Current results of the beam dynamics study for 6 nC bunches in photogun and RF-gun

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1. **Introduction;**
2. **Beam dynamics in photoguns;**
3. **Beam dynamics in RF-gun;**
4. **Problems and questions**

…more details – in our Report form 27.10.2016 and in additions from 16.02.2017.

1.Introduction

Base injection parameters (*are they still actual*???):

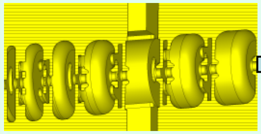
- Intensity up to $4\cdot10^{13}$ e^{-}/s;
- $4\cdot10^{10}$ e^{-} / bunch, 10 ps bunches,
- 10 bunches per pulse, bunches are separated with distance 25 or 50 ns (very good, decreases beam loading influence),
- up to 100 Hz pulse repetition rate;

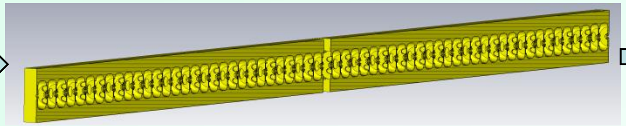
-Record space charge domination!!! About 6 nC per bunch

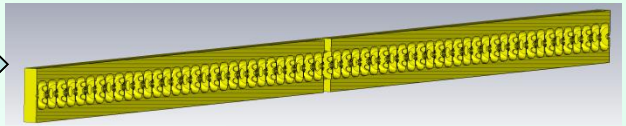
We preliminary discuss two operating frequencies: traditional ~3000 MHz and ~2000 MHz which gives brilliant matching with 400 MHz accelerating cavities proposed for booster. Both give 25 (50) ns bunches separation easily. It gives (for 10 ps laser pulse):

	3000 MHz	2000 MHz
RF period	~330 ps	500 ps
Bunch phase length	10 degree	6.7 degree
Physical bunch length (theoretically)	3 mm	5 mm
Current pulse duration (10 bunches per pulse)	25 or 50 ns ???	

Photogun **10-20 regular sections for 2 GeV in total (3000 or 2000 MHz)**







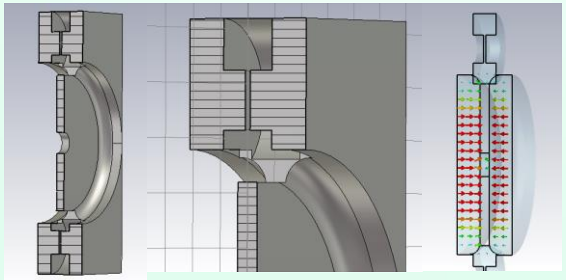
3000 MHz **or** **2000 MHz** **?**

π/2 mode, st. wave
12 BAS periods
~60 cm of length
12 MeV output
350 kV/cm on axe (for ~50 nC)

