Ultracold electron source

extraction of electron bunches from an ultra-cold plasma

Collaboration “Accelerator Physics” group and “Quantum Gases” group
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Gabriel Taban – PhD student
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CPS
CENTRUM VOOR PLASMAFYSICA EN STRALINGSTECHNOLOGIE

Erice 2005

FOM

Ultracold waterbags...

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...red-hot potatoes?

Brightness limitations

- Nonlinear space charge forces
- Thermal emittance

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- ☑ Nonlinear space charge forces

- ☐ Thermal emittance

6D brightness ~ 6D phase space density

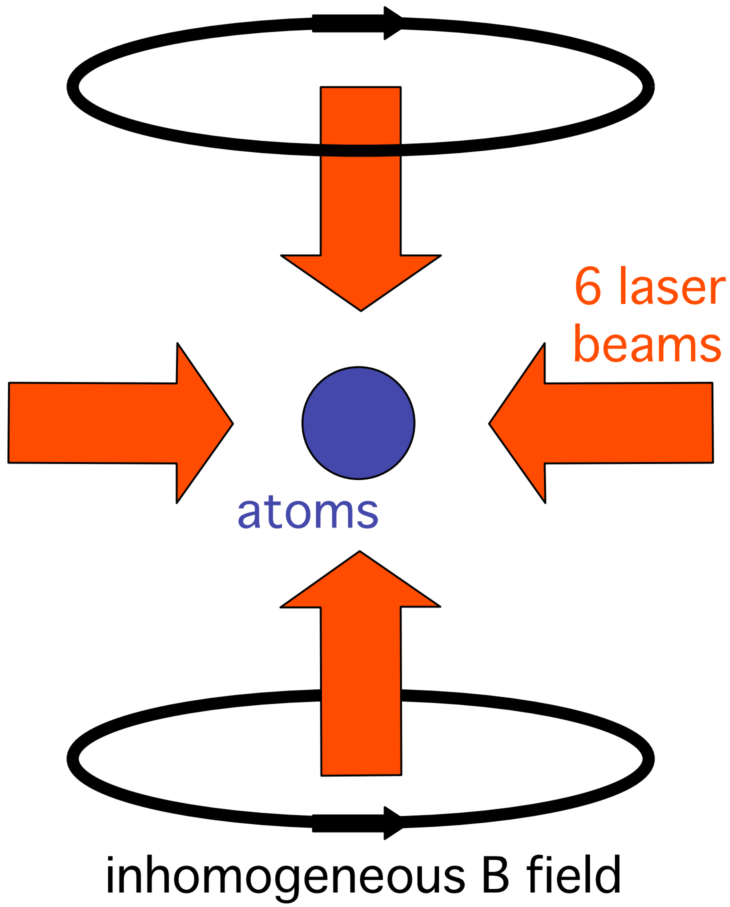
$$B = \frac{Q}{(2\pi)^3 mc \cdot \varepsilon_{n,x} \cdot \varepsilon_{n,y} \cdot \varepsilon_{n,z}} = \frac{B_\perp}{\sqrt{2\pi}\,\sigma_E}$$

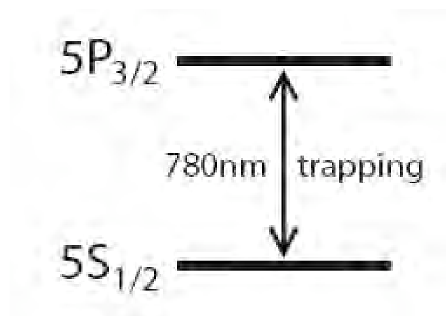
Transverse (5D) brightness:

$$B_\perp = \frac{I_p}{(2\pi)^2 \varepsilon_{n,x} \varepsilon_{n,y}} \leq \frac{mc^2 J_p}{\pi\, kT}$$

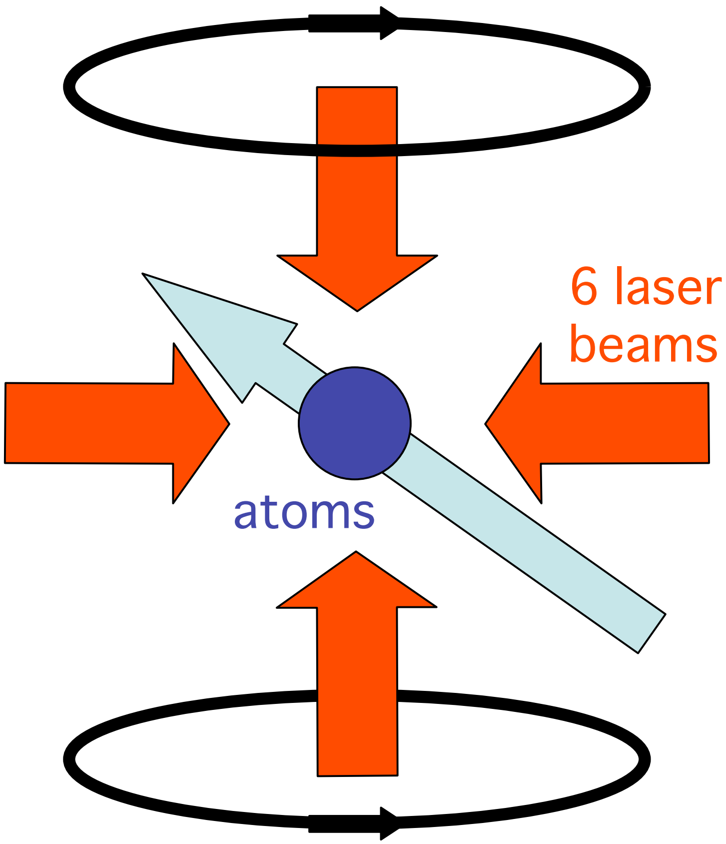
collect **Rb atoms** from beam/vapor

- Laser cooling
- Magneto-Optical Trap (MOT)
- $N > 10^9$ atoms, $R = 1$ mm, $n = 10^{18}$ m^{-3}
- $T_{atom} < 0.001$ K





Ultra-Cold Plasma (**UCP**)



inhomogeneous B field

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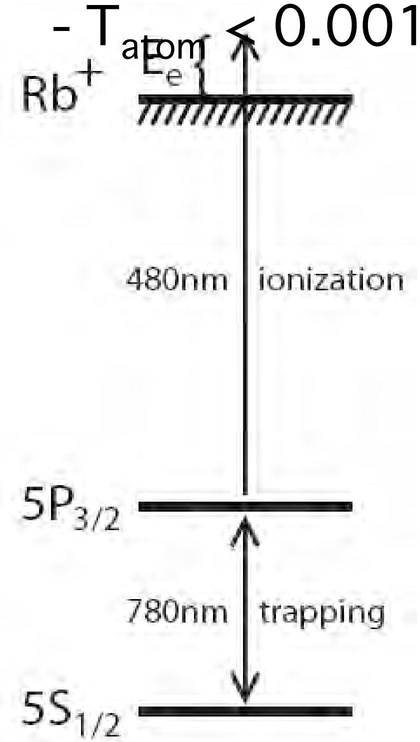


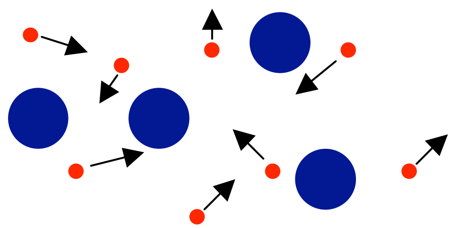
Ionize with **pulsed laser** (_$_{pulse}$ > 1 ns)

$T_{electron} = 0.001$ K

$kT = 10^{-7}$ eV

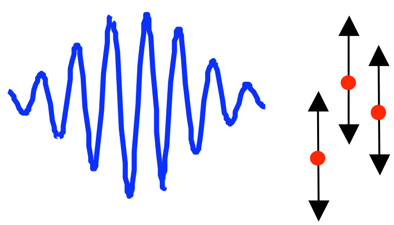
Heating processes:

- **Correlation heating**: $k_B T_e \approx \frac{e^2}{4\pi\varepsilon_0 n^{-1/3}}$ timescale $\omega_p^{-1} = \sqrt{\frac{m\varepsilon_0}{ne^2}}$



