Low and Medium Energy Beam Acceleration in High Intensity Linacs

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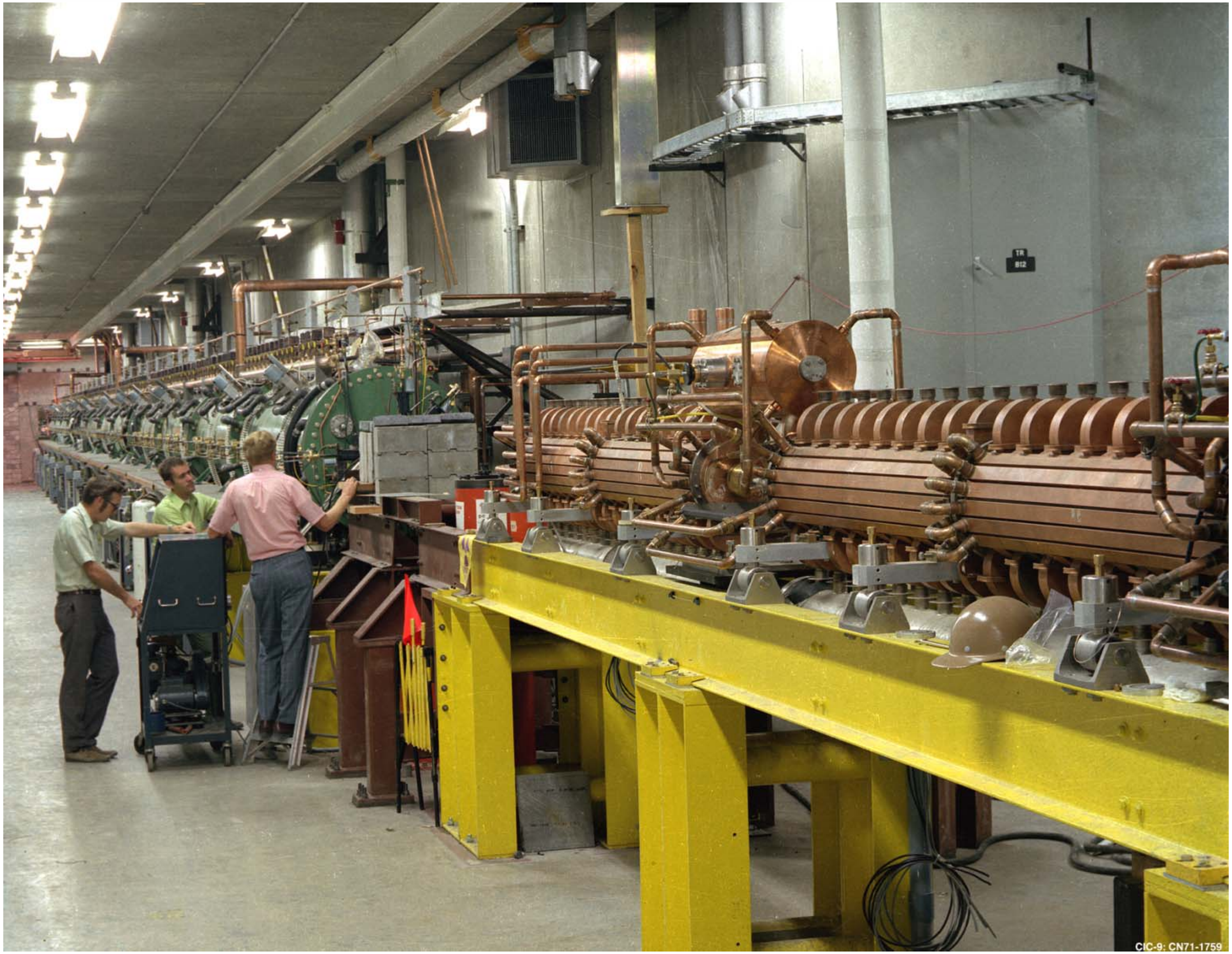
July 6, 2004

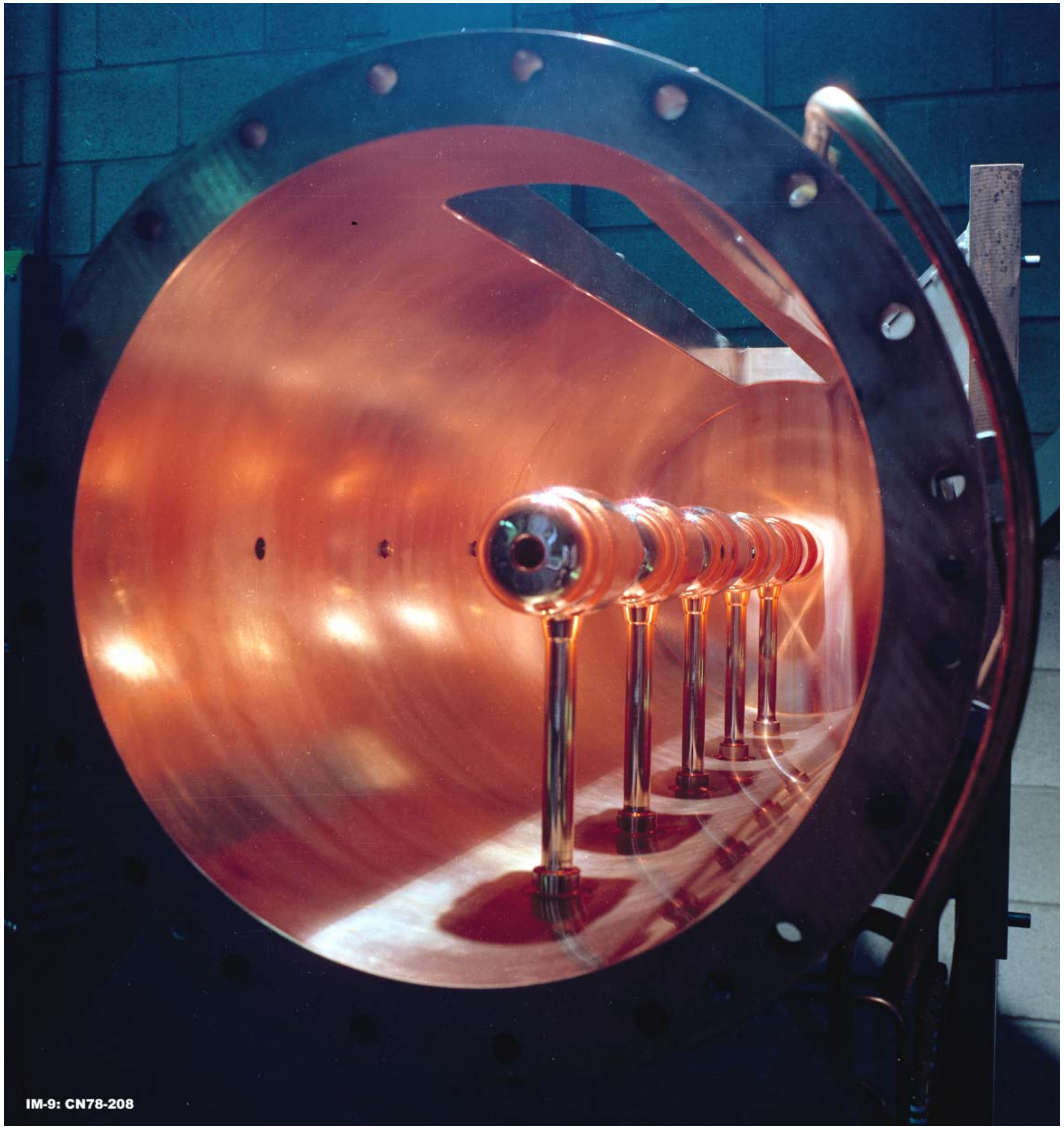
A 1-MW Proton Linac Commissioned in Los Alamos in 1972



