PHY542. Modeling photo-injectors

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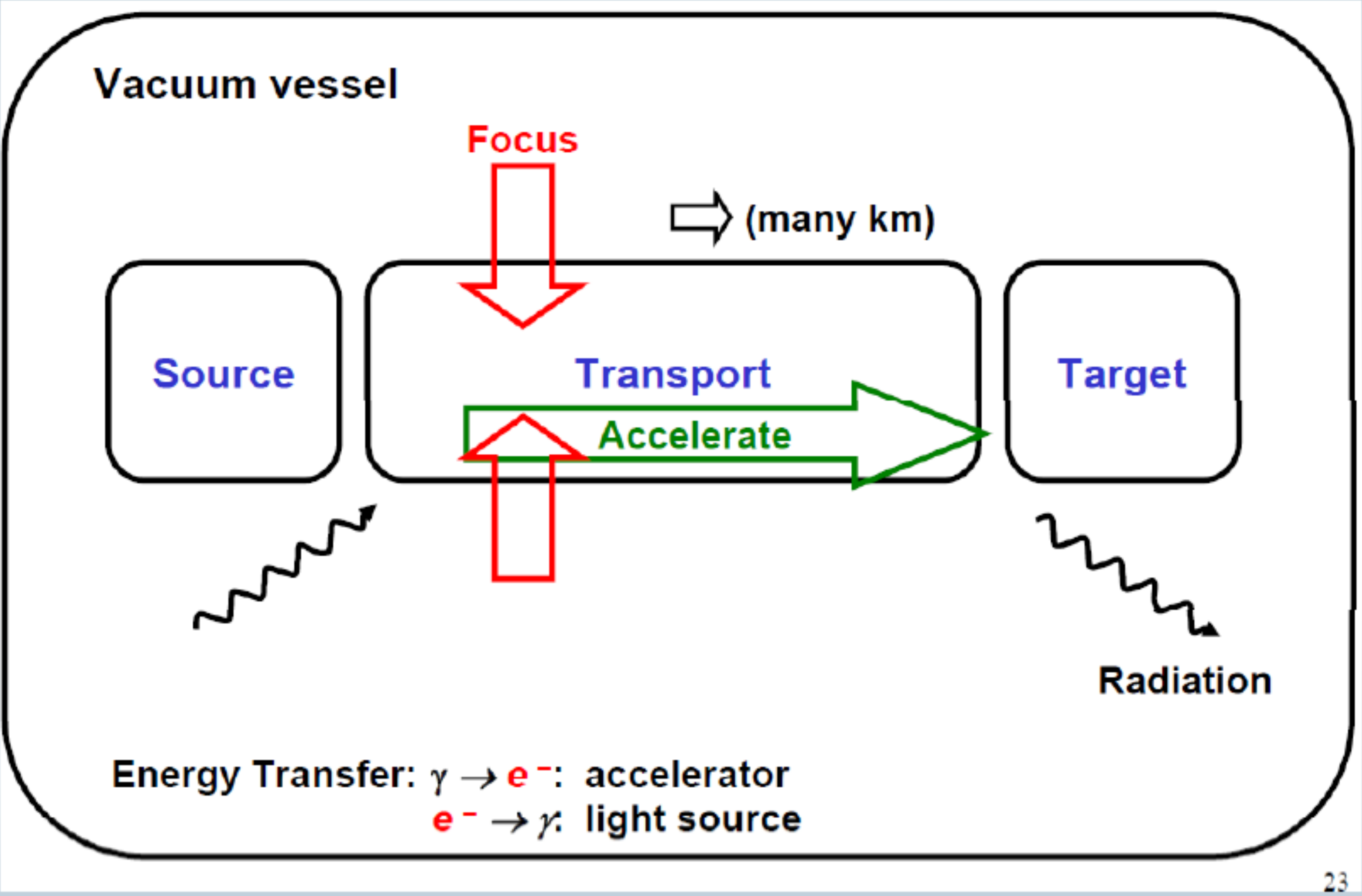
February 6, 2023

PHY 542 Fundamentals of Accelerator Physics and Technology with Simulations and Measurements Lab

Today schedule:

1. ATF status/schedule Update?
2. Modeling photo-injectors short introduction lecture
3. Modeling photo-injectors using ASTRA
4. If we have time Misha will give short description of UED line (located in different building)

Accelerator simplified schematic



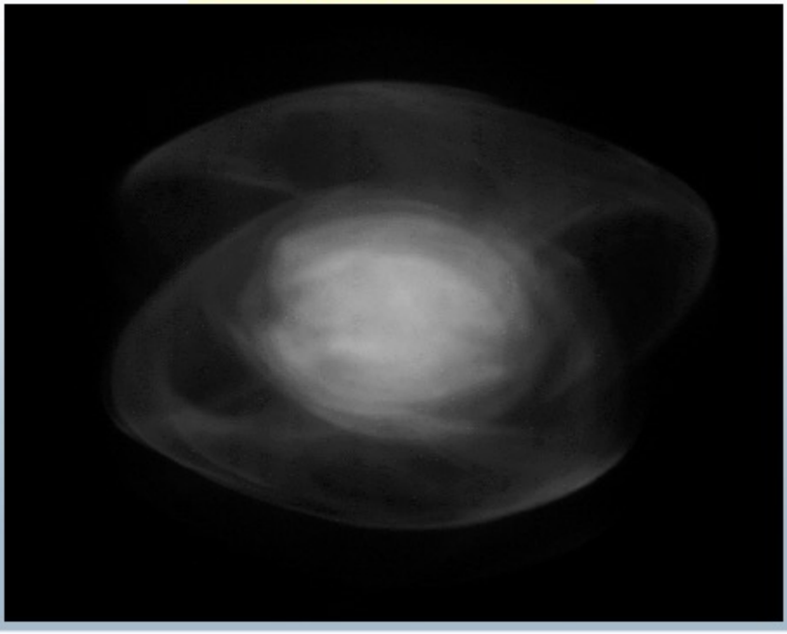
- Three main components: Source, transport, target

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: $E_r = \dfrac{Ir}{2\pi\varepsilon_0 R^2 v}$
- Ampere's Law: $B_\theta = \dfrac{\mu_0 Ir}{2\pi R^2} = \dfrac{vE_r}{c^2}$
- Lorenz Force Law: $F_{r,sc} = q(E + v \times B) = \dfrac{qI}{2\pi\gamma^2\varepsilon_0 vR^2} r = C(R)r = \dfrac{qE_r}{\gamma^2}$
- SC force is pushing the particles out
- SC can be strong near the beam source (small gamma)
- SC negligible at high energies!

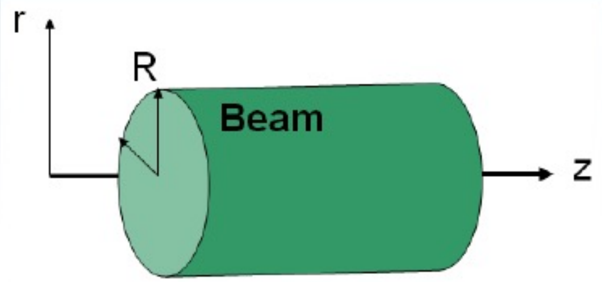
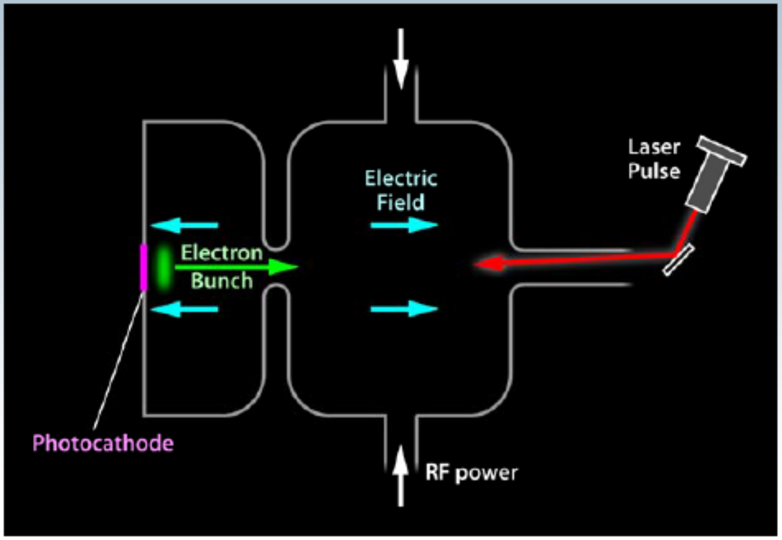
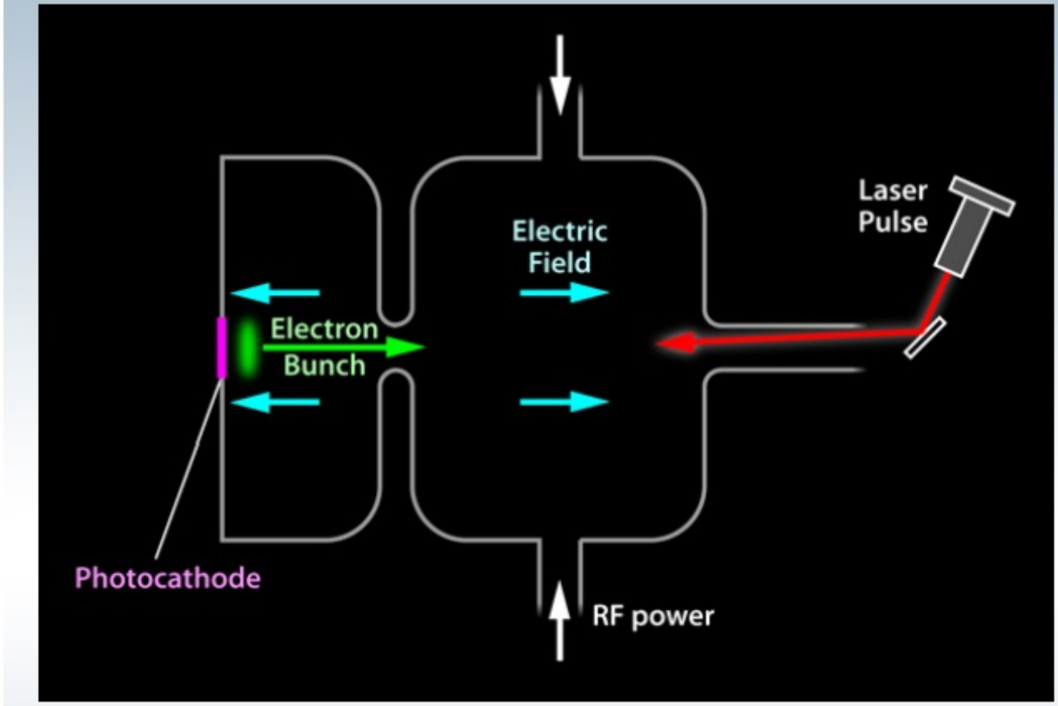


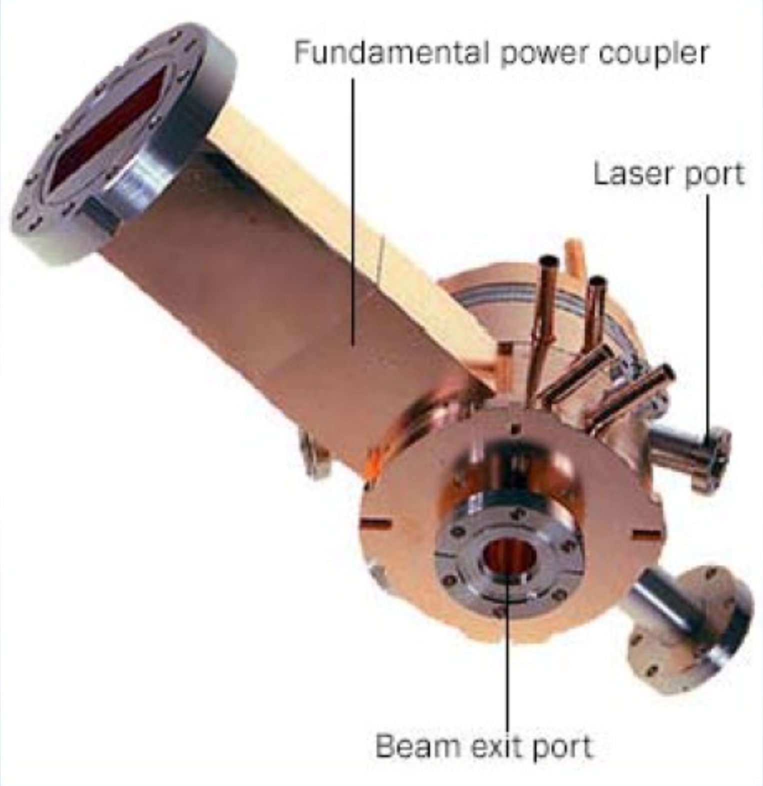
Photo-injectors

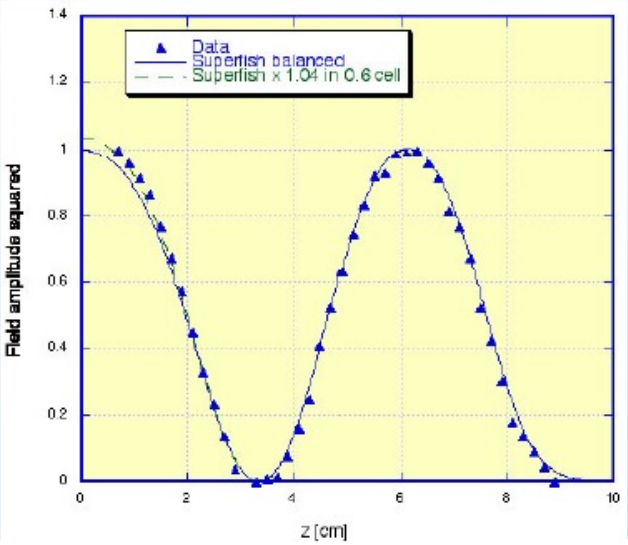


- Major components:
  - **Photocathode** that releases picosecond bunches when irradiated with optical pulses from a ultrafast laser
  - **Electron gun** that acceleates electron from the rest
  - **Solenoid** to properly focus the beam
  - **Drive laser** to gate the emission of the electrons from the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

