An X-band Compact Electron Linac Development For A Neutron Radiography

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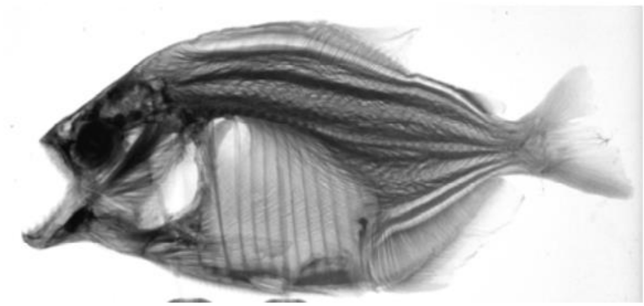
Neutron Radiography

(a)



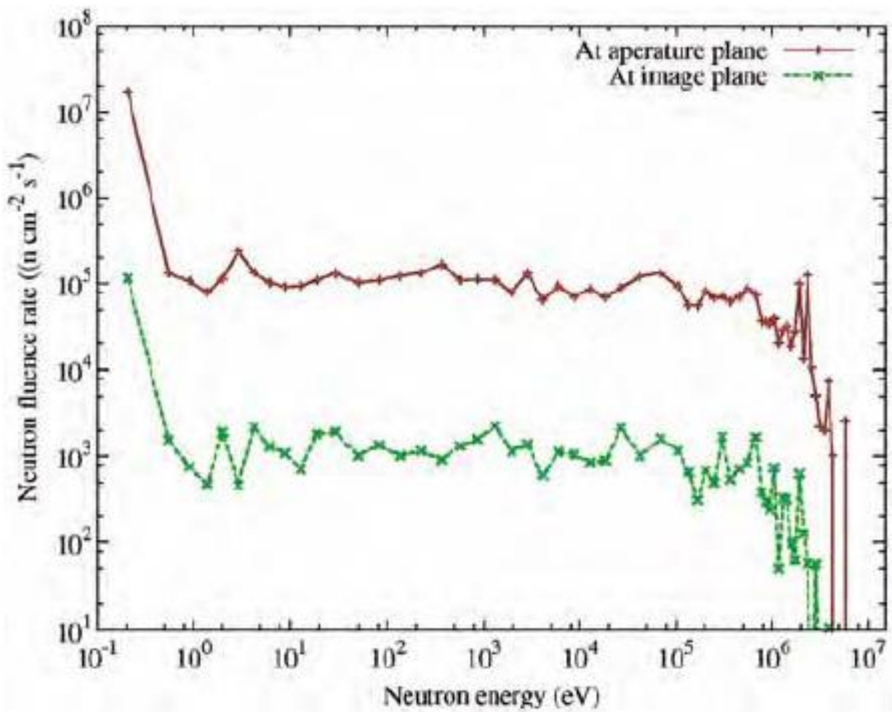
(b)

Typical neutron radiography images:
(a) injection nozzle for diesel engines
(b) dried fish (Piranha)

"Mercure from Thalwil" statue made of Roman bronze

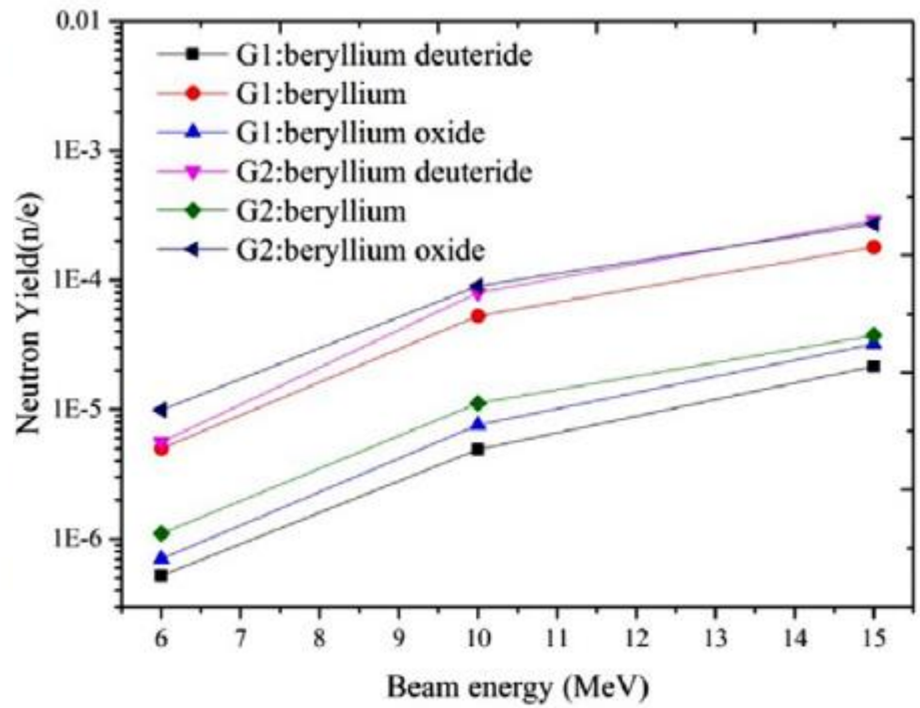
Image from IAEA-TECDOC-1604, Neutron Imaging: A Non-Destructive Tool for Materials Testing

Neutron Radiography



Neutron energy spectrum calculated at aperture and image plane

Reference from B J Patil, **FLUKA** simulation of 15 MeV linear accelerator based thermal neutron source for radiography



Neutron yield energy beam comparison of geometry G1 and geometry G2

Reference from Yoon Sang Kim, Estimation of photoneutron yield in linear accelerator with different collimation systems by **Geant4** and **MCNPX** simulation codes

For neutron radiography

- 10^5 $n/cm^2/s$ of thermal neutron is needed.
- Using Photoneutron reaction tungsten target for gamma, Be target for neutron 15 MeV, ~100 uA electron linac is needed