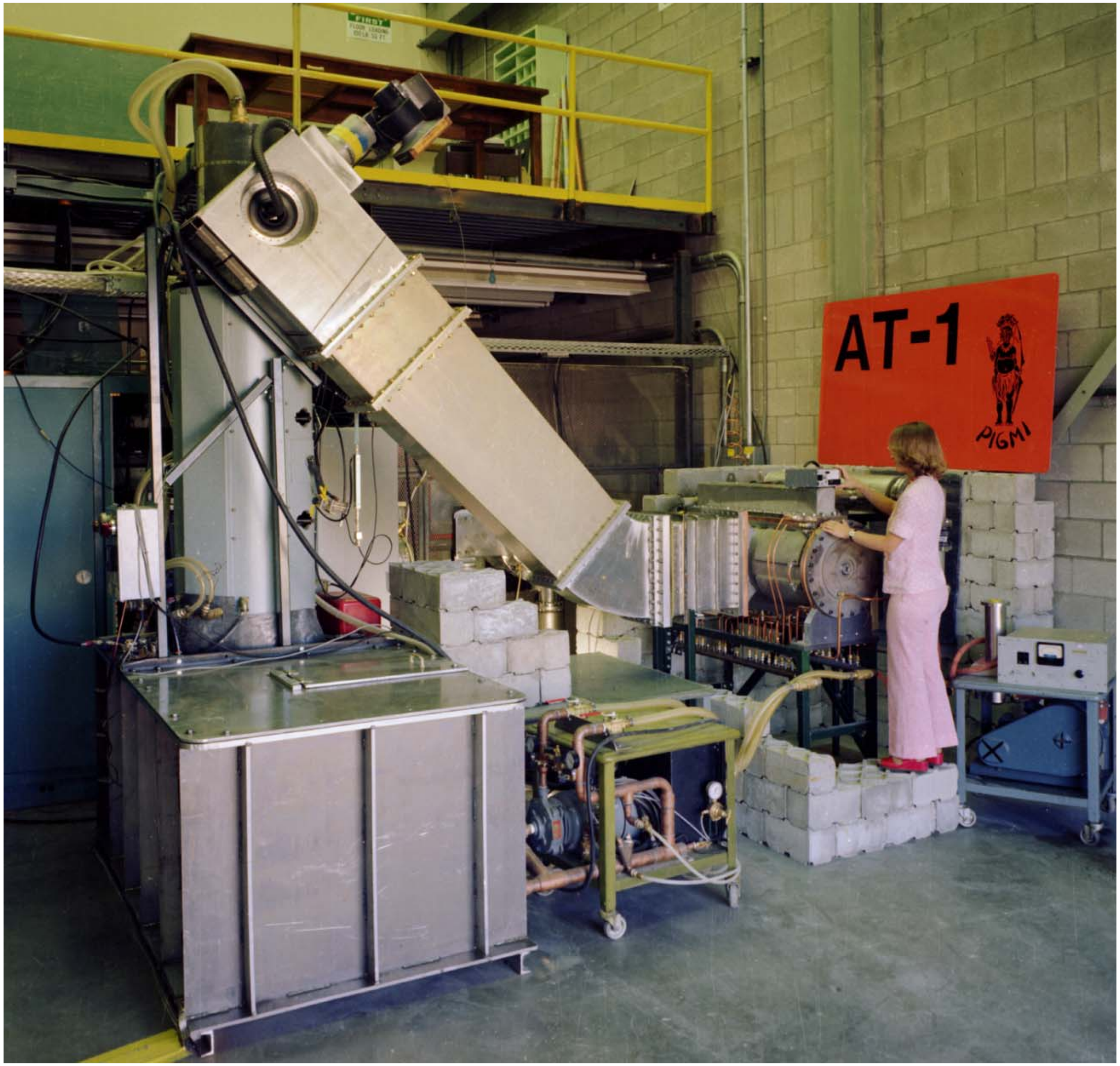
September 22-24, 2003

The PIGMI Project Proposed a 425 MHz Linac for Medical Applications

Copper Plated PIGMI DTL with 45 MeV Geometry Operated at E_0=8.0 MV/m at 6% Duty



The PIGMI RFQ Accelerated 30 mA from 100 to 650 keV in 1980

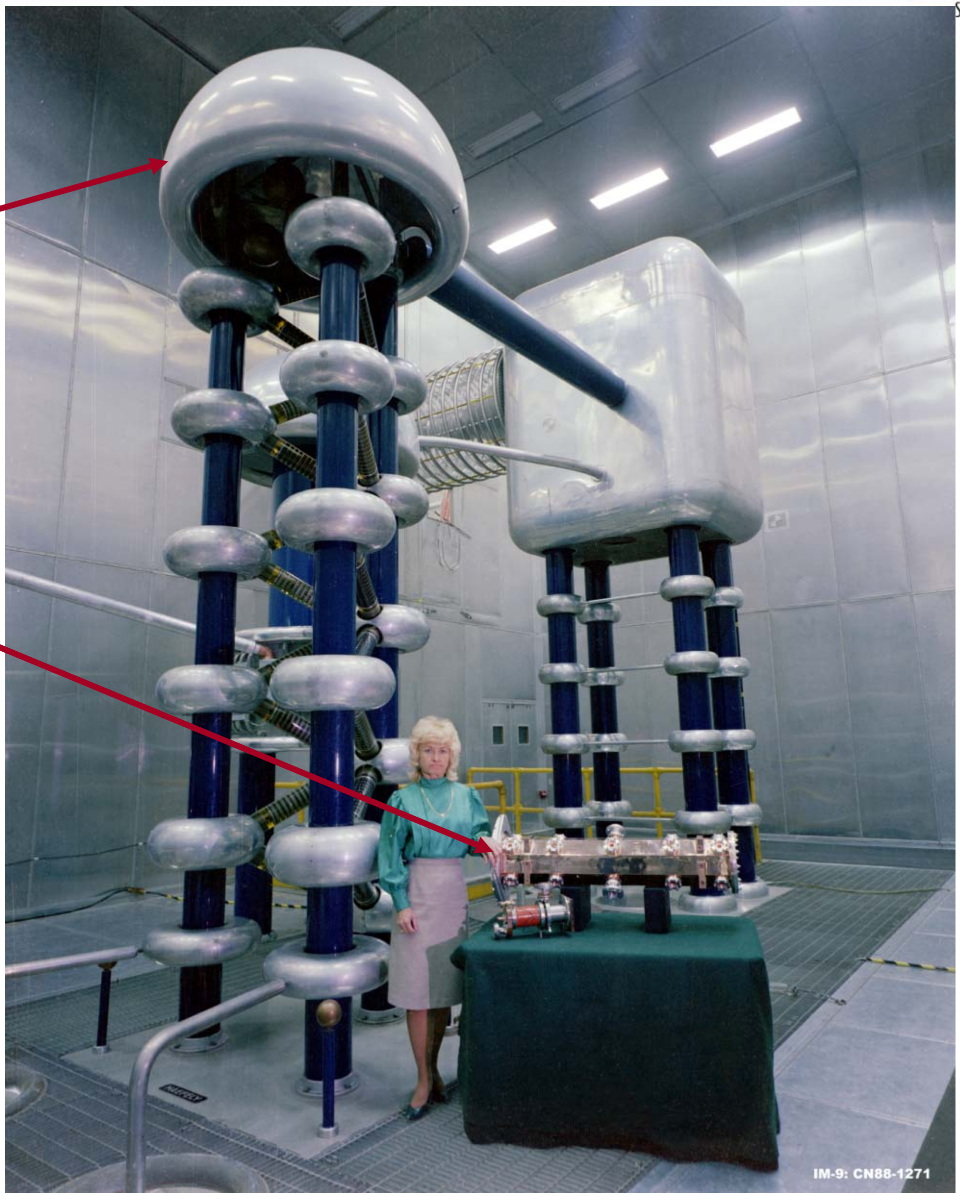


September 22-24, 2003

RFQs Represent the Enabling Technology for Designing High Intensity Linacs

- LANSCE 750 kV Cockroft Walton

- BEAR 1 MeV RFQ



Parameters of Some High Intensity Linacs

	J-PARC Japan	SNS Tennessee	PSB/ PSL CERN	IFMIF	CAT India	KOMAC Korea
Beam power (MW)	0.27	1.4	4	5x2	10	20
Final Energy (GeV)	0.4	1	0.12/2.2	.04	1	1
Peak current (mA)	50 H-	38 H-	40/21 H-	125 D+	10 H-	20 H+&-
Duty factor (%)	2.5	6	0.1/14	cw	cw	cw
rf Frequency (MHz)	324	402.5 & 805	352	175	350	350 & 700
Intermediate Energy Structures	DTL & SDTL	DTL & CCL	DTL & CCDTL	DTL or IH-DTL	DTL&/or SDTL	DTL & CCDTL

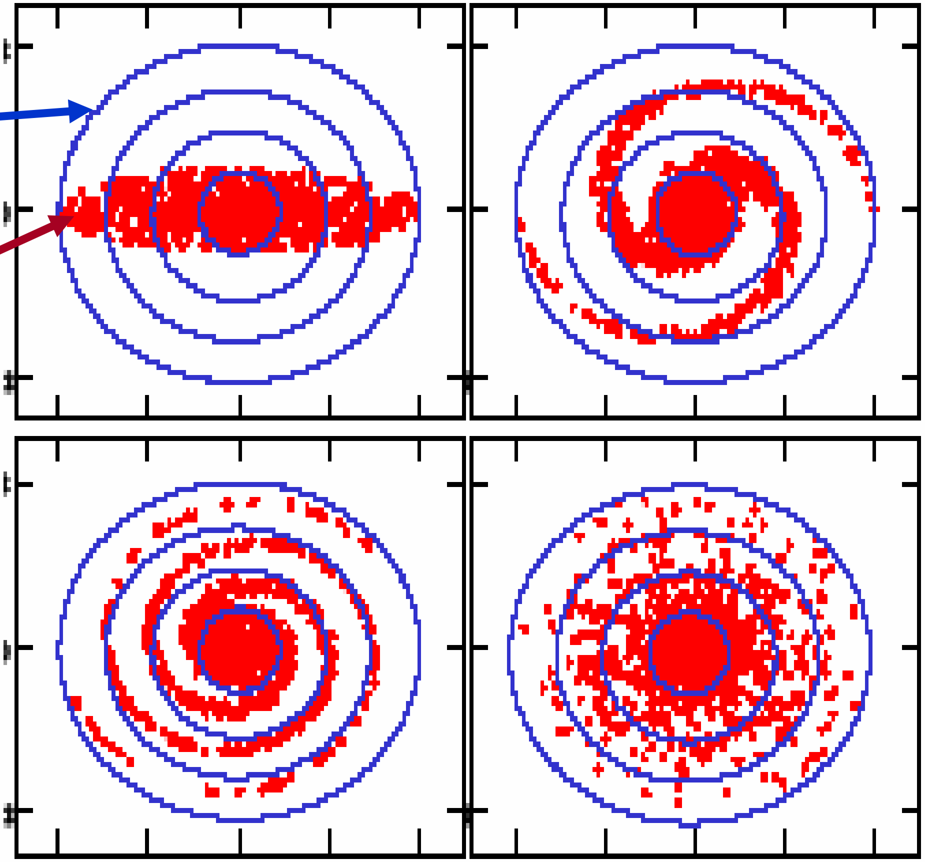
Primary Design Challenges are Reliability, Cost & Activation

- Reliability of brazed Cu structures speak for themselves
  - Extensive experience with DTLs at low duty factors
- Sources of beam loss include:
  - Gas Stripping, requires good vacuum
  - Magnetic Stripping, not significant at low β
  - Longitudinal beam loss
    - mismatches are a function of design
    - turn-on transients
    - rf phase & amplitude errors, static & dynamic
  - Transverse beam loss due primarily to halo
    - misalignments & missteering
  - Space charge is the vehicle for halo development and is due to several mechanisms
    - can be reduced by keeping the rms beam size small
    - argues for a short strong lattice

