RF Structures and Beam Dynamics Design for the Spallation Neutron Source

James H. Billen

Harunori Takeda

Summary

- Cavity design is efficient and conservative: electric fields are below sparking limits and power densities are manageable.
- Cavities have large enough stored energy to minimize the effect of chopping on the fields.
- There is ample space between cavity segments for focusing magnets, diagnostics, flanges, etc.
- The linac upgrade for 4-MW beam power is simple: add one klystron per rf module.
- Multiparticle beam-dynamics simulations without errors show excellent performance.

Topics

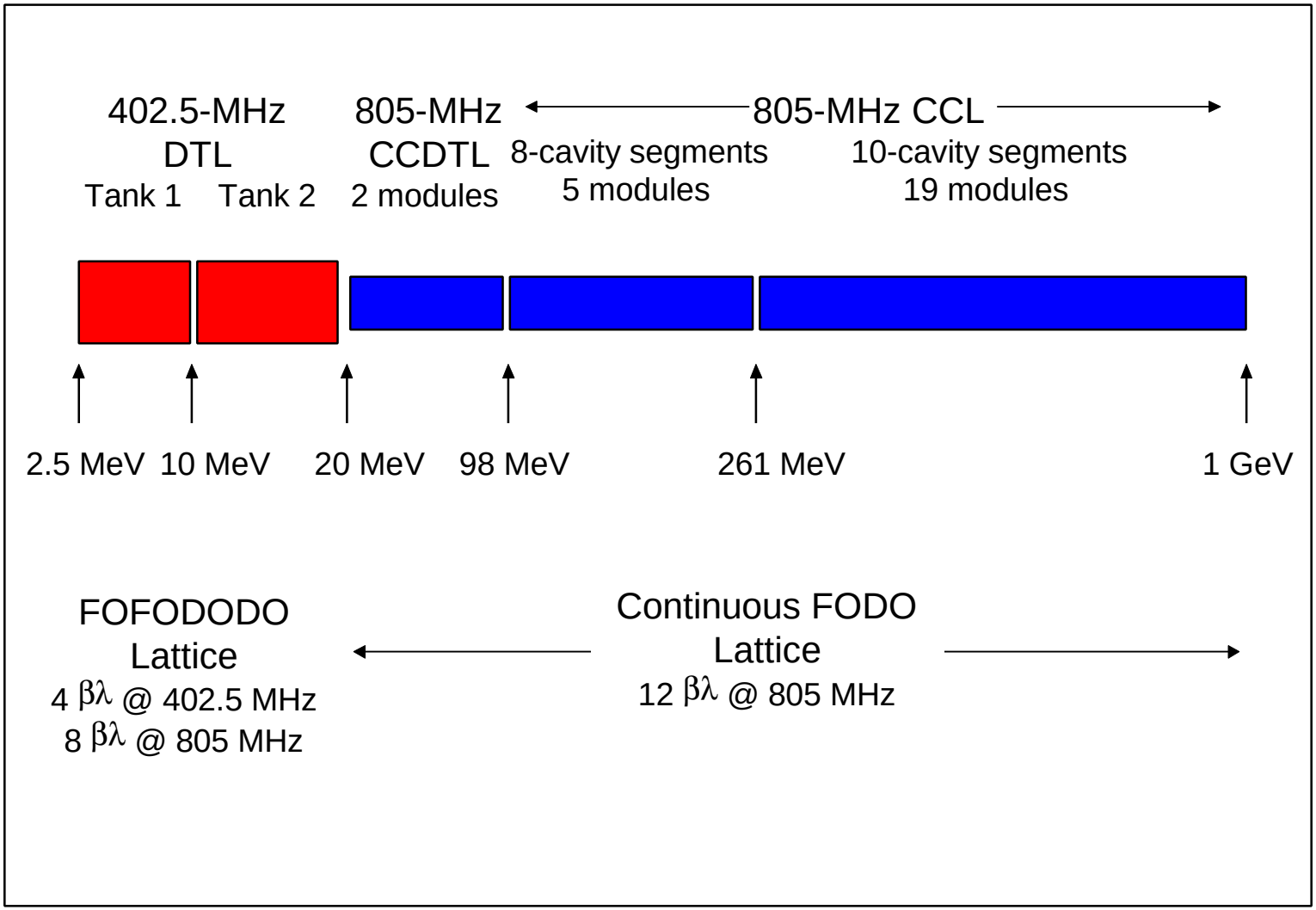
- Design goals
- Linac layout
- Beam-dynamics simulation results
- RF power partitioning
- Upgrade considerations

- Supplementary materials in handout:
  - Cavity design details
  - Terminology, acronyms, definitions
  - Brief description of a CCDTL
  - Partitioning table spreadsheets

Design Goals

- Maintain smooth average focusing strength per unit length transversely and longitudinally.
- Use high cavity stored energy to reduce the effect of beam chopping on the cavity fields.
- Increase the bore radius as early in the linac as practical, consistent with reasonable shunt impedance.
- Provide a method for upgrading the linac for operation at 4 MW beam power.

SNS Linac Layout for 1-MW Beam

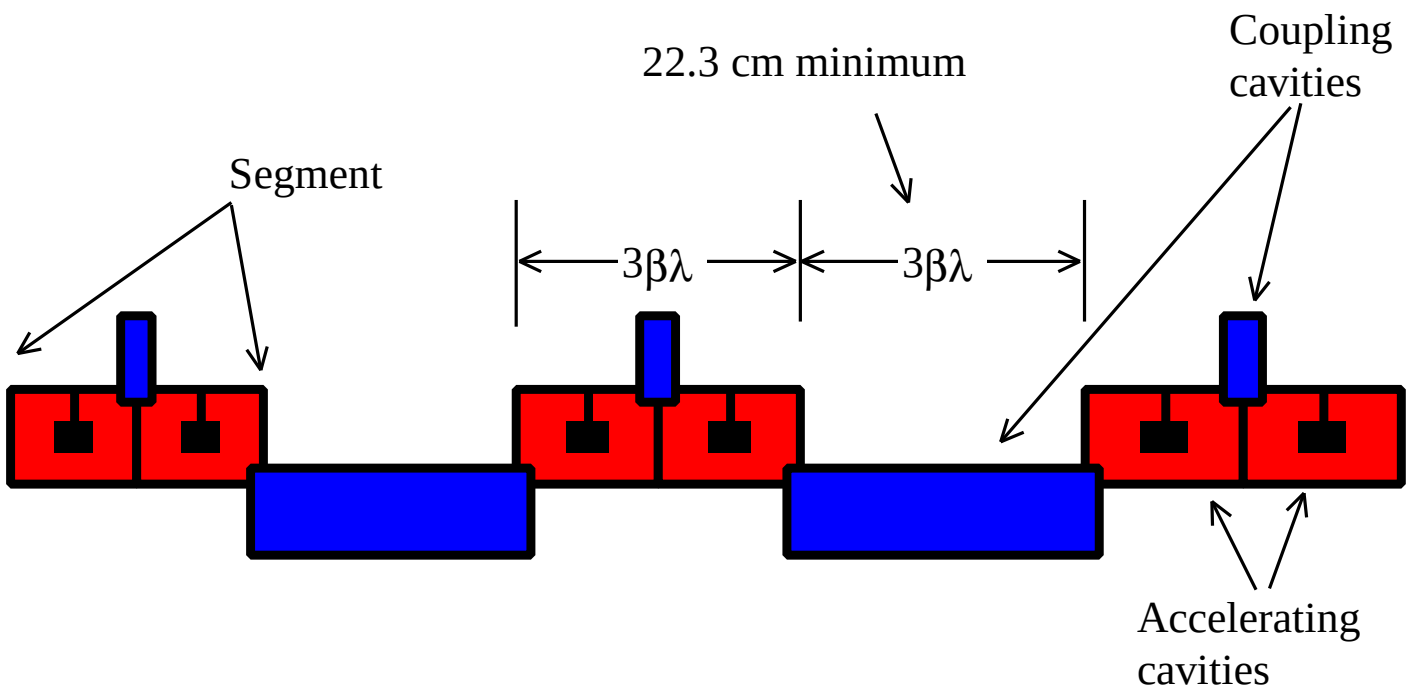


The Drift-Tube Linac (DTL)

