

# Modeling photo-injectors

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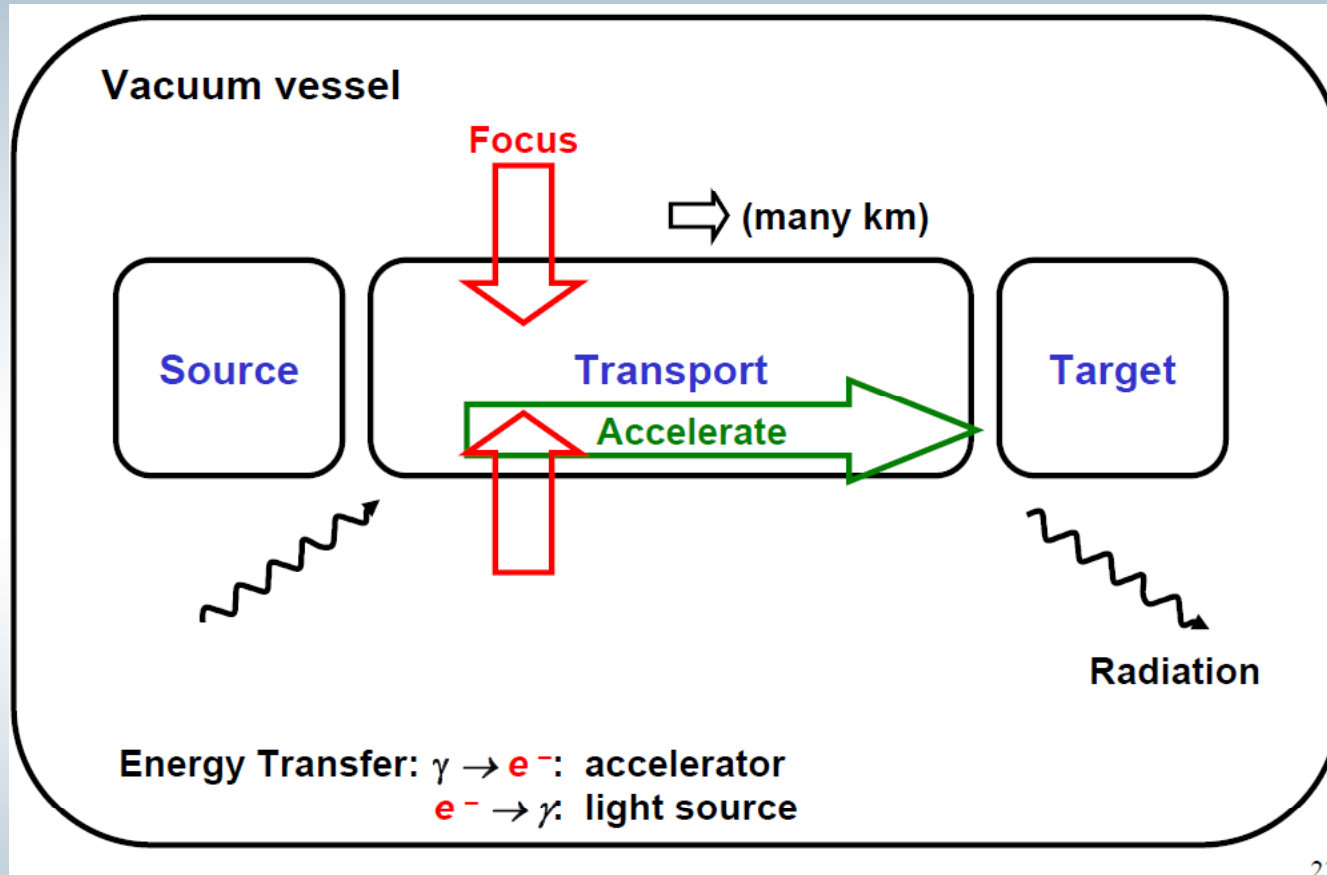
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PHY 542

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# Accelerator simplified schematic

