High Efficiency High Repetition Rate RF Structures for Linacs as Drivers for FELs

Sami G. Tantawi

SLAC

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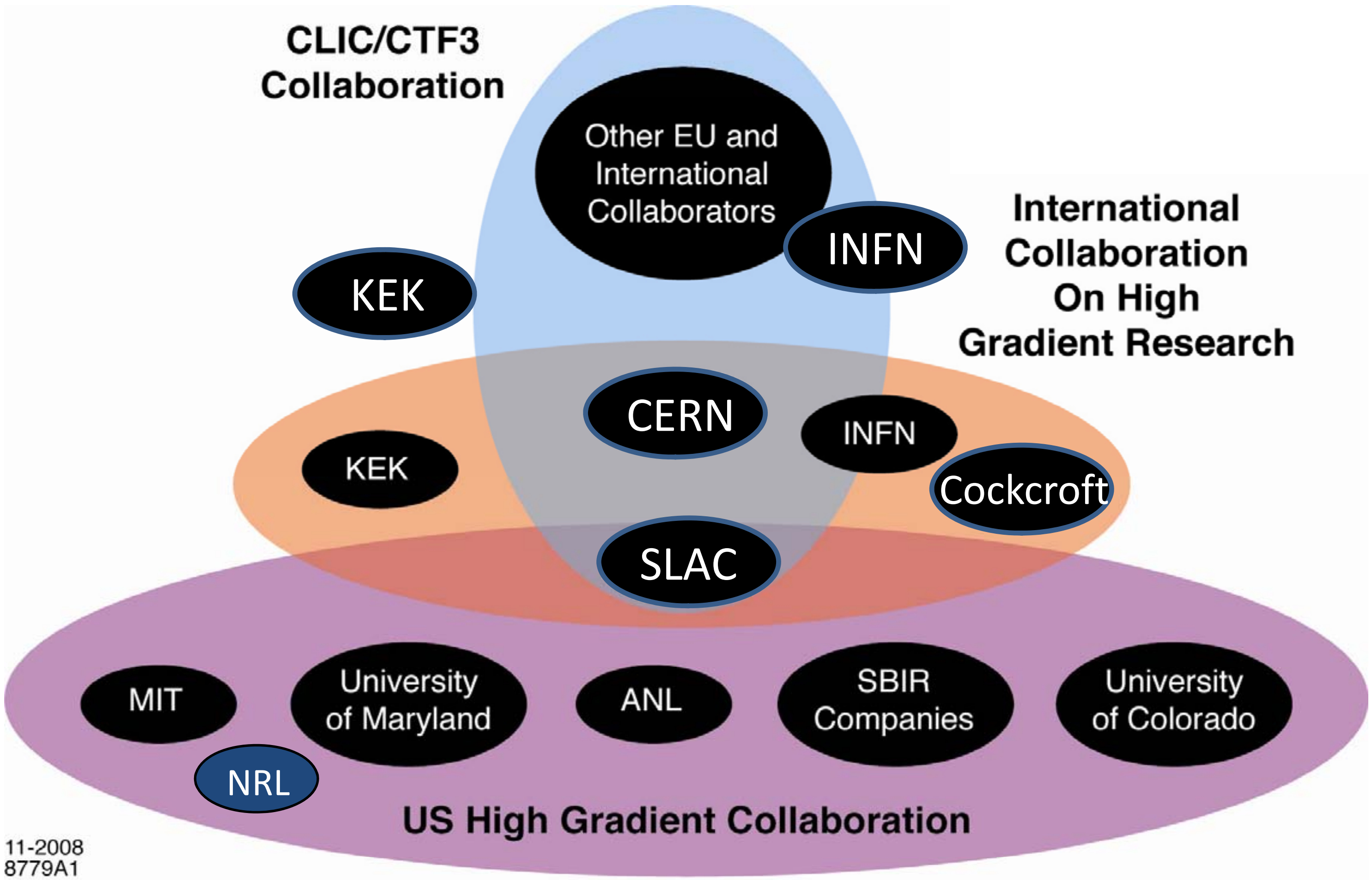
Outline

- High Gradient linac developments
- Motivation and scaling laws for room temperature linacs
- Linac efficiency optimization
- Discussion on wake fields
- Rf source optimization
- RF system Architecture
- Conclusion

International Collaboration on High Gradient Research



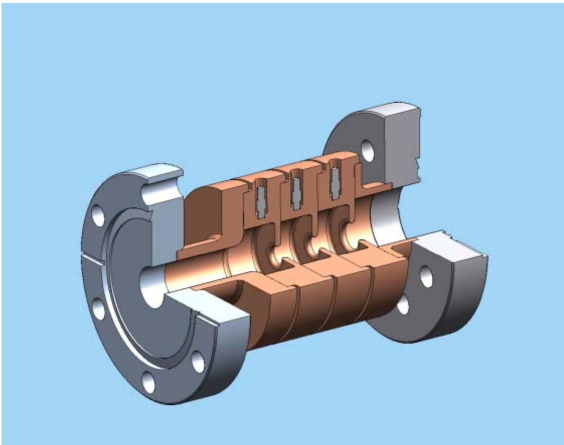
The Challenge

What gradient can be reliably achieved using warm technology?

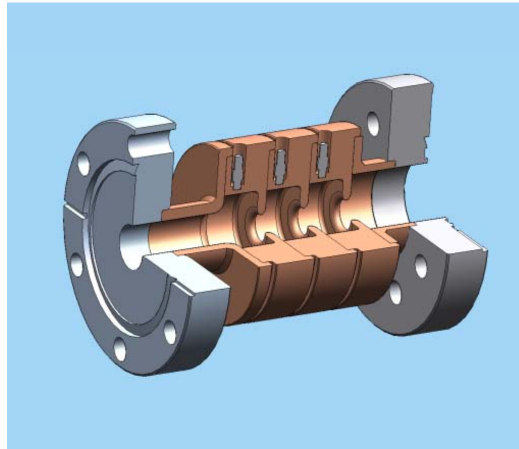
- The original, optimistic view (PAC 1986) : E. Tanabe, J. W. Wang and G. A. Loew, "Voltage Breakdown at X-Band and C-Band Frequencies," :
  - The authors report experimental results showing that the Surface Electric Field limit at 9.3 GHz (X-Band) exceeds 572 MV/m in pulses of up to 4.5 microseconds
  - Results predict an on-axis gradient of at least 250 MV/m
- Reality sets in (by 2001):
  - The operating limit determined by experiments on the NLC Test Accelerator showed that high gradient accelerator structure operating at X-band would not survive long term operation without computer/feedback protection and the breakdown rate above 65 MV/m can not be tolerated for a collider application.
- **The challenge**: we wish to ***understand*** the limitations on accelerator gradient in warm structures

- **Our goal** is to push the boundaries of the design to achieve:
  - Ultra-high-gradient; to open the door for a multi-TeV collider
  - High rf energy to beam energy efficacy, which leads to an economical, and hence feasible designs
  - Heavily damped wakefield

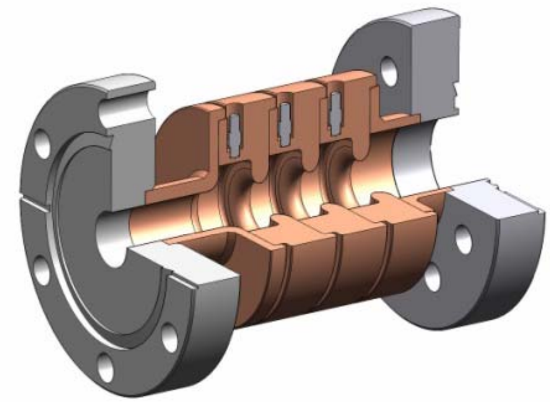
Geometrical Studies
Three Single-Cell-SW Structures of Different Geometries



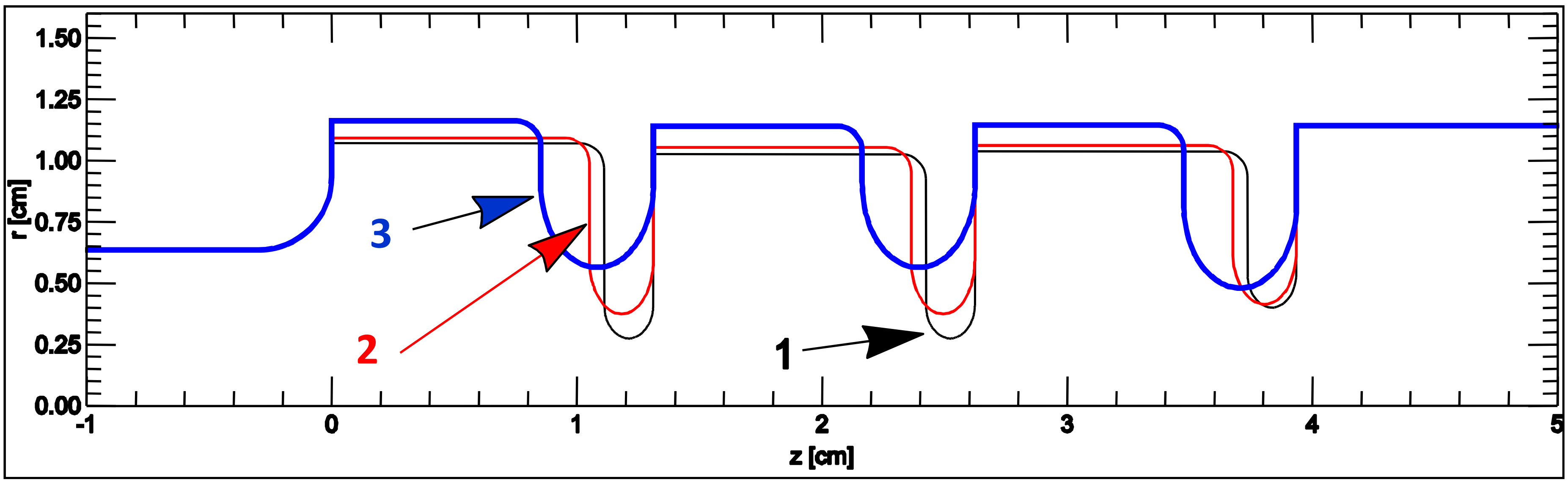
1)1C-SW-A2.75-T2.0-Cu



2) 1C-SW-A3.75-T2.0-Cu

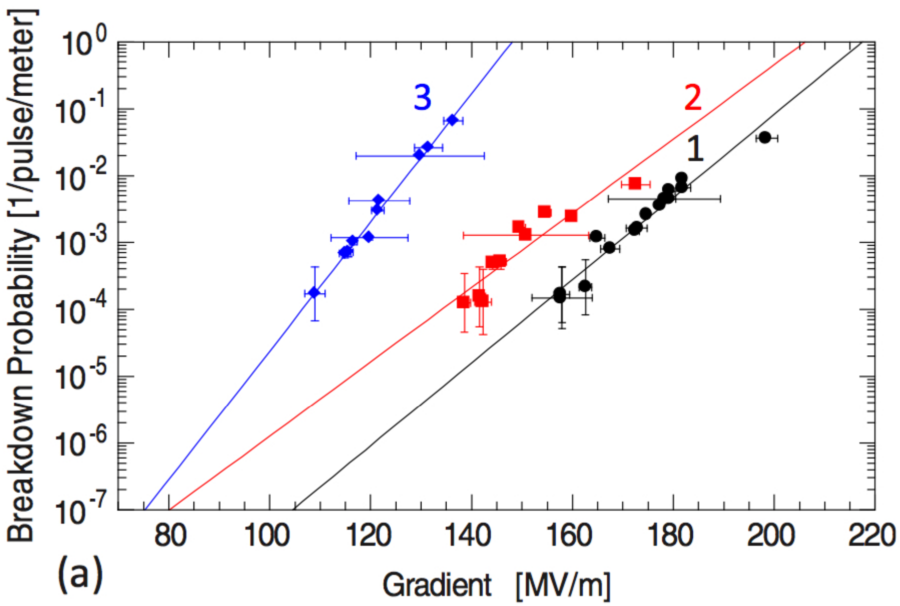


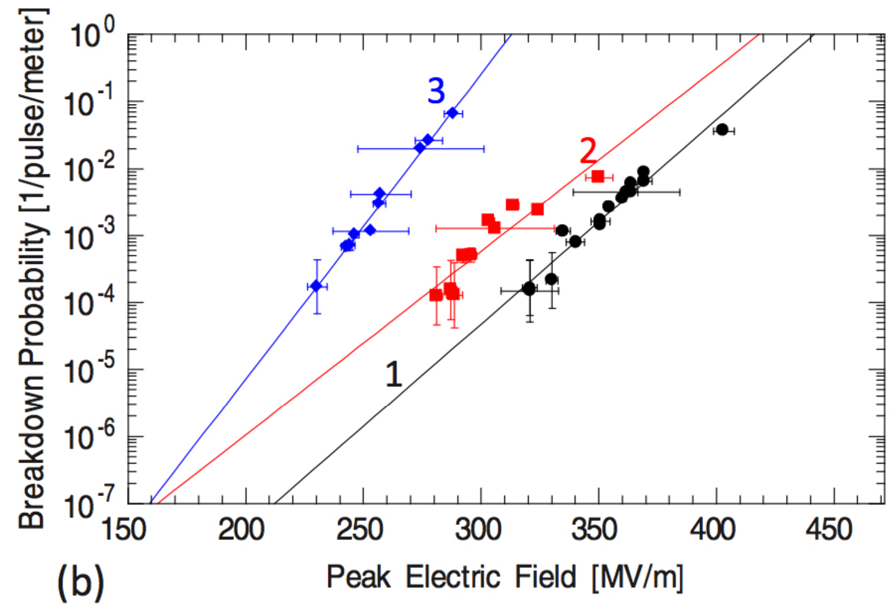
3) 1C-SW-A5.65-T4.6-Cu

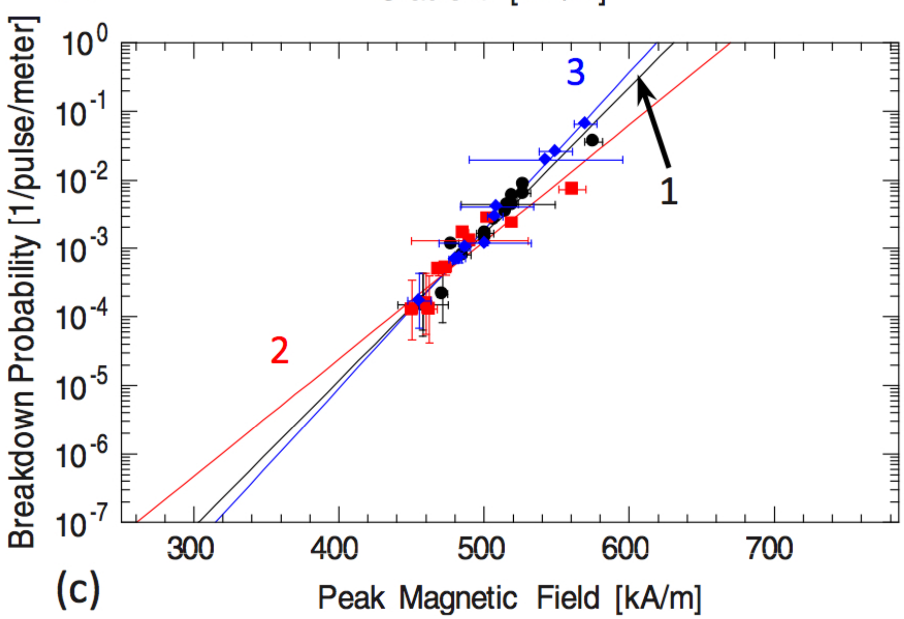


Geometrical Studies

Different single cell structures: Standing-wave structures with different iris diameters and shapes; $a/\lambda=0.215$, $a/\lambda=0.143$, and $a/\lambda=0.105$