- Tank 1: 2.5 to 10 MeV, 46 cells
- Tank 2: 10 to 20 MeV, 38 cells
- Each tank uses one 1-MW klystron.
- Total Length is 8.7 m (3.7 m + 5.0 m).
- Peak current I_{Beam} = 56 mA (one leg of funnel @ 4 MW total power).
- Constant average accelerating field E_0 = 3.0 MV/m.
- Bore radius R_b = 1.0 cm.
- Average shunt impedance ZT^2 = 39 MΩ/m including all losses.
- FOFODODO lattice produces acceptable beam size; drift tubes can accommodate the magnets (PMQs).
- Post-coupler stabilized at every other drift tube.

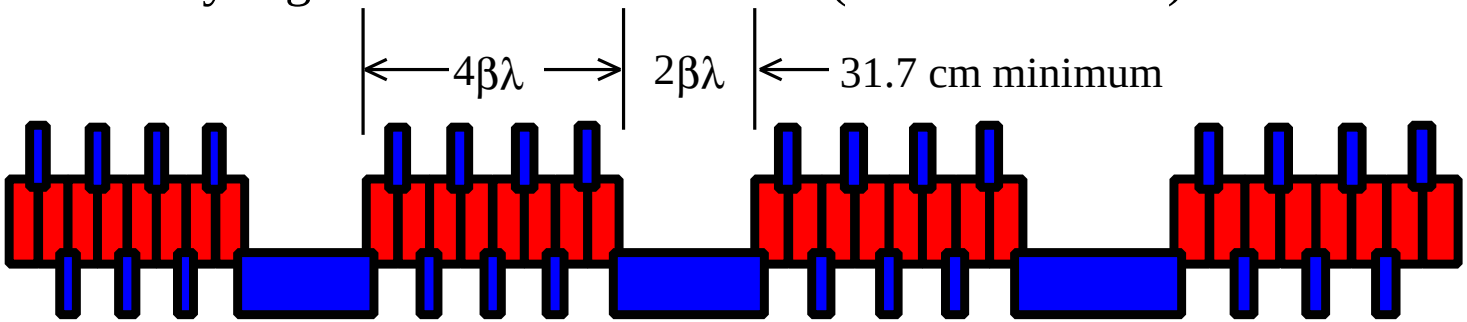
CCDTL Segments

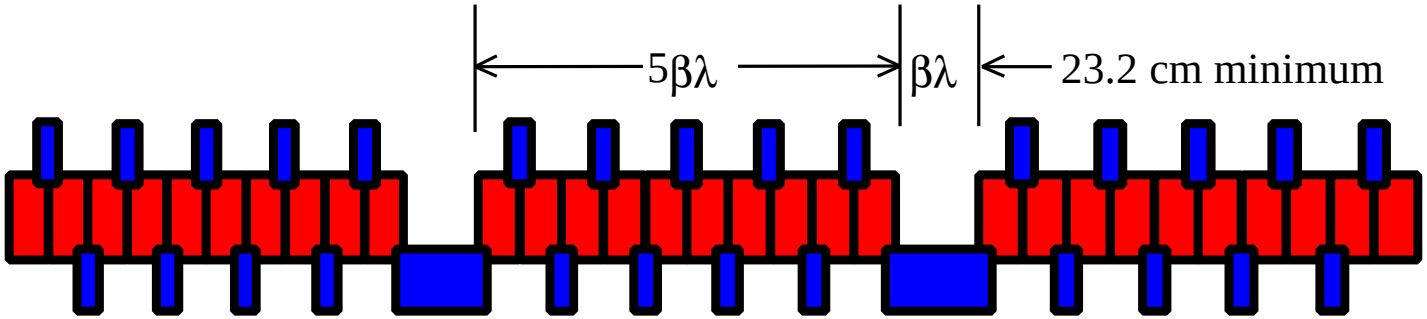
2-cavity segments, 2-gaps per cavity in modules 1 and 2 (20 to 98 MeV). Cavities within a segment are identical.



CCL Segments

8-cavity segments in modules 3 to 7 (98 to 261 MeV)





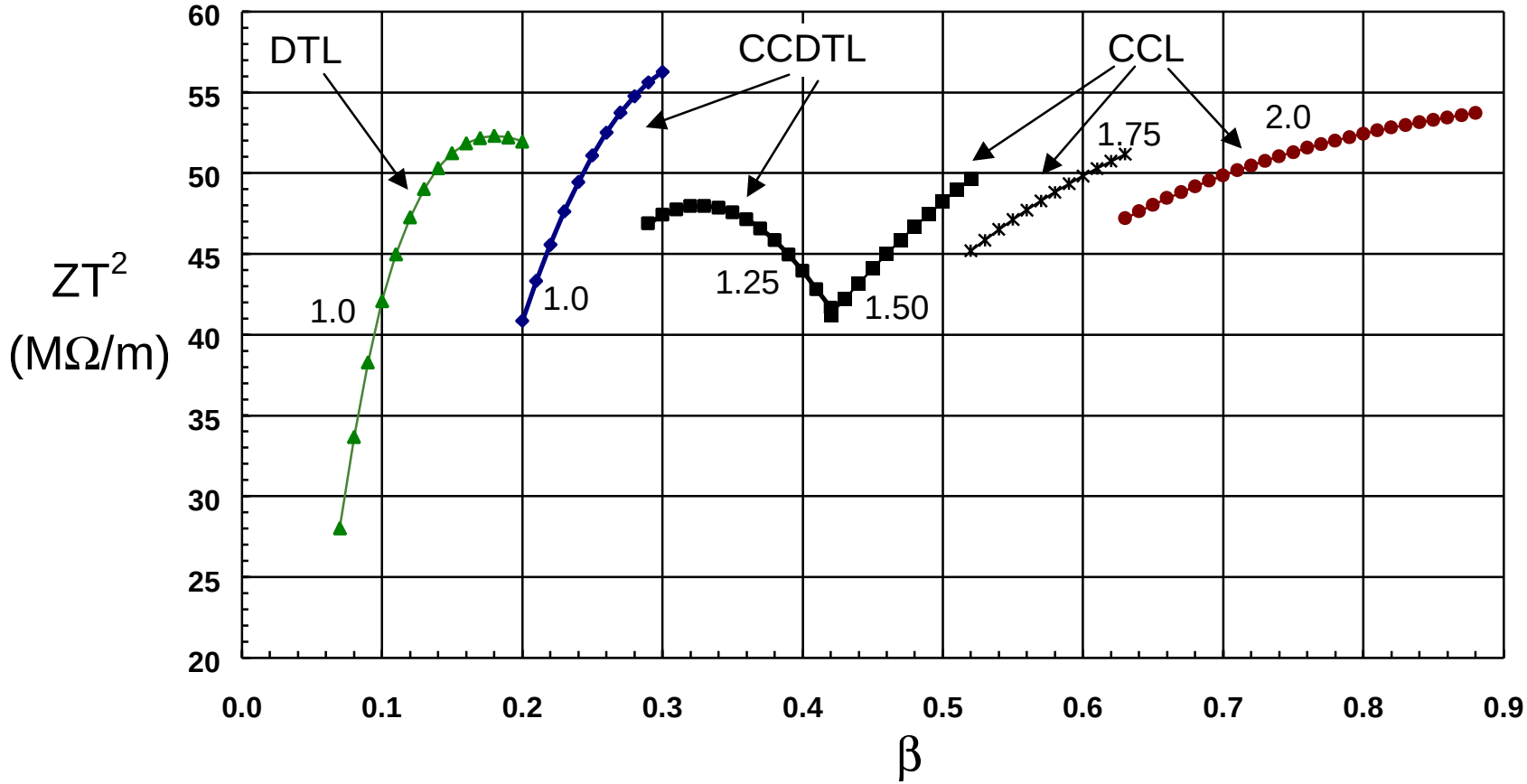
10-cavity segments in modules 8 to 26 (> 261 MeV)