Lattice Discontinuities => Mismatch => Halo

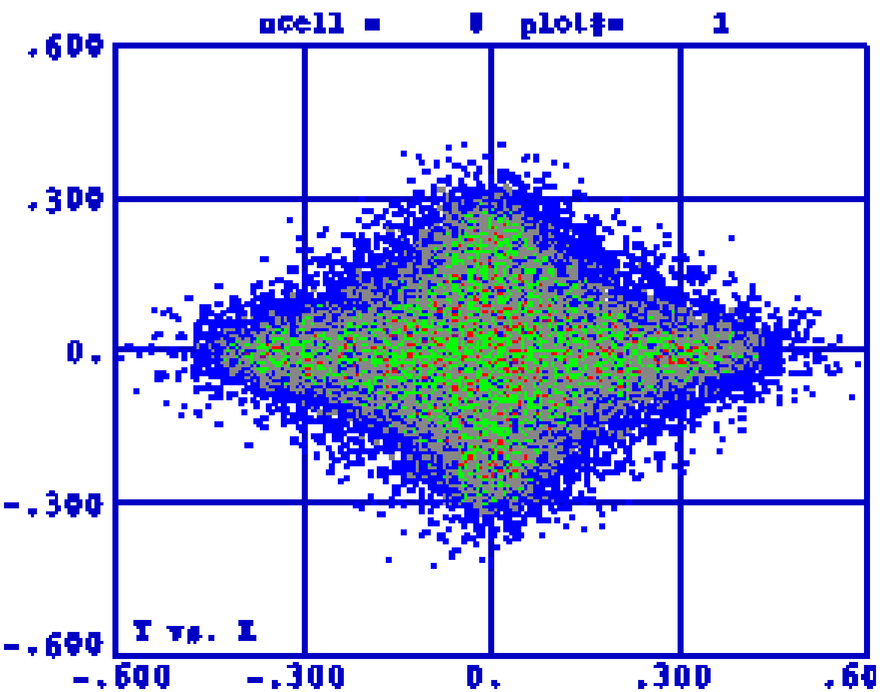
matched phase-space trajectories

mismatched beam

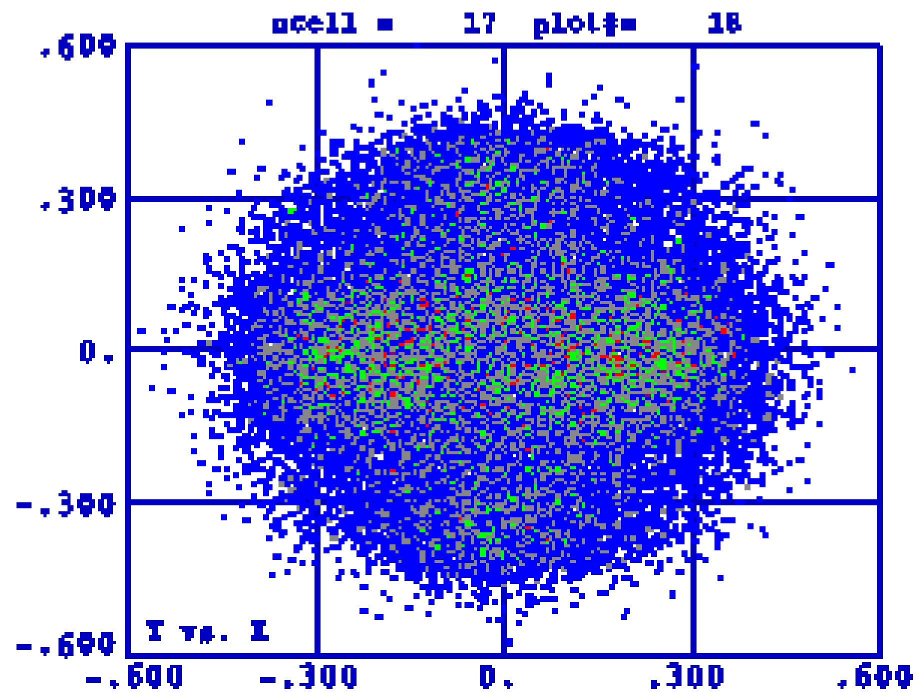


N. Pichoff

Redistribution in a New Lattice Causes Emittance Growth



Real-space projection at RFQ exit of 100 mA beam



Real-space projection after 3 lattice periods in DTL

L. Young

The Objective of Cavity Design is to Maximize ZT^2 Subject to Field & Power Constraints

- Cavity efficiency is measured by its shunt impedance, ZT^2, which relates cavity power dissipated per unit length to the average axial accelerating field

$$\frac{P}{L} = \frac{(E_0 T)^2}{ZT^2}$$

- E_{peak}, the peak surface electric field, must not exceed a "reasonable" value at the design E_0
  - Related to surface area at the highest voltage
  - ~1.8 E_K for RFQs
  - ~1.3 E_K for DTLs
  - Recent DTLs have been conditioned much higher
- ρ_{max}, the maximum cavity power dissipated per unit area, must be manageable
  - ≤20 W/cm^2
  - In cw applications, either E_0 or ZT^2 must be reduce

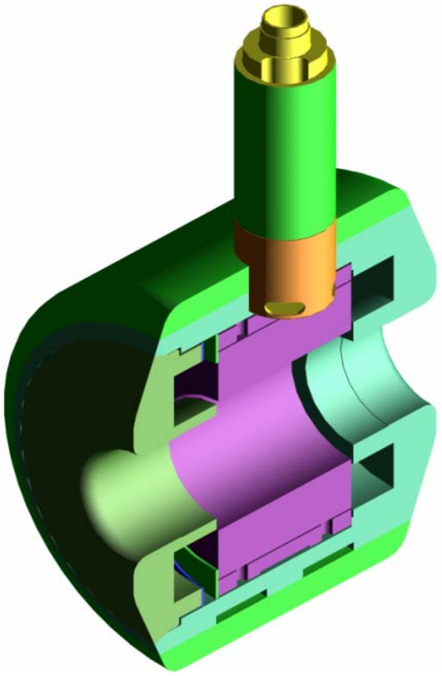
DTLs Have Two Additional Constraints

- Drift tubes must be of large enough to contain quadrupoles
- Dimensions must meet the “post-coupler criterion” that relates the drift tube diameter d to the tank diameter D

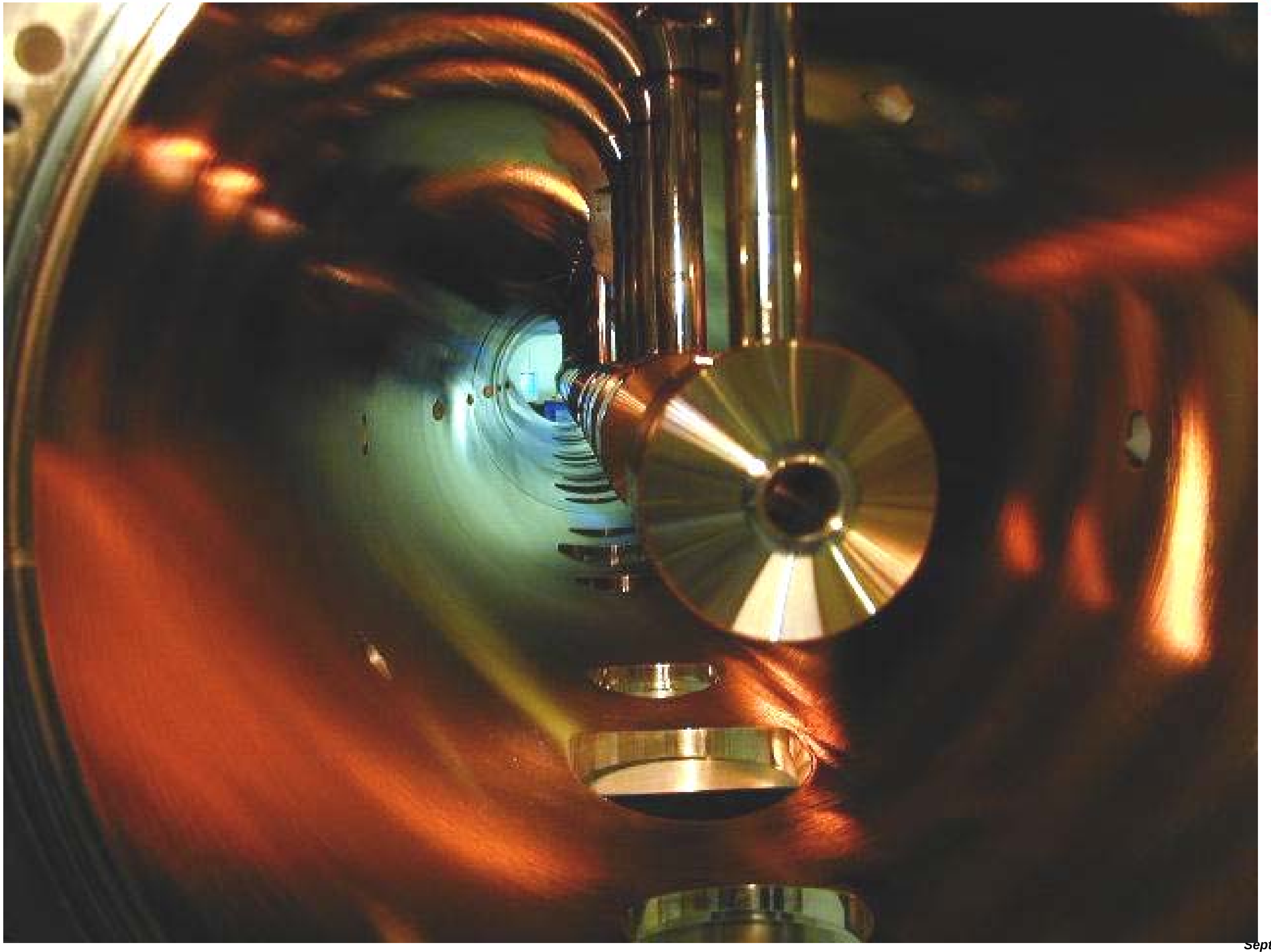
$$0.95 \geq \frac{\left[\left(D-d\right)/2\right]}{\left(\lambda/4\right)} \geq 0.90$$

The SNS DTL has Delivered 38 mA to 40 MeV

- Freq 402.5 MHz
- W 2.5-86 MeV
- I_{peak} 38 mA
- Beam duty 6 %
- E_0 1.3–3.77 MV/m
- ++0--0 PMQs
- GL 1.27 T



Diamond Machined Copper Drift Tubes Hold $E_{peak} > 1.6E_K$, $E_{dsgn} = 1.3E_K$



The J-PARC DTL has Delivered 30 mA to 20 MeV

- Freq 324 MHz
- W 3-50 MeV
- I_{peak} 50 mA
- E_0 2.5–2.9 MV/m
- rf duty 3 %
- +- Pulsed EMQs
- GL 4.1 T

