DEVELOPMENT OF AN ULTRA-HIGH REPETITION RATE S-BAND RF GUN FOR THE SPARX PROJECT

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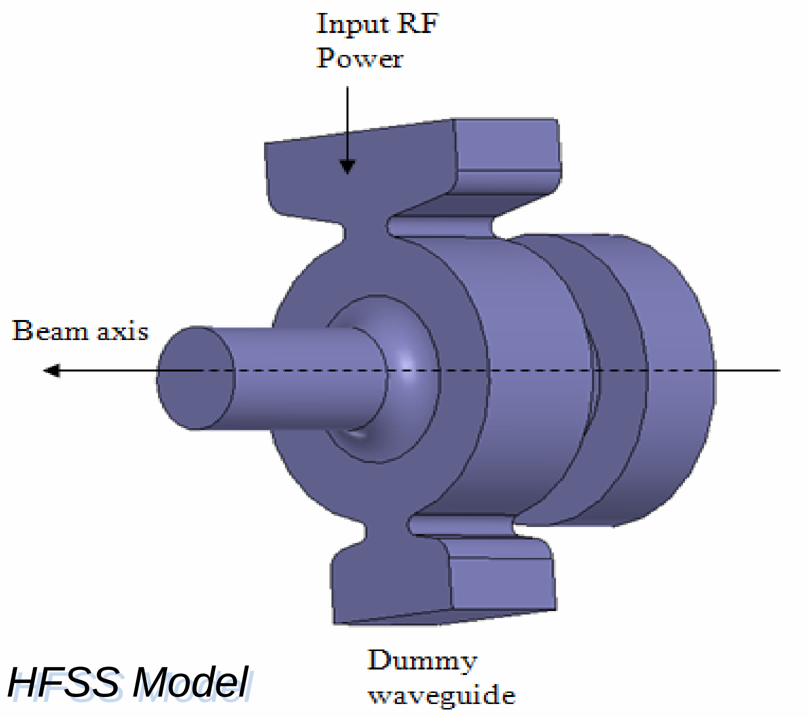
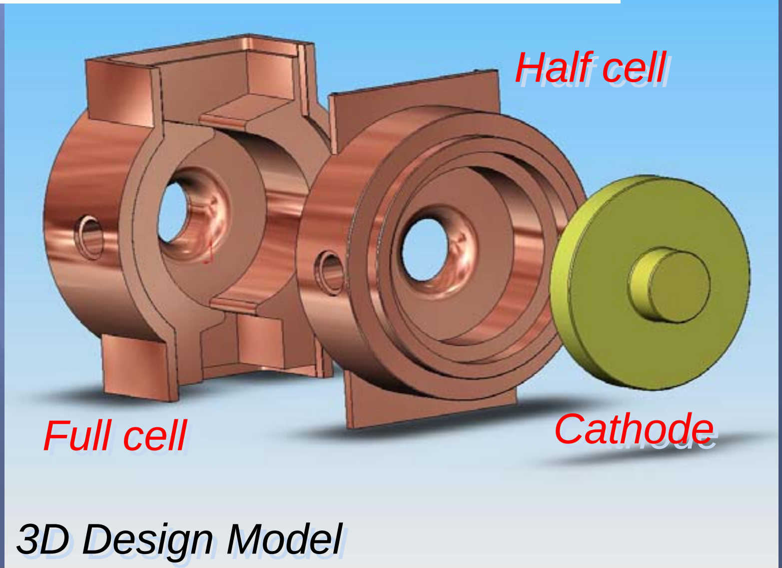
Abstract

We present here the design, including RF modelling, cooling, and thermal stress and frequency detuning, of a single feed S-band RF gun capable of running near 500 Hz for application to FEL and inverse Compton scattering sources. The RF design philosophy incorporates many elements in common with the LCLS gun, but the approach to managing cooling and mechanical stress diverges significantly. We examine the new proprietary approach of RadiaBeam Technologies for fabricating copper structures with intricate internal cooling geometries. We find that this approach may enable very high repetition rate, well in excess of the nominal project this design is directed for, the SPARX FEL.

