Challenges of Beam Cooling at Low Energy

Andreas Wolf
Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany

COOL13, Mürren, 10-14 June 2013

Low energy ion beam projects

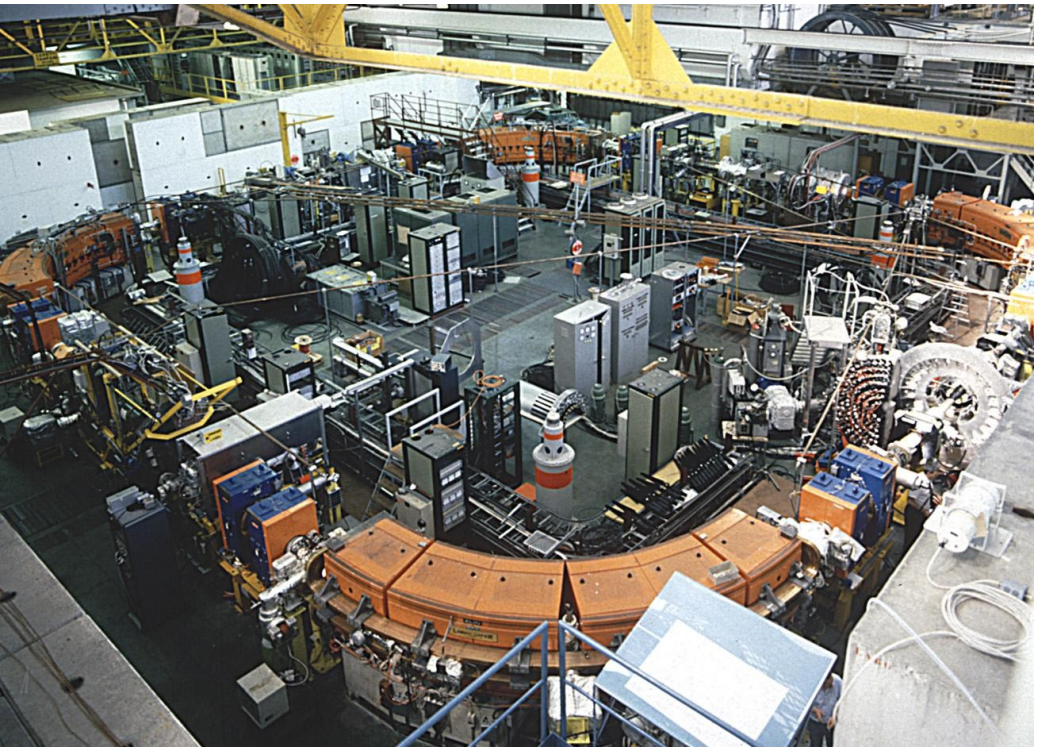
Parameters of low-energy ion beam storage and cooling

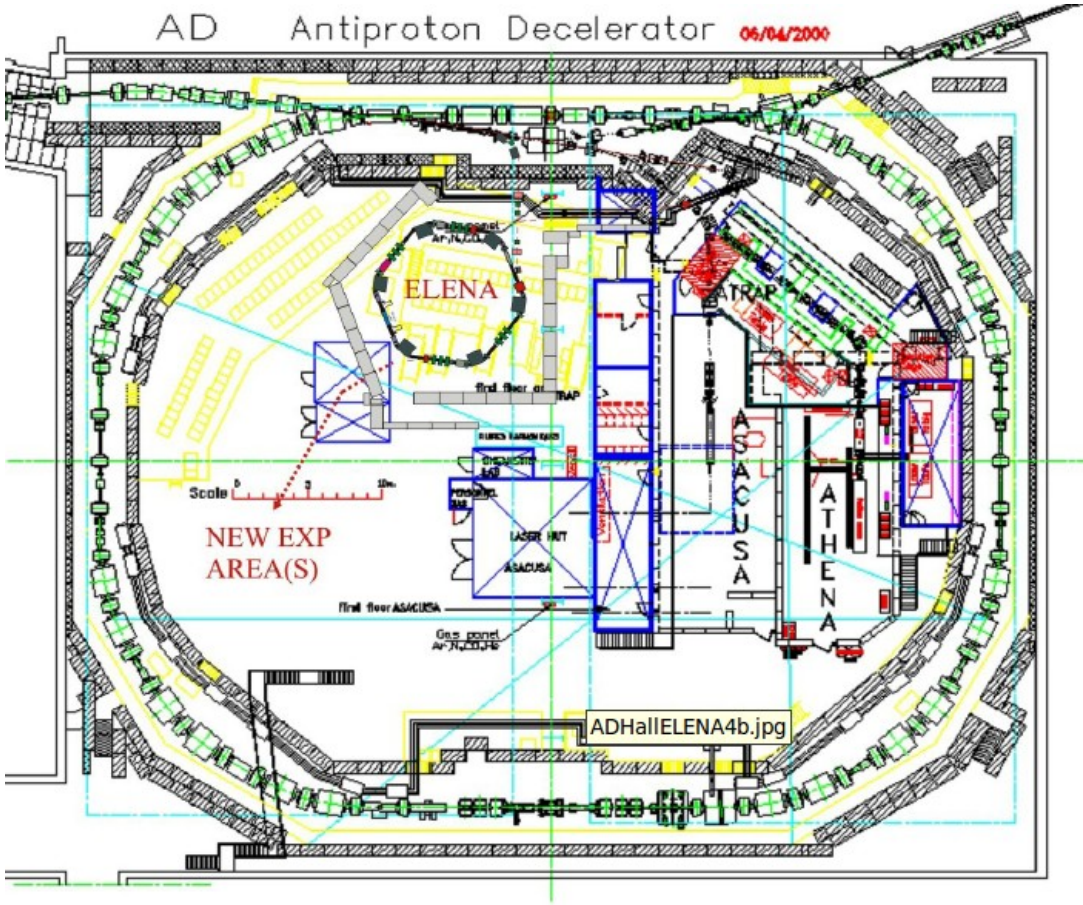
Low-energy electron coolers: S-LSR, TSR

Low-energy cooling in the cryogenic, electrostatic CSR

Low-energy stored ion beams for atomic, molecular and fundamental particle research

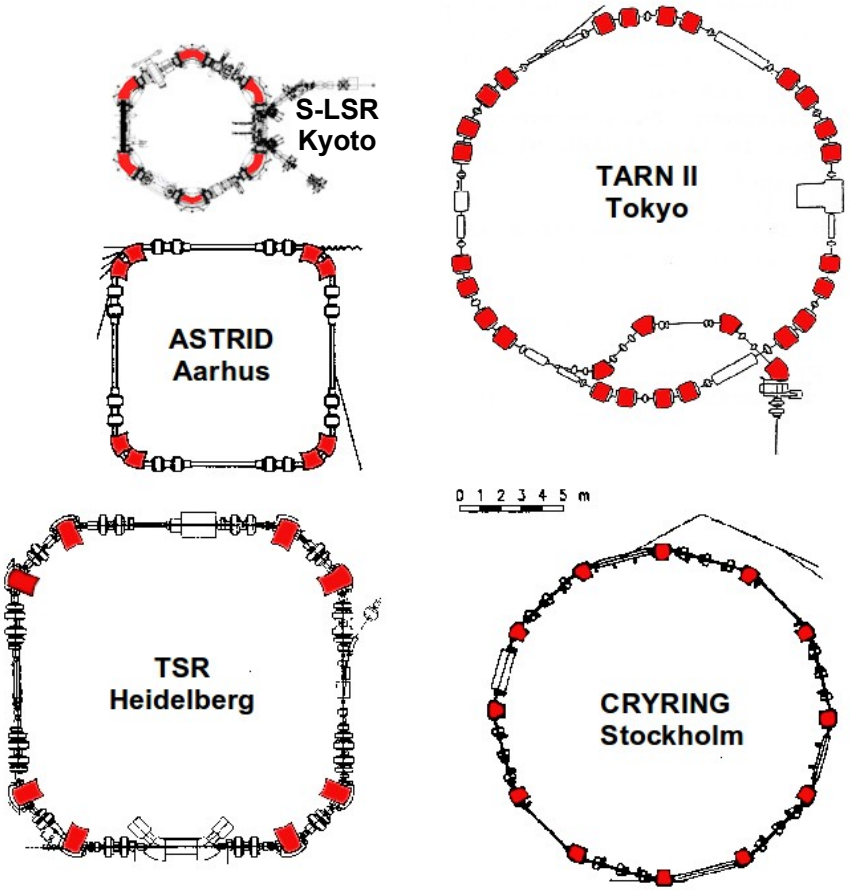
Low-energy *antiprotons* **LEAR, AAC, ELENA (CERN)** **down to 5 MeV (and below)**





Low-energy stored ion beams for atomic, molecular and fundamental particle research

Low-energy *antiprotons*	LEAR, AAC, ELENA (CERN)	down to 5 MeV (and below)
Cooler storage rings	CRYRING (Stockholm→ FAIR) TSR (Heidelberg→ISOLDE/ CERN) S-LSR (ICR Kyoto)	~5 MeV/u → ~100 keV/u (E_{kin} ~ few MeV)
Large ion rings (ESR, COSY, CSR Lanzhou, ...)		



Low-energy stored ion beams for atomic, molecular and fundamental particle research

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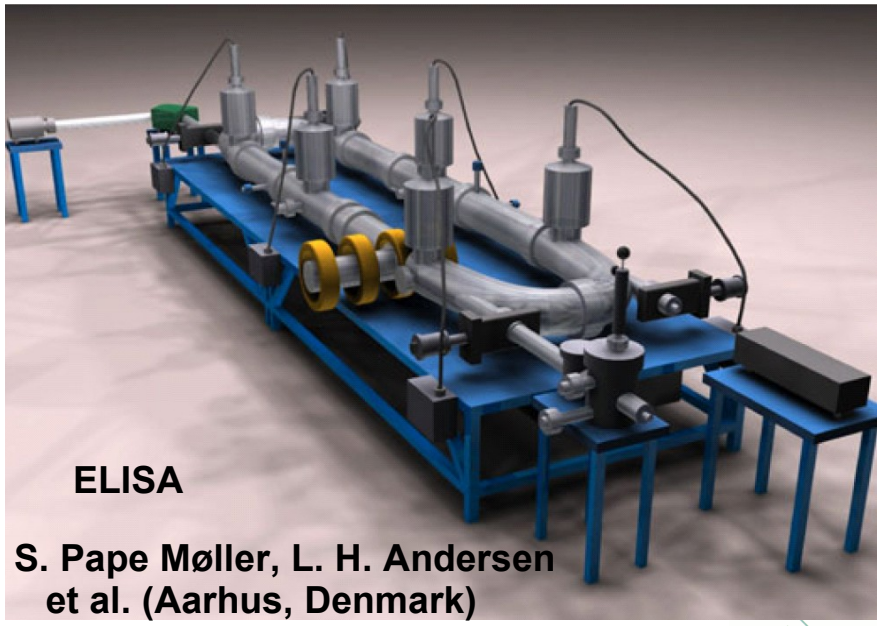
Electrostatic storage rings	ELISA (Aarhus) KEK & TMU (Tokyo) DESIREE (Stockholm) CSR Heidelberg	E_{kin} ~ 20-100 keV (300 keV, CSR)



ELISA

S. Pape Møller, L. H. Andersen et al. (Aarhus, Denmark)

Low-energy stored ion beams for atomic, molecular and fundamental particle research

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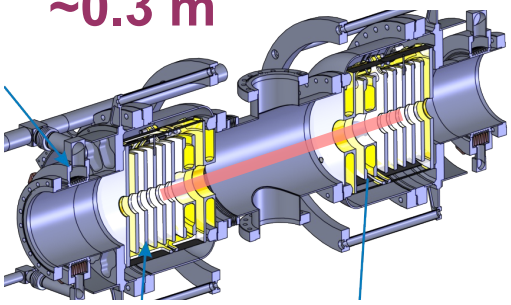
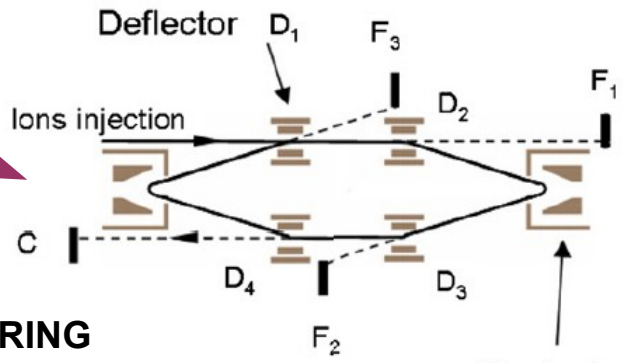
Electrostatic ion beam traps and table-top storage rings	Weizmann Inst., Israel Stockholm (Cone trap) Lyon, France (0.4 × 0.1 m ring) + ...	E_{kin} ~ 4 keV (typ.)

~0.3 m



Ion beam trap
(switched reflectron)

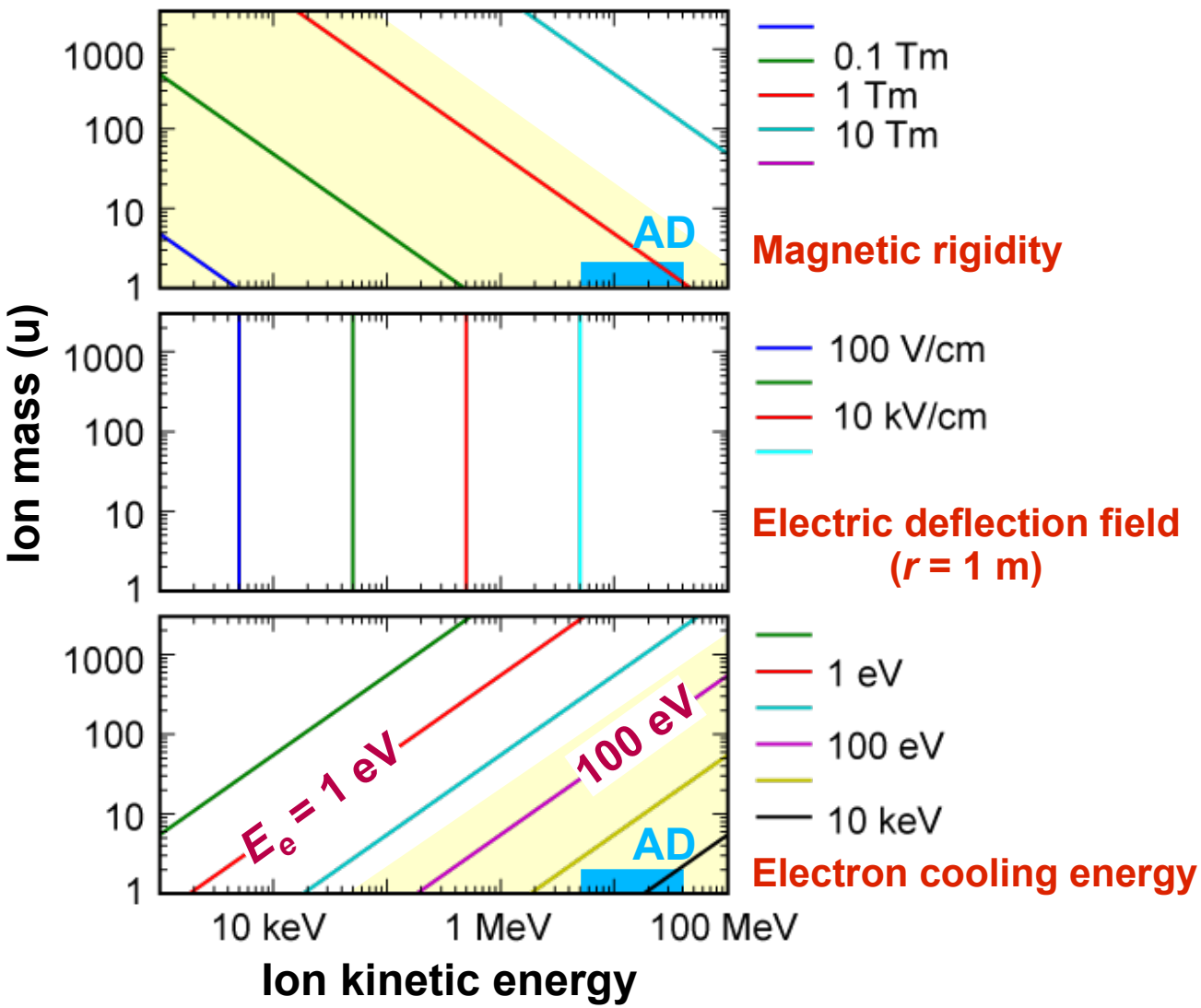
D. Zajfman et al. (WIS)
and meanwhile many other labs



