapole, while the axial field is obtained with a Helium-free superconducting system.

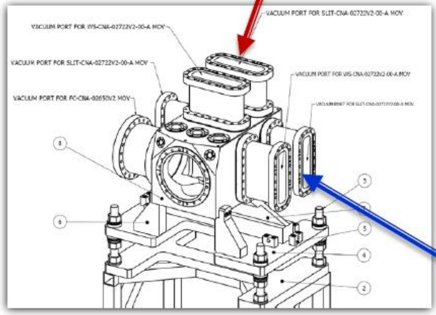
AISHa has been already commissioned at 18 GHz operating frequency and a second klystron amplifier operating in the 21 GHz band-1.5 kW, will be coupled to the source to carry out a two frequency heating mechanism, i.e. 21 + 18 GHz.
The plasma chamber, able to hold a maximum power rate of 2 kW, the three electrodes extraction
system and the waveguide DC break has been designed to permit reliable operation up to 50 kV.

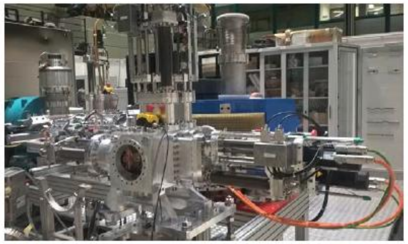


AISHa Experimental setup

AISHa Emittance measurements setup

Vertical slit and BWS





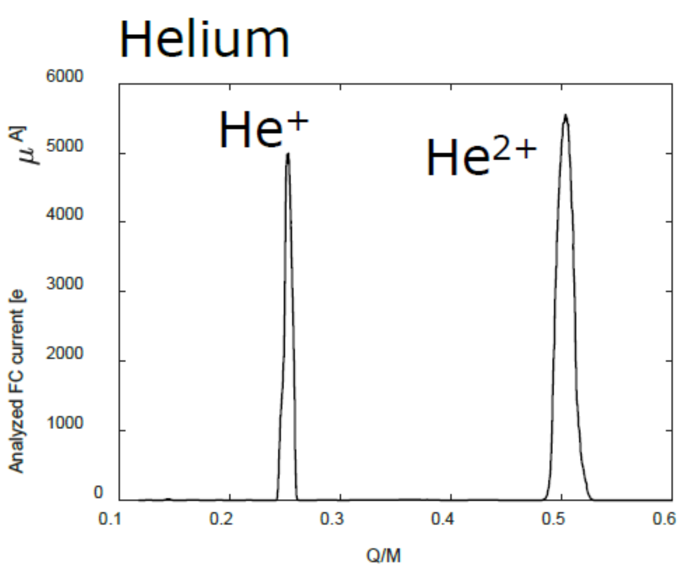
Horizontal slit and BWS

Ref.
G. Castro, L. Celona et al.” The AISHa ion source at INFN-LNS”, 2021

AISHA ECRIS

Results of preliminary commissioning at 18 GHz of AISHA show its ability to produce 5 mA CW of He2+, but with a with higher emittance than assumed for the Linac design.

Dedicated sessions need to be setup to minimize this figure working, on several areas (extraction mainly) which have not been yet fully exploited.

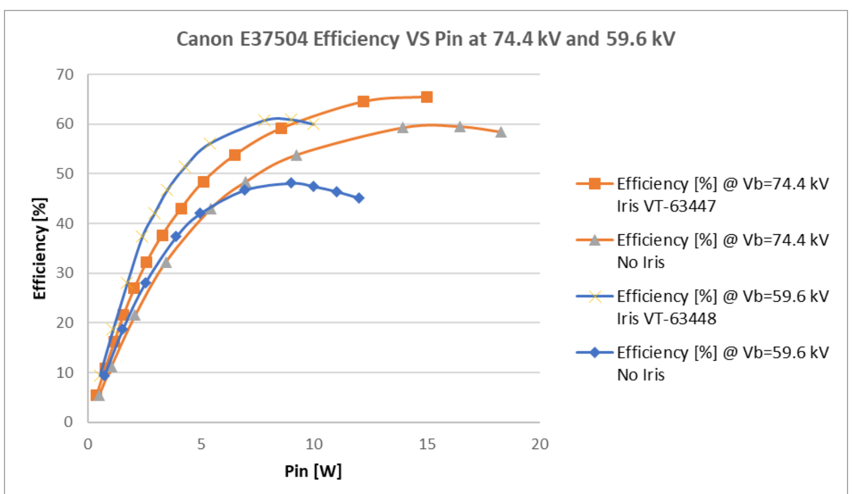


AISHa performances
SFH (17.3-18.4 GHz) – 1.5 kW max

Charge state	Beam intensity [eμA]	$\varepsilon_{rms.norm}$ [$\pi \cdot mm \cdot mrad$]
$^{16}O^{6+}$	1400	0.2198
$^{16}O^{6+}$	225	0.115
$^{16}O^{7+}$	350	0.247
$^{12}C^{4+}$	650	0.272
$^{12}C^{4+}$	150	0.222
$^{12}C^{5+}$	165	---
$^{40}Ar^{11+}$	155	0.201
$^{40}Ar^{12+}$	140	0.201
He^{2+}	5400	0.418
He^{2+}	700	0.245

Ref.
L. Celona et al.” Status of the AISHA ion source at INFN-LNS”, 202

RF system



The 352 MHz klystrons and modulators used for ESS linac can be used as RF sources for **alpha-Linac RFQ and DTL** with minor adjustments.

The klystrons, now optimized for 352 MHz – 2.8 MW – 14 Hz – 3.2 ms (5% duty cycle), can be used in our case at 1.4 MW peak power but 10% duty cycle. 50 Hz repetition rate is preferable for the modulator point of view (courtesy of Carlos Martins).

The klystrons, operating far from saturation point, will be **re-optimized in efficiency by acting on mode-anode voltage, coil focalizations, output line mismatch**. The ESS RF group successfully already applied those techniques to the ESS klystrons (courtesy of Chiara Marrelli and Morten Jensen).

INFN LNL
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

DTL energy regulation

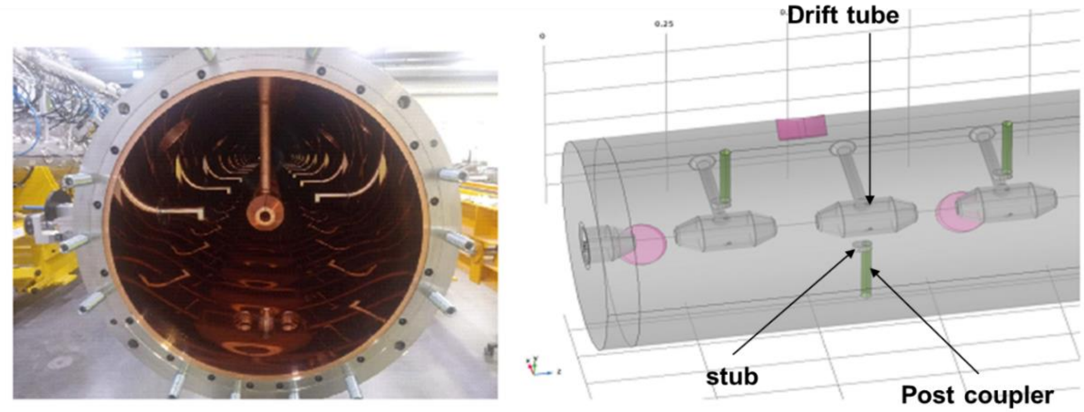
Alpha-DTL is equipped with a **set of post couplers terminated by stubs**, to stabilize and flatten the accelerating field E0.