Choices that Affect Shunt Impedance

- Maximizing ZT^2 is important for minimizing power losses.
- The bore radius is the most important factor affecting ZT^2. Large bores reduce shunt impedance, especially at low velocity.
  - DTL, R_b = 1.0 cm, ZT^2 = 28 to 52 MΩ/m.
  - CCDTL, R_b = 1.0 and 1.25 cm, ZT^2 = 42 to 56 MΩ/m.
  - CCL, R_b = 1.5, 1.75, and 2.0 cm, ZT^2 = 42 to 54 MΩ/m.
- In the DTL, post-couplers, joints, end walls, tuners, pumping ports, etc. reduce SUPERFISH-calculated ZT^2 by 20%.
- Coupling slots reduce ZT^2 by about 8% in the CCDTL and 15% in the CCL for 5% coupling chosen for SNS.

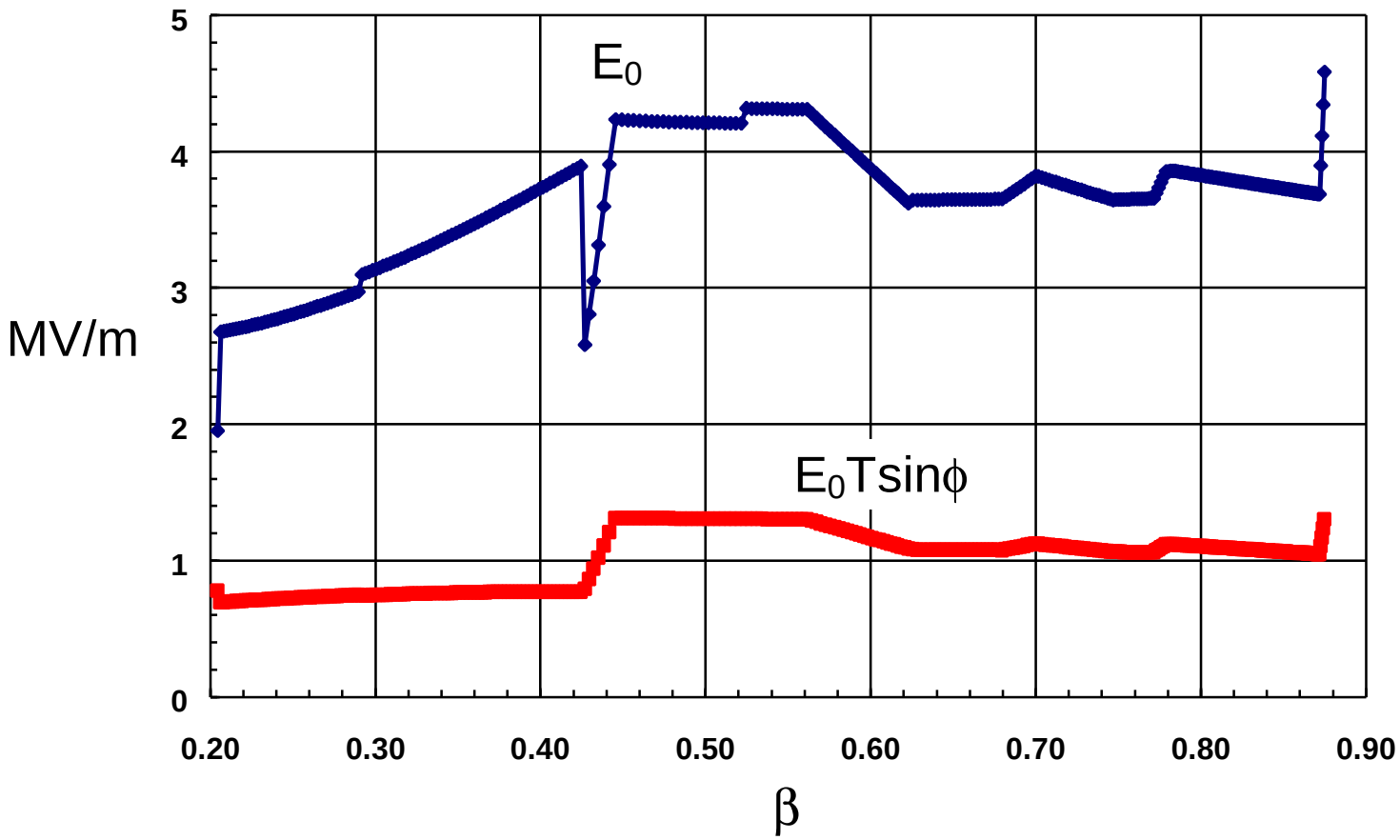
SUPERFISH-Calculated Shunt Impedance

Numbers next to the curves indicate the bore radius in cm.



Accelerating Field Profile

Fields have been adjusted to use available klystron power efficiently.



805-MHz Linac Design Summary

- 26 rf modules
- 347 segments, 2504 accelerating cavities, length = 457 m.
- 52 klystrons at 1 MW beam power, 77 klystrons at 4 MW beam power.
- Modules 1 and 2 are CCDTL to 98 MeV.
- Modules 3 to 7 are 8-cavity CCL to 261 MeV.
- Modules 8 to 26 are 10-cavity CCL to 1 GeV.
- Total copper power = 79.4 MW.