Photo-cathodes: Revisit



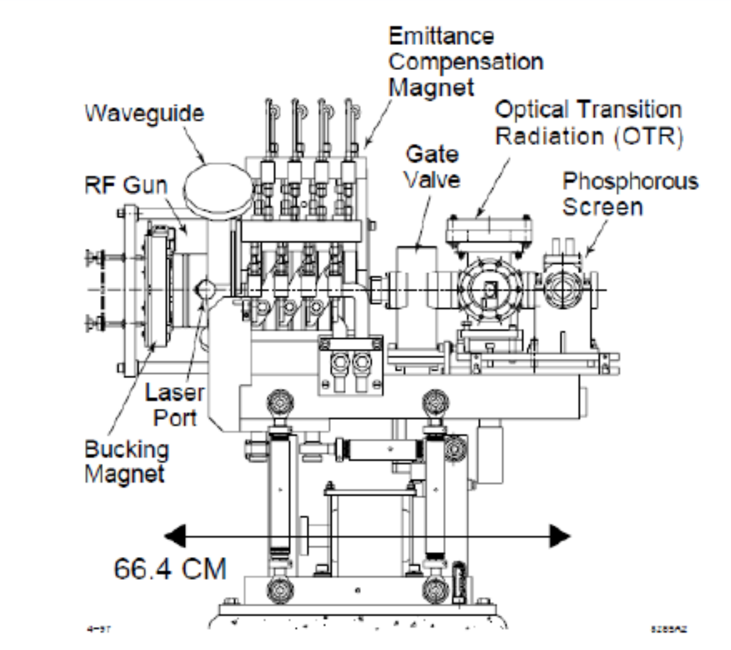




- Time structure of the electron beam is controlled by the laser

ATF Parameters

- 1.6 cell copper cavity
- 2856 MHz (S-Band)
- Cu cathode with QE=$4.5\text{x}10^{-5}$
- 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?

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_o} \qquad \nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \nabla \times \vec{B} = \mu_o \left(\vec{J} + \varepsilon_o \frac{\partial \vec{E}}{\partial t} \right)$$

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

$$\frac{\partial \vec{r}}{\partial t} = \frac{c\vec{p}}{\sqrt{m^2c^2 + \left|\vec{p}\right|^2}}$$

And … we're done, right?

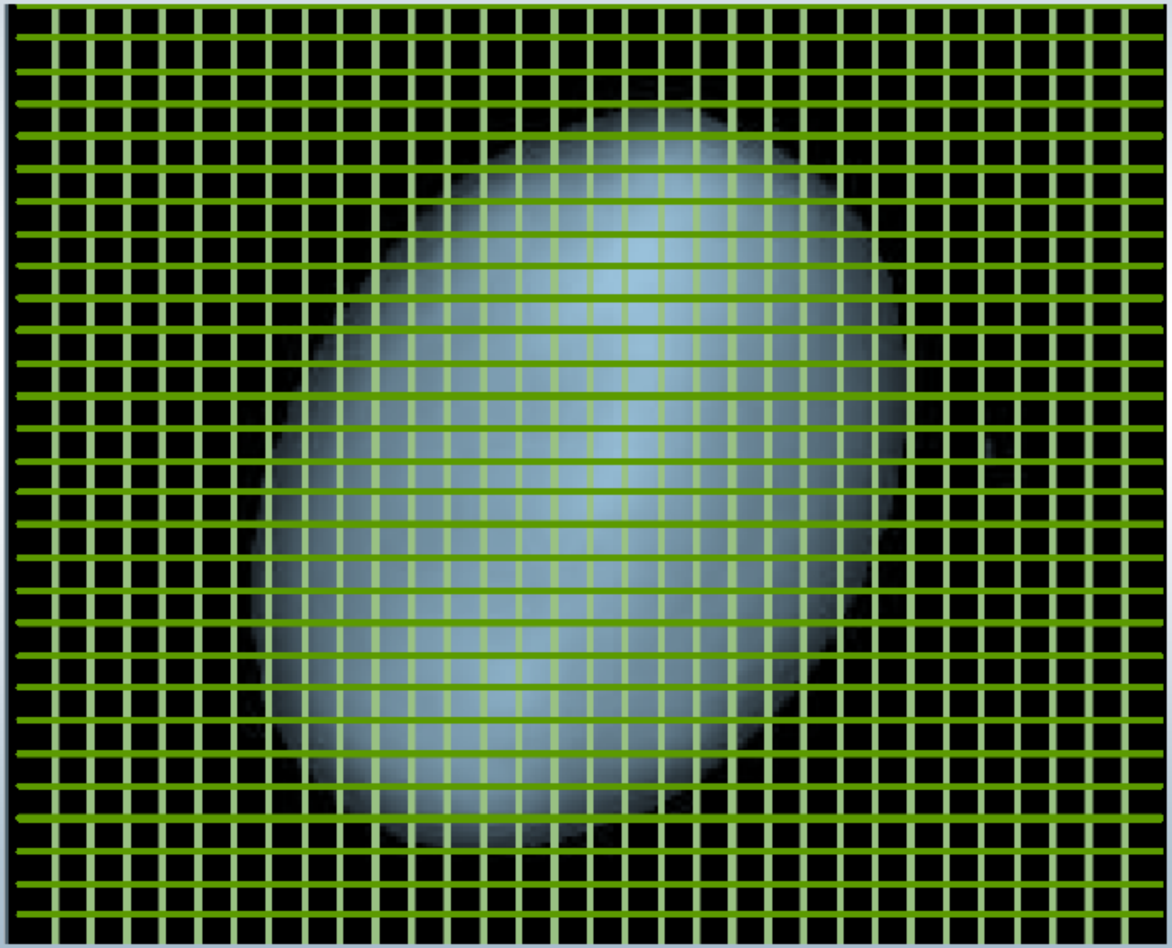
Where do the fields come from?

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

- 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

<u>Particle-in-Cell</u>

- 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

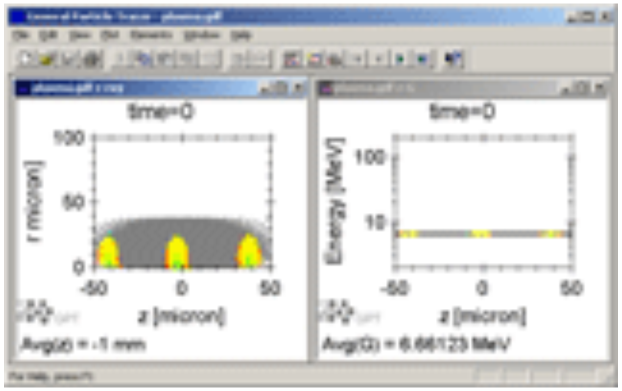
Many codes are available

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

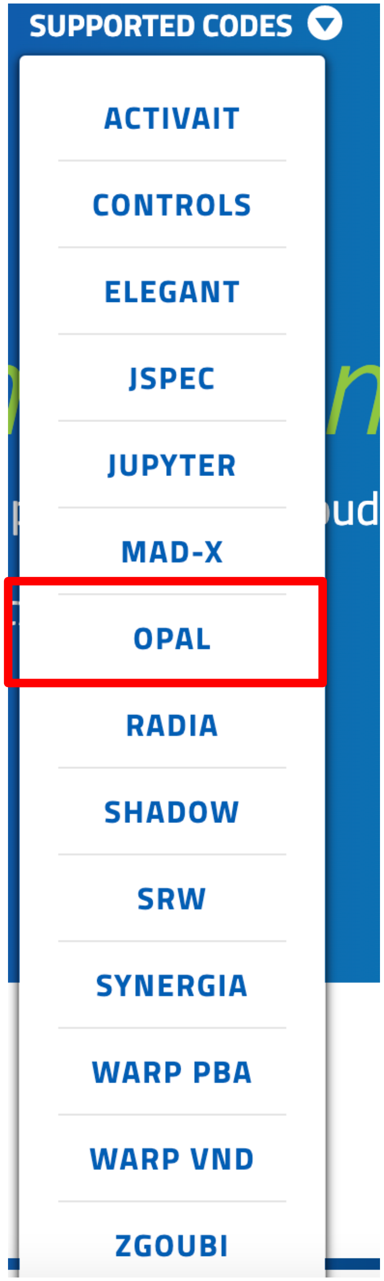
- ASTRA https://www.desy.de/~mpyflo/
- OPAL https://gitlab.psi.ch/OPAL/src/-/wikis/home

Introduction to OPAL/SIREPO

M. Fedurin

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

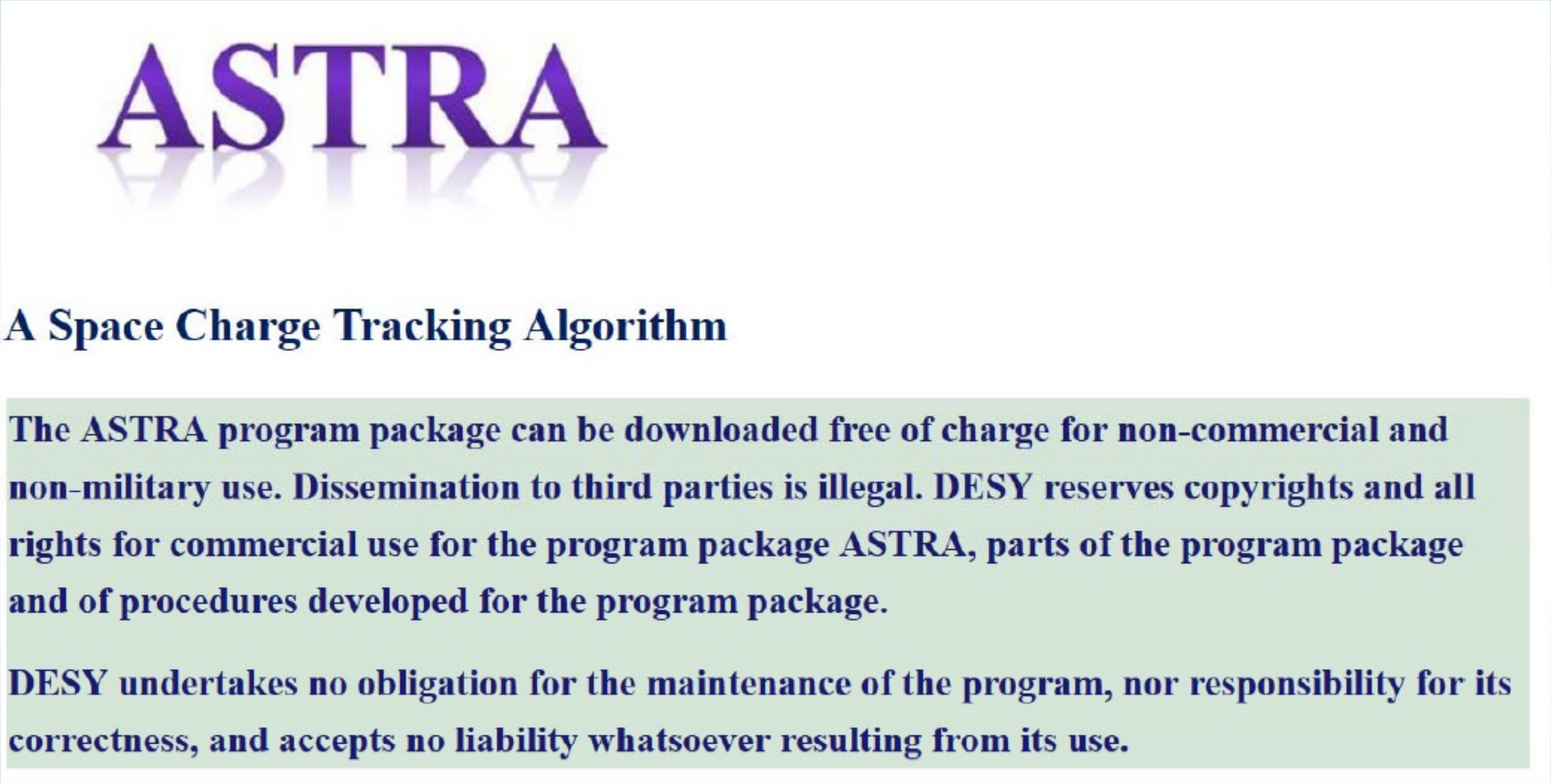
The Sirepo scientific gateway offers browser-based GUIs that support and enhance legacy codes such as Radia, elegant, MAD-X, SRW, **Opal,** and more. Basing our platform in the cloud means that you can share your simulations with others immediately and easily.