Modest perturbations to the symmetry of the Post-Coupler/Drift-Tube geometry can introduce few per cent cell-to-cell changes in the fields across the post coupler.

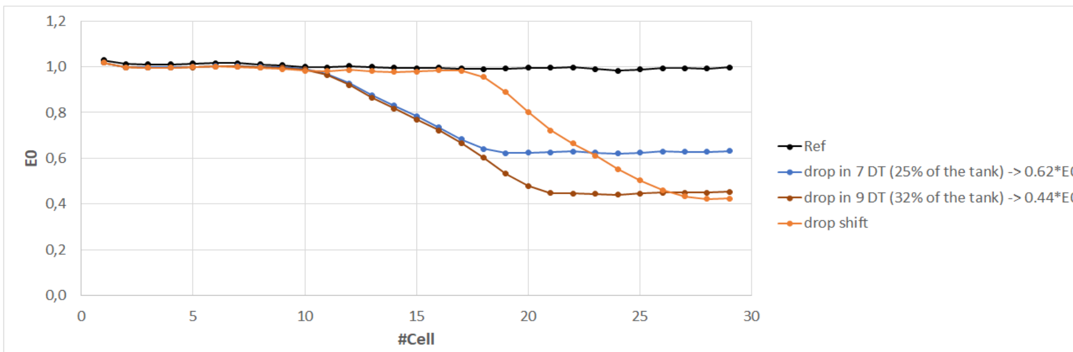
Several such perturbations on adjacent post couplers can introduce a sizable reduction in the fields over the region of a few cells.

Such steps in the fields can be used to drop the beam out of synchronism with the accelerating fields and provide a variable-energy capability for the single-tank, post-coupled DTL.

The max output energy will correspond to fully flat field over all the DTL gaps. The creation of the field step in different points of the DTL will provide different output energies.



DTL cavity inner view and 3d simulation model. Post couplers with stubs are visible



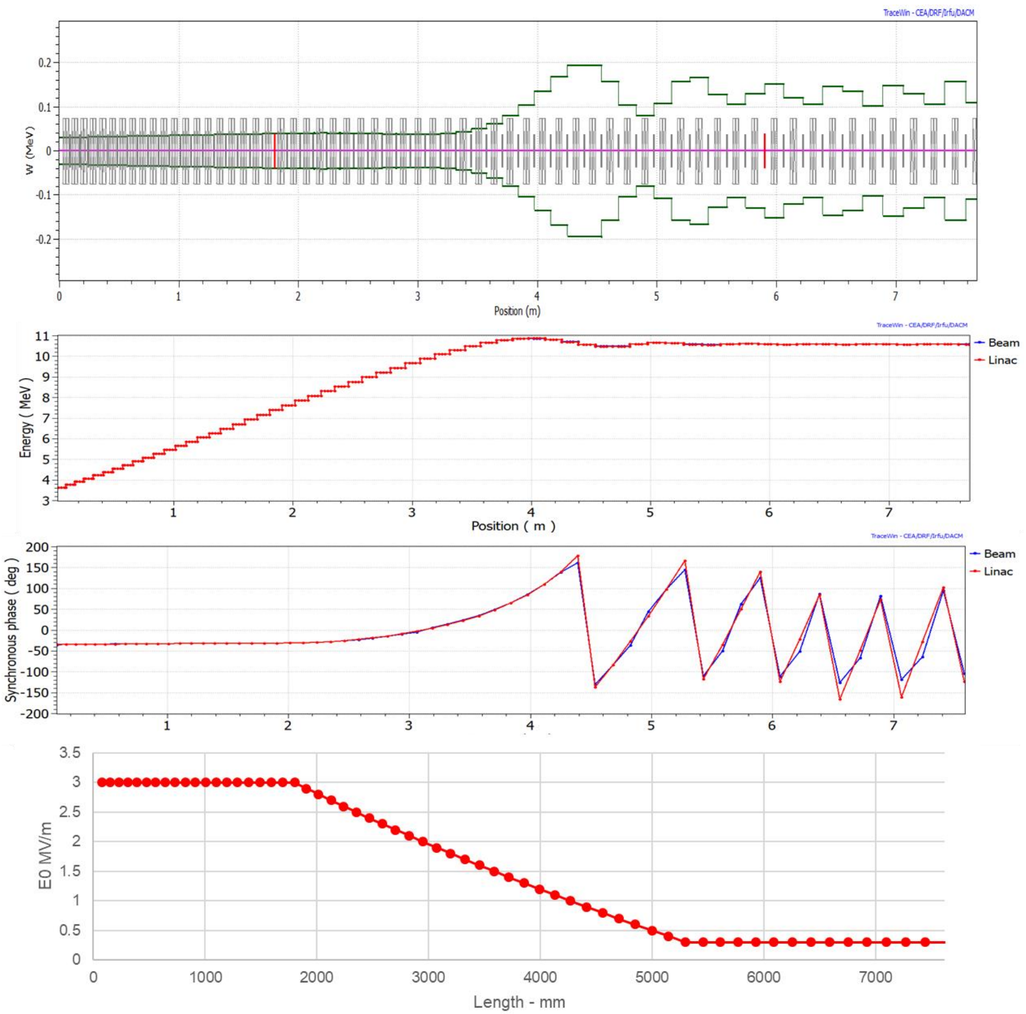
Field steps experimentally obtained by post coupler rotation in ESS-DTL3

