The Design of Electron and Ion Guns, Beams, and Collectors

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ABSTRACT.   The well known "SLAC Electron Trajectory Program" (EGUN) has been ported to PCs and has been developed into a family of programs for the design and the optimization of particle optics devices including electron and ion guns, beam transport sections and collectors. We will discuss the application of these tools for the design and the optimization of the essential parts of EBIS/T devices. The discussion will include conditions in which restrictions in the reliability of simulations may occur due to the mathematical modeling and how to overcome them.

INTRODUCTION

The electron beam formation, its focusing properties and the expansion and spreading of the beam over the collector surface need reliable tools for the design of magnetic shielding of solenoids as well as for the calculation of electron trajectories under the influence of electric, magnetic and self fields. This knowledge, acquired over many decades for the design of traveling wave tubes (TWTs), Klystrons, and gyrotrons has resulted in professional software, used in industry as well as in accelerator laboratories around the world. The anchestor of the family of simulation tools is EGUN [1,2,3,4], a finite difference Poisson solver, combined with a relativistic ray tracing routine, taking into account the magnetic field of the beam itself and the space charge of the beam. Numerous options became incorporated with time and today there is hardly to find an application, which cannot be simulated with this 2D rectangular and axisymmetric simulation program.

After porting of the program to PCs, giving the name EGN87c, adequate graphical software became necessary. Also the program POLYGON [5] made it much easier to set up boundaries for EGN. For the calculation of static magnetic fields without saturation, the boundary element program INTMAG [6,7] has been developed. By its calculus, the numerical values are very smooth and allow for the meaningful generation of 6th order axial field derivatives, which in turn allowed to calculate the off-axis fields in EGN87c with in a convenient, fast, and accurate way. The latest

member of such simulation programs is IGUN [8,9], a true child of EGUN, but with an option to simulate the plasma sheath for the extraction of positive ions. For the convenience of users some analyzing and graphic file converters have been added. The latest and most advanced of them is CPLCOMP, which is a print and file conversion composer for the graphics output files. The possible combination of these programs is shown by Fig. 1
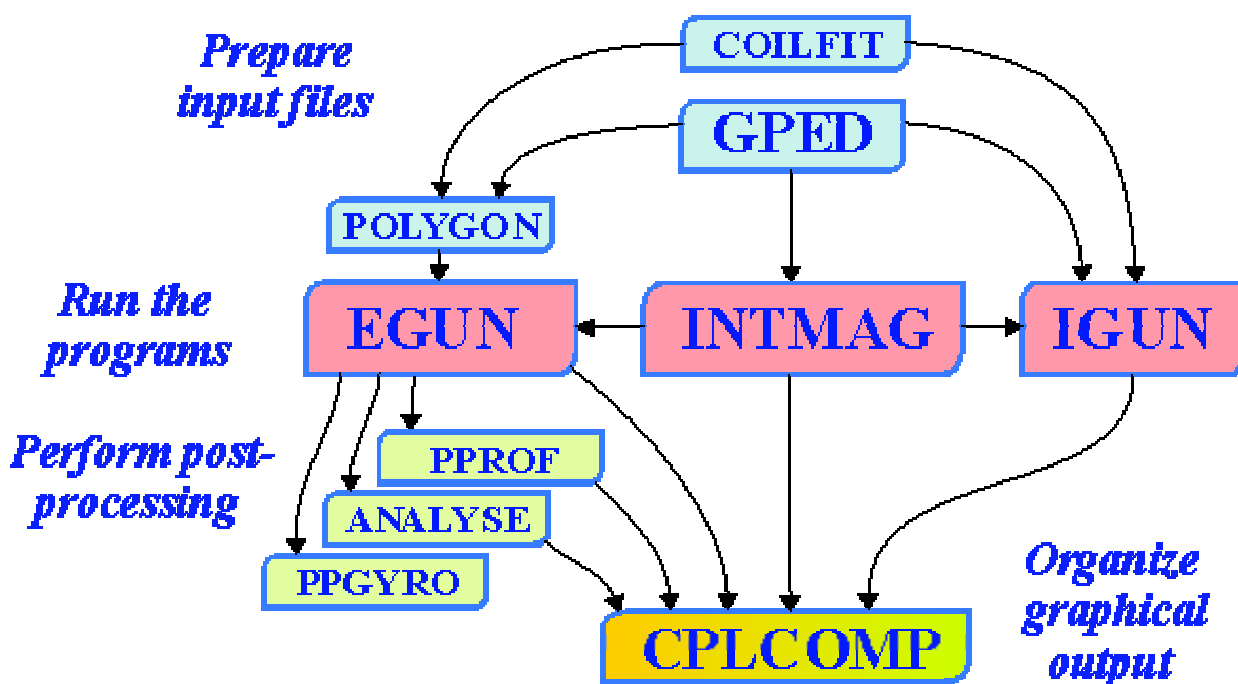

FIGURE 1. Schematic drawing of the connections between the programs of the EGUN/IGUN family, see also WWW.EGUN-IGUN.COM