Object Oriented Parallel Accelerator Library (*OPAL*)

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

ASTRA Code



ASTRA

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.

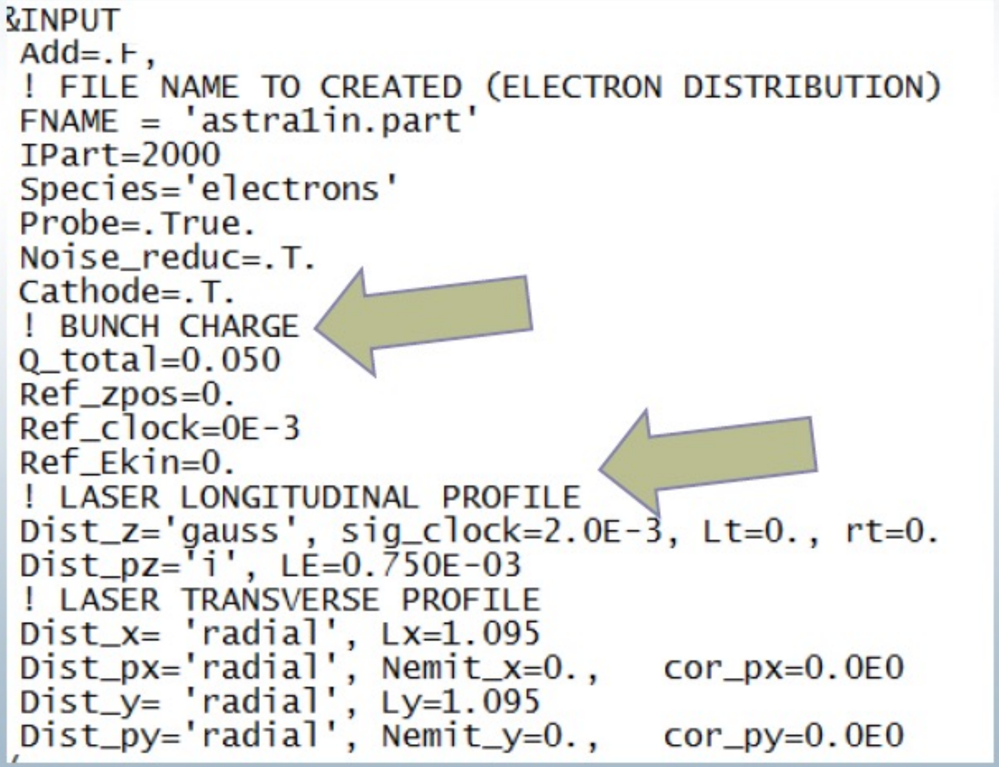
- Source: http://www.desy.de/~mpyflo/
- Very simple code! Commonly used for photo-injectors!

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)

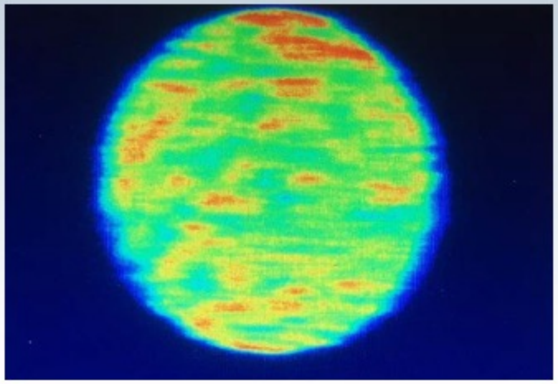
ASTRA : Beam generation

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

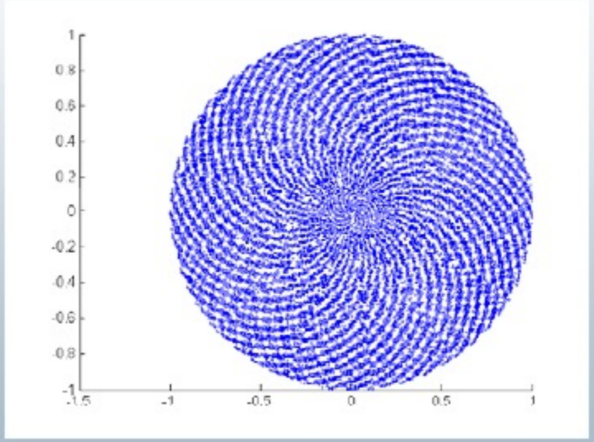


```
&INPUT
 Add=.F,
 ! FILE NAME TO CREATED (ELECTRON DISTRIBUTION)
 FNAME = 'astra1in.part'
 IPart=2000
 Species='electrons'
 Probe=.True.
 Noise_reduc=.T.
 Cathode=.T.
 ! BUNCH CHARGE
 Q_total=0.050
 Ref_zpos=0.
 Ref_clock=0E-3
 Ref_Ekin=0.
 ! LASER LONGITUDINAL PROFILE
 Dist_z='gauss', sig_clock=2.0E-3, 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

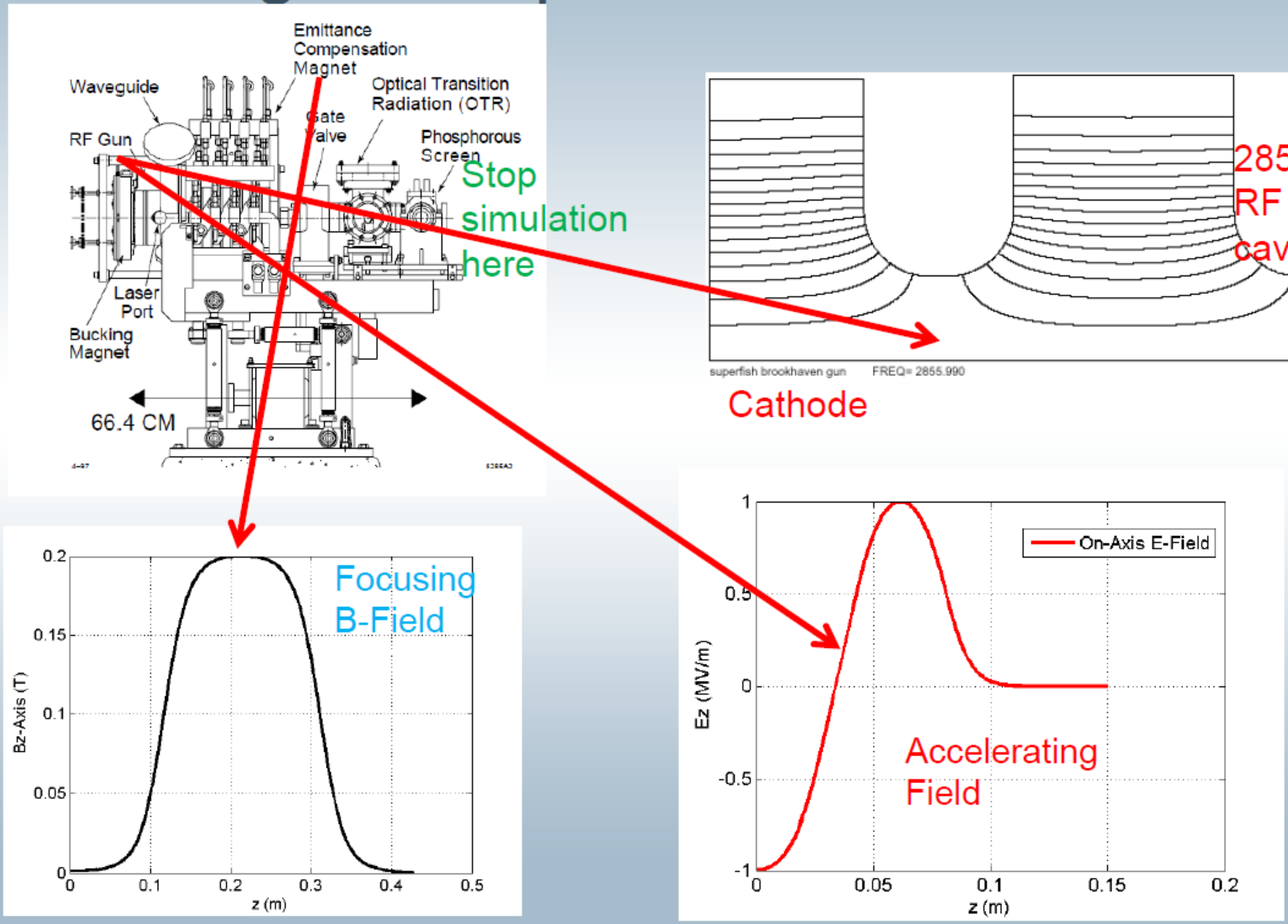


Beam in simulation



http://case.physics.stonybrook.edu/images/a/a0/Computational_HW1.pdf

Tracking inside photocathode with ASTRA



Stop simulation here

2856 MHz RF 1.6 cell cavity

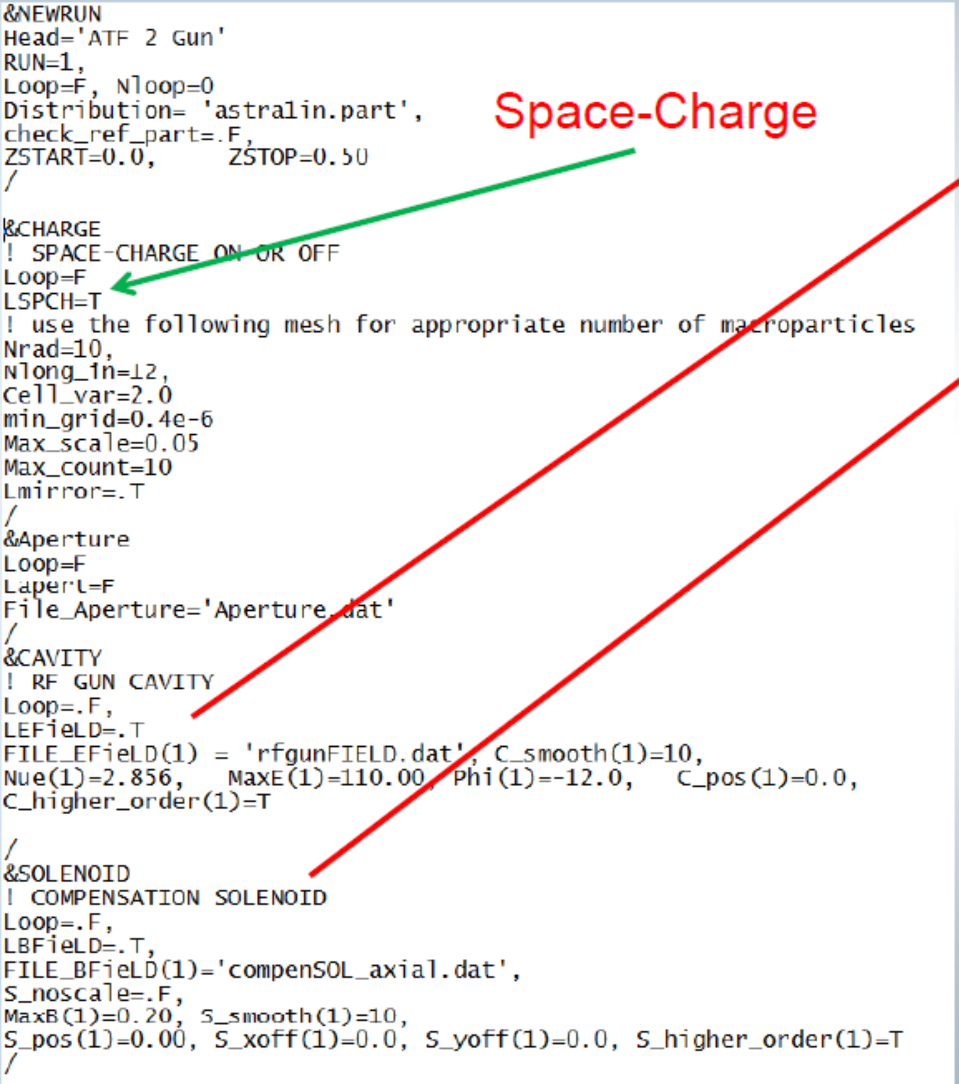
Cathode

Focusing B-Field

Accelerating Field

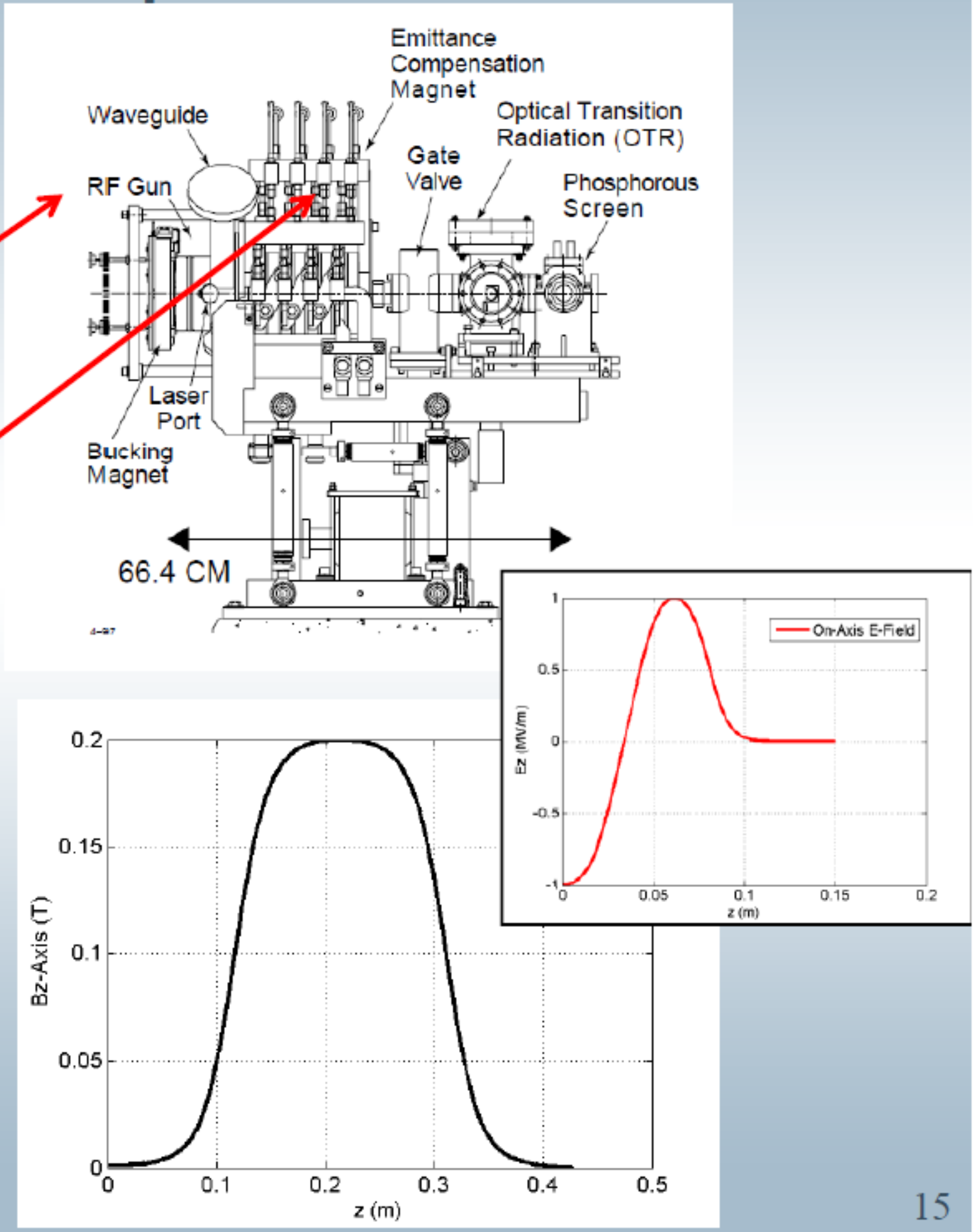
http://case.physics.stonybrook.edu/images/a/a0/Computational_HW1.pdf

ASTRA: Track inside photocathode



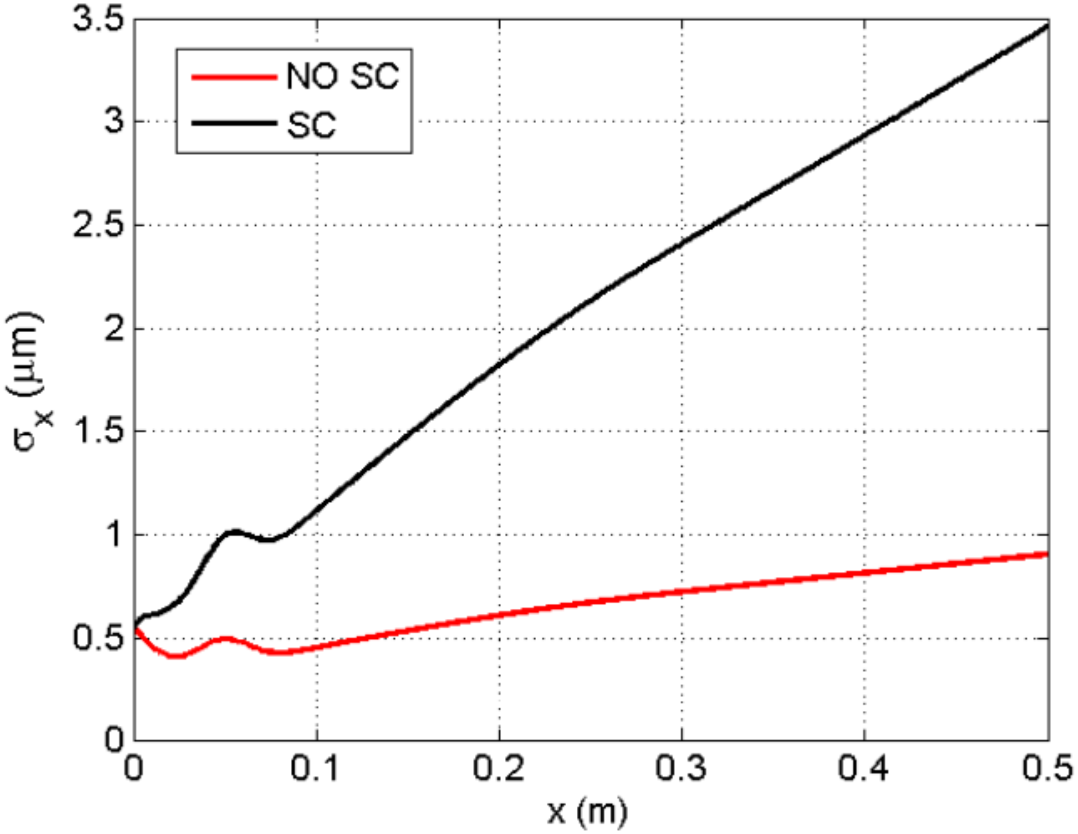
```
&NEWRUN
Head='ATF 2 Gun'
RUN=1,
Loop=F, Nloop=0
Distribution= 'astra1in.part',
check_ref_part=.F,
ZSTART=0.0,     ZSTOP=0.50
/