$n \leq 10^{18}\ \mathrm{m}^{-3} \Rightarrow$ T_e = 0.001 K _ ~10 K in ~100 ps

- **Ponderomotive heating** by ionization laser pulse:



$$k_B T_e \approx \frac{e^2 E_{opt}{}^2}{4m\omega^2} \qquad \frac{1\,\mathrm{mJ}}{(1\,\mathrm{mm}^2)\cdot(10\,\mathrm{ns})} \Rightarrow T_e \approx 0.001\,\mathrm{K}$$

- **Electron - neutral atom** scattering:

Very small cross section _ T_e < 0.001 K

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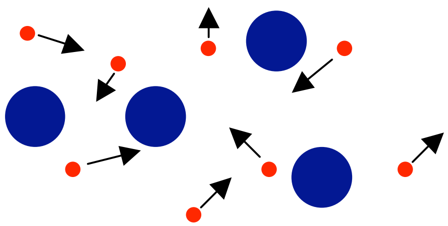

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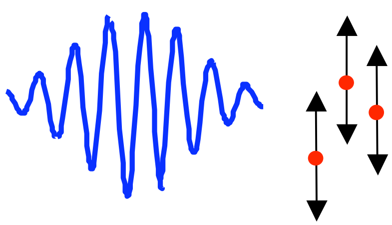

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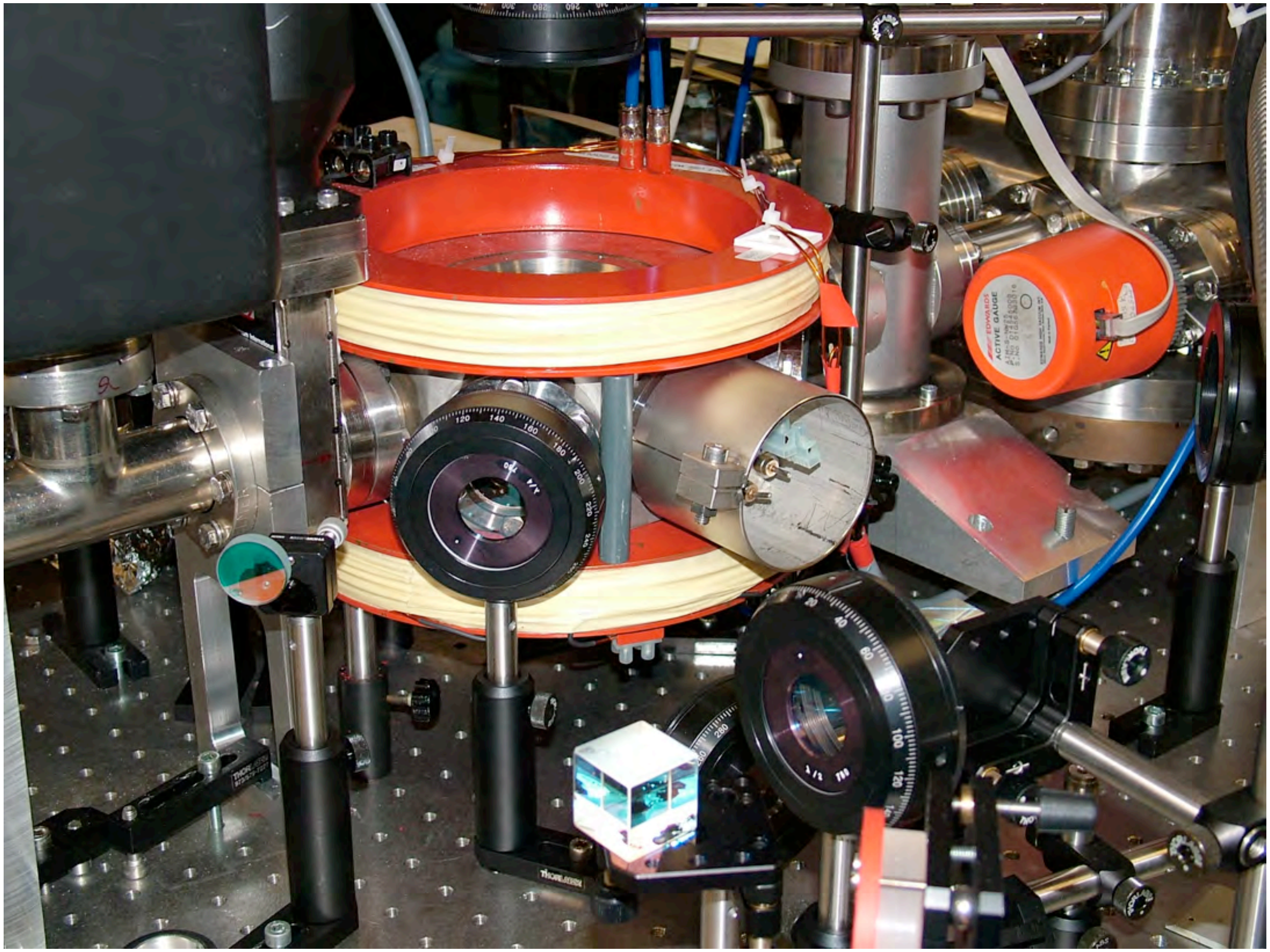
Magneto-Optical Trap (MOT)



3 October 2005:
Our first trapped sample of ultracold Rb gas

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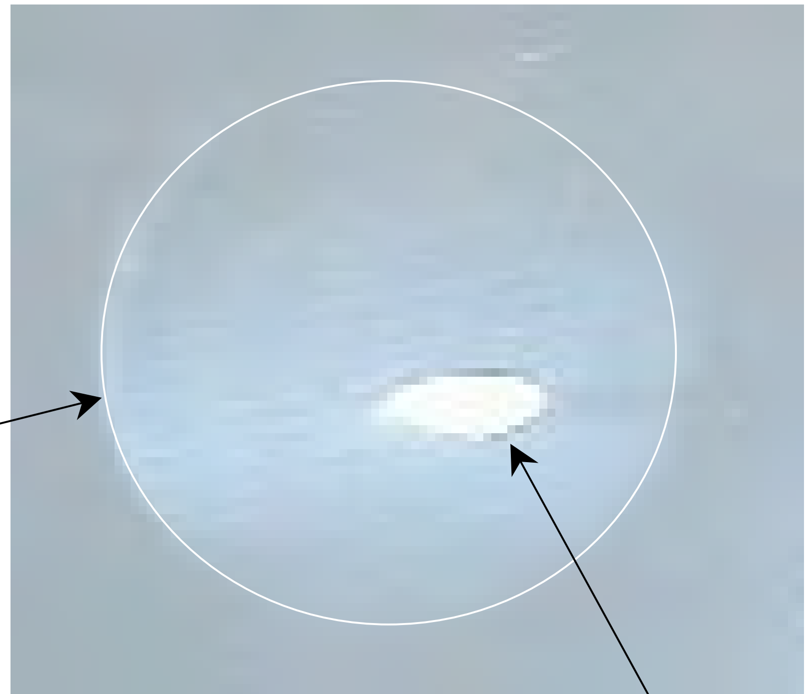
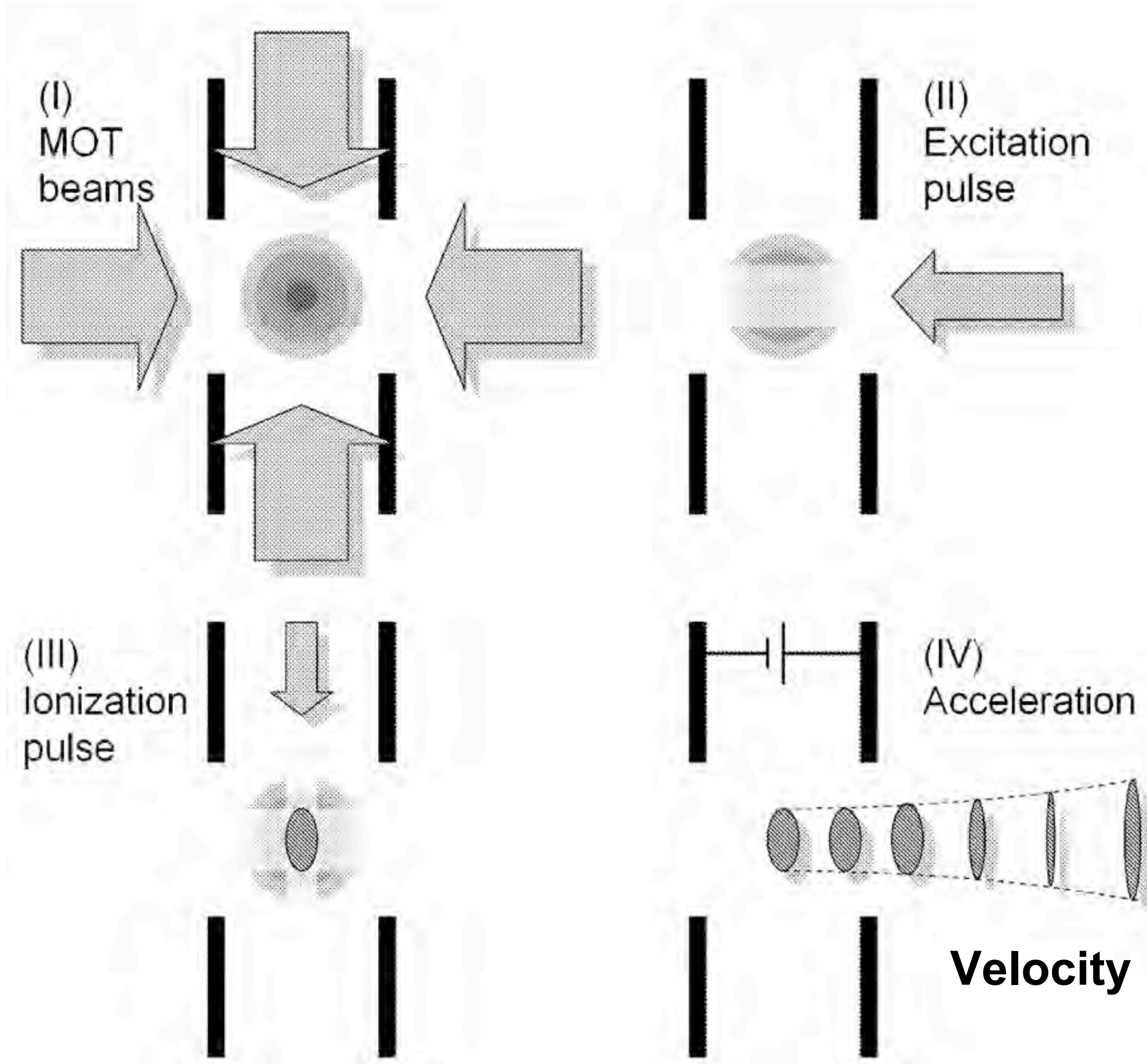


