Modeling photo-injectors

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Accelerator simplified schematic

- Three main components: Source, transport, target

Energy Transfer: $\gamma \rightarrow e^-$: accelerator  
$e^- \rightarrow \gamma$: light source
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: 
  \[ E_r = \frac{I_r}{2\pi\varepsilon_0 R^2 v} \]
- Ampere’s Law: 
  \[ B_\theta = \frac{\mu_0 I_r}{2\pi R^2} = \frac{\gamma E_r}{c^2} \]
- Lorenz Force Law: 
  \[ F_{r,sc} = q(E + v \times B) = \frac{qI}{2\pi\gamma^2 \varepsilon_0 v R^2} r = C(R)r = \frac{qE_r}{\gamma^2} \]
- 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=4.5x10^{-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?

\[ \nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0} \quad \nabla \cdot \vec{B} = 0 \]

\[ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad \nabla \times \vec{B} = \mu_0 \left( \vec{J} + \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \right) \]

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

\[ \frac{\partial \vec{r}}{\partial t} = \frac{c \vec{p}}{\sqrt{m^2 c^2 + |\vec{p}|^2}} \]

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

**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
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.

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- Source: [http://www.desy.de/~mpyflo/](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

$$
\text{INPUT} \\
\text{Add} = . T, \\
\text{! FILE NAME TO CREATED (ELECTRON DISTRIBUTION)} \\
\text{FNAME = 'astra1in.part'} \\
\text{IPart=2000} \\
\text{Species='electrons'} \\
\text{Probe=.True.} \\
\text{Noise_reduc=.T.} \\
\text{Cathode=.T.} \\
\text{! BUNCH CHARGE} \\
\text{Q_total=0.050} \\
\text{Ref_zpos=0.} \\
\text{Ref_clock=0E-3} \\
\text{Ref_Ekin=0.} \\
\text{! LASER LONGITUDINAL PROFILE} \\
\text{Dist_z='gauss', sig_clock=2.0E-3, Lt=0., rt=0.} \\
\text{Dist_pz='i', LE=0.750E-03} \\
\text{! LASER TRANSVERSE PROFILE} \\
\text{Dist_x='radial', Lx=1.095} \\
\text{Dist_px='radial', Nemit_x=0., cor_px=0.0E0} \\
\text{Dist_y='radial', Ly=1.095} \\
\text{Dist_py='radial', Nemit_y=0., cor_py=0.0E0}$$
Tracking inside photocathode with ASTRA

- 2856 MHz
- RF 1.6 cell cavity
- Cathode
- Focusing B-Field
- Accelerating Field
- Stop simulation here
ASTRA: Track inside photocathode

Space-Charge

RAW TEXT: 

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
LSPEC=T
! use the following mesh for appropriate number of macroparticles
Nrad=10,
Nion_1H=1/2,
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,
LField=T
FILE_Efield('rfgunFIELD.dat', C_smooth(1)=10,
MaxE(1)=110.00, Phi(1)=-12.0, C_pos(1)=0.0,
C_higher_order(1)=T
/

$SOLENOID
! COMPENSATION SOLENOID
Loop=F,
LField=T
FILE_Bfield('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
/

Waveguide
RF Gun
Gate Valve
Optical Transition (OTR)
Emittance Compensation Magnet
Bucking Magnet
Laser Port
66.4 CM

On-Axis E-Field

Bz-Axis (T)
You will check space-charge effect
You will optimize focusing
You will tune the emittance

- Can you reproduce this result for the ATF injector?