INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

The Drift Tube Linac for ESS and ideas for future applications

The contents of this seminar are a summary of the work and study of many colleagues at INFN-LNL, INFN-TO and ESS.

Abstract

The Drift Tube Linac, also called **Alvarez** linac by the name of the inventor, is a well-established accelerator structure, used for ion acceleration since the '50's.

The application of **some key inventions** as well as the general advance of the technologies (mechanics, RF, vacuum, materials) have continuously improved the DTL performances along the decades.

INFN is now committed to complete the construction, installation and commissioning of **Drift Tube Linac for the European Spallation Source**. An overview of the activities for this project will be given in the seminar.

As a consequence of the in-depth study of the DTL principles, some ideas for **new applications** has been developed. An example is the **Alpha-DTL**: a DTL based linac for alpha particle accelerator at variable energy.

Outline

- Historical overview
- Principles
- Key improvements:
  - Resonant coupling
  - Permanetn magnets
- ESS DTL
  - Design
  - Mechanics and assembly
  - Tuning
  - Commissioning
- From ESS DTL tuning to Alpha_DTL

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Hystorical Overview

1947 Berkeley Drift Tube Linac (Alvarez)

- 200 MHz
- 4-32 MeV, 2.2 MW peak power, 60uA peak current, 300us-15Hz (0.5%duty cycle)
- L= 12m, Dcav = 1m
- Grid focalization
- External tank vessel

THE
REVIEW OF SCIENTIFIC
INSTRUMENTS

VOLUME 26, NUMBER 2 FEBRUARY, 1955

Berkeley Proton Linear Accelerator*

Luis W. Alvarez, Hugh Bradner, Jack V. Franck, Hayden Gordon, J. Donald Gow, Lauriston C. Marshall,† Frank Oppenheimer,‡ Wolfgang K. H. Panofsky,§ Chaim Richman, and John R. Woodyard
Radiation Laboratory, Department of Physics, University of California, Berkeley, California

(Received July 8, 1954)

A linear accelerator is now in use which increases the energy of protons from a 4-Mev Van de Graaff injector to a final energy of 31.5 Mev. The accelerator consists of a cavity 40 feet long and 39 inches in diameter, excited at resonance in a longitudinal electric mode with a radio-frequency power of about 2.1×10^6 watts peak at 202.5 Mc. Acceleration is made possible by the introduction of 46 axial "drift tubes" into the cavity, which is designed so that the particles traverse the distance between the centers of successive tubes in one cycle of the rf power. The proton bunches are longitudinally stable as in the synchrotron, and are stabilized transversely by the action of converging fields produced by focusing grids. The electrical cavity is constructed like an inverted airplane fuselage and is supported in a vacuum tank. Power is supplied by 9 high-powered oscillators fed from a pulse generator of the artificial transmission line type. Output currents are 3×10^{-7} ampere, average, and 60 μa, peak. The beam has a diameter of 1 cm and an angular divergence of 10^{-3} radian.

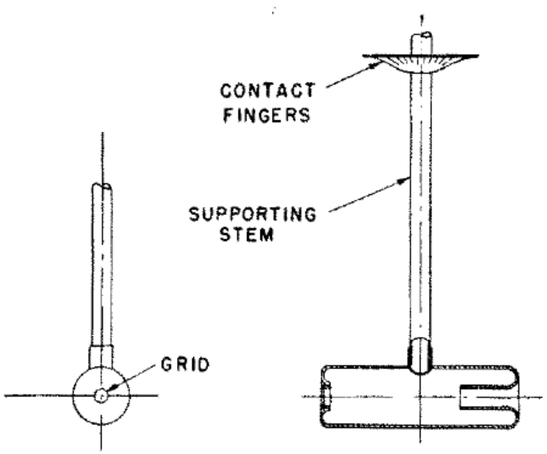
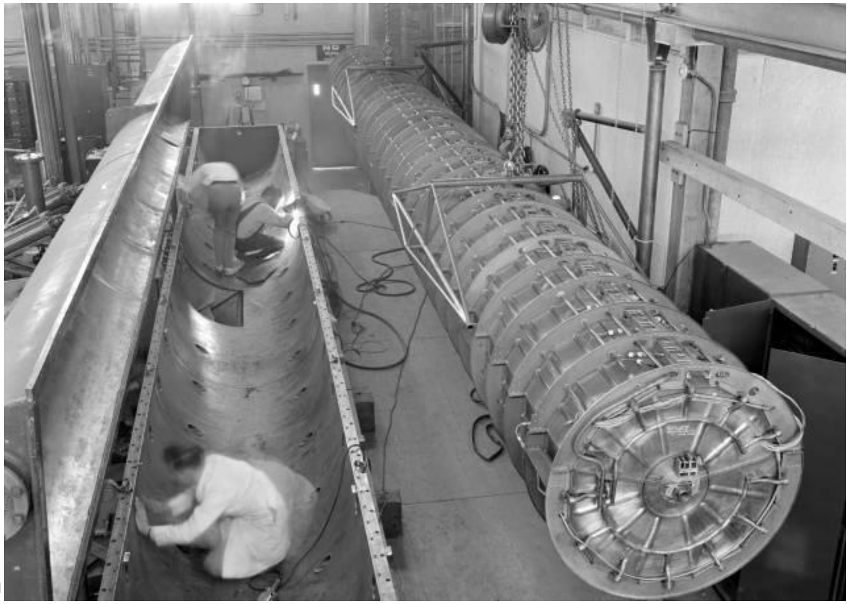
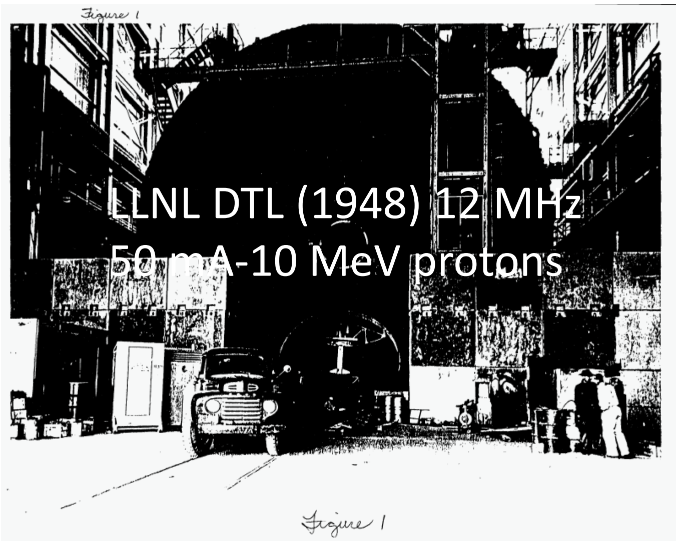


Fig. 18. Outline drawing of a typical drift tube.

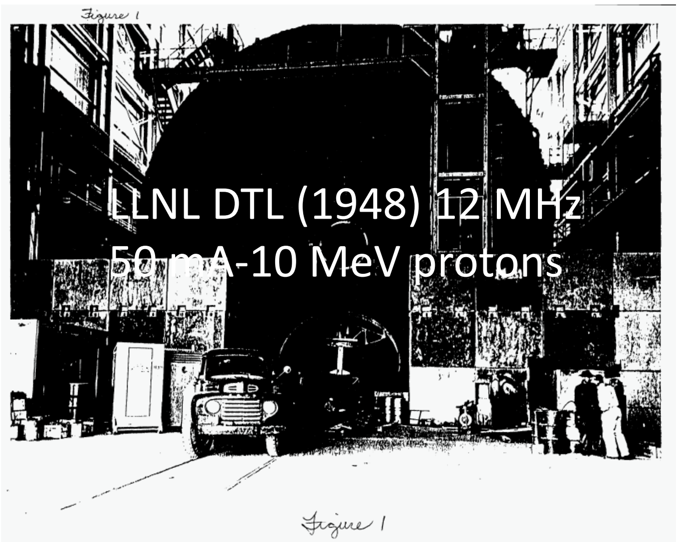


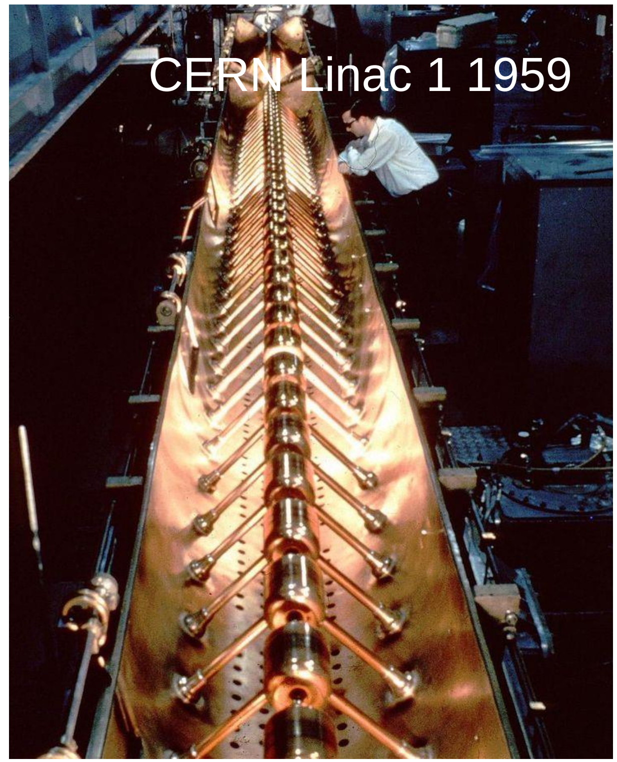
Historical overview



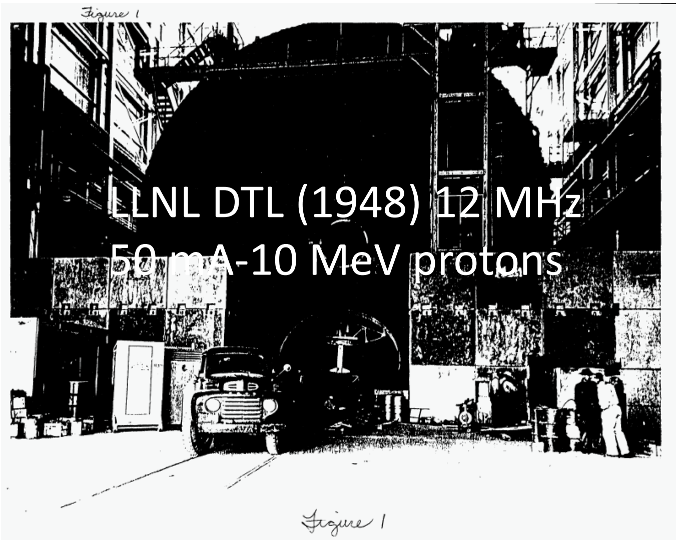
LLNL DTL (1948) 12 MHz
50 mA-10 MeV protons

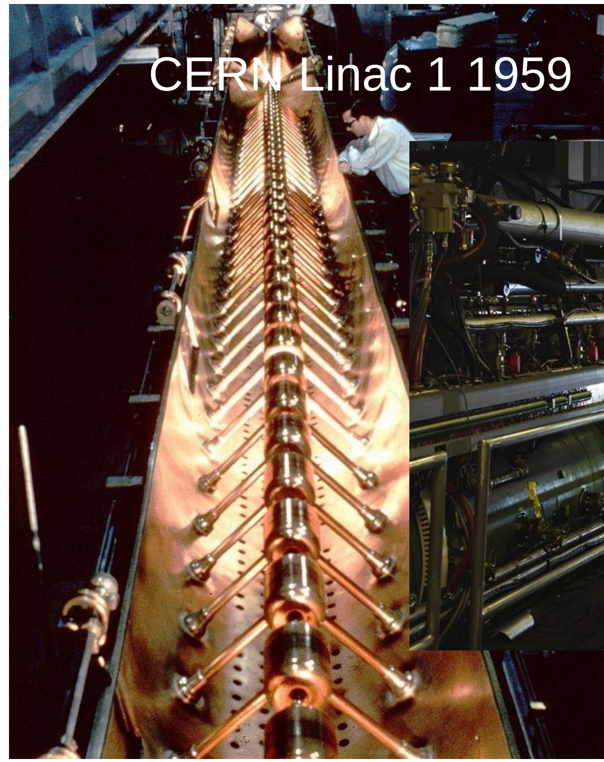
Historical overview



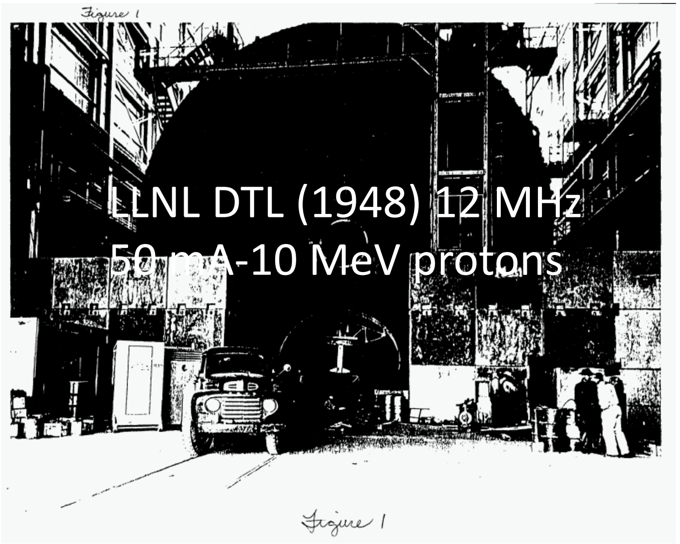


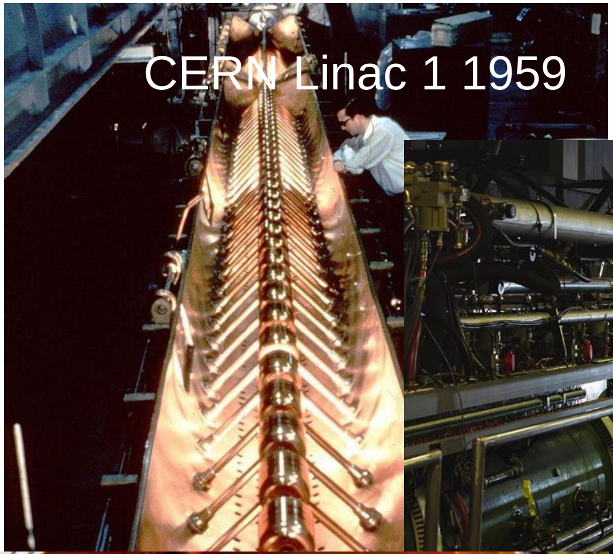
Historical overview

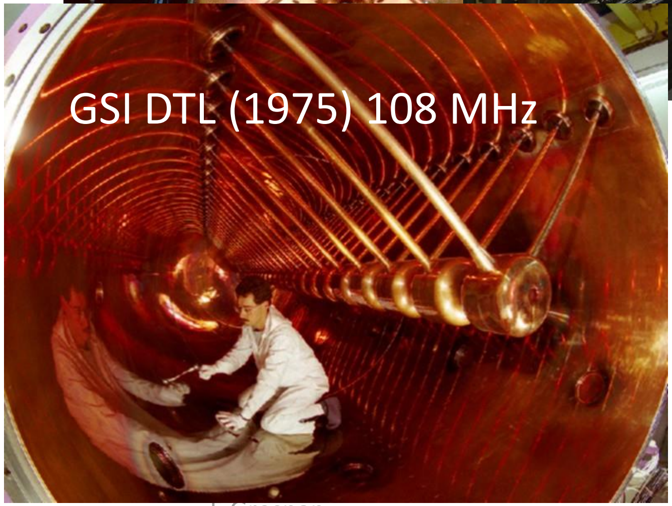




Historical overview







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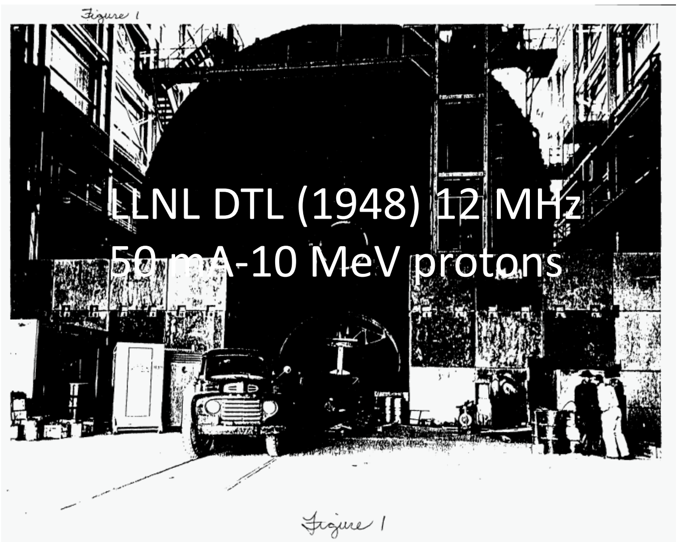
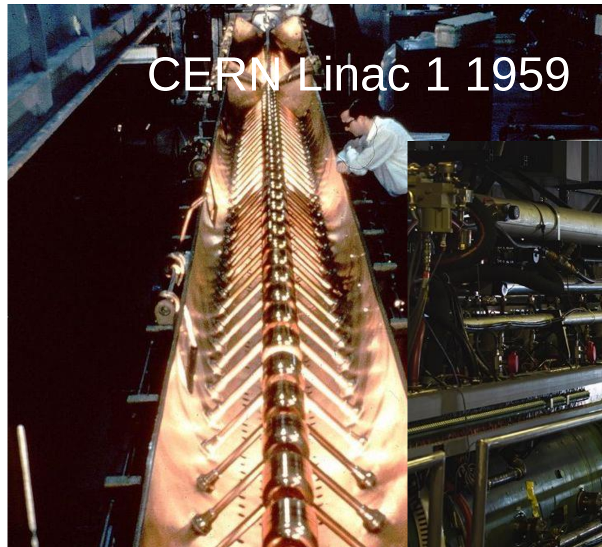
Historical overview