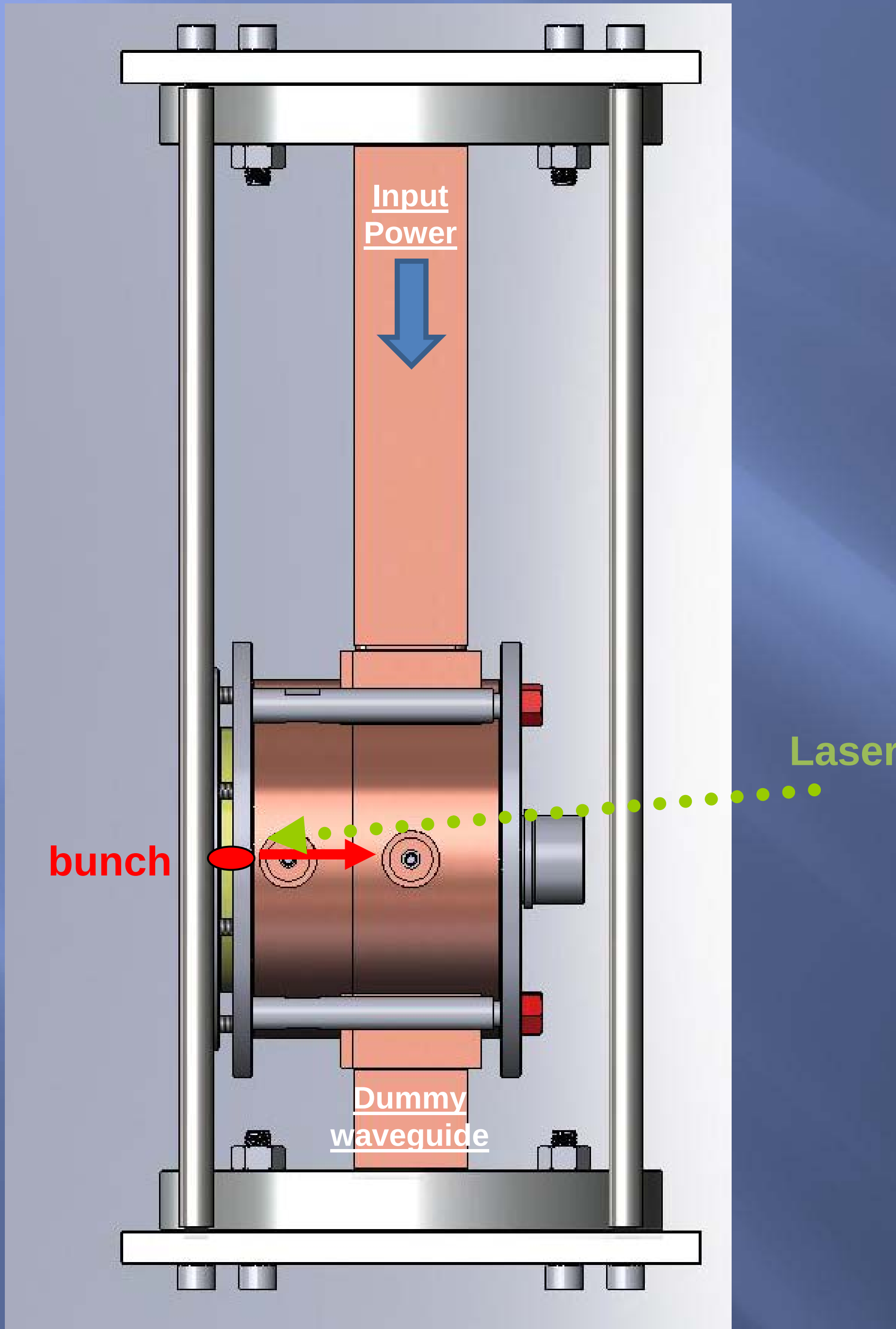
SPARX RF GUN DESIGN

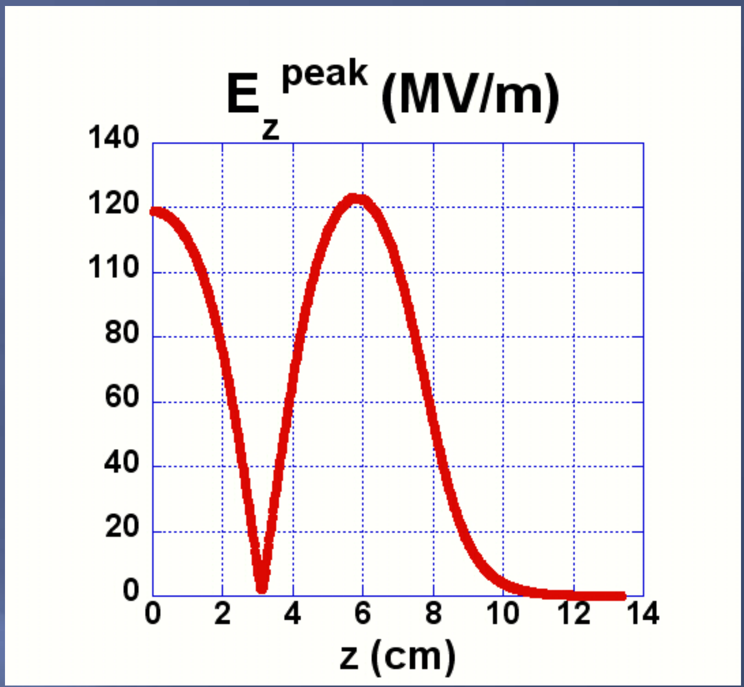




- Operation frequency 2.856 GHz, π-mode
- 1.6 cell gun
- Single feed
  - ✓use of a simpler RF power system than the case of dual feed
  - ✓Avoid phase shift between the two input waves
  - ✓Symmetric waveguide below cut-off to diminish dipole field
- Race track geometry
  - ✓To minimize quadrupole field
- “z-coupling”
  - ✓To reduce temperature rise at the coupling windows
- 100 Hz up to 500 Hz repetition rate
- Multibunch operation
- Numeric codes for simulations: HFSS, ePhysics and Superfish