window

Rb cloud (780 nm fluorescence)

Extraction of bunches



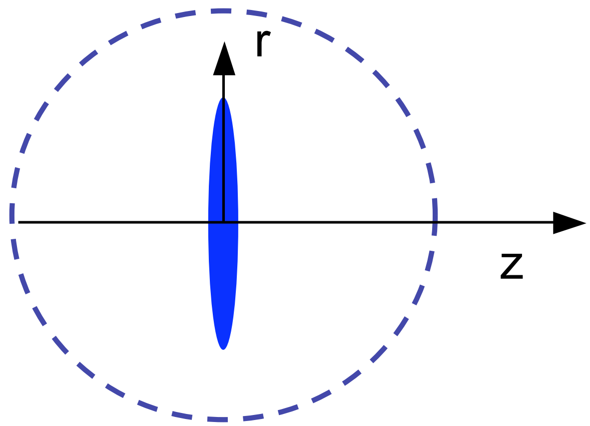
Velocity bunching!

Waterbag recipe:

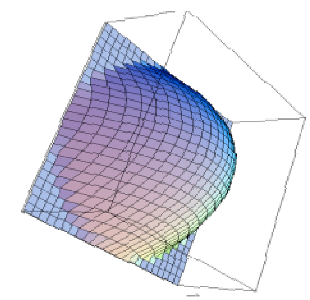
• Start with a ***flat ellipsoid*** _ can be 'cut out' with 2 intersecting laser beams;
• ***pancake*** _ ***'half-sphere'*** laser intensity profile;
• ***cigar*** _ ***parabolic*** laser intensity profile;
• **automatic evolution into 3D, uniform ellipsoid.**

2 initial bunch geometries:

Pancake geometry: cutting out a thin transverse slice

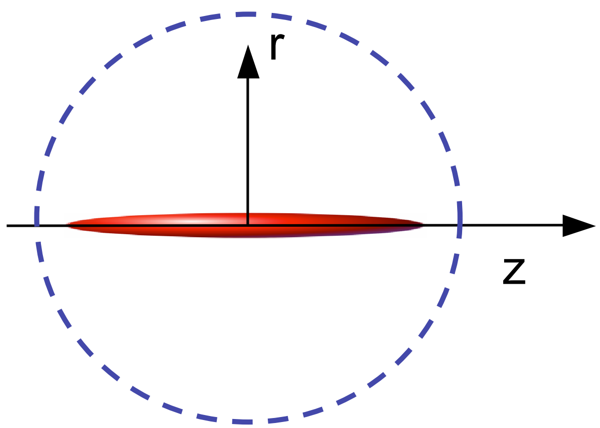


Q = 10 pC
R = 2 mm
L = 15 _m
T = 10 K

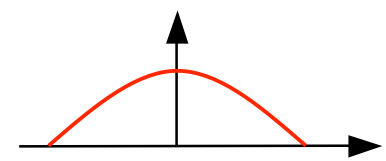


‘half-sphere’
transverse profile

Cigar geometry: cutting out a longitudinal needle

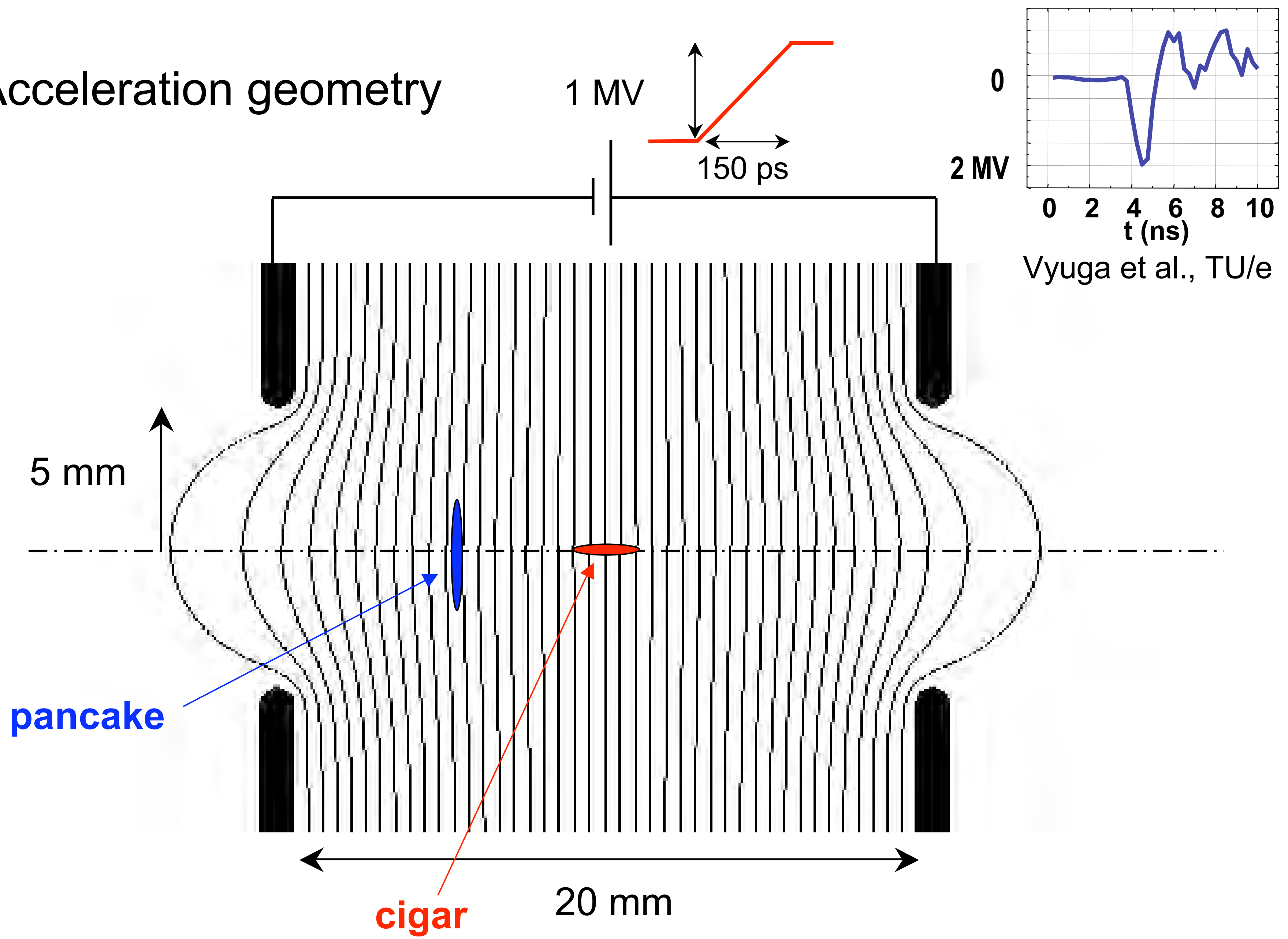


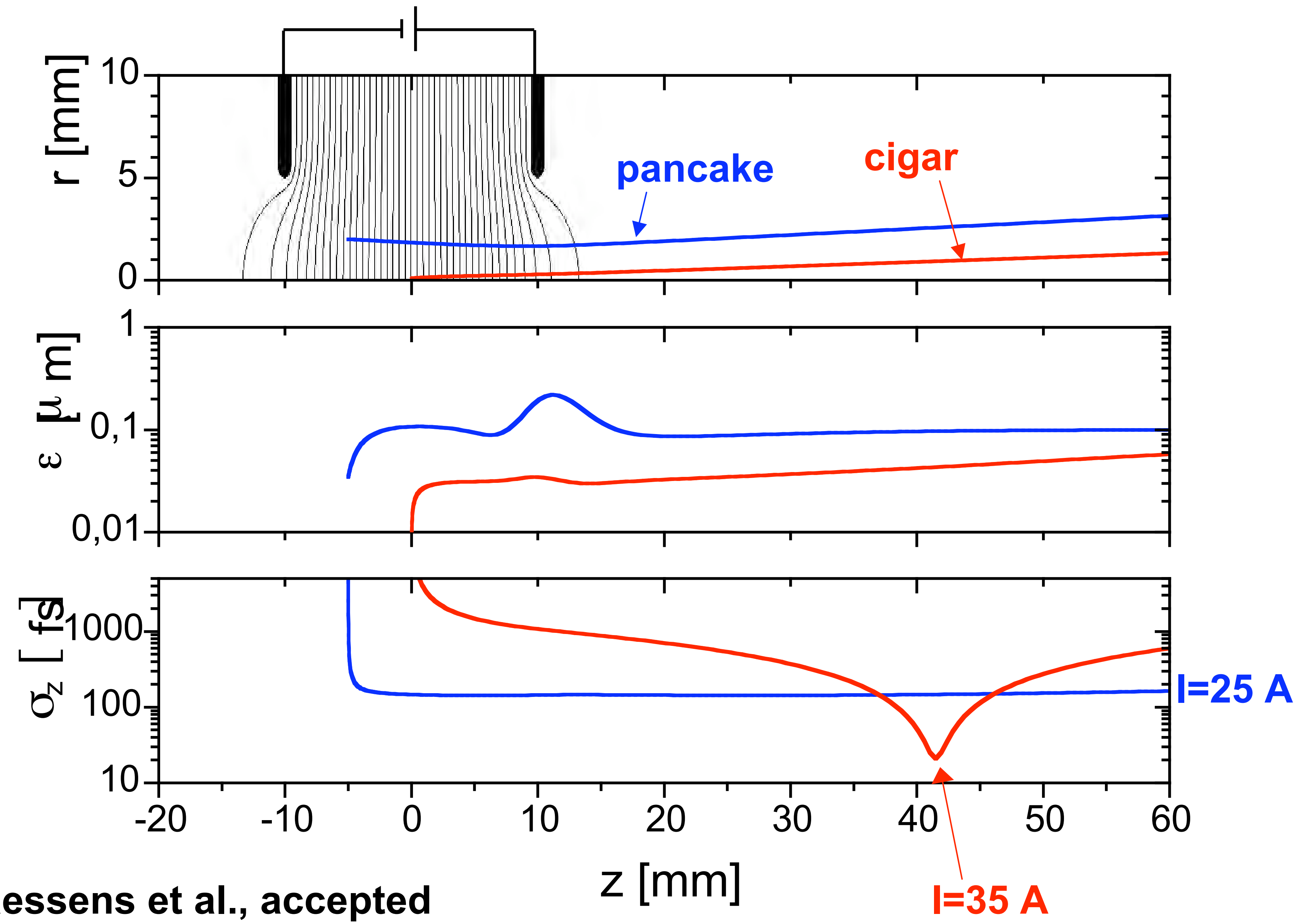
Q = 1 pC
R = 80 _m
L = 1 mm
T = 10 K



parabolic
longitudinal profile

Acceleration geometry





Claessens et al., accepted for publication in PRL

Beam parameters

	pancake	cigar
– Peak current:	25 A	35 A
– Emittance:	0.1 μm	0.04 μm
– Charge:	10 pC	1 pC
– Energy:	470 keV	270 keV
– Pulse length:	150 fs rms	20 fs rms
– Energy spread:	0.8 keV rms	7.5 keV
– Current density:	2 A/mm^2	1.7 kA/mm^2

