

PHY542. Modeling photo-injectors

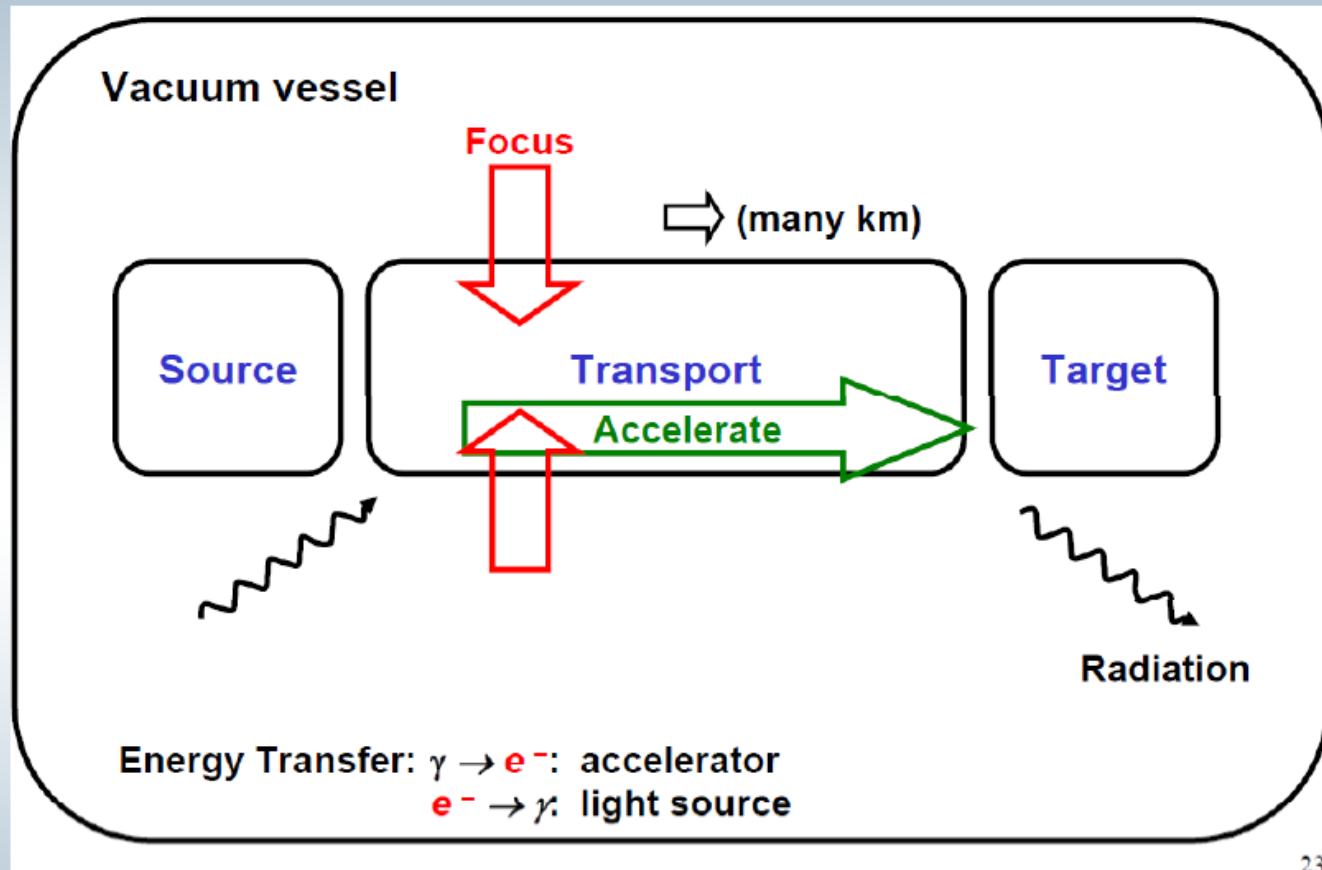
D. Kayran, M. Fedurin

February 6, 2023

Today schedule:

1. Modeling photo-injectors short introduction lecture
2. Modeling photo-injectors using ASTRA

Accelerator simplified schematic



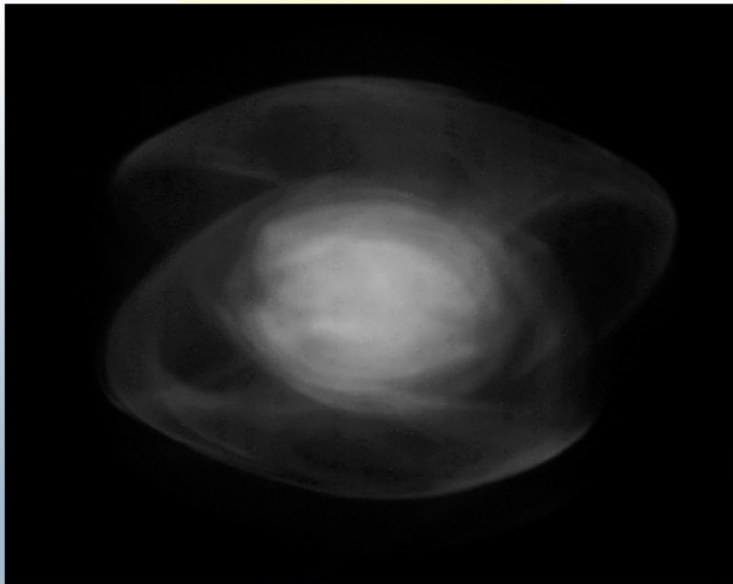
- Three main components: Source, transport, target

or users applications

Recall that beams are complex systems

- In reality beam distribution changes
- Observe exotic phenomena
- Quality degradation mainly from mutual repulsion of particles called space-charge (SC).

Irregular beam



Irregular galaxy



Recall space-charge effect

- Beam can be treated as a “continuous” charged medium

- Gauss' Law:
$$E_r = \frac{Ir}{2\pi\epsilon_0 R^2 v}$$

- Ampere's Law:
$$B_\theta = \frac{\mu_0 I r}{2\pi R^2} = \frac{v E_r}{c^2}$$

- Lorenz Force Law:
$$F_{r,sc} = q(E + v \times B) = \frac{qI}{2\pi\gamma^2 \epsilon_0 v R^2} r = C(R)r = \frac{qE_r}{\gamma^2}$$

- SC force is pushing the particles out

- SC can be strong near the beam source (small gamma)

- SC negligible at high energies!

