Room Temperature High Repetition Rate RF Structures for Light Sources

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SLAC

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Outline

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

Motivation

- The development of high gradient linacs necessitates the optimization 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 coupld 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:

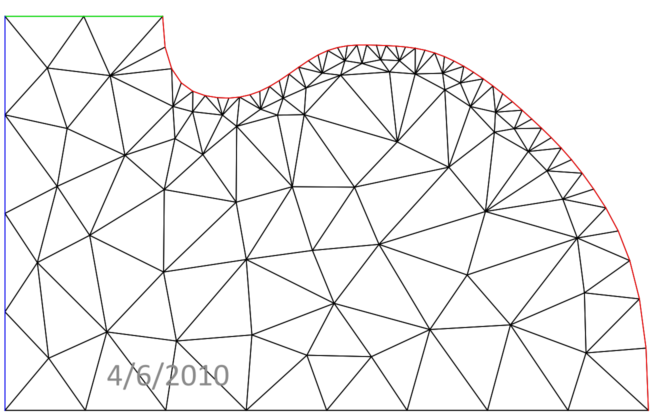
- High gradient requires high power density/unit length, quadratic with gradient. Hence the two beam choice for the CLIC design
- However, since one also accelerates in shorter length the total required RF power increases linearly with gradient.
- High gradient also implies reduced efficiency; $\eta \sim \frac{x}{1+x}; x = R_s I_0 / E_a$
- 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

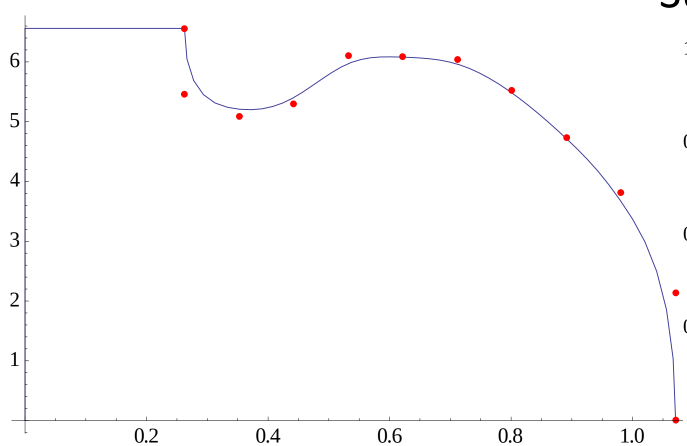
Yet another Finite Element Code

Motivated by the desire

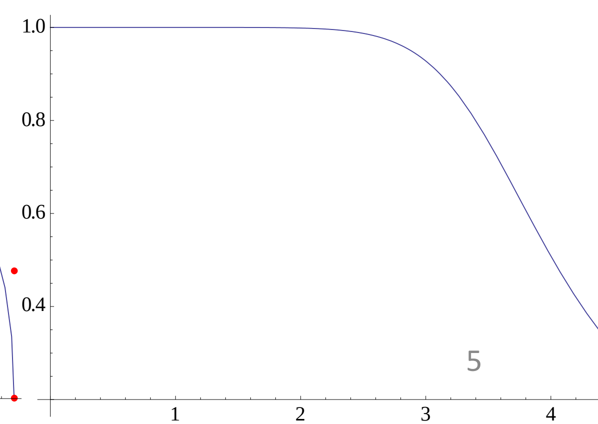
- to design codes to perform *Large Signal Analysis* for microwave tubes (realistic analysis with short computational time for optimization)
- study surface fields for accelerators
- the need of a simple interface so that one could "play"

- 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



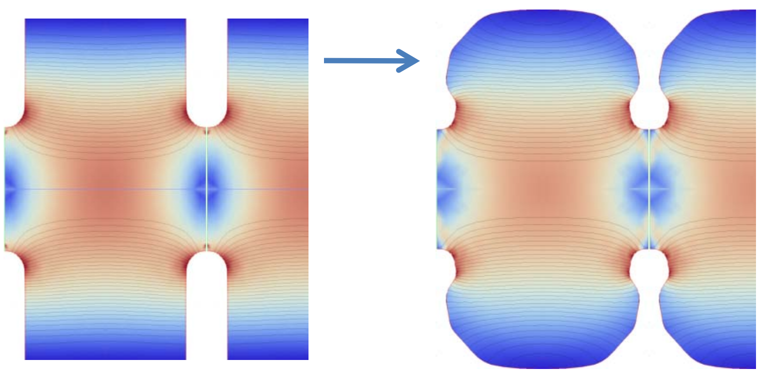


Surface field penalty function



Iris shaping for Standing-Wave π-mode structures

$a/\lambda=0.14$



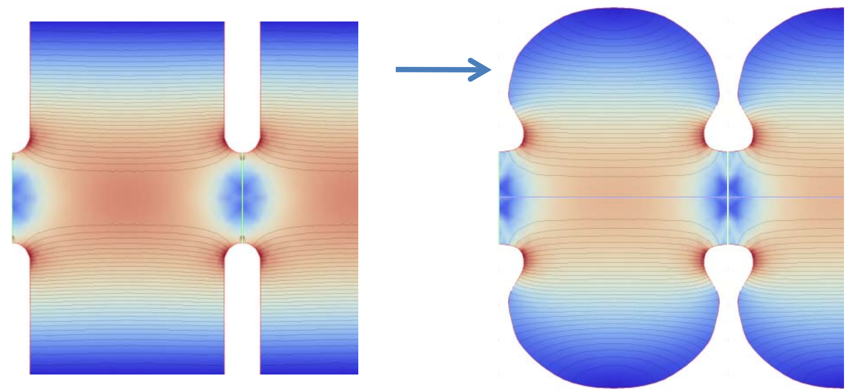
Shunt Impedance	83 MΩ/m
Quality Factor	8561
Peak E_s/E_a	2.33
Peak Z_0H_s/E_a	1.23

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

For the optimized structure:

- With 1 nC/bunch and bunch separation of 6, and loaded gradient of 100 MV/m rf cycles the RF to beam efficiency~70%
- The power required/m~287 MW

$a/\lambda=0.1$



Shunt Impedance	102 MΩ/m
Quality Factor	8645
Peak E_s/E_a	2.3
Peak Z_0H_s/E_a	1.09