MINRING

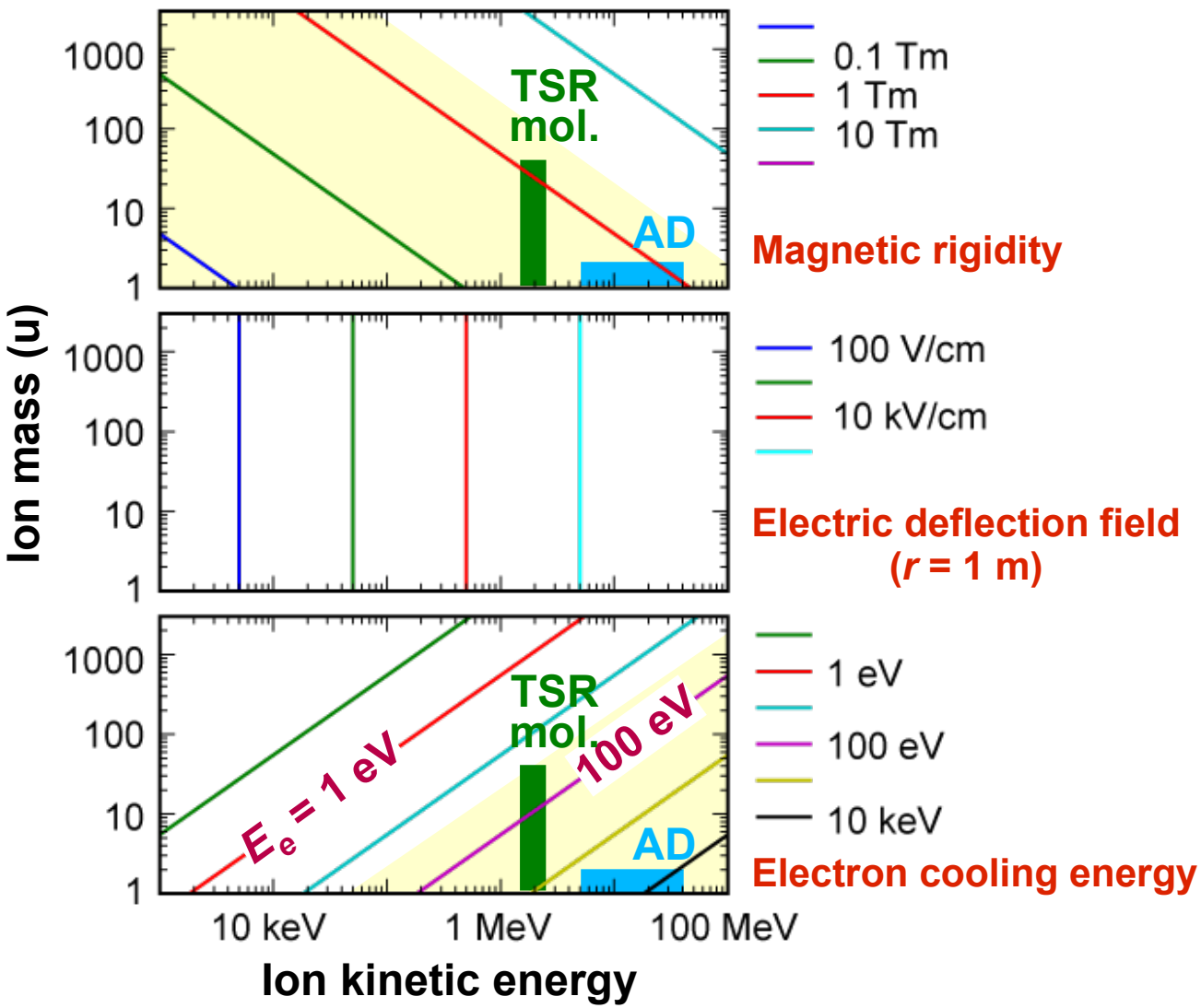
Bernard, Brédy,
Martin et al. (LASIM, Lyon)

Ion storage and electron cooling parameters



AD: CERN $\bar{p}$ decelerator

Ion storage and electron cooling parameters



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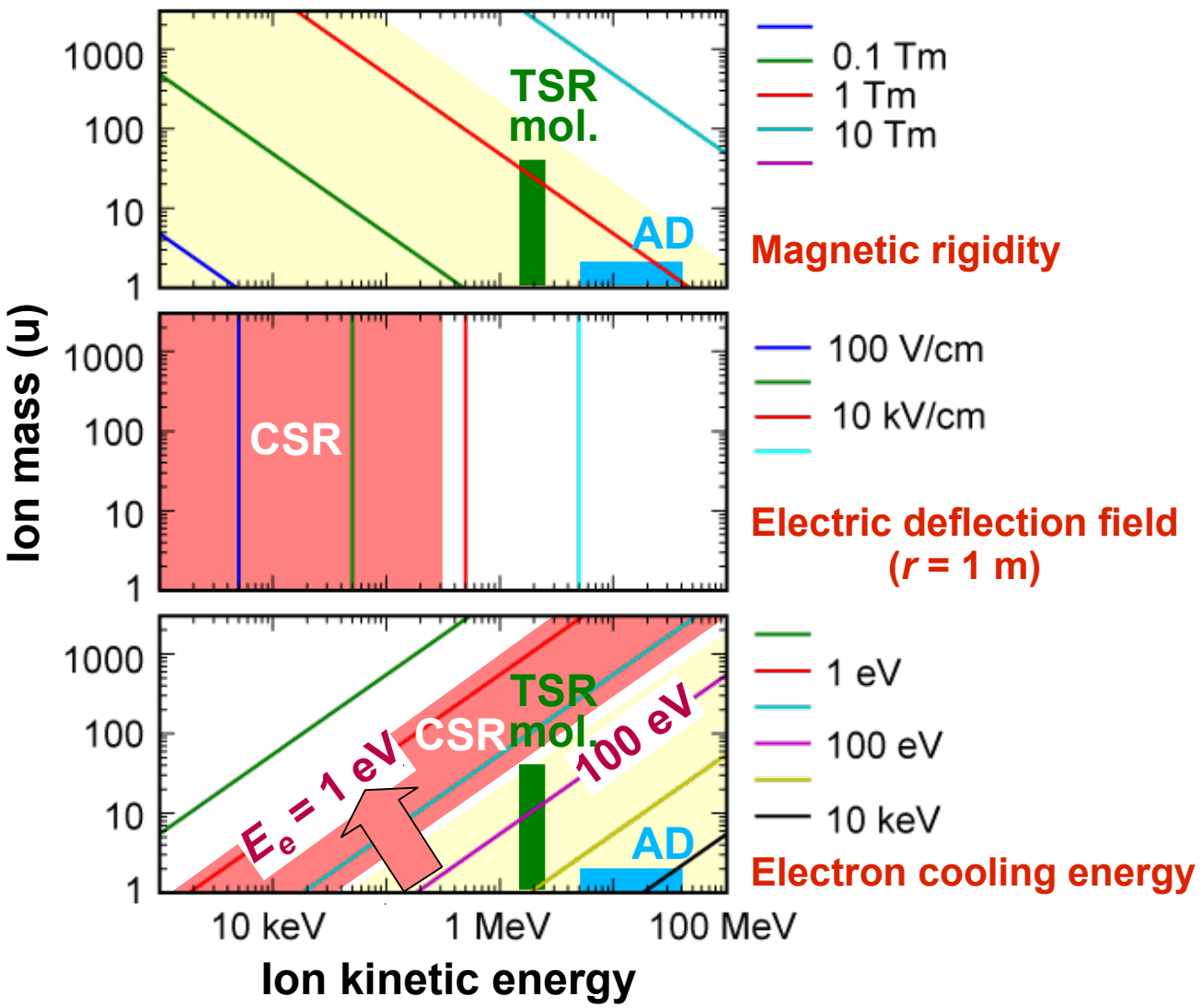
TSR: Molecular physics
Mass <40 u
E-cooling: >40 eV
Photocathode

Ion storage and electron cooling parameters



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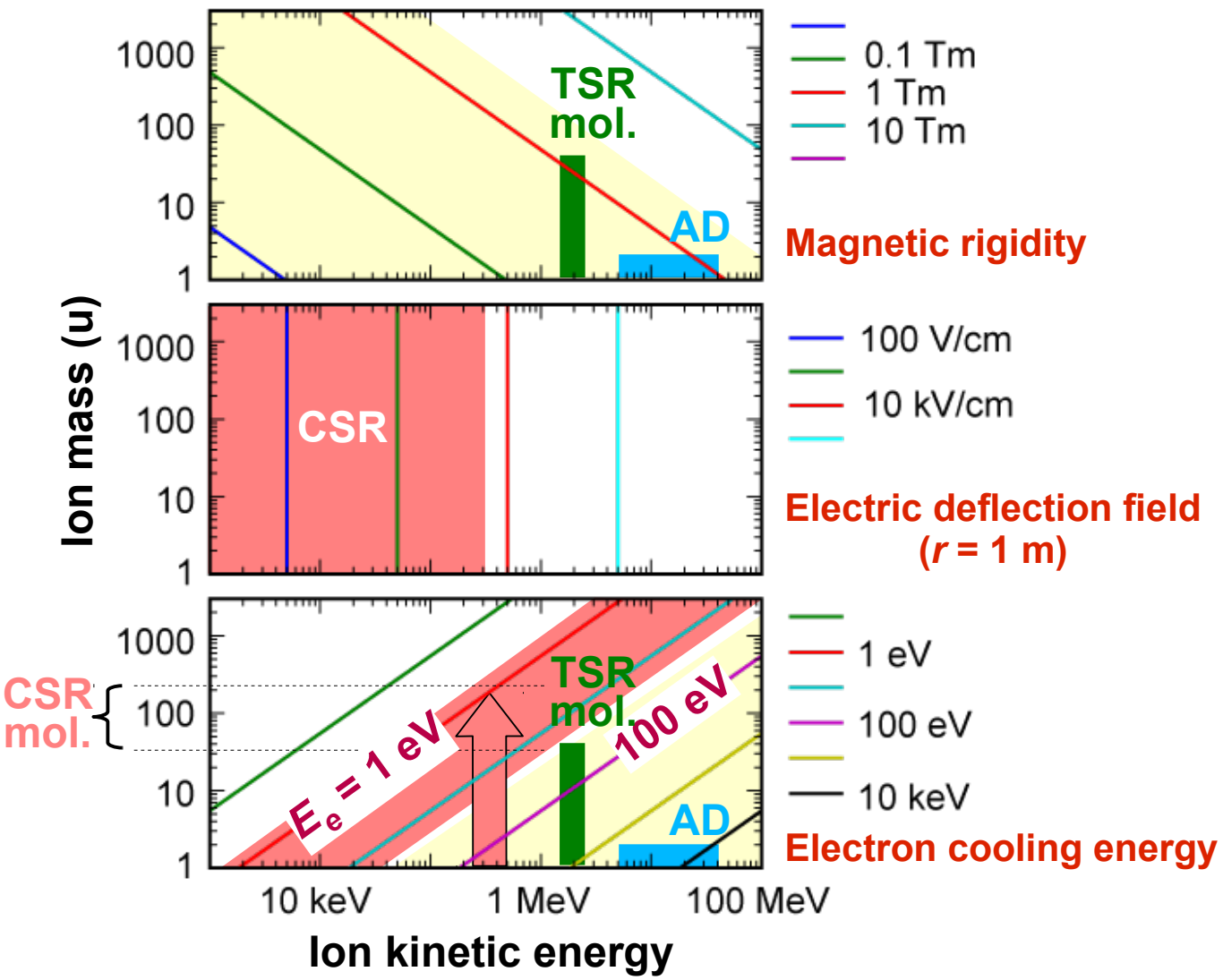
CSR: Molecular physics
Mass <165 u
E-cooling: >1 eV

Ion storage and electron cooling parameters



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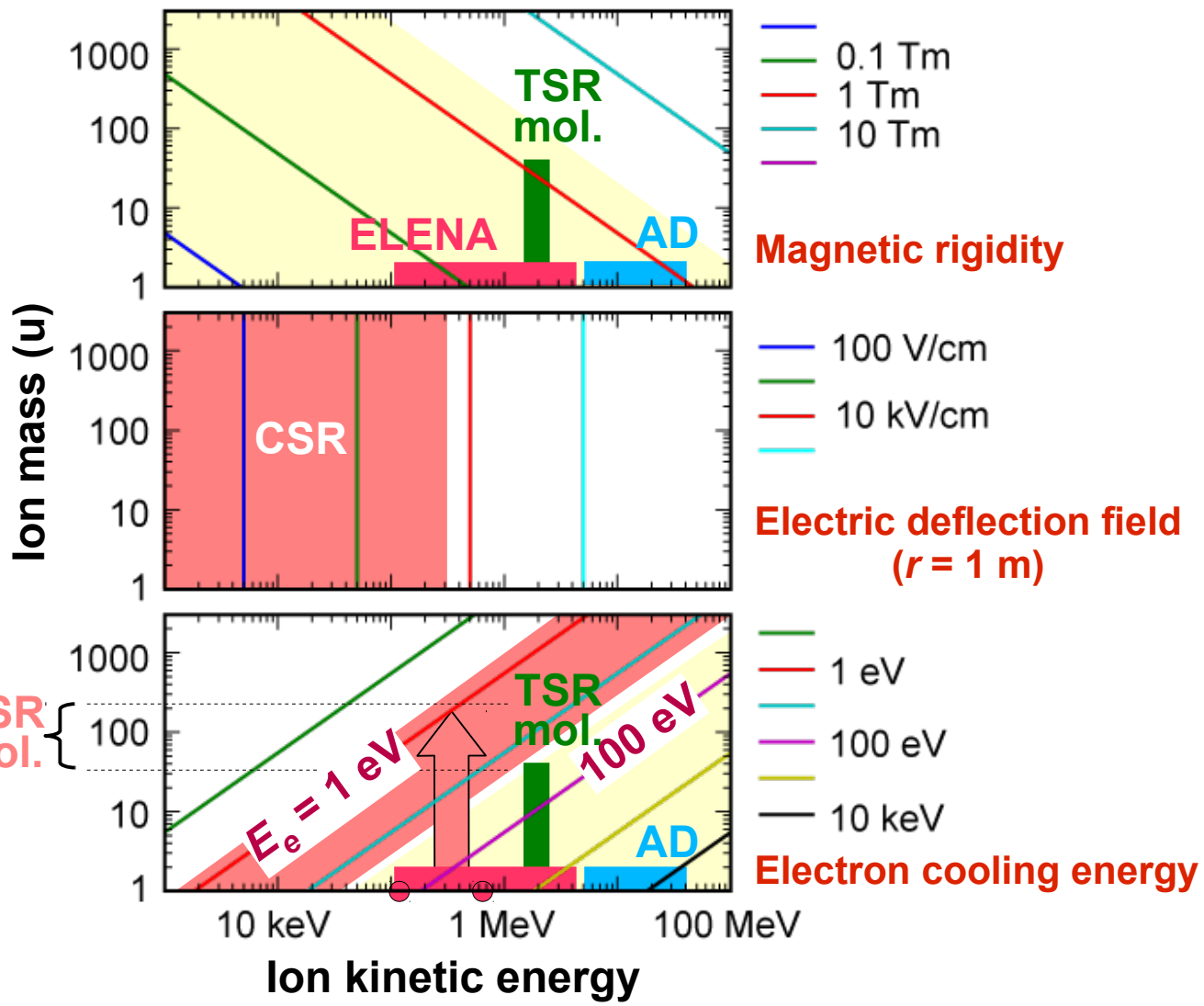