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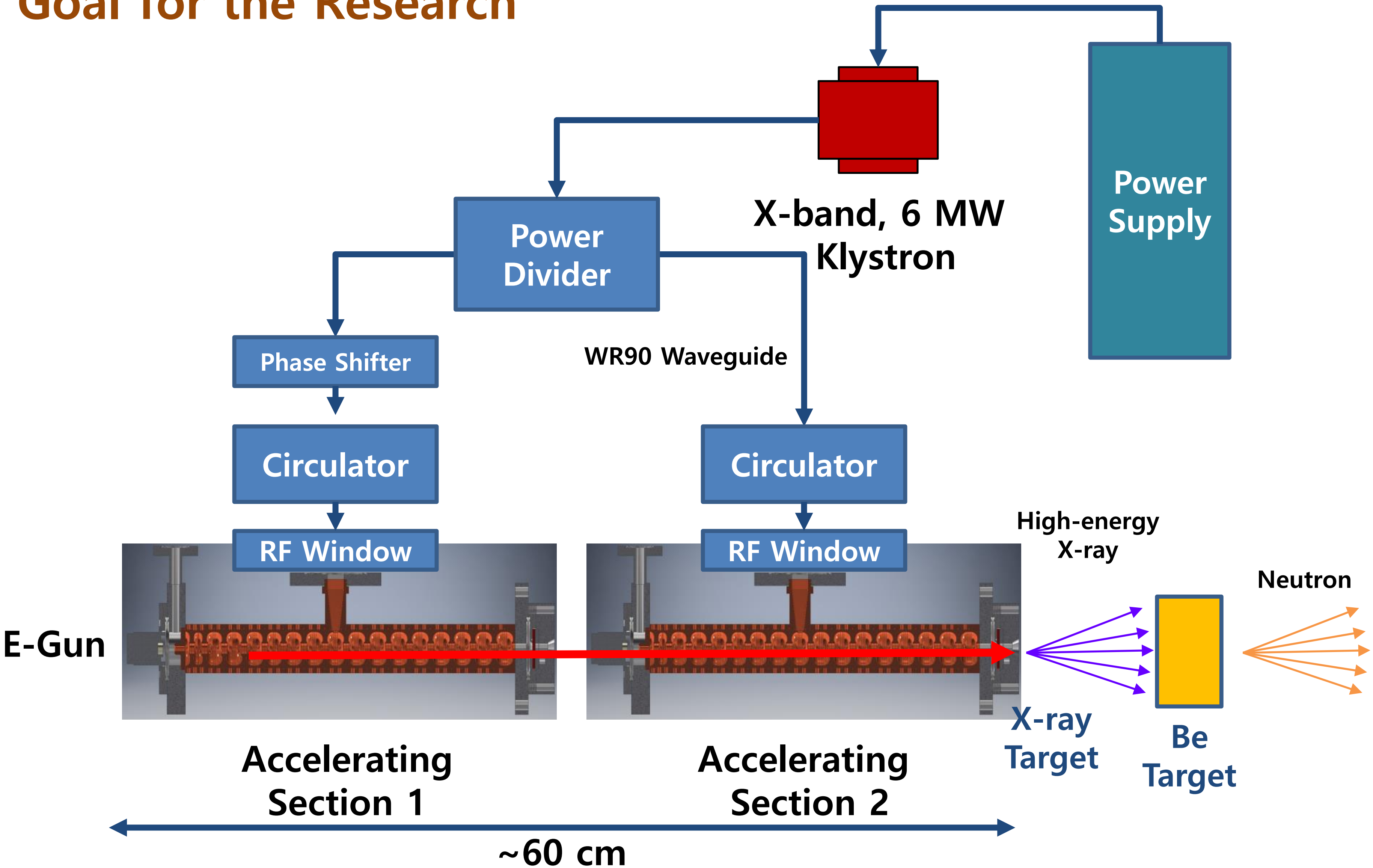
Goal for the Research



Toshiba E37113 Klystron

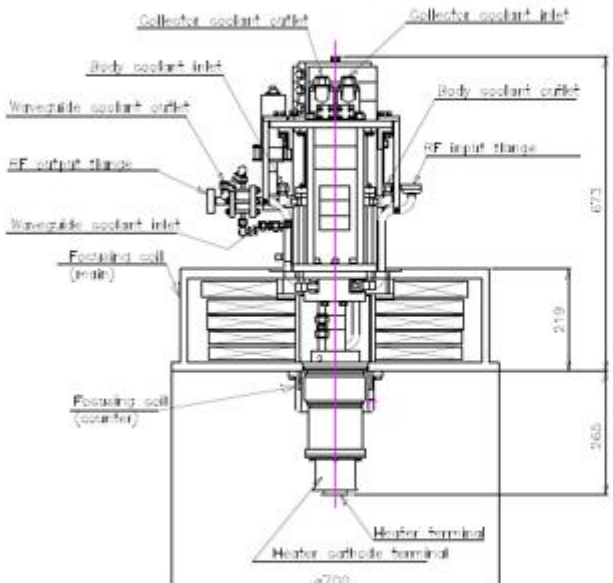


Table 1: Specification and Design Target

Parameters	Unit	Specification	Design target
RF Frequency	GHz	11.9942	11.9942
Peak RF power	MW	≥6	6
Power Efficiency	%	>40	≥45
Power Gain	dB	-	≥43
RF pulse length	μs	≥5	5
Pulse repetition rate	pps	400	400
RF average power	kW	≥12	12
Peak beam voltage	kV	-	≤175
Peak beam current	A	-	≤115
Output cavity type	-	-	3 cell
Number of window	-	-	one
Waveguide size	-	-	WR-90

Data from Yoshihisa Okubo, DEVELOPMENT OF AN X-BAND 6 MW PULSED KLYSTRON, Toshiba E37113 Klystron

Requirements of the Electron Linac

Parameters	Value
Operating Frequency	11.9942 GHz
Input RF power (pulsed)	< 5 MW
Pulse Length	4 us
Duty Factor	0.002
Output Beam Current(Pulsed Maximum)	50 mA
Average Beam Current	100 uA
Output Beam Energy	15 MeV
Effective Shunt Impedance per Unit Length	150 MΩ/m
Structure Type	Side-coupled Cavity
Length of the Accelerating Structure	~ 60 cm

Design Process of the Electron Linac

Compact Electron Linac Design

1st Stage • 2nd Stage • 3rd Stage • 4th Stage

1st Stage: Gathering Information

Limitations
- Size
- Thickness
- Length

System Requirement
- Beam energy
- Beam Current
- Beam size
- Frequency
- RF Power