&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
/
```

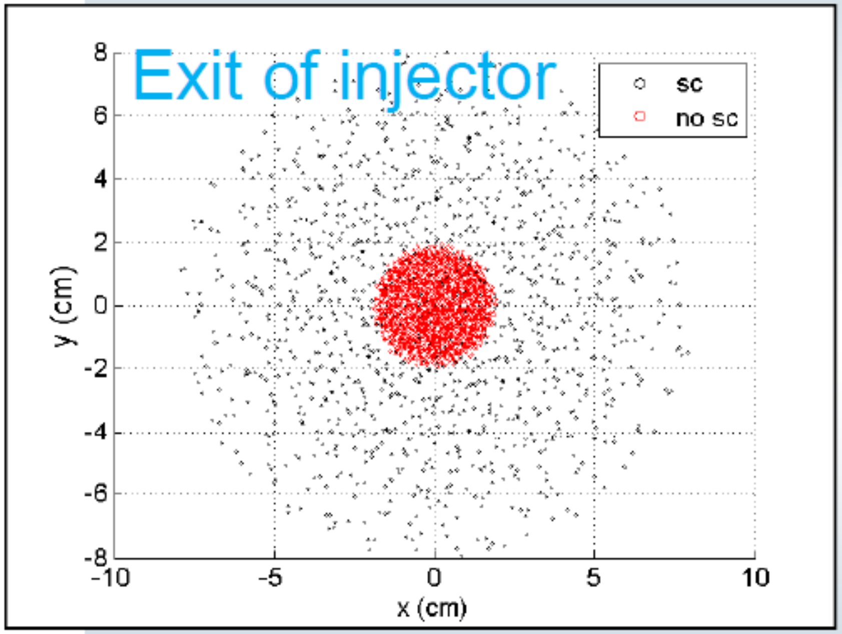
Space-Charge



http://case.physics.stonybrook.edu/images/a/a0/Computational_HW1.pdf

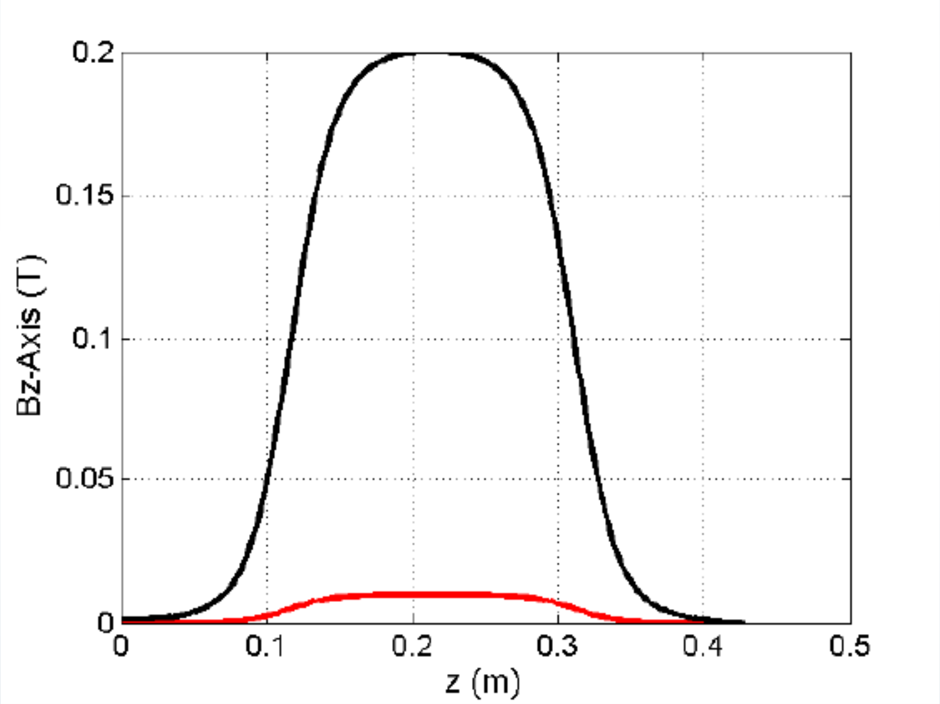
You will check space-charge effect

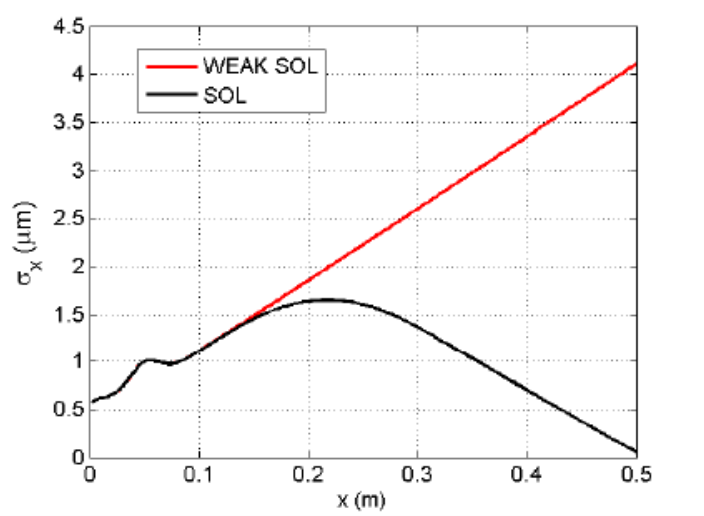


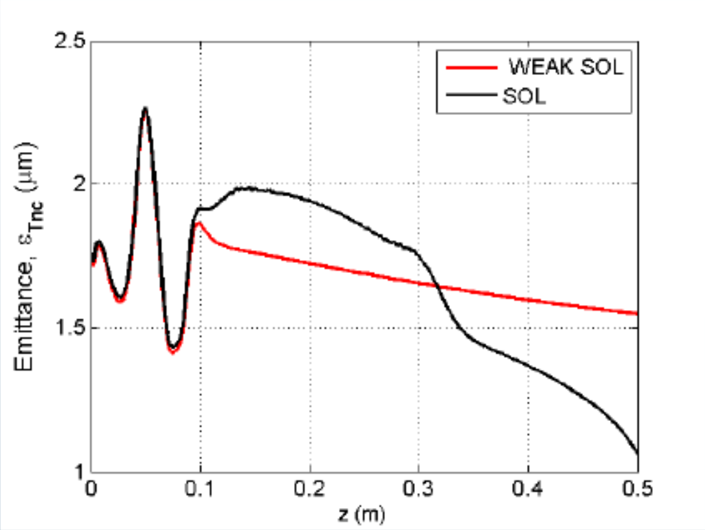


http://case.physics.stonybrook.edu/images/a/a0/Computational_HW1.pdf

You will optimize focusing

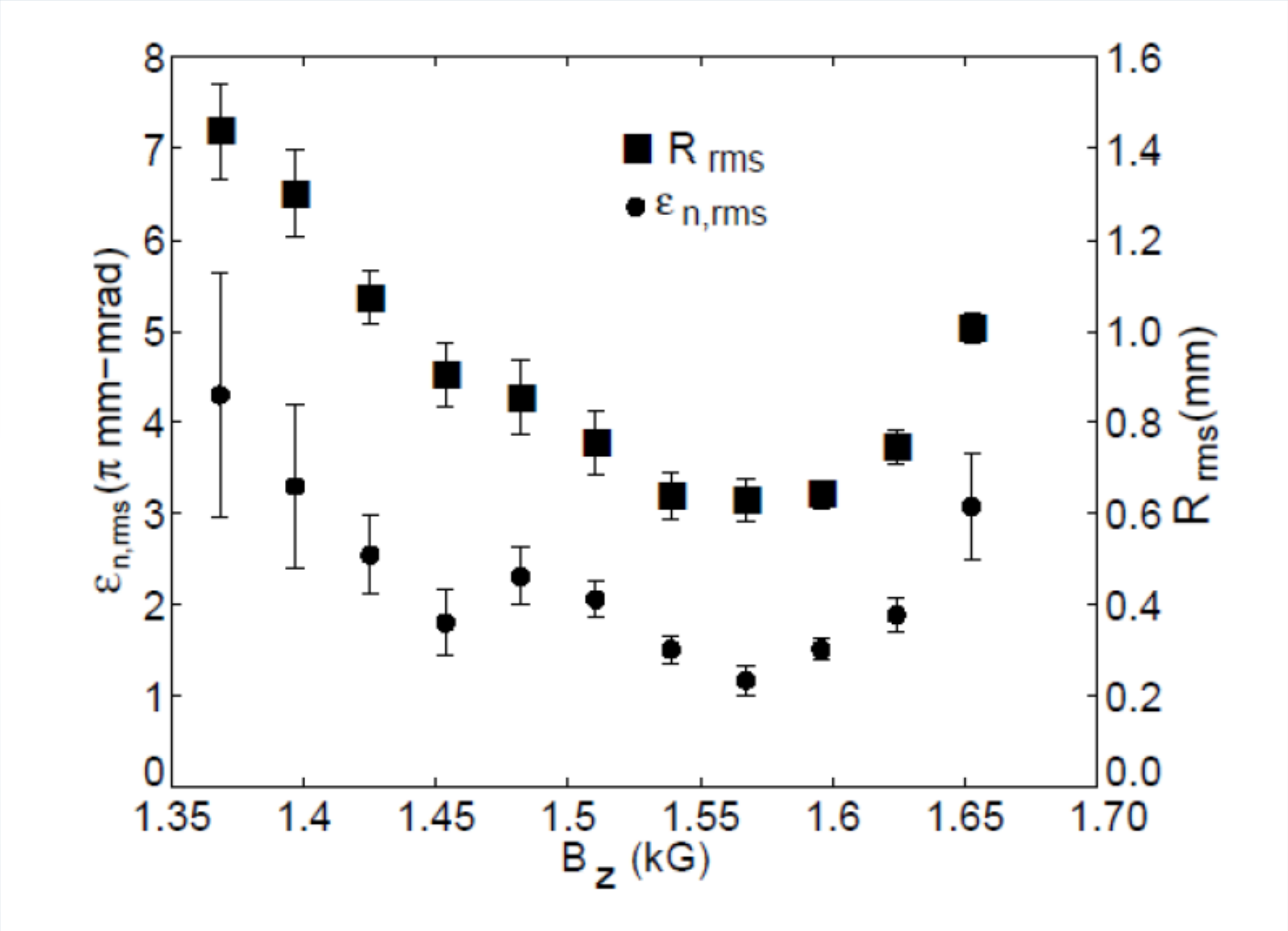






http://case.physics.stonybrook.edu/images/a/a0/Computational_HW1.pdf

You will tune the emittance



- Can you reproduce this result for the ATF injector?

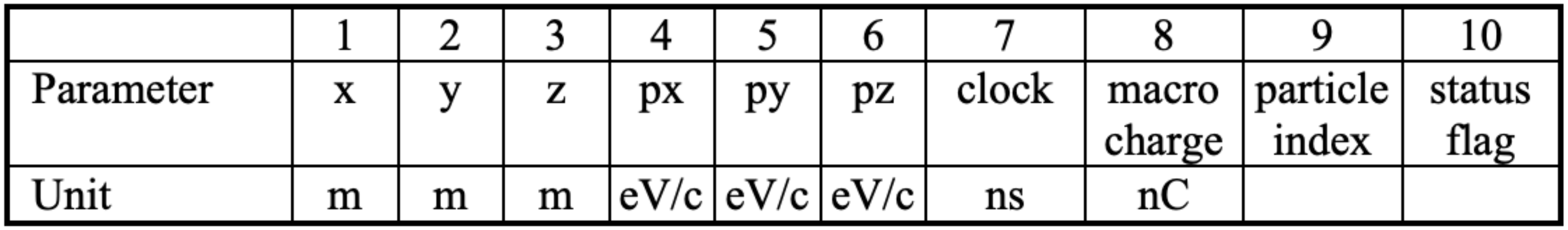
http://case.physics.stonybrook.edu/images/a/a0/Computational_HW1.pdf

Questions/comments from the last class

For MAC users:

- Don’t forget to make files: generate, Astra, lineplot and fieldplot executable.
  - chmod +x Astra

Question about Units:



	1	2	3	4	5	6	7	8	9	10
Parameter	x	y	z	px	py	pz	clock	macro charge	particle index	status flag
Unit	m	m	m	eV/c	eV/c	eV/c	ns	nC		

Table 1: Structure of particle distribution files.

More details about ASTRA code:
https://www.desy.de/~mpyflo/Astra_manual/Astra-Manual_V3.2.pdf

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.

http://case.physics.stonybrook.edu/images/a/a0/Computational_HW1.pdf

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.

http://case.physics.stonybrook.edu/images/a/a0/Computational_HW1.pdf

COMPUTATIONAL EXERCISE #1 – PHOTO-INJECTORS

Photo-injector optimization:

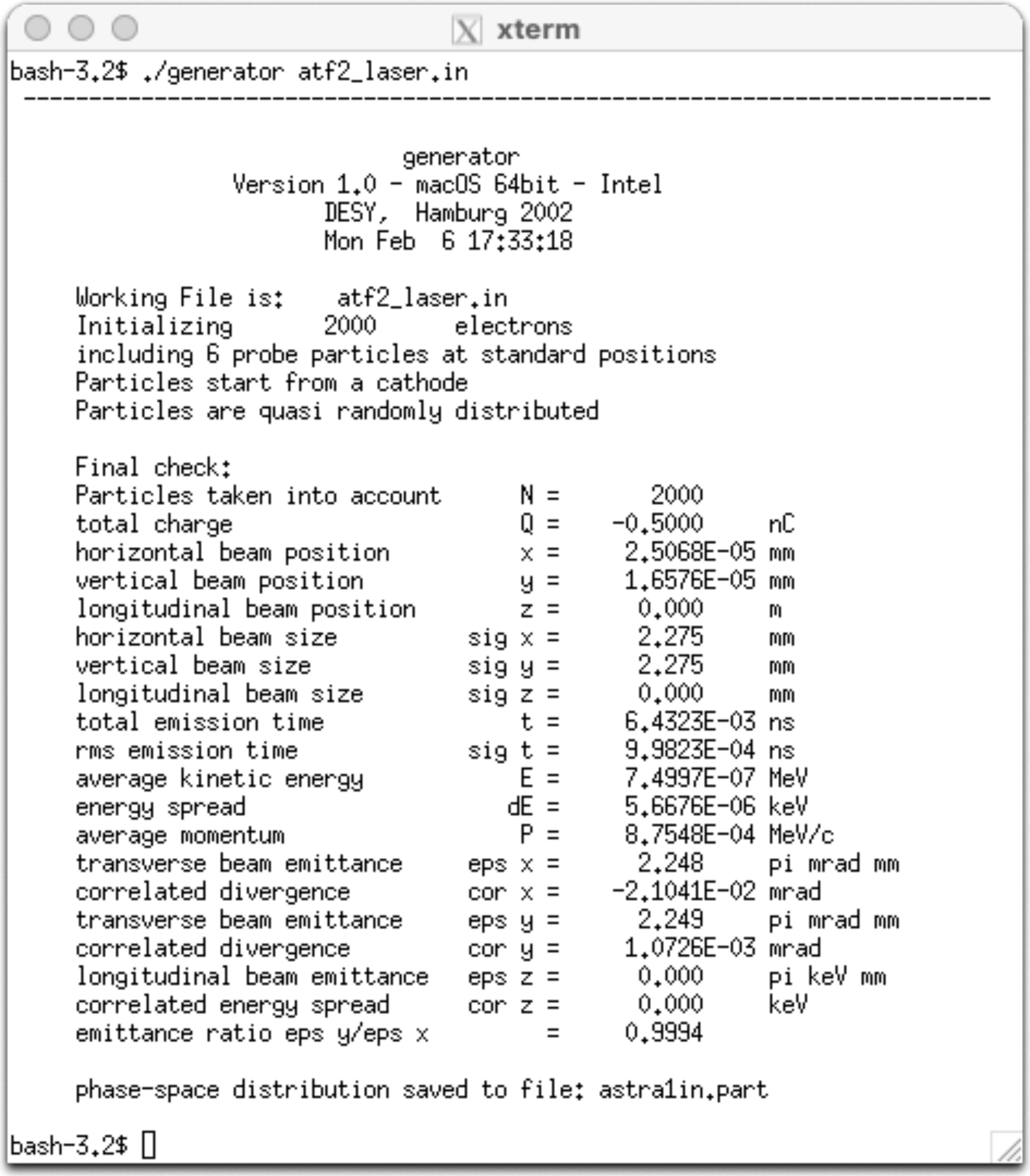
1. Space-Charge Effect: Turn off space-charge by setting LSPCH=F. Run ASTRA. Record the final emittance and rms beam size. Now please turn space-charge on. Record again the numbers. What do you see now? Can you explain the result? Run the program postpro by typing *postpro atf2_linac* and look at the 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?

http://case.physics.stonybrook.edu/images/a/a0/Computational_HW1.pdf

back up
/ some screen shots for troubleshooting

Expected output for default parameters

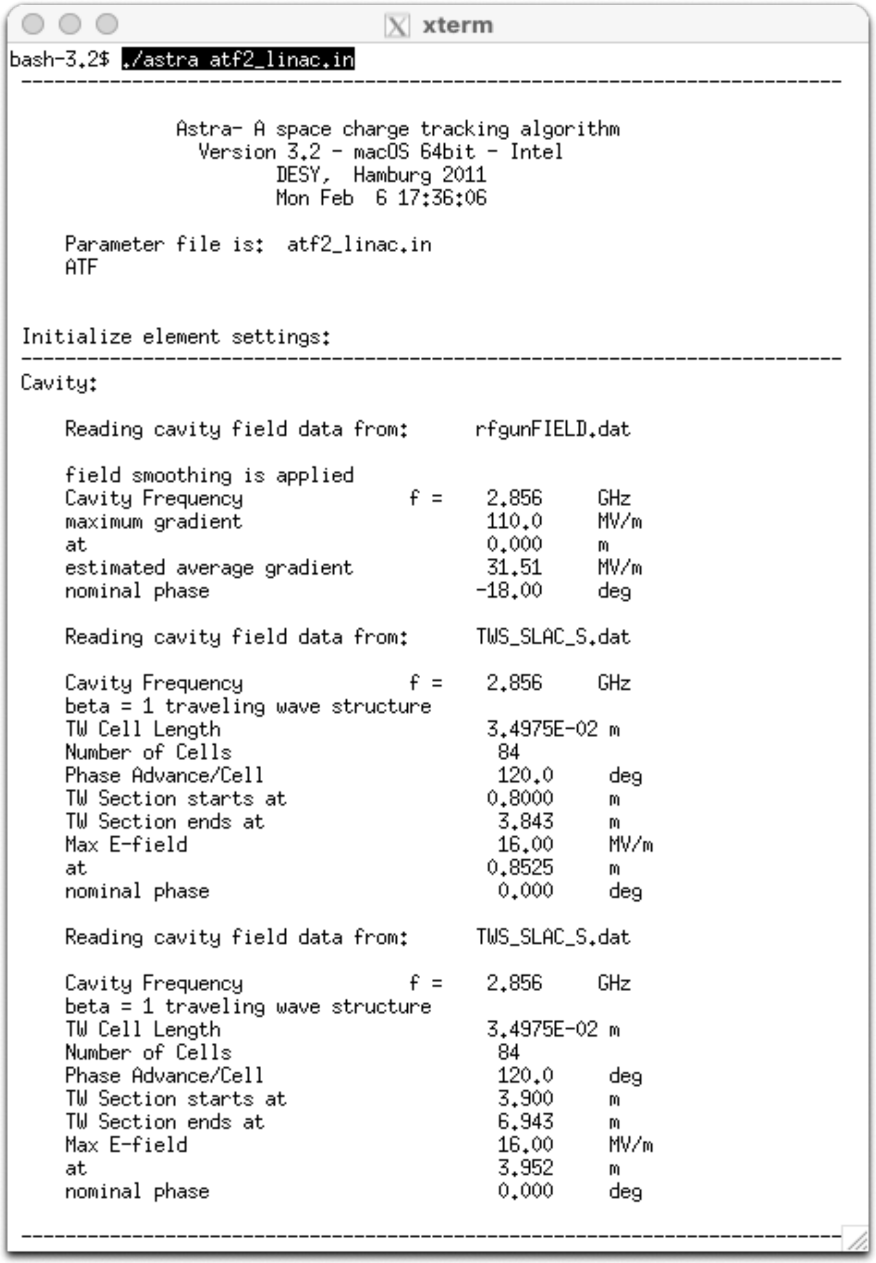
./generator atf2_laser.in



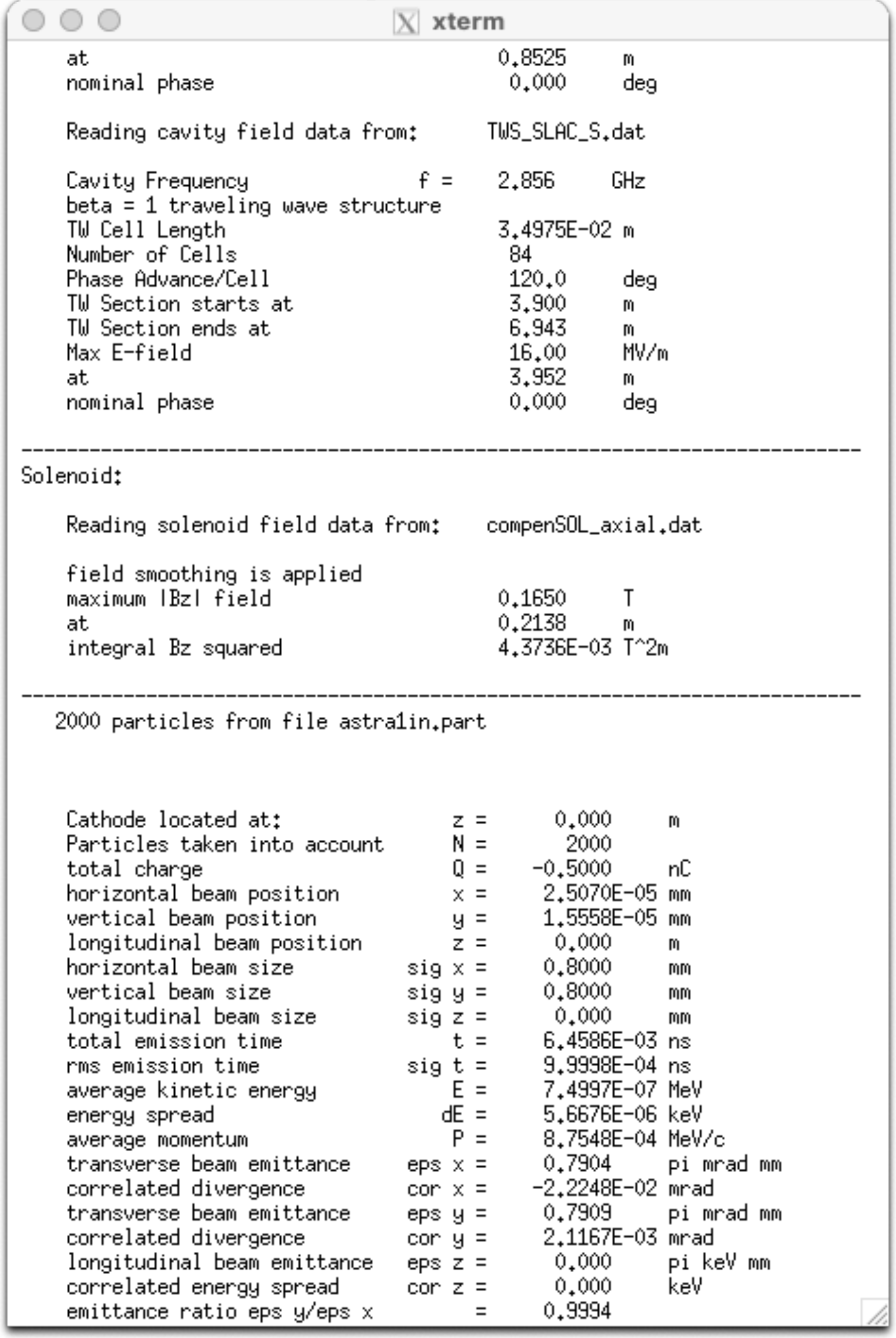
```
bash-3.2$ ./generator atf2_laser.in
 --------------------------------------------------------------------------