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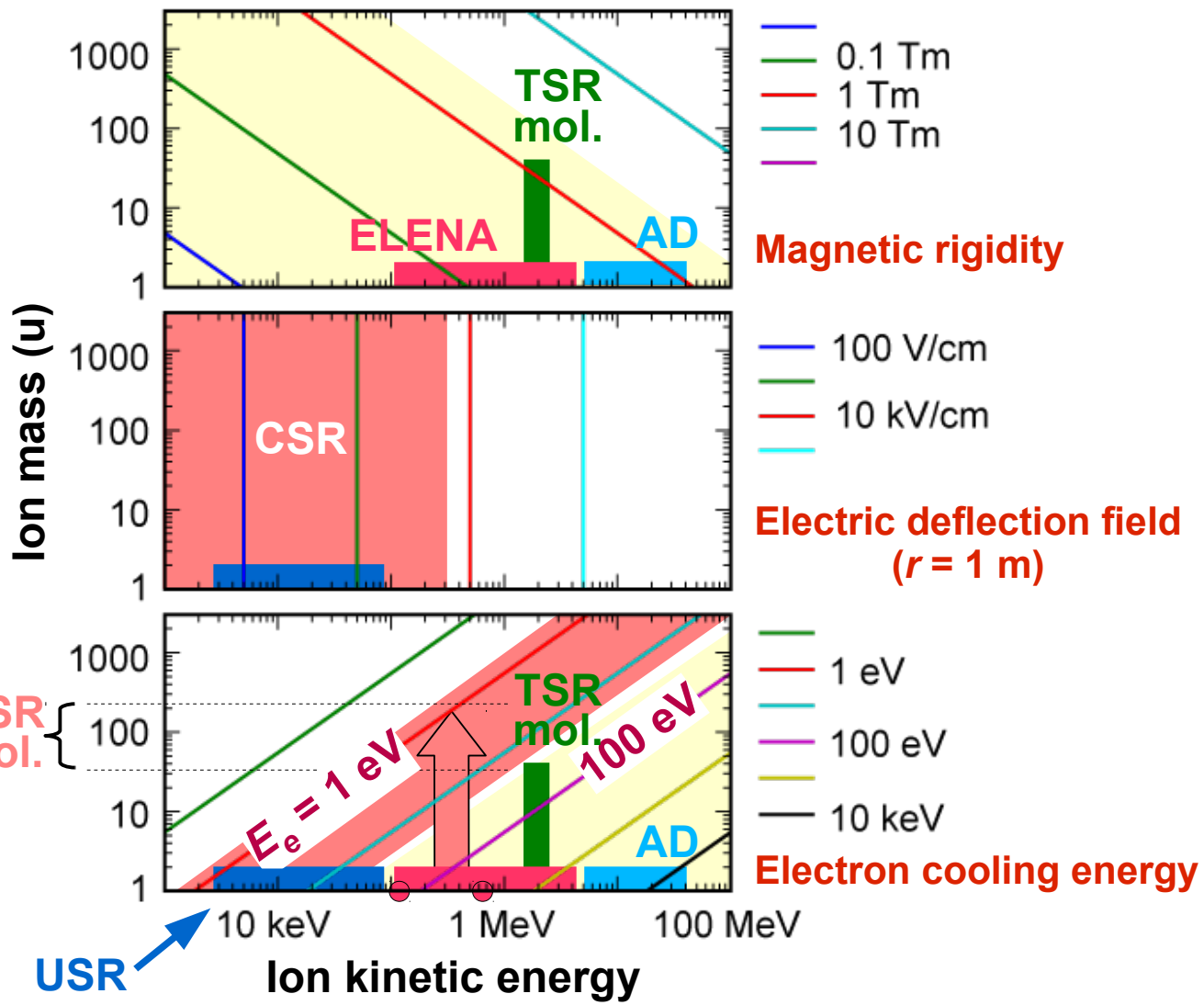
ELENA electron cooling:
650 keV (360 eV)
100 keV (55 eV)

Ion storage and electron cooling parameters



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TSR: Molecular physics
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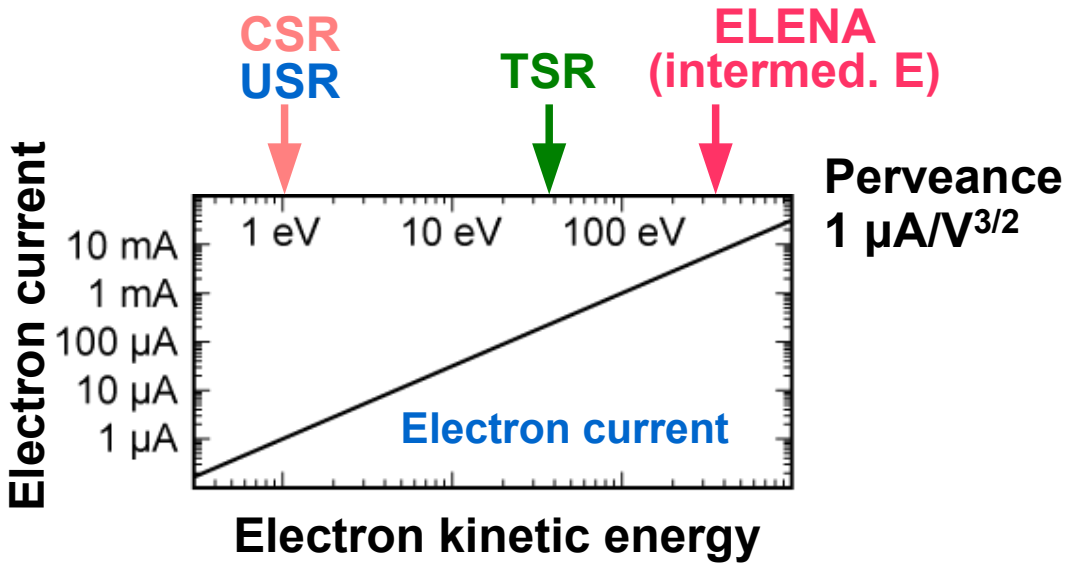
Mass <165 u
E-cooling: >1 eV

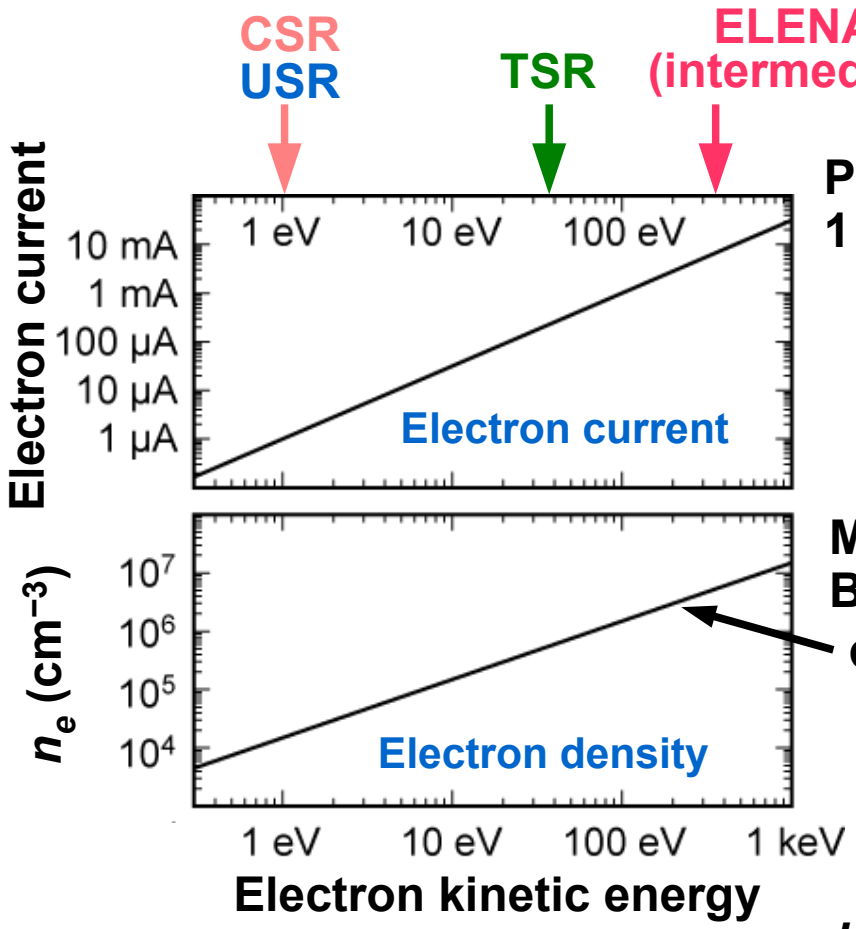
ELENA electron cooling:
650 keV (360 eV)
100 keV (55 eV)

USR: Ultra-low energy ring
for $\bar{p}$

Low energy electron beams for cooling



Low energy electron beams for cooling



Perveance
1 µA/V$^{3/2}$

Thermal emission cathode (near 1000 K):

kT_c = 0.1 eV

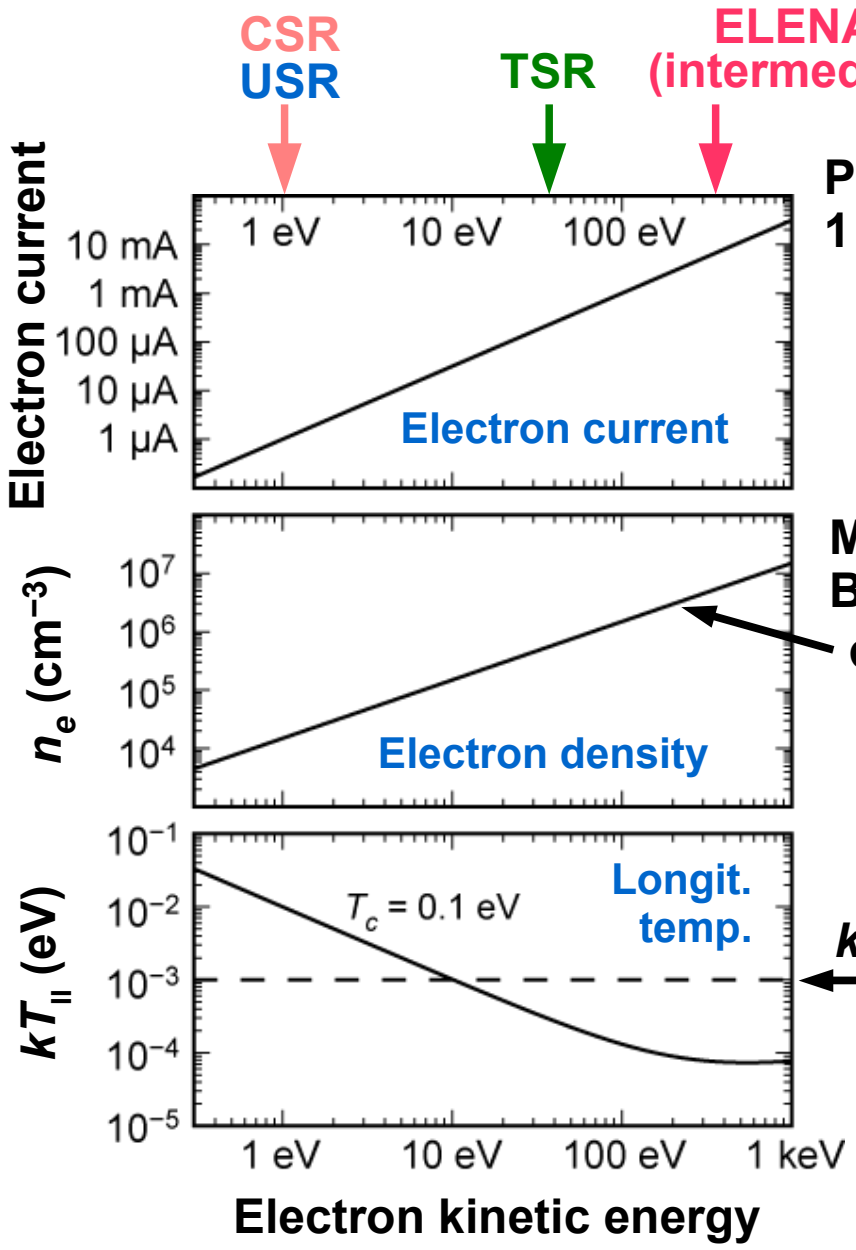
Magnetic expansion
Beam cross section ratio

α = 100 **(Cathode diam.: 3 mm)**

$kT_\perp = T_c/\alpha$

= 1 meV

Low energy electron beams for cooling



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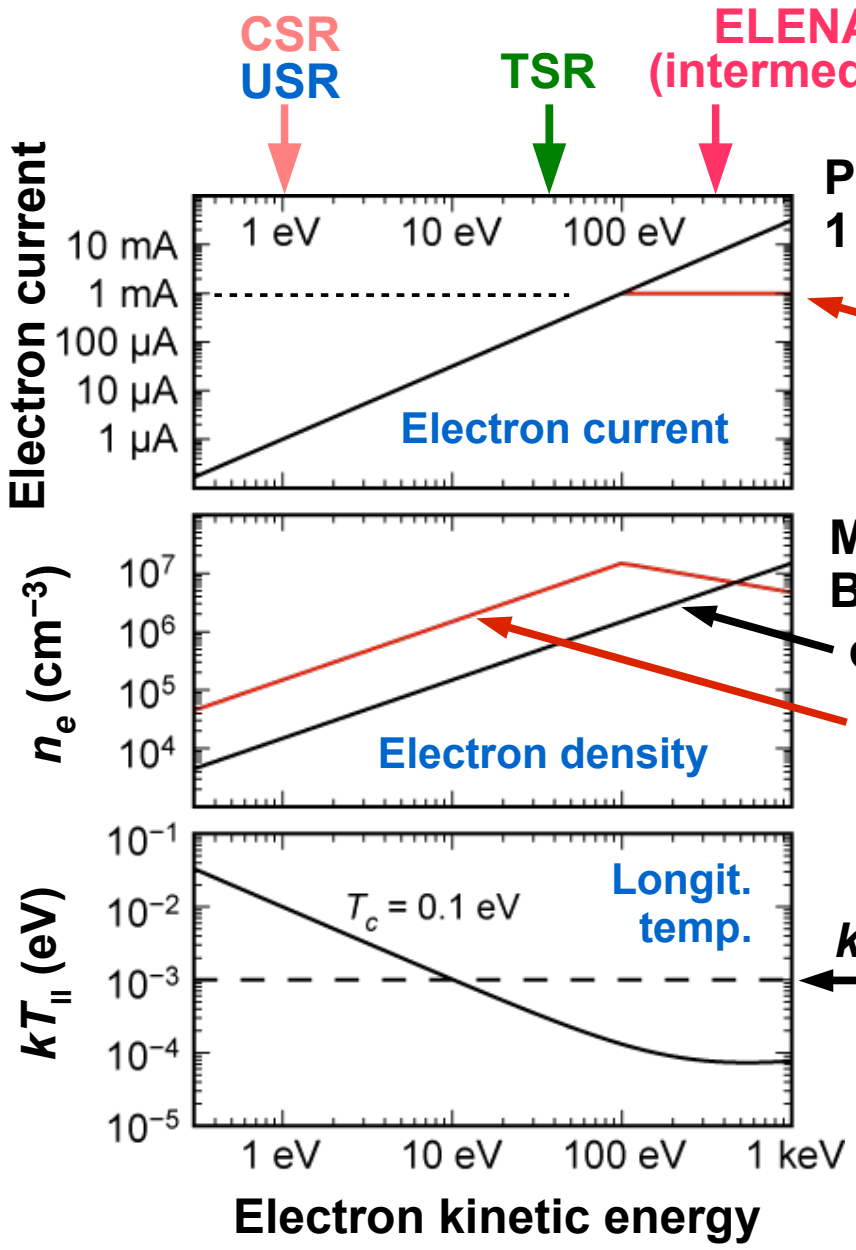
= 1 meV

