Linac4 Drift Tube Linac

RF Design

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Linac4 DTL – RF Design

- Introduction
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  - Peak Fields
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  - Principle of Consistent RF Design
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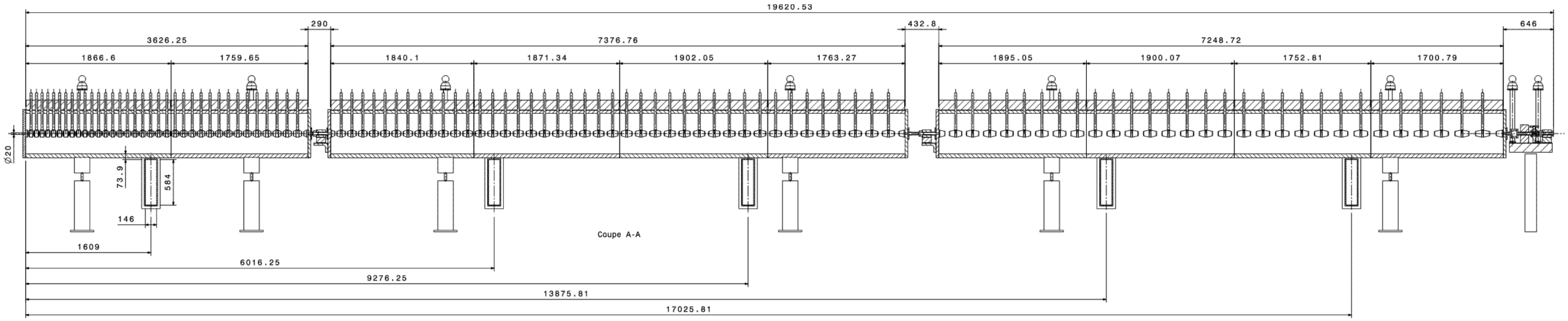
- Consistent RF Design – Part 2
  - Compensation of Field Tilts
  - Power Coupler Compensation
  - Position of Pick-Ups, Power Couplers & Pumping Grids

Linac4 DTL Design

DTL design parameters:

- DTL from **3 – 50 MeV** with 3 cavities and 1 LEP and 2 new klystrons
- Klystron output power at cavity port **1 MW** (Tank1) and **2 MW** (Tank2&3)
- Accelerating field at ~**3.2 MV/m**
- Peak electric field of **1.6 Kilpatrick** lowered to 1.2 Kilp. over the first cells
- **PMQ**s in **vacuum**
- Self supporting steel cylinders of **50 mm** thickness
- Maximum segment length of **2 m**



RF Breakdown

DTL designs might have problems with RF breakdown in the first cells

- **Origin of breakdowns unclear but:**
  - C.S. Taylor in Lapostolle/Septier 1970 citing MURA 1964:

    "Sparking is reported to be an occasional problem of the 1.7 MeV/m machines while at 1.5 MeV/m in long tanks it is apparently quite rare."

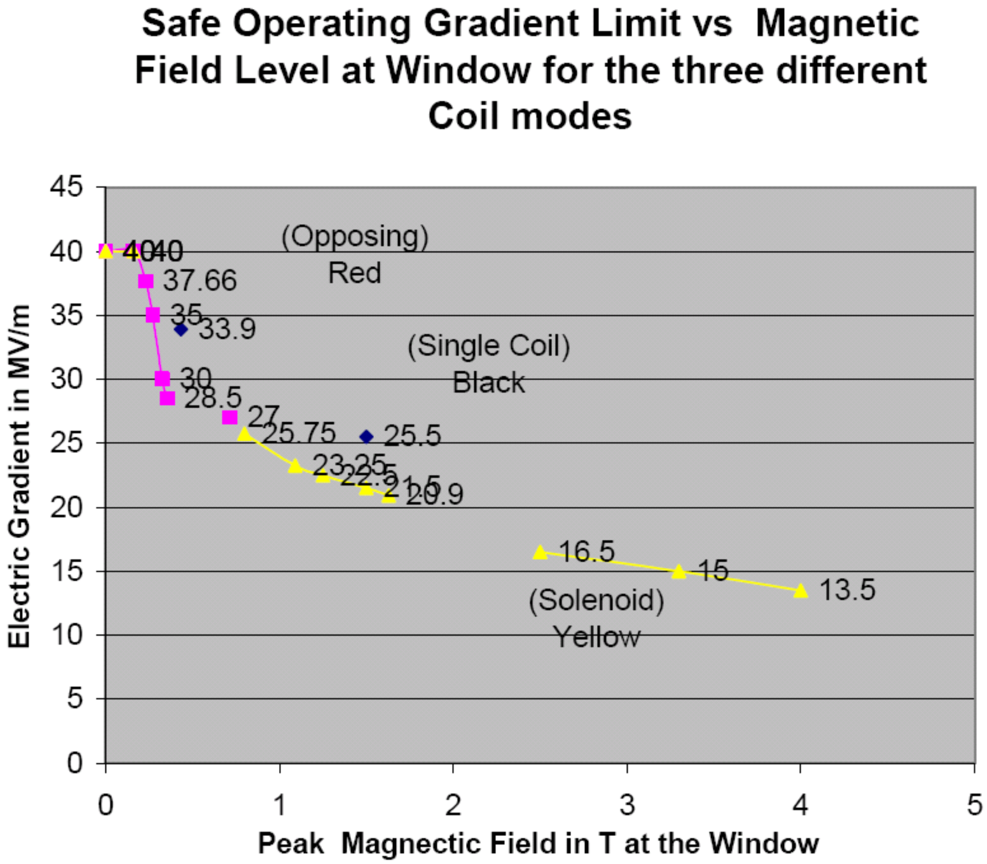
- **RF breakdown:**
  - electric discharges following field emission
  - Kilpatrick limit E_K = **18.4 MV/m** @ 352.2 MHz
  - Bravery factor for DTL: **1.7 Kilpatrick**
  - Enhanced by magnetic fields ⊥ to surface