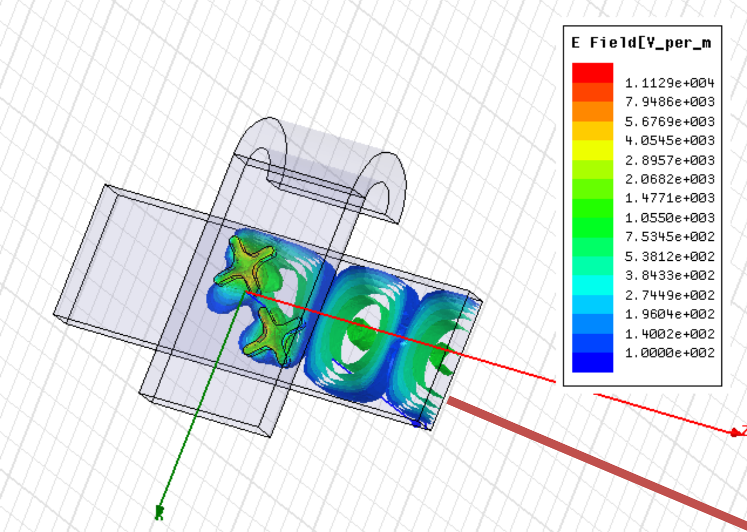
Shunt Impedance	128 MΩ/m
Quality Factor	9655
Peak E_s/E_a	2.5
Peak Z_0H_s/E_a	1.04

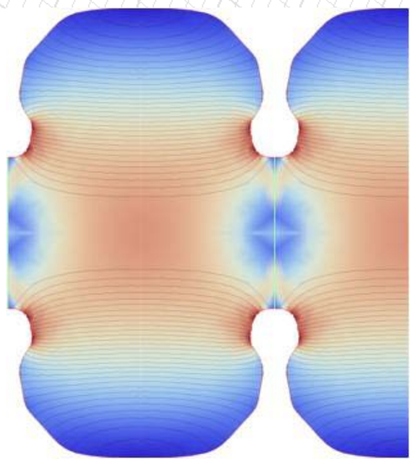
For the optimized structure:

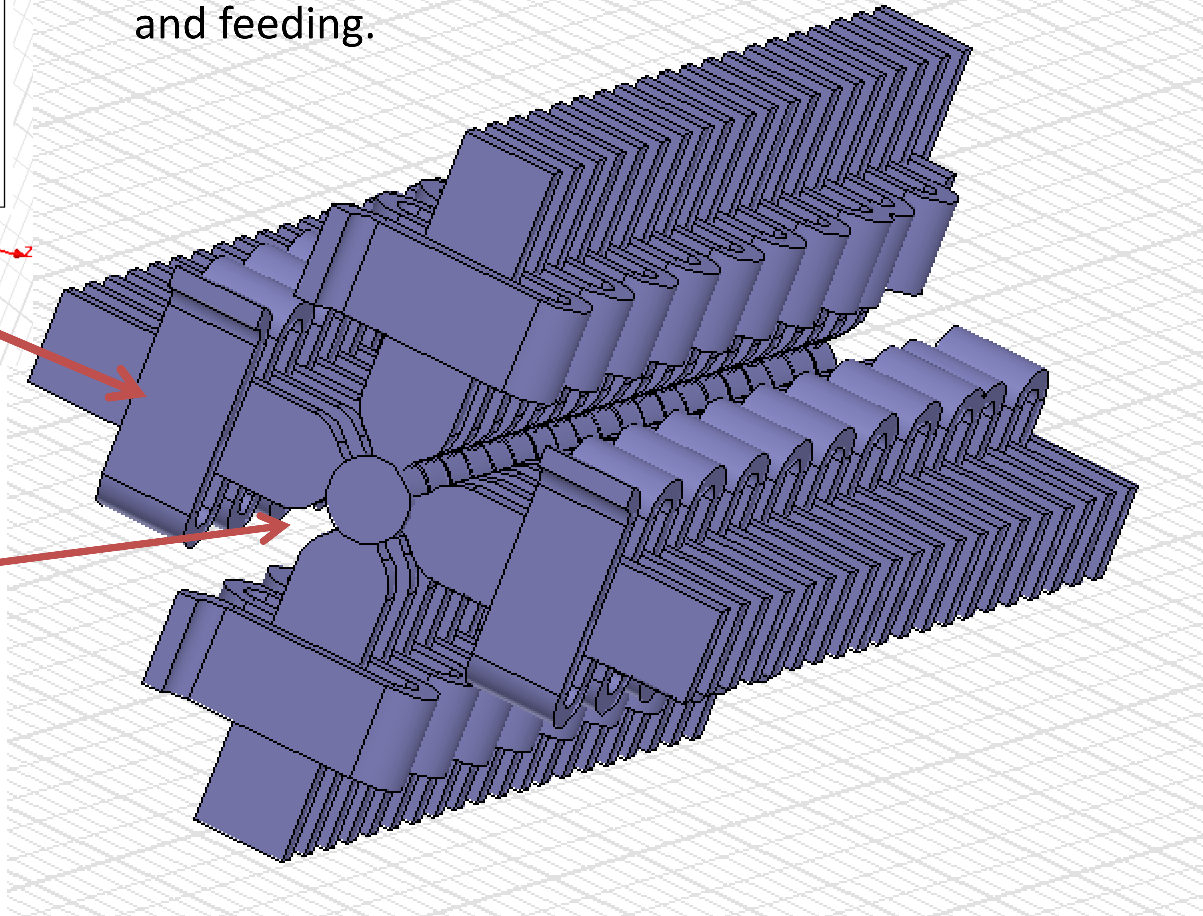
- With 0.5 nC/bunch, bunch separation of 6 rf cycles, and loaded gradient of 100 MV/m the RF to beam efficiency~53%
- The power required/m~173 MW

- For 10 MV/m the required power is 780kW/m
- Filling time for critically coupled structure (negligible beam loading) 134 nS

