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Application of Nb_3Sn cavity for femtosecond-pulsed electron microscope

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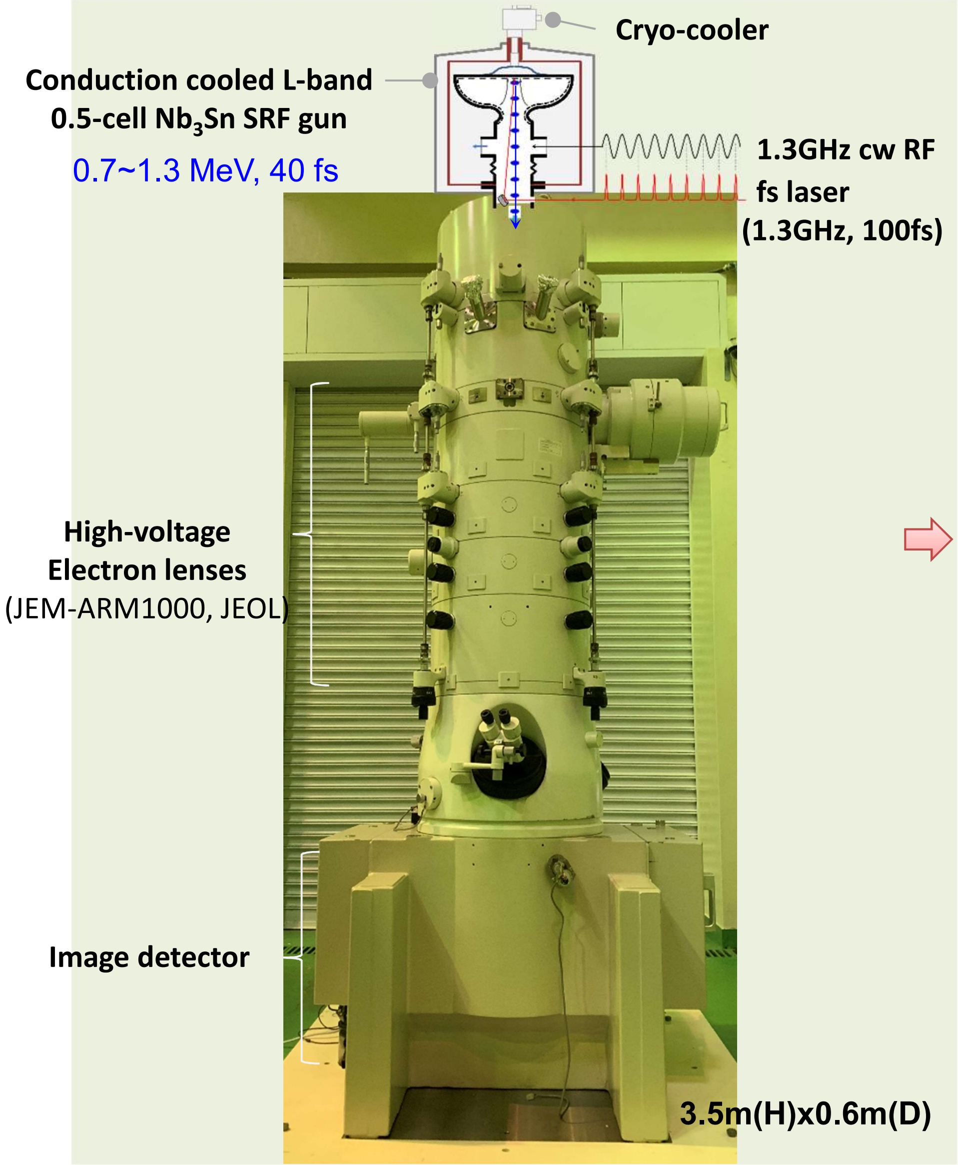
This study was proposed in collaboration with KEK and Osaka U.

Ultrafast electron microscopy using 0.5-cell Nb_3Sn SRF gun

proposed in collaboration with KEK and Osaka U.

