High Intensity heavy-ion Accelerator Facility

Design of an 80keV Electron Target at the Spectrometry Ring

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OUTLINE

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2 General design of the E-target

3 Summary

4 Acknowledgement

Introduction of the E-target for SRing

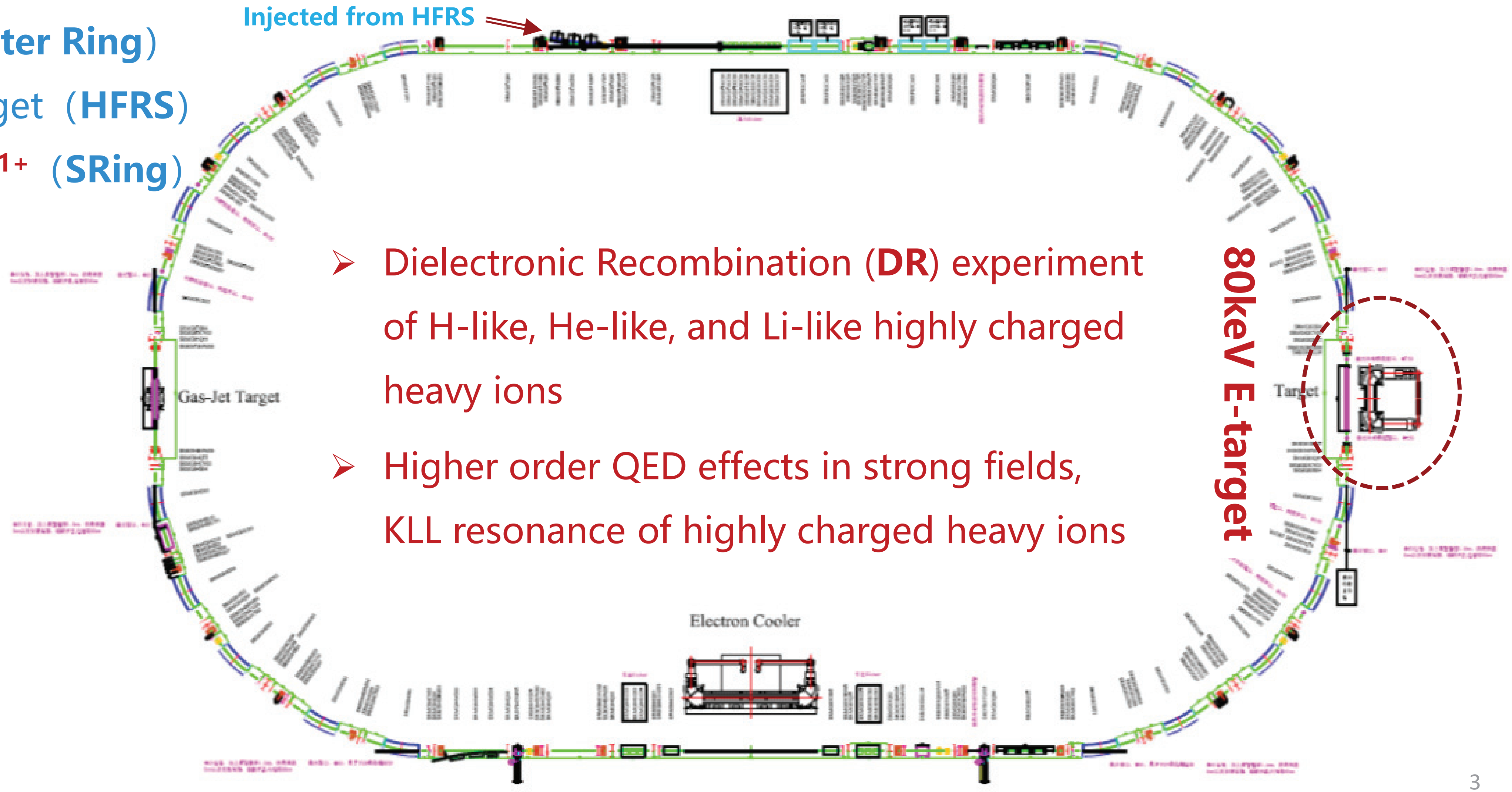
5 slides

E-target for Spectrometry Ring

U^{35+} (**Booster Ring**)

→ fixed target (**HFRS**)

→ $U^{89+,90+,91+}$ (**SRing**)



- Dielectronic Recombination (**DR**) experiment of H-like, He-like, and Li-like highly charged heavy ions
- Higher order QED effects in strong fields, KLL resonance of highly charged heavy ions

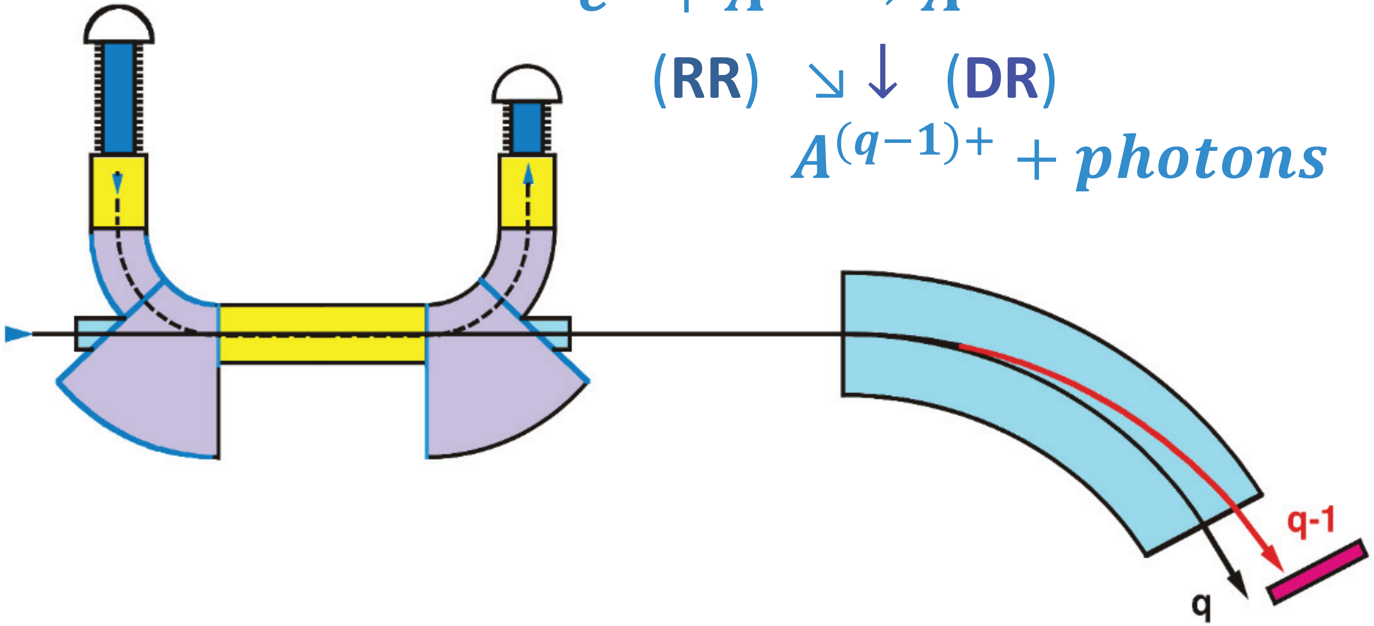
Introduction of the E-target for SRing

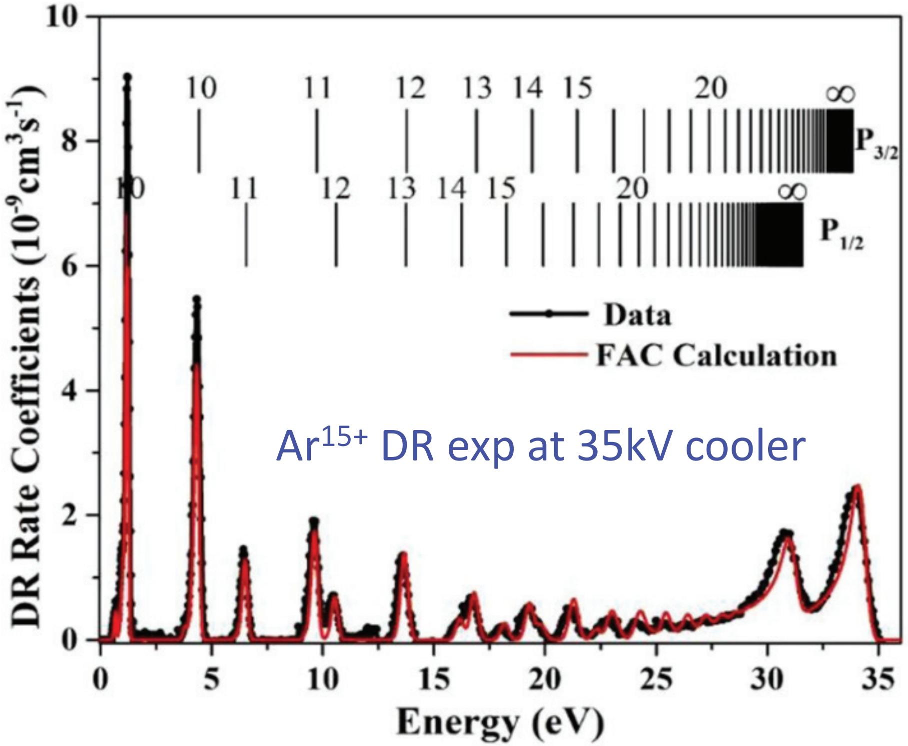
■ DR spectroscopy of highly charged ions

$$e^- + A^{q+} \rightarrow A^{(q-1)+**}$$

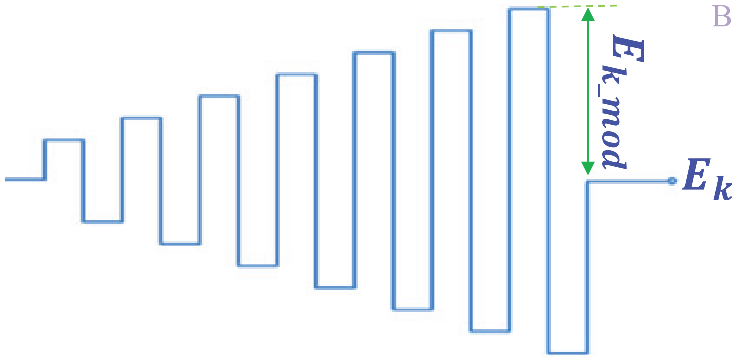
(RR) ↘ ↓ (DR)

$$A^{(q-1)+} + photons$$





Z.K. Huang et al. NIM B 83, 408, 2017

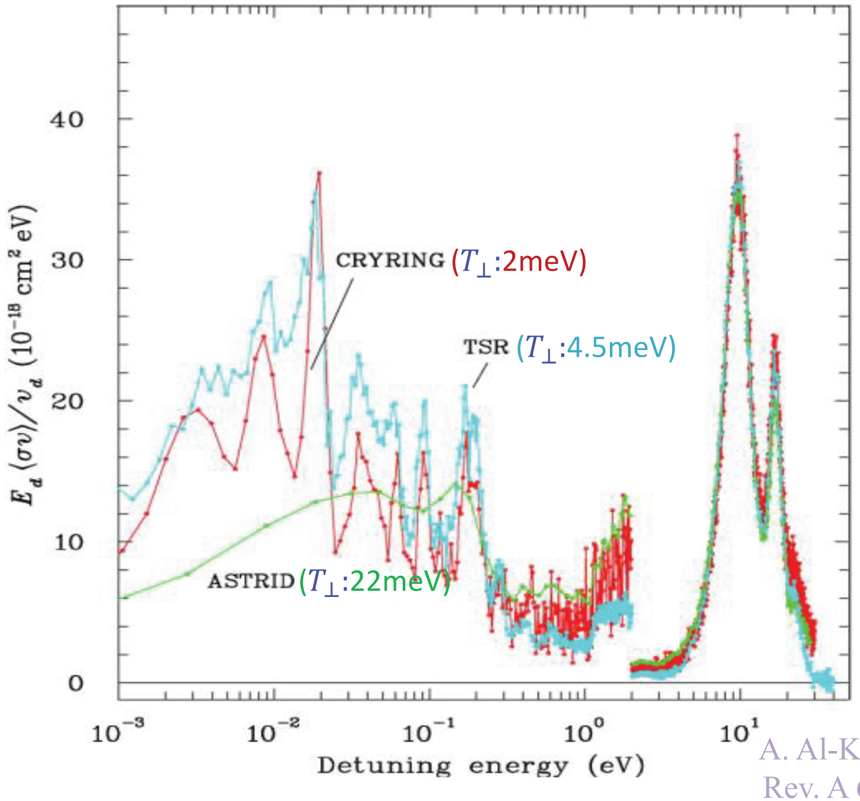


- ➢ To scan e-i collision energy by detuning e^- target energy
- ➢ To collect reaction products after downstream dipole
- ➢ Spectroscopy at CM energy coordinate