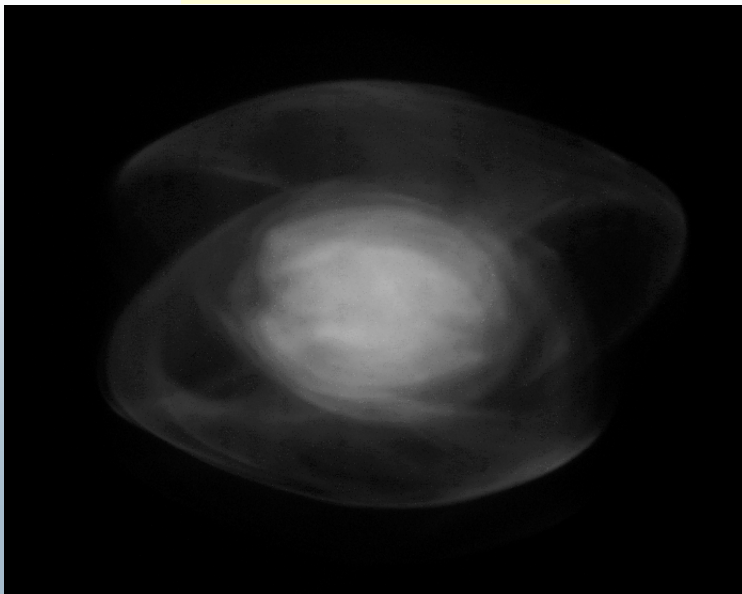


- Three main components: Source, transport, target

# 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:  $E_r = \frac{I r}{2\pi\epsilon_0 R^2 v}$

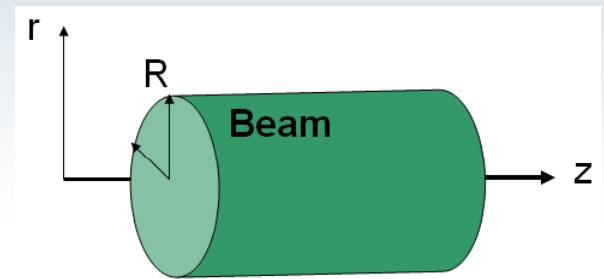
- Ampere's Law:  $B_\theta = \frac{\mu_0 I r}{2\pi R^2} = \frac{v E_r}{c^2}$

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

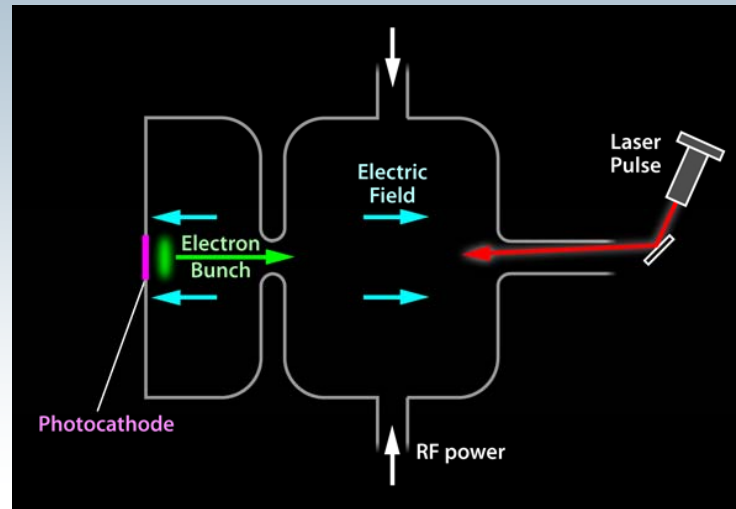
- SC force is pushing the particles out

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

- SC negligible at high energies!

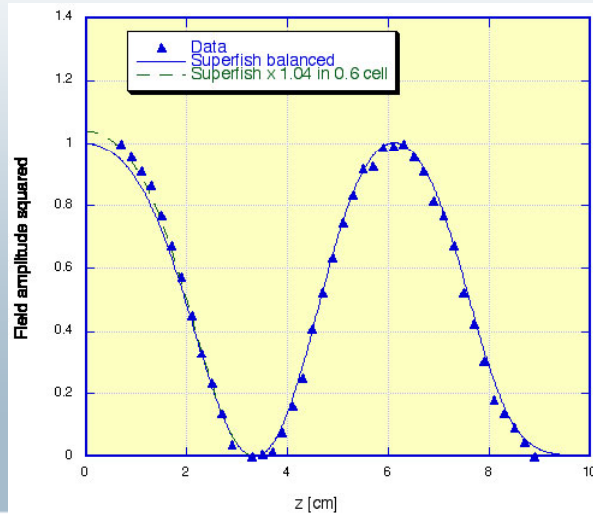
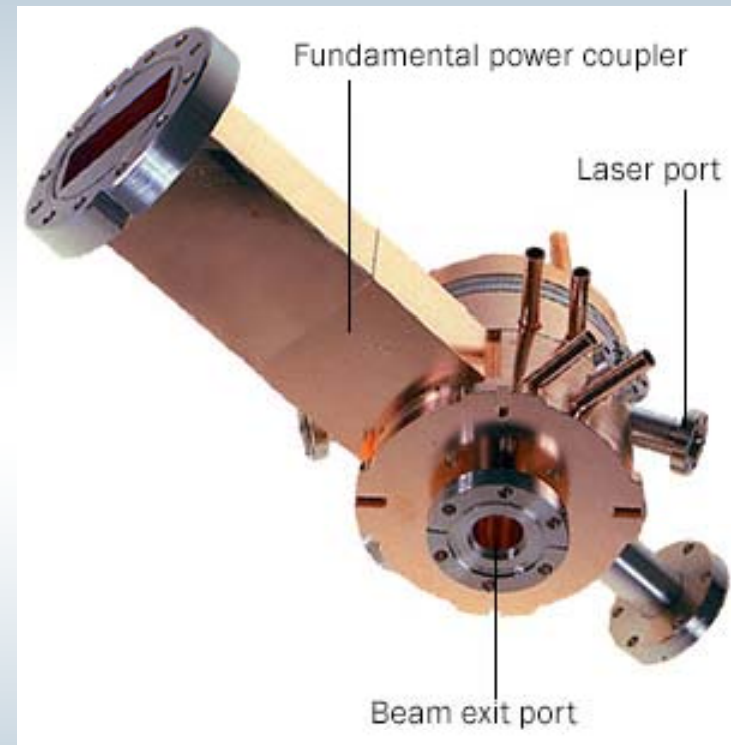
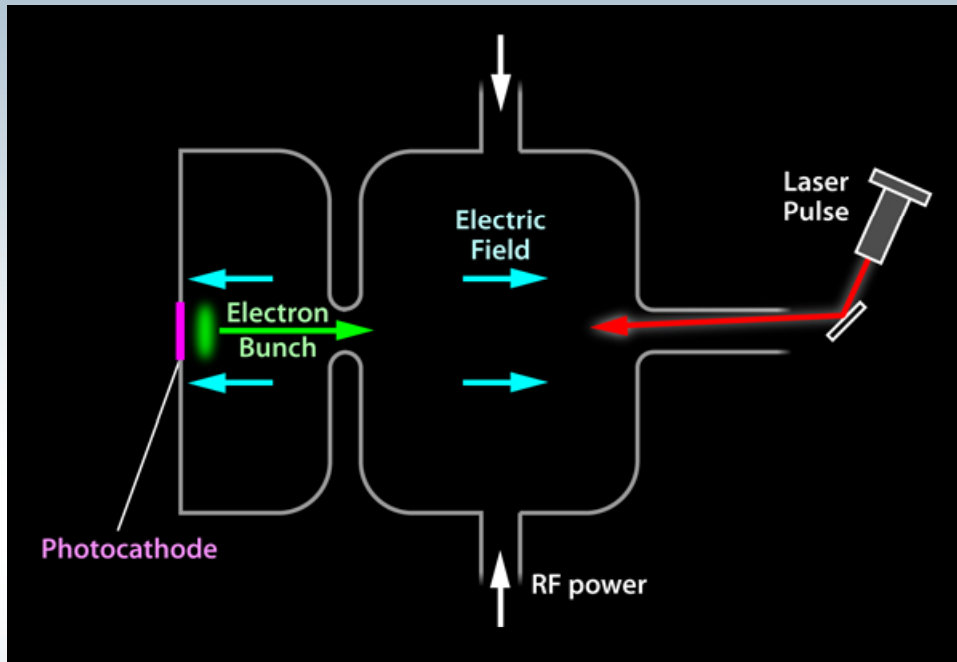