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



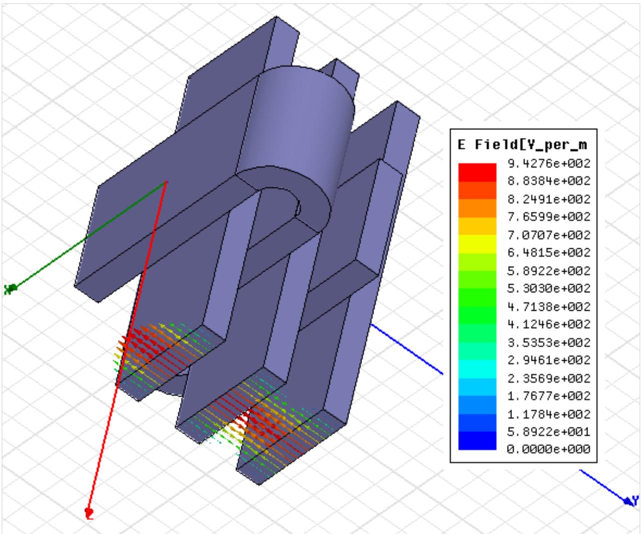


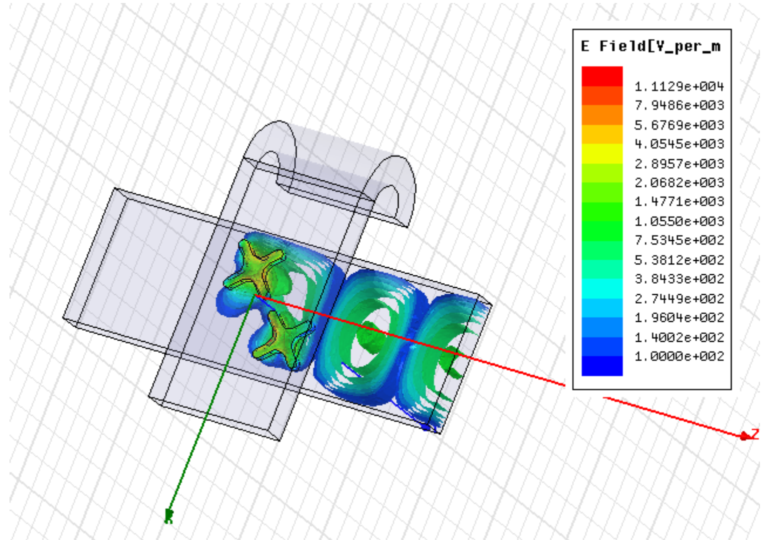


•This is proposed for an efficient high gradient linac for application to a warm collider. If one let go of the restrictions imposed by wake fields, the RF distribution system and cell feeding could be done with much more simpler structure

Jeff Neilson

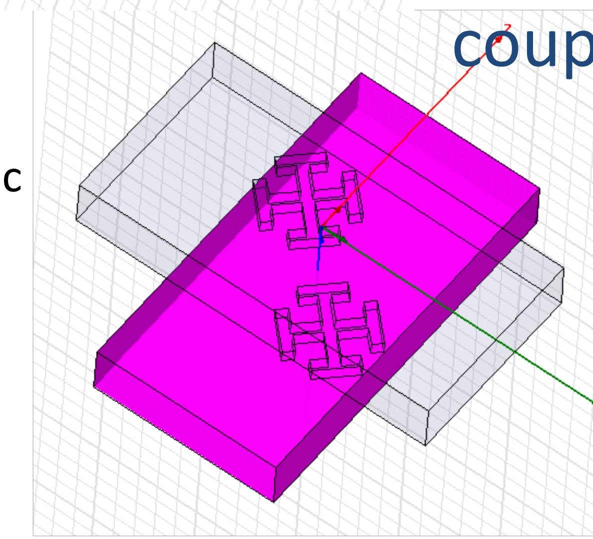
Feeding and wake field damping





-12-dB coupler

-3-dB coupler



Assuming 280 MW/m (for an accelerator loaded with 1 nc bunches with 6 rf cycles sepration) 80 cells.

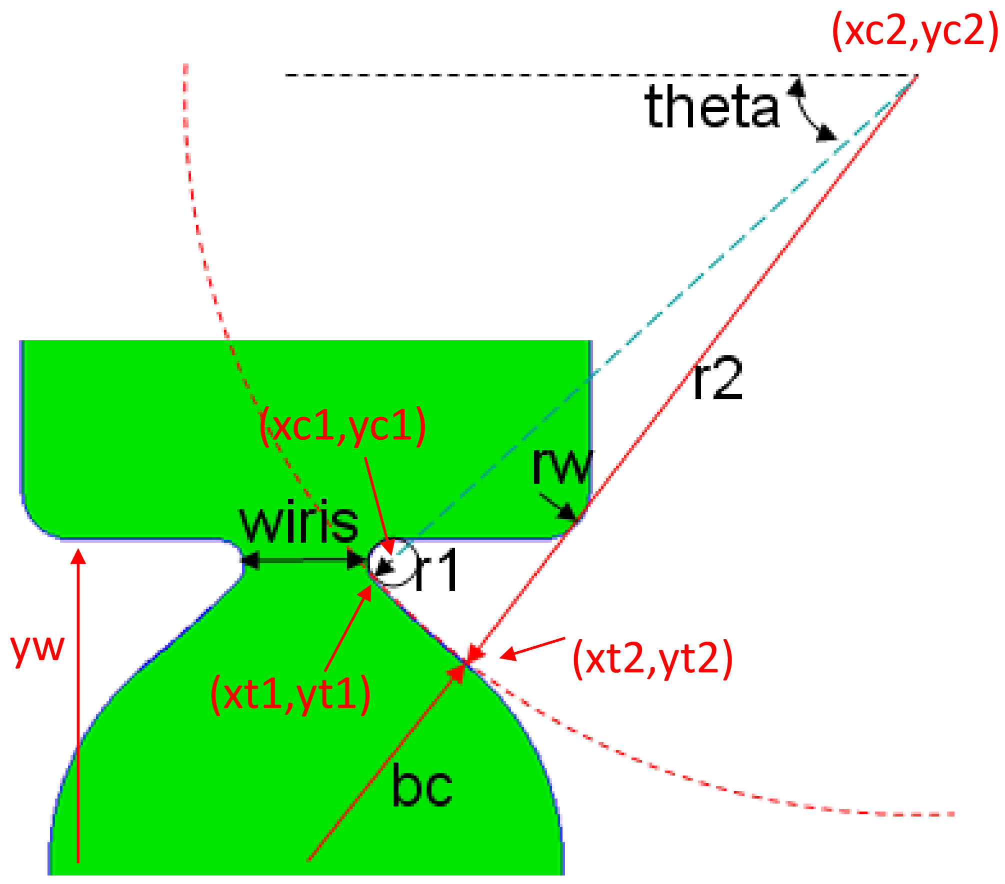
Four groups (20 cells/group) so 70 MW per group