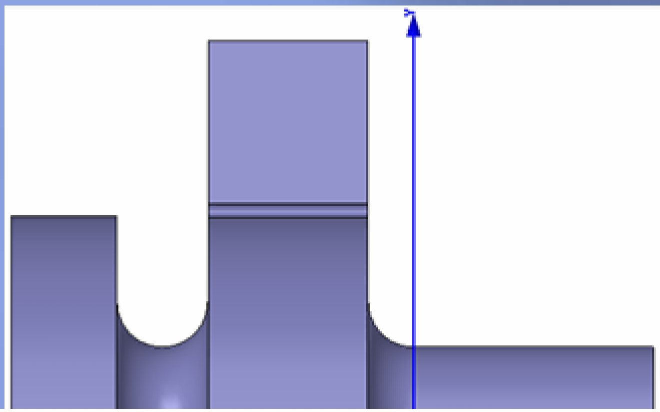
MAIN RF PARAMETERS

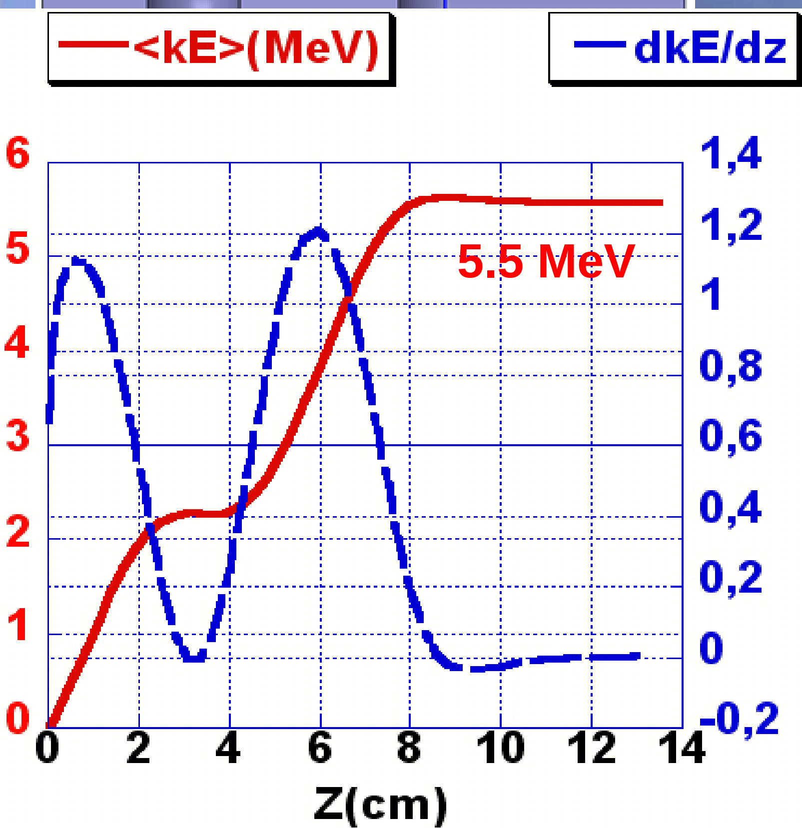




f_π	2.856 GHz
$\Delta f=f_\pi-f_0$	15 MHz
β	1.17
Q_0	13500
Q_{ext}	11490
R_s/Q_0	3630 Ω/m
E_{peak}	120MV/m @ P_{RF}=10MW

PRELIMINARY DYNAMICS RESULTS





Numeric code for simulations:
Parmela

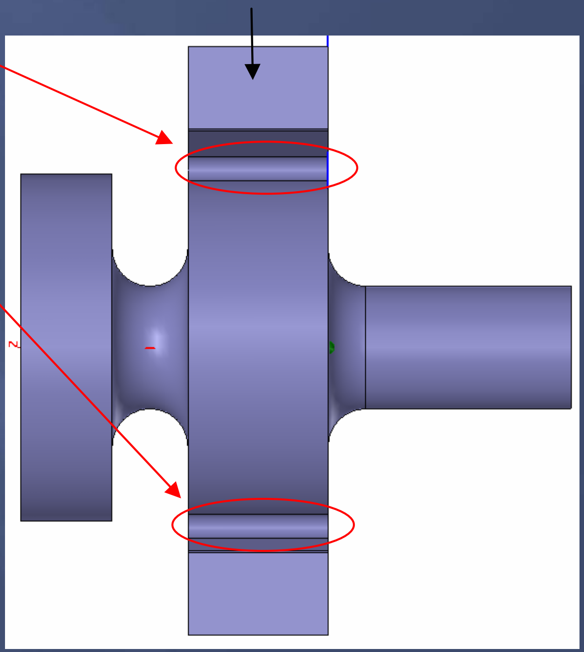
Beam charge Q = 1 nC
Beam current <I> = 0.3 A
Flat-top bunch

RF PULSED HEATING

RF pulsed heating, due to surface magnetic field, causes a temperature gradient on the metal.

- Crucial area are the waveguide-to-coupling-cell irises
- “rounded irises” are used (6mm diameter).
- The peak surface magnetic field is nearly
  *$H_{||}$= 3.9*10⁵ A/m @ input RF power = 10MW*

Input RF power



Dummy waveguide

$$\Delta T = \frac{|H_{||}|^2 \sqrt{t_{RF}}}{\sigma\delta\sqrt{\pi\rho' c_\varepsilon k}}$$

→ **ΔT = 56°C**

below the upper limit, in the S-band, of 60°C

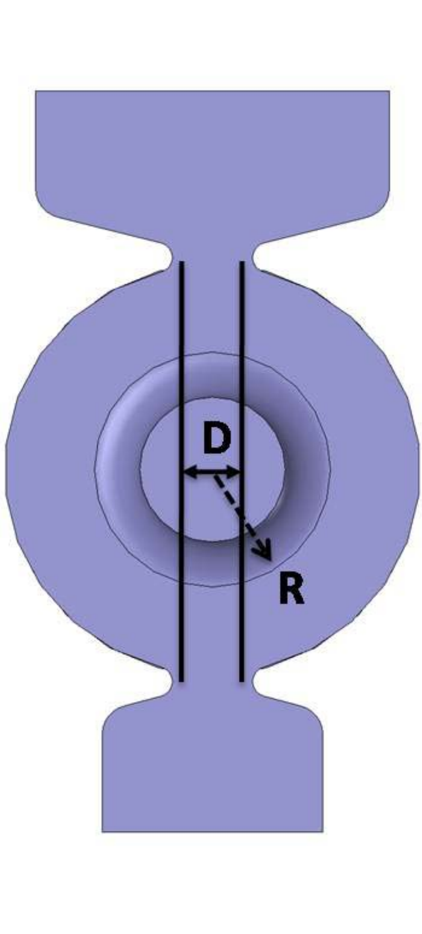
t_{RF} : pulse length
σ : electrical conductivity
δ : skin depth
ρ' : density
c_ε :specific heat
k : thermal conductivity

DIPOLE AND QUADRUPOLE MAGNETIC FIELD COMPONENTS

• A waveguide, below cut-off, symmetric to the input waveguide allows to erase the dipole field component.