2nd Stage: Single Cell Design

Maximize shunt impedance

Genetic algorithm adapted design

3rd Stage: Beam Dynamics

Minimize beam size

Maximize acceleration

Maximize capture coefficient

4th Stage: Full Cell Design

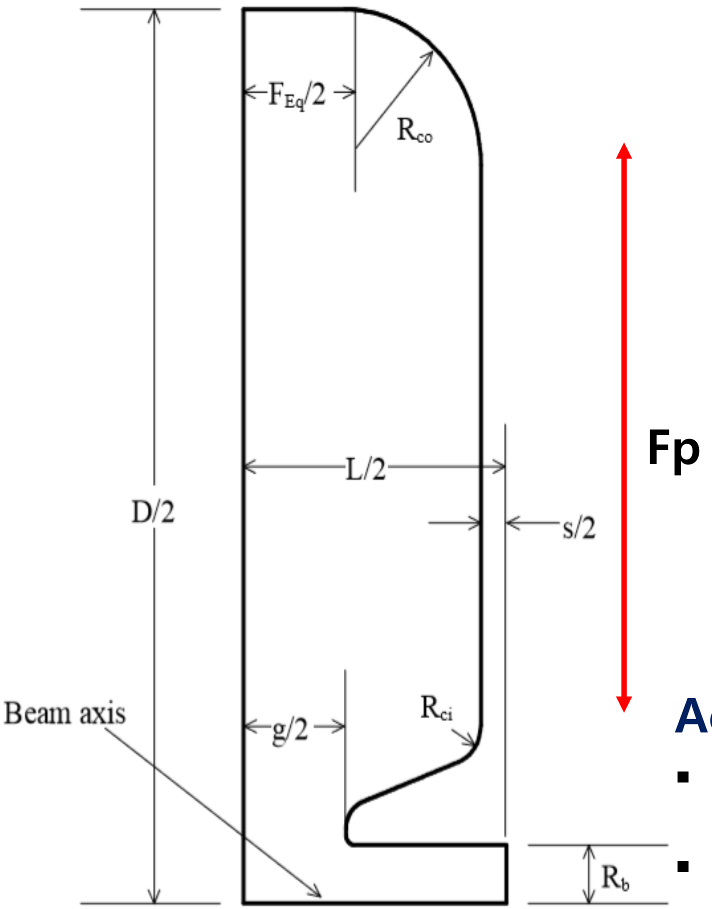
Side-coupling cell design

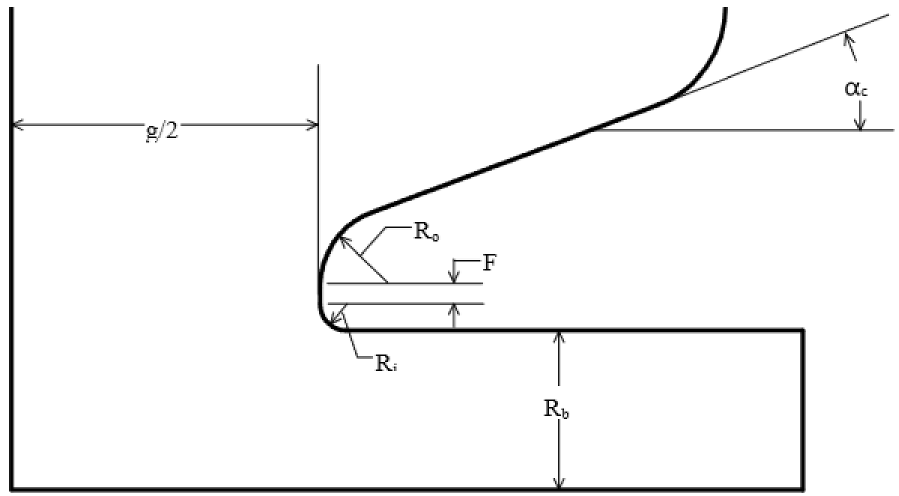
RF power coupler design

Whole cell simulation

Representative Cell Design

Parameters to be Concerned



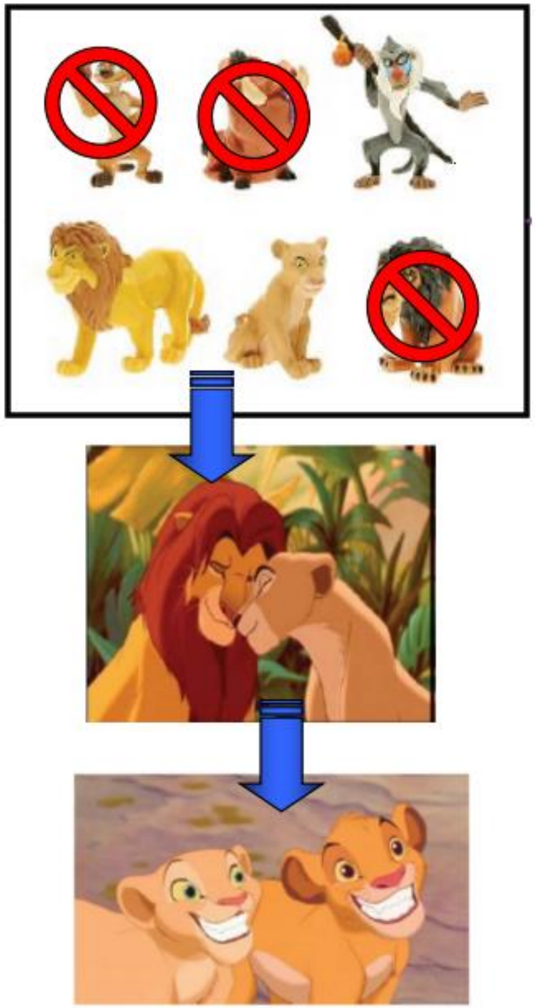


Accelerating Cell Optimization

- Total **11** parameters are controlled simultaneously in 1 cavity module during optimization process
- Usually optimal RF cavity design depends on designer's experience or can be found using parametric searching method.

Things About Genetic Algorithm

Mimicking the Nature – Biological Evolution



Population

↓

Mating Pool

↓

Selecting Mates

↓

Mating Process

↓

Offspring

↓

New Population

Applying to Computing Algorithm

Selection

Crossover

Mutation

Generation

Genetic Algorithm

Pseudo-code of the Genetic Algorithm

Procedure of Genetic Algorithm

Set k=0;

Create an initial population ***P***(k) – generate individuals;

Evaluate ***P***(k);

While <the termination conditions are not met>

    Set k=k+1;

    Reproduce mating pool $\tilde{P}$(k) from ***P***(k-1) using tournament selection;

    Crossover $\tilde{P}$ (k) to form a tentative population ***P***(k);

    Mutate $\tilde{P}$(k) to form the new population ***P***(k);

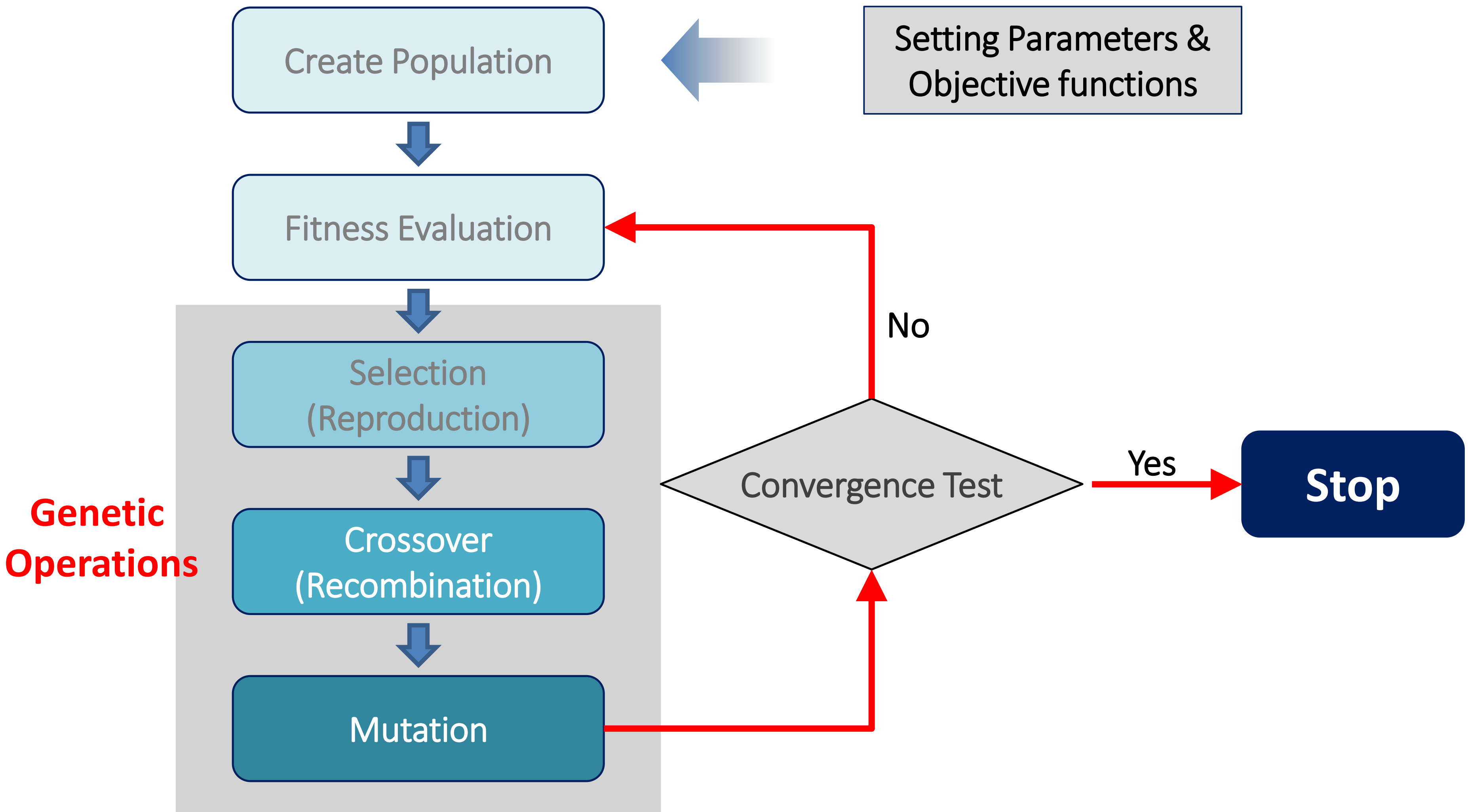
    Evaluate ***P***(k);