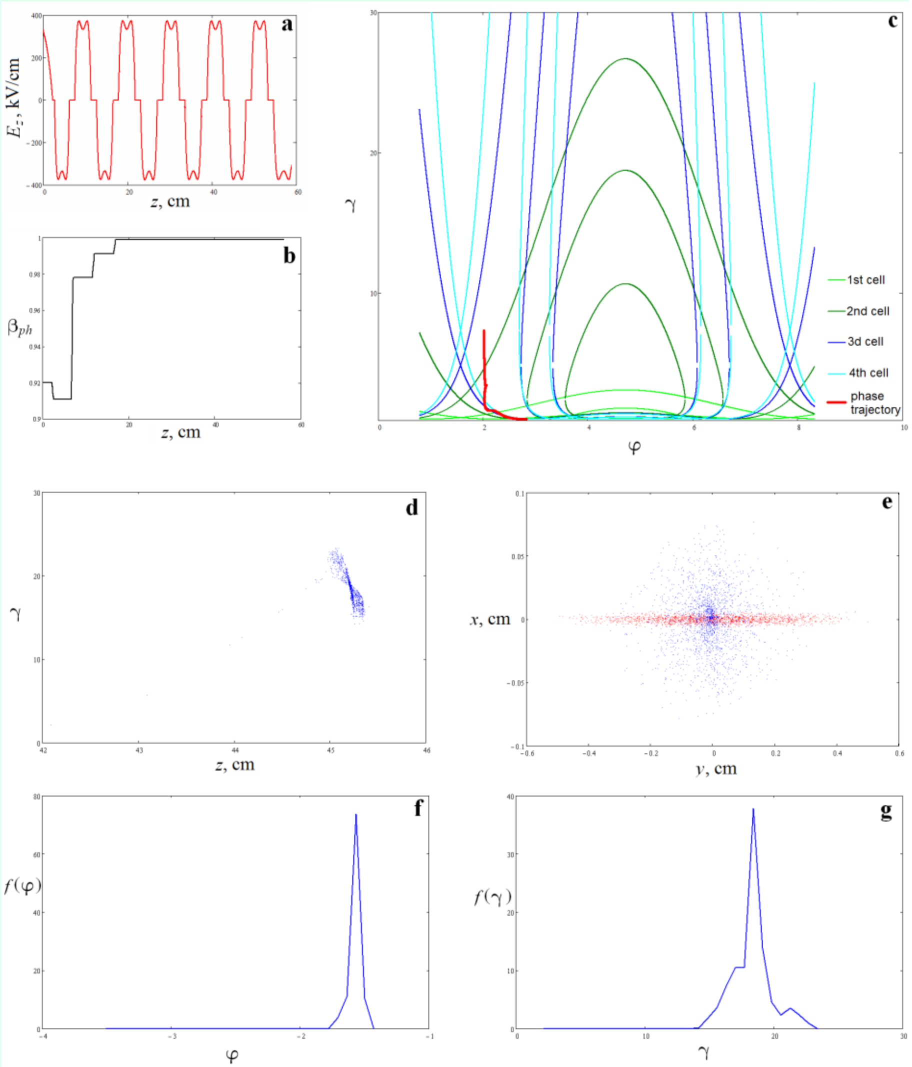
π/2 mode, st. wave
61 BAS periods
305 cm length
400/600/900 kV/cm
70/105/160 MeV
per section

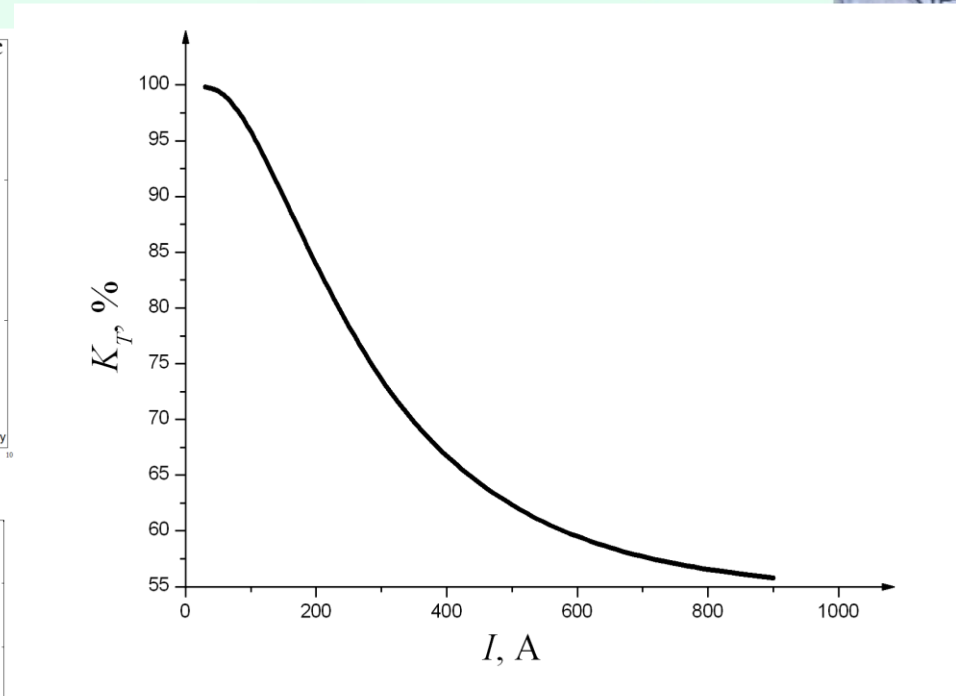
π/2 mode, st. wave
41 BAS periods
307.5 cm length
400/600/900 kV/cm
75/110/170 MeV
per section

Not enough place for first coupling cell in photogun!
side coupling should be used