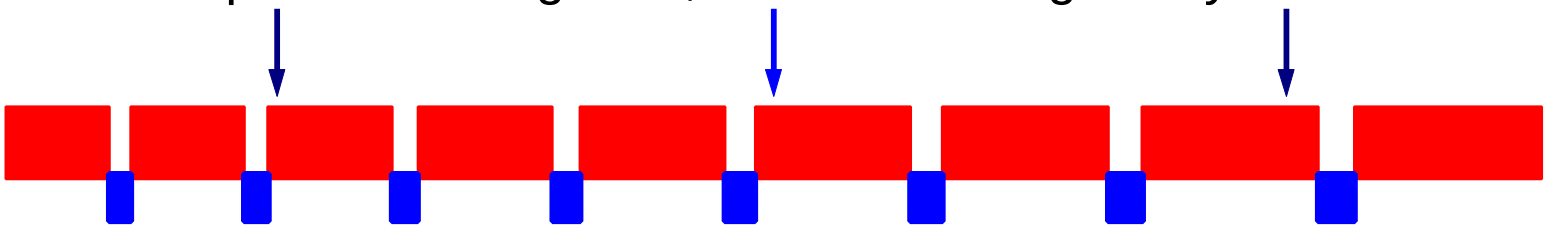
Other Criteria Satisfied by Partitioning

- Klystron power usage < 2.000 MW.
- Peak surface electric field < 1.5 Kilpatrick.
- Total cavities per module < 300.
- For thermal management, an rf module has only one structure type:
  - CCDTL ends at the end of module 2.
  - 8-cavity CCL ends at the end of module 7.
  - Bore changes at ends of modules (except one in CCDTL).
- Interface requirements:
  - Last quadrupole focuses in X.
  - Last module with $\phi_s = +24°$ increases energy spread to 0.66 MeV.

Upgrade Considerations

- RF modules have 3 drive irises, placed at 1/6, 3/6, and 5/6 power points, which is optimum for 4-MW operation.

Example for a 9-segment, 90-accelerating-cavity rf module:



- The 1-MW linac (with lower beam loading) uses the two outside irises.

- The only major shutdown required is for installation of the duplicate front end and the beam funnel. Upgrading the CCDTL and CCL can be accomplished by installing klystrons during scheduled down times with no impact on the SNS running schedule.

Changes in RF Cavity Design Since CDR

- For the CDR, to save time we used cavity dimensions similar to frequency-scaled APT cavities.
- More recently, we have modified the CCL geometry, taking advantage of lower power densities in SNS to improve shunt impedance:
  - CCL septum thickness reduced from 1.27 cm to 1.00 cm.
  - Cone angle in CCL cavities reduced from 20° to 10°.
- Based upon beam-dynamics performance, maximum bore radius has been reduced from 2.2 cm to 2.0 cm, also improving ZT^2.

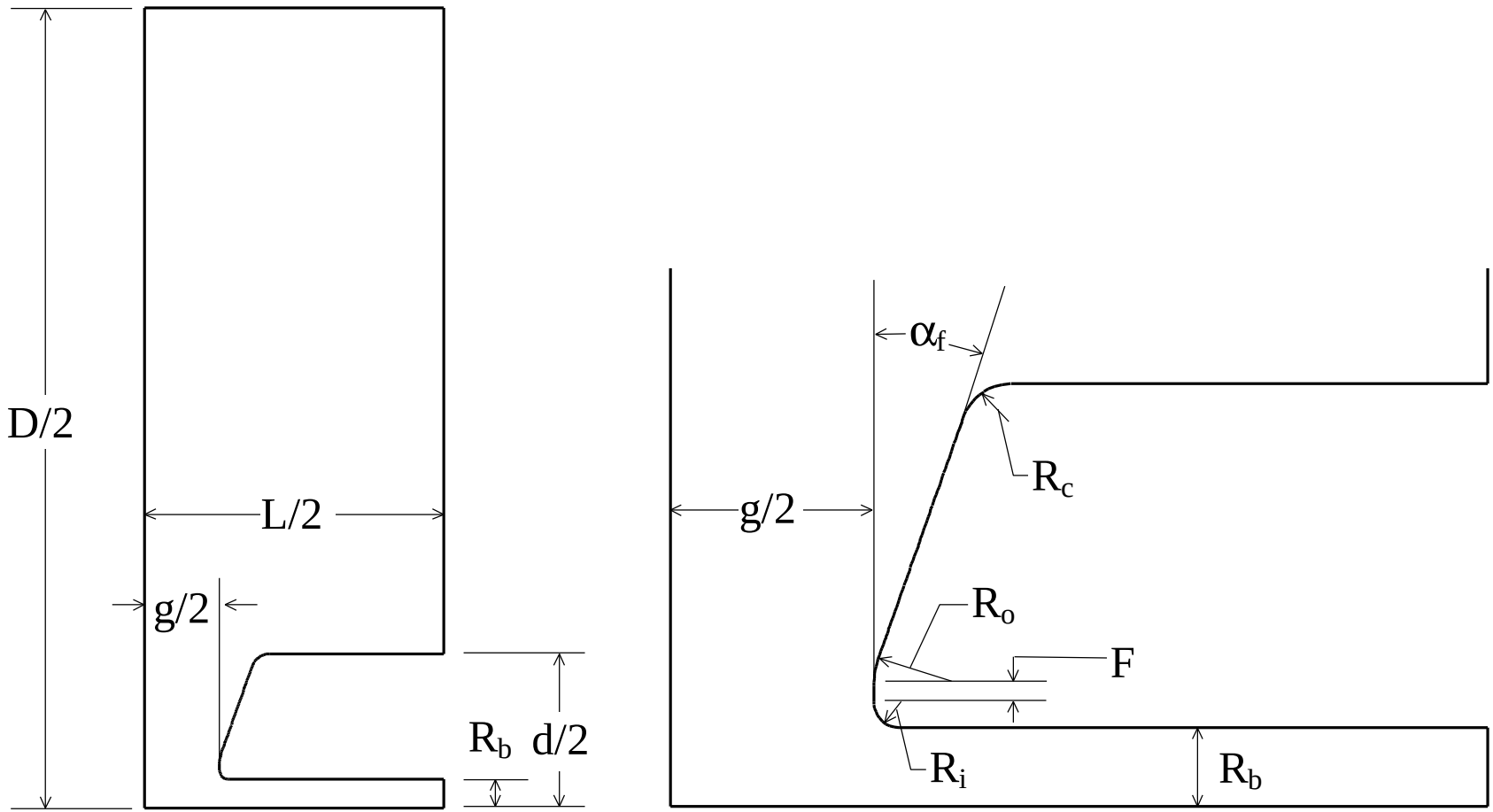
Summary

- Cavity design is efficient and conservative: electric fields are below sparking limits and power densities are manageable.
- Cavities have large enough stored energy to minimize the effect of chopping on the fields.
- There is ample space between cavity segments for focusing magnets, diagnostics, flanges, etc.
- The linac upgrade for 4-MW beam power is simple: add one klystron per rf module.
- Multiparticle beam-dynamics simulations without errors show excellent performance.

RF Cavity Details

- We optimize the rf cavity shapes at both ends of a range of velocity β by varying a few dimensions (e.g. drift-tube diameter, face angle, cavity corner radius).
- A velocity range uses a fixed bore radius.
- One dimension (usually the outer diameter) is adjusted to achieve resonance at the desired frequency.
- For each cavity type, handout includes:
  - Sketch showing geometric parameters.
  - Table of geometrical data selected for the SNS application.
  - Sample plots of fields computed by SUPERFISH.