Roughly $k(n)*E0(n)=k(n+1)*E0(n+1)$

BD energy regulation: loose of synchronism

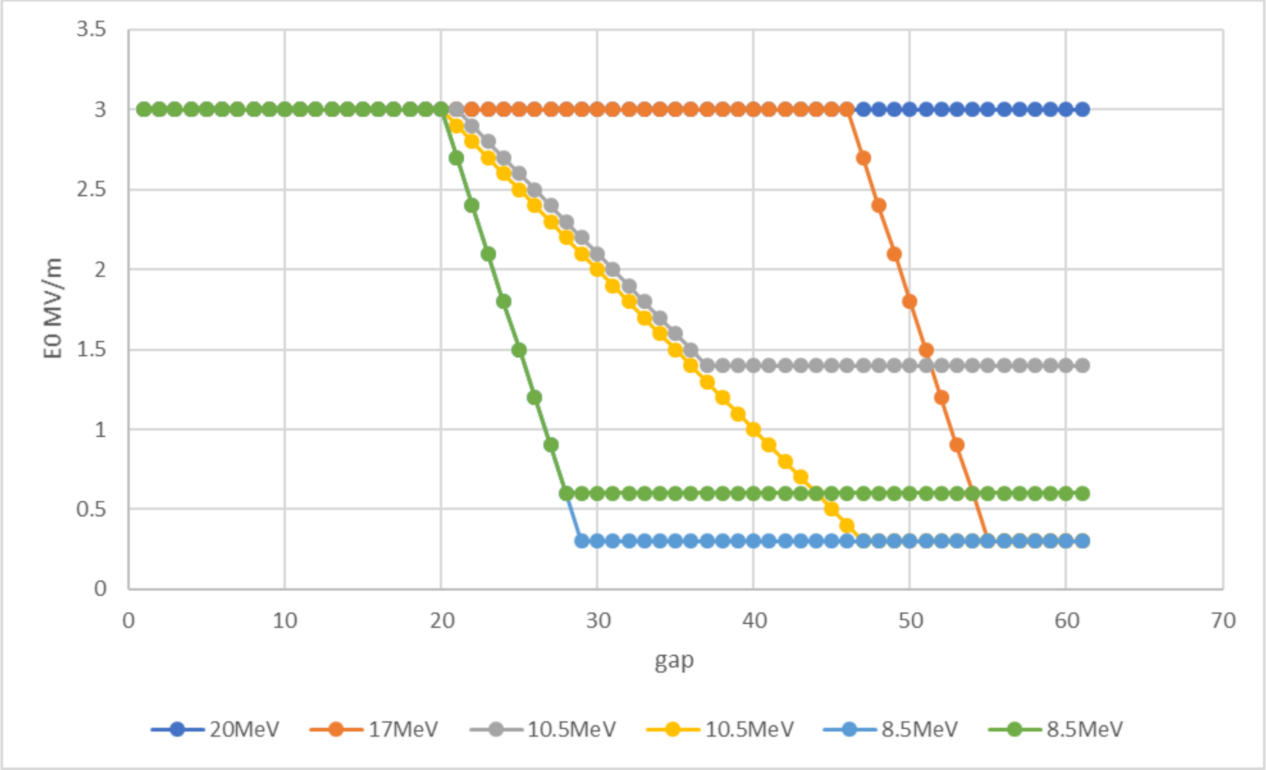
Particles in the ramped gaps start to loose synchronism, up to not being accelerated anymore.
The focusing given by the PMQs guarantees full transmission of the beam to the end of the DTL.

Increasing the number of Post Coupler per meter as well as the dimension of the stub, it will improve the capability of obtaining a sharper edge on the field. This condition will preserve the beam quality and the energy spread.

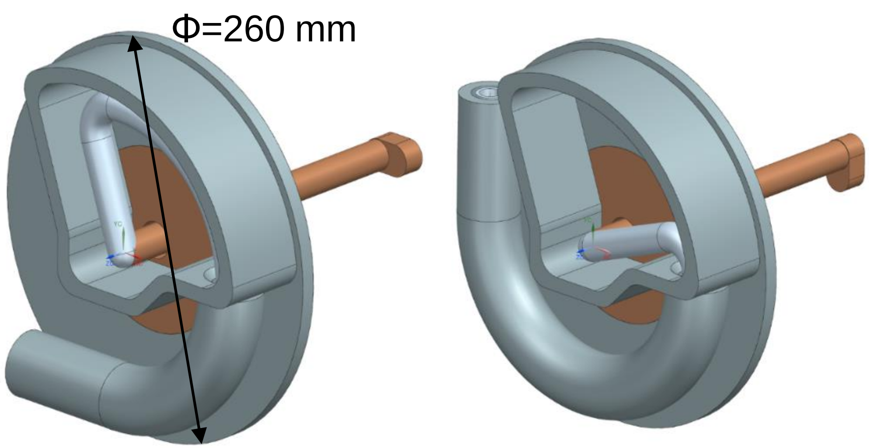


BD energy regulation: loose of synchronism

A set of beam dynamics simulations were undertaken on the lattice of ESS-DTL1 (protons from 3.6 to 20 MeV), with different E0 configurations.
The results are output energies of protons from 8 to 20 MeV, all with 100% transmission of the beam.



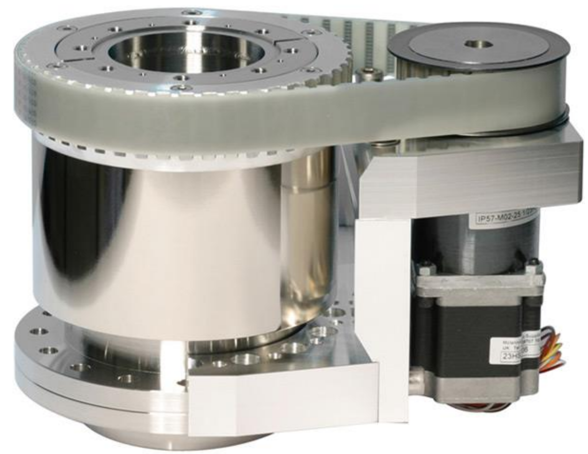
Mechanics of the Routable Post Coupler

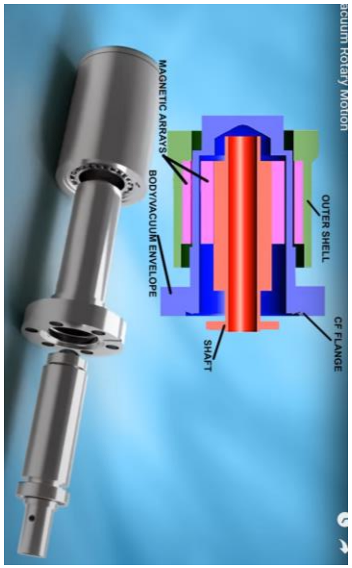


Soluzione disegnata @INFN, tutte tenute statiche.

Punti di ottimizzazione, ciclo virtuoso tra design RF e meccanica:

- Minimizzare angolo di rotazione richiesto: design RF della cavità che minimizzi la richiesta di rotazione per il campo nominale, massimizzando lo stroke angolare disponibile per la rampa
- Raffreddamento: sensibilità alla dilatazione in lunghezza durante High Power RF, ridurre il raffreddamento e di conseguenza le dimensioni del soffietto.