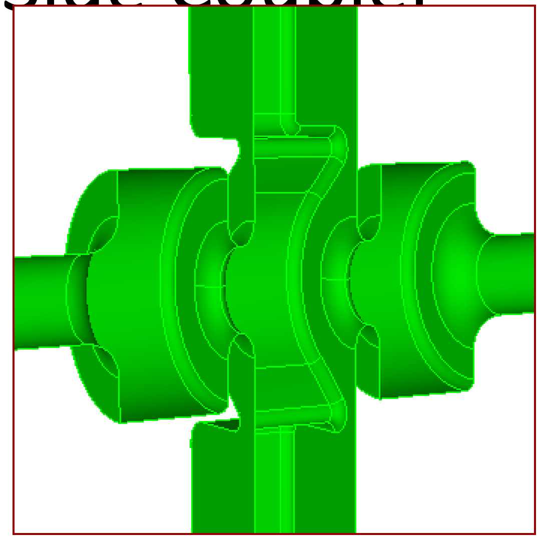
Four feed arms per group so 17.5 MW each arm

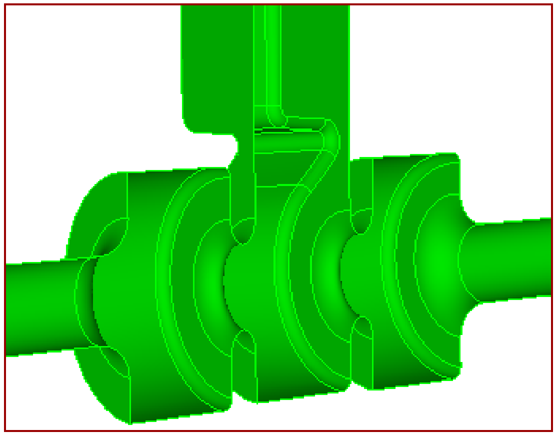
=> 30 MV/m peak field at first coupler, 34 MV/m at E-plane bend