                              generator
                 Version 1.0 - macOS 64bit - Intel
                        DESY,  Hamburg 2002
                        Mon Feb  6 17:33:18

     Working File is:    atf2_laser.in
     Initializing       2000      electrons
     including 6 probe particles at standard positions
     Particles start from a cathode
     Particles are quasi randomly distributed

     Final check:
     Particles taken into account      N =       2000
     total charge                      Q =    -0.5000     nC
     horizontal beam position          x =     2.5068E-05 mm
     vertical beam position            y =     1.6576E-05 mm
     longitudinal beam position        z =      0.000     m
     horizontal beam size          sig x =      2.275     mm
     vertical beam size            sig y =      2.275     mm
     longitudinal beam size        sig z =      0.000     mm
     total emission time               t =     6.4323E-03 ns
     rms emission time             sig t =     9.9823E-04 ns
     average kinetic energy            E =     7.4997E-07 MeV
     energy spread                    dE =     5.6676E-06 keV
     average momentum                  P =     8.7548E-04 MeV/c
     transverse beam emittance     eps x =      2.248     pi mrad mm
     correlated divergence         cor x =    -2.1041E-02 mrad
     transverse beam emittance     eps y =      2.249     pi mrad mm
     correlated divergence         cor y =     1.0726E-03 mrad
     longitudinal beam emittance   eps z =      0.000     pi keV mm
     correlated energy spread      cor z =      0.000     keV
     emittance ratio eps y/eps x         =     0.9994

     phase-space distribution saved to file: astra1in.part

bash-3.2$ []
```

Expected output for default parameters

./astra atf2_linac.in



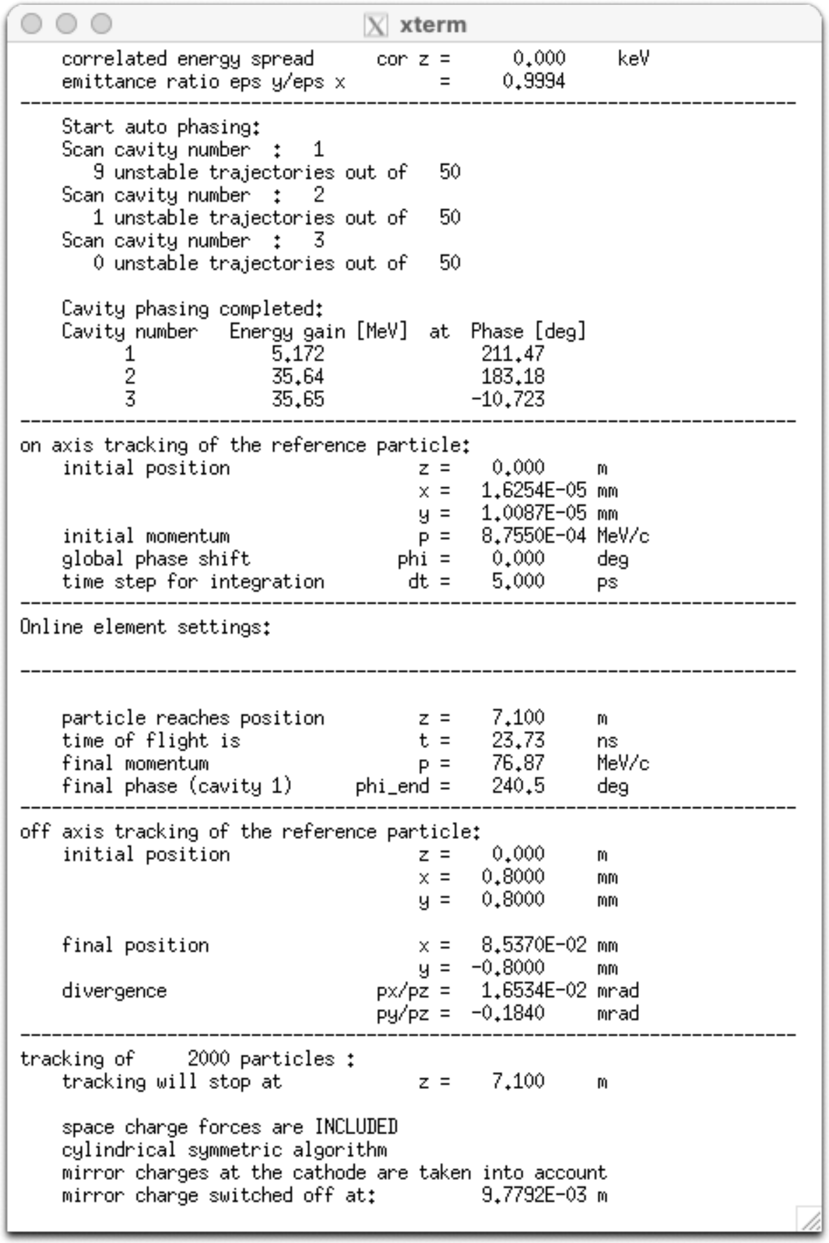
```
bash-3.2$ ./astra atf2_linac.in
 --------------------------------------------------------------------------


              Astra- A space charge tracking algorithm
                Version 3.2 - macOS 64bit - Intel
                       DESY,  Hamburg 2011
                       Mon Feb  6 17:36:06

     Parameter file is:  atf2_linac.in
     ATF


 Initialize element settings:
 --------------------------------------------------------------------------
 Cavity:

     Reading cavity field data from:      rfgunFIELD.dat

     field smoothing is applied
     Cavity Frequency               f =    2.856     GHz
     maximum gradient                      110.0     MV/m
     at                                    0.000     m
     estimated average gradient            31.51     MV/m
     nominal phase                        -18.00     deg

     Reading cavity field data from:      TWS_SLAC_S.dat

     Cavity Frequency               f =    2.856     GHz
     beta = 1 traveling wave structure
     TW Cell Length                        3.4975E-02 m
     Number of Cells                        84
     Phase Advance/Cell                     120.0     deg
     TW Section starts at                  0.8000     m
     TW Section ends at                     3.843     m
     Max E-field                            16.00     MV/m
     at                                    0.8525     m
     nominal phase                          0.000     deg

     Reading cavity field data from:      TWS_SLAC_S.dat

     Cavity Frequency               f =    2.856     GHz
     beta = 1 traveling wave structure
     TW Cell Length                        3.4975E-02 m
     Number of Cells                        84
     Phase Advance/Cell                     120.0     deg
     TW Section starts at                   3.900     m
     TW Section ends at                     6.943     m
     Max E-field                            16.00     MV/m
     at                                     3.952     m
     nominal phase                          0.000     deg