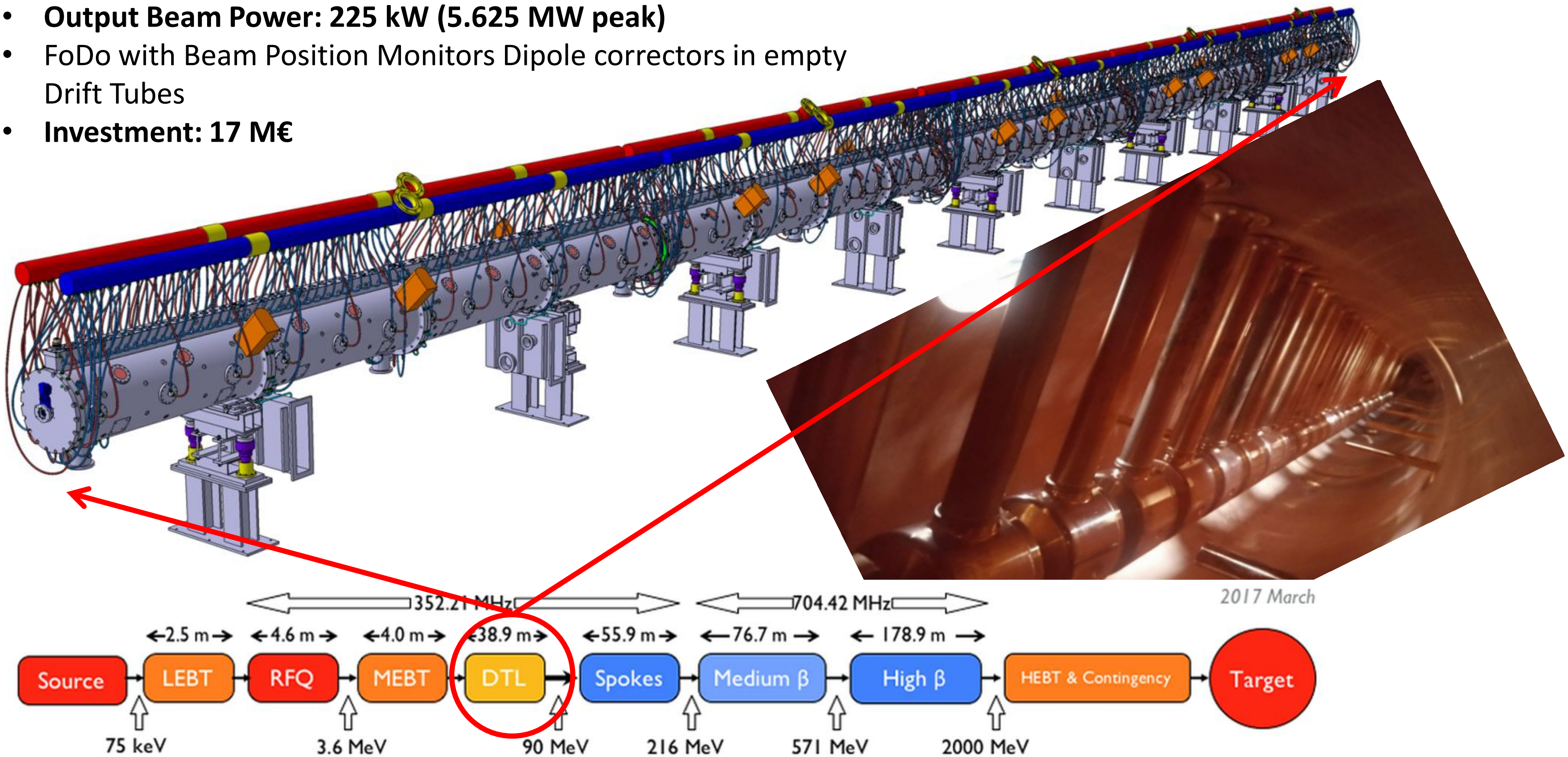
Soluzione commerciale? Passante ad albero cavo accoppiato magneticamente.

Da valutare la necessita’ di raffreddare il vacuum envelope e il livello di vuoto garantito.

ESS DTL

Main Normal Conducting Accelerator component:

- **Length: 40 m**
- Output Beam Energy: 90 MeV (protons at 40% speed of light)
- **Output Beam Power: 225 kW (5.625 MW peak)**
- FoDo with Beam Position Monitors Dipole correctors in empty Drift Tubes
- **Investment: 17 M€**



ESS DTL Layout

Parameter / Tank	1	2	3	4	5
Cells per cavity	61	34	29	26	23
Accelerating field [MV/m]	3.00	3.16	3.07	3.04	3.13
Maximum surface field [Kilp.]	1.55	1.55	1.55	1.55	1.55
Synchronous phase [deg]	-35 to -25.5	-25.5	-25.5	-25.5	-25.5
Total power per cavity* [KW]	2192	2191	2196	2189	2195
Power on copper** [KW]	870	862	872	901	952
Quadrupole length [mm]	50	80	80	80	80
Bore Radius [mm]	10	11	11	12	12
Number of modules	4	4	4	4	4
Length [m]	7.62	7.09	7.58	7.85	7.69
Beam output energy [MeV]	21.29	39.11	56.81	73.83	89.91

* Total power = 1.25 × Power on copper + Beam Power < 2.2 MW.

** MDTfish calculation, no margin.

DTL Tuning: Average field and Tilt sensitivity

Average Field E0 [MV/m]

It is the measure of the accelerating field of each cell, which must be compliant to specifications (< ±2% with respect to the nominal).

The unit is [MV/m], usually normalized to 1.

$$E_0 = \frac{V_0}{L_{cell}} = \frac{\int_{Lcell} \overline{E}(0,z)d\overline{z}}{L_{cell}}$$

Tilt sensitivity TS [%/MHz]

A tilt-sensitivity measurement indicates the effectiveness of post couplers in stabilizing the field. In this procedure, a change in the accelerating gap length in an end cell of a multicell cavity causes a frequency shift Δf from the cavity resonant frequency f_0. One then adjusts the opposite end-cell gap to cause an opposing frequency shift -Δf, restoring the operating frequency to f_0. The standard bead-pull technique determines the resulting axial electric-field profile. The tilt-sensitivity parameter for a cell of the linac is defined as

$$T = \left(\frac{X_P - X_U}{X_U}\right)\frac{1}{\Delta f} \quad , \qquad (1)$$

where X_U is the maximum field amplitude in the cell for the unperturbed case, and X_P is the maximum field amplitude when the end cells are perturbed by ±Δf as described above. Figure 2 shows the tilt sensitivity

- TS is evaluated on each cell → TS_i
- TS_i=100%/MHz→ a frequency error on the end cells that induce 1MHz detuning on the full tank will cause a tilt of 100% of the field of the cell(i).

The tuning monks of DTL1

A brief overview on the experience of tuning DTL1 at ESS.