2. Beam dynamics in photoguns





The capturing coefficient vs. bunch peak current for the case of using the photocathode (*half of lost particles forms back-current!!!*)

The *photogun_v1* beam dynamics simulation results for 300 pC bunches:
the accelerating field E_z (a) and β_{ph} (b) along the longitudinal axis *z*; beam dynamics simulation results for the single bunch: the center-of-mass trajectory in the (γ, φ) phase plane for first four cells (c), the phase distribution in the (γ, z) phase plane (d); the transverse emittance (e), the energy (f) and the phase (g) spectrums. All initial bunch characteristics are shown by red points and lines, output by the blue.

Photogun_v2 and beam dynamics:

Photogun_v2 consists of 7 acc. cells and 5 coupling cells (it was used side coupling for the 1st and the 2nd accelerating cells), the total length is 31 cm. Three cells (2nd, 3rd and 4th) with phase velocities β_{ph} =0.91, 0.98, 0.99. Channel aperture radius 10 mm, coupling cell length 4 mm, iris disk thickness 4 mm, operating frequency *f*=3000 MHz.

Bunch charge, nC	RF field amplitude, kV/cm	Optimal injection phase δφ	Output energy, MeV	Current transmission coefficient, %	Output beam spectrum FWHM %
0.3	400	3.0	6.54	100.0	±2.8
	500	3.1	8.36	99.9	±4.6
	600	**3.2**	**10.46**	**99.9**	**±3.1**
1	600	3.4	7.18	88.8	± 3.1
	700	**3.2**	**11.49**	**89.8**	**± 4.3**
	800	3.4	12.17	87.9	± 5.9
2	600	3.4	7.14	75.4	± 6.8
	700	3.4	10.98	75.4	± 7.8
	800	**3.5**	**10.51**	**75.1**	**± 4.6**
	900	3.6	10.69	76.6	± 5.5
3	600	3.4	7.23	67.6	± 7.6
	700	3.4	10.42	65.4	± 5.7
	800	**3.4**	**11.92**	**66.6**	**± 6.5**
	900	3.6	10.72	67.3	± 4.2
	1000	3.6	13.04	67.0	± 8.4
6	**600**	**3.4**	7.75	**53.3**	**± 7.4**
	800	3.5	10.05	53.6	± 11.4
	1000	3.6	12.24	56.1	± 8.8