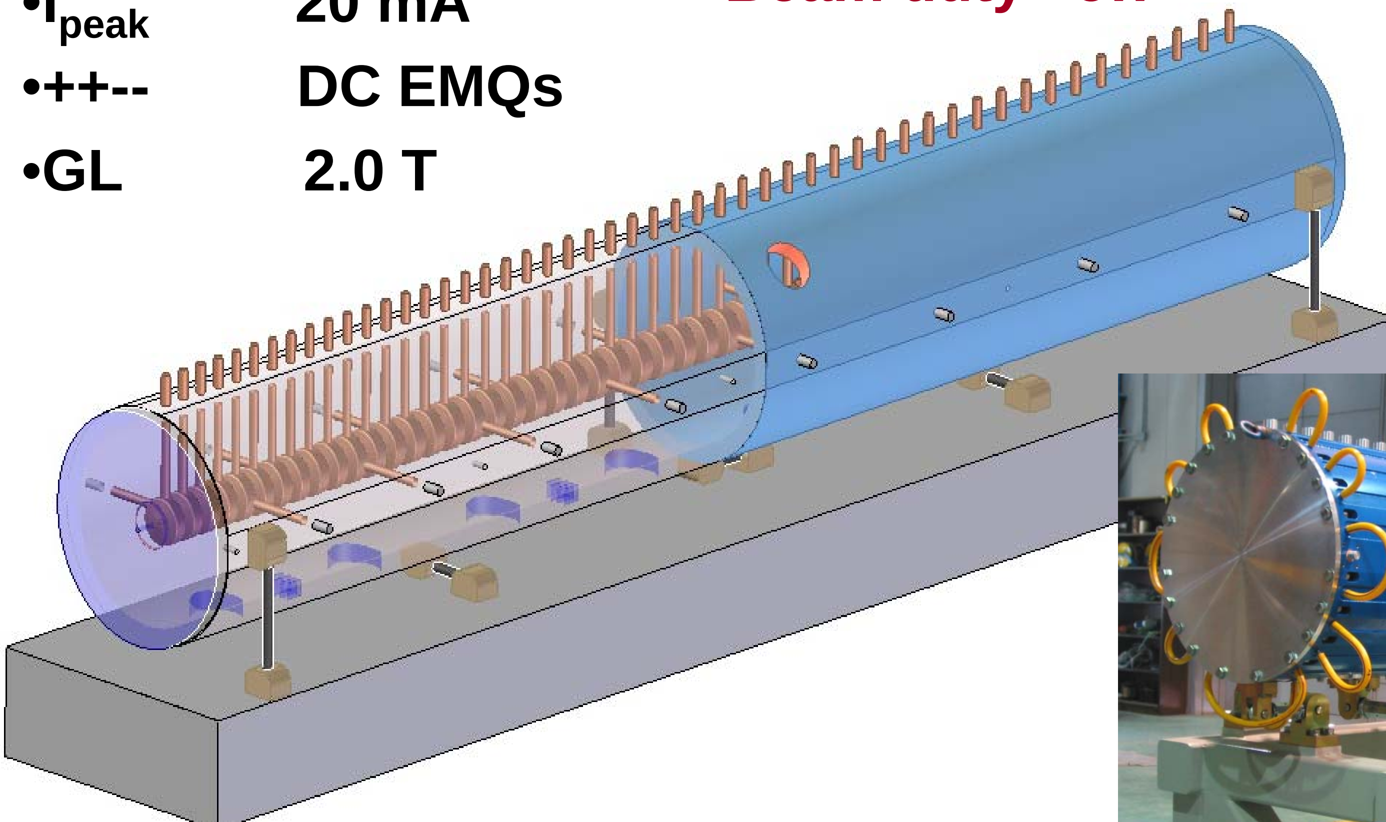
F. Naito

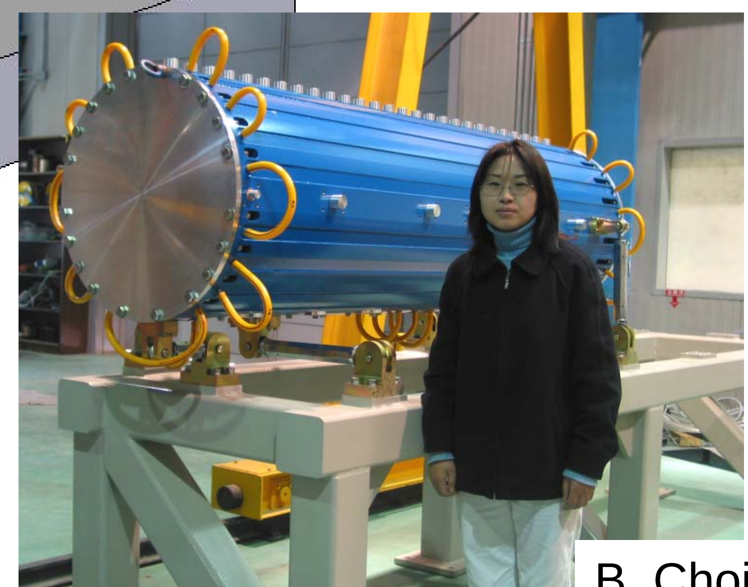
Se

KOMAC DTL Will Deiver 20 mA cw

- Freq 350 MHz
- W 3-20 MeV
- I_{peak} 20 mA
- ++-- DC EMQs
- GL 2.0 T

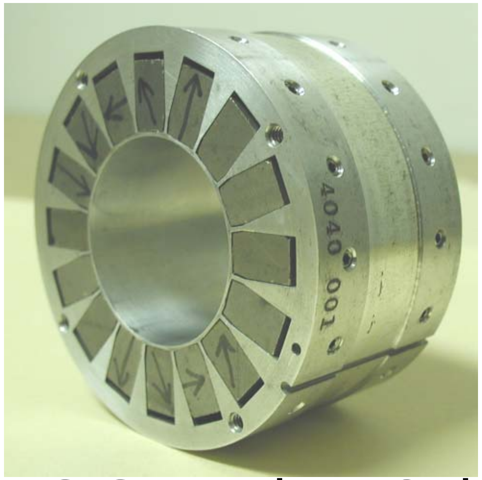
- E_0 1.3 MV/m
- E_{peak} ≤ 0.9 E_K
- Beam duty cw





B. Choi

DTL Quad Options



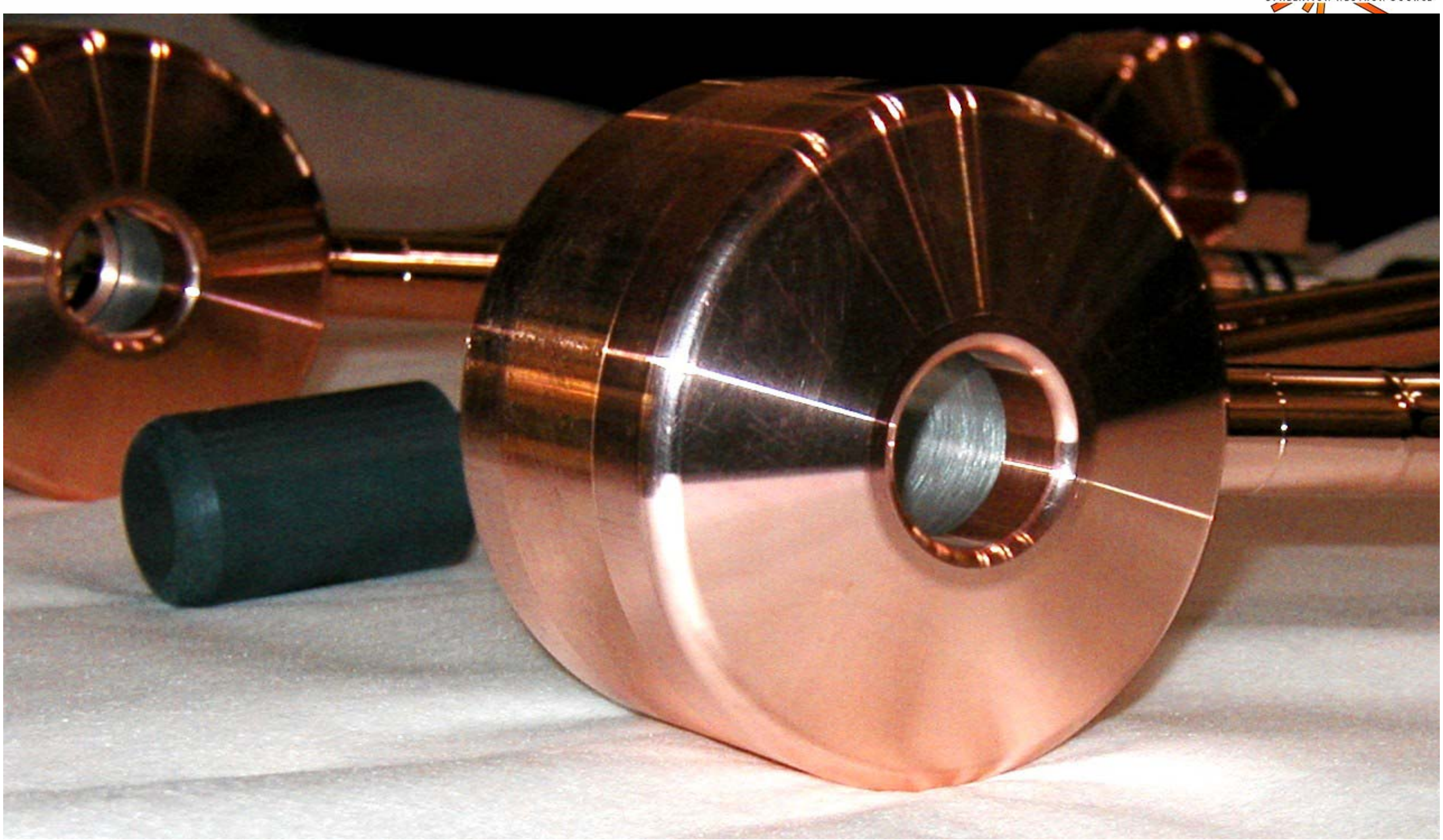
SNS Samarium Cobalt

J-PARC electroformed hollow coils, pulsed

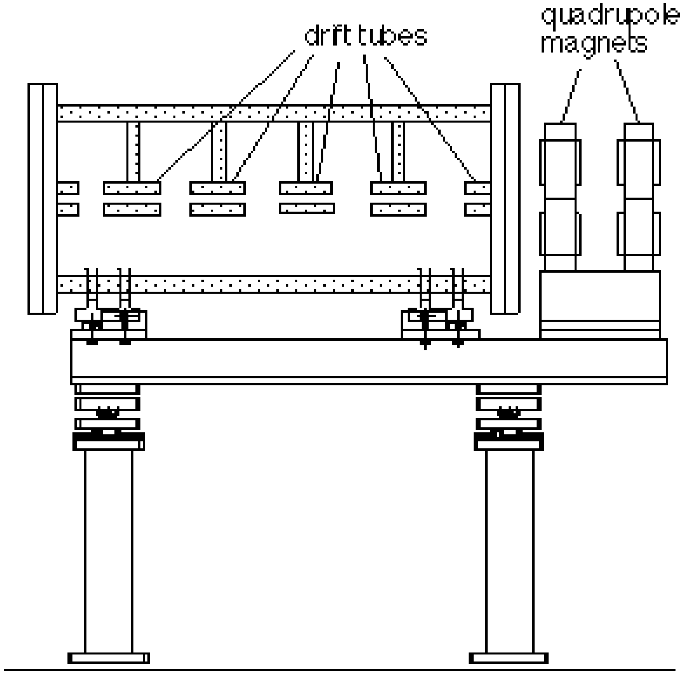
KOMAC solid conductor, flood cooled

CERN hollow conductor & flood cooled

SNS Drift Tubes have no Bore Tube



Separated Function or SDTL have no Quadrupoles or Post Couplers



- Comprised of short tanks containing 3-5 empty drift tubes
- Focusing is provided by doublets or triplets located between tanks
- The tanks are short so field stabilization is unnecessary
- Simpler to align & maintain