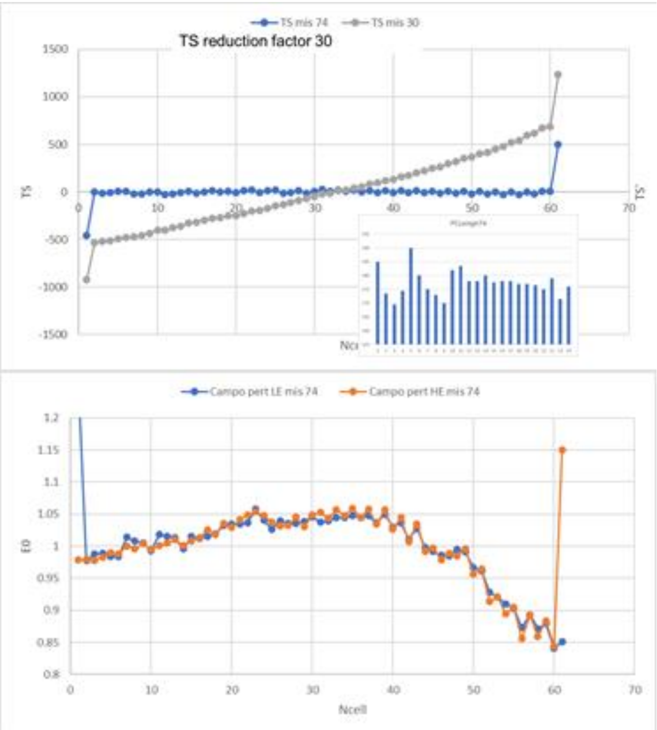
This activity covered 4 months of works between Nov 2020 and Feb 2021.

More than 1500 iterations and 4 months to reach specifications.

We organized our days with the St Benedict rule: “*tune et elabora*”.

Ref: Benedetto da Norcia, “Regula monachorum”

- Issue we found:
  - The DTL is well stabilized by Post Couplers (Sensitivity to errors reduced of factor 30)
  - But field flatness increased from 2% before stabilization to 20% (unexpected)
  - Field stabilized very difficult to counter-tune, as expected

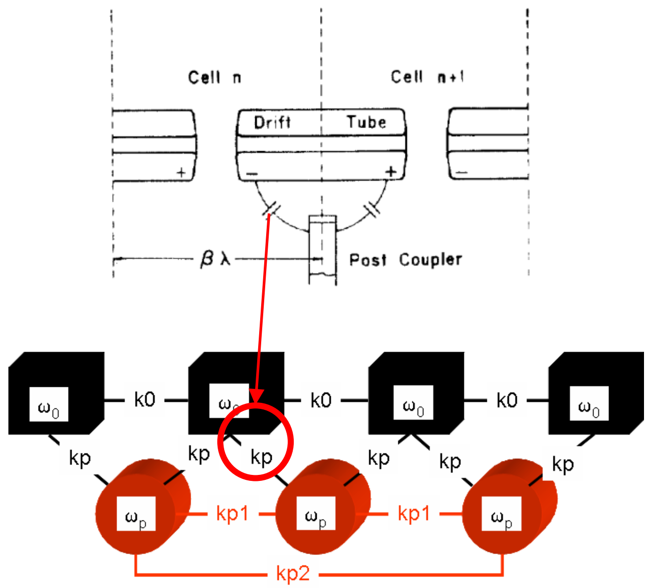


Tuning task force

Theory.

From the circuit model and the literature, unbalancing the capacitive coupling between adjacent gaps introduce a tilt on the field.

Roughly *k(n)*E0(n)=k(n+1)*E0(n+1)*



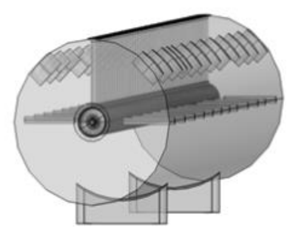
Ref:
J. Billen, “Post-coupler stabilization and tuning of a ramped-gradient drift-tube linac”
F. Grespan “Equivalent circuit for postcoupler stabilization in a drift tube linac”

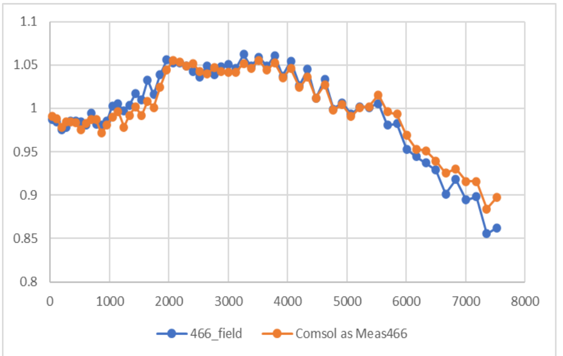
Simulations

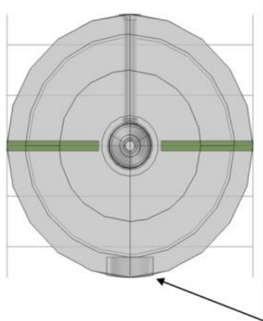
3D RF simulations nowadays of a full DTL with PCs well agree with reality. We demonstrated that:

1- the root cause of the issue is an electromagnetic coupling between Tuner and Post Couplers (intrinsecally 3D)

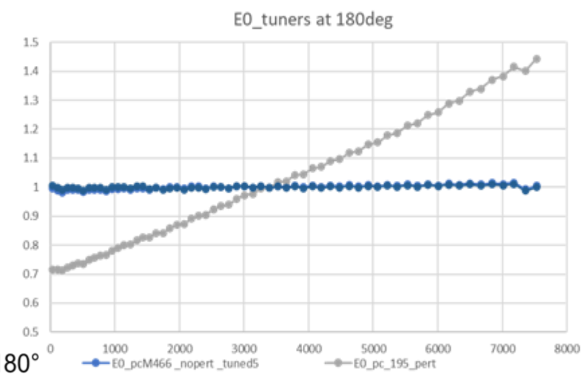
2- umbalancing the coupling between ajacent cells can be a solution.







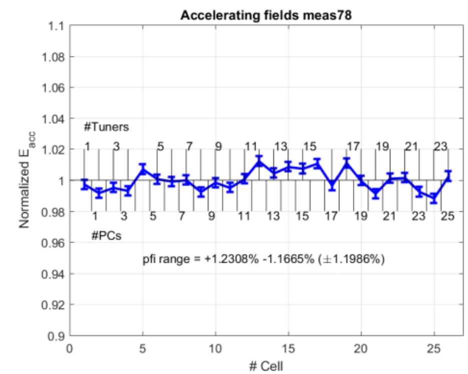
Tuner@180°

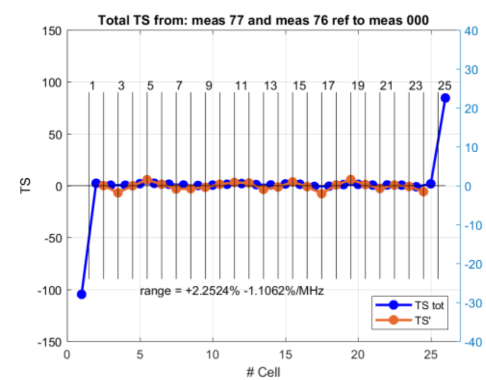


Tuning task force: post couplers with eccentric tab.