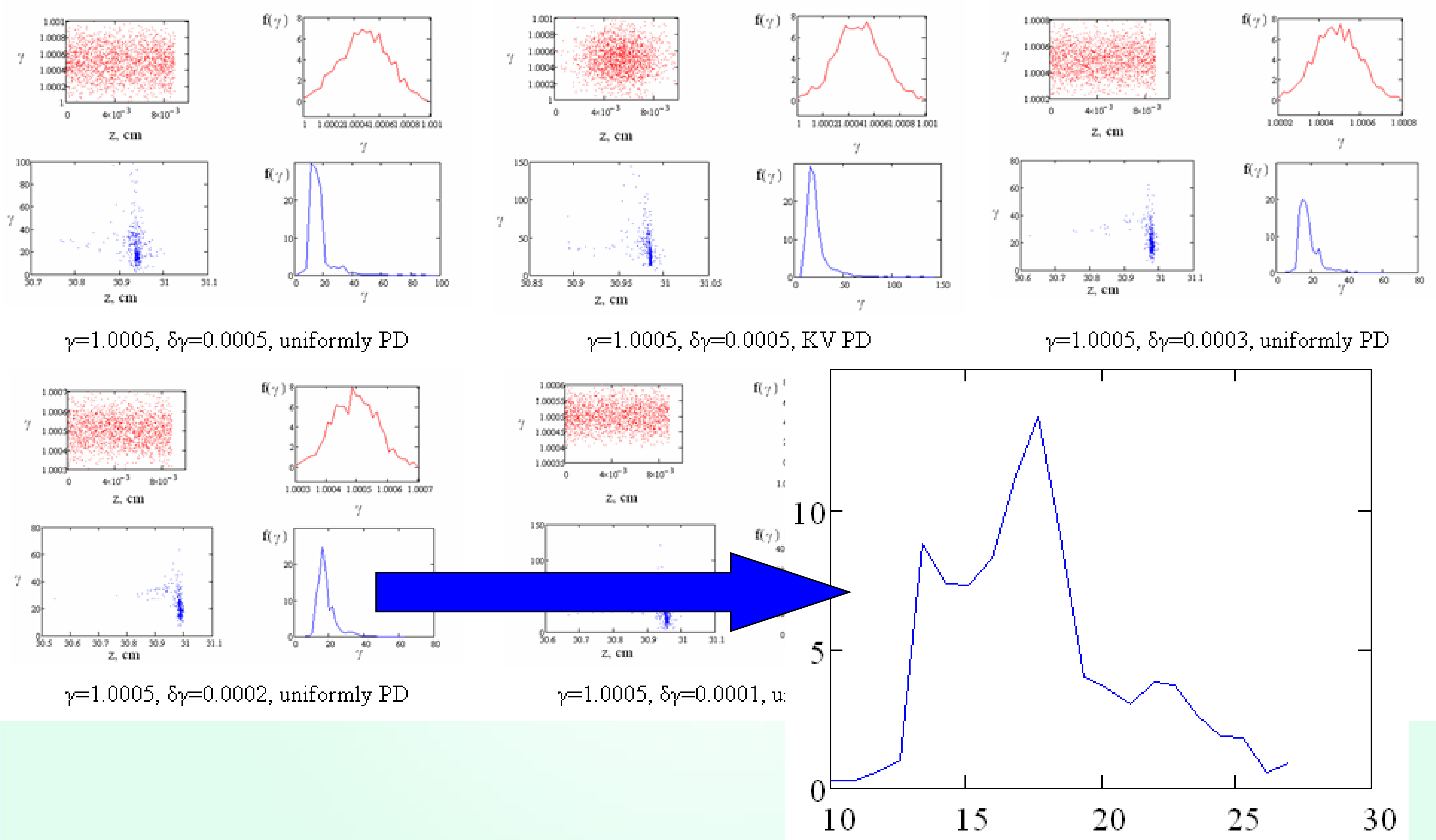
Photogun_v3:

Photogun_v3 is modified version of Photogun_v2. It also consists of 7 acc. cells and 5 coupling cells, but cell's lengths, RF field amplitudes and distribution were optimized and solenoid field value was correctly chosen.

Beam dynamics simulation results in "*Photogun-v3*" for 6 nC bunches, E_z=800 kV/cm

Injection energy γ	Injection energy spread $\delta\gamma$	Phase distri-bution	Solenoid field, T	Optimal injection phase $\delta\varphi$	Output energy, MeV	Current transmission coefficient, %	Output beam spectrum FWHM %
1.0005	0.0005	unif.	0.2	3.4	7.37	73.2	±26
1.0005	0.0003	unif.	0.2	3.4	7.88	74.8	±27
1.0005	0.0002	unif.	0.2	3.4	8.18	73.7	±18
1.0005	0.0001	unif.	0.2	3.4	7.76	72.3	±26
1.0005	0.0005	KV	0.2	3.2	8.01	75.5	±25
1.0005	0.0002	unif.	0	3.4	6.99	68.7	±23
1.0005	0.0002	unif.	0.05	3.4	6.75	70.2	±22
1.0005	0.0002	unif.	0.1	3.4	6.48	72.6	±24
1.0005	0.0005	unif.	0.4	3.4	8.80	79.2	±15
1.0005	0.0002	unif.	0.4	3.4*	8.60	77.4	±10
1.0005	0.0002	unif.	0.6	3.4*	8.59	80.9	±12
1.0005	0.0002	KV	0.6	3.4*	7.98	84.5	±12
1.0001	0.00002	unif.	0.2	3.4*	8.57	64.6	±21
1.0001	0.00002	KV	0.2	3.4*	9.02	63.8	±12

*** Optimal injection phase $\delta\varphi$=3.0–3.2 gives higher energy ≈12-12.5 MeV, but the energy spectrum will wider ≈±15-19 %, current transmission coefficient will the same. For the injection phase $\delta\varphi$=3.5 the energy spectrum is much better ≈±7-8 %, but output energy will only ≈5 – 5.5 MeV.**



Phase portraits and energy spectrums (initial by red, output by blue) for different initial conditions, E_z=800 kV/cm, the bunch charge 6 nC, uniformly and KV initial phase distributions, B=0.2 T.