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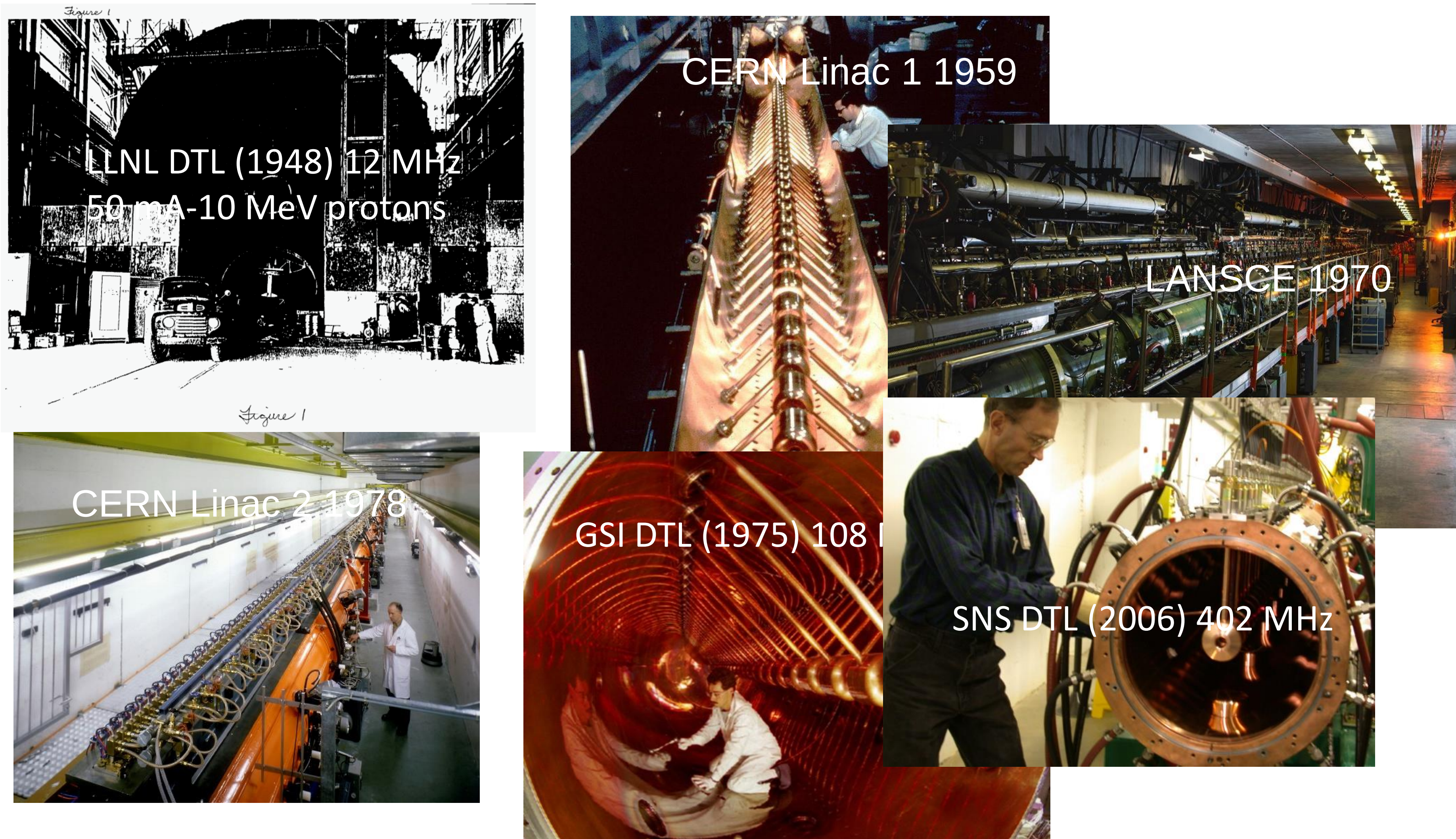

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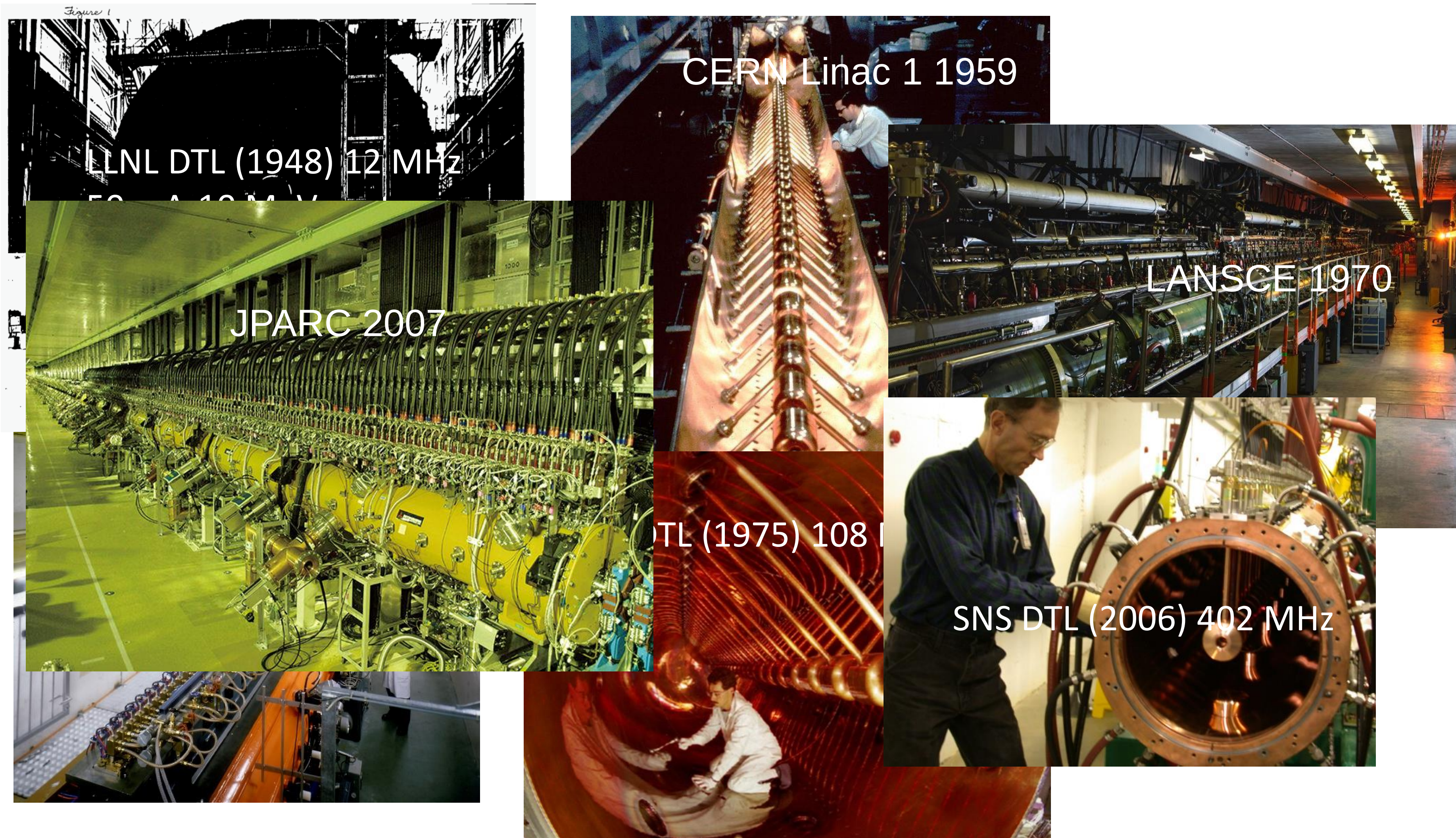
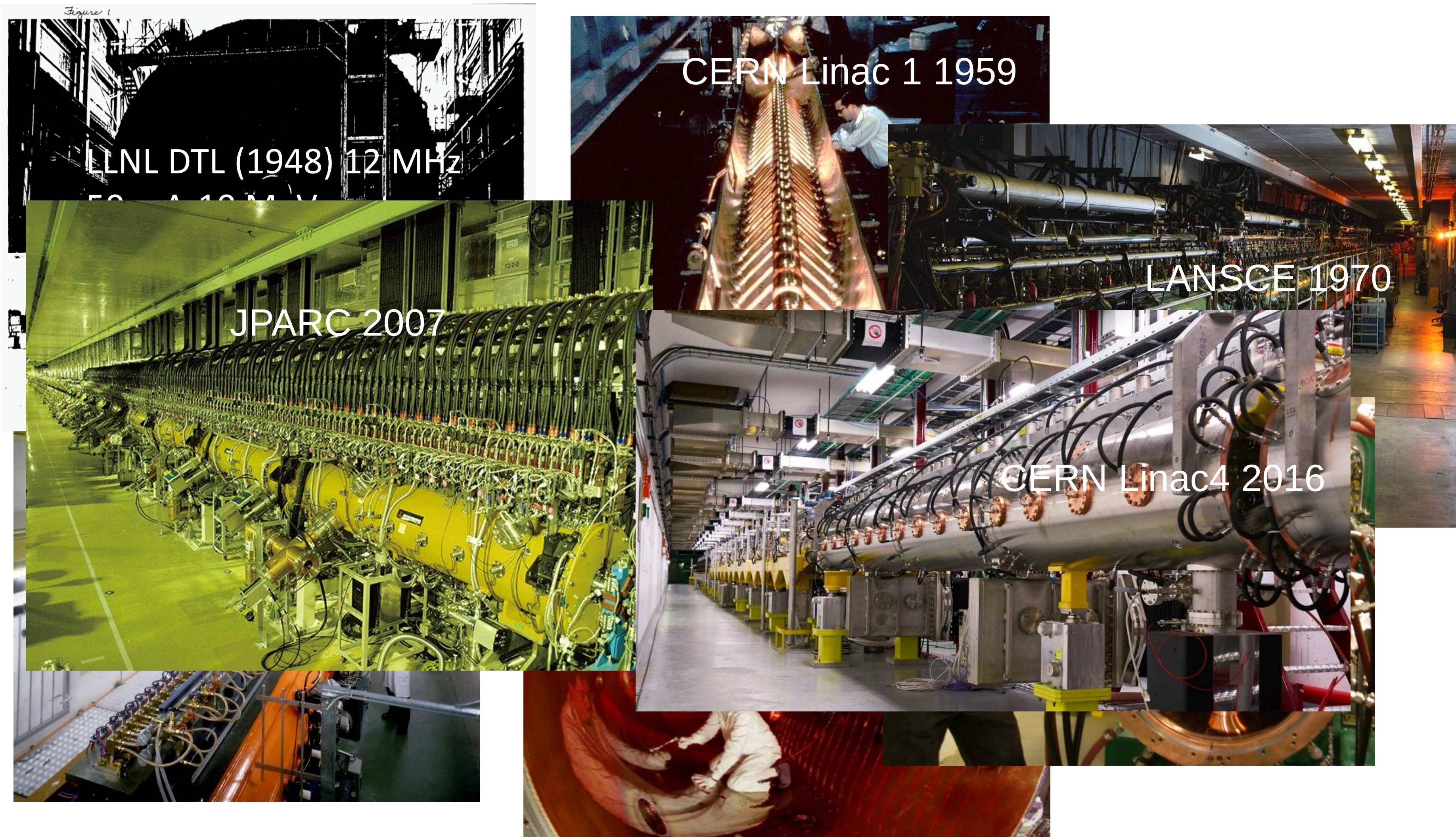


Historical overview



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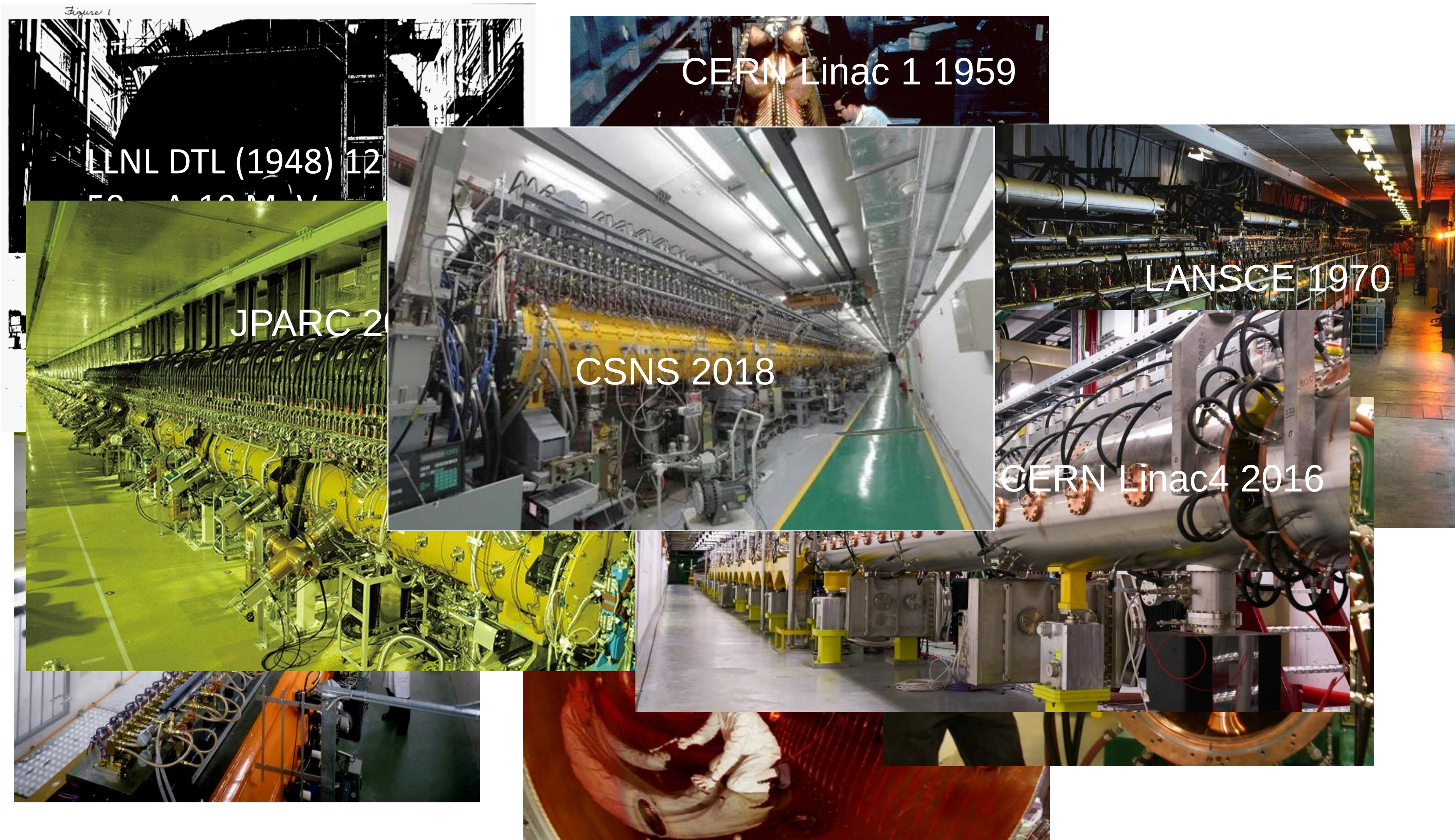
Historical overview



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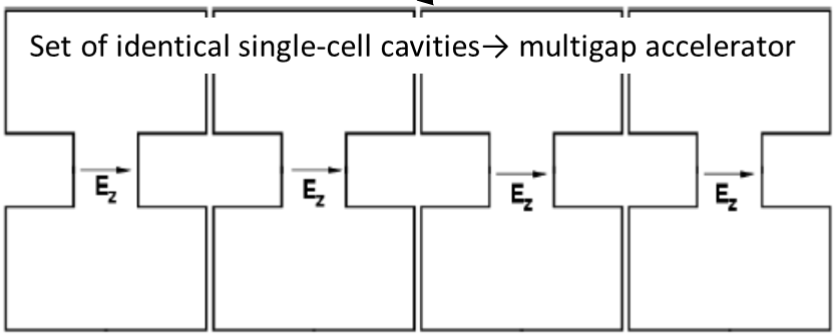
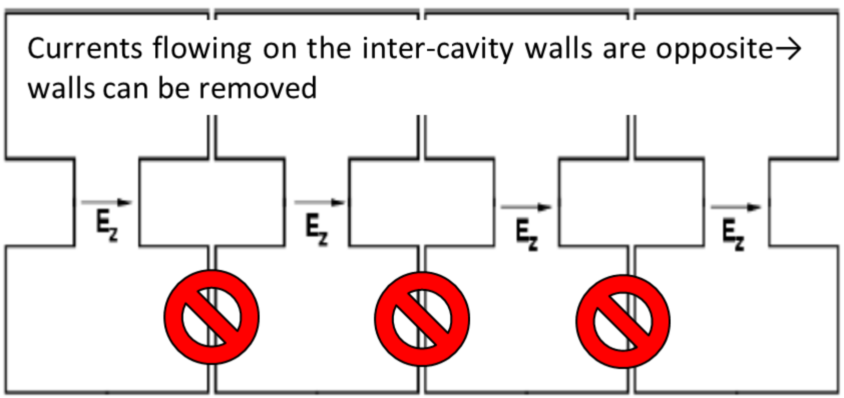
Drift tube linac: how does it work?