Kinematic velocity compression

$$kT_{II} = \left[1 + \left(1 - \frac{1}{\alpha}\right)^2\right] \frac{(kT_c)^2}{2E_{kin}} + C \frac{e^2}{4\pi\varepsilon_0} n_e^{1/3}$$

[D. Orlov et al., AIP Conf. Proc. 862, 274 (2006); $C \sim 2$]

Low energy electron beams for cooling



Perveance
1 µA/V$^{3/2}$

1 mA
max. current

Thermal emission cathode (near 1000 K):

kT_c = 0.1 eV

LN$_2$ cooled (near 100 K) GaAs photocathode:

kT_c = 0.01 eV

Magnetic expansion
Beam cross section ratio

α = 100 (Cathode diam.: 3 mm)

α = 10

$kT_\perp = T_c/\alpha$
= 1 meV

Kinematic velocity compression

$$kT_{II} = \left[1 + \left(1 - \frac{1}{\alpha}\right)^2\right] \frac{(kT_c)^2}{2E_{kin}} + C\frac{e^2}{4\pi\varepsilon_0} n_e^{1/3}$$

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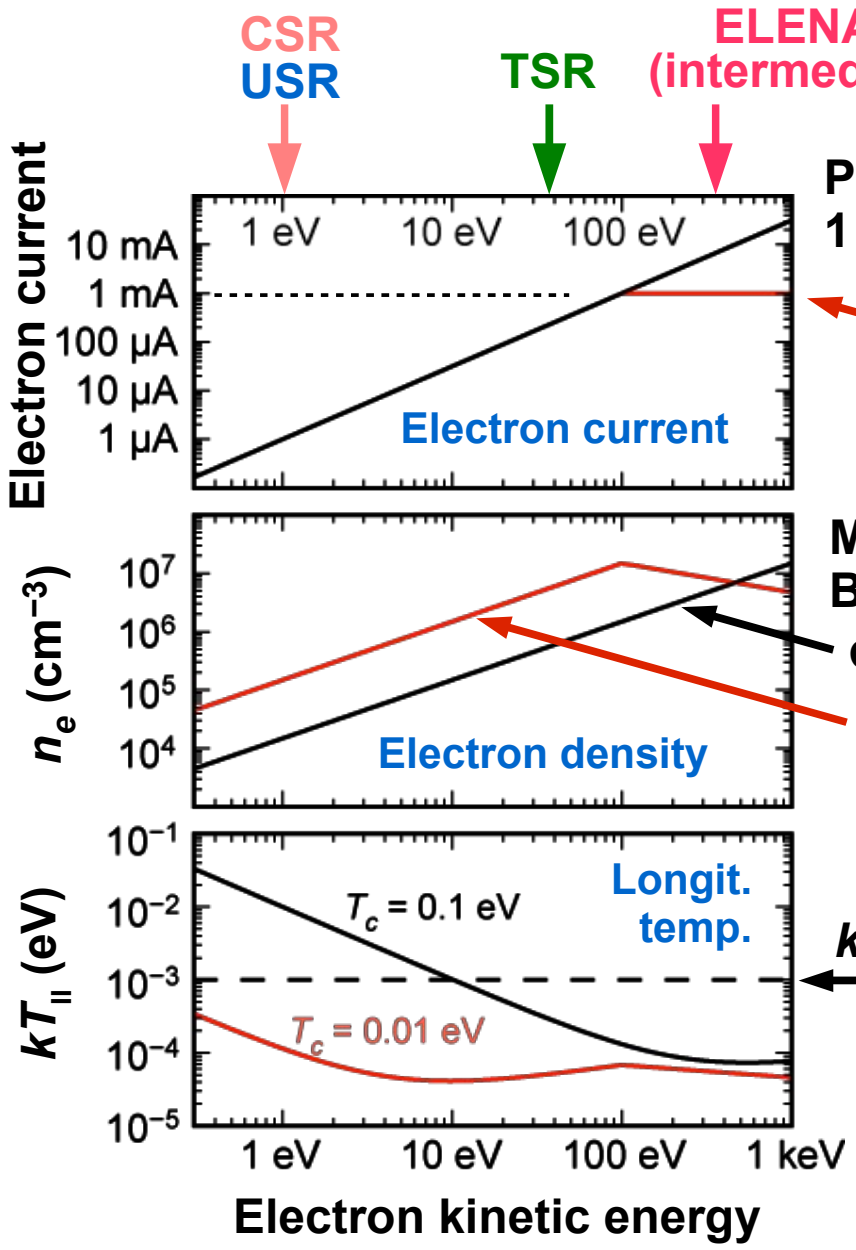
Low energy electron beams for cooling



Perveance
1 µA/V$^{3/2}$

1 mA
max. current

Thermal emission
cathode (near 1000 K):
kT_c = 0.1 eV

LN$_2$ cooled (near 100 K)
GaAs photocathode:
kT_c = 0.01 eV

Magnetic expansion
Beam cross section ratio
α = 100 (Cathode diam.: 3 mm)
α = 10

$kT_\perp = T_c/\alpha$
= 1 meV

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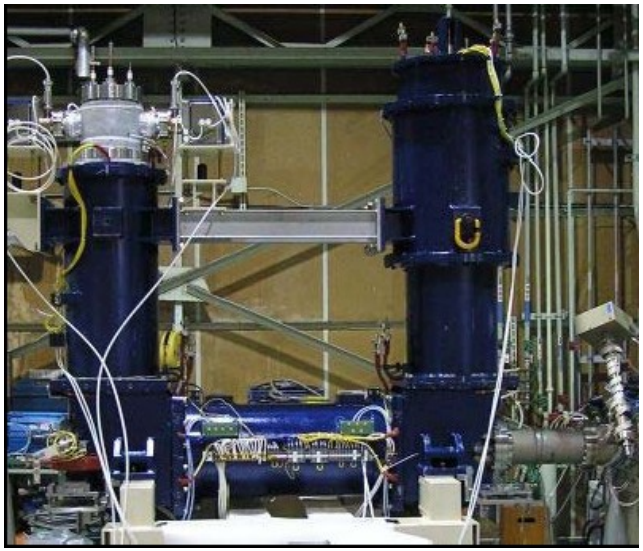
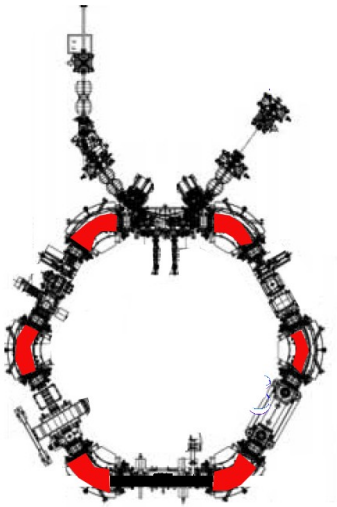
[D. Orlov et al., AIP Conf. Proc. 862, 274 (2006); $C \sim 2$]

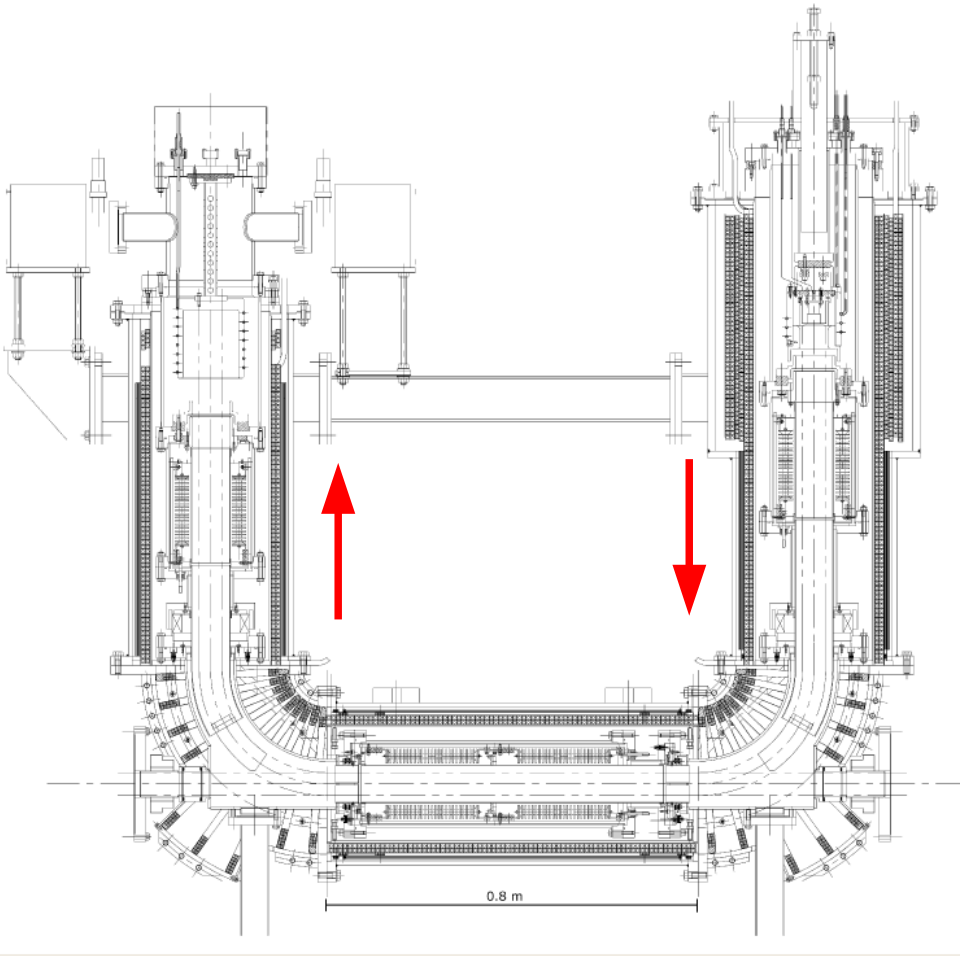
Low energy electron cooler at S-LSR



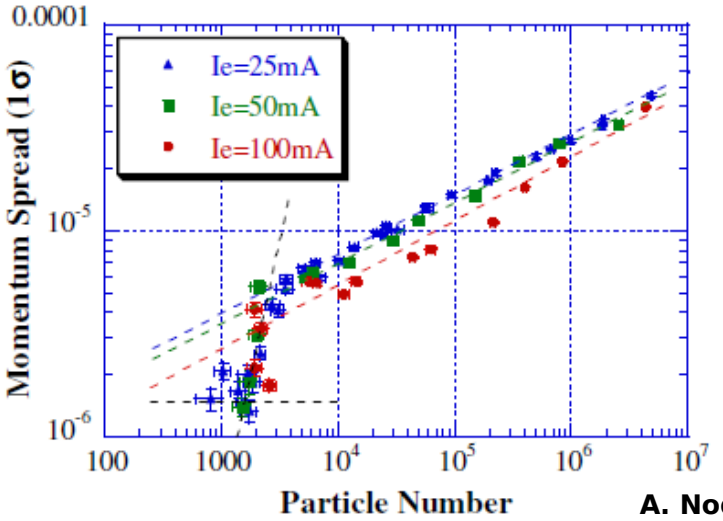
Proc. EPAC 2006, TUPLS064
H. Fadil et al.



S-LSR Kyoto



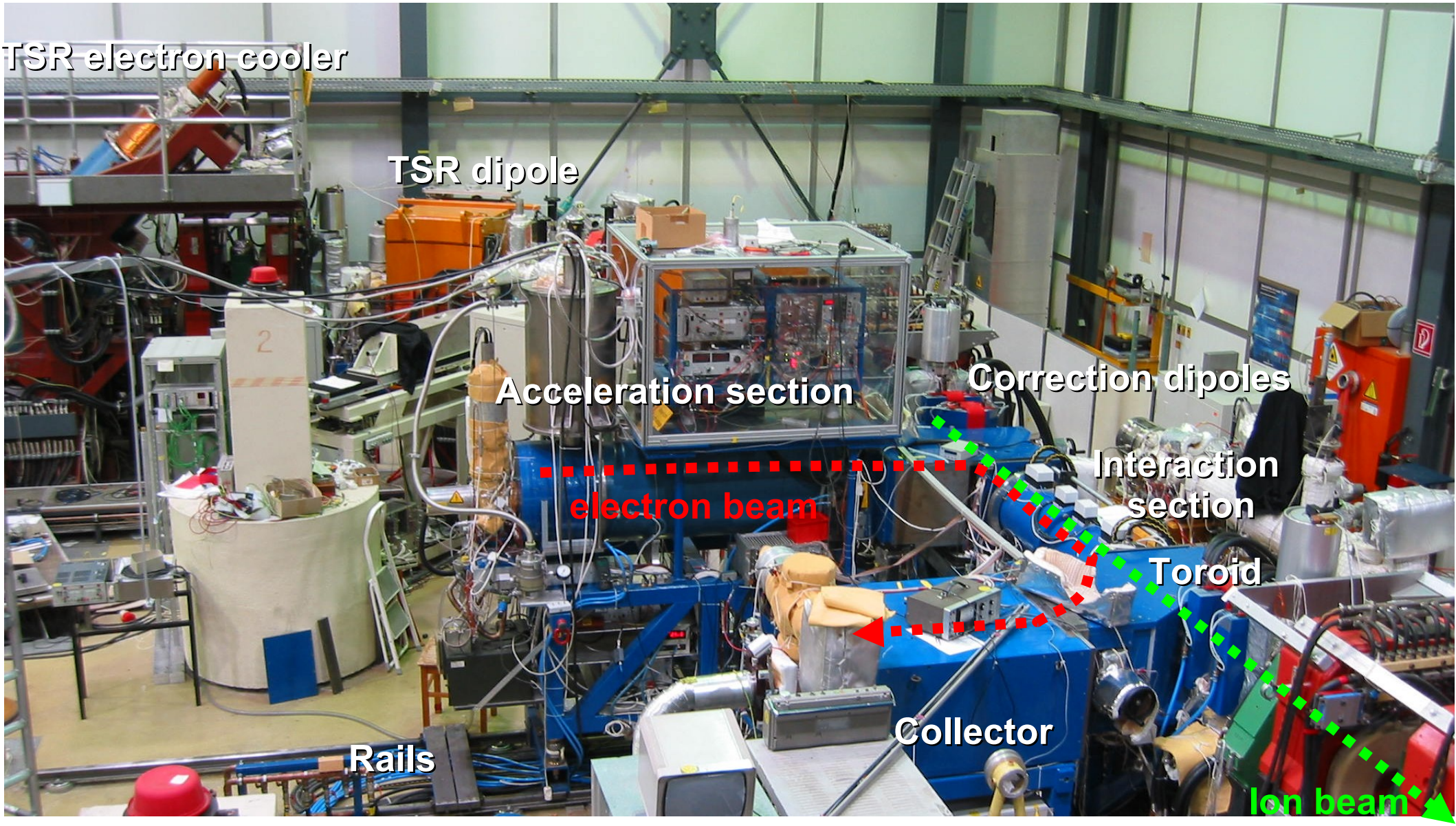
Fadil et al., COOL '03, NIM A 532 (2004) 446-450