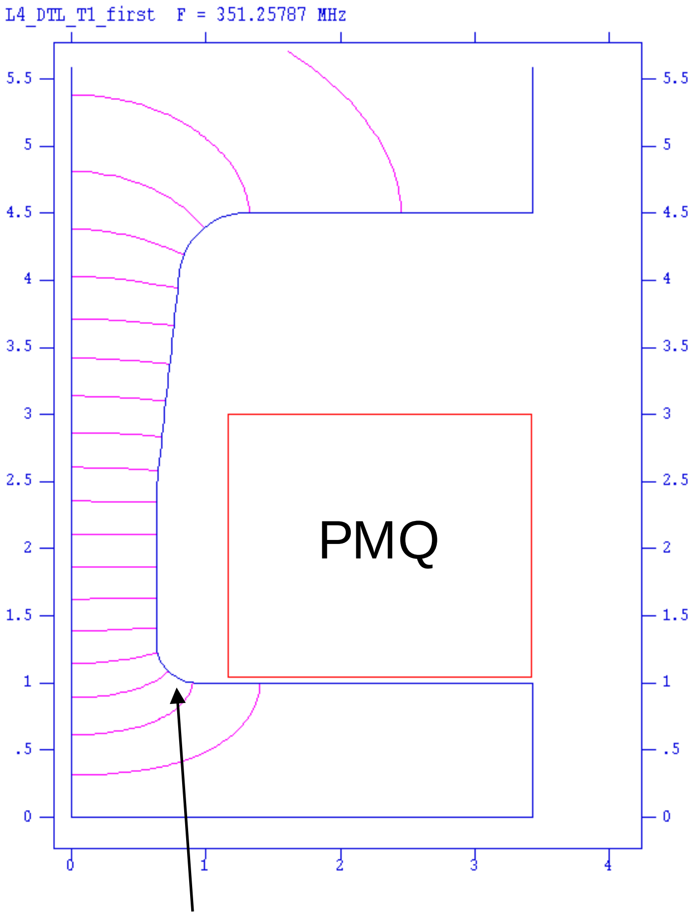

LAMPF
Jim Stovall

RF Breakdown in Muon Cooling

Role of magnetic fields in RF breakdown?

- **Recent study by Fermilab in MuCool program (A. Bross MICE CM17):**


Safe Operating Gradient Limit vs Magnetic Field Level at Window for the three different Coil modes