Two possible views of the DTL working principle

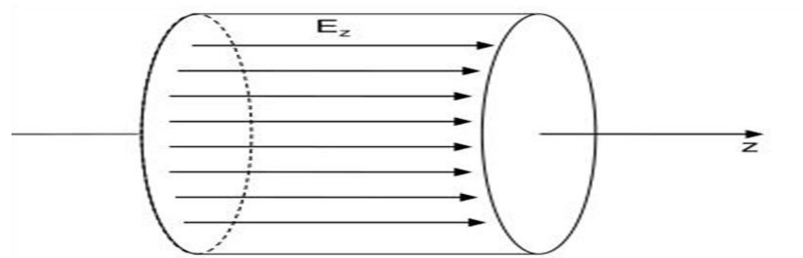
Set of identical single-cell cavities→ multigap accelerator



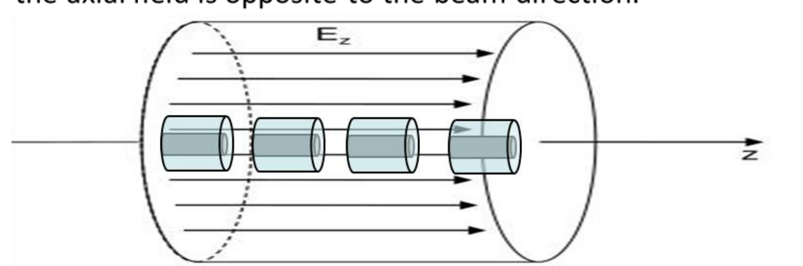
Currents flowing on the inter-cavity walls are opposite→ walls can be removed



Long pillbox cavity in TM010 mode, longer than the distance a particle travels in half an RF period ($\beta\lambda/2$)→ the particle is both accelerated and decelerated.



Install Drift Tubes along the axis → the particle will be inside a Faraday Cage that shields the particles when the polarity of the axial field is opposite to the beam direction.

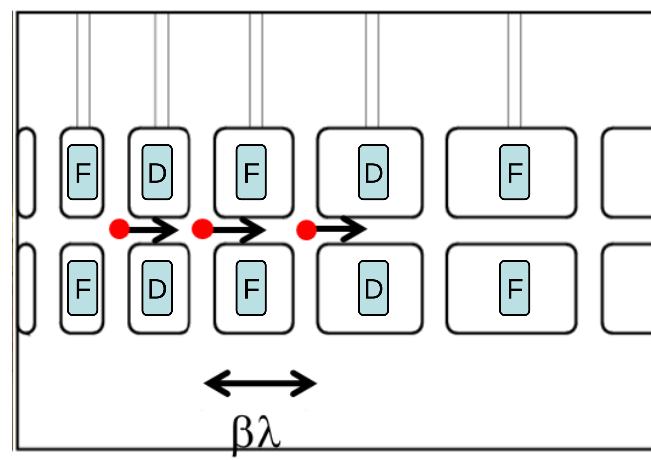


Ref: Wangler, "RF Linear accelerator".

Drift tube linac: how does it work?

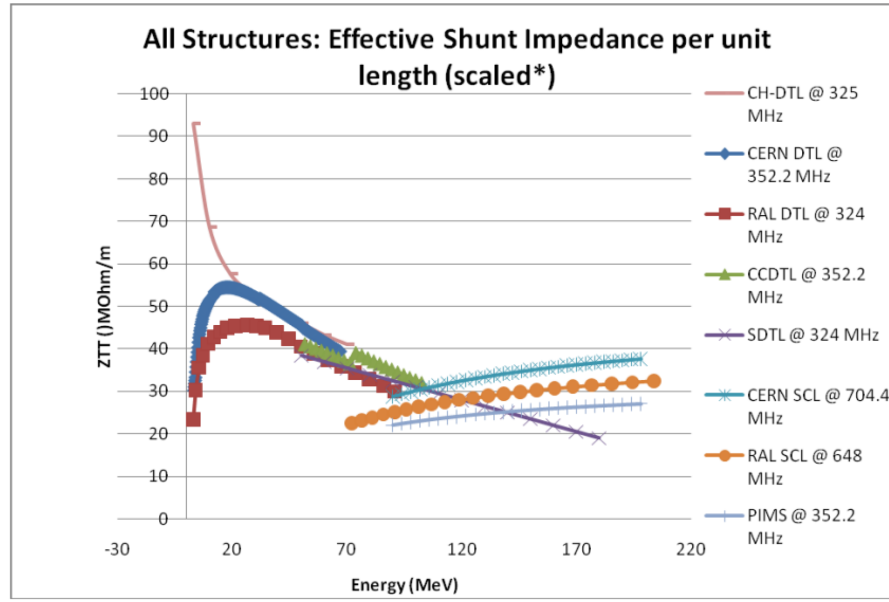
...but the same final result.

- Stems = support for drift tubes
- Gap-to-gap distance = βλ, cell lengths adapted to the beam velocity
- → particles in phase with accelerating field direction
- Mode 0 (all the gap in phase)
- Focusing magnets can be lodged in the Drift Tubes



Energy range

- Low-Medium energy accelerators for high intensity and high quality ion beams
- Shunt Impedance very convenient in the range of β= 0.05-0.4
- Beam dynamics very solid, let's say "academic".
- At higher energies π/2 structures are more convenient
- At lower energy RFQ more convenient for focusing



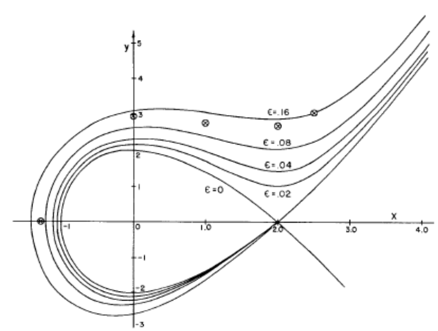
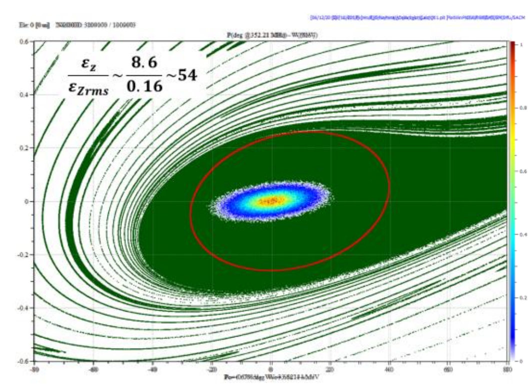


Fig. 1. Longitudinal phase acceptance of a proton linac. ⊗: Calculation from Blewett [1963] for ε = 0.12.

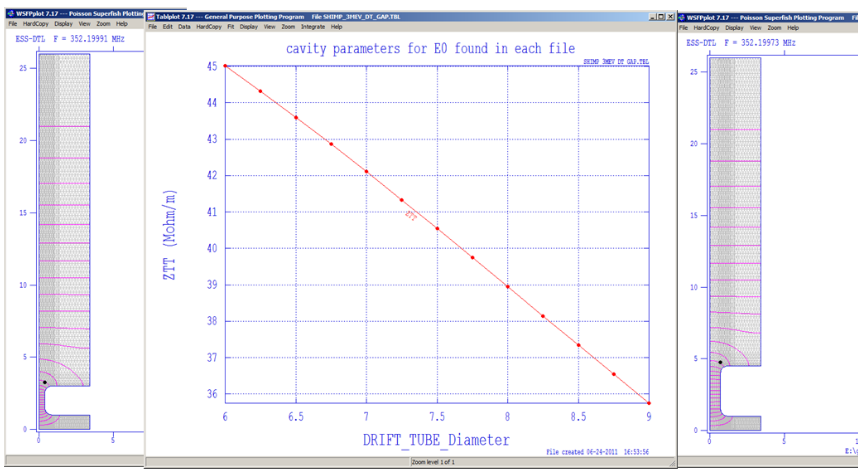


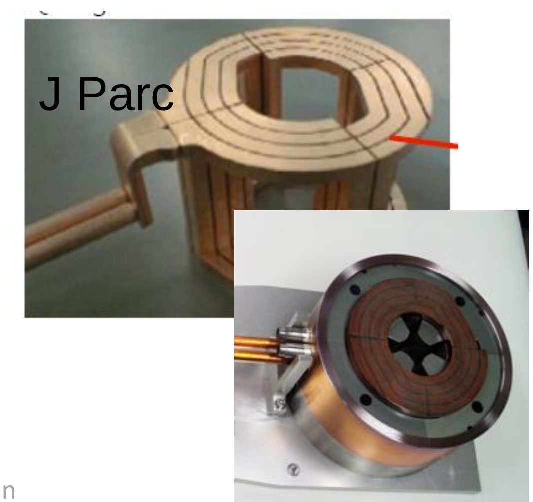
Key improvement: PMQ

The use of permanent magnet quadrupoles in place of electromagnets allows drift tube with smaller diameter (→**higher ZTT**), and without internal cooling.

$$ZT^2 = \frac{V_0^2}{P_{diss}}\frac{T^2}{L} \approx \frac{1}{\left(\omega \cdot C_{gap}\right)^2}\frac{T^2}{L}[M\Omega / m]$$

1. **Increase the ratio** $\frac{V_0^2}{P_{diss}}$ → From the circuit equivalence of a DTL-cell $\frac{V_0^2}{P_{diss}} = \frac{V_0^2}{R_{wall} I_{wall}^2}$ where $V_0 = \frac{I_{displ}}{\omega C}$, and $I_{displ} = I_{wall}$. Then a better ratio between axial voltage and wall current $\frac{V_0}{I_{wall}} = \frac{1}{\omega C}$ lead to decrease the gap capacitance, i.e. the Drift Tube Diameter.
2. **Increase the Transit Time Factor T** → $T = \frac{\sin(\pi g / \beta\lambda)}{\pi g / \beta\lambda}$ lead to decrease the gap length.





Key improvement: Post Couplers (PCs)

In order to manage high current beam in long (L>>λ) RF structures:

1. minimize the transient effects (RF pulse, beam loading) which perturb amplitude and phase distribution

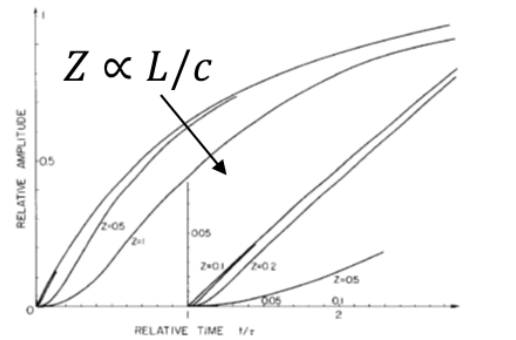


Fig. 1. Amplitude response at the end of a cut-off mode cavity calculated from the cylindri waveguide model (Lapostolle [1965a]).

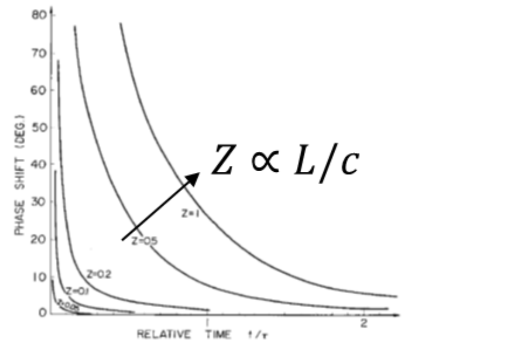


Fig. 2. Phase response at the end of a cut-off mode cavity calculated from the cylindrical waveguide model (Lapostolle [1965a]).

Ref:
”Proton Linear Accelerators. A theoretical and historical introduction”. PIERRE M. LAPOSTOLLE
Hereward “Some examples of energy flow in the Alvarez structure”
Nishikawa “BEAM LOADING EFFECTS IN STANDING WAVE LINACS”
Hereward, Lapostolle ”ENERGY FLOW AND TRANSIENTS IN THE ALVAREZ STRUCTURE”.

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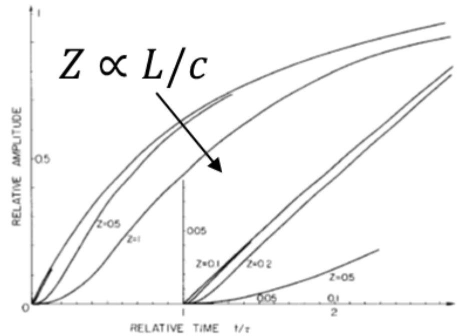
Key improvement: Post Couplers (PCs)

In order to manage high current beam in long (L>>λ) RF structures:

1. minimize the transient effects (RF pulse, beam loading) which perturb amplitude and phase distribution
2. reduce the sensitivity to errors



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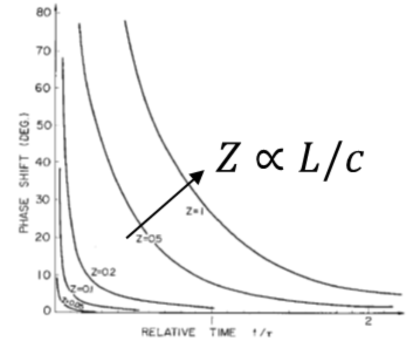

Fig. 2. Phase response at the end of a cut-off mode cavity calculated from the cylindrical waveguide model (Lapostolle [1965a]).

$$\frac{\delta E}{E} = -\frac{1}{S}\frac{\delta(\omega^2)}{\omega^2} \; where\; S = field\; stability = 2\left(\frac{\lambda}{2\pi L}\right)^2 \to 2\frac{v_g}{\omega L} for\; modes \neq 0$$

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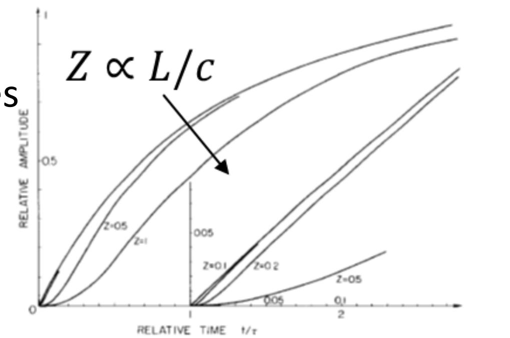
Key improvement: Post Couplers

In order to manage high current beam in long (L>>λ) RF structures:

1. minimize the transient effects (RF pulse, beam loading) which perturb amplitude and phase distribution
2. reduce the sensitivity to errors
3. Reduce phase shift due to RF losses



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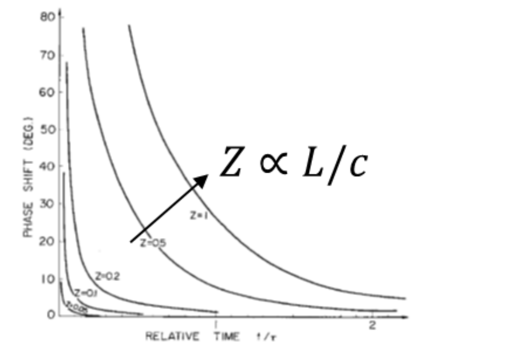

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$$\Delta\varphi \approx \frac{1}{Q}\left(\frac{L}{\lambda}\right)^2$$

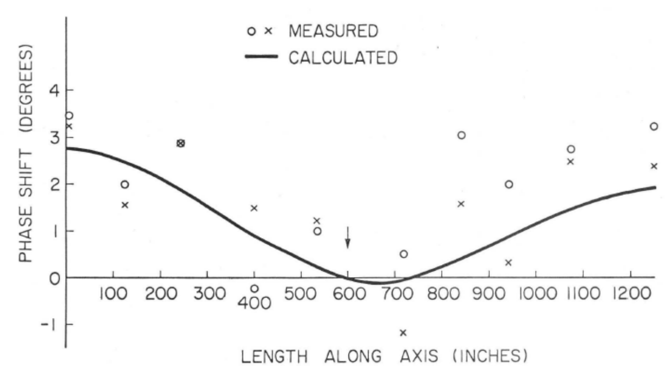

Fig. 1. Steady state phase shift along AGS linac cavity referred to the driving point (near the center of cavity).