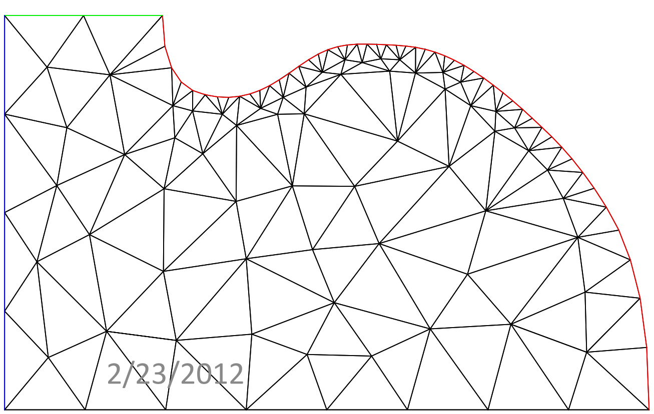


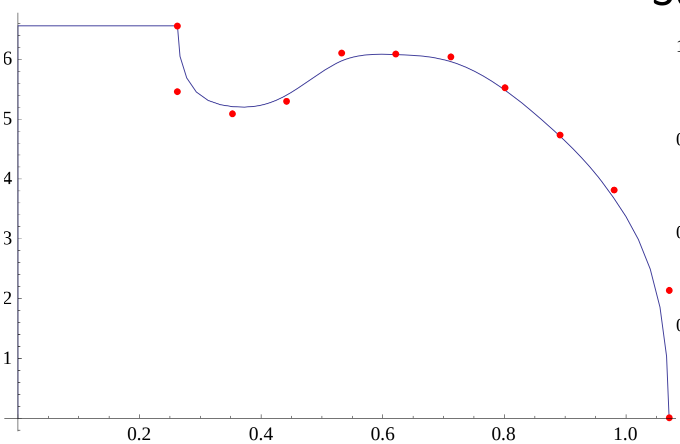
Global geometry plays a major role in determining the accelerating gradient, rather than the local electric field.

Yet another Finite Element Code

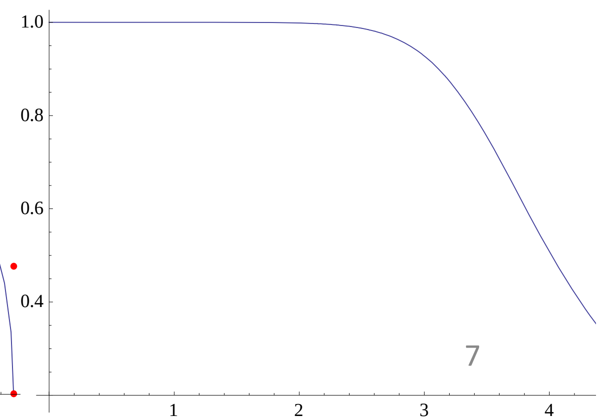
Motivated by the desire
- to design codes to perform *Large Signal Analysis* for microwave tubes (realistic analysis with short computational time for optimization)
- study surface fields for accelerators
- the need of a simple interface so that one could "play"

- A finite element code written completely in Mathematica was realized.
- To our surprise, it is running much faster than SuperFish or Superlance
- The code was used with a Genetic Global Optimization routine to optimize the cavity shape under surface field constraints



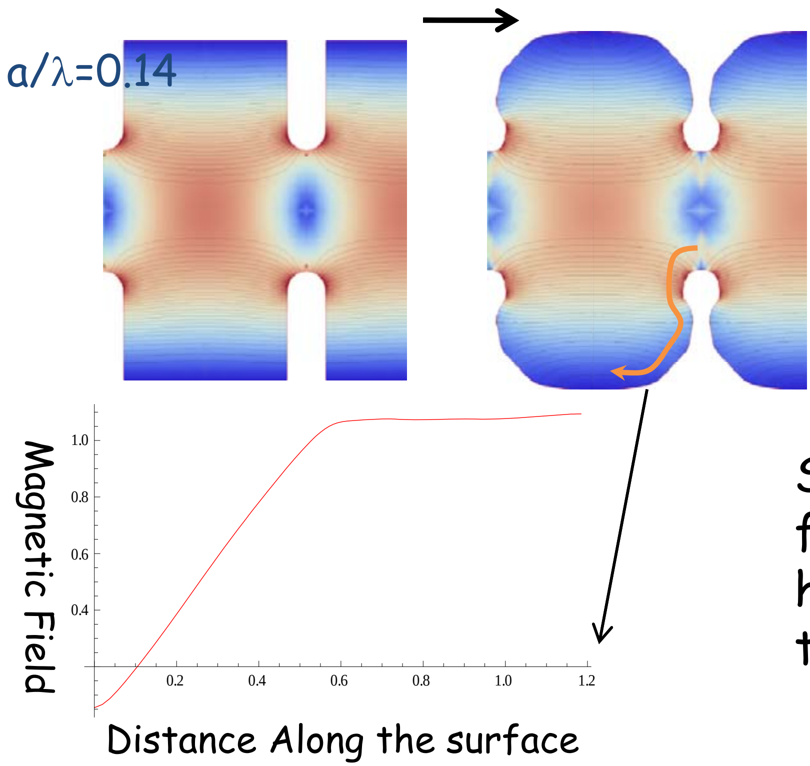


Surface field penalty function

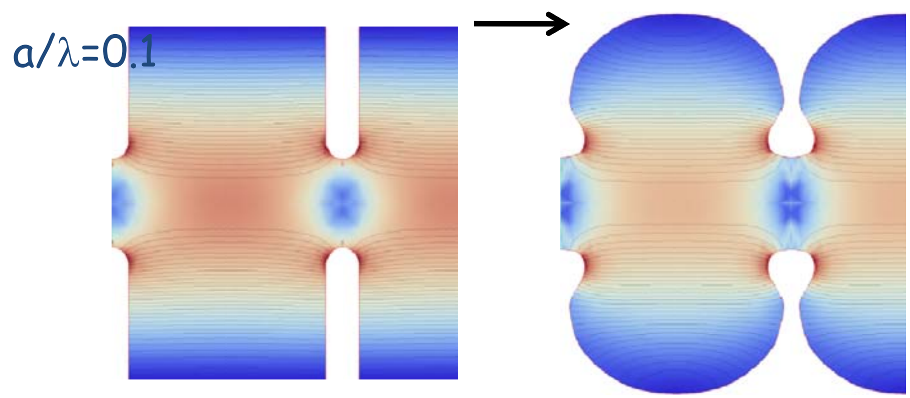


Iris shaping for Standing-Wave π-mode structures

Shunt Impedance	83 MΩ/m	Shunt Impedance	104 MΩ/m
Quality Factor	8561	Quality Factor	9778
Peak E_s/E_a	2.33	Peak E_s/E_a	2.41
Peak Z_0H_s/E_a	1.23	Peak Z_0H_s/E_a	1.12



Shunt Impedance	102 MΩ/m	Shunt Impedance	128 MΩ/m
Quality Factor	8645	Quality Factor	9655
Peak E_s/E_a	2.3	Peak E_s/E_a	2.5
Peak Z_0H_s/E_a	1.09	Peak Z_0H_s/E_a	1.04



Shape optimization reduces magnetic field on the surface, and hence, we hope to improve breakdown rate with the enhanced efficiency

Parallel Feeding (an old idea)

IEEE Transactions on Nuclear Science, Vol.NS-24, No.3, June 1977

PARALLEL COUPLED CAVITY STRUCTURE*

R. M. Sundelin, J. L. Kirchgessner, and M. Tigner
Laboratory of Nuclear Studies, Cornell University
Ithaca, New York 14853

Summary

A parallel coupled RF cavity structure which provides favorable solutions to all of the requirements for use in an e^+e^- storage ring is described. Properties of this structure have been determined mathematically and through measurements on S-band models. An L-band prototype is being constructed and will be tested at high power.

Introduction

An RF cavity structure suitable for use in Cornell's proposed CESR e^+e^- storage ring must satisfy a number of requirements. These are summarized in Table I.

TABLE I STRUCTURE REQUIREMENTS
Operate at 500 MHz
Maximize shunt impedance in the available space (four spaces, 6 meters each)
Minimize number of separately powered modules
Avoid passband mode overlap
Minimize sensitivity of amplitude and phase to individual cell frequency errors
Obtain intrinsic thermal stability
Provide adequate cooling
Provide simple means for tuning the structure to compensate for loading by the beam
Provide sufficient loading of all important TM_0 and TM_1 modes to prevent cavity-induced instabilities
Minimize construction costs
Avoid transverse gradients in the longitudinal electric field

shows the equivalent circuit of the structure. All cells, shown as R, L, and C, are effectively in series with the coupling line at half-wavelength intervals. The coupling iris adds an effective inductance L' in series with each cell.

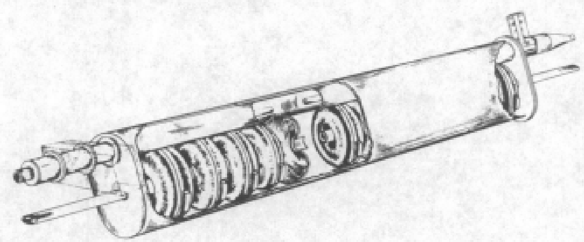


Fig. 1. Parallel coupled cavity structure, including water tank used for cooling.

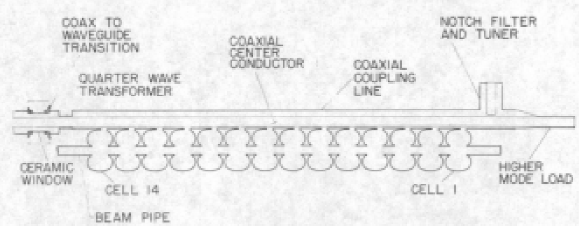
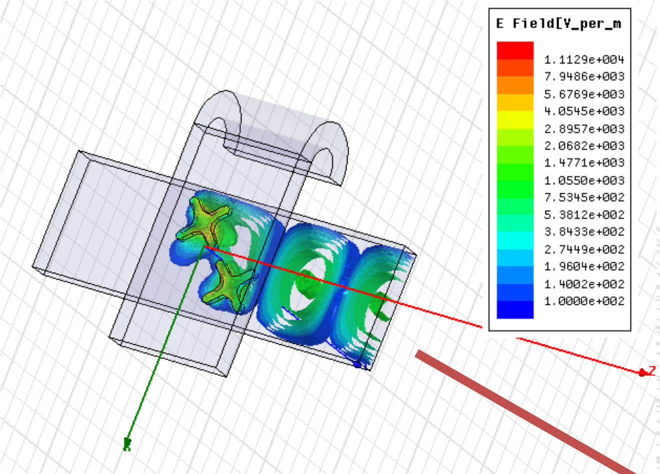
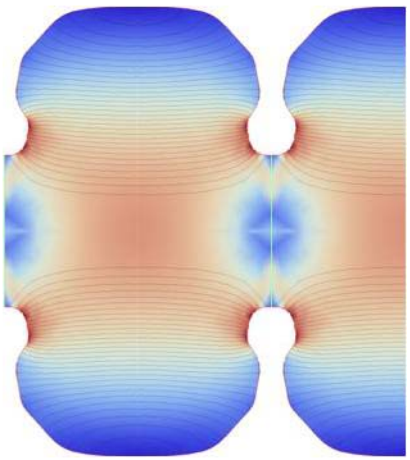
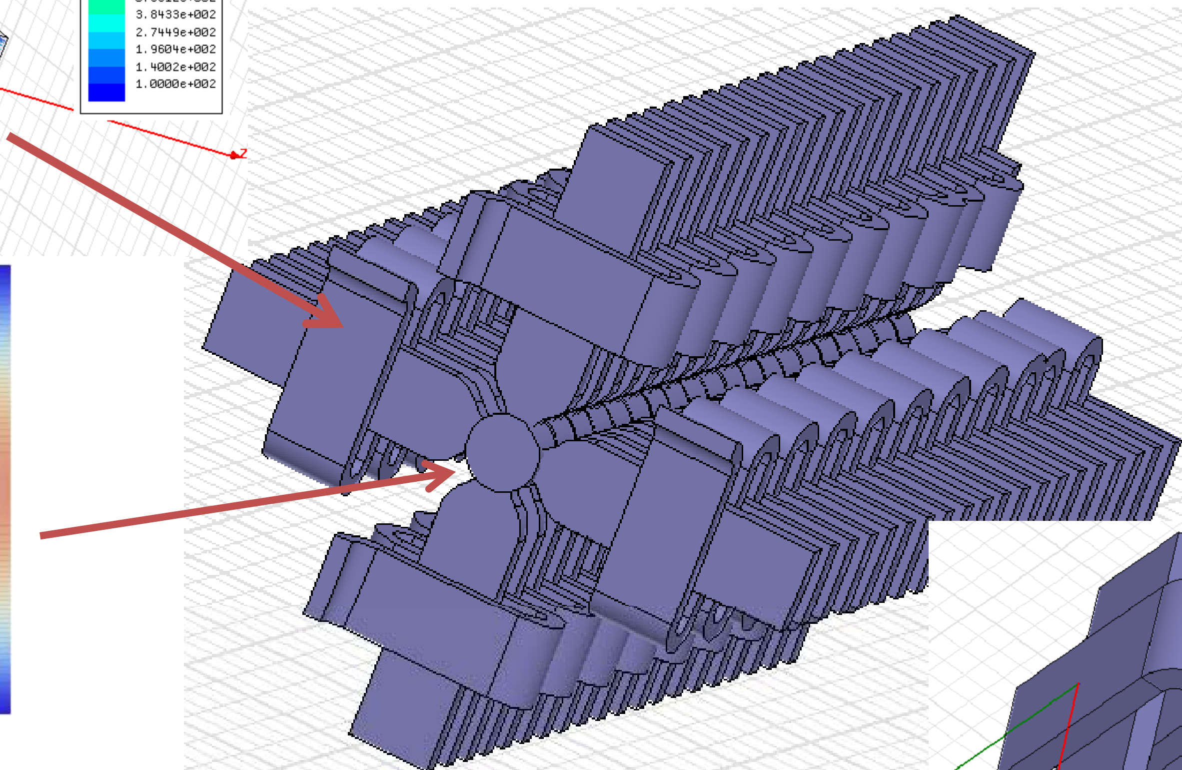


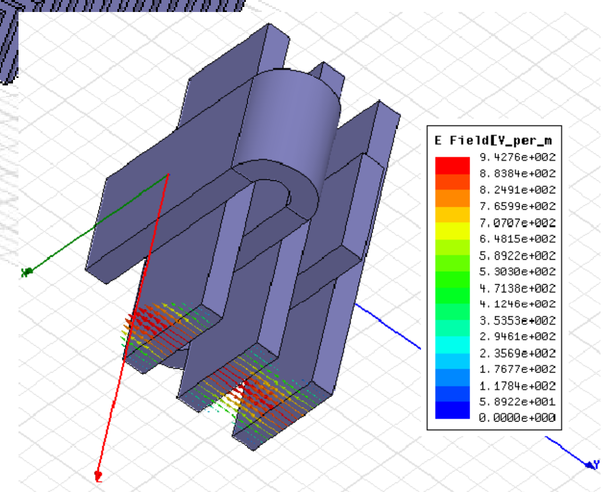
Fig. 2. Side sectional view of parallel coupled cavity structure.