We passed to use Post couplers equipped with end eccentric tab.

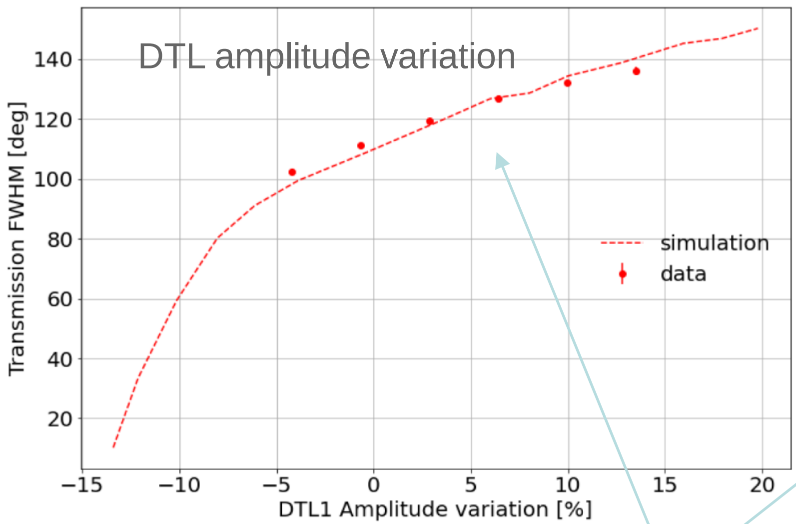
We solved the problem of DTL1 ad the next DTLs only required 2 days for tuning.

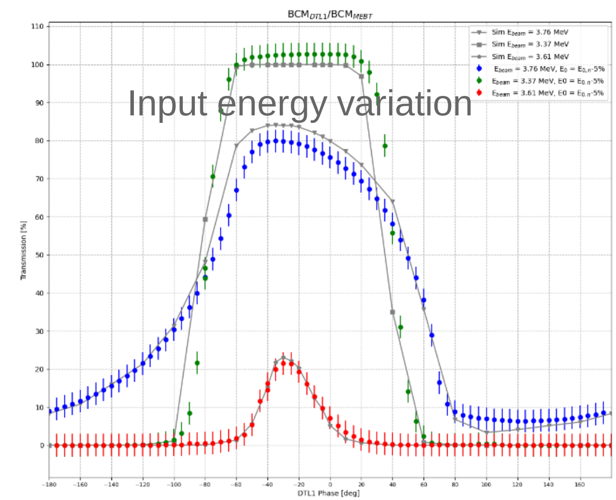


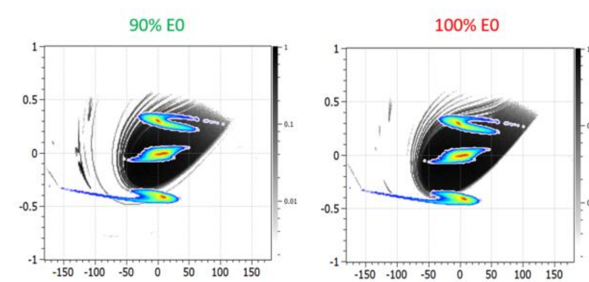


DTL1 conditioning and commissioning

- Conditioned to full RF power (1200 kW, 3.2ms, 14Hz)
- 62.5 mA, 5µs beam accelerated
- 100% transmission over nominal phase range
- Accelerating field calibration refined with beam
- Polarity of PMQs and Steerers confirmed
- Interesting scan of the long acceptance with input energy variation by the bunchers





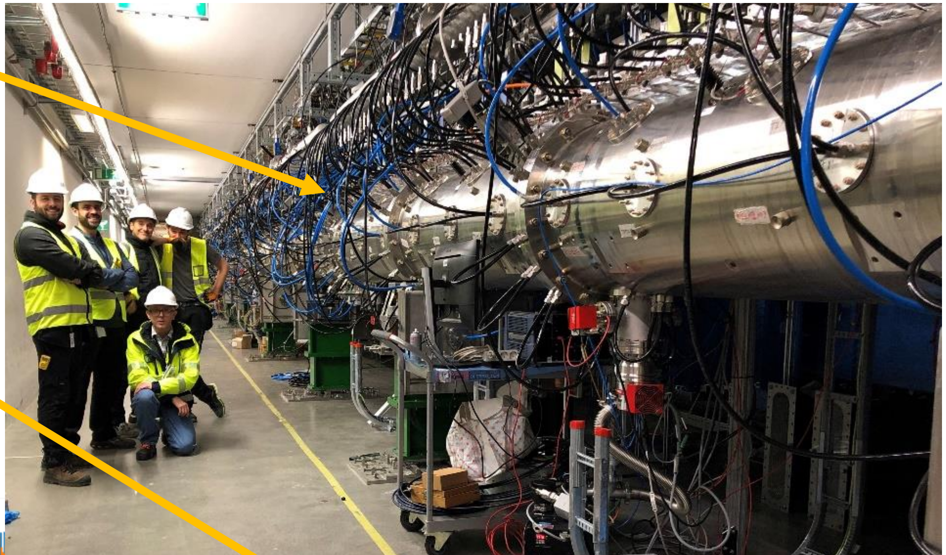


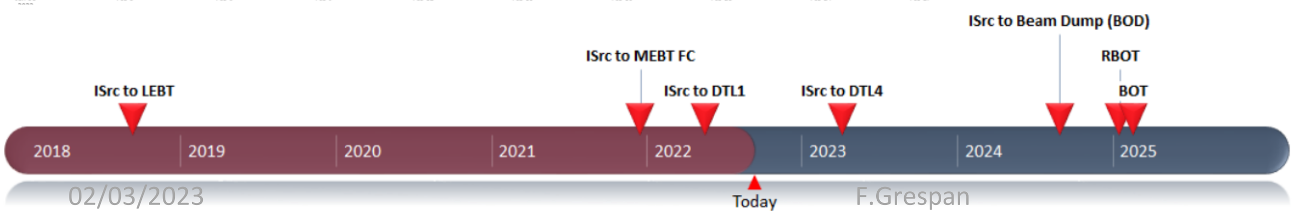
$E_{0,rf} \geq E_0 + 5\%$, from different techniques of long acceptance scan.