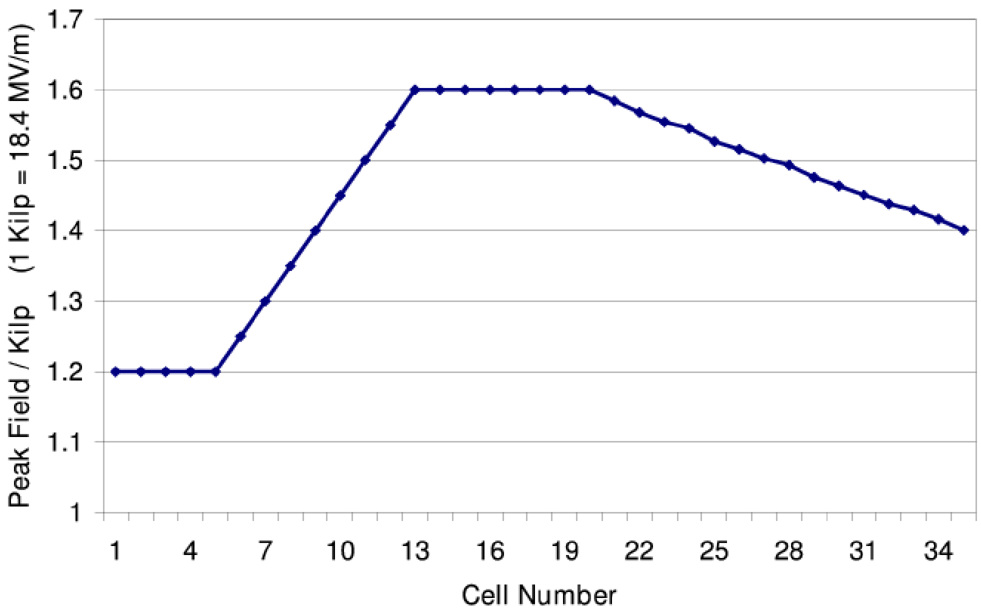
Peak electric field

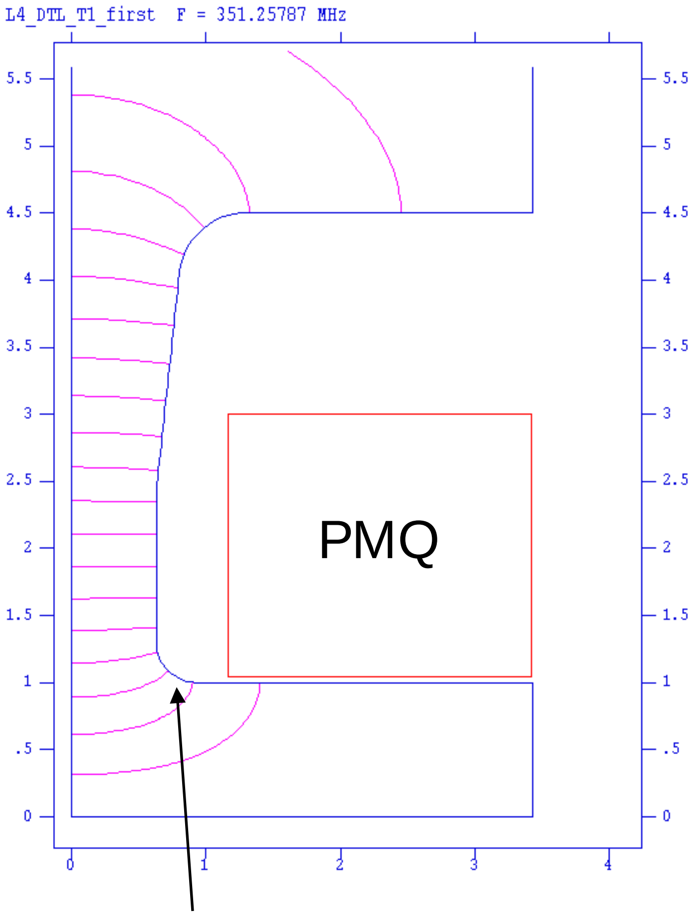
- **30 %** decrease: 1.7 => **~1.2 Kilpatrick**

Peak Surface Field

Trade-off E_{max} versus gap length, first cell:

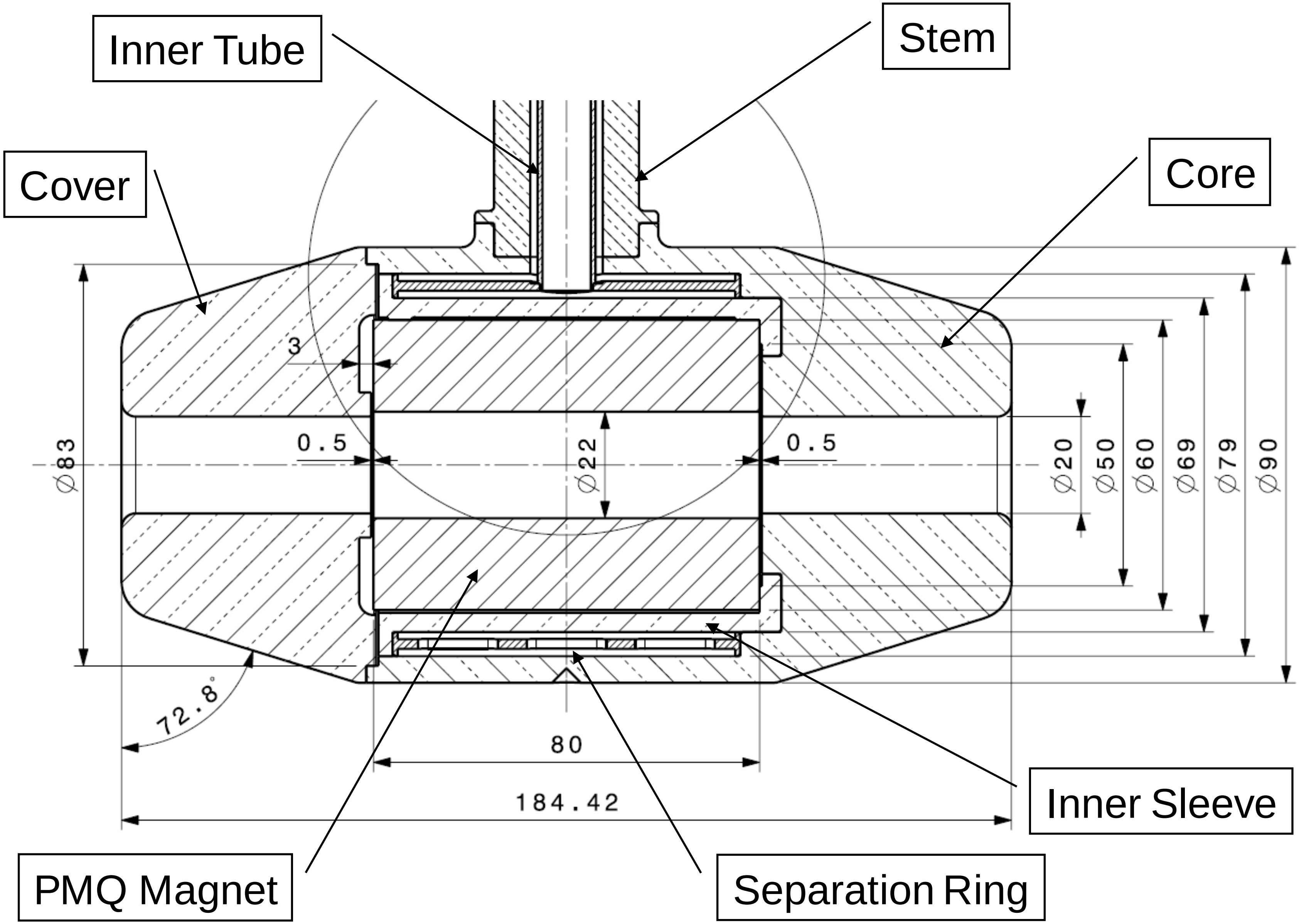
- E_{max} reduction: from 1.7 Kilpatrick to **1.2 Kilpatrick**
- **Gap length** increase: from 8.5 mm to **13 mm**
- **Tuning** by variation of **face angle**
- **Energy gain** $E_0T\cos(\varphi_s)$ decrease: **-4.1%**
- **Beam energy** decrease, first tank: **-1%**