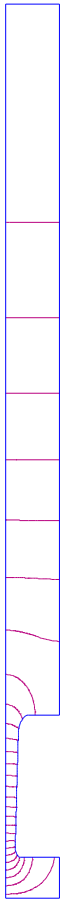
Geometric Parameters in a DTL Cell



DTL Cell Design Parameters

Parameter	Symbol	Value
Resonant frequency	f	402.5 MHz
Initial energy	W_i	2.5 MeV
Final energy	W_f	20.0 MeV
Bore radius	R_b	1.0 cm
Accelerating gradient	E_0T	2.7 MV/m
Tank diameter	D	44.0 cm
Drift-tube diameter	d	9.0 cm
Post-coupler space	$(D - d)/2$	$0.94(\lambda/4)$
Drift-tube face angle	α_f	3.0 degrees
Stem diameter	d_{stem}	1.905 cm
Corner radius	R_c	0.5 cm
Inner nose radius	R_i	0.25 cm
Outer nose radius	R_o	0.5 cm
Drift-tube flat length	F	0.0 cm
Frequency tolerance	δf	0.002 MHz
Smallest mesh size	δx	0.038 cm

SUPERFISH Fields for Two DTL Cells



$\beta = 0.07$

$W = 2.310$ MeV

$g/\beta\lambda = 0.1812$

$R_{Bore} = 1.0$ cm

$L = 5.213$ cm

$E_0 = 3.3$ MV/m

$T = 0.65400$

$E_{Peak} = 23.0$ MV/m

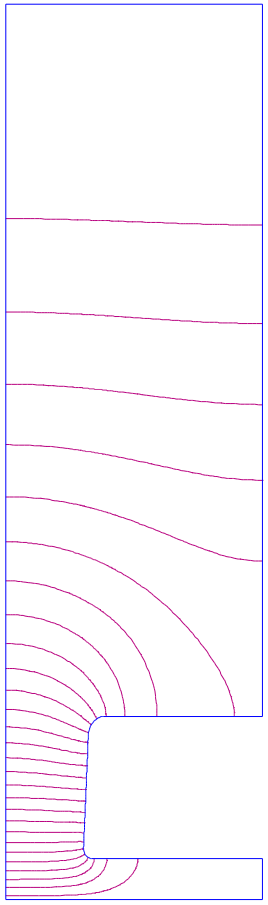
$ZT^2 = 28.03$ MΩ/m

$Q = 41{,}597$

At 6.76% duty:

$P_{Full\ cell} = 585$ W

$P_{Max} = 1.5$ W/cm^2



$\beta = 0.21$

$W = 21.423$ MeV

$g/\beta\lambda = 0.3019$

$R_{Bore} = 1.0$ cm

$L = 15.641$ cm

$E_0 = 3.3$ MV/m

$T = 0.80828$

$E_{Peak} = 18.8$ MV/m

$ZT^2 = 51.58$ MΩ/m

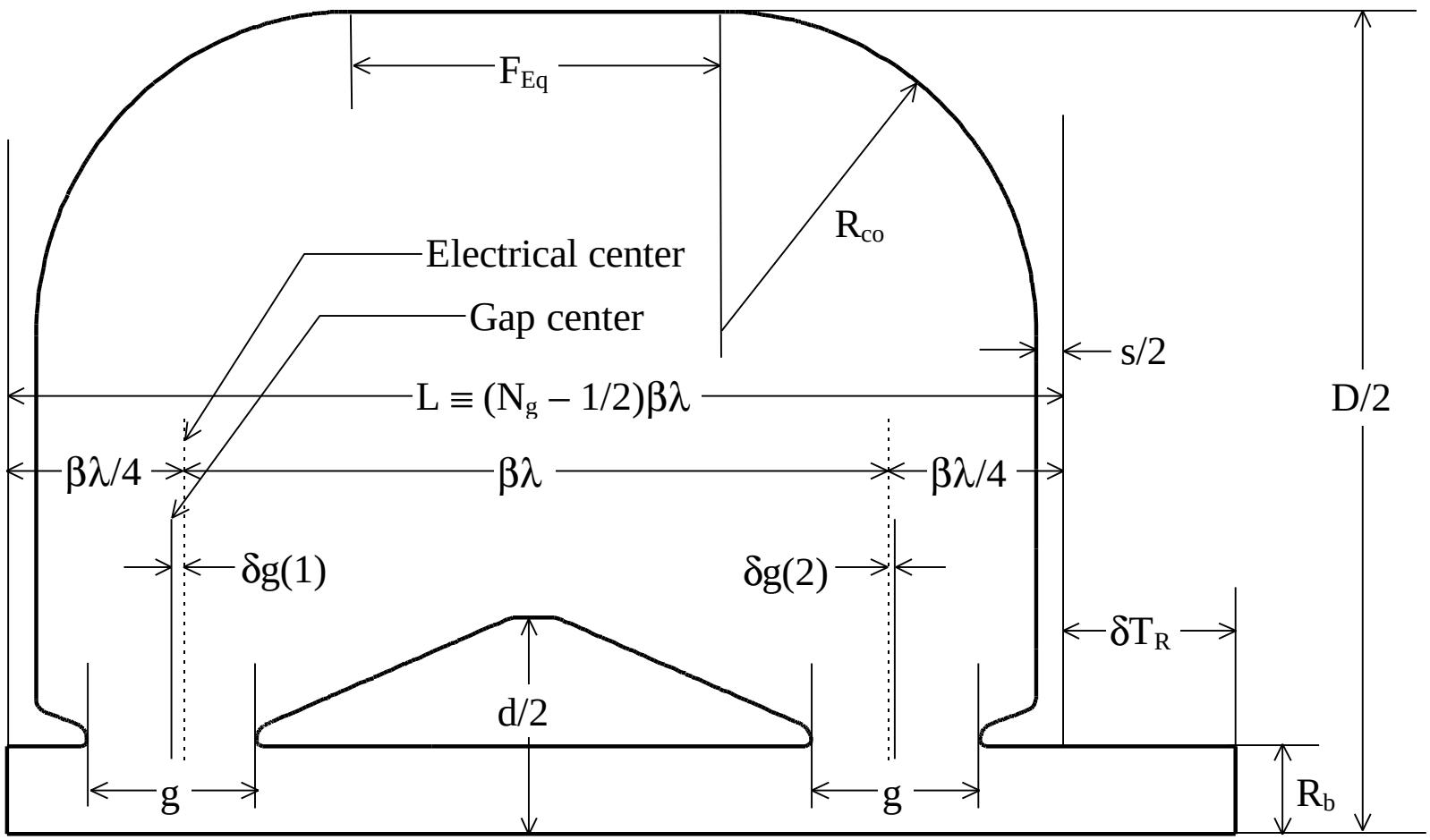
$Q = 50{,}292$

At 6.76% duty:

$P_{Full\ cell} = 1458$ W

$P_{Max} = 2.3$ W/cm^2

Geometric Parameters in a CCDTL Cavity



CCDTL Cavity Design: Common Parameters

The accelerating gradient is used to evaluate cavity peak surface fields. The linac design uses a lower gradient at the front end.