Status and next steps

- After tunnel declassification in summer, installation of DTL4 (Sept) DTL3 (Oct) DTL2 (Dec)
- <u>RF Conditioning started on Feb 1st 2023</u>
- Commissioning in April-May 2023
- DTL5 under assembly now, installation in Autumn 2023, commissioned with SCL

1st month of conditioning – E0 MV/m





WP1 Post Coupler R&D & budget

People: Marco Nenni (INFN-To), Luigi Ferrari (INFN-LNL), Andrea Pisent (INFN-LNL)

Program

- Design and develop the **motor system and the remote control to rotate the post couplers in vacuum** and in high RF power conditions. In particular Post coupler shall be water cooled.
- Production of the motorized post coupler.
- Test the post coupler movement in a vacuum chamber.

Budget

The cost includes the material, bellows, motor and actuator, the production and test. It is based on the budget of similar equipment for the ESS-DTL project (movable tuners).

WP1	**Movable Post coupler prototyping**	
MS# or DLV#	Description	Months from T0
MS2.1.a	Mech. Design of motorized post coupler	6
MS2.1.b	Production of 1 motorized post coupler and vacuum chamber	18
MS2.1.c	Test in vacuum of 1 motorized post coupler	24
DLV2.1	Report of test in vacuum of a motorized PC	24

WP1	**Movable Post coupler prototyping**	**2022**	**2023**	**Tot**
		kEuro	kEuro	kEuro
consumables	Motorized post coupler mech.design	5	0	5
equipment	Motorized post coupler production	25	10	35
consumables	Test motorized PC in vacuum chamber	0	10	10
Tot		30	20	50

WP2 RF system R&D and Budget

People: Antonio Palmieri (INFN-LNL), Francesco Grespan (INFN-LNL)

Program

The activities of this task want to demonstrate the **applicability of the ESS high power RF System to the alpha-LINAC** requirements in terms of Output power, repetition rate, pulse length, electrical efficiency. This task will involve for 2 years 2 RF technologist.

Budget

For the travels and the meetings with ESS staff, it will be harmonized in the activities to be done in Lund for ESS-DTL installation and commissioning.

The **technical design of the modulator will be outsourced**, since there is not internal expertise in the group.

WP2	**RF system development**	
MS# or DLV#	**Description**	**Months from T0**
MS2.2.a	Set up development program with ESS-RF group	6
MS2.2.b	Technical specifications of a modulator and RF system compliant with alpha-Linac requirements	15
DLV2.2	**Preliminary Design of Modulator and RF system for apha-DTL**	24

WP2	**RF system developemnt**	**2022**	**2023**	**Tot**
		kEuro	kEuro	kEuro
services	Modulator technical design	0	10	10
Tot		0	10	10

WP 3 ION SOURCE

People: Alessio Galatà (INFN-LNL), Luca Bellan (INFN-LNL), Ornella Leonardi (INFN-LNS), Luigi Celona (INFN-LNS)

Program.

- the experimental verification of the possibility to produce a stable He2+ beam with the required intensity and quality on one hand, possibly applying some “tricks” to improve the performances.
- the study and design of a space charge-optimized extraction system to improve beam quality.

The experimental campaign will be carried out at the AISHA test bench. All the tests will involve the verification of the beam emittance and the long-term stability of the extracted beam.

Budget.

WP3 budget includes travels for 20 k€, since most of the activity within WP3 will consists in **experiments at LNS** with the aim at verifying the possibility to produce the required intensity stably and with good beam quality.

WP3 also will spend 10 k€ in consumables.

The AISHA plasma chamber is presently made of stainless steel. To take advantage of the positive effect on the ion source performances coming from the use of aluminium, dedicated **Al liners** will be designed and built. other possible materials will be investigated

Ion Source	
Description	**Time from T0**
He2+ production by applying the frequency tuning	**6**
He2+ production with the optimized frequency at different extraction voltages	**12**
Simulation of plasma dynamics in AISHA	**12**
He2+ production with an Al liner at the optimized frequency and extraction voltage	**18**
Simulation of beam extraction in experimental conditions	**18**
Report on AISHA characterization in single frequency heating	**24**

WP3	Ion Source	2022	2023	Tot
		kEuro	kEuro	kEuro
travels	Experiment at AISHA LNS	5	5	20
consumable	Experiment at AISHALNS	5	5	10
Tot		15	15	30

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Risk analysis

- The risk analysis follows the risk matrix approach.
- For the impact we consider technical, cost and/or schedule impact.
- The identified impacts will be mostly addressed by the design of the entire facility, which is out of the scope of this experiment. It is important to recognize them as soon as possible.
- In a strongly integrated system as a linac, the underperformance of one of the components can have consequences on the performance of other components. In the other hand the overall performances of the linac can be recovered by adapting other parts to compensate the issues of one of the components.

IMPACT					
Very High (16)	HIGH (16)	HIGH (32)	VERY HIGH (64)	VERY HIGH (128)	VERY HIGH (256)
High (8)	MEDIUM (8)	HIGH (16)	HIGH (32)	VERY HIGH (64)	VERY HIGH (128)
Medium (4)	MEDIUM (4)	MEDIUM (8)	HIGH (16)	HIGH (32)	VERY HIGH (64)
Low (2)	LOW (2)	MEDIUM (4)	MEDIUM (8)	HIGH (16)	HIGH (32)
Negligible (1)	LOW (1)	LOW (2)	MEDIUM (4)	MEDIUM (8)	HIGH (16)
	Not Credible (1)	Unlikely (2)	Not Likely (4)	Likely (8)	Highly Likely (16)

LIKELIHOOD

Risk 1: the present IS cannot reach 5 mA peak current with acceptable* emittance.

Mitigations:

1. Design of a space charge-optimized extraction system to improve beam quality. This will be cover by this project.
2. Run at lower current but higher duty cycle. This 2nd mitigation will have high cost in terms of prototyping a new klystron/modulator as well as partially redesign of the DTL cooling system. This cost will not be part of this project.

IMPACT					
Very High (16)	HIGH (16)	HIGH (32)	VERY HIGH (64)	VERY HIGH (128)	VERY HIGH (256)
High (8)	MEDIUM (8)	HIGH (16)	HIGH (32)	VERY HIGH (64)	VERY HIGH (128)
Medium (4)	MEDIUM (4)	MEDIUM (8)	HIGH (16)	HIGH (32)	VERY HIGH (64)
Low (2)	LOW (2)	MEDIUM (4)	MEDIUM (8)	HIGH (16)	HIGH (32)
Negligible (1)	LOW (1)	LOW (2)	MEDIUM (4)	MEDIUM (8)	HIGH (16)
	Not Credible (1)	Unlikely (2)	Not Likely (4)	Likely (8)	Highly Likely (16)
	LIKELIHOOD				

* Acceptable ≈ RFQ transmission > 90% with E_{surf} < 1.8 Kilp, and RF power < 1MW

Risk 2: Modulator and RF system cannot run at 10% duty cycle.

Mitigations:

- Design and prototyping of a new series of klystron and modulator. The present systems already run at the same average power, so an optimization would be easy. The cost impact will not be part of this project.