Jeff Neilson

High Gradient Structure With Side Coupler

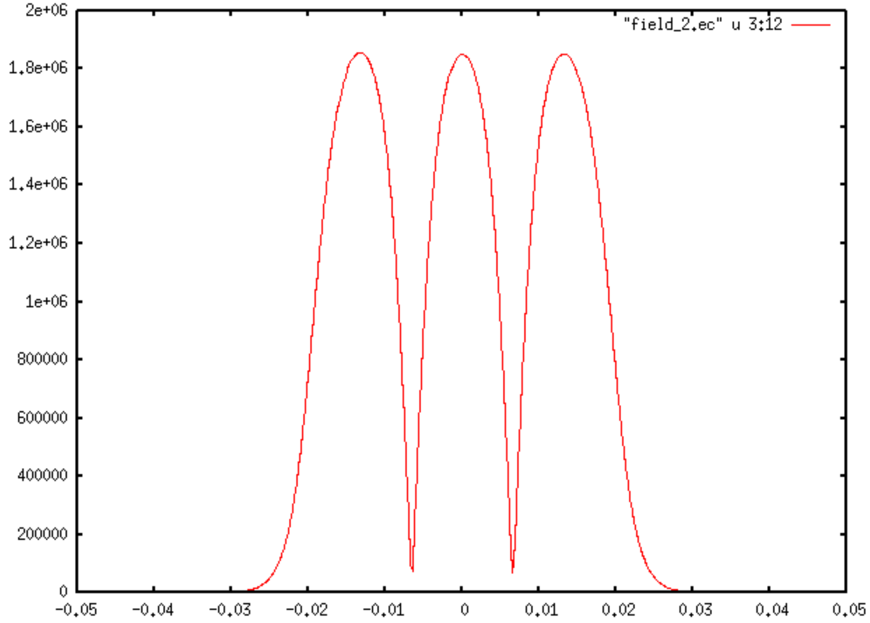


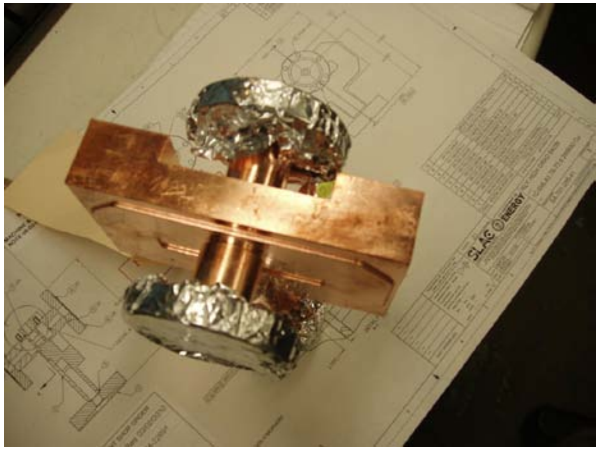


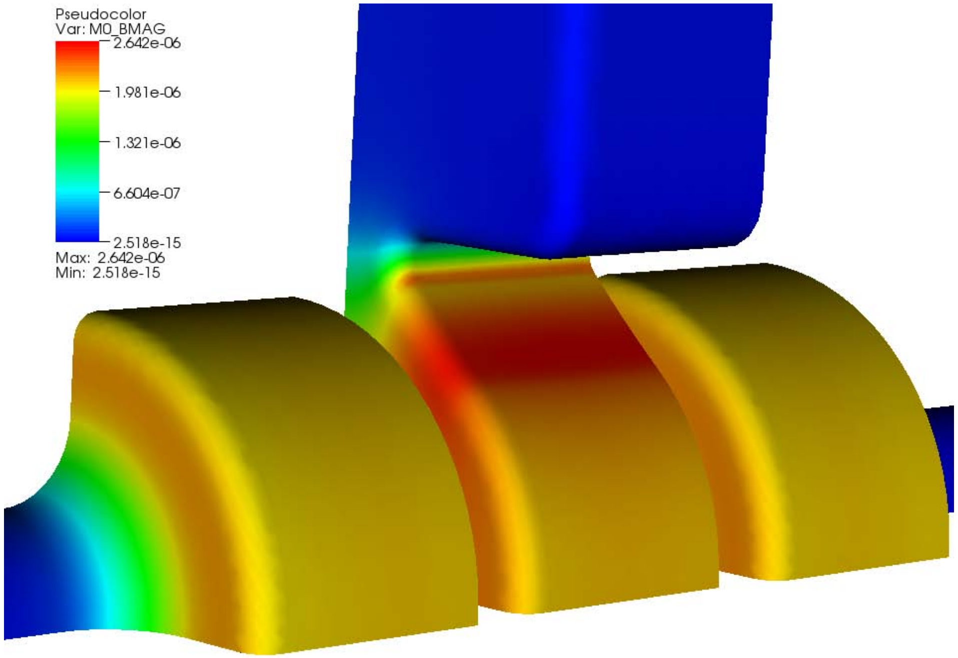


Z. Li

Dual-feed Uniform Field





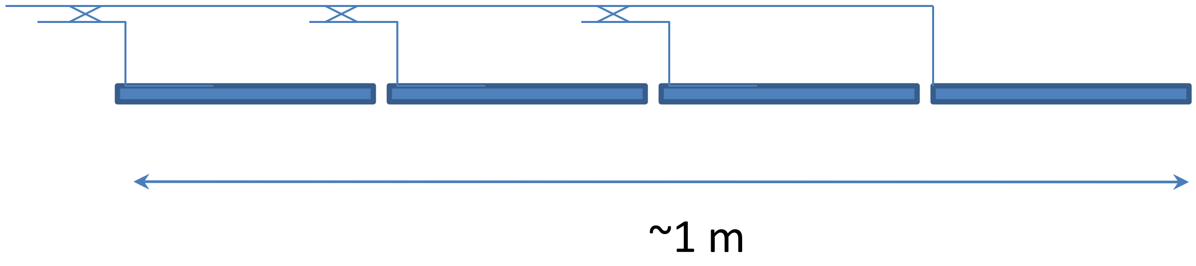


- Hs_max/Hs0_coupler_cell = 1.127
- Hs_max/Hs0_side_cell = 1.165

Z. Li

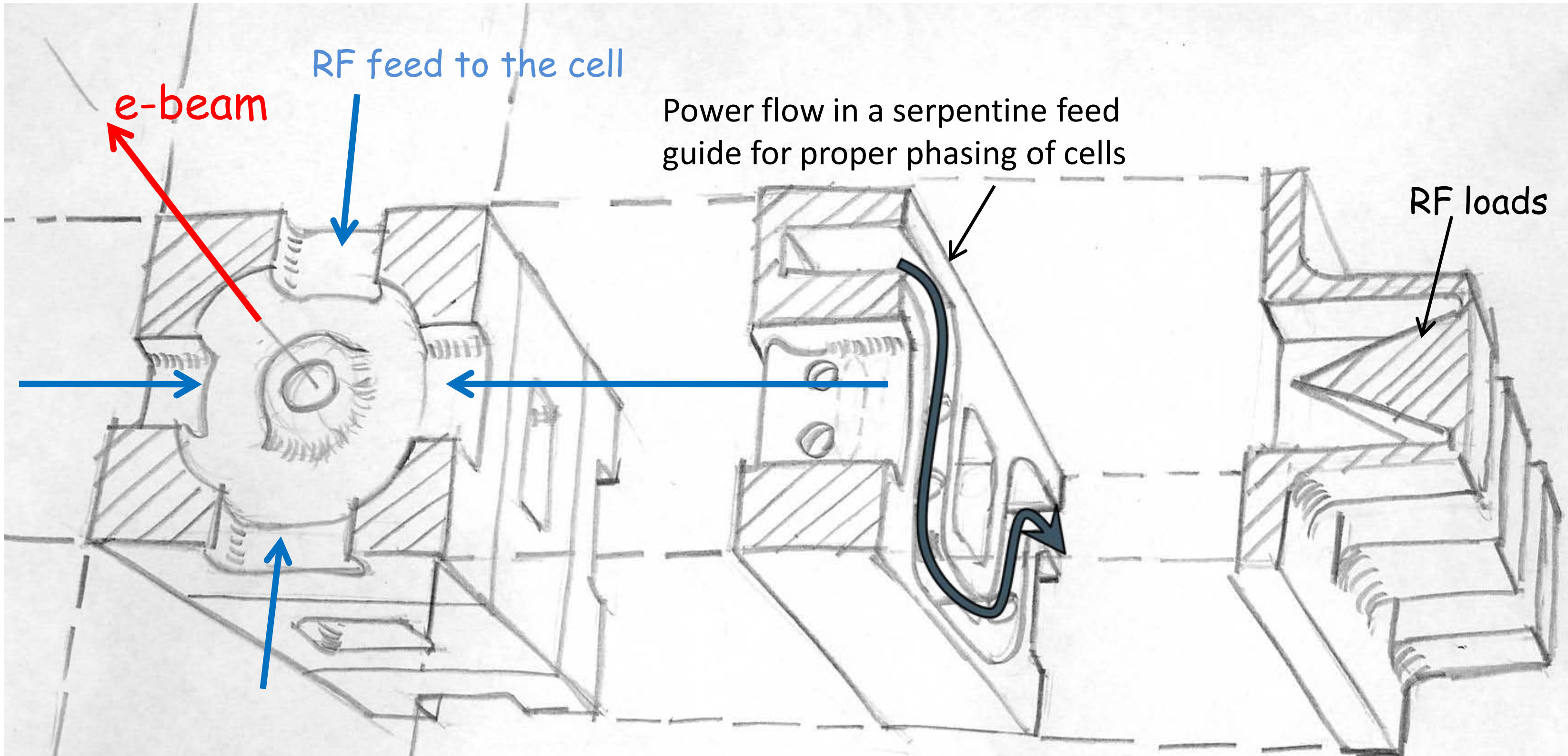
Structure Development

- 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.
- Several elements are still being designed
  - Combining the feeding of the four input waveguides
  - The exact details of the load.
- 1 m super structure is constructed by 4 structures with a small sepration of an extra l/4. This eliminate all reflections to the source*.