Peak electric field

Drift Tube Body


Inner Tube

Stem

Cover

Core

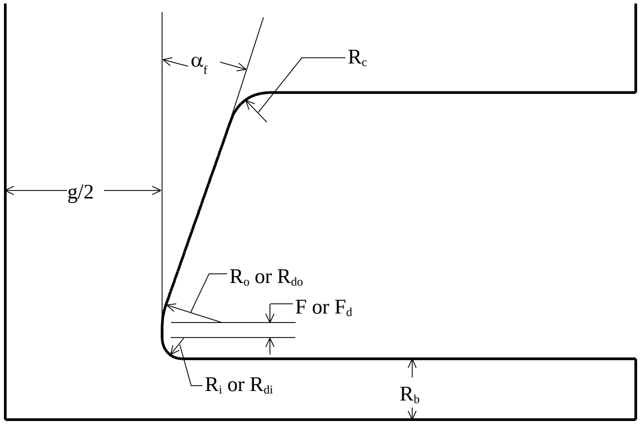
Inner Sleeve

PMQ Magnet

Separation Ring

DTL RF Design – Part 1

Consistent cell by cell RF design:



- A cell is designed with the design parameters:
  - Cell length, gap length, face angle
- With the following objectives:
  - The cell is resonant at the design frequency
  - The cell length is consistent with the particle speed (l=β·λ) & RF phase
  - The effective shunt impedance is maximum (within constraints)
- The constraints are:
  - The peak field
  - The feasible range of geometrical dimensions
- Tracing the synchronous particle, we find a new energy & RF phase.
- Design the next cell ↑ until:
  - The design energy is reached or
  - The available klystron power is used up

Linac4 DTL Design

Production design:

- Parameters compatible with mechanical realization
- Production drawings are ready and manufacturing started

Parameter \ Cavity	**1**	**2**	**3**
Cells per cavity	39	42	30
Accelerating field	3.1 MV/m	3.3 MV/m	3.3 MV/m
Maximum surface field	1.5 Kilp.	1.4 Kilp.	1.45 Kilp.
Synchronous phase	-35 to -24 deg	-24 deg	-24 deg
RF peak power per cavity	1.00 MW	2.03 MW	1.98 MW
Quadrupole length	45 mm	80 mm	80 mm
Flat Size	11 mm	7 mm	5 mm
Number of sections	2	4	4
Length per cavity	3.8958 m	7.3406 m	7.2508 m
Beam output power	11.88 MeV	31.45 MeV	50.14 MeV

DTL Comparisons

Comparison:

- Linac4 DTL more compact with constant high E_0
- Linac2 starts from a lower beam energy
- SNS uses ramped E_0 in tank1 to adiabatically capture the beam longitudinally
- J-PARC uses constant but lower E_0 with 1.3 Kilpatrick

RF stability:

- Tank lengths in λ similar to Linac2 and SNS and lower than at J-PARC

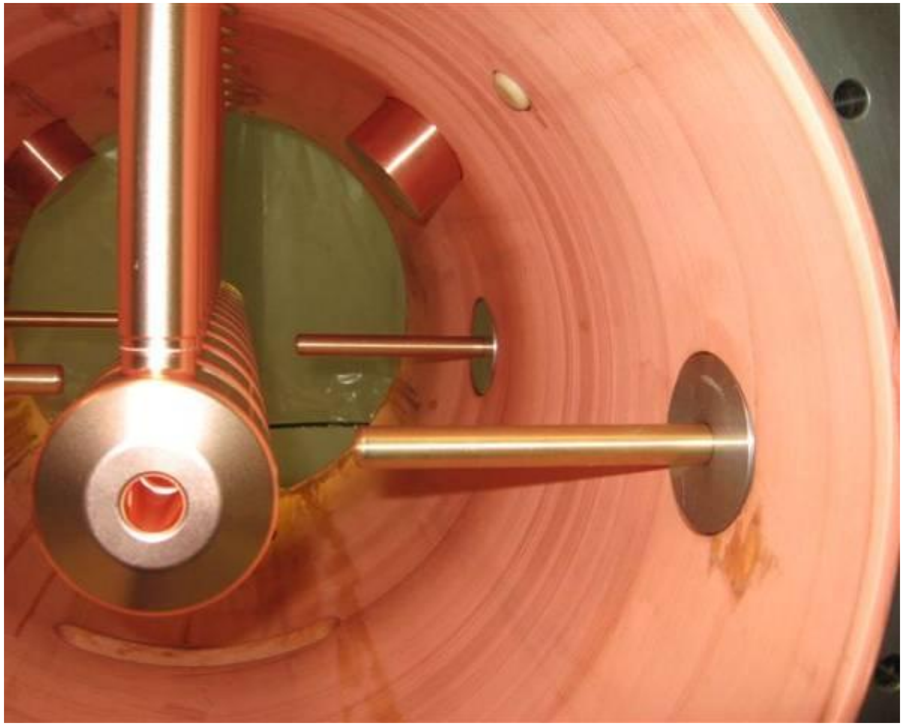
	E_0	freq	E_0	E_{max}	W_{in}	ramp	tank lengths
	MV/m	MHz	Kilp.	Kilp.	MeV	%	λ
Linac2	1.79 – 2.16	202.56	0.121 – 0.146	0.63 – 0.85	**0.75**	21	4.7 / 8.8 / 9.0
SNS	1.13 – 3.77	**402.5**	0.058 – 0.194	0.47 – 1.3	2.5	**62**	5.6 / 8.1 / 8.5
J-PARC	2.5 / 2.7 / 2.9	324	0.140 – 0.163	1.3	3.0	0	**10.7 / 10.2 / 7.9**
Linac4	**3.1 – 3.3**	352.2	**0.179**	1.2 – 1.5	3.0	0	3.9 / 7.3 / 7.3