Ref:
"Proton Linear Accelerators. A theoretical and historical introduction". Pierre M. Lapostolle
Hereward "Some examples of energy flow in the Alvarez structure"
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Hereward, Lapostolle "ENERGY FLOW AND TRANSIENTS IN THE ALVAREZ STRUCTURE".

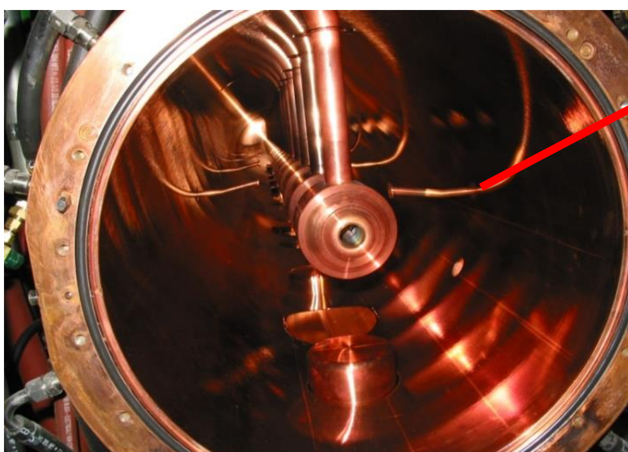
Post couplers: a resonant coupling solution for DTL

A solution for DTLs has been proposed in 1960's at Los Alamos. The long DTL cavity is stabilized by resonant coupling elements: simple internal metallic bars, which extend from the outer cylinder towards the drift tube, without touching the latter. These bars are called **Post Couplers (PCs).**

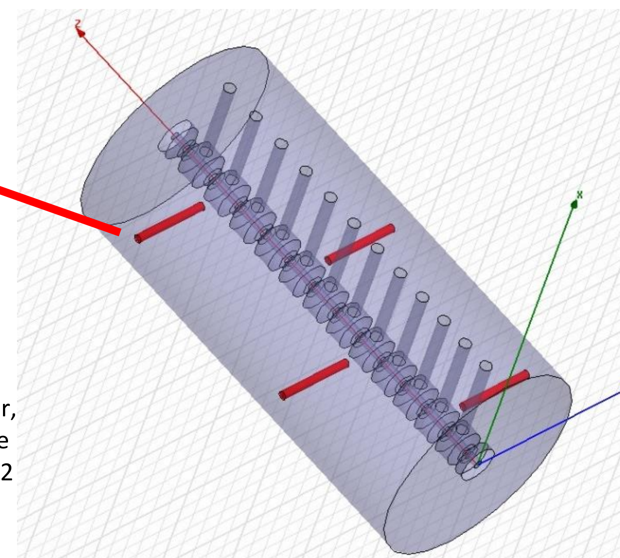
The post couplers are located at the points on the outer wall of the cavity that are aligned with the centers of the drift tubes, and oriented at 90° with respect to the stems, in order to minimize the coupling between posts and stems. Furthermore, the nature of the coupling between adjacent PCs is such that they must be placed on opposite sides of the cavity.

If the length of the Post Couplers is correct, the are excited in case of field perturbation → the field umbalance between adjacent gaps is «drained» by the post coupler.

The **sensitivity to errors** of DTL equipped with POST is reduced of a factor >= 30.



Post Coupler

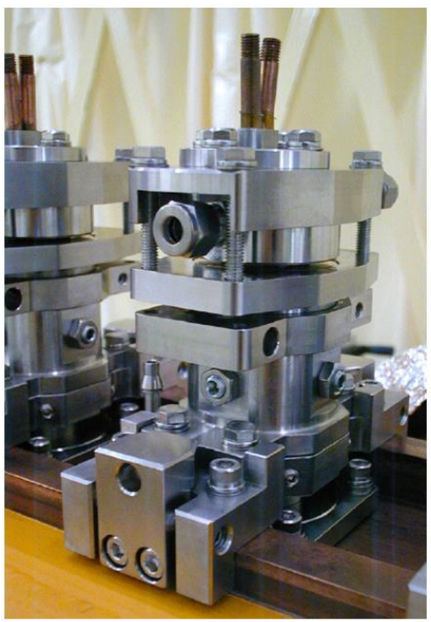


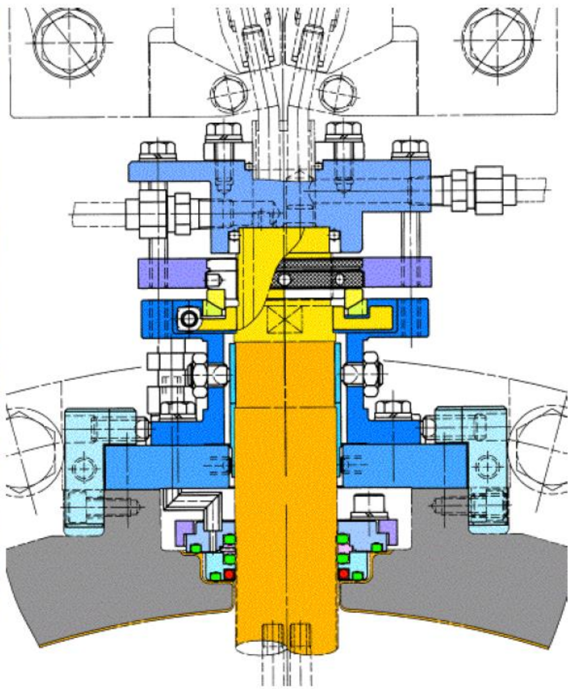
Ref: Knapp, J. M. Potter, E. J. Schneider, and D. A. Swenson, "Stabilization of the Drift Tube Linac by Operation in the π/2 Cavity Mode"

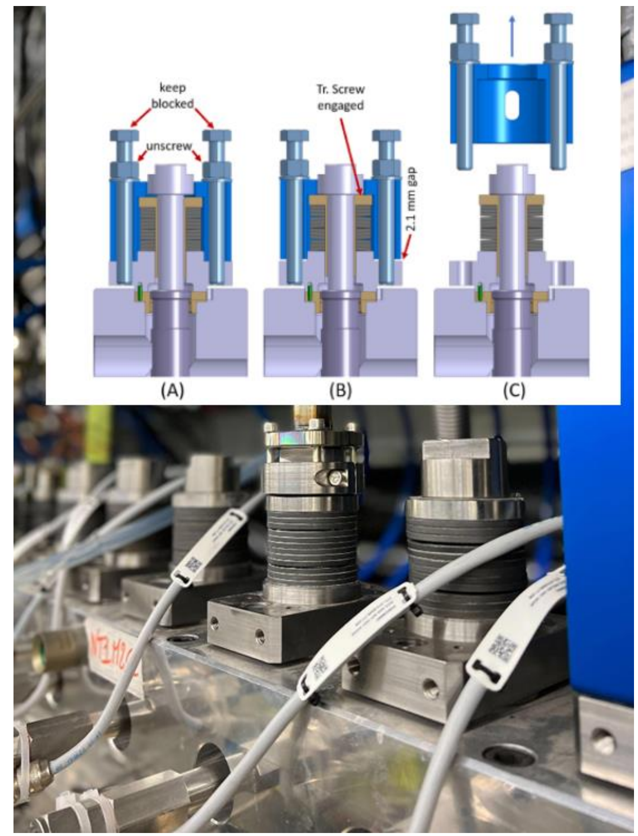
Mechanical technology advance

Improvement of the machining precision (for example, thermally controlled milling machines) allow to skip complicated alignment systems

Stem support



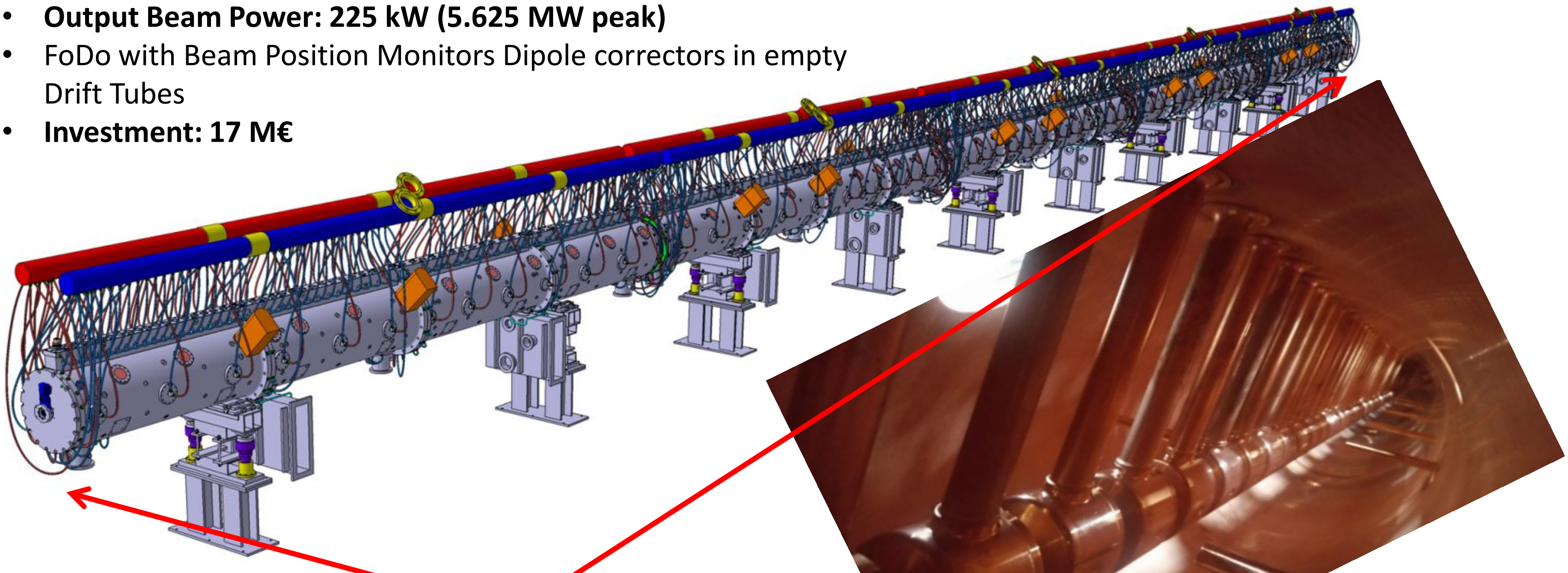


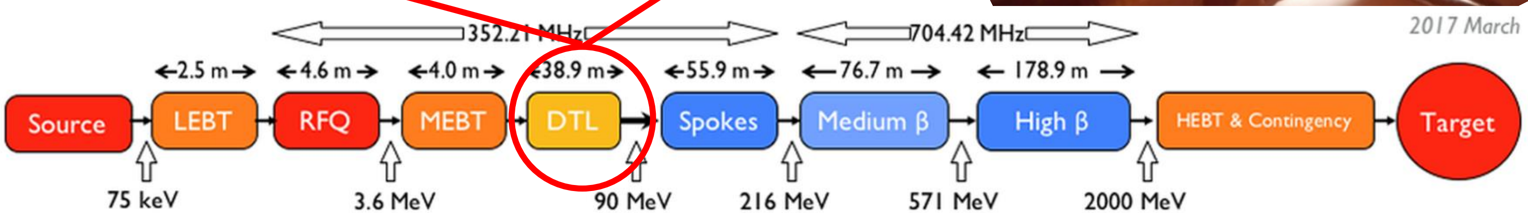


ESS DTL

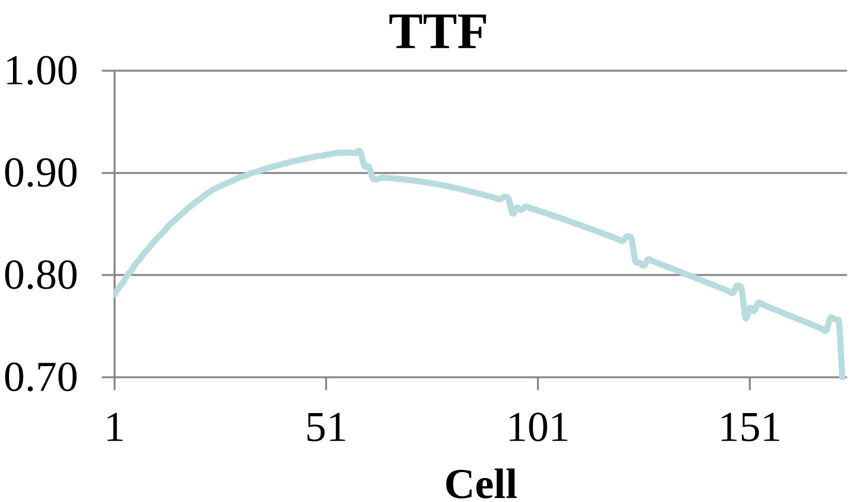
Main Normal Conducting Accelerator component:

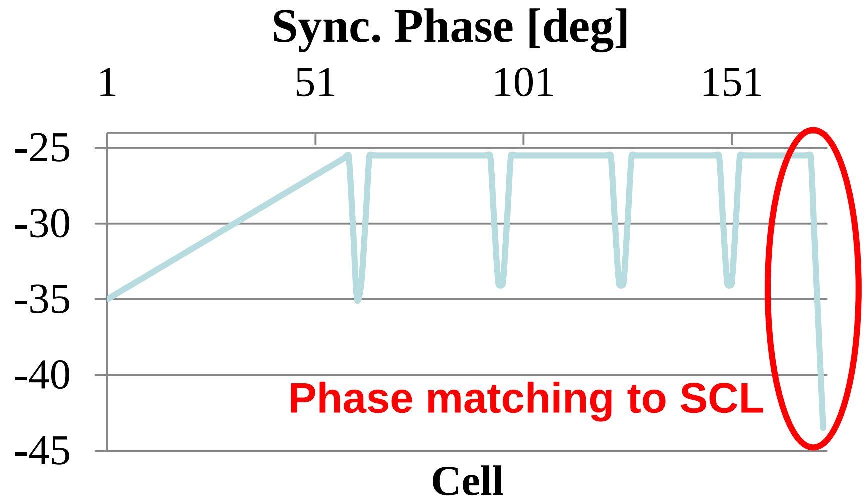
- **Length: 40 m**
- Output Beam Energy: 90 MeV (protons at 40% speed of light)
- **Output Beam Power: 225 kW (5.625 MW peak)**
- FoDo with Beam Position Monitors Dipole correctors in empty Drift Tubes
- **Investment: 17 M€**

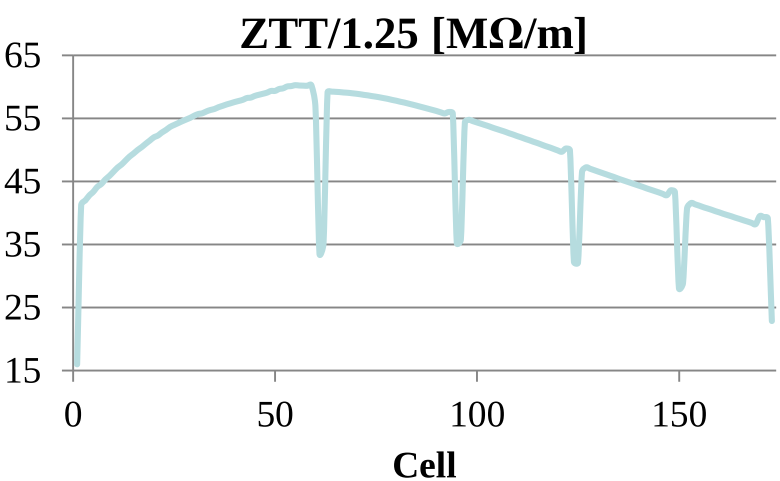


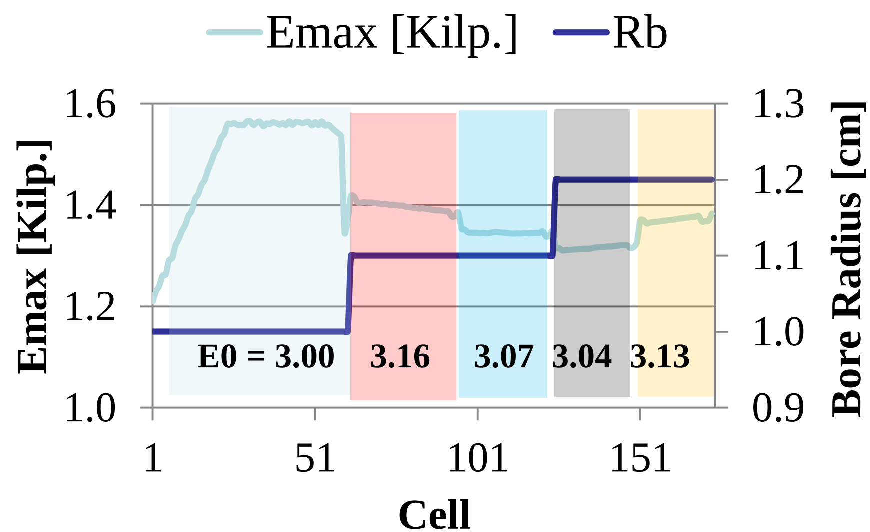


DTL Main Figures of Merit









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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.