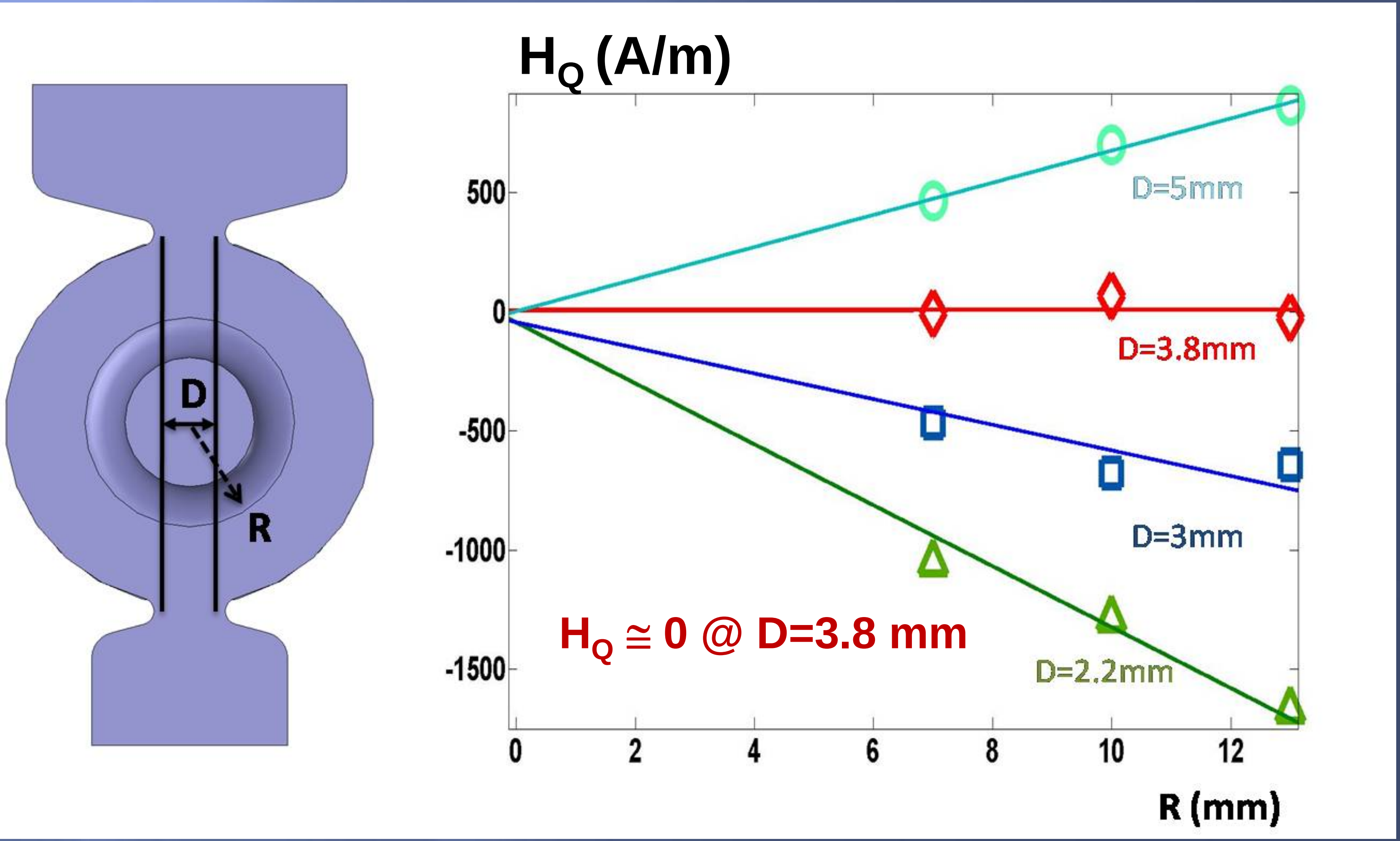
• The quadrupole component is eliminated by using a “race track” geometry.

• Higher order modes are considered negligible.

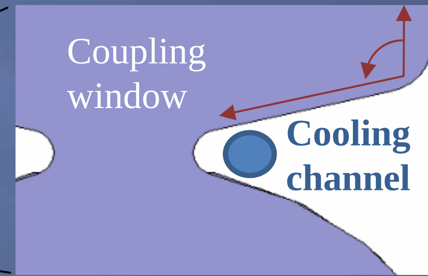


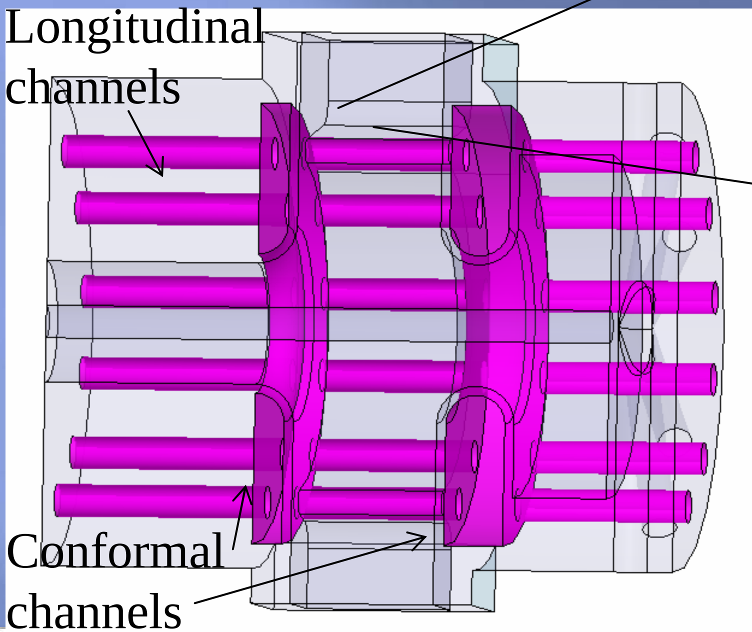
Cross section of the full cell. The field is calculated along circumferences with different radia R and for different values of the offset D, by which the two cell arcs are drifted apart.

QUADRUPOLE MAGNETIC FIELD COMPONENT H_Q



THERMAL ANALYSIS (cylindrical channels)



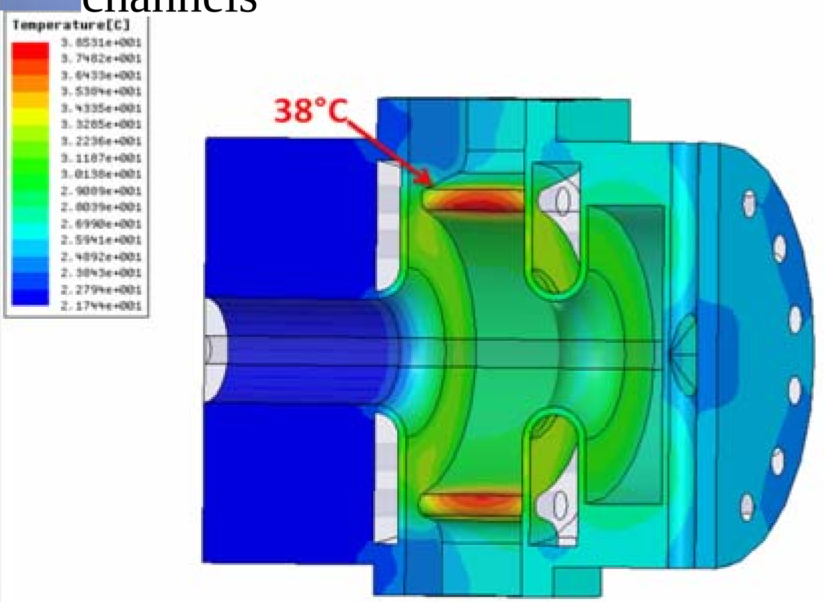


•Twelve longitudinal channels along the structure and six behind the cathode.