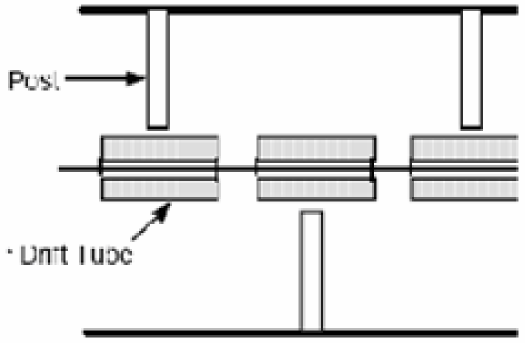
Post Coupler Distribution

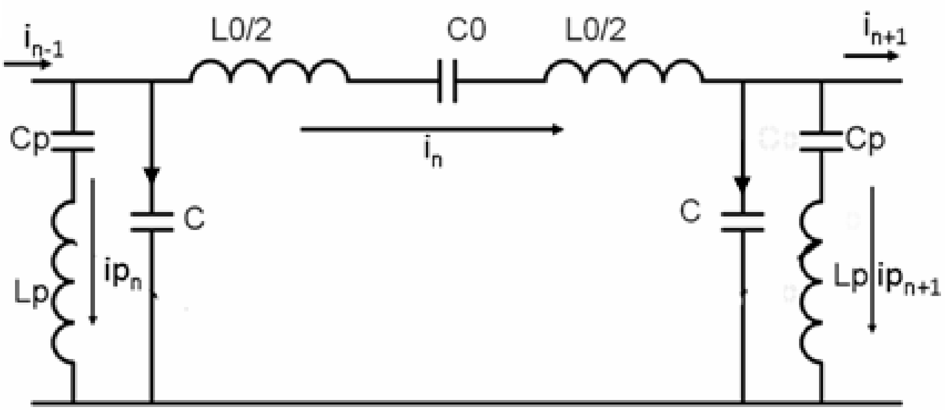
Post Coupler Circuit Model:

- The optimum post-coupler length can be deduced from frequency measurements

- Tank1: 1 PC per 3 DTs
- Tank2: 1 PC per 2 DTs
- Tank3: 1 PC per 1 DTs







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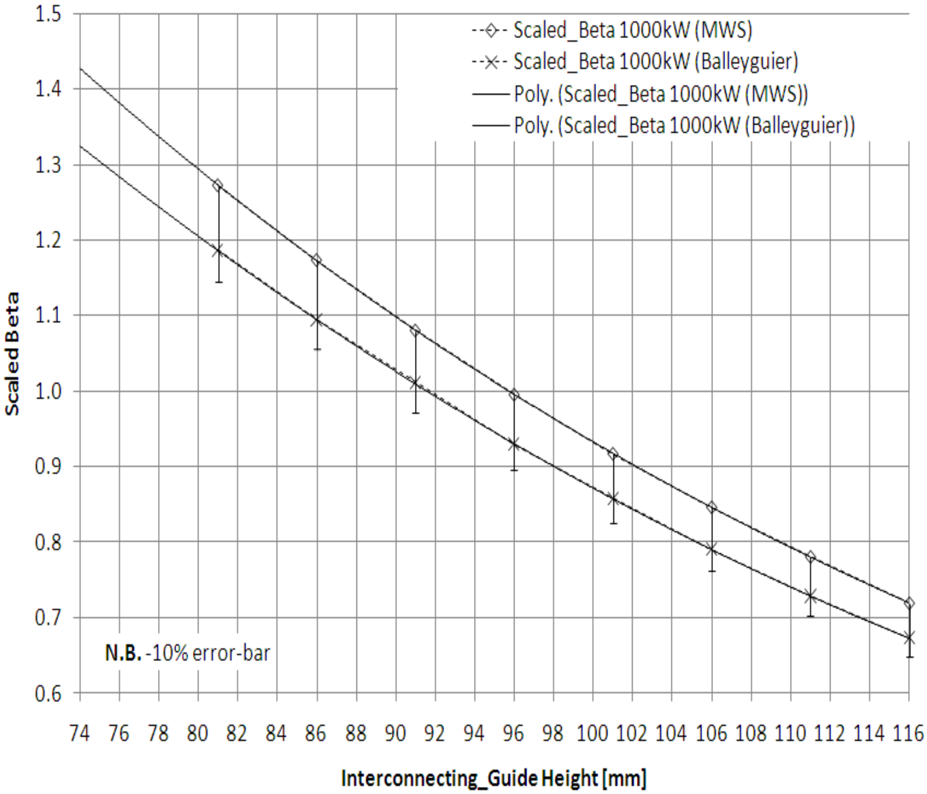
DTL Power Coupler