IMPACT					
Very High (16)	HIGH (16)	HIGH (32)	VERY HIGH (64)	VERY HIGH (128)	VERY HIGH (256)
High (8)	MEDIUM (8)	HIGH (16)	HIGH (32)	VERY HIGH (64)	VERY HIGH (128)
Medium (4)	MEDIUM (4)	MEDIUM (8)	HIGH (16)	HIGH (32)	VERY HIGH (64)
Low (2)	LOW (2)	MEDIUM (4)	MEDIUM (8)	HIGH (16)	HIGH (32)
Negligible (1)	LOW (1)	LOW (2)	MEDIUM (4)	MEDIUM (8)	HIGH (16)
	Not Credible (1)	Unlikely (2)	Not Likely (4)	Likely (8)	Highly Likely (16)

LIKELIHOOD

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Risk 3: Impossible to obtain a in-vacuum routable Post Coupler with motorized actuator

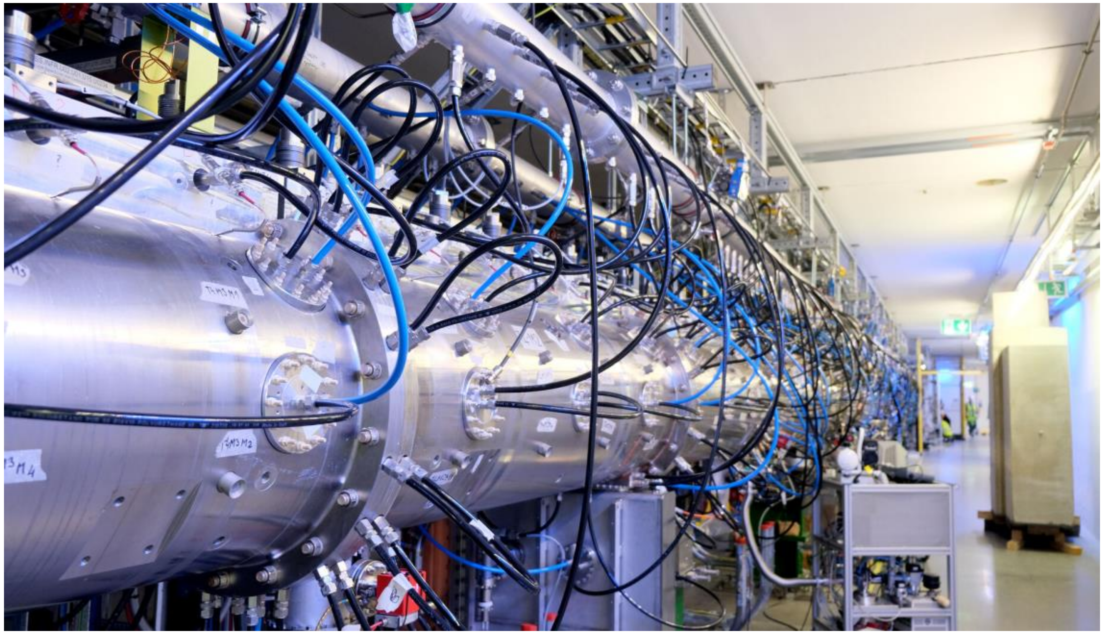
Mitigations:

- Implement a solution with vacuum break and in-tunnel rotation of the post couplers. This mitigation will require a different layout of the facility, in order to minimize contamination of the linac from the target. It will have also an impact on the flexibility of the beam schedule to be accelerated.

IMPACT					
Very High (16)	HIGH (16)	HIGH (32)	VERY HIGH (64)	VERY HIGH (128)	VERY HIGH (256)
High (8)	MEDIUM (8)	HIGH (16)	HIGH (32)	VERY HIGH (64)	VERY HIGH (128)
Medium (4)	MEDIUM (4)	MEDIUM (8)	HIGH (16)	HIGH (32)	VERY HIGH (64)
Low (2)	LOW (2)	MEDIUM (4)	MEDIUM (8)	HIGH (16)	HIGH (32)
Negligible (1)	LOW (1)	LOW (2)	MEDIUM (4)	MEDIUM (8)	HIGH (16)
LIKELIHOOD	Not Credible (1)	Unlikely (2)	Not Likely (4)	Likely (8)	Highly Likely (16)

Summary

- The R&D programs based on solid starting points in previous activities of the group (AISHA, ESS, TRASCO,IFMIF)
- The experiment will take advantage from link with other project also in terms of budget (presence at ESS)
- Some preliminary solutions for the routable Post Coupler can be explored and detailed
- Further physical design studies can introduce optimizations
- AISHA test bench is planned to be ready within 2023.
- 45 kEuros/year, 3 INFN sections (LNL, LNS, To), 1.2 FTE/year



Others ideas for applications

With the rules of thumbs derived from past projects, a wide spectrum of possible applications was considered for the linac development available at INFN: ion sources, nc structures, RF sources (besides klystrons, SS amplifiers and tetrode systems)

Listed in the table:

- ESS DTL (with the CEA RFQ)
- MUNES, the cw RFQ TRASCO to be used with Be target for BNCT application.
- cansDTL: a compact neutron source based on the MUNES RFQ+ESS DTL.
- alpha DTL
- nDTL: alphaDTL +1 tank, to accelerate 80 kW d beam at 40 MeV for neutron source.
- nDTL*: a nc partial IFMIF facility is considered (600 kW beam on target). IFMIF RFQ 175 MHz (but at 10% duty cycle). Beam Dynamic upgraded at 150 mA. Frequency jump in the MEBT + 2 x alpha-DTL at the same field level (2.6MV/m)
- nDTL**: DTL with half accelerating field than alpha DTL, to increase duty cycle (2400 kW on target). 4 tanks. Half of the nominal DONES beam power (5MW).

				RFQ			DTL		whole linac			RF power (approx)	
Linac	A/q	specie	wout	Length	freq	wout	#of tanks approx	focusing	duty cycle	peak curr.	**beam power**	peak	average
			MeV/u	m	MHz	MeV/u	8m each	structure	%	mA	**kW**	MW	MW
ESS DTL	1	p	3.6	5	352	90	5	FODO	4	65	**234**	12.05	0.48
BNCT MUNES	1	p	5	7.3	352	na	na		100	40	**200**	1.00	1.00
cansDTL	1	p	3	4	352	20	1	FODO	10	40	**80**	2.60	0.26
alphaDTL	2	4He+2	3	5	352	10	1	FFODDO	10	5	**10**	1.90	0.19
nDTL	2	d	3	5	352	20	2	FFODDO	10	20	**80**	3.70	0.37
nDTL*	2	d	2.5	10	176	20	2	TBD	10	150	**600**	8.90	0.89
nDTL**	2	d	2.5	10	176	20	4	TBD	40	150	**2400**	7.80	3.12