•Two conformal channels drilled around the irises.

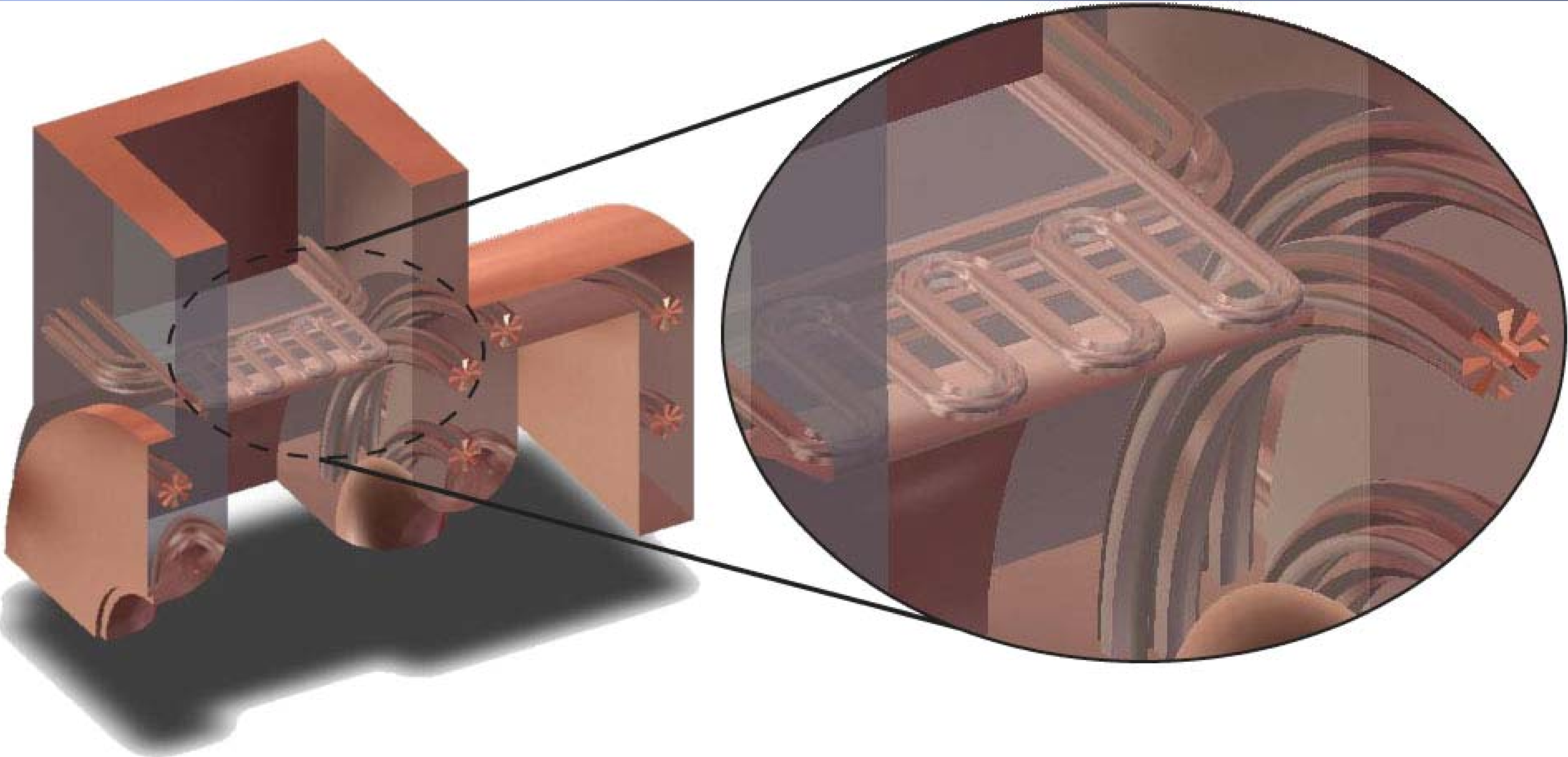
•A hot spot of 38°C for a 100Hz repetition rate is located at the coupling window.

•It has been verified that the temperature distribution shows a linear behavior with the repetition rate.



100Hz	500Hz	1kHz	Rep Rate
38°C	87°C	136°C	Hot Spot

THERMAL ANALYSIS (DMF^3 technique)

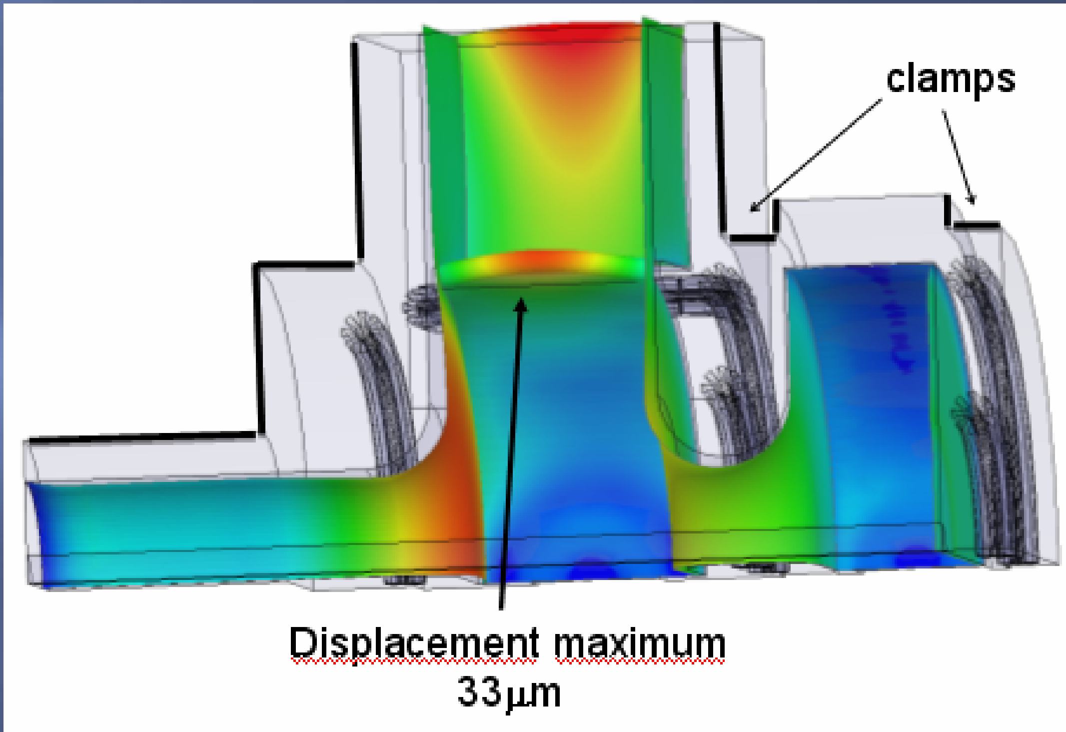


• Six conformal channels and four snake-like around the coupling iris regions with star-shaped cross-sections