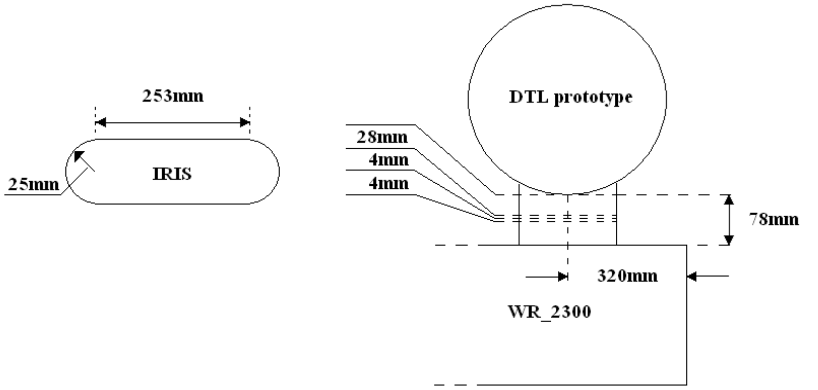
Power Coupler Simulation:

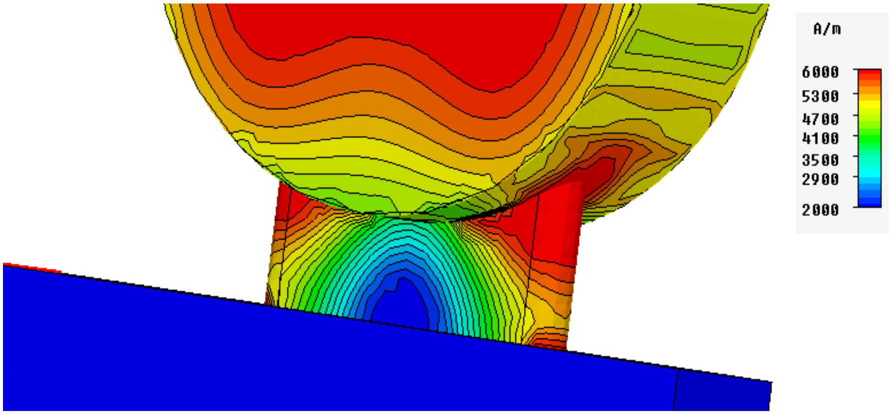
- Coupling factor
- Frequency Error
- Power dissipation

Cell 22-23	MWS	Superfish	HFSS
freq. [MHz] w/o WG	350.977	353.750	353.600
freq. [MHz] with WG	347.780	-	350.600
Δf [MHz]	3.197	-	3.000
Δf*l [kHz*m]	644	-	604



N.B. -10% error-bar





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Tuning Range

Tuning:

- The static tuners / plungers compensate static **manufacturing errors**
- The movable tuners compensate **thermal expansion**

Example: Drift Tube 1 of Tank1

Type	Nominal	Sensitivity	Tolerance Min	Max	Static Error Min	Max	Temper. Rise SPL	Thermal Expansion	Dynamic Error SPL
	mm	MHz/m	mm	mm	kHz	kHz	K	mm	kHz
shift_DT	0	-10.50	-0.15	0.15	1.575	-1.575	0	0.000	0
gap	11.8001	5905.10	-0.025	0.025	-147.628	147.628	50	-0.047	-277.530
len_cell	68.5613	4412.60	-0.01	0.01	-44.126	44.126	10	0.012	53.912
alpha		4525.50	-0.03	0.03	-135.765	135.765	0	0.000	0
d_DT	90	-723.40	-0.034	-0.012	24.596	8.681	50	0.075	-53.908
d_tank	520	-445.00	-0.035	0.09	15.575	-40.050	10	0.093	-41.235
stem	29	139.93	-0.025	0.025	-3.498	3.498	20	0.010	1.344
Sum					-363.961	372.762			-317.417
kHz*m					-24.954	25.557			-21.763

Tuning Range

Provide sufficient tuning range:

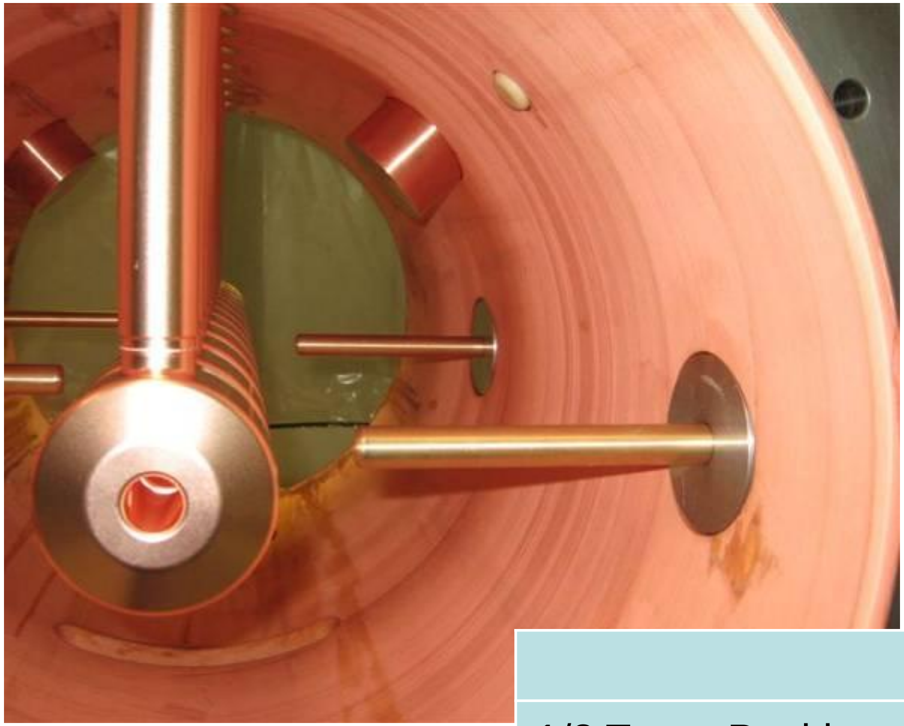
- Tolerances and thermal expansion define the maximum frequency error
- A sufficient number of tuners compensates the frequency error