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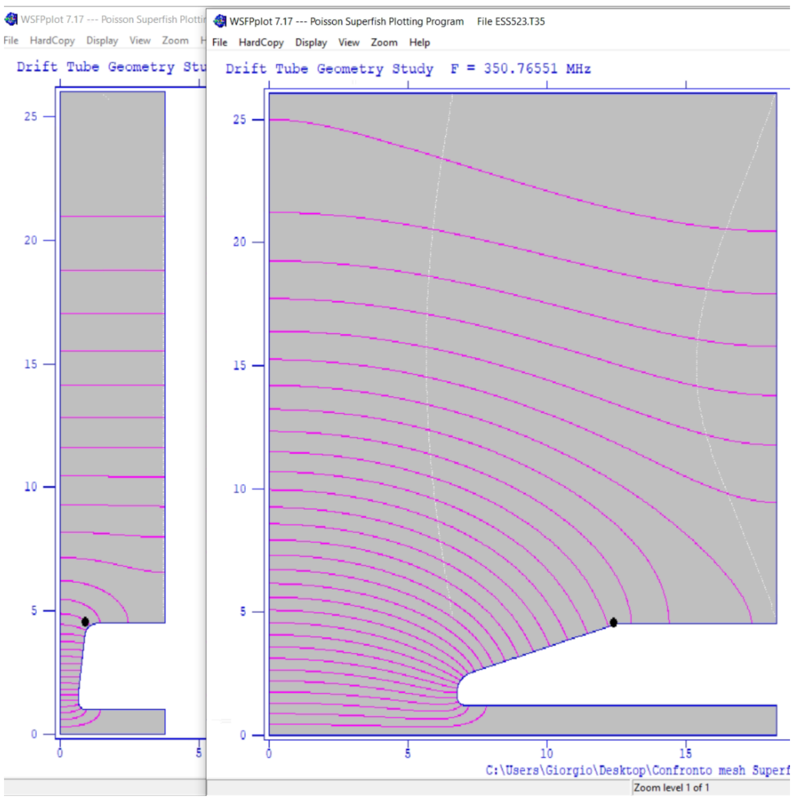
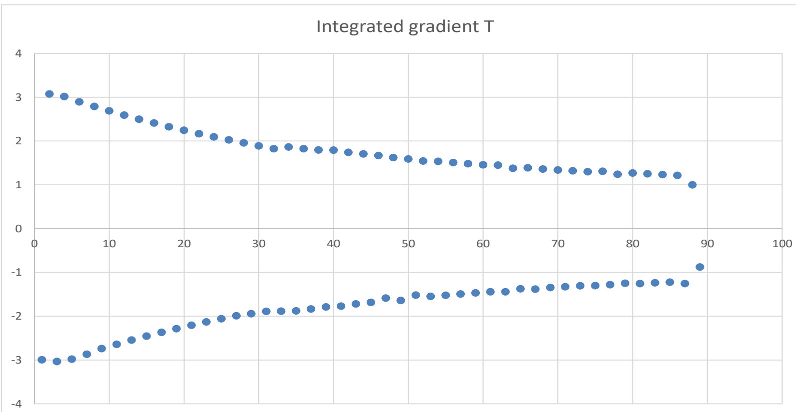
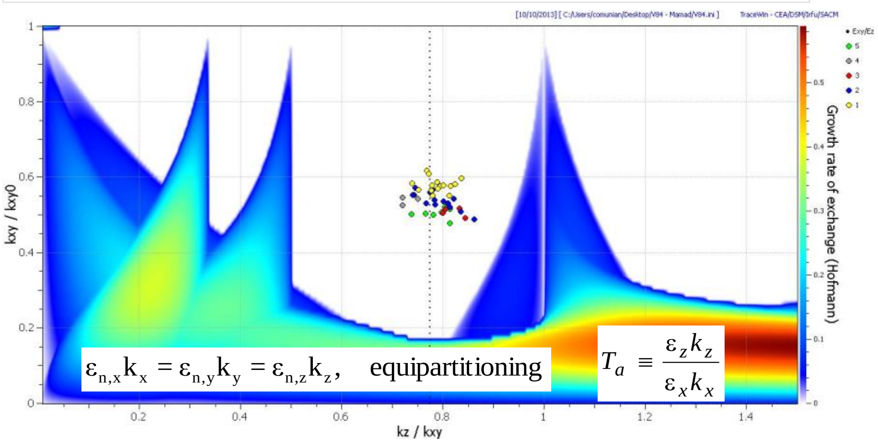
Some comments on the physical design

ZTT driven by TTF



Equipartioned design to limit emittance growth





DTL-Spoke transition optimization (50 MeV→90MeV)

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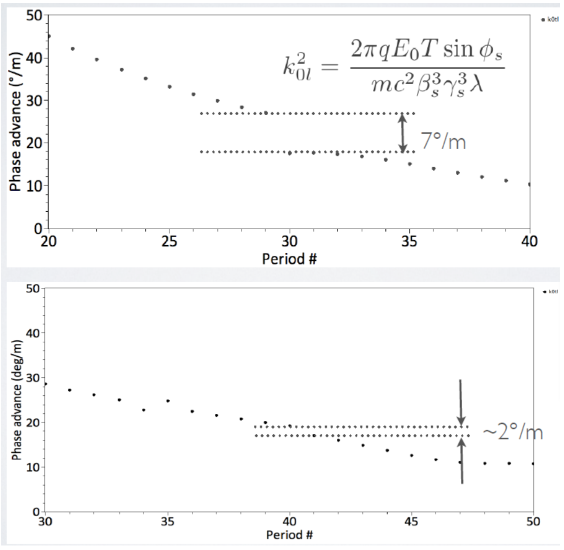
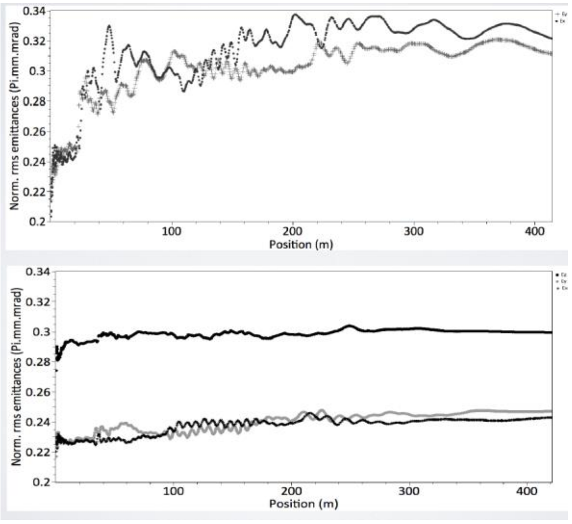
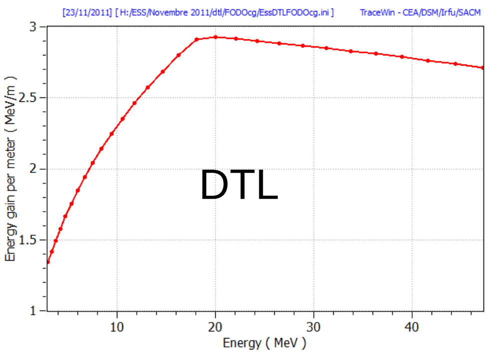
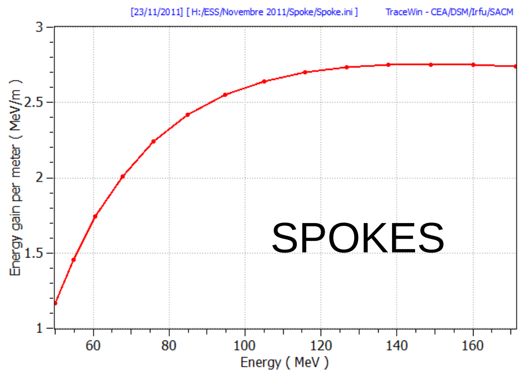
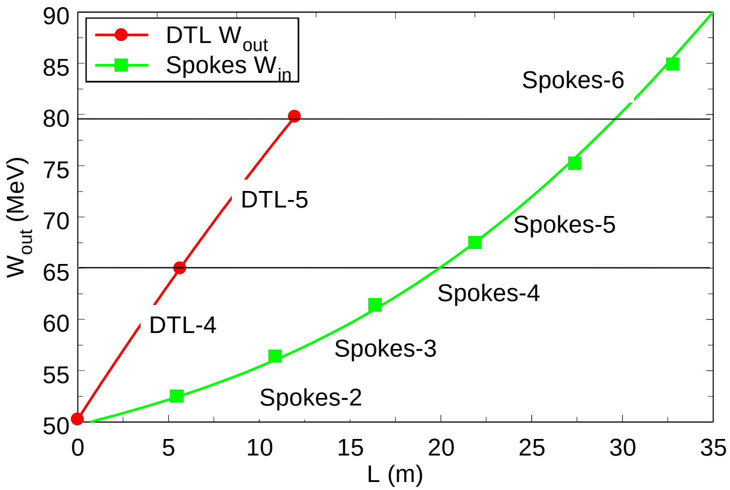
- k_{0L} discontinuity reduced to ~3° by replacing 16 Spoke cavities with 2 DTL tanks.
- Shortens linac by 18: Real Estate of DTL is higher than the Spoke up to 80-100 MeV
- Replaces 16 rf transmitters with 2 klystrons.
- Better emittance evolution
- Increase operating power by ~180 kW (average electrical)











Ciclo di Produzione INFN dei Drift Tubes

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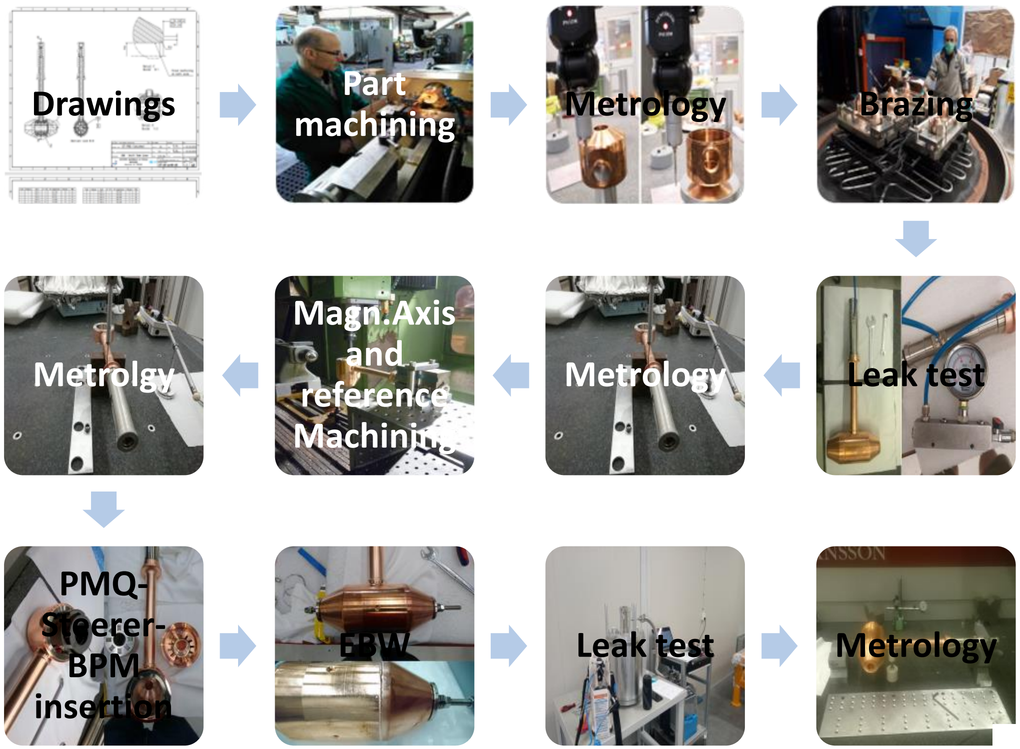
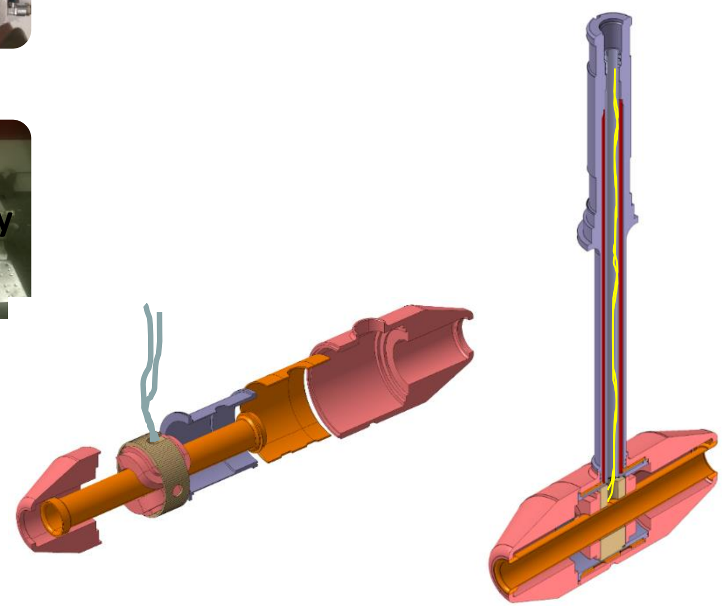
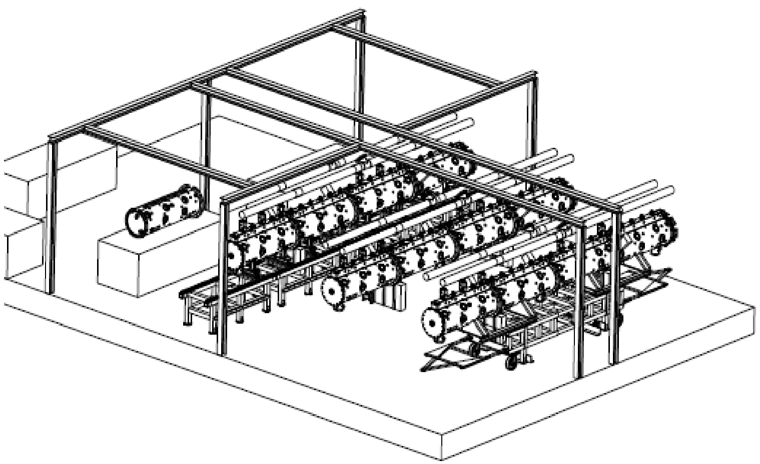
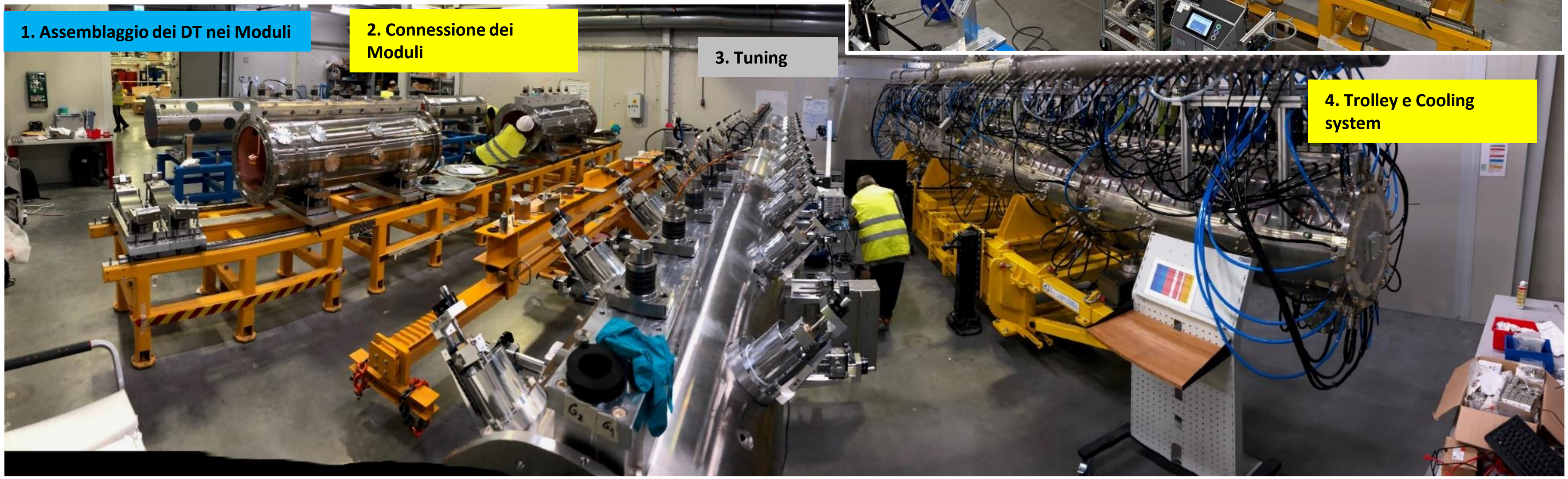