* Phys. Rev. ST Accel. Beams 9, 112001 (2006)

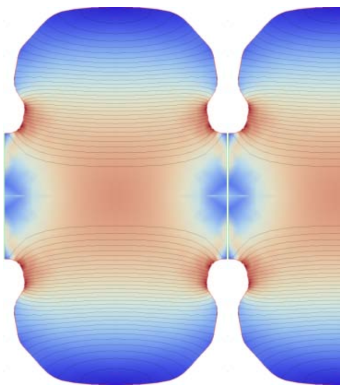
Feeding and Wakefield damping of a set of π-mode structures



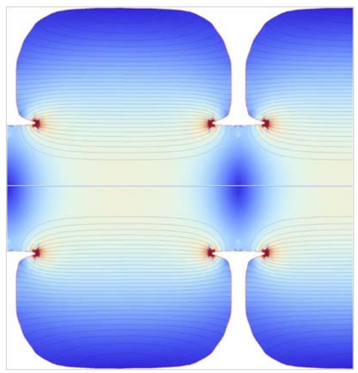
- Each cell is fed through a set of 4 directional couplers around the azimuth.
- The feeding port serve as the damping port for HOMs
- The system has a four-fold symmetry, only one section is shown

Optimization of Accelerator structure continued

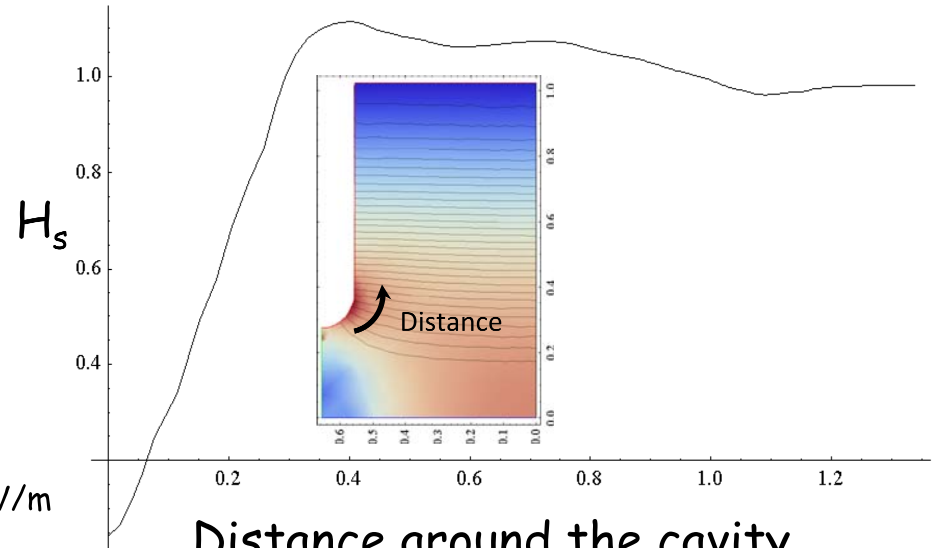
These optimizations were done for a 100MV/m accelerator structures. Better efficiency could be obtained if one let go of the constraints imposed by the surface fields



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



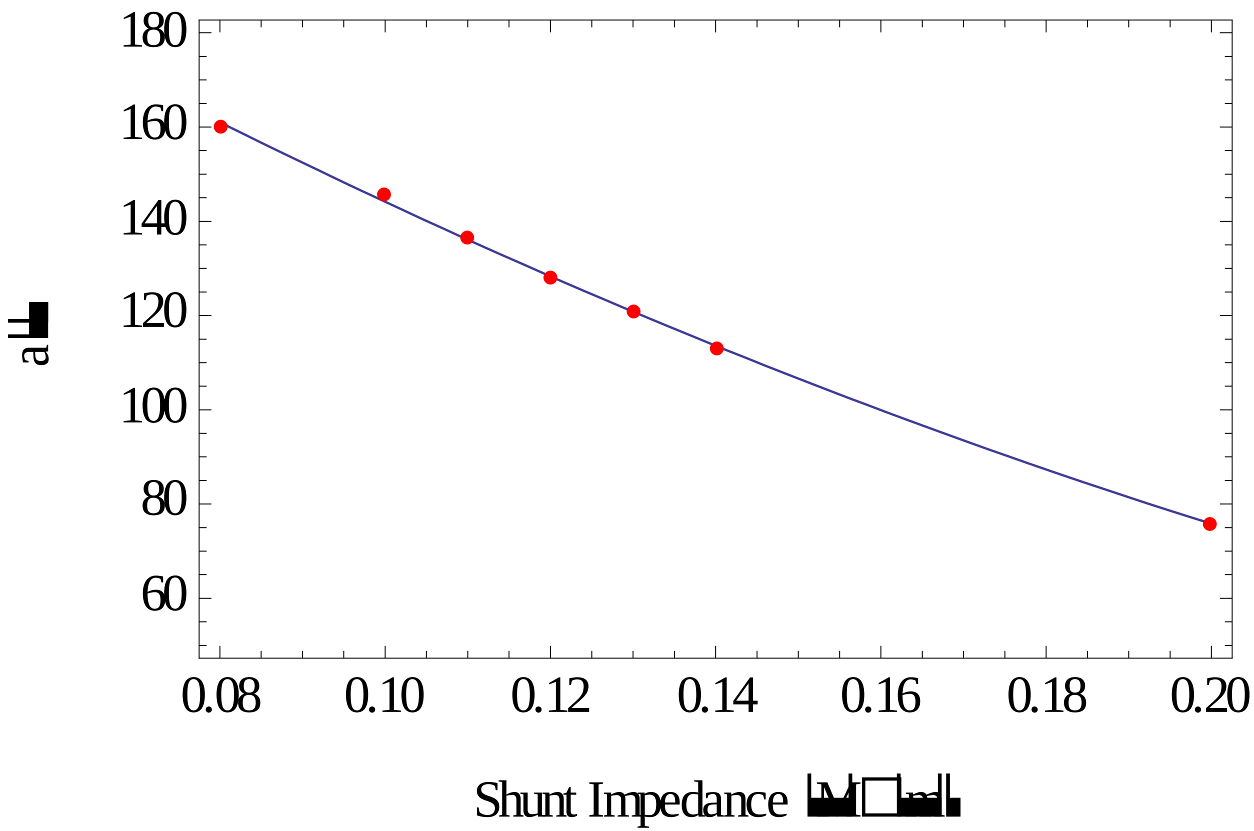
Shunt Impedance: 111 MW/m
Quality Factor :9358
Peak E_s/E_a :7.04
Peak Z_0H_s/E_a :1.11