• Temperature is kept significantly lower than the case with cylindrical channels (at least by 25°C), allowing a repetition rate up to 500 Hz.

STRESS ANALYSIS

• Maximum value for walls deformation, linear with repetition rate, is equal to 33μm (100 Hz case)



• Gun detuning estimated by using Slater perturbation theory

Rep Rate	100Hz	500Hz	1kHz
Max Deformation	33μm	56μm	92μm
Frequency Shift	+350kHz	+700kHz	1MHz

CONCLUSIONS

The choice of designing a single feed RF gun for the SPARX project leads to deal with many intersecting elements:

- RF field optimization and symmetrization
- Beam dynamics
- RF pulsed heating
- Thermo-mechanical distortions
- RF performance in the presence of distortions

The study we have presented here addresses all of these design constraints together, with extremely promising results

The DMF^3 approach can provide wide flexibility in cooling channel design and fabrication

Such innovations as star-shaped cross-sections, and arbitrary channel paths, allow to design the cooling system even more aggressively.

FUTURE WORK

- Prototype is being built
- Measurements of RF parameters and field components
- Solenoid for the Gun emittance compensation

REFERENCES

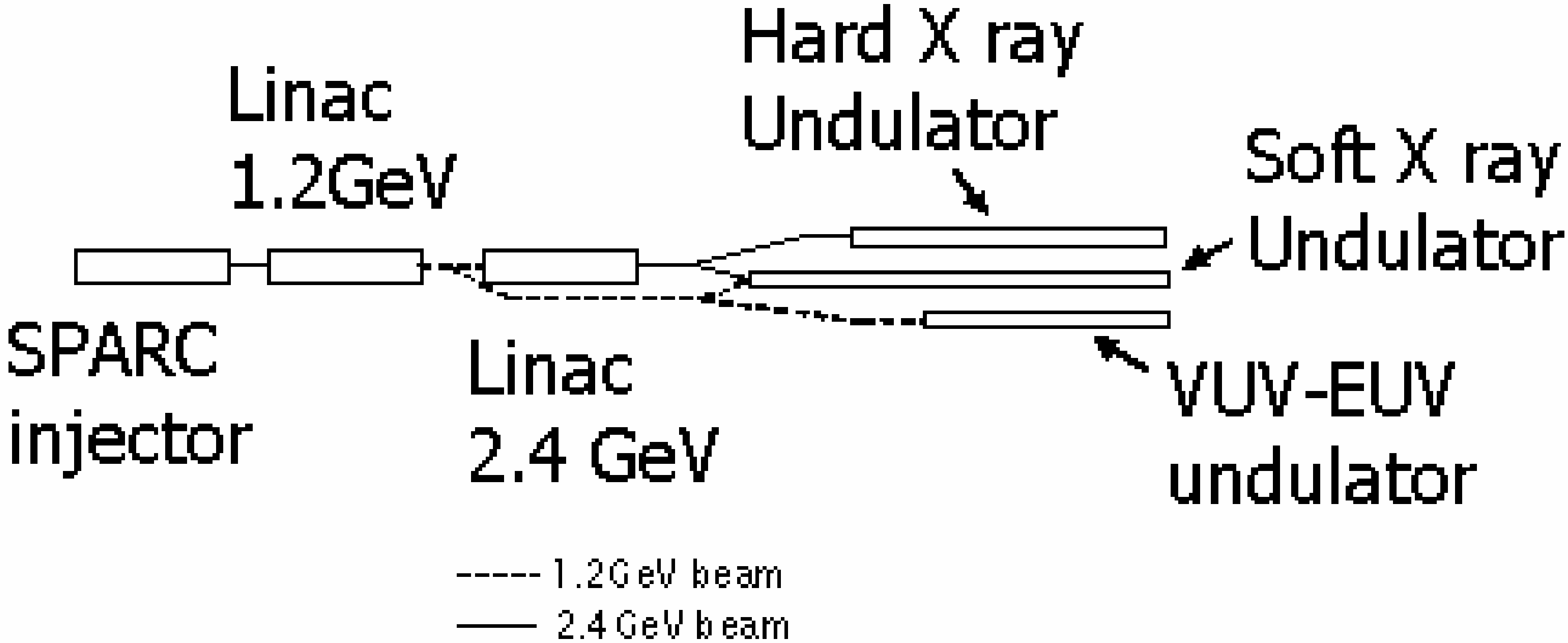
C.Limborg *et al., "RF Design of the LCLS Gun",* LCLS Technical Note LCLS-TN-05-3 (Stanford,2005).

V.A. Dolgashev, *"High Fields in Couplers of X-band Accelerating Structures",* PAC 03, Portland, Oregon USA, May 12-16,2003.