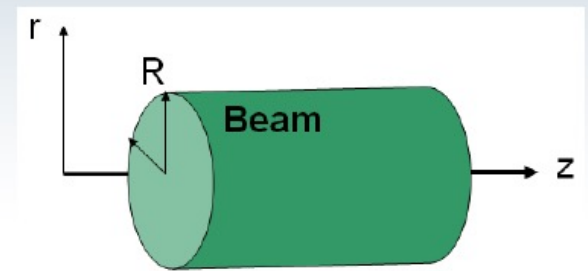
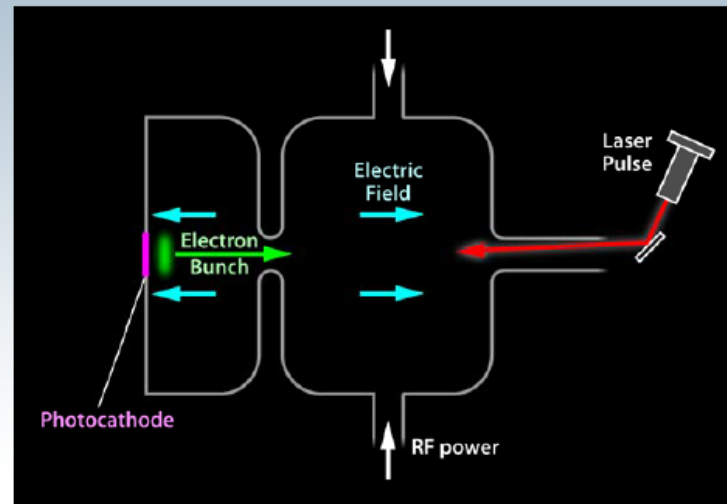


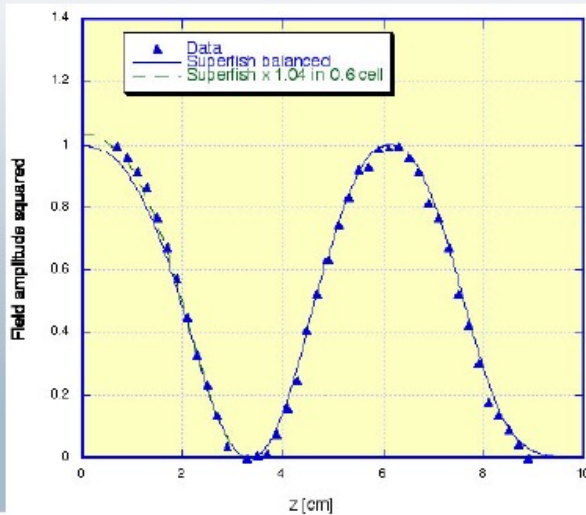
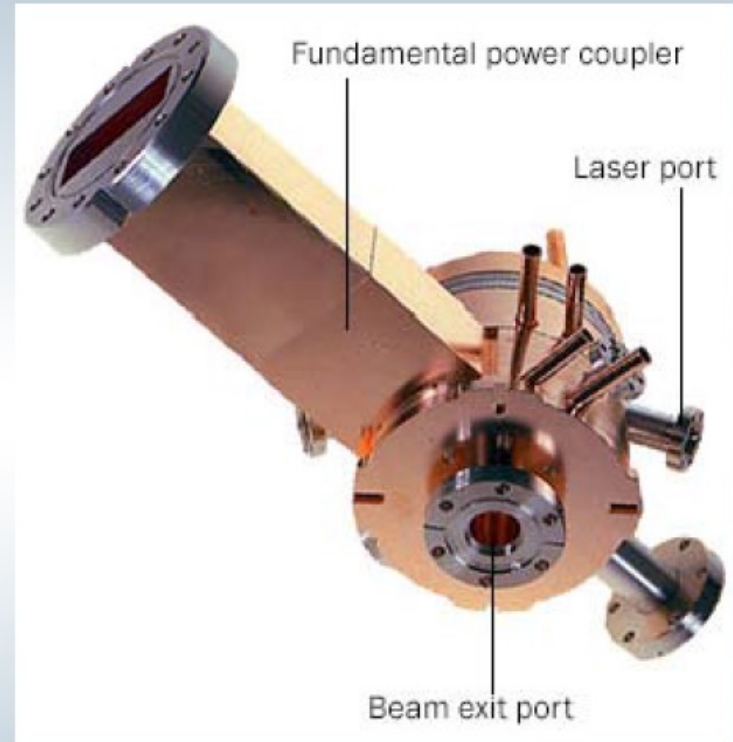
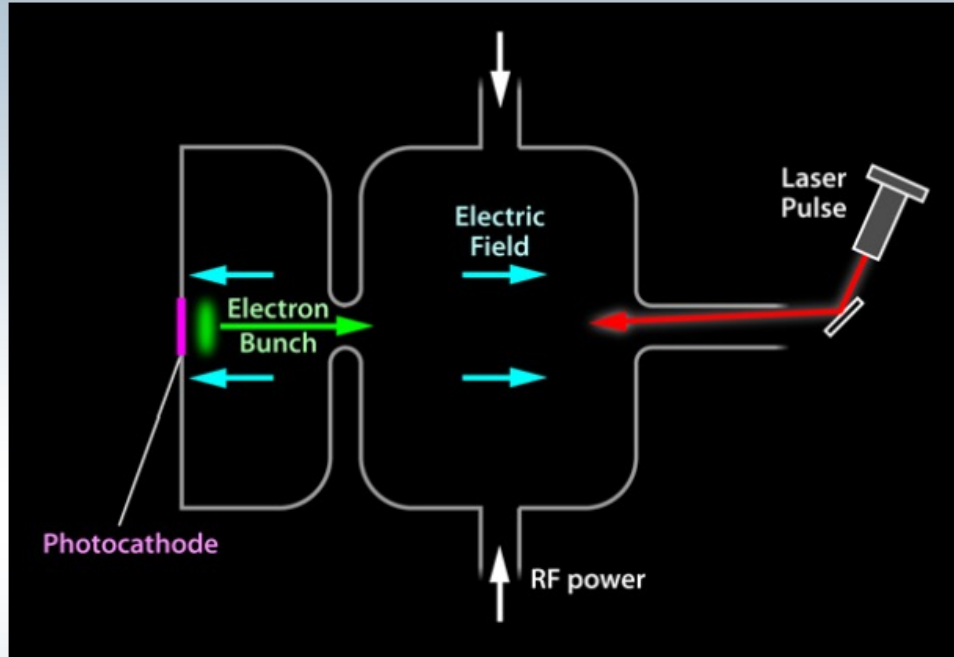
Photo-injectors