- 155 Drift Tubes internally produce at INFN
- Mech. Workshop of LNL and TO
- Brazing at LNL
- Machining post brazing for precise positioning of PMQ (<0.05mm)
- E-beam welding @ Zanon

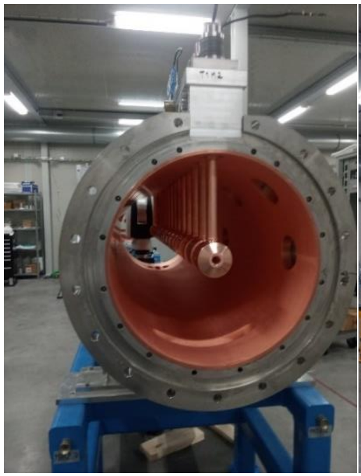


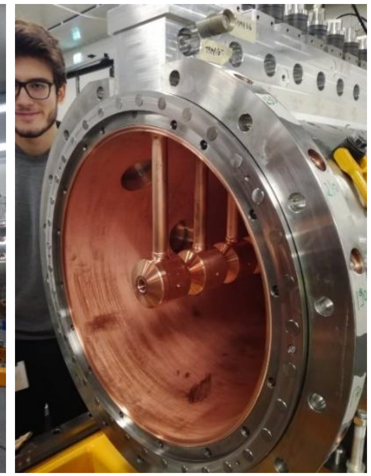
DTL assembly line at ESS





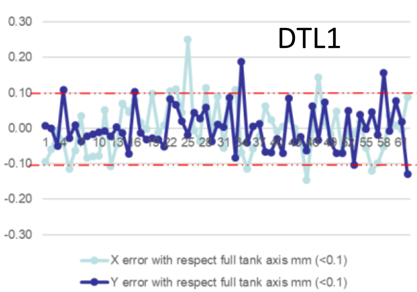
Mechanical Tolerances

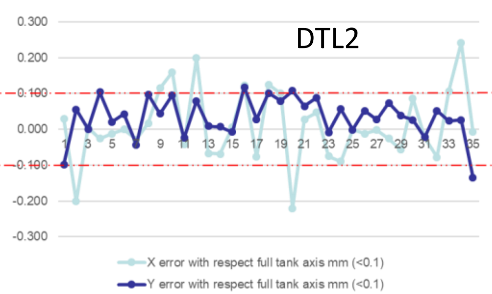


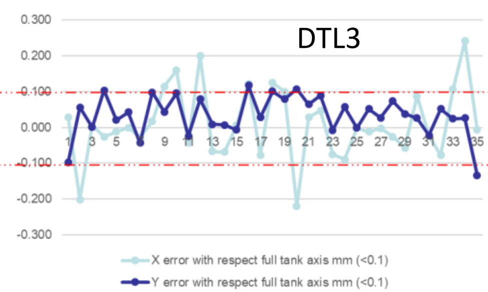


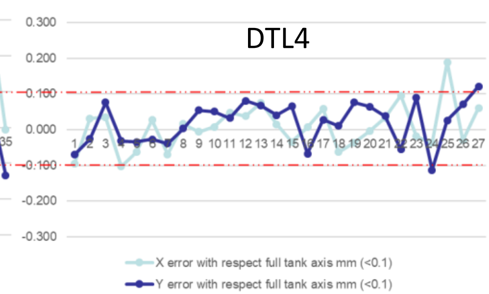
Alignment chain:

- PMQ magnetic axis on the DT beam axis
- DT installation in the module: aligned by the girder precise bushings
- Coupling module to module with calibrated shims and laser tracking
- Leak test every junction
- PMQs<0.1mm with respect to beam axis









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).

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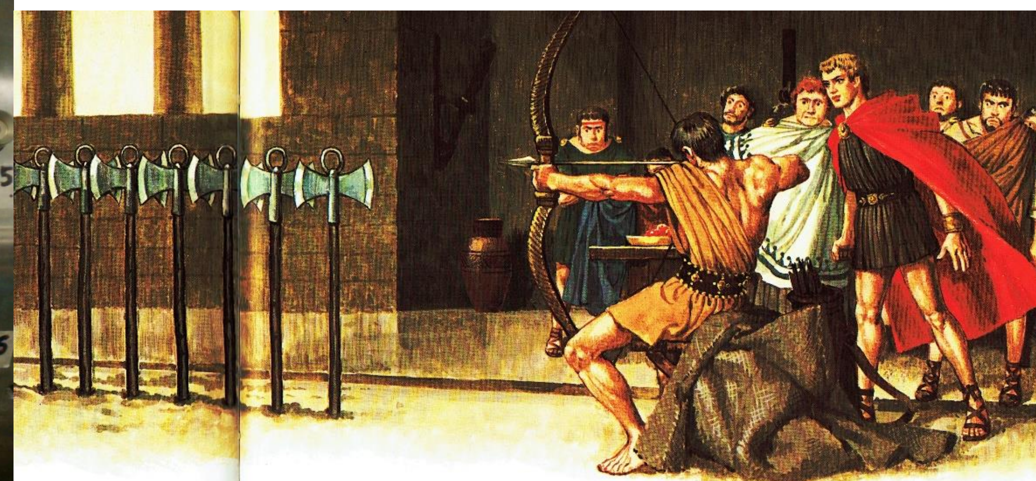
A solid bead pull equipment: the evidence of Odysseus

In order to avoid systematic errors on the measurements of E0, for ESS DTL a misalignment of the wire ≤ 1mm is required all along the 8m axis→ tension ≥ 50 kg



The man who can string the bow and shoot an arrow through a dozen axe heads will marry Penelope.

Ref: Homers, “Odyssey”

The tuning monks of DTL1

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

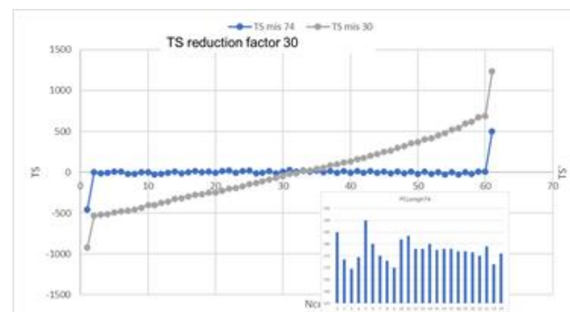
This activity covered 4 months of works between Nov 2020 and Feb 2021.

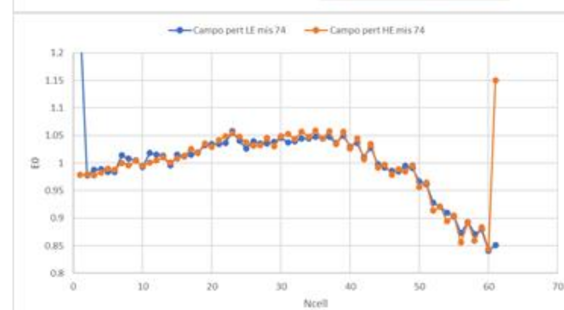
We organized our days with the St Benedict rule: "*tune et labora*".

Ref: Benedetto da Norcia, "Regula monachorum"

More than 1500 iterations and 4 months to reach specifications.

- 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





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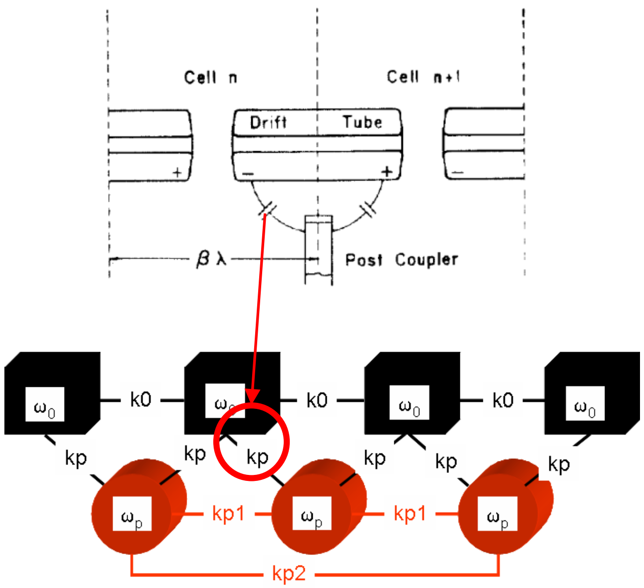
Tuning task force

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)*



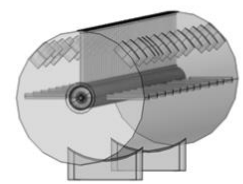
Simulations

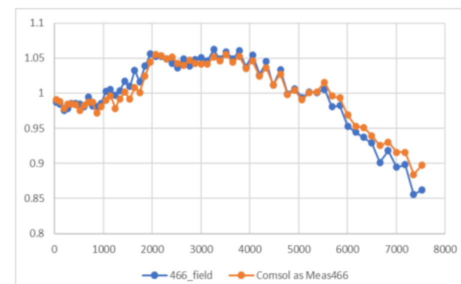
3D RF simulations nowadays of a full DTL with PCs well agree with reality.

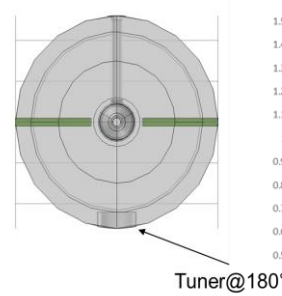
We demonstrated that:

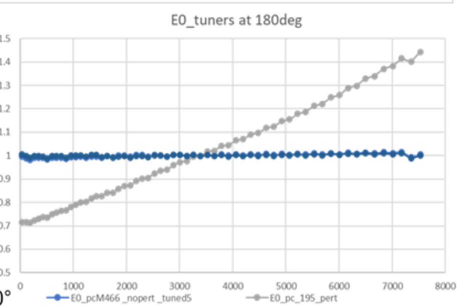
1- the root cause of the issue is an electromagnetic coupling between Tuner and Post Couplers (intrinsecally 3D)

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









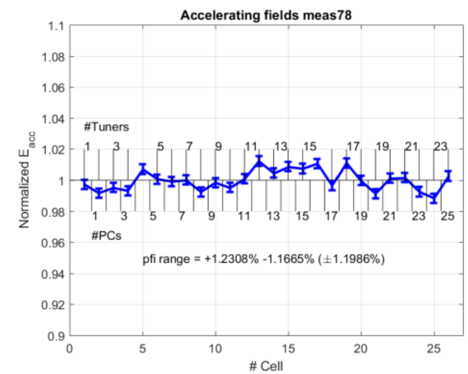
Ref:

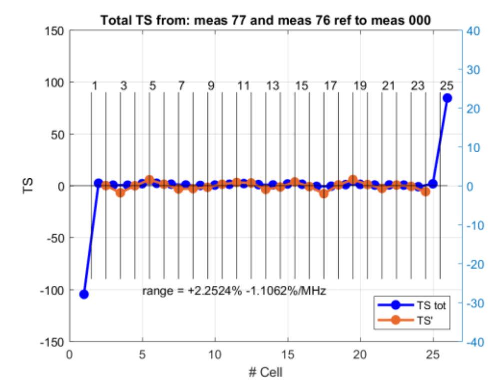
J. Billen, “Post-coupler stabilization and tuning of a ramped-gradient drift-tube linac”
F. Grespan “Equivalent circuit for postcoupler stabilization in a drift tube linac”

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.





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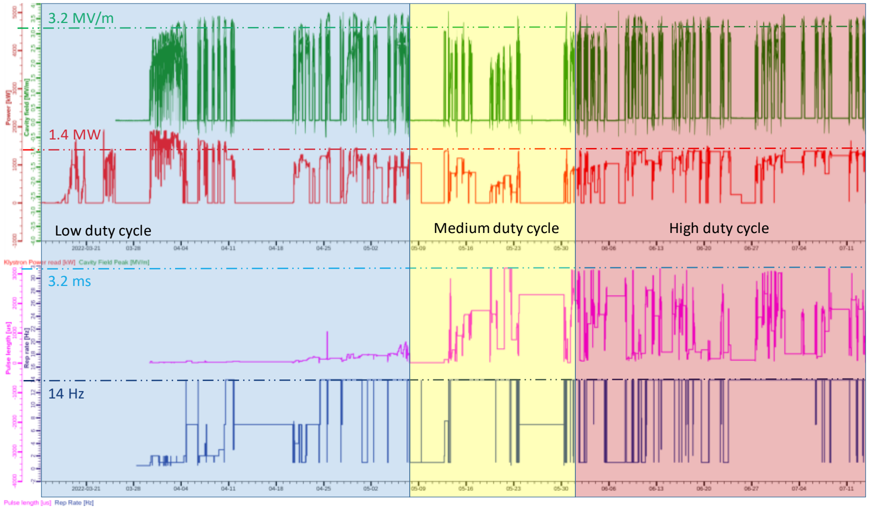
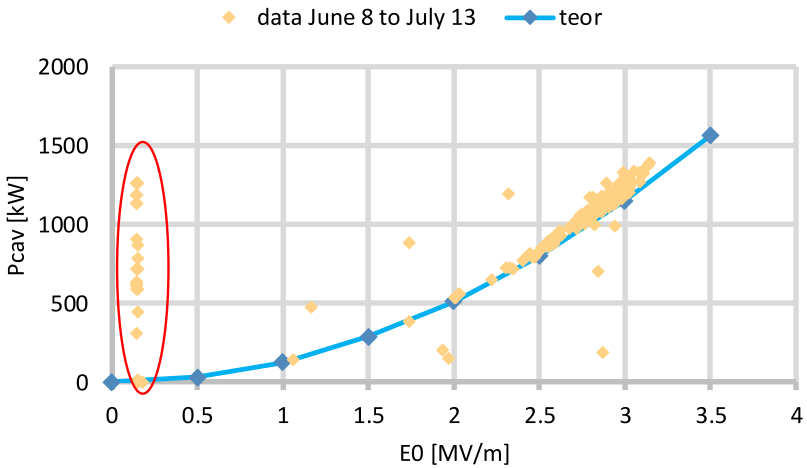
DTL1 Conditioning and beam commissioning

- Conditioned up to nominal power (1.3MW, 4% duty cycle)
- 1st probe beam 5 mA 1st June 2022, transmitted 100% in few minutes (only phasing)
- Full beam current 62mA 1st July 2022, 100% transmission in few minutes