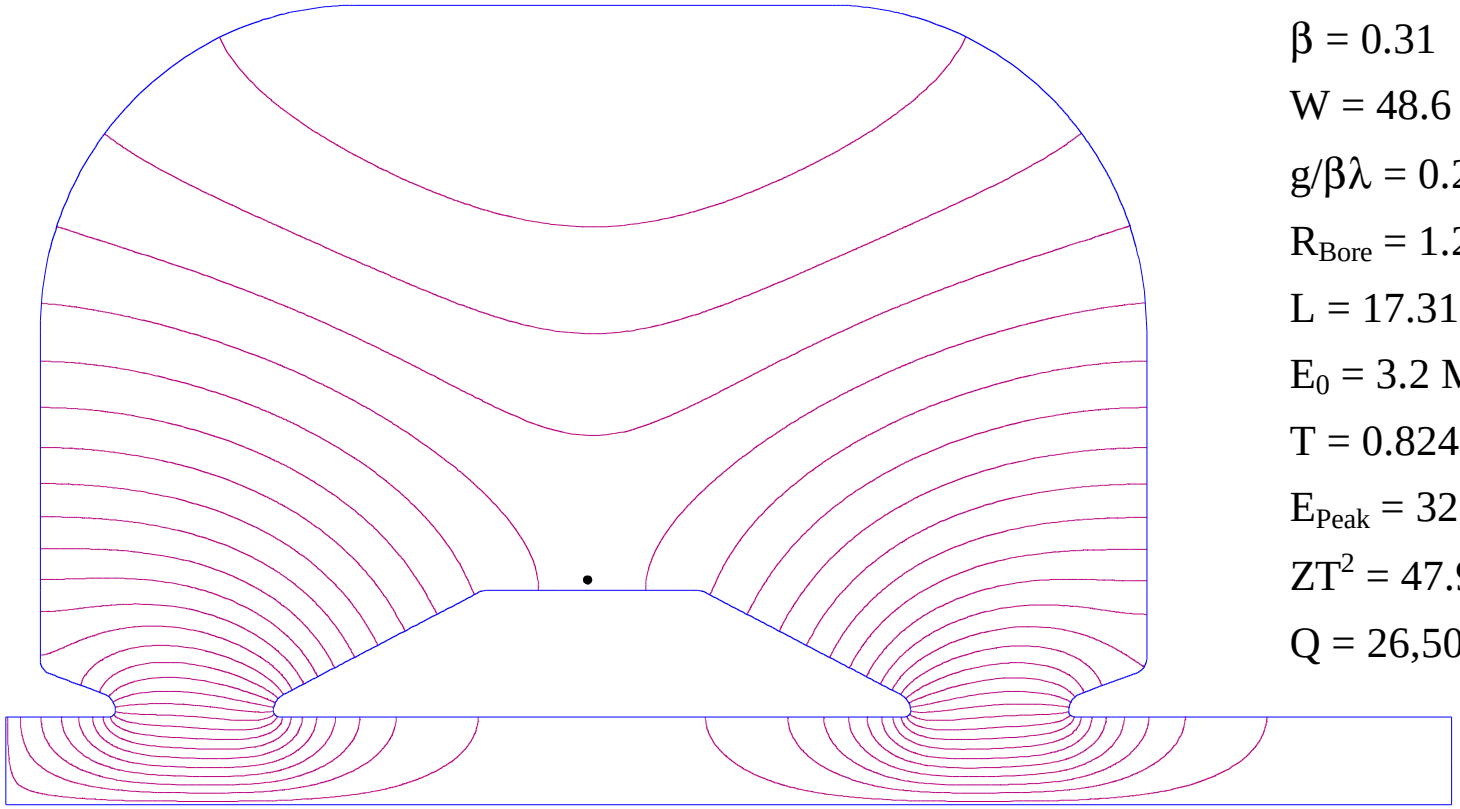
Parameter	Symbol	Value(s)
Resonant frequency	f	805 MHz
Operating temperature	T_{op}	90 F
Accelerating field maximum	E_0	3.9 MV/m
Number of gaps per cavity	N_g	2
Cone angle	α_c	20 degrees
Septum thickness	s	1.0 cm
Number of stems	N_{stem}	2
Stem diameter	d_{stem}	1.016 cm
Drift-tube corner radius	R_c	0.215 cm
Inner nose radius	R_i	0.085 cm
Outer nose radius	R_o	0.26 cm
Drift-tube flat length	F	0.0 cm
Frequency tolerance	δf	0.05 MHz
Smallest mesh size	δx	0.035 cm

CCDTL Cavity-Design Parameters for Each β Range

The CCDTL consists of two sections with different bore radii.

Parameter	Symbol	Value(s)	
Range of β	β	0.19-0.29	0.29-0.42
Cavity length	L (cm)	10.61-16.20	16.20-23.46
Bore radius	R_b (cm)	1.0	1.25
Gap length/$\beta\lambda$	$g/\beta\lambda$	0.13-0.19	0.20-0.30
Gap length	g (cm)	0.92-2.09	2.16-4.80
Cavity diameter	D (cm)	25.0-24.2	23.5-22.5
Drift-tube diameter	d (cm)	5.5-6.1	5.7-8.3
Drift-tube face angle	α_f (deg)	63.0-66.6	63.0
Equator flat length	F_{Eq} (cm)	1.65-5.24	5.40-10.84
Inner gap shift	δg_1 (cm)	0.062-0.086	0.109-0.505
Outer gap shift	δg_2 (cm)	0.009-0.065	0.063-0.432