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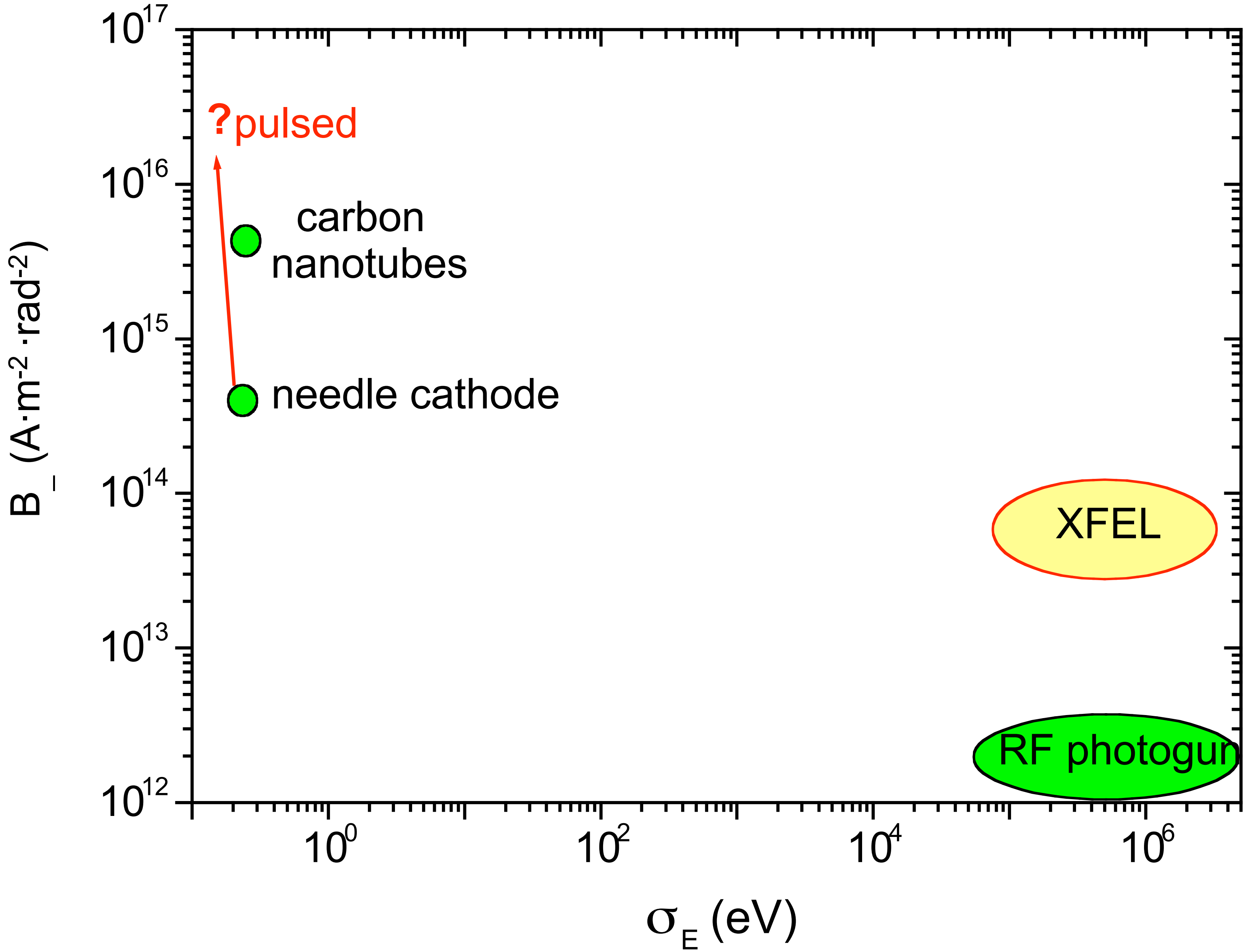
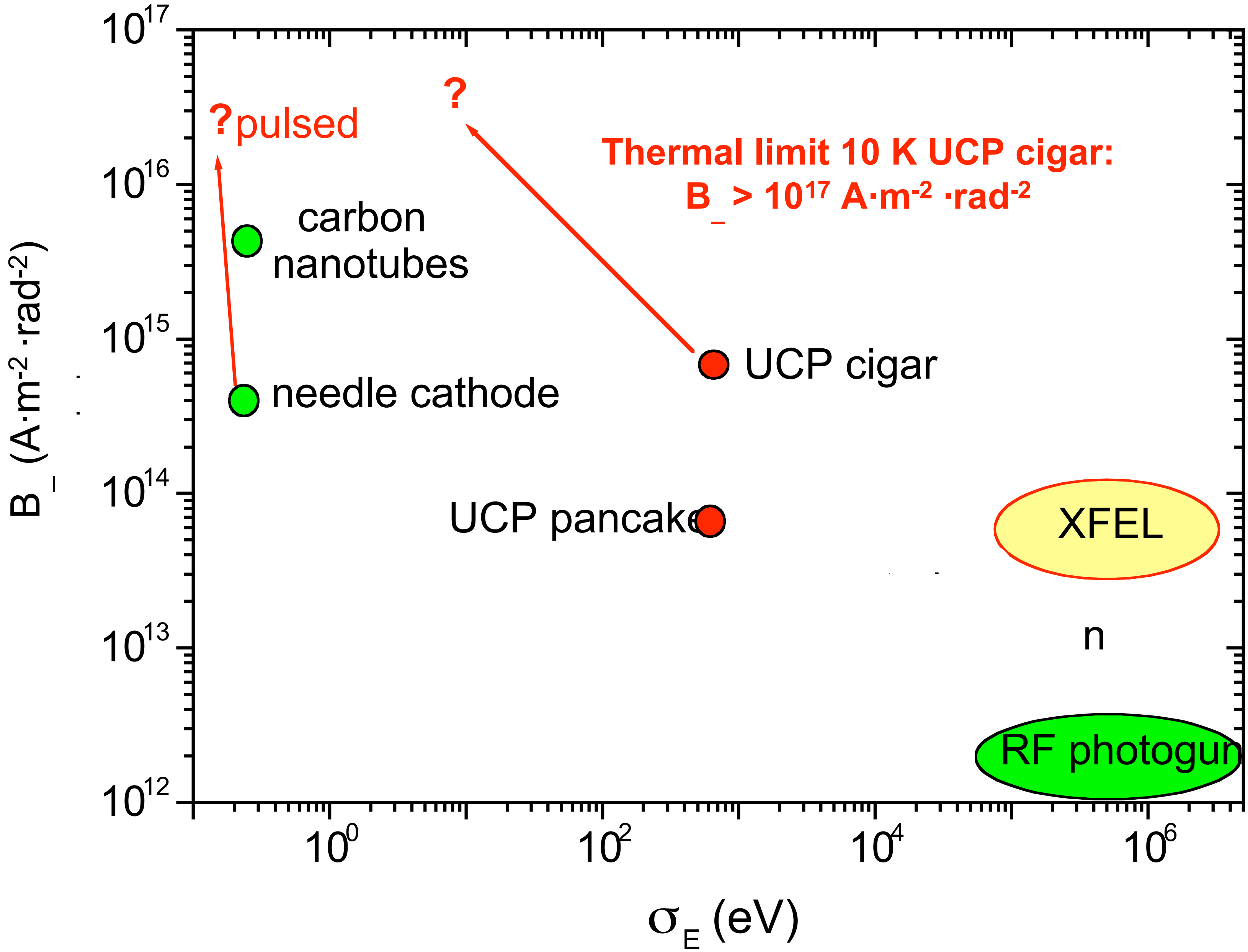
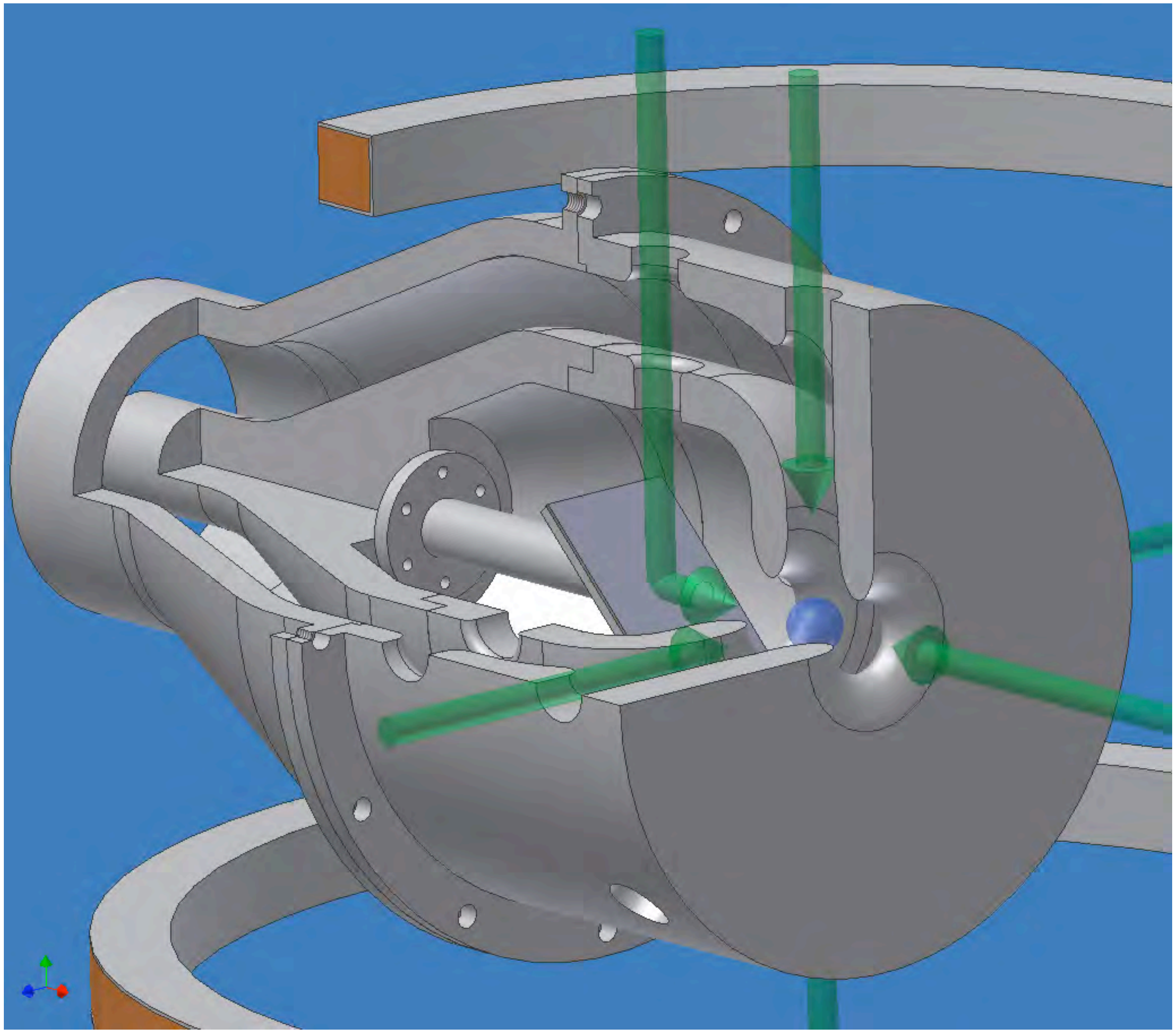