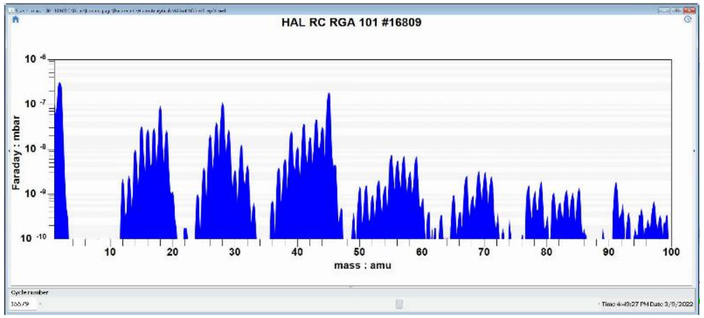
DTL1 conditioning

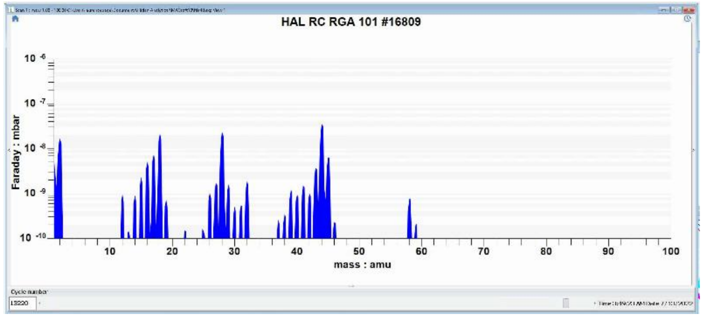




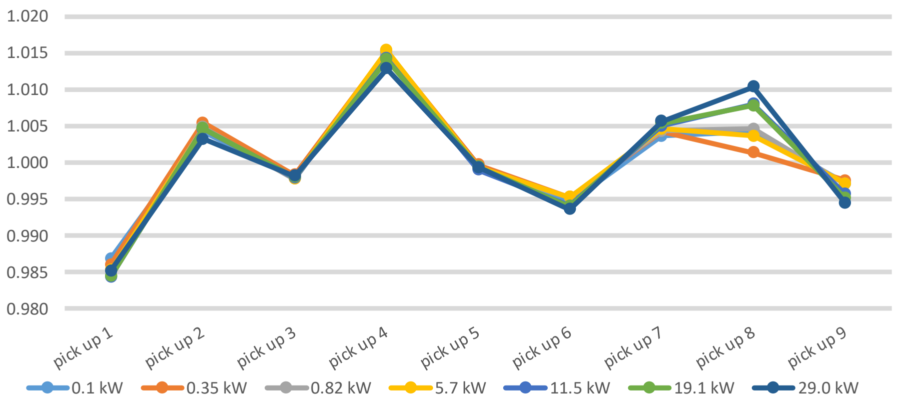
- Nominal cavity field reached with 10μs pulse in 1 week
- Over 4 months, the net time of RF into the DTL is equivalent to 36 days 24h/24h, including time shared with beam commissioning
- Full power of 1.3 MW in the cavity at 4% duty cycle reached

DTL1 conditioning





The comparison of RGA measurements before/after conditioning shows that the high mass components (typically hydrocarbons) have been removed. The vacuum pressure with RF ON at conditioning end was dominated by H_2, CO and CO_2.

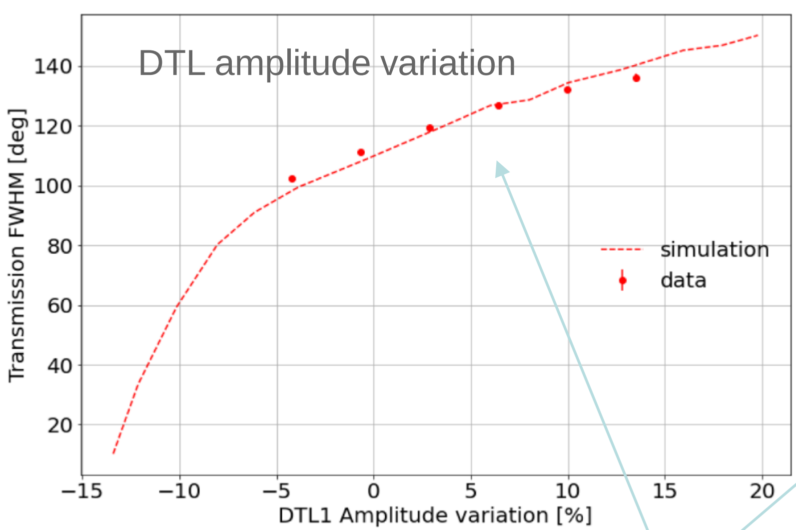


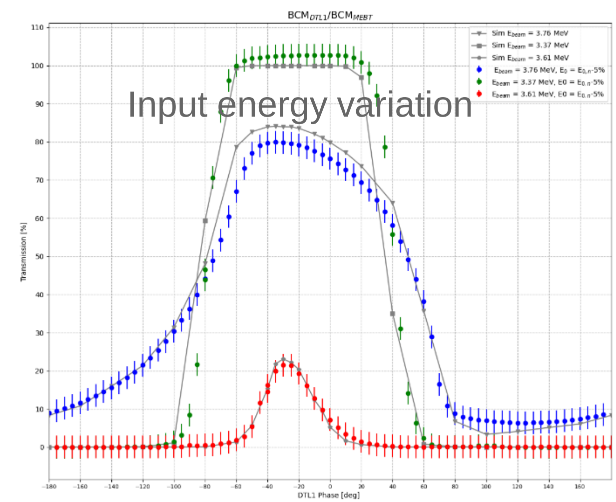
The first acquisition at 0.1 kW (E0 = 1 MV/m, PFWD=145 kW, pulse=600 us, rep. rate=1 Hz) is imposed to be equal to the last bead pull measurement. The last at 29 kW is obtained by E0=3MV/m PFWD=1380 kW, pulse=1.5 ms, rep. rate=14 Hz.

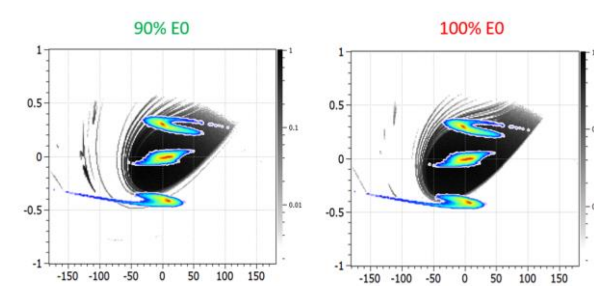
8 pick-ups over 9 **did not show any significant trends of the field, as expected in a stabilized cavity.** Only pick up n. 8 shows some disturbance due to a close movable tuner (the effect was observed in tuning phase).

DTL1 commissioning

- 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



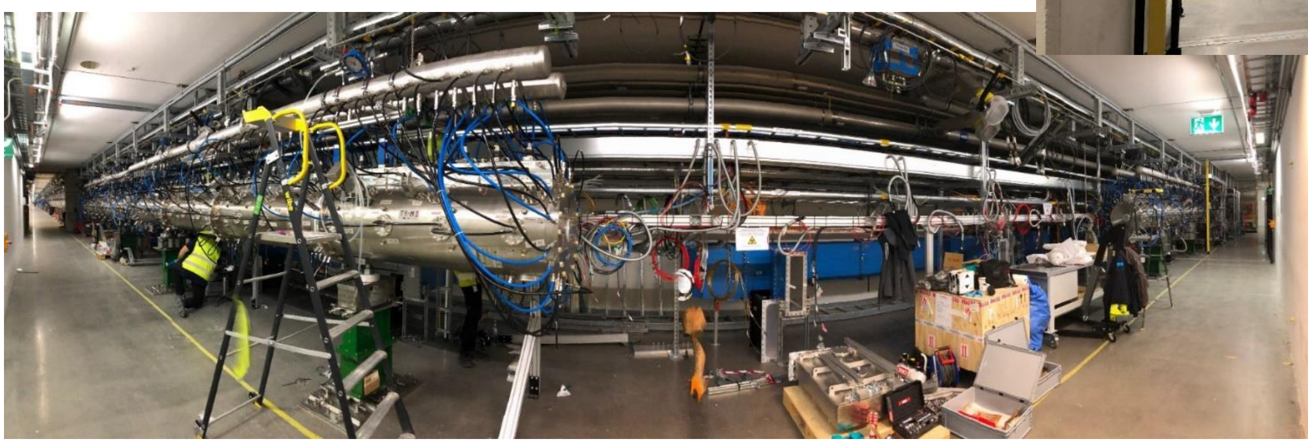


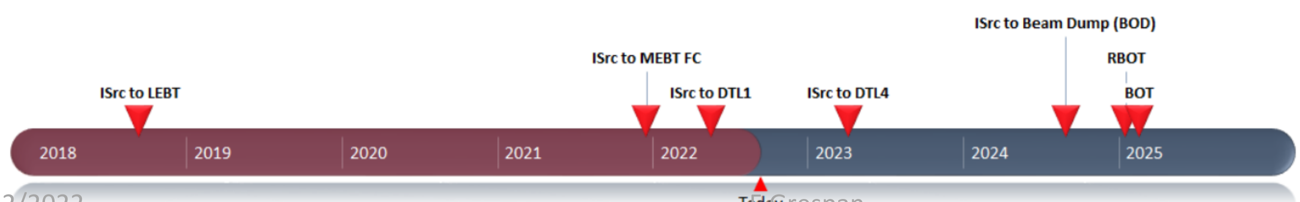


$E_{0,rf} \geq E_0 + 5\%$, from different techniques of long acceptance scan.

Status and next steps

- After tunnel declassification in summer, installation of DTL4 (Sept) and DTL3 (Oct)
- DTL2 in the tunnel before Christmas
- RF Conditioning will start in Feb 2023
- Commissioning in May 2023
- DTL5 installation in Autumn 2023, commissioned with SCL





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The idea for alpha-DTL

- From the experience and the studies on the ESS DTL:
  - 3D RF simulation are today very predictive (DTL1 and brothers)
  - If E0 is switched off after the 1^{st} meter of DTL1 the beam is fully transmitted
  - PCs with end-tab decoupled field tuning (PC tab angle) and stabilization (PC length)
  - PCs with end tab give flexibility to field shape.

Ciao Andrea,
Mi sembra una cosa molto interessante.

Non ho ancora letto gli articoli, ma sarebbe impulsato o CW?

Riguardo alla trasmissione con DTL spento, mi pare di ricordare che DTL1 non trasmettesse, quelli dopo si'. Forse possiamo tagliare il primo tank a 10MV tipo cern per avere l'energia minima?

Per quanto riguarda le scarpette e il campo variabile, bisognerebbe controllare quanto si destabilizza il campo ruotandole: occorre sempre fare un aggiustamento della lunghezza quando si cambia l'angolo, pero' magari e' accettabile se per esempio la TS passa da 0 a 5%.
Perche' non usiamo il tempo che ci separa dal taglio dei post per usare i T3 e T4 e fare qualche esperimento?
(questo te lo volevo proporre anche in vista di una pubblicazione sul tuning, potremmo approfondire qualcosa con le misure ora che i due tunatori sono un po' meno sotto pressione?)

Magari tuniamo con l'acqua, spostiamo i tuners dove non disturbano il campo o ne mettiamo meno, e riempiamo di pick up per vedere meglio il campo.

Ciao! Francesco

-----Original Message-----
From: Andrea Pisent <andrea.pisent@lnl.infn.it>
Sent: martedì 9 novembre 2021 10:03
To: francesco grespan <Francesco.Grespan@lnl.infn.it>
Subject: possibile BREVETTO (alpha linac)

Ciao, ieri ho un po' chicchierato con juan e poi con alessio per il possibile linac (RFQ+DTL 352MHz) per i 100 uA medi di particelle alpha.

le energie che interessano vanno dai 20 ai 60 MeV, a seconda dei processi che si vanno cercando. nota che 20 MeV significa 5 MeV/u e quindi 10 MV equivalenti. Uno dei nostri moduli fa circa 20 MV. Il problema è la scelta dell'energia.

i magneti permanenti dovrebbero traportare il fascio anche attraverso un tank spento. Quindi nella prima chiacchierata con Juan ci siamo detti, scegliamo 2 o 3 energie interessanti per applicazioni importanti, e disegnamo il DTL con delle transizioni di tank corrispondenti.

Mi è però poi venuta in serata una nuova idea per avere una regolazione fine dell'energia in usciata dal tank di un dtl (che può essere utile in questo caso, ma avere anche una valenza più ampia).

Se noi abbiamo un DTL stabilizzato con le scarpette, ruotando le scarpette possiamo in principio diminuire (o al limite "spegnere") il campo accelerante negli ultimi gaps (facendo nel dtl quel che facciamo con ALPI). Il mantenimento della stabilizzazione dovrebbe consentire di variare localmente il campo, secondo il principio che ciò che si regola si può sregolare.

si tratta chiaramente di avere degli attuatori che consentono di ruotare i

Pisent et al. "DESIGN OF A LINEAR ACCELERATOR FOR ISOTOPE PRODUCTION", Linac2022 proceedings

Alpha beams for radionuclides

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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.

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.

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 uA

.

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.

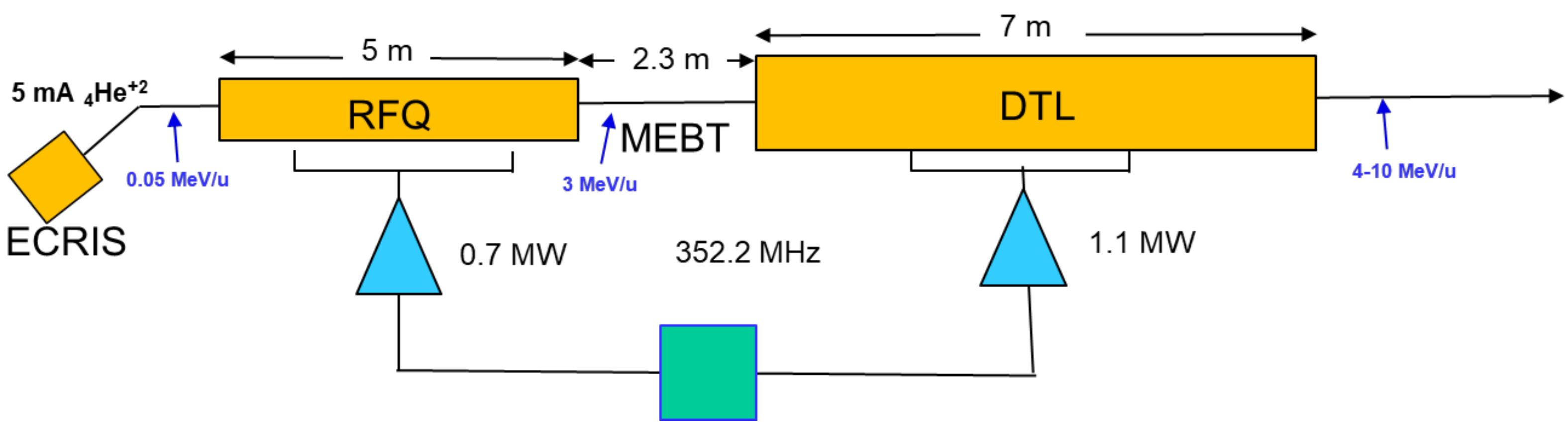
Ref. Qaim et al. “Uses of alpha particles, especially in nuclear reaction studies and medical radionuclide production”

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

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

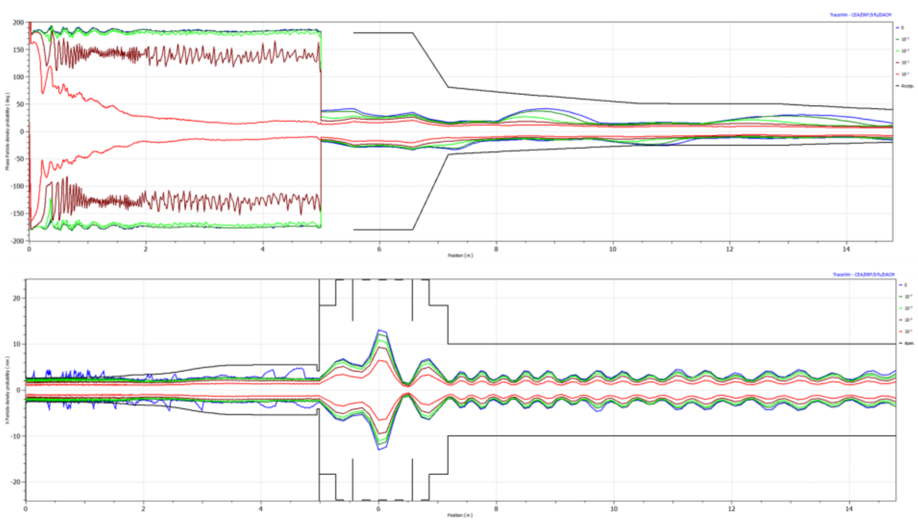


Fig. 5: Start to End simulation from the begin of RFQ to the end of DTL.