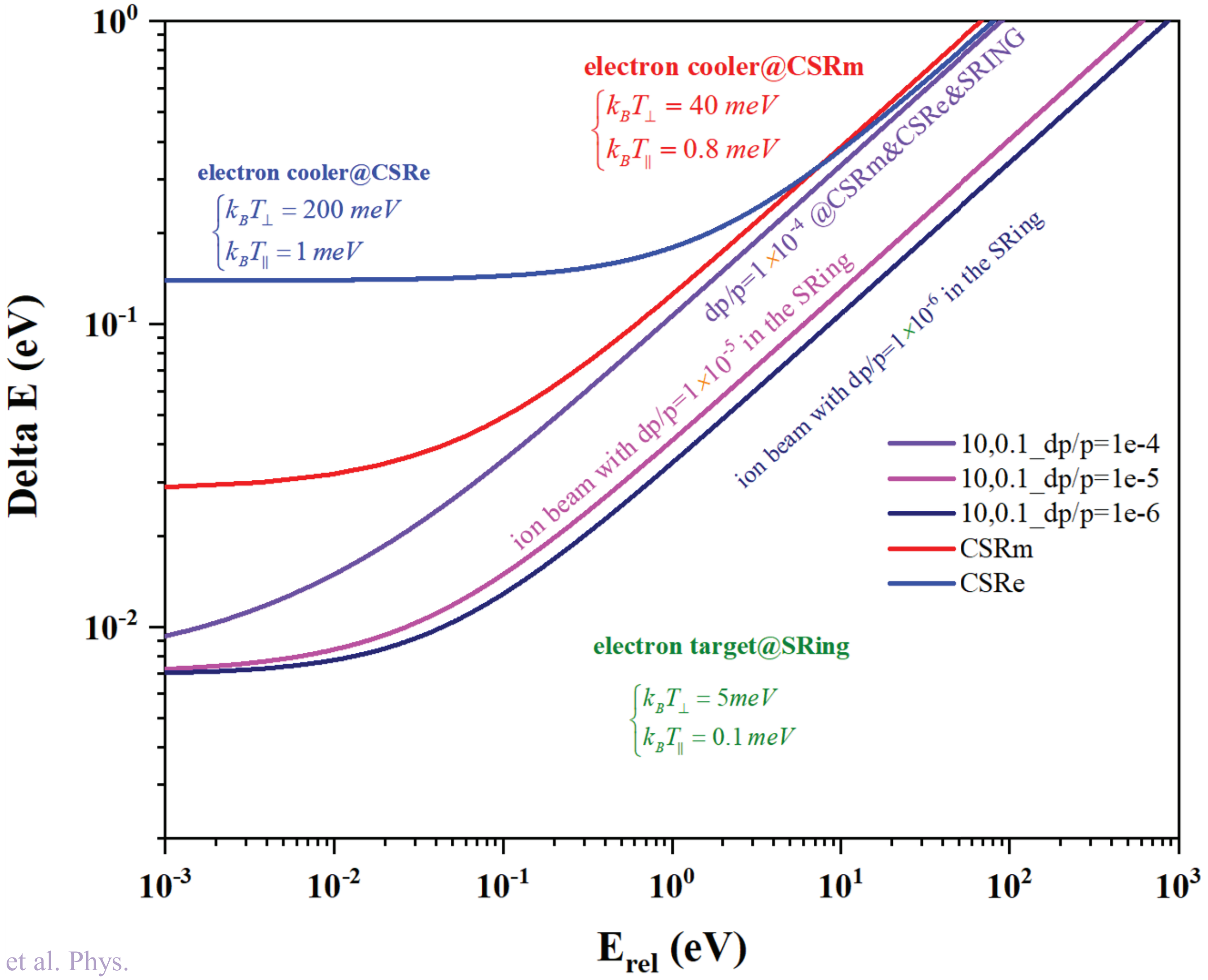
Introduction of the E-target for SRing

■ Motivation and goals

- ➢ **Higher energy revolution for DR**
  - Isotope shift and hyperfine splitting
- ➢ **Better efficiency and stability**



A. Al-Khalili et al. Phys. Rev. A 68, 042702 2003



Introduction of the E-target for SRing

Experimental requirement

Electron energy of target	**10-80keV**
Detuning voltage range	1-200V
Detuning voltage precision	1V
Detuning rising/trailing time	50μs
Transverse temperature of e^- beam	**5meV**
Longitudinal temperature of e^- beam	**0.1meV**
Electron density at interaction section	$2 \times 10^6 \mathrm{cm}^{-3}$
E-target thickness	$2 \times 10^{14} \mathrm{cm}^{-2} \mathrm{s}^{-1}$

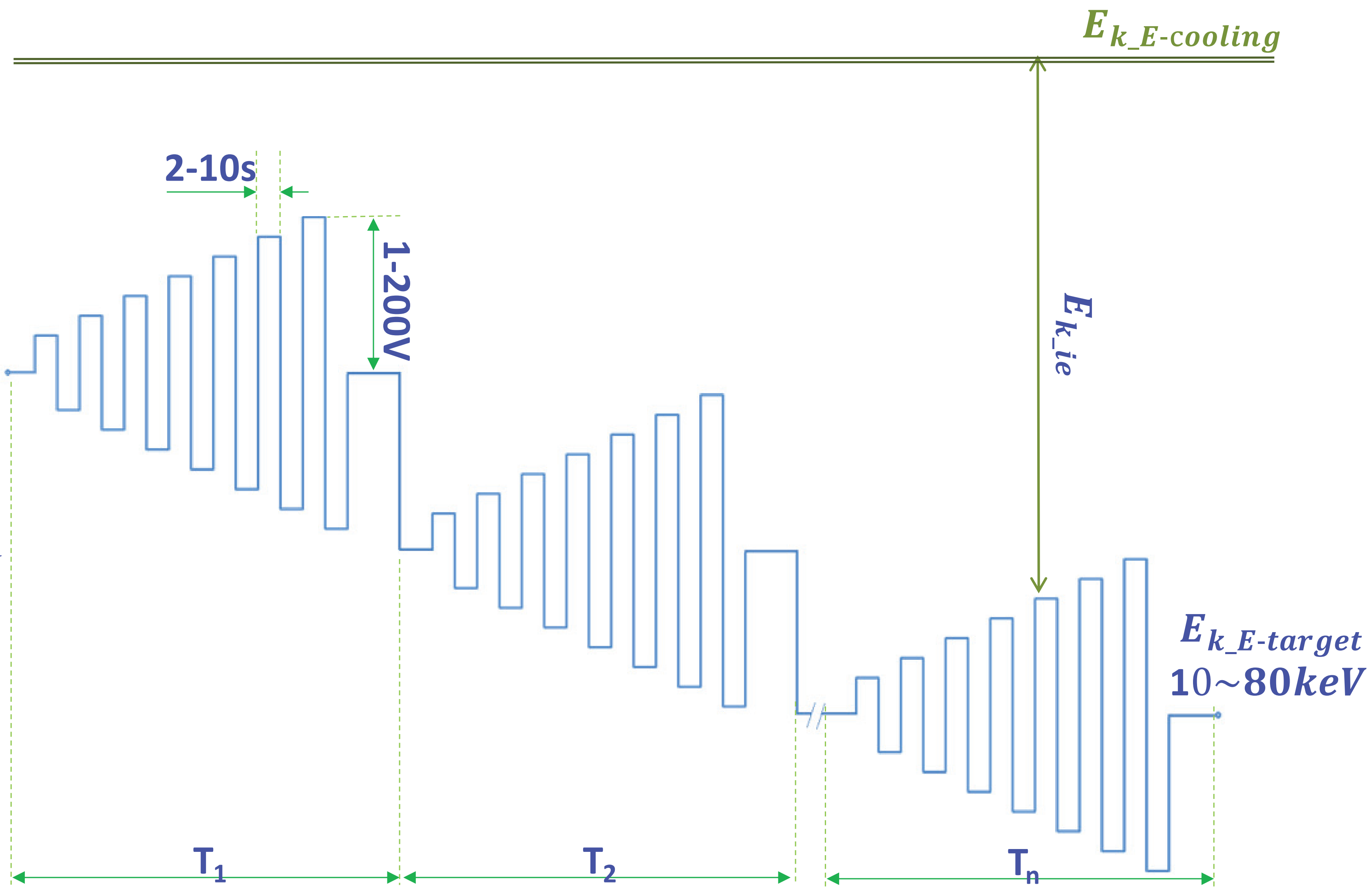
$$\delta E = \frac{1}{2} kT_{\parallel} + kT_{\perp} \pm \sqrt{2E_r kT_{\parallel}}$$

Key parameters for E-target : TEMPERATURE

Introduction of the E-target for SRing

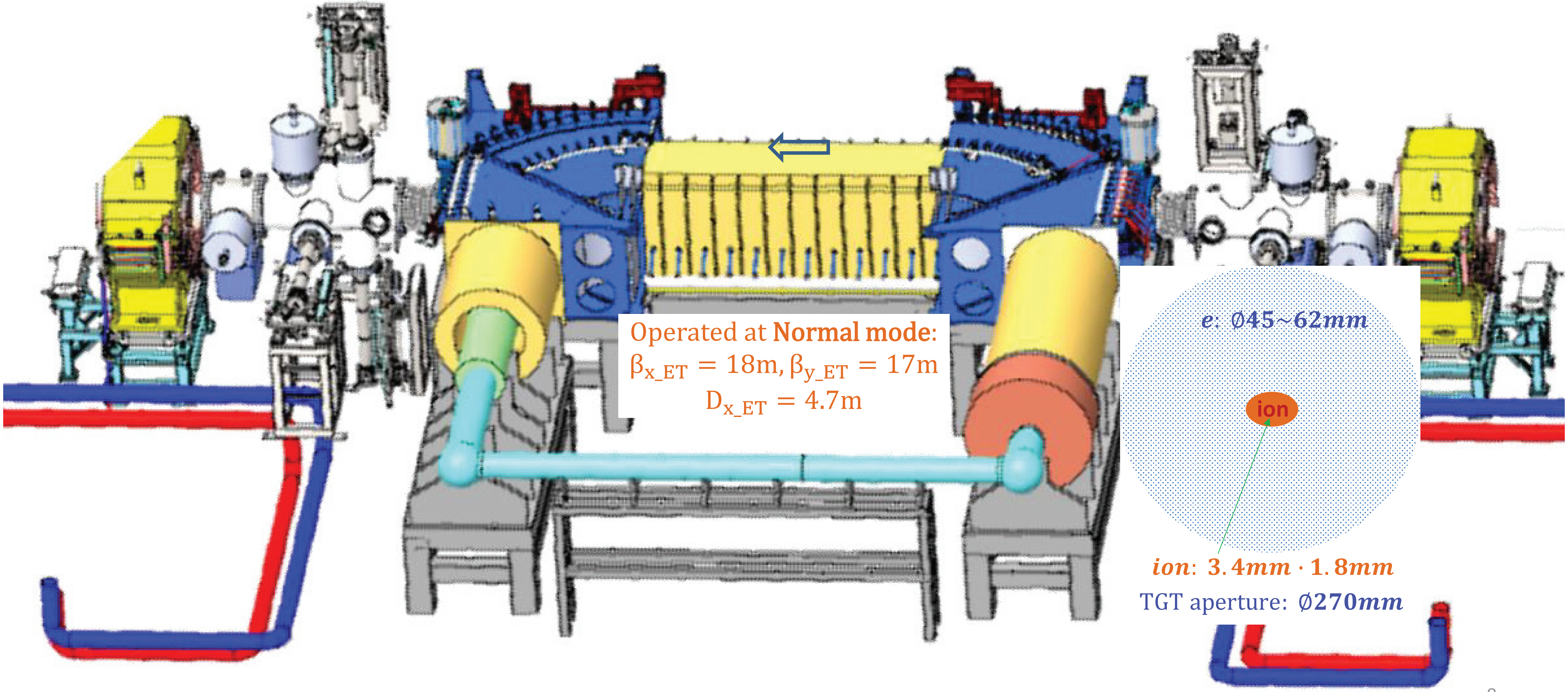
■ Detuning

- ➢ **HVPS + Detuning PS**
- ➢ **HV Amplifier PS**
  - Amplitude: $\pm 200V$
  - Ripple level: $5 \cdot 10^{-4}$
- ➢ Energy range: $n \cdot 200V$



General design of the E-target

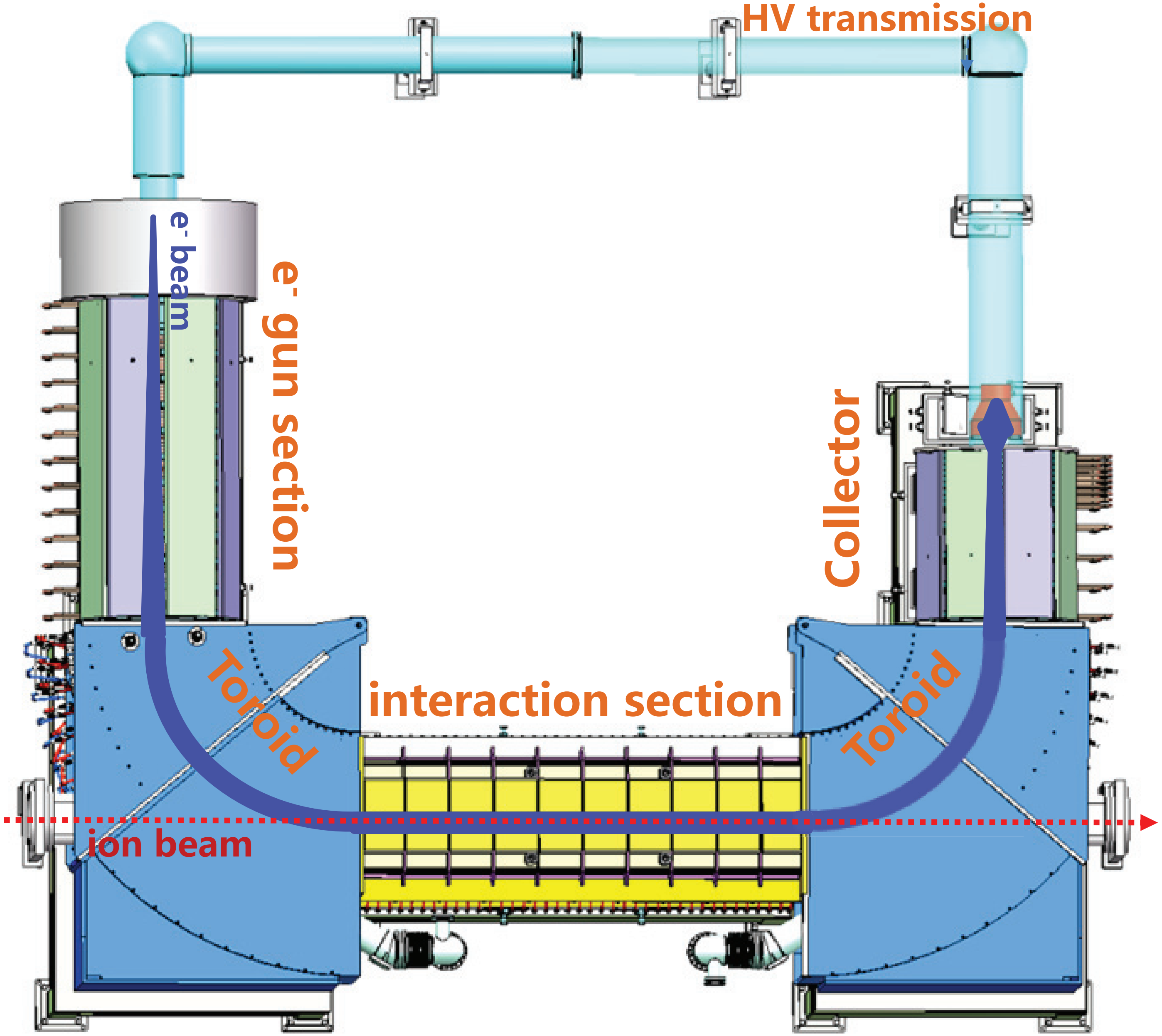
■ E-target layout at SRing



General design of the E-target

■ E-target layout

- ➢ e^- gun section
- ➢ Toroid section
- ➢ Interaction section
- ➢ Collector section
- ➢ HV transmission