- Major components:

- **Photocathode** that releases picosecond bunches when irradiated with optical pulses from a ultrafast laser
- **Electron gun** that accelerates electron from the rest
- **Solenoid** to properly focus the beam
- **Drive laser** to gate the emission of the electrons from the photocathode
- **Linear accelerator** to further accelerate electrons
- **Diagnostic tools** such as Faraday cup or deflecting cavity

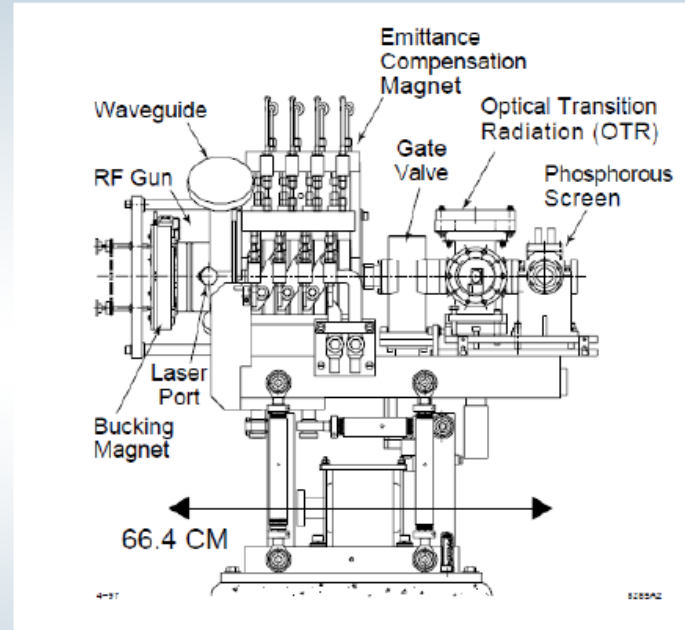
Photo-cathodes: Revisit



- Time structure of the electron beam is controlled by the laser

ATF Parameters

- 1.6 cell copper cavity
- 2856 MHz (S-Band)
- Cu cathode with $QE=4.5 \times 10^{-5}$
- Max rf gradient 110-130 MV/m
- Nd:YAG laser energy 30 microJ at 266 nm
- Laser spot size on cathode: 1 mm
- Charge: 0.001 -3 nC
- Energy: ~ 5 MeV



How do we model the beam?

$$\begin{aligned}\nabla \cdot \vec{E} &= \frac{\rho}{\epsilon_0} & \nabla \cdot \vec{B} &= 0 \\ \nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t} & \nabla \times \vec{B} &= \mu_0 \left(\vec{J} + \epsilon_0 \frac{\partial \vec{E}}{\partial t} \right)\end{aligned}$$

$$\begin{aligned}\frac{\partial \vec{p}}{\partial t} &= q(\vec{E} + \vec{v} \times \vec{B}) \\ \frac{\partial \vec{r}}{\partial t} &= \frac{c\vec{p}}{\sqrt{m^2 c^2 + |\vec{p}|^2}}\end{aligned}$$

And ... we're done, right?

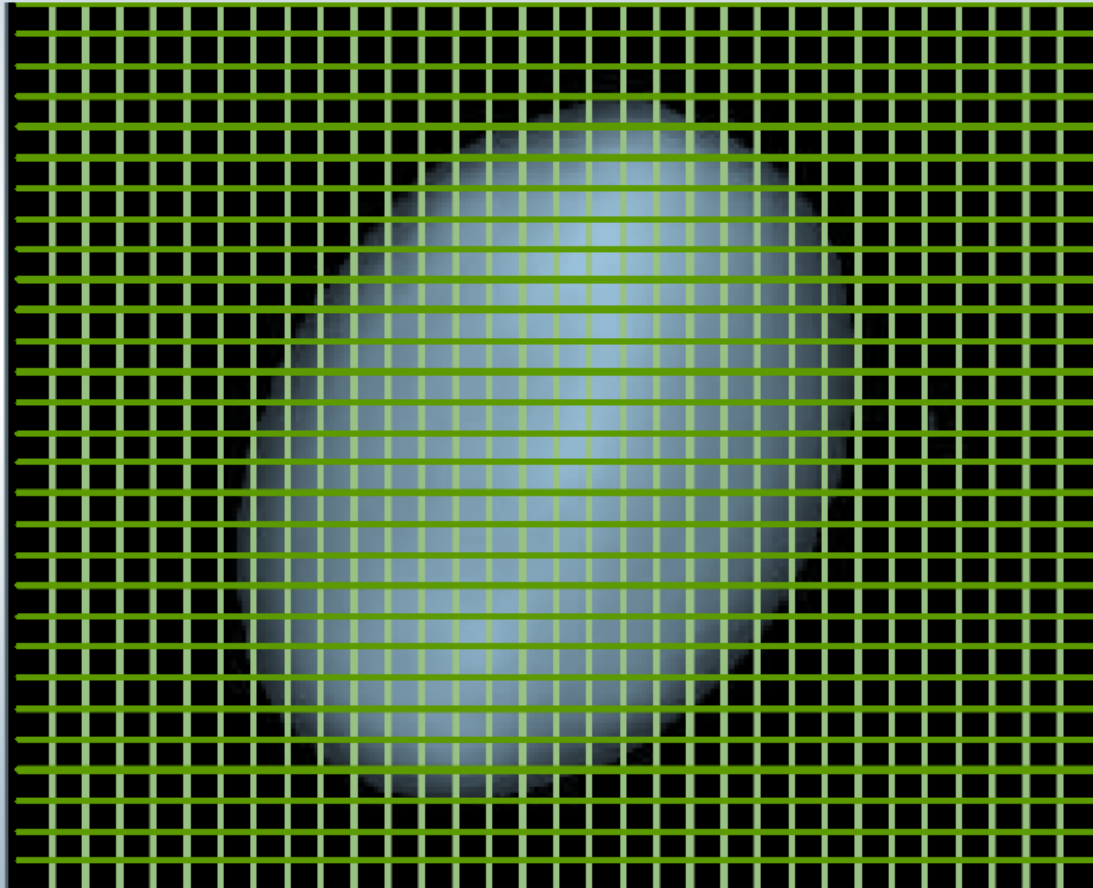
Where do the fields come from?