- No internal quadrupoles and post couplers make it an economical alternative to DTLs
- Drift-tube size & shape are not constrained, giving the designer more flexibility in optimizing the cavity geometry
- Long lattice period provides weak focusing for low energy beams
- Cavities must be individually powered and controlled

First J-PARC SDTL Tank Has been Conditioned to 170% of the Design Field

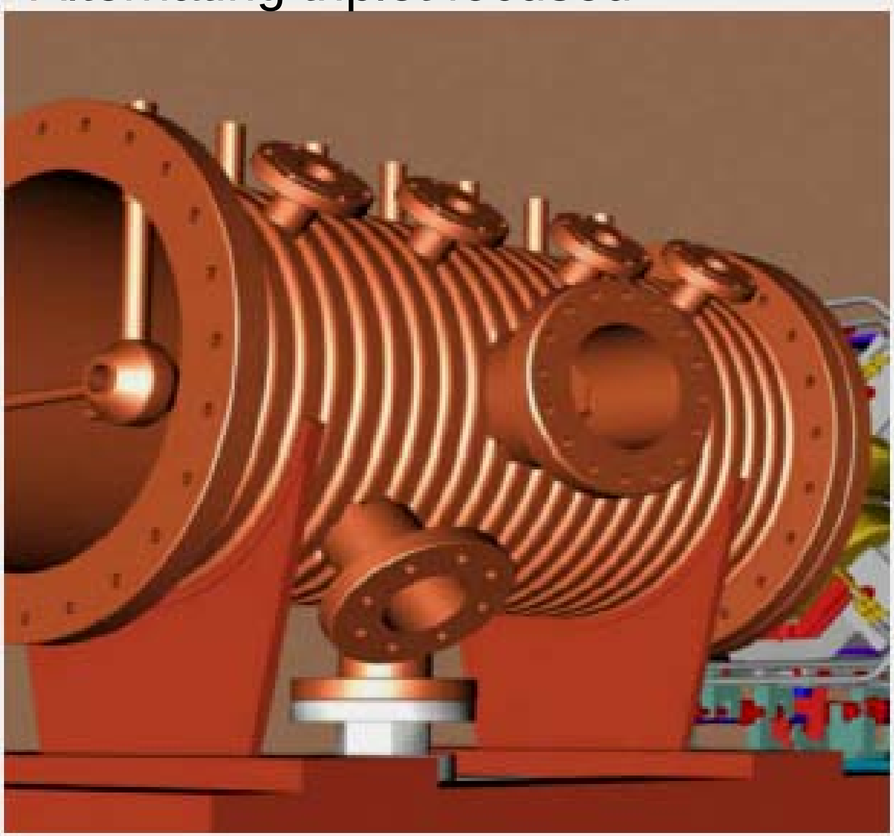
- Freq 324 MHz
- W 50-190 MeV
- I_{peak} 50 mA
- Rf duty 3 %
- Doublet focused

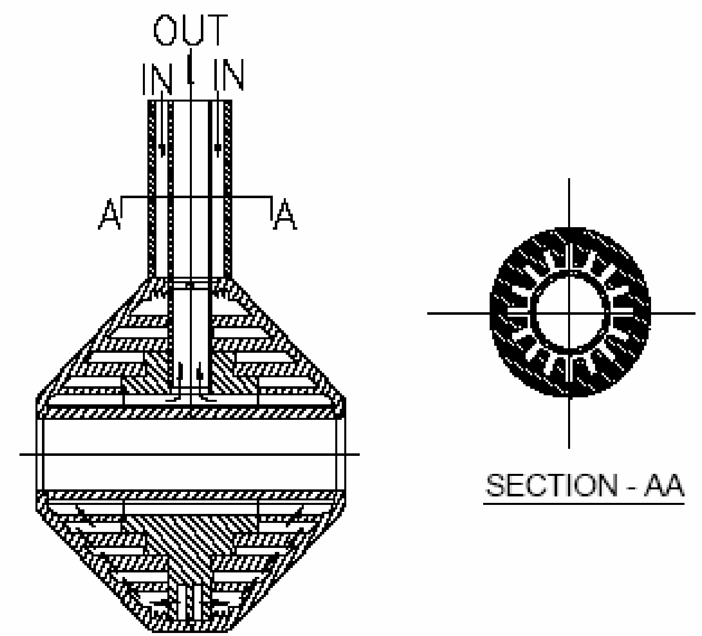
- No. of tanks 32
- Drift tubes/tank 4
- No tanks/klystrons 2
- E_0 2.5-3.7 MV/m
- E_{peak} 1.3 MV/m

CAT SDTL Design has been Optimized for cw Operation at 2 Frequencies

W 4.5/20 -100 MeV
I_{peak} 10 mA
E_0 1.6-2.2 MV/m
Rf duty cw
Alternating triplet focused

Freq	350	700 MHz
•No. of tanks	98	91
•Drift tubes/tank	3	3 - 5
•ρ_{max}	≤ 15	≤ 22 W/cm^2