DESIGN OF ELECTRON GUNS

The design of an electron gun usually starts with the definition of desired parameters, like current, energy, available focusing, life time of the cathode and other constraints. The suitable simulation tool is in any case EGN2W, how the new EGUN version for Windows is called today. The input files for EGN2W are provided by POLYGON, which converts polygonal boundary input to the required form of mesh oriented input for EGN2W. POLYGON also reads and augments input parameter lists in NAMELIST format, includes magnetic field data and provides a valid input file for EGN2W. The geometrical part of polygonal boundary definition is most conveniently processed with GPED, a graphical interactive editor for POLYGON syntax, useful for POLYGON, INTMAG, and IGUN. As an example, we show the steps for simulating the MEDEBIS gun [10,11], which has high perveance (2.1 $\mu A/V^{3/2}$) and high compression (110) under immersed flow conditions.

```
    MEDEBISGun (non-thermal, mesh=0.1 mm, 07.09.98,HOE)
  &INPUT1 RLIM=130,POTN=7,POT=0,3000,2000,0,3000,3700,2000,MAGSEG=-1,
        PUNIT=1E-3,POIS=3 &END
  &INPUT3 BMULT=2,BZA=
  1.200383642160E+01, 1.207735271118E+01, 1.215471079222E+01, 1.223594165980E+01,
...
  1.389147341865E+03, 1.396516129184E+03, 1.403942021605E+03, 1.411424923268E+03,
  1.418964726282E+03,
&END
1, 0, 0                              2, 3, 36.5
1, 8.725, 4.898                      1002, 4, 36.5
4, 8.725, 4.898                      1
4, 10.3, 15                          2, 10, 37.5
4, 10.3, 26                          2, 11, 36.5
1004, 12.3, 26                       2, 13, 36.5
2                                    6, 13, 39.5
4, 13, 28                            6, 4, 39.5
2, 13, 31                            1006, 4, 40.5
2, 6.5, 31                           1
2, 6.5, 10.5                         6, 3, 60
2, 5.5, 10.5                         0, 0, 60
2, 3, 24.7                           1, 0, 0
  &INPUT5 START ='SPHERE', RMAX =    87.250, RAD = 0.1022E+03, MAXRAY = -87,
  LSTRH = 1, UNIT =0.1000E-03 ,NS=15, AV=10, AVR=1, LM=1000 &END
```

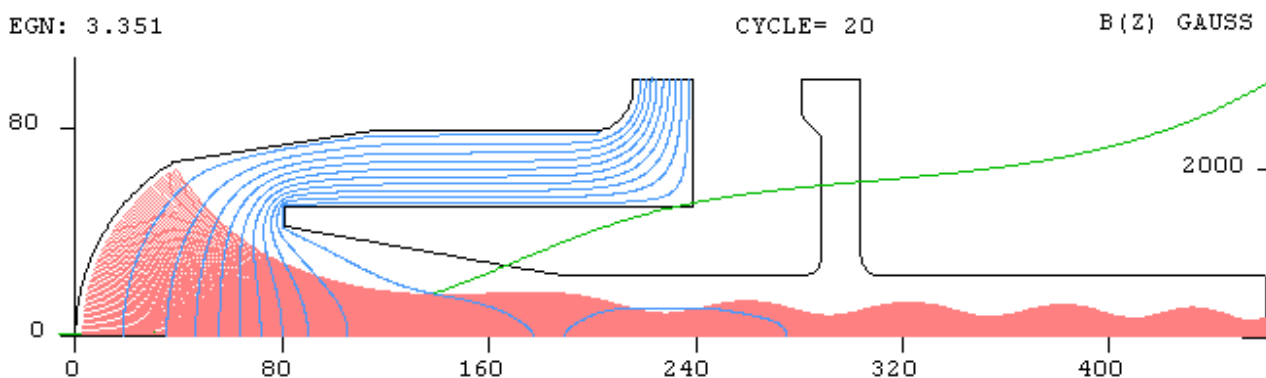**FIGURE 1.** Input file for POLYGON of the MEDEBIS gun

FIGURE 2. Result of EGN2W calculation for the MEDEBIS gun

The input file has 4 parts, which can be clearly distinguished in Fig. 1:
1) definition of the basic parameters (INPUT1)
2) axial values for the magnetic field (INPUT3 – truncated)
3) input of boundary points in POLYGON syntax (presented here in 2 columns)
4) definition of runtime variables (INPUT5).

While the definitions of NAMELISTs INPUT1, INPUT3, and INPUT5 are prescribed by the EGN2W manual, we will explain to some detail here the POLYGON syntax, comparing Fig. 1. and Fig. 2: A mesh independent boundary point is described by 3 numbers: an integer for the potential number and 2 floating point numbers for the values of the r and z coordinate. The first point is the cathode electrode (number 1) at r=0, z=0. The second point shows the end of the spherical cathode shape at r=8.725, z=4.898. POLYGON has a special interpretation for the cathode electrode: if only 2 points will be given, a spherical (in axisymmetric coordinates) or as cylindrical (in rectangular coordinates) shape will be assumed. Then input continues with the focusing electrode with potential number 4. No gap is assumed between the egde of the cathode and the begin of this electrode, therefore the same coordinate values as for the end of the cathode are used as a start for this electrode. Then we have these numbers:

4, 10.3, 26

1004, 12.3, 26

2

4, 13, 28

2, 13, 31

Adding 1000 to the potential number is a signal to POLYGON to insert a circle of radius 2 and center r=12.3, z=26 between points with r=10.3, z=26 and r=13, z=28. Then we see the electrode number changing from 4 to 2 at r=13, z=31. POLYGON will insert Neumann boundary points here automatically. Finally the first point is reached again, which is a signal to POLYGON that the boundary is closed and input complete.