New Accelerator Architecture for Standing wave accelerator structures withy a combined damping and feeding.



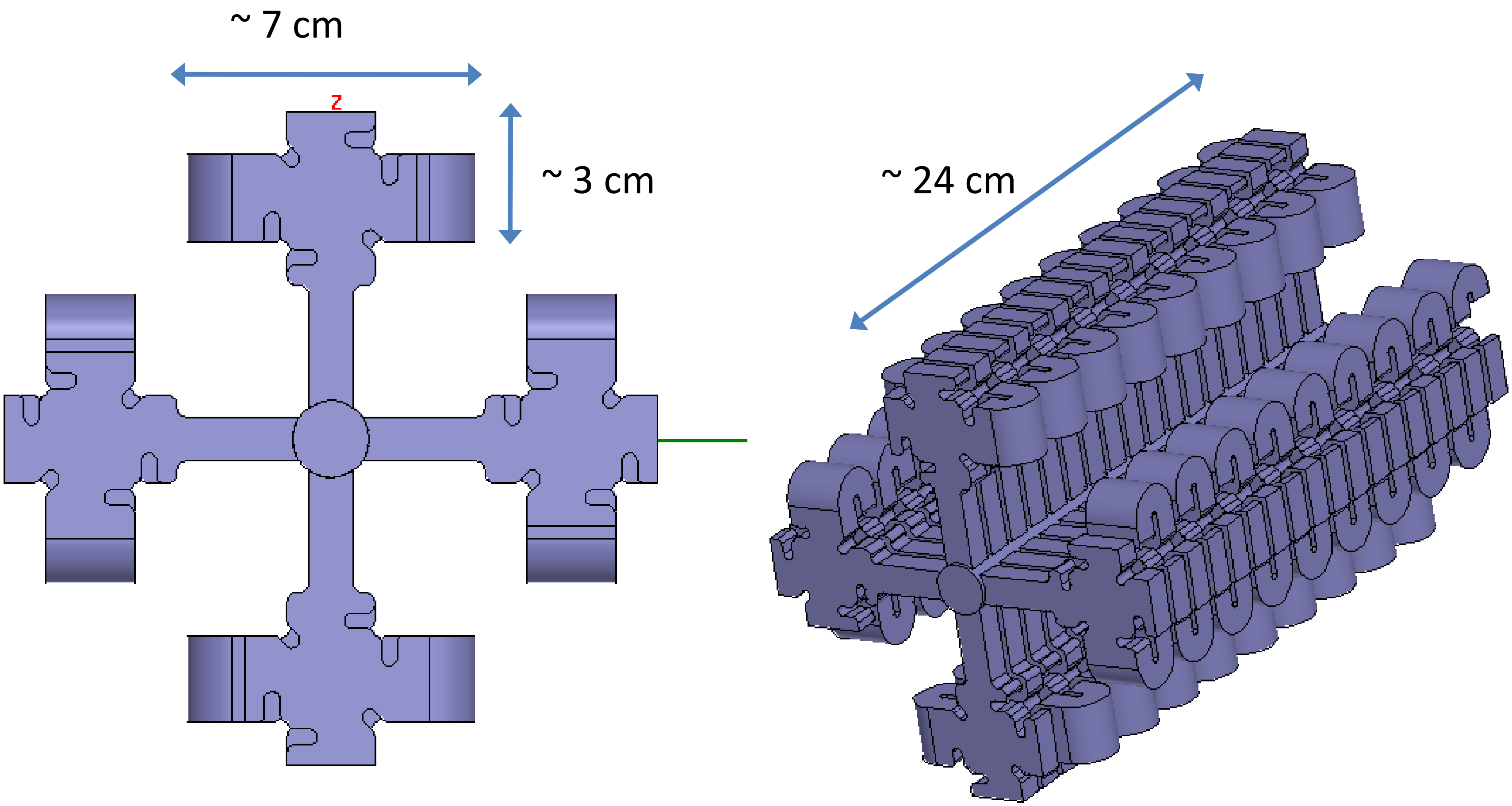




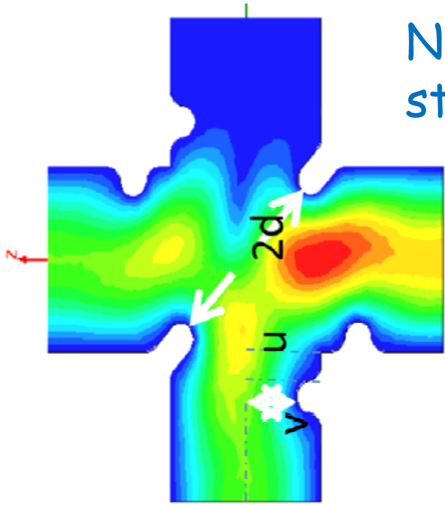
- This is proposed for an efficient high gradient linac for application to a warm collider.
- If one let go of the restrictions imposed by wake fields, the RF distribution system and cell feeding could be done with much more simpler structure.

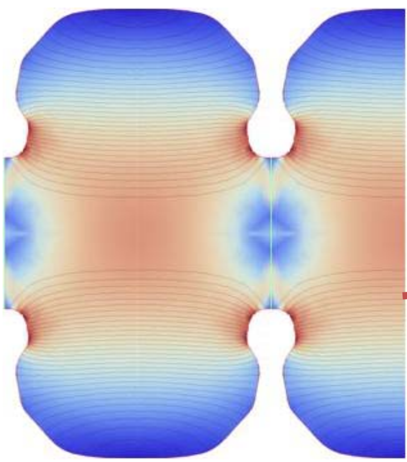
Jeff Neilson

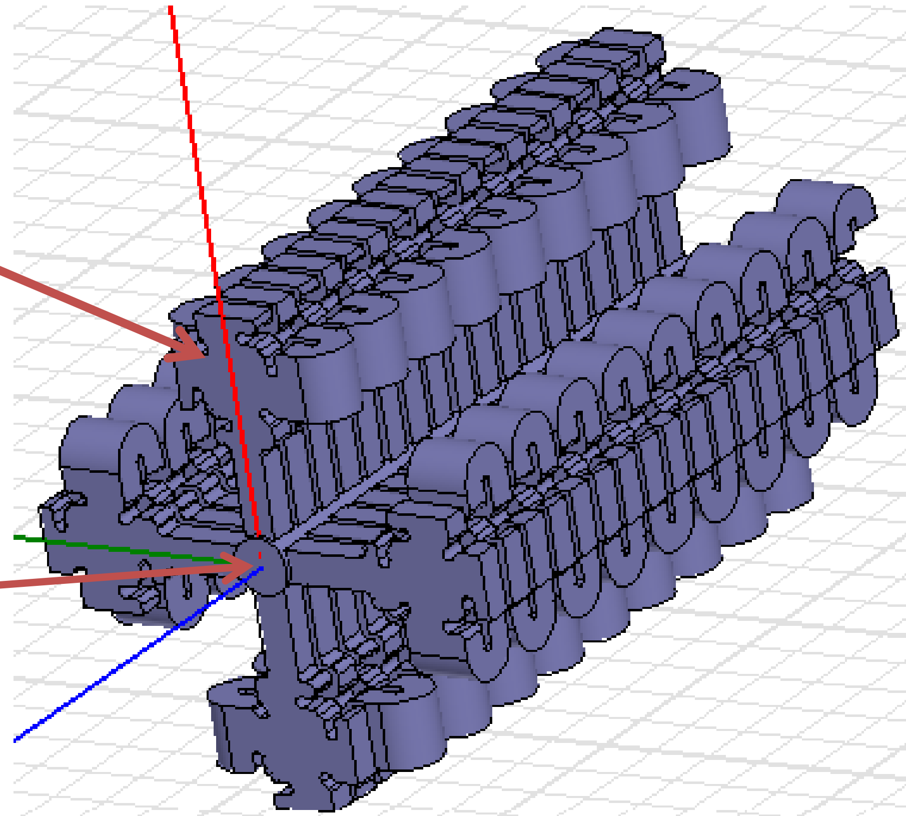
RF Feed Using Biplanar Coupler



New Accelerator Architecture for Standing wave accelerator structures withy a combined damping and feeding.



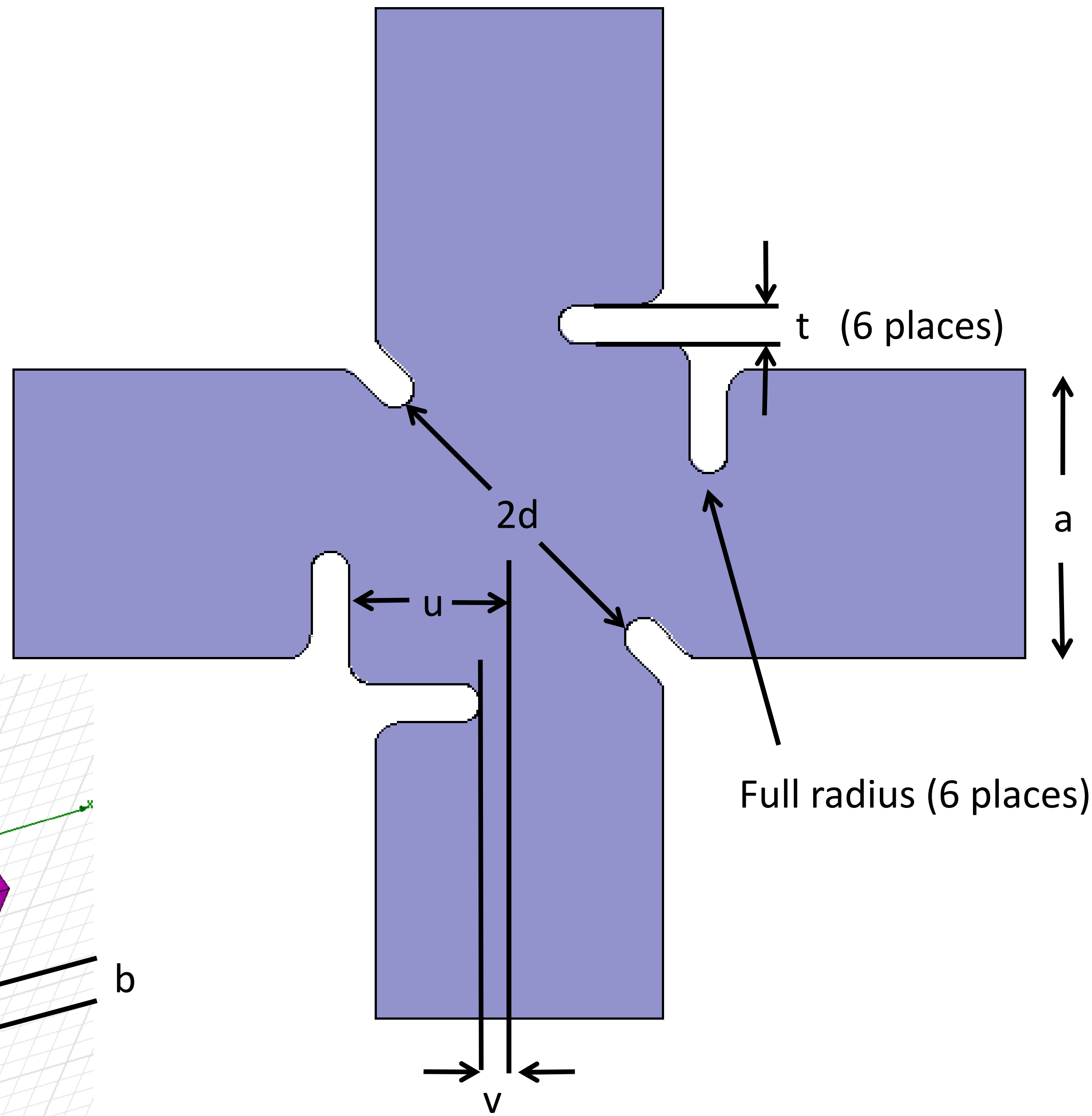


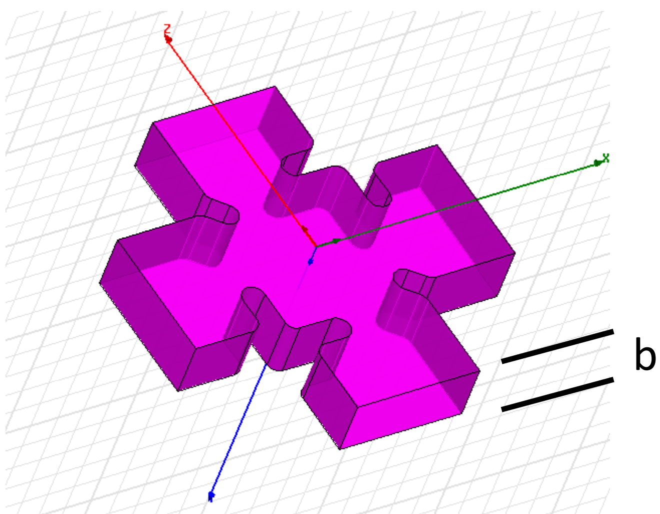


•With a “new” type of planner cross-guide coupler the structure could be made simpler