 --------------------------------------------------------------------------
```



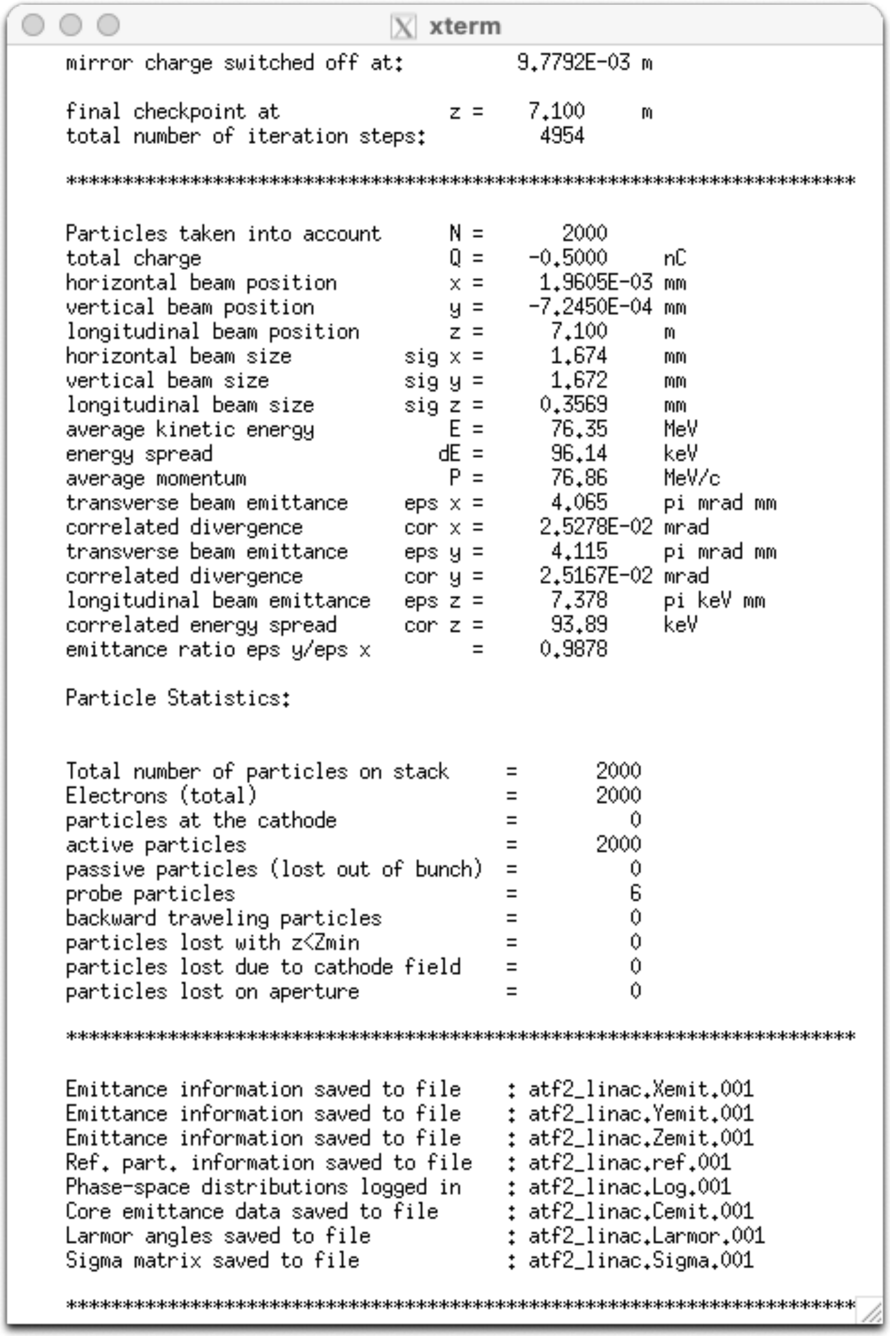
```
     at                                    0.8525     m
     nominal phase                          0.000     deg

     Reading cavity field data from:      TWS_SLAC_S.dat

     Cavity Frequency               f =    2.856     GHz
     beta = 1 traveling wave structure
     TW Cell Length                        3.4975E-02 m
     Number of Cells                        84
     Phase Advance/Cell                     120.0     deg
     TW Section starts at                   3.900     m
     TW Section ends at                     6.943     m
     Max E-field                            16.00     MV/m
     at                                     3.952     m
     nominal phase                          0.000     deg

 ----------------------------------------------------------------------------
 Solenoid:

     Reading solenoid field data from:    compenSOL_axial.dat

     field smoothing is applied
     maximum |Bz| field                    0.1650     T
     at                                    0.2138     m
     integral Bz squared                   4.3736E-03 T^2m

 ----------------------------------------------------------------------------
    2000 particles from file astra1in.part



     Cathode located at:                z =      0.000     m
     Particles taken into account       N =       2000
     total charge                       Q =    -0.5000     nC
     horizontal beam position           x =    2.5070E-05 mm
     vertical beam position             y =    1.5558E-05 mm
     longitudinal beam position         z =      0.000     m
     horizontal beam size           sig x =     0.8000     mm
     vertical beam size             sig y =     0.8000     mm
     longitudinal beam size         sig z =      0.000     mm
     total emission time                t =    6.4586E-03 ns
     rms emission time              sig t =    9.9998E-04 ns
     average kinetic energy             E =    7.4997E-07 MeV
     energy spread                     dE =    5.6676E-06 keV
     average momentum                   P =    8.7548E-04 MeV/c
     transverse beam emittance      eps x =     0.7904     pi mrad mm
     correlated divergence          cor x =   -2.2248E-02 mrad
     transverse beam emittance      eps y =     0.7909     pi mrad mm
     correlated divergence          cor y =    2.1167E-03 mrad
     longitudinal beam emittance    eps z =      0.000     pi keV mm
     correlated energy spread       cor z =      0.000     keV
     emittance ratio eps y/eps x          =     0.9994
```

Expected output for default parameters

./astra atf2_linac.in



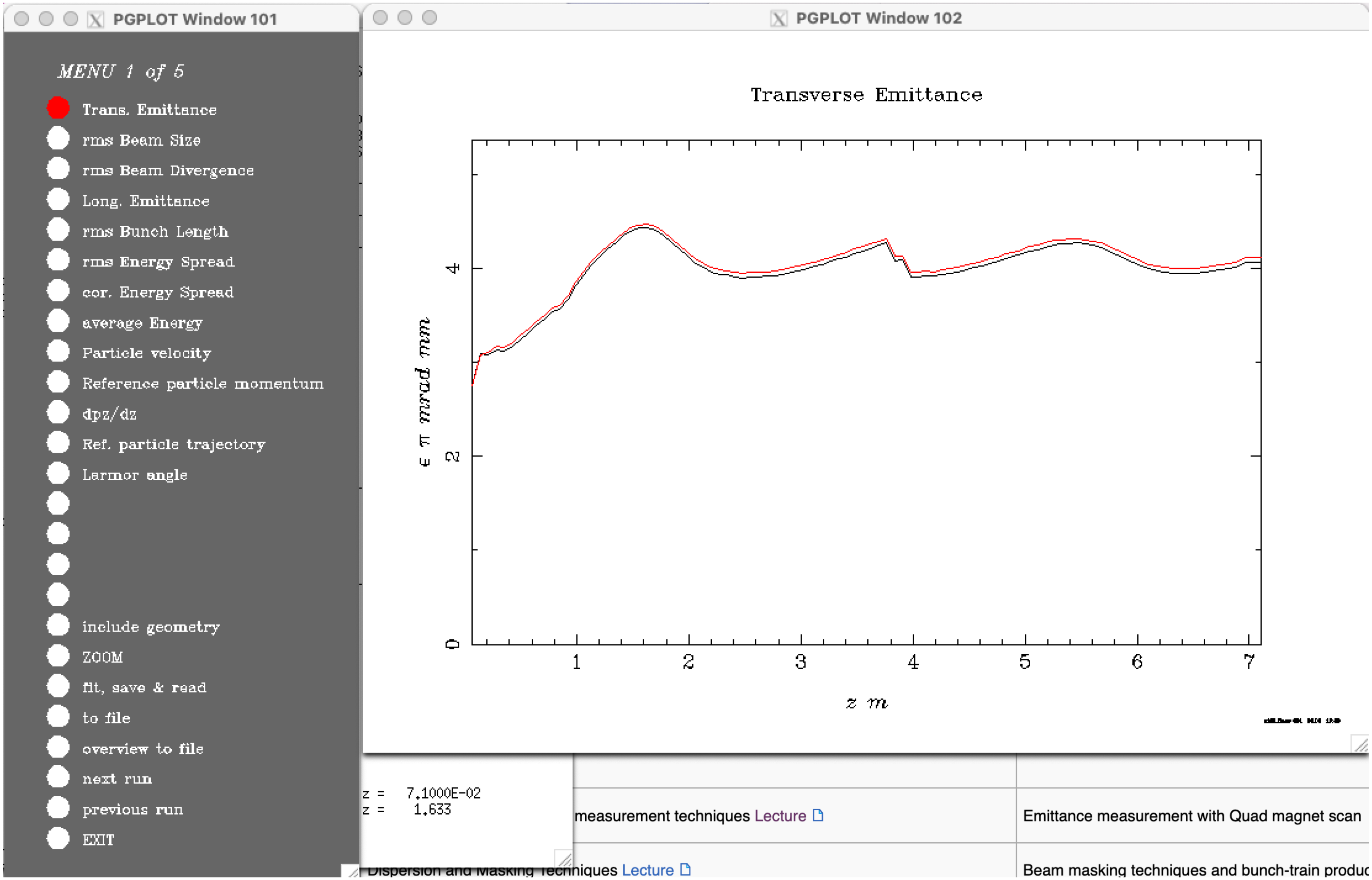
```
    correlated energy spread      cor z =       0.000      keV
    emittance ratio eps y/eps x         =     0.9994
--------------------------------------------------------------------------
    Start auto phasing:
    Scan cavity number  :   1
       9 unstable trajectories out of   50
    Scan cavity number  :   2
       1 unstable trajectories out of   50
    Scan cavity number  :   3
       0 unstable trajectories out of   50

    Cavity phasing completed:
    Cavity number   Energy gain [MeV]  at  Phase [deg]
          1              5.172              211.47
          2             35.64               183.18
          3             35.65              -10.723
--------------------------------------------------------------------------
on axis tracking of the reference particle:
    initial position                  z =    0.000      m
                                      x =   1.6254E-05 mm
                                      y =   1.0087E-05 mm
    initial momentum                  p =   8.7550E-04 MeV/c
    global phase shift              phi =    0.000      deg
    time step for integration        dt =    5.000      ps
--------------------------------------------------------------------------
Online element settings:

--------------------------------------------------------------------------


    particle reaches position         z =    7.100      m
    time of flight is                 t =    23.73      ns
    final momentum                    p =    76.87      MeV/c
    final phase (cavity 1)      phi_end =    240.5      deg
--------------------------------------------------------------------------
off axis tracking of the reference particle:
    initial position                  z =    0.000      m
                                      x =   0.8000      mm
                                      y =   0.8000      mm

    final position                    x =   8.5370E-02 mm
                                      y =  -0.8000      mm
    divergence                    px/pz =   1.6534E-02 mrad
                                  py/pz =  -0.1840      mrad
--------------------------------------------------------------------------
tracking of     2000 particles :
    tracking will stop at             z =    7.100      m

    space charge forces are INCLUDED
    cylindrical symmetric algorithm
    mirror charges at the cathode are taken into account
    mirror charge switched off at:          9.7792E-03 m
```



```
    mirror charge switched off at:          9.7792E-03 m

    final checkpoint at               z =    7.100     m
    total number of iteration steps:          4954

    **********************************************************************

    Particles taken into account      N =       2000
    total charge                      Q =    -0.5000     nC
    horizontal beam position          x =     1.9605E-03 mm
    vertical beam position            y =    -7.2450E-04 mm
    longitudinal beam position        z =      7.100     m
    horizontal beam size          sig x =      1.674     mm
    vertical beam size            sig y =      1.672     mm
    longitudinal beam size        sig z =     0.3569     mm
    average kinetic energy            E =      76.35     MeV
    energy spread                    dE =      96.14     keV
    average momentum                  P =      76.86     MeV/c
    transverse beam emittance     eps x =      4.065     pi mrad mm
    correlated divergence         cor x =     2.5278E-02 mrad
    transverse beam emittance     eps y =      4.115     pi mrad mm
    correlated divergence         cor y =     2.5167E-02 mrad
    longitudinal beam emittance   eps z =      7.378     pi keV mm
    correlated energy spread      cor z =      93.89     keV
    emittance ratio eps y/eps x         =     0.9878

    Particle Statistics:


    Total number of particles on stack     =       2000
    Electrons (total)                      =       2000
    particles at the cathode               =          0
    active particles                       =       2000
    passive particles (lost out of bunch)  =          0
    probe particles                        =          6
    backward traveling particles           =          0
    particles lost with z<Zmin             =          0
    particles lost due to cathode field    =          0
    particles lost on aperture             =          0

    **********************************************************************

    Emittance information saved to file     : atf2_linac.Xemit.001
    Emittance information saved to file     : atf2_linac.Yemit.001
    Emittance information saved to file     : atf2_linac.Zemit.001
    Ref. part. information saved to file    : atf2_linac.ref.001
    Phase-space distributions logged in     : atf2_linac.Log.001
    Core emittance data saved to file       : atf2_linac.Cemit.001
    Larmor angles saved to file             : atf2_linac.Larmor.001
    Sigma matrix saved to file              : atf2_linac.Sigma.001

    **********************************************************************
```

Results of lineplot command

./lineplot atf2_linac



```
z =    7.1000E-02
z =     1.633
```

measurement techniques Lecture

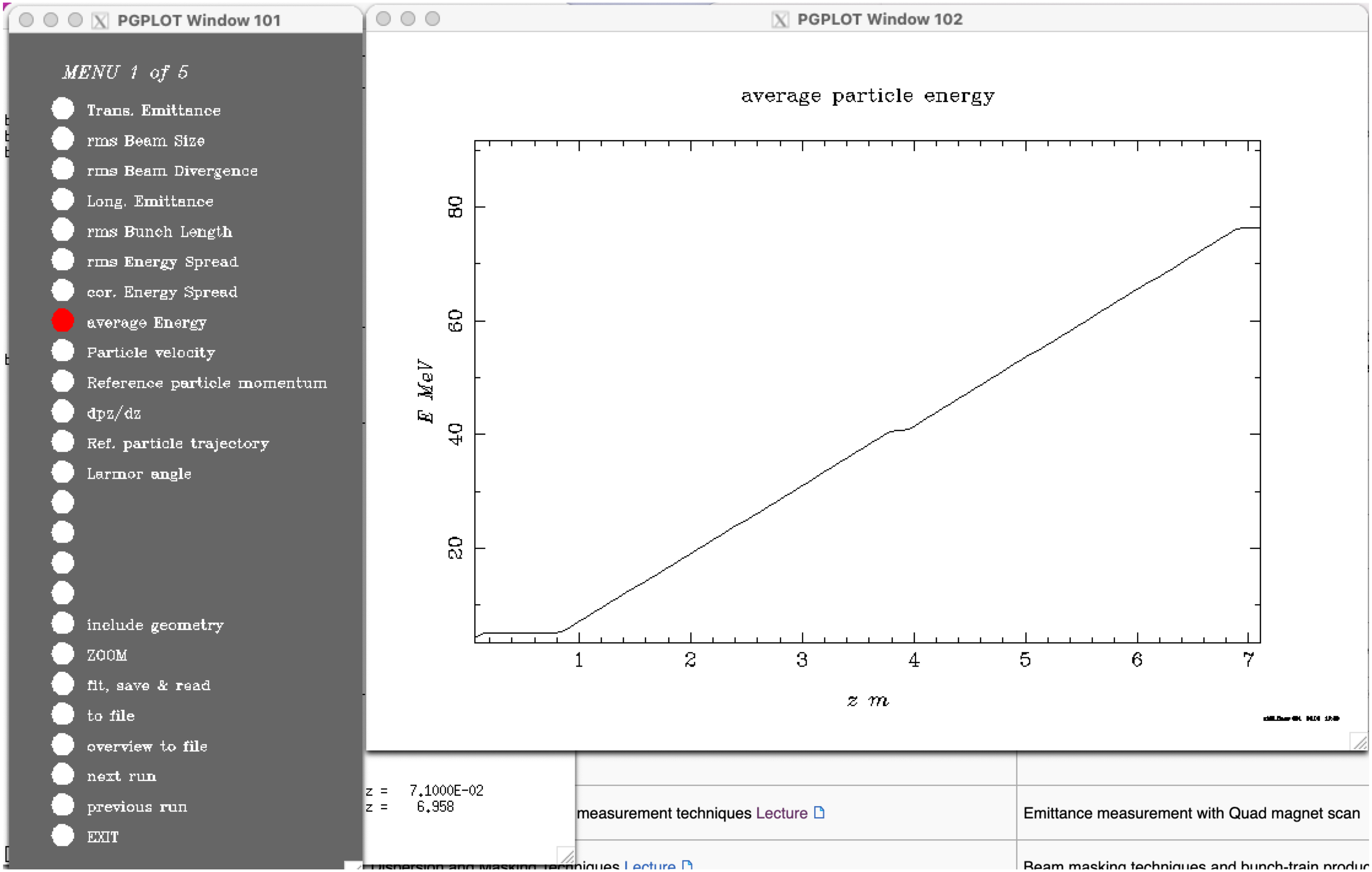
Emittance measurement with Quad magnet scan

Dispersion and Masking Techniques Lecture

Beam masking techniques and bunch-train produc

Results of lineplot command

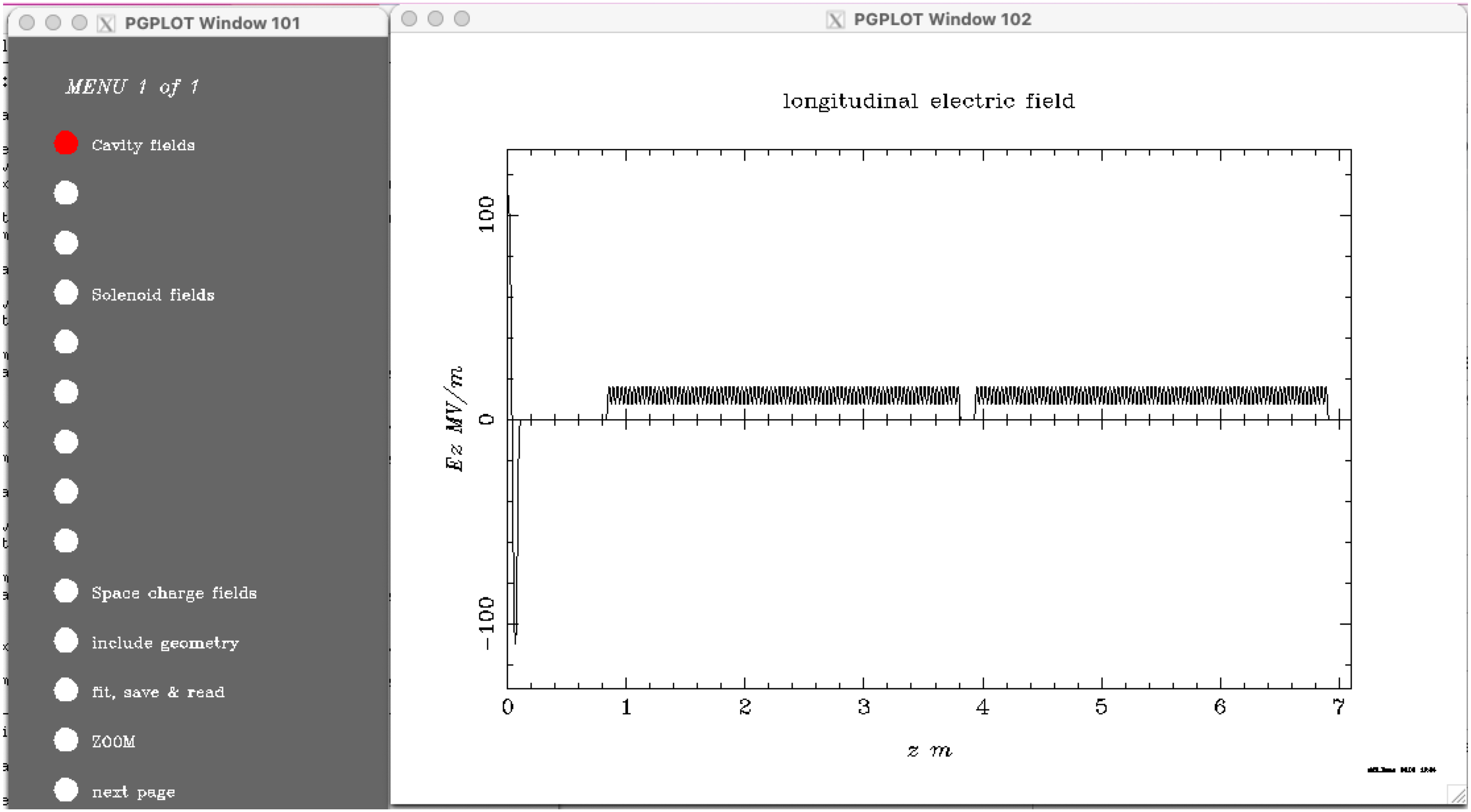
./lineplot atf2_linac



```
z =    7.1000E-02
z =     6.958
```

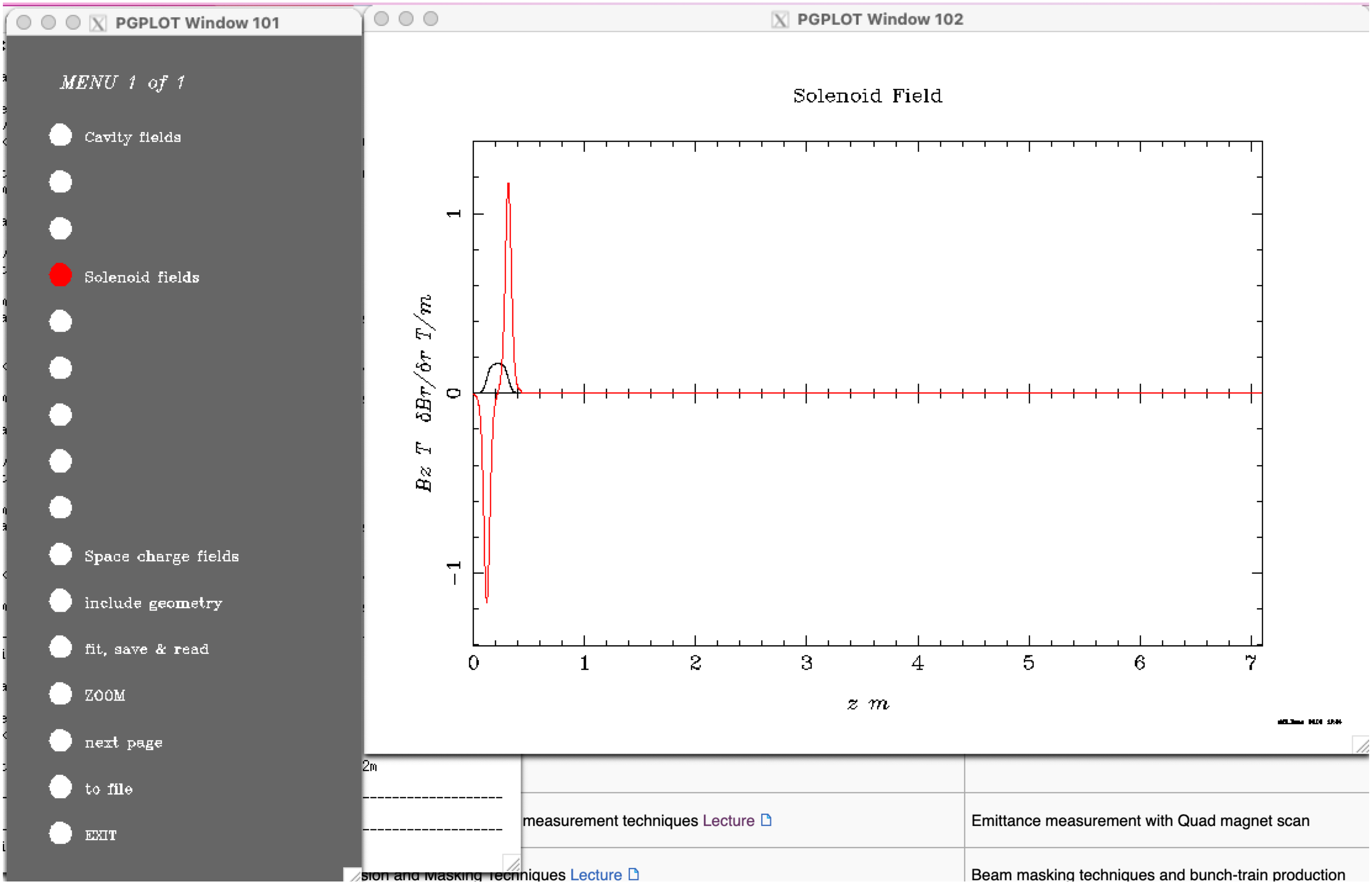
Expected fields plots

```
./fieldplot atf2_linac
```



Expected fields plots

./fieldplot atf2_linac



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