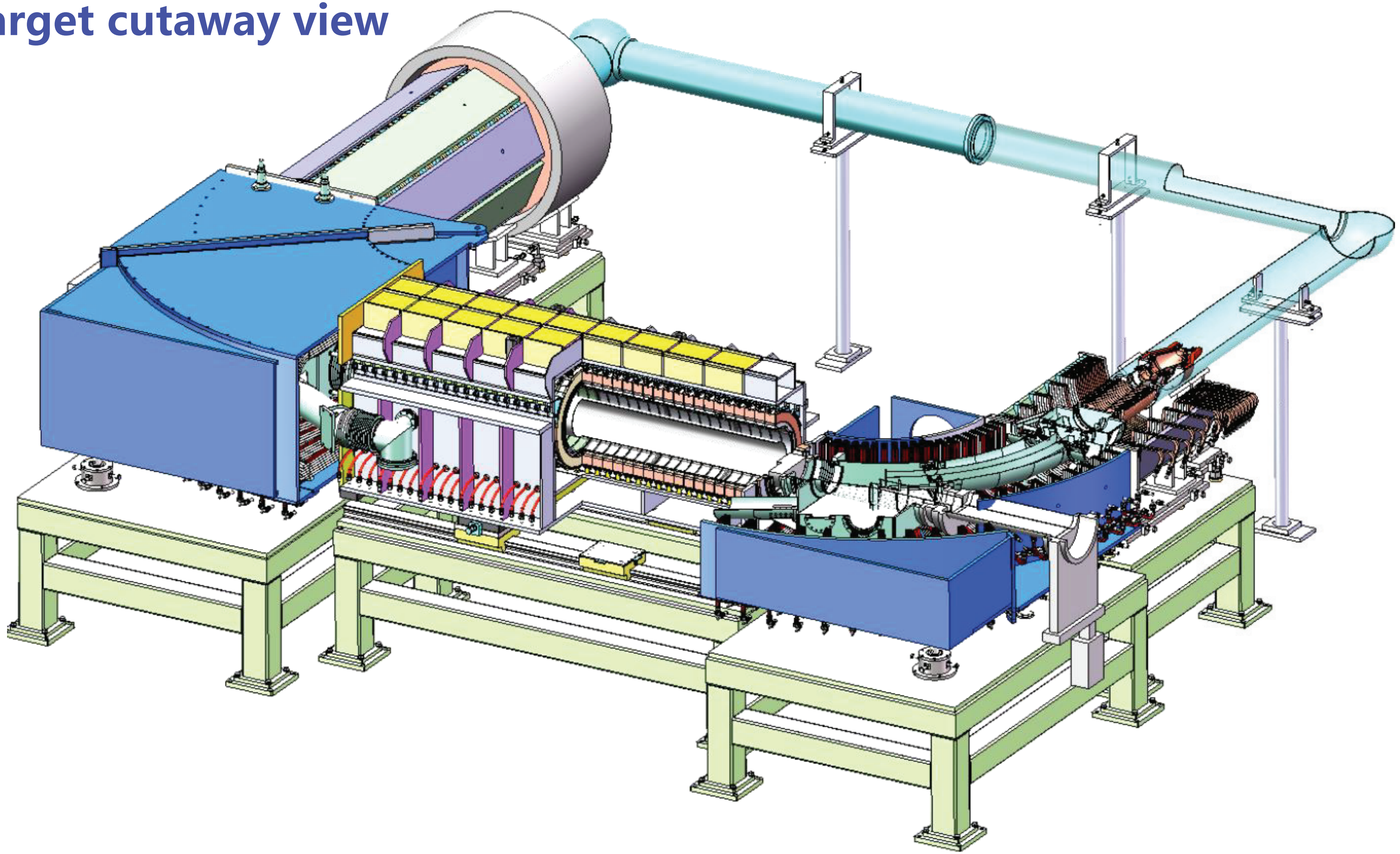
General design of the E-target

■ E-target technical parameters

Ripple of HV platform	$\pm 1 \times 10^{-5}$
Magnetic filed at cathode	**1.2 T**
Magnetic filed at interaction section	0.03~0.06 T
Magnetic adiabatic expansion factor	**20~40**
Field parallelism at interaction section	$\mathbf{1 \times 10^{-4}}$
Electron beam current	200 mA(hot cathode)
Cathode diameter	10 mm
Adiabatic acceleration length	**1.25 m**
Effective length of interaction section	**1.6 m**
Collection efficiency	99.95%
Total length of e-target	5.5 m
Beam aperture at interaction section	Φ270 mm
Vacuum pressure at interaction section	1×10^{-9} Pa
Interface flange of e-target	VF300

General design of the E-target

- E-target cutaway view



General design of the E-target

Key points on low–temperature electron beam

- Initial temperature at cathode: $kT_{\perp cathode}$=$kT_{\parallel cathode}$=**0.1eV**
- Low temperature at interaction section: $kT_{\perp target}$ ~5meV, $kT_{\parallel target}$ ~0.1meV

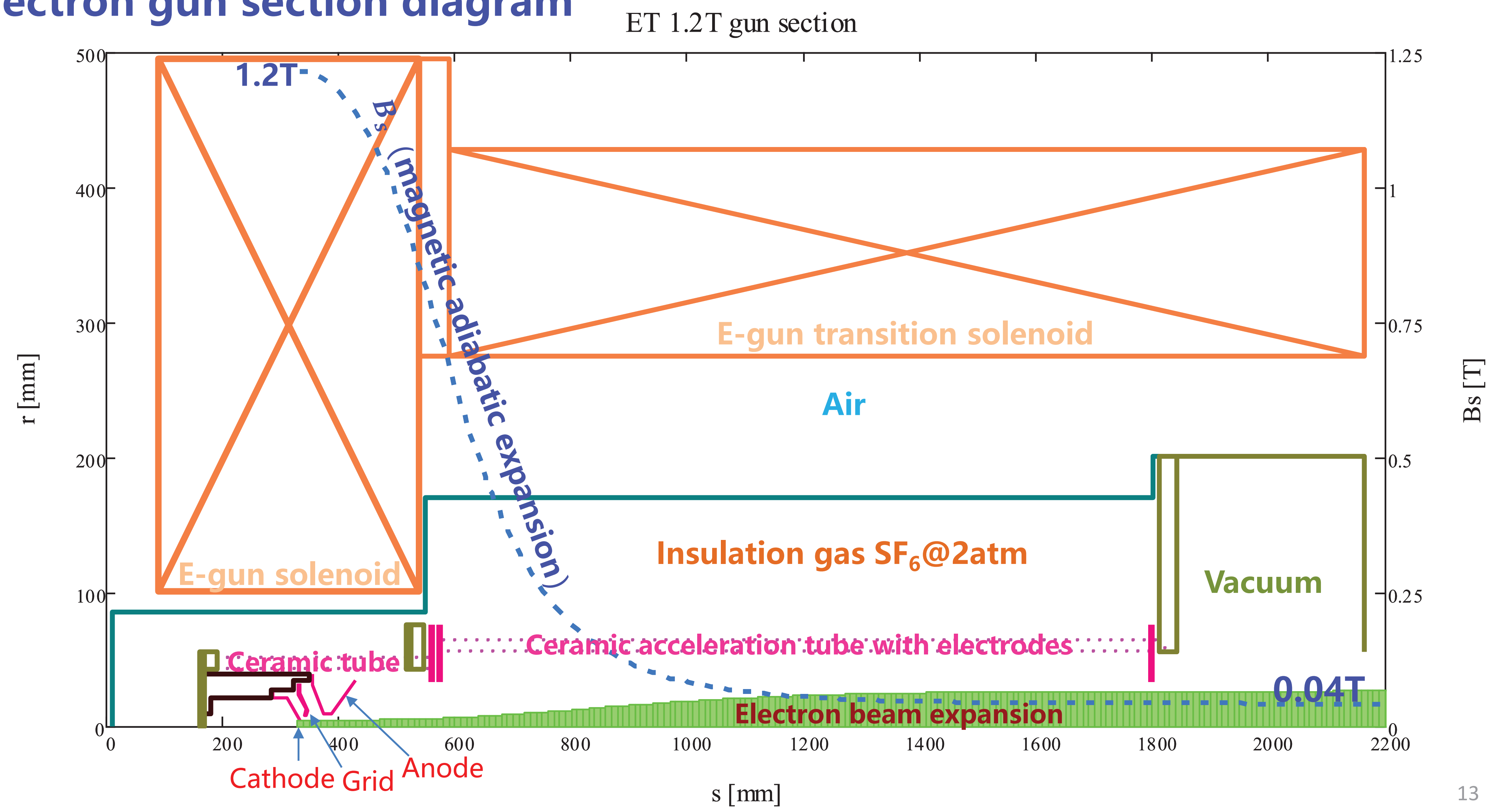
✓ **Transverse temperature**: Magnetic adiabatic expansion

✓ **Longitudinal temperature**: Adiabatic acceleration

➢ Typical parameters: $B_{s\_target} = 0.0395T$, $B_{s\_gun} = 1.2T$, $\alpha = 30$

General design of the E-target

■ Electron gun section diagram



General design of the E-target

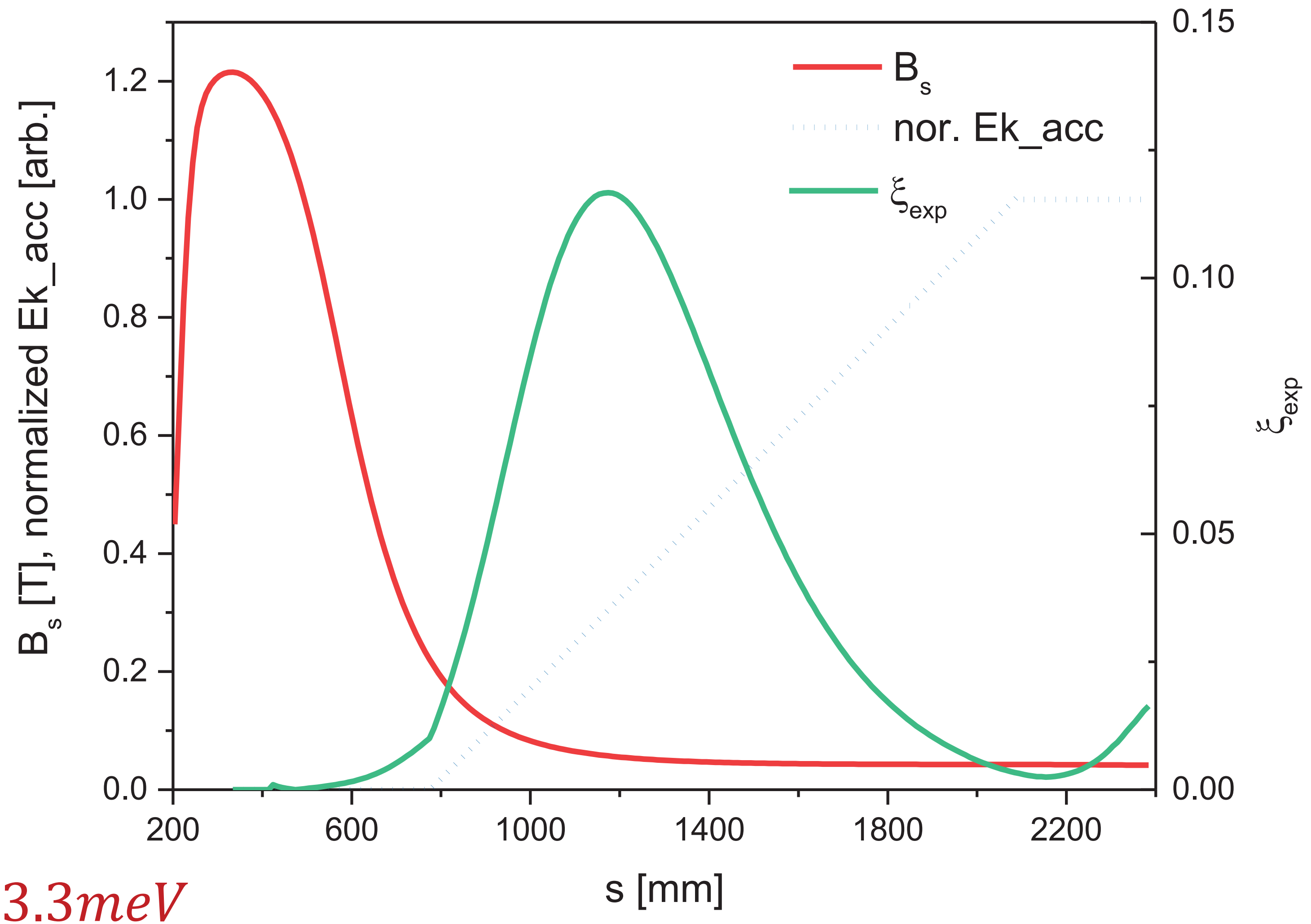
■ Transverse temperature

➢ **Magnetic adiabatic expansion**

$$\xi_{exp} = \frac{\lambda_L}{B_s} \cdot \frac{dB_s}{ds} < 0.12 \ll \mathbf{1.0}$$

$$\alpha = \frac{B_{s\_cathode}}{B_{s\_target}} = 30$$

$$kT_{\perp target\_exp} = \frac{kT_{\perp cathode}}{\alpha} = 3.3meV$$



General design of the E-target

■ Transverse temperature

➢ **By space charge field of electron beam**

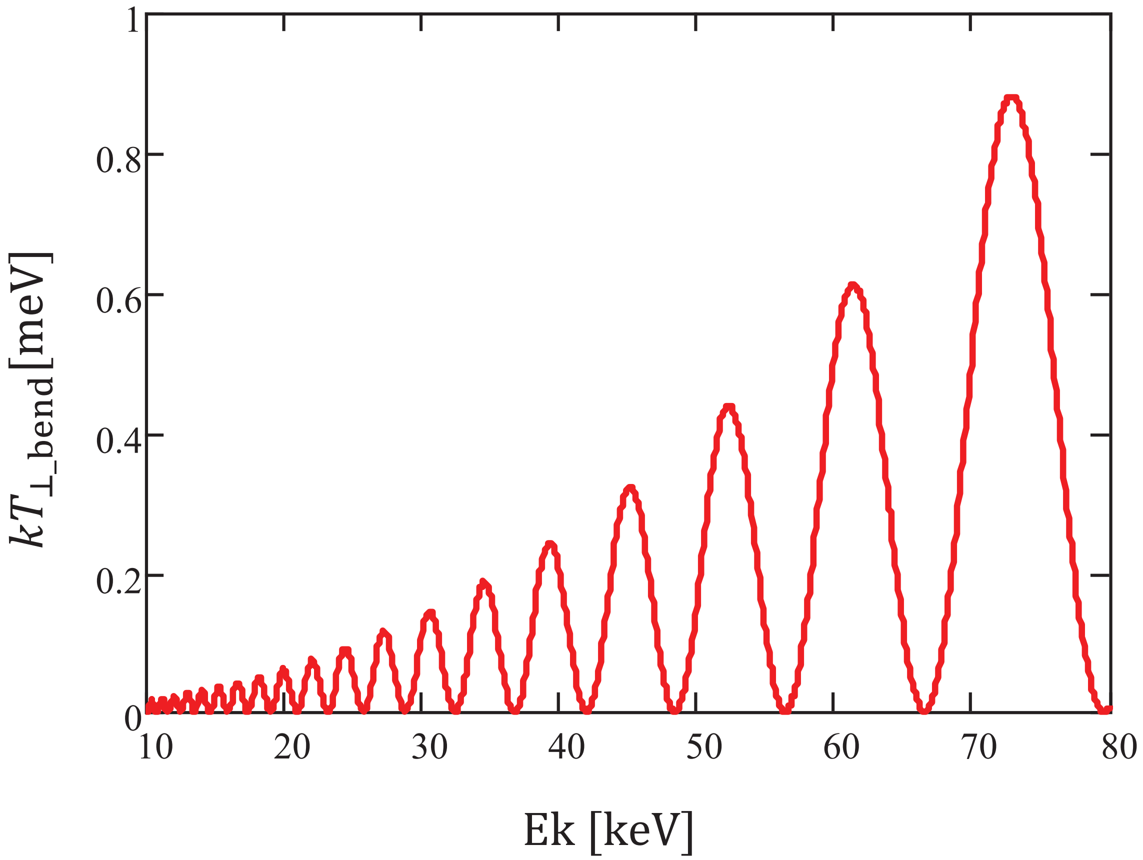
$$kT_{\perp sc} \propto \left(\frac{\gamma I_e}{\beta B_s} r\right)^2$$

$$= \begin{cases} 0.01meV & 10\text{keV} \\ 0.06meV & 80\text{keV} \end{cases}$$

➢ **By transition in Toroid field**

$$kT_{\perp \text{bend}} \propto \left(\beta \cdot \gamma \cdot \lambda_L \cdot \sin(\pi \cdot \frac{\Delta s}{\lambda_L})\right)^2$$

$$= \begin{cases} 0.003meV & 10\text{keV} \\ 0.01meV & 80\text{keV} \end{cases}$$



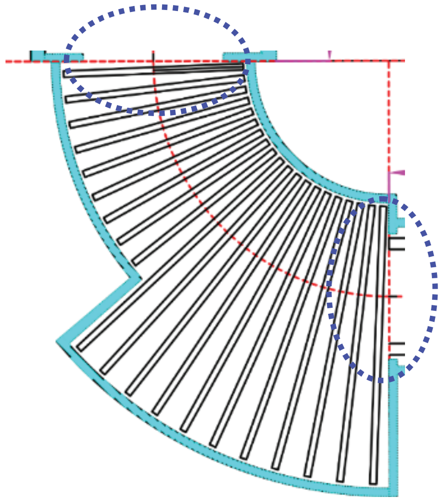
General design of the E-target

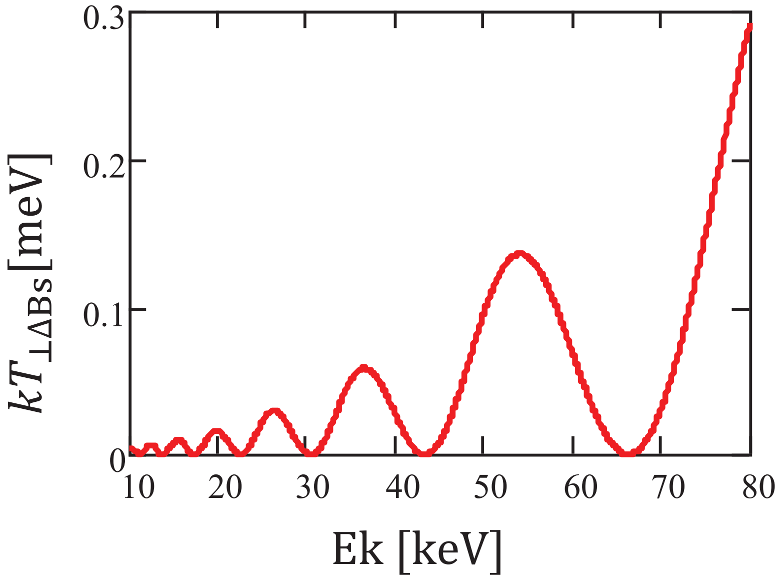
■ Transverse temperature

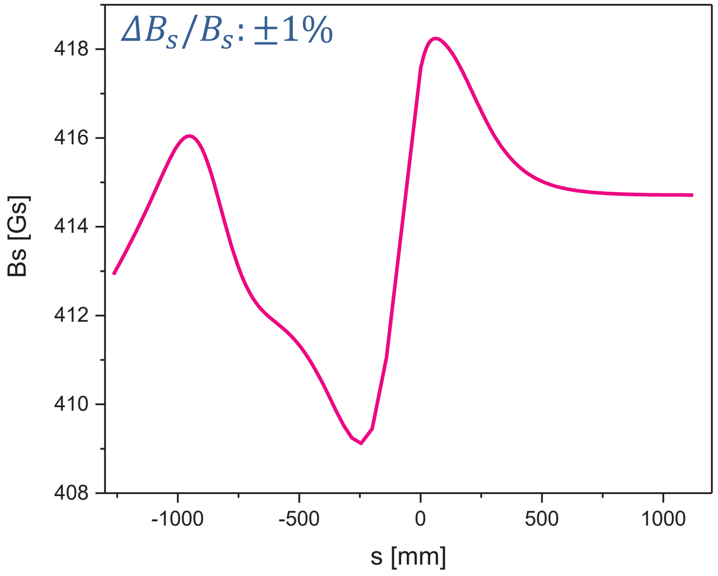
➢ **By field distortion at junctions of Toroid and solenoid**

$$kT_{\perp\Delta Bs} \propto \left(\frac{\beta\gamma}{\lambda_L} \cdot \frac{\Delta B_s}{\Delta B_s \Delta s_{dis}} \frac{\sin(\pi \cdot \frac{\Delta s_{dis}}{\lambda_L})}{1 - \frac{\Delta s_{dis}}{\lambda_L}^2} \right)^2$$

$$= \begin{cases} 0.0007 meV & 10\text{keV} \\ 0.3 meV & 80\text{keV} \end{cases}$$







General design of the E-target

- **Transverse temperature**

  - **By radial electric field at acceleration tube entrance and exit**

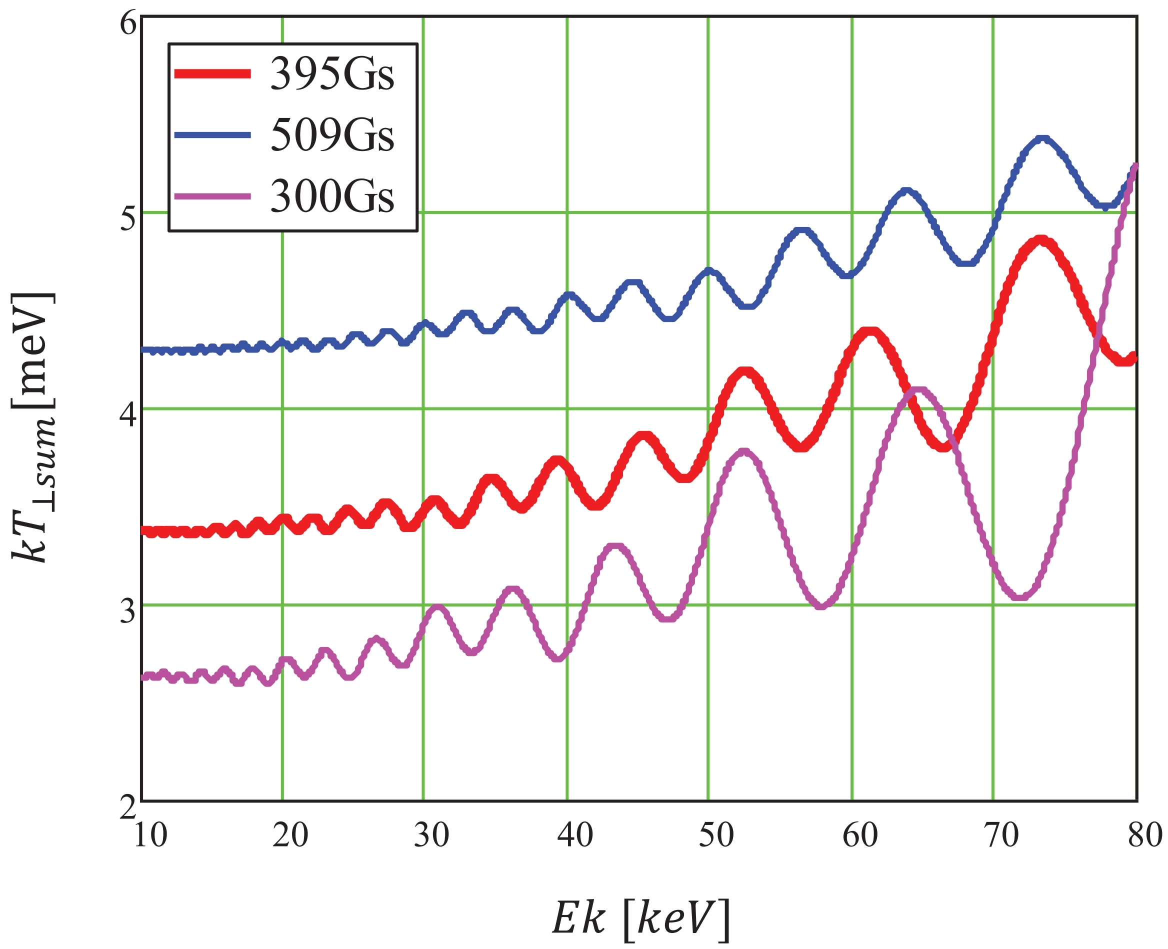
$$kT_{\perp accT} \propto \left(\gamma \cdot \frac{E_{acc}}{B_s} \cdot r\right)^2$$

$$= \begin{cases} 0.007meV & 10\text{keV} \\ 0.6meV & 80\text{keV} \end{cases}$$

  - **Sum of all listed influencing factors**

$$kT_{\perp sum} = kT_{\perp exp} + kT_{\perp accT}$$

$$+ kT_{\perp \Delta \text{Bs}} + kT_{\perp \text{bend}} + kT_{\perp sc}$$



$$kT_{\perp sum} < 5meV$$

General design of the E-target

■ Longitudinal temperature

➢ **By Longitudinal-Longitudinal Relaxation (LLR)**

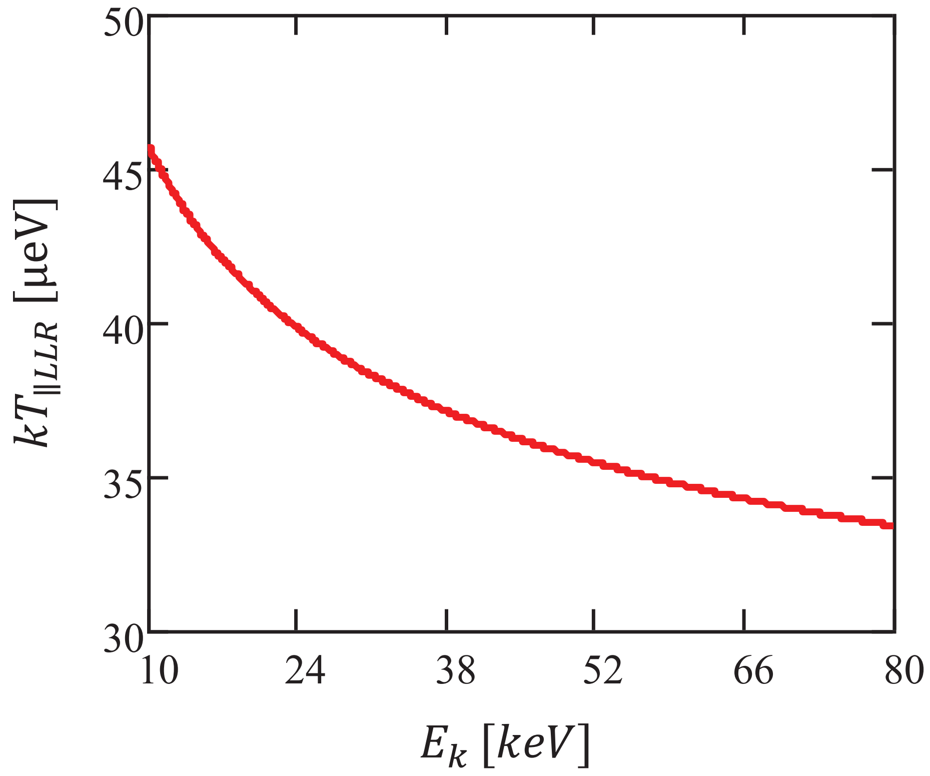
- Longitudinal density decrease by acceleration

$$kT_{\parallel LLR} = C_{LLR} \frac{e^2}{4\pi\epsilon_0} \cdot n_e^{\frac{1}{3}} = \begin{cases} 46\mu eV & 10\text{keV} \\ 33\mu eV & 80\text{keV} \end{cases}$$

✓ **LLR affect suppression**

- Acceleration in quasi-equilibrium state of electron plasma, i.e. adiabatic acceleration

$$\xi_{acc} = \frac{1}{\omega_p} \cdot \frac{1}{E_k} \frac{dE_k}{dt} < 1$$



T Schmöller et al. NIM A 441, 50, 2000

General design of the E-target

Longitudinal temperature

- Adiabatic acceleration:

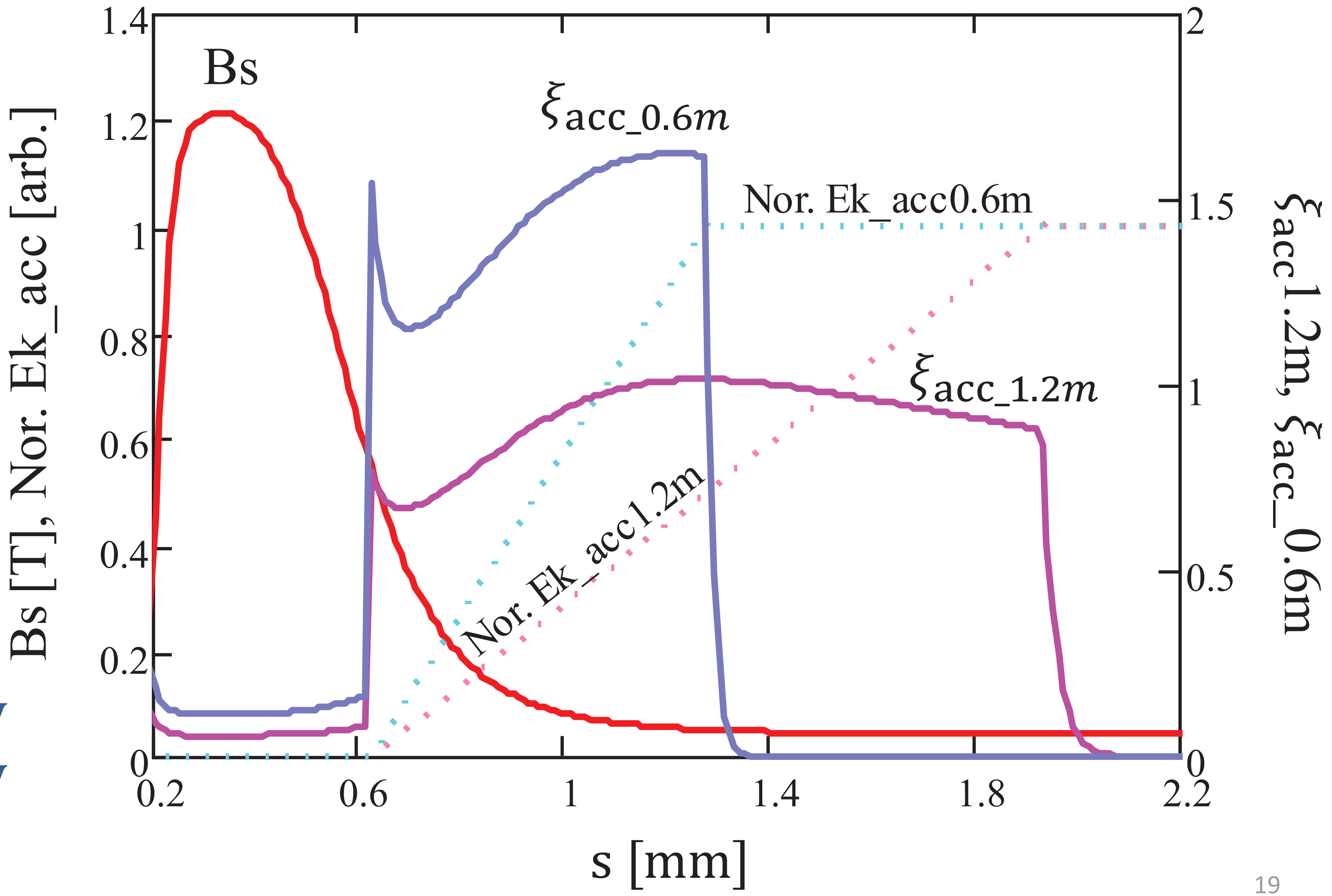
$$\xi_{acc} = \frac{1}{\omega_p} \cdot \frac{1}{E_k} \frac{dE_k}{dt}$$

$$= -\frac{\beta c}{\omega_p} \cdot \frac{1}{T_\parallel} \frac{dT_\parallel}{ds}$$

$$= \frac{\beta c}{\omega_p} \cdot \frac{1}{E_k} \frac{dE_k}{ds} < \mathbf{1}$$

$$kT_{\parallel adc} = \begin{cases} 23\mu eV & 10\text{keV} \\ 21\mu eV & 80\text{keV} \end{cases}$$

Energy: 80keV

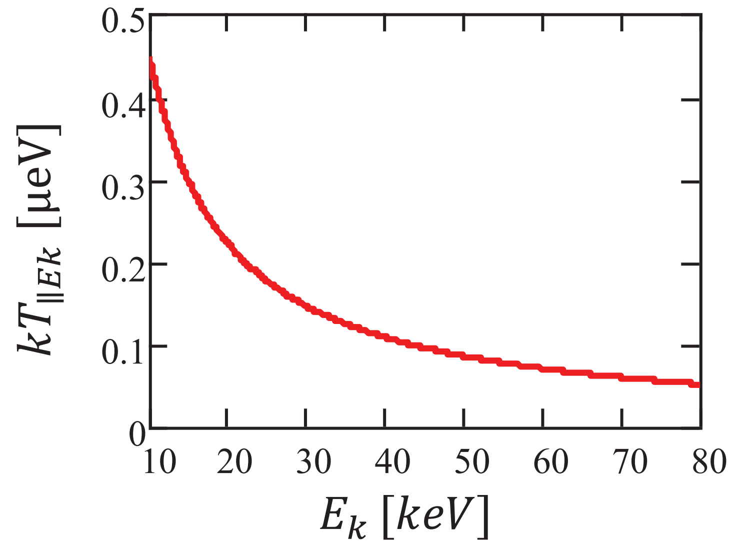


General design of the E-target

■ Longitudinal temperature

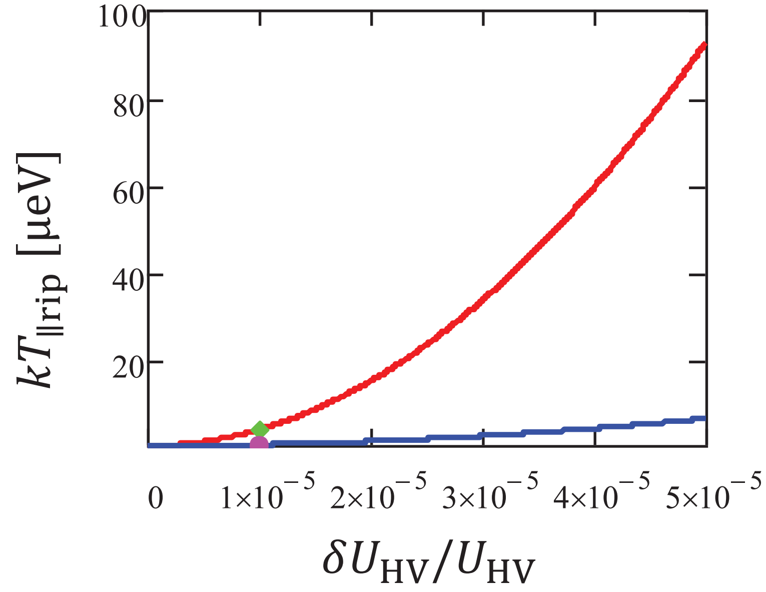
➢ **By energy increase of electron beam**

$$kT_{\parallel E_k} = \frac{{kT_{\perp cathode}}^2}{(\gamma+1)E_k} = \begin{cases} 0.45\mu eV & 10\text{keV} \\ 0.05\mu eV & 80\text{keV} \end{cases}$$



➢ **By ripples of HV platform**

$$kT_{\parallel \mathrm{rip}} = \frac{E_k}{(\gamma+1)}\left(\frac{\delta U_{\mathrm{HV}}}{U_{\mathrm{HV}}}\right)^2 = \begin{cases} 0.5\mu eV & 10\text{keV} \\ 3.7\mu eV & 80\text{keV} \end{cases}$$



General design of the E-target

■ Longitudinal temperature

➢ **Transverse-Longitudinal Relaxation (TLR)**

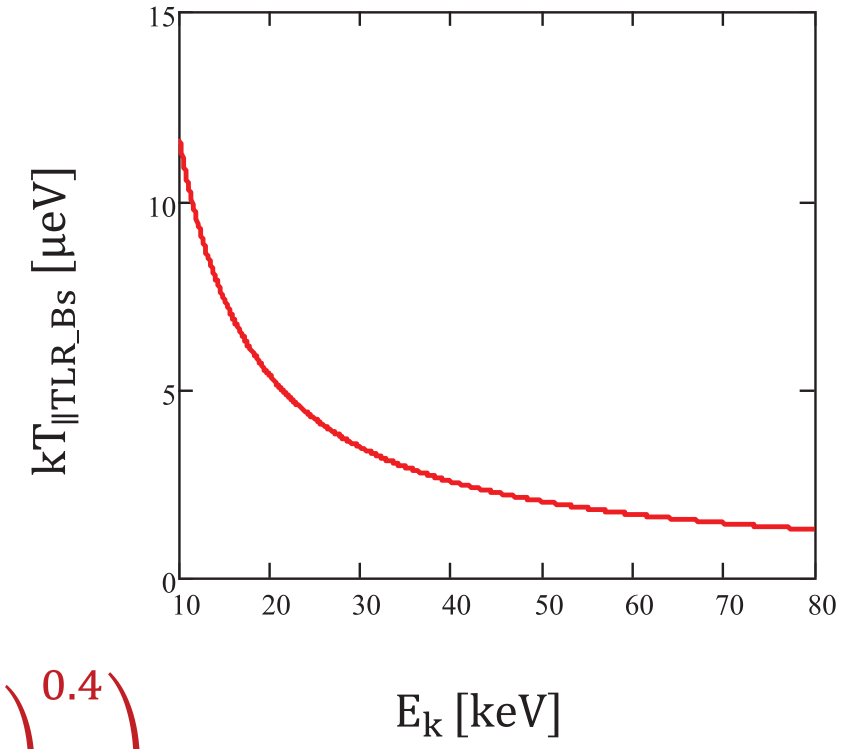
- $kT_{\parallel} \ll kT_{\perp}$ caused by acceleration
- $kT_{\parallel}$ increased by collision of electrons or relaxation

✓ **TLR affect suppression**

- **To increase guiding field** (> 0.027T)

$$kT_{\parallel TLR\_B_s} \propto \frac{\boldsymbol{n_e}}{\boldsymbol{E_k}} (kT_{\perp})^{-1/2} \ln\left(\frac{r_L}{2b_{\perp}}\right) \exp\left(-2.3\left(\frac{b_{\parallel}}{r_L}\right)^{0.4}\right)$$

$$= \begin{cases} 12\mu eV & 10\mathrm{keV} \\ 1.3\mu eV & 80\mathrm{keV} \end{cases}$$



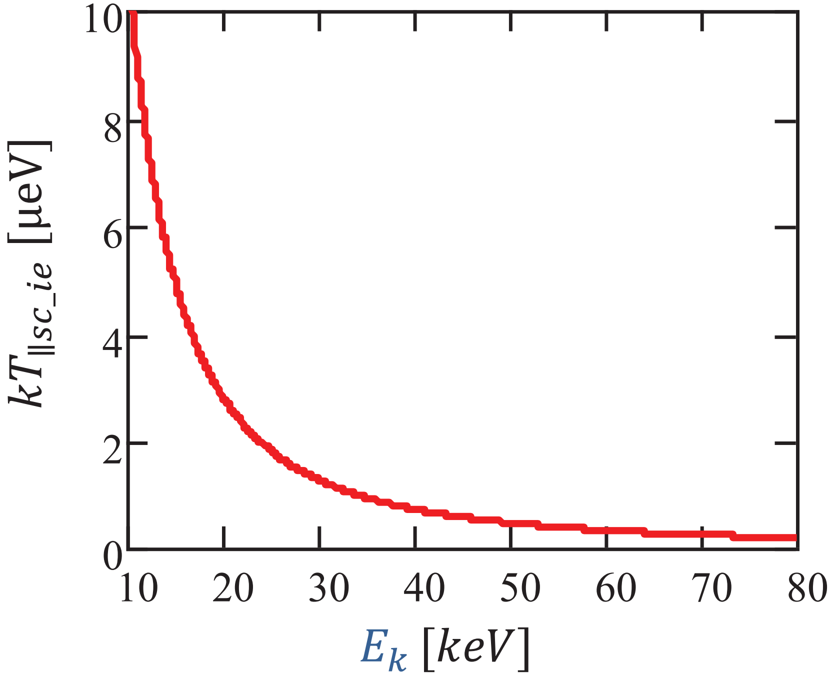
General design of the E-target

■ Longitudinal temperature

➢ **By space charge field of electron beam**

$$kT_{\parallel sc\_ie} \propto \frac{n_e}{\beta}\left(\delta r_{ie}, \vartheta_{ie} \cdot l_{target}\right)$$

$$= \begin{cases} 11\mu eV & 10\text{keV} \\ 0.2\mu eV & 80\text{keV} \end{cases}$$



General design of the E-target

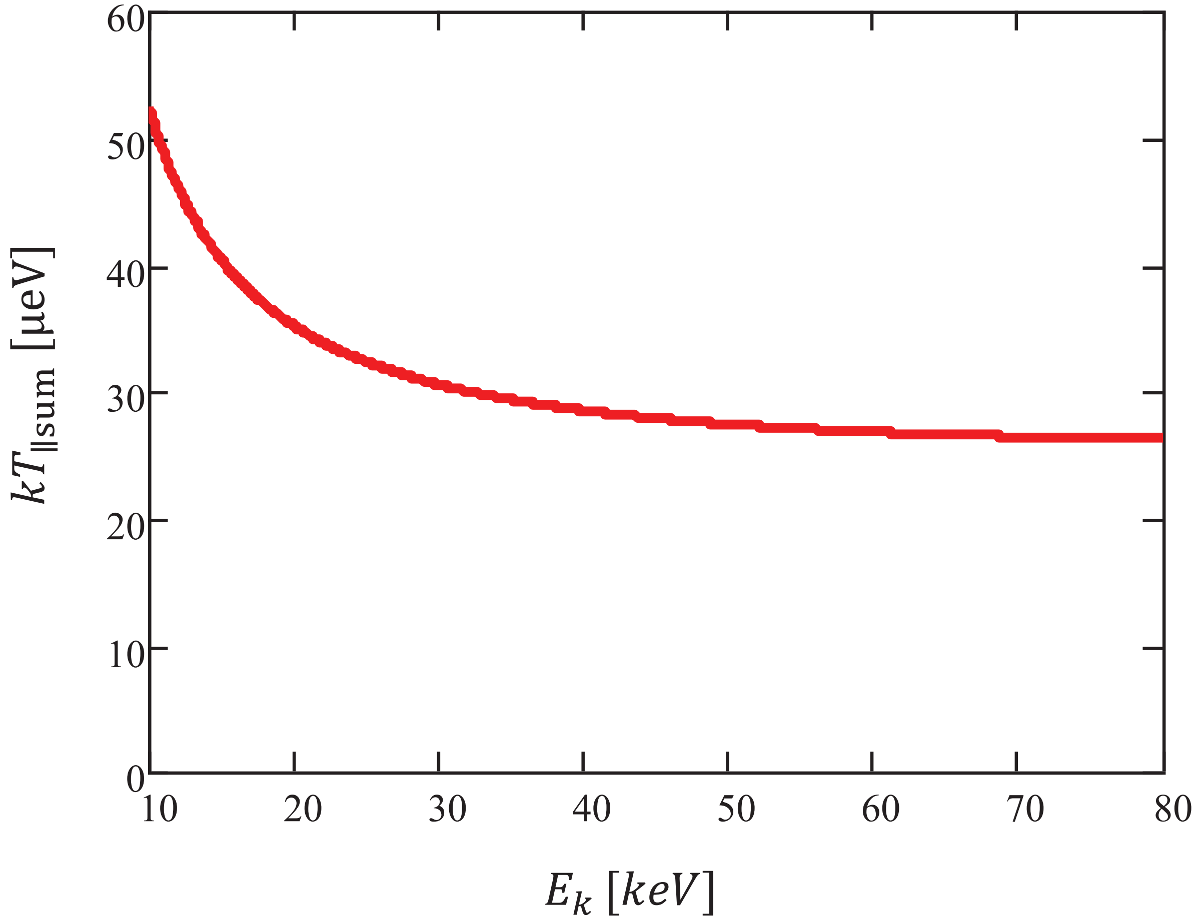
■ Longitudinal temperature

$$kT_{\|\mathrm{sum}} = \boldsymbol{kT_{\|adc}}$$

$$+kT_{\|TLR\_B_s} + kT_{\|E_k}$$

$$+kT_{\|\mathrm{rip}} + kT_{\|sc\_ie}$$

$$\boldsymbol{kT_{\|sum} < 100\mu eV}$$



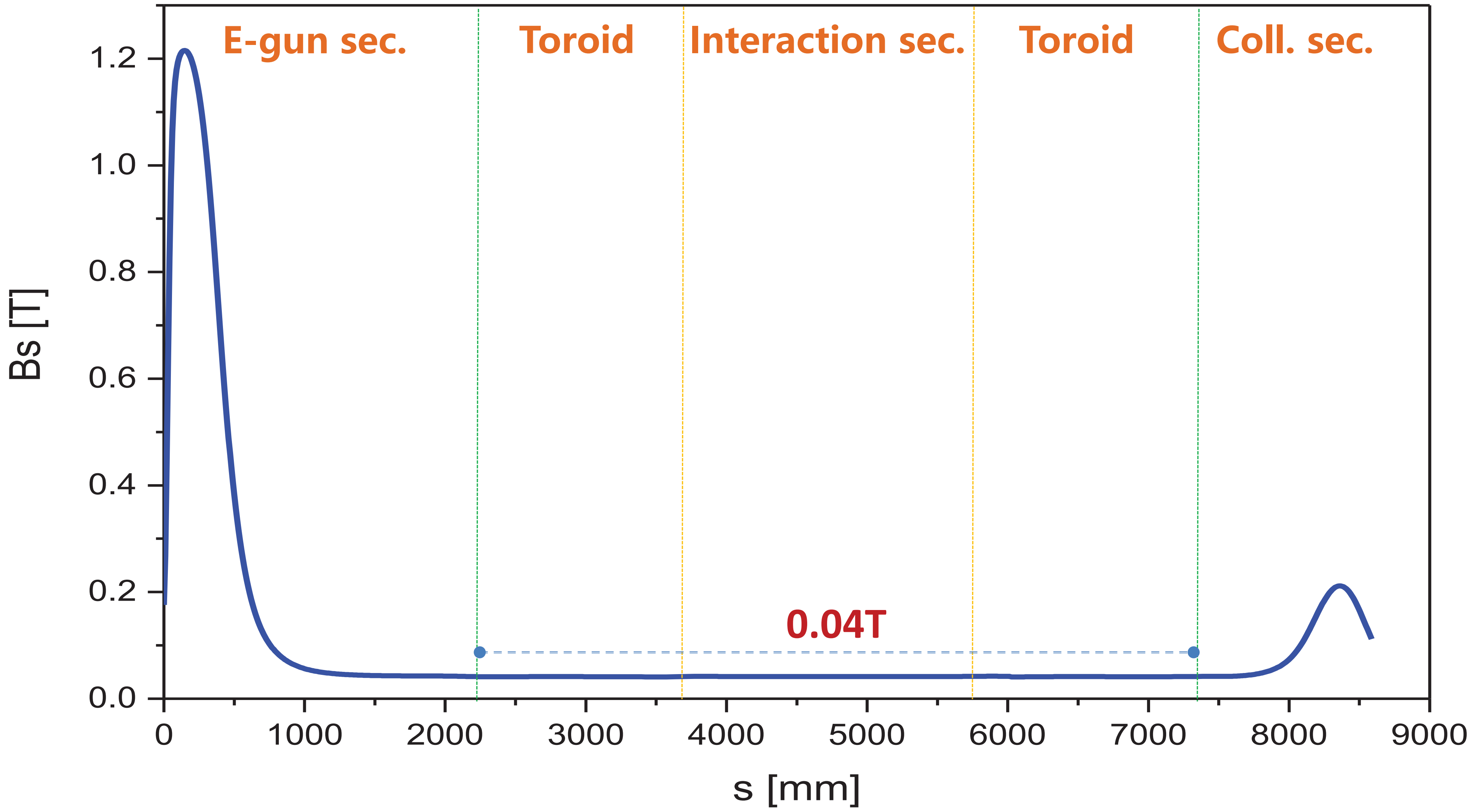
General design of the E-target

Solutions on low-temperature electron beam

- **Transverse temperature**: $kT_{\perp sum} < 5meV$
  - By expansion longitudinal magnetic field from 1.2T at cathode to 0.04T at interaction section adiabatically with $\boldsymbol{\xi_{exp} \ll 1.0}$
- **Longitudinal temperature**: $kT_{\parallel \mathrm{sum}} \sim 0.05meV < 0.1meV$
  - By 1.25m length of acceleration adiabatically with $\boldsymbol{\xi_{acc} \leq 1.0}$

General design of the E-target

- **Longitudinal magnetic field along orbit of electron beam**



General design of the E-target

Main coils arrangement

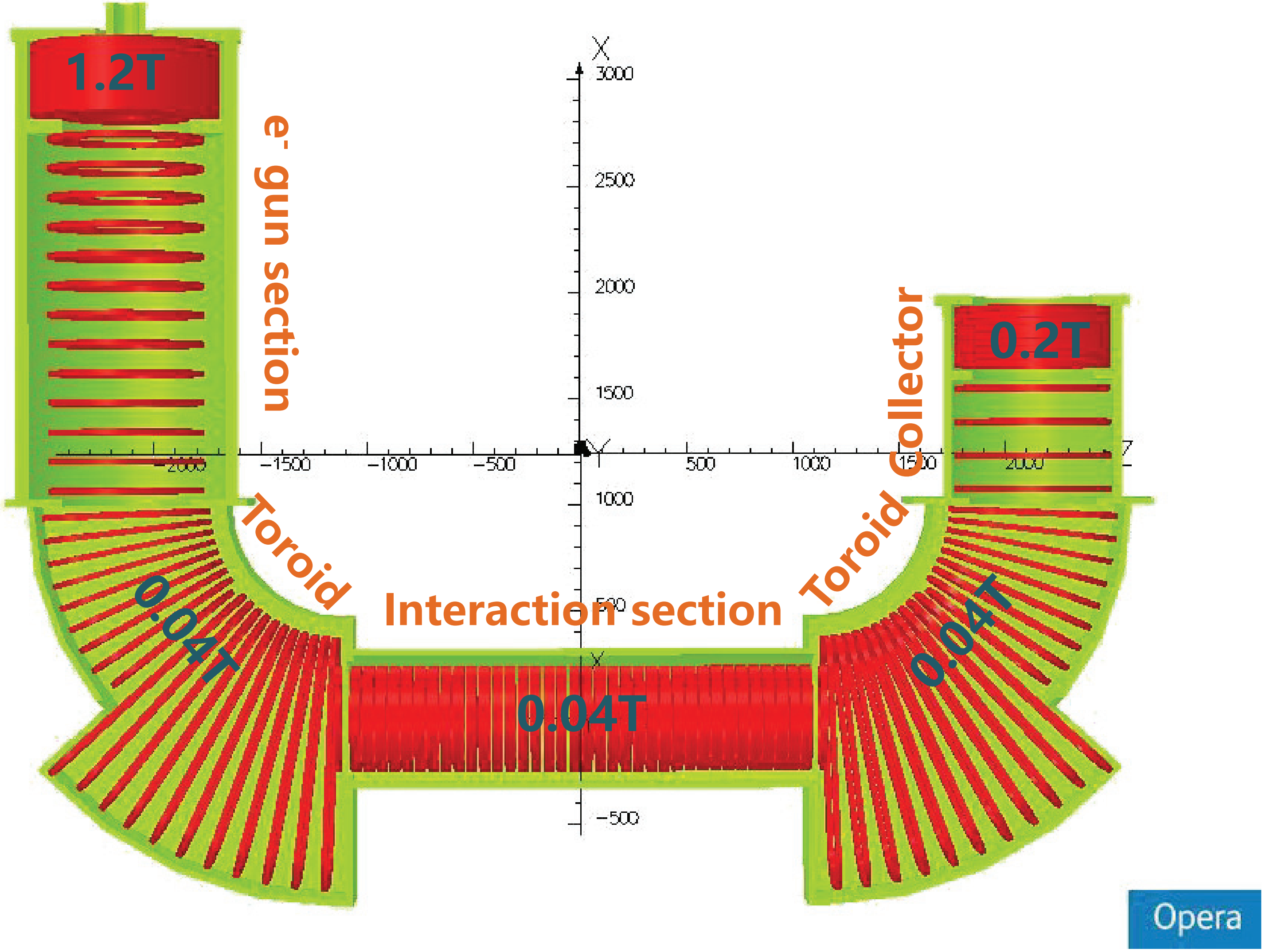
- Parallelism at interaction section

$$\frac{B_{s\perp}}{B_s} \sim \mathbf{1 \times 10^{-4}}$$

- Field distortion at junctions of Toroid and solenoid

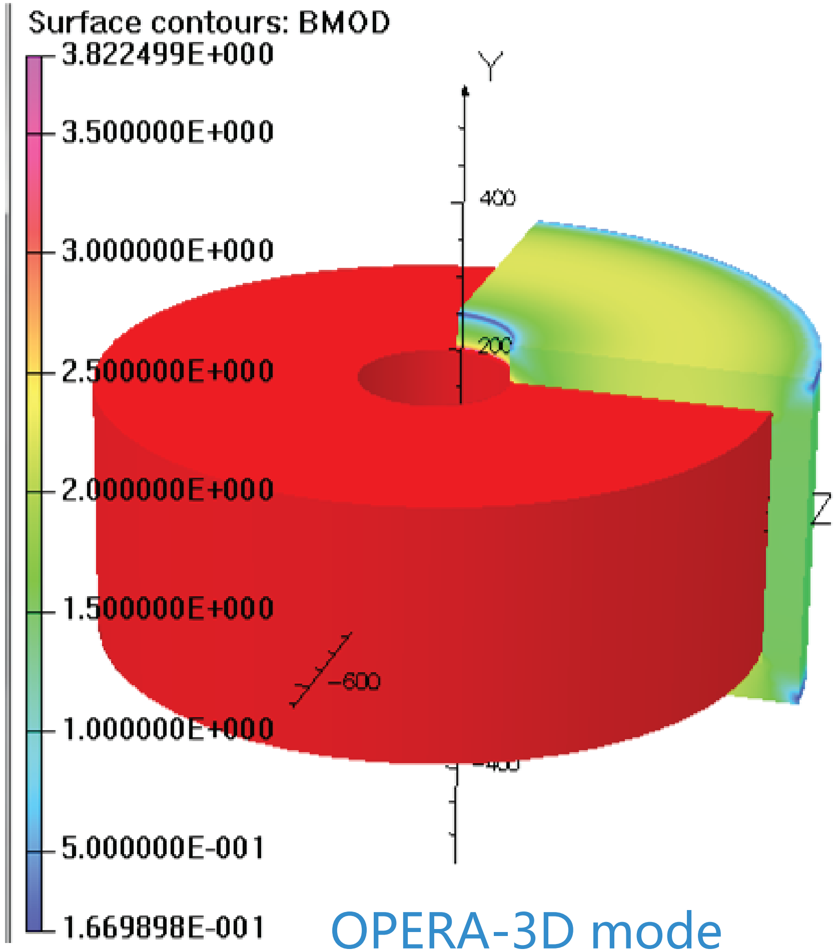
$$\frac{\Delta B_s}{B_s} \sim \pm \mathbf{5 \cdot 10^{-3}}$$

- 14 coils at gun section
- 20 coils at Toroid
- 36 coils at interaction section
- 13 coils at coll. section



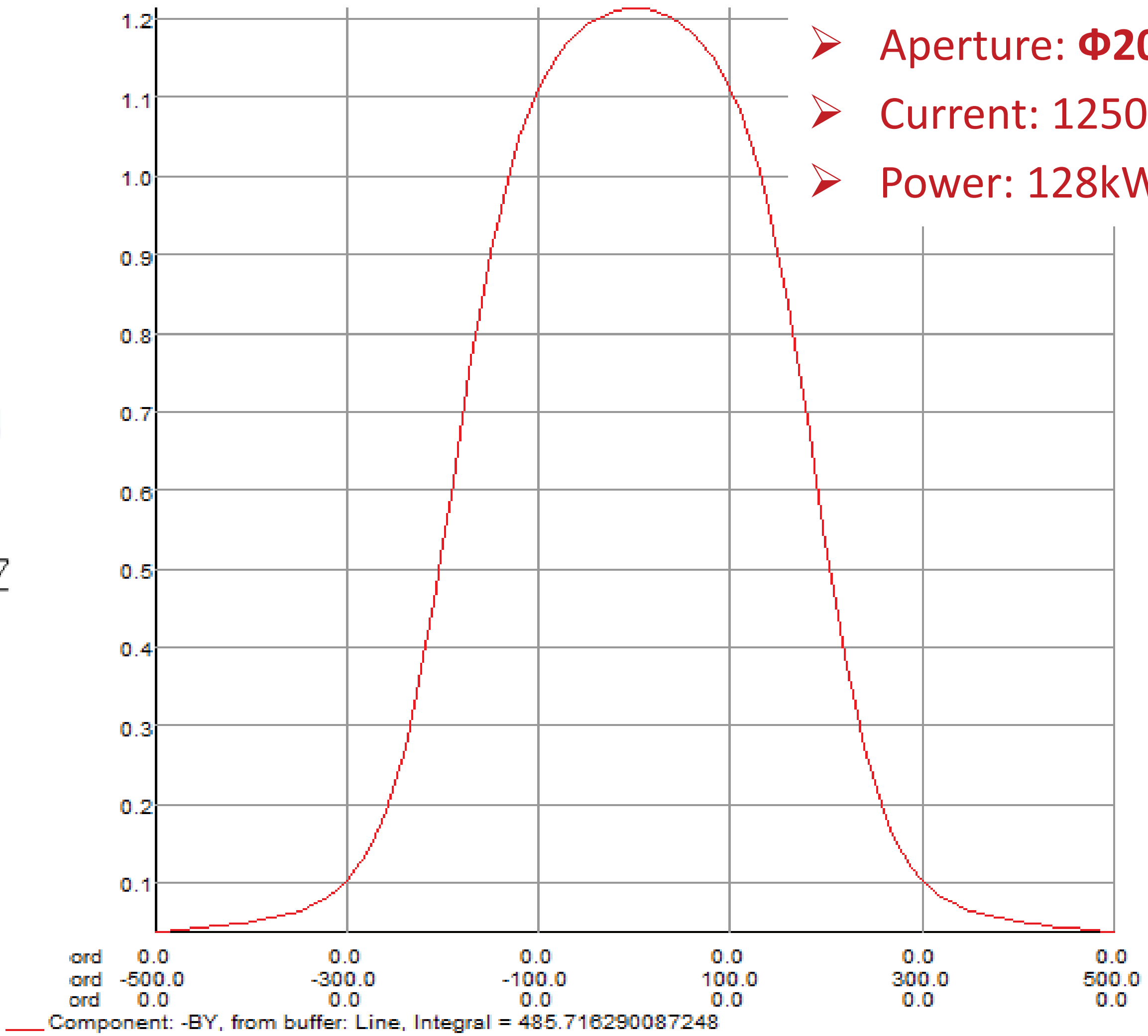
General design of the E-target

■ E-gun Solenoid



OPERA-3D mode

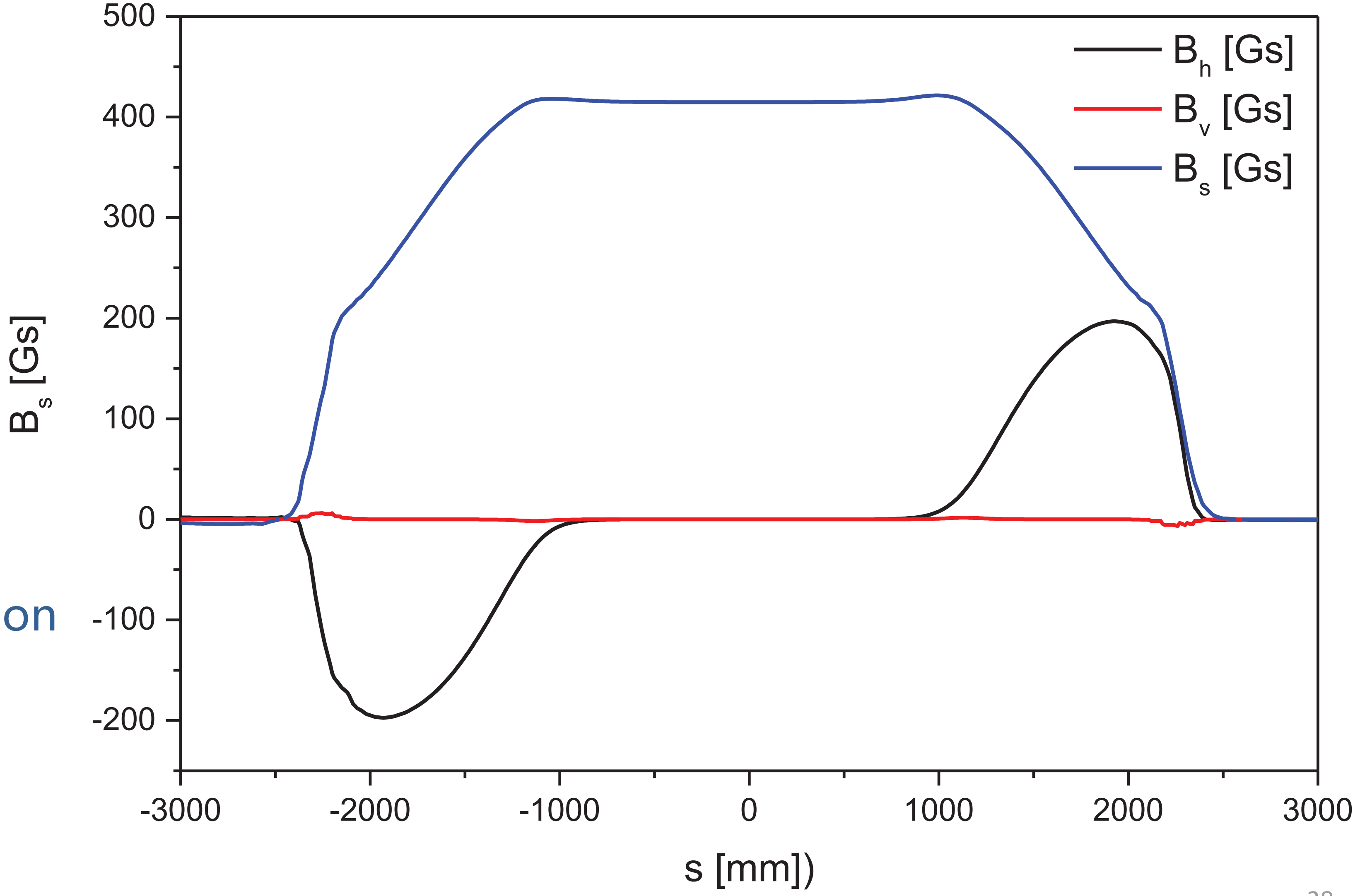
1.2T Solenoid axis magnetic field



- Aperture: **Φ200mm**
- Current: 1250A
- Power: 128kW

General design of the E-target

■ Magnetic field distribution along orbit of ion beam



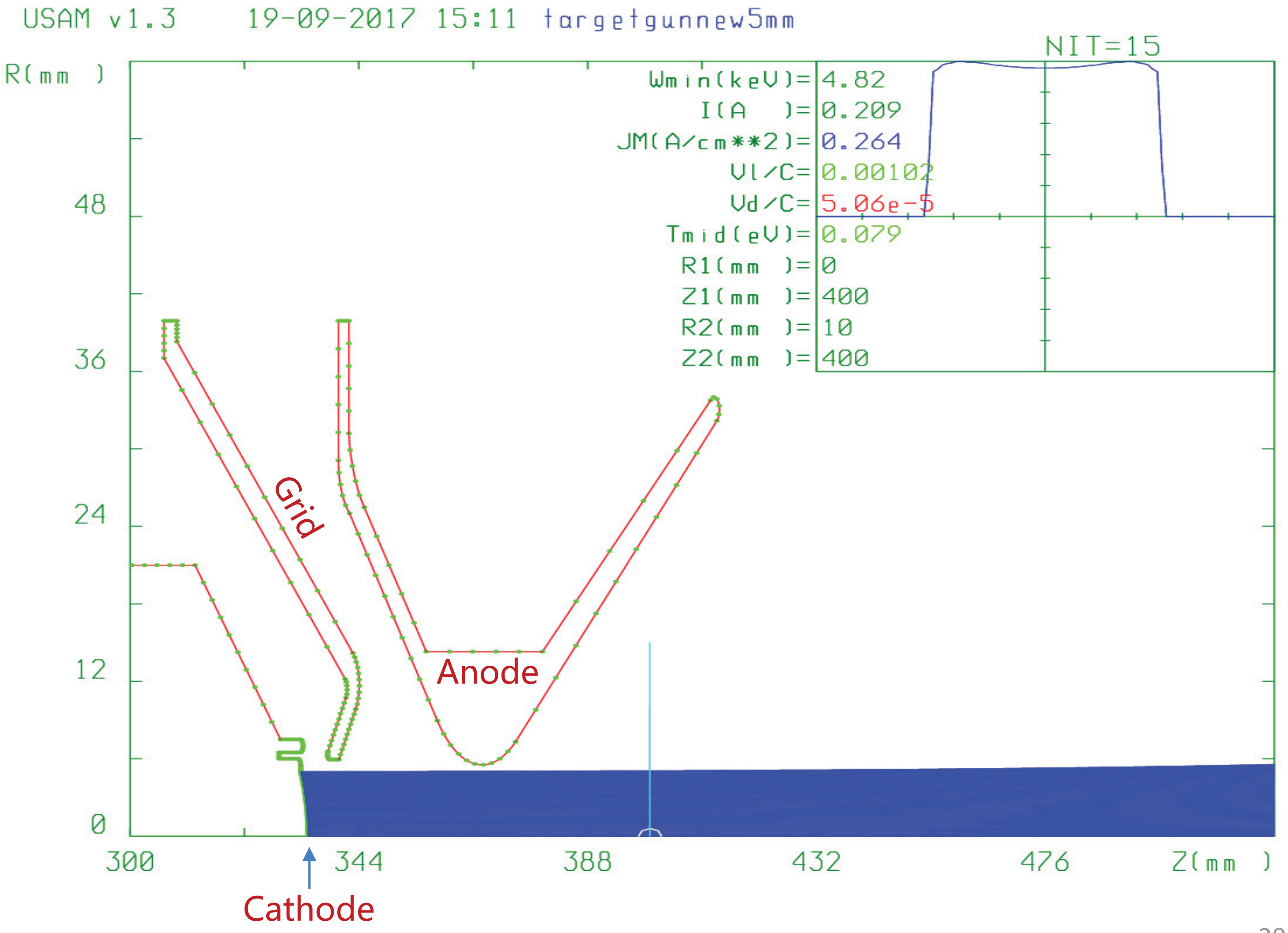
- ➢ **Field strength at half**
- • B_h - horizontal field
- • B_v - vertical field

- ➢ **Local orbit correction**
- • 4 H/**V** orbit correctors
- • No need of compensation of longitudinal field

General design of the E-target

Electron gun schematic diagram

- **Uniform electron beam**
- Convex oxide cathode
- Cathode size: Φ10mm
- Electron current: 209mA
- Anode voltage: 4.8kV
- Grid voltage: 800V
- Gun perveance: ~$0.6\mu P$



General design of the E-target

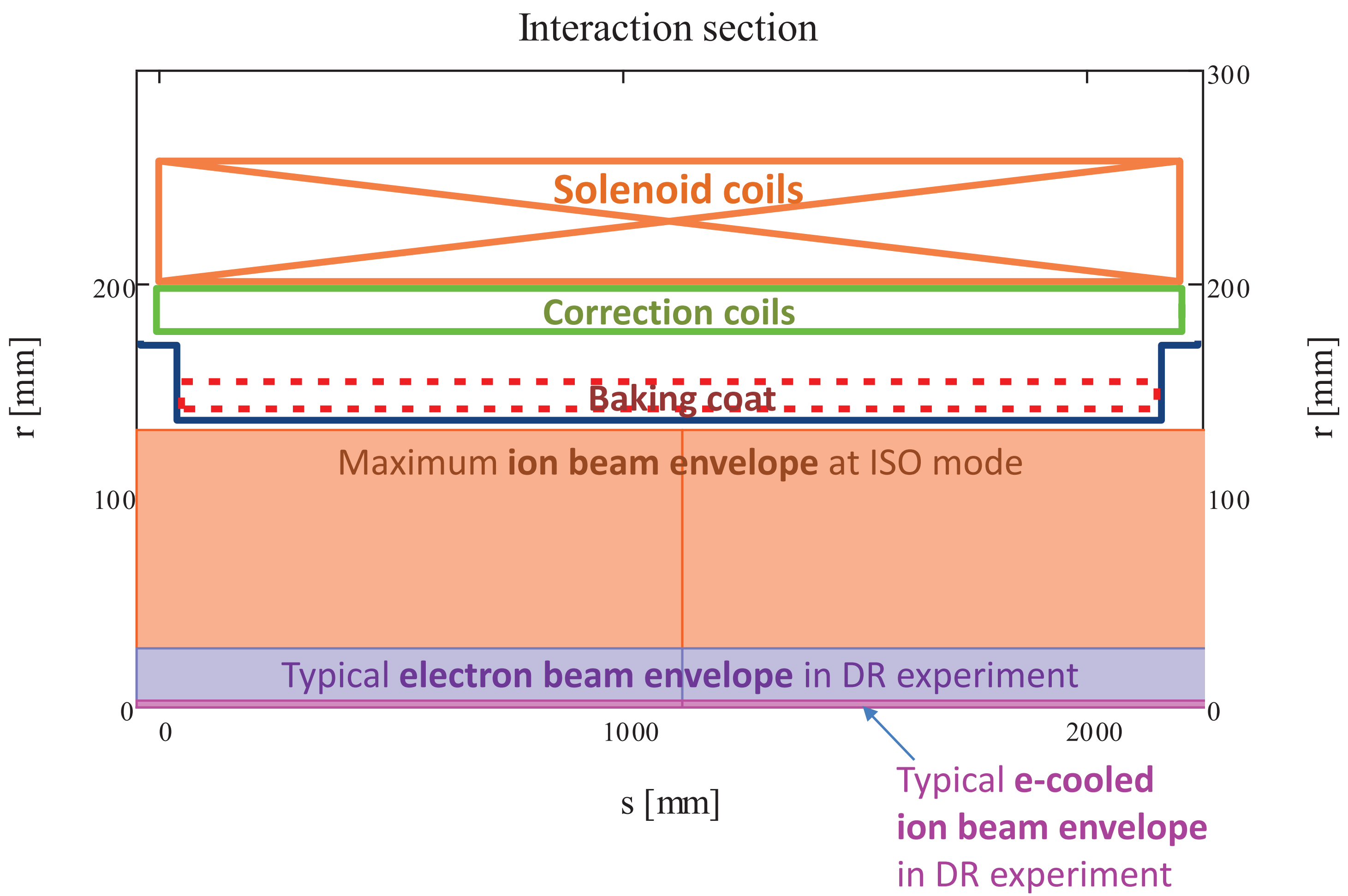
■ Acceleration tube

- ➢ Acceleration length 1250mm
- ➢ SF6 gas pressure 2atm
- ➢ Bakeable temperature 200°C
- ➢ Internal Pressure 1.0×10^{-8} Pa
- ➢ Non-magnetic electrode and welding
- ➢ Ceramic support (lay flat)

General design of the E-target

Interaction section solenoid

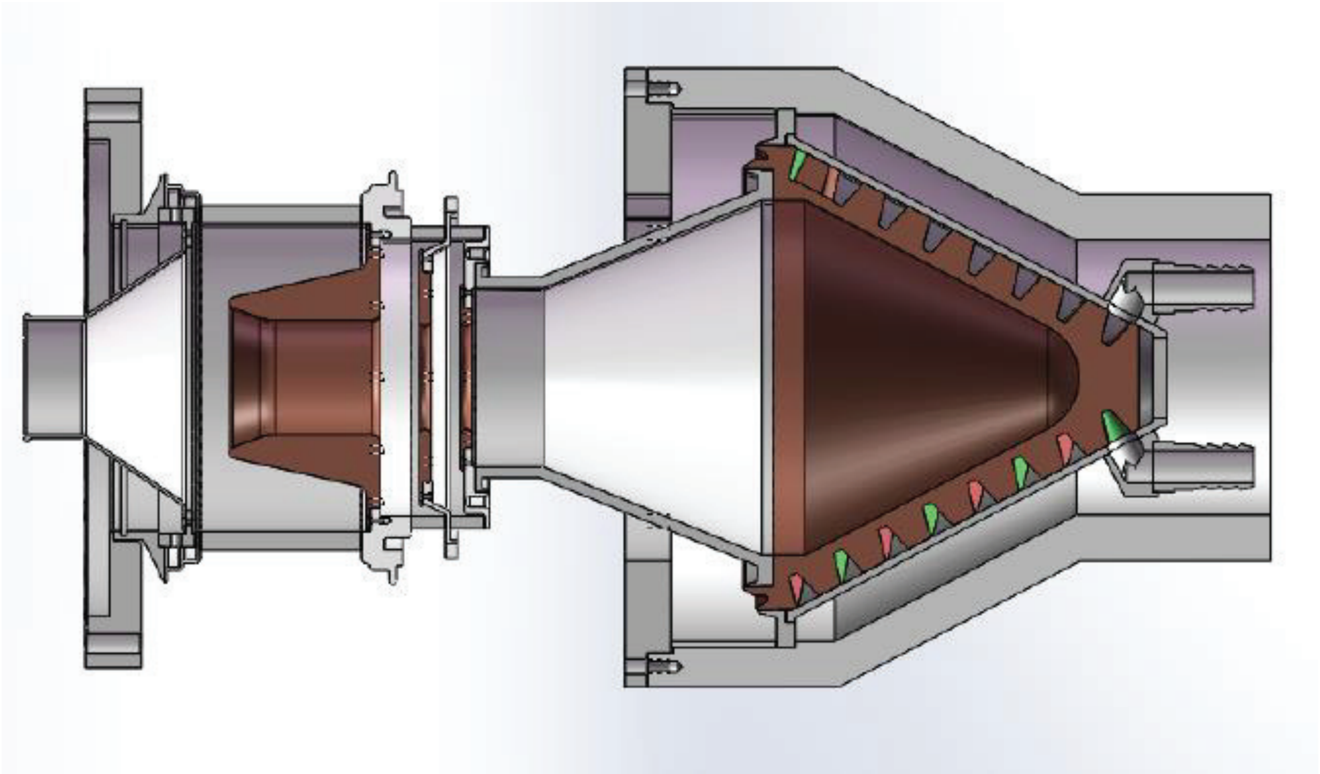
- Length: 2.23m
- Effective length: 1.6m
- Coil internal diameter: Φ400mm
- Aperture: Φ270mm
- Field Parallelism : 1×10^{-4}
- Number of separated coils: 36



General design of the E-target

■ Collector

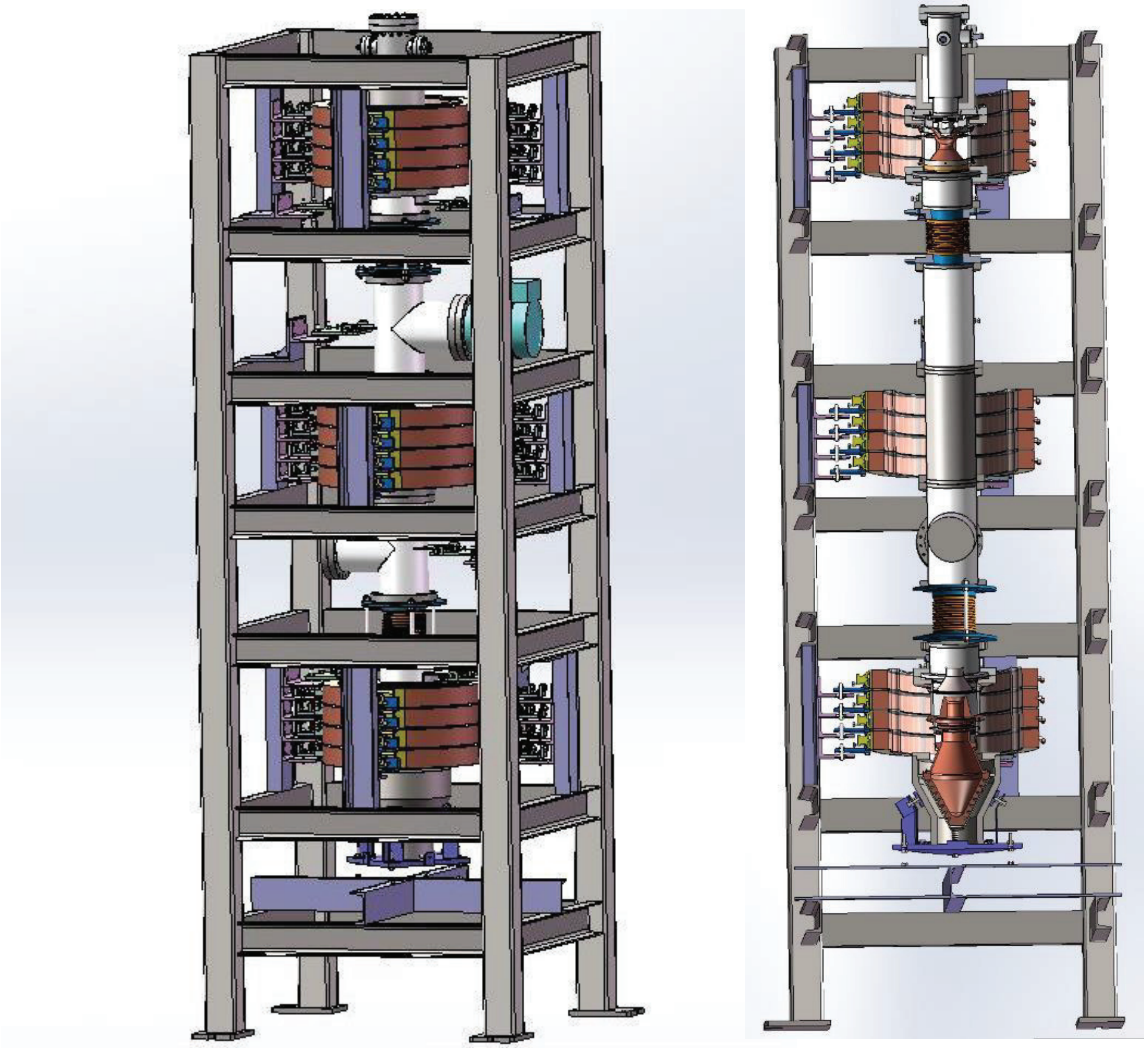
- ➢ Collection efficiency: 99.95%
- ➢ Power: 1kW
- ➢ Leakage current by water: 4μA@20$G\Omega$
- ➢ Bakeable temperature: 200°C
- ➢ Internal pressure: 1.0×10^{-8} Pa
- ➢ Ceramic support (lay flat)



General design of the E-target

■ Test bench

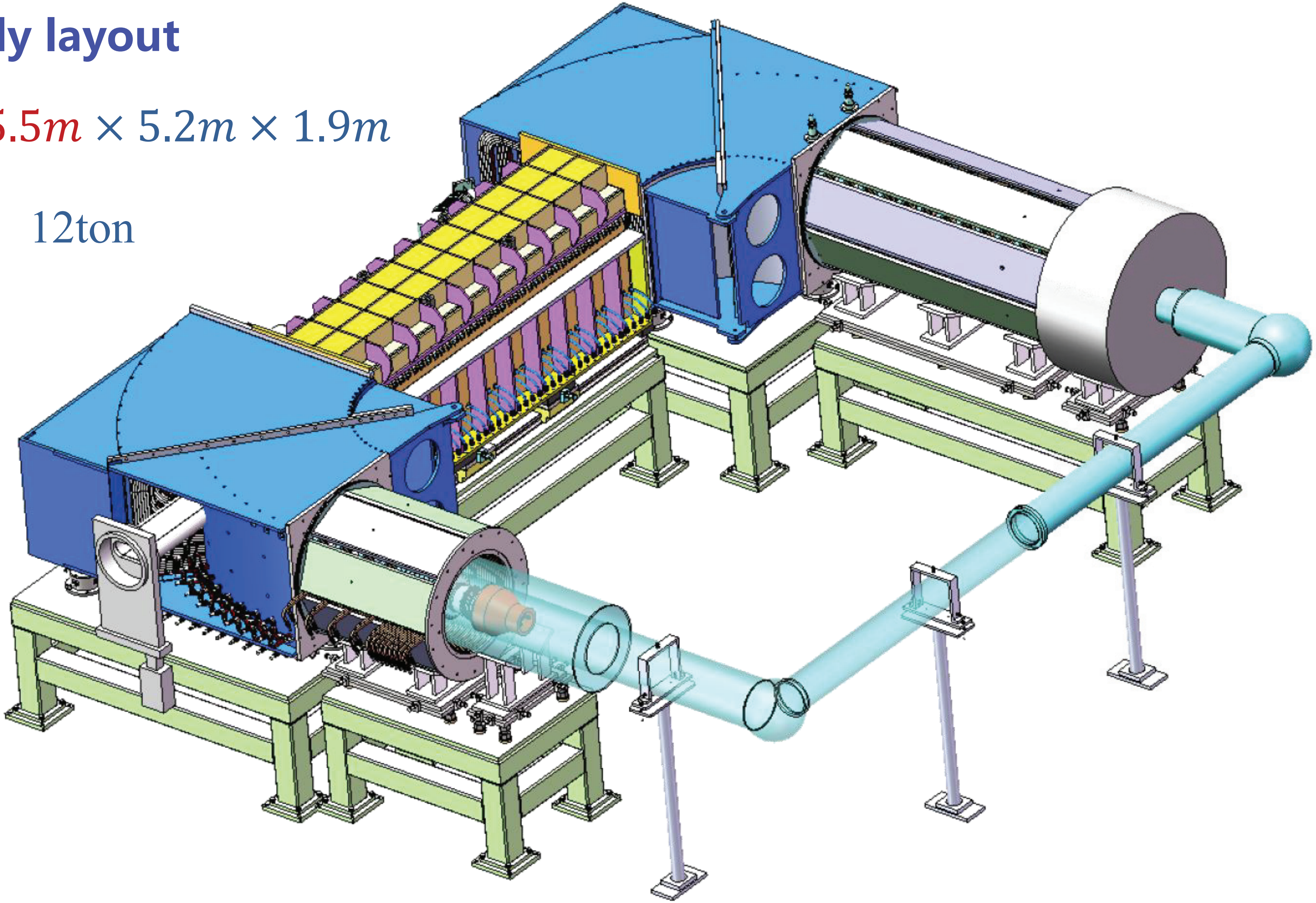
- Pressure: 10^{-5} ~10^{-6} Pa
- Electron gun test
- Collector test



General design of the E-target

■ Assembly layout

- Size： $5.5m \times 5.2m \times 1.9m$
- weight： 12ton



General design of the E-target

HV power supply system

Power supply	Voltage	Current	Remarks
HV platform	80 kV	5 mA	$Ripple \sim \pm 1.0 \times 10^{-5}$
Detuning PS	±200 V	>5 mA	$Rising\ time < 50\mu s$
Anode	8 kV	5mA	
Grid	-2~3 kV	5 mA	
Cathode Heating	20 V	5A	
Suppressor	3 kV	5 mA	
Collector	3 kV	1 A	

General design of the E-target

■ Vacuum system

➢ Pressure required at interaction section: $1 \cdot 10^{-9} Pa$

- Total surface of vacuum chamber: $\sim 5.6\ m^2$
- Total gas flux in case of unbaked vacuum chamber: $\sim 3.7 \cdot 10^{-2} Pa \cdot l/s$
- Total gas flux in case of baked vacuum chamber: $\sim 5.7 \cdot 10^{-6} Pa \cdot l/s$

➢ **Vacuum pumps**

- 2 ion pumps with speed of $400\ l/s$, and 16 titanium getter pumps

General design of the E-target

Power supply for magnetic field system

Power supply	Current	Power	Remark
Gun solenoid	1250A	128kW	
Transition solenoids	850A	60kW	Gun and collector
Toroid	480A	142kW	
Interaction solenoid	100A	15kW	
Collector solenoid	870A	32kW	
Dipole correctors	300A	36kW	Ion beam orbit correction
Internal correctors	10A	150W	Electron beam orbit correction

General design of the E-target

Water cooling system

- Number of Hydraulic supplies: 12
- Total water flow: 25ton/hr

	Gun solenoid	Gun transition solenoid	40° Toroid	50° Toroid	Interaction solenoid	Collector solenoid	Collector cooling	Dipole correctors
Water flow[L/s]	1.03	1.05	0.72	0.77	7.56	1.05	0.01	0.04
Number	1	1	2	2	1	1	1	2

Summary

1. Design parameters of 80keV e-target meet the requirement on electron temperature, energy, density and thickness on high-precision electron-ion recombination experiments at Spectrometry Ring

2. Main solutions to low temperature electron beam are magnetic expansion adiabatically from 1.2T and adiabatic acceleration within 1.25m length.

3. Basically, detailed design on subsystems are progressing smoothly. But on developing some key technologies such as acceleration tube and electron gun, the progresses goes slowly and details should be studied carefully. Maybe like the process of opening Matryoshka, there is still many further unknown inside for us.

Acknowledgement

- Thanks to accumulated practical experience and techniques from Prof. Parkhomchuk, Prof. Reva， and all members worked on e-coolers from **Budker INP** and my IMP colleagues on design, construction, installation, operation, experimental research, and later upgrade of the two e-coolers for CSR, as well as the strong support from **both the two institutes**
- Thanks extensive cooperation, and shared fruitful experiences from nearly **all the e-coolers and e-targets**
- These make possibility on design of the 80keV e-target for the SRing

Thanks for your attentions