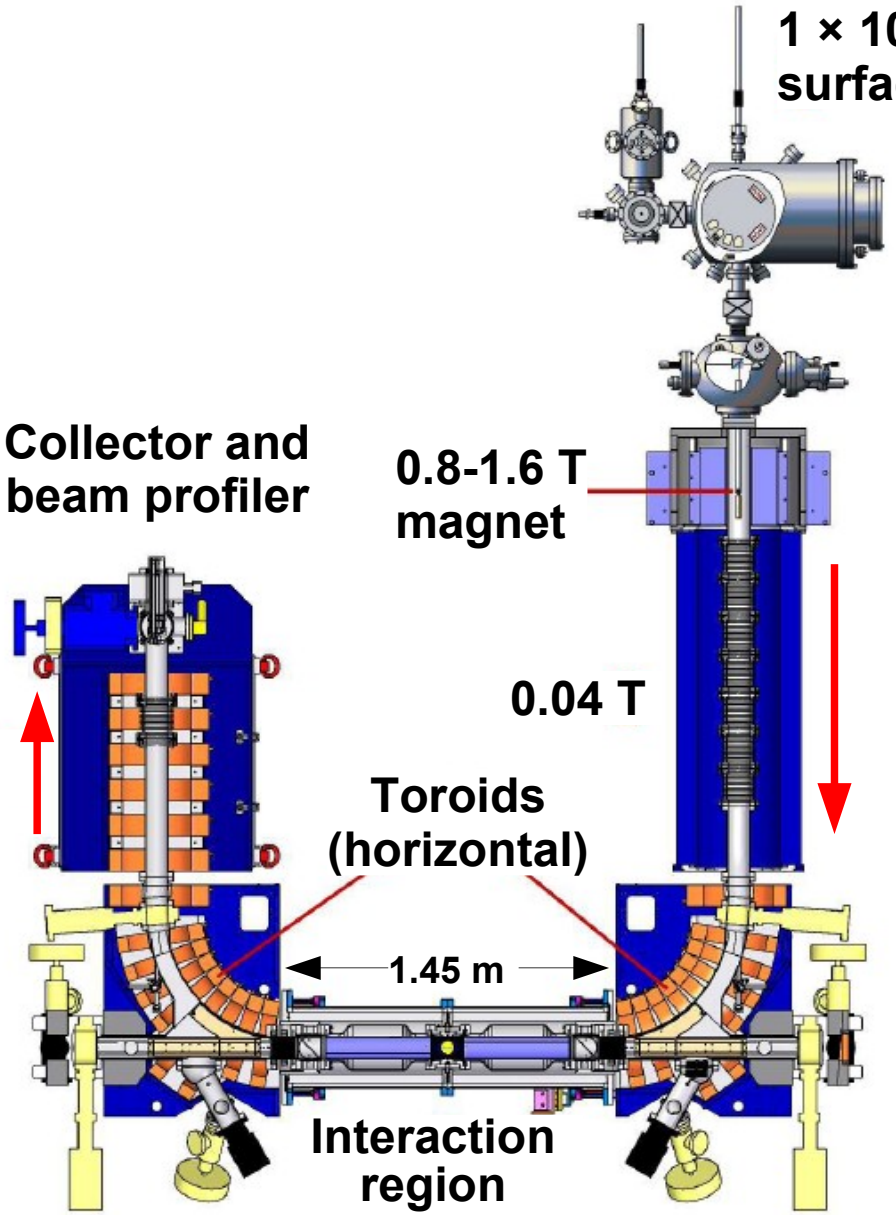
A. Noda et al., COOL '11, MOIO06

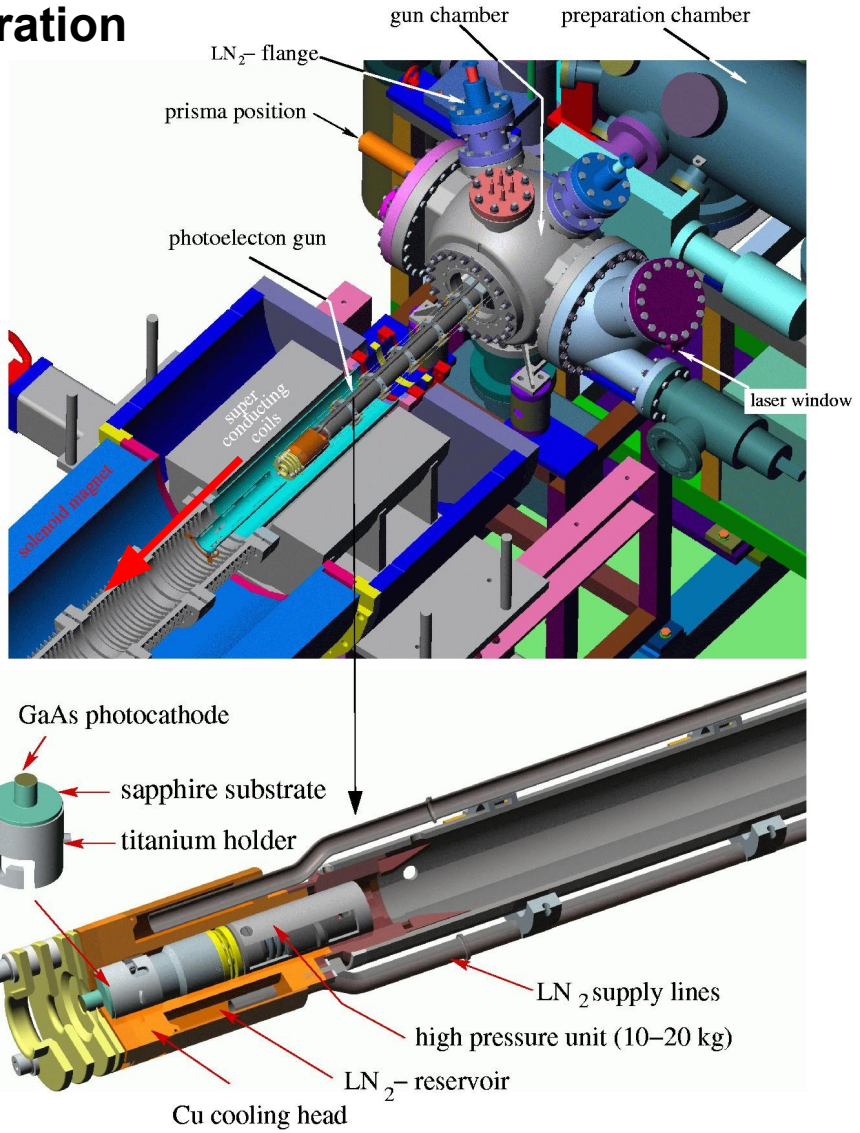
Electron Energy:	**3.8 keV**
Electron Density:	**2.2×10^6 /cm³**
Effective Cooler Length:	**0.44 m**
Expansion Factor:	**3**
Temperature at transition to ordered state:	**2 K long., 11 K transv.**

Photocathode electron target at TSR



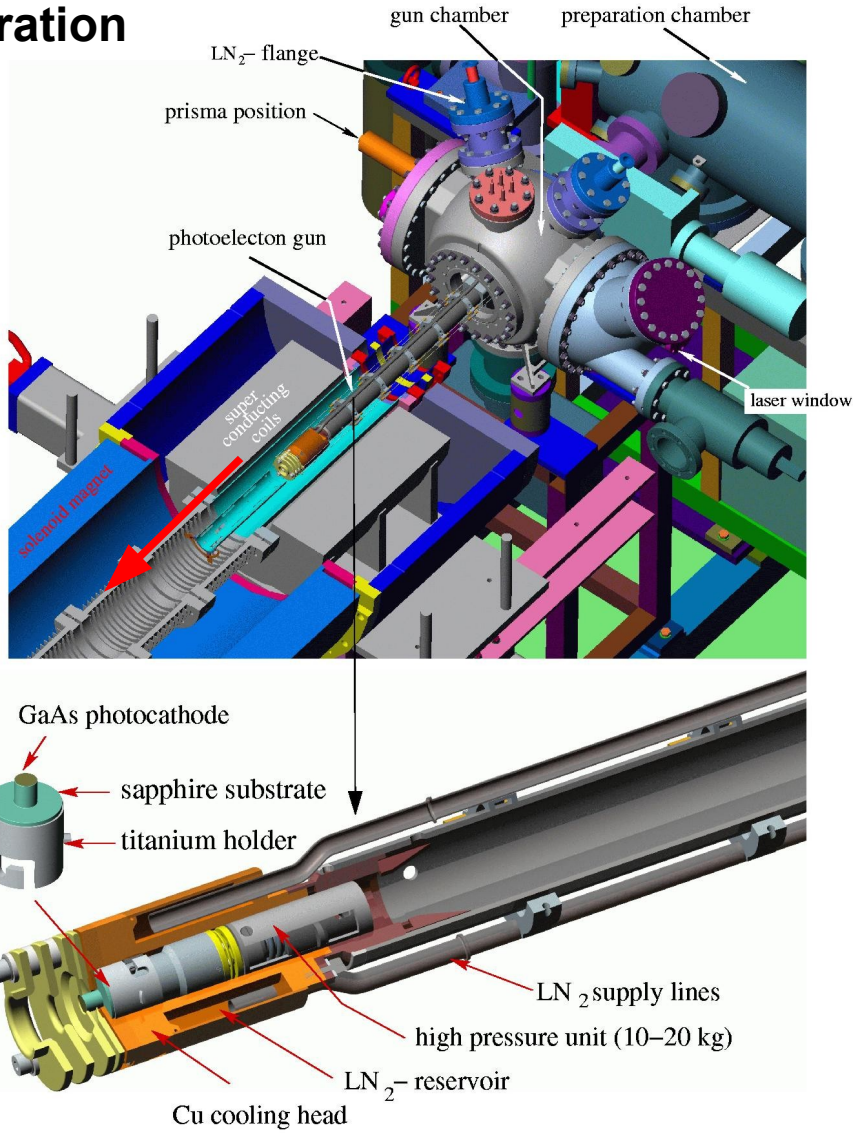
TSR electron target setup





TSR electron target setup

1×10^{-12} mbar
surface preparation



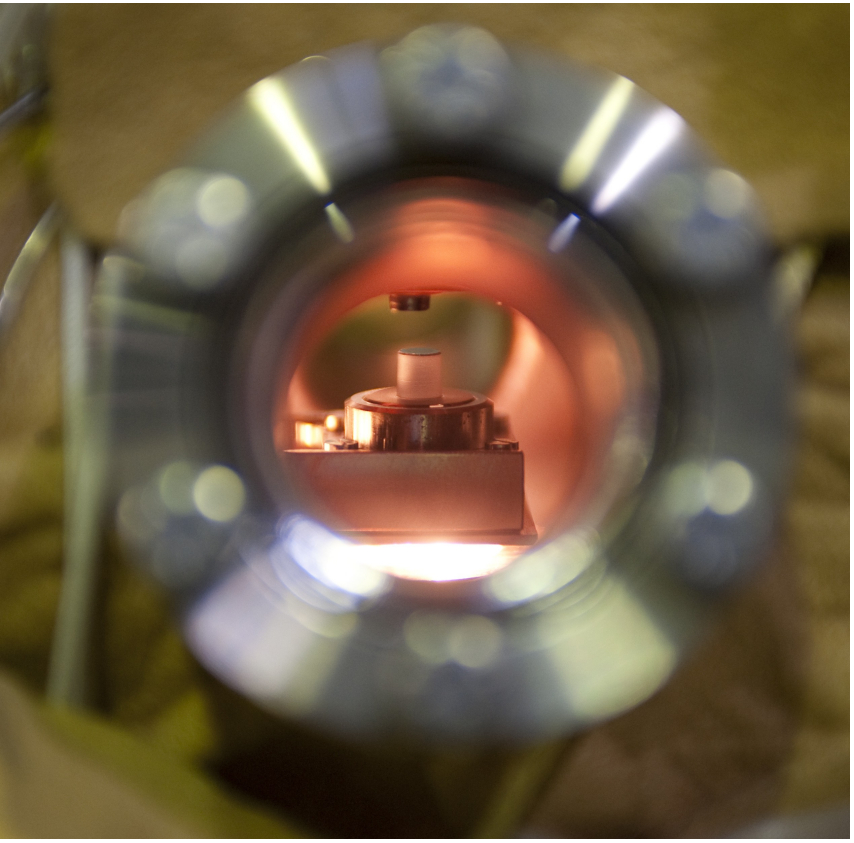
Laser illumination up to 1 W

Temperature rise 15-20 K/W at 90 K

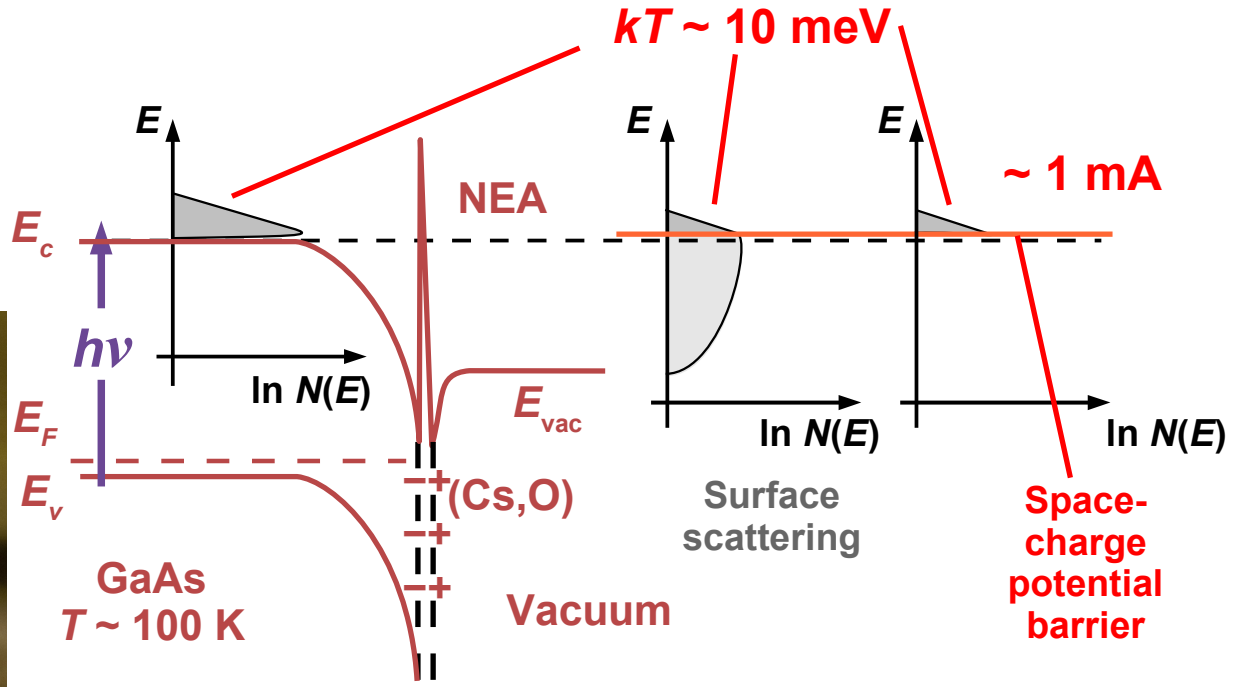
U. Weigel et al., NIM A 536 (2005) 323

Photocathode beam formation

GaAs photocathode
~100 K



D. A. Orlov et al., J. Appl. Phys. 106, 054907 (2009)



- Magnetic expansion (~0.4 T → 0.02 T) yields 0.5...1 meV electron temperature (~5...10 K)