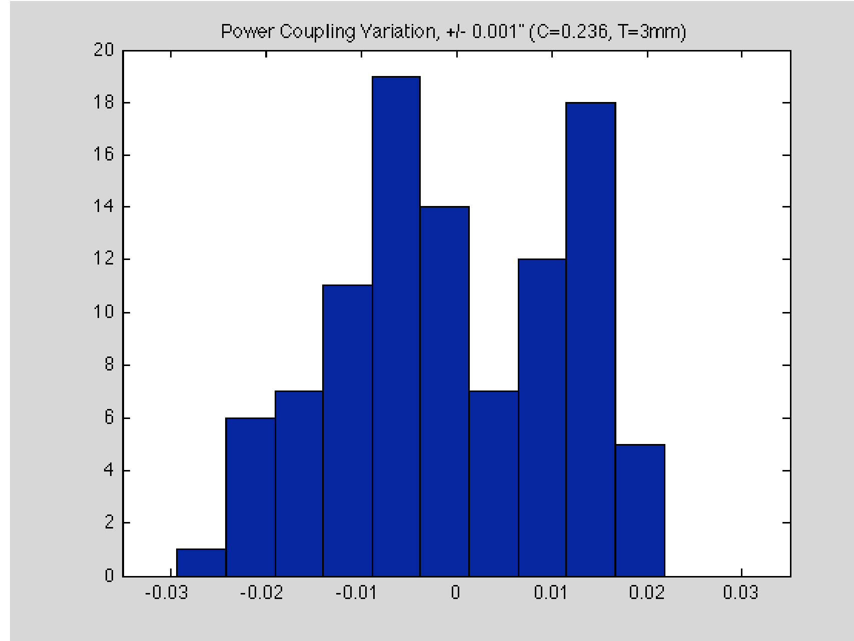
Jeff Neilson

Dimensions in inches
u = .0807 + a/2 = .5307
v = .1234
d = .4876
t = .1181
a = .9
b = .4
Corner radius = .0787

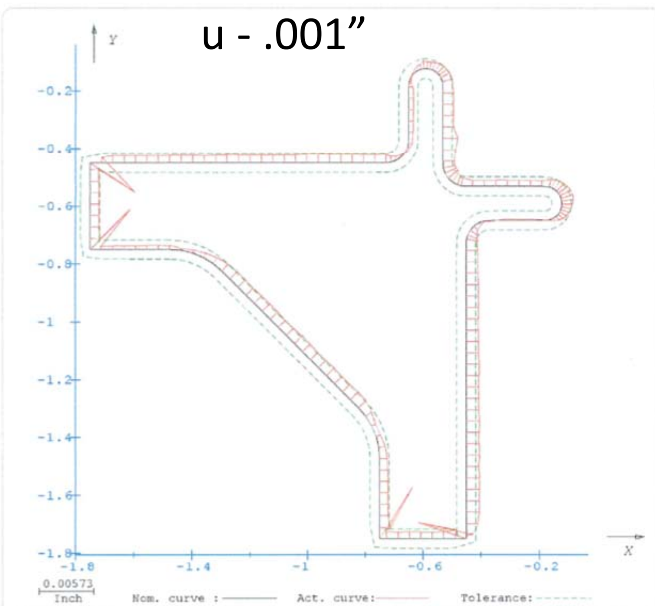


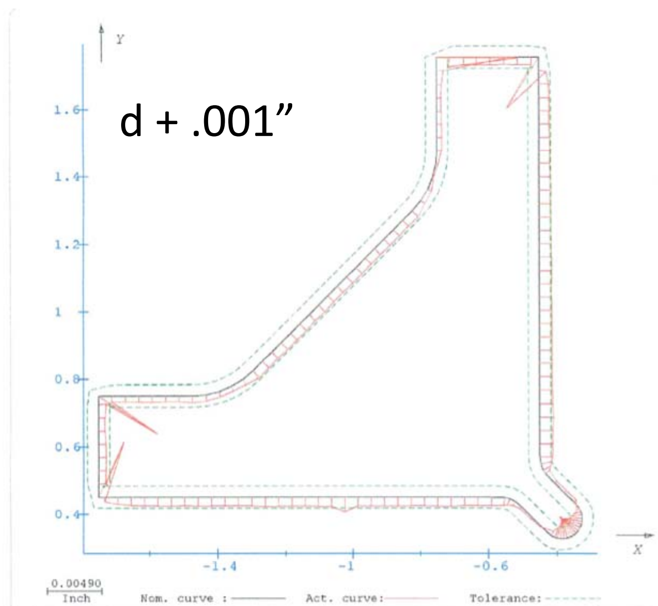


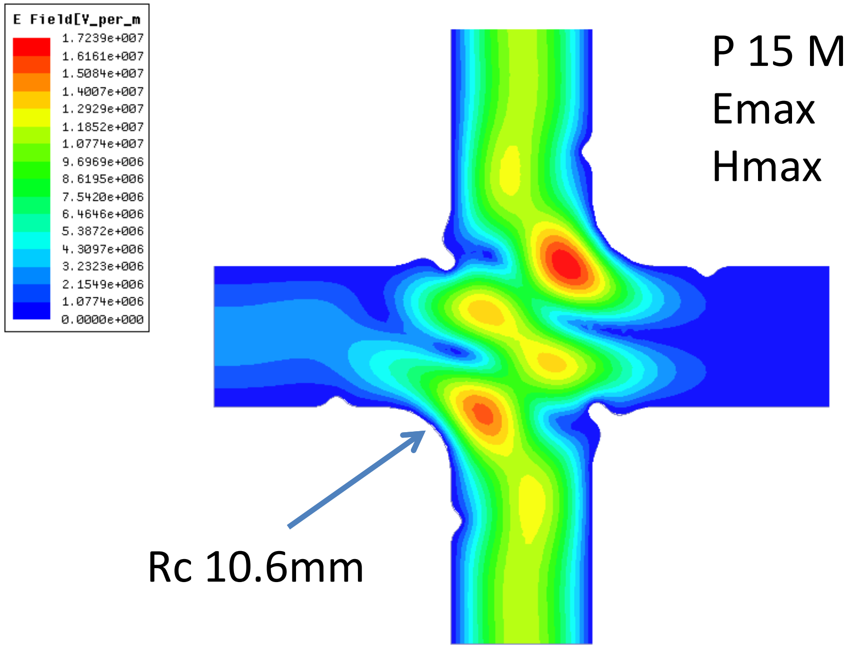
Design coupling factor	0.236 (-12.5 dB)
Measured (3 couplers)	0.20 (-14.0 dB)
Calculated with measured offsets to u, v, d	0.198 (-14.1 dB)



v - .001”