SUPERFISH Fields for a CCDTL Cavity



$\beta = 0.31$

$W = 48.6$ MeV

$g/\beta\lambda = 0.23$

$R_{Bore} = 1.25$ cm

$L = 17.317 + 4.0$ cm

$E_0 = 3.2$ MV/m

$T = 0.824$

$E_{Peak} = 32.1$ MV/m

$ZT^2 = 47.9$ MΩ/m

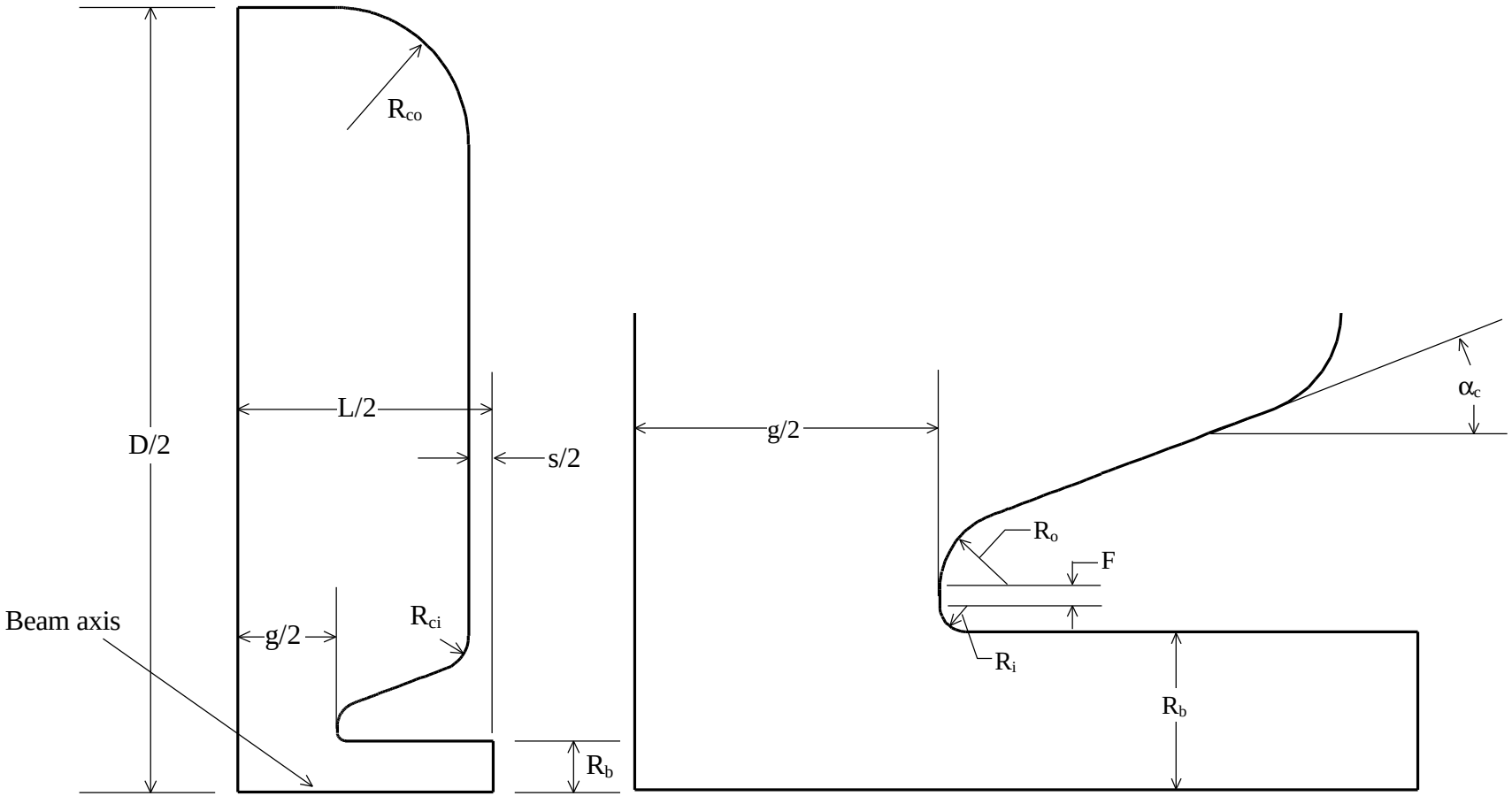
$Q = 26{,}500$

At 6.76% duty:

$P_{Full\ Cavity} = 1.8$ kW

$P_{Max} = 4.2$ W/cm^2

Geometric Parameters in a CCL Cavity

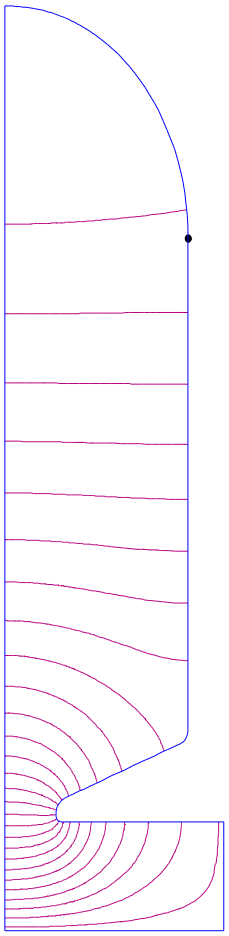


CCL Cell Design Parameters

Common Parameter	Symbol	Value(s)
Resonant frequency	f	805 MHz
Average accelerating field	E_0	3.8 MV/m
Cone angle	α_c	10 degrees
Septum thickness	s	1.0 cm
Inner nose radius	R_i	0.085 cm
Outer nose radius	R_o	0.26 cm
Frequency tolerance	δf	0.01 MHz
Smallest mesh size	δx	0.030 cm

Parameter	Symbol	Value(s)		
Range of β	β	0.42-0.52	0.52-0.63	0.62-0.88
Cavity length	L (cm)	7.63-9.68	9.68-11.73	11.73-10.80
Bore radius	R_b (cm)	1.50	1.75	2.0
Gap length/$\beta\lambda$	$g/\beta\lambda$	0.12-0.15	0.15-0.19	0.20-0.26
Gap length	g (cm)	1.87-2.89	3.10-4.45	4.65-8.40
Cavity diameter	D (cm)	25.2-25.5	25.7-26.5	26.0-27.1
Inner corner radius	R_i (cm)	0.88-1.08	1.17-1.41	1.51-2.30
Outer corner radius	R_c (cm)	3.20-3.89	4.18-5.32	4.70-6.35

SUPERFISH Fields for Two CCL Cells



$\beta = 0.42$

$W = 95.715$ MeV

$g/\beta\lambda = 0.117$

$R_{Bore} = 1.50$ cm

$L = 7.821$ cm

$E_0 = 3.8$ MV/m

$T = 0.89592$

$E_{Peak} = 36.1$ MV/m

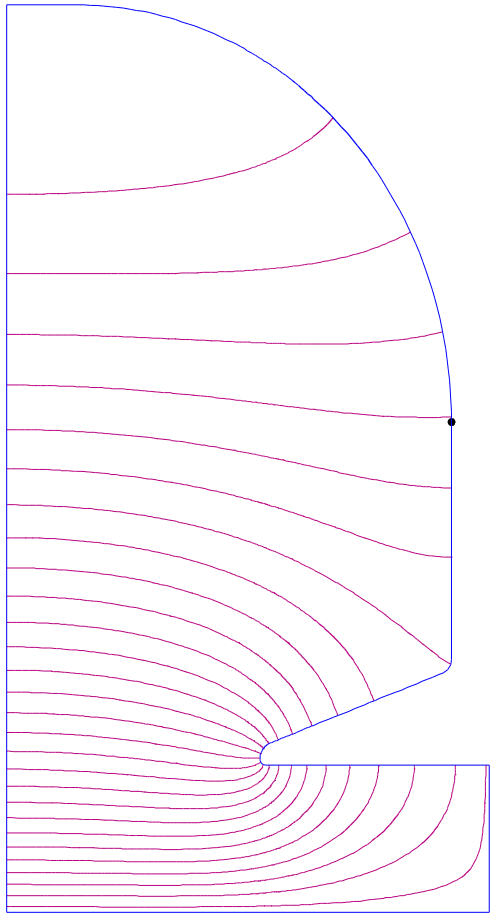
$ZT^2 = 38.05$ MΩ/m

$Q = 18{,}556$

At 6.76% duty:

$P_{Full\ Cavity} = 1610$ W

$P_{Max} = 3.0$ W/cm^2



$\beta = 0.87$

$W = 965.302$ MeV

$g/\beta\lambda = 0.25$

$R_{Bore} = 2.0$ cm

$L = 16.200$ cm

$E_0 = 3.8$ MV/m

$T = 0.82672$

$E_{Peak} = 28.4$ MV/m

$ZT^2 = 53.6$ MΩ/m

$Q = 29{,}240$

At 6.76% duty:

$P_{Full\ Cavity} = 2070$ W

$P_{Max} = 3.1$ W/cm^2

Terminology

Cavity	A resonant structure used to apply high electric fields near the beam axis to accelerate and focus the beam longitudinally.
Cell	A portion of a cavity containing a single gap. (Cell also refers to a half wavelength of the modulation in an RFQ.)
Segment	A contiguous section of accelerating structure between drift spaces. Drifts have the quadrupole magnets and diagnostics.
Module	One or more segments driven by one or more power supplies (klystrons), all cavities of which are locked together in phase.
β	"Beta" is the ratio v/c of the particle velocity to the speed of light, but we often refer to β itself as the "velocity."
$\beta\lambda$	"Beta Lambda" is the distance traveled by a particle of velocity βc in one rf period of the resonant mode, whose frequency is $f = c/\lambda$.