?pulsed
carbon nanotubes
needle cathode
XFEL
RF photogun
B_ (A·m-2 ·rad-2)
σE (eV)



?pulsed
?
Thermal limit 10 K UCP cigar:
B_ > 10^17 A·m^-2 ·rad^-2
carbon nanotubes
needle cathode
UCP cigar
UCP pancake
XFEL
n
RF photogun
B_ (A·m^-2 ·rad^-2)
σ_E (eV)
10^17
10^16
10^15
10^14
10^13
10^12
10^0
10^2
10^4
10^6

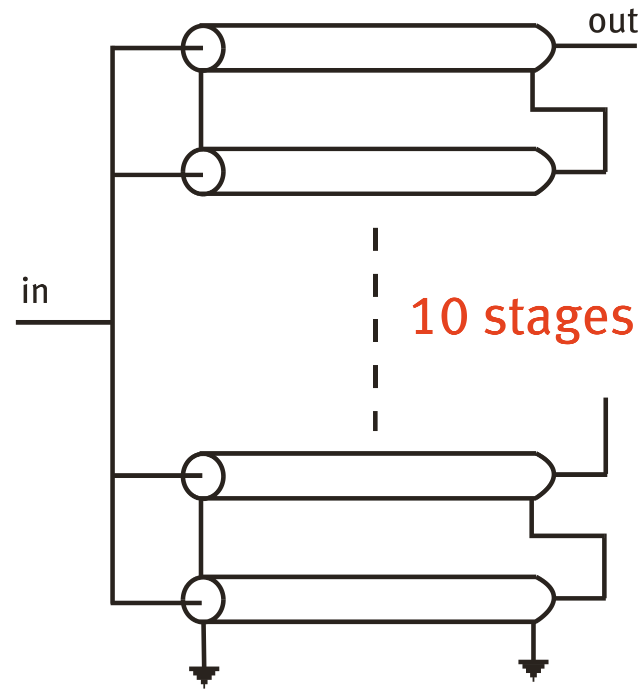
Experimental realization

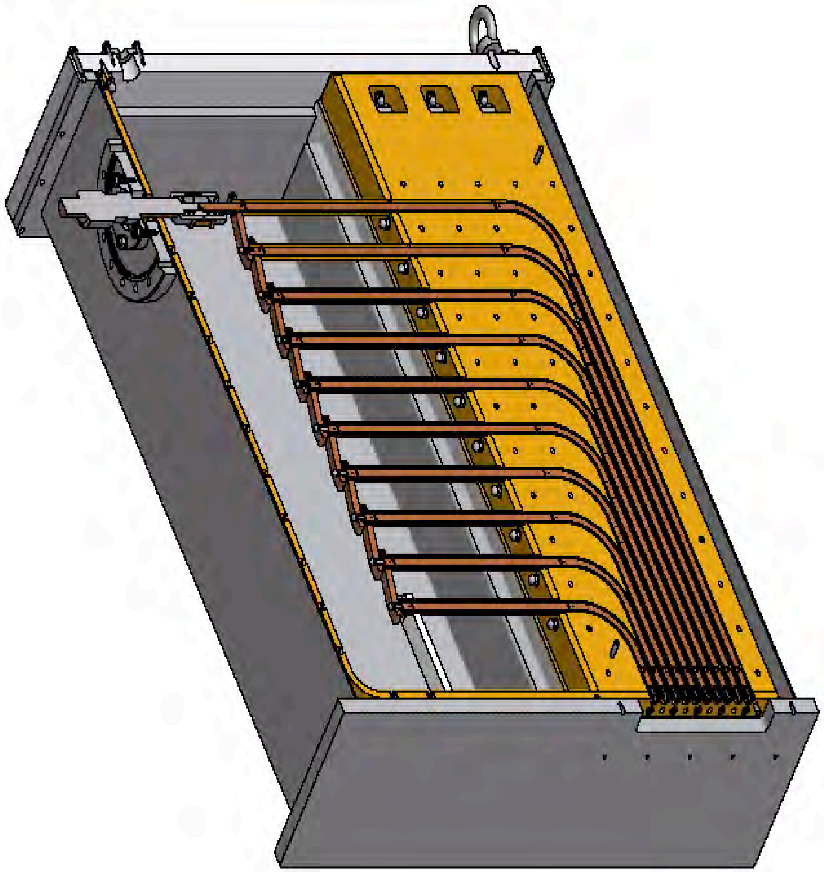


Technology challenge:
multi-100 kV voltage pulse with (sub-)ns risetime

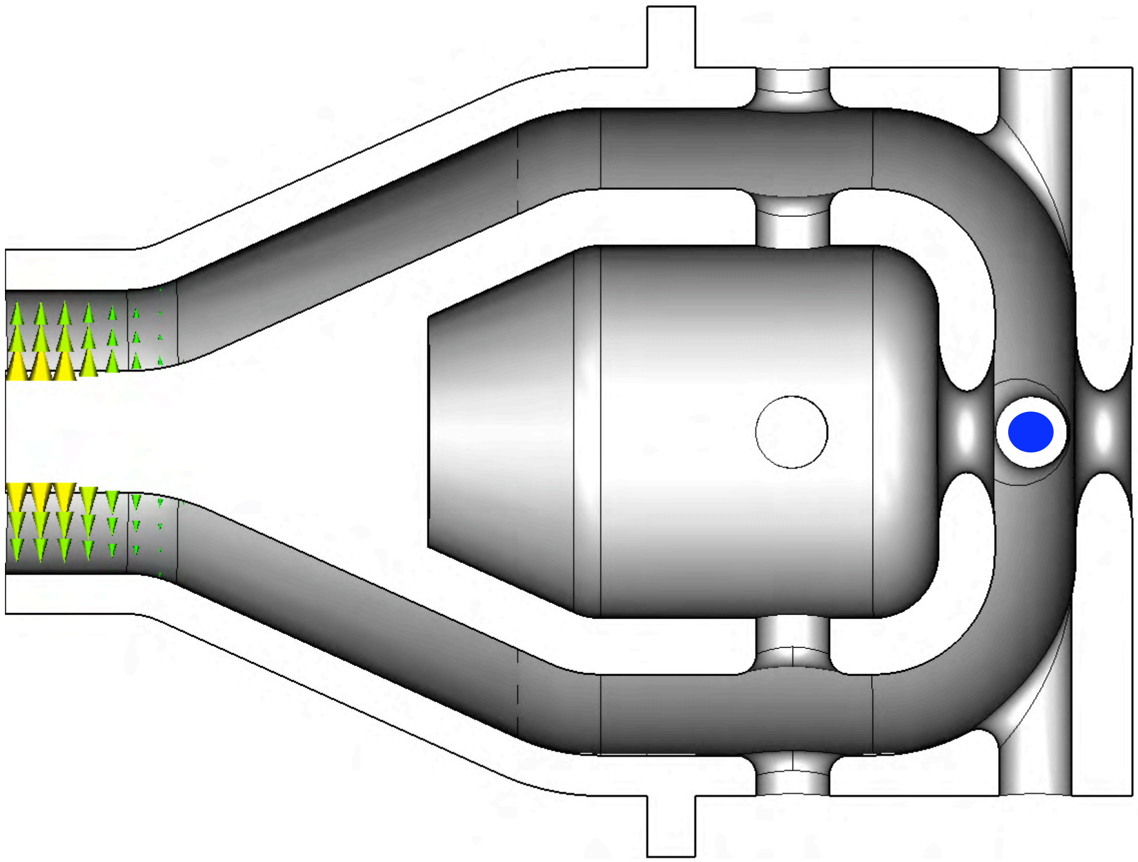
Method:

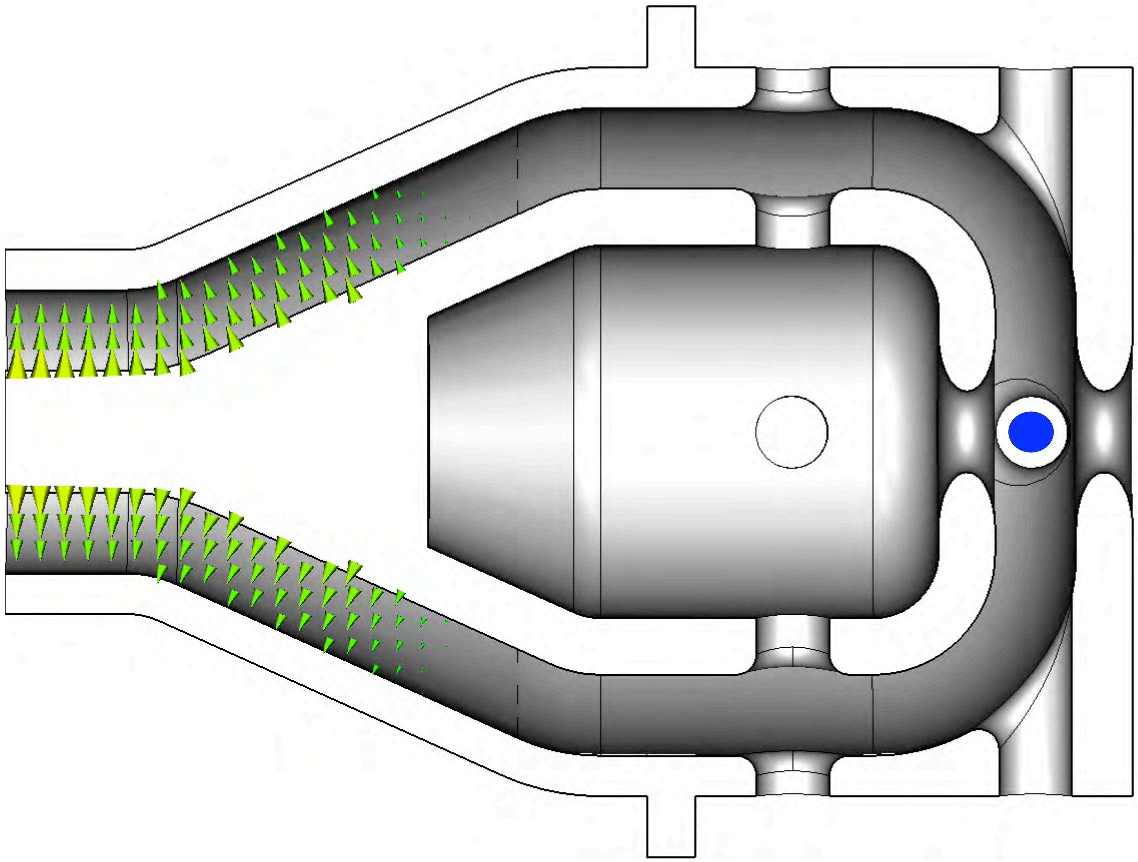
• 30 kV DC power supply with commercial 10 ns solid state switch;
• 'ferrite-sharpening' technology _ 30 kV with sub-ns risetime;
• broadband transmission line transformer _ 200 kV with sub-ns risetime.