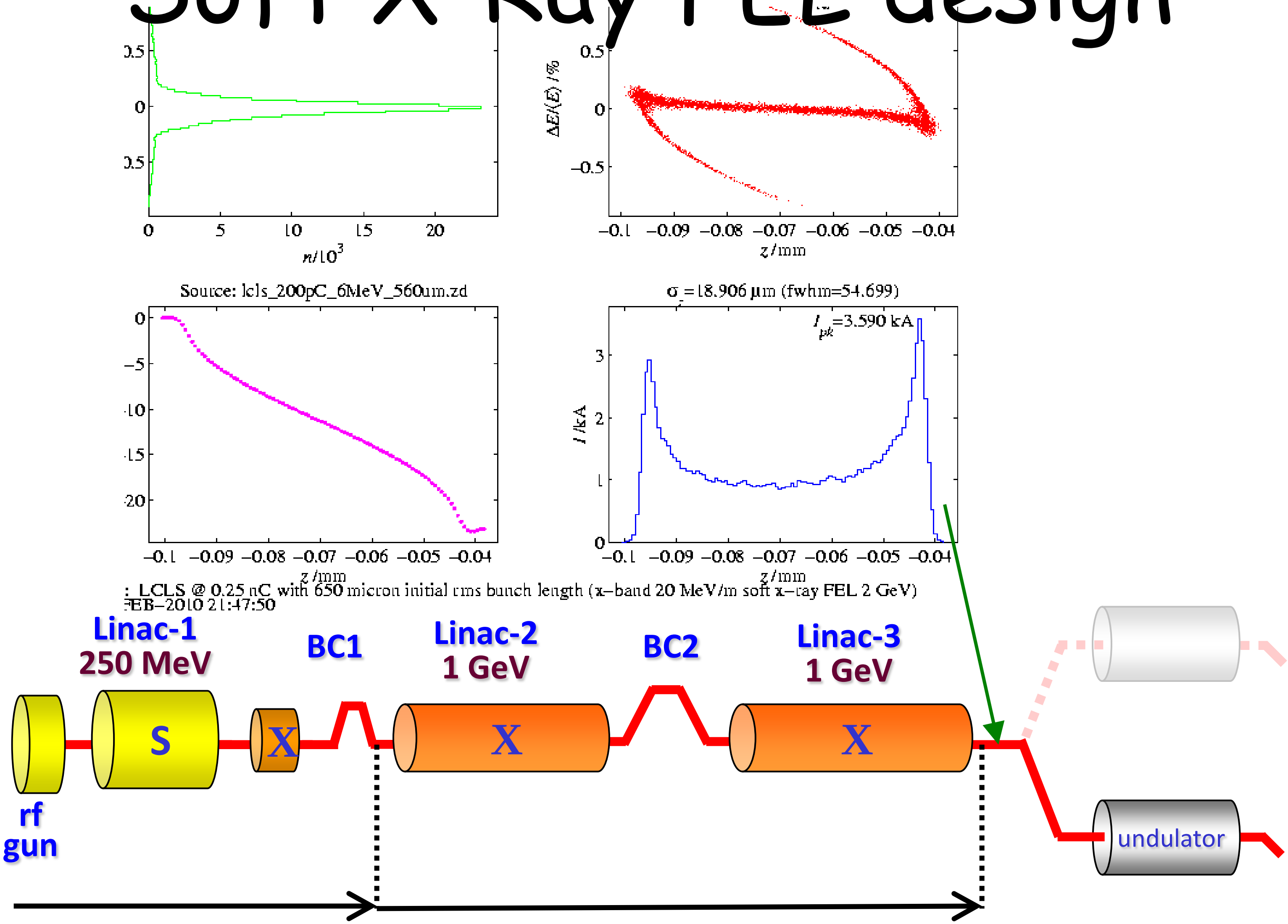
Distance around the cavity surface

- 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

The effect of a/λ on optimized shunt impedance



Soft X-Ray FEL design



LCLS-like injector

L~50 m

X-band main linac+BC2

G~20 MV/m, L~100 m

Zhirong Huang

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

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.
- LiTrack simulation 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.
- then tried 10 MV/m x-band gradient. haven't found a suitable solution yet.
- The LCLS injector works at 120 Hz. I don't know that is a problem for your high-rep. rate application.

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

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

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

Transverse Wakes Continued

- For 20 MeV/m 250 pc of charge, a/λ=0.13,β=10m
  - Y=1.2 for the first Linac
  - Y=0.2 for the second Linac
- For 20 MeV/m 250 pc of charge, a/λ=0.10,β=10m
  - Y=3.1 for the first Linac
  - Y=0.5 for the second Linac
- For 10 MeV/m 250 pc of charge, a/λ=0.10,β=10m
  - Y=6.4 for the first Linac
  - Y=0.9 for the second Linac
- For 10 MeV/m 250 pc of charge, a/λ=0.20,β=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/l=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

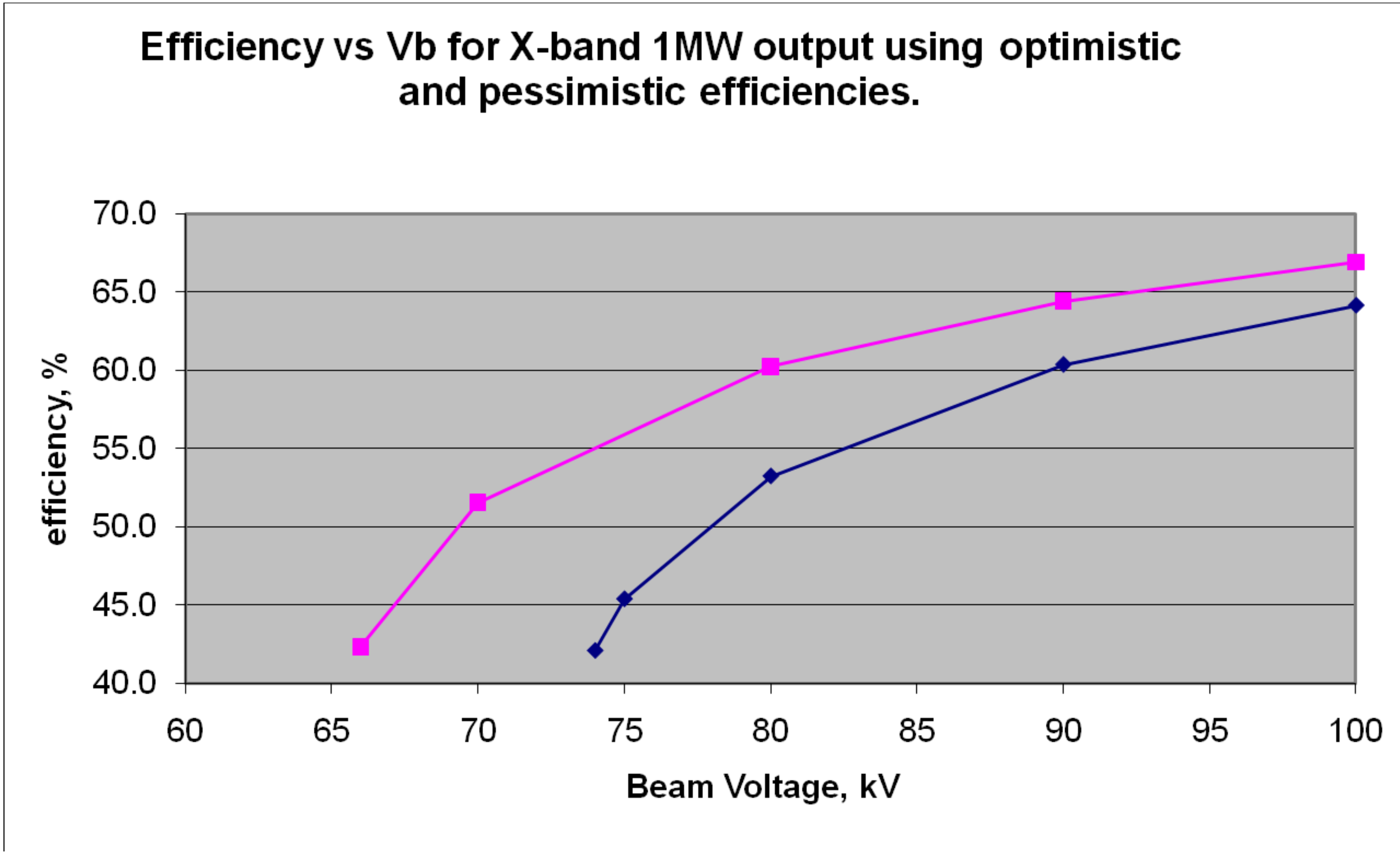
- Operating gradient of 10 MV/m
- Shunt impedance 145 M Ω/m for an accelerator structure with $a/\lambda=0.1$
- Pulse length~ 2 x the structure filling time
- Repetition rate~ 25kHz
- 690 kW/meter