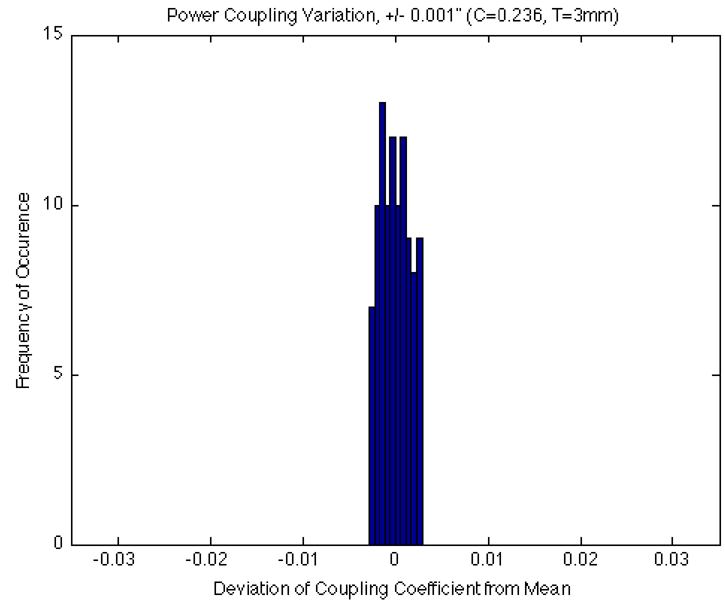


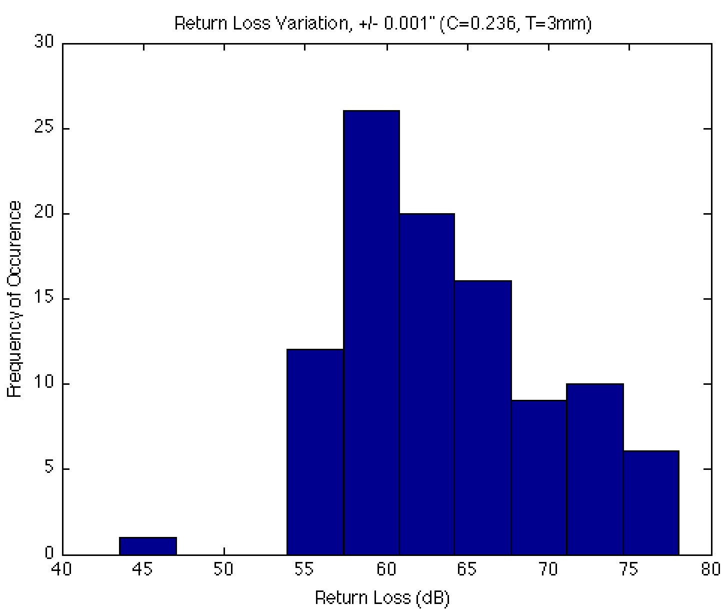


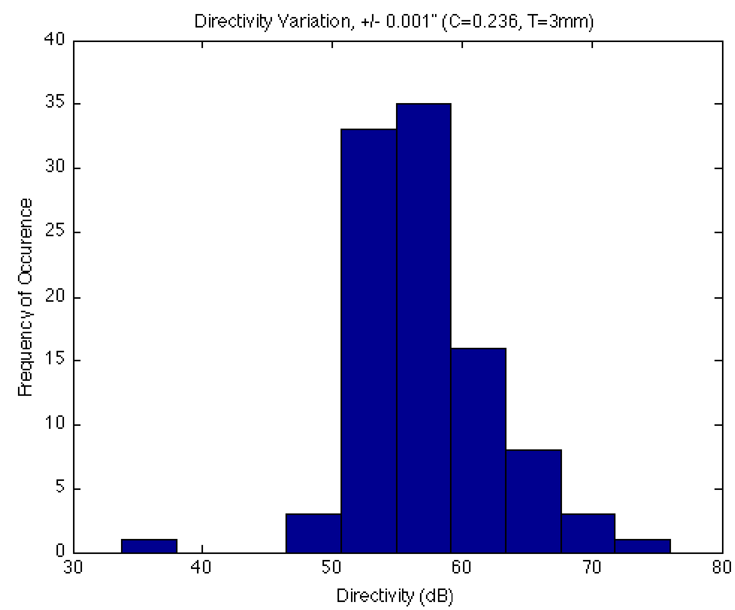
P 15 MW

Emax 17 MV/m

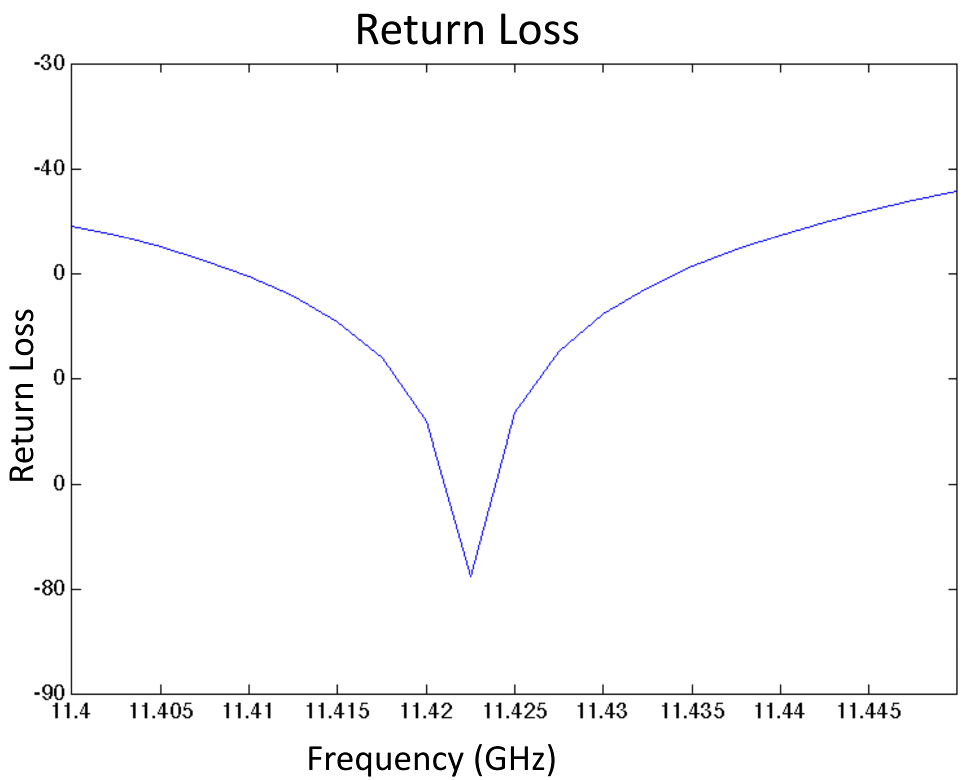
Hmax 50 kA/m

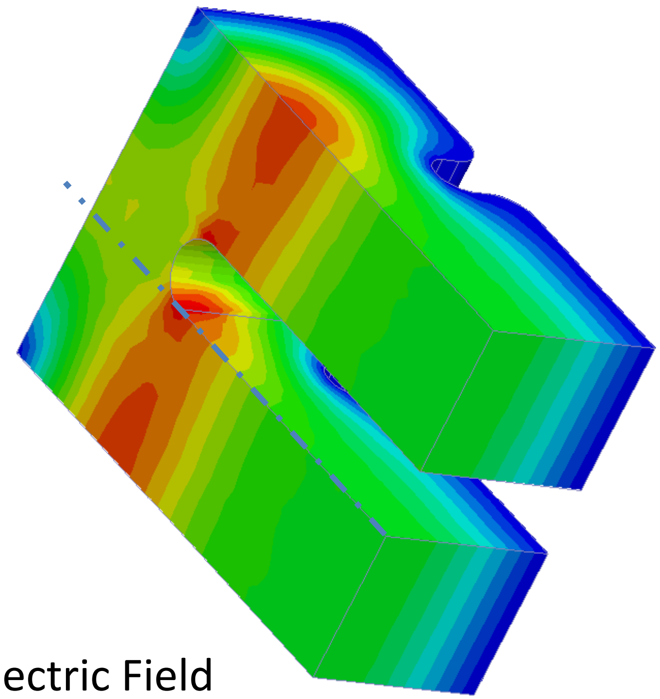






Planar Geometry 180 Degree Elbow

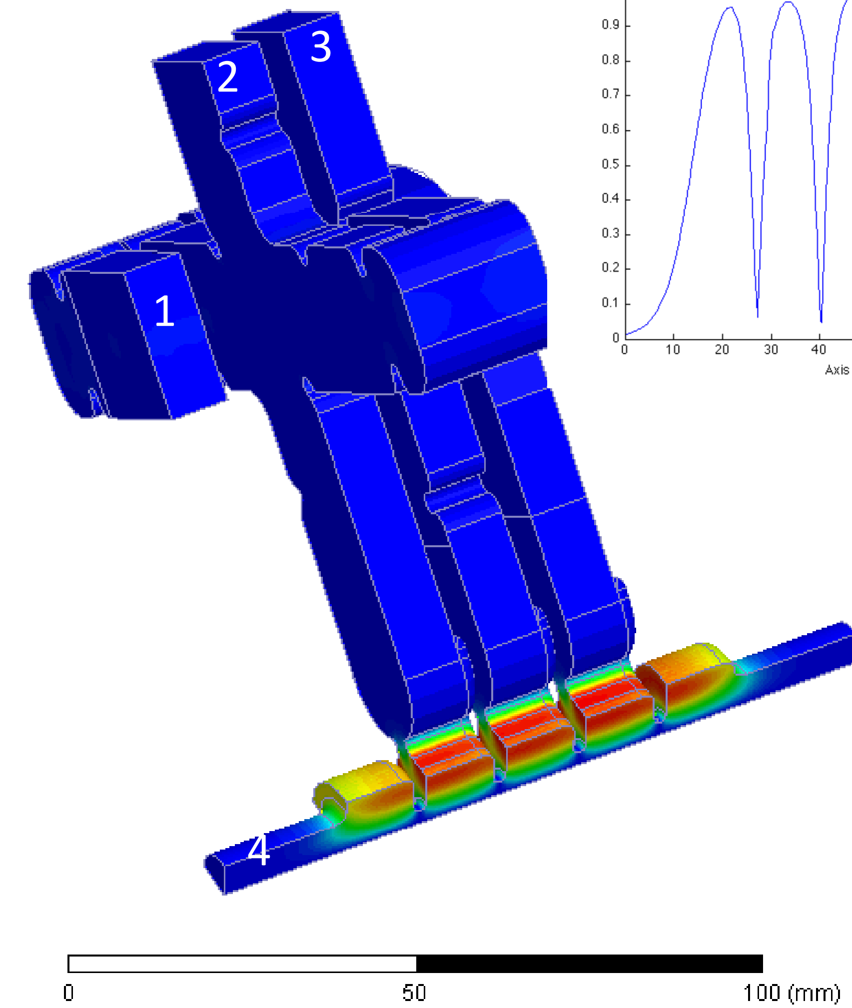




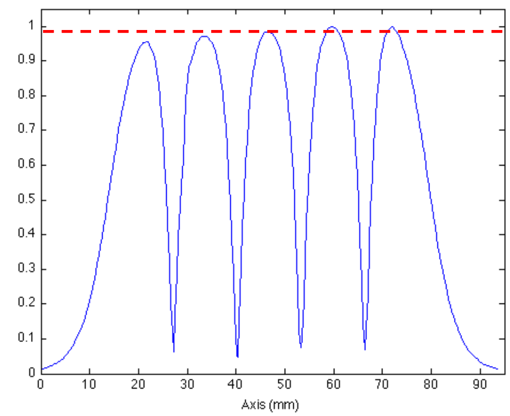
Electric Field

15 MW Input Power
Emax 23MV/m
Hmax 73kA/m

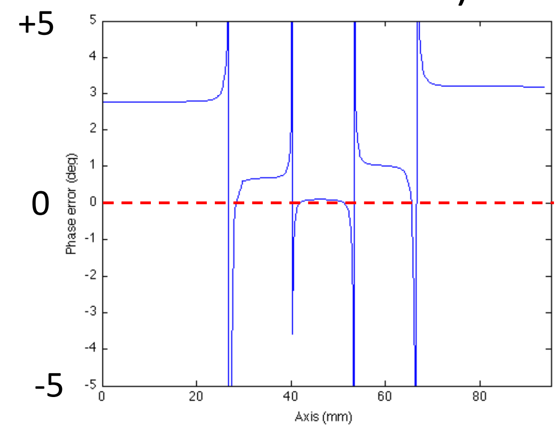
Cavity Driven Through RF Feed (F = 11.424GHz)



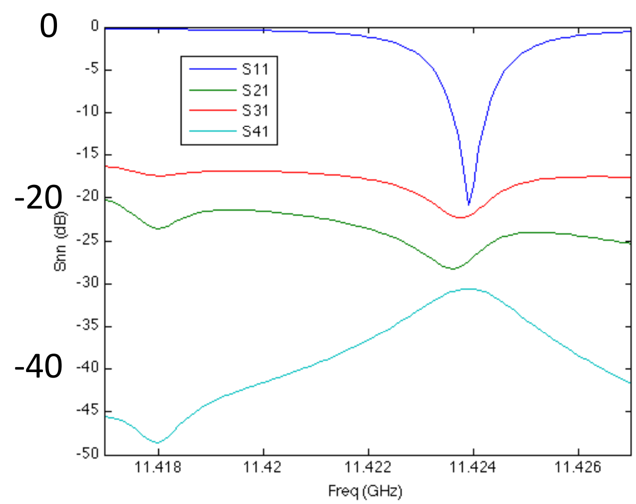
On Axis Field



Phase Error (degrees relative to □ shift)

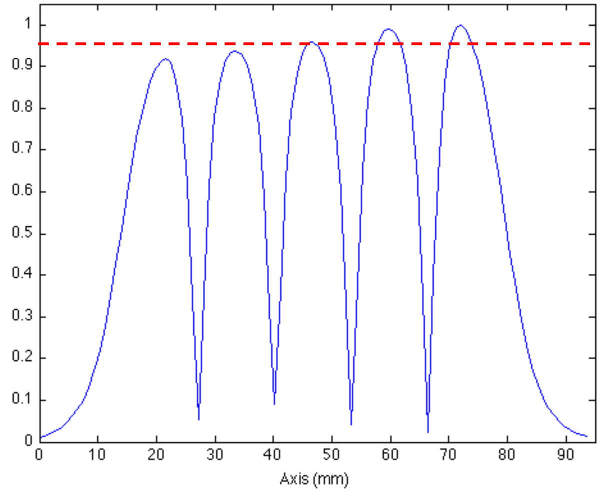


Frequency Response (dB)



Phase Arm Error on Last Cavity Feed (30 Deg)

On Axis Field

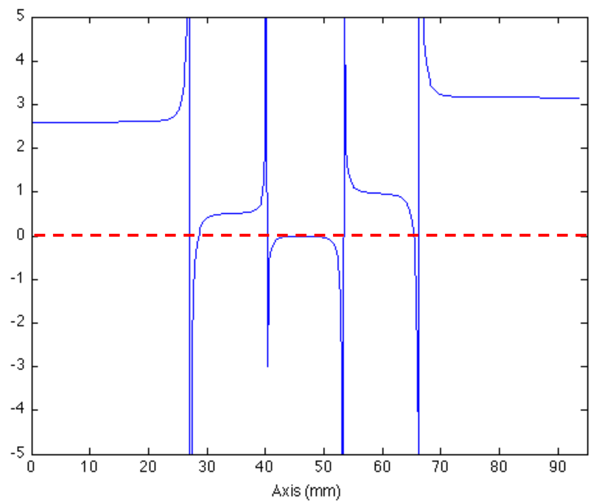


Phase Error (degrees relative to shift)

+5

0

-5

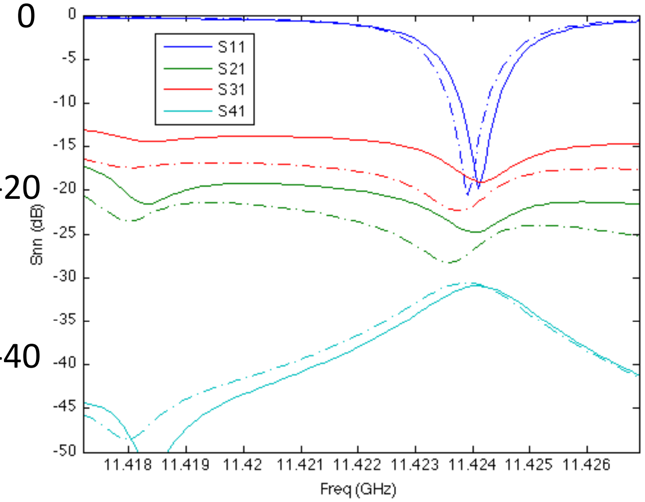


Frequency Response (dB)