Conclusions for Photogun's :

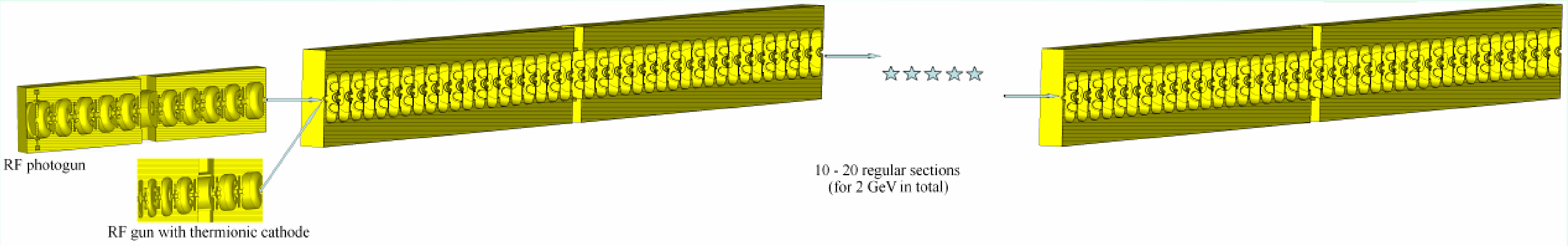
I) A bunch with charge up to 1-2 nC and 10 ps of duration can be easily accelerated using photogun (results were obtained for 3000 MHz structures). The current transmission coefficient is close to 100 % and RF field amplitude of 600 kV/cm is quite enough to have 10.5 MeV after photogun. Such energy is necessary for effective recapturing by the first regular section, as it was presented at FCC Meeting 2016. The bunch energy spread FWHM is ~±3-5 % (or ±300-500 keV) and we can suppose that output energy spread after 10 or 20 regular sections with β_{ph}=1 it will be not higher than 0.5-1.0 %.

II) Beam dynamics in photogun's structures was also simulated for 3-6 nC bunches. It was shown that current transmission coefficient will drop vs. high bunch charge, for example it will not be higher than 85 % for 6 nC bunches. The bunch spectrum will also fast increase with bunch charge increase and it is not better than ~±10 % for 10 nC bunches.

III) Simulations show that high bunch intensities lead to high back currents – approximately half of lost particles forms back-current. Sufficient Coulomb "head-tail" repulsion was observed. Head-tail difference of RF field amplitude due to high bunch phase size and beam loading effect leads to energy spectrum growth.

IV) We need to do more intensive studies of near-cathode processes including review of references in field of photo emission. Bunch duration of 10 ps is much higher than relaxation time in metal (*and semiconductor also*?) and we can have an electron depletion for laser exposed volume. Back current influence to beam emission, double layer problems and emission process including possible depletion should be studied in detail. We also need to find an experimental data about emission of a 6 nC / 10 ps bunches from photocathode (*can we to simulate it correctly by any specific code*?), about real 3D particles distribution and other emission-defined process.

Our further studies should be focused on these problems because they play the key role for structure parameters choice and beam dynamics and define finally the injection efficiency in FCC-ee booster ring.



Possible scheme of linac layout: RF gun with thermionic cathode is option for high intensity drive bunches production for *e*-/*e*+ conversion and photogun for <1 nC high quality bunches generation (close to SuperKEKB new injection scheme).

3. Beam dynamics in RF-gun

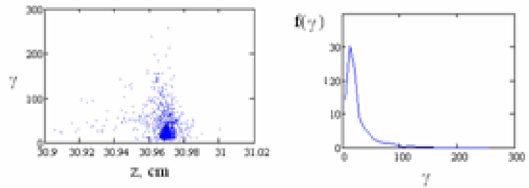
The optimized version (called *RF-gun-TC-3*) will have three cells with adiabatically increase of the phase velocity β_{ph}=0.92, 0.96, 0.99 (compared to four cells for *RF-gun-TC-2* with β_{ph} =0.9, 0.91, 0.98, 0.99, as it was discussed in our [Beam Dynamics in RF-guns Report, 24.10.16]). The solenoid field also should be increased up to 0.6 T on the channel axis (0.4 T for *RF-gun-TC-2*) to control the beam envelope and transverse emittance. The simulation was done for bunch charge 6 nC and bunch duration of 10 ps, the injection energies was chosen equal to 50±0.5 keV, 100±1.0 keV, 200±2.0 keV, the initial transverse emittance is 20 mm·mrad. Beam dynamics simulation results show that the capturing coefficient is ~85-90 % for 6 nC bunch (comparatively 70-80 % for *RF-gun-TC-2*) depending on injection phase, initial phase distribution and bunch current, output energy is about 6-7 MeV for 800 kV/cm, output beam spectrum FWHM is ±20-40 %.