End While

Output the solution;

Genetic Algorithm

Overall Procedures of the Genetic Algorithm



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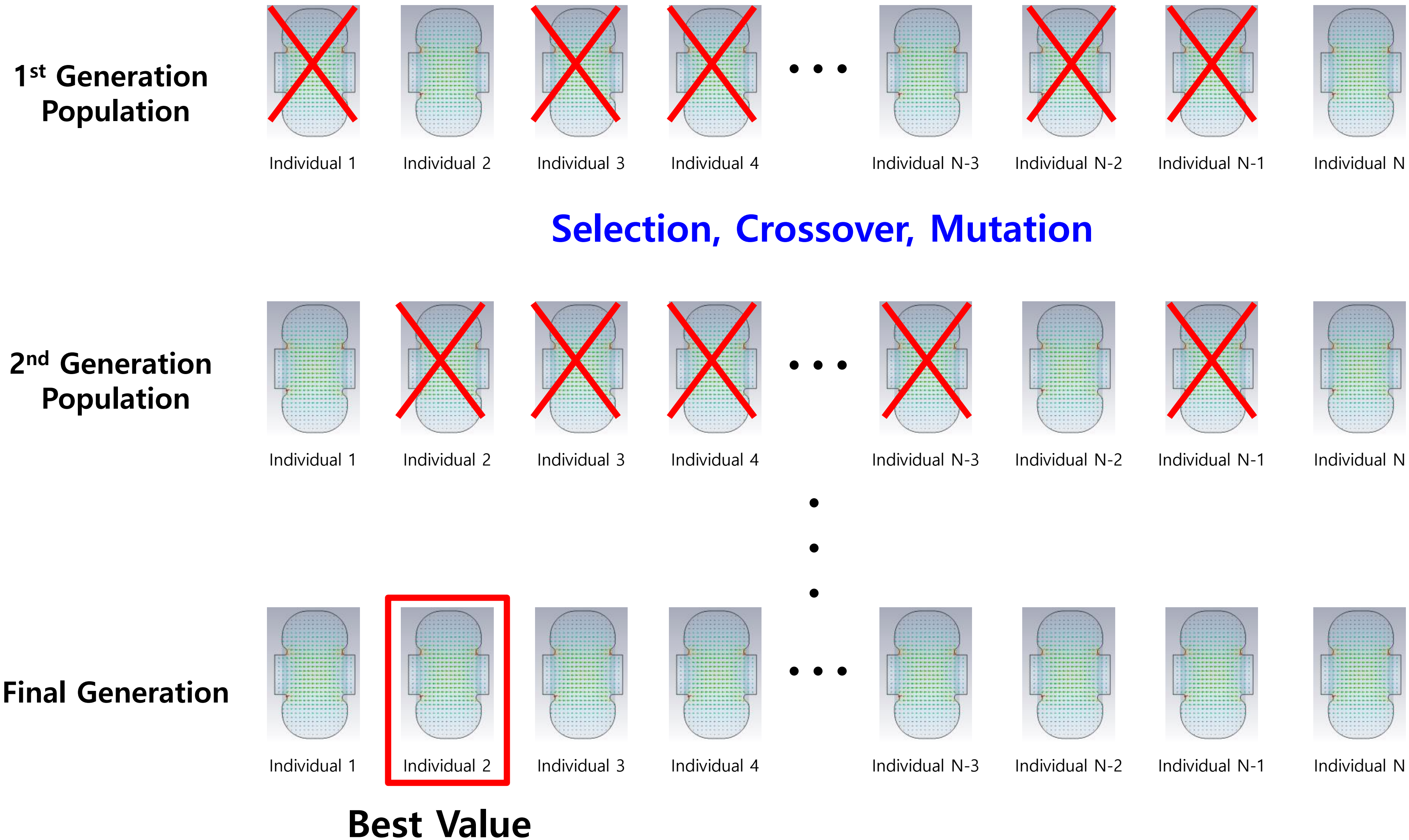
Genetic Algorithm

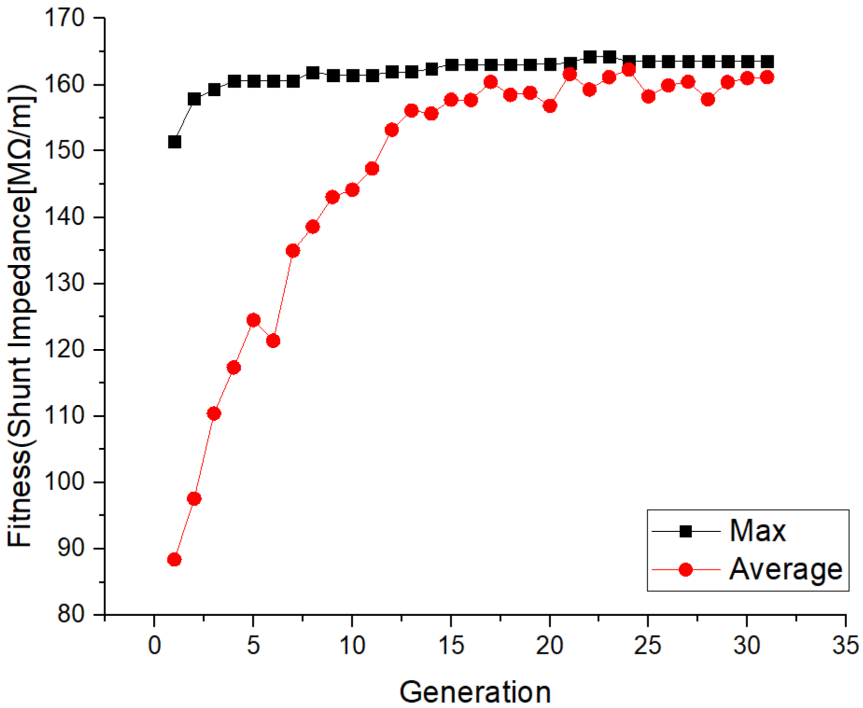
Overall Procedures of the Genetic Algorithm

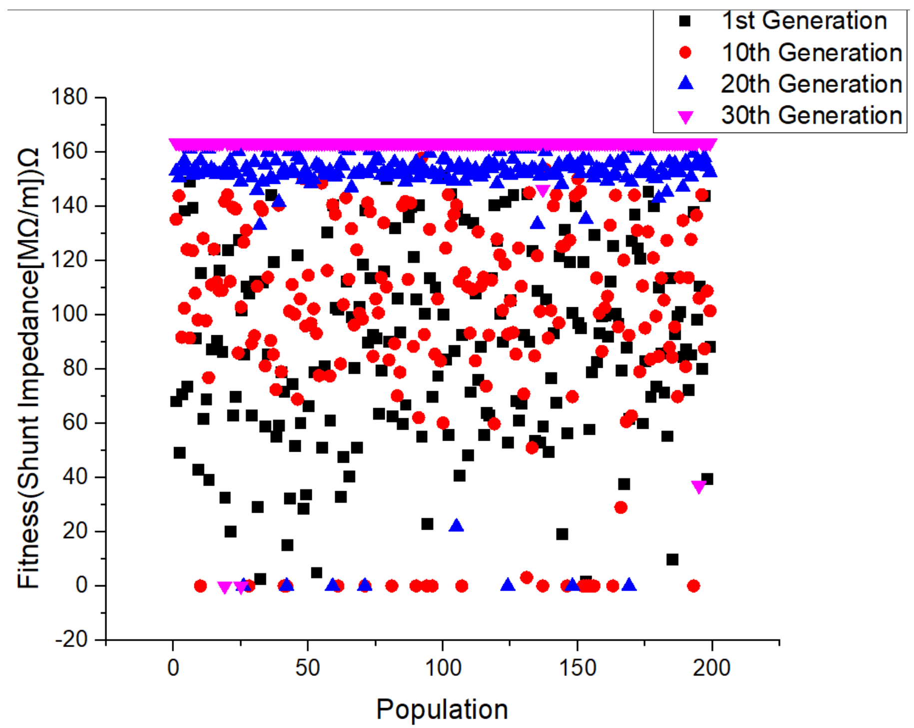
Fitness = Effective Shunt Impedance



Accelerating Structure Design by Using Genetic Algorithm

Optimized Results – Accelerating Cell





Effective Shunt Impedance Evolution Through Whole Generation

Accelerating Structure Design by Using Genetic Algorithm

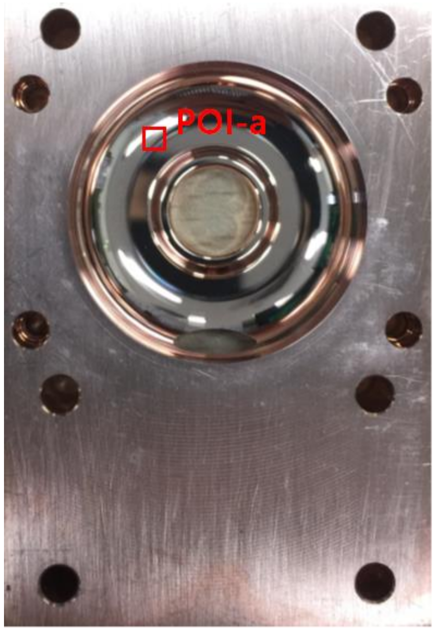
Properties of the Accelerating Cell

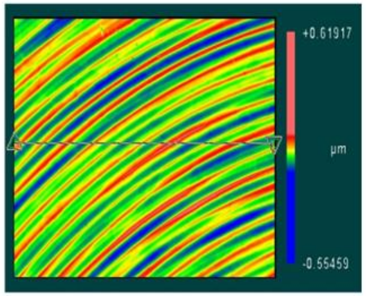
Parameters	Value
Operating Frequency	11994.19999 MHz
Transit-time factor	0.7851013
Stored energy	0.0057181 Joules
Power dissipation	98.558 kW
Quality factor	8744.63
Shunt impedance	264.534 MΩ/m
Rs*Q	249.855 Ω
Effective shunt impedance	163.055 MΩ/m
r/Q	115.607 Ω
Peak H-field	97145.1 A/m
Peak electric field	186.676 MV/m, 2.08363 Kilp.
Ratio of peak fields B_{peak}/E_{peak}	0.6539 mT/(MV/m)
Peak to average ratio of electric field	4.0711