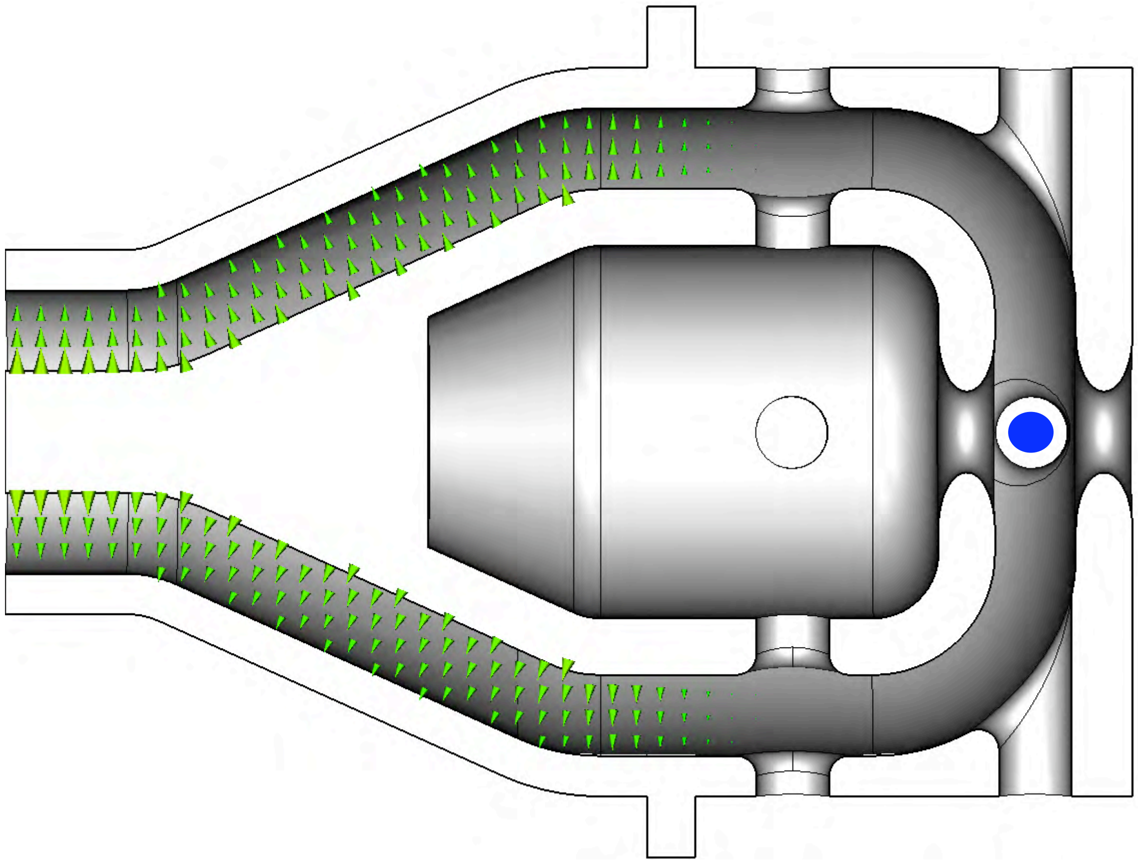


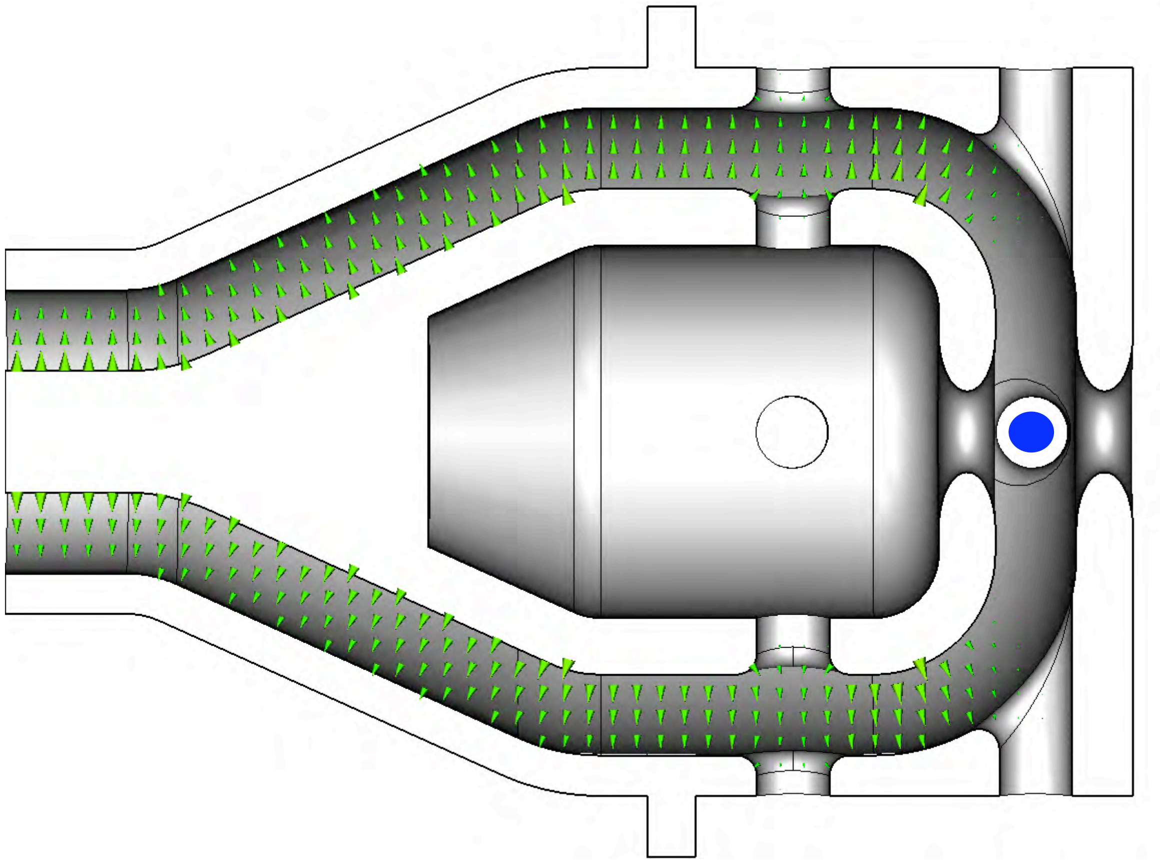


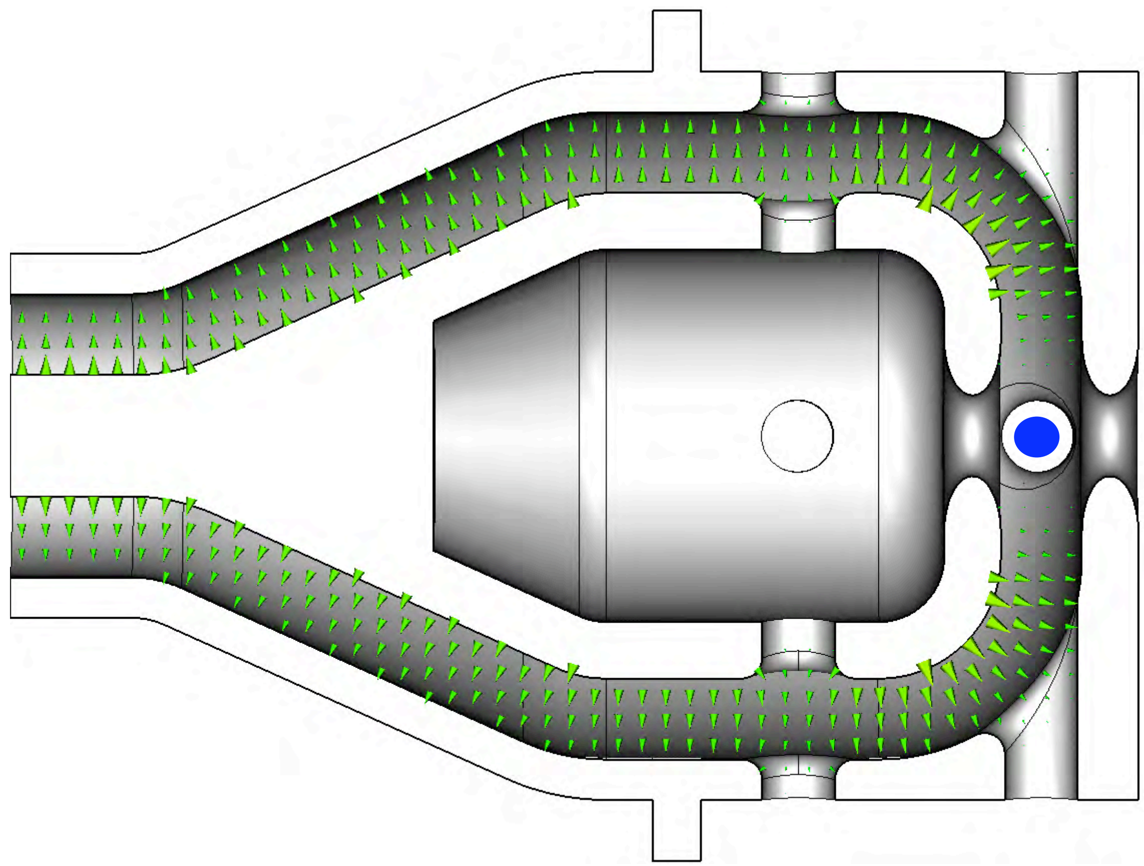
Under construction:
7X broadband transmission line transformer

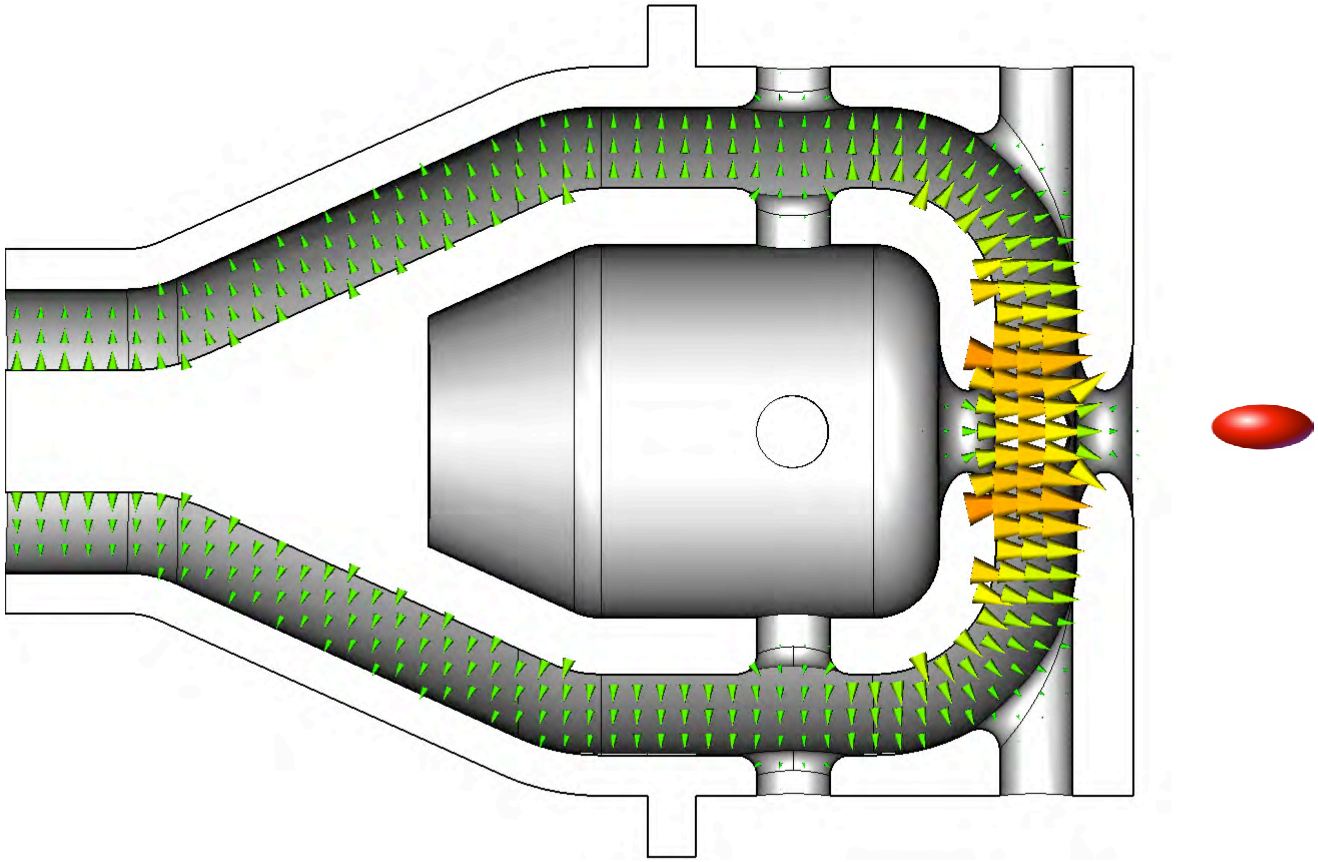












The ultimate beam recipe...

Ionize **Bose-Einstein Condensate** _ no correlation heating

_ $T_{electron}$ = 0.001 K

thermal De Broglie wavelength of electrons

$$\lambda_{th} = \frac{h}{\langle p \rangle} = \frac{h}{\sqrt{2\pi\, mkT}} = 2\ \mu\text{m}$$

larger than distance between electrons $n^{-1/3} \leq 1\ \mu\text{m}$

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Fermi degenerate electron beam!