- 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.

Klystron and Modulators

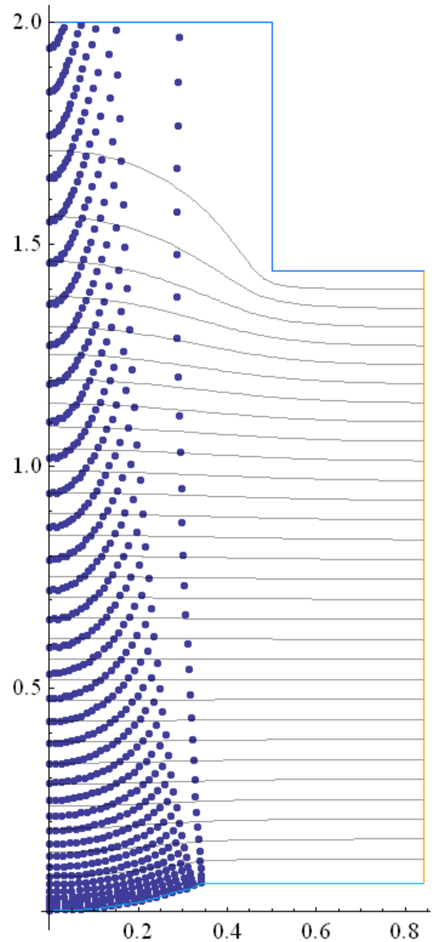
- Case 1: 20 MV/m and $a/\lambda=0.13$
  - RF average power at 5 kHz = 4kW
    - XL-4 at 50 MW, η=40%, 60 Hz, 1.5 μs = 4.5 kW avg RF power
    - The XL-4 is more peak power limited rather than average
  - For a 100 kV 3 MW Klystron(η=42%, and assuming a generous rise and fall time to ease the design 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.

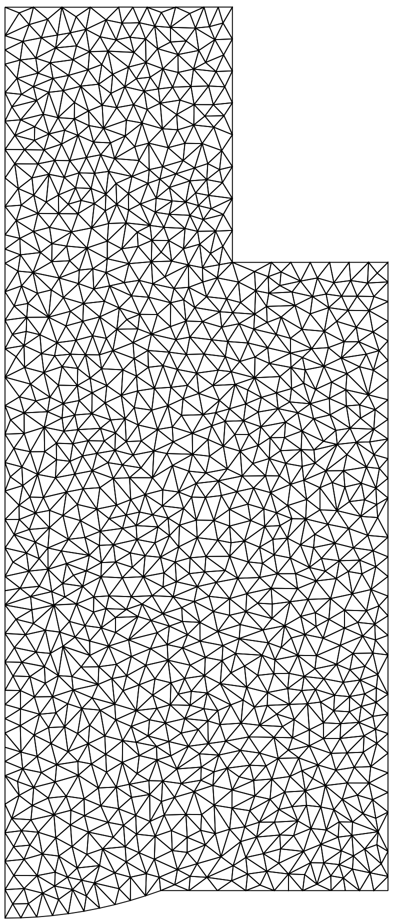
single-beam X-band klystron



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)

RF/Poisson Code





The hope is for a fast code that takes it all the way from the gun to the output, calculates the steady state rf parameters, and analyze the stability

Klystron Optimization

- Current PIC codes allow the verification of a design, it does not allow readily for optimization
- For cavity design it took ~ 200,000 times field calculations of the cavity geometry to reach a optimal shape. At the momenet this takes a bout 2 hours on a PC! The same should be for klystrons.
- The solution is to use *Large Signal Analysis Codes*. These are not readily available.
- These have been developed extensively by gyrotron community, where it is easy to neglect space charge effects.
- We are developing these codes which includes space charge effect.
  - Solving both Rf cavity modes and Poisson equation on the same mesh
  - Use symplectic integrators to push the particles
  - Search for a steady state self consistent solution.
  - The whole process need to talke only meli seconds for each full solution.
- Stability studies is carried out using a Generalized form of Madey's theorm
  - Essentially one calculates the perturbed energy to first order in a small RF field parameter, and then calculate the second order perturbation tern, exactly, using Madey's theorem. This in turn is all that is needed to get the growth rate of a mode.

Conclusion

- With recent advances on high gradient accelerator structures and related RF systems, it is possible to think of an "efficient" room temperature high repetition rate low gradient linacs.
- Reduced power levels/unit length "easily" permit designs with gradients of 10 MV/m-20 MV/m at repetition rates of 1 kHz-250 kHz
- System optimization may allow us to think of higher repetition rates, say 10 kHz, and perhaps higher gradients
- We assumed a very modular system architecture that does not contain any pulse compression system for optimum efficiency
- Wall plug power of these system range between 1- 3 MW for 2 GeV beam