Accelerator Fabrication

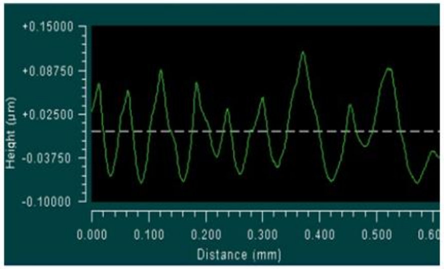
Surface Roughness

Ra = 39 nm





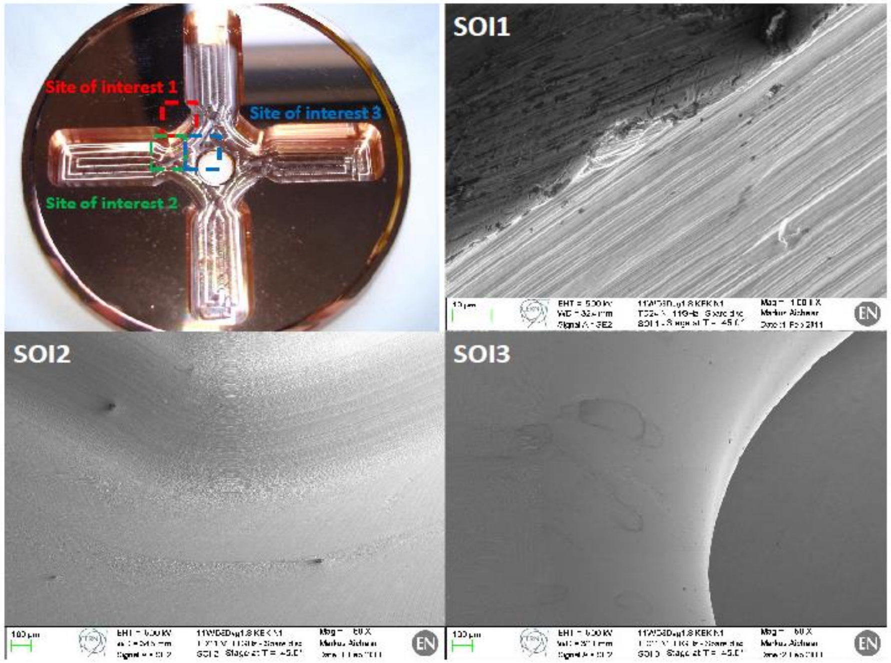
2D distribution



Roughness Profile

Developed at Sungkyunkwan University

Ra = 25 nm

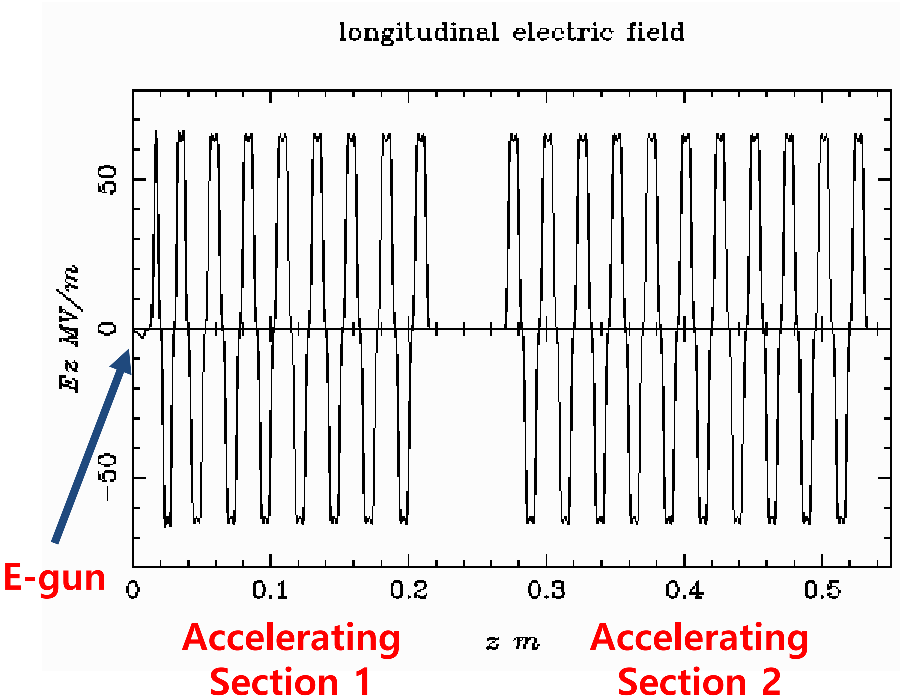


Developed at CERN

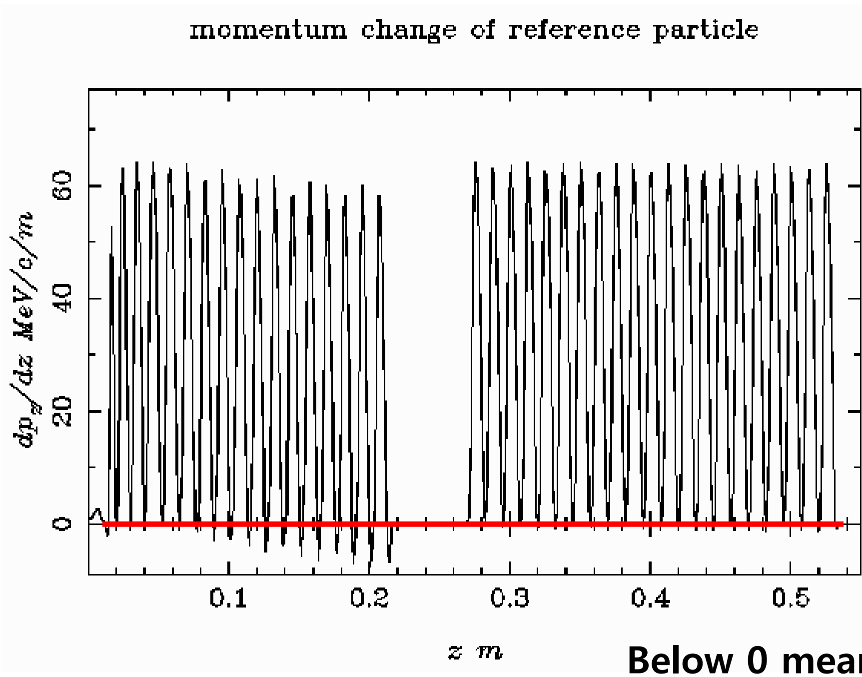
Peak electric field > 300 MV/m can be operated.

Beam Dynamics Design

Optimized Beam Line Design



Electric Field Distribution



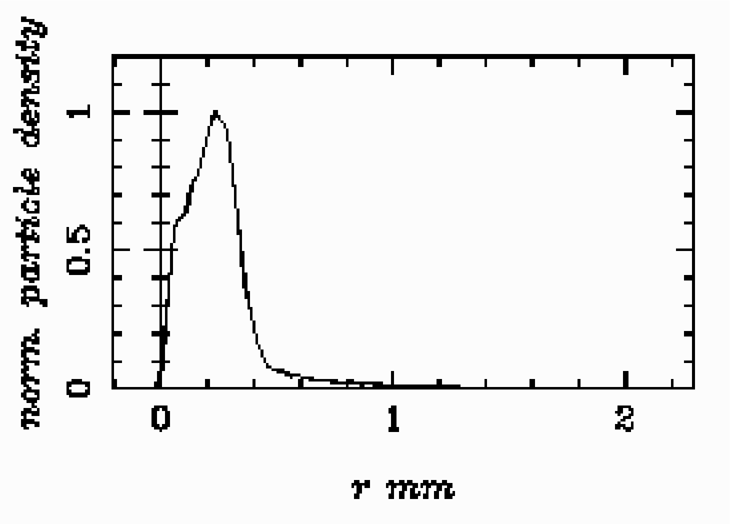
Below 0 means deceleration

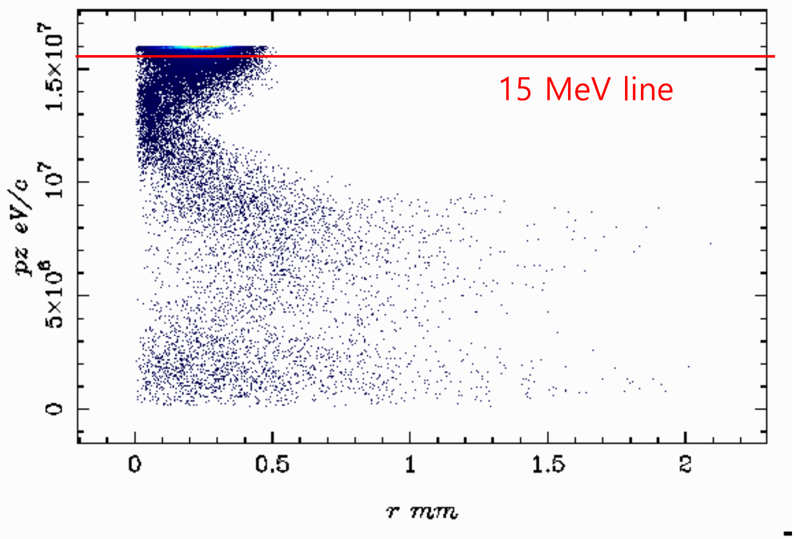
Energy Gain of the Electron Beam

Beam Dynamics Design

ASTRA Results – Multi-particle Simulation

Particles taken into account	N =	40191	
total charge	Q =	-2.0095E-02	nC
horizontal beam position	x =	-1.2416E-03	mm
vertical beam position	y =	1.4949E-04	mm
longitudinal beam position	z =	0.5758	m
horizontal beam size	sig x =	0.2156	mm
vertical beam size	sig y =	0.2178	mm
longitudinal beam size	sig z =	35.58	mm
average kinetic energy	E =	13.04	MeV
energy spread	dE =	3904.	keV
transverse beam emittance	eps x =	4.545	pi mrad mm
correlated divergence	cor x =	-0.1475	mrad
transverse beam emittance	eps y =	4.658	pi mrad mm
correlated divergence	cor y =	-0.1404	mrad
longitudinal beam emittance	eps z =	1.3596E+05	pi keV mm
correlated energy spread	cor z =	801.6	keV
emittance ratio eps y/eps x	=	0.9758	