Linac Acronyms

RFQ	Radio-frequency quadrupole invented by Kapchinskiy and Tepliakov. Group AT-1 at Los Alamos built and tested the first RFQ in the West in the late 1970s. There are now many RFQs operating around the world.
DTL	Drift-tube linac invented by Alvarez: a “tank” containing many cells, each cell slightly longer than the last one; examples are the LAMPF 201.25-MHz DTL, and the 425-MHz and 850-MHz lawn ornaments.
CCL	Coupled-cavity linac: Individual cavities connected though magnetic coupling slots (usually); an example is the LAMPF 805-MHz side-coupled linac (SCL).
CCDTL	Coupled-cavity drift-tube linac: a hybrid structure that combines features of the DTL and CCL. Low-energy demonstrator for APT may be the first operating CCDTL.

RF Cavity Design Terms

E_0	The spatially averaged axial electric field in a cavity at the peak of the rf cycle.
T	Transit-time factor, which accounts for the fact that the rf fields change in time as particles traverse a cavity.
E_0T	The effective accelerating field over the active part of the cavity. We also use the notation $(E_0T)_{RealEstate}$ to refer to an average accelerating field that includes the drift spaces.
ϕ_s	Synchronous phase is the rf phase when the synchronous particle (or design particle) crosses the center of the gap, typically ~30 degrees <u>earlier</u> in time than the wave crest.
ZT^2	Effective shunt impedance per unit length: a figure of merit that measures the efficiency of a cavity.
Q	Quality factor, another figure of merit measuring the cavity stored energy per unit energy loss per cycle.

Definitions

Coupling	A term commonly used for two purposes: one refers to “coupling” the electromagnetic energy from a waveguide into a cavity, the other to the mutual inductance (e. g. for slots) or mutual capacitance (e. g. axial electric field) between cavities.
Coupling cavity	The nominally unexcited cavity between accelerating cavities for a structure operating in the $\pi/2$ mode. In the CCDTL, coupling cavities have the conventional orientation (with the cavity axis parallel to the beam axis) for integer multiples of $\beta\lambda$ between accelerating cavities. Coupling cavities turned on their side allow half-integral $\beta\lambda$ intervals between accelerating cavities.
Post coupler	A resonant field-stabilization device in DTL tanks. The post couplers serve the same purpose as the coupling cavities do in CCL and CCDTL structures.

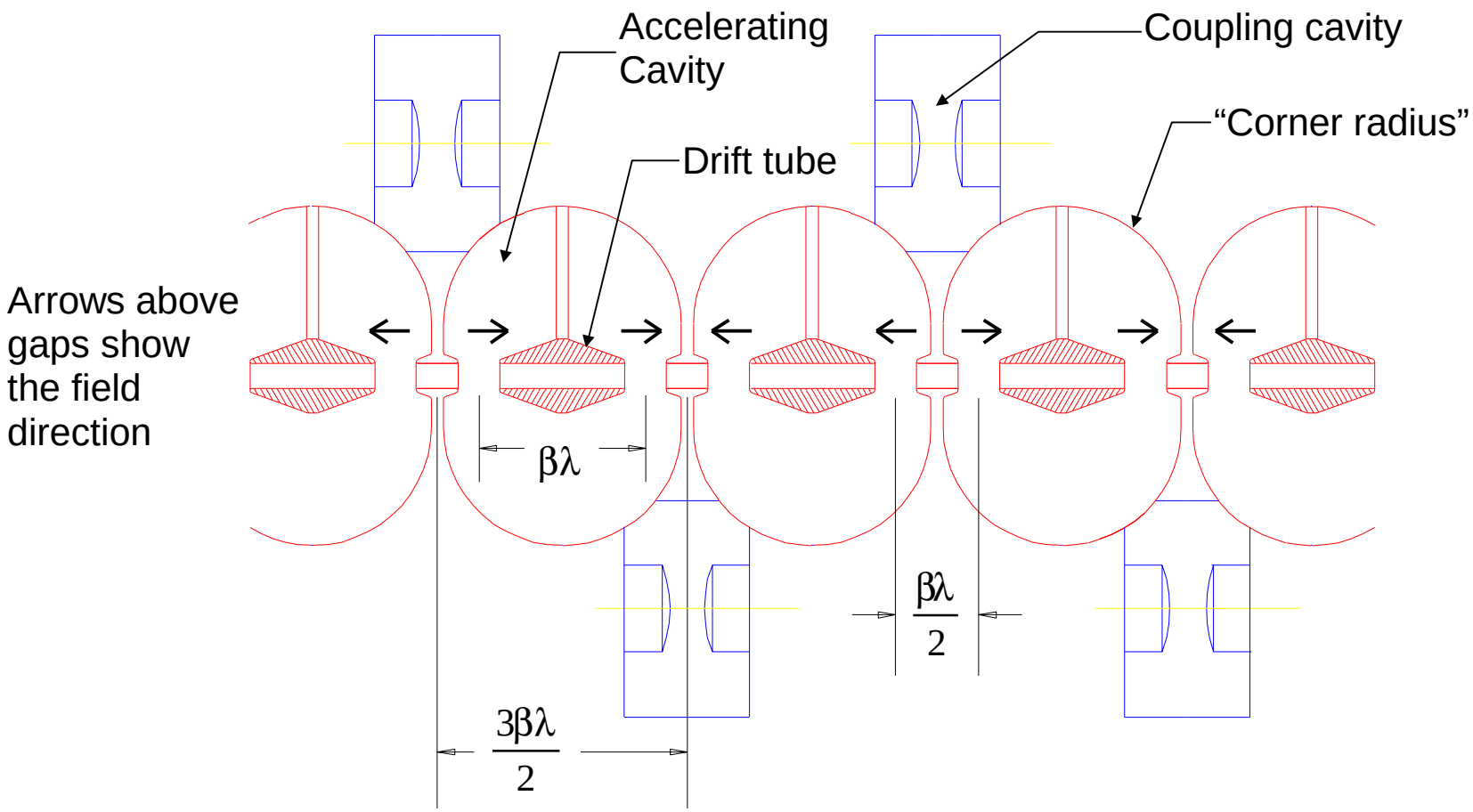
The Coupled-Cavity Drift-Tube Linac (CCDTL)

- An efficient accelerating structure for intermediate-velocity particles that combines features of the Alvarez drift-tube linac (DTL) with features of the coupled-cavity linac (CCL).

- Good shunt impedance compared to other structures in the velocity range $0.1 < \beta < 0.5$. Efficiency is comparable to the DTL, the usual structure of choice for this velocity range, but more efficient than π-mode structures such as the CCL.

- Like a CCL, the chain of cavities operates in a $\pi/2$ <u>structure</u> mode for very good field stability. Coupling cavities are nominally unexcited.

A Coupled-Cavity Drift-Tube Linac Structure



- Gaps inside an accelerating cavity are separated by $\beta\lambda$.
- Adjacent gaps in two cavities are separated by $\beta\lambda/2$.

CCDTL Advantages

- Electromagnetic quadrupole lenses are external to the rf cavity.
- Drift tubes can have larger apertures because they don't contain focusing magnets.
- Drift-tube shapes can be optimized for good shunt impedance.
- The cavity can be brazed, thus eliminating many rf and vacuum joints.
- Shunt impedance comparable to a drift-tube linac (DTL), higher than the coupled cavity linac (CCL) over the applicable velocity range.
- Excellent stability of the $\pi/2$ structure mode.
- Short cavities (always less than λ) for high field stability within individual cavities. (Post couplers are not required.)
- Uses the mature technology of the CCL in mechanical design, fabrication, installation, alignment, and operation procedures.