# Photo-injectors



- 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

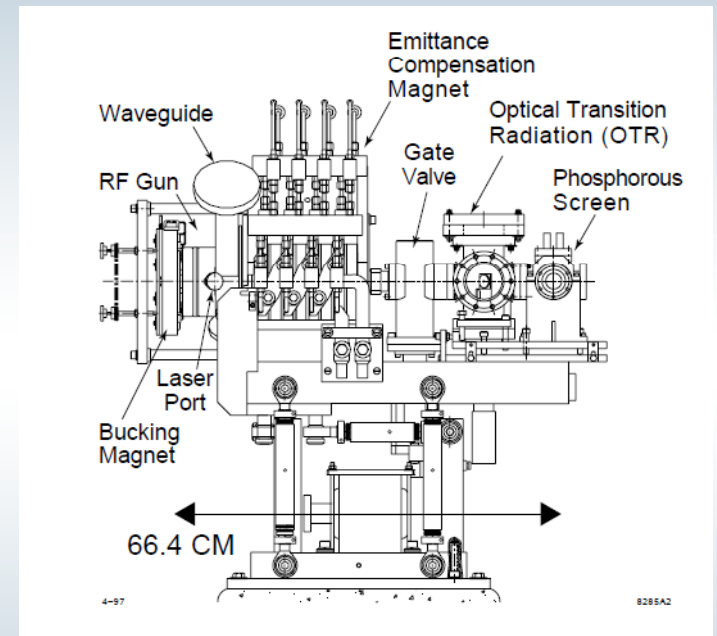
# Photo-cathodes: Revisit



- 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



**Check that those parameters are correct!**

# 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?



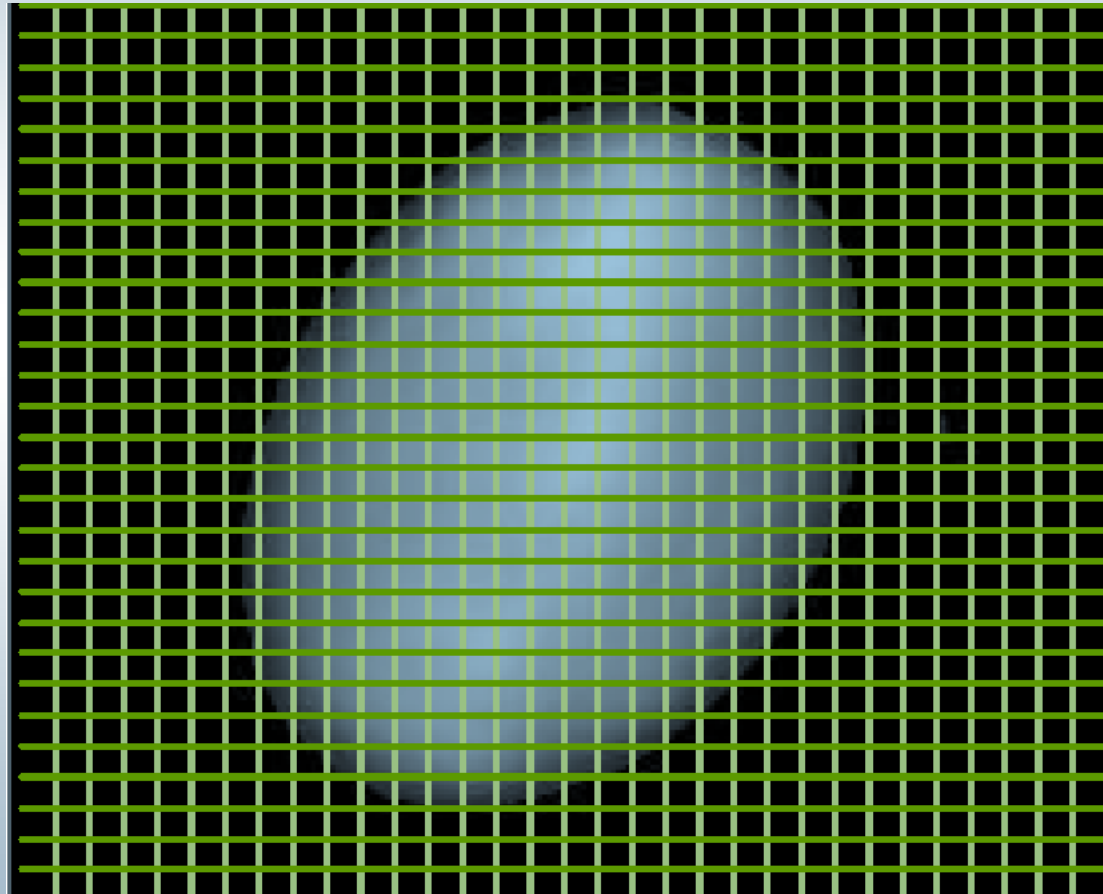
# Where do the fields come from?

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

- 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

# 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.**

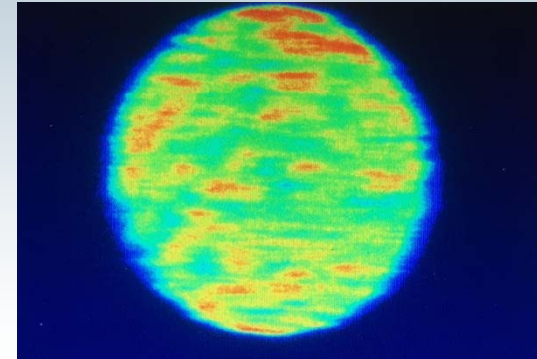
**DESY undertakes no obligation for the maintenance of the program, nor responsibility for its correctness, and accepts no liability whatsoever resulting from its use.**

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

# ASTRA : Beam generation

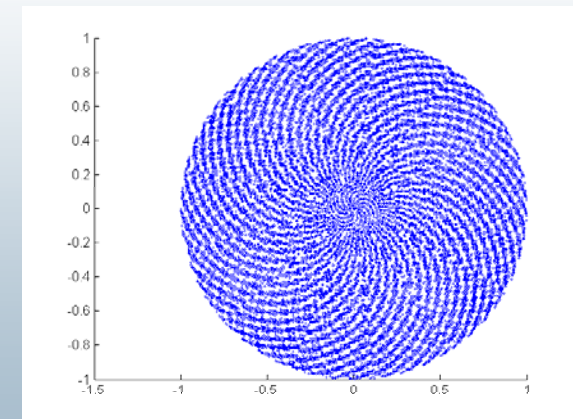
- Create the laser beam
- Sent the laser to cathode
- Produce electron beam