- Cathode lifetime typ. 24 h

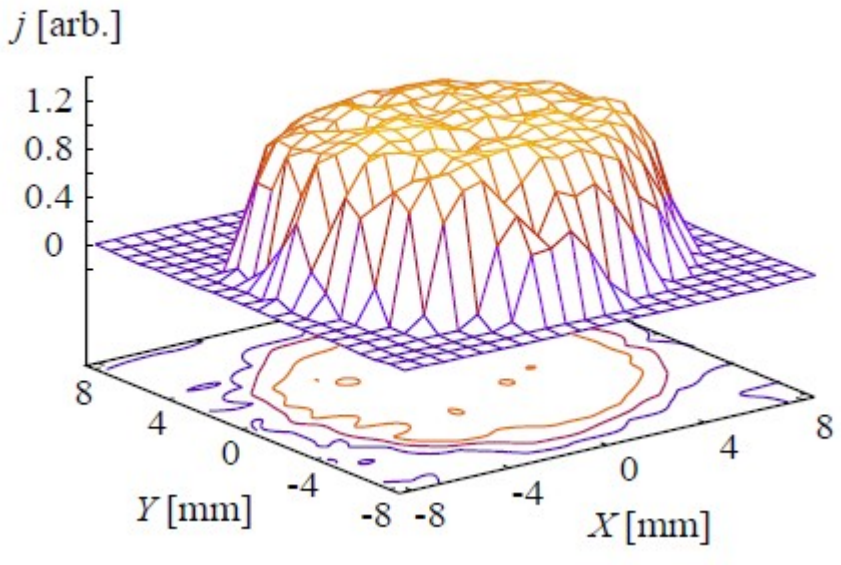
- ~4 cathodes under vacuum in closed-cycle operation since >2 years

- Beam transport down to < 1 eV with 10 µA current (0.01 T guiding field)

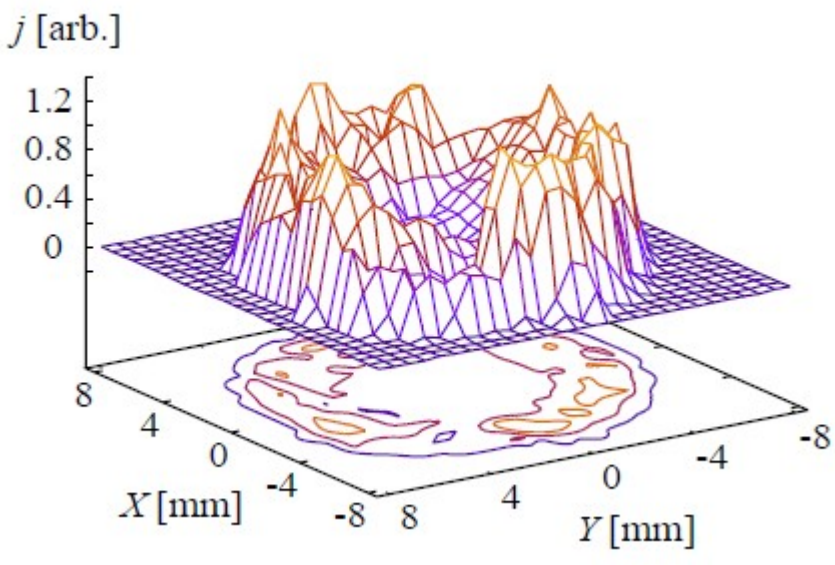
D. A. Orlov, C. Krantz, A. Shornikov
Collab. with Inst. f. Semiconductor Phys., Novosibirsk, A. N. Terekhov

Electron beam profile monitoring

225 V, 1 mA electron beam



After 7 hours of running (normal conditions)



Cathode damage by re-accelerated residual gas ions (after 5 hours)

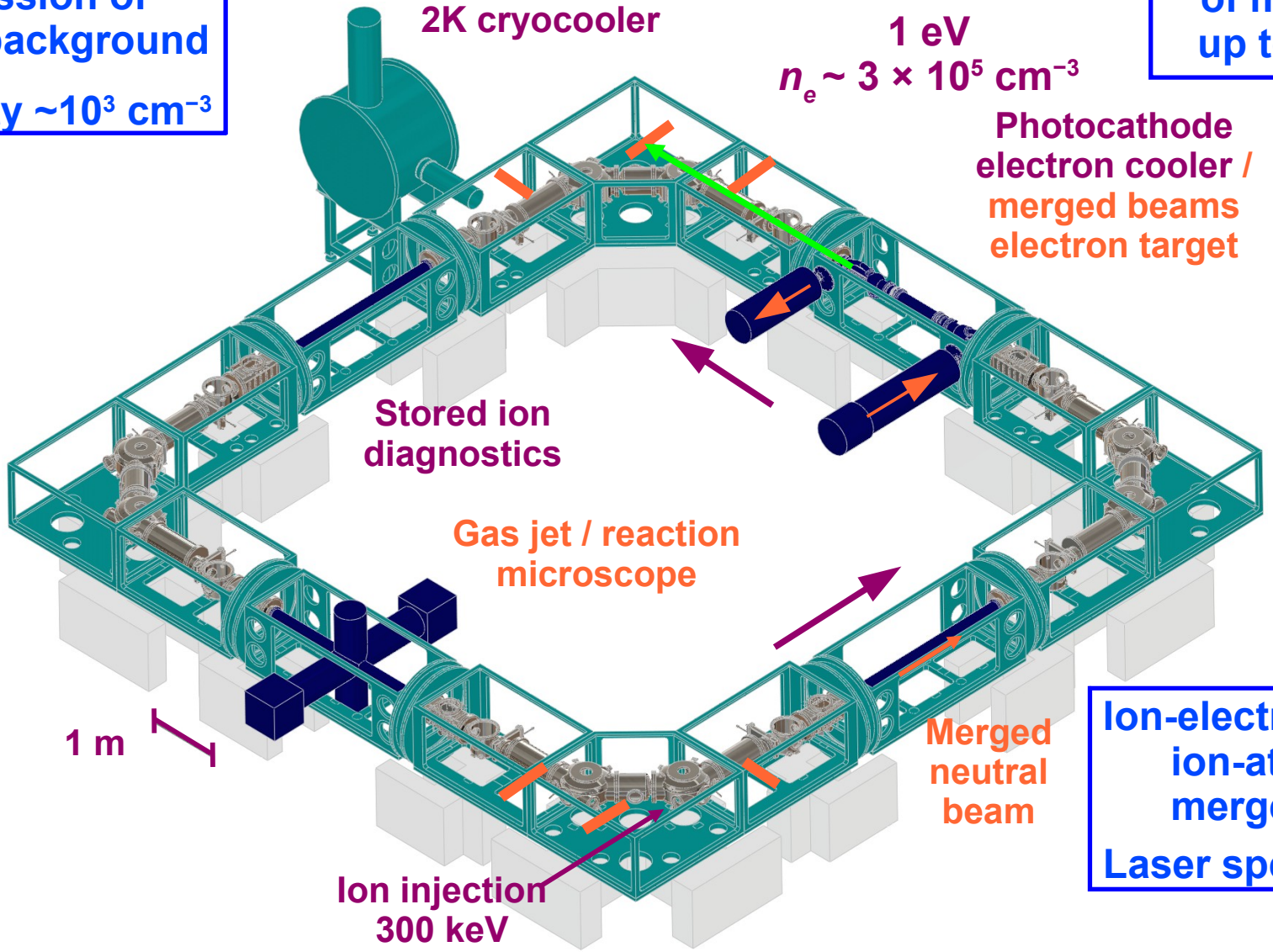
Claude Krantz, PhD thesis (2009)

Cryogenic electrostatic storage ring CSR

Stored ion beams with keV energies of large compounds, clusters (cations, anions), heavy atomic beams, highly charged ions

2 K cryopumping and suppression of radiation background

Gas density ~10^3 cm^{-3}



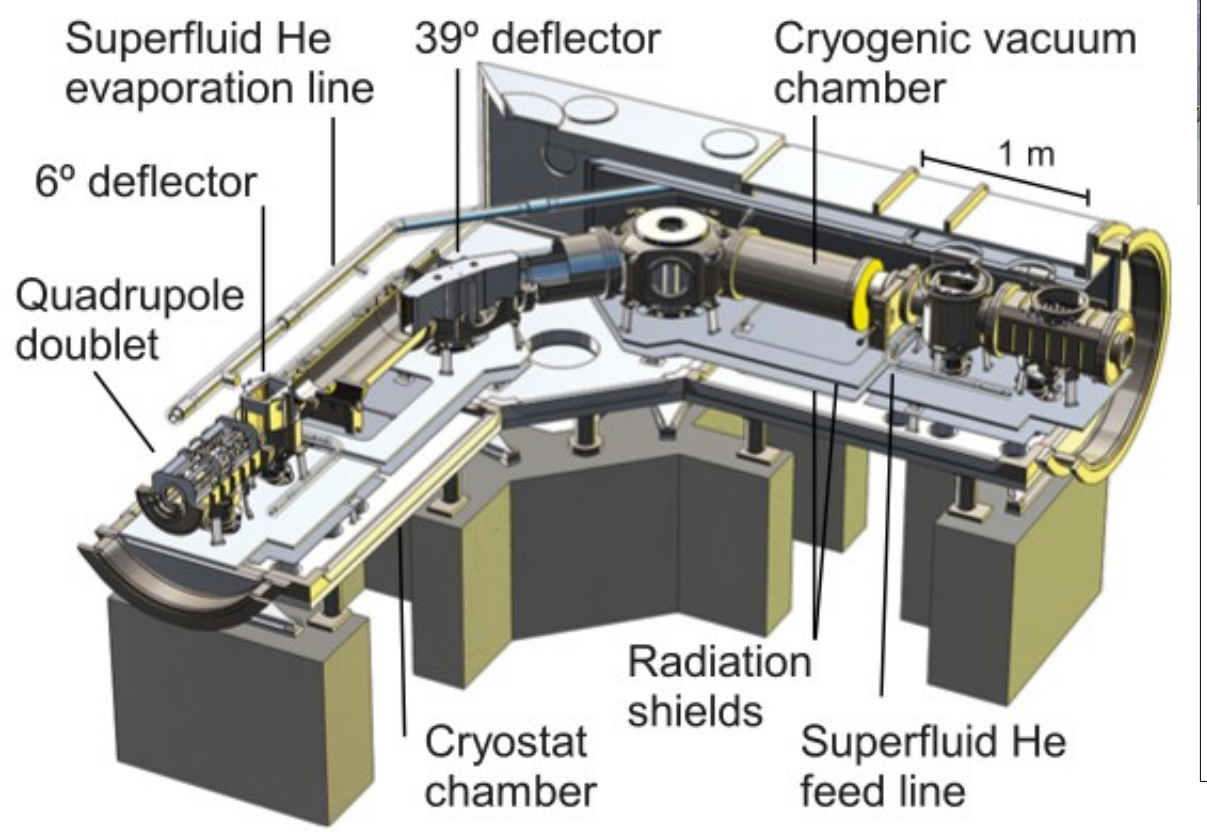
Electron cooling of molecules up to A ~ 160

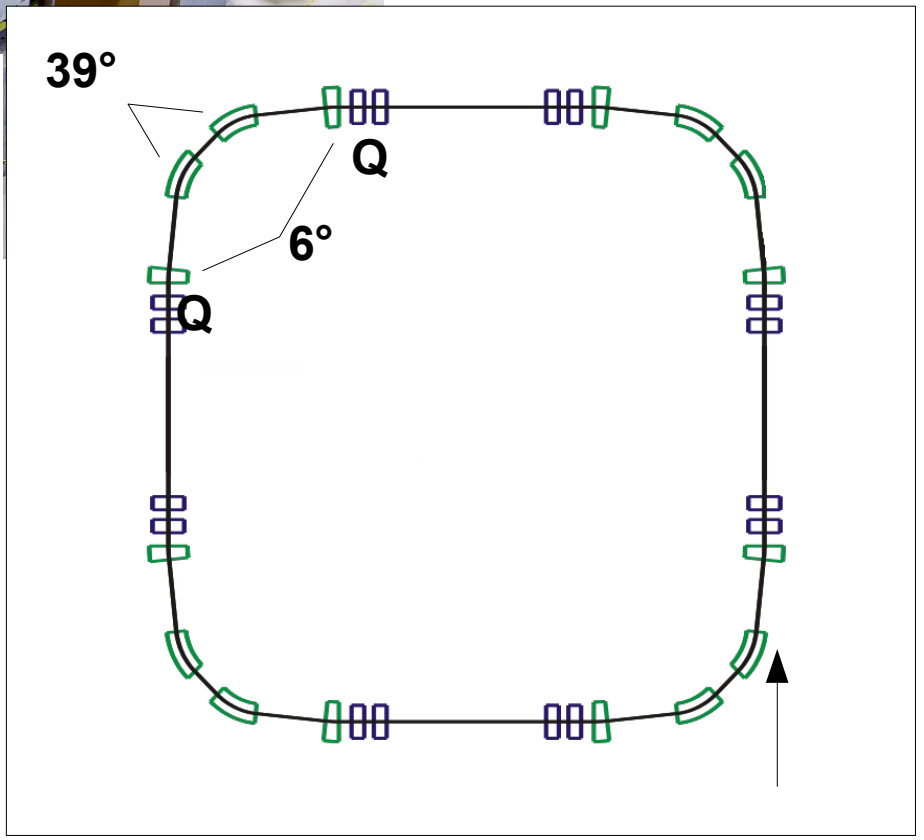
D. A. Orlov, C. Krantz, A. Shornikov et al.