$$\frac{\partial \vec{p}}{\partial t} = q(\vec{E} + \vec{v} \times \vec{B})$$

- Generally, E and B are or can be
 - Functions of both position and time
 - Generated by sources:
 - Outside the beam (magnets)
 - Generated by the beam itself (space-charge)
 - Arise as a result of the structures and elements the beam transverses (wakefields synchrotron radiation)

Approaches to modeling

Particle—in-cell codes (PIC codes)



PIC codes

Particle-in-Cell

- Place a grid over the simulation space
 - Find E, B on the grid points
 - external elements
 - fields from the beam
 - Extrapolate and apply to the beam
 - Integrate to advance the particle positions and momenta, fields
- Pros
 - somewhat intuitive
 - in principle, accurate to any desired order
 - does not rely on analytic description of the beam or elements of the accelerator
 - Cons
 - tends to be rather slow
 - large number of grid points
 - small timesteps
 - hard to model an entire machine
 - practically, still needs analytic models for “external” fields
 - getting the physics right can be challenging

Many codes are available

Some are free or need Nat.Lab or University affiliations

- PARMELA
- IMPACT, (and modifications -T and -Z)
- TRACK

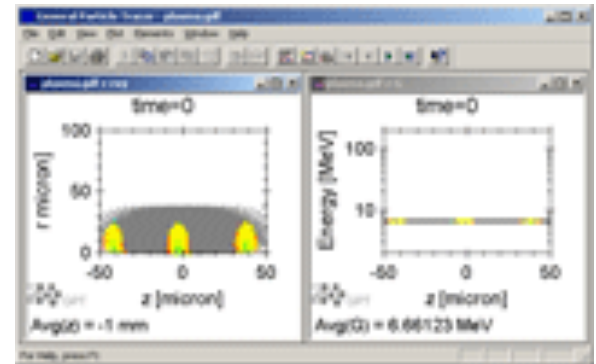
Some require license

- GPT (<http://www.pulsar.nl/gpt/>)

and many, many others

For this course we will introduce

- ASTRA <https://www.desy.de/~mpyflo/>
- OPAL <https://gitlab.psi.ch/OPAL/src/-/wikis/home>



Introduction to OPAL/SIREPO

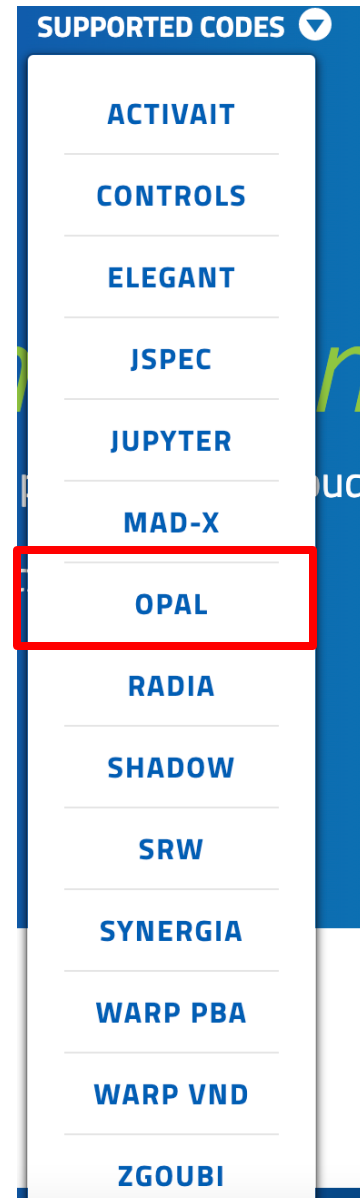
M. Fedurin

<https://www.sirepo.com/en/apps/particle-accelerators/>

The Sirepo scientific gateway offers browser-based GUIs that support and enhance legacy codes such as Radia, elegant, MAD-X, SRW, **Opal**, and more. Basing our platform in the cloud means that you can share your simulations with others immediately and easily.

Object Oriented Parallel Accelerator Library (*OPAL*)

<https://gitlab.psi.ch/OPAL/src/-/wikis/home>



ASTRA Code



A Space Charge Tracking Algorithm

The ASTRA program package can be downloaded free of charge for non-commercial and non-military use. Dissemination to third parties is illegal. DESY reserves copyrights and all rights for commercial use for the program package ASTRA, parts of the program package and of procedures developed for the program package.

DESY undertakes no obligation for the maintenance of the program, nor responsibility for its correctness, and accepts no liability whatsoever resulting from its use.

- Source: <http://www.desy.de/~mpyflo/>
- Very simple code! Commonly used for photo-injectors!

ASTRA is available for many platforms

Utility programs



[Astra for 64 Bit LINUX](#)



[Astra for Windows](#)



[Astra for macOS \(Intel\)](#)



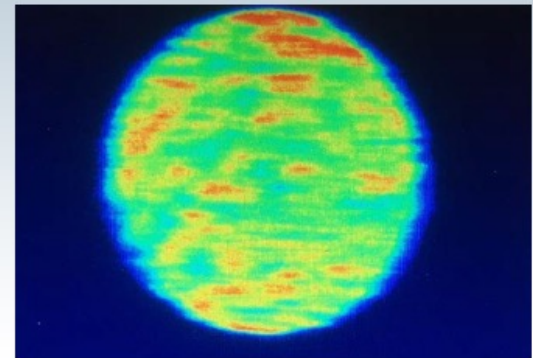
[Astra for macOS \(Apple Silicon\)](#)

ASTRA : Beam generation

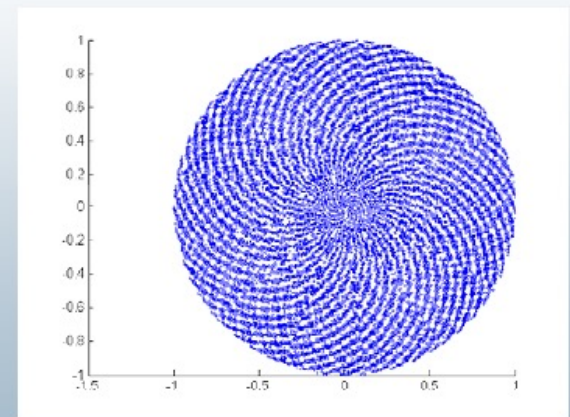
- Create the laser beam
- Sent the laser to cathode
- Produce electron beam

```
&INPUT
Add=.T,
! FILE NAME TO CREATED (ELECTRON DISTRIBUTION)
FNAME = 'astralin.part'
IPart=2000
Species='electrons'
Probe=.True.
Noise_reduc=.T.
Cathode=.T.
! BUNCH CHARGE
Q_total=0.050
Ref_zpos=0.
Ref_clock=0E-3
Ref_Ekin=0.
! LASER LONGITUDINAL PROFILE
Dist_z='gauss', sig_clock=2.0E-3, Lt=0., rt=0.
Dist_pz='i', LE=0.750E-03
! LASER TRANSVERSE PROFILE
Dist_x='radial', Lx=1.095
Dist_px='radial', Nemit_x=0., cor_px=0.0E0
Dist_y='radial', Ly=1.095
Dist_py='radial', Nemit_y=0., cor_py=0.0E0
```