POLYGON syntax has several features to ease the input of complicated boundary shapes, however, even simpler is the input and the modification of existing input files by GPED, which is a dedicated CAD system with interactive graphics for POLYGON syntax files.

As a result of running POLYGON with the above input file, an input file for EGN2W is obtained, which produces the plot of trajectories and equipotential lines as shown in Fig. 2. Clearly, this is an immersed field gun with a rippling beam after compression in the increasing magnetic field. By axially shifting the magnetic field against the electrostatic electrode part, the ripple can be minimized. This is facilitated by POLYGON: No new magnetic field interpolation will be needed, a single variable defines the axial displacement between the INTMAG and the EGN2W coordinates.

POST-PROCESSING OF EGN2W OUTPUT

EGN2W has been optimized for fast execution – most of the analysis and specific interpretation is left to programs for post-processing, like PPPROF for profiles and emittances, PPGYRO for Gyrotron relevant analsis, ANALYSE for surface fields, cathode loading, profiles, emittances, field lines to be used as slanted Neumann boundaries, equipotentials to be used as pseudo electrodes in runs with higher mesh resolution.

Here we show, how ANALYSE creates a plot of filled electrodes and of surface fields. The latter is especially important to optimise the contour of electrodes for low surface fields.
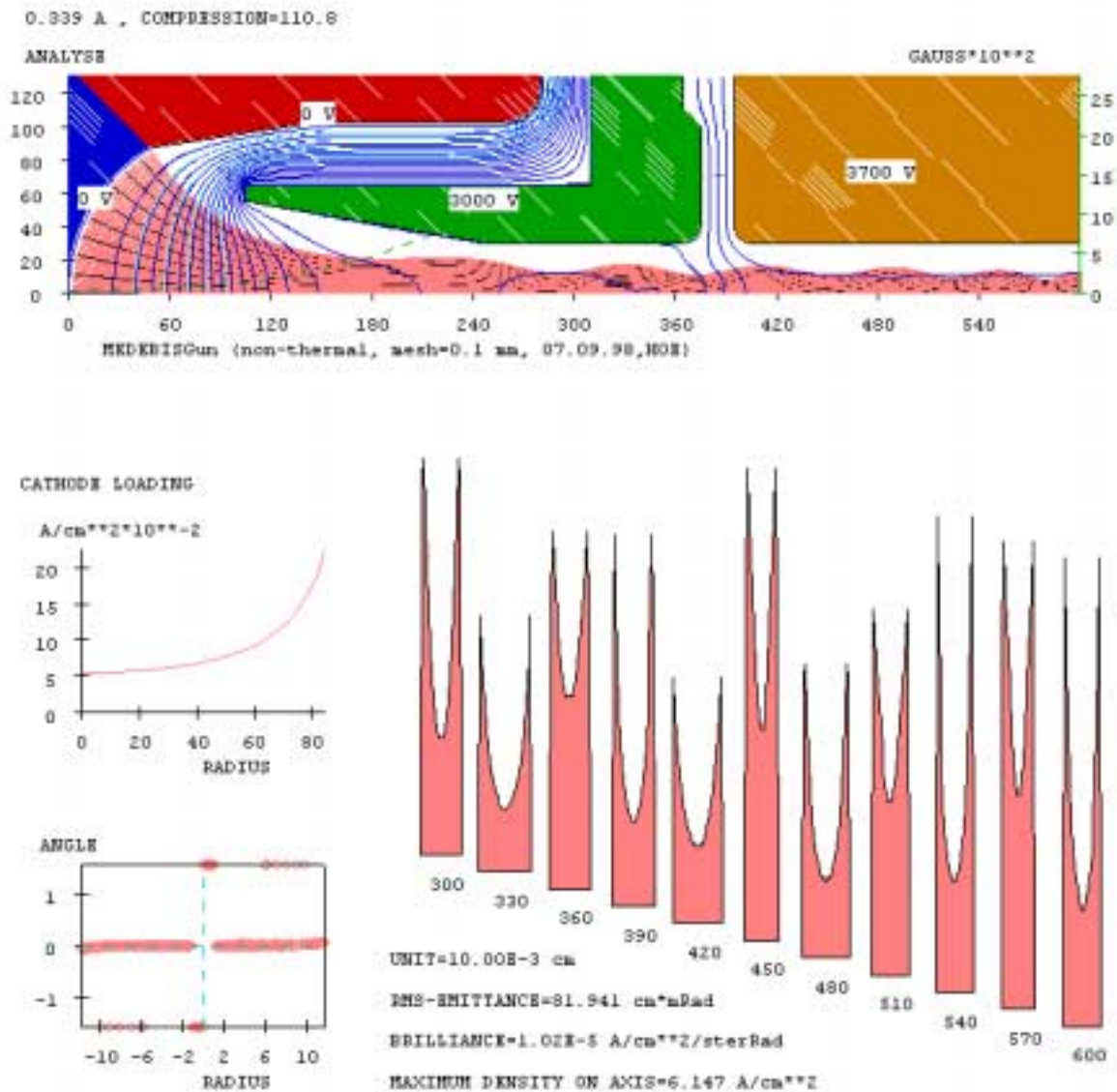