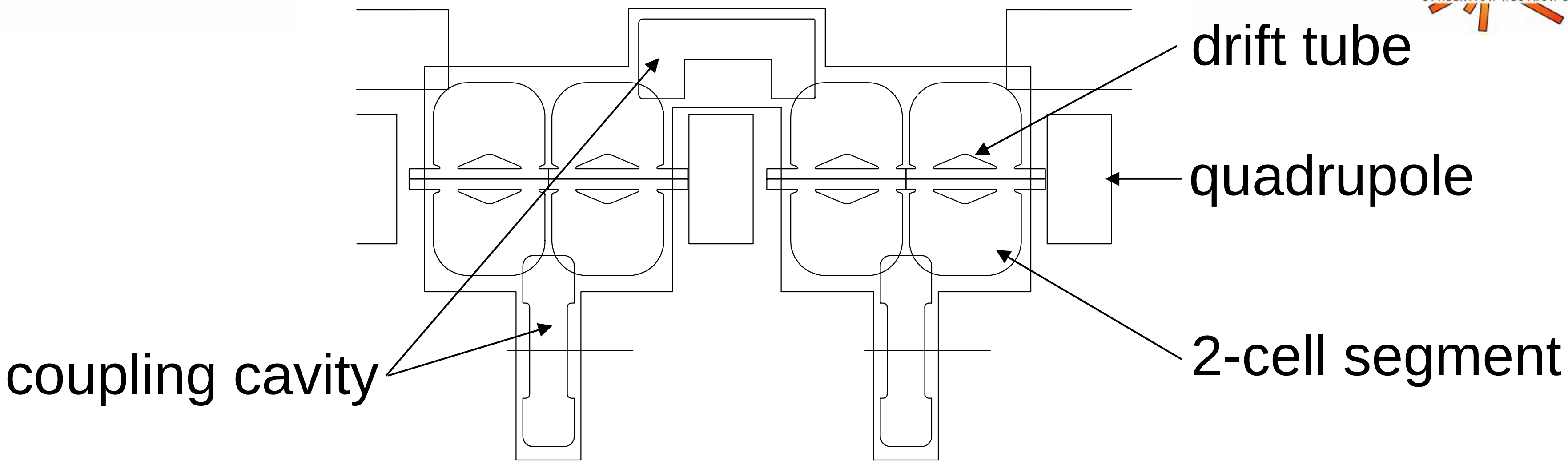




COOLING SCHEME OF DRIFT TUBE

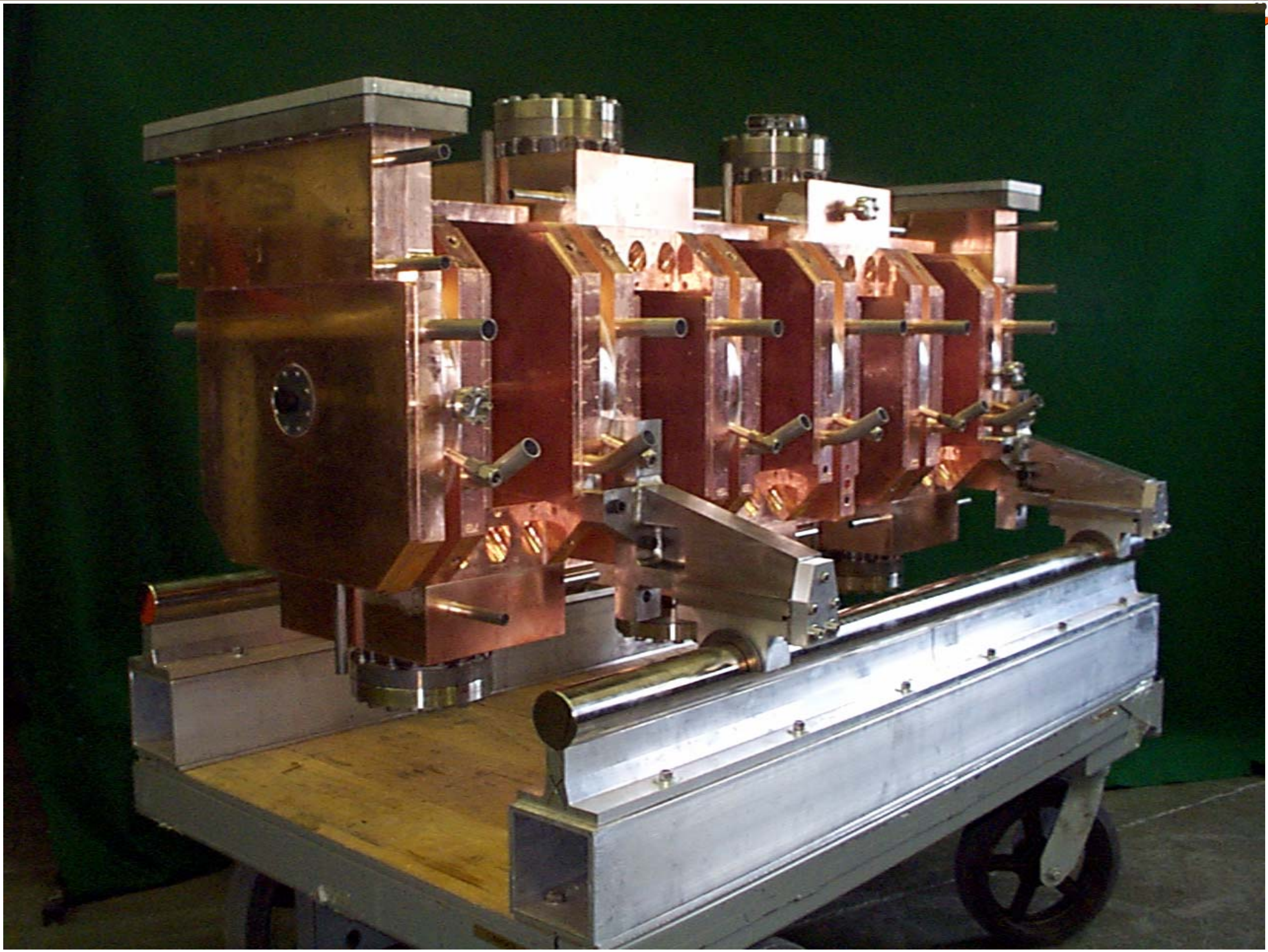
S. Pande

Coupled-Cavity DTL or CCDTL



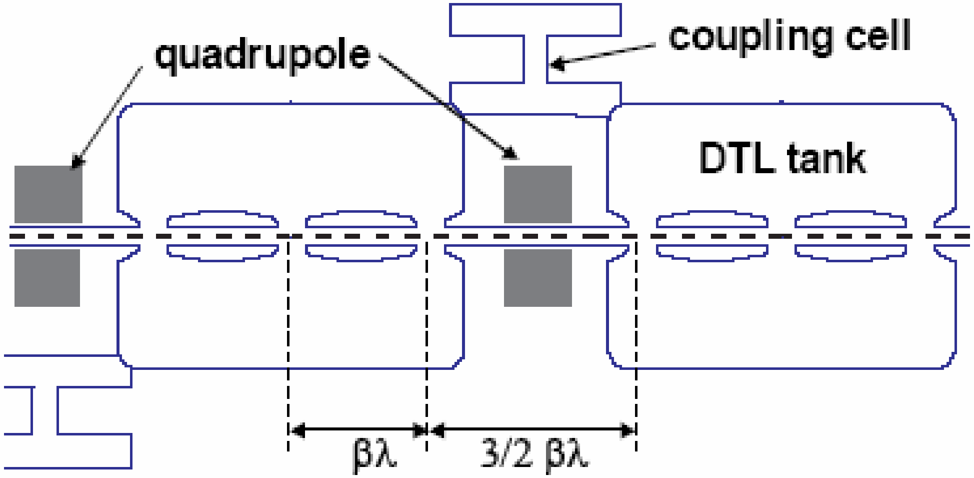
- Comprised of side-coupled CCL cavities containing one or more drift tubes
- Segments are resonantly coupled operating in $\pi/2$ cavity mode
- Chains of multiple segments driven from a single power source
- Focusing is provided by quadrupoles located between segments
- Short focusing period, especially at 2X frequency
- Good choice for funneling
- Impractical at low β and high frequency

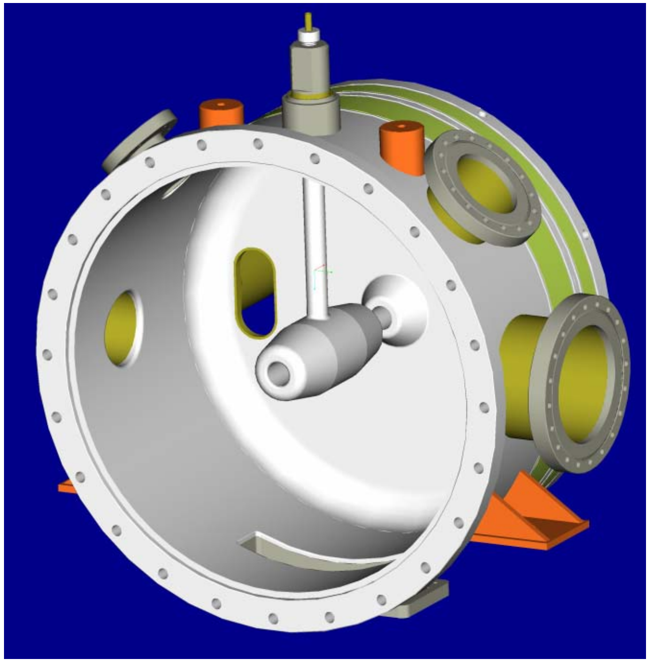
APT 1 & 2 Drift-Tube, 7-MeV CCDTL Operated at 700 MHz but Detuned when Operated cw

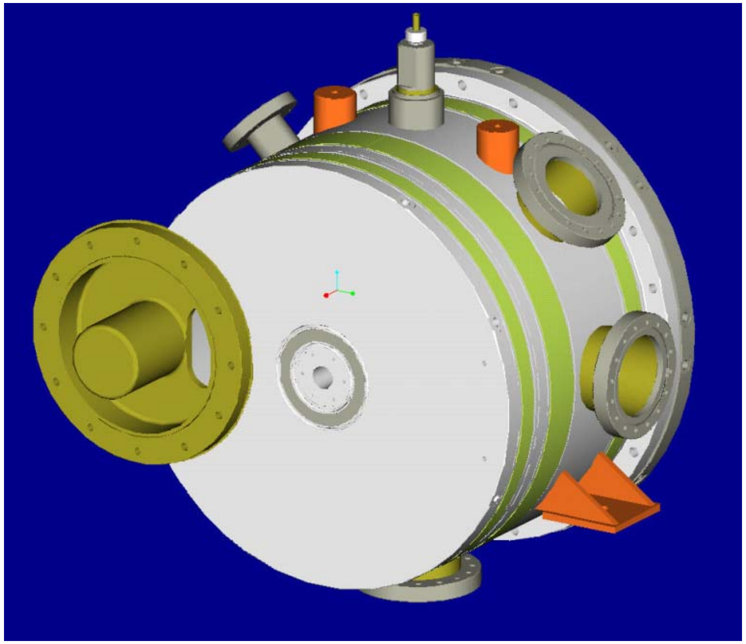


CERN CCDTL Prototype is Designed to Deliver High Average Current at 14% Duty

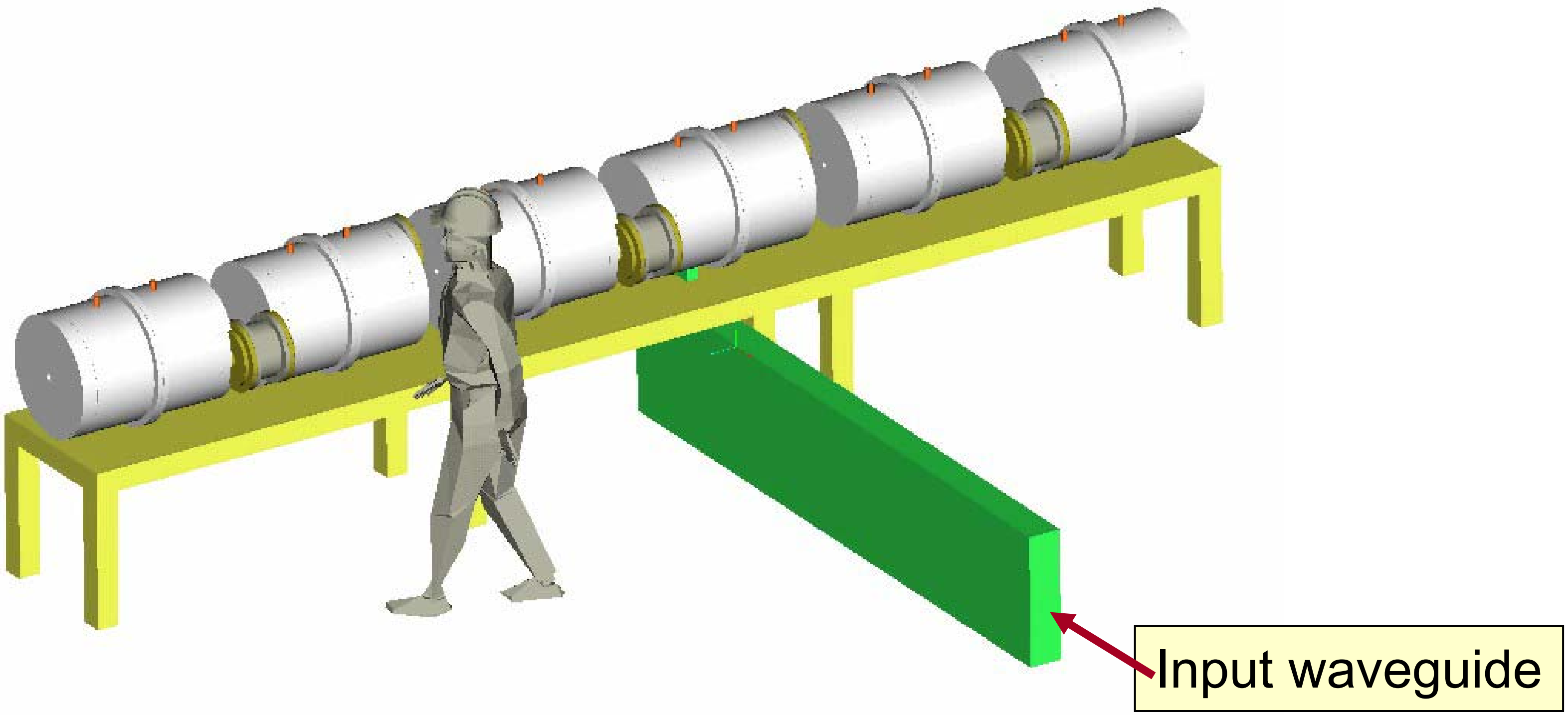
Freq	350 MHz
W	40 -120 MeV
I_{peak}	40 mA
Rf duty	14 %
E_0	3 MV/m
Epeak	1.3 E_K
No of segments	76