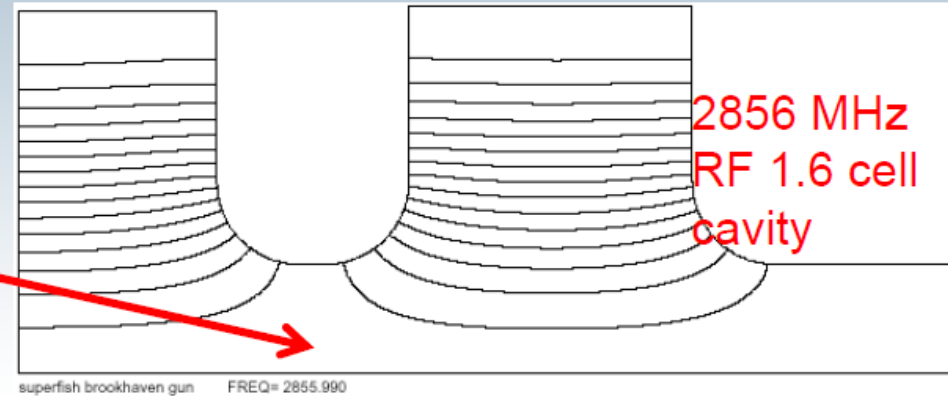
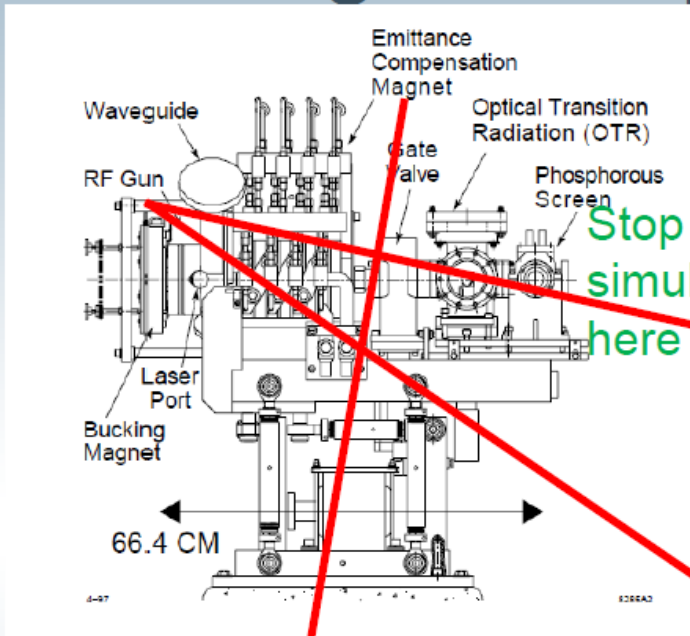
Beam in experiment



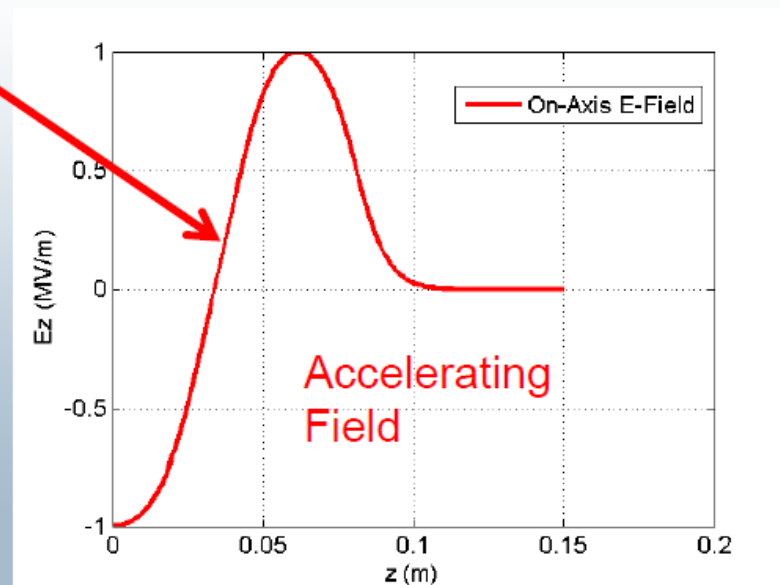
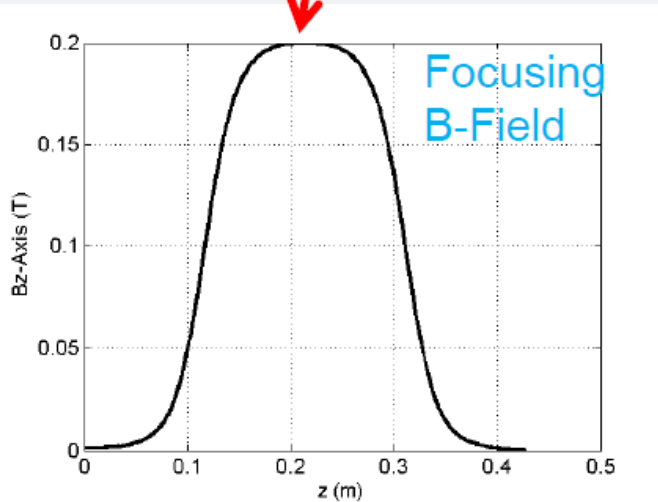
Beam in simulation



Tracking inside photocathode with ASTRA



Cathode



ASTRA: Track inside photocathode

```

&NEWRUN
Head='ATF 2 Gun'
RUN=1,
Loop=F, Nloop=0
Distribution='astralin.part',
check_ref_part=.F,
ZSTART=0.0, ZSTOP=0.50
/

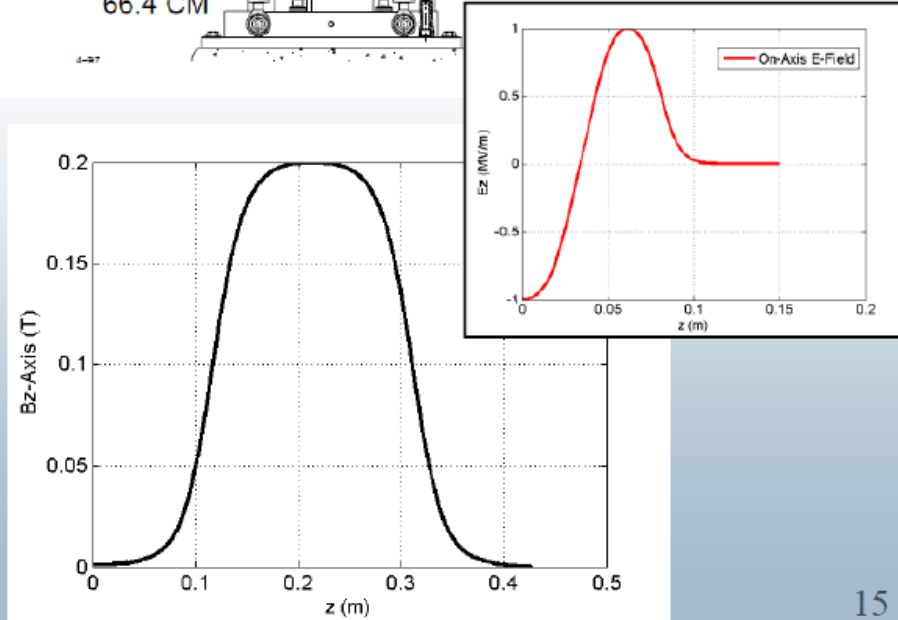
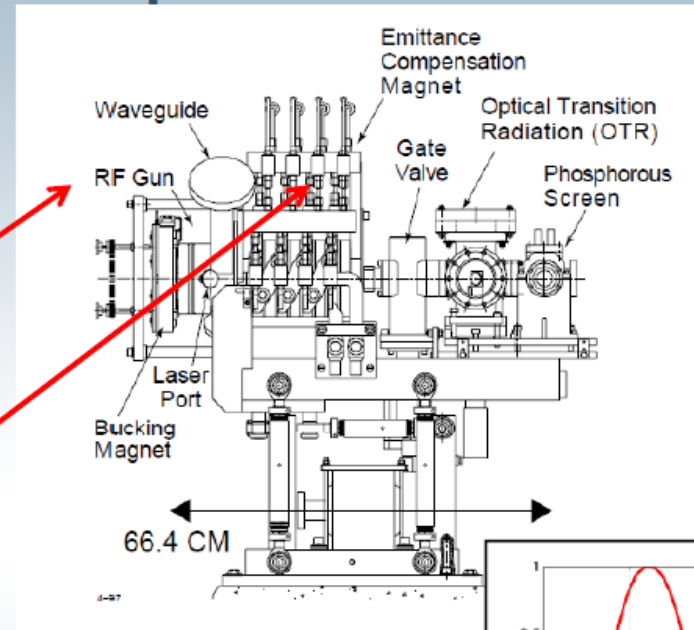
&CHARGE
! SPACE-CHARGE ON OR OFF
Loop=F
LSPCH=T
! use the following mesh for appropriate number of macroparticles
Nrad=10,
Nlong_in=12,
Cell_var=2.0
min_grid=0.4e-6
Max_scale=0.05
Max_count=10
Lmirror=.T
/

&Aperture
Loop=F
Laperl=F
File_Aperture='Aperture.dat'
/

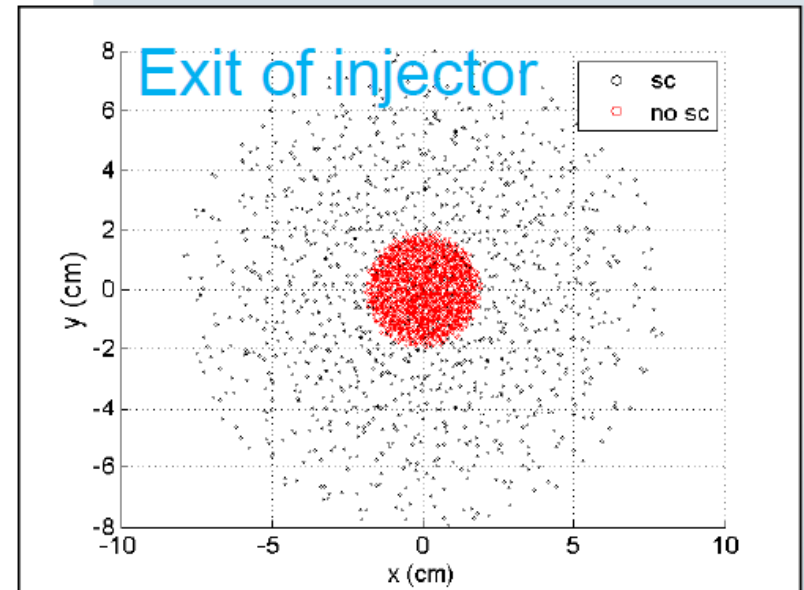
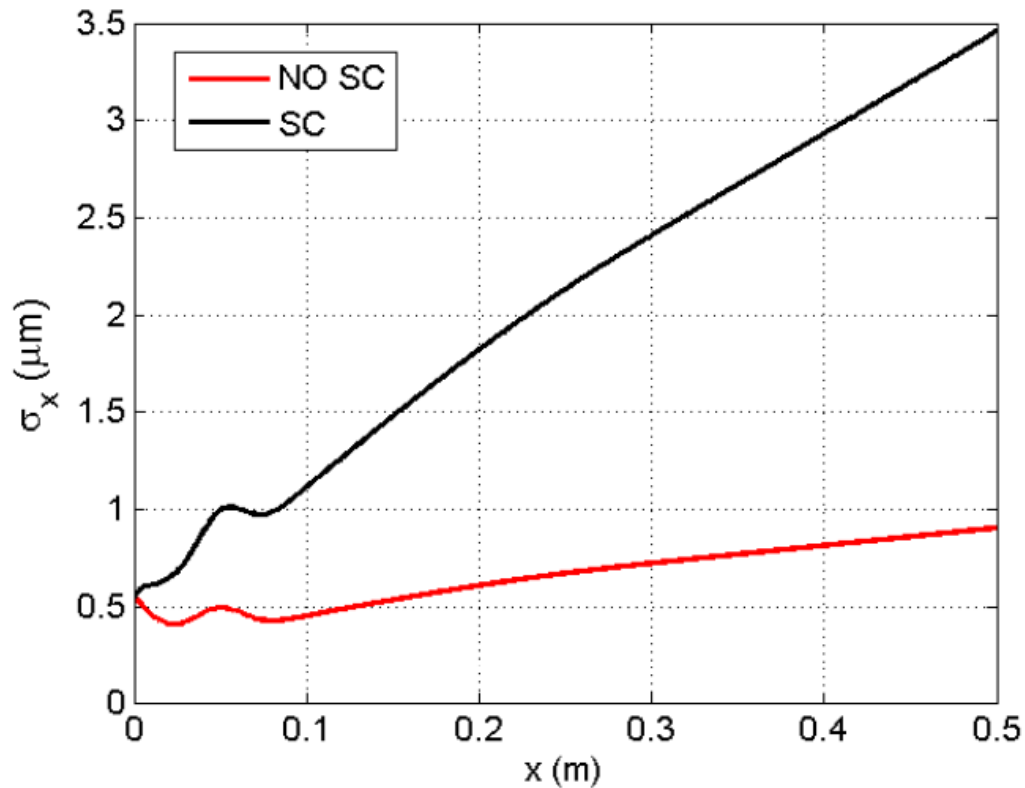
&CAVITY
! RF GUN CAVITY
Loop=.F,
LEFIELD=.T
FILE_EFIELD(1) = 'rfgunFIELD.dat', C_smooth(1)=10,
Nue(1)=2.856, MaxE(1)=110.00, Phi(1)=-12.0, C_pos(1)=0.0,
C_higher_order(1)=T
/

&SOLENOID
! COMPENSATION SOLENOID
Loop=.F,
LBFIELD=.T,
FILE_BFIELD(1)='compenSOL_axial.dat',
S_noscale=.F,
MaxB(1)=0.20, S_smooth(1)=10,
S_pos(1)=0.00, S_xoff(1)=0.0, S_yoff(1)=0.0, S_higher_order(1)=T
/
    
```

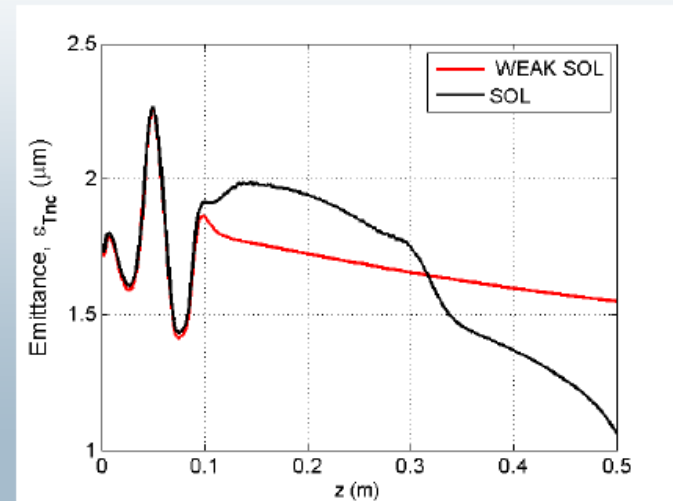
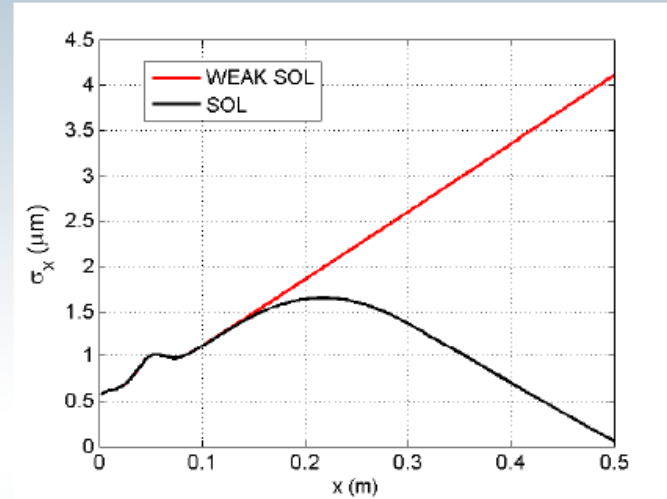
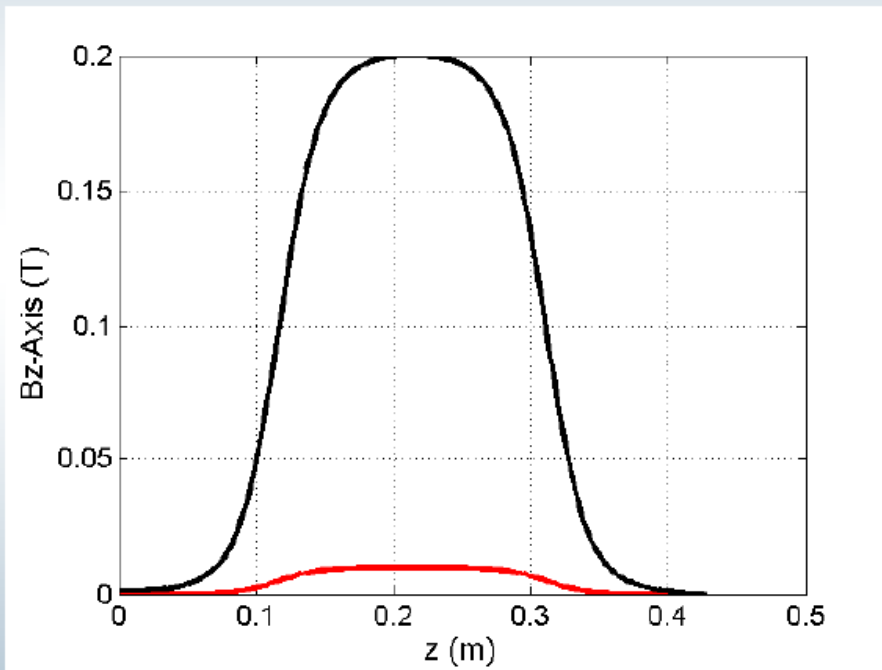
Space-Charge



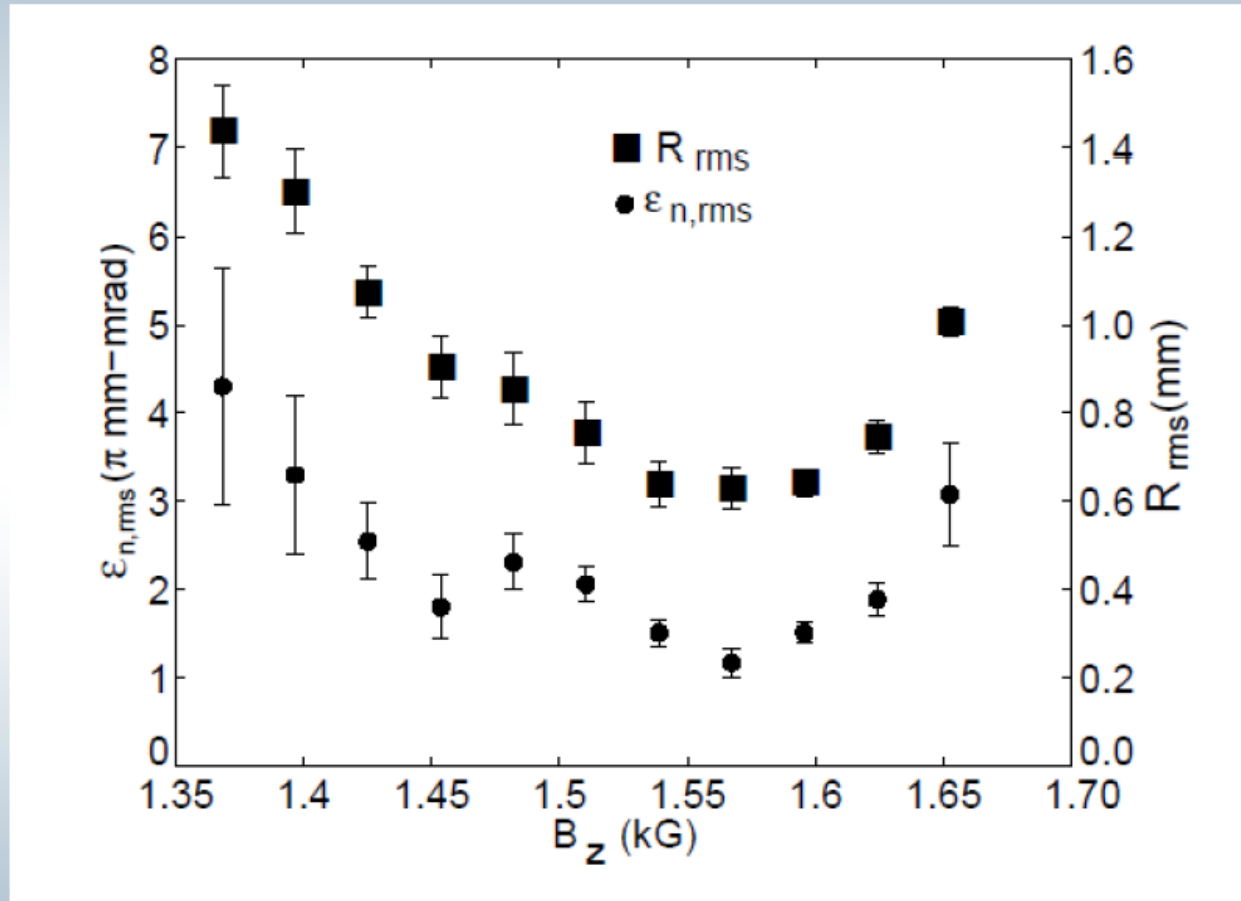
You will check space-charge effect



You will optimize focusing



You will tune the emittance



- Can you reproduce this result for the ATF injector?

COMPUTATIONAL EXERCISE #1 – PHOTO-INJECTORS

Exercise: Familiarize yourself with the ASTRA code

1. First you want to initiate the laser beam and sent it to the cathode.
2. So, please open the file *atf2_laser.in*. Set the number of particles to 2000 and make sure that the rms pulse length is set at 2 ps (*sig_clock*) and charge is at 100 pc = 0.1 nC (*Q_total*). Later you can change these parameters as you wish.
3. Please run the program *generator*. It will send the laser to the cathode and produce the electron distribution for you.
4. Type *generator atf2_laser.in* to execute the program
5. You have created your electron distribution at the cathode (should match the *FNAME* in your input deck)
6. Look at the command window: What is the transverse beam emittance? What is the beam size? What is the average energy? Please record those numbers.

COMPUTATIONAL EXERCISE #1 – PHOTO-INJECTORS

Exercise: Familiarize yourself with the ASTRA code

7. Now you will track the electron beam through the photo-injector. So please open the file *atf2_linac.in*. Make sure the distribution matches the file you have created.
8. Check the COMPENSATION SOLENOID and make sure LBFieLD=.T. T means ON and F means OFF. Note that MaxB(1)=0.10 is max field of the magnet and S_pos(1)=0.00 is the starting position. So if 0 it means it starts at the cathode.
9. Type *astra atf2_linac* to run ASTRA (suggest to leave ZEND at 0.5 m). If successful, a number of text files are created. How many particles are lost? How many go through?
10. Run *fieldplot atf2_linac.in* and look at the cavity and solenoid fields. What is the rf gradient at the cathode? What is the magnetic field on the cathode? What is the maximum value of the magnetic field?
11. Now run *lineplot*. Look at the transverse emittance and rms beam size and rest of the parameters. What is the beam energy at the exit of the gun? What is the emittance?
12. For fun, change the rf gradient and see what happens. You gain more energy?
13. Bring back the rf gradient at 110 MV/m.

COMPUTATIONAL EXERCISE #1 – PHOTO-INJECTORS

Photo-injector optimization:

1. Space-Charge Effect: Turn off space-charge by setting LSPCH=F. Run ASTRA. Record the final emittance and rms beam size. Now please turn space-charge on. Record again the numbers. What do you see now? Can you explain the result? Run the program postpro by typing *postpro atf2_linac* and look at the transverse phase-space. Is it an ellipse as we discussed in the lecture?
2. Run ASTRA with solenoid on and off. Check the rms beam size gain. What do you see? Record the emittance at the end of the channel and the peak value of the magnetic field.
3. Vary the magnetic field peak value (MaxB within 0.1-0.5 T) and record the bunch size emittance at the gun exit each time. What do you see? Make sure LBFieLD=.T
4. Make a plot of the emittance and position vs. the peak magnetic field. Find the optimum value of the field that you think works best. Can you explain why?
5. If you have time, feel free to run simulations for different bunch charges. For example, what happens when $Q=800$ pC?