DTL energy regulation

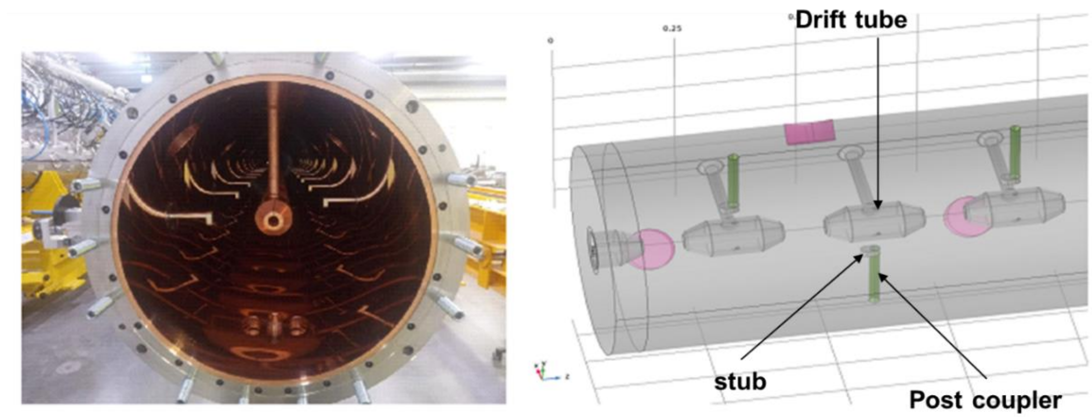
Alpha-DTL is equipped with a **set of post couplers terminated by stubs**, to stabilize and flatness the accelerating field E0.

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.

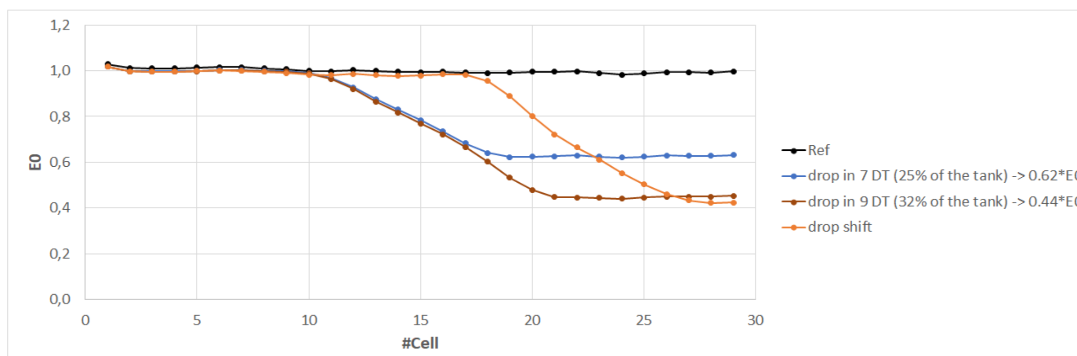
Several such perturbations on adjacent post couplers can introduce a sizable reduction in the fields over the region of a few cells.

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

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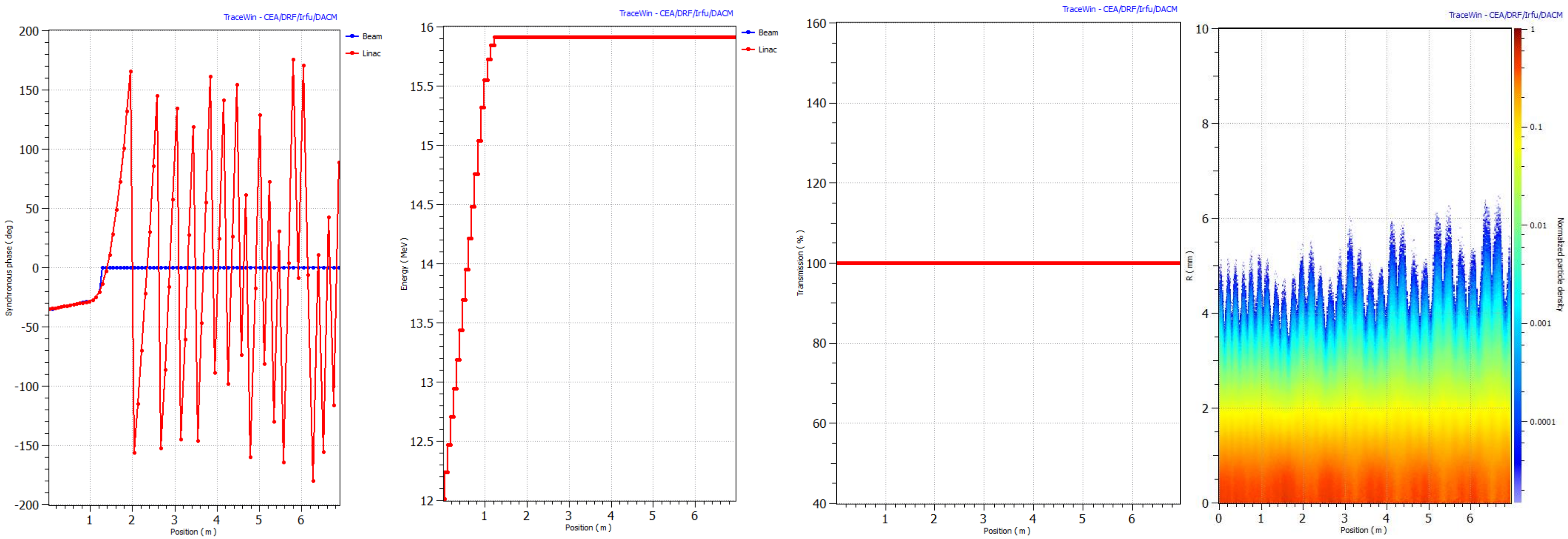
BD with field regulation…

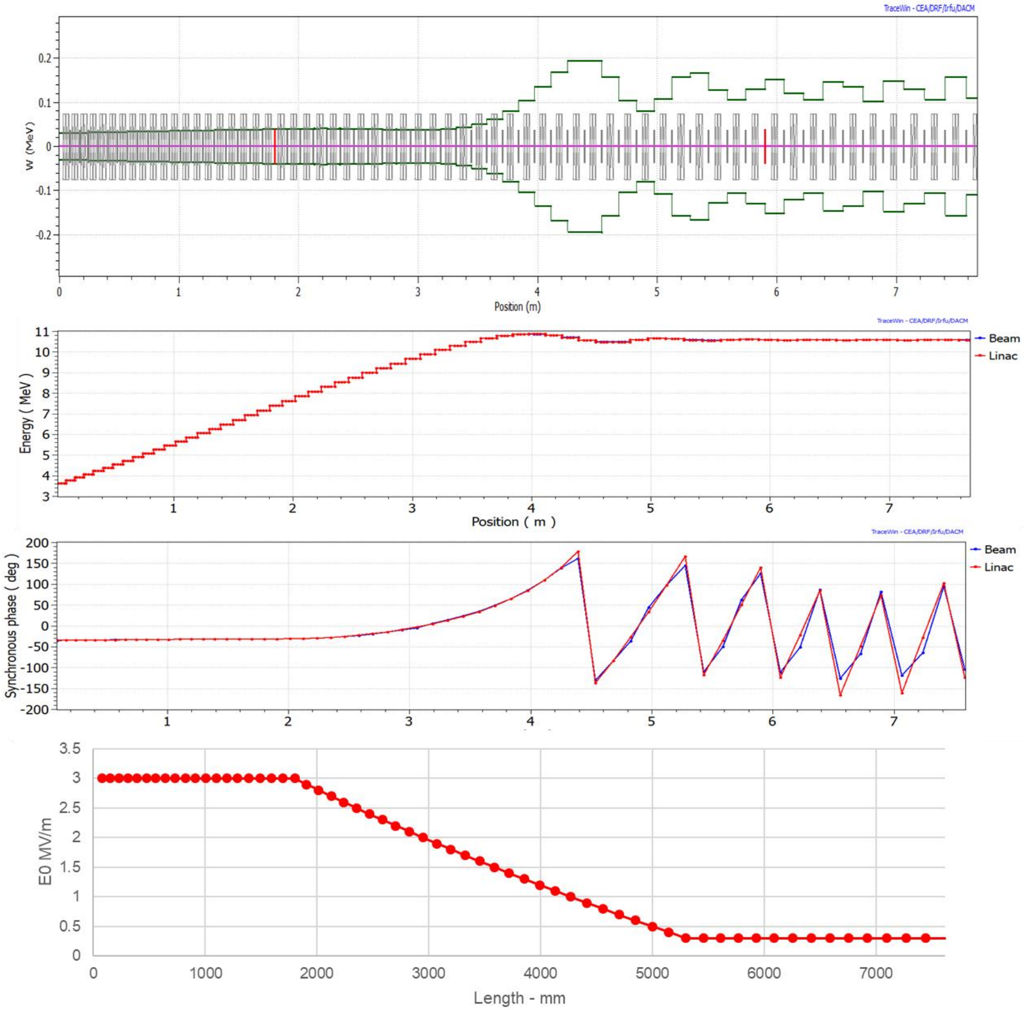


alpha-DTL with E_0=0 after 1 m has full transmission. But it is impossible to switch off part of the cavity. Nevertheless…

BD energy regulation: loose of synchronism

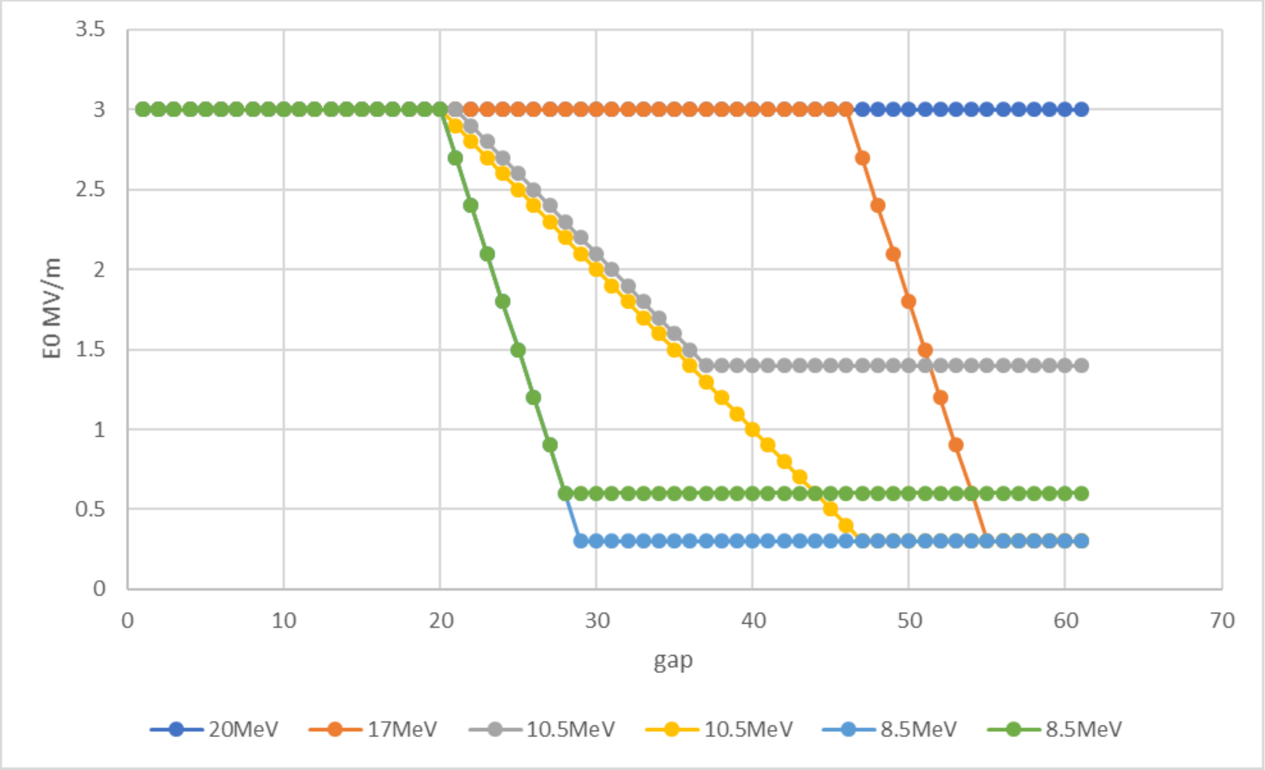
Particles in the ramped gaps start to loose synchronism, up to not being accelerated anymore.
The focusing given by the PMQs guarantees full transmission of the beam to the end of the DTL.

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.



Ideas for application: SPES-PIAVE-TANDEM(DTL)-ALPI complex

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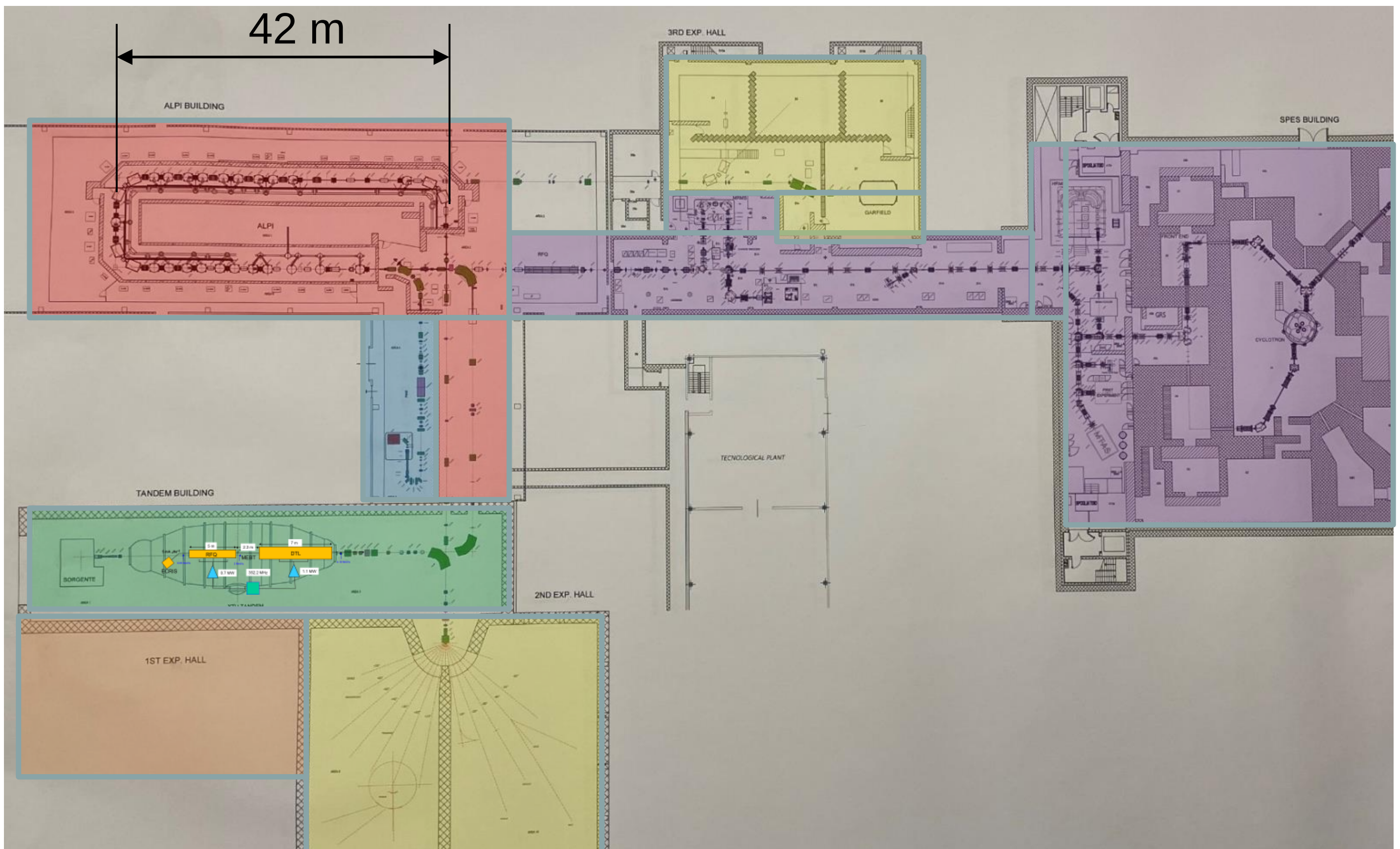
In a modified version for A/q=2.6 could deliver the light ions presently produced with TANDEM stand alone.



Experimental Halls

ALPI

TANDEM=>DTL

SPES

PIAVE

W_{max} (10 MeV/u)

^{13}C 120 MeV
^{7}Li 70 MeV
H 10 MeV
^{18}0 180 MeV
^{10}B 100 MeV
^{15}N150 MeV

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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	F0D0	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	F0D0	10	40	**80**	2.60	0.26
alphaDTL	2	4He+2	3	5	352	10	1	FF0DD0	10	5	**10**	1.90	0.19
nDTL	2	d	3	5	352	20	2	FF0DD0	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