- **Capture coefficient** is **40 %**

  100 k particles are involved to the calculation. 40,191 particles are survived
- Average Energy is 13.04 MeV, Energy spread is 3.9 MeV
- A kinetic energy of electron can be calculated from a momentum

  -> p: 15.51 MeV/c = E_k: 15 MeV for electron
- High energy particles are concentrated on the head of bunch

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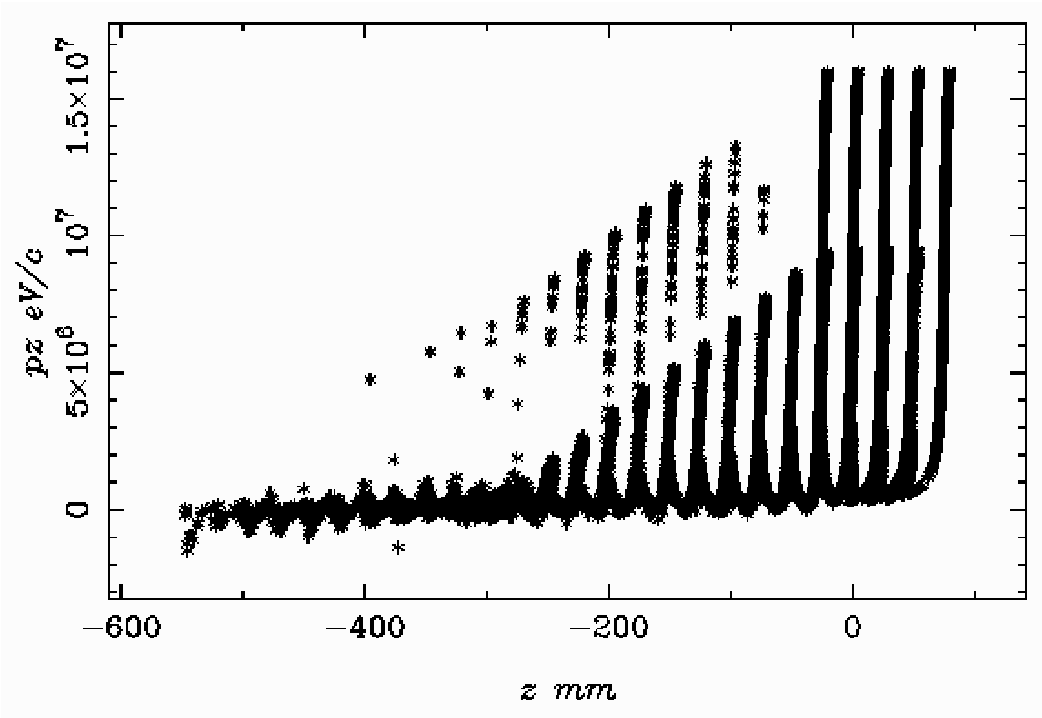
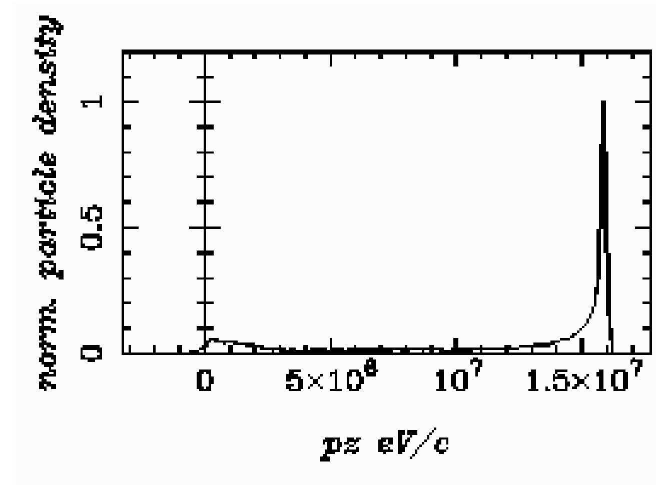
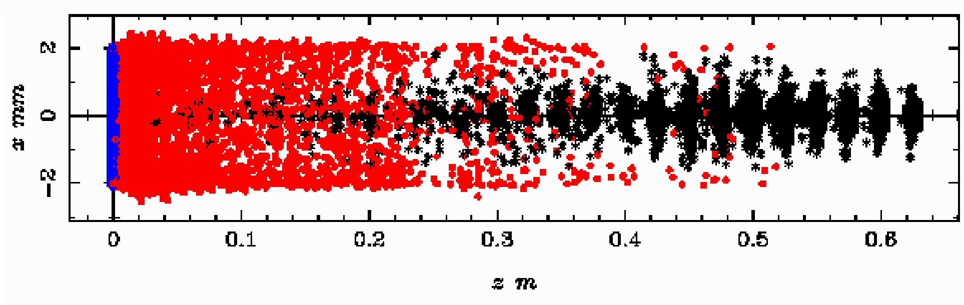
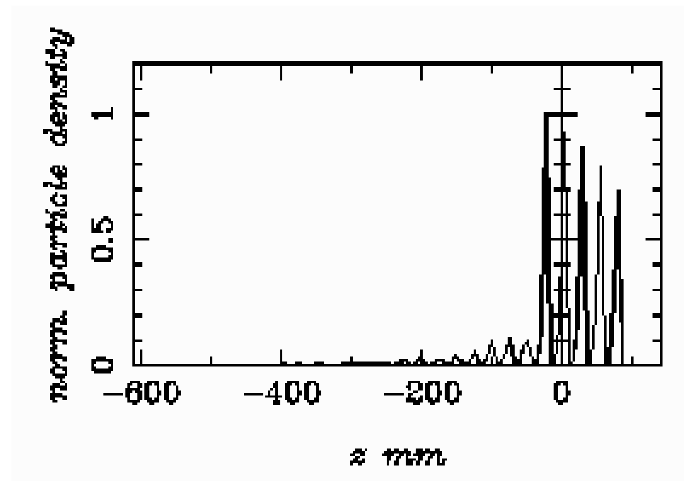
Beam Dynamics Design