## Beam in experiment

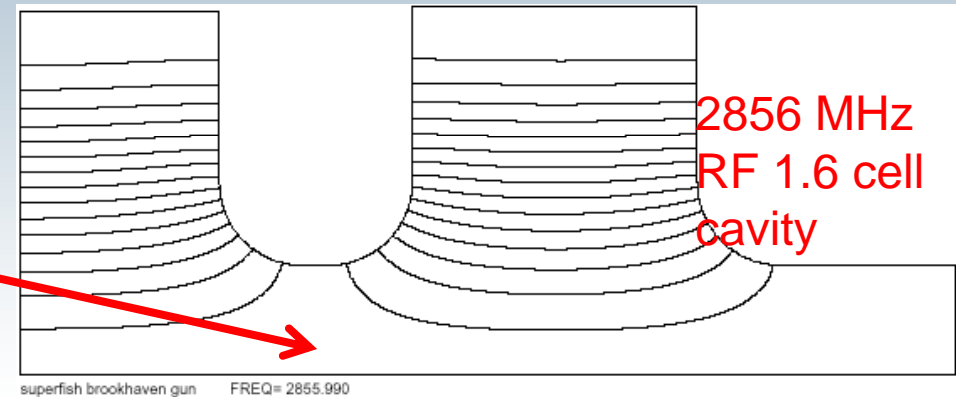
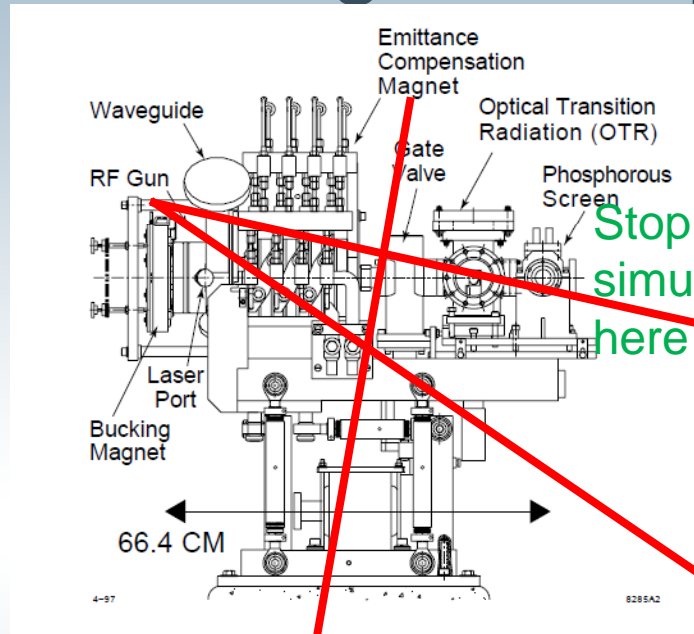


```
&INPUT
Add=.F,
! FILE NAME TO CREATED (ELECTRON DISTRIBUTION)
FNAME = 'astralin.part'
IPart=2000
Species='electrons'
Probe=.True.
Noise_reduc=.T.
Cathode=.T.
! BUNCH CHARGE
Q_total=0.050
Ref_zpos=0.
Ref_clock=0E-3
Ref_Ekin=0.
! LASER LONGITUDINAL PROFILE
Dist_z='gauss', sig_clock=2.0E-3, Lt=0., rt=0.
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
```

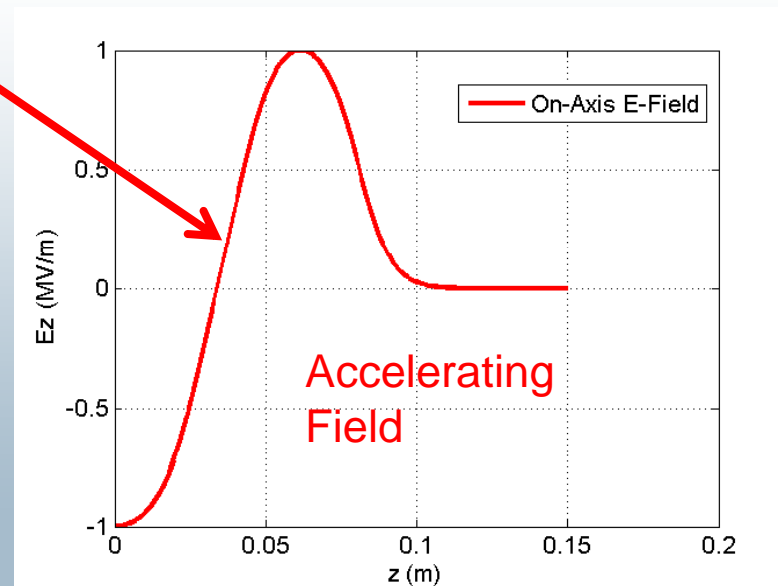
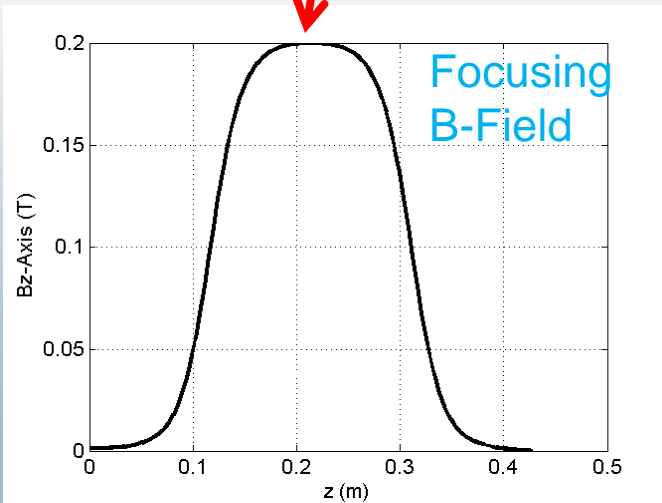
## Beam in simulation