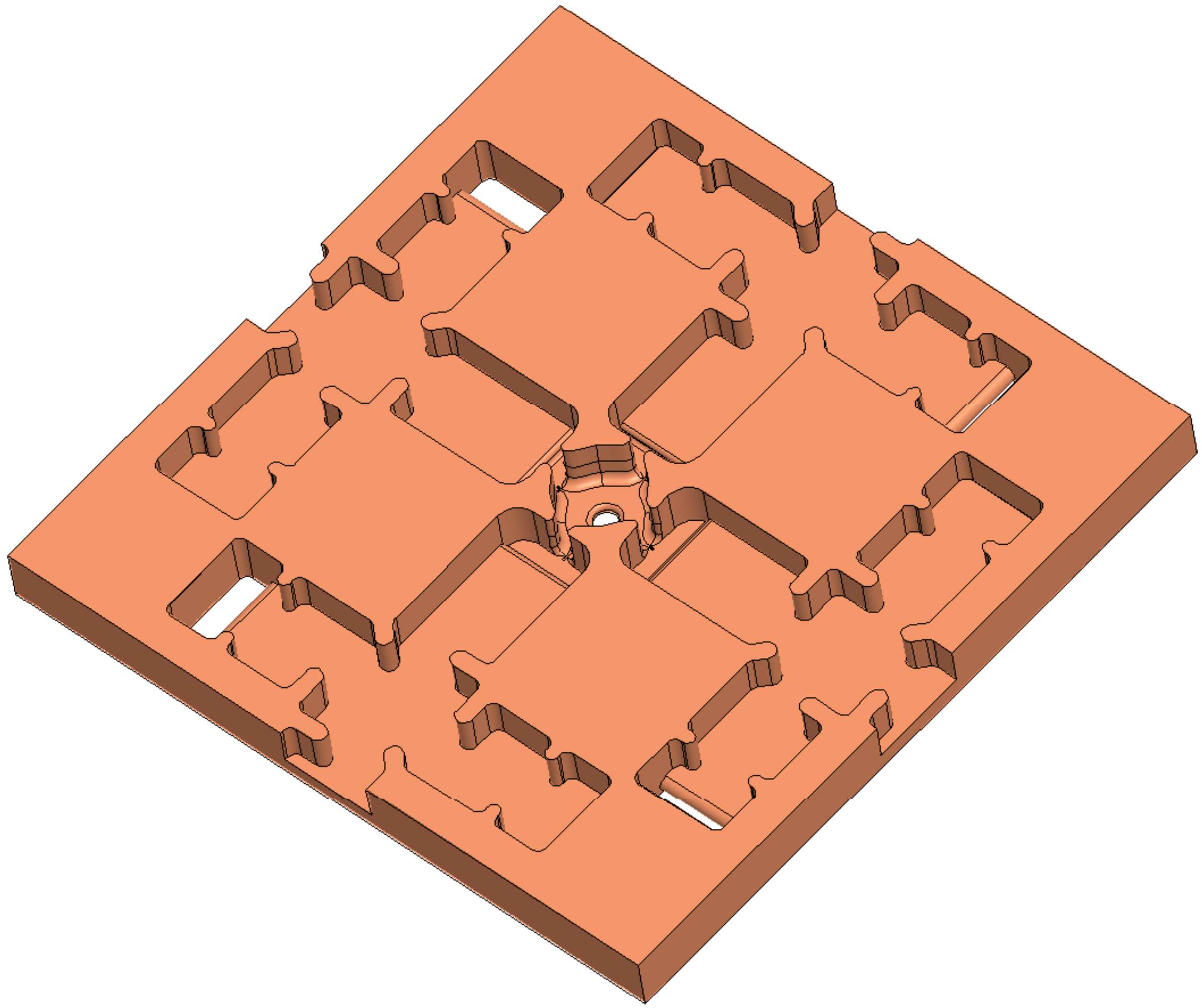
0

-20

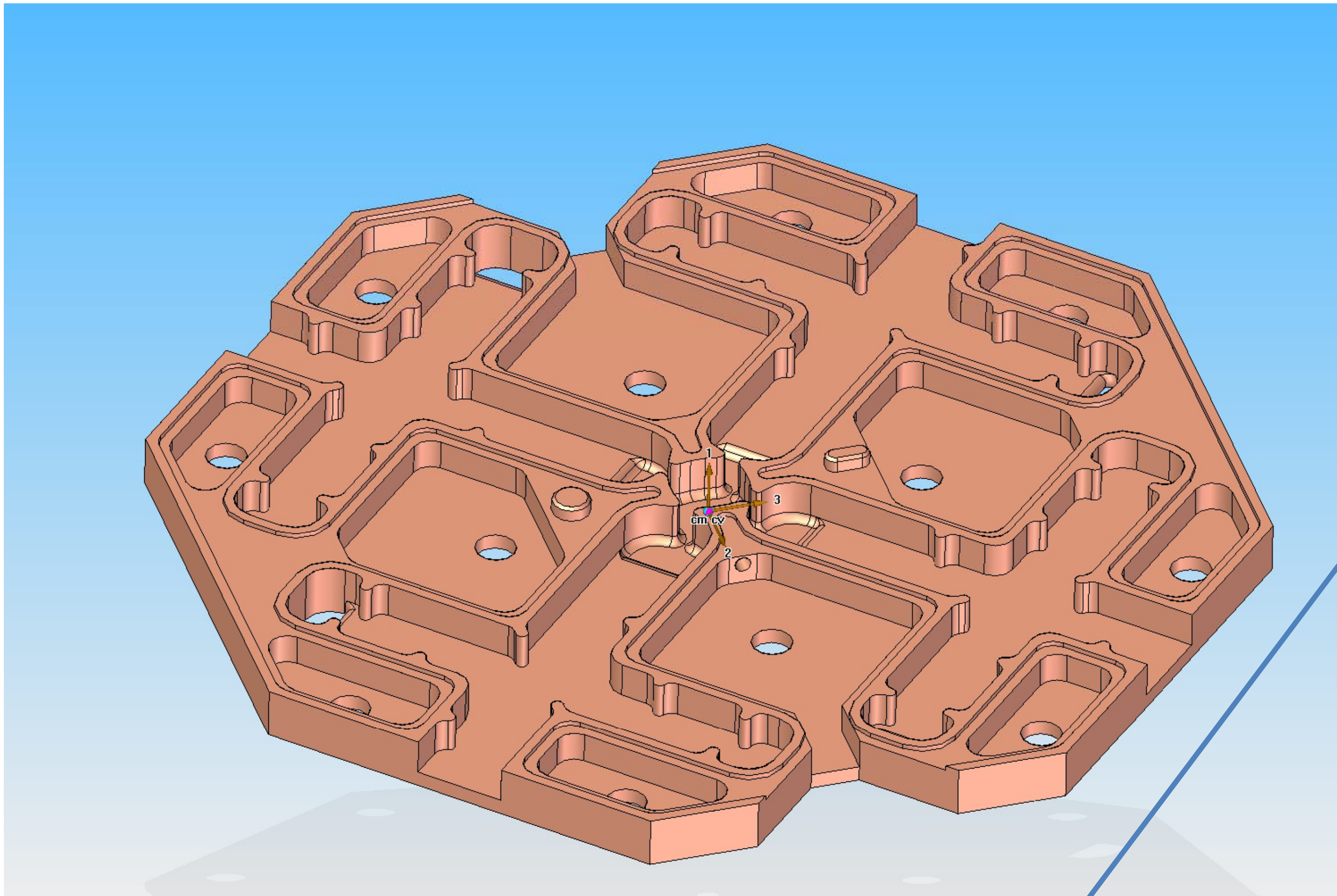
-40



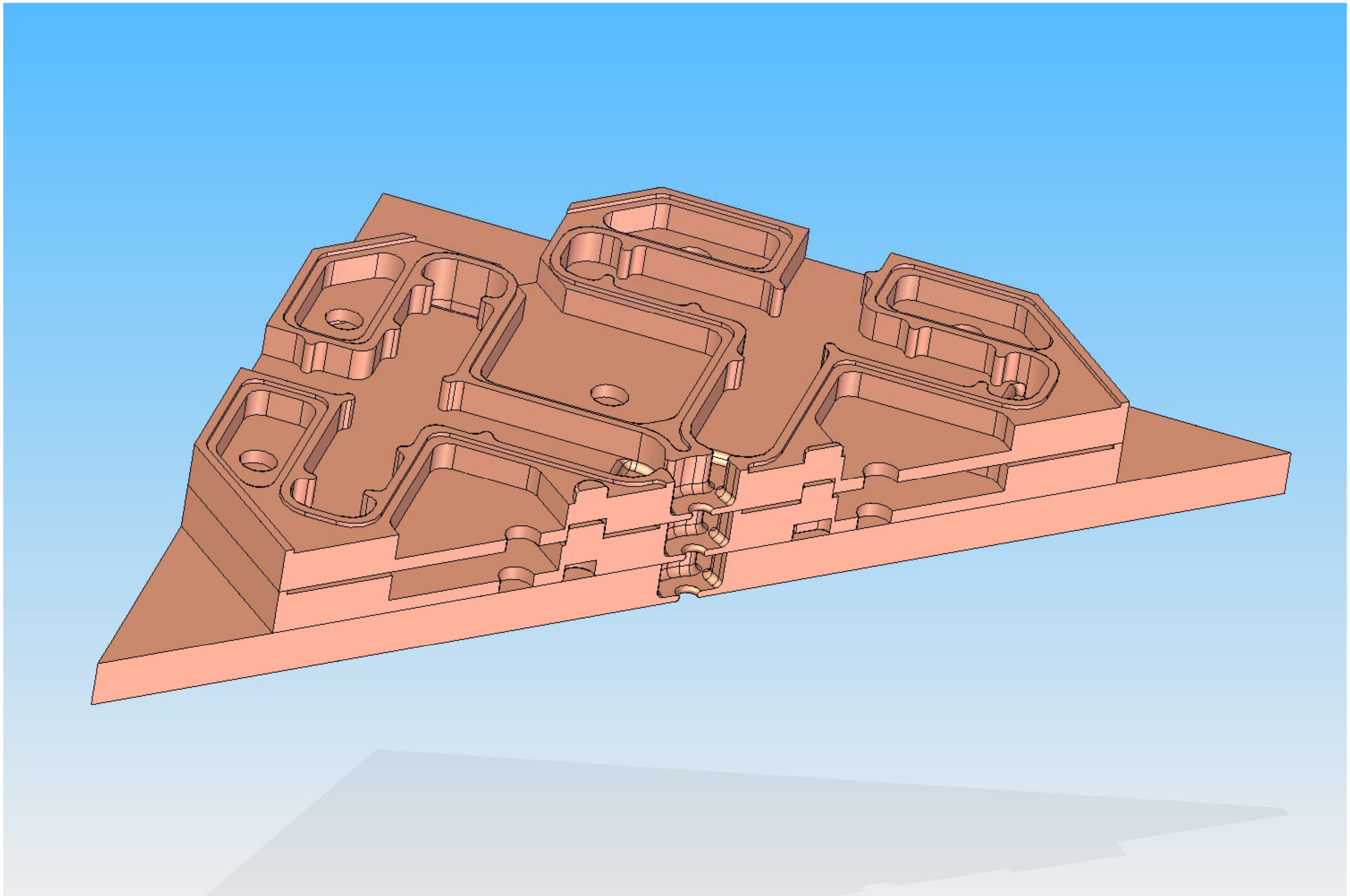
--- no phase error



Current Mechanical Design



~25 cm
2.7 kg



A Design Methodology for High Repetition Rate Low Gradient Structure

- The development of high of the structure efficiency, we had an effort on optimizing the cavity shapes and RF sources
- The shunt impedance is ~ $f^{1/2}$ and the filling time ~$f^{-3/2}$. Hence, *naively* and for a single bunch operation, going from S-band to X-band reduces the average power required by a factor of 16.
- The average power ~ the square of the gradient, hence reducing the gradient from 100 MV/m, achieved at X-band/Ku-band accelerators, to 10 MV/m makes it possible to afford a 100 times the repetition the rate for the same average power handled by the structure at the same pulse length.
- Further accelerating fewer bunches can get us even more gains up to a factor of 4 increase in the repetition rate
- Going to smaller gradient with efficient low power source could be a cost effective solution for a high rep-rate X-FEL.

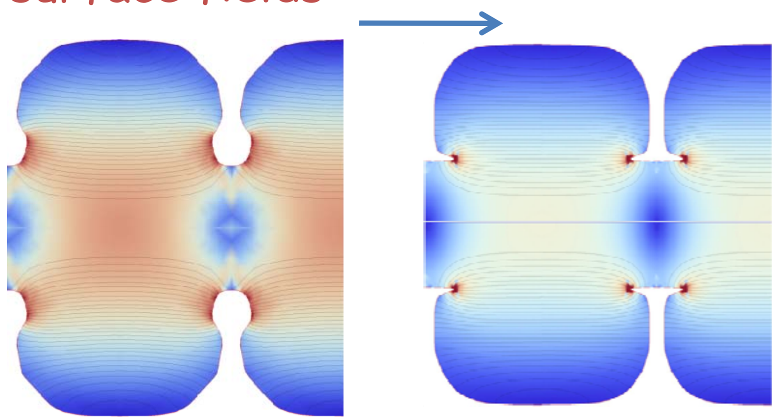
Structure Efficiency

The development of high gradient linacs necessitates the optimization of the structure efficiency:

- High gradient requires high power density/unit length, quadratic with gradient. Hence the two beam choice for the CLIC design
- However, since one also accelerates in shorter length the total required RF power increases linearly with gradient.
- High gradient also implies reduced efficiency; $\eta \sim \frac{x}{1+x}; x = R_s I_0 / E_a$
- However, one can compensate by increasing the efficiency the *accelerator structure* and *RF sources*.
  - Increasing the efficiency of the accelerator structure would reduce the power/unit length.
  - Higher efficiency RF source and accelerator efficiency imply lower RF system cost

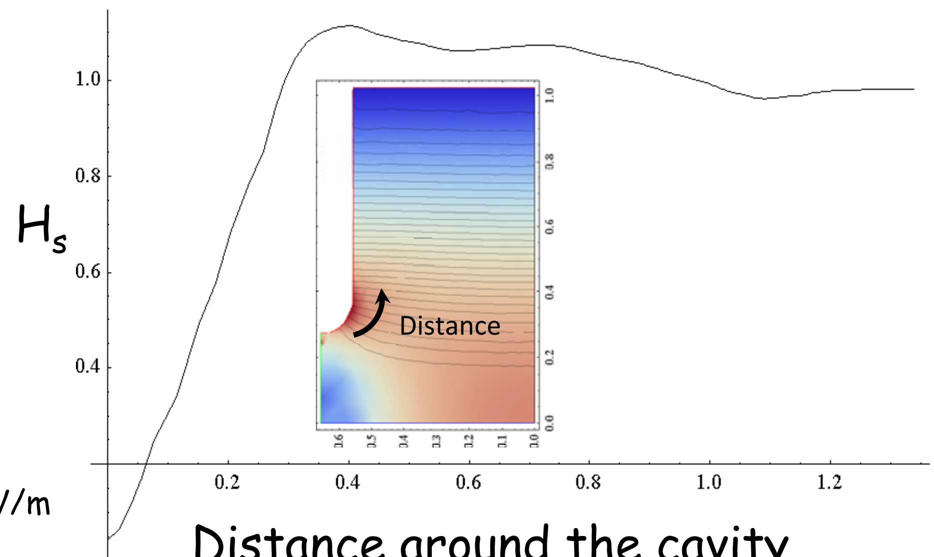
Optimization of Accelerator structure continued

These optimizations were done for a 100MV/m accelerator structures. Better efficiency could be obtained if one let go of the constraints imposed by the surface fields



Shunt Impedance 104 MΩ/m
Quality Factor 9778
Peak E_s/E_a 2.41
Peak Z_0H_s/E_a 1.12

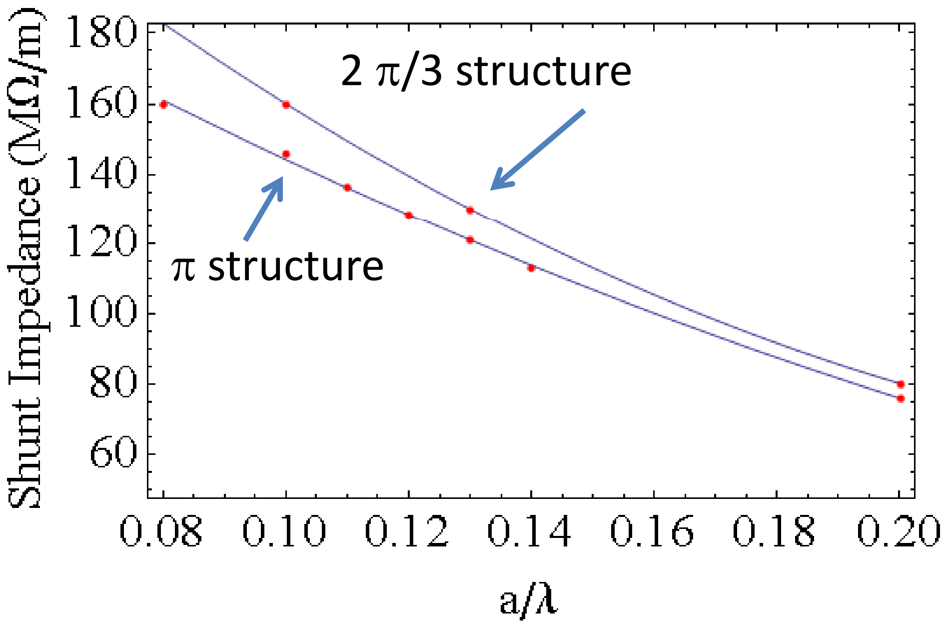
Shunt Impedance: 111 MW/m
Quality Factor :9358
Peak E_s/E_a :7.04
Peak Z_0H_s/E_a :1.11



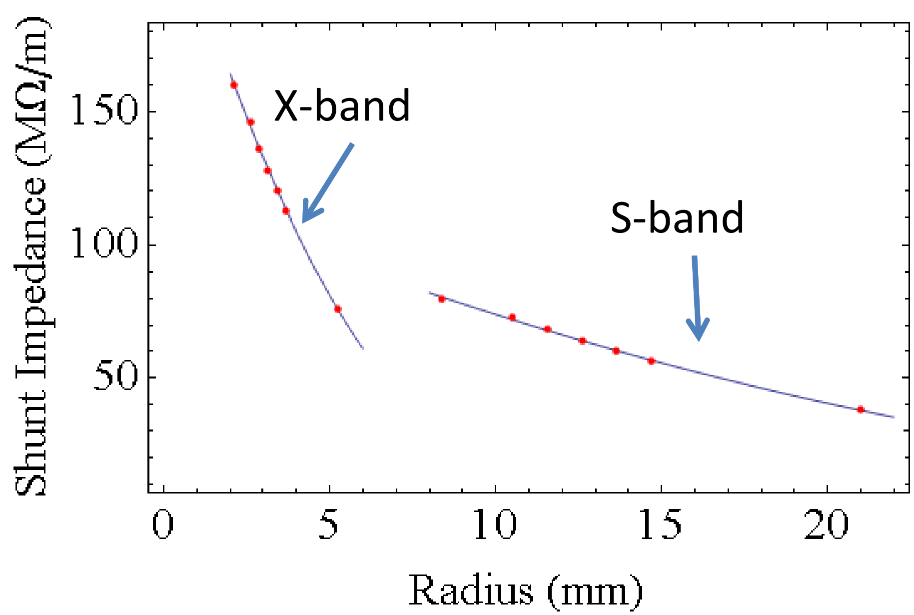
Distance around the cavity surface

- Shunt Impedance increased by about 7%. The increase in shunt impedance at lower a/l is up to 13 %.
- The only constraint on the optimization is that the minimum iris thickness is 1 mm

Shunt Impedance of Independently Coupled Cells

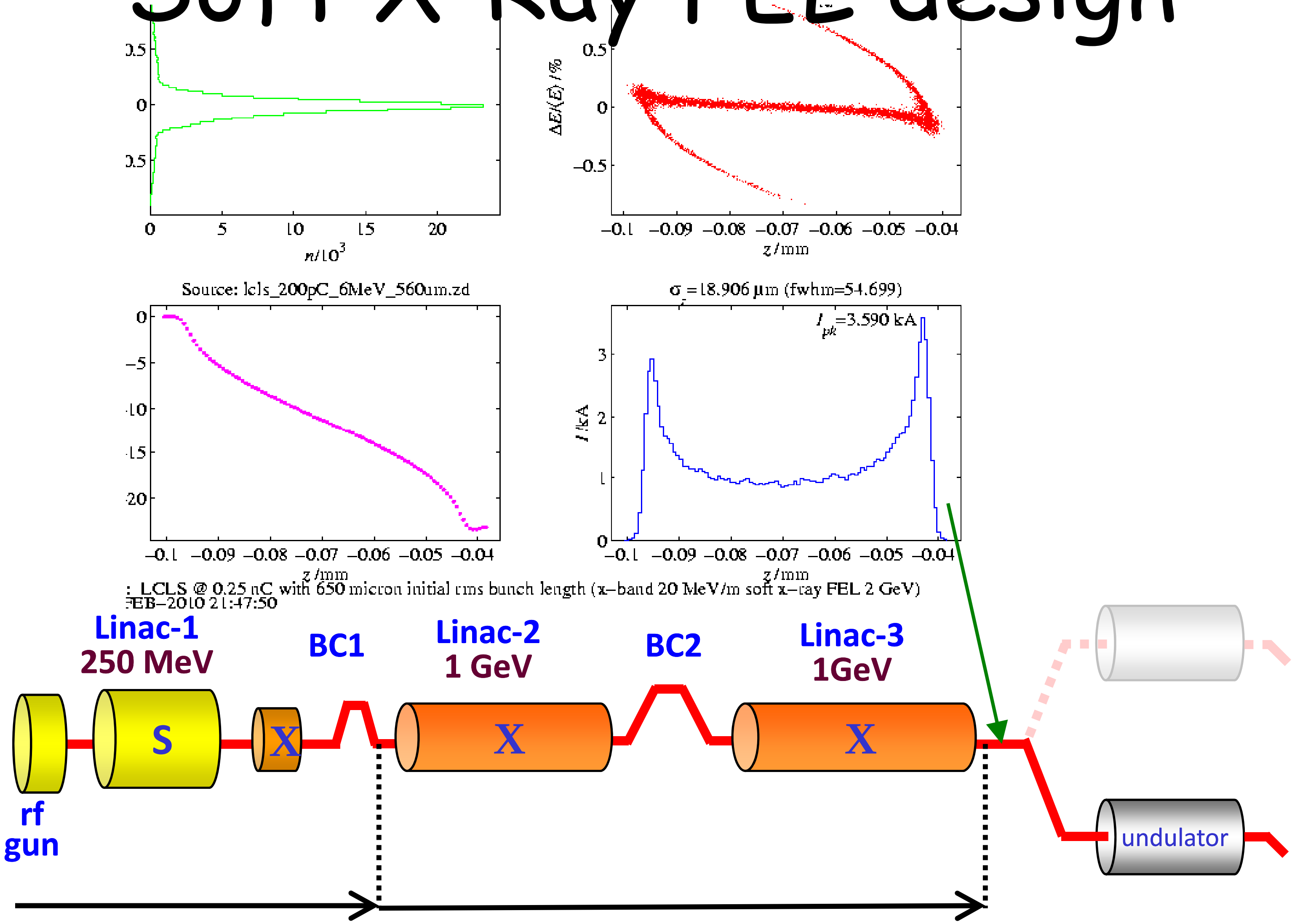


π structure



To take advantage of the high shunt impedance of the high frequency structure one has to be able to operate with small aperture.

Soft X-Ray FEL design



LCLS-like injector

L~50 m

250 pC, $\gamma\varepsilon_{x,y} \approx 0.4\ \mu m$

X-band main linac+BC2

G~20 MV/m, L~100 m

Zhirong Huang

Compact X-FEL using X-band Accelerators

- Simulation done with LiTrack
- LCLS s-band injector + x-band harmonic cavity before BC1 and a bunch charge 250 pC.
- adjusted x-band harmonic cavity phase to make the phase space more linear after compression.
- x-band gradient 20 MV/m with a/lambda =0.13, and implemented another BC (BC2) at 1.25 GeV with R56=22 mm.
- LiTracksimulation of longitudinal phase space at 2 GeV final point looks quite nice with a flat energy distribution and ~1 kA for the bunch core, should be sufficient for soft x-ray SASE FEL and may be OK for seeded FEL.
- Tried a/lambda=0.1 with the same gradient, the longitudinal phase space looks a bit worse but still tolerable.

Zhirong Huang

Transverse Wakes

1. *Fit equation for wakefield of disk loaded structure. For average cell a/λ*

$$W_x(s) = \frac{4Z_0 c s_0}{\pi a^4}\phi(s)\left[1 - \left(1 + \sqrt{\frac{s}{s_0}}\right)\exp\left(-\sqrt{\frac{s}{s_0}}\right)\right]$$

K. Bane, SLAC-PUB-9663, 2003

$$s_0 = 0.169\frac{a^{1.79}g^{0.38}}{L^{1.17}} \ .$$

2. *Calculate the beam breakup parameter and the corresponding emmitance growth*

$$\mathrm{Y} = \frac{g\left(\frac{e_f}{e_0}\right)\left(\mathrm{eN}l < W > \beta_0\right)}{2e_0}; g(x) = \frac{\ln(x)}{x-1}$$

Chao, Richter, Yao

$$for \ \ \mathrm{Y} << 1$$

$$\frac{\delta \grave{o}}{\grave{o}} = \frac{x_0^2 \mathrm{Y}^2}{2\sigma_{x_0}^2}$$

Transverse Wakes Continued

- For 20 MeV/m 250 pc of charge, $a/\lambda=0.13, \beta=10m$
  - $Y=1.2$ for the first Linac
  - $Y=0.2$ for the second Linac
- For 20 MeV/m 250 pc of charge, $a/\lambda=0.10, \beta=10m$
  - $Y=3.1$ for the first Linac
  - $Y=0.5$ for the second Linac
- For 10 MeV/m 250 pc of charge, $a/\lambda=0.10, \beta=10m$
  - $Y=6.4$ for the first Linac
  - $Y=0.9$ for the second Linac
- For 10 MeV/m 250 pc of charge, $a/\lambda=0.20, \beta=10m$
  - $Y=0.5$ for the first Linac
  - $Y=0.07$ for the second Linac

Average Power Considerations

We make the following assumption

- Operating gradient of 20 MV/m
- Shunt impedance 120 M Ω/m for an accelerator structure with a/λ=0.13
- Pulse length~ 2 x the structure filling time
- Repetition rate~ 5kHz
- 3-MW/meter

- Average power/m for the accelerator structures is ~4 kW. This is to be compared with a bout ~2 kW/m in X-band high gradient structures running at gradients close to 100 MV/m.
- For the klystrons, the state-of-the art is the XL-4 klystrons which operate routinely with 4.5 kW of average power and peak power of 50 MW, dropping the peak power to 3 MW with the same average power should reduce the cost and sustainably make these devices extremely reliable.
- One can also accelerate > 10 bunches for an effective repetition rate of 50 KHz. The bunch separation ~ 10 ns should be reasonable with the proposed local wake field damping.

Average Power Considerations (low charge)

We make the following assumption

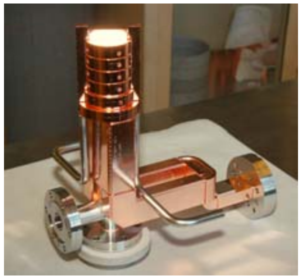
- Operating gradient of 10 MV/m
- Shunt impedance 145 M Ω/m for an accelerator structure with $a/\lambda=0.1$
- Pulse length~ 2 x the structure filling time
- Repetition rate~ 25kHz
- 690 kW/meter

- Average power/m for the accelerator structures is ~4 kW. This is to be compared with a bout ~2 kW/m in X-band high gradient structures running at gradients close to 100 MV/m.
- For the klystrons, the state-of-the art is the XL-4 klystrons which operate routinely with 4.5 kW of average power and peak power of 50 MW, dropping the peak power to 690kW with the same average power should reduce the cost and sustainably make these devices extremely reliable.
- One can also accelerate > 10 bunches for an effective repetition rate of 250 KHz. The bunch separation ~ 10 ns should be reasonable with the proposed local wake field damping.

X-BANDGUN HISTORY

1. "Compton Gun": 5.5 cell (2003)
   - Developed as driver for Compton Source
     SLAC klystron department + UC Davies
   - Demonstrated 200MV/m peak field
     (with "manageable" dark current 16 pC/RF cycle)
2. Mark-0 : 5.5 cell (assembled Jan. 2011)
   - Includes racetrack shape coupling cell
   - Cold-tested and tuned (April 2011)
   - Hot tests (July 2011)
3. Mark-1 gun (fabrication Aug. 2011)
   - increased ½ cell to ~0.6 (better for 200MV/m , 250 pC)
   - mode separation increased to 25 MHz
   - elliptical irises

A.Vlieks



X-BAND VS S-BAND

- X-Band injector performances vs those from LCLS Injector
  - 250 pC much better emittance ε, bunch length /3
  - 20 pC emittance ε/2, bunch length/ 2

Predictions for X-Band gun (ASTRA Simulations)

Q [pC]	$\varepsilon_{x,100\%}$, $\varepsilon_{x,95\%}$ [mm-mrad]	σ_l [mm]	B_{peak}= $Q/\sigma_l/\varepsilon_x/1e3$
250	0.38/0.25	0.228	4.39
250	0.42/0.28	0.184	4.85
20	0.1/0.075	0.109	2.44
10	0.092/0.076	0.055	2.39
10 (*)	0.140/0.118	0.042	2.01
1	0.022/0.016	0.080	0.78
1	0.042/0.036	0.025	1.11

LCLS Injector Measurements

Q [pC]	$\varepsilon_{x,95\%}$ [mm-mrad]	σ_l [mm]	B_{peak}= $Q/\sigma_l/\varepsilon_x/1e3$
250	0.40	0.62	1.01
20	0.15	0.22	0.61

LCLS Injector Simulations (ASTRA)

Q [pC]	$\varepsilon_{x,100,95\%}$ [mm-mrad]	σ_l [mm]	B_{peak}= $Q/\sigma_l/\varepsilon_x$ /1e3
250	0.67/0.4	0.61	1.02
20	0.19/0.14	0.32	446

- 10 pC calculations show very promising performances for compact X-Band FEL

Start-to-End : 2fs, 20GW, 6GeV, 200m, no linearizer

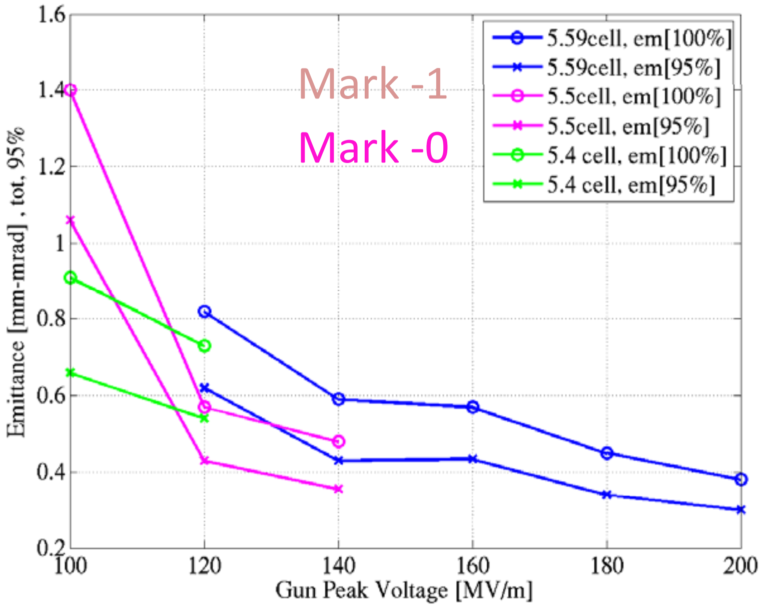
[Submitted Phys Rev. ST Y.Sun, et al.]

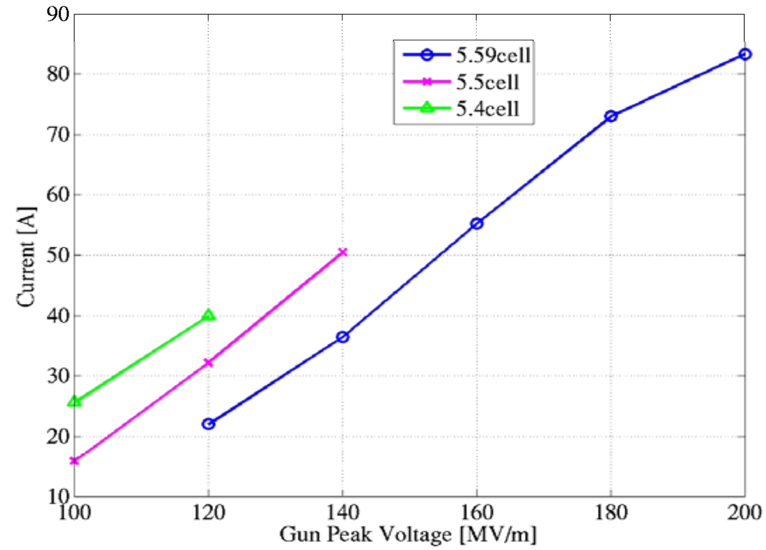
PROMISING RESULTS AT REDUCED V_{rf}

Operation with < 140 MV/m

still very good emittance

attractive for multibunch operation (Compton sources, FELs)



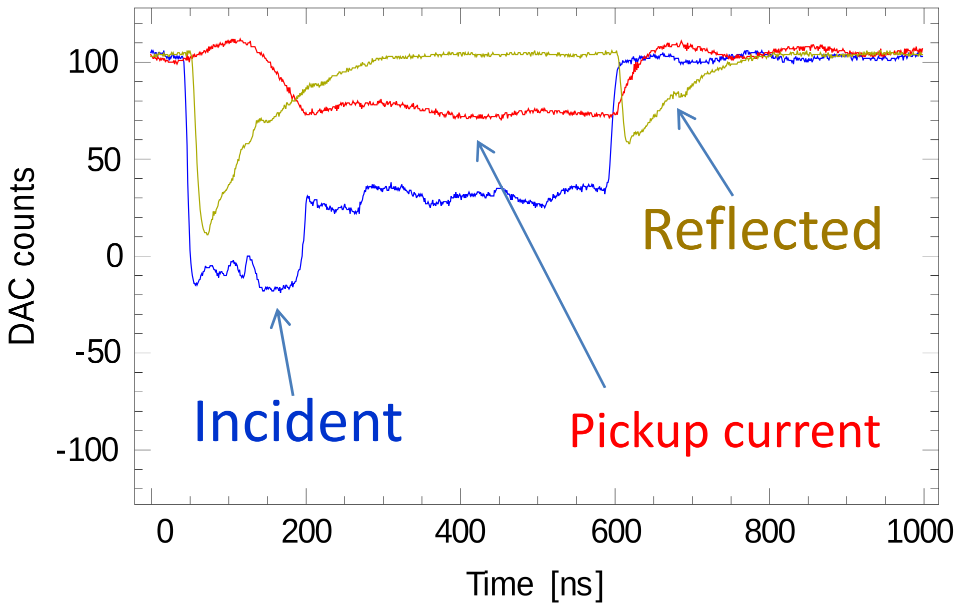


Simulations (ASTRA) for 100 pC

[published C.Limborg, PAC 11]

RF signals for breakdown in single-cell-SW structure

1C-SW-A3 .75-T2 .6-6N-HIP-Cu-KEK-#1



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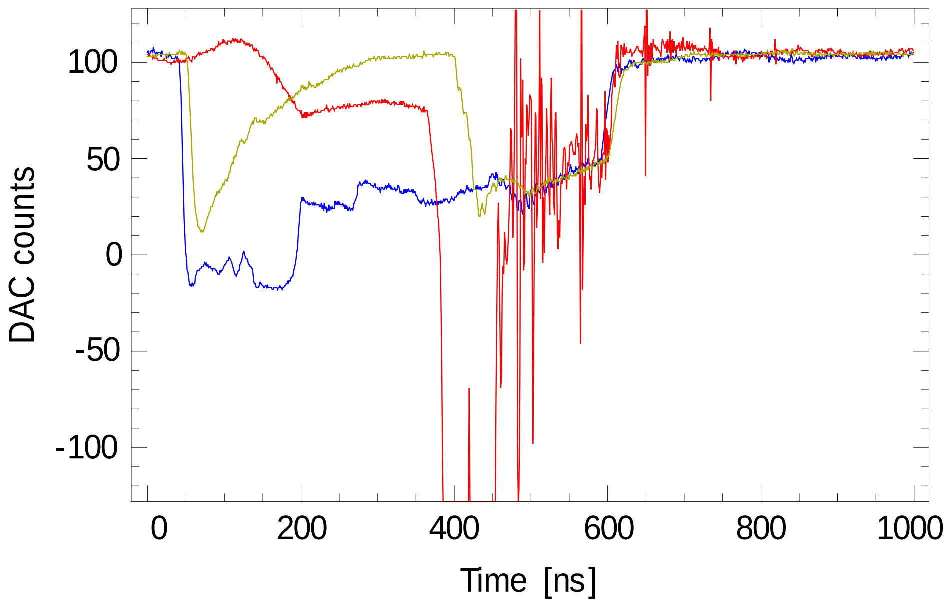

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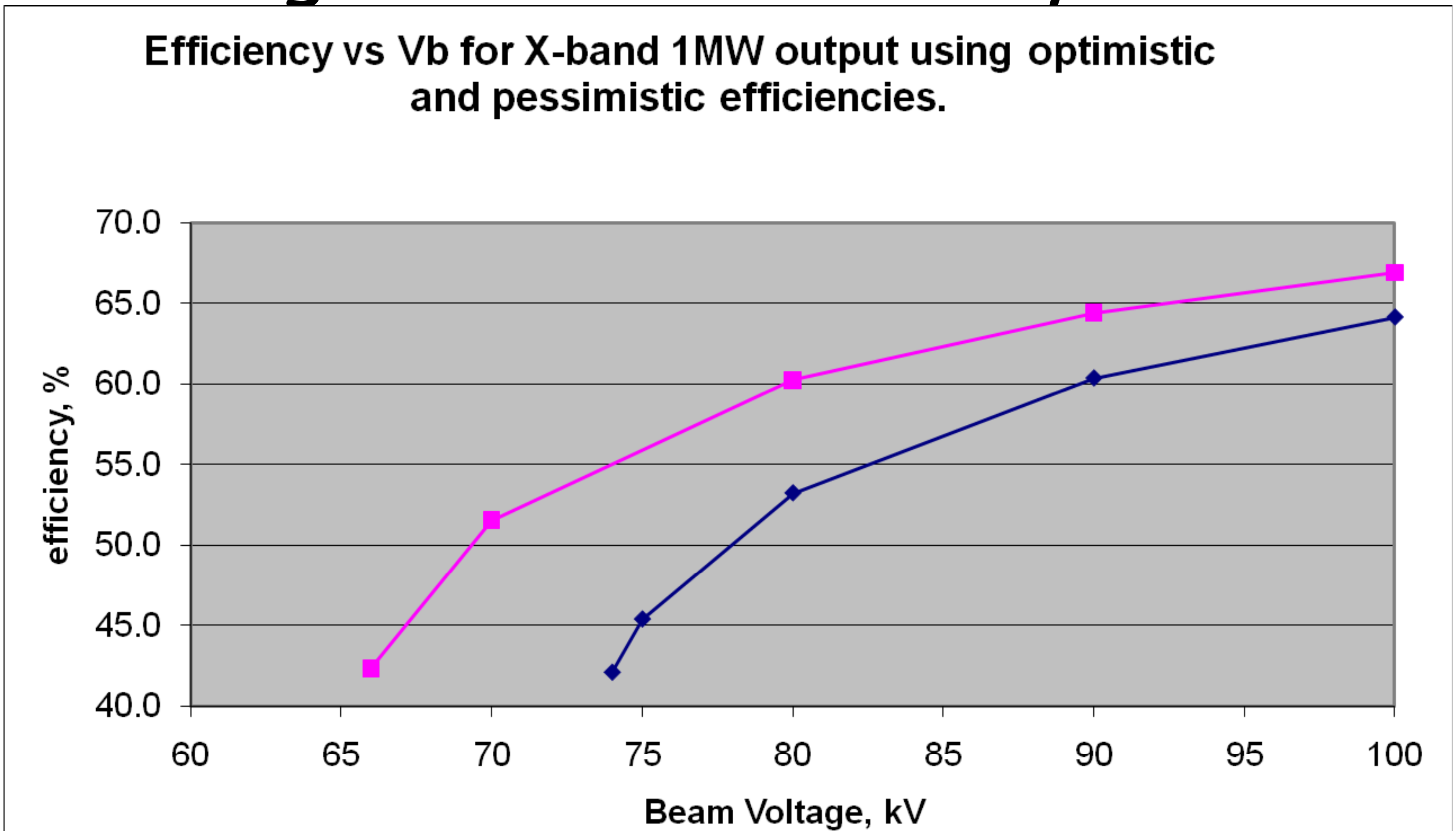
RF source Requirements

- To take advantage of the small filling time of the high frequency structure, one has to be able to switch and manipulate the RF pulse without loss of efficiency
  - This implies Low voltage high efficiency sources
  - Current manipulation
  - The common wisdom requires RF pulse compression but one losses efficiency because of the pulse compressor

Klystron and Modulators

- Case 1: 20 MV/m and $a/\lambda=0.13$
  - RF average power at 5 kHz = 4kW
    - XL-4 at 50 MW, η=40%, 60 Hz, 1.5 μs = 4.5 kW avg RF power
    - The XL-4 is more peak power limited rather than average
  - For a 100 kV 3 MW Klystron(η=42%, and assuming a generous rise and fall time to ease the design of the modulator) :
    - beam average power at = 9.5 kW
    - XL-4 beam average power (at 60 Hz)= 11.2kW
    - The XL-4 has run at 120 Hz (22.4 kW avg beam power),
  - Modulators need to supply the average power, the state of the art of solid state modulators supply power for 4-XL4 klystron simultaneously, i.e., average power of 18 kW at 400 kV. This is to be compared with 1 kW at 74kV.

single-beam X-band klystron



For single beam devices we need to operate ~70 kV or above since the efficiency quickly falls off below that beam voltage. This is to be compared with 400kV for the XL-4 device (which represent the state of the art in X-band tubes)

Curtsy of Daryl Sprehn and Erik Jongewaard

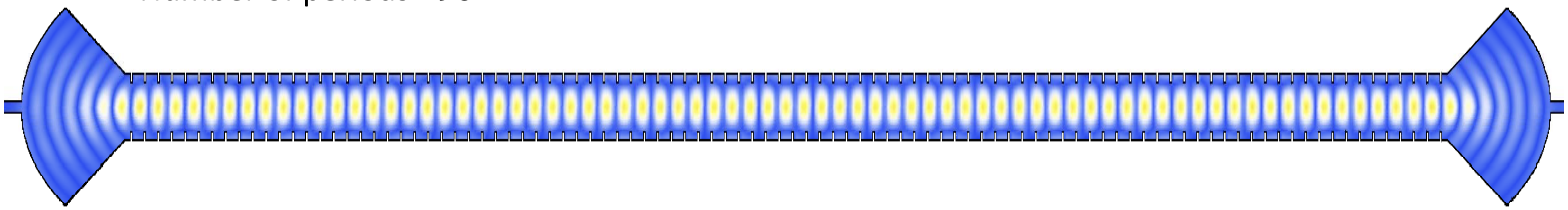
On Going Development/Future work on RF Sources

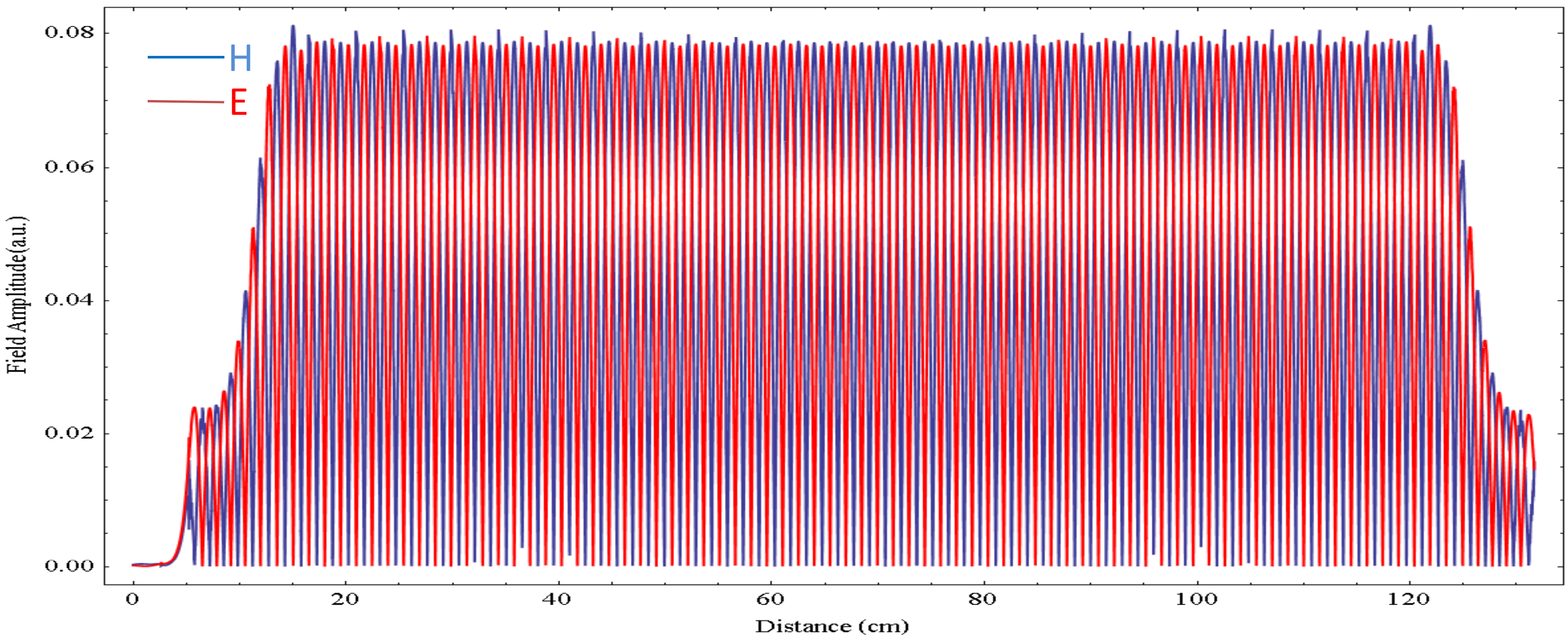
- New Ideas for highly efficient RF sources with extremely low voltages and integrated modulators are being developed by S. Tantawi/R. Ruth
- The design philosophy will allow for pulse shaping without loss of efficiency
- This is quit different than the *common wisdom* that uses ultra-high power klystrons coupled with pulse compressors

RF Undulator Design (WEPB07)

Corrugation Period=0.4254 λ
Inner Radius=0.75 λ
Outer radius= 1.01293 λ
Corrugation Thickness= λ/16
Number of periods =98

λ=2.6242296 cm
Undulator Wavelength=1.39306 cm
Power required (for linearly polarized, K=1)=48.8 MW
Q0=94,000





Conclusion

- Room Temperature accelerator structures can be optimized for efficiency with the use of parallel feeding structure.
- The common wisdom that depends on extremely high power klystrons coupled with pulse compression system would be very useful for high gradient short structures to derive FEL, still new development are needed to make them work at high repetition rate
- Our design philosophy for relatively low gradient high repetition rate require a new look at RF sources and system architecture, without pulse compression.
- New RF sources with low voltage high efficiency and special pulse shaping are under development