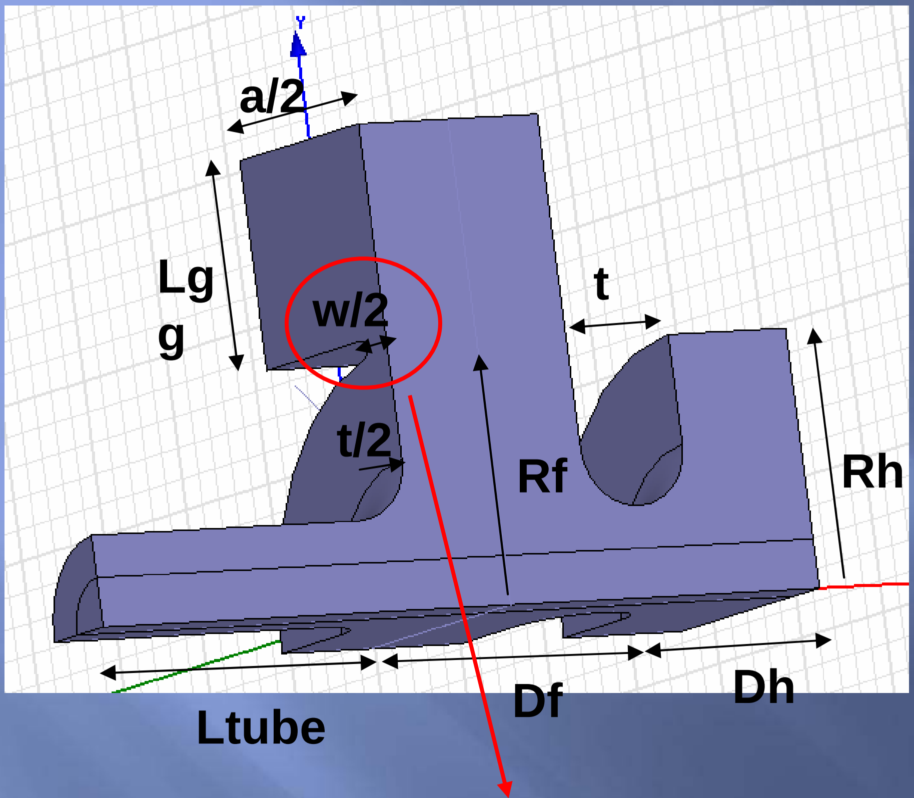
D.P. Pritzkau, *"RF Pulsed Heating"*, SLAC-Report- 577, PhD. Dissertation, Stanford Univ., 2001.

P. Frigola et al., *"Development of solid freeform fabrication (SFF) for the production of RF Photoinjectors",* in these proceedings

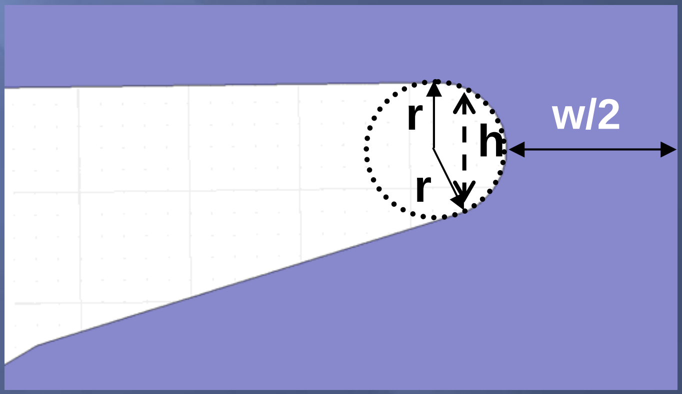
SPARX layout



Geometric dimensions



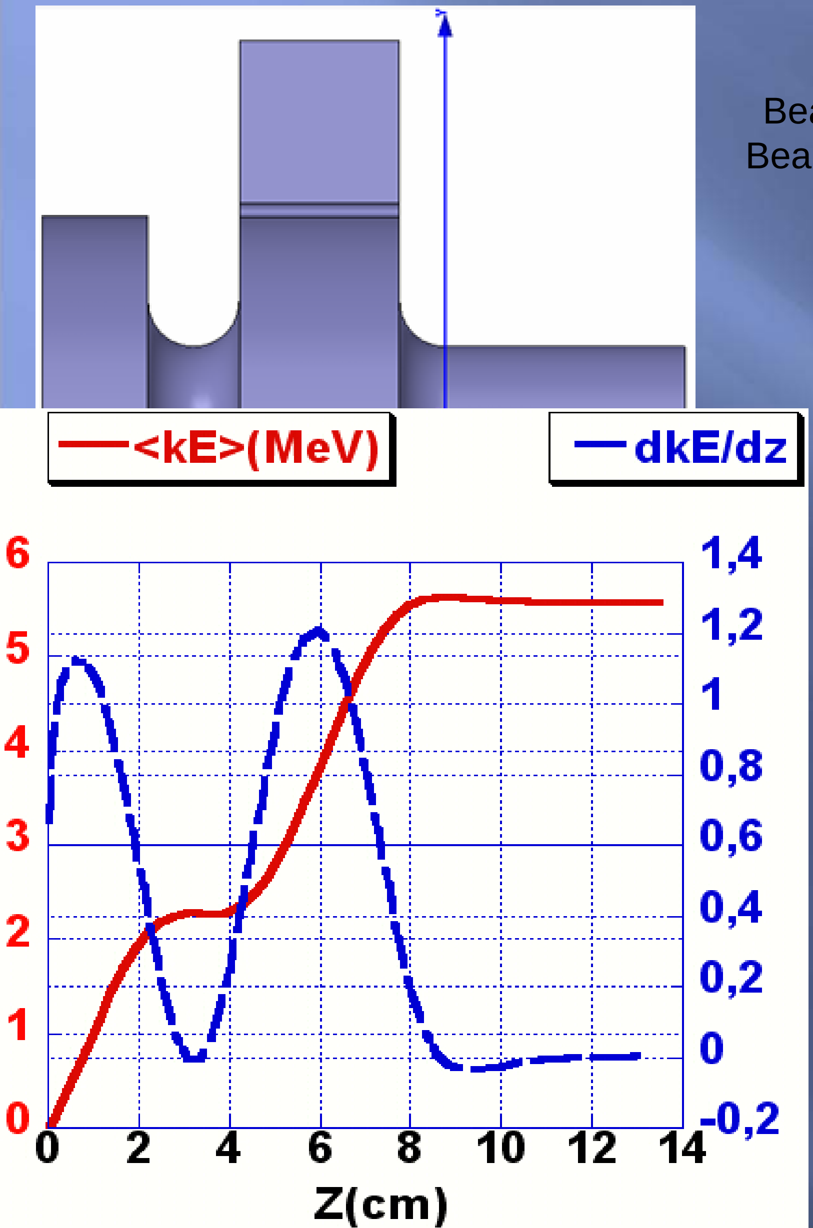
Rf	42.44 mm
Rh	42.19 mm
t	19.05 mm
Dh	31.4916 mm
Df	52.486 mm
w	12.308 mm
Lg	34 mm
a	72.14 mm
Ltube	50 mm



Coupling window

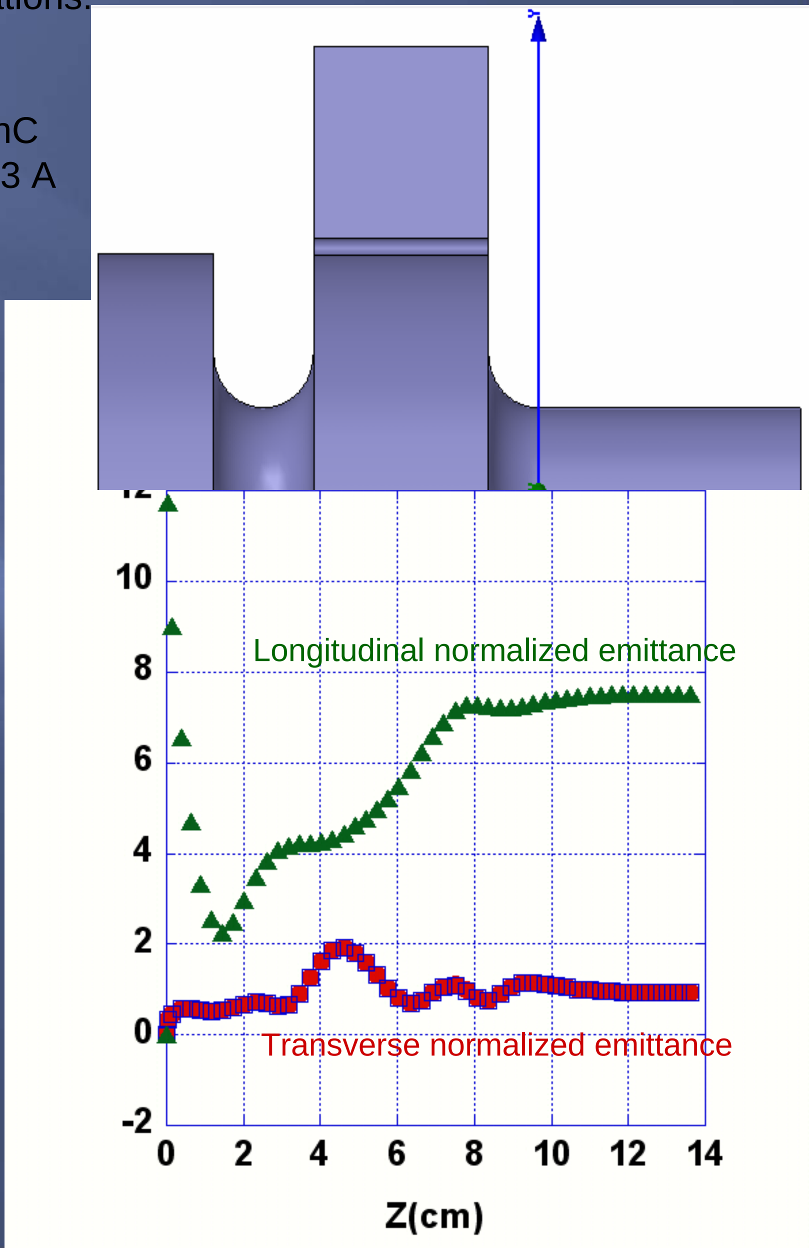
r = 1.523mm
h = 3mm
w/2 = 6.154mm

Preliminary dynamics results



Numeric code for simulations:
Parmela

Beam charge Q = 1 nC
Beam current <I> = 0.3 A
Flat-top bunch
No solenoid



COUPLING AND BEAM LOADING

τ_{RF} (pulse length)	**3μs**
f_{RF} (repetition rate)	**100Hz**
T_{RF} (pulse period)	**10ms**
DC_{RF} (τ_{RF}/T_{RF}) (pulse train duty cycle)	**$3*10^{-4}$**
P_g (Peak power)	**10MW**

τ_b (beam length)	**10ps**
f_b (beam frequency)	**300MHz**
T_b (beam period)	**3.3ns**
DC_b (τ_b/T_b) (beam duty cycle)	**$3*10^{-3}$**
Q_b (beam charge)	**1nC**

Gun data:
- E_0 = 55 MV/m
- L = 14 cm
- T = 0.68
- R_{Sh} = 6.86 MΩ

Beam power Pb =1.4 MW

Cavity power Pd =8.6 MW

↓ Beam loading

coupling coefficient
β= 1.17

Average power dissipated in the cavity per unit length < Pd >/L = 19 kW/m

This value is near the upper limit of power dissipation that the structure can support.

FOURIER ANALYSIS OF THE MAGNETIC FIELD

The azimuthal component of the magnetic field $H\Phi$ is the most sensitive to the asymmetry of the Gun!

$$H\Phi(r,\Phi) = \sum_{n=0}^{+\infty} \underline{H}_n(r)\cos(n\Phi)$$

where

$$\underline{H}_n(r) = 2/\pi \int_0^{\pi} H(r,\Phi)\cos(n\Phi)\,d\Phi$$

$n = 0$ $\longrightarrow$ $\underline{H}_0(r) \equiv \underline{H}_M(r)$ Monopole Component

$n = 1$ $\longrightarrow$ $\underline{H}_1(r) \equiv \underline{H}_D(r)$ Dipole Component

$n = 2$ $\longrightarrow$ $\underline{H}_2(r) \equiv \underline{H}_Q(r)$ Quadrupole Component

THERMAL AND STRESS ANALYSES

- Thermal and stress analyses are carried out by using ePhysics
- Input power considered is 10 MW
- Two different thermal boundary conditions are applied:

free (natural) convection on the copper cells outer walls
(room temperature of 20°C)

forced convection on the channels inner walls
(input water temperature of 20°C flowing with a velocity of 4 m/sec)

Two cooling systems are examined:

cylindrical channels

DMF^3 (Direct Metal Free Forming Fabrication) technique

OUTLINE

- ***SPARX RF Gun Design***
- ***Preliminary dynamics results***
- ***RF Pulsed Heating***
- ***Dipole and Quadrupole Field components***
- ***Thermal and Stress Analyses***
- ***Conclusions***