Tank	No Cells	Length	Max Cell-Effect	Max Freq Error	Max Tuner Effect	Min No Tuners	Nom. Comp.	Tot. No Tuners	No Tuners
		m	kHz*m	kHz	kHz*m	m^{-1}	kHz		m^{-1}
1	39	3.9	80	800	450	1.8	250	12	3.1
2	42	7.3	85	490	450	1.1	120	18	2.5
3	30	7.3	90	370	450	0.9	90	15	2.1

Movable tuners:

- At least 1 - better 2 - for tank1
- 2 for tank2 and tank3

Static Design Compensation



In simulations, a modified cavity diameter compensates

- Tuner Default Position
- Post couplers
- Simulation Errors (Meshing)

	Unit	Tank1	Tank2	Tank3
1/3 Tuner Position	kHz*m	1800	2700	2250
Post Couplers	kHz*m	117	263	511
Syst. Sim. Errors	kHz*m	390	438	438
Sum	kHz*m	2307	3401	3199
D Sensitivity	MHz*m/m	-1716	-3212	-3212
Diam. Comp.	mm	-1.34	-1.059	-0.996

DTL RF Design – Part 2

Consistent tank RF design:

- A tank is assembled from all cells of equal resonance frequency:
  - The resonance frequency of the tank is the same as of the cells (as long as the field distribution is the same)
  - The accelerating field increases along the tank ("tilt") (and the resonance frequency in reality is slightly off)
  - The field distribution can be corrected by
    - Tuners or
    - Shifting the end-walls
- Shifting end-walls, the remaining error gets well within ±1%
  - The field distribution can be further corrected by
    - Post-couplers with tips or
    - Slightly retuning cells with face angles

Compensation of Field Tilts

Origin of Field Tilts:

- Each cell has:
  - Same resonance frequency
  - Same average accelerating field
  - Different dimensions
  - Different wall currents (by few percents)
- Continuity of wall currents leads to natural tilt
- Further size dependent effects:
  - Amount of discretisation error
  - Size independent manufacturing errors (e.g. weld shrinkage)

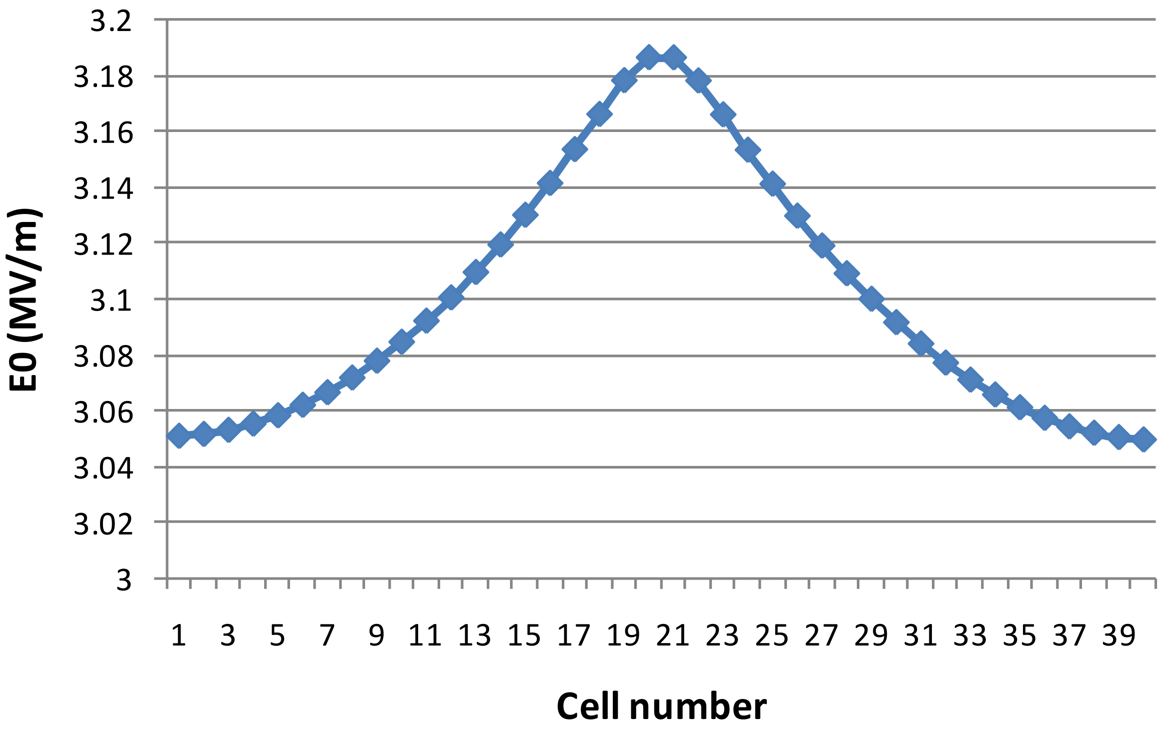
Compensation of Field Tilts:

- Re-machining of end walls before copper plating (single step)
- Adjustment of tuners + post-couplers

Power Coupler Compensation

Cell influence of Power Coupler:

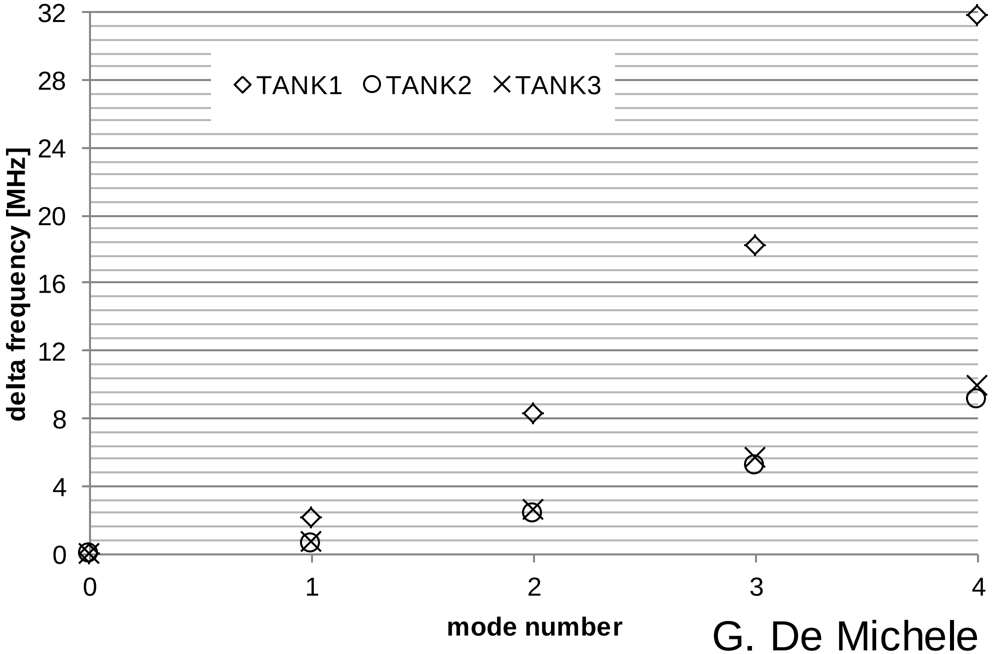
- The power coupler is installed at the center of Tank1
- The power coupler influences the accelerating fields in neighbouring cells
- Tuners can compensate the influence



Position of Pick-Ups

Position of Pick-Ups:

- 5 pick-up locations in Tank1:
  - Pick-up at ~½ point suppresses measurements of TM_{01n}, n odd
  - Sum of pick-ups at ¼ & ¾ point suppresses TM_{01n}, n odd & TM_{012}
  - Pick-up close to end-walls measures all TM_{01n} modes
- 9 pick-up locations in Tank2&3:
  - Pick-ups in the 1/8 points



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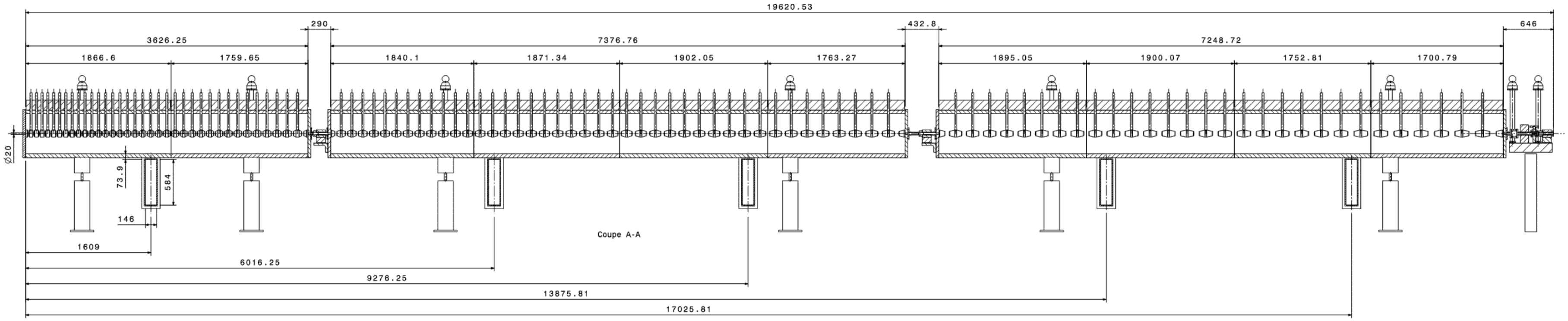
Position Power Couplers & Pumping Grids

Position of Power Couplers:

- 1 power coupler in Tank1, 2 power couplers in Tank2&3:
  - All wave-guides slightly off ½ and ¼ & ¾ point due to segmentation

Position of Pumping Grids:

- On segments that do not have power couplers:
  - 1 on Tank1, 2 each on Tank2&3



DTL RF Design – Conclusions

- Consistent
  - Particle Energy & Phase
  - Design Parameters & Constraints
  - Cell & Tank Design

- Manufacturable
  - Compatible with Segment & Tank Size
  - Post Coupler & Tuner Distribution
  - Cooling Circuits & Pumping Grids

- Complete
  - Tuning Range, Stabilization & Compensation
  - Power Coupler & Pick-Up Positions