Ion-electron and ion-atom merged beams

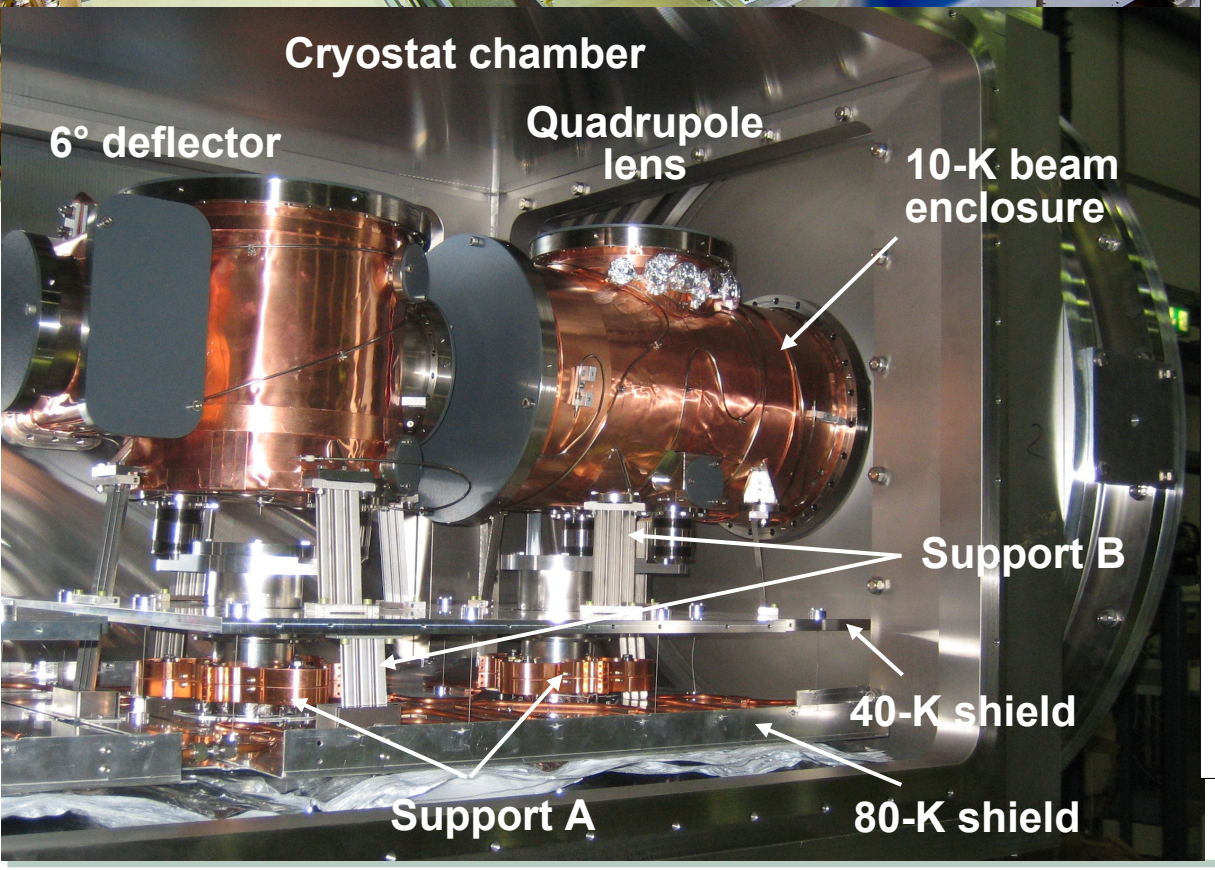
Laser spectroscopy

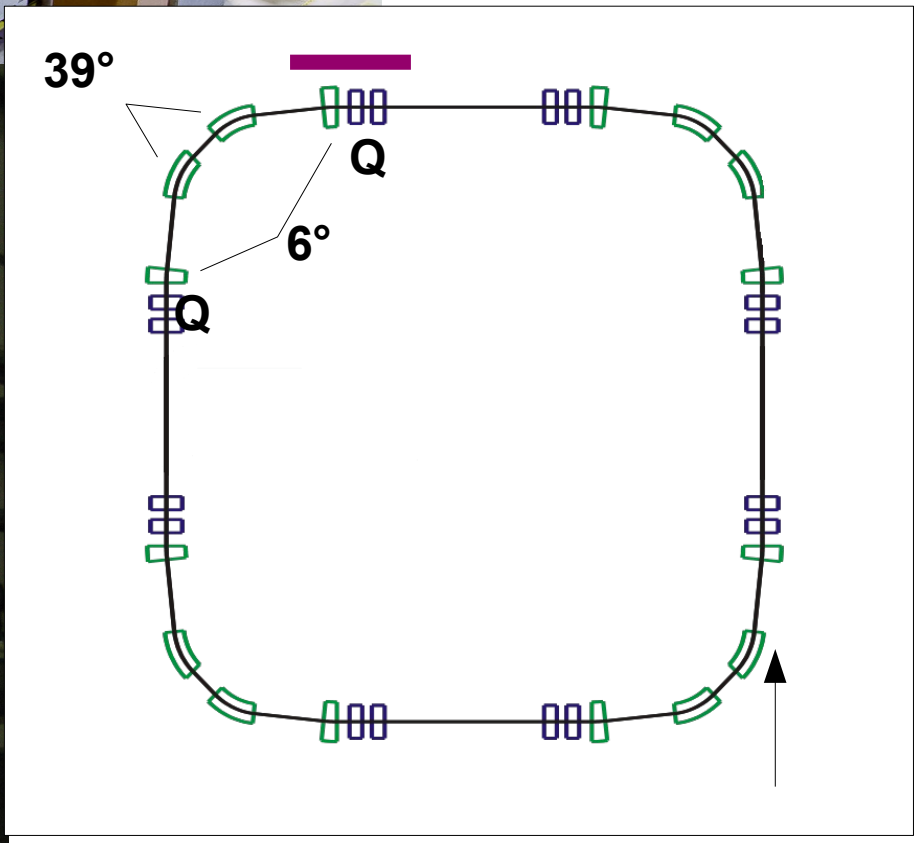
Cryogenic storage ring CSR



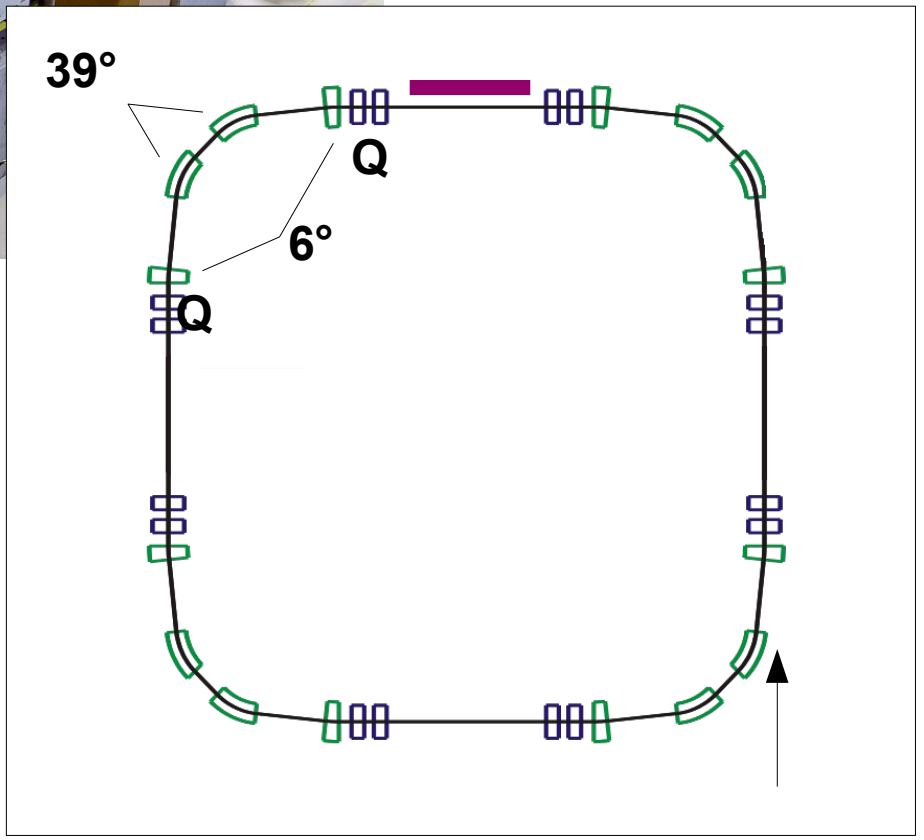


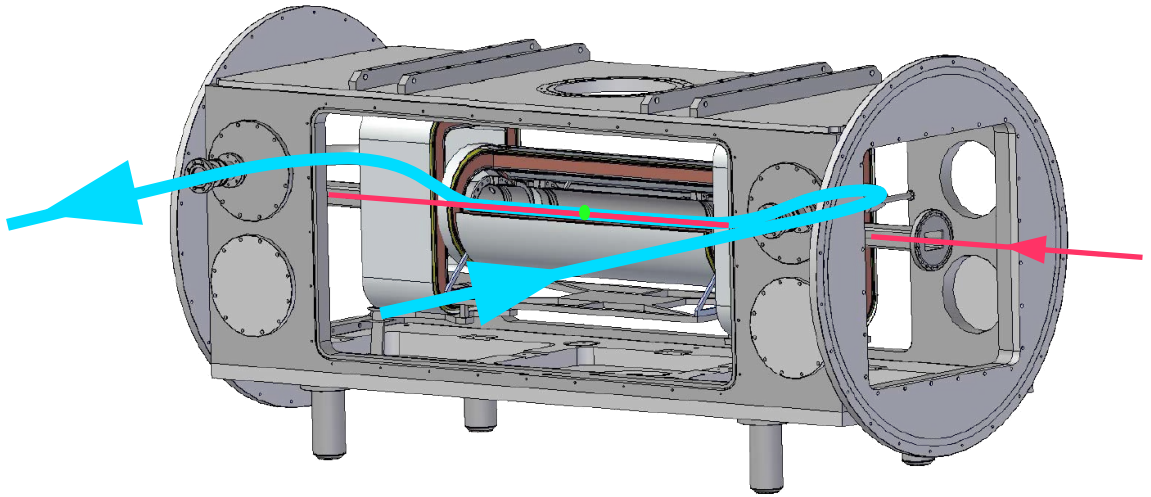
Cryogenic storage ring CSR





Cryogenic storage ring CSR





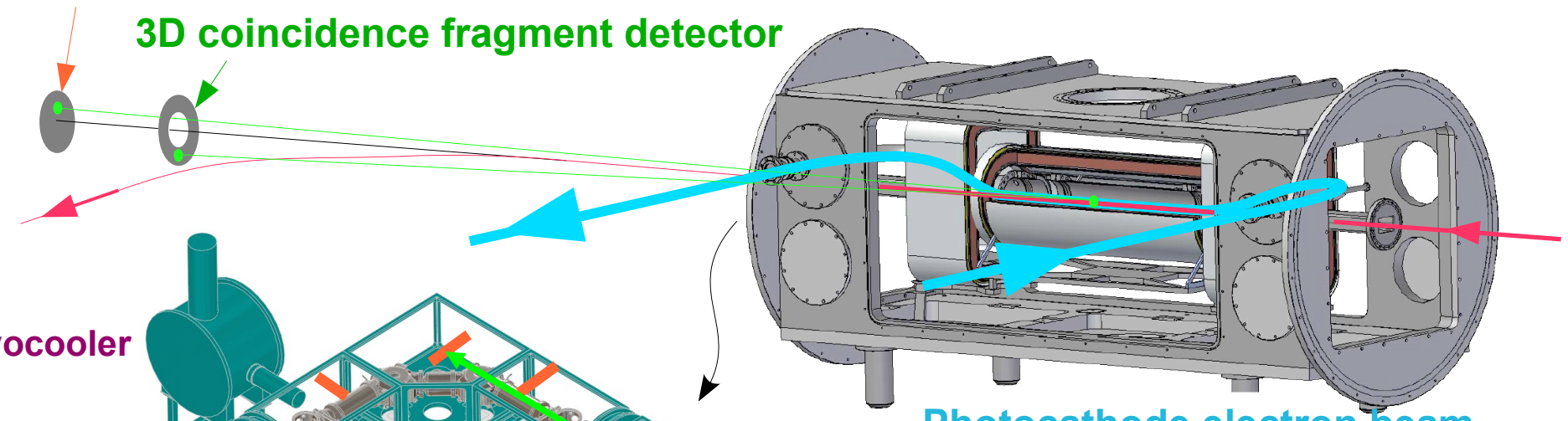
Photocathode electron beam

C. Krantz, S. Vogel, A. Shornikov

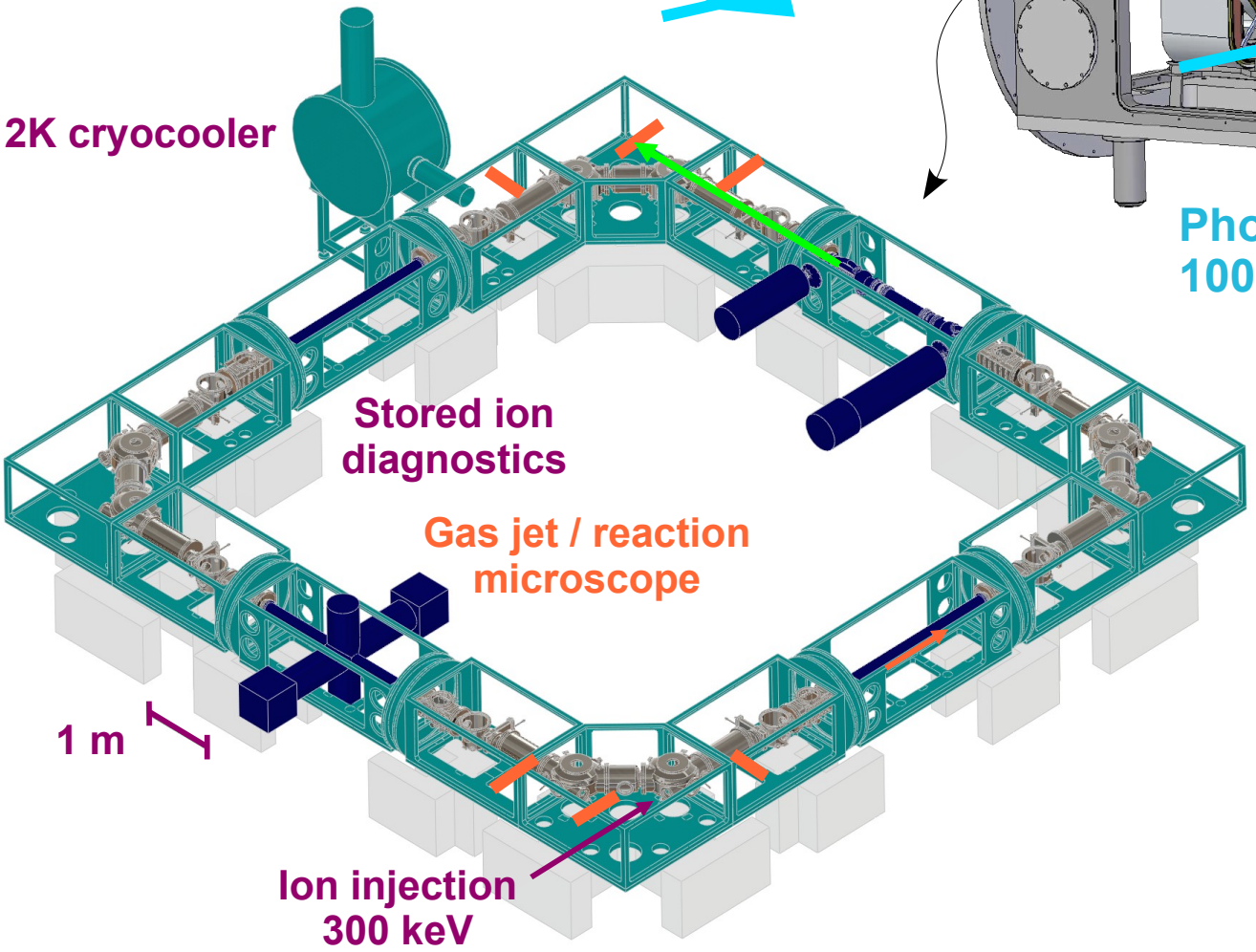
CSR electron cooler and target

In development: segmented microcalorimeter detector

3D coincidence fragment detector

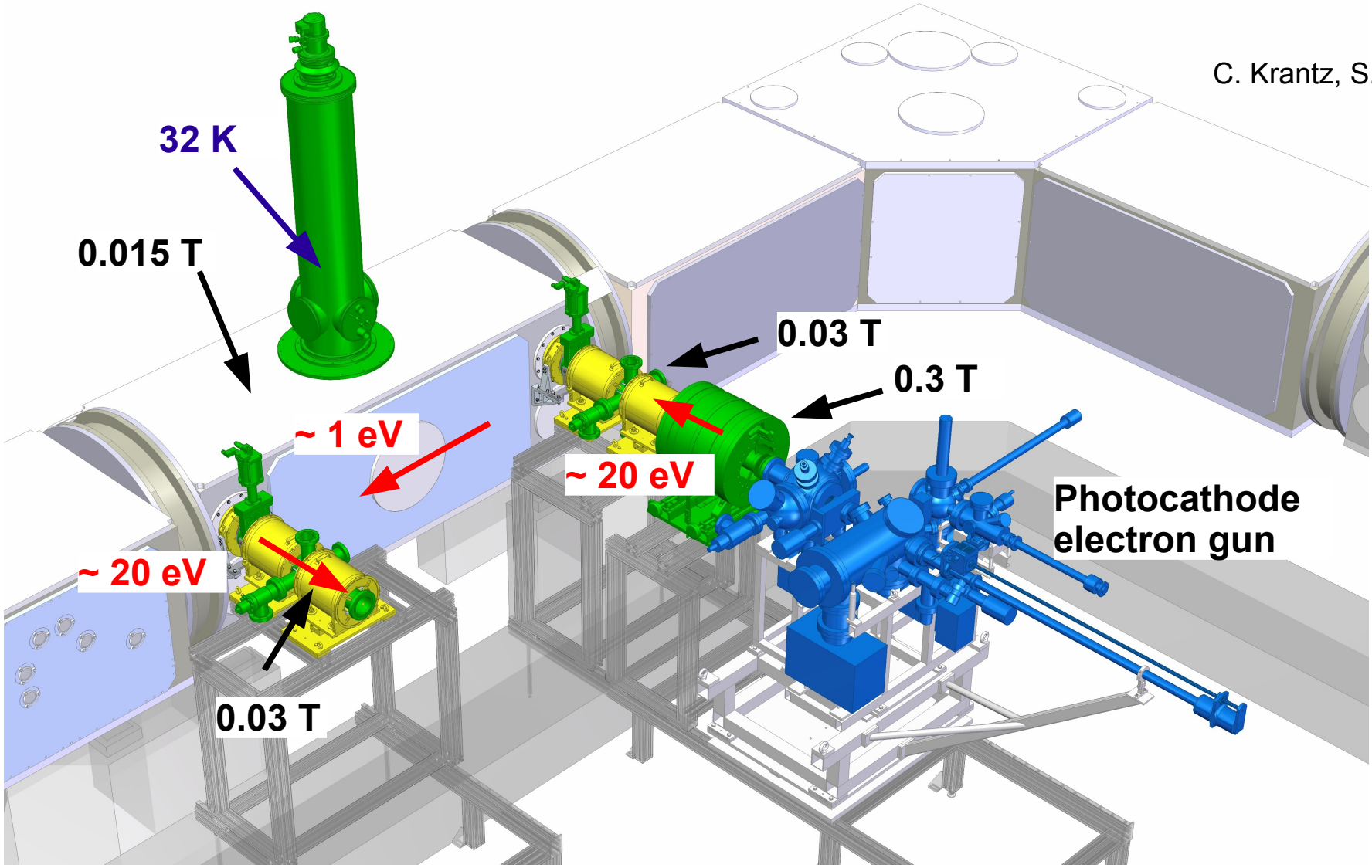


Photocathode electron beam
100 eV → ~1 eV



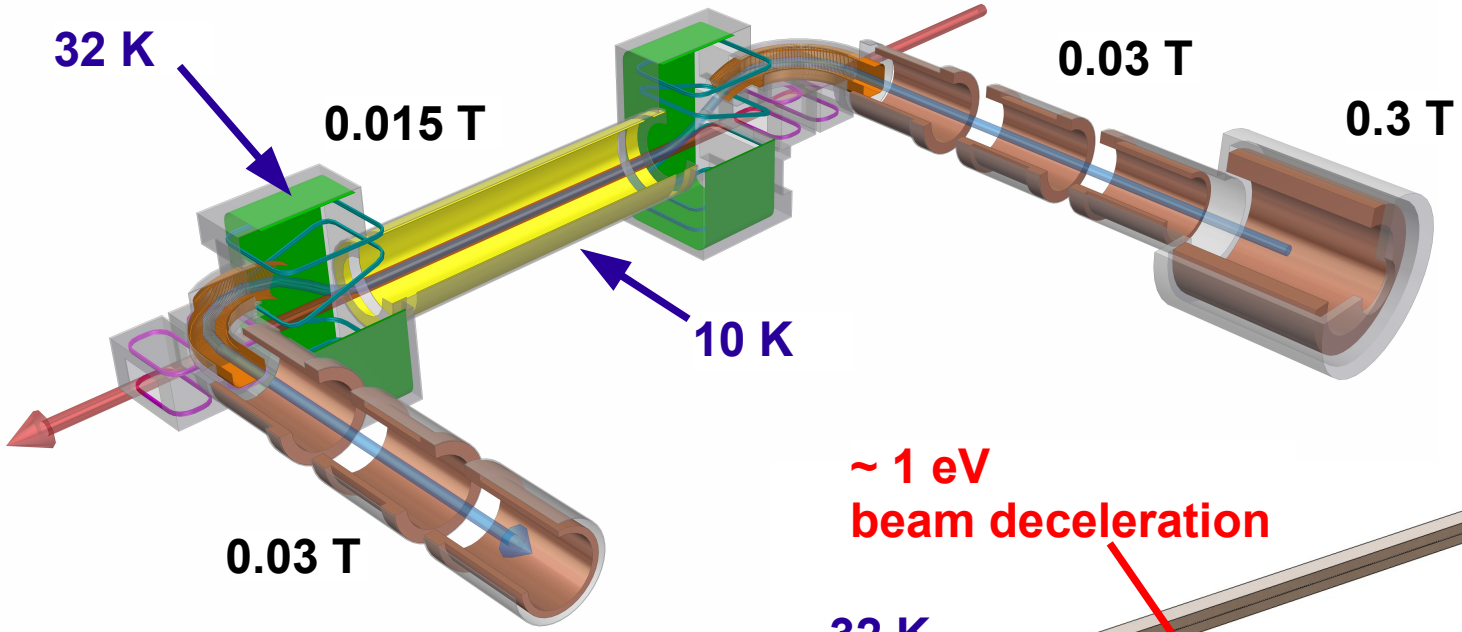
C. Krantz, S. Vogel, A. Shornikov

CSR electron cooler and target: setup

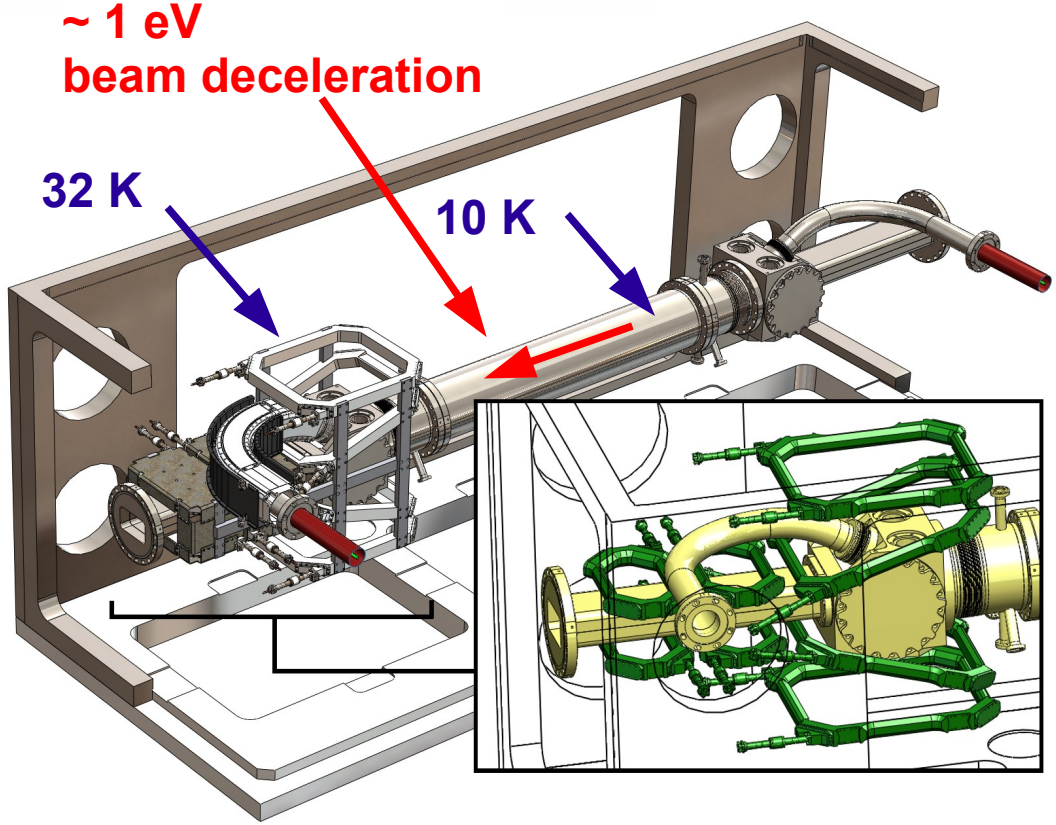


C. Krantz, S. Vogel

CSR electron cooler and target: setup



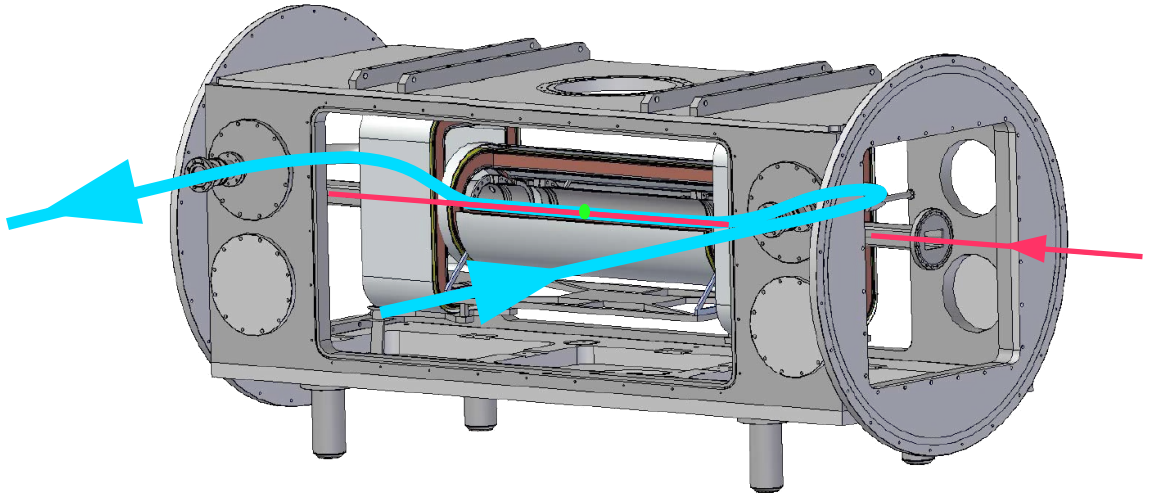
C. Krantz, S. Vogel



HTS
cryogenic
coils

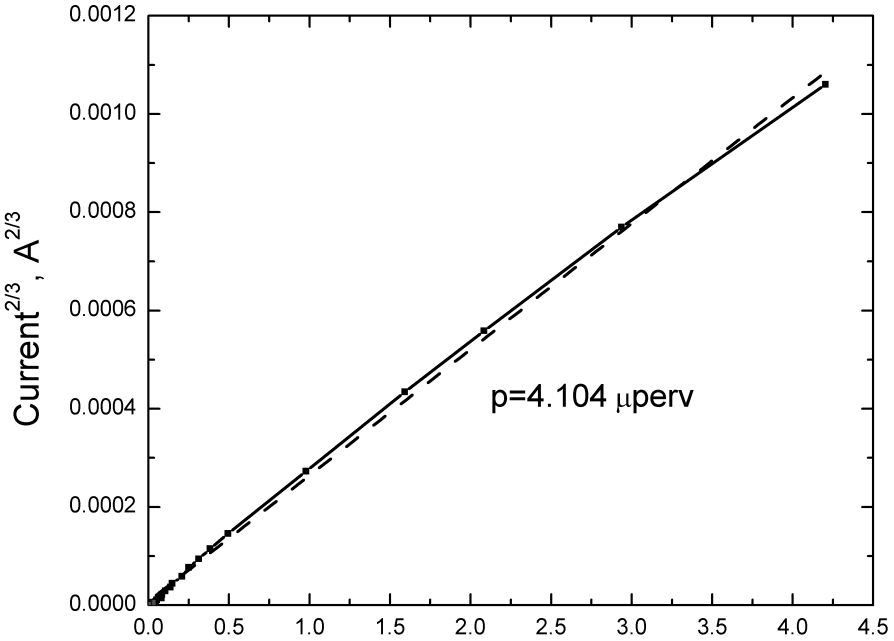
Low-energy photocathode electron beam

A. Shornikov, C. Krantz

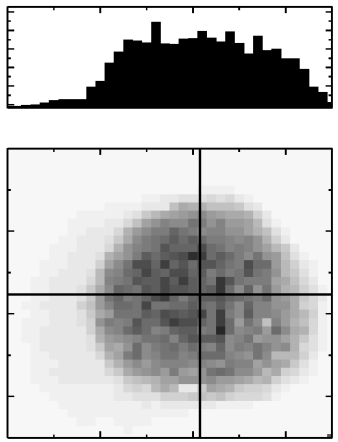


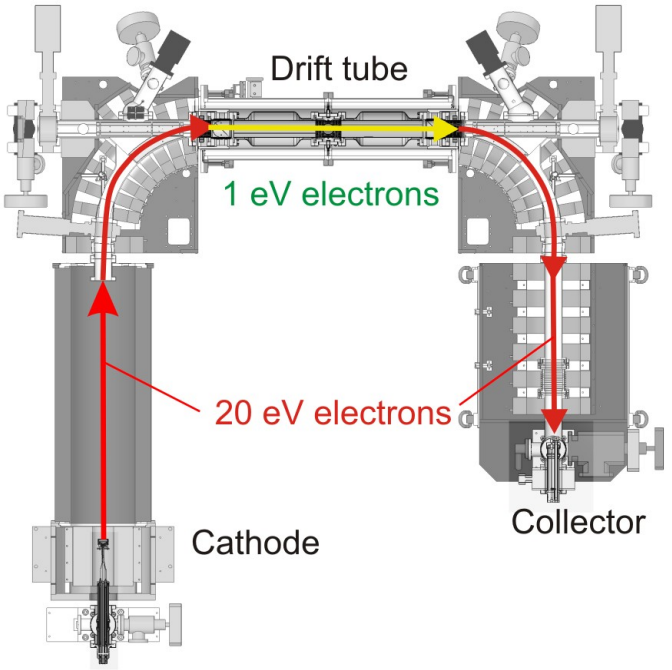
Tests at TSR electron target

Deceleration of low-current photocathode beams



$$I = pU_0^{3/2}$$





Beam profiles

Summary

Low-energy ion beam storage:
atomic, molecular, particle physics

Parameters of low-energy storage and cooling