# 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
/

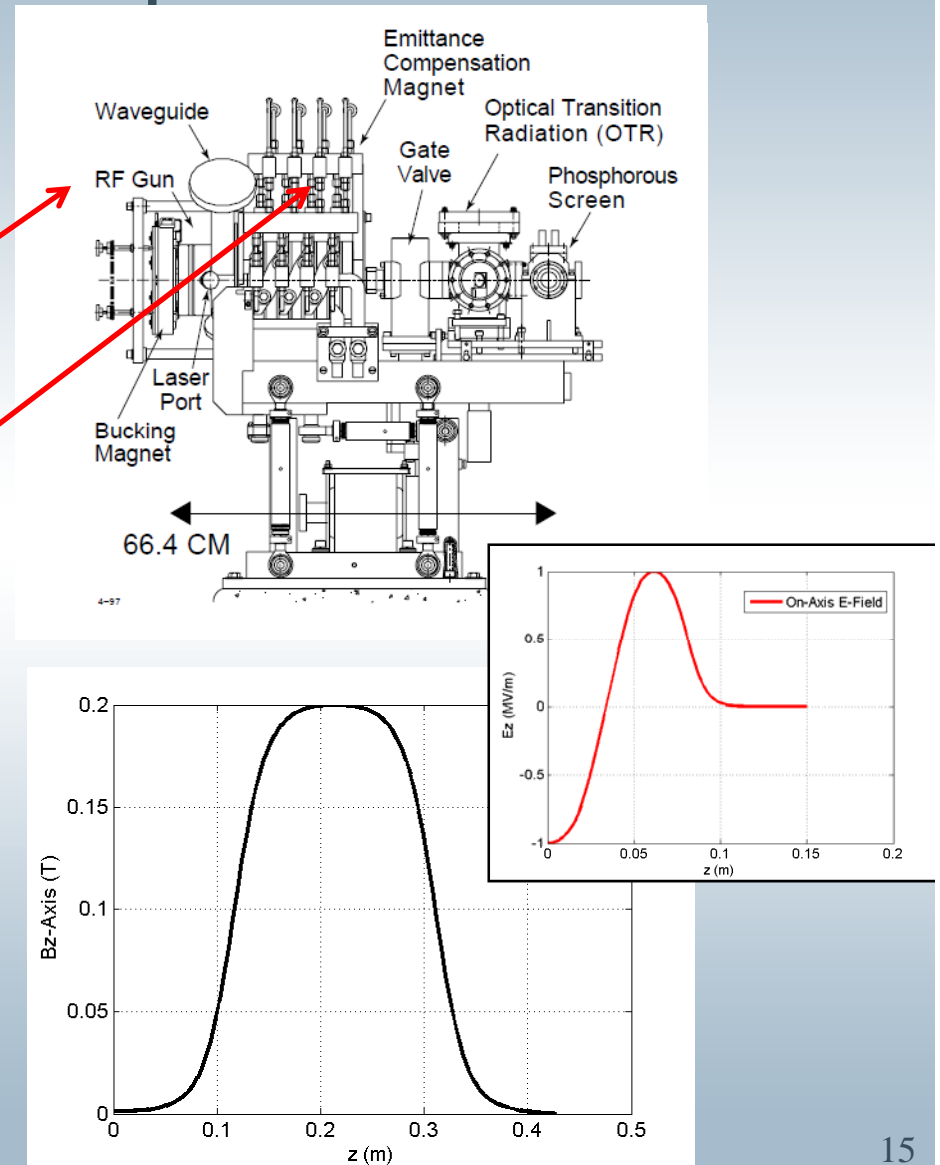
&CHARGE
! SPACE-CHARGE ON OR OFF
Loop=F
LSPCH=T
! use the following mesh for appropriate number of macroparticles
Nrad=10,
Nlong_in=12,
Cell_var=2.0
min_grid=0.4e-6
Max_scale=0.05
Max_count=10
Lmirror=.T
/

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

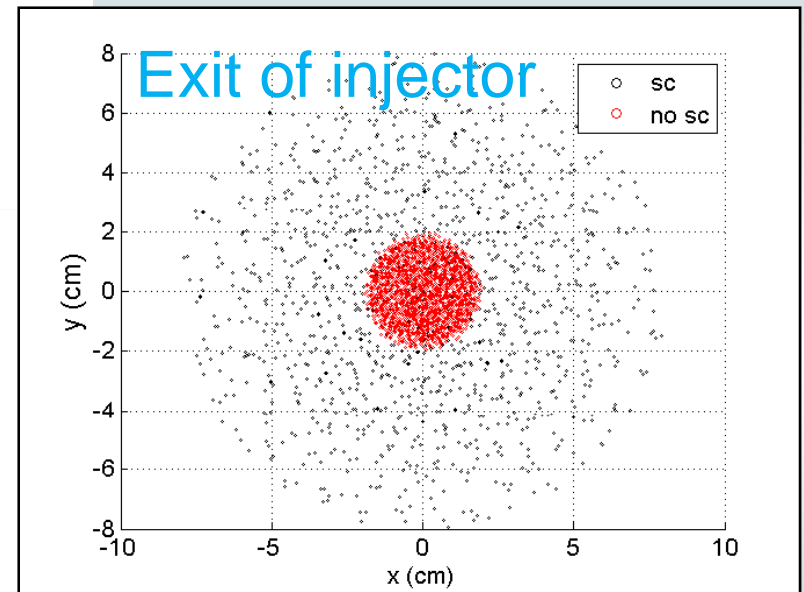
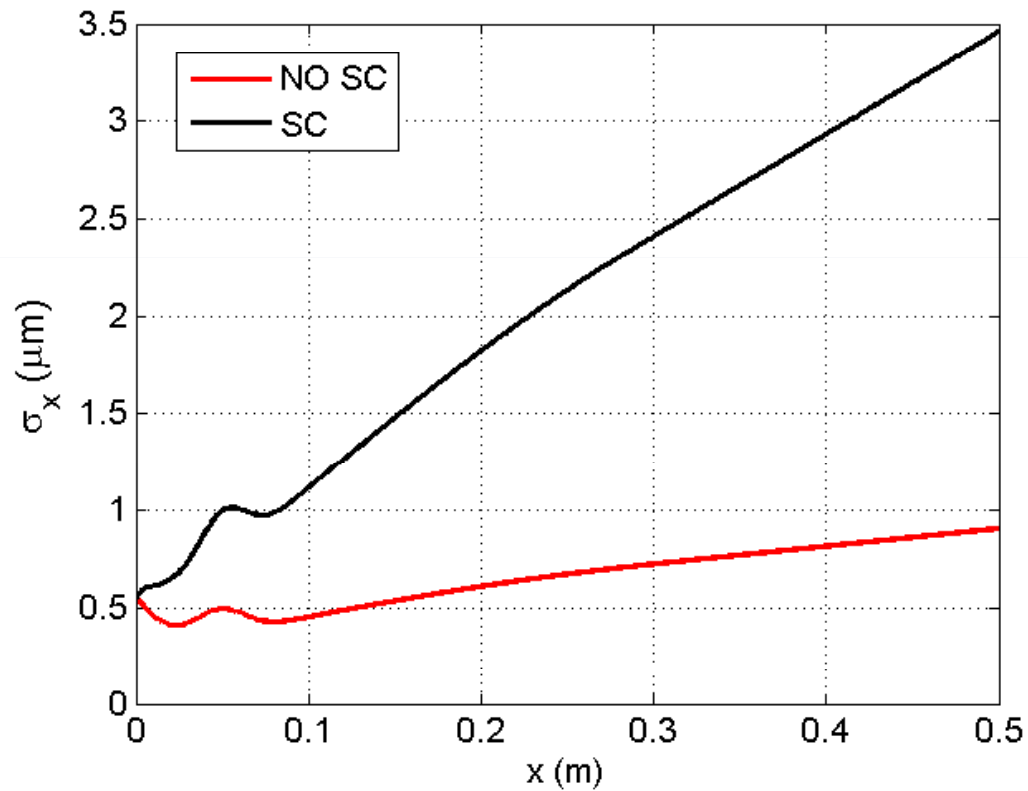
&CAVITY
! RF GUN CAVITY
Loop=.F,
LEFieLD=.T
FILE_EFieLD(1)='rfgunFIELD.dat', C_smooth(1)=10,
Nue(1)=2.856, MaxE(1)=110.00, Phi(1)=-12.0, C_pos(1)=0.0,
C_higher_order(1)=T
/

&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

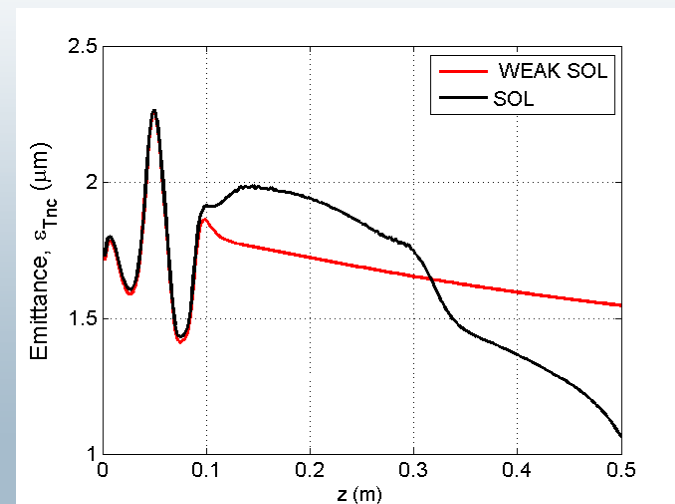
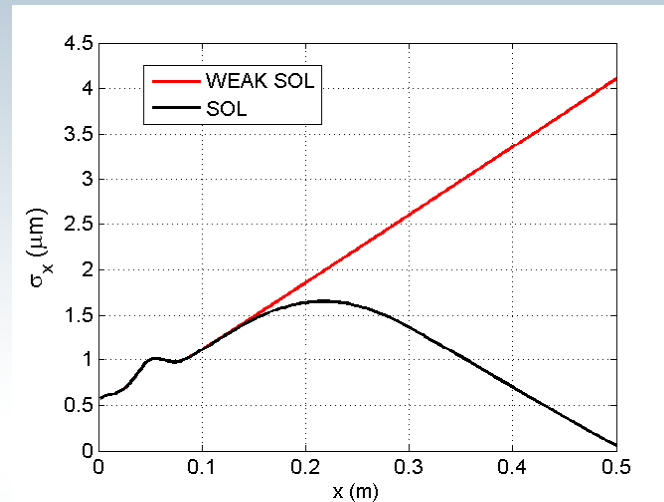
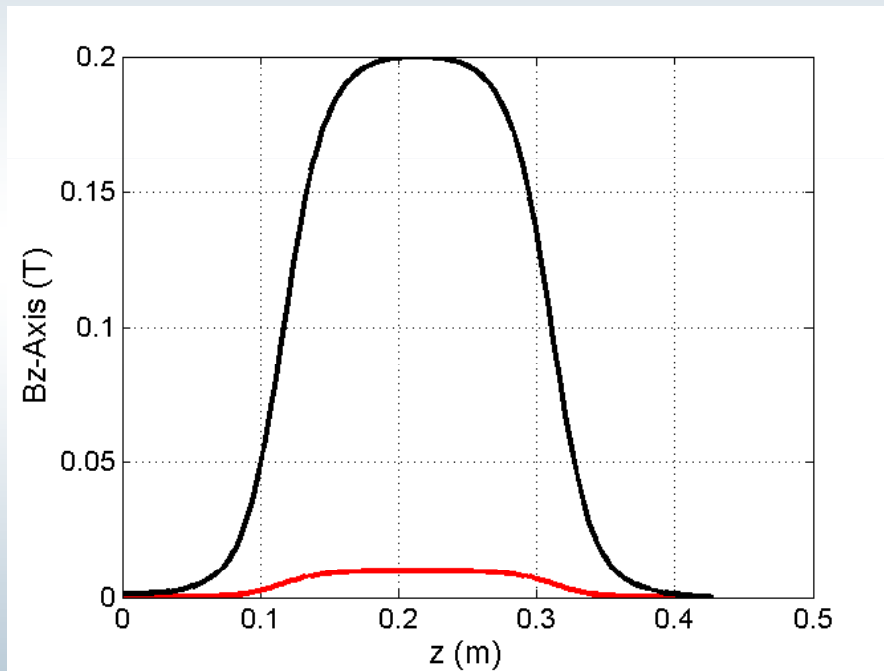


# You will check space-charge effect

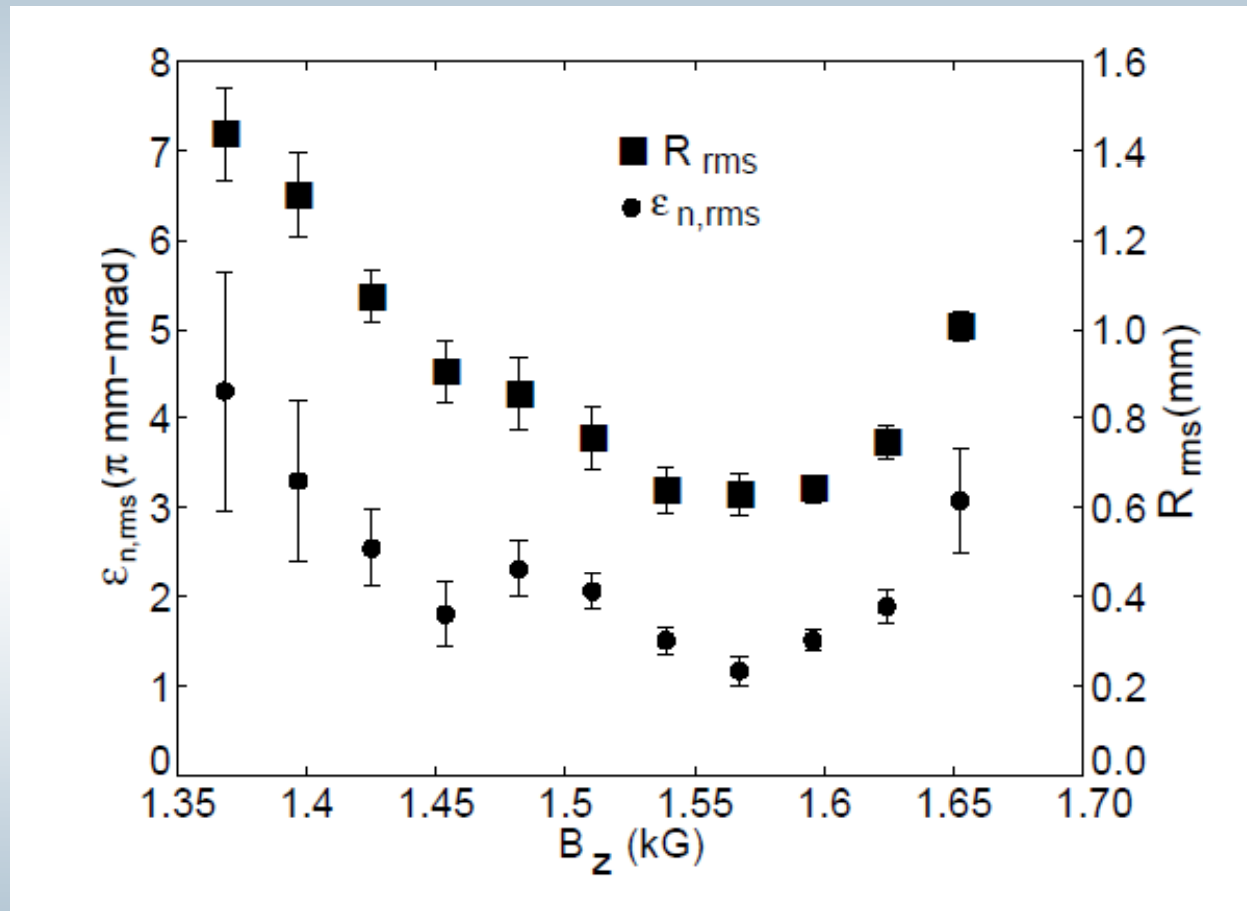




# You will optimize focusing



# You will tune the emittance



- Can you reproduce this result for the ATF injector?