ASTRA Results – Multi-particle Simulation









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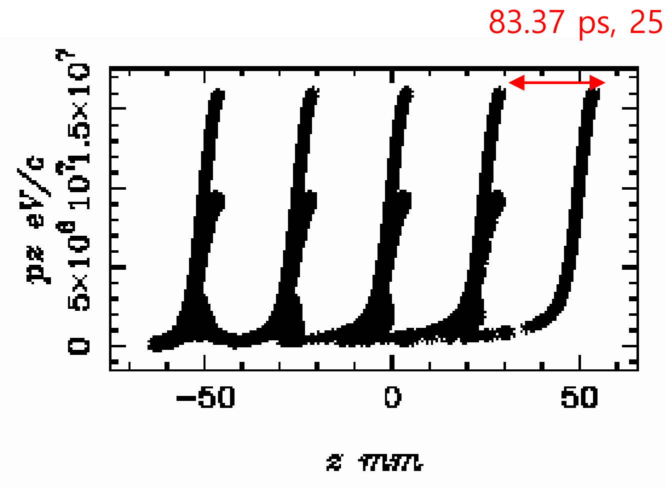
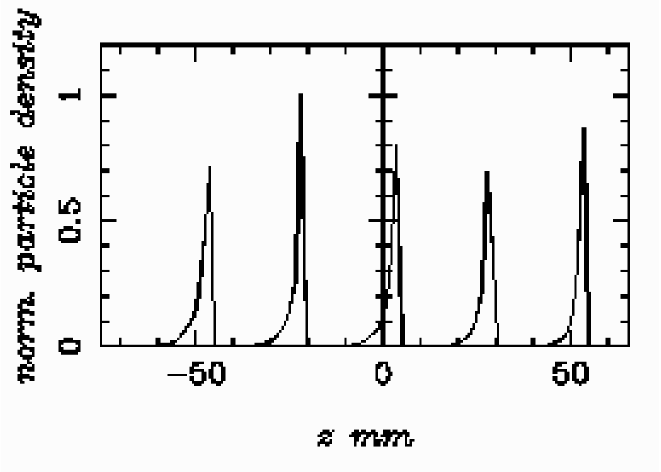
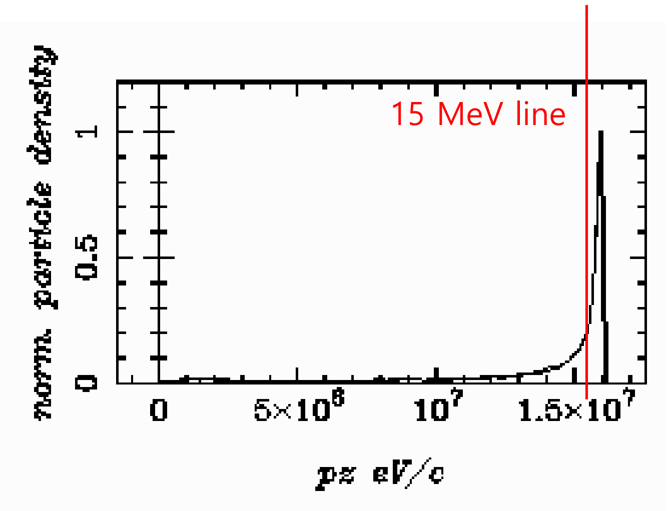
Beam Dynamics Design

ASTRA Results – Multi-particle Simulation





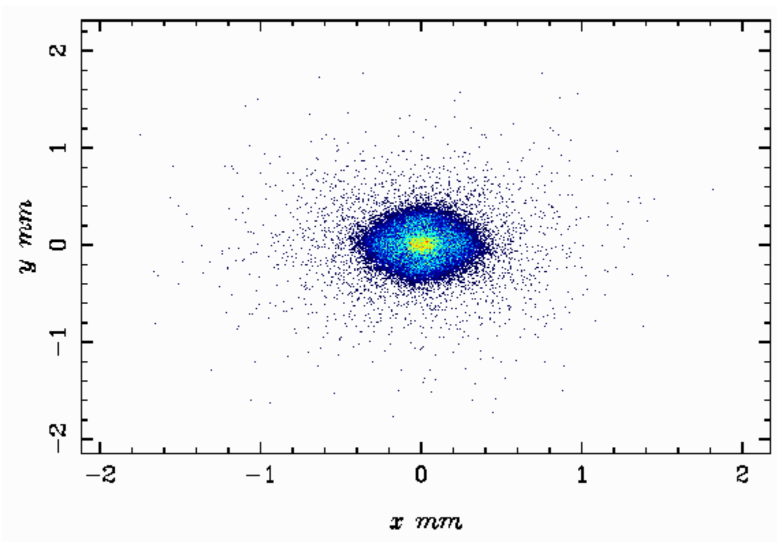
Longitudinal phase space



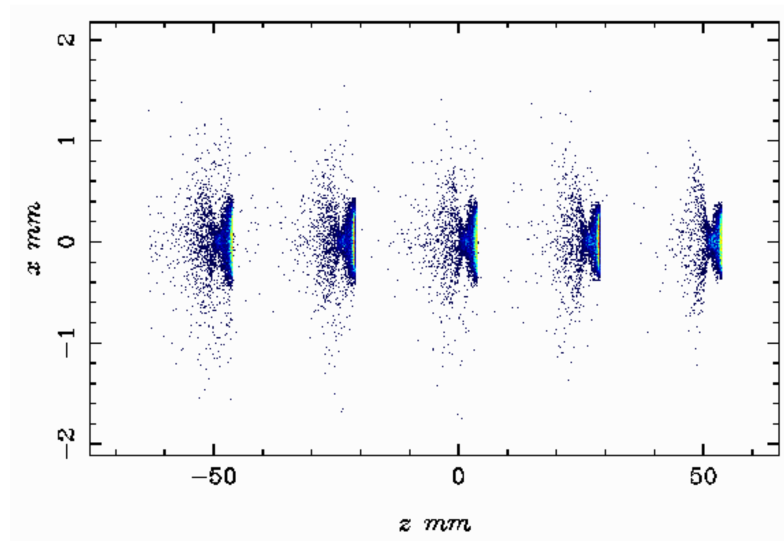
- Most of particles are concentrated at the head of the bunch and accelerated more than **15 MeV/c**
- Length of bunch in time is **83.37 ps** which is **1 RF period of 11.9942 GHz**, in other word, **25 mm** in length.

Beam Dynamics Design

ASTRA Results – Multi-particle Simulation



Transverse beam cross section



5 Beam bunches just before the target

- The size of the accelerated beam is roughly **2 mm diameter** but most of the low energy particles are **located at the halo** of the beam bunch. Therefore, those low energy particle can be eliminated to reduce energy spread and decrease beam size.

Summary

- **Compact electron linac** using an **X-band** RF technology to get a **15 MeV electron** for an X-ray generation was developed for a **compact neutron radiography machine.**
- **ASTRA** code was used for beam dynamics design stage, **Poisson/Superfish** was used for RF cavity design.
- **Genetic algorithm** was adapted for an efficient accelerating cell design.
- Design of **coupled structure** of accelerating cells and coupling cells, **power coupler** design is remained.
- For further works, **CST Microwave Studio** will be used for 3D electromagnetic simulation.

Thank you for your attention