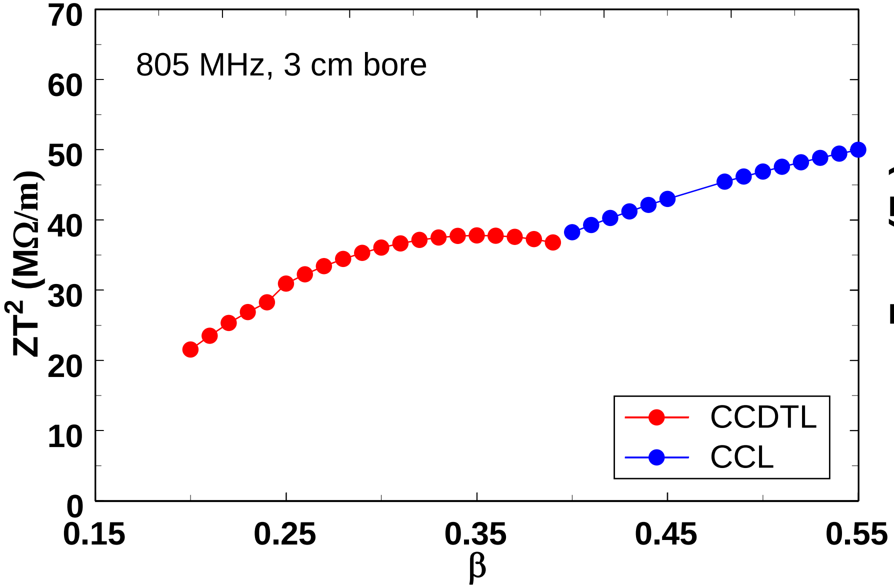


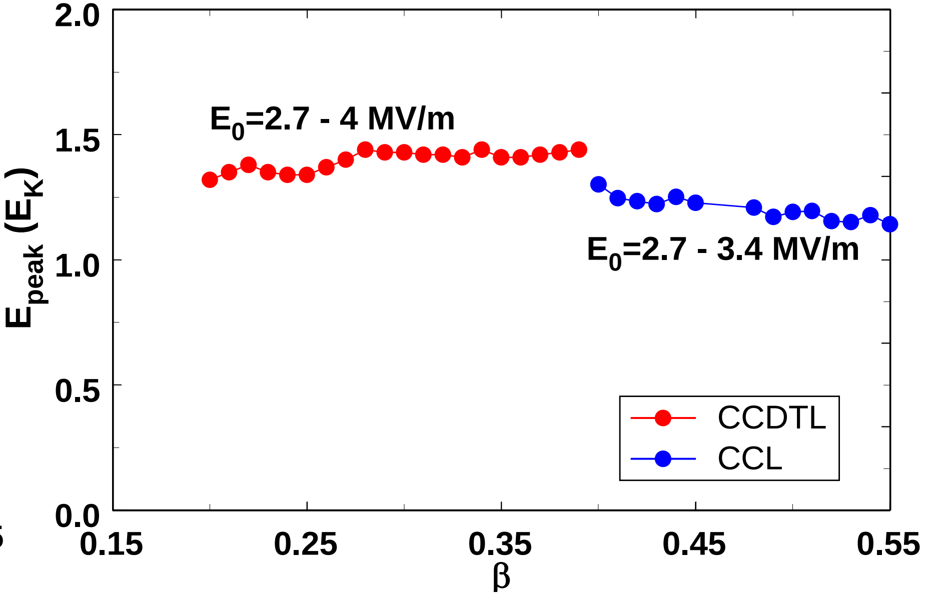


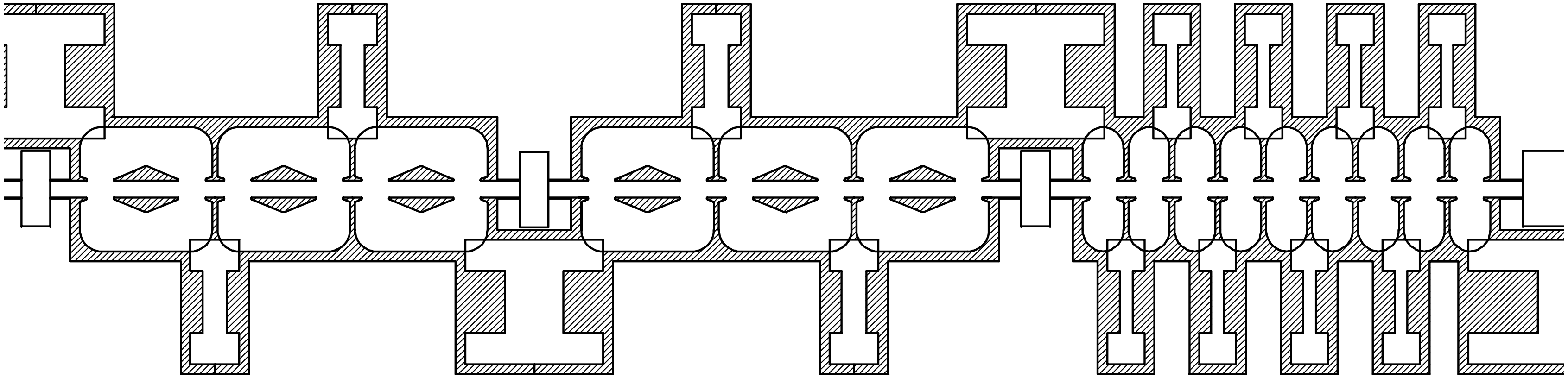
CCDTLs, Operate in the $\pi/2$ Cavity Mode, are Phase Locked, Very Sable and Require a Single Drive



SNS Single Drift-Tube 805 MHz CCDTL & CCL





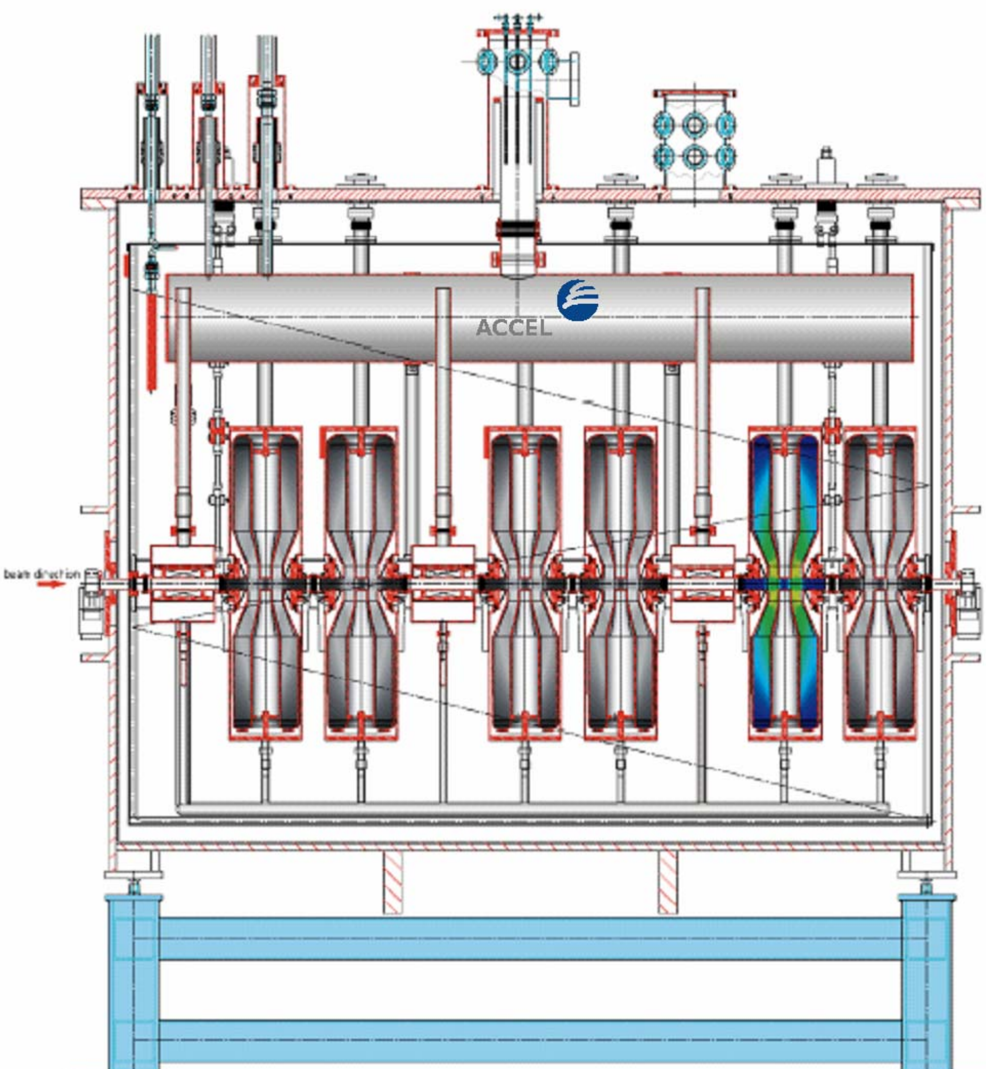


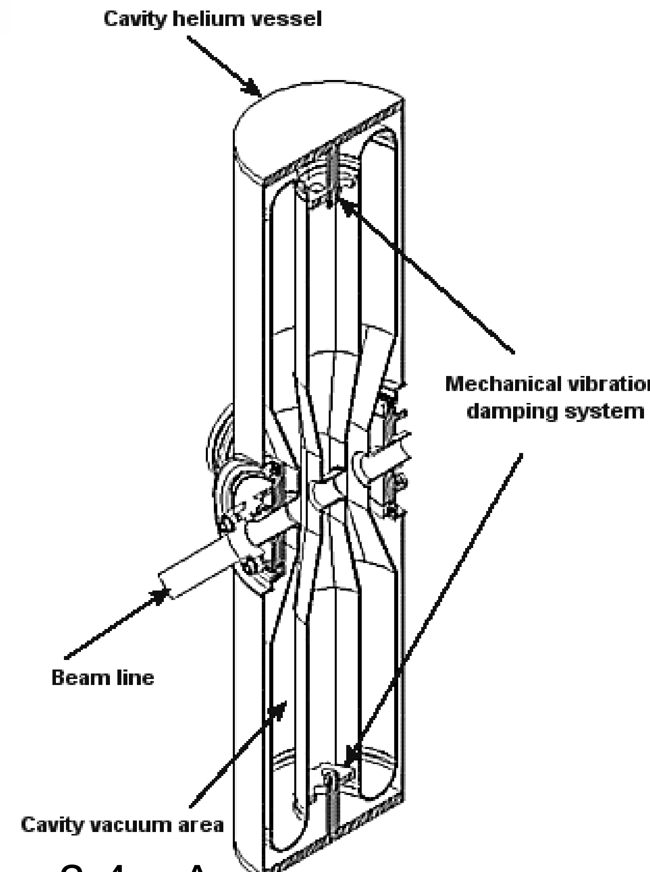
SNS 5-MW 805-MHz CCL Undergoing Final Tuning at Accel