Beam dynamics simulation results in "*RF-gun-TC-3*" for 6 nC bunches

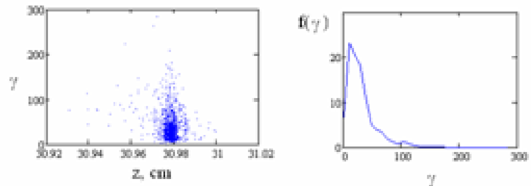
Bunch charge, nC	RF field amplitude, kV/cm	Solenoid field, T	Injection energy, keV	Optimal injection phase δφ	Output energy, MeV	Current transmission coefficient, %	Output beam spectrum FWHM %
6 (*uniformly phase distribution*)	800	0.4	50	2.8	6.42	87.4	±34
		0.4	100	3.0	6.92	87.1	±42
		0.3	100	3.6	7.35	83.6	±21
		0.2	100	3.2	7.19	87.5	±40
		0.1	100	2.0	7.18	81.4	±29
		0.4	200	3.4	7.11	75.9	±29
		0.2	**200**	**3.7**	**7.49**	**77.5**	**±20**
	1000	0.4	50	2.6	7.21	88.3	±44
		0.4	**100**	**3.4**	**8.83**	**90.9**	**±43**
		0.4	200	3.7	7.44	74.0	±33
6 (*KV phase distribution*)	800	0.4	50	3.0	6.69	90.9	±33
		0.4	100	2.4	6.31	88.2	±31
		0.4	**200**	**2.0**	**6.28**	**88.0**	±27
	1000	0.4	50	2.2	7.83	89.2	±38
		0.4	**100**	**3.4**	**8.70**	**90.5**	**±29**
		0.4	200	1.8	6.23	87.6	±28

W_{in}=100 keV, E=1000 kV/cm, (*uniform phase distribution*)

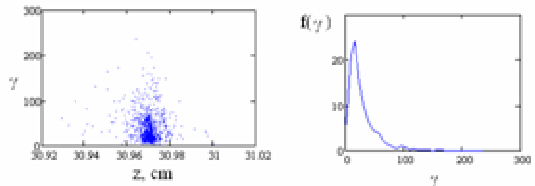
δφ=2.4
Kt=90.6 %
W=6.42 MeV
dW=± 65 %



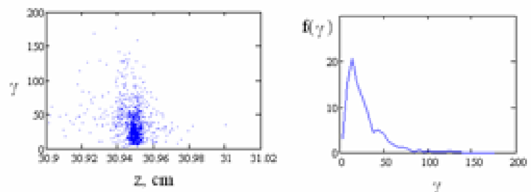
δφ=2.8
Kt=88.3 %
W=5.62 MeV
dW=± 70 %



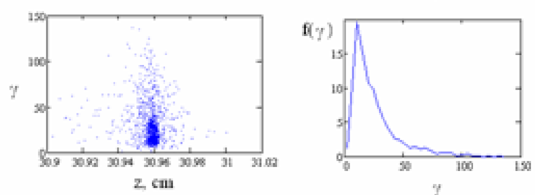
δφ=3.4
Kt=90.9 %
W=8.83 MeV
dW=± 43 %



δφ=3.5
Kt=87.3 %
W=7.22 MeV
dW=± 41 %

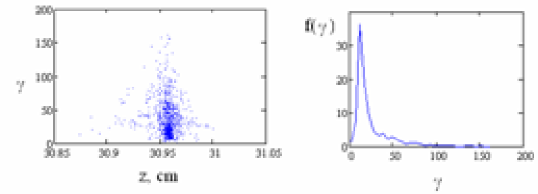


δφ=3.6
Kt=85.7 %
W= 5.57 MeV
dW= ± 61 %

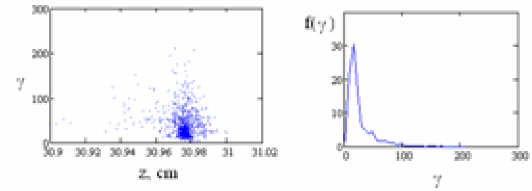


W_{in}=100 keV, E=1000 kV/cm, (*KV phase distribution*)