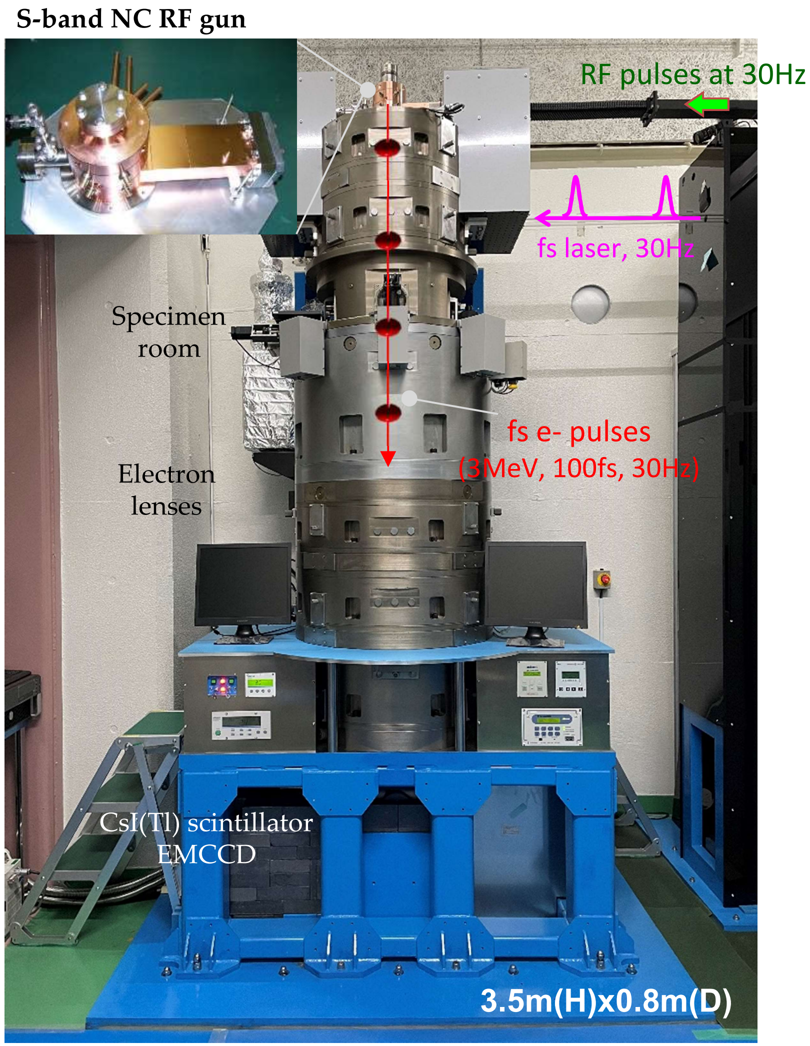


Temporal-spatial resol.
50 fs, 1 Å

Why 0.5-cell SRF gun in electron microscopy?

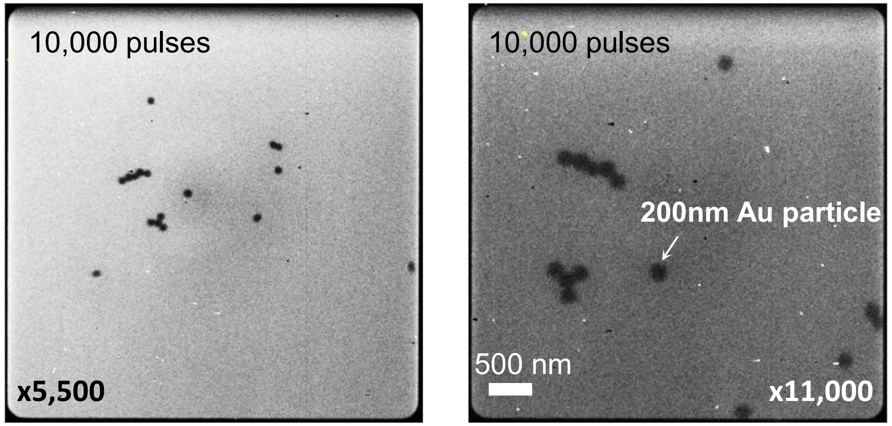
The first ultrafast electron microscopy using NC RF gun

developed at Osaka Univ.



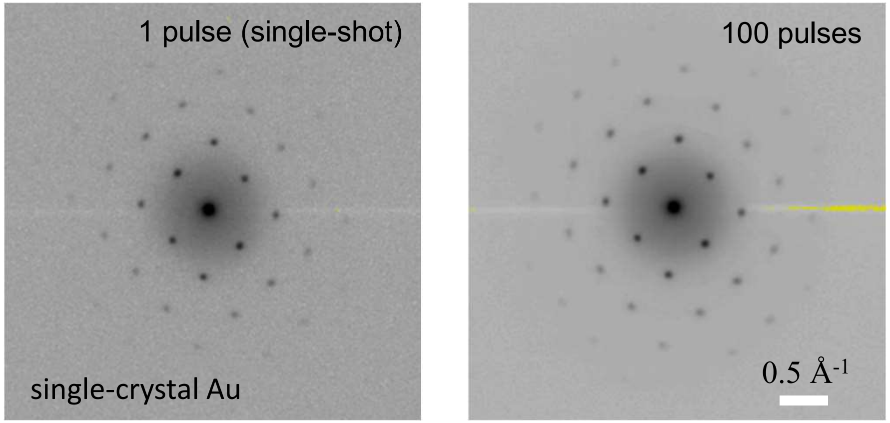
Compact High-Voltage Electron Microscopy (compact HVEM)

TEM Imaging with 3-MeV fs e- pulses



The RF-acceleration technology is expected to be used in EM!

Single-shot electron diffraction Imaging



Single-shot electron diffraction imaging is available.

However, for the NC RF gun , the averaged beam current is low & energy stability is not enough for EM.

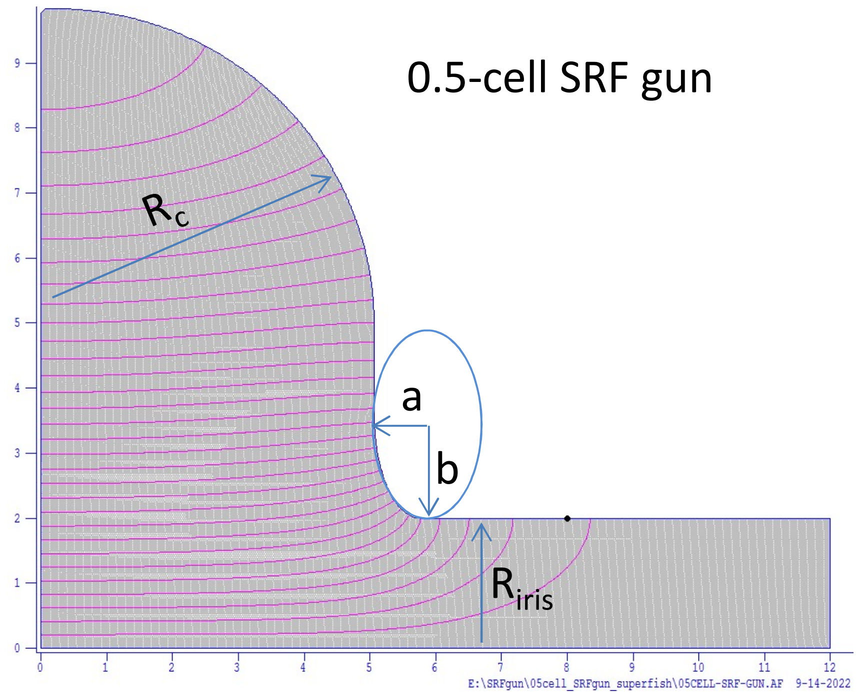
Electron sources for electron microscopy

	Commercial TE/FE gun in high-voltage EM	NC RF gun at Osaka Univ.	0.5-cell SRF gun (this proposal)
Accelerating type	DC	S-band RF, 1.4-cell	L-band RF, 0.5-cell
Operational temperature	room temp.	room temp.	4.2 K with Nb_3Sn
$E_{cathode}$	1~5 MV/m	50~70 MV/m	20~30 MV/m
Beam energy	0.5 ~ 1.2MeV, 3MeV(max.)	1 ~ 3 MeV	0.7 ~ 1.3 MeV
Bunch length	-	≤100 fs	≤50 fs
Bunch charge	-	~1 pC	≤10 fC
Repetition rate	-	30 Hz, 1 kHz at max.	1.3 GHz for cw operation
Averaged current	~10 μA	30 pA, 1nA at max	13 μA
Input RF power	-	2~7 MW (pulsed)	<1.5 W (cw)
Energy spread ($\Delta E/E$)	10^{-5} ~ 10^{-6}	10^{-5} in pulse	10^{-5} ~ 10^{-6} in pulse
Energy stability	10^{-6}	10^{-4}	10^{-5} ~ 10^{-6}

Both the averaged current and the energy stability in the 0.5-cell SRF gun are comparable to the e- beam in commercial high-voltage EM.

Cavity design of 0.5-cell SRF gun

Optimization of 0.5-cell SRF gun cavity

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Frequency                                    =   1300.05882 MHz
Particle rest mass energy                    =     0.511000 MeV
Beta =  1.0000000
Normalization factor for E0 =  8.658 MV/m =      869.645
Transit-time factor                          =    0.6352362
Stored energy                                =    0.6534936 Joules
Superconductor surface resistance            =      26.7976 nanoOhm
Operating temperature                        =       2.0000 K
Power dissipation                            =     510.6535 mW
Q    =    1.0453E+10      Shunt impedance =   1.7616E+07 MOhm/m
Rs*Q =   280.126 Ohm                 Z*T*T =   7.1085E+06 MOhm/m
r/Q  =    81.603 Ohm  Wake loss parameter =      0.16664 V/pC
Average magnetic field on the outer wall     =      29978.1 A/m, 1.20413 mW/cm^2
Maximum H (at Z,R = 0.0021955,9.75784)       =      30229.7 A/m, 1.22443 mW/cm^2
Maximum E (at Z,R = 5.17243,2.74824)         =      19.5537 MV/m, 0.608953 Kilp.
Ratio of peak fields Bmax/Emax               =       1.9427 mT/(MV/m)
Peak-to-average ratio Emax/E0                =       2.2584

Wall segments:
Segment   Zend        Rend          Emax      Power       P/A         dF/dZ     dF/dR
          (cm)        (cm)         (MV/m)     (mW)     (mW/cm^2)   (MHz/mm)   (MHz/mm)
-----------------------------------------------------------------------------------------
           0.0000      9.7370
   3      0.10000      9.8370      0.1844     11.72      1.214      -0.3491    -0.3482
   4      0.20000      9.8370      0.1280     7.447      1.205       0.000     -0.3474
   5       5.0650      4.9720       11.08     452.7      1.168      -9.097     -13.70
   6       5.0650      3.6000       17.11     29.70      0.8039      1.782      0.000
   7       5.7650      2.0000       19.56     8.999      0.2823      3.919      1.318
   8       12.000      2.0000       9.931  8.8213E-02  1.1259E-03    0.000      0.1094
-----------------------------------------------------------------------------------------
                                    Total     510.7
```

RF parameters	Values
Frequency [MHz]	**1300**
Q_0 at 2K (Rs=26.8 nΩ)	**1.045 x 10^{10}**
r/Q [Ω]	**81.6**
G=Rs/Q [Ω]	**280**
E_{sp}/E_{acc}	**1.96**
B_{sp}/E_{sp}	**1.94 (B_{sp}=38.0 mT)**
E_c at cathode [MV/m]	**20 (E_{acc}=10 MV/m) 30 (E_{acc}=15 MV/m)**
Wall power dissipation [W]	**0.511 at E_c=20MV/m 1.15 at E_c=30MV/m**

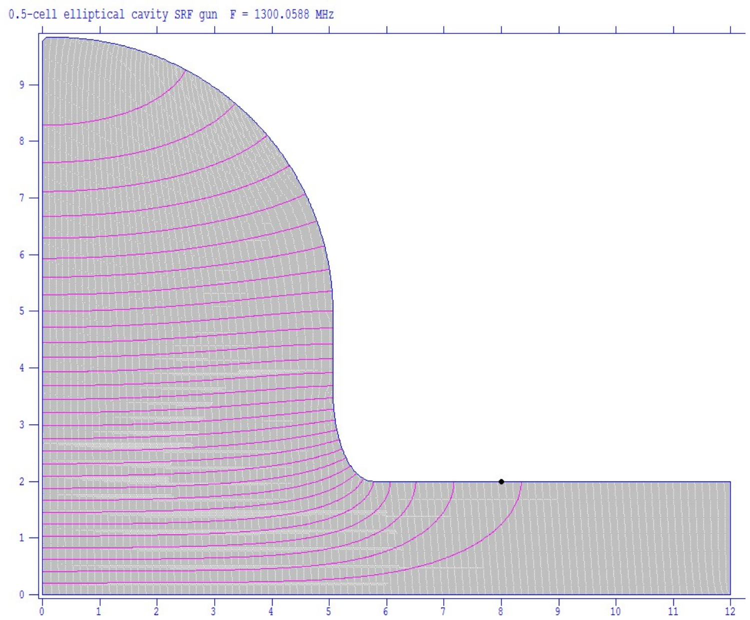
- Low loss shape
- Elliptical Iris
- small R_{iris}

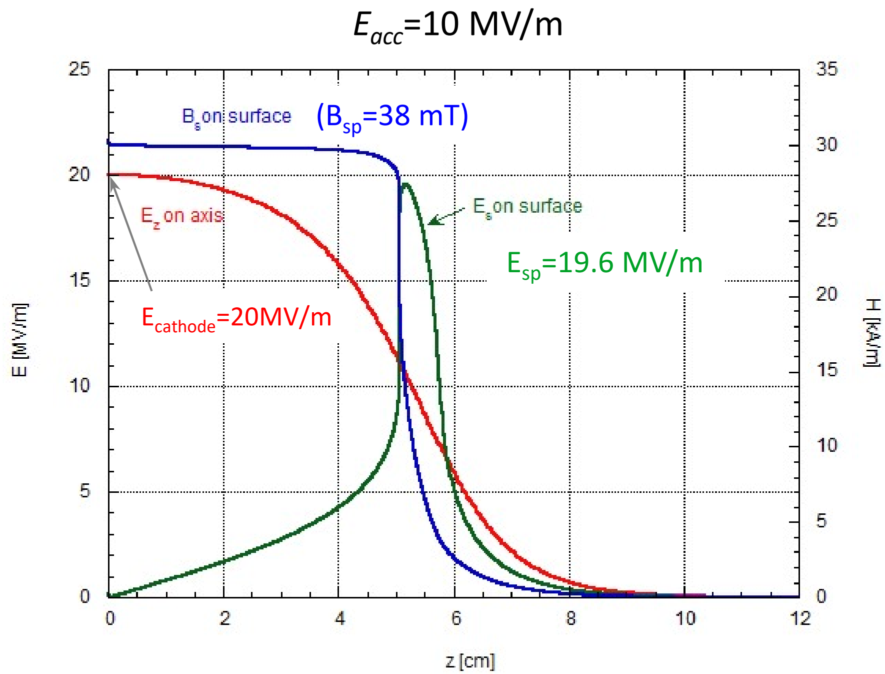
higher Q & r/Q,
lowest E_{sp} & B_{sp}

L_{cell} = 57.65 mm
R_c = 48.65 mm
α = 0 degree
a = 7 mm, b = 16 mm
(a/b = 0.4375)
R_{iris} = 20 mm

The Cavity is available to be conduction-cooled by a 1.5W cryo-cooler.

E & H fields on the surface of cavity





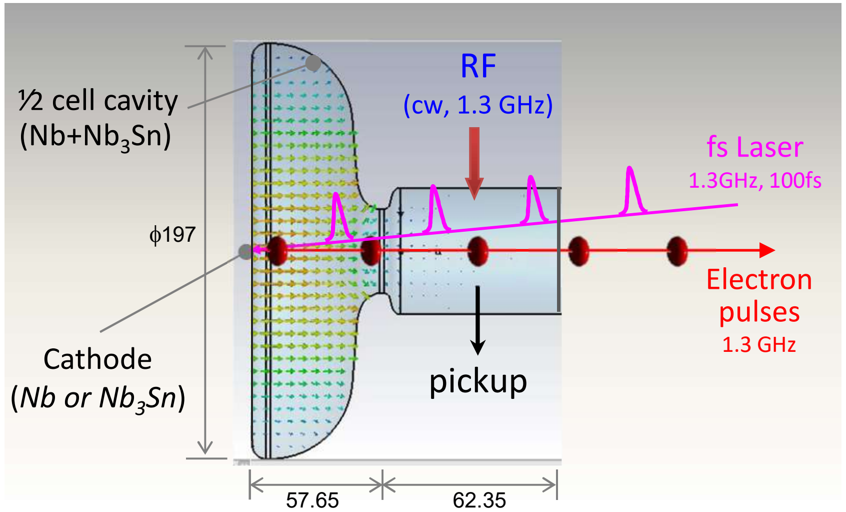
The peak surface electric field is less than the field on the cathode.

(E_{sp} < $E_{cathode}$)

Beam dynamics on 0.5-cell SRF gun

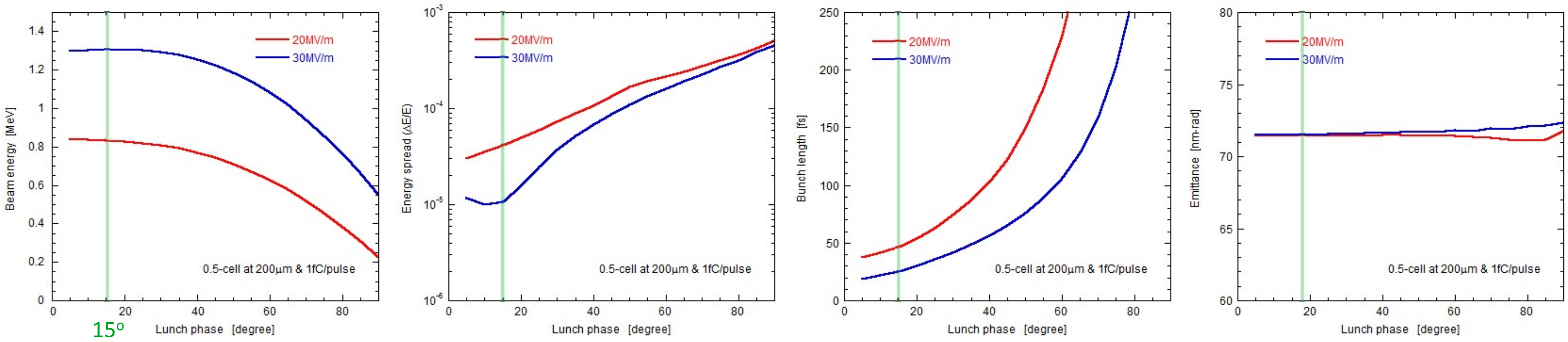
simulated with GPT

Beam simulation results on 0.5-cell SRF gun



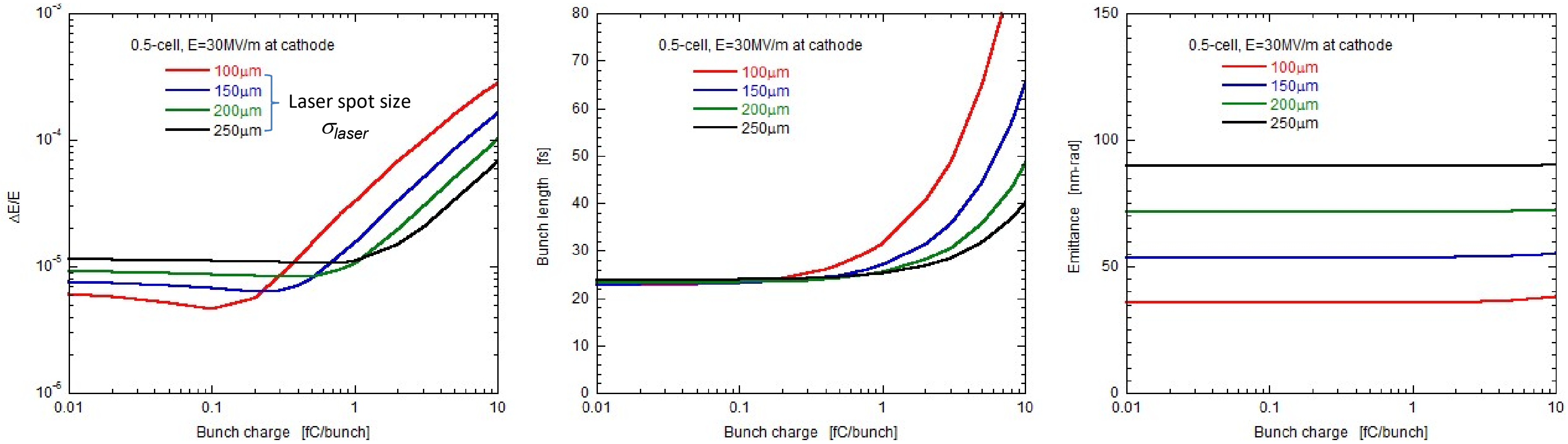
Simulated by GPT

Parameters	$E_{cathode}$=20MV/m	$E_{cathode}$=30MV/m
Laser pulse length [fs]	100 (FWHM)	
Laser spot size [μm]	200 (rms)	
Max. rep. rate [MHz]	1300	
Lunch phase	15°	
Beam energy [MeV]	0.83	1.31
Bunch charge [fC]	1	1
Bunch length [fs]	47	26
Energy spread (*ΔE/E*)	4.1 x 10^{-5}	1.1 x 10^{-5}



➢ *At the lunch phase of 15°, the 0.5-cell SRF gun produces a short-bunch e- beam with the max. energy and small energy spread.*

Beam simulation with laser optimization

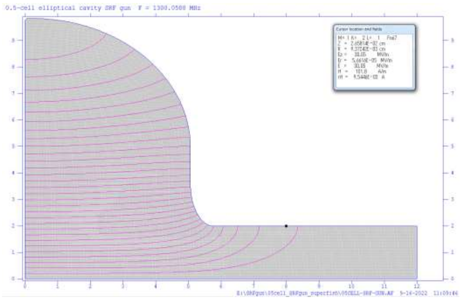


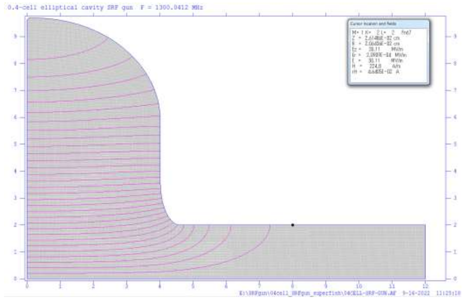
Optimize the laser spot size at $E_{cathode}$=30MV/m,

- σ_{laser}= 200μm → Q= 1fC, σ_z = 26fs with $\Delta E/E$ = 1.1x10^{-5}
- σ_{laser}= 100μm → Q=0.1fC, σ_z = 24fs with $\Delta E/E$ = 4.6x10^{-6} & ε = 36 nm-rad
- σ_{laser}= 250μm → Q=10fC, σ_z = 40fs with $\Delta E/E$ = 6.8x10^{-5} & avg. current of 13μA

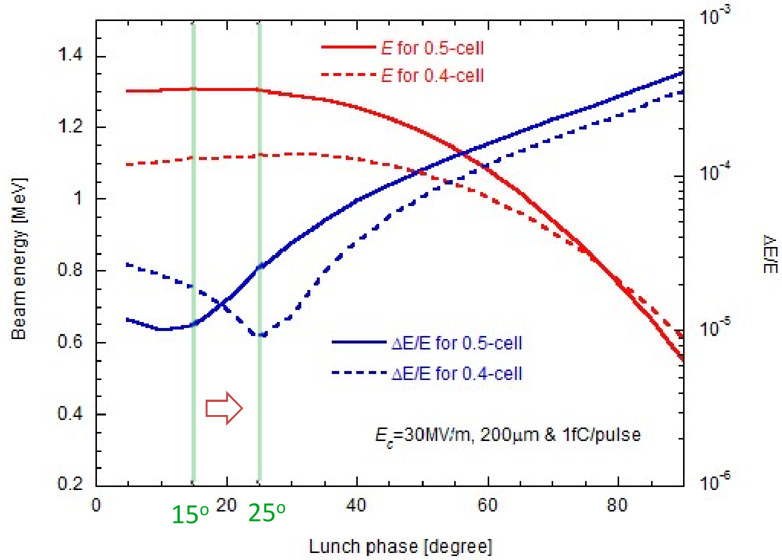
Comparable to the beam in commercial high-voltage EM.

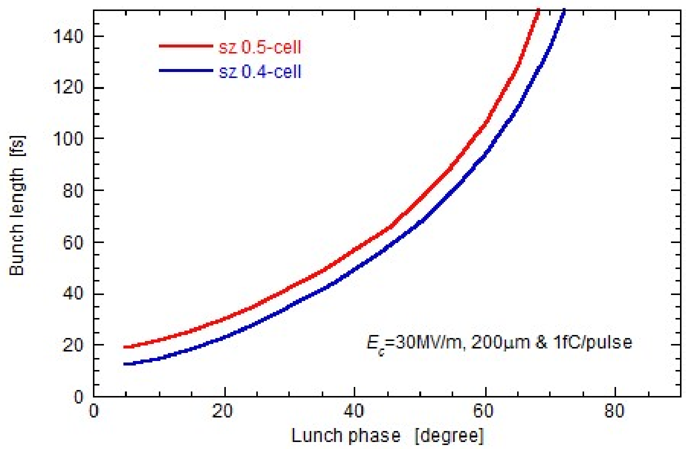
Beam dynamics: Comparison of 0.5-cell to 0.4-cell





Parameters	0.5-cell	0.4-cell
Cell length [mm]	57.65	46.12
Q	1.045 x 10^{10}	0.91 x 10^{10}
r/Q [Ω]	81.6	86.6
G=Rs/Q [Ω]	280	244
E at cathode [MV/m]	30 (E_{acc}=15MV/m)	
E_{sp} [MV/m]	29.3	31.1
Wall power dissipation [W]	1.15	1.11
Beam energy [MeV]	1.31	1.11
Lunch phase [degree]	15	25
Bunch length [fs]	26	23
Energy spread (relative)	1.1 x 10^{-5}	8.9 x 10^{-6}





Although the 0.4-cell gun can be operated at higher lunch phase to generate a short bunch and small energy-spread e- beam, **the 0.5-cell SRF gun is enough!**

Summary

- A conduction cooled L-band 0.5-cell Nb_3Sn SRF gun was proposed for ultrafast electron microscopy in collaboration with KEK and Osaka U.

  - The cavity design indicates that the RF power dissipation is 0.511W at $E_{cathode}$=20MV/m and 1.15W at $E_{cathode}$=30MV/m.

    → It is available to use a cryo-cooler cooling down the cavity to 4.2K.

  - The beam simulation shows that the 0.5-cell SRF gun can produce a 26-fs short-bunch e- beam with the energy spread of 1.1×10^{-5} at 1 fC/bunch. A high-current femtosecond e- beam is achievable with energy spread of 6.8×10^{-5} and averaged current of 13 μA.

    → Both the energy spread and the averaged current are comparable to the beam in the commercial high-voltage electron microscopy.

- Next step:

  Nb_3Sn coating, RF tuning, magnetic field shield, and conduction cooling will be discussed …