Room Temperature Structure Summary

- DTL is the preferred low-β structure for high-current beams
  - offers the highest real-estate ZT^2
  - Expensive to build with EMQs
  - EMQs are challenging and may be replaced with PMQs
  - Strong short lattice
- SDTL have highest cavity ZT^2
  - Long period precludes very high currents at low β
  - Economical to build
  - Requires extensive rf power distribution & control system
- CCLDTL is attractive only above 20 MeV
  - Difficult to cool cw at high frequency
  - Long stable structures
  - Strong short lattice
- CCL is the preferred structure above $\beta \approx 0.4$

Accel β=0.09 & 0.15 Half-Wave Resonators Accelerate H^+ & D^+ to 40 MeV





I_{peak}= 2-4 mA

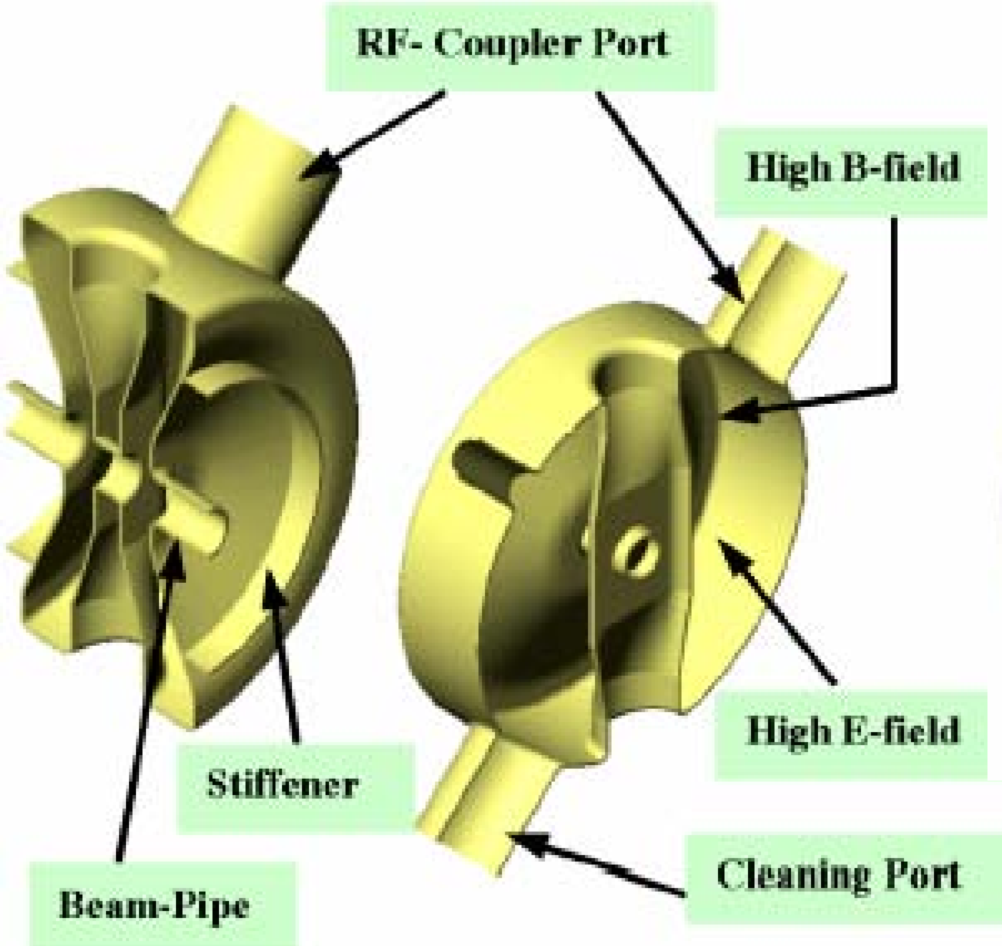
Duty= pulsed & cw

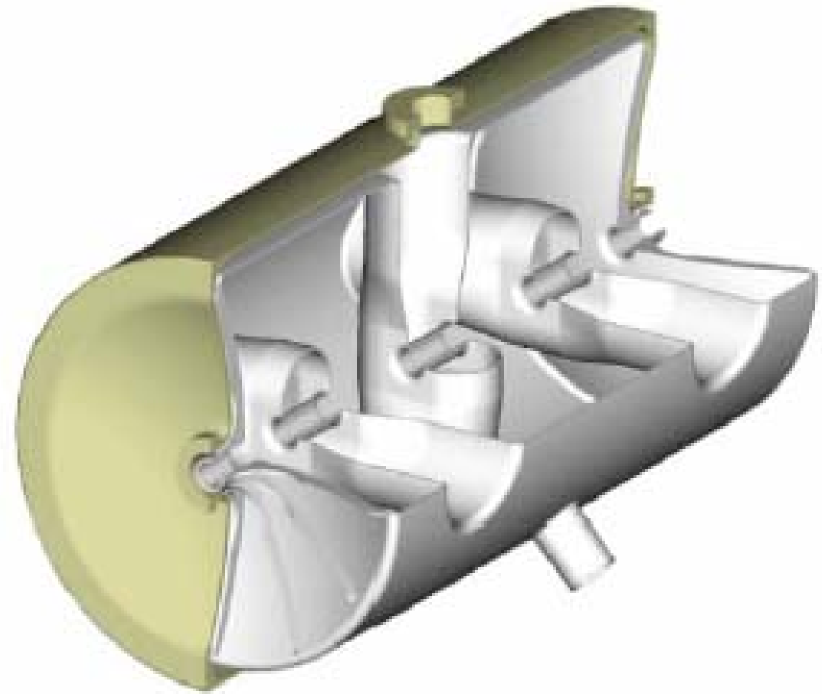
E_{max} = 25 MV/m

S.C. solenoid focused

Septe Accel

Superconducting Spoke Cavities have Demonstrated E_0=11.6 MV/m at 350 MHz





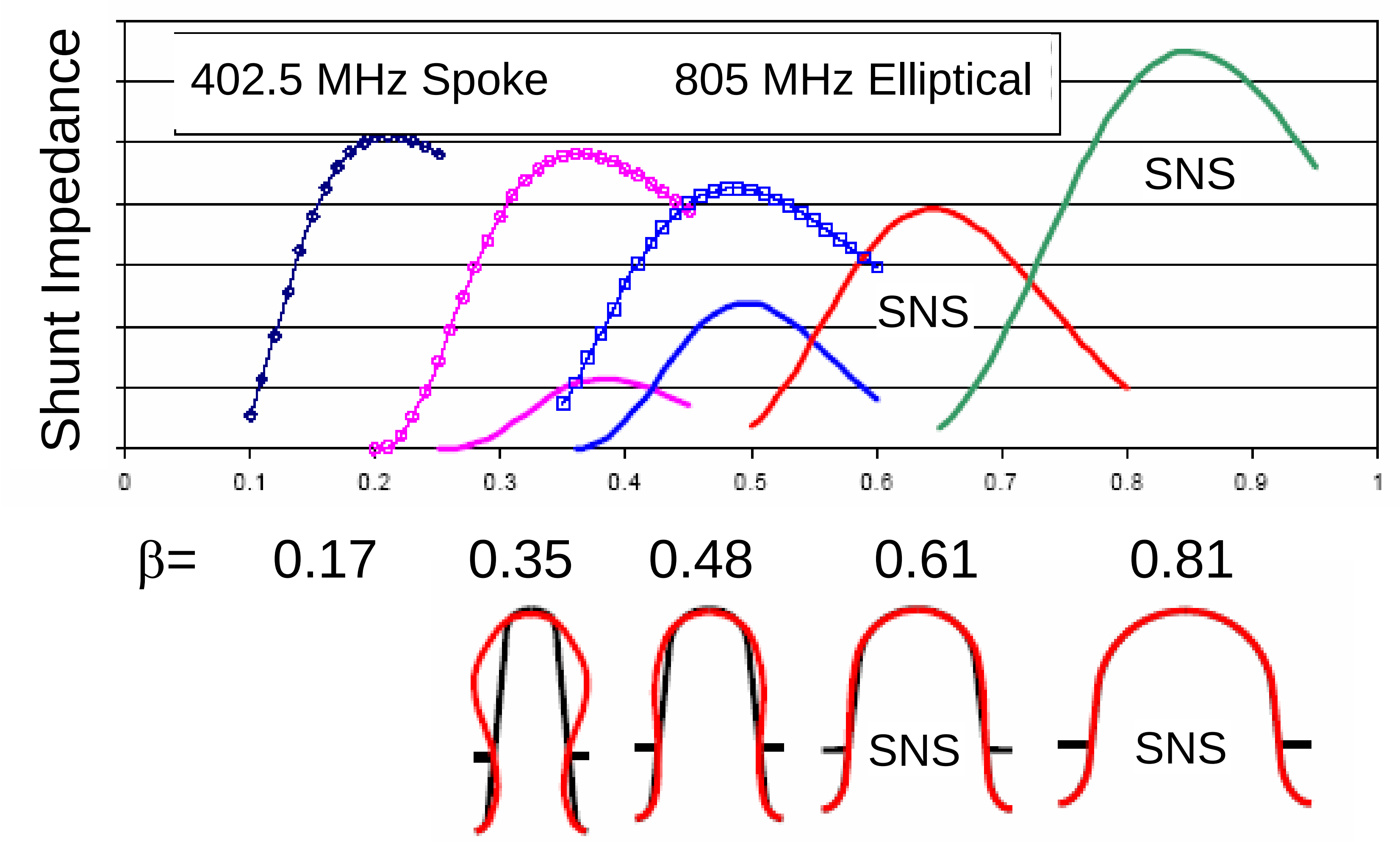
β=0.175, W=15 MeV

β=0.62, W=260 MeV

T. Tajima

K. Shepard

Elliptical Superconducting Cavities Perform Better Above ~200 MeV



S. Kim