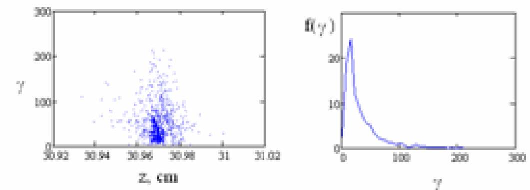
δφ=2.2
Kt=89.5 %
W=6.35 MeV
dW=± 31 %



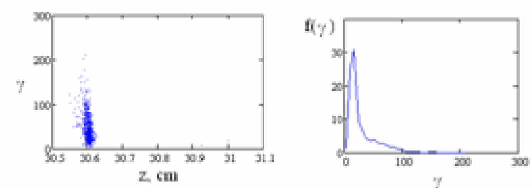
δφ=2.6
Kt=92.4 %
W=7.98 MeV
dW=± 42 %



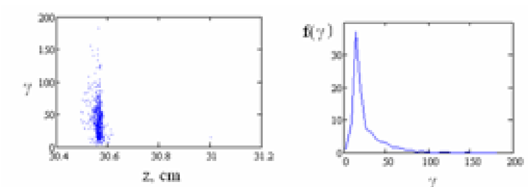
δφ=3.0
Kt=94.2 %
W=8.37 MeV
dW=± 41 %



δφ=3.4
Kt=93.4 %
W=8.70 MeV
dW=± 29 %



δφ=3.6
Kt=90.5 %
W= 7.17 MeV
dW= ± 32 %



Phase portraits and output energy spectrums for different bunch injection energy 100 keV, E_z=1000 kV/cm, the bunch charge 6 nC, uniform and KV initial phase distribution

Conclusions for RF-gun's :

- Capturing coefficient is higher for RF-TC guns comparatively photoguns, but energy spectrum is much wider. Back current is small and thermal cathode is much more stable for electron bombarding comparatively semiconductor photo cathode.
- We need more information about real initial phase-energy distribution for 600 A and 10 ps bunches in RF-guns with control grid(-s).
- It is clear that *RF-gun-TC-3* gives better results compared to *RF-gun-TC-2*, but parameters of the first accelerating cell and the RF field distribution should be further improved to increase the capturing coefficient and to decrease the energy spread.
- The necessary electric field value can be limit by 700-800 kV/cm, further field increase doesn't give any preferences for the output energy or the capturing coefficient but leads to the wider energy spectrum.
- We can try reduce the solenoid field from 0.6 T to 0.3-0.4 T, it seems quite enough for effective transverse stability. High B-field values leads to more sufficient effect of longitudinal-transverse motion coupling that finally leads to the energy spread growth.

4. Problems and questions

I. Work organization:

-A number of groups are working and more and more information is generated. We need to do the storage for all our reports, presentations, etc., and to organize access for main collaborators, but a moderator is also necessary.

-We are strongly need to define and finalize linac general parameters (regime, bunch charge, final energy, energy of e^-/e^+ conversion, …) and list of parameters should be now fixed. I so three versions of such list, they differs very strongly. Now we have only 16-18 months for CDR and we have not enough time for free parameters search.

- We need more close contact with team working for booster because they should to take part in formulation of the bunch parameters after linac and of the operation modes.

II. We need to discuss and fix the following parameters:

- operating frequency 2856 (easily available power sources, but challenging implementation with 400 MHz linac accelerating sections of a booster), 3000 or 2000 MHz.

-bunches parameters on e^-/e^+ conversion target and on linac output (emittance, etc.).

- we need to do an extensive study of photocathode processes as influence of the back current, double layer formation, cathode depletion due to long 10 ps laser pulse ets. (*may be we need to invite a specialist on semiconductor photocathodes who has an experience in near-cathode processes studies?*);

III. Main linac part:

We all are concentrate on initial section study (photogun or photogun+RF-gun or RF-gun). But the main section, sections feeding and matching are not studied in detail before now.

Thank you for attention!