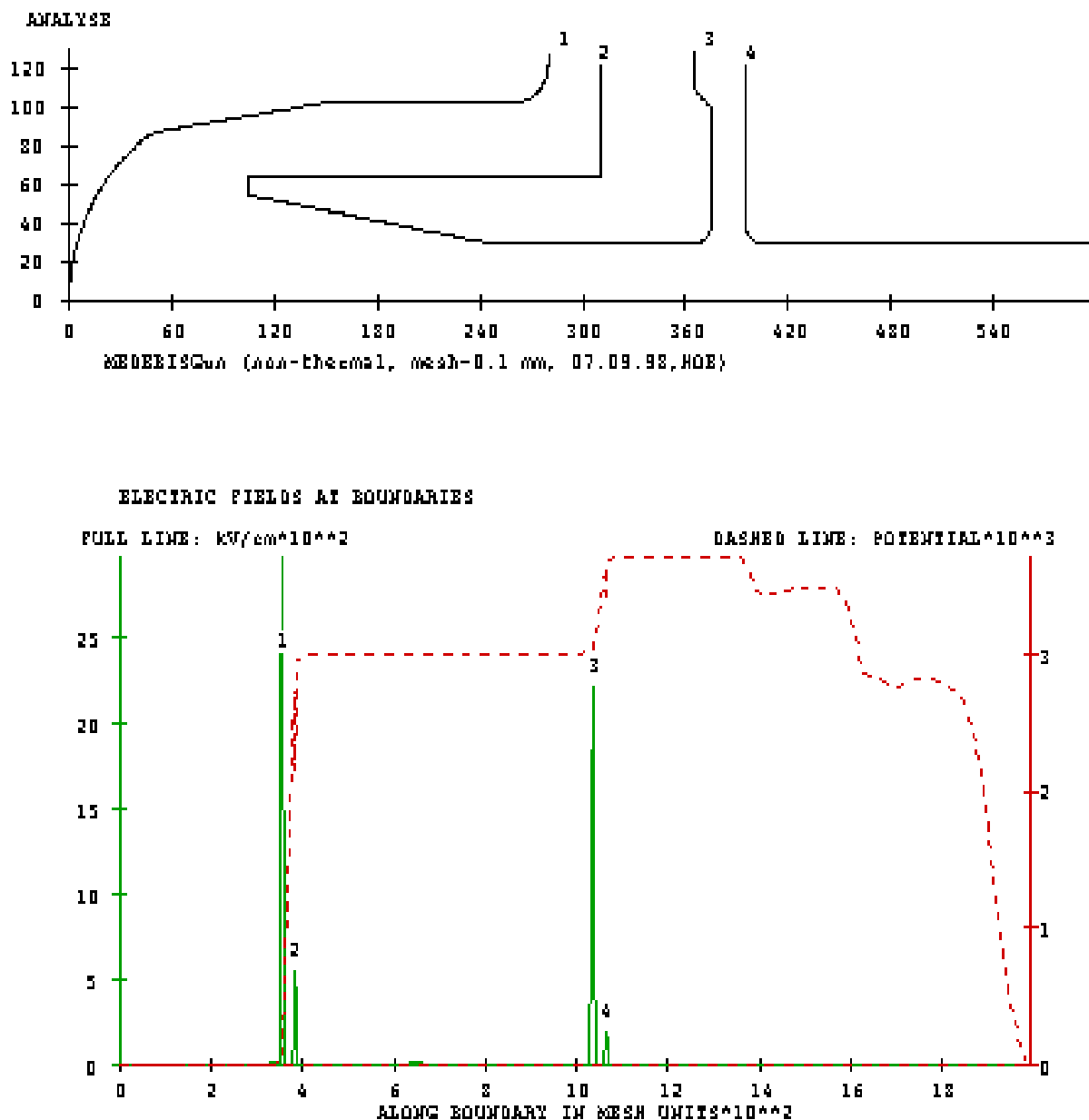**FIGURE 3.** ANALYSE output of the MEDEBIS gun

FIGURE 4. ANALYSE output of the MEDEBIS gun – surface fields and potentials

In Fig. 4 the surface fields (solid line in lower panel) are shown along the boundary of the MEDEBIS gun, together with the local potential (dashed line). Extrema of field are indicated in the upper plot of the boundary as well as in the lower one along the boundary, making it easy to spot positions, where the field could become dangerous for sparking. Here the maxima "1" and "3" are dangerous, because they are on relative negative potential.

CALCULATION OF MAGNETOSTATIC FIELDS

The MEDEBIS magnetic configuration has become quite complex, more with each step of refinement. It now consists of a short normal conducting solenoid, 3 pancakes, 3 iron discs and one solid cylinder of μ-metal to shield the flux lines to be perpendicular [12] to the cathode and another one, made of soft iron to shield the electron collector. The input file to INTMAG for the MEDEBIS magnetic circuit is given by Fig. 6:

```
MEDEBIS_Spule 3 Eisenscheiben/3 Pancakes 15.10.98
&DEFINE NCOIL=5, RECT=F, UNIT=0.001, NIRON=5 , ITER=500 &END
&RECTCOIL Z0=126, R0=39.75, HALFL=111.5, THICK=40.4, LAYERS=6, LTURN=35, AMPTRN=96800 &END
&RECTCOIL Z0=120, R0=79.5, HALFL=120, THICK=39, LAYERS=4, LTURN=25, AMPTRN=47500 &END
&RECTCOIL Z0=-147, R0=145, HALFL=7.5, THICK=60, LAYERS=10, LTURN=2, AMPTRN=9500 &END
&RECTCOIL Z0=347.5, R0=145, HALFL=7.5, THICK=90, LAYERS=13, LTURN=2, AMPTRN=3120 &END
&RECTCOIL Z0=485, R0=145, HALFL=15, THICK=90, LAYERS=13, LTURN=4, AMPTRN=-6000 &END
&IRON NFIL=240, PERM=500 &end                       1,11.9,-112.5
1,22,266                                            1,11.9,-62.5
1,222,266                                           &IRON NFIL=240, PERM=500 &END
1,222,256                                           1,15,323
1,22,256                                            1,15,403
1,22,266                                            1,40,403
&IRON NFIL=240, PERM=500 &END                       1,40,323
1,22,-16                                            1,15,323
1,222,-16
1,222,-26                                           &IRON NFIL=240, PERM=500 &END
1,22,-26                                            1, 80, -255
1,22,-16                                            1, 250, -255
&IRON NFIL=240, PERM=10000 &END                     1, 250, -265
1,11.9,-62.5                                        1,80, -265
1,49,-62.5                                          1, 80,-255
1,49,-112.5
&PROFILE RP1=0, RP2=0, ZP1=-85, ZP2=-20, NPROF=600 &END
&MAPS NMZ=0, NMR=0 &END
&FLUX NINT=0 &END
&EGUN EGNZ0=-84.8, EGNZLIM=480, EGNUNIT=0.000125 &END
&FLUXLINE ZMIN=-300, ZMAX=125, RMIN=0, RMAX=300, SMIN=1, SMAX=10, NLINE=50, LINEAR=F &END
```

FIGURE 5. Input file to INTMAG for the magnetic elements of the MEDEBIS
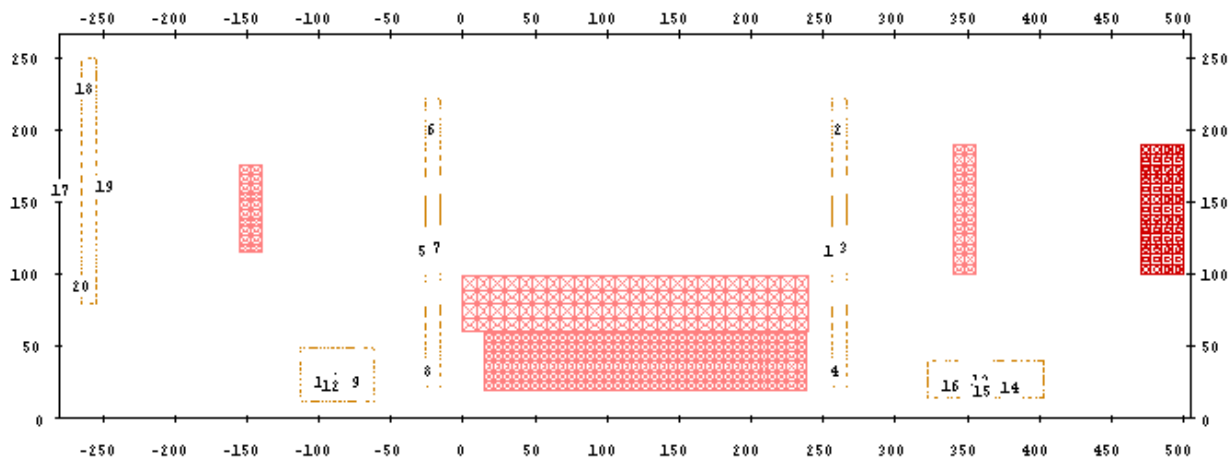
A drawing of all parts is provided by INTMAG:

FIGURE 6. Magnetic circuit of the MEDEBS, plotted by INTMAG

For the EGN2W simulation shown earlier, we are interested only in the gun region, which is between axial coordinate z = -85 to Z = 0. The results of INTMAG then can be shown as a plot of flux lines (Fig. 7.), while for the transfer of magnetic field data to EGN2W, the axial field values are written on a file.
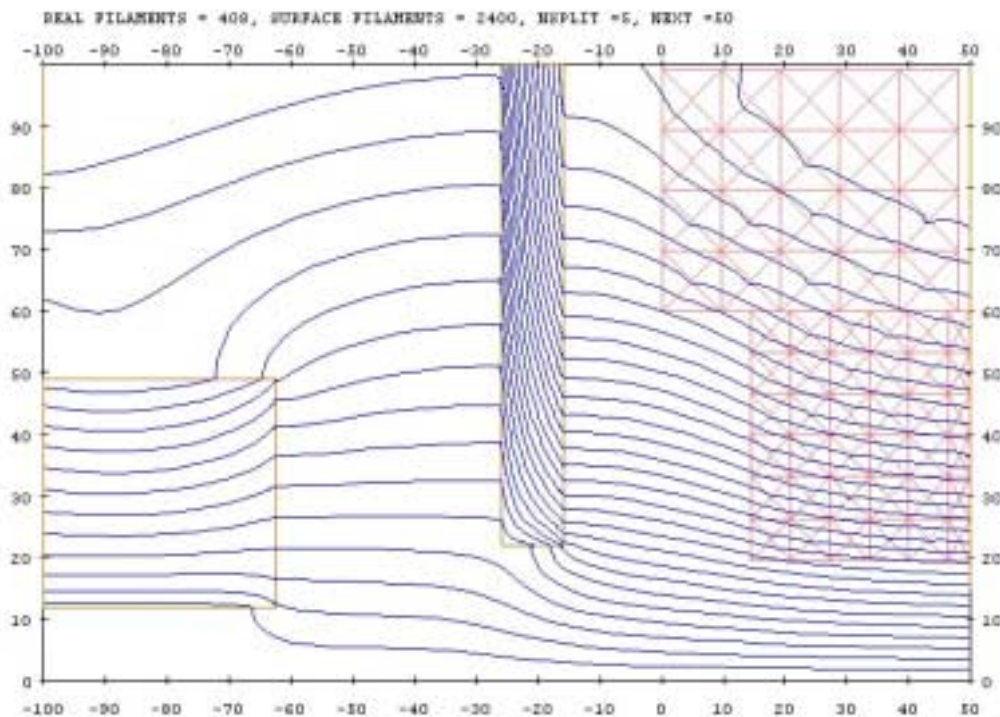

FIGURE 7. Flux lines, calculated by INTMAG for the gun region of MEDEBIS and plotted on top of the magnetic elements in there, left the cathode shielding cylinder, center the iron disc, to the right the normal conducting solenoid

ION EXTRACTION FROM PLASMAS

For the injection of singly charged ions into an EBIS, used for charge breeding, the optimization of a plasma ions source may be of interest. As an example we present the CHORDIS ions source, developed at GSI and calculated with IGUN. The input file for this is shown in Fig. 8:

```
    CHORDIS ion source
  &INPUT1 RLIM=80,POTN=5,POT=-4000,30000,0,0,0,PUNIT=2.5E-4,batch=f &END
3, 0, 0
3, 40, 0
2, 40, 5
2, 10, 5
2, 10, 7.5
2, 22.5, 20
2, 40, 20
1, 40, 40
1, 15, 40
1, 10, 42.5
1, 10, 52.5
1, 15, 55
1, 40, 55
5, 40, 67.5
5, 10, 67.5
5, 10, 75
5, 40, 75
0, 40, 100
0, 0, 100
3, 0, 0
  &INPUT5 MAXRAY=50,TE=5,UI=5,MASS=14,RP=10,ZP=7.5,NS=10,AV=4,DENS=0.1,
        HOLD=10,ZSCAN=50,DSCAN=10,NSCAN=6,NSPLIT=-1,TI=1,WRTEQU=28000,
        RFLD=16.25,ZFLD=13.75,USTART=30010,STARTL=11,zend=100 &END
  &BUNDLE CHARGE=2 &END
```

FIGURE 8. IGUN input file for the CHORDIS ion source

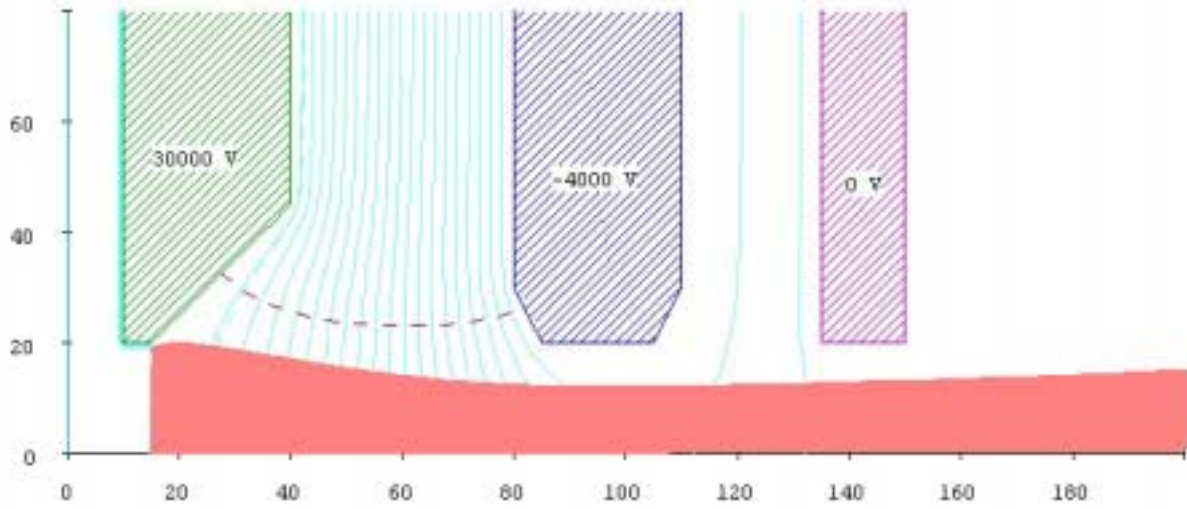The result of running IGUN is shown in Fig. 9-12:

FIGURE 9. Trajectories and equipotential lines for the CHORDIS ion source, calculated with IGUN

IGUN performs the same kind of surface field analysis, shown in Fig. 10 and demonstrating that the field maximum in position "4" is especially dangerous and may cause sparking:
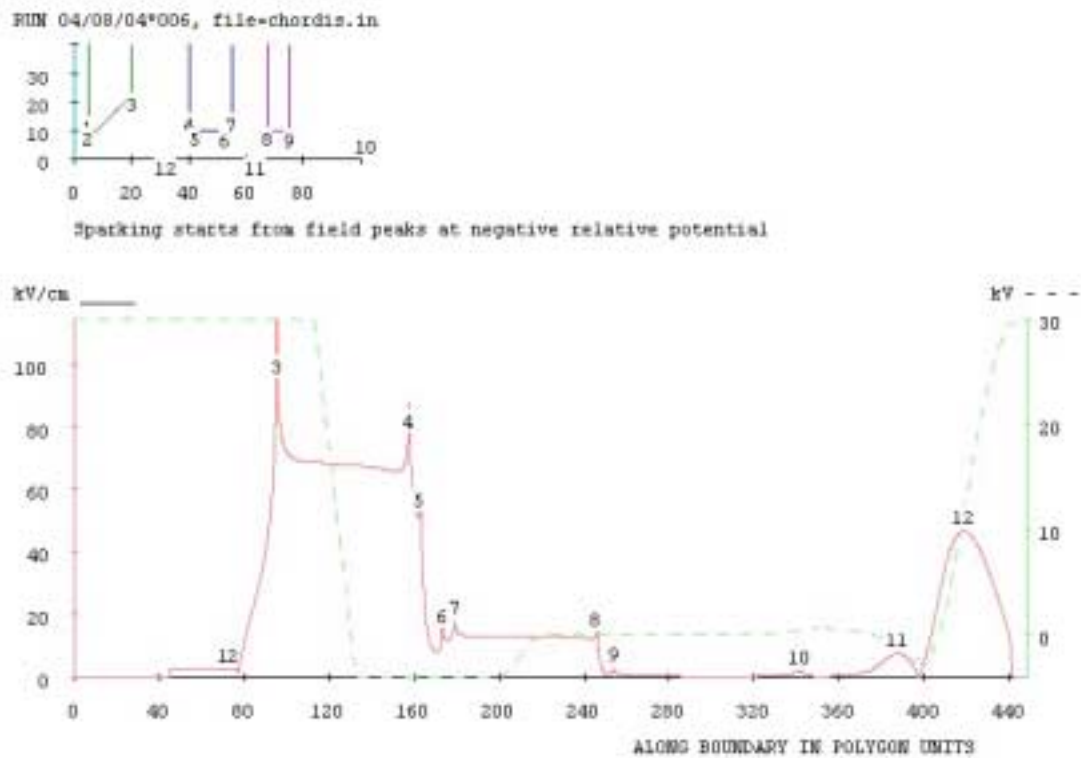

FIGURE 9. Surface fields (solid line) and potentials (dashed line) along the boundary of the CHORDIS ion source

Emittance plot of all trajectories at Zend =100.00 Punits

RMS-emittance = 0.756 cm*mRad

Amax = 52.930 mRad   Axial position Zx = 97.000 PUNIT

Current passing through aperture = -1.76E-2 A   Rmax = 0.189 cm
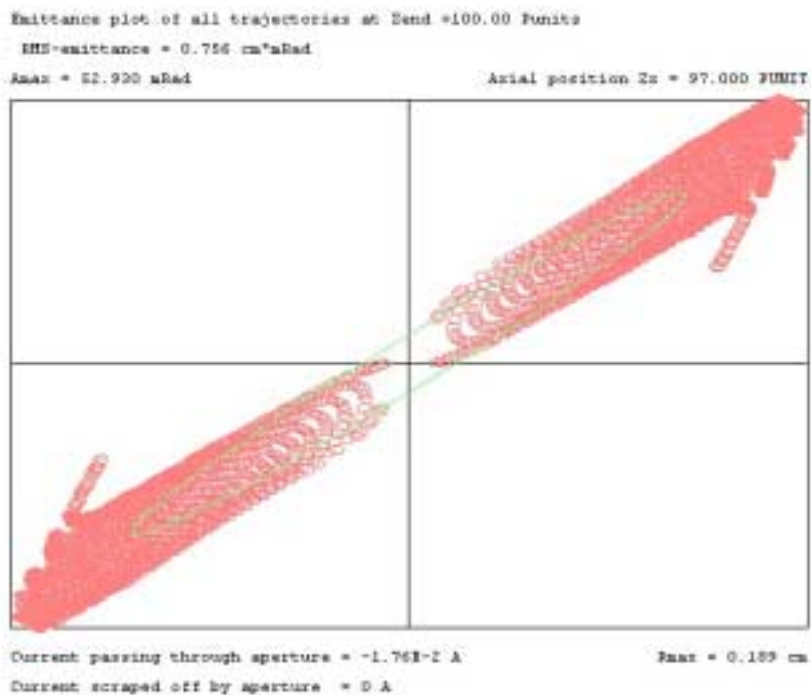Current scraped off by aperture = 0 A

FIGURE 10. Emittance diagram in the end position of trajectories, showing little aberration wings. The rms-ellipse is plotted on top of the trajectory spots.

Emittance shaped by scraping off aberrated tails100.00 Punits

RMS-emittance = 0.693 cm*mRad

Amax = 52.930 mRad   Axial position Zx = -56.500 PUNIT

Current passing through aperture = -1.69E-2 A   Rscrape = 3.59E-2 cm
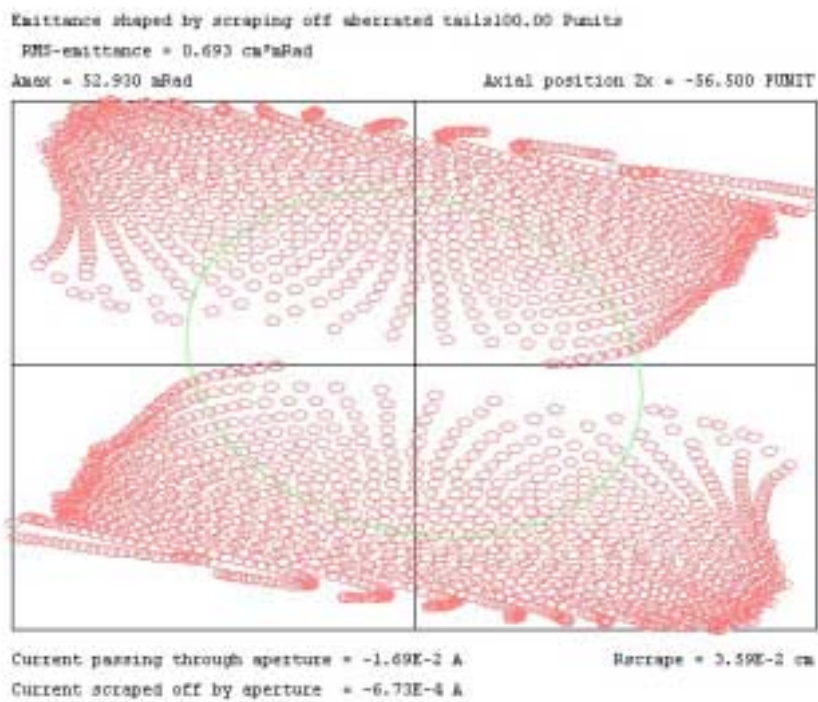Current scraped off by aperture = -6.73E-4 A

FIGURE 11. Emittance diagram in the extrapolated focus position at Z = -56. The aberrated wings have been cut away, reducing the emittance from 0.756 to 0.693 cm*mRad, and the current from 17.6 to 16.9 mA
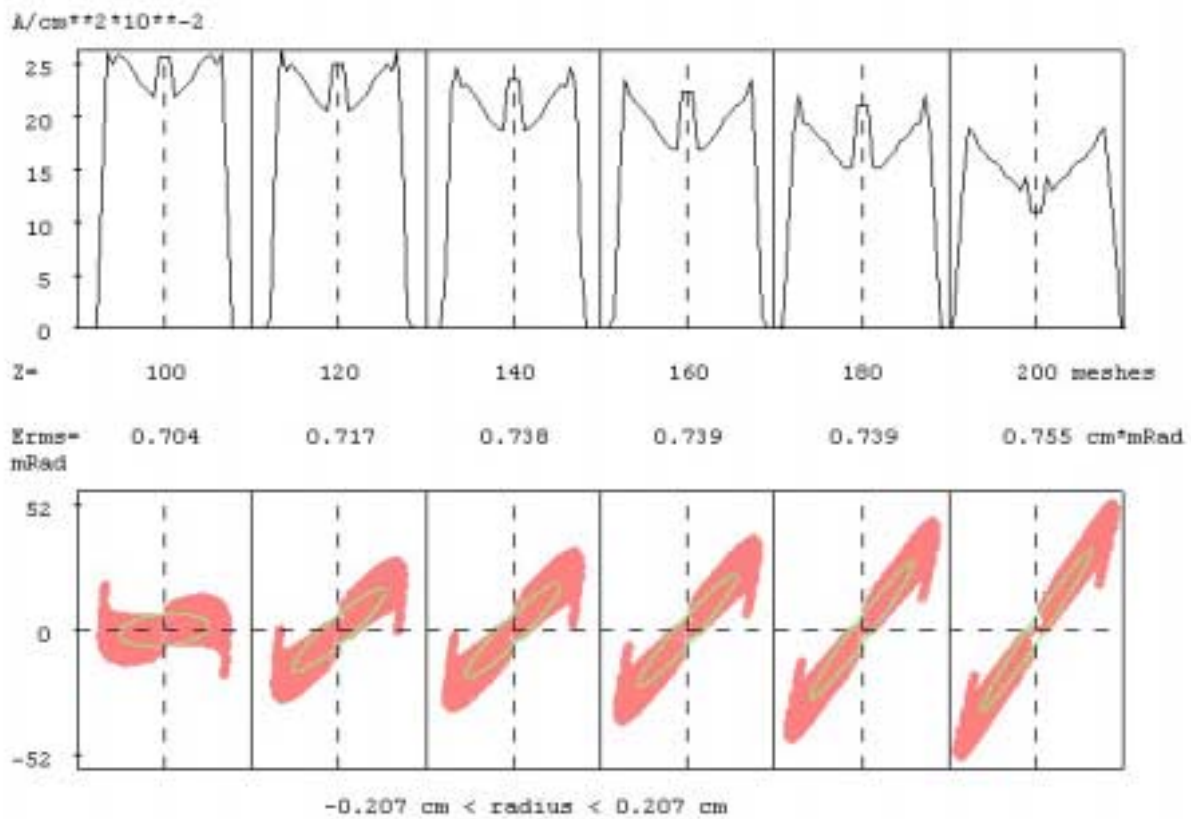
FIGURE 12. Current density profiles and emittance plots in selected positions along the beam

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