- **Advantages of electrostatic storage for high masses**
- **Photocathode: advantages in temperature and density at < 100 eV electron energy**

Low-energy electron cooling systems

S-LSR (~1 keV), TSR (~40 eV)

Ultra-low energy cooler for cryogenic (XHV) ion beam surrounding

In construction: CSR electron cooler / target (~1 eV)

The collaboration

Max-Planck-Insitut für Kernphysik, Heidelberg

Division on Stored and Cooled Ions (K. Blaum)

Atomic and molecular quantum dynamics

O. Novotný(*), C. Krantz, S. Menk, M. Lange

PhD: S. Vogel, A. Becker, P. Herwig, Bian Yang

Recently completed post-docs: H. Buhr, A. Petrignani

Recently completed PhD: J. Stützel, M. Berg, M. Mendes, D. Bing, F. Laux, A. Shornikov, C. Domesle

Cooled and stored ions instrumentation

M. Grieser, R. von Hahn, R. Repnow

PhD: F. Fellenberger, F. Berg

ASTROLAB

H. Kreckel, F. Grussie

Heidelberg collaborations

Kirchhoff Inst., Univ. Heidelberg

A. Fleischmann
C. Enss

Microcalorimeter ion detector

Max-Planck-Institut für Astronomie

Th. Henning
D. Semenov

External collaborations

Weizmann Institute of Science Rehovot, Israel

D. Zajfman, O. Heber, D. Schwalm

Columbia Univ., NYC

D. Savin,
O. Novotný(*)

Univ. Louvain-La-Neuve, Belgium

X. Urbain

Univ. of Illinois, Urbana

B. McCall

Univ. Stockholm

W. D. Geppert

Univ. Giessen, Germany

S. Schippers, A. Müller
K. Spruck

DFG

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK